Results on QCD jet production at the LHC (incl. Heavy flavours)

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On behalf of the ATLAS and CMS collaborations

Recontres du Vietnam
August 11th – 17th, 2013
“Windows on the Universe”

Outline

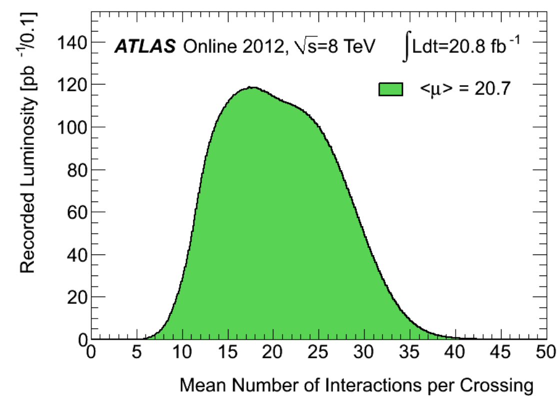
- Introduction
- Jet Reconstruction and Calibration
- Jet Cross Sections
- Determination of α_s
- Colour Coherence
- Heavy Flavours
- Summary and Conclusions

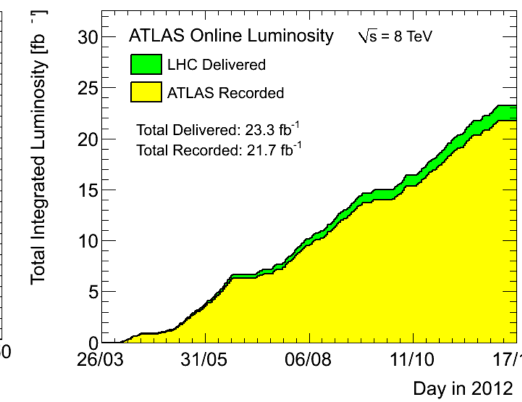
Introduction - QCD

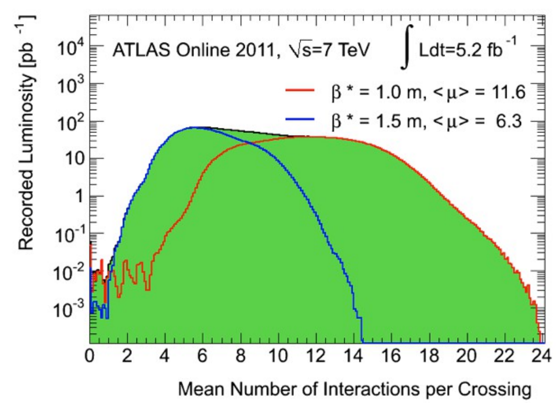
- LHC is a discovery machine (→Higgs 1st anniversary)
- Why doing QCD measurements ?
  - dominant process at LHC
  - LHC provides previously inaccessable energy regime
  - provides wealth of new measurements
  - constrain PDFs – parton density functions
  - last but not least: main background for many searches
- Why measuring (QCD) Jets ?
  - manifest confinement i.e. no free quarks
  - reflect approximately interactions of partons

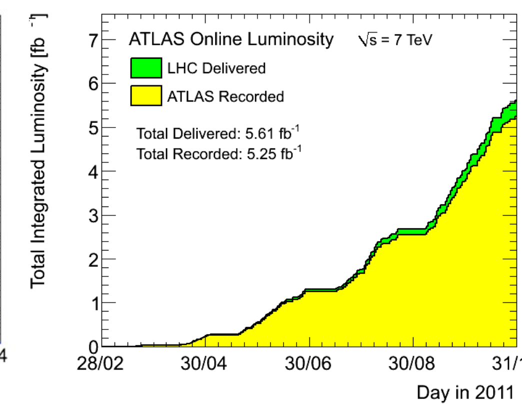
Introduction - LHC

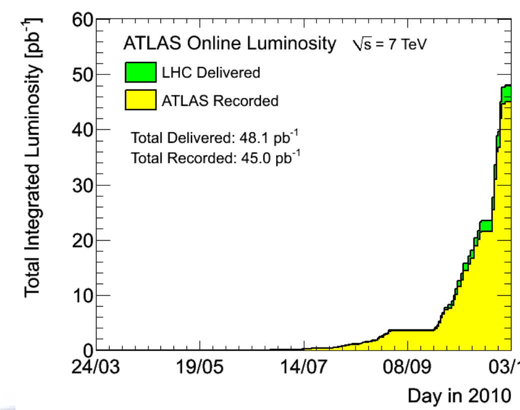
- excellent performance of LHC over last years
  → huge datasets to analyse
  ATLAS 2012: ~21 fb^{-1}
  2011: ~5 fb^{-1}
  2010: ~50 pb^{-1}
- varying levels of pileup during run 1, from ~zero up to almost 40 coll./xing!
- requires new techniques to deal with pileup
  → in active development
  → some QCD measurements done with low pileup data from (mostly) 2011 some even from 2010







