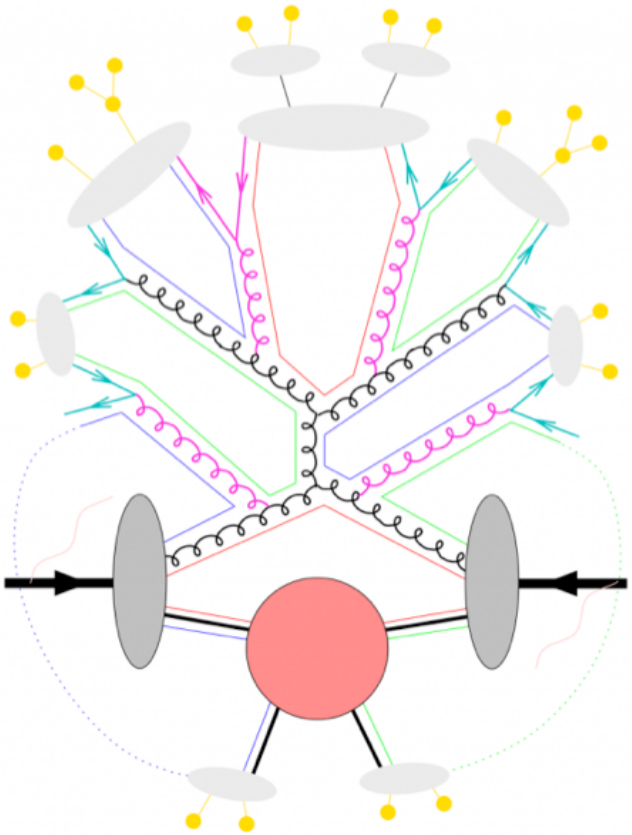
Inclusive jet and multijet measurements at CMS

Conference apero at ETH Dozentenfoyer

Mikko Voutilainen
University of Helsinki and Helsinki Institute of Physics
for the CMS collaboration

Motivation

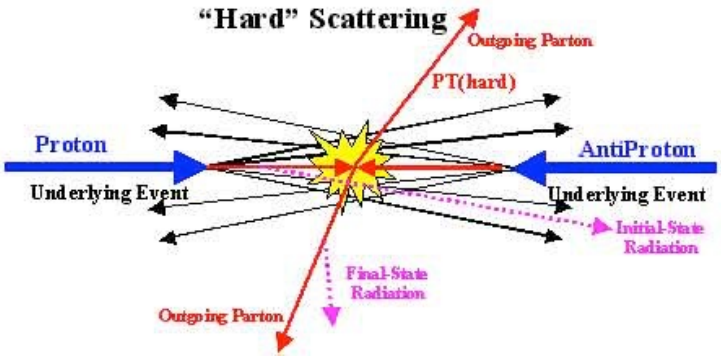
- First goal is to improve our detailed description of Standard Model physics
  - **hard QCD - high p_T:** proton parton distribution functions (PDFs), strong coupling, perturbation theory, initial and final state radiation, parton shower, (subjets)
  - soft QCD - low p_T: multiparton scattering, fragmentation, underlying event, etc.
- Second goal: searching new physics in high p_T events
- Bonus: gain understanding of reducible and irreducible backgrounds to searches

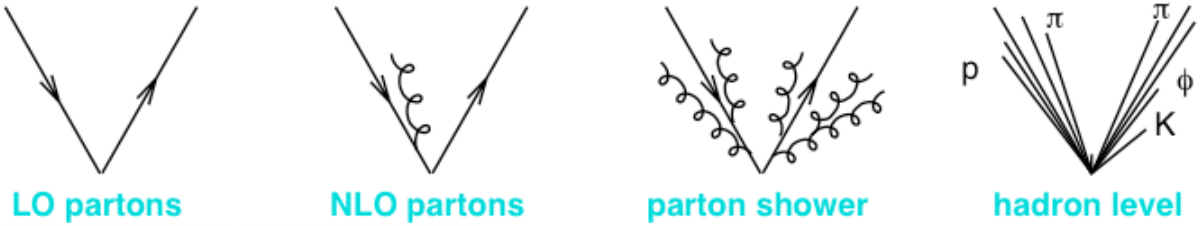


- hard scattering
- (QED) initial/final state radiation
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster → hadrons
- hadronic decays

and in addition

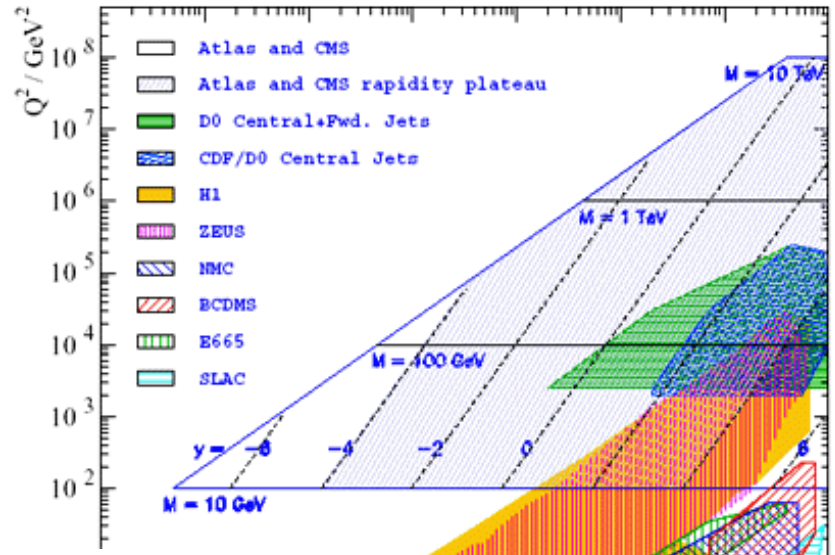
+ backward parton evolution
+ soft (possibly not–so–soft)

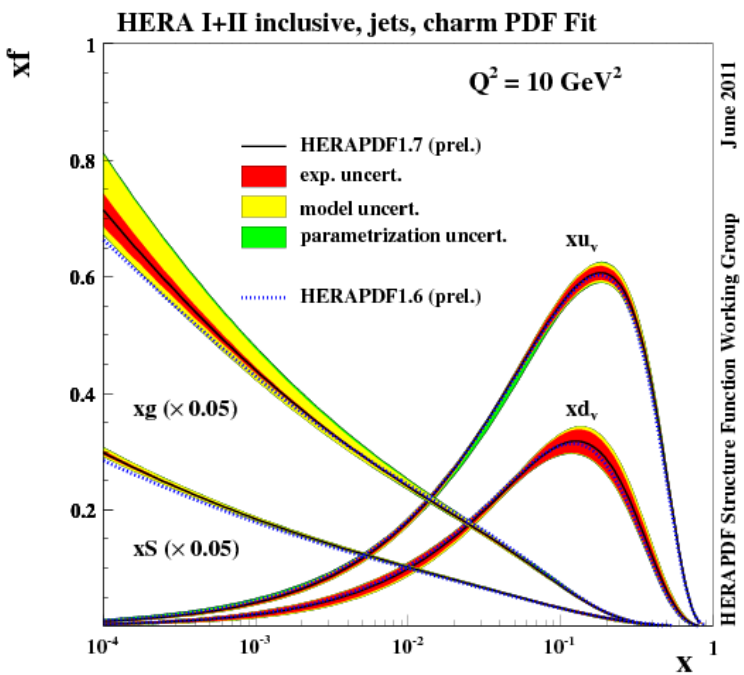


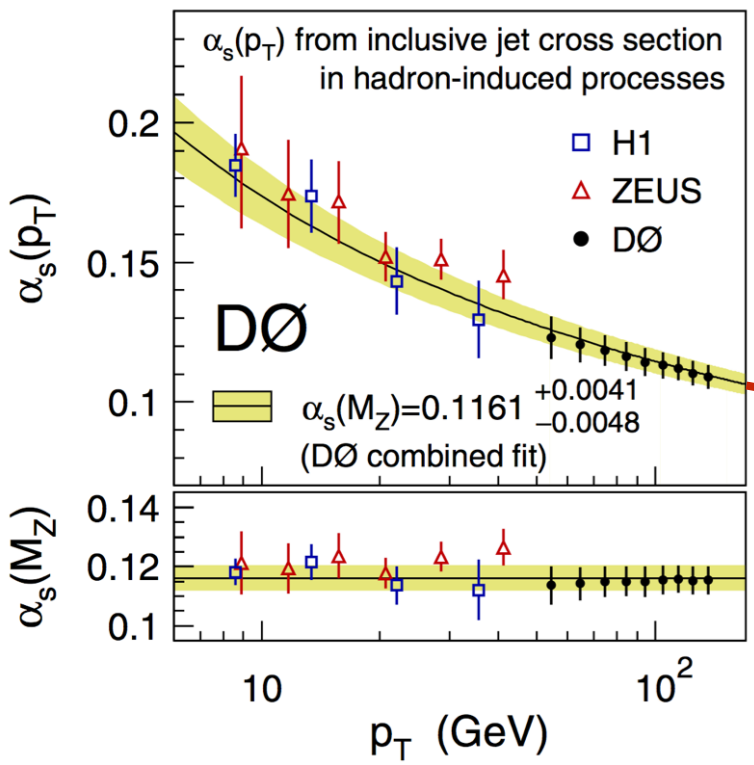


Parton distributions, α_s

- Hadron colliders are complementary to e-p colliders and fixed target experiments
- proton-proton collisions probe high Q^2 and wide range of Bjorken x
- E.g. inclusive jets useful for high-x gluon PDF and determination of α_s running





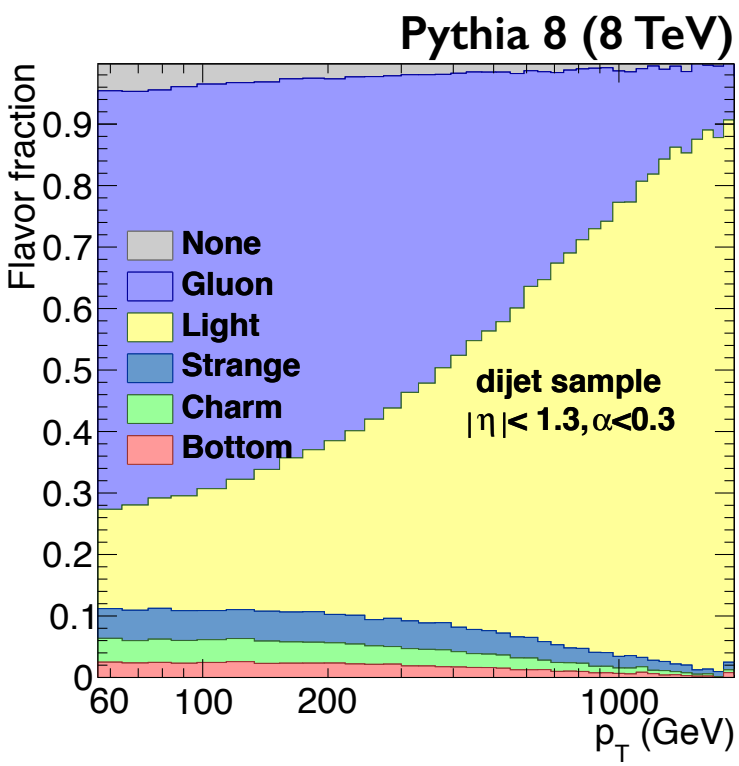


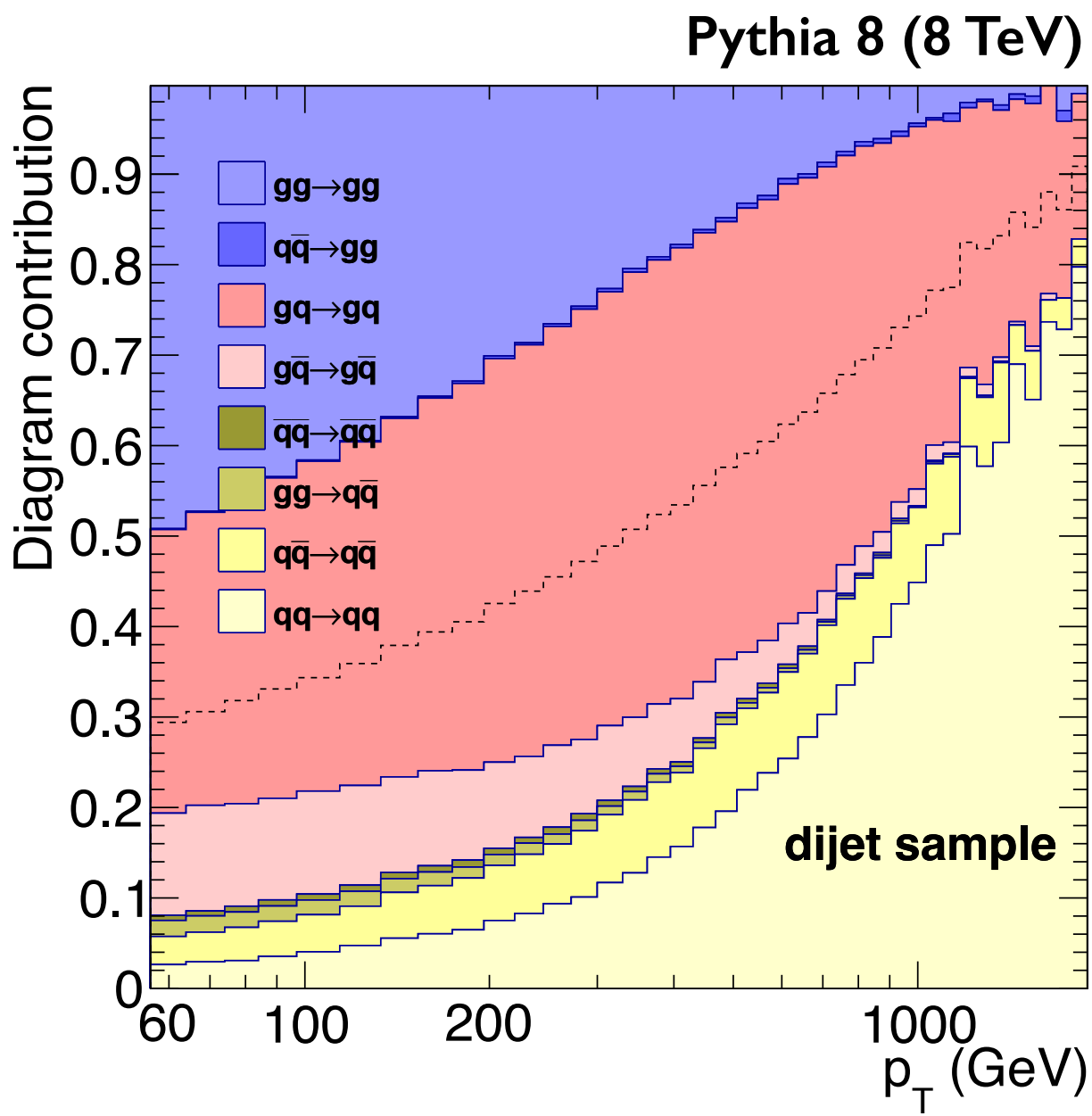
LHC

HERAPDF [link]

About high-x gluons

- At very high-x, dijet production dominated by qq scattering
- Sensitivity to gluon PDF through gq->gq scattering
- "Tagging" gluons in final state may provide a more direct access to gluon PDF

