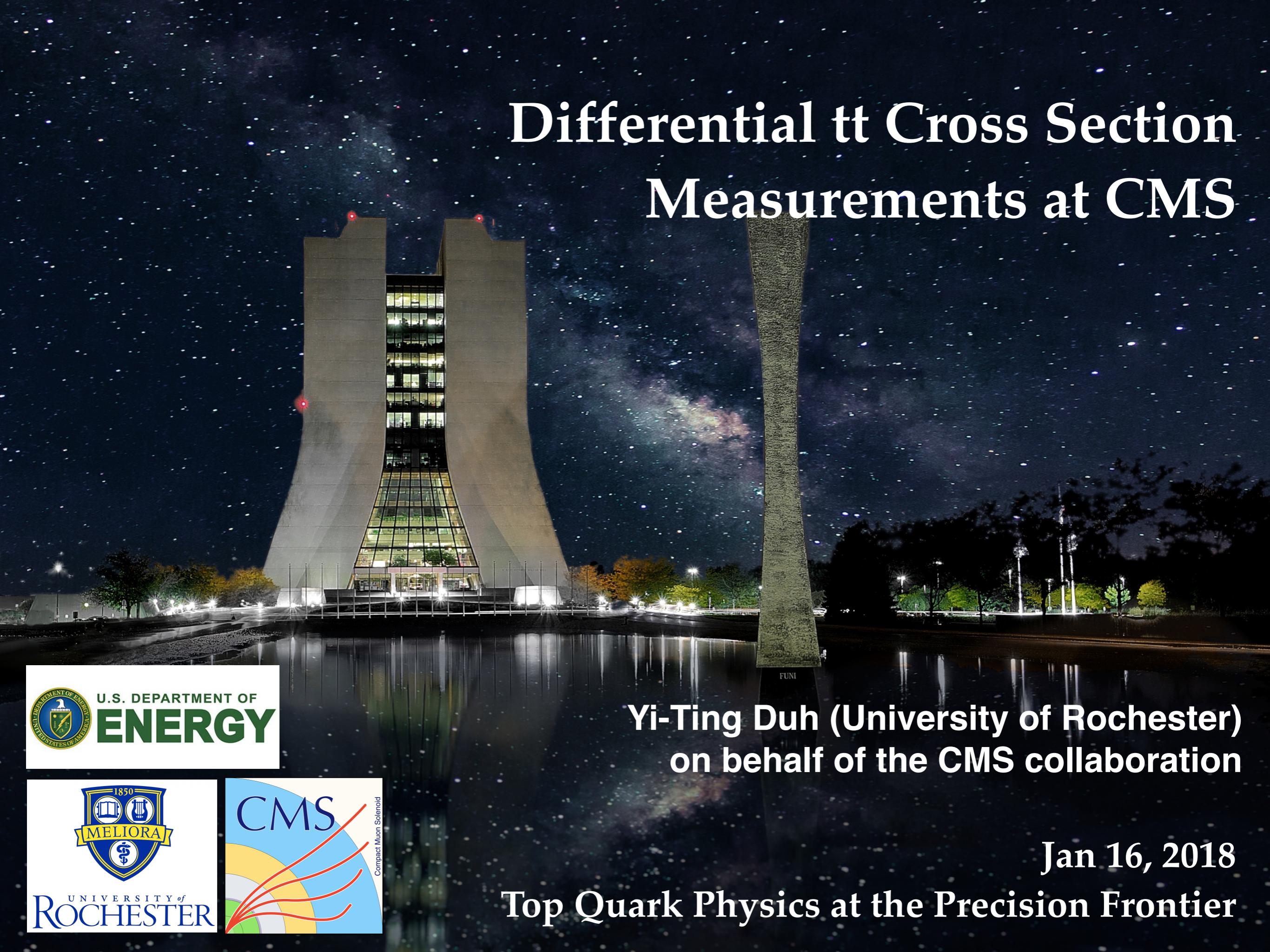


Differential $t\bar{t}$ Cross Section Measurements at CMS



U.S. DEPARTMENT OF
ENERGY



UNIVERSITY of
ROCHESTER



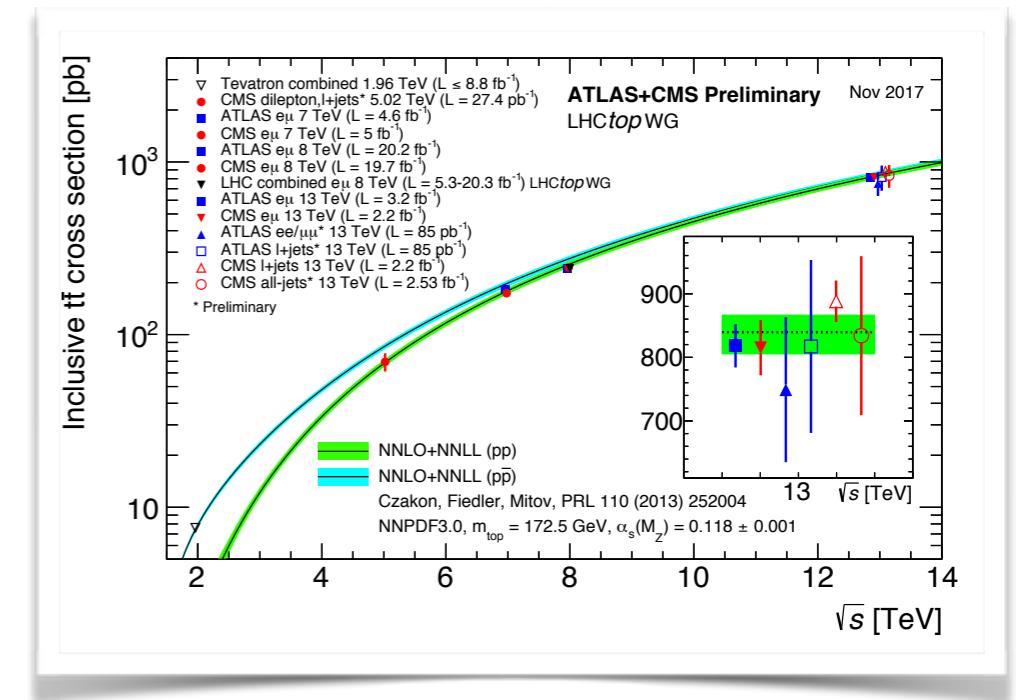
Yi-Ting Duh (University of Rochester)
on behalf of the CMS collaboration

Jan 16, 2018

Top Quark Physics at the Precision Frontier

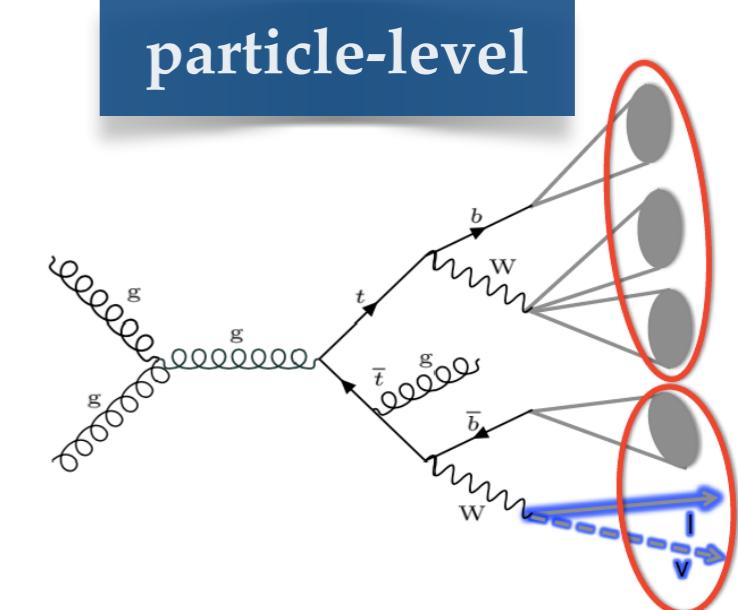
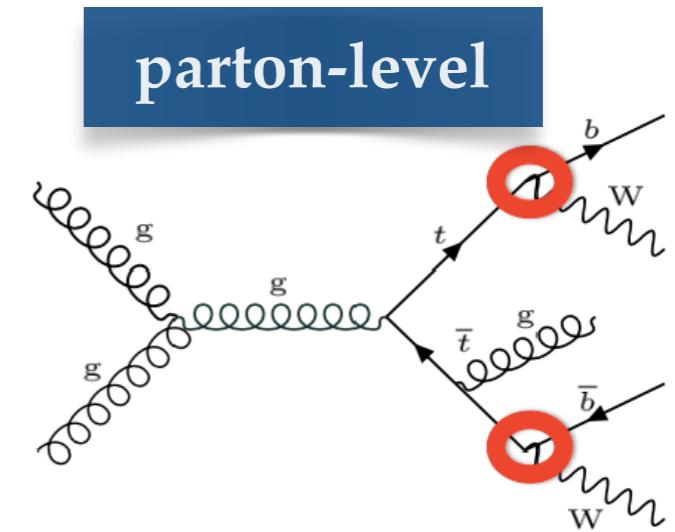
Overview

- The inclusive measurements show impressive agreement with the prediction
 - If you break the systematics down, luminosity is the largest individual source of uncertainties, however, it is tough to go down
 - Apart from taking ratios of measurements, one way that we can further study is to **go differential**
- With the end of LHC Run2, the high rate of tt production opens a new precision frontier
 - Statistics is not the limiting factor (more so in boosted regime)
 - High statistics of the tt samples allow to constrain the tunings of parton shower parameters and PDFs
 - Important background for many searches
 - Precision test of the Standard Model and search for Physics beyond



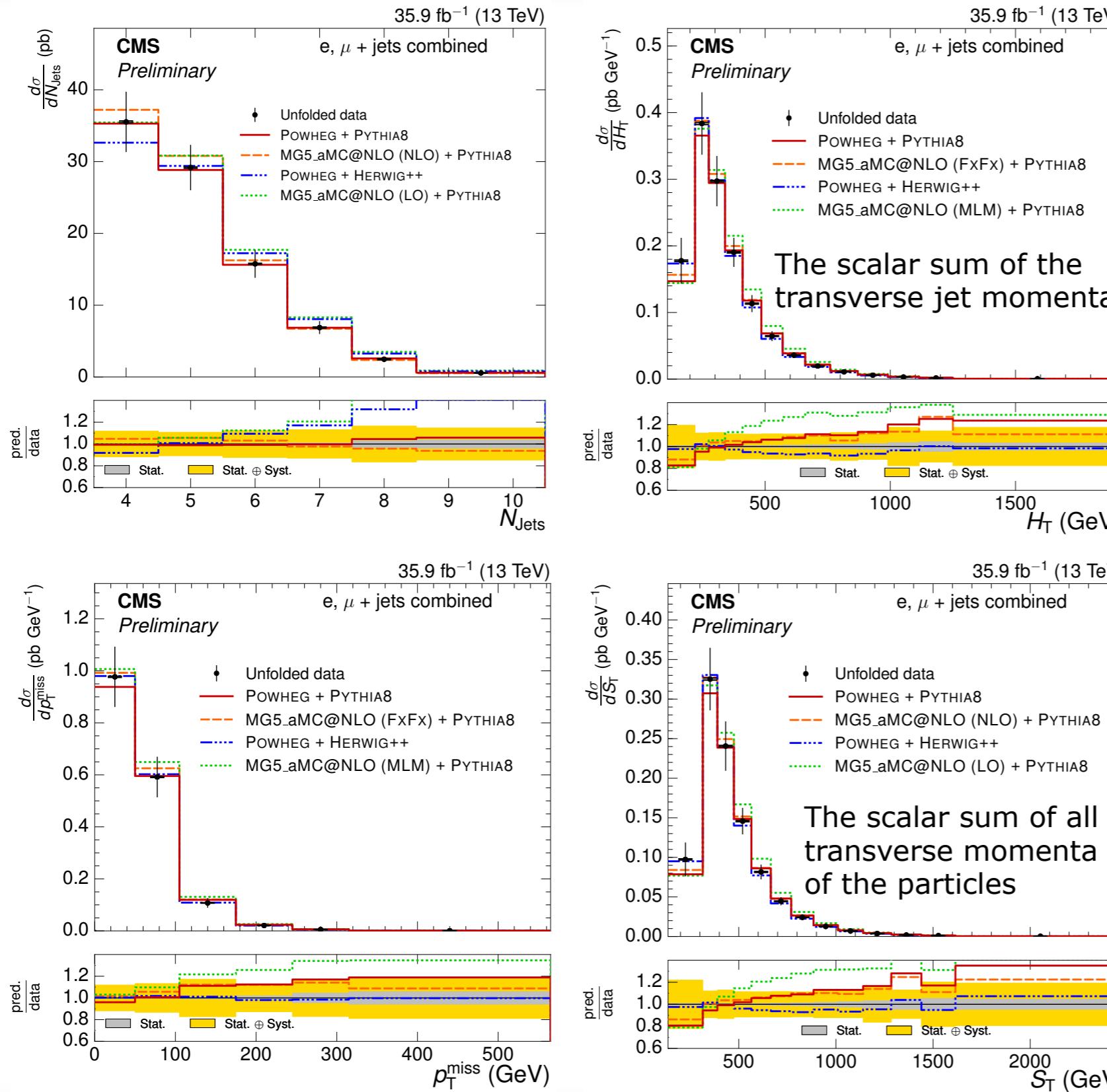
Types of cross sections

- **Absolute**: account for normalization difference to give the actual cross sections
- **Normalized**: provide shape information with higher precision (some experimental uncertainties are cancelled)
- **Parton-level**: top quark after radiation but before decays
 - ✓ Compared directly to QCD matrix element calculations
- **Particle-level**: top quark proxy reconstructed from top decay products after hadronization
 - ✓ Avoiding theory-based extrapolations from fiducial phase space to the full range, and from jets to partons
 - ✓ Reduce theoretical uncertainties in the experimental results



