

inclusive jet, dijets and heavy flavour jets at the LHC

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on behalf of the ATLAS and CMS collaborations



ICHEP16
Chicago, IL, 3 – 10 August 2016

- overview
- jet properties in dijet events
- inclusive jet cross sections
- heavy flavour jets



overview

- measurements probing properties of jets:
- **test Monte Carlo (MC) generator predictions**
 - fragmentation, hadronisation
- **test fixed order perturbative QCD calculations**
- **provide constraints on proton parton distribution functions (PDFs) and the strong coupling α_s**
- overview of most recent ATLAS and CMS jet measurements:
- **charged particle multiplicity in jets**
- **jet charge**
- **inclusive jet cross sections**
- **heavy flavour dijets**

(see also talk on ‘Multijets at the LHC’, Hans Van Haevermaet)

ATLAS and CMS jet property measurements in dijets



charged particle multiplicity inside jets

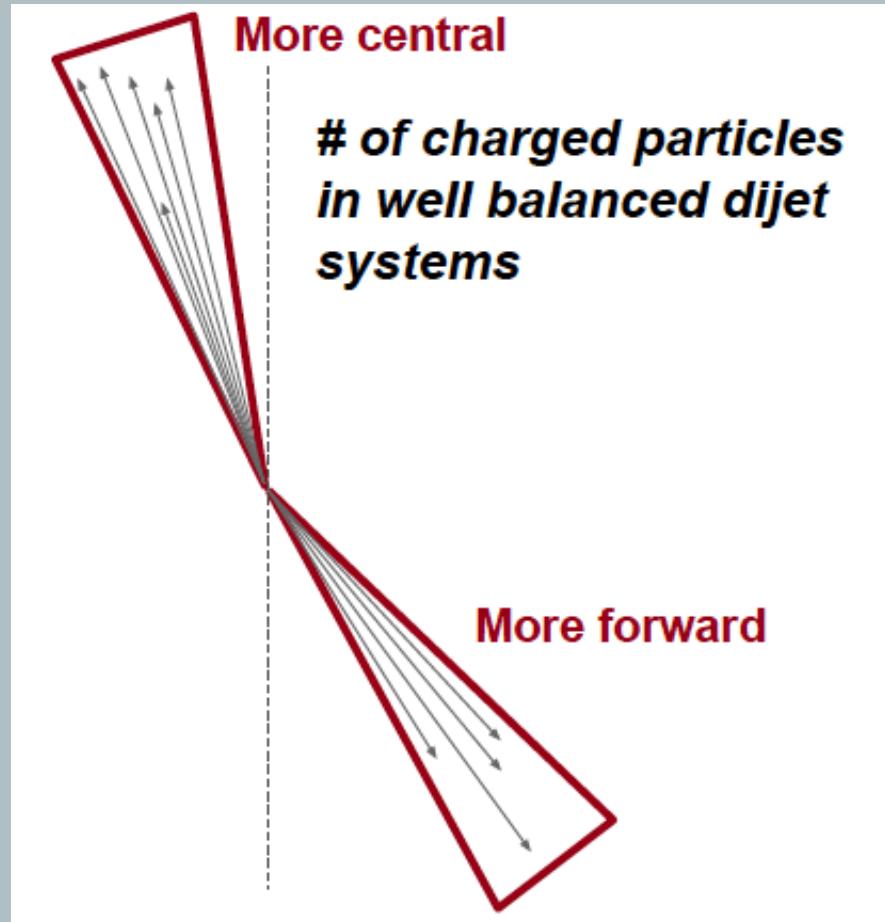
charged particles in jet:

- sensitive to flavour of jet (quark or gluon)
- sensitive to **fragmentation** model
- previous studies show **significant differences** between data and MC



arXiv:1602.00988

- well balanced dijet events
 $\text{pt} > 50 \text{ GeV}$, $|\eta| < 2.1$, $\frac{\text{pt1}}{\text{pt2}} < 1.5$
- classify jets as more **forward** or more **central**
(exploit rapidity dependence of jet type)
- count tracks: $\text{pt} > 500 \text{ MeV}$, $|\eta| < 2.5$



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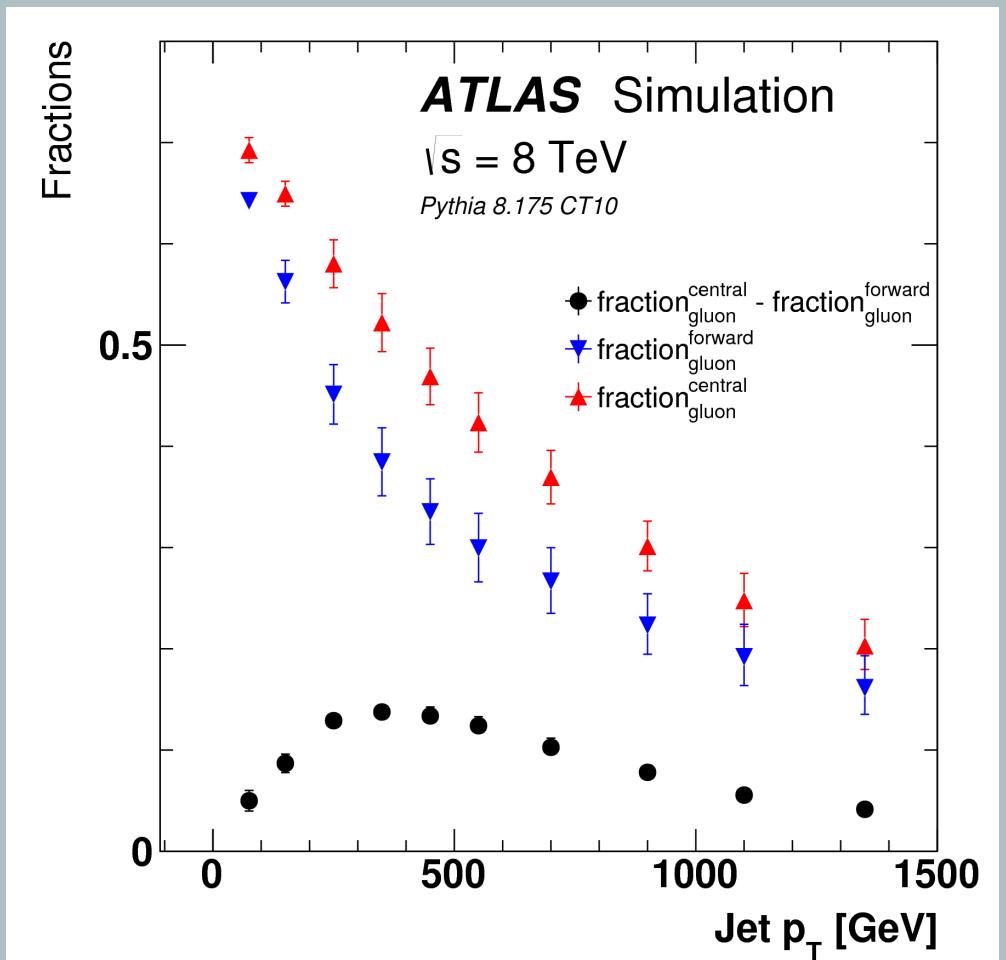
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forward jets less likely to be gluon-initiated

charged particle multiplicity inside jets

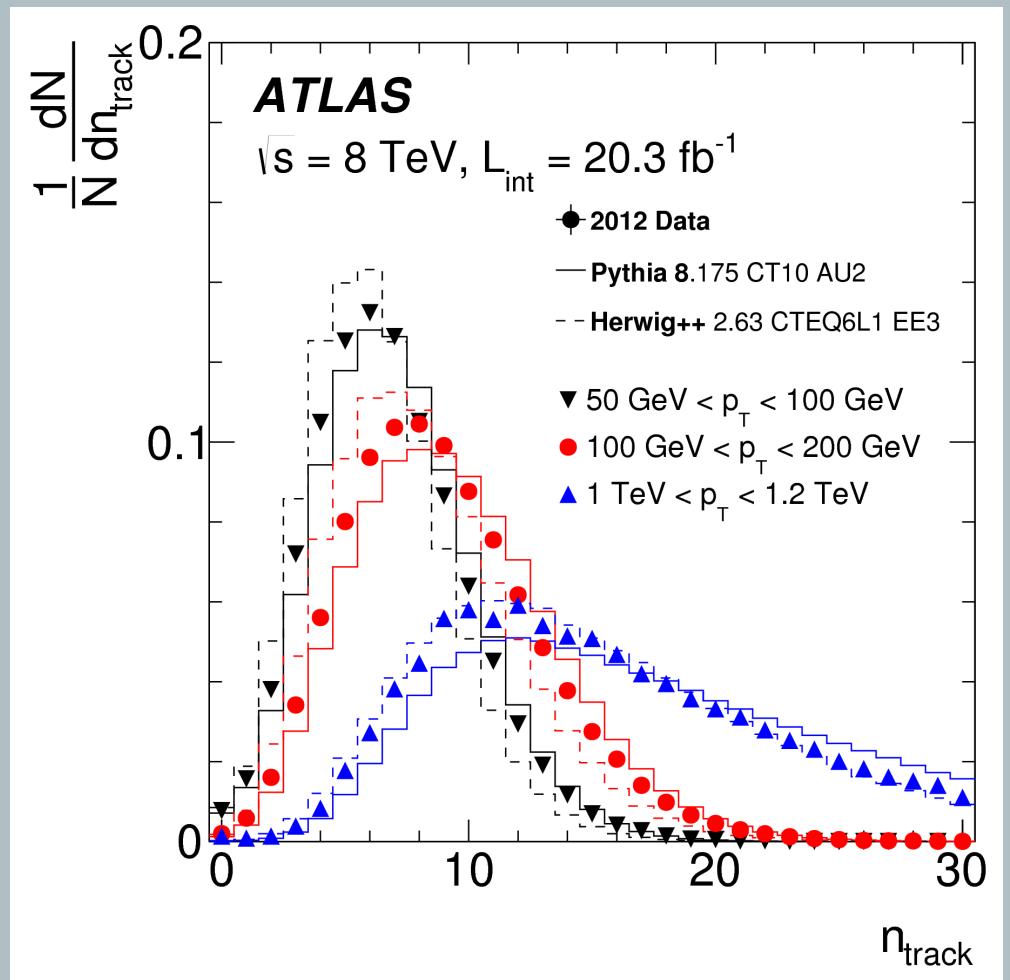
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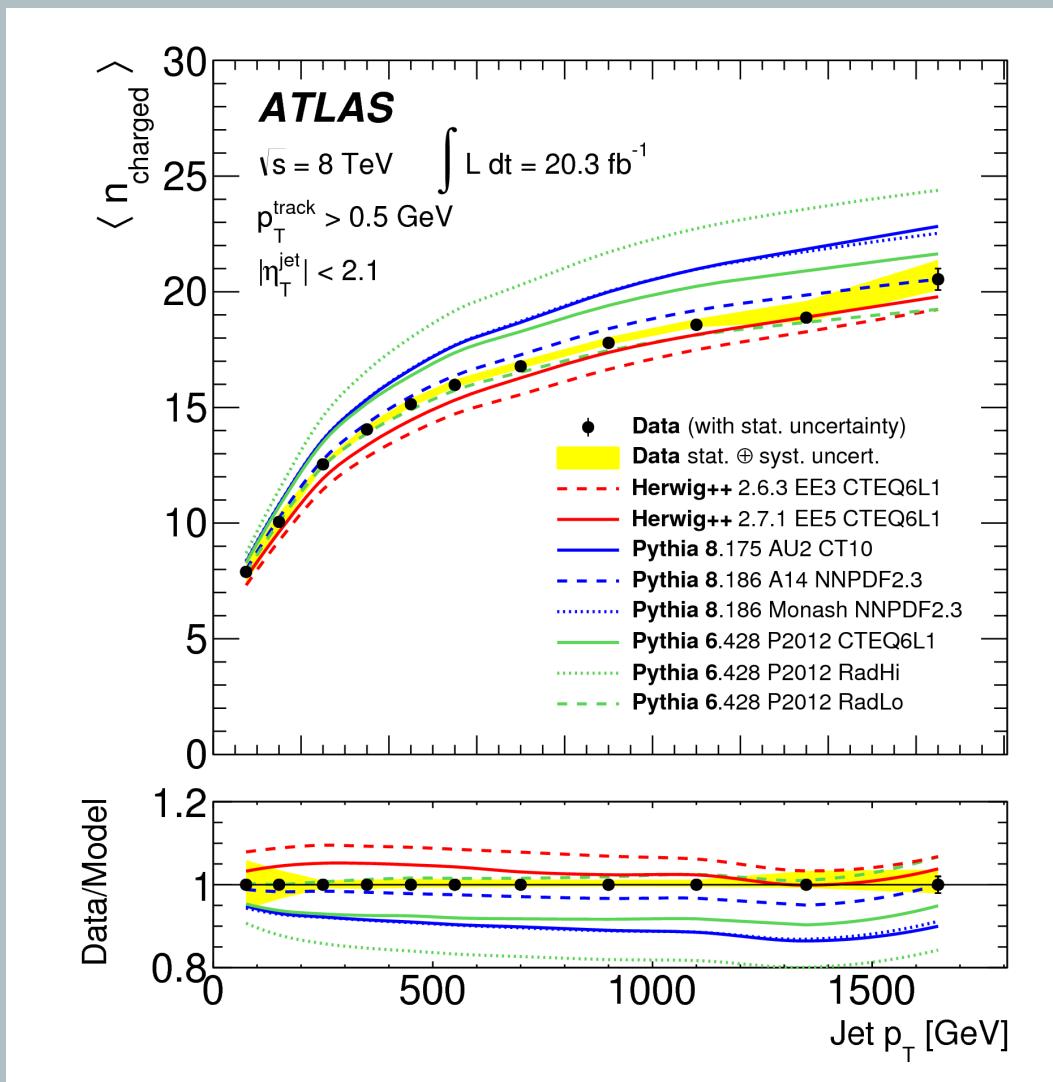


charged particle multiplicity inside jets



arXiv:1602.00988

- unfold average multiplicity to particle level in similar fiducial region
- comparison with several MCs with different fragmentation models
- PYTHIA6 Perugia2012 RadLo gives best overall description
- value of α_s governing amount of FSR has large impact on predictions



