QCD with jets and photons in CMS and ATLAS

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for the ATLAS and CMS collaborations

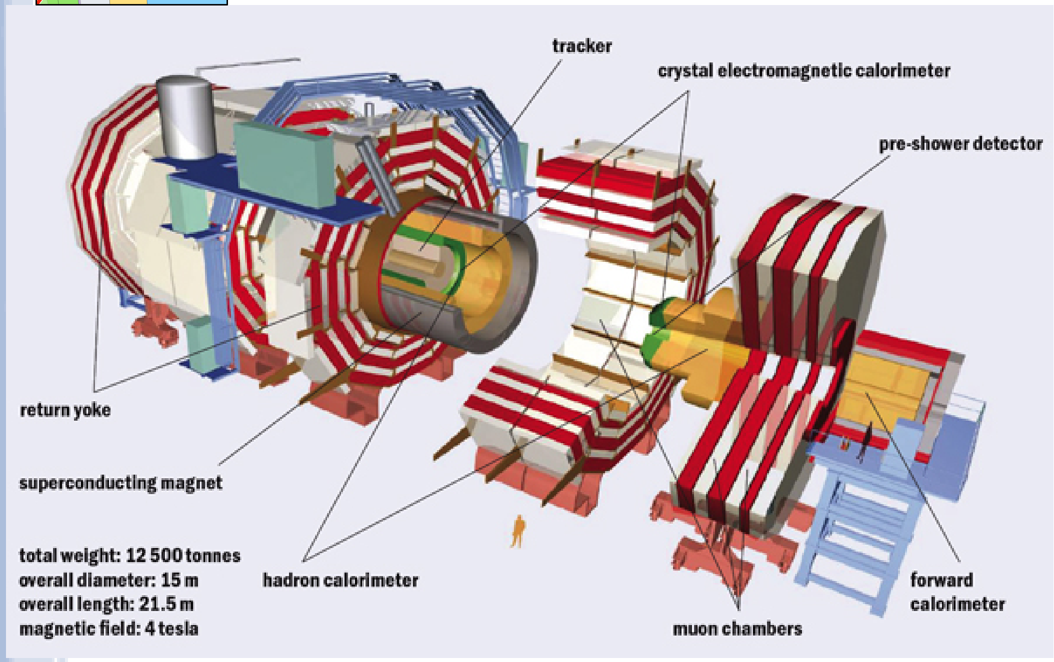
29th Rencontres de Blois on Particle Physics and Cosmology

May 31, 2017

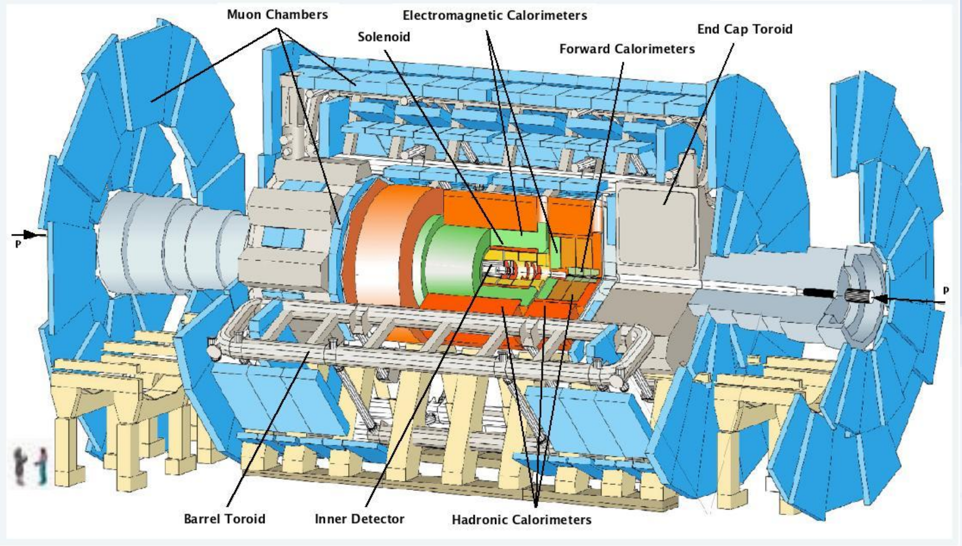
QCD at hadron colliders

- Precision measurements that complement DIS
- Important input to PDF and α_s fits, at high energy scales and x values
- Important input to understanding non-perturbative effects (parton shower, hadronization, underlying event)
- Vehicle for testing the SM and probing QCD-related discoveries
- QCD background significant in most LHC searches

ATLAS and CMS experiments at LHC

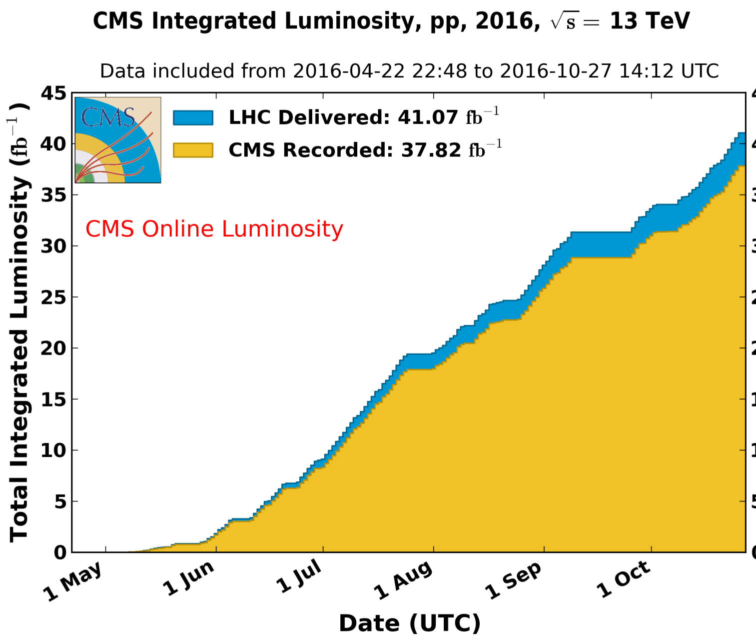


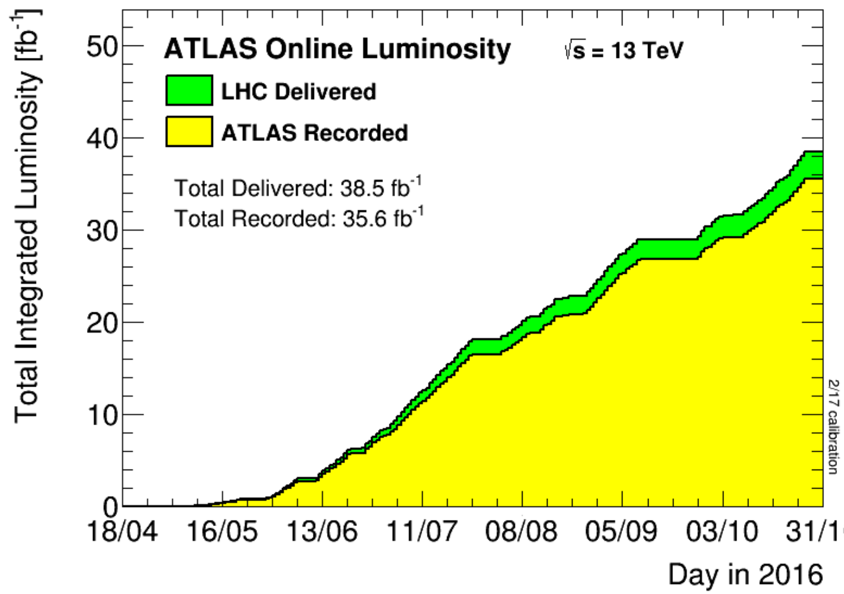
- Silicon pixel + strip tracker
- 3.8 T magnet
- Lead/Tungstate EM calorimeter
- Brass/Scintillator Had calorimeter
- Muon system embedded in return yoke

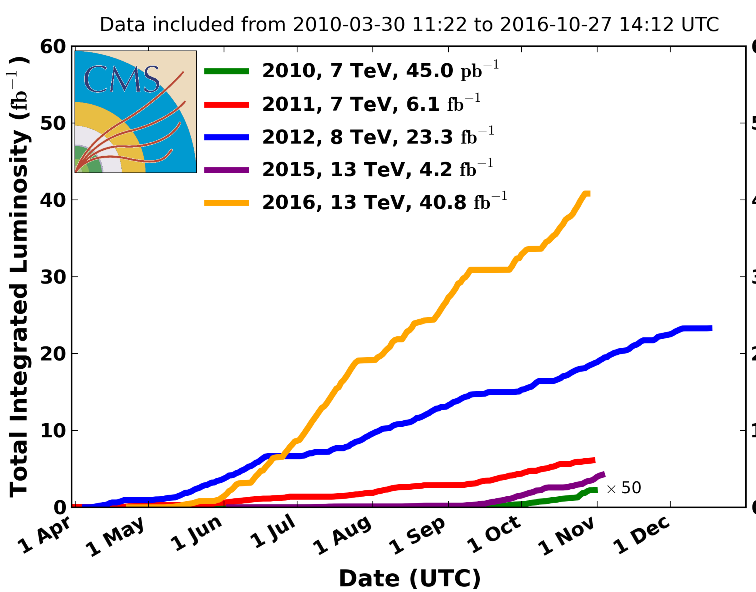


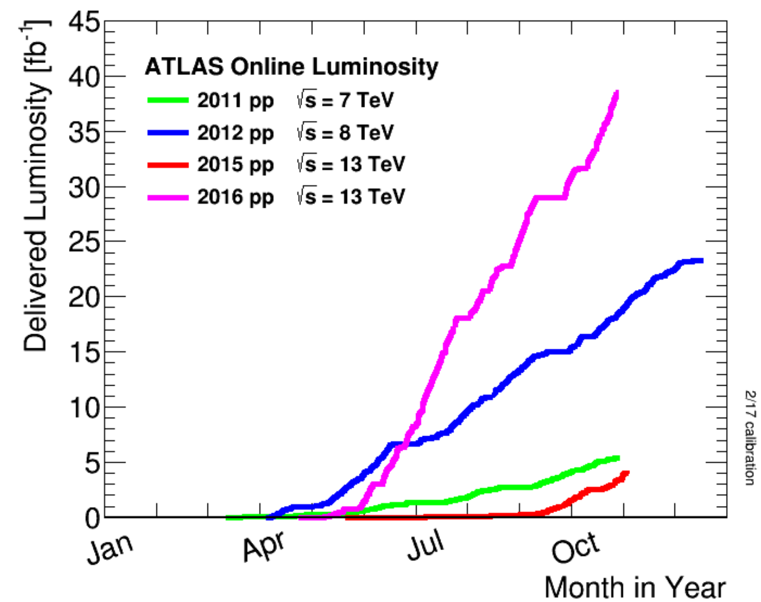
- Silicon pixel + strip tracker
- 2 T magnet
- LAr/lead EM calorimeter
- Iron/Scintillator central Had calorimeter (Cu/W+LAr forward calorimeters)
- Muon system utilizes toroid magnets

Performance of LHC and experiments







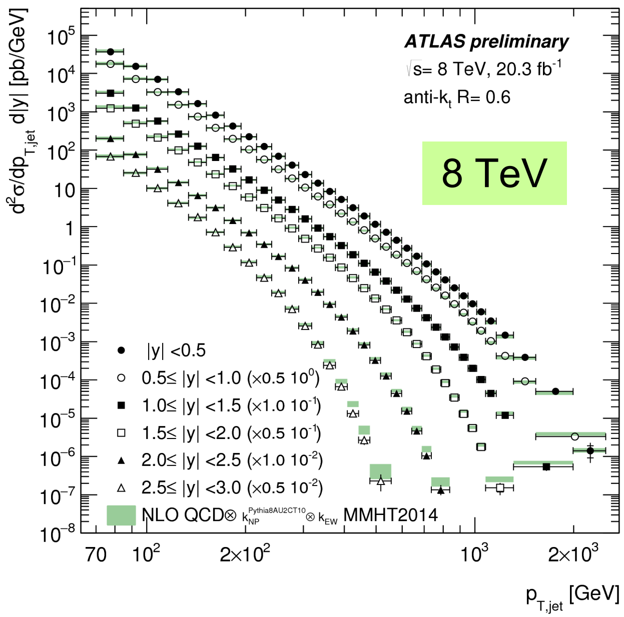


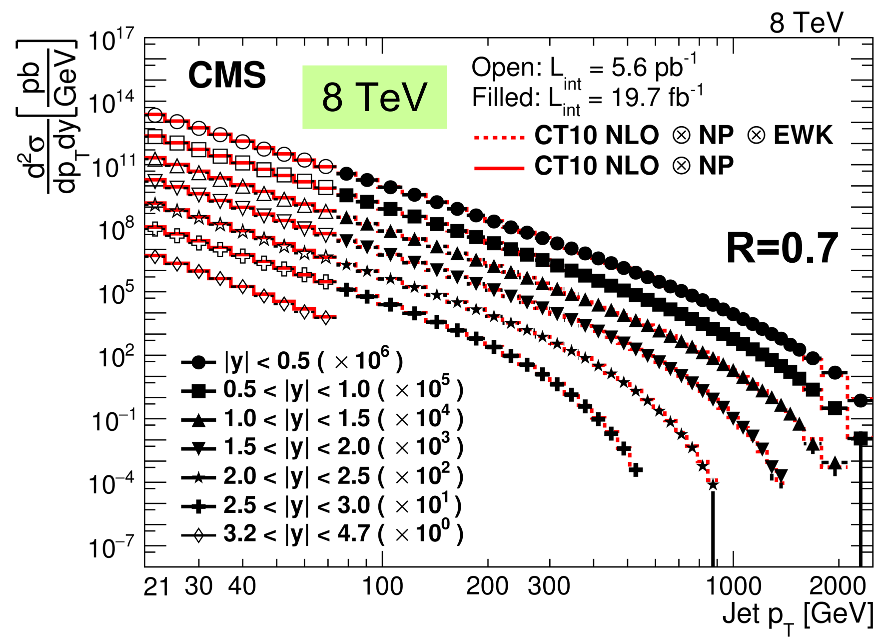
Analyses overview

- Legacy inclusive-jet cross sections (8 TeV, 13 TeV)
- Azimuthal jet correlations (13 TeV)
- Triple differential jet cross sections (8 TeV)
- Measurement of α_S with inclusive multijets (8 TeV)
- Measurement of α_S with transverse-energy correlations (8 TeV)
- QCD Inclusive isolated photon (13 TeV)
- QCD diphotons (8 TeV)
- QCD photon+jets (8 TeV)

