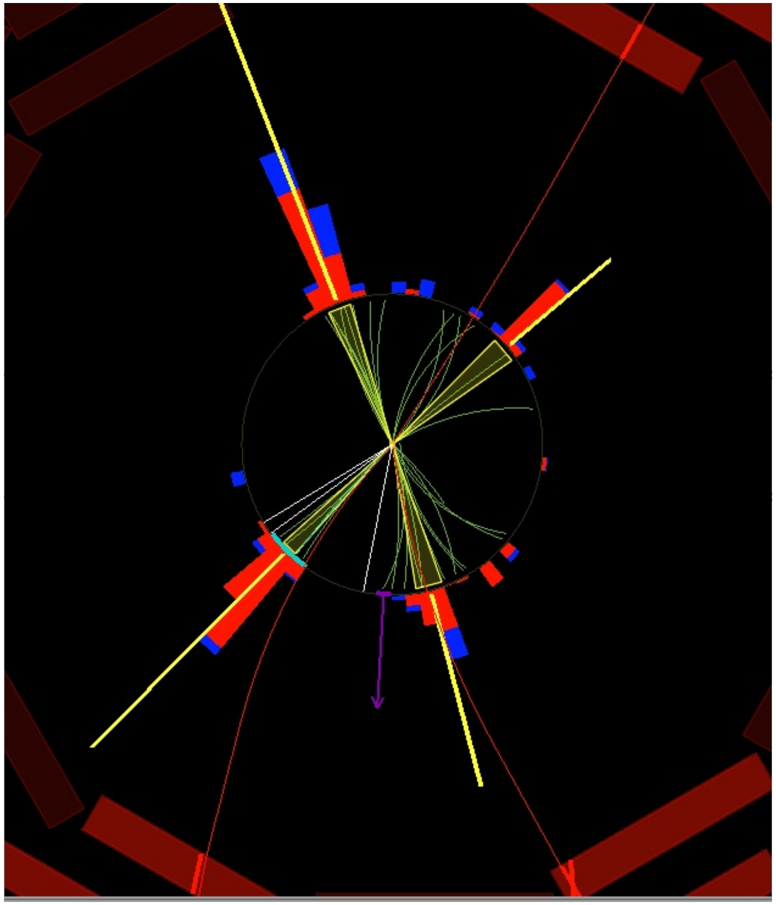
XXV Rencontres de Vietnam

ICISE, Qui Nhon – August 7, 2018

Top quark production in CMS

- Introduction
- Inclusive $t\bar{t}$ measurements:
  - eμ inclusive cross section
  - First ℓ+jets observation of $pPb \rightarrow t\bar{t}$
- Differential $t\bar{t}$ measurements
  - Dilepton cross section (ee, eμ, μμ)
  - ℓ+jets cross section
    - Doubly differential
- Single top t-channel cross section
- Single top tW cross section
- Conclusions



UNIVERSITY of ROCHESTER

Aran Garcia-Bellido

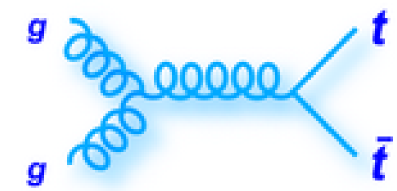
On behalf of the CMS Collaboration

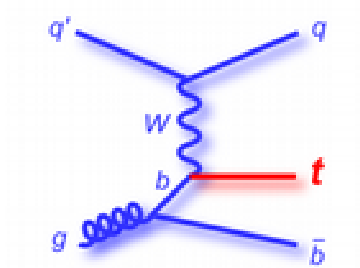
Introduction to top quarks at CMS

- 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, $t\bar{t}$H, etc...)
  - Can use to measure m_t, α_s, calibrate b-tagging, constrain PDFs
  - Sensitive to BSM physics
- The LHC is a top factory:

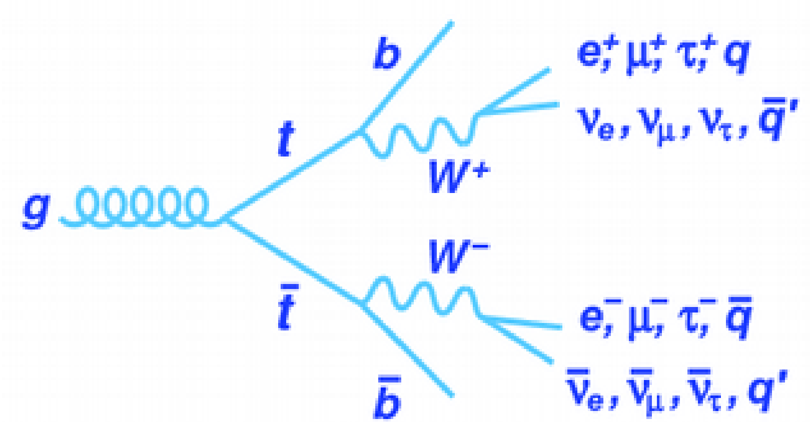
$$\sigma_{t\bar{t}} = 832^{+20}_{-29}(\text{scale}) \pm 35(\text{PDF} + \alpha_\text{s})\ \text{pb}$$

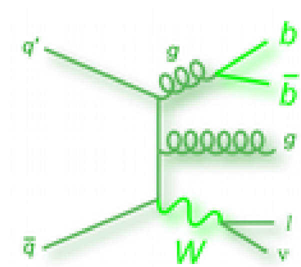
NNLO+NNLL, m_t=172.5 GeV, Czakon and Mitov

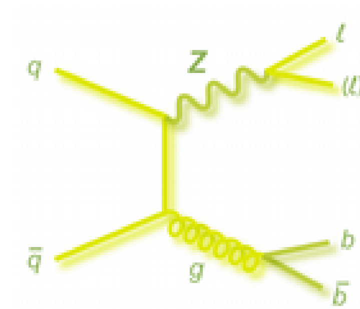




- Singletop: t-channel (217pb), tW (71pb), s-channel (10pb)
- Main backgrounds: W+jets, Z+jets, multijet







Inclusive eμ cross section

- Trigger: dilepton (eμ) trigger
- Event selection:
  - Isolated OS eμ pair, p_T>20 GeV, |η|<2.4
  - ≥2 jets, p_T>30 GeV, |η|<2.4
  - ≥1 b-tag: ε_b~67%, ε_{qg}~1%, ε_c~15%
  - $m_{e\mu}$ > 20 GeV
- Background estimation:
  - DY normalized 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

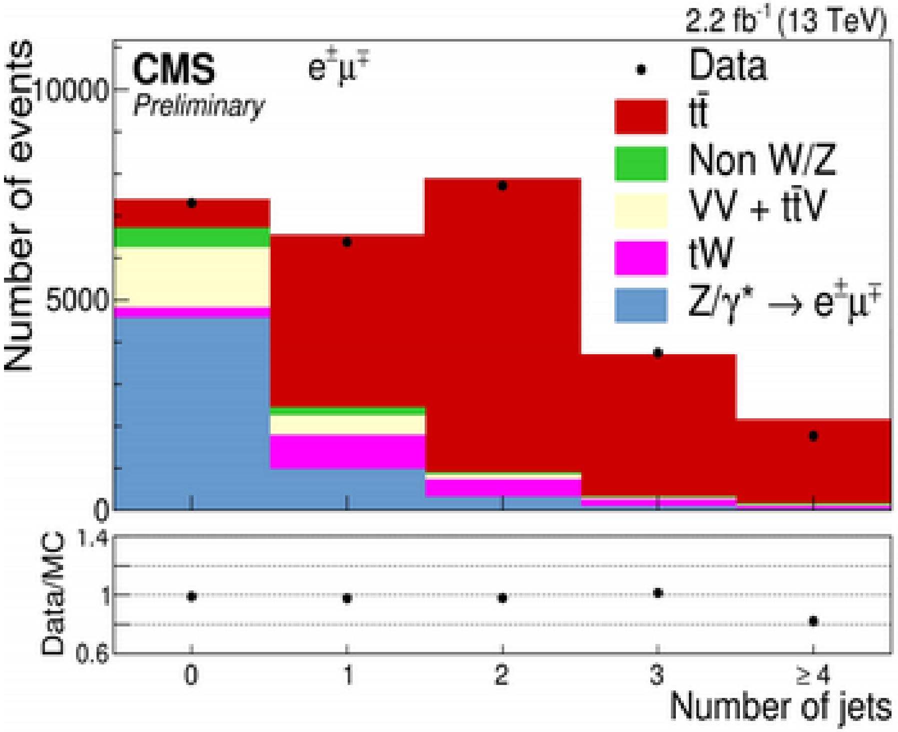
$$\sigma_{t\bar{t}} = \frac{N_{\rm data} - N_{\rm bkg}}{\varepsilon A \mathcal{L}}$$

$\sigma_{t\bar{t}}$ = 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)



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

98%

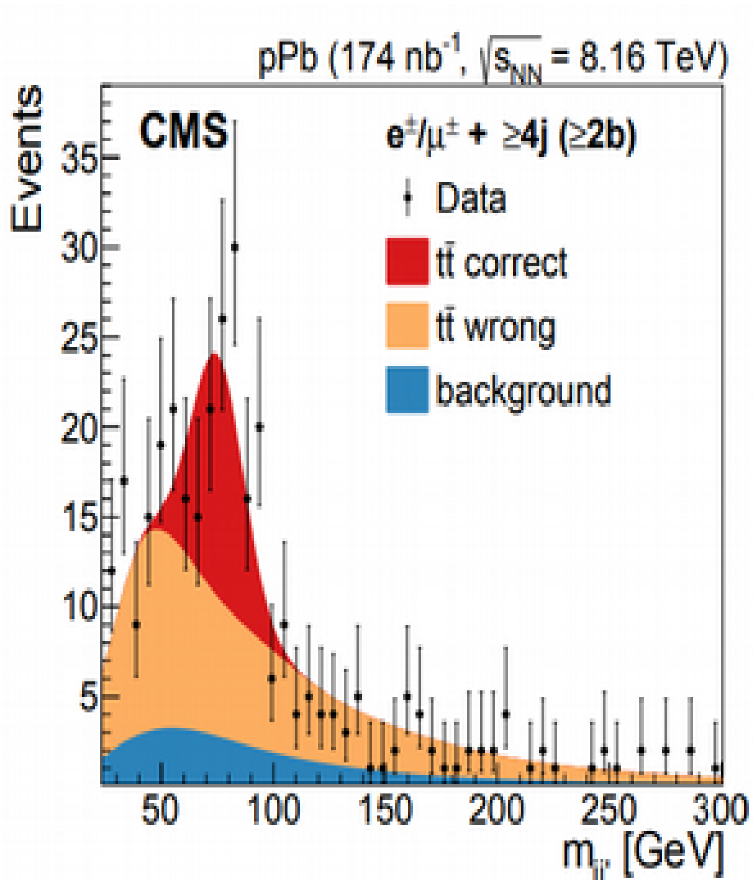
Observation of pPb → $t\bar{t}$ at 8.16 TeV

