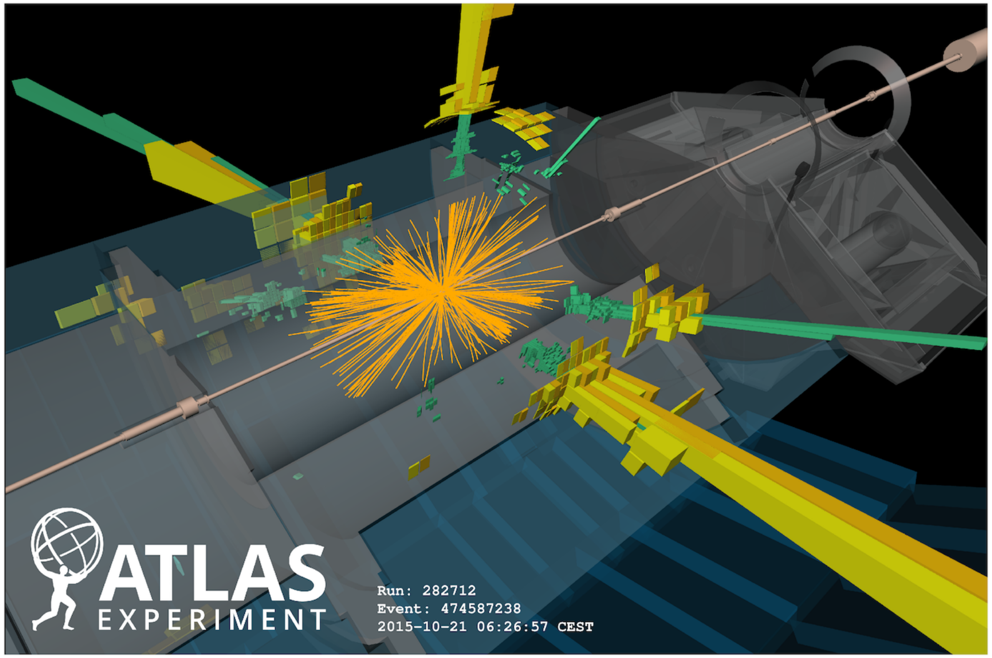
Overview of
Jet measurements at the LHC

Mikko Voutilainen, U. Helsinki and HIP
for the ALICE, ATLAS and CMS collaborations

Contents

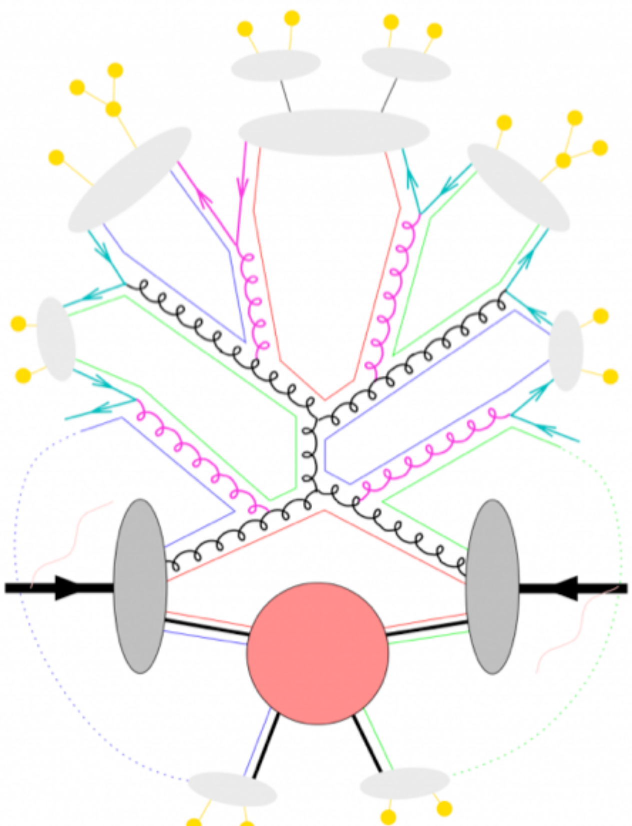
- **Motivation**
  - PDFs, α_s, energy frontier
- **Data, JES and JER**
  - and the pesky gluons
- **Inclusive jets (and dijets)**
  - ALICE (5 TeV), ATLAS (8/13) and CMS (8/13)
  - Deeper look into radius dependence
- **Multijets**
  - Event shapes, angles and hardness, Lund plane
  - Energy-energy correlations for α_s running
- **Jets with Z**
  - Complementary look at NNLO
- **Jet substructure**
  - First results on dynamical grooming
- **Jets in heavy ion collisions**
  - Modification of jets in dense QCD medium
- **Summary**



Motivation

this talk

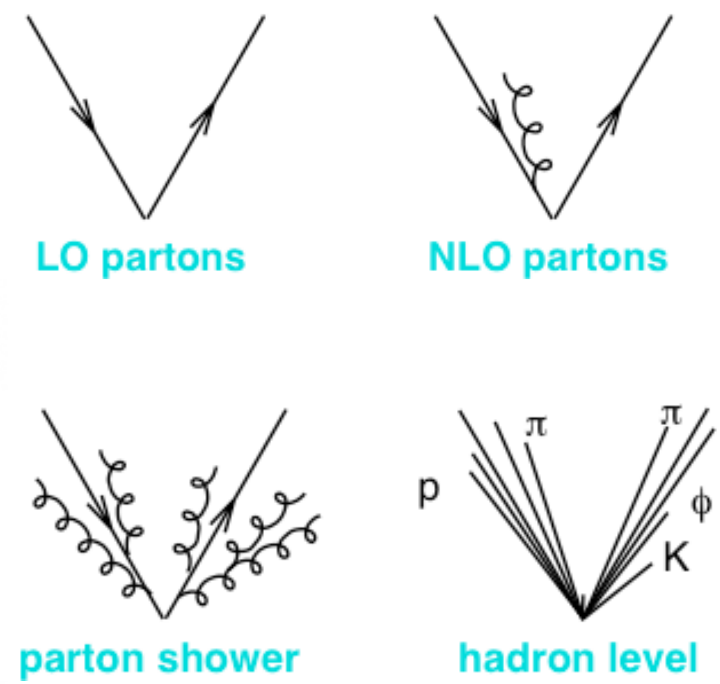
- First goal is to improve our detailed description of Standard Model physics
  - **hard QCD - high p_T:** parton distribution functions (Harland-Lang, Camarda / Tue), strong coupling (Alonso / Thu), perturbation theory (NNLO+NLL; Hus, Monni / Mon)
  - **intermediate QCD - inside jets:** parton shower, jet substructure (Harris, Soyez / Thu) BOOST!
  - soft QCD - low p_T: multiparton scattering, fragmentation, underlying event, etc.
- Second goal: searching new physics at the energy frontier (Saoulidou / Wed)



- hard scattering
- (QED) initial/final state radiation
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster → hadrons
- hadronic decays

and in addition

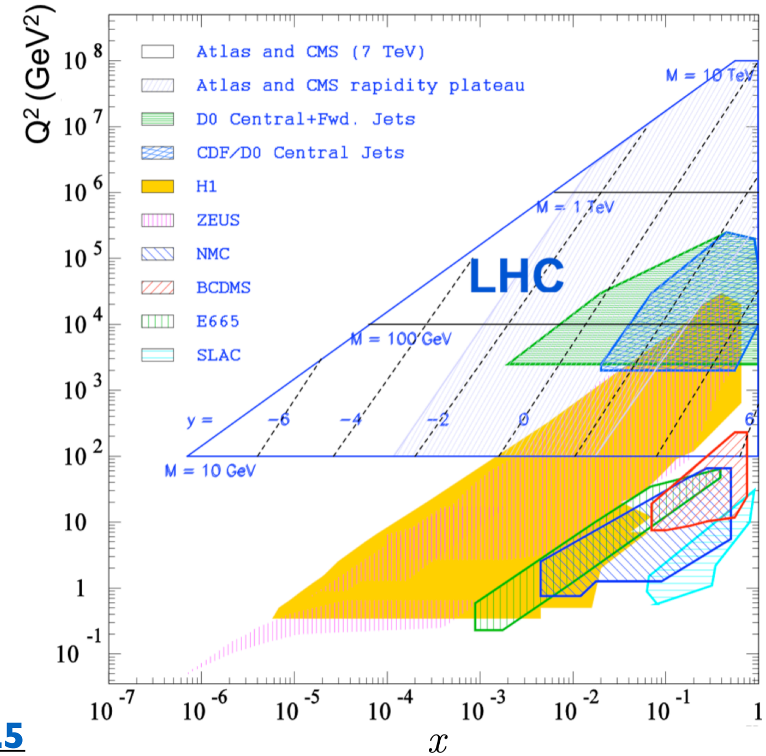
+ backward parton evolution
+ soft (possibly not-so-soft) underlying event



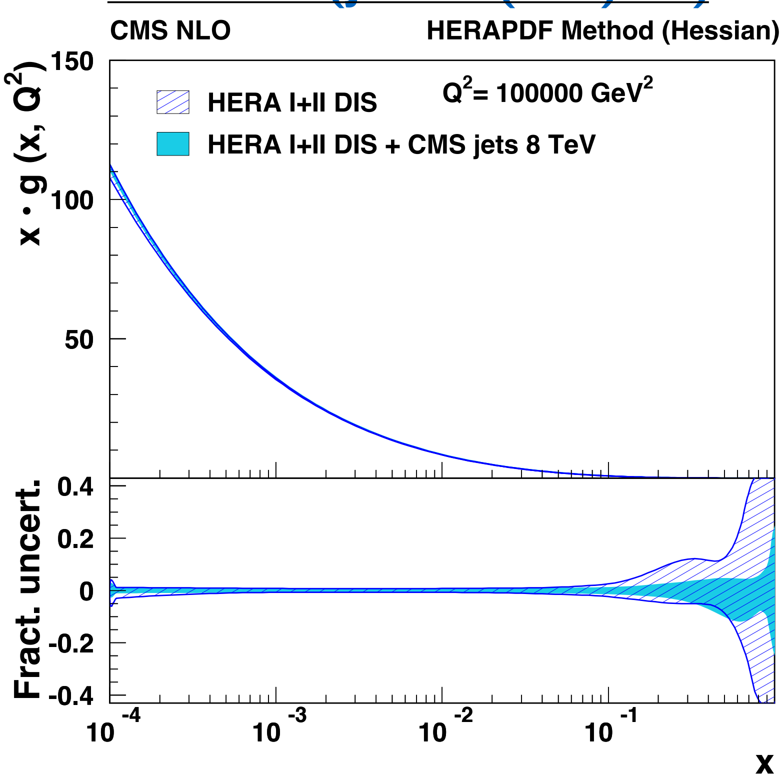
Parton distributions, α_s

- Hadron colliders are complementary to e-p colliders and fixed target experiments
- Proton-proton collisions probe high Q^2 and wide range of Bjorken x
- Inclusive jets and multijets useful for high-x gluon PDF and determination of α_s running

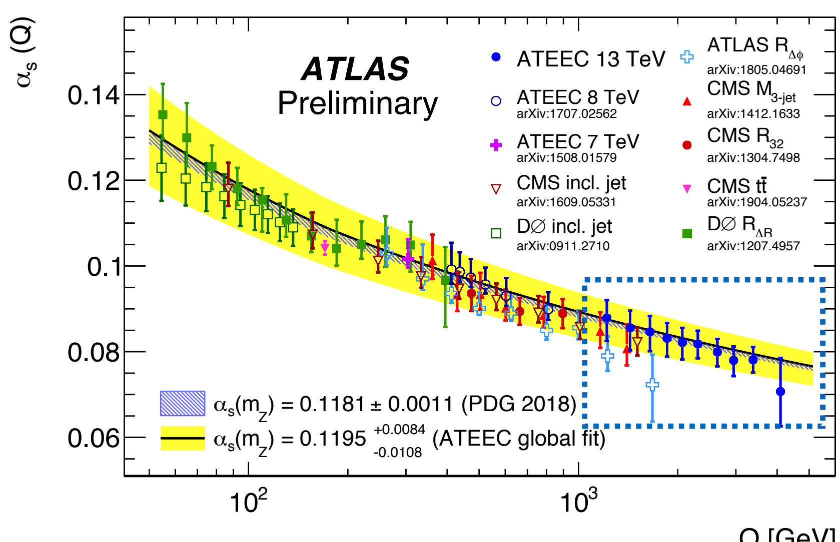
1809.09481 (PRD99, 054004 (2019))



1609.05331 (JHEP03 (2017) 156)



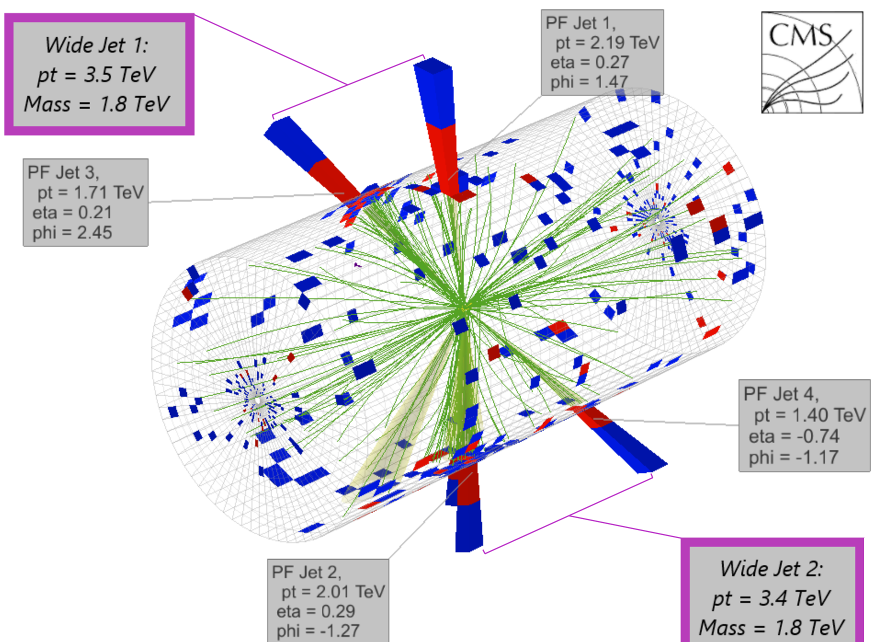
ATLAS-CONF-2020-025



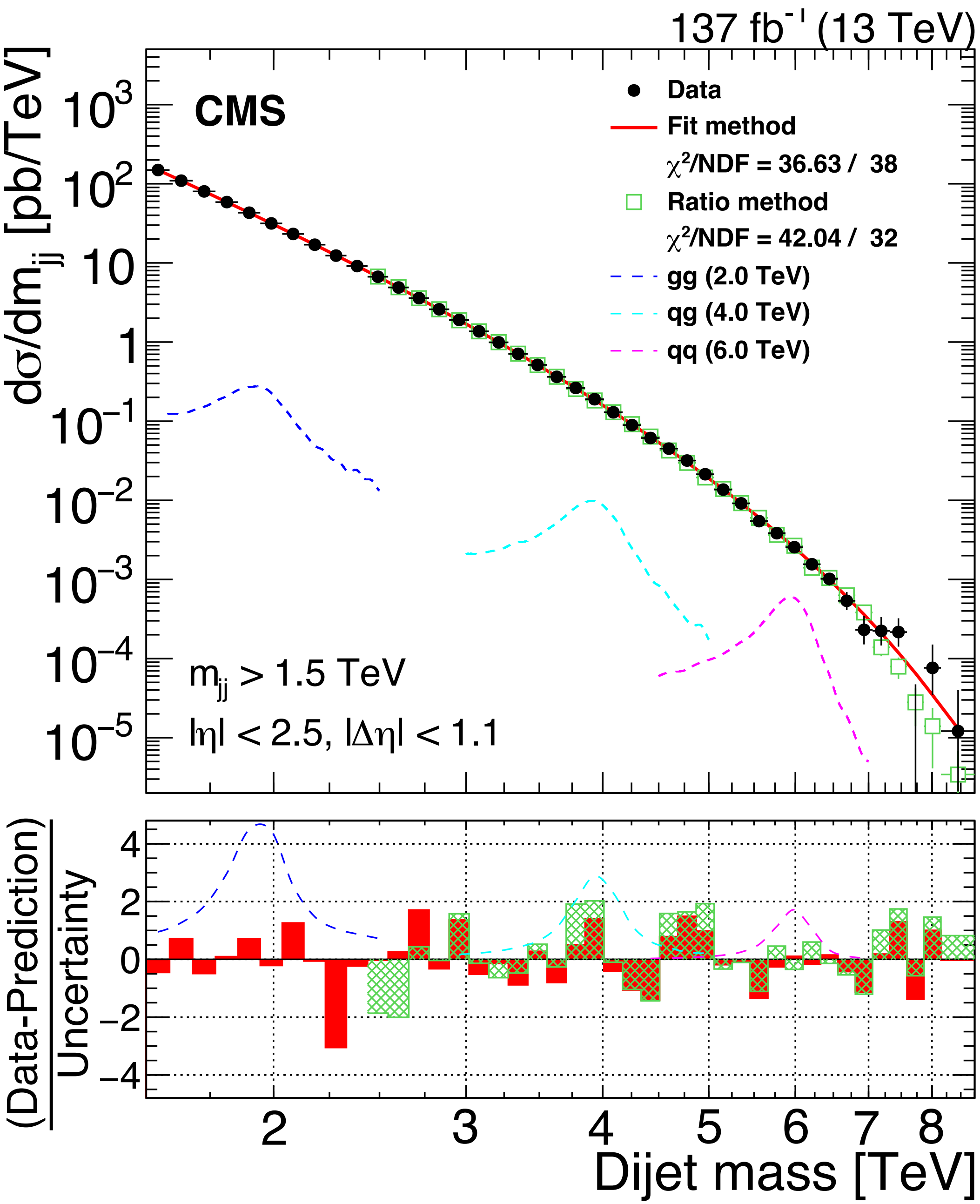
Energy frontier

- Jets reach the highest energies at LHC
- CMS highest p_T di-widejet event a challenge to multijet modelling
- Both CMS and ATLAS observe (excess of) 8 TeV jet pairs, at PDF extremes

