Overview of
Jet measurements at the LHC

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for the ALICE, ATLAS and CMS collaborations

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  - CMS PAS: (Z+c, Z/gamma+jets,) **Z+2jet/multijet (SMP-17-008), color singlet (SMP-19-006)?, substructure (jet mass)?**
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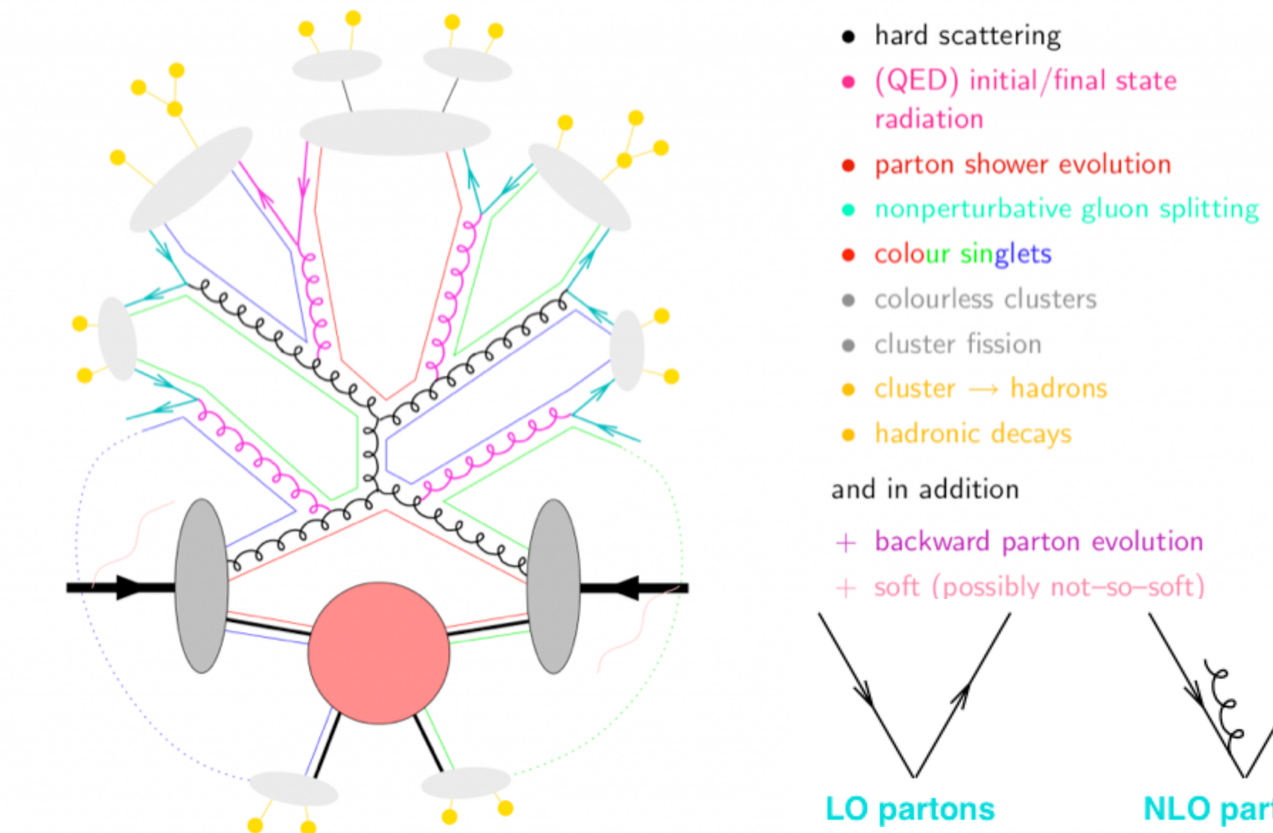
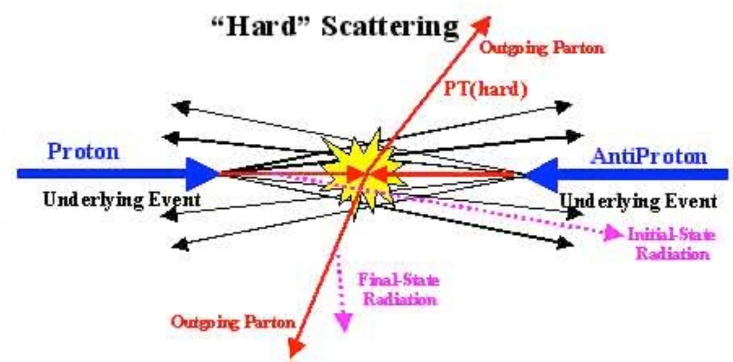
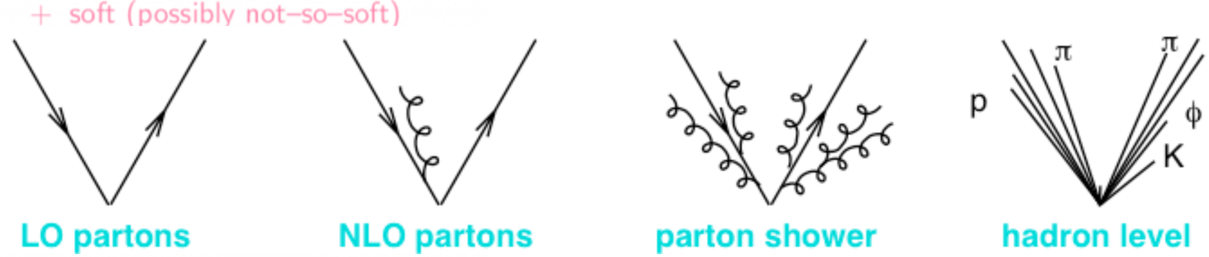
  - ATLAS soft drop?

Motivation

- 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)
  - soft QCD - low p_T: multiparton scattering, fragmentation, underlying event, etc.
- Second goal: searching new physics at the energy frontier (Saoulidou / Wed)

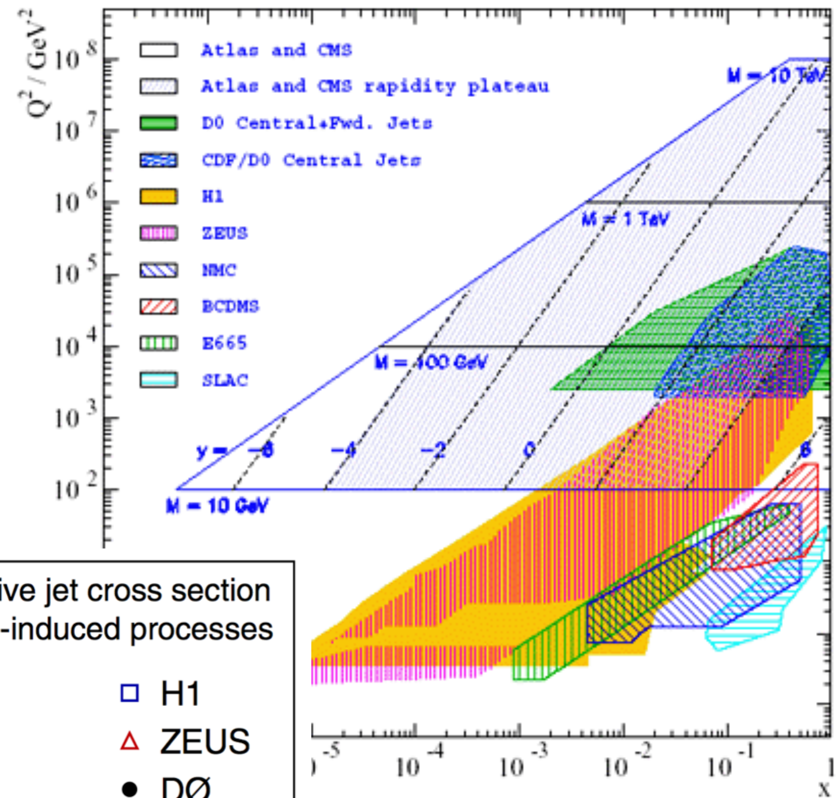


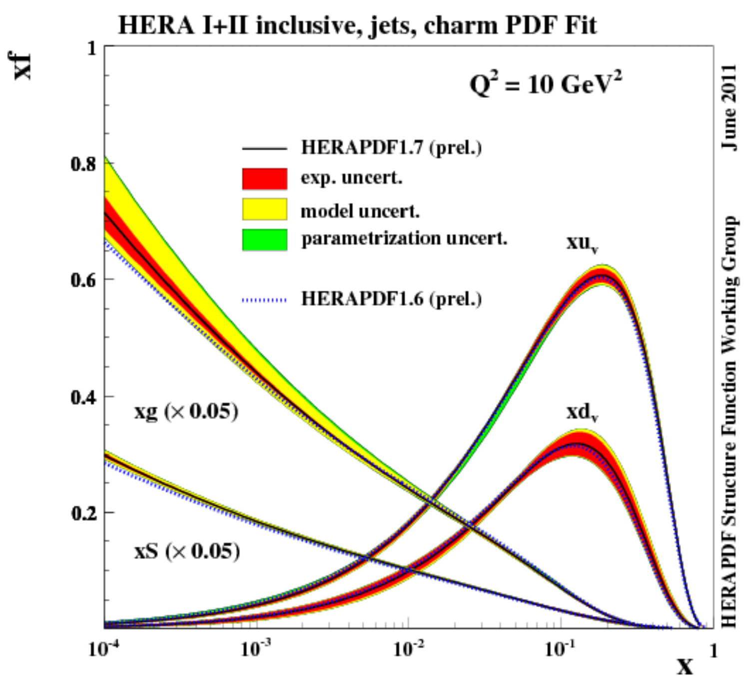


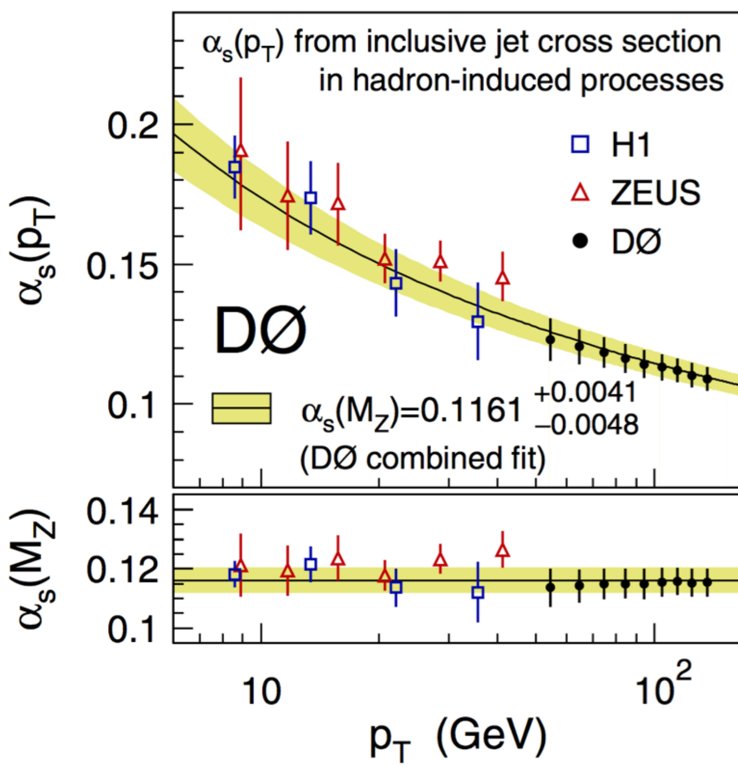


Parton distributions, α_s

- 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
- E.g. inclusive jets useful for high-x gluon PDF and determination of α_s running





