

# CMS measurements of differential $t\bar{t}$ cross sections

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**On behalf of the CMS collaboration**

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**TOP2017, Braga**

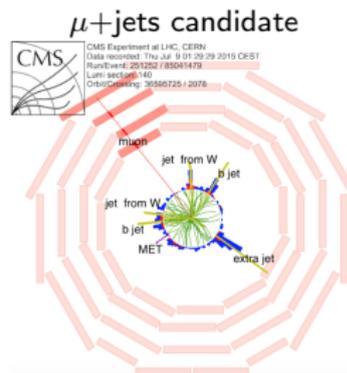
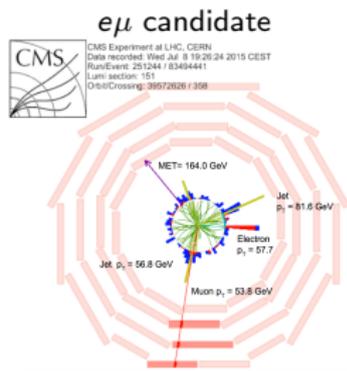
18.09.2017

## The high rate of $t\bar{t}$ production at the LHC (30m in 2016) allows for precise differential measurements:

- Precision test of the standard model (unique opportunity to observe a quark)
- Sensitive to physics beyond the standard model
- Important background for many searches

## Differential cross section measurements:

- Kinematics of top quarks and  $t\bar{t}$  system in all decay channels
- Results at parton and particle levels
- Double-Differential cross sections
- Multiplicities and kinematic properties of (additional) jets.



# Differential $t\bar{t}$ cross sections measurements

EPJC 75 (2015) 542,  $19.7 \text{ fb}^{-1}$ , 8 TeV — New arXiv:1708.07638 sub. to JHEP,  $2.1 \text{ fb}^{-1}$ , 13 TeV

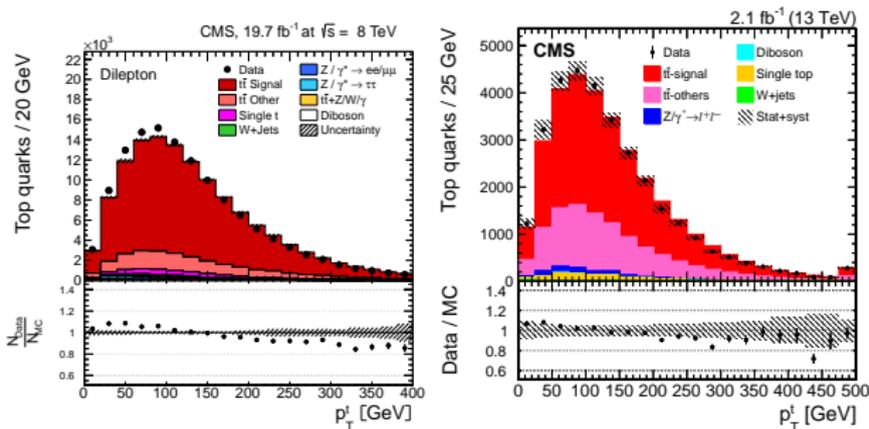
## In $e\bar{e}, \mu\bar{\mu}, e\mu$ final state

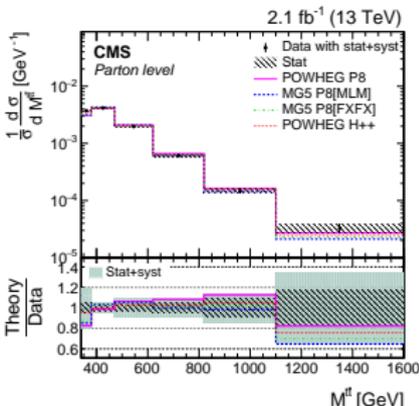
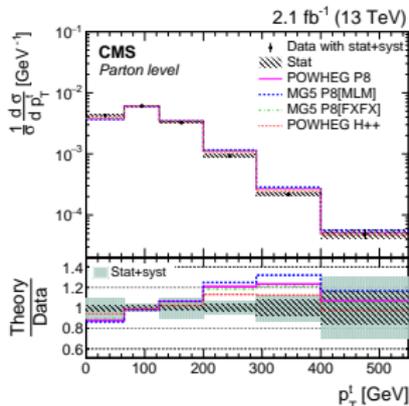
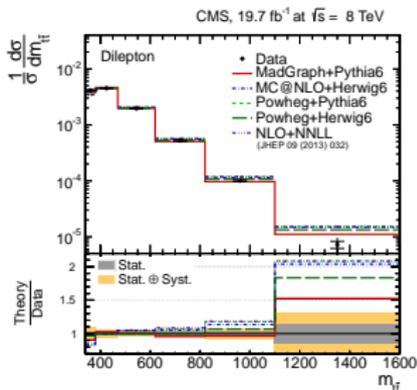
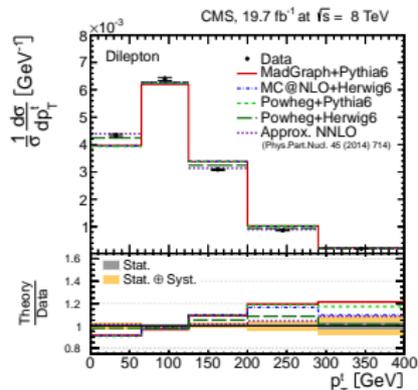
Selection:

- Selection: opp. charged lepton pair, 2 jets at least one b-tagged.
- In same flavor channels  $|m_Z - m_{\ell\bar{\ell}}| > 15 \text{ GeV}$  and  $p_T^{\text{miss}} > 40 \text{ GeV}$

Reconstruction:

- Algebraic reconstruction of neutrino momenta and jet assignment:
  - event  $p_T$  balance,  $M_t$ ,  $M_W$  constraints.
  - smearing according to detector resolution to increase number of solvable events.



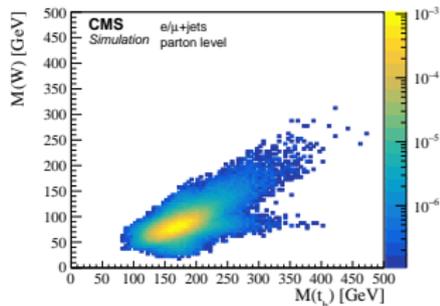
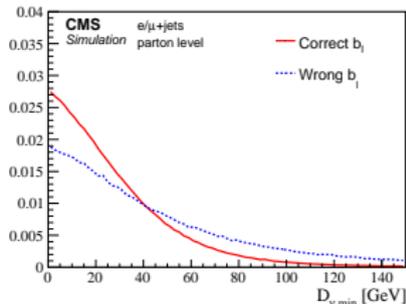
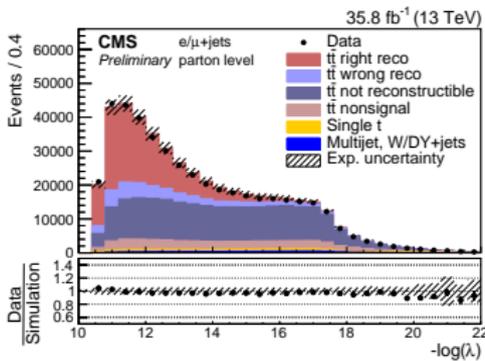