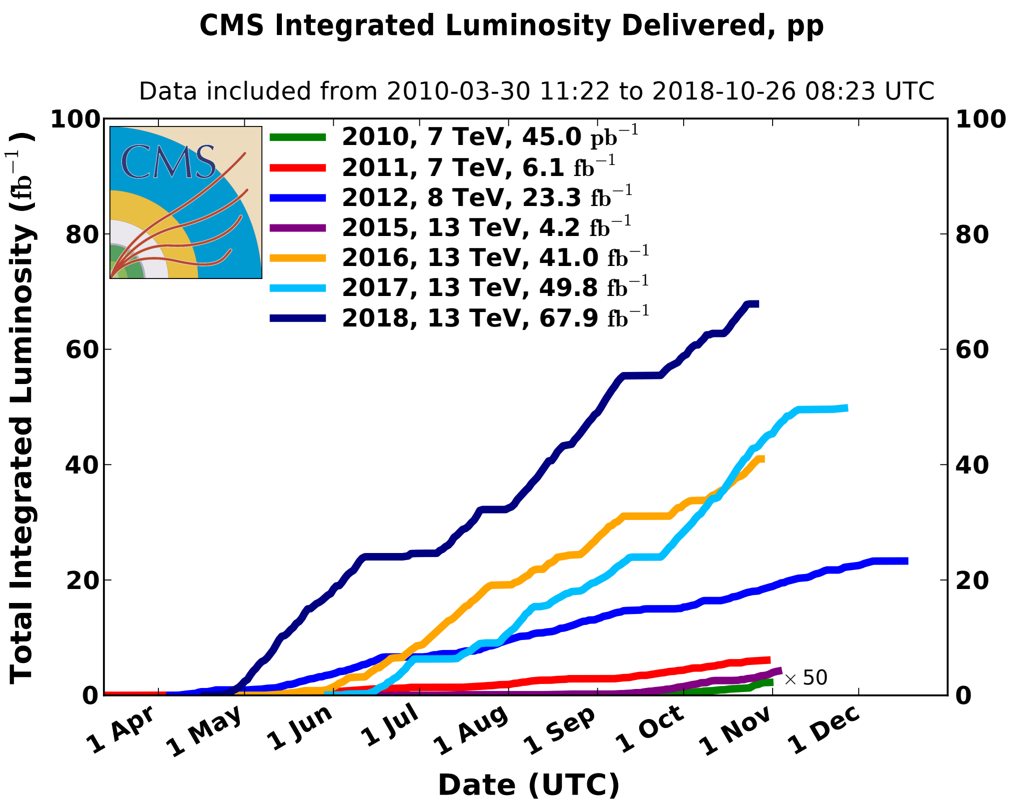
1911.03947 (JHEP05 (2020) 033)



1911.03947 (JHEP05 (2020) 033)



Run I and Run 2 data



Special runs (pp reference)

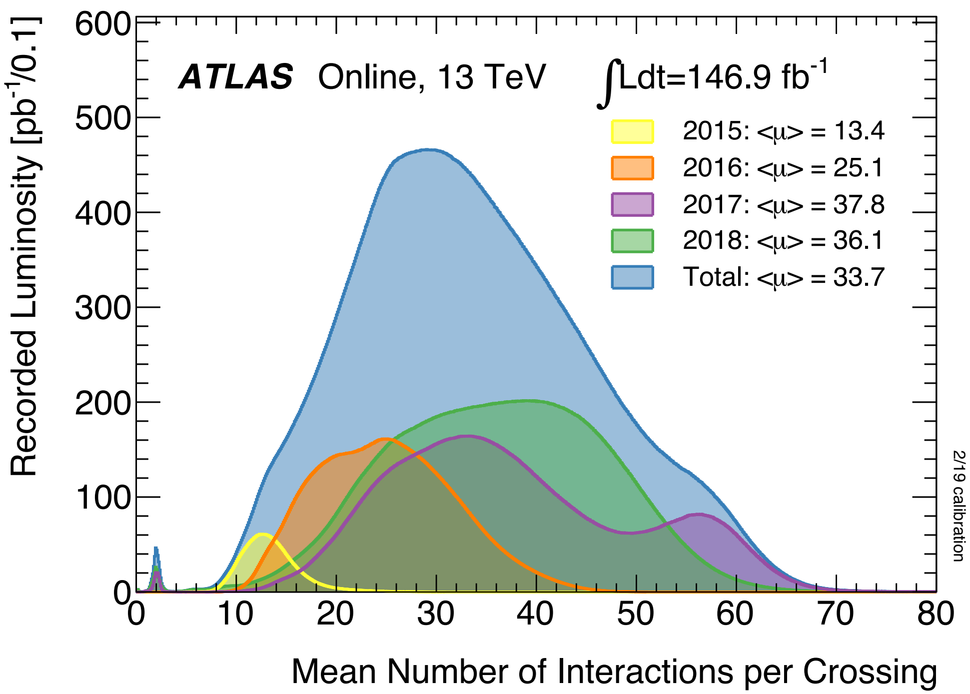
- 2.76 TeV, `0.0054/fb (2013)`
- 5.02 TeV, `0.026 /fb (2015)`

Run I

- 7 TeV, `6.1/fb`
- 8 TeV, `23.3/fb`

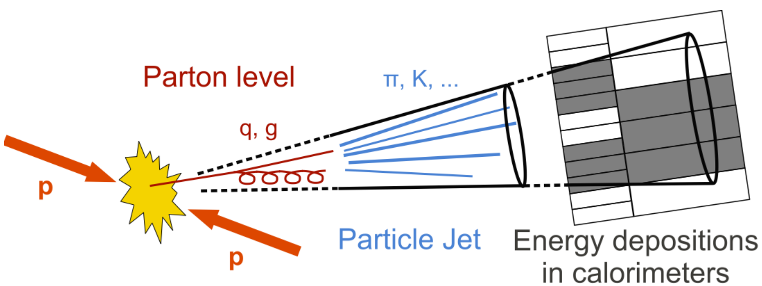
Run 2

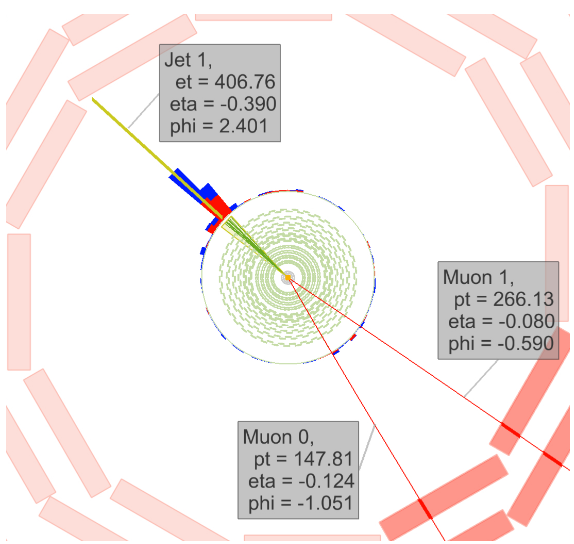
- 2015, `4.2/fb`
- 2016, `41.0/fb`
- 13 TeV, `162.9/fb (2015-18)`



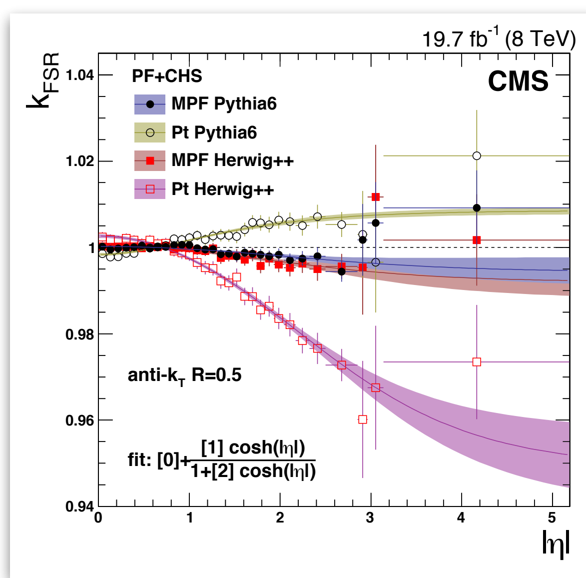
Jet corrections

- There is no precision jet physics without jet energy scale corrections
- Experimentally calibration defined at "particle level" ($c\tau$=1.0 cm, excluding neutrinos)
- However, data-based calibrations rely on momentum conservation and thus "parton level"
  - adds sensitivity to initial and final state radiation (ISR+FSR), underlying event (UE)
  - impact visible when changing restrictions on additional jets ("α") or when using missing-E_T (MPF)
  - Requires excellent MC modelling, and/or data-based bias corrections

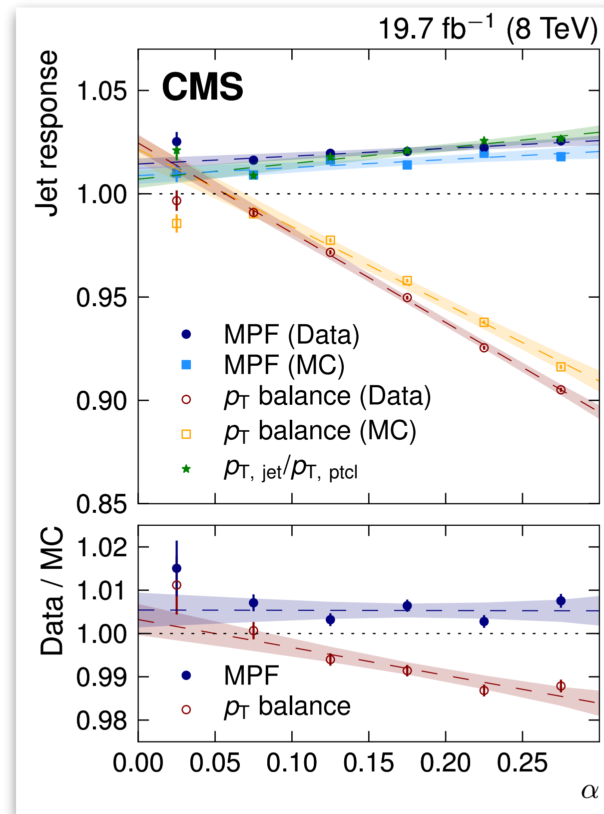




[1607.03663 (JINST12 (2017) P02014)]



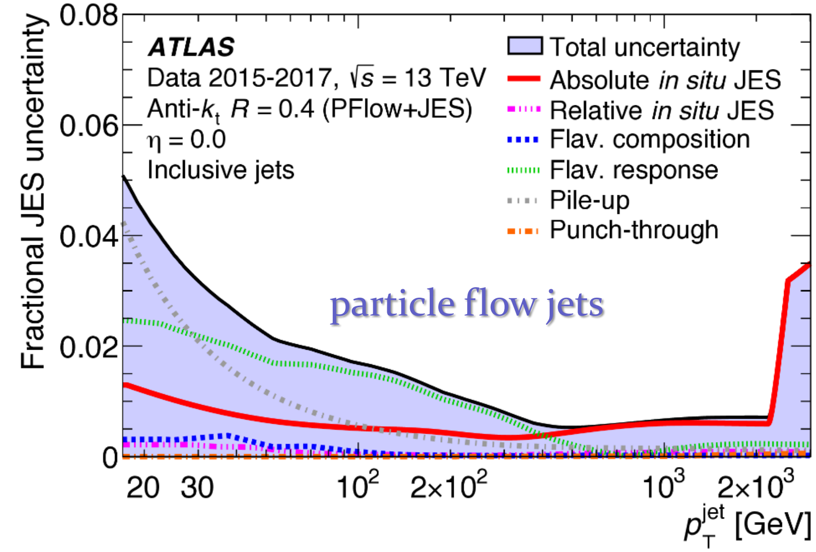
[1607.03663 (JINST12 (2017) P02014)]



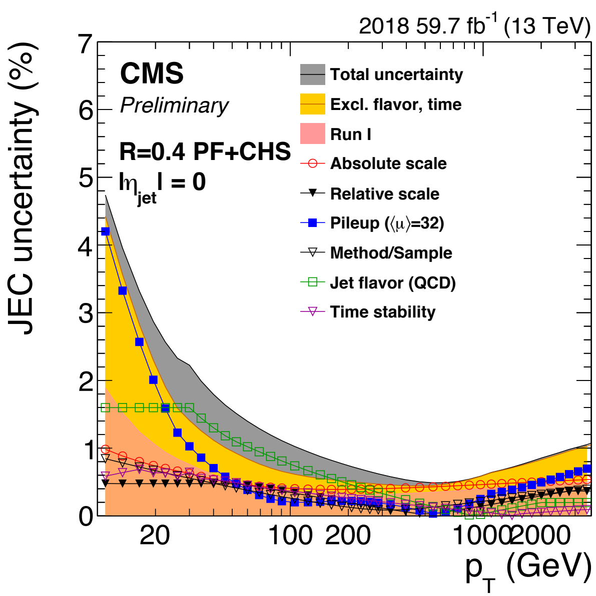
Jet scale at 13 TeV

- Both ATLAS and CMS combine Z+jet, γ+jet and multijet channels for ***sub-percent*** precision
- Data-based calibration versus reference MC
  - Absolute residuals 1—3% (±0.5%) on both expts.
  - Uncertainty dominated by flavour response (gluons)
  - Potential for high CMS-ATLAS correlation?
- Z(μμ)+jet stat.+syst. permits pushing toward 0.1%
  - Requires excellent ISR+FSR, UE and jet flavour modelling

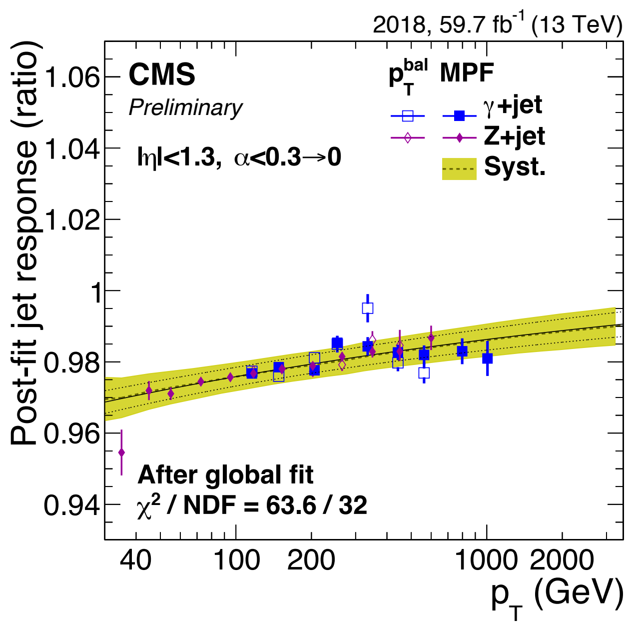
2007.02645 (subm. EPJC)



