Experimental results from CMS

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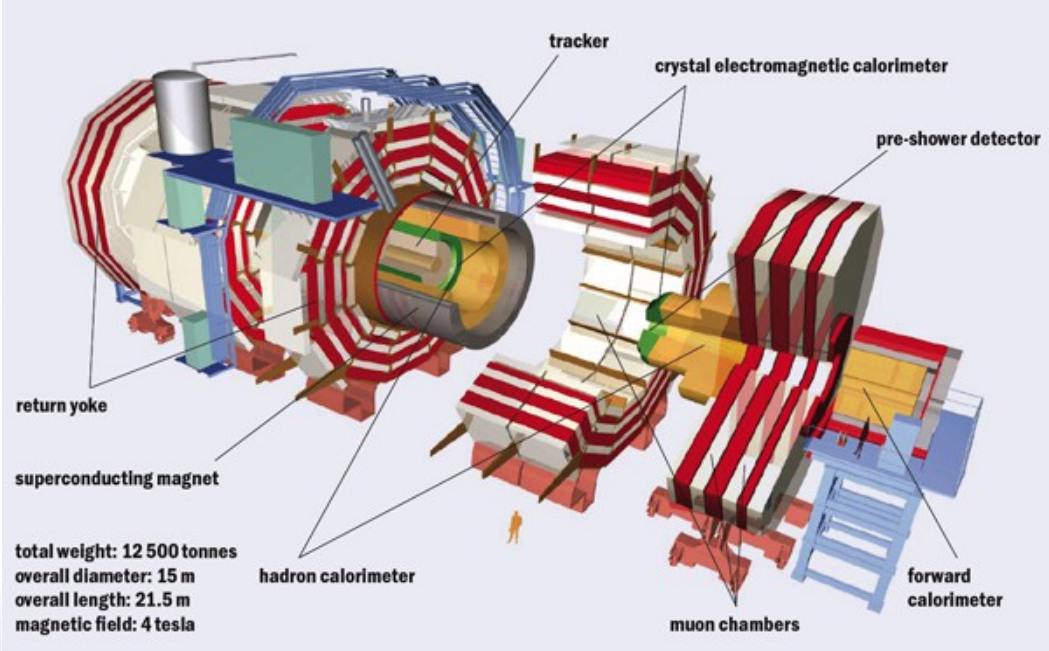
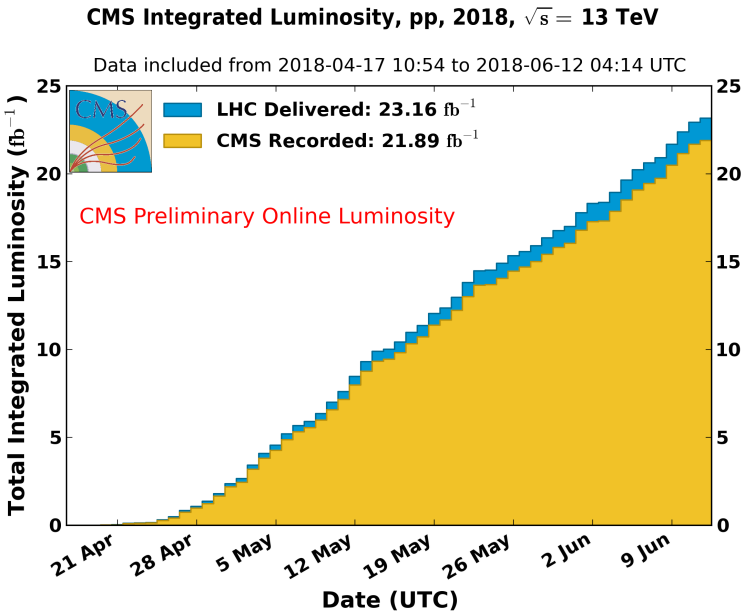
for the CMS collaboration

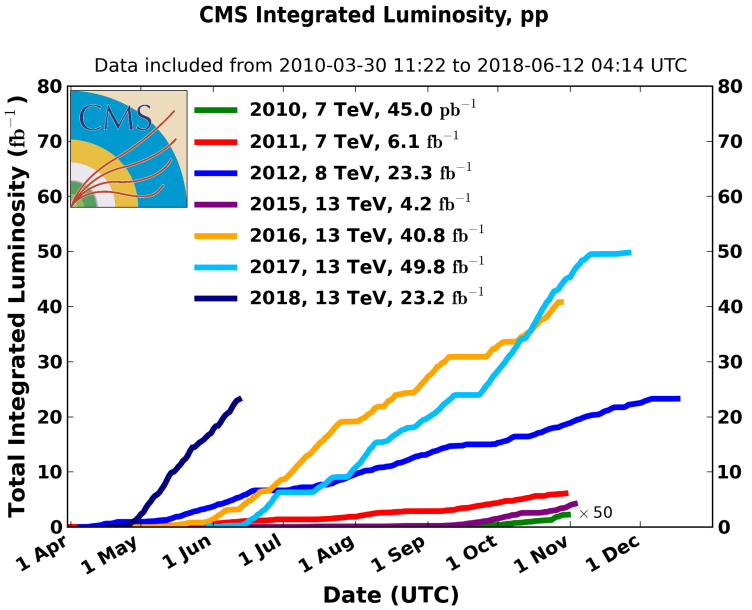
QCD@Work-18, Matera Italy
June 28, 2018

The CMS experiment at LHC



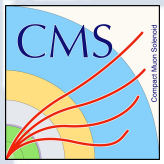
- Silicon pixel + strip tracker
- 3.8 T magnet
- Lead/Tungstate EM calorimeter
- Brass/Scintillator Had calorimeter
- Muon system embedded in return yoke





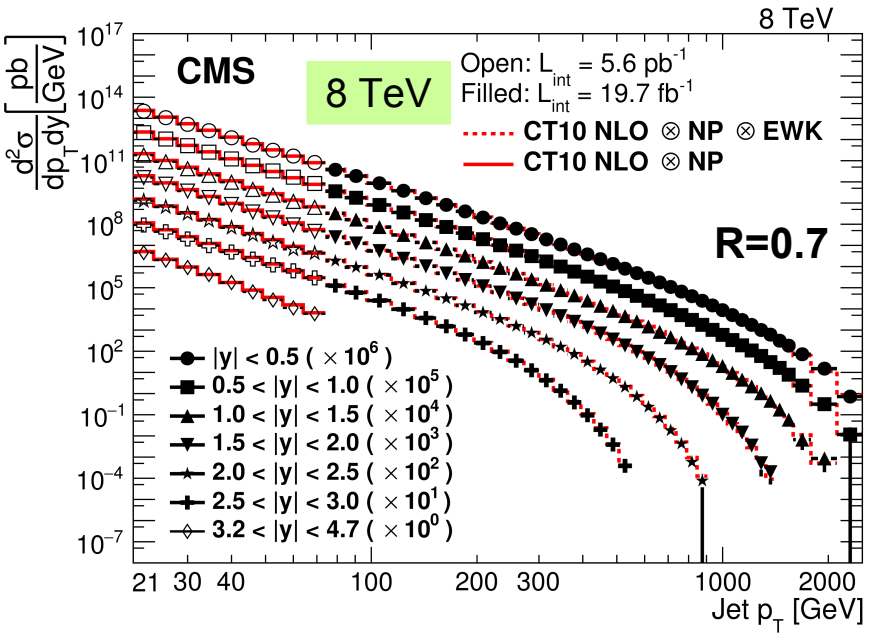
Presenting today

- Mostly recent results, plus legacy QCD multi-jet results
- QCD multi-jets
- Top physics
- Higgs
- Heavy-Ion and small-x
- B physics
- Exotic physics and SUSY

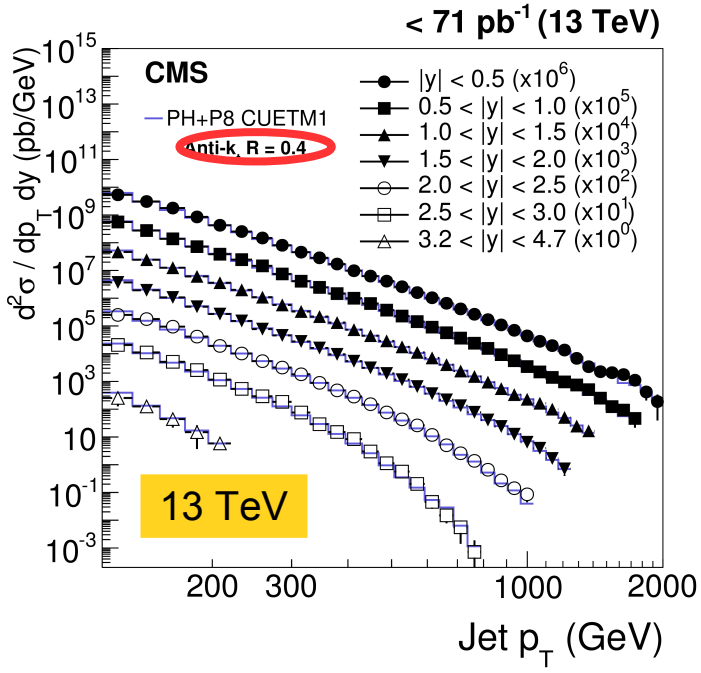


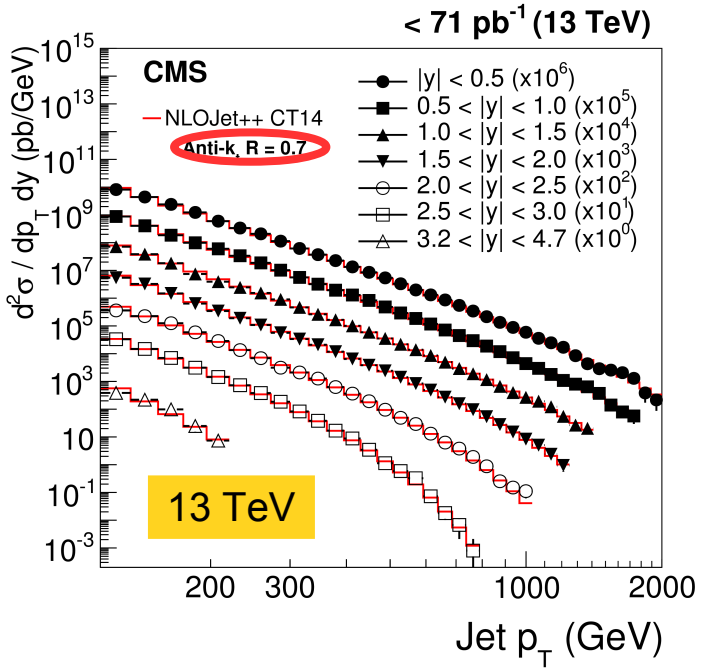
QCD multi-jet physics

Inclusive jet cross section (8 TeV and 13 TeV)



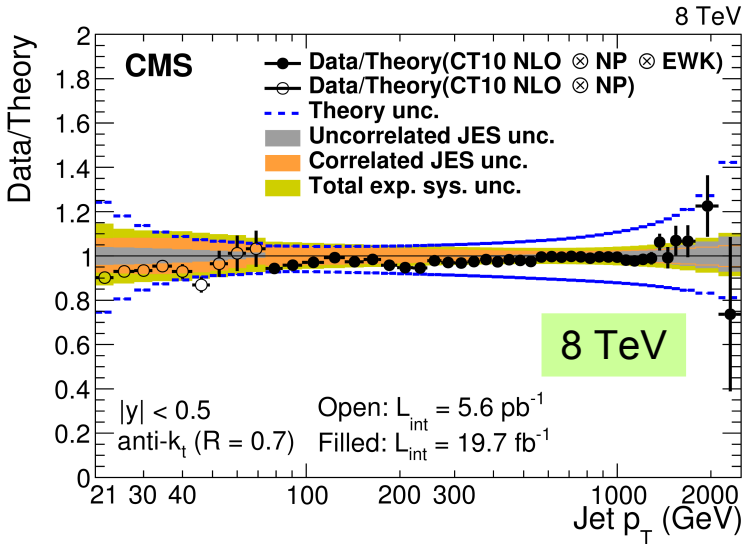
JHEP 03 (2017) 156



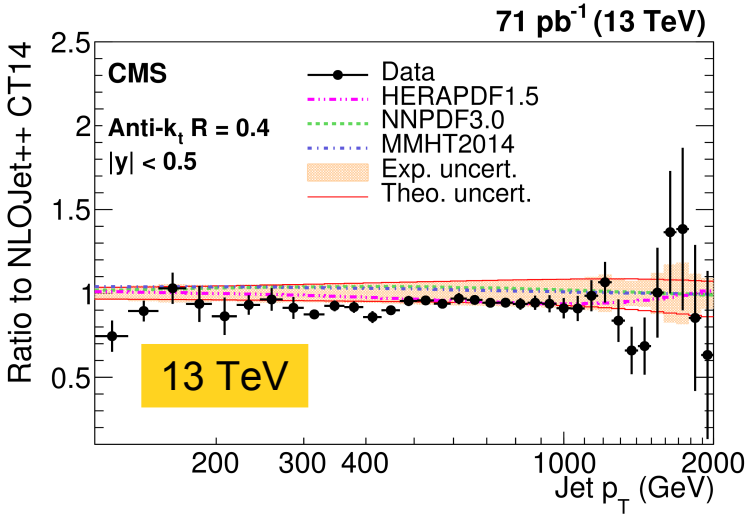


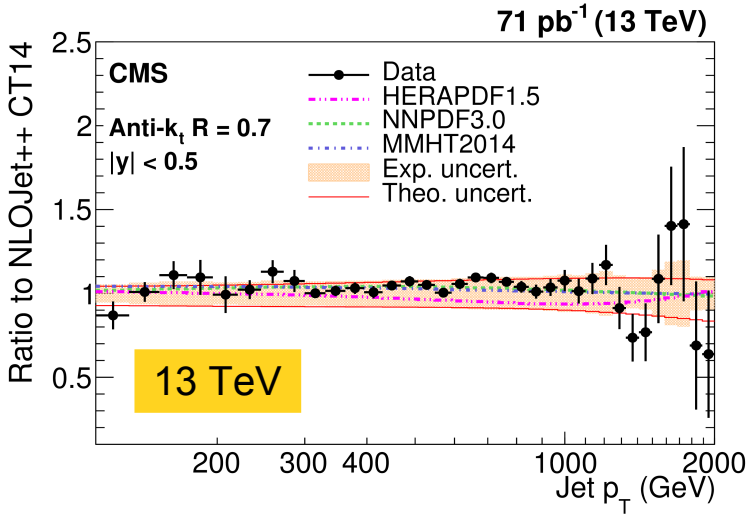
EPJC 76 (2016) 451

Inclusive jet cross section (8 TeV and 13 TeV)
– ratios with theory for |y|<0.5



JHEP 03 (2017) 156

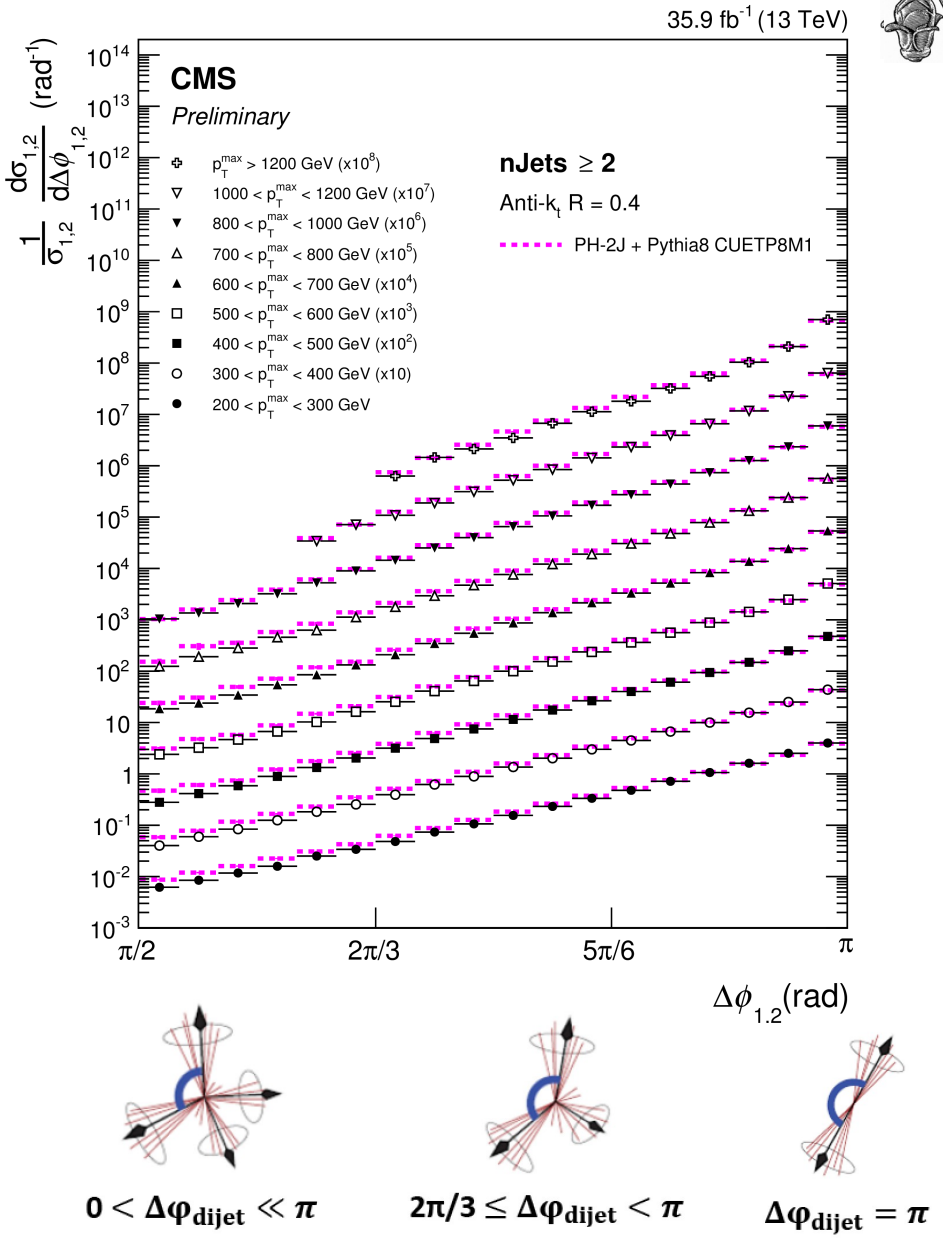




EPJC 76 (2016) 451

Azimuthal jet correlations (13 TeV)

- 13 TeV, 35.9 fb^{-1} , single-jet triggers
- Particle-flow jets, Anti-k$_T$ reco, R=0.4
  - Inclusive 2-jet, 3-jet, 4-jet analyses
- Leading jet p$_T$ >200 GeV (others >100 GeV) and all leading jets per analysis have |y|<2.5 (others <5)
- Normalized cross section: reduction of theoretical and experimental uncertainties
- Observables: $\Delta\varphi_{1,2}$ between leading two jets (2j, 3j, 4j) and $\Delta\varphi_{min}$ between any two jets (3j, 4j)
- Experimental systematic JES (<2%), JER (<1%), unfolding (~0.2%)
- Unfold to particle-level jets ala d'Agostini
- Theoretical predictions: LO: Pythia8, Herwig++, Madgraph+Pythia8, NLO: Powheg (2J and 3J) and Herwig7