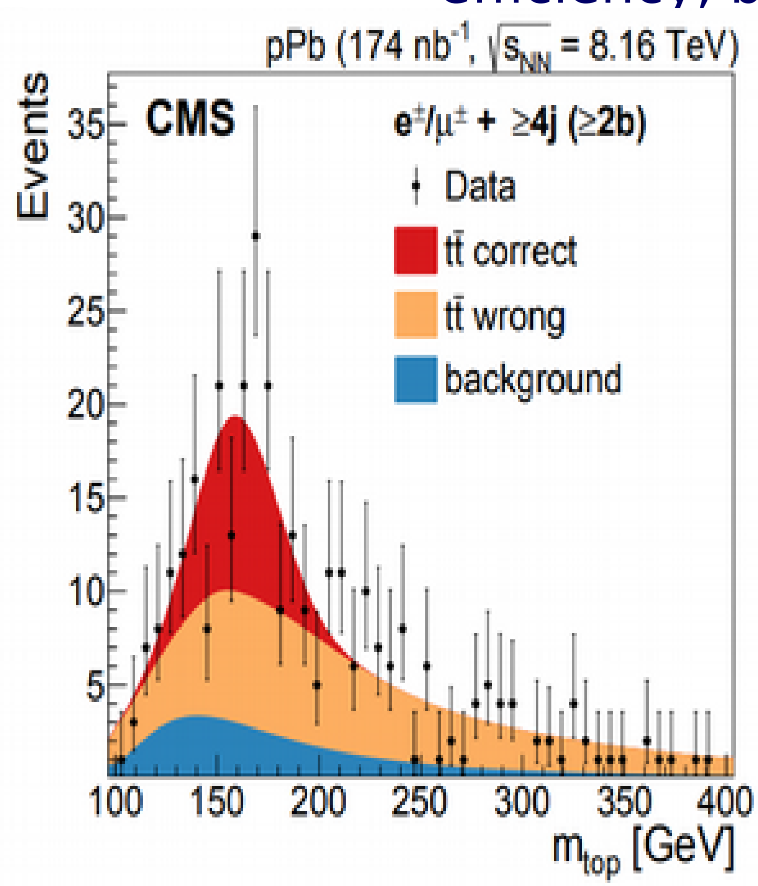
- Signal extraction based on fits of the W→jj' mass in different b-jet and lepton flavor categories
- Top candidates minimize the $m_{\ell\nu b}$ and $m_{jj'b}$ difference
- Use low MET 0 btag sample to cross check QCD modeling

Measured: σ=45±8 nb

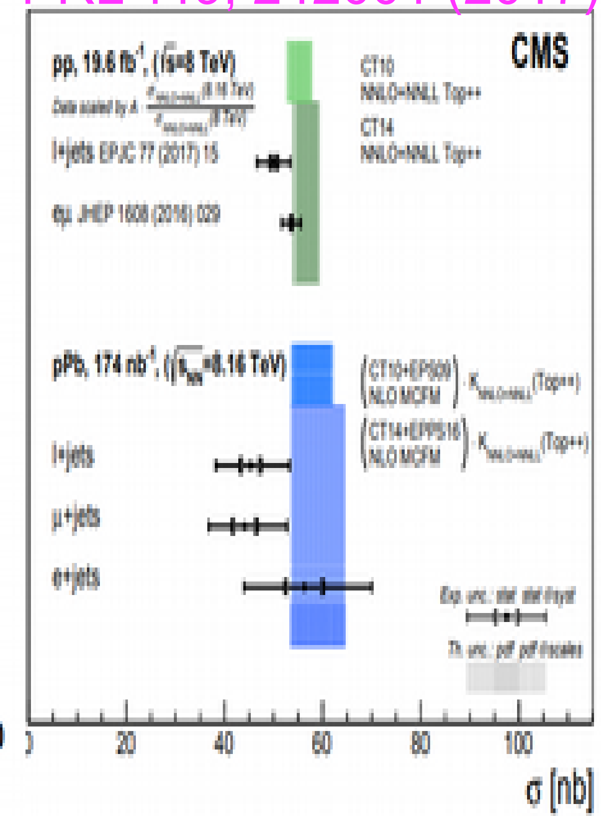
$\sigma=59.0\pm5.3(\text{PDF})^{+1.6}_{-2.1}(\text{scale})$ nb

- In agreement with NNLO+NNLL pQCD with NLO proton/nuclear PDFs
- Main uncertainties: b tagging efficiency, bkg prediction



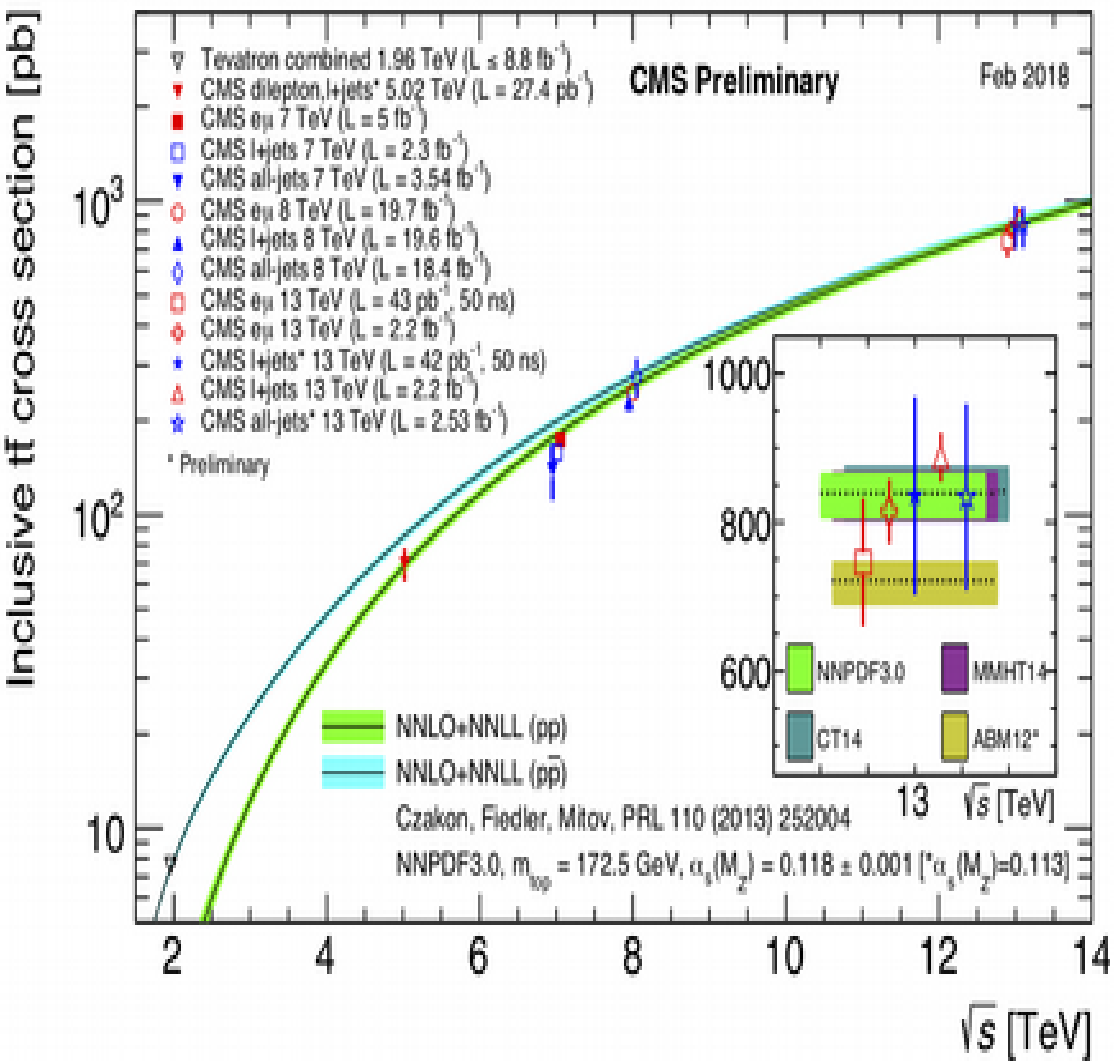


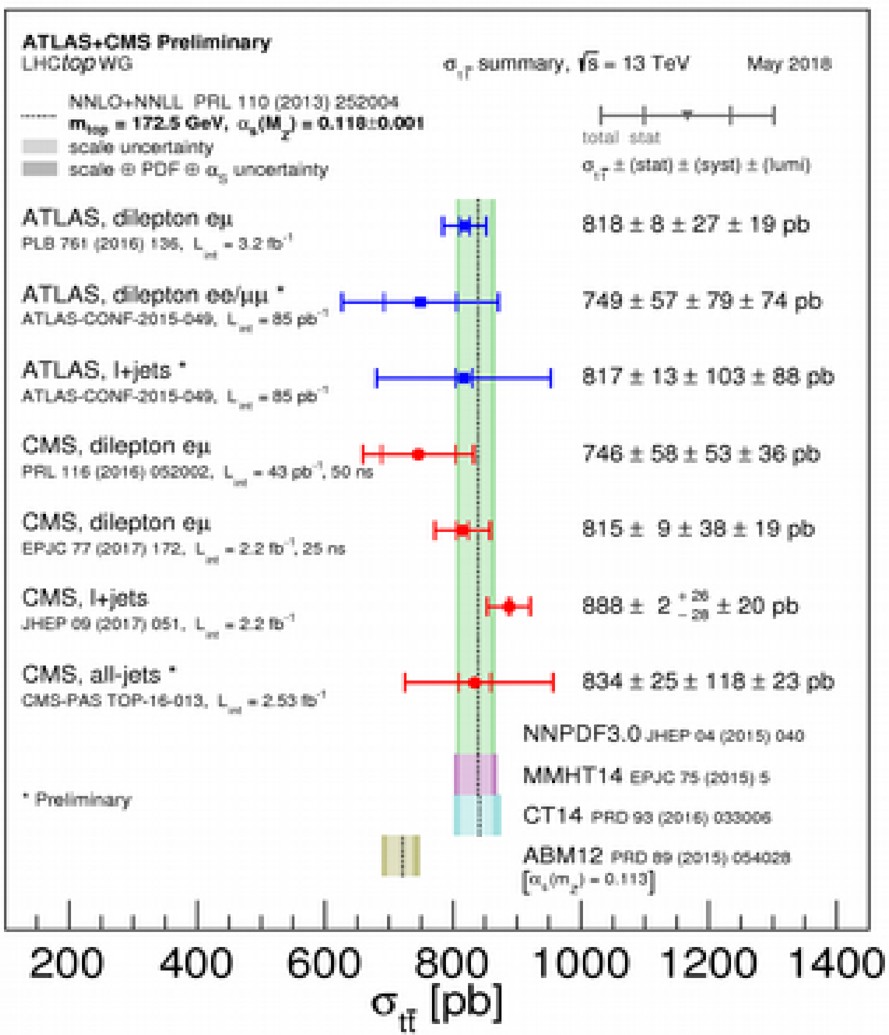
PRL 119, 242001 (2017)