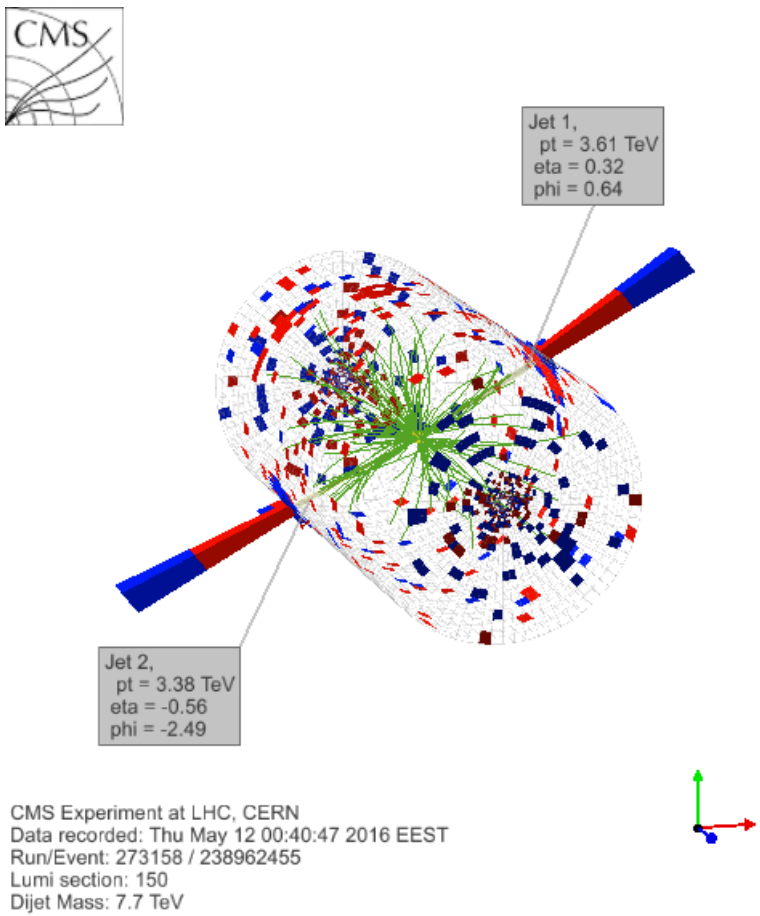


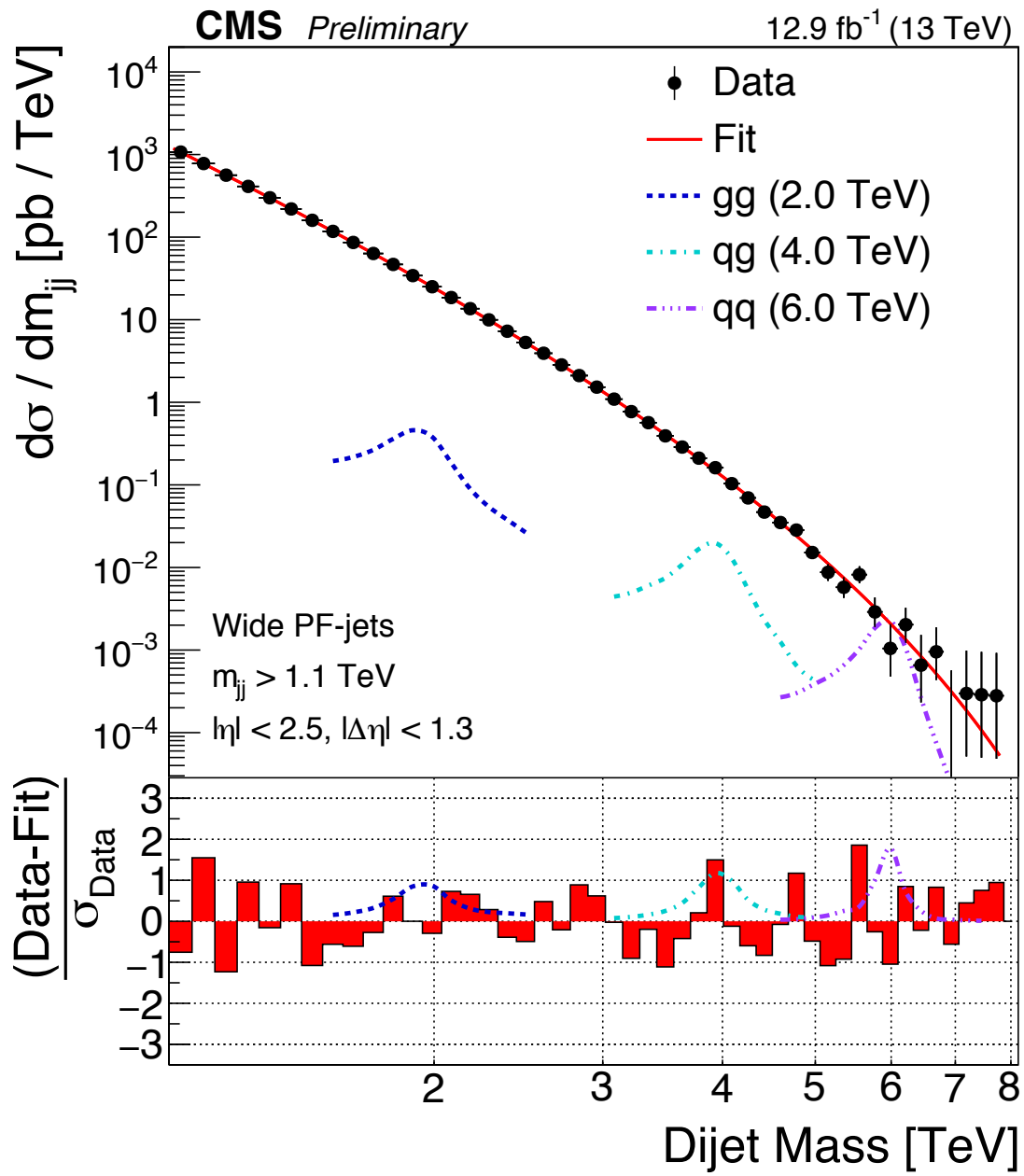


A. Abhishek, MSc Thesis, IIT Roorkee, 2015

New physics searches

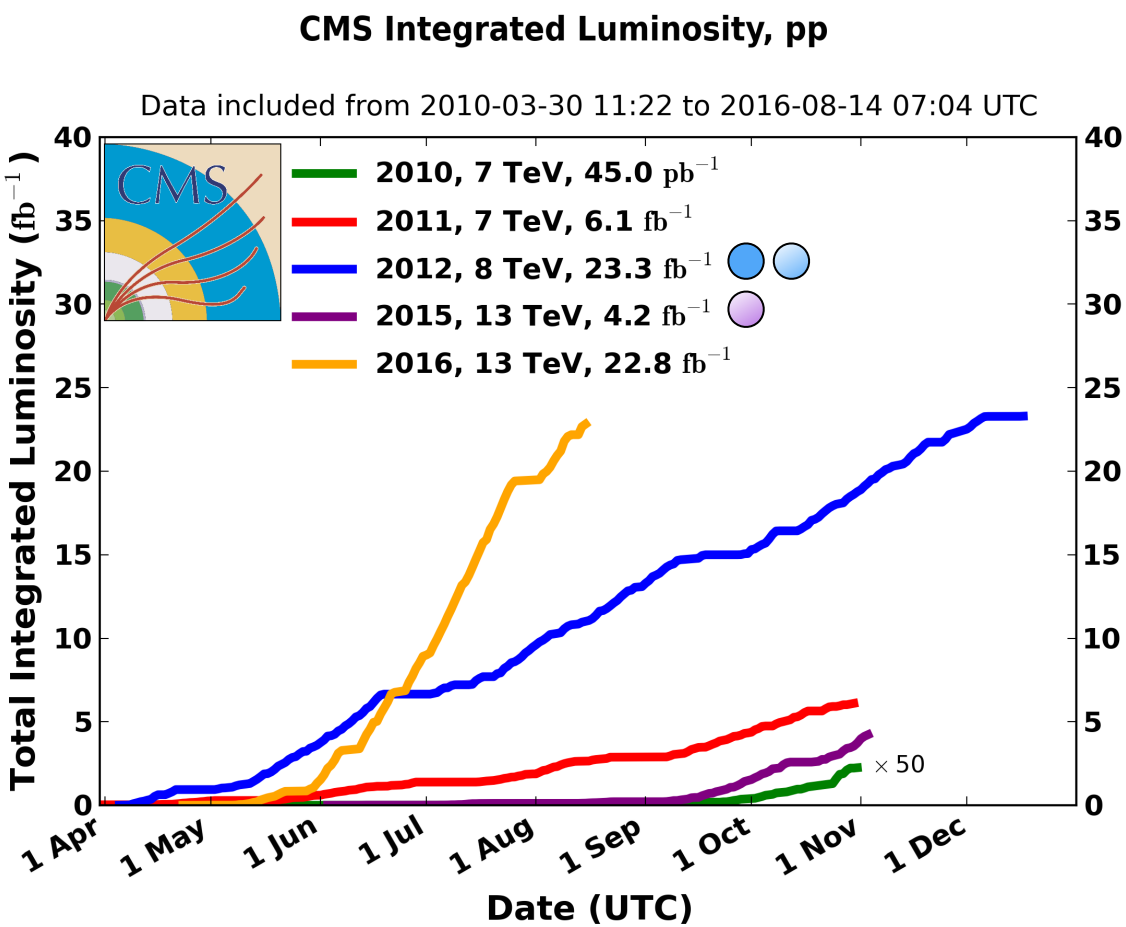
- Searches of new physics in dijet spectra currently find nothing
- QCD-inspired power law fit exceptionally good in TeV range
- Continue to increase precision





EXO-16-032

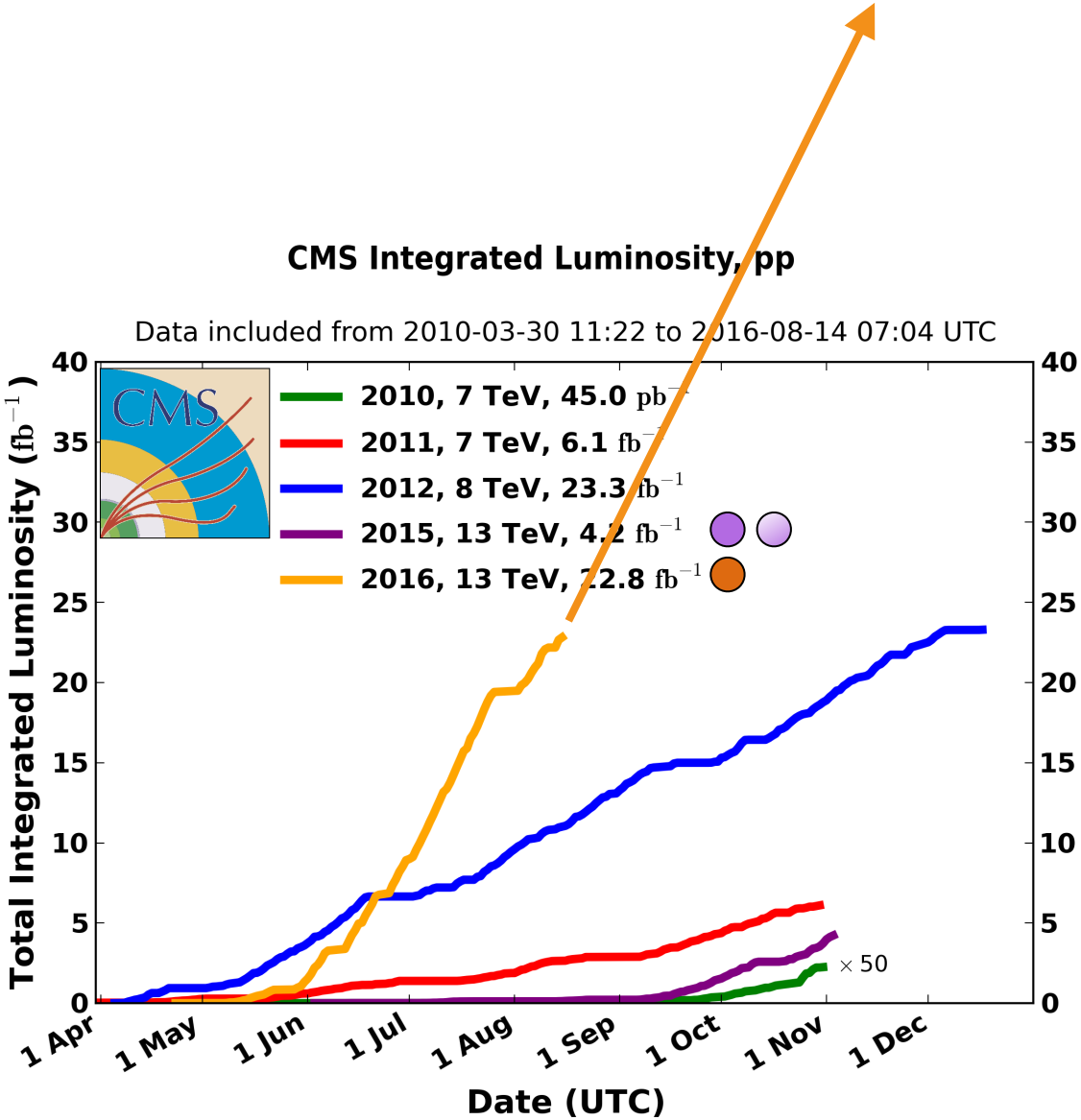
Data sets now



Data sets reported here

- 2.76 TeV - Feb 2013 (5.4 pb^{-1})
  - reconstruction and detector conditions very similar to 8 TeV
  - μ~0
- 8 TeV - 2012 (20 fb^{-1})
  - state-of-the art JEC reported in arrive (JME-13-004)
  - μ~20
- 13 TeV - 2015 (50 pb^{-1} @ 50ns)
  - JEC methods same as 8 TeV, but larger uncertainty
  - μ~20

In the future...

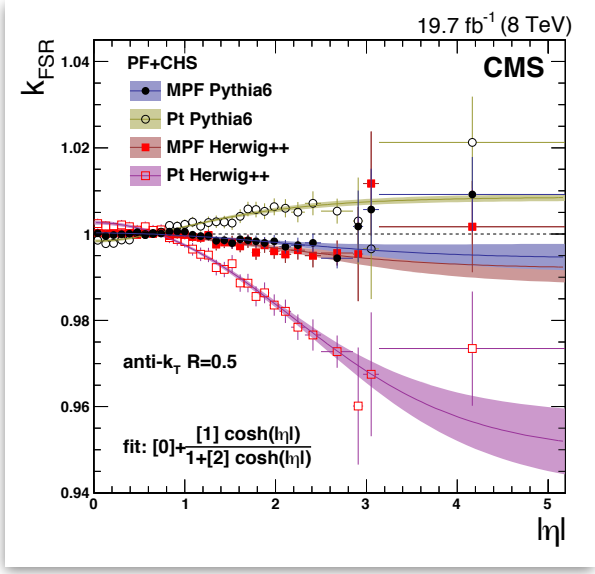


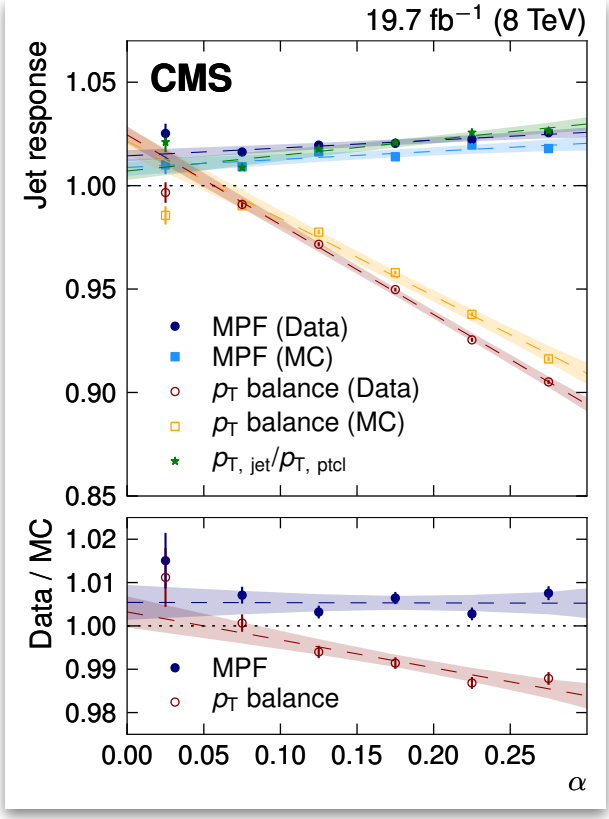
Data sets still to analyse

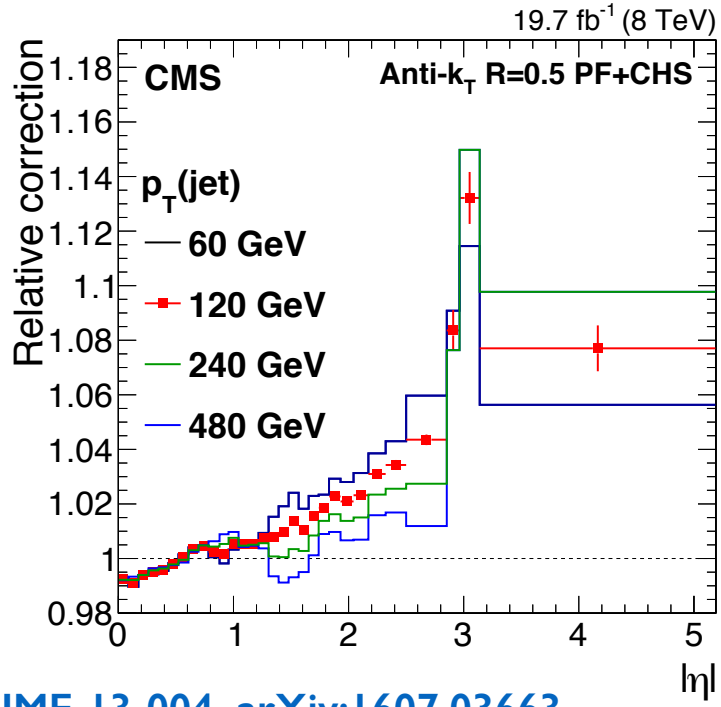
- 5 TeV - Nov 2015 (26 pb^{-1})
  - reference data for PbPb and pPb
  - μ~0
- 13 TeV - 2015 (2.2 fb^{-1} @25 ns)
  - Smallish data set with B field issues at CMS
  - μ~20
- 13 TeV - 2016 (>20 fb^{-1} @25ns)
  - Large, high-quality data set
  - Still growing rapidly
  - μ>20