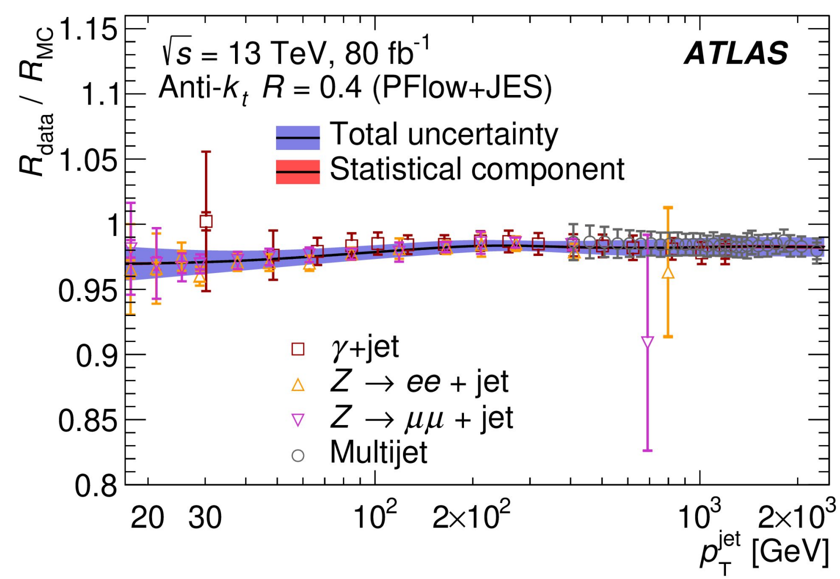
CMS DP-2020/019



CMS DP-2020/019



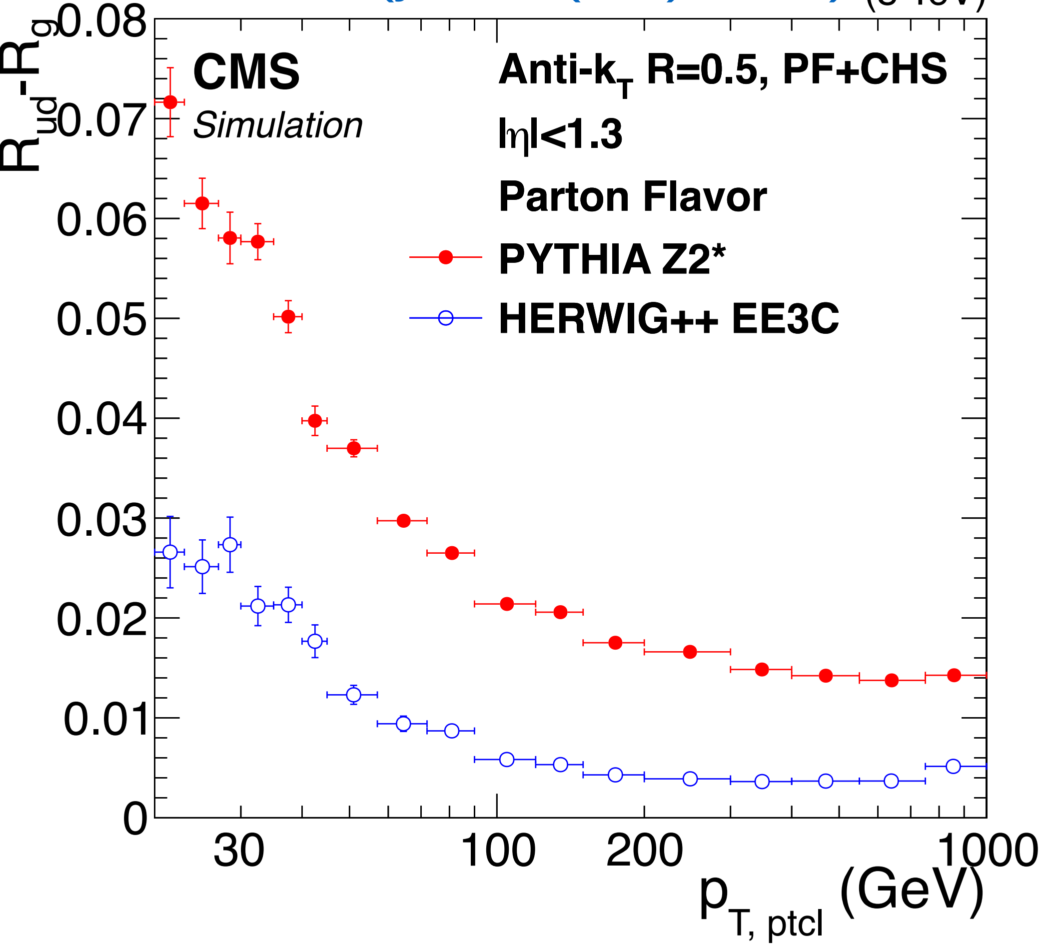
2007.02645 (subm. EPJC)



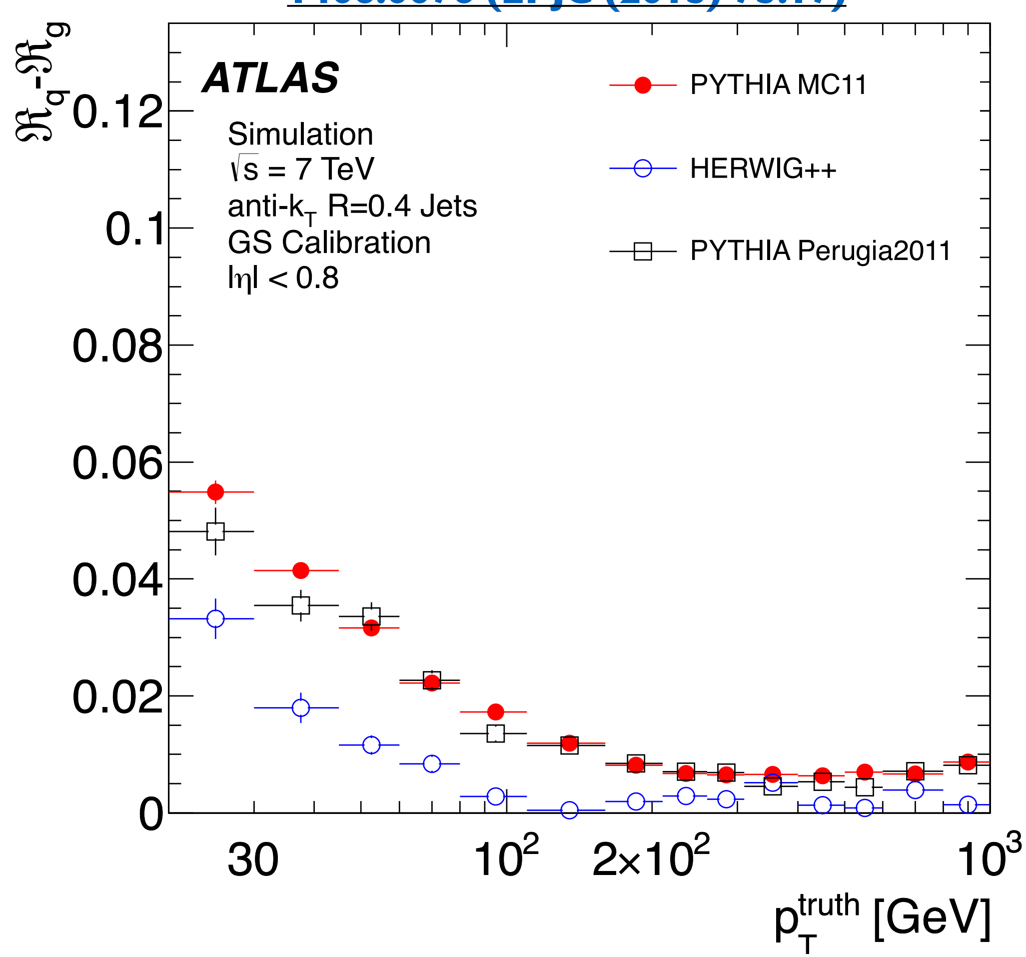
Gluon jets

- Flavour response uncertainty mostly from gluon jets versus well-modelled light quarks
- Similar effect in both CMS (PF) and ATLAS (GS or PF) when comparing parton shower (or fragmentation) in Pythia6/8 and Herwig++/7
- Jet substructure studies with jet flavour tag expected to help

1607.03663 (JINST12 (2017) P02014) (8 TeV)



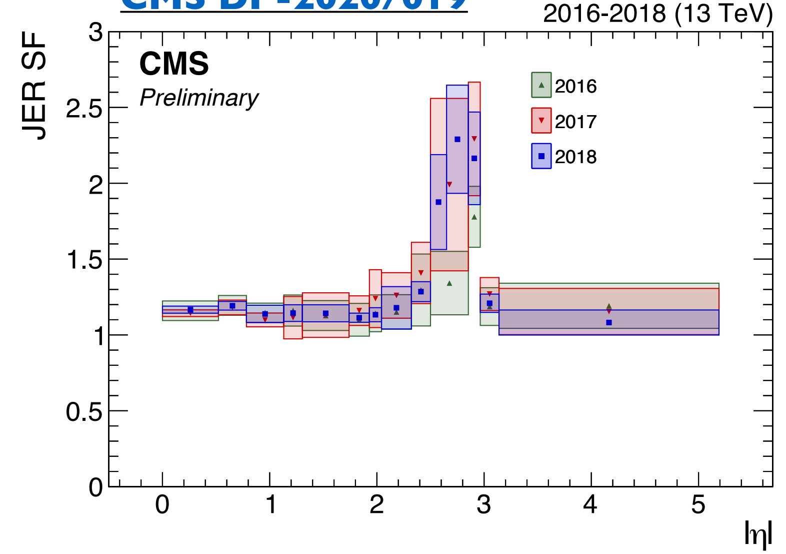
1406.0076 (EPJC (2015) 75:17)



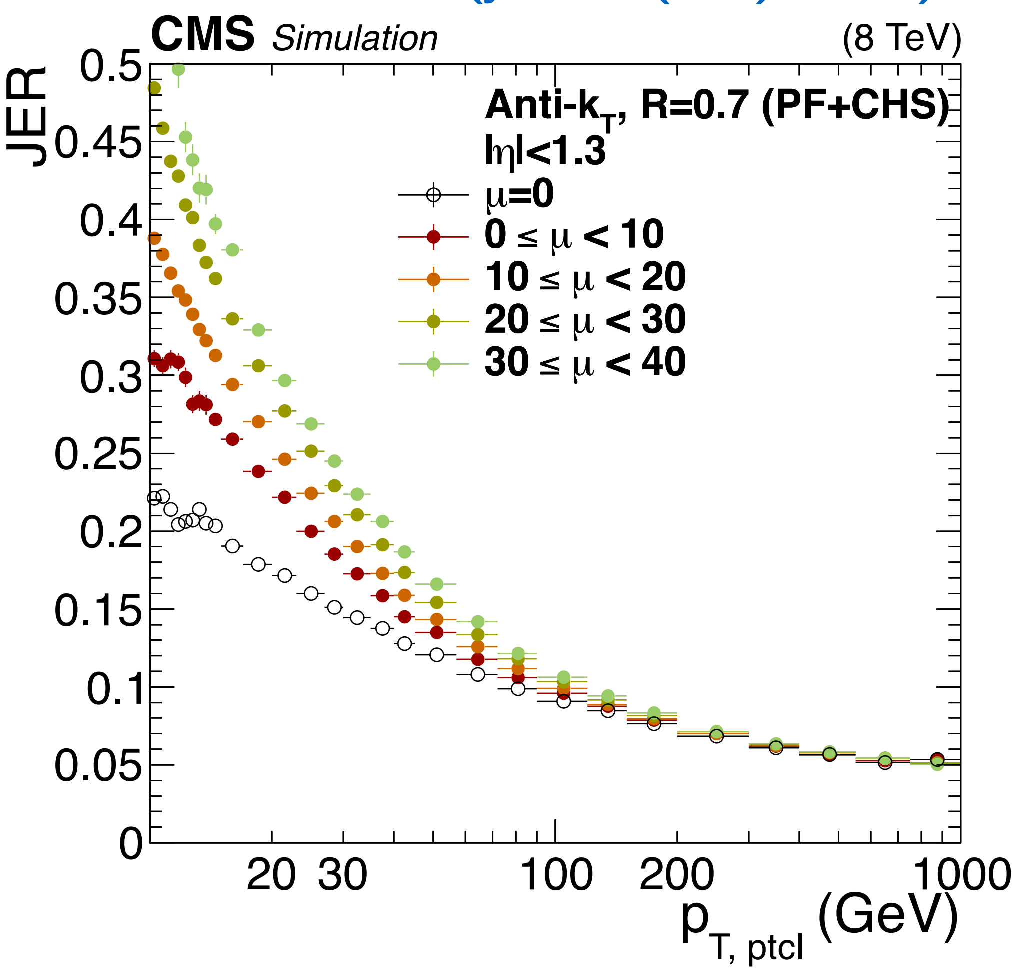
Jet p_T resolution

- Jet p_T resolution (JER) important for unfolding data
- Low p_T sensitive to noise term from pileup ($N^2 \sim \mu R^2$)
- Data/MC differences mostly at 10% level within tracker coverage; linked to MC PS/fragmentation model?

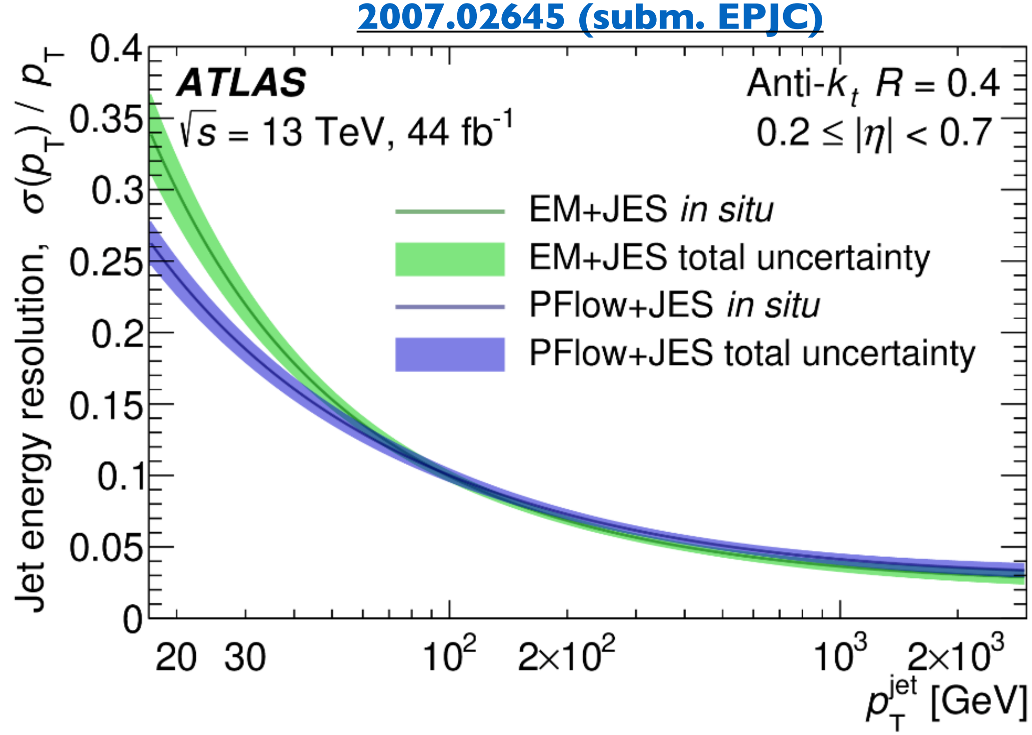
CMS DP-2020/019



1607.03663 (JINST12 (2017) P02014)



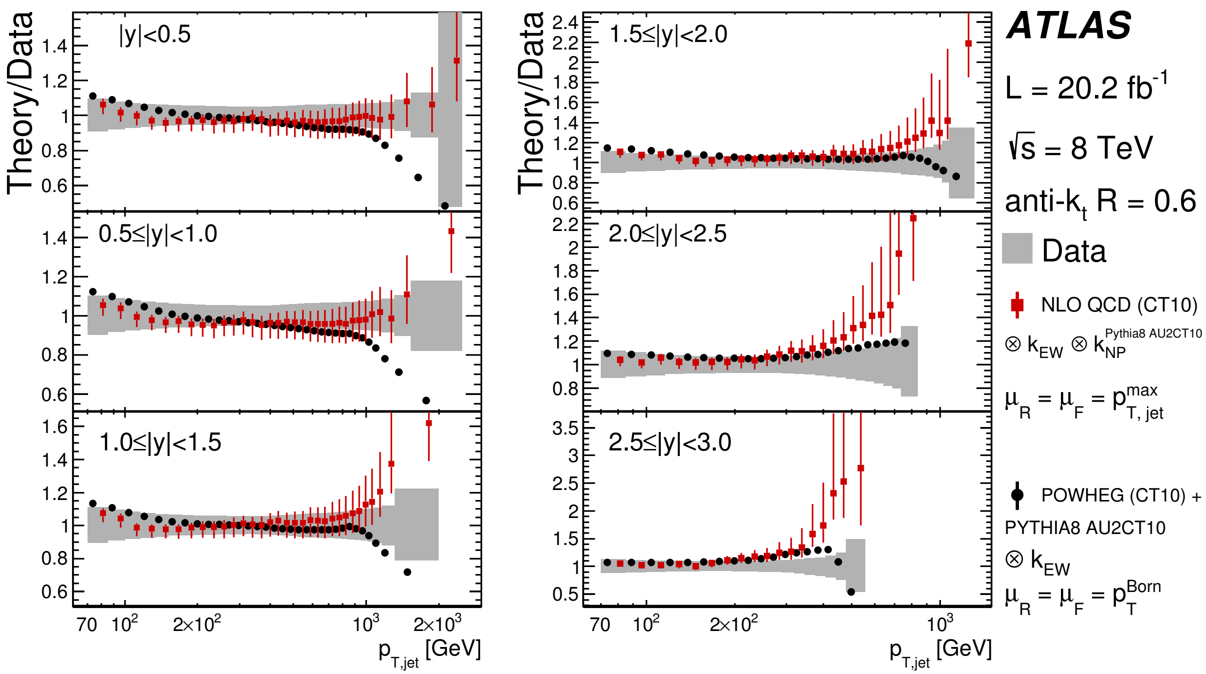
2007.02645 (subm. EPJC)



