Pheno 2016

University of Pittsburgh – May 9, 2016

Top quark production in CMS

- Introduction and dataset (2.2 fb^{-1} at 13 TeV)
- Dilepton channel
  - eμ inclusive cross section
  - Differential cross section (ee, eμ, μμ)
- Lepton plus jets channel
  - Differential cross section
- Comparison with ATLAS and theory
- Evidence for $t\bar{t}$ in association with a Z boson
- Single top t-channel cross section
- Conclusions

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On behalf of the CMS Collaboration

CMS

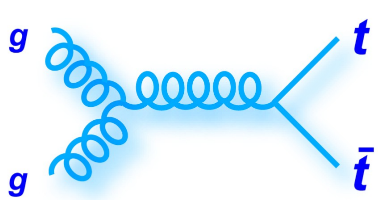
Introduction to top quarks at CMS

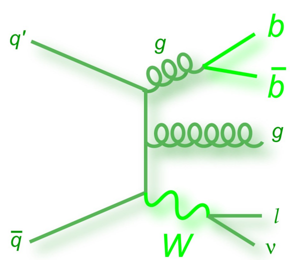
- Measuring top quark cross sections is important at 13 TeV:
  - Precision tests of QCD calculations
  - $t\bar{t}$ is a background in almost all other analyses (SUSY, ttH, etc...)
  - Can use to measure m_t, α_s, calibrate b-tagging
  - Sensitive to BSM physics
- All analyses shown here use 2.2 fb^{-1} good quality data (2015)
- $t\bar{t}$ MC (NLO): Powheg(v2)+Pythia8, NNPDF3.0, m_t=172.5 GeV
  - Alternative with MG5_aMC@NLO, Madgraph5, Powheg+Herwig

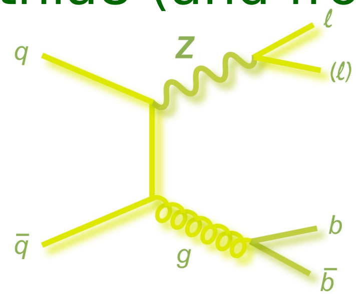
$$\sigma_{t\bar{t}} = 832^{+20}_{-29}(\text{scale}) \pm 35(\text{PDF} + \alpha_\text{s})\ \text{pb}$$

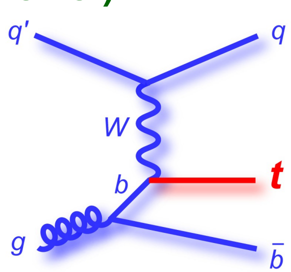
NNLO+NNLL, m_t=172.5 GeV, Czakon and Mitov

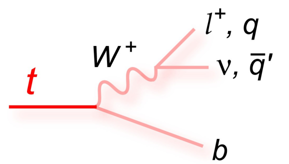
- Singletop tW (71pb), t-channel (217pb): Powheg, aMC@NLO+Pythia
- Main backgrounds:
  - W+jets, Z+jets: MG5_aMC@NLO + Pythia
  - QCD multijet, Diboson: Pythia8 (and from data)







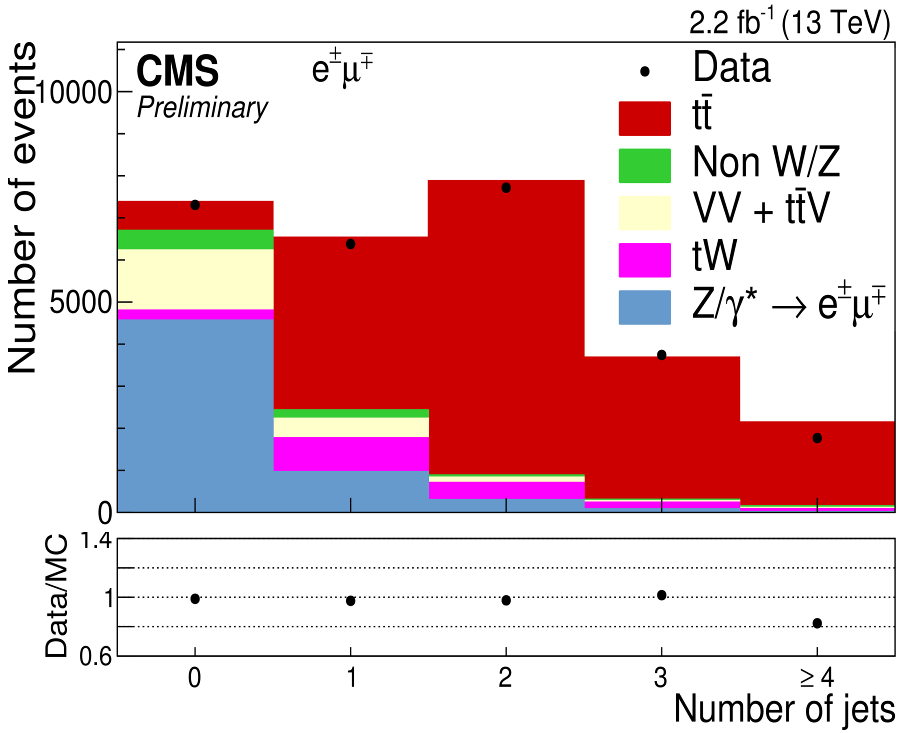




Inclusive eμ cross section

- Trigger: dilepton (eμ) trigger
- Event selection:
  - Isolated OS eμ pair, p_T>20 GeV, $|\eta|$<2.4
  - ≥2 jets, p_T>30 GeV, $|\eta|$<2.4
  - ≥1 b-tag: ε_b~67%, ε_{qg}~1%, ε_c~15%
  - $m_{e\mu}$ > 20 GeV
- Background estimation:
  - DY normalized to MC prediction by a data/MC SF from Z peak in data
  - Non-W/Z from SS control region
  - Single top, diboson from MC
- Cut and Count

$$\sigma_{t\bar{t}} = \frac{N_{\rm data} - N_{\rm bkg}}{\varepsilon A \mathcal{L}}$$



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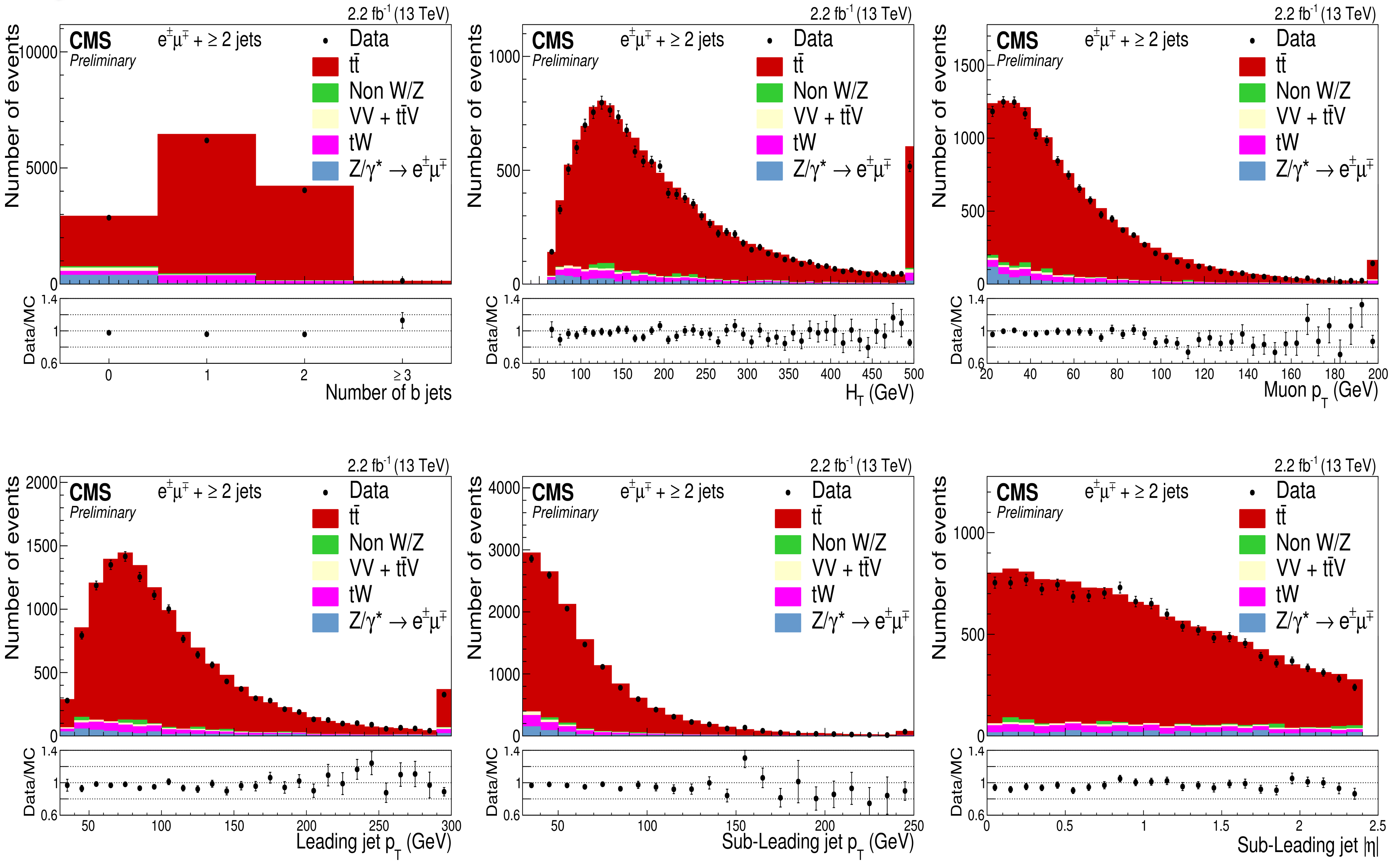
Source	Number of $e^{\pm}\mu^{\mp}$ events
Drell–Yan	$24 \pm 9 \pm 4$
Non-W/Z leptons	$109 \pm 50 \pm 33$
Single top quark	$463 \pm 6 \pm 145$
VV	$15 \pm 2 \pm 5$
$t\bar{t}$ V	$31 \pm 1 \pm 10$
Total background	$642 \pm 52 \pm 149$
98% $t\bar{t}$ dilepton signal	$10199 \pm 14 \pm 462$
Data	10368

