Soft and high-p_{T} QCD

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on behalf of the LHC collaborations

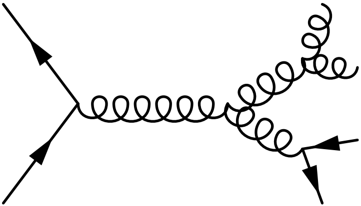
LHCP 2018, Bologna
5 June 2018

Science & Technology Facilities Council

Introduction

- LHC probes QCD at all scales

Elastic collisions $\Longleftrightarrow$ multi-TeV jet production



- Rich variety of physics
  - Non-perturbative physics
  - Differential cross sections
  - Fragmentation functions and PDFs
  - Underlying event

Introduction

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$$\text{Elastic collisions} \Longleftrightarrow \text{multi-TeV jet production}$$

- Rich variety of physics
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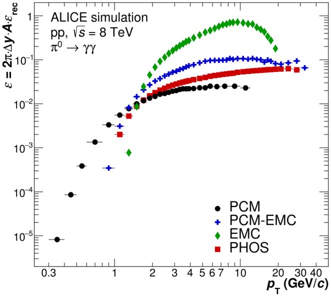
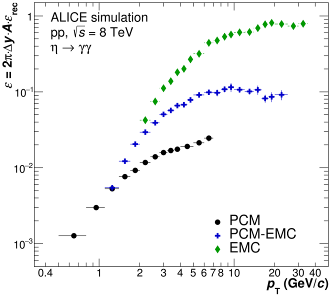
  - Fragmentation functions and PDFs
  - Underlying event

ALICE $pp \to \{\pi^0, \eta\} \to \gamma\gamma$ arXiv:1708.08745

- Transverse mass (m_{T}) scaling of π^0 and η production
- New input to fragmentation functions above TeV scale
- Experimental challenge: low p_{T} γ reconstruction

$$\pi^0 = \langle u\bar{u}, d\bar{d} \rangle$$
$$\eta = \langle u\bar{u}, d\bar{d}, s\bar{s} \rangle$$

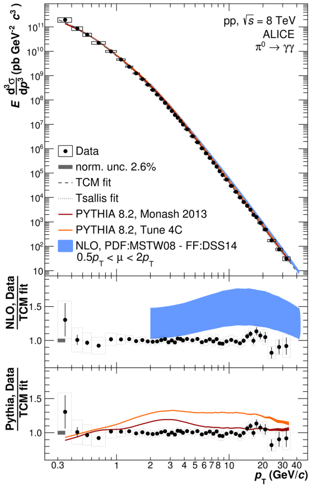


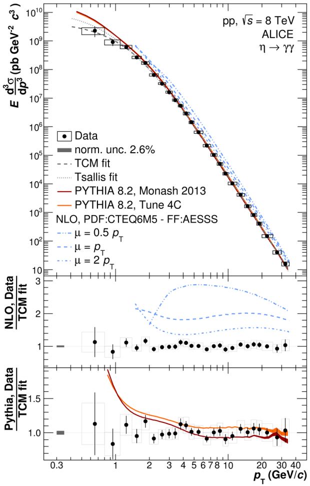


- PHOS (PHOton Spectrometer) $\phi < 60°$ coverage too low for $\eta \to \gamma\gamma$
- PCM = photon conversion method
- PHOS and EMCal triggers used

ALICE $\{\pi^0, \eta\} \rightarrow \gamma\gamma$ arXiv:1708.08745

- Two Component Model (TCM) fit used
- Largest NLO uncertainty is μ choice
- Previous ALICE π^0 at 7 TeV part of DSS14 FF

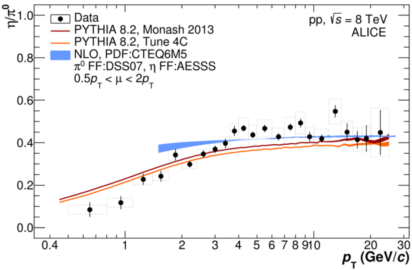


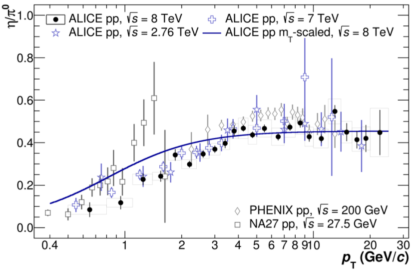


ALICE $\{\pi^0, \eta\} \rightarrow \gamma\gamma$ arXiv:1708.08745

- Pythia with Monash 2013 tune best describes data
- FF DSS07 (η), DSS14 (π^0)
- Good agreement with NLO calculation

- π^0/η ratio deviates from m_T scaling by 6.2σ for $p_\mathrm{T} < 3.5\,\mathrm{GeV}$

