New physics in final states with jets or vector bosons

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Introduction

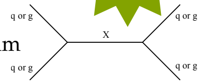
- The discovery of a Higgs–like particle by the ATLAS and CMS collaborations in July 2012: a triumph for the SM
- However, SM is not the end of the story: low energy effective theory?
- Indeed, there are phenomena for which SM offers no explanation:
  - Baryon asymmetry
  - Neutrino mass
  - Dark Matter candidate (DM)
  - Naturalness ("non fine-tuning")
  - Hierarchy problem, caused by the quadratic divergences in the quantum-loop corrections to the Higgs boson mass
- Many searches are performed to highlight theories beyond the SM which try to adress some of these problems
- This talk: overview of CMS searches for new physics in final states with jets or bosons

Outline

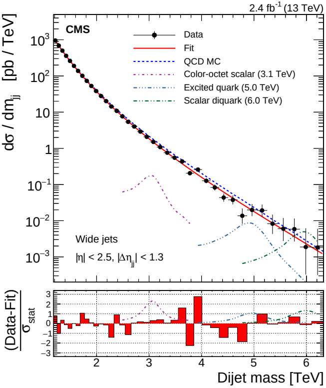
Outline

Search for narrow resonances in dijet mass distribution

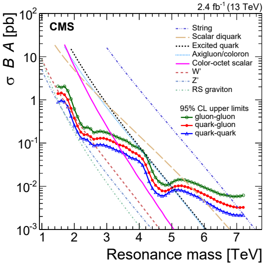
13 TeV

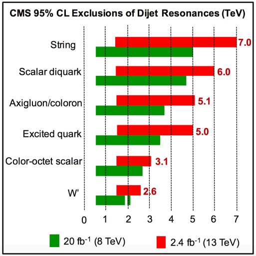


- Model-independent search for massive resonances in dijet mass spectrum
- More sensitive than previous studies for dijet masses above 2 TeV
- SM dijet spectrum well predicted by QCD: steeply and smoothly falling functional form fitted on data



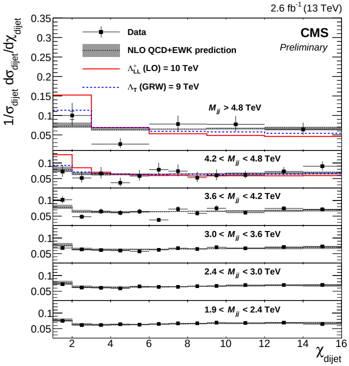
- Data well described by QCD prediction: no evidence of dijet resonance
- Set 95% CL upper limits using a Bayesian formalism





Search for NP signatures in dijet angular distribution

- Probe parton-parton scattering angle in dijet events: $\chi_{\text{dijet}} = \exp(|y_1 - y_2|), y \equiv \frac{1}{2} \ln\left(\frac{E+p_z}{E-p_z}\right)$
- Search for signatures of new physics:
  - Quark compositeness models: new interactions between quarks constituents at scale $\Lambda \gg m_q$, approximated by contact interaction (CI) at energies below Λ
  - Virtual graviton exchange for the Arkani-Hamed-Dimopoulus-Dvali (ADD) model of extra spatial dimensions
- ≥ 2 jets, $\chi_{\text{dijet}} < 16$, $|y_{\text{boost}}| < 1.11$ ($y_{\text{boost}} = \frac{1}{2}(y_1 + y_2)$), M_{jj} bins
- χ_{dijet} flat for leading QCD processes in particular in qq, qg and gg channels



- Set limits on scale Λ of CI and ADD models using modified frequentist approach (CL_S)
- Likelihood defined as product of Poissonian likelihood functions for each bin in χ_{dijet} for the 2 highest M_{jj} ranges

13 TeV

Model	Observed (expected) lower limit (TeV) 13 TeV	8 TeV
$\Lambda^{+}_{LL/RR}$ (LO)	12.1 (12.0 ± 1.1)	10.3 (9.8 ± 1.0)
$\Lambda^{-}_{LL/RR}$ (LO)	16.3 (15.3 ± 2.4)	12.9 (12.4 ± 2.2)
ADD Λ_T (GRW)	9.1 (9.0 ± 0.7)	7.1 (6.8 ± 0.5)
ADD M_S (HLZ) $n_{ED} = 2$	9.7 (9.6 ± 0.7)	6.9 (6.6 ± 0.4)
ADD M_S (HLZ) $n_{ED} = 3$	10.8 (10.7 ± 0.8)	8.4 (8.0 ± 0.6)
ADD M_S (HLZ) $n_{ED} = 4$	9.2 (9.0 ± 0.7)	7.1 (6.8 ± 0.5)
ADD M_S (HLZ) $n_{ED} = 5$	8.3 (8.1 ± 0.6)	6.4 (6.1 ± 0.5)
ADD M_S (HLZ) $n_{ED} = 6$	7.7 (7.6 ± 0.6)	5.9 (5.7 ± 0.4)

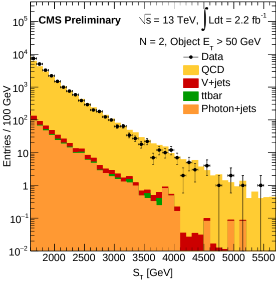
- No significant deviation from prediction observed

Outline

Inclusive black holes (BH) search for all possible final states at 13 TeV

- n-flat extra-dimensions introduced by ADD model: true Planck scale M_D $\mathcal{O}$(TeV)
- 2 BH models with M_{BH}>M_D considered (threshold BH production: $M_{BH}^{min} \geq M_D$):
  - Semi-classical BH (SCBH): $M_{BH} \gg M_D$, high multiplicity decay products ($\sim$ 75 % quarks/gluon)
  - Quantum BH (QBH): $M_{BH} \rightarrow M_D$, low multiplicity FS (typical decay: dijet)

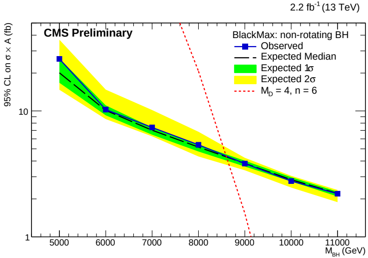
13 TeV



- Strategy: counting experiment on the S_T variable in various inclusive object multiplicity bins ($N \geq N_{min}$, N=jets, electrons, muons, photons with E_T>50 GeV)

$$S_T = \left(\sum_{i=1}^{N} E_{T,i} \right) + (E_T^{miss} > 50\,\mathrm{GeV})$$

- Signal manifests as broad excess in tails of S_T spectrum
- Use CL_S method to extract limits on M_{BH}^{min}



- SC non-rotating BH with M_{BH}^{min} = 8.7 TeV excluded
- QBH with M_{BH}^{min} =8.0 TeV excluded
- Extend significantly Run 1 searches sensitivity (limits in 4.3–6.2 TeV)

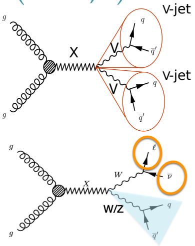
Outline

1. Introduction
2. Dijet search
    - Using dijet mass distribution
    - Using dijet angular distribution
3. Black holes
    - Black holes search
4. Massive resonances search
    - Massive resonances decaying into pairs of boosted W and Z
    - $X \rightarrow HH \rightarrow b\bar{b}\tau^+\tau^-$
    - Search for W′ boson
    - Search for $t\bar{t}$ resonances
5. Search for vector-like quarks
    - Search for $T\bar{T}$ and $B\bar{B}$ (legacy results from Run 1)
    - Search for $Q\bar{Q}$
    - Search for $X_{5/3}\bar{X}_{5/3}$
6. Conclusion
7. Links

Massive spin-1 and spin-2 resonances decaying to VV (V=W,Z)

13 TeV

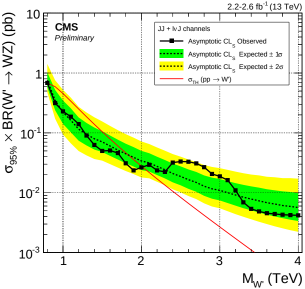
- Select events with boosted back-to-back V (= W, Z)
- All-hadronic VV channel
- Semileptonic VW channel
- Select V-jets: boosted V_{hadr} reconstructed as a single jet
  - Jet mass: V-jet originating from W/Z $\rightarrow$ 65 < M(pruned jet) < 105 GeV
  - Jet substructure: hadronic V decays result to 2 overlapping jets
- Select semileptonic events: exactly 1 iso e(μ), E_T^{miss} > 80(40) GeV



- After reconstructing V candidates, reconstruct diboson candidate: comparison between m_{VV} distribution observed in data and SM predictions shows no evidence of signal
- Set 95 % CL upper limits using the modified frequentist prescription (asymptotic CL_S method) combining $l\nu$+jet and dijet channel

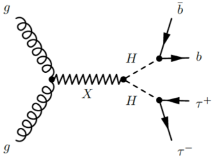
- Models:
  - Spin-2 RS bulk graviton (G_{bulk})
  - Spin-1 composite heavy vector triplet (HVT) model (W′)

Model	Upper limits
$\sigma_{95\%} \times \mathcal{B}(W' \rightarrow WZ)$	[755, 5.7] fb
$\sigma_{95\%} \times \mathcal{B}(G_{bulk} \rightarrow WW)$	[472, 4.0] fb
$\sigma_{95\%} \times \mathcal{B}(G_{bulk} \rightarrow ZZ)$	[227, 6.8] fb

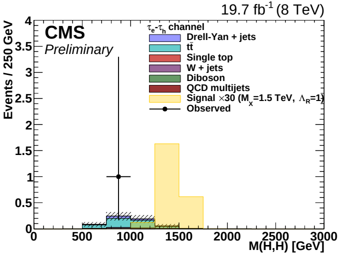


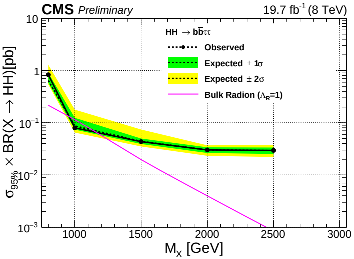
$X \to HH \to b\bar{b}\tau^+\tau^-$

New 8TeV



- Search for high mass ($\gtrsim$ 1 TeV) resonances decaying to $HH \to b\bar{b}\tau^+\tau^- \to b\bar{b}(l\nu\bar{\nu})((n\pi)(mK)\nu)$
- Dedicated reconstruction techniques for boosted $b\bar{b}$ and $\tau^+\tau^-$ pairs
- Reconstructing hadronic H ($b\bar{b}$ decay products merged in a single jet):
  - Jet mass: originating from H $\to$ 100 < M(pruned jet) < 140 GeV
  - Jet substructure: hadronic H decays result to 2 overlapping (**b**) jets
- Reconstructing $\tau\tau$ system: usual τ_{hadr} reco ; likelihood fit algo using $\vec{p}_T^{miss}$
- Looking at M_{HH} distributions: no significant deviation from SM expectations
- 95% CL upper limits using CL_S criterion, using profile likelihood ratio for test statistic, performing shape analysis by counting events
- KK excitations of spin-0 particle (radion) with UV mass scale parameter $\Lambda_R = 1$ TeV decaying to HH: masses between 950 and 1150 GeV excluded at 95 % CL

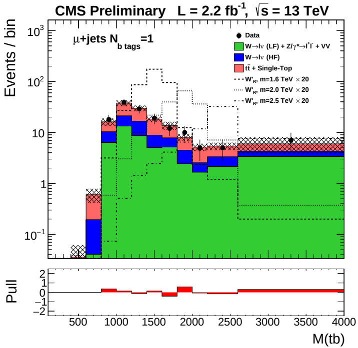


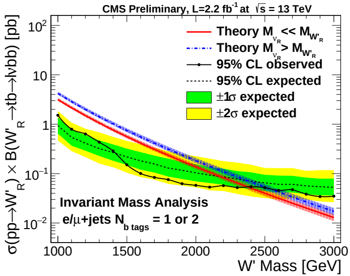


Search for $W' \to t\bar{b}$

$$\mathcal{L} = \frac{V_{q_iq_j}}{2\sqrt{2}} g_W \bar{q}_i \gamma_\mu (a^R_{q_iq_j}(1-\gamma^5) + a^L_{q_iq_j}(1+\gamma^5)) W' q_j + h.c.$$

- Couplings hypothesis:
  - Purely right-handed W'_R: $a^L_{q_iq_j} = 0$, $a^R_{q_iq_j} = 1$
- Leptonic t decay: W′ more boosted than at 8 TeV so no isolation requirement on lepton
  - 1 non-isolated e (μ), $\geq$2 jets, $\geq$1 b-tag jet, $E_T^{miss} > 120$ (50) GeV
- Using $M(tb)$ distributions to set limits on $\sigma_{W'_R}$ using Bayesian approach
- Observed (expected) limit of 2.38 (2.17) TeV ($M_{\nu_R} \ll M_{W'_R}$) already exceed their 8 TeV counterparts despite smaller integrated luminosity





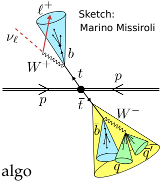
13 TeV

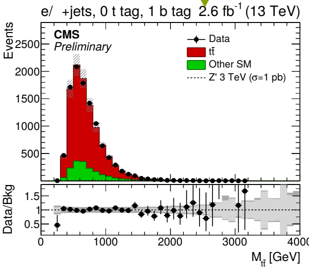
- Legacy 8 TeV results: see backup
  - Combining hadronic and leptonic W decay modes
  - W'_R with mass below 2.15 GeV excluded at 95% CL

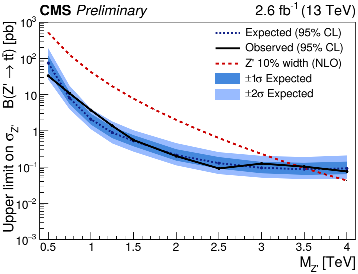
Search for $t\bar{t}$ resonances in boosted semileptonic final state

13 TeV

- Many BSM models predict heavy resonances with enhanced coupling to the top
  - Leptophobic topcolor Z′ bosons
  - KK excitations of a gluon in RS model
- Model-independent search for heavy res. decaying to $t\bar{t} \rightarrow (W^+b)(W^-\bar{b}) \rightarrow (q_1\bar{q}_2b)(l^-\bar{\nu}_l\bar{b})$
- Boosted topologies:
  - Hadronic t reconstructed as a single jet: top-tagging algo
  - No isolation requirement for lepton
- Reconstruct $M_{t\bar{t}}$ using a χ^2: no signal observed







- Set 95% CL upper limits on $\sigma_{sig} \times \mathcal{B}(sig \rightarrow t\bar{t})$ using Bayesian method
- Non-observation of $t\bar{t}$ resonances at 8 TeV confirmed here

	Expected (observed) 95% CL M(signal) exclusion limit (TeV)	
Signal	13 TeV (l+jets)	8 TeV (comb.)
Z′, $\Gamma_{Z'}/M_{Z'}$ = 1%	2.1 (2.3)	2.4 (2.4)
Z′, $\Gamma_{Z'}/M_{Z'}$ = 10%	3.5 (3.4)	2.8 (2.9)
Z′, $\Gamma_{Z'}/M_{Z'}$ = 30% ($M_{Z'}$ >1 TeV)	4.0 (4.0)	-
RS KK gluon	2.9 (2.9)	2.7 (2.8)

Outline

Search for vector-like charge 2/3 T and -1/3 B quarks: legacy results from Run 1

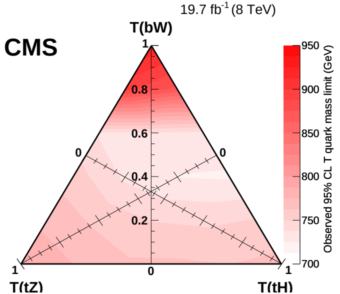
- VL charge 2/3 T quarks produced strongly in pairs, decaying to tH, tZ, bW (see backup)
  - Depending on the BR, expected (observed) 95% CL limits in [790, 890] GeV ([720, 920] GeV)

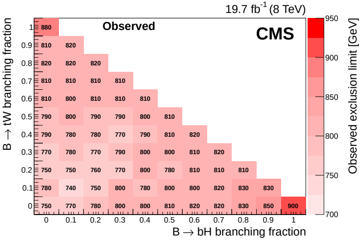
- VL charge -1/3 B quarks produced strongly in pairs, decaying to tW, bZ or bH (see backup)
  - Depending on the BR, expected (observed) 95% CL limits in [710, 890] GeV ([740, 900] GeV)

95% CL M(T) exclusion limit (GeV)		
Exclusive decay mode	Expected	Observed
$T \rightarrow tH$	840	770
$T \rightarrow tZ$	830	790
$T \rightarrow bW$	890	920

95% CL M(B) exclusion limit (GeV)		
Exclusive decay mode	Expected	Observed
$B \rightarrow tW$	890	880
$B \rightarrow bH$	810	900
$B \rightarrow bZ$	740	750

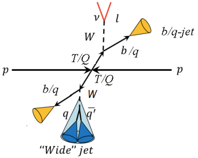
"Triangle plot" with expected and observed upper limits for different BR scenarios

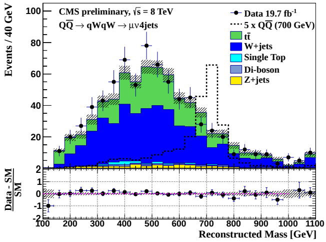




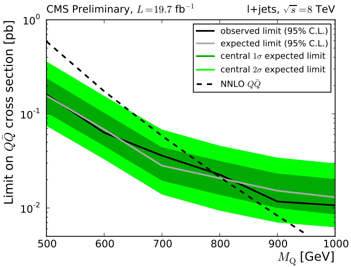
Search for $Q\bar{Q}$ with $Q \to qW$ in lepton+jets final states

- Search for strong production of $T\bar{T}$ or $Q\bar{Q}$ pair
- $T\bar{T} \to bW^+\bar{b}W^- \to bl\nu\bar{b}q\bar{q}'$: used in $T\bar{T}$ searches combination
- $Q\bar{Q} \to qW^+\bar{q}W^- \to ql\nu\bar{q}q\bar{q}'$
- Both resolved and boosted topologies considered
- Selection: exactly one charged lepton, ≥4 jets (either ≥ 4 narrow jets or ≥ 3 narrow jets and ≥ 1 wide jet for cases wide jet overlaps with a narrow jet), E_T^{miss}
- T/Q mass reconstruction using a kinematic fit
- Cut on $S_T = p_T^l + E_T^{miss} + p_T^{J1} + p_T^{J2} + p_T^{J3} + p_T^{J4}$ after KF: strongly suppress $t\bar{t}$ dominant bkg





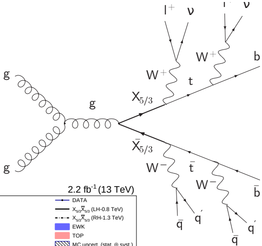
New 8TeV

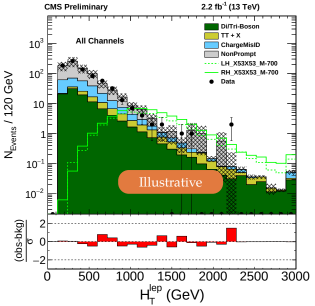


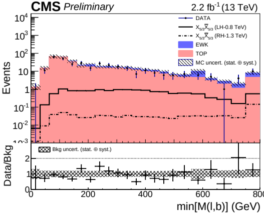
- No sign of possible signal: proceed to set 95% CL upper limits on the signal cross sections using Bayesian interpretation
- VL Q with mass below 788 (804) GeV excluded at 95% CL

Search for top partners with charge 5/3 at 13 TeV

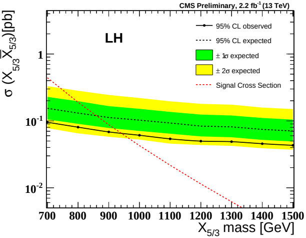
- Search for spin 1/2 top partners with exotic charge 5/3 ($X_{5/3}$) pair produced with $X_{5/3} \to tW^+ \to bW^+W^+$
- 2 considered analysis:
  - Same-sign (SS) leptons channel: 2 W^{lep}, looking at H_T^{lep} = sum p_T jets and leptons
  - Semi-leptonic channel: 1 W^{lep}, 3 (boosted) W^{hadr} ; min $M(l, b)$ main discri. var.





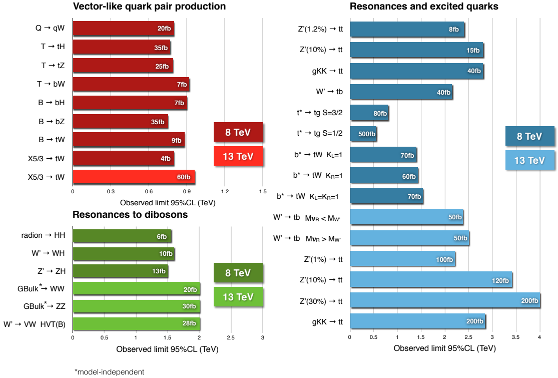


95% CL LH (RH) M($X_{5/3}$) exclusion limit (GeV)		
Analysis	Expected	Observed
SS+semilep 13 TeV comb.	860 (900)	940 (960)
SS 8 TeV	830 (-)	800 (-)



Outline

Conclusion



- Even if no sign of new physics beyond the SM have been found (yet), the Run1 analyses have allowed to establish limits on several BSM processes
- First 13 TeV results already allow to push the limits further, despite the integrated luminosity being an order of magnitude smaller
- Future Run2 data analyses will give new answers, as they will continue to scrutinize higher energy processes and reach better sensitivity

Thanks for your attention!

Outline

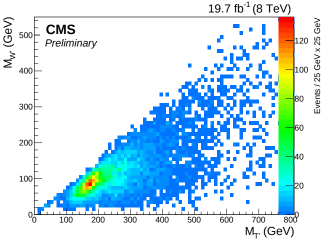
Links

- Dijet search:
  - Search for narrow resonances decaying to dijets in proton-proton collisions at $\sqrt{s} = 13$ TeV: CMS-EXO-15-001
  - Searches for quark contact interactions and extra spatial dimensions with dijet angular distributions in proton proton collisions at 13 TeV: CMS-PAS-EXO-15-009
- Black holes:
  - Search for black holes at $\sqrt{s} = 13$ TeV: CMS-PAS-EXO-15-007
- Massive resonances search:
  - Search for massive resonances decaying into pairs of boosted W and Z bosons at $\sqrt{s} = 13$ TeV: CMS-PAS-EXO-15-002
  - Search for resonant pair production of Higgs bosons decaying to $b\bar{b}$ and $\tau^+\tau^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV: CMS-PAS-EXO-15-008
  - W′:
    - Search for $W' \rightarrow tb$ in proton-proton collisions at $\sqrt{s} = 8$ TeV: B2G-12-009
    - Search for W′ boson resonances decaying into a top quark and a bottom quark in the leptonic final state at $\sqrt{s} = 13$ TeV: CMS-PAS-B2G-15-004
  - $t\bar{t}$ resonances
    - Search for $t\bar{t}$ resonances in boosted semileptonic final states in pp collisions at $\sqrt{s} = 13$ TeV: CMS-PAS-B2G-15-002
    - Search for resonant $t\bar{t}$ production in proton-proton collisions at $\sqrt{s} = 8$ TeV resonances: B2G-13-008
- Vector-like quarks:
  - Search for vector-like charge 2/3 T quarks in proton-proton collisions at $\sqrt{s} = 8$ TeV : B2G-13-005
  - Search for pair-produced vector-like B quarks in proton-proton collisions at $\sqrt{s} = 8$ TeV: B2G-13-006
  - Search for vector-like quarks in final states with a single lepton and jets in pp collisions at $\sqrt{s} = 8$ TeV: CMS-PAS-B2G-12-017
  - Search for top quark partners with charge 5/3 at $\sqrt{s} = 13$ TeV : CMS-PAS-B2G-15-006

Backup

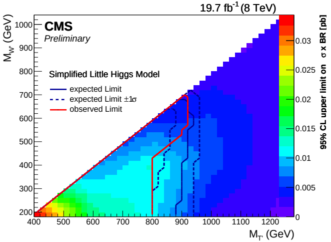
Simultaneous search for T′ and W′ (CMS-PAS-B2G-12-017)

- Simultaneous search for both a new heavy top partner and a heavy charged gauge boson in dilepton final states
- Model-independent search based on a 2D mass reconstruction of the $T'\bar{T}'$ system
- 2 isolated leptons, 2 jets and E_T^{miss}



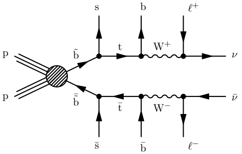
- 2D mass reconstruction:
  - Known masses: system can be solved analytically
  - Unknown masses: test every point of the $M_{T'}, M_{W'}$ plane for possible solutions
  - Mass plane scanned in steps of 5 GeV to produce the area in which a specific solution exists or not
  - A single point in the solution area chosen by picking the one which is more likely to originate from a pp collision according to its PDF

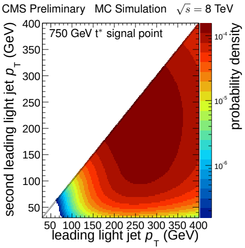
- No evidence of any excess found
- Setting upper limit on the signal cross section per mass point using a modified frequentist approach (CL_S method)
- Region up to a $M_{T'}$ range of 800-920 GeV depending on $M_{W'}$ is excluded

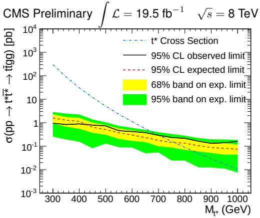


Search for t^* and $\tilde{b}$ (B2G-12-008)

- Search for pair produced BSM resonances coupling to a t and another parton in dilepton final state
  - Spin-3/2 t^* with $t^* \to tg$
  - RPV MSSM constrained to have minimal flavor violation, allowing $\tilde{b}$ to be the LSP with $\tilde{b} \to tq_d$ (q_d: down-type quark)



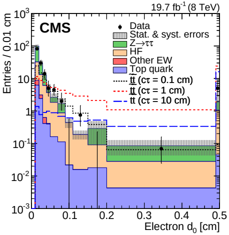


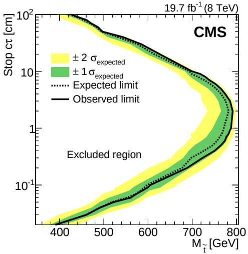


- Required: ≥ 2 isolated leptons, ≥ 2 loose btag, ≥ 2 medium btag and ≥ 2 failing loose btag jets
- Strategy: reconstruct light quarks or gluons jets p_T and resonance mass
- Build a 3D PDF using 2D light jets distributions and invariant mass distributions
- Extended unbinned likelihood to take into account the constraint distributions
- 95 % CL upper limits computed using the unified approach advocated by Feldman and Cousins
  - t^* masses between 300 and 703 GeV excluded
  - $\tilde{b}$ masses between 250 and 600 GeV excluded

Displaced SUSY (B2G-12-024)

- BSM models predict particles with significant lifetime: non-prompt decay signature, production vertex displaced from the interaction region
- Search for pair of displaced leptons with large impact parameters d_0 and opposite charges
- No assumptions about the event topology: analysis sensitive to a wide variety of still viable BSM scenarios
- Interpretation in context of displaced SUSY with LSP $\tilde{t}$ produced in pair, decaying through an RPV vertex: $\tilde{t} \to bl$
- Search only restricted to tracks with $d_0 < 2$ cm, for which the CMS triggering and reco algo have been previously optimized
- Selection: exactly 1 iso e and 1 iso μ oppositely charged, 3 signal regions (SR) depending on leptons d_0



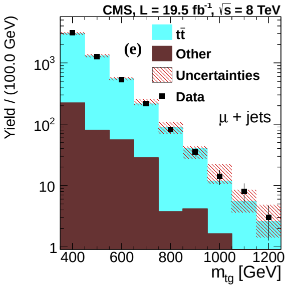


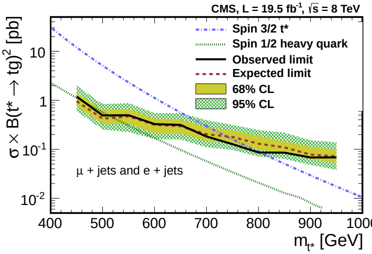
- No significant excess over background estimation
- 95 % CL upper limits on $\sigma(pp \to \tilde{t}\tilde{t}^*)$ using Bayesian calculation
- For $c\tau = 2$ cm, $M_{\tilde{t}}$ up to 790 GeV excluded

Search for excited t^* (B2G-12-014)

- Large top mass: may indicate it is not an elementary particle, but has a composite structure
- Existence of an excited top (t^*): direct test of this possibility

- Search for the pair production of t^* with spin 3/2 that decay 100 % in t+g
- Lepton+jets decay channel:
  $t^*\bar{t}^* \rightarrow (tg)(\bar{t}g) \rightarrow (W^+bg)(W^-\bar{b}g) \rightarrow (l^+\nu_l bg)(\bar{q}q'\bar{b}g)$
- Strategy: reconstruct m_{tg}
  - Assign reconstruct objects to their progenitor particles ($\not{E}_t \equiv$ neutrino's p_t, require b jet assigned to one b quark)
  - Constrained kinematic fit
  - Choose jet permutation with the smallest χ^2

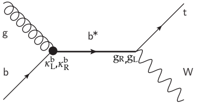




- Binned likelihood fit
- No excess found: set limit on inclusive $t^*\bar{t}^*$ σ using Bayesian statistics, combining e+jets and μ+jets channels
- Observed (expected) limit for m_{t^*} of 803 (739) GeV at 95 % C.L.