Inclusive jet cross section (8 TeV and 13 TeV)

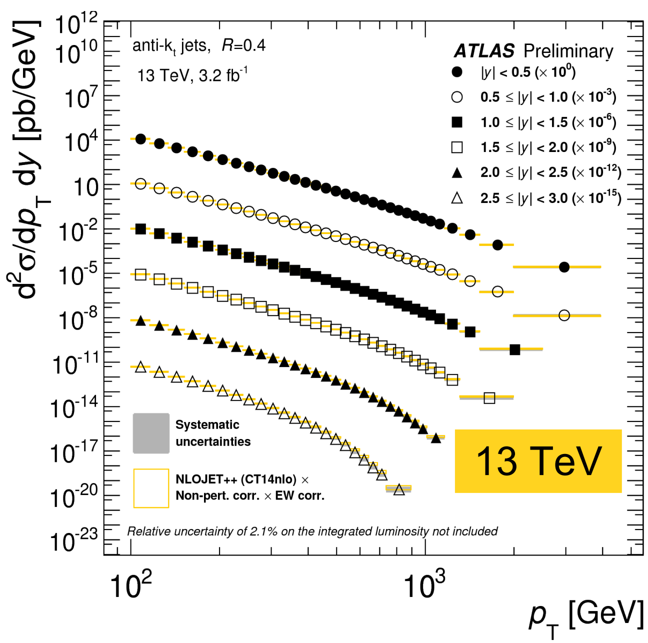
NEW

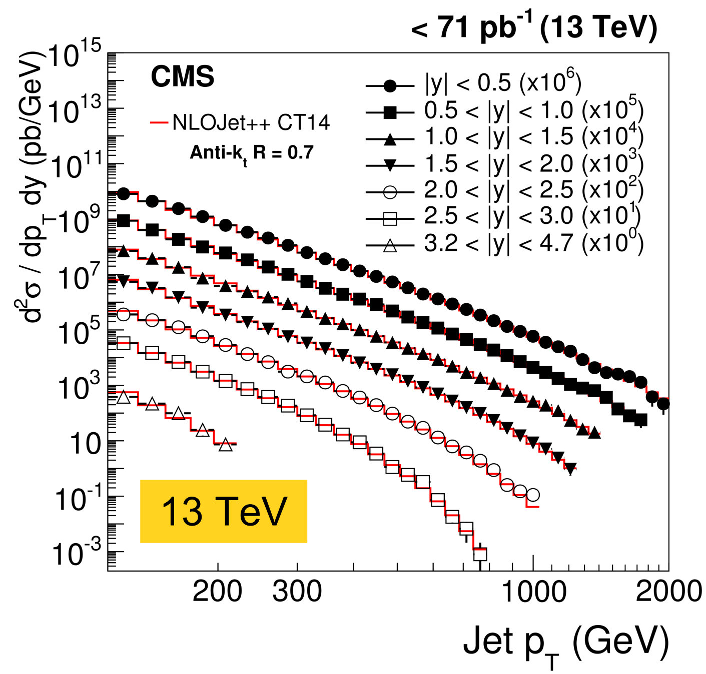




JHEP 03 (2017) 156

ATLAS-CONF-2016-092

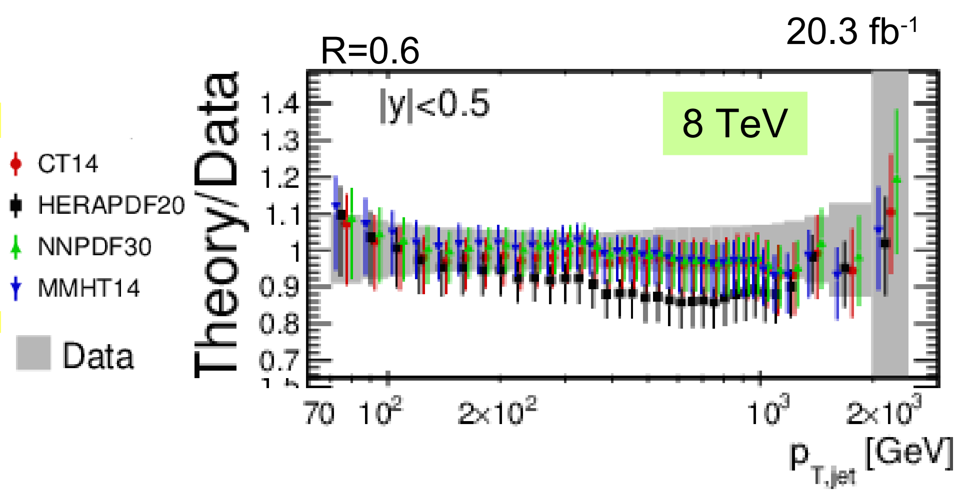


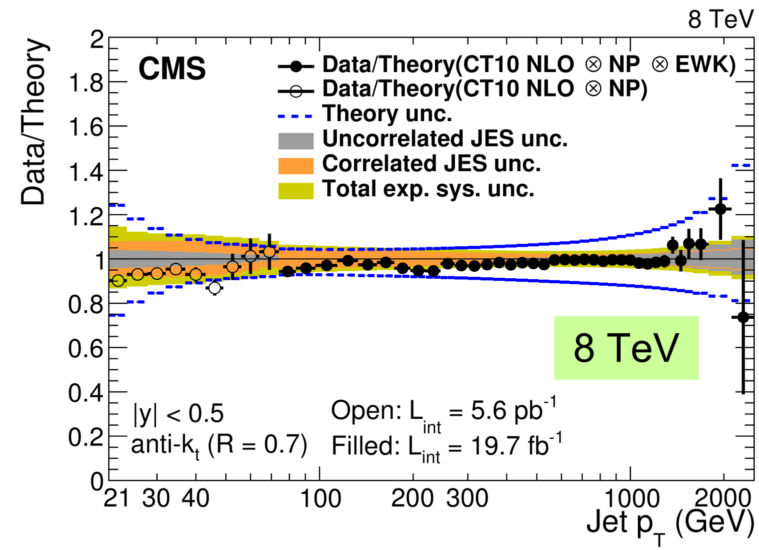


EPJC 76 (2016) 451

Inclusive jet cross section (8 TeV and 13 TeV)
– ratios with theory for |y|<0.5

NEW





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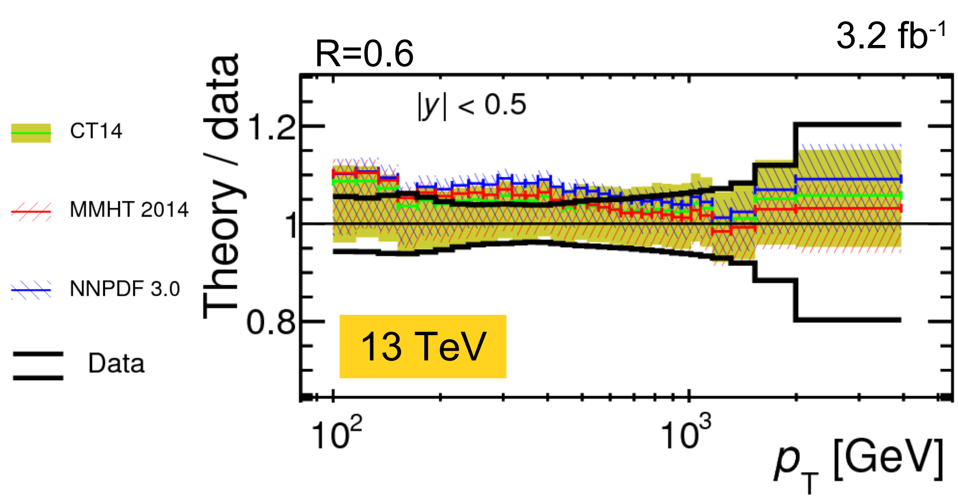
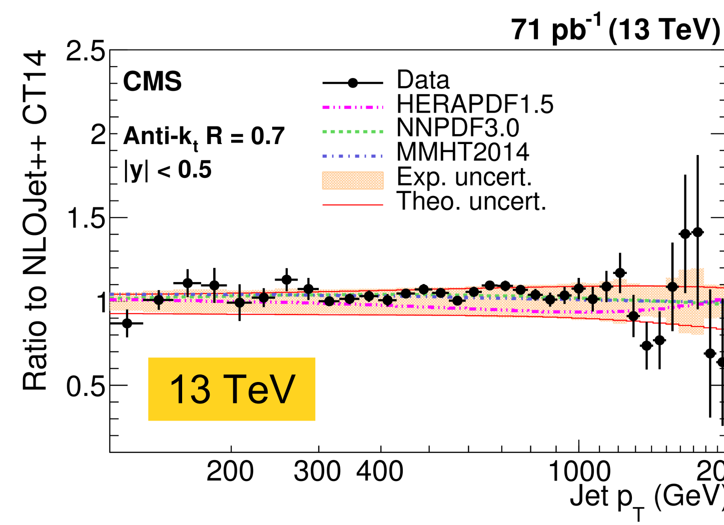




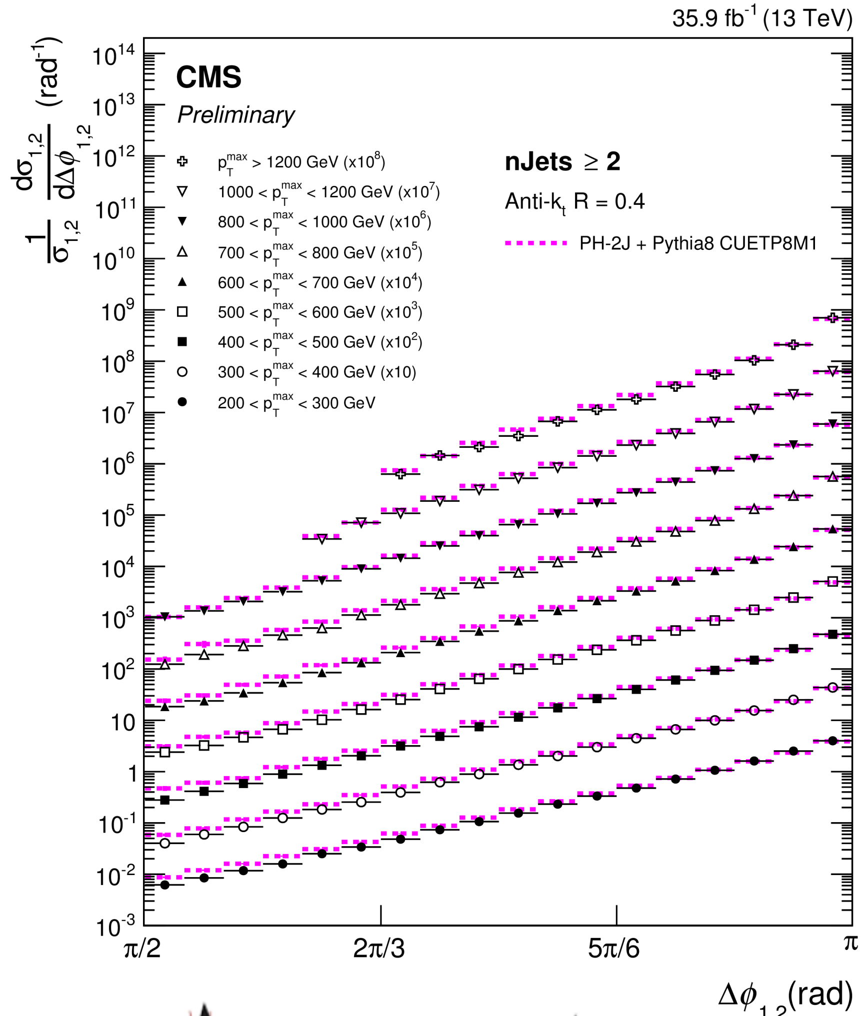
EPJC 76 (2016) 451

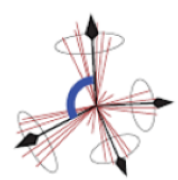
(all |y| regions in backup)

NEW

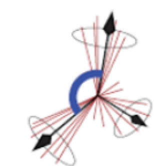
Azimuthal jet correlations (13 TeV)