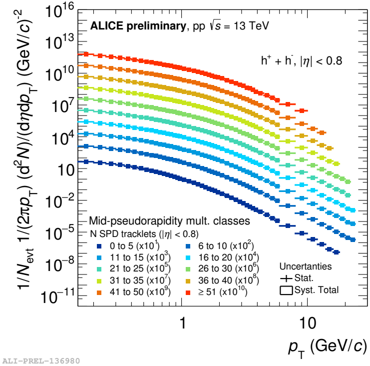


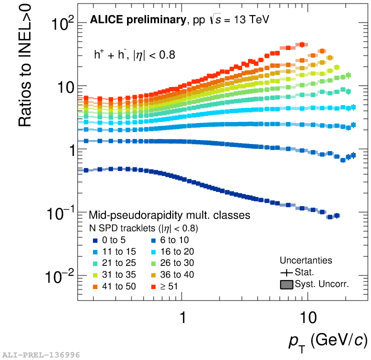


- Agreement within uncertainties for NA27, PHENIX and ALICE data from $\sqrt{s} = 27.5\,\mathrm{GeV}$ to $8\,\mathrm{TeV}$

ALICE unidentified hadron production Preliminary figures

- Measure charged hadron spectra in tracklet multiplicity classes
- Observe enhancement relative to minimum bias data for $N_{\text{tracklets}} > 20$





- More details here

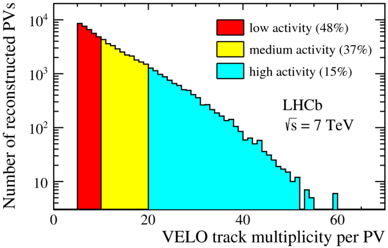
LHCb Bose-Einstein correlations arXiv:1709.01769

- BEC between identical bosons enhanced when bosons are close in phase space
- Seen in ratio of correlated and reference correlation functions ρ:

$$C_2(Q) = \rho_2^{\text{identical}}(Q)/\rho_2^{\text{non-identical}}(Q) \sim [1 + e^{-RQ}](1 + \delta Q)$$

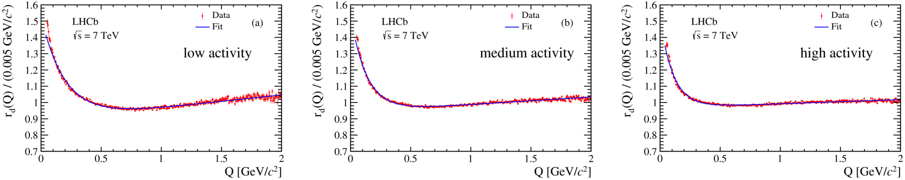
  - $Q^2 = -(p_1 - p_2)^2$
  - δQ = long-distance correlation effects
  - R = effective source radius
  - λ = "chaoticity", strength of effect
- Select non-identical bosons by mixing events

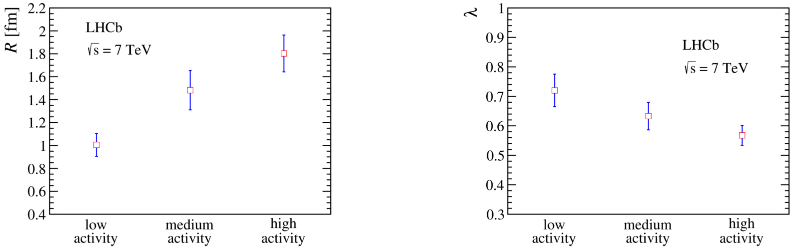
- Measure $r_d(Q) \equiv C_2^{\text{data}}(Q)/C_2^{\text{MC}}$ to incorporate Coulomb and spin effects
- Investigate dependence on event activity



LHCb Bose-Einstein correlations arXiv:1709.01769

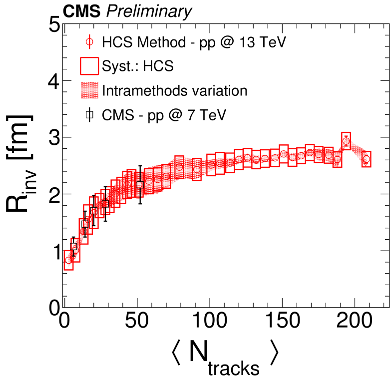
- Use LHCb PID to select 98% pure π sample
- Effective source radius R increases with n_{ch}, chaoticity λ decreases
- Fit quality not perfect: need different parameterisation?
- Compatible with ATLAS results (limited rapidity overlap)

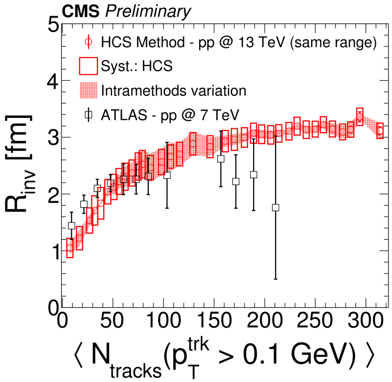




CMS Bose-Einstein correlations at 13 TeV CMS-PAS-FSQ-15-009

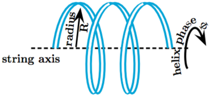
- Comprehensive comparison of BEC results with double ratio, cluster subtraction, hybrid cluster subtraction (arXiv:1712.07198)
- Compatibility between 7 TeV CMS and ATLAS results