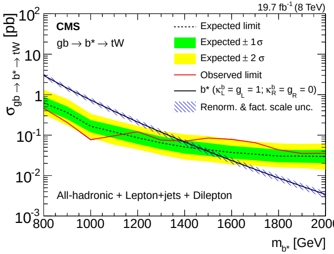
Search for excited b^* decaying to tW (B2G-14-005)

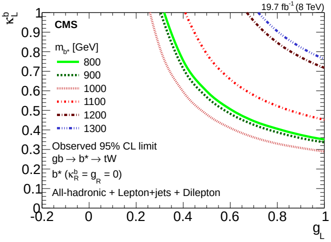
- Benchmark cases:
  - Purely left-handed: $g_L = \kappa_L^b = 1, g_R = \kappa_R^b = 0$
  - Purely right-handed: $g_L = \kappa_L^b = 0, g_R = \kappa_R^b = 1$
  - Vector-like: $g_L = \kappa_L^b = g_R = \kappa_R^b = 1$



All hadronic	Lepton+jets	Dilepton
0 l, boosted top and W jets	1 l, 1 b-jet, ≥ 2 jets, E_T^{miss}	2 l, ≥ 1 jet, E_T^{miss}
m_{tW}	m_{tW}	$S_T = p_T^{l_1} + p_T^{l_2} + p_T^{lead.\,jet} + E_T^{miss}$

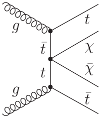
- Binned maximum likelihood fit to m_{tW}/S_T distributions to extract signal cross-section
- No excess found: set limits on $\sigma_{gb \to b^* \to tW}$ using Bayesian method
- Combining results taking into account systematics correlation between channels
- Expected (observed) mass exclusion at 95% CL for the LH, RH, and VL b: below 1480, 1560, and 1690 GeV (1390, 1430, and 1530 GeV) respectively

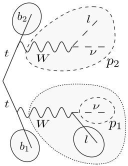




Search for Dark Matter (DM) (B2G-14-004 and CMS-PAS-B2G-13-004)

- Simplified scenario: only one new Dirac fermion related to DM within the energy reach of the LHC
- Search for the production of DM particles in association with a t pair, considering only scalar interaction at scale M_*: $\mathcal{L}_{int} = \frac{m_q}{M_*^3}\bar{q}q\bar{\chi}\chi$





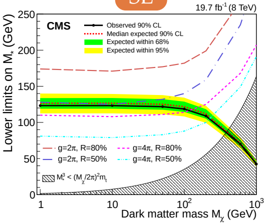
- Single-lepton analysis:
  - ≥ 3 jets, ≥ 1 b-jet, 1 isolated lepton, E_T^{miss}, min $\Delta\phi(j_{1,2}, \vec{E}_T^{miss})$
  - $M_T \equiv \sqrt{2E_T^{miss}p_T^l(1-\cos(\Delta\phi))} > 160$ GeV required
  - Discriminate dileptonic $t\bar{t}$ background events with 1 undetected lepton from signal by requiring $M_{T2}^W > 200$ GeV

$$M_{T2}^W = \min\left(m_y \text{ consistent with } \left\{ \begin{array}{c} \vec{p}_1^T + \vec{p}_2^T = \vec{p}_T^{miss}, p_1^2 = 0, (p_1+p_l)^2 = p_2^2 = M_W^2, \\ (p_1+p_l+p_{b_1})^2 = (p_2+p_{b_2})^2 = m_y^2 \end{array} \right\} \right)$$

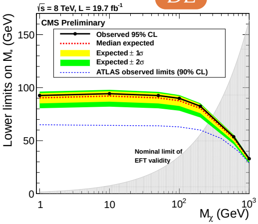
- Di-lepton analysis: 2 leptons, ≥ 2 jets, $p_T^{l_1} + p_T^{l_2}$, $p_T^{j_1} + p_T^{j_2}$, $\Delta\phi_{ll}$

- 90% CL limits on σ for $M_* = 100$ GeV: $\sigma > 20$ to 55 fb (0.09 to 0.31 pb) excluded in SL (DL)
- Lower limits on M_* set: for $m_\chi = 100$ GeV, $M_* <$ 118 (90) GeV excluded at 90% CL with SL (DL) analysis

SL



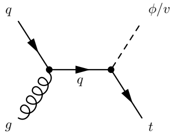
DL

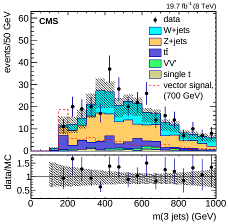


Search for monotop signatures

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{kin} + a^0_{FC}\phi\bar{u}u + a^1_{FC}v_\mu\bar{u}\gamma^\mu u + h.c.$$

- New neutral massive invisible particles predicted in BSM models (SUSY, extra-dimensions)
- Focus on invisible scalar (ϕ) or vector (v) boson produced via FC interaction with a single t ($t \to bW \to bq\bar{q}'$)
- 3 jets, 1 b-jet, no isolated lepton, significant E_T^{miss}, cut on $m_{jet1+jet2+jet3}$





- Signal σ and multijet (MJ) background estimation:
  - Number of events with or without a single b-tagged jet:

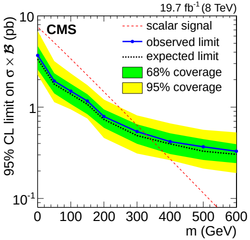
$$N^{0b} = \mathcal{P}^{0b}_{sig}.N_{sig} + \mathcal{P}^{0b}_{MJ}.N_{MJ}\,\mathcal{P}^{0b}_{other}.N_{other}$$

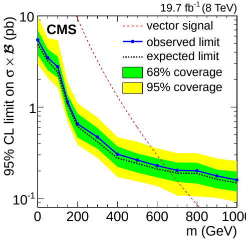
$$N^{1b} = \mathcal{P}^{1b}_{sig}.N_{sig} + \mathcal{P}^{1b}_{MJ}.N_{MJ}\,\mathcal{P}^{1b}_{other}.N_{other}$$

  - N_{sig} and N_{MJ} estimated by numerical minimization of the likelihood:

$$\mathcal{L}(\sigma_{sig}, \nu) = \text{Poisson}(N^{0b}_{obs}|N^{0b}) \times \text{Poisson}(N^{1b}_{obs}|N^{1b})$$

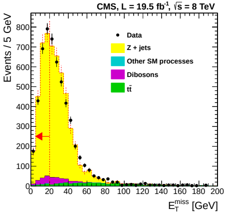
- No excess observed above the bkg expectation: 95% CL limits computation using CL_S technique
- Observed lower limits: M = 330 (650) GeV for scalar (vector) invisible particle (B2G-12-022)





Search for baryon number violation (B2G-12-023)

- BNV predicted in many BSM models: SUSY, grand unification, models with black holes
- Search for $t\bar{t}$ production, 1 BNV decay ($t \to \bar{b}\bar{c}l^+$, $t \to \bar{b}\bar{u}l^+$), 1 SM decay ($t \to bW \to bq\bar{q}'$)



Low E_T^{miss} simulation validation on Z+4 jets events-enriched data sample

- Selection:
  - Basic: exactly 1 isolated lepton, $\geq$ 5 jets, $\geq$ 1 b-tagged jet
  - Tight: $E_T^{miss} < 20$ GeV, $\chi^2 = \chi^2_{m_W^{hadr}} + \chi^2_{m_t^{hadr}} + \chi^2_{m_t^{BNV}} < 20$
- Strategy: counting events $N^T_{obs,exp}$ passing tight selection for each value of BNV decay branching fraction $\mathcal{B}$
  - Basic sel. level: $N^B_{exp(sig+bkg)}$ normalised to N^B_{obs} (reduces impact of some systematics and thus improves expected upper limit on $\mathcal{B}$ by 2.5)
  - Tight sel. level: significantly more efficient for signal ; N^T_{exp} depends on tight/basic selection efficiency which depends on $\mathcal{B}$

Assuming $\mathcal{B} = 0$

<table>
<tr><th>Process</th><th>Cross section (pb)</th><th>Basic</th><th>Corrected basic</th><th>Tight</th></tr>
<tr><td>$t\bar{t}$</td><td>246</td><td>38800 ± 7800</td><td>38700 ± 3600</td><td>2210 ± 220</td></tr>
<tr><td>W+jets</td><td>37500</td><td colspan="2">6300 ± 3200</td><td>230 ± 120</td></tr>
<tr><td>Z+jets</td><td>3500</td><td colspan="2">380 ± 190</td><td>32 ± 18</td></tr>
<tr><td>tW</td><td>22.2</td><td>1160 ± 180</td><td>1160 ± 220</td><td>49 ± 9</td></tr>
<tr><td>t-channel</td><td>87.1</td><td colspan="2">250 ± 130</td><td>5.7 ± 3.0</td></tr>
<tr><td>s-channel</td><td>5.55</td><td colspan="2">31 ± 16</td><td>0.84 ± 0.52</td></tr>
<tr><td>WW</td><td>54.8</td><td colspan="2">86 ± 43</td><td>3.1 ± 1.7</td></tr>
<tr><td>WZ</td><td>33.2</td><td colspan="2">41 ± 21</td><td>1.43 ± 0.78</td></tr>
<tr><td>ZZ</td><td>17.7</td><td colspan="2">5.5 ± 2.8</td><td>0.49 ± 0.28</td></tr>
<tr><td>$t\bar{t}$ W</td><td>0.23</td><td colspan="2">128 ± 64</td><td>5.9 ± 3.0</td></tr>
<tr><td>$t\bar{t}$Z</td><td>0.17</td><td colspan="2">79 ± 40</td><td>4.1 ± 2.1</td></tr>
<tr><td>QCD</td><td>—</td><td colspan="2">760 ± 530</td><td>112 ± 56</td></tr>
<tr><td>Total exp.</td><td>—</td><td>48000 ± 8600</td><td>47950 ± 220</td><td>2650 ± 130</td></tr>
<tr><td>Data</td><td>—</td><td colspan="2">47951</td><td>2614</td></tr>
</table>

- Build likelihood function with observable N^T_{obs} and parameter of interest $\mathcal{B}$ and set 95% CL upper limit on $\mathcal{B}$ with the Feldman-Cousins approach

Channel	95% CL	Expected	68% CL exp. range
Muon	0.0016	0.0029	[0.0017, 0.0046]
Electron	0.0017	0.0030	[0.0017, 0.0047]
Combined	0.0015	0.0028	[0.0016, 0.0046]

Dijet search (dijet mass)

Smoothness test

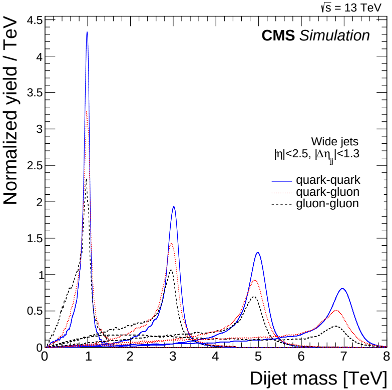
- Reduce sensitivity to gluon radiation from final state partons:
  - Combining geometrically close jets into 2 wide jets, using the 2 leading jets as seed
- t-channel dijet bkg suppression: $|\Delta\eta_{jj}| < 1.3$
- These requirements enhance sensitivity to isotropic decays of dijet resonances in presence of QCD dijet bkg
- To test the smoothness of the measured dijet mass spectrum, we fit the data with the parameterization:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

- $x = m_{jj}/\sqrt{s}$ and P_0, P_1, P_2 and P_3 fitted parameters
- $\chi^2/ndf = 31/35$

Signal shapes

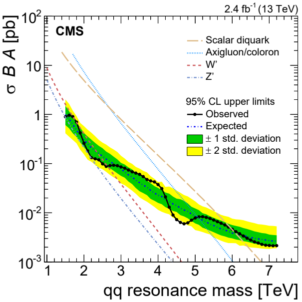
- Gaussian cores: from the jet energy resolution
- Tails towards lower mass values:
  - QCD radiation: resonances containing gluons which emit QCD radiation more strongly than quarks, have a more pronounced tail
  - High-mass resonances: significant contribution that depends both on the PDF and on the natural width of the Breit–Wigner resonance.
    - For resonances produced through interactions of nonvalent partons in the proton, the low-mass component of the Breit–Wigner resonance distribution is amplified by the rise of the parton probability distribution at low fractional momentum $\rightarrow$ large tail at low mass values
- Dijet mass resolution: from 7% at 1.5 TeV to 4% at 7 TeV (neglecting the tails)

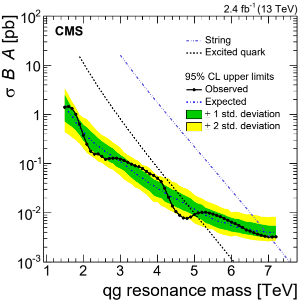


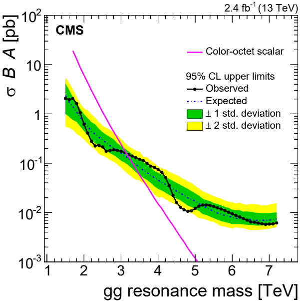
Setting limits

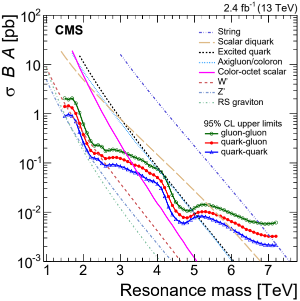
- Amount of signal in each bin determined by the signal resonance shape
- Background comes from the background component of a S+B fit to the data (performed separately for each resonance mass hypothesis)
- Using a Bayesian formalism with flat prior for the positive signal cross section and zero otherwise
- Systematic uncertainties introduced as nuisance parameters
- Signal posterior marginalized over nuisance parameters to get 95% CL upper limits on the signal cross section for each resonance mass hypothesis
- For significance estimate with statistical uncertainties only using a likelihood ratio significance estimator
- A separate limit is determined for each final state (qq, qg, and gg) because of the dependence of the dijet resonance shape on the type of the two final-state partons

Limits plots









Limits: numbers for considered *s*-channel dijet resonances models

- String resonances: the observed mass limit of 7.0 TeV extends the previous CMS limit of 5.0 TeV
- Scalar diquarks: the observed mass limit of 6.0 TeV extends the previous CMS limit of 4.7 TeV
- Axigluons and colorons: the observed mass limit of 5.1 TeV extends the previous CMS limit of 3.6 TeV
- Excited quarks: set a mass limit of 5.0 TeV compared to the ATLAS limit of 4.06 TeV
- A color-octet scalar: the observed mass limit of 3.1 TeV improves the ATLAS limit of 2.70 TeV
- W′ boson: exclude masses up to 2.6 TeV, just beyond the ATLAS limit of 2.45 TeV

Model	Final State	Obs. Mass Limit [TeV]	Exp. Mass Limit [TeV]
String	qg	7.0	6.9
Scalar diquark	qq	6.0	6.1
Axigluon/coloron	$q\bar{q}$	5.1	5.1
Excited quark (q^*)	qg	5.0	4.8
Color-octet scalar	gg	3.1	3.3
Heavy W (W′)	$q\bar{q}$	2.6	2.3

Search for quark contact interactions and extra spatial dimensions with dijet angular distributions at 13 TeV

Quark compositeness models

- Appearance of new interactions between quark constituents at a characteristic scale Λ that is much larger than the quark masses
- At energies well below Λ, these interactions are approximated by a contact interaction characterized by a four-fermion coupling
- In this letter, flavor-diagonal color-singlet couplings between quarks are studied, described by the effective Lagrangian

$$L_{qq} = \frac{2\pi}{\Lambda^2} \; \eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) + \eta_{RR}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_R\gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_L\gamma_\mu q_L)$$

- L, R: chiral projections of the quark fields ; η_{LL}, η_{RR}, η_{RL} = 0, +1 or -1
- Various combinations of η_{LL}, η_{RR}, η_{RL} correspond to different CI models
- CI scenario under investigation here: $\Lambda = \Lambda_{LL}^{\pm}$ for (η_{LL}, η_{RR}, η_{RL}) = ($\pm$ 1, 0, O)

ADD extra dimension models

- Possible solution du the hierarchy problem of the SM
- Gravity is assumed to propagate in the entire higher-dimensional space, while SM particles are confined in a 3+1 dimensional subspace
- Fundamental Planck scale M_D is much smaller than the 3+1 dimensional Planck energy scale M_{Pl}
- A tail in the angular distribution could be produced from virtual graviton exchange
- 2 parametrizations for virtual graviton exhange in ADD model:
  - GRW (Giudice, Rattazzi, Wells) convention: the phenomenology after summing over the Kaluza-Klein states is controlled by a single parameter Λ_T
  - HLZ (Han, Lykken, Zhang) convention: describes the phenomenology in terms of the parameters M_S (string scale, $\mathcal{O}(M_D)$ and n_{ED} number of extra dimensions in a 4+n_{ED} dimensional space, which may be directly related to Λ_T

Selection

- Preselection:
  - HT trigger, HT>650-800 GeV depending on the run
- $\geq$ 2 AK4 PF jets passing tight PF jet ID
- M_{jj} bins: $[1.9, 2.4]$, $[2.4, 3.0]$, $[3.0, 3.6]$, $[3.6, 4.2]$, $[4.2, 4.8]$, $[4.8, \infty]$ (higest observed value: 6.8 TeV)
- χ_{dijet}<16
- $|y_{\text{boost}}|$<1.1

Systematics

- Prediction of perturbative QCD (pQCD) at NLO:
  - Factorisation (μ_f) and renormalization (μ_r) scales set to the average p_T of the 2 jets
  - The choice of theses scales dominates the uncertainties on pQCD prediction
  - Evaluate uncertainty by varying the default choice of scales in 6 combinations: $(\mu_f/<p_T>, \mu_r/<p_T>)$ = (1/2, 1/2), (1/2, 1), (1, 1/2), (2, 2), (2, 1), (1, 2)
- Unfolding:
  - Fluctuations in the jet response due to the finite jet p_T resolution of the detector can cause low- energy jets to be misidentified as the leading jets
  - These fluctuations result in event migrations in χ_{dijet} and in M_{jj}
  - χ_{dijet} distributions are corrected for these migrations and unfolded to particle-level using a Bayesian methodimplemented in the ROO-UNFOLD package

Uncertainty	$1.9 < M_{jj} < 2.4$ TeV	$M_{jj} > 4.8$ TeV
Statistical	1.6%	24%
Jet energy scale	3.0%	9.5%
Jet energy resolution (core)	<1%	2.0%
Jet energy resolution (tails)	<1%	2.5%
Unfolding, MC modeling	<1%	<1%
Unfolding, detector simulation	1.0%	3.0%
Pileup	<1%	<1%
Total experimental	9.7%	26%
NLO scale (6 variations of μ_R and μ_F)	$^{+7.9\%}_{-2.8\%}$	$^{+13\%}_{-4.9\%}$
PDF (CT14 eigenvectors)	0.15%	0.4%
Non-perturbative corrections (Pythia8 vs. Herwig++)	<1%	<1%
Total theoretical	7.9%	13%

Search for black holes at 13 TeV

ADD model

- ADD model with n large extra spatial dimensions that give rise to strong gravity due to the fact that in 4+n dimensions the fundamental Planck mass M_D can be as low as few TeV
- Gauge interaction localized in (3+1)-dimension brane
- Gravity propagates in n flat extra-dimensions compactified on torus or sphere with radius R (size of extra dimensions)
- Apparent Planck scale in our 4D time-space: $M_{Pl}^2 = M_D^{n+2} R^n$
- n=1 case requires the compactification radius R of order of the size of the solar system, and thus is ruled out by the very existence of our solar system

Semiclassical BH

- Stricly valid if $M_{BH} \gg M_D$
- Semiclassical BHs decay via thermal Hwking radiation into a large number of energetic objects (hadrons ie jets, leptons, photons...)
- Relative abundance of various particle produced in BH evaporation process follows ndof per particle in SM
  - Decay products are ~ 75 % quarks/gluons du to their large number of color dof
- A lot of models can be explored:
  - Nonrotating, no gravitons (BlackMax)
  - Nonrotating (Charybdis)
  - Rotating, no gravitons (Blackmax + Charybdis)
  - Rotating black holes (Charybdis)
  - Rotating black holes, mass and angular momentum loss (Charybdis)
  - Rotating black holes, boiling remnant (Charybdis)
  - Rotating black holes, stable remnant (Charybdis)

Quantum black holes

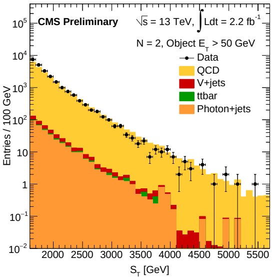
- When M_{BH} approaches M_D, the semiclassical approximation is expected to break down and the BH becomes a quantum object
- Decay before thermalization
- Typically decays into a pair of quarks (dijet)
- Could also violate baryon and lepton number conservation: possible $e\mu$ final state

Selection

- **Preselection:**
  - Good primary vertex
  - Standard loose PF Jets ID, $|\eta| < 5.2$
  - $S_T > 1000$ GeV (HLT_PFHT800 trigger fully efficient), $E_T > 50$ GeV
- **Electron:**
  - Cut-based Electron ID with medium operating point
  - $I_{rel} < 0.1$
  - $E_T > 50$ GeV
- **Photon:**
  - Cut-based photon ID with medium operating point
  - ρ-corrected PF photon isolation
  - $E_T > 50$ GeV
- **Muon:**
  - Muon medium ID
  - $I_{rel} < 0.15$
  - $E_T > 50$ GeV

Background estimation

- Inclusive search for BH decays in all possible final states:
  - dominated by multijet ones for semiclassical BH
  - dominated by dijet ones for QBH
- Background of the analysis:
  - QCD multijet: dominant one by far
  - V+jets (V=W,Z)
  - γ+jets
  - $t\bar{t}$+jets



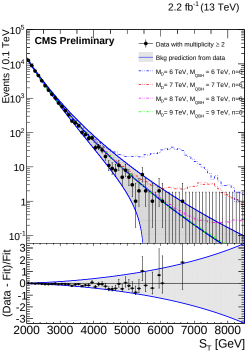
- Non-QCD background contribution to the total bkg very small (see fig): neglected in the analysis
- Main challenge of the search: describe the inclusive multijet background in robust way
- Cannot rely on MC simulation: higher-order calculations that fully describe multijet production simply do not exist
- Background estimated exclusively from control sample in data
- A novel method of predicting the QCD background developed for the Run 1 analysis

