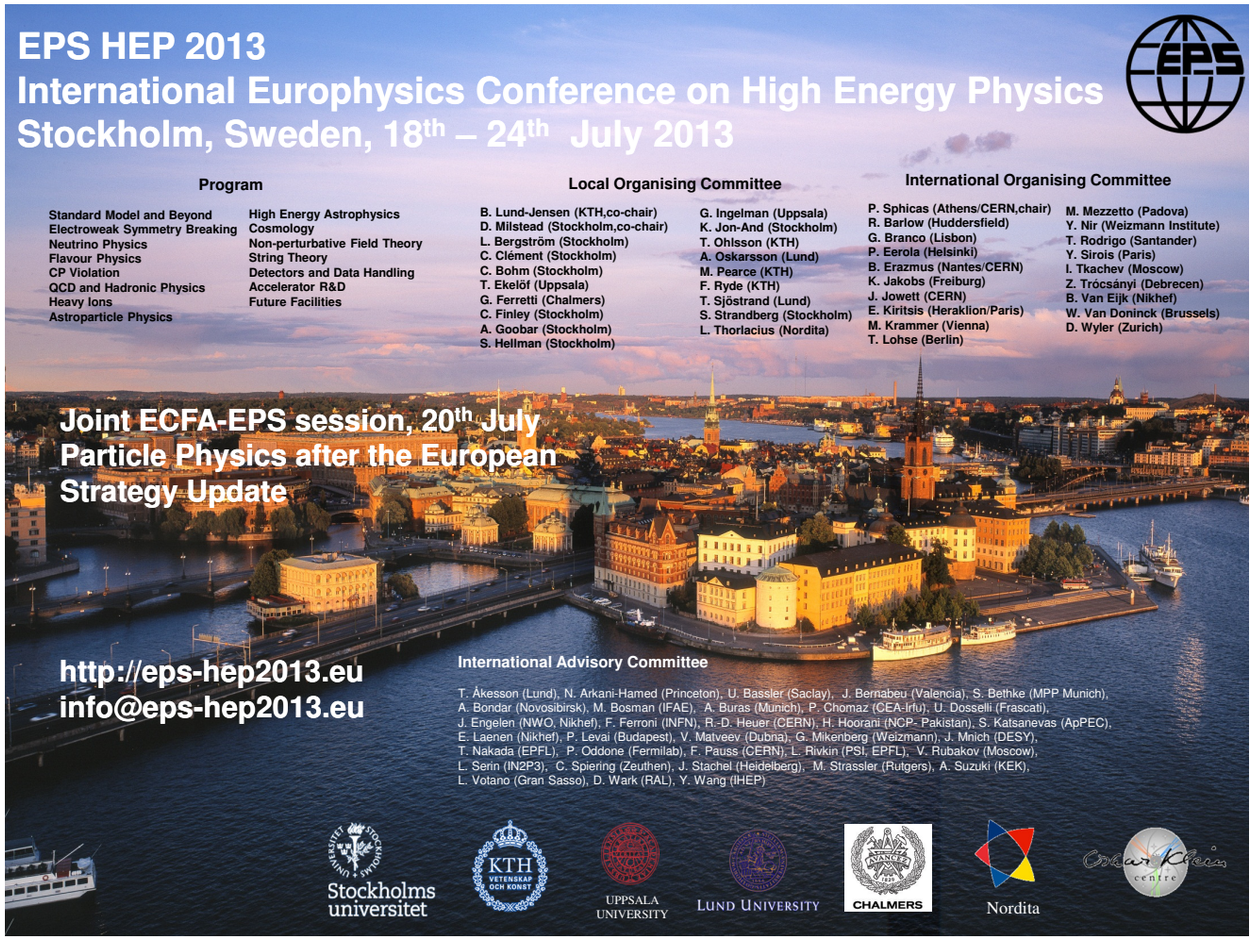
Recent Results on Experimental QCD

Konstantinos Kousouris



Outline

- introduction
- soft QCD & radiation effects
- perturbative QCD & PDFs with jets
- measurements of α_S
- photon production
- associated production of jets with vector bosons

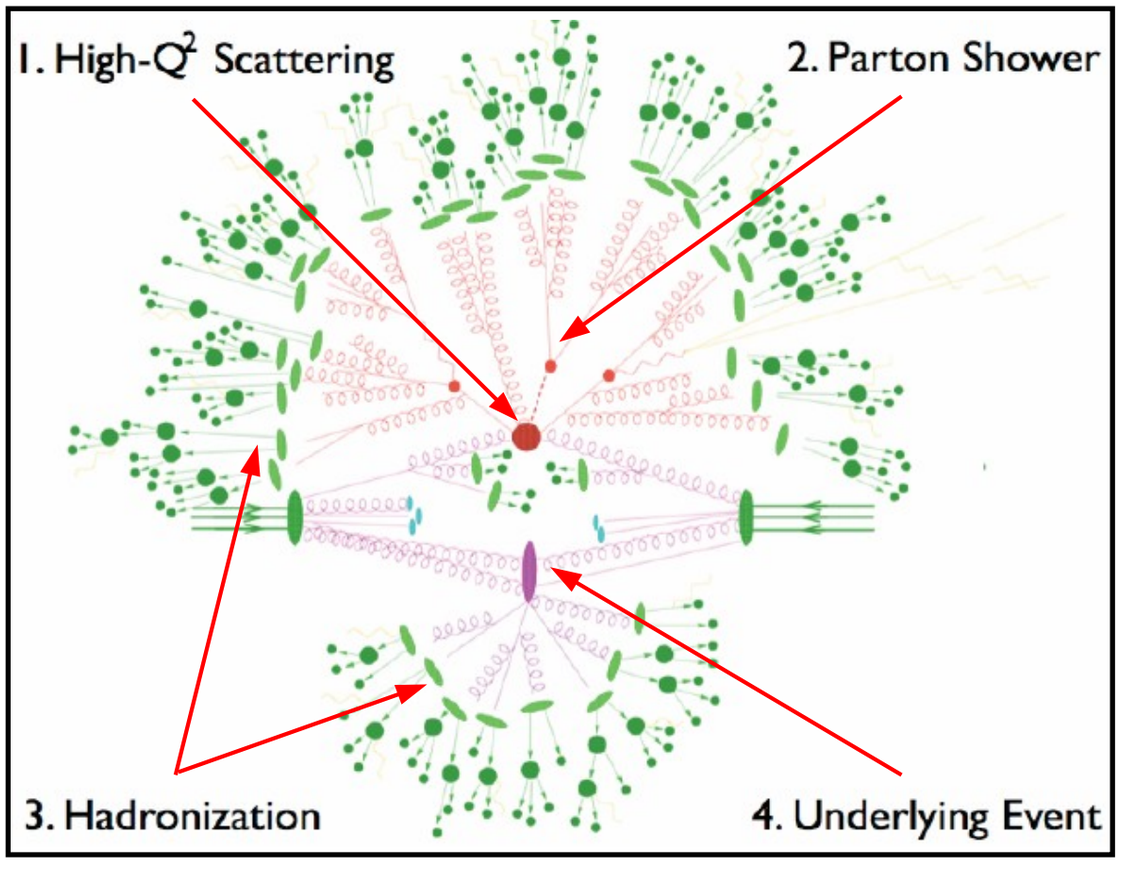
A very incomplete list of topics

- **latest results with new insights on QCD**
  - **primarily from LHC but also from Tevatron & HERA**
- **many important results are not shown**
  - **many more results presented at the QCD parallel sessions and posters**

Hadron colliders & detectors

- **Large Hadron Collider at CERN**
  - in operation since 2009
  - delivered proton-proton collisions at 900 GeV, 2.76, 7, & 8 TeV
  - also delivered Pb-Pb and p-Pb collisions (not discussed here)
  - 4 detectors/experiments: ATLAS, CMS, ALICE, LHCb
- **Tevatron at Fermilab**
  - Run II lasted from 2002 to 2011
  - delivered proton-anti-proton collisions at 300, 900 GeV & 1.96 TeV
  - total integrated luminosity per experiment 10 fb^{-1}
  - 2 detectors/experiments: CDF, D0
- **HERA at DESY**
  - Run ended in 2007
  - delivered electron-proton collisions at 318 GeV
  - 2 detectors/experiments: H1, ZEUS

The complexity of QCD



- QCD events: immensely complicated
  - theoretical predictions very hard
  - experimental challenges
- basic elements of a QCD process
  - structure of the proton
    - ➡ *encapsulated into the universal PDFs*
  - hard scatter
    - ➡ evaluated with perturbation theory
  - parton shower & hadronization
  - multiple parton scattering & underlying event activity
    - ➡ approximated by Monte-Carlo programs with few tunable parameters
- practical QCD: the elements above can be factorized and combined at the end
  - reasonable approximation for hard enough processes

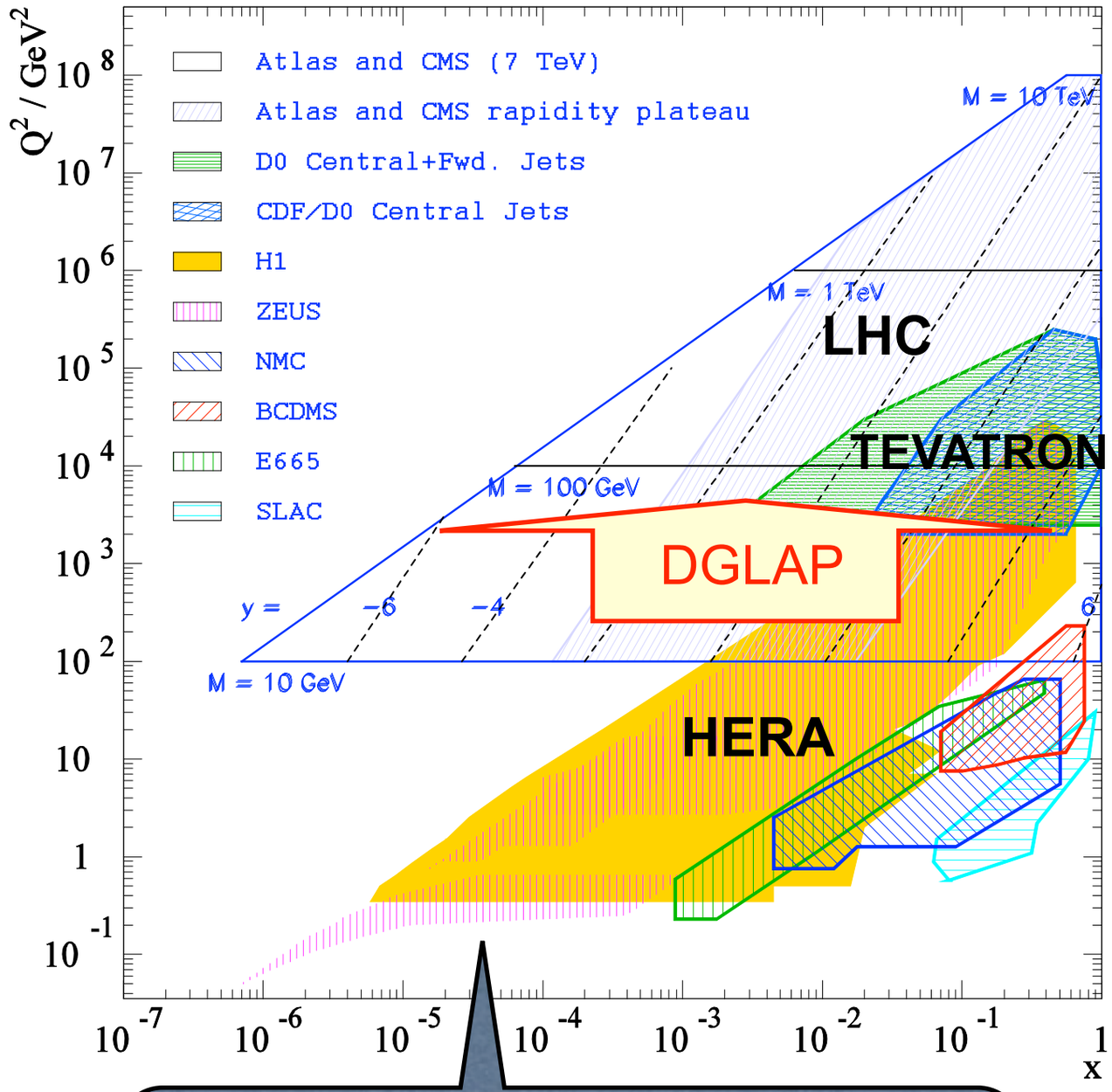
Why do we care about QCD?

- **it is interesting !!**
  - very rich theory: deserves exploration and understanding

- **it is inevitable !!**
  - hadron collisions: QCD always present

- **important background for new physics searches**
  - enormous cross section: QCD can hide many possible signals of new physics

- **introduces uncertainties on other measurements**
  - e.g. uncertainties on the PDFs affect the measured Higgs properties



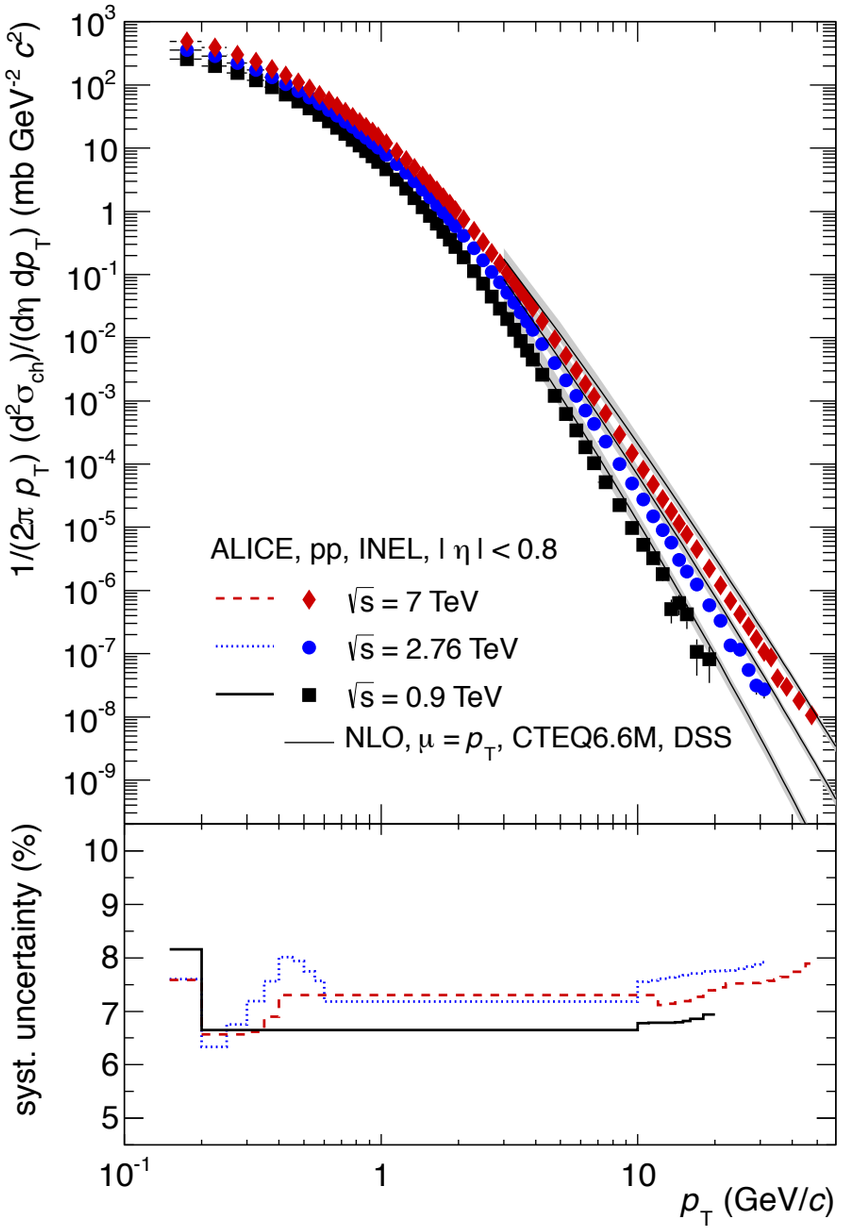
soft QCD & radiation effects

Charged particle p_T spectra

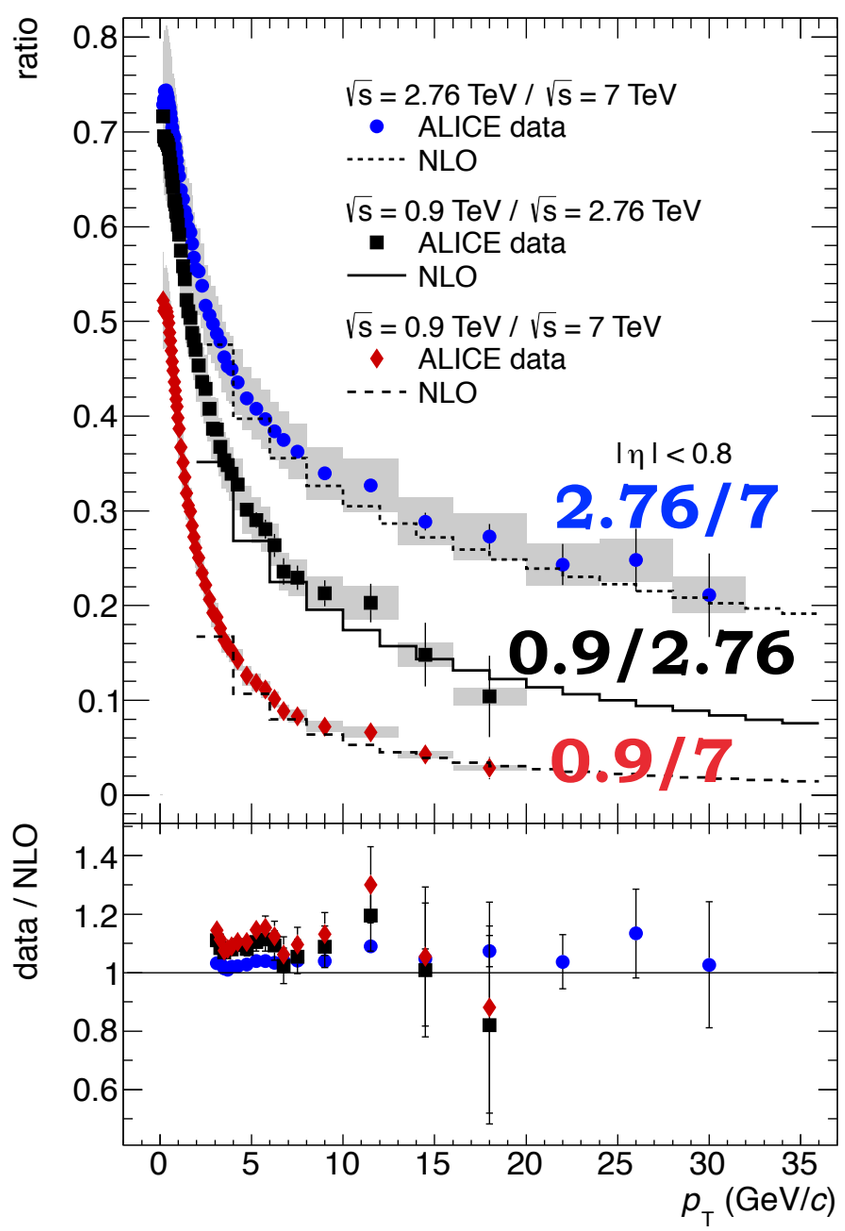
arXiv:1307.1093

- ALICE: a detector for HI studies
  - also pursuing a pp program
- fundamental measurement
  - test of pQCD
  - input for MC tuning
  - reference for HI collisions
- three collision energies
  - 0.9, 2.76, 7 TeV
- theory overshoots individual collision energy spectra by a factor 2
  - contradicts the jet data: what does it mean for parton-to-hadron FFs?
- good description of collision energy dependence

Absolute cross sections

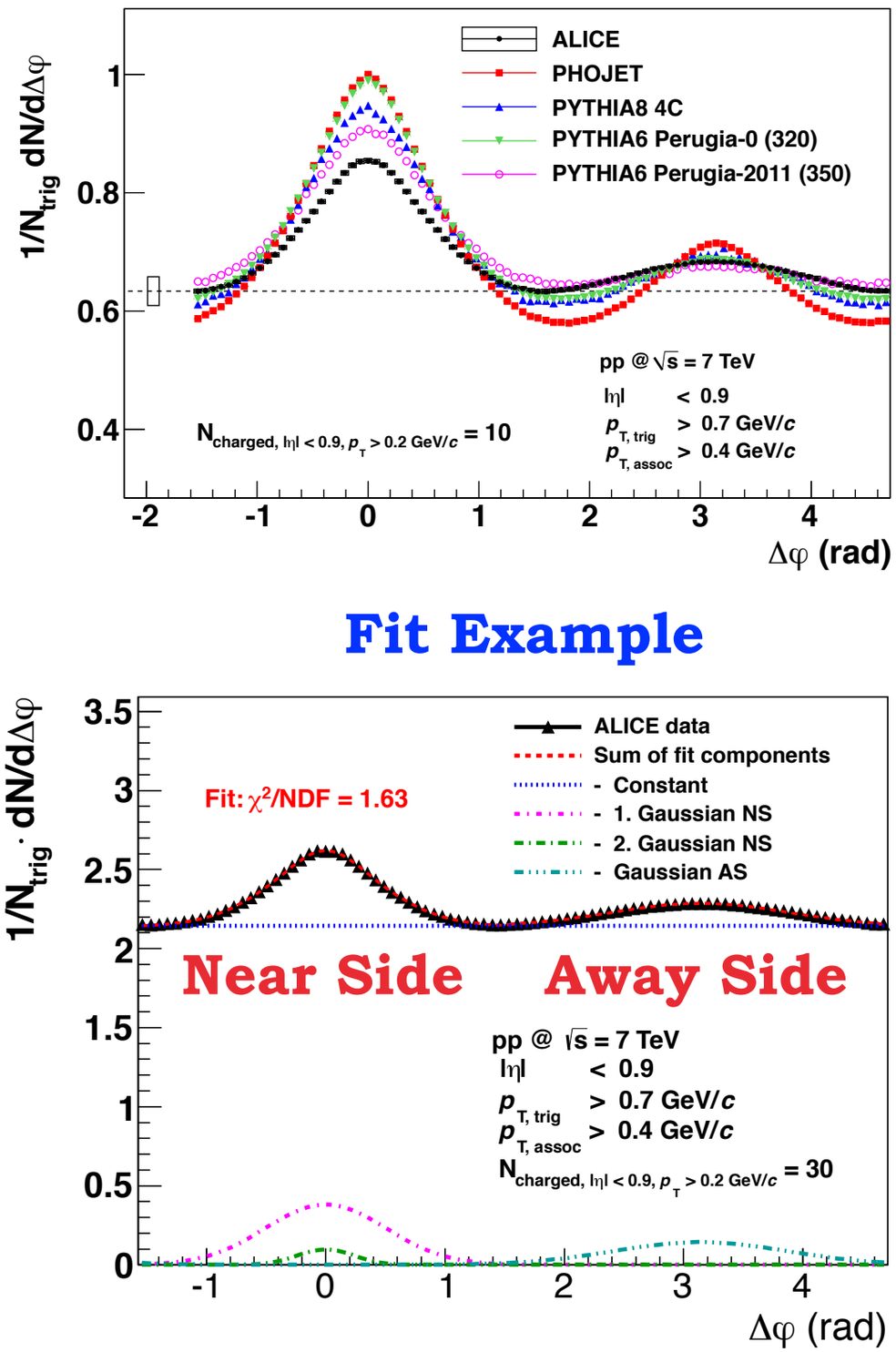


Ratios



Two-particle azimuthal correlations

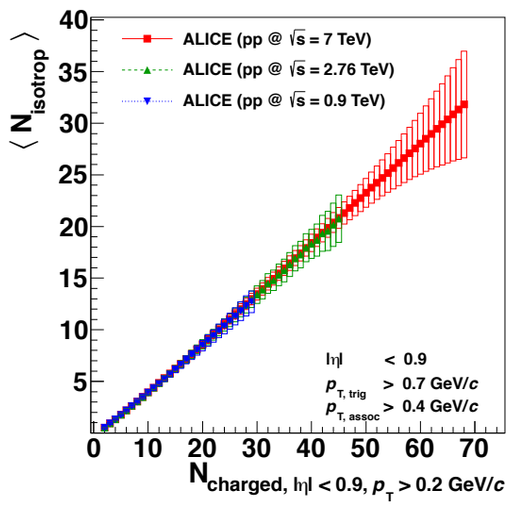
arXiv:1307.1249



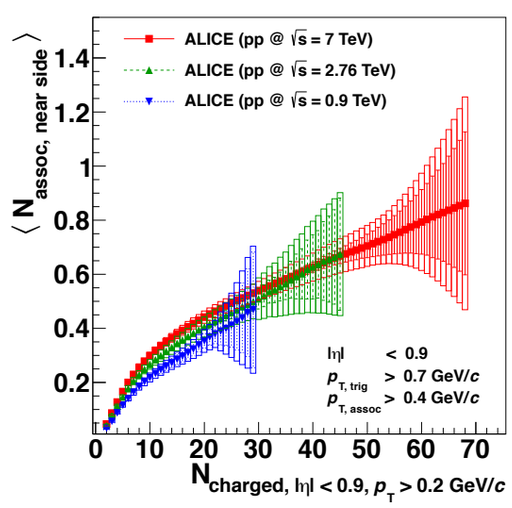
- probe the mechanism of particle production
  - **key measurement for MC tuning**
  - near-side ($\phi \sim 0$) due to parton fragmentation
  - opposite side ($\phi \sim \pi$) due to back-to-back fragments
- measurement
  - 3 pp collision energies (0.9, 2.76, 7 TeV)
  - 4-component fit to extract the yields
- correlations vs multiplicity
  - no MC model can describe all regions
  - models tuned to LHC data perform better

Fit Example

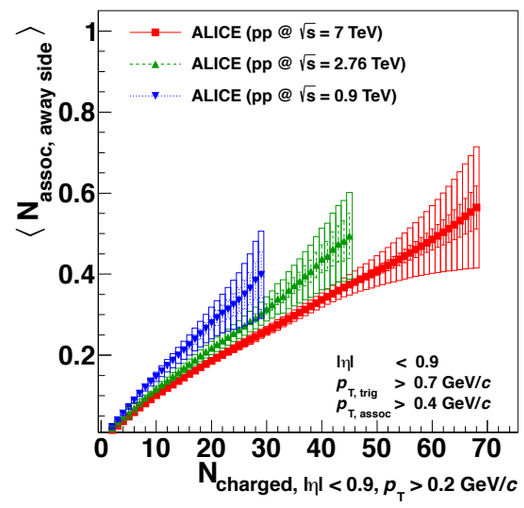
Combinatorics



Near Side



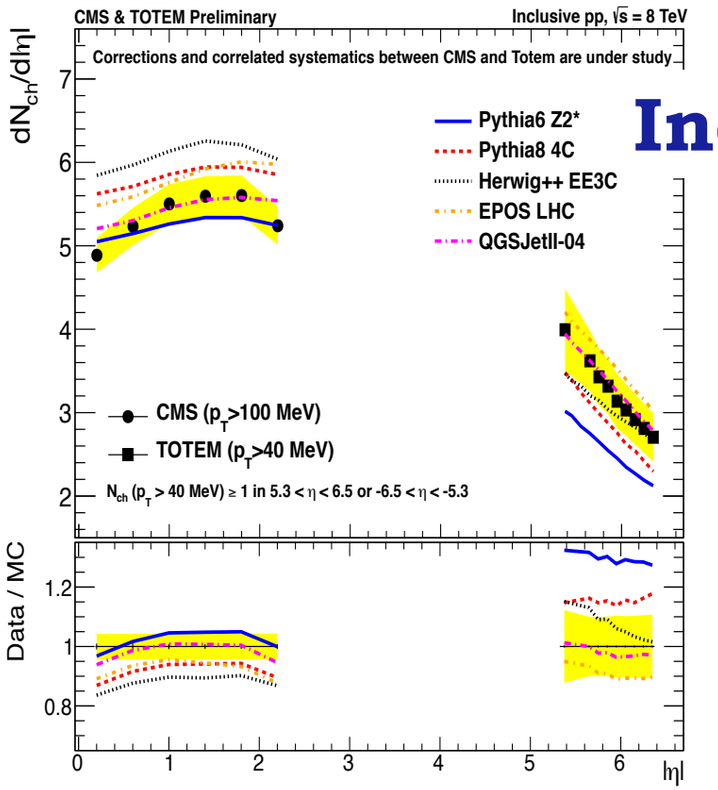
Away Side

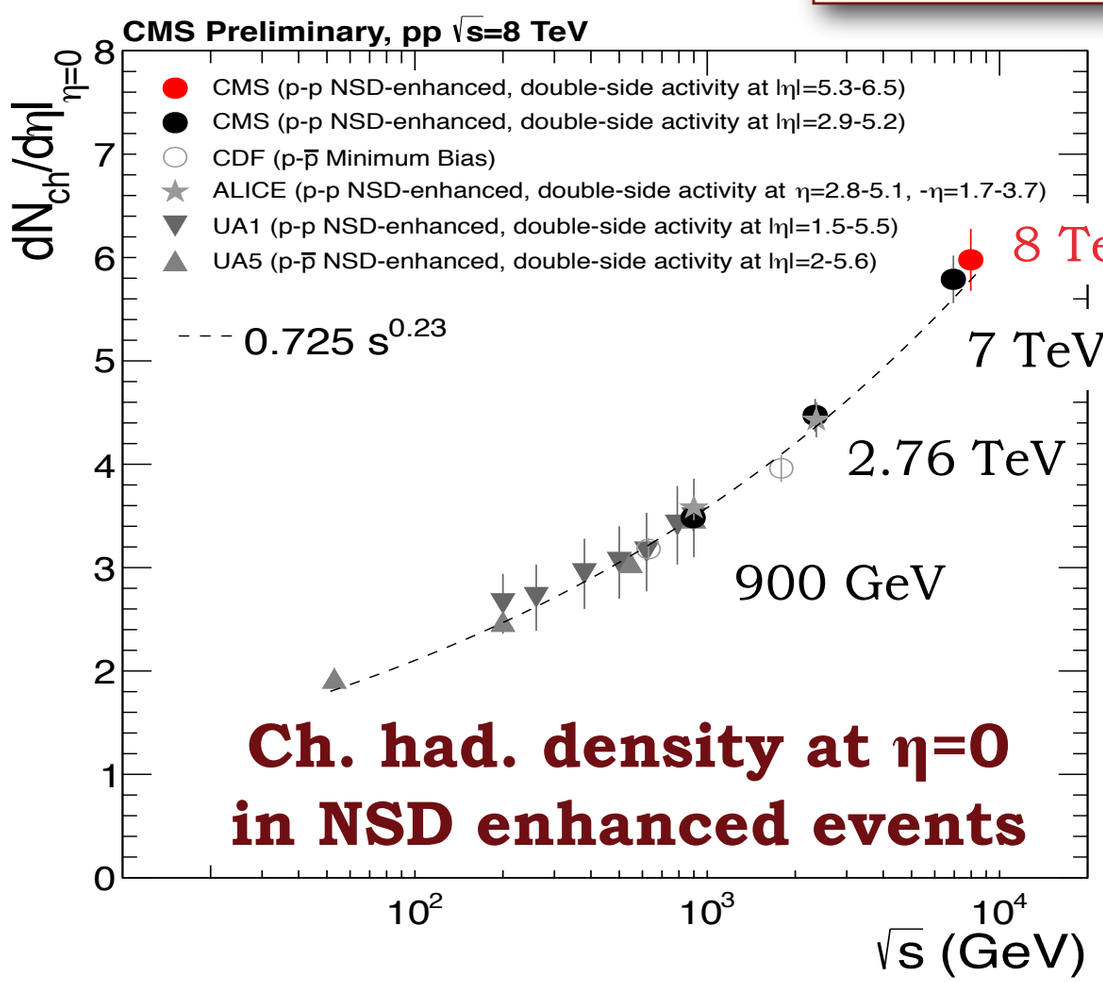


Hadron production in pp @ 8 TeV

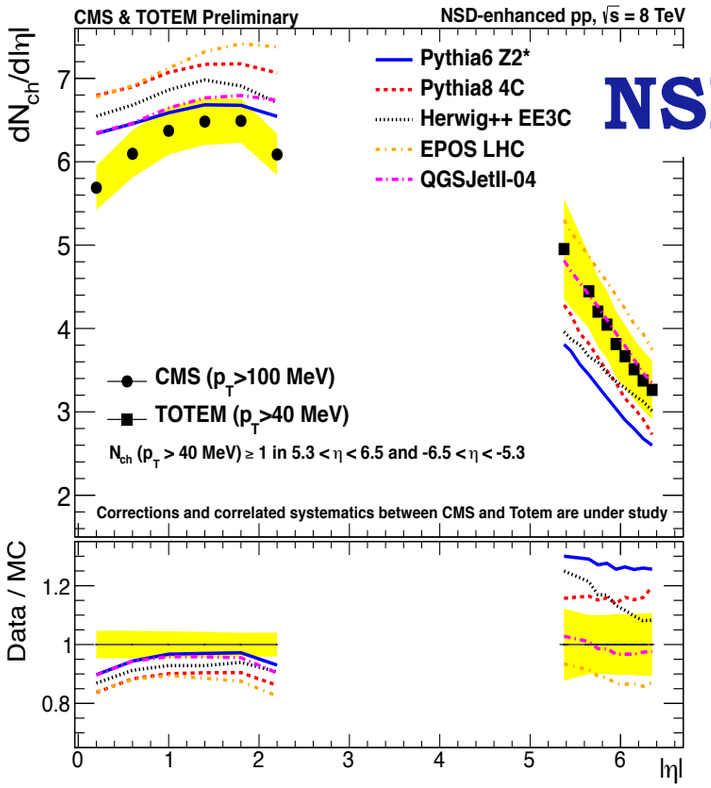
CMS-PAS-FSQ-12-026

Inclusive





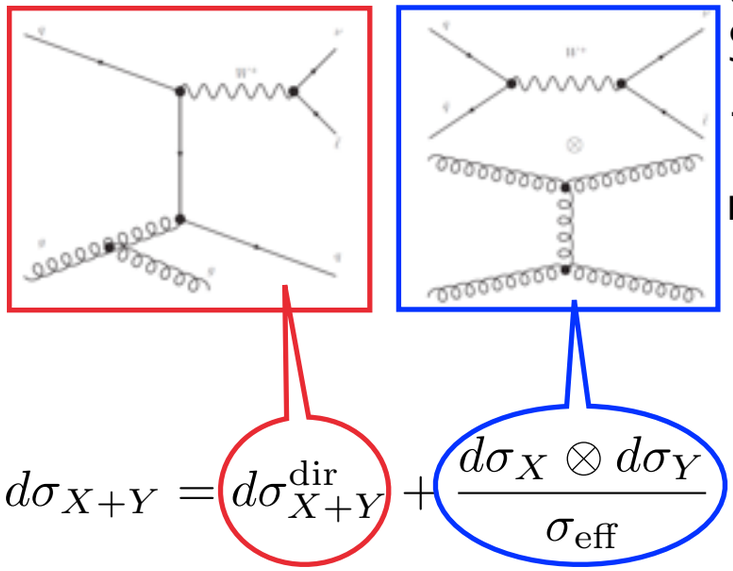
NSD enhanced



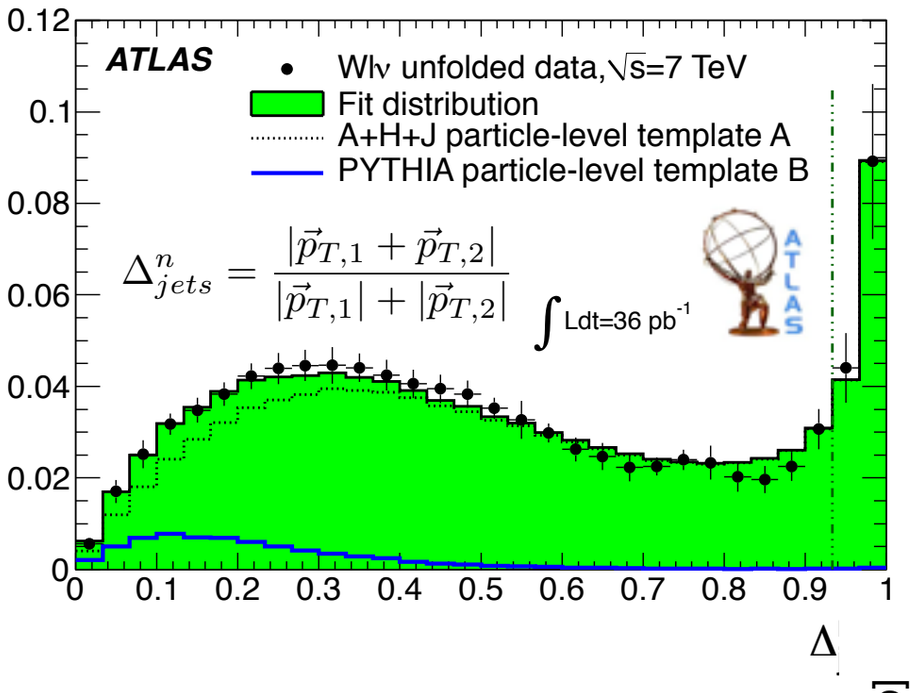
- confronts MC generators and tunes
- inclusive setup
  - activity in TOTEM T2 telescopes at **either** side
  - good description by Pythia6
- non-single-diffractive enhanced setup
  - activity in TOTEM T2 telescopes at **both** sides
  - generators do not describe the data