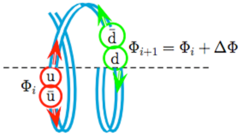


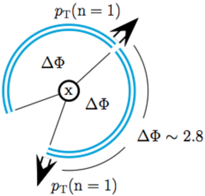


ATLAS ordered hadron chains 1709.07384

- Inspired by string model of hadronisation
- Helicity suppresses collinear $q \to gg$ and $g \to gg$ emission $\to$ helical QCD string
- Construct hadron chains algorithmically from particles (assume pions)
- Minimum bias dataset

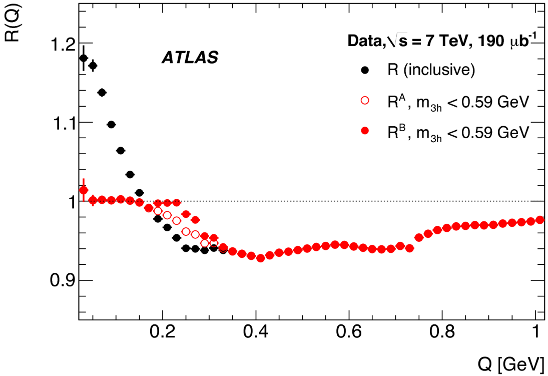






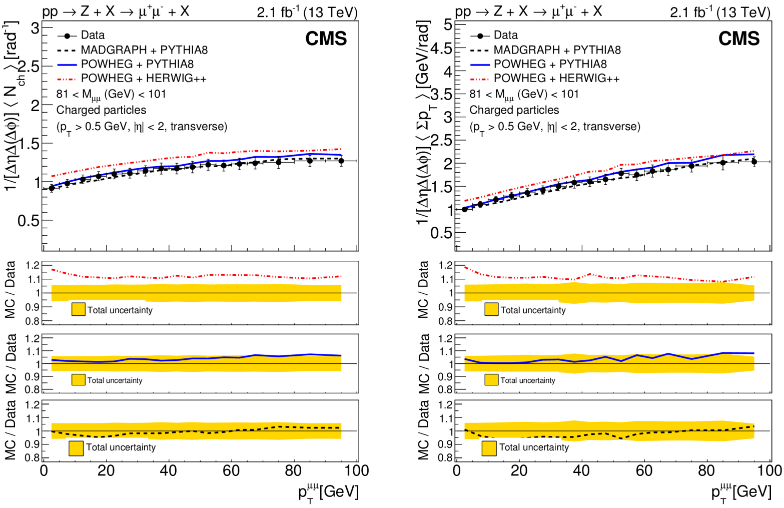
ATLAS ordered hadron chains 1709.07384

- Fit to string model gives maximum triplet hadron chain mass $M_{3h} < 575 \pm 20\,\mathrm{MeV}$
- Enhanced correlation of like-sign vs. opposite-sign pairs at low Q can be explained by ordered hadron chains



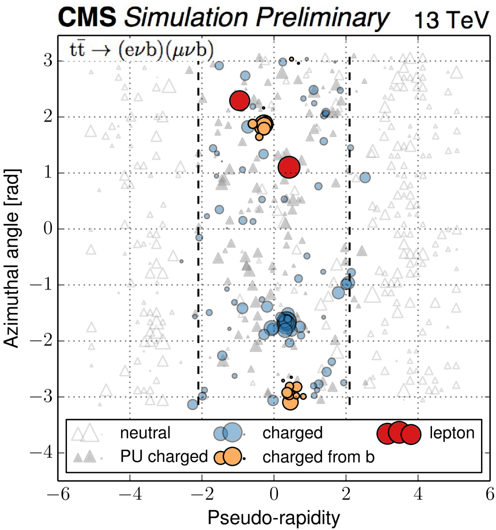
CMS underlying event in $Z \to \mu\mu$ arXiv:1711.04299

- ISR/FSR dominant at high $p_T^{\mu\mu}$
- Agrees with tunes based on lead track/jet measurements → UE independent of hard process



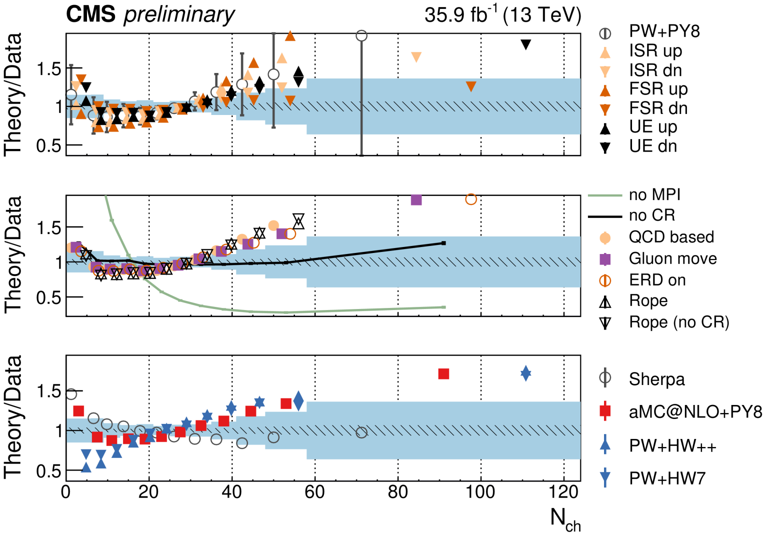
CMS underlying event in $t\bar{t} \to e\mu$ + jets CMS-PAS-TOP-17-015