Kinematic distributions

- $t\bar{t}$ normalized to NNLO+NNLL



eμ inclusive cross section results

Source	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics	8.3	1.0
Trigger efficiencies	9.7	1.2
Lepton efficiencies	18.4	2.3
Lepton energy scale	0.3	0.04
Jet energy scale	17.0	2.2
Jet energy resolution	0.8	0.1
b tagging	11.0	1.4
Mistagging	0.5	0.06
Pileup	1.5	0.2
Single top quark	11.8	1.5
VV	0.4	0.06
Drell–Yan	0.3	0.04
Non-W/Z leptons	2.7	0.3
$t\bar{t}$ V	0.8	0.1
PDF	4.8	0.6
Scale (μ_F and μ_R)	0.8	0.1
Parton shower scale	6.4	0.8
$t\bar{t}$ NLO generator	16.8	2.1
$t\bar{t}$ hadronization	10.2	1.3
Total systematic (no integrated luminosity)	38.0	4.8
Integrated luminosity	21.4	2.7
Total	44.4	5.6

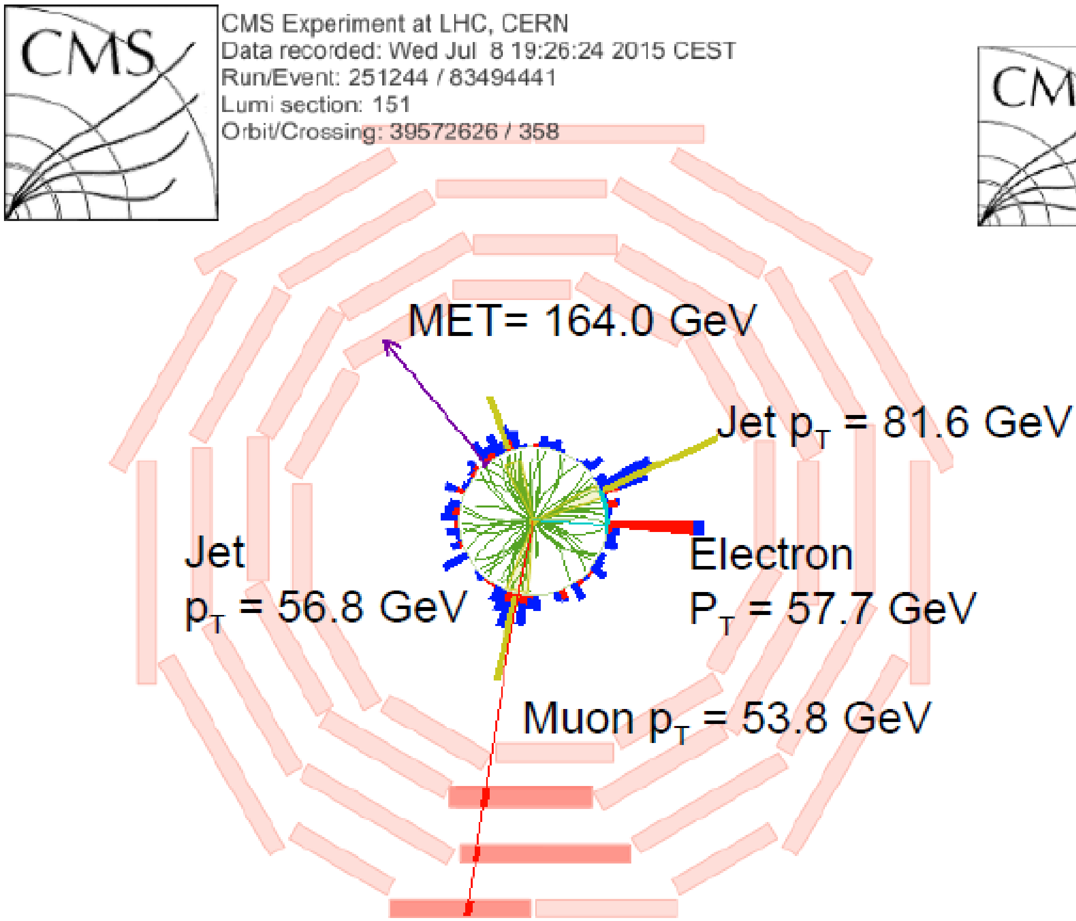
- Luminosity uncertainty dominates
- Still room to improve calibrations, efficiencies

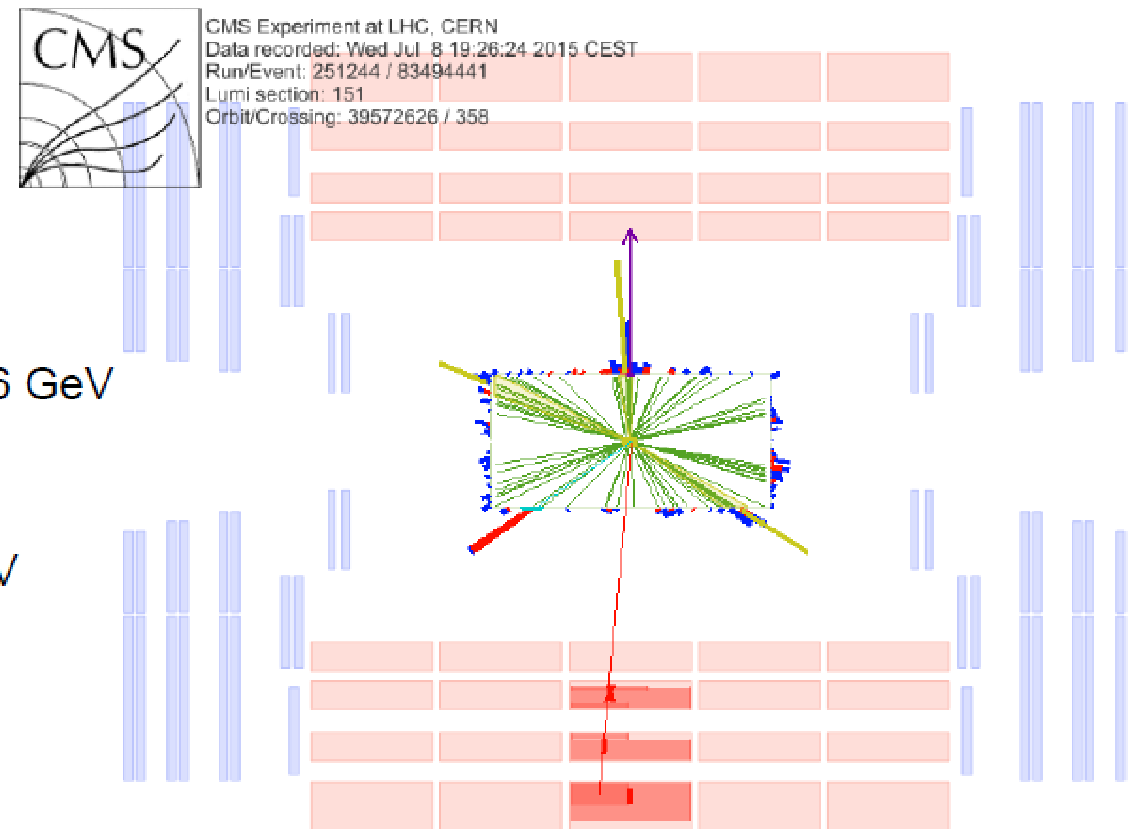
$\sigma_{t\bar{t}}$ = 793 ± 8 (stat) ± 38 (syst) ± 21 (lumi) pb

Values for m_t=172.5 GeV. For m_t=173.34 GeV $\sigma_{t\bar{t}}$ decreases by ~0.7%.