Differential σ_{tt} in global variables

CMS-TOP-16-014

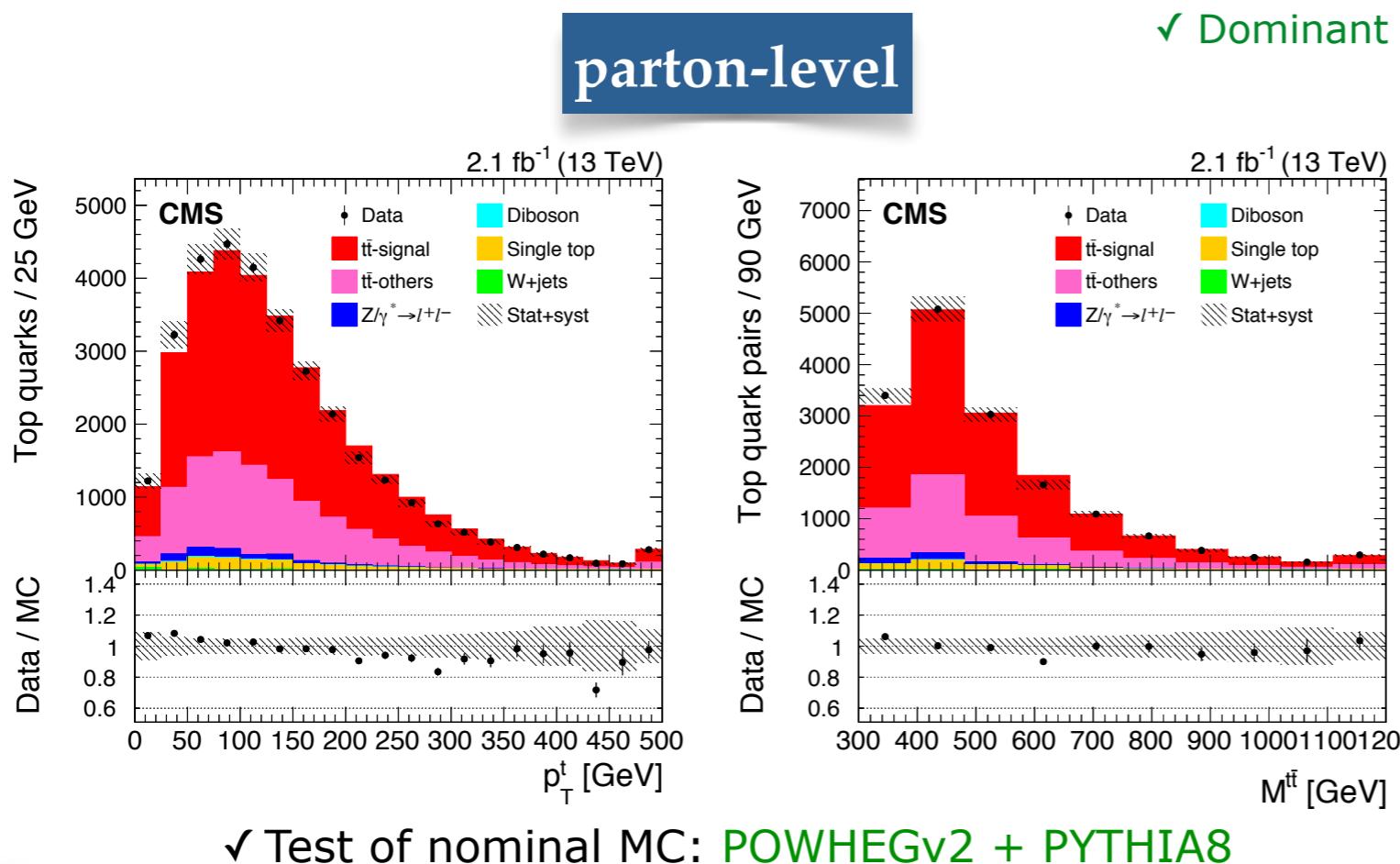


- Select 1 e or μ , at least 4 jets, and 2 b-tagged
- Measurements with respect to global event variables:
- Do not require the reconstruction of the $t\bar{t}$ system

Dilepton differential σ_{tt}

arXiv:1708.07638 sub. to JHEP

- Select 2 opposite charged leptons ee, $\mu\mu$, or $e\mu$, at least 2 jets, and 1 b-tagged
- In the same lepton flavor channels $|m_z - m_{\ell\ell}| > 15 \text{ GeV}$ and $\text{MET} > 40 \text{ GeV}$
- Algebraic reconstruction of neutrino momenta and jet assignment by applying W mass and top mass constraints
- Smearing of jet and lepton energy and direction to account for detector resolution

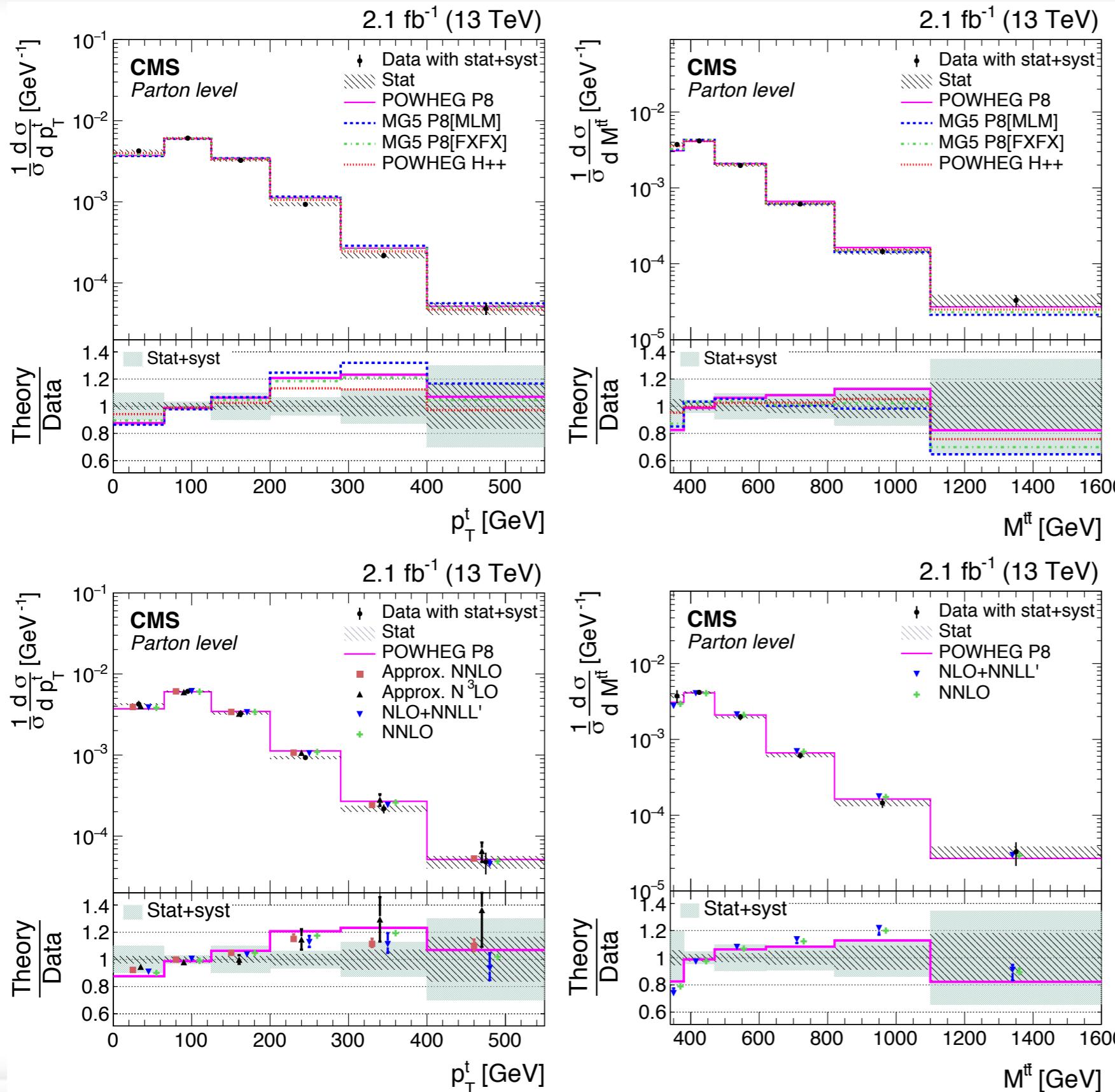


✓ Dominant uncertainties from generator, top mass, etc

| Uncertainty source | Parton level [%] |
|------------------------------|------------------|
| Statistical | 0.37 – 0.70 |
| Pileup modeling | 0.10 – 0.51 |
| Trigger efficiency | 0.06 – 0.85 |
| Lepton efficiency | 0.09 – 1.0 |
| JES | 0.31 – 1.8 |
| JER | 0.29 – 0.94 |
| b jet tagging | 0.32 – 1.2 |
| Background | 0.10 – 1.4 |
| PDFs | 0.17 – 1.0 |
| MC generator | 1.8 – 10 |
| Fact./renorm. | 0.21 – 4.6 |
| Top quark mass | 0.73 – 4.2 |
| Top quark p_T | 0.04 – 1.3 |
| Hadronization | 0.49 – 8.3 |
| Total systematic uncertainty | 3.3 – 13 |

