Differential measurements of top quark pair production at CMS

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On behalf of the CMS collaboration

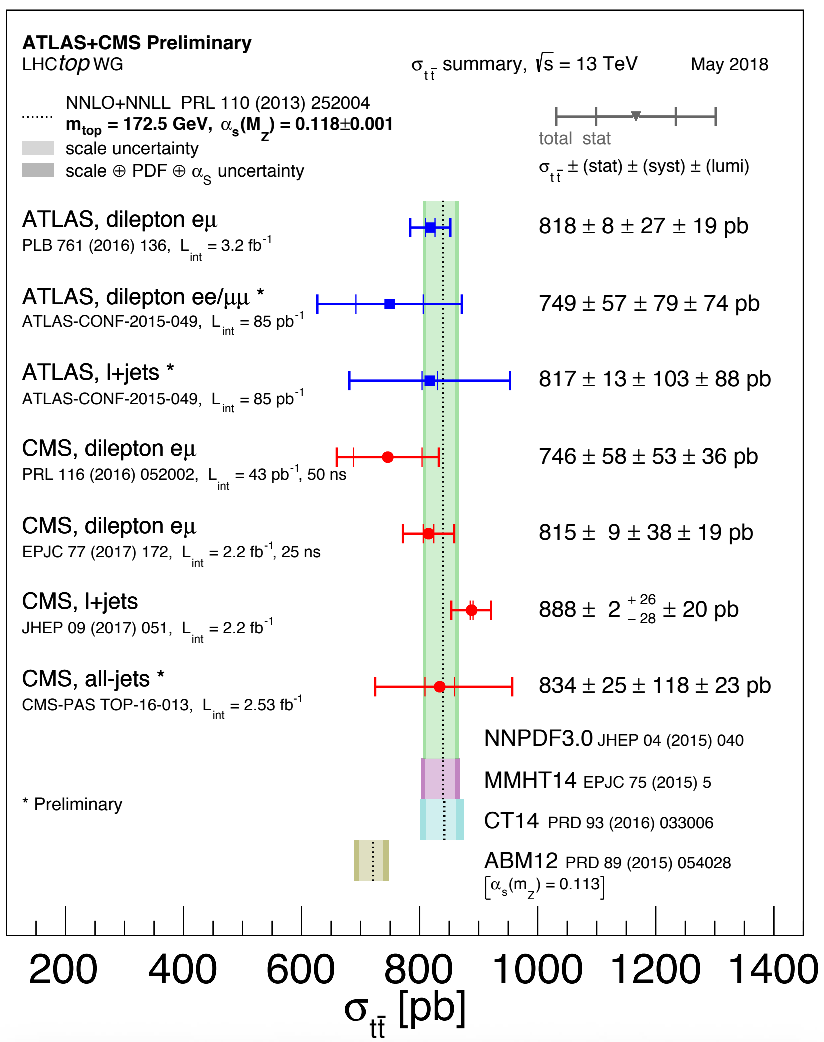
11th International Workshop on Top Quark Physics (TOP2018)

Outline

- motivation & challenges
  - why differential measurements
  - dominant systematic uncertainties
- latest measurements @ 13 TeV in the lepton+jets channel
  - differential vs event kinematic variables
  - differential vs top and top pair properties
  - double differential vs selected observables
- latest measurements @ 13 TeV in the dilepton channel
  - differential vs various event, top, and top pair quantities
  - comparisons with state of the art theory calculations

Why differential measurements?

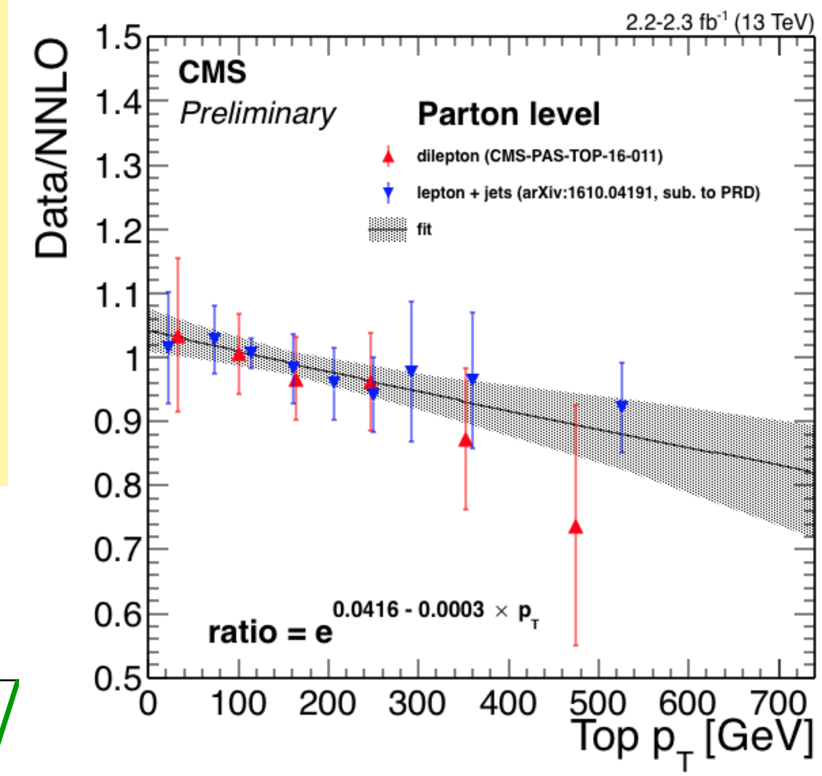
inclusive cross sections: the top of the iceberg

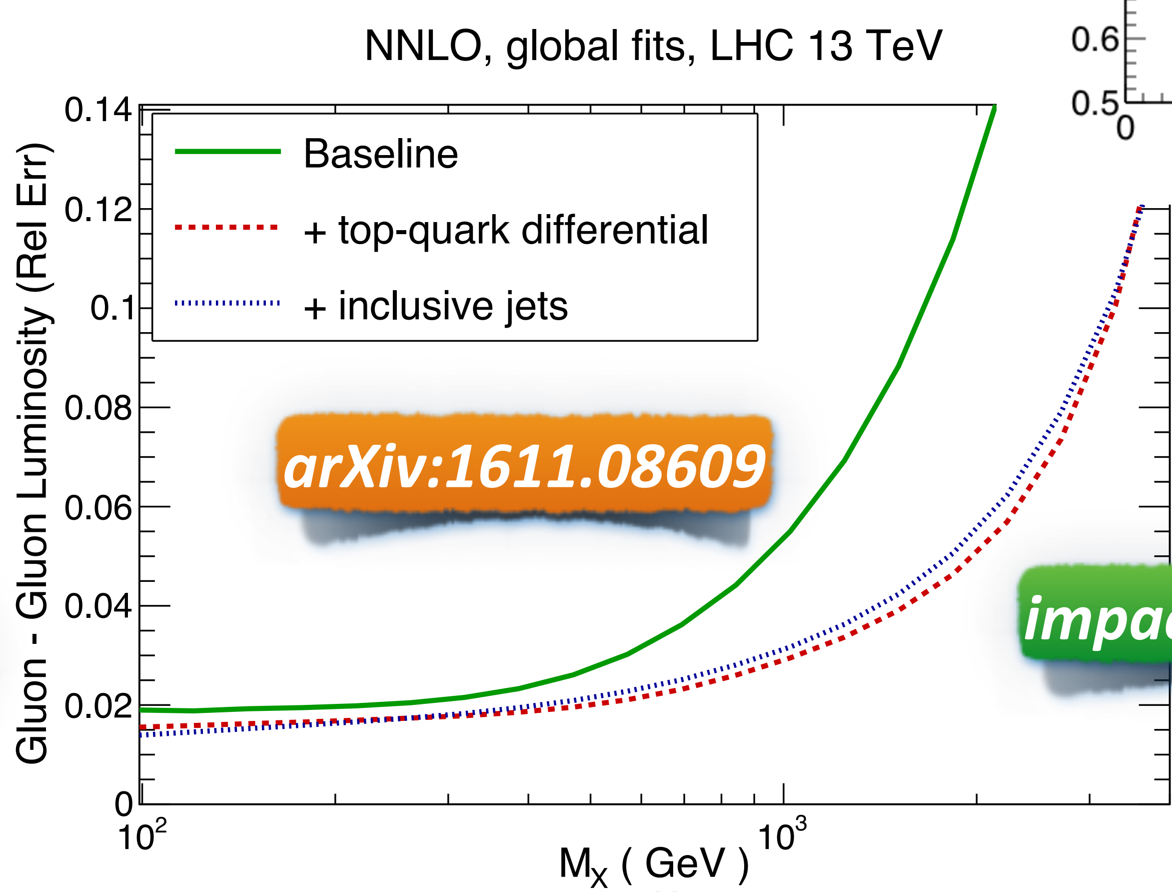


details in M. Defranchis's talk

- confront the theory in every corner of the phase space
- constrain fundamental QCD parameters
- probe BSM physics
- reduce modelling uncertainties

theory fails to describe the top p_T spectrum

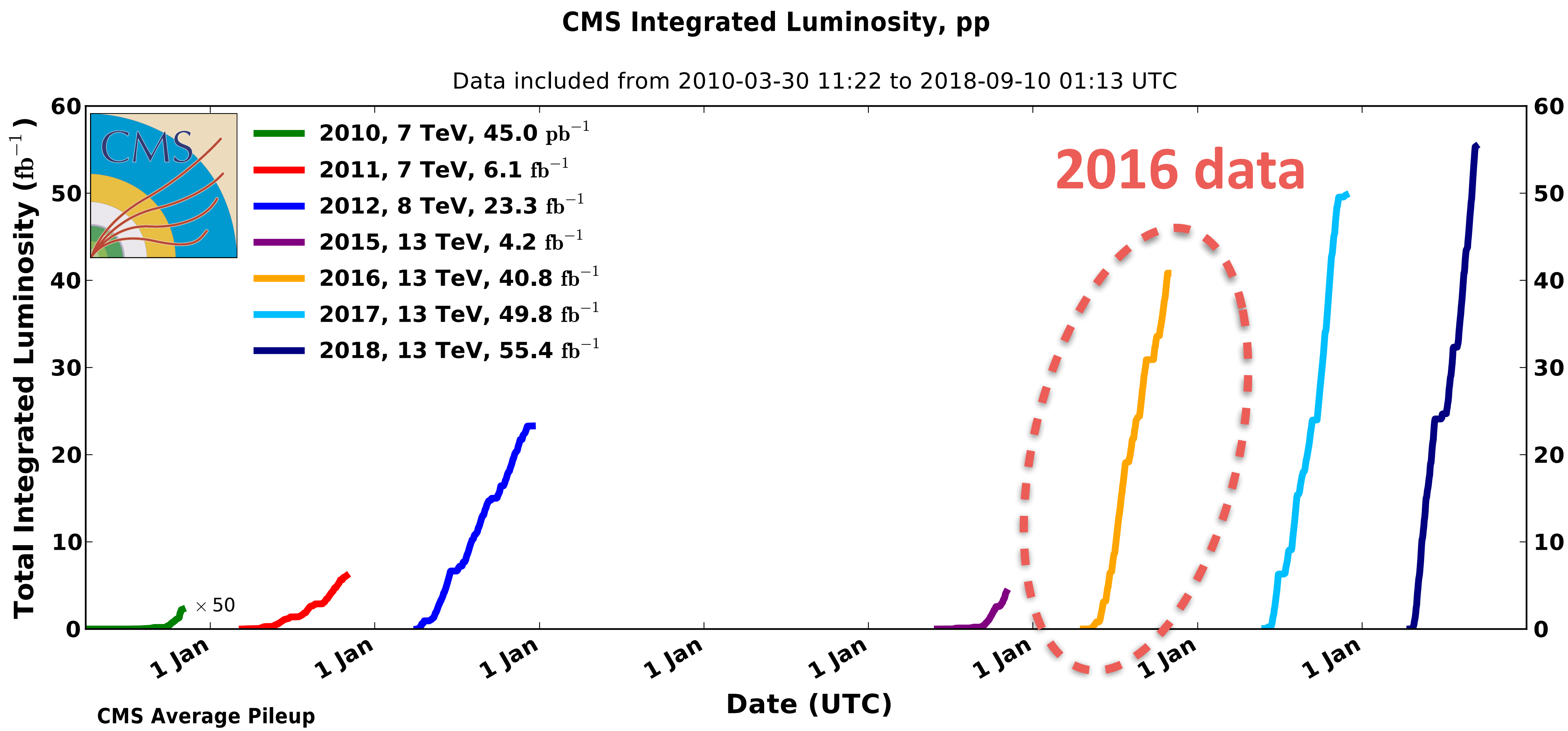


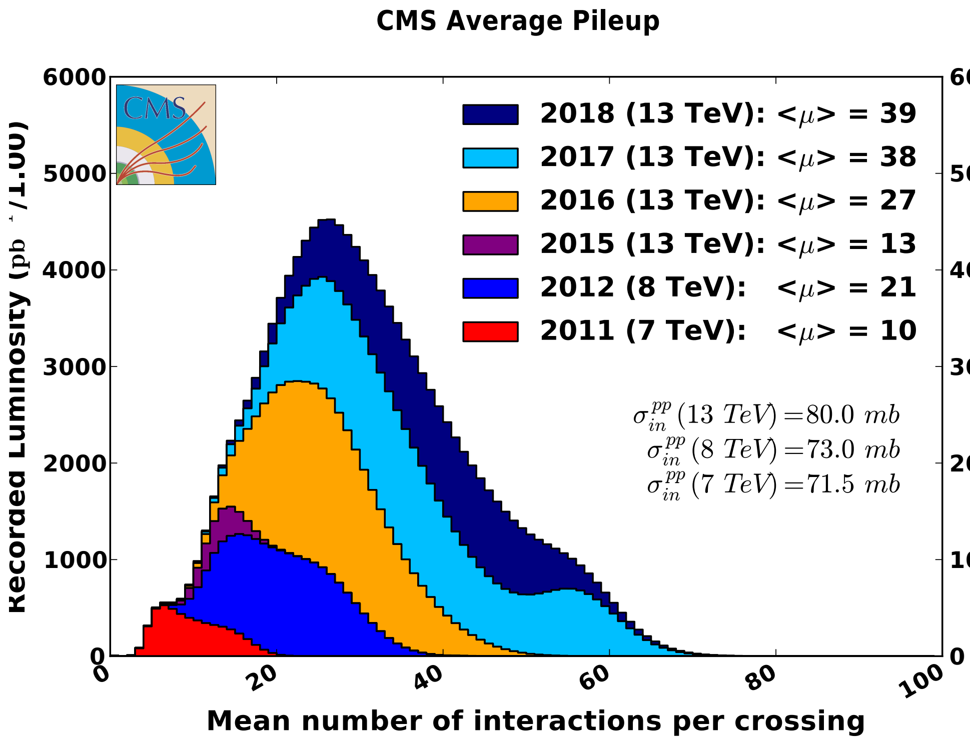


arXiv:1611.08609

impact on high-x gluon PDF

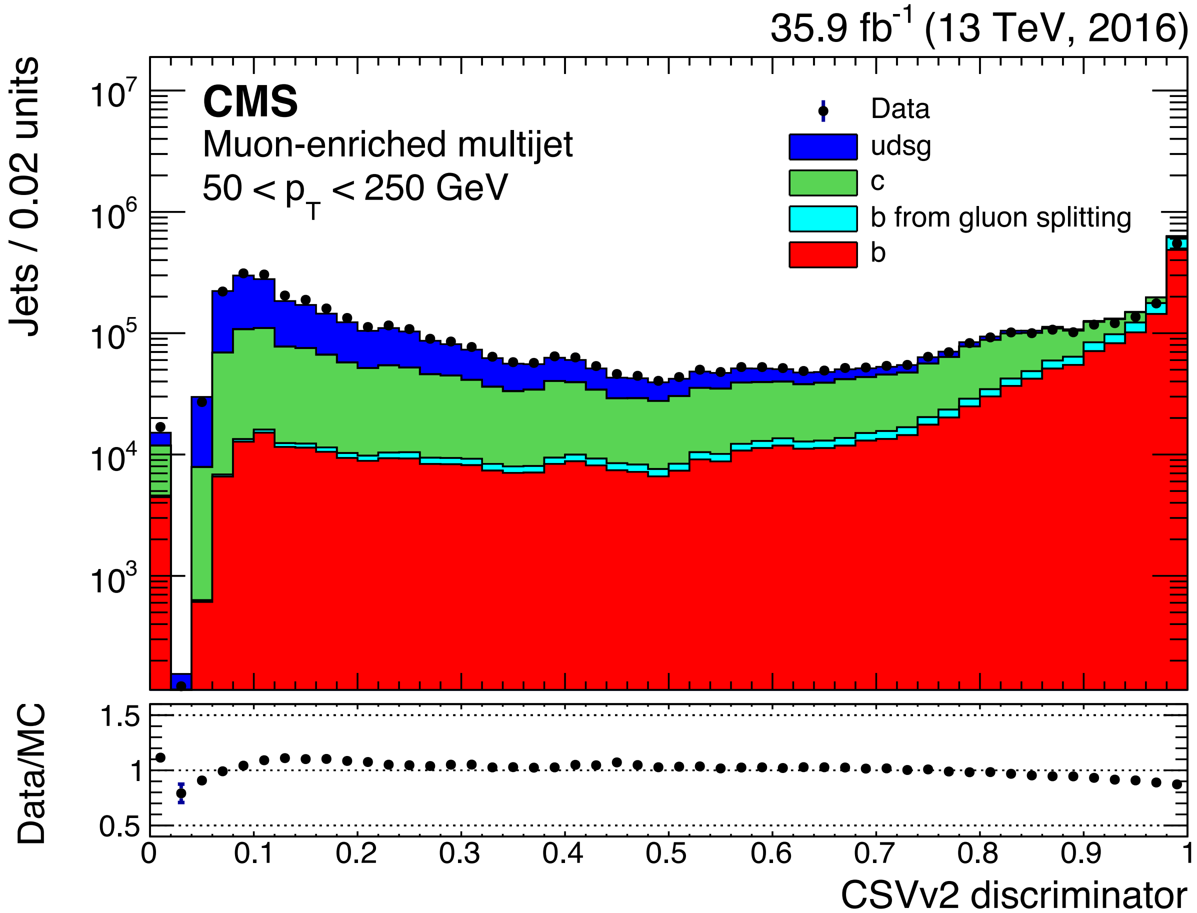
The dataset

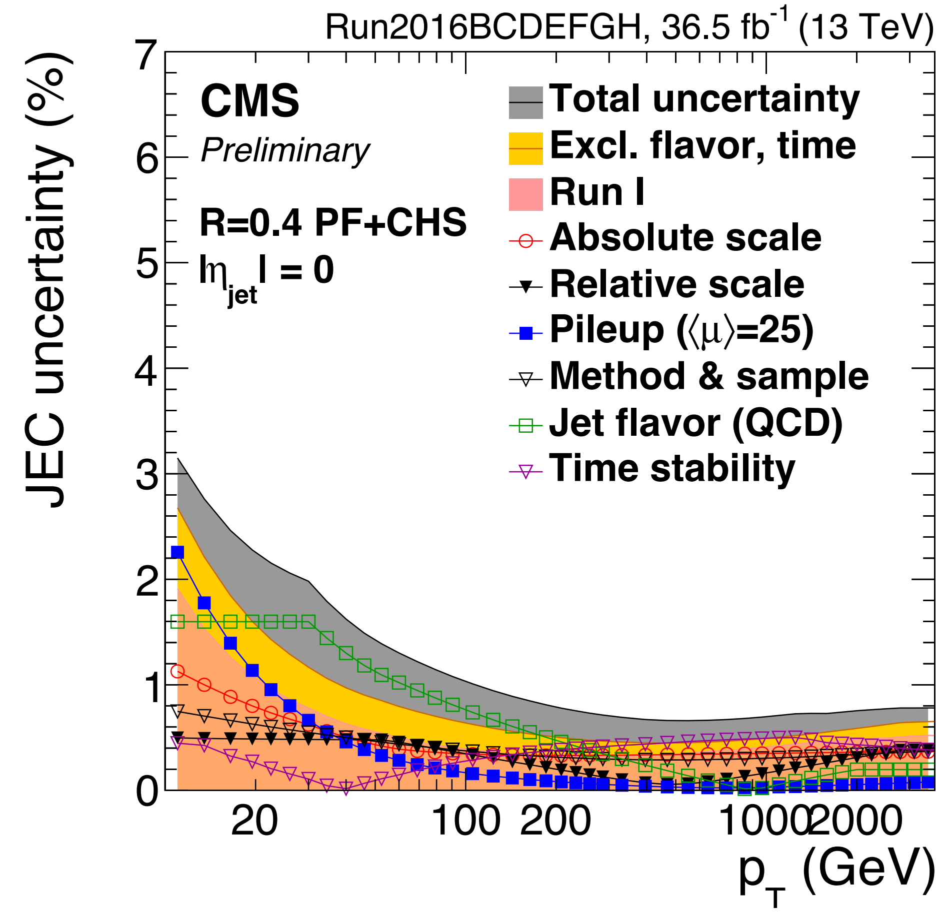




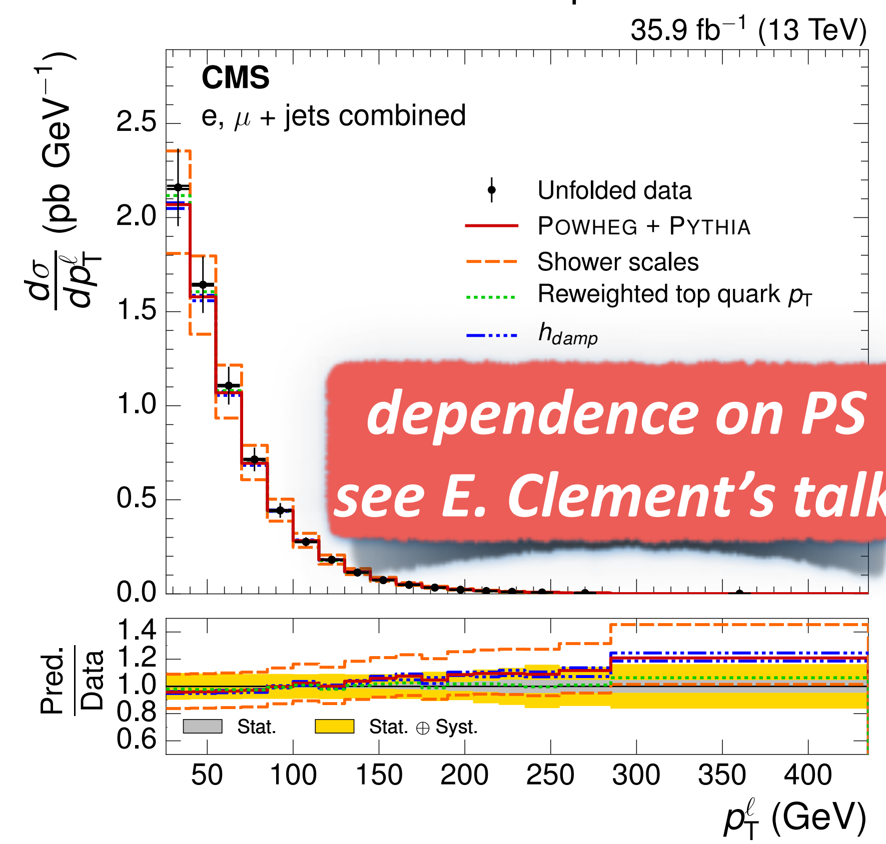
- proton-proton collisions @ **13 TeV**
- **2016** run
  - ≈ **36 fb^{-1}** of useful data for analysis
  - the best understood dataset
- on average **27** interactions per bunch crossing

Challenges



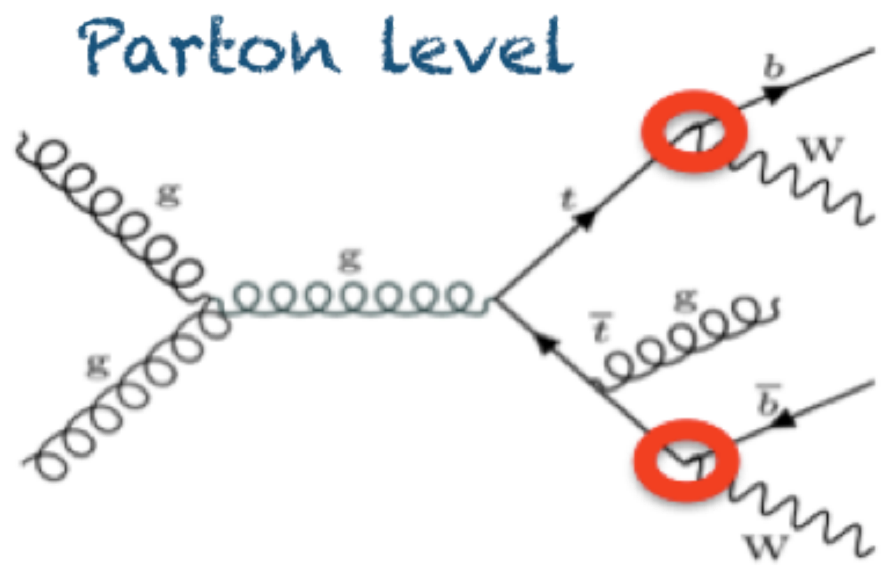


- **Experimental challenges**
  - jet energy scale (< 2%)
  - b-tagging efficiency (< 3%) & fake rate
  - lepton triggering & identification (< 2%)
- **Theoretical challenges**
  - enter through unfolding to parton & particle level
  - parton shower & underlying event modelling
  - **great effort has been put to reduce these uncertainties**

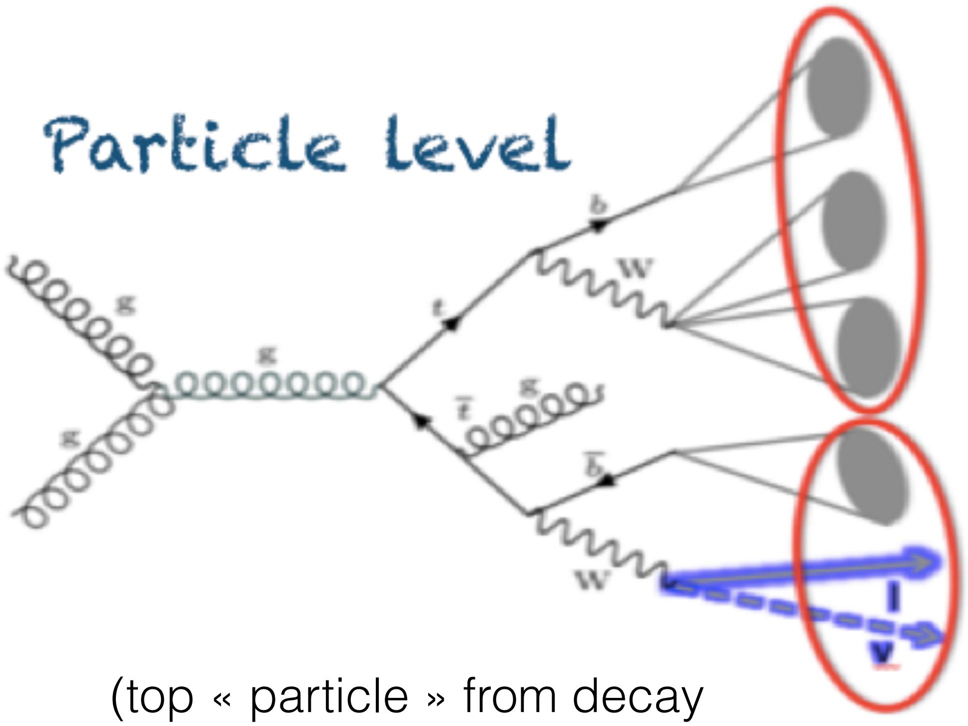


dependence on PS
see E. Clement's talk

Definitions of objects



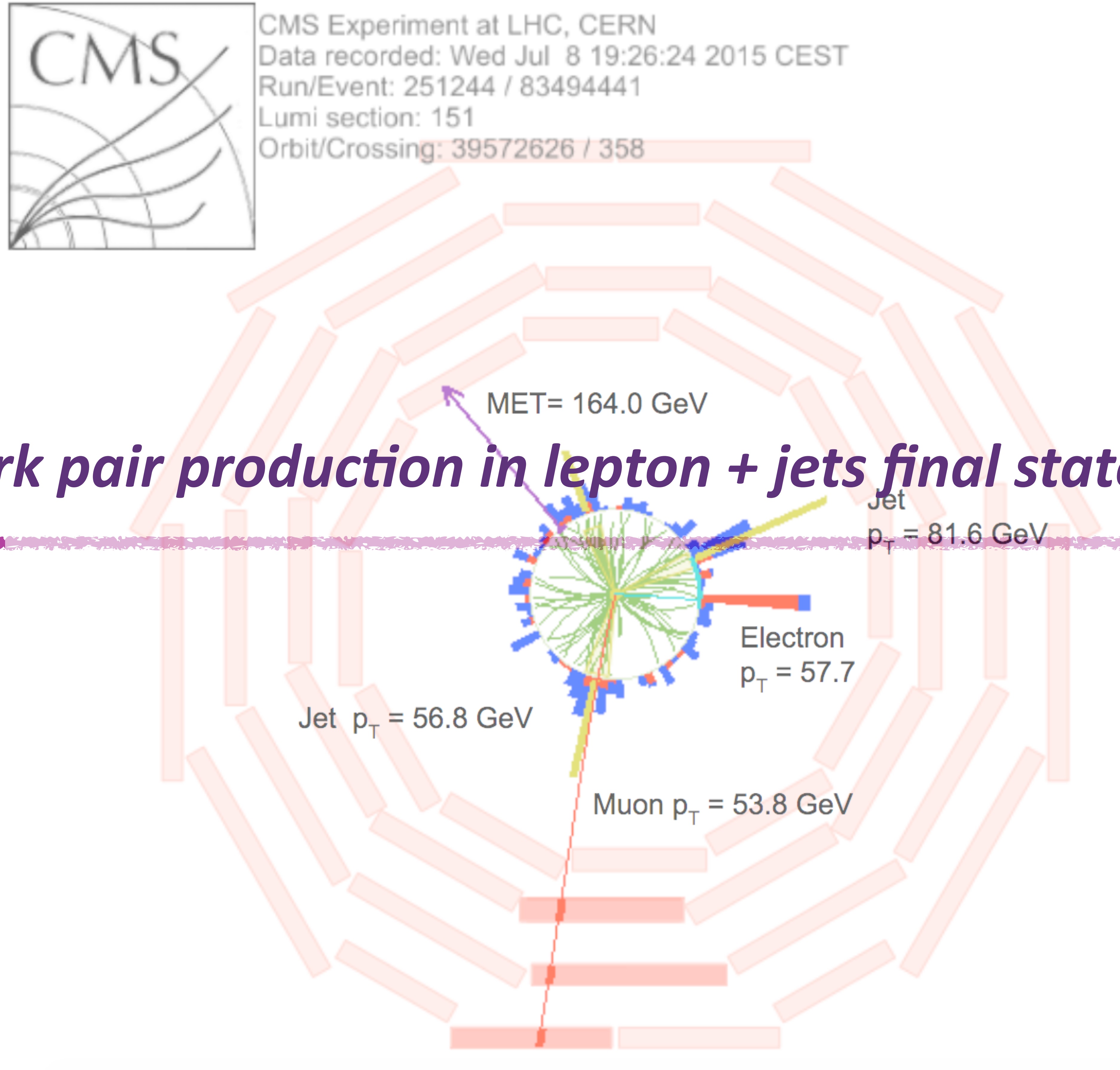
(before decay after radiation)



(top « particle » from decay products after hadronization)

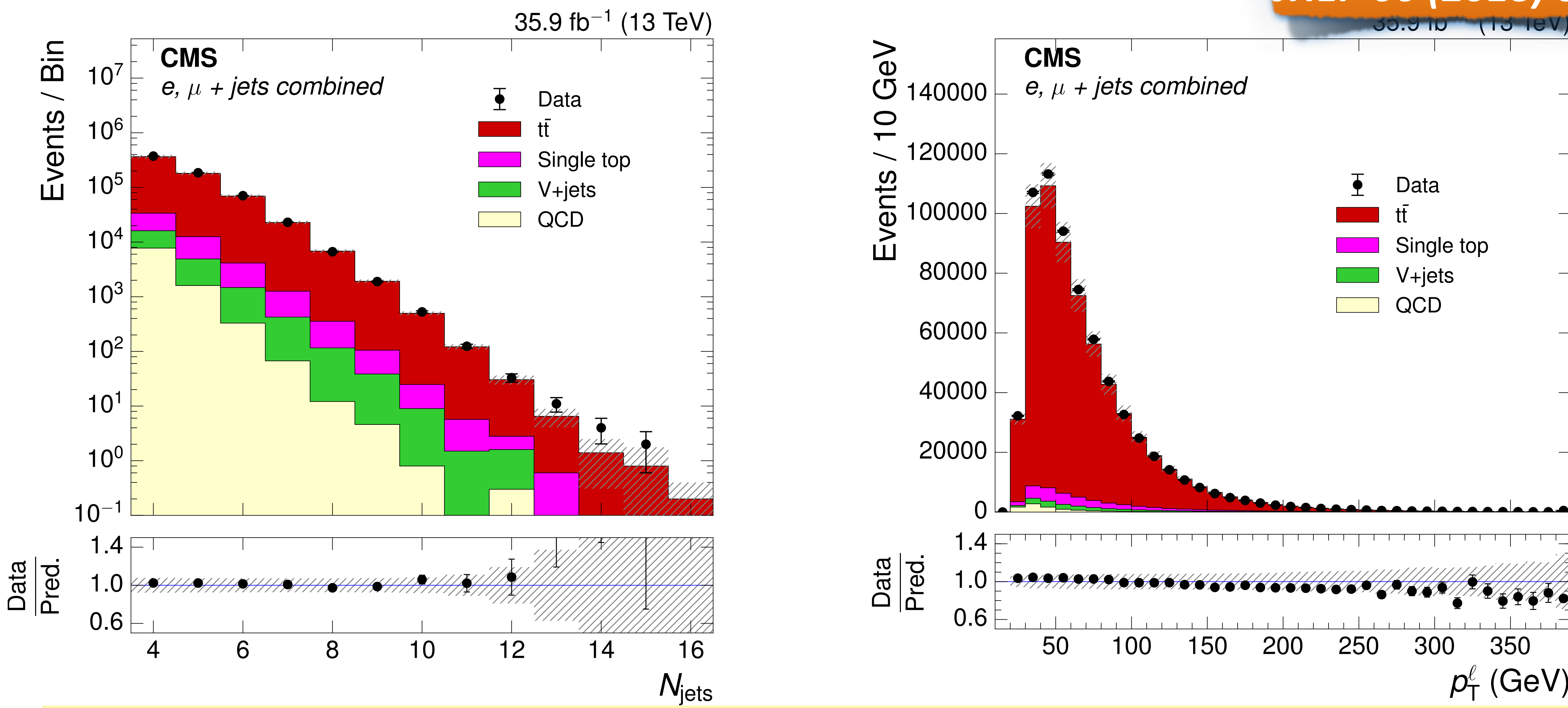
- **Detector level**
  - objects reconstructed from energy depositions in the detector
  - direct comparison with MC generators folded with detector simulation
- **Parton level**
  - top quarks before decay but after radiation
  - analytical calculations at fixed order
  - unfolding needed from detector level
  - large uncertainties involved
- **Particle level**
  - top "particle" from decay products after hadronization
  - unfolding needed from detector level
  - closer definition to the actual measurement ==> smaller uncertainties

Top quark pair production in lepton + jets final state



Cross section vs event variables: reconstruction

JHEP 06 (2018) 002



- **Select high purity ttbar sample (no top reconstruction)**
  - one isolated muon (electron) with $p_T > 24$ (32) GeV and $|\eta| < 2.4$ (2.1)
  - at least 4 jets (anti-k_T, R=0.4) with $p_T > 30$ GeV and $|\eta| < 2.4$
  - at least 2 jets b-tagged (~70% efficiency and 1% mis-id probability)
- **Measurements (unfolded at particle level)**
  - absolute & normalised
  - kinematic event variables (H_T, S_T, p_T^{miss}, N_{jets}, p_T^W, p_T^{ℓ}, $|\eta^{\ell}|$)

details in D. Burn's YSF talk

Cross section vs number of jets

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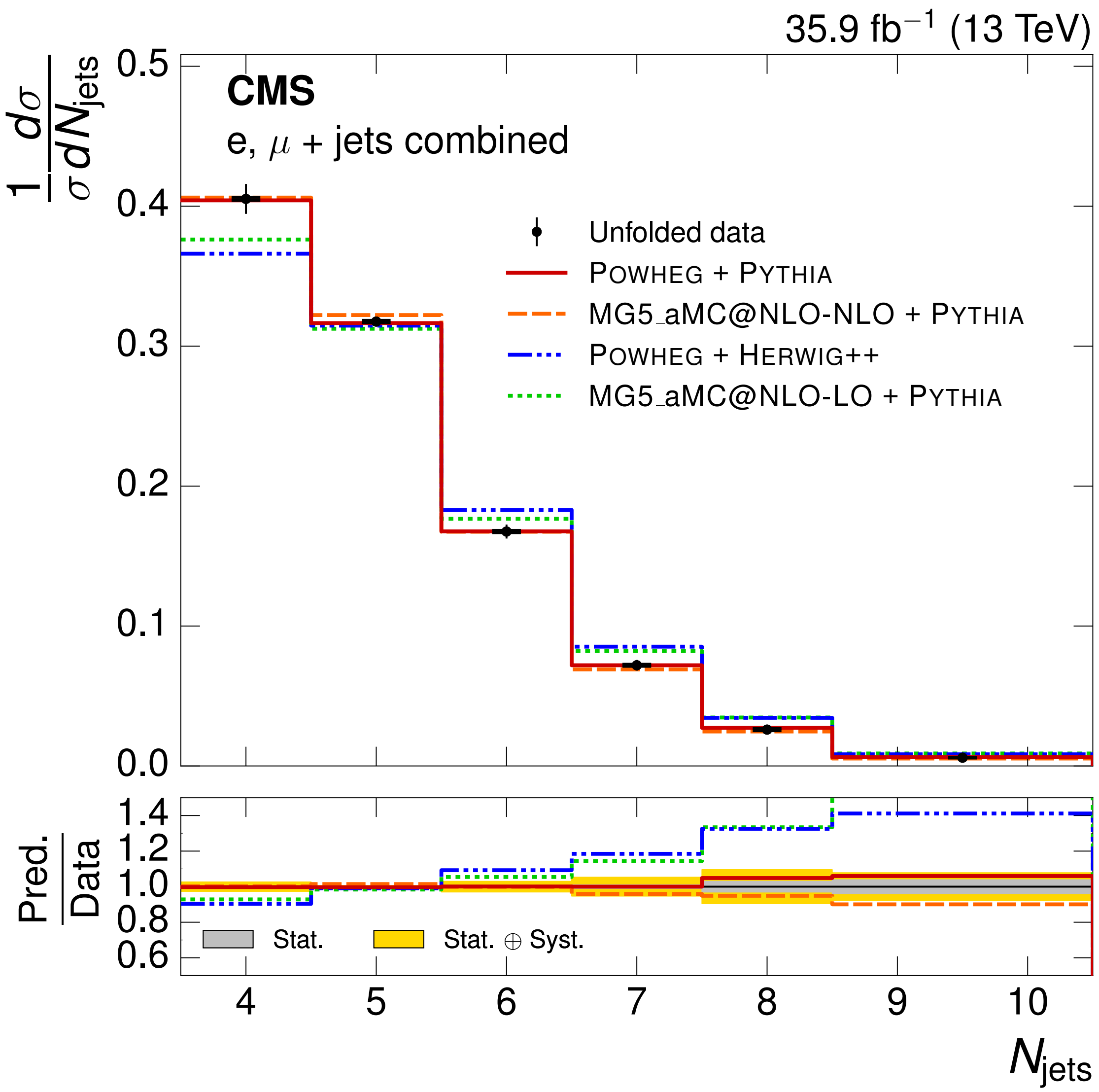

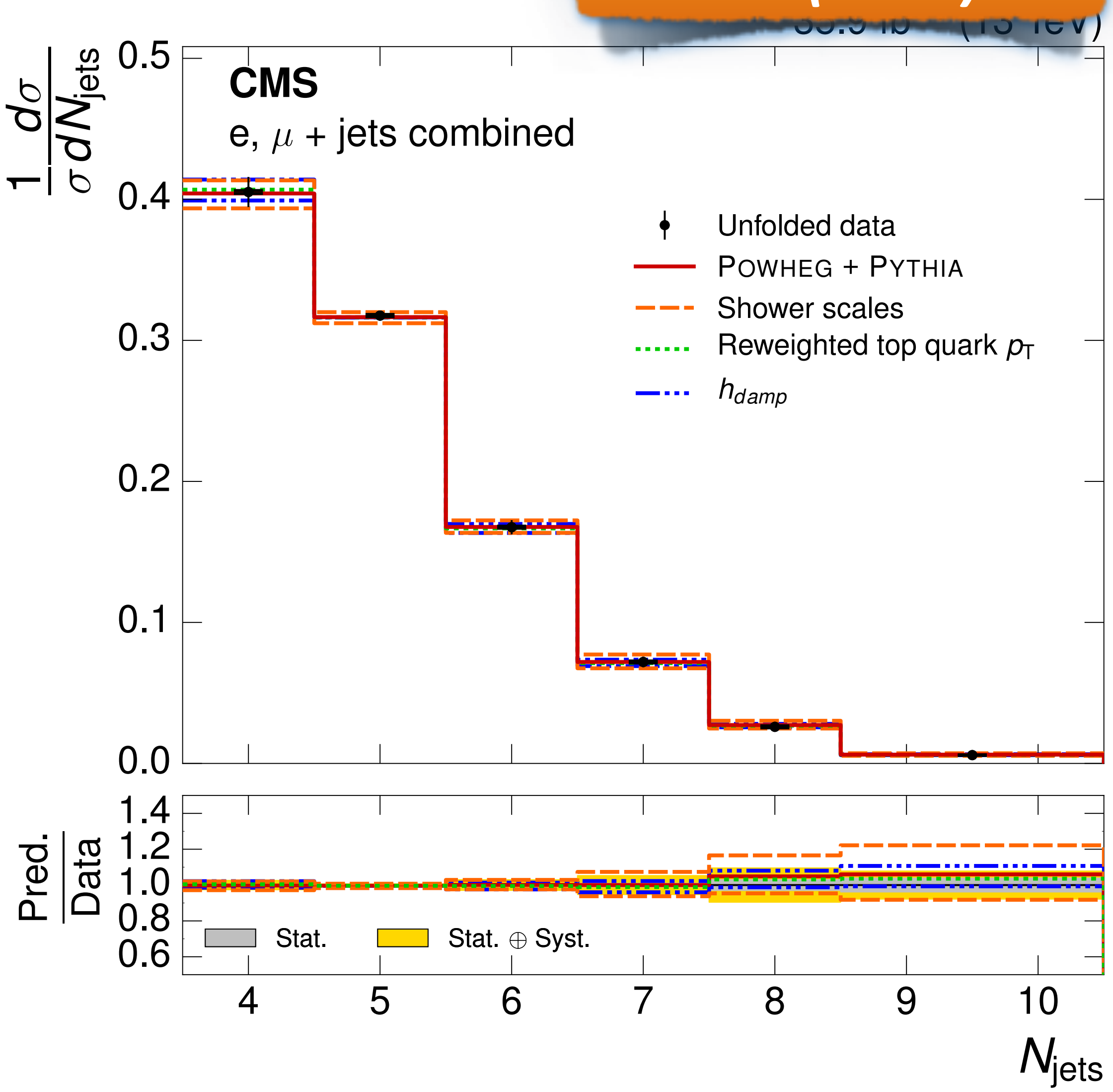

- **Significant differences between MC generators**
  - Powheg+Pythia8 & MG5_aMC@NLO-NLO+Pythia8 describe the data well
  - Powheg+Herwig++ & MG5_aMC@NLO-LO+Pythia8 predict higher jet multiplicity
- **Sensitive to the MC settings**
  - in particular to the parton shower scales

the comparisons refer to the MC settings used by CMS

Cross section vs global variables

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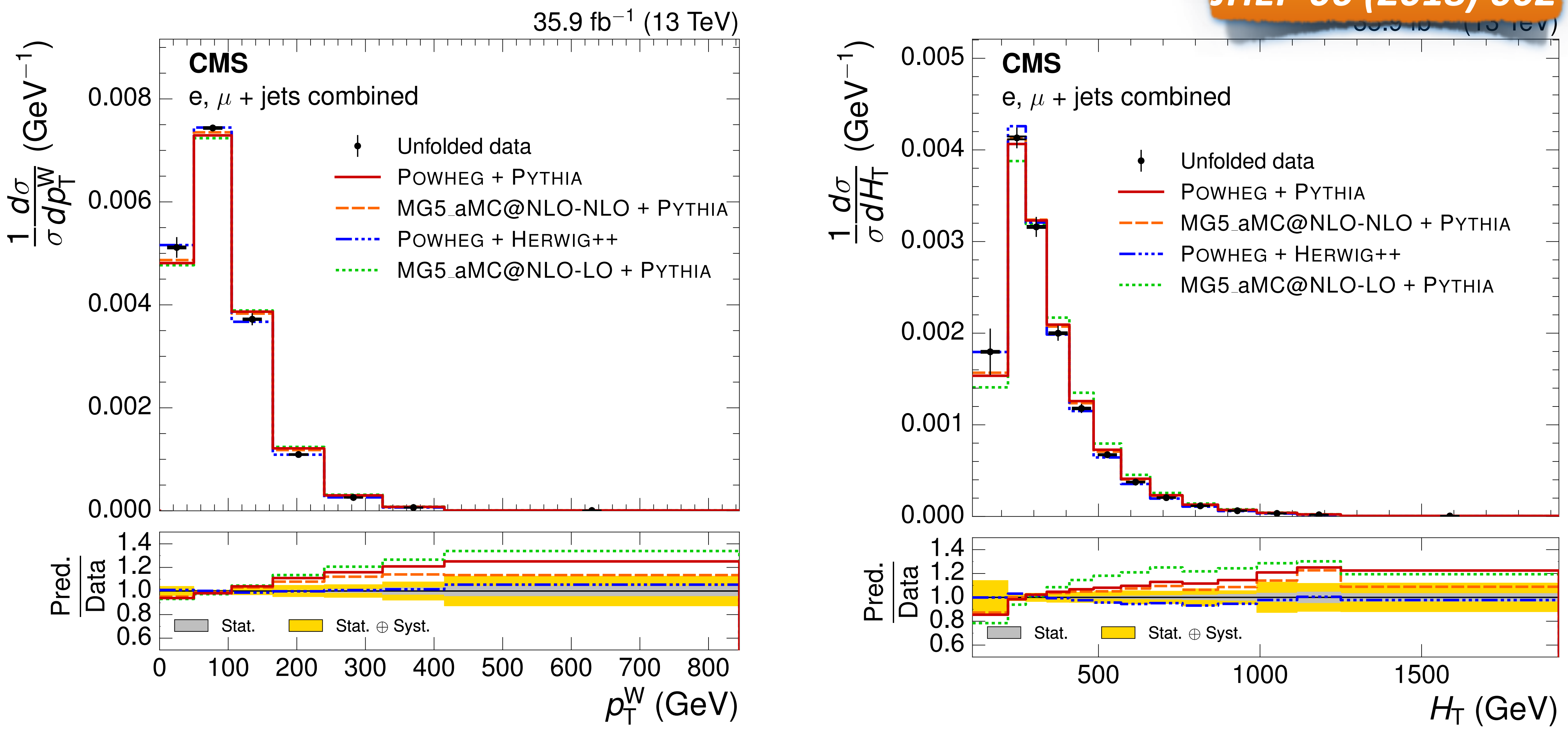
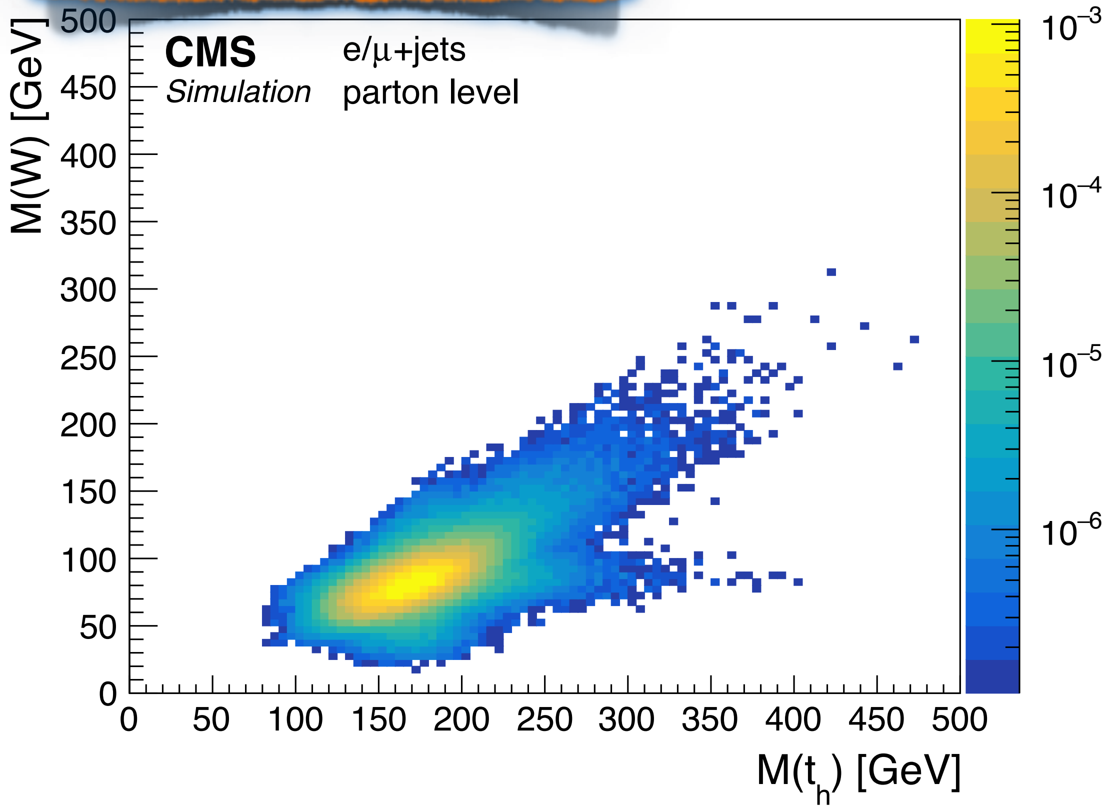
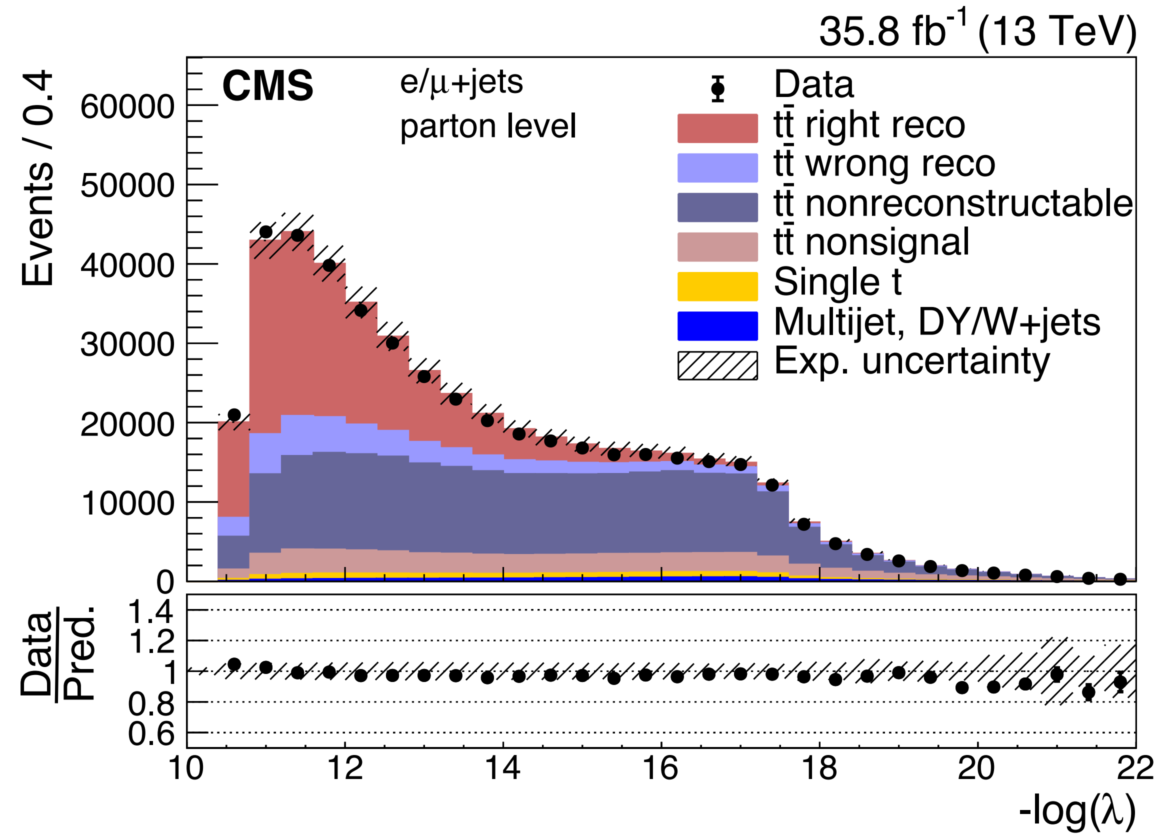


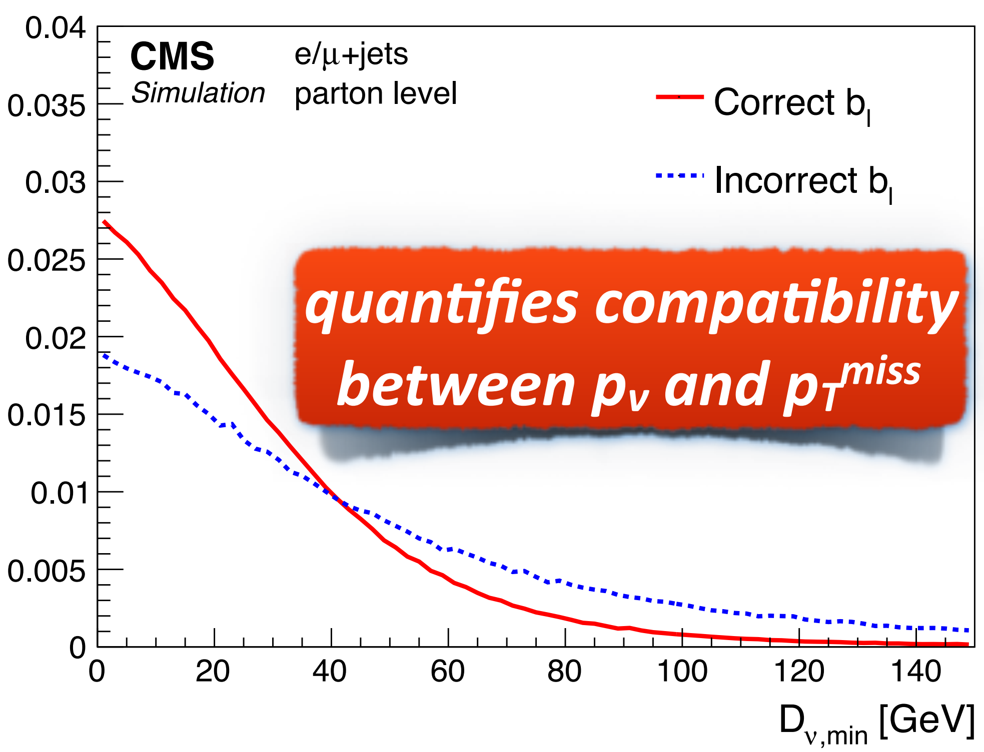
- **Kinematic variables**
  - p_T^W: built from the lepton and the missing momentum
  - H_T: built from the jet transverse momenta
- **Sensitive to the MC generators (same trends in both observables)**
  - Powheg+Herwig++ agrees best with data
  - Powheg+Pythia8 and MG5_aMC@NLO-LO+Pythia8 predict much harder spectra

Differential cross sections: top reconstruction

PRD 97 (2018) 112003







quantifies compatibility between p_ν and p_T^{miss}

- **Object selection**
  - exactly one isolated lepton (muon or electron) with $p_T > 30$ GeV and $|\eta| < 2.4$
  - at least 4 jets with $p_T > 30$ GeV and $|\eta| < 2.4$
  - at least 2 jets b-tagged (~63% efficiency and 3% mis-id probability)
- **Top reconstruction**
  - choose jet permutation that minimises $-\log(\lambda)$
  - ***$-\log(\lambda) = -\log(P_m(m_2,m_3)) - \log(P_\nu(D_{\nu,min}))$***

Differential cross sections: efficiency

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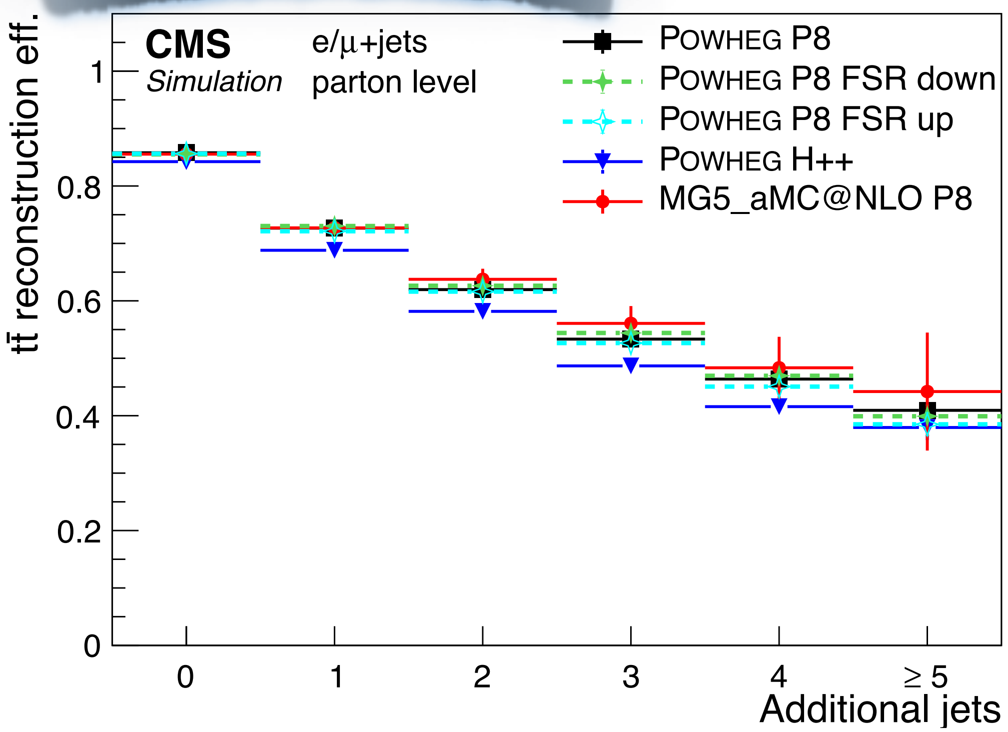

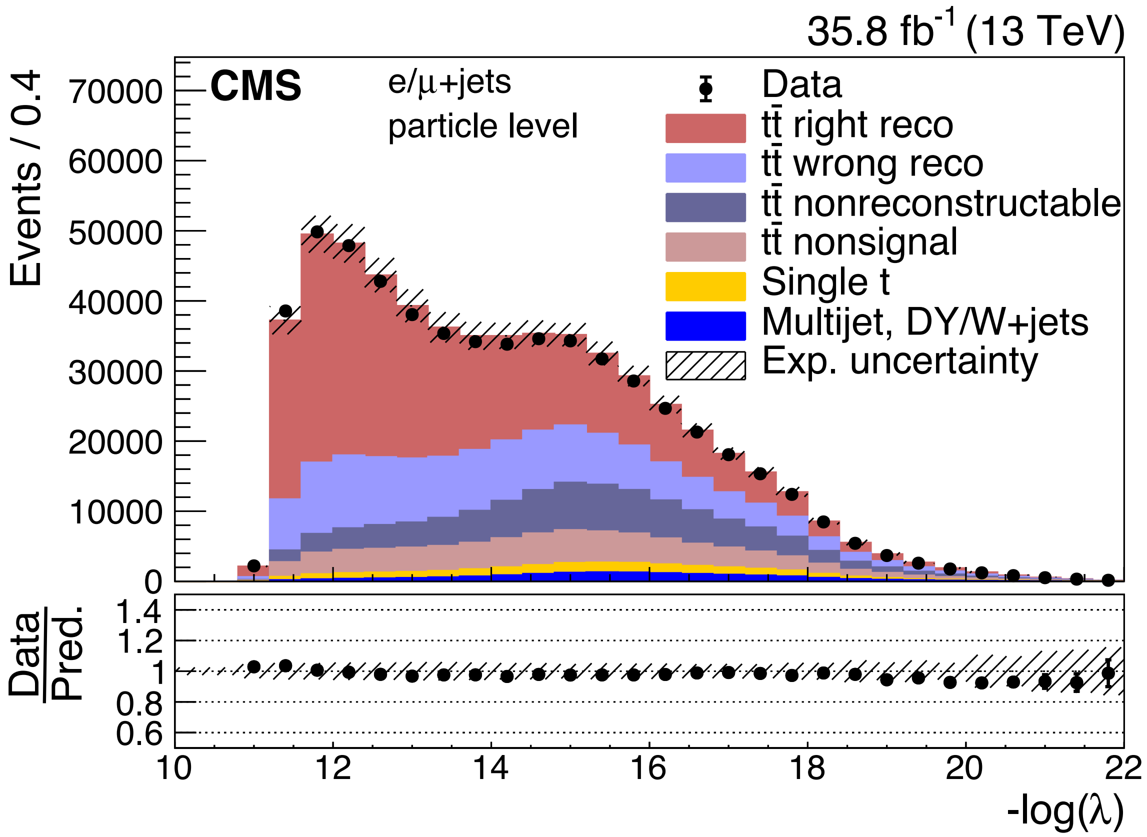

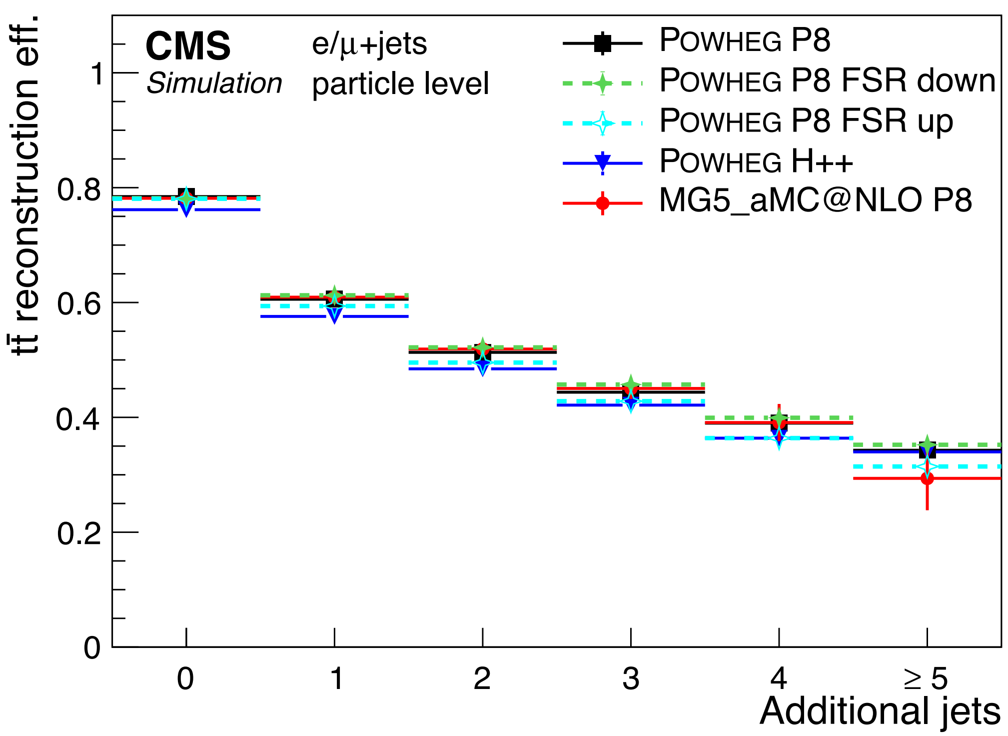

- **Particle level**
  - lower efficiency due to weaker mass constraints
- **Strong dependence on jet multiplicity**
  - number of permutations increases dramatically with increasing number of jets
  - more probable to make a wrong assignment

Differential cross sections: uncertainties

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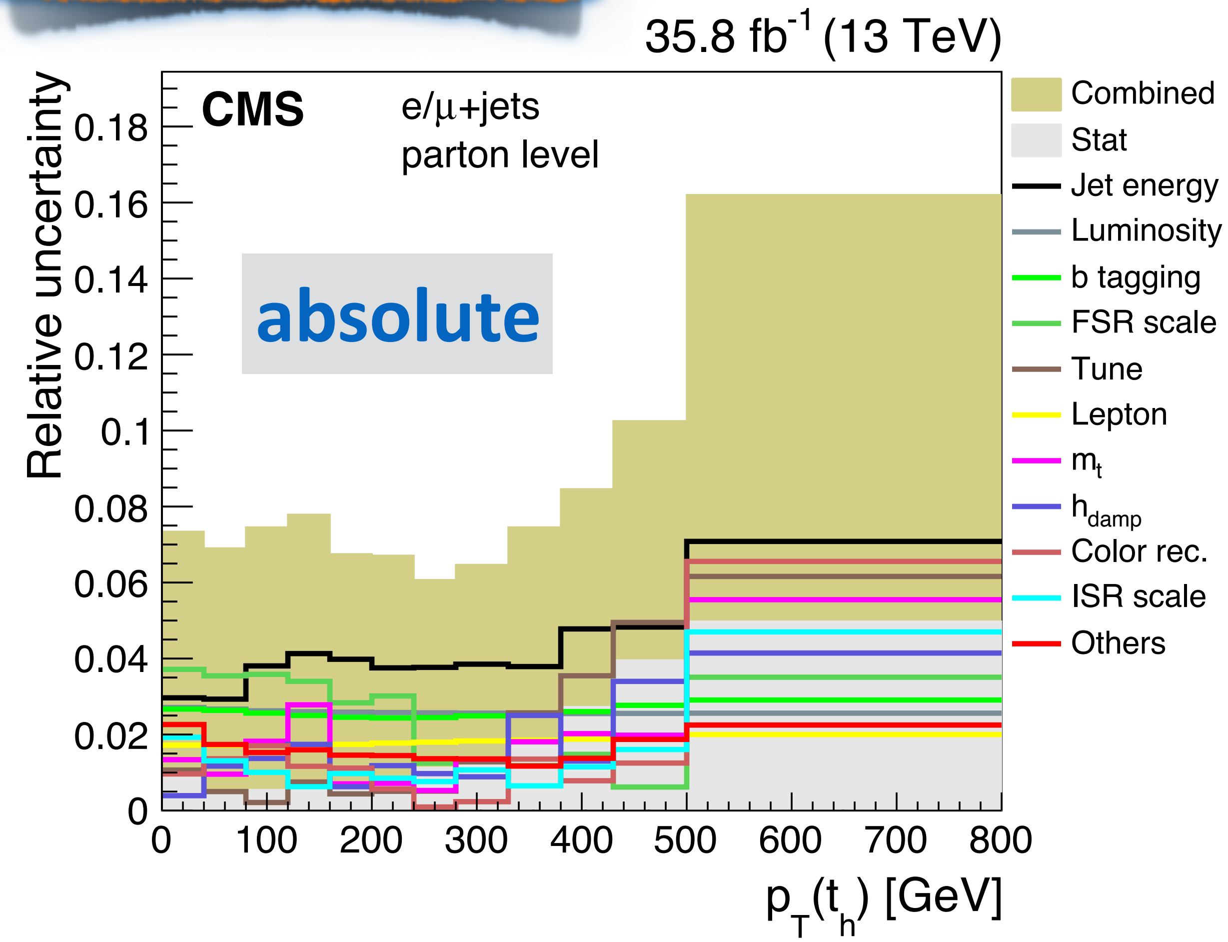

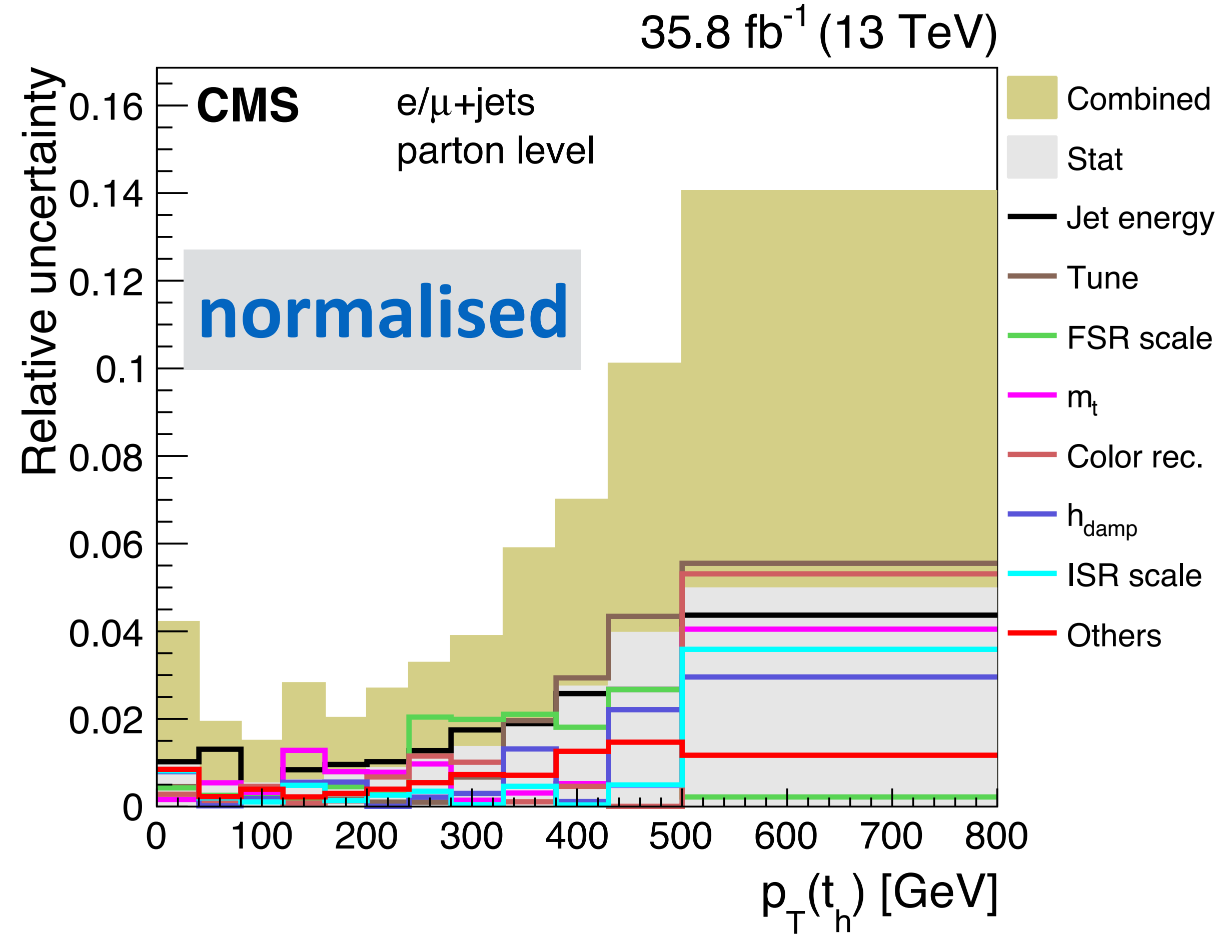

- **Experimental**
  - dominant: jet energy scale
  - subdominant: lepton reconstruction & b-tagging (mostly affecting the absolute cross sections)
- **Theoretical**
  - underlying event tune, parton shower settings, colour reconnection, top mass
  - PDFs, scale variations
  - **reduced at particle level (no extrapolation, closer to detector level)**

Differential cross sections vs top kinematics

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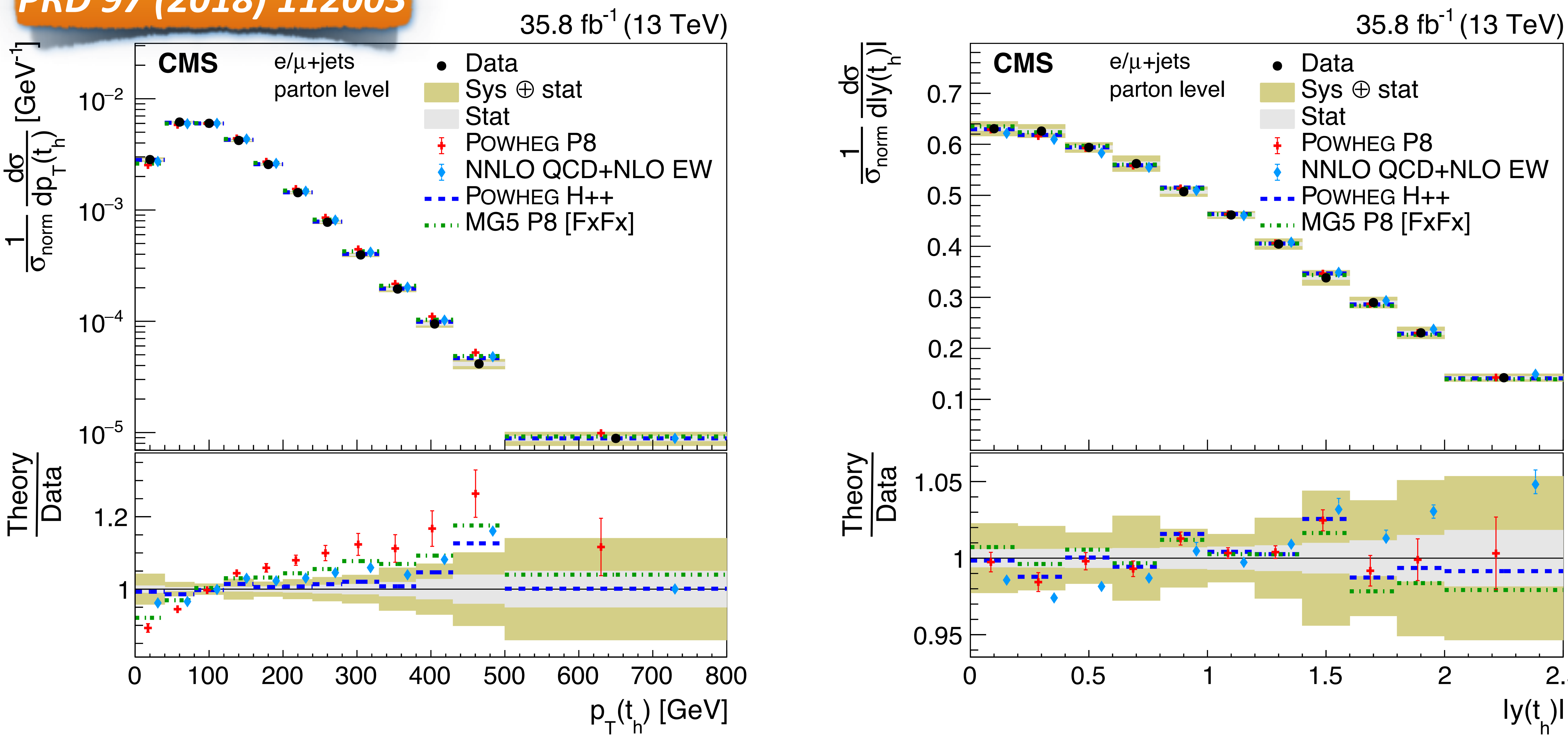

- **softer top p_T spectrum in data**
  - Powheg+Herwig++ in better agreement
  - NNLO QCD + NLO EWK calculation closer to the data
- **rapidity spectrum reproduced well**
  - MC generators in good agreement
  - NNLO QCD + NLO EWK calculation shows a trend (better precision in data needed)

Differential cross sections vs top pair observables

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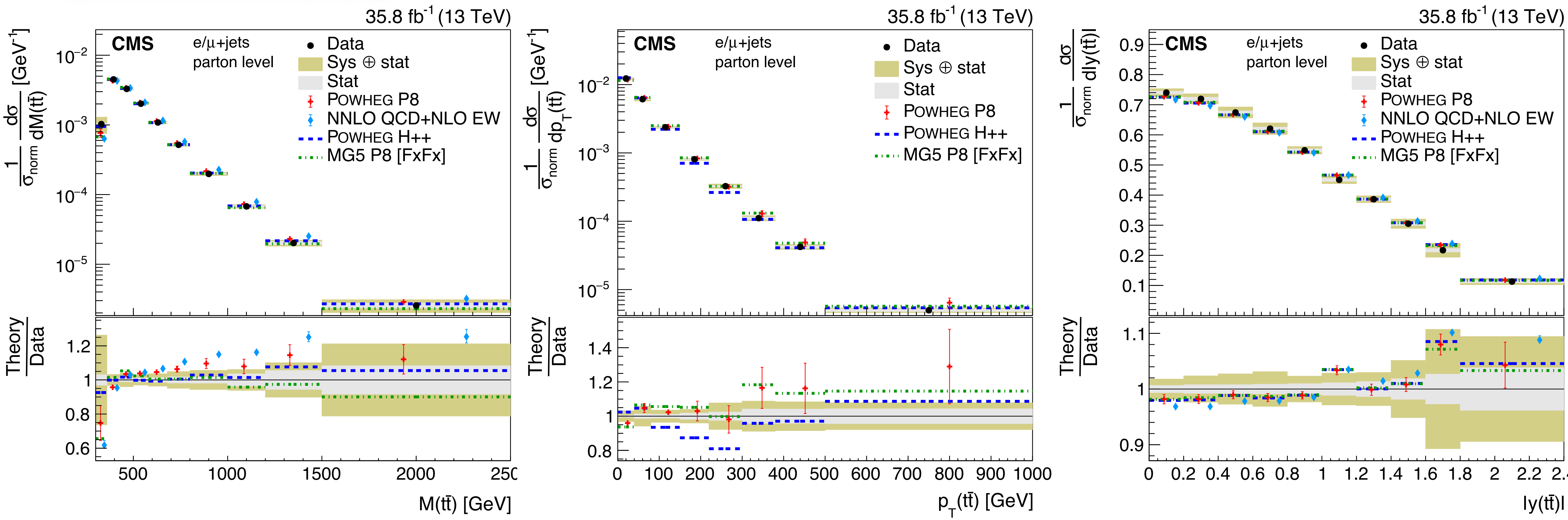

- **softer mass spectrum**
  - correlated with the softer top p_T spectrum
  - NNLO QCD + NLO EWK calculation disagrees significantly
- **marginal agreement in p_T and |y|**
  - largest deviation in p_T for Powheg+Herwig++

Double differential cross sections

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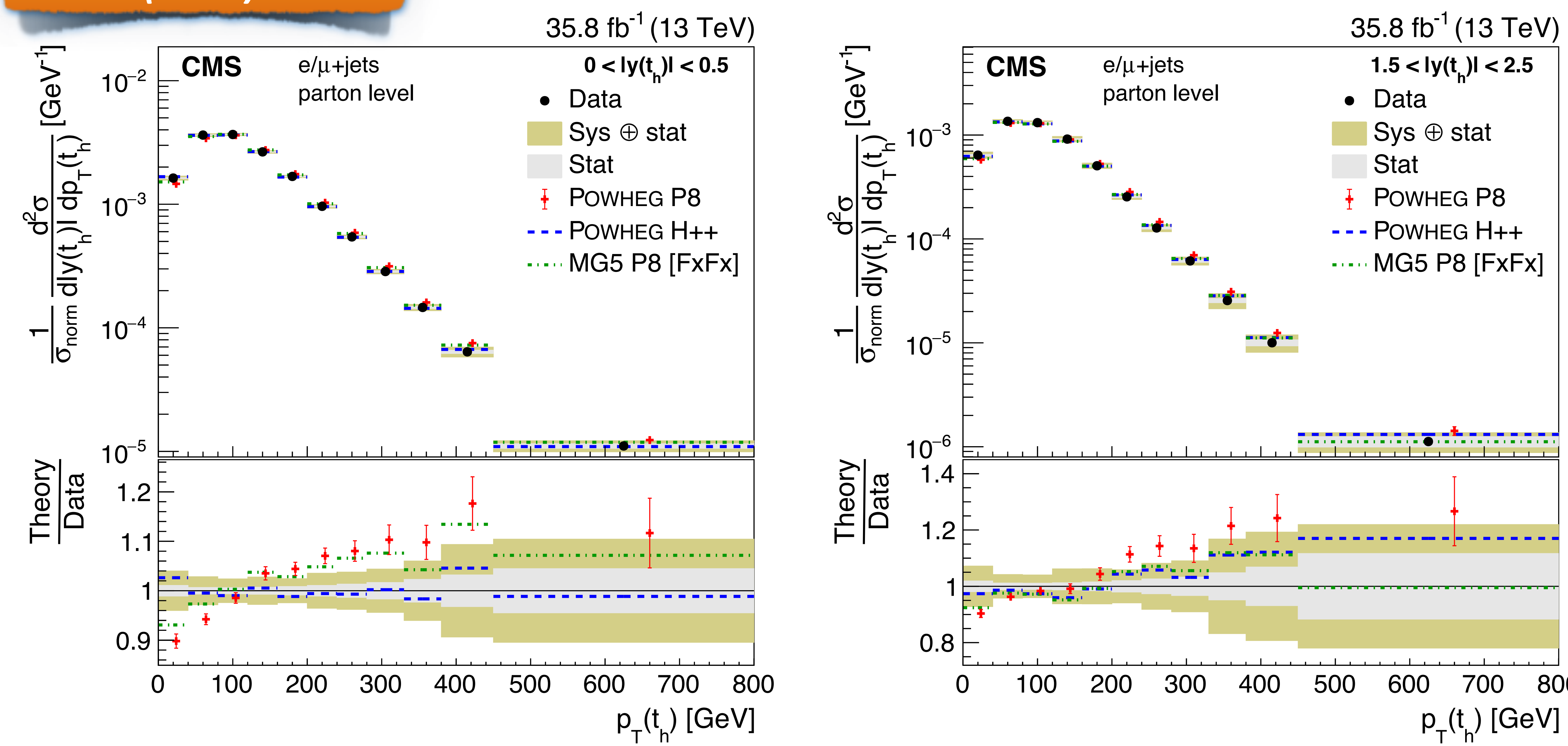

- **double differential in various observables**
  - $p_T(t_h)$ vs $|y(t_h)|$, $|y(tt)|$ vs m_{tt}, m_{tt} vs $p_T(t_h)$,
  - accompanied by full covariance matrices ==> **valuable for further theoretical use!**
- **same trends observed as in the 1D differential measurements**
  - e.g. a softer $p_T(t_h)$ spectrum is observed in all $|y(t_h)|$ regions

Differential cross sections vs jet properties

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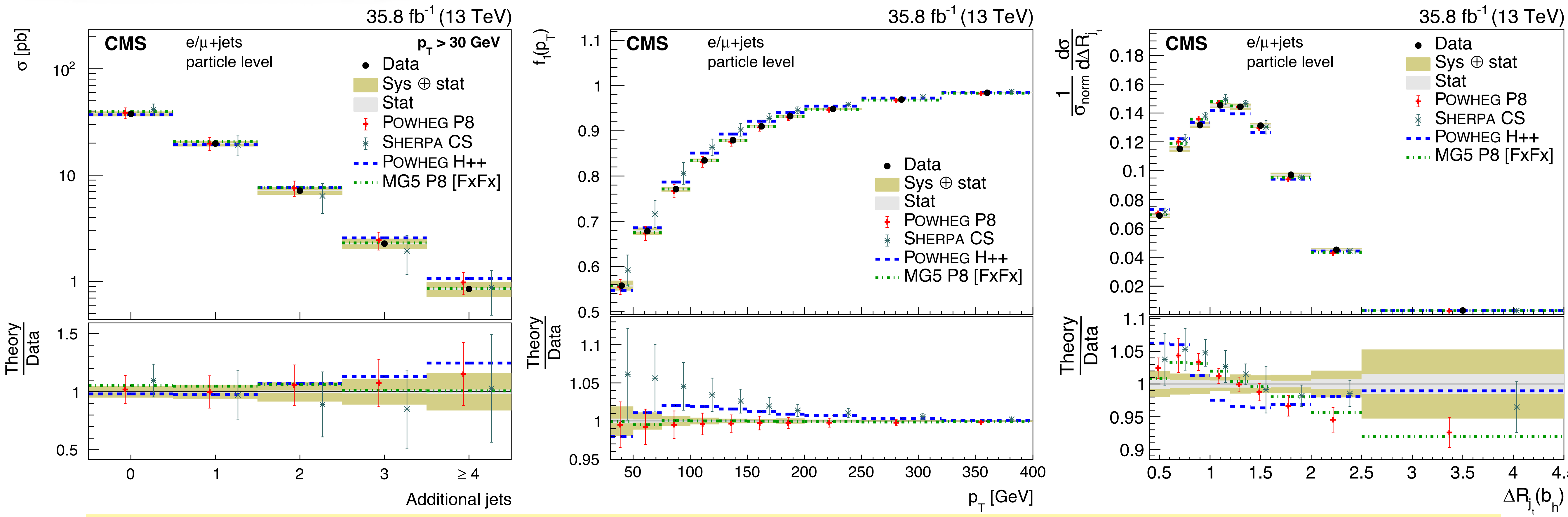
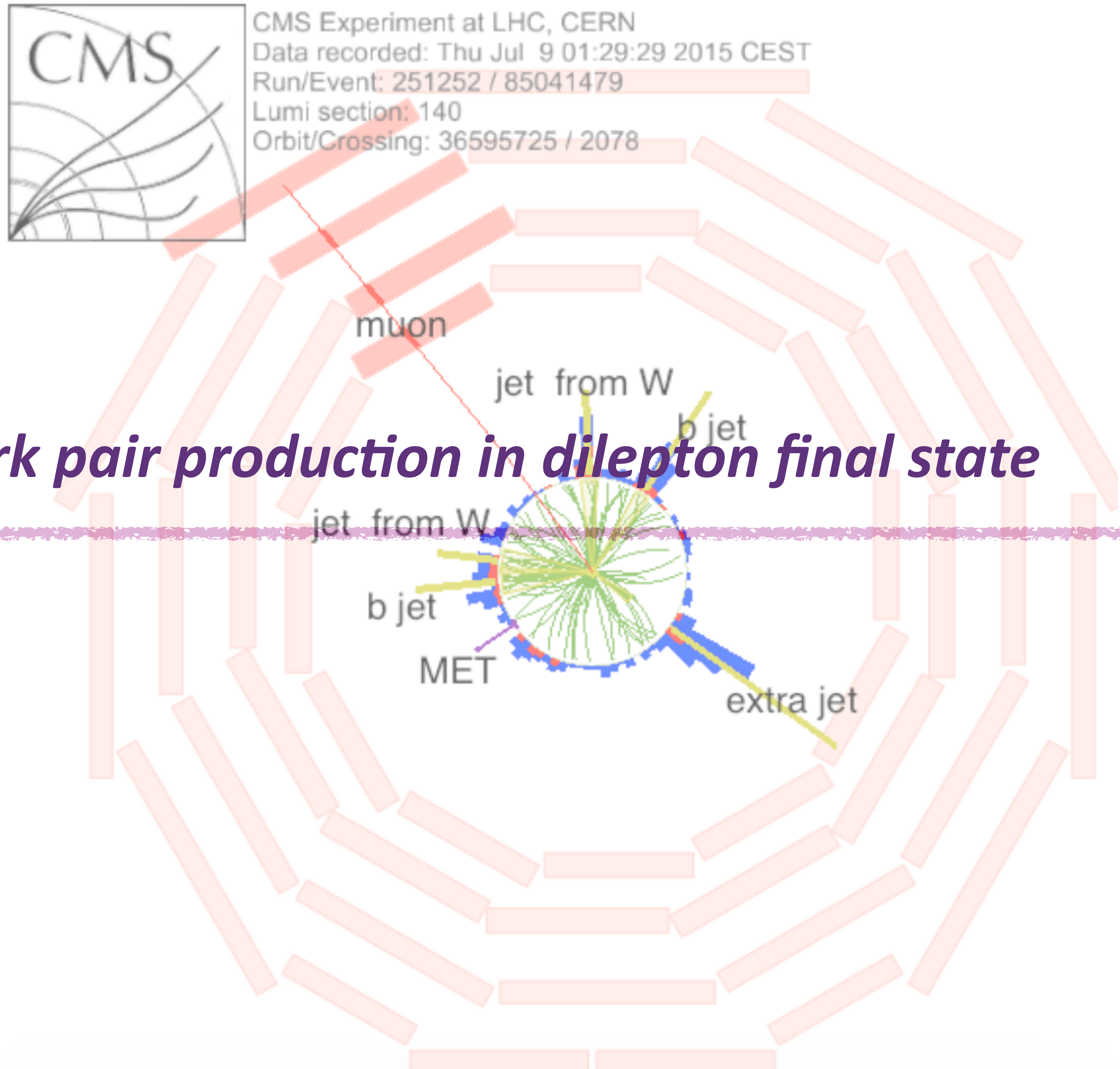


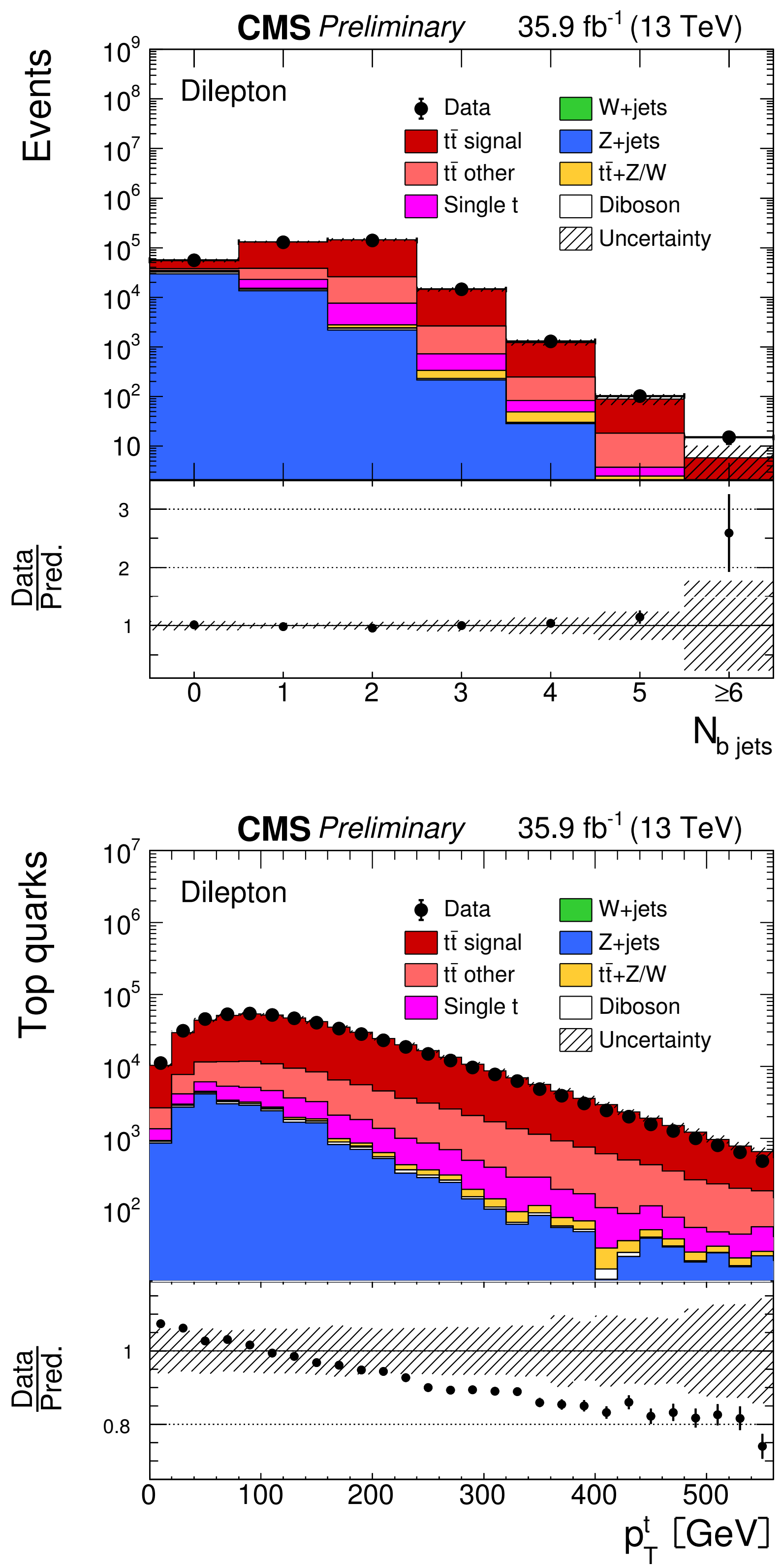
- **reported at particle level only**
- **additional jet multiplicity described well by all models**
- **gap fractions $f_n(p_T)$**
  - fraction of unfolded events that contain less than n=1,2 jets above p_T
  - trend observed wrt the central value of Sherpa
- **angular distance between jets in the tt system**
  - MC generators fail to describe the data

Top quark pair production in dilepton final state



Top quark pairs in dilepton final state

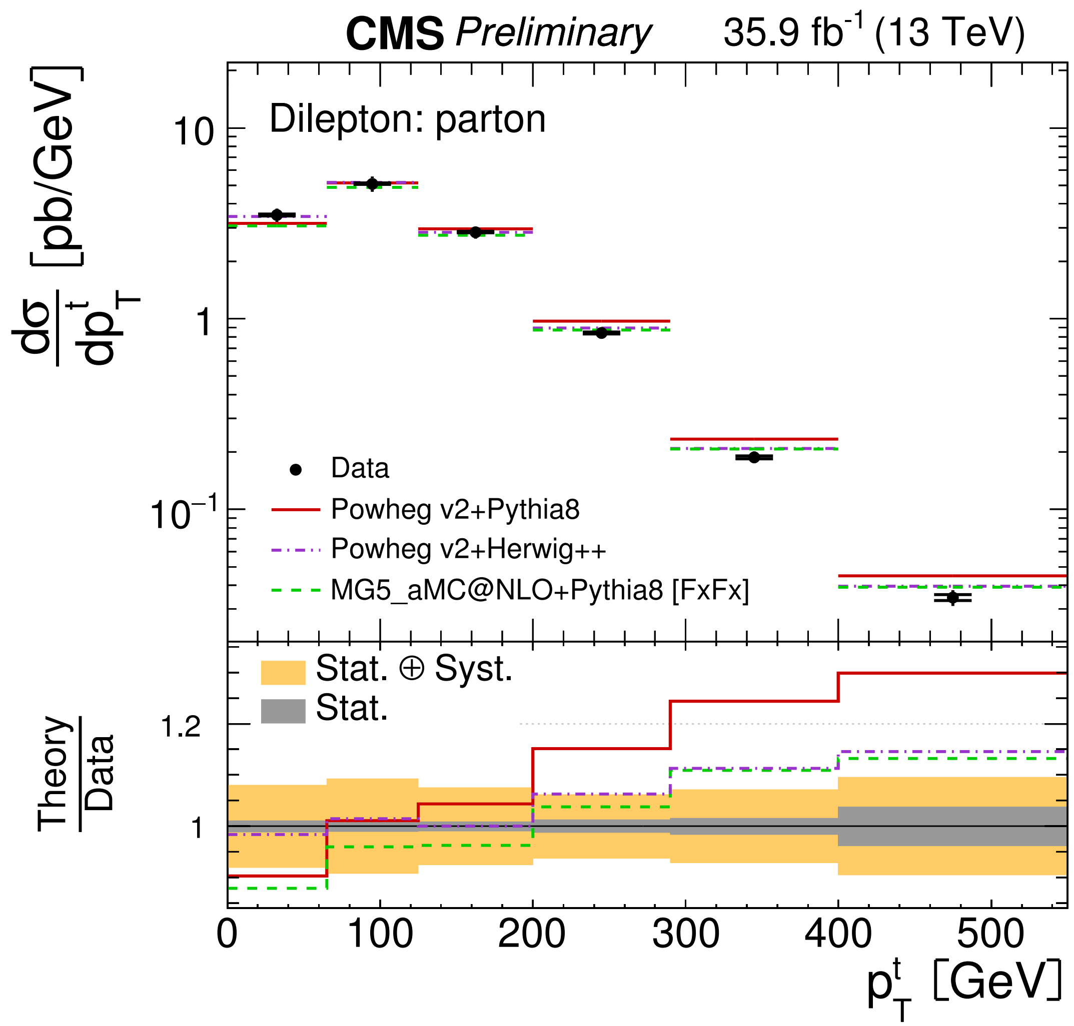
CMS-PAS-TOP-17-014

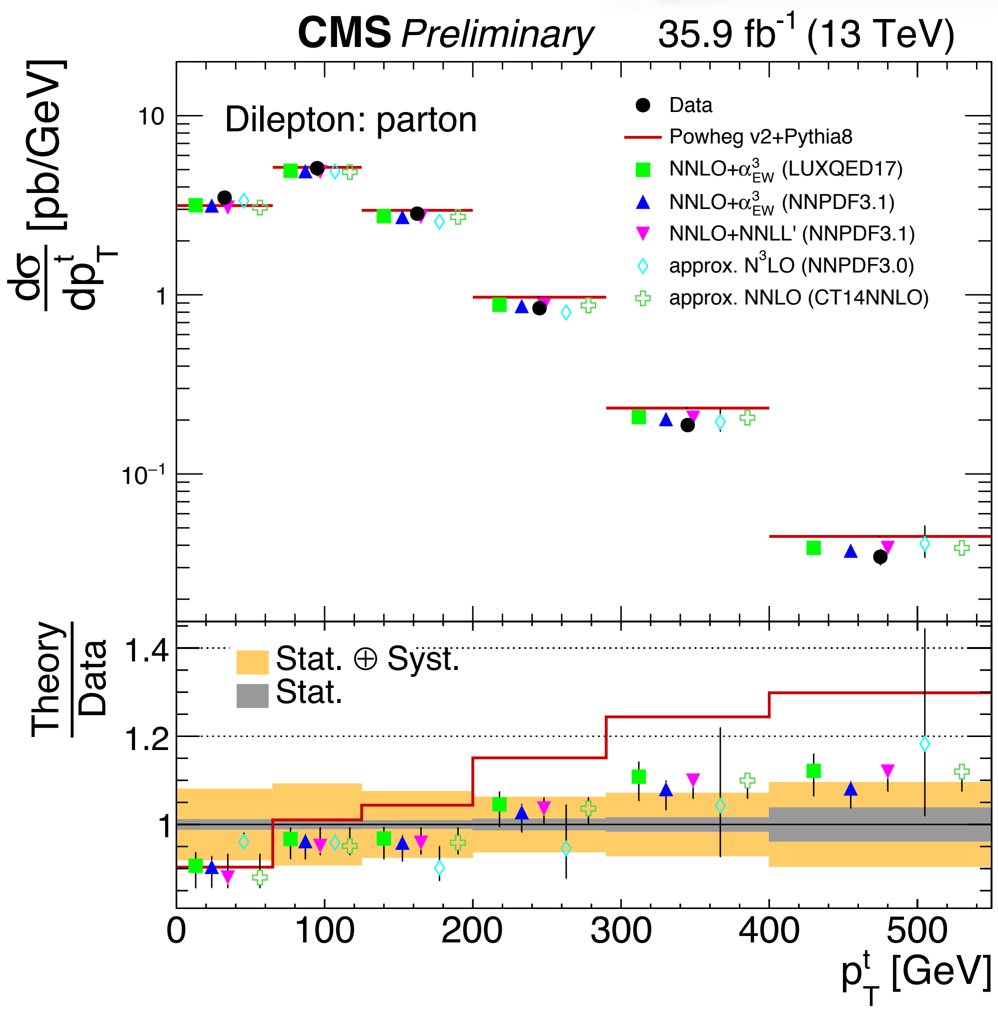


- **Selection**
  - single & double lepton triggers
  - electrons & muons $p_T > 25, 20$ GeV and $|\eta| < 2.4$
  - at least 2 jets with $p_T > 30$ GeV and $|\eta| < 2.4$
  - at least 1 jet b-tagged (~79-87% efficiency and 10% mis-id probability)
- **Top reconstruction**
  - kinematic reconstruction algorithm
  - W ant top mass constraints
  - neutrino momentum solution yielding the smallest tt invariant mass
  - random smearing of objects according to their resolutions
  - weighted average (weight taken from simulated m_{lb} distribution) of top kinematic variables after 100 random smearings
  - efficiency close to 90%

Differential cross sections vs top p_T

CMS-PAS-TOP-17-014

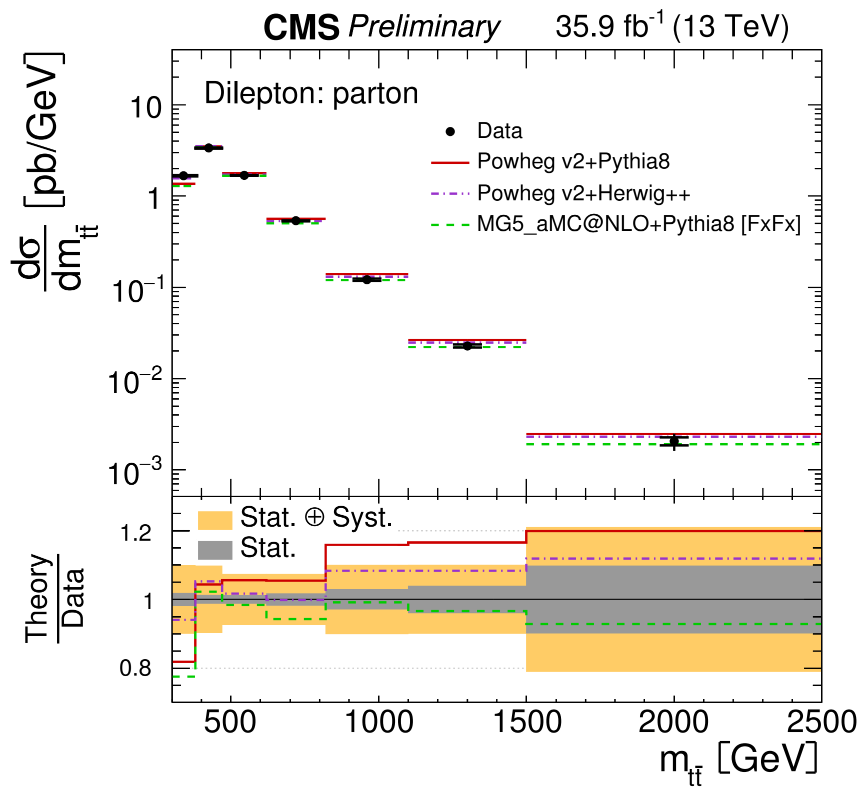


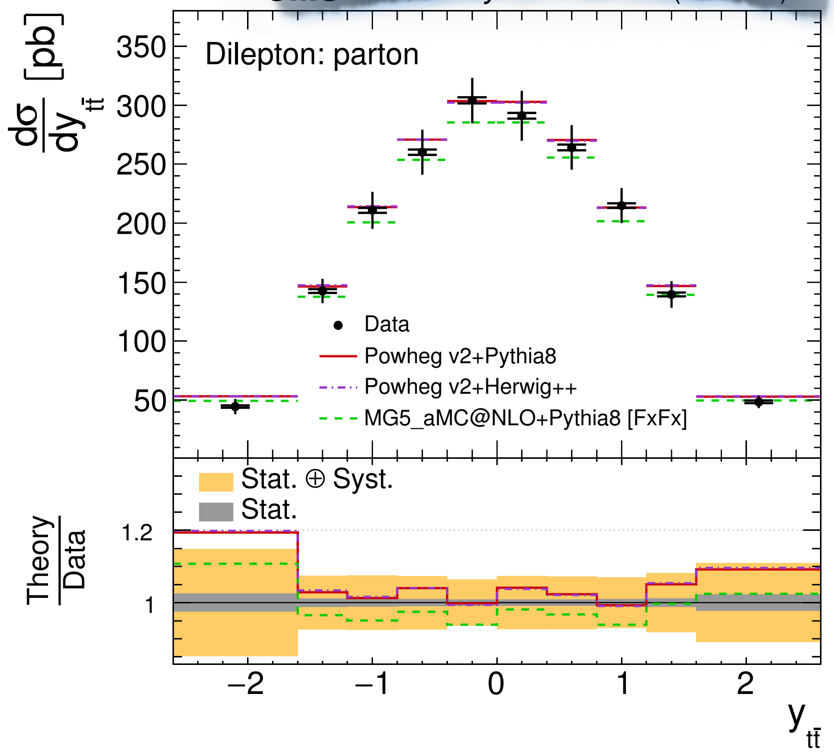


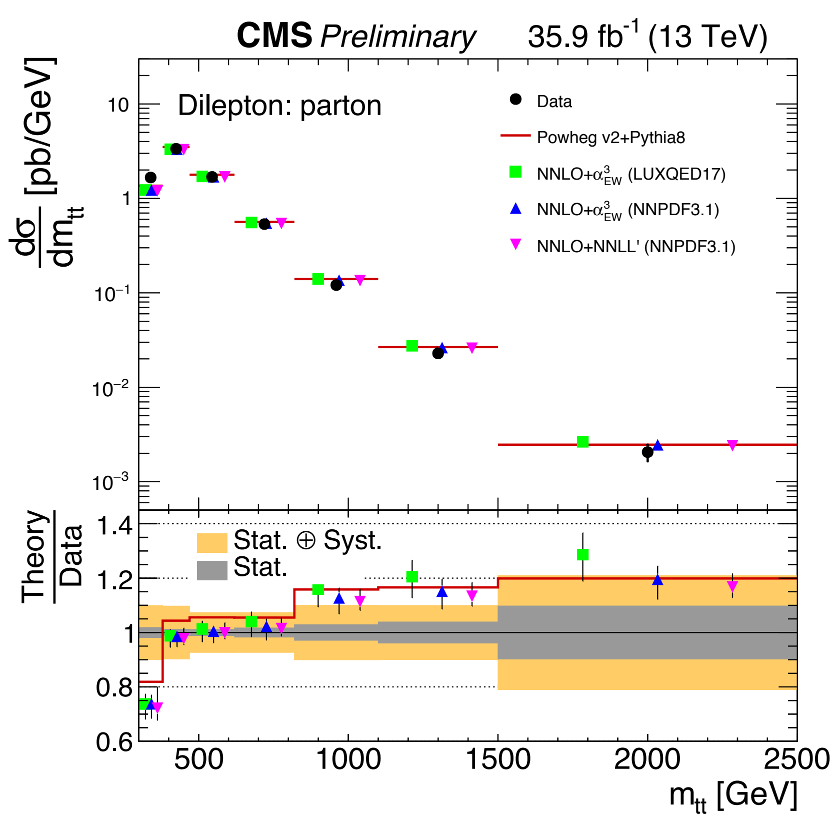
- **softer top p_T spectrum**
  - confirms the observations in the l+jets channel
  - largest deviation for Powheg+Pythia8.
- **theory calculations at various orders**
  - **state of the art: first comparison with data!**
  - much closer to the measurement

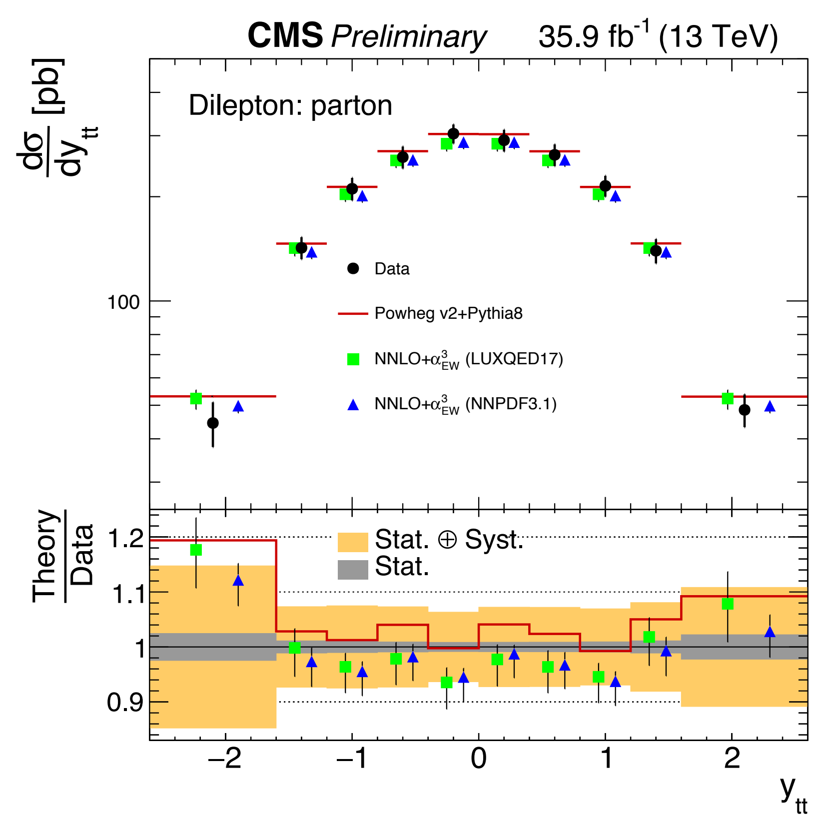
Differential distributions vs top pair observables

CMS-PAS-TOP-17-014



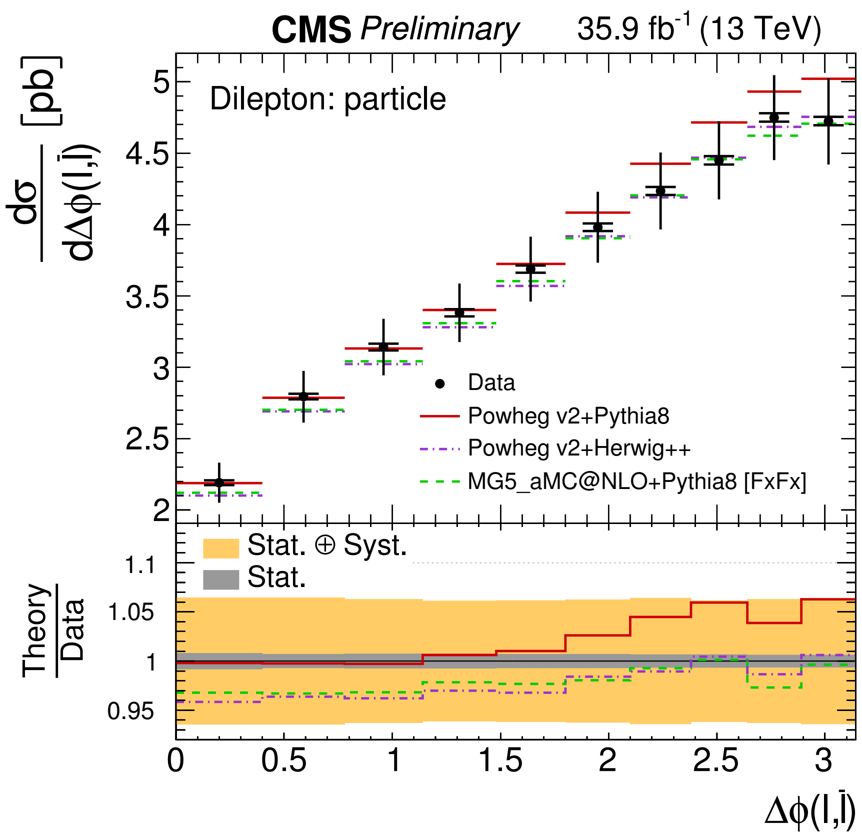


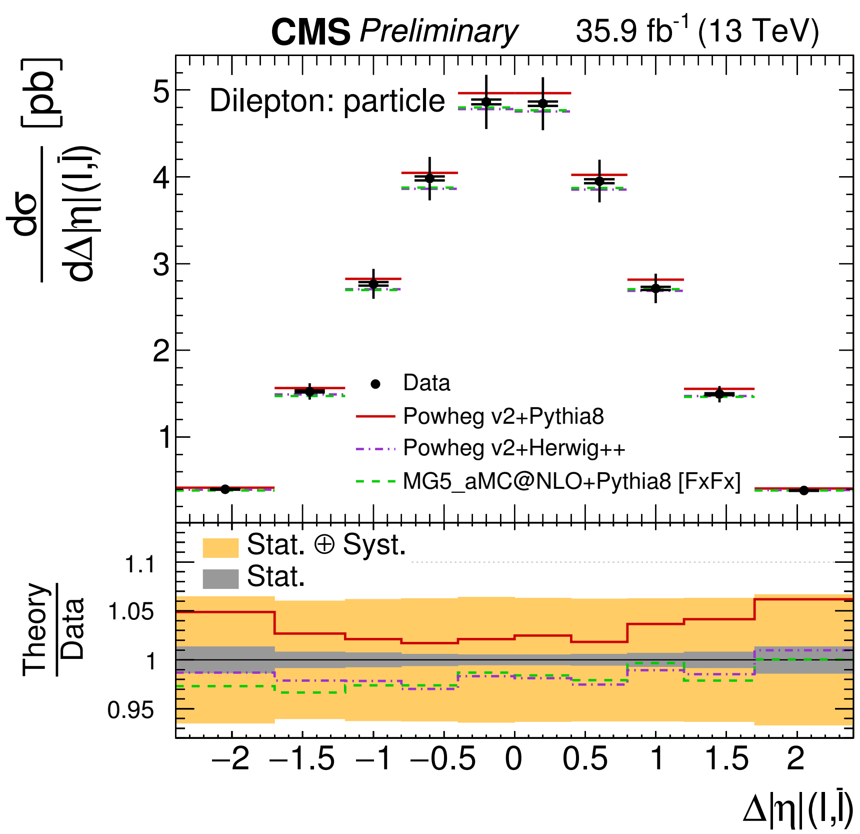


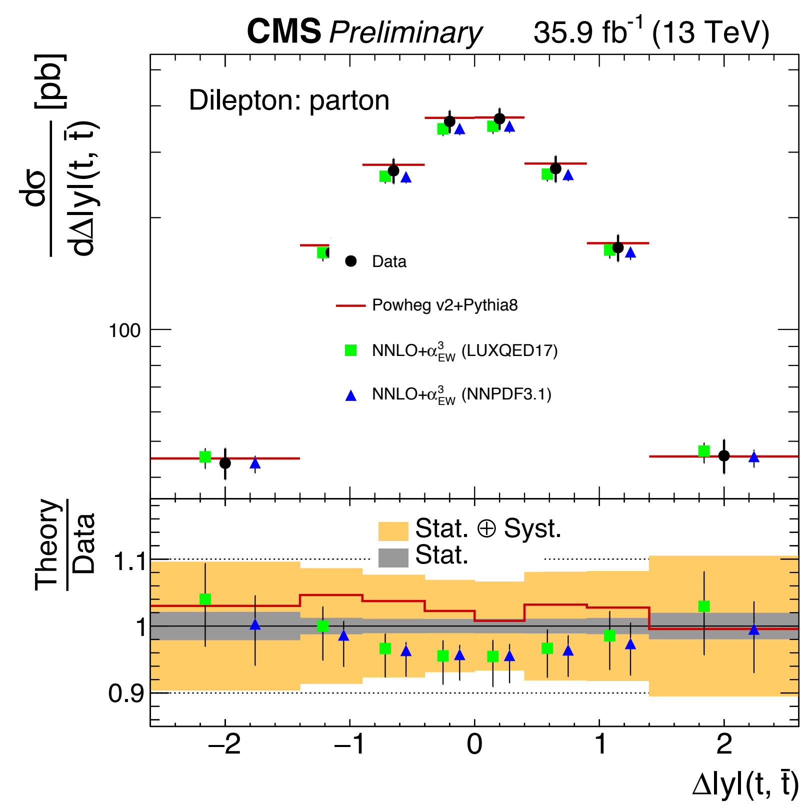


Prospects for BSM searches

CMS-PAS-TOP-17-014







- **differential measurements can probe BSM signals**
  - see talks from G. Smith and P. Van Mulders
- **azimuthal angle between leptons**
  - depends on top pair spin correlations
  - sensitive to BSM signals
- **top charge asymmetry**
  - manifests itself on the rapidity difference of the tops or the associated leptons
  - modified by BSM models (axigluons, Z’, W’)

Summary & Outlook

- **LHC is a top pair factory!**
  - possible to explore the entire phase space of top production
- **differential measurements are important**
  - powerful constrains on QCD parameters
  - tune MC generators
  - provide more accurate background estimates for BSM searches

for a comparison between ATLAS and CMS see F. Fabri's talk

- **presented new results using the 2016 dataset**
  - in l+jets and dilepton channels
  - improved experimental precision
  - limited by theory uncertainties (MC modelling)
    - but a lot of progress has been made to reduce them
- **more results will be available soon by CMS**
  - including boosted topologies and multi-differential distributions
  - **stay tuned for the full Run II dataset (x5 more data)**

References

Publications & preliminary results

(1) *"Measurements of differential cross sections of top quark pair production as a function of kinematic event variables in proton-proton collisions at sqrt(s) = 13 TeV"*, **JHEP 06 (2018) 002**, http://dx.doi.org/10.1007/JHEP06(2018)002

(2) *"Measurement of differential cross sections for the production of top quark pairs and of additional jets in lepton+jets events from pp collisions at sqrt(s) = 13 TeV"*, **PRD 97 (2018) 112003**, http://dx.doi.org/10.1103/PhysRevD.97.112003

(3) *"Measurements of differential cross sections for ttbar production in proton-proton collisions at sqrt(s) = 13 TeV using events containing two leptons"*, **CMS-PAS-TOP-17-014**, https://cds.cern.ch/record/2621975

(4) *"Pinning down the large-x gluon with NNLO top-quark pair differential distributions"*, **arXiv:1611.08609**

Related talks & posters @ TOP2018

- *"Inclusive ttbar cross section measurements"* (ATLAS + CMS), **M. Defranchis**
- *"Comparative overview of differential ttbar measurements at ATLAS and CMS"*, **F. Fabri**
- *"FCNC, anomalous couplings, EFT" (ATLAS + CMS)*, **G. Smith**
- *"Top properties" (ATLAS + CMS)*, **P. Van Mulders**
- *"Modeling and tuning" (CMS)*, **E. Clement**
- *YSF: "Measurements of differential cross sections of top quark pair production as a function of kinematic event variables at 13 TeV"*, **D. Burns**
- *"Measurements of differential ttbar pair production cross sections as a function of kinematic event variables at 13 TeV at CMS"*, **D. Burns**