Status of CMS experiment at LHC

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On behalf of CMS collaboration

QCD@Work, Martina Franca, Italy. June, 2016.

In a nutshell

- LHC Run 2 operation (pp collision at √s =13 TeV) started in 2015.
- CMS experiment running well in 2016.
- Magnet on with field strength B=3.8 T.

- Physics: > 500 papers submitted/published based on LHC collision data.
- **Energy barrier for probing TeV scale physics is overcome in Run 2.**
- Present focus is for analyses of Run2 data →
- ~ 100 public results already.
- Few more analyses continuing with Run 1 data focusing on precision measurements.

Many interesting results in near future as CMS accumulates more data volume.

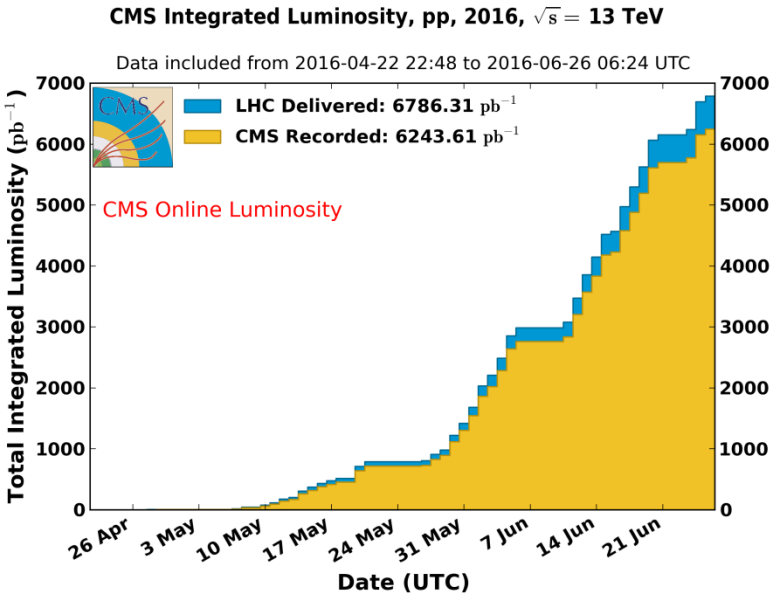
Detector upgrades:

- Presently Phase I upgrade continuing well, some installations scheduled for next EYETS .
- Phase II upgrade for HL-LHC is being crystalized.

→ Extensive R&D efforts during next few years.

→ Technical Design Reports for upgrade of various subsystems during 2017.

Data collection in 2016 and Physics reach



- Data collection efficeiency > 92%
- Uncertainty in luminosity measurement in Run 2 ~ 2.7%

Precision studies

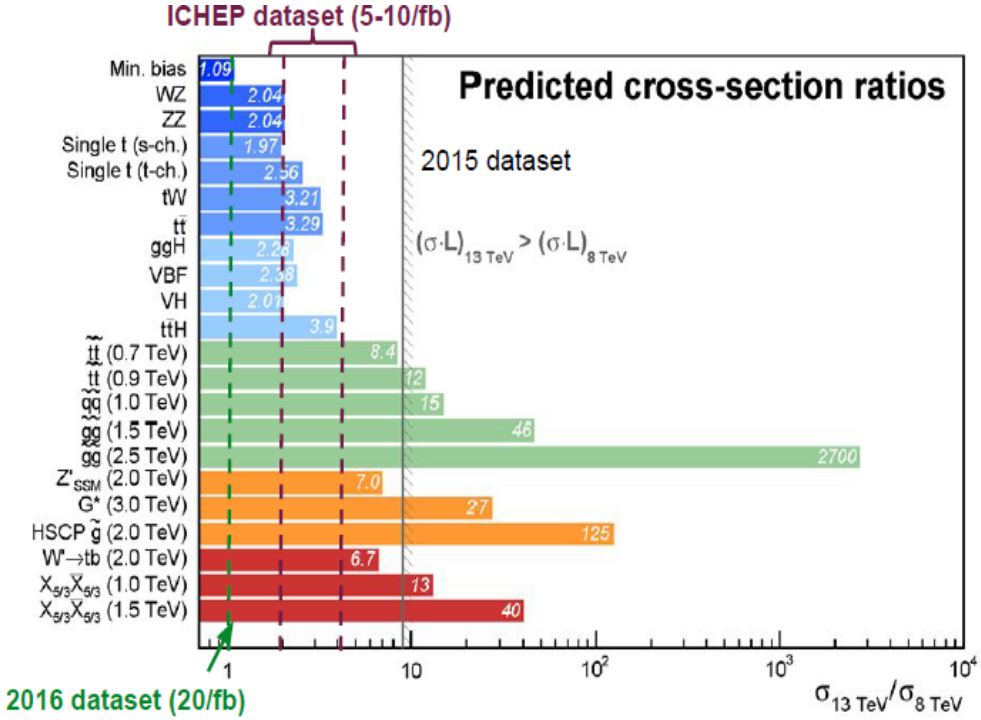
- W+jets, multijet studies, 2D/3D differential,

New processes

- High-mass final states : ttW, ttZ, tttt, multiboson

Example physics potential with L ~ 10 fb^{-1}

- 750 GeV mass resonance searches (if gg-produced)
- H(125) full programme
- Better sensitivity for Dark Matter in high-mass mediator region
- Searches for X->VV with M_X ~ TeV
- New vector-like quarks
- SUSY via EWK interactions
- Search for anomalous couplings



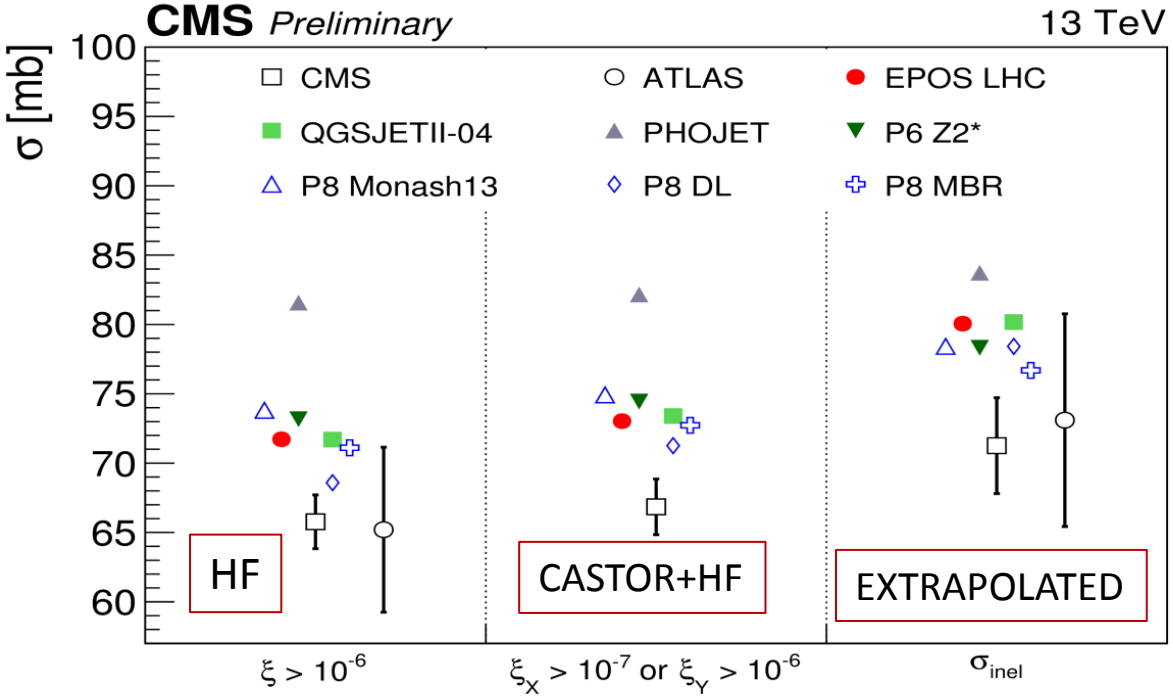
Soft QCD, forward scattering, quarkonia production, Heavy ions

Total Inelastic cross section at √s = 13 TeV

- Experimental measurement within 3.0 <η <5.2 & -6.6<η<-3.0
- Within full phase space of inelastic domain,

FSQ-15-005

σ = 71.3 ± 0.5 (exp.) ± 2.1 (lumi.) ± 2.7 (extrapolation) mb



$$\xi = M^2/s$$

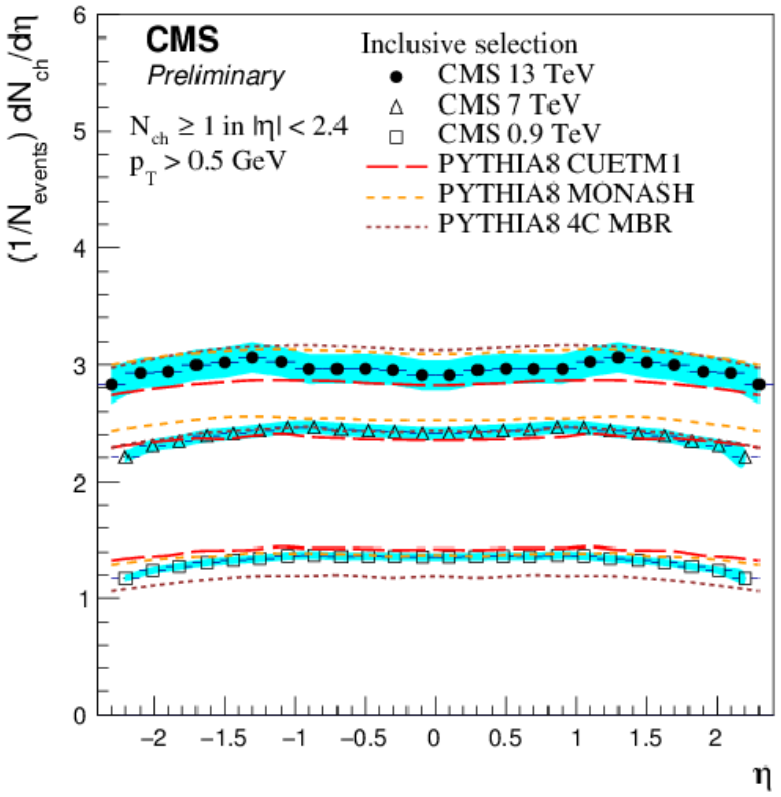
ς = fractional momentum loss of the scattered proton

M= mass of the diffractive dissociated system moving in a particular rapidity direction

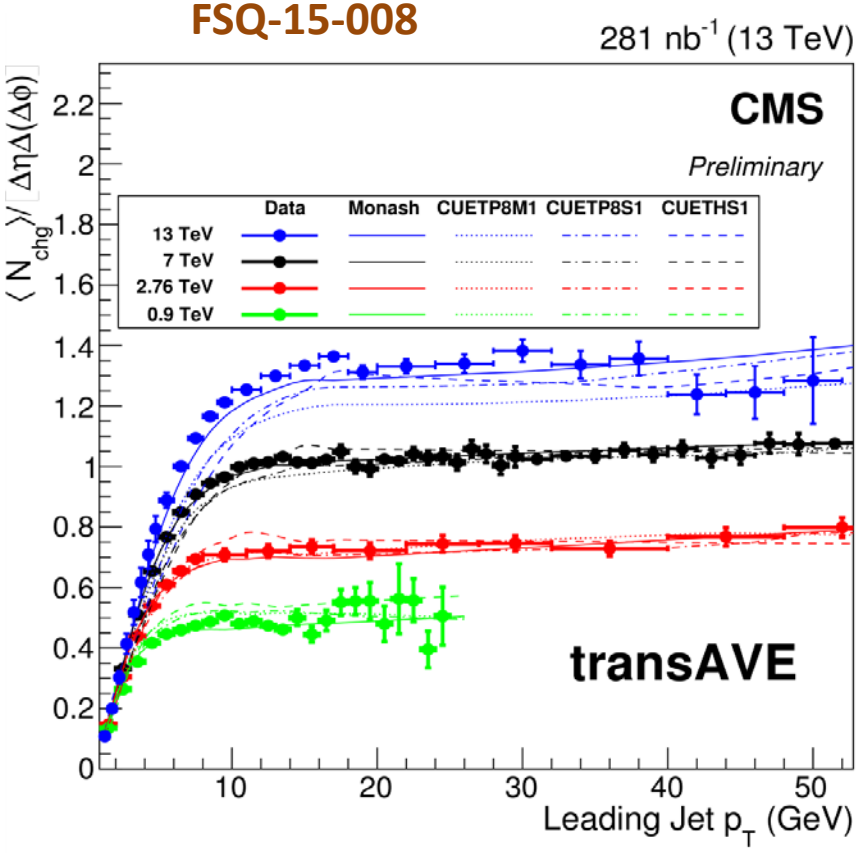
Charged particle production

- Soft particle production from low energy processes,
  → test description of MC models with various tunes.
  →underlying events accompanying hard scattering
  → also important for description of pile-up.

FSQ-15-007

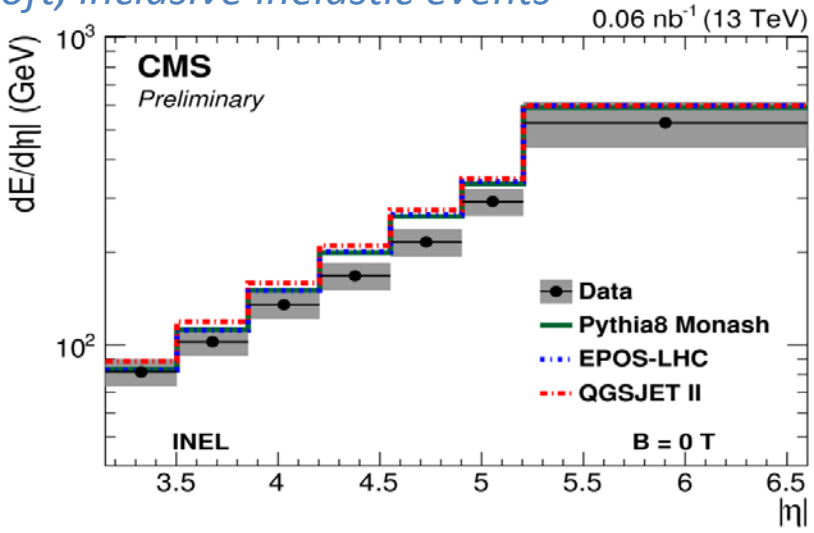


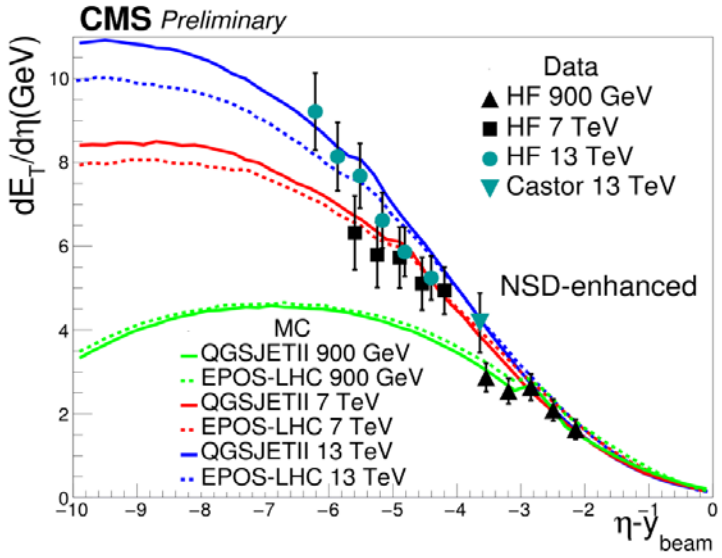
FSQ-15-008



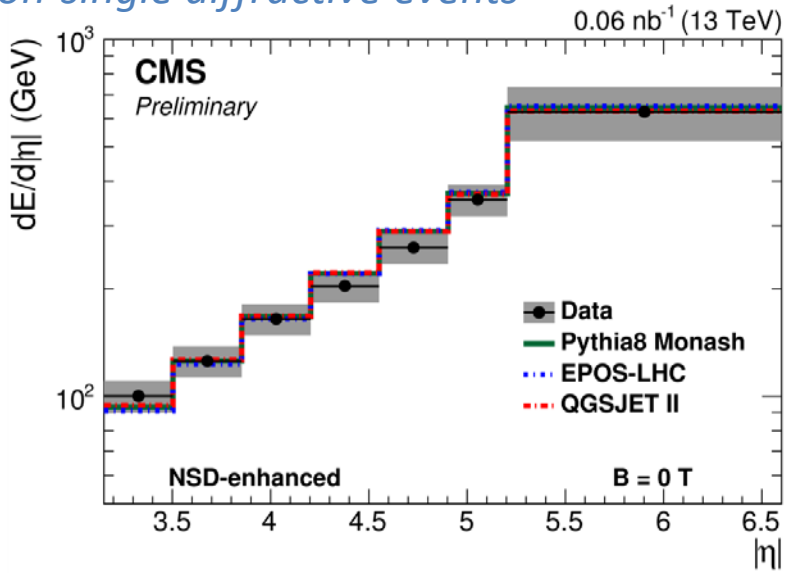
Energy flow in forward direction (3.5 <|η| 6.6) at √s = 13 TeV

Soft, inclusive inelastic events





Non-single diffractive events

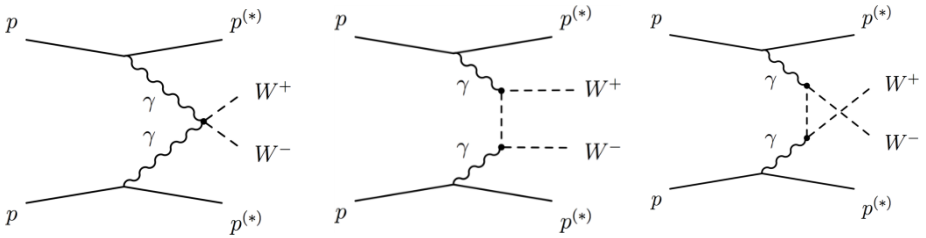


FSQ-15-006

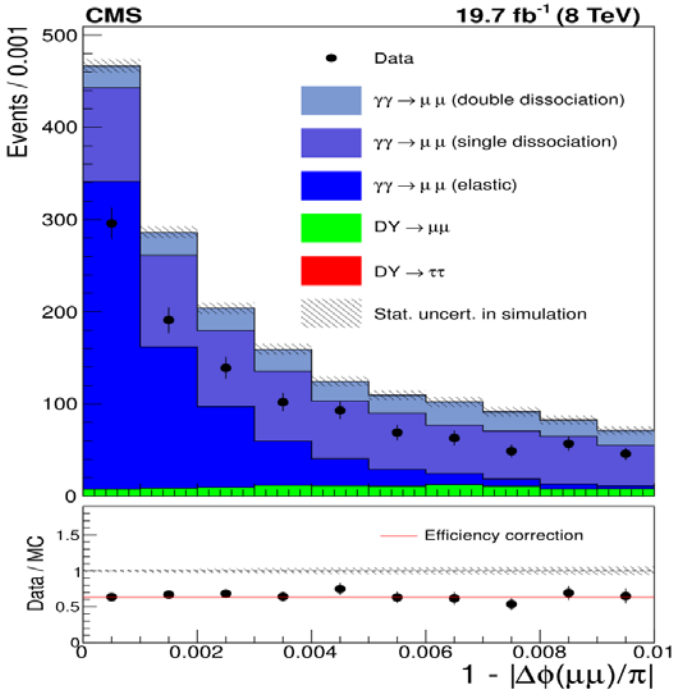
- Consistent results with limiting fragmentation hypothesis.