A14: ATLAS default tune for Run2
(α_s governing FSR 10% lower in A14 than in Monash)

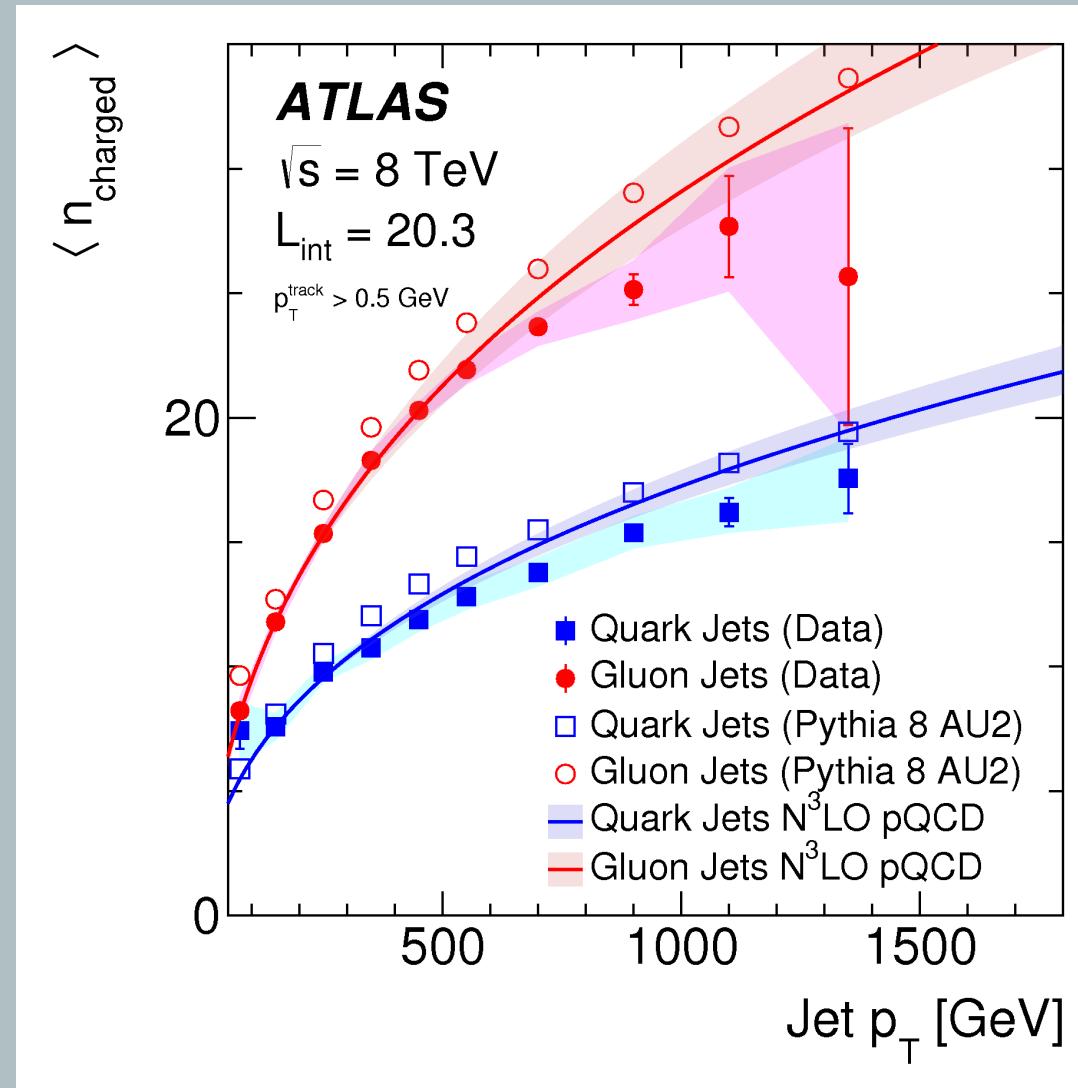
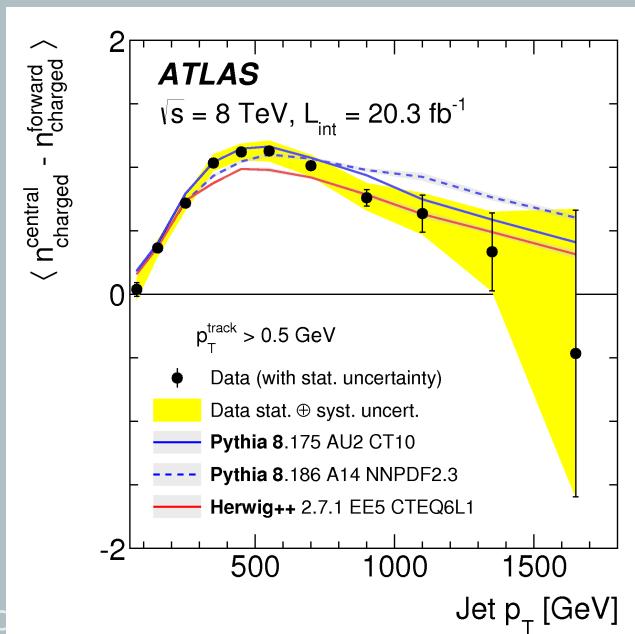
charged particle multiplicity inside jets



arXiv:1602.00988

- average charged multiplicity for quarks and gluon jets extracted

$$\langle n_{\text{charged}}^f \rangle = f_q^f \langle n_{\text{charged}}^q \rangle + f_g^f \langle n_{\text{charged}}^g \rangle$$
$$\langle n_{\text{charged}}^c \rangle = f_q^c \langle n_{\text{charged}}^q \rangle + f_g^c \langle n_{\text{charged}}^g \rangle.$$



jet charge in dijet events



- can also consider **jet charge**
- based on momentum weighted sum of charges of tracks associated with jet
- **good flavour discriminant; probes PDFs and fragmentation**

$$Q_J = \frac{1}{(p_{TJ})^\kappa} \sum_{i \in \text{Tracks}} q_i \times (p_{T,i})^\kappa$$

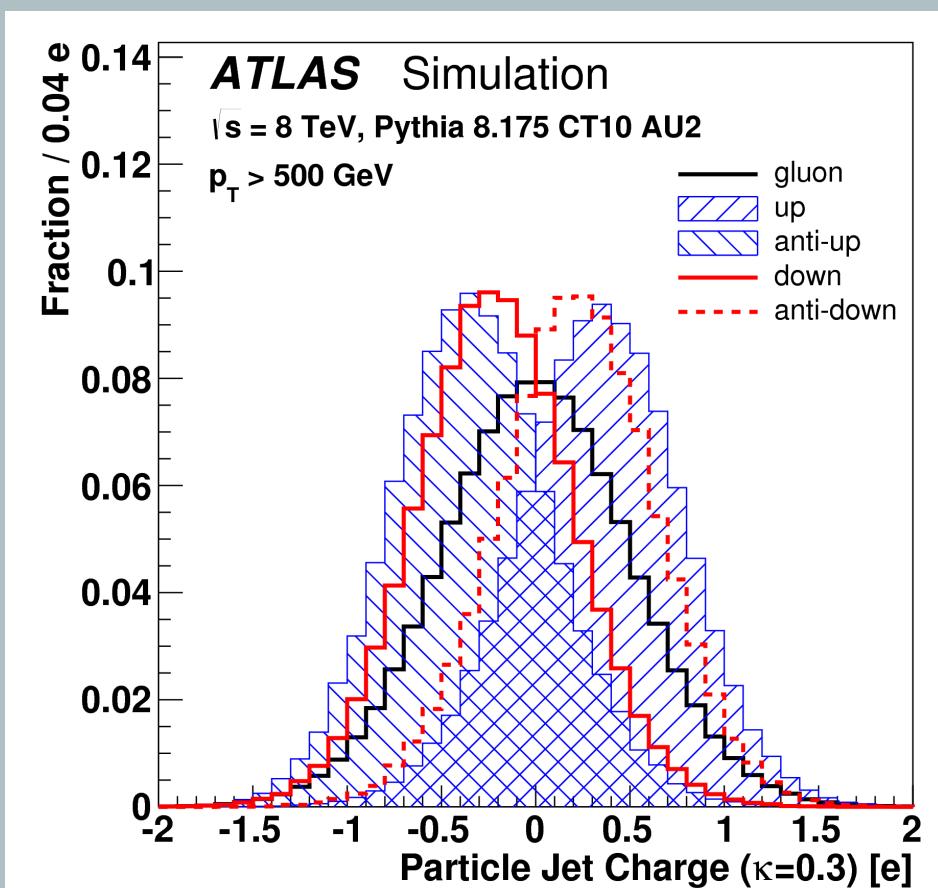
K changes sensitivity to soft radiation
(higher K \equiv the more high pt tracks contribute)

ATLAS: arXiv:1509.05190

same selection as for # charged particles in jets;
**jet charge measured for more central and
more forward jets separately**

CMS: CMS PAS SMP-15-003

$p_T > 400 \text{ GeV}$, $p_T > 100 \text{ GeV}$, $|\eta| < 2.1$
jet charge measured for leading jet