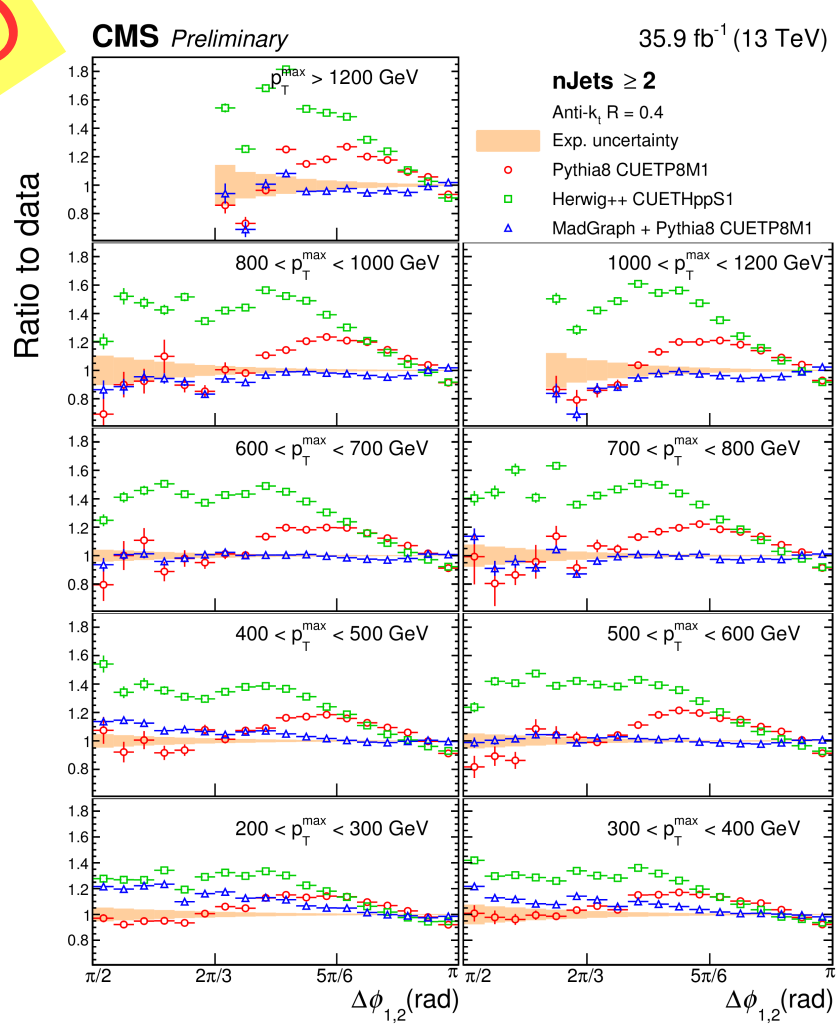


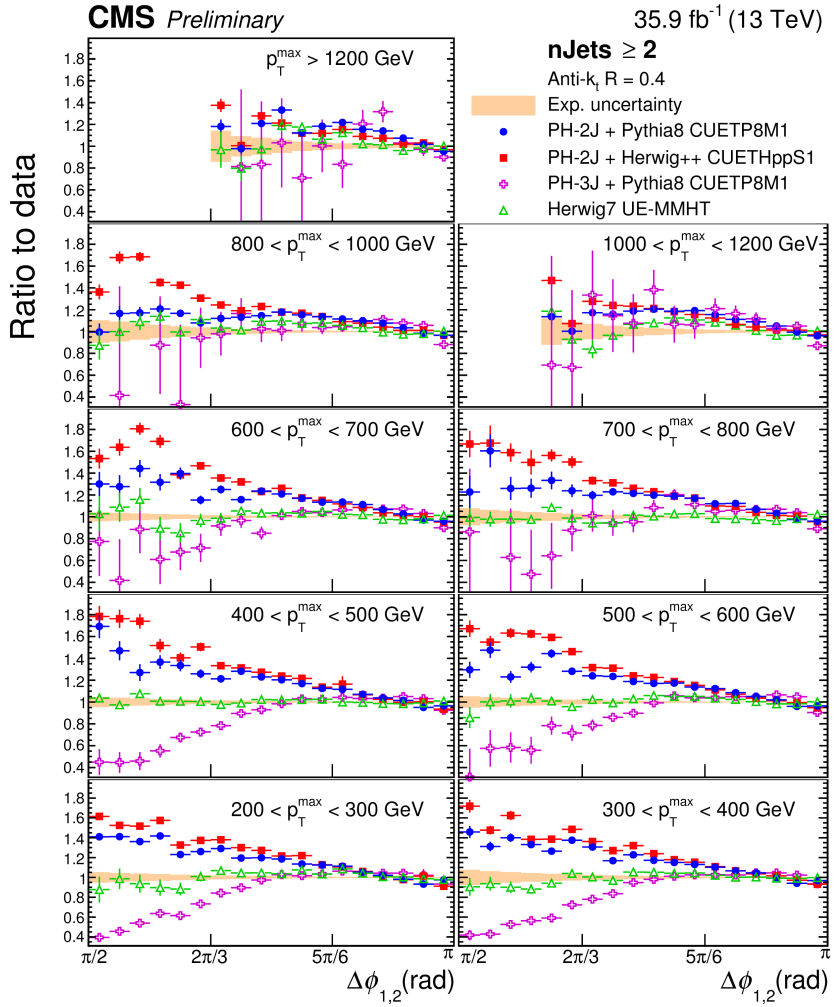
CMS-PAS-SMP-16-014

Azimuthal jet correlations ($\Delta\varphi_{1,2}$) ≥2 jets

LO

NLO



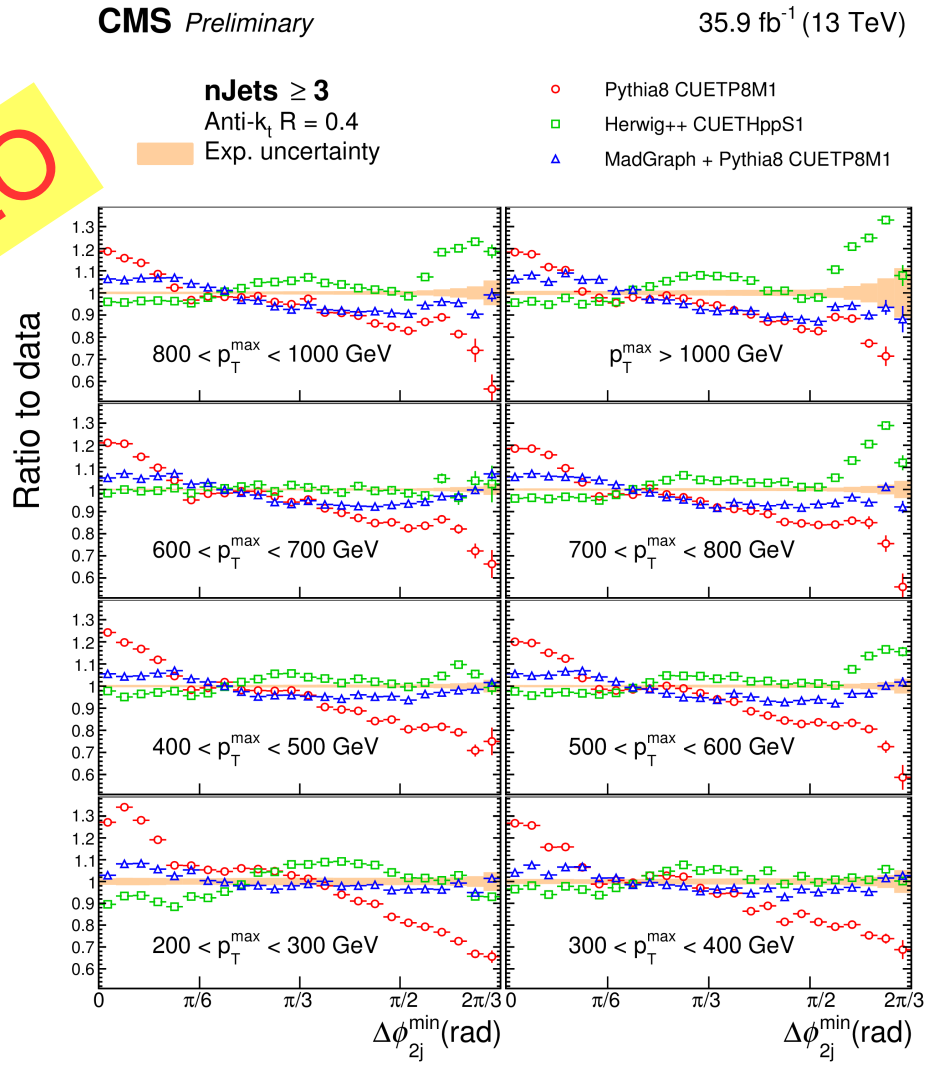


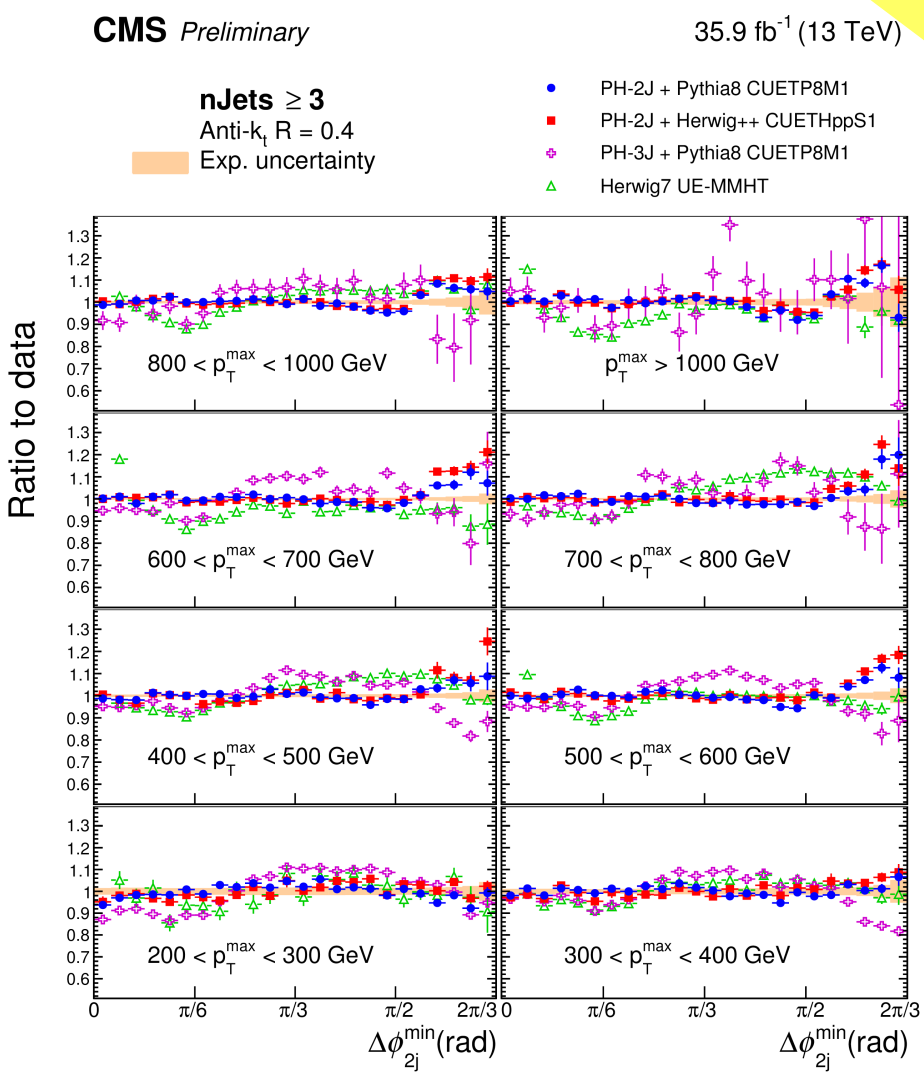
- From the LO generators, Madgraph+Pythia describes the data the best
- From NLO generators, Herwig7 describes data

Azimuthal jet correlations ($\Delta\varphi_{min}$) ≥3 jets

LO

NLO

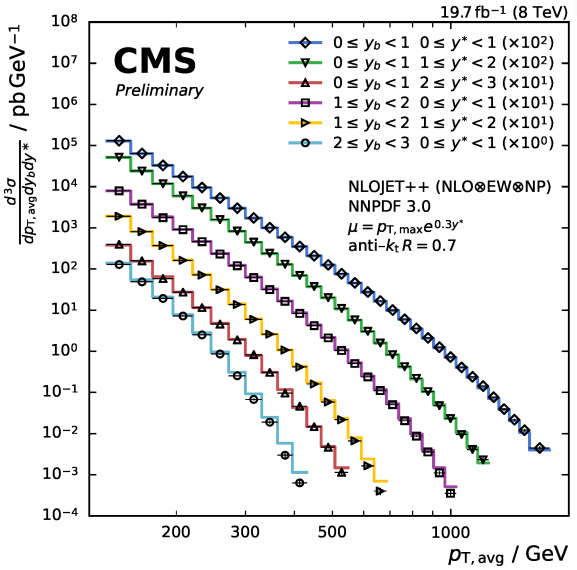


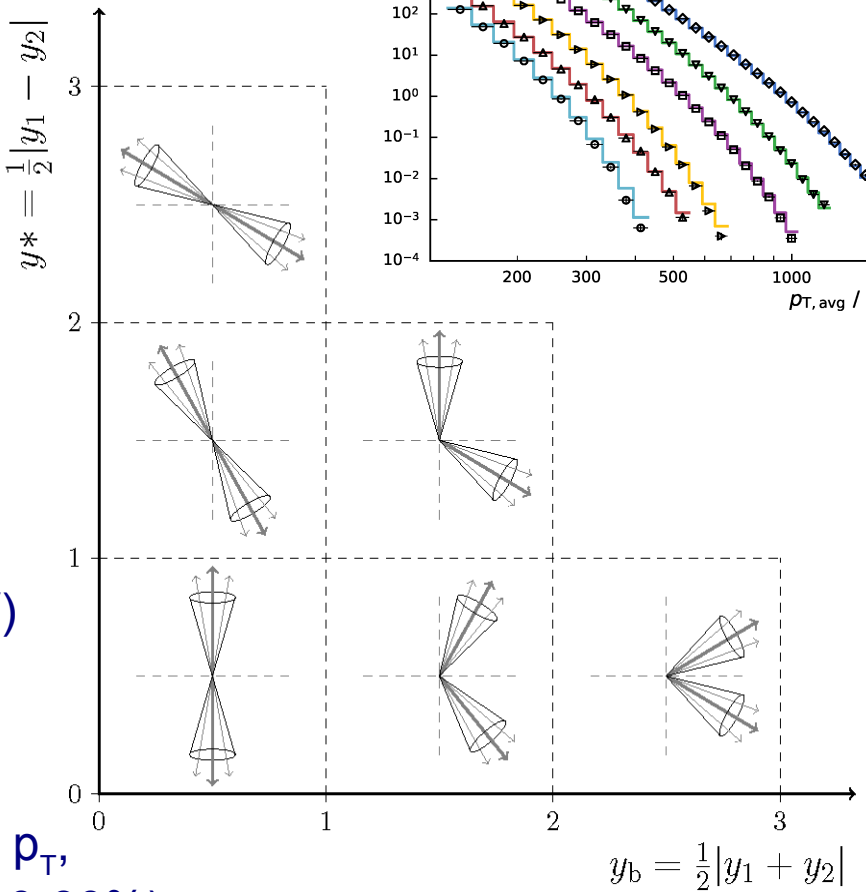


- From the LO generators, Herwig++ best for 3j and 4j, Pythia8 4j only
- From NLO generators PH2J (matched to Herwig++ or Pythia8) describes data best

Triple differential dijet cross section (8 TeV)

- 8 TeV, 19.7 fb^{-1}, single-jet triggers
- Dijet differential cross section as a function of 3 variables
  - Average momentum of jets $p_{T,ave} \equiv (p_{T,1}+p_{T,2})/2$
  - $y_B \equiv ½ |y_1 + y_2|$
  - $y^* \equiv ½ |y_1 - y_2|$
- Large boosts sensitive to higher values of x for one of the partons
- Particle-flow jets, Anti-k_T reco, R=0.7
- Leading two jets >50 GeV, with |y|<3
- Toy MC for response matrix (smeared with p_T resolution 8% @ 100 GeV)
- Major exp systematics: JEC (2.5%-12% forward), Lumi (2.6%), JER (1-2%)
- Major theoretical systematics: scales at low p_T, **PDF at high p_T esp. high boosts** (2% → 10-30%)



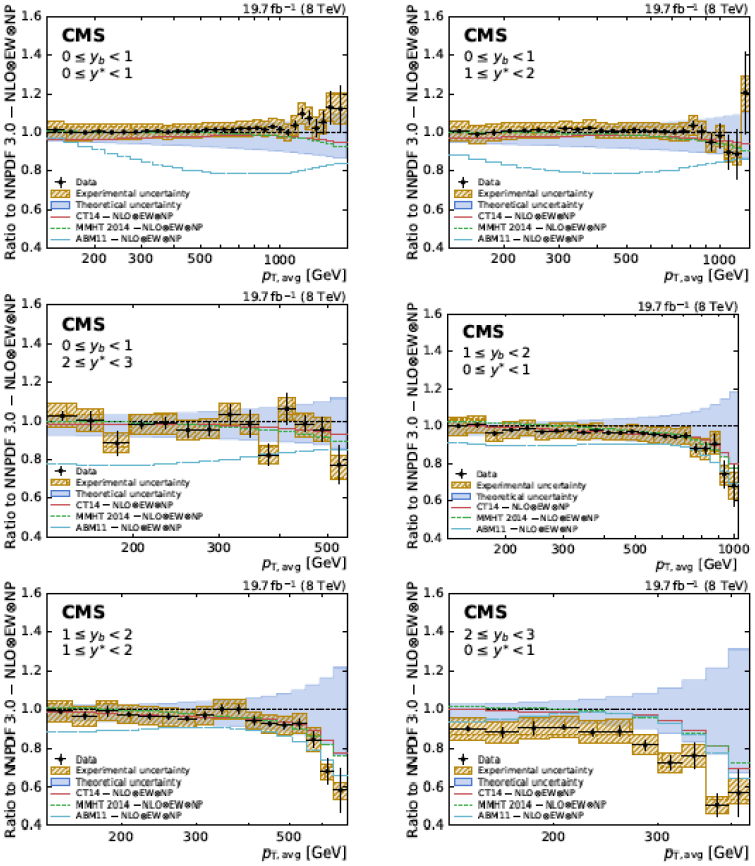


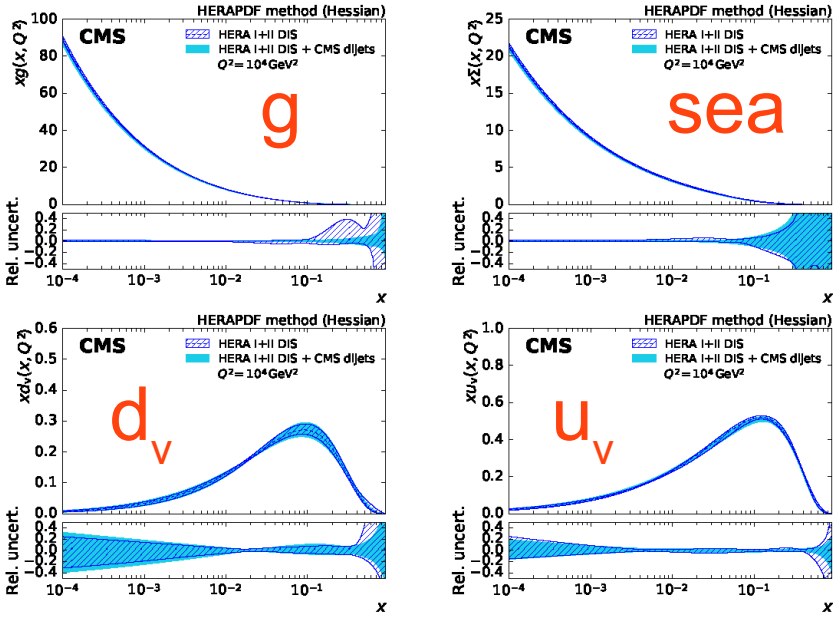
Triple differential dijet cross section (8 TeV)

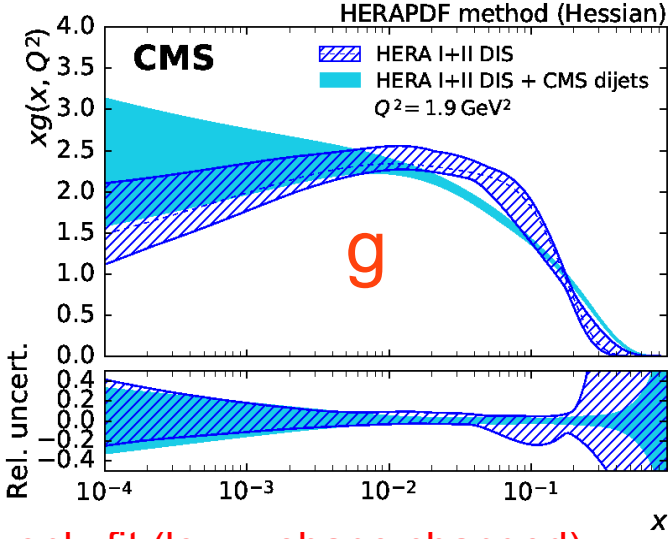
EPJC **77** (2017) 746

Theory: NLOJet++ with FastNLO framework and NP&EW corrections

Generators: Herwig7 better in central region, Powheg better forward



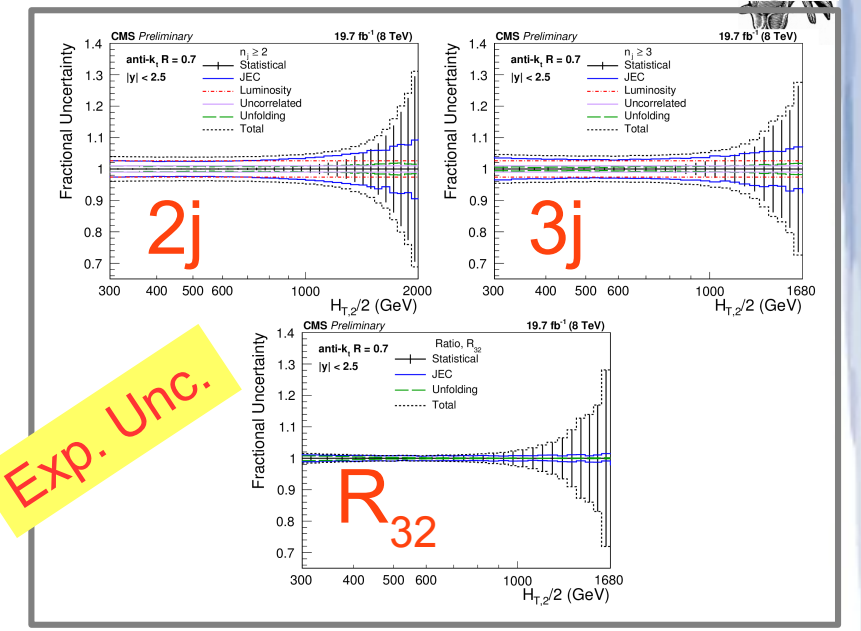




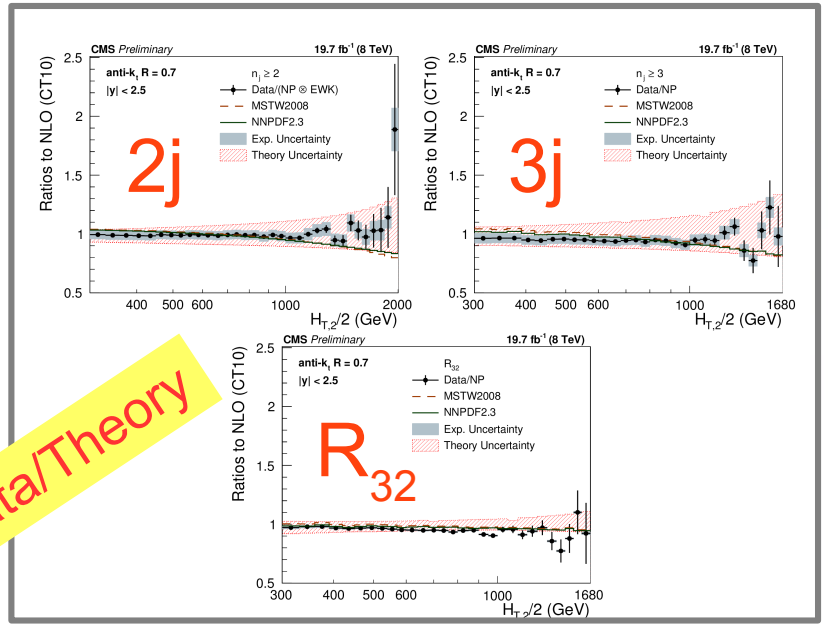
- High-p_T and particularly high boosts are not described well by NLO (with NP and EW corrections)
  - Sensitive to PDF uncertainty
- Fits to PDFs (16 parameters) constrain PDF
  - Gluon PDF uncertainty reduced compared to DIS-only fit (low-x shape changed)
- $\alpha_S(M_Z) = 0.1199 \pm 0.0015\,(\text{exp}) \pm 0.0002\,(\text{mod})\ ^{+0.0002}_{-0.0004}(\text{par})\ ^{+0.0031}_{-0.0019}(\text{scale, refit})$

α_S with inclusive multijets (8 TeV)

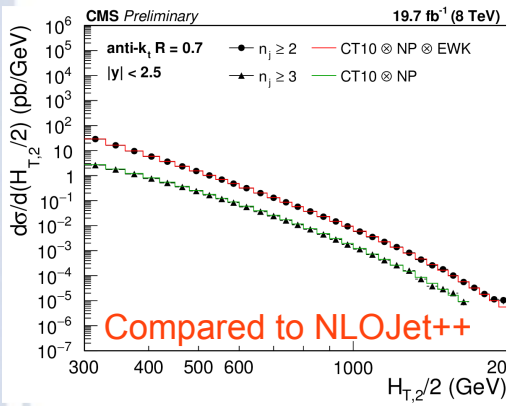
- 8 TeV, 19.7 fb^{-1}, single-jet triggers
- Inclusive 2 jet and 3 jet and ratio R_{32}
  - As a function of $H_{T,2}/2 \equiv \frac{1}{2}(p_{T,1} + p_{T,2})$
- PF jets anti-k_T reco, R=0.7
- At least 2 jets with p_T>150 GeV, |y|<2.5
- Analysis cuts and unfolding as previous analysis
- R_{32} has low systematics; it's used for α_S fit
  - Scale (2-6%), PDF (2-7%), NP (1%)

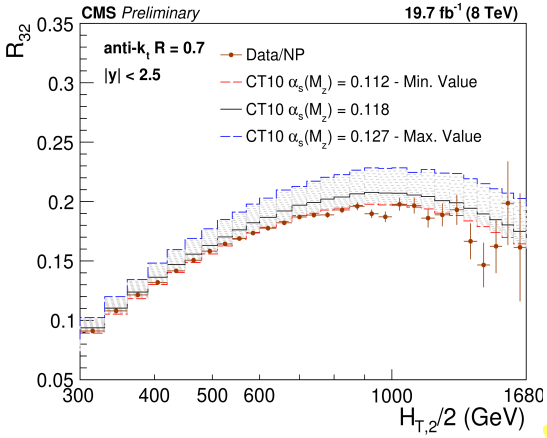


Exp. Unc.



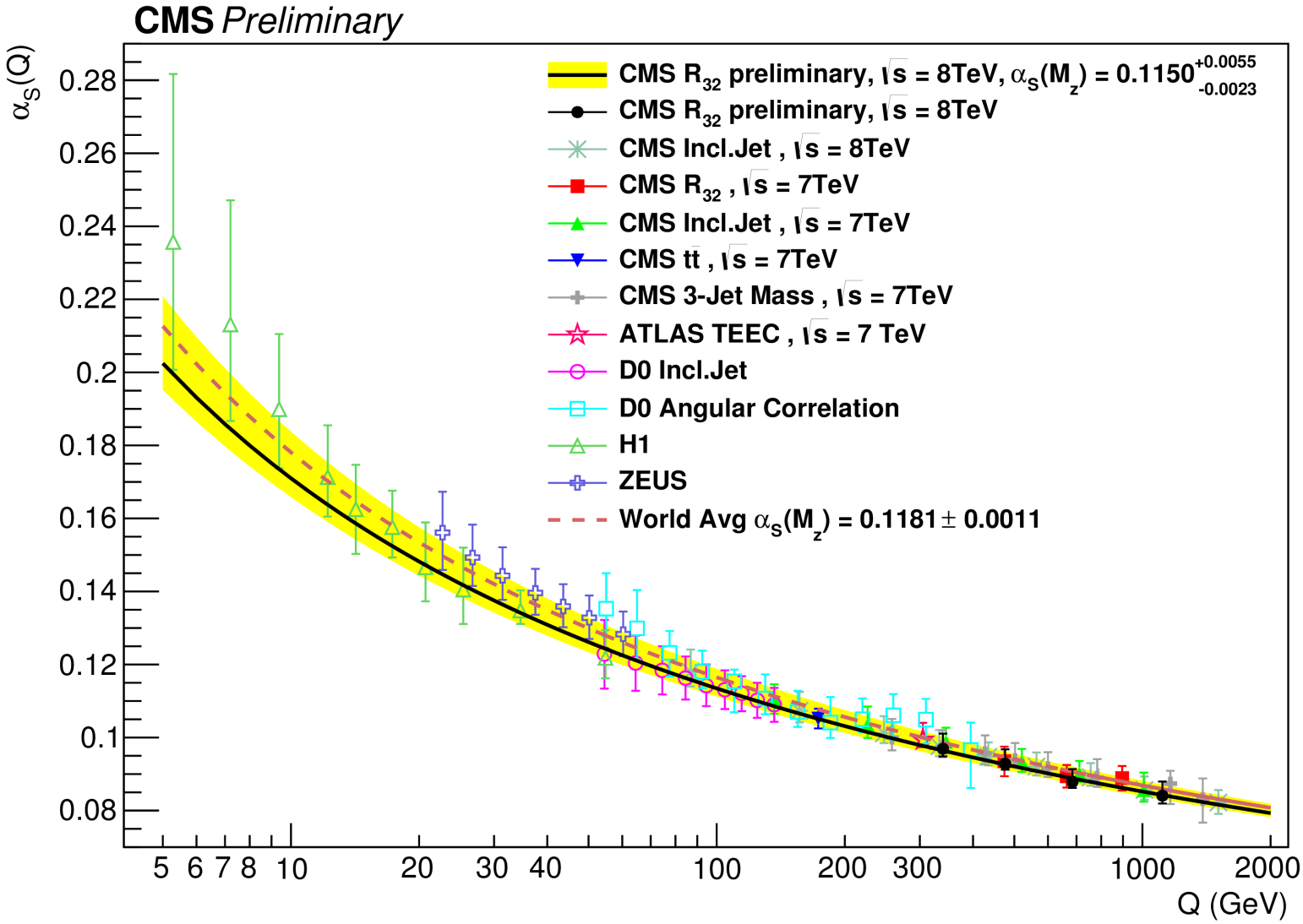
Data/Theory





CMS-PAS-SMP-16-008

Measurement of α_s with inclusive multijets

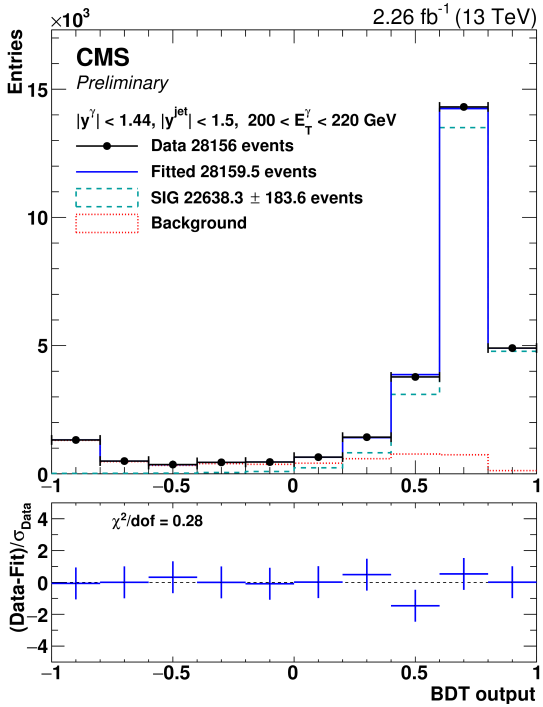


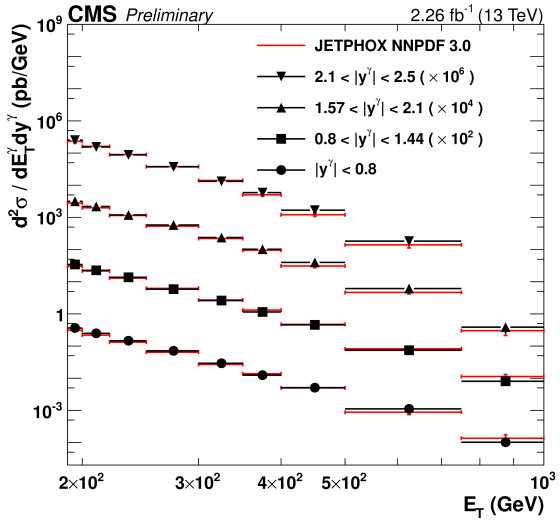
- $\alpha_S(M_Z) = 0.115 \pm 0.0010\,(\text{exp}) \pm 0.0013\,(\text{PDF}) \pm 0.0015\,(\text{NP})^{+0.0050}_{-0}(\text{scale})$
  $= 0.115 \pm 0.0023\,(\text{all except scale})^{+0.0050}_{-0}(\text{scale})$