Relative error of 5.6% (was 3.9% for 20 fb^{-1} 8 TeV data)

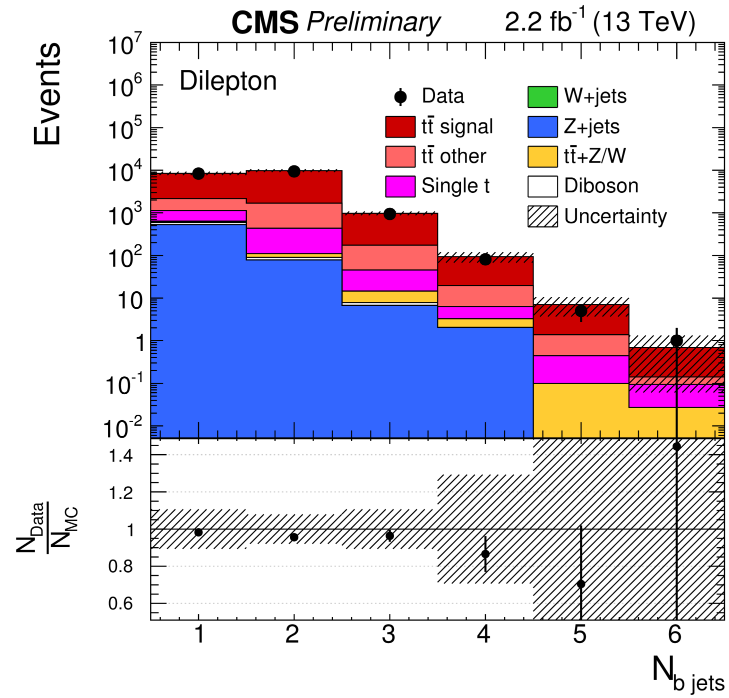
$t\bar{t} \to e\nu_e b\mu\nu_\mu b$ candidate event

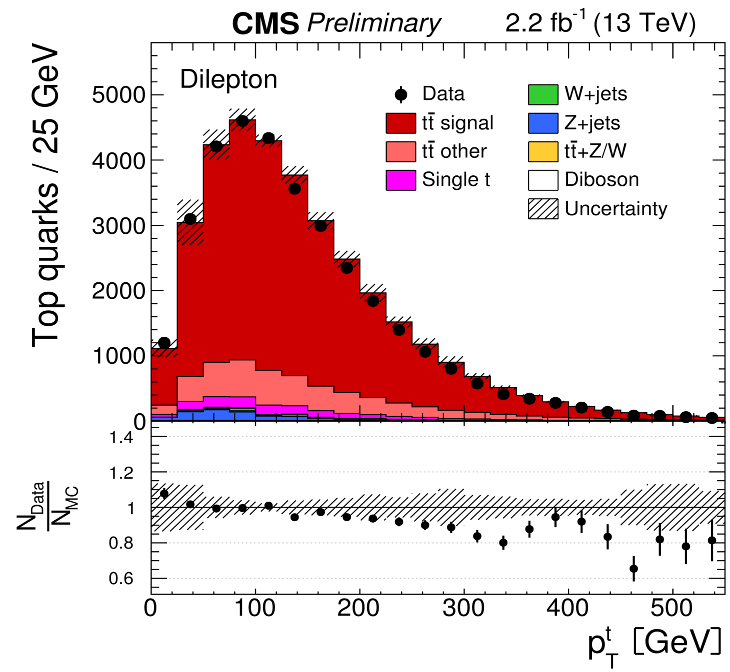




Dilepton differential cross section

- Trigger on isolated dileptons and $\ell\ell$+jets topologies
- Event selection (ee, eμ, μμ)
  - Isolated OS leptons: p_T>20 GeV, |η|<2.4
  - ≥2 jets: p_T>30 GeV, |η|<2.4
    - ≥1 b-tag jet (CSV): ε_b≈85% ; ε_{qg}≈10%
  - $m_{\ell\ell}$>20 GeV
  - ee, μμ: MET>40GeV and |91-$m_{\ell\ell}$|>15GeV
- Same background estimations as inclusive σ
- Kinematic reconstruction (94% efficient)
  - Constraints: m_t=172.5 GeV (x2), m_W=80.4 GeV (x2), $(p_\nu+p_{\bar{\nu}})_T$=MET
  - Reconstruct each event 100 times, smearing inputs by their resolution
  - Consider weighted average
  - Derive scale factor $\varepsilon_{DATA}/\varepsilon_{MC}$





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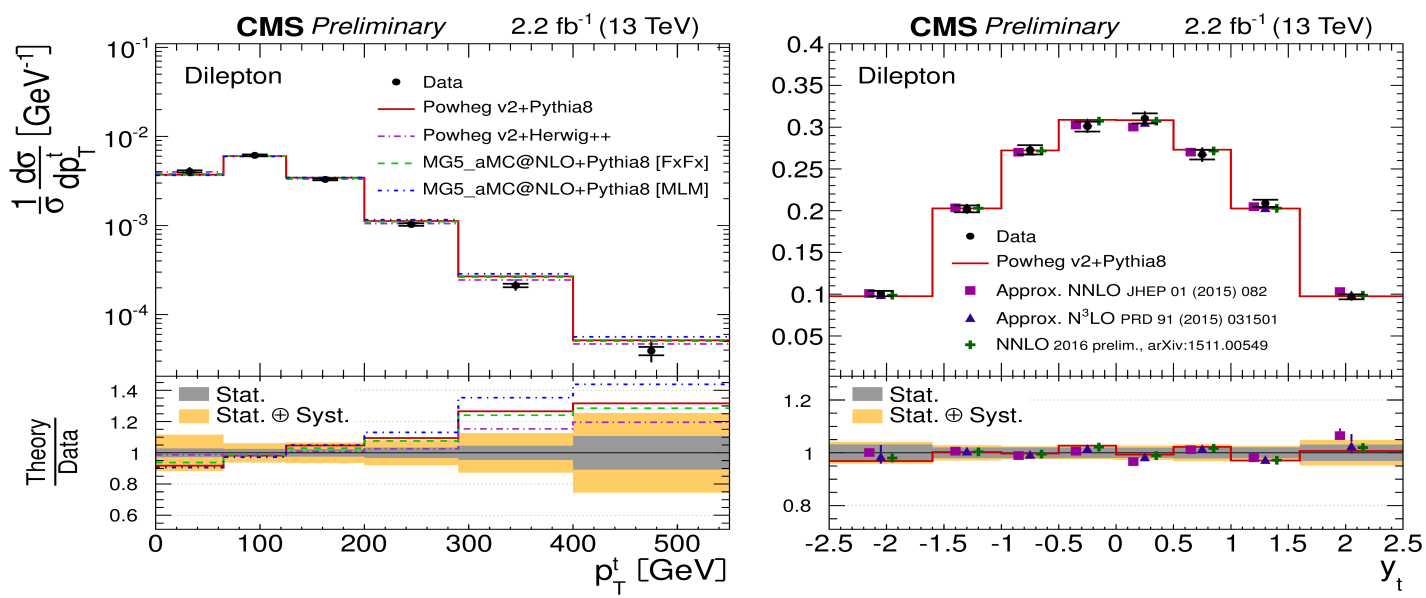
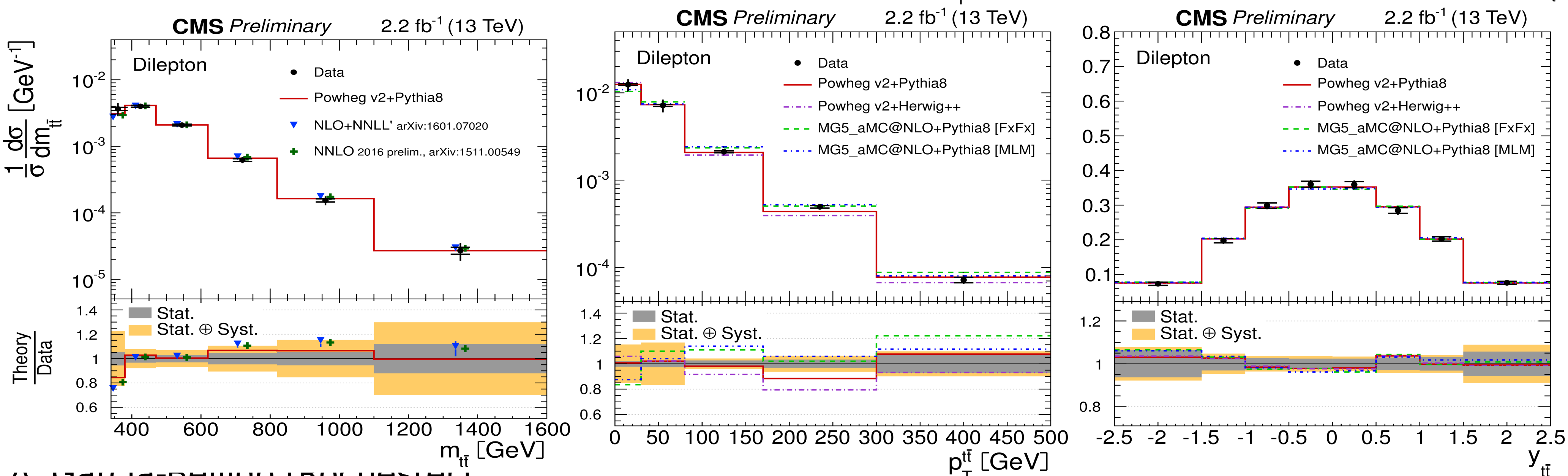
Dilepton differential results