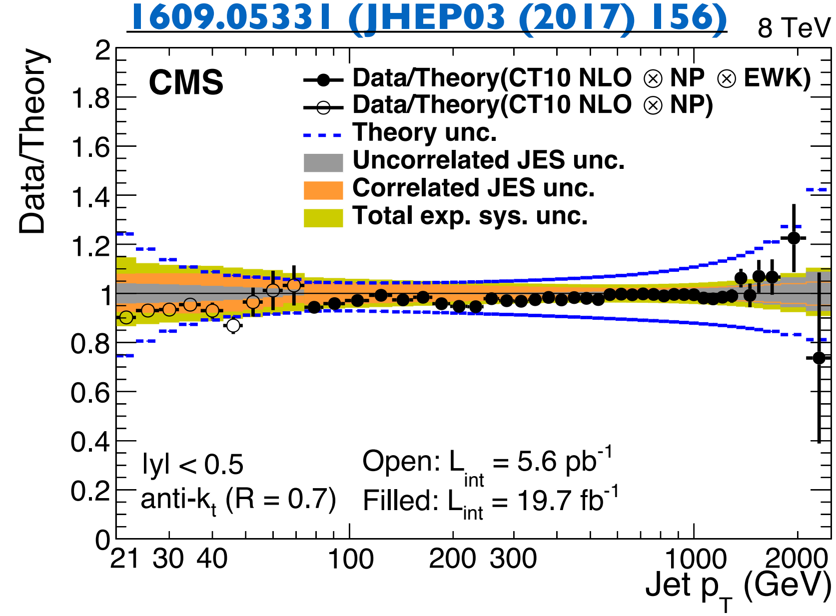
Inclusive jets 8 TeV

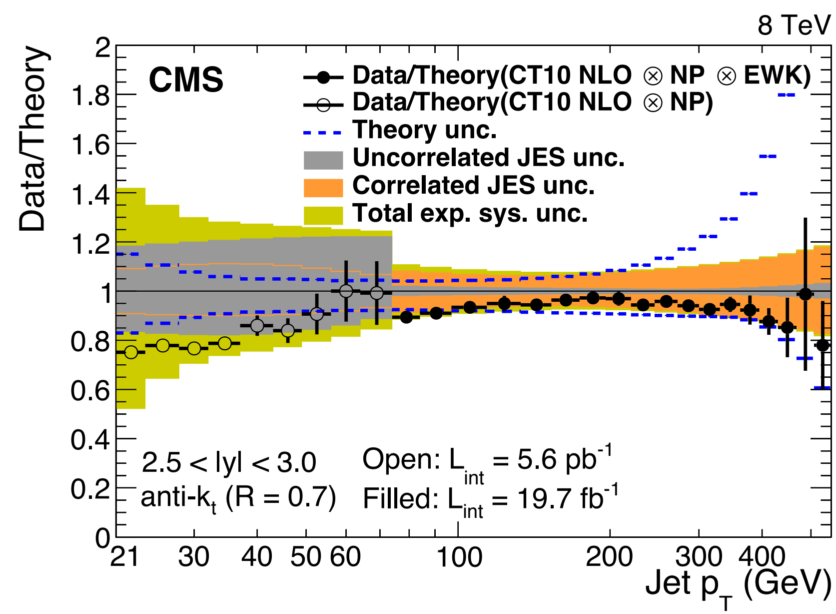
- Present state-of-the-art at ATLAS and CMS, until legacy 13 TeV results published on full Run 2 data
- Smallest uncertainty ~5% at $|y|<0.5$, p_T=400 GeV
- Results consistent with theory and each other at central rapidities, slight tension at high $|y|$ and p_T

1706.03192 (JHEP09 (2017) 020)



1609.05331 (JHEP03 (2017) 156)

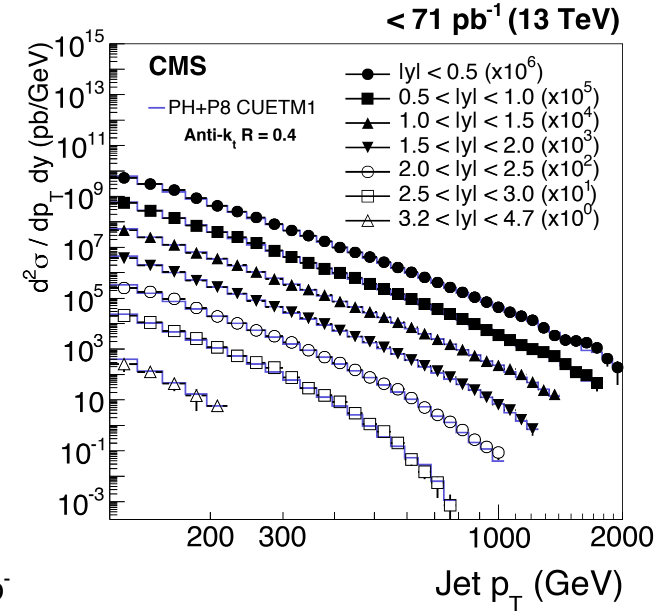




Inclusive jets 13 TeV

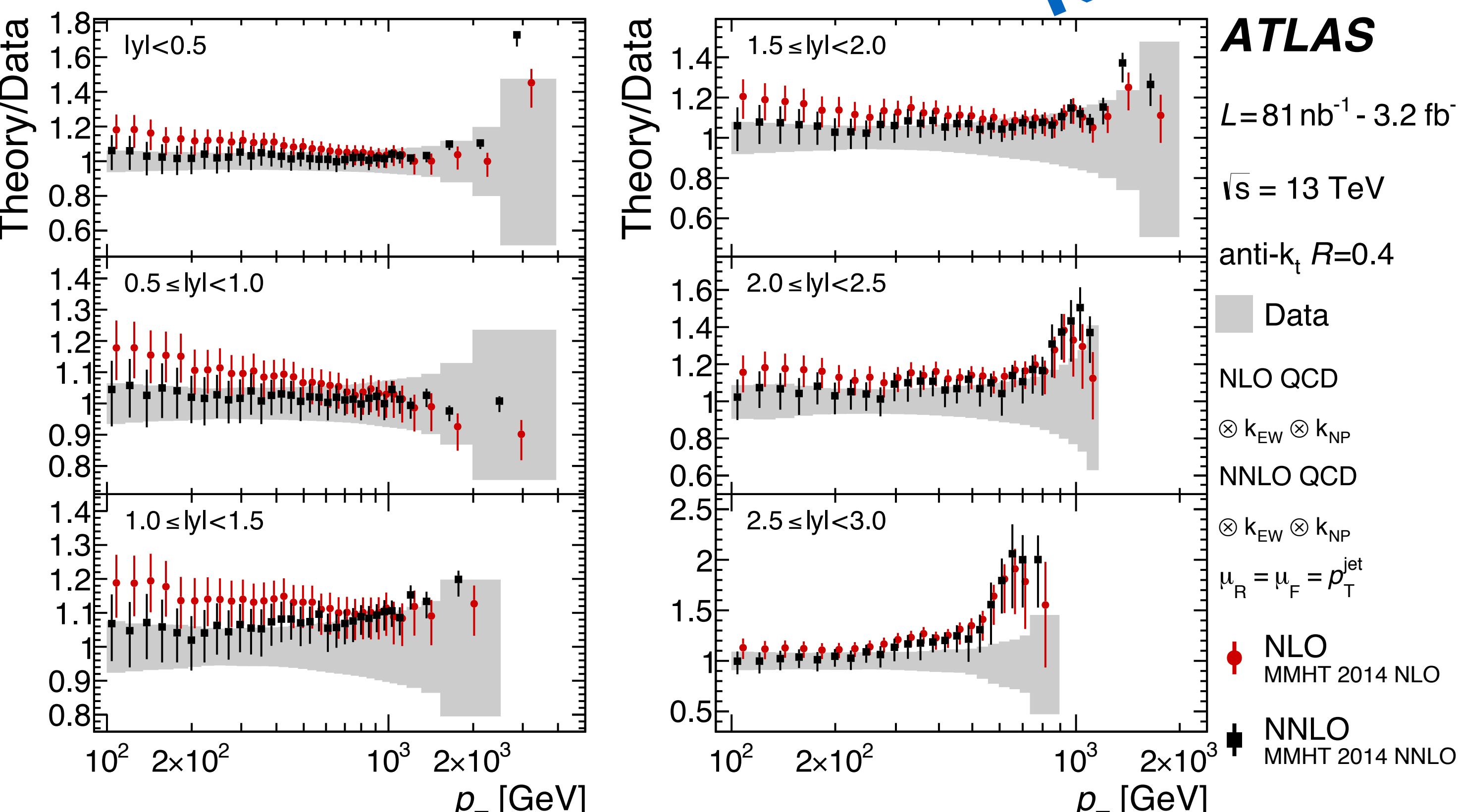
- CMS (first) 13 TeV results use 71/pb of early 2015 data, ALICE preliminary has 4/pb and good low p_T reach
- ATLAS results with 4.2/fb of 2015 data, but only R=0.4
  - Uncovered difference between $\mu_{R,F}=p_{T\mathrm{jet}}$ and $\mu_{R,F}=p_{T\mathrm{max}}$ at NNLO (first for this!), which is much smaller at NLO
- Much more precision with ~140/fb and final calibrations!

1605.04436 (EPJC76 (2016) 451)

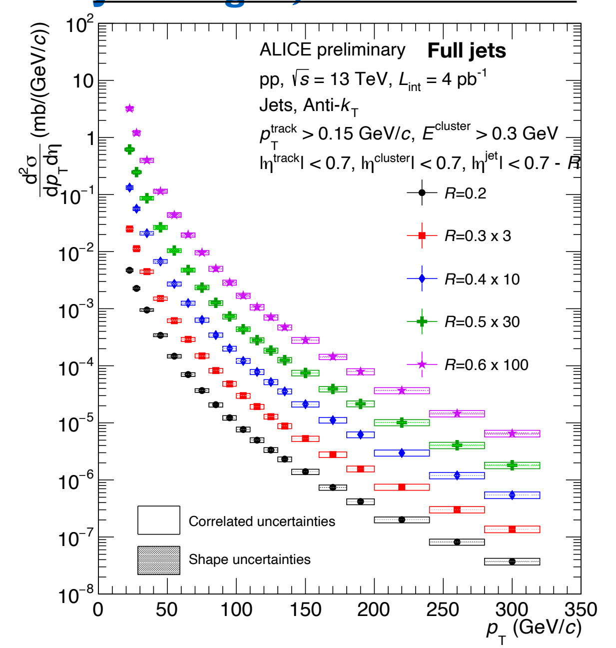


NNLO!

1711.02692 (JHEP05 (2018) 195)



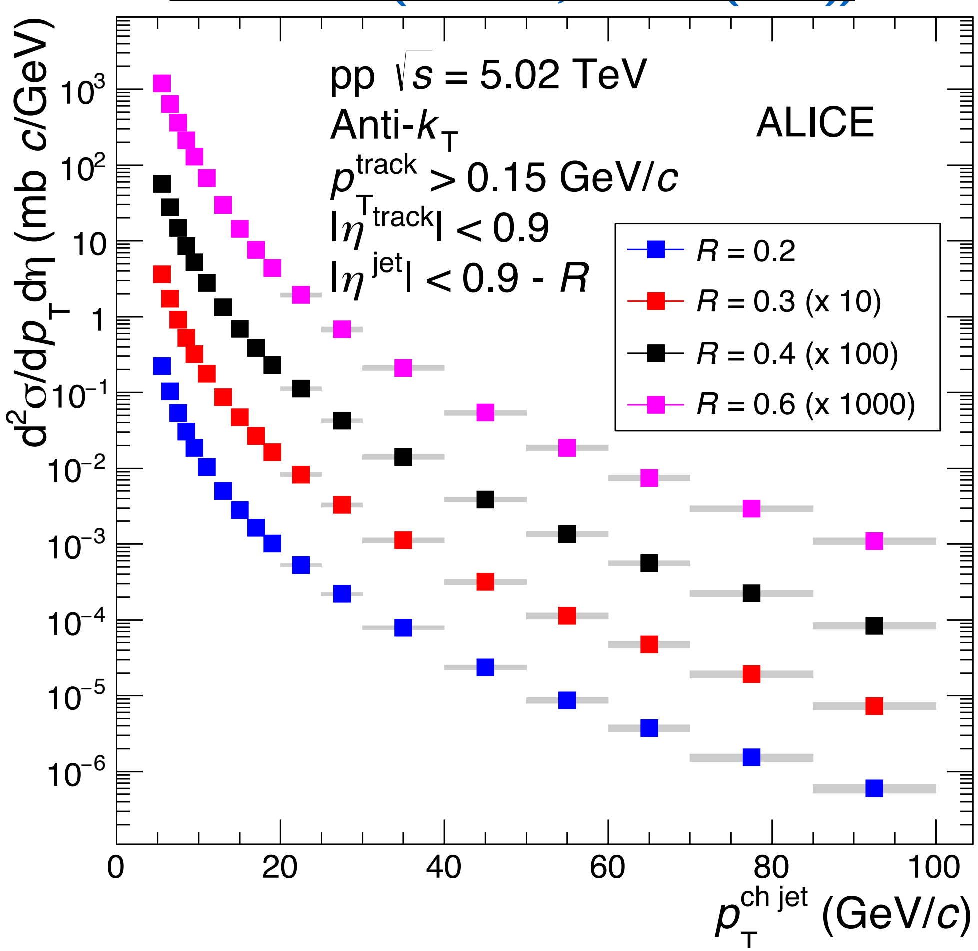
J. Mulligan, Santa Fe 2020



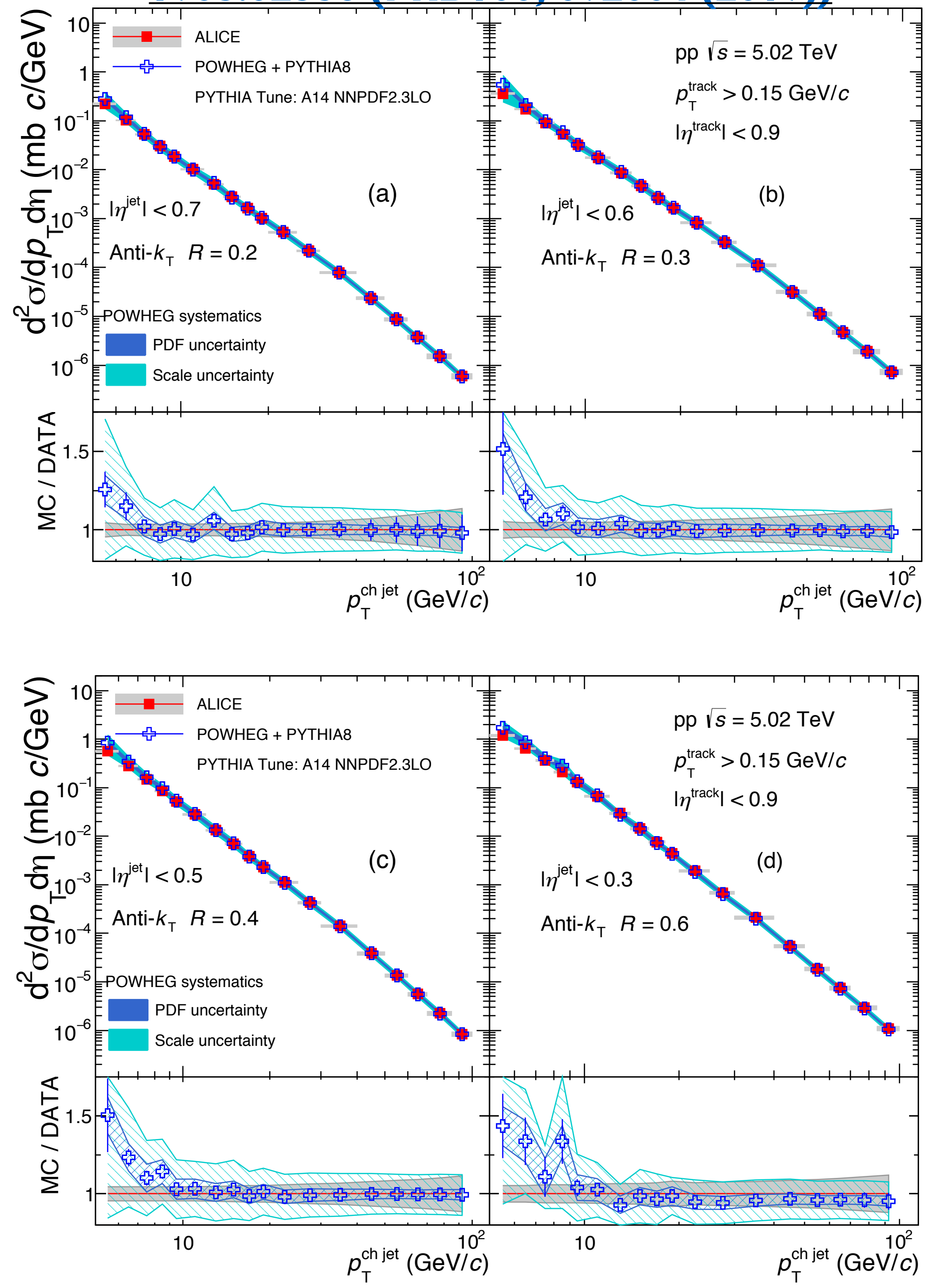
Charged jets at 5 TeV

- First 5.02 TeV pp measurement from ALICE
- Track jets avoid calorimeter non-linearities, very precise reference scale down to low p_T
- Good agreement with **Powheg** above 10 GeV (jet charged fraction typically ~60–65%)

1905.02536 (PRD100, 092004 (2019))