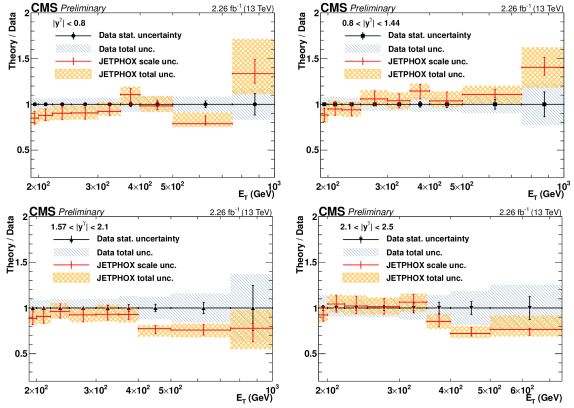
Differential cross sections of inclusive gamma and gamma+jets

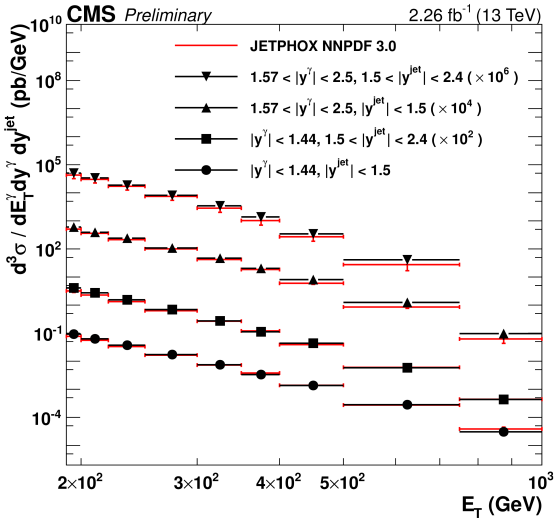
June

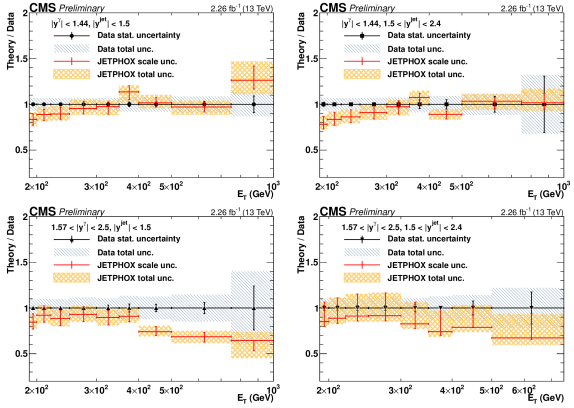
CMS-PAS-SMP-16-003











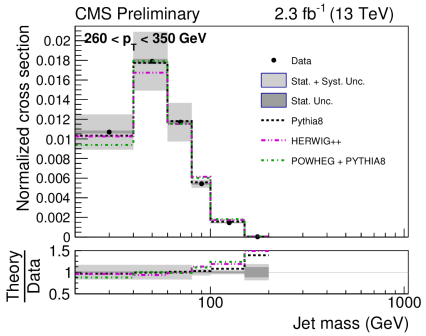
- 13 TeV, 2.26 fb^{-1}
- Extraction of signal from BDT (eta, phi, energy of photons and shapes of shower)
- Inclusive photon double differential and γ+jet triple differential results agree with NLO-in-QCD JetPhox

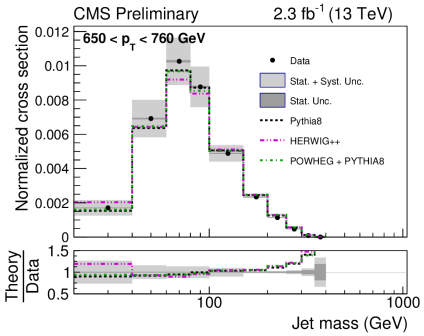
Jet mass (distributions)

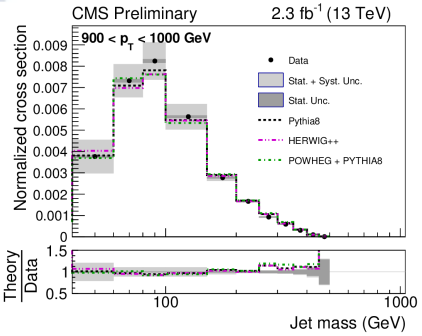
CMS-PAS-SMP-16-010

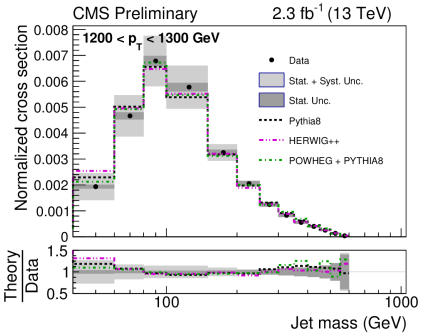
Ungroomed

(unfolded)



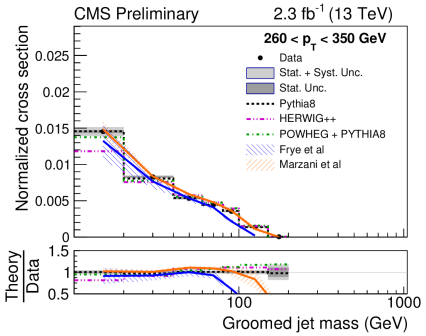


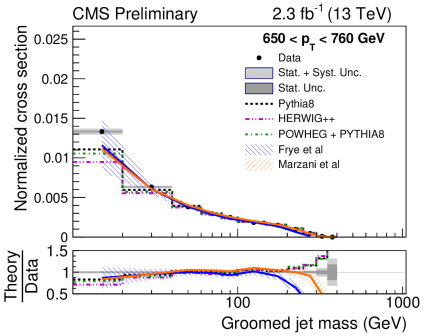


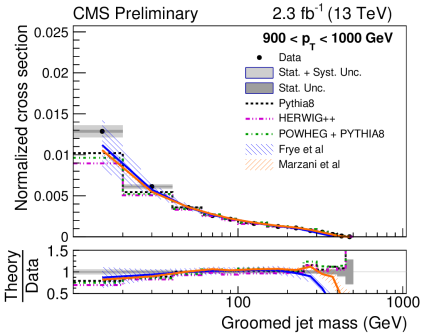


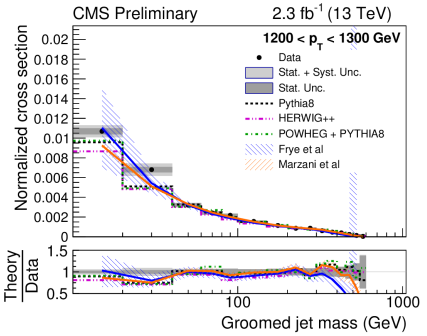
Groomed

(unfolded)









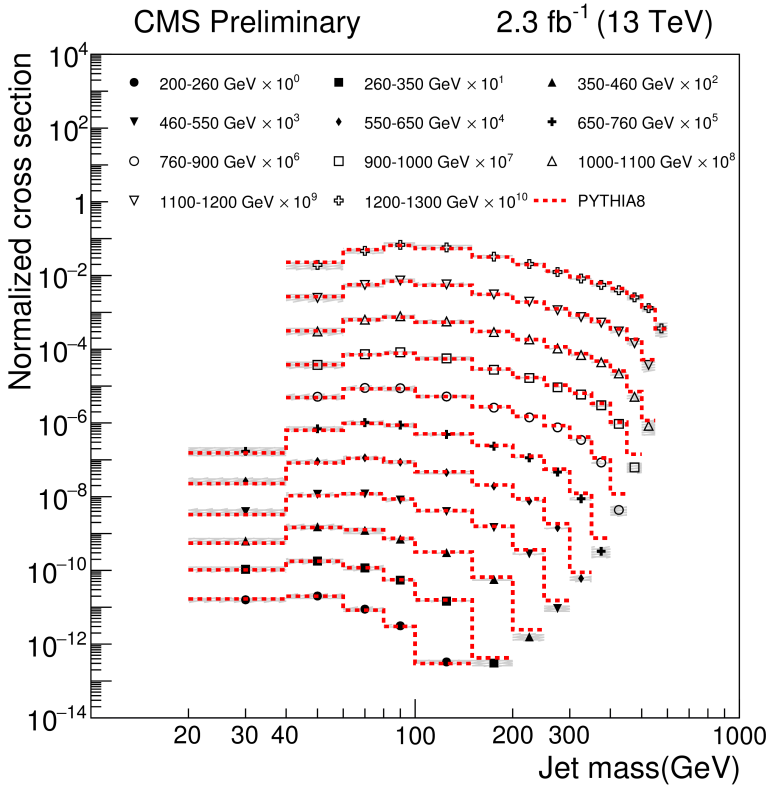
- 13 TeV, 2.3 fb^{-1}, inclusive two anti-k_T jets, ΔR=0.8, >200 GeV, $|\eta|$<2.4
- Results for groomed and ungroomed jets (to study effects of soft QCD)
- Unfolding in both pT and m – Softdrop without filtering/pruning/trimming

Jet mass (cross sections)

CMS-PAS-SMP-16-010

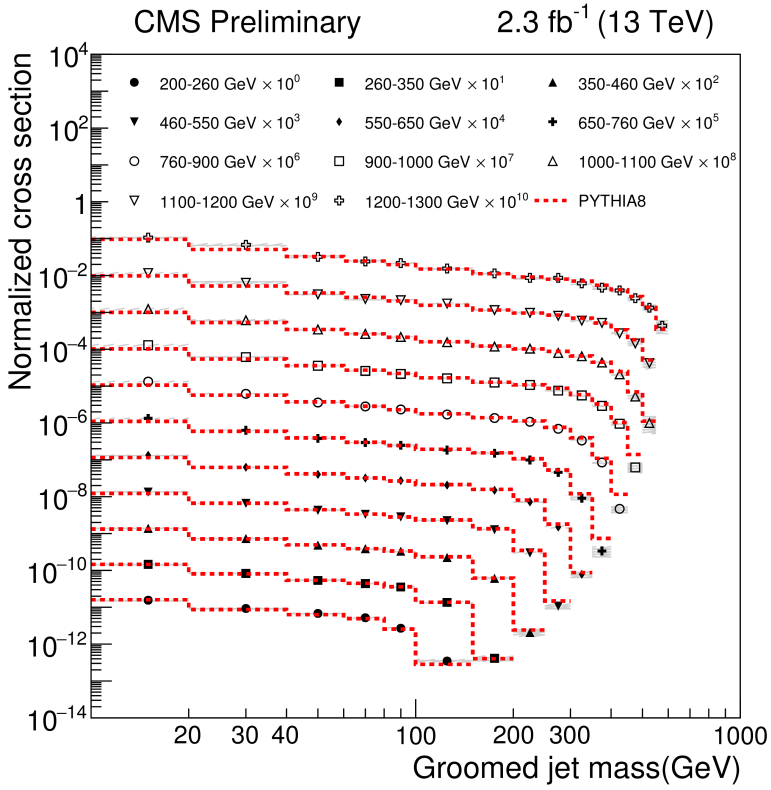
Ungroomed

(unfolded)



Groomed

(unfolded)



- 13 TeV, 2.3 fb^{-1}, inclusive two anti-k_T jets, ΔR=0.8, >200 GeV, $|\eta|$<2.4
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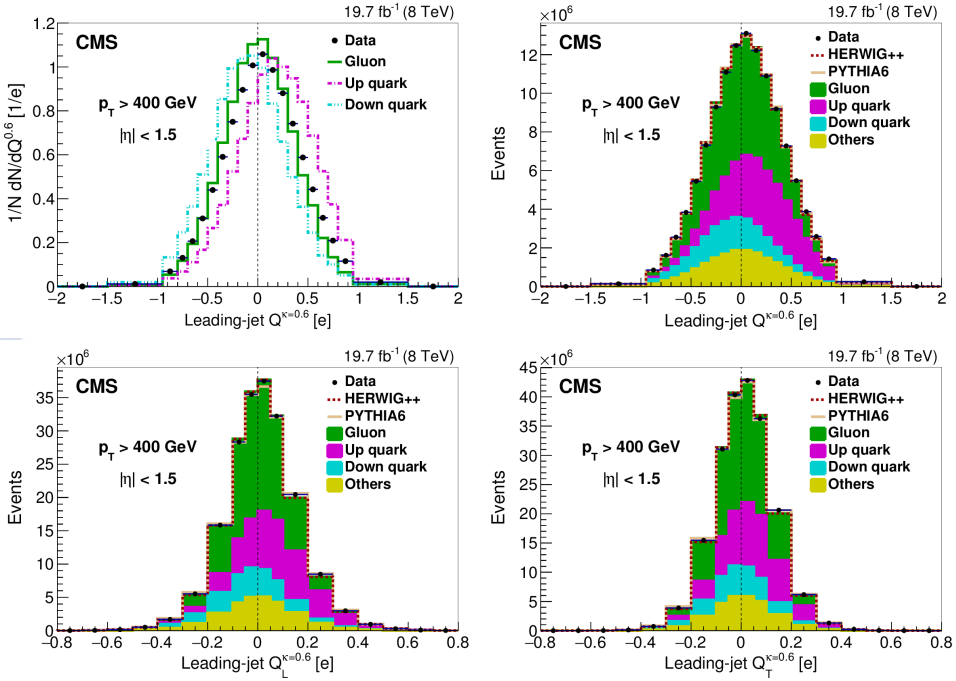
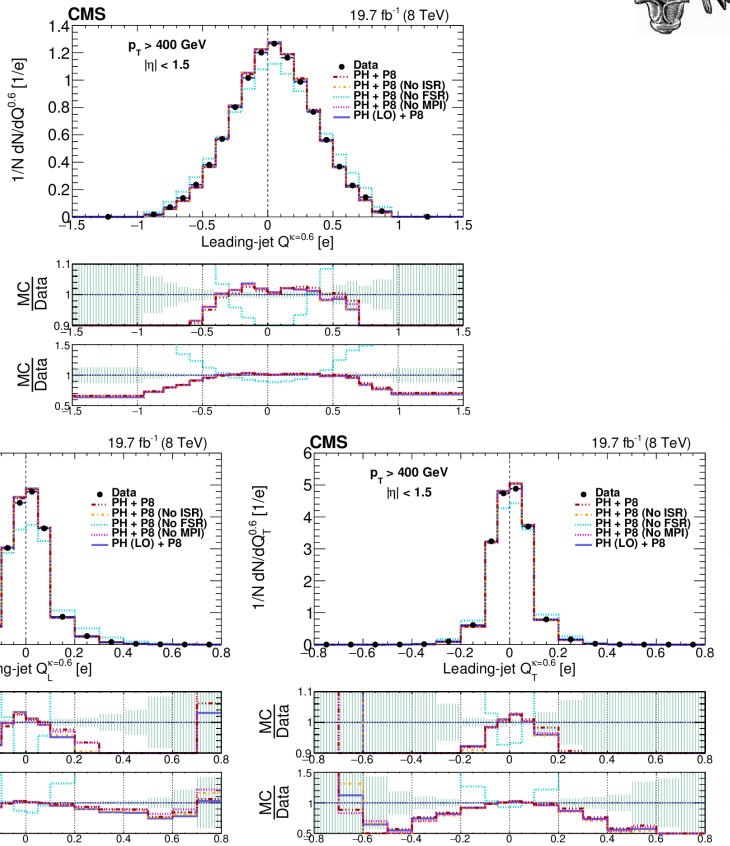
- Unfolding in both pT and m – Softdrop without filtering/pruning/trimming

Measurement of jet charge

JHEP **10** (2017) 131



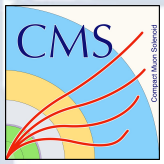


- 8 TeV, 19.7 fb^{-1} – measurement helps understand parton showering and hadronization
- Dijet events, ΔR=0.5, >400 GeV, 100 GeV, |η|<1.5
- Unfolded results as a function of leading jet-p_T

$$Q^{\kappa} = \frac{1}{(p_{\mathrm{T}}^{\mathrm{jet}})^{\kappa}} \sum_i Q_i (p_{\mathrm{T}}^i)^{\kappa},$$

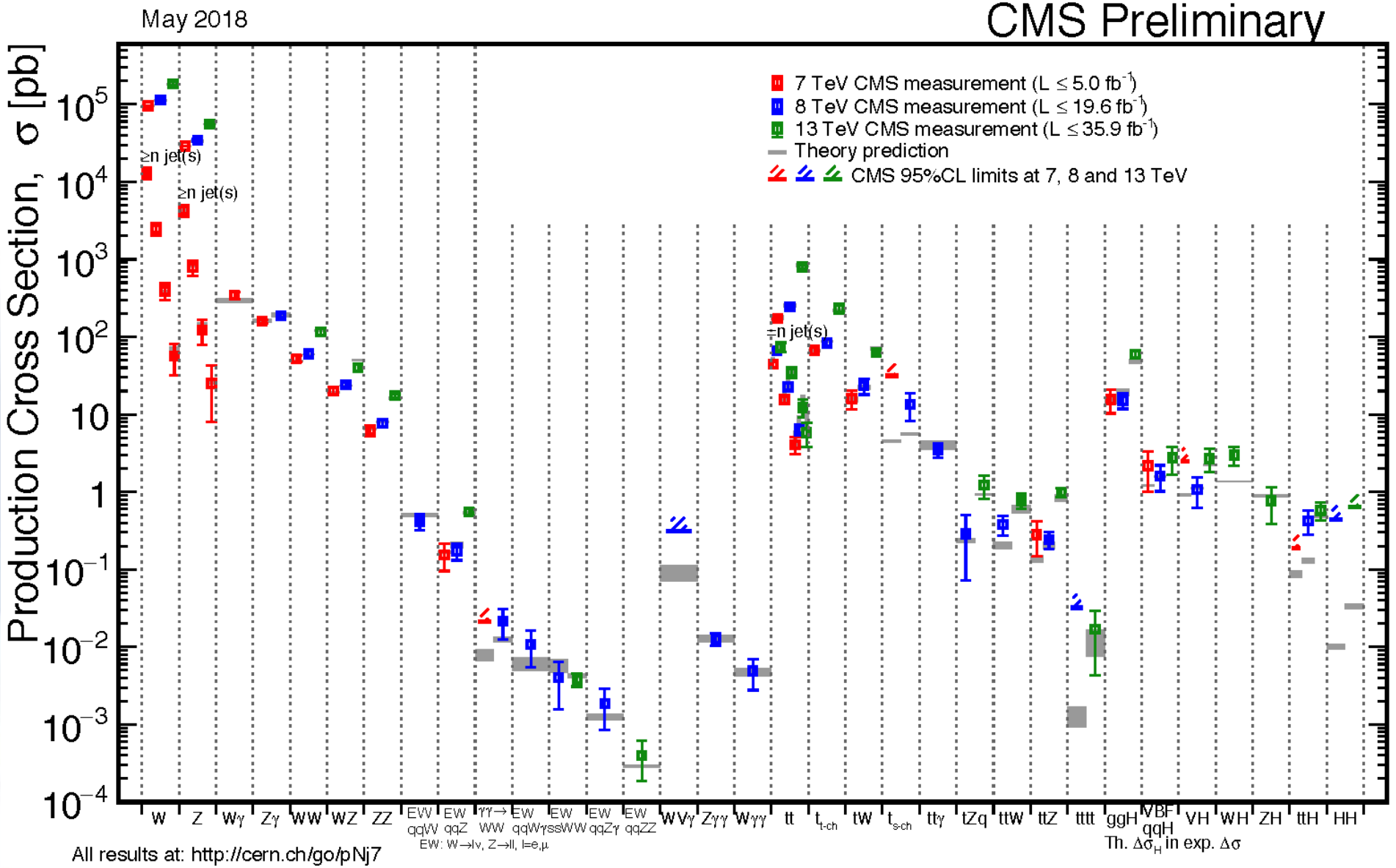
$$Q_L^{\kappa} = \sum_i Q_i \left(p_{\parallel}^i\right)^{\kappa} \Big/ \sum_i \left(p_{\parallel}^i\right)^{\kappa}$$

$$Q_T^{\kappa} = \sum_i Q_i \left(p_{\perp}^i\right)^{\kappa} \Big/ \sum_i \left(p_{\perp}^i\right)^{\kappa}$$