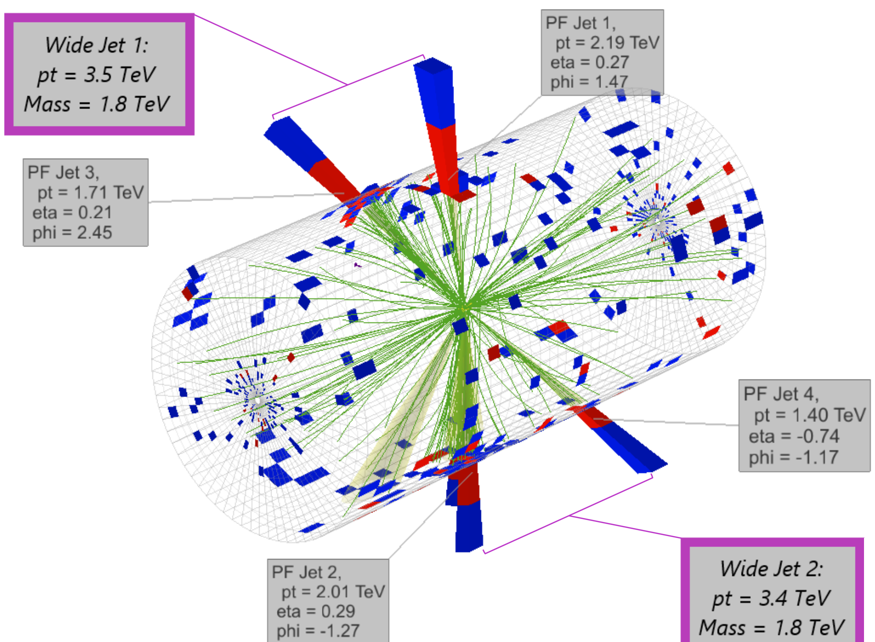


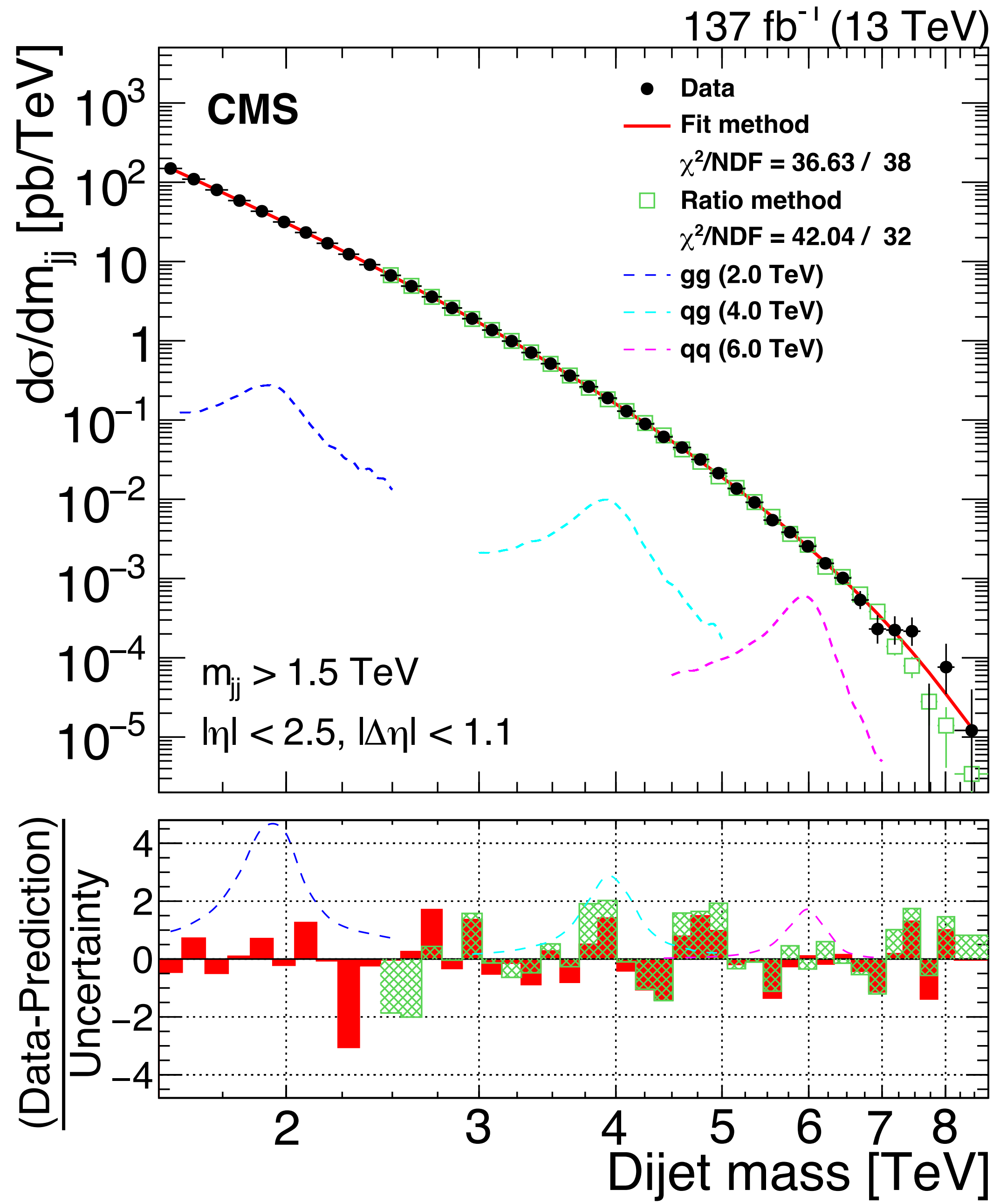
LHC

HERAPDF [link]

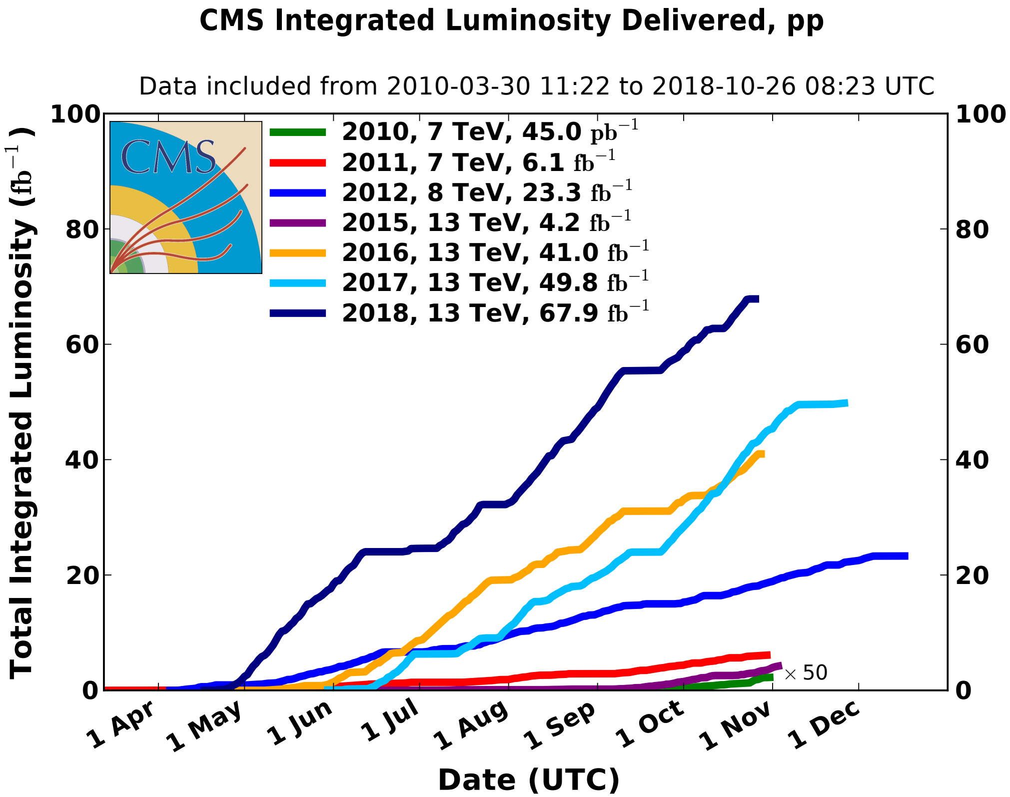
Energy frontier

- 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





EXO-19-012



Run 2

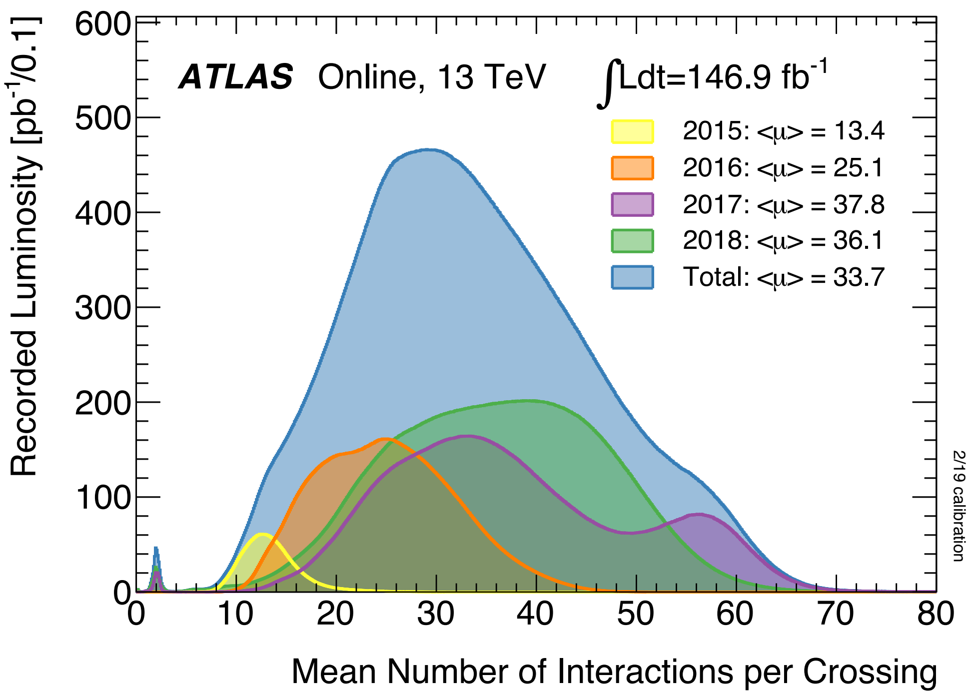
- 2015, `4.2/fb`
- 2016, `41.0/fb`
- 13 TeV, `162.9/fb (2015-18)`