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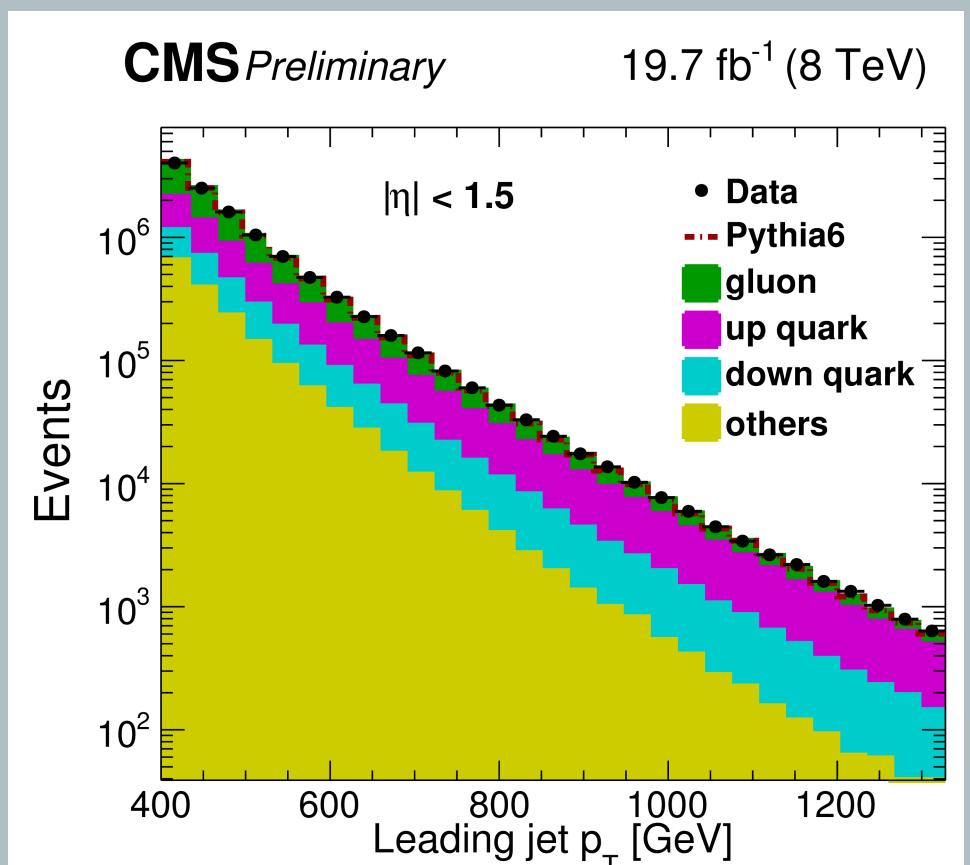
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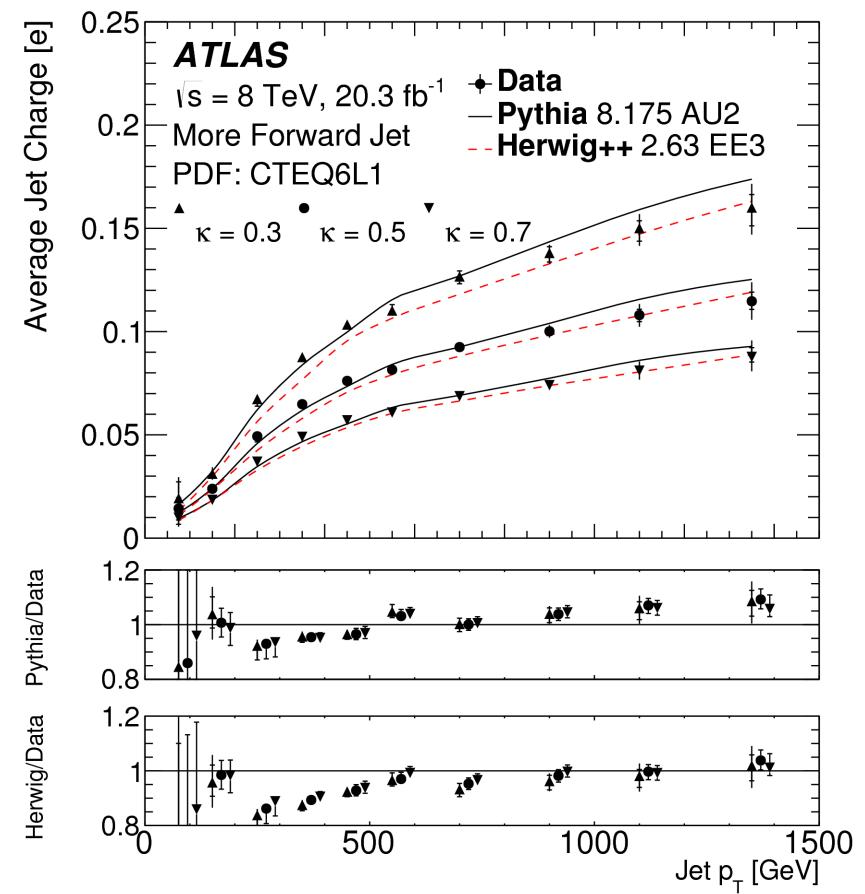
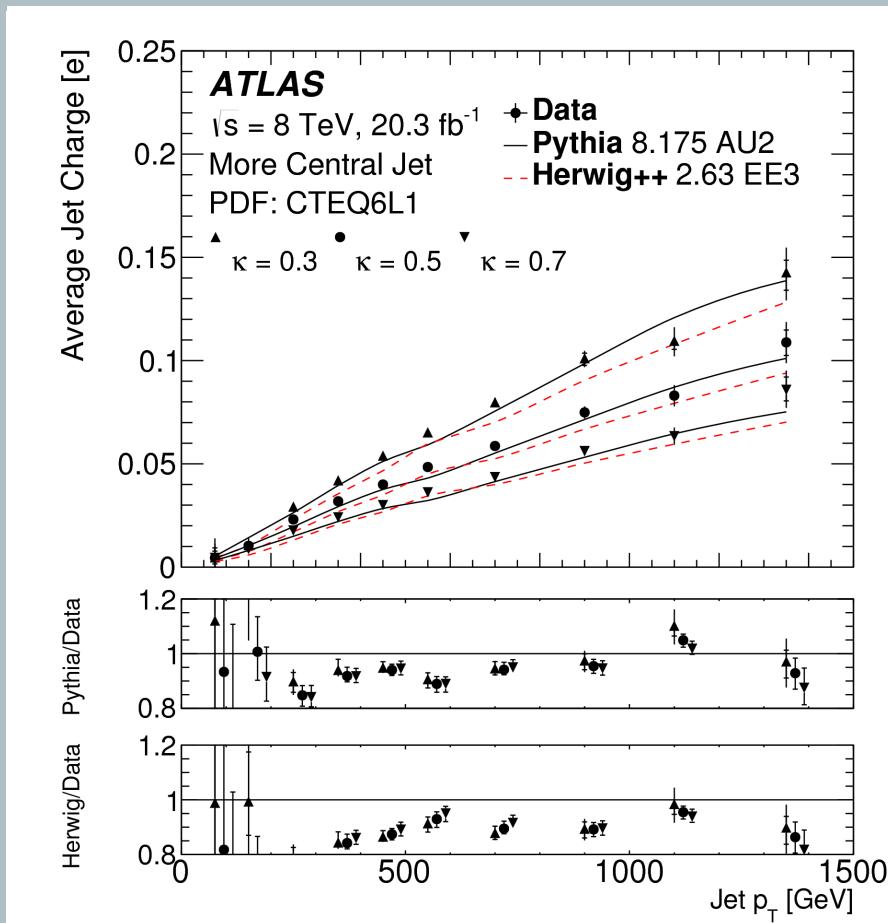
(flavour composition varied by exploiting **rapidity** (ATLAS) or **pt** (CMS) dependence of jet type)

jet charge in dijet events



- **average jet charge distribution corrected to particle level**
- more forward jets less likely to be associated with gluon
- comparison with LO MCs

arXiv:1509.05190

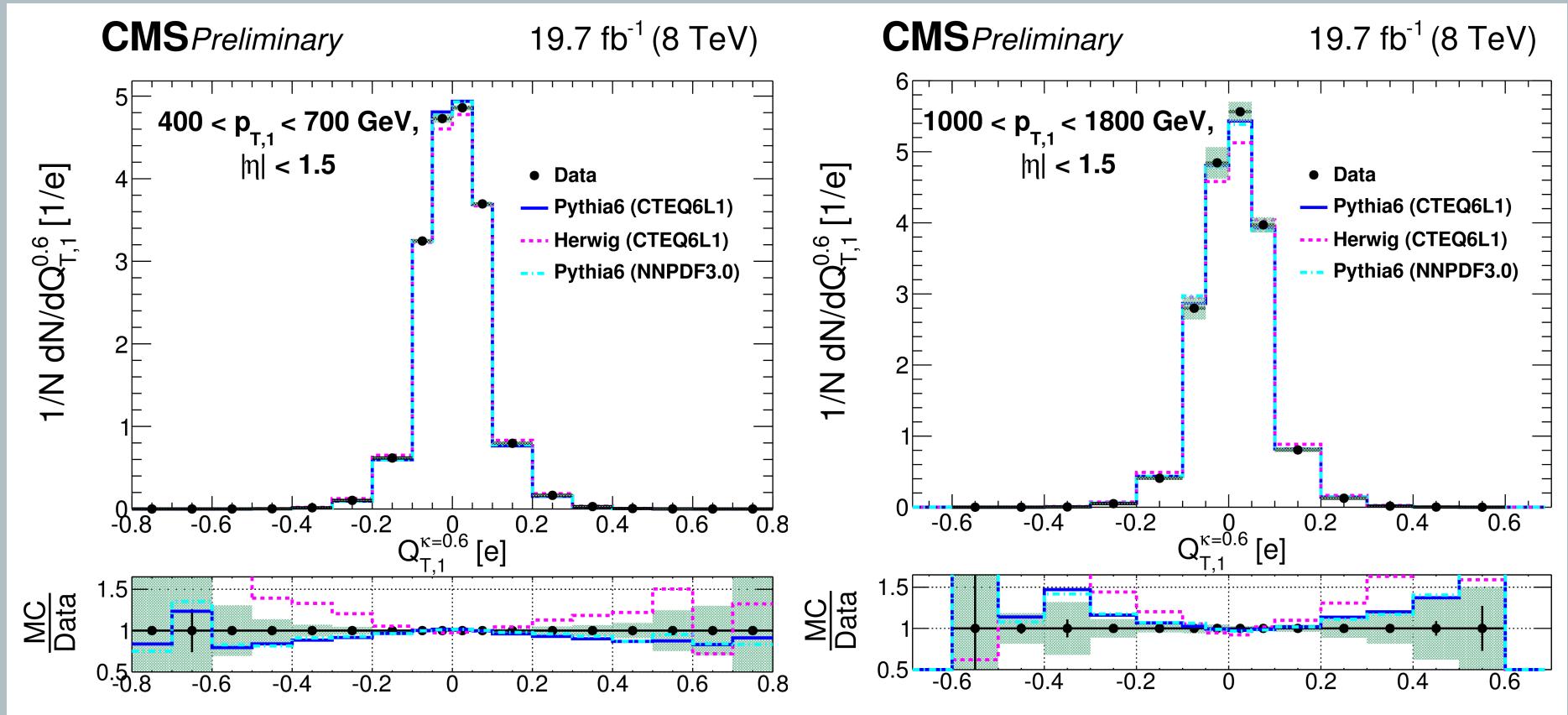


jet charge in dijet events



- CMS additionally measured two related jet charge observables using momentum of tracks parallel (Q_L) and perpendicular (Q_T) to jet axis
- Q_T especially sensitive; fragmentation model more important than PDF choice

CMS PAS SMP-15-003



gluon contribution decreases at higher leading jet pt ➡

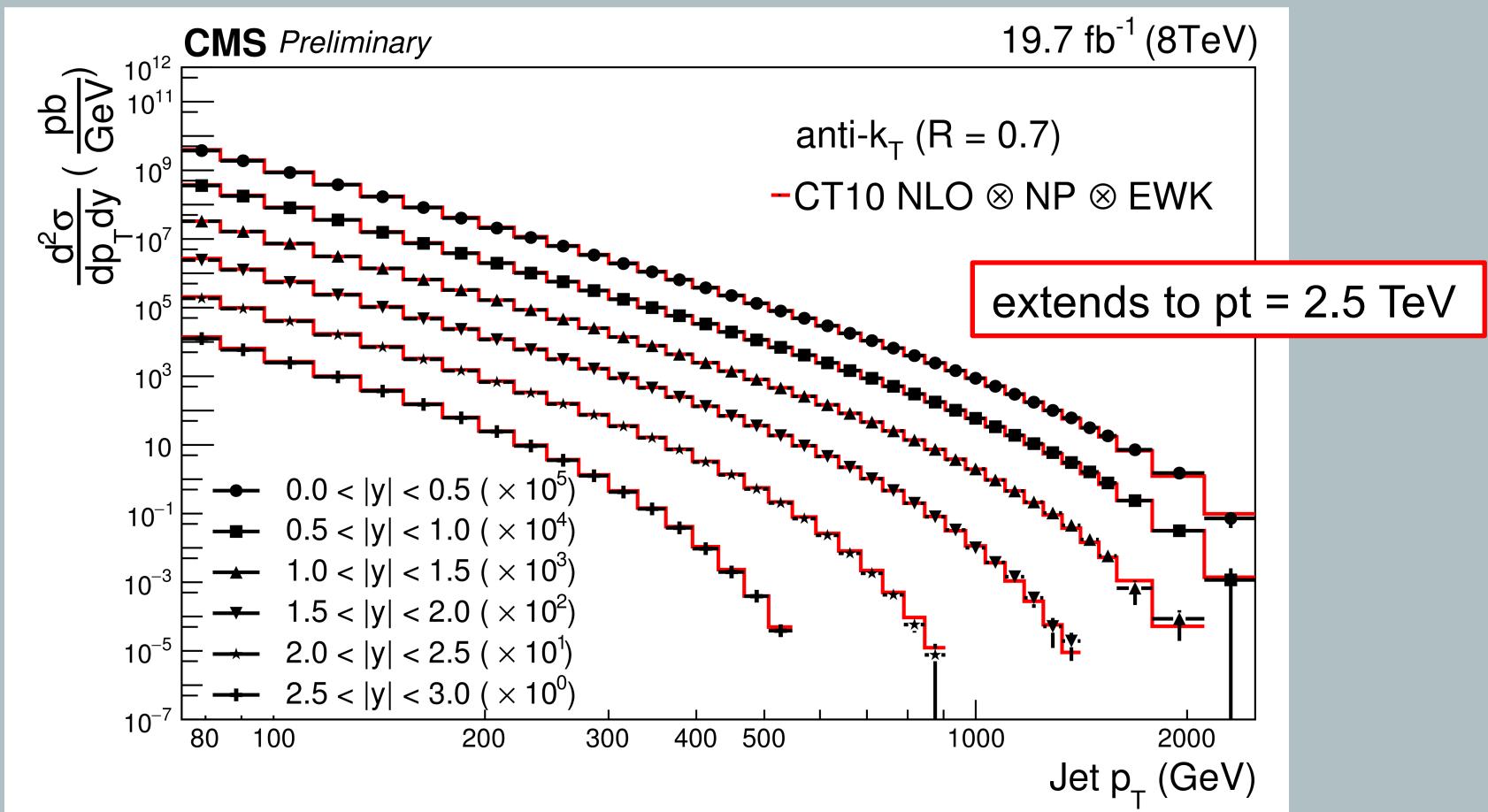
ATLAS and CMS inclusive jet and heavy flavour dijet cross sections



inclusive jet cross sections @ 8TeV



- double differential cross section in p_T and y CMS PAS SMP-14-001
- NLO QCD calculation (NLOJet++) corrected for non-perturbative (NP) and electroweak (EWK) effects; **data well described**