- Calculate normalized differential cross sections to reduce systematics
- Perform regularized unfolding to parton level
- Good agreement overall with beyond NLO QCD calculations

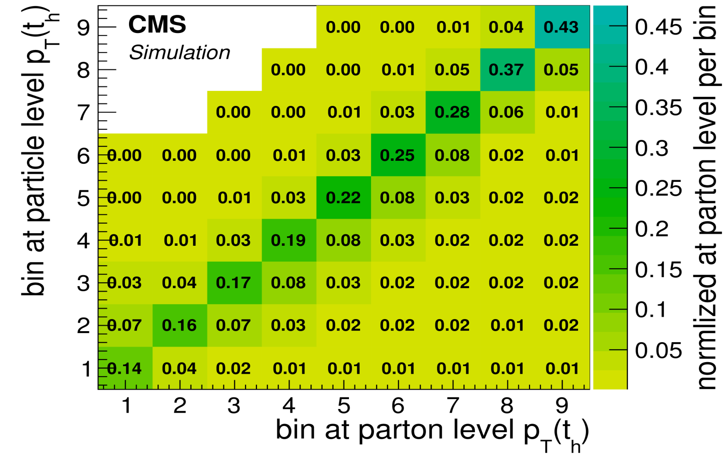
Process	Events
DATA	10257
$t\bar{t}$ signal	81%
$t\bar{t}$ other	13%
Single top (tW)	3%
Z+jets	2%
VV, W+jets, QCD neglible	

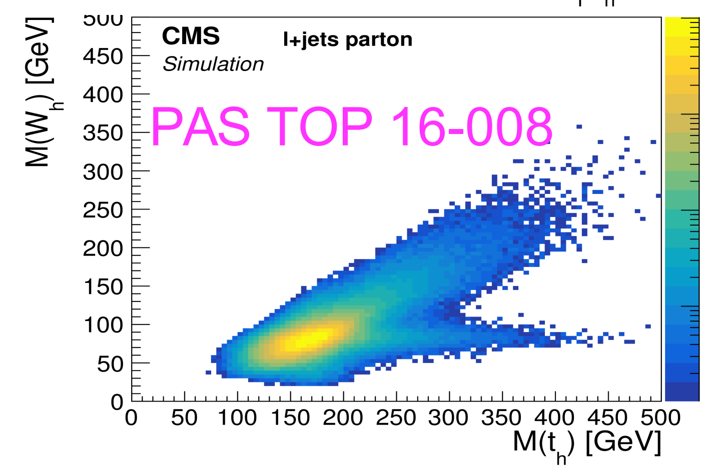


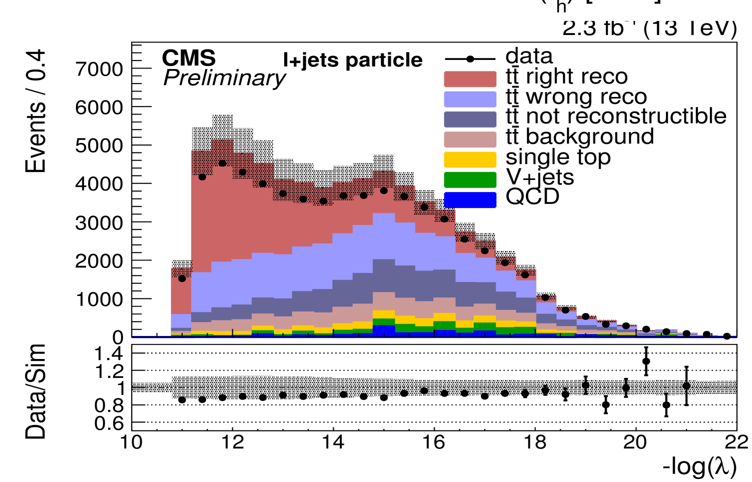


Differential ℓ+jets cross section

- Triggers based on single isolated lepton
- Event selection:
  - 1 isolated lepton with p_T>30 GeV, $|\eta|$<2.1
  - ≥4 jets with p_T>25 GeV, $|\eta|$<2.4
    - ≥1 b-tagged (ε_b≈65% ; ε_{qg}≈3%)
    - b-tag jet and leading non-b jet: p_T>35 GeV
- Unfold to parton level and to particle level
- Kinematic reconstruction
  - Use mass constraints of m_t, m_W on leptonic side to obtain neutrino momentum (NIM 736, 169 [2014]) and correct b-jet on leptonic side
  - Calculate probability λ_m according to 2D mass distributions of m_t, m_W on hadronic side to obtain best permutation of jets
  - Cut $-\log(\lambda_m)$<10
  - Correct $t\bar{t}$ reconstruction efficiency: 63% on average, 80% for 4jet, ~40% for 7jet events