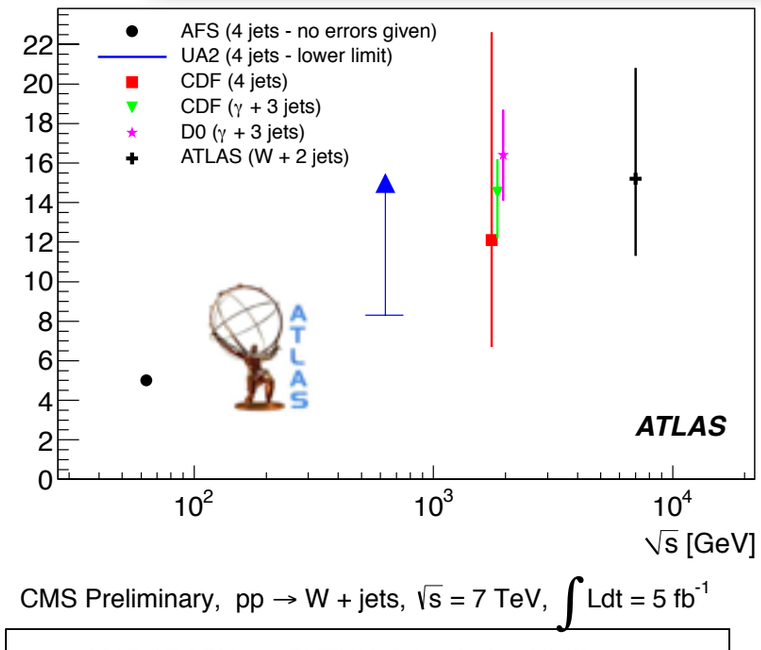
Double-parton scattering

New J. Phys. 15 (2013) 033038

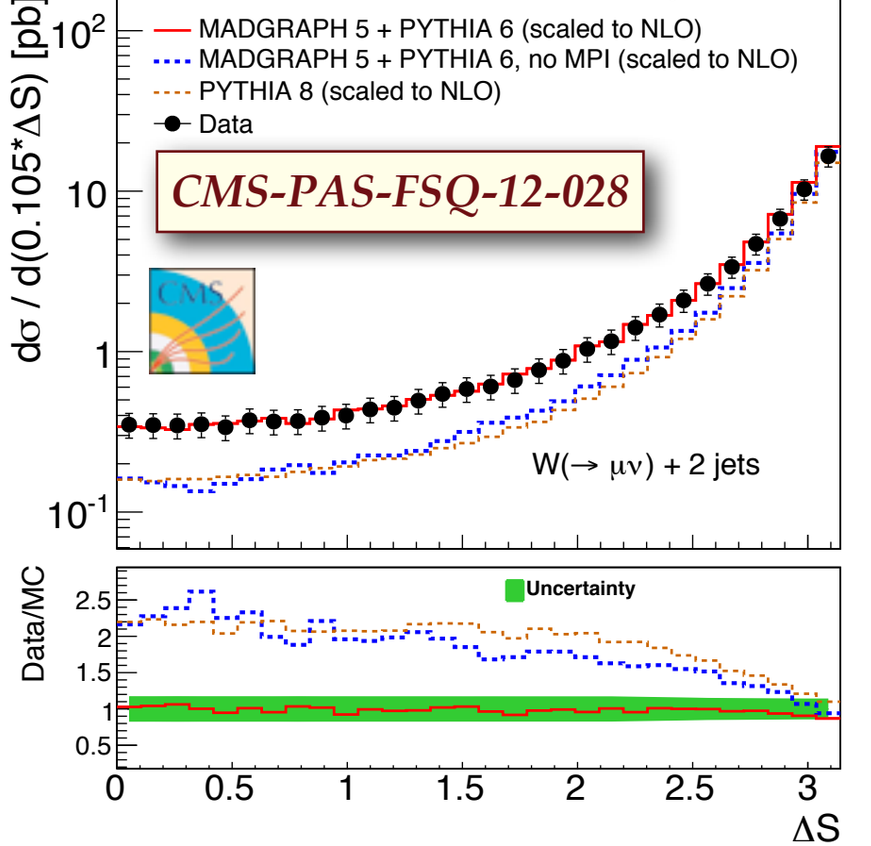


$$d\sigma_{X+Y} = d\sigma^{\mathrm{dir}}_{X+Y} + \frac{d\sigma_X \otimes d\sigma_Y}{\sigma_{\mathrm{eff}}}$$

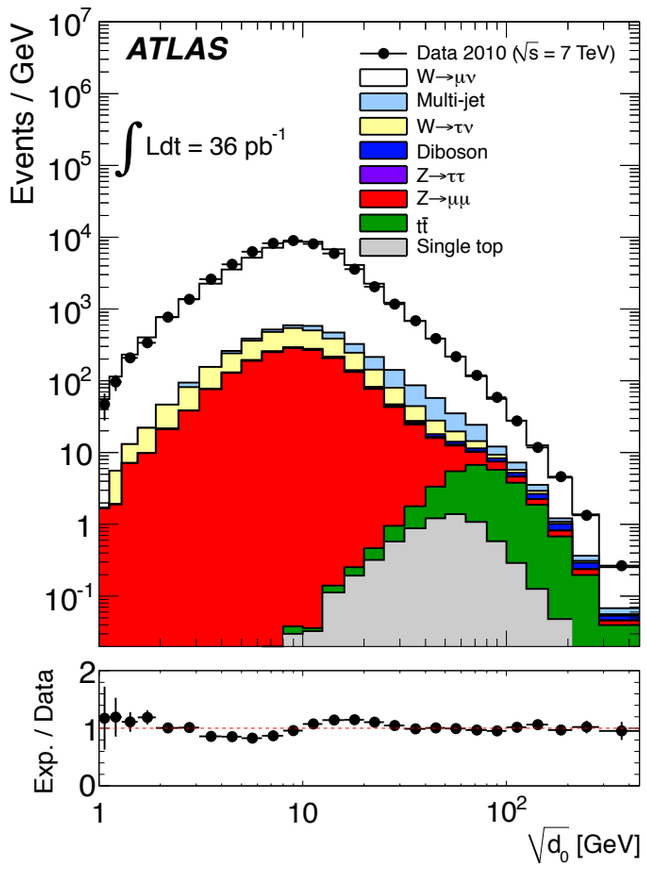


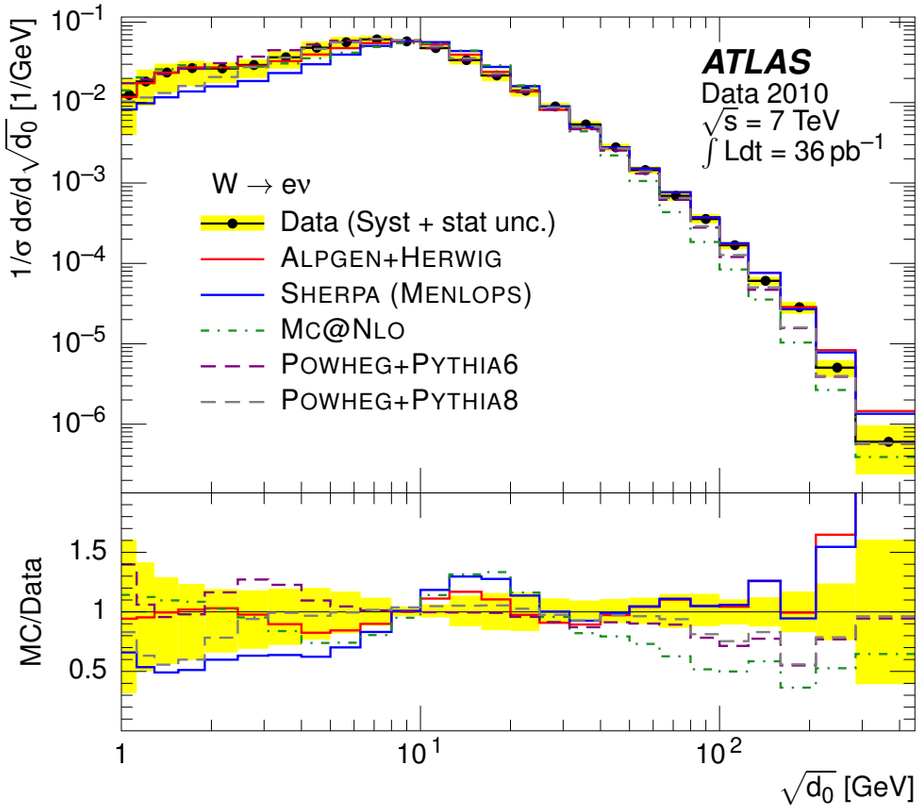


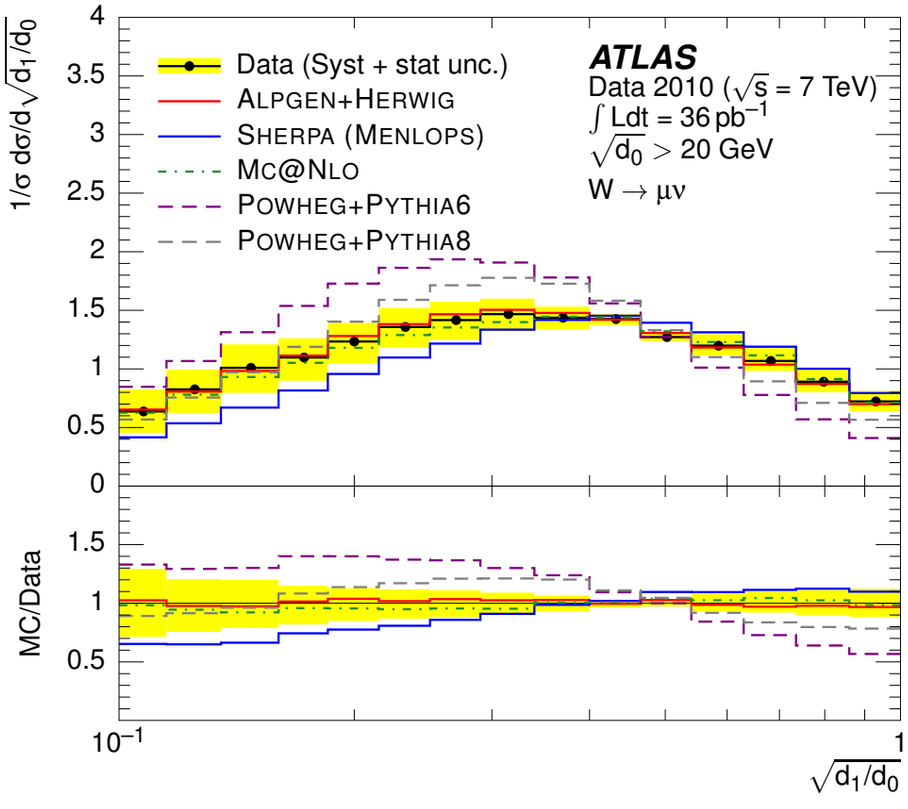
- two hard parton scatters from the same pp collision
  - theory not complete
    - ➡ relying on approximations
- factorized model for final state X+Y
  - parameter σ_{eff} encapsulates all unknowns of DPS
    - ➡ experimentally measured
- experimental setup: W+jj
  - look for DPS at low Δ^n_{jets} (balanced dijet system) or at ΔS (angle between W and jj)
- fit data for DPS component
  - extracted σ_{eff} compatible with previous measurements



k_T splitting scales



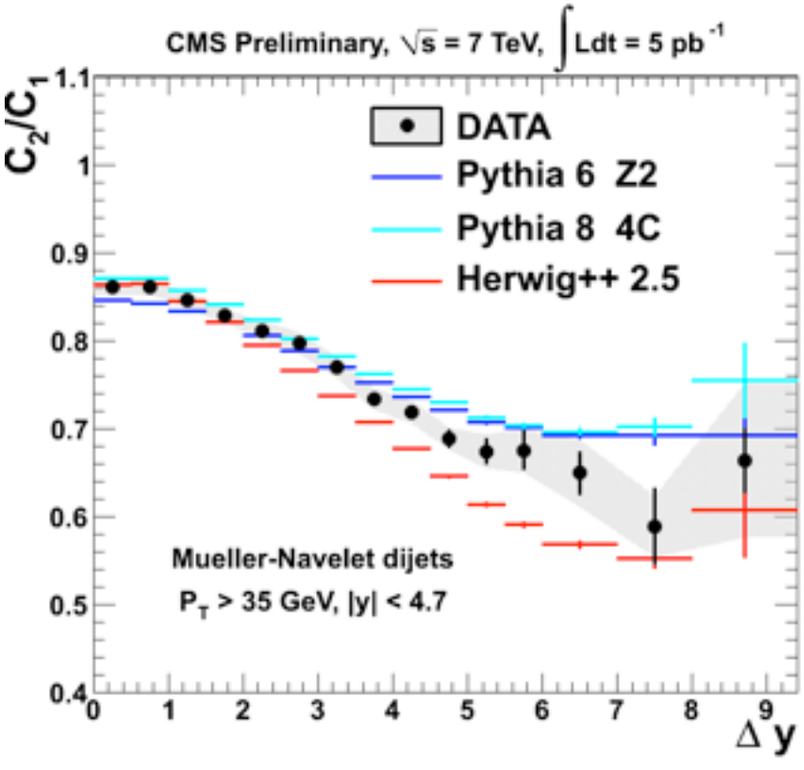


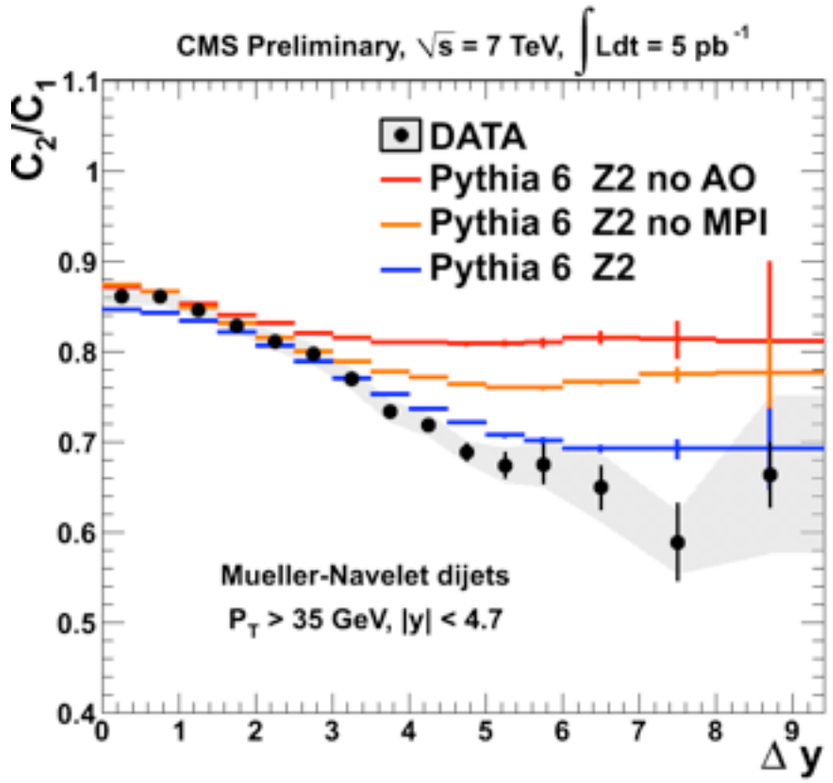


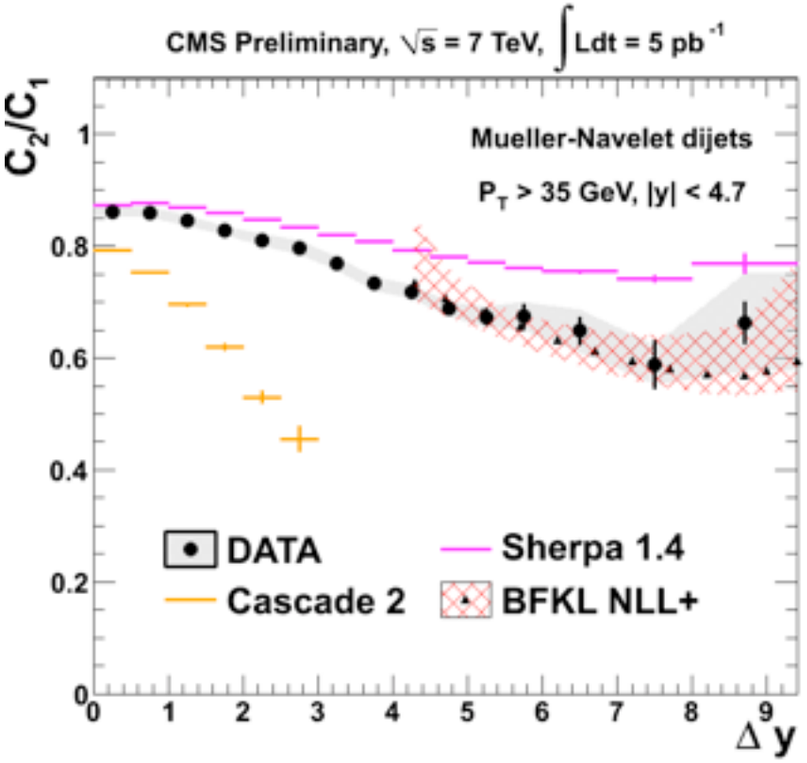
arXiv:1302.1415

- motive: investigate the evolution of the parton shower
- tool: the k_T jet clustering algorithm
  - sequential recombination algorithm that mimics the parton shower
  - at each clustering step, the algorithm decides if a jet has been identified according to a characteristic scale $\mathbf{d_n \sim p_T^2}$
- k_T splitting scales probe the hadronic structure of the event
- measurement performed in W+X events
  - the various generators have different performance in describing the data
    - good agreement for ME+PS

Mueller-Navelet dijet azimuthal decorrelations





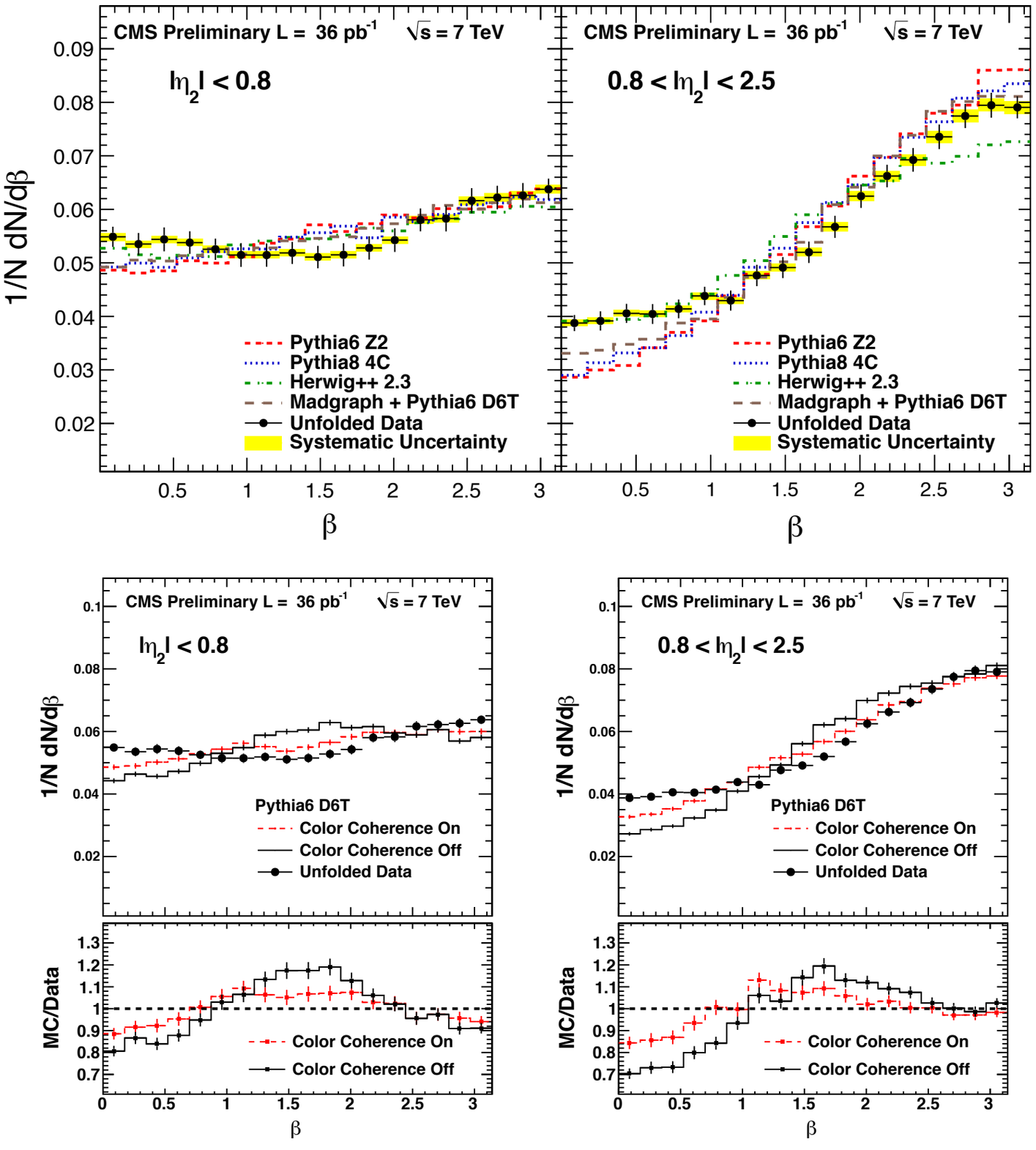


CMS-PAS-FSQ-12-002

- Mueller-Navelet dijets: pair of jets with the largest Δy
- decorrelation (Δϕ) of MN pair: sensitive to QCD dynamics
- cross section vs. Δϕ expanded in terms of cos[n(π-Δϕ)]
  - expansion coefficients and their ratio depend on Δy
  - region of large Δy probes the BFKL evolution
- perturbative calculations based on DGLAP evolution do not describe the data
- NLL+ BFKL prediction is compatible with the data
- MC generators vary significantly at large Δy
  - sensitivity to multiple parton interactions and angular ordering

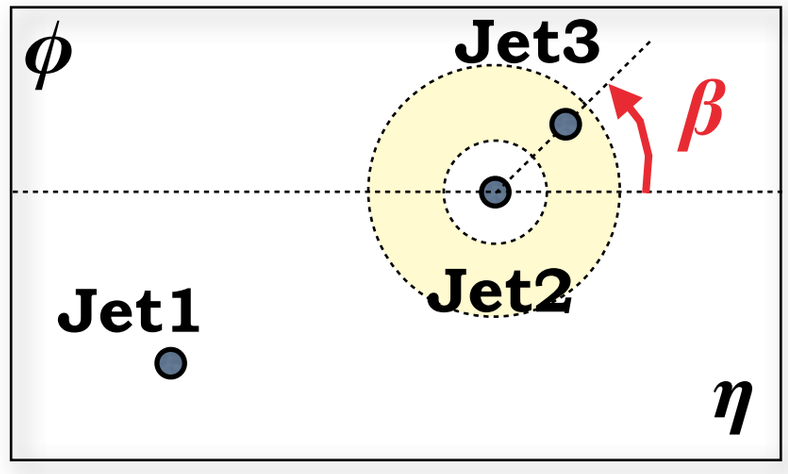
$$\frac{1}{\sigma}\frac{d\sigma}{d(\Delta\phi)}(\Delta y, p_{Tmin}) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty}\mathbf{C_n}(\Delta y, p_{Tmin})\cdot\cos(n(\pi-\Delta\phi))\right]$$

Color Coherence



CMS-PAS-SMP-12-010

- interference between the radiation of partons
  - approximated by angular ordering
- experimental setup:
  - at least 3 jets
  - leading jets back-to-back in ϕ
  - 3rd jet close to the 2nd ($0.5<\Delta R<1.5$)
  - phase space divided by η_2
- comparison to predictions:
  - unfolded to particle level
  - models don't describe the data
  - stronger color coherence in PS is favored

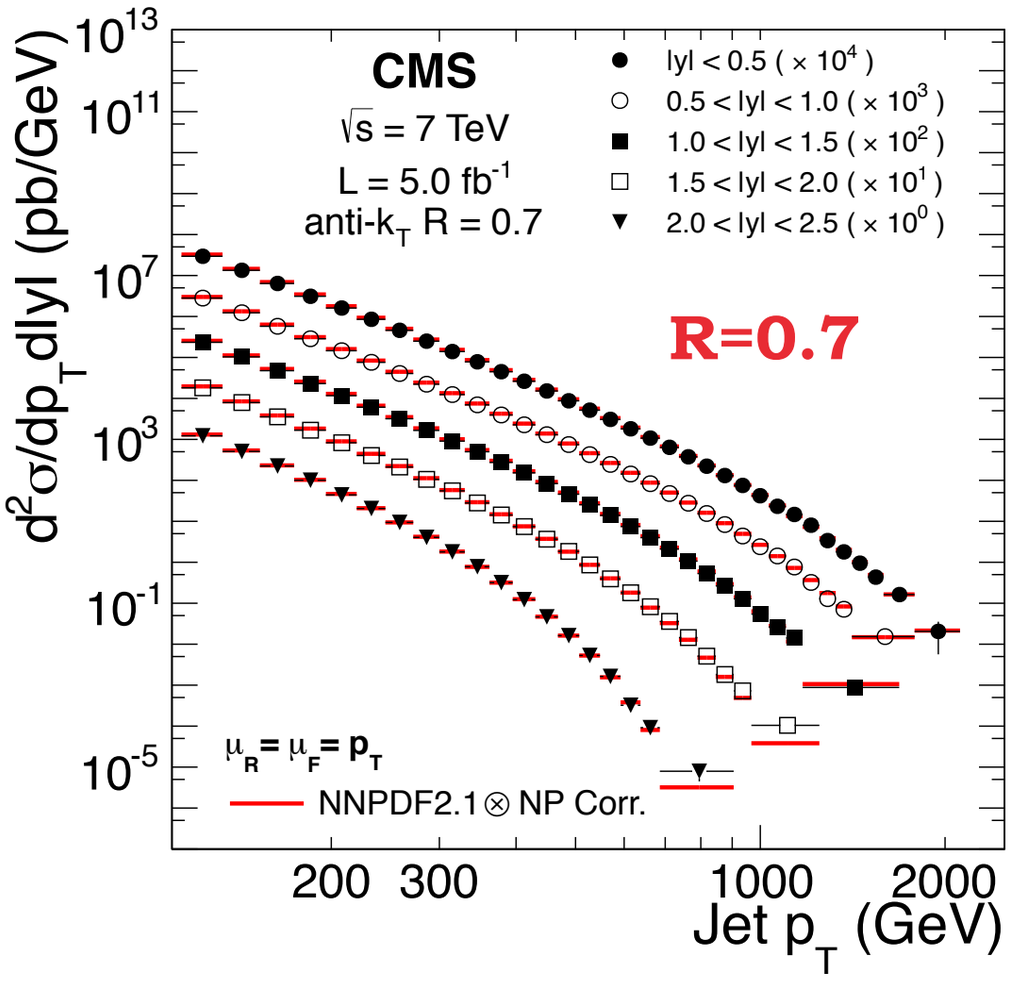


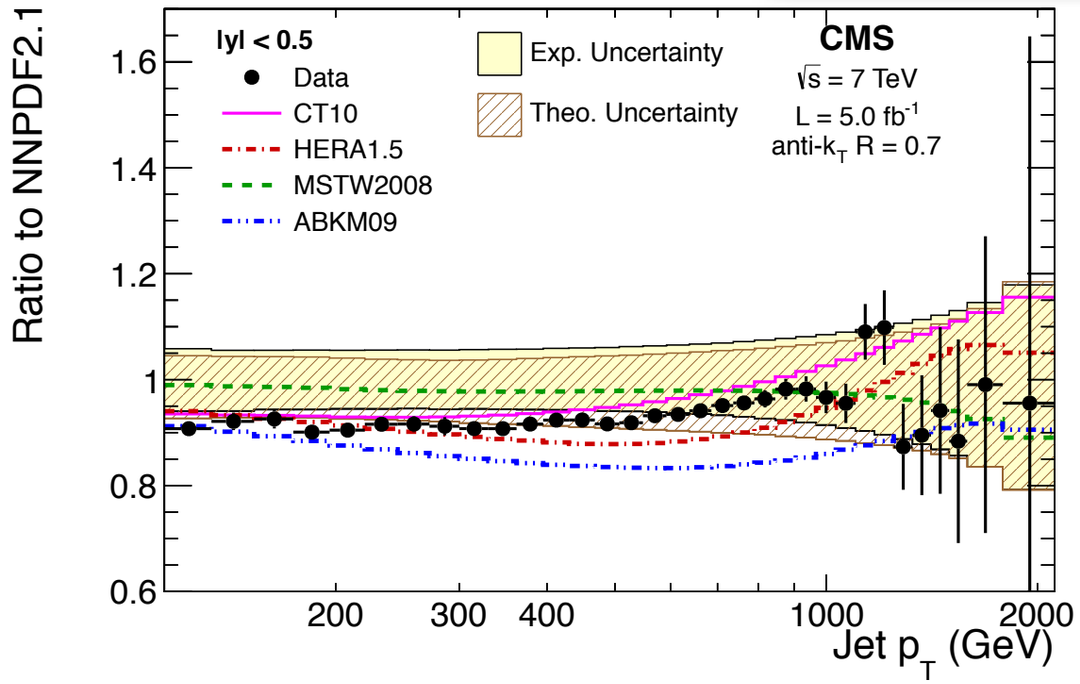
$$\beta = \tan^{-1}\left[\frac{\mathrm{sign}(\eta_2)\Delta\phi_{32}}{\Delta\eta_{32}}\right]$$