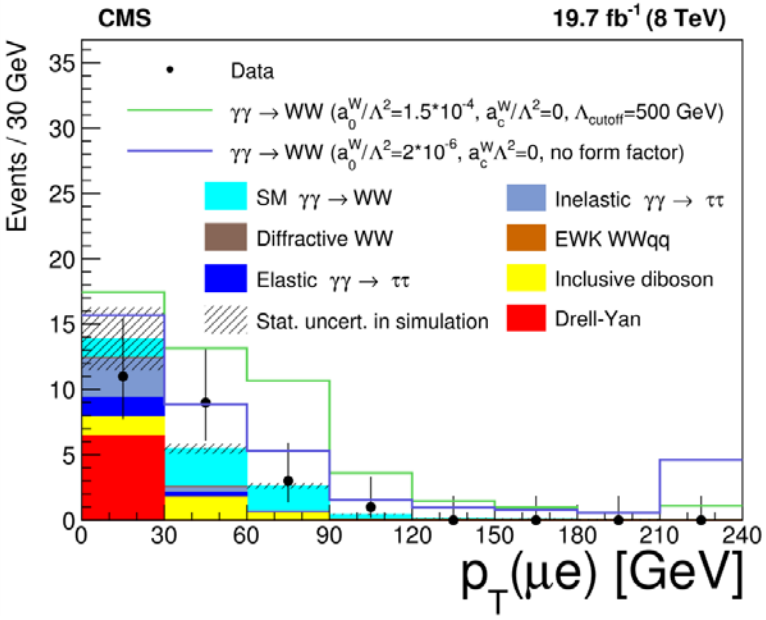
Exclusive γγ → WW production at √s = 8 TeV

FSQ-13-008



- *No additional track in the detector* other than decay product of Ws (e, μ)
- 3.4 σ excess over background (15 events vs. ~ 3.5 background expected)



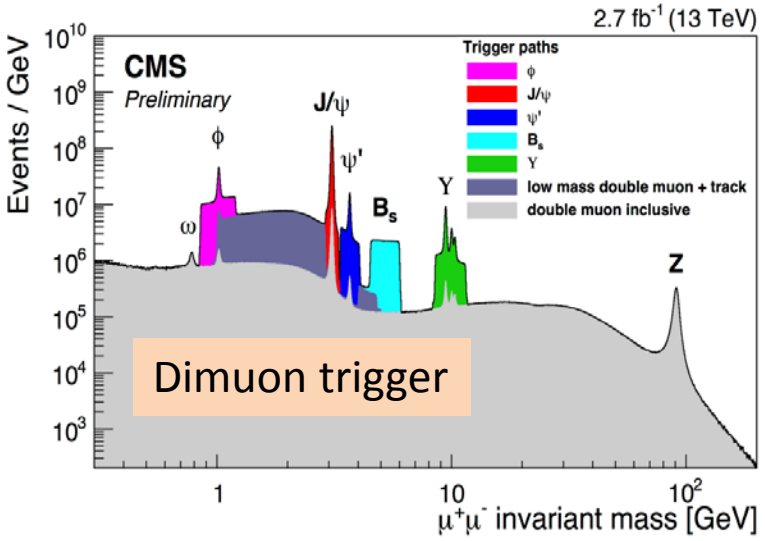


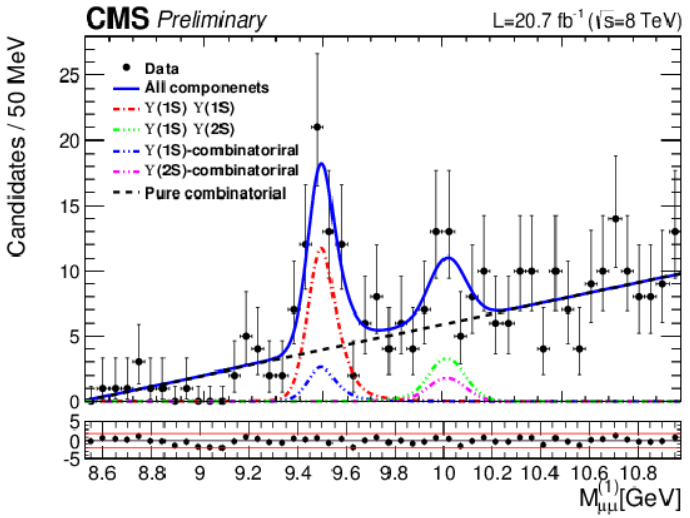
- Acoplanarity of dileptons in elastic process

- **Best limits on anomalous quartic gauge couplings !**

Quarkonia production at √s = 8, 13 TeV

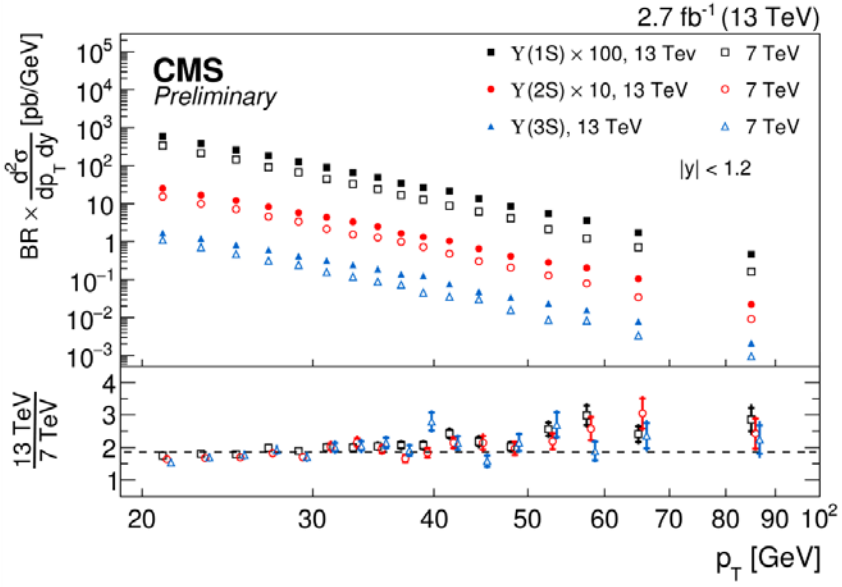
BPH-15-005

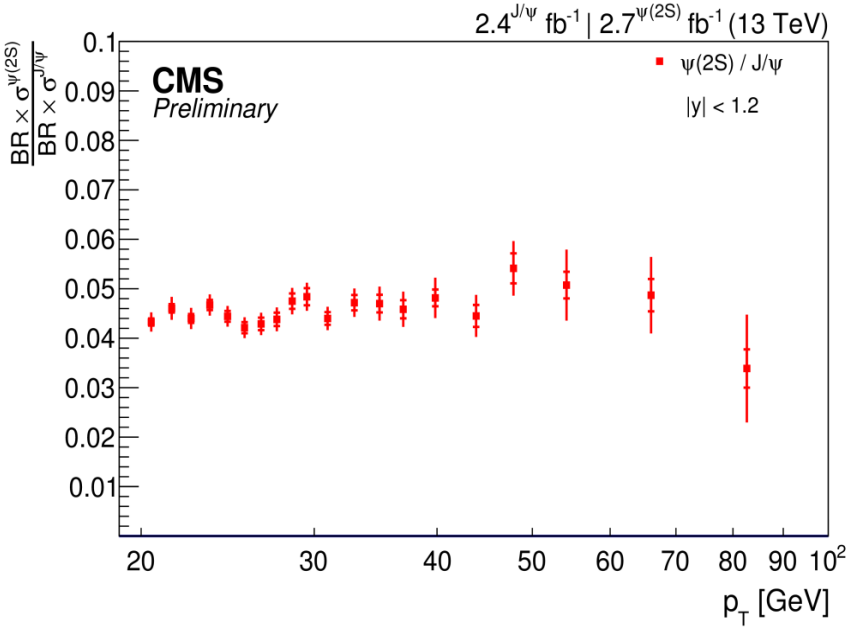




Υ(1s) Υ(1s) prod.

- ~69 pb @ 8 TeV
- 38 events
- > 5σ Obs.

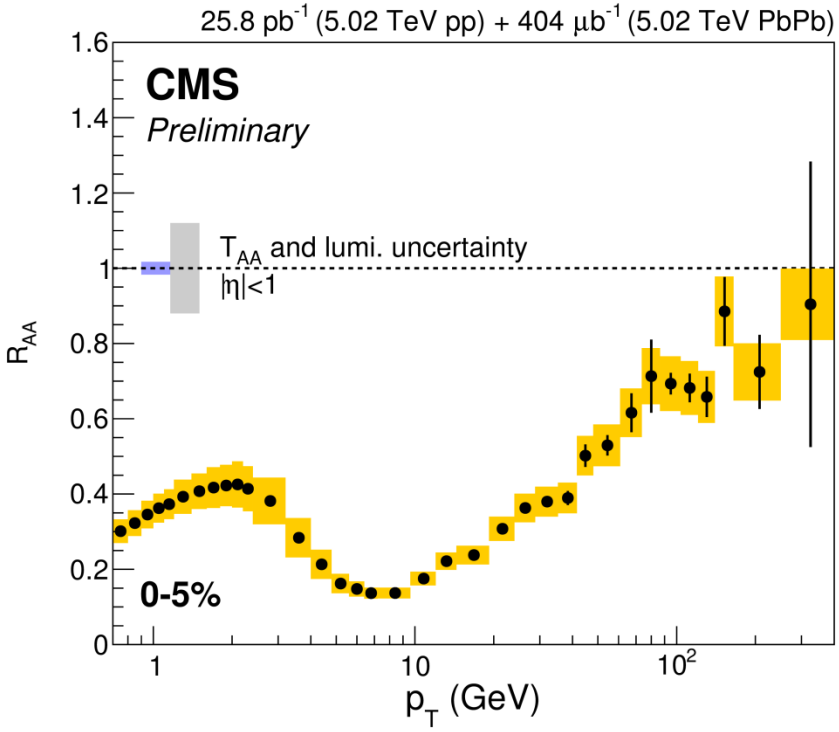




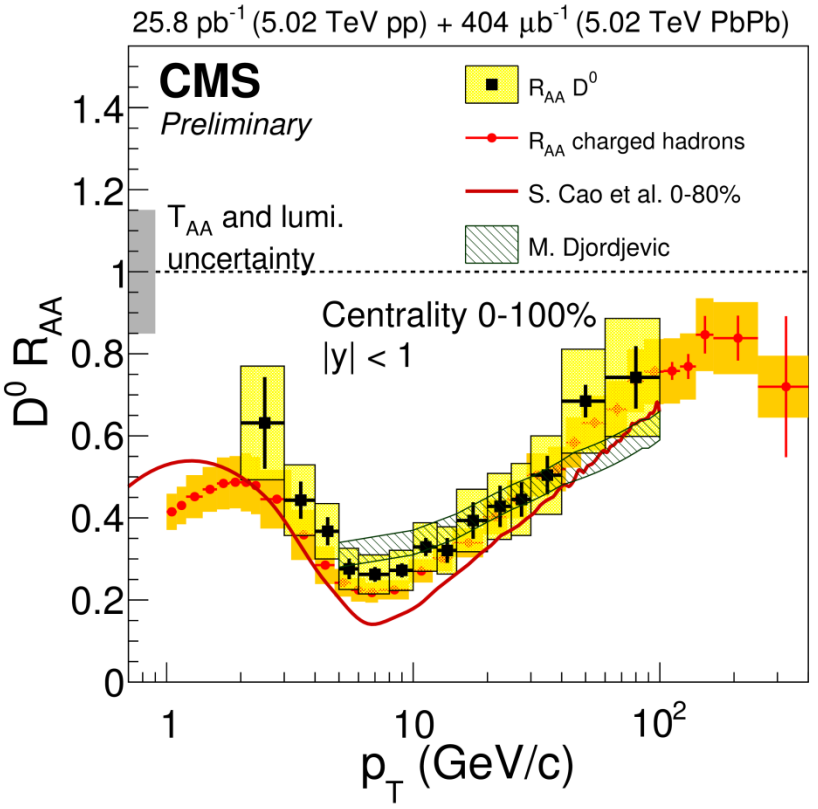
Nuclear modification factor in Pb-Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV

HIN-15-015

For charged particles



For D-mesons

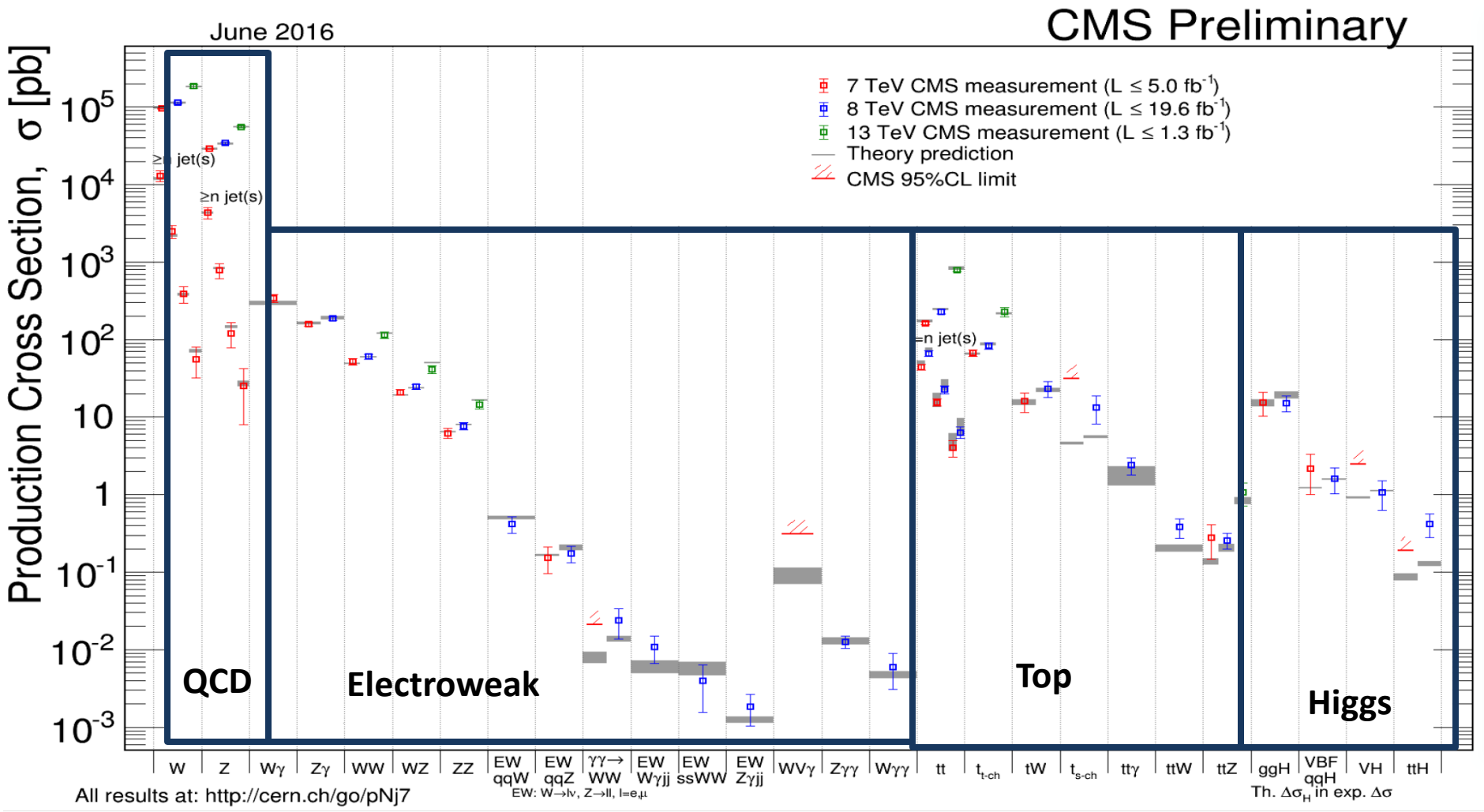


- Strong suppression of light and heavy flavours with comparable magnitude over wide p_T range