- Yesterday's signal is today's UE hard process
- Interesting event topology: many different physics objects

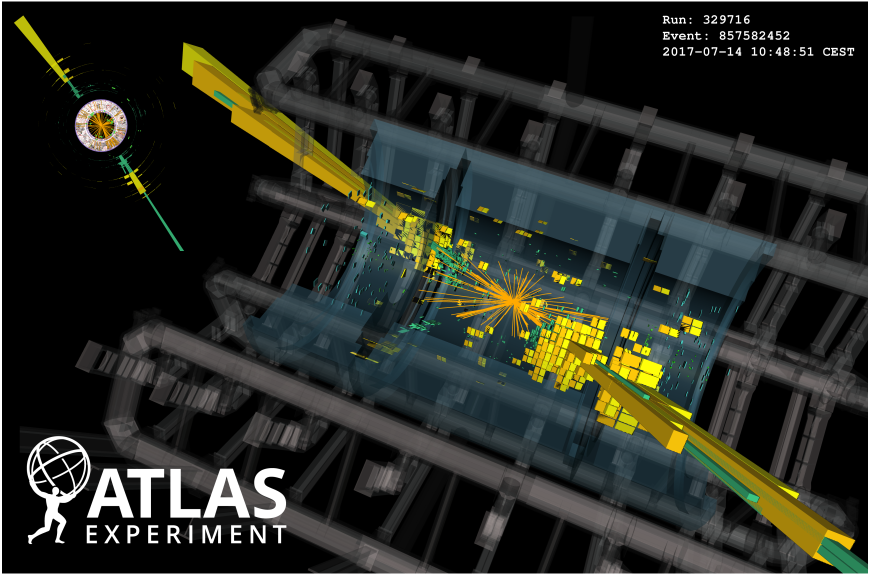


CMS underlying event in $t\bar{t} \to e\mu$ + jets CMS-PAS-TOP-17-015

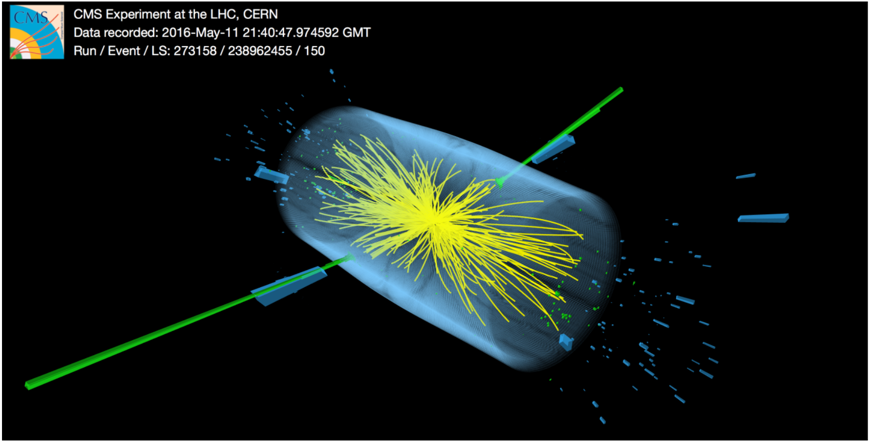
- Measuring UE properties at $\mu_R, \mu_F \approx 2m_t$
- Comparisons with a range of generators, tunes and settings



High p_{T} QCD ($m_{jj} = 9.3$ TeV)



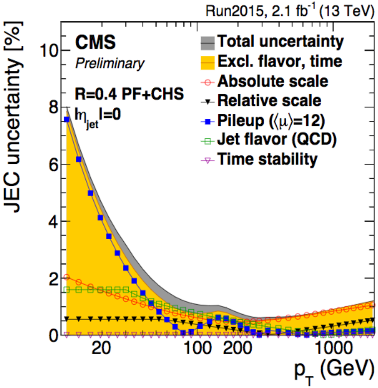
High p_{T} QCD ($m_{jj} = 6.14\,\mathrm{TeV}$)

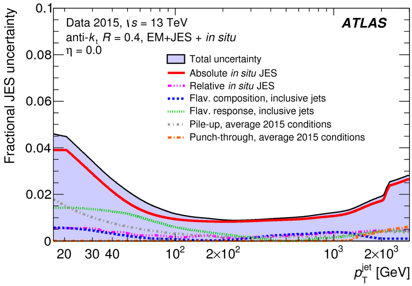


Jet reconstruction (K. Pachal, Performance I)