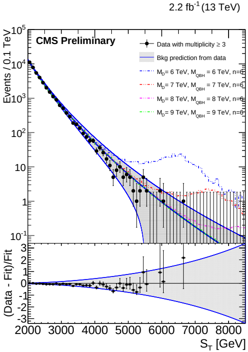
Background estimation

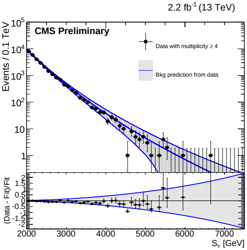
- Background directly derived from data
- Assumption: the shape of S_T distribution for dominant QCD multijet background doesn't depend on the multiplicity of the final state (above a certain turn-on threshold)
- Shape of bkg (bkg template) extracted from data at low multiplicity and then rescaled at higher multiplicities
- Bkg template obtained by fitting an ansatz function $\frac{P_0(1+x)^{P_1}}{x^{P_2+P_3\log(x)}}$ to N=2 S_T distribution with negligible signal contamination (NP contributions ruled out by Run 1 analysis for this region)
  - N=2: default
  - Add 5% systematics to account for difference between predictions based on N=2 and N=3 templates
- 2 additional functions $\frac{P_0}{(P_1+x)^{P_2}}$ and $\frac{P_0}{(P_1+P_2x+x^2)^{P_3}}$ making an uncertainty envelope
- Bkg template extracted by fitting N=2 S_T distribution normalized to obtain a bkg estimate for S_T spectra at higher multiplicities
- Normalization scale factors: $SF = \frac{N_{events}(N \geq N_{min})}{N_{events}(N=2)}$

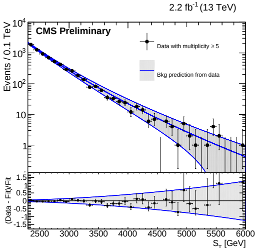
Multiplicity	Normalization region [GeV]	Normalization scaling
≥ 2	2000 – 2300	8.47± 0.05
≥ 3	2000 – 2300	7.45± 0.04
≥ 4	2000 – 2300	5.52± 0.03
≥ 5	2300 – 2600	3.29± 0.03
≥ 6	2300 – 2600	1.71± 0.01
≥ 7	2300 – 2600	0.744± 0.006
≥ 8	2500 – 2800	0.328± 0.004
≥ 9	2500 – 2800	0.125± 0.001
≥ 10	2600 – 2900	0.046± 0.001

S_T distributions for different inclusive multiplicities

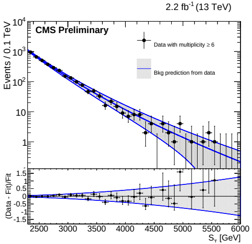


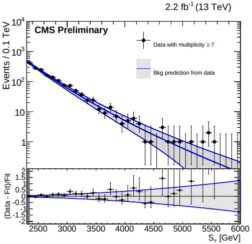


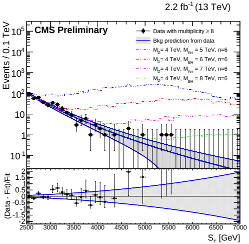


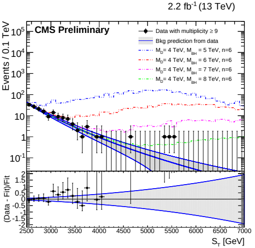


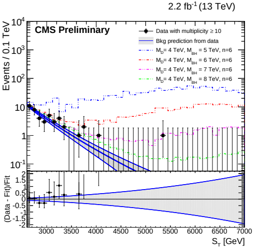
S_T distributions for different inclusive multiplicities











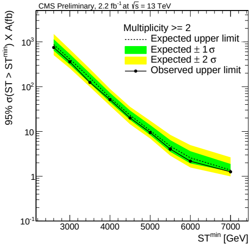
Systematics

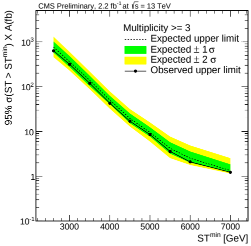
Uncertainty du to final-state radiation

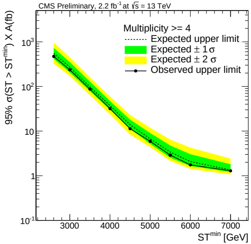
- Migration from one multiplicity class to another du to FSR
- Estimate the effect by varying the parameters of the Pythia 8 generator used to hadronize and fragment the parton-level BH samples
- Effect of FSR on the signal acceptance in a typical inclusive bin used to set limit is 1.2 %

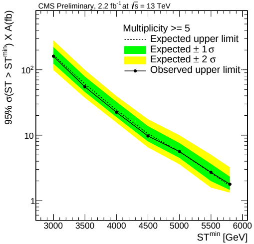
Uncertainty	Effect on signal acceptance	Effect on the background estimate
JES	$\pm 5\%$	–
JER	$\pm 4\%$	–
PDF	$\pm 6\%$	–
FSR	$\pm 1.2\%$	–
Background normalization	–	$\pm(0.5-5.2)\%$
Background shape	–	$\pm(1-200)\%$, depends on the S_T value.

Model-independent limits as a function of S_T^{min}

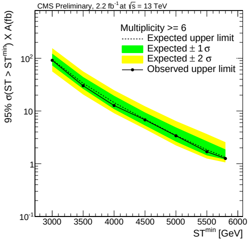


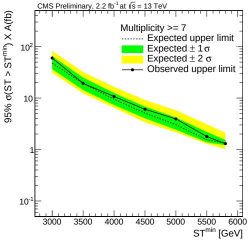


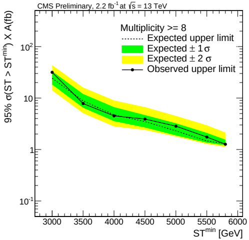


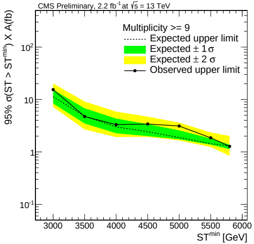


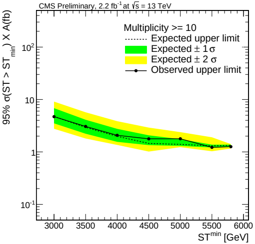
Model-independent limits as a function of S_T^{min}





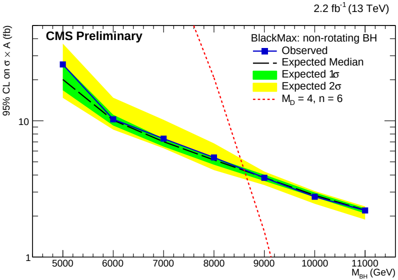


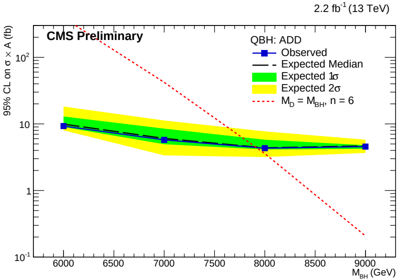




Model-depend limits

- Compute optimum S_T^{min} and N_{min} wrt M_{BH}^{min} from point of view of maximization of Z_{BI} test statistics based on the expected bkg

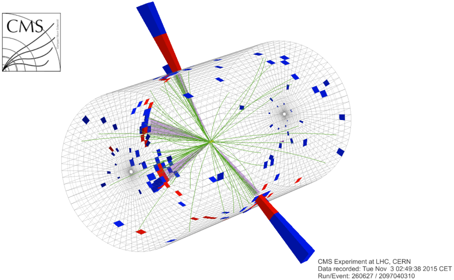


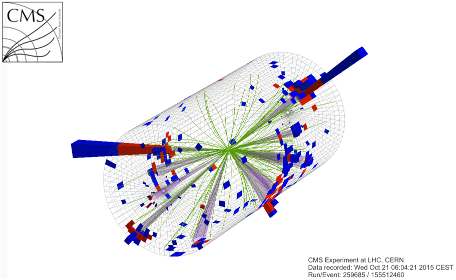


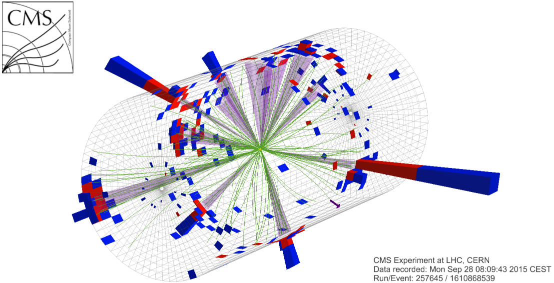
Event candidates

S_T, TeV	M, TeV	N	E_T^{miss}, TeV	Jet p_T's, TeV
Run 260627, Event 2097040310				
6.67	6.69	4	0.11	2.63, 2.49, 1.17, 0.27
Run 259685, Event 155512460				
5.56	7.02	9	0.01	1.96, 1.65, 0.58, 0.41, 0.37, 0.17, 0.14, 0.13, 0.12
Run 257645, Event 1610868539				
5.35	6.42	12	0.11	1.80, 0.88, 0.54, 0.40, 0.37, 0.36, 0.36, 0.26, , 0.09, 0.07, 0.07, 0.05

Event candidates: event display







Diboson search

Channels

- Search for massives resonances decaying to VV (V=W,Z)
- Boosted Vs: when they decay hadronically, their decay products are merged in a single jet
- Dijet channel: $X \rightarrow VV \rightarrow q\bar{q}'q\bar{q}'$
- $l\nu$+jets channel: $X \rightarrow WV \rightarrow l\nu q\bar{q}'$, W decays leptonically, the other V boson decays hadronically
  - Special high-momentum isolated lepton reconstruction algo
  - $l = e$ or μ
  - However, the results include the case where $W \rightarrow \tau\nu \rightarrow l\nu\nu$
  - Gain in sensitivity from the decay channels including τ leptons is limited du to small BR
  - 8 TeV legacy results: spin 2 RS bulk graviton G^* with g=1 and W′ with mass below 700 and 1490 GeV respectively are excluded

Simulated signal samples

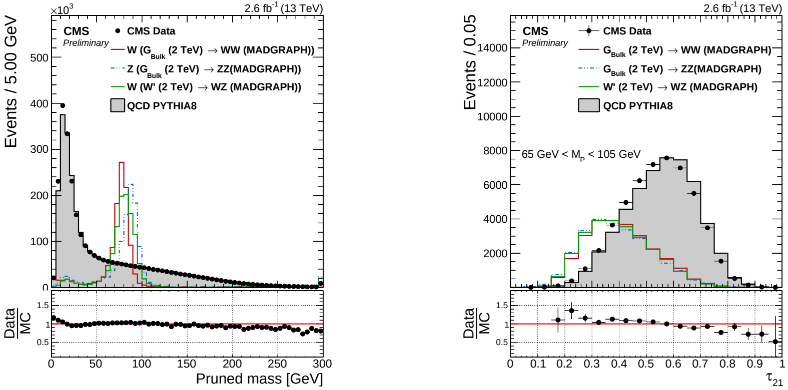
- Bulk graviton model
- Heavy vector triplet (HVT) model (W')
  - scenario (model B) where the W' predominantly couple to bosons (most representative of a composite Higgs model)
- In both models, vector gauge bosons with longitudinal polarisation V_L

Trigger and offline selection

- $l\nu$+jets:
  - Trigger requires either 1 eletron or 1 muon, p_T > 45 GeV for muon, E_T > 105 GeV for electron, no isolation requirement, loose ID
- Dijet channel:
  - Trigger based on jets: H_T > 800 GeV or (H_T > 650-700 GeV and a single jet with p_T > 360 GeV and trimmed mass > 30-50 GeV)

V-tagging selection: $W \to q\bar{q}'$ and $Z \to q\bar{q}$ identification

- Use AK8 hets to reconstruct W-jet and Z-jet candidate
- Jet mass reconstruction:
  - Jet pruning algorithm
  - $65 < m_{jet} < 105$ GeV
- N-subjettiness reconstruction: τ_N variable
  - quantifies the capability of clustering the jet constituents in exactly N subjets, with small values representing configurations more compatible with the N-subjets hypothesis
  - $\tau_{21} = \tau_2/\tau_1 < 0.75$



$l\nu$+jets specific preselection

- Exactly one isolated muon (electron) with p_T > 53 (120) GeV and $|\eta|$< 2.1 (2.5)
  - Stringent identification and isolation criteria optimised for high-p_T electron
- E_T^{miss} > 40 (80) for muon (electron) channel
  - Associated to neutrino
  - p_z^{ν} obtained by solving a second-order equation that sets $l\nu$ invariant mass = M_W

Final selection

After reconstructing the 2 vector bosons, apply final selection:

- $l\nu$+jets channel:
  - ΔR(l, V-jet) > $\pi/2$ (back-to-back V bosons)
  - $\Delta\phi(W, E_T^{miss}) > 2$ radians
  - $\Delta\phi(W, V) > 2$ radians
  - no b-tagged AK4 jets
- Hadronic channel:
  - $|\Delta\eta_{jj}| < 1.3$
  - m_{jj}> 1000 GeV

Categorisation

- According to τ_{21}:
  - Semileptonic channel:
    - High-purity (HP): $\tau_{21} \leq 0.6$
    - Low-purity (LP): $0.6 < \tau_{21} < 0.75$
  - Fully hadronic channel:
    - High-purity (HP): $\tau_{21} \leq 0.45$
    - Low-purity (LP): $0.45 < \tau_{21} < 0.75$
- According to pruned mass jet:
  - 65 GeV < M(pruned jet) < 85 GeV: V-jet deemed a W-candidate
  - 85 GeV < M(pruned jet) < 105 GeV: V-jet deemed a Z-candidate
  - 105 GeV < M(pruned jet) < 135 GeV: not considered in the analysis and not displayed in any plots to avoid experimenter's bias in future searches for WH, ZH, HH resonances with the same dataset
    - Semileptonic channel: 2 categories (WW and WZ)
    - Hadronic channel: 3 categories (WW, WZ, ZZ)
- According to lepton flavor (for semileptonic channel only): e or μ

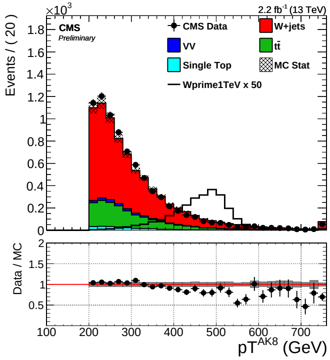
In summary:

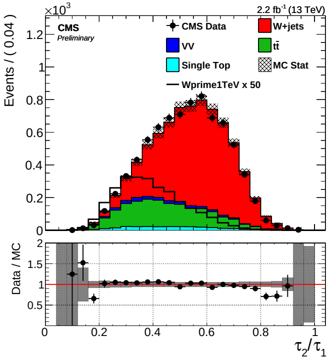
- 8 categories for semileptonic channel
- 6 categories for hadronic channel

Keep only one diboson candidate:

- In case several possible diboson candidate: diboson pairs in HP category are prefered to those in LP
- If still multiple choices of diboson candidates, keep candidate with highest p_T V-jet

After final selection

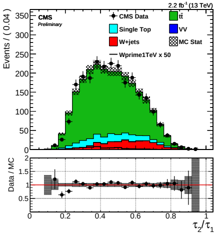


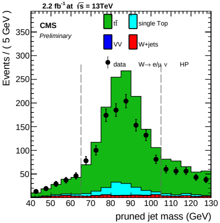


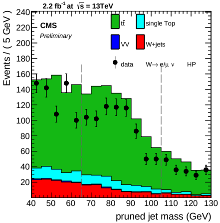
- τ_{21} distributions: discrepancy between data and simulation
- Previous studies suggest it is du to mismodeling of the parton showering in simulation
- Analysis designed to be robust again these differences between data and MC (see next slides)

Parton shower mismodeling: W-tagging in top enriched control sample

- Top quark enriched control sample ($t\bar{t}$ and signle top events):
  - Obtained by applying all $l\nu$+jets requirements but inverting b-tag veto (requiring $\geq$ 1 btag jet)
- Discrepancies between data and simulation are corrected using SF for:
  - top bkg normalization
  - V-tagging efficiency
  - peak and resolution of V-jet mass distribution
- Distribution in the top quarl enriched control sample:







- Normalization correction factor for $t\bar{t}$ and single-t processes evaluated on signal jet mass window

Category	Definition	W scale factor
Dijet channel HP	$(\tau_{21} < 0.45)$	0.69 ± 0.14
Dijet channel LP	$(0.45 < \tau_{21} < 0.75)$	1.46 ± 0.38
$\ell\nu$+jet channel HP	$(\tau_{21} < 0.6)$	1.03 ± 0.13
$\ell\nu$+jet channel LP	$(0.6 < \tau_{21} < 0.75)$	0.88 ± 0.49

Parton shower mismodeling: W-tagging in top enriched control sample

- Extract W-jet mass peak position and resolution from the same fit
- Mass peak position shifted du to extra energy deposited in jet cone (PU, underlying event, ISR not completely removed from jet pruning...)
- Same corrections used in the case where V-jet is assumed to come from a Z (similar kinematic properties between Z and W))

$\tau_{21} < 0.45$	m [GeV]	σ [GeV]
Data	84.7 ± 0.4 GeV	8.2 ± 0.5 GeV
Simulation	85.3 ± 0.4 GeV	7.3 ± 0.4 GeV

Background

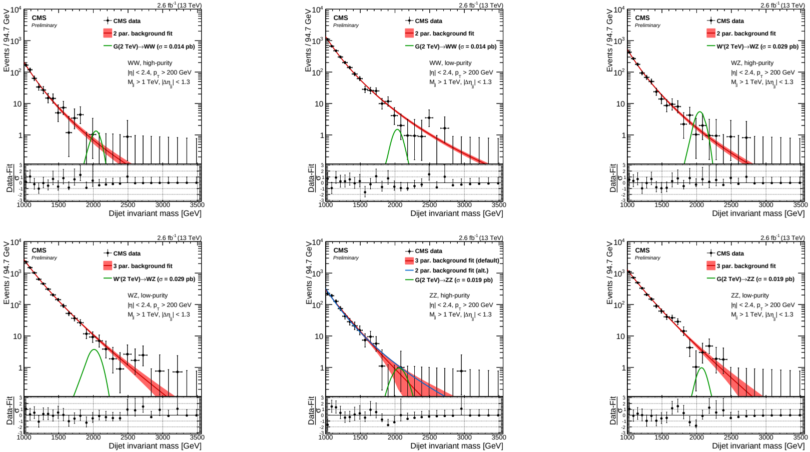
- SM processes where a quark or gluon jets are falsely identified as V-jets
- Dominant background for $l\nu$+jets channel: inclusive W boson production
- Dominant background for dilepton channel: QCD multijet
- Data-driven

QCD multijet background estimation (dijet channel): dijet fit method

- Assume SM bkg described by a smooth parametrisable, monotonically decreasing distribution

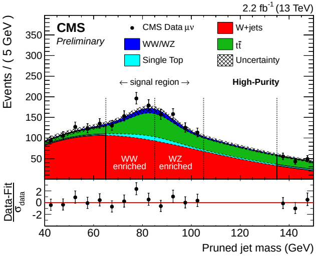
$$\frac{dN}{dm_{jj}} = \frac{P_0(1 - m_{jj}/\sqrt{s})^{P_1}}{(m_{jj}/\sqrt{s})^{P_2}} \text{ (3-par. form)}, \qquad \frac{dN}{dm_{jj}} = \frac{P_0}{(m_{jj}/\sqrt{s})^{P_2}} \text{ (2-par. form)},$$

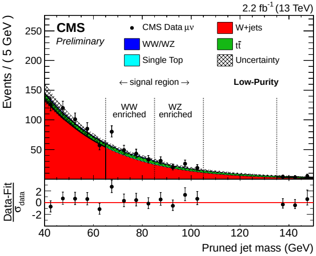
- ML fit to the data
- Start from 2 parameters functional form
- Fischer F-test to check at 10% CL if additional parameters are needed



Inclusive W bkg ($l\nu$+jets channel): alpha ratio method

- Assume there is a correlation between m_{Vjet} and m_{VV} for W+jet bkg
- Other minor bkg ($t\bar{t}$, single-t, diboson) taken from simulation
- Signal depleted region (sideband):
  - 40 GeV < m_{Vjet} < 65 GeV
  - 135 GeV < m_{Vjet} < 150 GeV
- Overall normalization of W+jets bkg in signal region determine from a fit to the m_{Vjet} in lower and upper sidebands of observed data





Inclusive W bkg ($l\nu$+jets channel): alpha ratio method

- Shape of m_{VV} of the V+jets bkg determined from lower m_{Vjet} sideband, extrapolated to signal region via a transfer function $\alpha_{MC}(m_{VV})$

$$\alpha_{\mathrm{MC}}(m_{\mathrm{VV}}) = \frac{F^{\mathrm{V+jets}}_{\mathrm{MC,SR}}(m_{\mathrm{VV}})}{F^{\mathrm{V+jets}}_{\mathrm{MC,SB}}(m_{\mathrm{VV}})}, \quad (3)$$

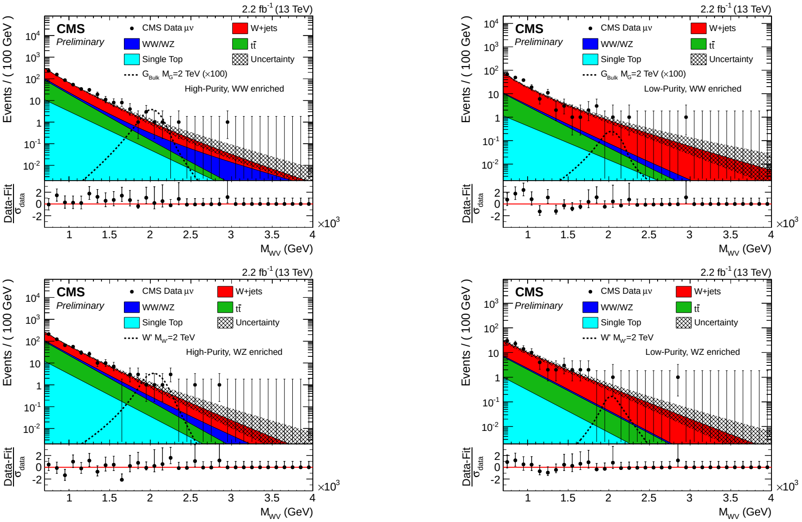
where $F(m_{\mathrm{VV}})$ is the probability density function used to describe the m_{VV} spectrum in the different regions, and has the functional form of a levelled exponential

$$F(m_{\mathrm{VV}}) = \mathrm{N}_0 \cdot \exp\left(-\frac{m_{\mathrm{VV}} - m_0}{\sigma + k(m_{\mathrm{VV}} - m_0)}\right), \quad (4)$$

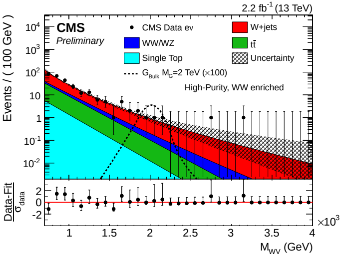
where N_0 is a normalisation parameter obtained as described above, $m_0 = 800\,\mathrm{GeV}$ is a pivot parameter for the exponential, and σ and k control the shape of the function tail.