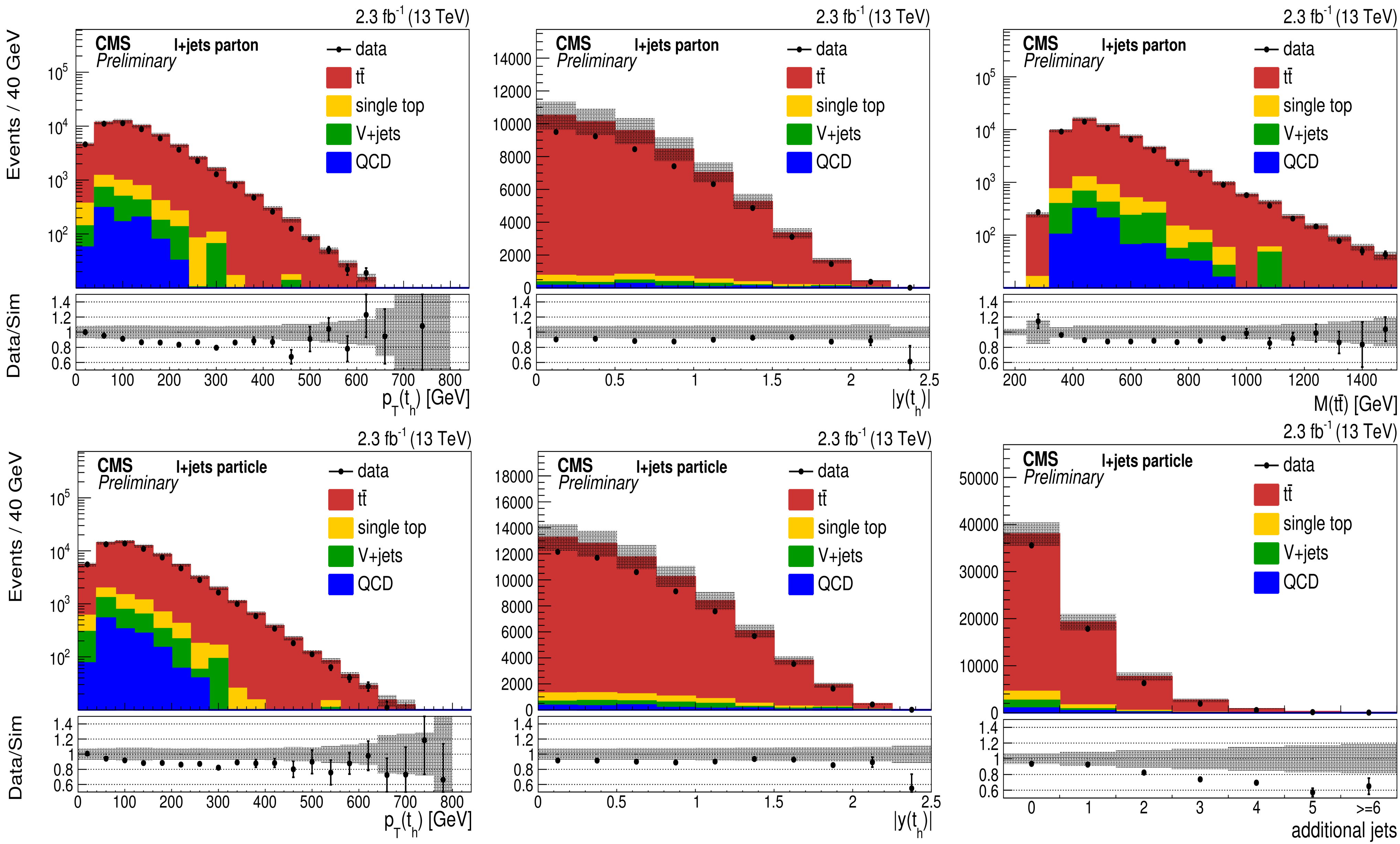






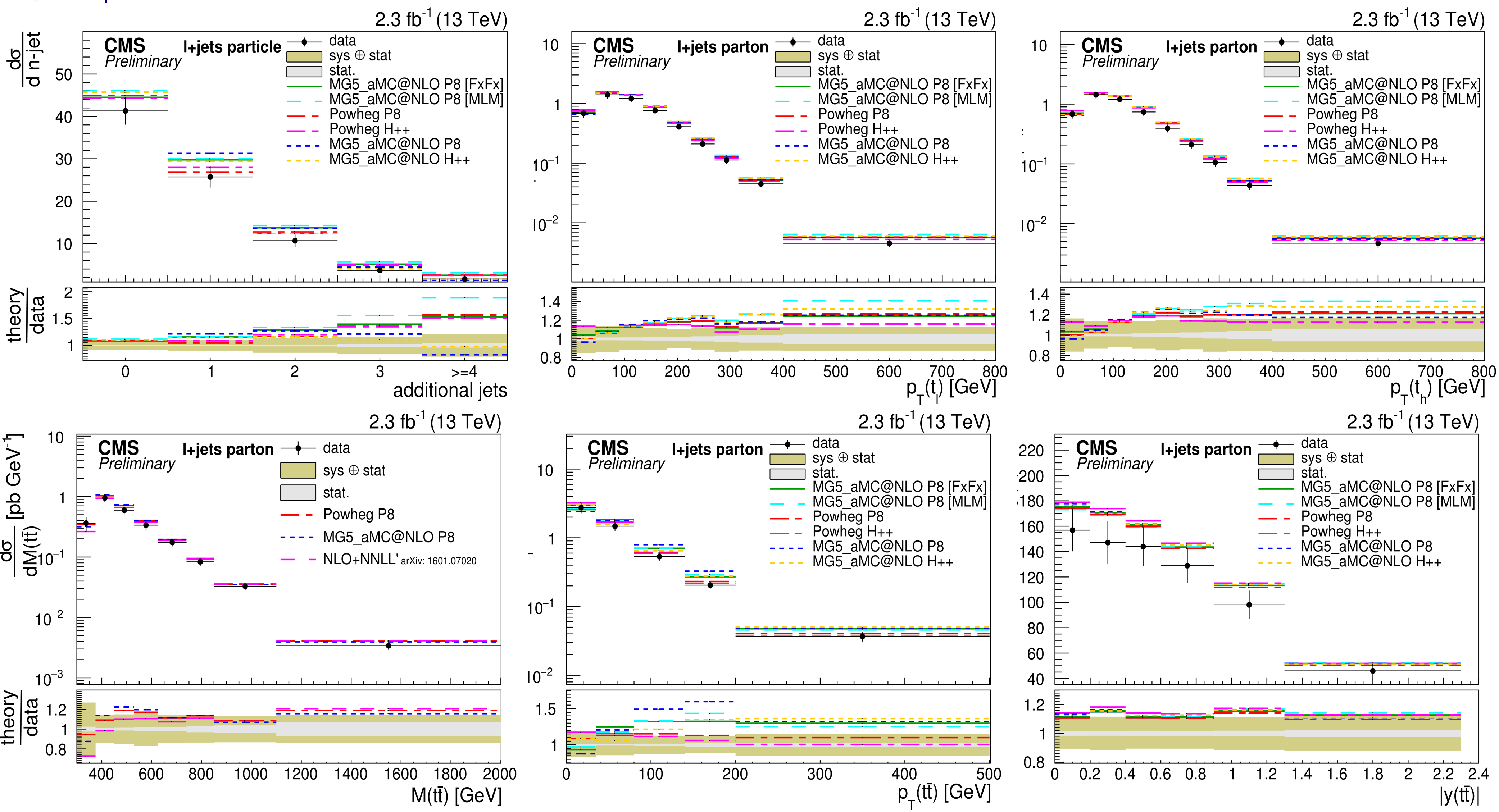
Kinematic distributions

- $t\bar{t}$ normalized to NNLO+NNLL cross section
- Backgrounds from MC simulations (50% syst. on their normalization)



Parton level distributions ℓ+jets

- Unfolded and extrapolated to full phase space
- Binning optimized to have similar number of events per bin
- $p_T(t)$ still a bit too hard: Powheg+Pythia6 was harder in previous 8 TeV results
- $p_T(t\bar{t})$ better described by Powheg than MG5_aMC@NLO or Madgraph (+≤3 jets)



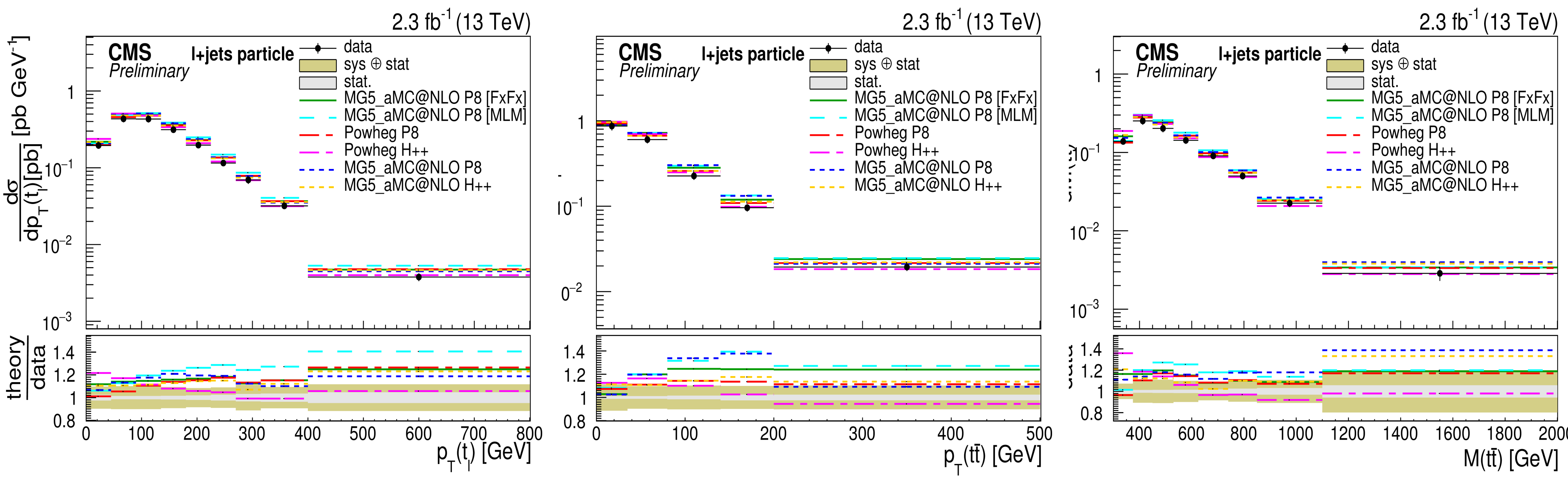
ℓ+jets differential cross section

- Particle level calculations avoid theoretical extrapolations to full phase space → smaller uncertainties
- Top proxy: ℓ (including radiative losses), ν not from hadrons, stable particles clustered in ΔR=0.4 jets, b-jets contain b-hadrons (unstable), with p→0

$$K^2=[M(p_N+p_l+p_{b_1})-m_t]^2+[M(p_{j_1}+p_{j_2})-m_W]^2+[M(p_{j_1}+p_{j_2}+p_{j_3})-m_t]^2$$