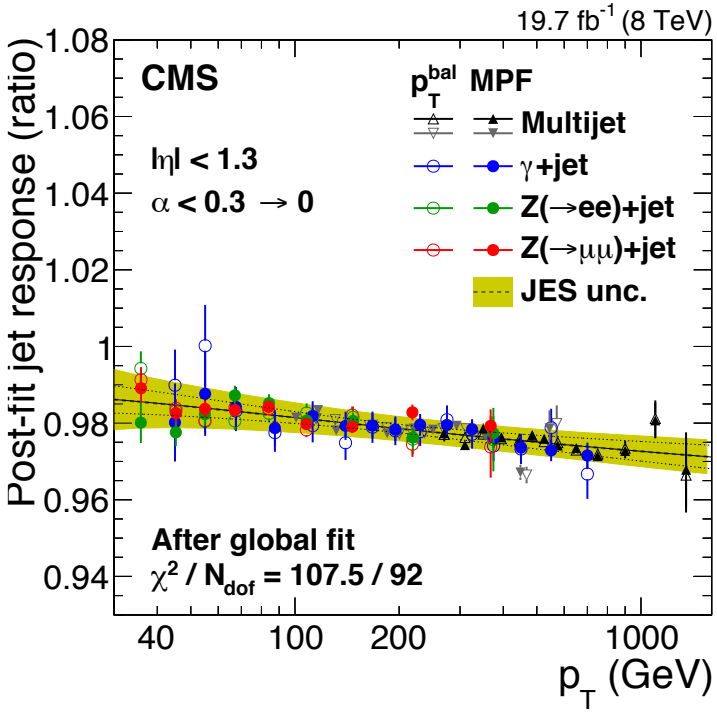
Jet energy scale at 8 TeV

- There is no jet physics without jet energy scale corrections
- Driven to **extreme** precision at CMS with years of work
  - use MET projection + correct to zero extra jet activity
  - statistically combine channels and methods, with physical response parameterisations







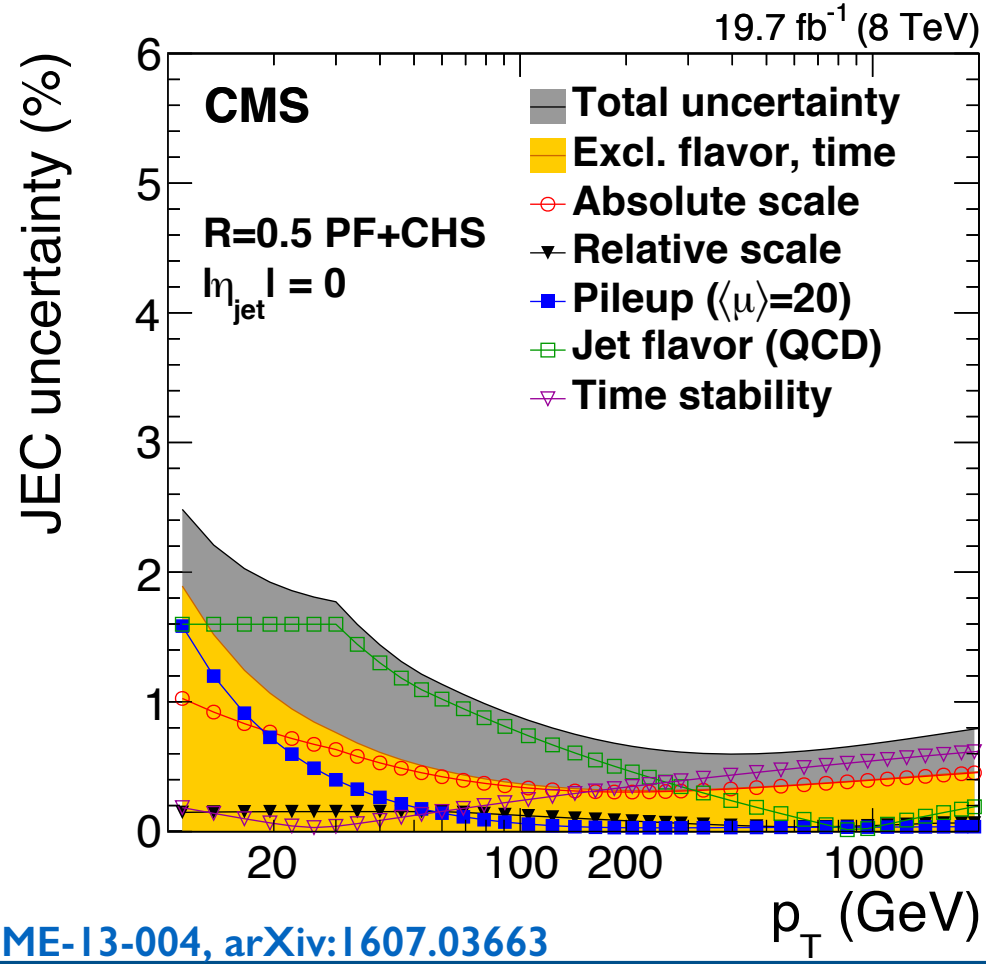


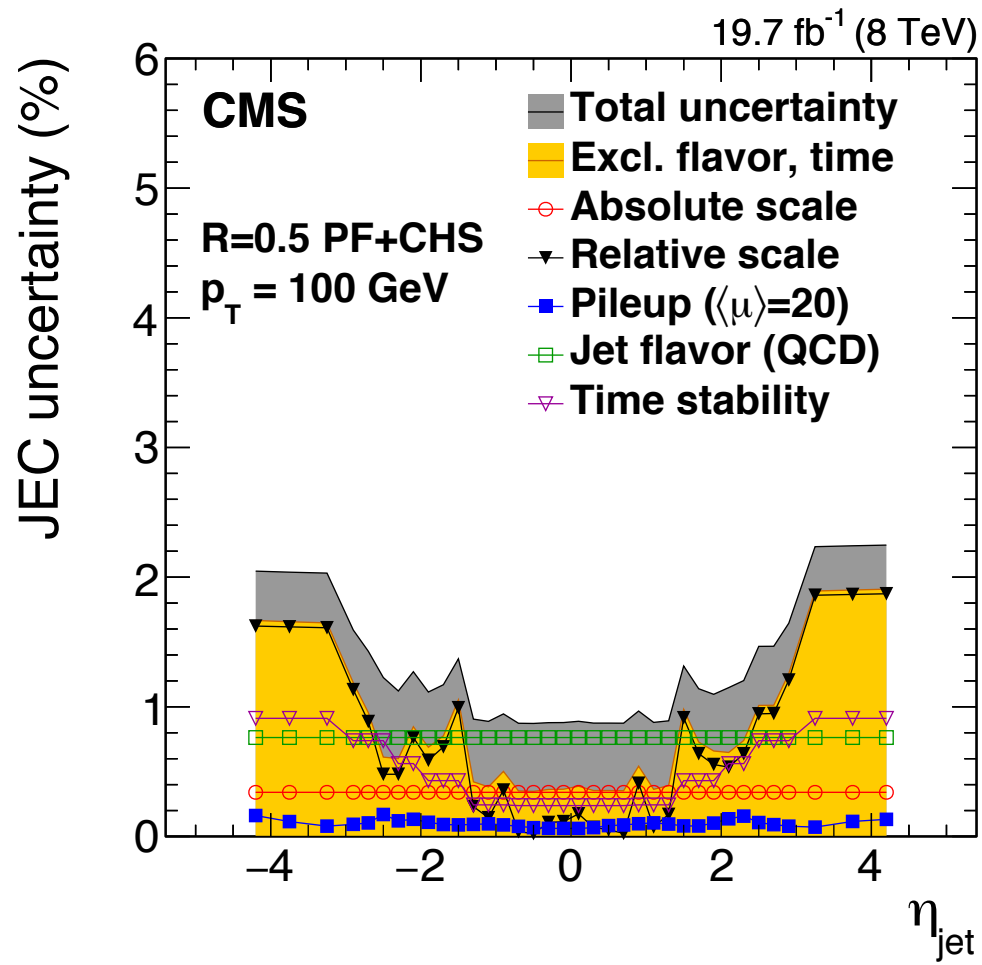
JME-13-004, arXiv:1607.03663

- CMS Legacy Jet Energy scale submitted to JINST
- High-lights:
  - 8 TeV inclusive jets (here)
  - Run I top quark mass, with precision 0.49 GeV

Jet energy scale at 8 TeV

- Lowest uncertainty at y~0, p_T~200 GeV is **0.32%** (excluding flavor and time dependence)
- Well below 1% across much of the kinematic range
- For jet physics, the relevant uncertainty is golden band + green curve, "Jet flavor (QCD)"
  - this is entirely driven by MC-based uncertainty on gluon jet response



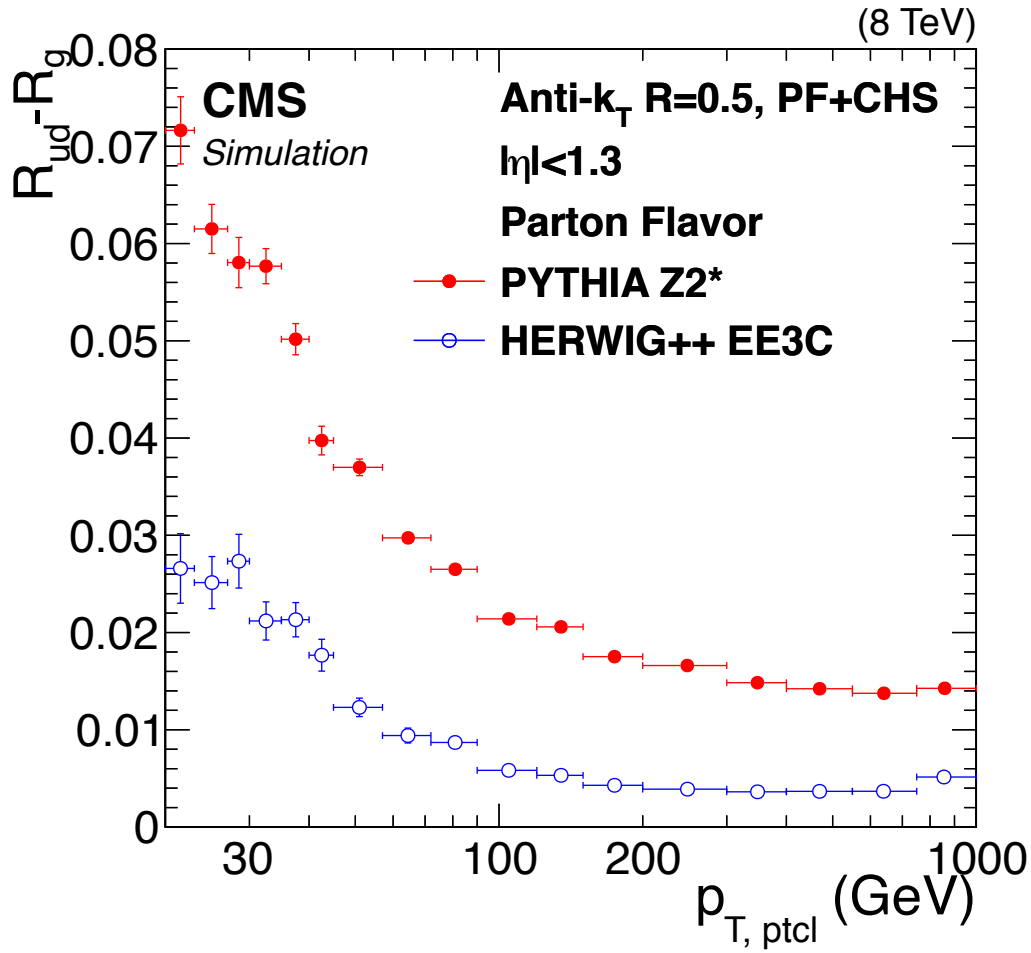


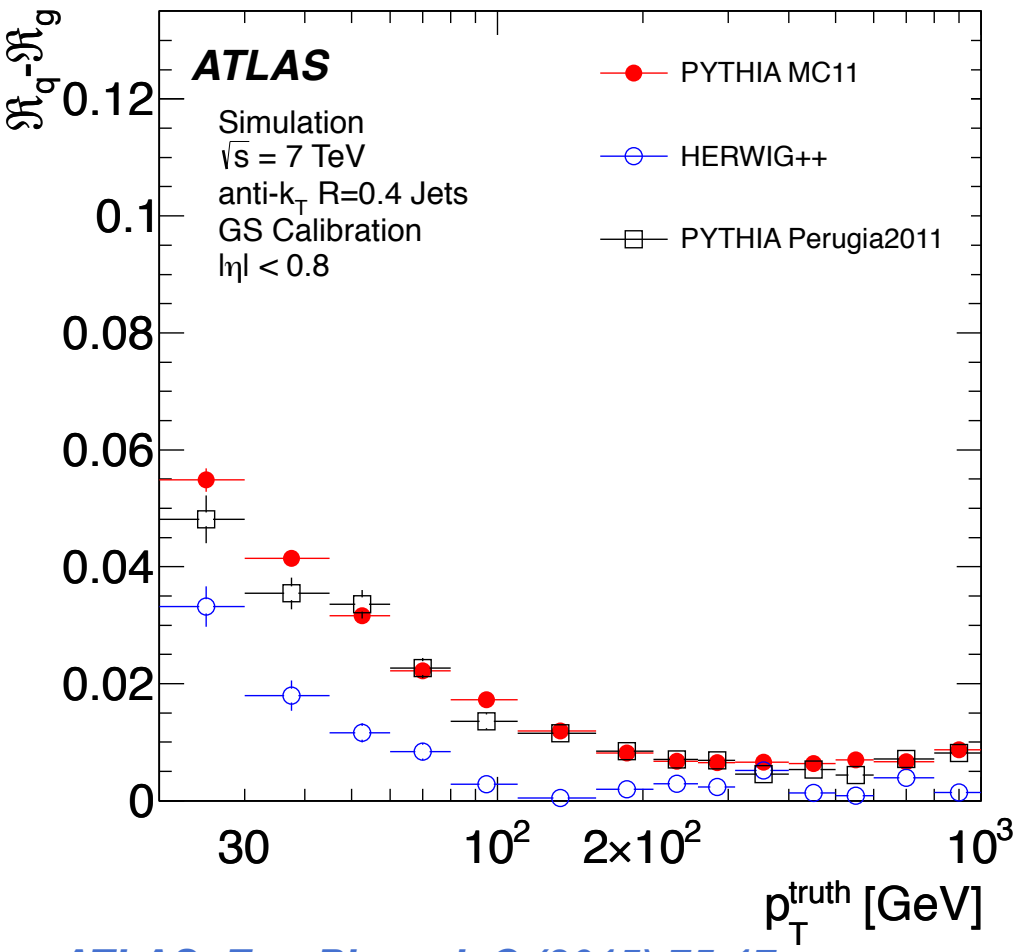
JME-13-004, arXiv:1607.03663

Gluon jets

- "Jet flavor (QCD)" uncertainty mostly from gluon jets
- Not a feature unique to CMS: parton shower (or fragmentation) in Pythia6 and Herwig++, affects ATLAS response in a very similar fashion (GS vs PF, EM+JES vs Calo)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/PERF-2012-01/



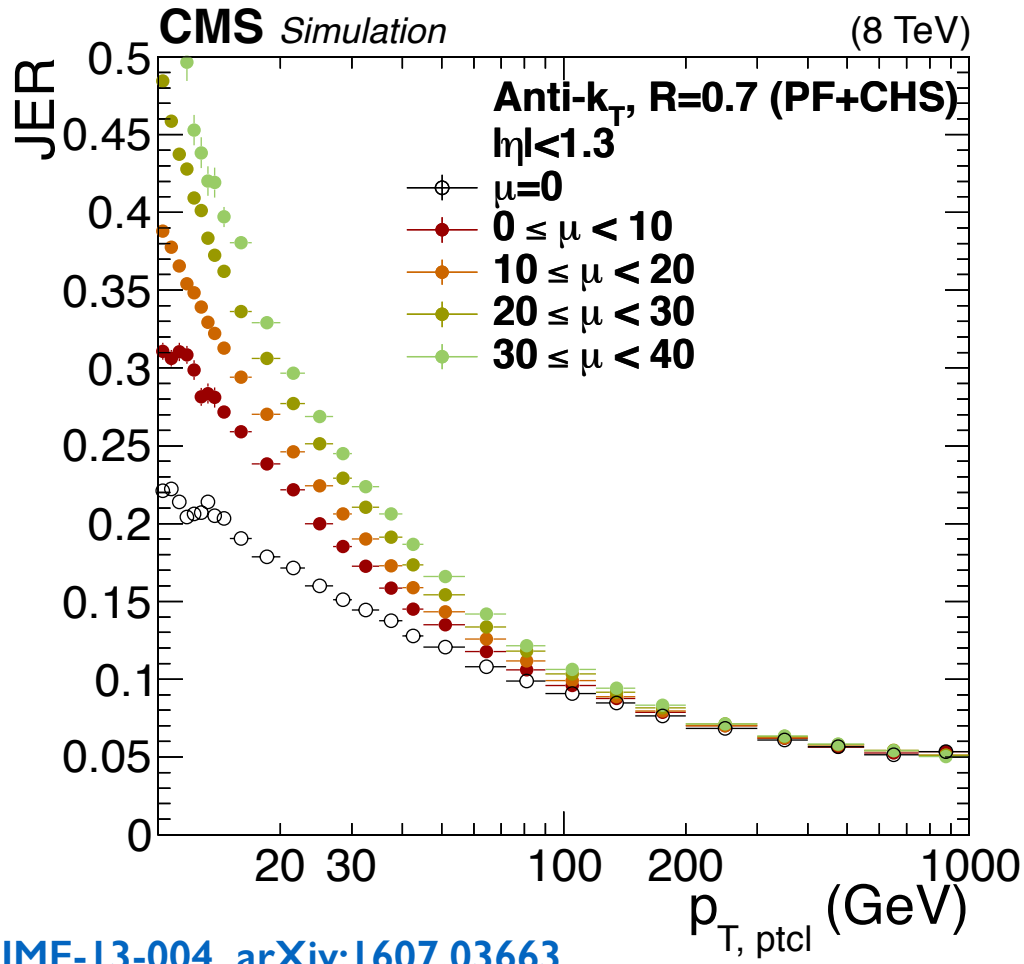


JME-13-004, arXiv:1607.03663

ATLAS, Eur. Phys. J. C (2015) 75:17

Jet p_T resolution

- Jet p_T/energy resolution (JER) also important for jet measurements (unfolding)
- Well understood, leading effect from pileup offset adding to noise term ($N^2 \sim \mu R^2$)
- Data/MC differences at 10% level, stable since early Run I