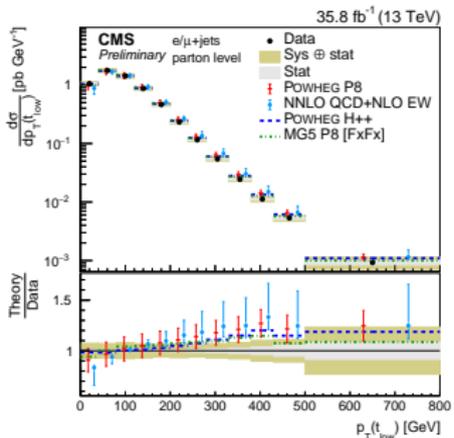
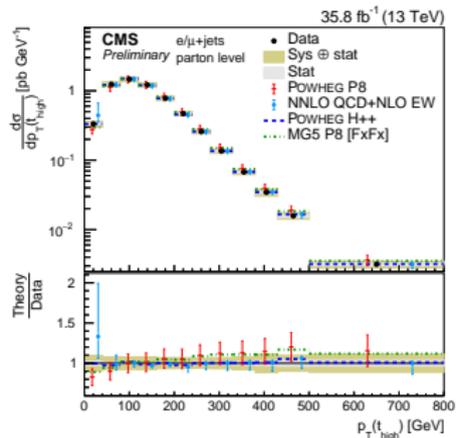
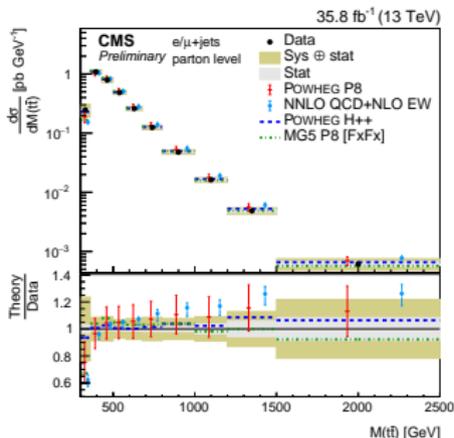
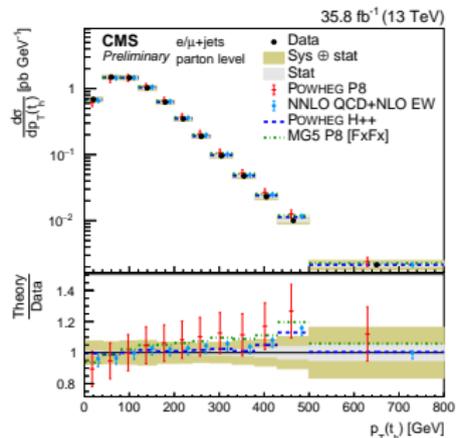
## Parton-level measurements

- Extrapolation from measured distributions to partonic top quarks.
- Measured  $p_T(t)$  softer than predicted by most of the calculations at both energies.
- $M(t\bar{t})$  and other distributions well described.

In  $e/\mu$ +jets final state.

- Exactly 1  $e/\mu$ , at least 4 jets, 2 b-tagged jets.
- Based on lepton and  $\cancel{E}_T$  use mass constraints of  $M_t$ ,  $M_W$  on leptonic side to obtain  $p_z$ -component of neutrino momentum, and correct b-jet.
- Calculate likelihood  $\lambda$  according to 2D mass distributions of  $M_t$ ,  $M_W$  on hadronic side and compatibility of b-jet on leptonic side.





- Softer  $p_T(t)$  confirmed in  $\ell$ +jets channel for POWHEG/MG5+PYTHIA8, HERWIG++ better.
- Better agreement with NNLO QCD + NLO EW [M. Czakon et al., 2017] calculation, but leading and trailing  $p_T(t)$  show different trends.

# Measurements at particle level

New CMS-TOP-17-002, 35.8 fb<sup>-1</sup>, 13 TeV – CMS-NOTE-2017-004 “Particle level definitions”

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

- clean definition of “top quark” observable.
- avoid theoretical extrapolations.

**Definition of particle-level top quarks** (see poster by M. Seidel)

- $e/\mu$ +jets

Events with exactly 1 electron or muon, 2 b jets, in total at least 4 jets

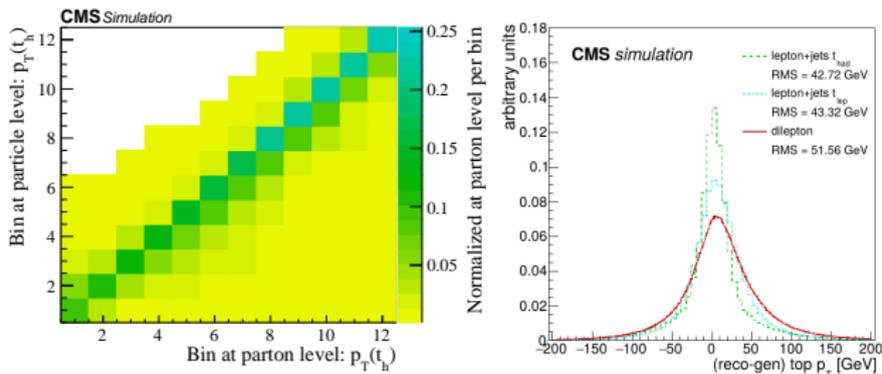
Sum momenta of all neutrinos  $p_N$  and find the permutation of jets that minimizes:

$$K^2 = (M(p_N + p_\ell + p_{b_1}) - m_t)^2 + (M(p_{j_1} + p_{j_2}) - m_W)^2 + (M(p_{j_1} + p_{j_2} + p_{b_2}) - m_t)^2$$

- Dilepton

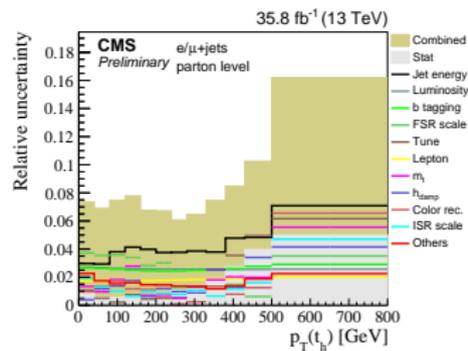
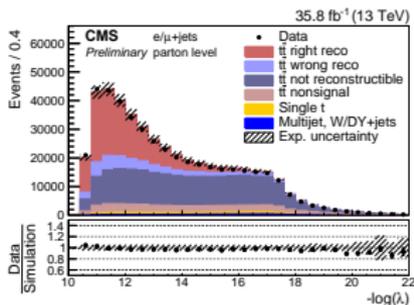
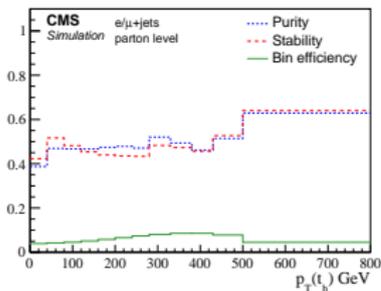
Events with 2 electrons/muons, 2 neutrinos and 2 b jets.

Use  $M(W)$  and  $M(t)$  constraints to select best combination of leptons, neutrinos, and b jets.

