SEARCH FOR NEW MASSIVE PARTNERS OF THE THIRD GENERATION QUARKS

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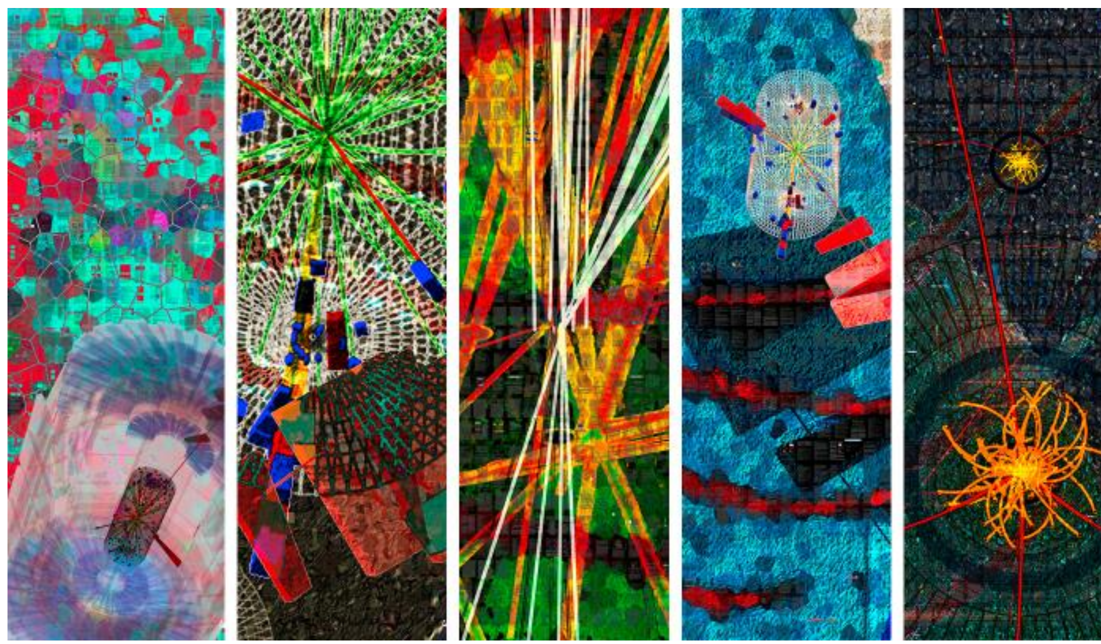


Outline

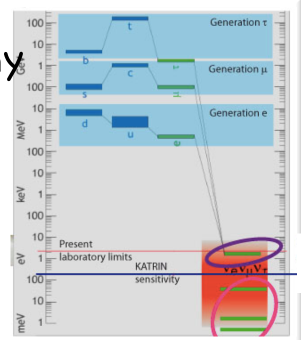
- Introduction
- Instrument
  - LHC and detectors
  - Techniques to identify objects from heavy VLQ decays
- The VLQ digest of results
  - Single VLQ production
  - Double VLQ production
- Outlook
  - Near term
  - and VLQs @ HL-LHC
- Summary

Fundamental Problems → Proposed Solutions → New Particles

Naturalness

What stabilizes Higgs at the electroweak scale ?

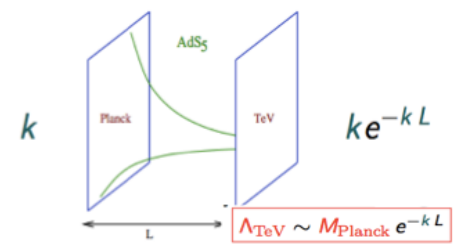
Mass Hierarchy



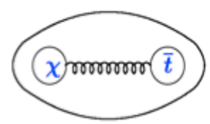
Particles and Unification of Forces

u up	c charm	t top	γ photon
d down	s strange	b bottom	Z Z boson
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson
e electron	μ muon	τ tau	g gluon

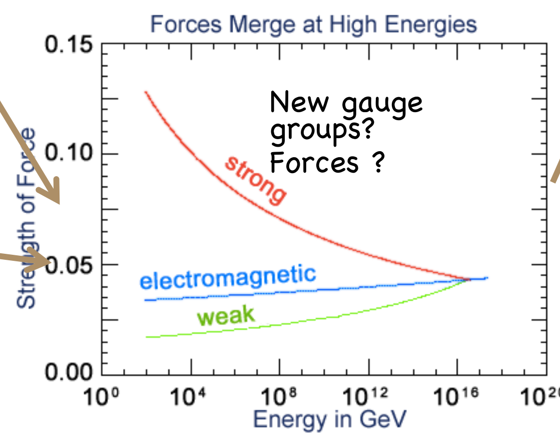
Extra Dimensions



Composite Higgs



Higgs is NOT elementary, composite particle like a pion



Vector-like quarks

Fundamental Problems → Proposed Solutions → New Particles

Naturalness

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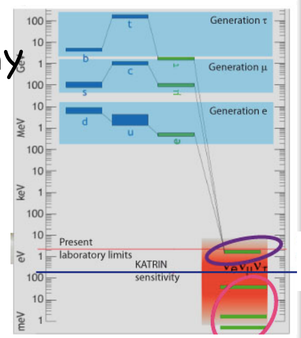
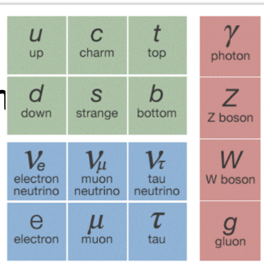
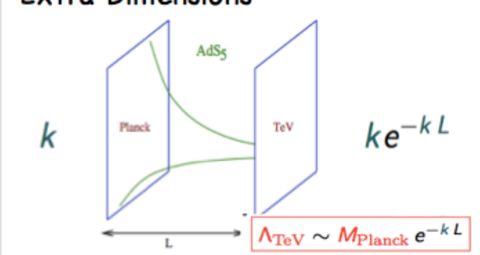


Particles and Unification of Forces



Extra Dimensions



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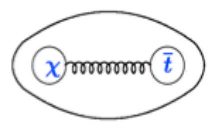

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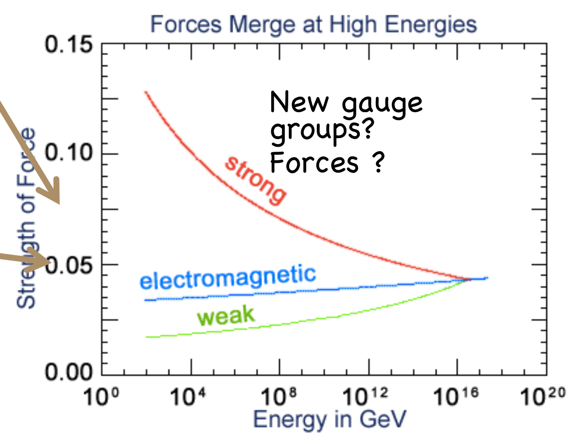


Vector-like quarks

Simplest type of colored fermions which are still allowed by experiment!

VLQs at the TeV scale are strongly motivated by two theoretical ideas:

- they can explain the observed lightness of the Higgs and
- they emerge as fermion resonances in the partial-compositeness theory of flavor

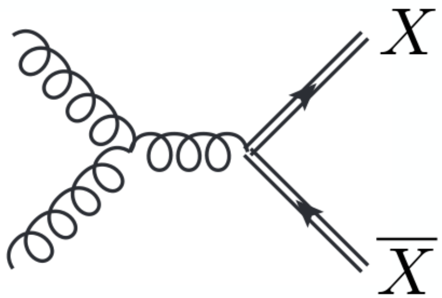
Due to the large Yukawa coupling of the top quark, both mechanisms give rise to a sizable mixing of the VLQs with 3rd gen quarks: "top partners"

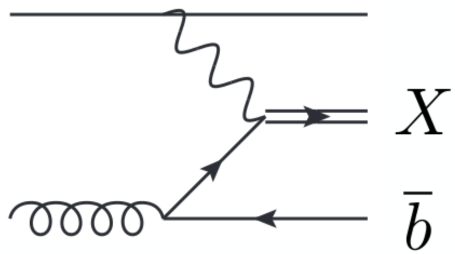
Allowed representation for Vector-like quarks

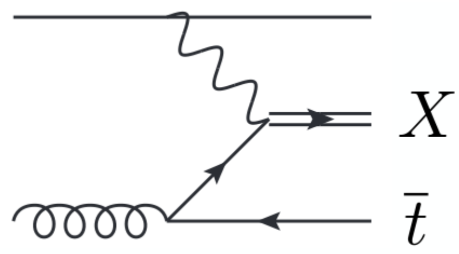
	SM quarks			Singlets		Doublets			Triplets	
	$\binom{u}{d}$	$\binom{c}{s}$	$\binom{t}{b}$	(U)	(D)	$\binom{X}{U}$	$\binom{U}{D}$	$\binom{D}{Y}$	$\begin{pmatrix}X\\U\\D\end{pmatrix}$	$\begin{pmatrix}U\\D\\Y\end{pmatrix}$
$SU(2)_L$		$q_L = 2$ $q_R = 1$		1			2		3	
$U(1)_Y$		$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$		$2/3$	$-1/3$	$7/6$	$1/6$	$-5/6$	$2/3$	$-1/3$
$\mathcal{L}_Y$		$-y_u^i \bar{q}_L^i H^c u_R^i$ $-y_d^i \bar{q}_L^i V_{CKM}^{i,j} H d_R^j$		$-\lambda_u^i \bar{q}_L^i H^c U_R$ $-\lambda_d^i \bar{q}_L^i H D_R$			$-\lambda_u^i \psi_L H^{(c)} u_R^i$ $-\lambda_d^i \psi_L H^{(c)} d_R^i$		$-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a$	
$\mathcal{L}_m$		Not allowed					$-M\bar{\psi}\psi$			

$X^{5/3}$, $T^{2/3}$ or t', $B^{-1/3}$ or b', $Y^{-4/3}$

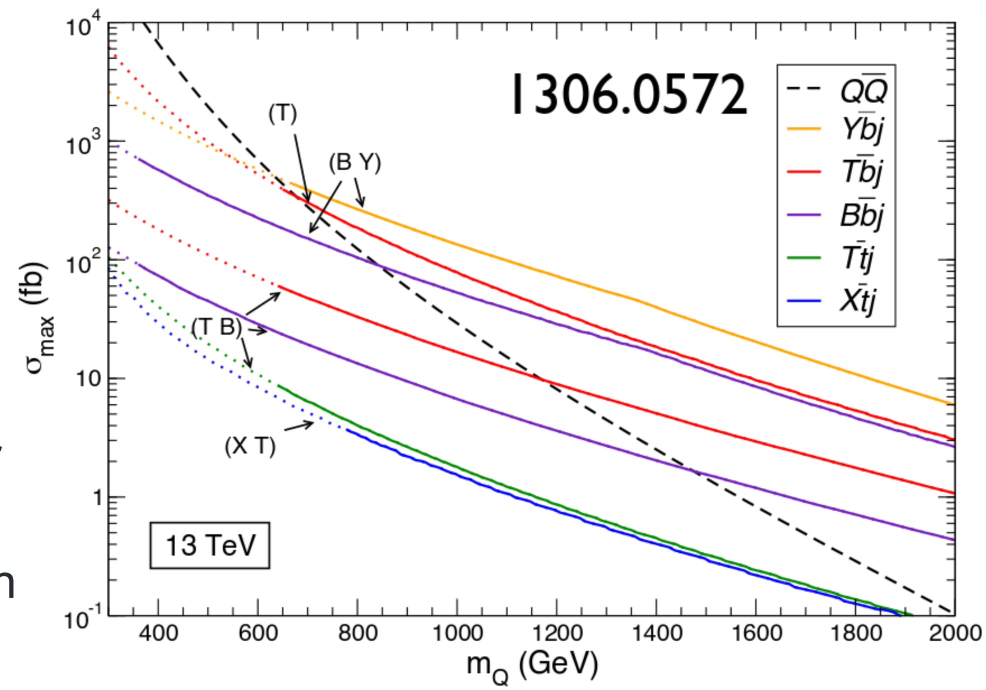
VLQ production







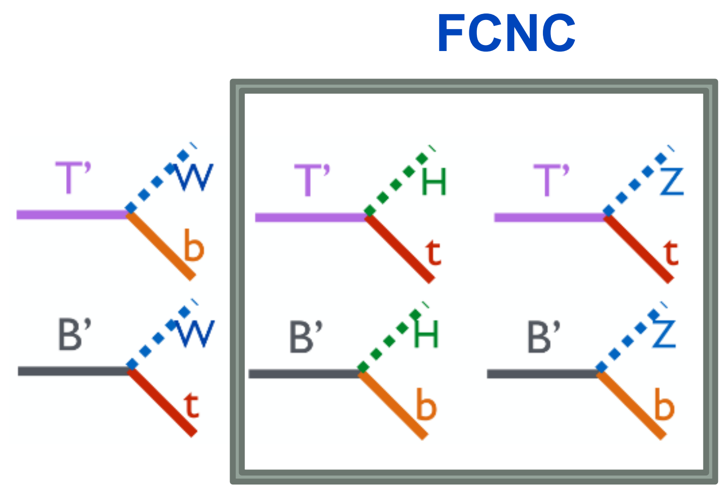
VLQs: $X^{5/3}$, $T^{2/3}$, $B^{-1/3}$, $Y^{-4/3}$



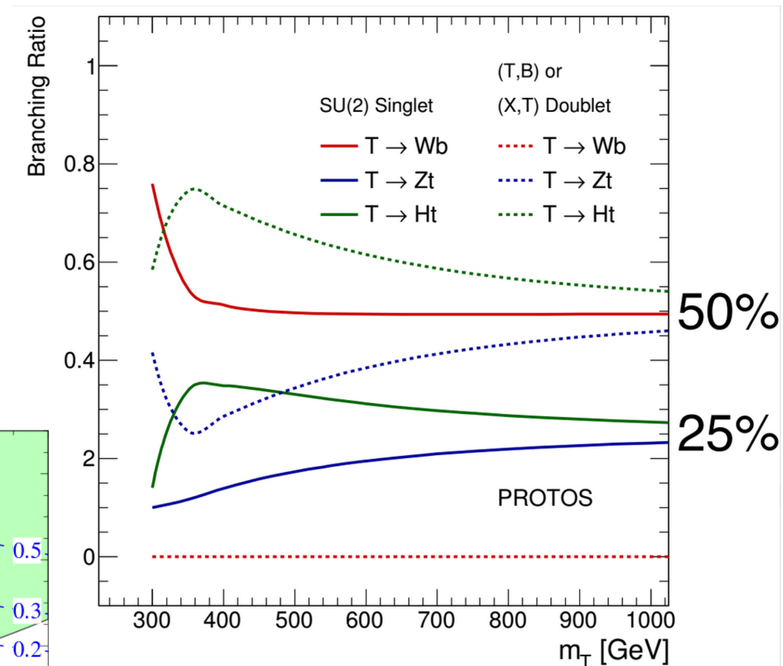
- Pair or single production
  - Pair production through QCD
  - Single production associated with t or b quark
    - Single production may dominate at high masses but depends on coupling
    - Forward jet gives a unique topology to tag

VLQ Decays

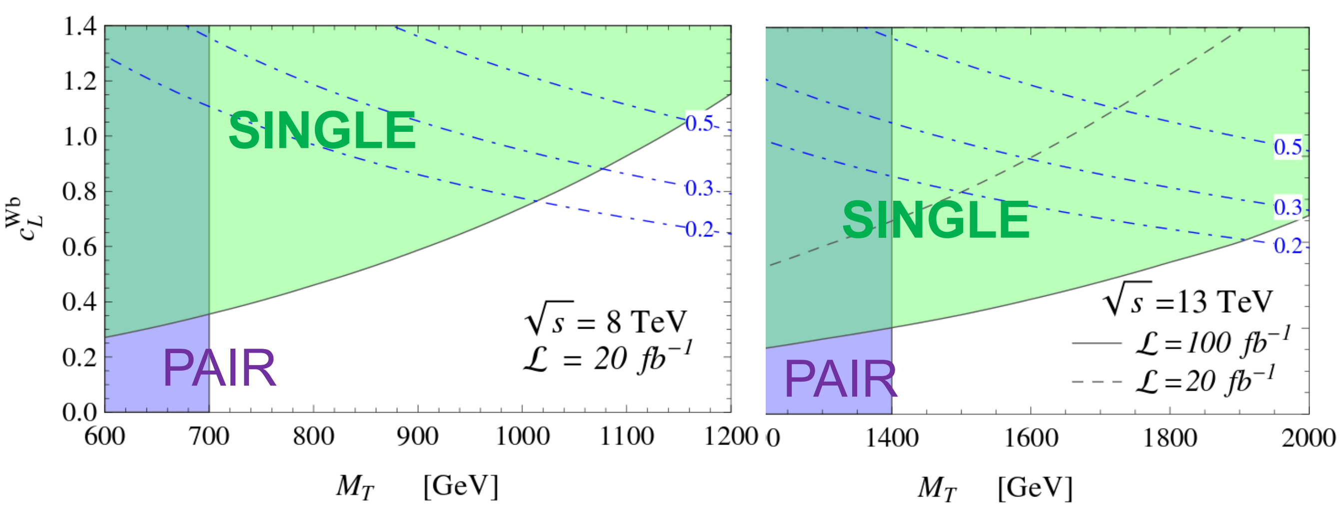
- Decays to 3rd gen quarks & SM bosons
- In the presence of VLQs, FCNC decays are possible (though constrained by rare top decays, D meson mixing and EW precision)
- Also potential for decays to quark + DM
- Branching ratios depend on multiplet



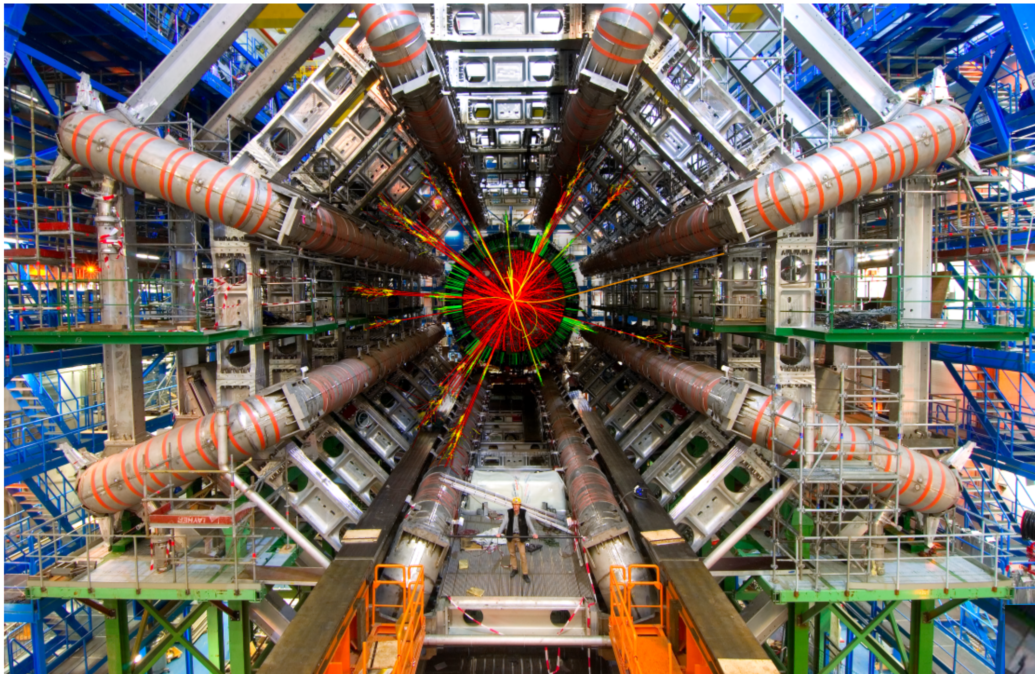
- Pair production searches set σ x BR limits depending on the partner mass
- Single production searches also depend on coupling to SM quarks and set limits in the c_L – M(X) plane

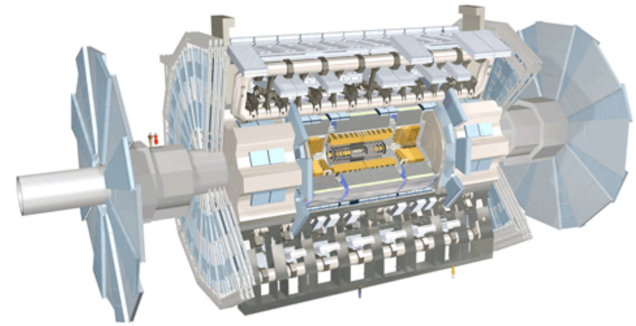


CMS pair production result (1311.7667) + single production recast (1409.0100)