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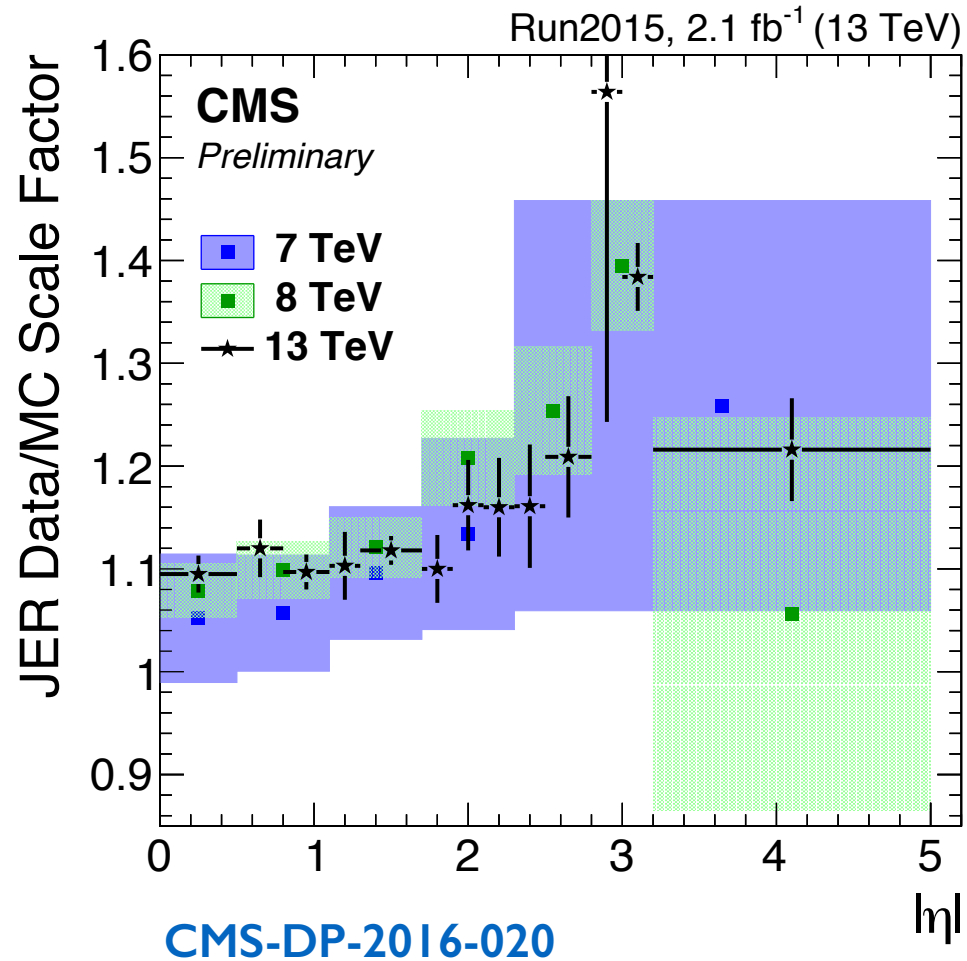
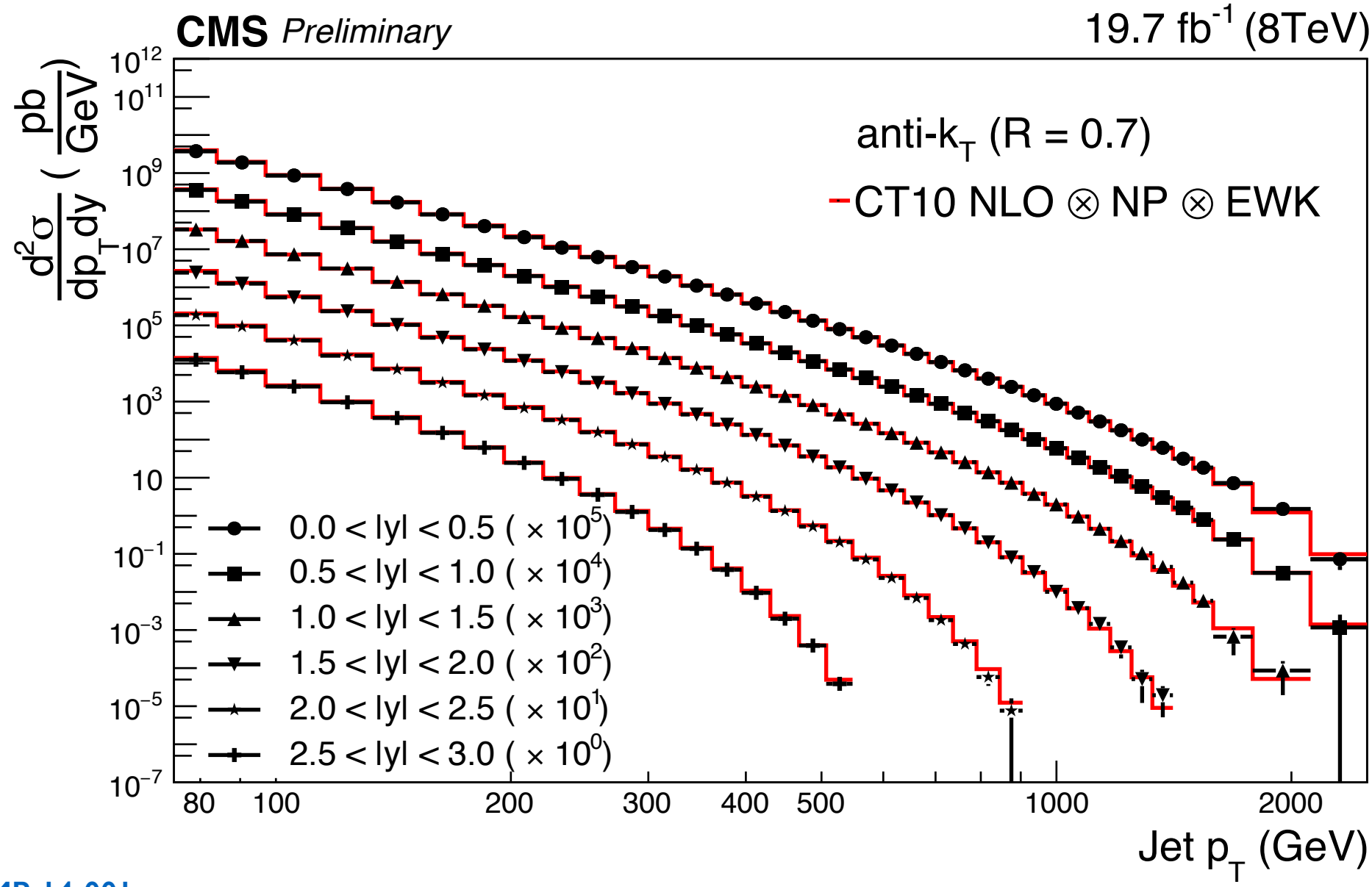


CMS-DP-2016-020

Inclusive jets at 8 TeV

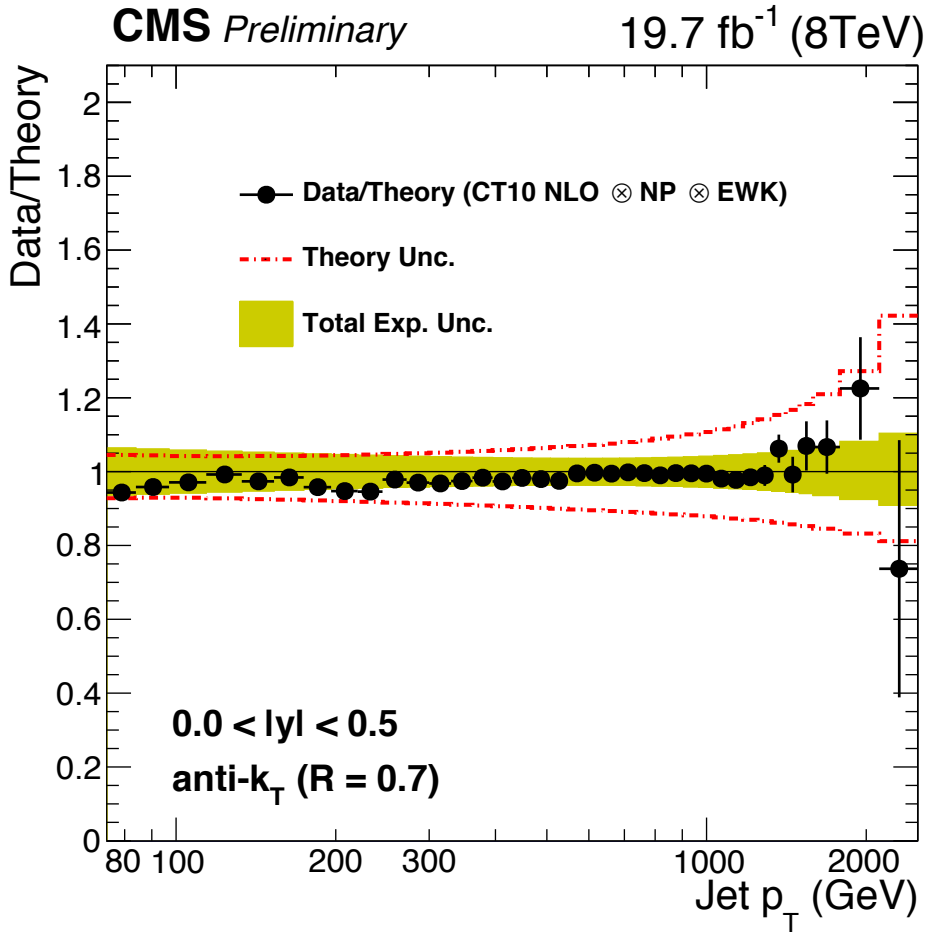
- Inclusive jets are the jet group flagship analysis, used for PDFs and α_S

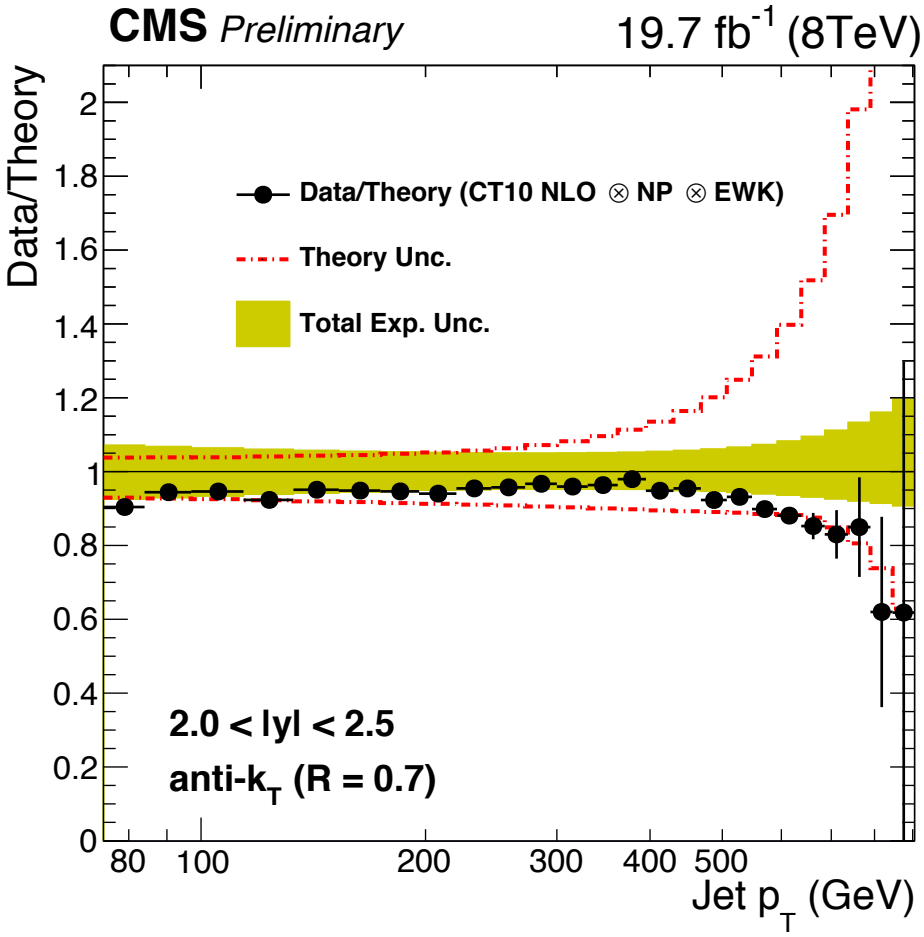


SMP-14-001

Inclusive jets at 8 TeV

- Experimental uncertainty mainly from JES and luminosity, down to 4% at lowest
- Lower than theory (CT10 PDF + scale) uncertainty across most of the phase space
- Particularly large impact in the more forward regions (e.g. 2<|y|<2.5)