- Uses particle flow (define and follow all particles through detector)
- CMS jet energy uncertainties DP-2016-020

- Uses topological cell clustering based on signal and noise thresholds
- ATLAS jet energy uncertainties arXiv:1703.09665

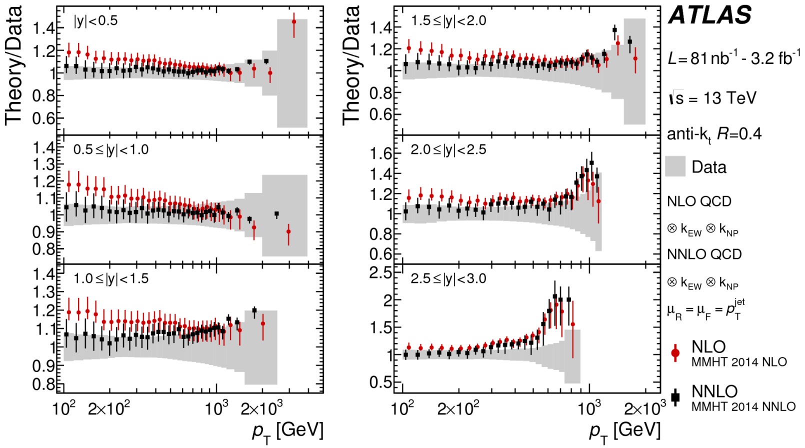




$< 2\%$ uncertainty for 100 GeV $< p_{\mathrm{T}} <$ 2 TeV!

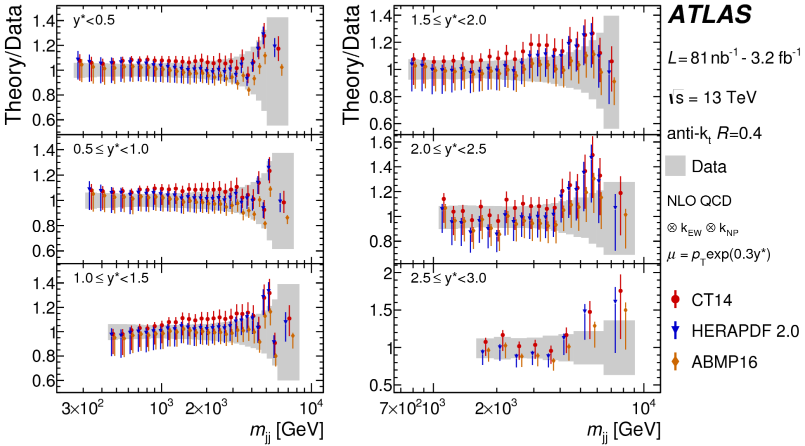
ATLAS inclusive jet and dijet cross sections arXiv:1711.02692

- Inclusive jets: $p_{\mathrm{T}} > 100\,\mathrm{GeV}$, $|y| < 3$
- Better agreement with NNLO
  - "p_{T}^{jet}": weight each jet in event according to $\mu_R = \mu_F = p_{\mathrm{T}}^{\mathrm{jet}}$
  - $p_{\mathrm{T}}^{\mathrm{max}}$ scale choice overestimates: see backup



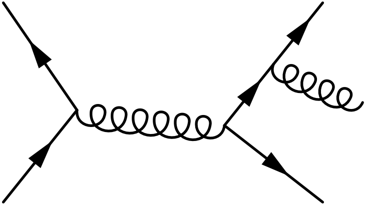
ATLAS inclusive jet and dijet cross sections arXiv:1711.02692

- Dijets: $p_{\rm T} > 75\,{\rm GeV}$, $p_{\rm T}^1 + p_{\rm T}^2 > 200\,{\rm GeV}$
- Excellent agreement across a broad $p_{\rm T}$ and y range
- All PDFs overestimate slightly at high $p_{\rm T}$ and $2.5 < y^* = |y^1 - y^2| < 3$



Azimuthal correlations

- Azimuthal angles between jets are sensitive to ISR, FSR
- Testing ground for pQCD, MC tunes