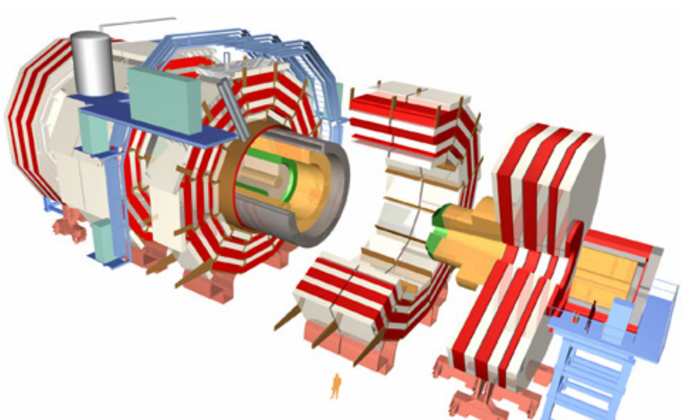


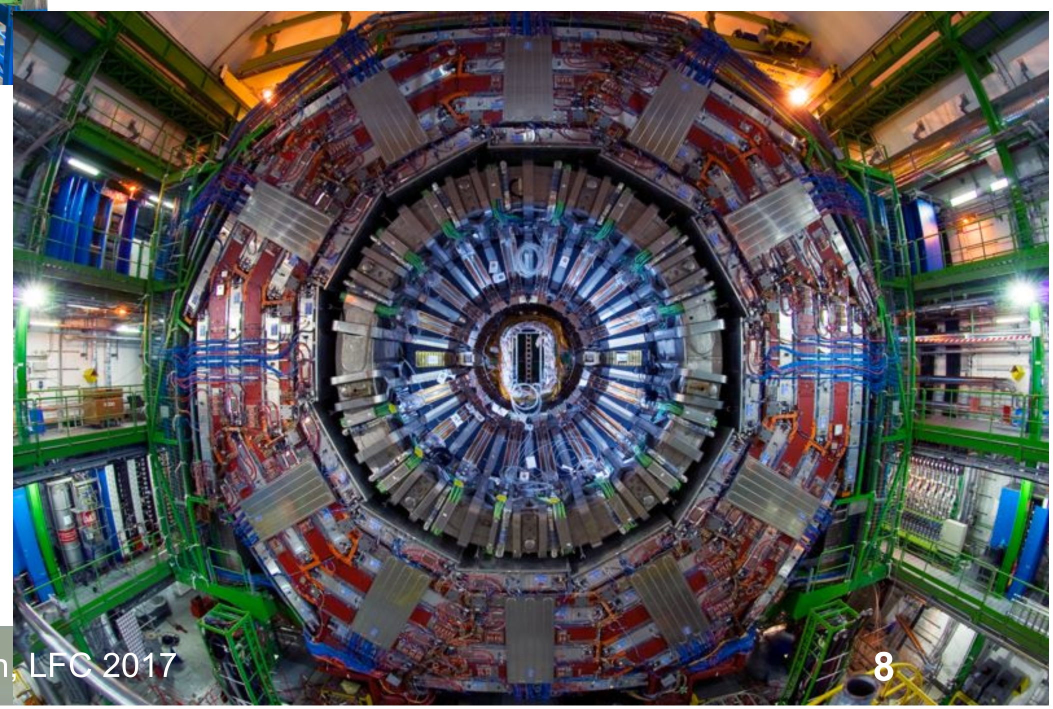
ATLAS & CMS





General-purpose experiment

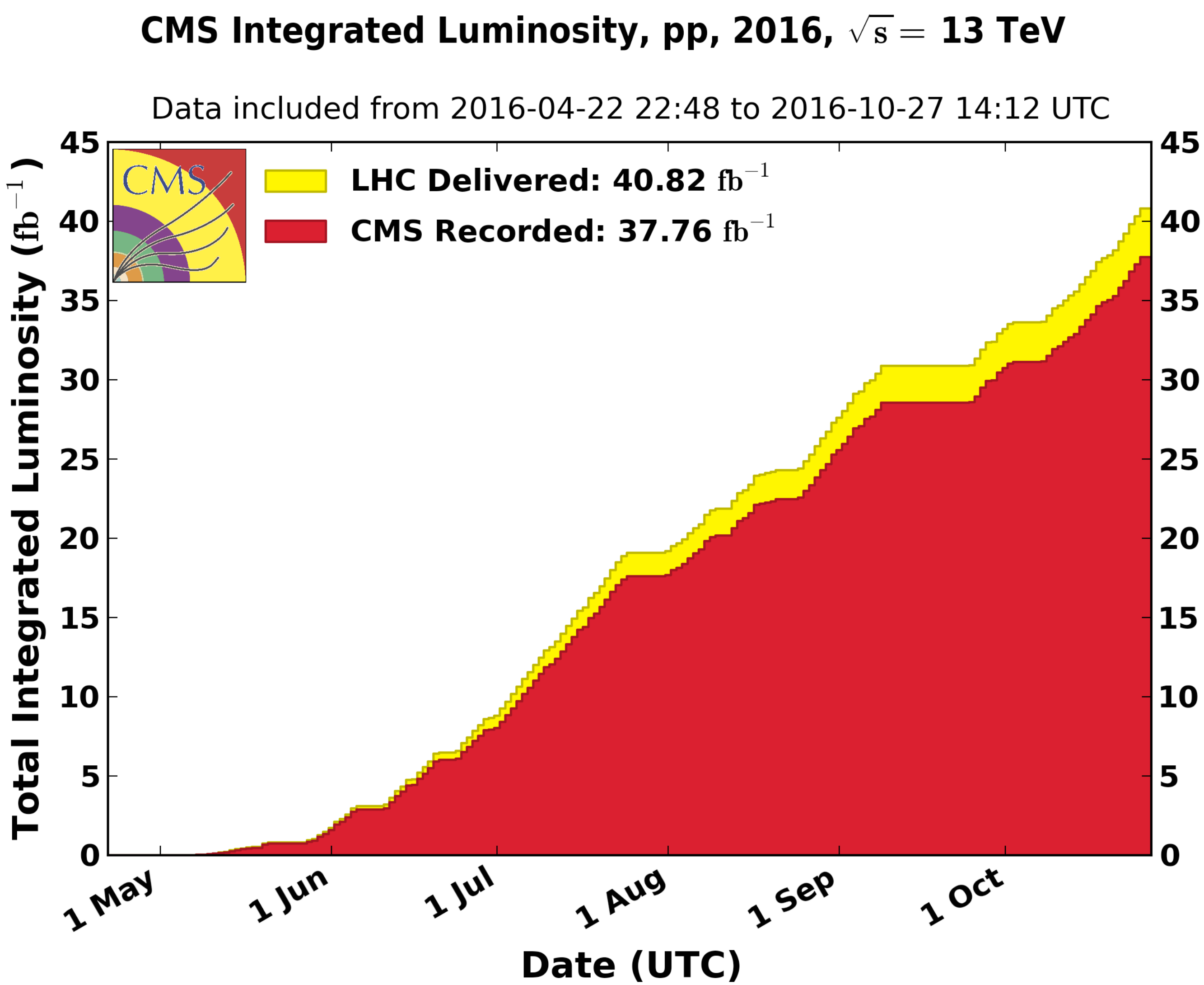




General-purpose experiment

Data delivered by the LHC (2016)

- Spectacular running and ~37/fb delivered



~4000

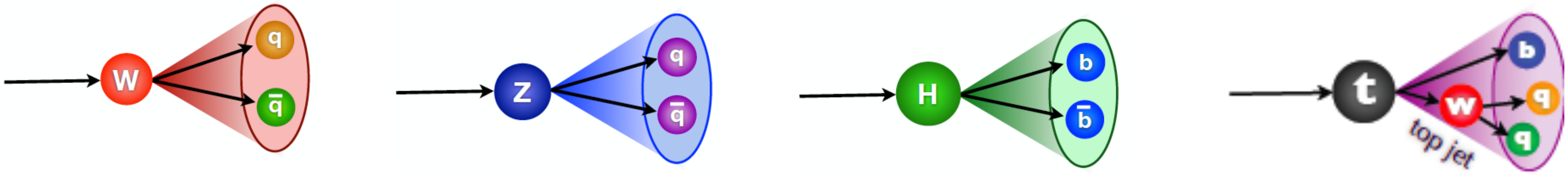
VLQs produced

w/ M(VLQ)~1 TeV

A SHORT DICUSSION ABOUT BOOSTED PARTICLE IDENTIFICATION

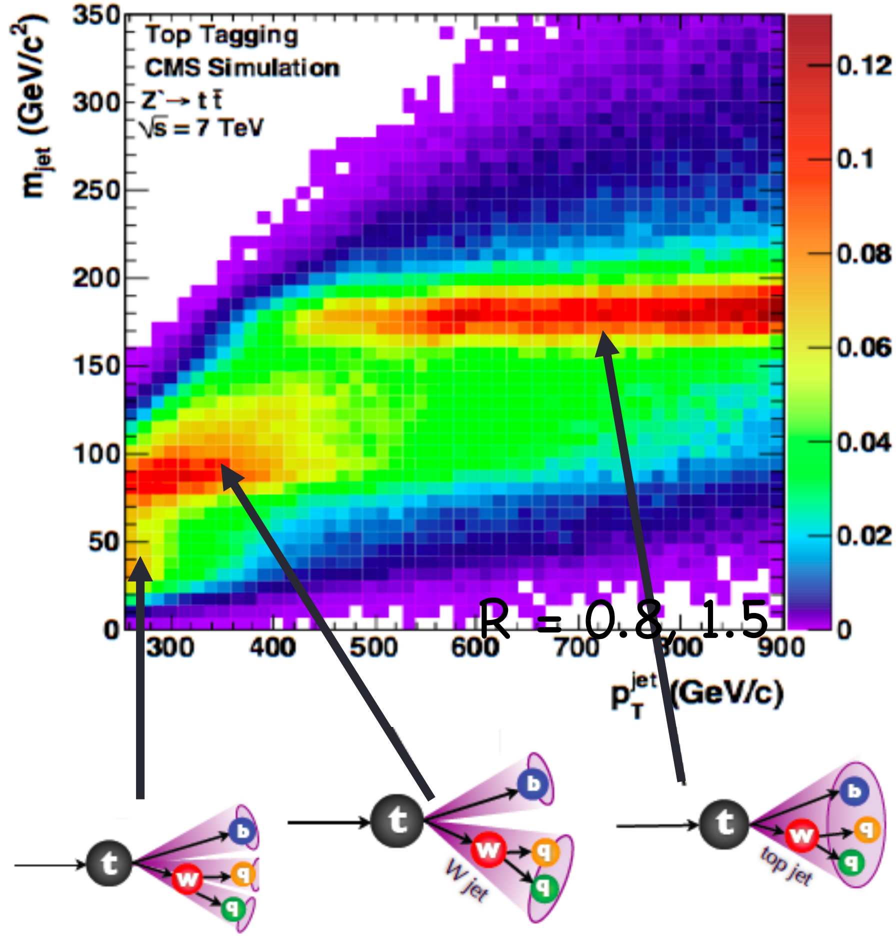
Boosted Quarks and Bosons

[CMS-PAS-JME-13-006]



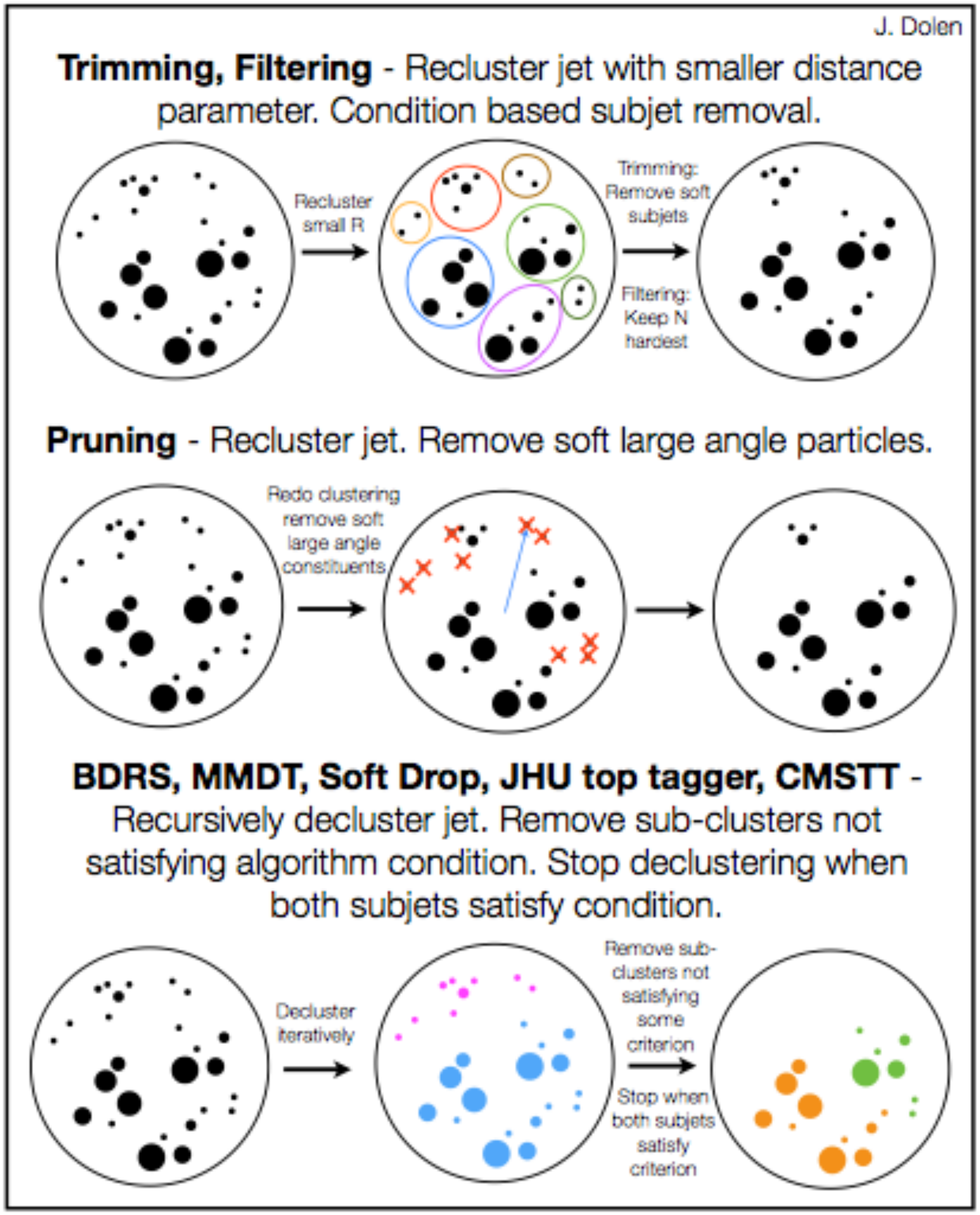
- At higher energies and heavier new particles produce boosted decay products
- We employ jet substructure techniques to tag SM bosons and tops

- angular separation: $\Delta R \approx 2M/p_T$
- efficiency for 2 jets drops with p_T
- The jet mass is relatively stable at the heavy particle mass
- Choose correct cone size to catch all decay products in a jet.
  - R =0.8 for W/Z/H
  - R=0.8 and 1.5 for top

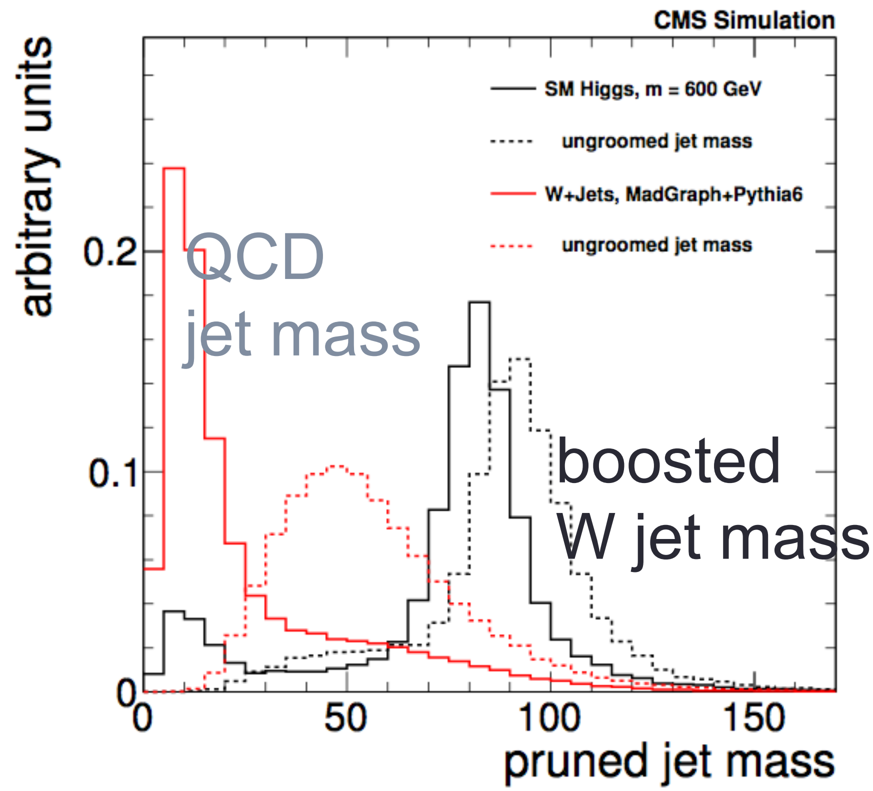


jet grooming

[CMS-PAS-HIG-13-008]



high mass H→WW:



improves jet mass resolution

reduces QCD jet mass

jet shapes

[CMS-PAS-JME-13-006]

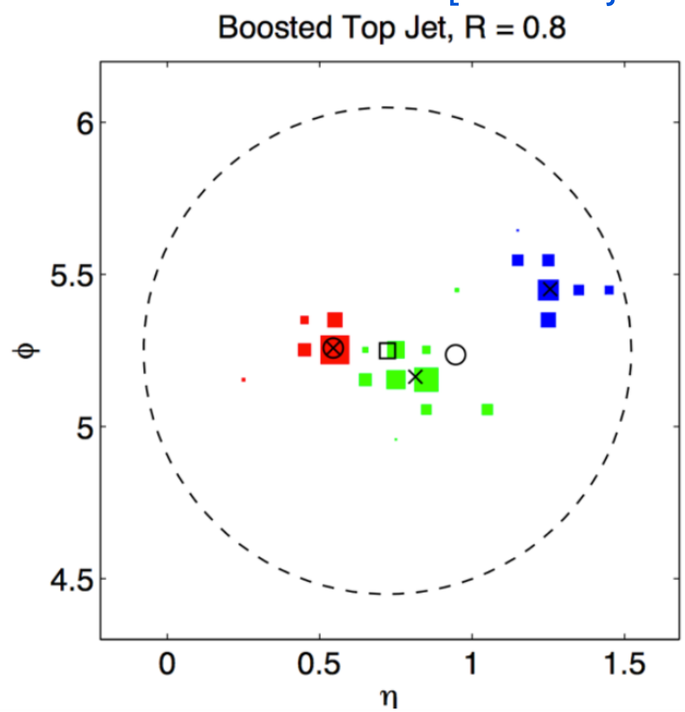
- energy patterns within a jet:
- characterize multi-prong properties
- many definitions and varieties

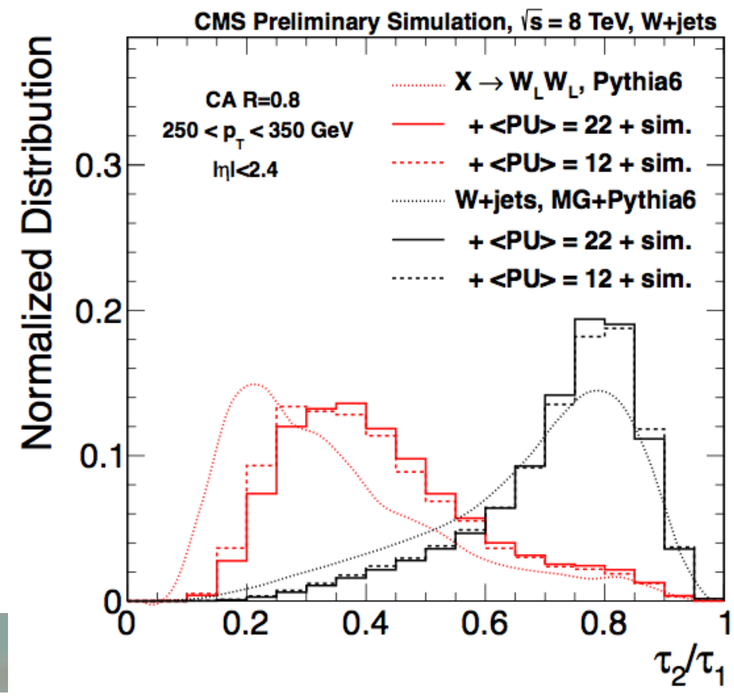
- n-subjettiness:

$$\tau_N = \frac{\sum_{i=1}^{n_{\text{constituents}}} p_{\mathrm{T},i} \min\{\Delta R_{1,i}, \Delta R_{2,i}, ..., \Delta R_{N,i}\}}{\sum_{i=1}^{n_{\text{constituents}}} p_{\mathrm{T},i} R}$$

- how consistent is jet with having N subjets
- ratios discriminate hypotheses: $\tau 2/\tau 1$

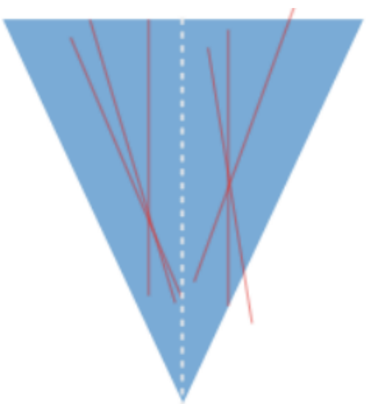
- many other on the market:
- energy correlation functions
- Q-jet volatility
- …



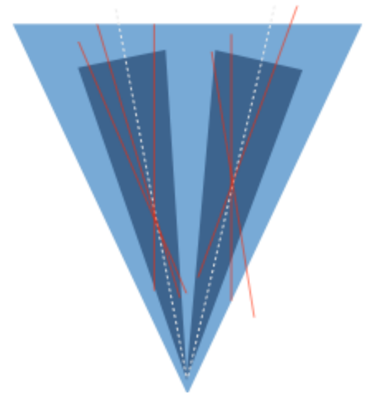


b-tagging in boosted topologies

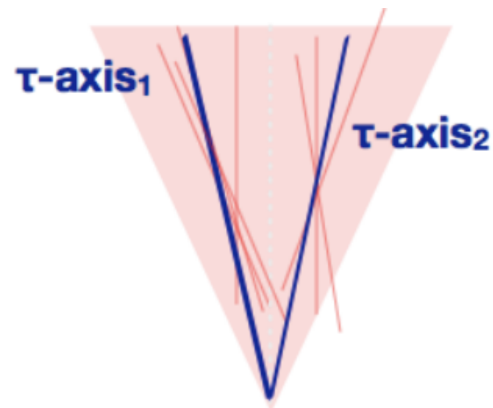
- several approaches:



fat jet



subjets



double b

run standard b-tagging algorithm on wide jets

not able to distinguish two from one b jets

run standard b-tagging algorithm on subjets

can distinguish two from one b jets

dedicated double tagger

specialised for boosted H→bb

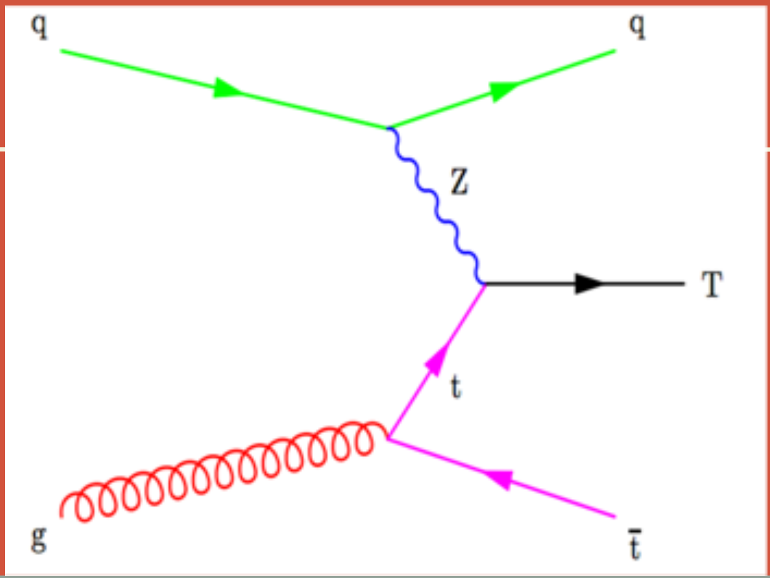
VLQ SEARCH DIGEST

List of VLQ Searches

- Single Production
  - T/Y→bW (ℓjets)
  - T→tH (all had)
  - T→tH (ℓjets)
  - T→tZ (Z→ℓℓ)