Dilepton differential σ_{tt}

arXiv:1708.07638 sub. to JHEP



parton-level

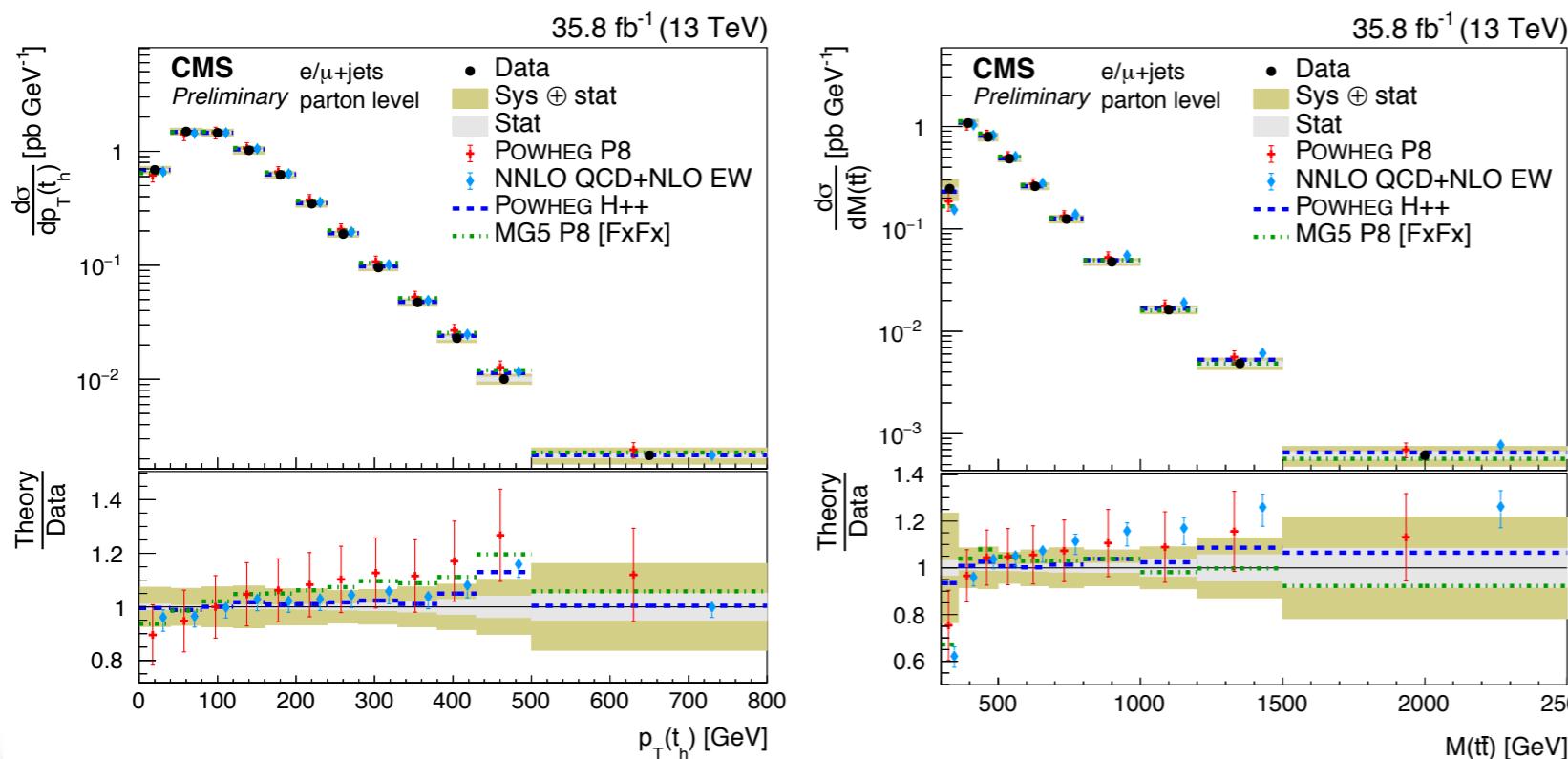
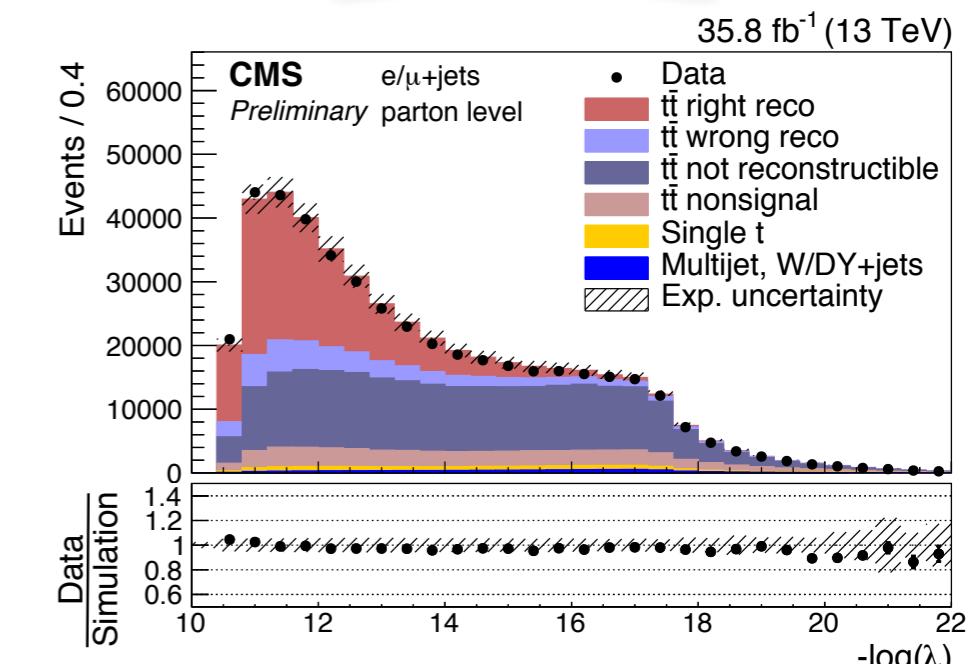
- ✓ Test of nominal MC and compare to different generators/predictions
- ✓ Differential distributions described reasonably well in different variables (top p_T is softer but covered by current uncertainties)

$\ell + \text{jets}$ differential σ_{tt}

CMS-TOP-17-002

- Select 1 e or μ , at least 4 jets, and 2 b-tagged
- Applying W mass and top mass constraints on leptonically decaying top
- Using MET and the leptonic mass constrains to obtain p_z -component of neutrino momentum that distinguish the leptonic b-jet [Nucl. Instrum. Meth. A 736 (2014) 169]
- Calculate the likelihood λ according to the 2D hadronic M_t and hadronic M_W mass distribution, and the compatibility of the leptonic b-jet

parton-level



- ✓ Softer top p_T observed is confirmed
- ✓ Better agreement with NNLO QCD +NLO EW calculation [M. Czakon et al., 2017] on top p_T (scale variation uncertainty only)
- ✓ Uncertainty are correlated across bins

Measurements at particle-level

CMS-NOTE-2017-004

- Define proxy of top quark based on measurable objects (leptons, jets) in experimental acceptance

- Consider two leading- p_T neutrinos per event, the permutation of leptons, neutrinos, and b-jets:

Pseudo W^\pm from $(\nu_{1/2}, \ell^\pm)$ pairs that minimize:

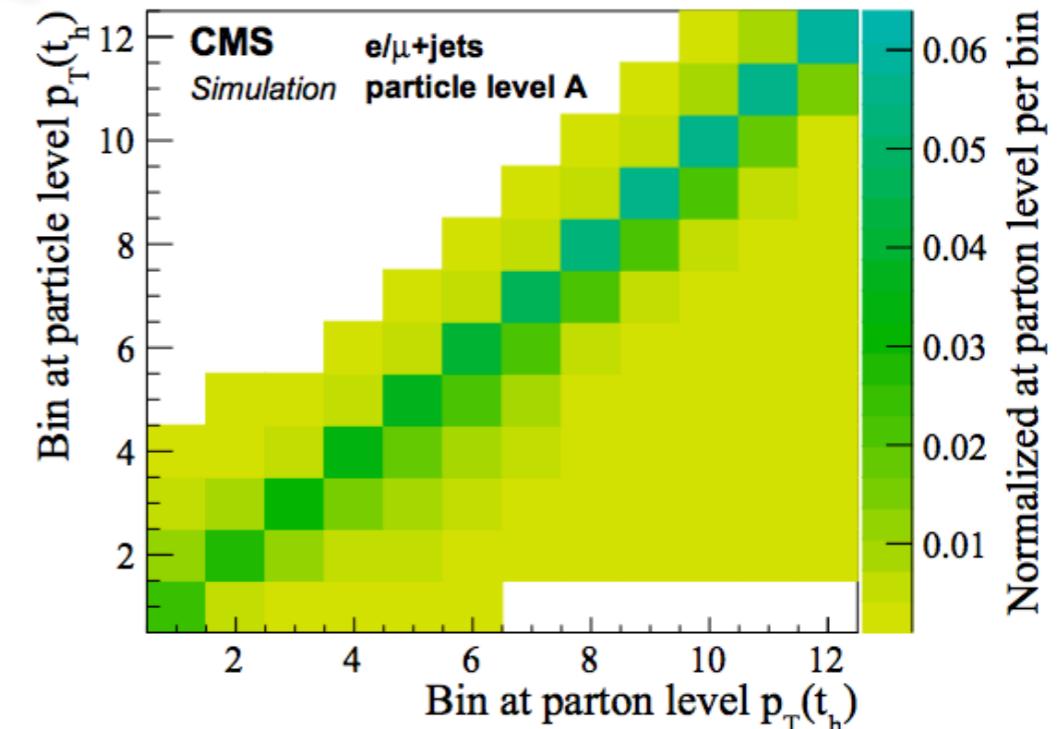
$$|m_{W,1} - m_W| + |m_{W,2} - m_W|$$

Pseudo top from $(b_{1/2}, W^\pm)$ pairs that minimize:

$$|m_{t,1} - m_t| + |m_{t,2} - m_t|$$

where $m_W = 80.4$ GeV, $m_t = 172.5$ GeV

dilepton



- Sum of the momentum of neutrino p_ν in the permutation of jets that minimizes:

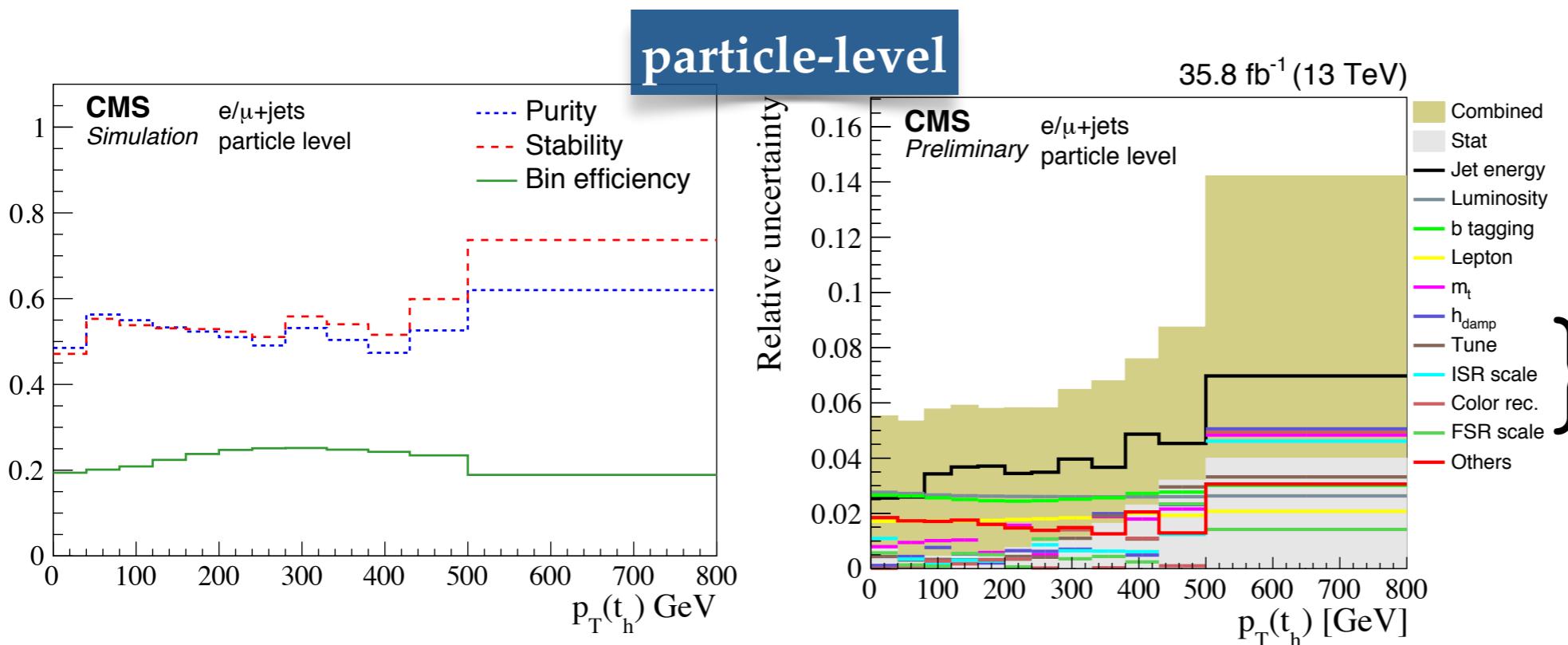
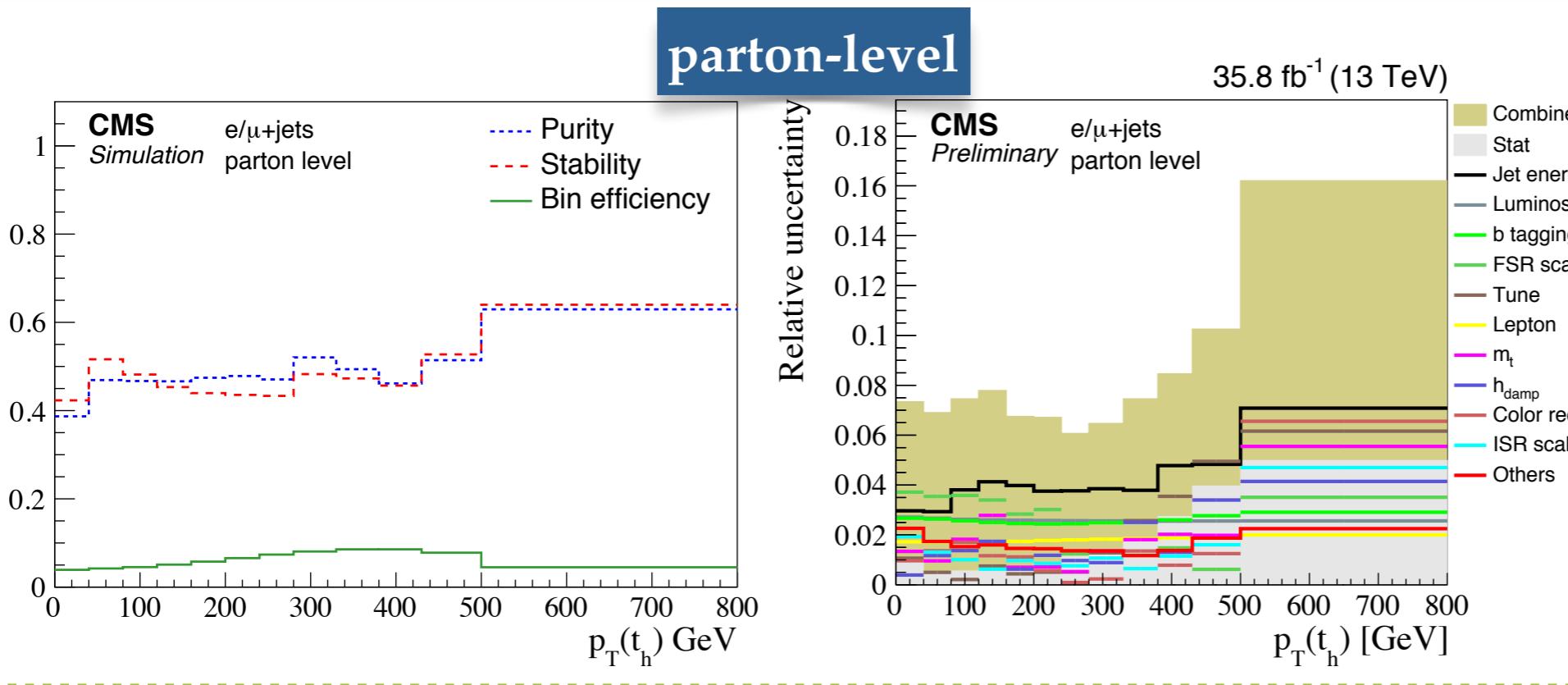
$$K^2 = |M(p_\nu + p_\ell + p_{b\ell}) - m_t|^2 + |M(p_{j1} + p_{j2}) - m_W|^2 + |M(p_{j1} + p_{j2} + p_{bh}) - m_t|^2$$

where $m_W = 80.4$ GeV, $m_t = 172.5$ GeV

$\ell+jets$

Parton-/Particle-level comparison

CMS-TOP-17-002



Purity: The fraction of parton-(particle-)level in the same bin at detector level

Stability: The fraction of detector level in the same bin at parton-(particle-)level

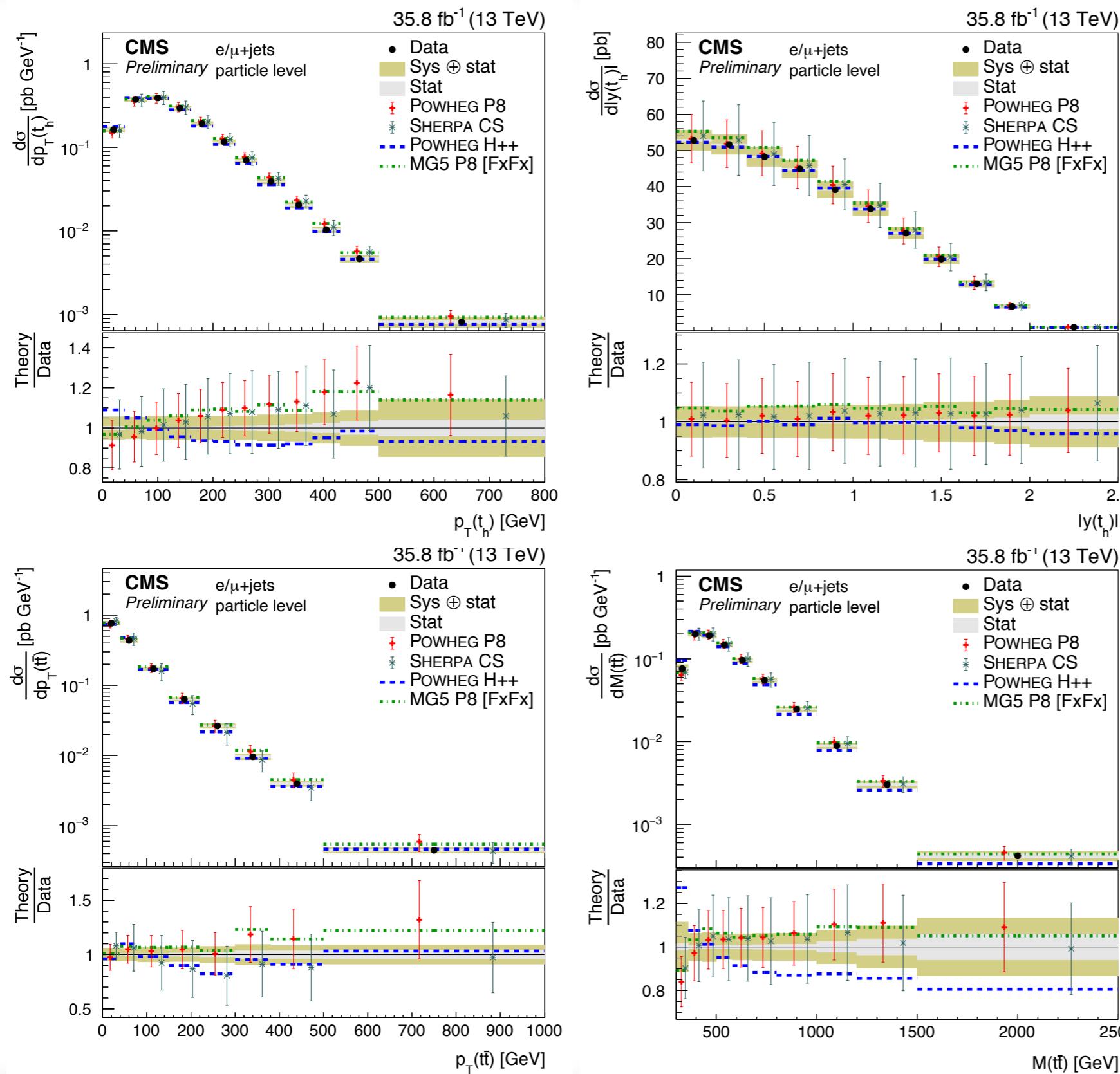
eff: The ratio of the detector to parton-(particle-) level

✓ At particle-level:
more correctly
reconstructed events
(higher purities) and
lower uncertainties

PS systematics

$\ell + \text{jets}$ differential σ_{tt}

CMS-TOP-17-002



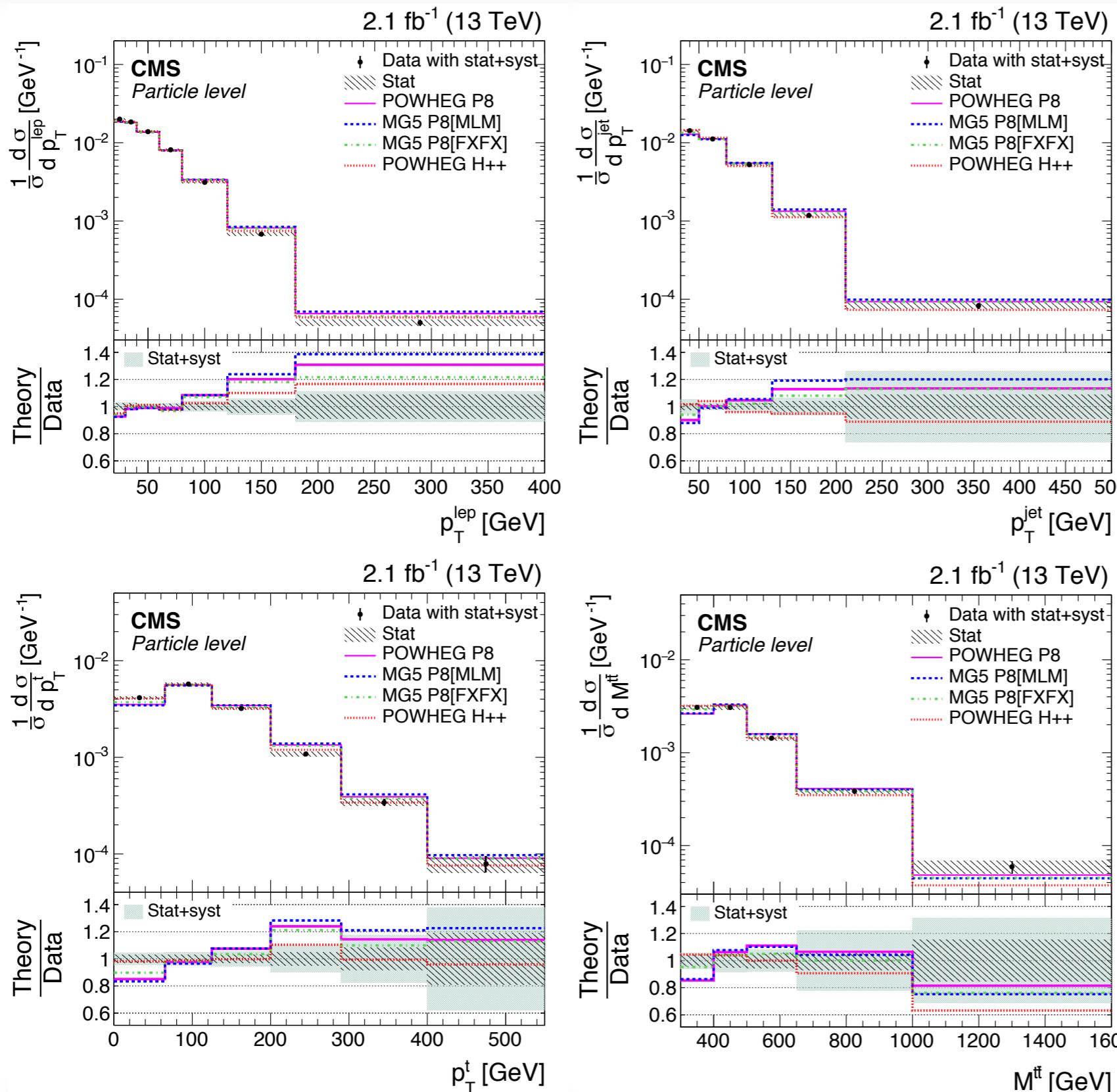
particle-level

✓ Good data and MC agreement;
measured top p_T softer than
expected

✓ Trends similar at parton-level
and particle-level except for
HERWIG++, which predicts
softer top p_T and M_{tt}