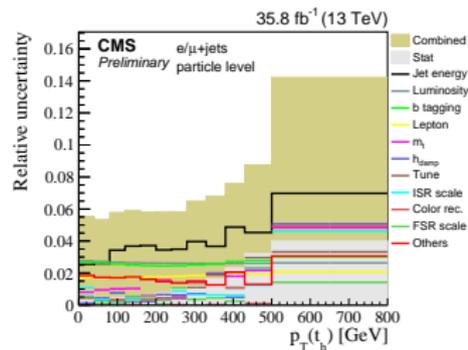
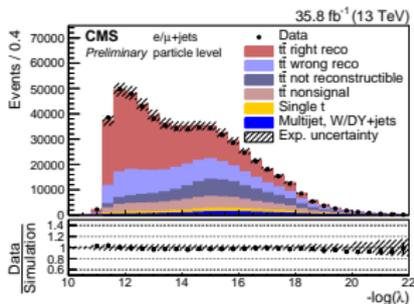
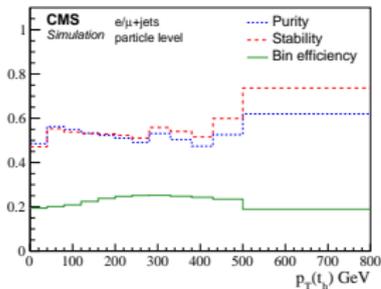


## Comparison parton and particle level reconstruction in e/ $\mu$ +jets final state

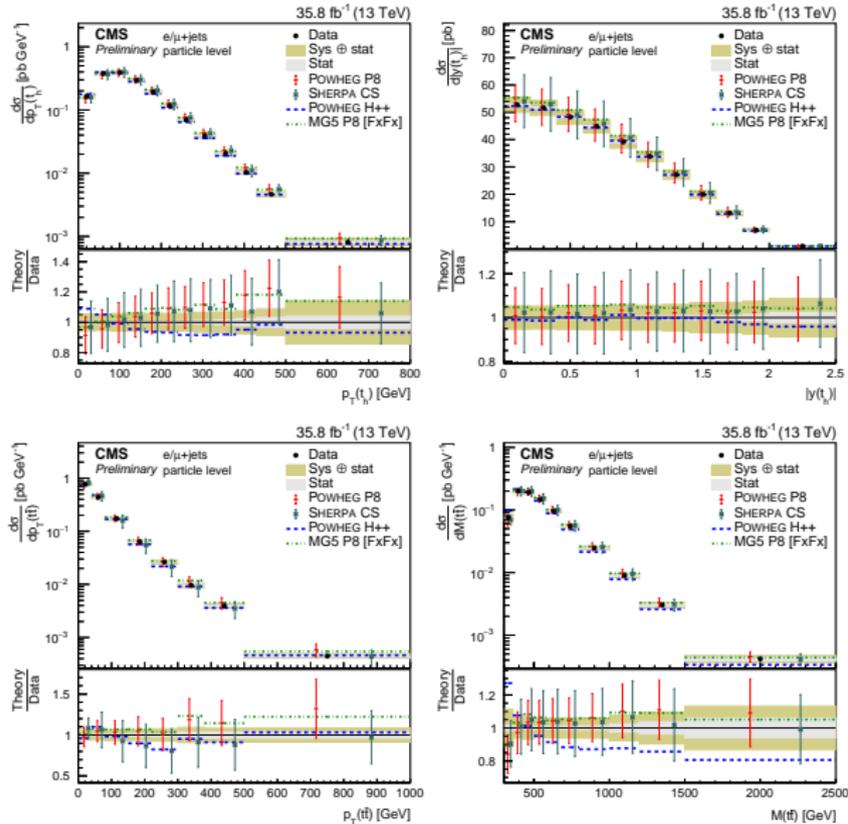
### Parton level



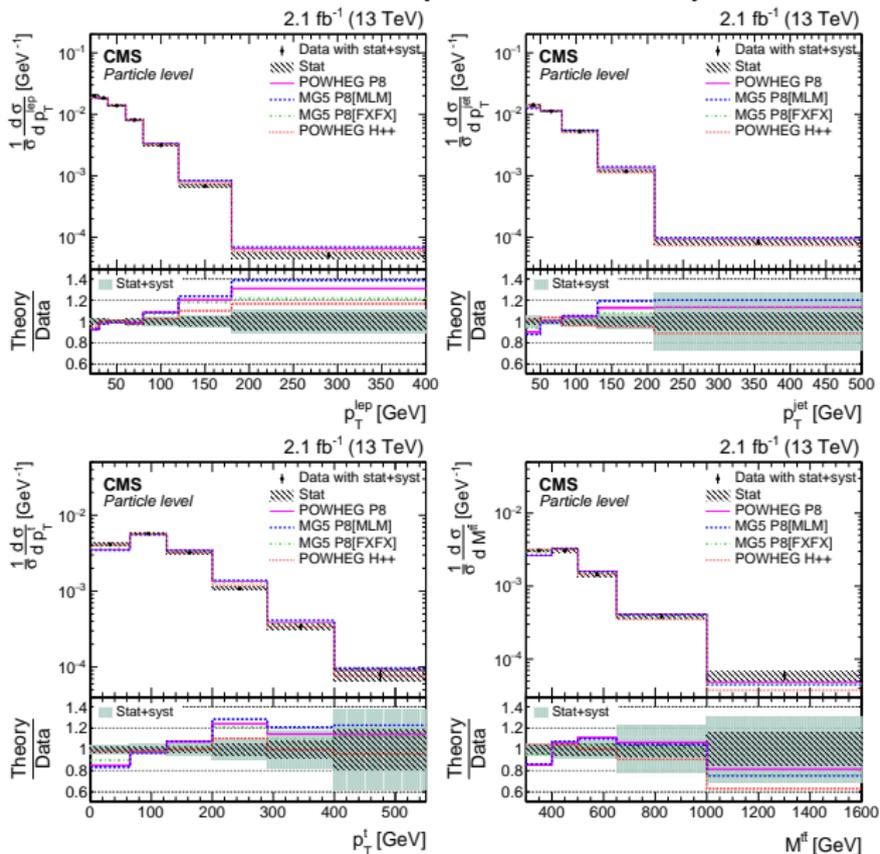
### Particle level



At particle level: more correct reconstructed events, higher purities, and lower uncertainty.  
 purity(stability) fraction of correct reconstructed events in detector(generator) level bin.

Differential cross sections at particle level in  $e/\mu$ +jets final state.

## Differential cross sections at particle level in dilepton final state.



- Softer  $p_T$  confirmed for  $t$  decay products (leptons and jets).
- Lepton  $p_T$  softer in all MCs including HERWIG++.