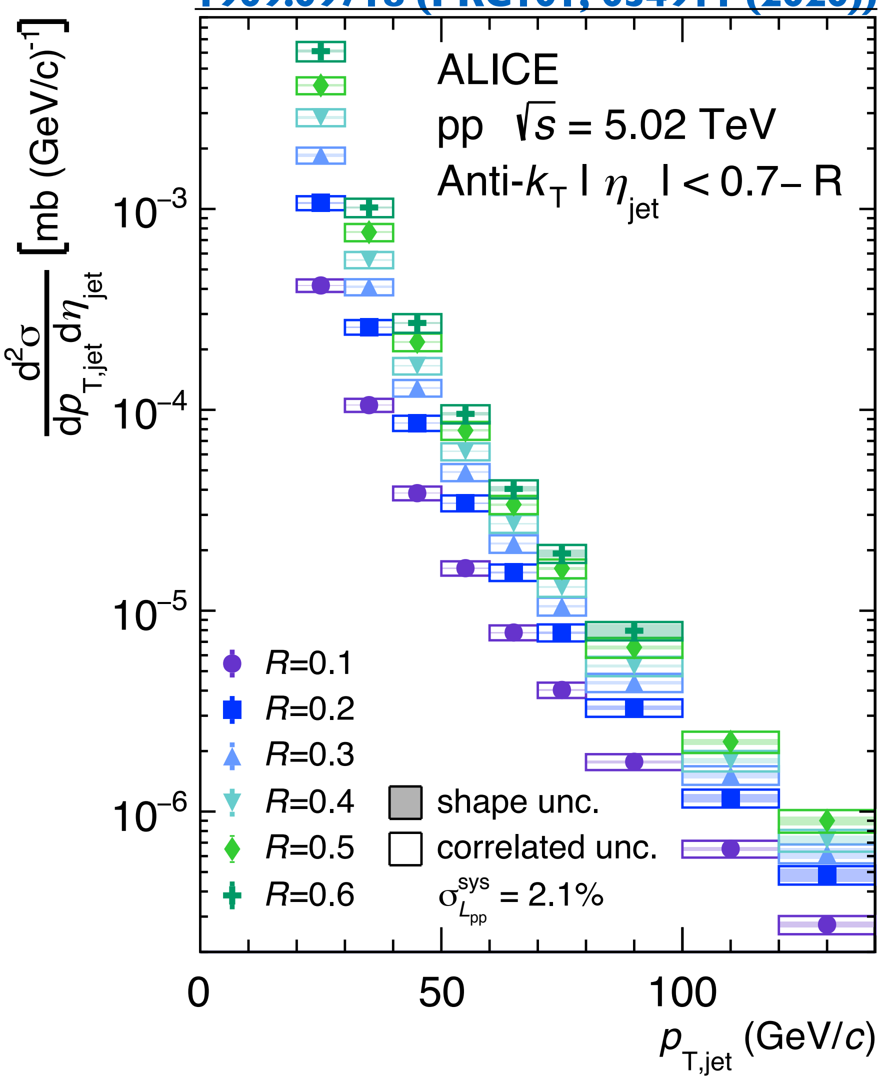
1905.02536 (PRD100, 092004 (2019))



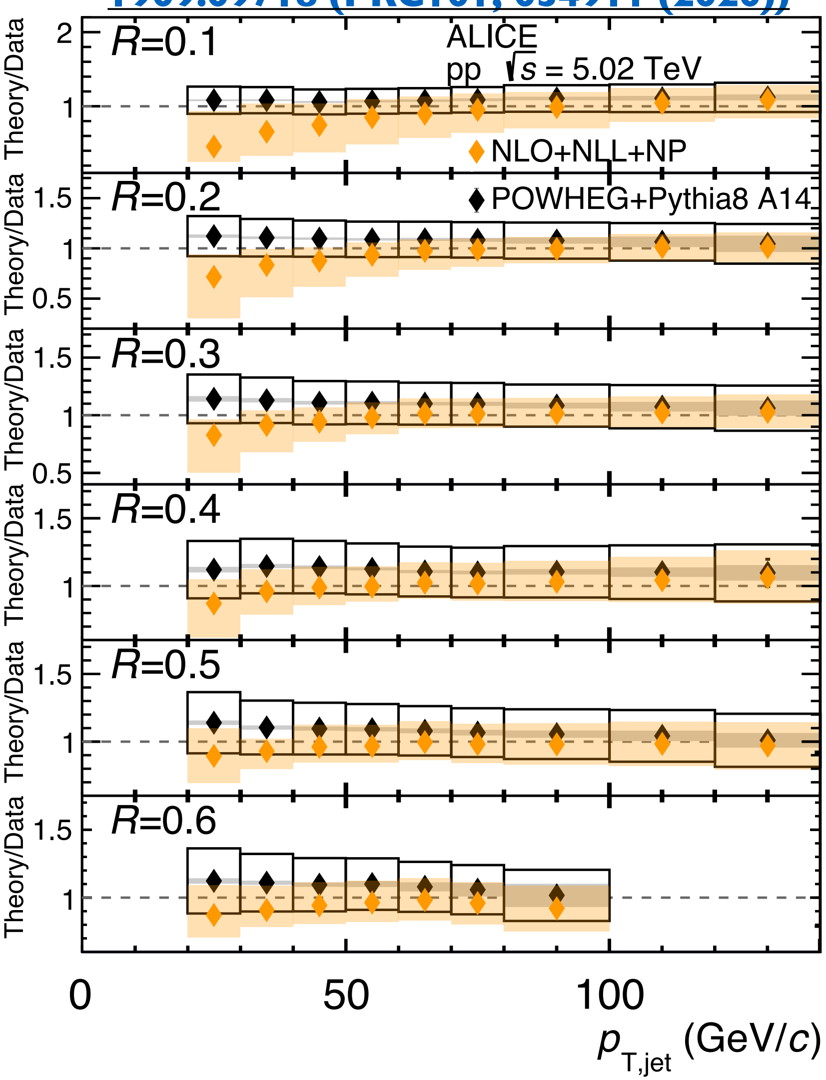
Inclusive jets 5 TeV

- Second ALICE 5.02 TeV pp measurement uses tracking+calorimetry for more inclusiveness
- Comprehensive R scan to small R and low p_T versus **Powheg** and **NLO+NLL+NP**
- Small sample with low pileup and low $\sqrt{s}$, so p_T reach from 20 GeV only up to 140 GeV

1909.09718 (PRC101, 034911 (2020))



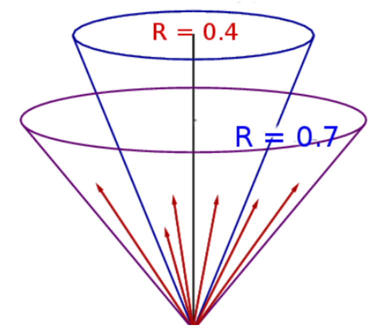
1909.09718 (PRC101, 034911 (2020))



NNLO: see [J. Mulligan, Santa Fe 2020]

- CMS complements ALICE scan up to high p_T (~1.2 TeV) and large R (1.2), although going only to 84 GeV at low p_T
  - relative to AK4, with large cancellation of uncertainties
- Radius scan powerful test of high-order pQCD
  - NLO(1.0/0.4) = NNLO(1.0) / NNLO(0.4), i.e. "one up"
  - also test of parton shower and NLL radius resummation
  - NP mostly relevant at p_T<100–200 GeV

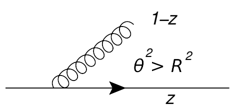
AK4 chosen as reference because it is the standard *R* in CMS during Run-2



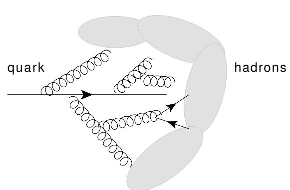
Different distance parameter *R* are sensitive to different parts of jet formation.

$\delta p_T \equiv$ "lost" transverse momentum outside jet cone at LO in small-radius approximation $R \ll 1$

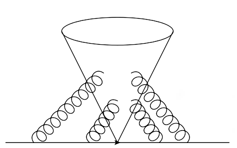
Parton shower: $(\delta p_T)_{PS} \sim \ln(1/R)$

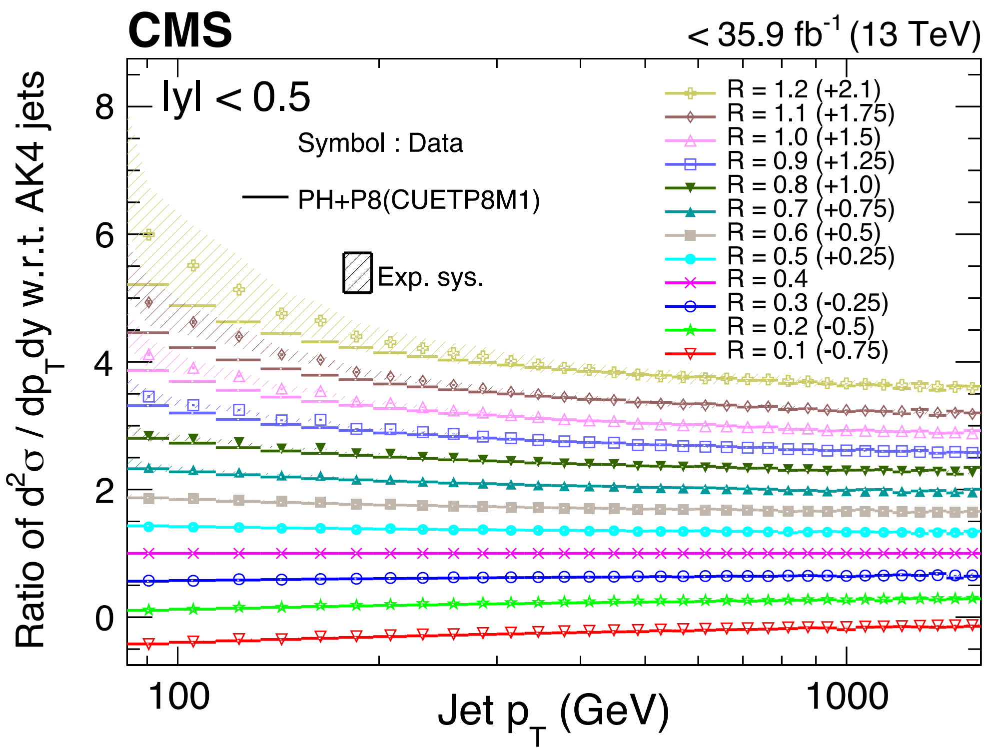


Hadronization: $(\delta p_T)_{HAD} \sim R^{-1}$



Underlying event activity: $(\delta p_T)_{UE} \sim R^2$.





C. Baldenegro, Kansas @ ICHEP2020

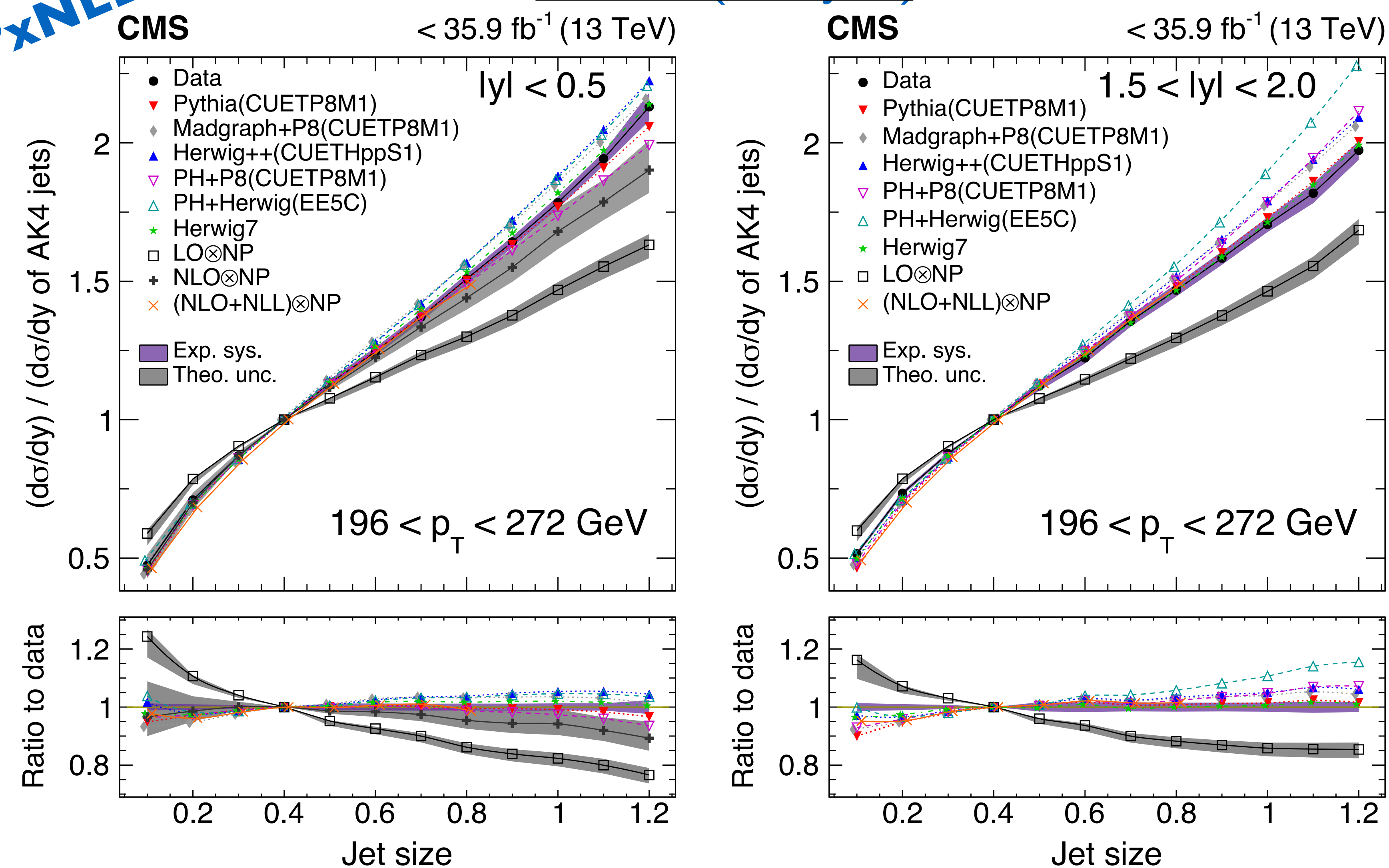
2005.05159 (subm. JHEP)

CMS radius scan

- **(NLO+NLL)xNP** performs well down to small R; same as ALICE sees at high p_T
- LO(1.0)xNP, i.e. NLO(1.0)xNP / NLO(0.4)xNP off by sizeable 15–20% (NLL~1 for R=1.0)
  - similar discrepancy as seen in NLOxNP vs ATLAS 13 TeV data with R=0.4

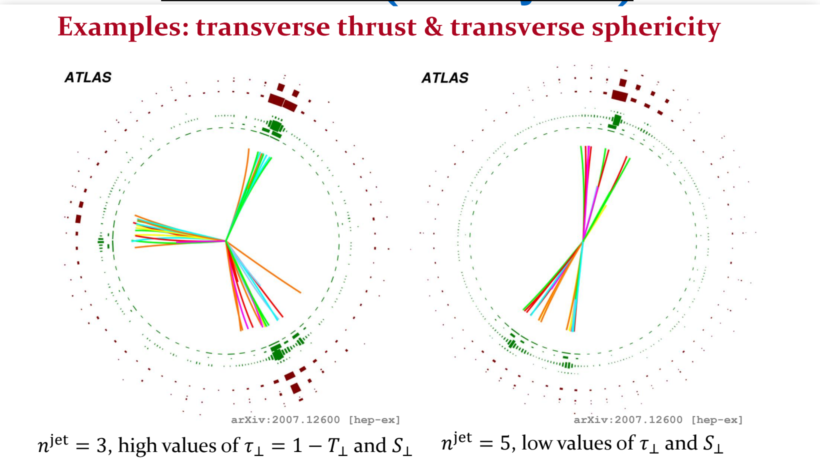
2005.05159 (subm. JHEP)

"NNLO"xNLL



Multijets

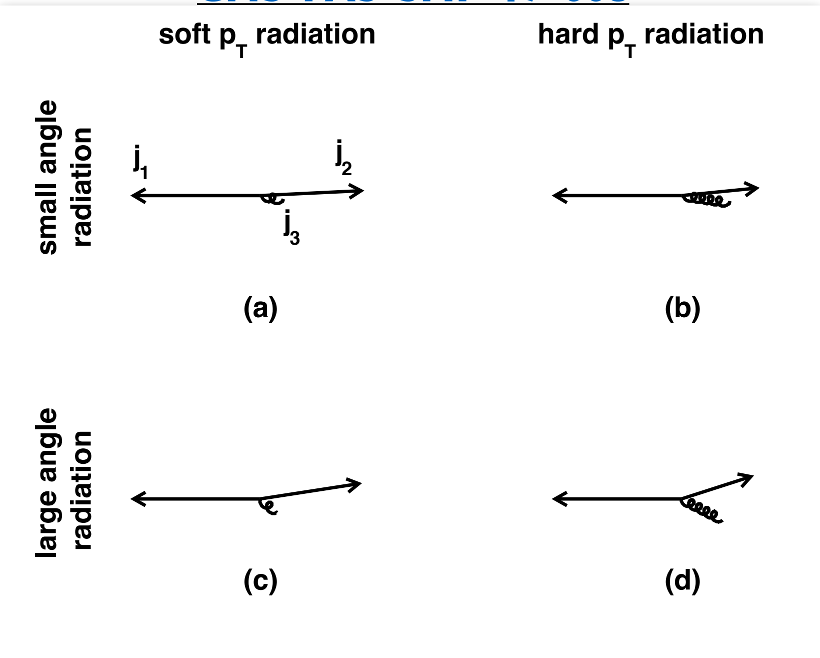
2007.12600 (subm. JHEP)