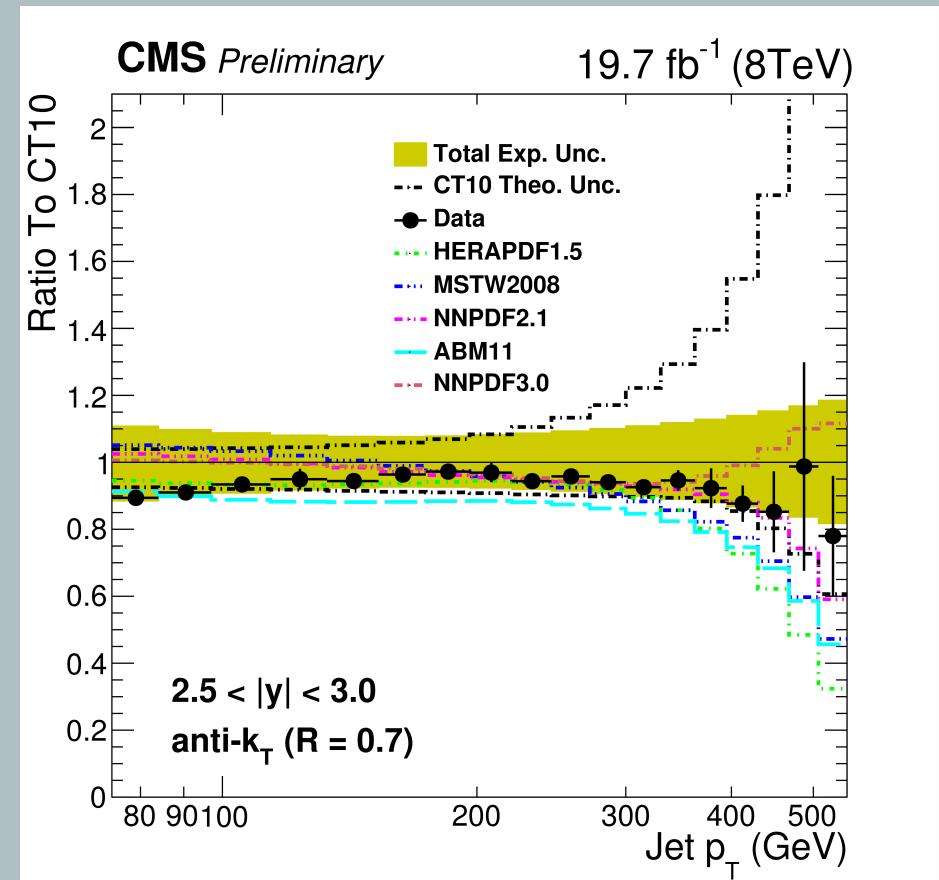
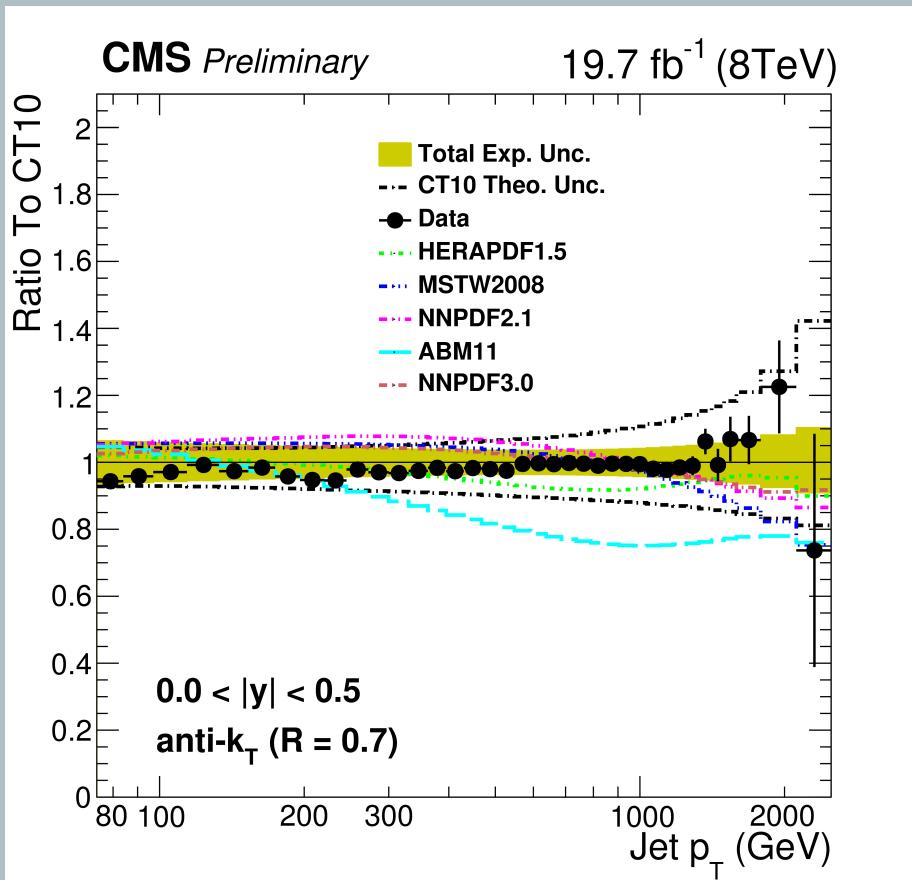


inclusive jet cross sections @ 8TeV



- comparison with **NLO QCD** using several PDFs
(two representative rapidity bins shown)

CMS PAS SMP-14-001

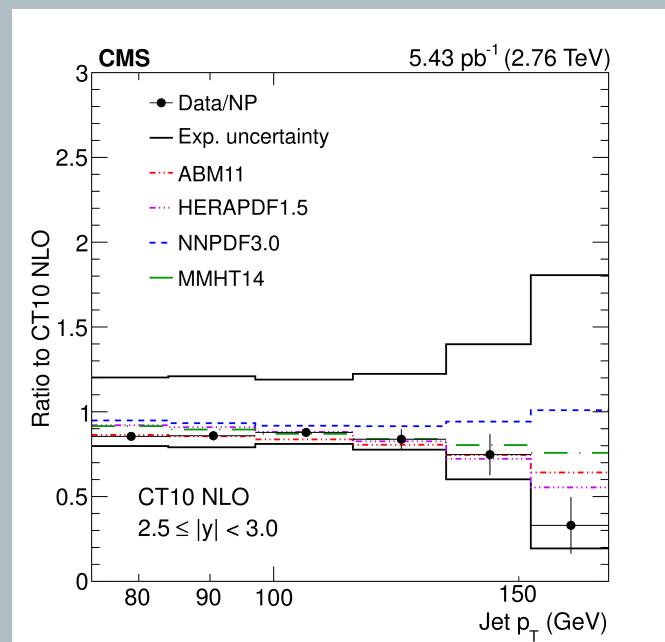
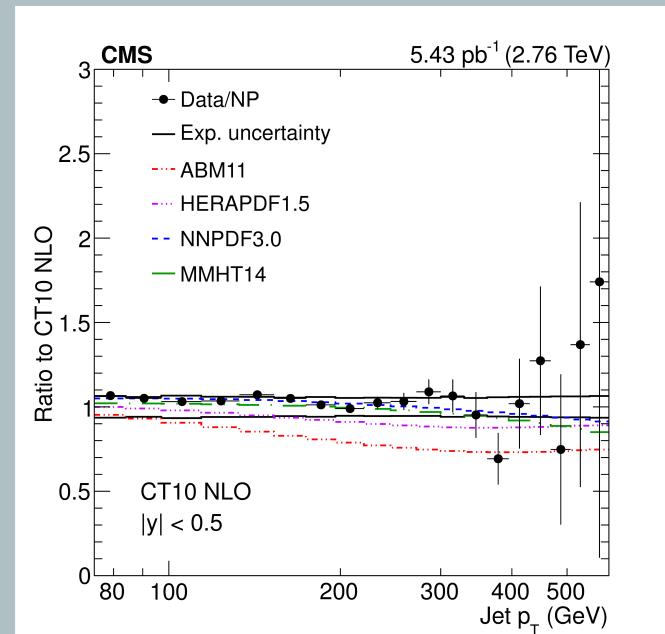
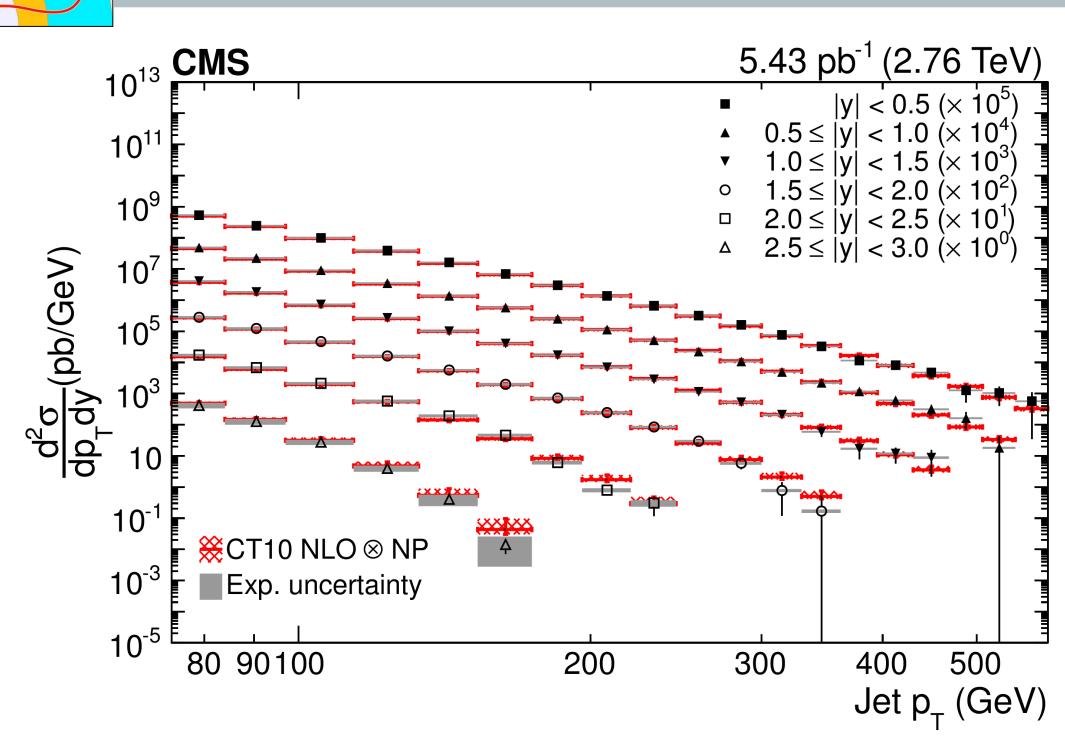


inclusive jet cross sections @ 2.76TeV

- also measured at $\sqrt{s}=2.76$ TeV
- anti- k_T 0.7, p_T range up to 592 GeV
- good description by **NLO QCD**



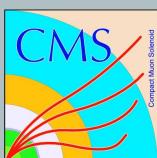
arXiv:1512.06212



inclusive jet cross section ratio 2.76/8 TeV

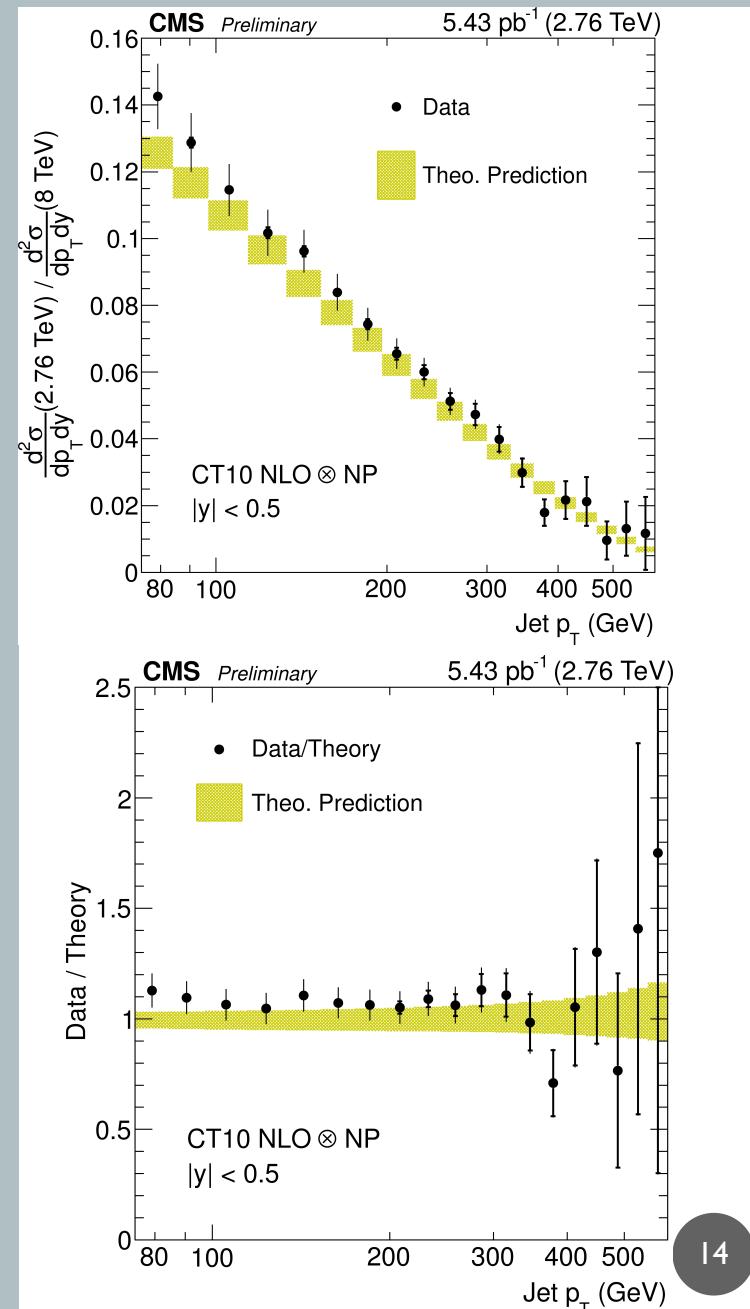
- careful study of uncertainty correlations between 8 and 2.76 TeV measurements
- **partial cancellation of experimental and theory systematics**
- useful for future PDF constraints