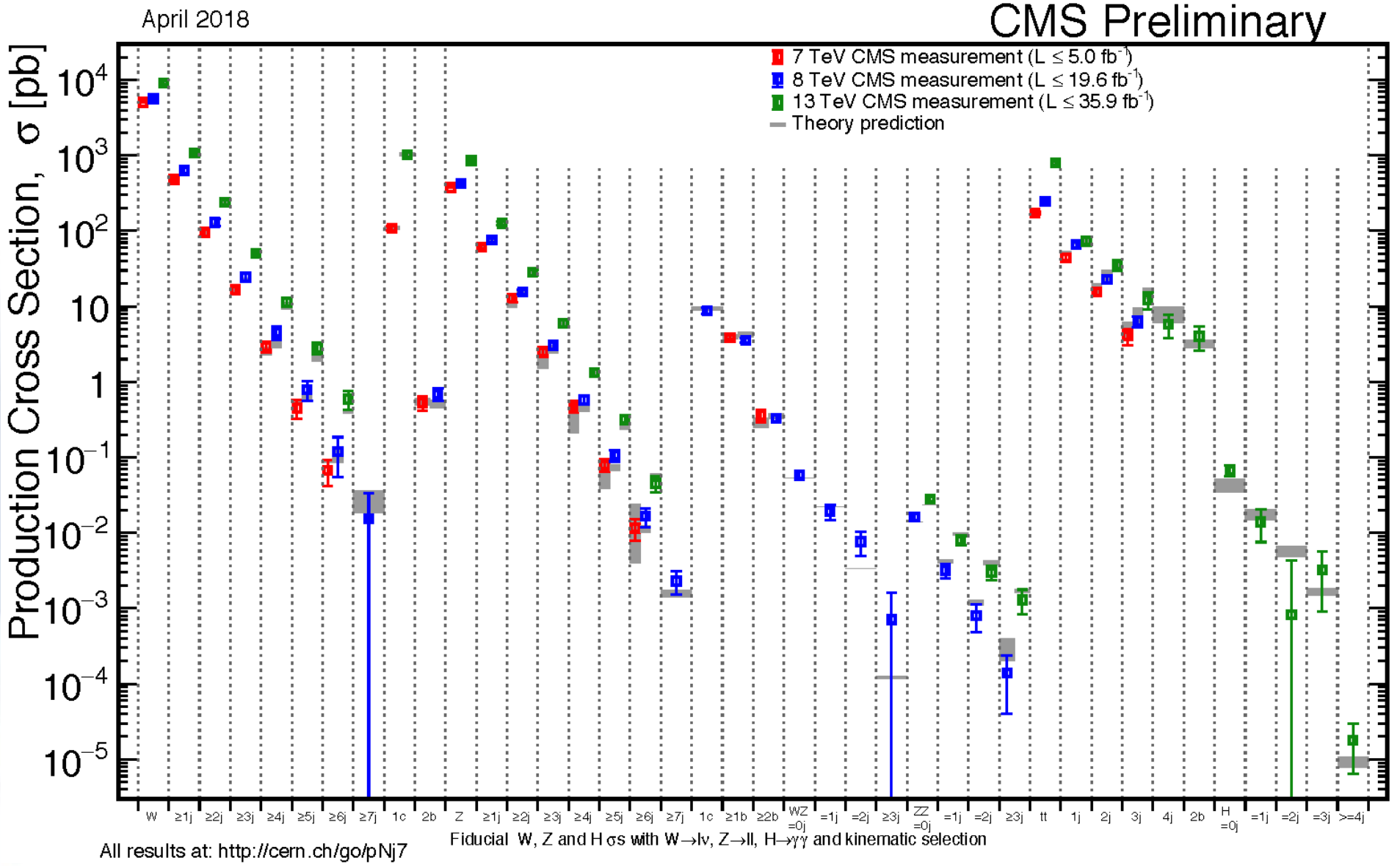


Overview of SM cross sections

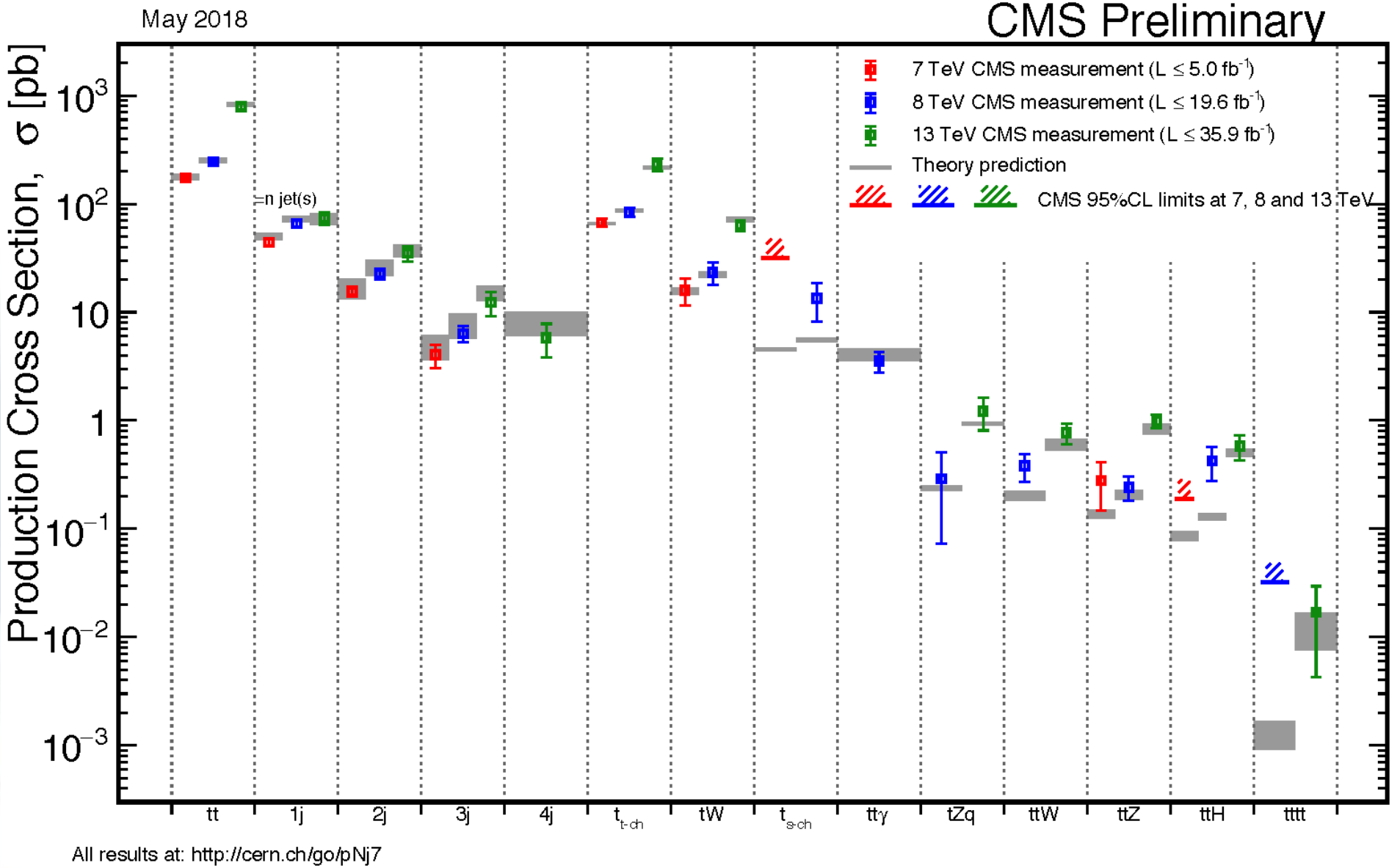
Cross sections (A)

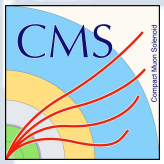


Cross sections (B)



Cross sections (C)





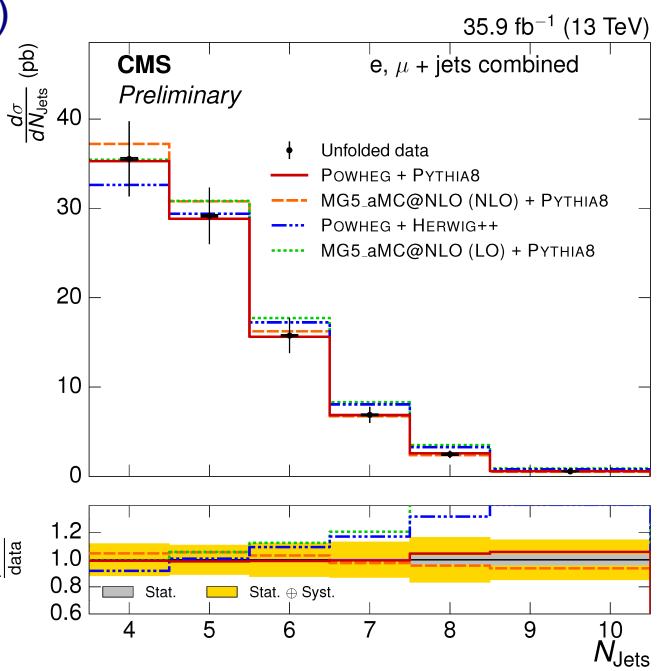
Top physics

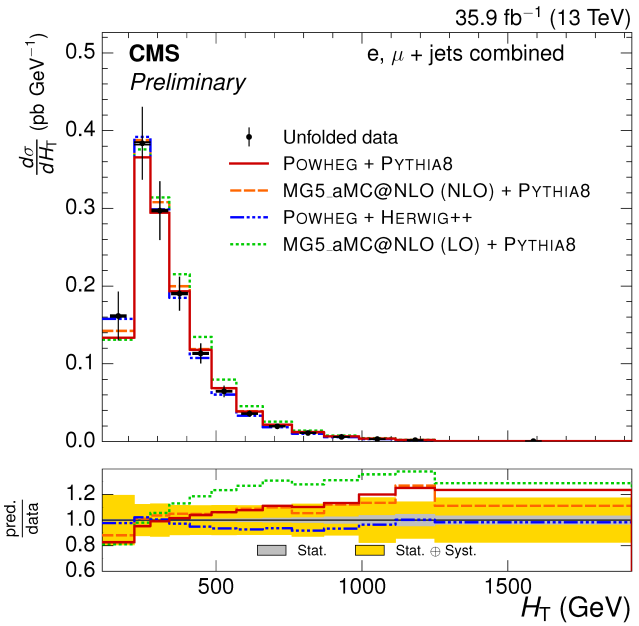
t-tbar→ (lepton+jets) and study of extra jets

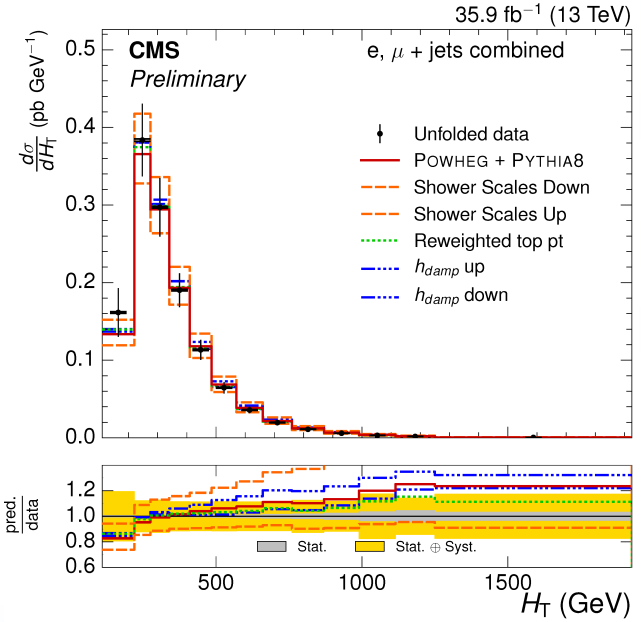
Published this month

JHEP 06 (2018) 002

- Lepton+jets (13 TeV, 35.8 fb^{-1}, single-lepton triggers)
  - at least 4 jets, at least 2 b-tagged
- Extra jets studied (QCD tests, backgrounds for searches with top and extra jets)
- Main background single-top and QCD multijet, W+jet, Z+jet and other ttbar channels
- Studied Powheg with Pythia or Herwig++ showering and Madgraph and *LO or NLO matching* with Pythia-showered jets
- Powheg+Pythia describes N_{jet} mutliplicity, but some kinematics are consistent with prediction only after inclusion of theoretical uncertainties in unfolding.





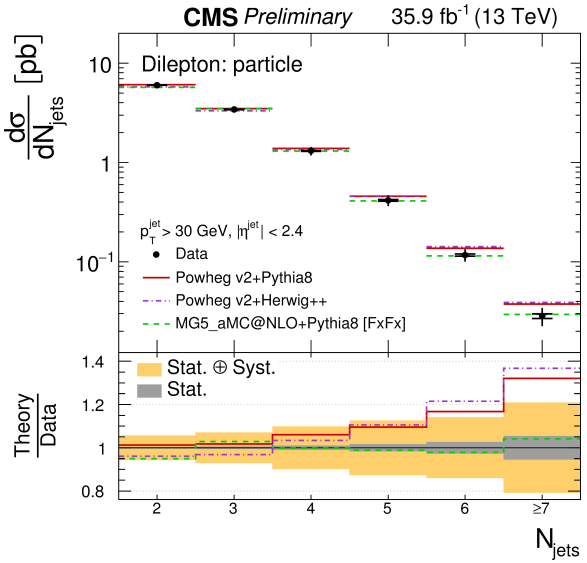


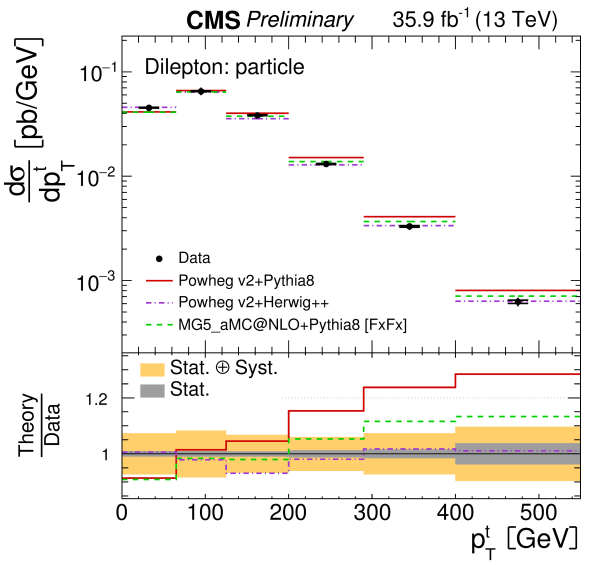
t-tbar→ (dileptons)

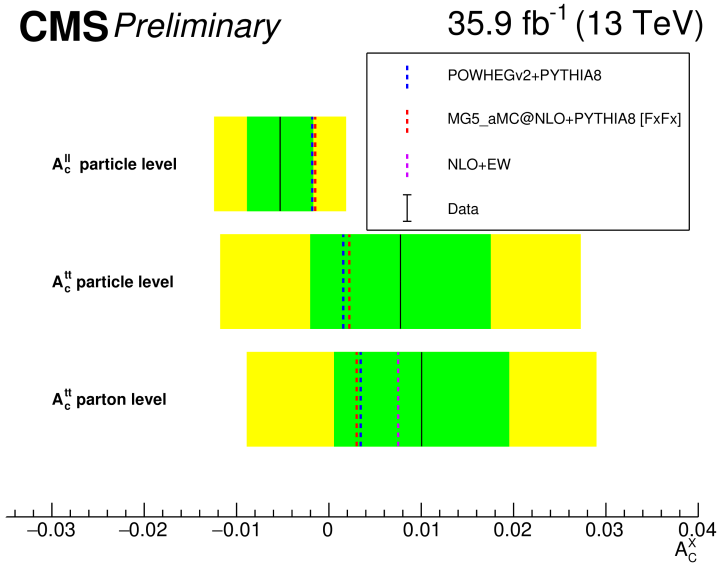
June

CMS-PAS-TOP-17-014

- Dileptons (13 TeV, 35.8 fb^{-1}, dilepton triggers)
  - 2 leptons, at least 2 jets, at least 1 b-tagged
  - ee, μμ, eμ channels studied separately and combined
- Extra jets studied as well
- Main background top+W, W+jet, Z+jet, diboson, ttbar+W
- Same MC as in l+jets
- Particle-level and parton level | unfolding, variety of kinematic observables
- Mismodeling of tails of pT distributions and N_{jets} partially covered by systematics
- Measurement of top chromomagnetic dipole moment and y charge asymmetry





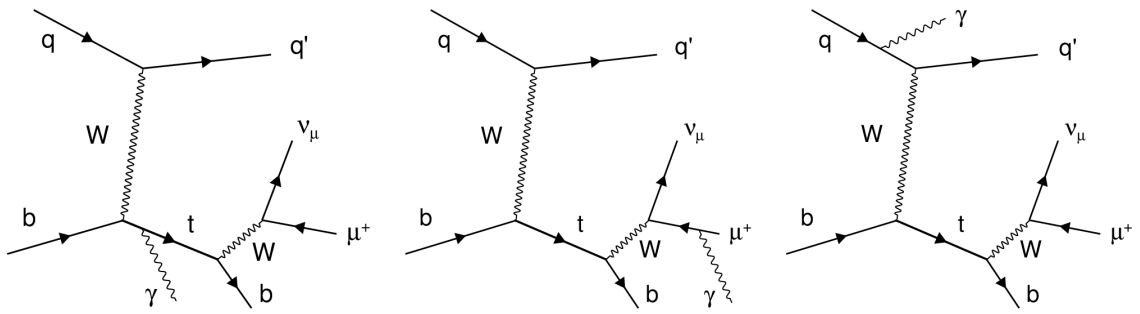


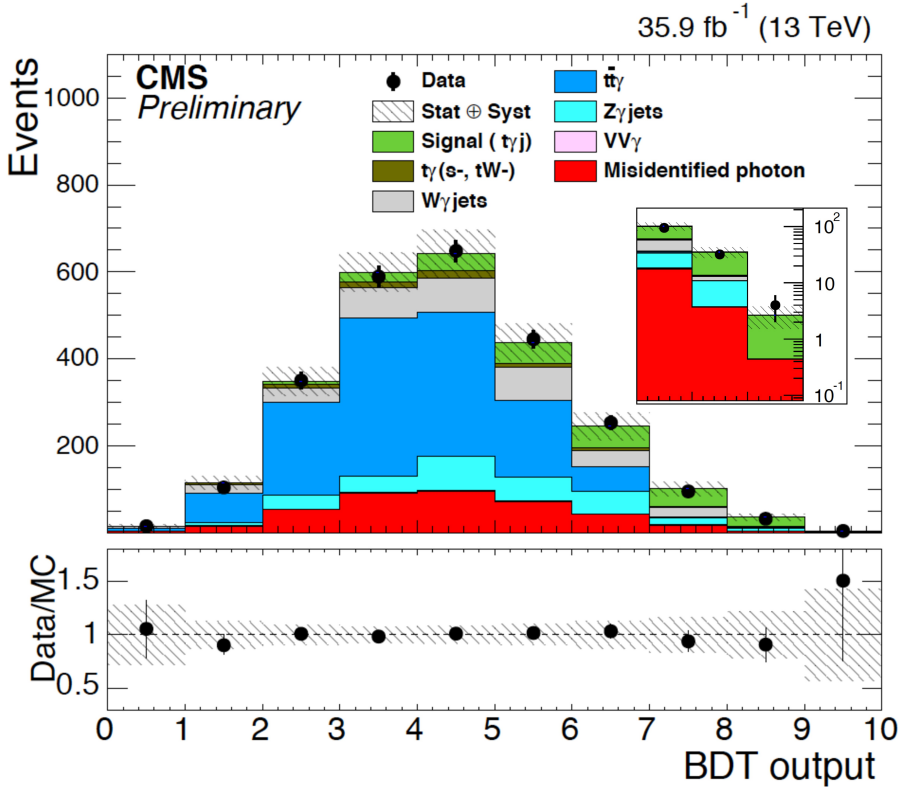
(t →μνb)+γ

June

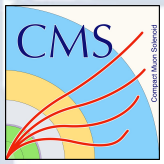
CMS-PAS-TOP-17-016

- 13 TeV, 35.9 fb^{-1}
- Muon, photon, missing p_T and at least 2 jets
- Fake and real photon backgrounds
- $\sigma(t\gamma+jets)*B(t \rightarrow \mu\nu b) = 115 \pm 17(stat)\ ^{+33}_{-27}(syst)$ fb (SM: 81 ± 4 fb)





Process	Event yield
$t\bar{t} + \gamma$	1401 ± 131
$W\gamma$ + jets	$329\ ^{+79}_{-77}$
$Z\gamma$ + jets	$232\ ^{+59}_{-52}$
Misidentified photon	374 ± 74
$t\gamma$(s-,tW-channel)	$57\ ^{+8}_{-9}$
$VV\gamma$	8 ± 3
Total background	$2401\ ^{+180}_{-177}$
Expected signal	154 ± 24
Total SM prediction	$2555\ ^{+182}_{-179}$
Data	2535



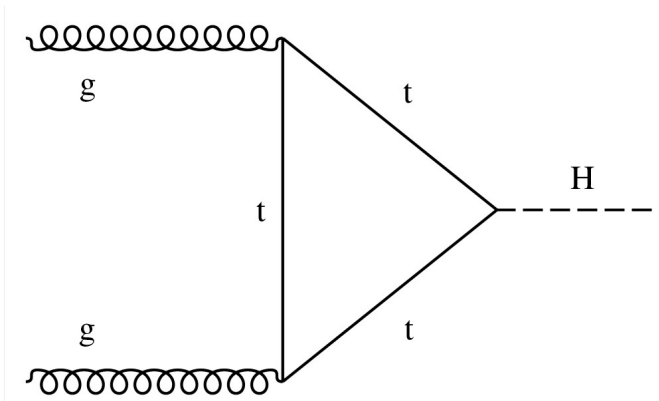
Higgs physics

Combined Higgs rates and couplings

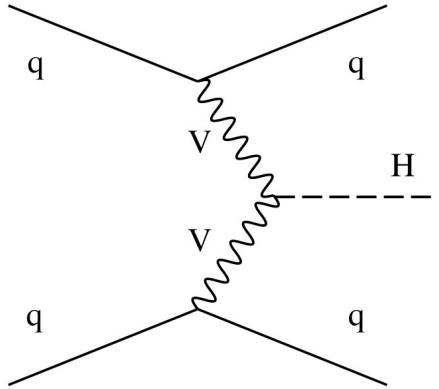
13 TeV, 35.9 fb^{-1}

Production:

- Gluon fusion,
- vector-boson fusion,
- H+W/Z,
- H+ttbar

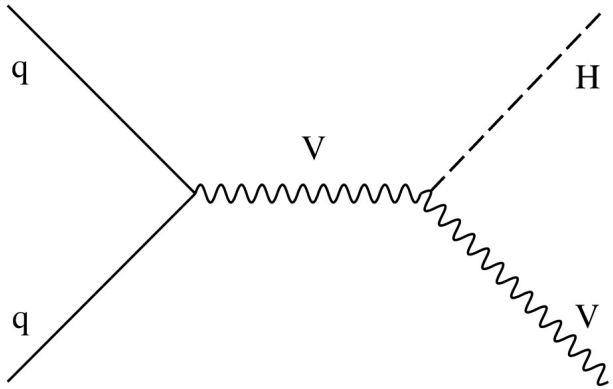


(a)

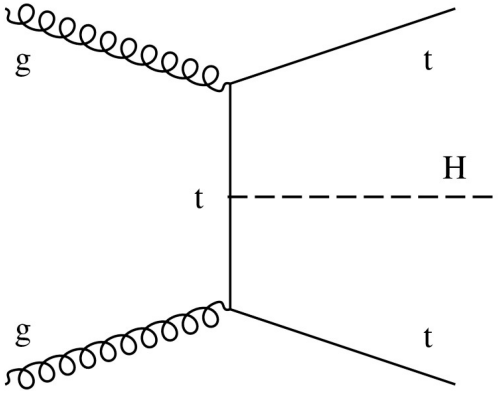


(b)

This includes gg initial states with a quark triangle or square (in the Z channel)



(c)



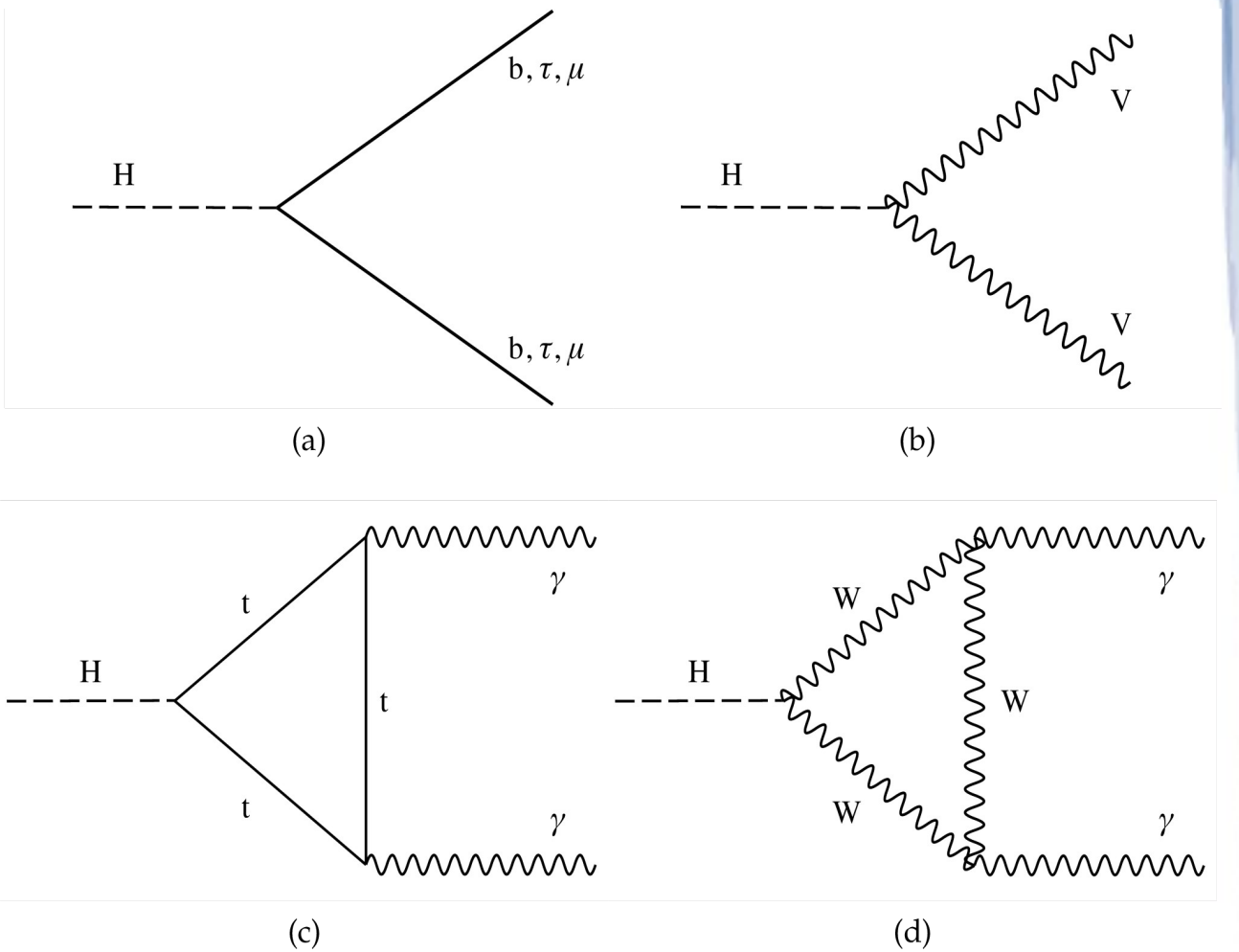
(d)