- Measure $\Delta\phi_{2j}^{\min}$ maximised by

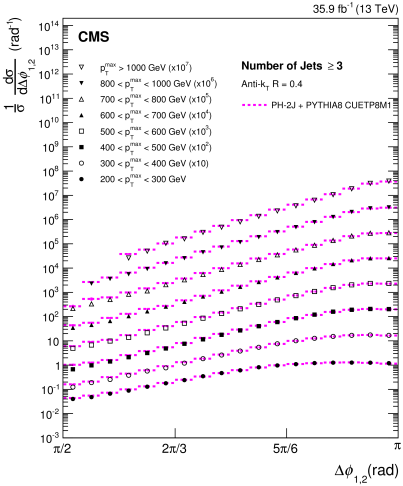
$2\pi/3$, 3 jets

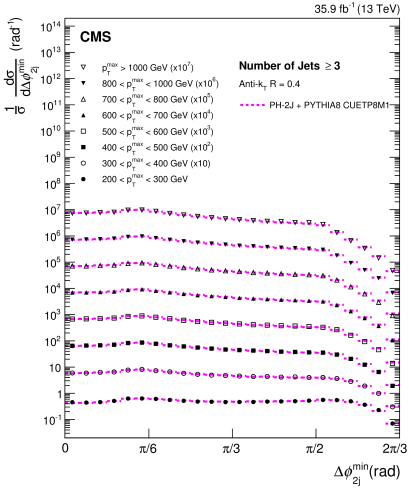
$\pi/2$, 4 jets

- Interesting for ≥ 3 jets, infrared safe

CMS azimuthal correlations arXiv:1712.05471

- PH-2J - PowHeg, 2-jet NLO mode
- $\Delta\phi_{1,2}$ and $\Delta\phi_{2j}^{min}$ have complementary kinematics

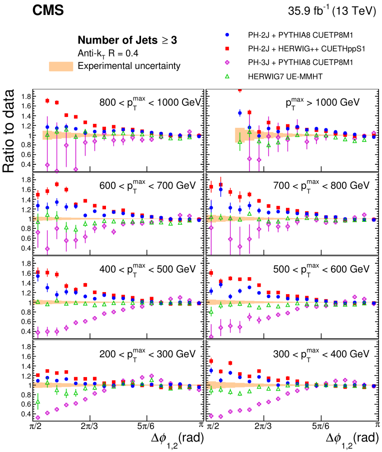


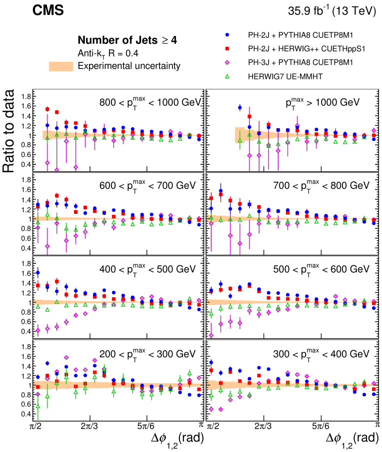


CMS azimuthal correlations arXiv:1712.05471

$\Delta\phi_{1,2}$

- Exclude $\Delta\phi < \pi/2$: large $t\bar{t}$ and W/Z + jet backgrounds
- Best overall description given by MC@NLO in Herwig7

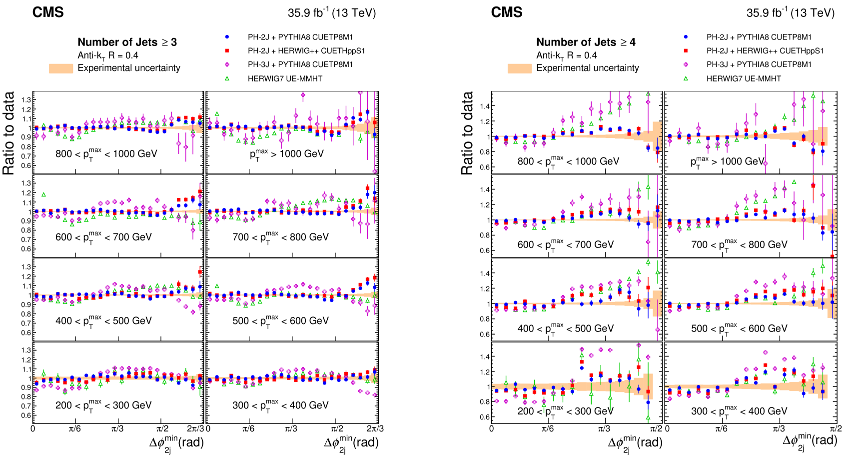




CMS azimuthal correlations arXiv:1712.05471

$\Delta\phi_{2j}^{\min}$

- PH-2J with Herwig7 and Pythia8 PS models $\Delta\phi_{2j}^{\min}$ best
- Compare with LO generators (Pythia8, Herwig++, MadGraph ($2 \to 4$))

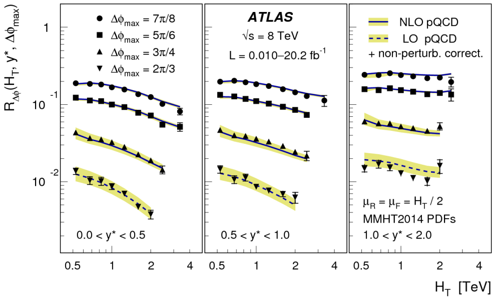


ATLAS jet azimuthal decorrelations arXiv:1805.04691

- Measure

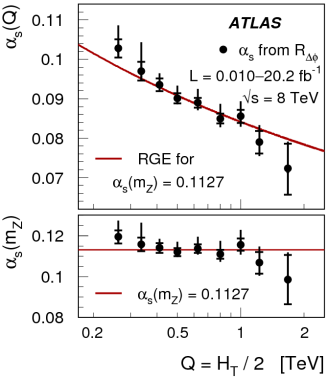
$$R_{\Delta\phi}(H_T, y^*, \Delta\phi_{max}) = \frac{\frac{d^2\sigma_{dijet}(\Delta\phi_{dijet} < \Delta\phi_{max})}{dH_T dy*}}{\frac{d^2\sigma_{dijet}(inclusive)}{dH_T dy*}}$$