March of standard model

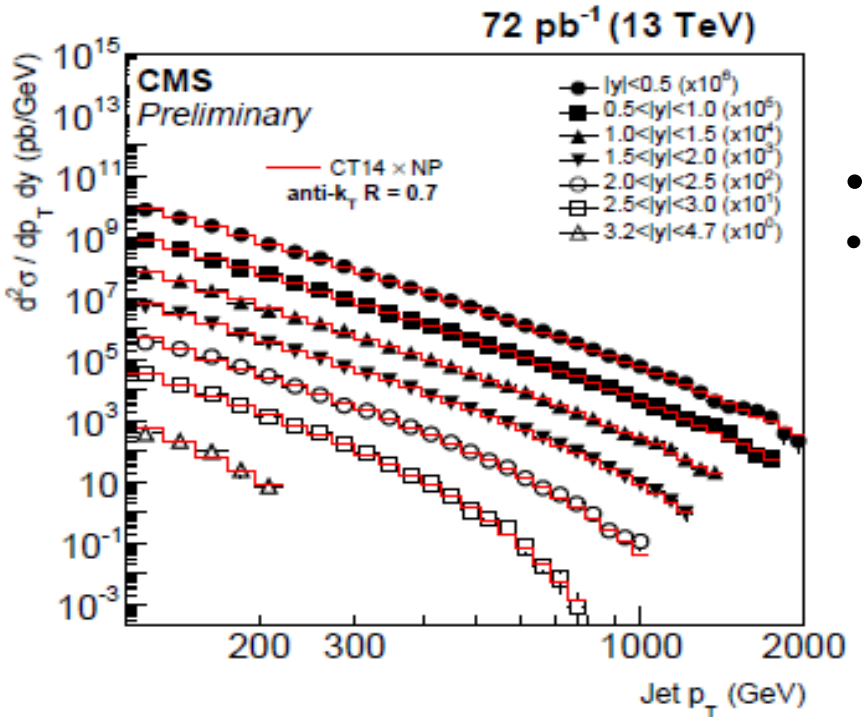
Cross section measurements at √s =7, 8, 13 TeV

All measurements consistent with standard model



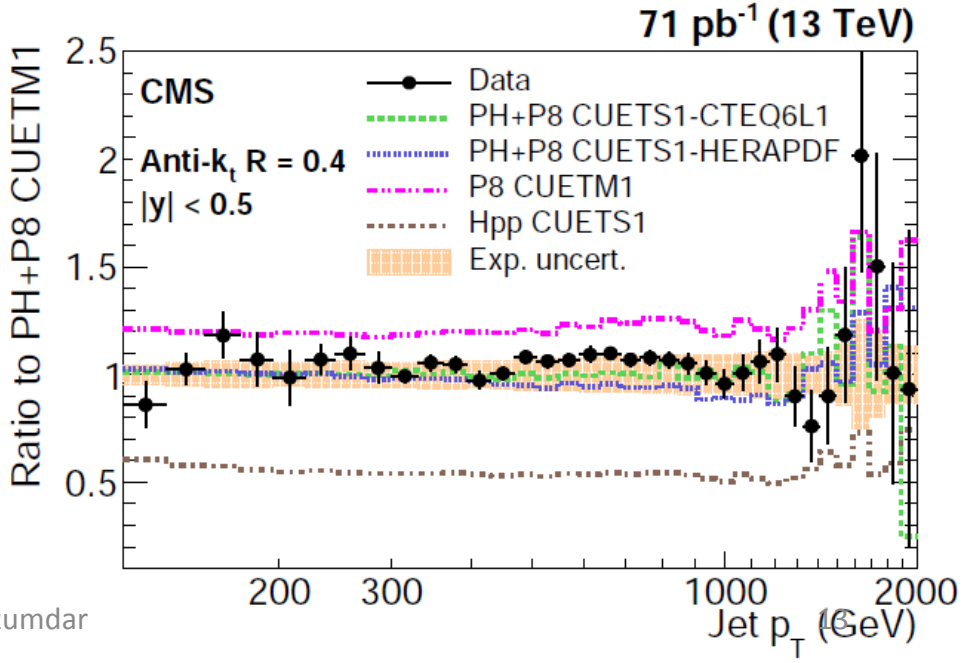
Inclusive jet measurements at √s = 13 TeV

SMP-15-007
arXiv:1605.04436
Submitted to EPJC

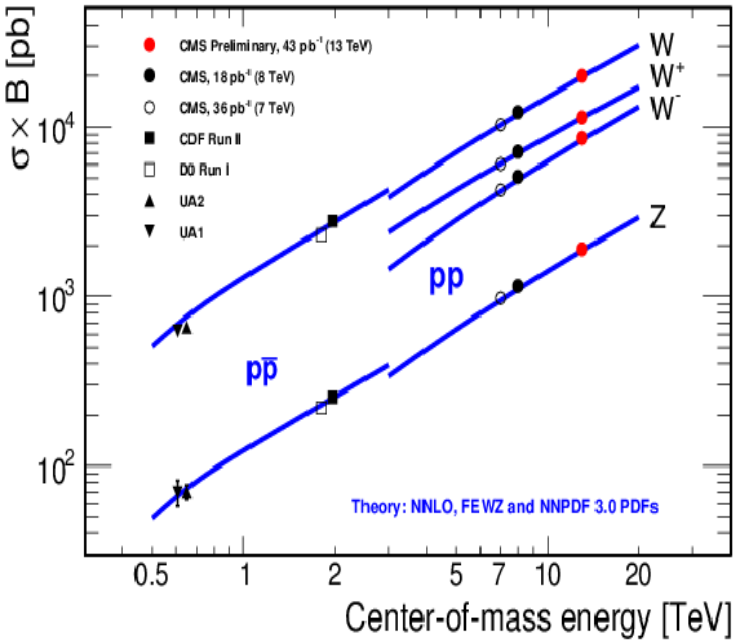


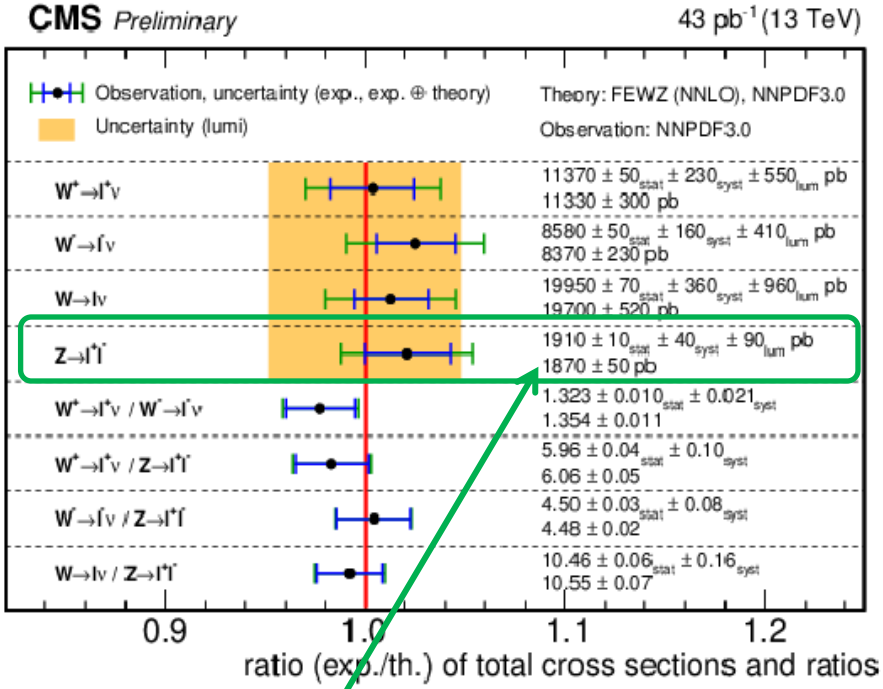
- Measurements up to jet p_T = 2 TeV
- Data matches better with cone radius of 0.7

- Over accessible kinematic range data agrees well with POWHEG+Pythia8



Inclusive W,Z production at √s = 13 TeV

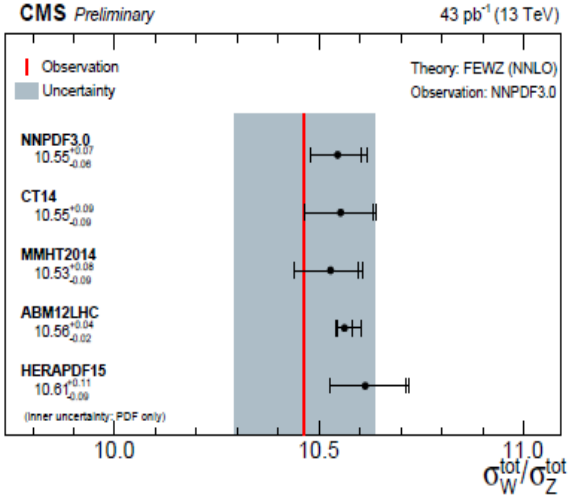




- Measured values, including √s dependence, agree with NNLO QCD predictions

$$\sigma(pp \to ZX) \times \mathcal{B}(Z \to \mu^+\mu^-) = 1870 \pm 2\,(\text{stat}) \pm 35\,(\text{syst}) \pm 51\,(\text{lumi})\ \text{pb}$$

- Ratios of production rates → tools to constrain PDFs
- W^+/W^- → valence quarks at low x
- W/Z → strange quark content of proton



SMP-15-004

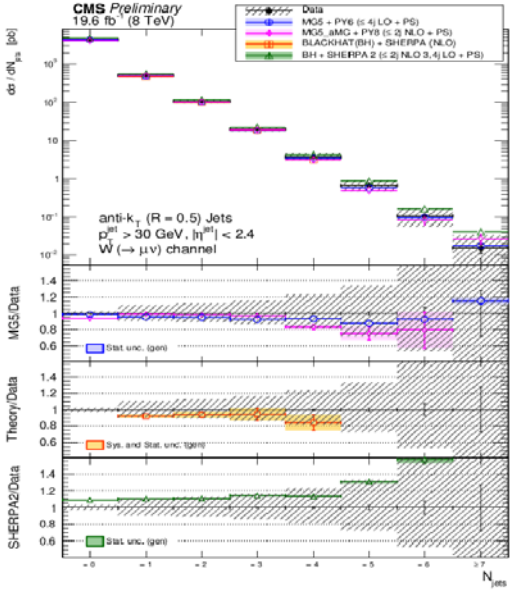
SMP-15-011

W/Z+jets production

- Fundamental test of predictions for QCD radiations.
- Theory calculation W/Z productions with up to V+1 jet at NNLO or at NLO (up to V+2 jets, with 0,1,2 multiplicities combined) + parton-shower .
- Angular correlations sensitive to modeling of higher order corrections.

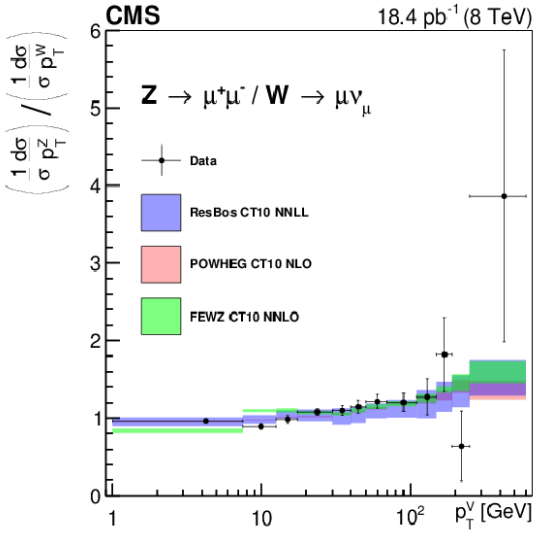
- Background for many analyses

➔ contributions must be estimated well.



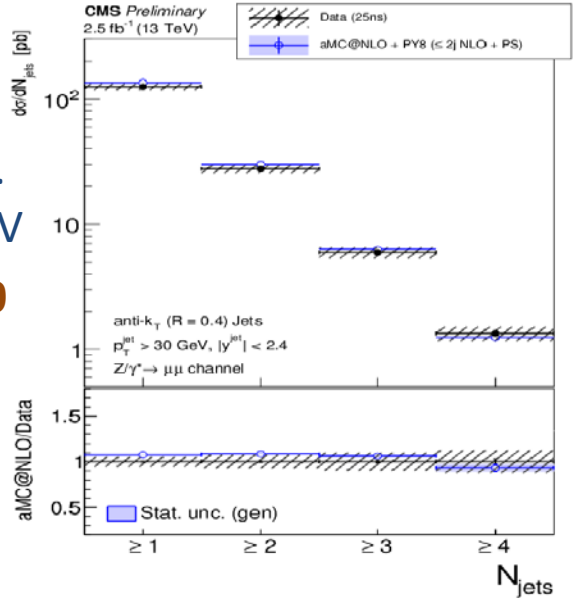
Jet multiplicity in incl. W production at 8 TeV

SMP-14-023



Ratio of Z to W for normalized p_T distributions

SMP-14-012



Jet multiplicity in incl. Z production at 13 TeV

SMP-15-010

Transverse boost of boson (q_T)

- Higher range of q_T → quark-gluon hard scattering described by fixed order perturbative QCD ➔ does not work as q_T → 0
- Low values of q_T due to ISR, parton intrinsic kinematics,..

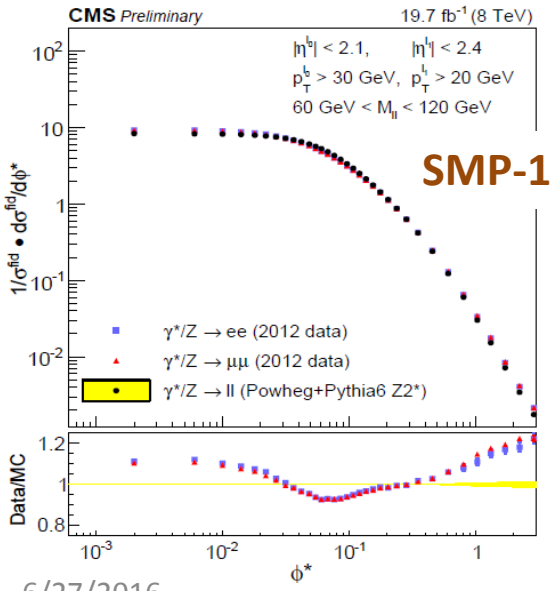
→ best described by soft gluon re-summation or shower models

→ Experimental precision at low q_T limited by systematic uncertainty

- Angular correlation between leptons: unique probe of boson q_T
- Depends only on leptons' directions → ϕ^* can be measured very precisely

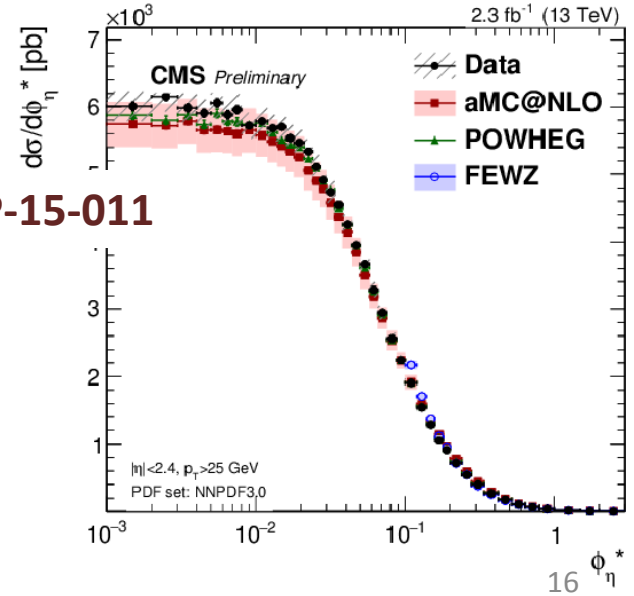
$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin(\theta^*_\eta)$$
$$\cos(\theta^*_\eta) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right),$$

8 TeV, ϕ^* normalized spectrum



SMP-15-002

13 TeV, ϕ^*absolute cross section



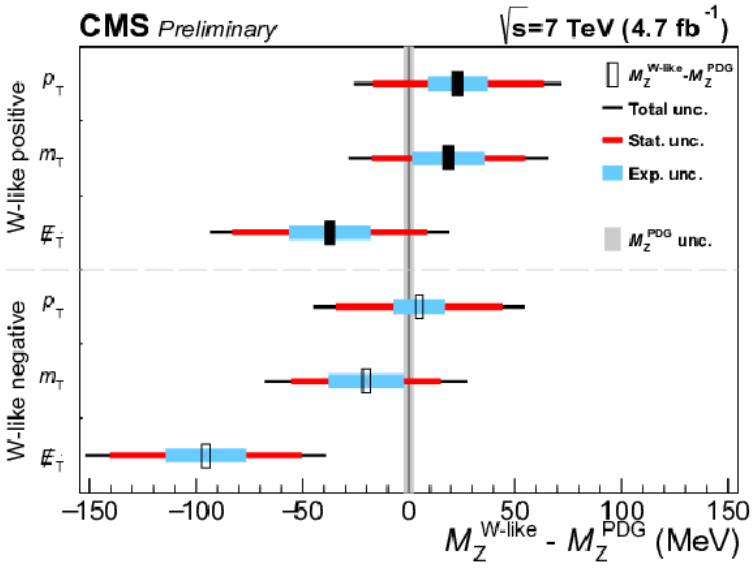
SMP-15-011

Precision in W-like mass measurement

SMP-14-007

- Carry out *W-like* measurement using Z→ μμ events (mask one μ to treat it like a ν)

➔ Proof of principle for high precision measurement of W-mass



Sources of uncertainty	$M_Z^{W_{like}+}$ p_T	m_T	$\not{E}_T$	$M_Z^{W_{like}-}$ p_T	m_T	$\not{E}_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Total experimental syst. uncertainties	14	17	19	12	18	19
Alternative data reweightings	5	4	5	14	11	11
PDF uncertainties	6	5	5	6	5	5
QED radiation	22	23	24	23	23	24
Simulated sample size	7	6	8	7	6	8
Total other syst. uncertainties	24	25	27	28	27	28
Total systematic uncertainties	28	30	32	30	32	34
Statistics of the data sample	40	36	46	39	35	45
Total stat.+syst.	49	47	56	50	48	57