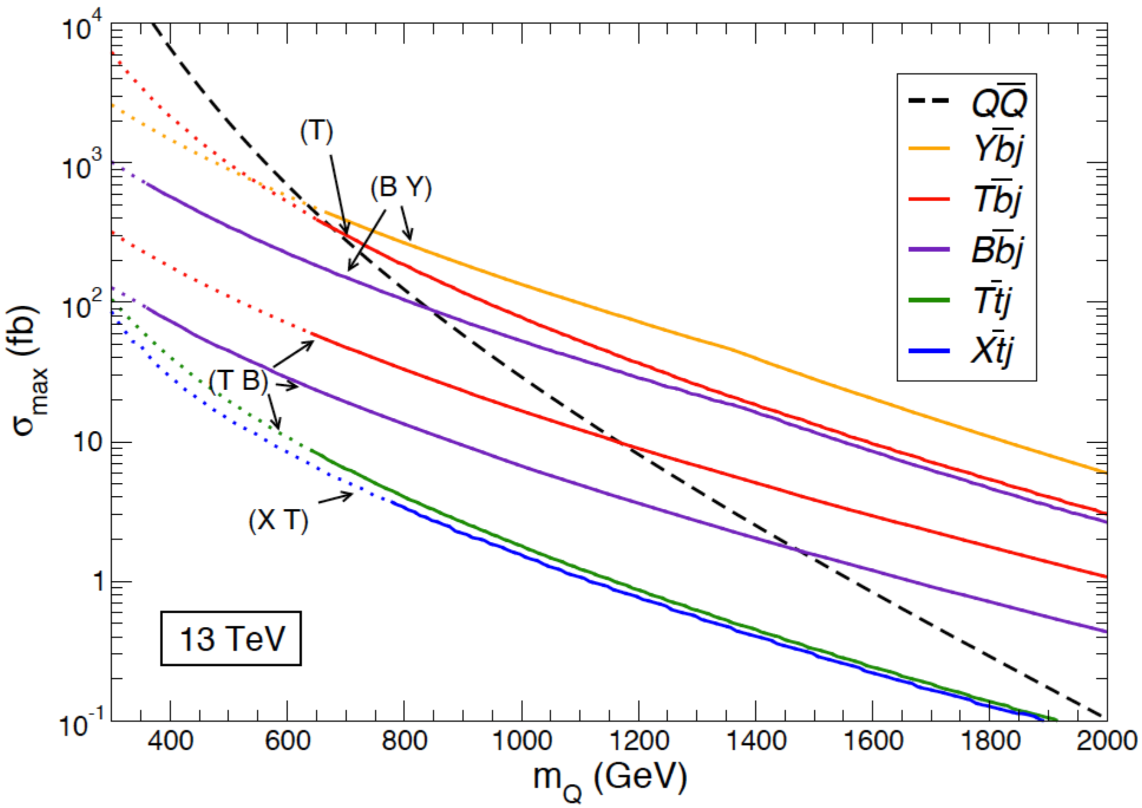
- Pair Production
  - T→bW (ℓjets)
  - T→tH (ℓjets)
  - T→tZ, bH, B→bZ, bH (OSℓℓ)
  - X→tW (SSℓℓ + ℓjets)

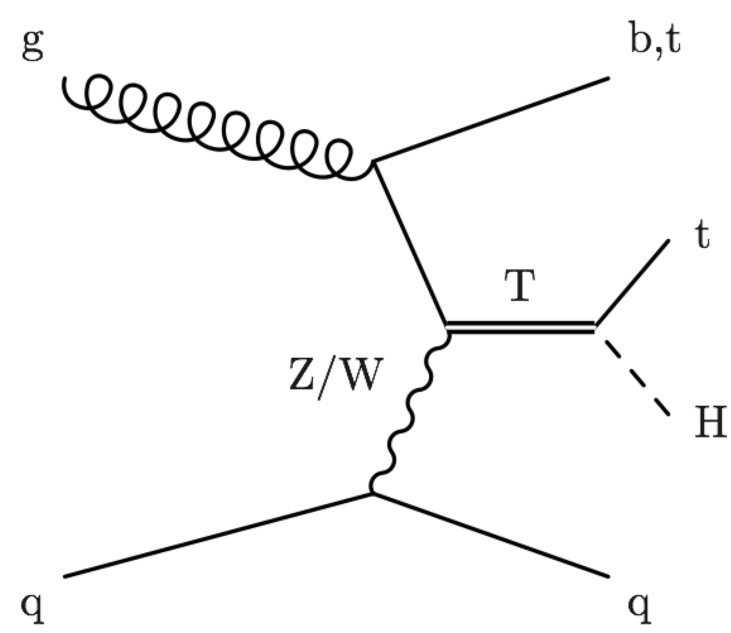
SEARCHES USING SINGLE VLQ PRODUCTION SIGNATURES



Single production

production cross-section:

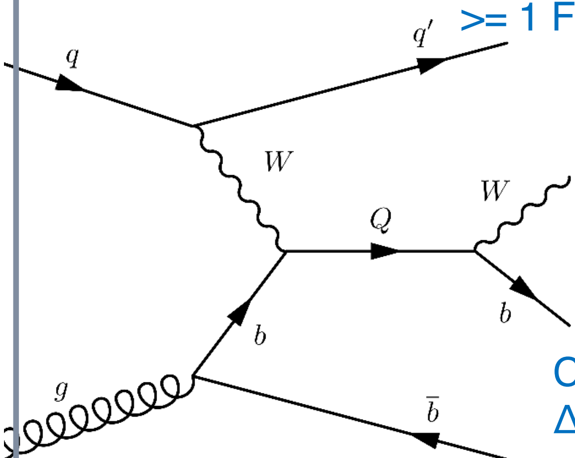




forward jet

higher cross sections at high masses
allows to set limits on model parameters

Single $T^{2/3}/Y^{-4/3} \rightarrow bW$, ℓjets (CMS)



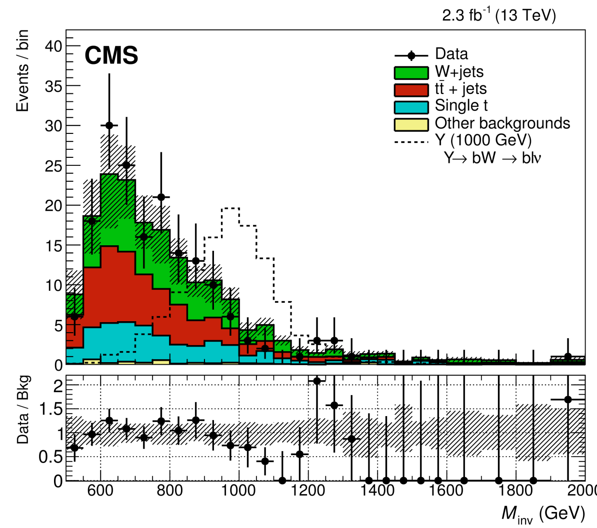
>= 1 Forward jet, pT > 30 GeV

Isolated lepton
ΔR > 1.5 from any jet

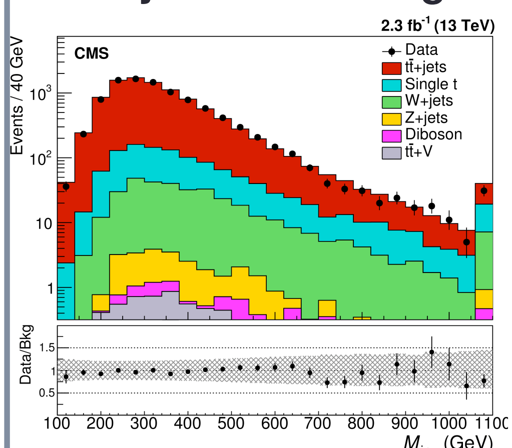
$p_T(\ell) > 40$ GeV
MET > 50 GeV
M_T (W) > 130 GeV

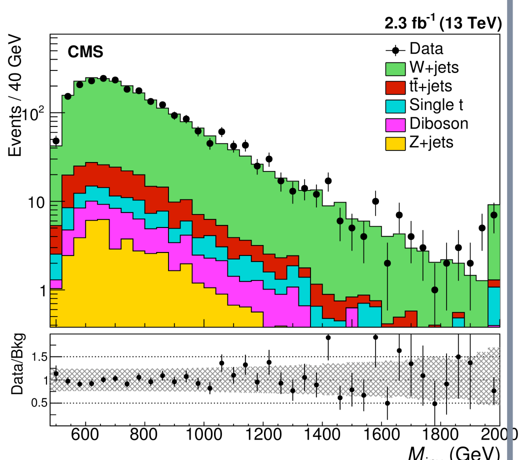
Central b jet, $p_T > 200$ GeV
$\Delta\varphi(\ell, b) > 2$

Reconstruct M(Y) from b jet & leptonic W decay

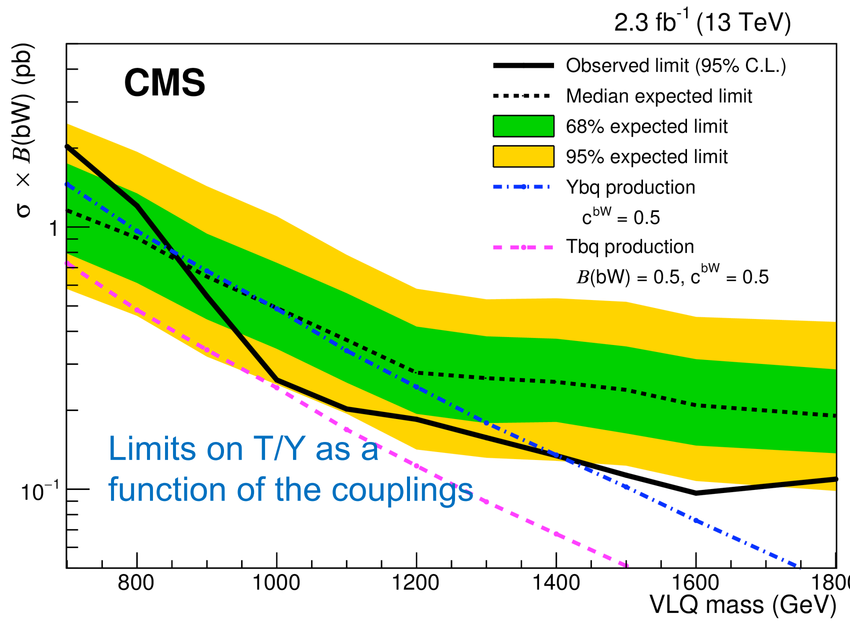


- **Background modeling checked in ttbar and Wjets control regions**





- **Limits in narrow-width approximationvalid for M(Y) > 1.4 TeV, c(bW) ≤ 0.5 BR (Y->bW)= 100%,**

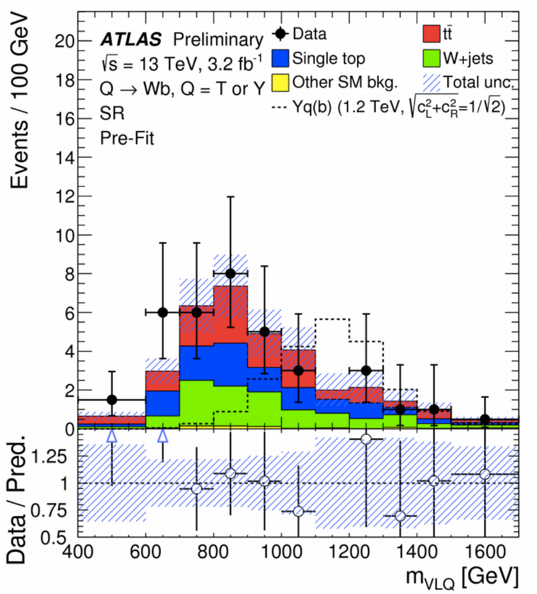


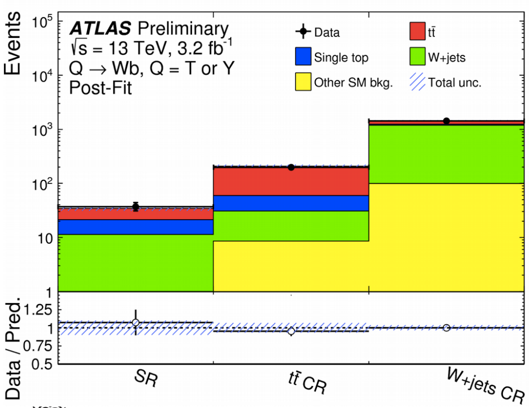
arXiv:1701.08328

ATLAS-CONF-2016-072

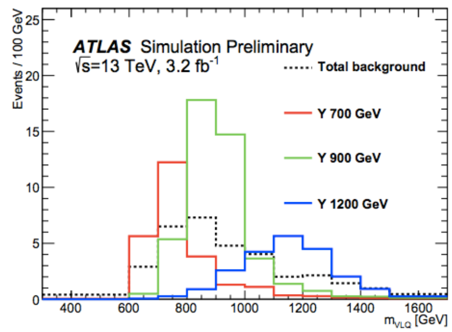
Search for bW (ATLAS)

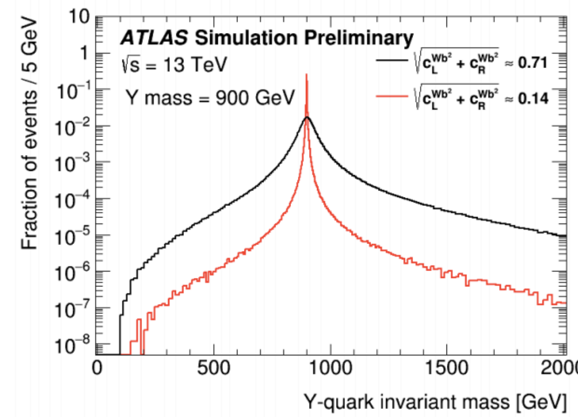
Signal Region



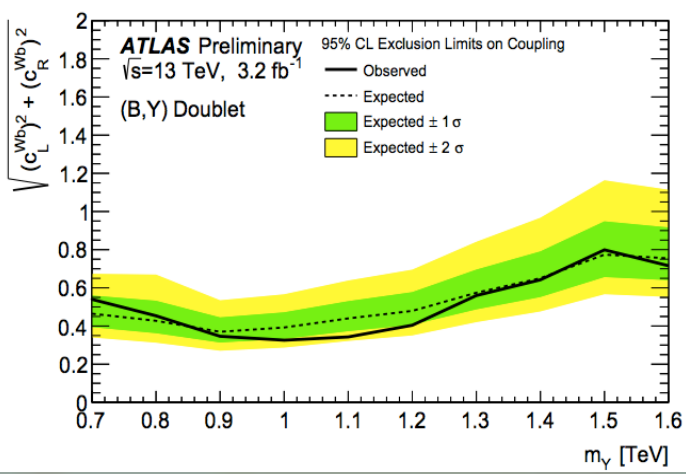


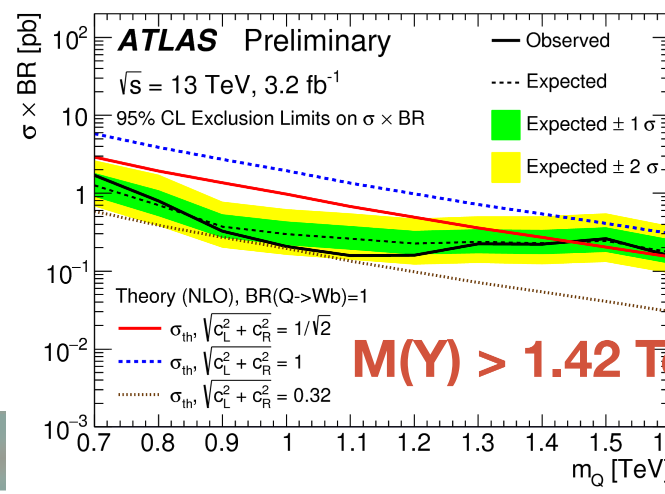
- Single production of T or Y
- Lep + b + MET > 350 GeV, forward jet, Reconstruct VLQ M(Wb) mass assuming the lower of two solutions for neutrino P_Z.





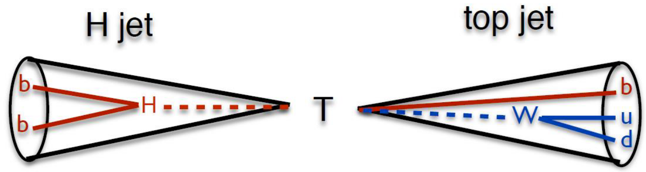
- CR: tt, W+jet used in limit setting fit.
- Coupling dependent limits
- Quark width as the function of coupling is taken into account





M(Y) > 1.42 TeV

Single $T^{2/3} \rightarrow$ tH, all Had (CMS)

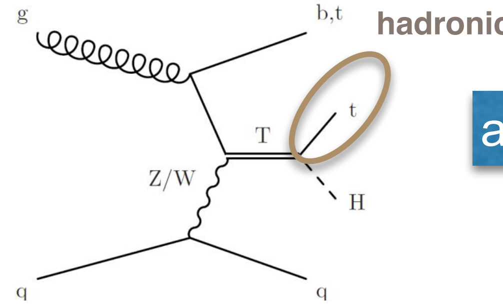


M_{Prune}: 105 –135 GeV
$\tau_2/\tau_1 < 0.6$
2 b tagged subjets

M_{SD}: 110 –210 GeV
$\tau_3/\tau_2 < 0.54$
1 b tagged subjets

Reconstruct M_T by identifying boosted Higgs & top jets

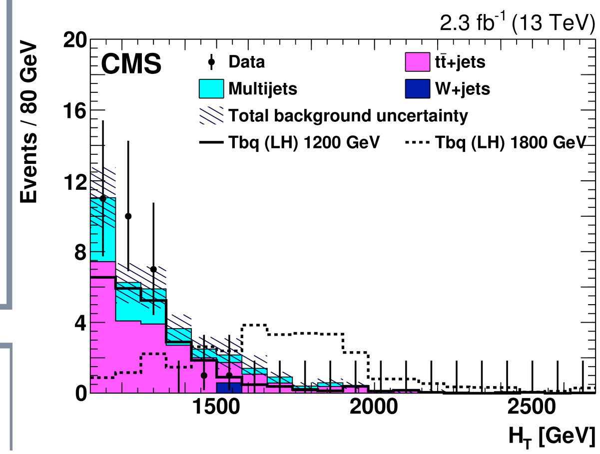
High jet activity: H_T > 1.1 TeV

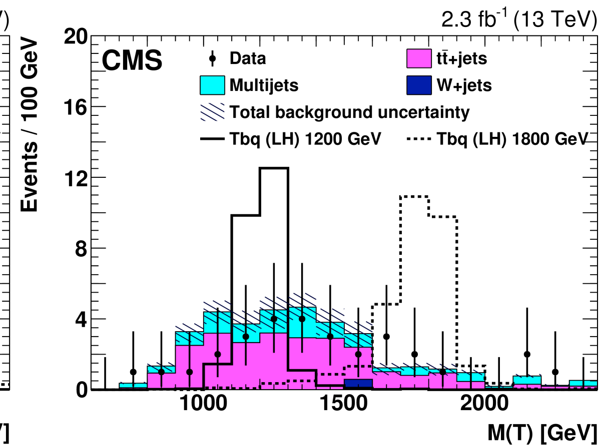


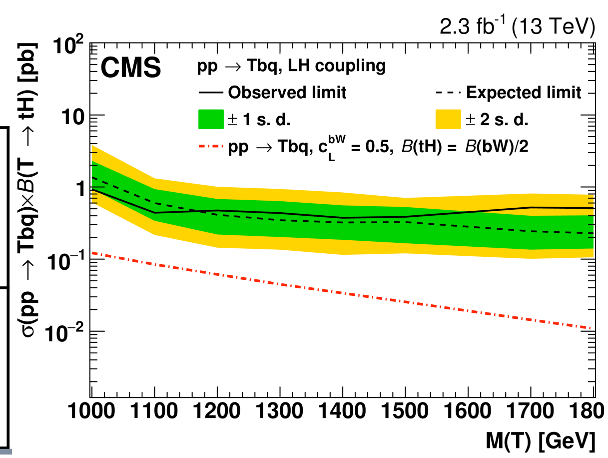
arXiv:1612.05336

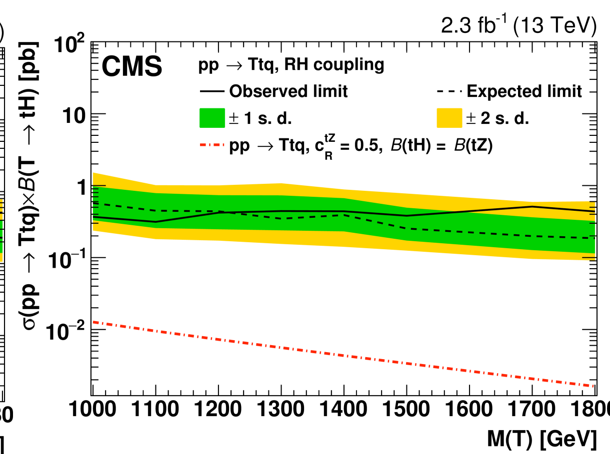
- QCD background evaluation: "ABCD method" using three new regions by vetoing the tags
- Rest from simulation

A 0 H tag, ≥1 anti-H 0 top tag	B 0 H tag, ≥1 anti-H 1 top tag
C ≥1 H tag 0 top tag	**D** Signal Region



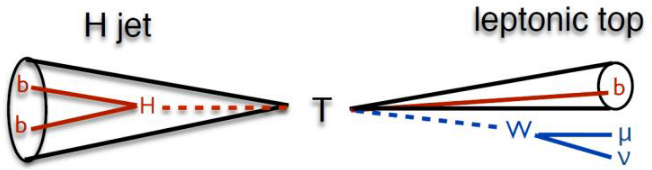






* Boosted jets with both subjets failing the b tagging criteria but otherwise satisfying the H tagging criteria ("anti-H-tagged")