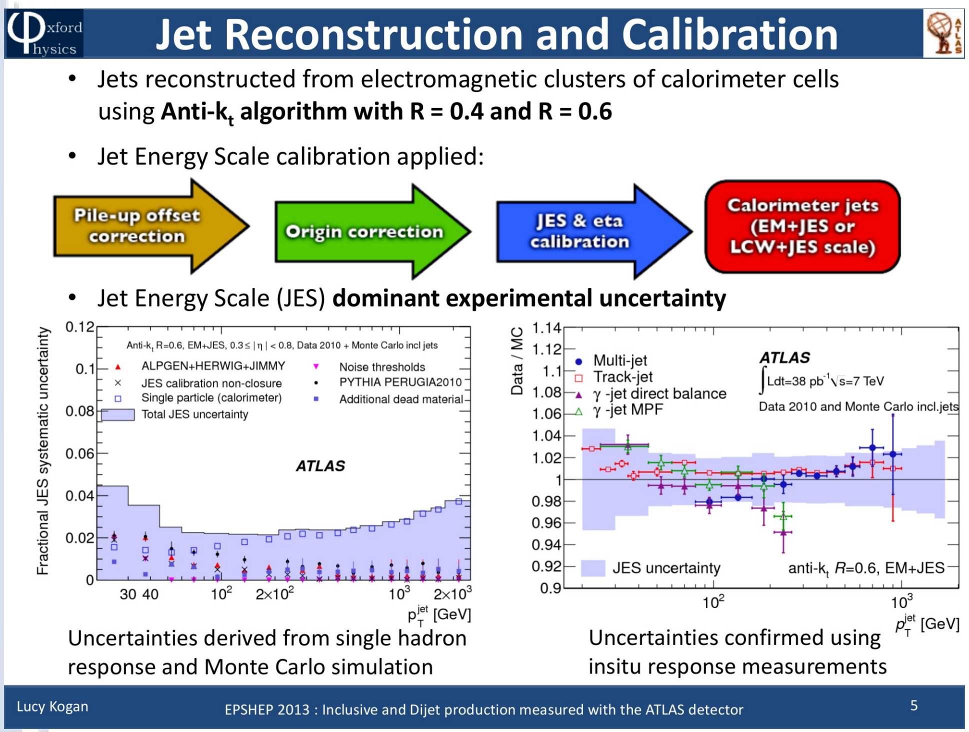


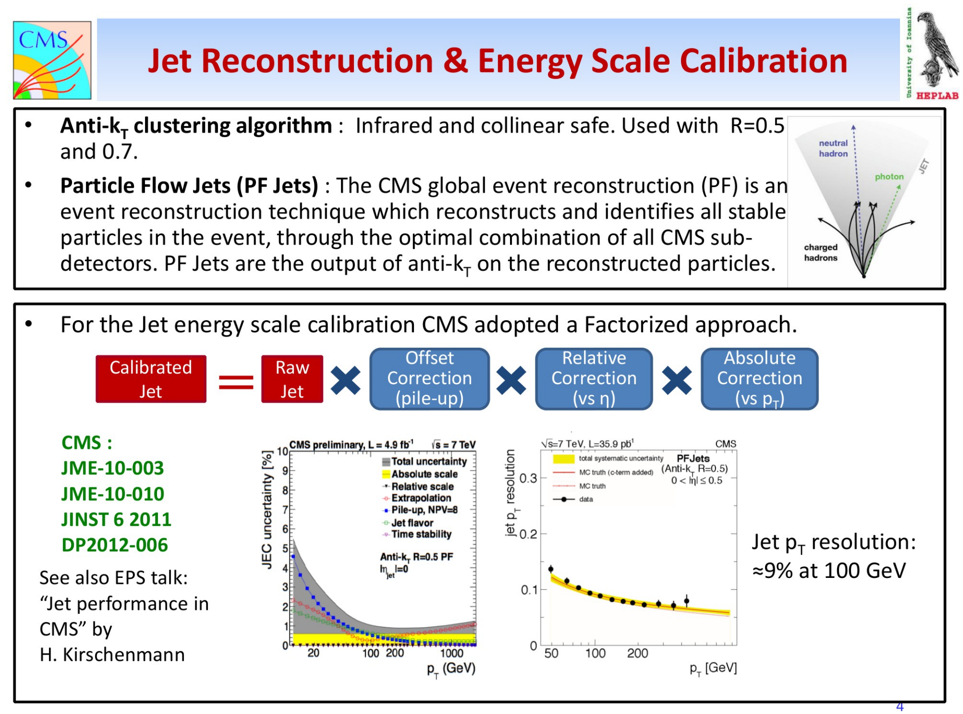


Jet Reconstruction + calibration

Jet Algorithm: iterative procedure to cluster particles to new pseudo particles based
on a measure of distance until a cut-off R is reached
now anti-k_T recombination scheme commonly used

both ATLAS and CMS have non-compensating calorimeters for hadrons
requires dedicated jet energy calibration (JES)



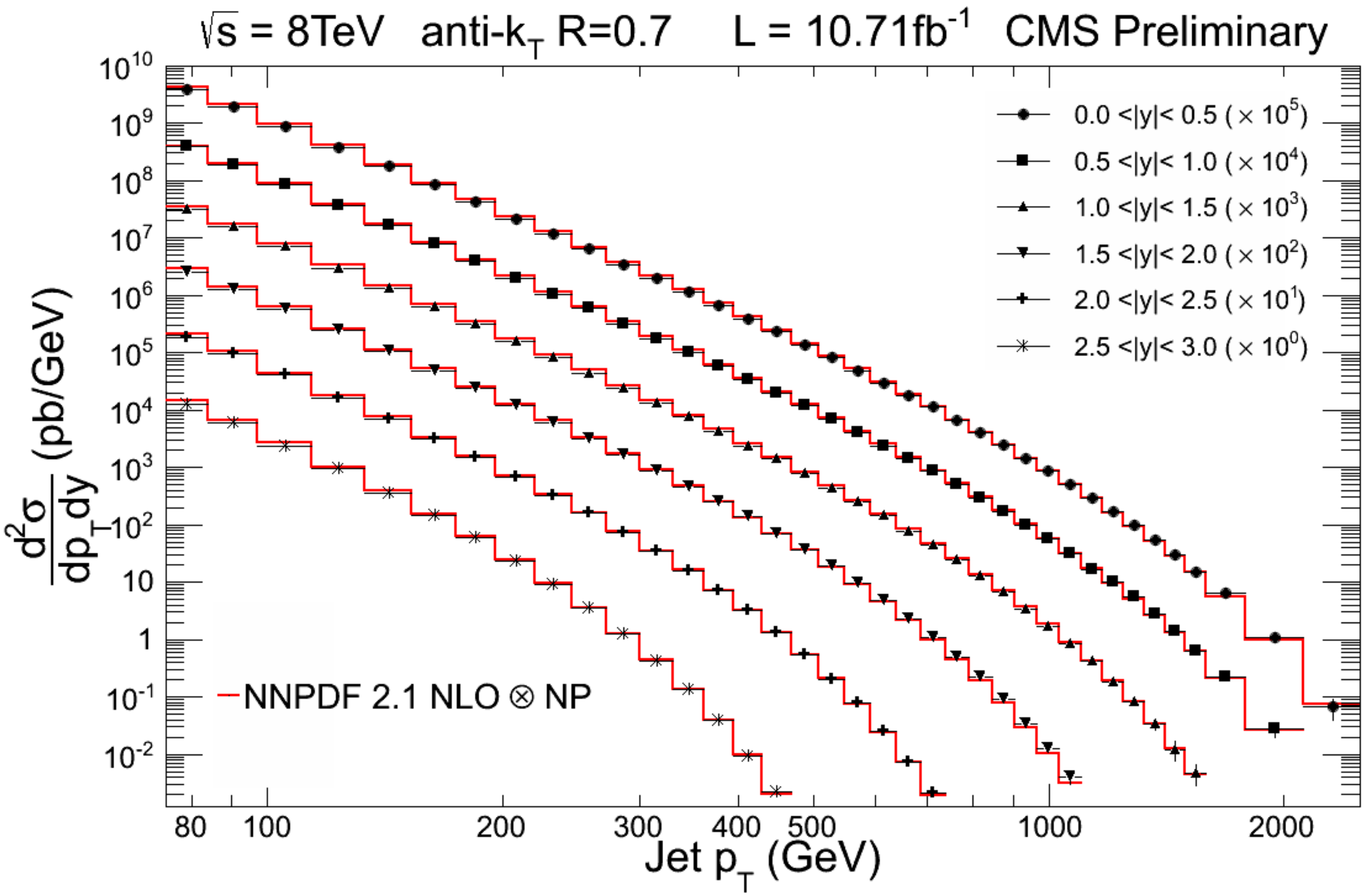


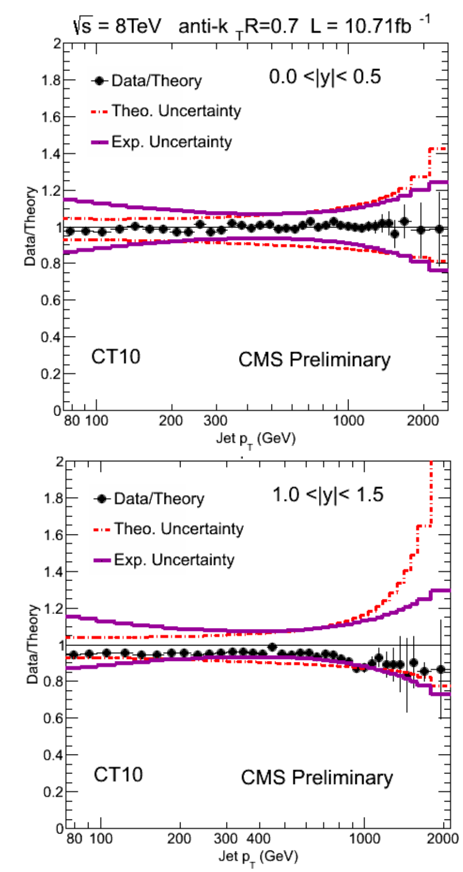
for 2012 new calibration and new pileup subtraction schemes are being developed

Inclusive Jet Cross Section at 8 TeV

CMS SMP-12-012

JES dominating experimental systematic uncertainty





→ good agreement over several orders of magnutide !
differences data – MC mostly smaller than systematic uncertainties
NLO PDF sets agree well with data (except ABM11 – not shown here)