Combined Higgs rates and couplings

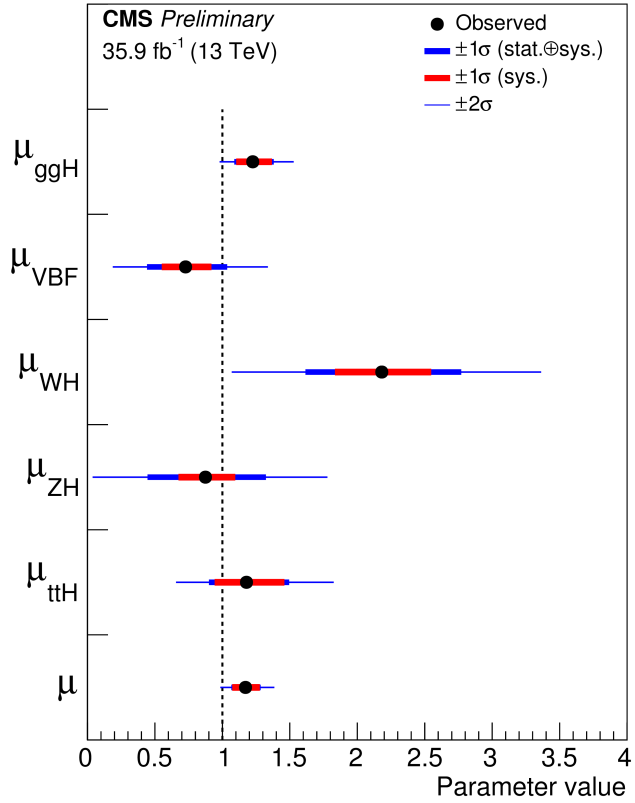
13 TeV, 35.9 fb^{-1}

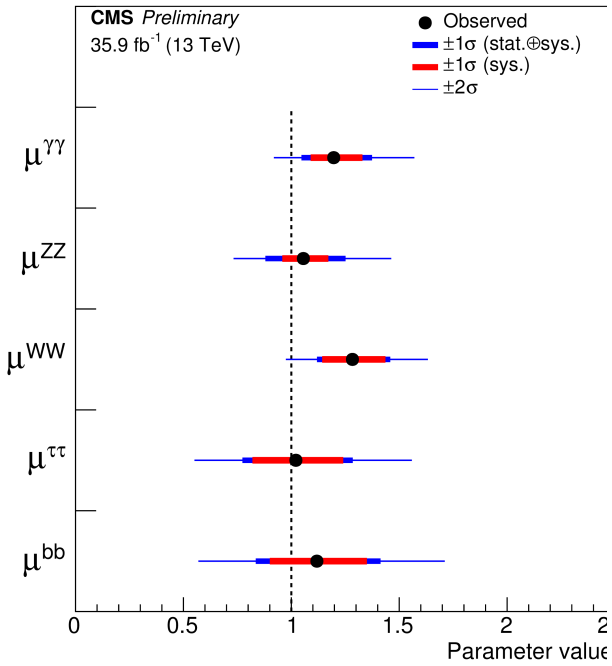
Decay:

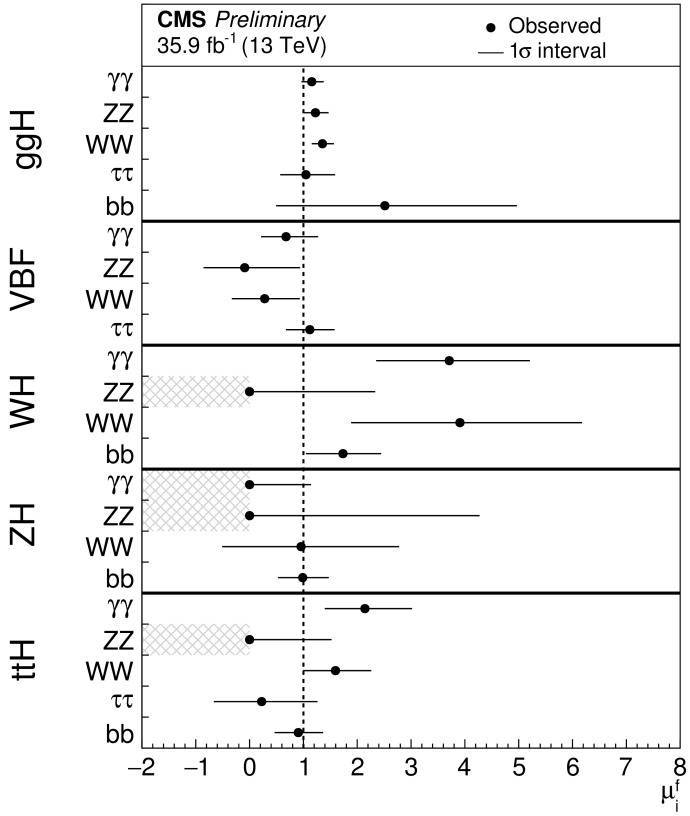
- γγ,
- ττ, μμ
- bb,
- WW, ZZ
- invisible



Signal strengths (production, decay, combination)





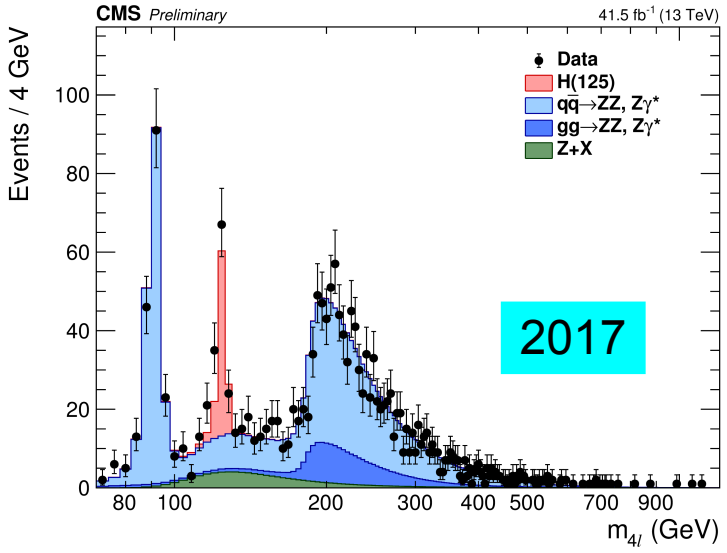


- The combined signal yield relative to the SM prediction has been measured as 1.17+0.10−0.10. Improvements in the precision of the ggH production rate of around Ґ50% is achieved compared to previous ATLAS and CMS measurements.

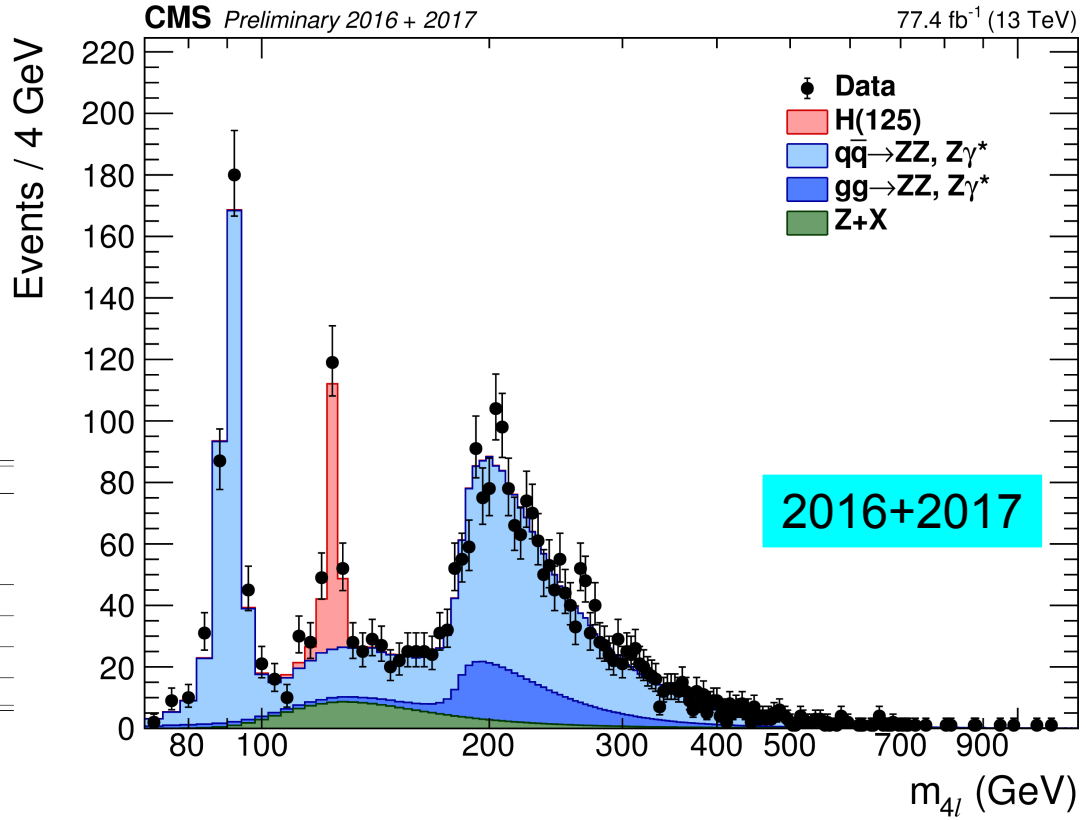
H → ZZ → 4 leptons

June

CMS-PAS-HIG-18-001



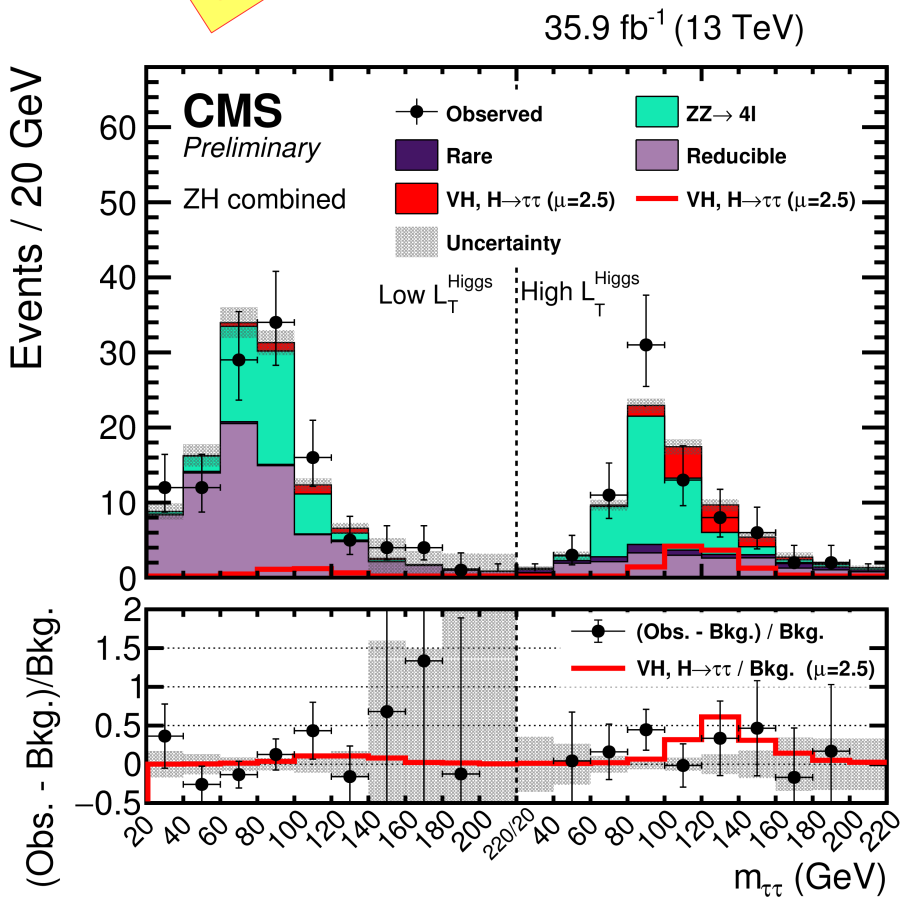
Channel	4e	4μ	2e2μ	4ℓ
$q\bar{q} \to ZZ$	235^{+32}_{-36}	443^{+36}_{-40}	572^{+50}_{-54}	1250^{+104}_{-114}
$gg \to ZZ$	$49.1^{+8.7}_{-8.8}$	$81.8^{+11.2}_{-10.7}$	$121.5^{+17.1}_{-16.3}$	$252.4^{+35.1}_{-33.5}$
$Z + X$	$17.1^{+6.4}_{-6.1}$	$35.4^{+12.7}_{-11.4}$	$47.8^{+16.4}_{-15.8}$	$100.3^{+21.3}_{-20.6}$
Sum of backgrounds	301^{+39}_{-43}	560^{+43}_{-47}	741^{+62}_{-65}	1602^{+126}_{-135}
Signal ($m_H = 125$ GeV)	$13.9^{+1.9}_{-2.1}$	$28.9^{+2.5}_{-2.6}$	35.8 ± 3.3	$78.5^{+7.0}_{-7.1}$
Total expected	315^{+41}_{-45}	589^{+45}_{-49}	777^{+64}_{-67}	1681^{+131}_{-140}
Observed	307	602	797	1706

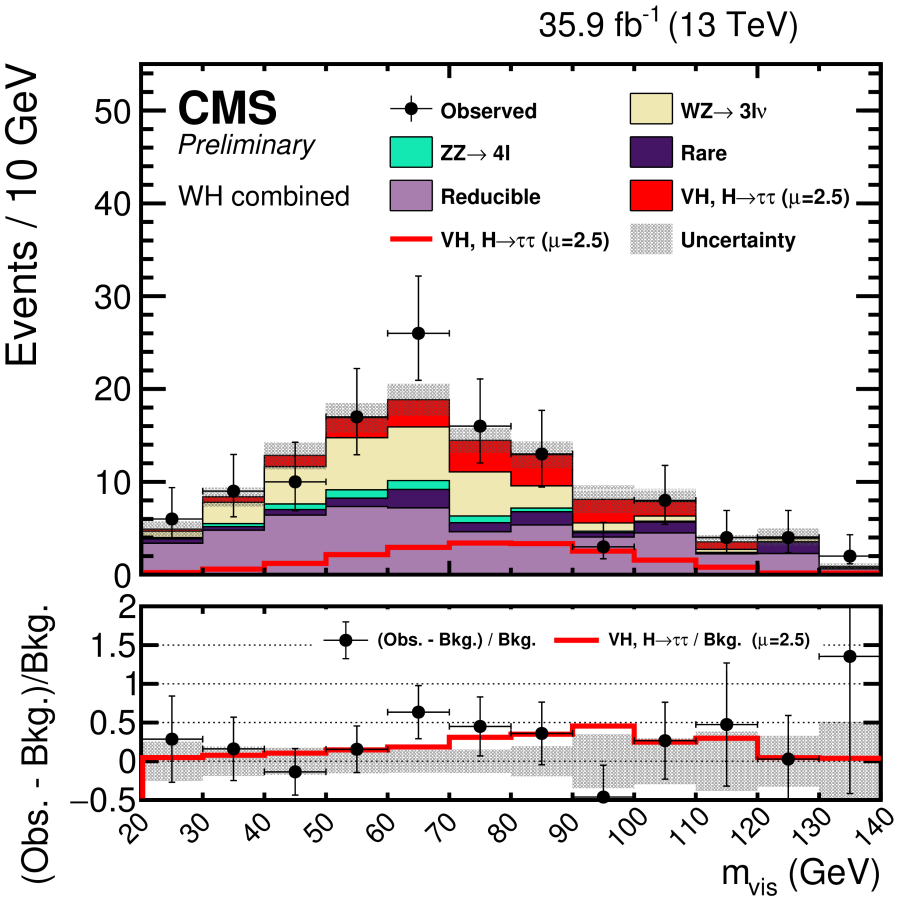


	Inclusive	$\mu_{ggH,b\bar{b}H}$	μ_{VBF}	μ_{VHhad}	μ_{VHlep}	$\mu_{t\bar{t}H,tqH}$
Expected	$1.00 \pm 0.10(\text{stat})^{+0.08}_{-0.06}(\text{exp. syst})^{+0.07}_{-0.05}(\text{th. syst})$	$1.00^{+0.17}_{-0.16}$	$1.00^{+0.86}_{-0.67}$	$1.00^{+2.39}_{-1.00}$	$1.00^{+2.30}_{-1.00}$	$1.00^{+1.80}_{-1.00}$
Observed	$1.06 \pm 0.10(\text{stat})^{+0.08}_{-0.06}(\text{exp. syst})^{+0.07}_{-0.05}(\text{th. syst})$	$1.15^{+0.18}_{-0.16}$	$0.69^{+0.75}_{-0.57}$	$0.00^{+1.16}_{-0.00}$	$1.25^{+2.46}_{-1.25}$	$0.00^{+0.53}_{-0.00}$

V+(H → ττ)

June



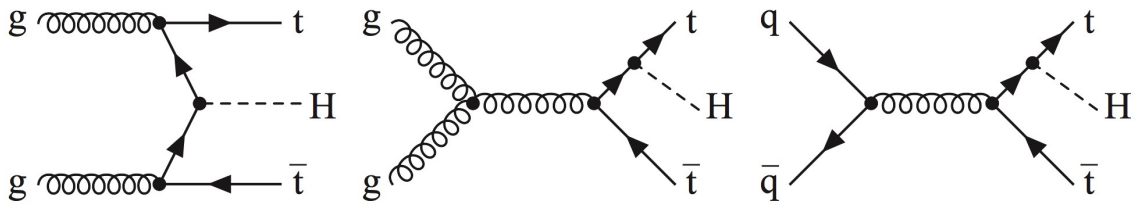


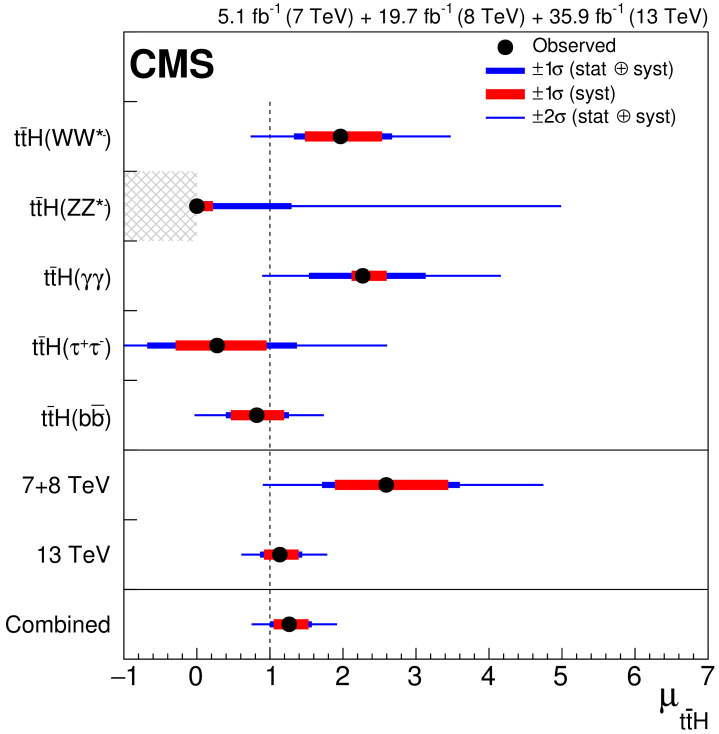
CMS-PAS-HIG-18-007

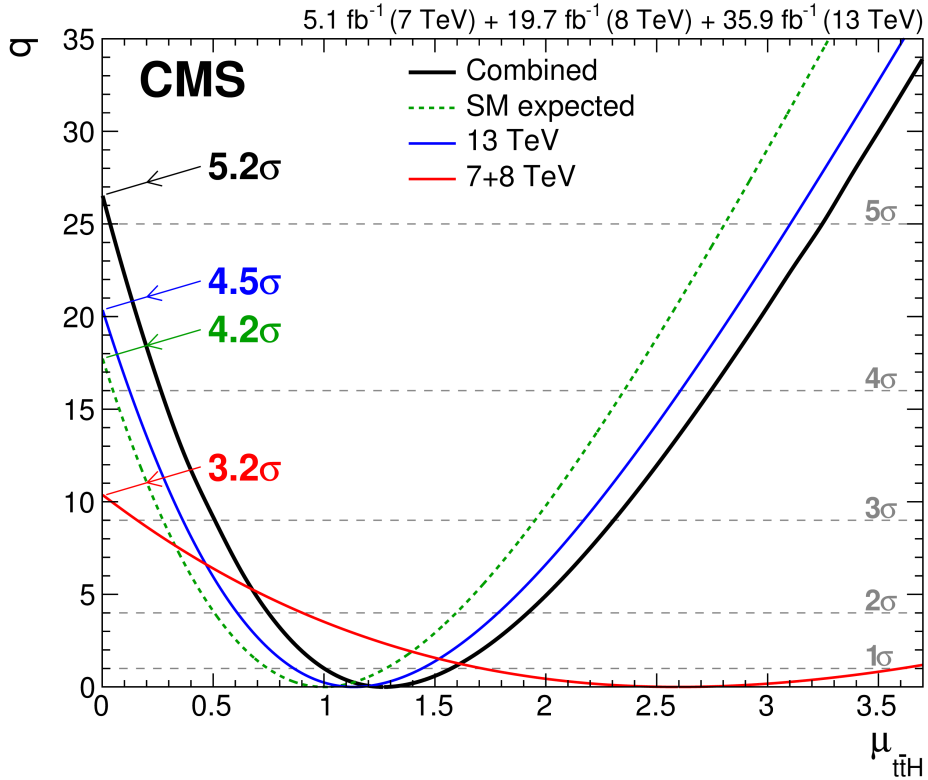
- 13 TeV, 35.9 fb^{-1}, at least one hadronically decaying tau
- μ= 2.54+1.35−1.26 (μ= 1.00+1.08−0.97 expected) for a significance of 2.3 standard deviations (1.0 expected)

Observation of Htt

Published this month

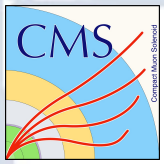






- Combination of 7 TeV, 8 TeV, 13 TeV data
- Observed significance: 5.2 σ (expected 4.2 σ)

Phys. Rev. Lett. **120**, 231801



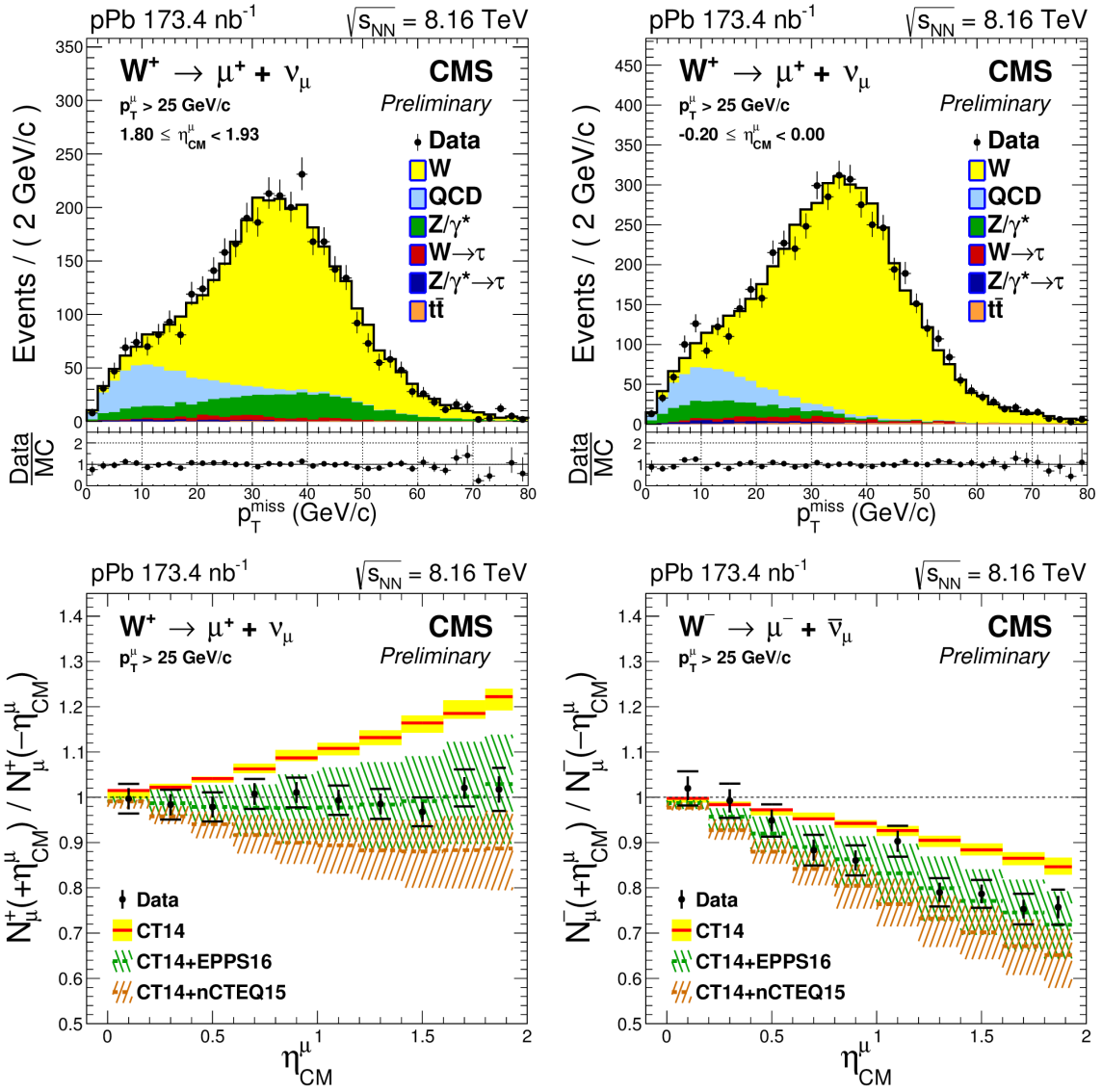
Heavy Ion

nPDF with W production in pPb

May

- 8.16 TeV p-Pb, 173 nb^{-1}
- $W \rightarrow \mu\nu$, $p_T^{\mu} > 25$ GeV, $|\eta|<2.4$
- Yields extracted with log-likelihood fits in bins of muon CM $\eta \rightarrow$ 180K events
- Probes nuclear PDF (u and d) at $10^{-3} < x < 10^{-1}$
- Modified PDF needed to describe η^{μ}_{CM}