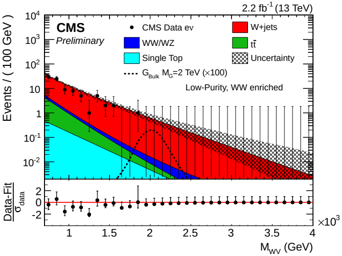
- Estimate observed V+jets bkg in sideband region, correcting for presence of minor bkg: $F^{Vjets}_{DATA,SB}(m_{VV})$
- Obtain V+jets bkg distribution in SR: $F^{Vjets}_{DATA,SR}(m_{VV}) = \alpha_{MC}(m_{VV}) \times F^{Vjets}_{DATA,SR}(m_{VV})$

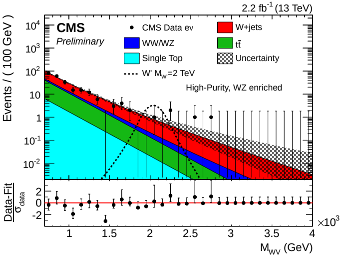
Inclusive W bkg ($l\nu$+jets channel): alpha ratio method

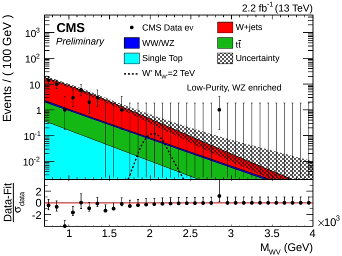


Inclusive W bkg ($l\nu$+jets channel): alpha ratio method



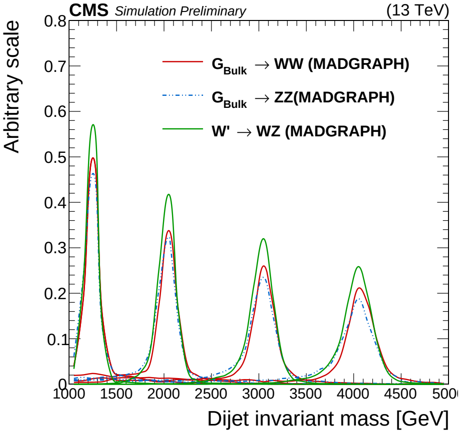






Signal modeling

- Simulated m_{jj} distribution for resonances masses from 1 to 4 TeV
- Experimental resolution for dijet channel ranges from 10% at 1 TeV to 3% at 4 TeV (slightly better for semileptonic channel)
- Analytical description of the signal: double-sided Crystal-Ball function



Signal efficiencies

Signal	Mass	Dijet channel						$\ell\nu$+jet channel			
		WW		WZ		ZZ		WW		WZ	
		HP	LP	HP	LP	HP	LP	HP	LP	HP	LP
$G_{bulk} \to WW$	1.2 TeV	3.1	5.7	2.3	4.0	0.4	0.5	13.2	0.5	3.8	0.1
$G_{bulk} \to WW$	2.0 TeV	4.1	9.3	1.3	2.9	0.1	0.3	15.4	0.9	2.9	0.1
$G_{bulk} \to WW$	3.0 TeV	3.1	8.0	1.5	3.4	0.1	0.3	14.7	1.2	3.2	0.2
$G_{bulk} \to WW$	4.0 TeV	2.7	8.2	1.8	4.0	0.2	0.5	14.1	1.2	3.9	0.2
$G_{bulk} \to ZZ$	1.2 TeV	0.3	0.6	1.7	2.5	1.9	2.3	-	-	-	-
$G_{bulk} \to ZZ$	2.0 TeV	0.4	1.1	1.6	3.4	1.5	2.2	-	-	-	-
$G_{bulk} \to ZZ$	3.0 TeV	0.3	1.2	1.4	3.6	1.2	2.3	-	-	-	-
$G_{bulk} \to ZZ$	4.0 TeV	0.3	1.3	1.2	3.7	1.1	2.2	-	-	-	-
HVT $W' \to WZ$	1.2 TeV	1.7	3.0	4.6	6.9	0.9	1.3	2.8	0.1	6.3	0.1
HVT $W' \to WZ$	2.0 TeV	1.9	4.8	3.8	6.8	0.5	0.8	3.9	0.3	6.4	0.2
HVT $W' \to WZ$	3.0 TeV	1.4	4.6	3.2	6.9	0.6	0.8	3.9	0.4	6.4	0.2
HVT $W' \to WZ$	4.0 TeV	1.9	2.8	4.5	4.7	1.1	0.8	3.9	0.4	6.1	0.3

Systematics: dijet channel

Source	Relevant quantity	HP+HP uncertainty	HP+LP uncertainty
Jet energy scale	Resonance shape	2%	2%
Jet energy resolution	Resonance shape	10%	10%
Jet energy and m_{jet} scale	Signal yield	[0.4%–1.5%]	[0.1%–1.7%]
Jet energy and m_{jet} resolution	Signal yield	[0.1%–1.3%]	[0.1%–1.4%]
Pileup	Signal yield	2%	2%
Integrated luminosity	Signal yield	4.6%	4.6%
Jet energy and m_{jet} scale	Migration	[1%–46%]	[1%–55%]
W-tagging τ_{21}	Migration	44%	14%
W-tagging p_{T}-dependence	Migration	3.6%	6%

Systematics: semileptonic channel

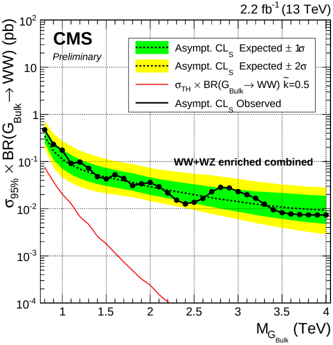
- General uncertainties

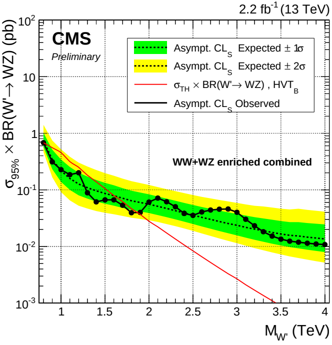
Source	Relevant quantity	$\mu\nu$+jet uncertainty	$e\nu$+jet uncertainty
Lepton trigger	Signal yield	1%	1%
Lepton identification	Signal yield	1%	3%
Jet energy scale	Signal yield	See Tab. 6	
Jet energy scale	Resonance shape (mean)	1.3%	
Jet energy scale	Resonance shape (width)	[2%–3%]	
Jet energy resolution	Signal yield	See Tab. 6	
Jet energy resolution	Resonance shape (mean)	0.1%	
Jet energy resolution	Resonance shape (width)	4%	
Integrated luminosity	Signal yield	4.6%	
PDF uncertainties (W′)	Signal yield	[0.5%–8.5%]	
PDF uncertainties (G_{bulk})	Signal yield	[10%–45%]	
W-tagging τ_{21} (HP/LP)	Migration	13%/49%	

- Jet-specific uncertainties

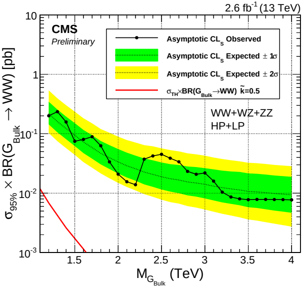
Source	G_{bulk} signal normalisation		W′ signal normalisation	
	WW-enriched	WZ-enriched	WW-enriched	WZ-enriched
Jet Energy Scale	−[4%–7%] +[3%–5%]	+[16%–33%] −[15%–27%]	−[11%–15%] +[14%–17%]	+[3%–9%] −[4%–12%]
Jet Energy Resolution	<0.1%		<0.1%	
Jet Mass Scale	−[4%–10%] +[3%–9%]	+[16%–30%] −[16%–25%]	−[11%–16%] +[12%–20%]	+[1%–8%] −[3%–10%]
Jet Mass Resolution	−[2%–4%] +[2%–4%]	+[1%–12%] −[4%–11%]	−[1%–10%] +[2%–9%]	+[1%–5%] −[2%–4%]

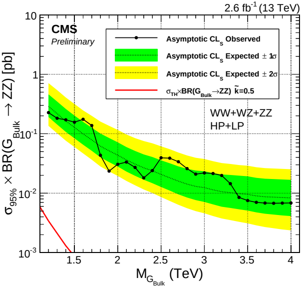
Limits (semileptonic channel)

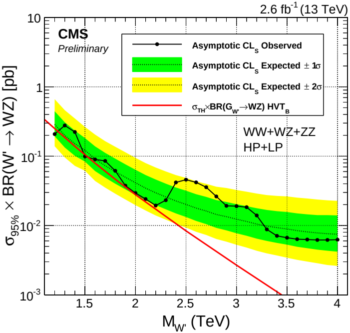




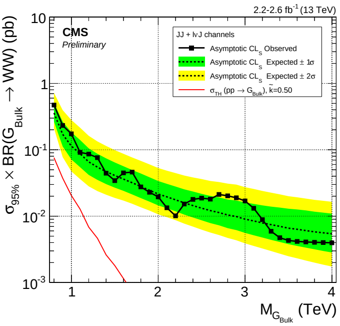
Limits (dijet channel)

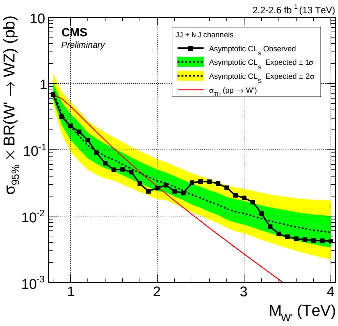






Limits (combination)



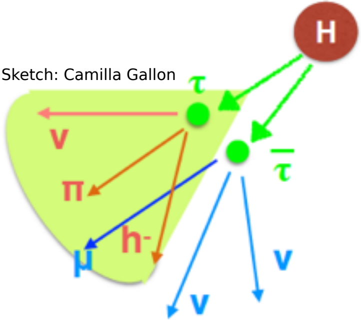


$$X \to HH \to b\bar{b}\tau^+\tau^-$$

Reconstructing "tauic" H

- Leptons (e, μ) reconstruction: tight ID, isolation (corrected from decay products of identified τ which are removed from isolation cone)
- Hadronic τ reconstruction: jets cleaned from identified leptons and fed to hadronic τ identification algo
- τ_{hadr} candidates contain only detectable particles (no ν)
- Likelihood fit algo for $\tau\tau$ system reconstruction: combined $\vec{p}_T^{miss}$ ($|\vec{p}_T^{miss}|$>50 GeV) and visible momenta

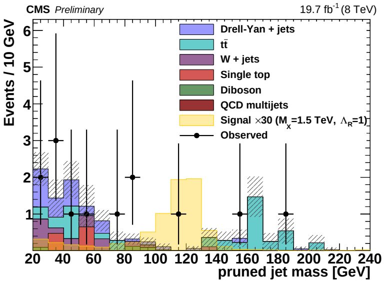
Sketch: Camilla Gallon

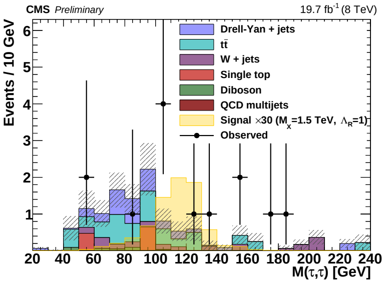


Full selection

Selection
$p_{\mathrm{T},\tau\mathrm{vis}} > 35\,\mathrm{GeV}$, $p_{\mathrm{T},\ell} > 10\,\mathrm{GeV}$
$0.1 < \Delta R_{\ell,\tau\mathrm{vis}} < 1.0$, $m_{\mathrm{vis}}(\ell, \tau_{\mathrm{vis}}) > 10\,\mathrm{GeV}$
$\lvert\vec{p}_{\mathrm{T}}^{\mathrm{miss}}\rvert > 50\,\mathrm{GeV}$
$p_T(\tau\tau)$ from SVFit $> 100\,\mathrm{GeV}$
$p_{T,\mathrm{jet}} > 400\,\mathrm{GeV}$ and $\lvert\eta_{\mathrm{jet}}\rvert < 1$
$100 < m_{\mathrm{jet}}^{P} < 140\,\mathrm{GeV}$, $\tau_{21} < 0.75$
Higgs-b-tagging: 1 CSVL-tagged fat jet if ΔR(sj1,sj2) < 0.3
or 2 CSVL-tagged subjets if ΔR(sj1,sj2) > 0.3
$N_{\text{extra b-tagged jets}} = 0$

Pruned jet mass and SVFit mass (complete selection except pruned jet mass window)





Background estimation

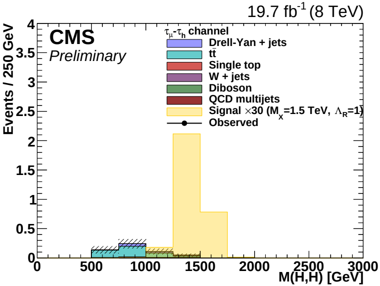
- $t\bar{t}$, W+jets, DY: main backgrounds ; other background components negligible
- Perform predominantly data-driven prediction
  - Background shape: from simulation
  - Background yiel and composition: estimated on observed sideband events
- Estimate data-to-simulation SF on background normalisation (second part of formula: check depedencies of SF on the b-tagging requirement, higer statistic by inverting isolation region):

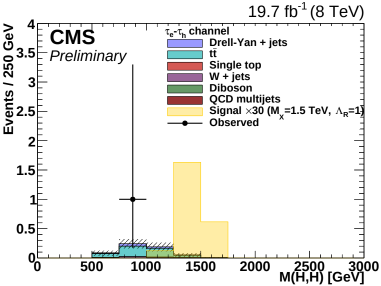
$$\xi_{SR} = \xi^{Untagged}_{IntermediateIso} \times \xi^{b-tagged}_{InvertedIso} / \xi^{Untagged}_{InvertedIso}$$

Region	Pruned jet mass [GeV]	Higgs-b-tagging	Tau isolation region
Signal	100–140	b-tagged	loose
IntermediateIso	20–240	untagged	intermediate
	derive data-to-simulation scale factors for backgrounds assumption: data-to-simulation agreement same as with loose isolation		
InvertedIso	20–240	untagged b-tagged	inverted
	extrapolate data-to-simulation agreement from untagged to b-tagged sample assumption: b-tag scale factor same as with loose isolation		
Mass sideband	20–100, 140–240	untagged	loose
	cross check background estimation procedure assumption: pruned jet mass spectrum correctly described		
Untagged	100–140	untagged	loose
	obtain simulated background shapes for signal region assumption: background shape not changed by b-tag requirement		

Channel	**Background**	$\xi^{Untagged}_{IntermediateIso}$	$\xi^{b-tagged}_{InvertedIso}$	$\xi^{Untagged}_{InvertedIso}$	ξ_{SR}
$\mu\tau_h$	$\mathrm{t\bar{t}}$	1.04 ± 0.17	0.65 ± 0.12	0.74 ± 0.06	0.91 ± 0.24
	other	0.68 ± 0.13	0.94 ± 0.17	0.93 ± 0.06	0.69 ± 0.19
$e\tau_h$	$\mathrm{t\bar{t}}$	0.95 ± 0.18	0.86 ± 0.12	0.78 ± 0.07	1.05 ± 0.28
	other	1.02 ± 0.16	0.62 ± 0.18	0.98 ± 0.07	0.65 ± 0.22

Results





	Mass [TeV] (N_{obs})	$\tau_\mu \tau_h$	$\tau_e \tau_h$
N_{bkg}	[0.68,0.92] (1)	0.20 ± 0.09	0.22 ± 0.10
	[0.85,1.15] (0)	0.25 ± 0.11	0.25 ± 0.10
	[1.25,1.75] (0)	0.05 ± 0.02	0.06 ± 0.02
	[1.70,2.30] (0)	0.005 ± 0.002	0.006 ± 0.002
	[2.10,2.90] (0)	0.001 ± 0.0003	0.002 ± 0.0005

Systematics

Source	$\tau_\mu \tau_h$ channel	$\tau_e \tau_h$ channel
Luminosity	2.6%	2.6%
Pile-up	0.2–1.4%	0.7–1.2%
Mass window and τ_{21}	8.9%	8.9%
Higgs-b-tag	2.4–10%	2.4–10%
b-tag for veto	6.2–8.8%	6.0–8.5%
Jet energy scale	2.2–2.4%	1.1–2.2%
Jet energy resolution	$<$ 0.5–1.1%	0.5–1.2%
Electron ID	-	1.3–1.8%
Electron energy resolution	-	0.2–0.7%
Electron energy scale	-	0.1–0.4%
Muon ID	0.8–0.9%	-
Muon momentum resolution	$<$ 0.5%	-
Muon momentum scale	$<$ 0.5–0.8%	-
Lepton modified iso	1.2–14.3%	3.5–20.8%
Tau ID	8.9–12.4%	8.5–11.9%
Tau Scale	$<$ 0.5–1.1%	$<$ 0.5–2.4%
Tau-jet cleaning	0.4–7.0%	0.5–15.7%
MET	Included in lepton and jet uncertainties	
Total	16–27%	21–34%

Signal efficiencies

- Signal efficiencies including acceptances and tau pairs branching ratios $\mathcal{B}(\tau\tau)$
- Statistical and systematic uncertainties are included
- The branching ratio of the τ pair in the final state is also shown

	Mass [TeV]	$\tau_\mu\tau_h$	$\tau_e\tau_h$
$\mathcal{B}(\tau\tau)$		22.6%	23.1%
$\varepsilon_{sig}(\%)$	0.8	0.19 ± 0.03(stat) ± 0.03(syst)	0.14 ± 0.03(stat) ± 0.03(syst)
	1.0	1.70 ± 0.09(stat) ± 0.31(syst)	1.10 ± 0.07(stat) ± 0.20(syst)
	1.5	3.16 ± 0.13(stat) ± 0.63(syst)	2.44 ± 0.11(stat) ± 0.48(syst)
	2.0	5.07 ± 0.17(stat) ± 1.17(syst)	3.95 ± 0.15(stat) ± 0.91(syst)
	2.5	4.02 ± 0.14(stat) ± 1.09(syst)	2.60 ± 0.11(stat) ± 0.88(syst)

Limits

- Use the CL s criterion to extract upper bounds on the cross section, combining both event categories
- Test statistic: profile likelihood ratio
- Systematic uncertainties treated as nuisance parameters
  - described with log-normal prior probability distribution functions, except for those related to the extrapolation from sideband events, which are expected to follow a Γ distribution
- For each resonance mass hypothesis, only events in a region corresponding to $\pm$ 2.5 times the expected resolution around each mass point in the resonance mass distribution are considered in the likelihood, thus a shape analysis by counting events in these regions is performed

Search for $W' \rightarrow tb$, Summary

Search for $W' \to t\bar{b}$

$$\mathcal{L} = \frac{V_{q_iq_j}}{2\sqrt{2}} g_W \bar{q}_i \gamma_\mu (a^R_{q_iq_j}(1-\gamma^5) + a^L_{q_iq_j}(1+\gamma^5)) W' q_j + h.c.$$

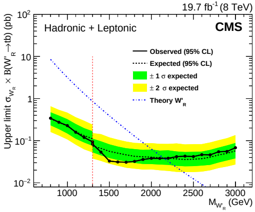
- 3 couplings hypothesis:
  - Purely right-handed W'_R: $a^L_{q_iq_j} = 0, a^R_{q_iq_j} = 1$
  - Purely left-handed W'_L: $a^L_{q_iq_j} = 1, a^R_{q_iq_j} = 0$
  - Mixed-coupling W'_{LR}: $a^L_{q_iq_j} = a^R_{q_iq_j} = 1$

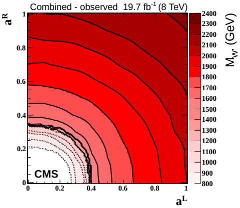
  } interference with SM s-channel single t production

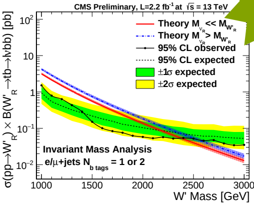
Hadronic t decay	Leptonic t decay
1 t-tag jet + 1 b-tag jet in opposite hemispheres	1 iso lepton (e,μ), ≥2 jets, ≥1 b-tag jet, E_T^{miss}

- Set limits on $\sigma_{W'_R}$ using Bayesian approach, combining hadronic and leptonic W decay modes to enhance sensitivity of the analysis: W'_R with a mass below 2.15 GeV excluded at 95 % C.L.
- Constraints on LH and RH couplígs of W′ to quarks
- Update of **leptonic analysis at 13 TeV**: observed (expected) limit of 2.38 (2.17) TeV already exceed their 8 TeV counterparts despite smaller integrated luminosity

13 TeV







Lept. channel only

Search for $W' \to tb$, 8 TeV, leptonic decay of top

Signal samples

- Sets of signal samples:
  - Purely right-handed W'_R: $a^L_{ud} = a^L_{cs} = a^L_{tb} = 0, a^R_{ud} = a^R_{cs} = a^R_{tb} = 1$
  - Purely left-handed W'_L: $a^L_{ud} = a^L_{cs} = a^L_{tb} = 1, a^R_{ud} = a^R_{cs} = a^R_{tb} = 0$
  - Mixed-couplig W'_{LR}: $a^L_{ud} = a^L_{cs} = a^L_{tb} = a^R_{ud} = a^R_{cs} = a^R_{tb} = 1$
- Interference:
  - W'_L couples to the same fermion multiplets as SM W boson: interference between s-channel tb production via a W and via a W'_L
  - These 2 processes therefore cannot be generated separately: W'_L and W'_{LR} samples include SM s-channel tb production including its interference with W'_L
  - Production of a tb final state via a W'_R does not interfere with tb production via a W: W'_R sample only includes W′ production
- RH neutrino mass:
  - $M(\nu_R) + M(l) < M(W')$: W'_R can decay leptonically
  - Too large $M(\nu_R)$: W'_R can only decay to $q\bar{q}'$ FS $\Rightarrow BR(W'_R \to tb) \neq BR(W'_L \to tb)$

Selection

- Exactly one isolated electron/muon
- At least 2 jets with $p_T > 120/40$ GeV
- At least one CSVM b-tagged jet
- $E_T^{miss} > 20$ GeV

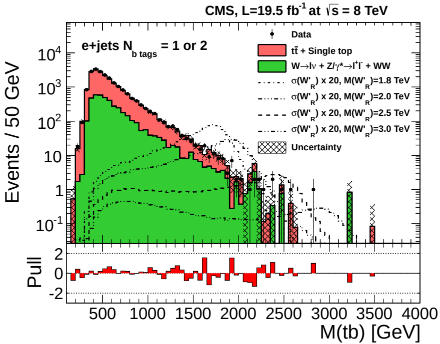
tb invariant mass reconstruction

Reconstructed from the combination of the charged lepton, the neutrino, the jet which gives the best top-quark mass reconstruction, and the highest-p_T jet in the event that is not associated with the top quark

- W candidate:
  - p_x^ν and p_y^ν obtained from E_T^{miss}
  - p_z^ν calculated by constraining the invariant mass of the lepton-neutrino pair to the W mass
  - Quadratic equation in p_z^ν:
    - 2 real solutions: both are used to reconstruct W candidates
    - Complex solutions: the real part is assigned to p_z^ν and imaginary part forced to 0 by relaxing W mass constraint and recomputing p_T^ν ; p_T^ν that gives the invariant mass of lepton-neutrino pair closest to 80.4 is chosen
- Top candidate:
  - Using W candidate and all selected jets
  - Chosing top candidate with mass closest to 172.5 GeV

tb invariant mass

- Reconstructed invariant-mass distribution of the W′-boson candidates after the final selection
- All events are required to have one or both of the two leading jets tagged as b-jets
- The hatched bands represent the total normalisation uncertainty in the predicted backgrounds



Number of selected data, signal, and background events

- Final selection to improve the signal-to-background discrimination:
  - Top quark candidate $p_T^t > 85$ GeV
  - Vector sum of the 2 leading jets $p_T^{jet1,jet2} > 140$ GeV
  - Top quark cnadidate mass 130 GeV $< M(t) <$ 210 GeV

	Number of selected events							
	Electron sample				Muon sample			
	Preselection		Final selection		Preselection		Final selection	
Process	1 b-tag	2 b-tags	1 b-tag	2 b-tags	1 b-tag	2 b-tags	1 b-tag	2 b-tags
Signal:								
$M(W'_R) = 1.8$ TeV	45.2	12.7	32.2	9.3	38.0	10.8	26.3	7.7
$M(W'_R) = 2.0$ TeV	20.9	5.6	14.6	4.0	17.5	4.7	11.8	3.2
$M(W'_R) = 2.5$ TeV	3.5	0.9	2.3	0.6	3.0	0.8	1.8	0.5
$M(W'_R) = 3.0$ TeV	0.8	0.3	0.5	0.2	0.7	0.2	0.4	0.2
$M(W'_L) = 1.8$ TeV	143.0	60.9	57.1	19.7	148.8	63.7	58.1	19.5
$M(W'_L) = 2.0$ TeV	125.2	57.9	44.7	17.8	128.3	61.0	45.7	18.1
$M(W'_L) = 2.5$ TeV	115.8	58.6	38.4	17.2	122.3	62.6	41.6	17.7
$M(W'_L) = 3.0$ TeV	121.3	58.1	41.0	16.7	126.6	64.4	42.2	17.9
Background:								
$t\bar{t}$	34561	7888	12383	1639	35349	8191	12610	1650
s-channel (tb)	175	93	58	28	196	102	63	32
t-channel (tqb)	2113	357	710	108	2275	373	747	114
tW-channel	2557	362	847	107	2645	372	861	113
$W(\to \ell\nu)$+jets	19970	563	3636	99	19697	679	3704	62
$Z/\gamma^*(\to \ell\ell)$+jets	1484	83	260	10	1497	73	275	17
WW	205	9	47	3	219	7	47	2
Total bkg.	61065 $\pm$6188	9357 $\pm$1504	17942 $\pm$2514	1993 $\pm$399	61877 $\pm$6098	9797 $\pm$1524	18307 $\pm$2488	1991 $\pm$400
Data	63050	9646	18175	2063	62955	9865	18558	2081
Total bkg. / Data	0.969 $\pm$0.10	0.970 $\pm$0.16	0.987 $\pm$0.14	0.966 $\pm$0.19	0.983 $\pm$0.10	0.993 $\pm$0.15	0.986 $\pm$0.13	0.957 $\pm$0.19

Background modeling

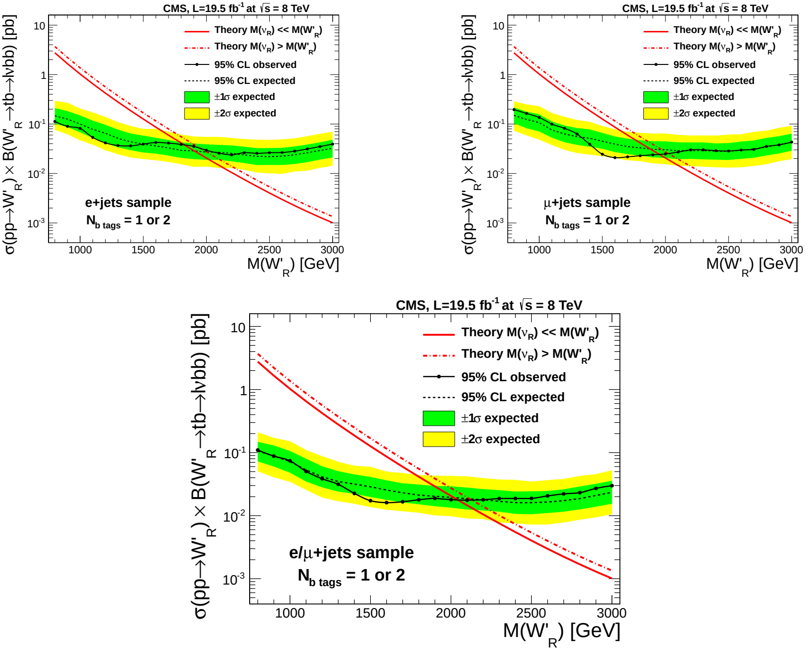
- The $t\bar{t}$, W+jets, single-top-quark (s-channel, t-channel, and tW associated production), Z/γ^*+jets, and diboson (WW) background contributions are estimated from simulation, with corrections to the shape and normalisation derived from data
- W+jets: major backgrounds for W' signal process (see table), study performed to check that the W+jets mass distribution is well-modelled by the simulation
  - Utilizes the fact that events that have no b-tagged jets, but satisfy all other selection criteria, are expected to originate predominantly from W+jets events
  - The purity of W+jets events for this control sample is greater than 85%
  - The shape of the W+jets background is obtained by subtracting the backgrounds from sources other than W+jets from the distributions in data
  - The resulting invariant-mass distribution is compared to the distribution from the W+jets MC sample with zero b-tagged jets
  - The difference between the distributions is included as a systematic uncertainty in the shape of the W+jets background
  - Using simulated events, the W+jets background was verified to be independent of the number of b-tagged jets by comparing the mass distribution with zero b-tagged jets with that obtained by requiring one or more b-tagged jets