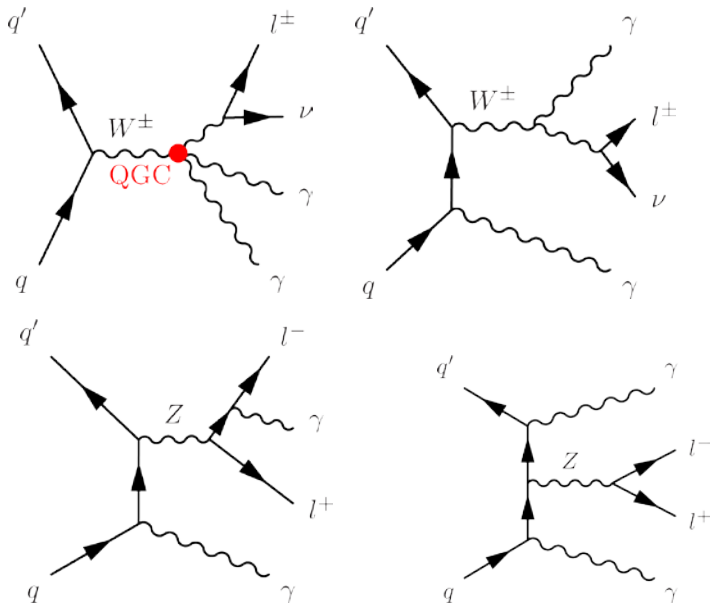
- Helps to validate experimental control of
  -- muon momentum scale and resolution
  -- resolution in missing transverse energy

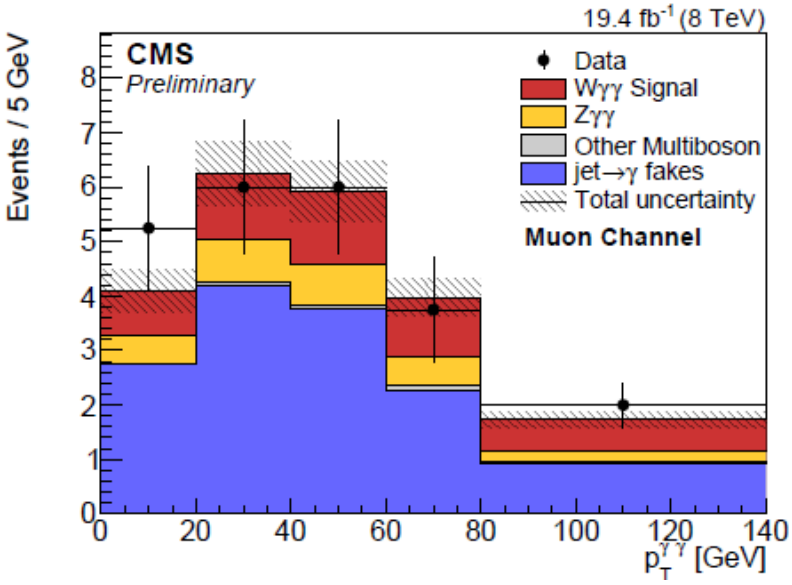
- *Theoretical systematics cannot be directly translated on real M_W measurement, though*

- Achievable precision in W-mass measurement: < 20 MeV

Wγγ, Zγγ production and quartic gauge coupling at √s = 8 TeV

SMP-15-008





$$\sigma^{\text{fid}}_{\text{W}^{\pm}\gamma\gamma} \cdot \text{BR}\,(\text{W} \to \ell\nu) = 6.0 \pm 1.8\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 0.2\,(\text{lumi})\,\text{fb}\,.$$

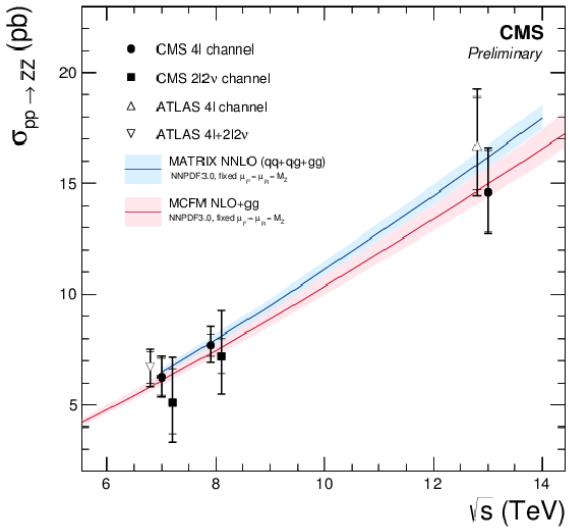
$$\sigma^{\text{fid}}_{\text{Z}\gamma\gamma} \cdot \text{BR}\,(\text{Z} \to \ell\ell) = 12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 0.3\,(\text{lumi})\,\text{fb}$$

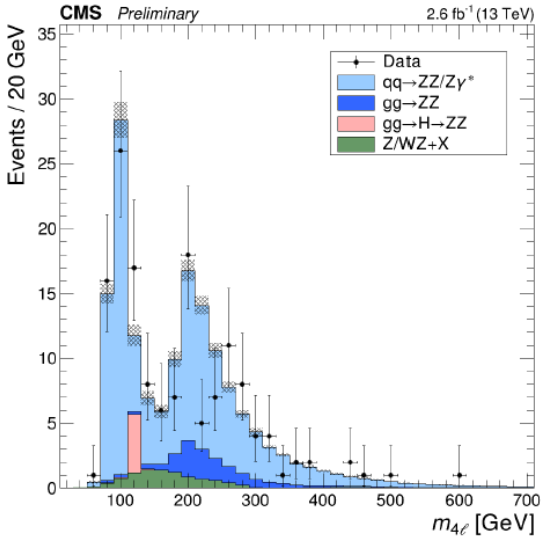
- Wγγ process observed with significance 2.4 σ
- Zγγ process observed with significance 5.9 σ

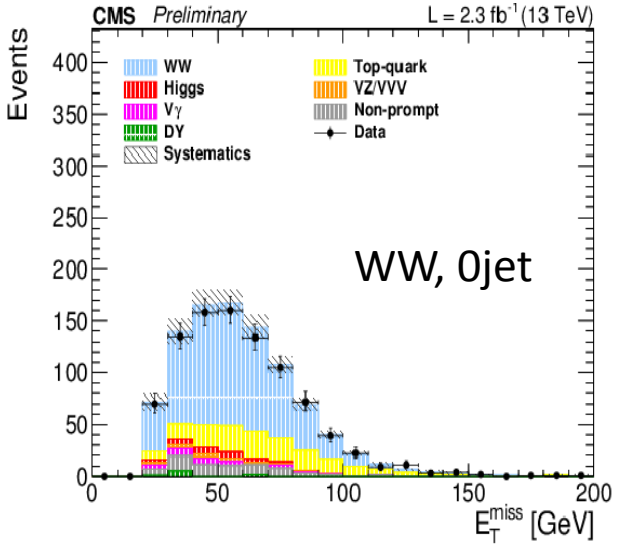
- Upper limit on anomalous quartic gauge (dim-8) coupling: $-37.5 < \frac{f_{\text{T},0}}{\Lambda^4} < 38.1$

Diboson productions at √s = 13 TeV

- Measurements test SM prediction
- Theoretical predictions accurate up to NNLO
- Diboson are backgrounds to many searches ➔ need to know the rates accurately





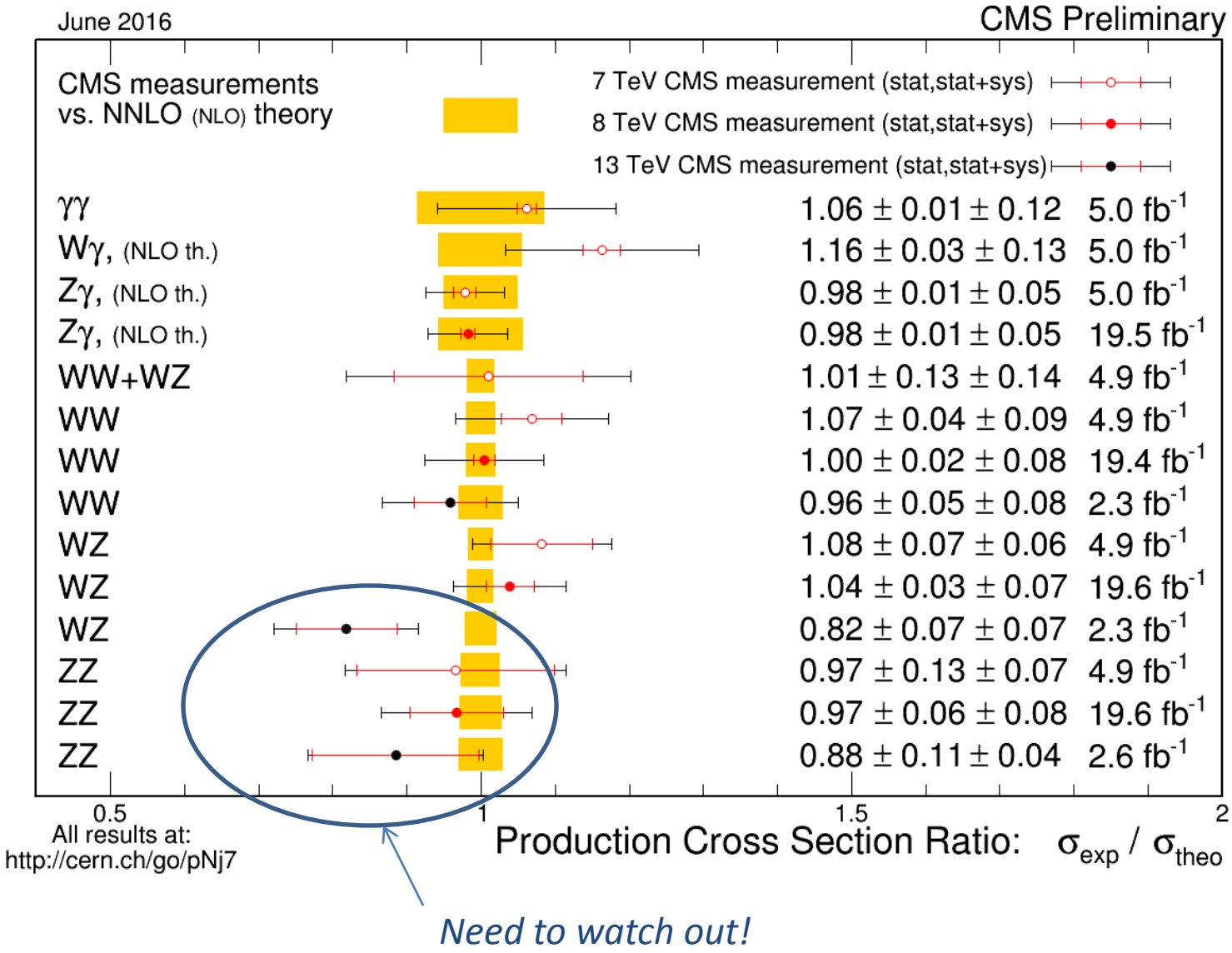


σ (pp→ W^+W^-) = 115.3 ± 5.8 (stat) ± 5.7 (exp) ± 6.4 (theo) ± 3.6 (lumi) pb **SMP-16-006**

$$\sigma(\mathrm{pp} \to \mathrm{ZZ}) = 14.6^{+1.9}_{-1.8}\,(\mathrm{stat})^{+0.5}_{-0.3}\,(\mathrm{syst}) \pm 0.2\,(\mathrm{theo}) \pm 0.4\,(\mathrm{lum})\ \mathrm{pb}.$$ **SMP-16-001**

$$\sigma(\mathrm{pp} \to \mathrm{WZ}) = 40.9 \pm 3.4\,(\mathrm{stat})\ ^{+3.1}_{-3.3}\,(\mathrm{syst}) \pm 0.4\,(\mathrm{theo}) \pm 1.3\,(\mathrm{lumi})\ \mathrm{pb}$$ **SMP-16-002**

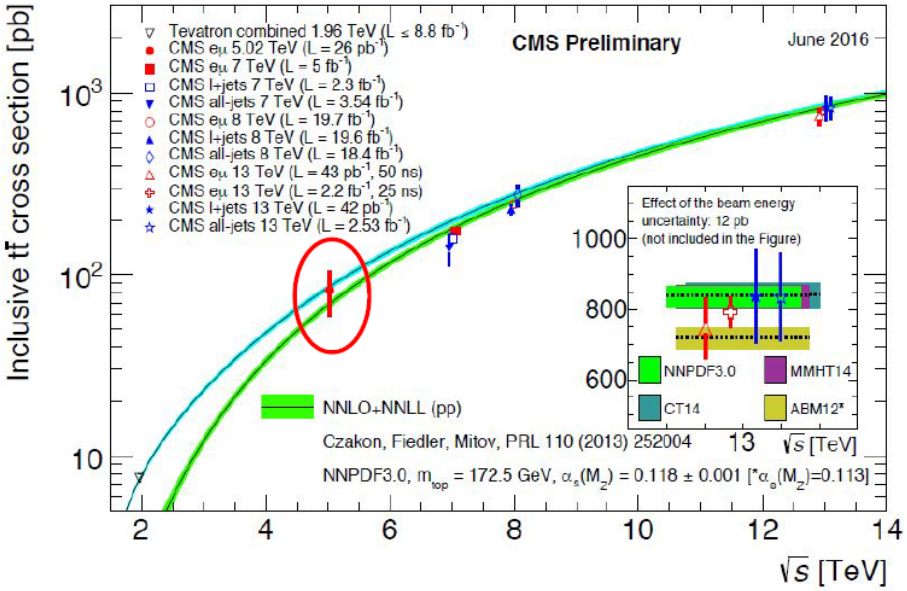
Summary of diboson production at Run 1 & Run 2



Need to watch out!

Top Physics

Top pair production



TOP-16-015

$\sigma(tt)$ @ 5.02 TeV , 26 pb^{-1}

= 82 ±20(stat)± 5(syst) ±10 (lumi) pb

first measurement!

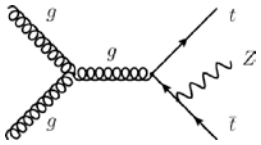
$\sigma(tt)$ @ 13 TeV , 2.2 fb^{-1}

= 793 ± 8(stat)± 38 (syst) ±21 (lumi) pb

TOP-16-005

- **Top-pair in association with Zat √s = 13 TeV**

Channel	Expected significance	Observed significance
3ℓ analysis	2.9	3.5
4ℓ analysis	1.2	0.9
3ℓ and 4ℓ combined	3.1	3.6



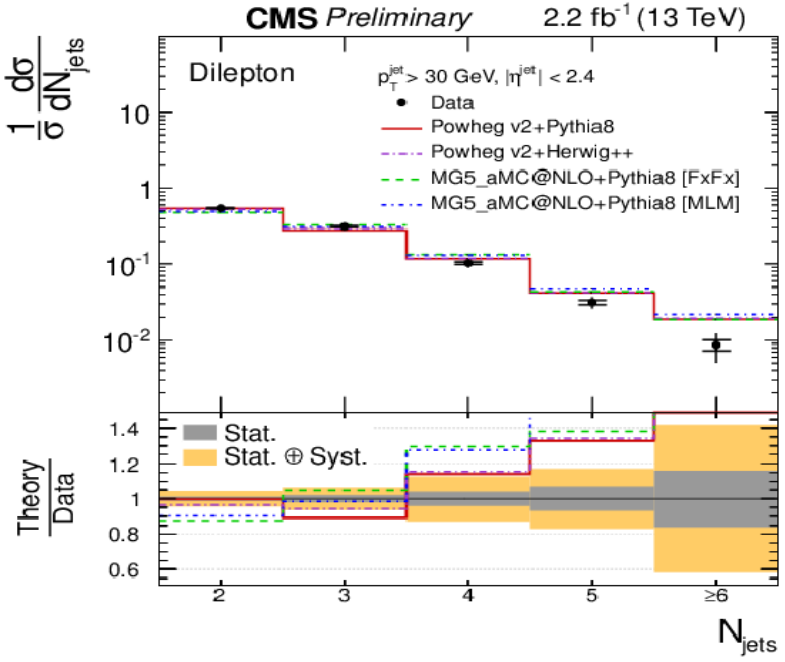
TOP-16-009

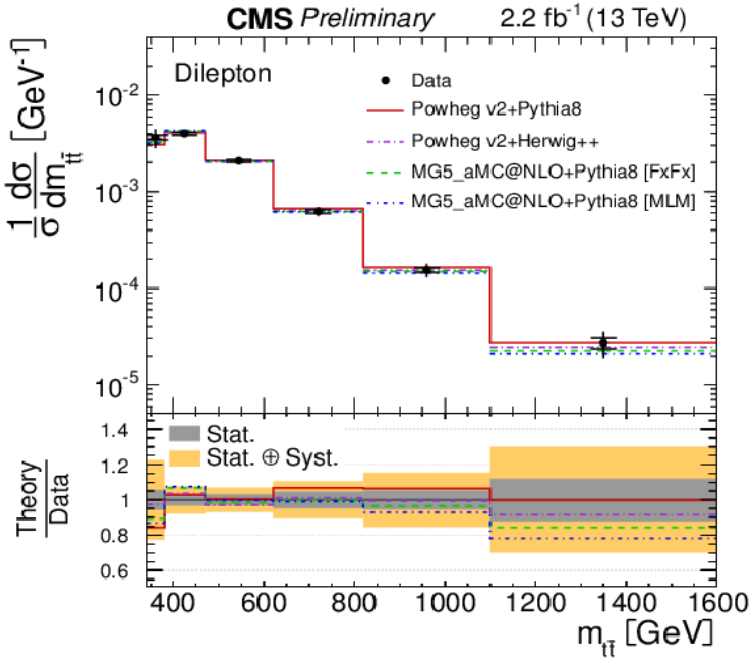
$\sigma(ttZ) = 1065\ ^{+352}_{-313}\ (stat)\ ^{+168}_{-142}\ (sys.)$ fb

Top pair differential cross sections at √s = 13 TeV

TOP-16-011

- Tests QCD description
- New ME generator and PS codes used in Run 2
- P_T spectrum better described by NNLO+NNLL