Summary of inclusive measurements

- ℓ+jets at 5 TeV: JHEP 03 (2018) 115
  - σ_{tt}=69.5±6.1(stat)±5.6(syst)±1.6(lumi) pb → tot unc: 12%
- New measurements at 13 TeV agree with each other and NNLO+NLL prediction
- Now working on reducing systematic uncertainties
  - Hadronization, PS, modelling, JES, b-tagging, efficiencies

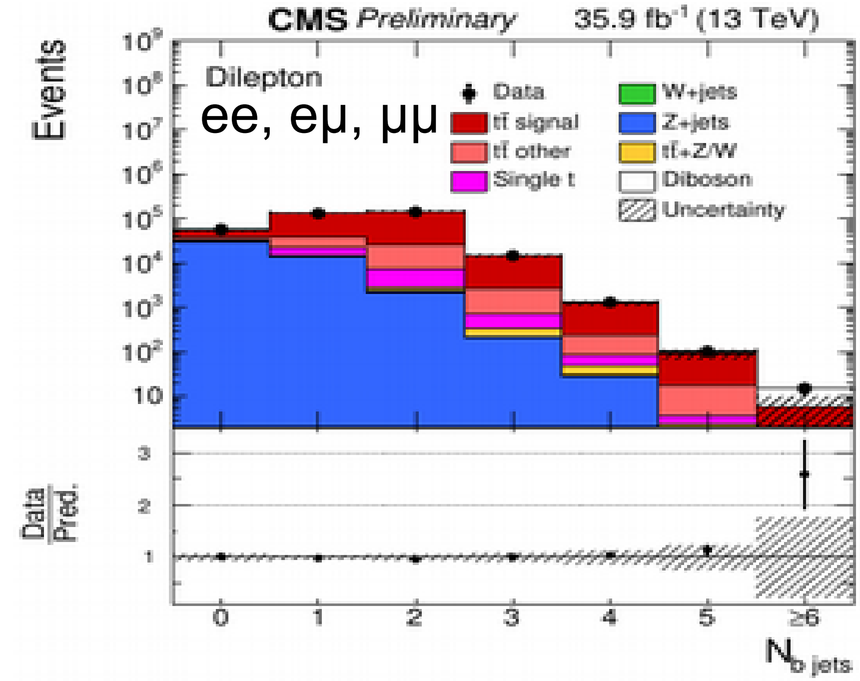


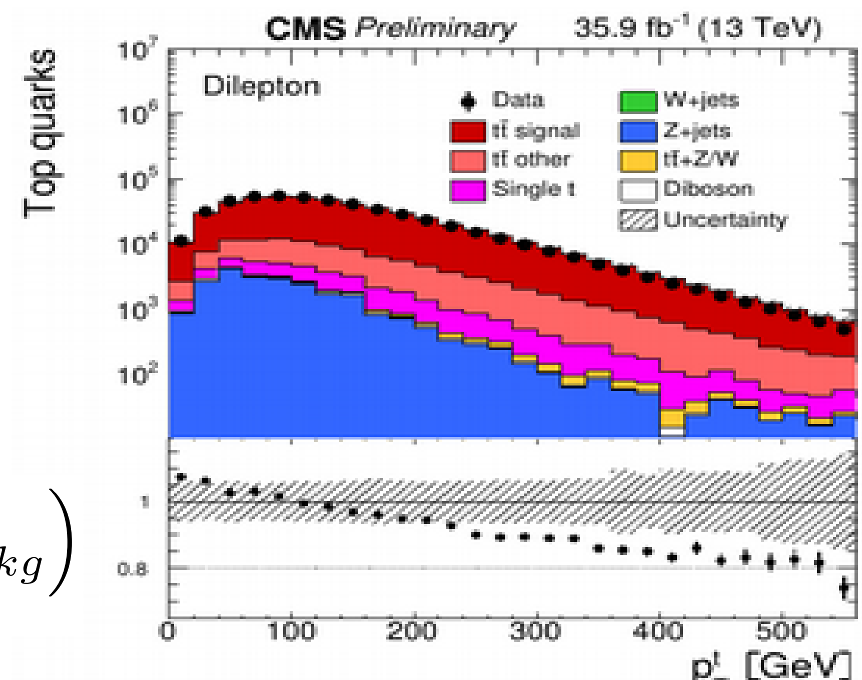


Dilepton differential cross section

- Trigger on isolated dileptons and $\ell\ell$+jets topologies
- 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 $\varepsilon_{DATA}/\varepsilon_{MC}$
- Unfold to remove detector effects
  - Particle level: proxy of top quark based on ℓ, jets inside acceptance
  - Parton level: after radiation but before decays → compare to theory

$$\frac{d\sigma}{dX^i} = \frac{1}{\int \mathcal{L}dt \cdot \Delta X^i} \sum_j M^{-1}_{ij} f^j_{\text{acc}} \left(N^j_{obs} - N^j_{bkg} \right)$$



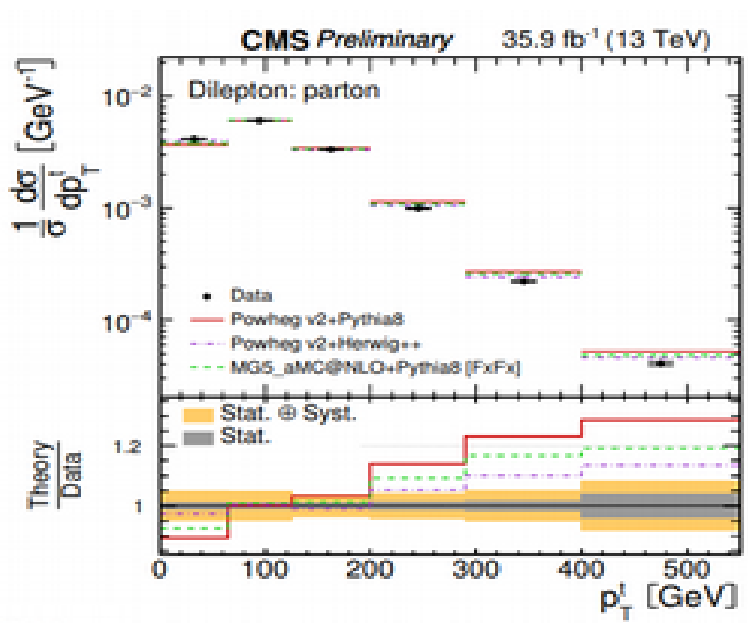


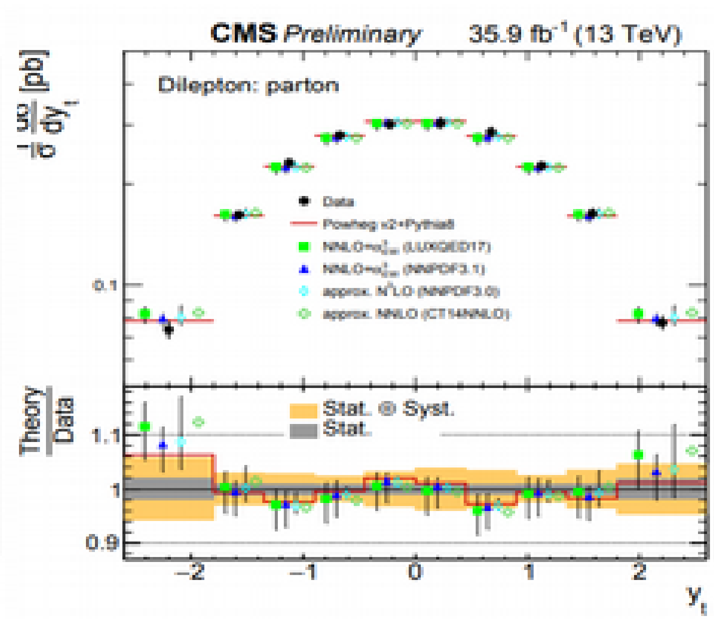
PAS TOP 17-014

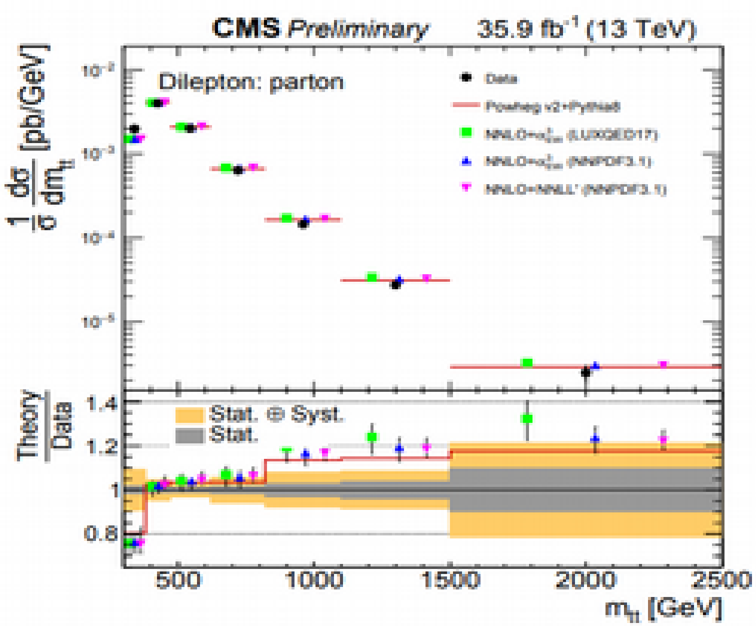
Dilepton differential results

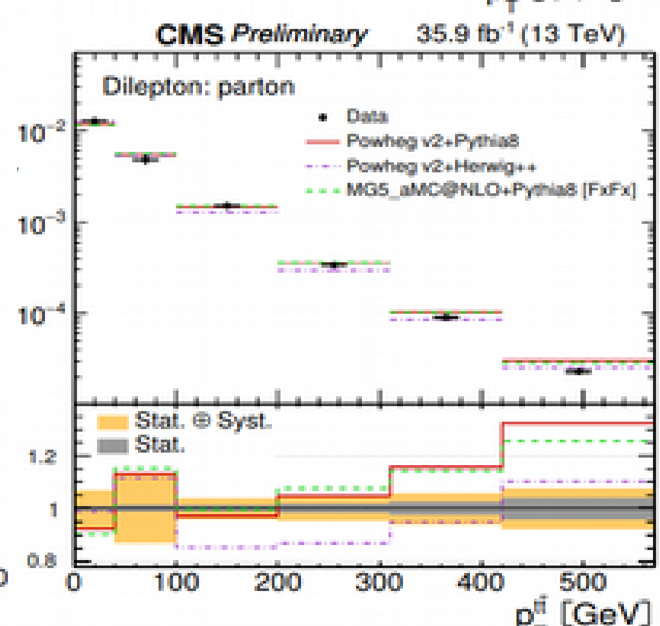
- Calculate normalized differential cross sections to reduce systematics
- Good agreement overall with beyond NLO QCD calculations