(previous proof of principle from ATLAS 2.76/7 TeV ratio [EPJC (2013) 73, 2509])



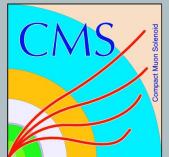
CMS PAS SMP-14-017
(8 TeV data from CMS PAS SMP-12-012)

C. Gwenlan, Jet results from ATLAS and CMS, ICHEP16

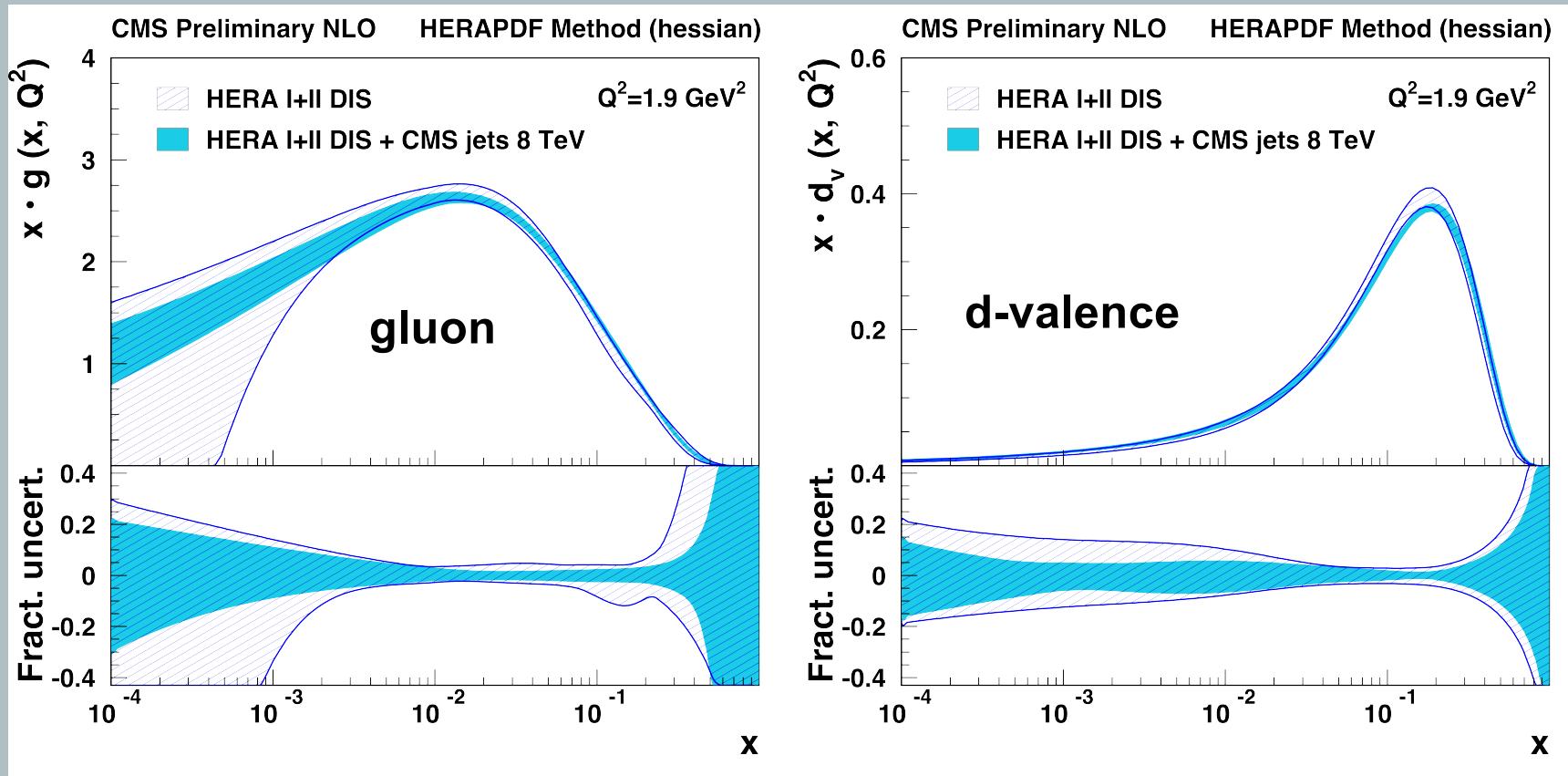


impact of jet measurements on PDFs

- jet cross sections used as input to QCD fits to extract PDFs
- sensitive to gluon and (at high pt) quarks



CMS PAS SMP-14-001

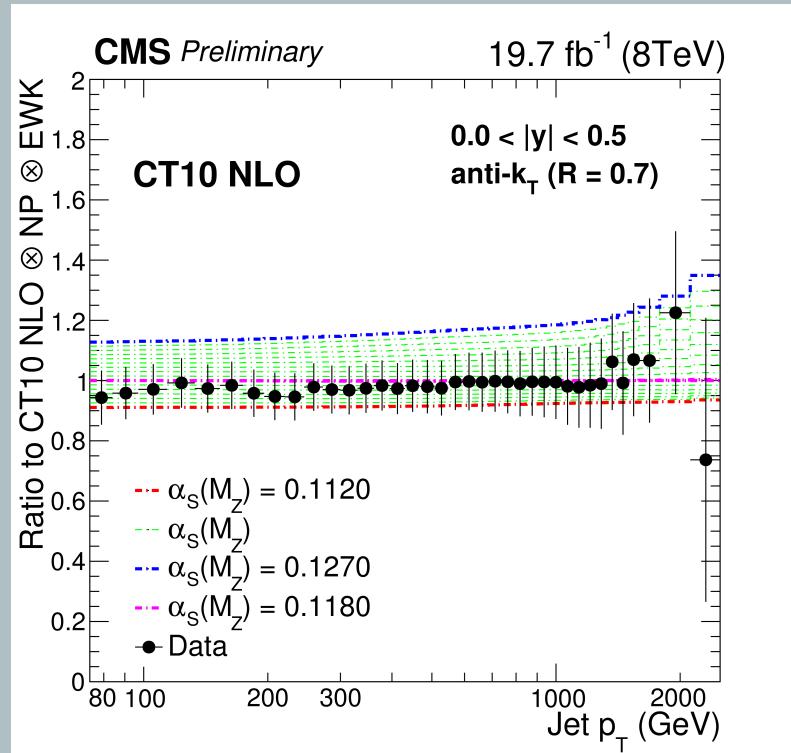


- NLO QCD analysis:** HERA I+II DIS [Eur. Phys. J. C75 (2015) 2604] and CMS inclusive jet cross sections at 8 TeV [CMS PAS SMP-14-001]



strong coupling α_s

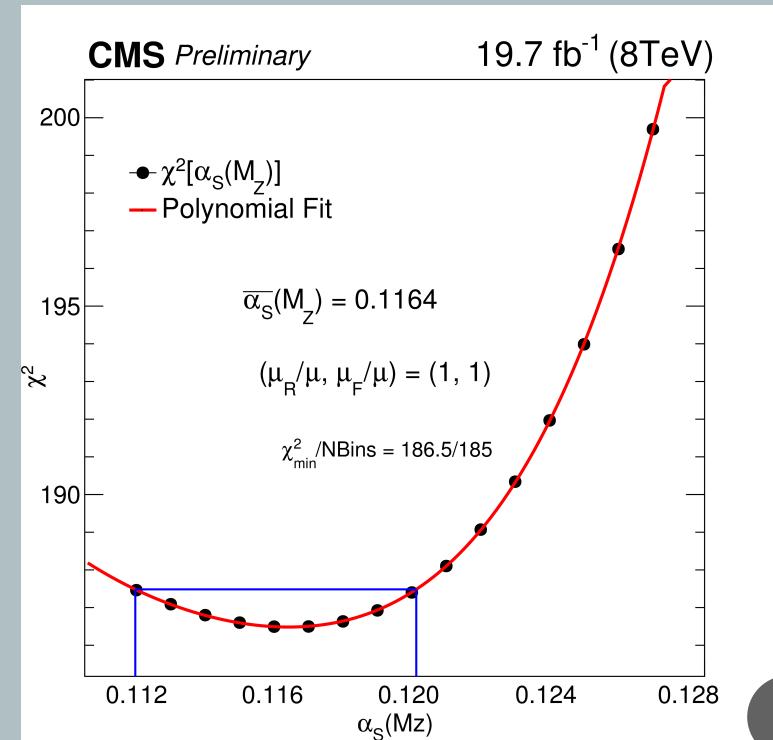
- CMS inclusive jet cross section measurement used to extract α_s
($\sqrt{s} = 8 \text{ TeV}$, $L = 19.7 \text{ fb}^{-1}$, CMS PAS SMP-14-001)



with the CT10 NLO PDF:

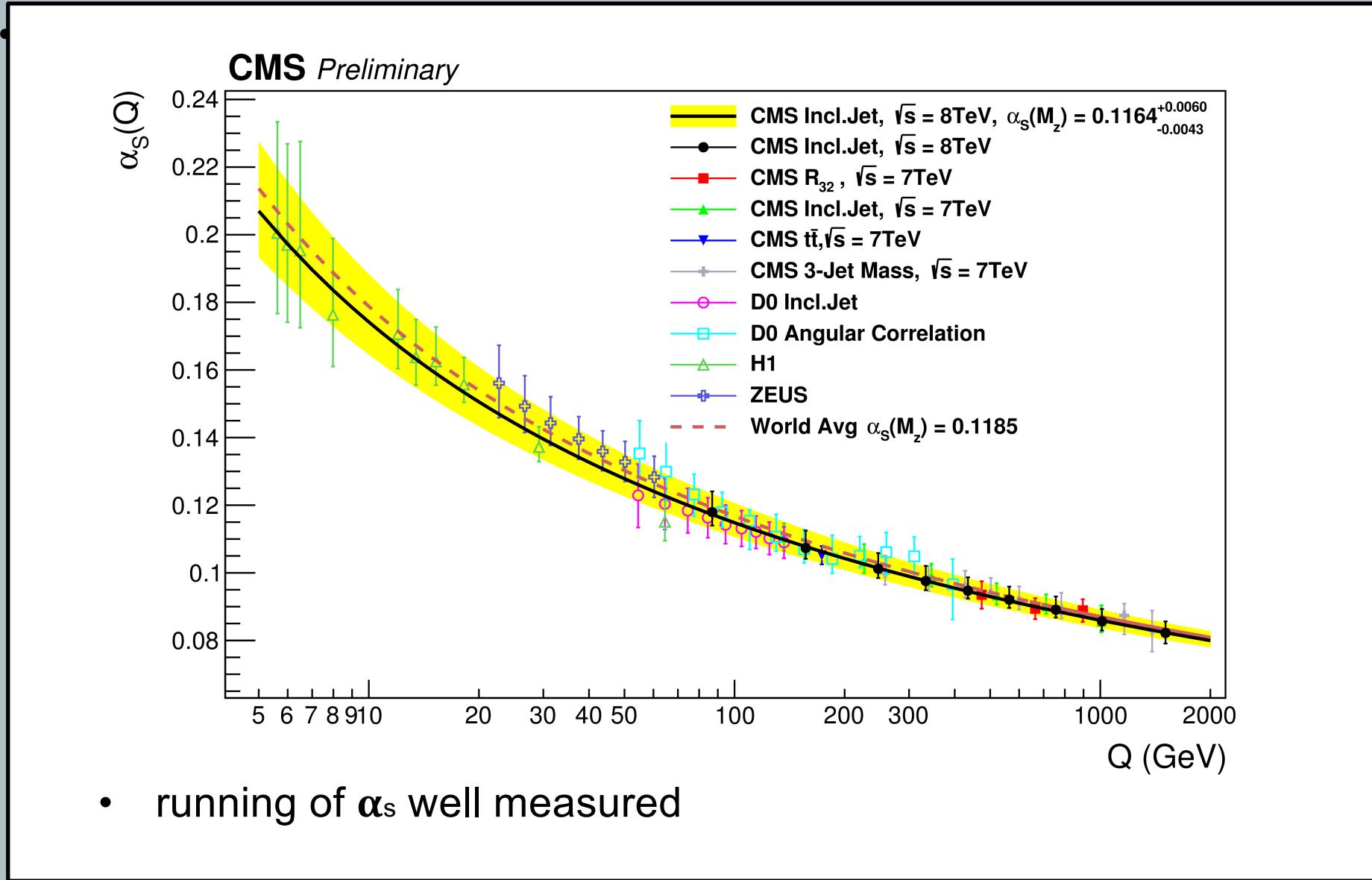
$$\alpha_s(M_Z)(\text{NLO}) = 0.1164^{+0.0025}_{-0.0029}(\text{PDF})^{+0.0053}_{-0.0028}(\text{Scale}) \\ \pm 0.0001(\text{NP})^{+0.0014}_{-0.0015}(\text{Exp}) = 0.1164^{+0.0060}_{-0.0043}$$

theory recomputed with different $\alpha_s(M_Z)$ values
 α_s determined by minimising χ^2 between data and NLO theory, using data from all rapidity bins





strong coupling α_s



$$\pm 0.0001(\text{NP})^{+0.0014}_{-0.0015}(\text{Exp}) = 0.1164^{+0.0060}_{-0.0043}$$