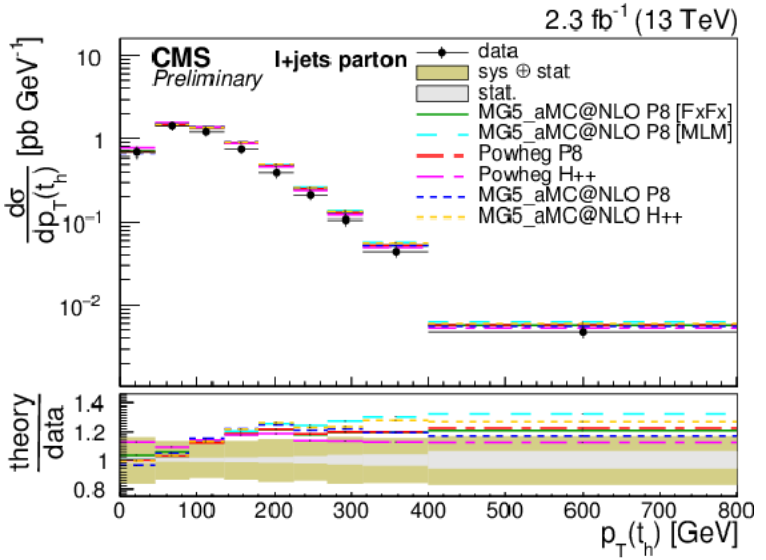
TOP-16-008

- **Measurement of top helicity**

$F_0 = 0.681 \pm 0.012(\text{stat}) \pm 0.023(\text{syst})$

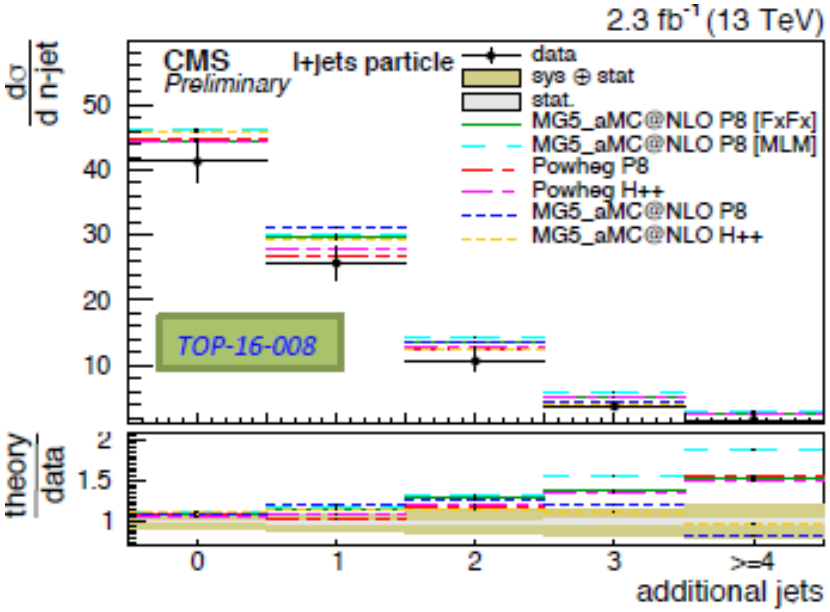
$F_L = 0.323 \pm 0.008(\text{stat}) \pm 0.014(\text{syst})$

TOP-13-008

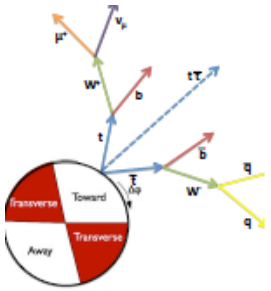


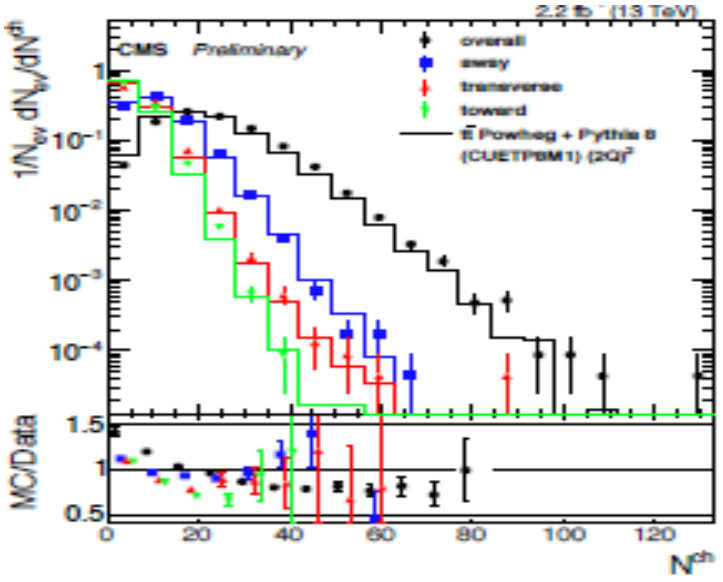
Jet multiplicity & underlying event activity in top events

TOP-15-017



- UE characteristics
  → Investigate and improve event modeling
  ➔ Charged particle activity



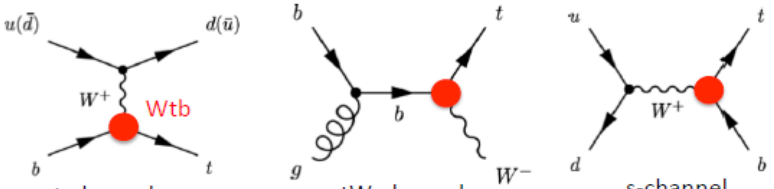


- Low jet multiplicity → sensitive to ME and matching to parton shower
- High jet multtiplicity → parton shower α_s tuning

- tt+jets important background to ttH

- No need for separate UE tunes for heavy quarks
- UE is sensitive to QCD scales

Electroweak production of single top at √s = 13 TeV



$$\sigma_{t-chan}^{13TeV} \sim 2.5 \times \sigma_{t-chan}^{8TeV}$$

NNLO precision for single top t-channel production rate

- Theory: ~ 1%
- Measurements:

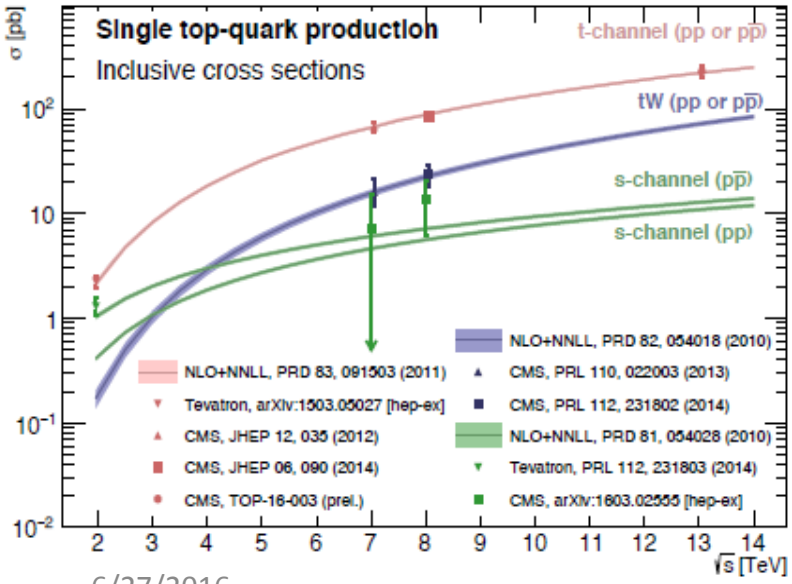
~10% at 8 TeV, with 20 /fb

~15% at 13 TeV with 2.3 /fb

$$\sigma_{t\text{-ch.,t}} = 141.5 \pm 6.7\,(\text{stat.}) \pm 9.4\,(\text{exp.})\,^{+19.3}_{-19.6}\,(\text{theo.}) \pm 3.8\,(\text{lumi.})\,\text{pb} = 141.5\,^{+22.8}_{-23.0}\,\text{pb},$$

$$\sigma_{t\text{-ch.,}\bar{t}} = 81.0 \pm 6.2\,(\text{stat.}) \pm 8.1\,(\text{exp.})\,^{+10.9}_{-10.9}\,(\text{theo.}) \pm 2.2\,(\text{lumi.})\,\text{pb} = 81.0\,^{+15.1}_{-15.1}\,\text{pb}.$$

TOP-16-008



$$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{t-ch.}}{\sigma_{t-ch.}^{th}}},$$

$$|f_{LV}V_{tb}| = 1.02 \pm 0.07(\text{exp.}) \pm 0.02(\text{theo.})$$

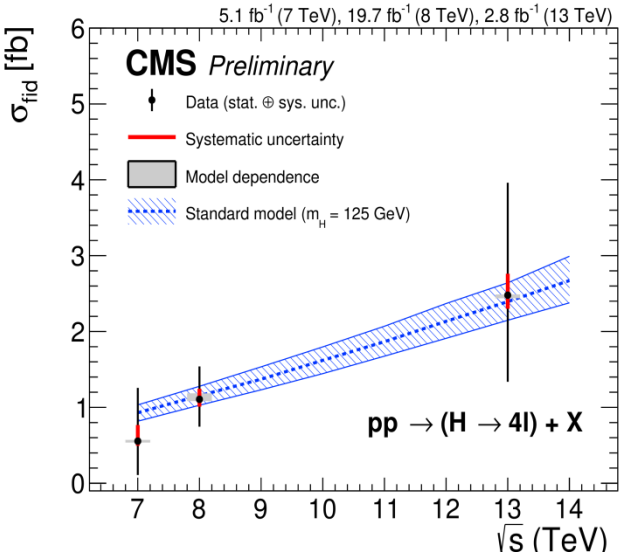
Anomalous form factor

- Within experimental uncertainty no significant deviation observed wrt theoretical predictions based on 4FS or 5FS

Higgs Physics

Standard Model Higgs measurements at 13 TeV

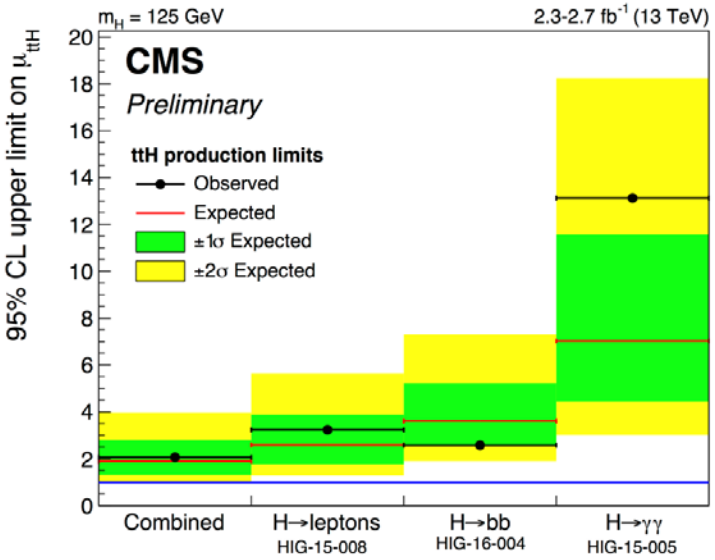
H→ ZZ*→ 4l HIG-15-004

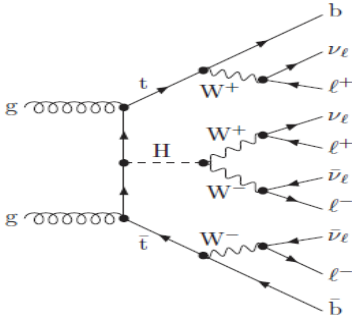


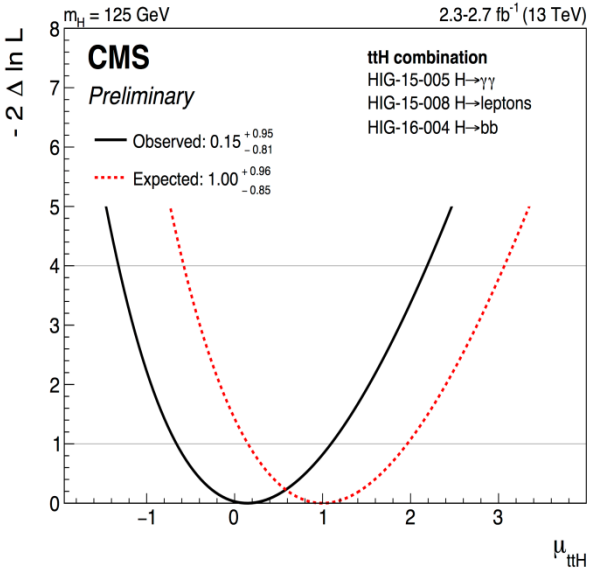
HIG-15-008

- **VBF H, H—>bb,**
  μ for combined 8 and 13 TeV = $1.3^{+1.2}_{-1.1}$

- **ttH , H → WW, ZZ, ττ**
  Explored same sign dilepton or 3 lepton (+b-tagged jets) final states
  μ_{ttH} = 0.15 + 0.95 -0.81
  Compare with SM expectation: 1.00+0.96 -0.85

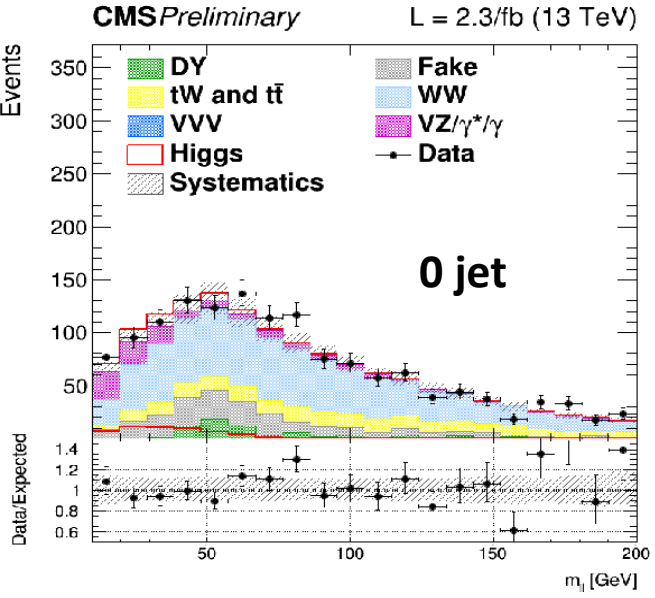


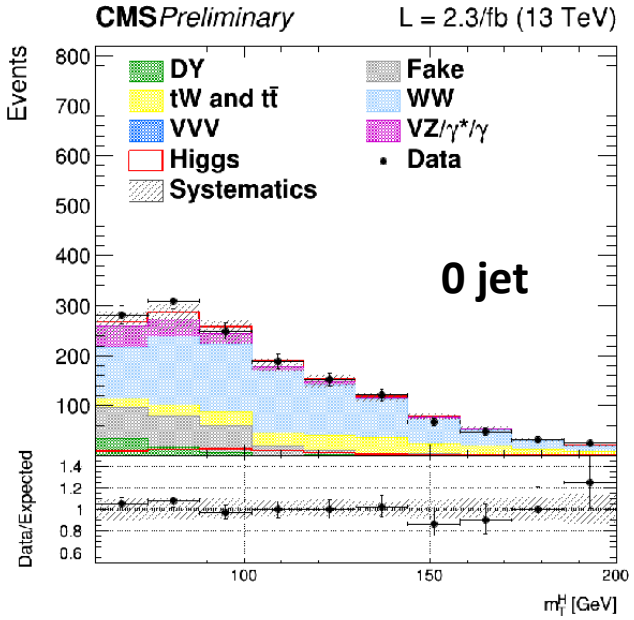


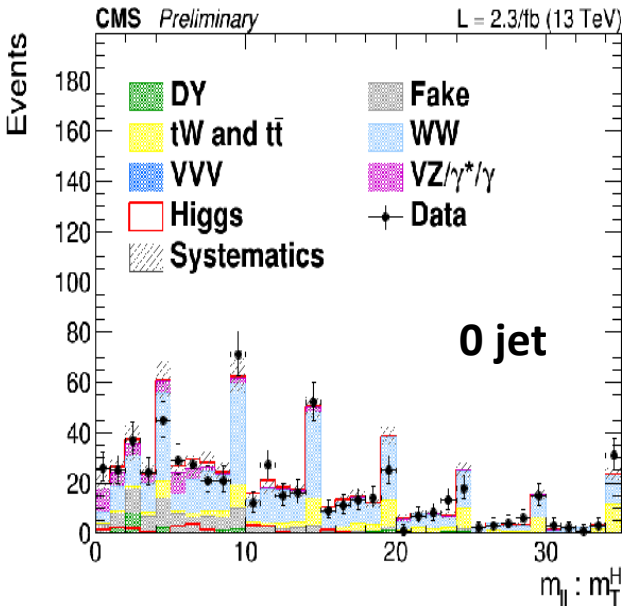


H→ WW (→e μ +X) at 13 TeV

HIG-15-003

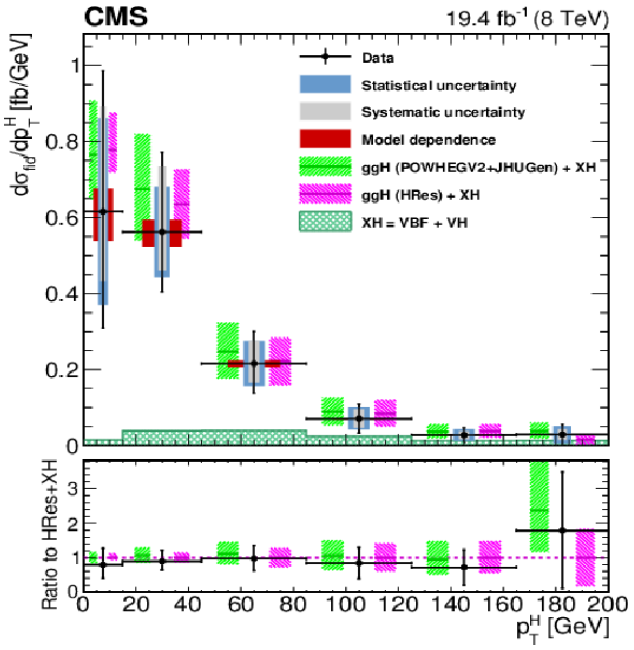






- Similar for 1-jet category
- Bi-dimensional analysis in m_{ll} (5 bins) m_T^H (10 bins)