Special runs (pp reference)

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

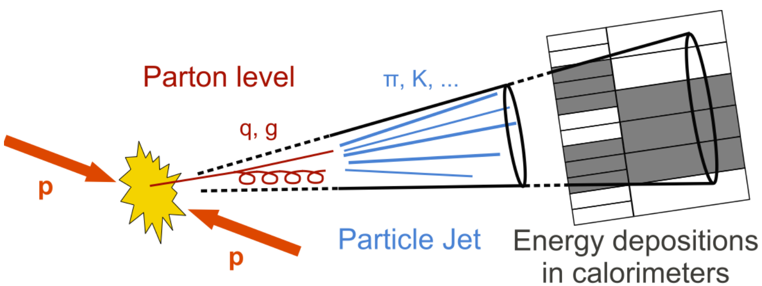
Run I

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

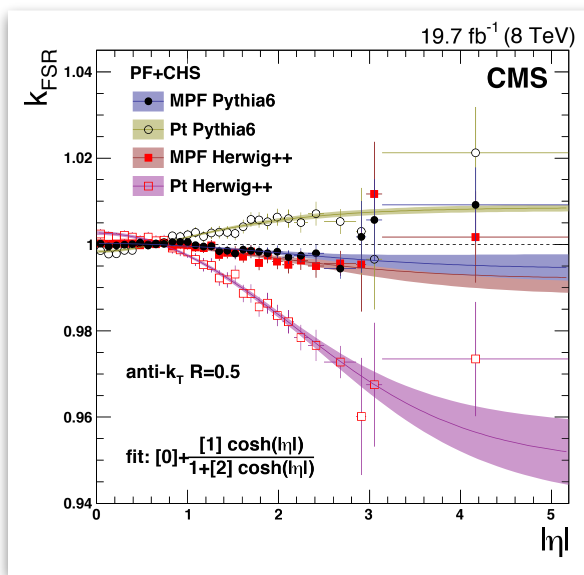


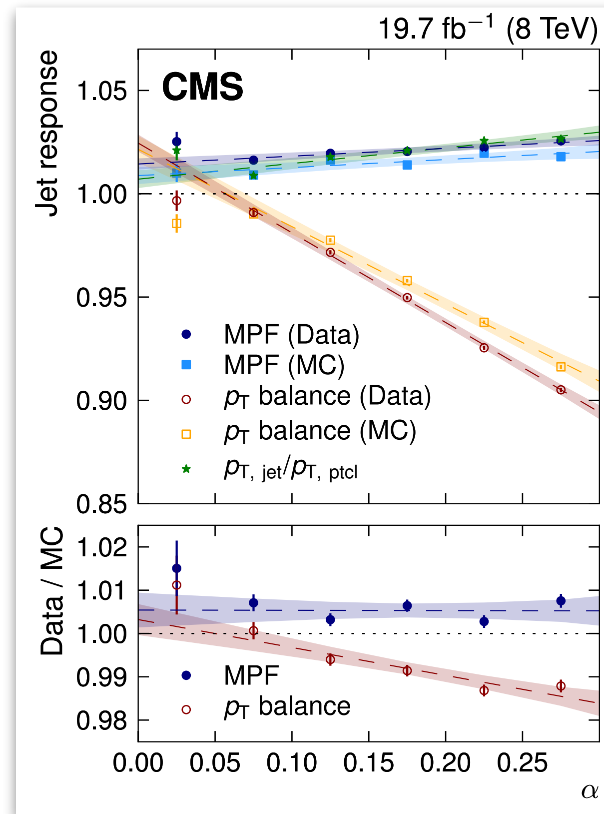
Jet corrections

- 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)
  - ideally: publish auxiliary measurements such as Z($\mu\mu$)+jet and dijet balance to correlate expts?