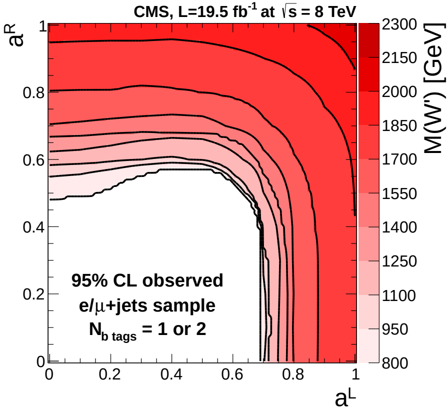
Limits on coupling strength

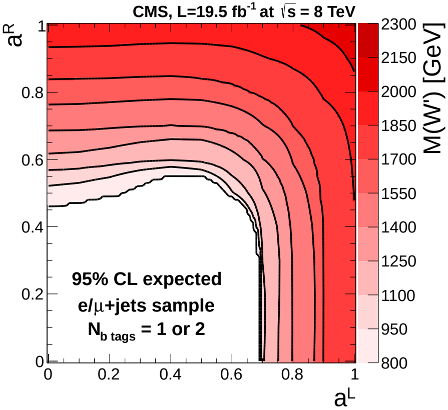
- Effective Lagrangian: $\mathcal{L} = \frac{V_{q_i q_j}}{2\sqrt{2}} g_W \bar{q}_i \gamma_\mu (a^R_{q_i q_j}(1-\gamma^5) + a^L_{q_i q_j}(1+\gamma^5)) W' q_j + h.c.$
- Can be analysed for arbitrary combinations of LH or RH couplings strenghts
- Cross section for single-top-quark production in presence of W′ for any set of coupling can be written in terms of cross sections of signal MC samples:
  - σ_L for purely LH couplings $(a^L, a^R) = (1, 0)$
  - σ_R for purely RH couplings $(a^L, a^R) = (0, 1)$
  - σ_{LR} for mixed couplings $(a^L, a^R) = (1, 1)$
  - σ_{SM} for SM couplings $(a^L, a^R) = (0, 0)$

$$\sigma = \sigma_{SM} + a^L_{ud} a^L_{tb} (\sigma_L - \sigma_R \sigma_{SM}) + \left((a^L_{ud} a^L_{tb})^2 + (a^R_{ud} a^R_{tb})^2 \right) \sigma_R + \frac{1}{2} \left((a^L_{ud} a^R_{tb})^2 + (a^R_{ud} a^L_{tb})^2 \right) (\sigma_{LR} - \sigma_L - \sigma_R)$$

- a_{ud}: couplings to first-generation quarks (important for W′ production)
- a_{tb}: couplings to third-generation quarks (important for W′ decay)
- Assumption: $a_{ud} = a_{tb}$
- Event samples are combined wrt previous equation to give predicted invariant mass distributions for each a^L and a^R


CMS, L=19.5 fb^{-1} at $\sqrt{s}$ = 8 TeV
Theory M(ν$_R$) << M(W'$_R$)
Theory M(ν$_R$) > M(W'$_R$)
95% CL observed
95% CL expected
±1σ expected
±2σ expected
e+jets sample
N$_{b\ tags}$ = 1 or 2
μ+jets sample
N$_{b\ tags}$ = 1 or 2
e/μ+jets sample
N$_{b\ tags}$ = 1 or 2
σ(pp→W'$_R$) × B(W'$_R$→tb→lνbb) [pb]
M(W'$_R$) [GeV]

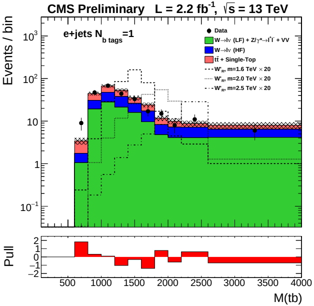

CMS, L=19.5 fb^{-1} at $\sqrt{s}$ = 8 TeV
a^R
a^L
M(W') [GeV]
2300
2150
2000
1850
1700
1550
1400
1250
1100
950
800
95% CL observed
e/μ+jets sample
$N_{b\ tags}$ = 1 or 2

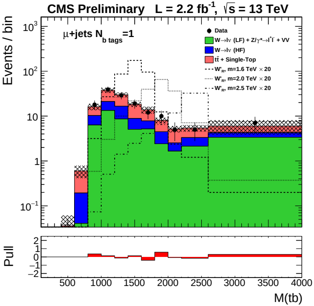

CMS, L=19.5 fb^{-1} at $\sqrt{s}$ = 8 TeV
a^R
a^L
M(W') [GeV]
2300
2150
2000
1850
1700
1550
1400
1250
1100
950
800
95% CL expected
e/μ+jets sample
$N_{b\ tags}$ = 1 or 2

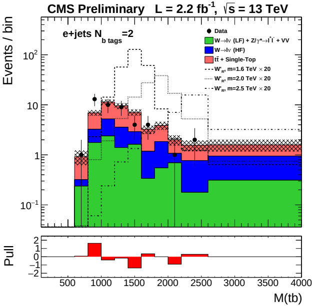
Search for $W' \to tb$, 13 TeV, leptonic decay of top (only W'_R)

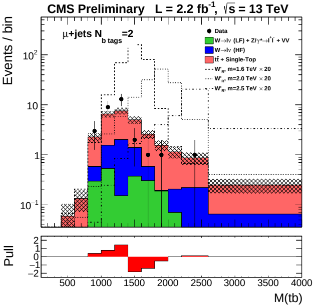
Selection

- Exactly 1 electron (muon) with $p_T > 180$ GeV (180) and $|\eta| < 2.5$ (2.1)
    - Veto on additional charged leptons with $p_T > 35$ GeV and $|\eta| < 2.4/2.5$ (muon/electron)
- Leading jet $p_T > 350$ GeV (450 GeV)
- Second jet $p_T > 30$ GeV
- $E_T^{miss} > 120$ (50) GeV
- ΔR(lepton, closest jet) > 0.4 or p_T^{rel}(lepton, closest jet) > 60 (50) GeV
- for electron channel: $|\Delta\Phi(E_T^{miss}, e)| < 2$


CMS Preliminary L = 2.2 fb-1, √s = 13 TeV
e+jets N b tags =1
Data
W→lν (LF) + Z/γ*→l+l- + VV
W→lν (HF)
tt̄ + Single-Top
W'R, m=1.6 TeV × 20
W'R, m=2.0 TeV × 20
W'R, m=2.5 TeV × 20
Events / bin
Pull
M(tb)


CMS Preliminary L = 2.2 fb-1, √s = 13 TeV
μ+jets N b tags =1
Data
W→lν (LF) + Z/γ*→l+l- + VV
W→lν (HF)
tt̄ + Single-Top
W'R, m=1.6 TeV × 20
W'R, m=2.0 TeV × 20
W'R, m=2.5 TeV × 20
Events / bin
Pull
M(tb)


CMS Preliminary L = 2.2 fb-1, √s = 13 TeV
e+jets N b tags =2
Data
W→lν (LF) + Z/γ*→l+l- + VV
W→lν (HF)
tt̄ + Single-Top
W'R, m=1.6 TeV × 20
W'R, m=2.0 TeV × 20
W'R, m=2.5 TeV × 20
Events / bin
Pull
M(tb)

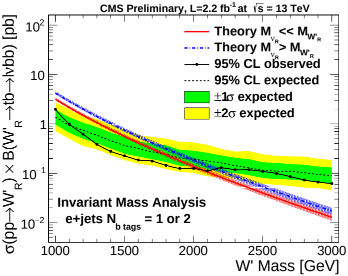

CMS Preliminary L = 2.2 fb-1, √s = 13 TeV
μ+jets N b tags =2
Data
W→lν (LF) + Z/γ*→l+l- + VV
W→lν (HF)
tt̄ + Single-Top
W'R, m=1.6 TeV × 20
W'R, m=2.0 TeV × 20
W'R, m=2.5 TeV × 20
Events / bin
Pull
M(tb)

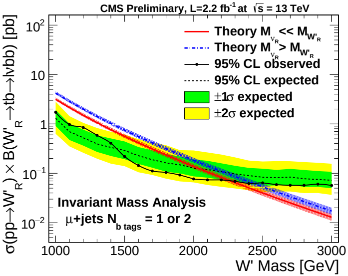
Number of selected data, signal, and background events in the muon channel

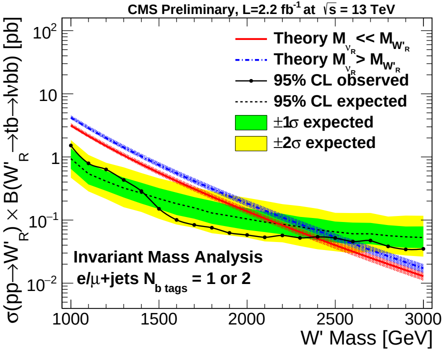
Process	Number of Events					
	Object Selection				Final Selection	
	≥ 0 b-tags	$= 0$ b-tags	$= 1$ b-tags	$= 2$ b-tags	$= 1$ b-tags	$= 2$ b-tags
Data:	770	431	281	58	143	30
Background:						
$t\bar{t}$	124	36	64	25	46	16
tqb	7	2	4	1	3	1
tW	17	5	9	3	4	1
$\bar{t}W$	16	3	9	4	5	2
tb	1	0	0	0	0	0
W($\rightarrow \ell\nu$)+jj	304	218	80	6	25	1
W($\rightarrow \ell\nu$)+bb/cc	283	132	128	23	45	7
Z($\rightarrow \ell\ell$)+jets	47	26	21	0	12	0
VV	20	17	3	0	0	0
Total Background	819±60	439±36	318±24	62±5	140±11	28±3

Number of selected data, signal, and background events in the electron channel

Process	Number of Events					
	Object Selection				Final Selection	
	≥ 0 b-tags	$= 0$ b-tags	$= 1$ b-tags	$= 2$ b-tags	$= 1$ b-tags	$= 2$ b-tags
Data:	802	435	309	58	256	44
Background:						
$t\bar{t}$	132	40	68	24	52	17
tqb	8	2	5	2	4	1
tW	22	5	11	6	10	5
$\bar{t}W$	20	4	11	4	9	4
tb	1	0	1	0	1	0
W($\rightarrow \ell\nu$)+jj	359	262	89	8	77	7
W($\rightarrow \ell\nu$)+bb/cc	306	146	139	22	119	18
Z($\rightarrow \ell\ell$)+jets	9	8	3	-1	4	-1
VV	26	17	9	0	7	0
Total Background	883±83	484±50	336±32	65±7	283±22	51±5


CMS Preliminary, L=2.2 fb^{-1} at $\sqrt{s}$ = 13 TeV
Theory $M_{\nu_R} << M_{W'_R}$
Theory $M_{\nu_R} > M_{W'_R}$
95% CL observed
95% CL expected
±1σ expected
±2σ expected
Invariant Mass Analysis
e+jets $N_{b\ tags}$ = 1 or 2
$\sigma(pp \to W'_R) \times B(W'_R \to tb \to l\nu bb)$ [pb]
W' Mass [GeV]


CMS Preliminary, L=2.2 fb^{-1} at $\sqrt{s}$ = 13 TeV
Theory $M_{\nu_R} << M_{W'_R}$
Theory $M_{\nu_R} > M_{W'_R}$
95% CL observed
95% CL expected
±1σ expected
±2σ expected
Invariant Mass Analysis
μ+jets $N_{b\ tags}$ = 1 or 2
$\sigma(pp \to W'_R) \times B(W'_R \to tb \to l\nu bb)$ [pb]
W' Mass [GeV]


CMS Preliminary, L=2.2 fb^{-1} at $\sqrt{s}$ = 13 TeV
Theory $M_{\nu_R} << M_{W'_R}$
Theory $M_{\nu_R} > M_{W'_R}$
95% CL observed
95% CL expected
±1σ expected
±2σ expected
Invariant Mass Analysis
e/μ+jets $N_{b\ tags}$ = 1 or 2
$\sigma(pp \to W'_R) \times B(W'_R \to tb \to l\nu bb)$ [pb]
W' Mass [GeV]

Search for $W' \to tb$, 8 TeV, hadronic decay of top

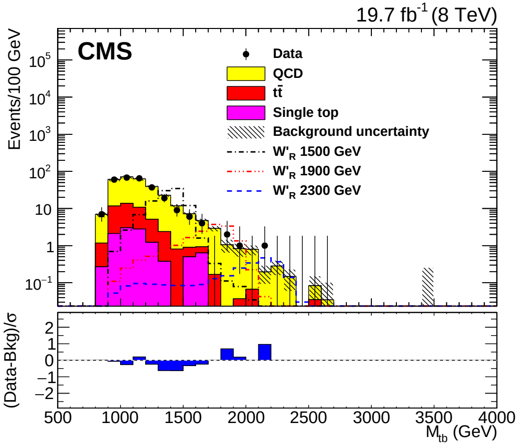
Combined CMS t-tagging algorithm

- $t \to bW \to bq\bar{q}'$ and high boost: the 3 jets merged in a large single jet
- Jets are reclustered using CA algorithm with distance parameter 0.8
- Combined CMS t-tagging: t-tagger + N subjettiness + b tag info
  - t-tagger:
    - 140 < $M_{CA\ Jet}$ 250 GeV
    - $N_{subjets}$ > 2 (found by the algortihm)
    - Minimum pairwise mass M_{min} > 50 GeV (consistency with W mass)
  - N subjettiness algorithm:
    - Variables τ_N describe consistency between the jet energy and the number N of assumed subjets
    - $\tau_N = \frac{1}{d}\sum_i p_{T,i}\min(\Delta R_{1,i}, \Delta R_{1,i}, \ldots, \Delta R_{N,i})$, specific constituent particle i, subjet candidate J, d the normalisation factor ($d = \sum_i p_{T,i} R$)
    - τ_3/τ_2 < 0.55
  - b-tag info:
    - CSV b-tag algo applied to all subjets found by the top-tagging algo
    - We require maximum CSV discriminator value to pass CSVM WP ($SJ_{CSVMAX} \geq 0.679$)

Selection

$W' \rightarrow tb$ candidate selected after applying the following selection on the 2 leading jets:

- One jet with p_T 450 GeV and t-tagged
- One jet with p_T 370 GeV and b-tagged (CSVM) and mass < 70 GeV
- 2 jets in opposite hemispheres: $|\Delta\phi| > \pi/2$
- $|\Delta y| < 1.6$ between the 2 jets



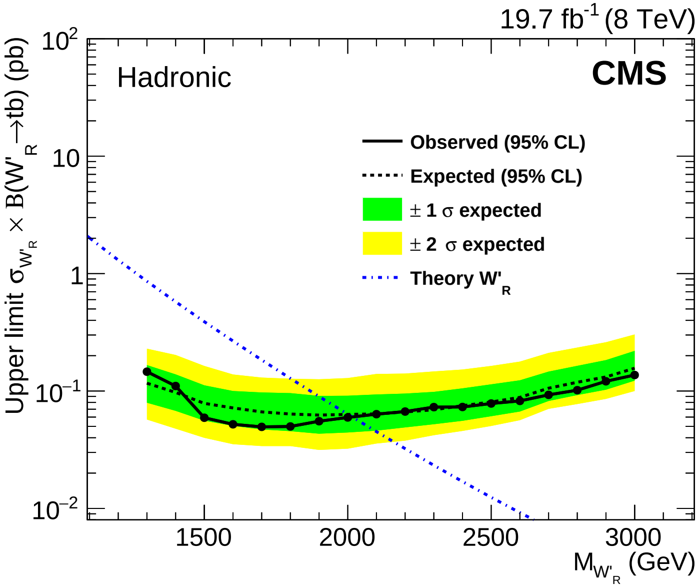
Numbers of observed and expected events at successives stages of the event selection

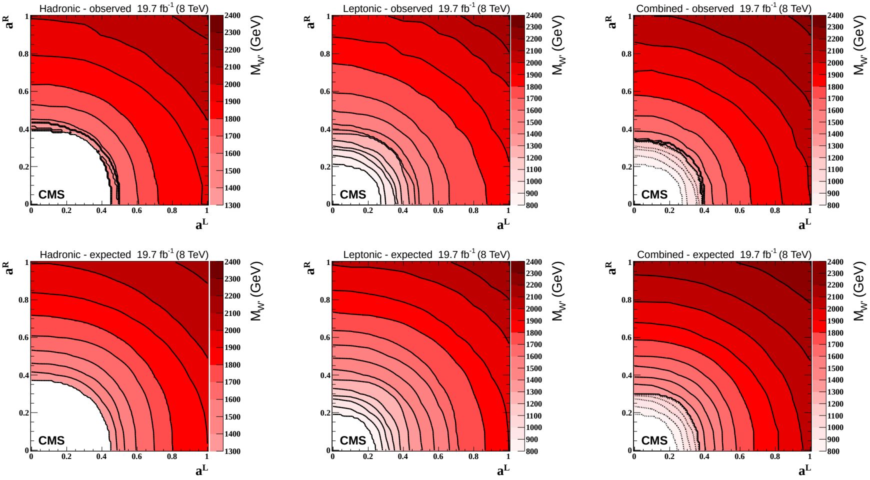
Selection	Data	QCD	$t\bar{t}$	$M_{W'_R}$ 1.90 TeV	$M_{W'_R}$ 2.10 TeV	$M_{W'_L}$ 1.90 TeV	$M_{W'_L}$ 2.10 TeV
2 jets	13854873	—	12190 ± 27	806 ± 1	401 ± 0.7	796 ± 2	430 ± 2
p_T	4305244	—	4720 ± 18	739 ± 1	372 ± 0.7	703 ± 2	364 ± 2
$\lvert\Delta y\rvert$	3376771	—	4220 ± 17	553 ± 1	268 ± 0.6	531 ± 2	268 ± 1
M_t	992949	—	3220 ± 14	429 ± 1	209 ± 0.5	414 ± 2	205 ± 1
$N_{subjets}$	557489	—	2740 ± 13	340 ± 0.9	163 ± 0.5	312 ± 2	152 ± 1
M_{min}	318520	—	2510 ± 13	304 ± 0.9	143 ± 0.4	274 ± 2	130 ± 0.9
SJ_{CSVMAX}	50642	—	1690 ± 10	170 ± 0.6	76 ± 0.3	138 ± 1	63 ± 0.6
τ_3/τ_2	7200	—	1024 ± 8	88 ± 0.5	38 ± 0.2	58 ± 0.7	27 ± 0.4
M_b	4463	—	178 ± 4	68 ± 0.4	29 ± 0.2	44 ± 0.6	20 ± 0.3
CSV	277	248 ± 4	37 ± 1	16 ± 0.2	6 ± 0.1	10 ± 0.3	4 ± 0.2

Background modeling

- Primary sources of background: SM QCD multijet and $t\bar{t}$ production
- Principal background: QCD multijet production, estimated using a data-driven technique to extract both the shape and the normalization
- Shape of the M_{tb} distribution for $t\bar{t}$ production is estimated from MC simulation, and the yield is measured from data using a control sample enriched in $t\bar{t}$ events
- Control region closure test

Expected limit for the hadronic channel




Hadronic - observed 19.7 fb^{-1} (8 TeV)
Leptonic - observed 19.7 fb^{-1} (8 TeV)
Combined - observed 19.7 fb^{-1} (8 TeV)
Hadronic - expected 19.7 fb^{-1} (8 TeV)
Leptonic - expected 19.7 fb^{-1} (8 TeV)
Combined - expected 19.7 fb^{-1} (8 TeV)
a^R
a^L
$M_{W'}$ (GeV)
CMS

Search for resonant $t\bar{t}$ production in boosted semileptonic final states at 13 TeV

Selection

- 1 muon (electron) with $p_T > 50$ (50) GeV and $|\eta| < 2.1$ (2.5)
- ≥ 2 jets with $|\eta| < 2.4$
  - $p_T^{jet1} > 150$ (250) GeV for muon (electron) channel
  - $p_T^{jet2} > 50$ (70) GeV for muon (electron) channel
- No isolation for leptons but 2D requirement instead:
  - $\Delta R(l,j) > 0.4$ or $p_T^{rel}(l,j) > 20$ GeV (j: small-radius jet with minimum angular separation to the lepton ; p_T^{rel}: magnitude of p_T lepton orthogonal to jet axis)
  - measurement of lepton 2D-cut efficiency in data using $Z \to ll$ (tag-and-probe method) CR
- $H_T^{lep} = E_T^{miss} + p_T^{lep} > 150$ GeV (muon channel)
- $E_T^{miss} > 50$ (120) GeV for muon (electron) channel
- Veto on additional lepton

$M_{t\bar{t}}$ reconstruction

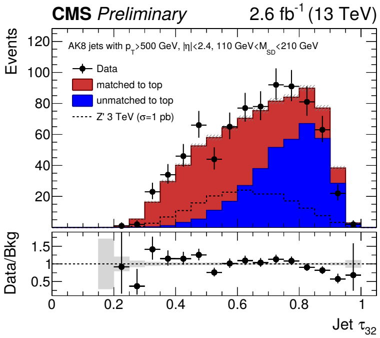
- 2 collections of jets:
  - Small-radius jets (AK4 jets)
  - Large-radius jets (AK8 jets)
- Use small-radius jets for b-tagging
- Use large-radius jets for top tagging
  - Soft-drop mass: $110 < M_{SD} < 210$ GeV
  - $\tau_{32} < 0.69$
- Events without top-tagged jet: only small-radius jets are used for both hadronic and leptonic top reconstruction
- Events with top-tagged jet: top-tagged jet assigned to hadronic top and only small-radius jets with $\Delta R > 1.2$ from t-tagged jet are used to reconstruct leptonic top decay

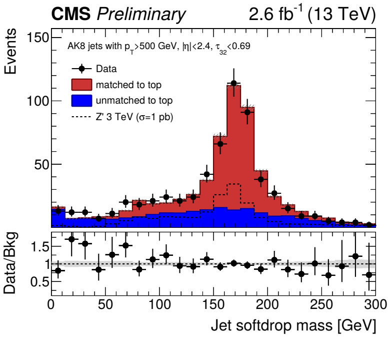
$$\chi^2 = \left(\frac{M_{lep} - \bar{M}_{lep}}{\sigma_{M_{lep}}}\right)^2 + \left(\frac{M_{had} - \bar{M}_{had}}{\sigma_{M_{had}}}\right)^2$$

- Take hypothesis with smallest χ^2 (χ^2_{min})
- Signal region: events are required to have $\chi^2_{min} < 30$

Validation of t-tagging variables distributions

- $\chi^2_{min} < 30$: events dominated by $t\bar{t}$ background (plots)
- $\chi^2_{min} > 30$: events dominated by W+jets background
- Good agreement between data and simulation





Categorization

- 6 categories based on lepton flavour, number of b-tagged and t-tagged jets:
  - 1 t-tag, 0 t-tag + 1 b-tag, 0 t-tag + 0 b-tag

Background model and normalization

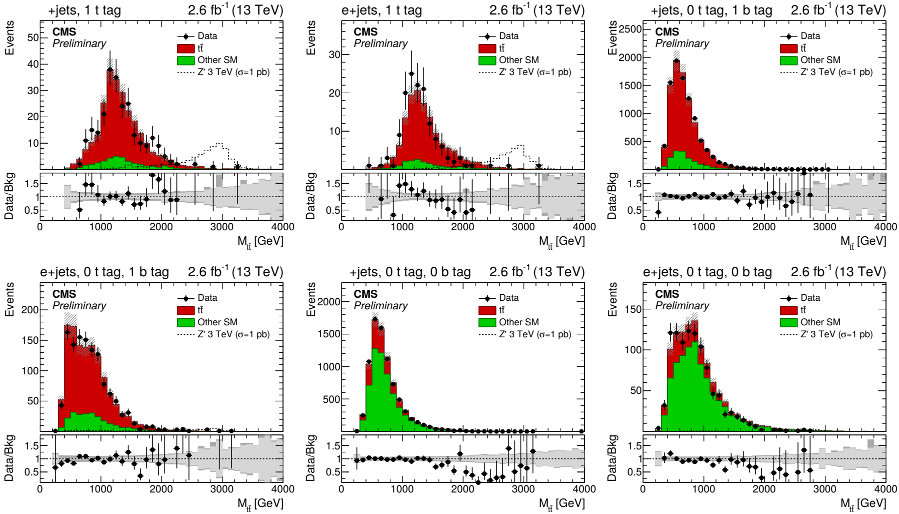
- Final background estimates determined by fitting background-only hypothesis to the data
- Several observables used simultaneously in a binned maximum likelihood fit to constraint different uncertainties of bkg model using the data
- Different observables:
  - $M_{t\bar{t}}$ in low-mass l+jets SR ($M_{t\bar{t}}$ < 2 TeV, χ^2_{min} < 30):
  - $M_{t\bar{t}}$ in high-χ^2 CR (χ^2_{min} > 30):
  - M_{ll} in dilepton CR (remove lepton veto, Z-mass window 71 < M_{ll} < 111 GeV):
- $\sigma_{t\bar{t}}$, σ_{W+jets}, σ_{Z+jets} and t-tag SF left unconstrained in the fit
  - Derived from MLFit

Main systematics

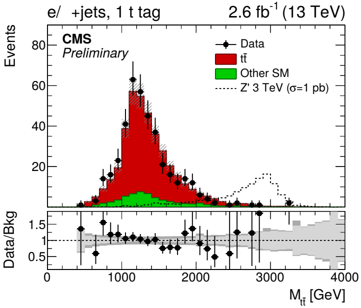
Table 1: Summary of largest systematic uncertainties for the $t\bar{t}$ and $W+$jets backgrounds and a Z' signal with mass of 2 TeV and relative width of 1%. Shown are the posterior values. Uncertainties affecting all categories equally originate from the luminosity measurement (2.7%), the trigger efficiency (1.3%) and the lepton identification (1.2%). The posterior uncertainties on the cross sections are 6% for both, $t\bar{t}$ and $W+$jets production.