Single $T^{2/3} \rightarrow tH$, ℓjets (CMS)

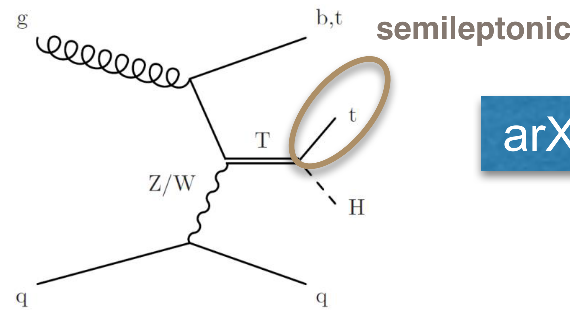


M_{SF}: 90 –160 GeV
2 b tagged subjets
$\Delta R(H,\ell) > 1.0$

$p_T(e/\mu)$ > ~50 GeV
1st and 2nd Jet p_T (e/μ) > (250,70/100,50)

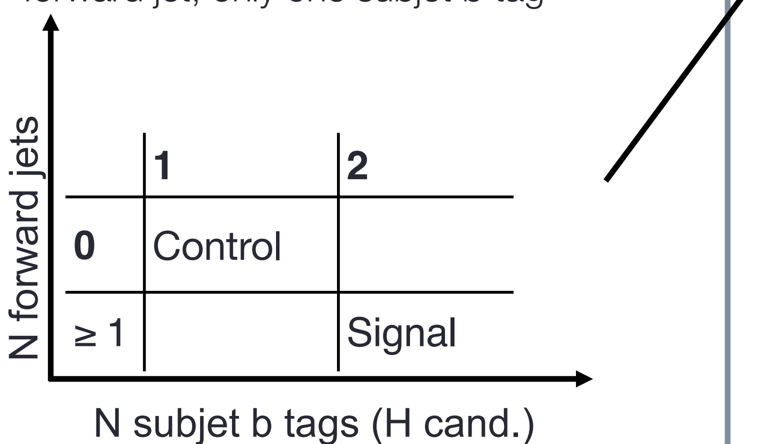
Reconstruct M_T by identifying boosted Higgs & top jets

Require S_T > 0.4 TeV

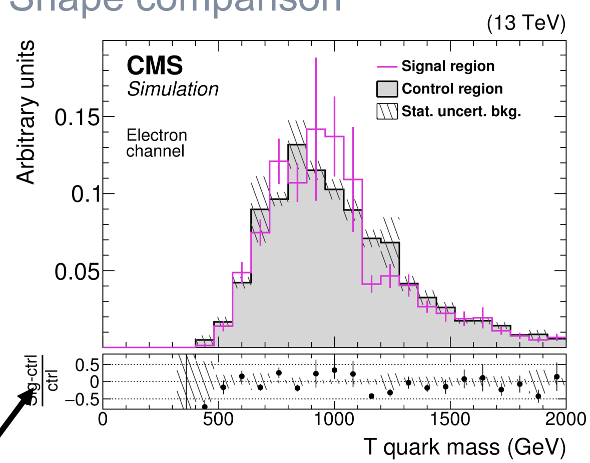


arXiv:1612.00999

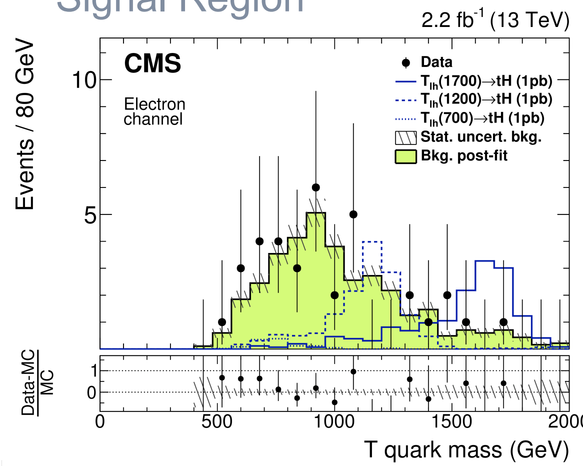
- Background constrained using data with no forward jet, only one subjet b tag

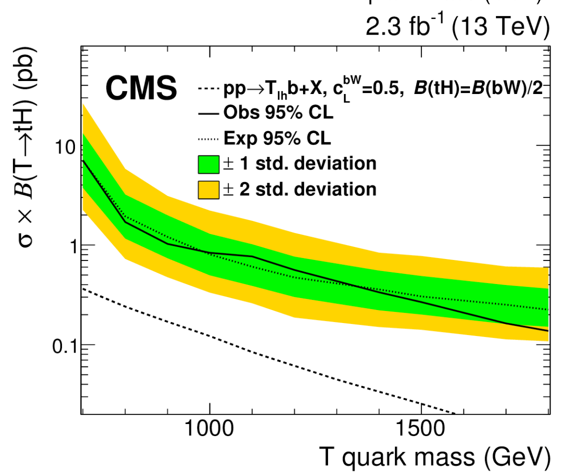


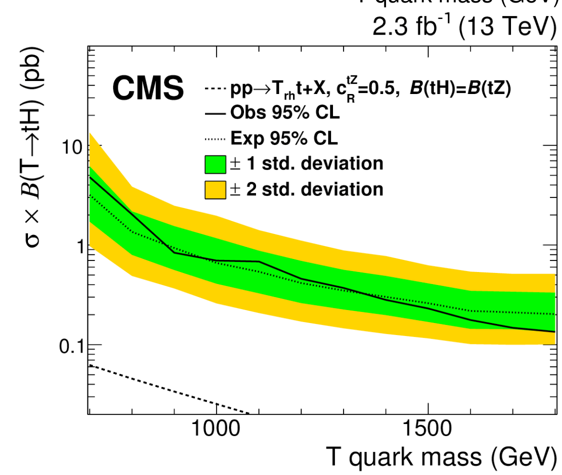
Shape comparison



Signal Region





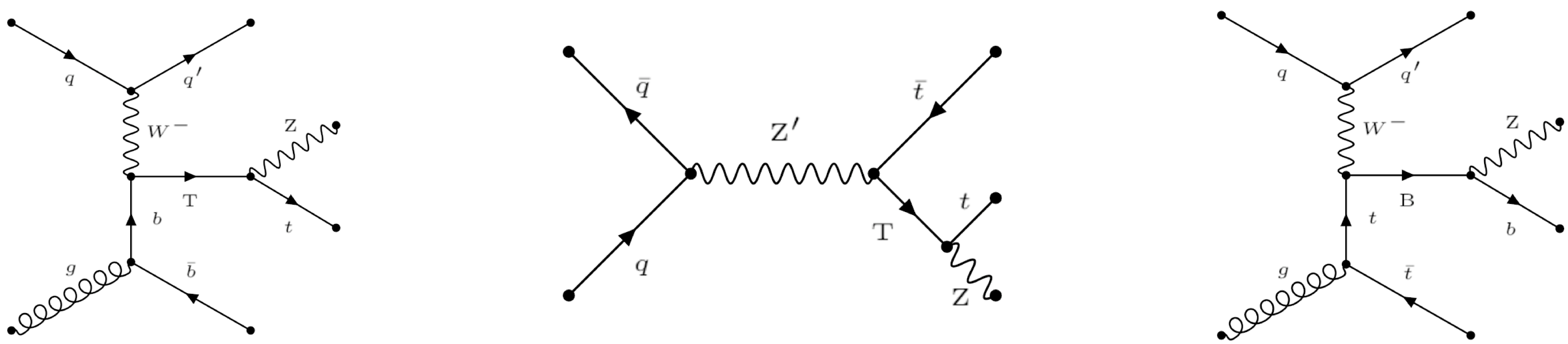


Single $T^{2/3} \rightarrow tZ$

arXiv:1701.07409

B2G-17-007

- Search for $T \rightarrow tZ \rightarrow t + 2\ell$ and $B \rightarrow bZ \rightarrow b + 2\ell$



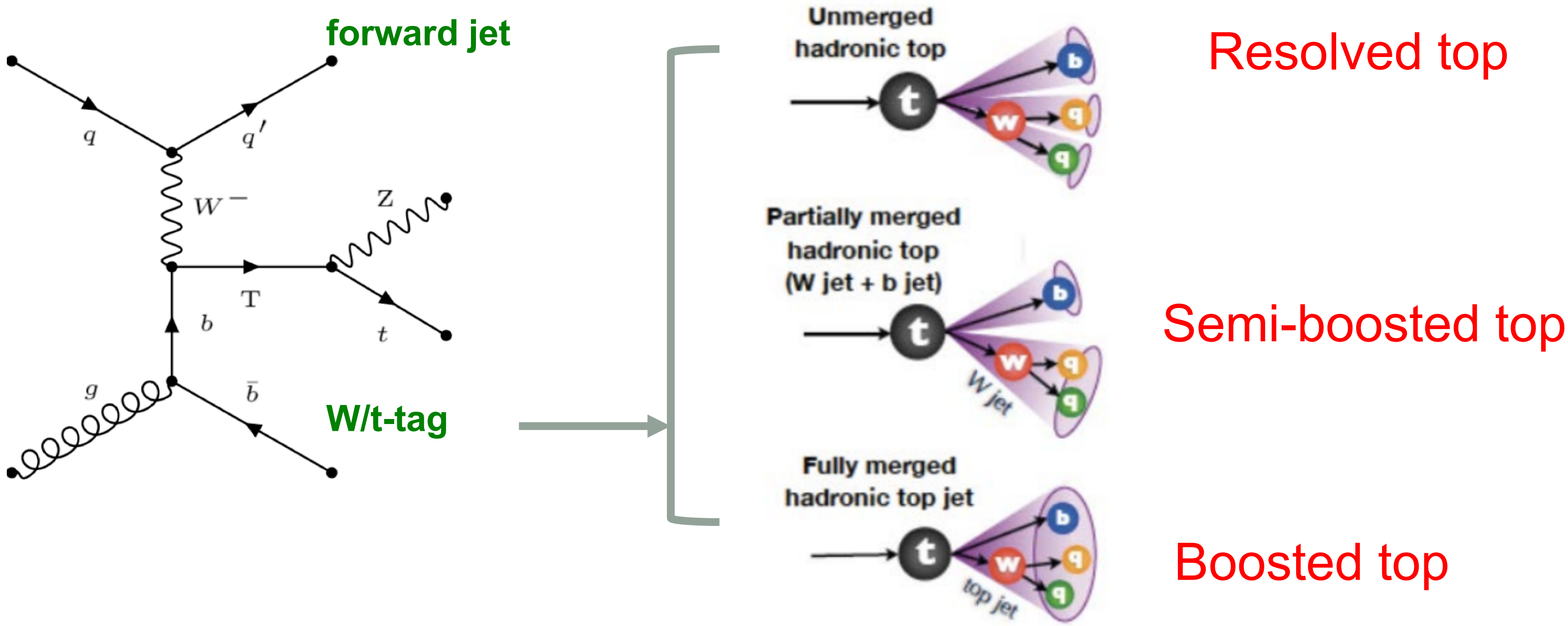
- Several T width (10%, 20%, 40%) are considered for different benchmark masses between 0.8 – 1.6 TeV

Mass [TeV]	$\bar{\sigma}_{FW}$ (σ) for pp $\rightarrow$ Tbq $\rightarrow$ tZbq [pb] 10%	20%	30%	$\bar{\sigma}_{FW}$ (σ) for pp $\rightarrow$ Ttq $\rightarrow$ tZtq [pb] 10%	20%	30%
0.8	226 (0.675)	108 (0.650)	70 (0.631)	19 (0.144)	9 (0.139)	6 (0.135)
1.0	183 (0.314)	87 (0.299)	55 (0.284)	17 (0.075)	8 (0.072)	5 (0.069)
1.2	145 (0.158)	68 (0.149)	43 (0.141)	14 (0.042)	6 (0.039)	4 (0.037)
1.4	112 (0.084)	52 (0.079)	33 (0.074)	11 (0.024)	5 (0.022)	3 (0.021)
1.6	85 (0.047)	39 (0.043)	29 (0.041)	8 (0.014)	4 (0.013)	2 (0.012)

B2G-17-007

Single $T^{2/3} \rightarrow tZ$ (CMS, 35.9 fb-1)

- Main tool: leptonic Z + hadrons from heavy particles
- Make use of Top jets, W-jets, and b-jets



- Performed with a set of very sophisticated categorization
- Use M(VLQ) for discrimination
  - Hadronic tops allow direct reconstruction of VLQ mass
  - Reconstruct M(VLQ) using leptons and boosted jets

B2G-17-007

Single $T^{2/3} \rightarrow tZ$

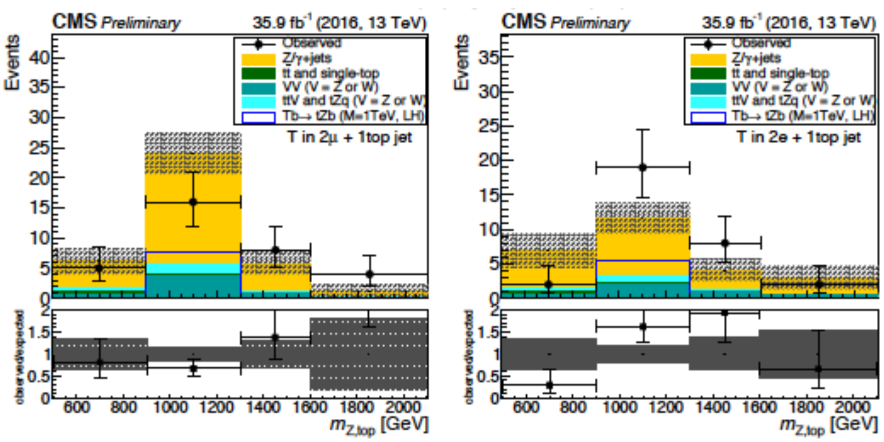
- Background yield in the signal region is evaluated by using alpha ratio method from a control region where loosely identified b-jets are vetoed

$$N_{bkg}(M_{t,Z}) = N_{cr}(M_{t,Z}) \cdot \alpha(M_{t,Z})$$

data in the control region

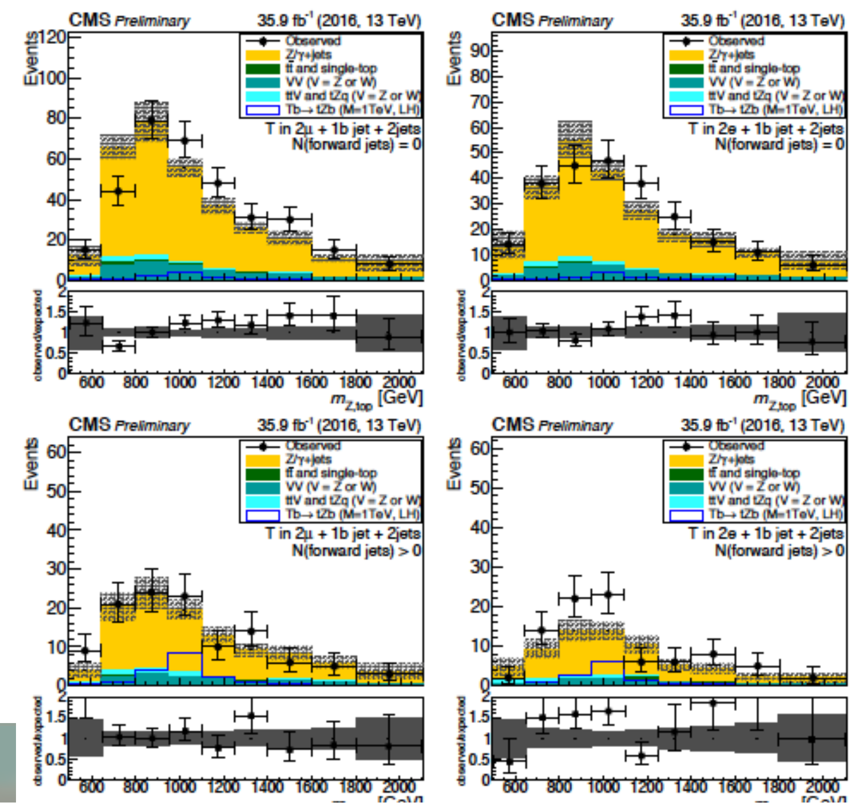
binned ratio between the shapes of the $M_{t,Z}$ in signal and sideband

Two boosted categories



- Most sensitive categories: $N_{\text{foward jets}} \geq 1$

Resolved categories: 0 or ≥ 1 forward jet

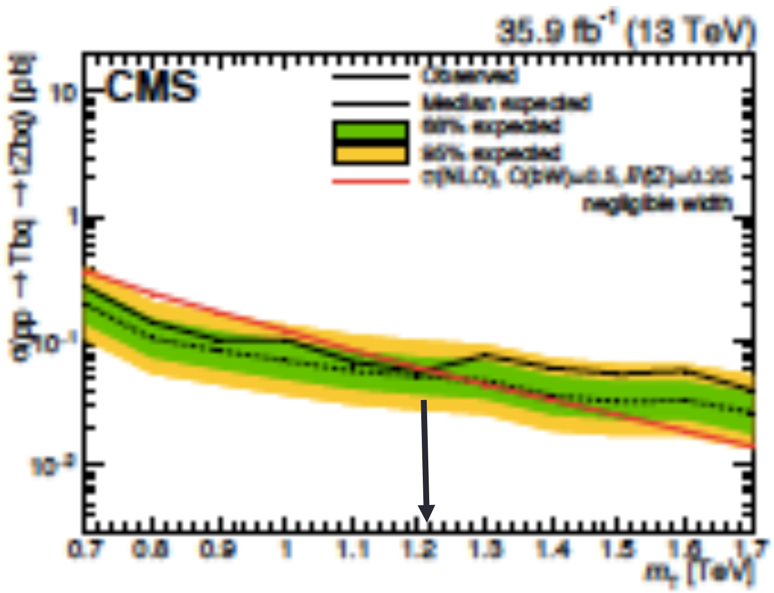


Single T$^{2/3}$→ tZ (CMS)

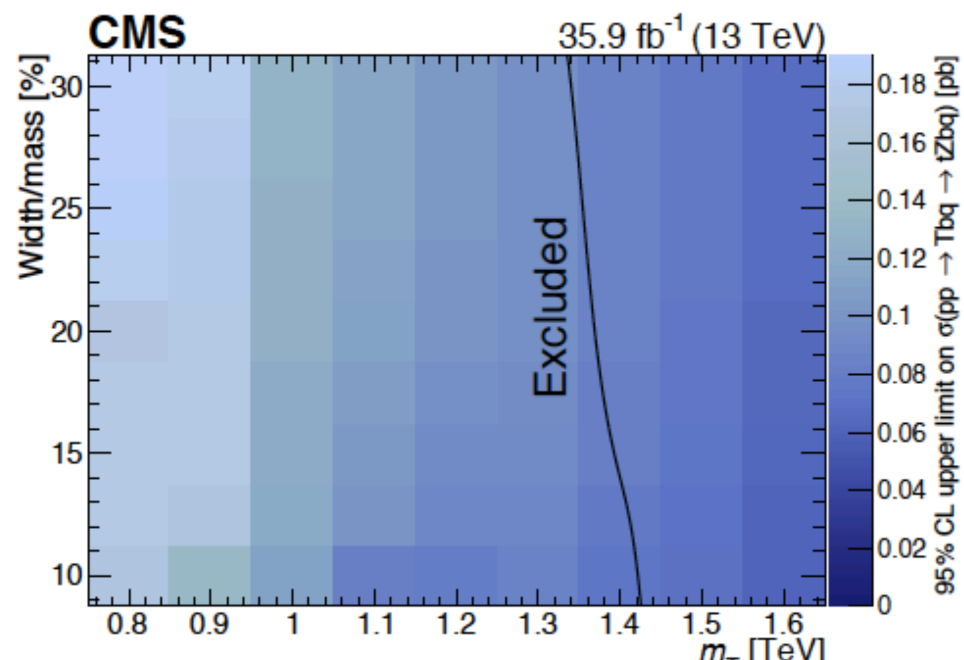
- Limits on $\boldsymbol{B}$ x σ for T(b/t) and B(t/b) production modes excludes values at 95% CL, where

$$\sigma(C_1, C_2, M, \Gamma) = C_1^2 C_2^2 \sigma(M, \Gamma), where$$
$$for\ pp \to Ttq \to tZtq: \ C_1 = C_2 = C(tZ)$$
$$for\ pp \to Tbq \to tZbq: \ C_1 = C(tZ), C_2 = C(bW)$$

- Large couplings <-> large widths
- Similar limits for larger quark widths
- Singlet MT > 1.2 TeV, C(bW) = 0.5. BR (T->tZ)= 25%