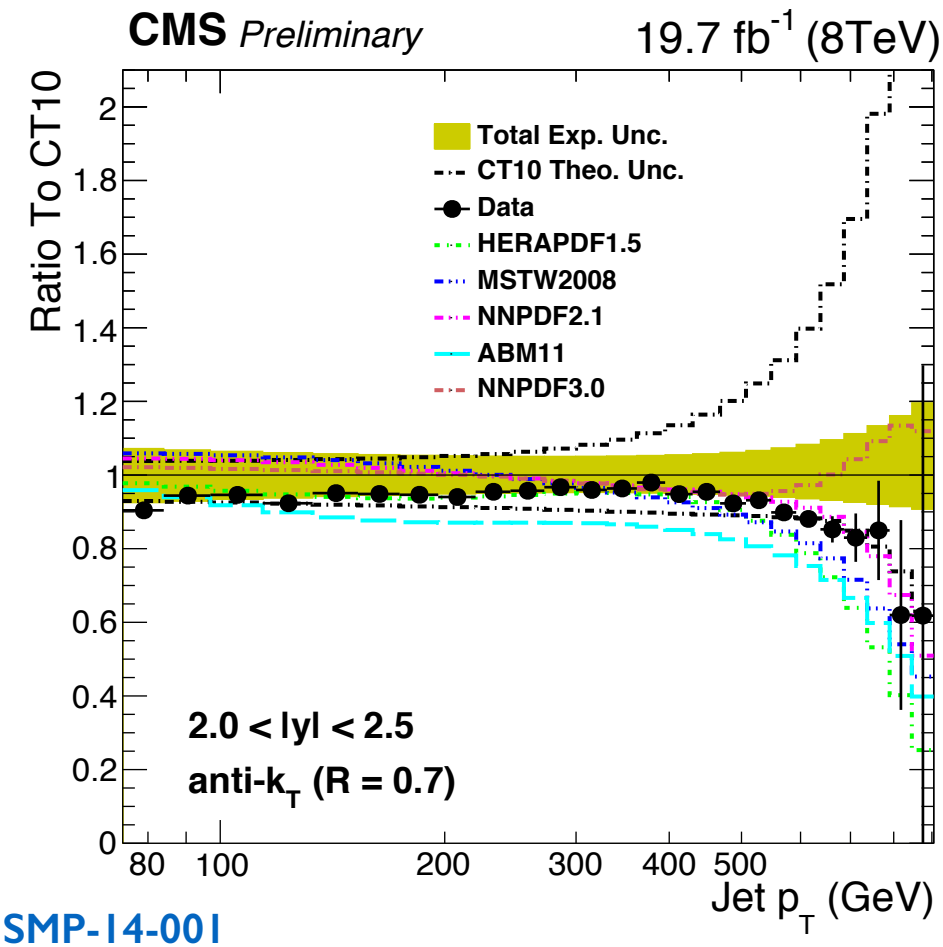


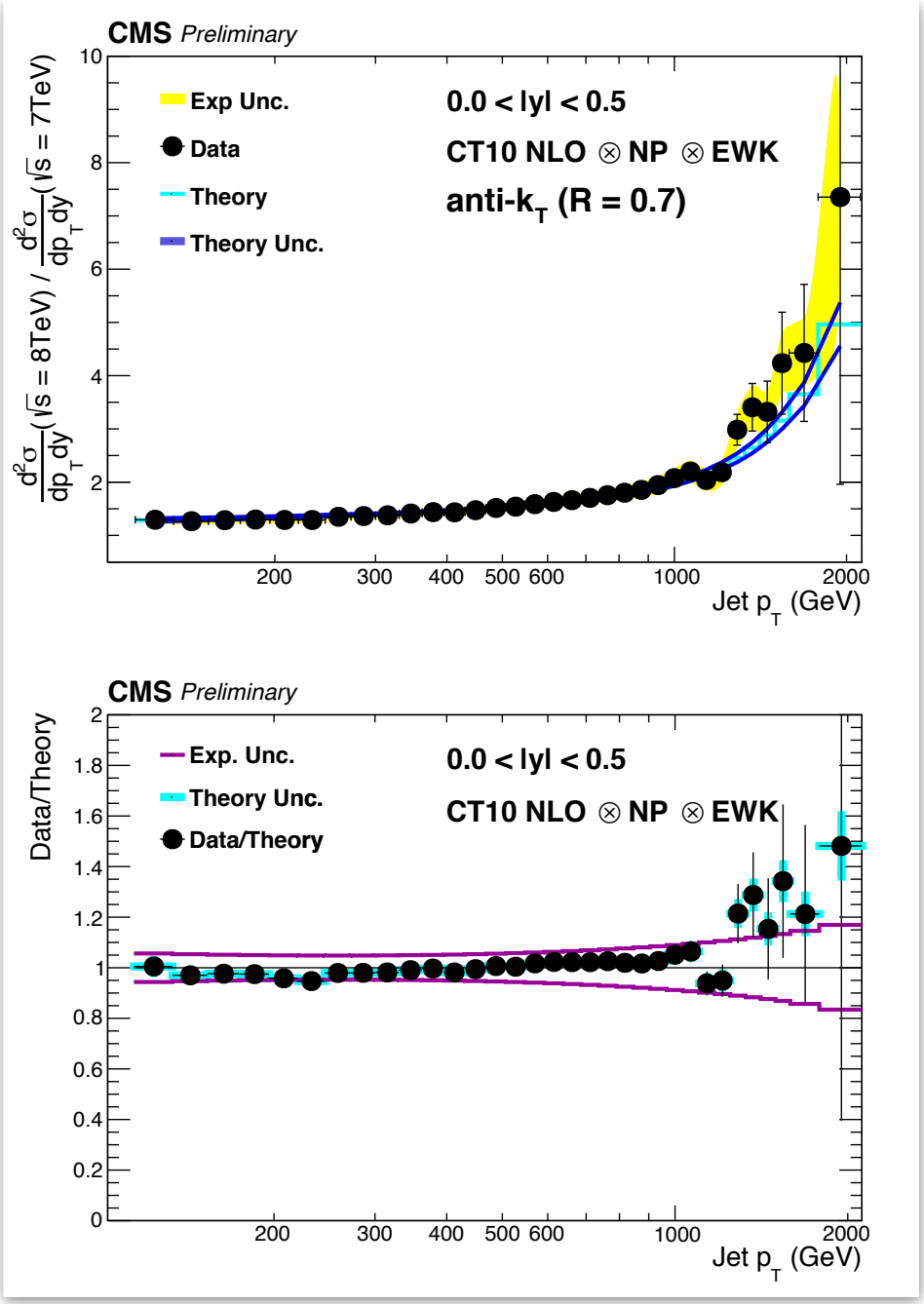


SMP-14-001

Inclusive jets at 8 TeV

- CT10 PDF uncertainty may be conservative, but still impact at the level of PDF set differences
- Good agreement with less precise 7 TeV data set within experimental uncertainty (uncertainty correlations considered)

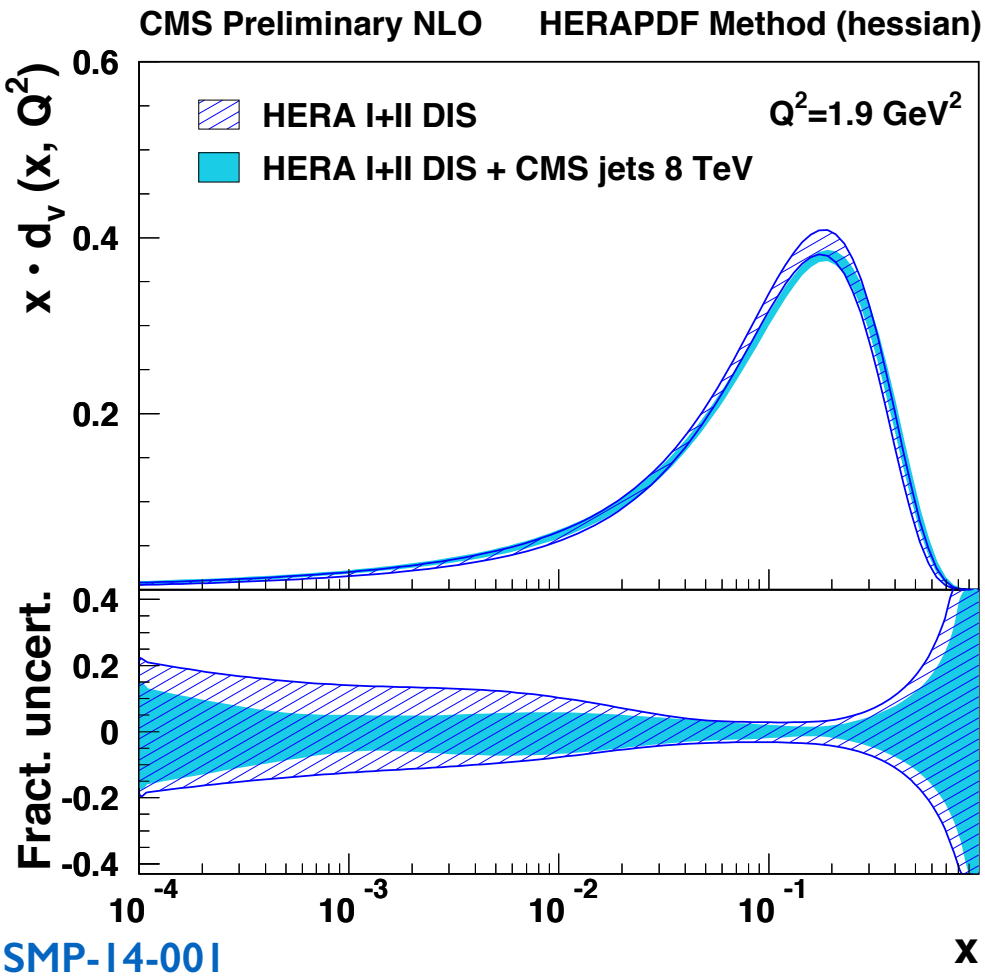


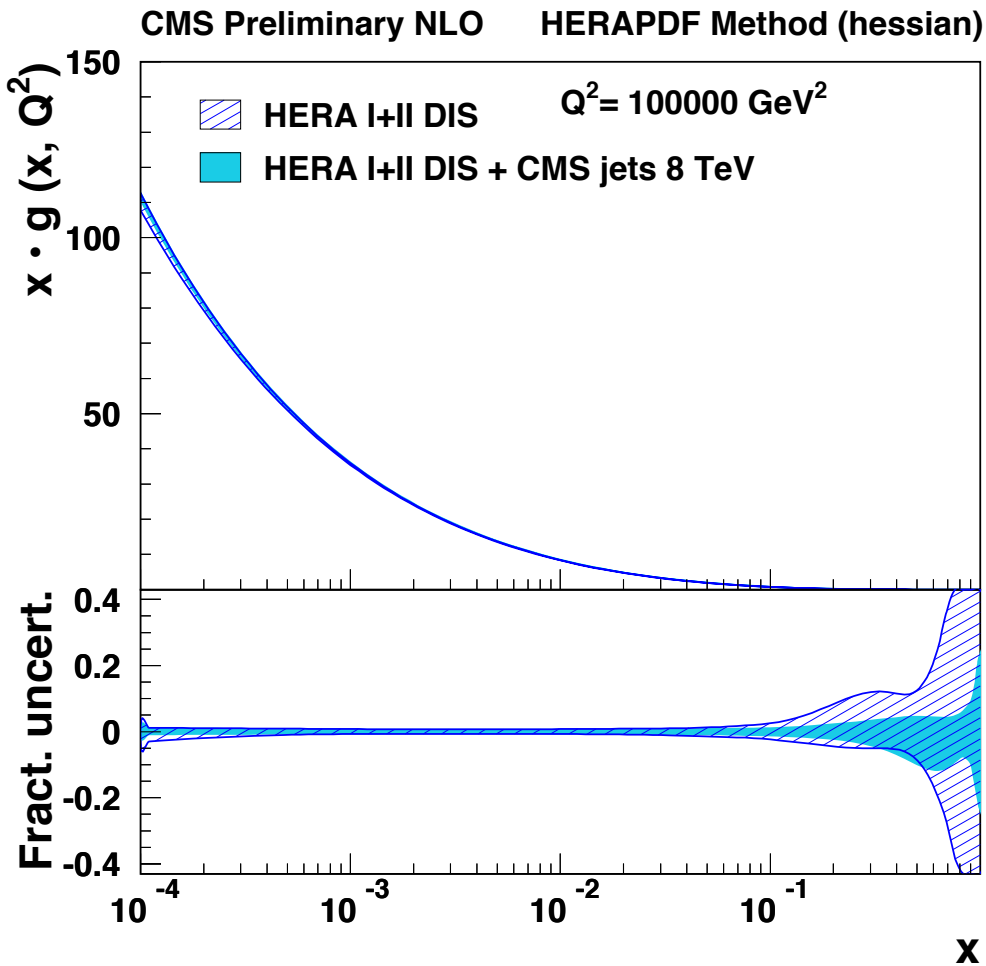


SMP-14-001

Inclusive jets at 8 TeV

- Expect significant impact on global PDF fits (more in Bora Isildak's talk on Thursday)
- Valence quark PDF stable, uncertainty reduced overall
- Sizeable reduction in high-x gluon uncertainty
  - relevant for new physics searches

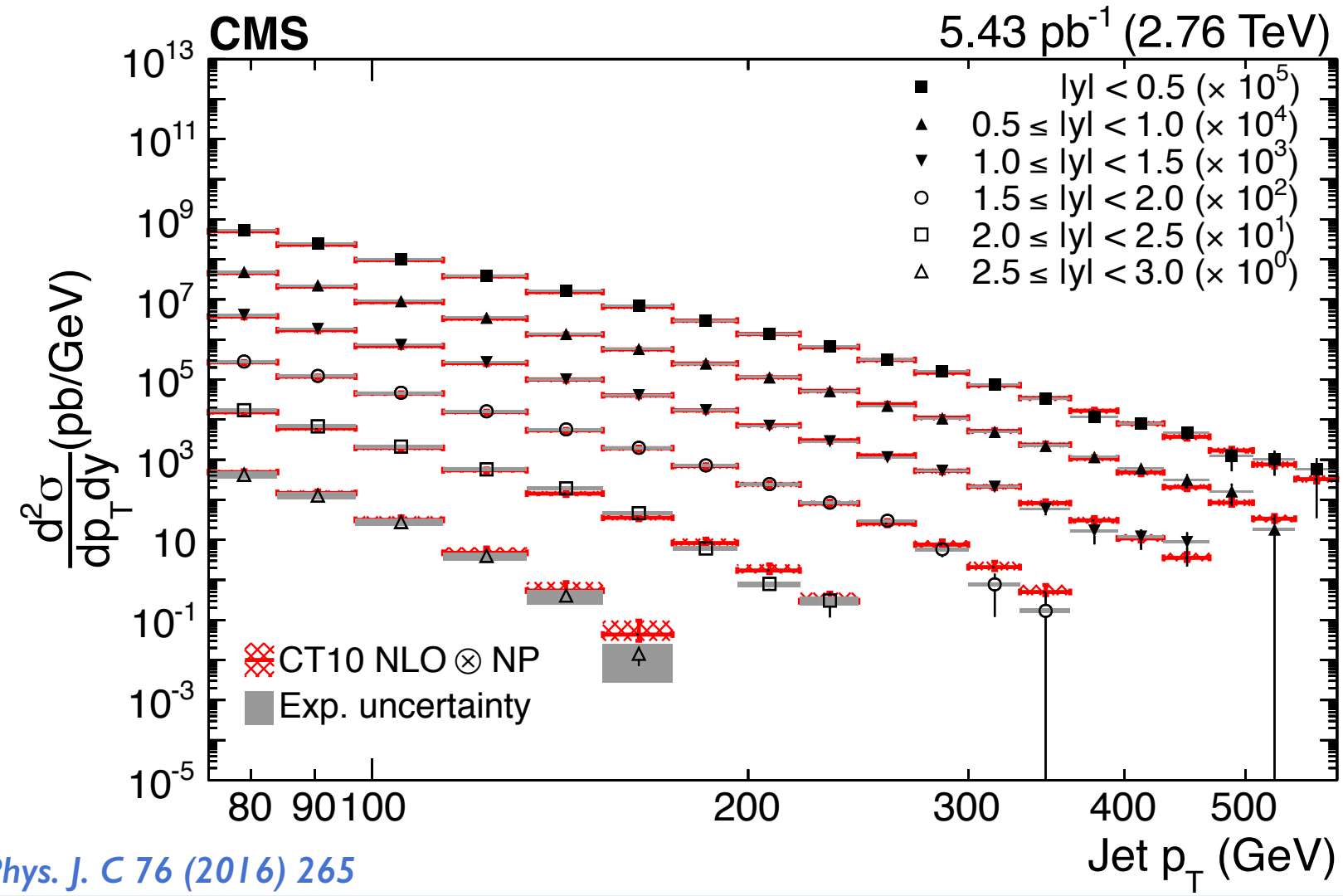




SMP-14-001

Inclusive jets at 2.76 TeV

- Data taken right after 8 TeV (Feb 2013, last Run I data) ensuring consistency with 8 TeV
- CERN Courier: "CMS bridges the gap in jet measurements" [link]
  - fills in the region between Tevatron's 1.96 TeV and LHC's 7 and 8 TeV (and 13 TeV)