- observed (expected) significance: 0.7 σ (2.0 σ)
- signal strength μ = 0.3 ±0.5



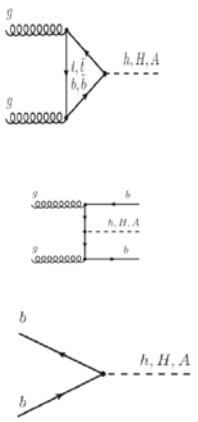
Transverse momentum of Higgs at √s =8 TeV

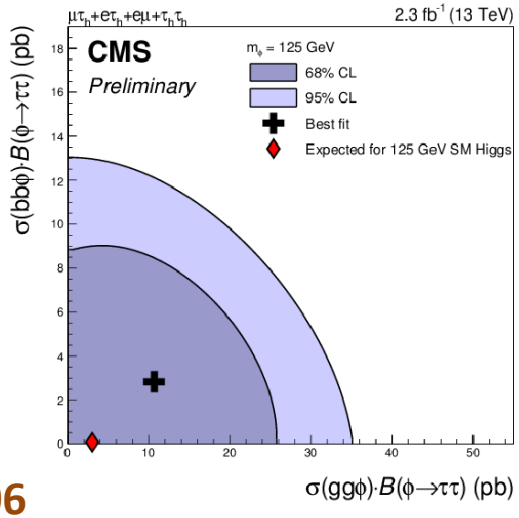
HIG-15-010

Search for beyond standard model physics

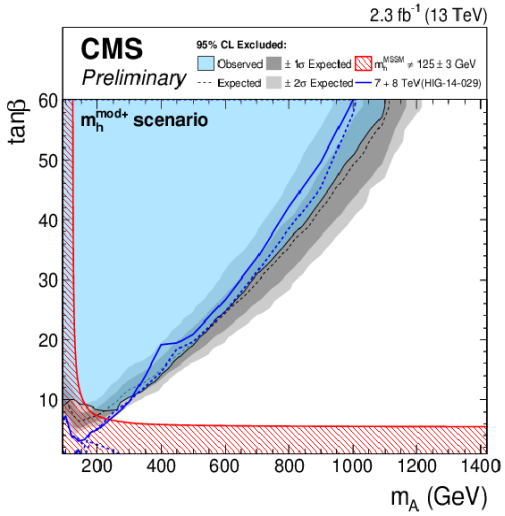
Searches for BSM Higgs at √s = 13 TeV

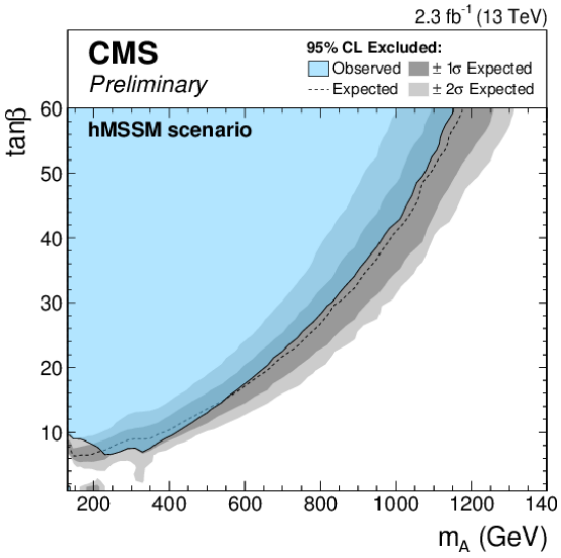
MSSM H→ ττ



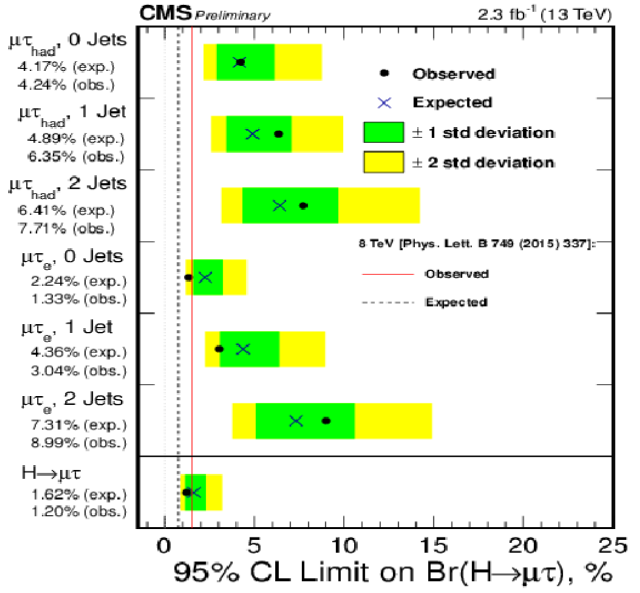


HIG-16-006

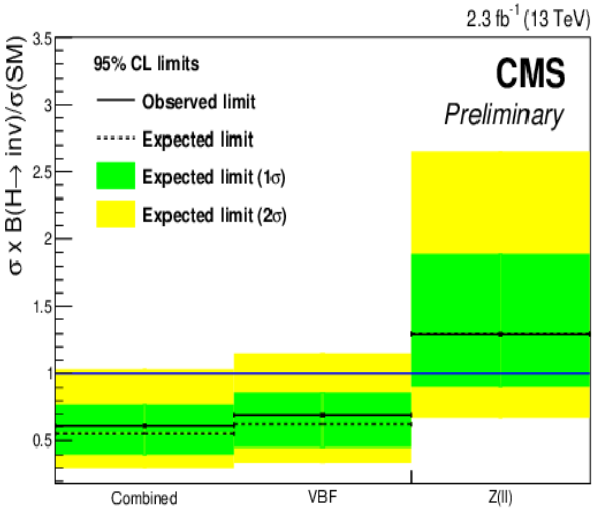




Lepton Flavour Violation H→ τμ HIG-16-005



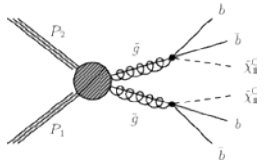
Invisible Higgs HIG-16-009



8 and 13 TeV combination
→ Observed (expected) UL on Br(H→ inv.)= 32% (26%)

Search for Supersymmetry at √s = 13 TeV

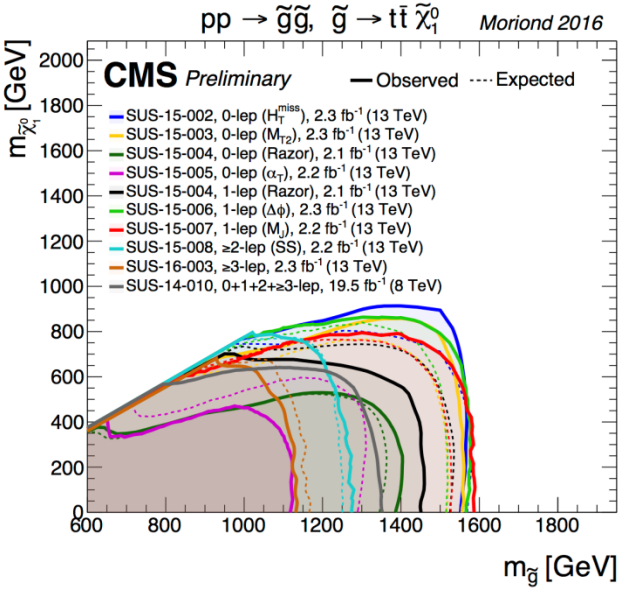
- Many searches with jets, leptons , photons, missing energy in final state
- ➔ Sensitivity for both strong and weak production of SUSY particles.
- Interpretation of final states in terms of simplified models, eg. T1bbbb



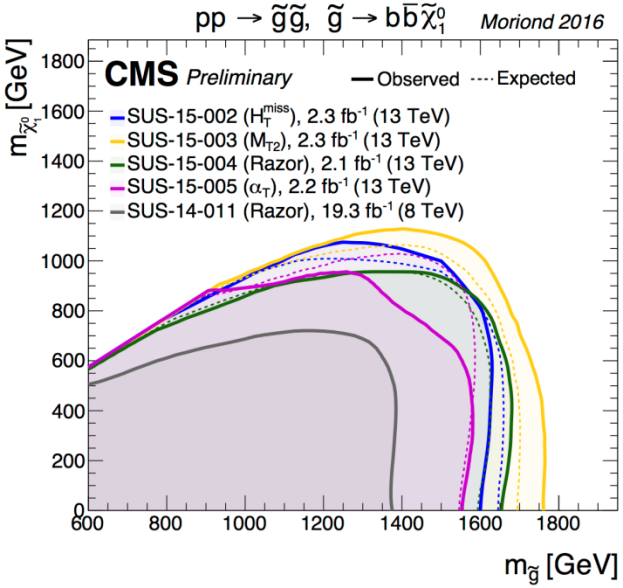
Gluino searches

SUS-15-002, PLB 758(2016) 152

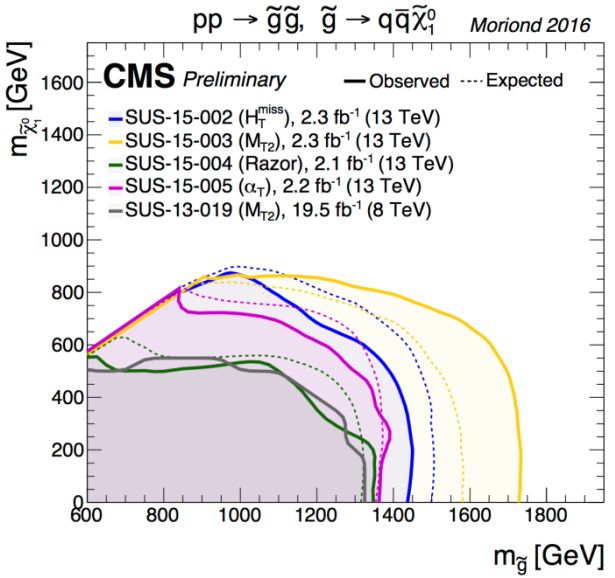
Gluino pair to 4 tops



Gluino pair to 4 bottoms



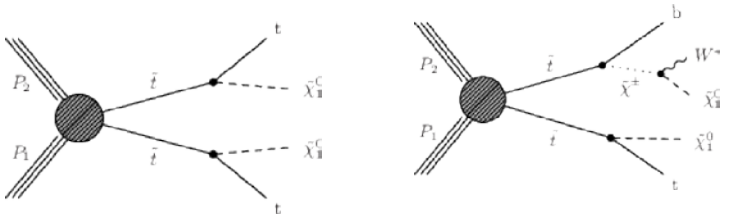
Gluino pair to light quarks

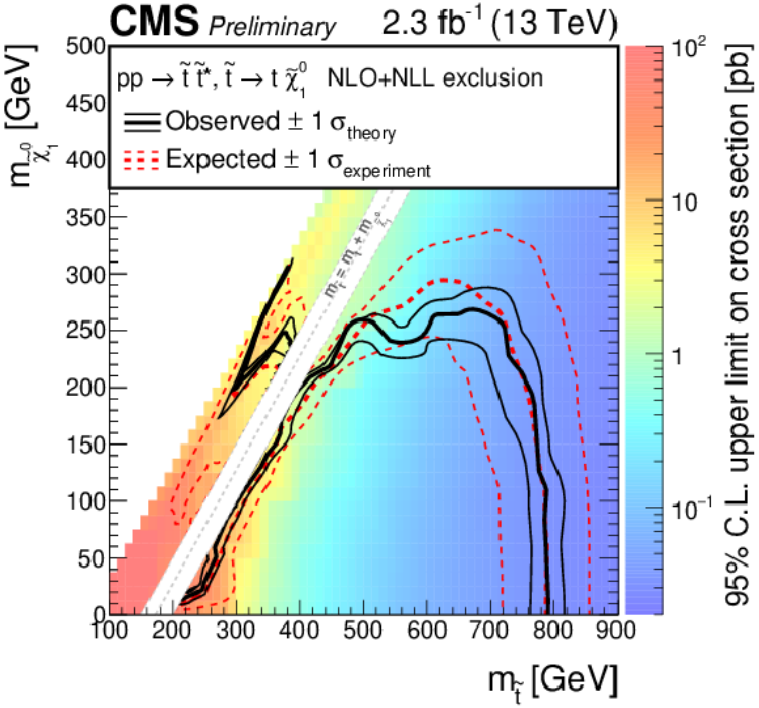


- Run 2 searches focus on compressed scenario

Direct production of stop pairs

Searches in hadronic final state





m_{stop} > 800 GeV for low m_{LSP}

SUS-16-007

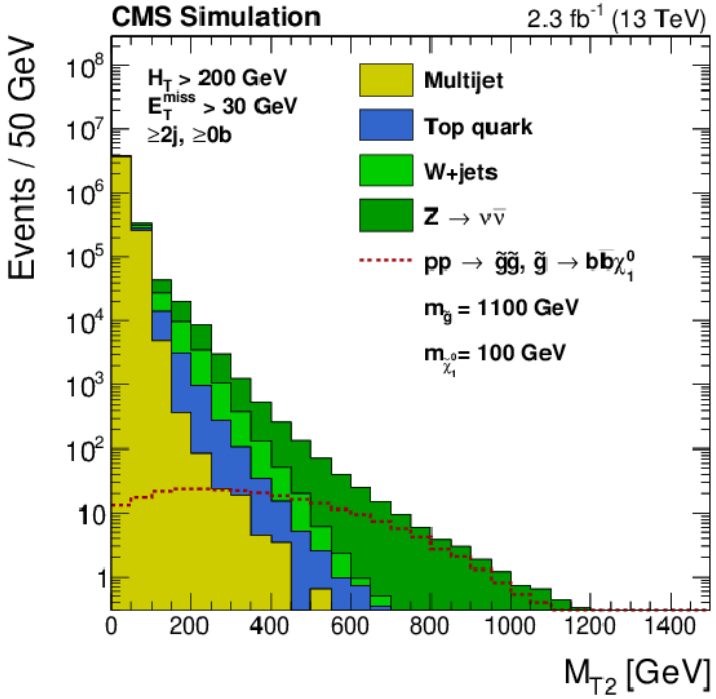
Search in multijet + E_T^{miss} final state

use kinematic variables with categorization

$$\vec{E}_T^{miss} = \vec{\not{E}}_T = -\sum_{i \in particles} \vec{p}_{Ti} \qquad \vec{H}_T^{miss} = \vec{\not{H}}_T = -\sum_{i \in jets} \vec{p}_{Ti}$$

$$M_T(\vec{p}_T, \vec{q}_T) = \sqrt{2\left(|\vec{p}_T||\vec{q}_T| - \vec{p}_T \cdot \vec{q}_T\right)}$$

$$M_{T2} = \min_{\vec{q}_T + \vec{r}_T = \vec{E}_T^{miss}} \left[\max\left(M_T(\vec{p}_T^{j_1}, \vec{q}_T), M_T(\vec{p}_T^{j_2}, \vec{r}_T)\right)\right]$$



SUS-15-003, JHEP

Combination of diboson (WW, ZZ, WH, ZH) productions

- Exotica searches

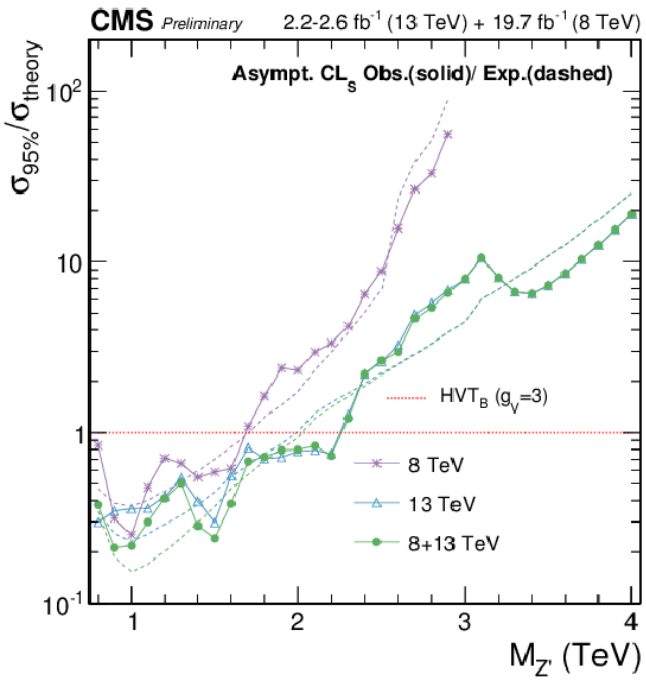
  1. Heavy Vector Singlet/Triplet model: W' → WZ, WH or Z' → WW, ZH

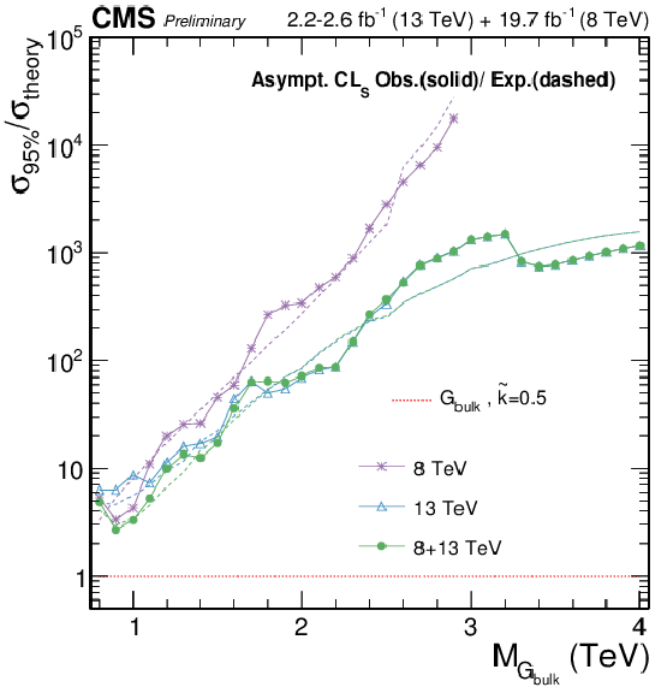
     exclusion: W' > 2.3 TeV, Z' > 1.8 TeV, triplet > 2.4 TeV

  2. A narrow Bulk Graviton → WW, ZZ

     0.9σ significance for W' (1.9-2 TeV)

B2G-16-007

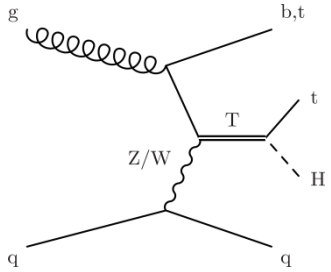


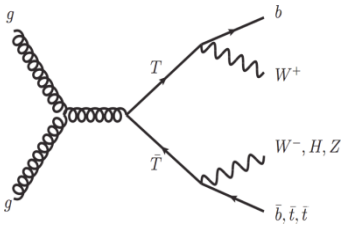


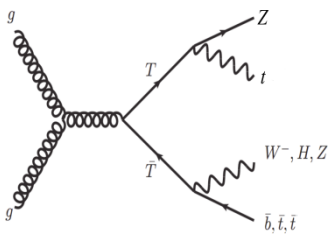
- Run 1 had anomaly (slight excess around 2 TeV) at the level of 2 to 2.5 σ
- Not confirmed at Run 2.