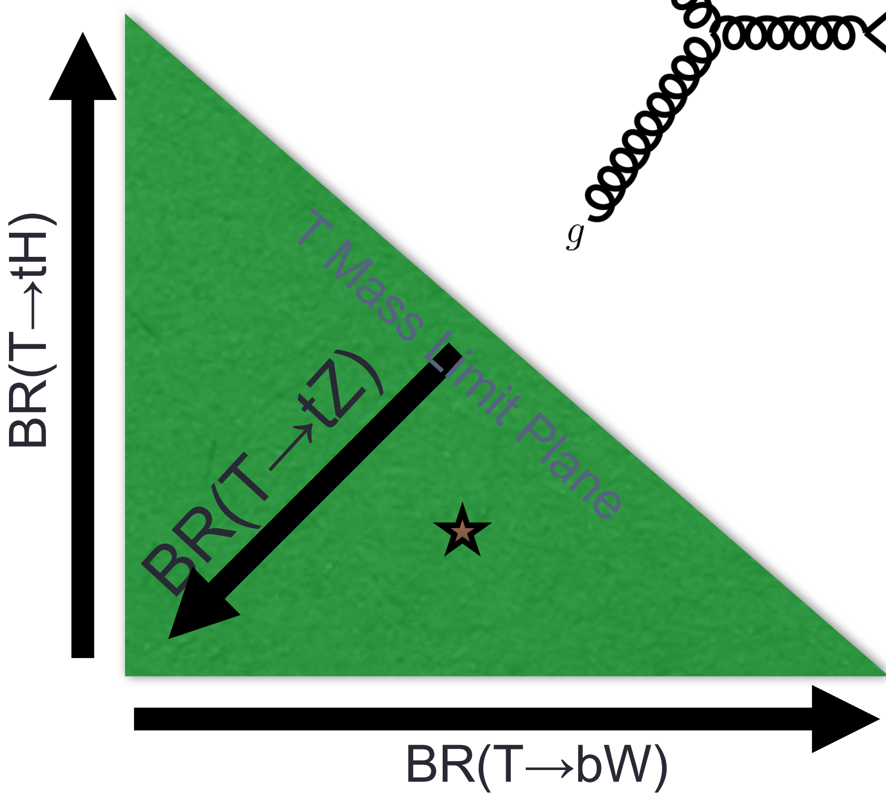


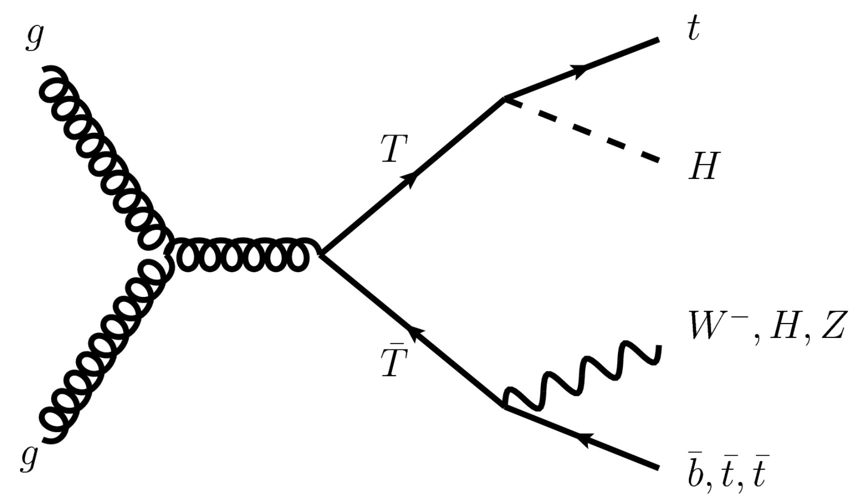
Singlet (LH T)



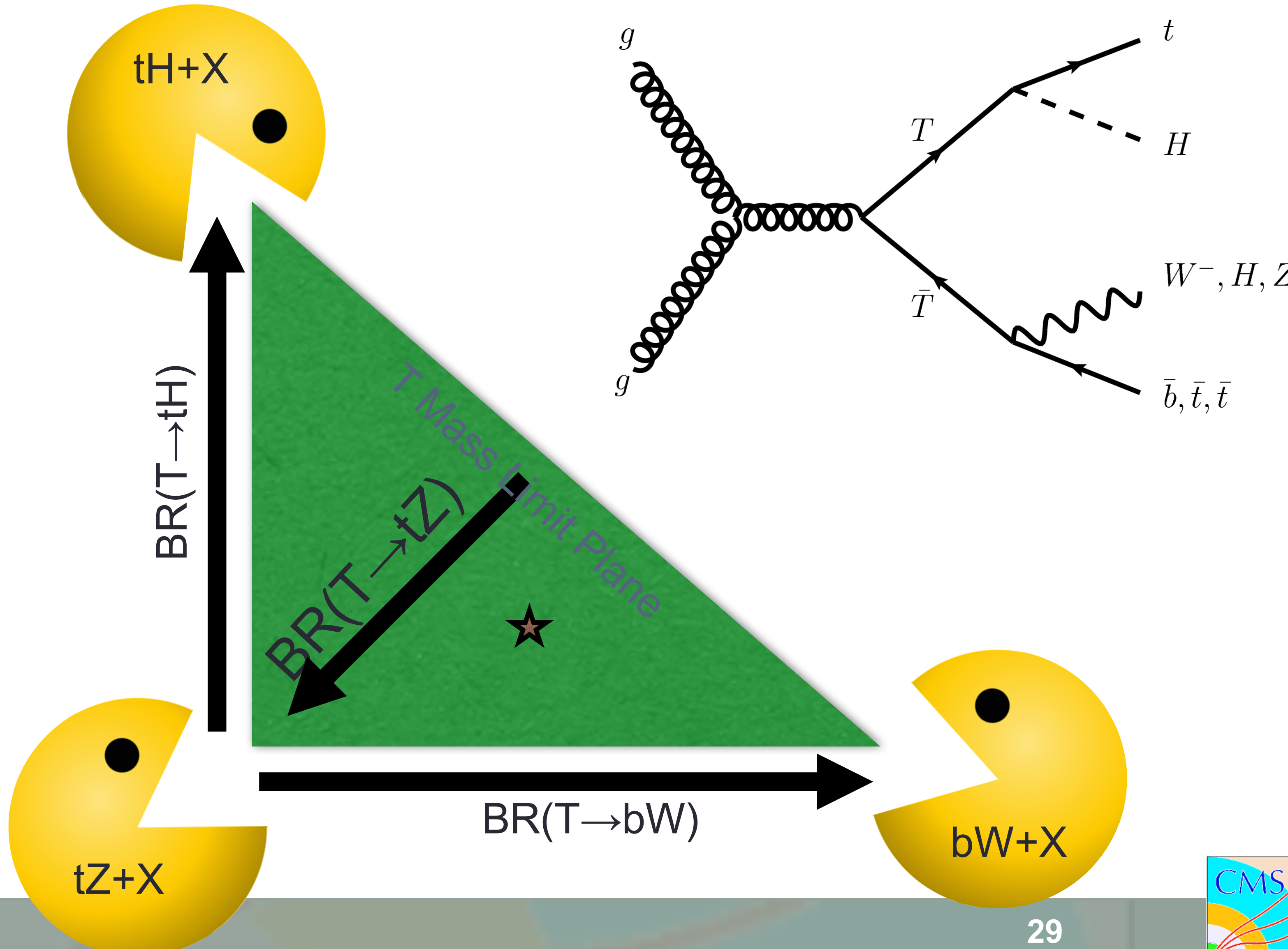
SEARCHES USING VLQ PAIR PRODUCTION SIGNATURES

Vector-like Quark Pair Production

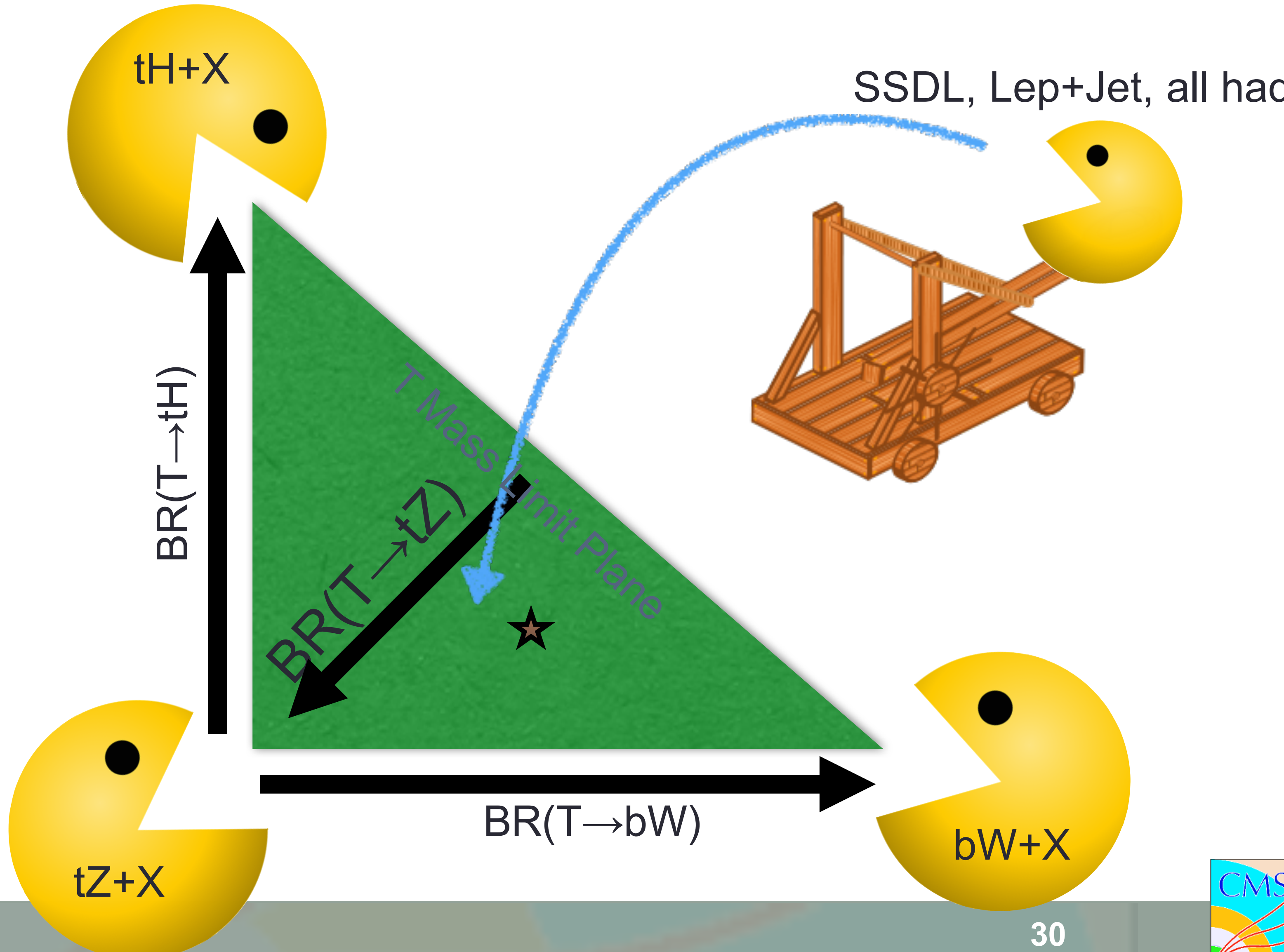




Vector-like Quark Pair Production



Vector-like Quark Pair Production



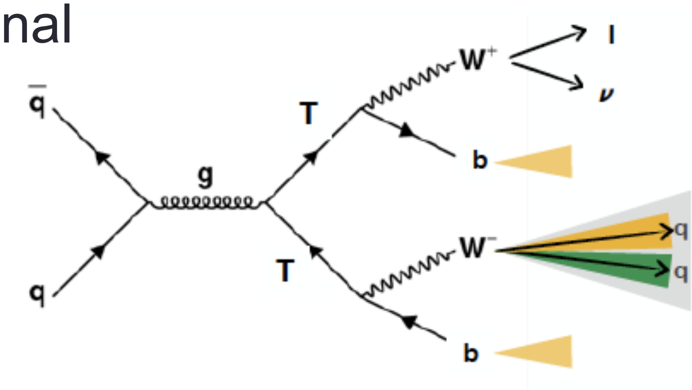
$T^{2/3}/Y^{-4/3}$: Pair production. (CMS Wb)

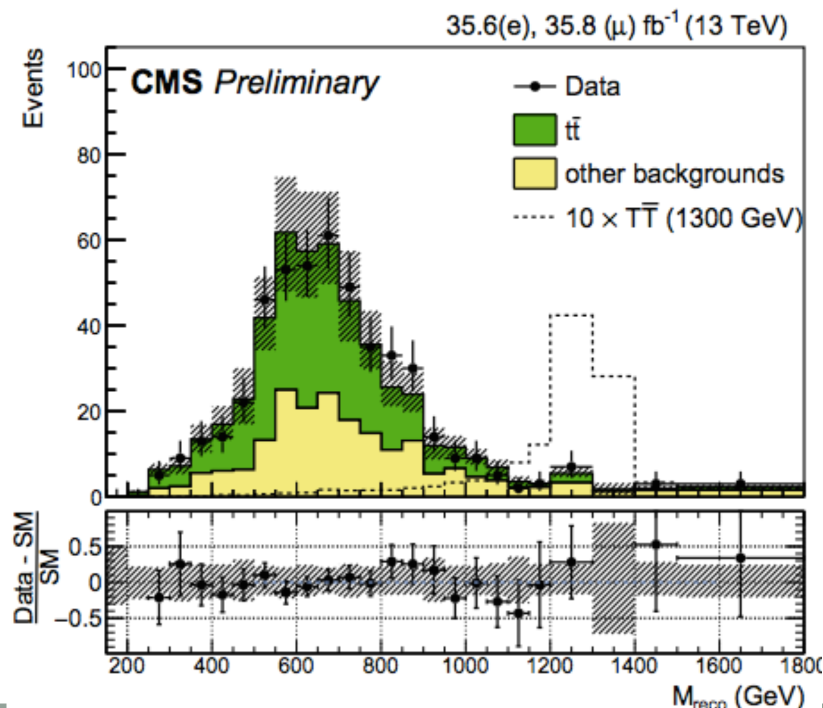
- Search for $T^{2/3}T^{2/3}/Y^{-4/3}/Y^{-4/3} \rightarrow bW\ bW$ in ℓ+jets

B2G-17-003

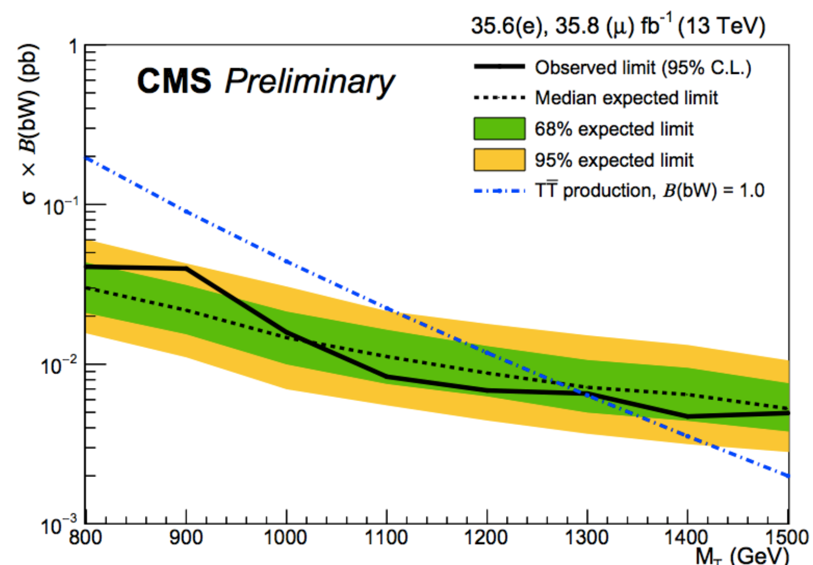
- Perform a kinematic fit identical to the one used in top quark mass measurement to fully reconstruct the final state kinematic and obtain the T mass

- Highly boosted W bosons merge into single jets
- Use W-tag sub-jets for the fit input





Masses below 1.3 TeV excluded

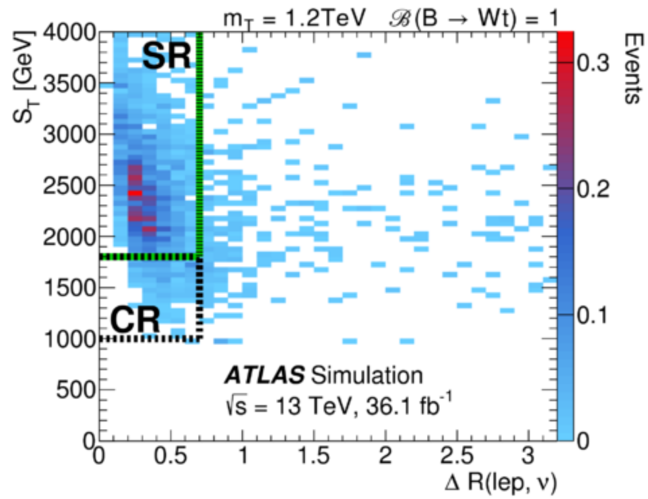


$T^{2/3}$: Pair production (ATLAS Wb)

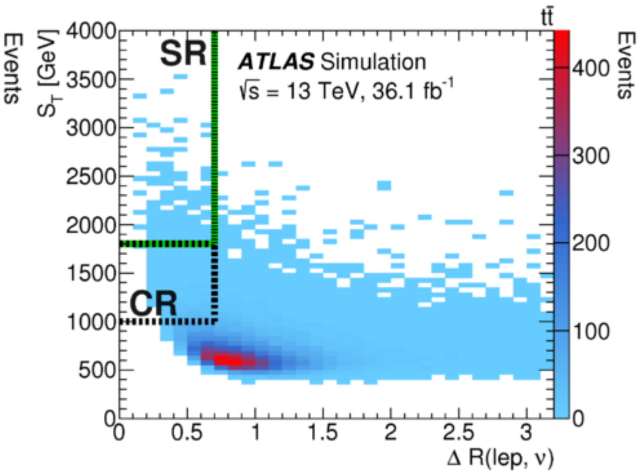
Particularly TT→bW(leptonic)+bW(Hadronic): largest BR

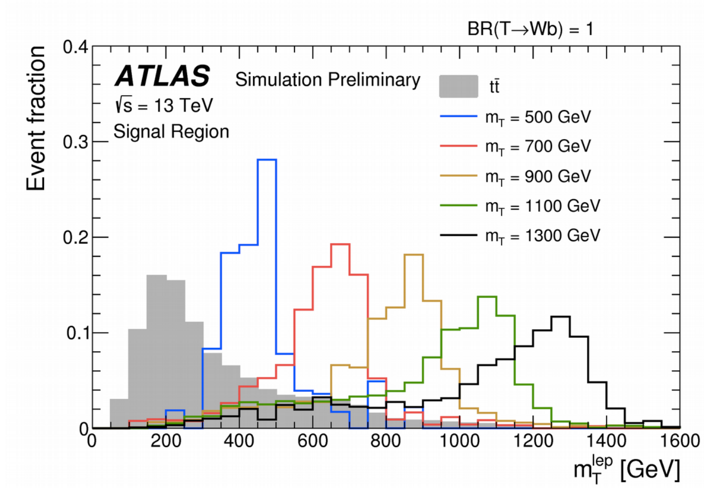
- Require a lepton, multi-jets, MET, high ST, ≥1 b.
- Considers un-boosted and boosted topologies with a large radius jet
- Reconstruct the neutrino assuming MET from W
  - Use $\Delta R(lep, \nu)$, picking one $P_{z\nu}$ solution
  - Use S_T
- Discriminant with $M_T(lep)$
- Profile likelihood fit

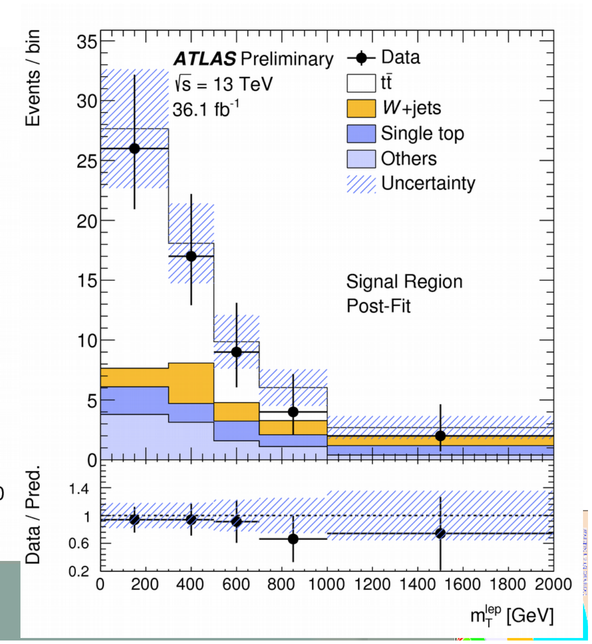
Signal



tt background





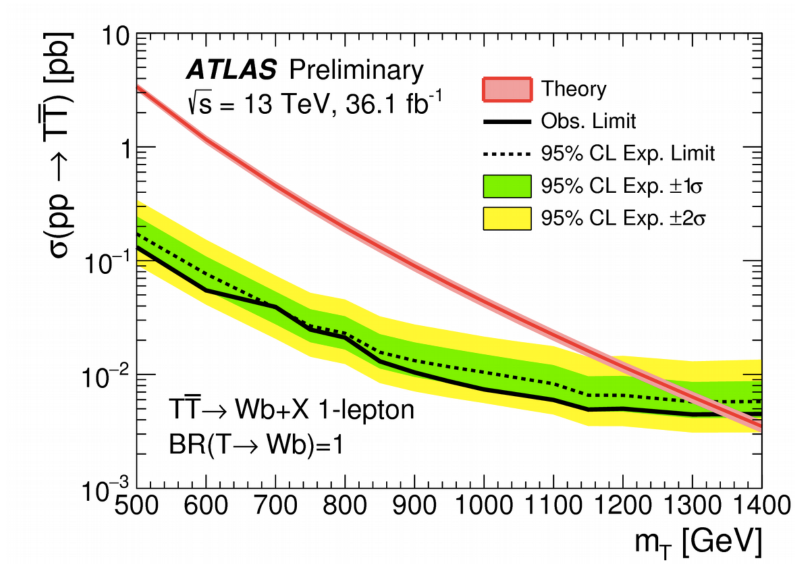


ATLAS-CONF-2016-14

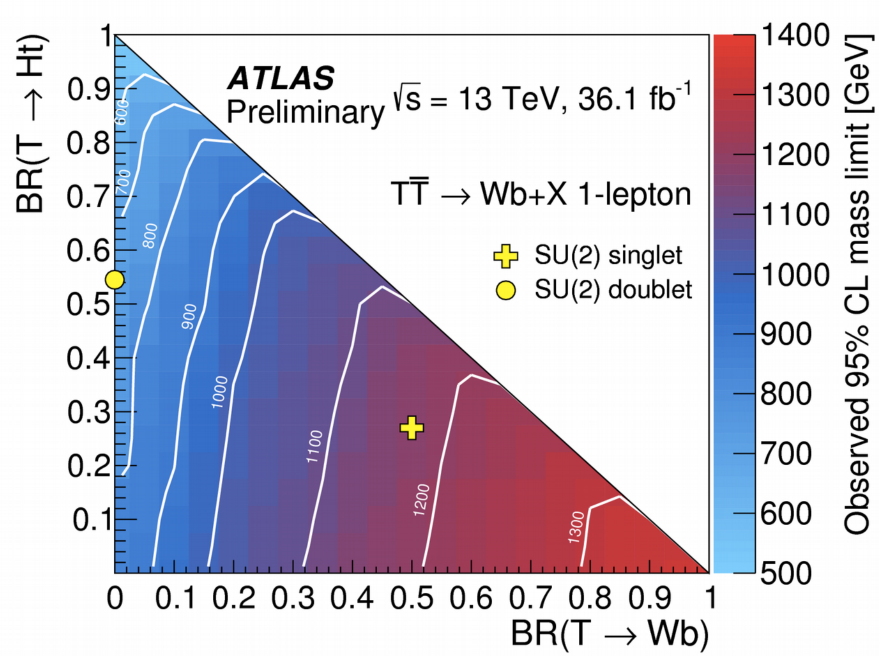
$T^{2/3}$: Pair production (ATLAS Wb)