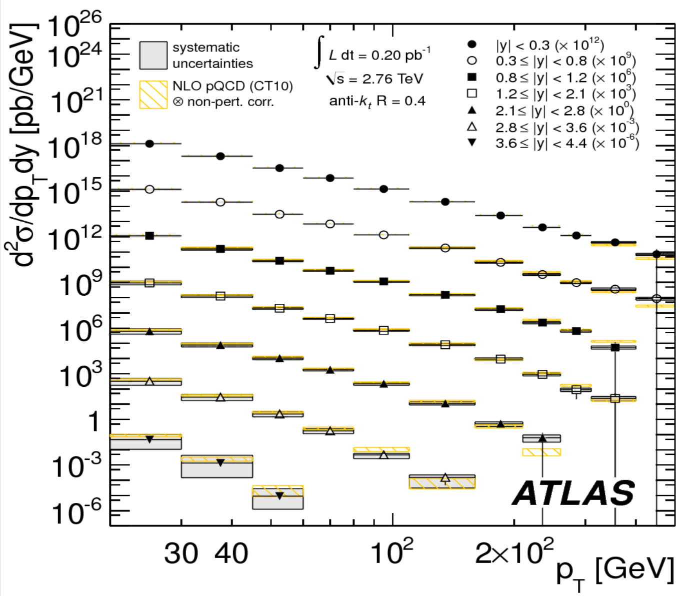
Ratio of Jet Cross Sections at 2.76 TeV and 7 TeV

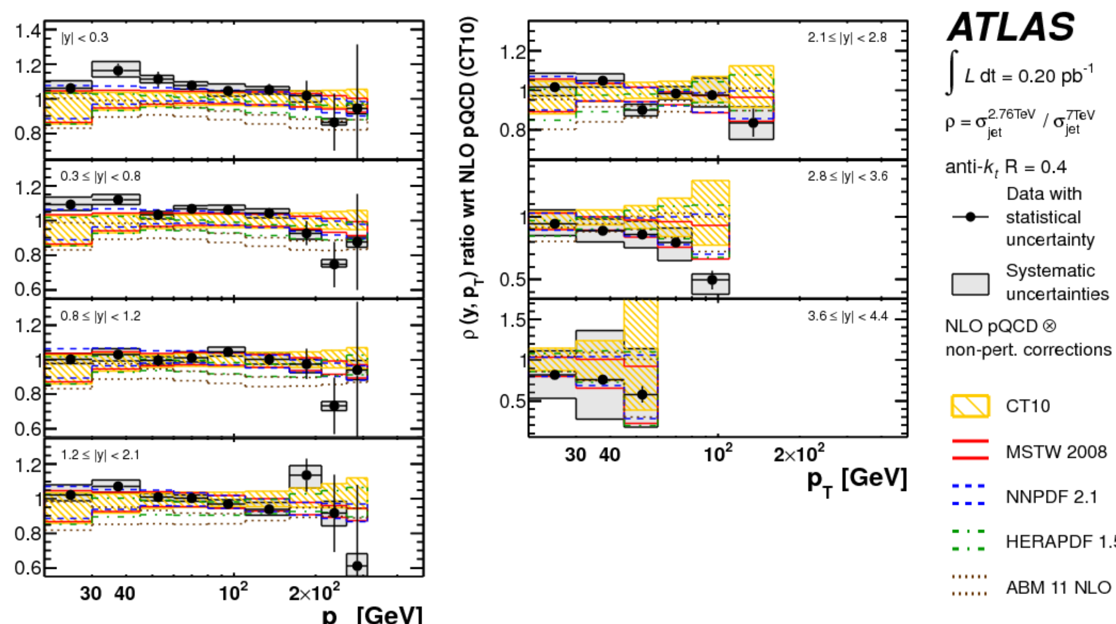
ATLAS arXiv: 1304.4739

correlations reduce systematic uncertainties such that PDF can be constrained
$\sqrt{s}$=2.76TeV, L=0.20pb^{-1}, anti-k$_T$ with R=0.4 and R=0.6

$x_T = 2\, p_T / \sqrt{s}$

x_T and p_T have both advantages, p_T lower experimental systematics due to common uncertainty on JES → p_T preferred observable





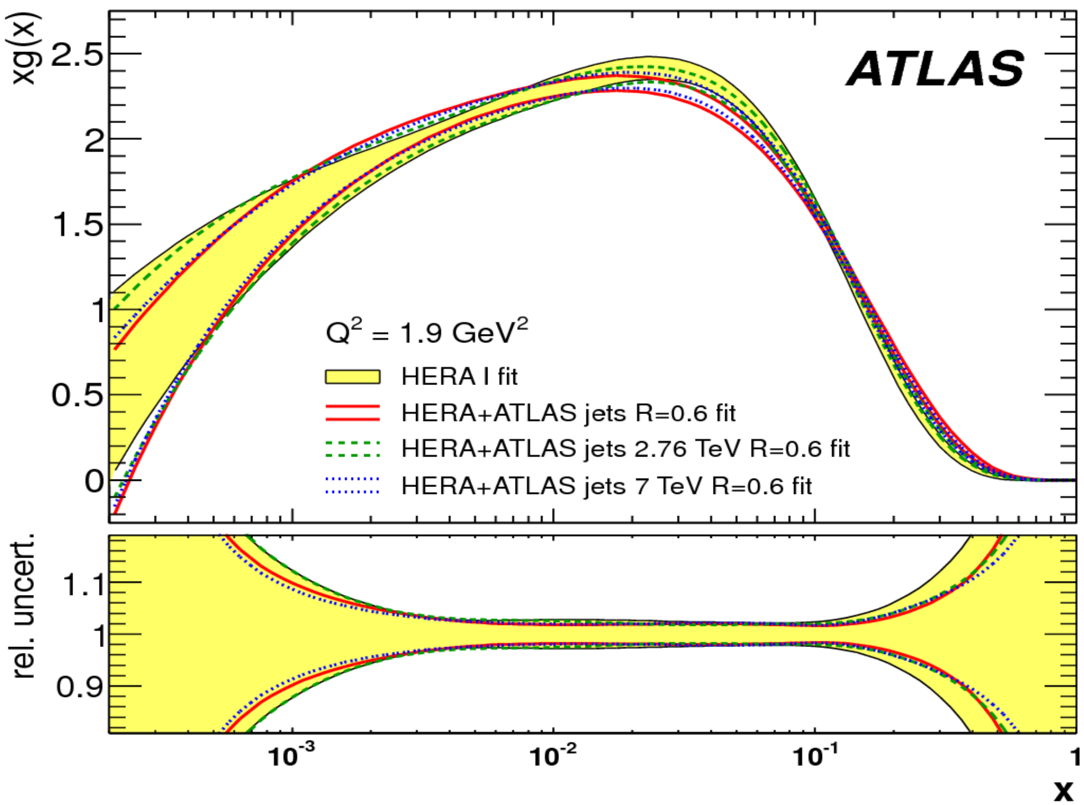
this ratio becomes sensitive to constrain PDF → next slide

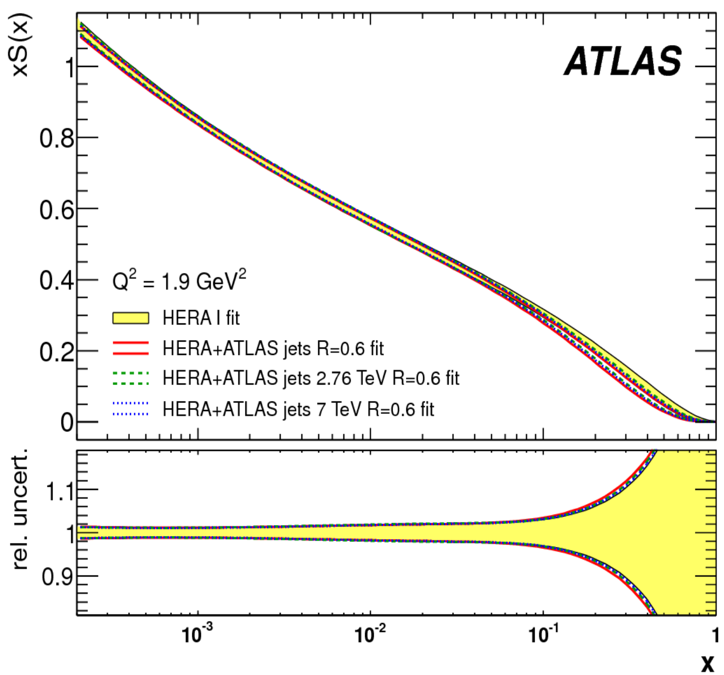
Gluon contribution to PDF

ATLAS arXiv: 1304.4739

in general well constrained by PDF fits from HERA data
gluon momentum distribution below x<0.01 less well known

in this analysis due to large NP uncertainties, jets below 45 GeV excluded in fits
2.76 TeV and 7 TeV considered fully correlated in jet calibration