- 13 TeV, 35.9 fb^{-1}, single-jet triggers
- Particle-flow jets, Anti-k_T reco, R=0.4
  - Inclusive 2-jet, 3-jet, 4-jet analyses
- Leading jet p_T >200 GeV (others >100 GeV) and all leading jets per analysis have |y|<2.5 (others <5)
- Normalized cross section: reduction of theoretical and experimental uncertainties
- Observables: $\Delta\varphi_{1,2}$ between leading two jets (2j, 3j, 4j) and $\Delta\varphi_{min}$ between any two jets (3j, 4j)
- Experimental systematic JES (<2%), JER (<1%), unfolding (~0.2%)
- Unfold to particle-level jets ala d'Agostini
- Theoretical predictions: LO: Pythia8, Herwig++, Madgraph+Pythia8, NLO: Powheg (2J and 3J) and Herwig7

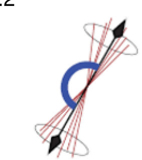




$0 < \Delta\varphi_{dijet} \ll \pi$



$2\pi/3 \leq \Delta\varphi_{dijet} < \pi$



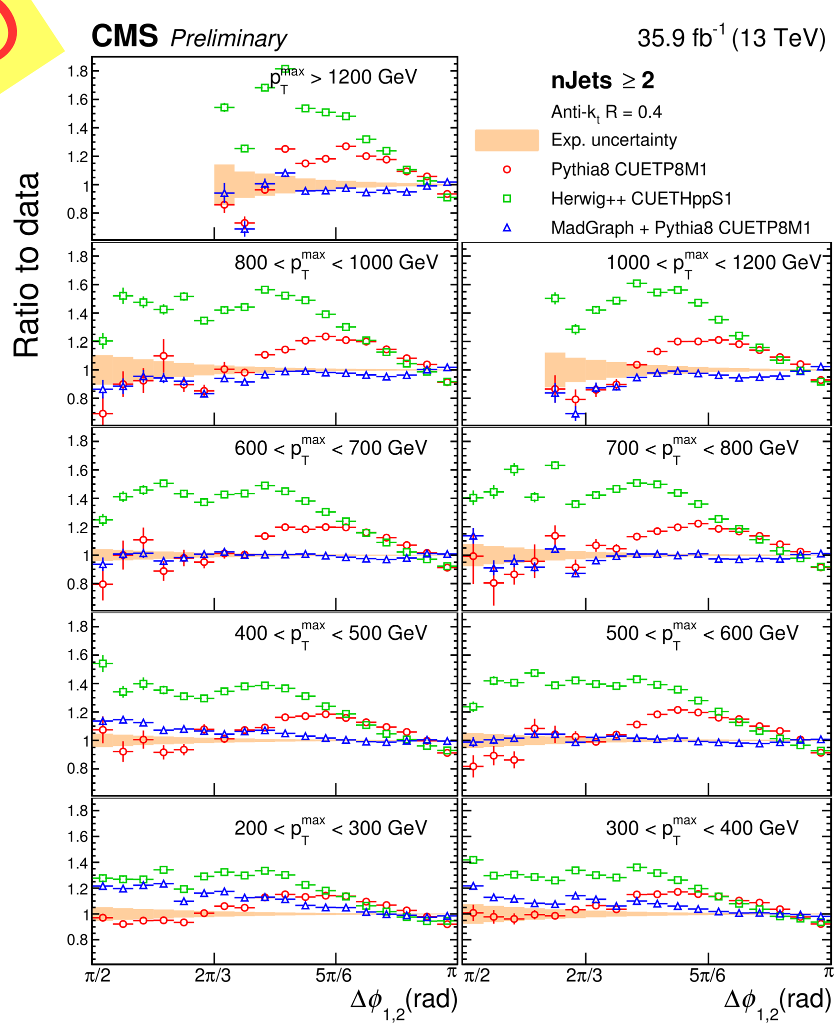
$\Delta\varphi_{dijet} = \pi$

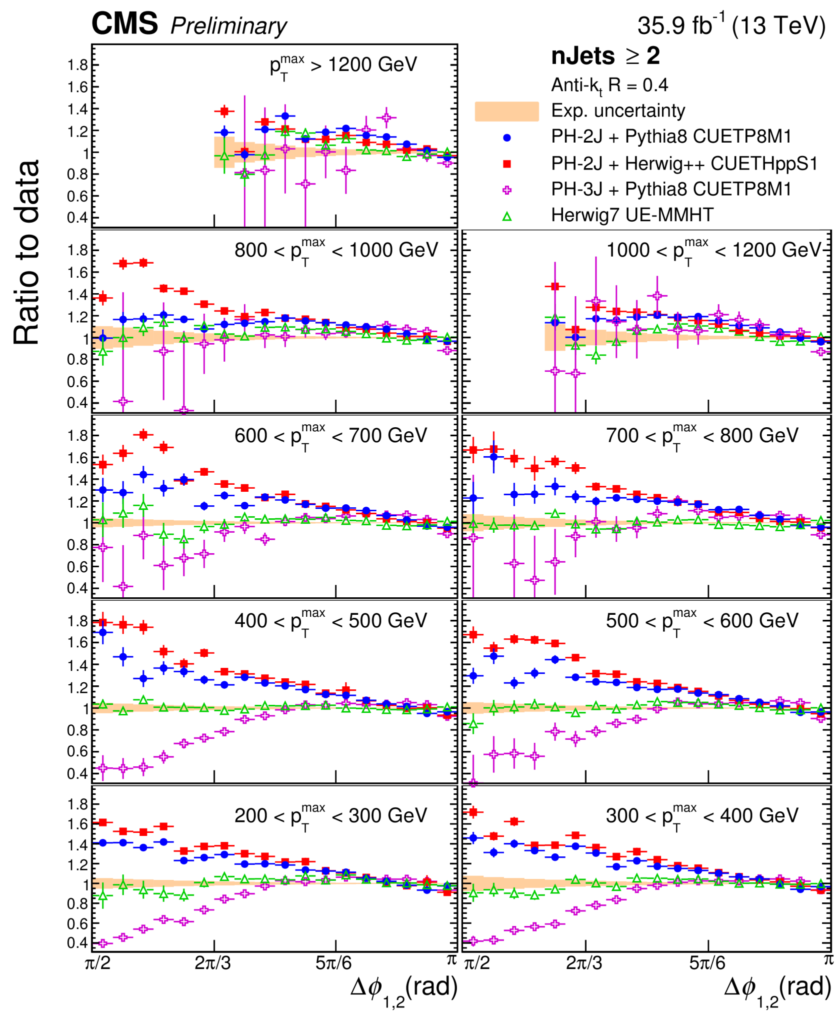
CMS-PAS-SMP-16-014

Azimuthal jet correlations ($\Delta\varphi_{1,2}$) ≥2 jets

LO

NLO

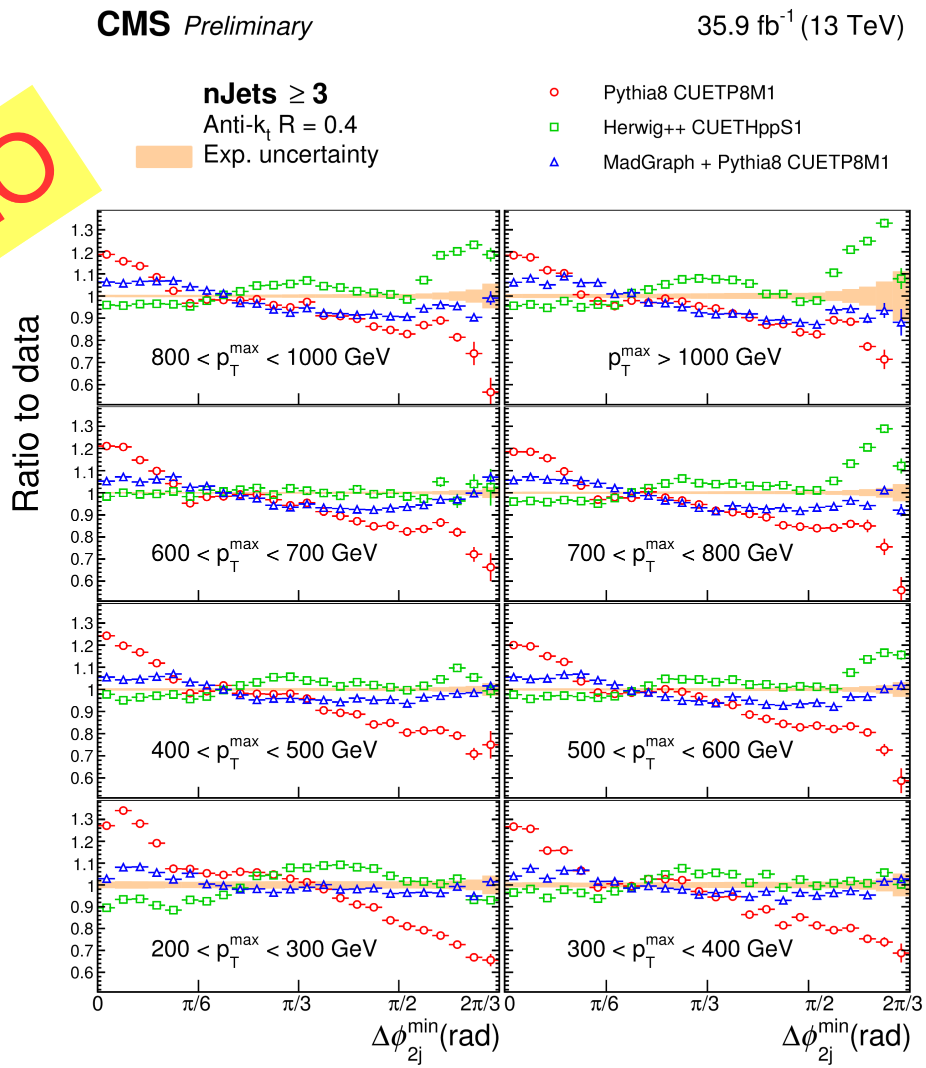




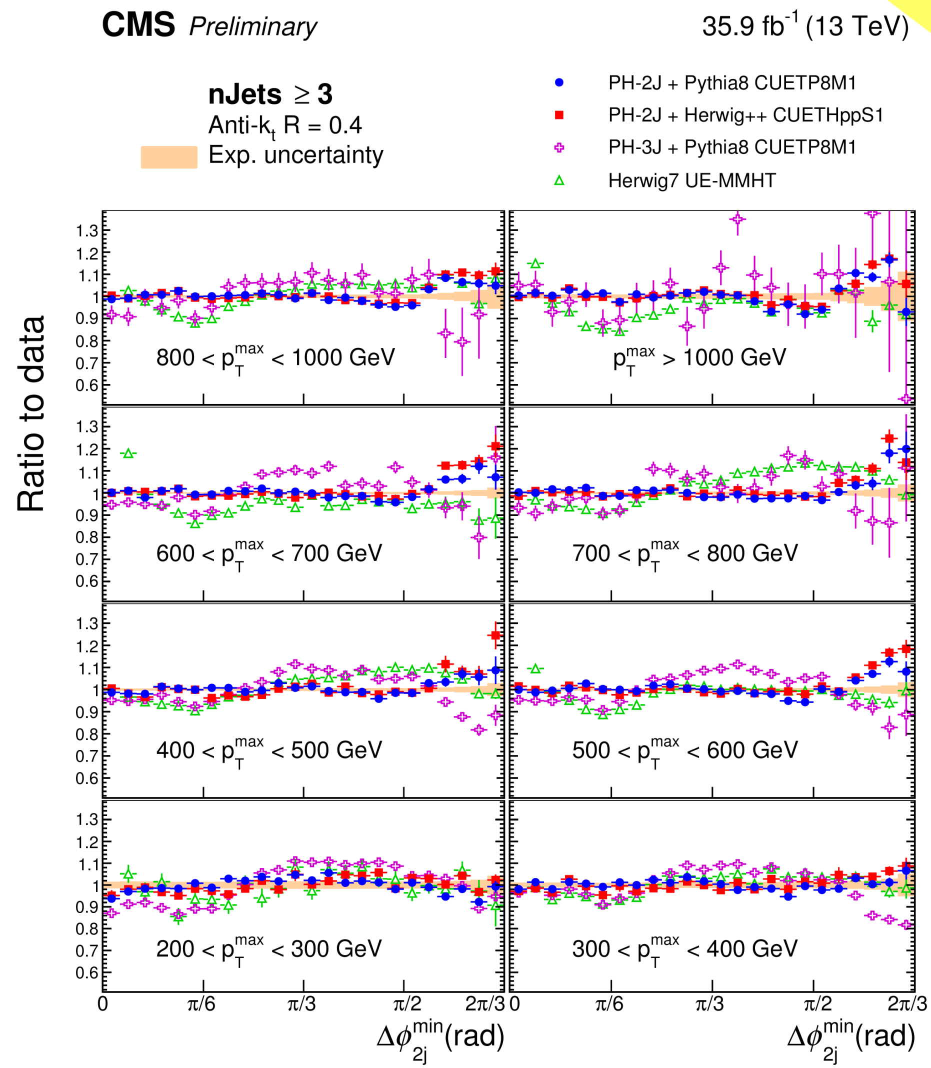
- From the LO generators, Madgraph+Pythia describes the data the best
- From NLO generators, Herwig7 describes data