Dilepton differential σ_{tt}

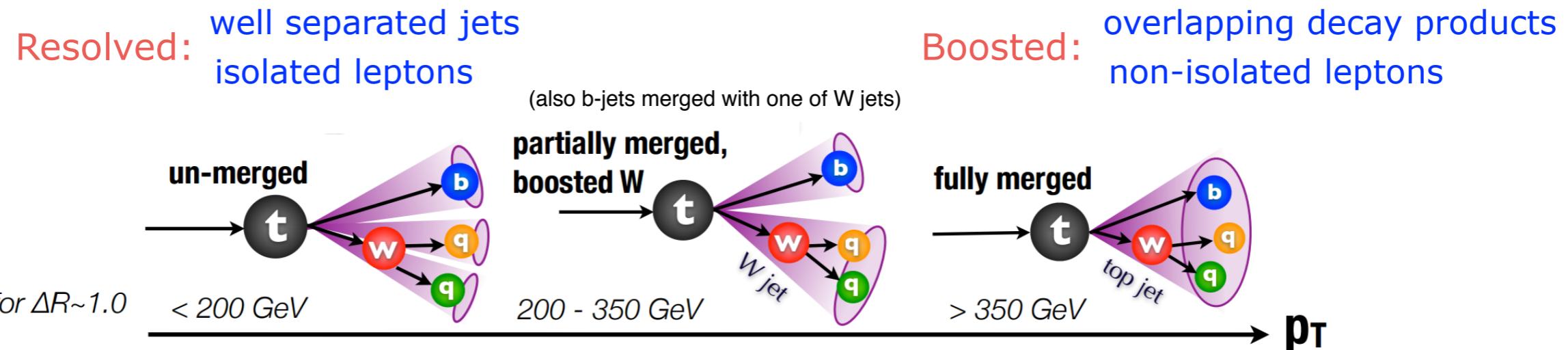
arXiv:1708.07638 sub. to JHEP



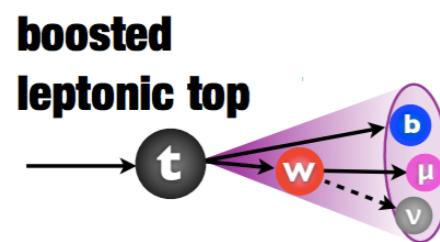
particle-level

- ✓ Softer p_T in top decay products (leptons and jets)
- ✓ Lepton p_T softer in all MCs including HERWIG++

Boosted top quarks

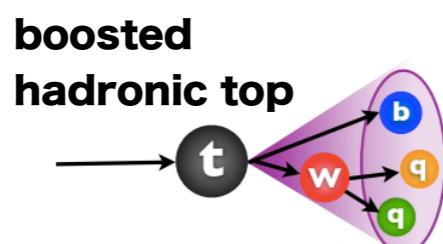


Resolved reconstruction relays on one-to-one jet-to-parton assignment, while in boosted reconstruction:



- ◆ Lepton close to b-jet
- ◆ Standard lepton isolation suboptimal (alternative definitions)

kinematic cuts,
variable isolation
cone, etc



- ◆ Cluster decay products in single large-R jet
- ◆ Jet substructure to distinguish signal from QCD background

top tagger,
jet substructure,
grooming, etc

✓ MANY different techniques, here focus more on the results

All-jets differential σ_{tt}

CMS-TOP-16-013

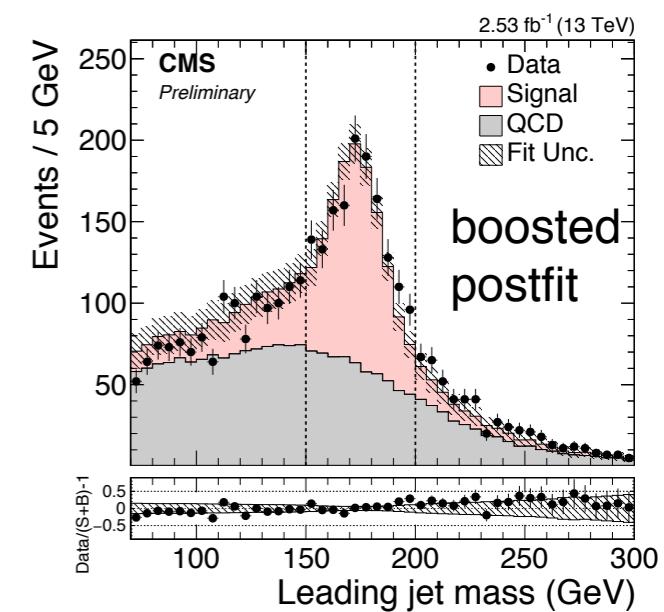
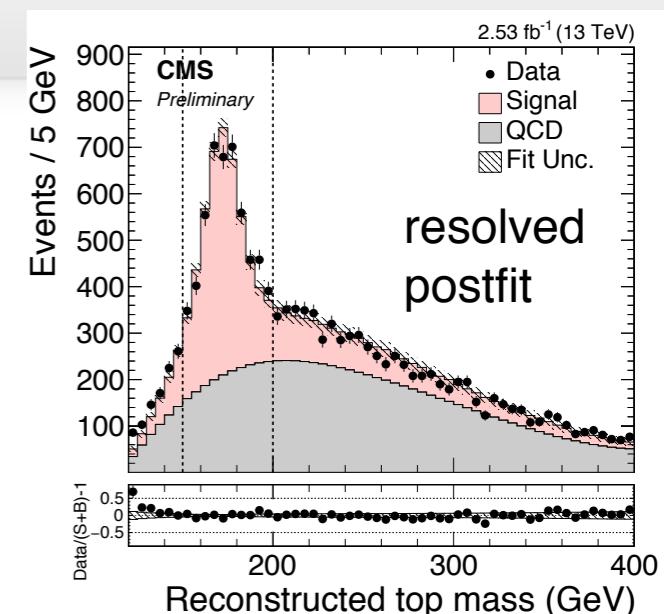
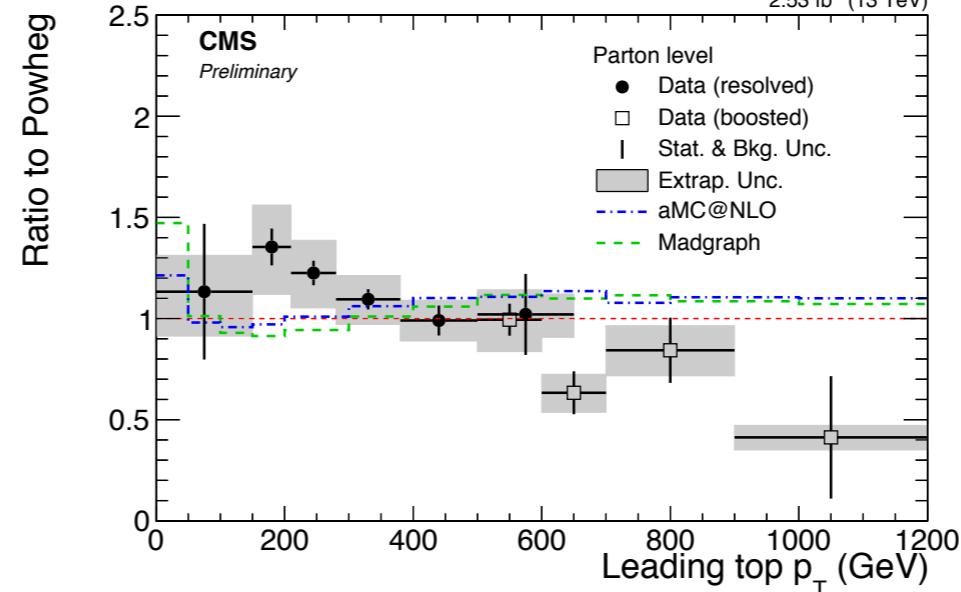
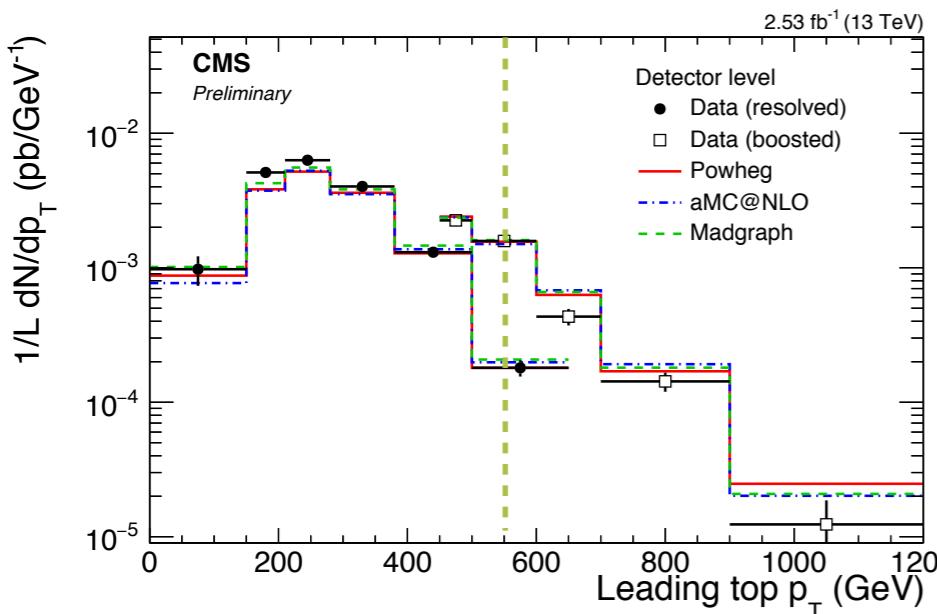
- Resolved regimes:

- Select at least 6 jets, 2 b-tagged
- Kinematic fit tt reconstruction

Template Fit: Signal template from MC, background template from data by inverting b tagging

- Boosted regimes:

- $N_{\text{jets}} \geq 2$ AK8 jets, $150 < m_{SD} < 200$ GeV
- Leading jets $p_T > 450$ GeV
- Leading and subleading jets: b-tagged subjet and n-subjetiness



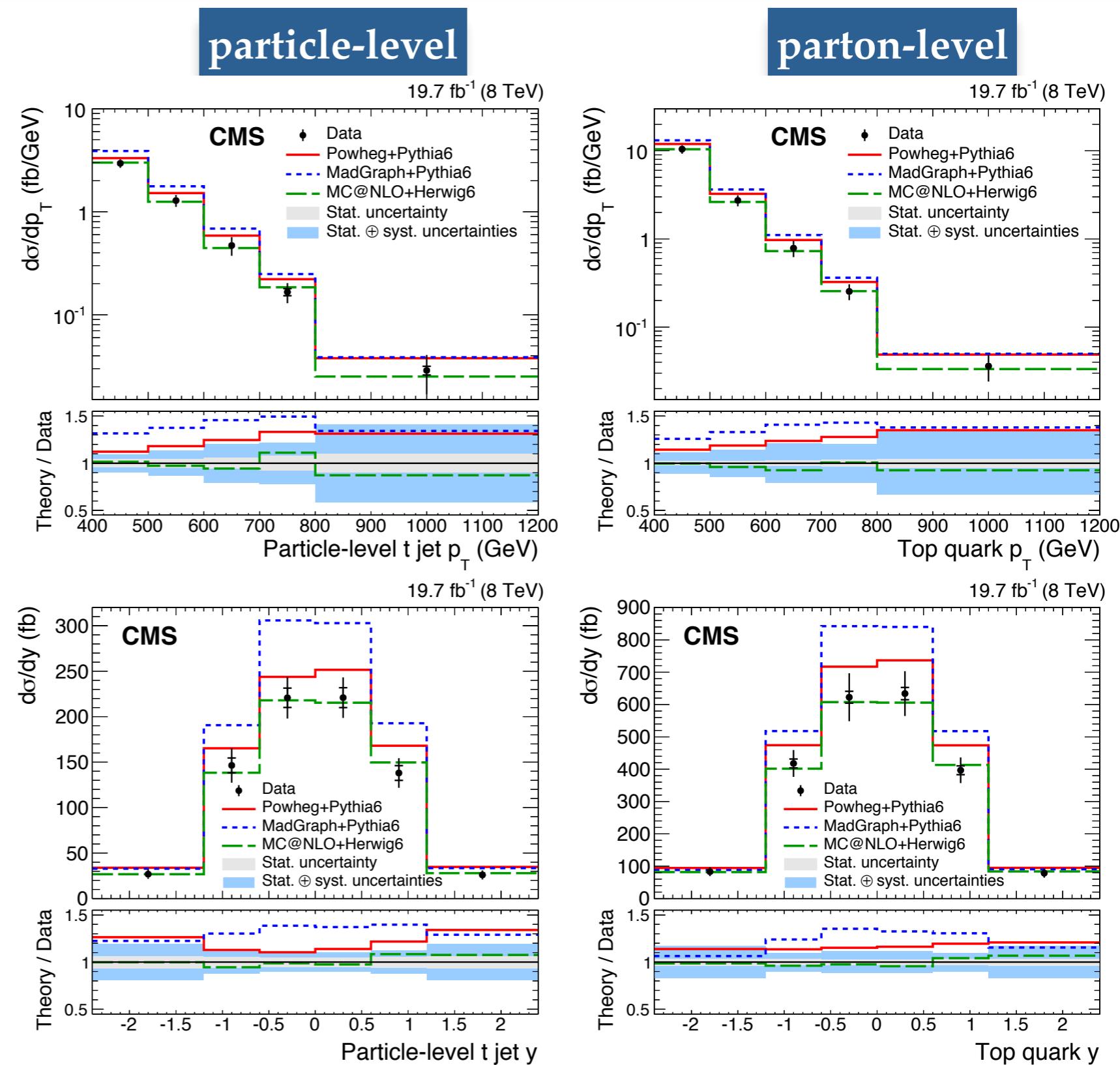
✓ Agreement in the overlapping region
✓ A similar slope of top p_T