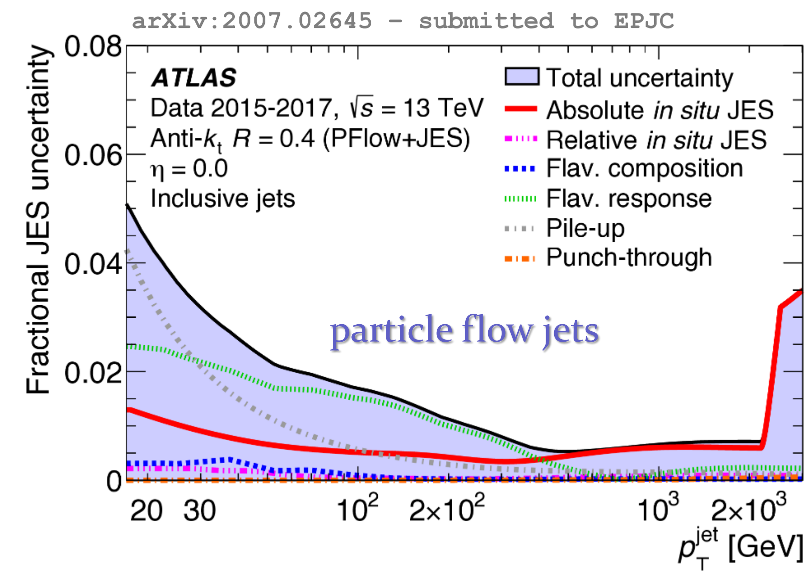
CMS, arXiv:1607.03663

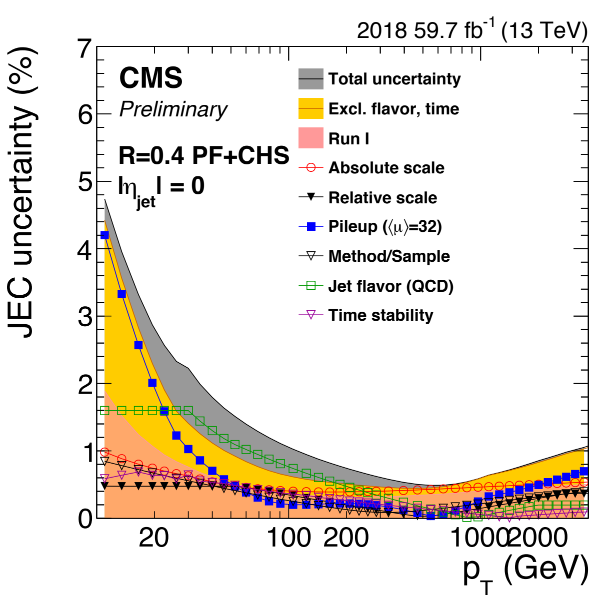




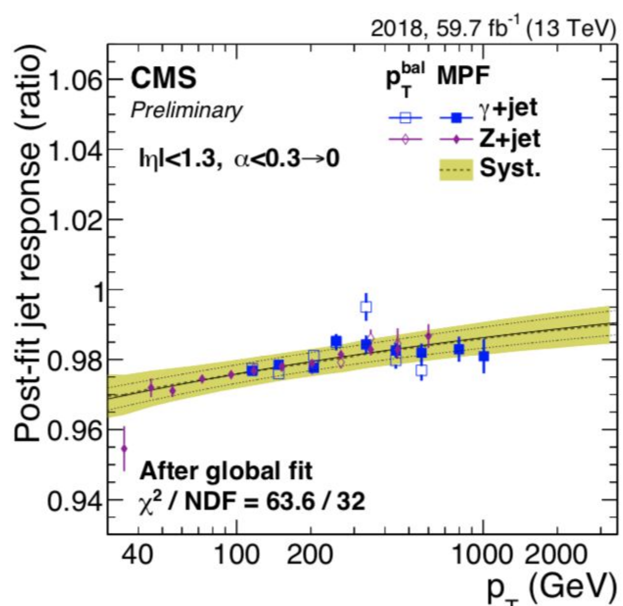
Jet scale at 13 TeV

- 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

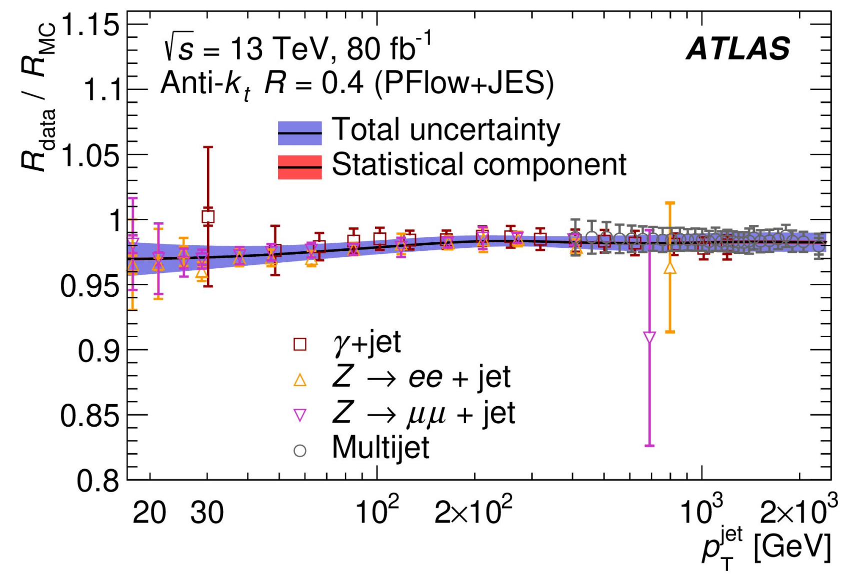




CMS DP-2020/019

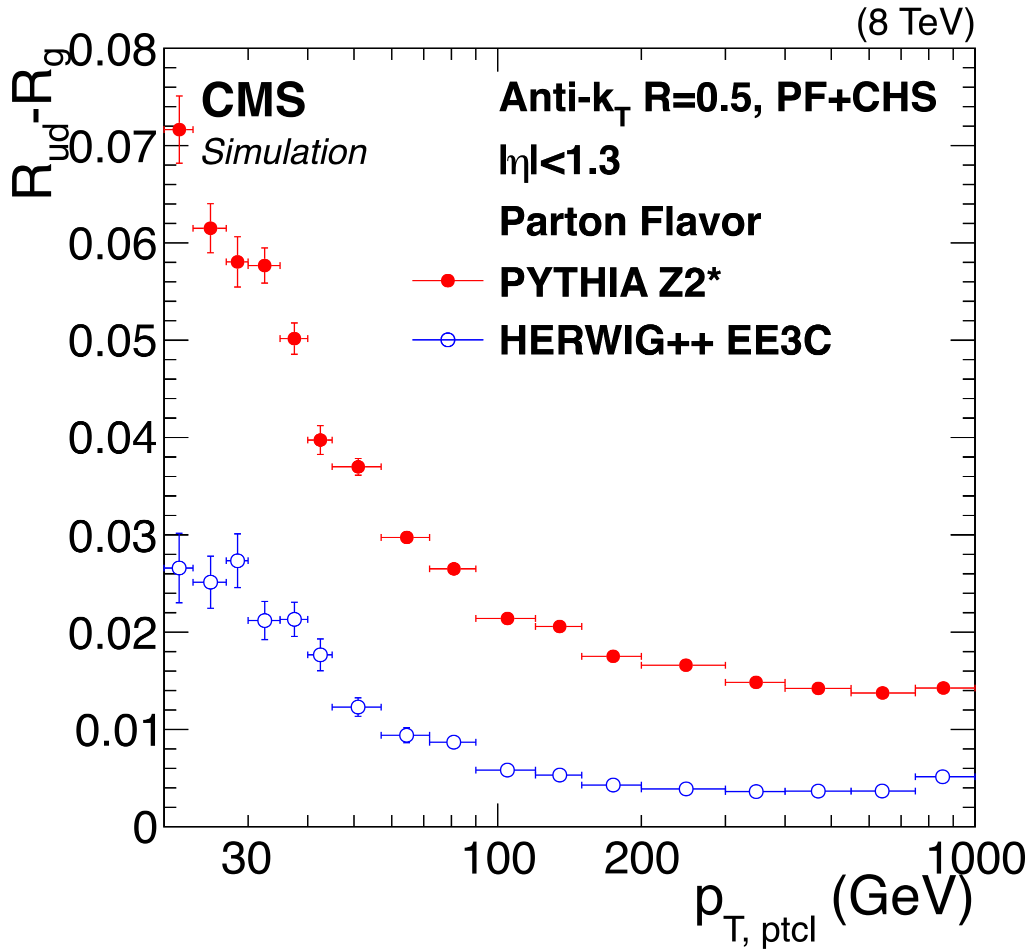


CMS DP-2020/019

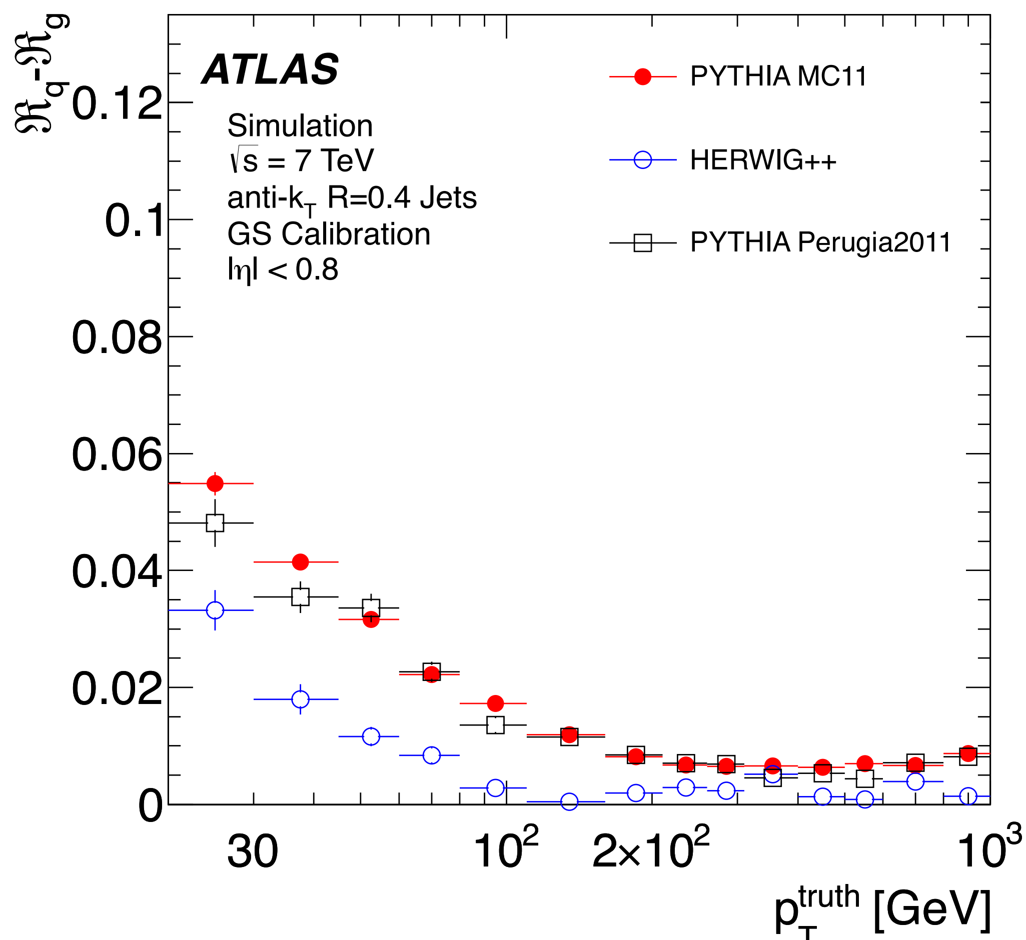


Gluon jets

- 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



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/PERF-2012-01/

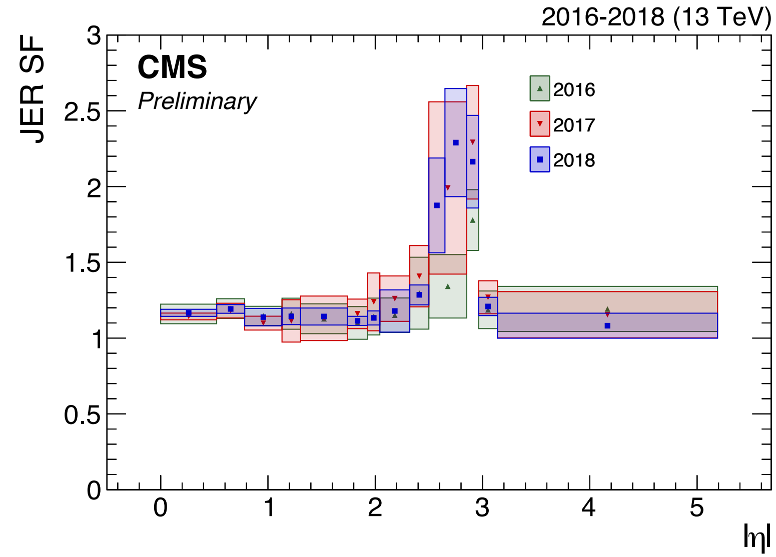


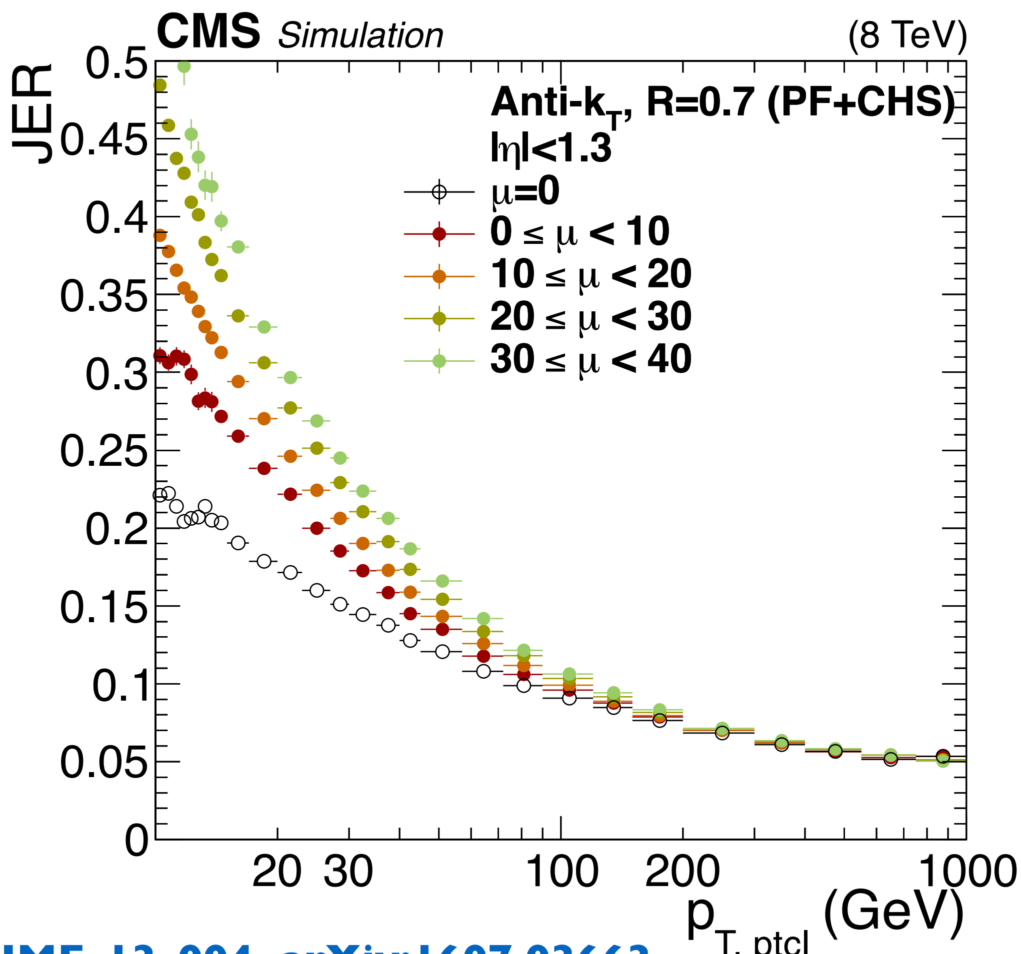
CMS, arXiv:1607.03663

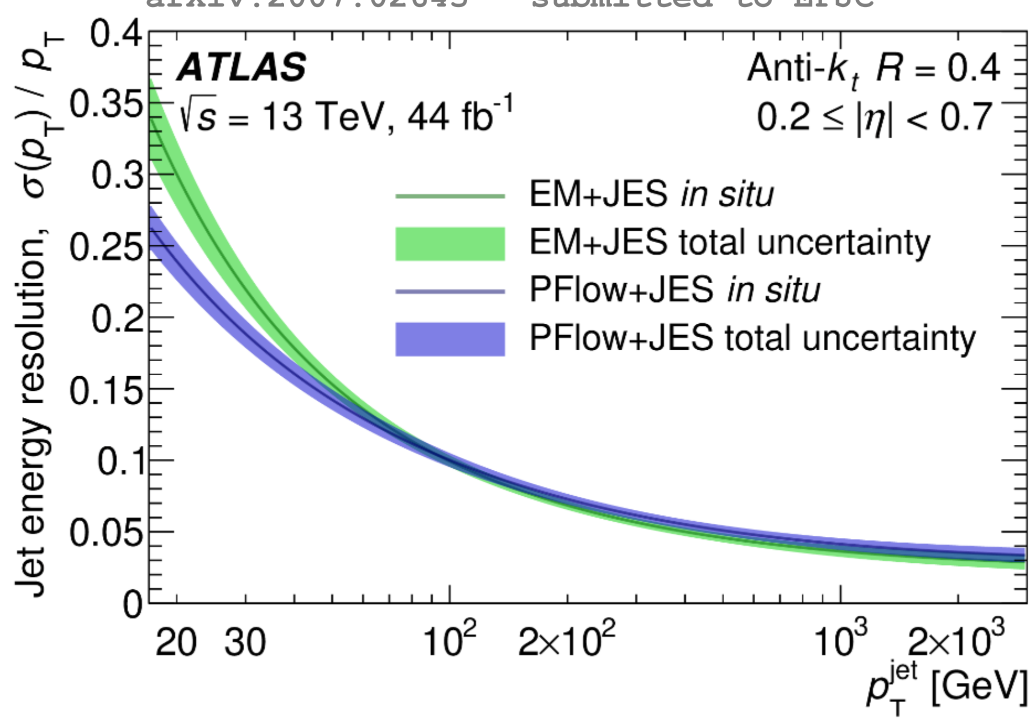
ATLAS, Eur. Phys. J. C (2015) 75:17

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?







JME-13-004, arXiv:1607.03663

Inclusive jets overview

- Cone sizes and luminosity for experiments at each sqrt(s)
- Bold measurements are current state-of-the-art in precision from each expt.

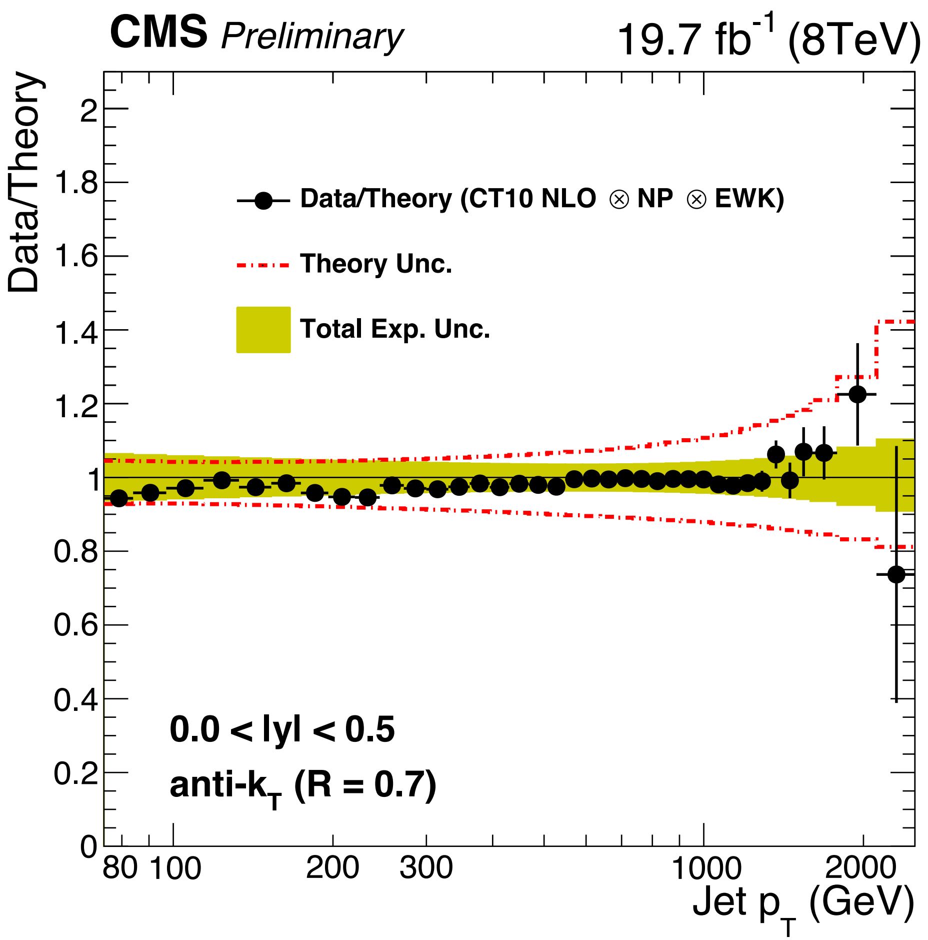
	ALICE	ATLAS	CMS
2.76			
5.02			
7			
8			
13 TeV			

Inclusive jets 5 TeV

- Small-R reference for PbPb: ALICE https://alice-publications.web.cern.ch/node/5560
  - substructure: https://alice-publications.web.cern.ch/node/5256
  - charged jets: https://alice-publications.web.cern.ch/node/5257

Inclusive jets 8 TeV

- Present state-of-the-art at CMS and ATLAS, until new 13 TeV results published



- Upcoming contender with full Run 2 data. ATLAS 4.2/fb (2015) result compared to NNLO

Inclusive jet and di-jet cross section