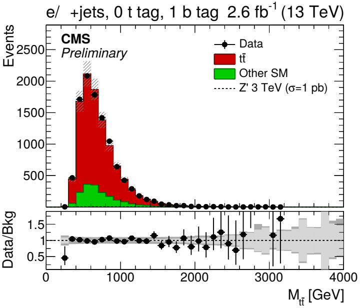
	1-toptag			0-toptag, 1-btag			0-toptag, 0-btag		
	$t\bar{t}$	$W+$jets	Z'	$t\bar{t}$	$W+$jets	Z'	$t\bar{t}$	$W+$jets	Z'
t- and b-tagging	6.7%	17.0%	7.3%	1.7%	3.6%	5.8%	6.1%	1.1%	12.1%
Scale uncertainty	4.1%	9.9%	–	5.3%	6.1%	–	5.7%	5.8%	–
PDF	2.7%	4.8%	4.2%	1.5%	3.6%	4.2%	1.8%	3.2%	4.8%

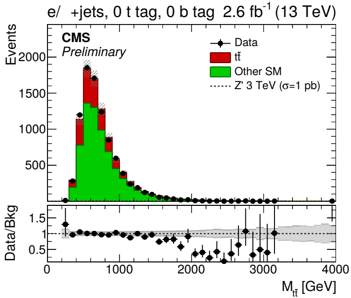
$M_{t\bar{t}}$ distributions after maximum likelihood fit



$M_{t\bar{t}}$ distributions after maximum likelihood fit: summing e and μ







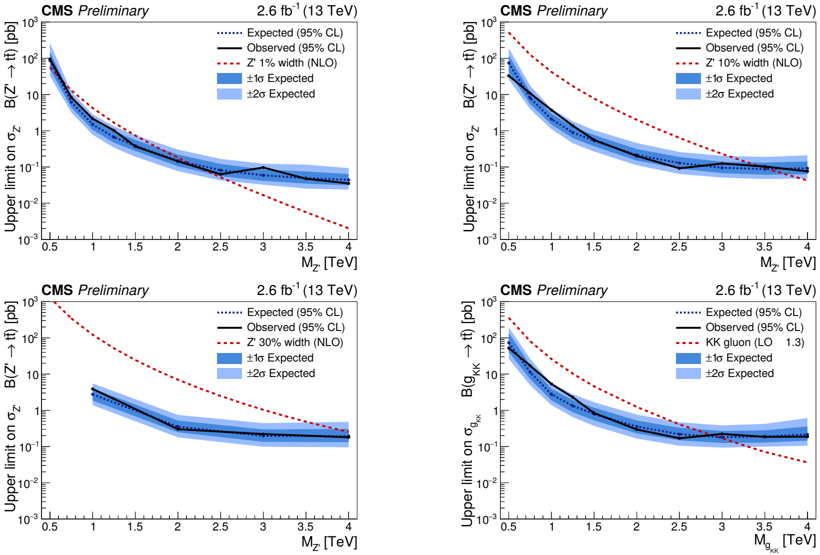
Number of events in signal region

Table 2: Number of events in the signal region. The expected yields for SM backgrounds are obtained from the maximum-likelihood fit to the data described in the text. The uncertainties reported for the background processes include the MC statistical uncertainties and the posterior systematic uncertainties on the SM cross sections.

μ + **jets signal region**	1-toptag	0-toptag, 1-btag	0-toptag, 0-btag
$t\bar{t}$	218 ± 36	7599 ± 1252	1964 ± 324
W + jets (light-f)	26 ± 2	546 ± 42	4665 ± 353
W + jets (heavy-f)	4 ± 1	332 ± 27	779 ± 61
single-top + DY + VV	10 ± 2	683 ± 118	635 ± 80
Total Background	258 ± 36	9160 ± 1258	8043 ± 489
DATA	252	9230	7966

e + **jets signal region**	1-toptag	0-toptag, 1-btag	0-toptag, 0-btag
$t\bar{t}$	119 ± 20	1015 ± 167	247 ± 41
W + jets (light-f)	13 ± 1	97 ± 8	680 ± 52
W + jets (heavy-f)	2 ± 0	44 ± 4	84 ± 7
single-top + DY + VV	4 ± 1	103 ± 19	75 ± 10
Total Background	138 ± 20	1259 ± 168	1086 ± 67
DATA	142	1217	1005

Limits



CMS Preliminary
2.6 fb^{-1} (13 TeV)
Expected (95% CL)
Observed (95% CL)
Z' 1% width (NLO)
±1σ Expected
±2σ Expected
Upper limit on $\sigma_{Z'}$ B($Z' \to t\bar{t}$) [pb]
$M_{Z'}$ [TeV]
CMS Preliminary
2.6 fb^{-1} (13 TeV)
Expected (95% CL)
Observed (95% CL)
Z' 10% width (NLO)
±1σ Expected
±2σ Expected
Upper limit on $\sigma_{Z'}$ B($Z' \to t\bar{t}$) [pb]
$M_{Z'}$ [TeV]
CMS Preliminary
2.6 fb^{-1} (13 TeV)
Expected (95% CL)
Observed (95% CL)
Z' 30% width (NLO)
±1σ Expected
±2σ Expected
Upper limit on $\sigma_{Z'}$ B($Z' \to t\bar{t}$) [pb]
$M_{Z'}$ [TeV]
CMS Preliminary
2.6 fb^{-1} (13 TeV)
Expected (95% CL)
Observed (95% CL)
KK gluon (LO 1.3)
±1σ Expected
±2σ Expected
Upper limit on $\sigma_{g_{KK}}$ B($g_{KK} \to t\bar{t}$) [pb]
$M_{g_{KK}}$ [TeV]

Limits summary

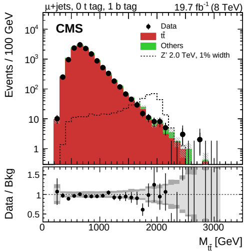
Table 3: Observed and expected excluded mass ranges for the BSM models considered in the statistical analysis. Mass limits are given for the $\mu+$jets and $e+$jets channels separately and for their combination.

signal	excluded mass regions [TeV] $\mu+$jets observed (expected)	$e+$jets observed (expected)	combination observed (expected)
Z' (1% width)	$0.5-1.8$ $(0.6-1.9)$	$1.0-1.1, 1.3-2.2$ $(0.9-1.7)$	$0.6-2.3$ $(0.6-2.1)$
Z' (10% width)	$0.5-3.2$ $(0.5-3.3)$	$0.5-3.2$ $(0.5-3.2)$	$0.5-3.4$ $(0.5-3.5)$
Z' (30% width)	$0.5-3.9$ $(0.5-4.0)$	$0.5-3.8$ $(0.5-3.8)$	$0.5-4.0$ $(0.5-4.0)$
KK gluon	$0.5-2.7$ $(0.5-2.8)$	$0.6-2.7$ $(0.6-2.5)$	$0.5-2.9$ $(0.5-2.9)$

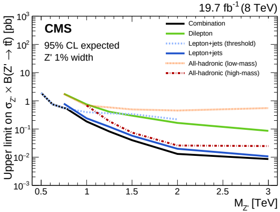
Search for resonant $t\bar{t}$ production at 8 TeV

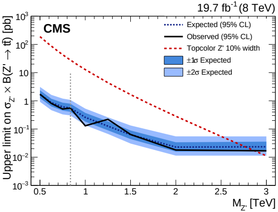
Search for $t\bar{t}$ resonances

- Many BSM models predict heavy resonances with enhanced coupling to the top
  - Leptophobic topcolor Z′ bosons
  - Kaluza–Klein excitations of a gluon in the Randall–Sundrum model
- Model-independent search for the production of heavy resonance decaying into top pair
- Dedicated analyses depending on W decay mode:
  - Dilepton
  - Lepton+jets: one analysis optimized for boosted topologies, one for threshold production of $t\bar{t}$ (best sensitivity for resonance masses below 0.75 TeV)
  - All-hadronic: 2 different selections, one optimized for higher resonance masses, one for lower resonance masses (decay products still collimated)
- $M_{t\bar{t}}$ distributions show no evidence of signal



- Combining analyses (lepton+jets thresold result below 0.75 TeV, combination of boosted analysis above) to set 95% CL upper limits on $\sigma_{sig} \times \mathcal{B}(sig \to t\bar{t})$ using Bayesian method (likelihood: product of Poisson laws in each bin for each cat. in each channel)

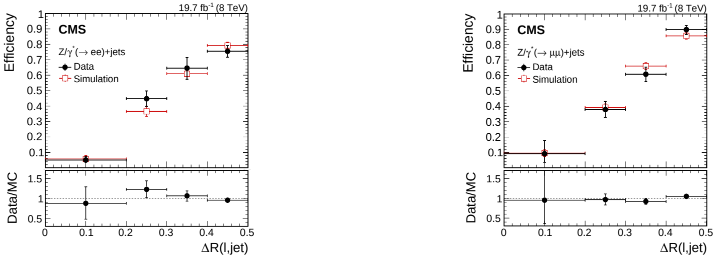




	95% CL M(signal) exclusion limit (TeV)	
Signal	Expected	Observed
$Z', \Gamma_{Z'}/M_{Z'} = 1.2\%$	2.4	2.4
$Z', \Gamma_{Z'}/M_{Z'} = 10\%$	2.8	2.9
RS KK gluon	2.7	2.8

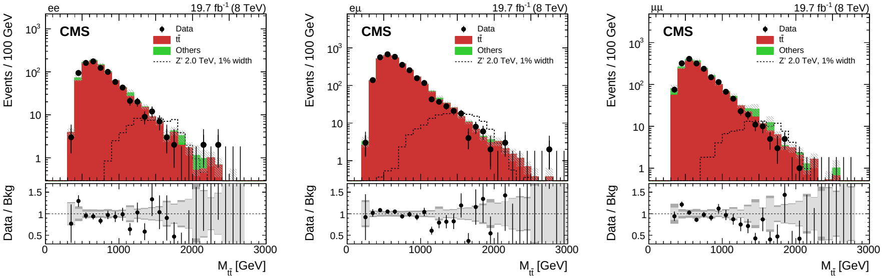
Selection: dilepton channel

- 2 leptons of opposite charges (from highly Lorentz-boosted top: non isolated lepton that partially or fully overlaps with the b jet)
  - ee channel: 2 electrons with $p_T > 85/20$ GeV, $|\eta| < 2.5$
  - eμ channel: 1 muon with $p_T > 45$ GeV and $|\eta| < 2.1$, and 1 electron with $p_T > 20$ GeV, $|\eta| < 2.5$
  - $\mu\mu$ channel: 2 muons with $p_T > 45/20$ GeV and $|\eta| < 2.1/2.4$
- $M_{ll} > 12$ GeV and outside $76 < M_{ll} < 106$ GeV (ee and $\mu\mu$ channels)
- At least 2 jets with $p_T > 100/50$ GeV and $|\eta| < 2.5$
- 2D isolation variable: $\Delta R(l, jet) > 0.5$ or $p_{T,rel}(l, jet) > 15$ GeV ($p_T(l)$ wrt the axis of the closest jet) (using only jets with $p_T > 30$ GeV)
- $E_T^{miss} > 30$ GeV (ee and $\mu\mu$ channels)
- At least 1 of the 2 leading jets required to be b-tagged (CSVM) OR both b-tagged (CVSL)
- $\Delta R(l_1, jet) < 1.2$ and $\Delta R(l_2, jet) < 1.5$



Dilepton channel: mass reconstruction

- $M(p_{l_1} + p_{l_2} + p_{j_1} + p_{j_2} + p_{\nu_1} + p_{\nu_2}) \sim M(t\bar{t})$
- Use $\vec{p}_T^{miss}$ x and y components as p_x and p_y of the pair of neutrinos, p_z components of each neutrino is set to 0

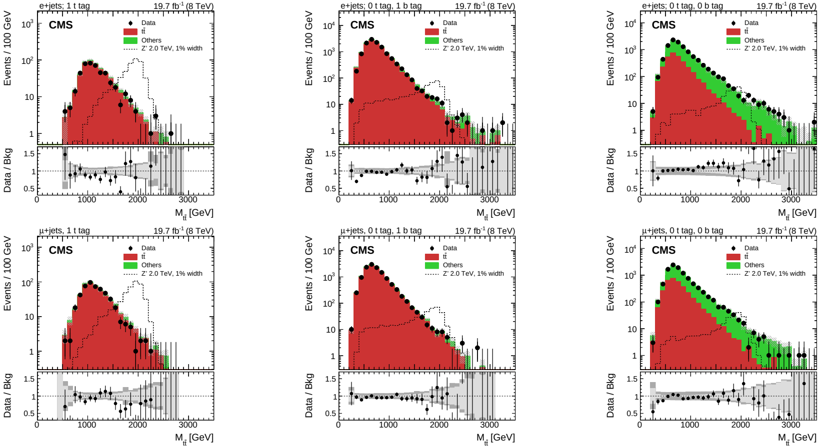


Selection: lepton+jets channel (boosted analysis)

- Exactly 1 electron with $p_T > 35$ GeV and $|\eta| < 2.5$ or 1 muon with $p_T > 45$ GeV and $|\eta| < 2.1$
- Veto on a second reconstructed lepton (avoid overlap with dilepton channel)
- At least 2 jets with $p_T > 150/50$ GeV and $|\eta| < 2.4$
- Reject event with $\geq$2 CA8 t-tagged jets (avoid overlap with all-hadronic channel)
- $E_T^{miss} > 50$ GeV
- $p_T^l + E_T^{miss} > 150$ GeV
- 2D isolation criteria: $\Delta R(l, jet) > 0.5$ or $p_{T,rel}(l, jet) > 25$ GeV (using only jets with $p_T > 25$ GeV)
- Ensure $\vec{p}_T^{miss}$ not pointing along transverse direction of electron or leading jet: $|\Delta(e\,or\,jet, \vec{p}_T^{miss}) - 1.5| < E_T^{miss}/50$ GeV

Lepton+jets: mass reconstruction

- $\chi^2 = \chi^2_{m_t^{Lep}} + \chi^2_{m_t^{Hadr}} < 50$, choosing jets combination with smallest χ^2
- In case a CA8 t-tagged jet found: all jets with $\Delta R < 1.3$ from the t-tagged jet removed from list of possible hypotheses
- Electron channel: $p_T^{t,Lep} > 140$ GeV (multijet bkg suppression)



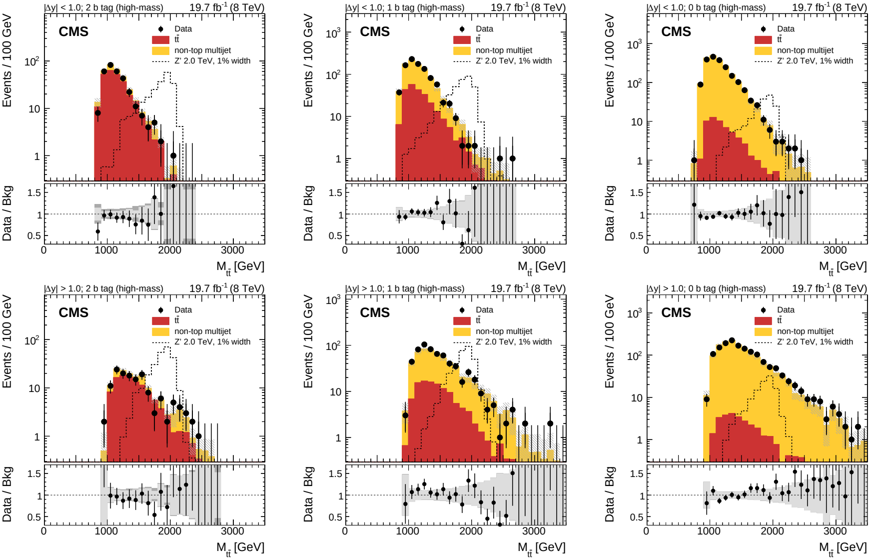
Selection: all-hadronic channel

Two exlusive selection:

- One optimized for higher resonance masses:
  - 2 CA8 t-tagged jets with p_T > 400 GeV and $|y| < 2.4$
  - $|\Delta\phi| > 2.1$ radians between jets (separated in azimutal angle)
  - Rapidity difference between the 2 jets used to divide events in 2 categories : $|\Delta y| < 1.0$ and $|\Delta y| > 1.0$ (QCD multijet bkg with light-quark and gluon FS dominantly populating this region), Z′ signal with m = 2 TeV equally split
  - Subdivided again, depending on number of CA8 t-tagged jets containing b-tagged subjet (0, 1, 2) $\rightarrow$ 6 exclusive search regions with highest sensitivity in the categories with 2 b-tagged CA8 jets
- One optimized for lower resonance masses (decay products still somewhat collimated):
  - Applied to events that failed high mass selection
  - Decay product less collimated
  - 2 CA15 t-tagged jets with p_T > 200 GeV and $|y| < 2.4$
  - Sample split: $H_T < 800$ GeV or $H_T > 800$ GeV ($H_T = \sum p_T^{jet}$, using $p_T^{jet} > 50$ GeV)
  - Subdivided again wrt number of b-tagged CA15 jets

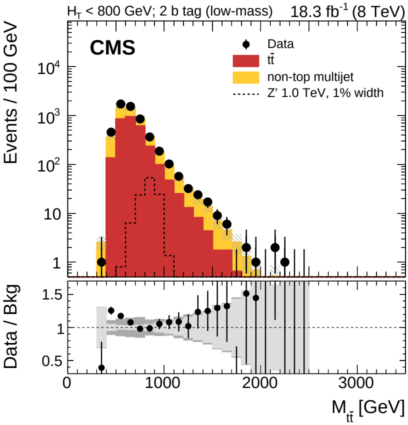
All-hadronic: mass reconstruction

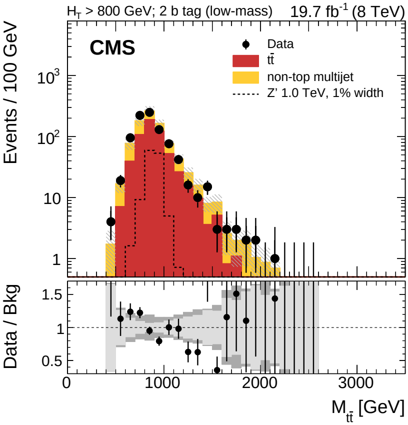
High mass selection



All-hadronic: mass reconstruction

Low mass selection





Background normalization

Boosted analyses:

- Main source of irreducible background in all channels arises from SM $t\bar{t}$ production
- In the lepton+jets channels, W+jets production contributes to events without a CA8 t-tagged jet
- Single top quark, Z+jets, and diboson production constitute small backgrounds overall (dilepton and lepton+jets channels)
- Except for the non-top-quark multijet backgrounds in the all-hadronic channels, the shapes of all SM backgrounds are estimated from simulation
- The total yield of the simulated samples is obtained with a maximum likelihood fit to the $M_{t\bar{t}}$ distributions
  - Nuisance parameters are included in the fit to take into account the effect of systematic uncertainties
  - The parameters are constrained using log-normal probability density functions and are fitted simultaneously with the parameters corresponding to the background normalization

Threshold analysis (lepton+jets channel):

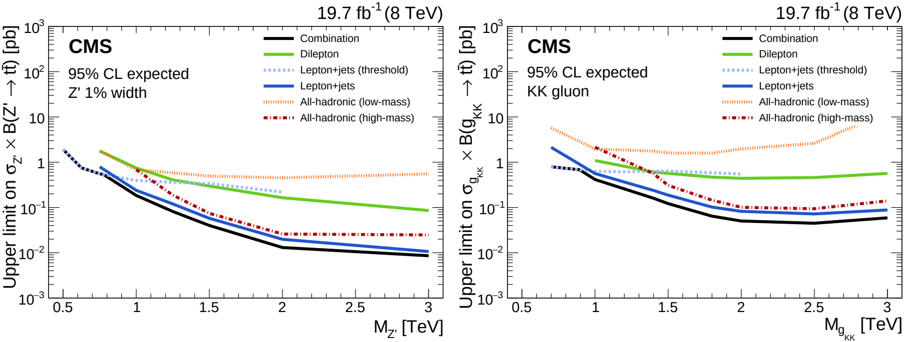
- Background estimated using data-driven technique

- ⊙: uncorrelated uncertainties that apply to a given channel
- ⊕: uncertainties correlated between channel

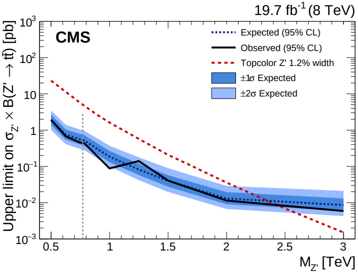
Source of uncertainty	Prior uncertainty	2ℓ	ℓ+jets	Had. channel high-mass	Had. channel low-mass
Integrated luminosity	2.6%	⊕	⊕	⊕	⊕
$t\bar{t}$ cross section	15%	⊕	⊕	⊕	⊕
Single top quark cross section	23%	⊕	⊕		
Diboson cross section	20%	⊕	⊕		
Z+jets cross section	50%	⊕	⊕		
W+jets (light flavor) cross section	9%		⊙		
W+jets (heavy flavor) cross section	23%		⊙		
Electron+jet trigger	1%		⊙		
H_T trigger	2%			⊕	⊕
Four-jet trigger	$\pm 1\sigma(p_T)$				⊙
Single-electron trigger	$\pm 1\sigma(p_T, \eta)$	⊙			
Single-muon trigger and id	$\pm 1\sigma(p_T, \eta)$	⊕	⊕		
Electron ID	$\pm 1\sigma(p_T, \eta)$	⊕	⊕		
Jet energy scale	$\pm 1\sigma(p_T, \eta)$	⊕	⊕	⊕	⊕
Jet energy resolution	$\pm 1\sigma(\eta)$	⊕	⊕	⊕	⊕
Pileup uncertainty	$\pm 1\sigma$	⊕	⊕	⊕	⊕
b tagging efficiency[(†)]	$\pm 1\sigma(p_T, \eta)$	⊕	⊕		⊕
b tagging mistag rate [(†)]	$\pm 1\sigma(p_T, \eta)$	⊕	⊕		⊕
CA8 subjet b tagging	unconstrained			⊙	
CA8 t tagged jet efficiency	unconstrained		⊕	⊕	
CA8 t-tagged jet mistag	$\pm 25\%$		⊙		
CA15 t-tagged jet efficiency	$\pm 1\sigma(p_T, \eta)$				⊙
QCD multijet background	sideband			⊙	⊙
PDF uncertainty	$\pm 1\sigma$	⊕	⊕	⊕	⊕
$t\bar{t}$ ren. and fact. scales	$4Q^2$ and $0.25Q^2$	⊕	⊕	⊕	⊕
W+jets ren. and fact. scales	$4Q^2$ and $0.25Q^2$		⊙		
W+jets matching scale μ	2μ and 0.5μ		⊙		
MC statistical uncertainty		⊙	⊙	⊙	⊙

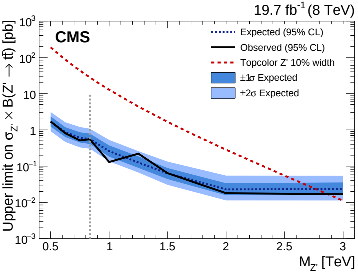
(†) AK5 and CA15 subjets

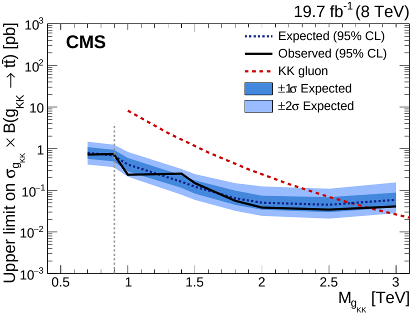
Limits combination



Limits results







Lower mass limits

	Mass limit [TeV]							
	Dilepton channel		Lepton+jets channel		All-hadronic channels		Combined	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
$Z', \Gamma_{Z'}/M_{Z'} = 1.2\%$	1.4	1.5	2.2	2.3	2.1	2.1	2.4	2.4
$Z', \Gamma_{Z'}/M_{Z'} = 10\%$	2.1	2.2	2.7	2.8	2.5	2.5	2.8	2.9
RS KK gluon	1.8	2.0	2.5	2.5	2.4	2.3	2.7	2.8

Observed and expected limits

$M_{Z'}$ (TeV)	Expected (pb)	Expected range ($\pm 1\sigma$) (pb)	Expected range ($\pm 2\sigma$) (pb)	Observed (pb)
	$Z', \Gamma_{Z'}/M_{Z'} = 1\%$			
0.75	0.61	0.89 — 0.43	1.3 — 0.32	0.86
1.0	0.18	0.27 — 0.13	0.37 — 0.099	0.088
1.25	0.082	0.12 — 0.058	0.18 — 0.042	0.14
1.5	0.04	0.057 — 0.028	0.089 — 0.02	0.041
2.0	0.013	0.02 — 0.009	0.029 — 0.0067	0.011
3.0	0.0086	0.013 — 0.0059	0.021 — 0.0043	0.0059

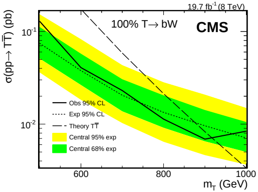
$M_{Z'}$ (TeV)	Expected (pb)	Expected range ($\pm 1\sigma$) (pb)	Expected range ($\pm 2\sigma$) (pb)	Observed (pb)
	$Z', \Gamma_{Z'}/M_{Z'} = 10\%$			
0.75	0.83	1.2 — 0.57	1.8 — 0.42	0.89
1.0	0.26	0.37 — 0.18	0.53 — 0.14	0.13
1.25	0.13	0.19 — 0.09	0.26 — 0.067	0.22
1.5	0.063	0.089 — 0.044	0.13 — 0.03	0.064
2.0	0.023	0.034 — 0.016	0.055 — 0.011	0.018
3.0	0.023	0.036 — 0.016	0.055 — 0.011	0.017

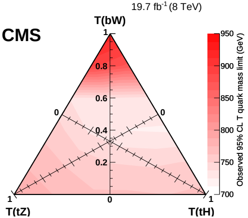
$M_{g_{KK}}$ (TeV)	Expected (pb)	Expected range ($\pm 1\sigma$) (pb)	Expected range ($\pm 2\sigma$) (pb)	Observed (pb)
	RS KK gluon			
0.7	1.7	2.5 — 1.2	3.8 — 0.84	3.5
1.0	0.42	0.6 — 0.28	0.84 — 0.21	0.24
1.4	0.16	0.23 — 0.11	0.32 — 0.078	0.25
1.5	0.12	0.17 — 0.083	0.24 — 0.059	0.15
1.8	0.064	0.098 — 0.045	0.15 — 0.032	0.056
2.0	0.05	0.074 — 0.034	0.12 — 0.024	0.038
2.5	0.045	0.068 — 0.03	0.11 — 0.021	0.034
3.0	0.059	0.088 — 0.039	0.15 — 0.028	0.041

Search for $T\bar{T}$

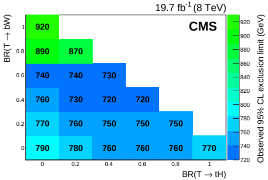
Search for vector-like charge 2/3 T quarks: summary

- Vector-like quarks predicted in BSM models as little Higgs, composite Higgs, extra-dimensions: could solve the hierarchy problem by canceling the divergent radiative corrections to the Higgs mass
- Benchmark model: vector-like T quarks with charge 2/3 produced in pairs via strong interaction, decaying to tH, tZ, bW
- Combination of 5 analyses optimized for different event topologies:
  - Inclusive in branching fractions (single and multi leptons channel): can set limits for all T decay modes
  - $T \to bW$: both T decay in bW (single lepton channel)
  - All-hadronic search for $T \to tH$ (at least one T decay as $T \to tH \to (bq\bar{q}')(b\bar{b})$)
  - All-hadronic search for $T \to bW$ (both T in bW and W in $q\bar{q}'$)
  - $T \to tH$ with $H \to \gamma\gamma$ (leptonic and hadronic channel targetting different t decay modes)
- High Lorentz boost: boosted t and boosted W identified using t- and W-tagging
- Statistical combination using a Bayesian method:
  - To avoid double counting between 1 and 2: in 1, use results from 2 if $\mathcal{B}(T \to bW) > 80\%$, else use results from 1
  - No overlap between 3-5 and 1: always combined
- Depending on the BR, expected (observed) 95% CL limits in [790, 890] GeV ([720, 920] GeV)