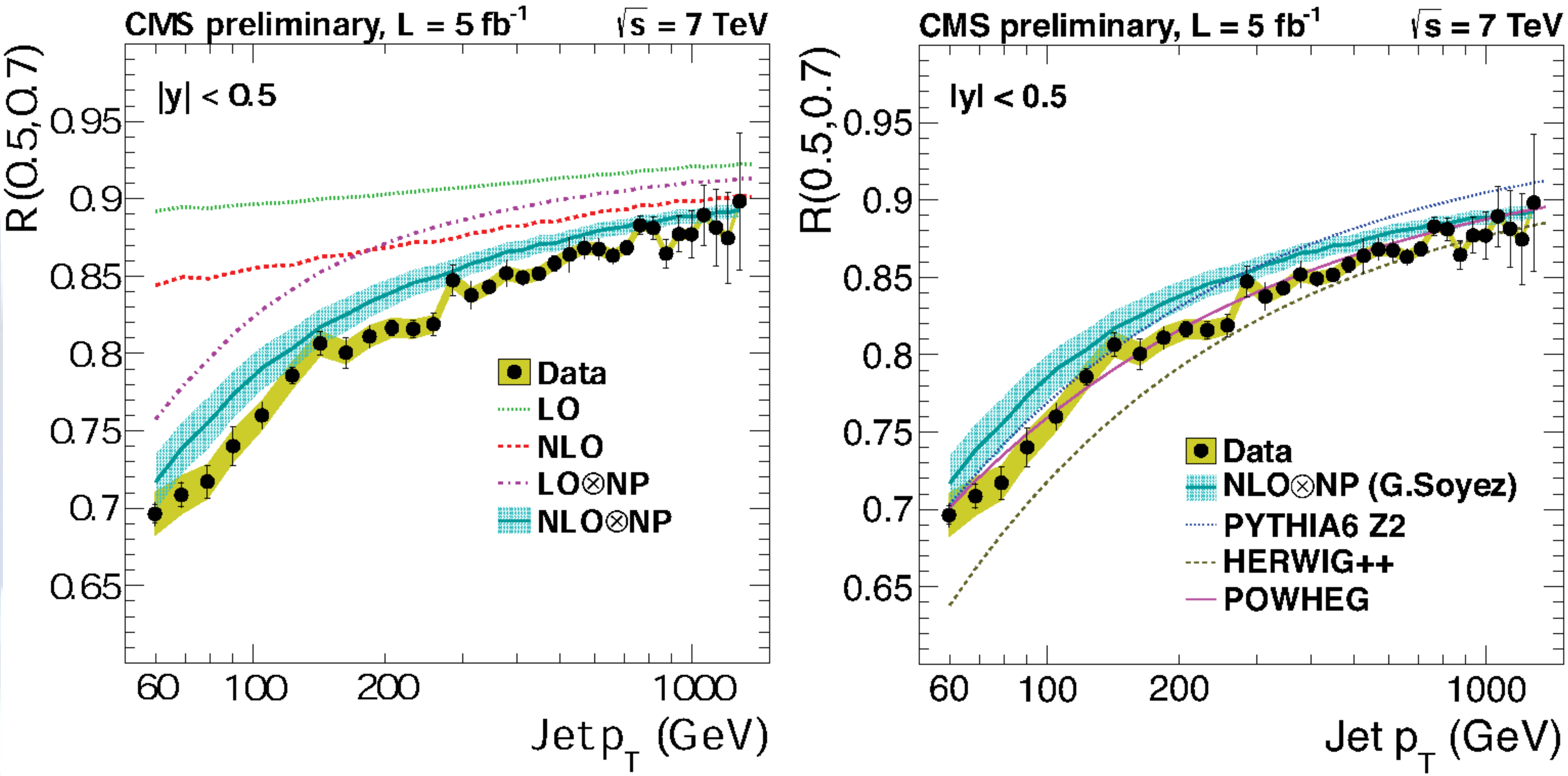


→ Harder gluon spectrum after including ATLAS data
As a result, sea quark momentum spectrum softer

Ratio of Jet X Sections – different R

CMS PAS SMP-13-002

R(0.5,0.7) = σ(R=0.5) / σ(R=0.7)   ratio of unfolded cross sections



R=0.5 jets show bigger deviations (not shown here) →
non-perturbative corrections needed to improve description of jets with small radii
partonshowers in modern Monte Carlo generators mimick the NP corrections well

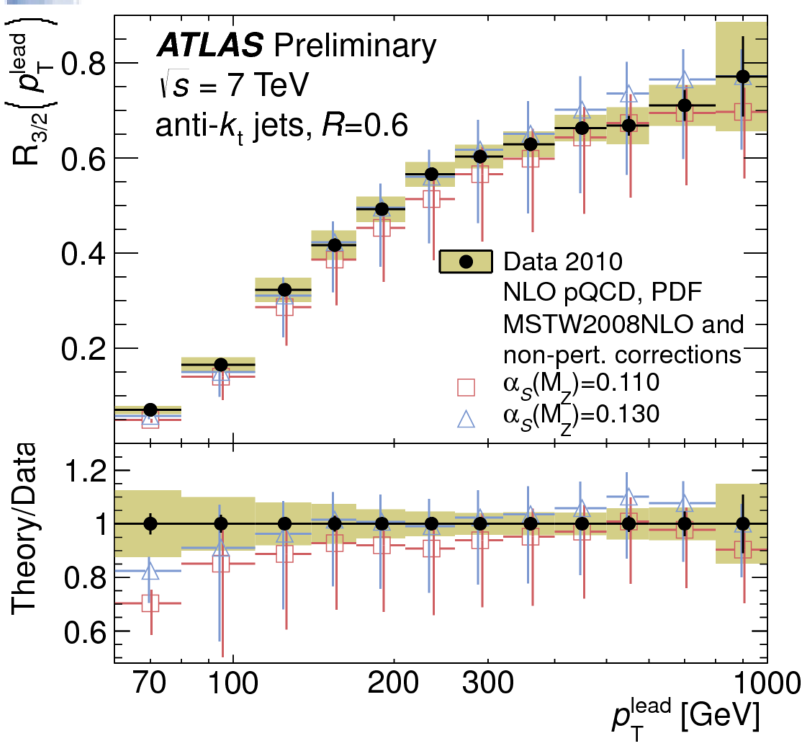
Ratio of Jet X Sections – different N_{jet}

