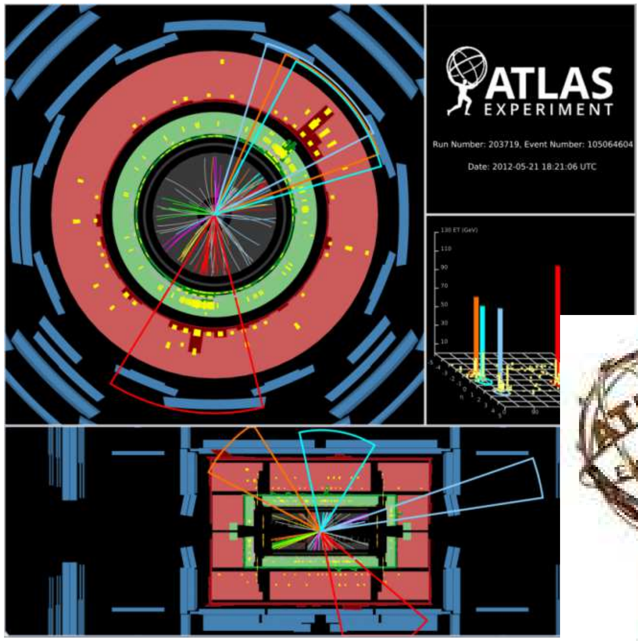
Multijet measurements at LHC

Achim Geiser, DESY Hamburg (CMS group)

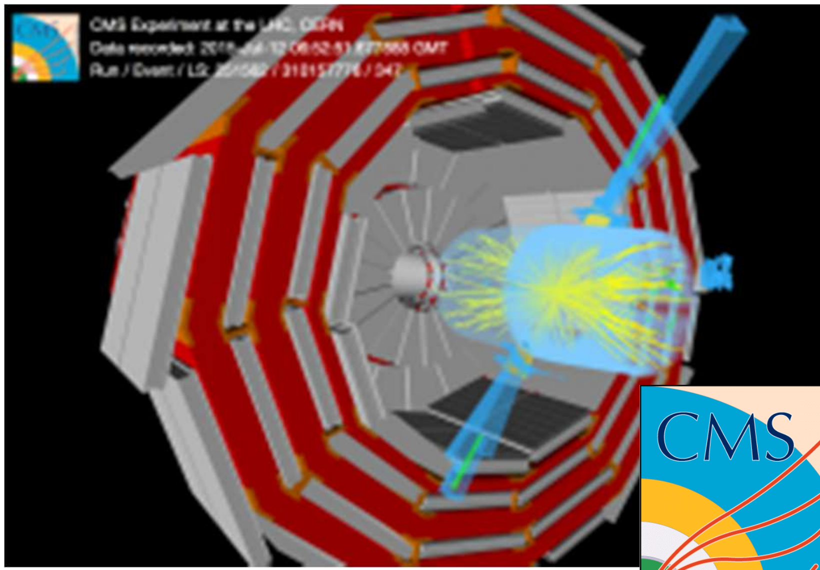
LHC physics discussion, DESY, 4.7.2016



originally:

SM@LHC, Pittsburgh, USA

May 3, 2016

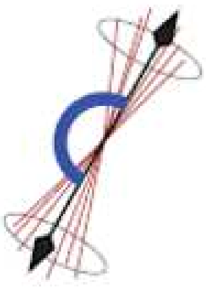


on behalf of the **ATLAS and CMS** collaborations

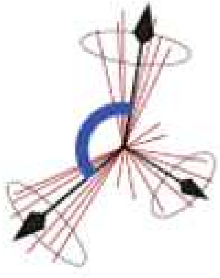
Outline:
- **direct 4-jet (and 3-jet) measurements**
- **dijet azimuthal decorreleations**
- **Mueller-Navelet dijet decorrelations**
- **transverse energy-energy correlations**

Motivation: Why study multijets?

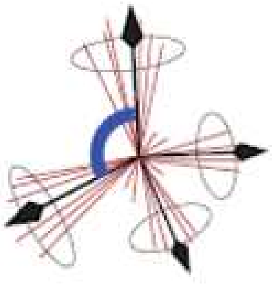
- **inclusive jet measurements** dominated by dijets: 2 back-to-back final state partons (LO QCD configuration, $O(\alpha_s^2)$)



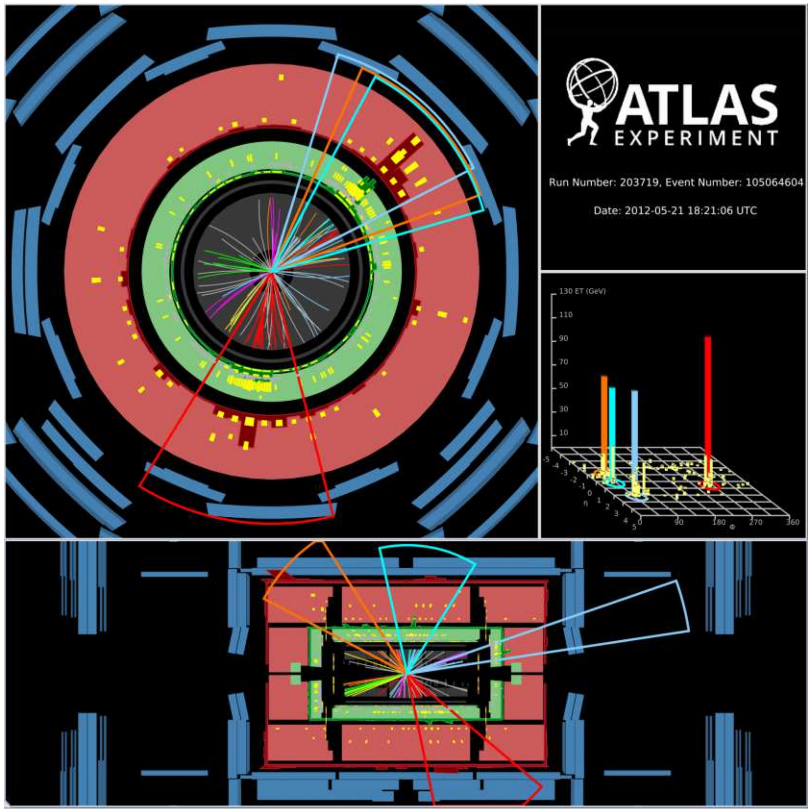
- production of **third jet**
-> radiation of third parton
(NLO QCD configuration, $O(\alpha_s^3)$, is effectively LO),
-> decorrelation in dijet azimuthal angle
(but angle between two leading jets remains > 2/3 π)



- **four-jet** final state requires two additional parton radiations (at least $O(\alpha_s^4)$)
-> **excellent probe for higher order QCD corrections**
(angle between two leading jets can go down to 0)



Direct 4-jet (and 3-jet) measurements



Direct 4-jet measurements: 4-jet mass @ 8 TeV

ATLAS, JHEP 12 (2015) 105

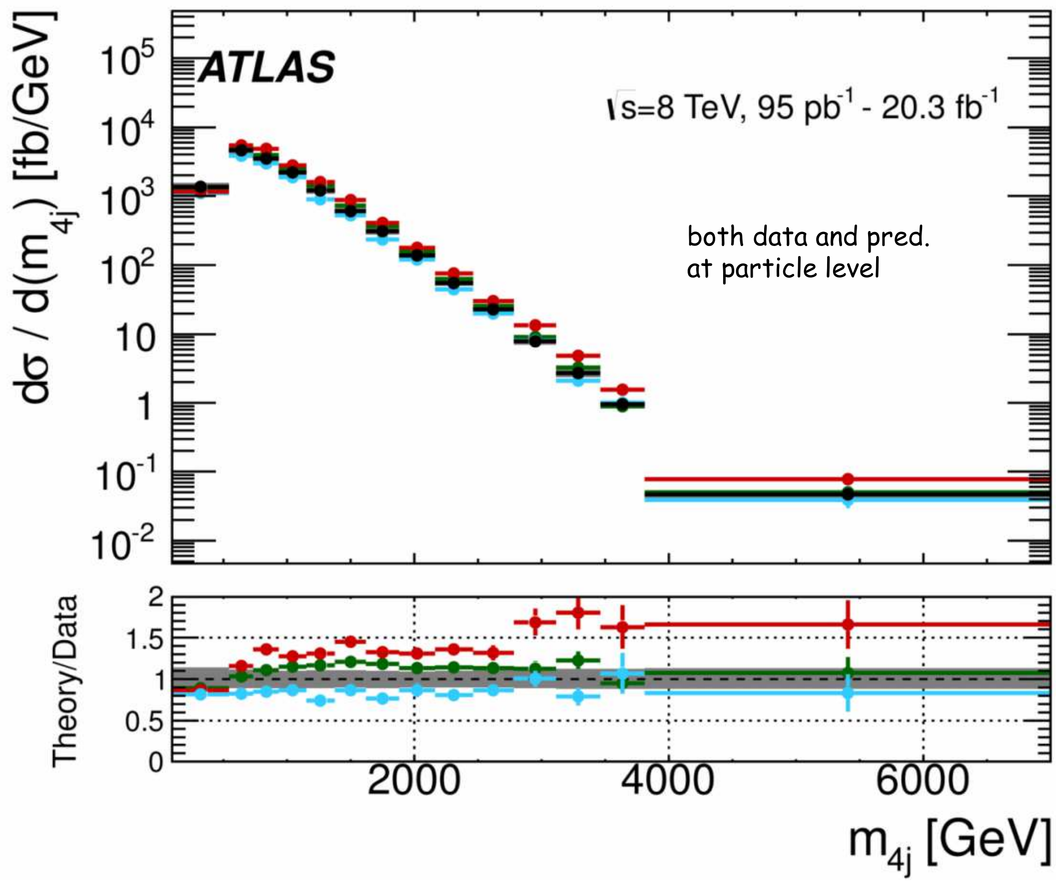
- four-jet-events: background to many searches
- **topological variables** sensitive to
  - QCD colour factors
  - spin of gluons
  - hadronisation

reasonably described by 'LO' ME ($O(\alpha_s^2)$) (PYTHIA, HERWIG) or $O(\alpha_s^4)$ tree (MADGRAPH)) + LL PS

(if normalized to data)

- **4-jet mass:**

(cross section def. in backup)