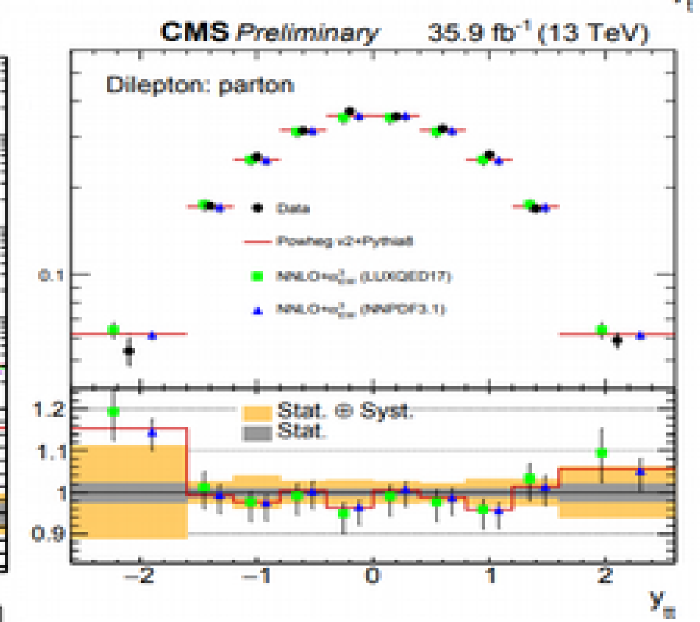
Process	Events
DATA eμ	150410
DATA μμ	70346
DATA ee	34890
Signal purity	80.6%









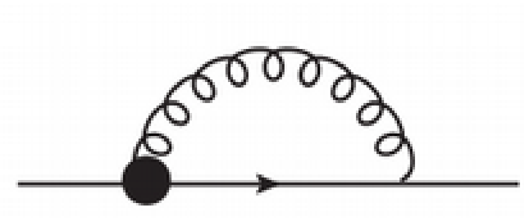


Dilepton differential: EFT constraint

- The top quark chromomagnetic dipole moment is constrained from the differential tt cross section as a function of Δφ(ℓ,ℓ)

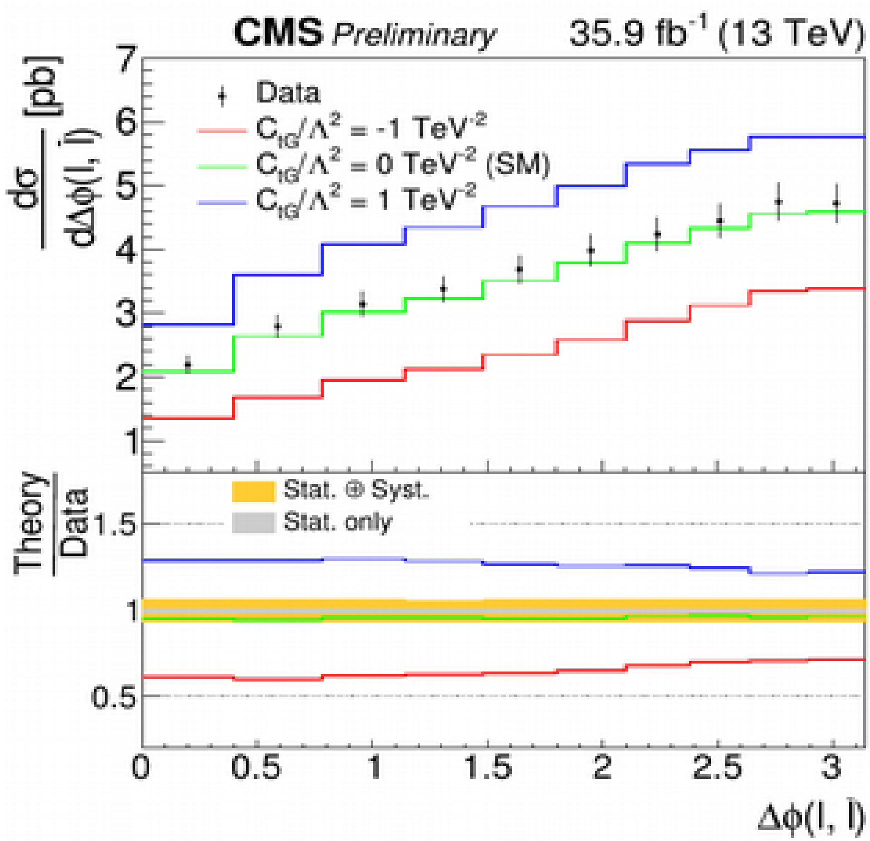
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \frac{C_{tG}}{\Lambda^2} O_{tG}$$

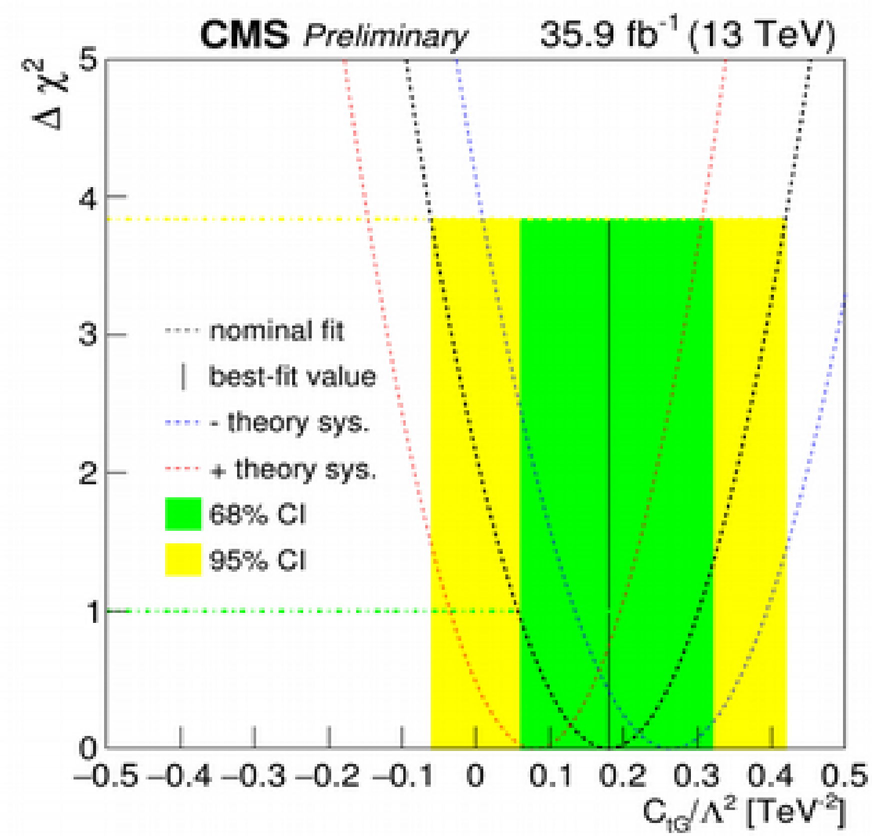
- O_{tG} alters ttg coupling and adds new ttgg
  - Flips t chirality → alters spin correlation → observable in Δφ(ℓ,ℓ)
  - Increases overall $t\bar{t}$ rate



- Sensitivity to CMDM parameterized with C_{tG}/Λ^2

$-0.06 < C_{tG}/\Lambda^2 < 0.41$ 95%CI

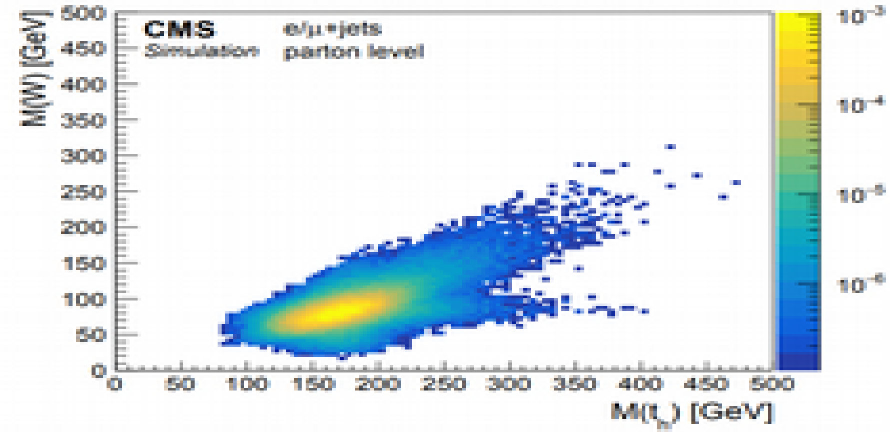


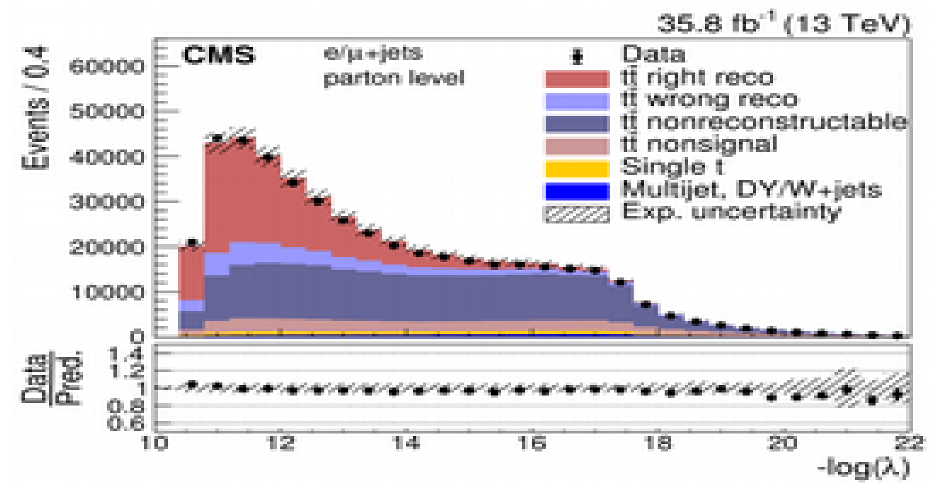


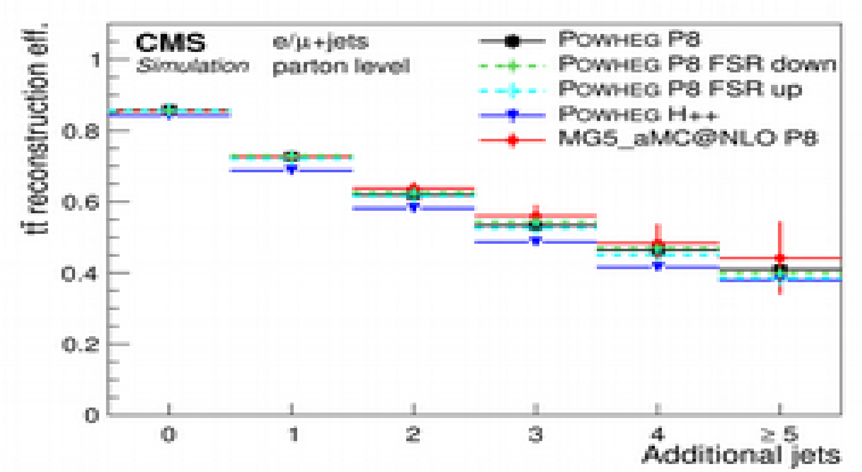
PAS TOP-17-014

Differential ℓ+jets cross section

- Triggers based on single isolated lepton
- Event selection:
  - 1 isolated lepton with p_T>30 GeV, |η|<2.1
  - ≥4 jets with p_T>25 GeV, |η|<2.4
    - ≥2 b-tagged (ε_b≈65% ; ε_{qg}≈3%)
- Kinematic reconstruction
  - Use mass constraints of m_t, m_W on leptonic side to obtain neutrino p_z neutrino (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
  - Choose lowest combined -log(λ) solution
  - Correct $t\bar{t}$ reconstruction efficiency: 63% on average, 80% for 4jet, ~40% for 7jet events