JHEP 05 (2018) 195

Data collected from pp collisions at $\sqrt{s} = 13$ TeV in 2015

Inclusive jet cross section measured in terms of jet transverse momentum with 100 GeV $< p_{\mathrm{T}}^{\mathrm{jet}} <$ 3.5 TeV and $|y^{\mathrm{jet}}| < 3$

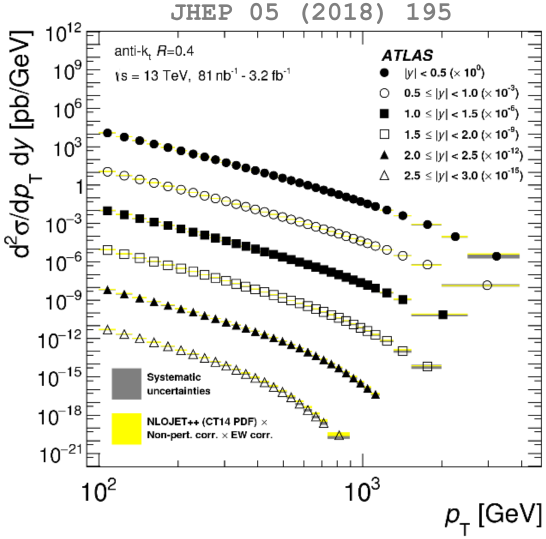
Inclusive dijet production cross section measured in terms of the invariant mass of the two leading jets 900 GeV $< m_{\mathrm{jj}} <$ 9 TeV and $y^* = \left|\left(y_{\mathrm{lead}}^{\mathrm{jet}} - y_{\mathrm{sublead}}^{\mathrm{jet}}\right)/2\right| < 3$

Comparison to QCD predictions

NLO & NNLO calculations with non-perturbative QCD and electroweak corrections and various PDFs

Comparison to theory favors QCD @ NNLO for $|y^{\mathrm{jet}}| < 2$

JHEP 05 (2018) 195



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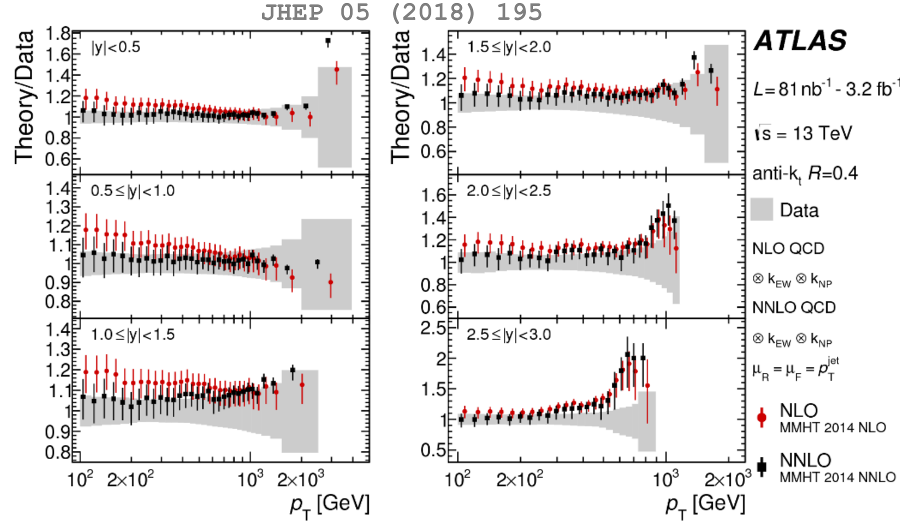
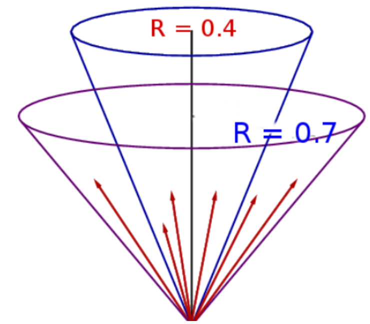


Slide 4 Peter Loch – *ICHEP 2020* July 28, 2020

CMS radius scan

- Radius scan powerful test of high-order pQCD
  - NLO(1.0/0.4) = NNLO(1.0) / NNL(0.4), i.e. "one up"
- Also test of parton shower and radius resummation
  - particularly of new NLL resummation
- Comprehensive scan from R=0.1 to R=1.2 in steps of 0.1
  - relative to AK4; absolute AK4 results to appear in next paper

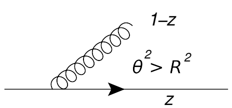
AK4 chosen as reference because it is the standard *R* in CMS during Run-2



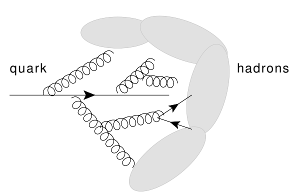
Different distance parameter *R* are sensitive to different parts of jet formation.