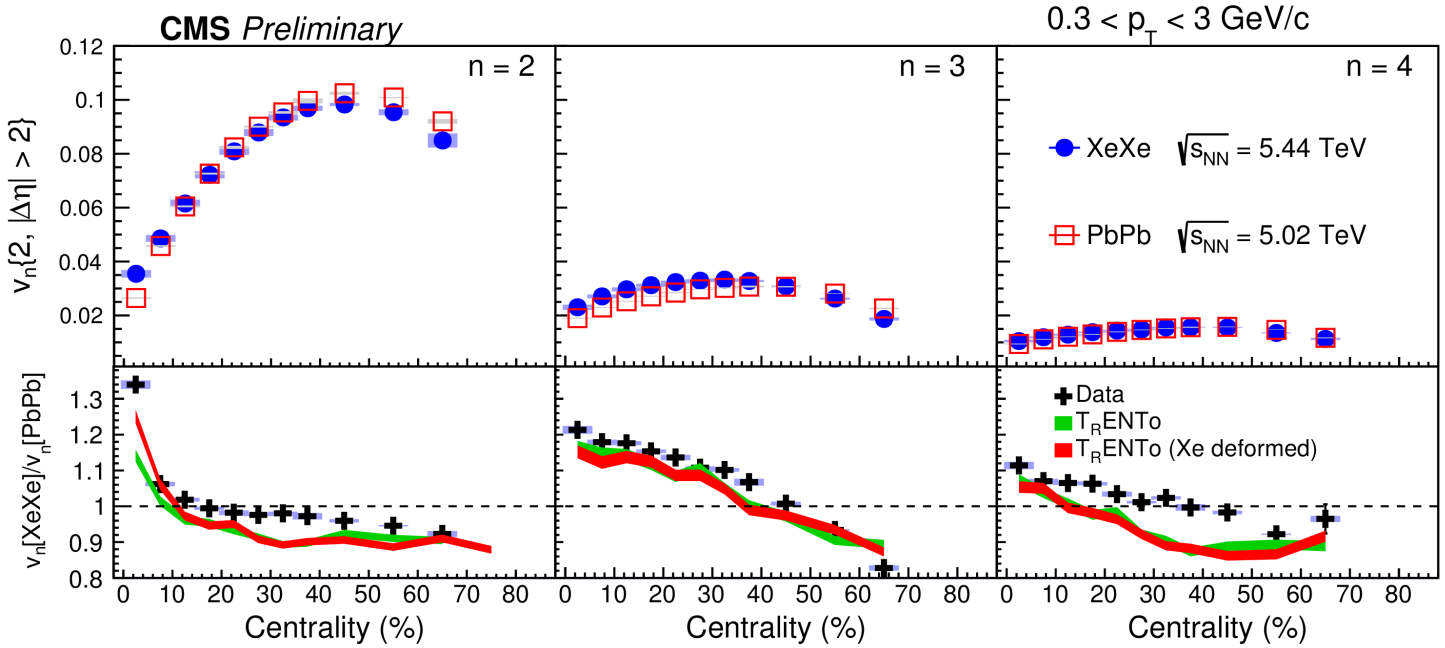
CMS-PAS-HIN-17-007



("forward" is the direction of proton)

Particle flow in Xe-Xe collisions

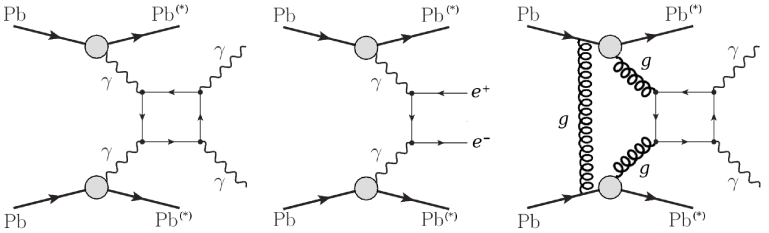
- 5.44 TeV, Xe-Xe
- Differences in particle flow between Xe-Xe and Pb-Pb probe system-size dependence in medium response



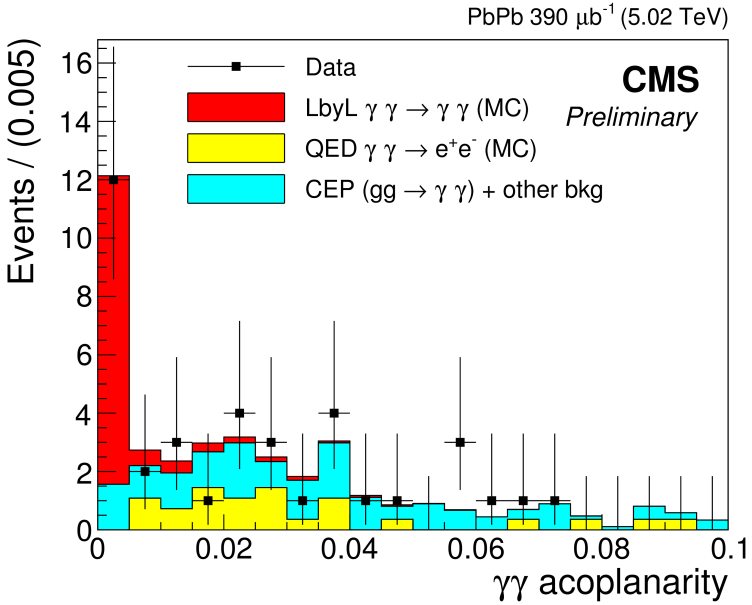
CMS-PAS-HIN-18-001

Light-by-Light scatter

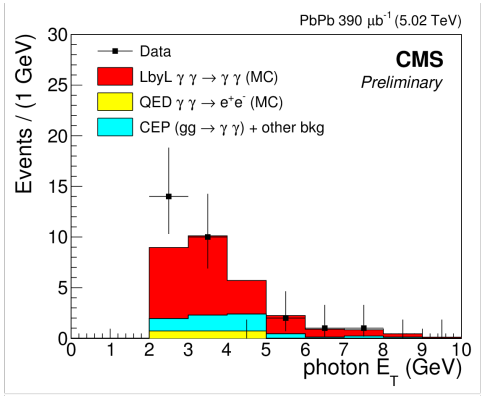
May

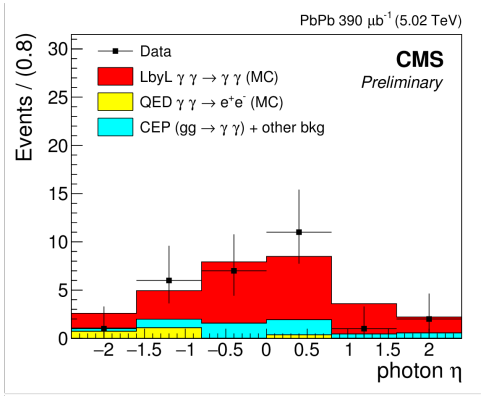


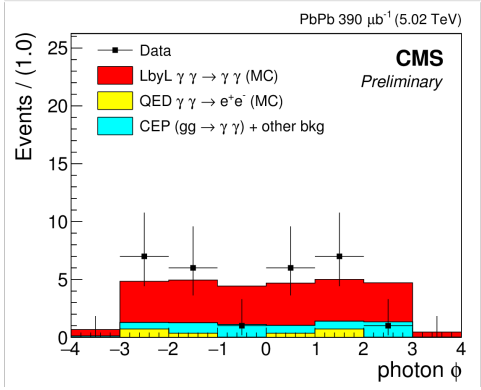
- 5 TeV Pb-Pb, 390 μb^{-1}, di-photon triggers
- Background from misidentified γ → ee and gg → γγ
- Observed 14 events (expected 11.1 ± 1.1 signal and 3.8 ± 1.3 backround)
- 4.1-sigma evidence, $\sigma_{fid}(\gamma\gamma \rightarrow \gamma\gamma)$ = 122 ± 46(stat) ± 29(syst) ± 4(th) nb

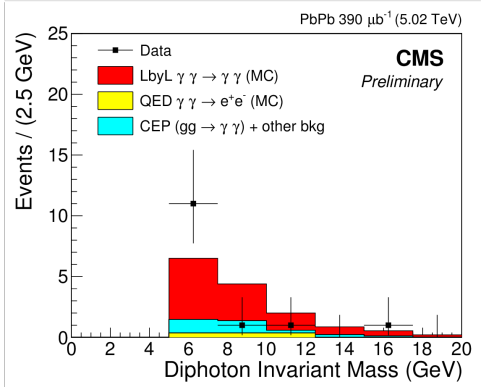


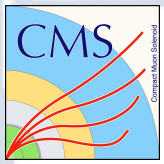
CMS-PAS-FSQ-16-012











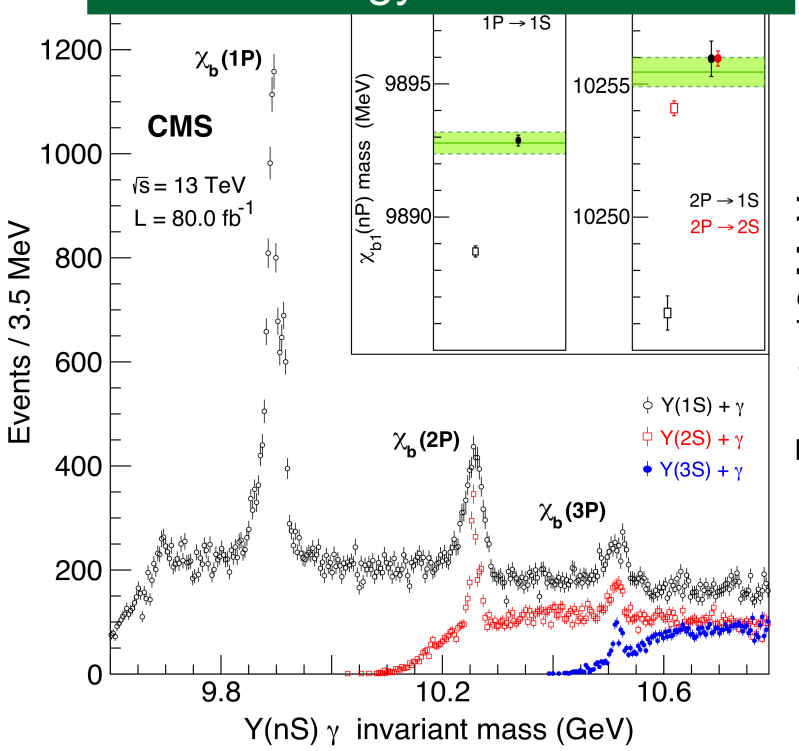
B physics

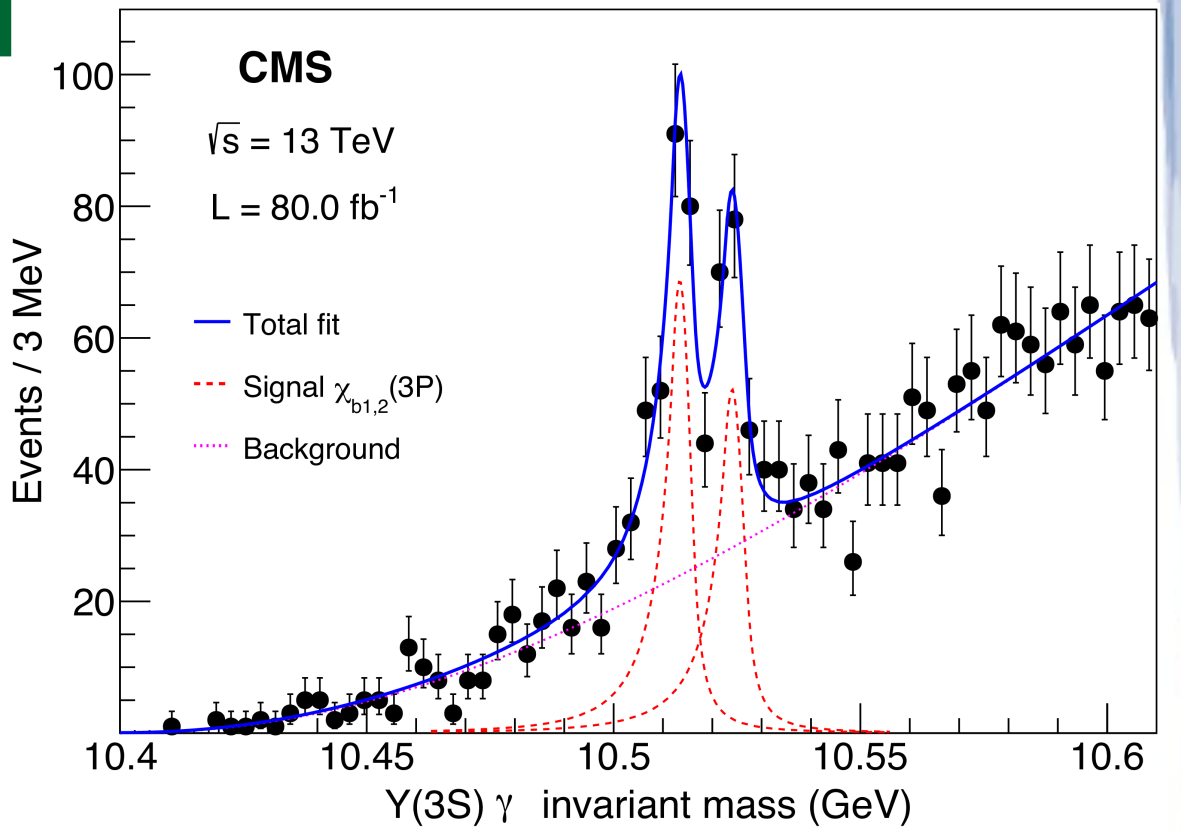
First Observation of resolved $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$

May

CMS-BPH-17-008

Photon energy scale calibration

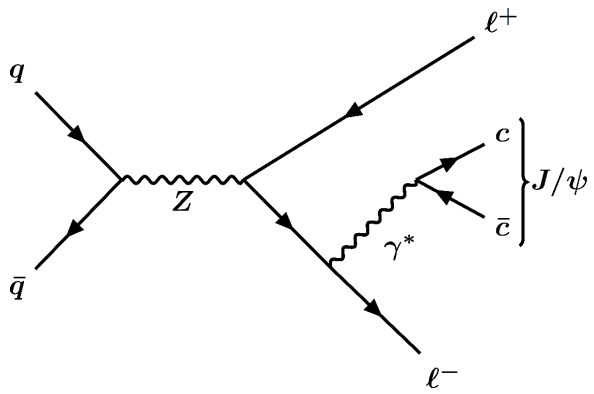




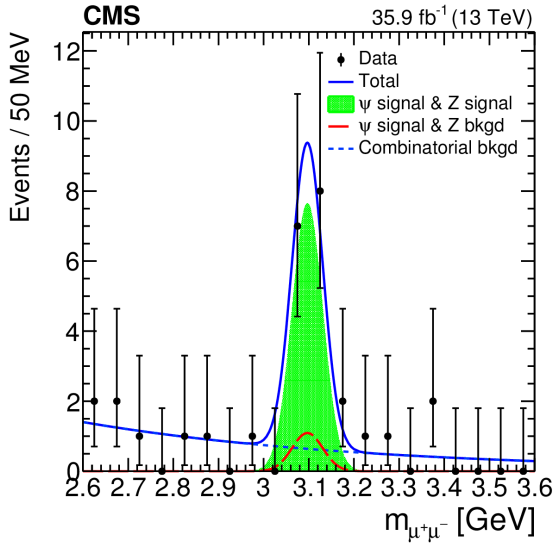
- 13 TeV, 80 fb^{-1}, Decays to (Υ(3S) → μμ)(γ → ee) – dimuon triggers (8.5-11.5 GeV dimuon mass
- Bottomonia allow for Perturbation and Lattice calculations of non-relativistic potentials
- Mass resolution 2.2 MeV
- 10,513.42 ± 0.41 (stat) ± 0.18 (syst) MeV, 10,524.02 ± 0.57 (stat) ± 0.18 (syst) MeV

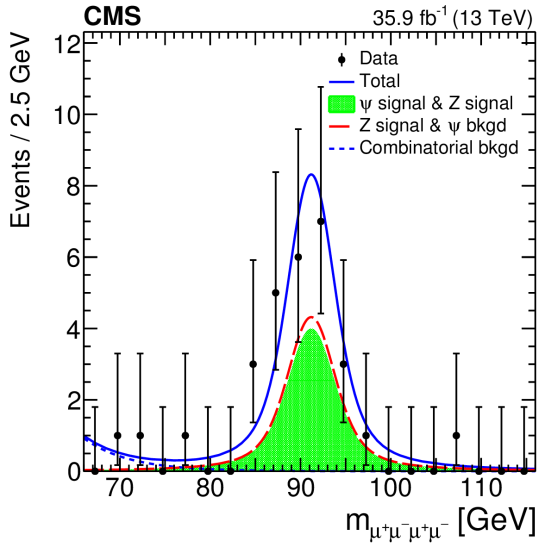
First observation of Z → ψ + ll

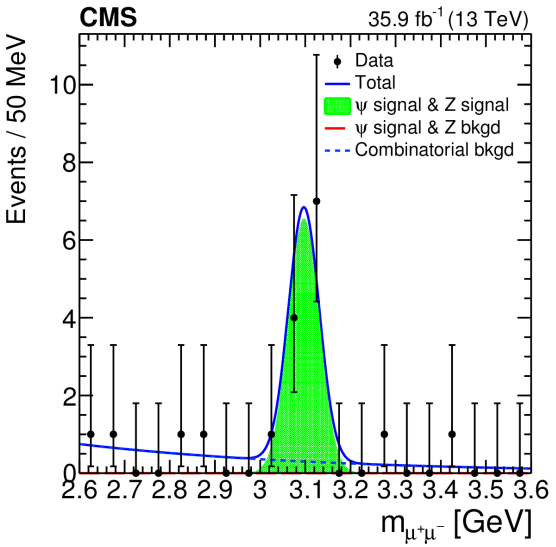
March

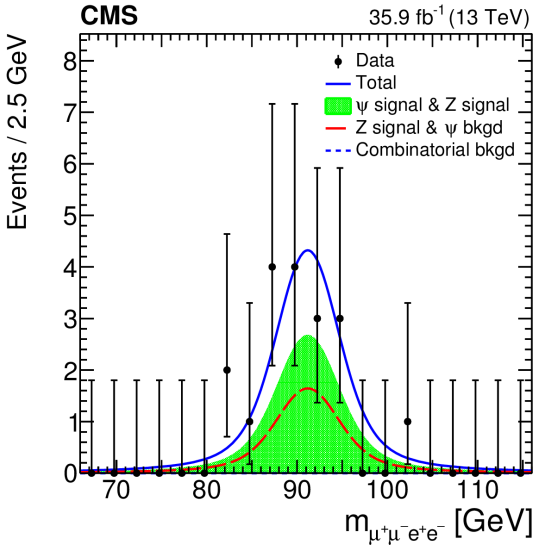


CMS-PAS-BPH-16-001

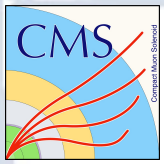








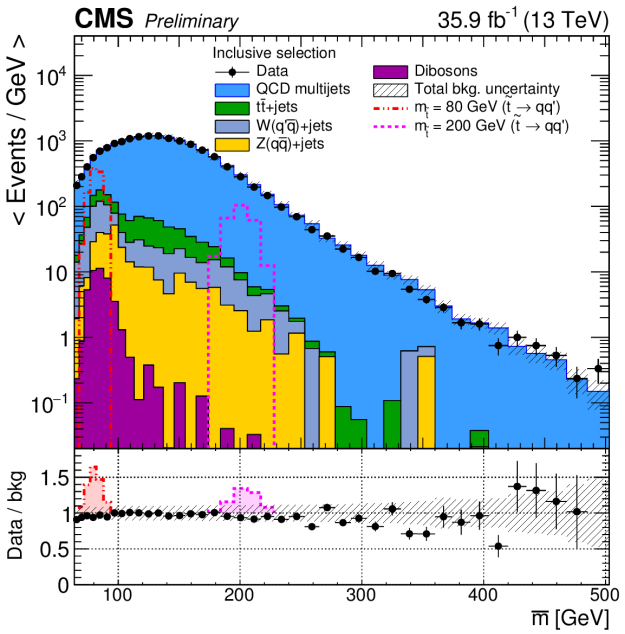
- 13 TeV, 35.9 fb^{-1}
- Both direct production of J/ψ and through ψ(2S) → J/ψ + X
- 13 ± 3.9 (stat) μμμμ events and 11.2 ± 3.9 (stat) eeμμ events

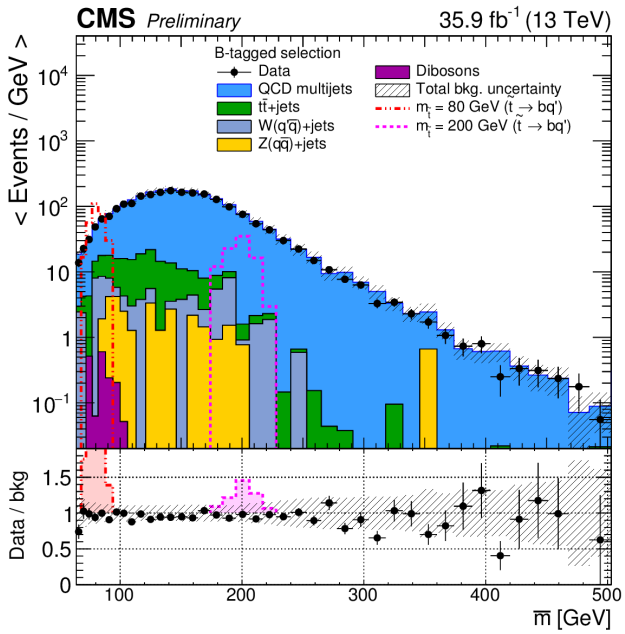


Exotica and SUSY

Pair-produced resonances decaying to diquark pairs

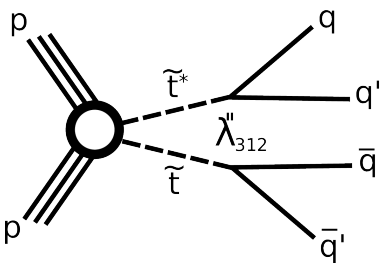
June

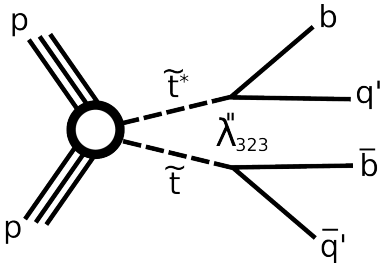




← Boosted search

CMS-PAS-EXO-17-021

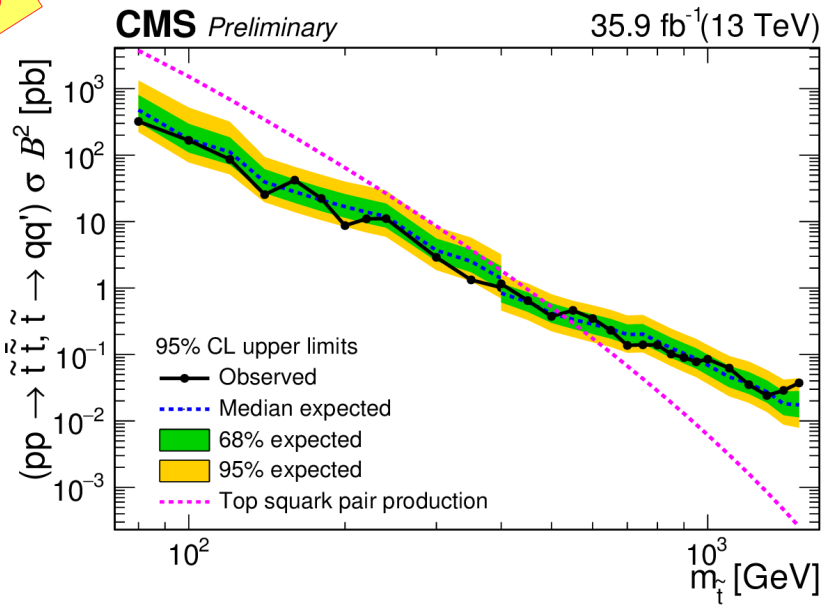


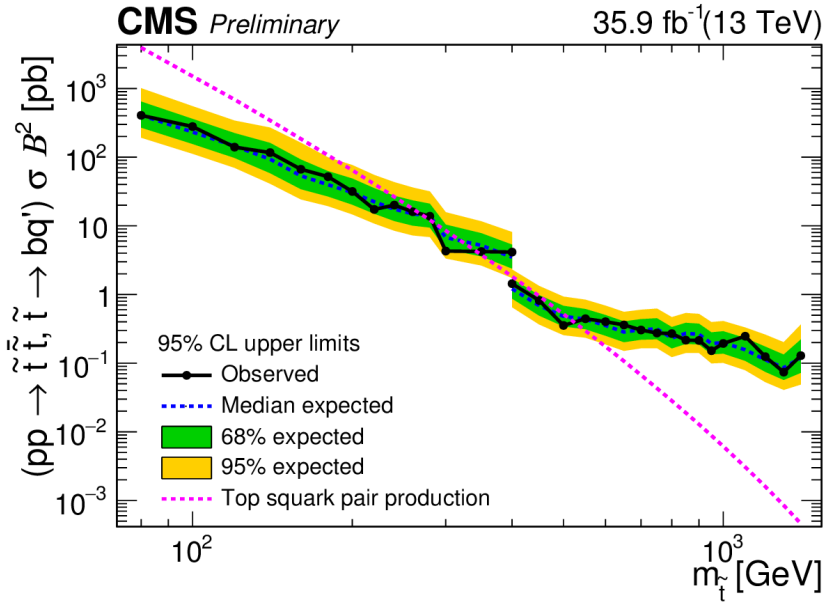


- 13 TeV, 35.8 fb^{-1}
- Either resonances between 80-400 GeV → boosted dijet (grooming used) or above 400 GeV → resolved 4 jet
- Extra b-tagging requirement used (for both boosted and resolved)
- Interpretation in R-parity violating SUSY with pair scalar top decays