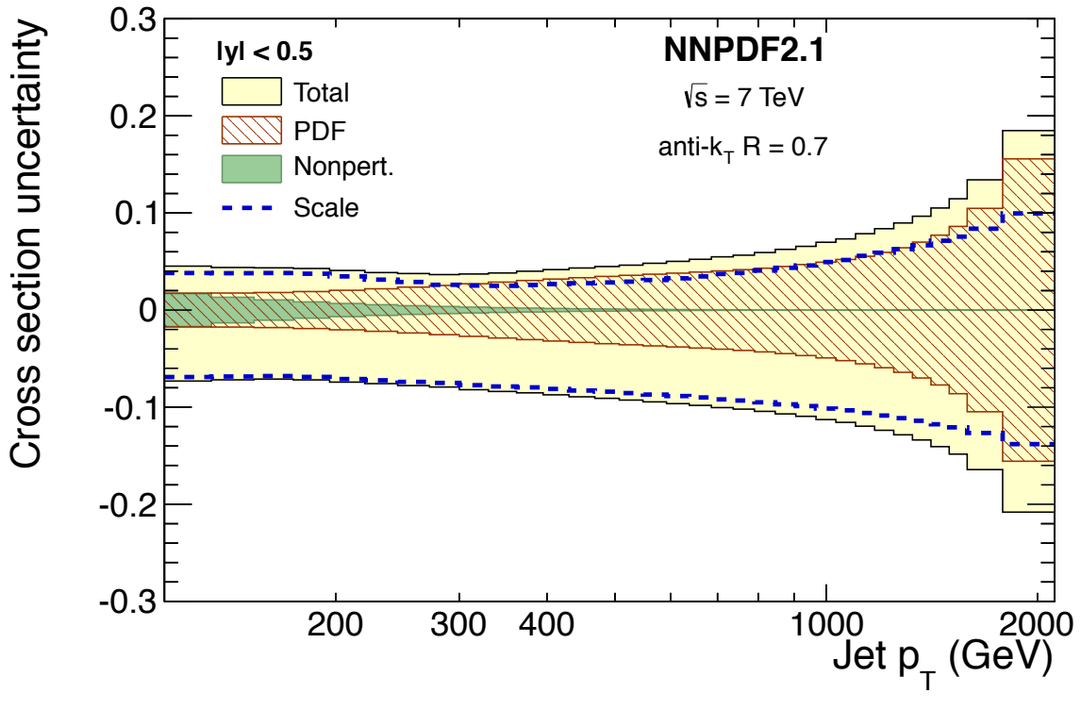
perturbative QCD & PDFs with jets

Inclusive jet cross sections @ 7 TeV

PRD 87, 112002 (2013

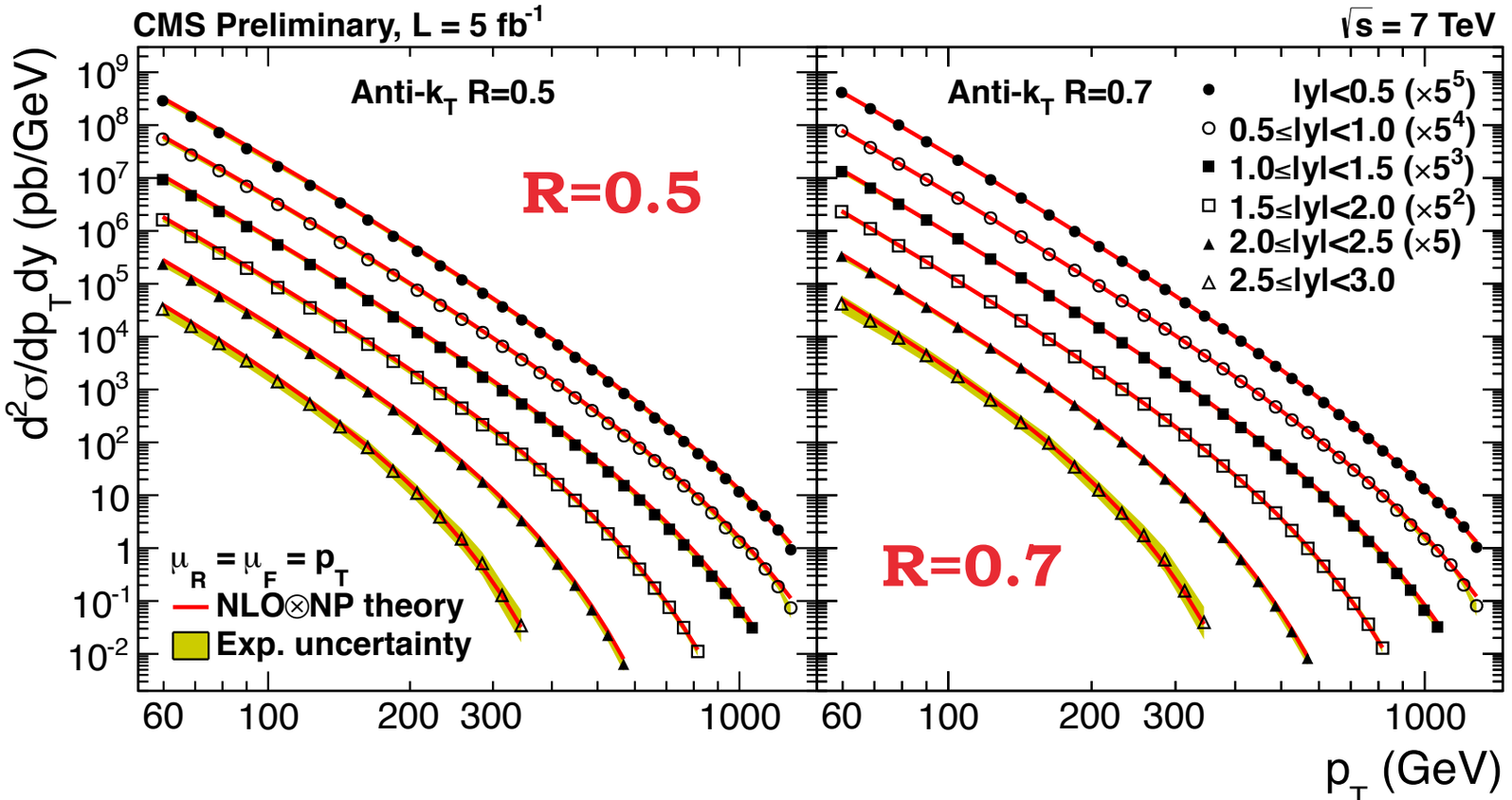


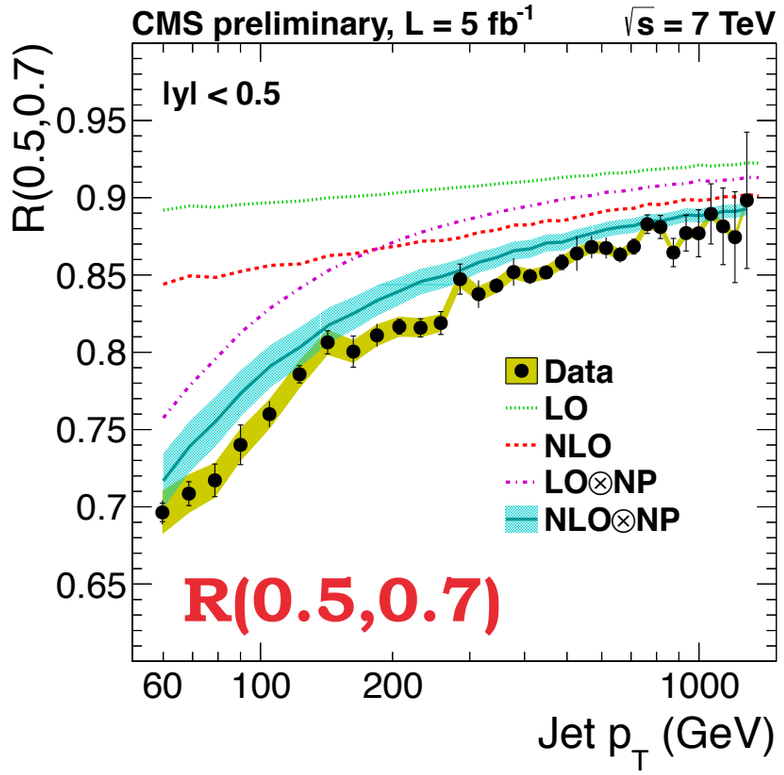


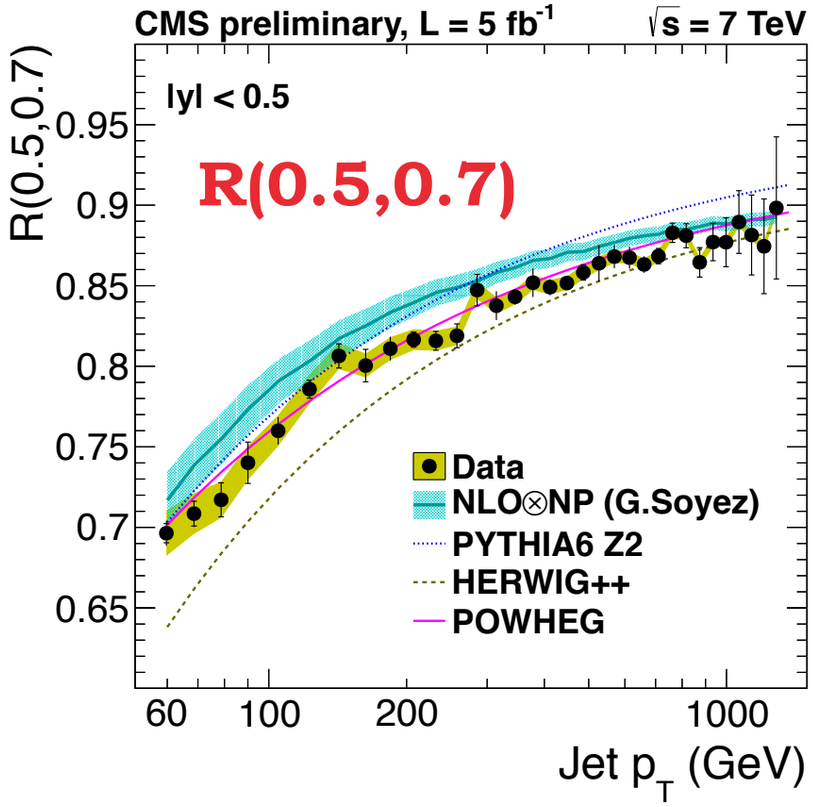


- exploring the kinematic range from 100 GeV to 2 TeV and up to |y| = 2.5
  - full 2011 dataset
- experimental and theoretical uncertainties of roughly the same size
  - exp. unc. dominated by jet energy scale
  - th. unc. dominated by scale choice and PDFs
- NLO pQCD predictions compatible with data

Comparison of jet sizes @ 7 TeV



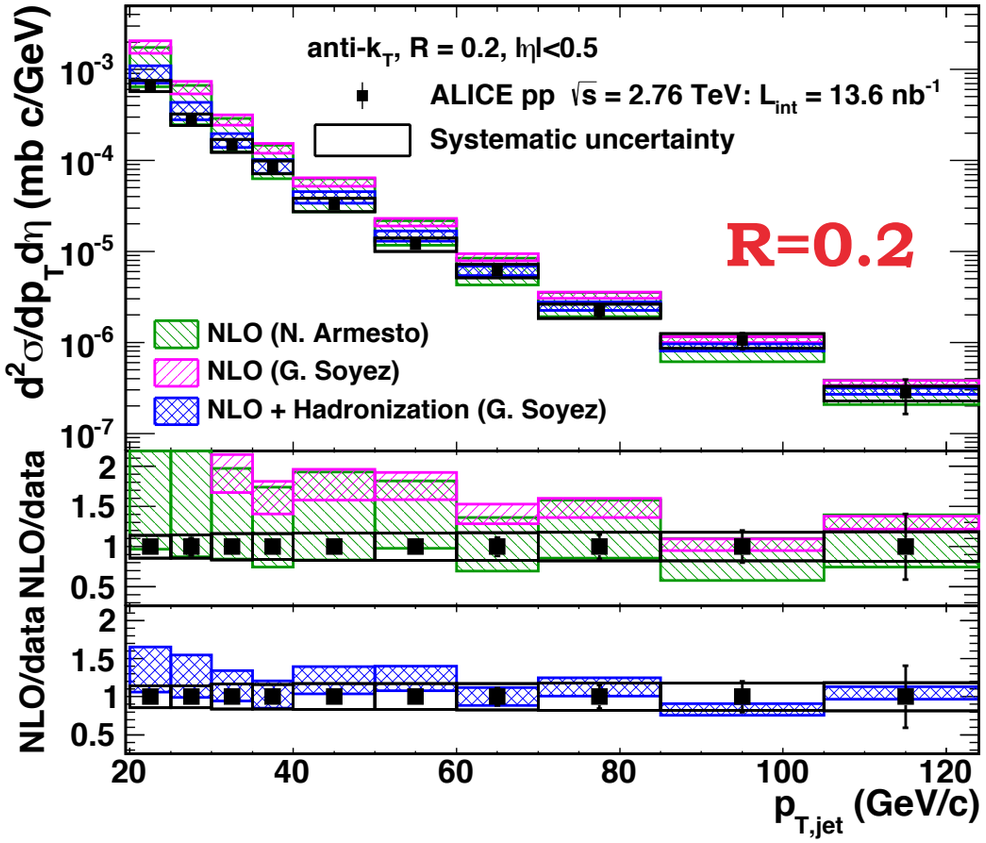


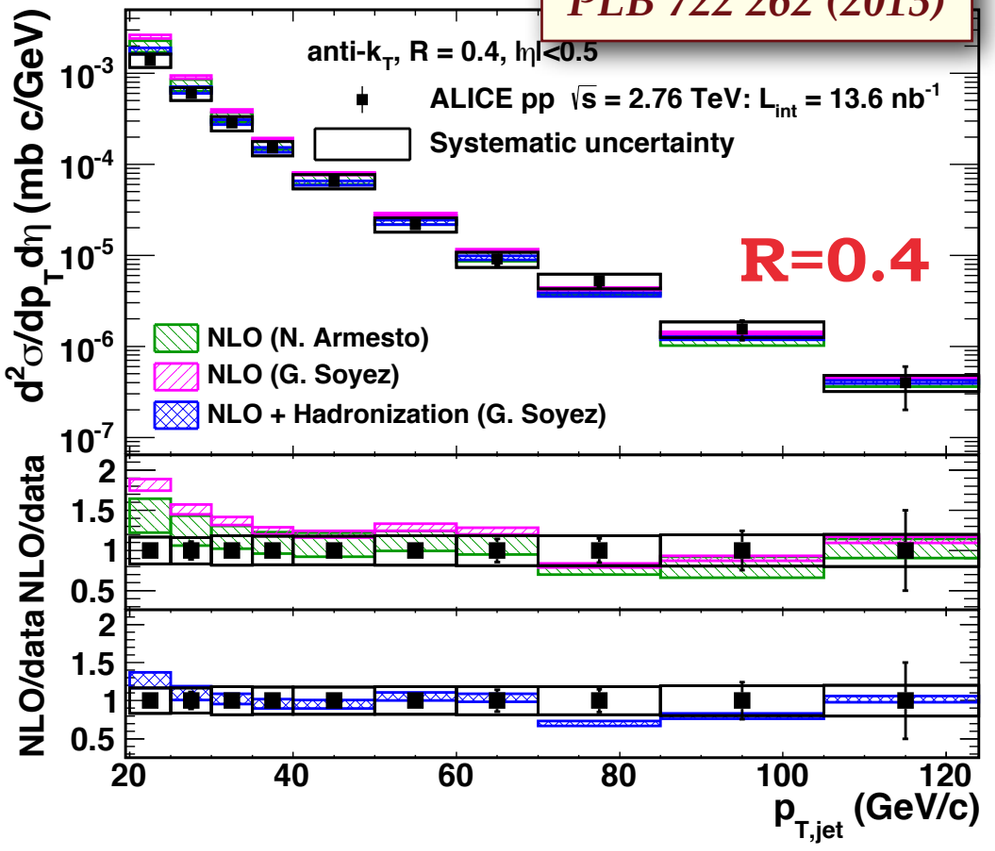


- inclusive jet cross section measured with different jet sizes (R=0.5, R=0.7)
  - both measurements in agreement with theory predictions (but R=0.7 agrees better--backup slides)
- ratio of cross sections R(0.5, 0.7) gives insight into QCD effects beyond fixed order
  - non-perturbative corrections
  - parton shower
  - Powheg gives the best description of the data at central rapidities

CMS-PAS-SMP-13-002

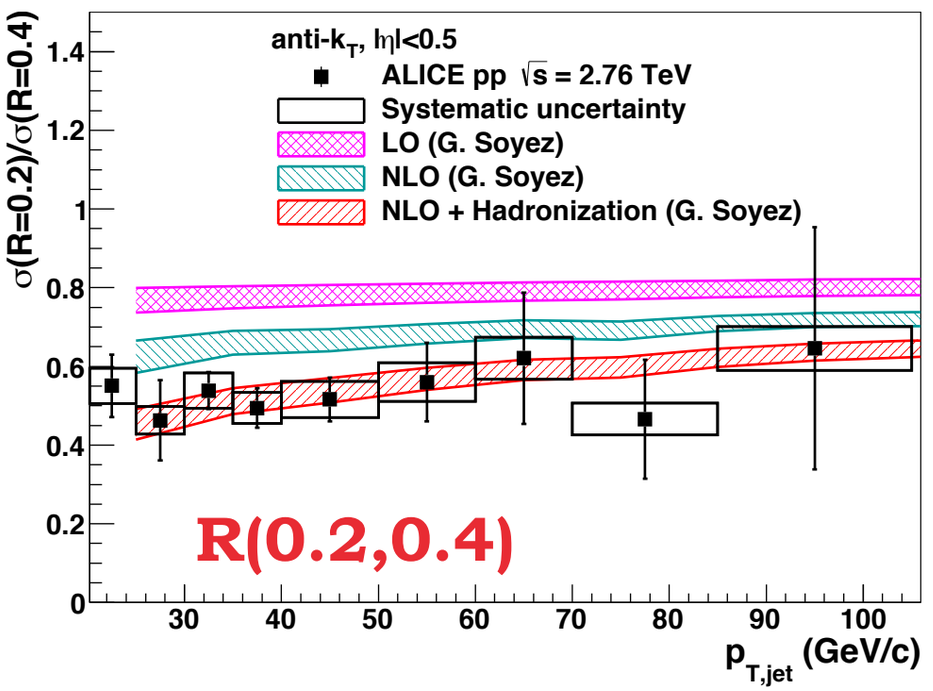
Inclusive jet cross sections @ 2.76 TeV



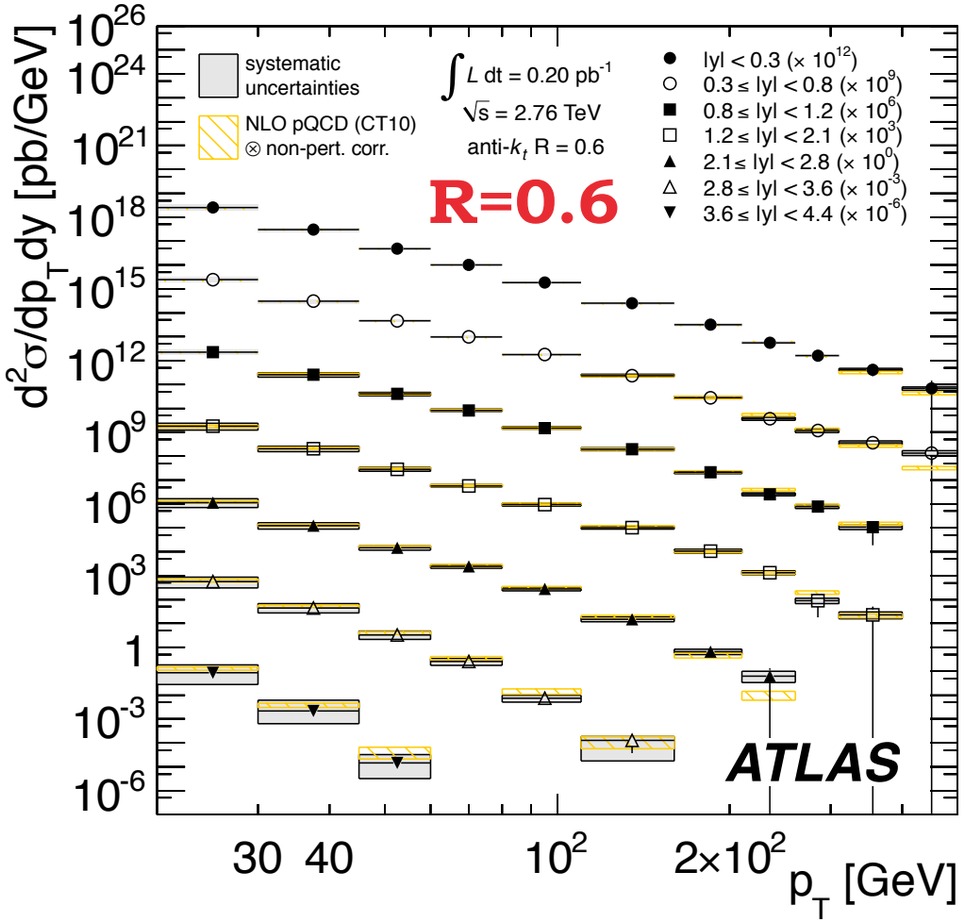


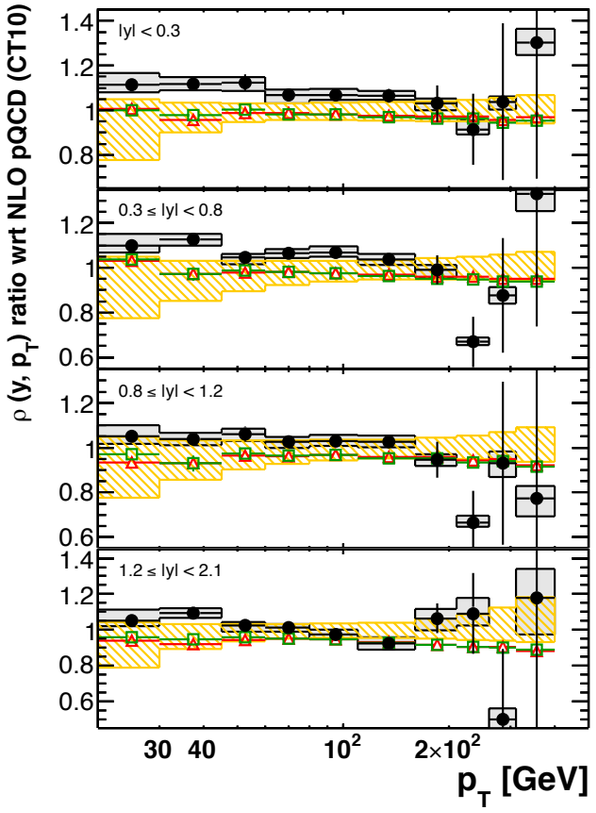
PLB 722 262 (2013)

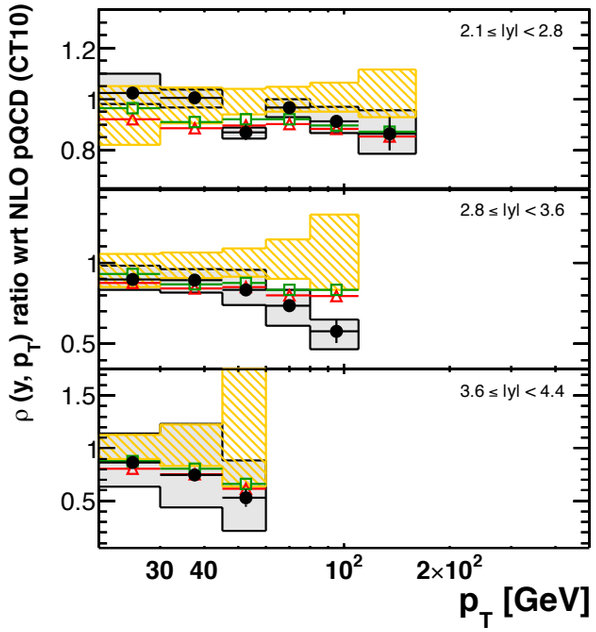
- inclusive jet spectra @ 2.76 TeV with ALICE
  - up to 120 GeV in p_T and $|y| = 0.5$
  - jet sizes R = 0.2 & R = 0.4
- ratio of cross sections from different jet sizes
  - cancellation of experimental uncertainties
  - NLO+Hadronization prediction in agreement with data (but large uncertainties)



Inclusive jet cross sections @ 2.76 TeV







ATLAS

$\int L\,dt = 0.20\ pb^{-1}$

$\rho = \sigma_{jet}^{2.76TeV} / \sigma_{jet}^{7TeV}$

anti-k_t R = 0.6

- Data with statistical uncertainty
- Systematic uncertainties
- NLO pQCD ⊗ non-pert. corr. (CT10, $\mu=p_T^{max}$)
- POWHEG ⊗ PYTHIA tune AUET2B (CT10, $\mu=p_T^{Born}$)
- POWHEG ⊗ PYTHIA tune Perugia 2011 (CT10, $\mu=p_T^{Born}$)

R(2.76 TeV, 7 TeV)

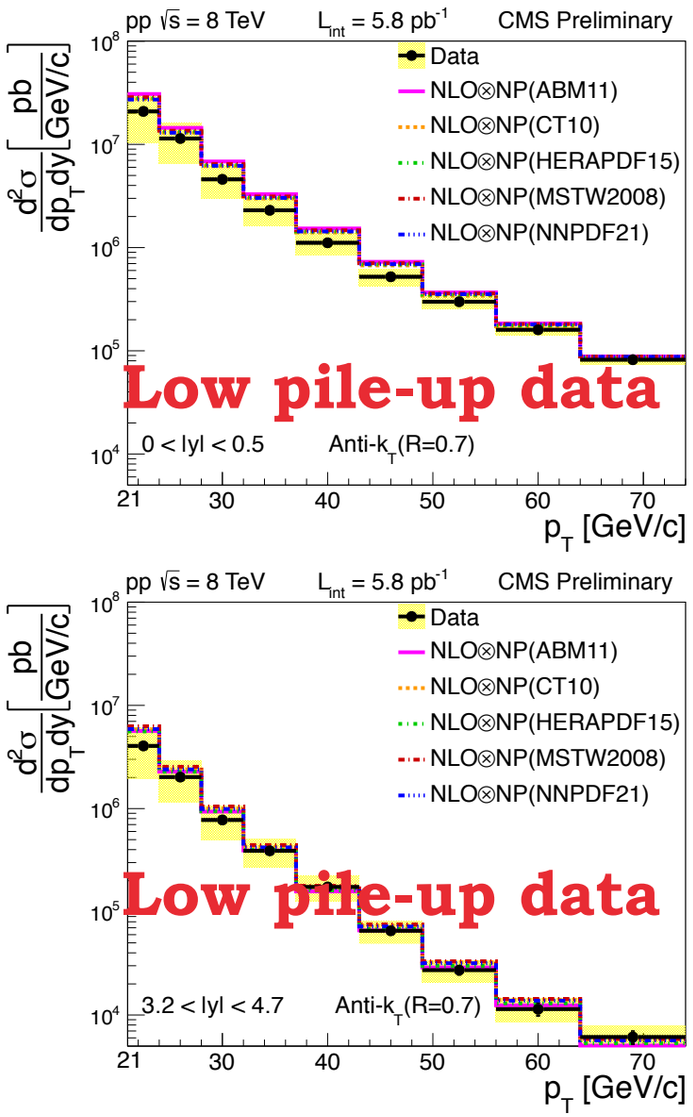
arXiv:1304.4739

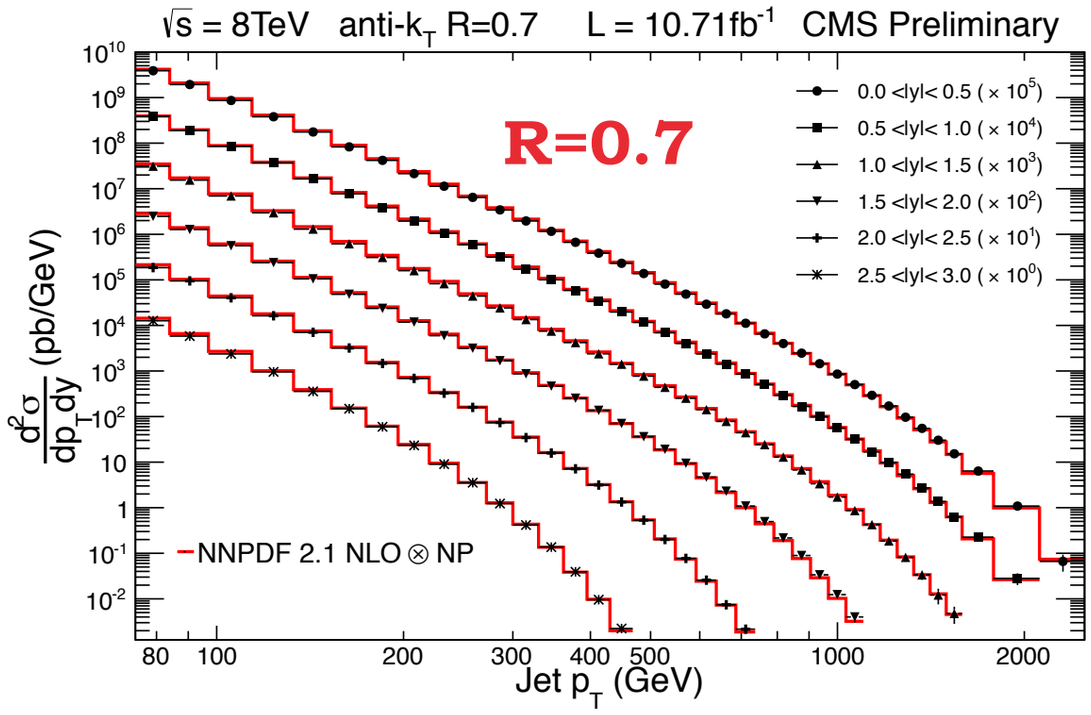
- inclusive jet spectra @ 2.76 TeV
  - up to 500 GeV in p_T (limited luminosity at this energy) and |y| = 4.4
- double ratio **$(data/theory)_{2.76\ TeV}/(data/theory)_{7\ TeV}$**
  - cancellation of experimental uncertainties
  - very precise measurement that can be used to constrain the theory
- NLO pQCD predictions compatible with data
  - but tension observed at high rapidities
    - ➡ in these regions, the NLO generator interfaced with PS describes better the data

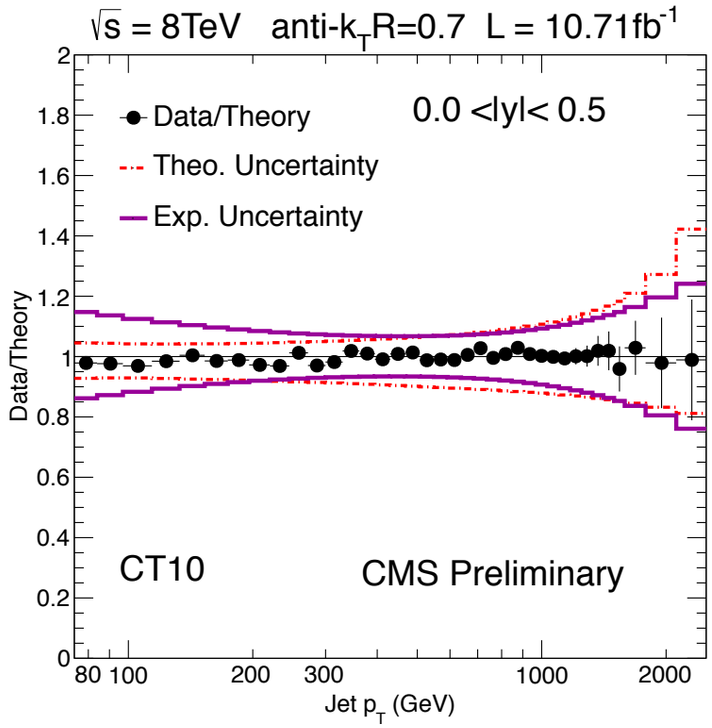
Inclusive jet cross sections @ 8 TeV

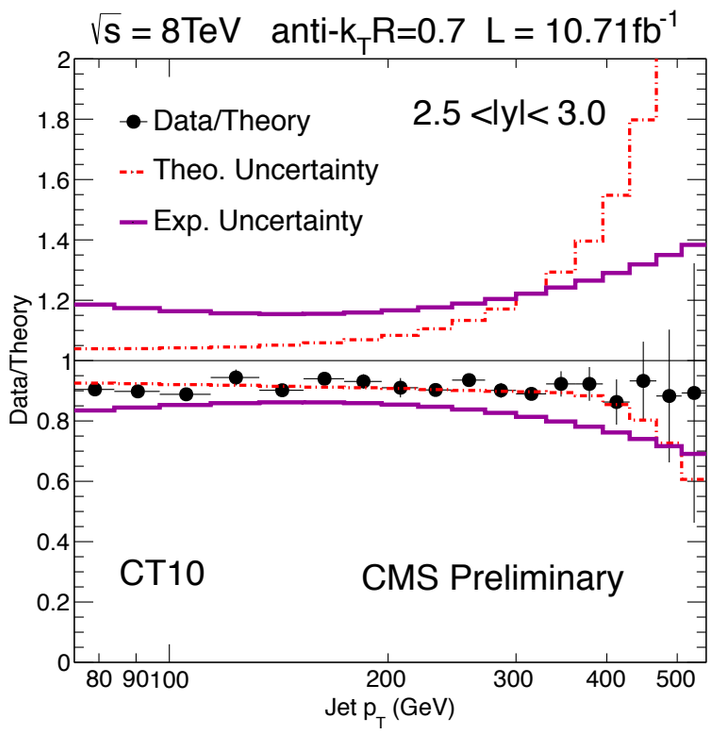
CMS-PAS-FSQ-12-031

CMS-PAS-SMP-12-012









- first (preliminary) measurement @ 8 TeV up to |y| = 3.0
  - ~half 2012 dataset
- dedicated measurement with low pileup data
  - starting from p_T = 20 GeV and reaching |y|=4.7
- experimental uncertainties at high p_T smaller than theoretical
  - potential for PDF constrains
- NLO pQCD predictions compatible with data

Dijet cross sections @ 7 TeV

ATLAS-CONF-2012-021

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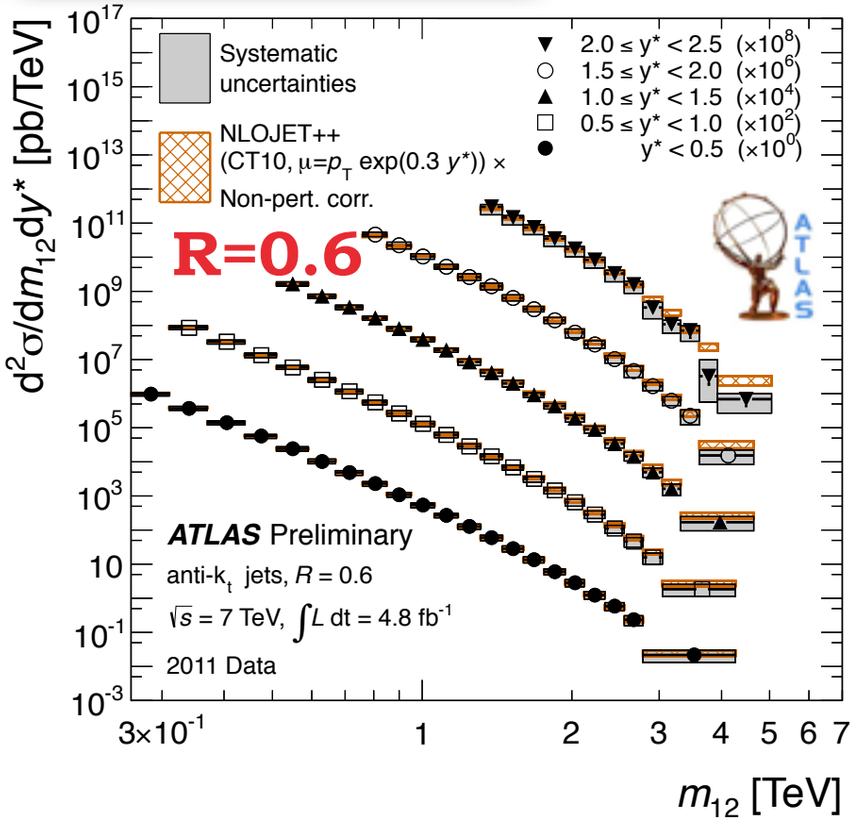
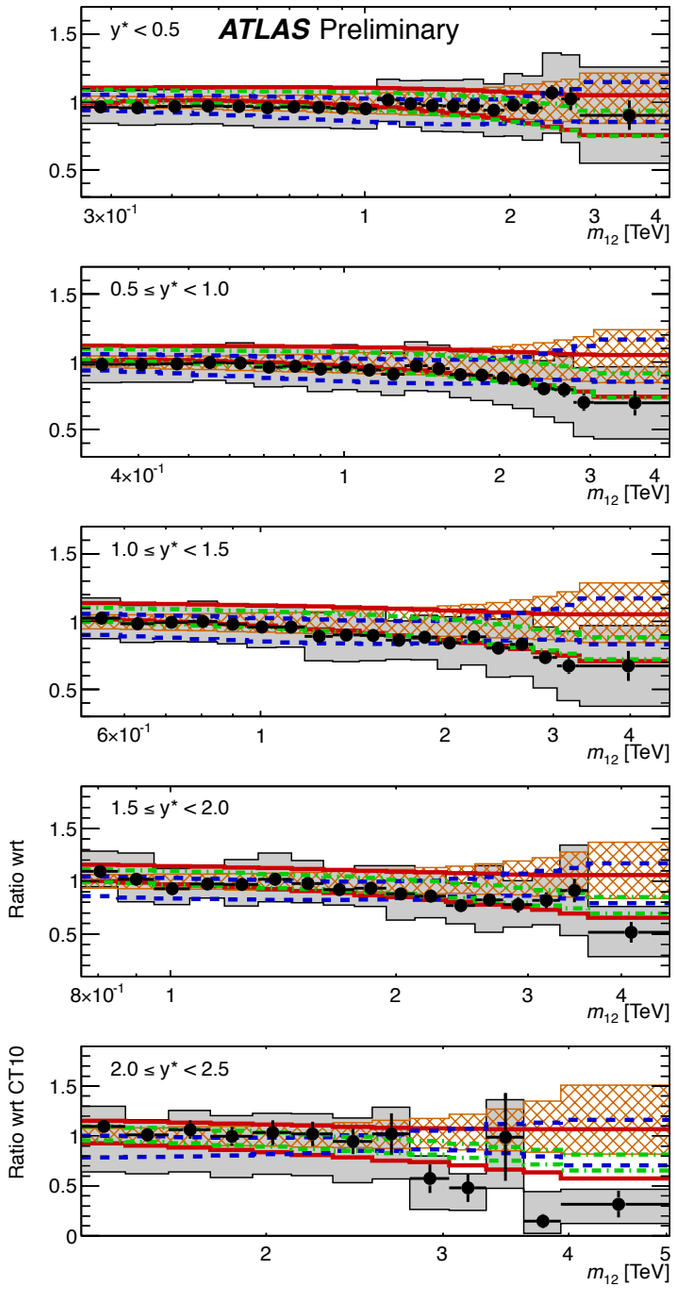
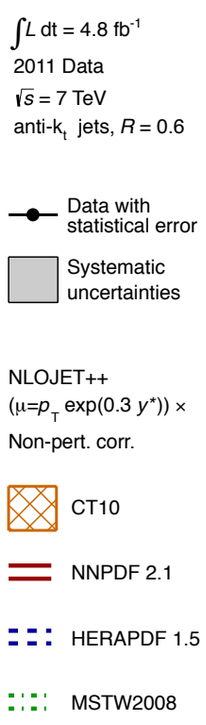
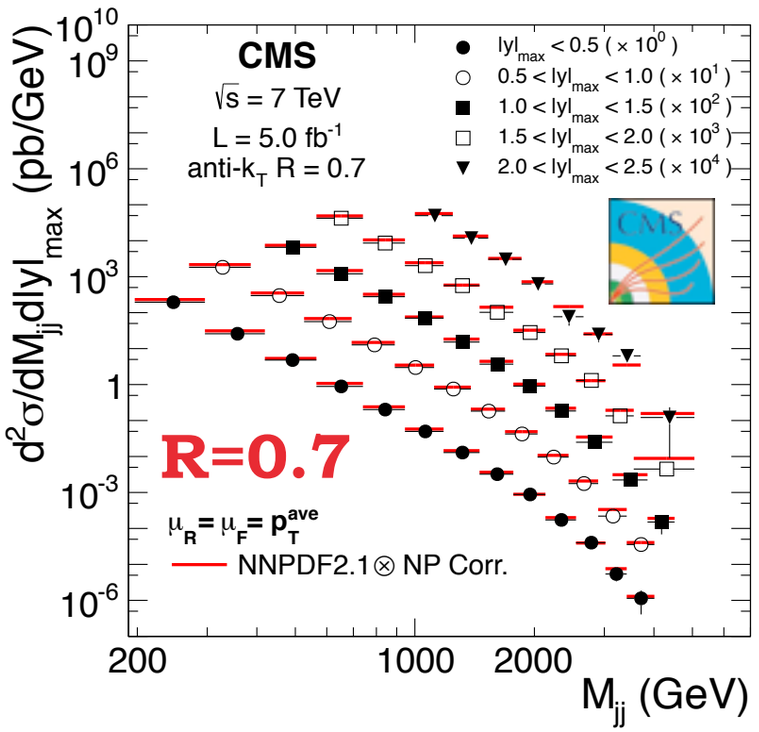
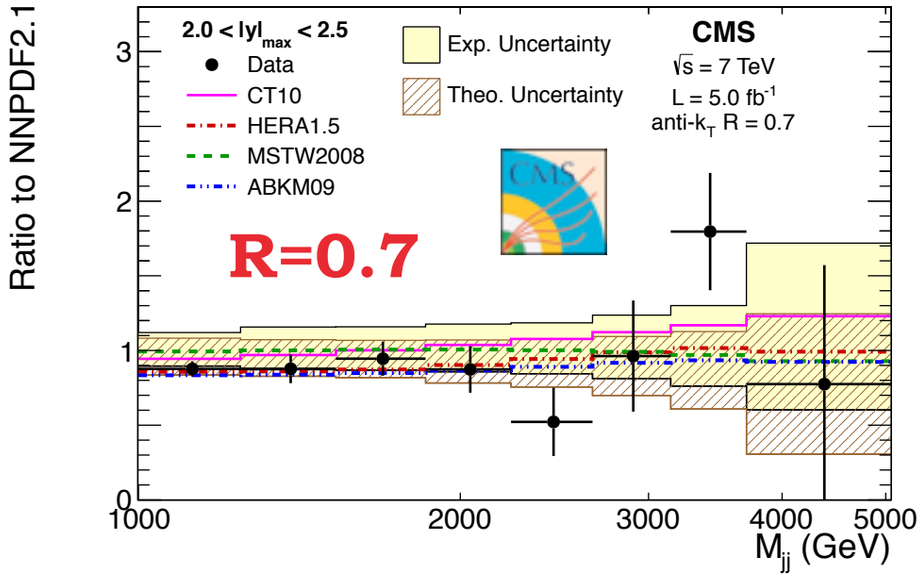