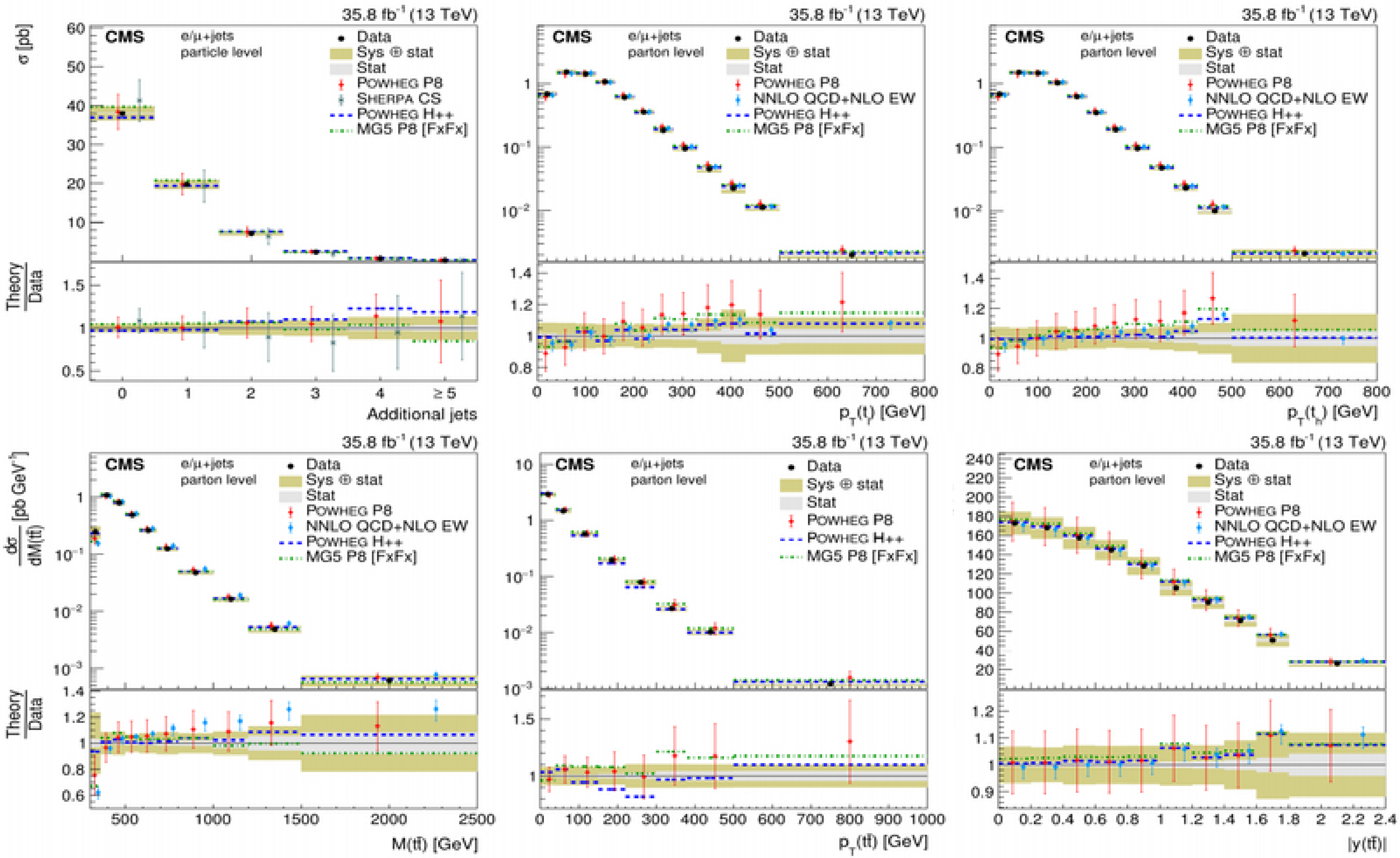




Parton level distributions ℓ+jets

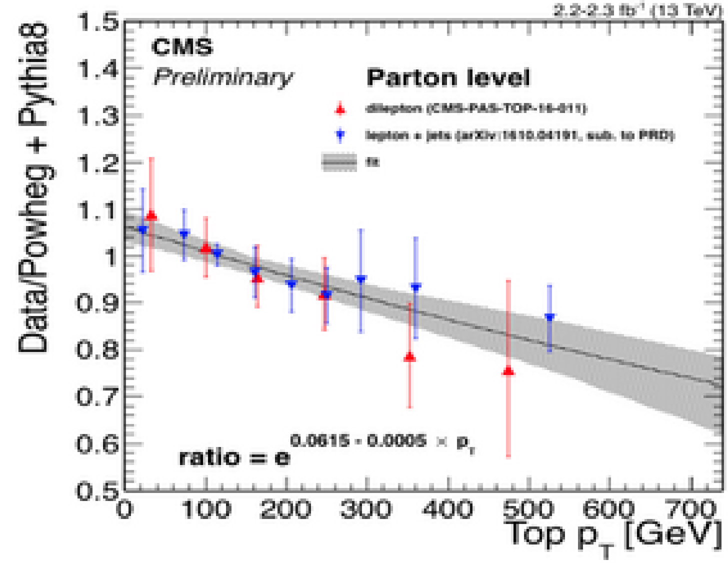
PRD 97 112003 (2018)

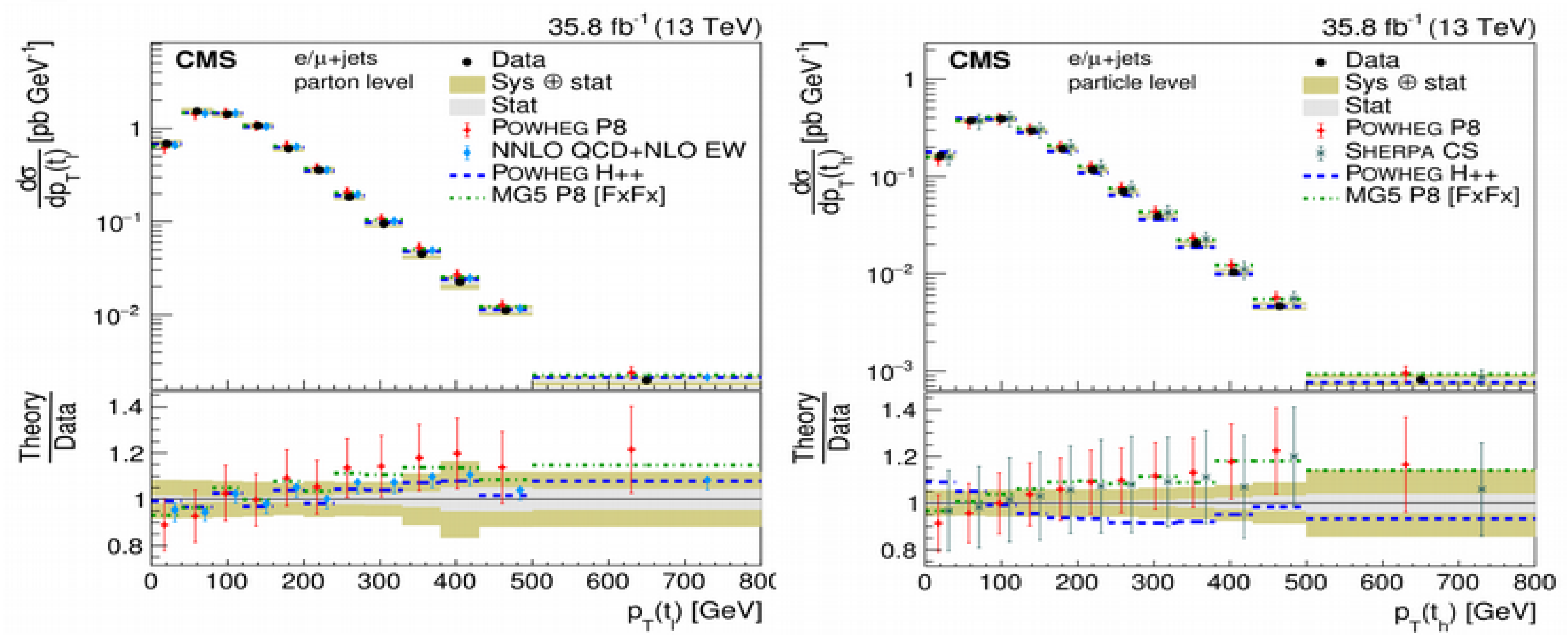
- Unfolded and extrapolated to full phase space
- Powheg+Herwig++ better at parton level, but too soft at particle level
- Also performed additional jet measurements



Top p_T mismodeling?