Main uncertainties

source	particle [%]	parton [%]
statistical uncertainty	1–5	1–5
b tagging	2–3	2–3
jet energy scale	5–7	6–8
NLO generator	1–6	1–10
parton shower scale	1–5	2–9
POWHEG + PYTHIA8 vs. HERWIG++	< 3	1–12

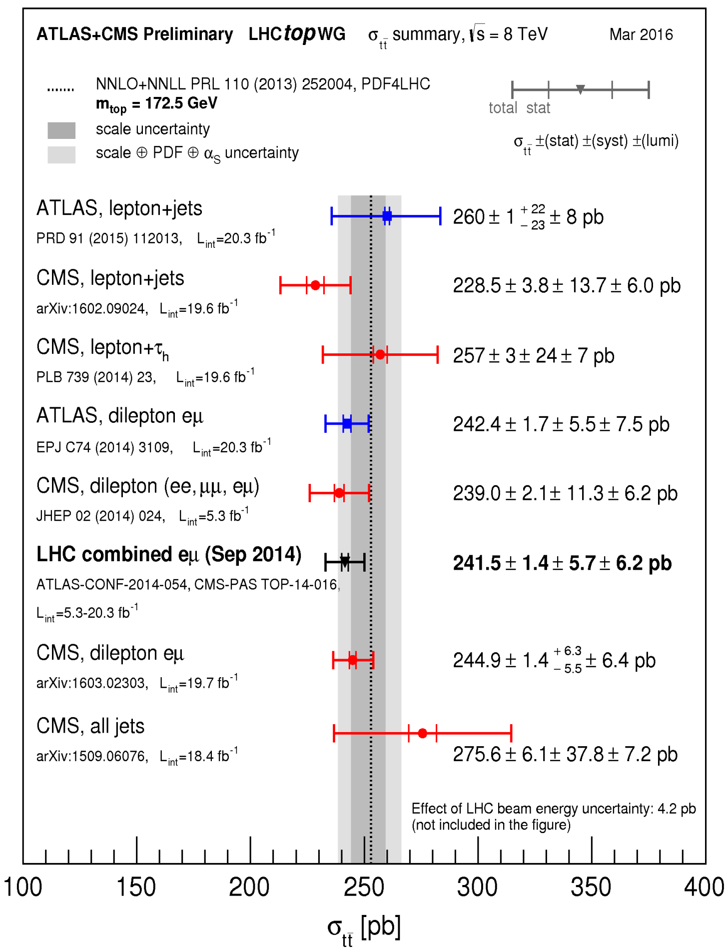


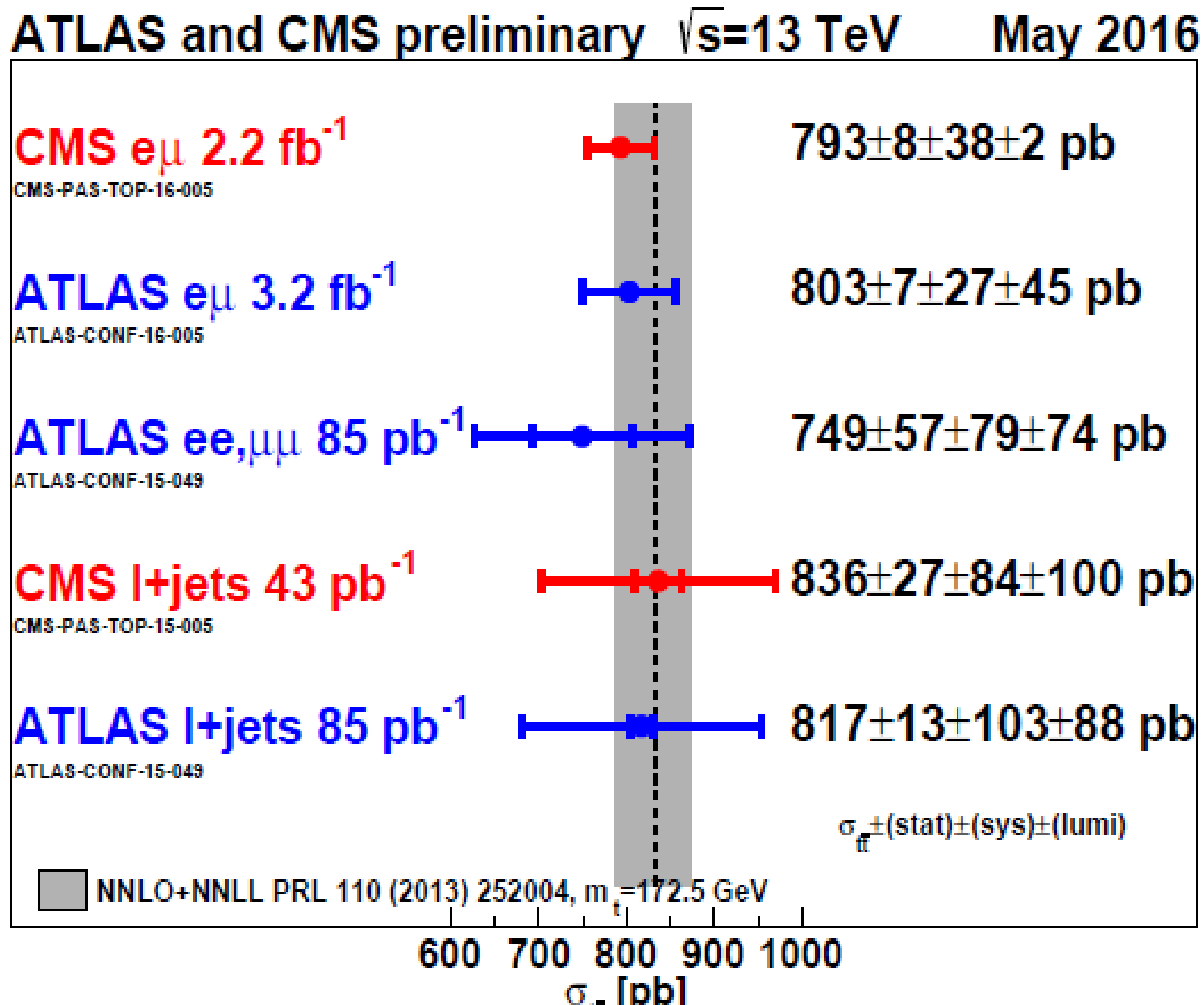
$\sigma_{t\bar{t}}$ = 836 ± 27 (stat) ± 84 (sys) ± 100 (lumi) pb [43 pb^{-1}]

Values for m_t=172.5 GeV. Slope: -6.3 pb/GeV

$\sigma_{t\bar{t}}$ comparison with ATLAS and theory

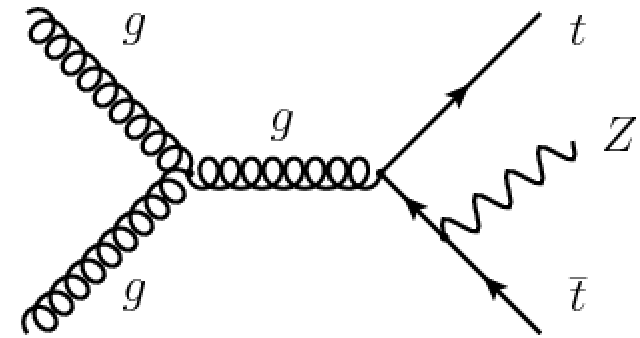
- New measurements at 13 TeV are in agreement between each other and the NNLO+NLL prediction
- Now working on reducing systematic uncertainties
  - Hadronization, PS, modelling, JES, b-tagging, efficiencies





$t\bar{t}$+Z production

- Select events with 3 or 4 leptons and at least 2 jets
- Data-driven estimates for non-prompt leptons, control regions for WZ and ZZ
- Binned likelihood fit to all categories, including nuisance parameters