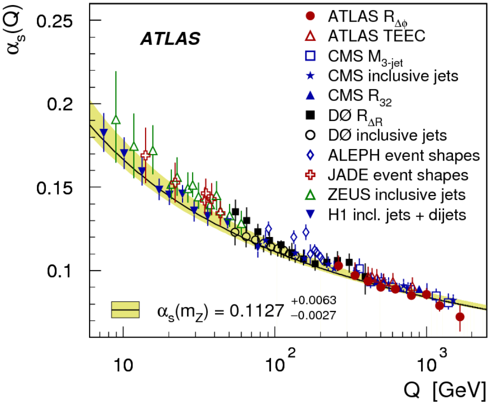
- $R_{\Delta\phi}$ is a function of several aspects of QCD
  - $H_T/2$: hard scale
  - $y^* = |y_1 - y_2|$: kinematics
  - $\Delta\phi_{max}$: hardness of additional jet production
- Choose data points with good theory prediction for α_S determination



ATLAS jet azimuthal decorrelations arXiv:1805.04691

- Calculate running with renormalisation group equation
- 1 σ below world average $\alpha_S^{PDG} = 0.1181 \pm .0011$
- Highest measured $\alpha_S(Q)$ value to date

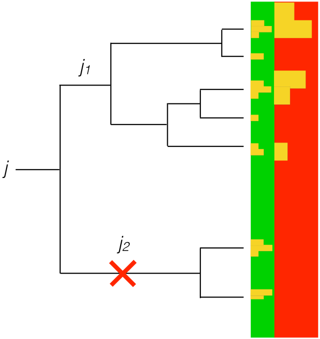




ATLAS soft drop jet mass measurement arXiv:1711.08341

- Soft drop jet grooming: decluster jet constituents (calo-clusters): see A. Larkoski's talk
- Remove soft and collinear radiation

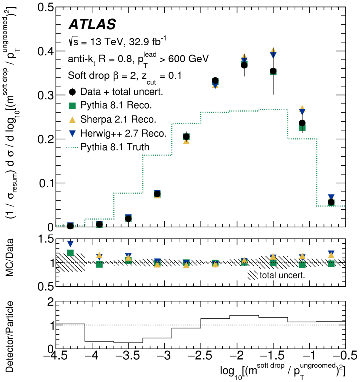
$$\frac{\min(p_T^{j_1}, p_T^{j_2})}{p_T^{j_1} + p_T^{j_2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

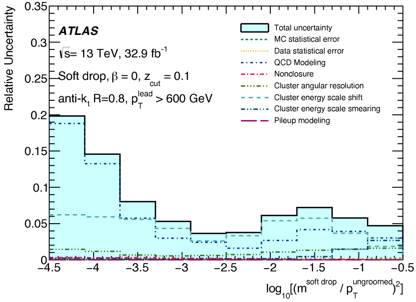


- Can construct precise observables insensitive to e.g. non-global logarithms
- ATLAS measured scaled jet mass $\rho = m^{\text{soft drop}}/p_T^{\text{ungroomed}}$ for anti-$k_T R = 0.8$ jets
  - Keep energy scale $z_{\text{cut}} = 0.1$ to avoid z_{cut} resummation, vary $\beta \in 0, 1, 2$

ATLAS soft drop jet mass measurement arXiv:1711.08341

- Select dijet events with $p_{\mathrm{T}}^{j_1} > 600\,\mathrm{GeV}$, $p_{\mathrm{T}}^{j_2}/p_{\mathrm{T}}^{j_1} < 1.5$
- Unfold to detector-level simulation: substantial differences between truth and reconstructed distributions



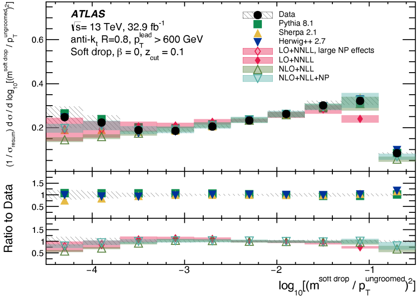


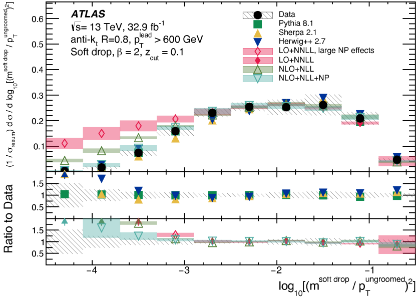
- Uncertainties vary widely with ρ
- High ρ: jet constituent energy scale dominates
- Low ρ: MC modelling dominates