$\mathcal{B}(T \to bW) + \mathcal{B}(T \to tZ) + \mathcal{B}(T \to tH) = 1$



Inclusive search with single and multiple leptons

Single lepton channel

Selection:

- Exactly 1 isolated muon or electron with $p_T > 32$ GeV
- At least 5 AK5 jets with $p_T > 120/90/50$ GeV
- A 4th AK5 jet with $p_T > 35$ GeV required if no W jet found
- Boosted W tag algorithm:
  - Requires 2 subjets reconstructed by pruning algorithm
  - Pruned jet mass should be compatible with W mass: $p_T > 200$ GeV and $60 < M < 130$ GeV
- Jets must be separated from the muon (electron) by $\Delta R > 0.4$ (0.3)
- $E_T^{miss} > 20$ GeV

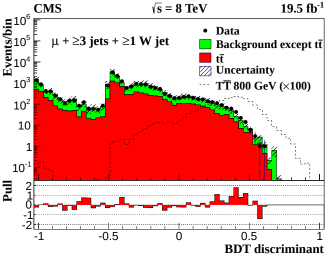
Background discrimination: BDT

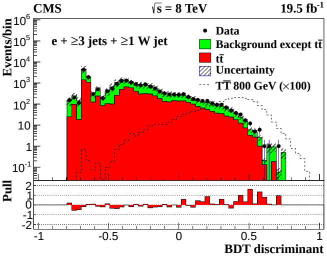
- Different BDTs for event with and without W jets, and for each T mass hypothesis, trained irrespective of BR of T (no improvement)
- Variables: jet multiplicity, b-tagged jet multiplicity, E_T^{miss}, lepton p_T, 3rd jet p_T, 4th jet p_T, $H_T = \sum p_T^{all\ jets}$ with $p_T^{jet} > 30$ GeV
- Events with $\geq$ W tagged jet: add W jet multiplicity, W jet p_T, number of t-tagged jets

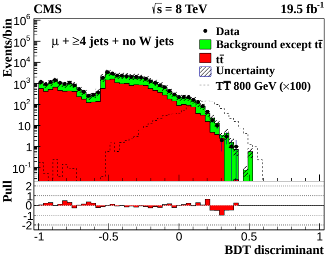
	Muon	Electron
Total background	61900 ± 13900	61500 ± 13700
Data	58478	57743

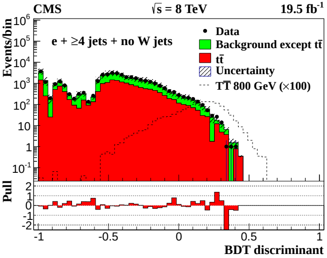
Inclusive search with single and multiple leptons

Single lepton channel



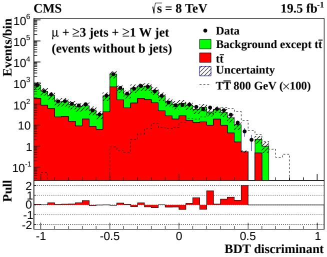


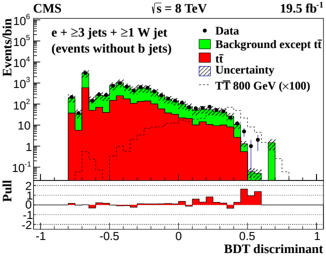


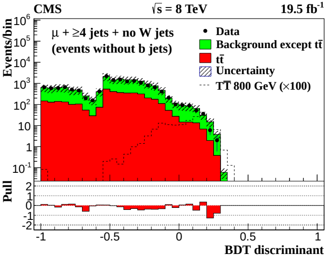


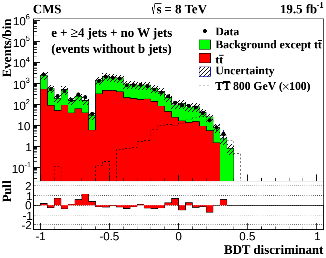
Inclusive search with single and multiple leptons

Single lepton channel









Inclusive search with single and multiple leptons

Multilepton channel

- 4 mutually exclusive subsamples with at least 2 leptons:
  - Multilepton sample: $\geq$ 3 leptons
  - OS1 dilepton sample: targets events where both T decay to bW
  - 0S2 dilepton sample: targets events where both T decay to tZ
  - SS sample: targets events where at least 1 T decays to tZ or tH

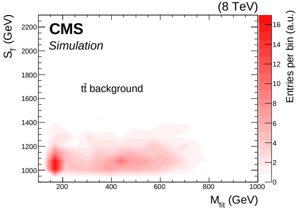
	OS1	*OS2*	*SS*	Multileptons
H_T (GeV)	> 300	> 500	> 500	> 500
S_T (GeV)	> 900	> 1000	> 700	> 700
Number of jets	2 or 3	≥ 5	≥ 3	≥ 3
b tags	≥ 1	≥ 2	≥ 1	≥ 1
E_T^{miss} (GeV)	> 30	> 30	> 30	> 30
$M_{b\ell}$ (GeV)	> 170	—	—	—
$M_{\ell\ell}$ (GeV)	> 20	> 20	> 20	> 20
Z boson veto	yes	no	no	no

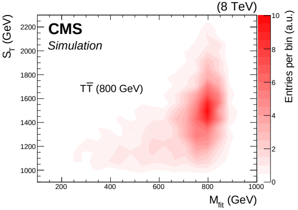
	OS1	*OS2*	*SS*	Multileptons
Total background	17.4 ± 3.7	84 ± 12	16.5 ± 4.8	3.7 ± 1.3
Data	20	86	18	2

Search for $T \to bW$ with single leptons

- Analysis optimized for events where both T decay into bW
- At least 4 jets: either 4 AK5 jets or 3 AK5 + 1 CA8 jets
- CA8 jet used to identified merged hadronic decays of W with high Lorentz boost
- AK5 jets replaced by the 2 pruned subjets of CA8 W tagged jet if mathching criterion fullfilled: $\Delta R(Jet_{CA8}, Jet_{AK5}) < 0.04$
- Unmatched AK5 jets and subjets of matched W-tagged CA8 used as input for a kinematic fit
- Kinematic fit:
  - Hypothesis: $T\bar{T} \to bW^{+}\bar{b}W^{-} \to l\nu bq\bar{q}'\bar{b}$
  - Constraints: $m(l\nu) = m(q\bar{q}') = M_W$ and $m(l\nu b) = m(q\bar{q}'b) = M_{fit}$ (fitted mass of selected T candidate)
  - E_T^{miss} attributed to the undetected neutrino
  - Only events with $p(\chi^2) > 1\%$ considered
  - Best combination selected from groups of fit combinations with decreasing b tag multiplicity, ranked by the b tagging operating point

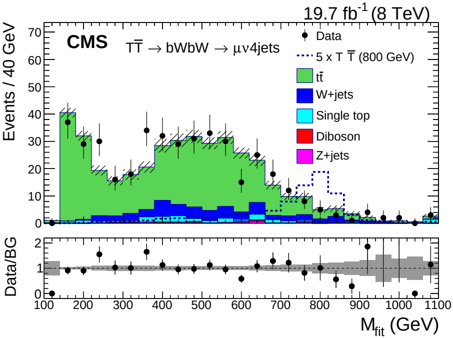
Variable	Selection
p_T muon	>45 GeV
p_T electron	>30 GeV
Number of jets	≥4
p_T jets	>120, 90, 50, and 30 GeV
W tags	0 or 1
b tags	1 or 2
S_T	>1240 GeV
E_T^{miss}	>30 GeV

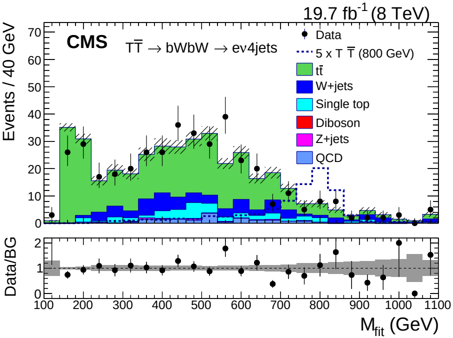




Search for $T \to bW$ with single leptons

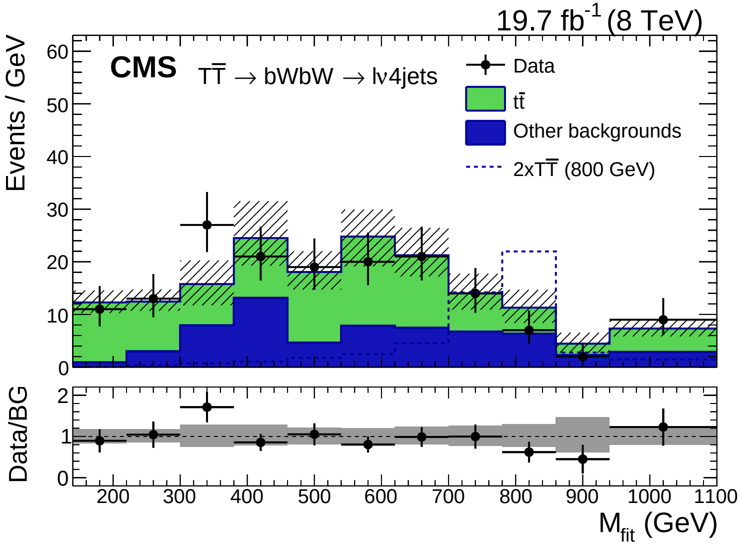
	Selection ($S_T > 1000$ GeV)		Selection ($S_T > 1240$ GeV)	
	μ+jets	e+jets	μ+jets	e+jets
$t\bar{t}$	325 ± 37	279 ± 35	51 ± 6	52 ± 6
W+ $\geq$ 3jets	49 ± 8	60 ± 9	18 ± 3	19 ± 4
Single top	20 ± 5	36 ± 10	6.9 ± 2.3	10 ± 4
$Z/\gamma^*+ \geq$ 3jets	3.9 ± 0.8	3.3 ± 0.6	1.4 ± 0.4	1.1 ± 0.3
WW, WZ, ZZ	3.1 ± 1.0	< 1	< 1	< 1
Multijet	< 1	18 ± 4	< 1	6.1 ± 1.7
Total background	401 ± 38	396 ± 38	77 ± 7	88 ± 9
Data	417	398	81	83





Search for $T \to bW$ with single leptons

After the full selection, combining μ+jets and e+jets



Search for $T \to tH$ in all-hadronic channel

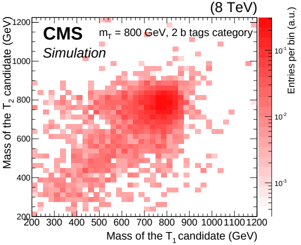
- $T \to tH$ with $t \to bW \to bq\bar{q}'$ and $H \to b\bar{b}$
- Significant Lorentz boost for t and H
- Events divided in 2 categories to maximize the analysis sensitivity: 1 H tag and $\geq$ 2 H tag categories
- H_T^{sub} (sum p_T of subjets of CA15 jets) and $m_{b\bar{b}}$ (mass of 2 b-tagged subjets in H-tagged jets):
  - Used for setting limits on T production cross section
  - Combined in a single discriminator using a likelihood ratio method for the final event selection

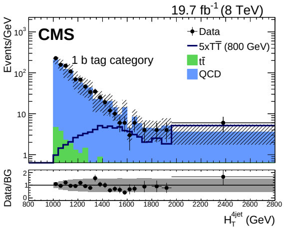
Variable	Selection
$H_{\mathrm{T}}^{\mathrm{sub}}$	$> 720\,\mathrm{GeV}$
Number of CA15 jets	≥ 2
p_{T} CA15 jets	$> 150\,\mathrm{GeV}$
p_{T} t-tagged jets	$> 200\,\mathrm{GeV}$
Number of t tags	≥ 1
Number of H tags	≥ 1

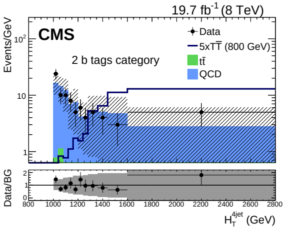
	Single H tag category	Multiple H tags category
Total background	1403 ± 14	182 ± 5
Data	1355	205

Search for $T \rightarrow bW$ in all-hadronic channel

- Optimized for events where both T decay as: $T \rightarrow bW \rightarrow bq\bar{q}'$
- 2 categories: 1 or ≥ 2 b-tagged jets
- After selection, reconstruct 2 T candidates T_1 and T_2 indentifying the combinations of W jets and AK5 jets having the smallest invariant mass difference
- $a_f = |m(T_1) - m(T_2)|/(m(T_1) + m(T_2))$
- $H_T^{4\,jets}$: scalar p_T sum of the 4 jets used to reconstruct the T candidates





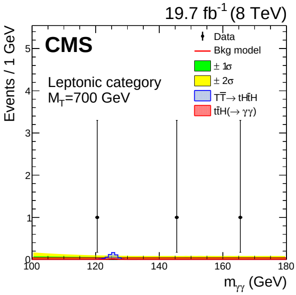


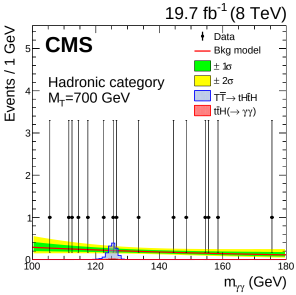
Variable	Selection
Number of AK5 jets	$\geq$2
p_T AK5 jets	$>$ 50 GeV
Number of W-tagged jets	$\geq$2
p_T W-tagged jets	$>$ 150 GeV
Reconstructed T candidate mass	$>$ 200 GeV
a_f	$<$10%
$\Delta\phi(\mathrm{T}_1, \mathrm{T}_2)$	$>5\pi/6$
H_T^{4jet}	$>$1000 GeV

	1 b tag channel	$\geq$2 b tags channel
$t\bar{t}$	20.3 ± 1.3	3.45 ± 0.55
QCD multijet	979 ± 29	80.2 ± 6.4
Total background	999 ± 31	84 ± 7
Data	998	84

Search for $T \to tH$ with $H \to \gamma\gamma$

- Optimized for events where one T decays as: $T \to tH \to t\gamma\gamma$
- Main advantage: $m_{\gamma\gamma}$ precisely measured ($m_{\gamma\gamma}$ would be present for signal events)
- Disadvantage: small $H \to \gamma\gamma$ BR ($\sim 2.10^{-3}$)
- 2 channels:
  - Leptonic channel: events with a pair of photons and at least one isolated high p_T muon or electron
  - Hadronic channel: events with a pair of photons and no isolated muon or electron





Variable	Leptonic channel	Hadronic channel
$p_T(\gamma_1)$	$>\frac{1}{2}m_{\gamma\gamma}$	$>\frac{3}{4}m_{\gamma\gamma}$
$p_T(\gamma_2)$	25 GeV	35 GeV
Number of jets	≥ 2	≥ 2
S_T	≥ 770 GeV	≥ 1000 GeV
Leptons	≥ 1	0
b tags	—	≥ 1

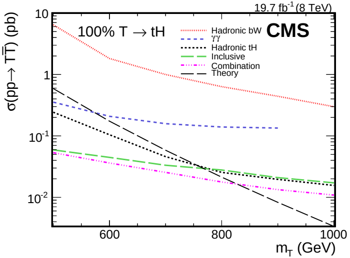
	Leptonic channel	Hadronic channel
$t\bar{t}H$	$0.039^{+0.005}_{-0.006}$	$0.042^{+0.005}_{-0.006}$
Nonresonant background	$0.11^{+0.07}_{-0.03}$	$0.65^{+0.16}_{-0.13}$
Total background	$0.15^{+0.07}_{-0.03}$	$0.69^{+0.16}_{-0.13}$
Data	0	2

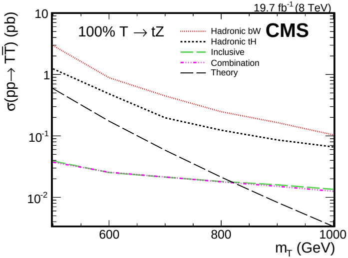
Combination: systematics

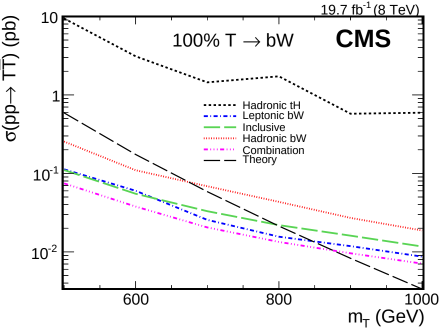
- ✓: uncertainty has been taken into account in the analysis, but is not correlated with the other analyses
- Otherwise : uncertainty has been taken into account in the analysis, but is correlated with the other analyses

Uncertainty	Single leptons	Inclusive leptons	Multiple leptons	All-had. $T \to bW$	All-had. $T \to tH$	$H \to \gamma\gamma$
Int. luminosity	☑	☑	☑	☑	☑	☑
Trigger	✓	✓	✓		✓	✓
Lepton ID	☑	☑	☑			☑
Photon ID						✓
Photon energy						✓
Pileup jet ID						✓
Jet energy scale	☑	☑	☑	☑	☑	☑
Jet energy resolution	☑	☑	☑	☑	☑	☑
Unclustered energy	✓					
b tag SF	☑	☑	☑	☑	☑	
b tag mistag SF	☑				☑	
t tagging SF					✓	
$t\bar{t}$ μR and μF scale	☑	☑	☑	☑	☑	
$t\bar{t}$ cross section	☑	☑	☑	☑	☑	
$t\bar{t}$ PDF	☑			☑	☑	
QCD background				✓	✓	
Other backgrounds	✓	☑	☑	✓		✓

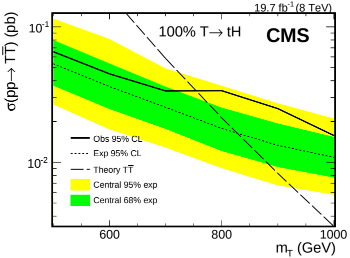
Combination: results

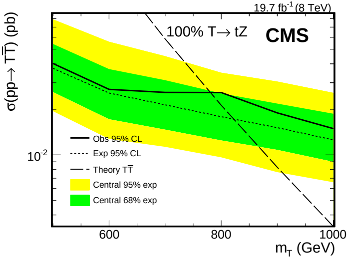


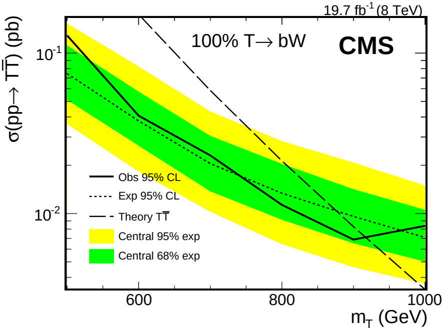




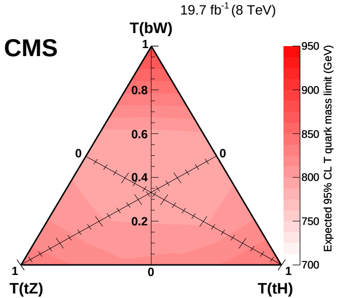
Limits on T production cross section

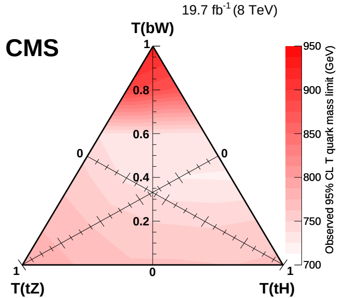


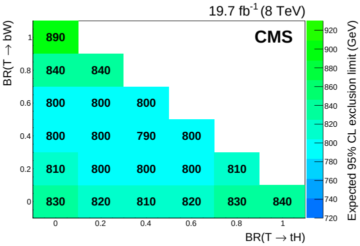


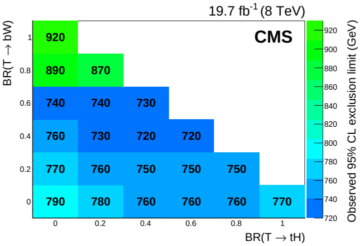


Limits on branching fractions





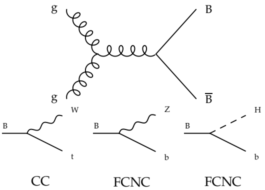




Search for vector-like charge -1/3 B quarks

$\mathcal{B}(B \to tW) + \mathcal{B}(B \to bZ) + \mathcal{B}(B \to bH) = 1$

- Search for vector-like charge -1/3 B quarks produced strongly in pairs, decaying to tW (charged-current process) or to bZ or bH (FCNC)
- 5 combined channels defined by signal discriminating variable and B decay mode providing the best sensitivity for the channel
- We define $H_T = \sum_i p_T^{jet\ i}$ and $S_T = \sum_i p_T^{jet\ i} + p_T^l + E_T^{miss}$

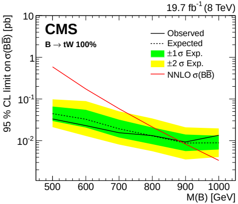


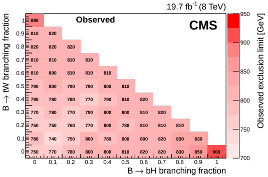
Channel	$N_{leptons}$	Discr. var.	Best decay mode
l+jets	1	S_T	tW
SS dilept.	2	S_T	tW
OS dilept.	2	M(llb)	bZ
Multilept.	≥ 3	S_T	tW, bZ
All-hadr.	0	H_T	bH

- High Lorentz boost regime: hadronically decaying W, Z or Higgs products merged in a single jet (CA clusterisation, pruning, N-subjetiness, mass drop)
- Combination: joint likelihood maximization performed using a Bayesian approach

- No significant excess above SM expectations: set limits

95% CL M(B) exclusion limit (GeV)		
Exclusive decay mode	Expected	Observed
$B \to tW$	890	880
$B \to bH$	810	900
$B \to bZ$	740	750

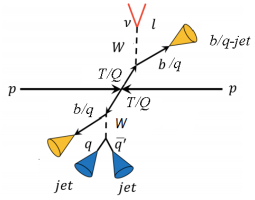


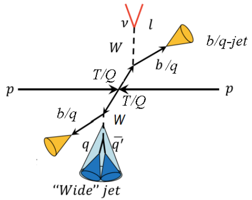


Search for $T\bar{T}$ / $Q\bar{Q}$

Selection

- Exactly one charged isolated muon (electron) with p_T > 45 (30) GeV and $|\eta|$ < 2.1 (2.5)
  - Veto events with a second loose electron or muon
- At least 4 jets ($|\eta|$<2.4):
  - at least 4 AK5 jets (p_T > 30 GeV)
  - OR at least 3 AK5 jets and at least 1 CA8 jet (p_T > 200 GeV) for the case when CA8 jet overlaps with AK5 jet
- E_T^{miss} > 20 (30) GeV
- Pruning algo to reveal CA8 jet substructure:
  - 60 GeV < M(pruned jet) < 100 GeV (close to W mass) $\rightarrow$ then jet is tagged as W
- For each W-tagged CA8 jet:
  - Check if it overlaps with an AK5 jet
  - If so, replace AK5 jet by the 2 subjet of matching CA8 jet
  - Mathcing criteria: ΔR(CA8 jet, AK5 jet) < 0.04
  - For further analysis, use unmatched AK5 jets and subjets of matched W-tagged CA8 jets (used as input of KF)
- Highest p_T ordered four jets of the collection: p_T > 120 GeV, 90 GeV, 50 GeV, 30 GeV





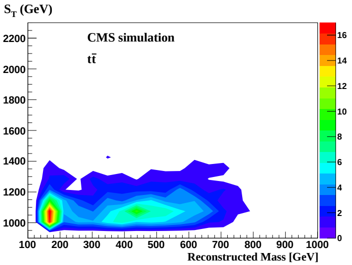
T/Q mass reconstruction

- Assignment of reconstructed objects to the final state objects
- Constrained kinematic fit which improves reco objects resolution
- E_T^{miss} used as an estimate of p_T^{ν} for the fit
- W-tagged subjets used in pair and are assigned to W hadronic
- $\chi^2 > 0.1\%$ required
- For $T\bar{T} \rightarrow b_l b_h WW$:
  - Choose combination with smallest χ^2, selected from groups of fit combinations with decreasing b-tag content of the jet pair matched to the quark pair b_l, b_h:
    - 2 CSVM btags
    - 1 CSVM and 1 CSVL btags
    - 1 CSVM btag only
    - 2 CSVL btags
- For $Q\bar{Q} \rightarrow q_l q_h WW$:
  - Use of QGT info: impose a 2D cut excluding combinations in which both light quark jets have discriminant values favoring gluons
  - Events with W-tagged jet: choose combination with smallest χ^2, selected from groups of fit combinations with decreasing CSVL b-tag content of q_l, q_h jet pair:
    - 0 CSVL b-tags
    - 1 CSVL btag only and no CSVM btags
    - 2 CSVL btags and no CSVM btags
  - Events without W-tagged: btag veto on q_l, q_h quark pair (require no b-tag to be present)
- $S_T = p_T^l + E_T^{miss} + p_T^{J1} + p_T^{J2} + p_T^{J3} + p_T^{J4}$>1000 GeV computed after KF strongly suppress $t\bar{t}$ dominant background

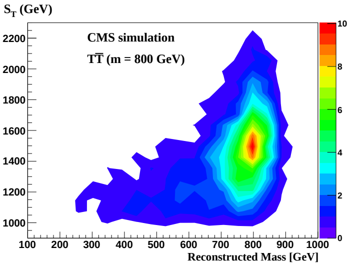
KinFit constraints

$$m(l\nu) = M_W$$
$$m(q\bar{q}') = M_W$$
$$m(l\nu b) = m(q\bar{q}'b) = M_{fit}$$
$$(\text{or } m(l\nu q) = m(q\bar{q}'q) = M_{fit})$$