Azimuthal jet correlations ($\Delta\varphi_{min}$) ≥3 jets

LO



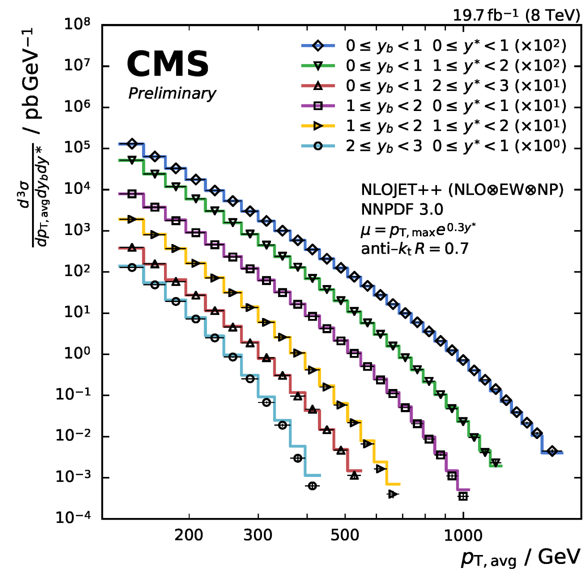
NLO

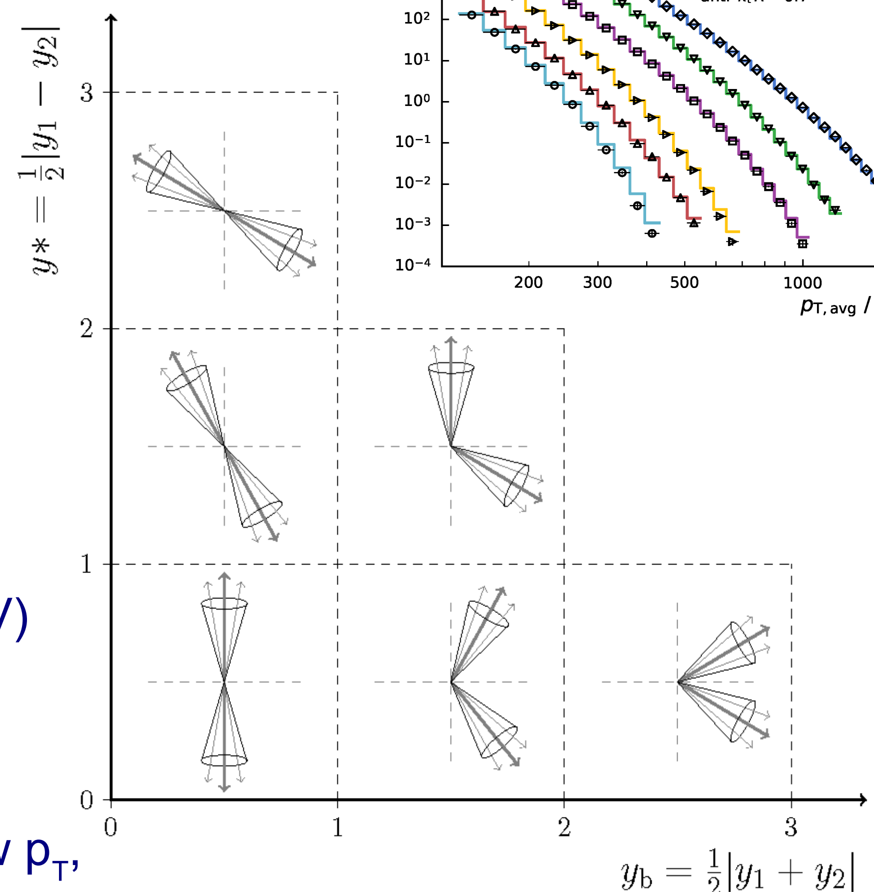


- From the LO generators, Herwig++ best for 3j and 4j, Pythia8 4j only
- From NLO generators PH2J (matched to Herwig++ or Pythia8) describes data best

Triple differential jet cross section (8 TeV)

- 8 TeV, 19.7 fb^{-1}, single-jet triggers
- Dijet differential cross section as a function of 3 variables
  - Average momentum of jets $p_{T,ave} \equiv (p_{T,1}+p_{T,2})/2$
  - $y_B \equiv ½ |y_1 + y_2|$
  - $y^* \equiv ½ |y_1 – y_2|$
- Large boosts sensitive to higher values of x for one of the partons
- Particle-flow jets, Anti-k_T reco, R=0.7
- Leading two jets >50 GeV, with |y|<3
- Toy MC for response matrix (smeared with p_T resolution 8% @ 100 GeV)
- Major exp systematics: JEC (2.5%-12% forward), Lumi (2.6%), JER (1-2%)
- Major theoretical systematics: scales at low p_T, PDF at high p_T esp. high boosts (2% → 10-30%)



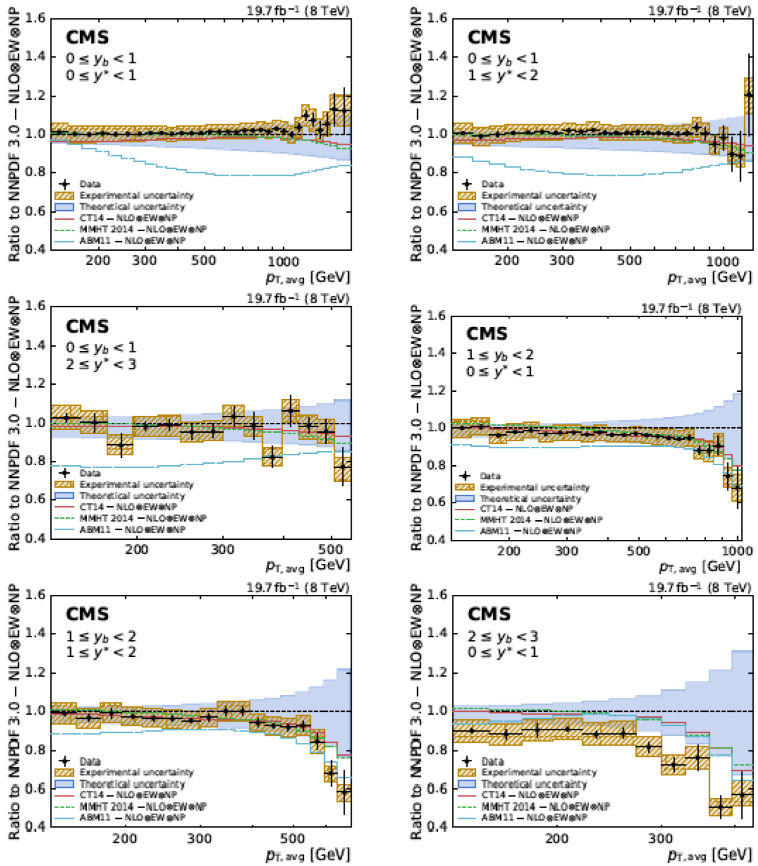


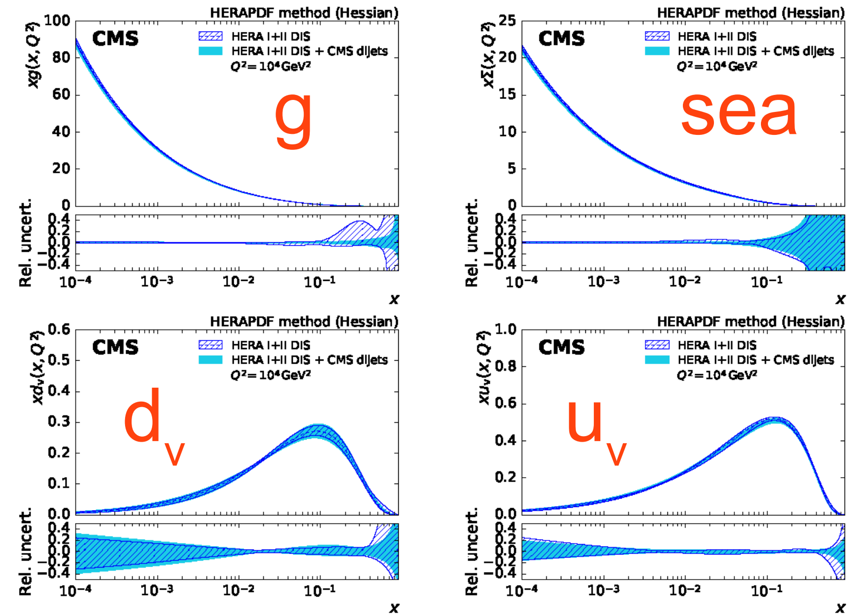
arXiv: 1705.02628, submitted to EPJC

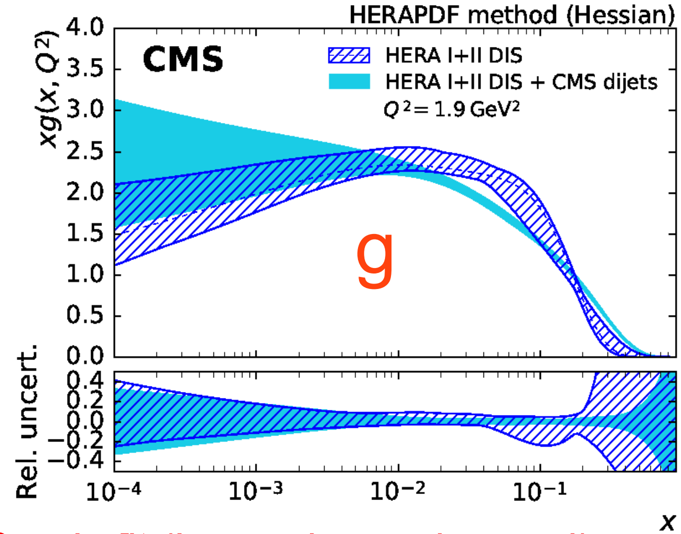
Triple differential jet cross section (8 TeV)

Theory:
NLOJet++ with FastNLO framework and NP&EW corrections

Generators:
Herwig7 better in central region, Powheg better forward



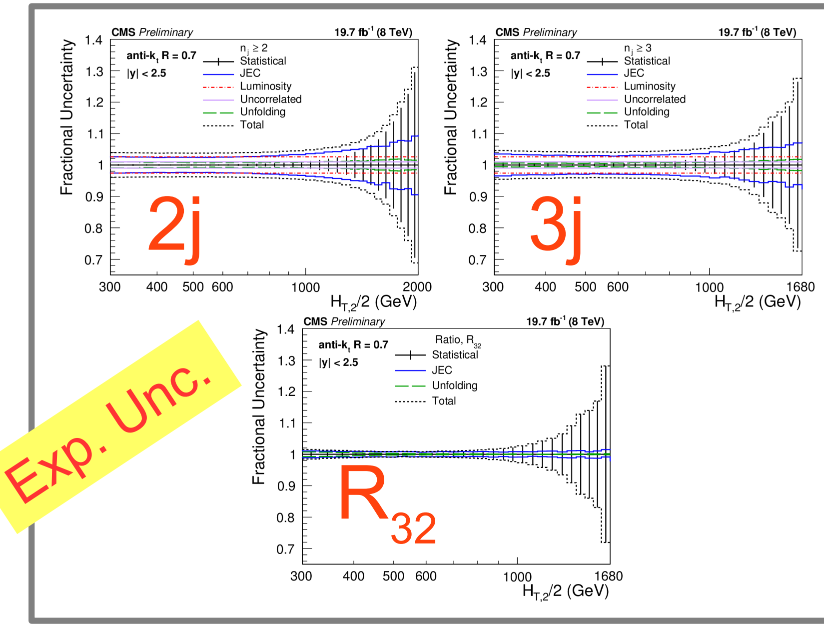


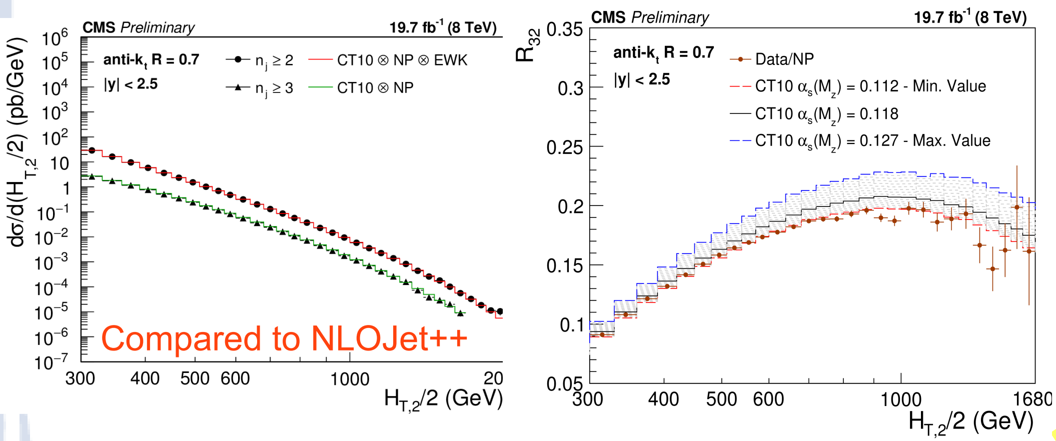


- High-p_T and particularly high boosts are not described well by NLO (with NP and EW corrections)
  - Sensitive to PDF uncertainty
- Fits to PDFs (16 parameters) constrain PDF
  - Gluon PDF uncertainty reduced compared to DIS-only fit (low-x shape changed)
- $\alpha_S(M_Z) = 0.1199 \pm 0.0015\,(\text{exp}) \pm 0.0002\,(\text{mod})\,_{-0.0004}^{+0.0002}(\text{par})\,_{-0.0019}^{+0.0031}(\text{scale, refit})$