- complementary to inclusive jets
- probe differently the partonic sub-processes
- compatible with pQCD @ NLO
  - tension at higher rapidities
  - agreement improves for larger jet sizes

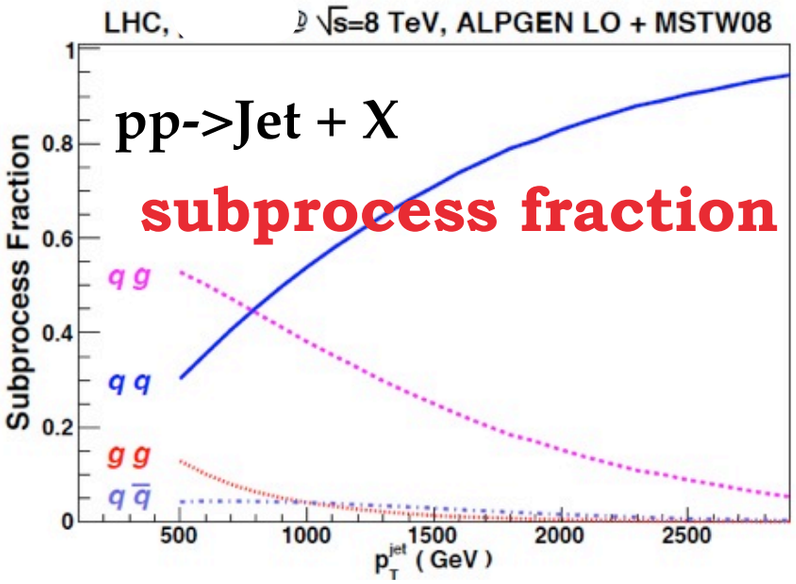


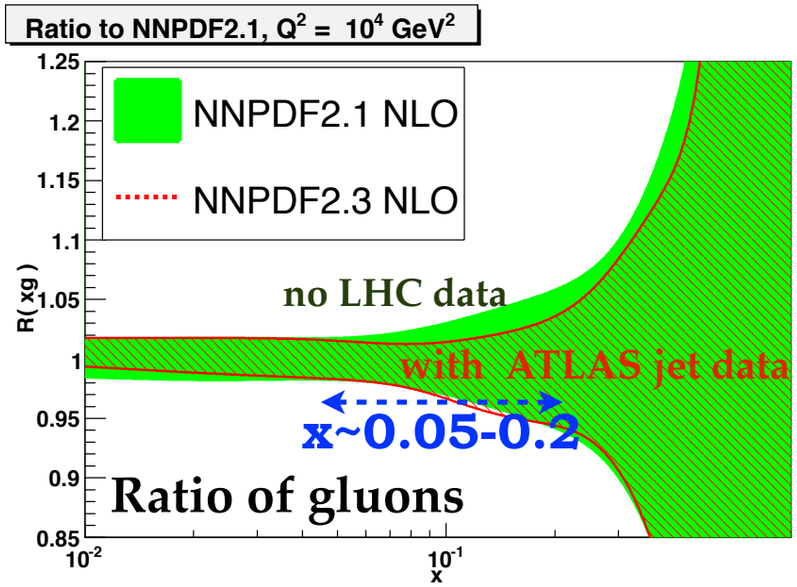


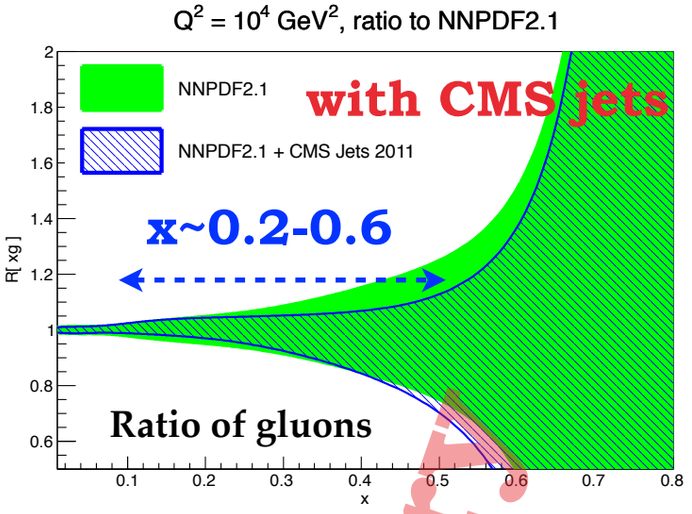


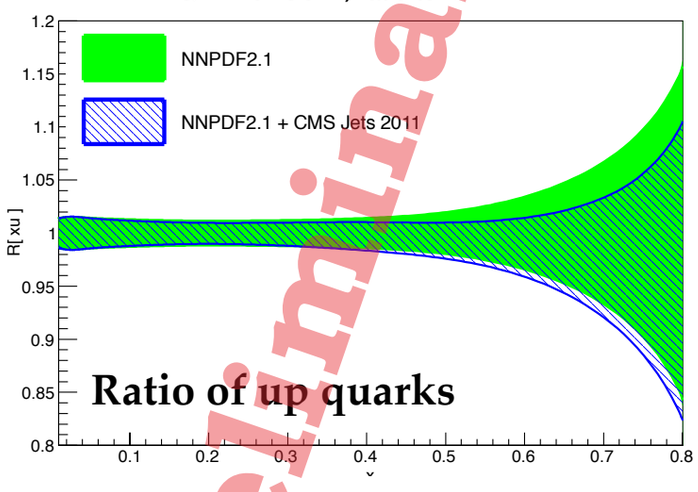


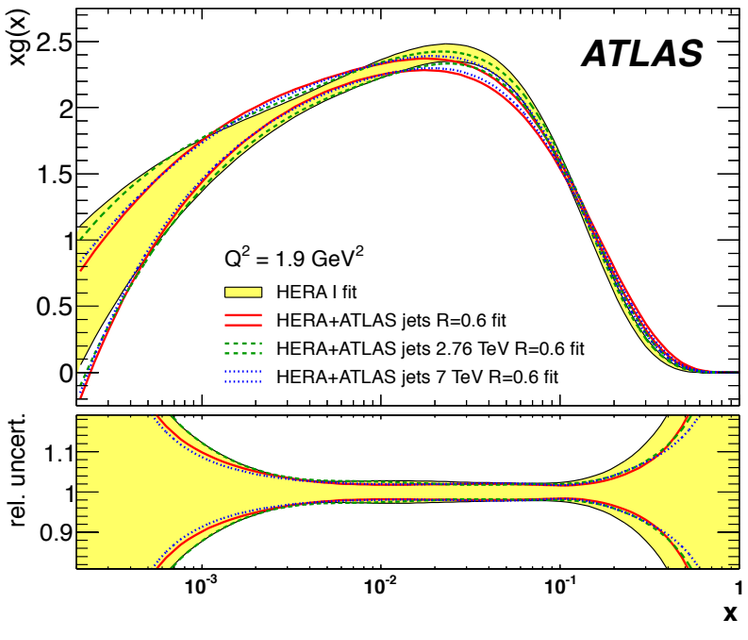
Impact of jet measurements on PDFs



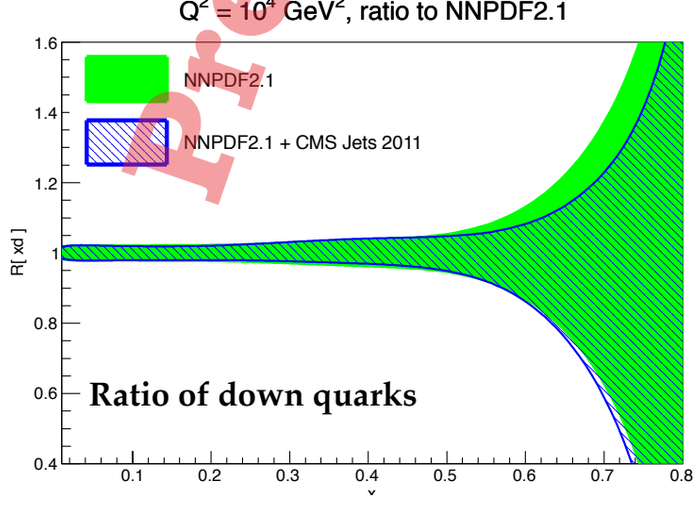






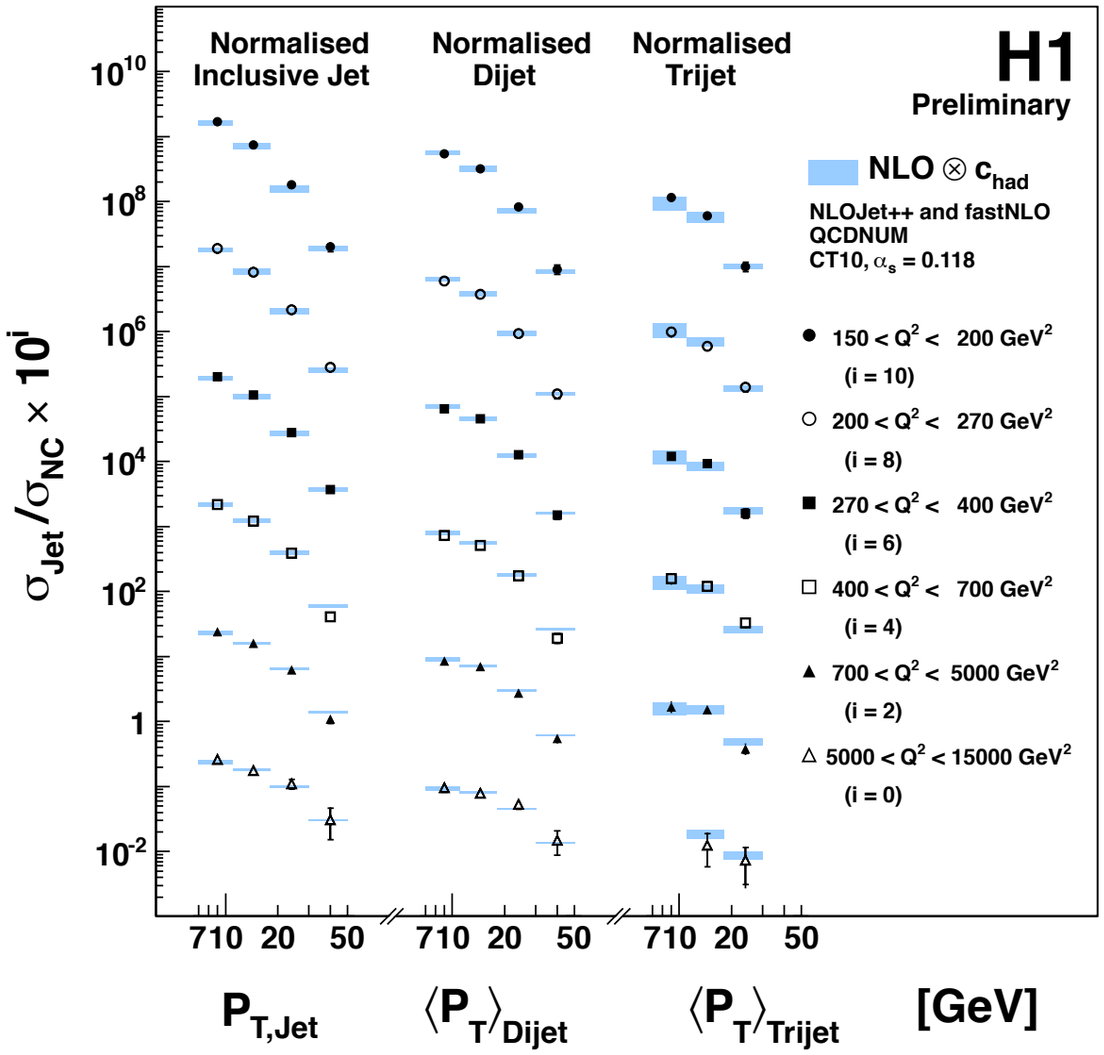


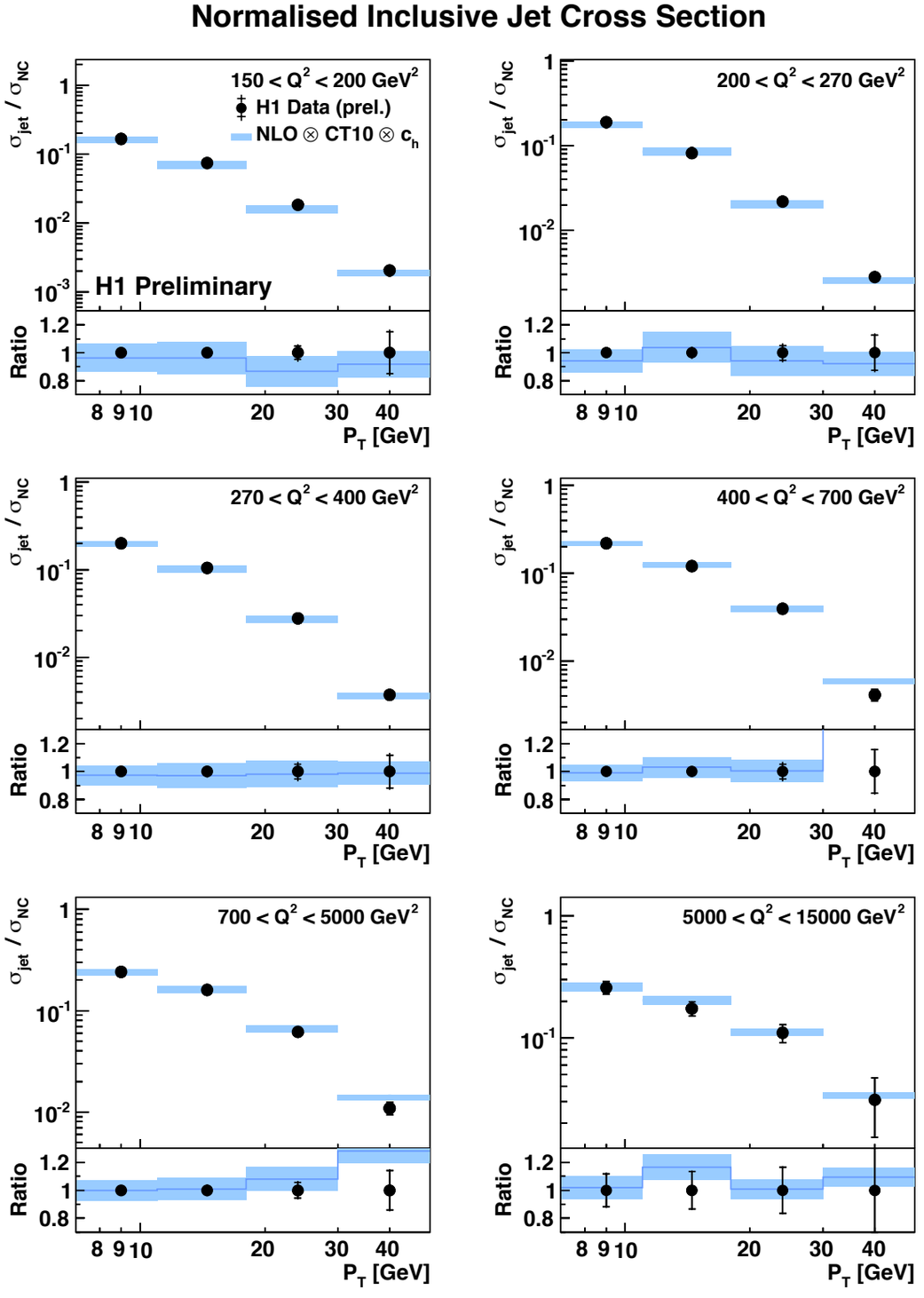
- ATLAS and CMS data public
- first attempts from PDF fitters to include the LHC jet data
  - preliminary studies: jet data constrain the gluon PDF up to x~0.6 but also the u,d PDFs at higher x
- ratios between c.m. energies can constrain the PDFs further



measurements of α_s

Jets @ HERA

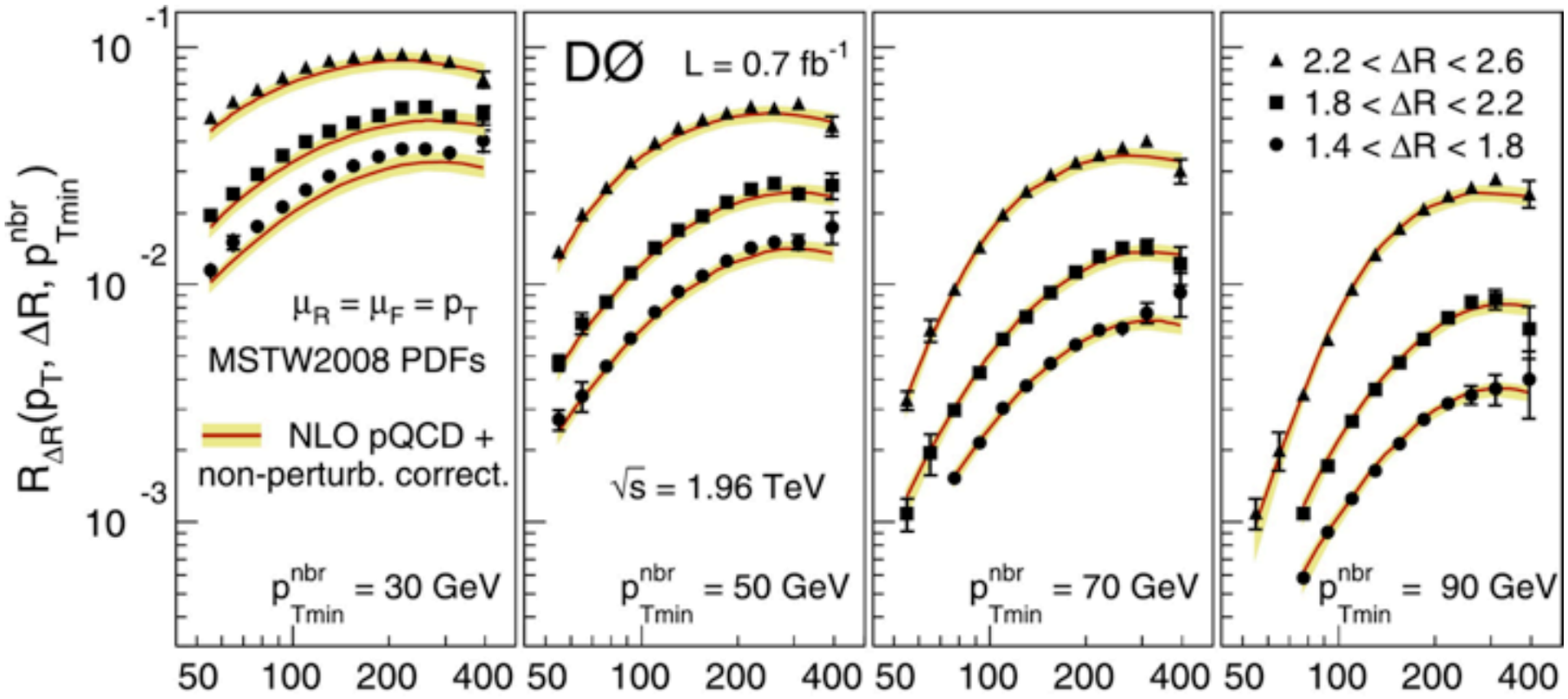




- inclusive, 2-jet, 3-jet cross sections
- probe pQCD calculations at lower scales
  - good agreement between data & theory
- used to extract α_S

H1prelim-12-031

Jet angular correlations



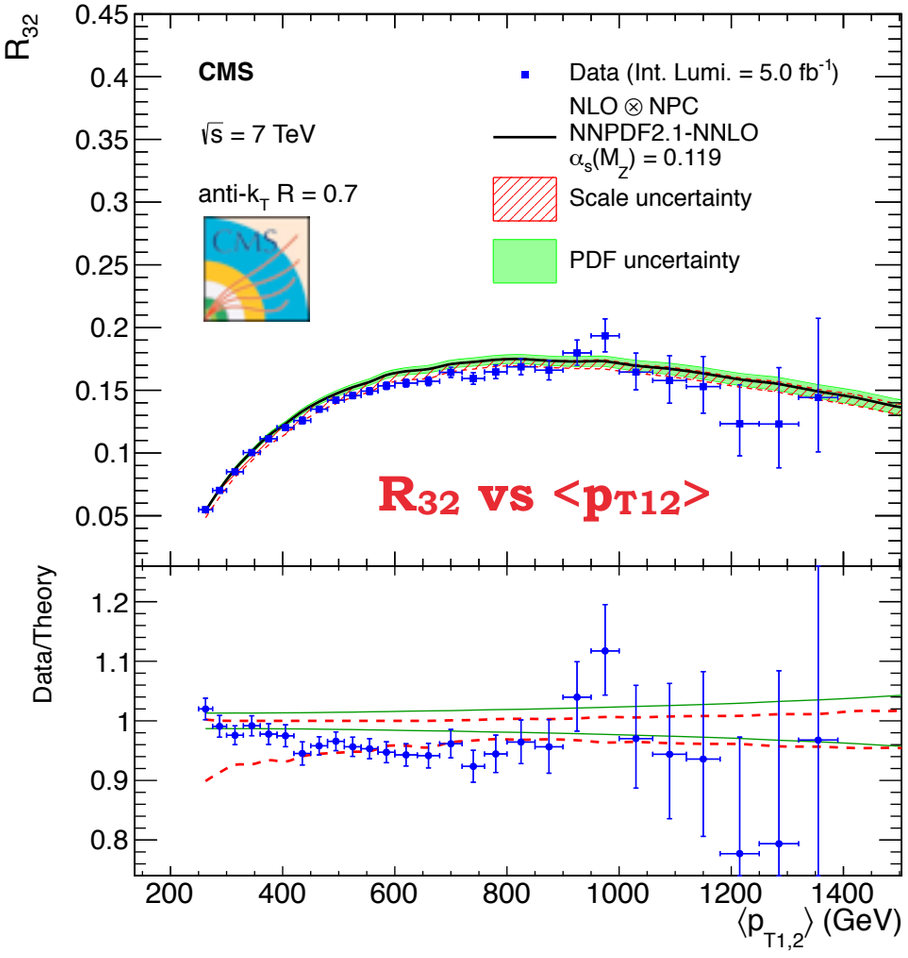
$$R_{\Delta R}(p_T, \Delta R, p_{T\,\mathrm{min}}^{\mathrm{nbr}}) = \frac{\sum_{i=1}^{N_{\mathrm{jet}}(p_T)} N_{\mathrm{nbr}}^{(i)}(\Delta R, p_{T\,\mathrm{min}}^{\mathrm{nbr}})}{N_{\mathrm{jet}}(p_T)}$$

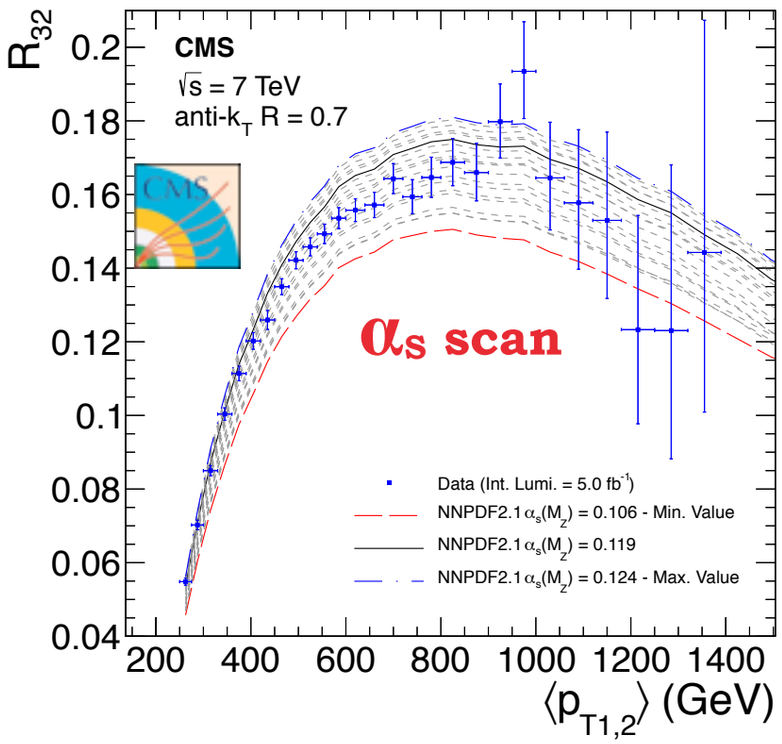
- novel observable:
  - number of jets, above $p_{T,min}$, that accompany jet in angular distance ΔR
  - sensitive to gluon emission
- good agreement observed with pQCD @ NLO
  - tension at low $p_{T,min}$ and small ΔR
- reduced scale choice and exp. uncertainties for this observable
  - used to measure α_S

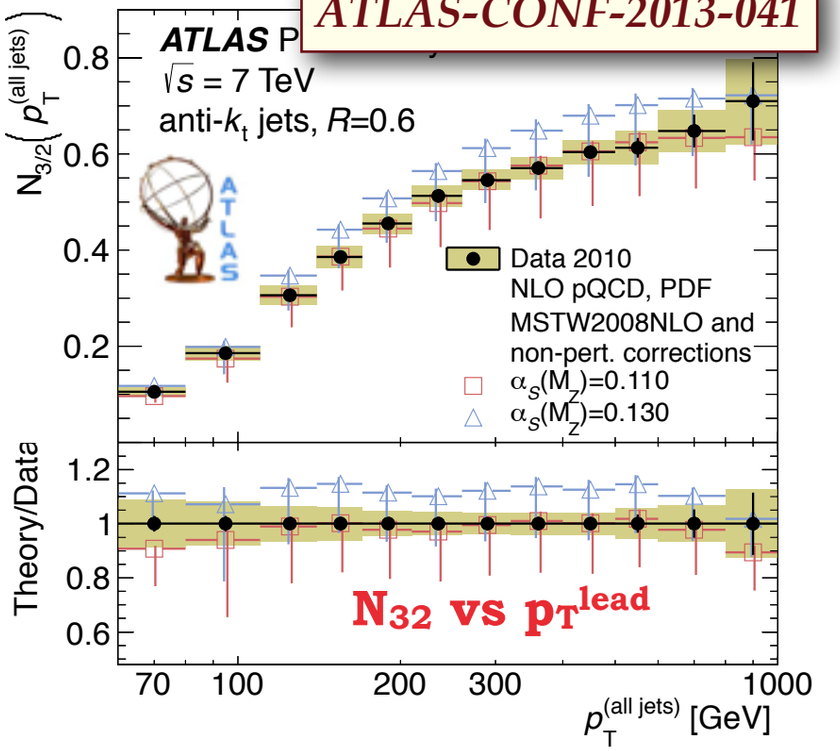
PLB 721 212 (2013)

3-jet over 2-jet cross-section ratio

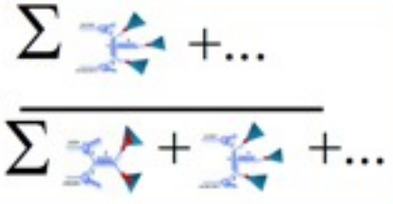
ATLAS-CONF-2013-041







$$N_{3/2}(p_{\mathrm{T}}^{(\mathrm{all\,jets})}) = \frac{\sum_i^{N_{\mathrm{jet}}} \left(d\sigma_{N_{\mathrm{jet}}\geq 3} / dp_{\mathrm{T},i} \right)}{\sum_i^{N_{\mathrm{jet}}} \left(d\sigma_{N_{\mathrm{jet}}\geq 2} / dp_{\mathrm{T},i} \right)}$$