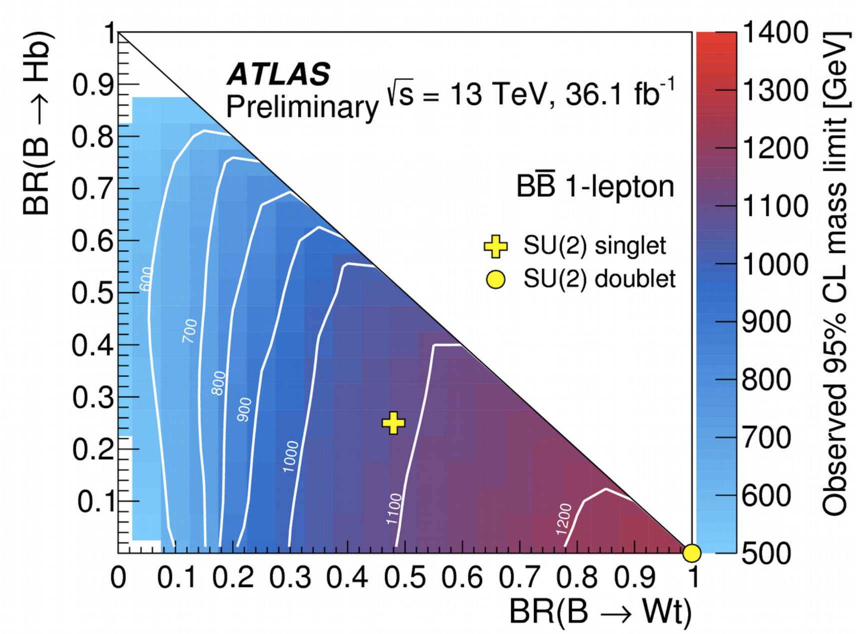
Particularly TT→bW(leptonic)+bW(Hadronic): largest BR

- Significantly improved limits (Run I)
  - $m_{T/Y}$ (Wb=100%) > 1350 (782) GeV
  - m_T (singlet) > 1170 GeV
  - $m_{B/X}$ (Wt=100%) > 1250 GeV
  - m_T (singlet) > 1180 GeV

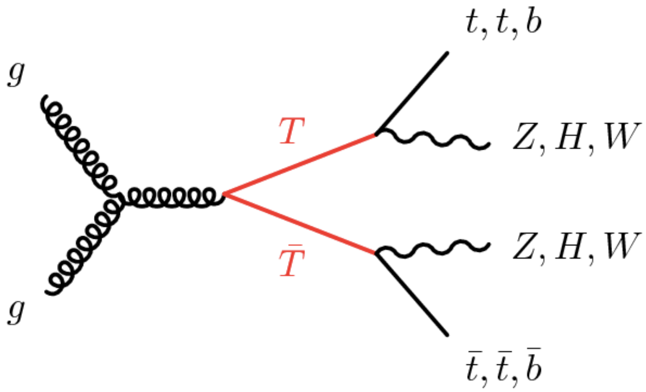


- Statistically dominated
- Main systematics: t & tt modelling

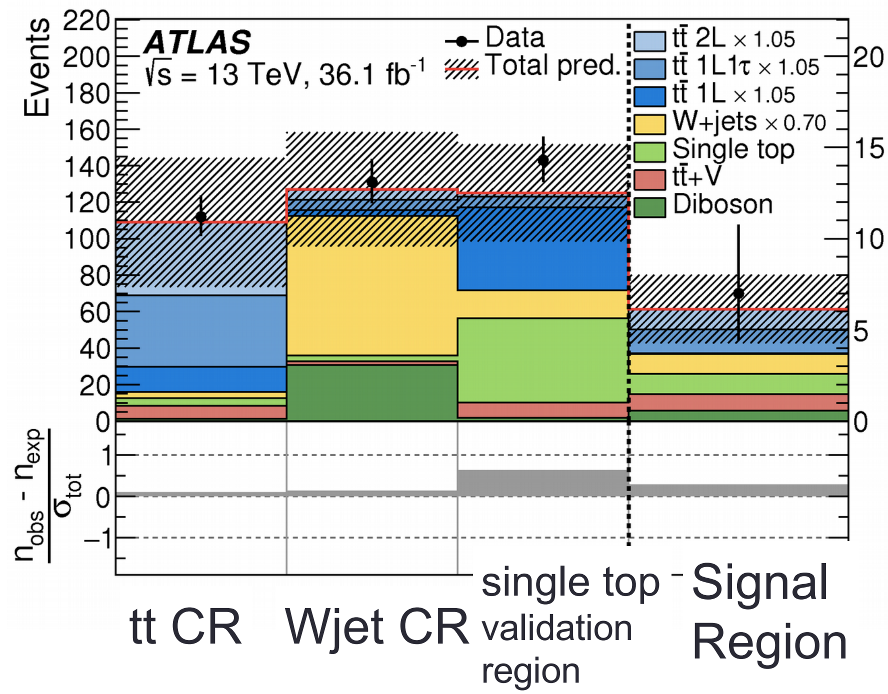




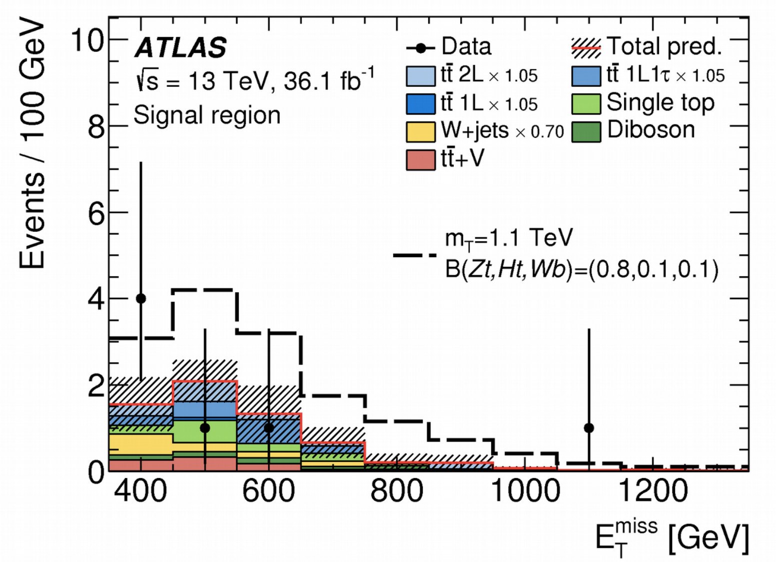
$T^{2/3}$: Pair production (ATLAS tZ($\nu\nu$))



- Require exactly 1 lepton, ≥ 4 jets, large MET, ≥ 2 large-R jets



- Validate in single top
- Profile likelihood simultaneous fit to SR and CR's to constrain bkg cross section.

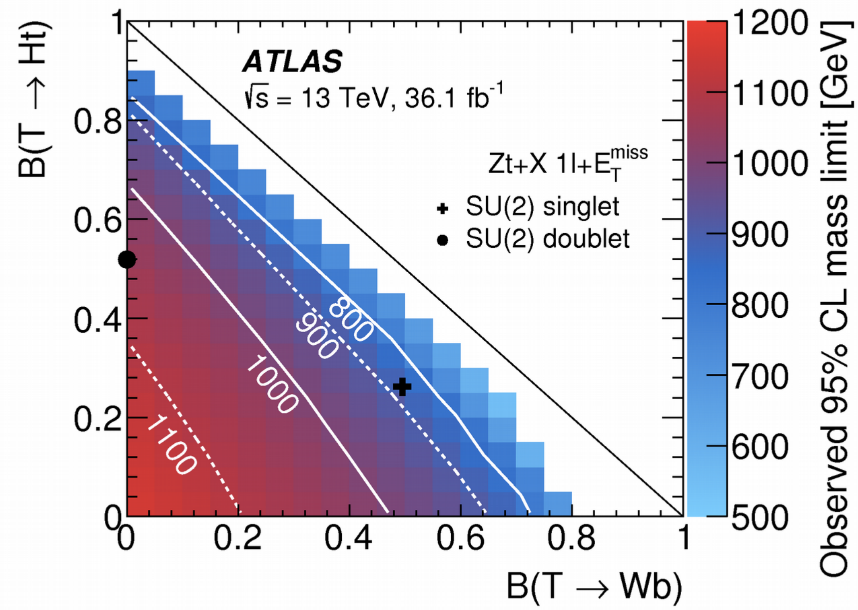


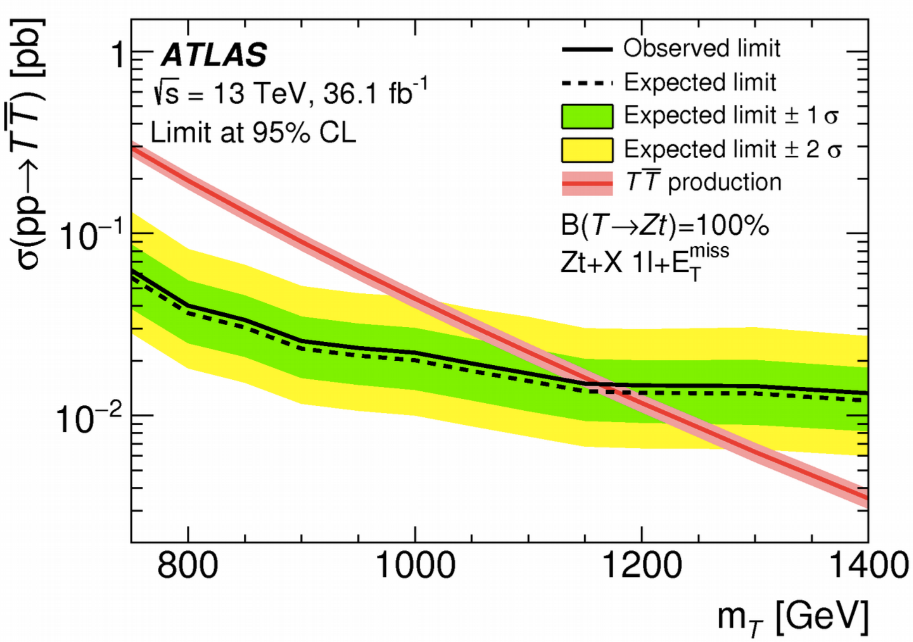
ATLAS-CONF-2016-15. arxiv:1705.10751

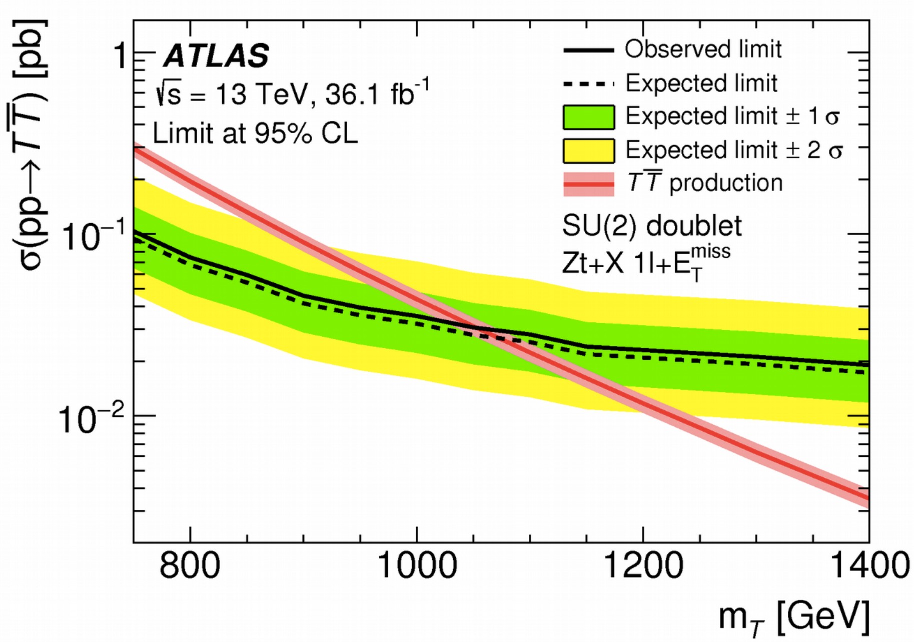
$T^{2/3}$: Pair production (ATLAS tZ($\nu\nu$))

- Profile likelihood simultaneous fit to SR and CR's to constrain bkg cross section.

- Observed (expected) mass limits
- – m_T (Zt=100%) > 1160 (1170) GeV
- – m_T (singlet) > 870 (890) GeV
- – m_T (doublet) > 1050 (1060) GeV





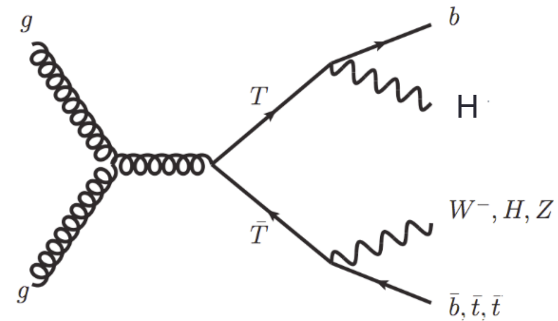


$T^{2/3}$: Pair production (CMS tH)

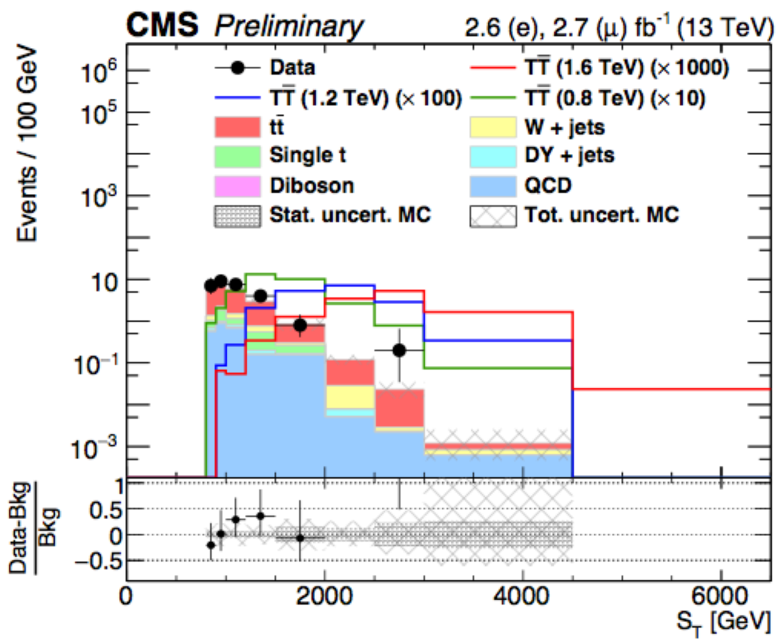
B2G-16-011

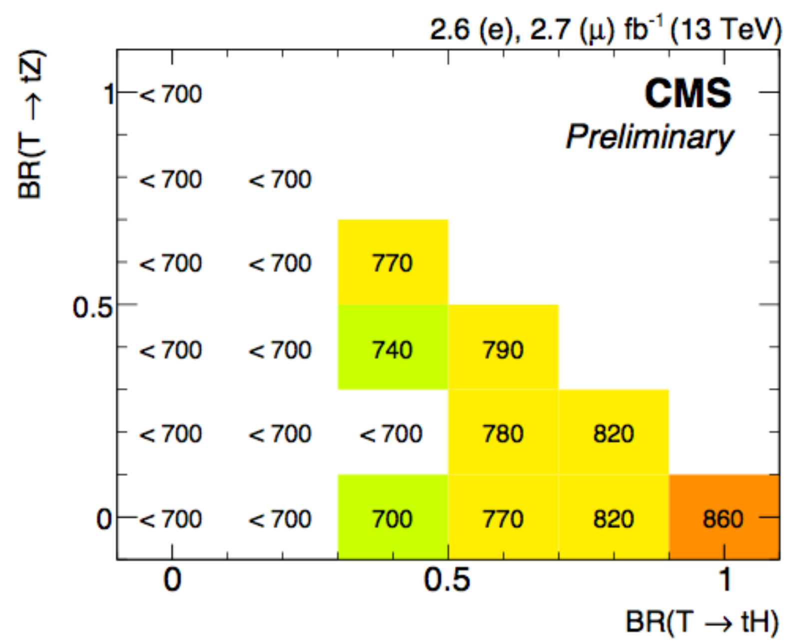
- Search for $T^{2/3} \rightarrow tH$ in ℓ+jets

- Maximize sensitivity by categorization events into tagged jets: (e/μ) x (1, 2 subjet b tags=Htag)
- Background modeling verified in control regions with 0 H-tag, MET > 100 GeV
  - ttbar : ≥ 2 b-tag
  - Wjets: 0 b-tag



Mass limits between 0.70 and 0.86 TeV

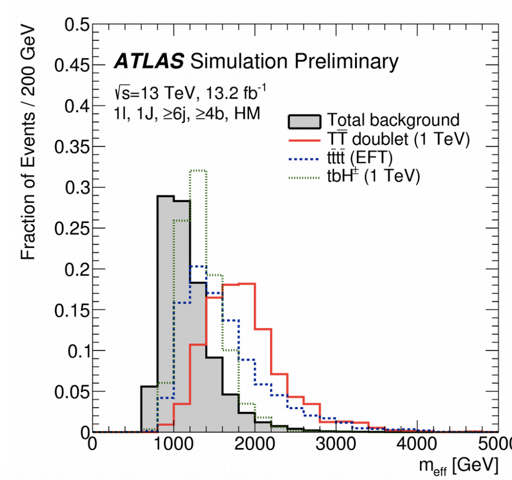




ATLAS-CONF-2016-104

$T^{2/3}$: Pair production (ATLAS tH)

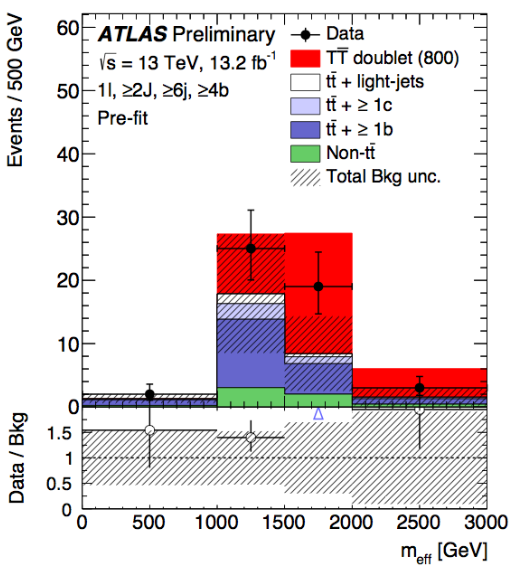
- Search for $T^{2/3} \rightarrow tH$ in ℓ+jets or jets+high Missing ET



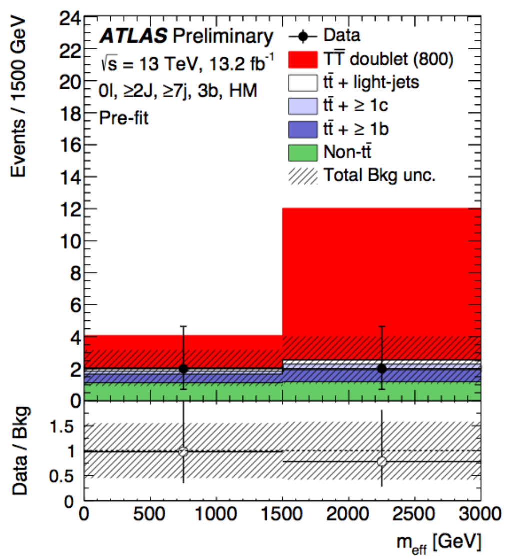
- Maximize sensitivity by categorization events into 0 and 1 lepton
  - Multiple bins in #jet, #b
  - consider large radius jets from boosted objects

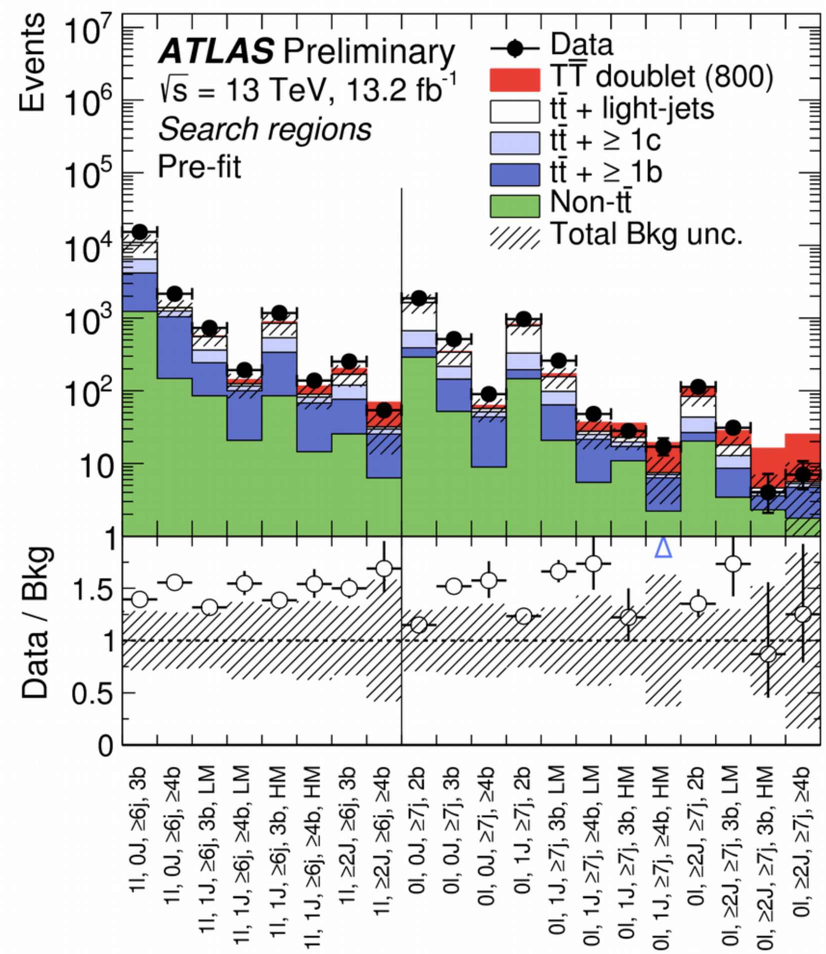
- Discriminate with
  Meff = ∑|Ptlep|, selected |Ptjet|, MET