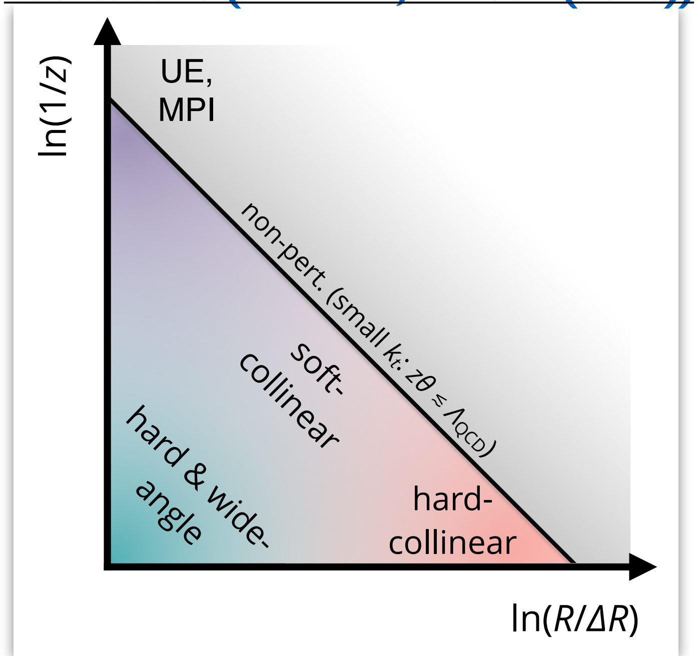
Several new multi jet measurements in past year:

- Classic ATLAS measurement of multijet event shapes (transverse thrust, sphericity, etc.)
- CMS measurement versus ΔR_{23} and p_{T3}/p_{T2}
- Novel ATLAS measurement using Lund plane similar to CMS approach, but more general
  - $\Delta R_{23} \sim \ln(R/\Delta R)$, $p_{T3}/p_{T2} \sim \ln(1/z)$

CMS-PAS-SMP-17-008



2004.03540 (PRL 124, 222002 (2020))

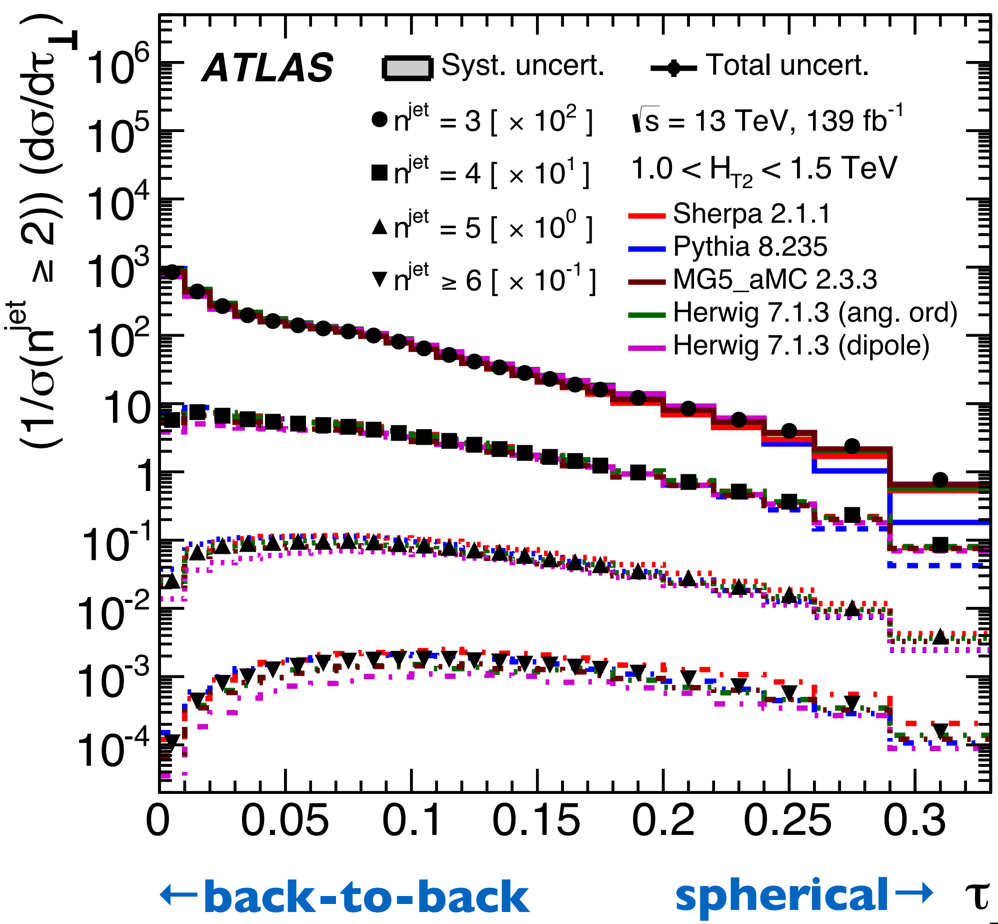


ATLAS event shapes

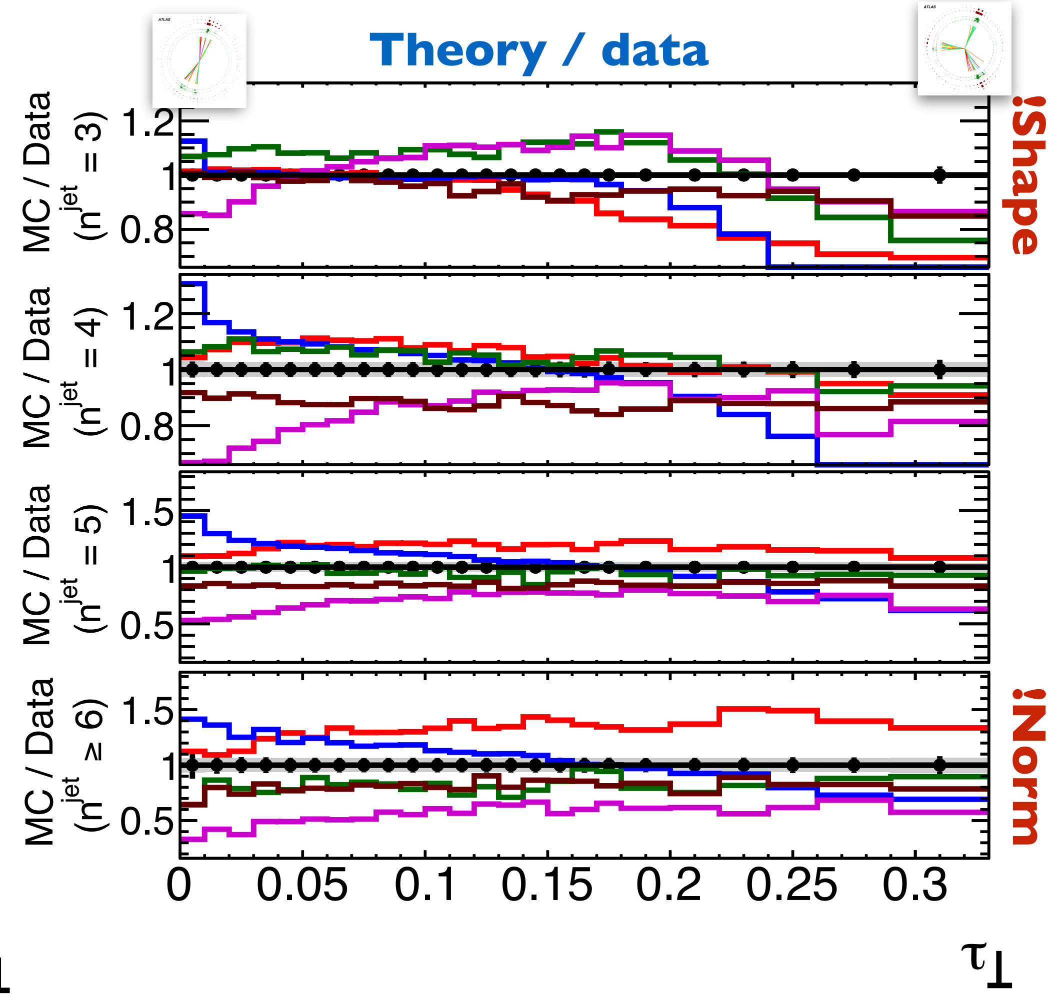
- Comparing six event shape variables in bins of N_{jet} and H_{T2}
  - No MC works across full phase space
  - At low jet multiplicities, shape differences vs MC
  - At high jet multiplicities, normalisation differences vs MC

[2007.12600 (subm. JHEP)]

Transverse thrust



Theory / data

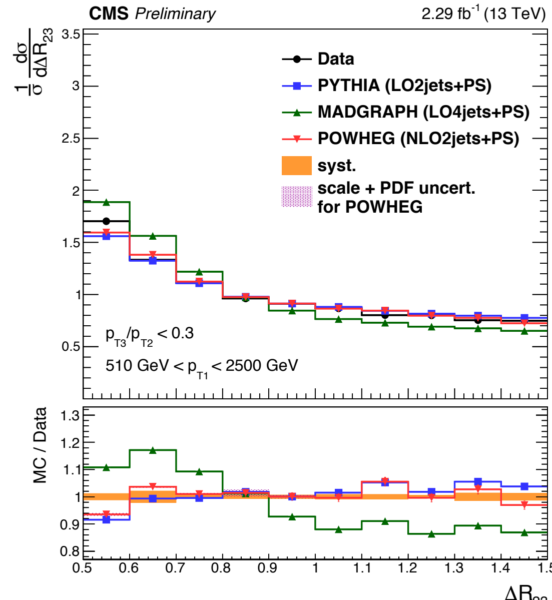


CMS multijet

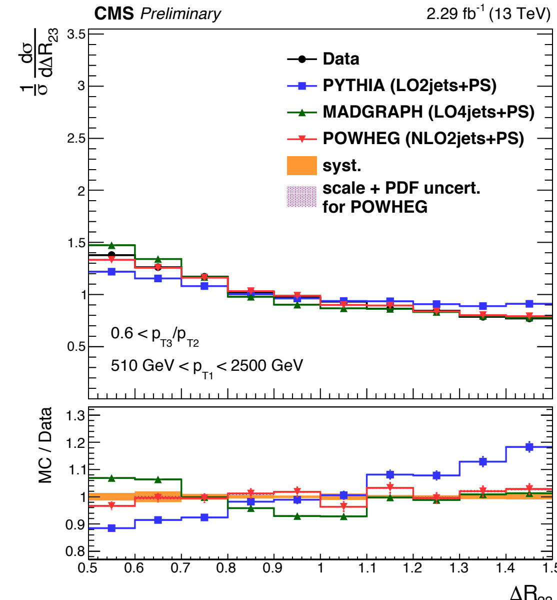
- **Pythia** good for angle of soft emissions, but bad for hardness
- **MadGraph** reversely good for (far) hardness and angle of hard emissions, but bad for soft and collinear
- **Powheg** good for angles, but bad for hardness
- Behavior as expected for LO parton shower, multileg predictions and NLO pQCD
  - Results quantify magnitude of discrepancies as O(10–20%)
  - No generator works everywhere