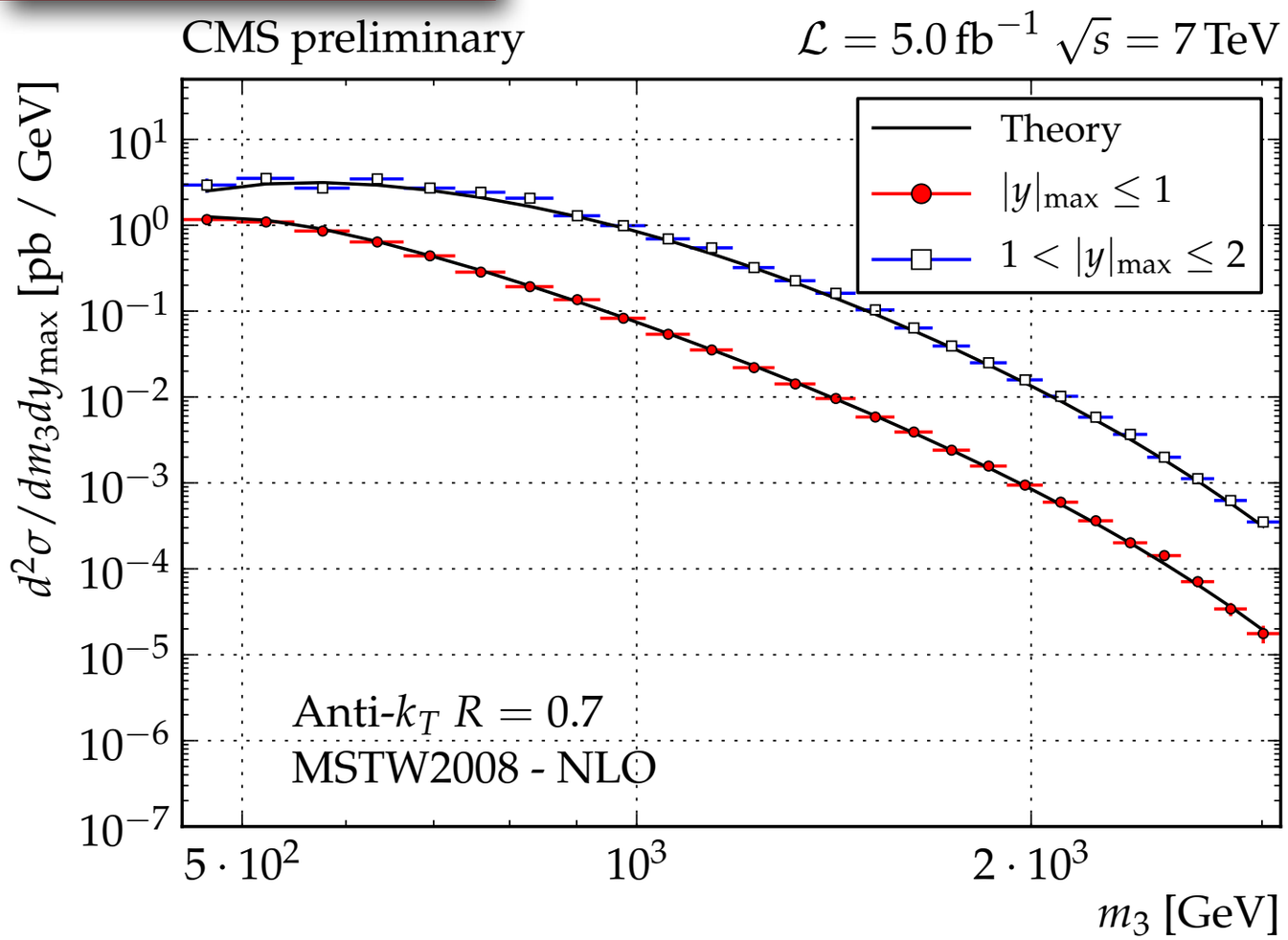
$R_{3/2} = \sigma_{3\text{-jet}} / \sigma_{2\text{-jet}} =$ 

arXiv:1304.7498

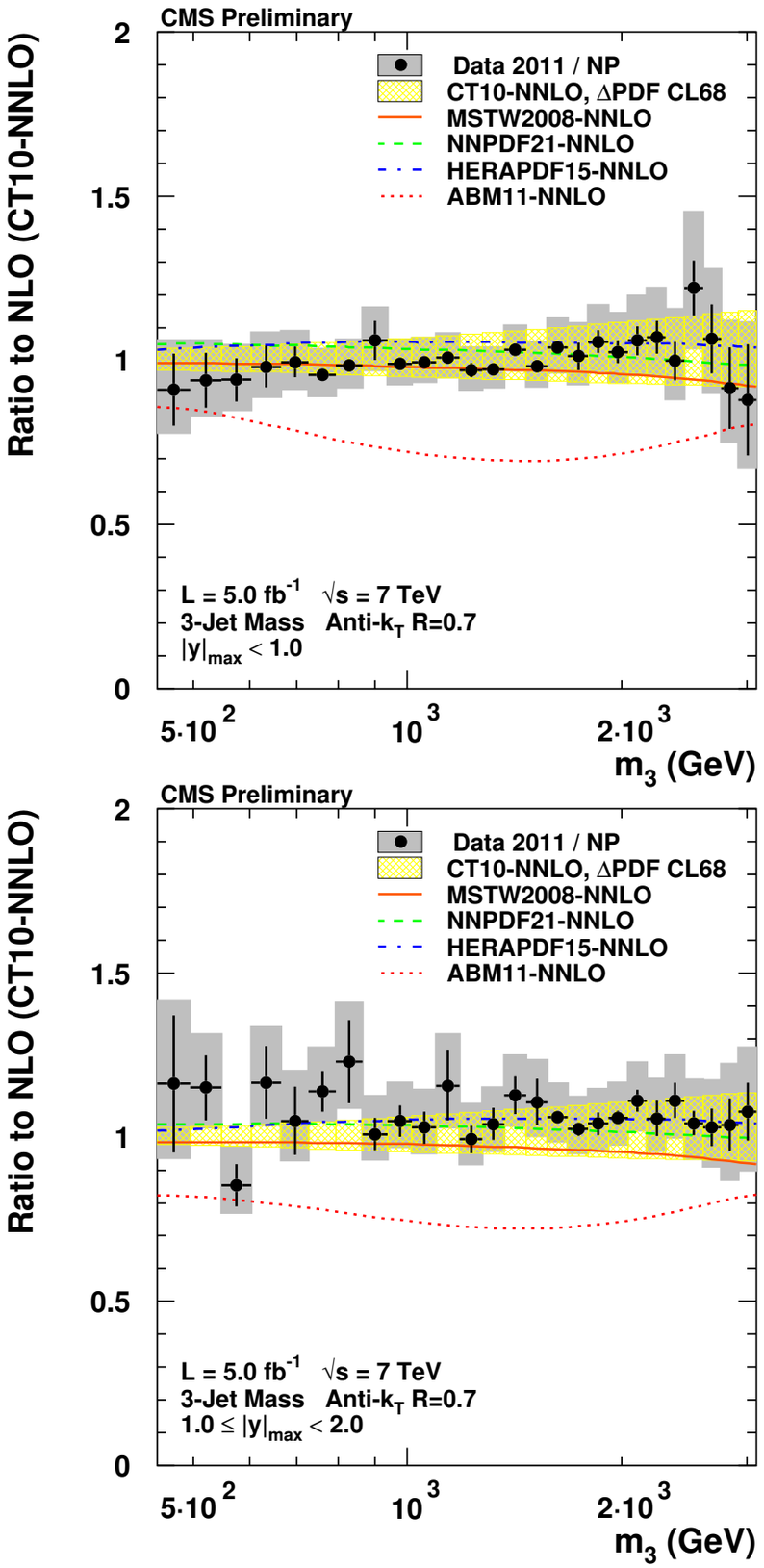
- cross-section ratios R_{32} & N_{32}:
  - inclusive 3-jet over 2-jet production
  - **sensitive to α_S**
- multiple alternative phase-space options
  - depending on the cut imposed on the 3rd jet p_T
  - expressed vs. different observables
  - measuring the α_S: vital to reduce scale uncertainty

3-jet invariant mass @ 7 TeV

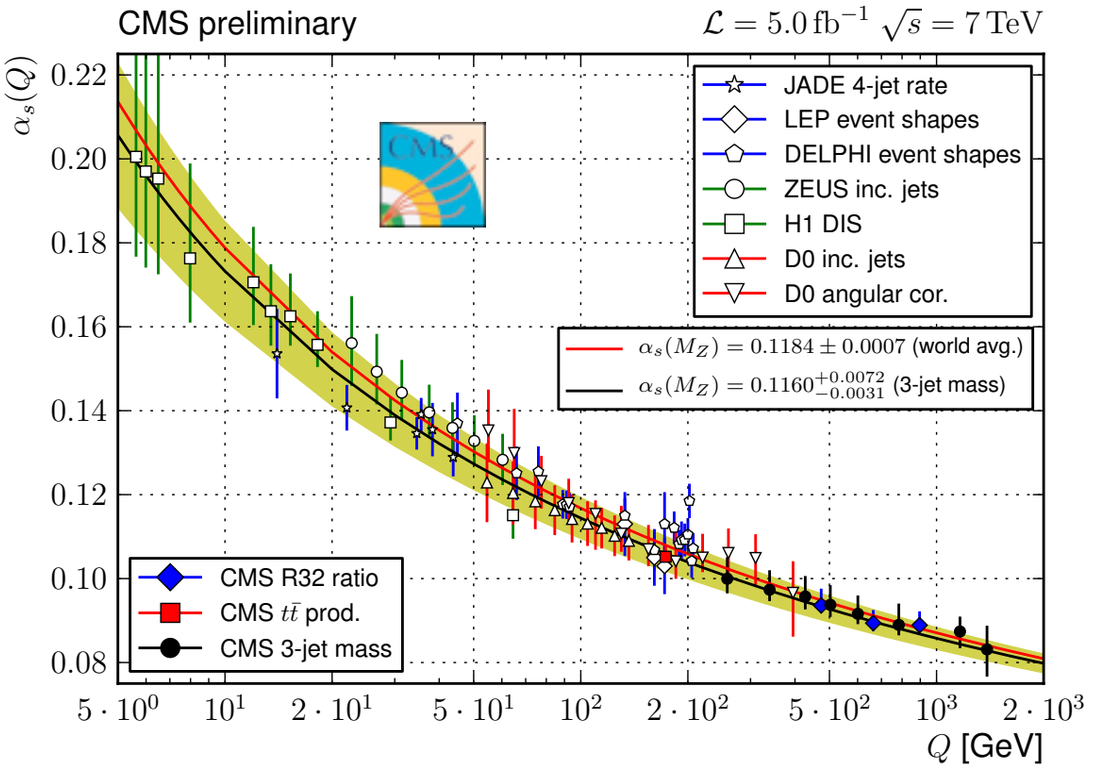
CMS-PAS-SMP-12-027

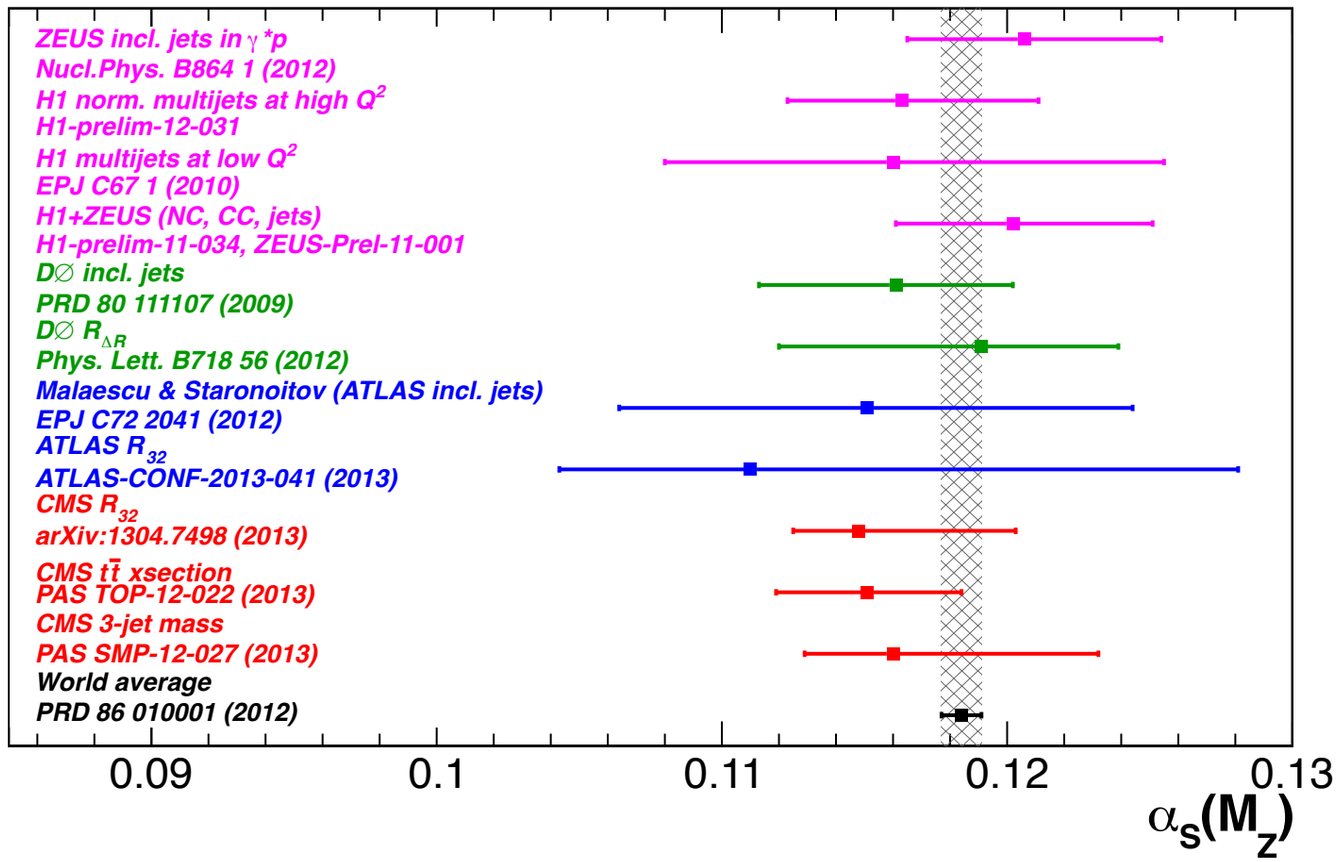


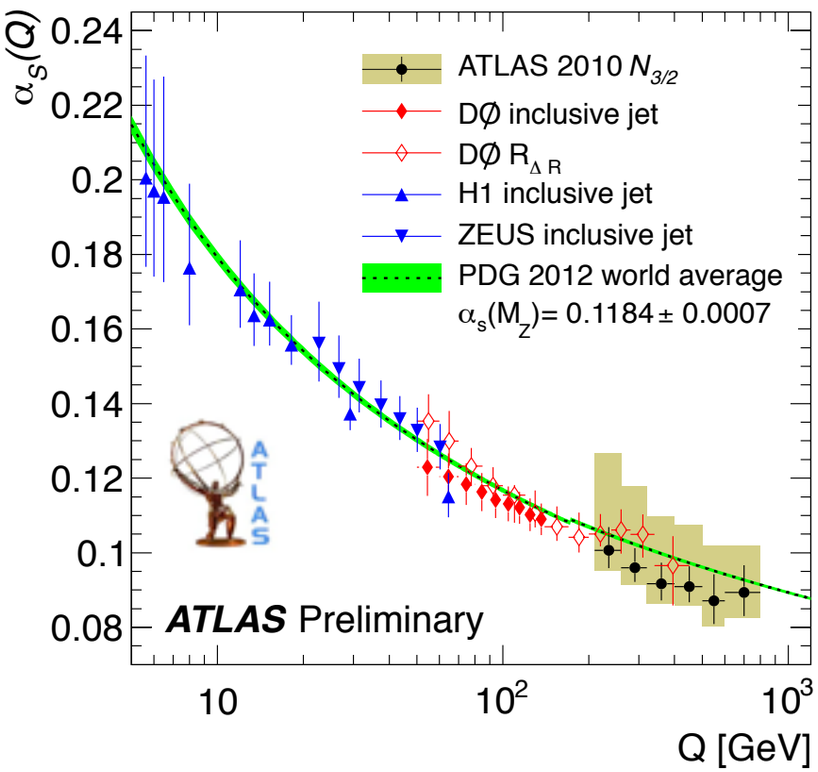
- measurement of the 3-jet invariant mass
  - sensitive to PDFs
  - **sensitive to α_s**
- phase space determined by the maximum rapidity of the 3 leading jets
  - up to $|y|_{max} = 2$ and $m_{3j} \sim 3$ TeV
- compatible with pQCD @ NLO



Measurements of α_s





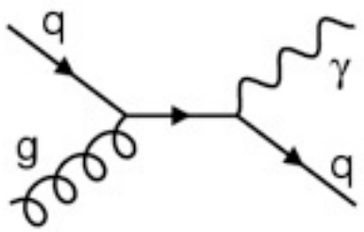


- measurements compatible with the world average
- **precision dominated by theoretical uncertainty (scale choice)**
  - will improve with pQCD @ NNLO
  - enough LHC data to exploit phase-space regions with small scale uncertainty (hard 3rd jet)
- measurements at different hard scales up to 1.5 TeV confirm the running of the coupling constant

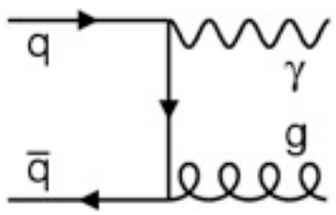
measurements with photons

Direct photon production

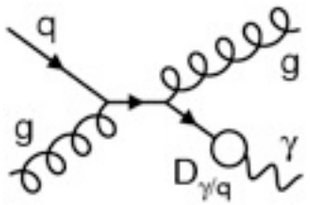
Compton

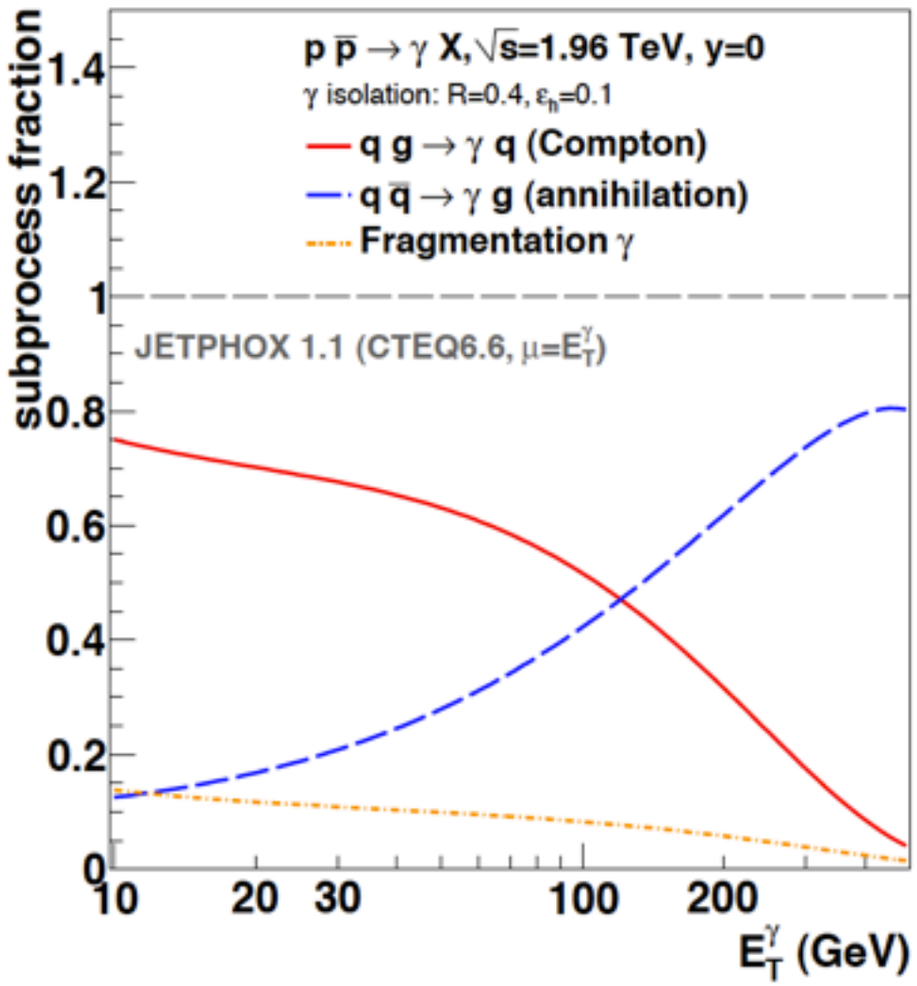


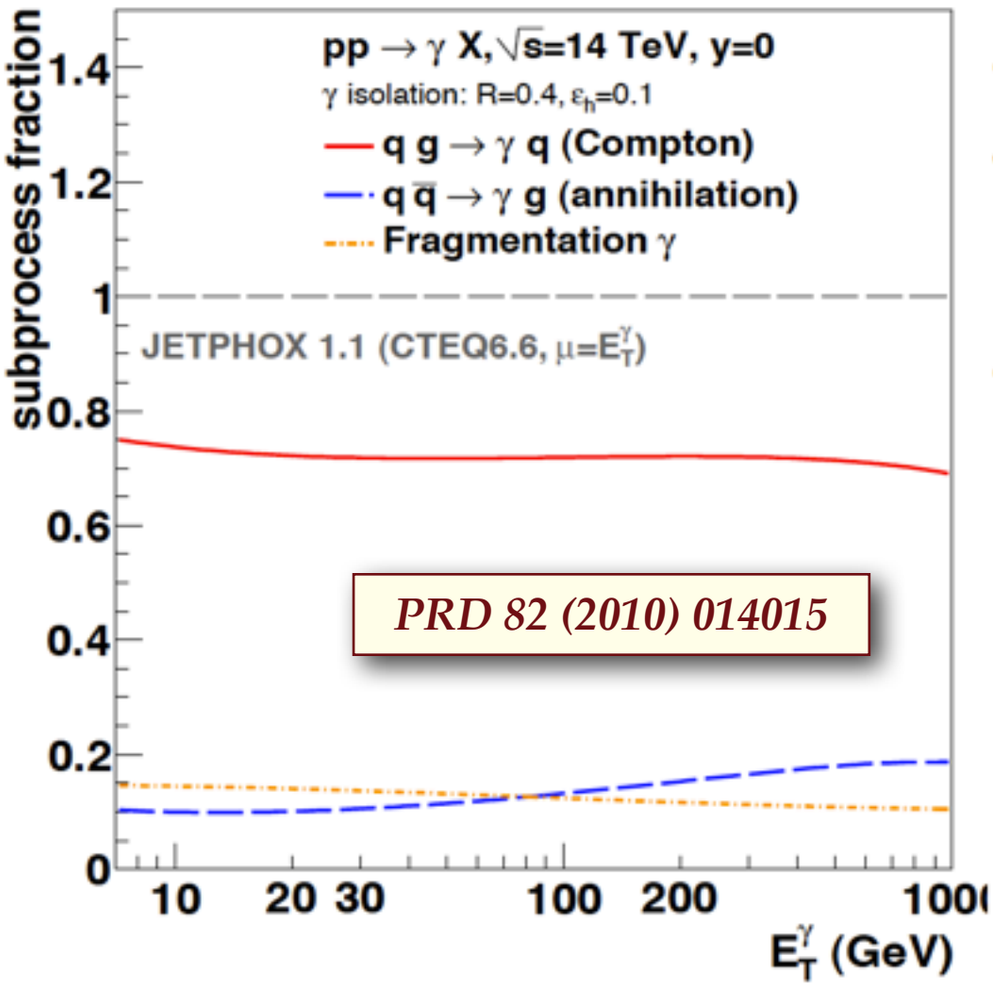
Annihilation



Fragmentation





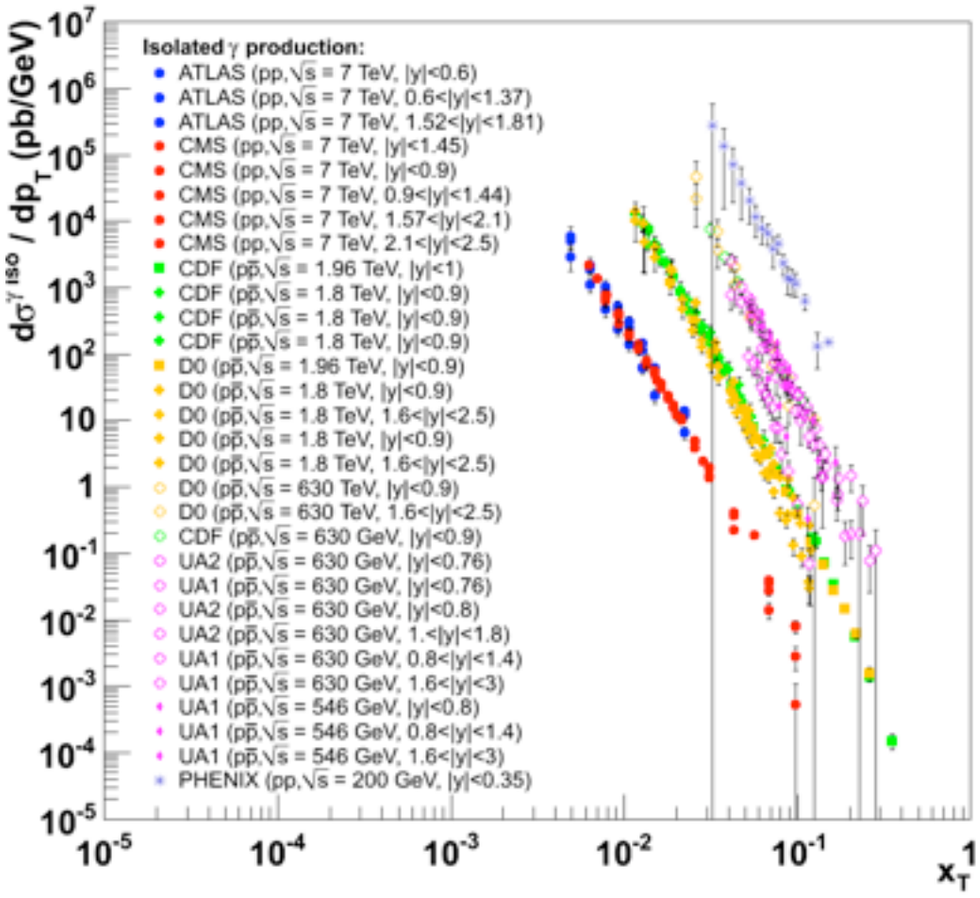


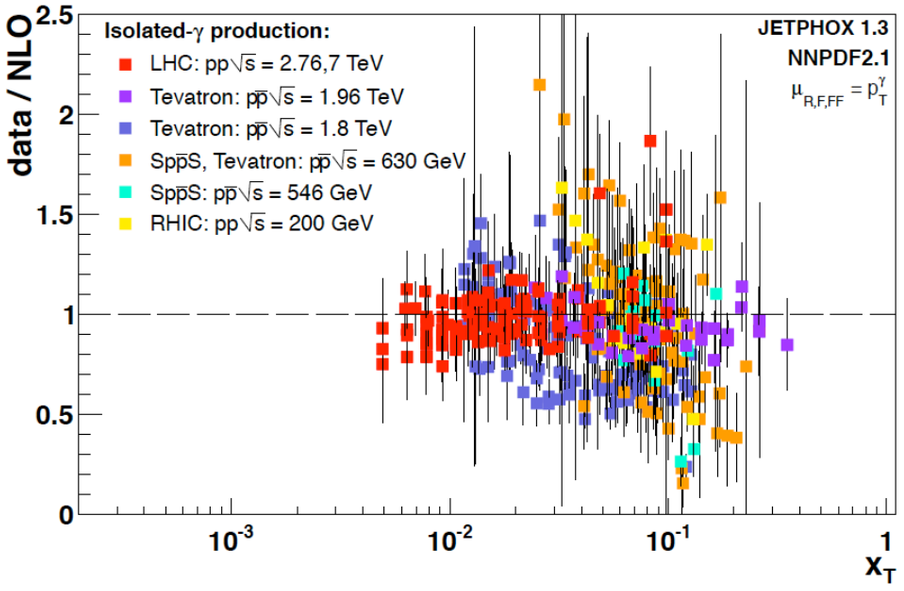
PRD 82 (2010) 014015

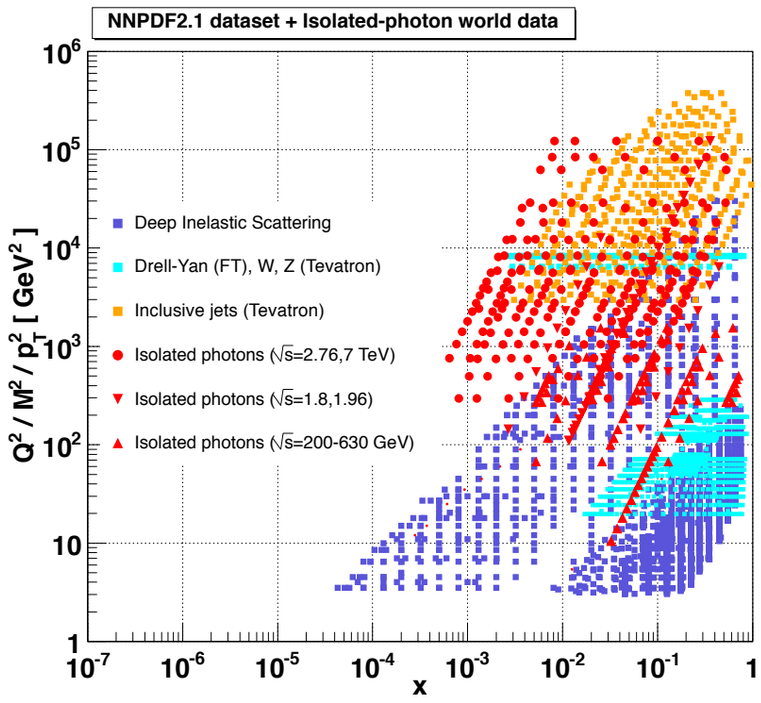
- production mechanisms
  - quark-gluon Compton scattering (dominant at LHC)
  - quark-antiquark annihilation
  - fragmentation of colored partons (greatly suppressed by requiring isolation)
- test of pQCD
  - NLO calculations
  - sensitive to gluon PDF

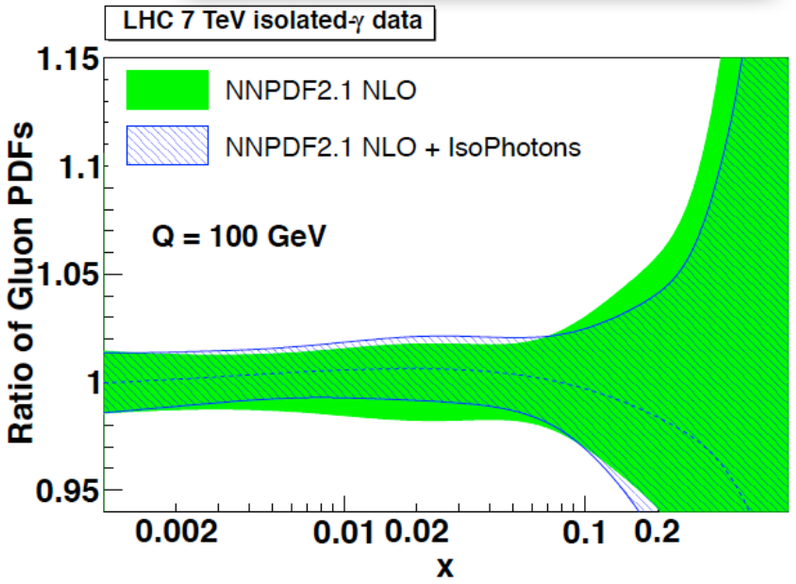
Direct photon production

Nucl. Phys. B860 (2012) 311



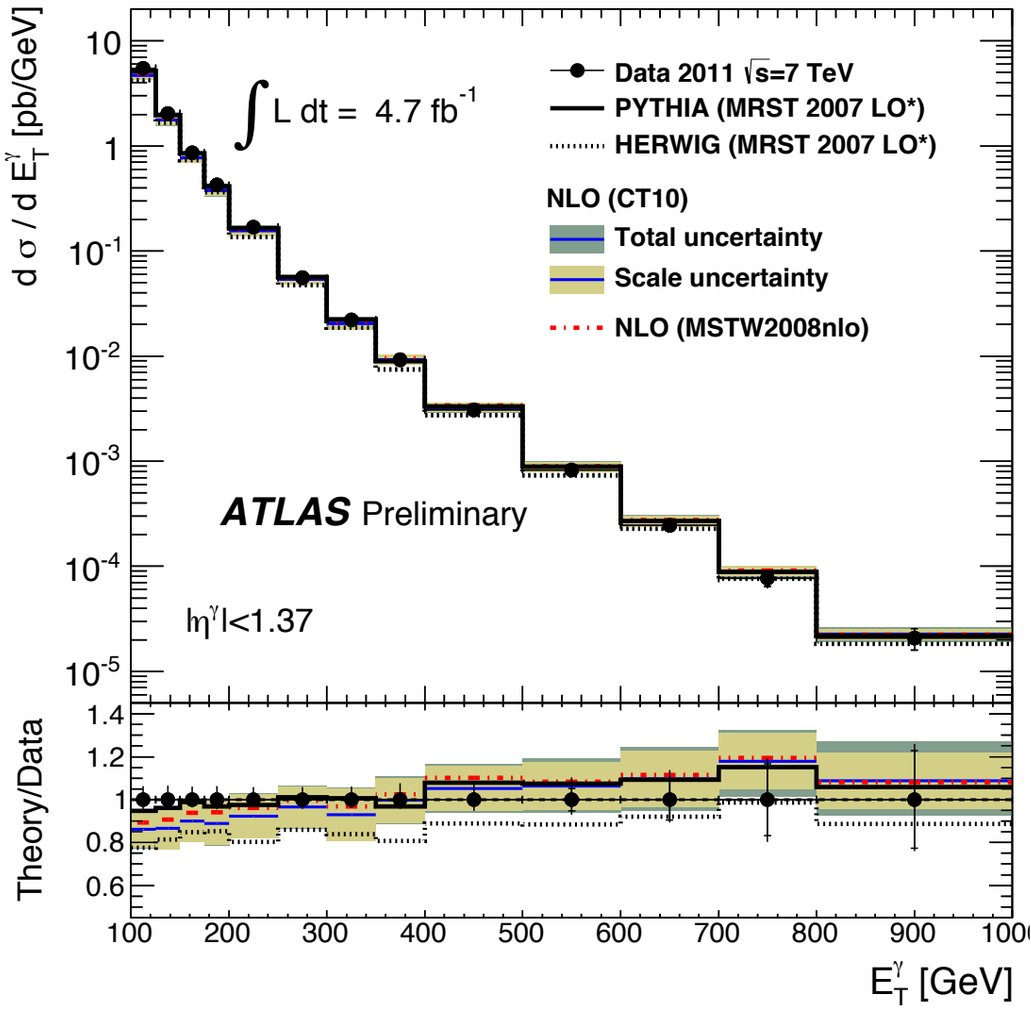


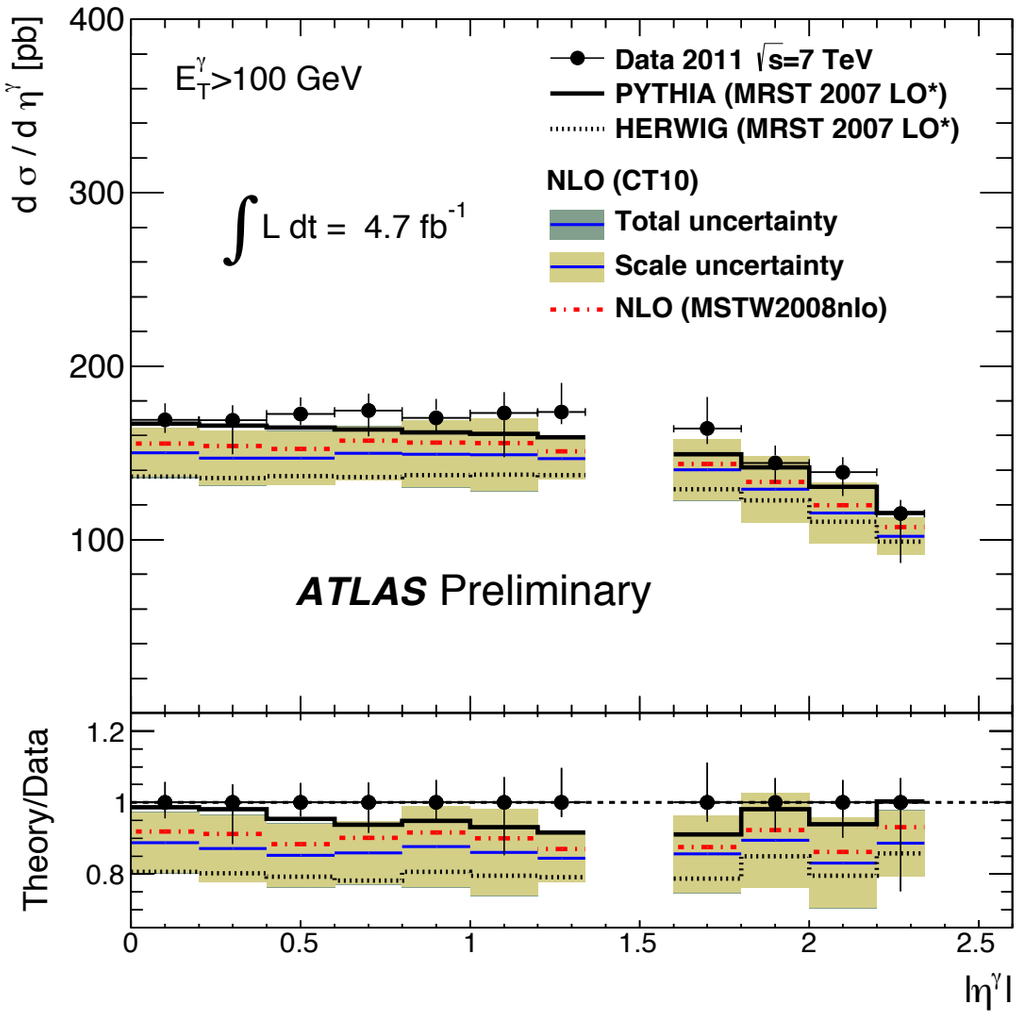




- large amount of photon measurements accumulated over the years
- not used so far in the PDF fits
  - probably missing the correlation of uncertainties?
- first attempt to include the photon measurements
  - in the NNPDF framework
  - moderate impact on the gluon PDF
- more photon data needed