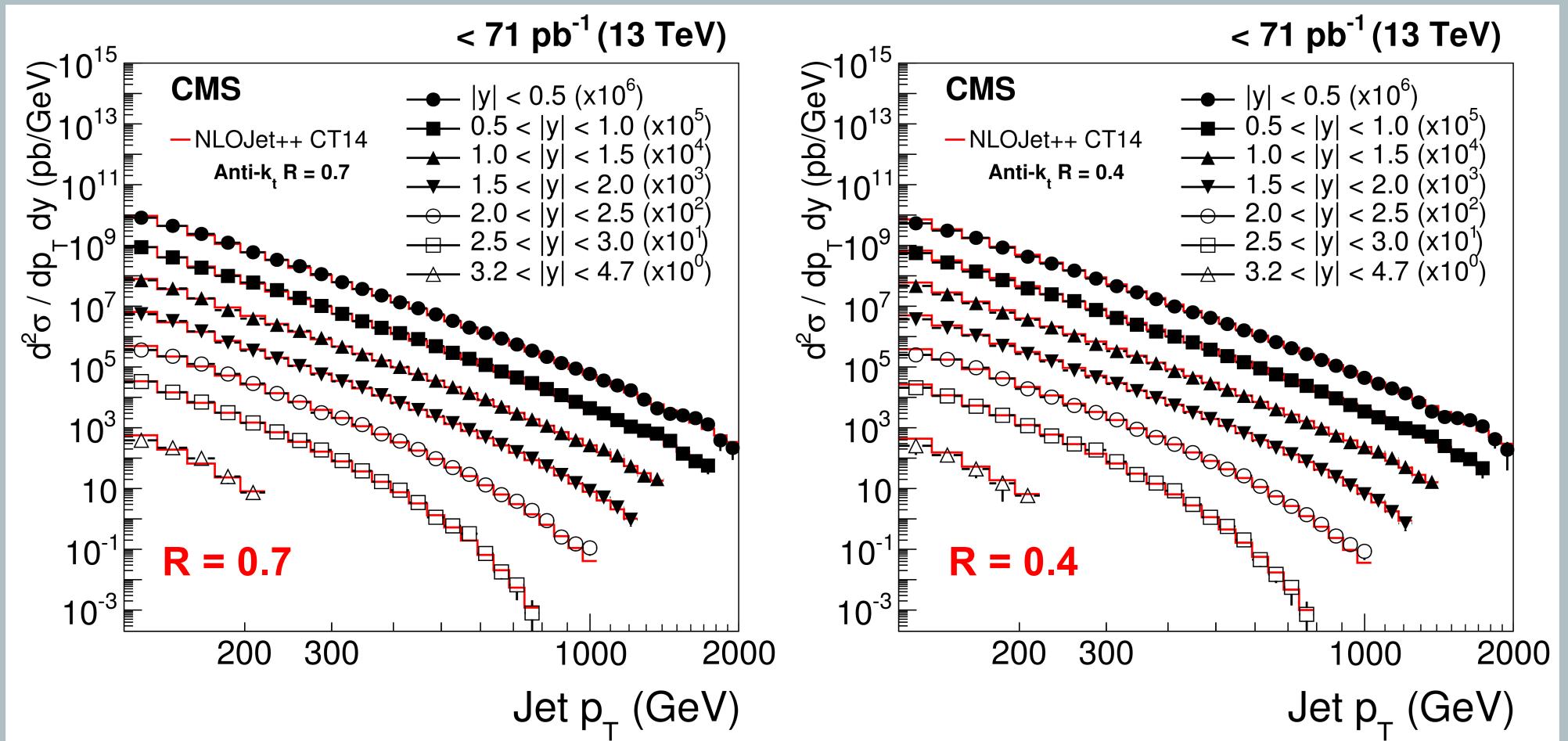
$$0.112 \quad 0.116 \quad 0.120 \quad 0.124$$

$$\alpha_s(M_z)$$

inclusive jet cross sections @ 13 TeV

- inclusive jet measurement at $\sqrt{s} = 13 \text{ TeV}$
- extends to $|y| = 4.7$, $p_T = 2 \text{ TeV}$
- anti- k_T $R=0.4$ and 0.7

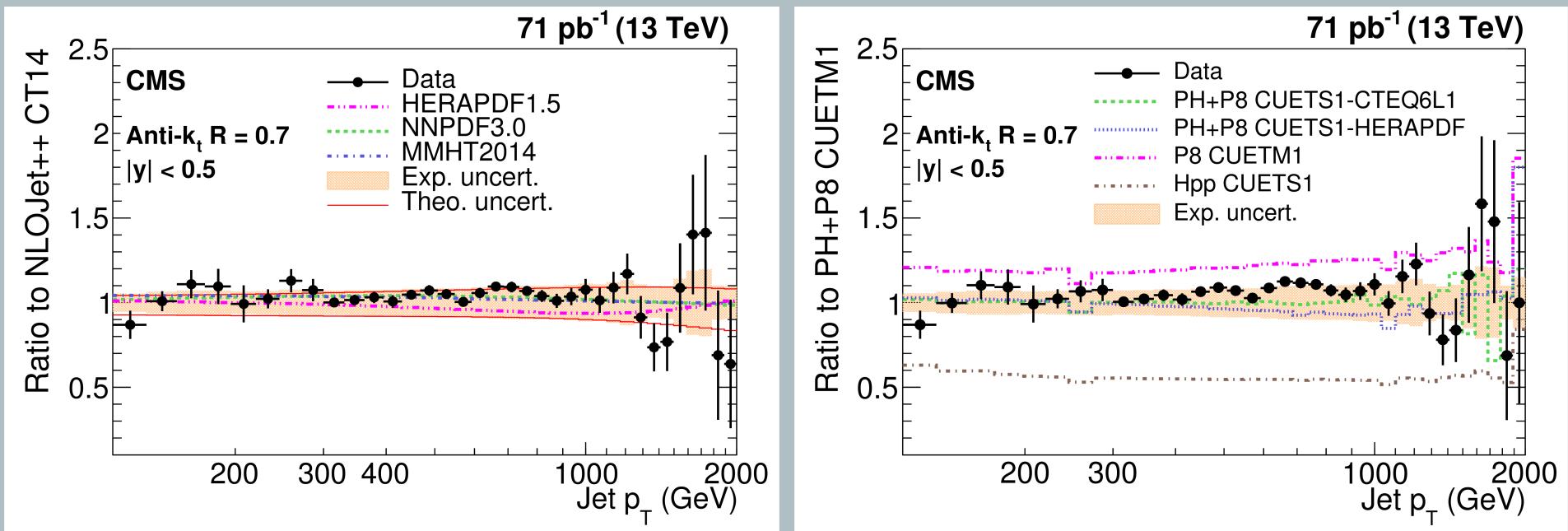
arXiv: 1605.04436



inclusive jet cross sections @ 13 TeV

- compared to predictions from:
- NLO QCD calculation (NLOJET++) corrected for NP and EWK effects
- NLO dijet + PS (Powheg+Pythia8), LO 2→2 MC (Pythia8, Herwig++)

arXiv: 1605.04436

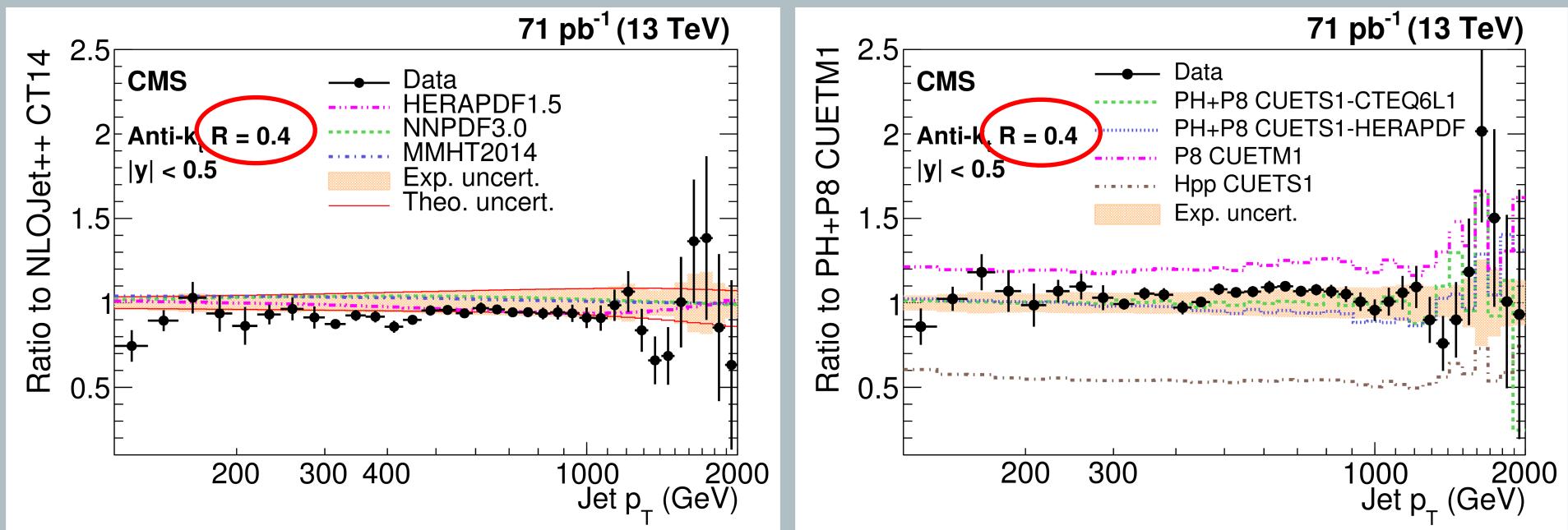


- similar performance from fixed order calcs. (left) and MC (ME+PS) (right)

inclusive jet cross sections @ 13 TeV

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- with smaller cone size, MC generators perform better than fixed order

heavy flavour jets: b-bbar dijets

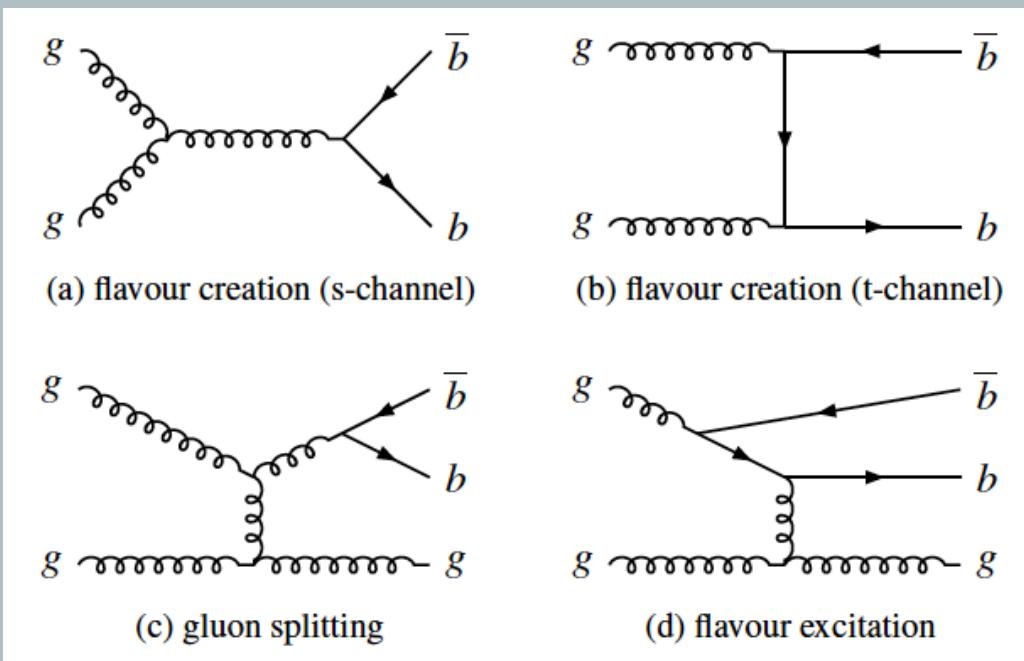
- **b-quark pair production:**
- mixture of production diagrams
- tests QCD heavy flavour calcs.



arXiv:1607.08430

- two jets $\text{pt} > 20 \text{ GeV}$, $|\eta| < 2.5$, both tagged as b-jets
- $\text{pt1} > 270 \text{ GeV}$
enhances gluon splitting and flavour excitation relative to flavour creation c.f. previous analyses
- cross sections differential in several observables: m_{bb} , pt_{bb} , $y_B = \frac{1}{2} |y_1+y_2|$, $y^* = \frac{1}{2} |y_1-y_2|$, $\Delta\Phi$, ΔR