Boosted ℓ +jets differential σ_{tt}

PRD 94 (2016) 072002

- Select one lepton close to jet ($R=0.5$) and jet ($R=0.8$) $p_T > 400$ GeV, $140 < m_j < 250$ GeV
- Merged top jet: invert Cambridge-Aachen algorithm to identify hard subjects ($> 5\%$ of p_T), at least 3 subject required
- Differential cross sections extracted from 1t+0b and 1t+1b categories

✓ Soft top p_T confirmed in ℓ +jets boosted regime



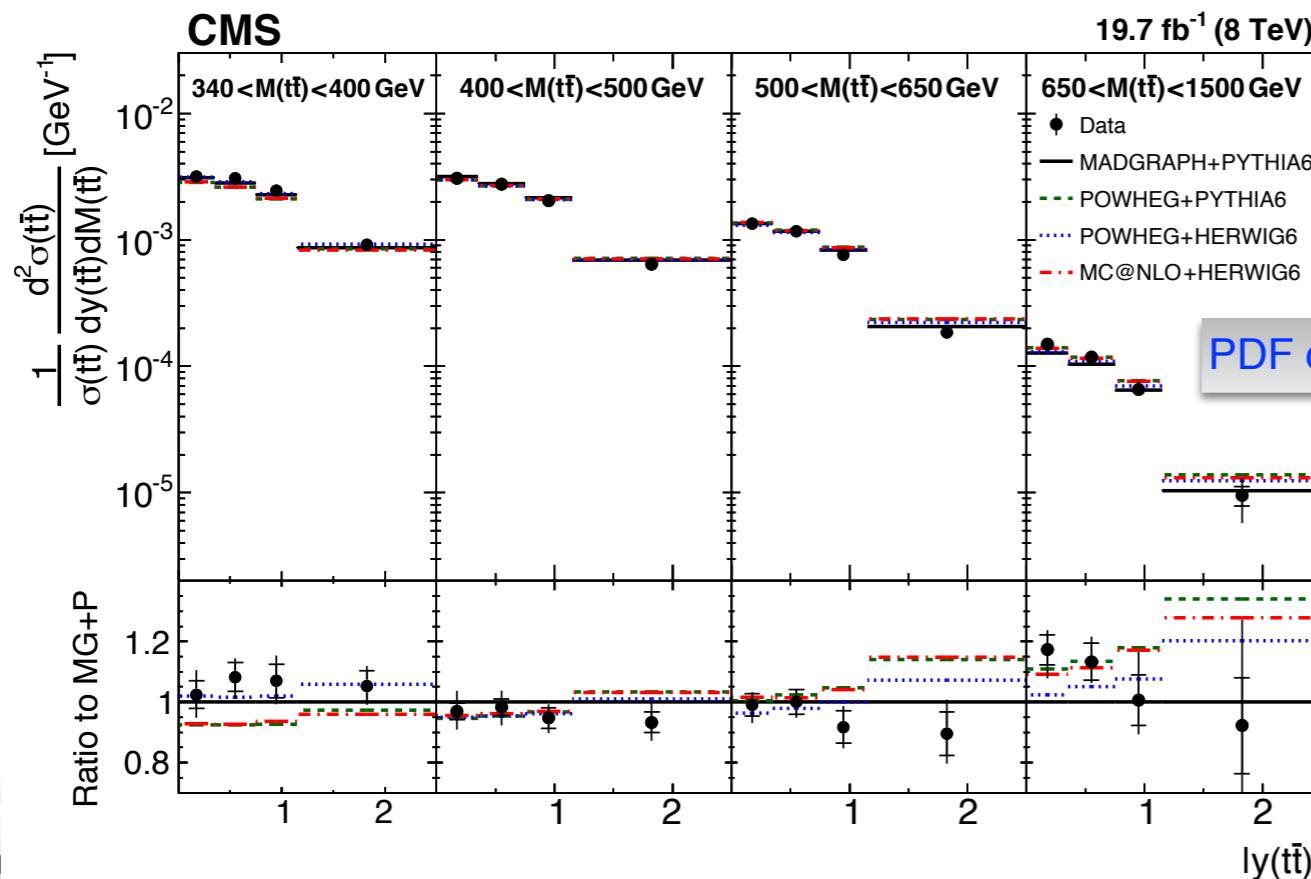
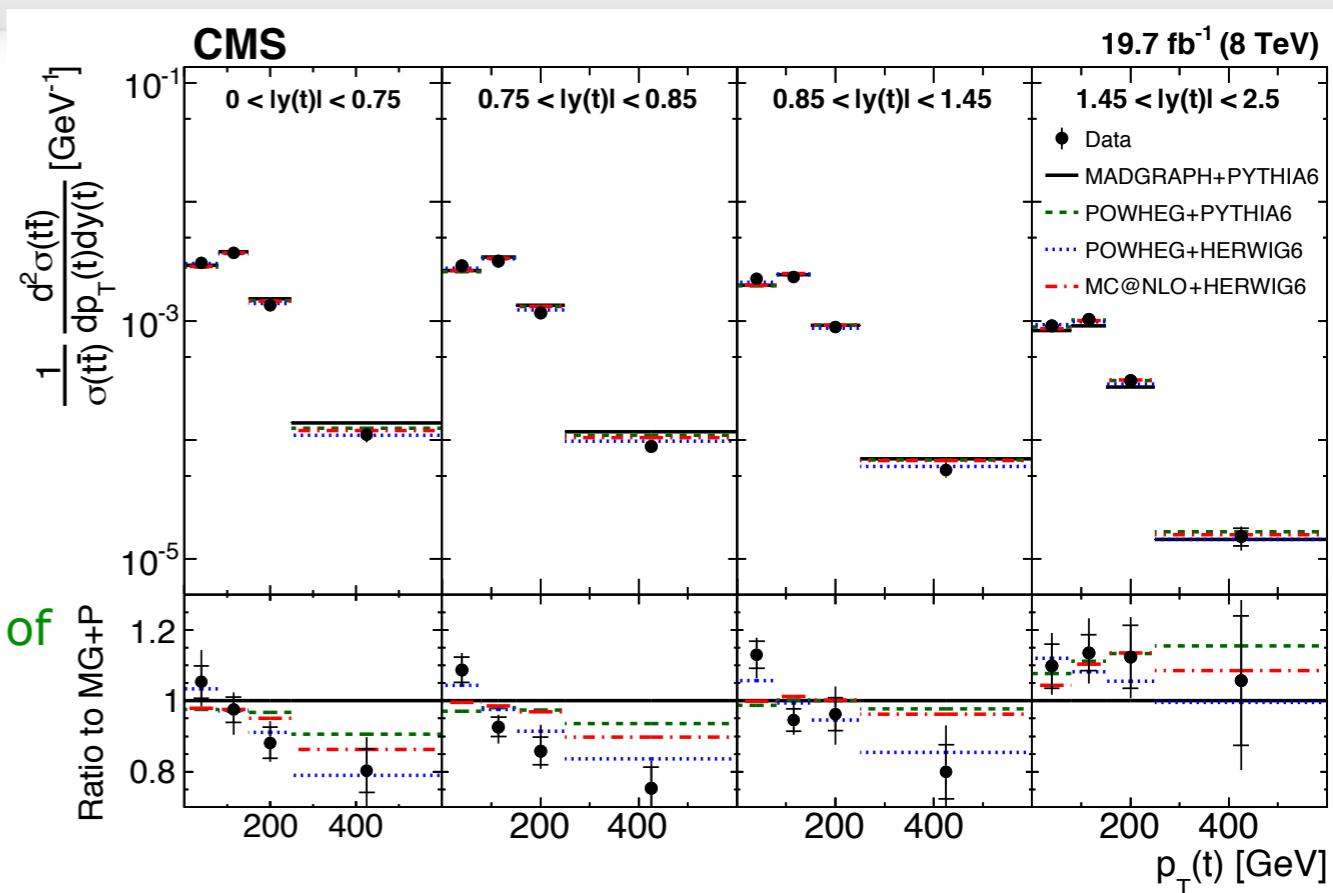
Double differential $\sigma_{t\bar{t}}$

EPJC 77 (2017) 459

- 2D differential cross sections provide further more information in the corner of phase spaces
- Provide good PDF constraints