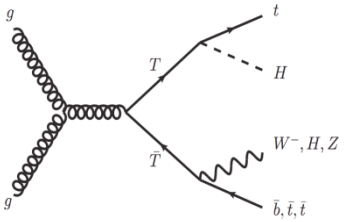
Search for massive vector-like quark (charge 2/3) production

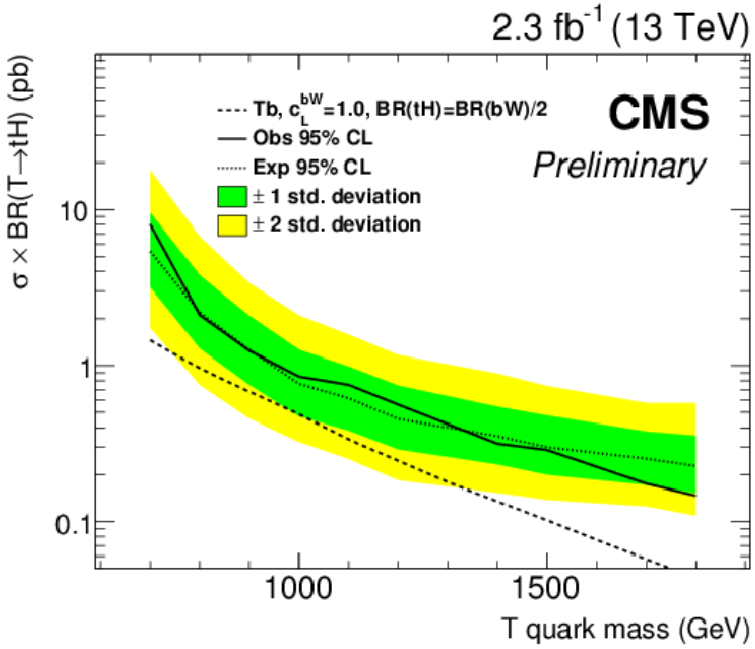
B2G-16-002

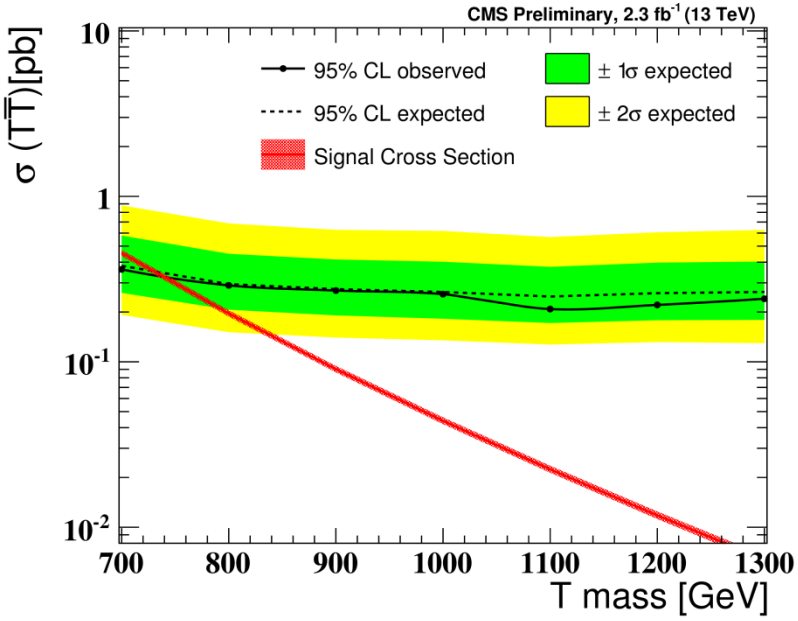






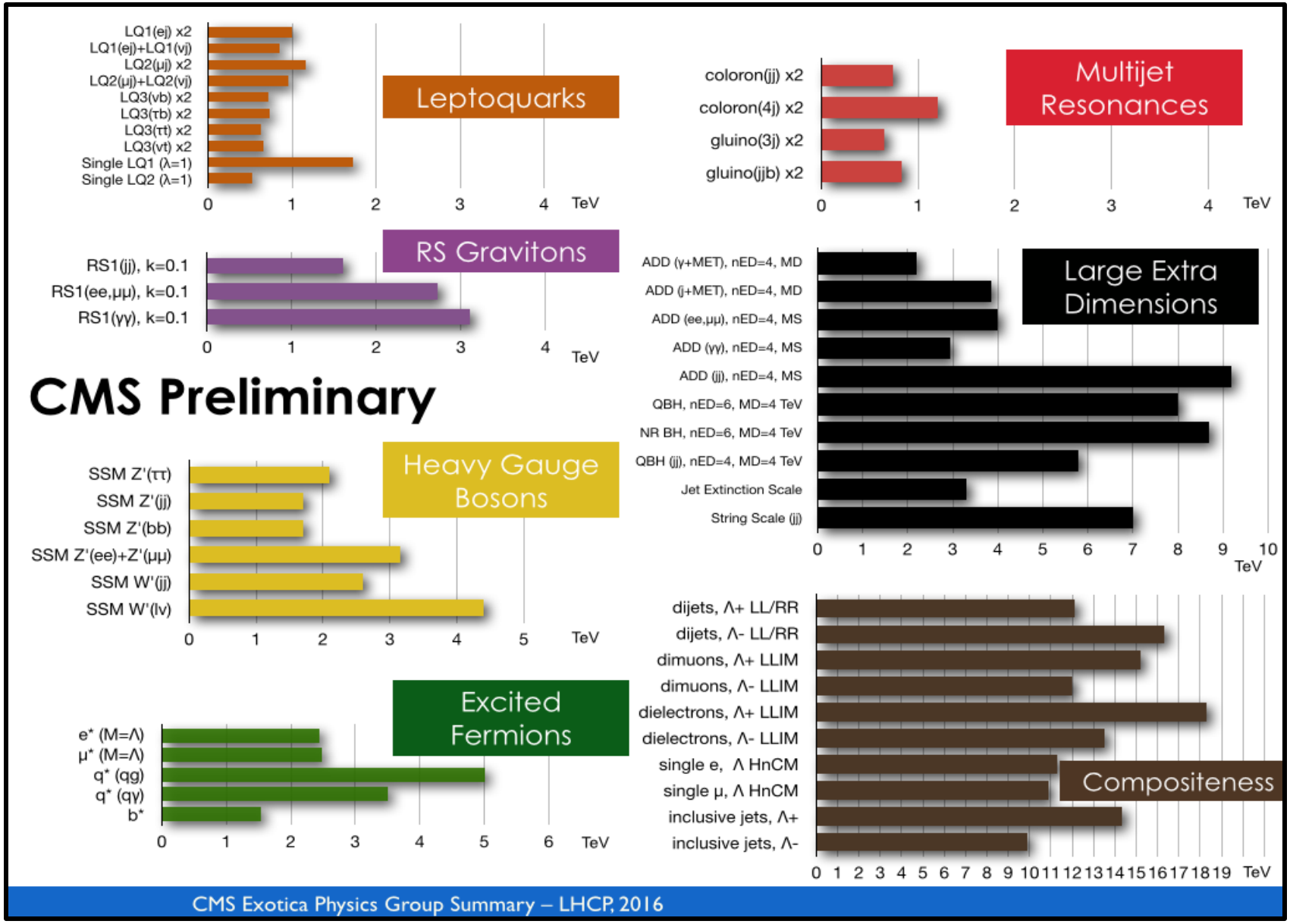




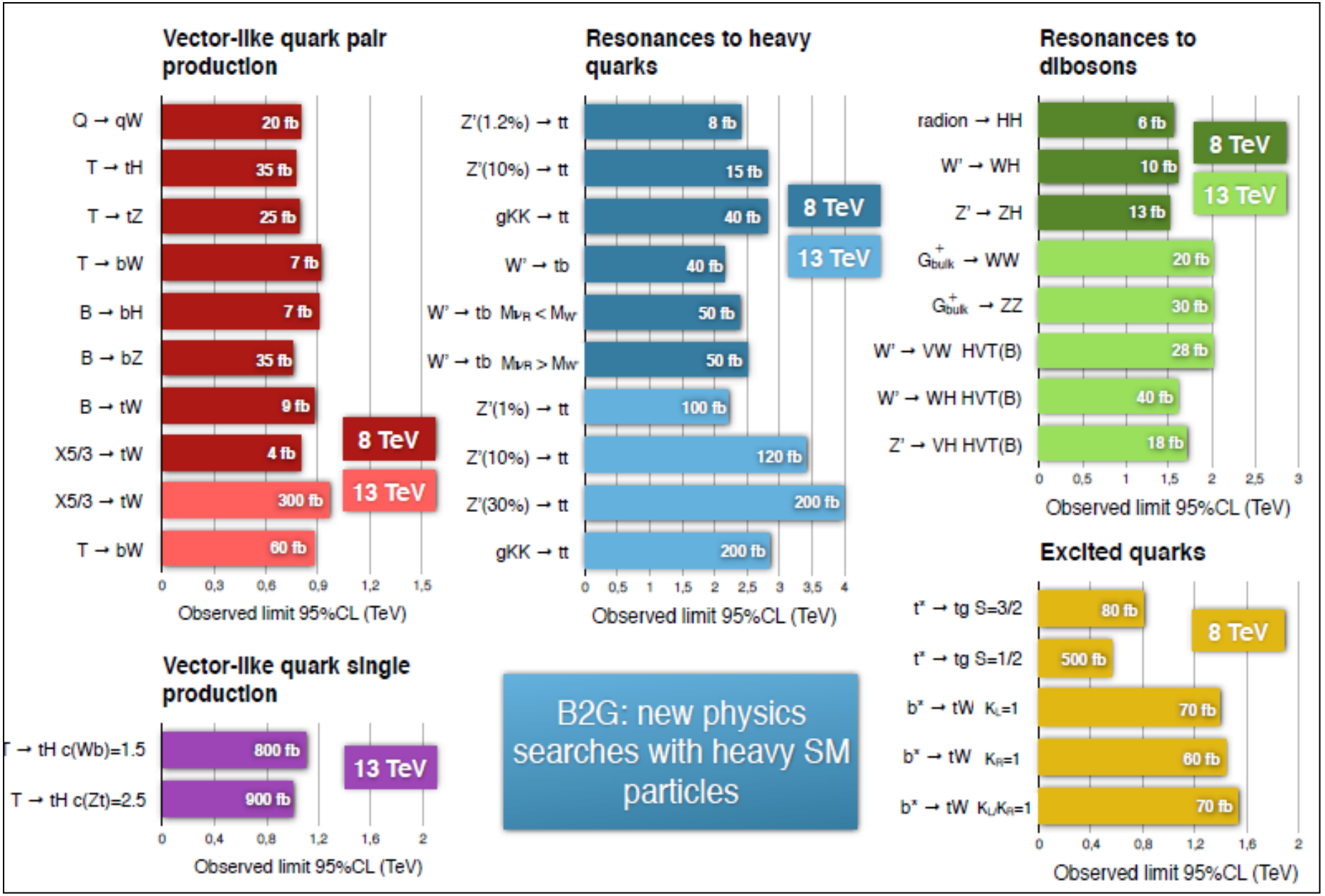


Left handed, in association with b --quark

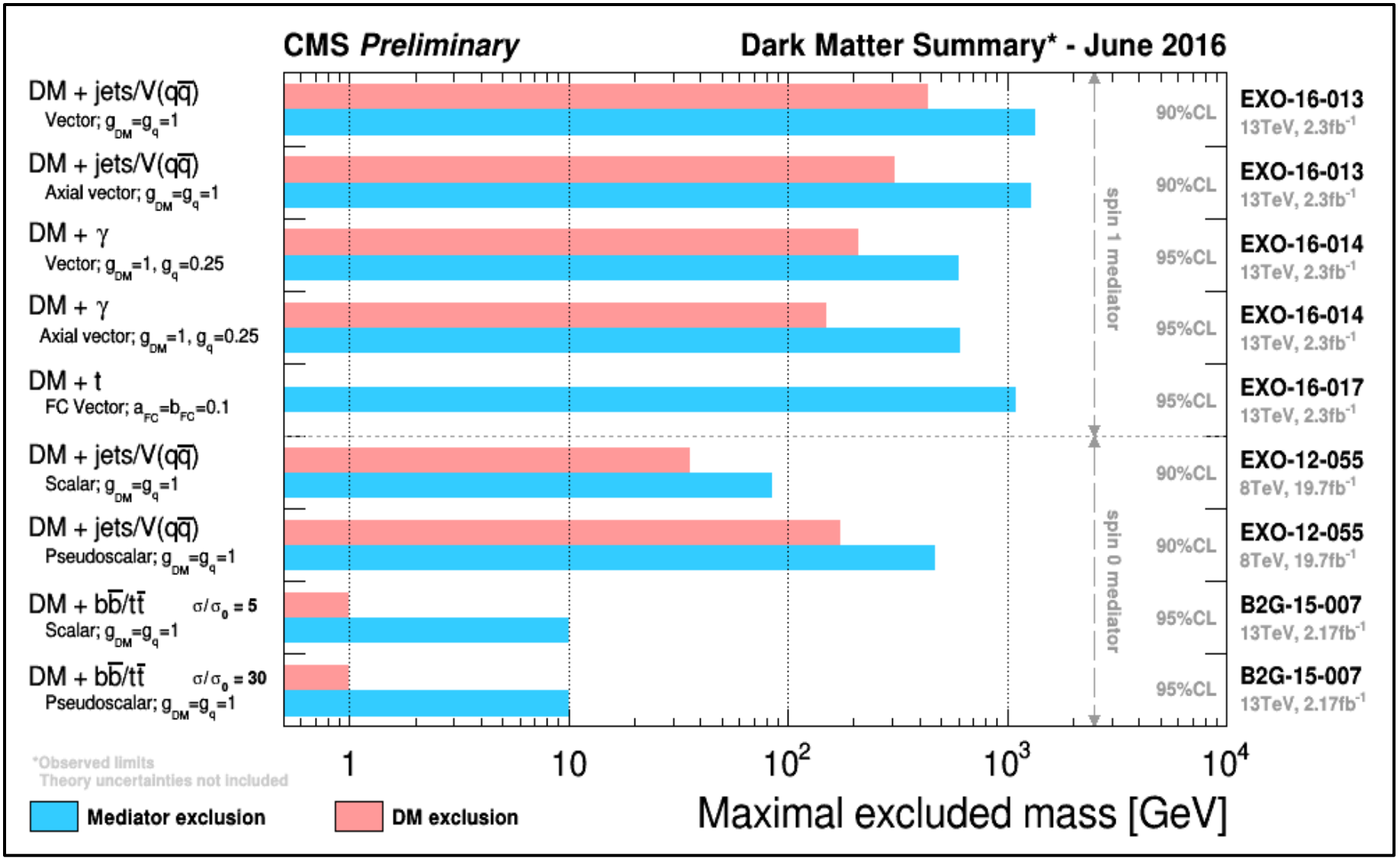
Exotica searches: June 2016



Summary of searches for beyond 2nd generation

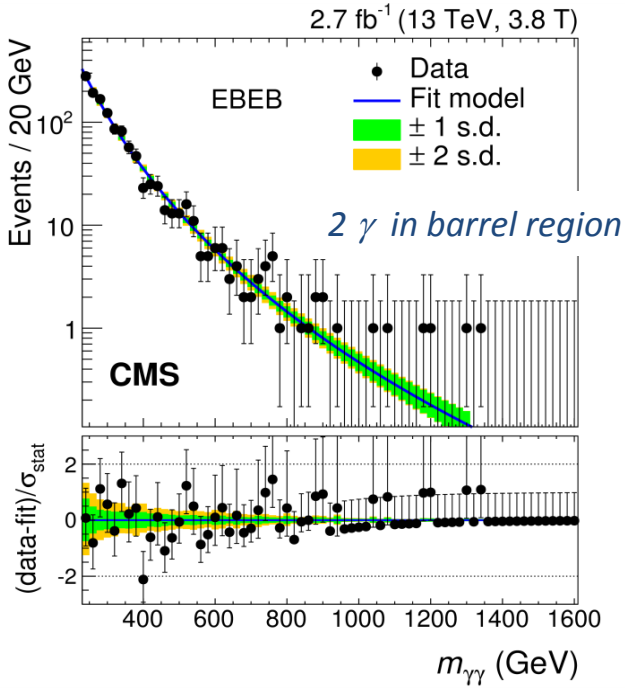


Dark Matter searches, June 2016

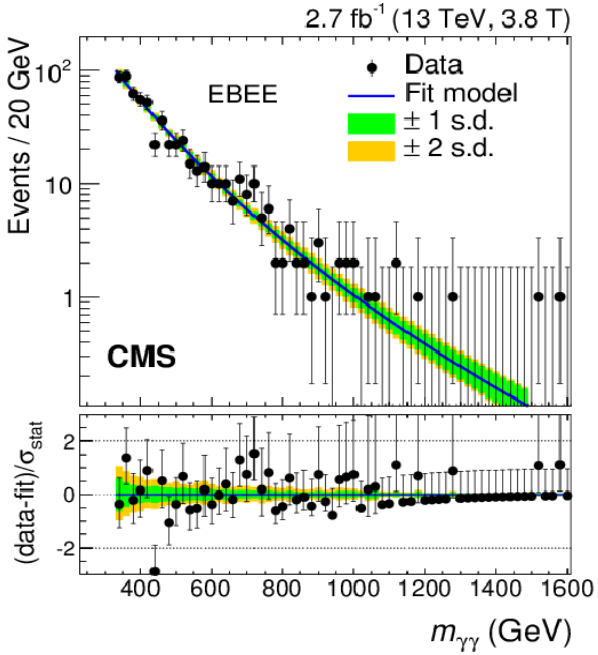


Search for high mass resonances

Resonance structure in Diphoton spectrum?