Photon cross section @ 7 TeV

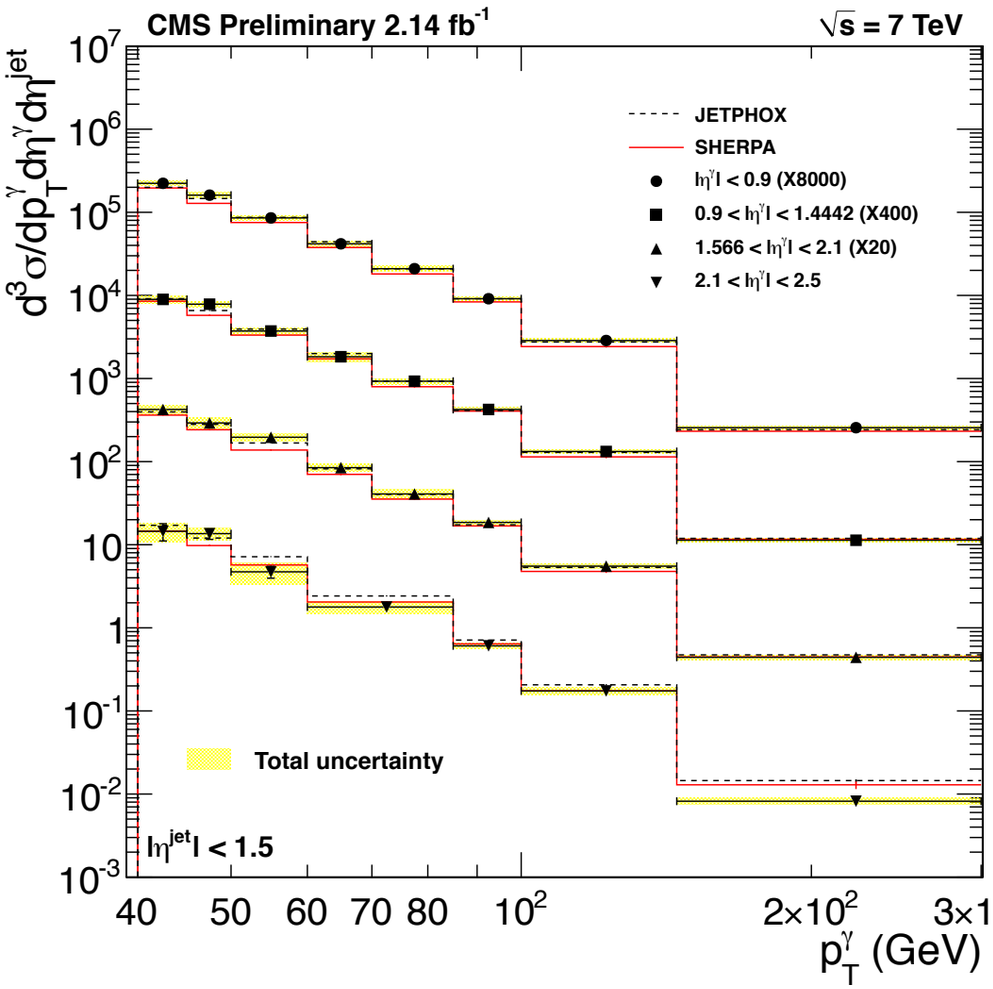




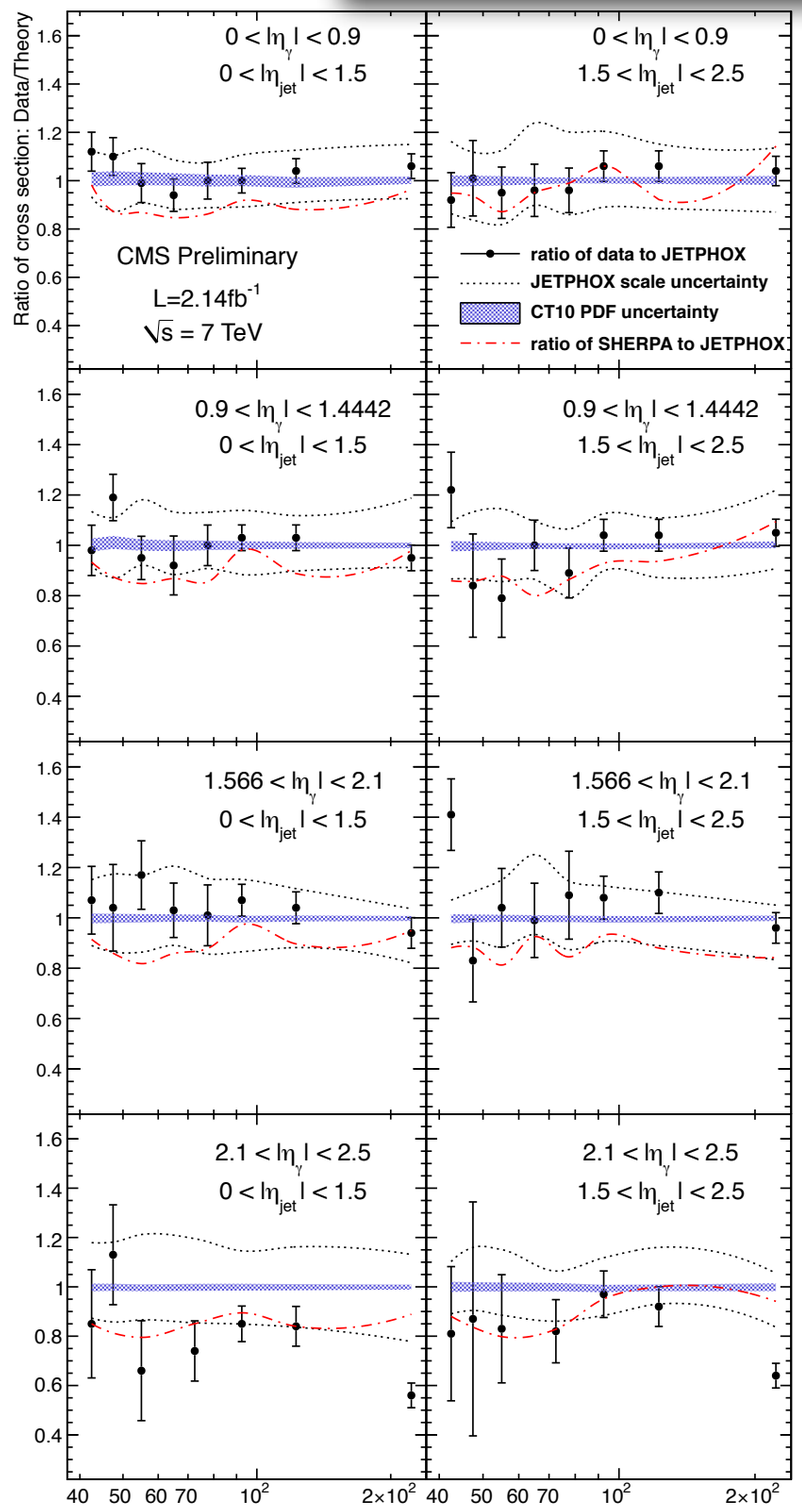
- new ATLAS measurement using the full 2011 dataset at 7 TeV
  - extending the E_T reach up to 1 TeV
- theory uncertainty dominated by the scale choice
  - similar or larger than the experimental uncertainty
- theory prediction @ NLO agree with the data, within uncertainties
  - tension observed in the pseudorapidity spectrum

ATLAS-CONF-2013-022

Photon+jet cross section

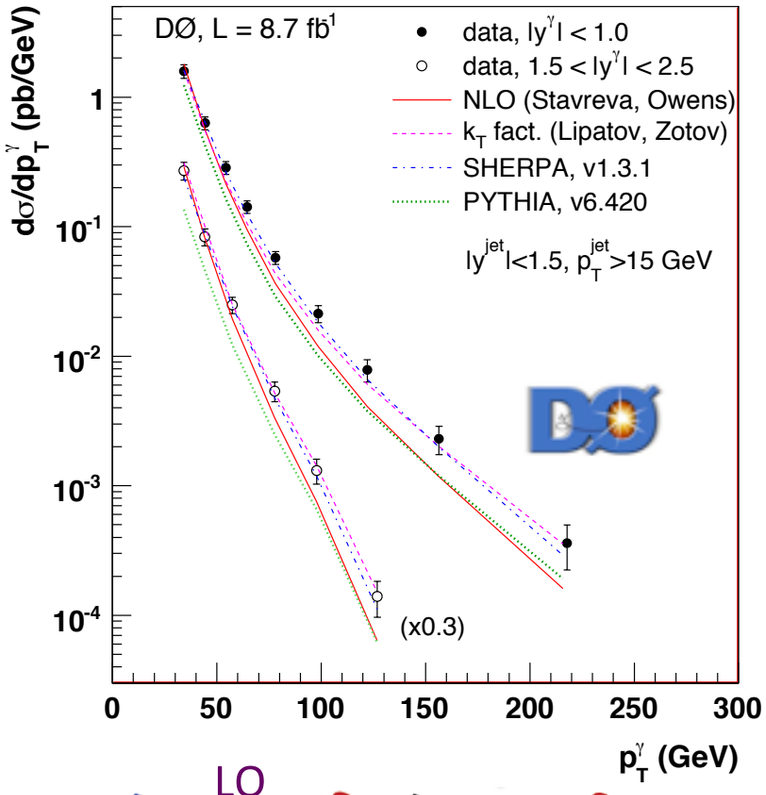


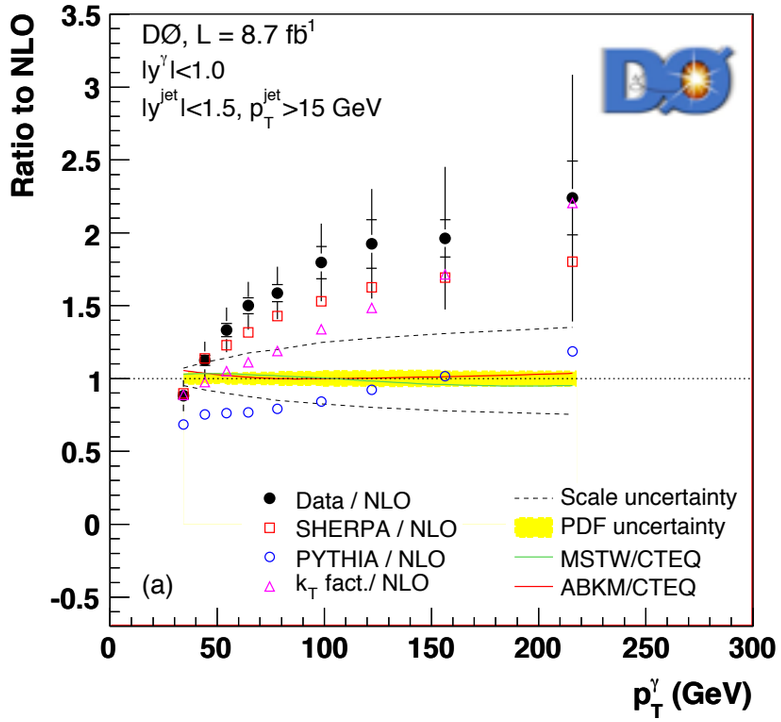
CMS-PAS-QCD-11-005

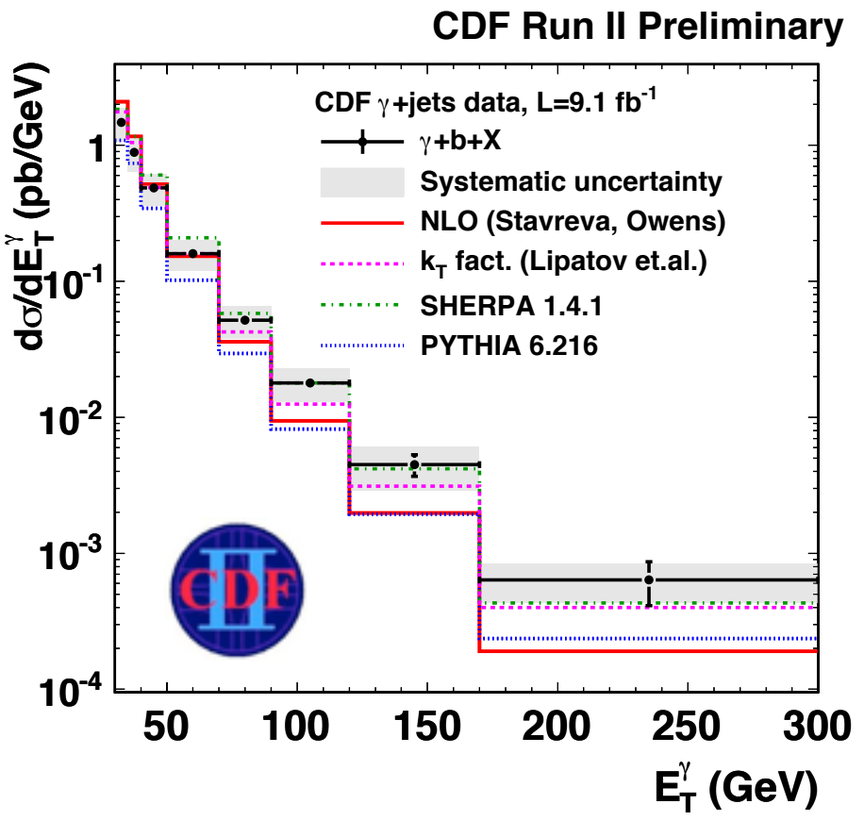


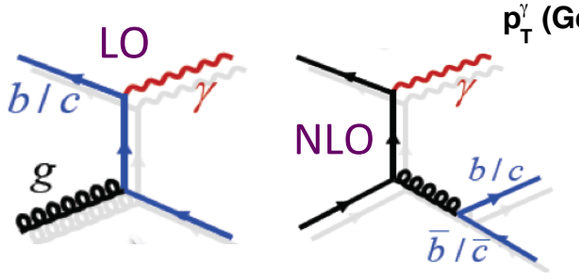
- photons produced in association with jets
  - various configurations according to the jet and photon η
  - additional information on the QCD dynamics and PDF constraints
- theory uncertainty dominated by scale choice
- theory prediction @ NLO agree with the data
- Sherpa describes the data well

Photon+b production







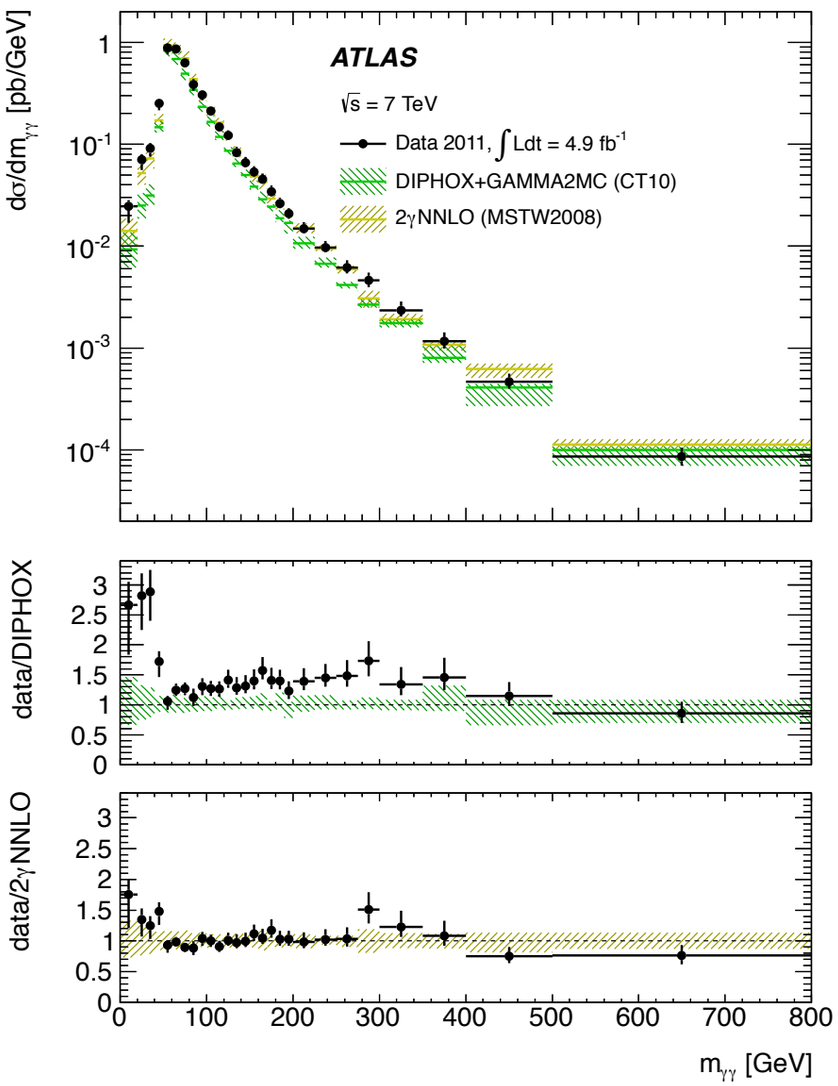


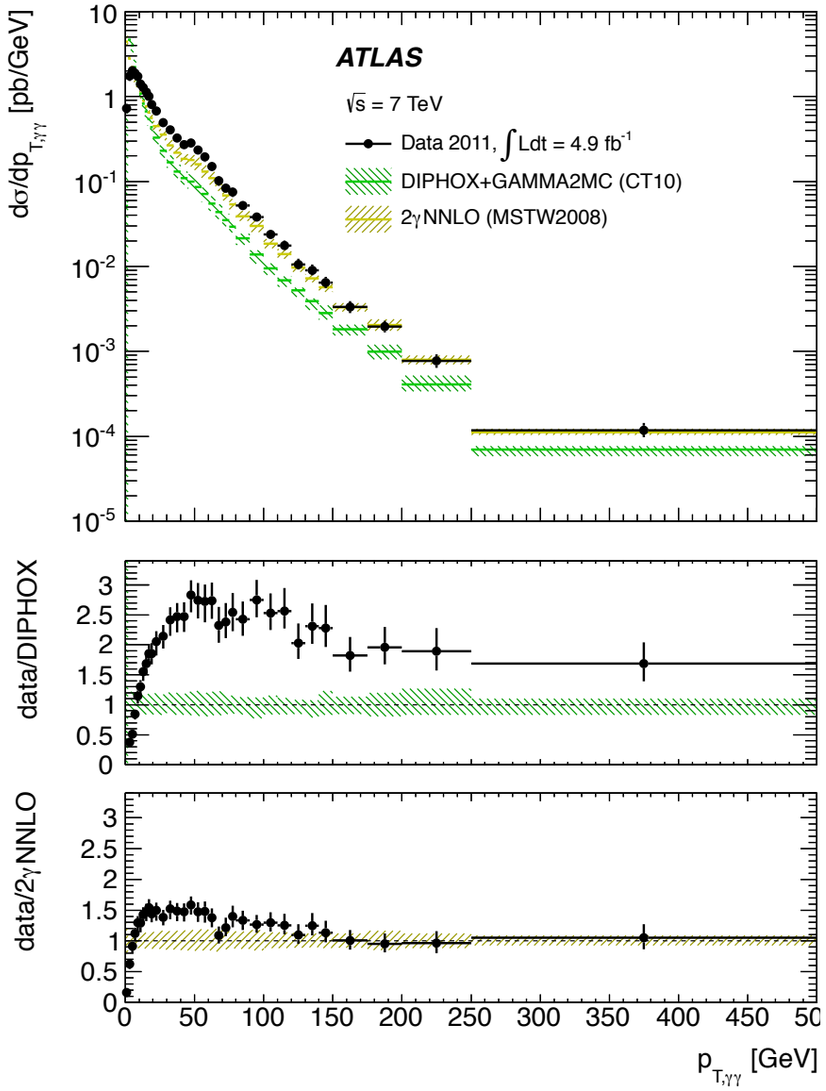
Phys. Lett. B714 (2012) 32

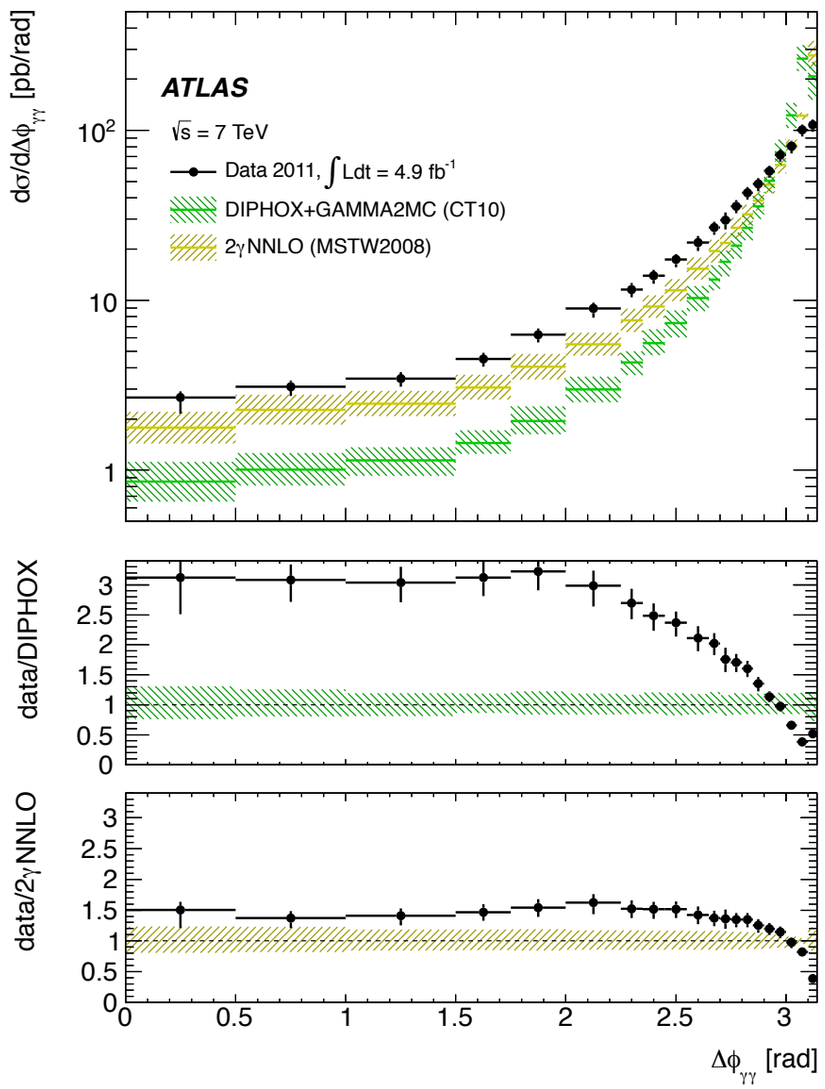
CDF note 10818

- photons produced in association with b jets
  - at low p_T Compton scattering dominates: b-quark comes from the proton (probe of the b-quark PDF)
  - at high p_T quark annihilation dominates: b-quark comes from gluon splitting
- theory uncertainty dominated by the scale choice
- theory prediction @ NLO does not describe the data
- Sherpa describes the data well

Prompt isolated di-photon production







$m_{\gamma\gamma}$

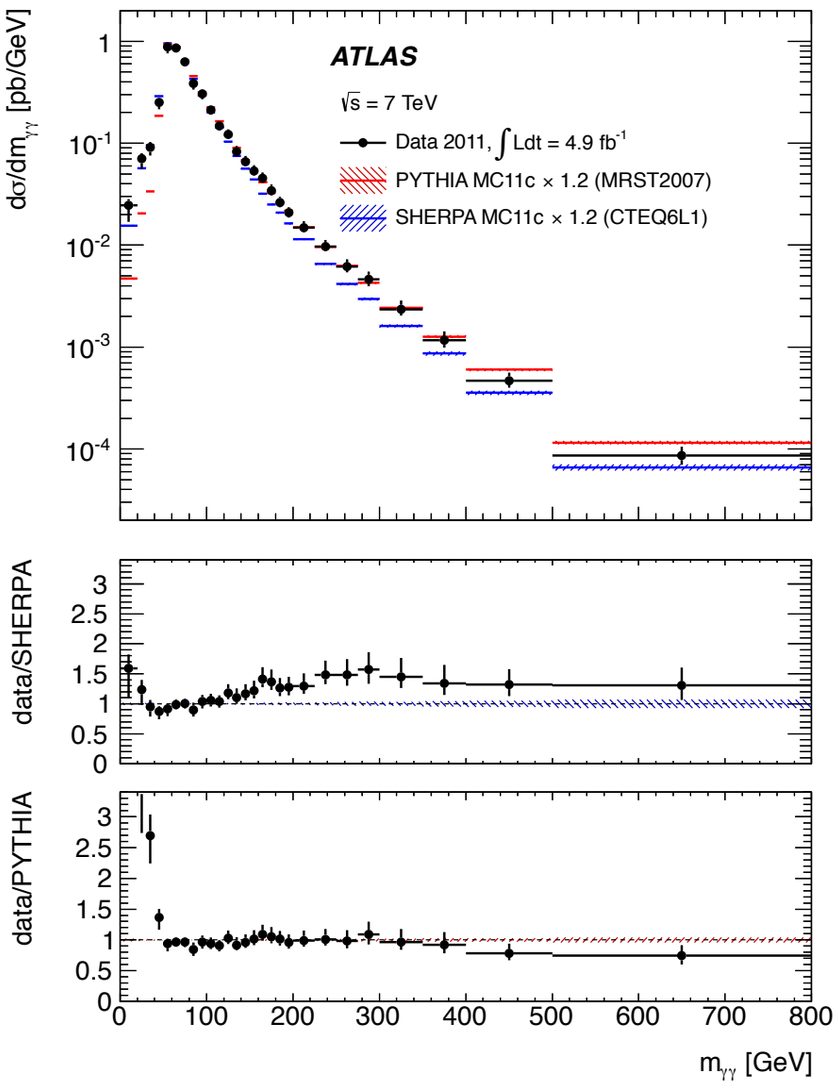
- Higgs background
- probe of new physics
- sensitive to PDFs

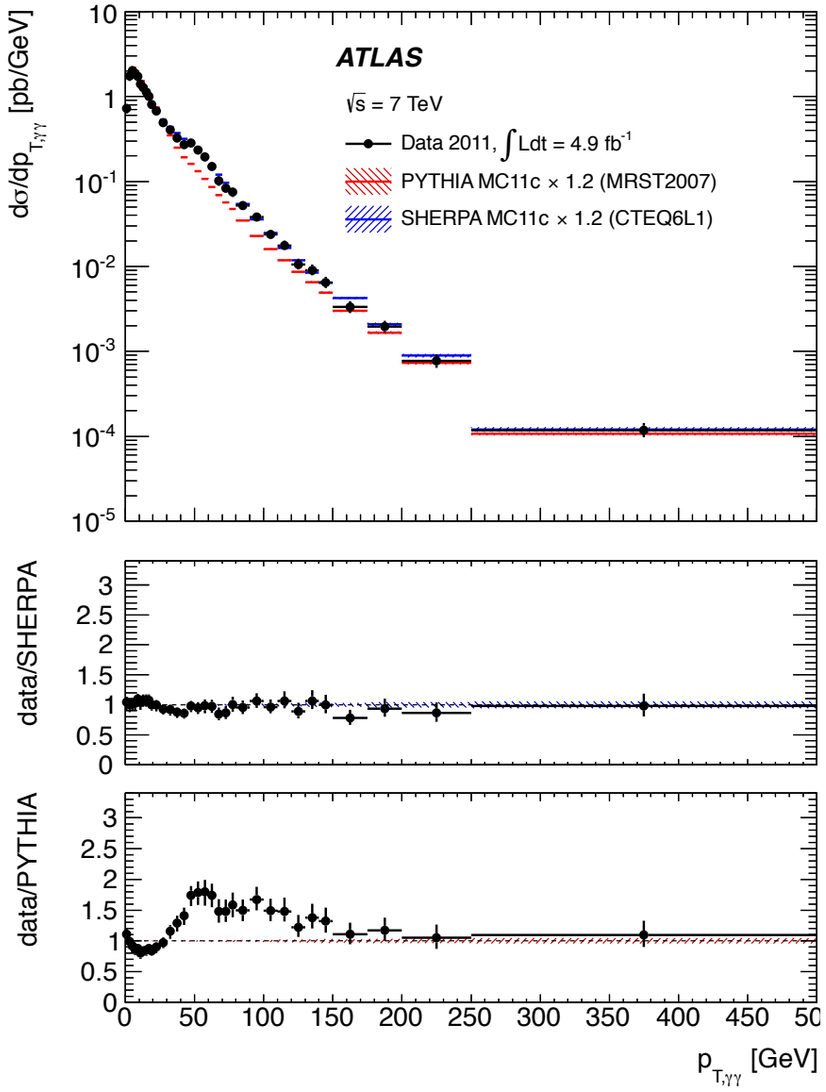
$p_{T\gamma\gamma}$, $\Delta\phi_{\gamma\gamma}$

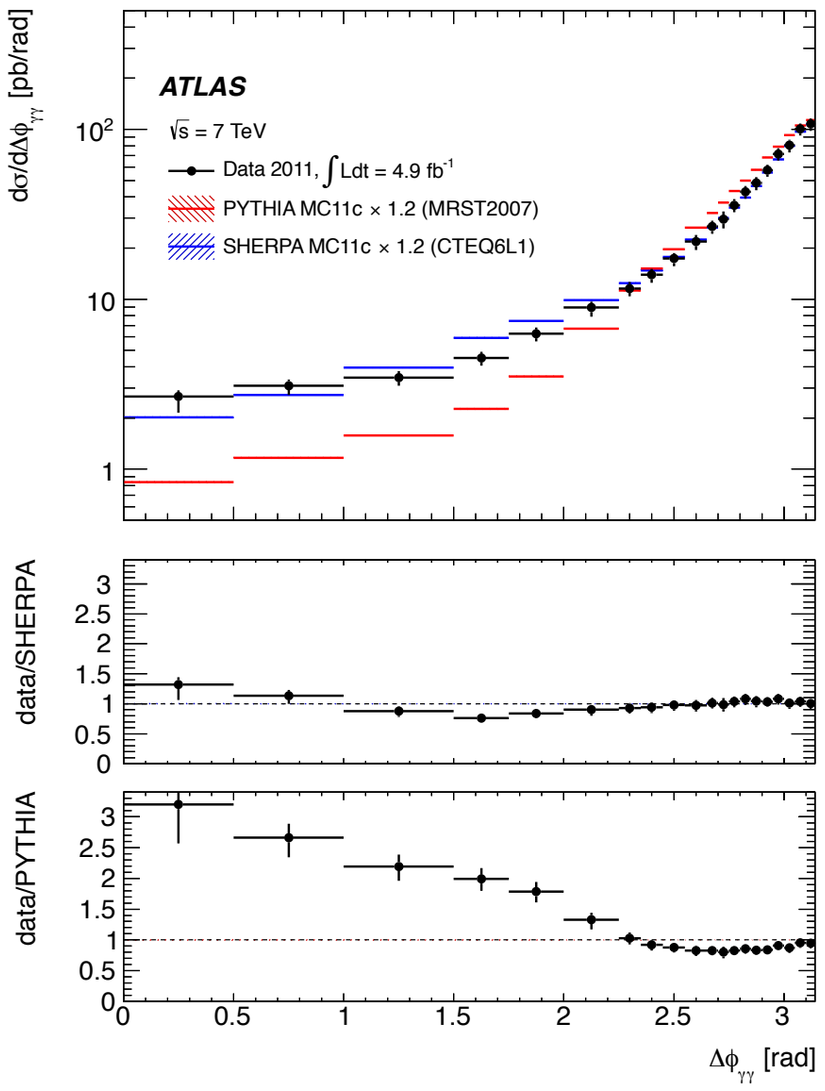
- sensitive to ISR and fragmentation
- re-summation important at $\Delta\phi\sim\pi$ ($p_T\sim0$)
- collinear region ($\Delta\phi<2.5$) needs NNLO

JHEP 01 (2013) 086

Prompt isolated di-photon production







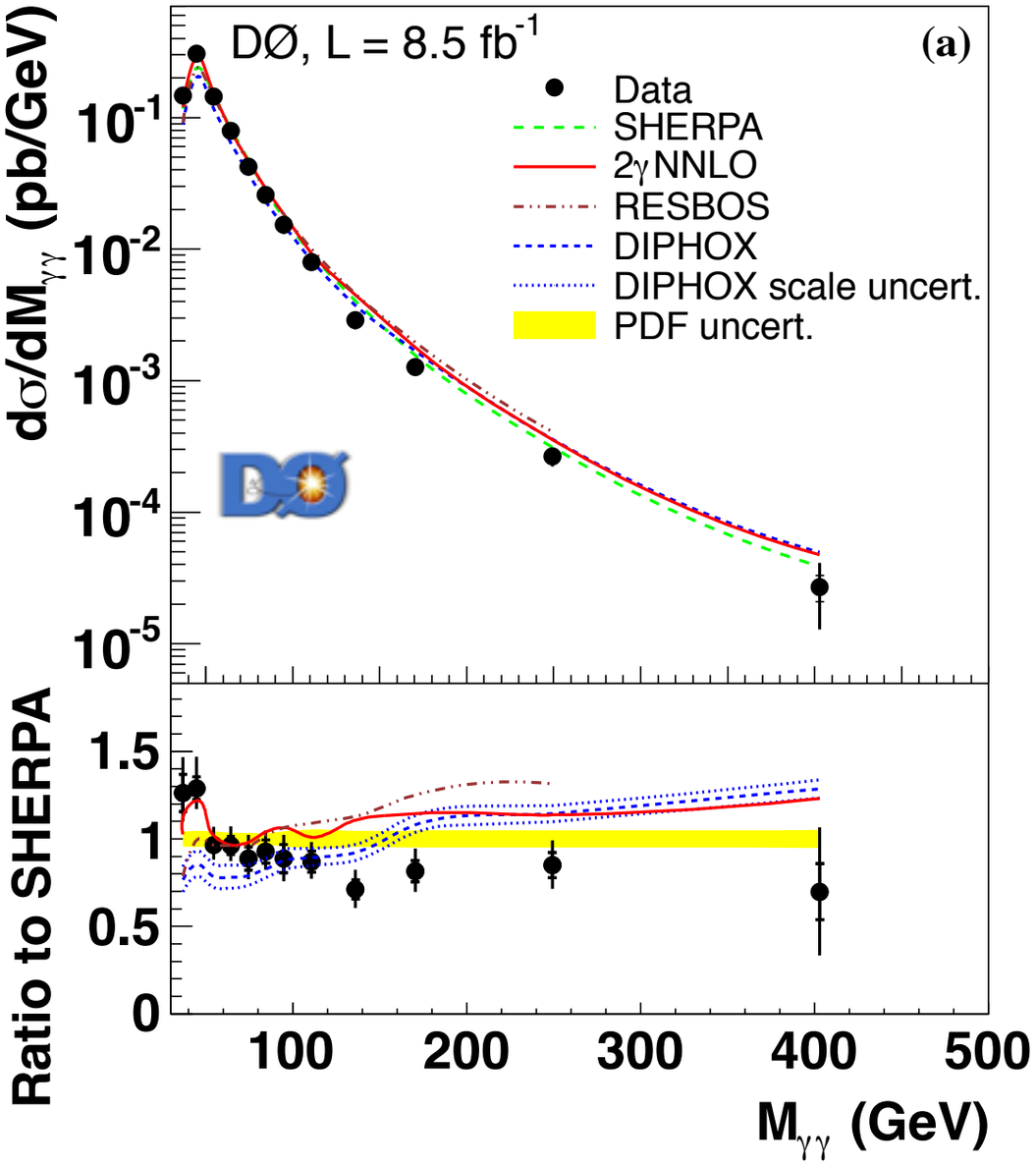
- parton-shower generators provide good description of the data
  - mimicking NNLO contributions by extra jet and photon radiation
  - better description of fragmentation

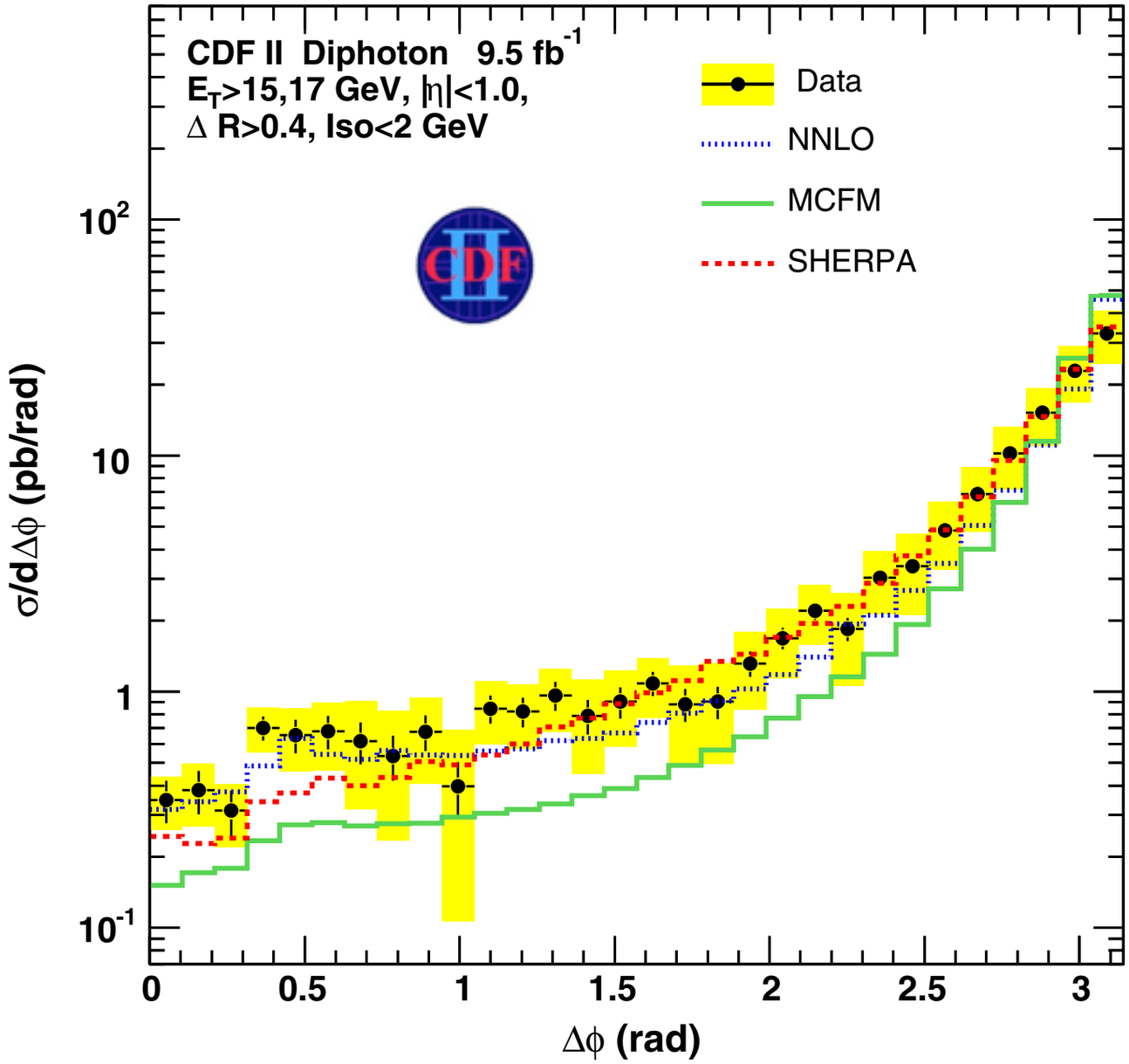
JHEP 01 (2013) 086

Prompt isolated di-photon production

arXiv:1301.4536

Phys. Rev. Lett. 110 (2013) 101801



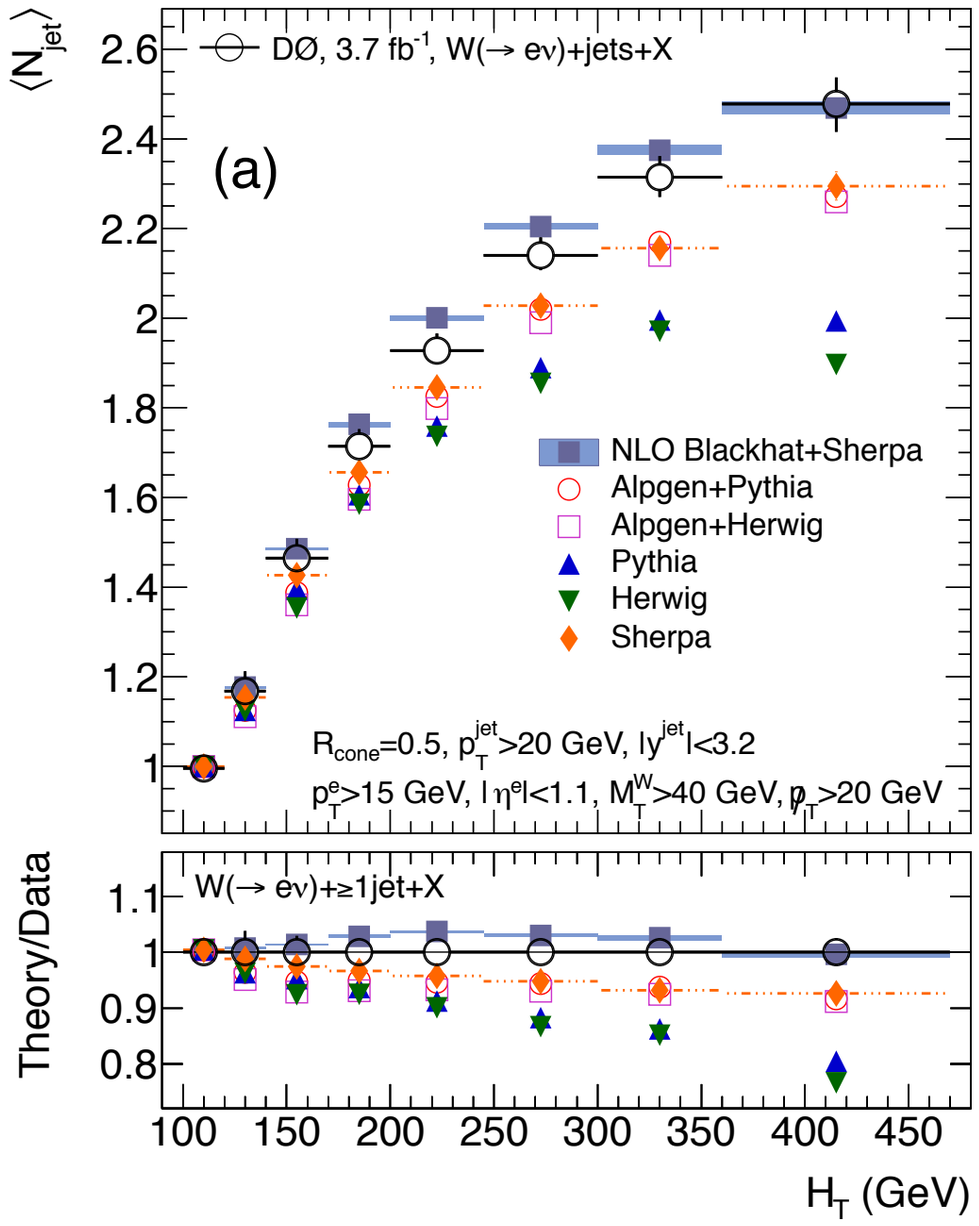


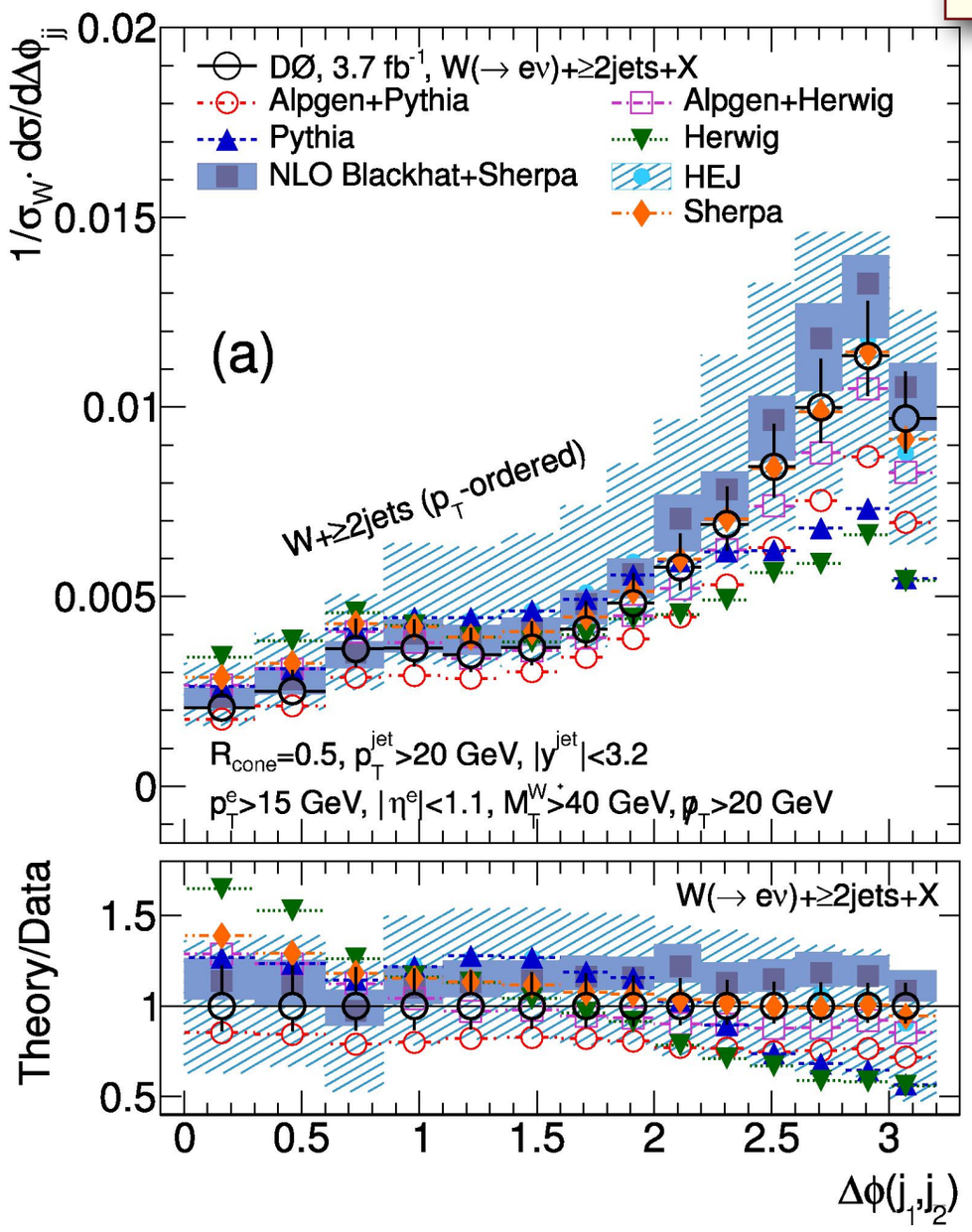
similar conclusions from Tevatron measurements

measurements with vector bosons + jets

W+jets

arXiv:1302.6508

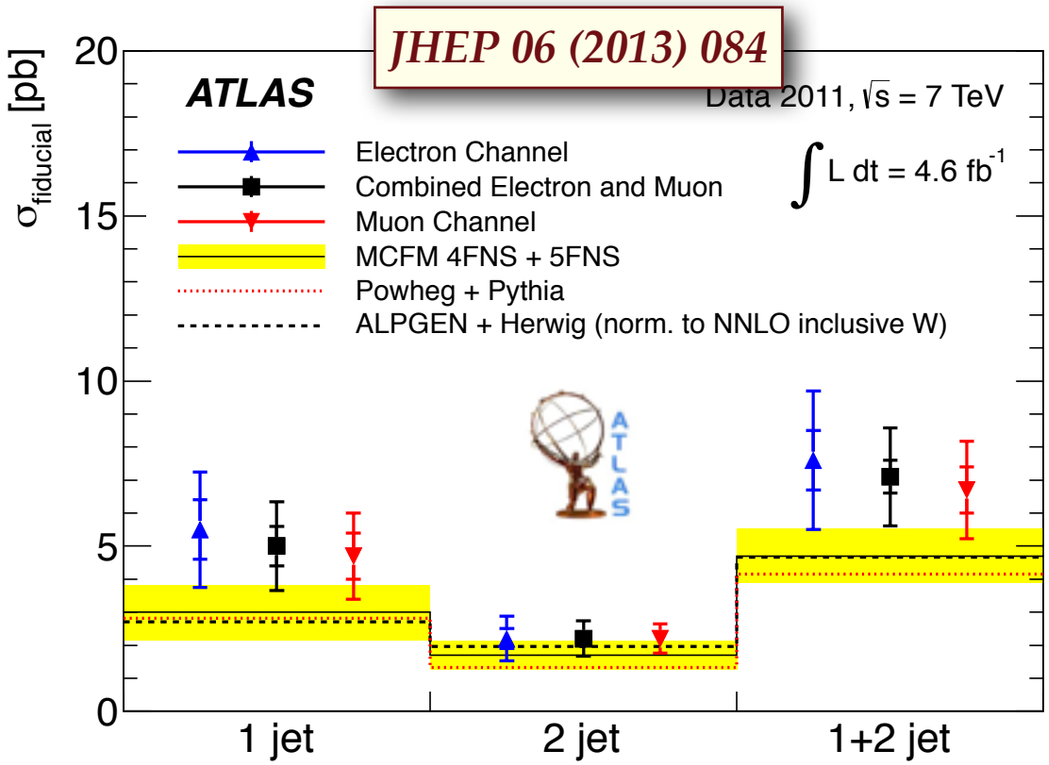


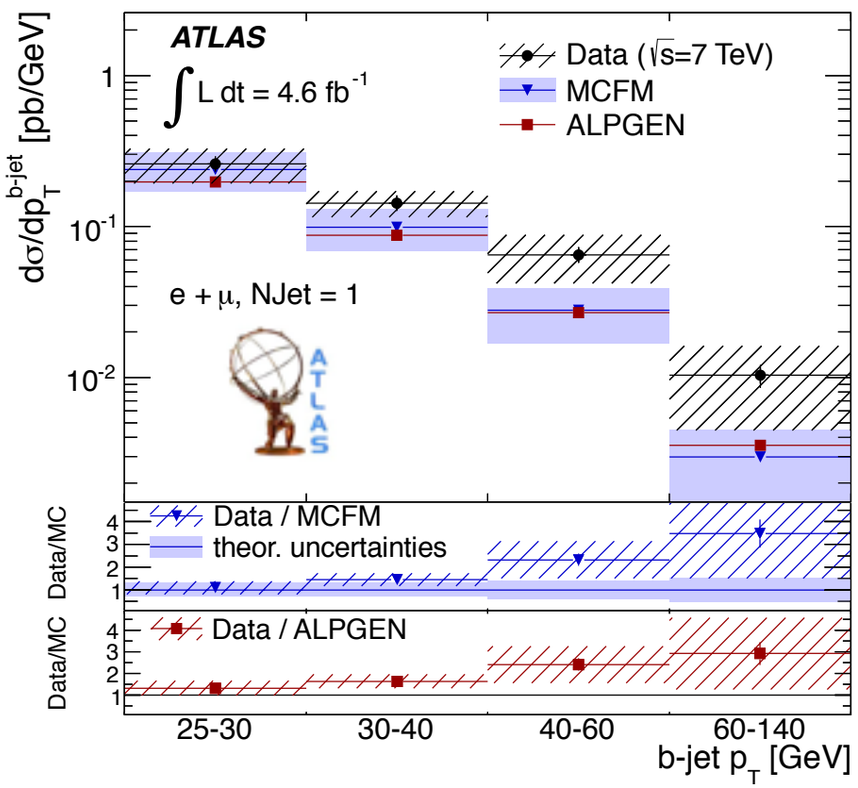


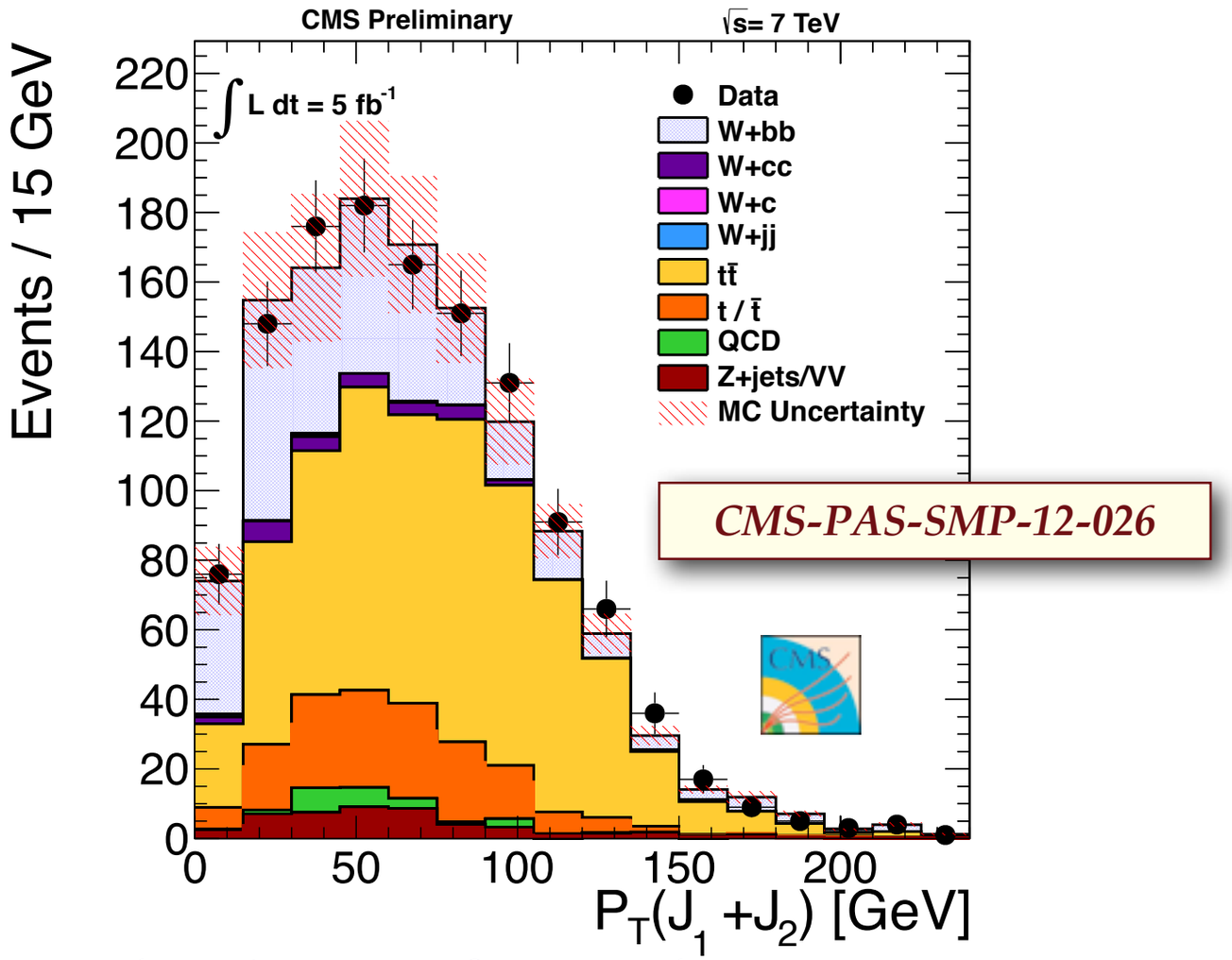
- comprehensive study of W+jets kinematics
  - important background for many new physics searches
- QCD @ NLO sufficient to describe the data
  - LO generators (PS, or ME+PS) fail to describe the data at high jet multiplicities

W+b(b)

JHEP 06 (2013) 084



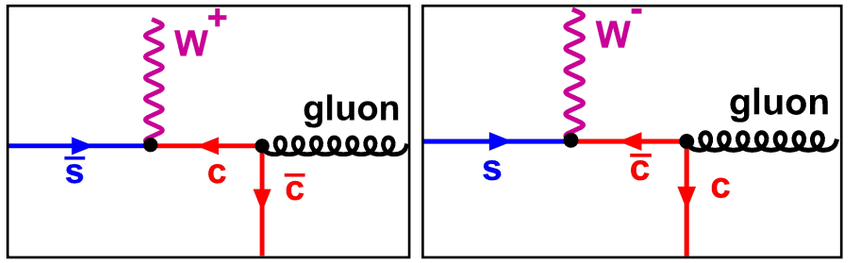


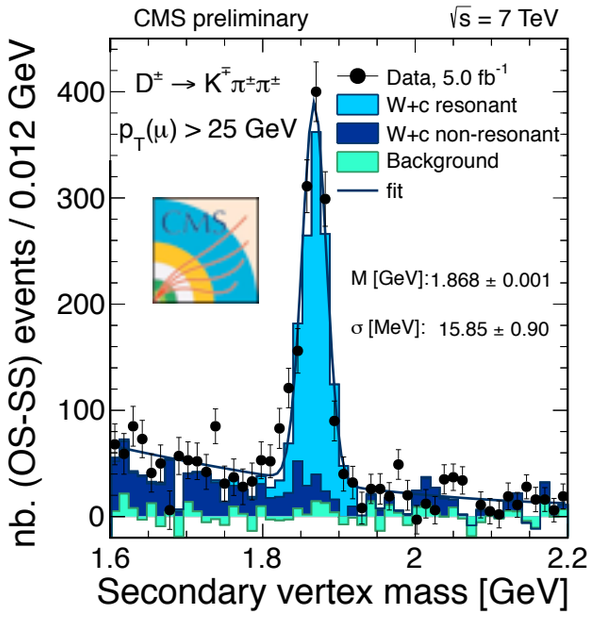


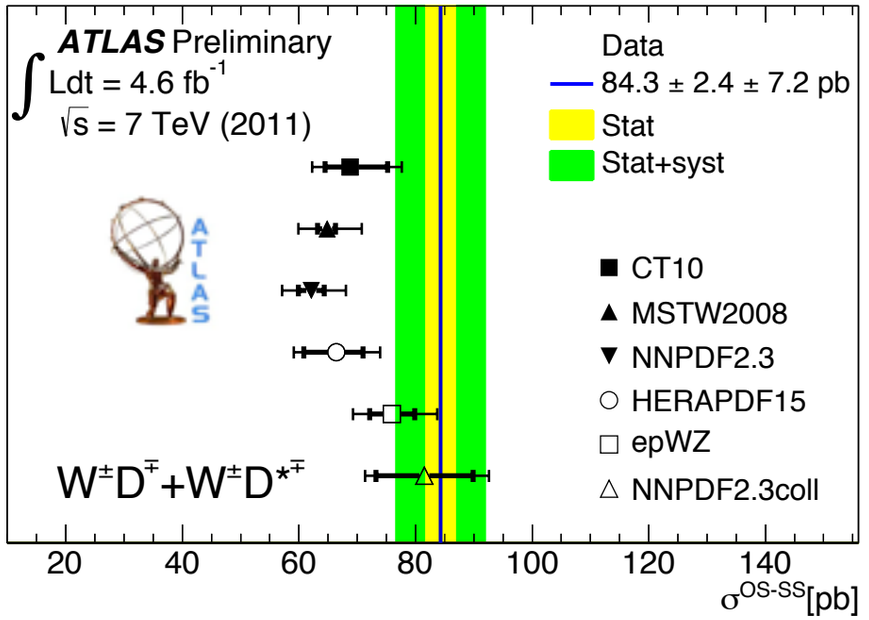
CMS-PAS-SMP-12-026

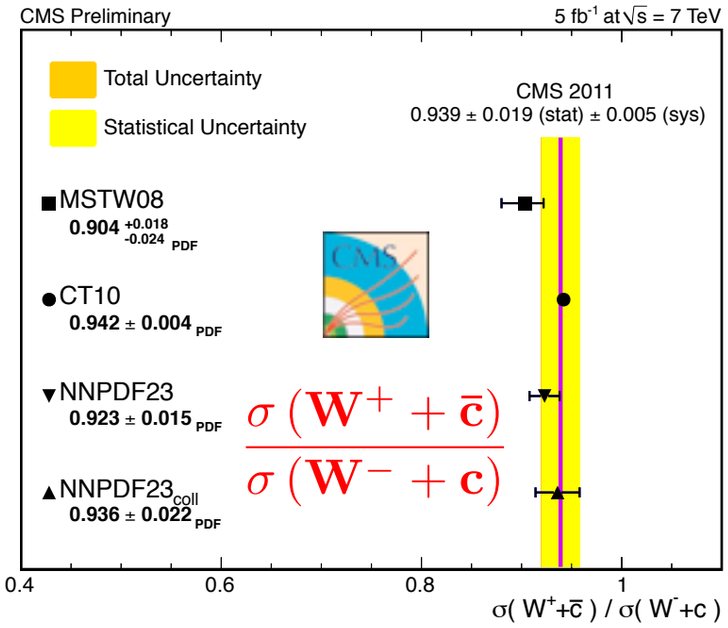
- W+b(b) production confronts the pQCD predictions in the presence of heavy quarks
- fiducial cross section of W+b(b) consistent with MCFM prediction within 1.5σ
- differential cross section shows some tension for increasing b-jet p_T
  - but compatible within uncertainties

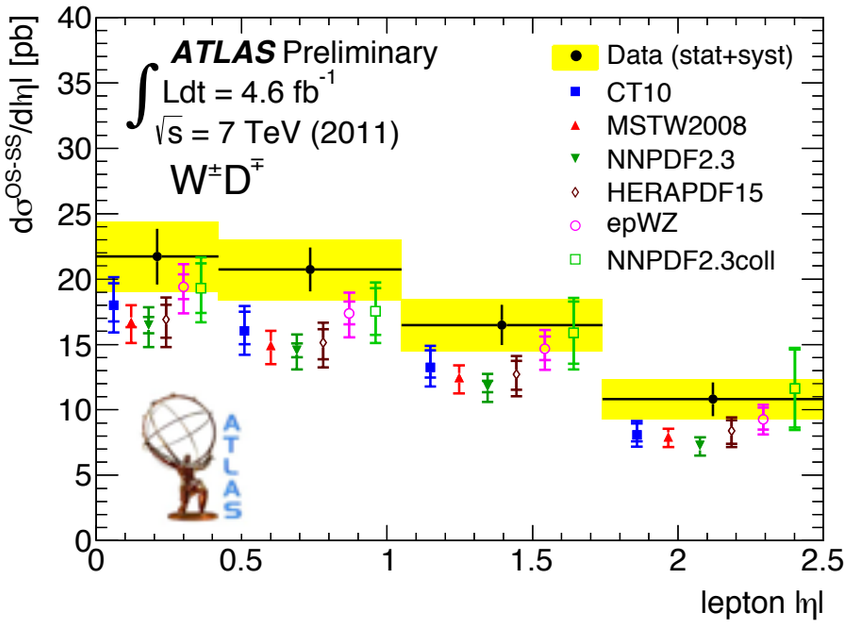
W+c











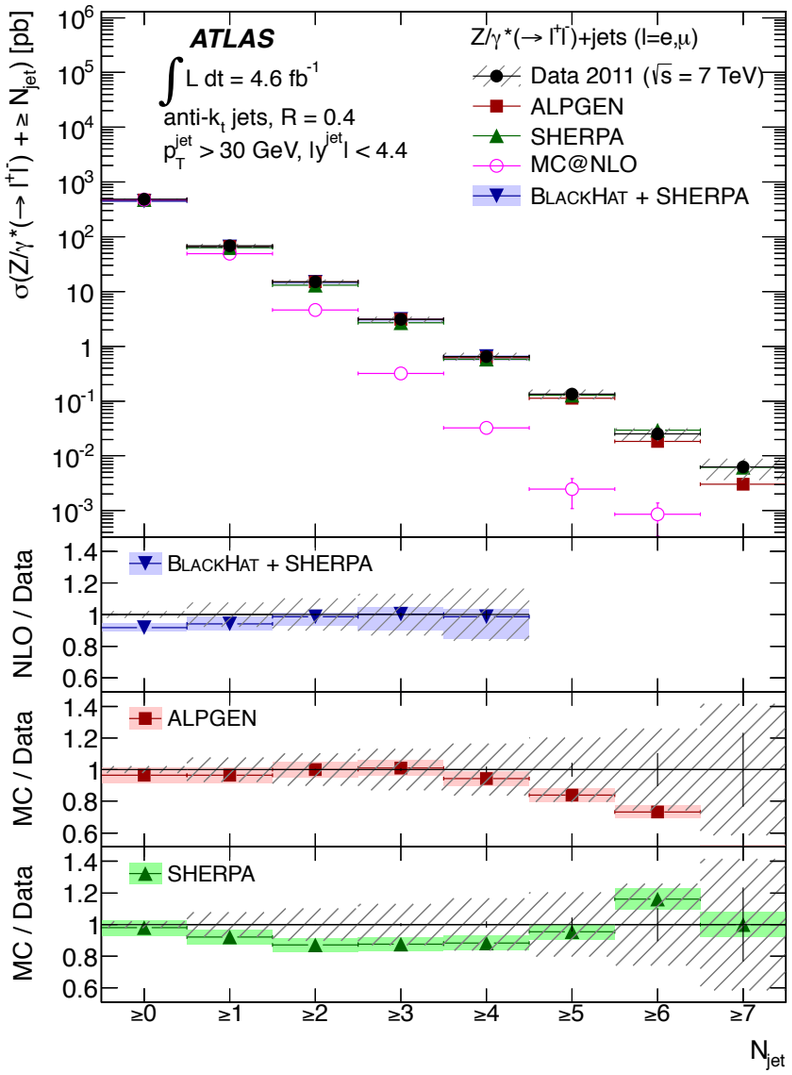
- **probes the strange content of the proton**
  - contribution from d quark about ~10% (Cabibbo suppressed)
- characteristic signature
  - W boson and D meson with opposite sign (OS)
  - backgrounds suppressed by subtracting OS - SS
- experimental techniques for c identification
  - ATLAS: D reconstruction from tracks combination
  - CMS: jets with c content using secondary vertices
- theory predictions
  - ATLAS: aMC@NLO
  - CMS: MCFM
- overall agreement between data and theory
  - measurement systematics limited
  - differential distributions reproduced
  - tension with some PDF sets