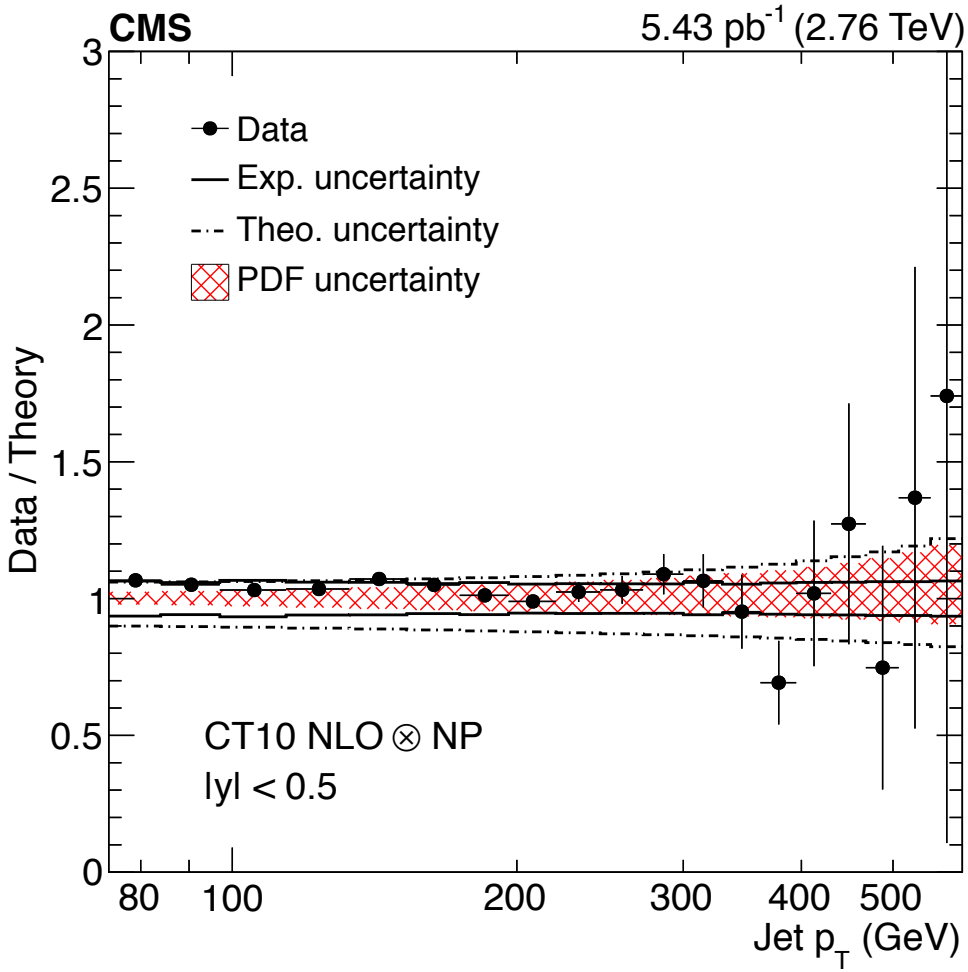


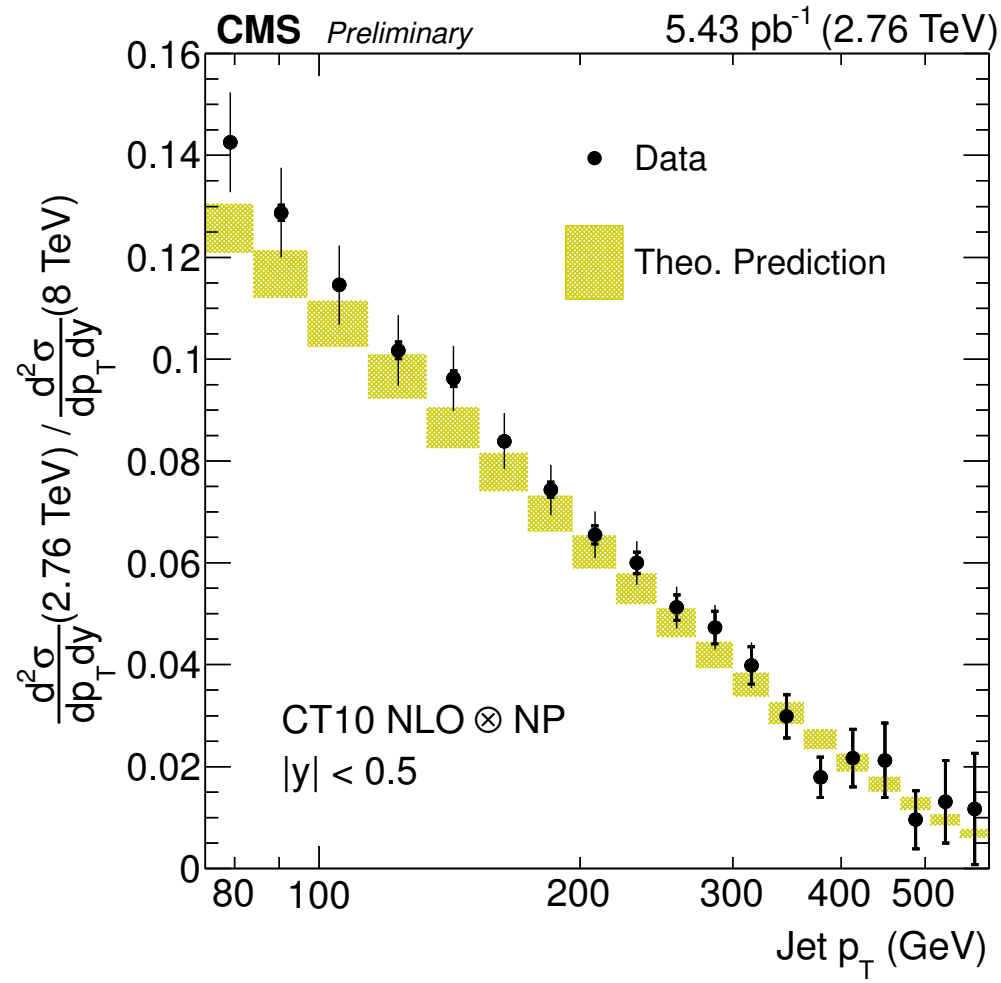
Eur. Phys. J. C 76 (2016) 265

[HEPDATA]

Inclusive jets at 2.76 TeV

- Cancellation of uncertainties between 2.76 TeV and 8 TeV promises to be interesting
  - cancellations of leading uncertainties on both experimental side (JES) and theoretical side (scale)
  - (2.76/8 TeV ratio plot to be included in 8 TeV paper)

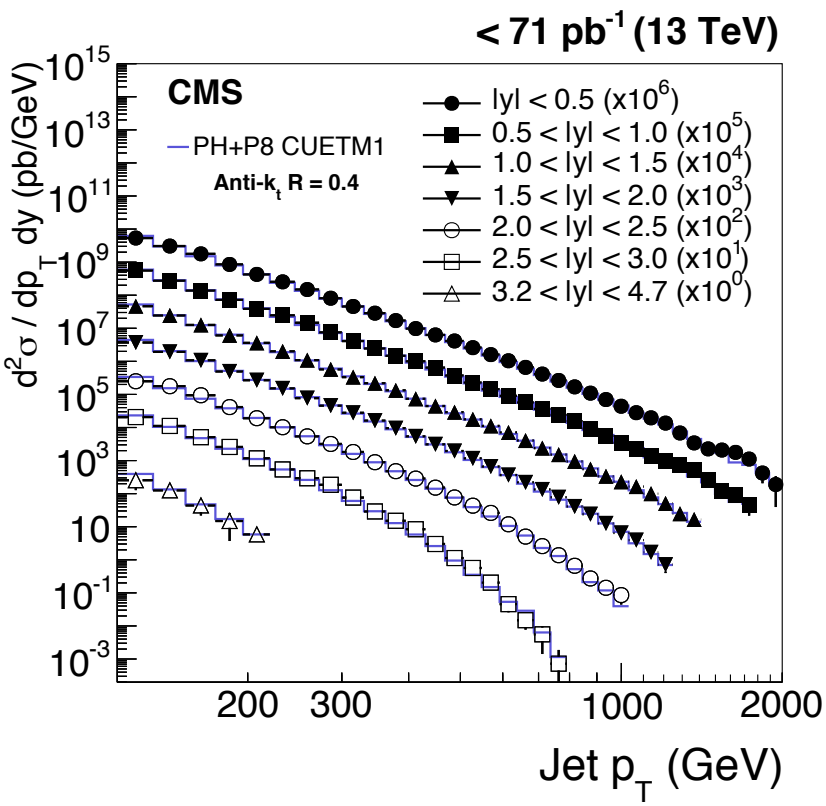


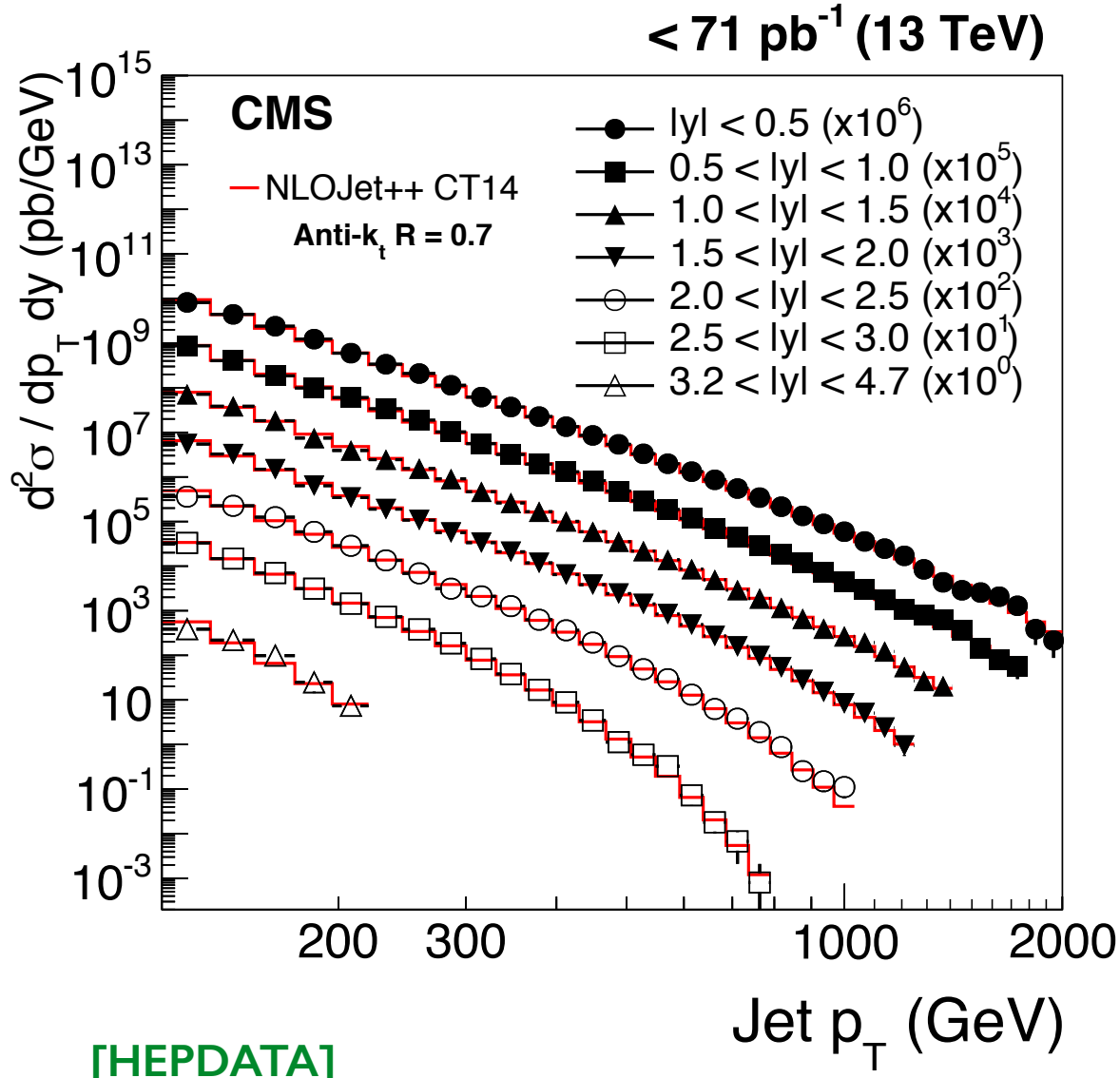


Eur. Phys. J. C 76 (2016) 265 [HEPDATA] SMP-14-017

Inclusive jets at 13 TeV

- With just 71 pb^{-1}, kinematic reach in p_T already similar to 8 TeV
- Early 50 ns reconstruction similar to Run I, enabling quick data analysis
- First(!) Standard Model Physics publication at 13 TeV from CMS
- Smaller cone size, R=0.4, enables direct comparisons to ATLAS





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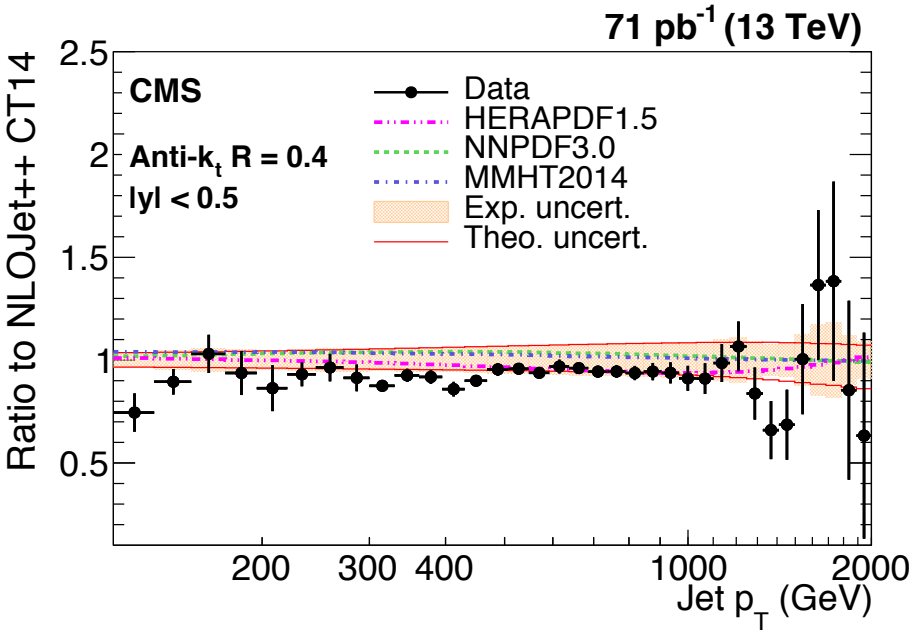
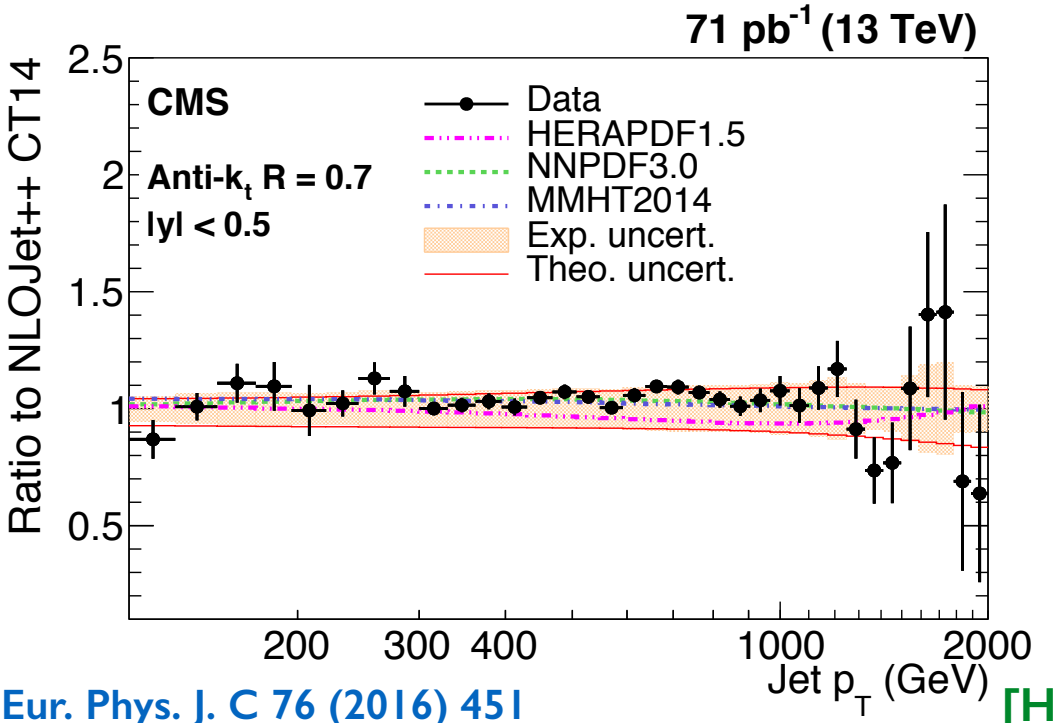
[HEPDATA]

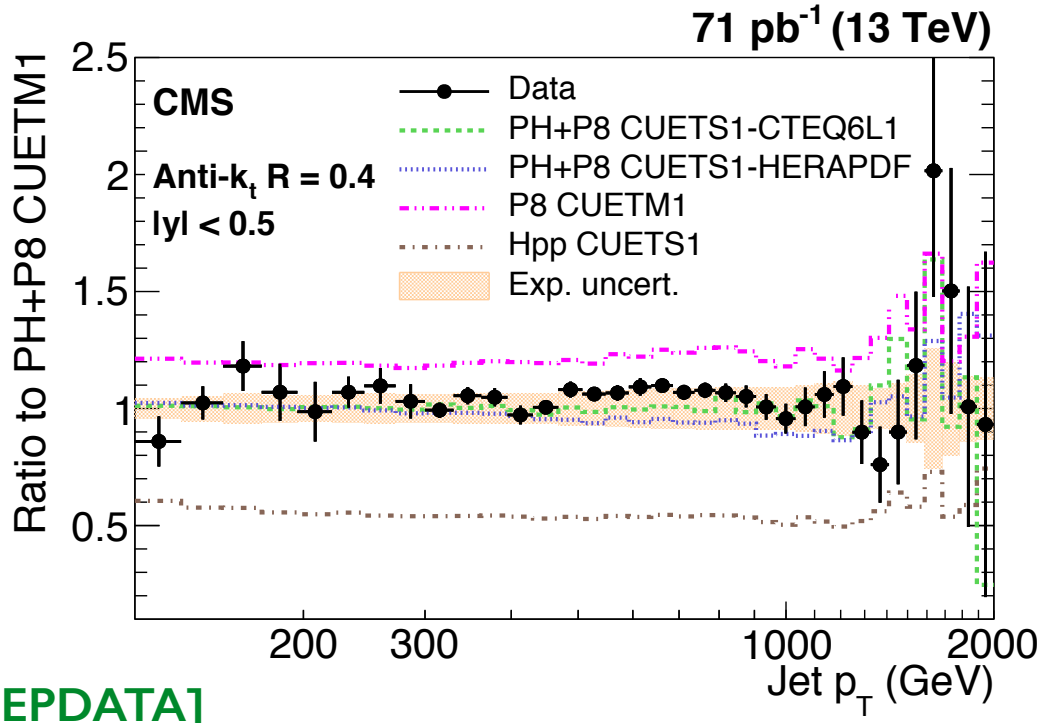
Inclusive jets at 13 TeV

- Large R=0.7 cone confirms agreement with NLO predictions is still good, as in Run I
- PowHeg+Pythia8 similarly good performance

- Small R=0.4 cone in tension with NLO pQCD
- Good agreement with PH+P8 predictions for R=0.4 suggests this is due to missing orders