$O(\alpha_s^4)$ better than $O(\alpha_s^2)$

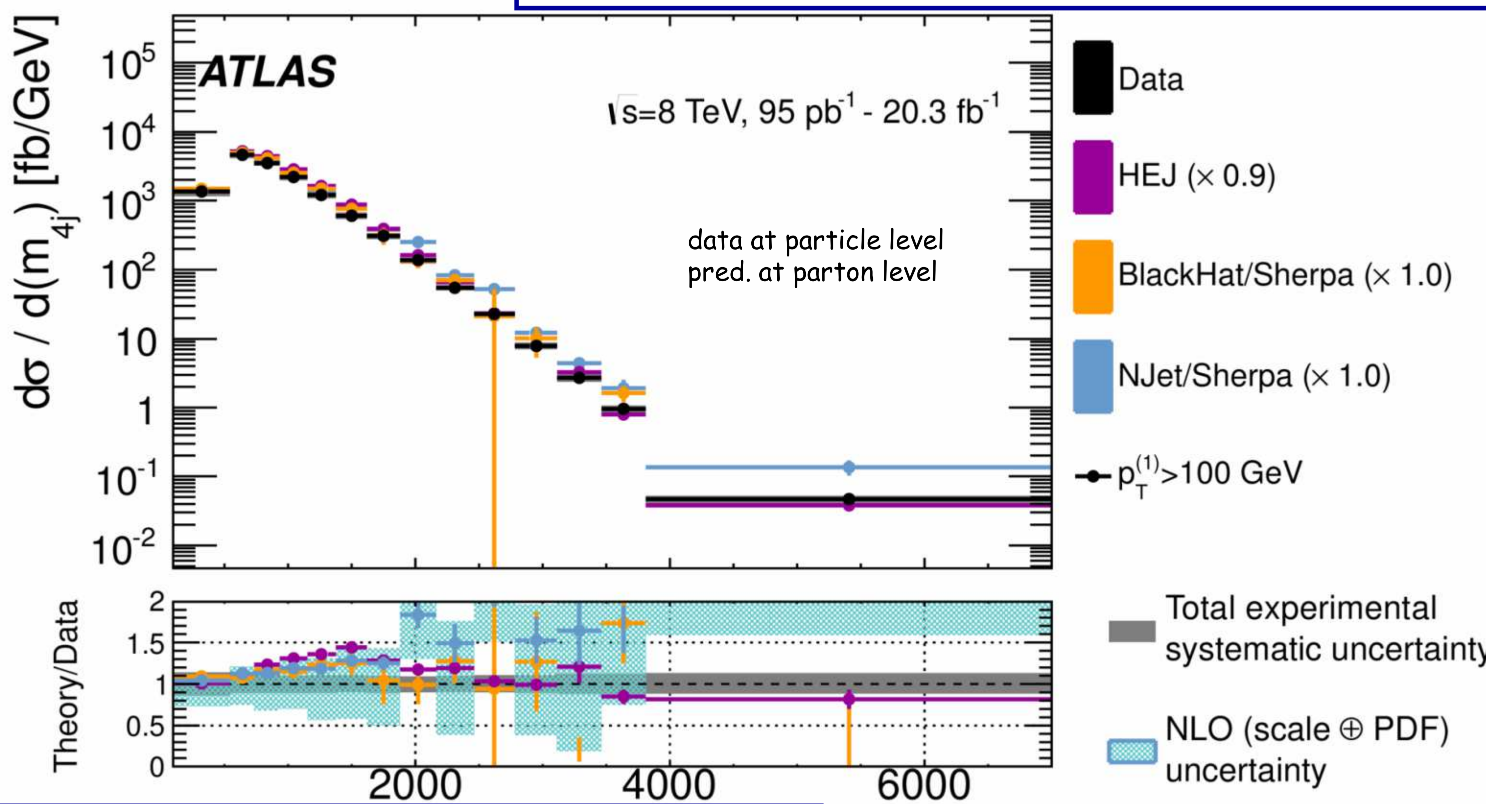
Direct 4-jet measurements: **4-jet mass @ 8 TeV**

ATLAS, JHEP 12 (2015) 105

- four-jet-events: background to many searches
- **topological variables** sensitive to
- QCD colour factors
- spin of gluons
- (hadronisation)

reasonably described by
NLO ($O(\alpha_s^5)$) Blackhat or Njet/Sherpa)
or approx. all order (HEJ) QCD

- **4-jet mass:**
  (cross section def. in backup)

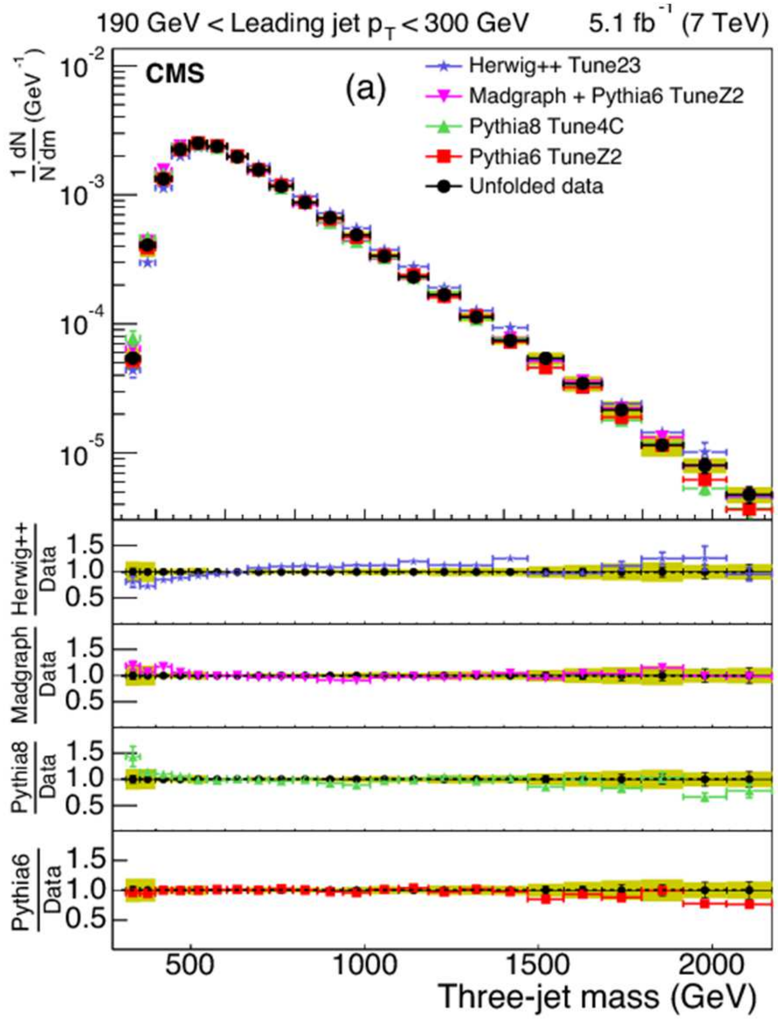


full $O(\alpha_s^5)$ better than $O(\alpha_s^4)$+approx. $O(\alpha_s^\infty)$

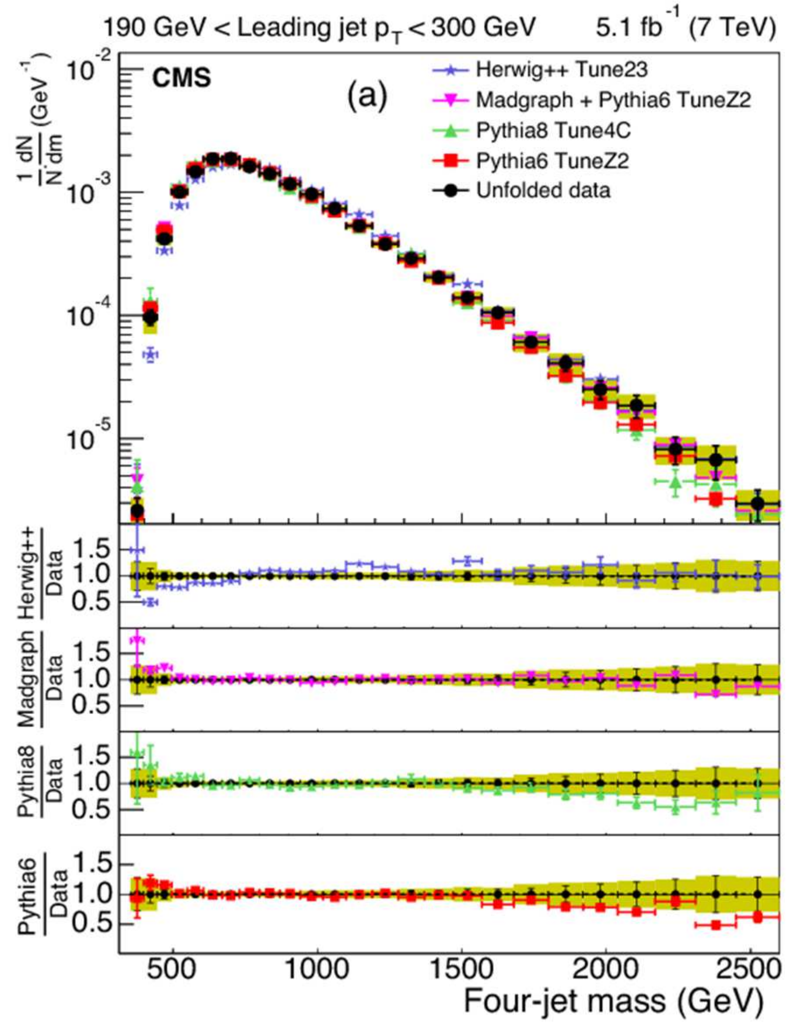
3-jet mass and 4-jet mass @ 7 TeV

CMS, Eur Phys J C 75 (2015) 302

3-jet mass



4-jet mass



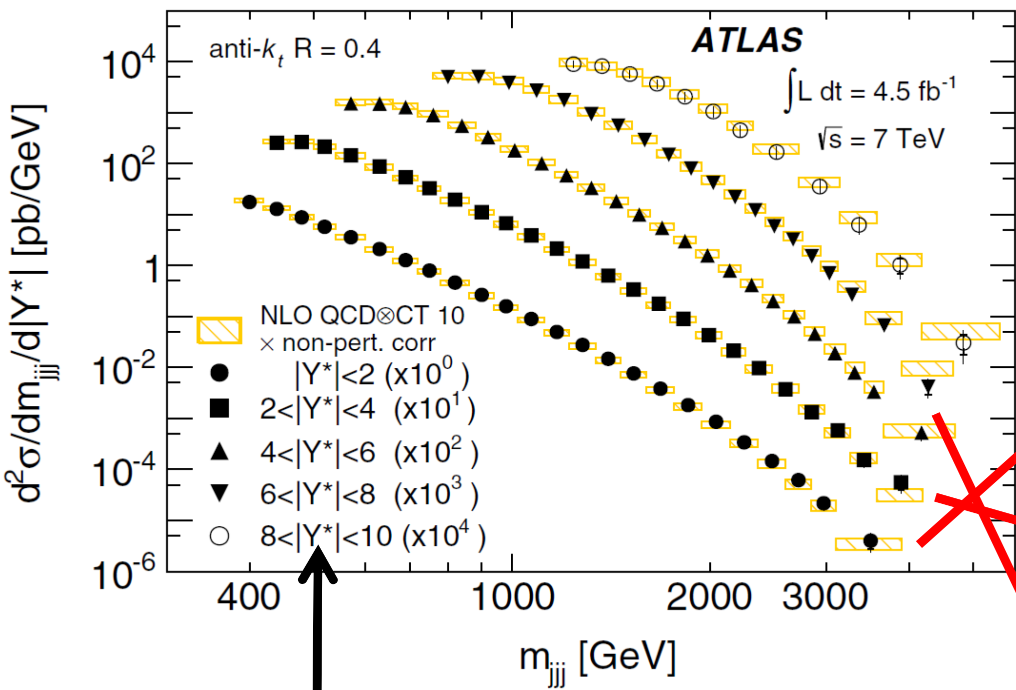
similar conclusions (for MC, at particle level)

agreement worse for $p_{T,leading}$ > 500 GeV (not shown)

3-jet mass @ 7 TeV

ATLAS, Eur Phys J C 75 (2015) 228

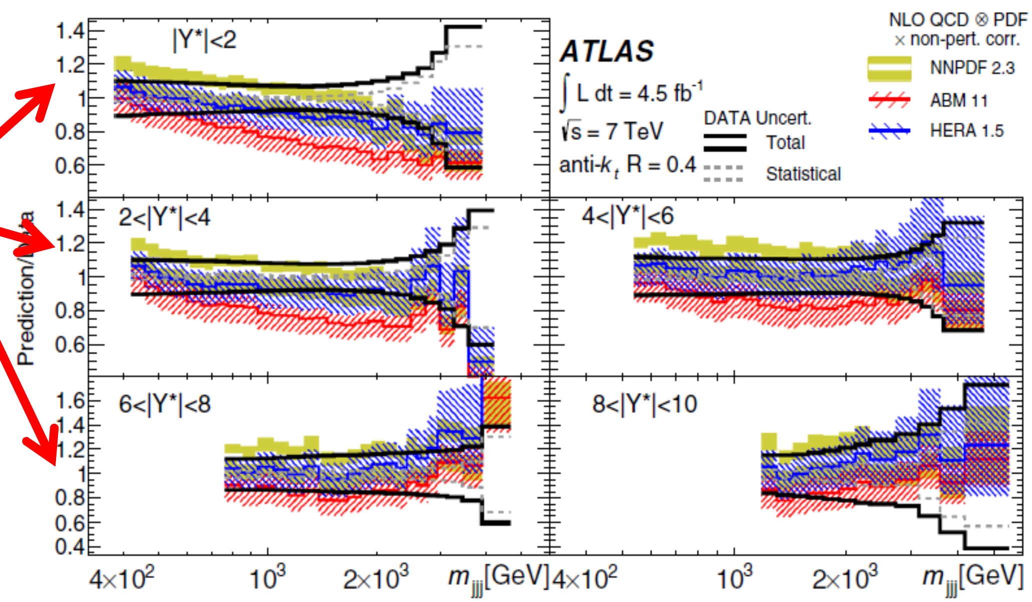
3-jet mass



summed rapidity separation

ratio NLO QCD/data,

example:



reasonable description (by NLO QCD, at particle level)

some discrimination between different PDFs

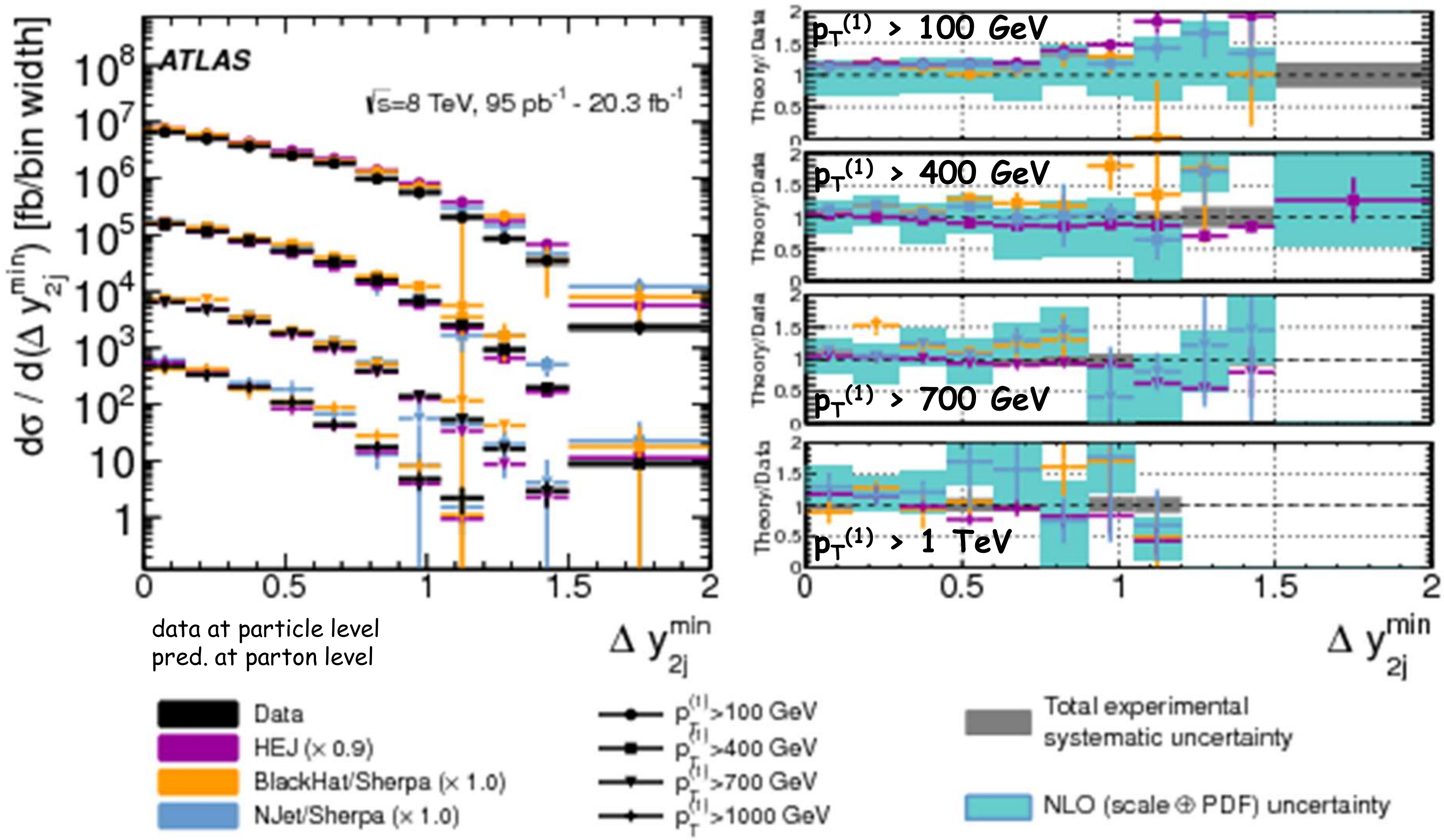
see also ATLAS,
Eur Phys J C 71 (2011) 1763

Other 4-jet variables @ 8 TeV

test small and wide angle radiation

ATLAS, JHEP 12 (2015) 105

- variables: $p_T^{(1),(2),(3),(4)}$, H_T, m^{min}_{2j}/m_{4j}, $\Delta\phi^{min}_{2j}$, $\Delta\phi^{min}_{3j}$, Δy^{min}_{2j}, Δy^{min}_{3j}
- **similar conclusions**, except **Δy between two leading jets:**



$O(\alpha_s^4)$+approx. $O(\alpha_s^\infty)$ better than full $O(\alpha_s^5)$ at high $p_T^{(1)}$

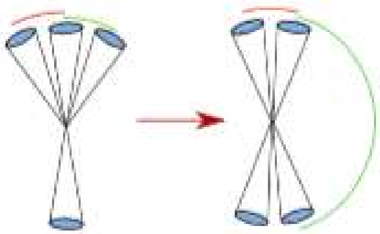
but worse at low $p_T^{(1)}$

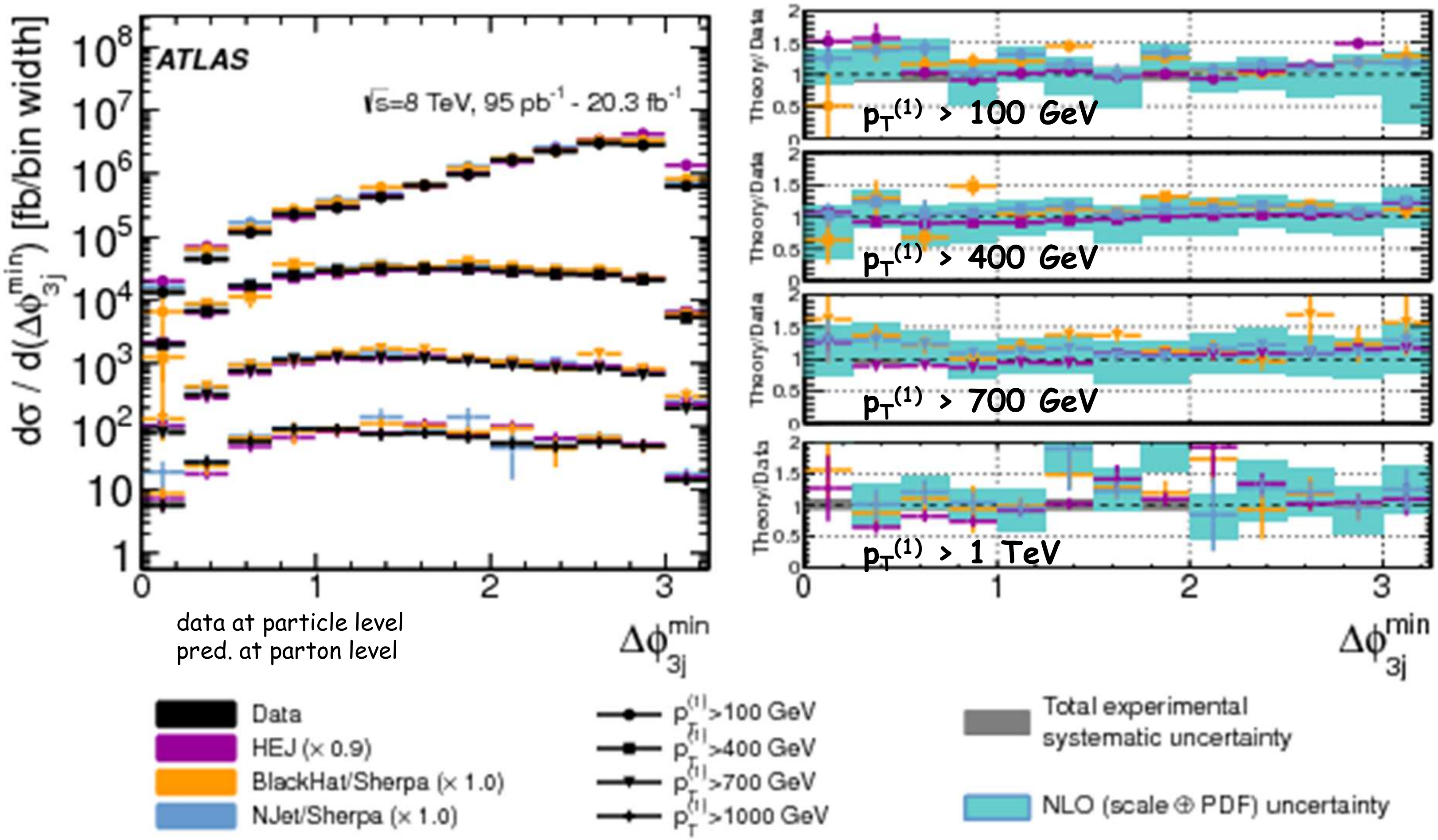
Other 4-jet variables @ 8 TeV

test small and wide angle radiation

ATLAS, JHEP 12 (2015) 105

- **Other example: $\Delta\phi^{min}_{3j}$**



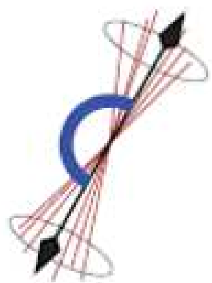


both kinds of predictions describe data well within large uncertainties

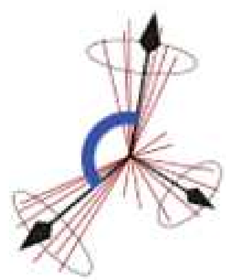
HEJ a bit worse at low $p_T^{(1)}$

Dijet azimuthal decorrelations:

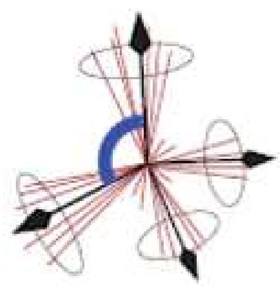
$\Delta\phi$



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



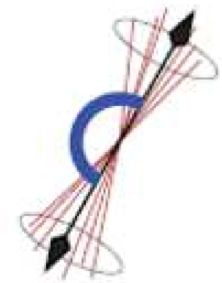
$\Delta\varphi_{dijet} < \pi$



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

Dijet azimuthal decorrelations

- **inclusive jet measurements** dominated by dijets: 2 back-to-back final state partons (LO QCD configuration, $O(\alpha_s^2)$)



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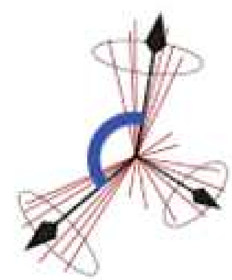
but angle between two leading jets remains > 2/3 π

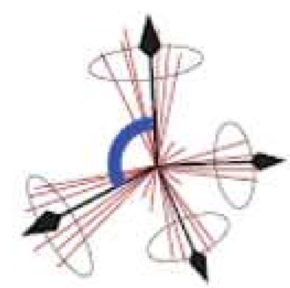


$\Delta\varphi_{dijet} < \pi$

- **four-jet** final state requires two additional parton radiations (at least $O(\alpha_s^4)$)

angle between two leading jets can go down to 0

-> low angles test >= 4 parton dynamics

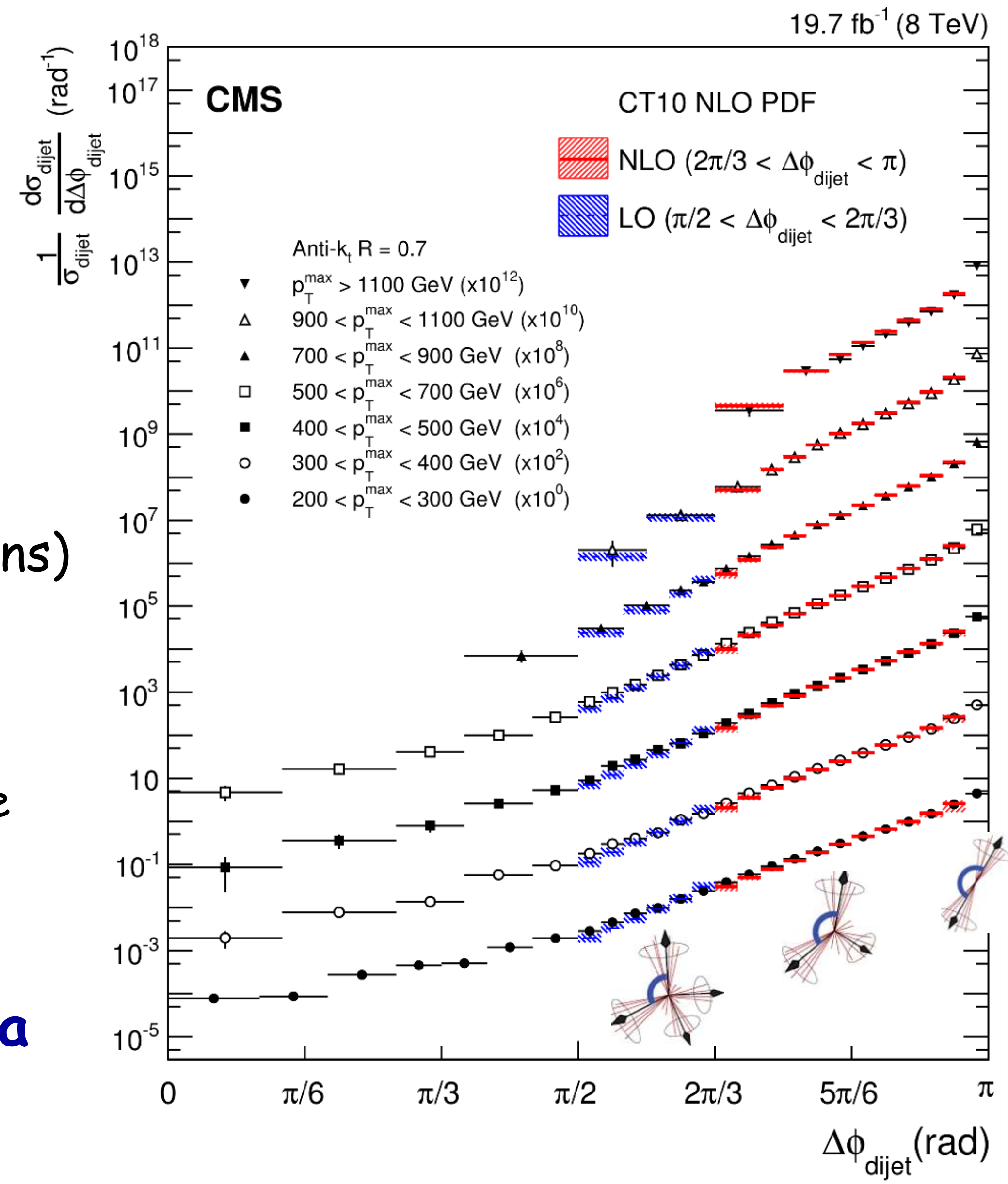


$\Delta\varphi_{dijet} << \pi$

Dijet azimuthal decorrelations

CMS, arXiv:1602.04384, subm. to Eur Phys J C

- **normalized $\Delta\phi$ cross section** of two leading jets for 7 p_T^{max} bins
- **"NLO" (full $O(\alpha_s^4)$) QCD cross section calculation** (NLOJET++ + FASTNLO, 3-4 partons) -> NLO in 3 parton region (red) LO in 4-parton region (blue) (incomplete/unreliable in small angle and 2-parton regions)
- **reasonable description of data**



Ratio data/theory

CMS, arXiv:1602.04384

- theory uncertainty includes:

  - **scale variations**

    (factor 2, independent variation)

    around $\mu_r=\mu_f=p_T^{max}$

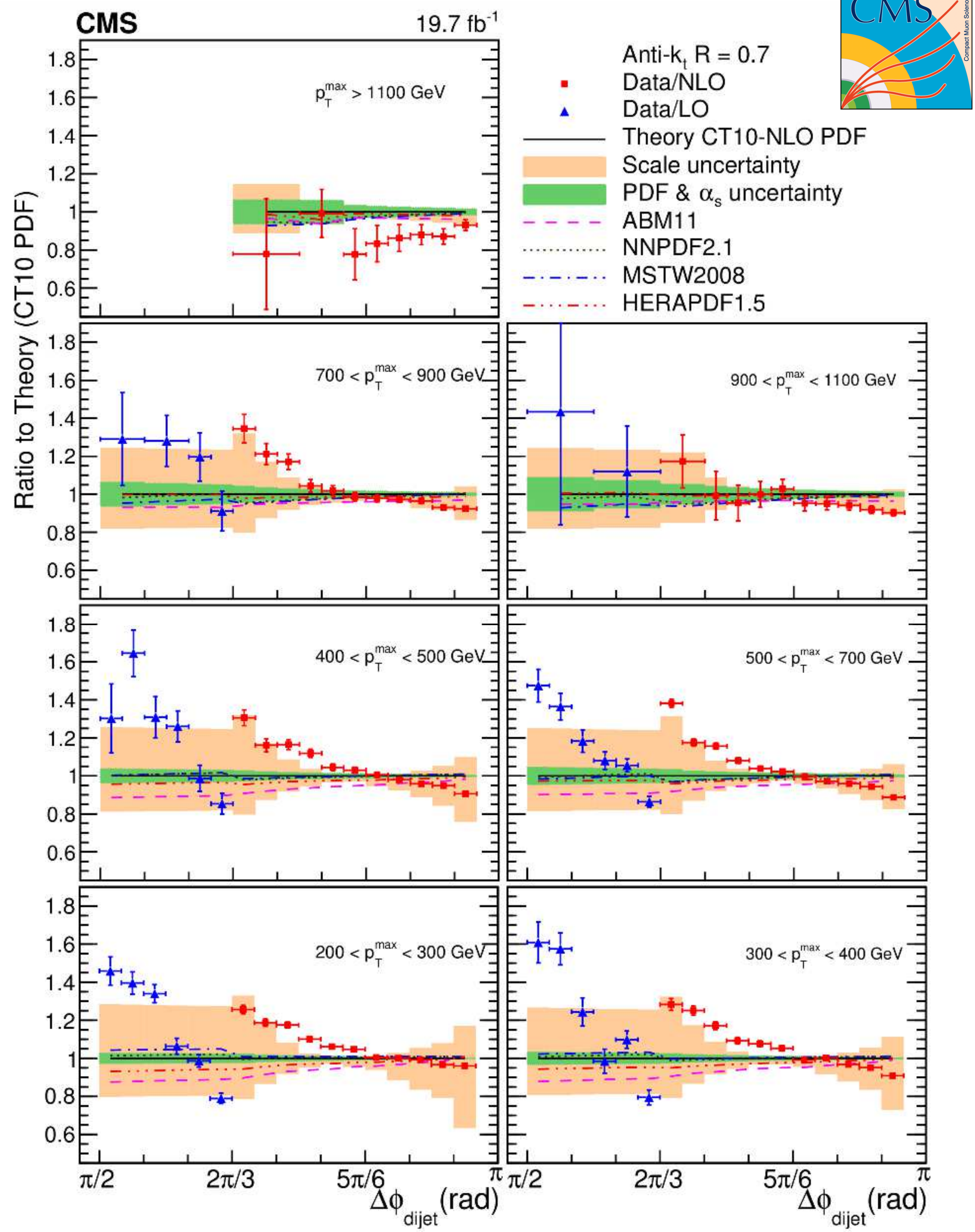
  - **PDF and α_s variation**:

    ABM11, CT10, HERAPDF1.5

    MSTW2008, NNPDF2.1

    $\alpha_s \sim 0.1176\text{-}0.1207$

- **data reasonably described,**
  (N)NLO ($O(\alpha_s^5)$) calculation desirable

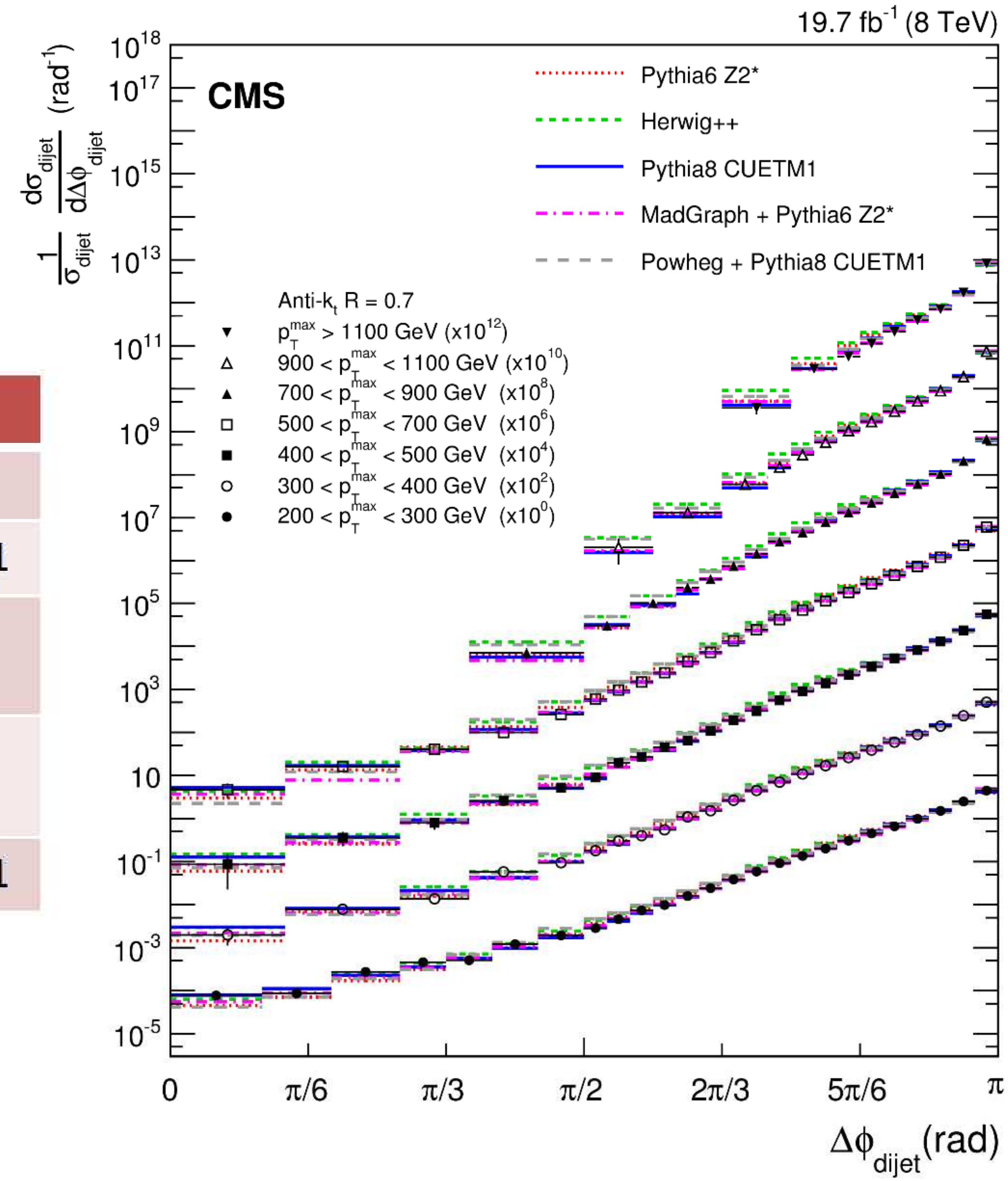


Comparison to MC models

CMS, arXiv:1602.04384

- MC generators used:

Generator	Calculation	PS	Tune
Pythia6	LO dijet	pT-ordering	Z2*
Pythia8	LO dijet	pT-ordering	CUETM1
Herwig++	LO dijet	angular ordering	EE3C
MadGraph	LO 2 to 4 partons	Pythia6	Z2*
Powheg	NLO dijet	Pythia8	CUETM1



- **reasonable description**

Ratio data/MC

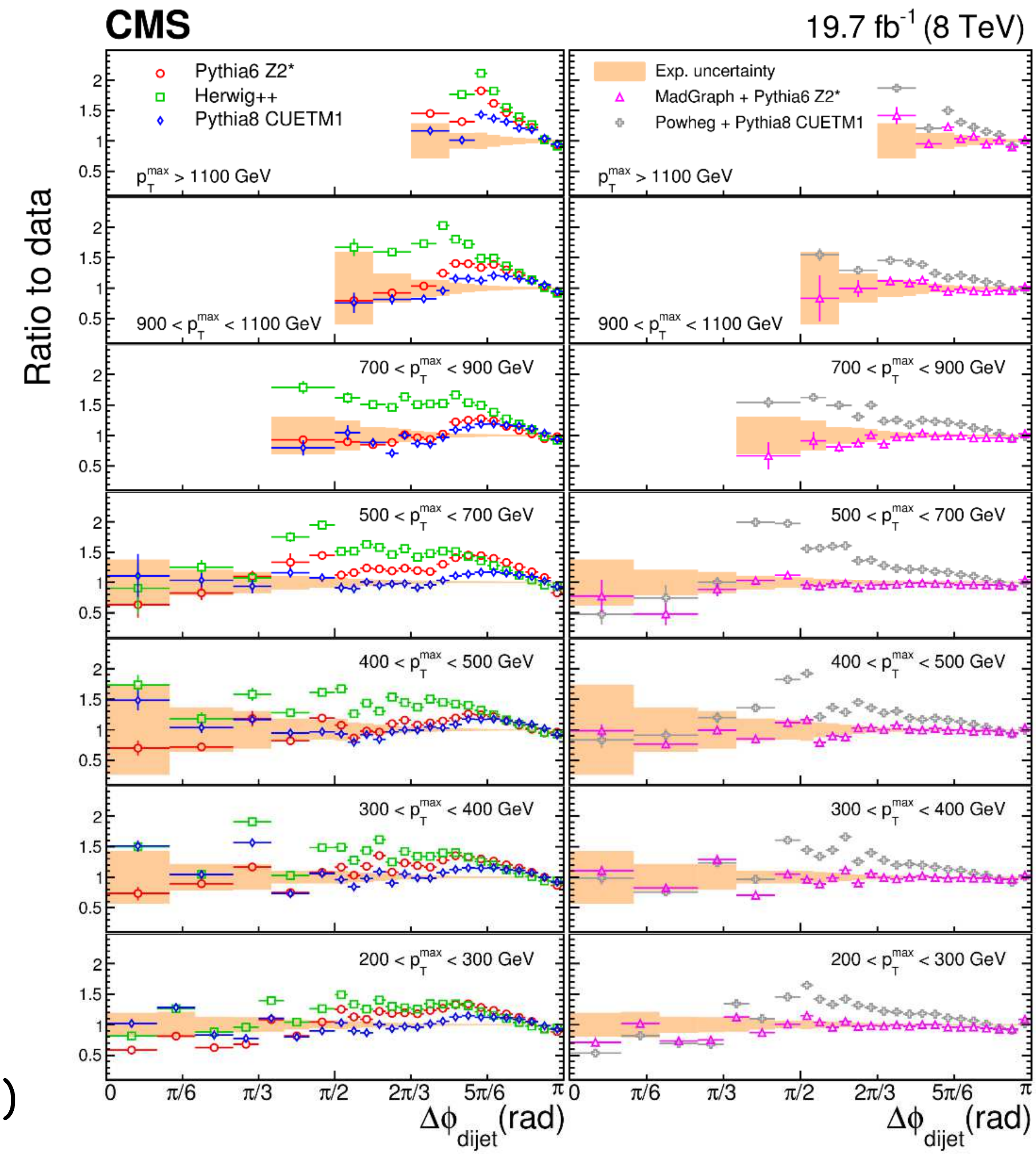
CMS, arXiv:1602.04384

- all generators 'LO'
  (except POWHEG for last bin)

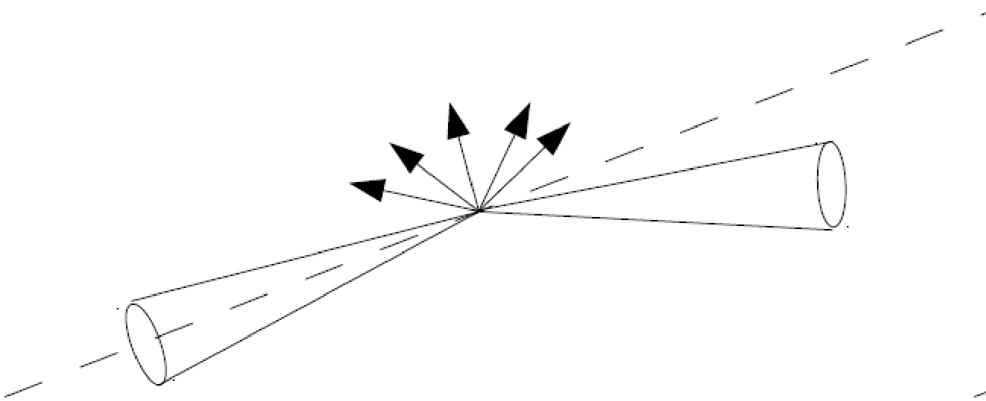
- **best description by Madgraph**
  $O(\alpha_s^4)$ tree + LL PS

  followed by PYTHIA8
  $O(\alpha_s^2)$ + LL PS

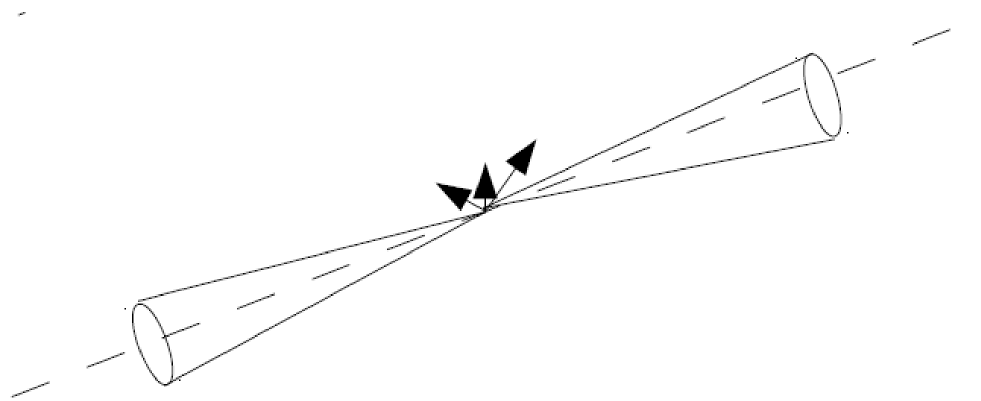
  POWHEG + PYTHIA8
  $O(\alpha_s^3)$ + LL PS
  worse
  (PS matching nonoptimal?)



Mueller-Navelet dijet decorrelations: $\Delta\phi$ for large Δy



BFKL: large jet $\Delta\eta$:
parton emissions, decorrelation



DGLAP: low p_T emissions,
independent of jet $\Delta\eta$: no decorrelation

Azimuthal decorrelation of jets at large Δy

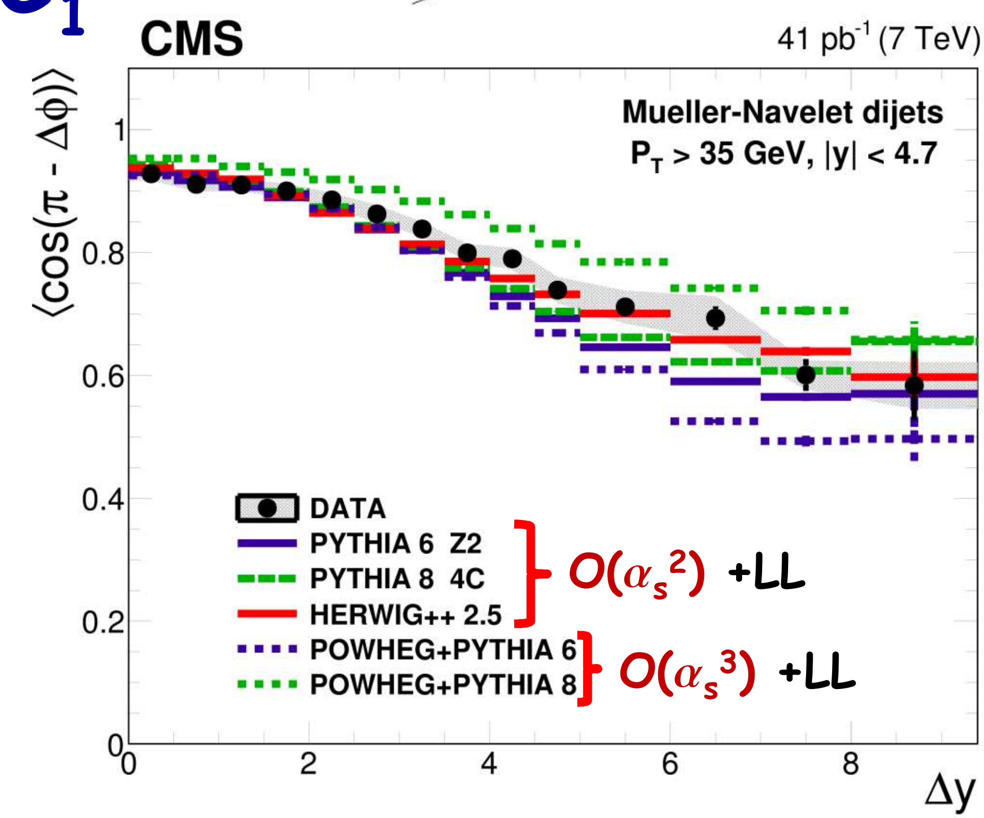
CMS, arXiv:1601.06713, subm. to JHEP

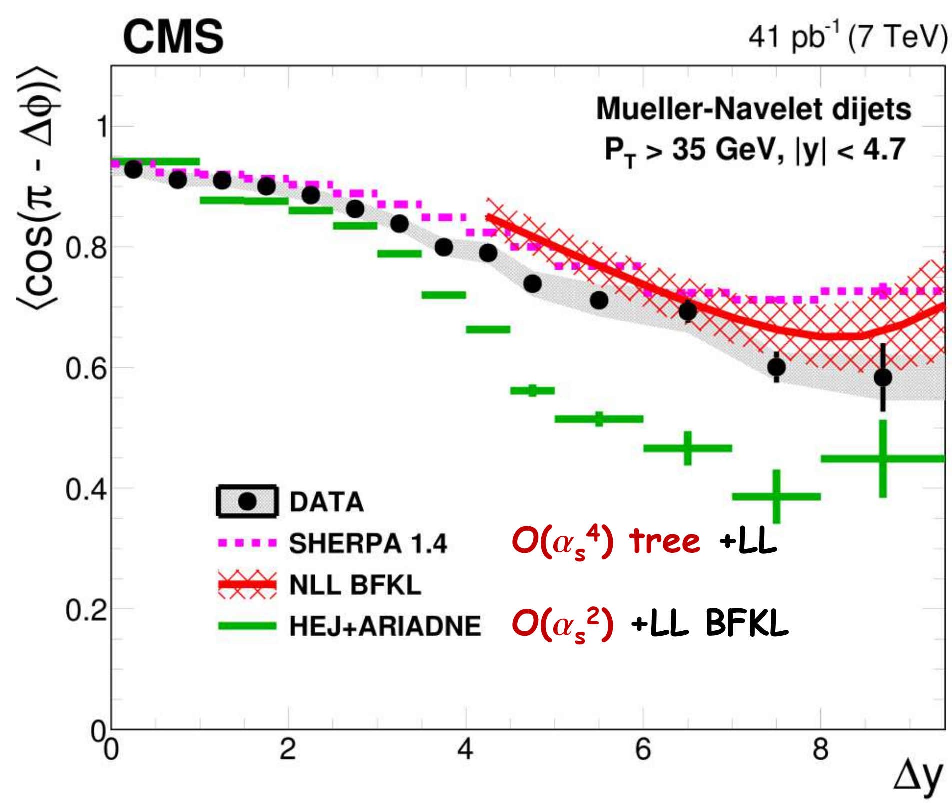
The observables used:

Δϕ between the two jets with largest Δy
(Mueller-Navelet jets)

- We will study Fourier-harmonics: C_n=<cos(n(π-Δϕ))>

C_1





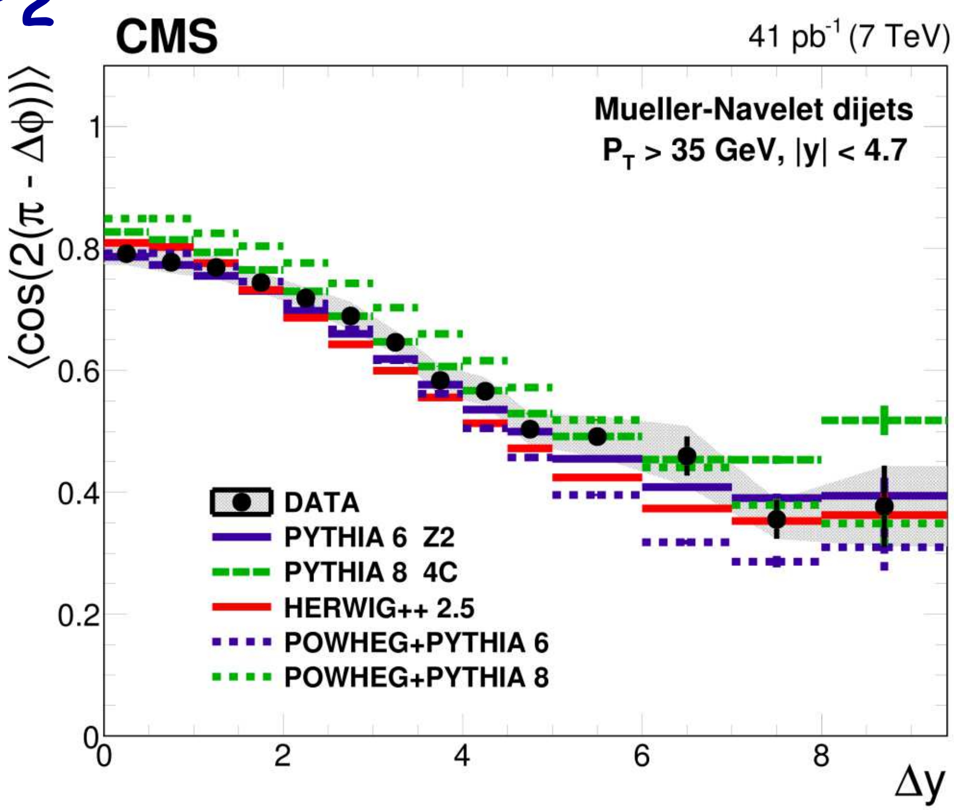
Same for 2nd moment C_2

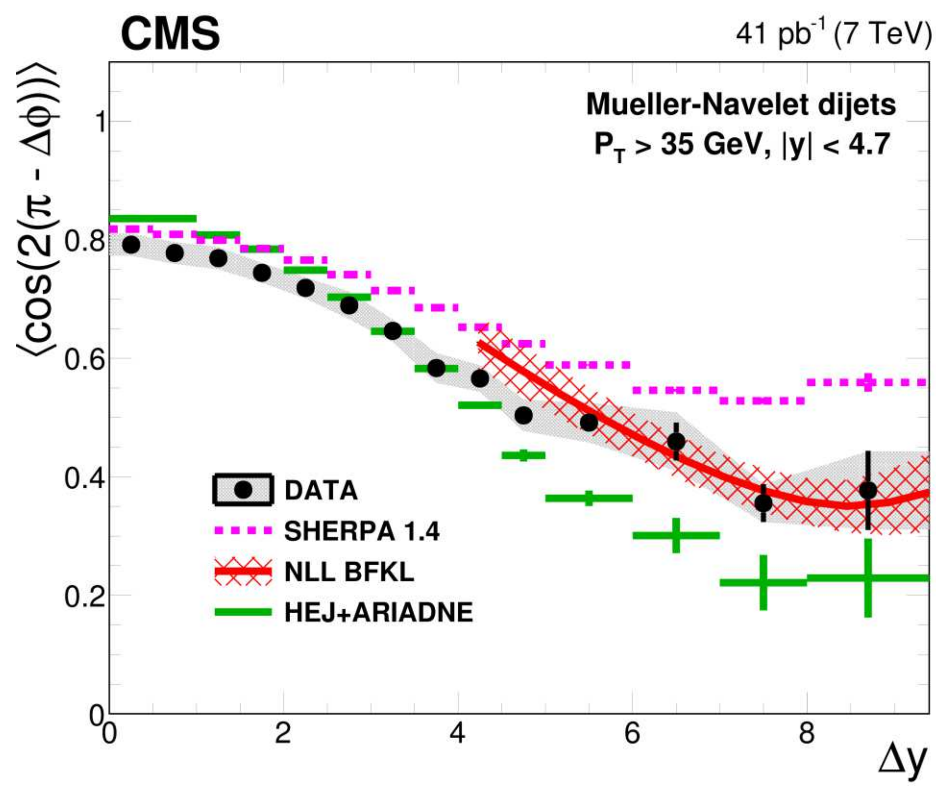
CMS, arXiv:1601.06713

similar for C_3, see backup

- **BFKL describes data**
  - ... **but so does DGLAP** (with suitable LL tuning)