ATLAS soft drop jet mass measurement arXiv:1711.08341

- Normalise σ to resummation region $(-3.7 < \log_{10}(\rho^2) < -1.7)$
- $\beta \in 1, 2 \rightarrow$ less soft radiation is subtracted
  - NP corrections more important

$\log_{10}(\rho^2) < -3.7$	NP
$-3.7 < \log_{10}(\rho^2) < -1.7$	LO+NNLL
$\log_{10}(\rho^2) > -1.7$	NLO+NLL

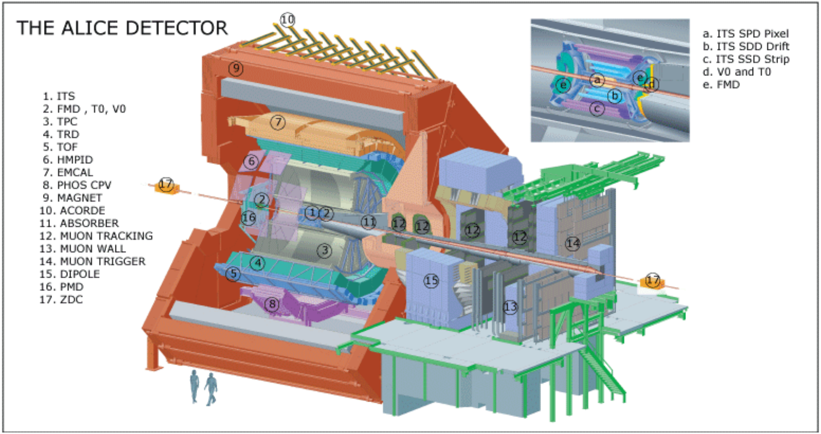




Conclusions

- Thanks to all the collaborations for such an impressive range of results
- Sorry I couldn't include everything!
- Please join the QCD parallel sessions to learn more

Backup: ALICE detector

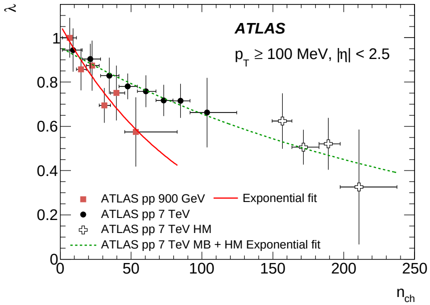


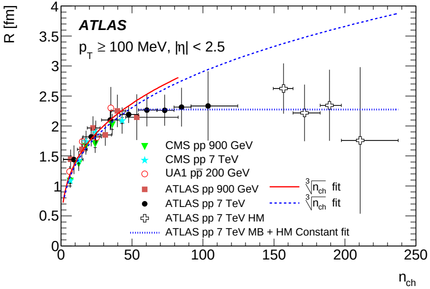
Backup: Cluster subtraction in Bose-Einstein correlations

- Use only single ratios
- Fit opposite-sign correlation function to phenomenological function
- Exclude resonances from fit

Backup: ATLAS BEC arXiv:1502.07947

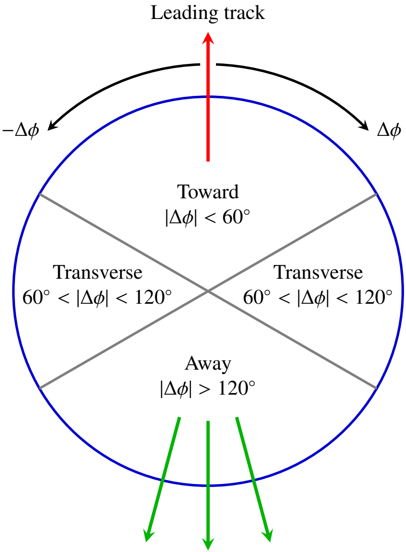
- Three datasets used:
  - 0.9 TeV, $n_{ch} \geq 2$, $\approx$ 4.5M events
  - 7 TeV, $n_{ch} \geq 2$, $\approx$ 10M events
  - 7 TeV, $n_{ch} \geq 150$, $\approx$ 18k events





- R and λ are $\approx$ independent of energy to within uncertainties
- First evidence for saturation of R at high multiplicity, as predicted by pomeron-based models

Backup: underlying event



Backup: ATLAS soft drop jet mass measurement arXiv:1711.08341

- Jet substructure technique "soft drop": insensitive to non-global logarithms

1. Start with usual $anti - k_{\mathrm{T}}$ jet
2. Re-cluster with Cambridge-Aachen
3. Traverse the clustering tree backwards
4. Remove branch points that don't satisfy soft drop condition

$$\frac{\min(p_{\mathrm{T}}^{j_1}, p_{\mathrm{T}}^{j_2})}{p_{\mathrm{T}}^{j_1} + p_{\mathrm{T}}^{j_2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R} \right)$$