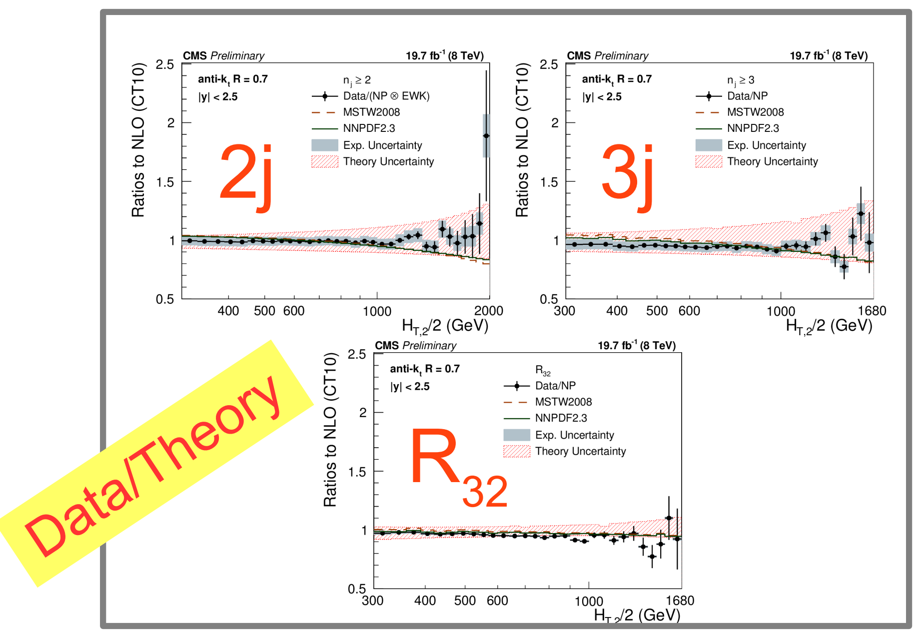
α_S with inclusive multijets (8 TeV)

- 8 TeV, 19.7 fb^{-1}, single-jet triggers
- Inclusive 2 jet and 3 jet and ratio R_{32}
  - As a function of $H_{T,2}/2 \equiv ½ (p_{T,1} + p_{T,2})$
- PF jets anti-k_T reco, R=0.7
- At least 2 jets with p_T>150 GeV, |y|<2.5
- Analysis cuts and unfolding as previous analysis
- R_{32} has low systematics; it's used for α_S fit
  - Scale (2-6%), PDF (2-7%), NP (1%)

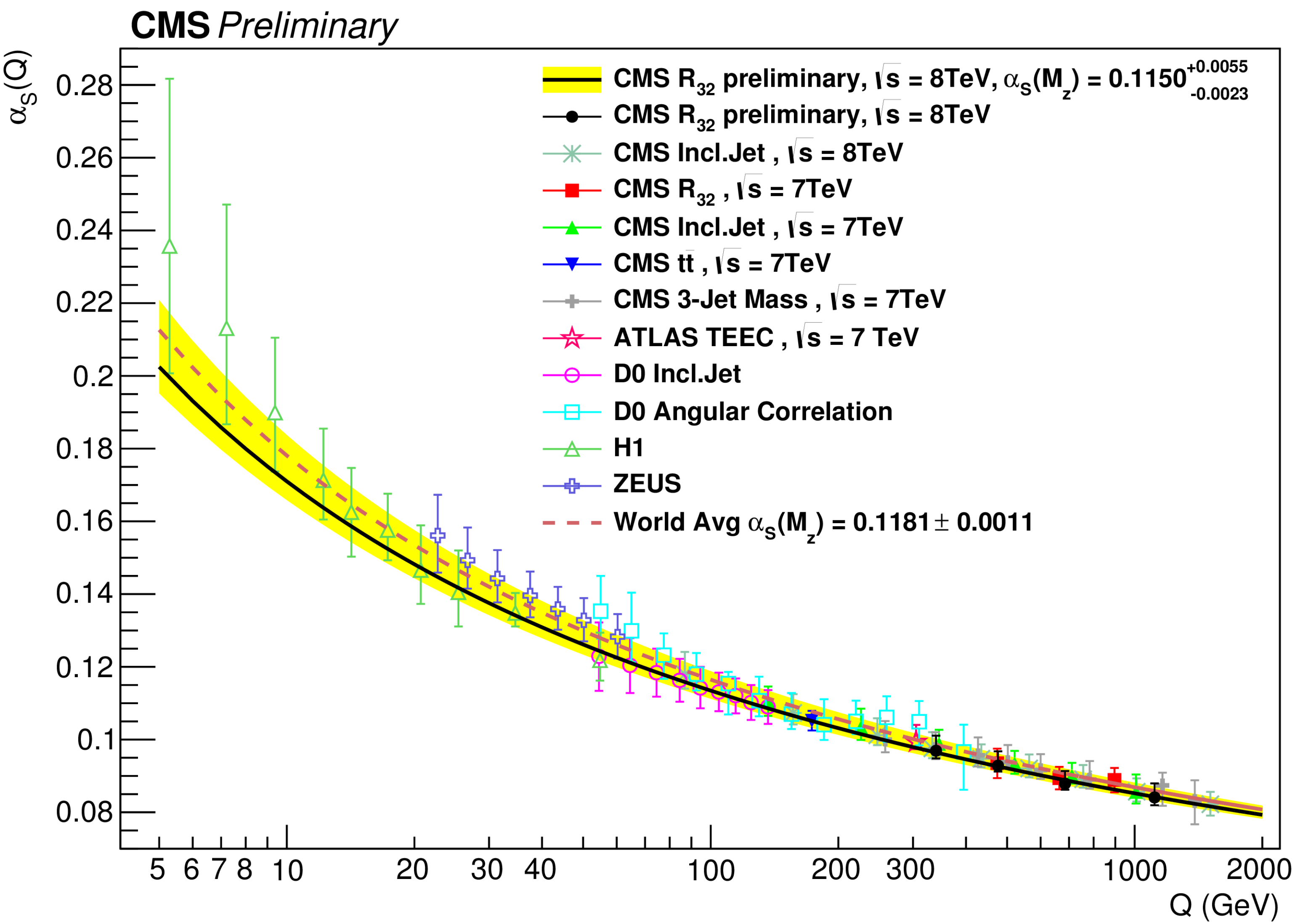




CMS-PAS-SMP-16-008



Measurement of α_S with inclusive multijets



- $\alpha_S(M_Z) = 0.115 \pm 0.0010\ (\text{exp}) \pm 0.0013\ (\text{PDF}) \pm 0.0015\ (\text{NP})_{-0}^{+0.0050}(\text{scale})$
  $= 0.115 \pm 0.0023\ (\text{all except scale})_{-0}^{+0.0050}(\text{scale})$

Measurement of α_s from transverse energy-energy correlations (TEEC) in multijet events (8 TeV)

NEW

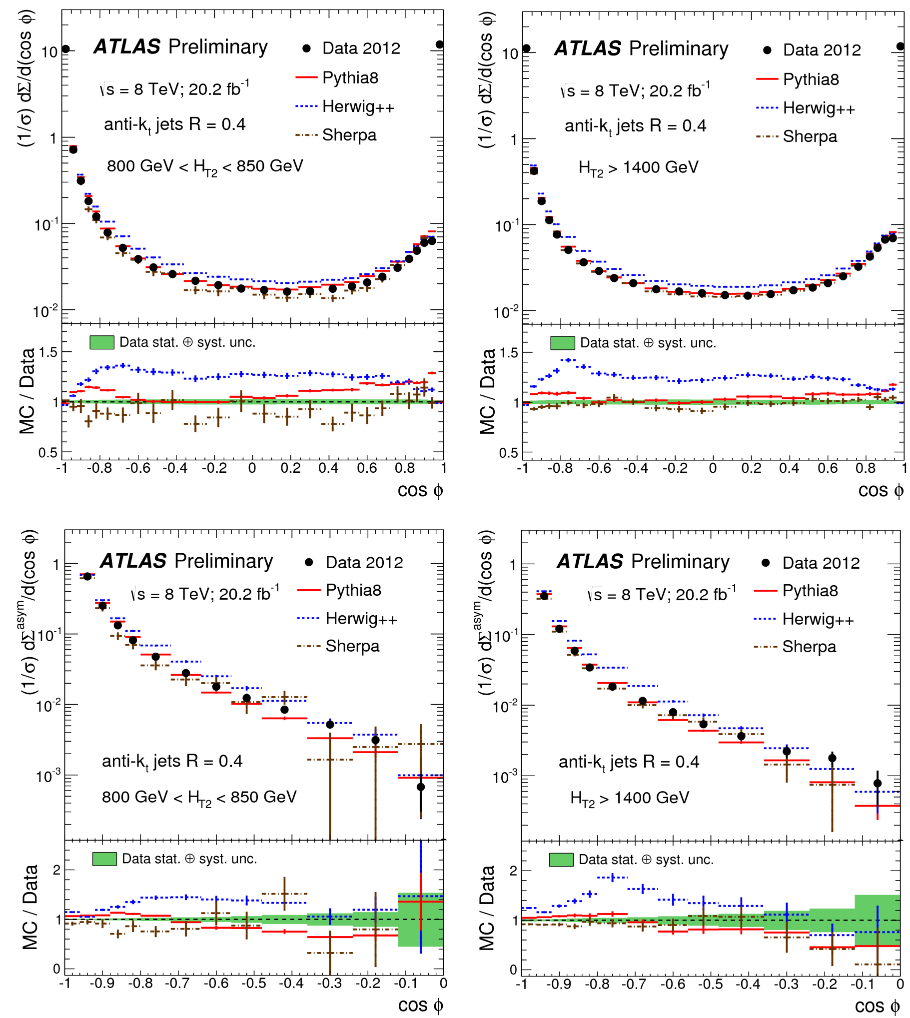
- 8 TeV, 20.2 fb^{-1}, single-jet triggers
- Calorimeter jets, anti-k_T reco, R=0.4
- Observables:

$$TEEC = \frac{1}{\sigma}\frac{d\Sigma}{dcos\varphi} \equiv \frac{1}{N}\sum_{A=1}^{N}\frac{\sum_{ij} E_{Ti}^{A} E_{Tj}^{A}}{\sum_{k}\left(E_{Tk}^{A}\right)^{2}}\delta\left(cos\varphi - cos\varphi_{ij}\right)$$

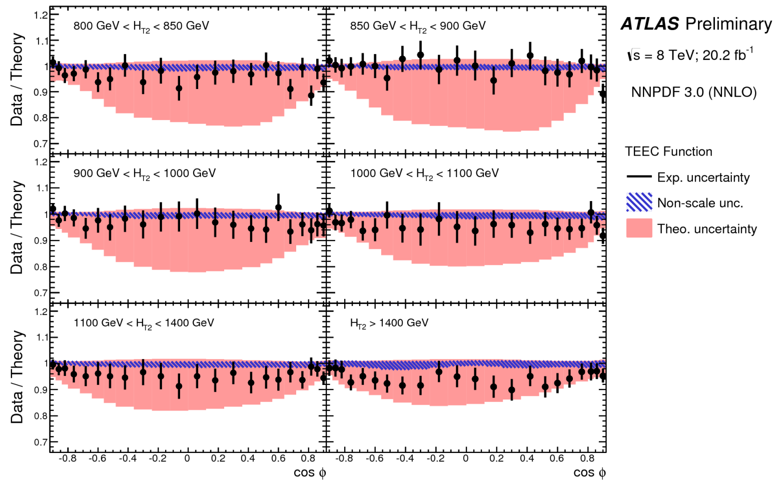
$$ATEEC = \frac{1}{\sigma}\frac{d\Sigma}{dcos\varphi}(\varphi) - \frac{1}{\sigma}\frac{d\Sigma}{dcos\varphi}(\pi - \varphi)$$

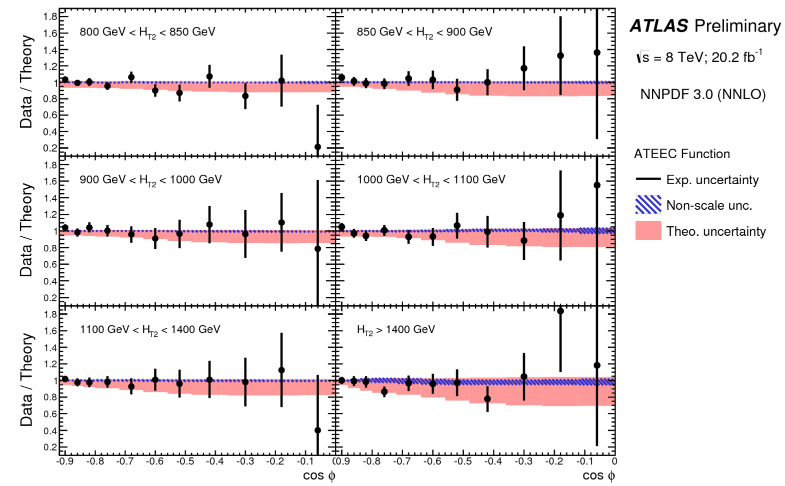
- p_T>100 GeV, |η|<2.5 $H_{T,2}$>800 GeV
- $<N_{jet}>$=2.3
- Unfolding ala D'Agostini
- Separate fits to α_s for TEEC and ATEEC