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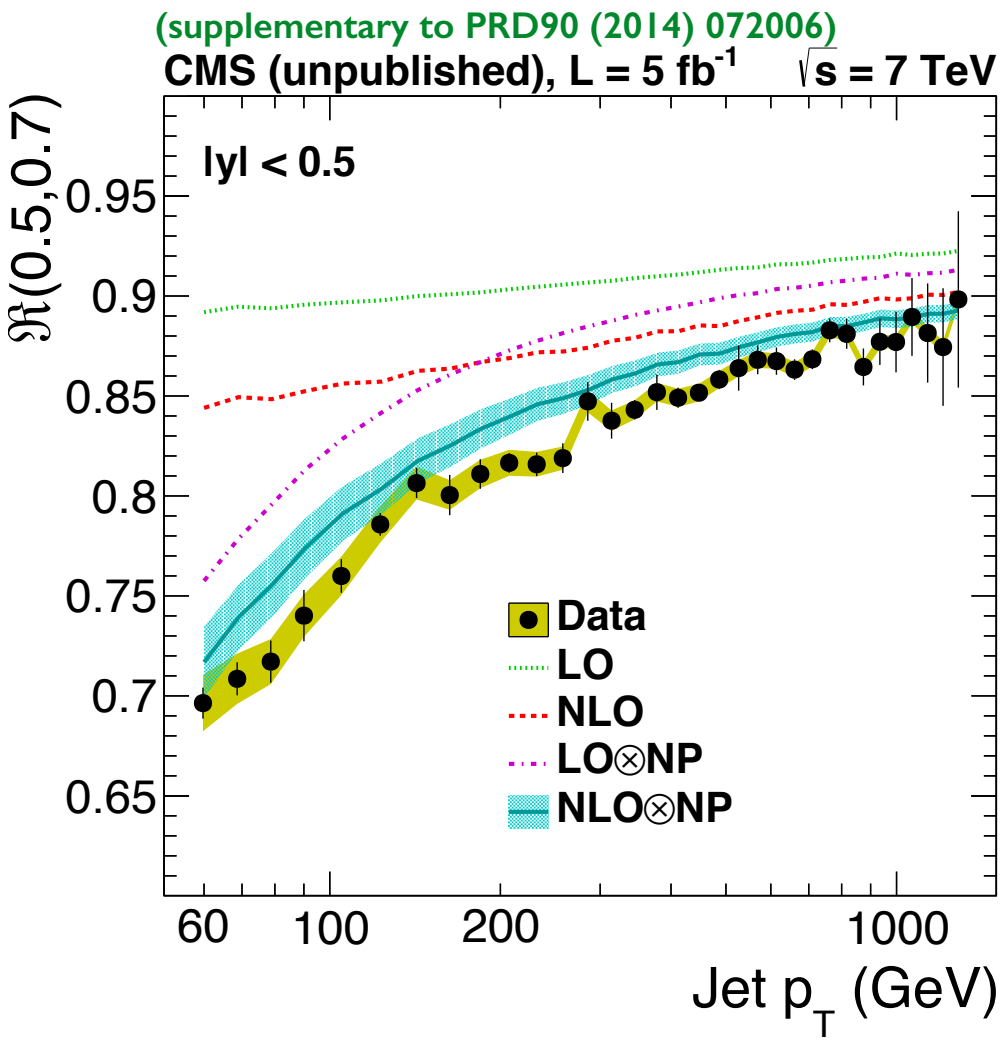
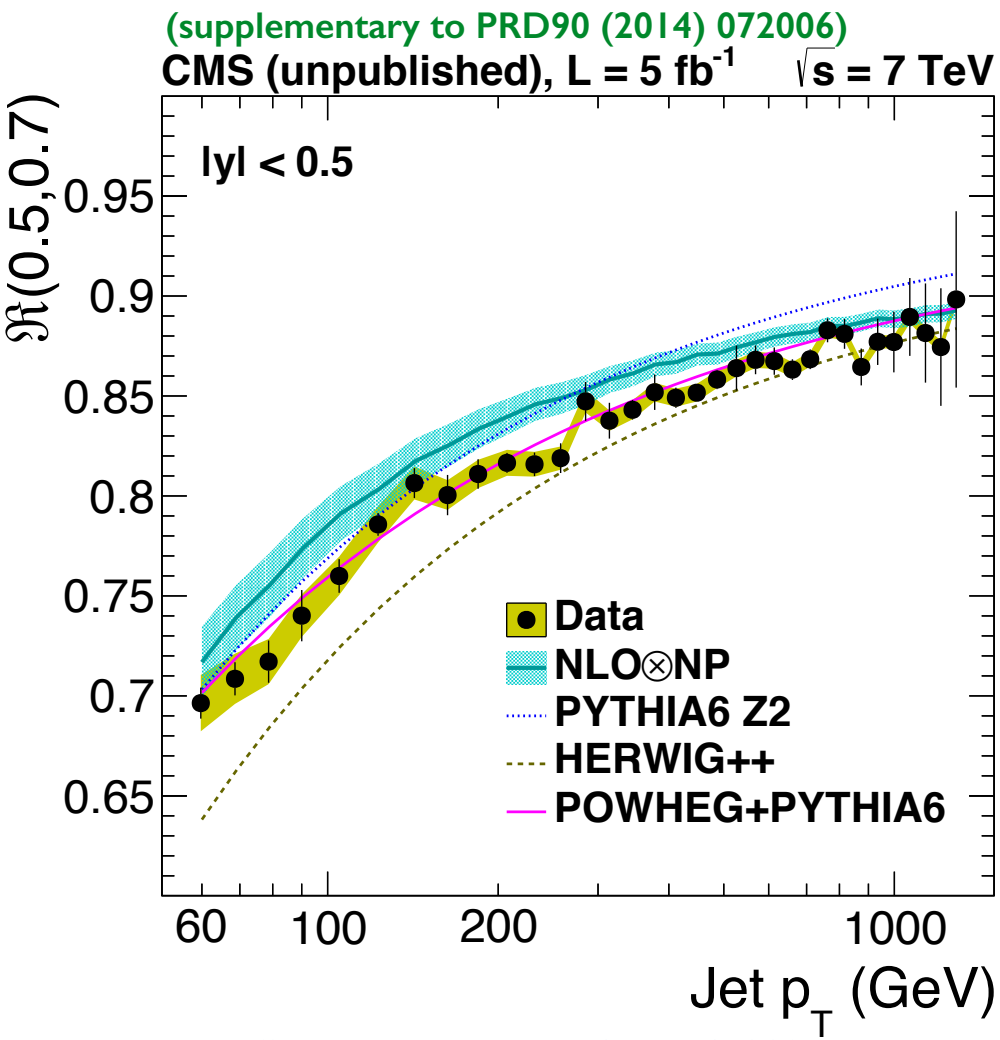
[HEPDATA]

About jet radius ratios

- Tension between NLO pQCD and small R=0.5 already seen in Run I analysis
- Adding extra legs from NNLO (NLO for ratio) improved agreement for R(0.5, 0.7)
- Best agreement observed with PowHeg+Pythia6, for an effective LO+PS for the ratio

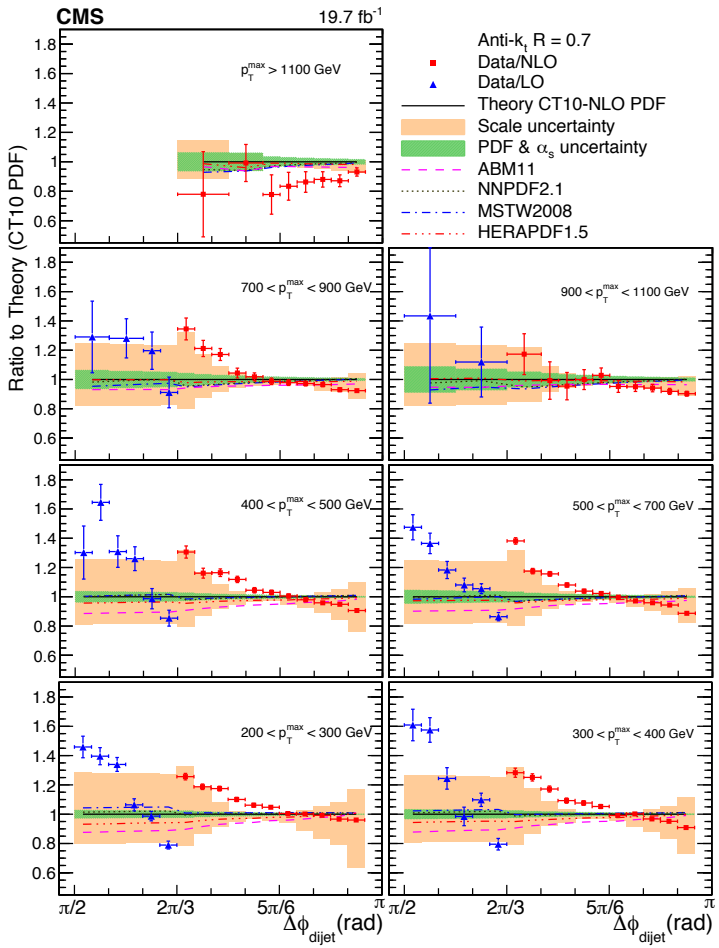


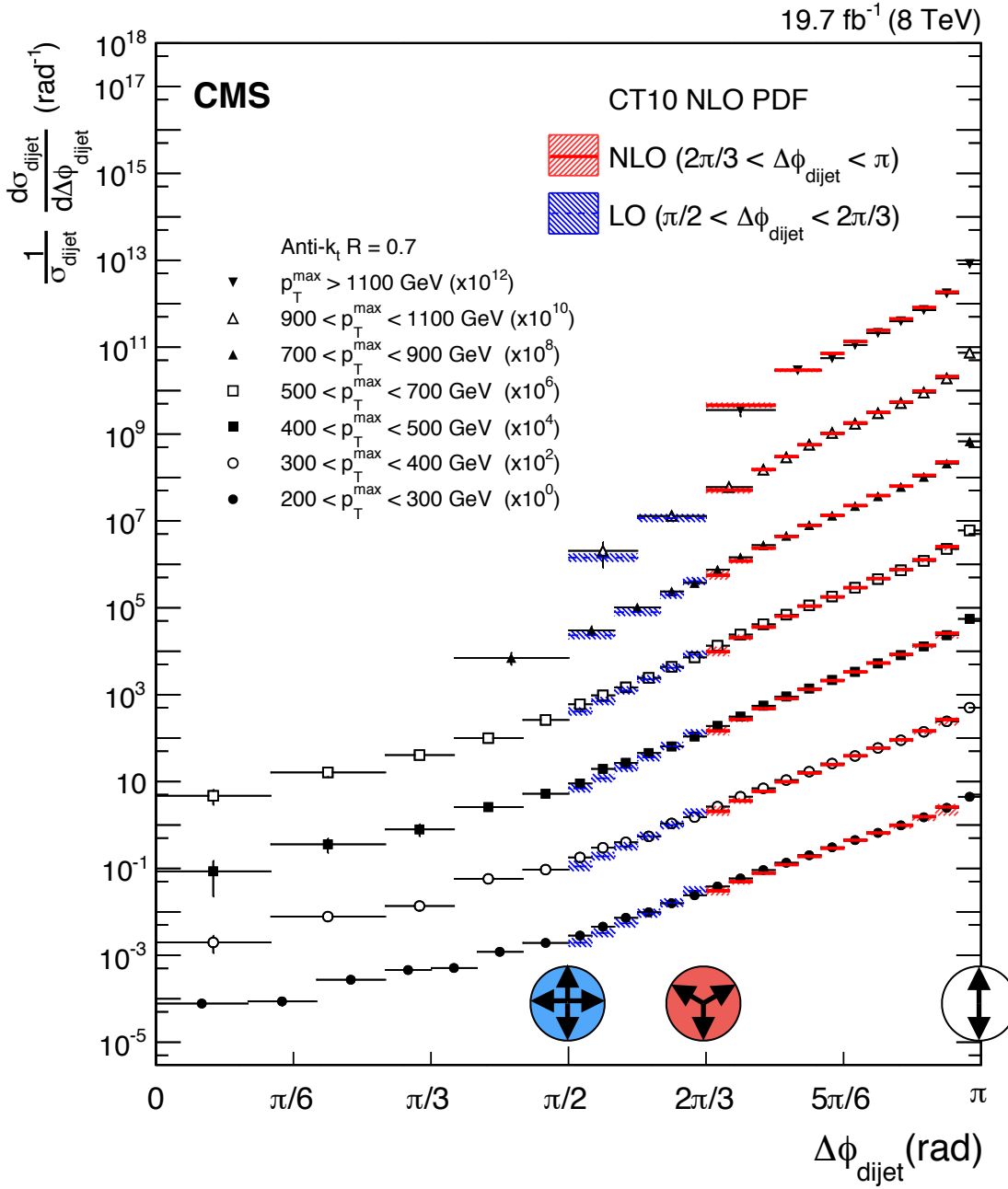


Phys. Rev. D 90 (2014) 072006 [HEPDATA] NB:"unpublished"=supplementary, [SMP-13-002 public TWiki]

Dijet azimuthal decorrelations

- Dijet azimuthal decorrelation probes production of additional jets in event, without explicitly reconstructing them
- Compared to pQCD predictions for 3-jet production with up to 4 final partons

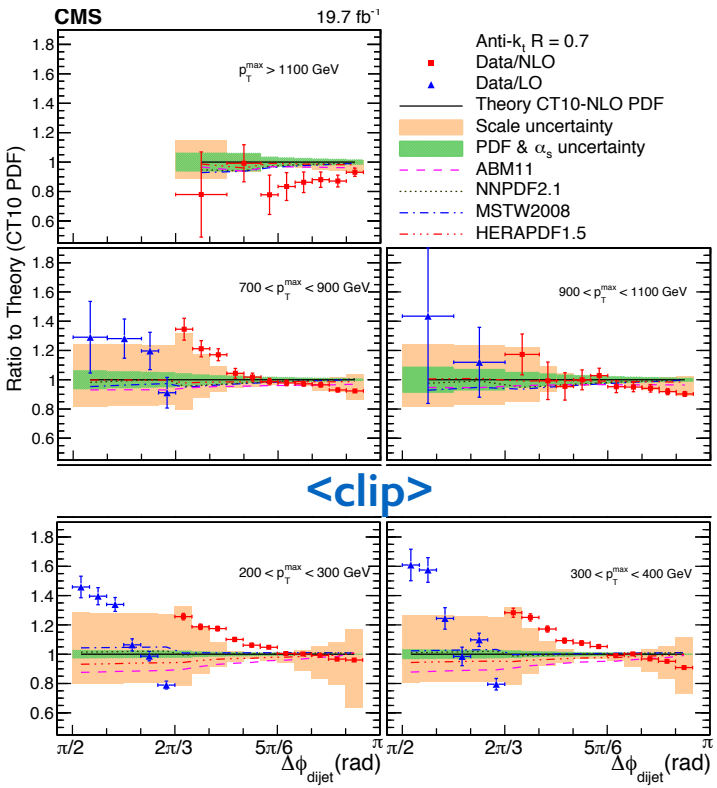


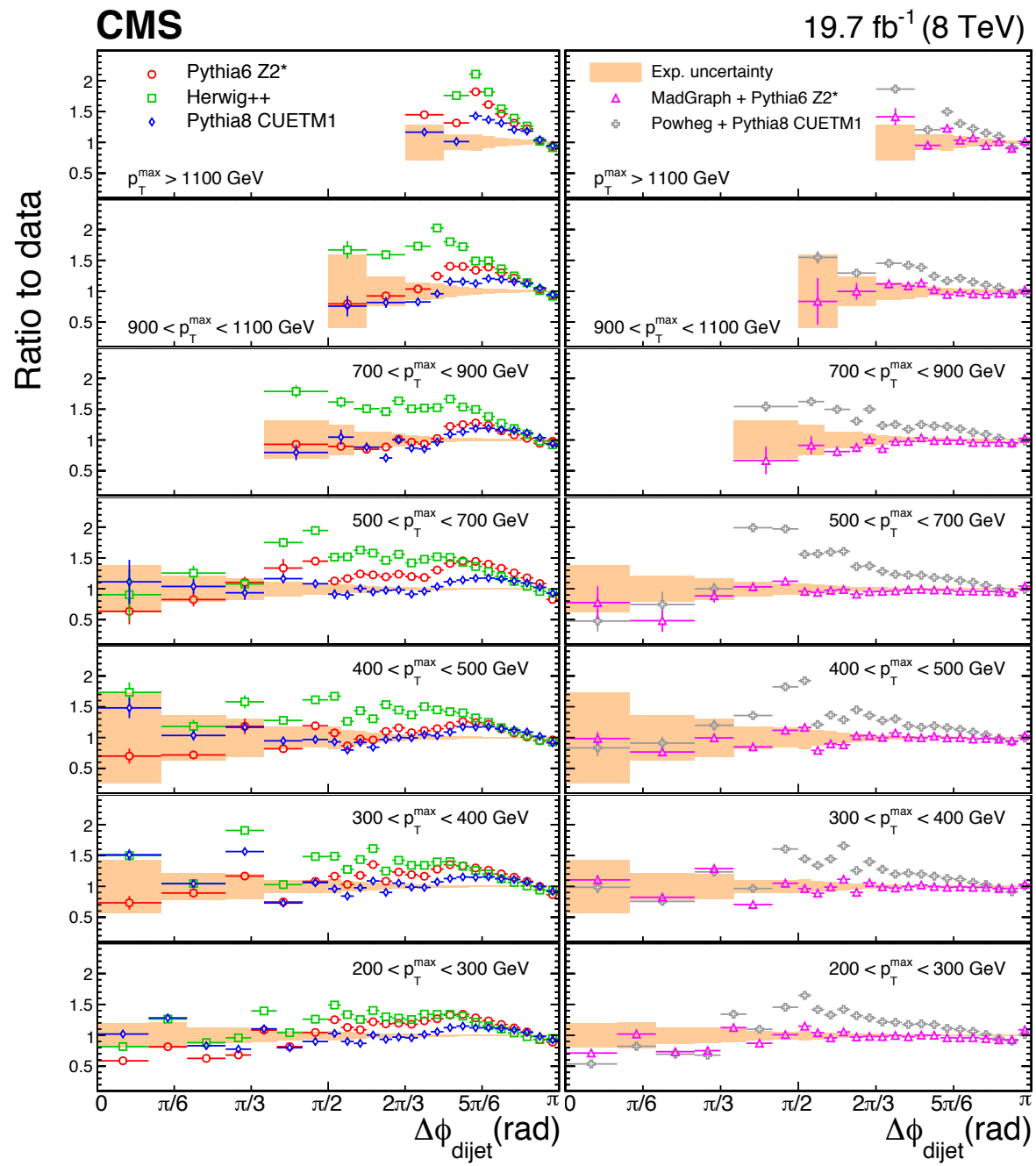


SMP-14-015, arxiv:1602.04384

Dijet azimuthal

- Multileg event generators (MadGraph+P6) describe data well
- LO+PS and NLO+PS generators (Pythia, Herwig, Powheg) worse
- Emphasises need to improve predictions for multijet production