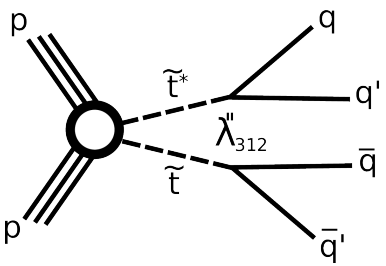
Pair-produced resonances decaying to diquark pairs

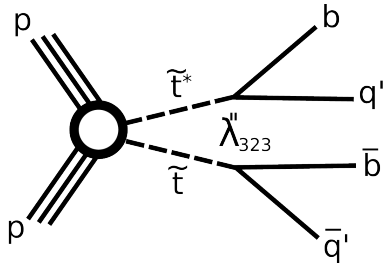
June





CMS-PAS-EXO-17-021

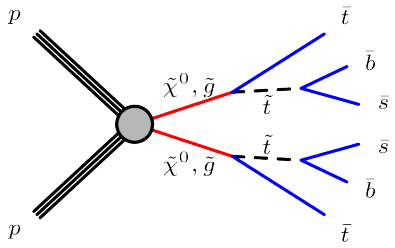


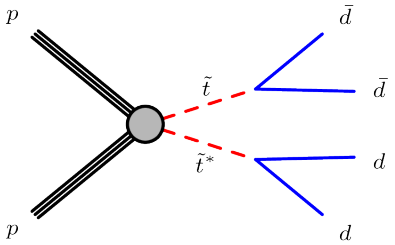


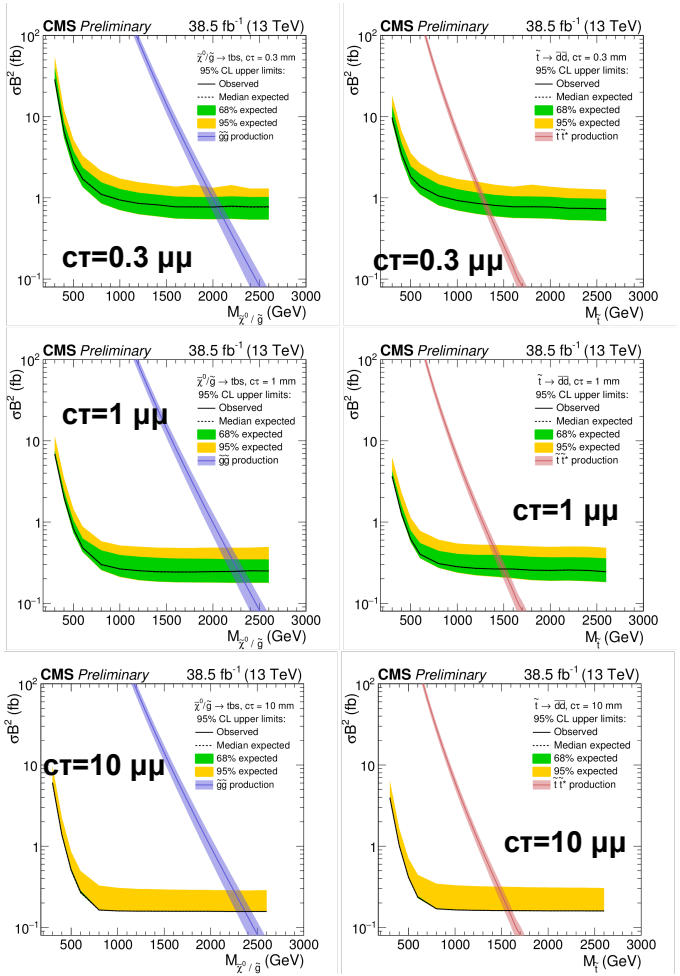
- 13 TeV, 35.8 fb^{-1}
- Either resonances between 80-400 GeV → boosted dijet
  or above 400 GeV → resolved 4 jet
- Extra b-tagging requirement used (for both boosted and resolved)
- Interpretation in R-parity violating SUSY with pair scalar top decays

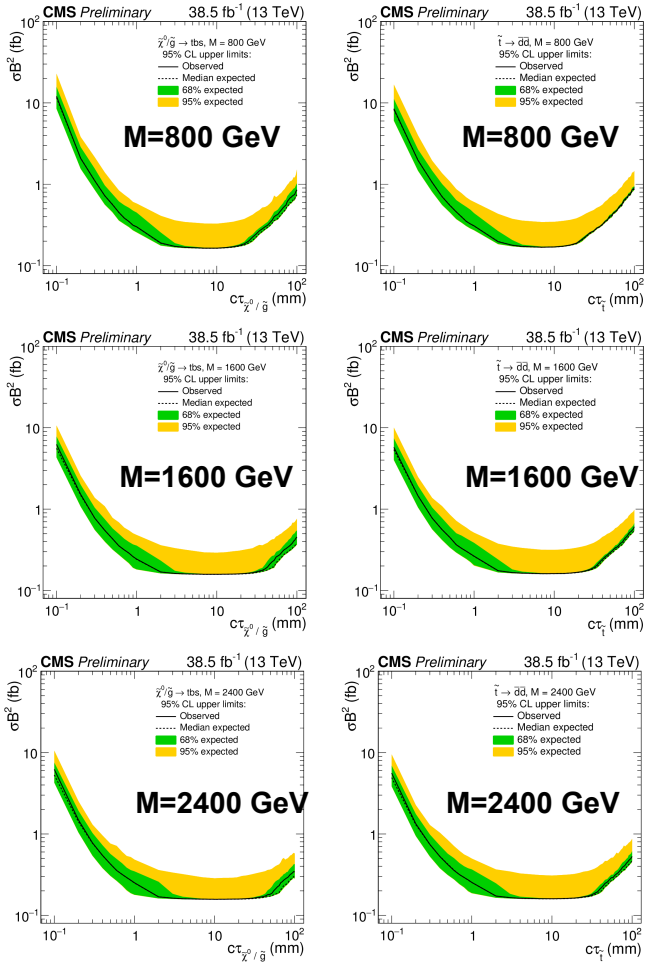
Search for long-lived particles with displaced vertices

June







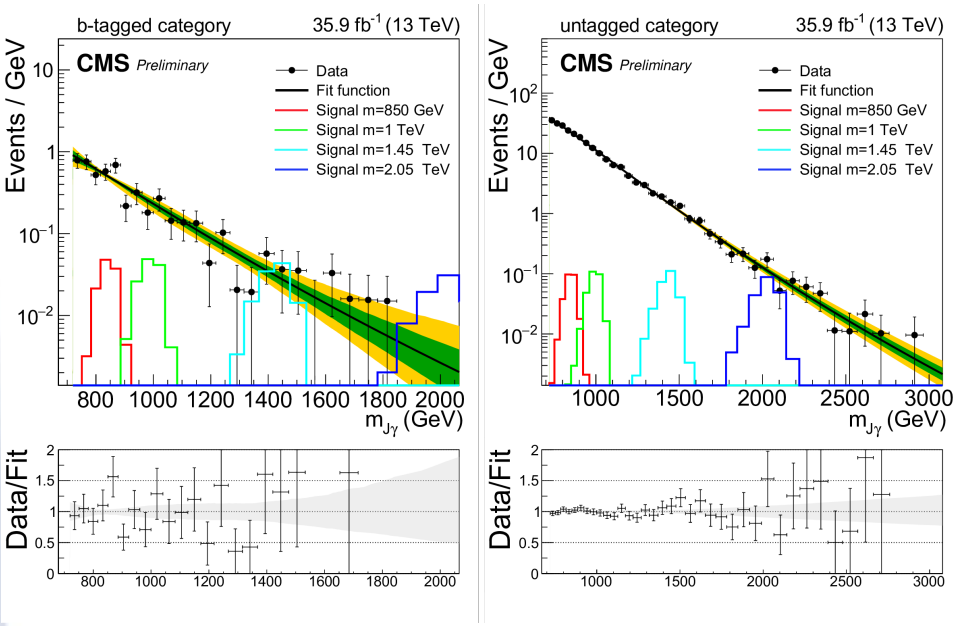


- 13 TeV, 35.8 fb^{-1}
- Search for multijets or dijets with two displayed vertices
- Interpretation in R-parity violating SUSY (gluino or stop)
- Cross section upper limits as a function of mass and lifetime of particles

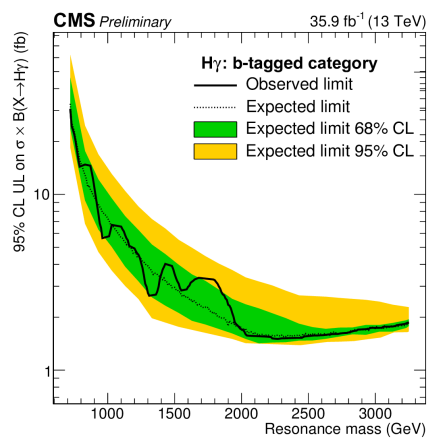
CMS-PAS-EXO-17-018

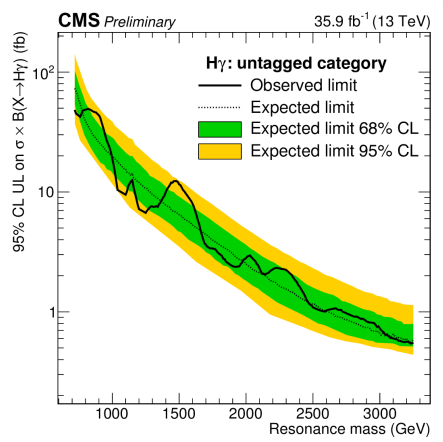
Z' → Hγ

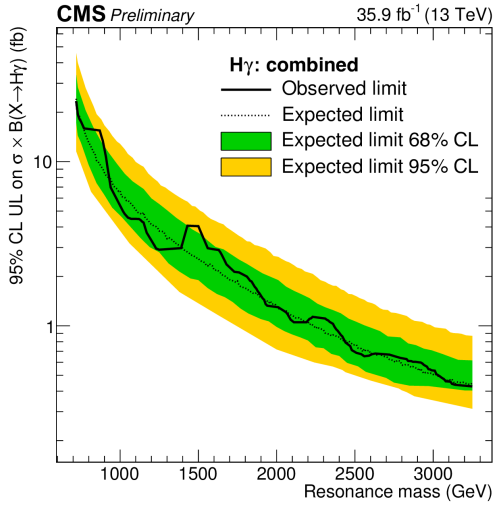
June



CMS-PAS-EXO-17-019



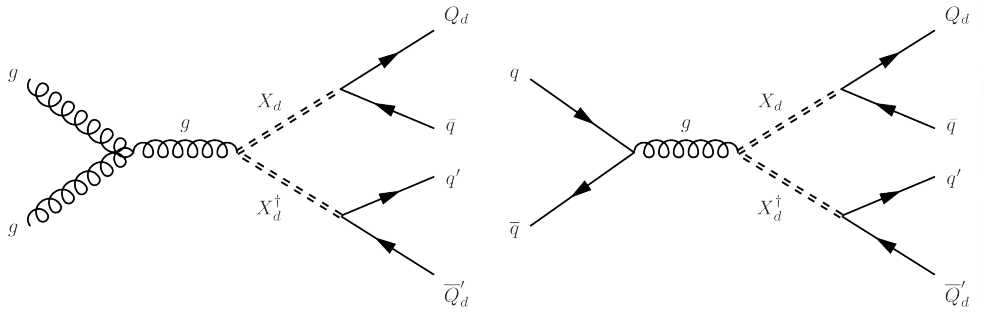


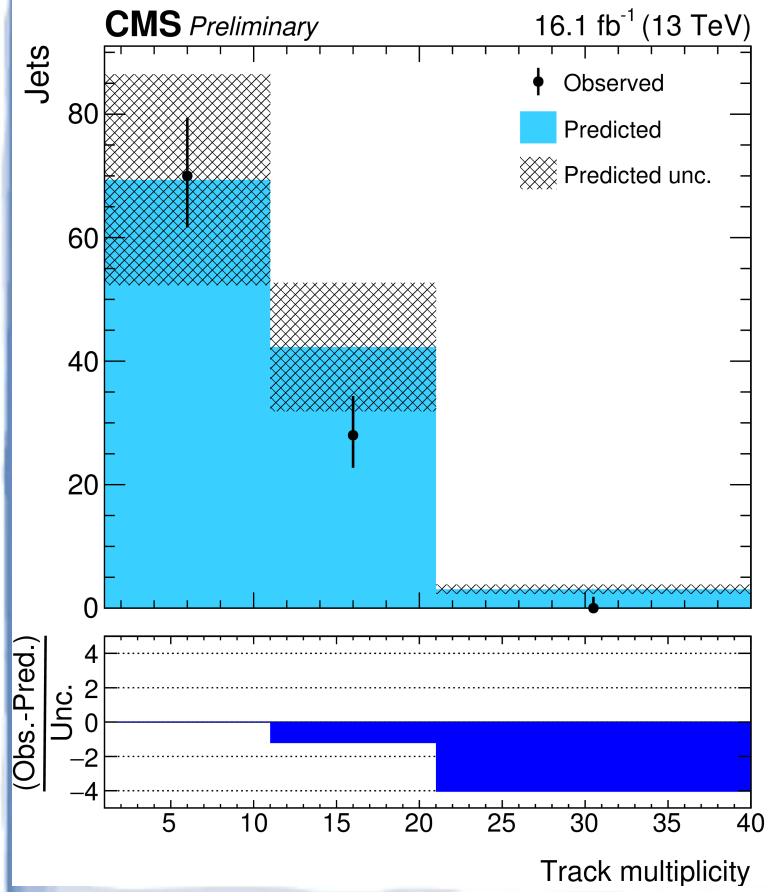


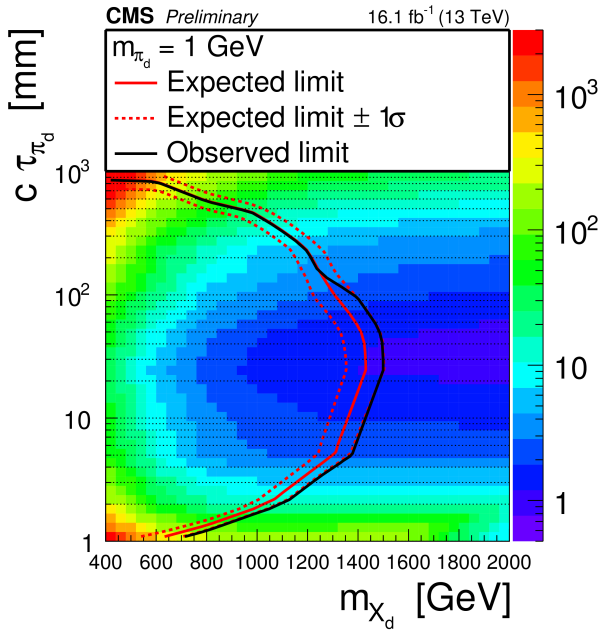
- 13 TeV, 35.8 fb^{-1}, photon triggers
- Investigate Z' masses above 700 GeV → Higgs boosted, its decay to b-bbar is reconstructed as one jet
- Anti-k_T jets, ΔR=0.8, with soft-drop grooming and dedicated double-b-tagging
- P_t^{γ}>165 or 175 GeV (backgrounds: QCD multijet, W/Z+jets)

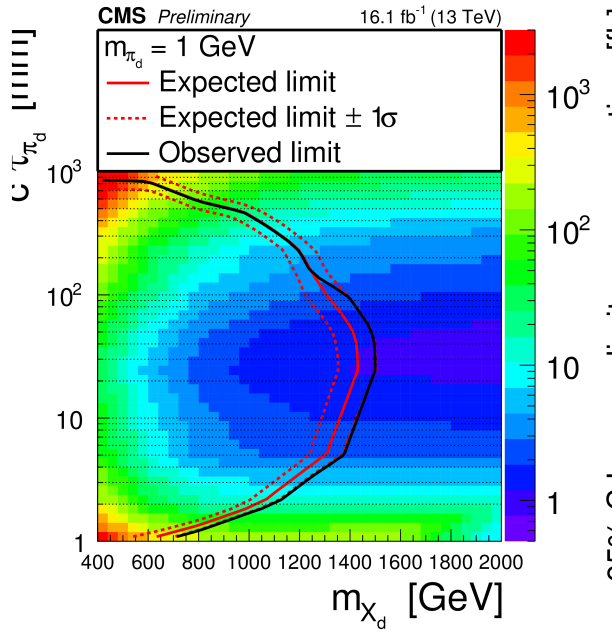
Hot off the press (June 21)

- Search for dark quarks (decay products of heavy mediators)
  - That create long-lived dark hadrons
- Signature is an “emerging jet” from dark hadron decaying to SM hadrons
- 13 TeV, 16.1 fb^{-1}



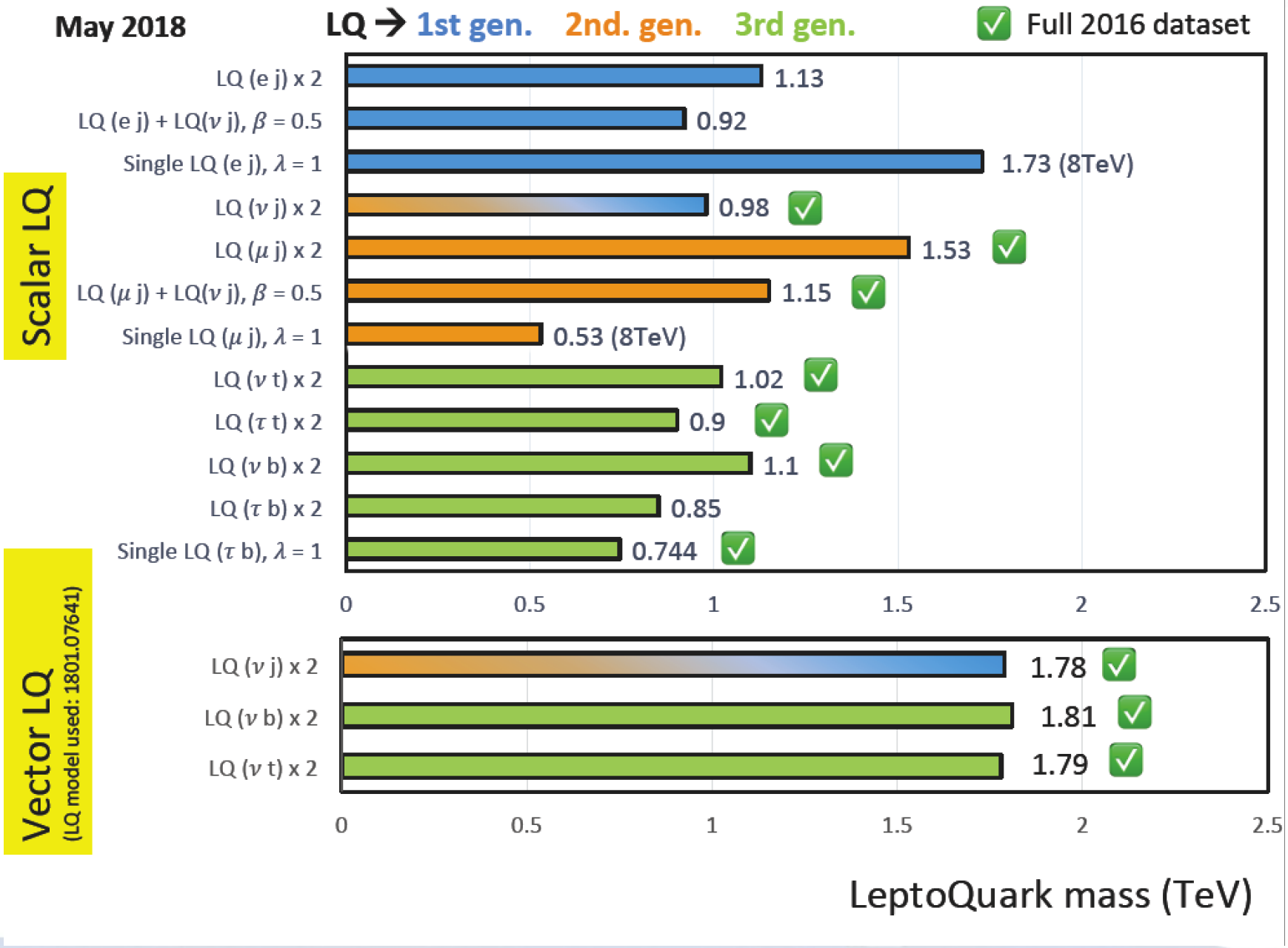






CMS-PAS-EXO-18-001

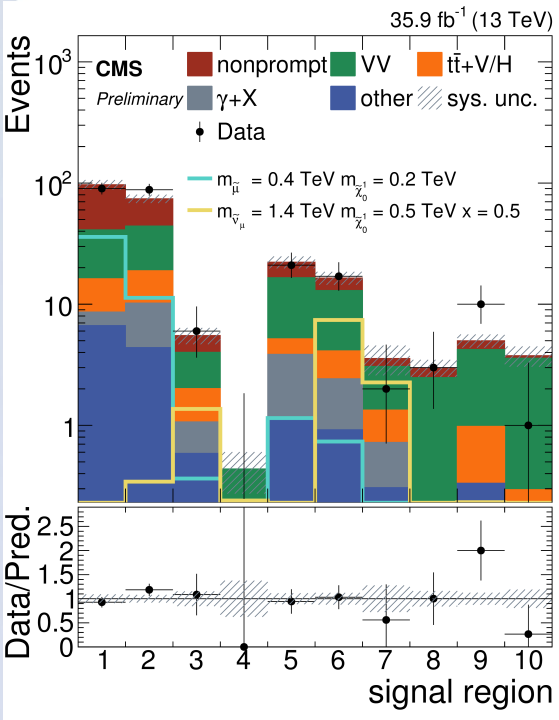
Leptoquark searches

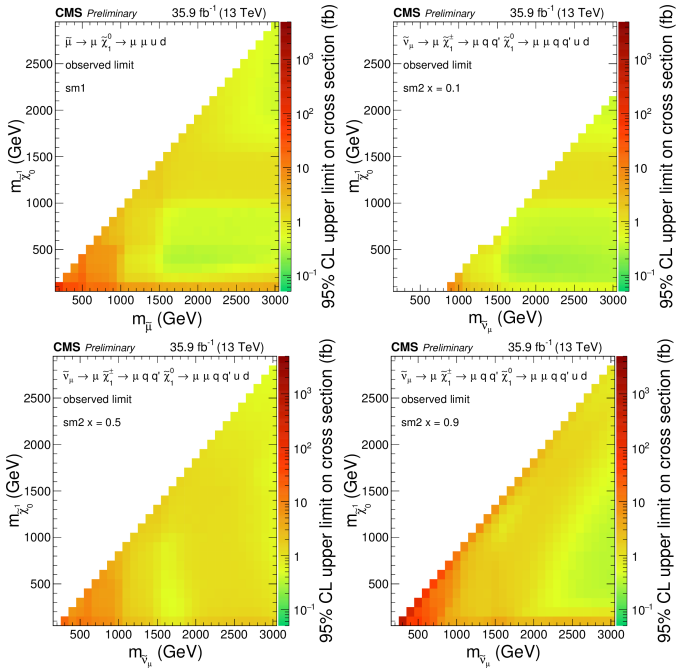


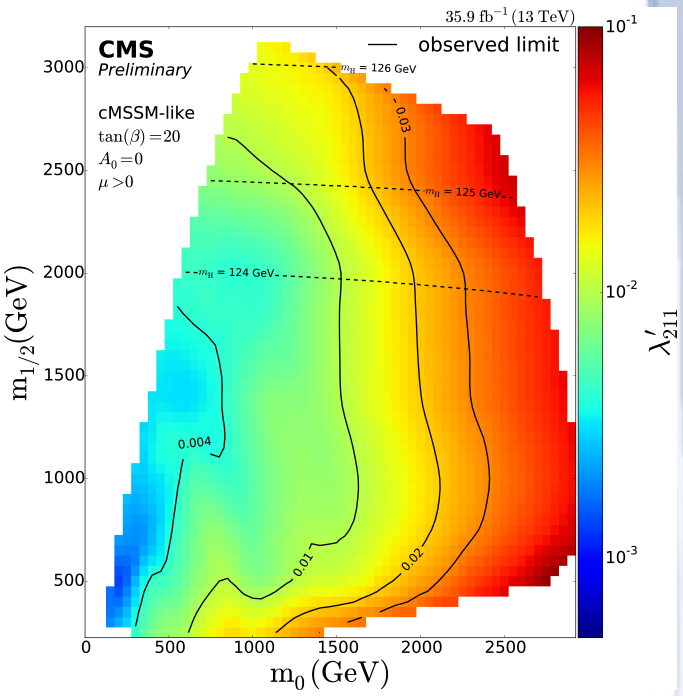
Search for second-generation sleptons with same-sign dimuons