1 lepton



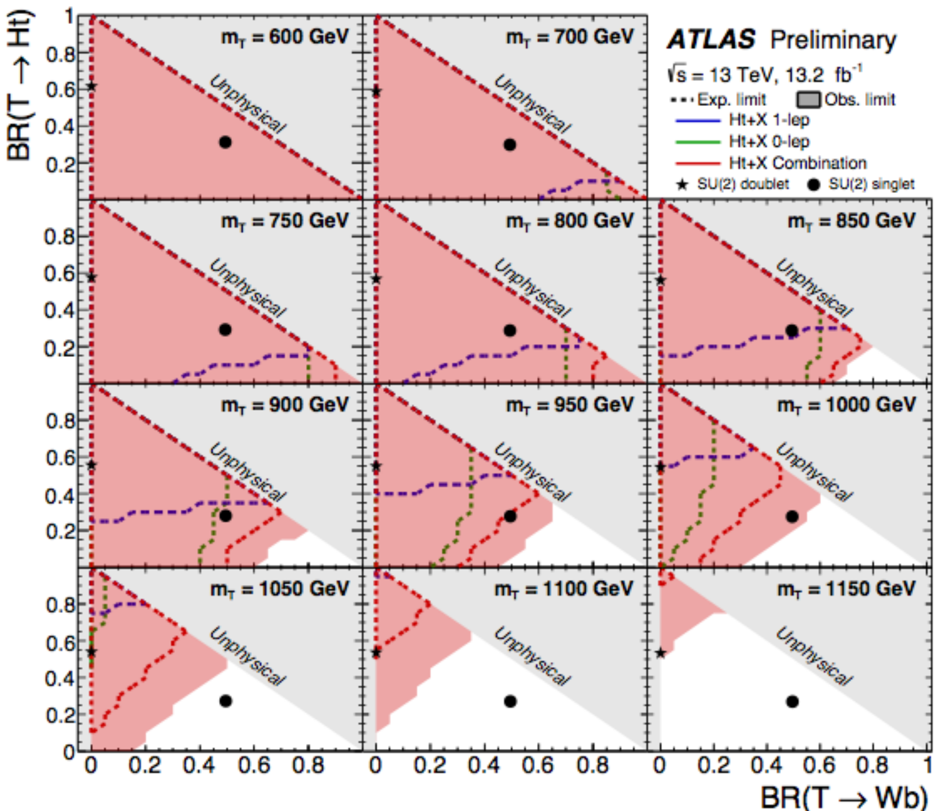
0 lepton

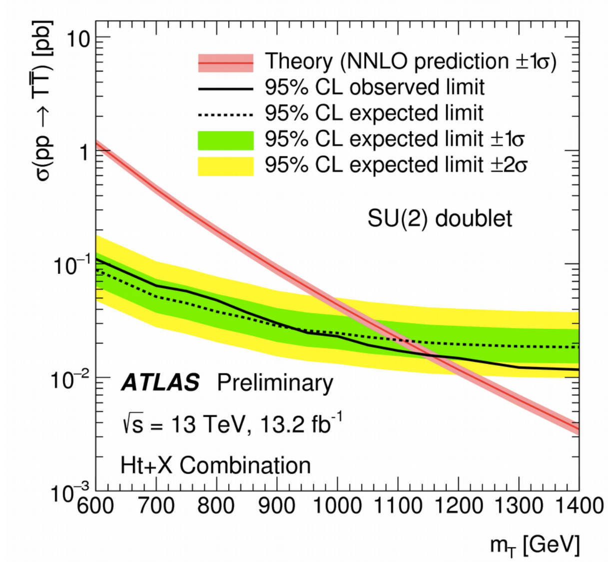


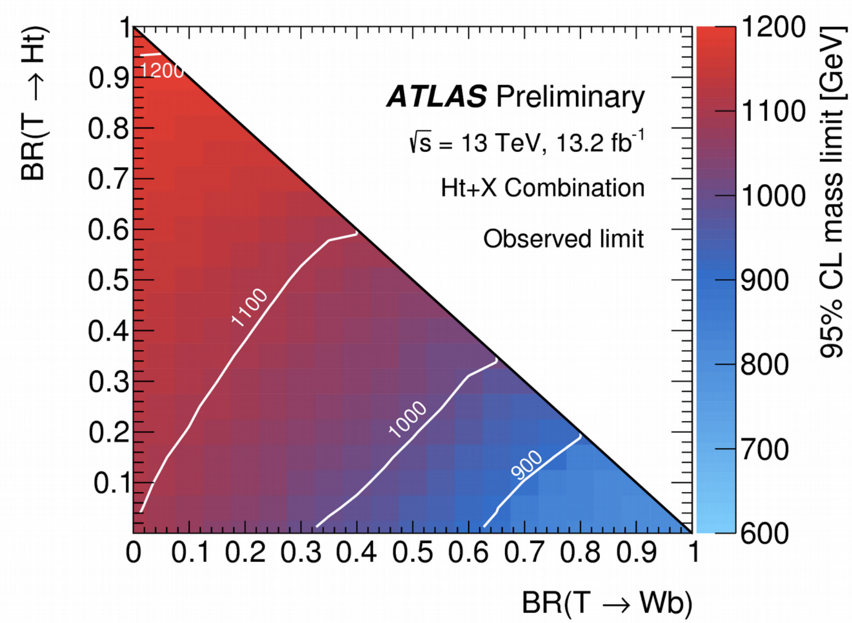


$T^{2/3}$: Pair production (ATLAS tH)

- Search for $T^{2/3} \rightarrow tH$ in ℓ+jets or jets+high Missing ET







1 TeV Limit for T singlet
higher for doublet

Observed (Expected)

95% CL lower limits on T quark mass [GeV]				
Search	BR($T \to Ht$) = 1	BR($T \to Zt$) = 1	Doublet	Singlet
1-lepton channel	1180 (1120)	740 (820)	1060 (1000)	900 (880)
0-lepton channel	1090 (1070)	1060 (1010)	1090 (1060)	950 (890)
Combination	**1200 (1160)**	**1100 (1040)**	**1160** (1110)	**1020** (960)

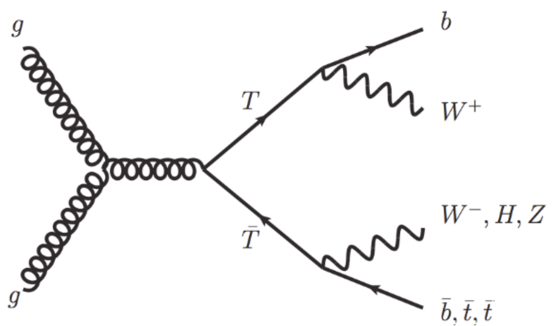
$T^{2/3}$: Pair production. (CMS Wb, tZ, tH)

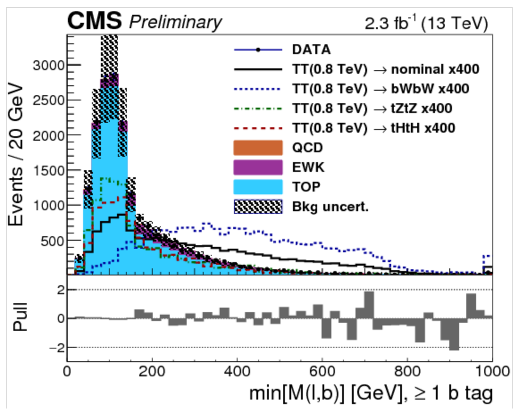
- Search for $T^{2/3} \rightarrow bW/tH/tZ$ in ℓ+jets

B2G-16-002/024

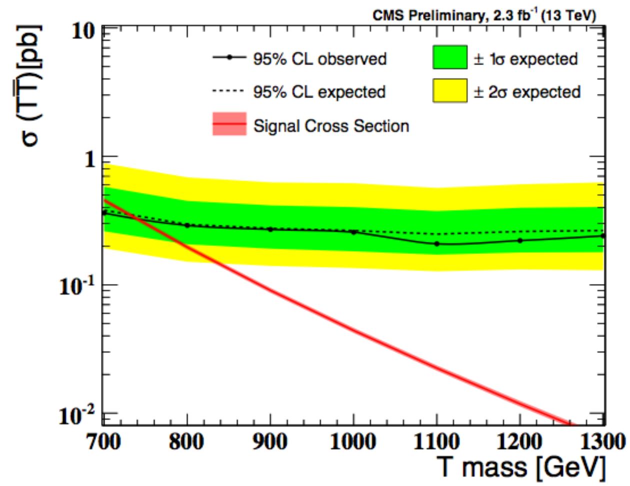
$T_{2/3} \rightarrow$ bW (50%), tZ (25%), tH (25%)

- Maximize sensitivity by categorization events into tagged jets: (e/μ) x (0,1,2,≥3 b-jets) x (0, ≥1 Wjets)

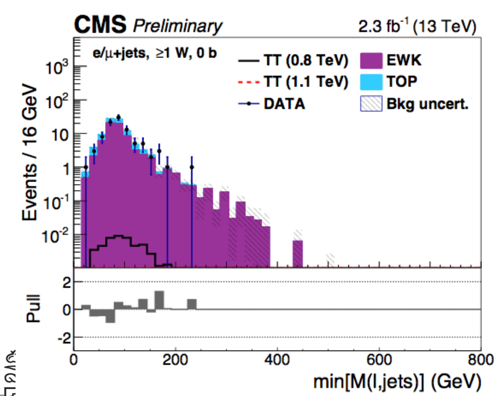


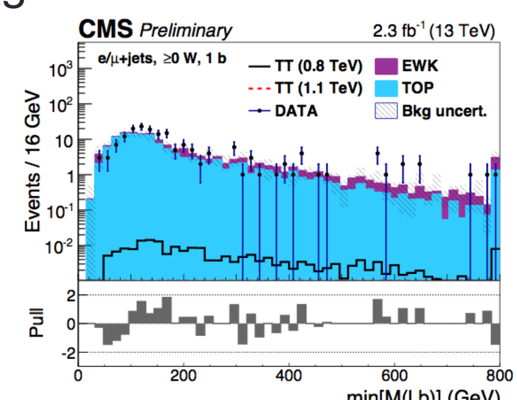


Masses below 0.75 TeV excluded

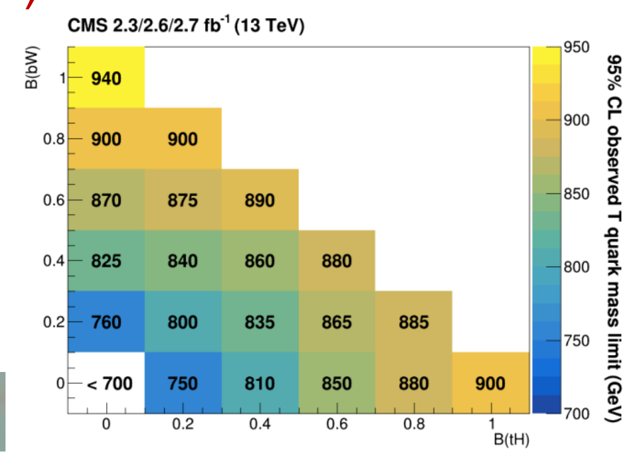


- Background modeling verified in control regions: W: 0 b-tag; top: ≥ 2 b-tags



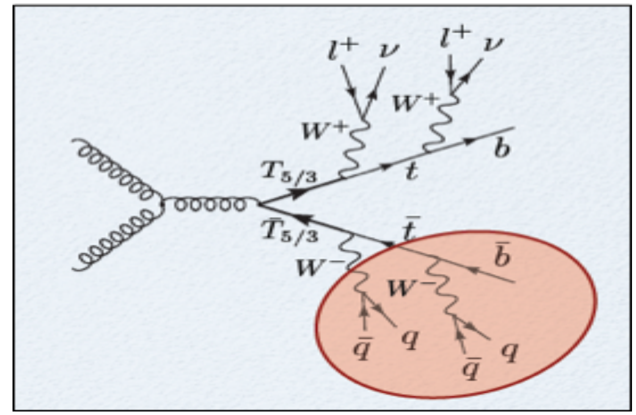


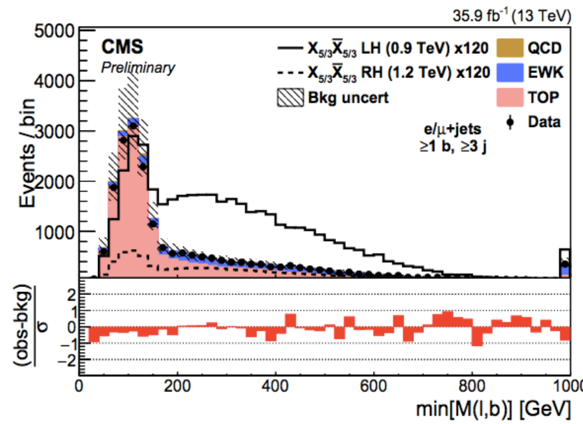
M(T) > 750 –940 GeV

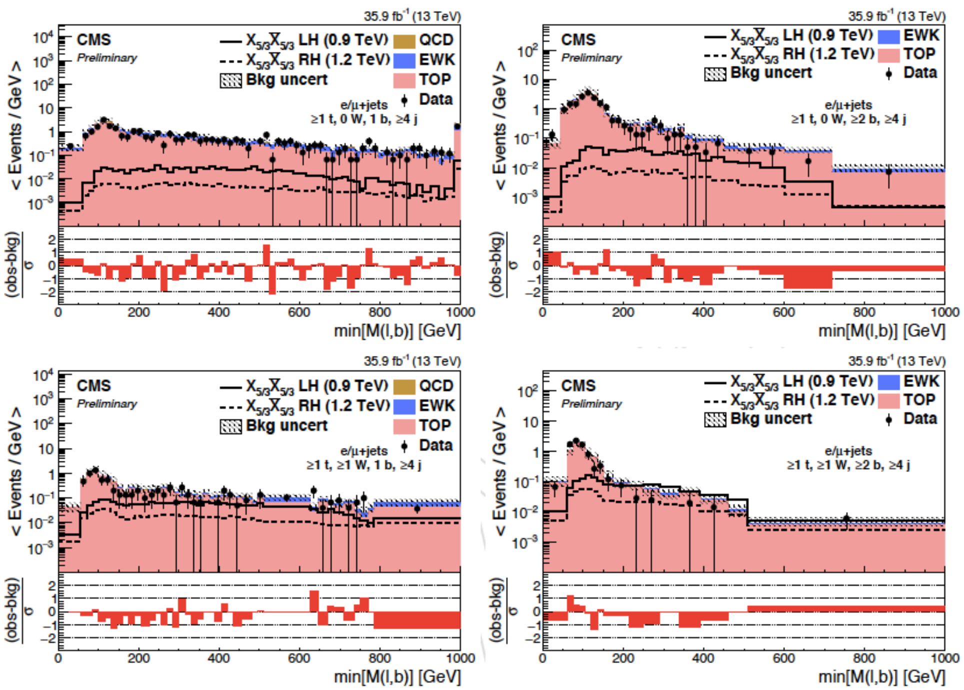


$X^{5/3}$: Pair production

- Search for $X^{5/3} \to tW$ in ℓ+jets final states
- Event categorization based into W/b-tags
  - 16 categories based on W-tagged and t-tagged jet multiplicity
- key variable is the min(Mlb)
- background modeling validated in signal depleted ttbar and W+jets control regions

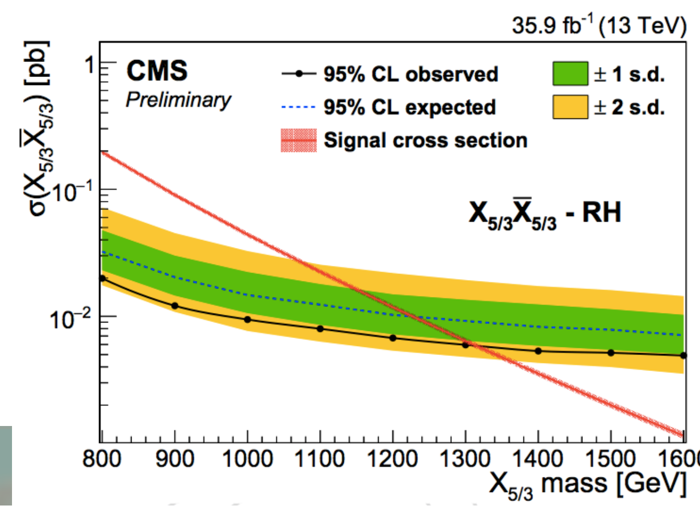






LH(singlet or triplet) / RH(doublet)

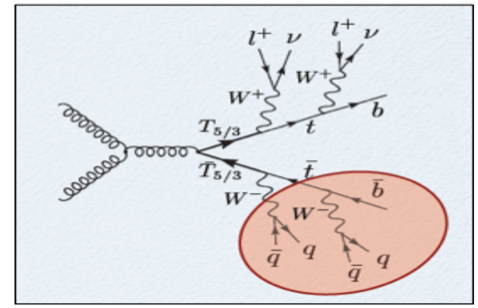
M_X > 1.30 TeV / 1.32 TeV



B2G-15-006

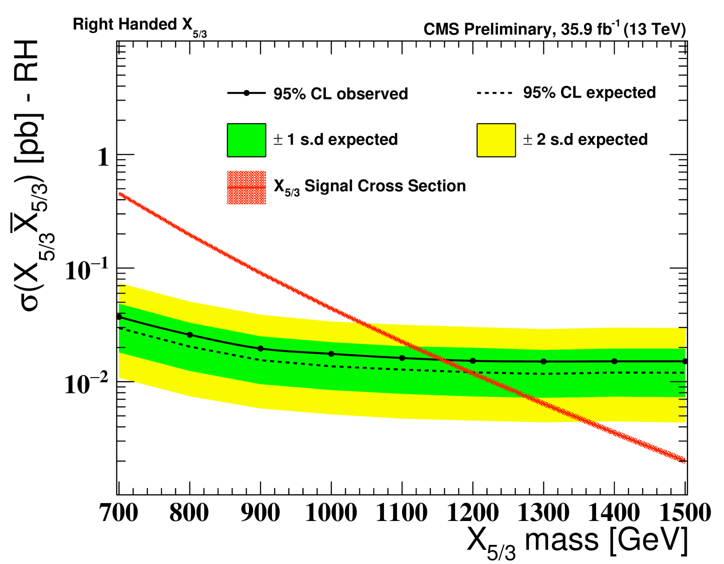
B2G-16-019

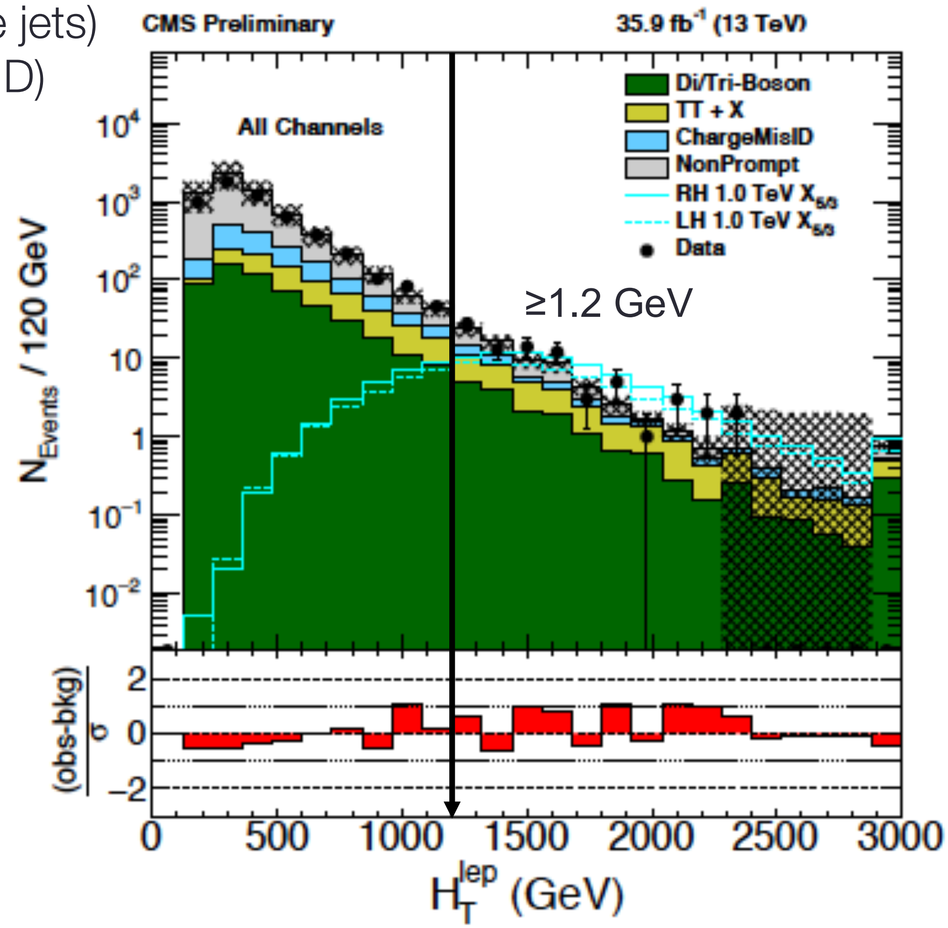
$X^{5/3}$: Pair production



- Search for $X^{5/3} \rightarrow tW$ in same-sign 2ℓ
  - Select two same-sign leptons (e or μ) outside Z window
    - Primary Z Veto: same 2ℓ
    - Associated Z Veto: any ℓ not from SS2ℓ
  - 5 or more "constituents = Wjet (2)/top jet (3)"+ extra leptons
  - Backgrounds from prompt and non-prompt (fake jets) leptons, opposite-sign leptons (with charge mis-ID)
  - Require $H^{lep}_T > 1.2$ TeV

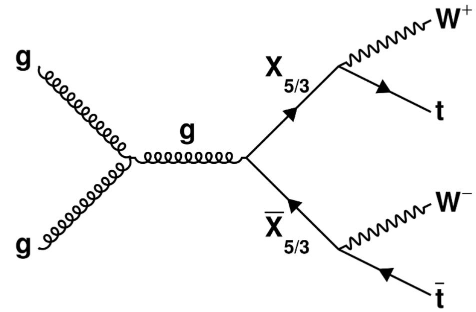
LH(singlet or triplet) / RH(doublet)
$M_X > 1.16$ TeV / 1.10 TeV