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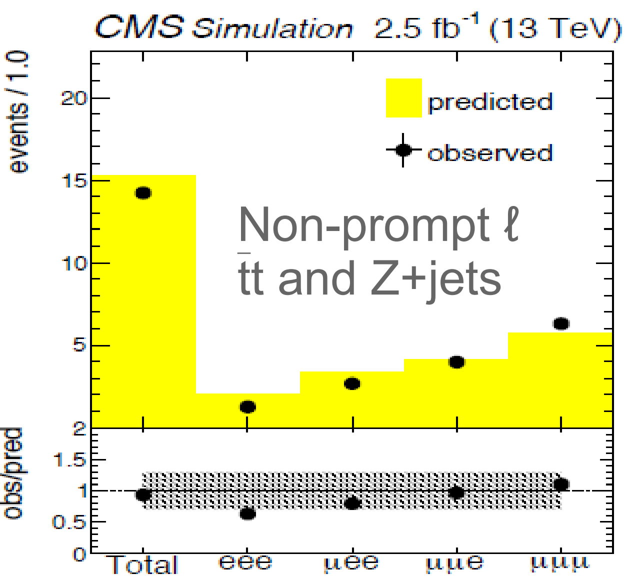
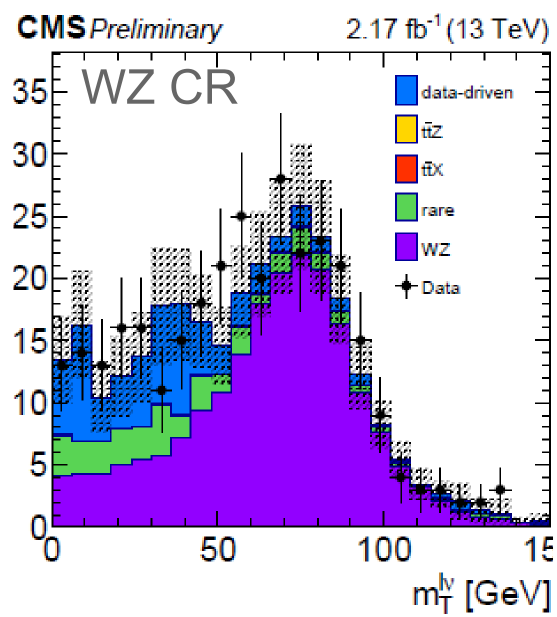
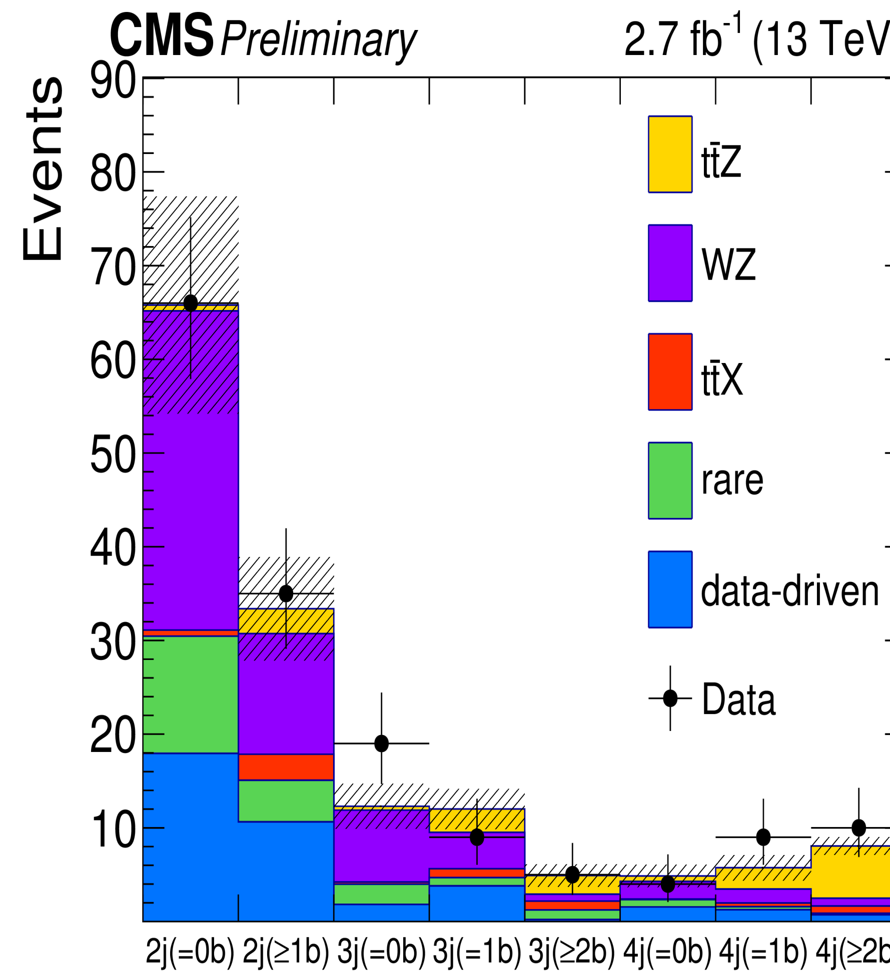






$\sigma_{t\bar{t}Z}$ = 1.07 ± 0.33(stat) ± 0.15(sys) pb

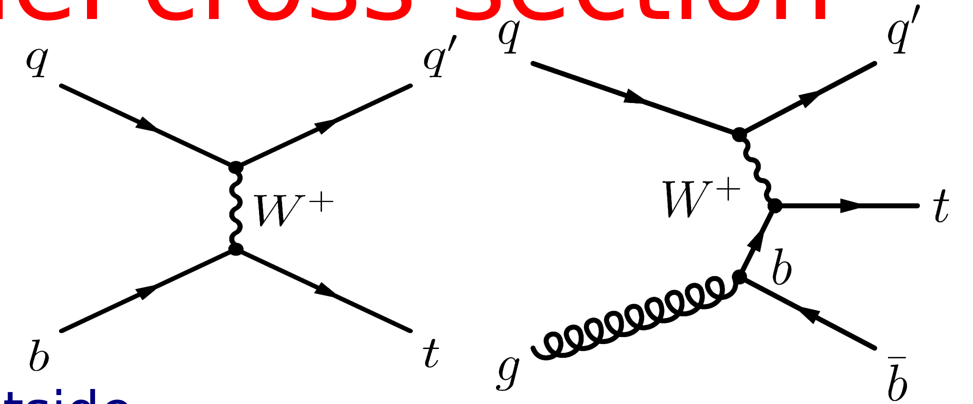
$\sigma_{t\bar{t}Z}$ = 0.76 ± 0.08 pb [aMC@NLO]

Significance: 3.1σ exp., 3.6σ observed

μ = 1.7 ± 0.40(stat) ± 0.19(sys)

Single top t-channel cross section

- Event selection
  - 1 isolated μ, p_T>22 GeV, |η|<2.1
  - 2 jets, p_T>40 GeV, |η|<4.7
  - 1 b-tag (MVA) ($\varepsilon_b \approx 45\%$; $\varepsilon_{qg} \approx 0.1\%$)
- W+jets from simulation, validated outside top mass window: 130<$m_{\ell\nu b}$<225 GeV
- QCD shape from data, normalization from fit of $m_T(W)$ in SB and cut: $m_T(W)$>50 GeV
- 2j1t is the signal region, use 3j1t and 3j2t to constrain $t\bar{t}$
- Use 11 variables combined in MVA
  - $\eta(q)$, $m_{\ell\nu b}$, m_{jj}, $m_T(W)$, $\cos(\theta_{q\ell})$, ...