LO Feynman diagrams for b-bbar production

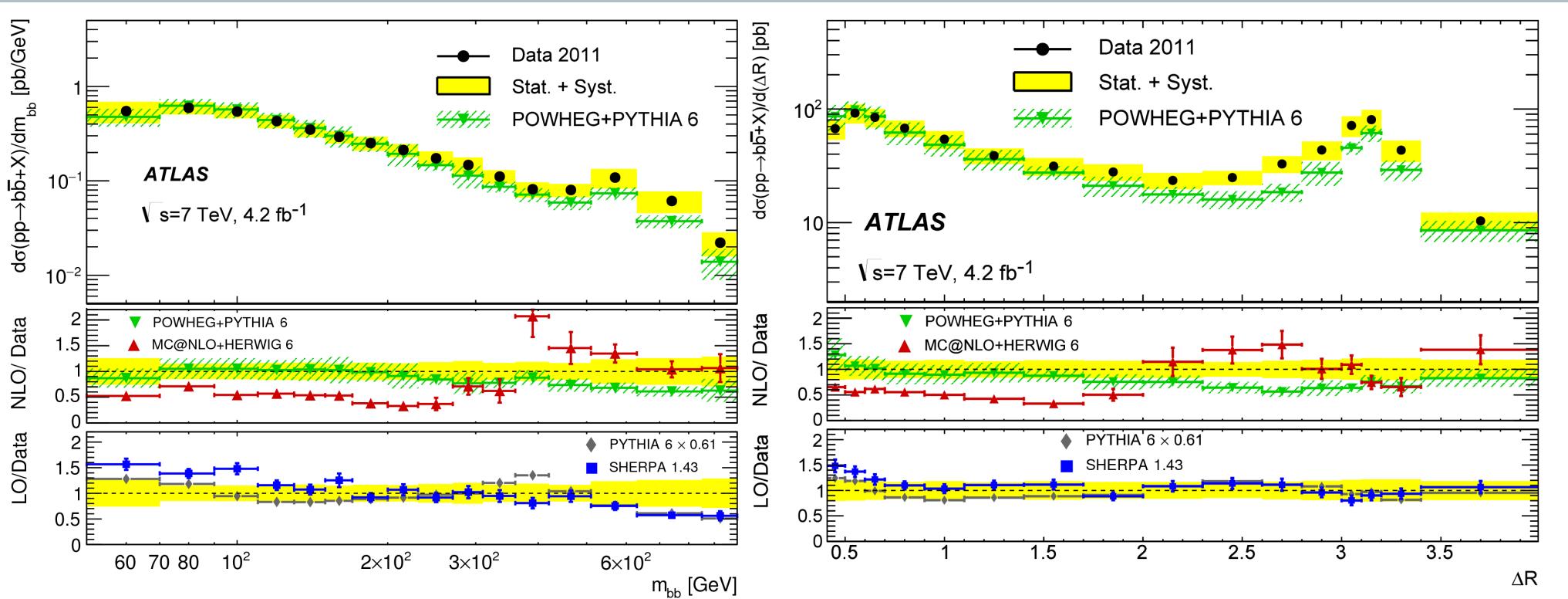


different ranges of measured observables probe different production mechanisms

heavy flavour jets: b-bbar dijets

- compared to LO and NLO MCs
- reasonable agreement with Powheg+PYTHIA6
- MC@NLO shows significant deviations in all variables
- LO MCs generally reproduce shape of data for most observables (though some bins deviate)

arXiv:1607.08430



(significant contribution from flavour creation for $m_{bb} > 550$ GeV and $\Delta R \approx 3$)

summary



- **excellent LHC performance, highly efficient data collection, and a thorough understanding of jet reconstruction and calibration has led to precision jet measurements**
- **ATLAS and CMS have performed wide range of jet measurements** at various collision energies, improving our understanding of QCD
- state-of-the-art MC simulations provide decent description of many **jet properties** (generator, and/or tune dependent)
- **jet cross sections important** for tests of pQCD, as well as for extraction of PDFs and α_s
 - precision measurements now available for medium-to-high p_t
 - entering new regime with $p_t \sim 3$ TeV for first time
 - new $\sqrt{s} = 13$ TeV measurements: **no big surprises so far**
 - theory uncerts. currently dominate (NNLO QCD inclusive and dijet calcs. on the way)

extras

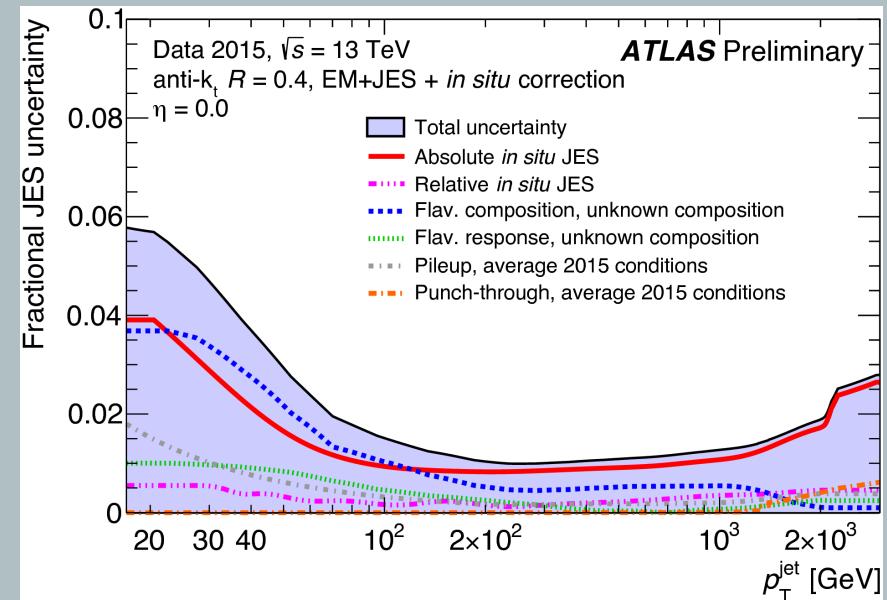


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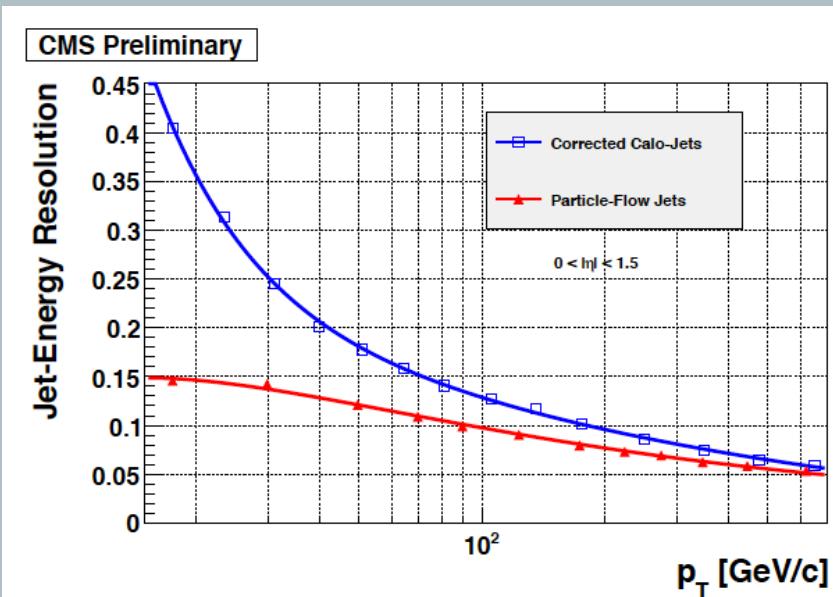
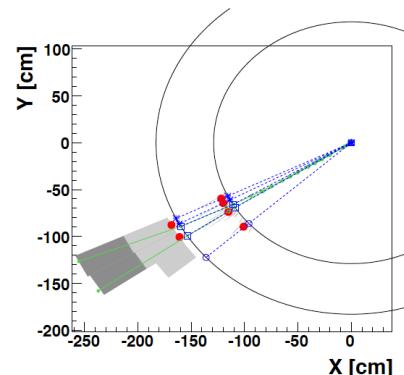
jet reconstruction

- **ATLAS:** merge calo. cells with strong signal over noise into **topoclusters**
- input to jet clustering
- several a posteriori corrections applied to jets: JES O(1%) for intermediate p_T

0	0	0	0	0	0	0	0
0	0	0	2	2	0	0	0
0	0	2	2	2	2	0	0
0	0	2	2	2	2	0	0
0	2	2	4	2	0	0	0
0	0	2	2	2	0	0	0
0	0	0	2	0	0	0	0
0	0	0	0	0	0	0	0



- **CMS:** constituents are **particle flow** objects, from matching tracker information to ECAL and HCAL clusters
- better performance c.f. calo-only jets (CMS PAS PFT-09-001)
- JES 1–3% in 2015 (central region)

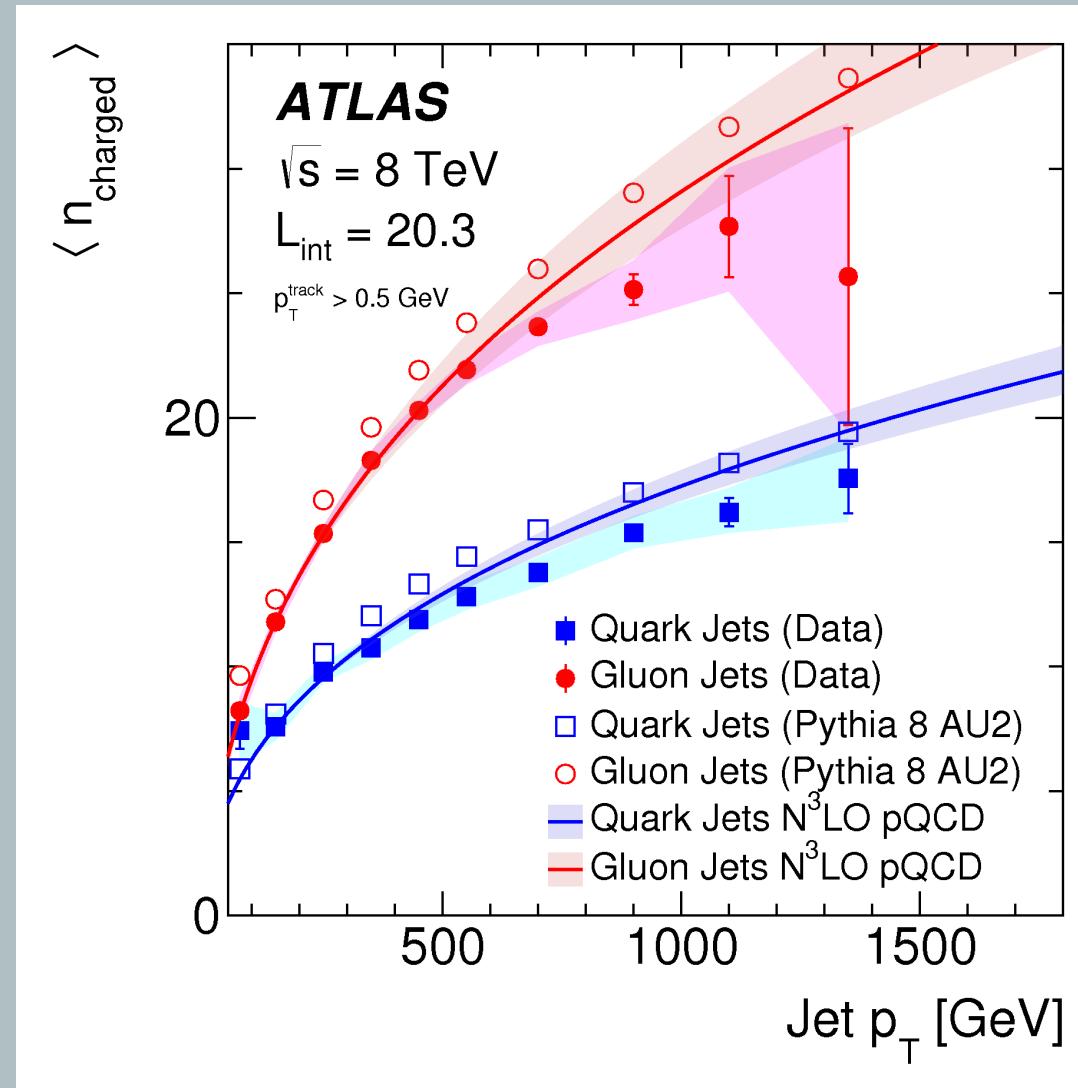


charged particle multiplicity inside jets



arXiv:1602.00988

- average charged multiplicity for quarks and gluon jets extracted based on gluon fraction from Pythia8 with CT10 PDFs, exploiting difference between more **forward** and **central** jets
- comparison with N³LO predictions (good agreement)