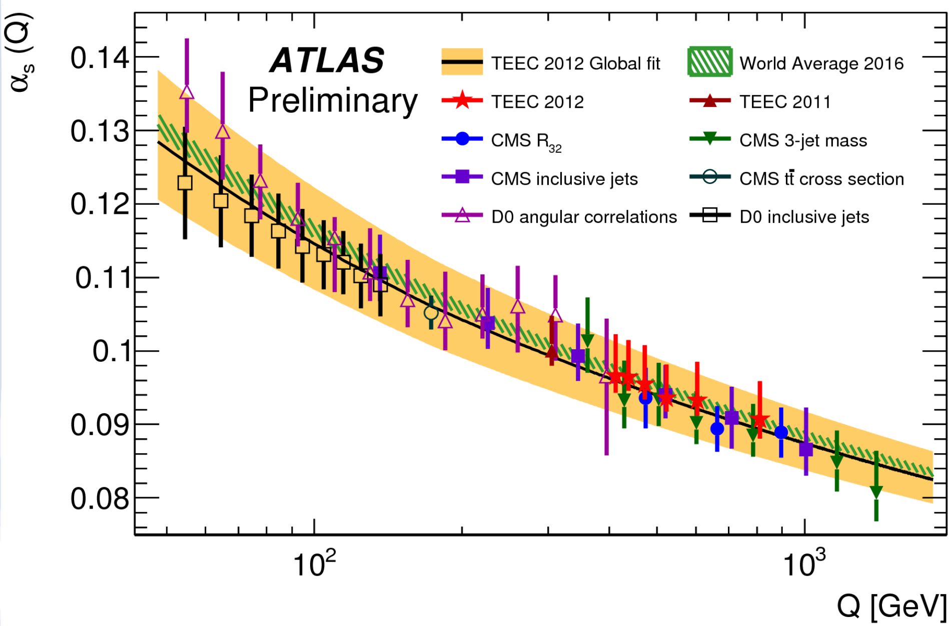
Detector-level comparisons

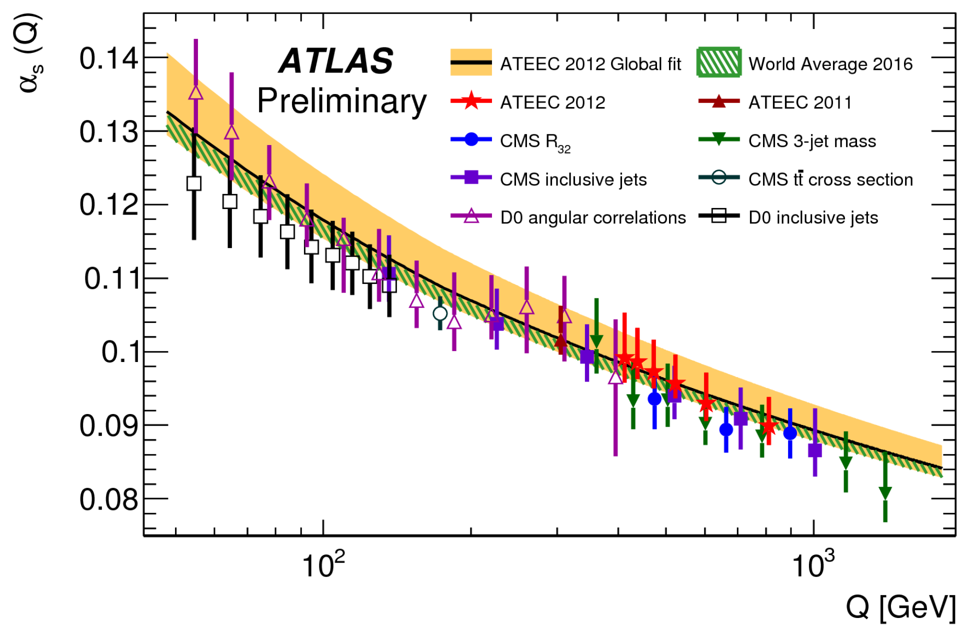


Measurement of α_s from (A)TEEC in multijet events





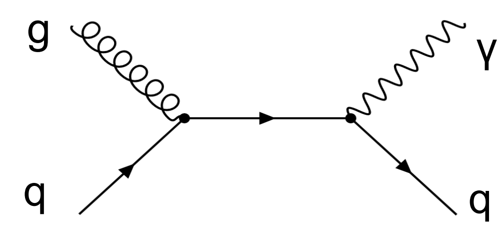


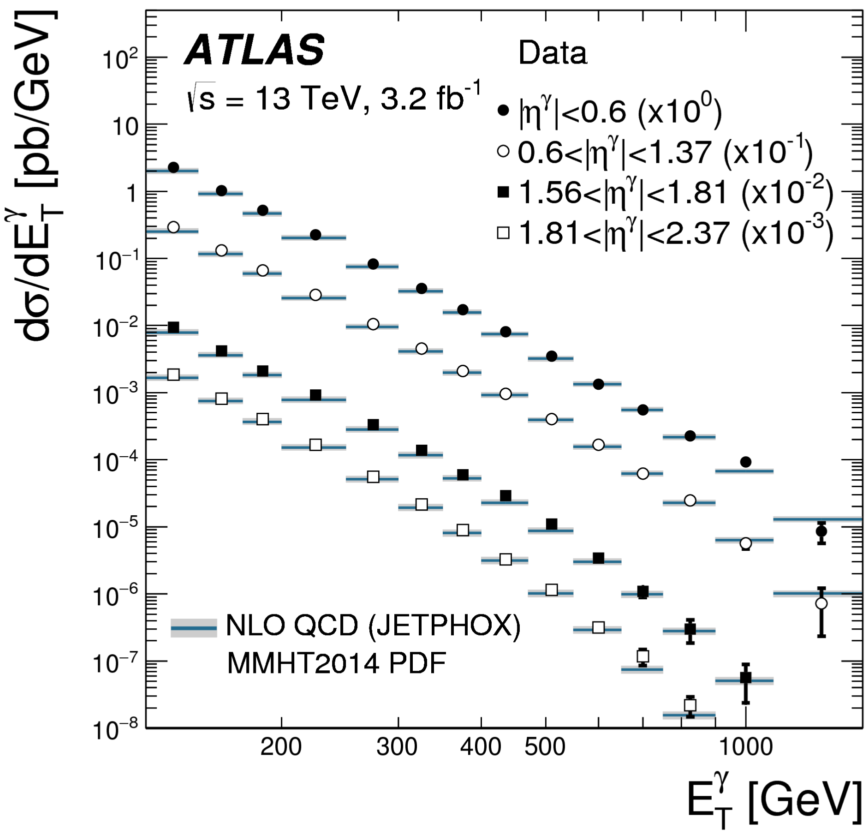


- $\alpha_S(M_Z) = 0.1196 \pm 0.0013\,(\text{exp}) \pm 0.0017\,(\text{PDF}) \pm 0.0004\,(\text{NP})_{-0.0013}^{+0.0061}(\text{scale})$
  $= 0.115 \pm 0.0023\,(\text{all except scale})_{-0}^{+0.0050}(\text{scale})$

Inclusive isolated photon (13 TeV)

- All photons that are not secondaries from hadron decays are considered prompt
  - Direct and fragmentation photons
- Dominant production at LHC **qg → qγ**
- Use inclusive isolated photons to constrain gluon PDF, Tune MC, understand backgrounds in isolated-photon searches
- 13 TeV, 3.2 fb^{-1}, single-photon 120 GeV trigger, fully efficient above 125 GeV
- $E_T^\gamma > 125$ GeV, $|\eta^\gamma| < 2.4$ (excluding trans. region)
- 4 η^γ regions considered
- Photon ID based on HAD calo cuts and EM lateral shower shapes – converted if there is associated track or conversion vertex
- Energy-based isolation with a sliding cut $E_T^{iso} < 4.8 + 4.2\times10^{-3}\times E_T^\gamma$ (GeV)
- QCD background (π/η) estimated with data-driven iso vs tightness method

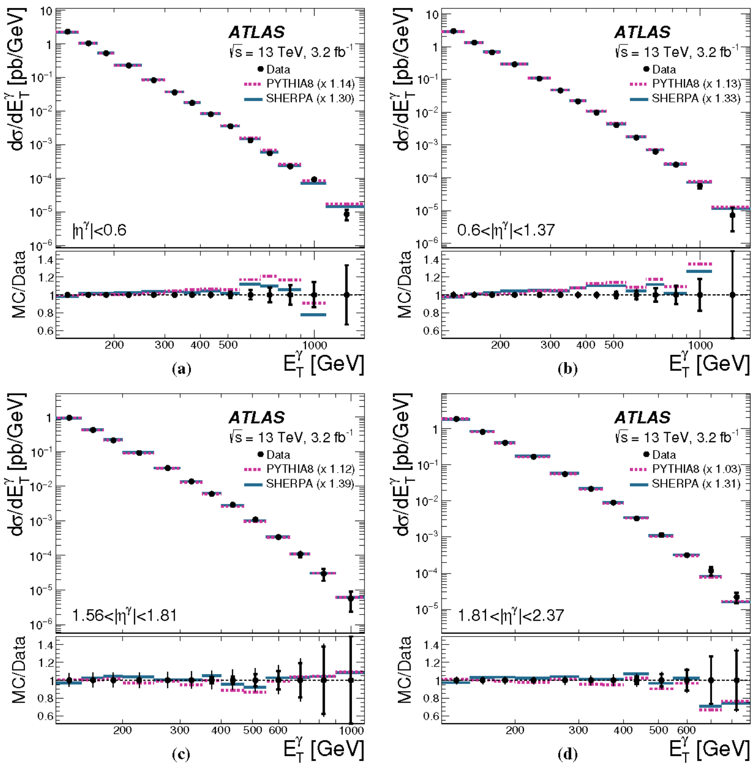




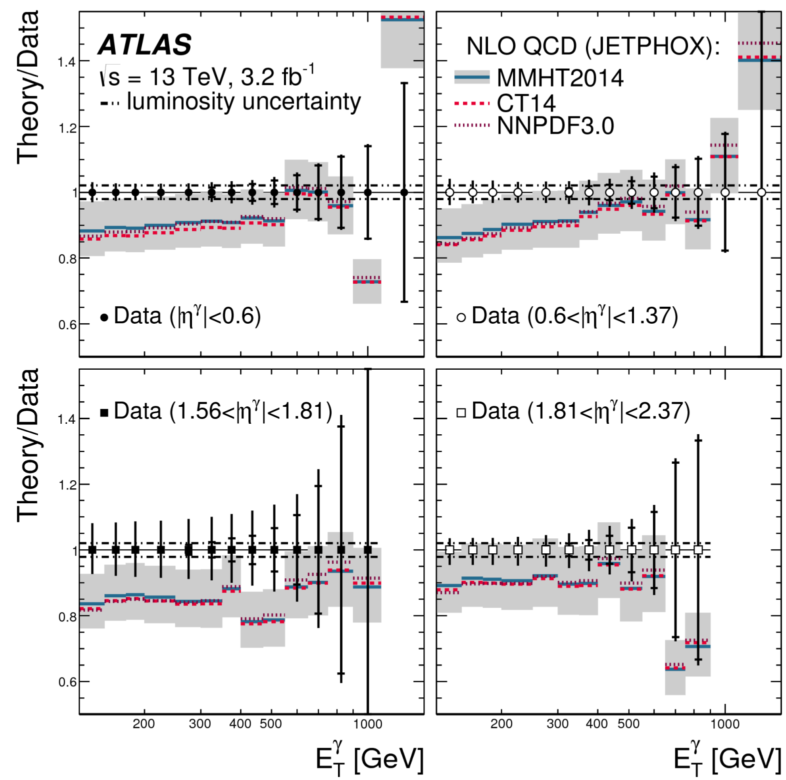
Phys.Lett. B770, 473 (2017)

Inclusive isolated photon (13 TeV)