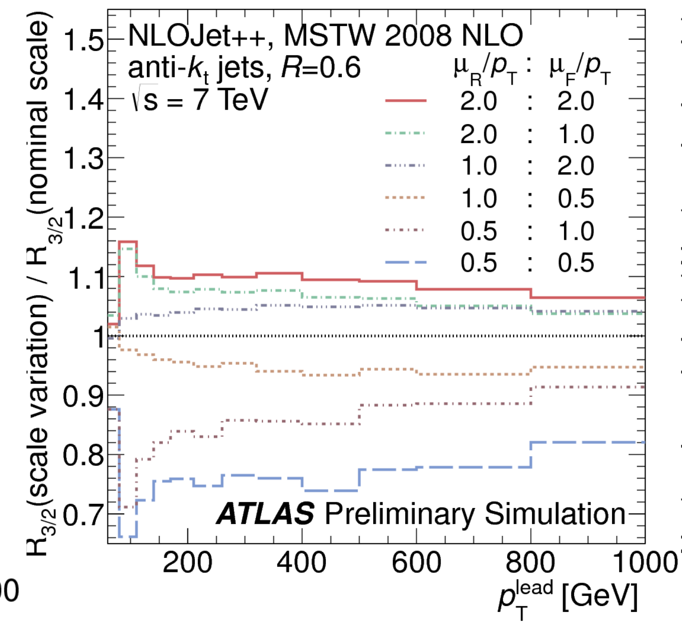
ATLAS CONF-2013-041

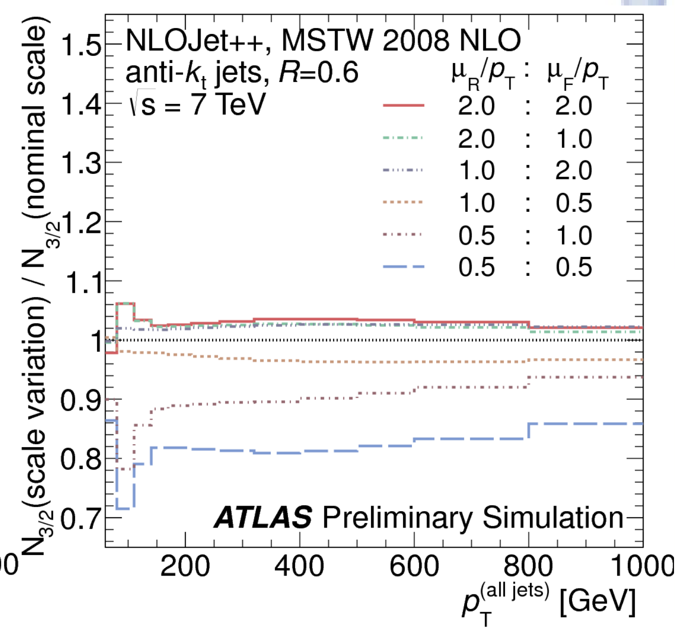
both $R_{3/2}$ and $N_{3/2}$ have sensitivity to α_s

$$R_{3/2}(p_T^{lead}) = \frac{d\sigma_{N_{Jet}\geq 3}/dp_T^{lead}}{d\sigma_{N_{Jet}\geq 2}/dp_T^{lead}}$$

$$N_{3/2}(p_T^{all\ jets}) = \frac{\sum_i (d\sigma_{N_{Jet}\geq 3}/dp_{T,i})}{\sum_i (d\sigma_{N_{Jet}\geq 2}/dp_{T,i})}$$





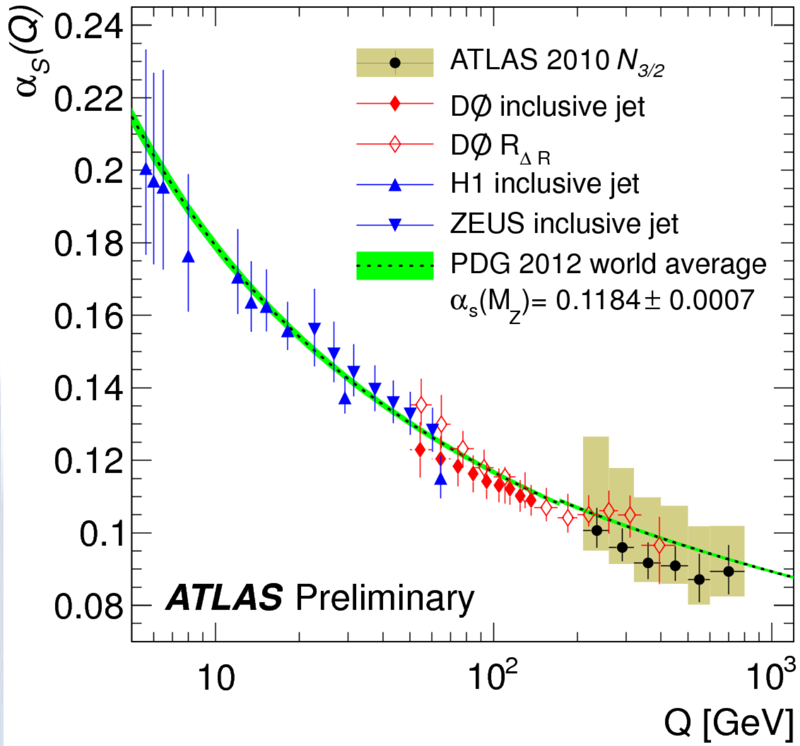


$N_{3/2}$ has lower sensitivity to variations in scales

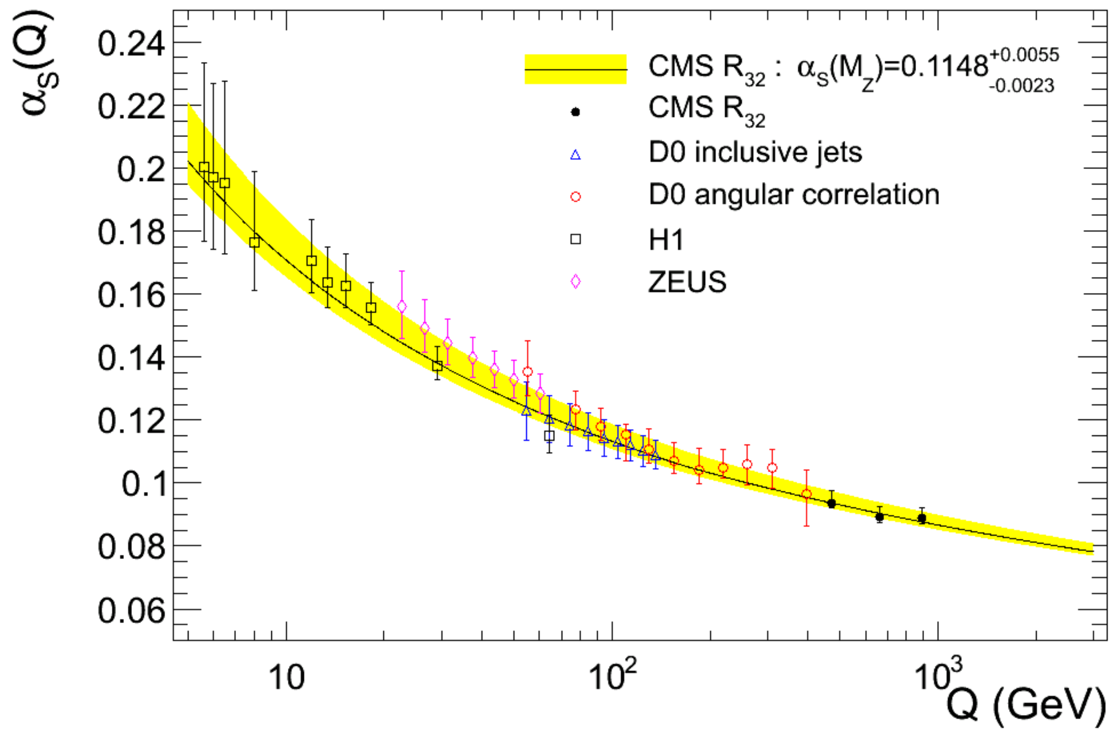
→ used to determine α_s shown on next slide

Determination of Running of α_s

ATLAS CONF-2013-041



arXiv: 1304.7498



ATLAS:

$$\alpha_S(M_Z)=0.111\pm0.006(\text{exp})^{+0.016}_{-0.003}(\text{theory})$$

previous measurement from CMS with similar technique:

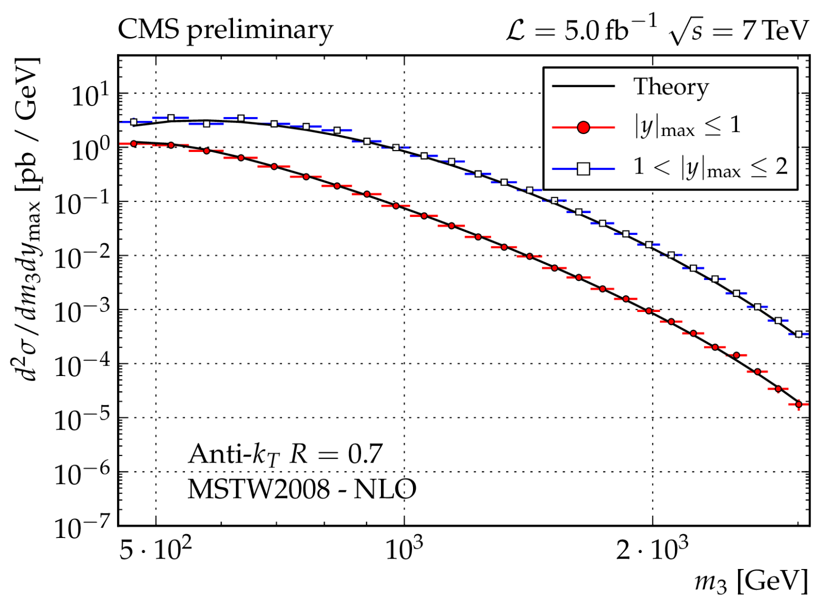
$$\alpha_S(M_Z)=0.1148\pm0.0014(\text{exp})\pm0.0018(\text{PDF})^{+0.0050}_{-0.0000}(\text{scale})$$

α_s measurement from Jet Masses

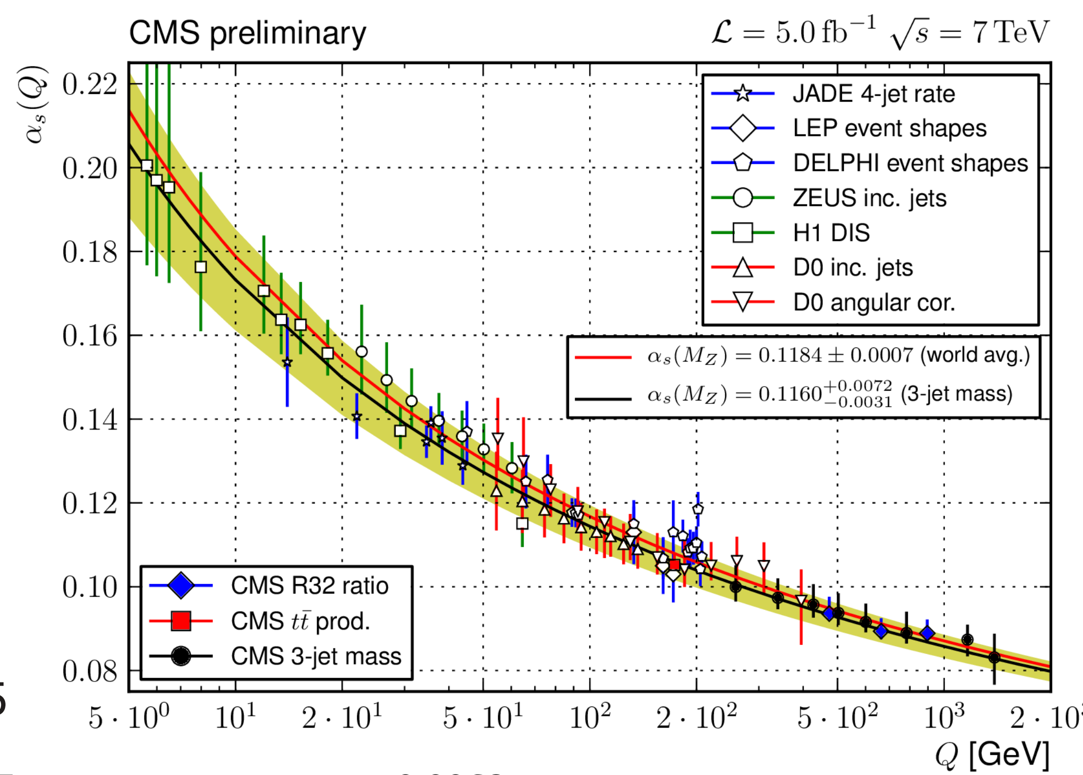
CMS SMP-12-027

$$m_3^2 = (p_1 + p_2 + p_3)^2$$

$$y_{max} = \text{sign}\left(|max(y_1, y_2, y_3)| - |min(y_1, y_2, y_3)|\right) \cdot max(|y_1|, |y_2|, |y_3|)$$



unfolded spectra agree well with theory over five orders of magnitude and up to m_3 of 3 TeV

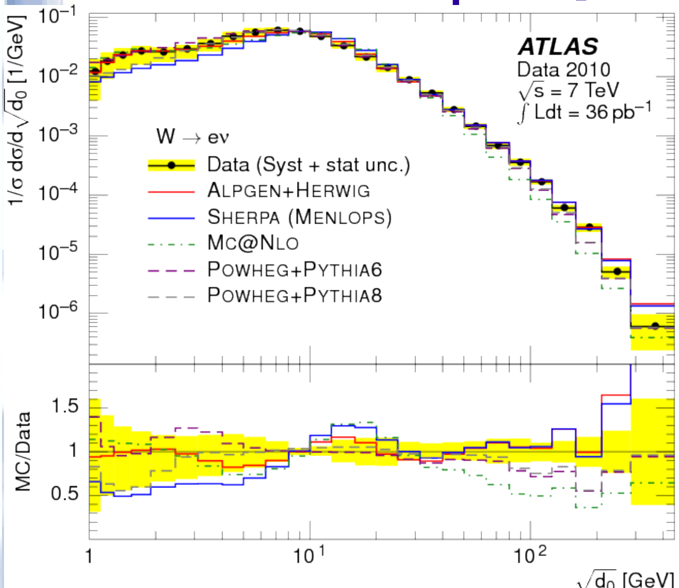


running of alpha_s agrees well with prediction up to Q ~1.4 TeV

initial studies show sensitivity of m_3 to gluon distribution between 0.05<x<0.5

$$\alpha_s(M_Z) = 0.1160\,^{+0.0025}_{-0.0023}\,(\text{exp,PDF,NP})\,^{+0.0068}_{-0.0021}\,(\text{scale})$$

k_T splitting scales in W->lv



ATLAS Eur. Phys. J. C (2013) 73:2432

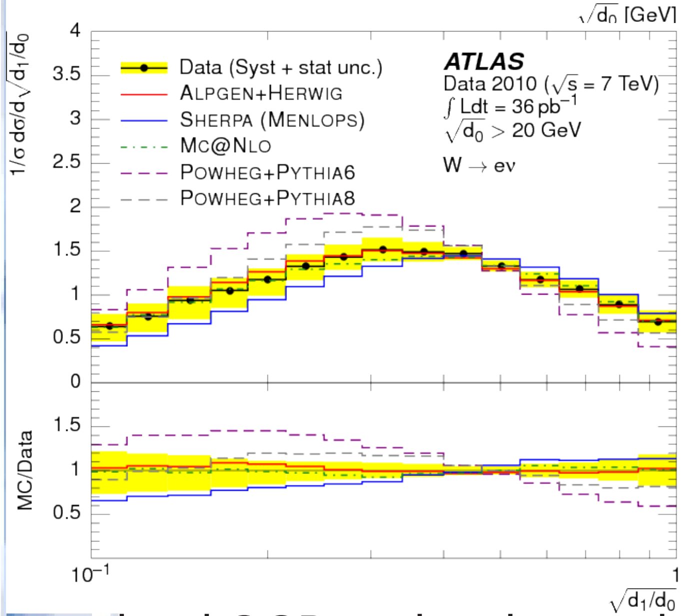
k_T jet algorithm:

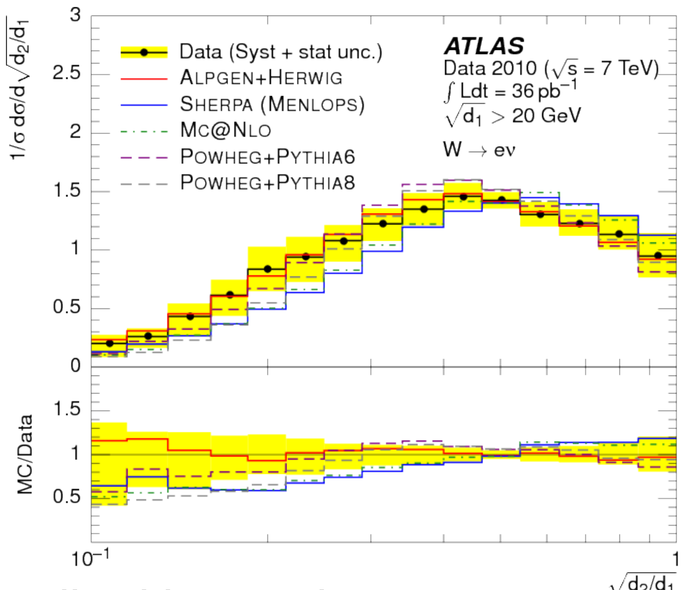
$$d_{ij}=min(p_{T_i}^2, p_{T_j}^2)\frac{\Delta R_{ij}^2}{R^2} \qquad \Delta R_{ij}^2=(y_i-y_j)^2+(\phi_i-\phi_j)^2$$

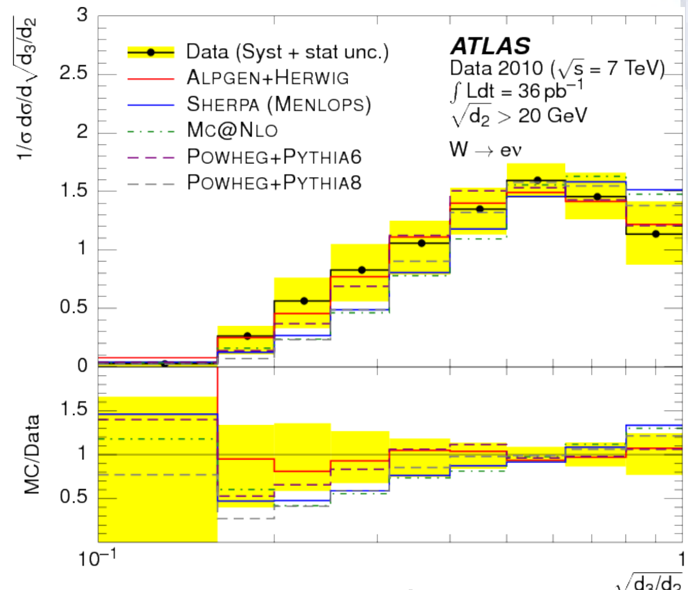
$$d_{iB}=p_{T_i}^2$$

k_T recombination approximates QCD evolution

partial cancelation of systematic uncertainties in ratio of splitting scales







hard QCD regime better described by multi-leg generators ALPGEN+HERWIG / SHERPA
HERWIG PS gives better description for $\sqrt{d1/d0}$ (two hardest branchings)

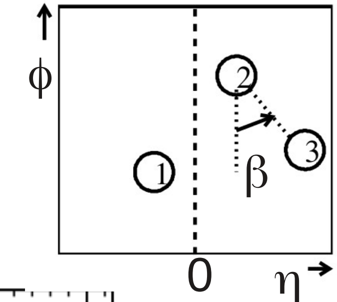
Colour Coherence

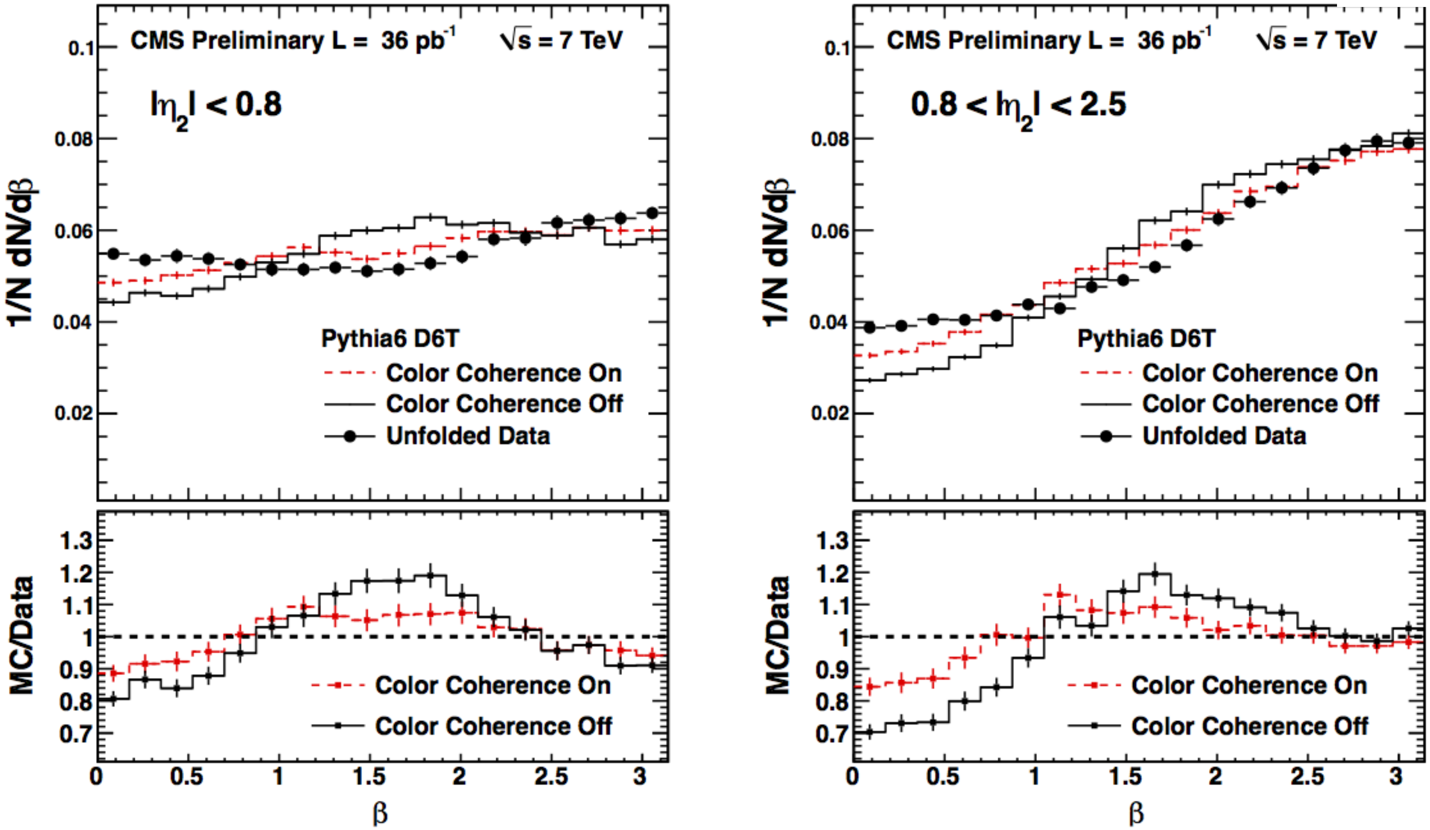
CMS PAS-SMP-12-010

$\beta = |\text{atan2}(\Delta\Phi_{23}, \Delta\eta_{23})|$

anti-kT with R=0.5

colour coherence suppresses particle emission around pi/2
and enhances emission at 0, pi