## In all-jets final state

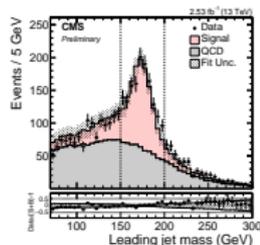
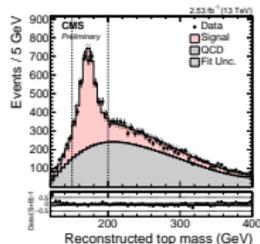
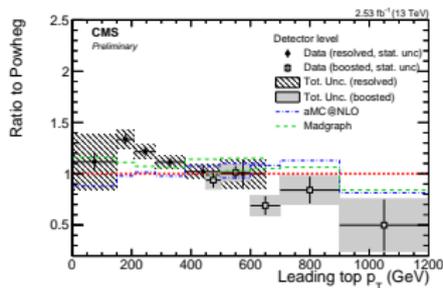
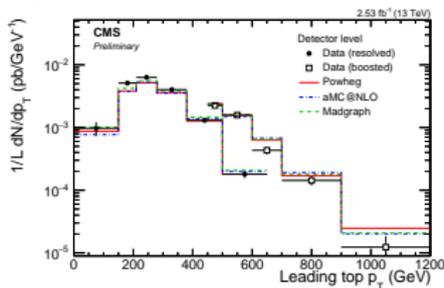
## Resolved

- Selection: at least 6 jets, 2 b tagged
- Perform kinematic fit for  $t\bar{t}$  reconstruction (based on W and top mass constrains)
- Accept events with  $150 < m_t^{\text{fit}} < 200$  GeV, and fit probability greater than 0.02.

## Boosted

- 1 jet  $p_T > 200$  GeV and 1 jet  $p_T > 450$  GeV
- each jet: softdrop mass  $> 50$  GeV, b tagged subjet, n-jettiness requirements.

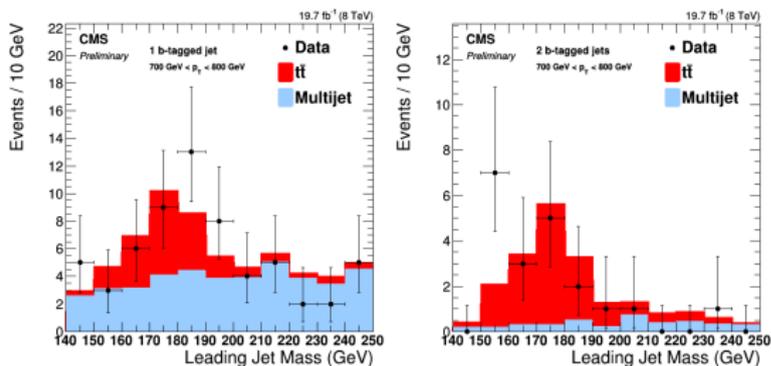
Template Fit: Signal template from MC, background template from data by inverting b tagging.



Soft  $p_T(t)$  confirmed in all-jets channel and persisting in boosted regime.

## Boosted all-jets final state, $p_T(t) > 500$ GeV

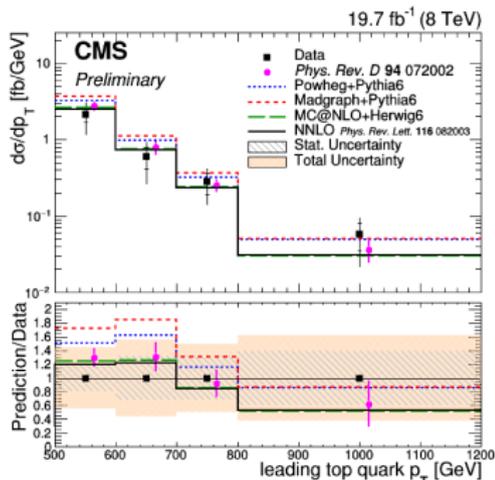
- 2 CA ( $R = 0.8$ ) jets  $p_T > 400$  GeV, soft drop mass 140–250 GeV, jettiness  $\tau_{32} < 0.55$ .
- Signal yield in  $p_T$  bins extracted by simultaneous template fit of leading jet mass in b-tagging and  $\tau_{32}$  categories.



Inclusive cross section  $p_T(t/\bar{t}) > 500$  GeV:

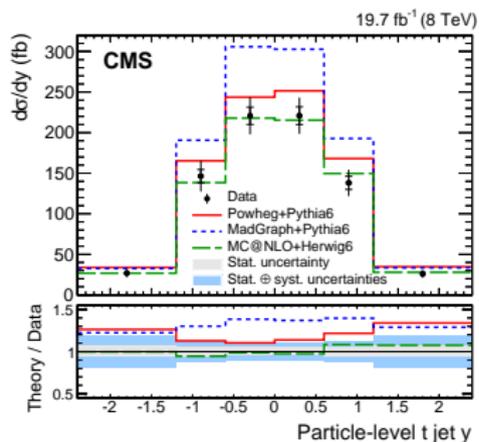
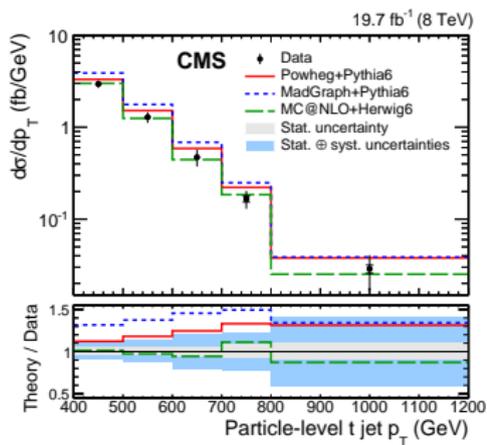
$$\sigma = 404 \pm 23(\text{stat}) \pm 25(\text{exp}) \pm 140(\text{theory}) \text{ fb}$$

compatible with expected 470 fb (NLO)



**Boosted  $e/\mu$ +jets final state,  $p_T(t) > 400$  GeV**

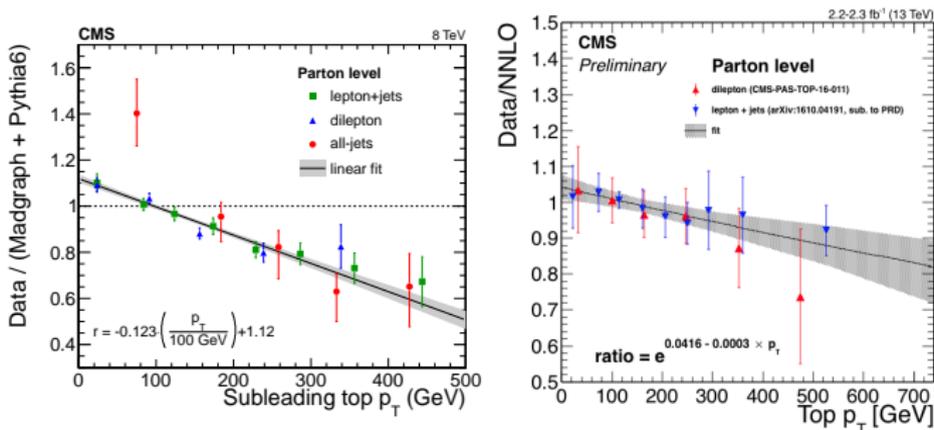
- Selection: one  $e/\mu$  close to jet ( $R = 0.5$ ) and jet ( $R = 0.8$ )  $p_T > 400$  GeV,  $140 < m_j < 250$  GeV .
- Merged top jet: invert Cambridge-Aachen algorithm to identify hard subjects ( $> 5\%$  of  $p_T$ ), at least 3 subject required.
- Differential cross sections extracted from 1t+0b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



Soft  $p_T(t)$  confirmed in  $\ell$ -jets in boosted regime.