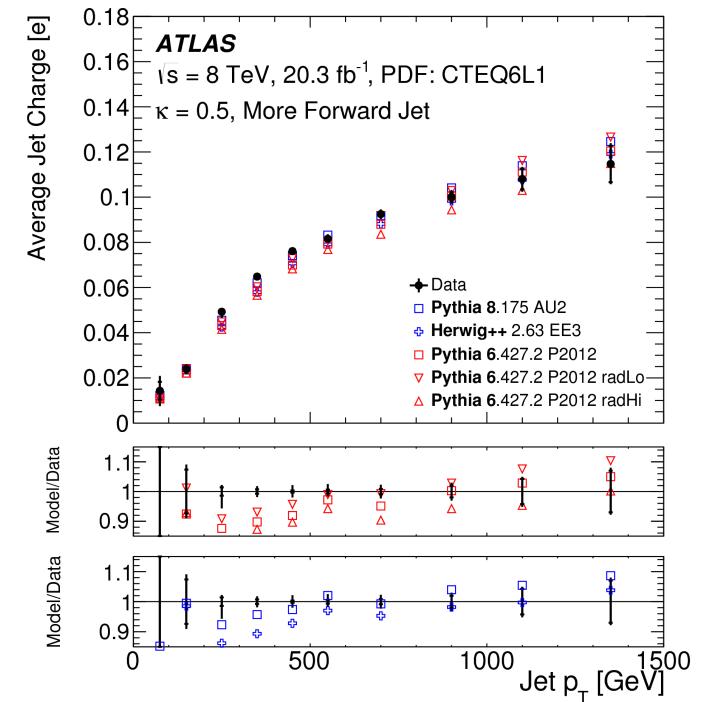
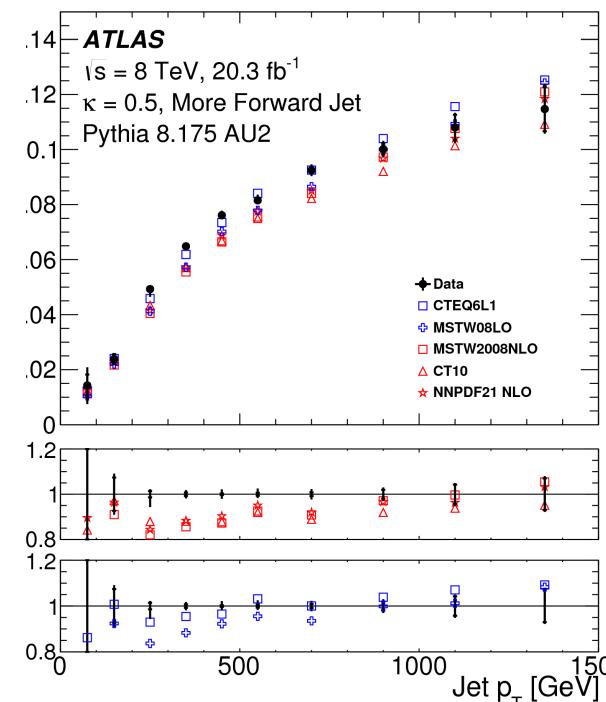
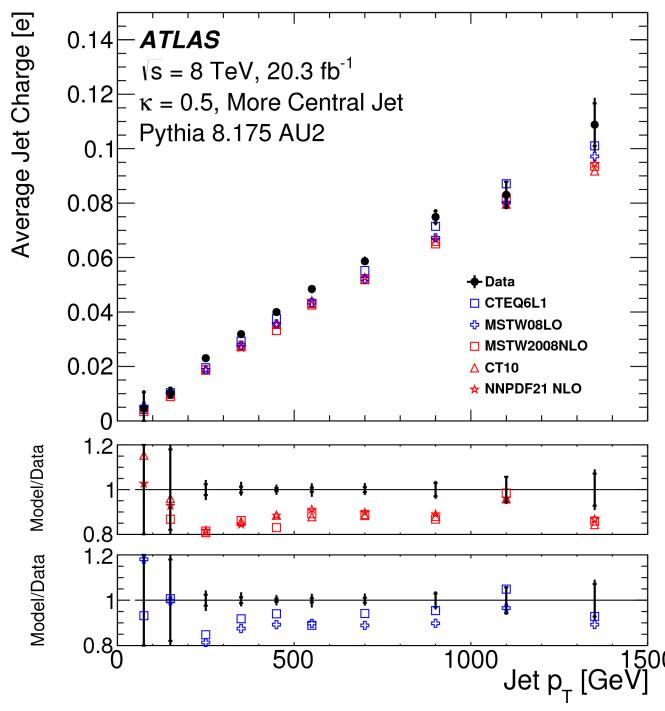


jet charge in dijet events

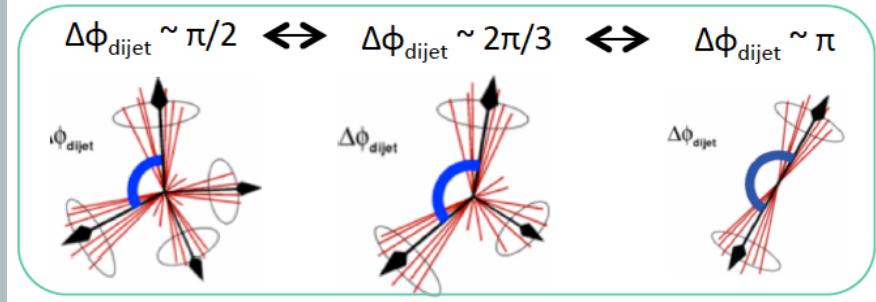


- **average jet charge distribution corrected to particle level**
- more forward jets less likely to be associated with gluon
- comparison with LO MCs with different PDFs and tunes

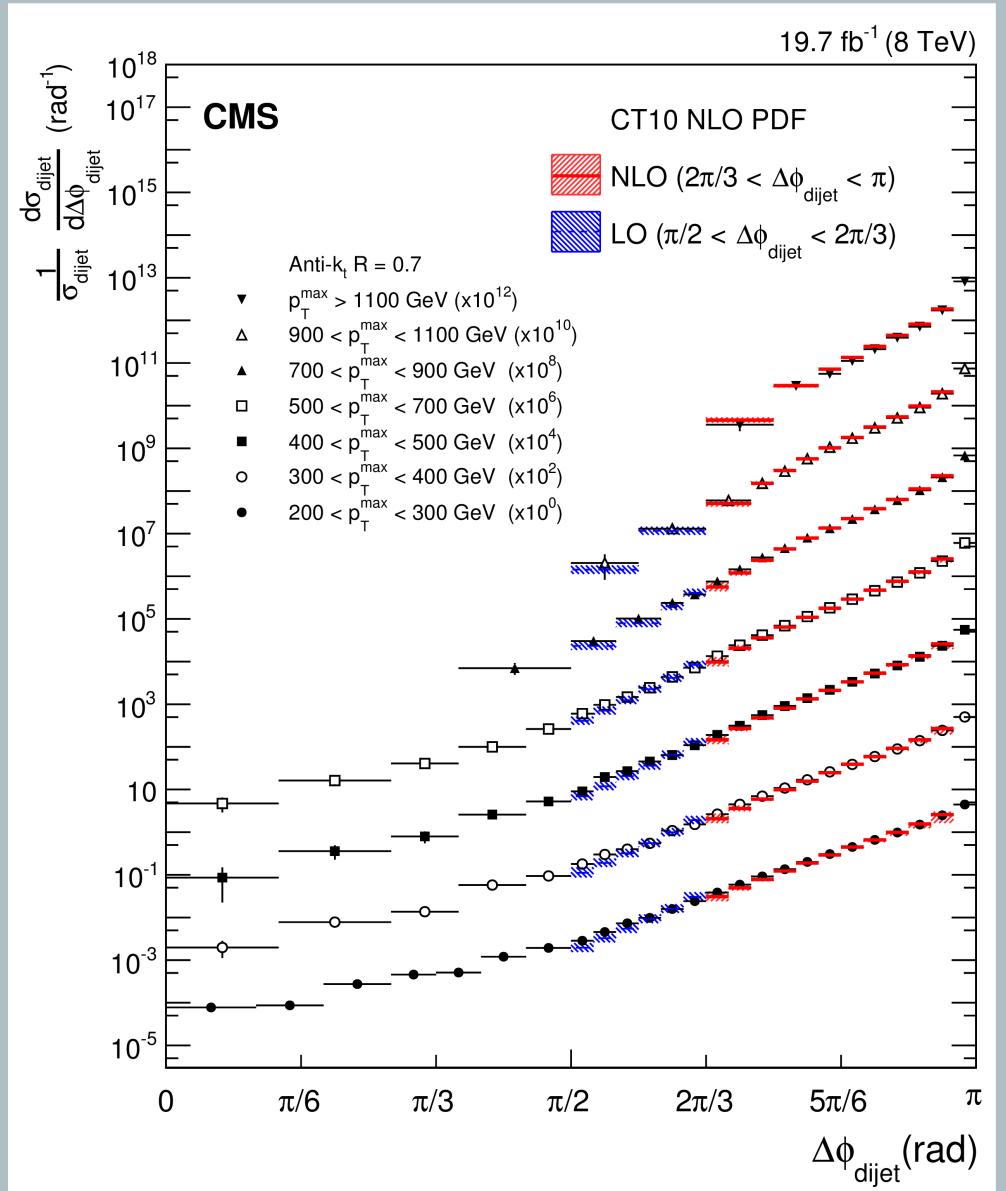
arXiv:1509.05190



dijet azimuthal decorrelations



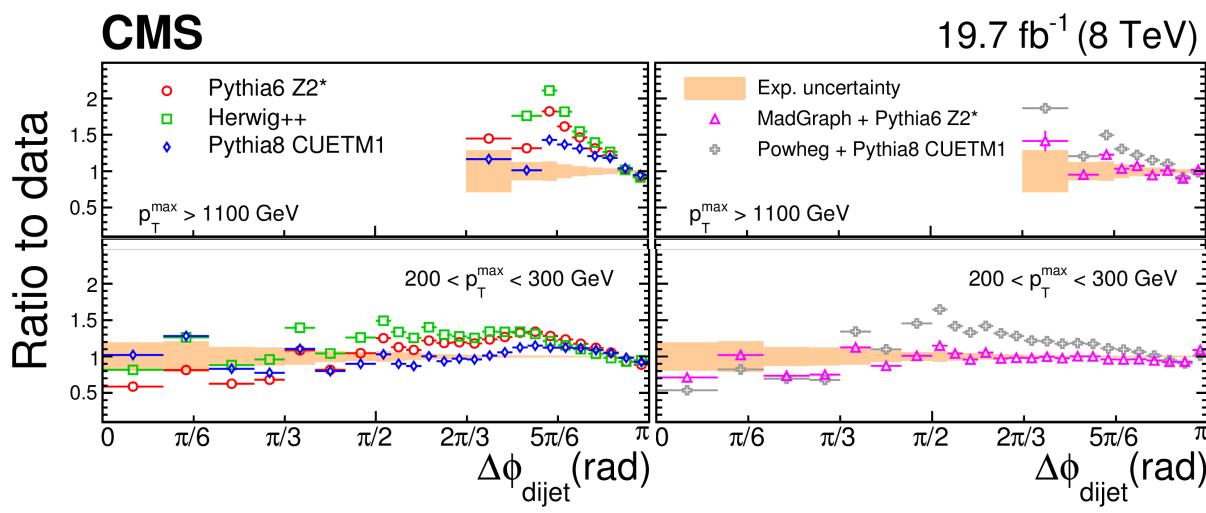
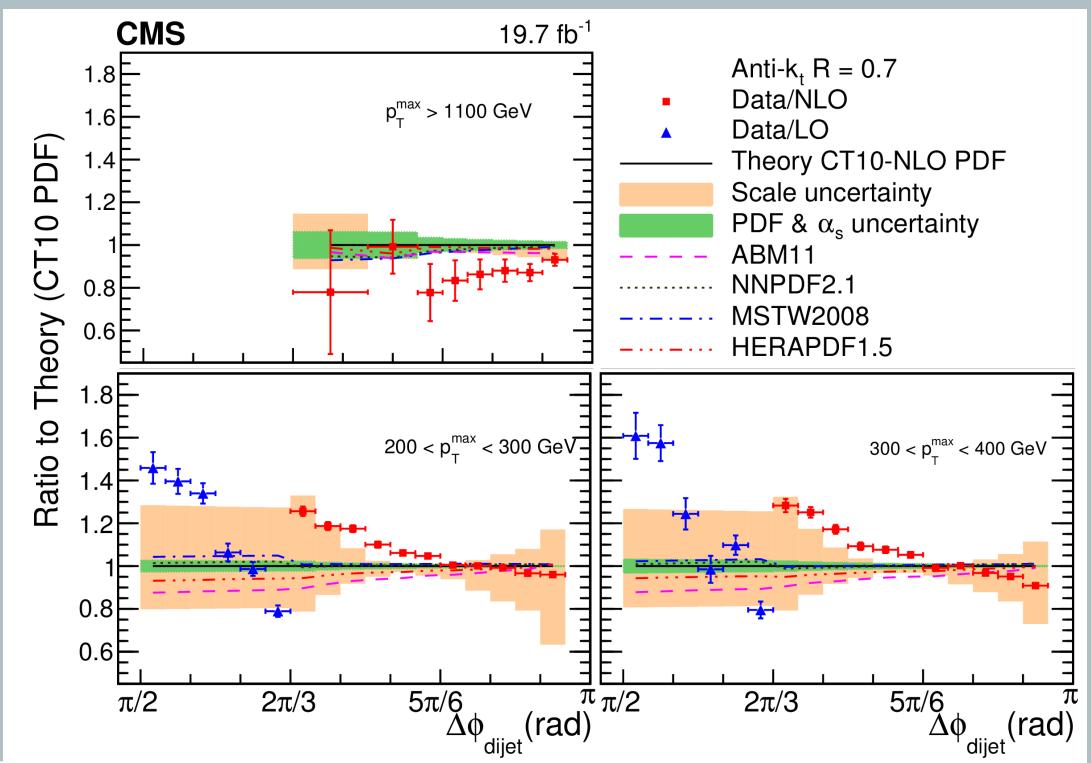
- probe radiation of additional jets by measuring angular separation of two leading jets
- normalised differential cross section as function of
 $\Delta\Phi_{\text{dijet}} = |\Phi_{\text{jet1}} - \Phi_{\text{jet2}}|$
 $(p_T > 100 \text{ GeV}, |y| < 2.5)$
- compared to 3-jet NLO calc.



dijet azimuthal decorrelations

- comparison with various PDF sets
- good agreement with fixed order calc. for $\Delta\Phi_{\text{dijet}} > 5\pi/6$
- deviations at smaller $\Delta\Phi_{\text{dijet}}$

arXiv:1602.04384



- comparison with various MCs (ME matched to PS)
- good description by MadGraph (LO multileg)

inclusive jet cross sections @ 13 TeV

- forward region:

arXiv: 1605.04436