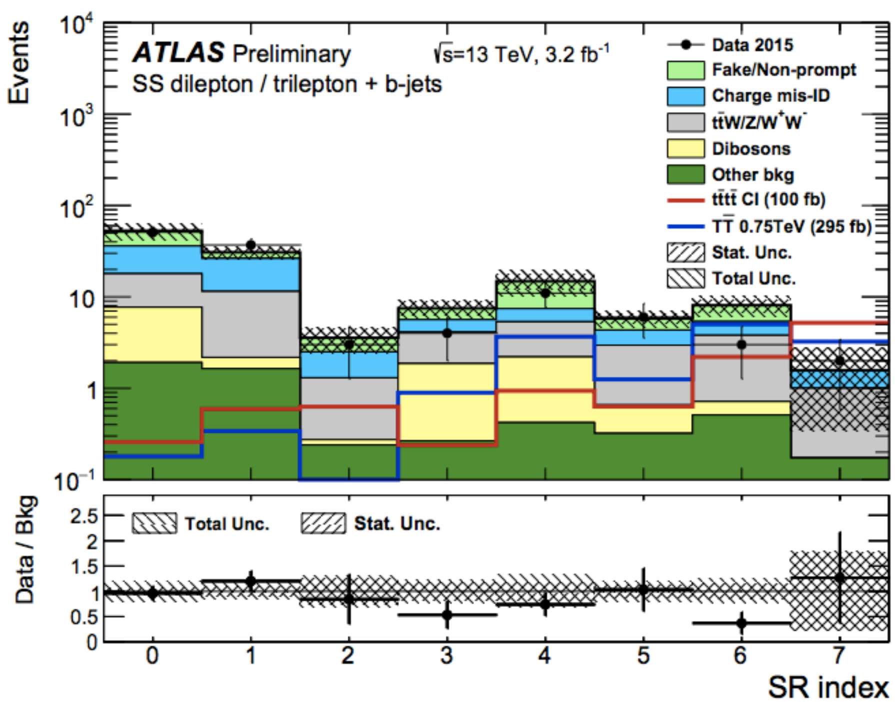
ATLAS-CONF-2016-032

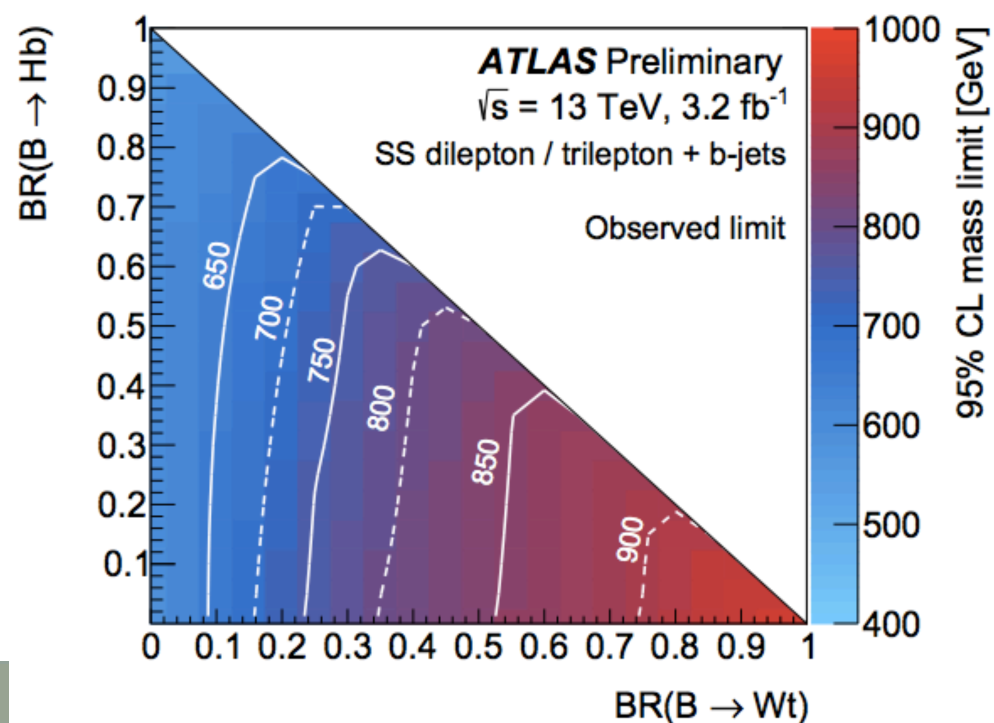
$X^{5/3}$: Pair production



- Search for $X^{5/3}$→tW in same-sign 2ℓ
- Signature: 2 same-sign charge leptons + jets OR 3 leptons + jets
- Signal regions are split
  - based on 1,2,3+ b-tags,
  - MET=[40,100] GeV, or > 100 GeV, and
  - HT=[400,700] GeV or > 700 GeV
- Determine lepton fake rates from lepton-depleted data samples
- Evaluate charge-misID rates using Z->ee events
- Background estimate are validated in control regions, with signal region cuts inverted

M_X > 0.99 TeV





FUTURE PROSPECTS

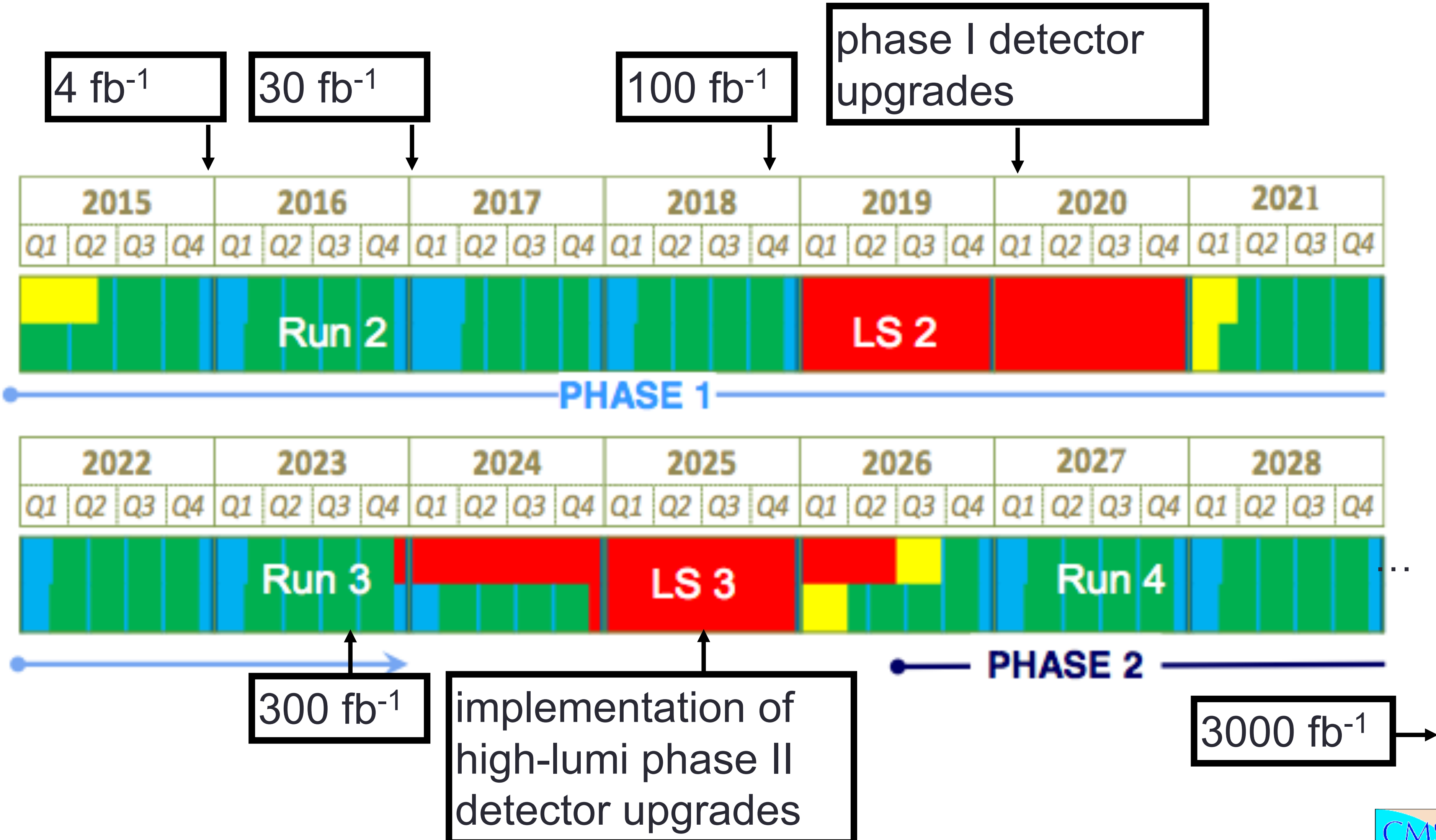
Near Term Outlook

- The analyses of 2016 datasets are still ongoing
- Focus on developing techniques to
  - Understand and identify efficiently boosted boson jets. New algorithms are being develop to characterize the boosted objects signatures and events with boosted objects.
  - Develop control regions for background which are similar to the phase space of the heavy particles. Much of uncertainty arises from the CRs.

- Many VLQ search results, both in the single and double production modes will be completed in the next 6 months.
  - These have the potential to probe upto masses of about 1-1.2 TeV
  - In the next year or two with the full sample of data collected during Run2 (100 fb^{-1}), reach maybe extended somewhat.
  - With Run3 (300 fb^{-1}), and augmented search techniques, expect to probe around 1.5 TeV with both single (depends on couplings) production searches

future of LHC

- "Europe's top priority should be the exploitation of the full potential of the LHC"
- (from the European strategy for particle physics)



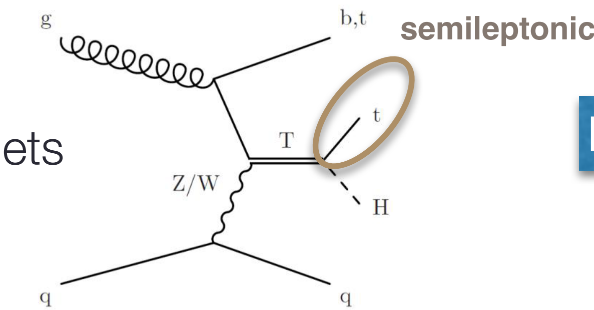
(F. Bordry)

Single $T^{2/3} \rightarrow tH$, ℓjets: Phase-2 Upgrade

- Full analysis based on DELPHES with 200 PU.
- Events with lower thresholds on $p_T(\ell)$ and (PUPPI) jets

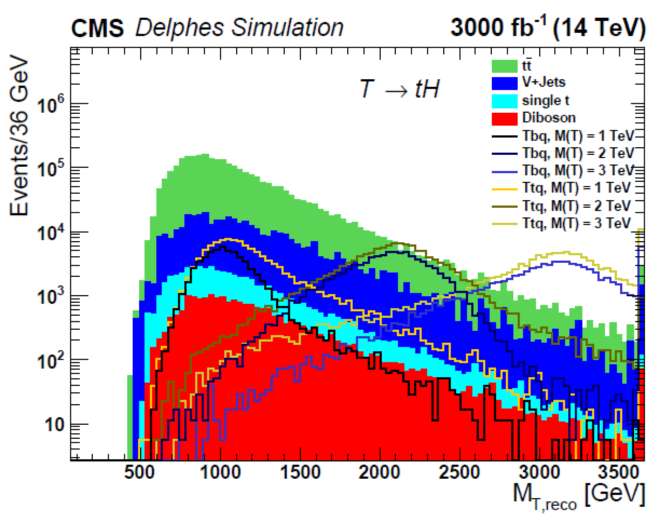
M_{SF}: 90 –160 GeV
no b tagged subjets
$\Delta R(H,\ell) > 1.0$

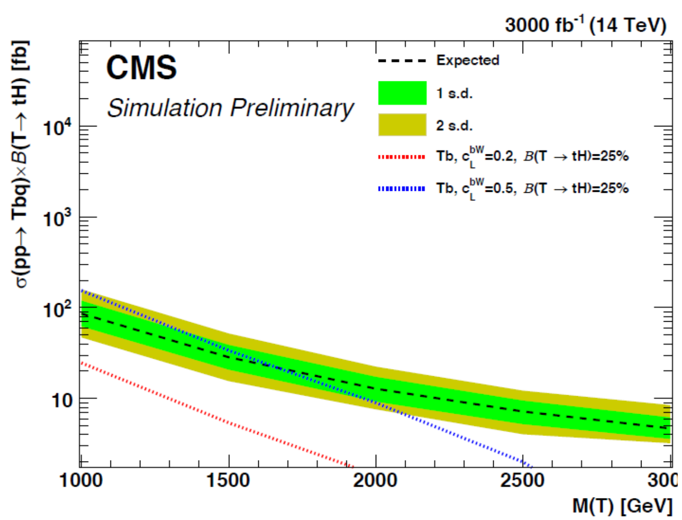
$p_T(\ell) > 40$ GeV and $|\eta|$
1st and 2nd Jet $p_T > 200{,}80$ GeV

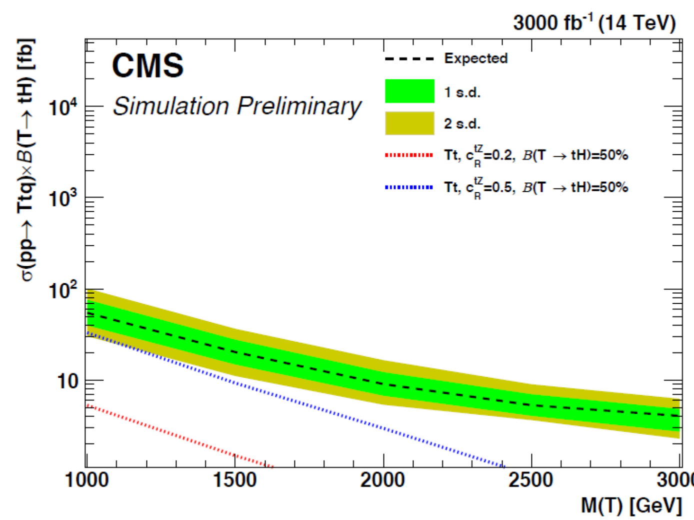


DP-16/064

Mass (GeV)	Expected cross section upper limit (fb)	
	Tbq (LH)	Ttq (RH)
1000	85.9	54.7
1500	28.4	20.3
2000	12.8	9.06
2500	7.20	4.64
3000	4.69	4.69







SUMMARY

Conclusion:

- VLQs have very rich phenomenology
- many nice results already now
- CMS searched for single VLQ for the first time
- For pair production, the 13 TeV results with 2015 data have comparable sensitivities to 8 TeV results!

- standard model still rules
- continue probing unknown territory

References

- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsCONFnotes
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

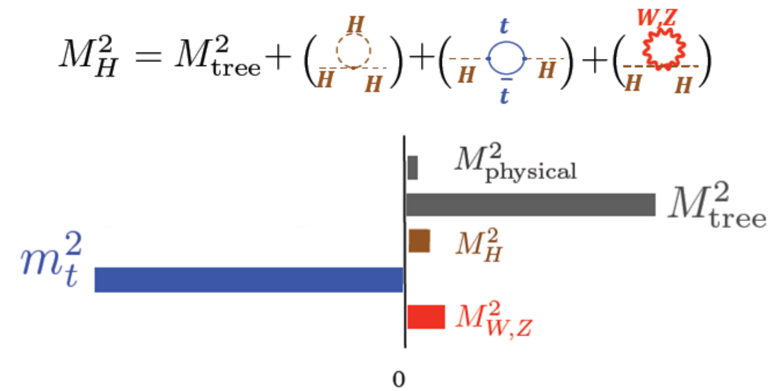
- Slides of previous talks by colleagues
  - Some of which have borrowed from my previous talk slides, so I have also shamelessly borrowed from them (with permission & appreciation).
  - Many Thanks.

Backup

Fine Tuning

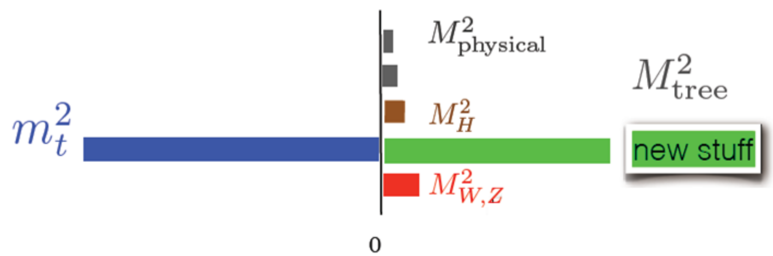
- If Λ_{NP} extends up to the Planck scale, a cancellation of 1 part in 10^{34} is required in order to get agreement with the measured Higgs mass!

36127890984789307394520932878928933023 -
36127890984789307394520932878928917398 =
= $m^2_H = 125^2$

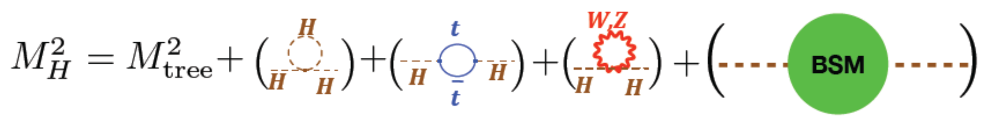


Top Partners

- A solution to this problem invokes the existence of top quark partners:



  - fermionic (vector-like quarks)
  - bosonic (stops in SUSY)



arXiv 1306.0572

Implications

- Simplest type of colored fermions which are still allowed by experiment!

- They mix with the SM quarks & modify their couplings to the Z, W & Higgs
- Introduce new sources of CP Violation

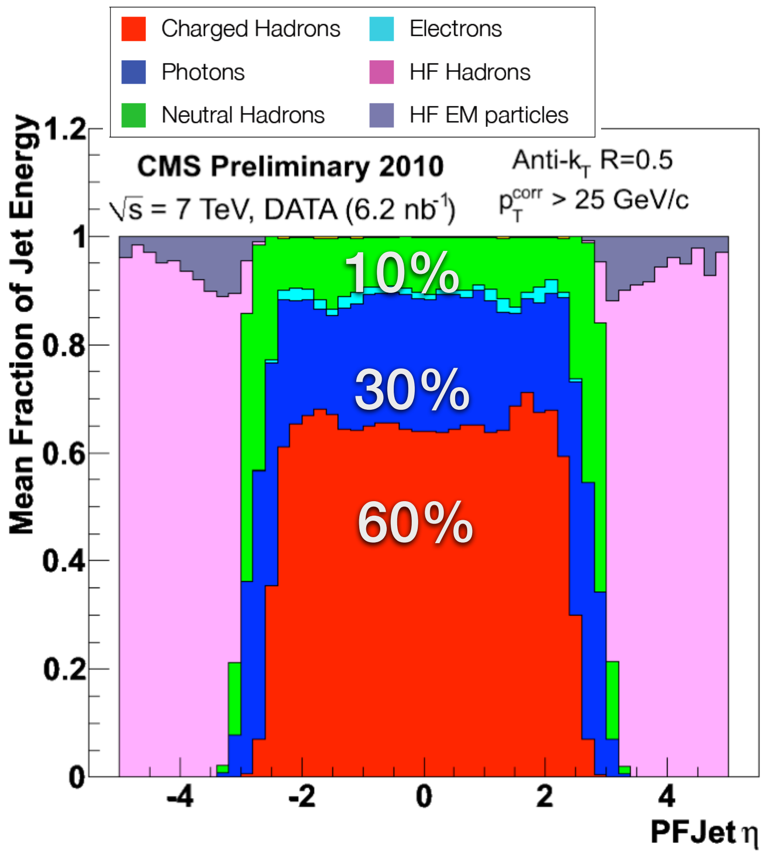
- VLQs at the TeV scale are strongly motivated by two theoretical ideas:
  - they can explain the observed lightness of the Higgs and
  - they emerge as fermion resonances in the partial-compositeness theory of flavor
- Due to the large Yukawa coupling of the top quark, both mechanisms give rise to a sizable mixing of the VLQs with 3rd gen quarks: "top partners"

- VLQ's appear in several non-SUSY models: extra dimensions, composite Higgs, Little Higgs, or their holographic versions.
- Improve the theory fit to electroweak observables:

$$\chi^2_{SM} = 10.97, \chi^2_{VLQ} = 1.61$$

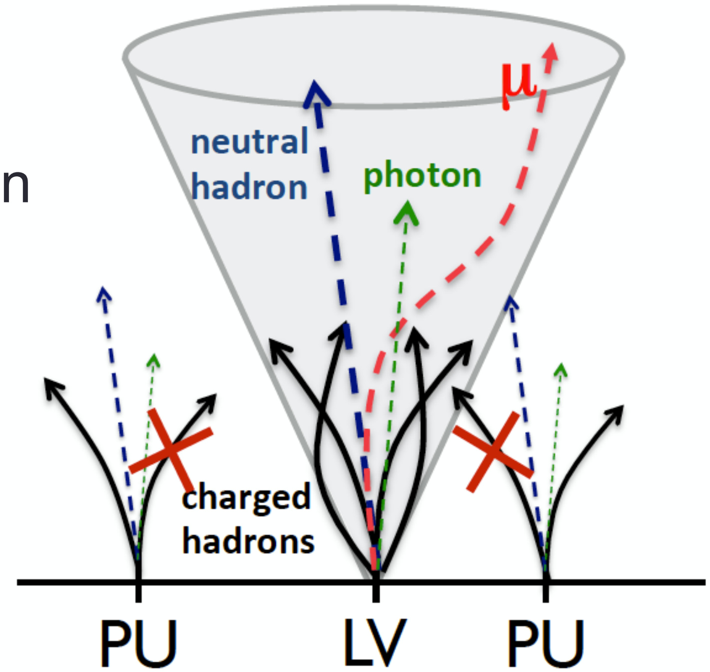
[CMS DP-2012/012]

particle flow event reconstruction



Jet composition

charged hadron subtraction:



PF combines information from detectors to optimise resolution:

Detector	p_T-resolution (range)	η/Φ-segmentation
Tracker	0.6% (0.2 GeV) – 5% (500 GeV)	0.002 x 0.003 (first pixel layer)
ECAL	1% (20 GeV) – 0.4% (500 GeV)	0.017 x 0.017 (barrel)
HCAL	30% (30 GeV) – 5% (500 GeV)	0.087 x 0.087 (barrel)