## Summary differential cross sections

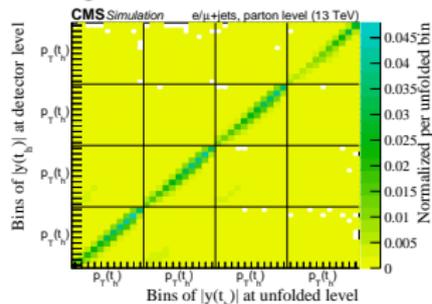
- Measurements at 7, 8, and 13 TeV in various  $t\bar{t}$  decay channels.
- $p_T(t)$  observed softer, but compatible with standard model within uncertainties in measurement and theory.
- Persistent in boosted regime  $p_T(t) > 400$  GeV.



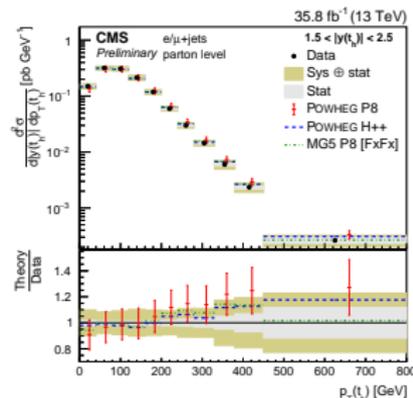
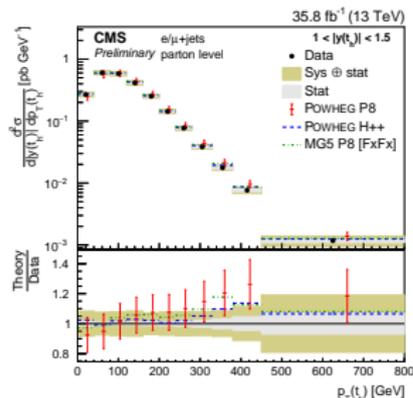
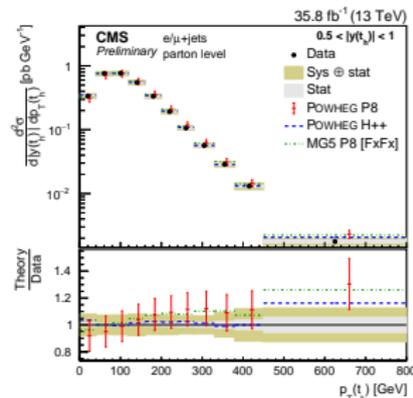
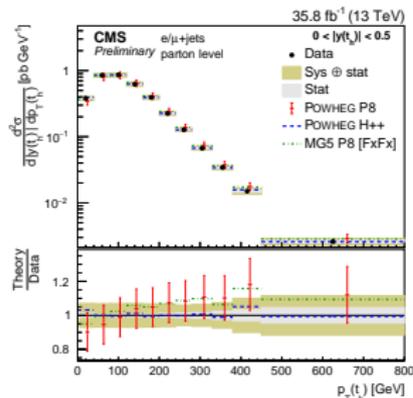
# Double-Differential $t\bar{t}$ cross sections measurements

New CMS-TOP-17-002,  $35.8 \text{ fb}^{-1}$ , 13 TeV

Results unfolded in 2 dim.  
 → correction for migrations among all bins.



- Provide more details in corners of phase space.
- $p_T(t)$  softer in all rapidity regions.

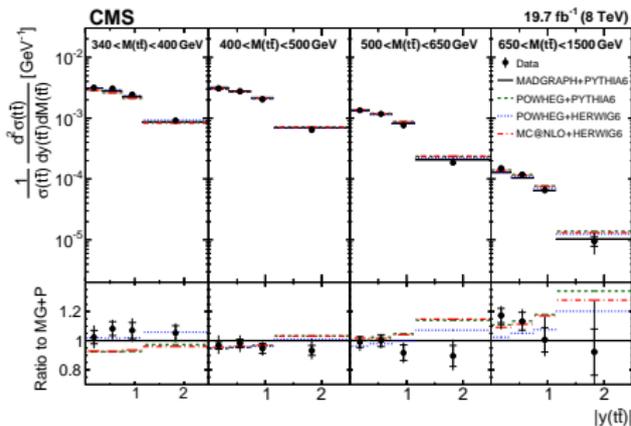
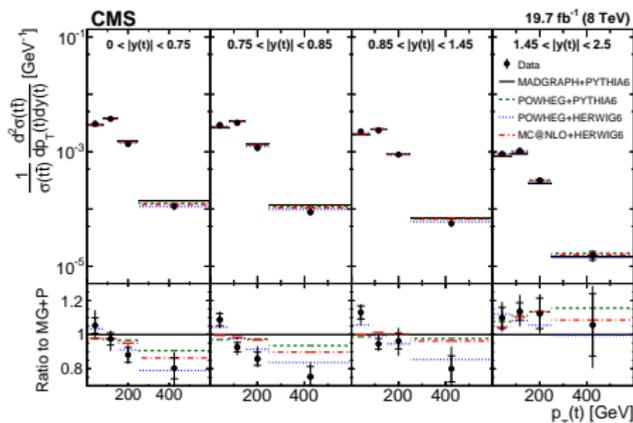


# Double-Differential $t\bar{t}$ cross sections measurements

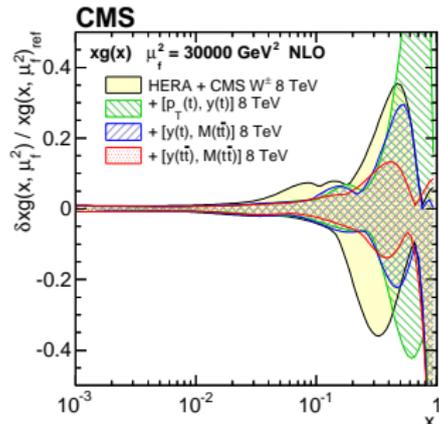
EPJC 77 (2017) 459 ,  $19.7 \text{ fb}^{-1}$ , 8 TeV

## In dilepton channel

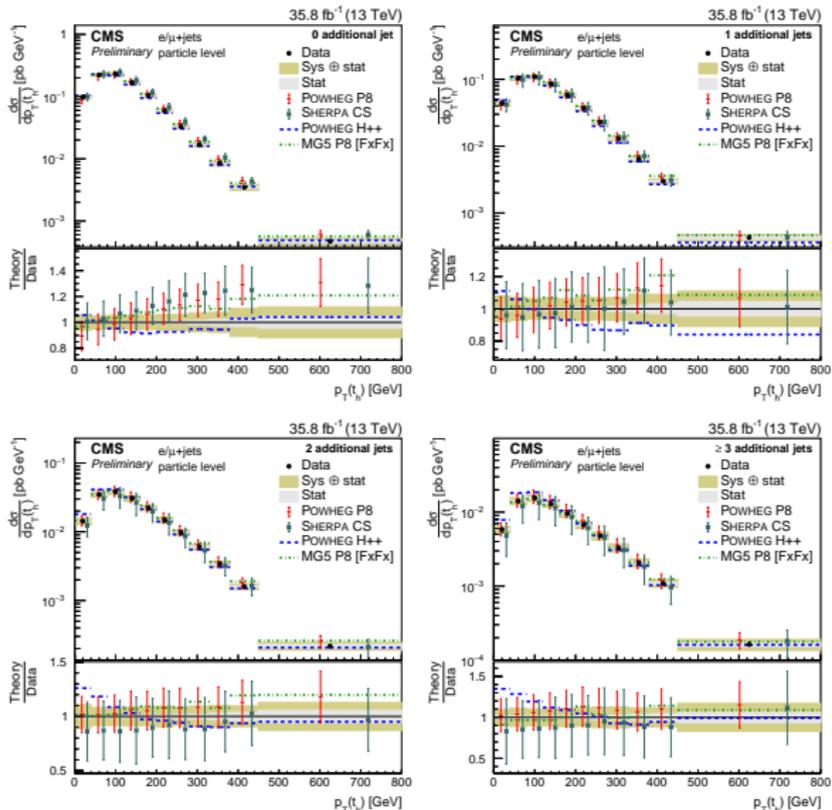
- $p_T(t)$  softer in all rapidity regions.



PDFs constrains (gluon at high  $x$ ):



## $p_T(t)$ in bins of jet multiplicity ( $p_T(\text{jet}) > 30 \text{ GeV}$ )

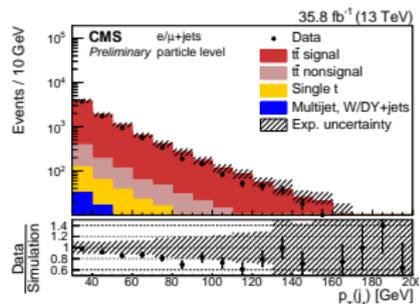
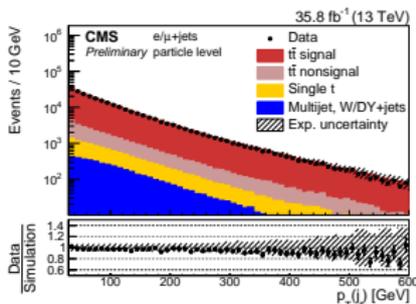
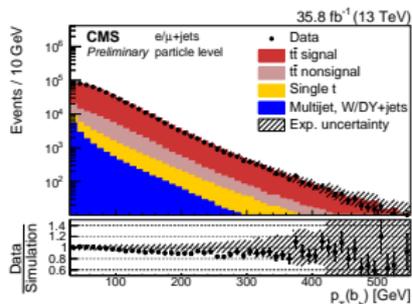
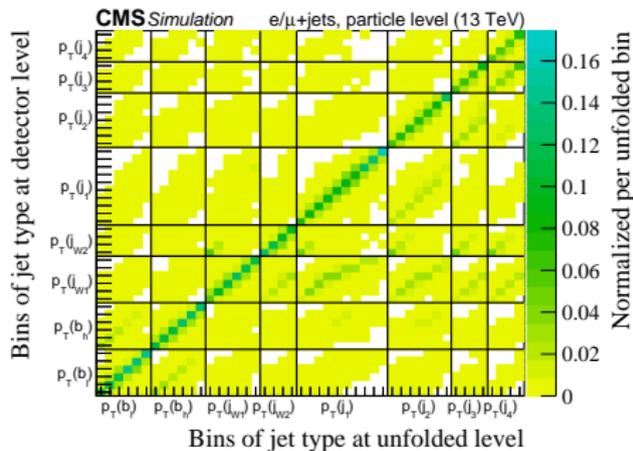


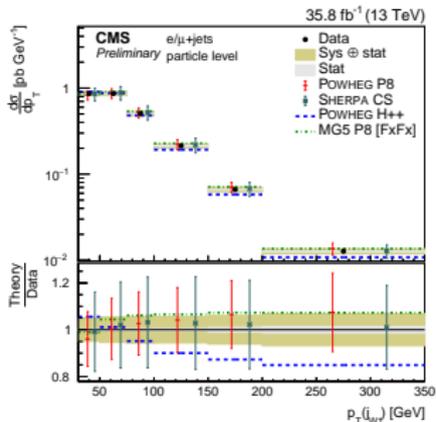
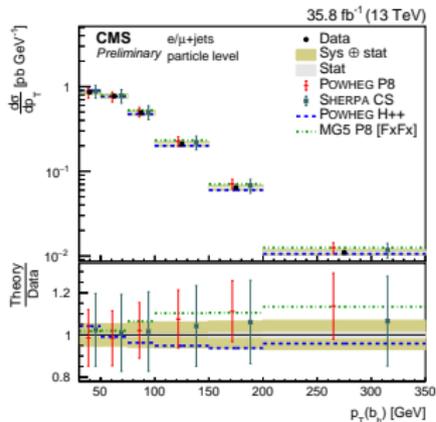
2 Dim. unfolding in  $p_T(t)$  and number of additional jets.

- $p_T$  better described with one or more additional jets.
- HERWIG++ shows different behavior. (probably due to switched off matrix element corrections in parton shower.)

## Jet properties

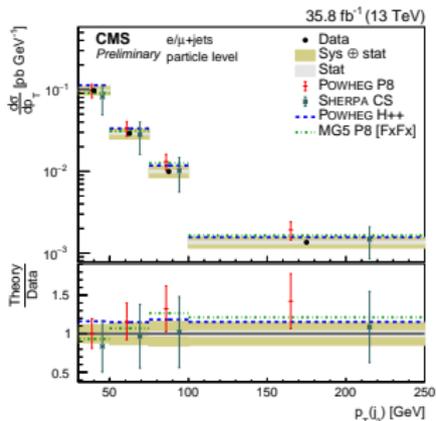
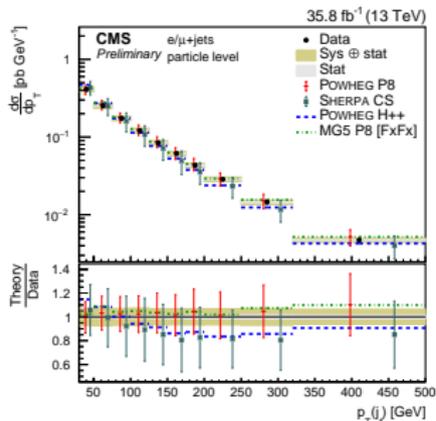
- Measurement of kinematic properties of jets in  $t\bar{t}$  system ( $b_l$ ,  $b_h$ ,  $j_{W1}$ ,  $j_{W2}$ ) and up to four additional jets ( $j_1 \dots j_4$ ) ordered by  $p_T$ .
- Correct for effects of resolution and misidentification of jets.
- Provides us with detailed information about  $t\bar{t}$  events.



Jets of the  $t\bar{t}$  system

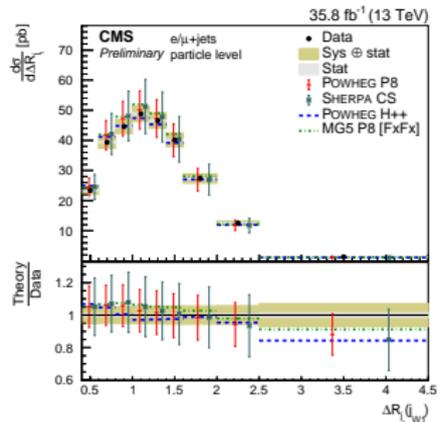
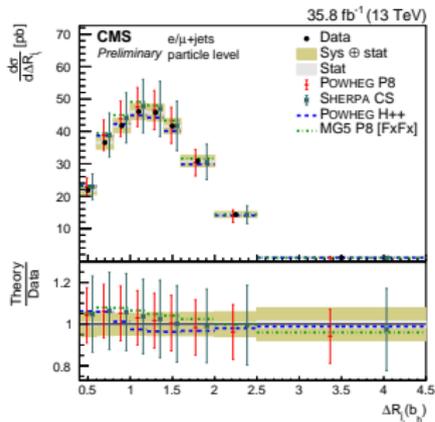
- POWHEG+PYTHIA8 describes data, but  $> 1$  jet from parton shower.
- MG5+PYTHIA8 [FxFx] ( $t\bar{t}$  + up to 2 jets NLO) and SHERPA ( $t\bar{t}$  + 0,1 jet NLO, up to 4 jets LO), reasonable agreement.
- POWHEG+HERWIG++: jets in  $t\bar{t}$  system too soft (explains soft  $p_T$  at particle level).

## Additional Jets

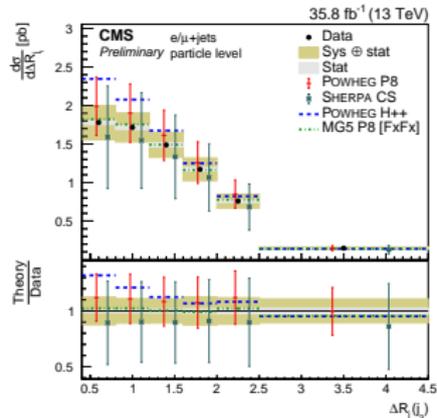
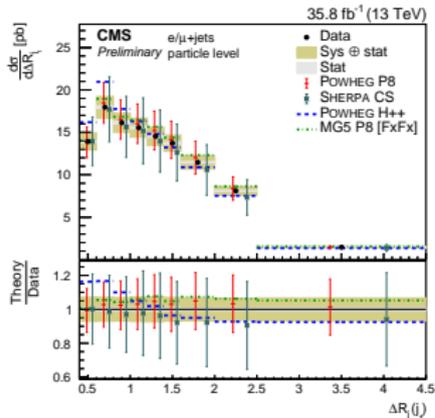


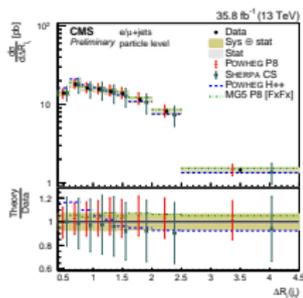
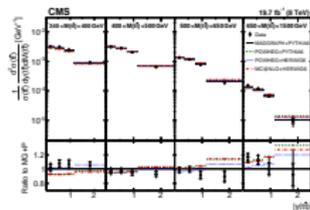
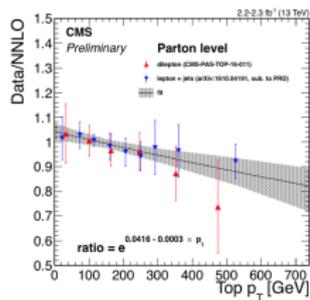
Jets of the  $t\bar{t}$  systemMinimum separation between a jet and the jets of  $t\bar{t}$  system

- Jets of  $t\bar{t}$  decay closer due to higher top  $p_T$  in Simulation.
- Additional jets well described, but POWHEG+HERWIG++ predicts more jets close to  $t\bar{t}$  jets.



## Additional Jets

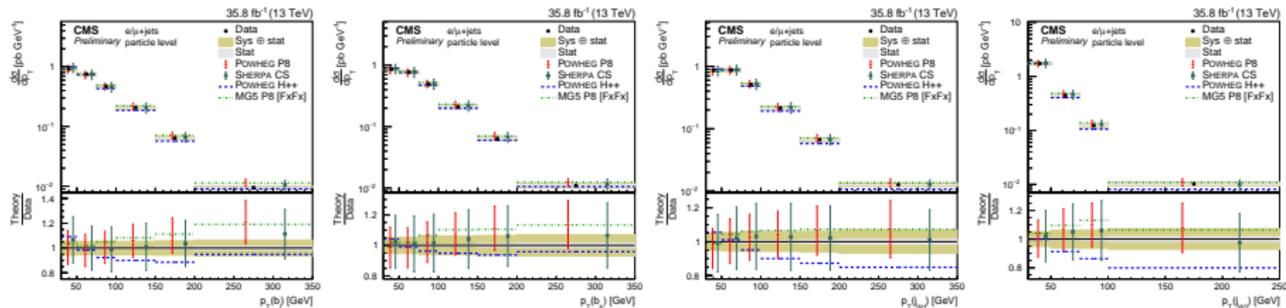




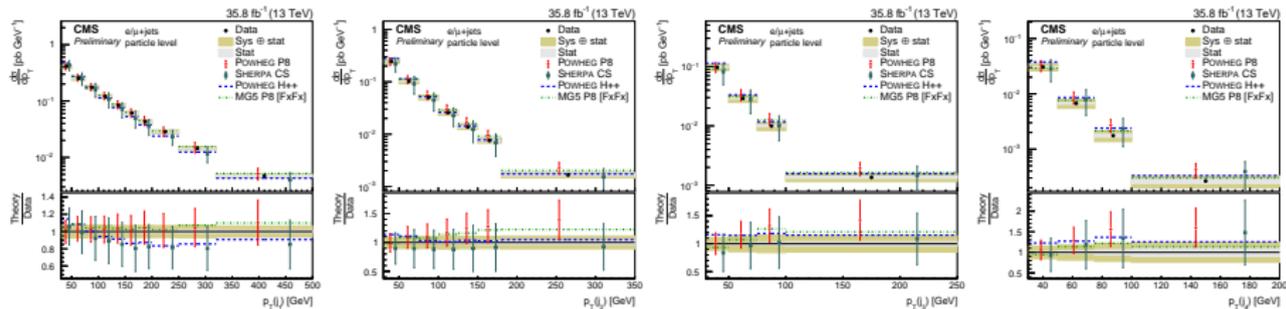
- Performed differential cross section in all decay channels and multiple energies.
- Measurements in boosted regime available.
- Double-differential measurements.
  - precision limited by systematics except for boosted regime.
  - most distributions well described.
  - tendency towards softer  $p_T(t)$  than expected.
- Detailed measurements of jet kinematics and multiplicities.
  - directly related to top and  $t\bar{t}$  properties.
  - descriptions at high jet multiplicities either by parton shower or LO
    - precision of measurement high compared to expected MC precision.

# Backup

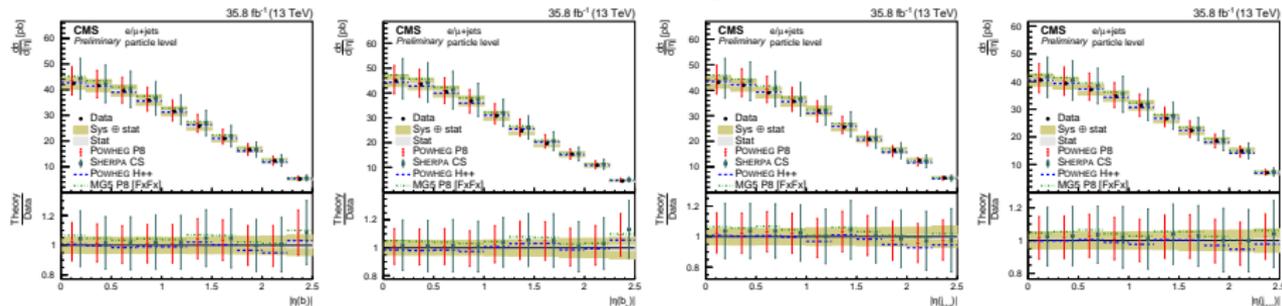
### Jets of the $t\bar{t}$ system



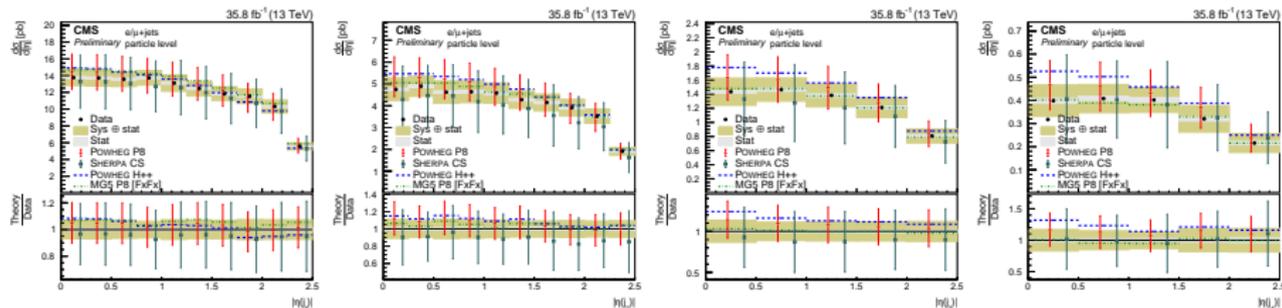
### Additional Jets



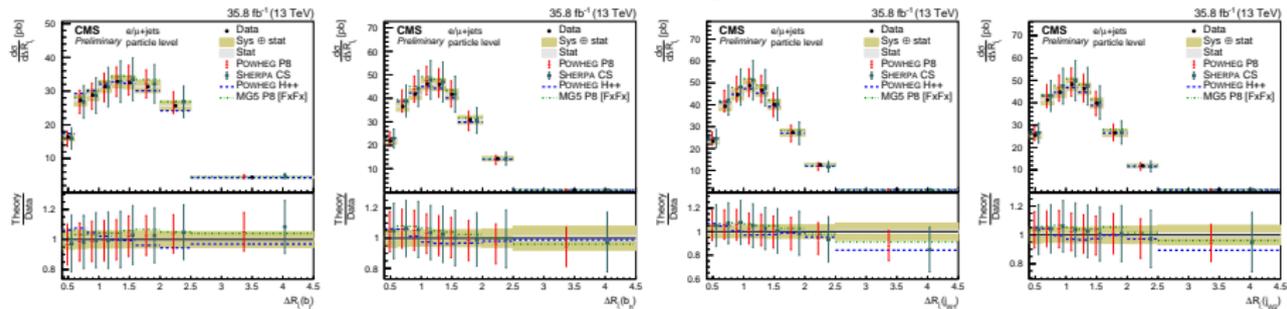
### Jets of the $t\bar{t}$ system



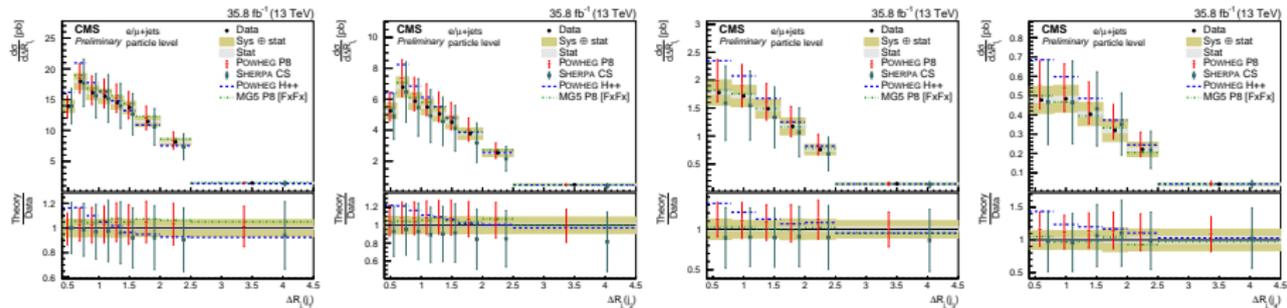
### Additional Jets



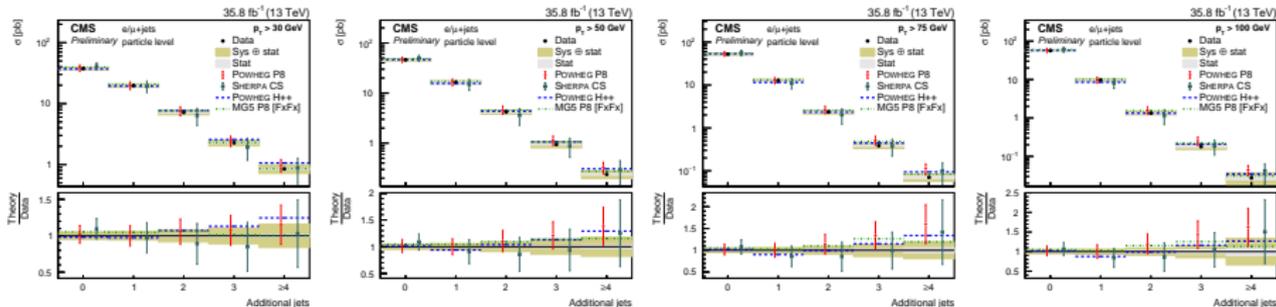
## Jets of the $t\bar{t}$ system



## Additional Jets

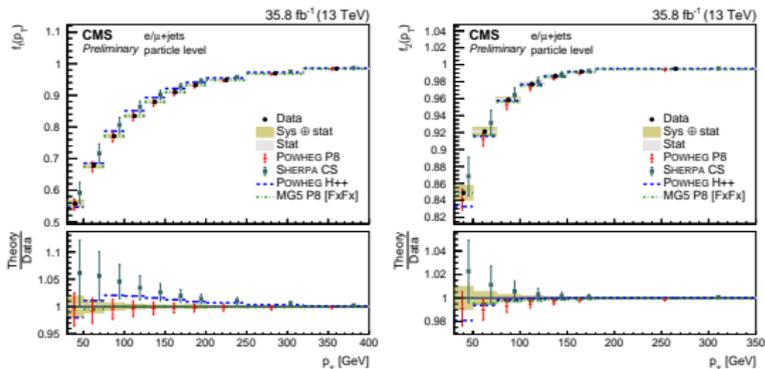


### Jet multiplicities for various $p_T(jet)$ thresholds:



### Gap fraction:

Fraction of events without at least  $n$  jets above  $p_T$  threshold.



- Well described by POWHEG+PYTHIA8 and MG5+PYTHIA8 [FxFx].
- POWHEG+HERWIG++ and SHERPA some differences.