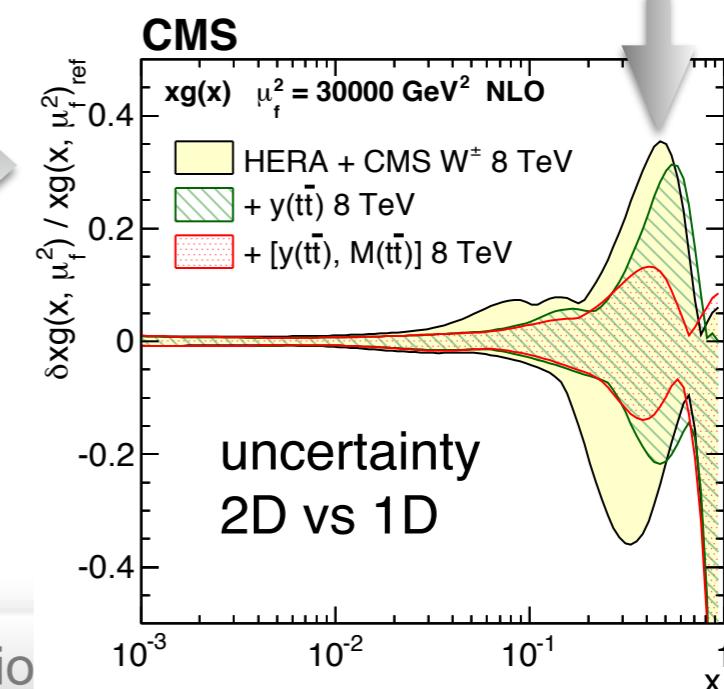
8 TeV
dilepton

✓ top p_T is observed softer among most of the rapidity regions



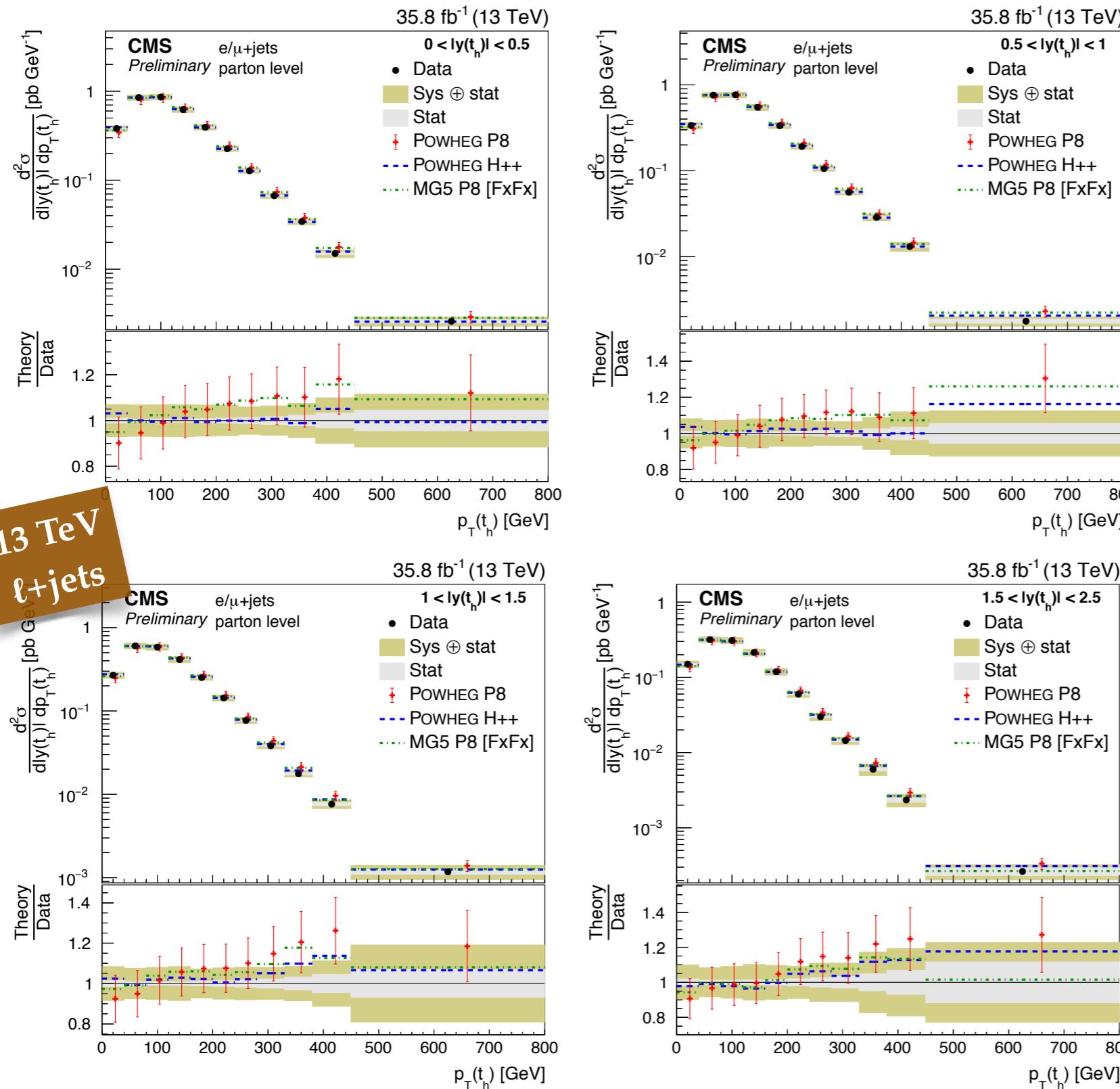
PDF constraints

✓ significantly reduce PDF uncertainty in high- x



Double differential σ_{tt} : $p_T(t)$ - $|y(t)|$

CMS-TOP-17-002

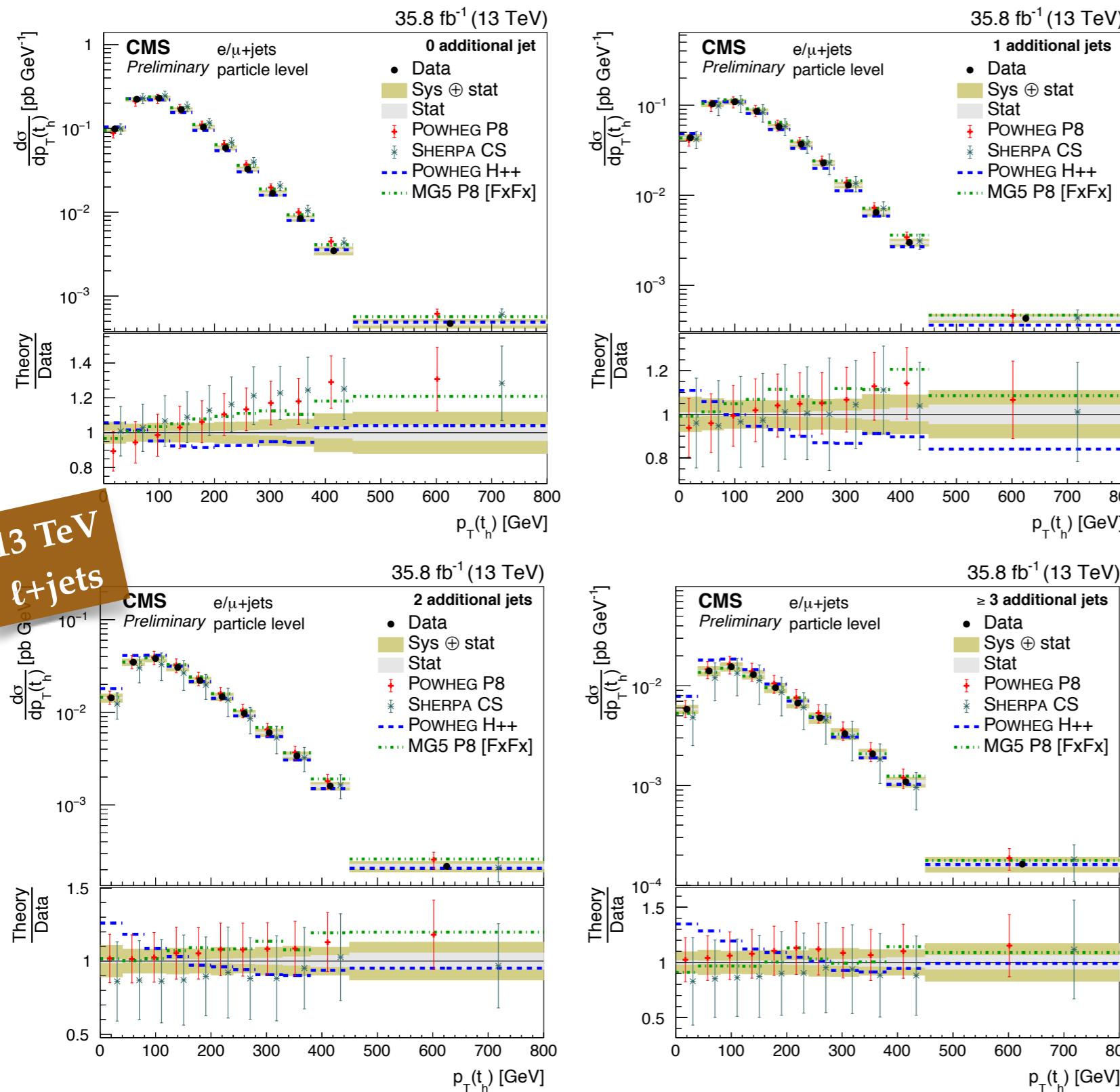


parton-level

- ✓ 2D unfolding in bins of $p_T(t)$ and $|y(t)|$
- ✓ Top p_T is observed softer among all rapidity regions (although it is within the uncertainties)
- ✓ Particle-level distributions show the similar tendency

Double differential σ_{tt} : $p_T(t)$ - N_{jets}

CMS-TOP-17-002



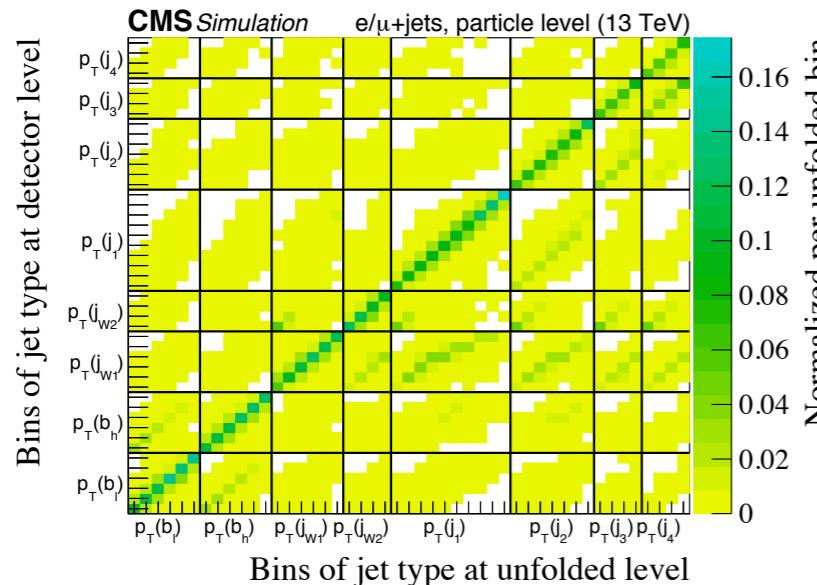
particle-level

- ✓ 2D unfolding in bins of $p_T(t)$ and the numbers of additional jets
- ✓ Selection of jet $p_T > 30 \text{ GeV}$
- ✓ Top p_T distributions are better described in one or more additional jets

Jet properties: p_T of jets

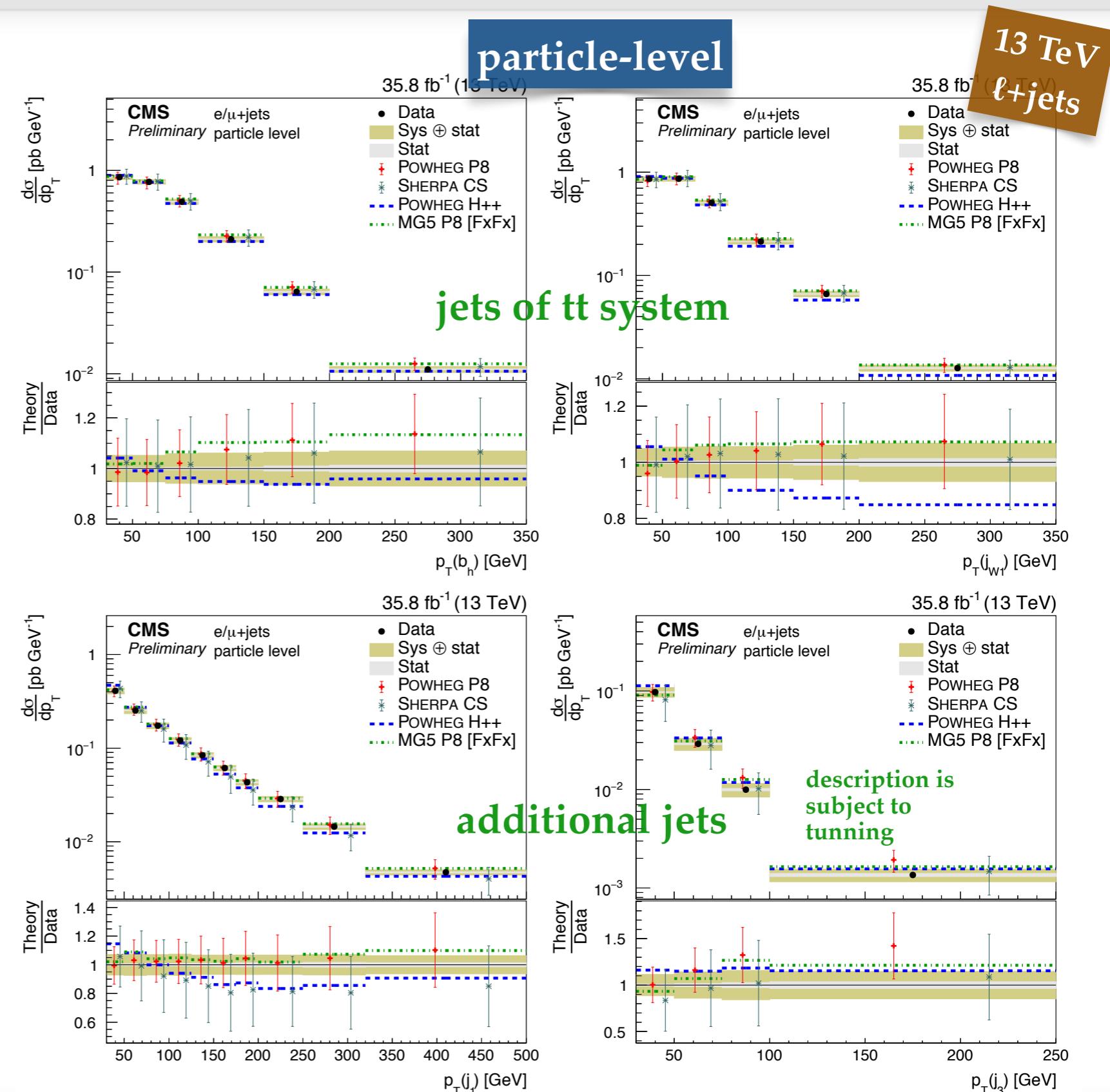
CMS-TOP-17-002

- Measurements of kinematic properties of jets in $t\bar{t}$ system ($b_\ell, b_h, j_{W1}, j_{W2}$) and the additional jets ordered by p_T (j_1, j_2, j_3, j_4)