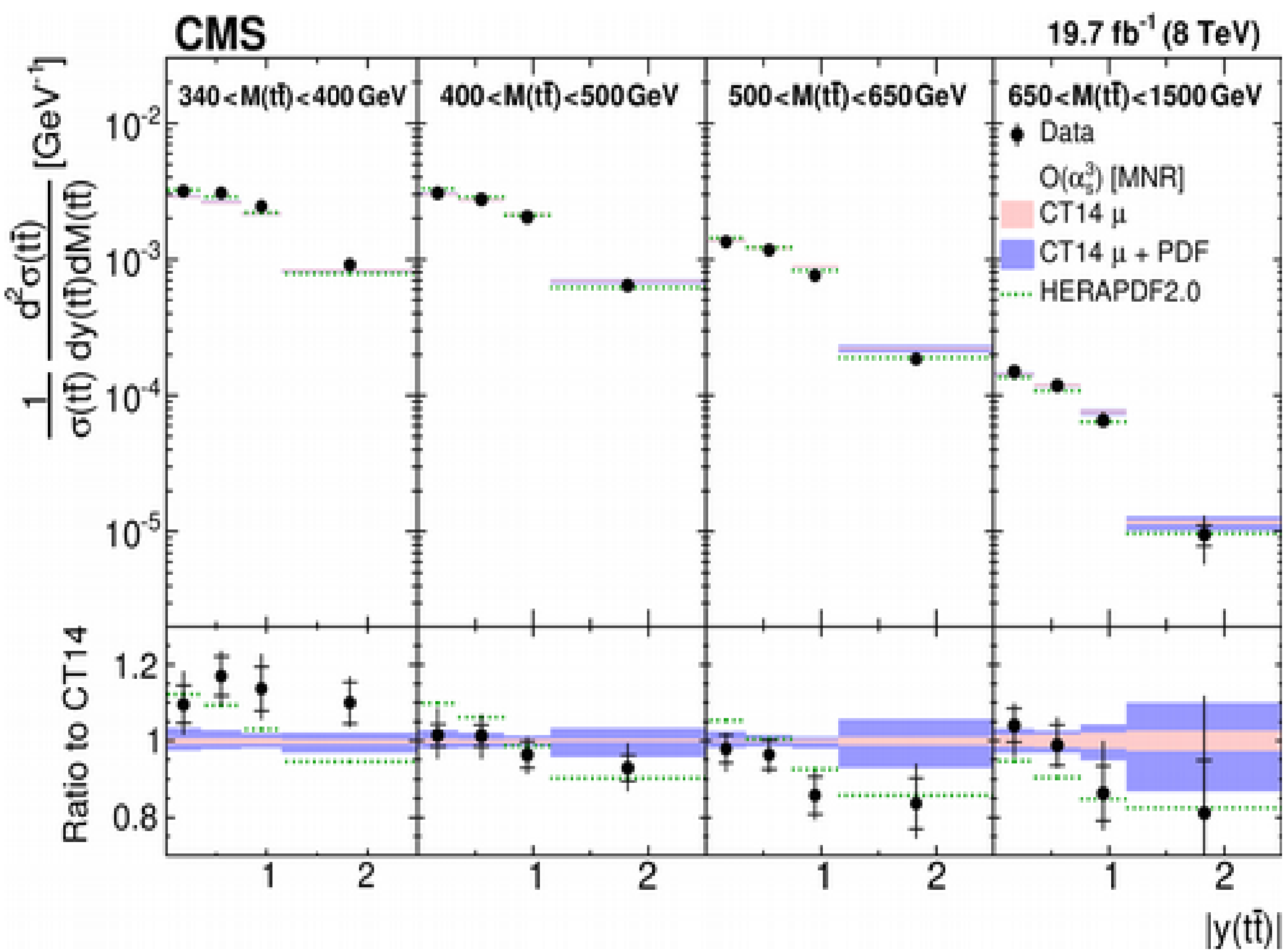
- Slope in top p_T distribution: data was softer than MC in 8 TeV
  - Largely improved by NNLO QCD + NLO EW calculations [Czakon, 2017]
- Big effect from different PS models
- Both in parton and particle level
- Trend still continues in 13 TeV data

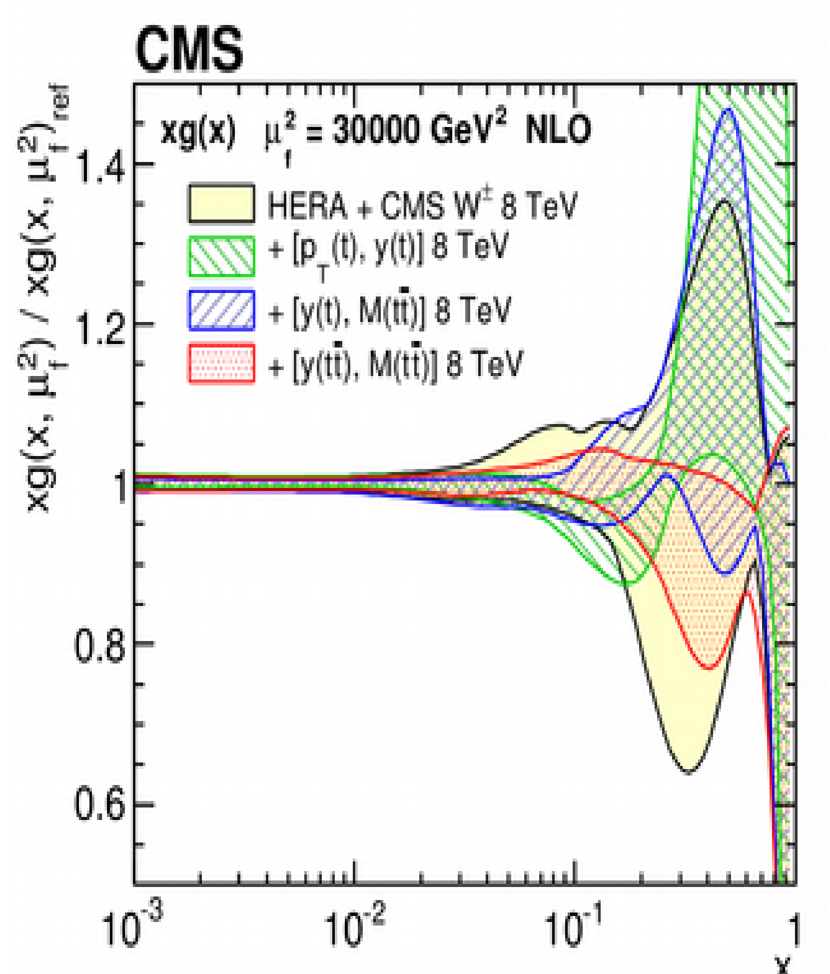




Impact on PDFs

- Doubly differential $t\bar{t}$ cross sections are sensitive to the gluon PDF
  - W asymmetry especially sensitive to u/d ratio and sea PDFs
  - Similar sensitivity as inclusive jet data (arXiv:1609.05331)
- Approximate NNLO $O(\alpha_s^4)$ are not yet available
- Powerful constraints for $0.01<x<0.3$ → Now included in NNPDF 3.1!





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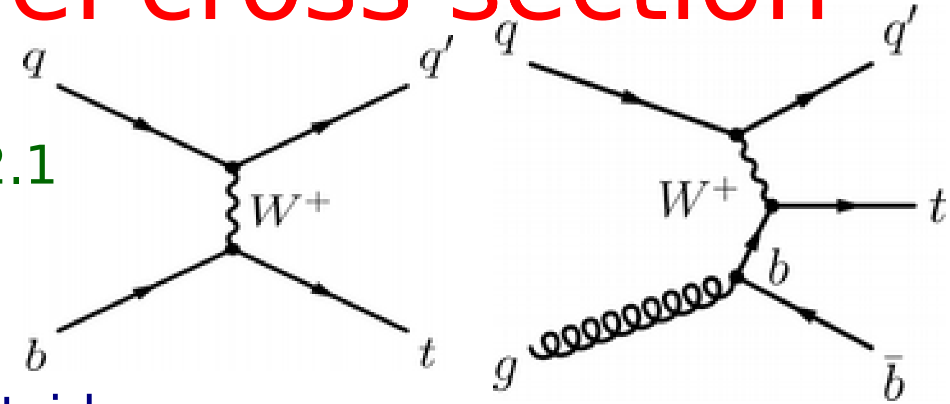
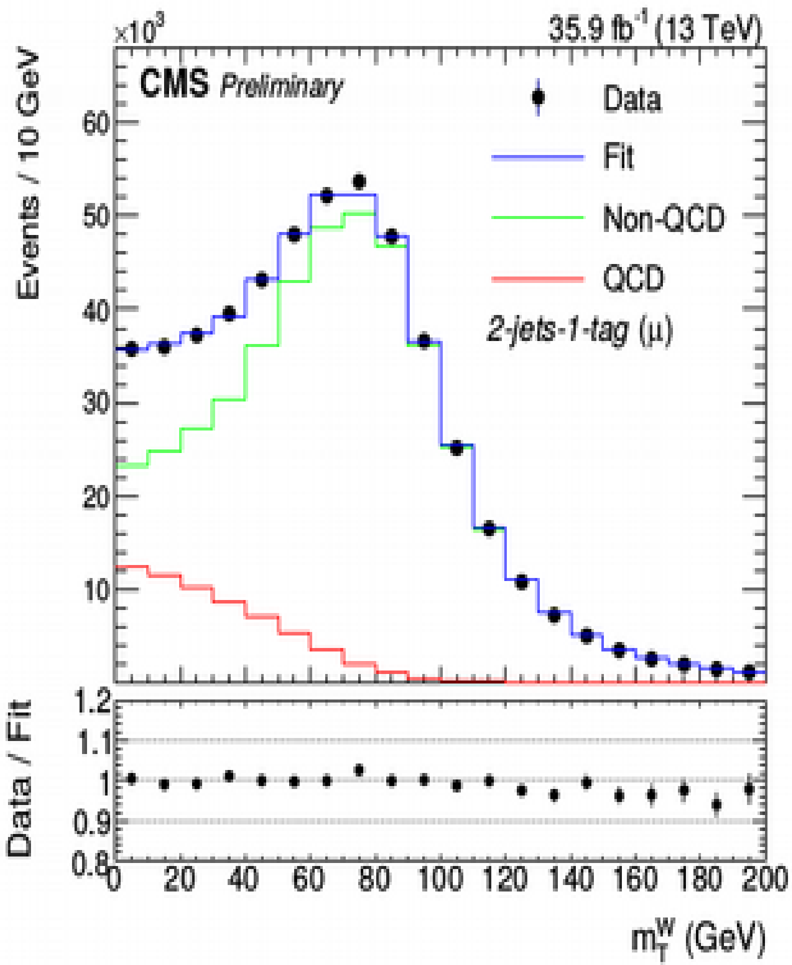
Single top t-channel cross section