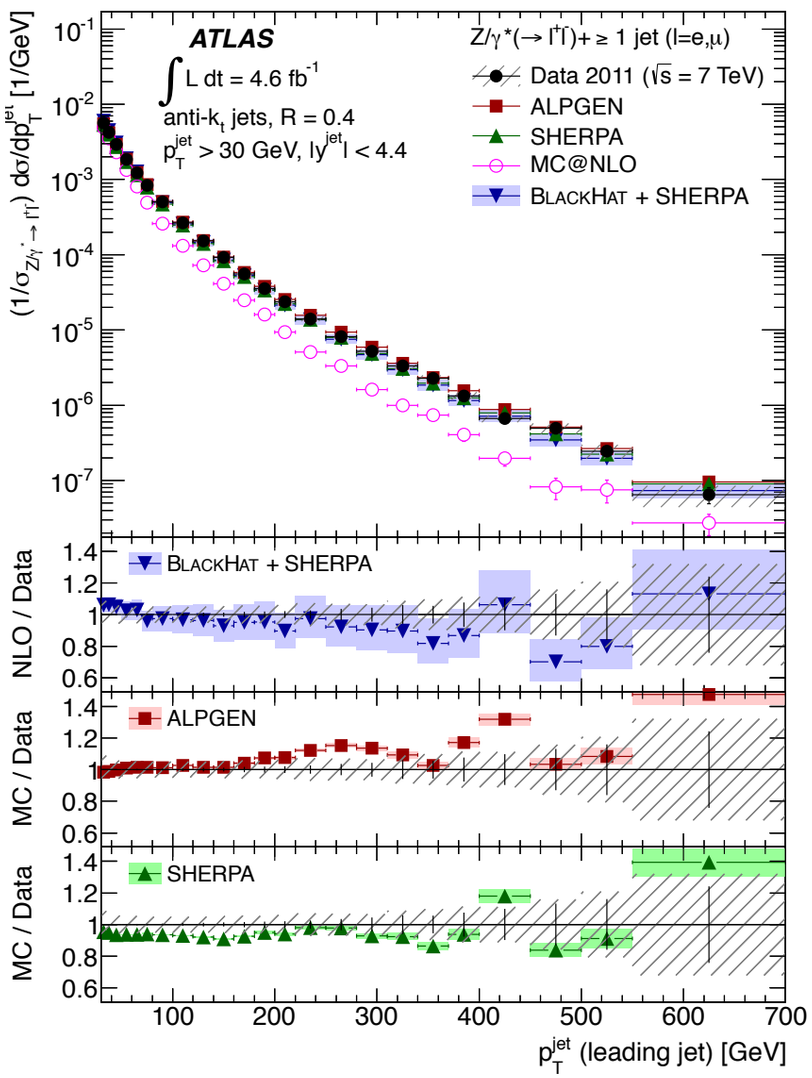
ATLAS-CONF-2013-045

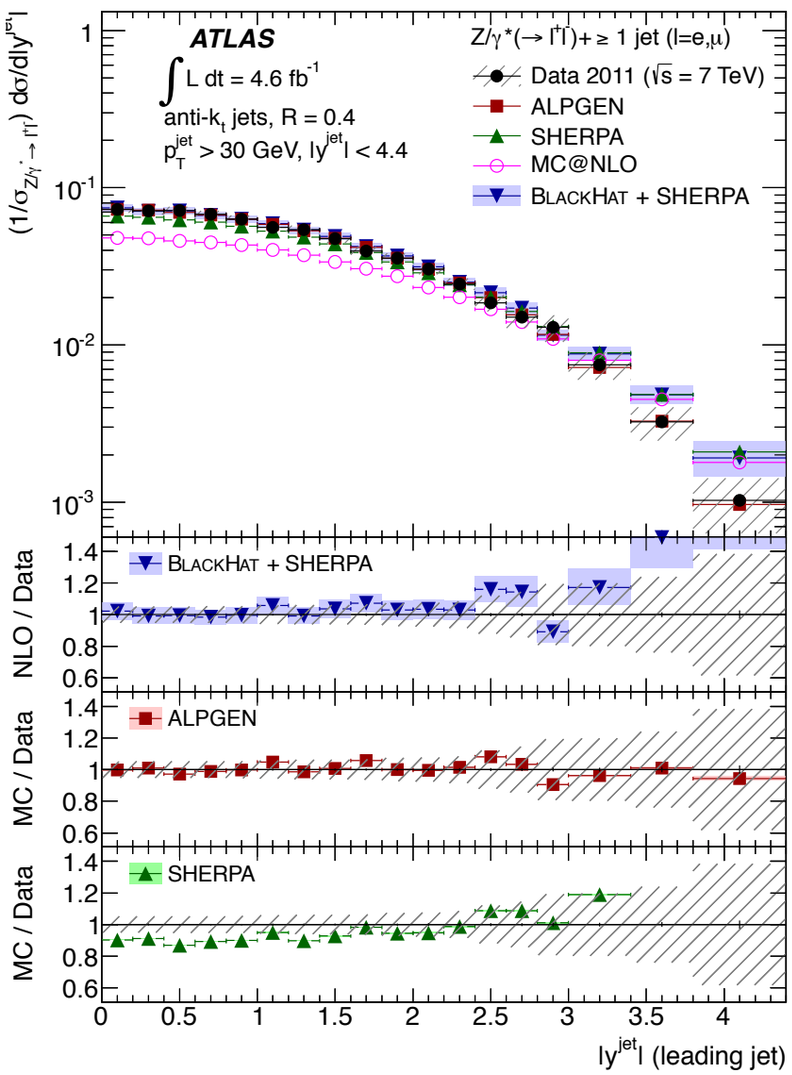
CMS-PAS-SMP-12-002

Z+jets

JHEP 07 (2013) 032

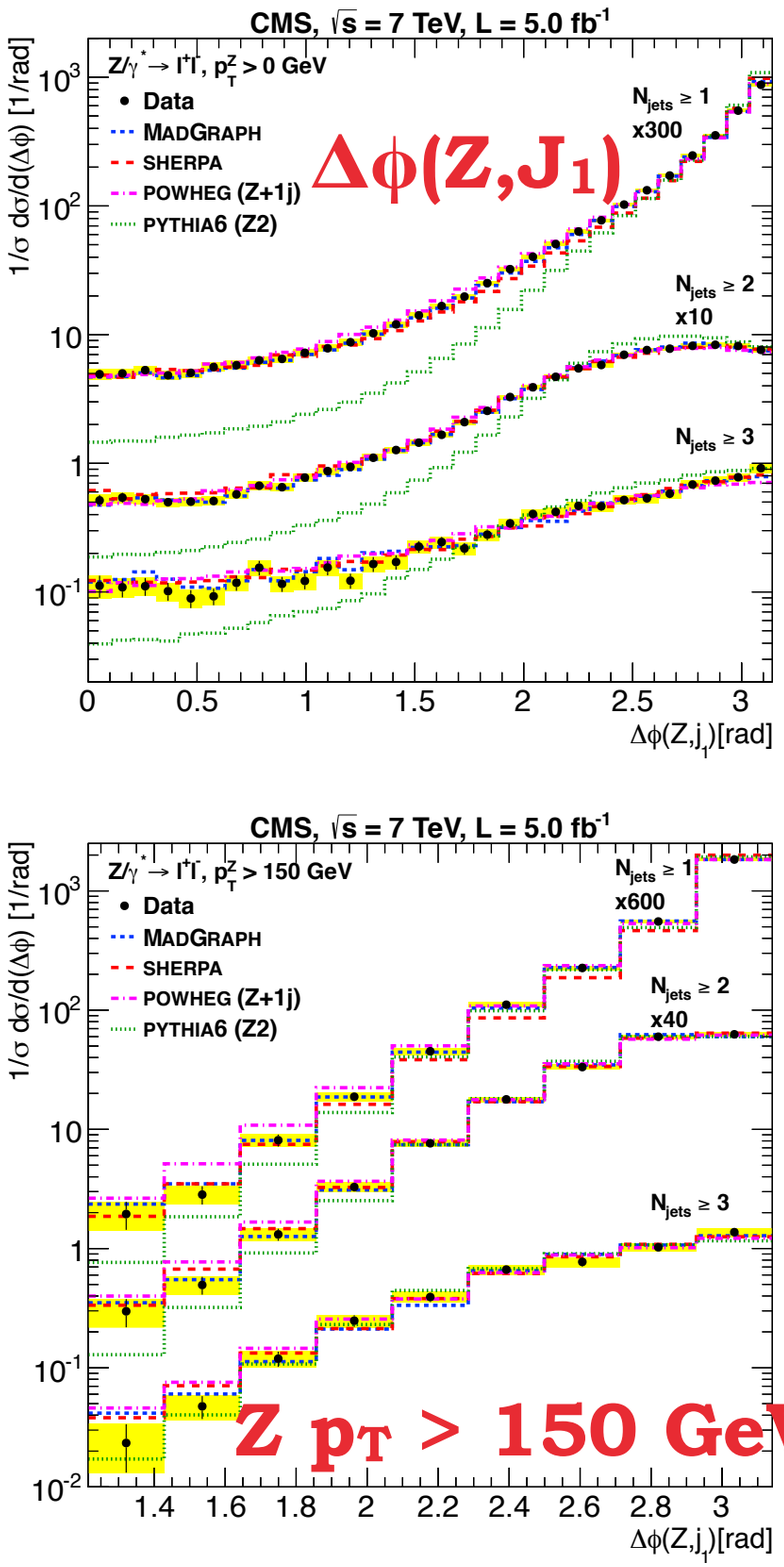




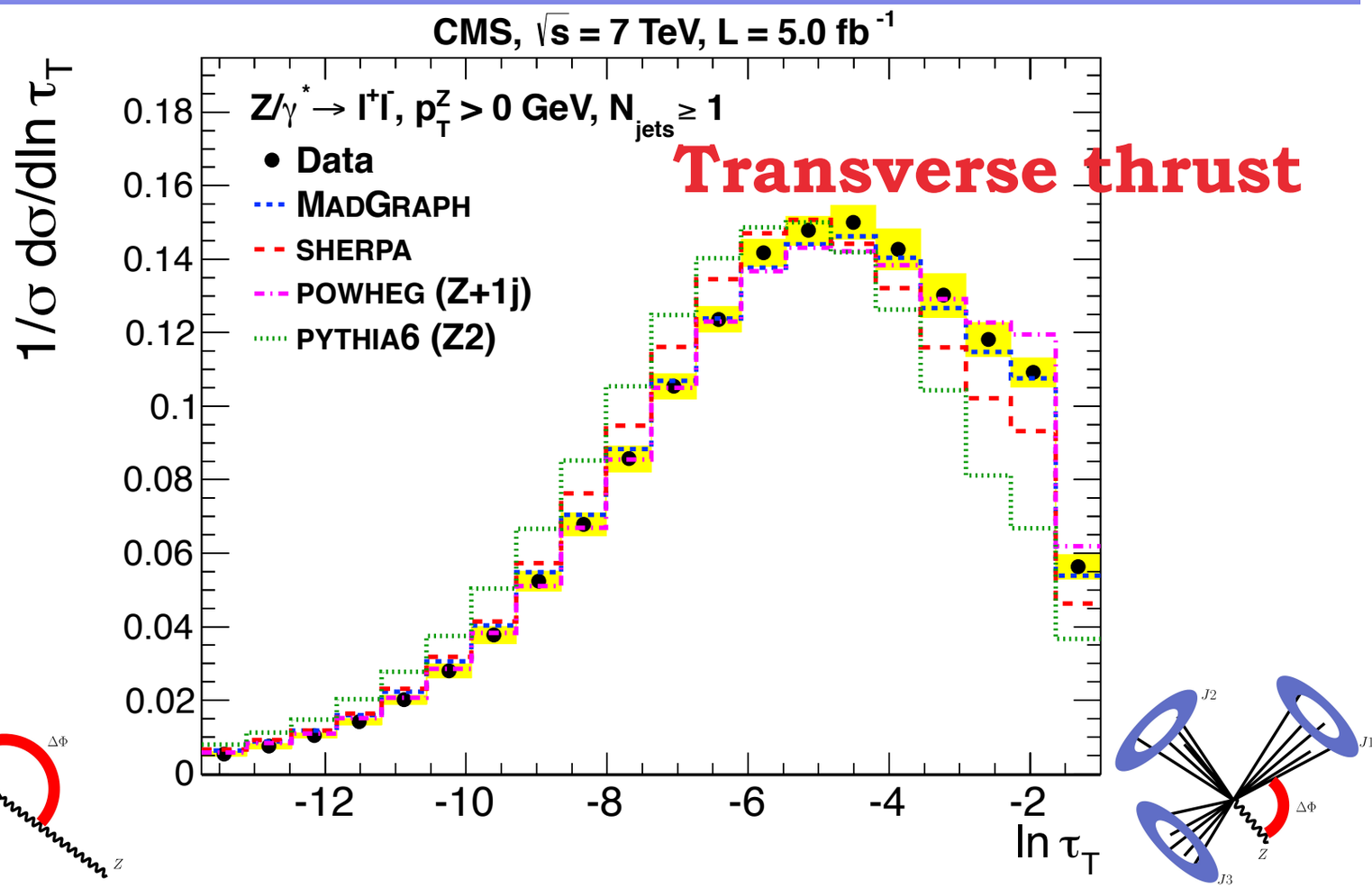


- important background for Higgs and new physics searches
- test of pQCD and MC generators
- study of jet multiplicity and kinematic properties
  - huge phase-space opened at the LHC energies and luminosities
- NLO at parton level interfaced with PS provides good description up to Njet=4 and of the entire leading jet p_T spectrum
- ME+PS and PS generators describe the data as well
  - MC@NLO predicts a much softer spectrum of the leading jet pT

Z+jets: topological properties



Z p_T > 150 GeV

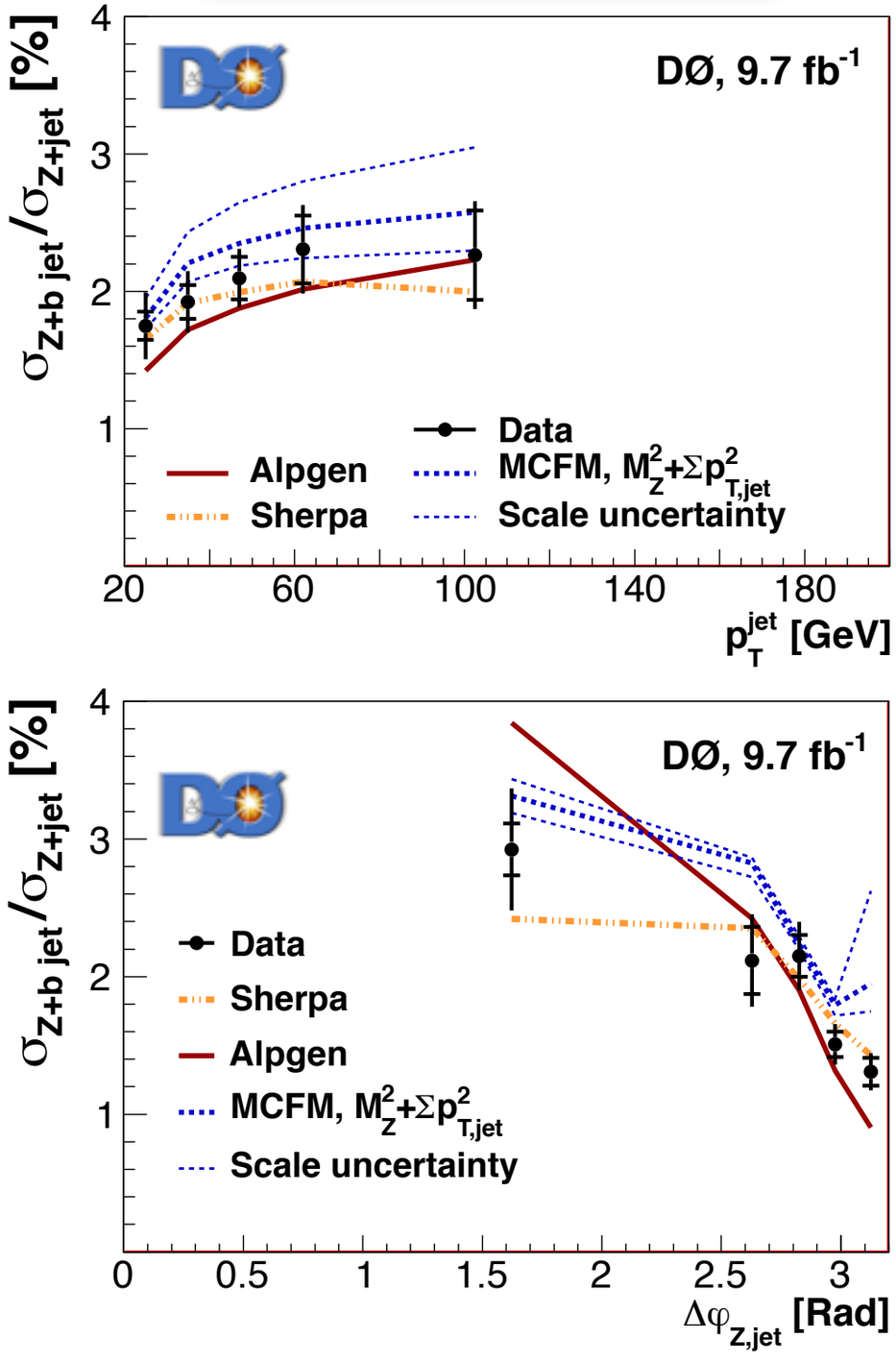


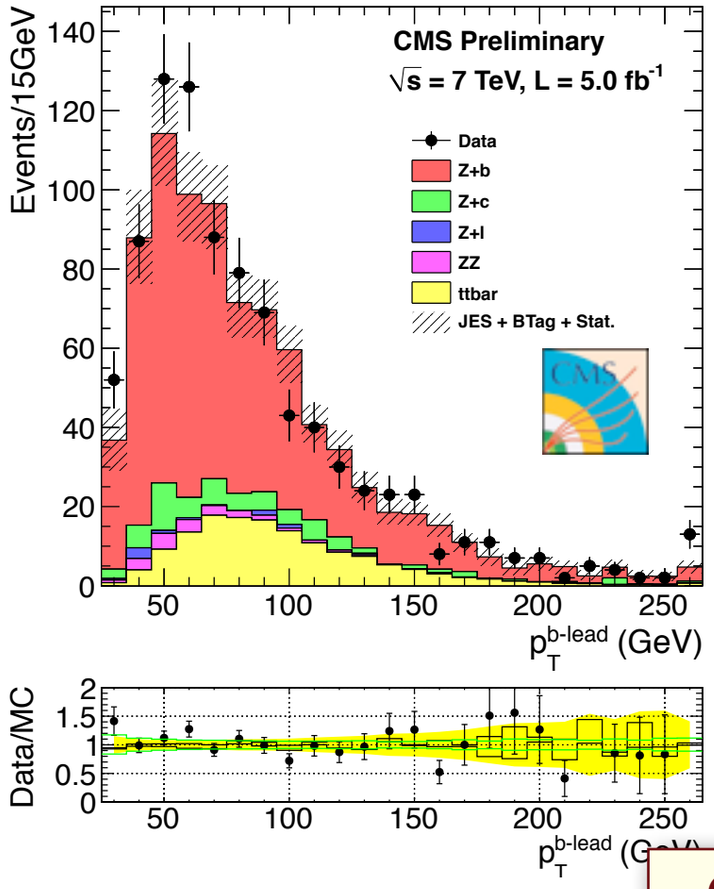
- topological properties on azimuthal plane, inspired by dijet observables
  - $\Delta\phi$ correlations between Z and up to the 3rd jet,and between jets
- LO 2→n ME + PS MC models describe data well
- **boosted Z (p_T > 150 GeV) explored for the first time**

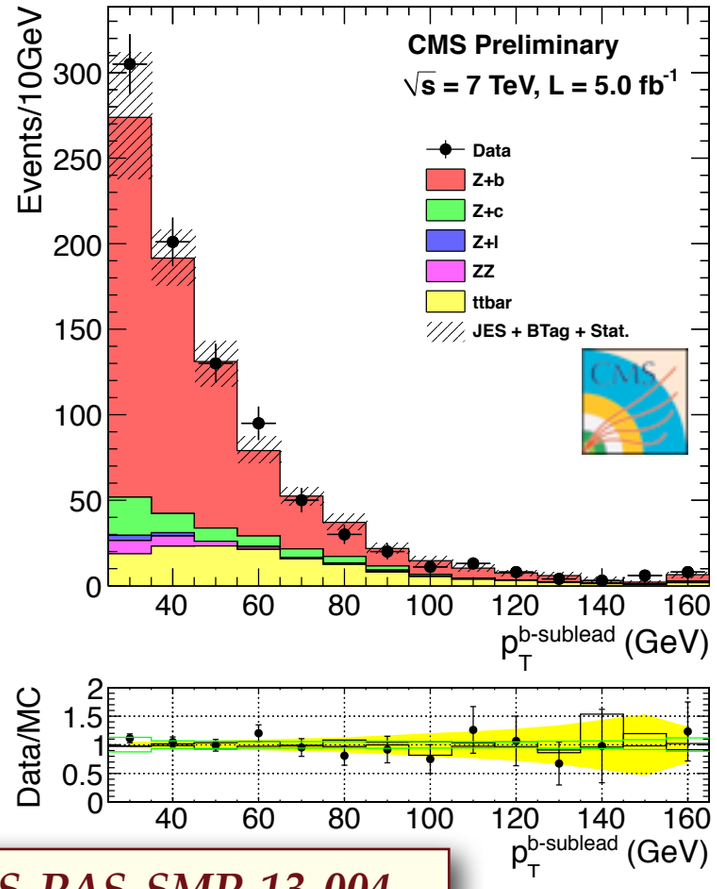
Phys. Lett. B722 (2013) 238

Z+b(b)

arXiv:1301.2233







CMS-PAS-SMP-13-004

Multiplicity bin	Measured	MadGraph 5F	MadGraph 4F
$\sigma(Z(\ell\ell)+1b)$ (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.02	3.11 ± 0.03
$\sigma(Z(\ell\ell)+2b)$ (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.01	0.38 ± 0.01
$\sigma(Z(\ell\ell)+b)$ (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.02	3.49 ± 0.03
$\sigma(Z(\ell\ell)+b)/\sigma(Z(\ell\ell)+j)$ (%)	$5.15 \pm 0.03 \pm 0.25$	5.35 ± 0.02	4.60 ± 0.03

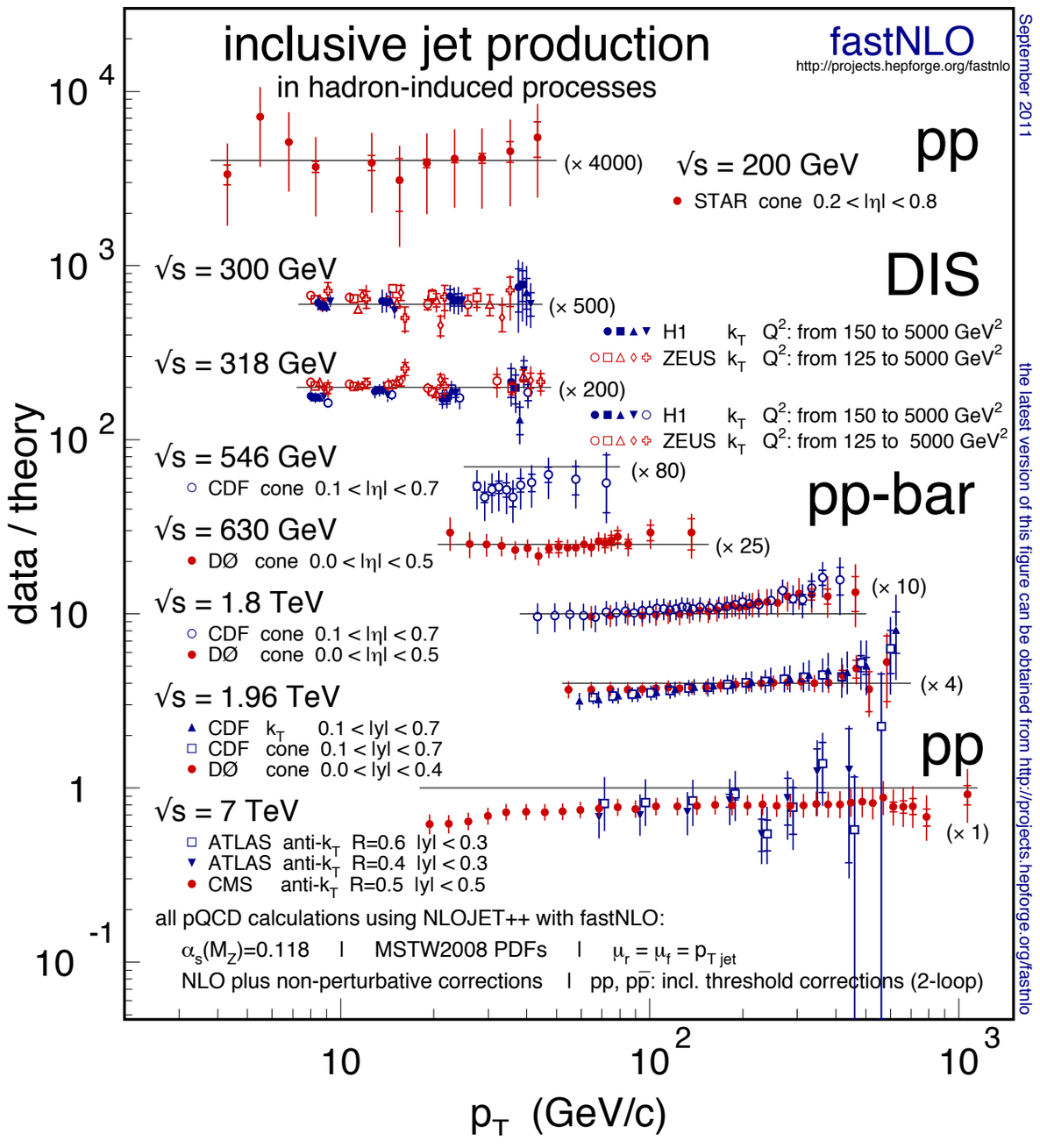
- Z+b(b) cross section
  - in agreement with theory predictions
- Z+b/Z+j ratio
  - inclusive measurement
  - differential measurement vs jet p_T and $\Delta\phi_{Z,jet}$

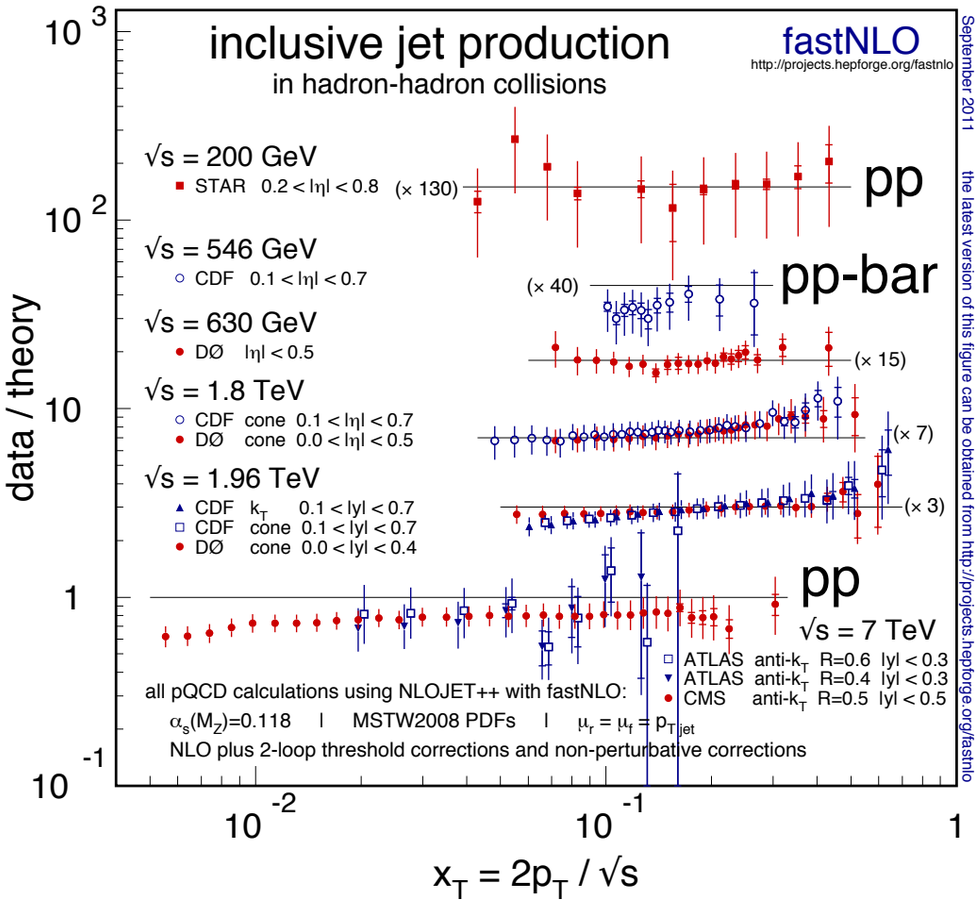
Summary

- **significant ongoing effort to improve our understanding of QCD**
  - both experimental and theoretical
  - rich QCD programs pursued by hadron collider experiments
- **large datasets available**
  - Tevatron & HERA keep producing new and interesting results
  - LHC has provided access to a huge phase space
  - will take a significant amount of time to analyze and digest all the collected data
- **much recent progress**
  - precise soft QCD measurements with sensitivity to diffraction, radiation modeling, multiple parton interactions and underlying event activity
  - jet data have considerable impact on gluon and u/d quark PDFs
  - photon data can be used for PDF fits as well
  - measurements of α_S at the TeV scale for the first time
  - detailed measurements of W/Z + jets provide further insights into the QCD dynamics
- **comments on the theoretical tools**
  - in many areas the exp. precision reached makes the NLO predictions insufficient: NNLO needed for further progress in precision measurements !!
  - with some tuning of the parameters, the LO ME or NLO interfaced with PS models provide adequate description of the data (e.g. suitable for background predictions)

backup

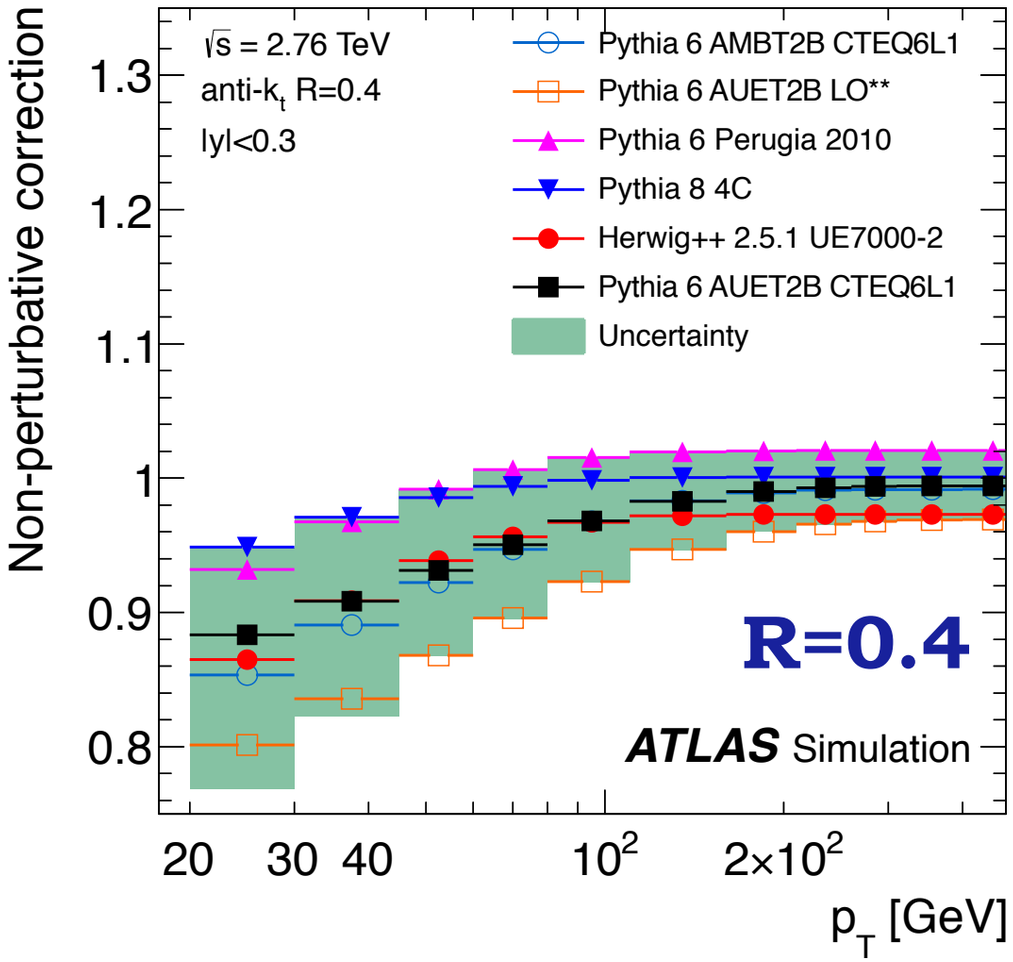
Inclusive jet production

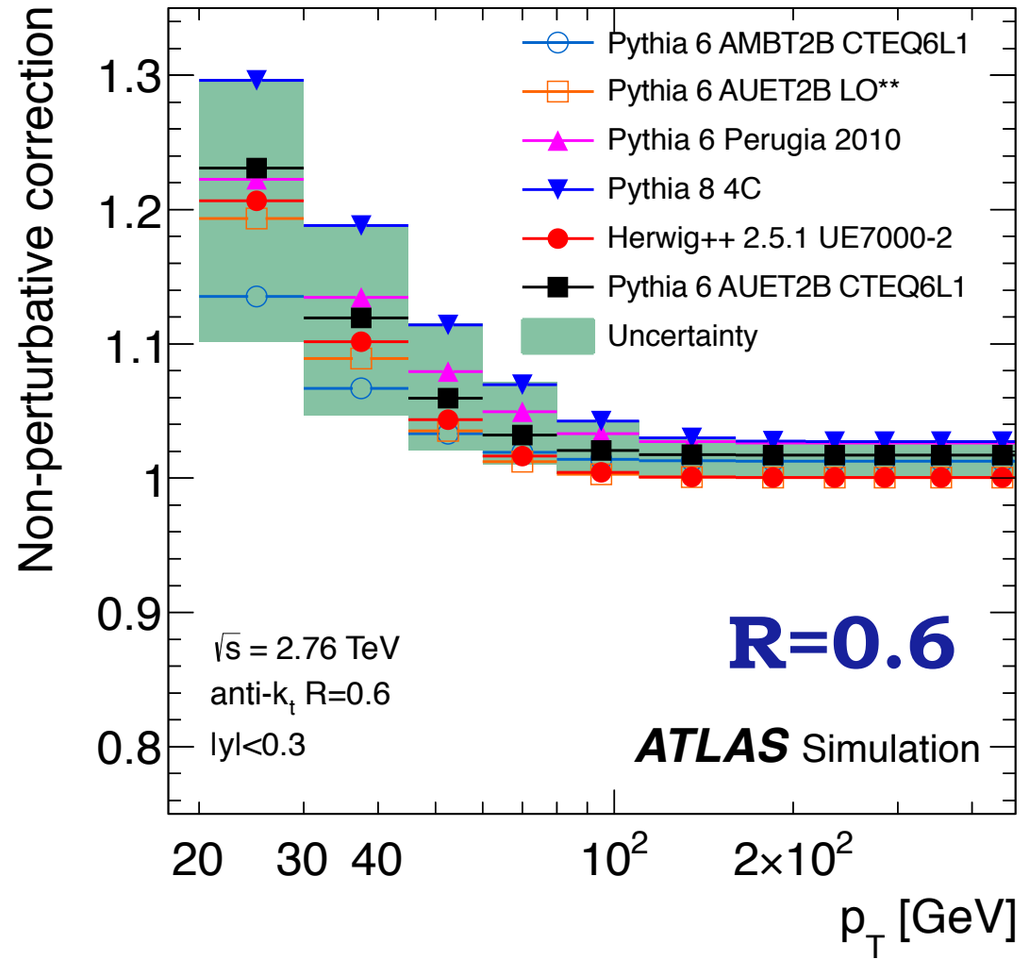




- probes the dynamics of QCD
  - counting the number of jets as a function of rapidity and p_T
- stringent test of QCD
  - PDFs, strong coupling constant, perturbative calculations

Non-perturbative corrections

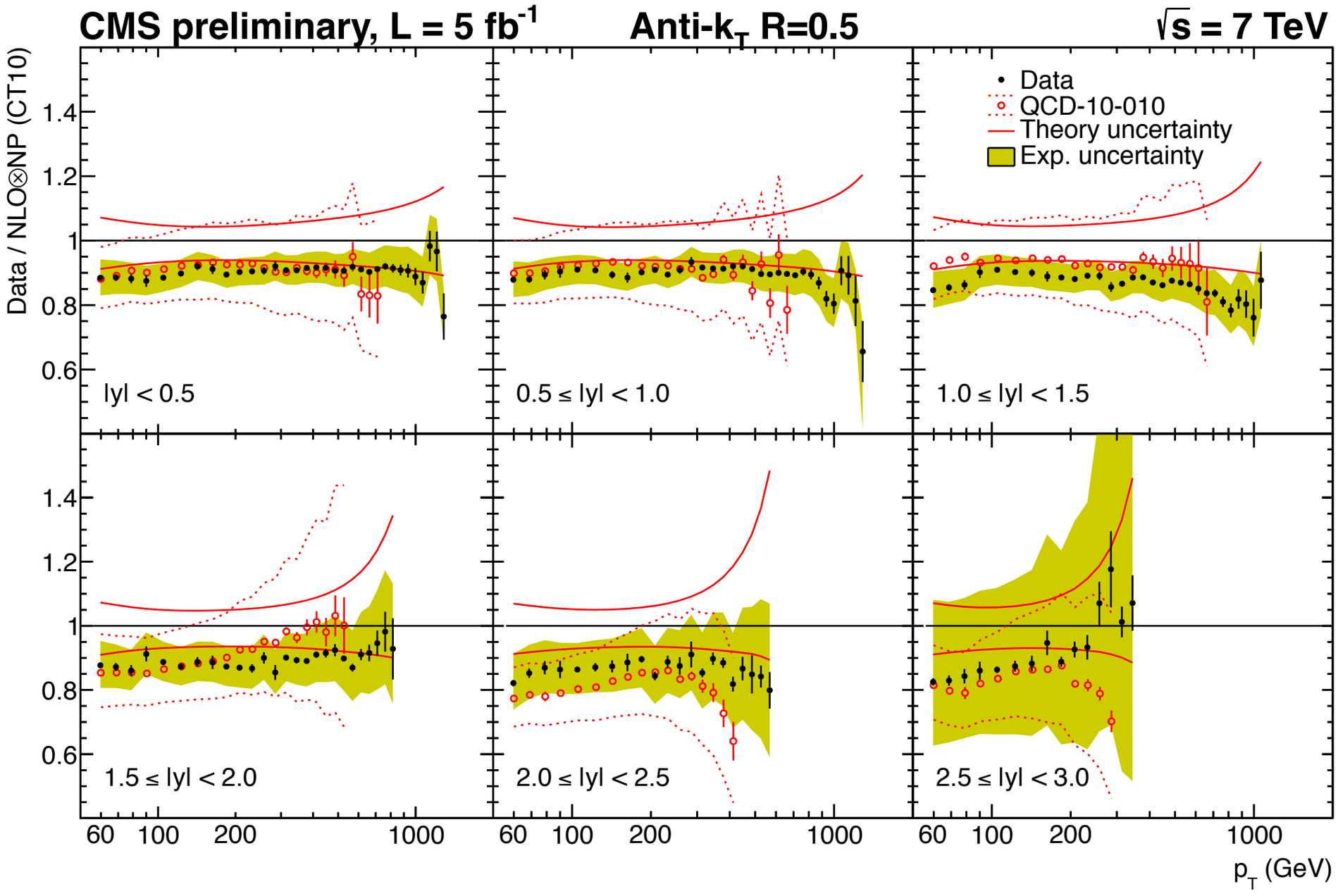




- data and theoretical predictions at the "particle level"
  - data unfolded for detector smearing effects
  - pQCD predictions corrected for MPI, PS, and hadronization effects
- non-perturbative correction
  - important for low-p_T jets
  - very sensitive to the size of the jet
  - heavily dependent on the MC generators

arXiv:1304.4739

Inclusive jets (R=0.5)



Inclusive jets (R=0.7)