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

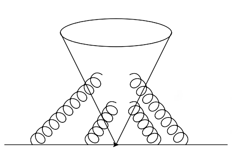
Parton shower: $(\delta p_T)_{PS} \sim \ln(1/R)$

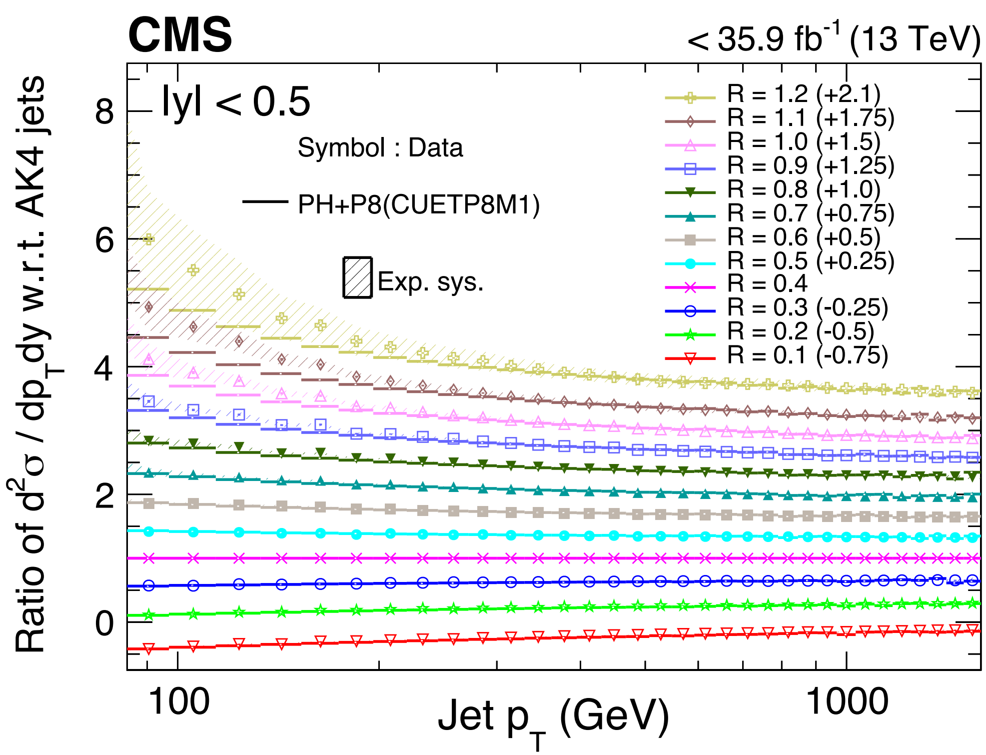


Hadronization: $(\delta p_T)_{HAD} \sim R^{-1}$



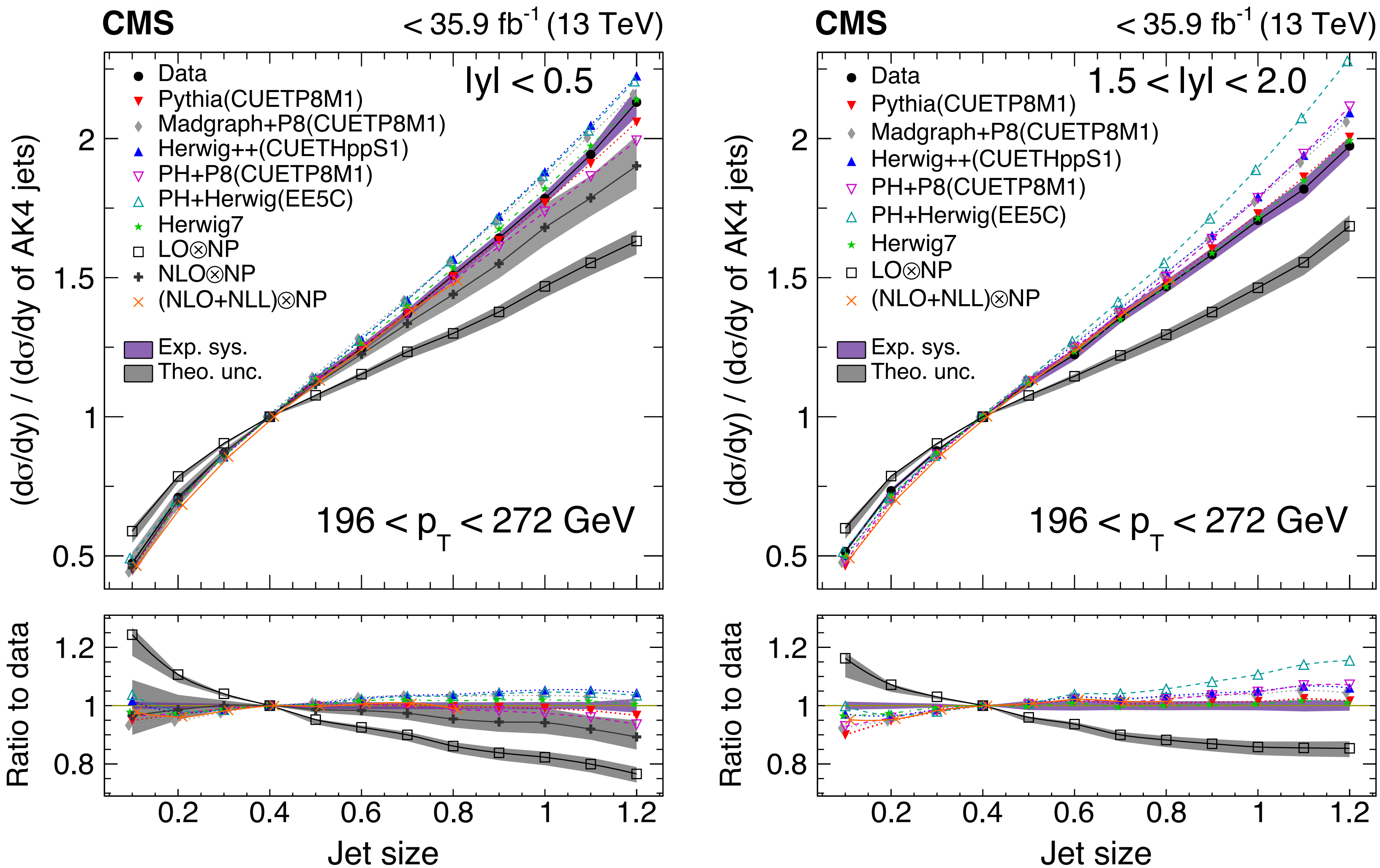
Underlying event activity: $(\delta p_T)_{UE} \sim R^2$.





arXiv:2005.05159

CMS radius scan

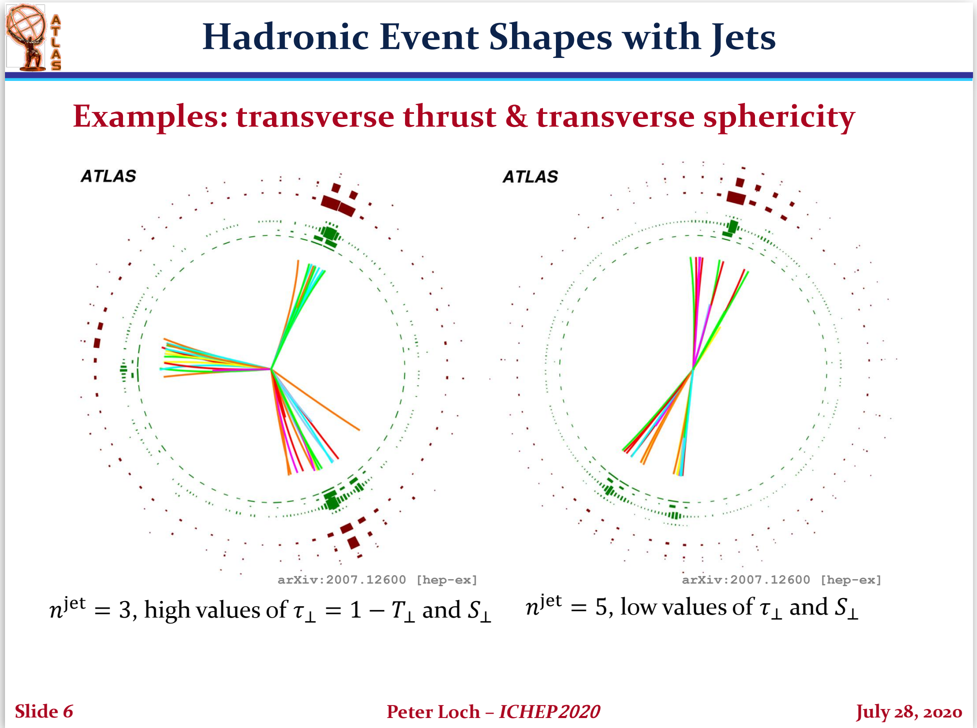


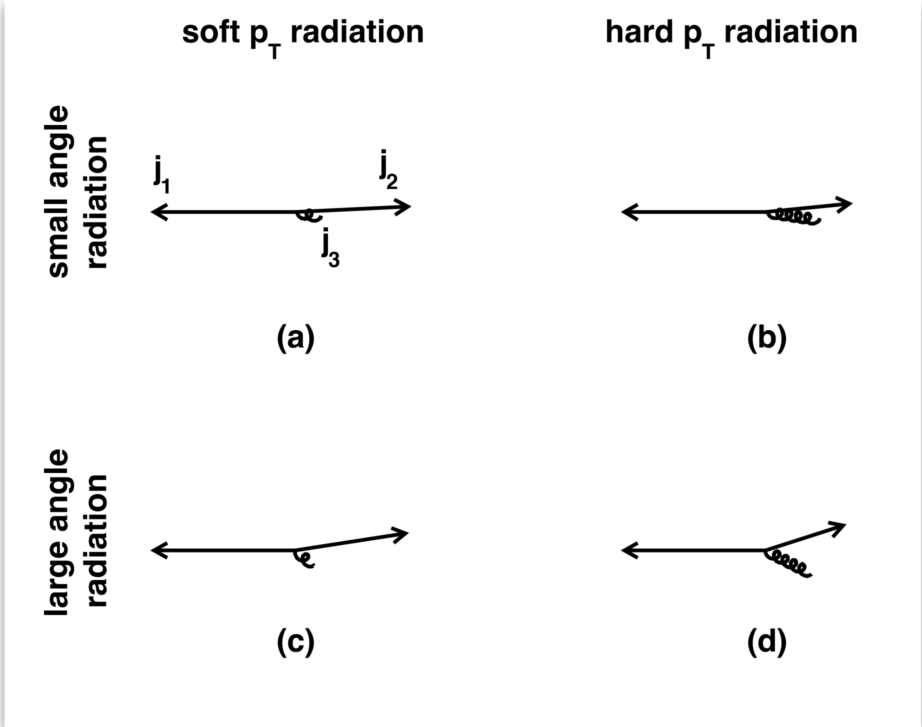
arXiv:2005.05159

- Central region $|y| < 0.5$ (**Left**) and forward region $1.5 < |y| < 2.0$ (**Right**).
- Best agreement achieved by NLO predictions in general R parameter range.
- NLO predictions slightly overshoot data at larger R values in forward region.