C_2

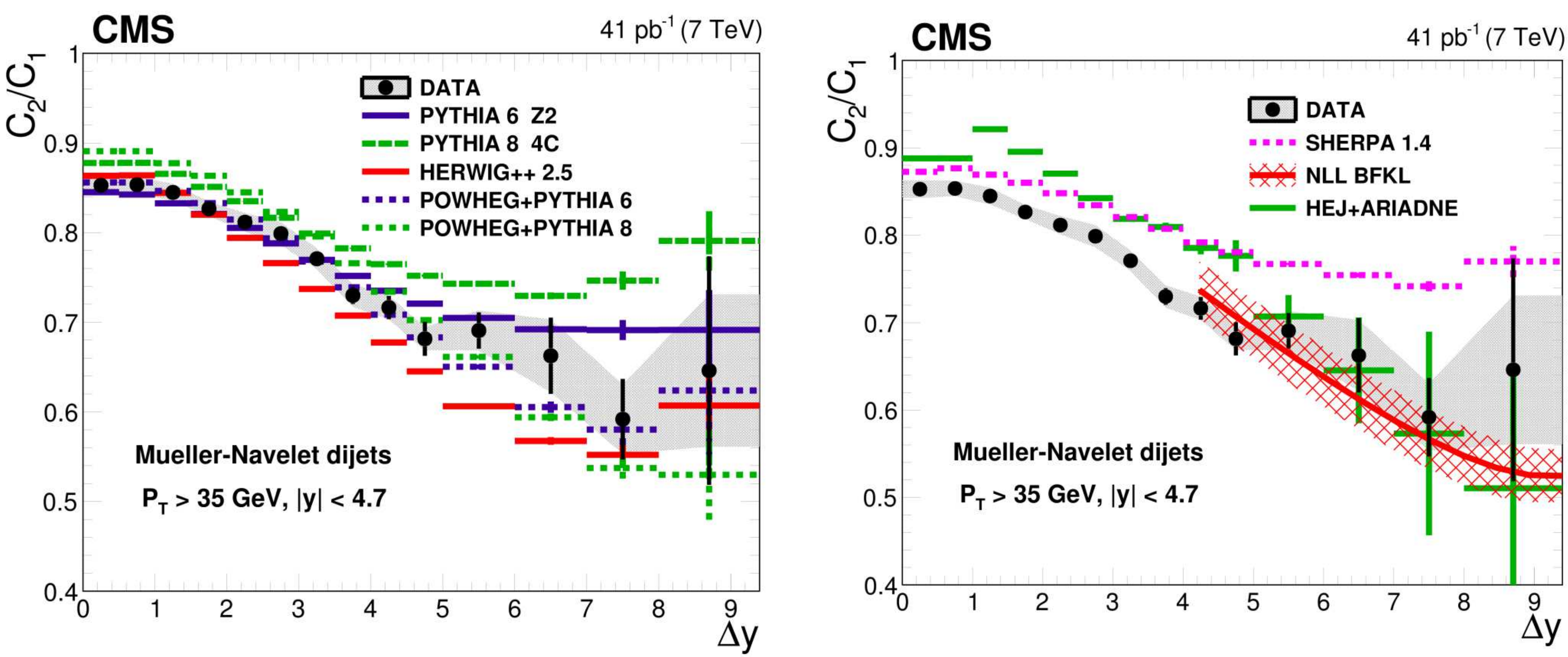




C_2/C_1 ratio

CMS, arXiv:1601.06713

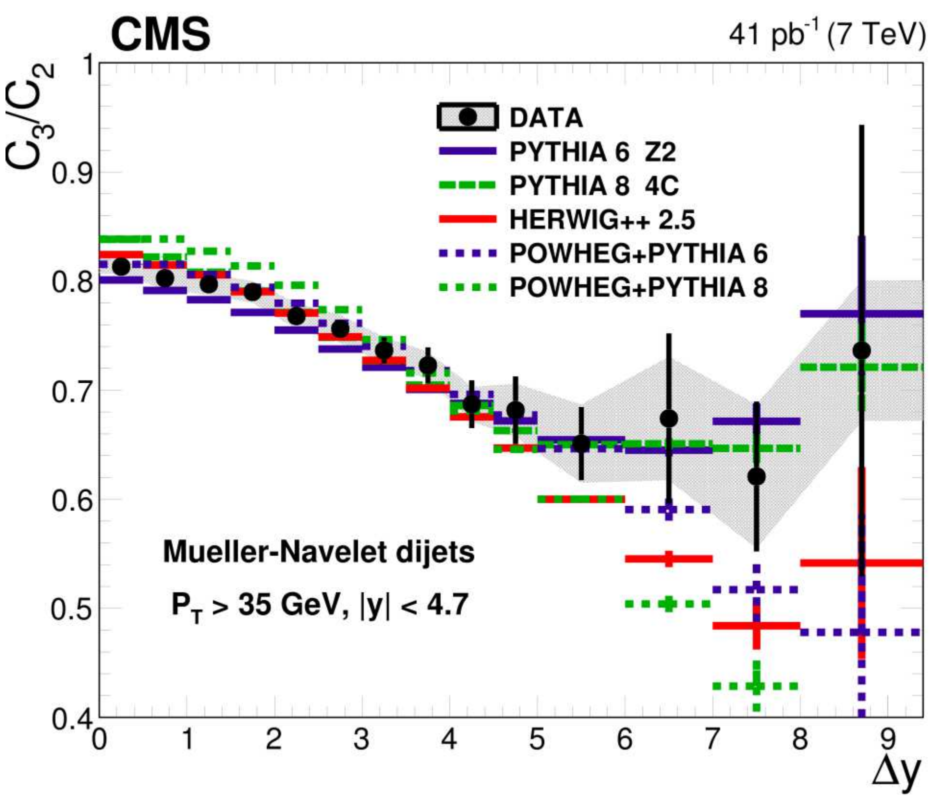
- "suppresses DGLAP effects"

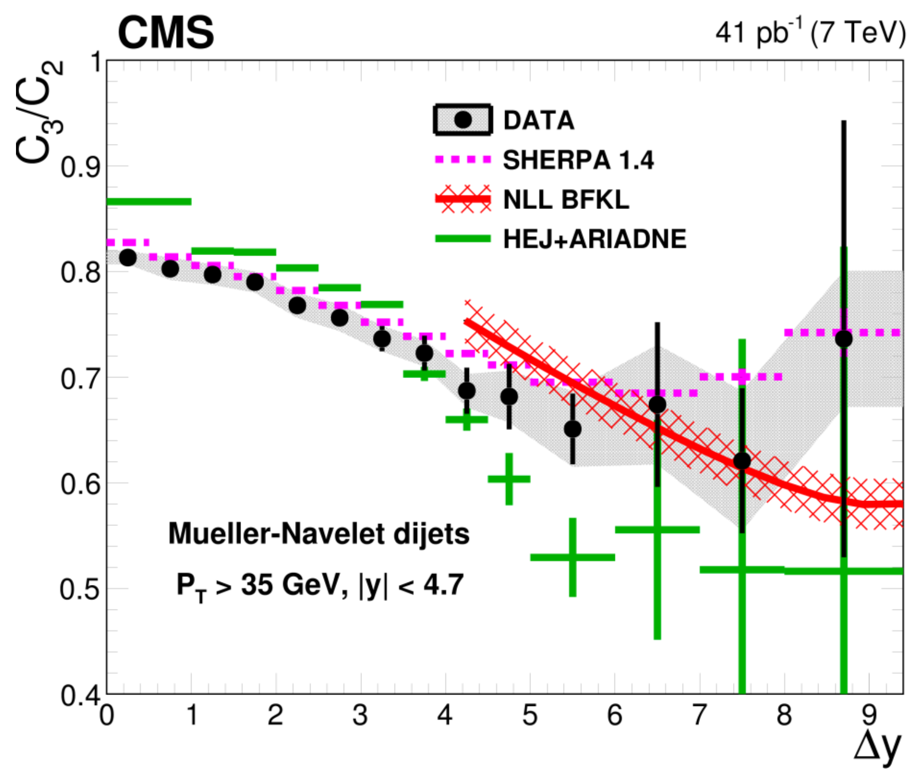


C_3/C_2 ratio

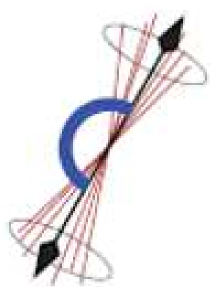
CMS, arXiv:1601.06713

- **BFKL describes data**
  - **… but so does DGLAP** (with suitable LL tuning)

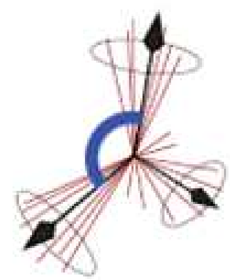




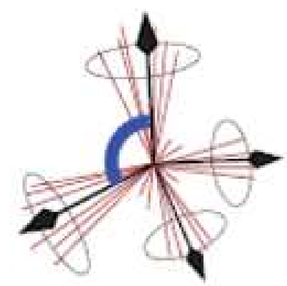
Transverse energy-energy correlations:
E_T-weighted angular distributions



$E_T^1 = E_T^2$



$E_T^1 \neq E_T^2 \neq E_T^3$



$E_T^1 \neq E_T^2 \neq E_T^3 \neq E_T^4$

Transverse energy-energy correlations

ATLAS, Phys Lett B 750 (2015) 427

event shape variable:

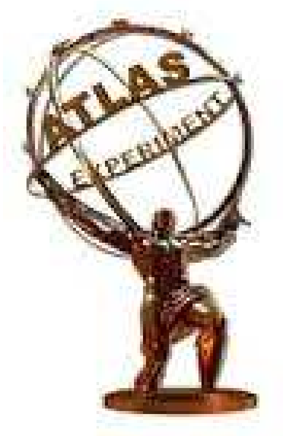
tranverse energy-energy correlation function

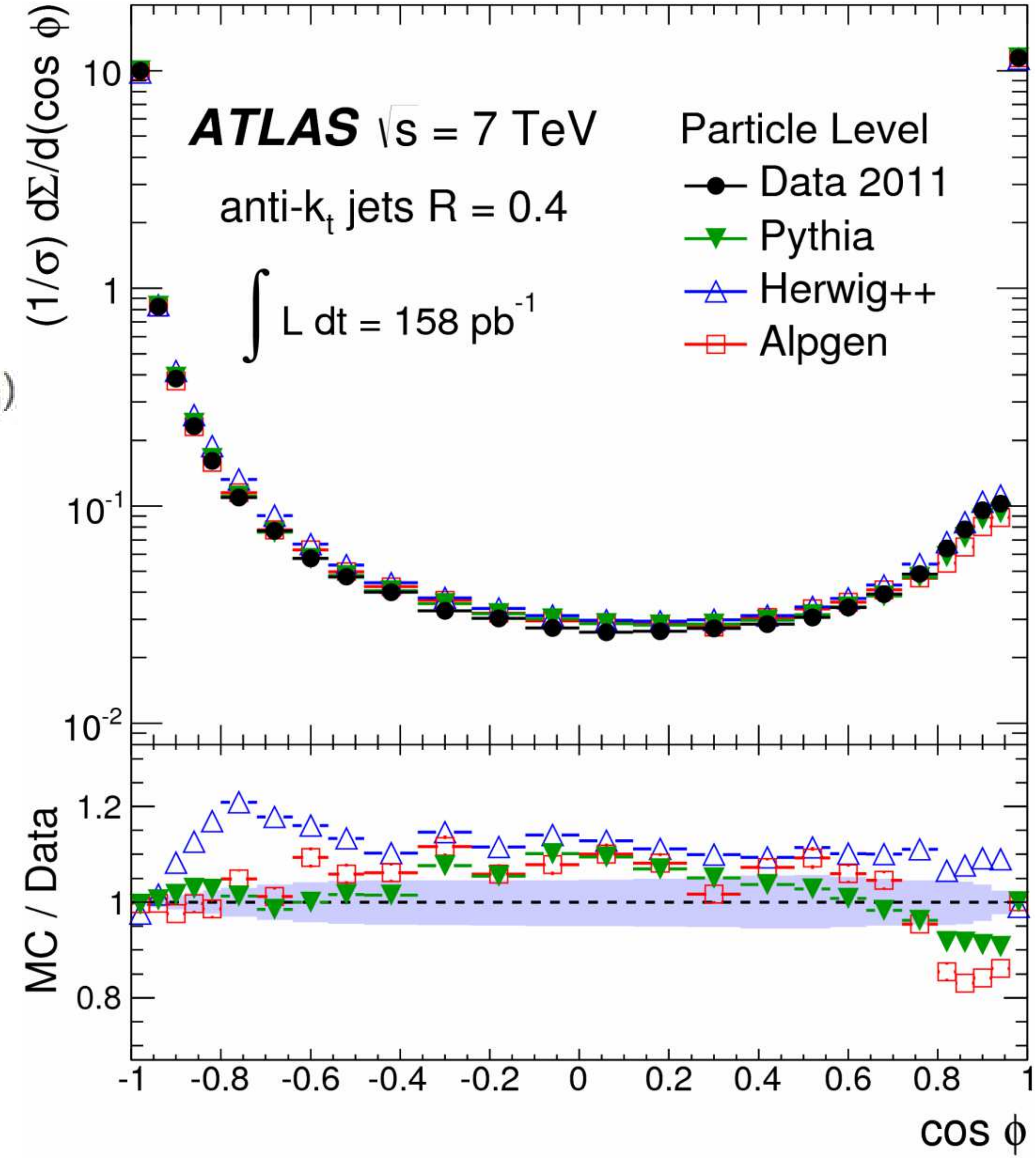
$$\frac{d\Sigma}{\sigma d\cos\phi} = \frac{1}{N\Delta\cos\phi}\sum^{N_{events}}\sum_{ij}^{N_{jets}} \frac{E_T^i E_T^j}{\left(\sum_k^{N_{jets}} E_T^k\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

phase space:

at least two jets with $p_T > 50$ GeV,

$p_T^1 + p_T^2 > 500$ GeV, $|y_{jet}| < 2.5$

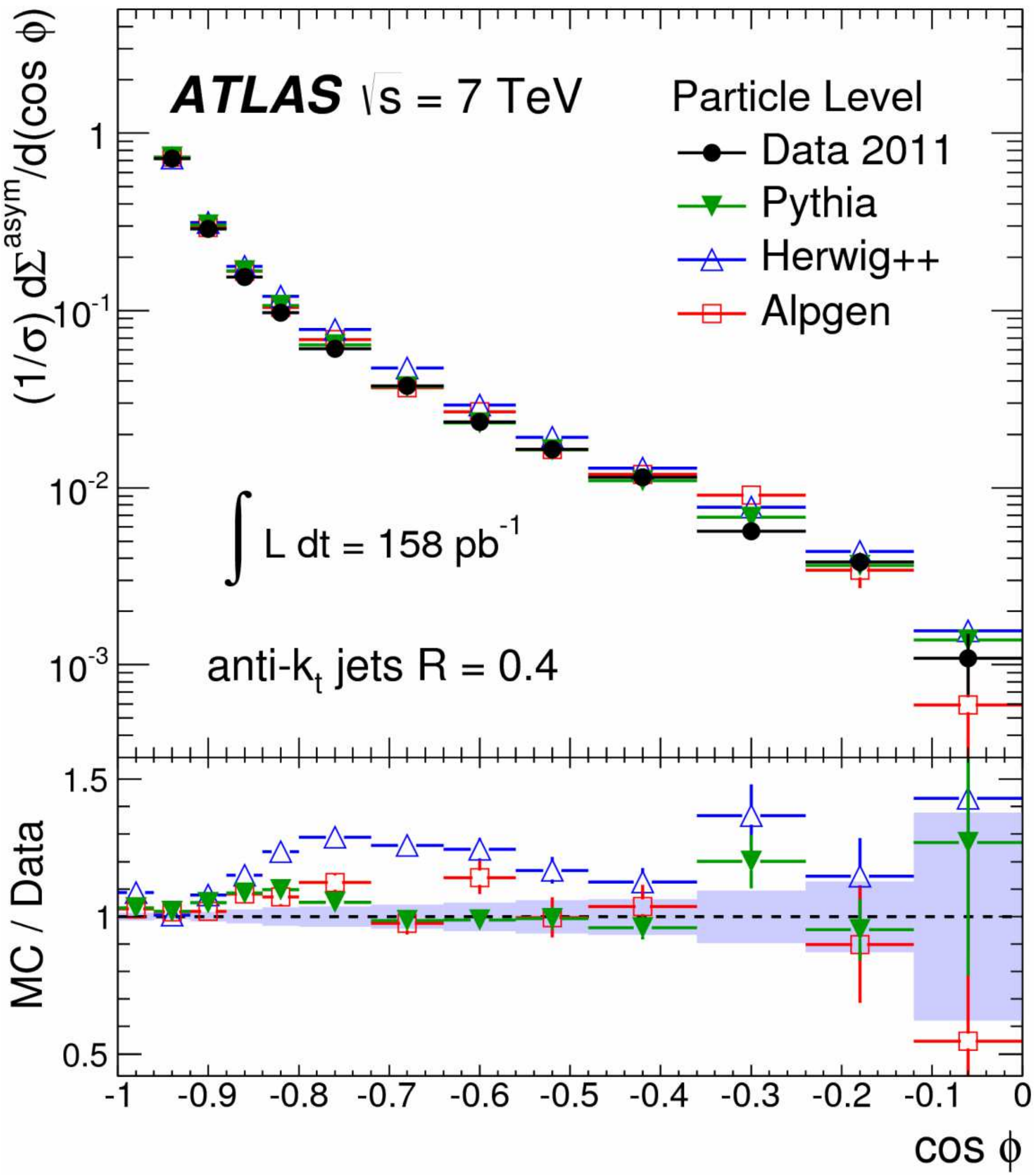




Asymmetry of correlation function

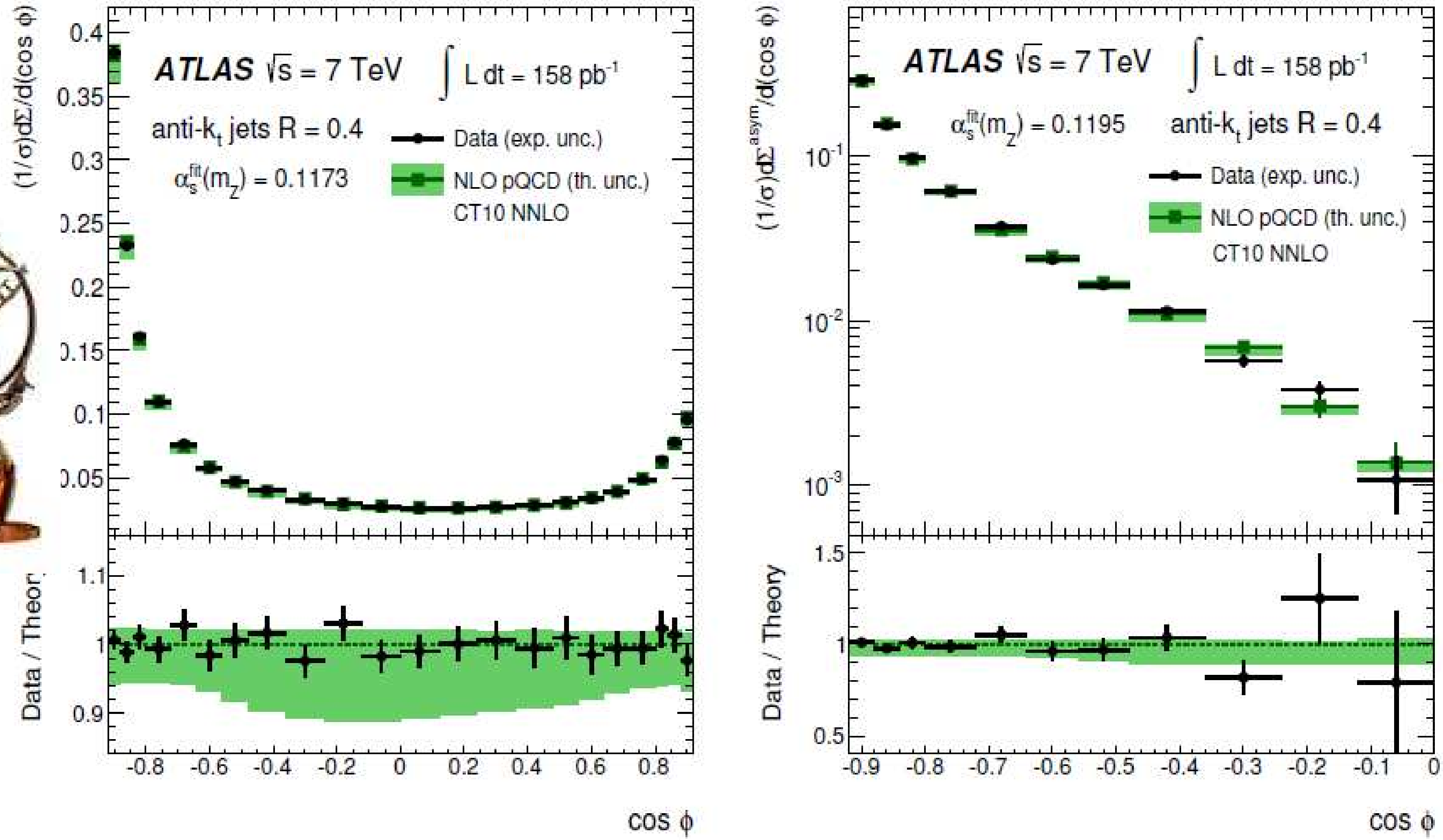
ATLAS, Phys Lett B 750 (2015) 427

- enhances differences
- reasonable description by some of the LO +PS MCs



Comparison to NLO predictions

ATLAS, Phys Lett B 750 (2015) 427



very good agreement with $O(\alpha_s^4)$ calculation (NLOJET++ + FASTJET)

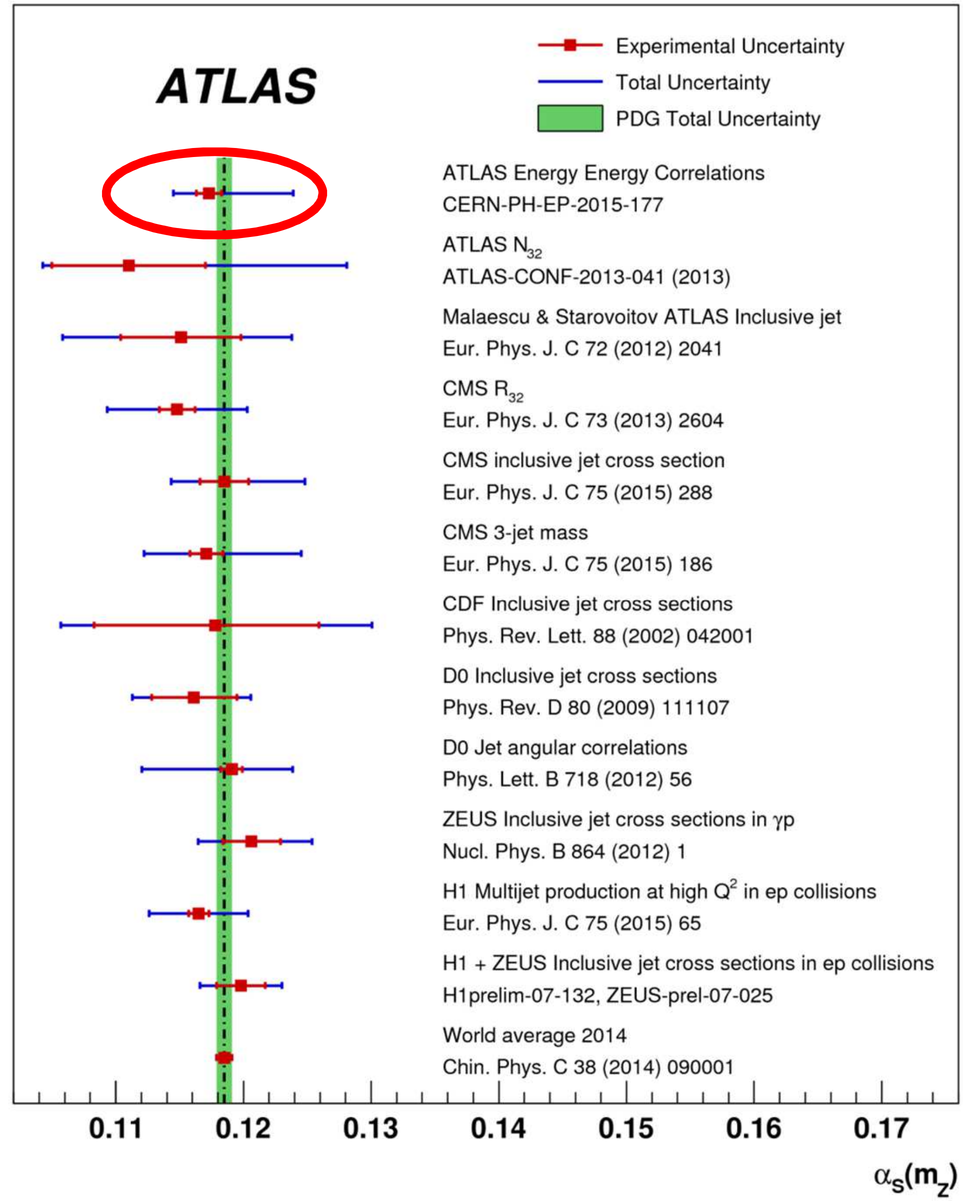
(NLO for 3-jet, LO for 4-jet) **-> can use to measure α_s**

Measurement of strong coupling constant

ATLAS, Phys Lett B 750 (2015) 427

$$\alpha_s(m_Z) = 0.1173 \pm 0.0010\ (\text{exp.})\ {}^{+0.0063}_{-0.0020}\ (\text{scale})\ \pm 0.0017\ (\text{PDF})\ \pm 0.0002\ (\text{NPC})$$

- **one of the most precise measurements from LHC**



Conclusions

- Measurements of multijet production at LHC are a great tool to test higher order QCD corrections and dynamics

- Direct detailed results on four-jet production, and more indirect studies of dijet decorrelations in $\Delta\phi$, Δy, and E_T from ATLAS and CMS were presented and compared to QCD predictions.

- Overall, current QCD predictions (LO+LL, NLO, NLL, …) describe the data remarkably well within uncertainties, but theory uncertainties typically much larger than those of the data

-> still significant room for improvements

- Generic observation (with exceptions): the higher the fraction of QCD calculated in matrix elements (rather than parton showering), the better the theory describes the data

Backup

Same for 2nd moment C_3

CMS, arXiv:1601.06713

- **BFKL describes data**
  - **… but so does DGLAP** (with suitable LL tuning)

C_3