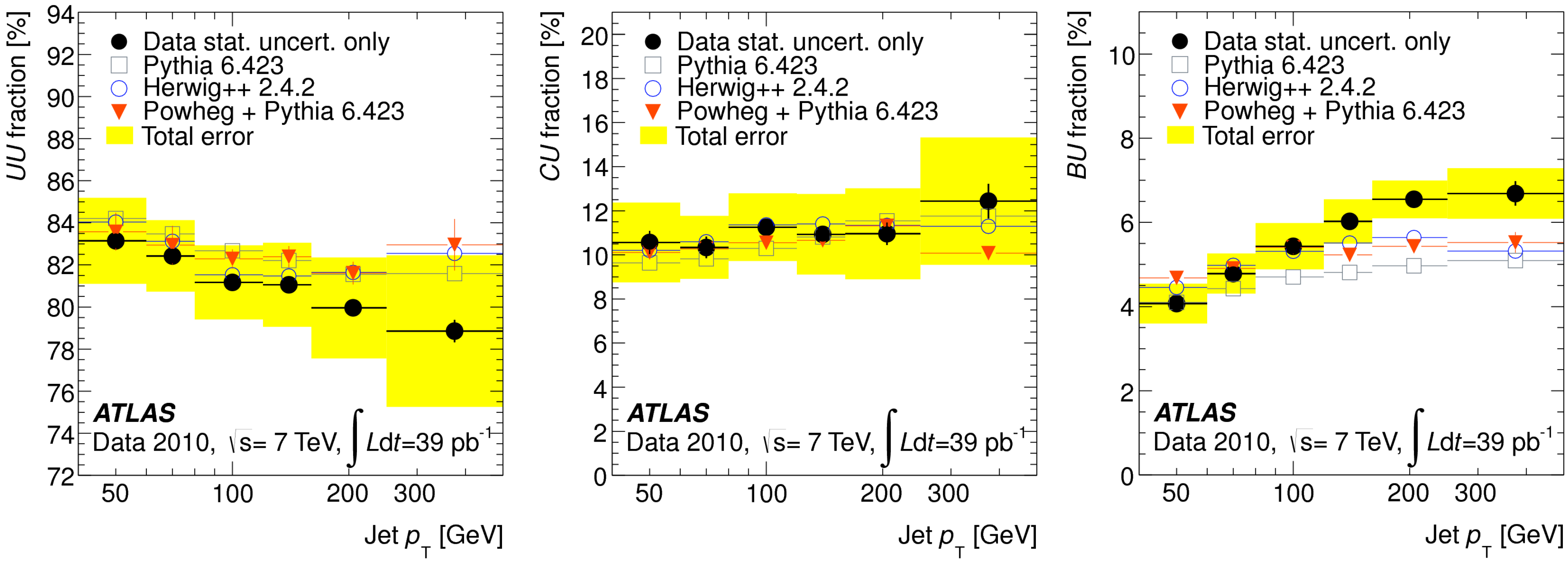


→ colour coherence in MC improves description, but still does not describe it fully
can be used for new tuning of MC to further improve description

Flavour Composition of Di-Jets

ATLAS Eur. Phys. J. C (2013) 73:2301

classify jets according to initial flavour: light quarks (U) and heavy quarks (C) and (B)
6 combinations for di-jets BB, CC, UU and mixed CU, BU, BC
create 2D templates in two kinematic variables for found vertices in jets and fit simultaniously all 6 combinations

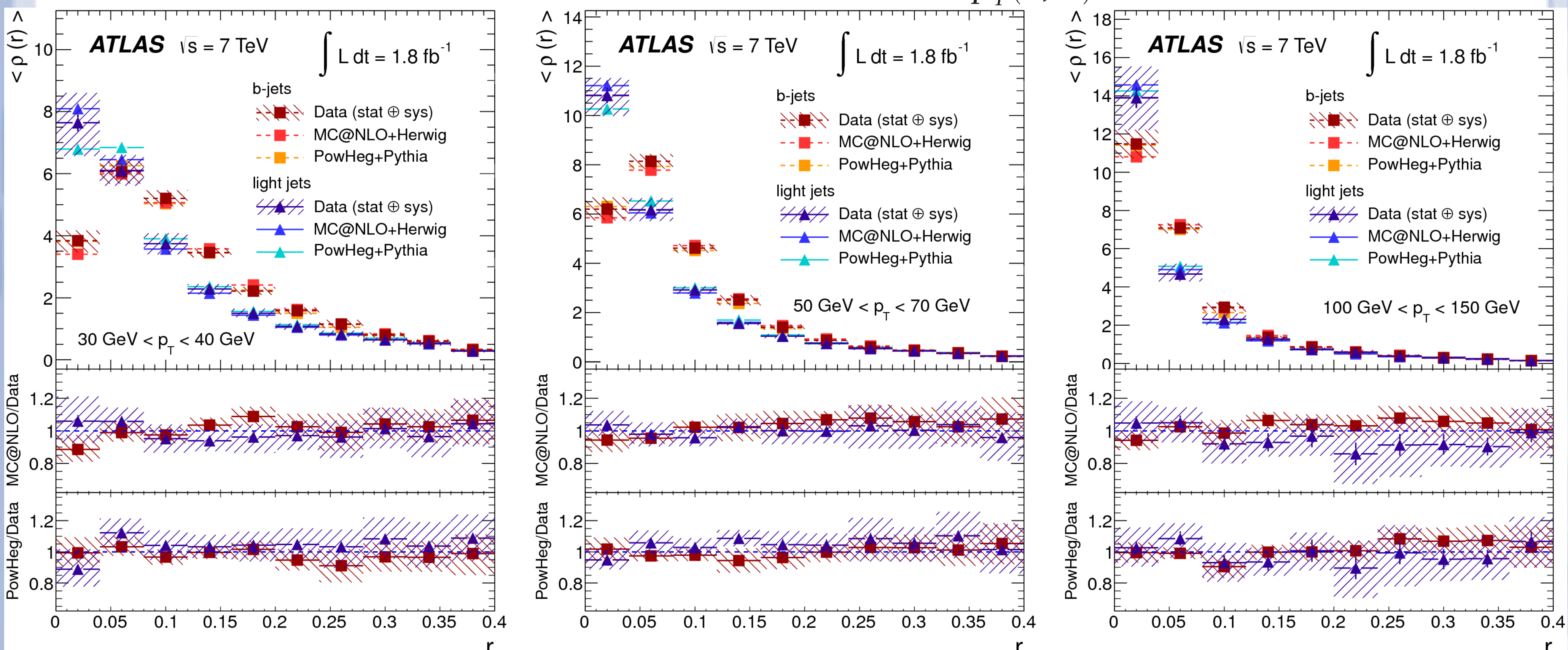


good agreement between data and MC prediction for all 6 combinations except BU which is higher for p_T>100GeV than LO and NLO MC predictions

Jet Shapes in Light & b Quark Jets

ATLAS arXiv: 1307.5749

1.8 fb^{-1} collected beginning of 2011
use $t\bar{t}$ events as source of clean b (from t) and light (from W) jets;
di-lepton and single-lepton channels show compatible results and were combined
mild dependence on pseudorapidity of jet; strong dependence on p_T of jet
calculate differential jet shape: $$\rho(r)=\frac{1}{\Delta r}\cdot\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)}$$



→ light jets are narrower than b-jets and is more pronounced at low jet p_T
well MC description of the measurement

Other, New Results not shown

- Jet Substructure
  - grooming, trimming, more aimed pileup suppression as well as searches and investigating heavy particles

    ATLAS: arXiv: 1306.4945 (submitted to JHEP)

    CMS: JHEP 05 (2013) 090
- other Vector Boson + Jets
- complete list of (all) publications available at:

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults#Jet_Physics

CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

Summary and Conclusions

- many interesting new results in QCD
- in general good agreement with theory predictions
  - few exceptions e.g. heavy and light flavour QCD production
- running of strong coupling constant confirmed well above 1 TeV scale
- QCD well understood at LHC !