CMS-PAS-SMP-17-008

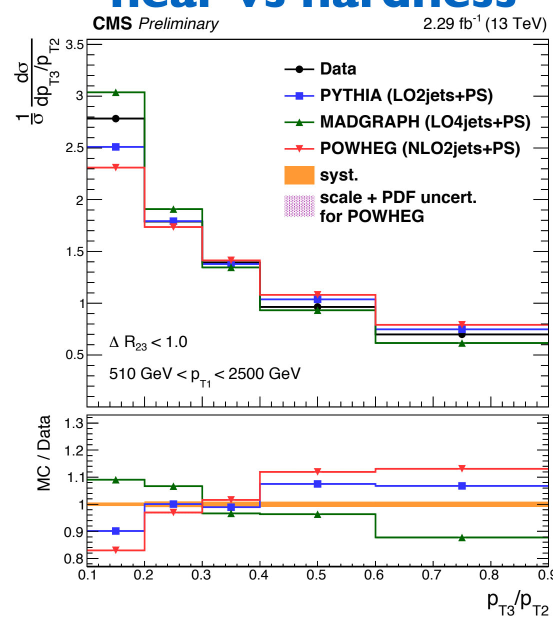
soft vs angle



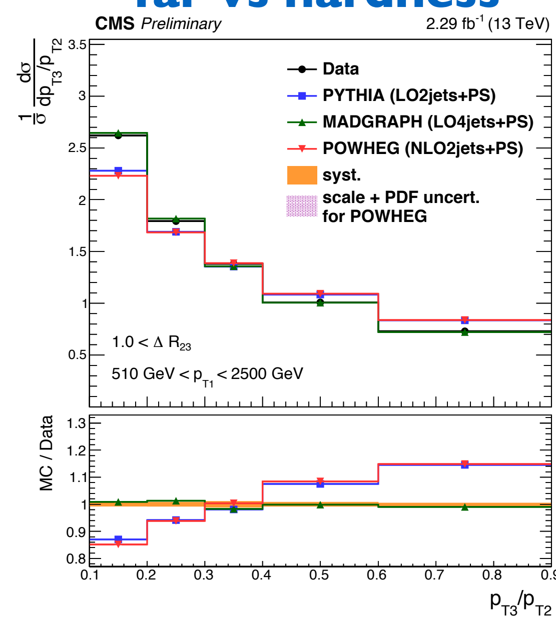
hard vs angle



near vs hardness



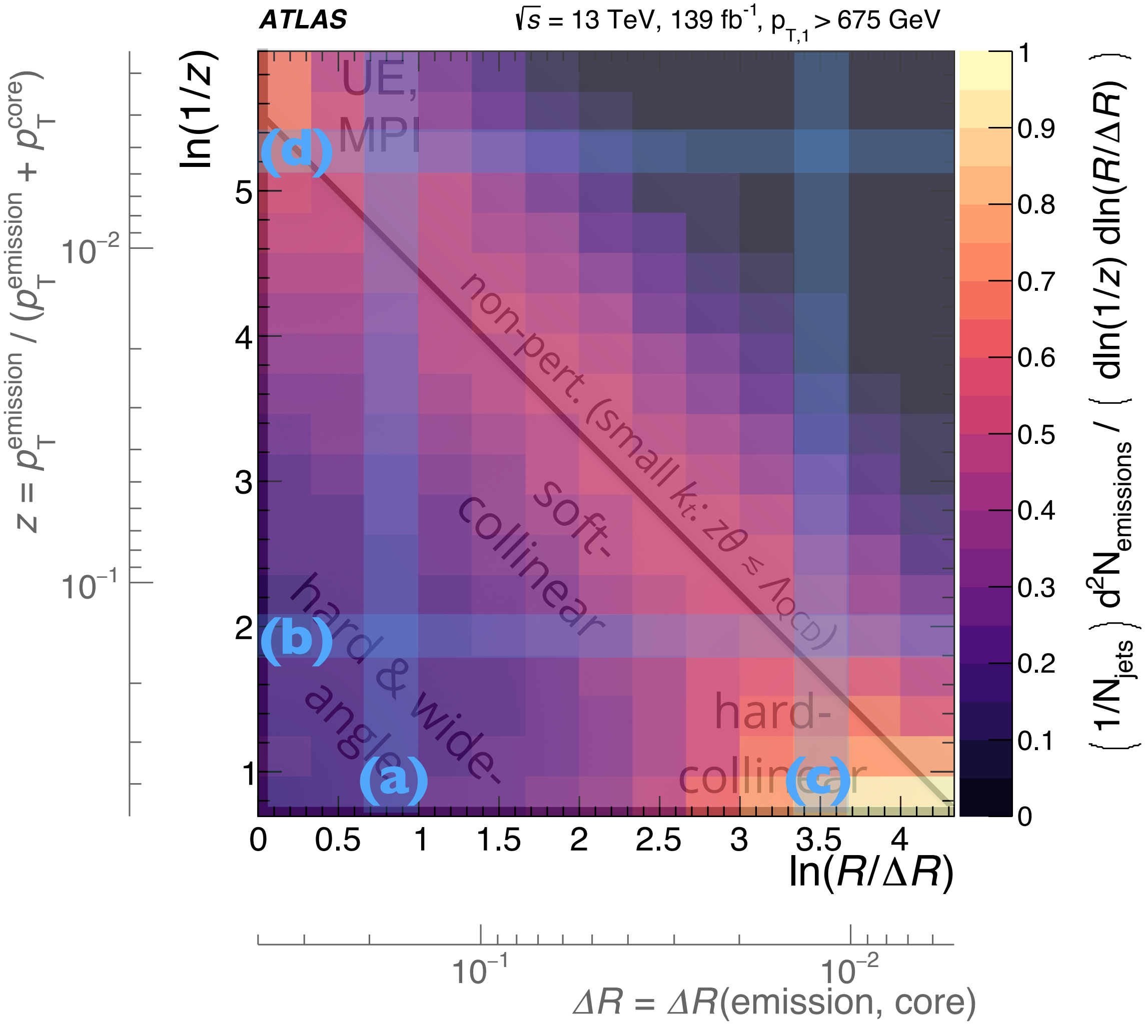
far vs hardness



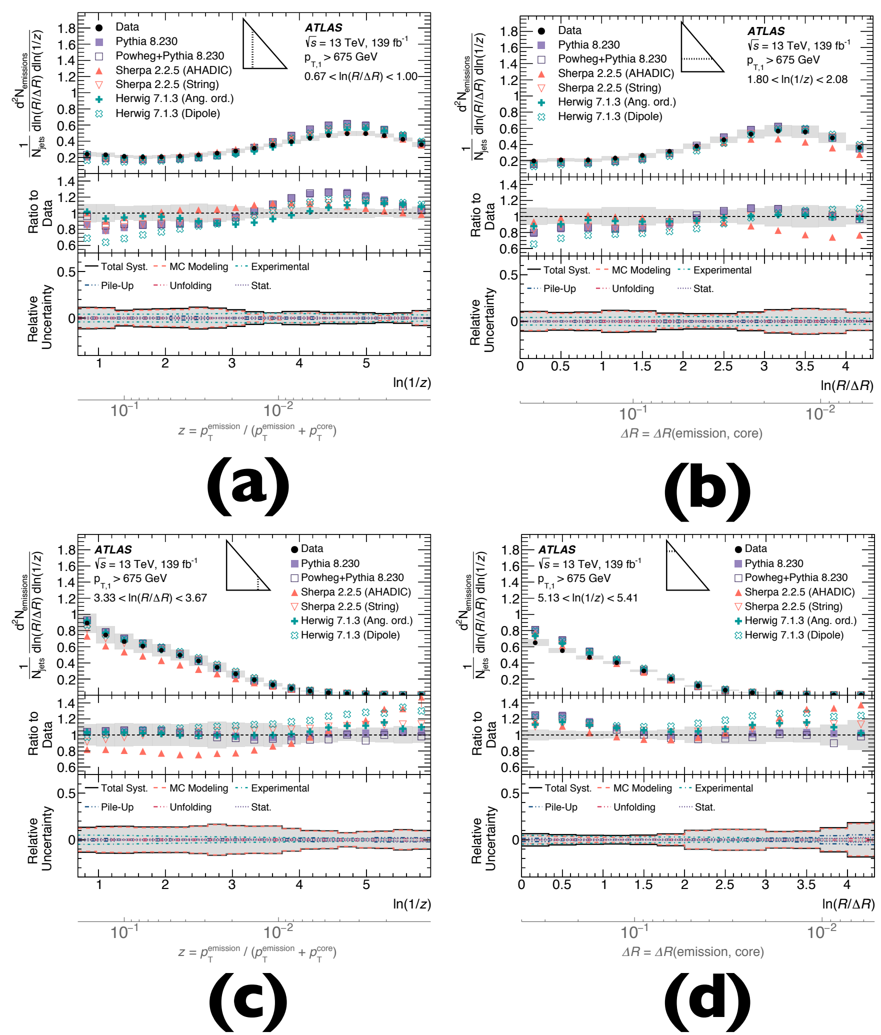
ATLAS Lund plane

- Lund plane separates various effects, similar to CMS multijets but more general
- Similar observations to CMS: no generator works across full phase space
- Useful input to both perturbative and non-perturbative model development and tuning

2004.03540 (PRL 124, 222002)



2004.03540 (PRL 124, 222002)

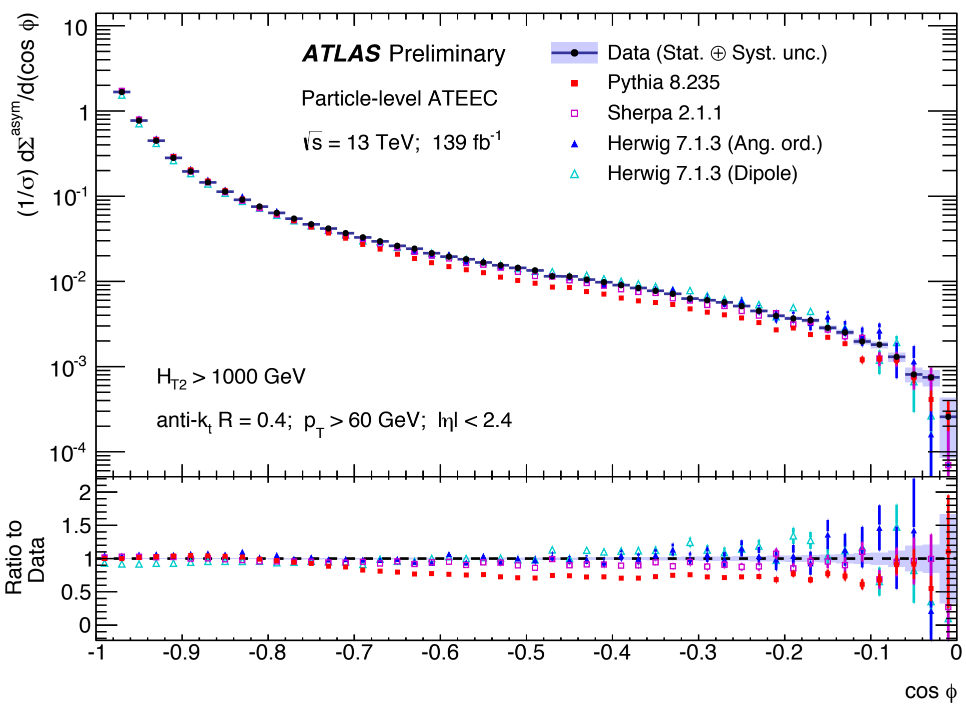


ATLAS α_s running

- α_s determination inspired by Energy-Energy Correlation (EEC) used for QCD at e^+e^-
- Transverse energy-energy correlation (**TEEC**) and their associated azimuthal asymmetries (**ATEEC**) based on jets (p_T>60 GeV, |y|<2.4) rather than hadrons
- Unfolded results compared to NLO pQCD x NP to extract values of α_s
  - uncertainty completely dominated by theory scale uncertainty at NLO

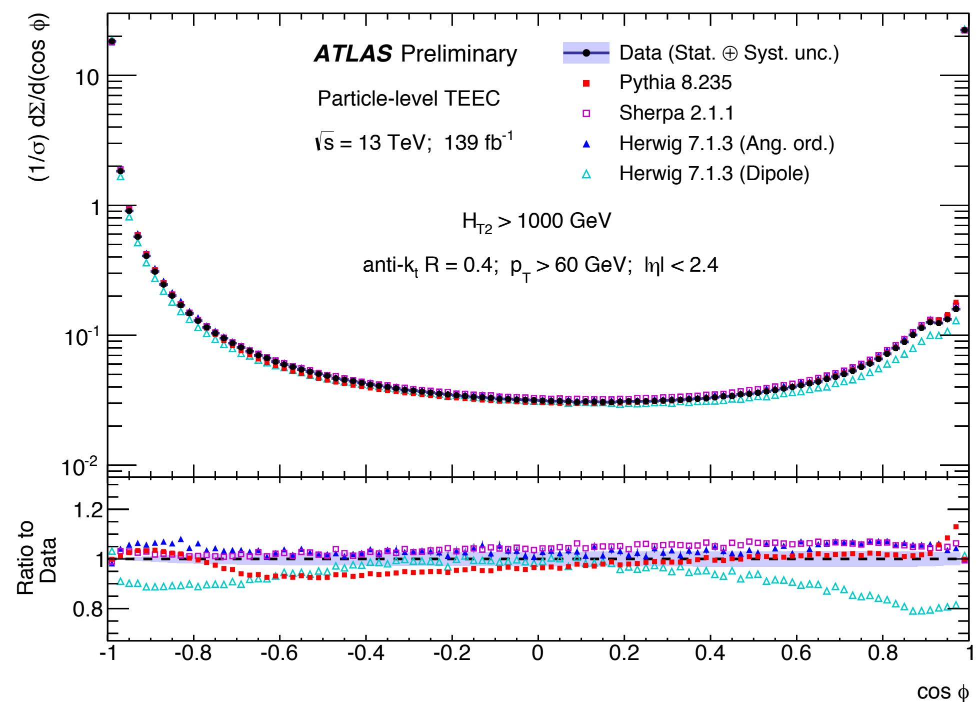
ATEEC

ATLAS-CONF-2020-025



TEEC

ATLAS-CONF-2020-025



ATLAS α_s running

- Two variants of α_s determination from (A)TEEC functions
  - Testing α_s running: local determination of $\alpha_s(Q)$
  - Assuming RGE: global $\alpha_s(m_Z)$ = 0.1196 ± **0.0004** (exp.) +0.0072 **-0.0105** (theo.)
- α_s running tested up to 4 TeV, central value consistent with global average (±**0.0011**)

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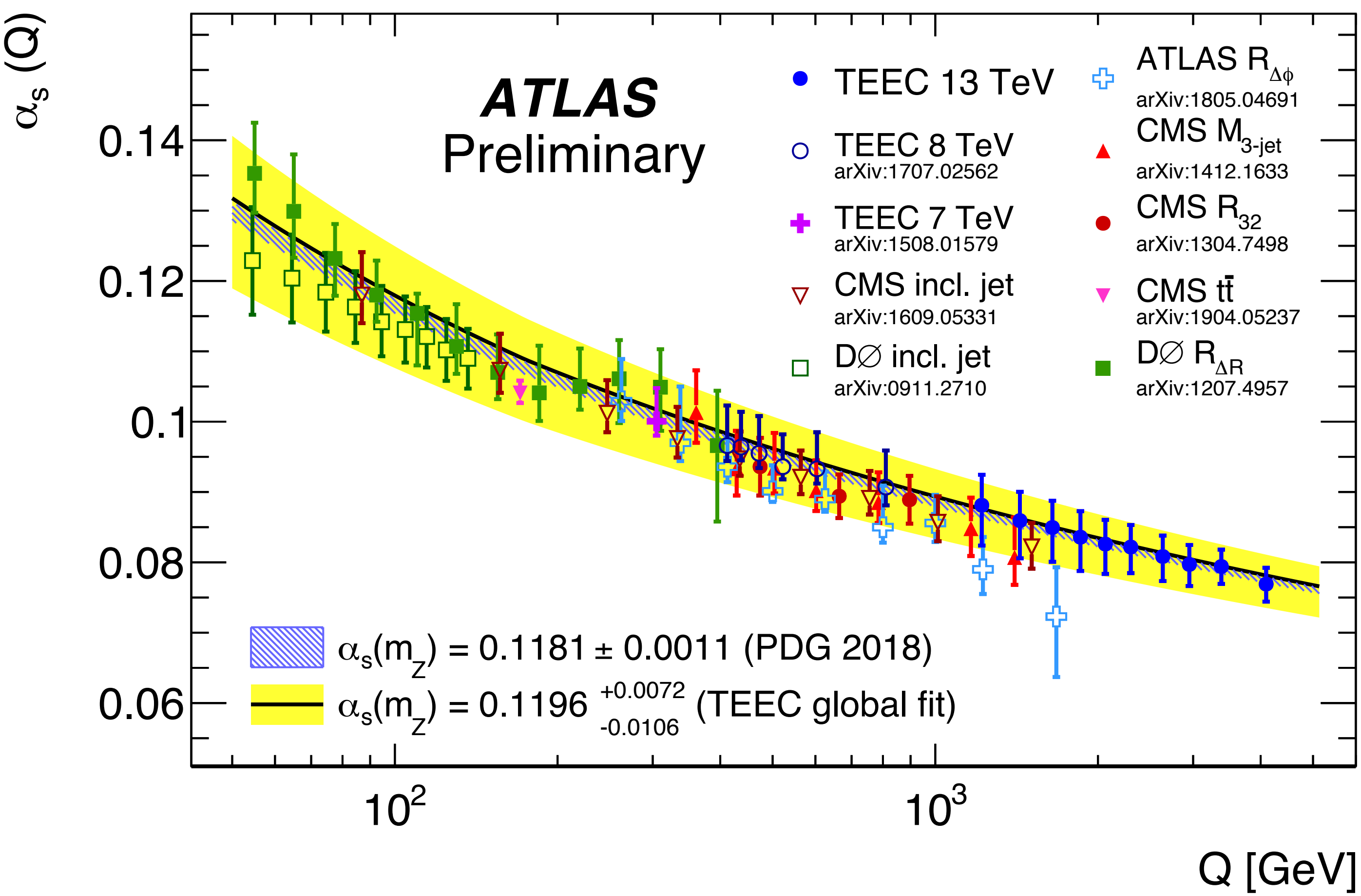
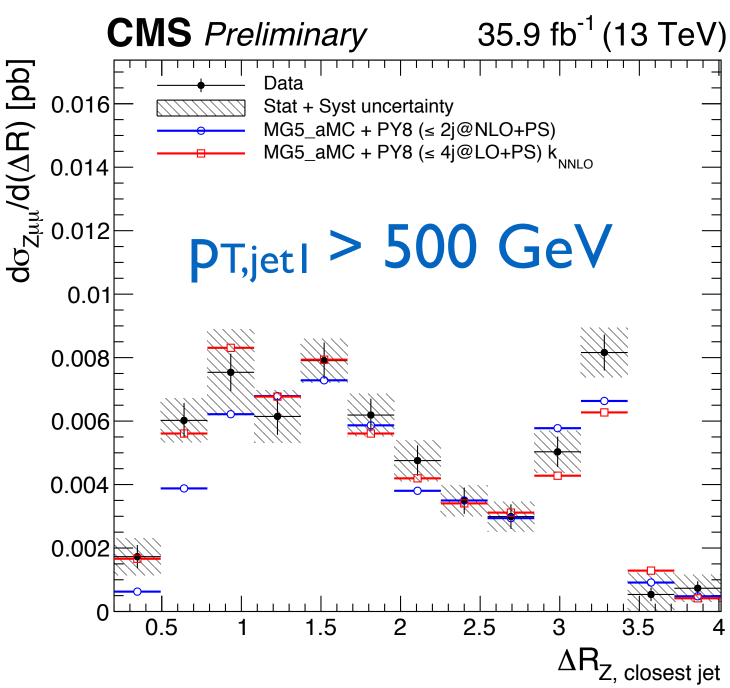


Jets with Z/γ

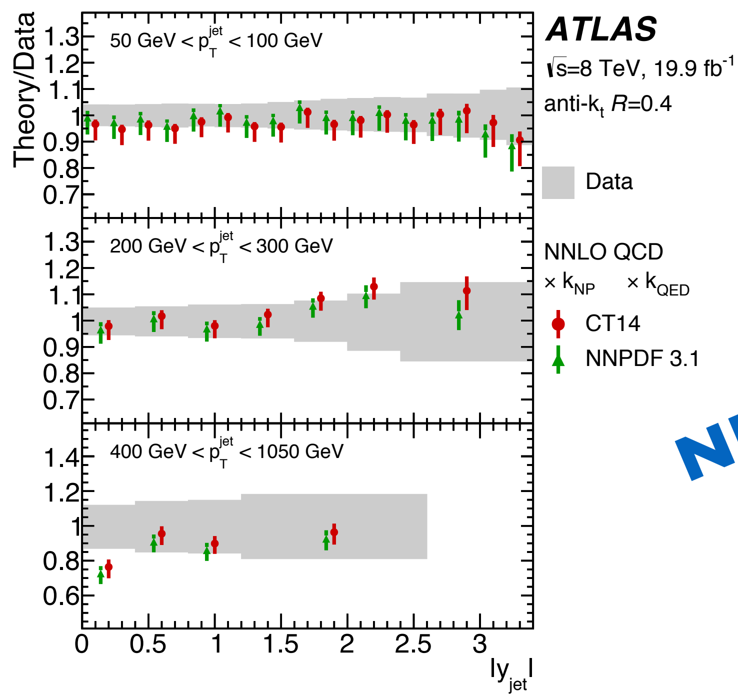
- Z+jet primarily qg>qZ, while inclusive jets gg>gg or qg>qg
  - complementary look at QCD processes
- At high jet p_T, Z also produced collinear with jets (qq>qqZ)
  - useful to separate back-to-back and collinear Z+jet
- Z+jet increasingly numerous, extend beyond 1 TeV at 13 TeV
  - coupled with now NNLO precision, many opportunities

Collinear Z+jet

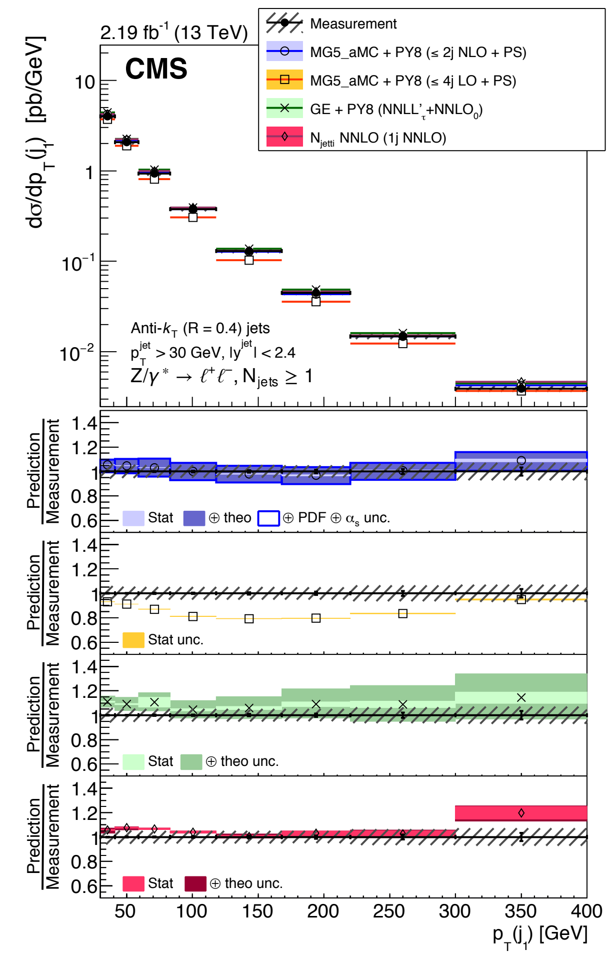
CMS-PAS-SMP-19-010



1907.06728 (EPJC79 (2019) 847)



1804.05252 (EPJC78 (2018) 965)

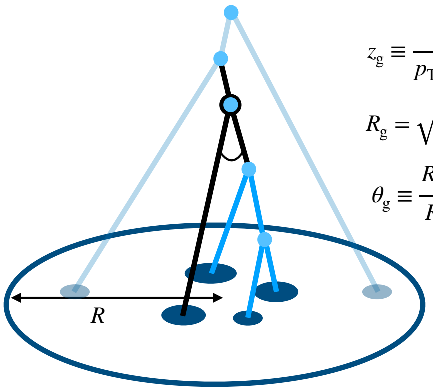


NNLO!