Unfolded data compared to LO

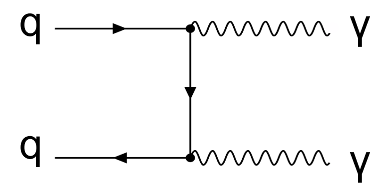


Unfolded data compared to NLO

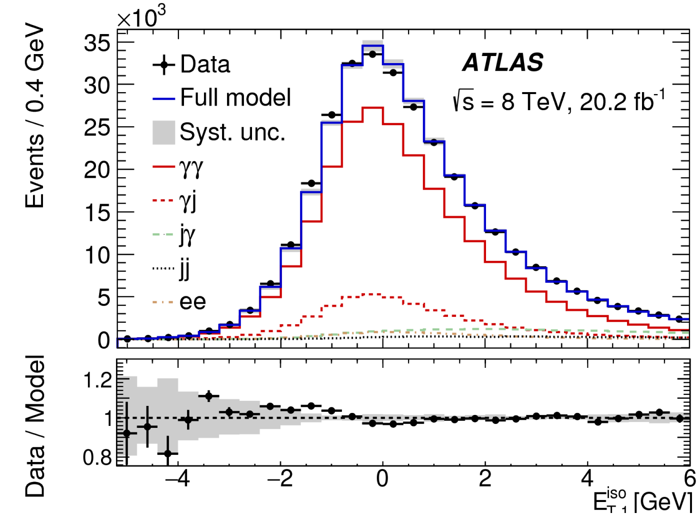


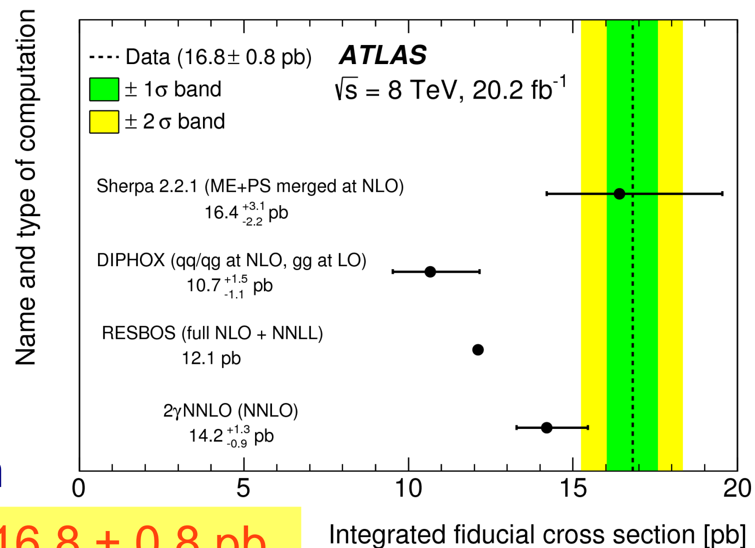
- Bin-by-bin unfolding
- Main Exp uncertainties: Photon energy scale and resolution, ID efficiency and QCD modeling (total 2 -19% depending on η and p_T)
- Main Theo uncertainties: Scales, PDF, α_S ,UE (total 10-15%, mostly due to scales)

Pair of isolated photons (8 TeV)



- Systematics reduced by factor of 2, due to better background estimation (compared to 7 TeV work)
- Observables $\Delta\varphi_{\gamma\gamma}$, $m_{\gamma\gamma}$, $|\cos\theta^*|=\tanh(|\Delta\eta_{\gamma\gamma}|/2)$, $p_{T,\gamma\gamma}$, $\varphi^*=\tan[(\pi-\Delta\varphi_{\gamma\gamma})/2]$, a_T (component of $p_{T,\gamma\gamma}$ along the thrust axis)
- Comparisons with NNLO pQCD, NLO+parton shower, NLO+resummation of soft gluons at NNLL
- 8 TeV, 20.2 fb^{-1}, Diphoton trigger (35 GeV, 25 GeV)
- Dominant background: QCD jet+fake photon
- Same pseudorapidity cuts as previous analysis
- $E^{\gamma}_{T,1}>40$ GeV, $E^{\gamma}_{T,2}>30$ GeV, $\Delta R_{\gamma\gamma}>0.4$
- Apply both energy and track isolation (6 GeV and 2.6 GeV, respectively)
- Create templates for jj, γj, jγ from data and γγ from Sherpa MC
- Fit in $E^{\gamma}_{T,ISO,1}$ vs $E^{\gamma}_{T,ISO,2}$ space

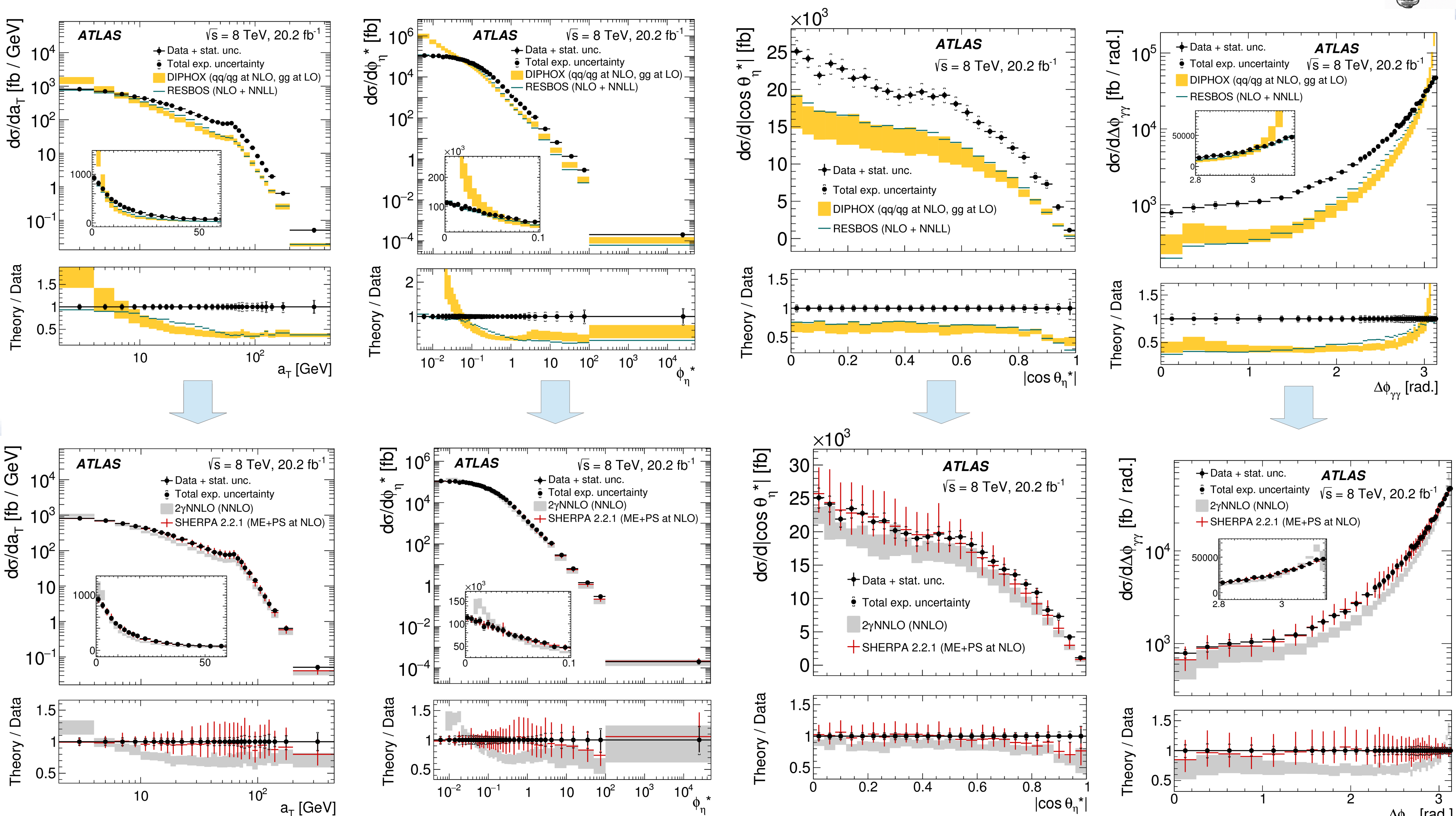




$\sigma = 16.8 \pm 0.8$ pb

arXiv: 1704.03839, submitted to PRD

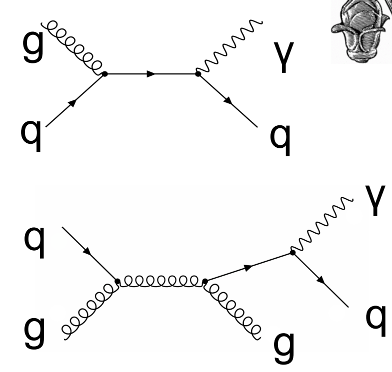
Pair of isolated photons (8 TeV)

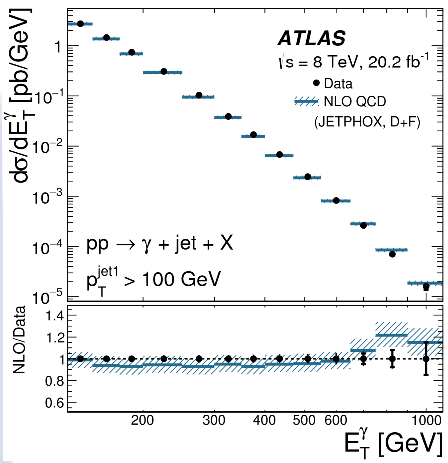


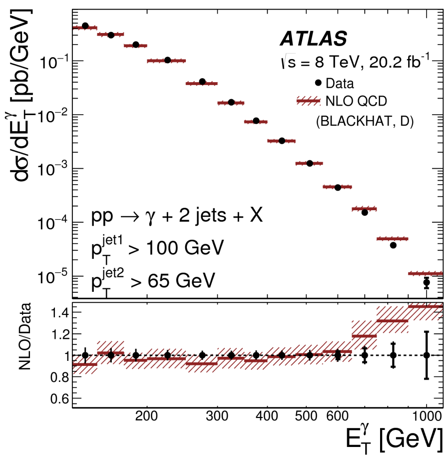
- DiPhox and Resbos don't describe data – 2γγNLO better, <u>Sherpa the best</u>

Photon+jets (8 TeV)

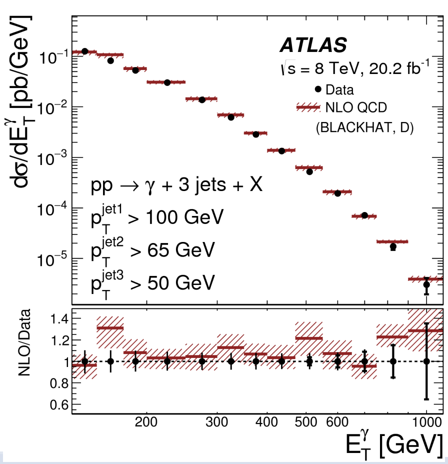
- 8 TeV, 20.2 fb^{-1}, single-photon 120 GeV
- At least one photon with E^{γ}_{T}> 130 GeV and $|\eta^{\gamma}|$ <2.37 (excl. trans.), transverse-energy-based isolation in cone of ΔR=0.4
- At least one calo jet, anti-k_T reco, R=0.6, ΔR>1 away from photon
- A rich set of observables: E^{γ}_{T}, p^{j}_{T}, $m^{\gamma j}$, $|\cos\theta^{*}|$, $\Delta\varphi^{jj}$, $\Delta\varphi^{jj}$







Final state	Measured cross section [pb]	NLO QCD prediction JETPHOX/ BLACKHAT [pb]	PYTHIA prediction [pb]	SHERPA prediction [pb]
Photon plus one-jet	134 ± 4	128^{+11}_{-9} (J)	120	132
Photon plus two-jet	30.4 ± 1.8	$29.2^{+2.8}_{-2.7}$ (B)	26.4	27.4
Photon plus three-jet	8.7 ± 0.8	$9.5^{+0.9}_{-1.2}$ (B)	8.2	7.9



- γ + jet : Best described by Jetphox
- γ + 2/3 jets : Best described by Blackhat (Sherpa better than Pythia)

Nucl.Phys. B918 (2017) 257-316

And theorists are keeping up

- As of November 4, 2016, we have NNLO inclusive jet cross section calculations (arXiv:1611.01460)

PRL **118,** 072002 (2017) PHYSICAL REVIEW LETTERS week ending 17 FEBRUARY 2017

Next-to-Next-to Leading Order QCD Predictions for Single Jet Inclusive Production at the LHC

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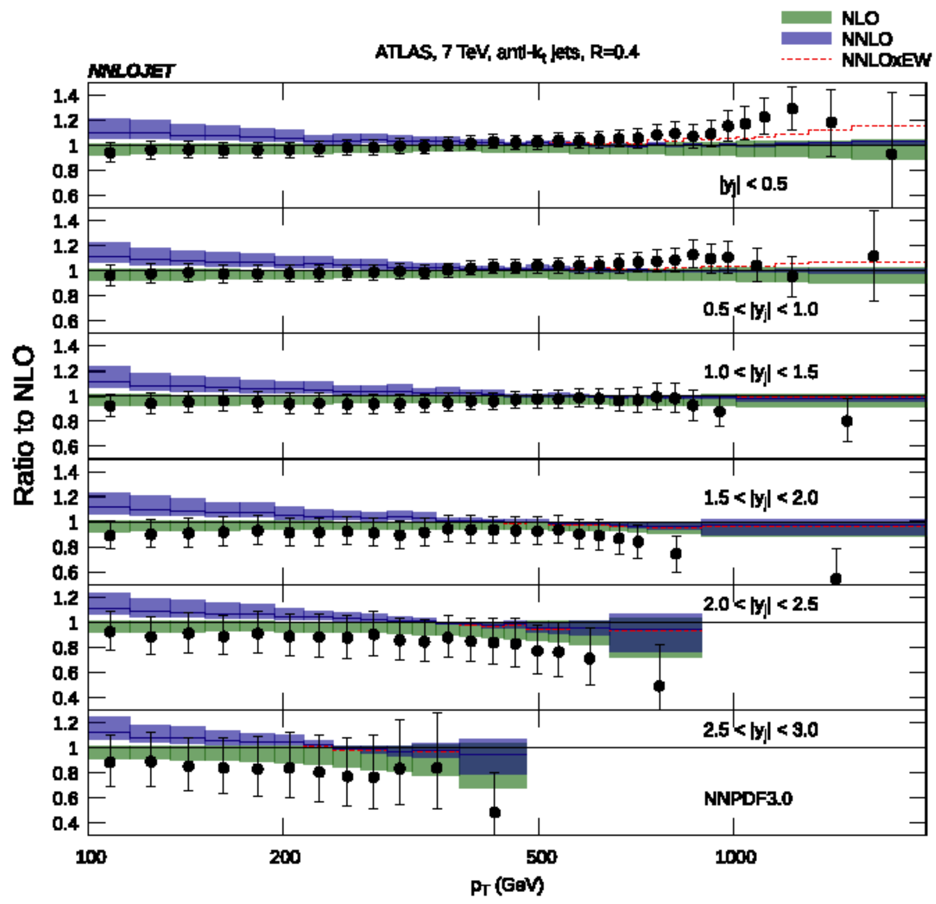
(Received 16 November 2016; published 17 February 2017)

We report the first calculation of fully differential jet production at leading color in all partonic channels at next-to-next-to leading order in perturbative QCD and compare to the available ATLAS 7 TeV data. We discuss the size and shape of the perturbative corrections along with their associated scale variation across a wide range in jet transverse momentum, p_T, and rapidity, y. We find significant effects, especially at low p_T, and discuss the possible implications for parton distribution function fits.