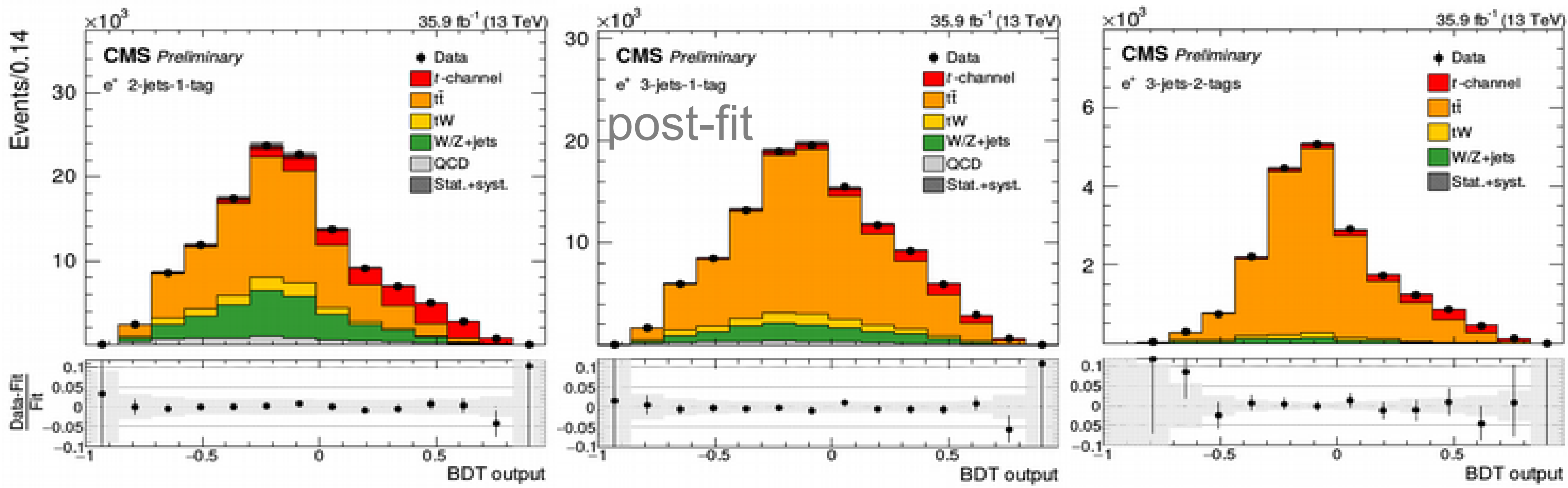
- Event selection
  - 1 isolated e or μ, p_T>22 GeV, |η|<2.1
  - 2 jets, p_T>40 GeV, |η|<4.7
  - 1 b-tag (MVA) (ε_b≈45% ; ε_{qg}≈0.1%)
- W+jets from simulation, validated outside top mass window: 130<$m_{\ell\nu b}$<225 GeV
- QCD shape from data, normalization from fit of m_T(W) and cut: m_T(W)>50 GeV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



Process	μ^+	μ^-
Top quark pair production	81172 ± 13480	81572 ± 13517
tW	8755 ± 1799	8762 ± 1843
W/Z+jets	38199 ± 12334	33373 ± 10568
QCD	6732 ± 3241	6713 ± 3235
Single top quark t-channel	23628 ± 2918	14574 ± 1883
Total expected	158486 ± 18870	144994 ± 17658
Observed	166446	151440

Single top t-channel results

- Cross section is limited by systematics:
  - 15% overall unc., 12% modeling, 6% exp.
- Ratio $\sigma_t/\sigma_{\bar{t}}$ = 1.65 ±0.02(stat) ±0.04(syst) ← Most precise measurement!



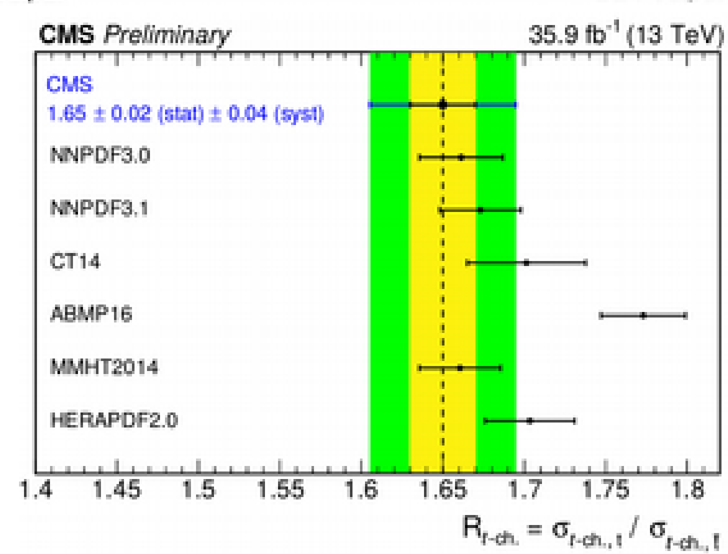
σ_{tch} = 219 ± 1.5(stat) ± 33(sys) pb

σ_{tch} = 217.0 ± 6.6(scale) ± 6.2(PDF) pb [NLO]

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

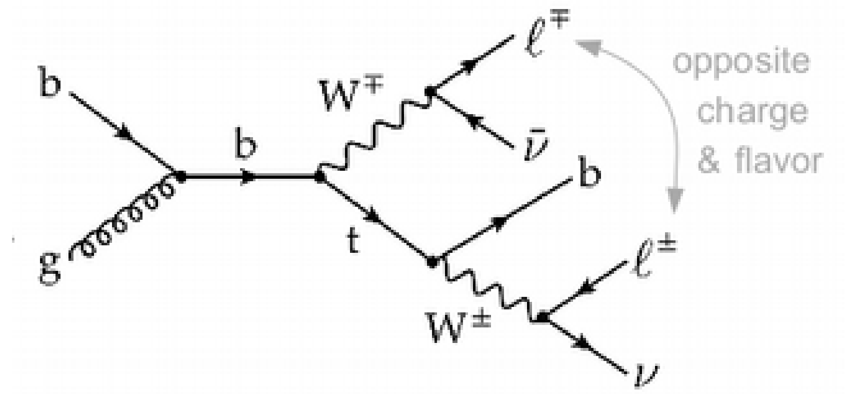
$|fV_{tb}|$ = 1.00 ± 0.05(exp) ± 0.02(th)

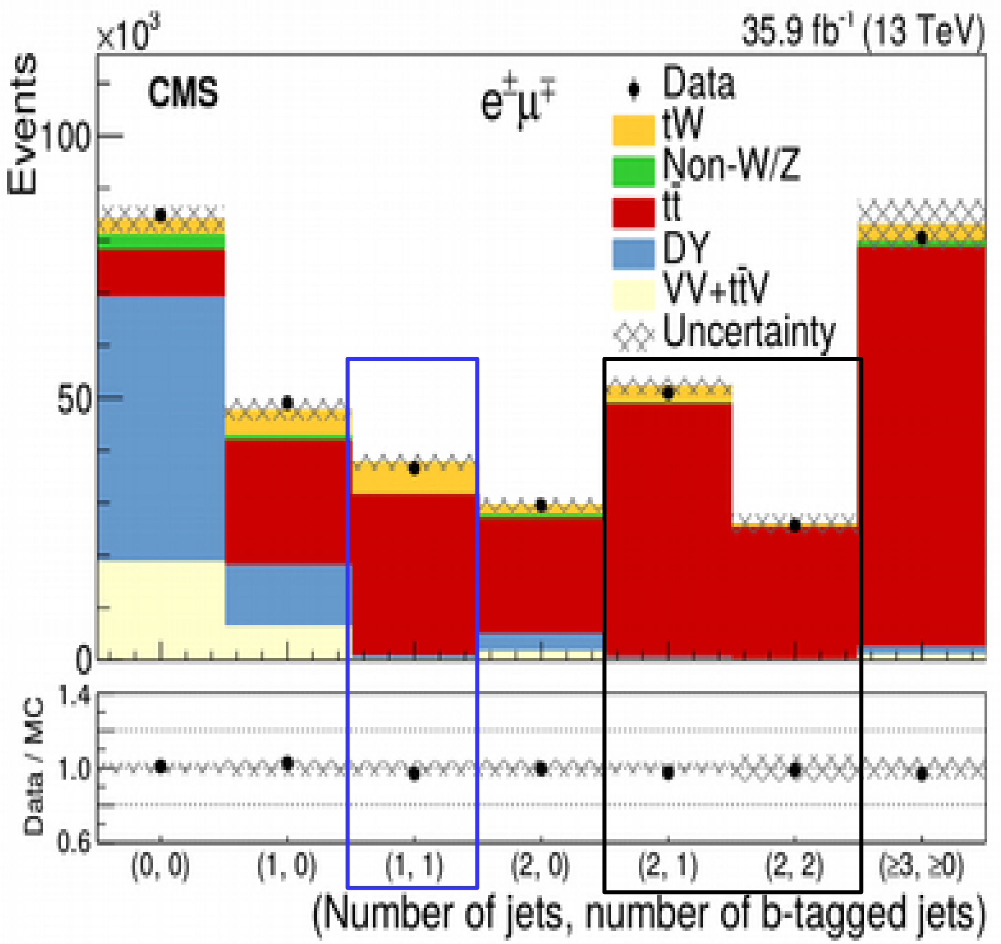
CMS-PAS-TOP-17-011



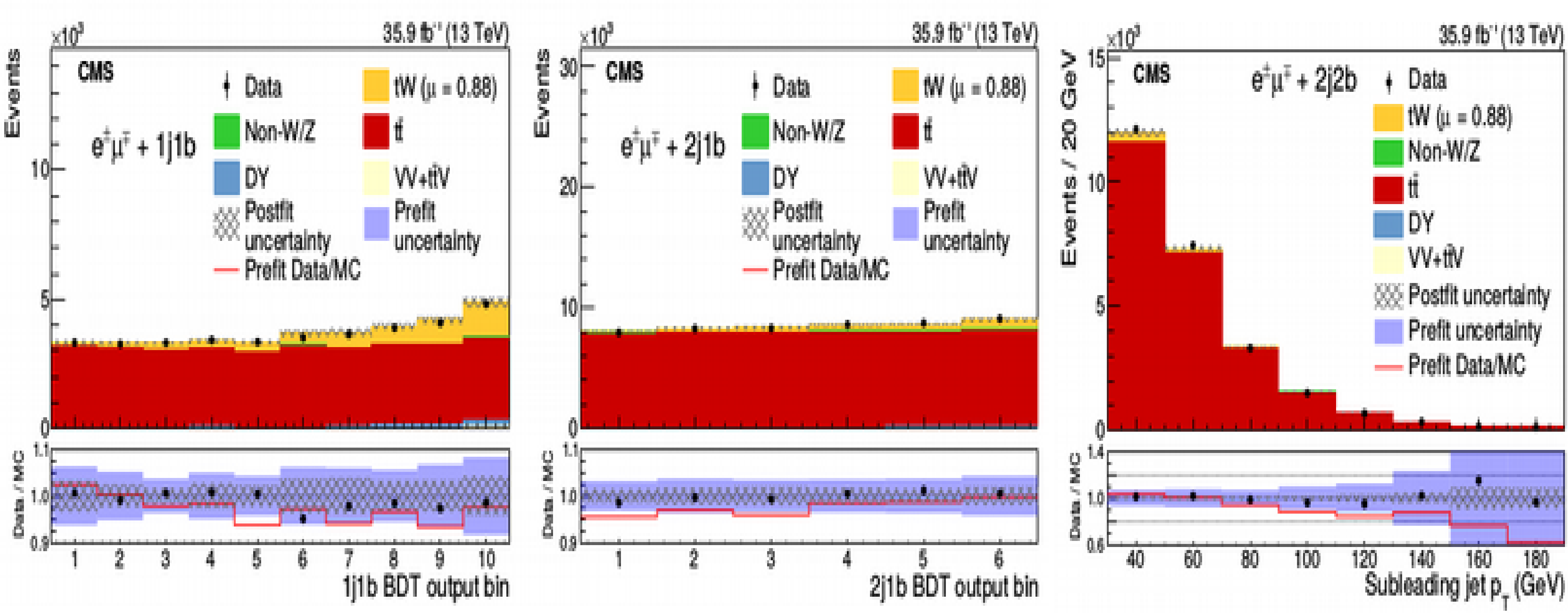
Single top tW channel

- Event selection:
  - Isolated $e^{\pm}$ and $\mu^{\mp}$ p_T>20 GeV, $|\eta|$<2.4
  - 1 jet p_T>30 GeV, $|\eta|$<2.4
  - 1 b-tag MVA ε_b~70%, ε_q~1%, ε_c~15%
- Signal sample: diagram removal scheme to remove overlap with $t\bar{t}$ at NLO
- $t\bar{t}$ regions: 2 jets+1 or 2 b-tags
- Signal strength measured through ML fit to BDT in 1j1b, 2j1b and subleading jet p_T in 2j2b
- BDT inputs: leading loose jet p_T, p_T^{sys}, leading jet p_T, $(p_T^e+p_T^\mu)/H_T$, $N_{loosejets}$, …
  - Loose jets: 20<p_T<30 GeV (expect 0 in signal, several in $t\bar{t}$ events)