ALICE jet substructure

- Jet substructure is currently a hot field (with conference series BOOST)
  - too many new results from ATLAS and CMS to show here, so highlight ALICE's growing program
- ALICE well suited for low p_T jet substructure, with tracking+particle ID down to 150 MeV
- Many tools: soft drop ($z<z_{cut}\theta^{\beta}$), **dynamical grooming (z_g,θ_g),** jet angularities (λ^{κ}_{β}) etc.

ALICE-PUBLIC-2020-006

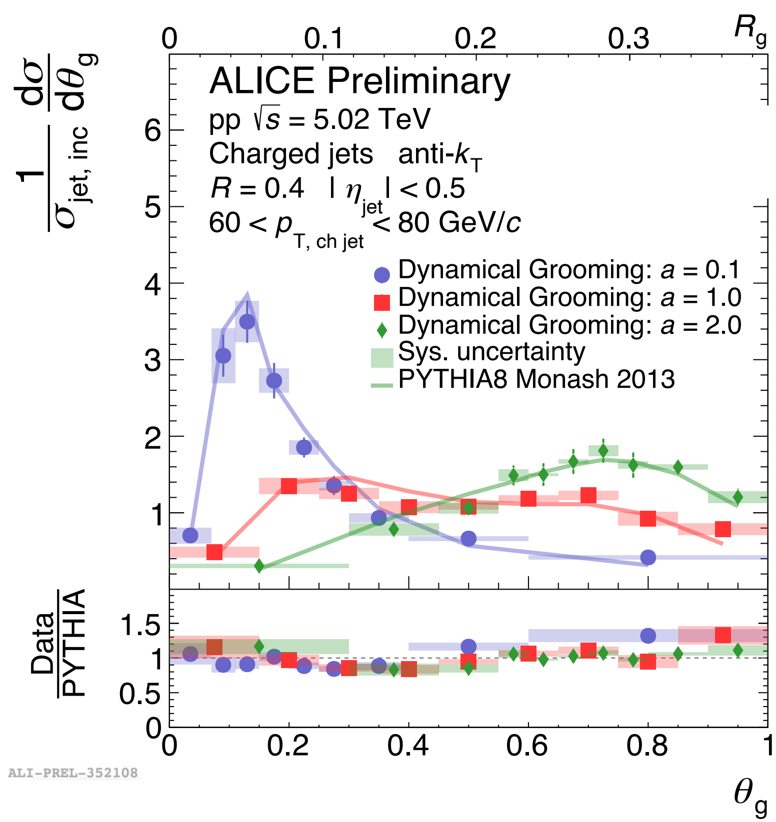


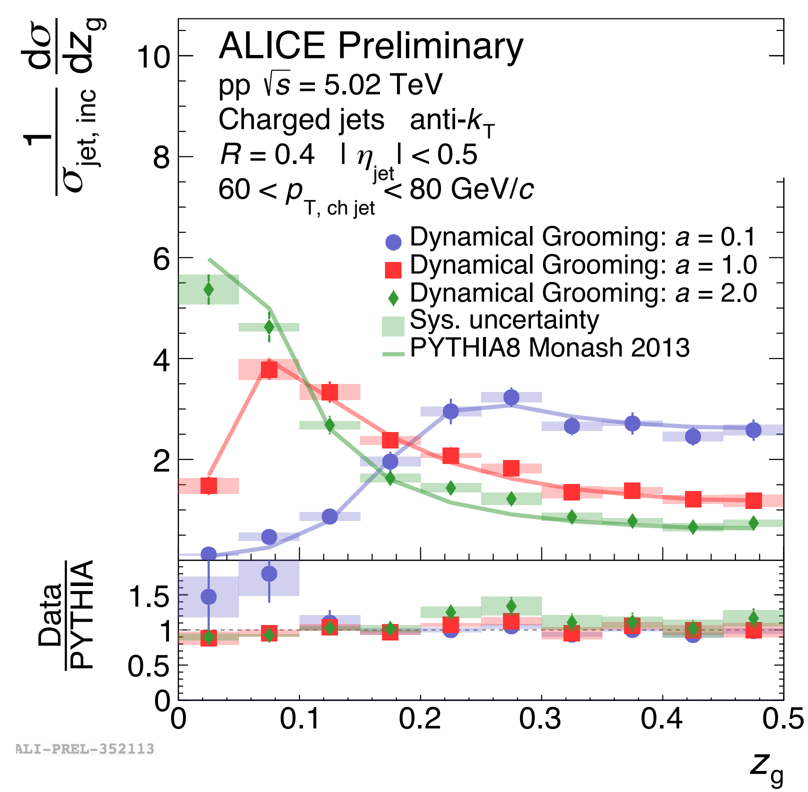
$$z_g \equiv \frac{p_{T,\mathrm{subleading}}}{p_{T,\mathrm{leading}} + p_{T,\mathrm{subleading}}}$$

$$R_g = \sqrt{\Delta y^2 + \Delta\varphi^2}$$

$$\theta_g \equiv \frac{R_g}{R}$$

Dynamical grooming: **max** split of C/A tree's $z_i\,(1-z_i)\,p_{T,i}\,\theta^{a}_i$

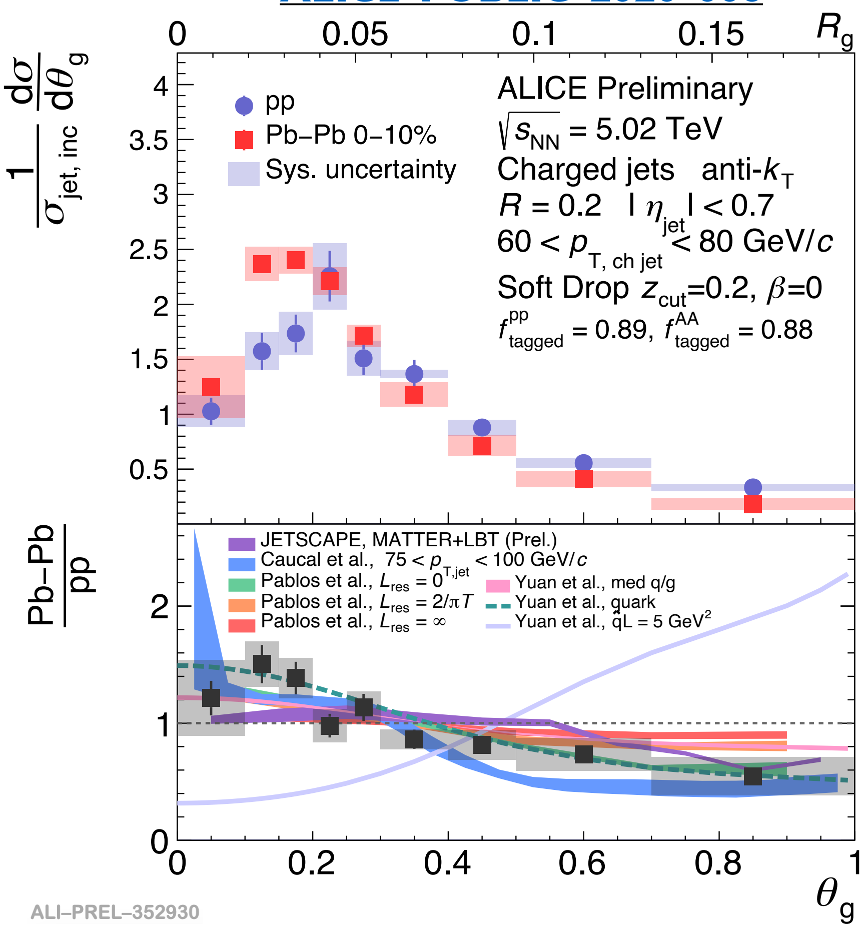




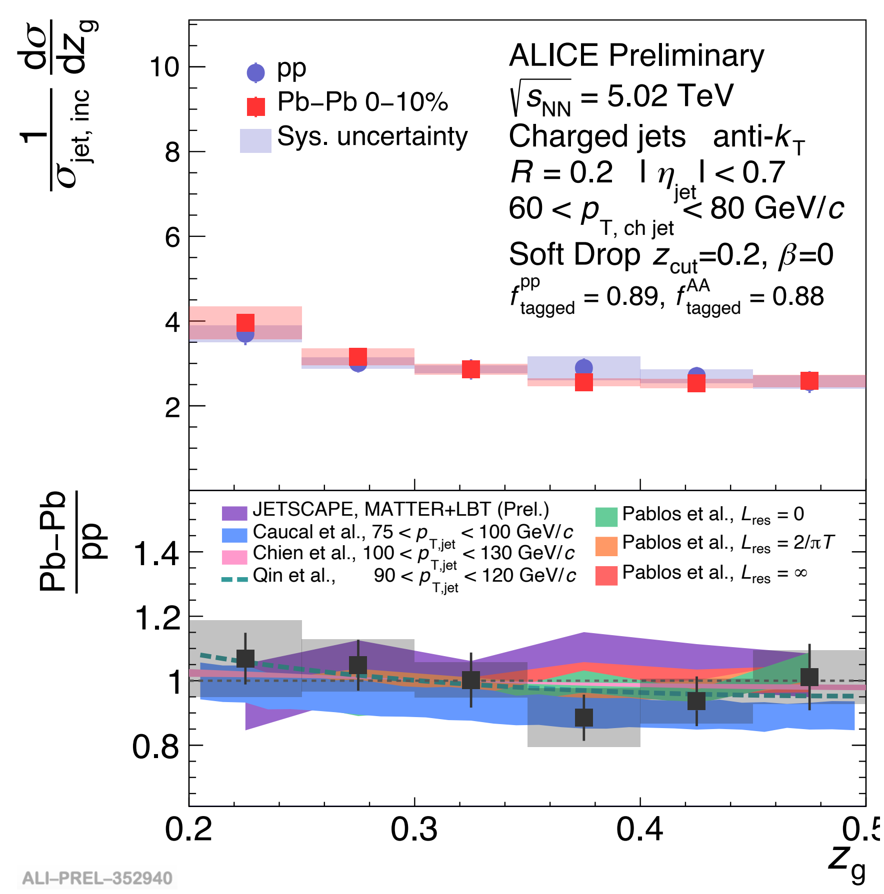
ALICE dense medium

- Jets in heavy ion collisions studied by ATLAS, CMS and ALICE, but real forte of ALICE
- Dense QCD medium of heavy ion (PbPb) collisions modifies jets, but exactly how?
- Ratio of z_g and θ_g in PbPb and pp suggests collimation of θ_g, but little modification of z_g

ALICE-PUBLIC-2020-006



ALICE-PUBLIC-2020-006



more to explore: 1905.02512 (PLB802 (2020) 135227)

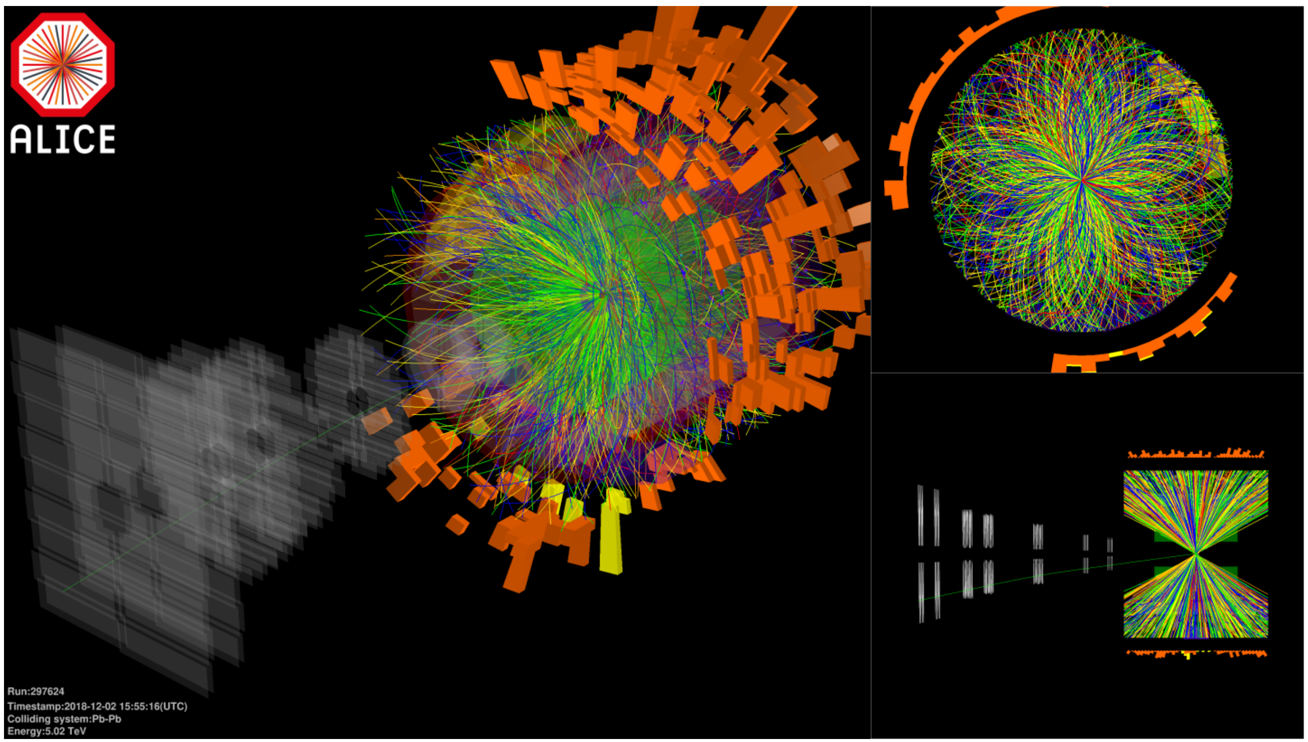
Summary and outlook

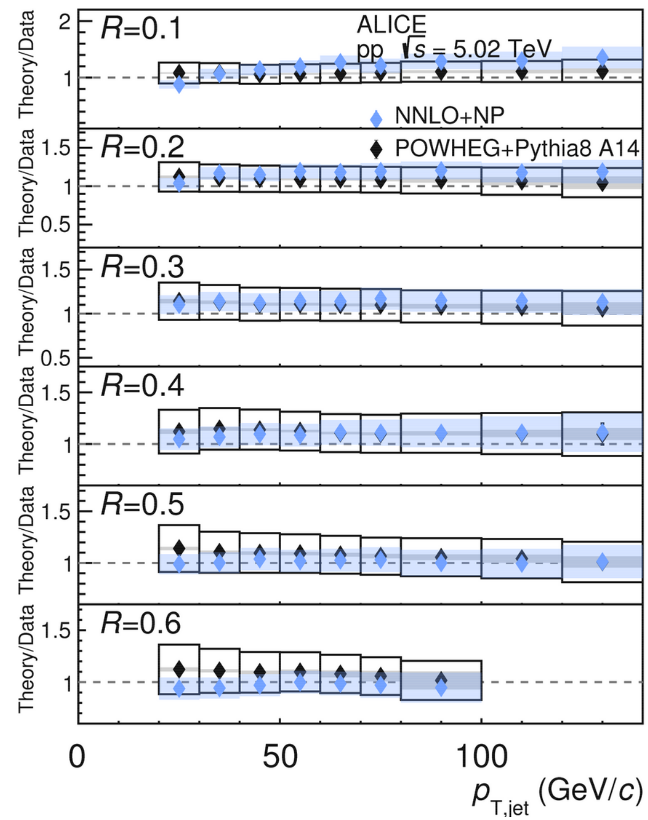
- Lots of data extending to high p_T, precise Run 2 results starting to come out
- NNLO(xNLL) precision way forward for α_s, PDFs
- Improved modelling of multijets, jet substructure pays dividends for JES in a virtuous cycle
- Jet substructure now a big community, ALICE grown into an important player in jets

NNLO

Currie, Glover, Pires PRL 118 072002 (2017)

See also: Czakon et al. JHEP 262 (2019)





Inclusive jets overview

- Partial listing of inclusive jet measurements at the LHC, as shown in this talk

	ALICE	ATLAS	CMS
2.76			
5.02	1905.02536 (ch. only) 1909.09718	-	-
7	-		
8	-	1706.03192	1609.05331
13 TeV	Santa Fe 2020	1711.02692	1605.04436 (71/pb) 2005.05159 (R)