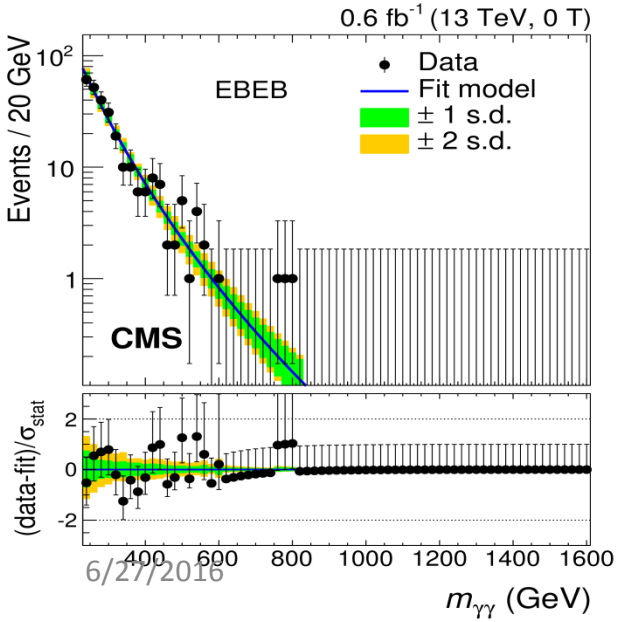


2 γ in barrel region



EXO-16-018

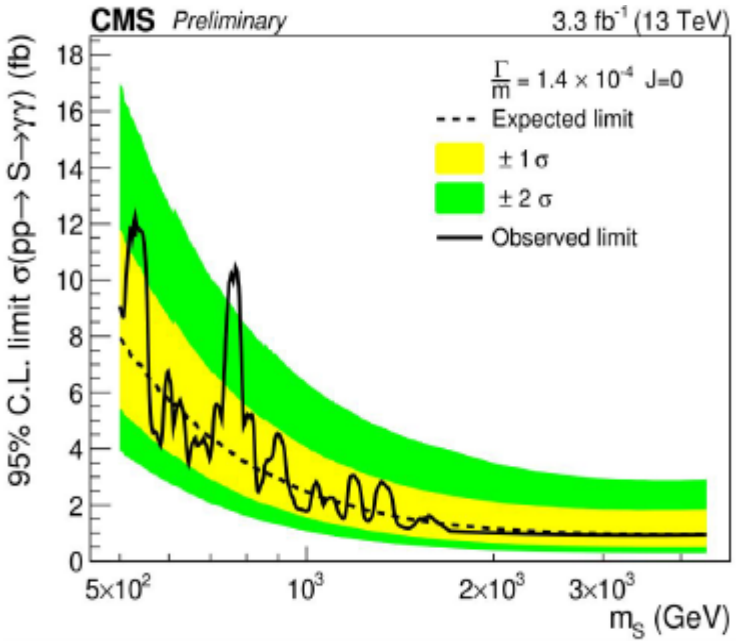
1γ in barrel, another in endcap region

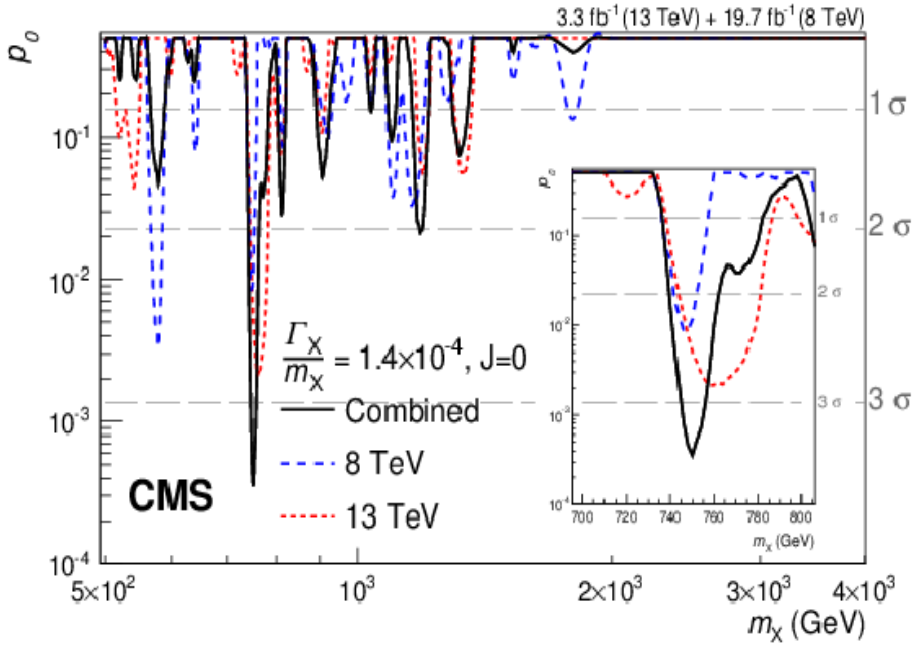


- Total 2015 data analysed: 3.3 fb^{-1} (B=3.8T, 0T)
- Consistent with 8 TeV data: 19.7 fb^{-1}
- Local significance = 3.4σ,
- Global significance (accounts for mass range, spin, width) = 1.6 σ

- Search for spin 0, spin-2 resonance,
- mass between 500 GeV to 4 TeV
- Γ/m between 1.4*10^{-4} to 5.6*10^{-2}

Limits





- Set limits assuming gg fusion, RS-graviton (spin 2)
- Excess observed at 750 GeV, for $\Gamma_X / m_X = 1.4*10^{-4}$

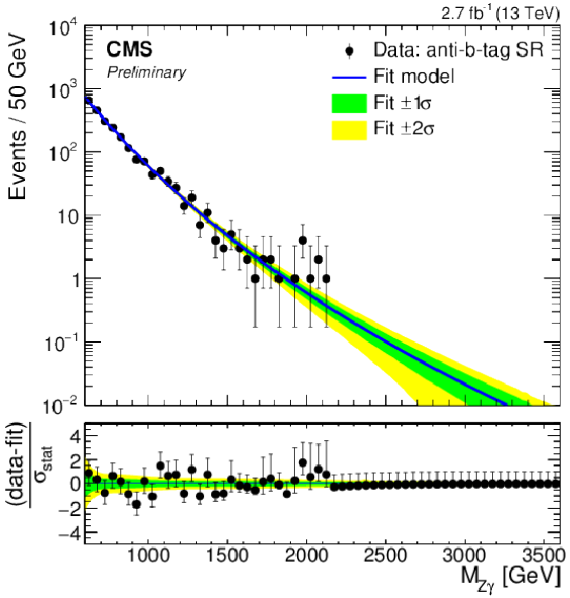
EXO-16-018

- More data required to confirm existence of resonance.
- 2016 data highly crucial.
- in August (ICHEP) : update with ~ 10 fb $^{-1}$

Results from some of the related searches

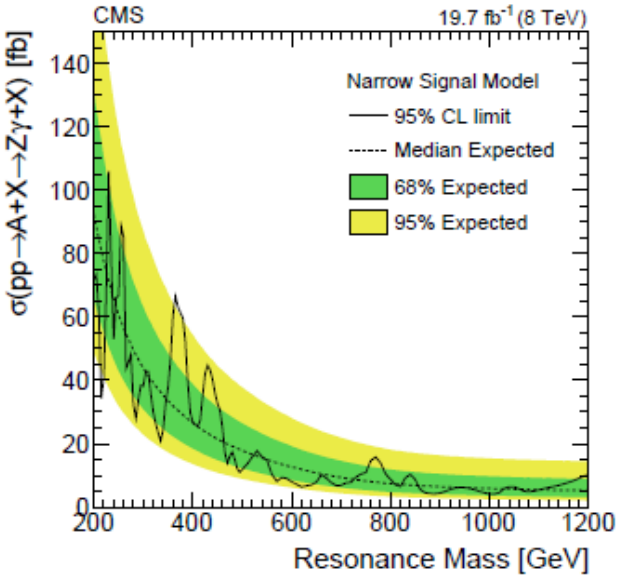
Z(qqbar)γ

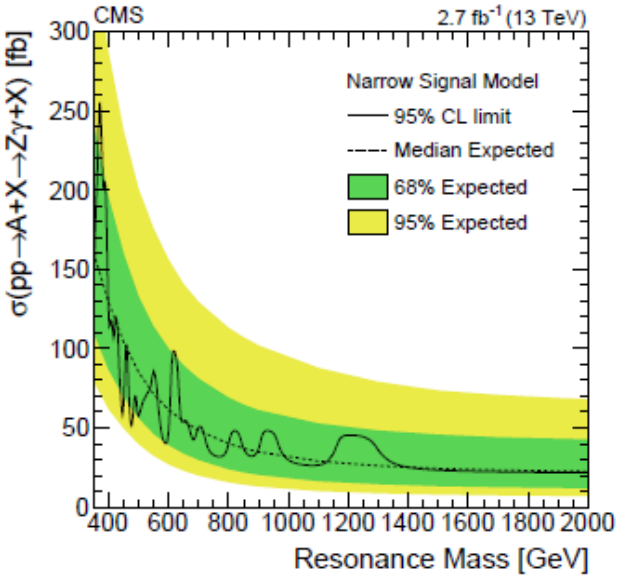
EXO-16-020

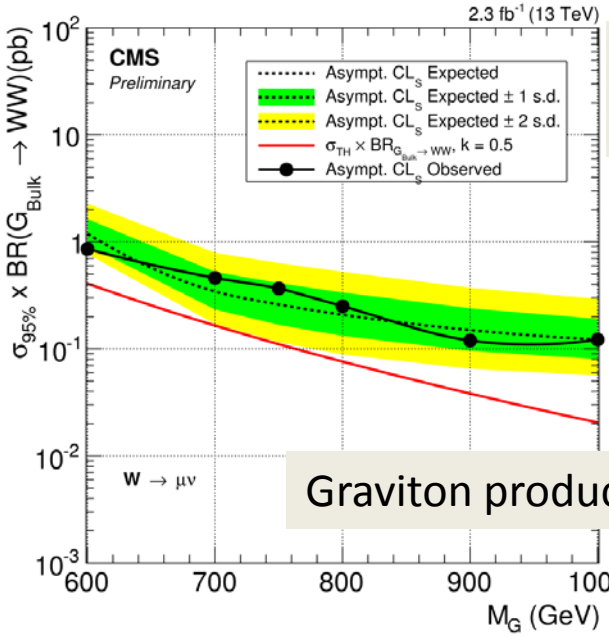


A (spin0) → Z(ll)γ

EXO-16-021





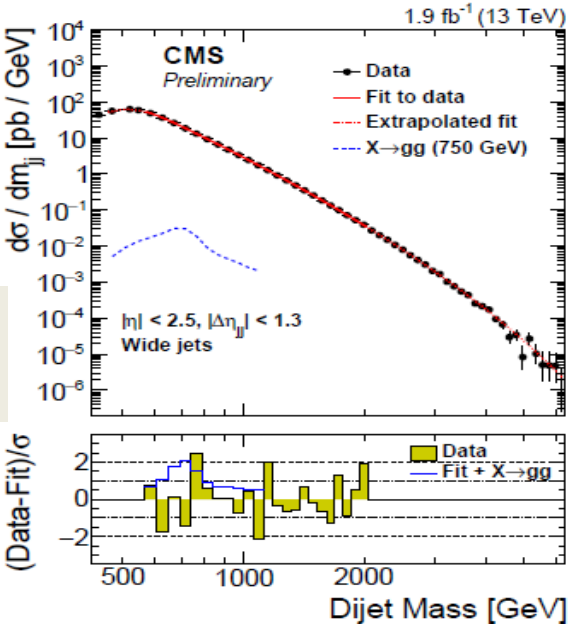


High mass search in WW→ lνqq

B2G-16-004

Graviton production in bulk?

dijet final state (scouting data)



Summary

- CMS experiment is performing well in Run 2.
- **Many new, interesting results at new energy regime continue to pour in. Could discuss only few.**
- Precision results using Run 1 data crucial for better understanding of LHC physics.
- Energy barrier for probing TeV scale physics is overcome

➔ exciting times ahead!

- **Data collected in 2016 is crucial to settle the issue of 750 GeV resonance.**

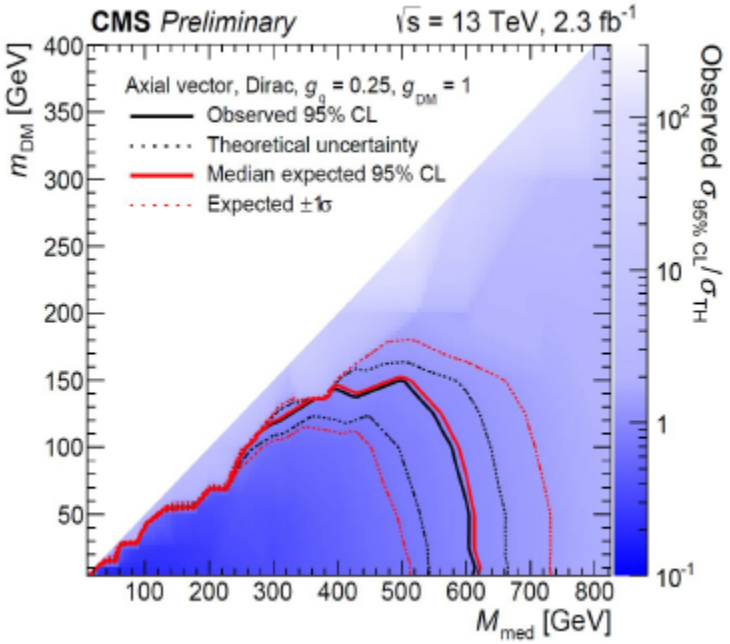
Stay tuned!

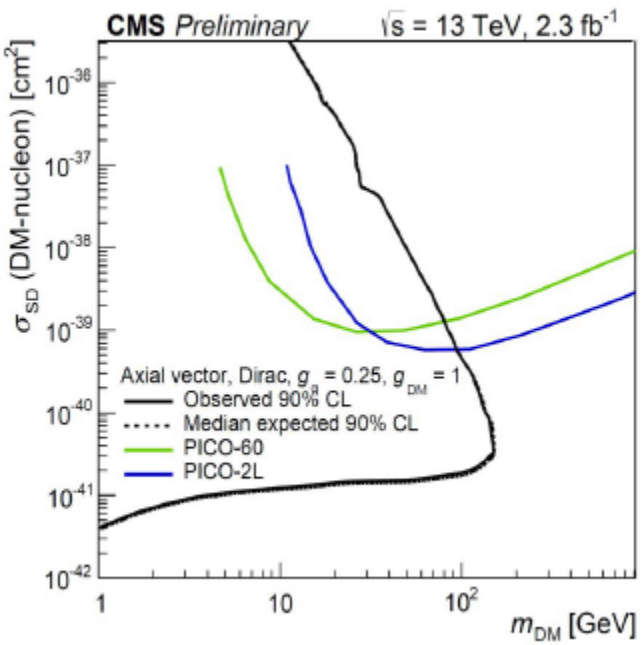
Back up

Production of Dark matter

1. lone production → search via initial state radiation ➔ mono-photon EXO-16-014

➔ Results interpreted in simplified model where DM produced in s-channel via heavy mediator



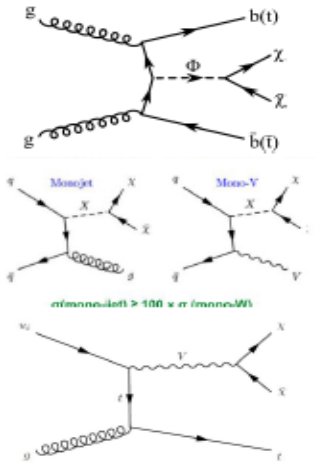


2. Associated productions

i) b(b), t(t) + MET B2G-15-007

ii) Monojet, Mono V : ExO-16-013

iii) Monotop : EXO-16-017



Other searches for X (750 GeV)

- **$pp \rightarrow X \rightarrow Z\gamma$** LH
  - **$ll\gamma$:** EXO-16-016 (13 TeV), HIG-16-014 (8 TeV), EXO-16-021 (8+13 TeV combination)
  - **$qq\gamma$:** EXO-16-020
- **$pp \rightarrow X \rightarrow ZZ$**
  - **4 lepton:** HIG-15-004
  - **2l 2ν:** HIG-16-001
- **$pp \rightarrow X \rightarrow ZH(125)$**
  - H(125) → bb: B2G-16-003
- **$pp \rightarrow X \rightarrow HH$**
  - **bbbb:** HIG-16-002
  - **$bb\tau\tau$:** HIG-16-013 (13 TeV), HIG-15-013 (8 TeV)
  - **WWbb:** HIG-16-011
- **$pp \rightarrow X \rightarrow WW$**
  - **lνqq:** B2G-16-004
- **$pp \rightarrow X \rightarrow t\bar{t}$**
  - **Semileptonic:** B2G-15-002
  - **All-hadronic:** B2G-15-003