Multijets

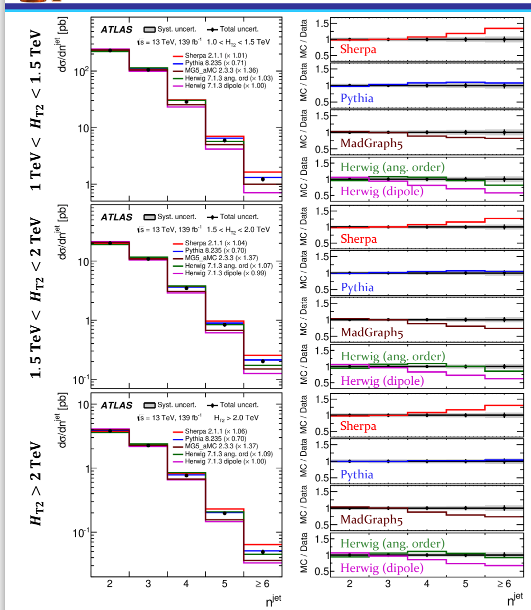
- ATLAS measures multijet event shapes (transverse thrust, sphericity)
- CMS measures multijets versus ΔR_{23} and p_{T3}/p_{T2}





ATLAS multijets

Modeling of Jet Multiplicities



Fiducial cross section

Measured as function of n^{jet}

Evaluated in same three regions of H_{T2} used for event shape measurements – provides normalization

Modeling $d\sigma/dn^{\mathrm{jet}}$ shapes

Pythia 8.235

$2 \to 2$, LO accuracy

Generally good agreement for all n^{jet}

Sherpa 2.2.1

$2 \to \{2,3\}$, LO accuracy (multi-leg)

Overestimation (increasing) for $n^{\mathrm{jet}} > 4$

Herwig 7.1.3 (angular ordered PS)

$2 \to 2$ NLO accuracy, $2 \to 3$ LO

Good description with slight underestimation for $n^{\mathrm{jet}} \geq 6$

Herwig 7.1.3 (dipole PS)

$2 \to 2$ NLO accuracy, $2 \to 3$ LO

Good description for low n^{jet}, underestimation for higher n^{jet}

MadGraph5_aMC 2.3.3

$2 \to \{2,3,4\}$ NLO accuracy

Good description for low n^{jet}, underestimation for higher n^{jet}

Modeling normalization

Well predicted at low n^{jet}

Only small differences between models

Large spread in normalization at high n^{jet}

Sherpa predicts 30% more than data

Herwig (dipole PS), MadGraph predict 30% less

arXiv:2007.12600 [hep-ex]

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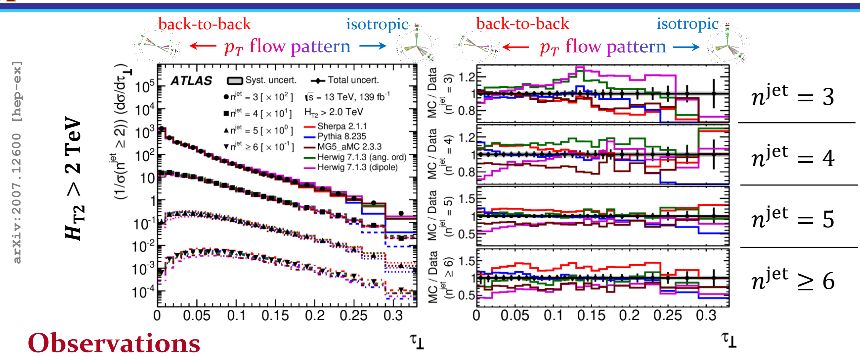
Transverse Thrust with Jets



Observations

Evolution with increasing hardness of interaction

More events with more isotropic flow at softer interactions (lower H_{T2})

Increasing H_{T2} yields increased contribution from events with close to back-to-back flow patterns

Comparisons to models

Evaluation of predictions

Generally fewer isotropic events in MC than in data at low n^{jet} – better agreement at higher jet multiplicities

Shapes of cross sections

None of the considered MC generators gives good description in full phase space

Similar distribution shapes at high n^{jet} from all considered model

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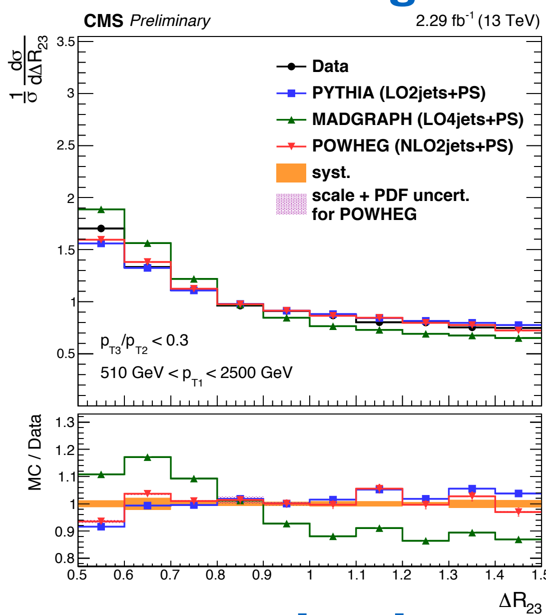
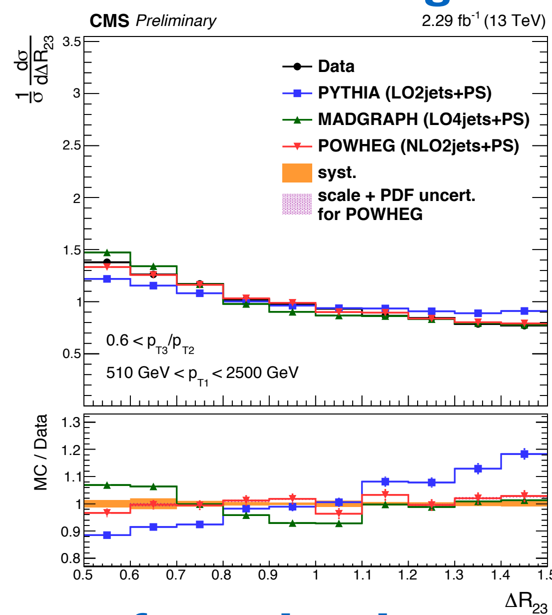
CMS multijet

- **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

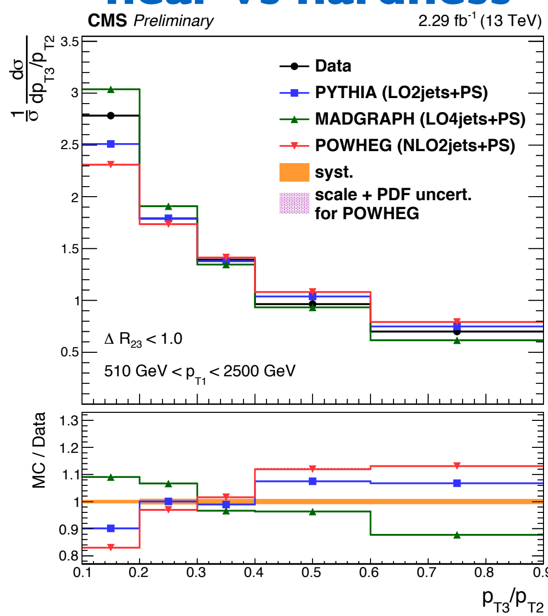
soft vs angle



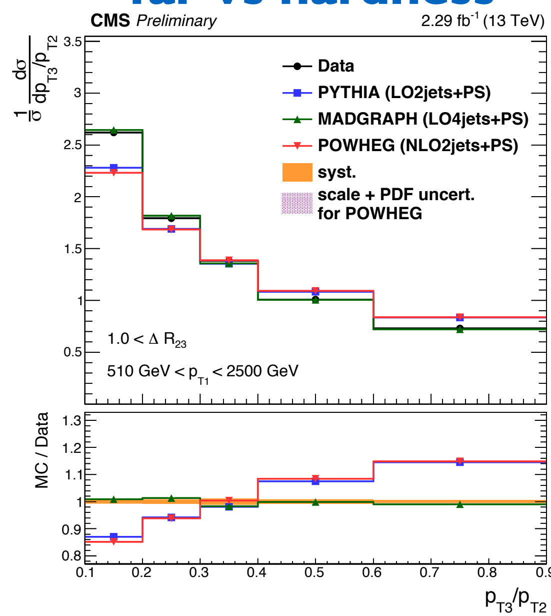
hard vs angle



near vs hardness



far vs hardness

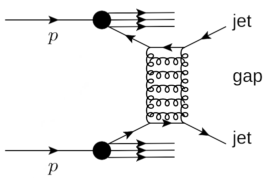


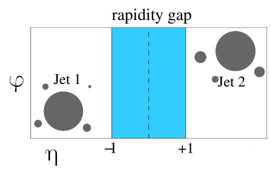
CMS-PAS-SMP-17-008

ATLAS Lund plane

- Lund plane separates various effects, similar to CMS paper but more general
- Similar observations to CMS: no generator works across full Lund plane

Jet-gap-jet process as a probe of BFKL dynamics (CMS-PAS-SMP-19-006)





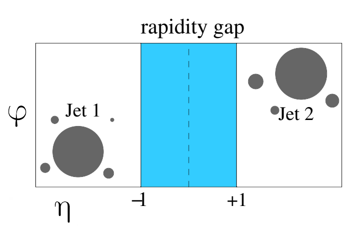
- In collisions with t-channel color singlet exchange between partons, color-flow is neutralized → Rapidity interval void of particle production between jets (rapidity gap). Jets are produced back-to-back with very little additional jet activity.
- In high-energy limit of QCD ($\hat{s} \gg -\hat{t} \gg \Lambda^2_{\text{QCD}}$), color-singlet exchange corresponds to perturbative pomeron exchange (two-gluon ladder). Jet-gap-jet as a probe of Balitsky-Fadin-Kuraev-Lipatov (BFKL) evolution (resummation of $\alpha_s^n \log^n(\hat{s}/|\hat{t}|) \sim \mathcal{O}(1)$ terms).
- Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) dynamics are strongly suppressed in jet-gap-jet events (Sudakov form factor for gap) → Clean probe of BFKL dynamics.

Jets separated by a pseudorapidity gap (CMS-PAS-SMP-19-006)

Analysis based on 2015 data $\sqrt{s} = 13$ TeV with low pileup (PU ∼ 0.05-0.10).

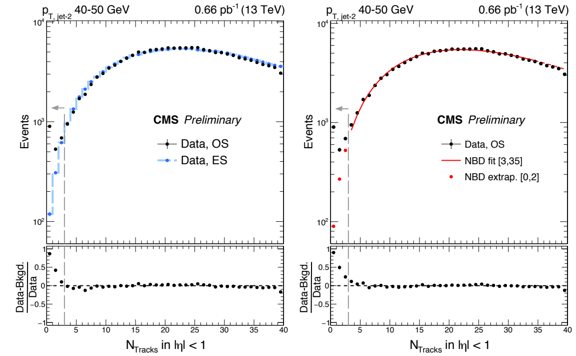
Event selection:

- Anti-k_t jets with $R = 0.4$.
- Leading two jets have $p_T > 40$ GeV and $1.4 < |\eta_{\text{jet}}| < 4.7$ with $\eta_{j1} \times \eta_{j2} < 0$ → Favors t-channel color singlet exchange.
- At most one reconstructed primary vertex $N^{PV} \leq 1$.



Pseudorapidity gap corresponds to absence of charged particle tracks between jets ($p_T^{\text{ch}} > 200$ MeV & $|\eta| < 1$).

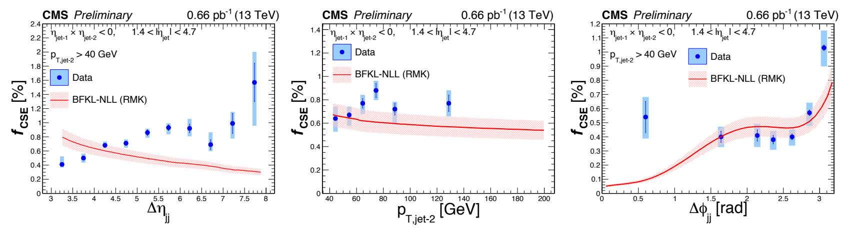
Multiplicity of charged particles between jets (CMS-PAS-SMP-19-006)



Standard dijet events dominate at high-multiplicities → Use as control region to estimate fluctuations at low multiplicities. Two data-based approaches:

- Orthogonal data sample: two jets on equal sides (ES) of the CMS detector, $\eta_{j1} \times \eta_{j2} > 0$. Normalize to events with jets in opposite sides (OS) of CMS, $\eta_{j1} \times \eta_{j2} < 0$, in $3 < N_{\text{Tracks}} < 40$.
- Negative binomial distribution (NBD) function: Fit data with NBD in $3 \leq N_{\text{Tracks}} \leq 35$, extrapolate down to $N_{\text{Tracks}} = 0$. (Baseline method)

Results on color-singlet exchange fraction $f_{\text{CSE}} \equiv N_{\text{CSE}}/N_{\text{dijet}}$



CMS-PAS-SMP-19-006

- f_{CSE} generally increases with increasing $\Delta\eta_{jj} \equiv |\eta_{j1} - \eta_{j2}|$. Weak dependence of f_{CSE} on $p_{T,j2}$ within uncertainties. f_{CSE} increases at $\Delta\phi_{jj} \equiv |\phi_{j1} - \phi_{j2}| \approx \pi$, uniform at $\Delta\phi_{jj} < 2.7$. Typical values of $f_{\text{CSE}} = 0.6$–1.0%.
- Comparison to Royon, Marquet, Kepka (RMK) model based on BFKL NLL calculations + LO impact factors (Phys. Rev. D 83.034036), and survival probability $|S|^2 = 0.1$.
- Challenging to describe all features of the measurement simultaneously → Guidance for further theory development.

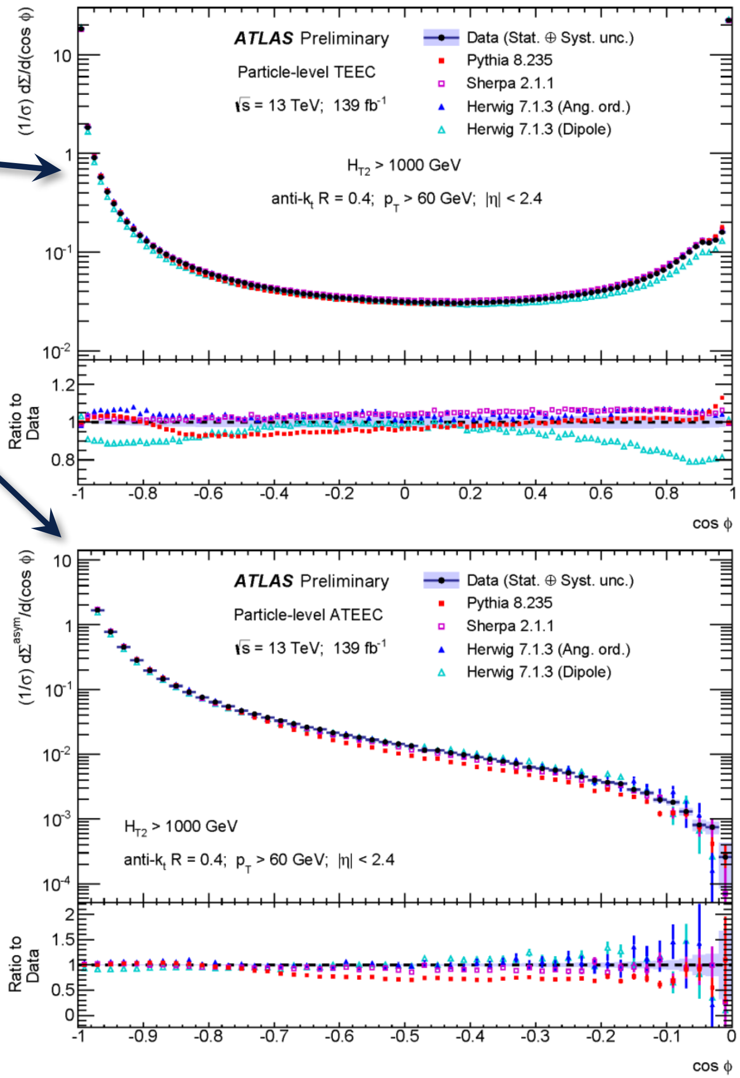
Measurement of Strong Coupling

Transverse energy-energy correlations (TEEC)

- TEEC function in multi-jet events
  - $$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{\sigma}\sum_{i,j}\int d\sigma \frac{E_{\mathrm{T},i}E_{\mathrm{T},j}}{E_{\mathrm{T}}^2}\delta(\cos\Delta\varphi_{ij} - \cos\phi),$$ with $E_{\mathrm{T}} = \sum_i E_{\mathrm{T},i}$
- Associated azimuthal asymmetries (ATEEC)
  - Measures difference between forward ($\cos\phi > 0$) and backward ($\cos\phi < 0$) parts of TEEC
  - $$\frac{1}{\sigma}\frac{d\Sigma^{\mathrm{asymm}}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$

Measurement

- Determine α_s from evolution of TEEC/ATEEC with varying hard scale
  - $H_{\mathrm{T2}} = p_{\mathrm{T}}^{\mathrm{lead}} + p_{\mathrm{T}}^{\mathrm{sublead}}$ serves as proxy for hard interaction scale Q
- Jets
  - Anti-k_t jets with $R = 0.4$ from particle flow objects ($p_{\mathrm{T}} > 60$ GeV, $|\eta| < 2.4$)
- Events
  - Two leading jets with $H_{\mathrm{T2}} > 1$ TeV
- Results
  - Data unfolded to particle level



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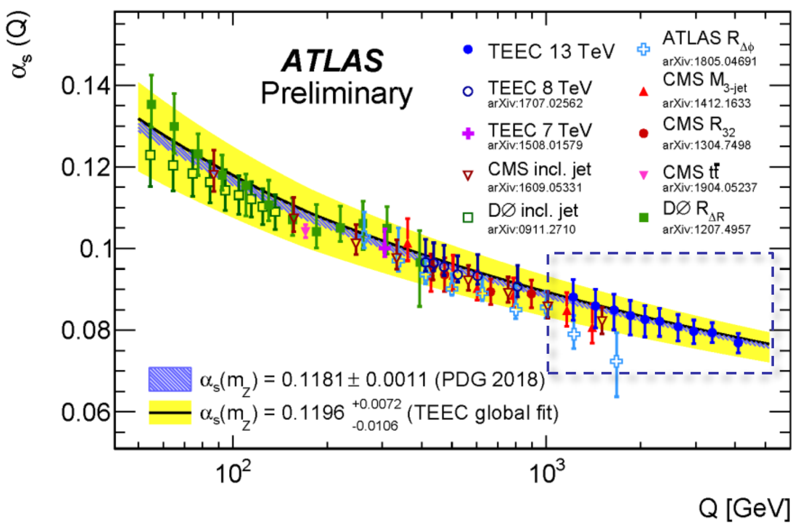
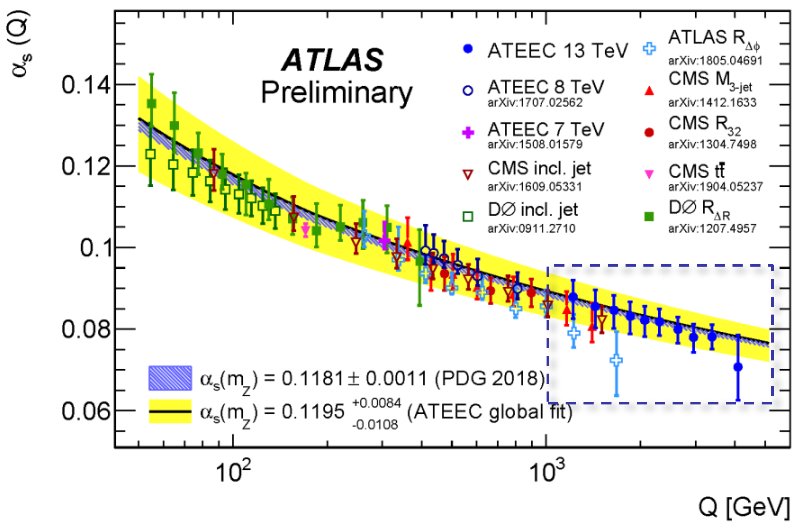
Evolution of α_s with Momentum Transfer





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Determination of α_s

- Fit theoretical predictions to measured (A)TEEC distributions
  - Inclusive $\alpha_s(m_Z)$ from global fit
    - $H_{\mathrm{T2}} > 1$ TeV
  - Local $\alpha_s(m_Z)$ fits in bins of H_{T2}
  - Evolution $\alpha_s(m_Z) \to \alpha_s(Q)$ uses NLO solutions to RGE

Running α_s measurement using (A)TEEC

- Tests RGE predictions at the highest energy scales ever
  - Running of $\alpha_s(Q)$ for $Q > 1$ TeV observed in data agrees very well with predictions
- Inclusive measurement
  - Compares very well to world average $\alpha_s(m_Z)$ within uncertainties

Summary