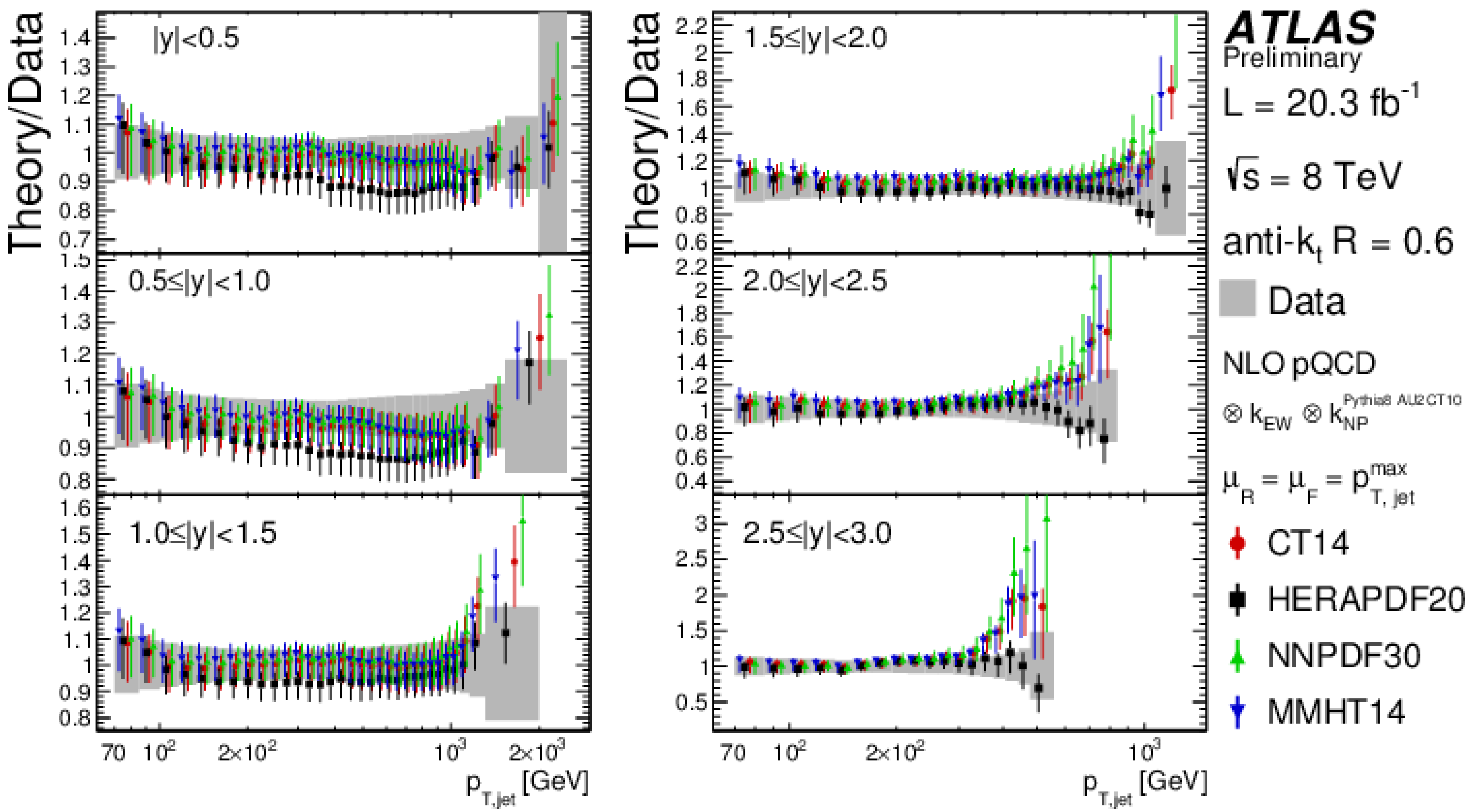
- Problem is that the NNLO prediction is moving away from ATLAS data
- Possible explanation: The NNLO PDF used in the measurement had wrong assumptions about the NNLO effects. Also low p_T data were not included in that PDF fit --- Finally, also the choice of scale (leading jet p_T or average jet p_T) could be the culprit, according to authors.

Conclusions

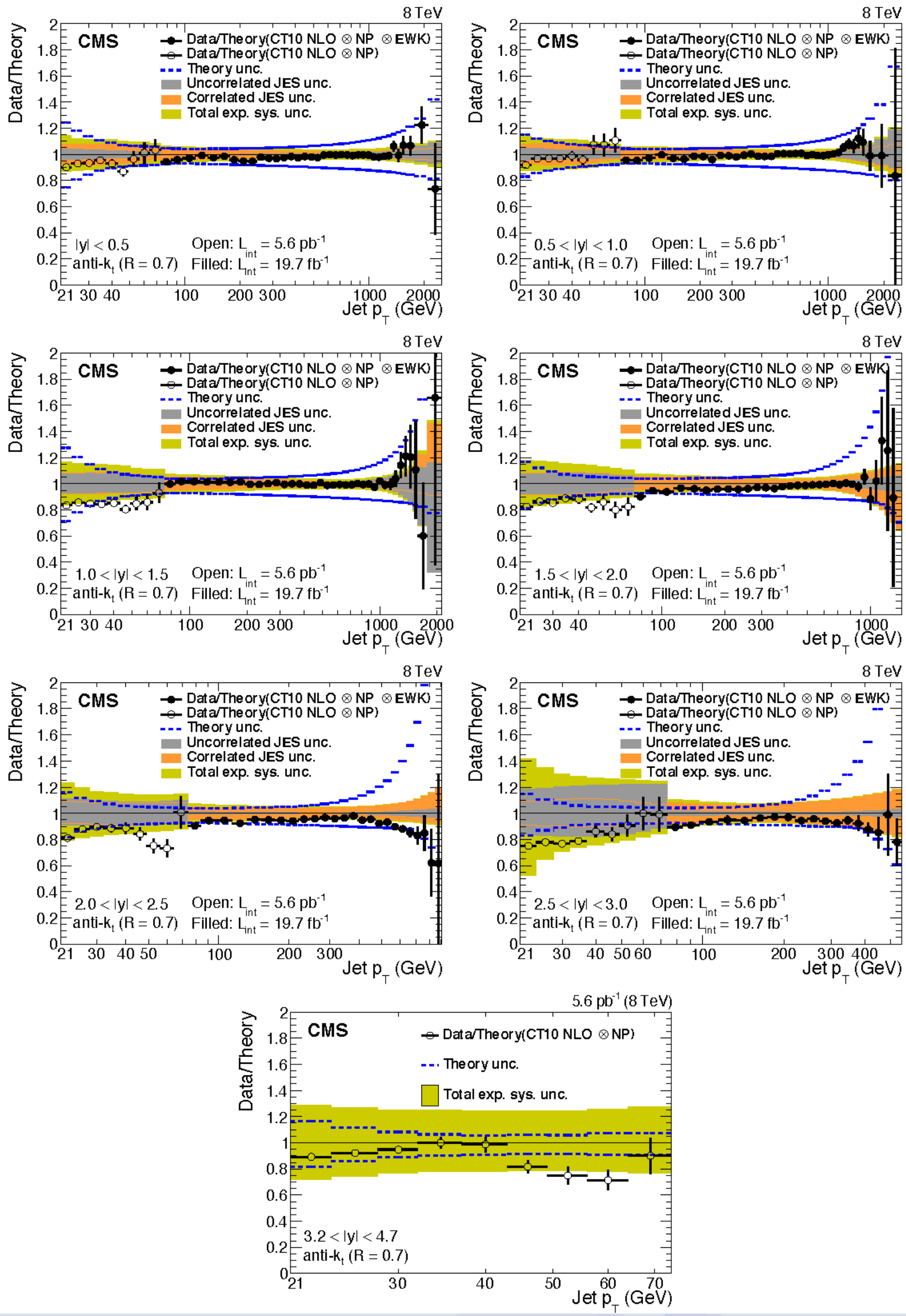
- Presented only some of the most recent QCD analyses at CMS and ATLAS
  - Please find the long list of analyses at current and previous LHC energies at
    - CMS:http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html
    - ATLAS:https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
- The interplay between experimental measurement and theoretical predictions continues and it is very fruitful
  - PDF and α_S determined with higher and higher accuracy
  - Angular and energy distributions of jets/photons studied in detail
  - Non-perturbative and fixed order calculations fine tuned
  - Still several topologies and phase space regions that need to be understood by both experimentalists and theorists

Backup

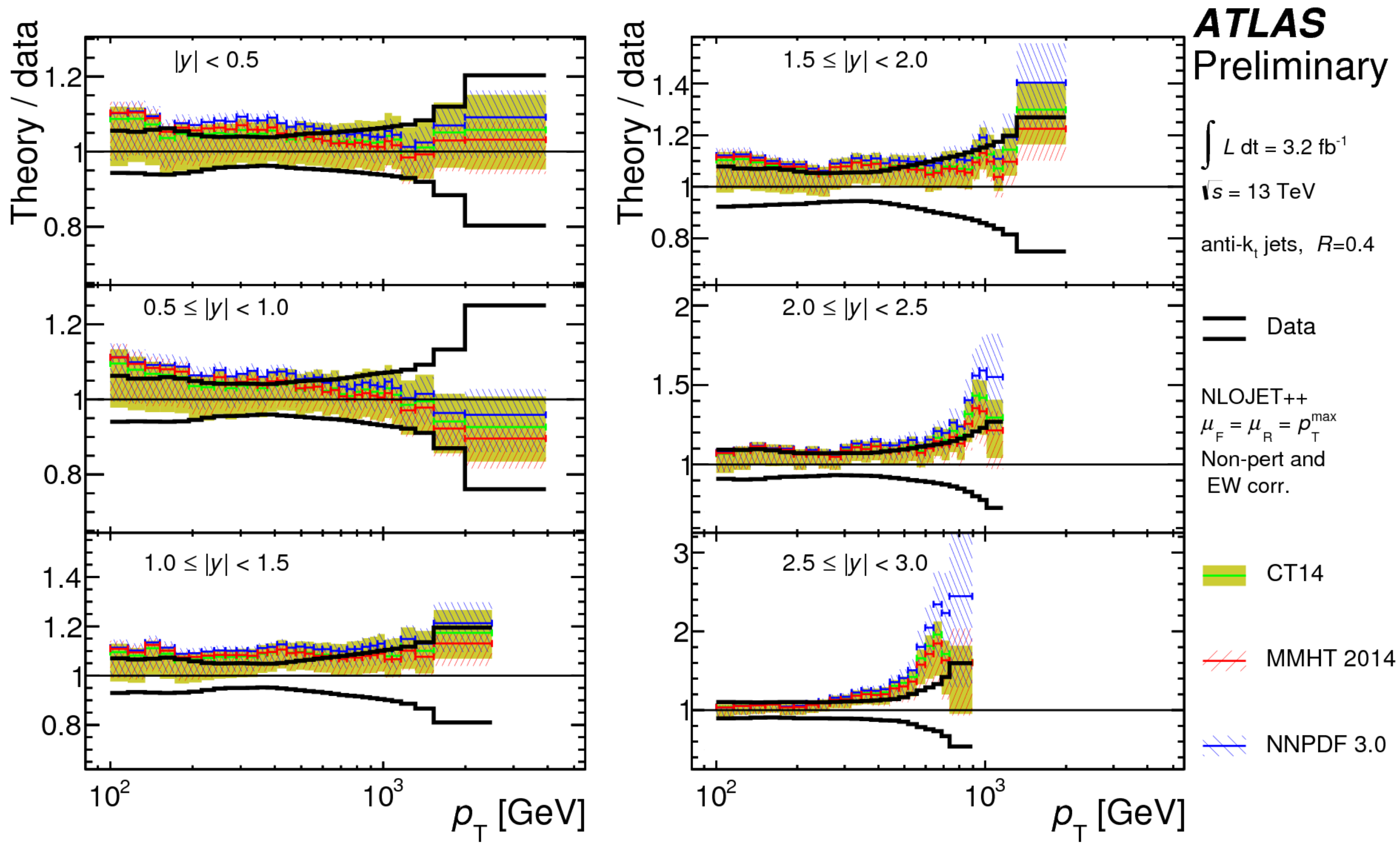
ATLAS inclusive jet cross section (8 TeV)



CMS inclusive jet cross section (8 TeV)



ATLAS inclusive jet cross section (13 TeV)



CMS inclusive jet cross section (13 TeV)