June

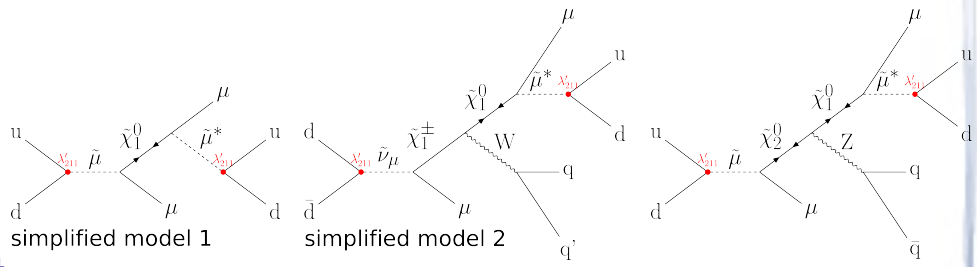
CMS-PAS-SUS-17-008





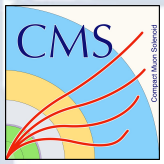


- 13 TeV, 35.9 fb^{-1}
- Two same-sign muons and at least two jets
- Interpretation in R-parity violating SUSY
- Yields consistent with SM → Upper limits set



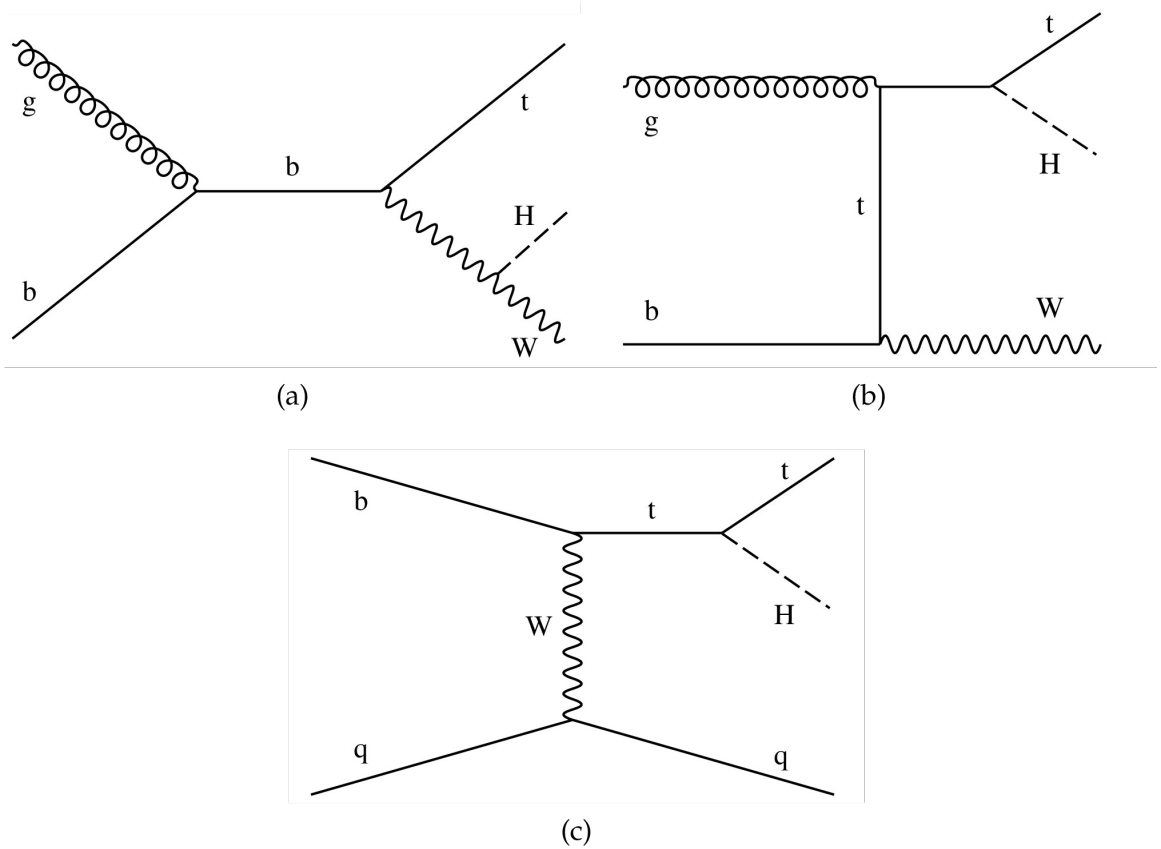
Conclusions

- CMS manages an extremely rich and wide physics program
  - Only a small portion of analyses presented today
- Precision measurements of Standard-Model processes lead to better understanding of theoretical calculations at N^nLO and N^nLL
  - Understanding of QCD is a prime example
  - More precise backgrounds to new-physics signals
- Searches for new physics continue
  - Although model-inspired, the unexpected could/should be discovered
- Please keep in touch with CMS results at:
  https://cms-results.web.cern.ch/cms-results/public-results/publications/
- Thank you !



Additional material

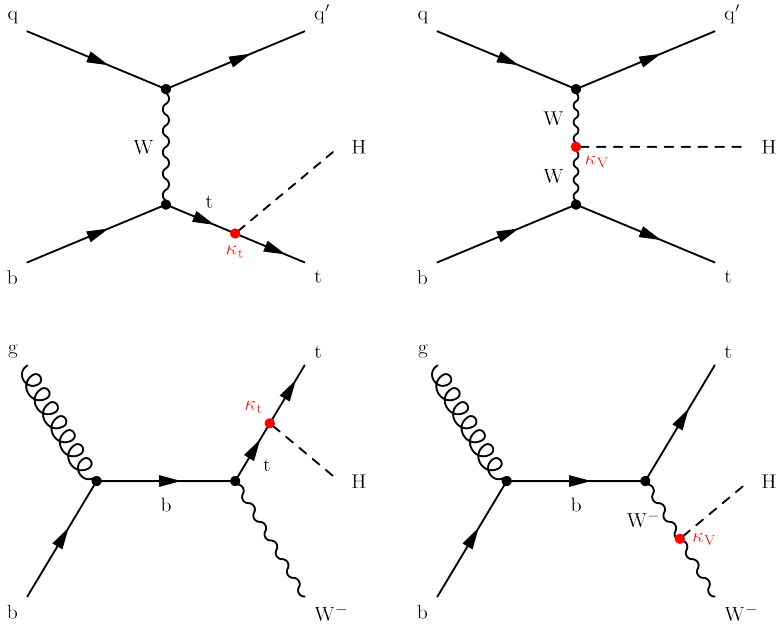
Production of Higgs in the single-top channel

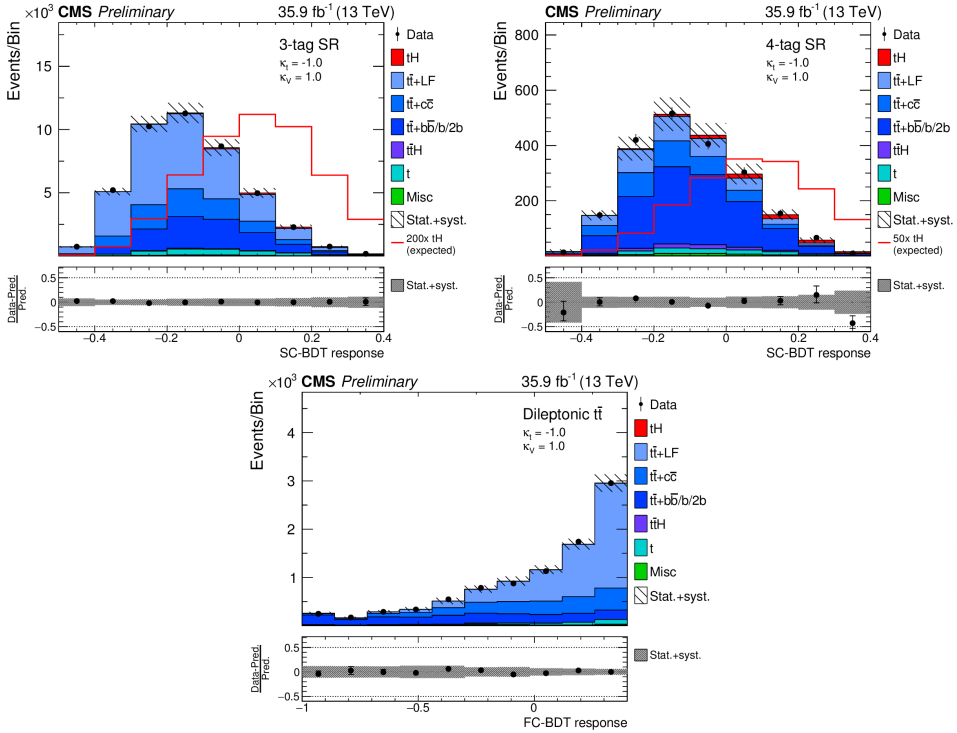


- Included in analyses when they are non-negligible

Search for t(H → bb)

CMS-PAS-HIG-17-016

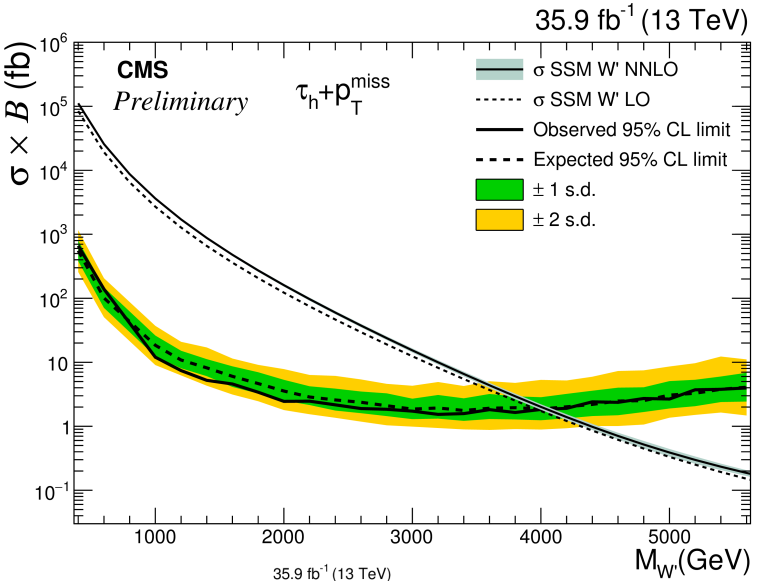


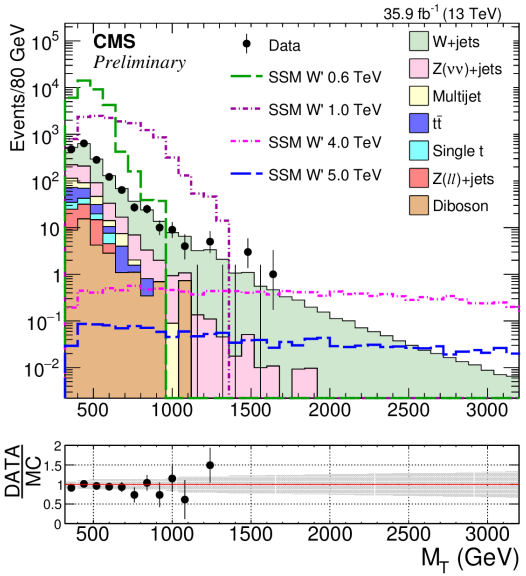


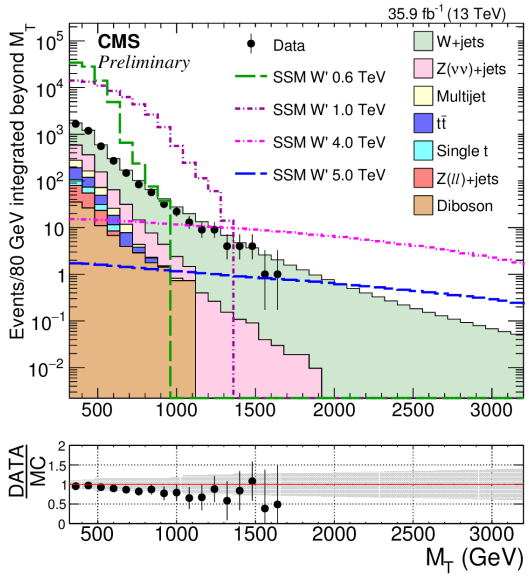
- 13 TeV, 35.9 fb^{-1}
- Two b-jets and leptonically decaying top
- No discovery, no exclusion

Search for W' → τν

Range of M_T	$M_T < 0.5$ TeV	$0.5 < M_T < 1$ TeV	$M_T > 1$ TeV
W+jets	786 ± 110	355 ± 68	21.8 ± 6.2
$Z \to \nu\nu$ + jets	238 ± 120	68 ± 35	0.9 ± 0.5
Multijet	68 ± 35	18 ± 10	0 ± 0
$t\bar{t}$	68 ± 15	14.5 ± 4.5	0 ± 0
$Z (\to \ell\ell)$+ jets	35.8 ± 8.7	10.4 ± 5.1	0 ± 0
Diboson (WW, WZ, ZZ)	24.9 ± 6.4	9.6 ± 3.5	0.7 ± 0.1
Single top quark	21.5 ± 6.5	7.0 ± 2.9	0 ± 0
Total background	1243 ± 160	485 ± 77	23.4 ± 6.2
SSM W′ $M = 600$ GeV	28229 ± 4388	14012 ± 2798	45.6 ± 7.7
SSM W′ $M = 1$ TeV	3767 ± 590	10079 ± 1581	355 ± 98
SSM W′ $M = 4$ TeV	0.7 ± 0.1	3.03 ± 1.8	11.4 ± 3.9
Data	1203	452	15

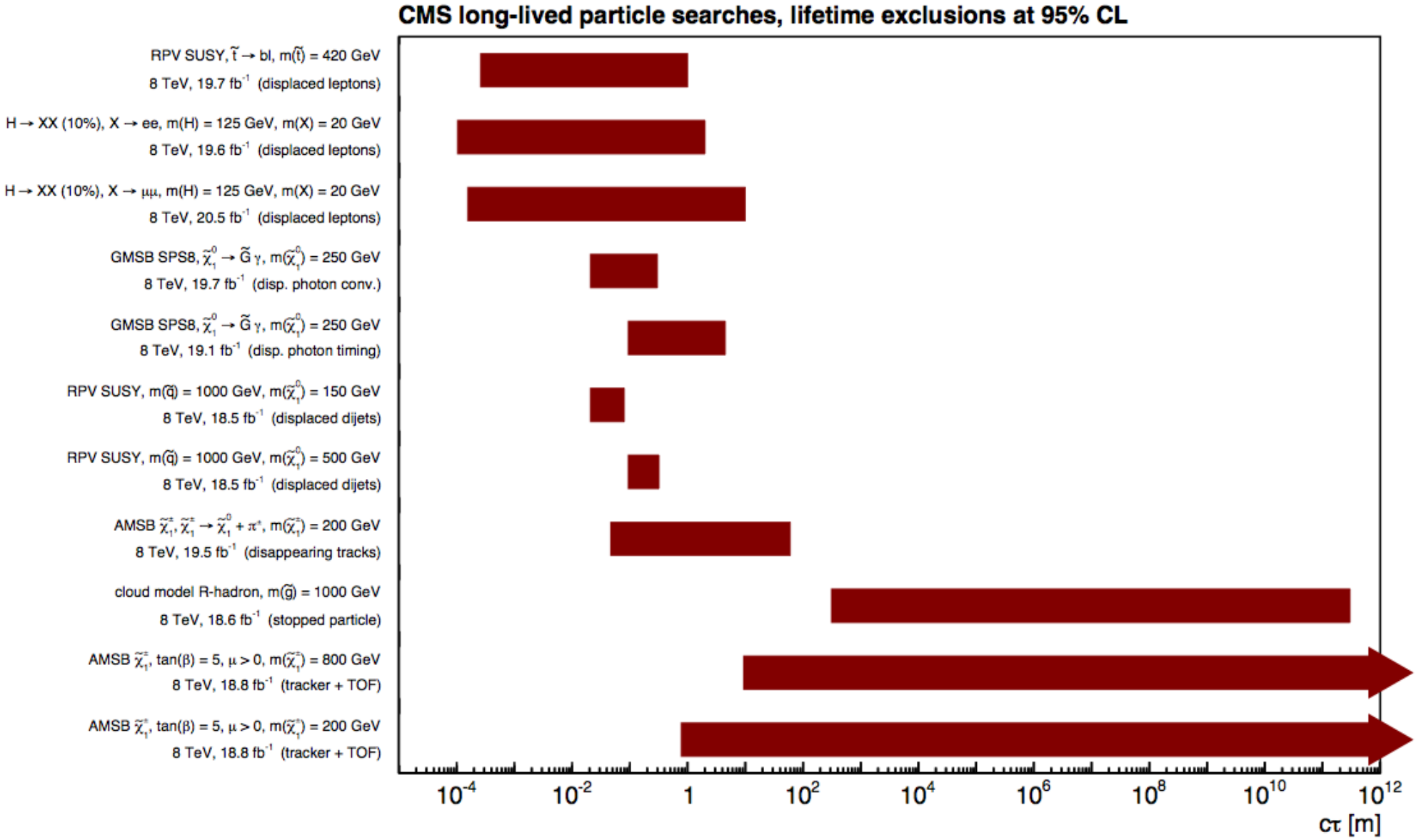




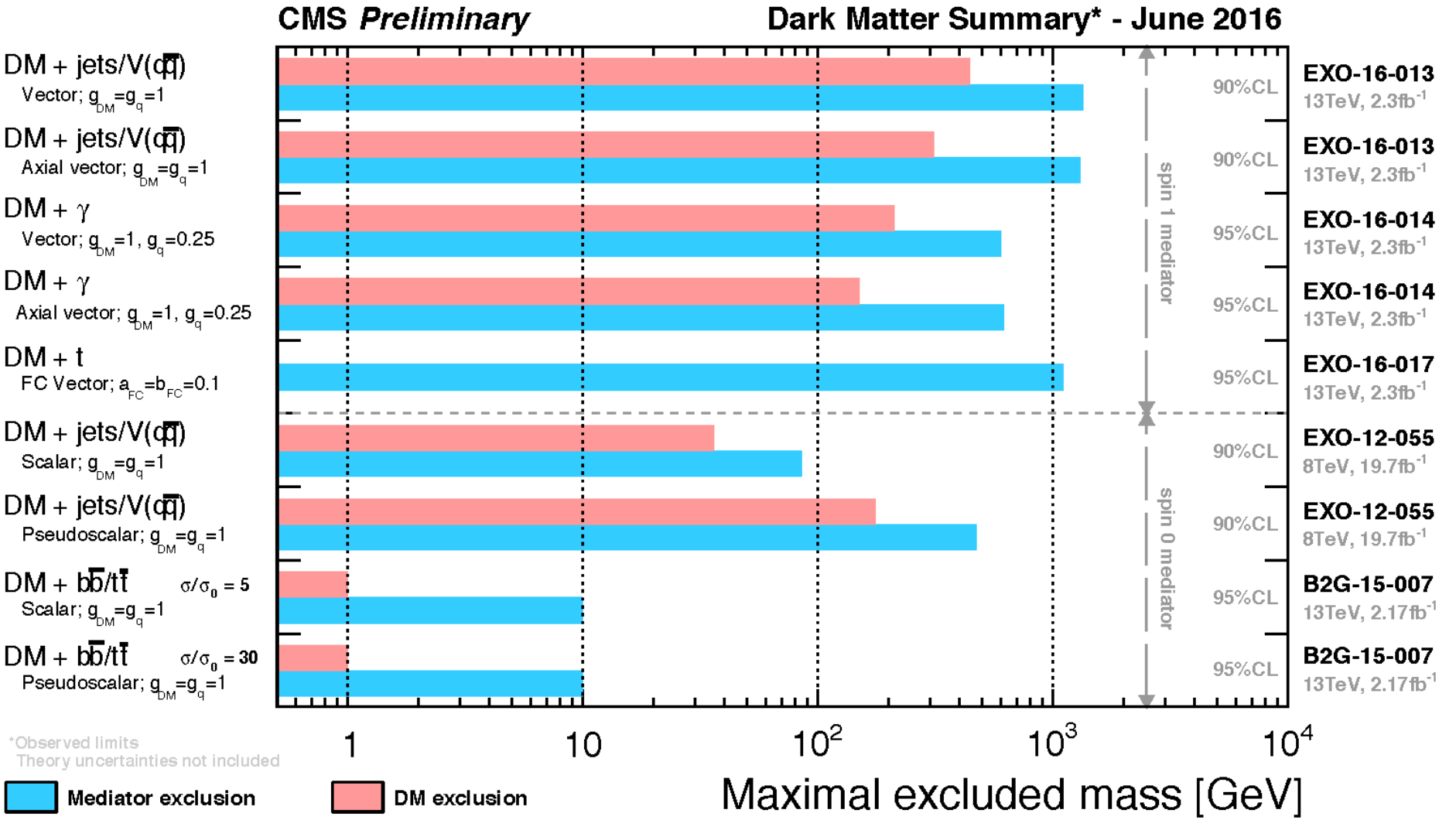


CMS-PAS-EXO-17-008

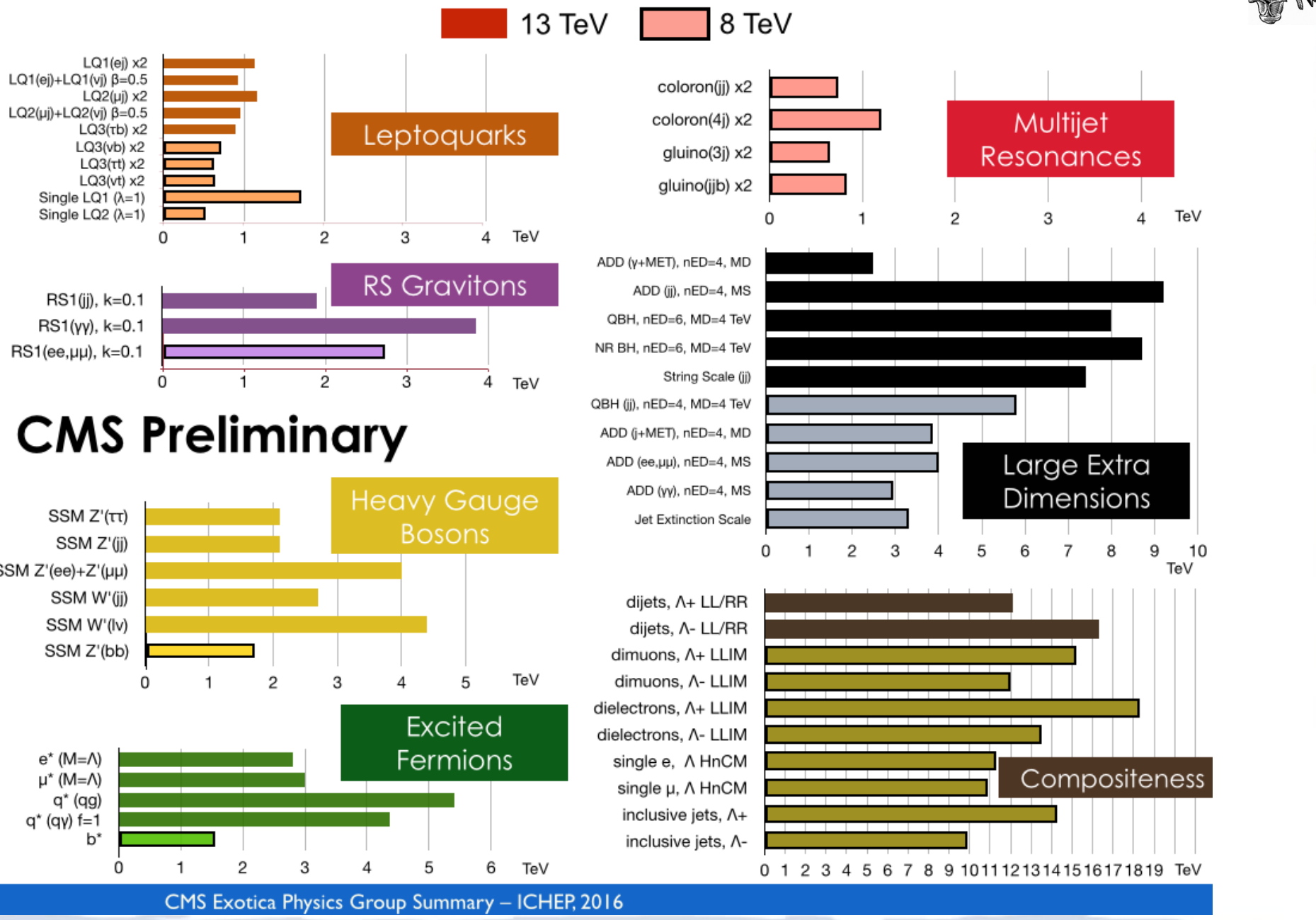
Lifetime searches



Dark matter searches



Exotic searches summary



Rare B^0_s and B^0 to dimuons