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SMP-14-015, arxiv:1602.04384

Jet charge measurement

- Initial quark or gluon charge leaves a small imprint on jet charge
- Three definitions of jet charge (regular, longitudinal, transverse tested)
- Variation of κ parameter provides different sensitivity to softer and harder particles in jet

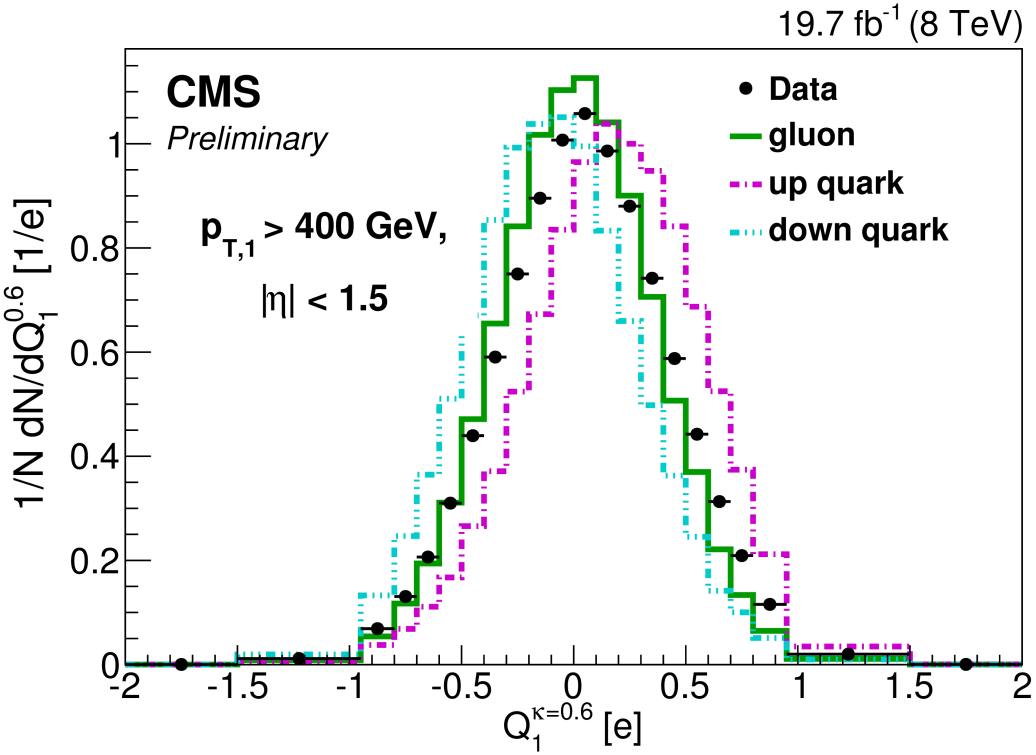
$$Q^{\kappa} = \frac{1}{(p_T)^{\kappa}} \sum_i Q_i (p_T^i)^{\kappa}$$

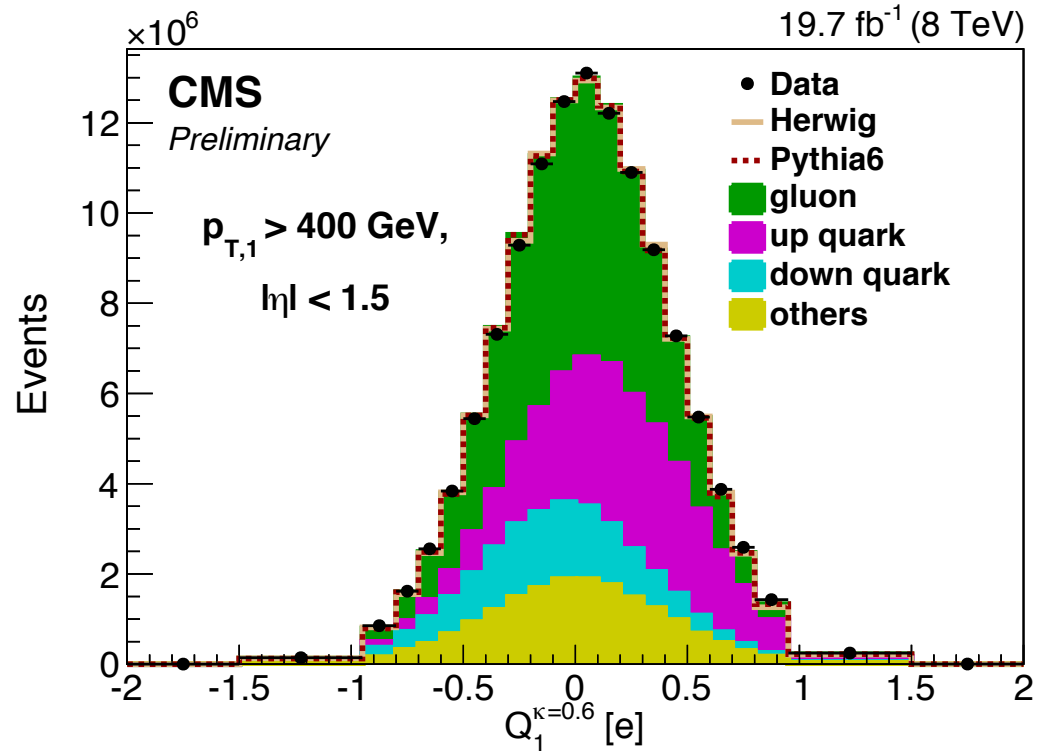
κ = 0.3, 0.6, 1.0

$p_{T,1}$ > 400 GeV
400 < $p_{T,1}$ < 700 GeV
700 < $p_{T,1}$ < 1000 GeV
1000 < $p_{T,1}$ < 1800 GeV

$$Q_L^{\kappa} = \sum_i Q_i \left(p_{\parallel}^i\right)^{\kappa} / \sum_i \left(p_{\parallel}^i\right)^{\kappa}$$

$$Q_T^{\kappa} = \sum_i Q_i \left(p_{\perp}^i\right)^{\kappa} / \sum_i \left(p_{\perp}^i\right)^{\kappa}$$

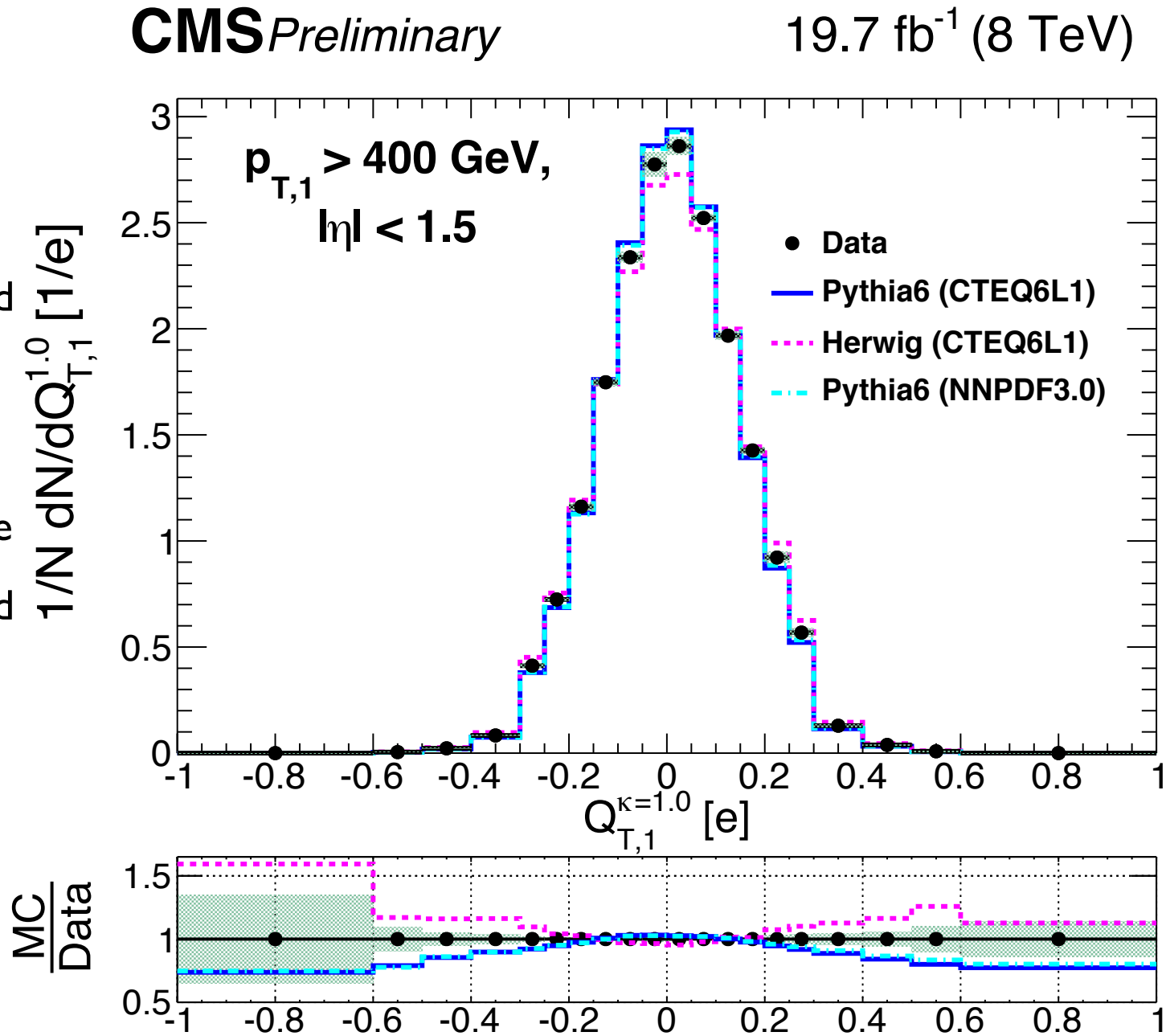




SMP-15-003

Jet charge

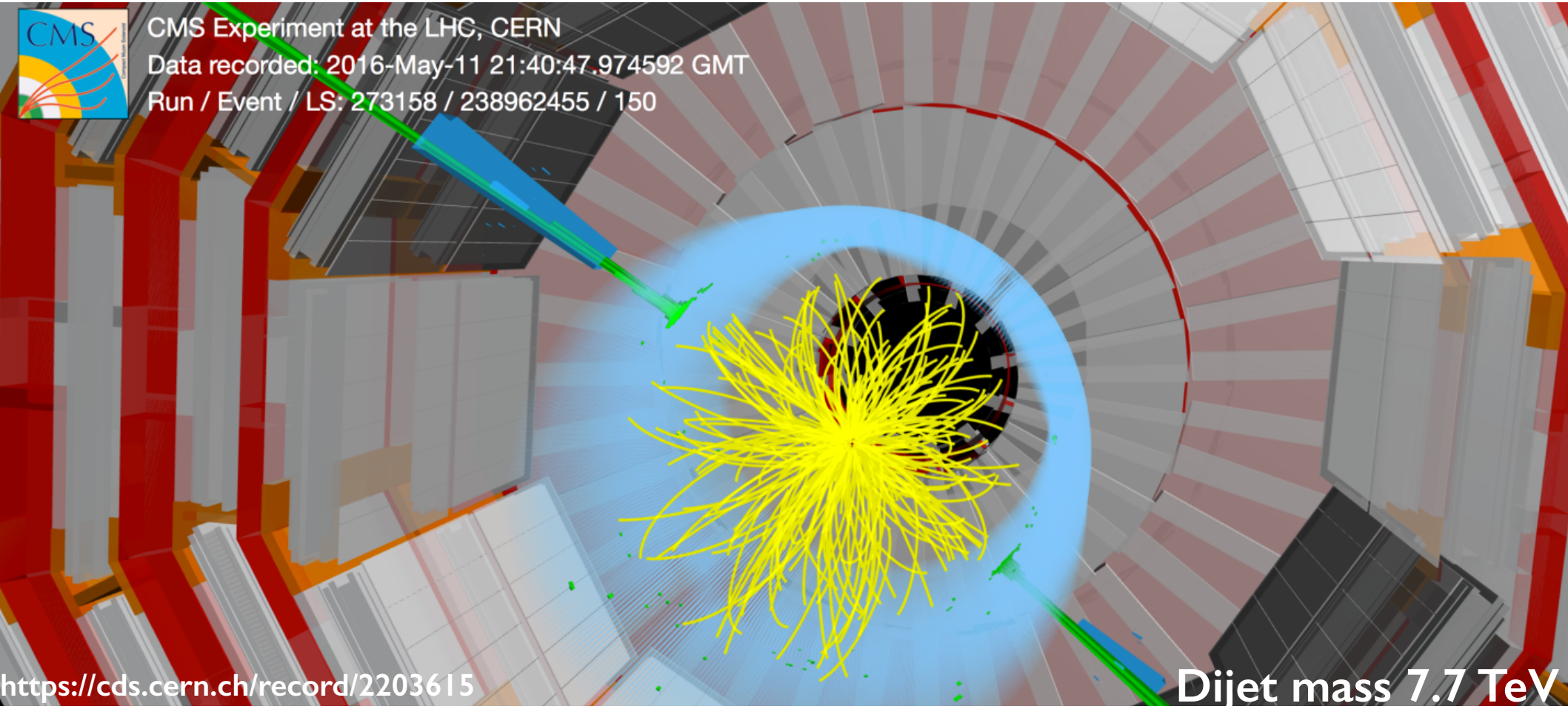
- Pythia 6 and Herwig++ generators show only mild discrepancies with data. However, …
- The two generators are systematically different and could be constrained by these measurements
- Parton shower and fragmentation modelling differences in Pythia and Herwig for gluon jets are among leading JES uncertainties at CMS and ATLAS
- Better modelling could significantly improve precision measurements
- Spectrum of unfolded results for κ=0.3,0.6,1.0 x Q^{κ},Q^{κ}_{L},Q^{κ}_{T} x p_T bins available for tuning MC



SMP-15-003

Conclusions

- We presented inclusive jet measurements at 2.76, 8 and 13 TeV and multijets at 8 TeV, as well as latest public results on jet energy scale and jet charge
- pQCD agrees with data, with NLO+PS (Powheg) and multijet (MadGraph) state-of-the-art
  - still room for improvement in consolidating the two, however



- New data promises to have significant impact on PDFs and α_s running
  - among leading experimental systematics, shared between CMS and ATLAS, is gluon jet modelling

Papers and PASes

- Papers:
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/JETS.html
    - SMP-15-007: 13 TeV inclusive jets, 71 pb^{-1} (Eur. Phys. J. C 76 (2016) 451, Aug 2016) **[HEPDATA]**
    - SMP-14-015: 8 TeV dijet azimuthal (submitted to EPJC, Feb 2016)
    - SMP-14-017: 2.76 inclusive jets (EPJC 76 (2016) 065, Dec 2015) **[HEPDATA]**
    - SMP-13-002: 7 TeV jet radius ratio (PRD 90 (2014) 072006, July 2014) **[HEPDATA]**
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/JME/index.html
    - JME-13-004: 8 TeV jet energy scale (submitted to JINST, July 2016), **[arXiv:1607.03663]**
- PASes:
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP/index.html
    - SMP-15-003: 8 TeV jet charge (June 2016)
    - SMP-14-001: 8 TeV inclusive jets (Oct 2015)
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html
    - EXO-16-032: 13 TeV dijets with 12.9 fb^{-1} (Aug 2016)
- Other:
  - CMS-DP-2016-020, JES+JER at 13 TeV, https://cds.cern.ch/record/2160347
  - Eur. Phys. J. C (2015) 75:17, ATLAS JES at 7 TeV, [link top plots]