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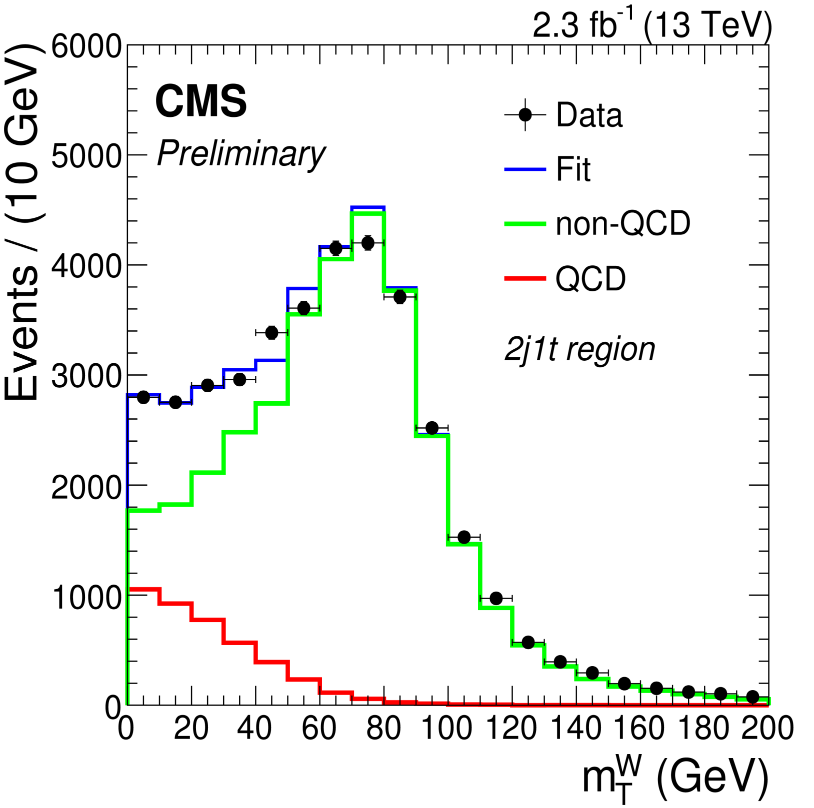
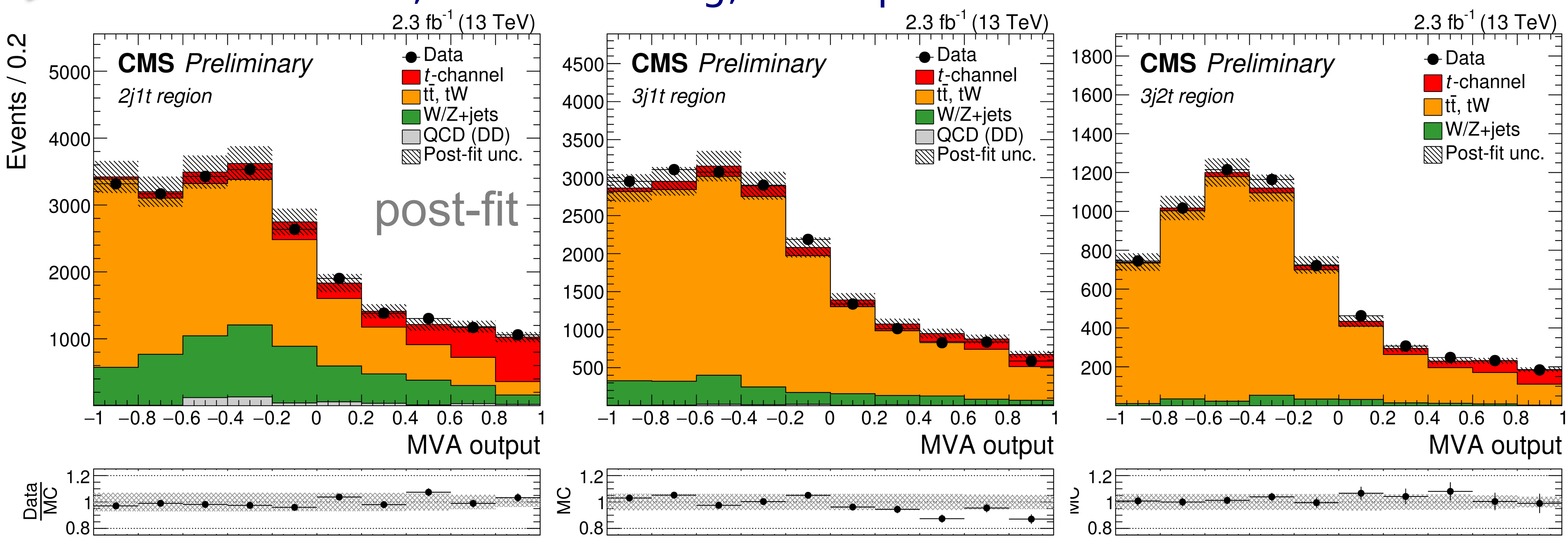
Process	μ^+	μ^-
Top ($t\bar{t}$ and tW)	7048±13	7056±13
W+jets and Z+jets	3039±102	2399±90
QCD multijet	241±121	219±110
Single top *t*-channel	1539±13	977±10
Total expected	11867±159	10651±143
Data	11877	11017



t-channel results

- Fit MVA output for μ^+, μ^- and inclusive
  - Bkg norm. constrained (10% tt, 30% EW, 50% QCD from prediction)
- Ratio $\sigma_t/\sigma_{\bar{t}}$ = 1.75 ±0.16(stat) ±0.21(syst)
- 15% overall unc., 12% modeling, 6% exp.



σ_t = 228 ± 9(st) ± 14(ex) ± 29(th) ± 6.2(lum) pb

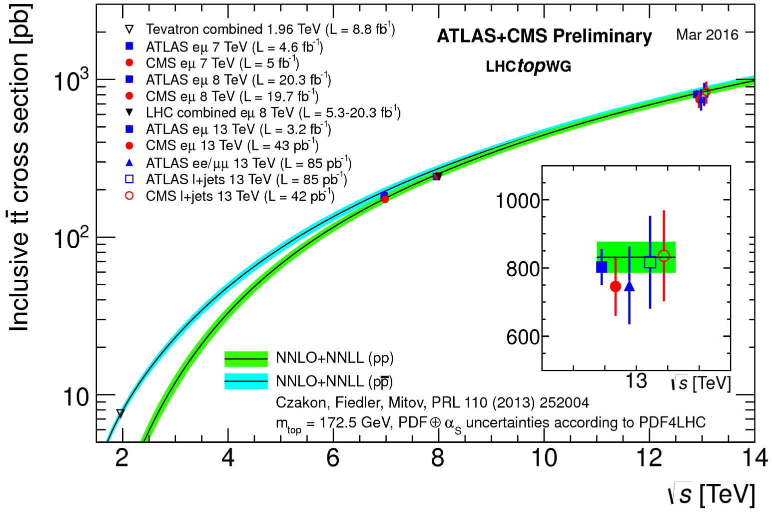
σ_t = 217.0 ± 6.6(scale) ± 6.2(PDF) pb [NLO]

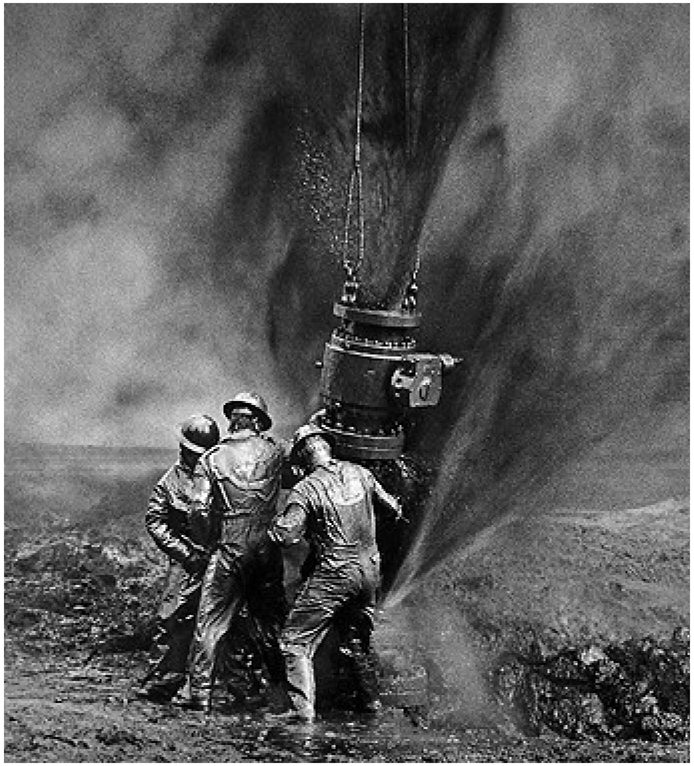
NNLO available: 214.5 ± 0.6 [PLB 736, 58 (2014)]

$|fV_{tb}|$ = 1.02 ± 0.07(exp) ± 0.02(th)

Conclusions

- Robust measurements with early Run II data
- Results are overall in good agreement with theory and ATLAS
  - No signature of new physics yet!
- Dilepton analyses lead in precision: 5.6%
- Will focus now on reducing systematics
  - Better understanding of JES, trigger, and b-tagging
  - Constrain hadronization, PS, modelling
- Single top entering new era of differential measurements and properties
- More papers coming with new tools: boosted top tagging, pile-up cleaning algorithms, more channels, new fitting techniques





https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP