Karlsruhe Institute of Technology

# Measurement of Differential Cross Sections in Top Pair Production with the CMS Detector

*European Physical Society Conference on High Energy Physics*
*Vienna, Austria, July 22–29, 2015*

EUROPEAN PHYSICAL SOCIETY HEP2015


ULRICH HUSEMANN on behalf of the CMS Collaboration


# Differential Cross Sections: Why?


- **Properties** of the top quark:
  - Detailed **test of perturbative QCD** (and MC generators) at the highest scales
  - Search for **BSM physics** involving top quarks
- Top quarks as a **tool**:
  - **Detailed understanding** of TeV-scale standard model processes → benefit for **Higgs physics** and **searches** for BSM physics
  - Extraction of **parton distribution functions**
- This presentation: **differential cross section results from the CMS experiment**
  - $t\bar{t}$ differential cross sections and jet multiplicity
  - Event-level observables in $t\bar{t}$ events



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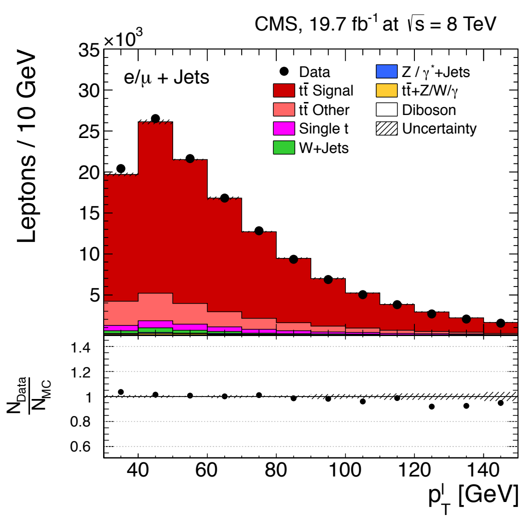
# Differential Cross Sections: How?

- General strategy of differential cross section measurements
  1. Object reconstruction and tight event selection (lepton+jets, dilepton) → **pure** $t\bar{t}$ sample
  2. Top quark **kinematic reconstruction**
  3. Background subtraction
  4. Corrections: detector acceptance, resolution → regularized **unfolding** techniques
  5. **Comparison** with **theory** (visible or full phase space)

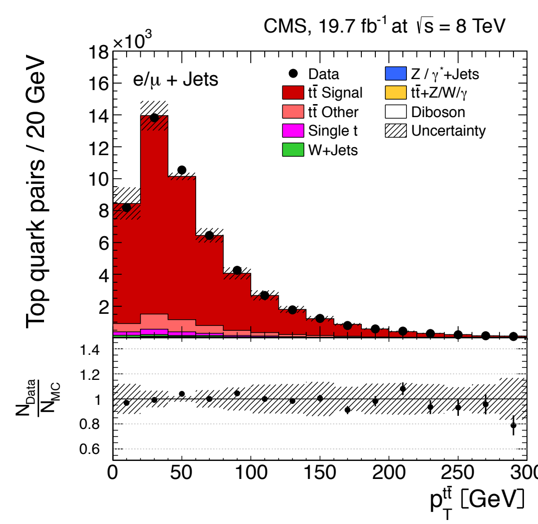
Normalized Differential Cross Section: Master Formula

$$\frac{1}{\sigma}\frac{d\sigma_i}{dX} = \frac{1}{\sigma}\frac{\text{unfold}\left(s_i^X - b_i^X\right)}{\Delta_i^X \cdot \int \mathcal{L}\, dt}$$

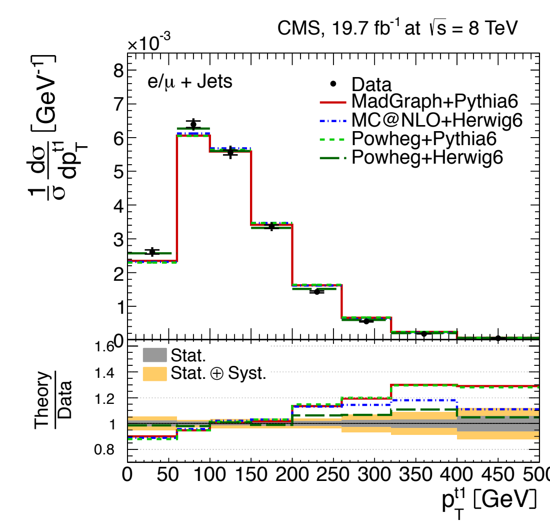
**Object Reconstruction**




**Top Kinematic Reconstruction**




**Theory Comparison**




[arXiv:1505.04480 [hep-ex]], submitted to EPJC]



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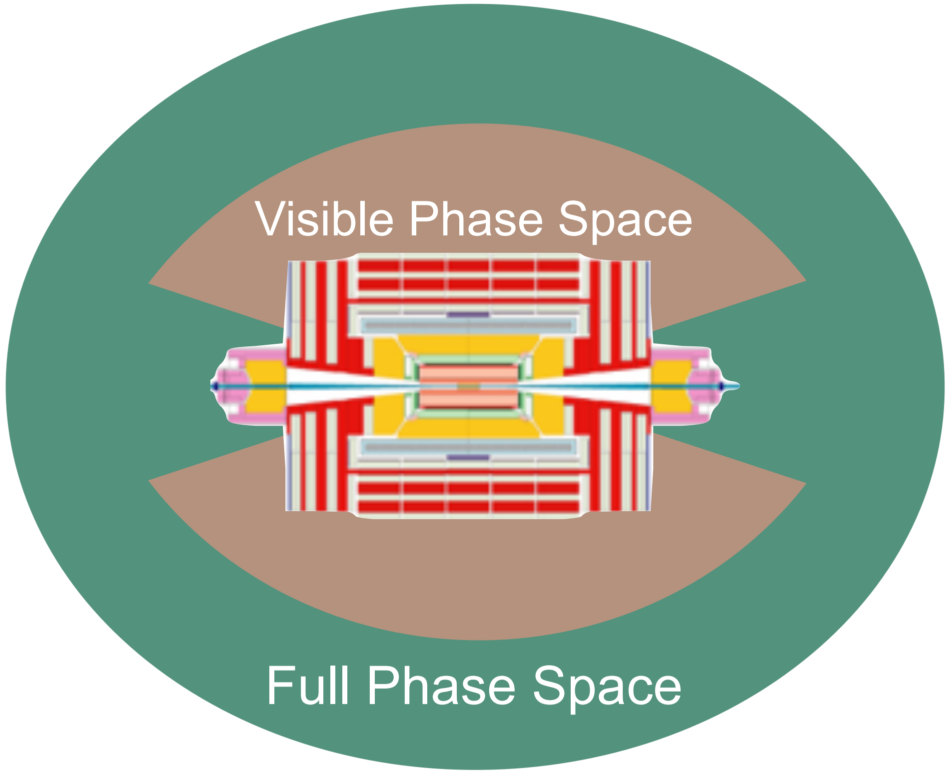
# Visible Phase Phase & Observables

- **Acceptance** corrections:
  - Limitation for cross section measurements: **extrapolation** from limited detector acceptance **to full phase space** with theory/simulation tools
  - Measurement of differential cross sections in **visible phase space** (aka fiducial cross sections) → reduced dependence of measurement on signal/background **modeling**
  - Corrections to level of **stable particles** (some analyses: parton-level information on tops)




- **Observables** in differential cross section measurement:
  - **Directly** measured quantities, e.g. kinematics of leptons and b jets: **visible** phase space → comparison with Monte Carlo (MC) simulations
  - **Reconstructed** quantities (top and $t\bar{t}$ system): **visible** and **full** phase space → comparison with **MC** and **calculations** (e.g. fixed-order NNLO)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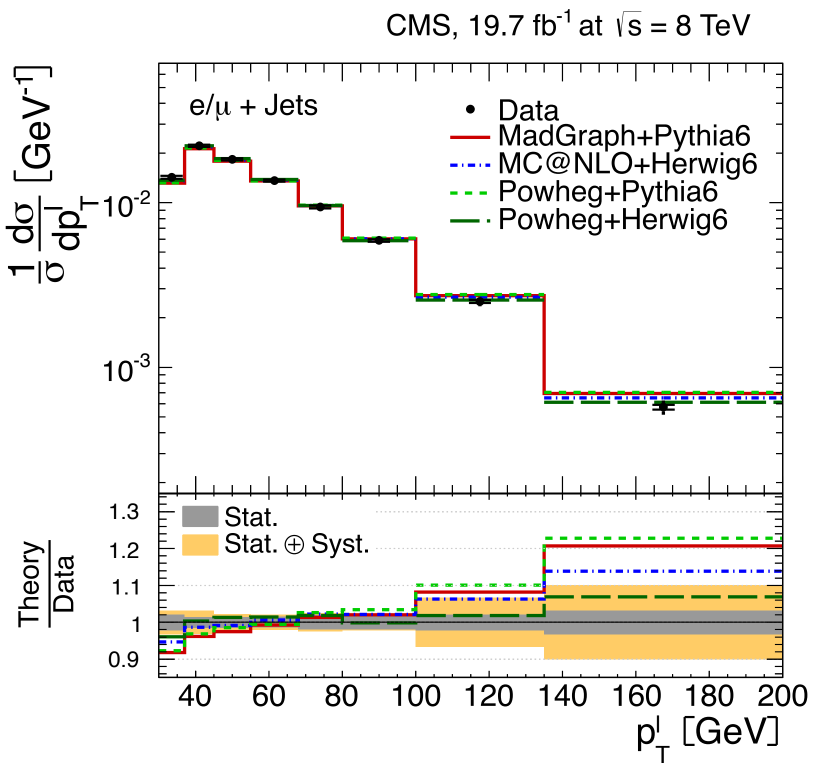
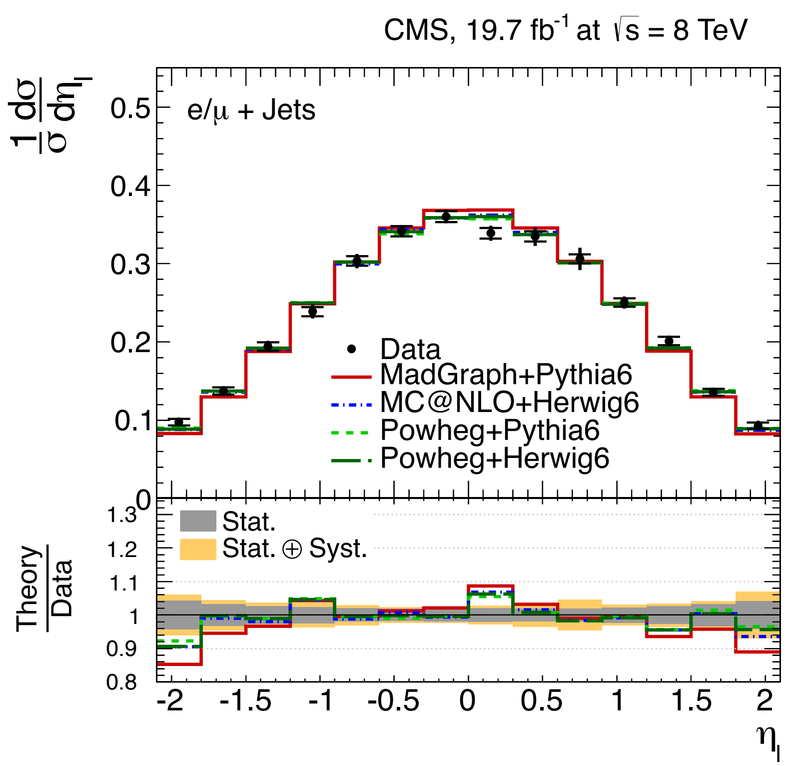
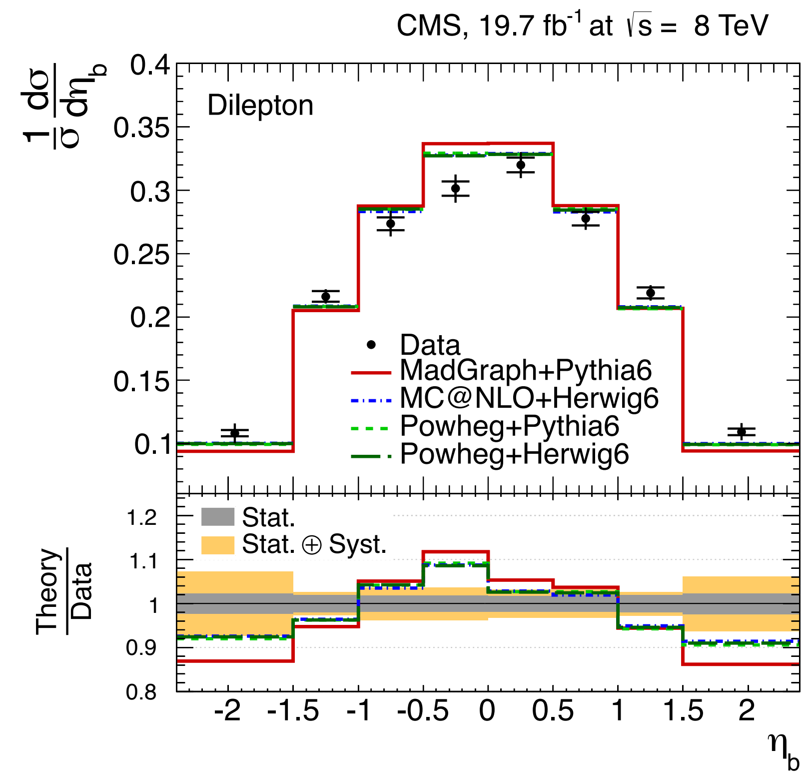
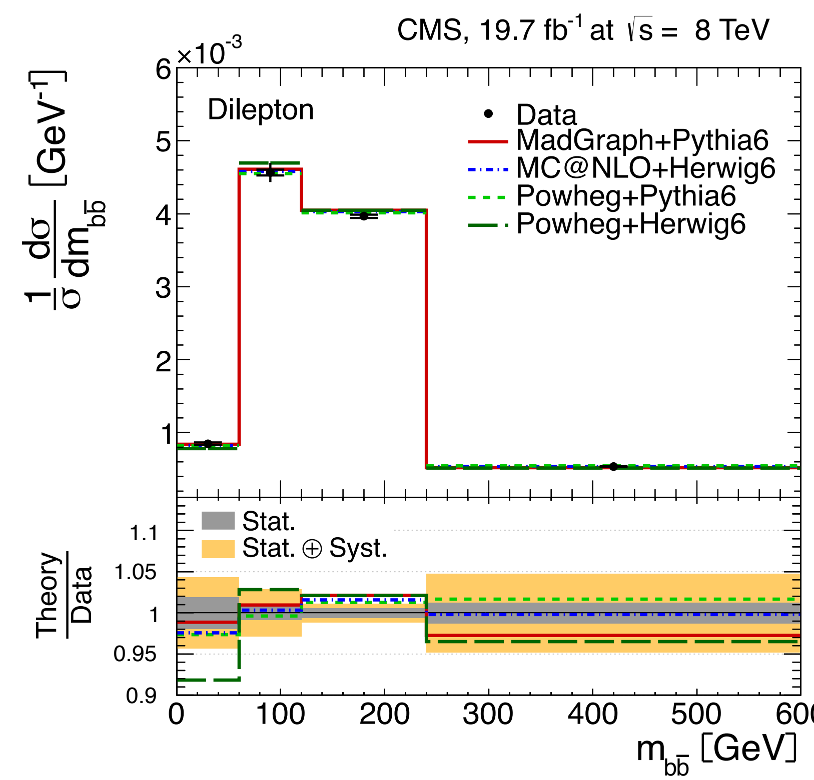
# Leptons and b-Jets



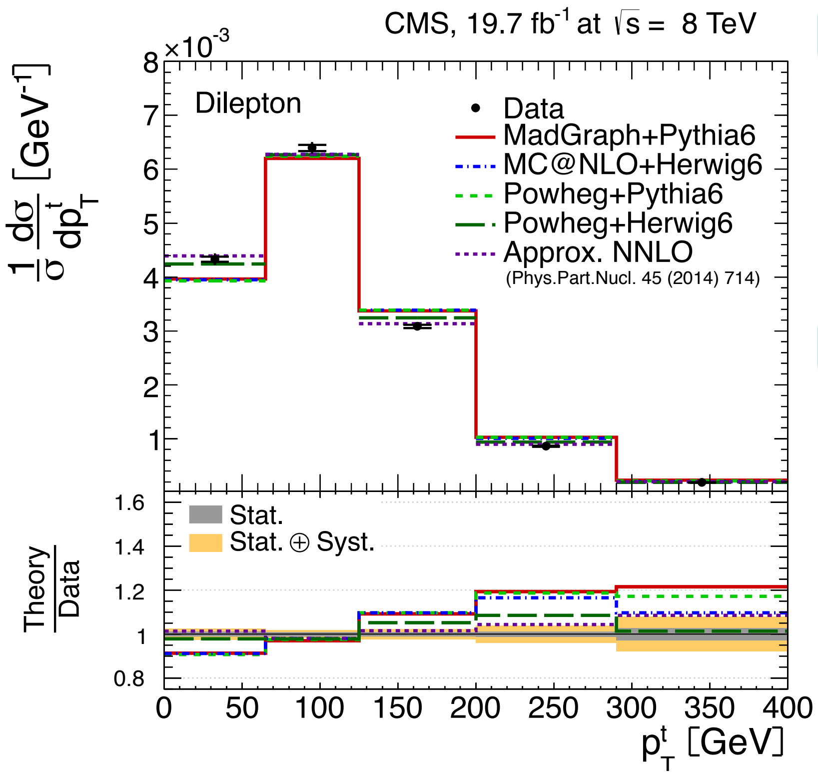

- **Measurement in visible phase space**
- **Leptons** (left):
  - Example: e/μ+jets
  - $p_T$ spectrum slightly softer in data
- **b-Jets** and $b\bar{b}$ system (right):
  - Example: dilepton
  - $\eta_b$ slightly less central in data
- Good description of all distributions: **Powheg+Herwig6**

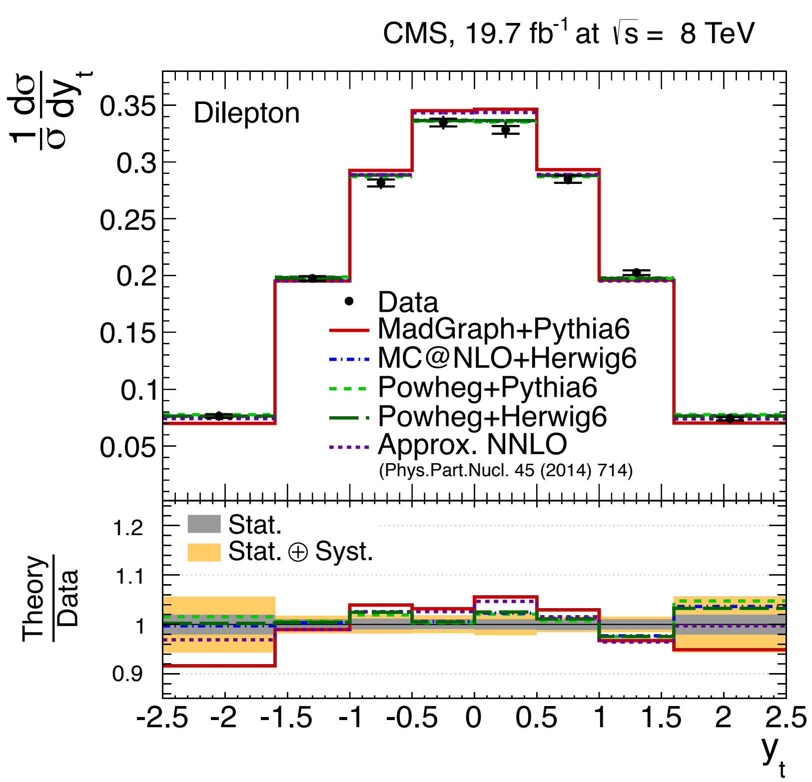


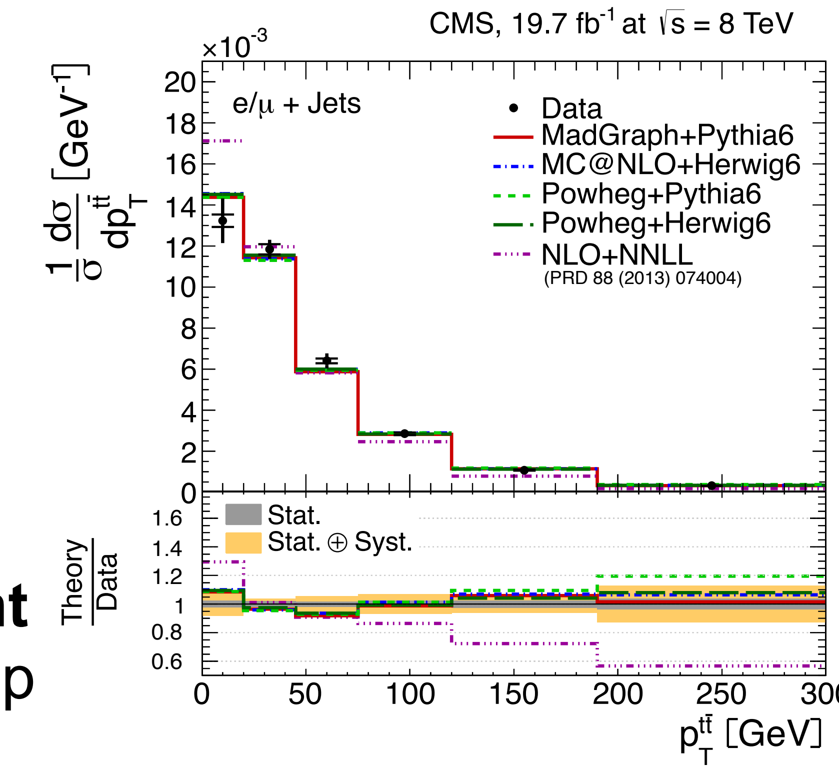

[arXiv:1505.04480 [hep-ex], submitted to EPJC]

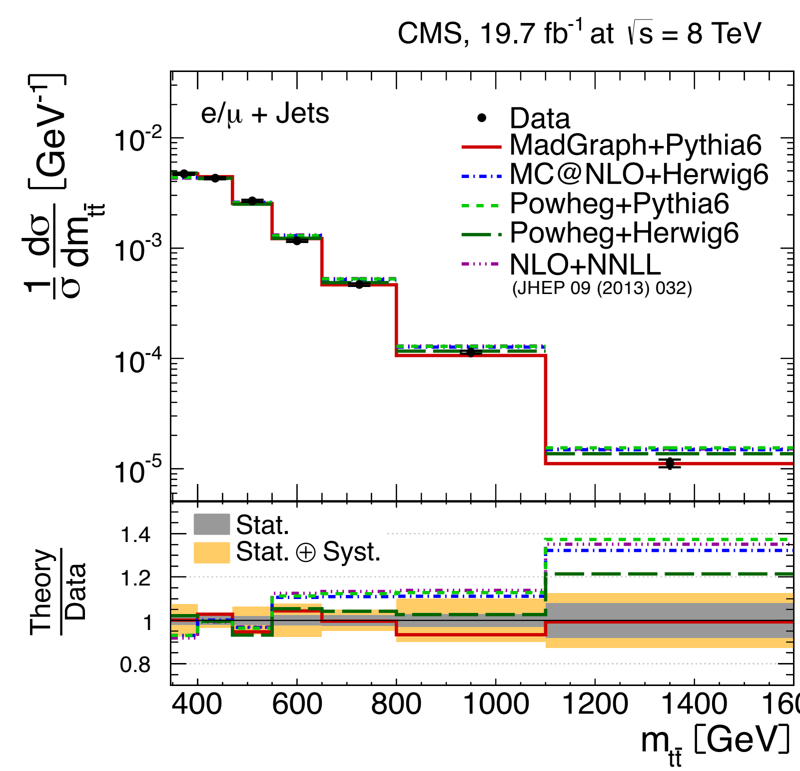
# Top and $t\bar{t}$ System




- All distributions corrected to **parton level** (before decay, but after radiation)
- Top kinematics (left):
  - Examples: top transverse momentum and rapidity
  - Generally **good agreement** with MC and calculations up to approx. NNLO
  - Measured $p_T$ spectrum softer than most MC predictions, best description by Powheg+Herwig6
- $t\bar{t}$ kinematics (right):
  - $p_T^{t\bar{t}}$ well described (except NLO+NNLL calculation)
  - $m_{t\bar{t}}$ tails in data lower than predictions




[arXiv:1505.04480 [hep-ex], submitted to EPJC]



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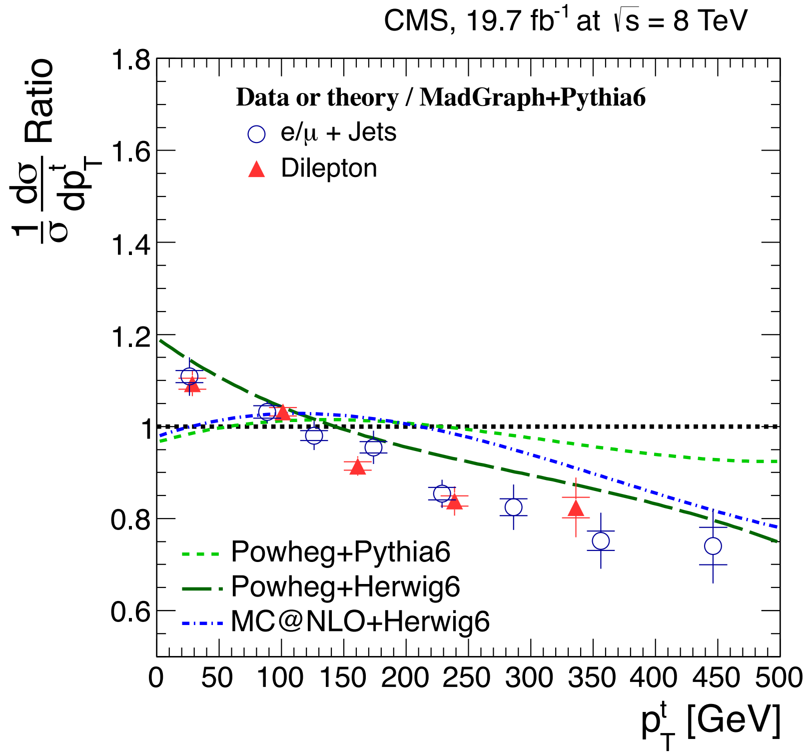
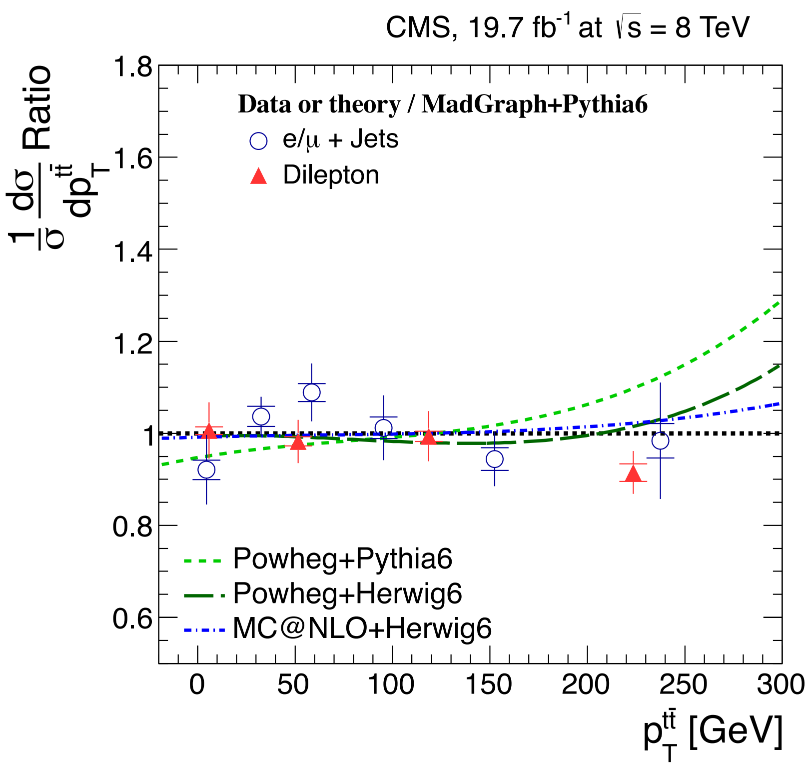
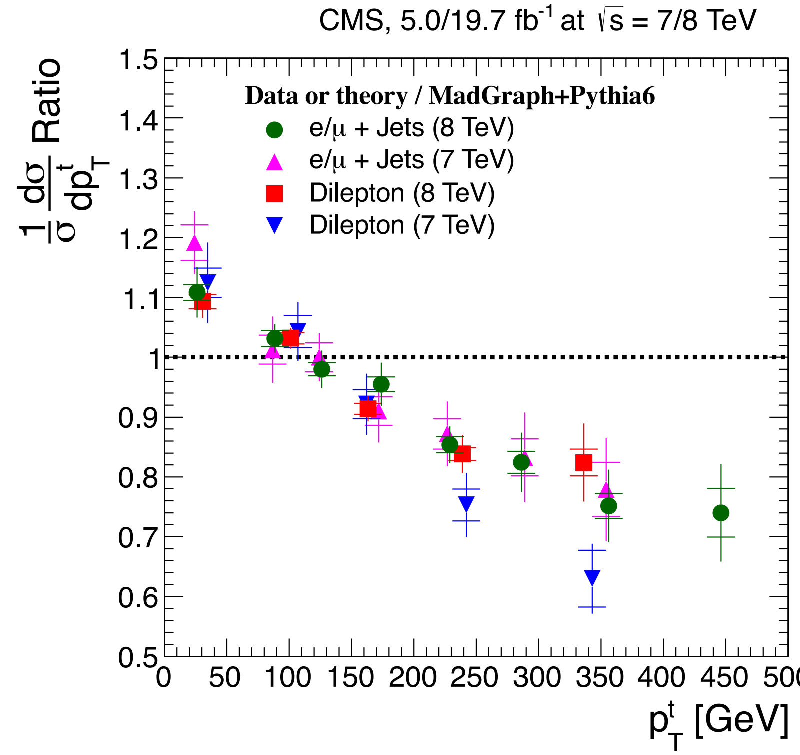
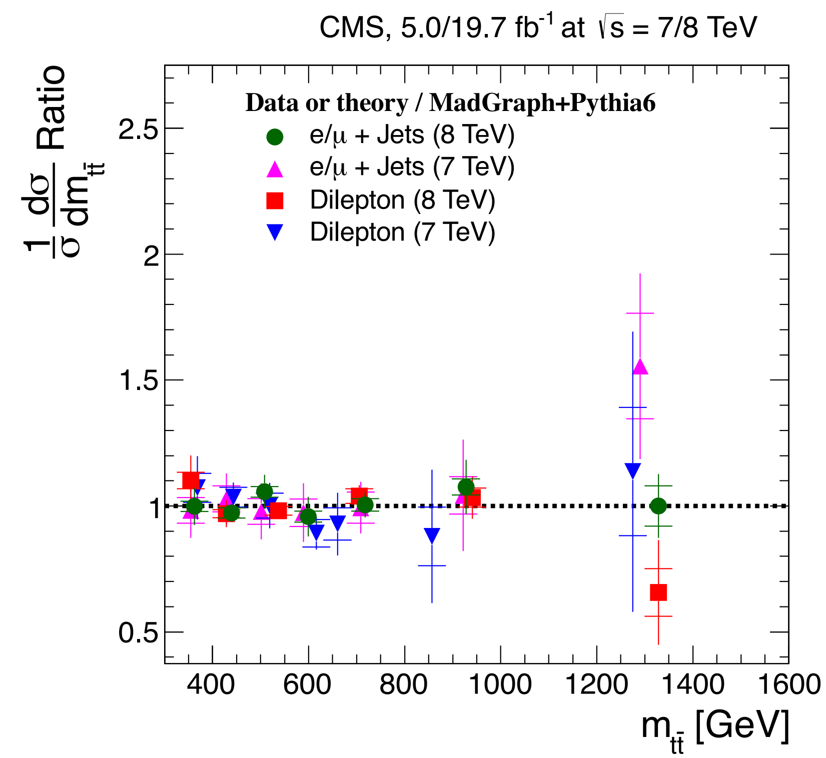
# Consistency of Results




- Results **consistent** among all CMS measurements
  - e/μ+jets vs. dilepton
  - 7 TeV vs. 8 TeV
- Comparison with ATLAS results:
  - Generally **good agreement**
  - Some **differences** in low top $p_T$ region (under investigation at LHCTOPWG)

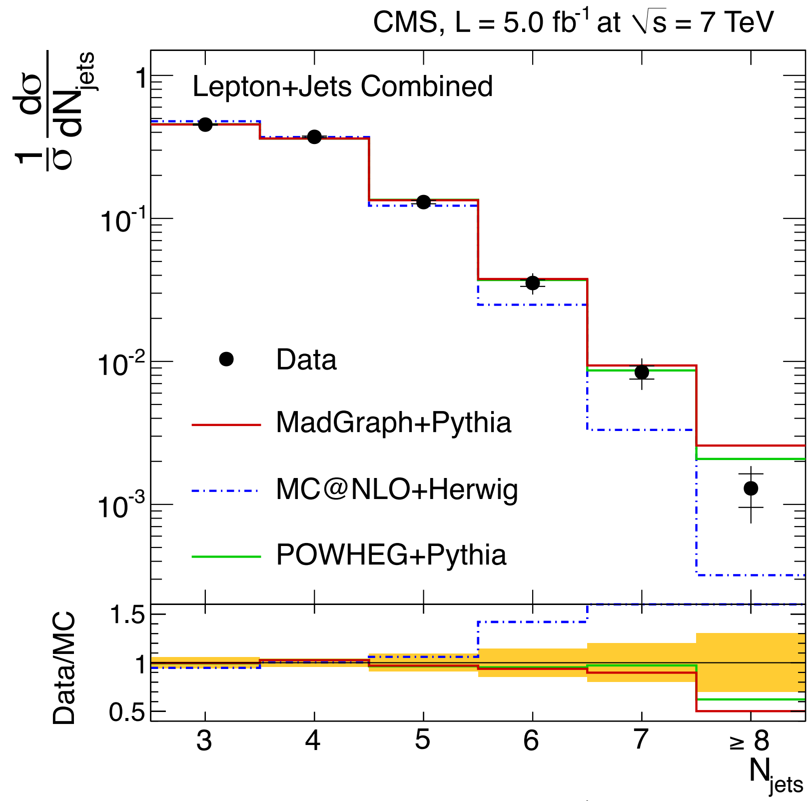


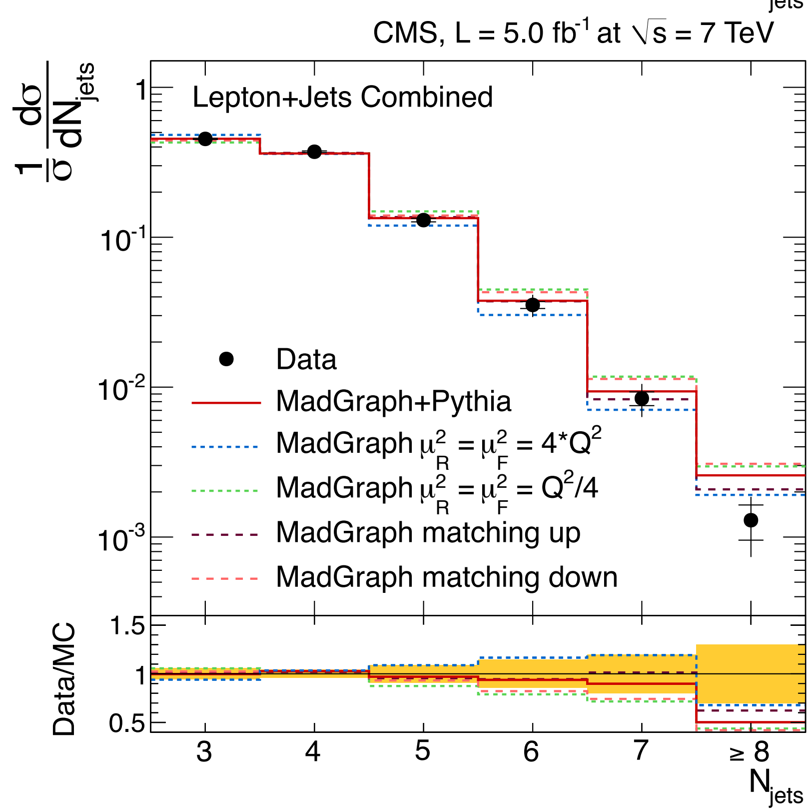




[arXiv:1505.04480 [hep-ex], submitted to EPJC]