Single top tW channel results



- Dominant uncertainties: ℓ ID efficiencies, trigger, JES, $t\bar{t}$ modeling
  - 10% systematic, 3.3% lumi, 2.8% statistical → Total 11%

Measured: σ_{tW} = 63.1 ± 1.8(stat) ± 6.4(syst) ± 2.1(lum) pb

aNNLO: σ_{tW} = 71.7 ± 1.8(scale) ± 3.4(PDF) pb [Kidonakis, arXiv:1506.04072]

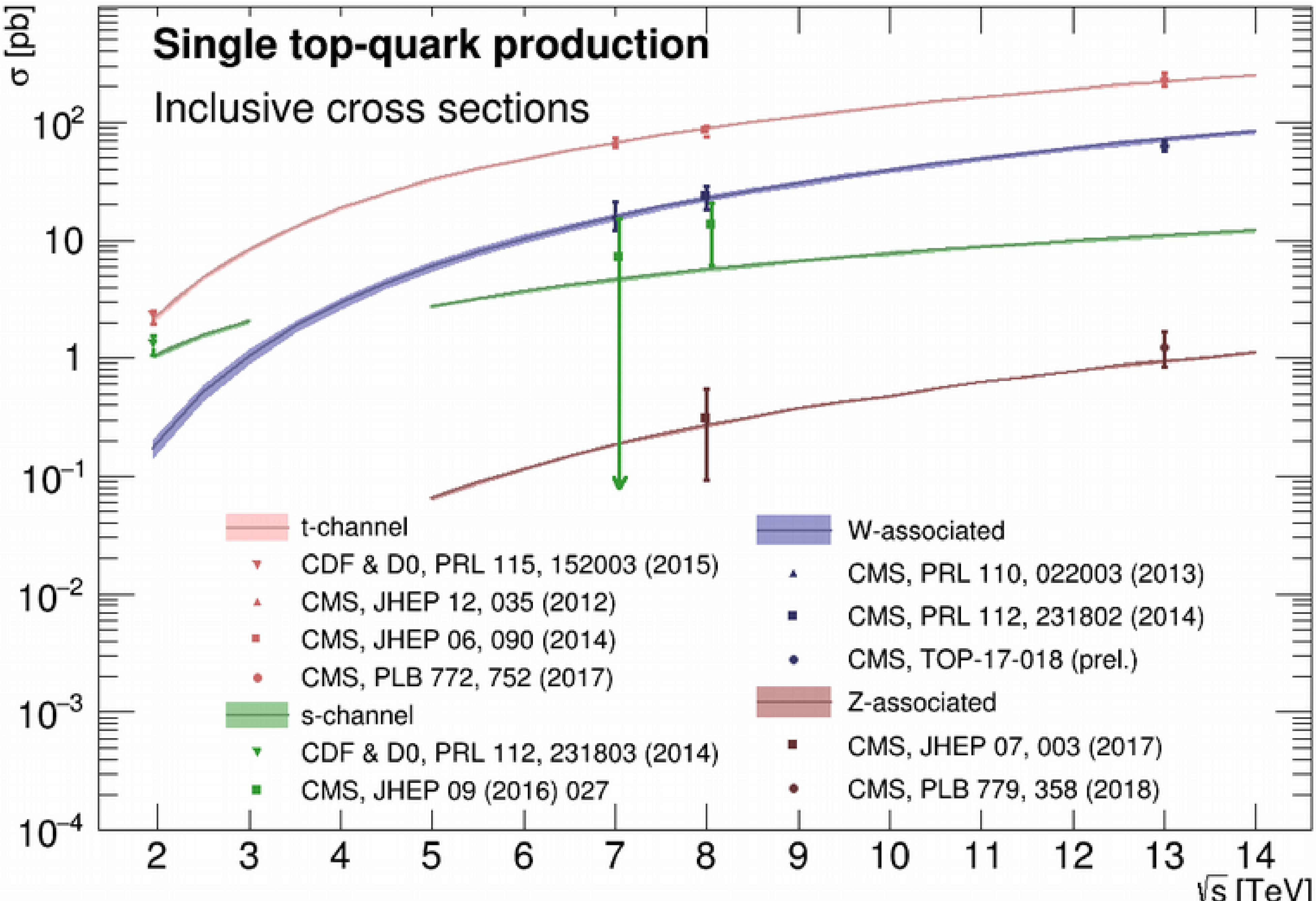
arXiv: 1805.07399

Conclusions

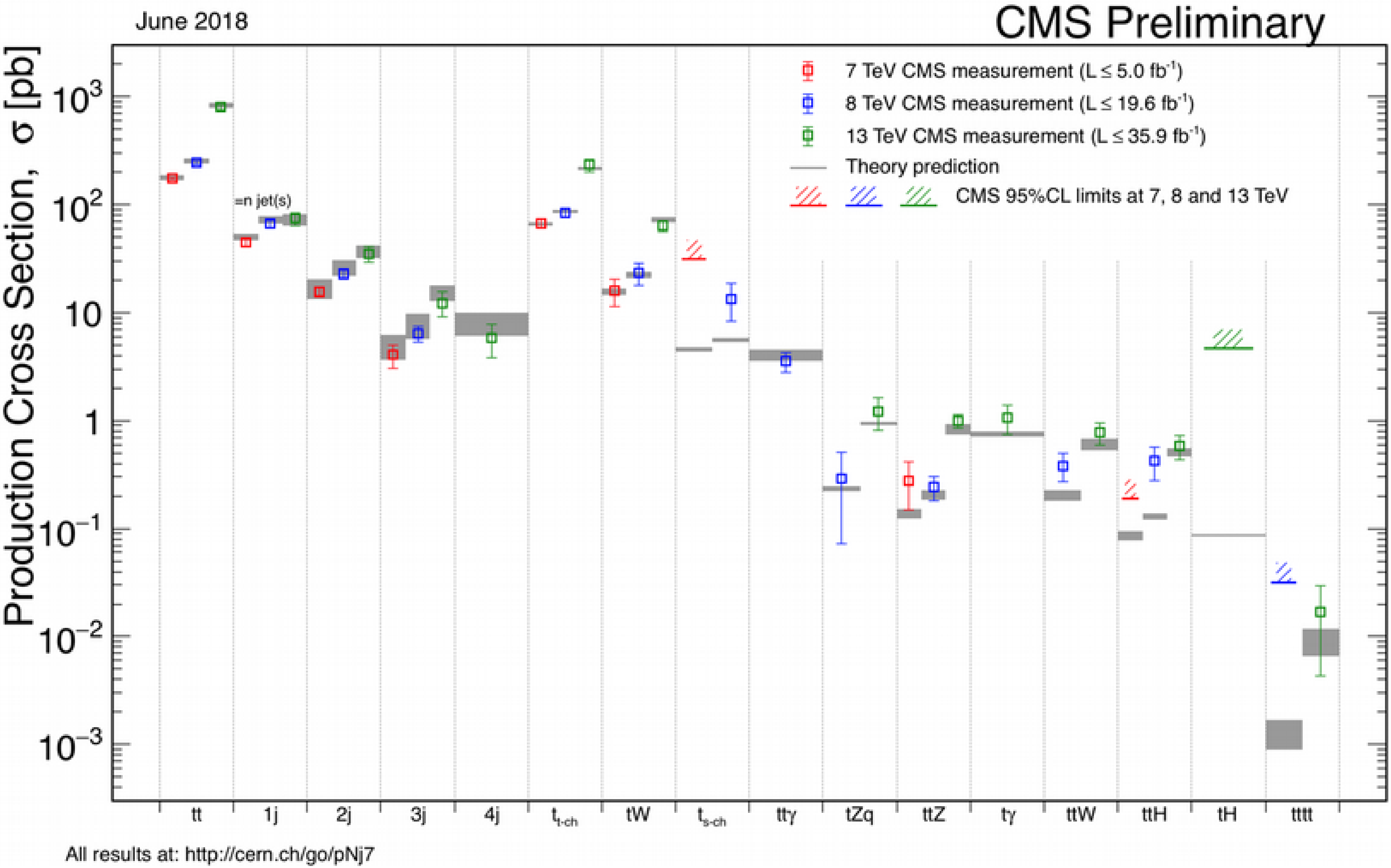
- We use the $t\bar{t}$ sample to calibrate b-tagging, PDFs, α_s in PS, high multiplicity events and top kinematics...
  - Are we hiding any new physics in top sector?
- Wealth of measurements in Run2
  - No signature of new physics yet!
  - Very useful for other searches
  - Need precise measurements of $t\bar{t}b\bar{b}$ and additional jets properties
- Many measurements now constrained by generator and parton shower uncertainties
- Tough times ahead reducing systematics
  - Constrain hadronization, PS, modelling
    - New two-dimensional measurements probe differences in PS
- 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

Extras


Single top-quark production
Inclusive cross sections
σ [pb]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
t-channel
CDF & D0, PRL 115, 152003 (2015)
CMS, JHEP 12, 035 (2012)
CMS, JHEP 06, 090 (2014)
CMS, PLB 772, 752 (2017)
s-channel
CDF & D0, PRL 112, 231803 (2014)
CMS, JHEP 09 (2016) 027
W-associated
CMS, PRL 110, 022003 (2013)
CMS, PRL 112, 231802 (2014)
CMS, TOP-17-018 (prel.)
Z-associated
CMS, JHEP 07, 003 (2017)
CMS, PLB 779, 358 (2018)
2 3 4 5 6 7 8 9 10 11 12 13 14
√s [TeV]

$t\bar{t}$+X


June 2018
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 35.9 fb-1)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
=n jet(s)
tt
1j
2j
3j
4j
tt-ch
tW
ts-ch
ttγ
tZq
ttZ
tγ
ttW
ttH
tH
tttt
All results at: http://cern.ch/go/pNj7

Low pileup event μ+jets