S_T vs M_{fit}

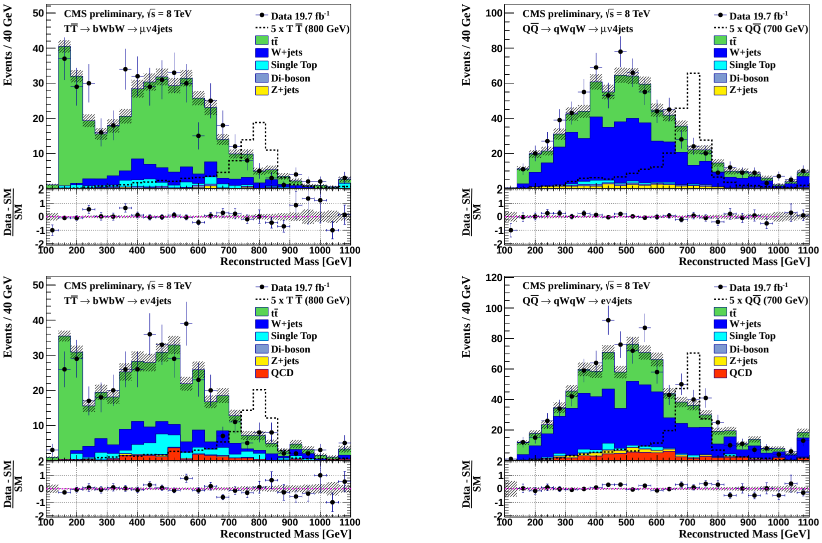


S_T (GeV)
CMS simulation
$t\bar{t}$
Reconstructed Mass [GeV]



S_T (GeV)
CMS simulation
$T\bar{T}$ (m = 800 GeV)
Reconstructed Mass [GeV]

M_{fit}


CMS preliminary, √s = 8 TeV
TT̄ → bWbW → μν4jets
Data 19.7 fb⁻¹
5 x T T̄ (800 GeV)
tt̄
W+jets
Single Top
Di-boson
Z+jets
Events / 40 GeV
Data - SM / SM
Reconstructed Mass [GeV]
CMS preliminary, √s = 8 TeV
QQ̄ → qWqW → μν4jets
Data 19.7 fb⁻¹
5 x QQ̄ (700 GeV)
tt̄
W+jets
Single Top
Di-boson
Z+jets
Events / 40 GeV
Data - SM / SM
Reconstructed Mass [GeV]
CMS preliminary, √s = 8 TeV
TT̄ → bWbW → eν4jets
Data 19.7 fb⁻¹
5 x T T̄ (800 GeV)
tt̄
W+jets
Single Top
Di-boson
Z+jets
QCD
Events / 40 GeV
Data - SM / SM
Reconstructed Mass [GeV]
CMS preliminary, √s = 8 TeV
QQ̄ → qWqW → eν4jets
Data 19.7 fb⁻¹
5 x QQ̄ (700 GeV)
tt̄
W+jets
Single Top
Di-boson
Z+jets
QCD
Events / 40 GeV
Data - SM / SM
Reconstructed Mass [GeV]

Results on event selection

- Number of data and expected MC background events for bWbW and qWqW channels after the event selection
- The cross sections used to normalize the MC backgrounds are also shown
- The first uncertainty on the MC prediction is statistical and the second systematic

		bWbW	bWbW	qWqW	qWqW
Channel		μ + jets	e + jets	μ + jets	e + jets
Backgr. proc.	Cross sect.	Events	Events	Events	Events
$t\bar{t}$	239 pb	$325 \pm 5 \pm 37$	$279 \pm 5 \pm 35$	$257 \pm 5 \pm 34$	$269 \pm 5 \pm \pm 36$
$W+ \geq$ 3jets	885 pb	$49 \pm 5 \pm 6$	$60 \pm 5 \pm 7$	$396 \pm 13 \pm 30$	$462 \pm 14 \pm 39$
Single-t	116 pb	$20 \pm 2 \pm 5$	$36 \pm 4 \pm 9$	$13 \pm 2 \pm 3$	$25 \pm 3 \pm 6$
$Z/\gamma^* + \geq$ 3jets	89 pb	$3.9 \pm 0.6 \pm 0.5$	$3.3 \pm 0.5 \pm 0.4$	$27 \pm 2 \pm 2$	$27 \pm 2 \pm 4$
WW, WZ, ZZ	107 pb	$3.1 \pm 0.8 \pm 0.6$	< 1	$10 \pm 1 \pm 4$	< 1
Multijets		< 1	$18 \pm 3 \pm 2$	< 1	$59 \pm 4 \pm 8$
Total backgr.		$401 \pm 7 \pm 37$	$396 \pm 8 \pm 37$	$703 \pm 14 \pm 45$	$842 \pm 16 \pm 54$
Total observed		417	398	741	896

Selection efficiency

- Assumed T/Q masses, theoretical cross sections, selection efficiencies (including acceptance and the branching fraction of the bWbW and qWqW system into single-muon and single-electron final states) and numbers of expected bWbW and qWqW signal events in the μ+jets and e+jets channels

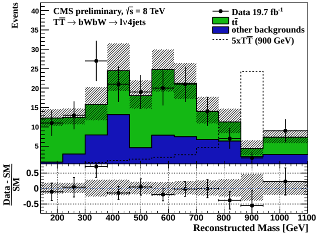
M_T (GeV)	Cross section (pb)	μ+jets eff. (%)	Events	e+jets eff. (%)	Events
500	0.590	1.73 ± 0.04	202	1.59 ± 0.04	183
600	0.174	2.93 ± 0.06	101	3.07 ± 0.06	104
700	0.0585	3.70 ± 0.06	43	3.70 ± 0.06	42
800	0.0213	3.93 ± 0.07	17	4.10 ± 0.07	17
900	0.00828	4.01 ± 0.07	6.6	4.19 ± 0.07	6.9
1000	0.00336	3.83 ± 0.07	2.5	4.20 ± 0.07	2.7
M_Q (GeV)	Cross section (pb)	μ+jets eff. (%)	Events	e+jets eff. (%)	Events
500	0.590	1.96 ± 0.05	228	1.93 ± 0.05	222
600	0.174	3.26 ± 0.06	112	3.46 ± 0.06	117
700	0.0585	4.18 ± 0.07	48	4.26 ± 0.07	48
800	0.0213	4.66 ± 0.07	20	4.67 ± 0.07	20
900	0.00828	4.95 ± 0.08	8.1	5.04 ± 0.08	8.2
1000	0.00336	5.02 ± 0.11	3.3	5.01 ± 0.11	3.3

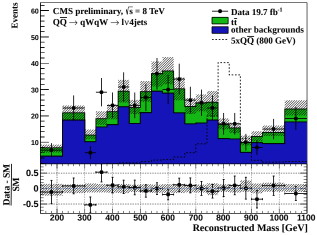
Systematics

	bWbW signal	bWbW BG	qWqW signal	qWqW BG
JES	1.5%	5.2%	1.3%	5.0%
JER	0.2%	1.7%	0.2%	1.6%
b-tag heavy flavour	3.1%	2.2%	0.3%	1.4%
b-tag light flavour	0.1%	1.1%	0.9%	1.9%
Unclustered energy	0.2%	0.4%	0.2%	0.6%
Q^2 scale	-	6.1%	-	3.0%
Pileup	0.3%	0.5%	0.3%	0.5%
PDF	1.5%	+9.6% -7.3%	1.4%	+9.0% -6.5%

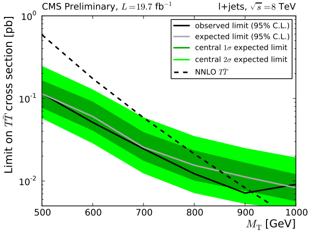
Limits extraction

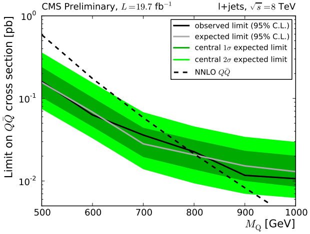
- Monte Carlo studies show that fit sensitivity is optimized with the requirement $S_T > 1240$ GeV
- Distributions below: after $S_T > 1240$ GeV requirement, used for limit calculation





- The 95% CL upper limits on the production cross section of $T\bar{T}/Q\bar{Q}$ computed using a Bayesian interpretation
- Perform binned likelihood fit to the data distribution

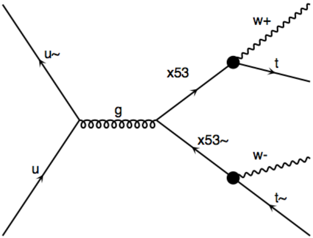


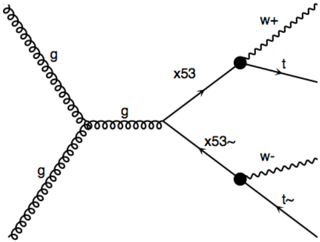


Search for $X_{5/3}$

Production

- Pair production via QCD process
- In this note, 2 different final states:
  - Dilepton channel: the 2 W bosons decay into same sign leptons while the other 2 decay inclusively
  - Semileptonic channel: 1 W decays leptonically (1 lepton, 1 neutrino) and the other 3 W decay hadronically





MC samples

- $X_{5/3}$ signal samples produced with Madgraph 5 and Pythia 8 generators for both LH and RH coupling scenarios

$X_{5/3}$ Mass (GeV)	Cross Section [fb]
700	442
800	190
900	88
1000	43
1100	22
1200	11
1300	6.2
1400	3.4
1500	1.9
1600	1.1

SS dilepton channel: selection

Charge measurement for electron:

- Require that different charge measurementsagree
- 2 measurements based on 2 different tracking algorithms:
  - the standard CMS track reconstruction algorithm
  - the Gaussian Sum Filter algorithm
- 3rd measurement: based on the relative position of the calorimeter cluster and the projected track from the pixel seed
- Good agreement between the 3 measurements for electrons with $p_T < 100$ GeV
- For higher p_T, 5-10% loss in signal efficiency related to the 3rd measurement: do not impose a requirement on the 3rd charge measurement

SS dilepton channel: selection

- 2 tight isolated (I_{rel} < 0.1 (0.2) for electron (muon)), same-sign leptons with p_T > 30 GeV
- Quarkonia Veto: M_{ll} > 20 GeV
- Associated Z-boson Veto: veto any event where either of the leptons in the same-sign pair reconstructs to within 15 GeV of the mass of the Z-boson with any other lepton in the event not in the same-sign pair
- Primary Z-boson Veto: invariant dilepton mass (M_{ll}) > 106.1 or < 76.1 GeV for dielectron channel only. If the muon charge is mismeasured, its momentum will also be mismeasured so a selected muon pair from a Zboson will not fall within this invariant mass range
- Leading lepton p_T > 40 GeV
- Number of Constituents = N(AK4 jets) + N(other leptons ie not in the SS pair) ≥ 5
- $H_T^{lep} = \sum_i p_T^{jet\ i} + p_T^{tight\ leptons}$ > 900GeV

SS dilepton channel: background

Backgrounds fall into 3 main categories:

- **Same-sign prompt leptons**: standard model processes leading to prompt, same-sign dilepton signatures. Their contribution is obtained from theoretical predictions
  - Diboson production (WZ or ZZ) or rare processes like $t\bar{t}$W, $t\bar{t}$Z, $t\bar{t}$H, WWZ, ZZZ, WZZ, $W^{\pm}W^{\pm}$ etc
- **Opposite sign prompt leptons**: prompt leptons could be mis-reconstructed with the wrong charge leading to a same-sign dilepton final state (data driven method)
- **Same-sign events arising from the presence of one or more non-prompt leptons**: this is the primary instrumental background arising from jets being mis-identified as leptons, non-prompt leptons passing tight isolation selection criteria, etc. This con- tribution is estimated using a data driven method

SS dilepton channel: opposite sign prompt leptons background

- For muons: charge misidentification rate is extremely small (of order 10^{-4}) and its contribution to the background is negligible
- For electrons:
  - Charge misidentification probability ($\sim 10^{-3}$) derived from a data sample dominated by Z+jets events obtained by selecting dileptons with M_{ll} consistent with M_Z, Proba = N(SS Z candidates)/N(total Z candidates)
  - The number of expected same-sign events due to charge misidentification is then estimated by considering the total number of events passing the full selection, but having oppositely charged leptons
  - These events are weighted by the charge misidentification probability parametrized as a function of the electron p_T and η to obtain the contribution of this background type

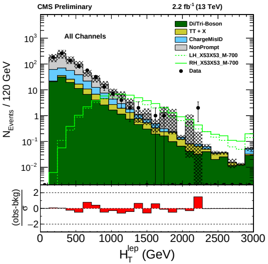
SS dilepton channel: Systematics

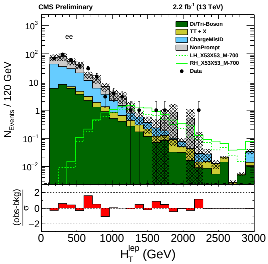
Source	Value	Application
Electron ID	1%	per electron
Electron ISO	1%	per electron
Electron Trigger	3%	per event
Muon ID	1%	per muon
Muon ISO	1%	per muon
Muon Trigger	3%	per event
Electron-Muon Trigger	3%	per event

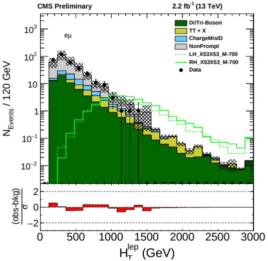
Background Process	JES	Theory
ttW	4%	20%
ttZ	3%	12%
ttH	8%	14%
WZ	5%	12%
ZZ	4%	12%
W+W+	4%	50%
WWZ	4%	50%
WZZ	6%	50%
ZZZ	6%	50%
tttt	6%	50%

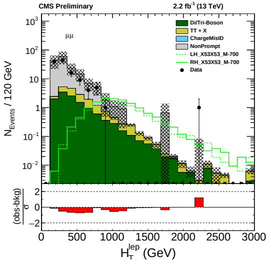
SS dilepton channel: H_T^{lep} distributions

- After applying the quarkonia veto, associated Z-boson veto, primary Z-boson veto, and a requirement of at least two AK4 jets in the event
- Illustrative purposes only: the full selection is not applied to them due to limited statistics
- Both statistical and systematic uncertainties are included





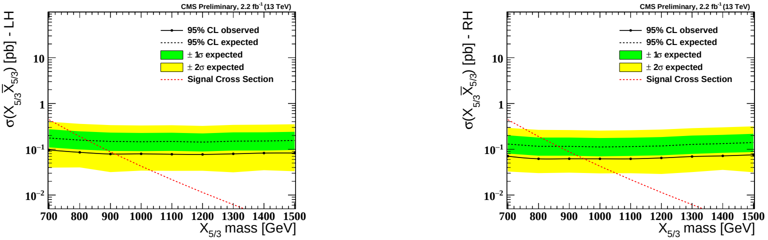




SS dilepton channel: results

- No significant excess in the data over the background prediction
- Proceed to set limits and calculate both expected and observed limits using the theta package and Bayesian statistics using a flat prior on the signal
- Expected/observed limits of 860/950 (820/910) GeV for a right (left) handed $X_{5/3}$ at 95% CL
- Table: right handed $X_{5/3}$ of mass 800 GeV

Channel	PSS MC	NonPrompt	ChargeMisID	Total Background	800 GeV $X_{5/3}$	Observed
Di-electron	2.41 ± 0.29	2.16 ± 1.91	1.90 ± 0.60	6.47 ± 2.02	4.38	7
Electron-Muon	2.98 ± 0.36	5.20 ± 3.21	0.54 ± 0.18	8.72 ± 3.24	9.14	3
Di-muon	0.70 ± 0.12	2.09 ± 1.69	0.00 ± 0.00	2.80 ± 1.70	3.55	1
All	6.09 ± 0.67	9.45 ± 5.49	2.44 ± 0.76	17.98 ± 5.58	17.06	11



Semileptonic channel: selection

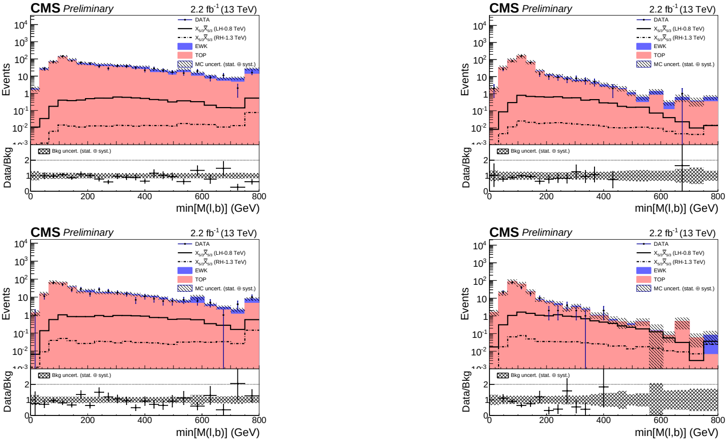
- Preselection:
  - $p_T^l > 50$ GeV
  - $E_T^{miss} > 100$ GeV
  - N(AK4 jets with $p_T > 30$ GeV and $|\eta| < 2.4$) ≥ 3
  - Leading jet $p_T > 200$ GeV
  - Subleading jet $p_T > 90$ GeV
  - ≥ 1 btag jet
  - High Lorentz boost for $X_{5/3}$ $\rightarrow$ boosted hadronic W decay products merge in a single jet: ≥ 1 W-tagged jet
    - Pruning algo
    - $p_T > 200$ GeV
    - $|\eta| < 2.4$
    - 65 GeV < M(pruned jet) < 105 GeV
    - $\tau_2/\tau_1 < 0.55$
- Final selection:
  - ≥ 4 jets
  - $p_T^l > 80$ GeV
  - $\Delta R(l$, sub-leading jet) > 1.0

Defining 8 categories depending on:

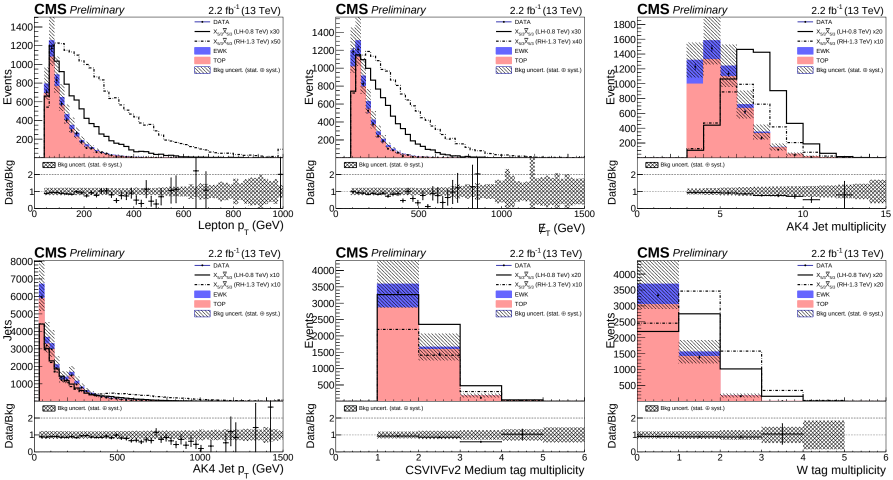
- lepton flavor (e, μ)
- b tagged jets (1, 2+)
- W tagged jets (0, 1+)

Semileptonic channel: $\min[M(l, b)]$

- $\min[M(l, b)]$: mass constructed from the lepton l and b-tagged jet
- In case of more than 1 btagged jet: minimum mass from the possible pair pairs of lepton and b-tagged jet
- Plots after final selection, (top) 0 or (bottom) 1+ boosted W tagged jets and (left) 1 or (right) 2+ b tagged jets categories for combined electron and muon samples

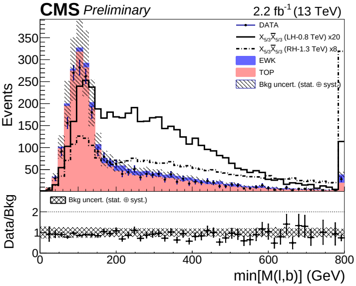


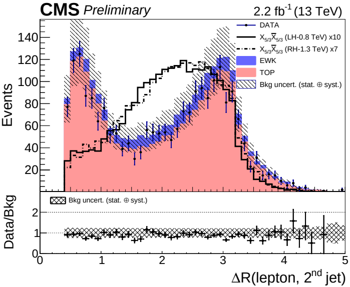
Semileptonic channel: plots at preselection level



Semileptonic channel: discriminating variables

- After preselection + $\geq$ 4 jets + $p_T^l > 80$ GeV





Semileptonic channel: number of events after final selection

Sample	0 W, 1 b	0 W, 2+ b	1+ W, 1 b	1+ W, 2+ b
LH $X_{5/3}$ (0.8 TeV)	8.02 ± 0.48	7.04 ± 0.43	14.15 ± 0.83	12.53 ± 0.74
RH $X_{5/3}$ (1.2 TeV)	0.598 ± 0.036	0.486 ± 0.029	1.381 ± 0.080	1.116 ± 0.065
EWK	185 ± 47	25.8 ± 6.7	48 ± 12	7.1 ± 2.0
Top	664 ± 90	421 ± 87	337 ± 46	222 ± 46
QCD	2.03 ± 2.02	0.006 ± 0.006	0.001 ± 0.001	< 0.001
Total Bkg	850 ± 105	446 ± 87	384 ± 48	229 ± 46
Data	768	400	347	182

Semileptonic channel: backgrounds

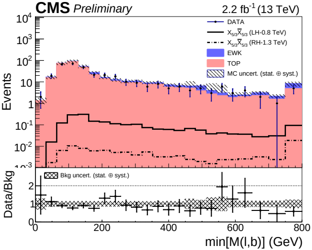
- top quark backgrounds: dominated by $t\bar{t}$ pair production ; also single top quark production process and the rare SM processes $t\bar{t}$W and $t\bar{t}$Z
- EW backgrounds: dominated by W+jets ; also Z+jets, diboson (WW, WZ, ZZ)
- QCD multijet backgrounds

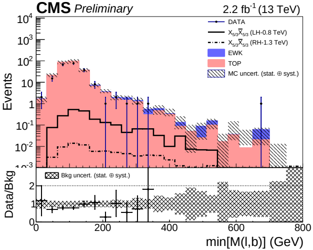
Semileptonic channel: backgrounds modeling

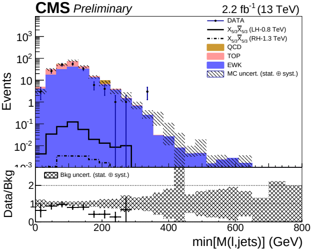
- Bkg is estimated from simulation
- Cross-check: define 2 different CR for the 2 dominant bkgs:
  - $t\bar{t}$ CR:
    - All final selection but reversed $\Delta R(l$, sub-leading jet) selection (< 1.0) and ≥ 1 btag jet (as in final selection)
    - 2 categories: exactly 1 btagged jet and ≥ 2 btagged jets
  - V+jets CR:
    - All final selection but reversed $\Delta R(l$, sub-leading jet) selection (< 1.0) and 0 btag jet
    - Use all jets in the event as b jet candidate to construct $\min[M(l,b)]$ (denoted as $\min[M(l, jets)]$)
    - 2 categories: 0 W-tagged jets and ≥ 1 W-tagged jets
- In both CRs, bkg predictions based on MC in reasonable agreement with the data (see next slide)
- Comparison of the observed and the predicted yields in the CRs for each of the 8 categories used as a closure test for background modeling
- Difference in the yields is assigned as a systematic uncertainty in background modeling

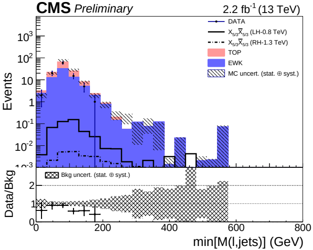
Semileptonic channel: bkg CRs

- $t\bar{t}$ CR, for 1 b tagged jet (top left) and 2+ b tagged jets (top right) categories
- V+jets CR, for zero W tagged (bottom left) and 1+ W tagged jet (bottom right) categories
- For combined electron and muon event samples





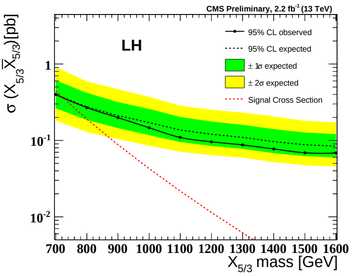


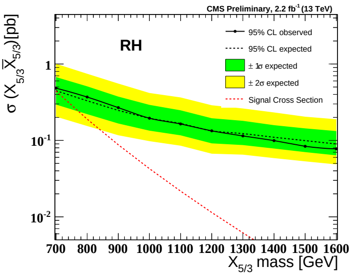


Semileptonic channel: systematics

Source	Uncertainty	Signal	Background
Normalization only			
Luminosity	4.6%	Yes	All
Trigger Efficiency	3%	Yes	All
Lepton efficiencies	1%	Yes	All
"Top bkg": $t\bar{t}$, Single top, $t\bar{t}$+W/Z cross-sections	5.5%	No	
"EWK bkg": W+jets, Diboson cross sections	5%	No	
"Top bkg" modeling, based on the CR	11-19%	No	
"EWK bkg" modeling, based on the CR	24%	No	
QCD multijet cross-sections	50%	No	
Shape and Normalization			
Jet Energy Scale	$\pm\sigma(p_T, \eta)$	Yes	All
Jet Energy Resolution	$\pm\sigma$	Yes	All
b tagging	$\pm\sigma$	Yes	All
W tagging: mass resolution	$\pm\sigma$	Yes	All
W tagging: mass scale	$\pm\sigma$	Yes	All
W tagging: τ_2/τ_1	$\pm\sigma$	Yes	All
Top p_{T}	Δ(weighted,nominal)	No	$t\bar{t}$
Pileup	$\sigma_{\mathrm{minbias}} \pm 5\%$	Yes	All
Parton Shower Scale	$\pm\sigma$	No	$t\bar{t}$, single top
Shape only			
PDF	$\pm\sigma$	Yes	All
Renormalization Scale	$\pm\sigma$	Yes	All
Factorization Scale	$\pm\sigma$	Yes	All

Semileptonic channel: limits





Semileptonic and SS dileptons channels combination: limits