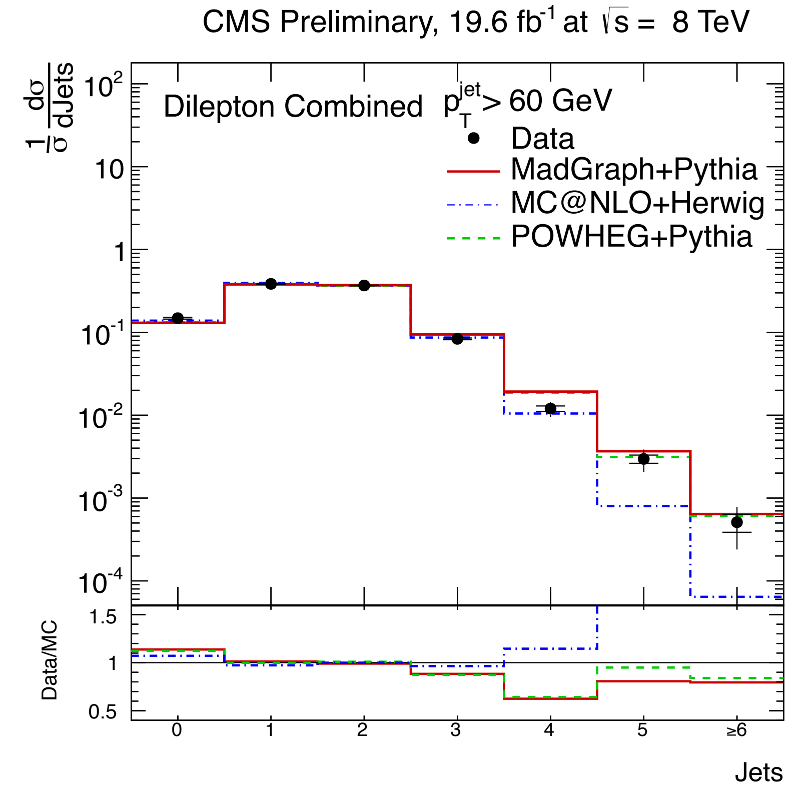
# Jet Multiplicity in $t\bar{t}$ Events

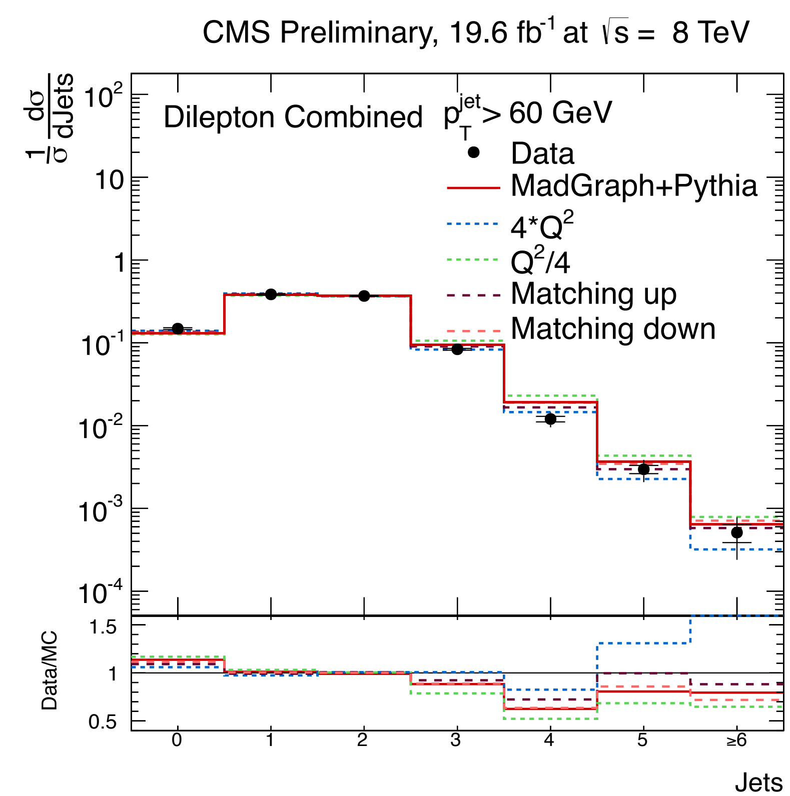
- $t\bar{t}$+jets:
  - Results from 7 TeV and 8 TeV data
  - e/μ+jets & dilepton
- Main results:
  - Jet **multiplicity** (unfolded to particle level)
  - Comparison with **MC generators** → good agreement with MadGraph and Powheg
  - Comparison with **Q² scale variations** (MadGraph)




[EPJ C74 (2014) 3014]




[CMS-PAS-TOP-12-041]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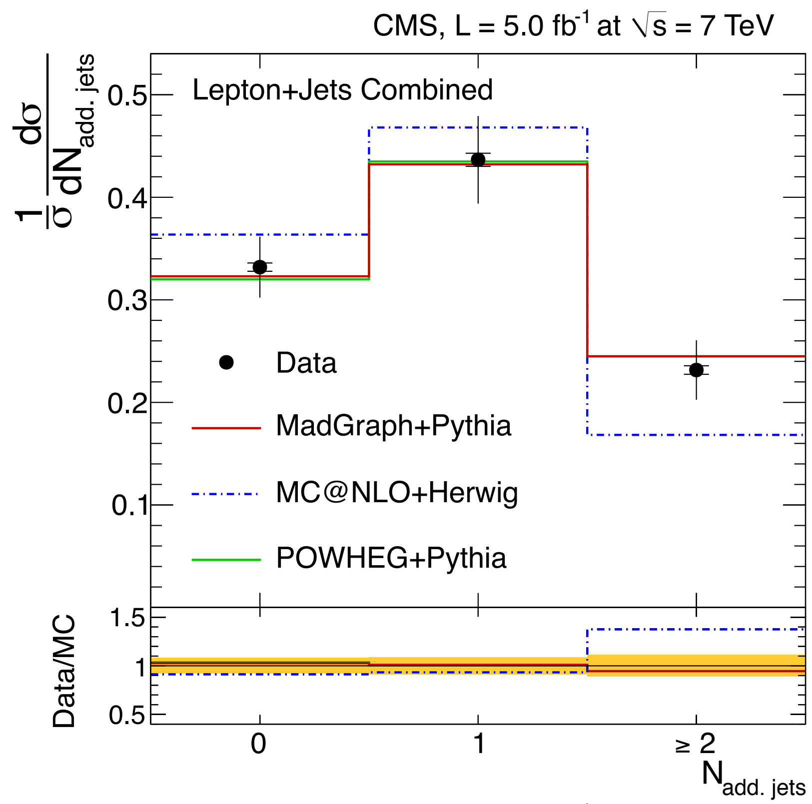
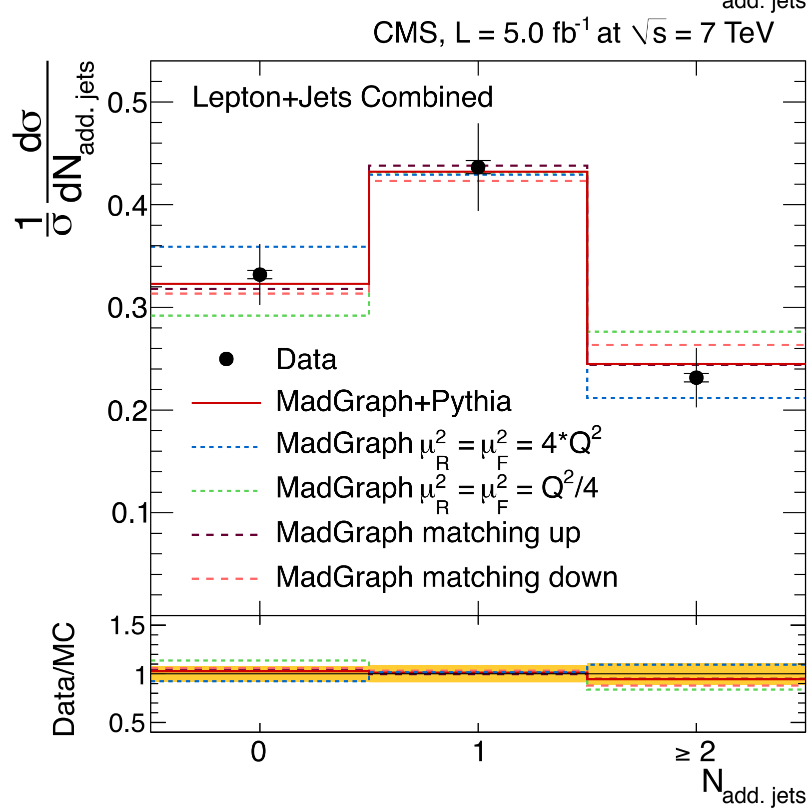
# Jet Multiplicity in $t\bar{t}$ Events

- $t\bar{t}$+jets:
  - Results from 7 TeV and 8 TeV data
  - e/μ+jets & dilepton
- Additional results:
  - Multiplicity of **additional** jets (not matched to top partons)
  - **Gap fractions:**

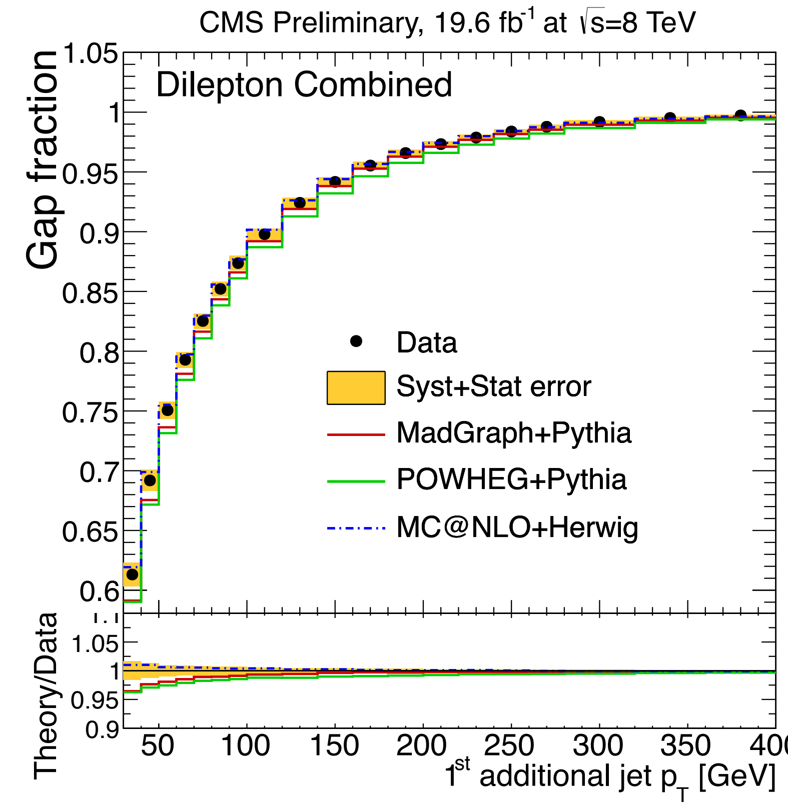
$$f(X_0) = \frac{N(X < X_0)}{N_{\text{total}}}$$

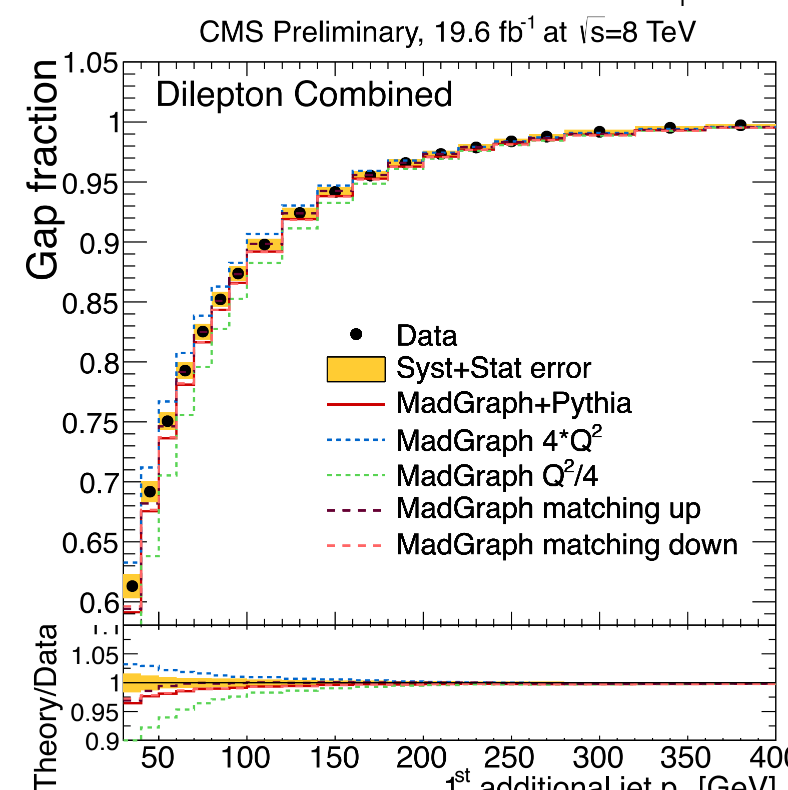
(X = $p_T$ of two additional jets, $H_T$)




[EPJ C74 (2014) 3014]

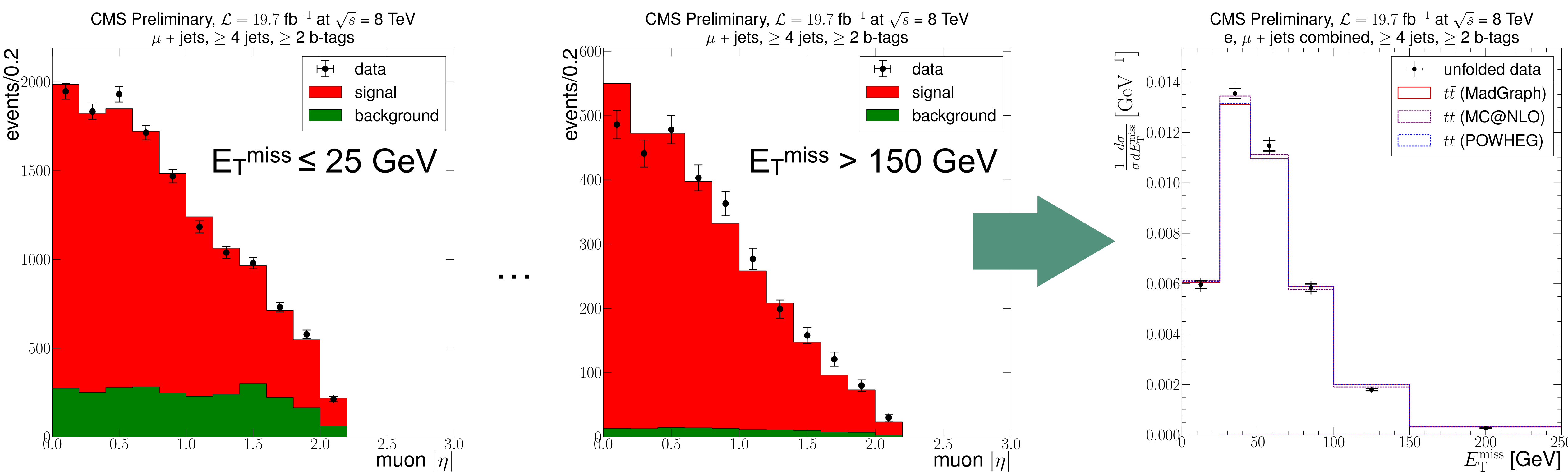



[CMS-PAS-TOP-12-041]

# Event-Level Observables in $t\bar{t}$

- Event-level observables (e.g. $E_T^{miss}$, $H_T$) sensitive to **rare processes** (e.g. $t\bar{t}$ + W/Z/H) and **new physics** in lepton + multijet final states
- Analysis strategy:
  1. Standard **lepton+jets event selection** with ≥2 b-tagged jets → **pure** $t\bar{t}$ sample
  2. **Split samples** into bins of event-level observables
  3. Obtain top content from **fit to lepton |η|** distribution
  4. Correct for leptons from **tauonic top** decays and **single top** process
  5. Correct for **migration** effects (regularized unfolding)




[CMS-PAS-TOP-12-042]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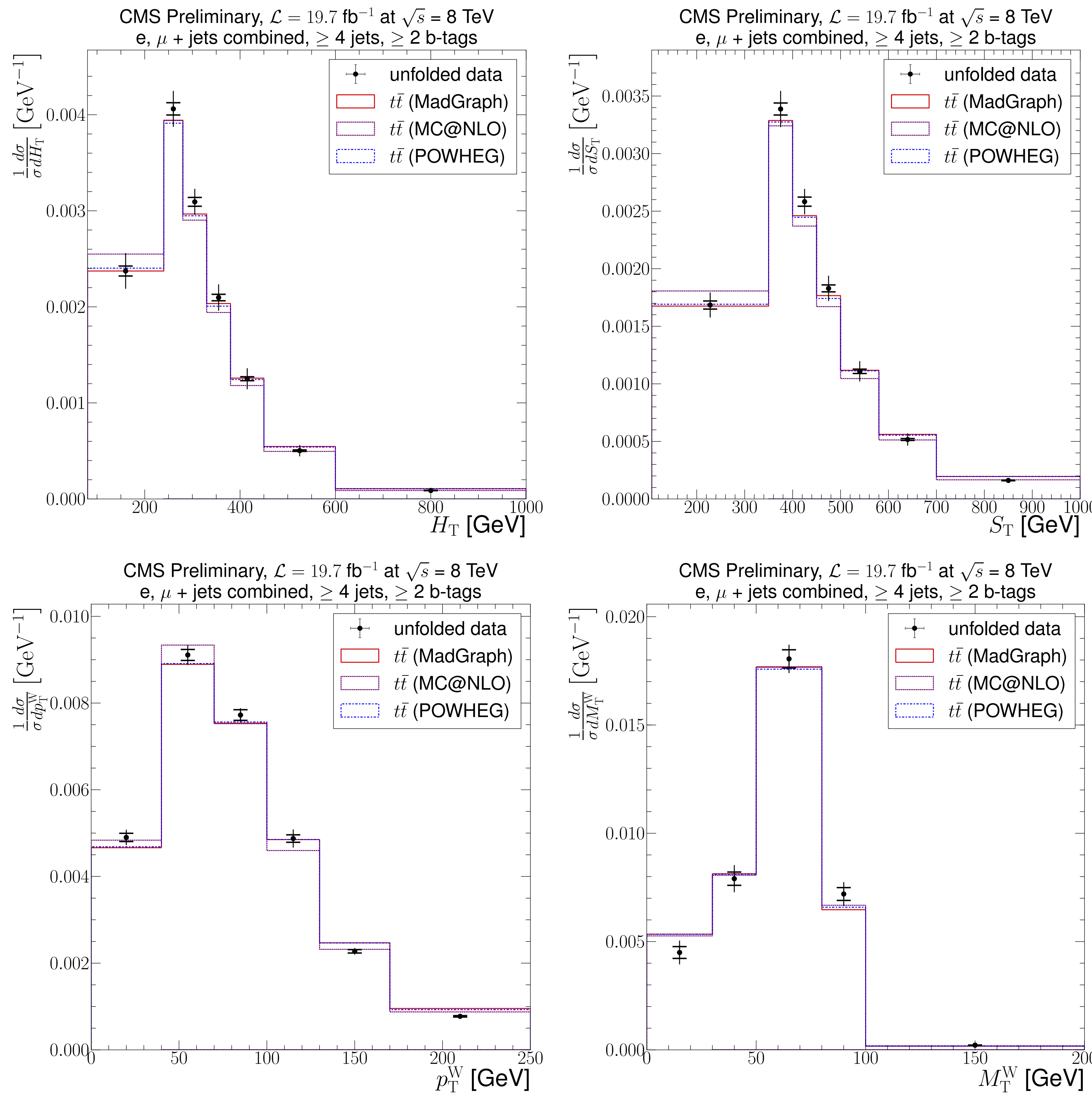
# Event-Level Observables in $t\bar{t}$

- Observables:
  - Missing transverse energy $E_T^{miss}$ (previous slide)
  - Scalar sum of transverse momenta: all jets ($H_T$), all objects ($S_T$)
  - $W \rightarrow l\nu$ decay: transverse momentum ($p_T^W$), transverse mass ($m_T^W$)
- Results: **good agreement** with MC generators




[CMS-PAS-TOP-12-042]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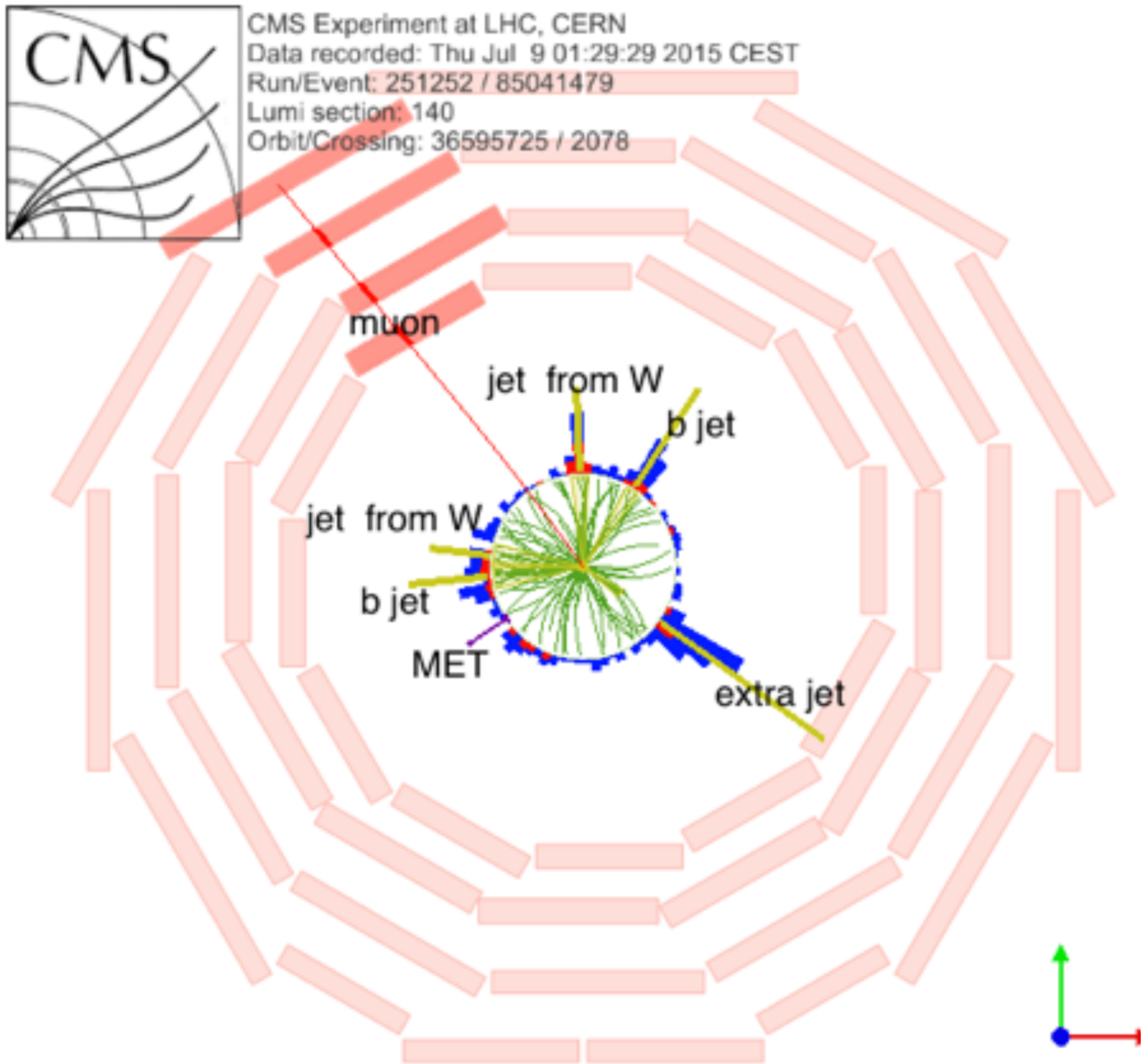
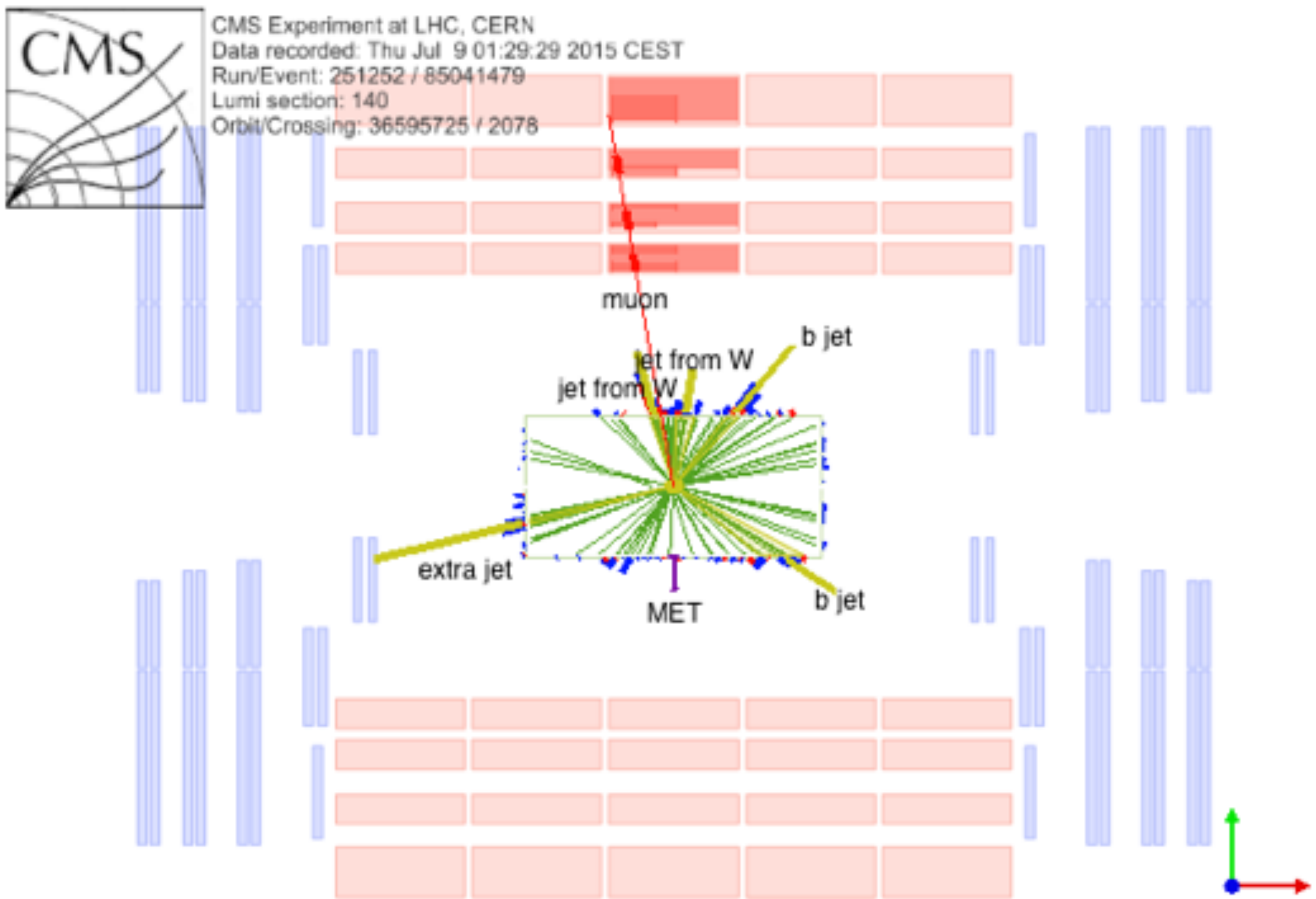
# Summary and Conclusions

- Towards **precision top physics**: differential cross sections
- This presentation: CMS results with LHC Run 1 data on
  - Differential cross sections as a function of **lepton** and **b-quark** kinematics
  - Kinematics of **top quark** and $t\bar{t}$ **system**
  - Modeling of QCD radiation: **jet multiplicity** in $t\bar{t}$ events
  - **Event-level observables** in $t\bar{t}$ events
  - Generally **good agreement** with standard MC generators, working on remaining discrepancies with ATLAS and theory/MC community

# Outlook: First Tops at 13 TeV

### Event Display: μ+Jets Event with Two b-Tags

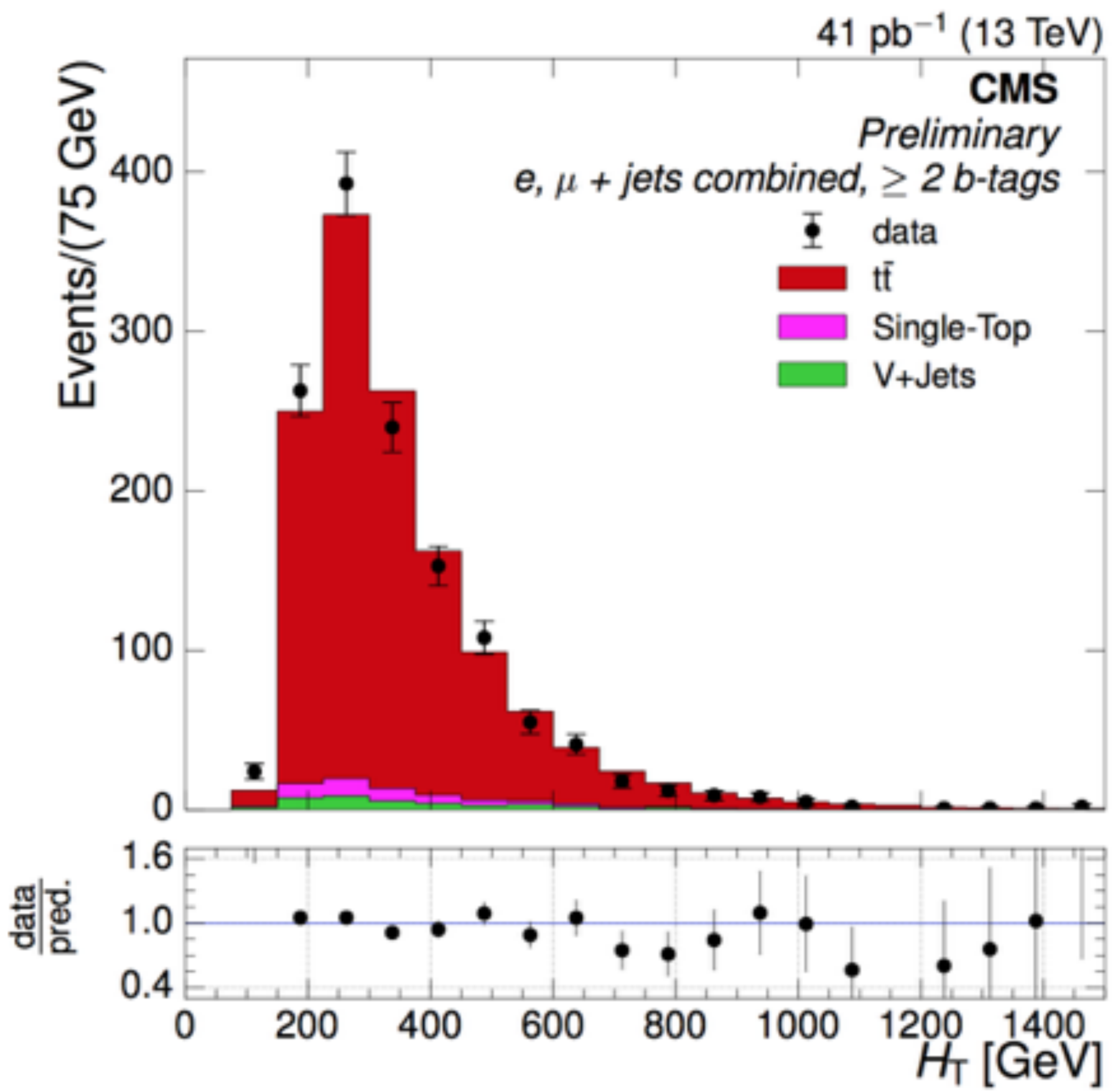


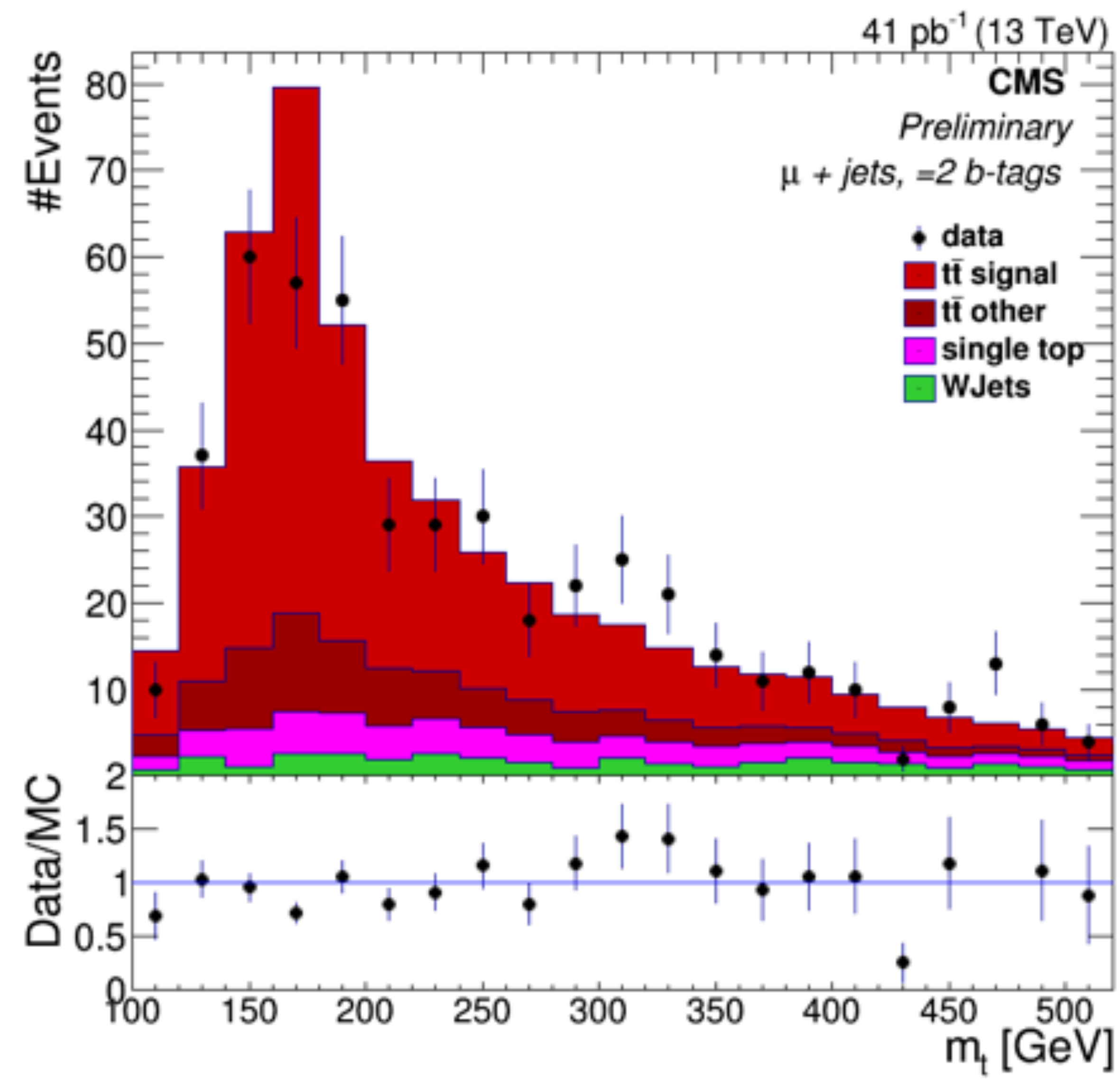




[CMS DP-2015/019]

# Outlook: First Tops at 13 TeV

## Kinematic Distributions: $H_T$ and Hadronic Top Mass




[CMS DP-2015/019]



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# Bibliography

- Please refer to the **original publications** for more details


- Differential cross sections:
  - arXiv:150504480, submitted to EPJC (8 TeV), additional material (8 TeV)
  - EPJ C73 (2013) 2339 (7 TeV)

- Jet multiplicity:
  - CMS-PAS-TOP-12-041 (8 TeV)
  - EPJ C74 (2014) 3014 (7 TeV)

- Event-level observables:
  - CMS-PAS-TOP-12-042 (8 TeV)
  - CMS-PAS-TOP-12-019 (7 TeV)



- This work was supported by the German Bundesministerium für Bildung und Forschung (BMBF) under contract 05H15VKCCA