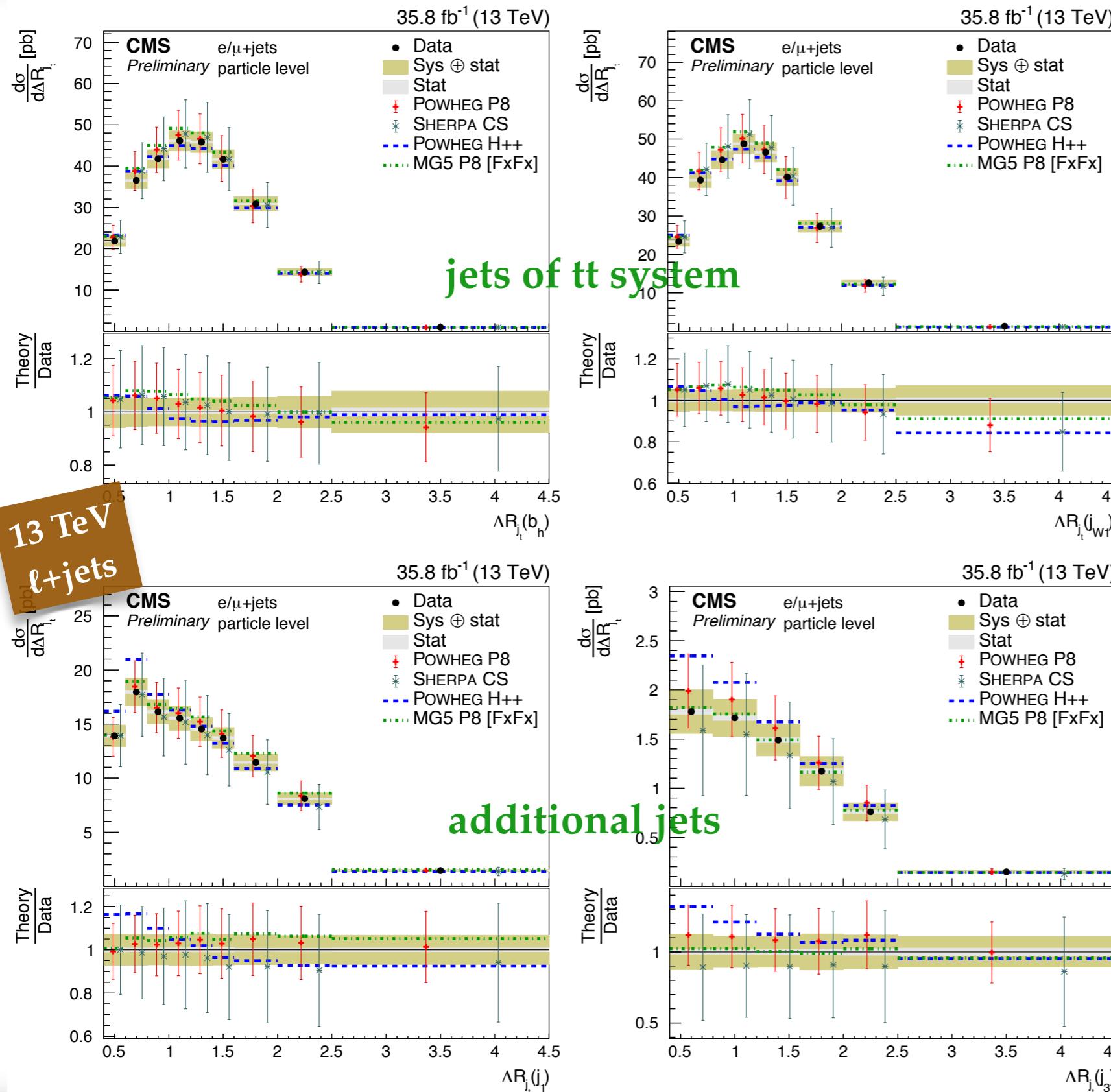
2D unfolding: correction for migrations matrix among all bins

- Reasonably well agreement in MG5+P8[FxFx] ($t\bar{t}$ +up to 2 jets NLO) and SHERPA ($t\bar{t}$ +0,1 jet NLO and up to 4 jets LO)
- POWHEG HERWIG++ jets in $t\bar{t}$ system are softer



Jet properties: minimum separation

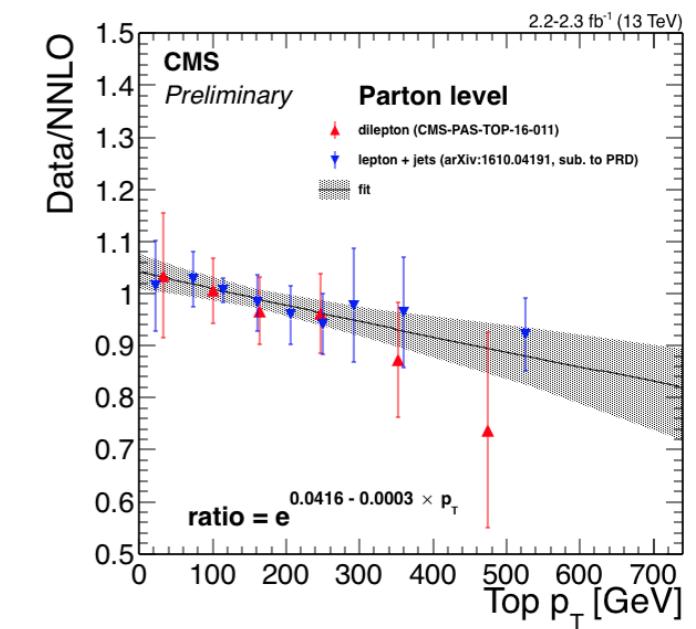
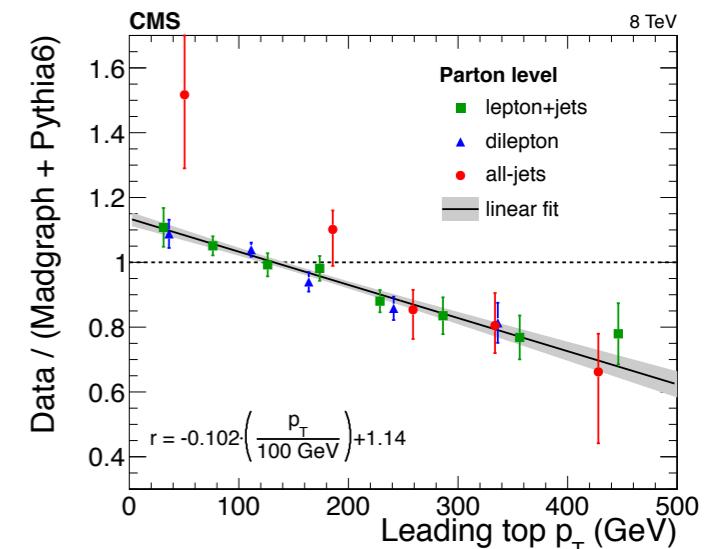
CMS-TOP-17-002



- Minimum separation between top and jets from top decay
 - ✓ Smaller separation due to larger simulated top p_T
 - ✓ Additional jets are well described, but POWHEG + HERWIG++ predicts jets closer to top

Summary & Outlook

- Statistical gains from future data can benefit
 - Statistically-limited phase space, ex: boosted regime
 - Allow finer 2D binning in double differential measurements
- Data are described by MC/fixed-order calculation to a reasonable level
 - Discrepancies observed in top p_T spectra, however covered by current systematic uncertainties
 - Consistent in parton and particle-levels, boosted and resolved regimes, and 2D measurements
 - Better description with NNLO QCD+ NLO EW, but not satisfactory
- Reduce uncertainties to push measurements further
- Beyond cross section measurements
 - Constraining effective field theories of new physics by re-interpreting precise measurements
 - Indirect measurements of important SM parameters, e.g. top-Higgs Yukawa coupling



Recent top differential measurements

★ updates presented here

| | 7, 8 TeV | 13 TeV |
|----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| dilepton | EPJC 75 (2015) 542, 19.7 fb^{-1} (1D) EPJC 77 (2017) 459, 19.7 fb^{-1} (2D and PDFs) ★ | arXiv:1708.07638 sub. to JHEP, 2.1 fb^{-1} (parton/particle-level) ★ |
| $\ell + \text{jets}$ | PRD 94 (2016) 052006, $5.0+19.7 \text{ fb}^{-1}$ (global variables) PRD 94 (2016) 072002, 19.7 fb^{-1} (boosted; p_T) ★ EPJC 77 (2017) 467 (boosted; jet mass) | PRD 95 (2017) 092001, 2.3 fb^{-1} (parton/particle-level; 1D/2D) CMS-TOP-16-014, 35.9 fb^{-1} (global variables) ★ CMS-TOP-17-002, 35.8 fb^{-1} (parton/particle-level; 1D/2D; jet properties) ★ |
| all-jets | CMS-TOP-16-018, 19.7 fb^{-1} (boosted) | CMS-TOP-16-013, 2.5 fb^{-1} (resolved & boosted) ★ |

This talk more focus on 13 TeV results including:
Normalized & Absolute, Particle- & Patron -levels,
1D/2D/Jet properties, Resolved & Boosted regimes

Backup

CMS MC

| Event generator | Parton shower |
|-------------------|-------------------------------------------------------|
| POWHEG (v2) | Pythia 8 |
| POWHEG | Herwig++ |
| MadGraph5_aMC@NLO | Herwig++/Pythia 8 with FxFx ($t\bar{t} + 0, 1, 2j$) |
| MadGraph5 (LO) | Pythia 8 with MLM ($t\bar{t} + 0, 1, 2, 3j$) |
| SHERPA | CS based on the SHERPA default tune |

parton & particle -level comparison

dilepton

arXiv:1708.07638 sub. to JHEP

| Uncertainty source | Particle level [%] | Parton level [%] |
|------------------------------|--------------------|------------------|
| Statistical | 0.24 – 0.70 | 0.37 – 0.70 |
| Pileup modeling | 0.02 – 0.57 | 0.10 – 0.51 |
| Trigger efficiency | 0.03 – 0.74 | 0.06 – 0.85 |
| Lepton efficiency | 0.06 – 0.94 | 0.09 – 1.0 |
| JES | 0.14 – 2.0 | 0.31 – 1.8 |
| JER | 0.04 – 1.2 | 0.29 – 0.94 |
| b jet tagging | 0.12 – 1.2 | 0.32 – 1.2 |
| Background | 0.16 – 2.3 | 0.10 – 1.4 |
| PDFs | 0.15 – 1.2 | 0.17 – 1.0 |
| MC generator | 0.66 – 12 | 1.8 – 10 |
| Fact./renorm. | 0.10 – 4.7 | 0.21 – 4.6 |
| Top quark mass | 0.49 – 2.0 | 0.73 – 4.2 |
| Top quark p_T | 0.03 – 0.96 | 0.04 – 1.3 |
| Hadronization | 0.70 – 6.0 | 0.49 – 8.3 |
| Total systematic uncertainty | 1.7 – 17 | 3.3 – 13 |