Jet and particle correlations with ATLAS experiment

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Outline

- Correlations measured using very large-p_{T} and very low-p_{T} objects

- Transverse energy-energy correlations of jets, STDM-2016-10
  - Very precise test of perturbative QCD
  - Extraction of strong coupling α_s

- Measurement of hadronic chains, STDM-2014-08
  - Study low-mass pion triplets
  - Source of charge correlation between particle pairs at low Q
  - Indication of helix string fragmentation

Observable definition

The transverse energy-energy correlation (TEEC) is defined as

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi} \equiv \frac{1}{\sigma}\sum_{ij}\int \frac{\mathrm{d}\sigma}{\mathrm{d}x_{\mathsf{T}i}\mathrm{d}x_{\mathsf{T}j}\mathrm{d}\cos\phi} x_{\mathsf{T}i}x_{\mathsf{T}j}\mathrm{d}x_{\mathsf{T}i}\mathrm{d}x_{\mathsf{T}j} \qquad x_{\mathsf{T}i} \equiv \frac{E_{\mathrm{T}i}}{\sum_k E_{\mathrm{T}}}$$

For a sample of N events, calculated for the jet pairs (i,j) as

$$\frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi - \cos\phi_{ij}),$$

Transverse TEEC asymmetry (ATEEC) defined as

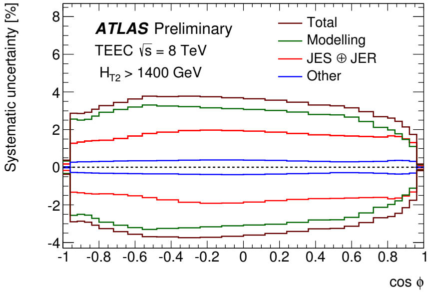
$$\frac{1}{\sigma}\frac{d\Sigma^{\mathrm{asym}}}{d\cos\phi} \equiv \left.\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\right|_{\phi} - \left.\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\right|_{\pi-\phi}$$

- Large sensitivity to α_s (more radiation) and a mild sensitivity to other theoretical effects such as PDF or scale choice
- Reduced sensitivity to systematic effects such as JES or JER because of the $E_{\mathrm{T}i}E_{\mathrm{T}j}/(\sum E_{\mathrm{T}})^2$ weighting

Event selection and systematic uncertainties

- Using $20\,\text{fb}^{-1}$ of 8 TeV data
- Jet selection: anti-k_T (R=0.4) with $p_T > 100$ GeV, $|\eta| < 2.5$ for each jet
- The two leading jets have to fulfill $p_{T1} + p_{T2} > 800$ GeV
- Binning in $H_T = p_{T1} + p_{T2}$ variable
- $\alpha_s(Q^2)$ studied in 6 bins of $Q = H_T/2$

TEEC, $H_T > 1400$ GeV



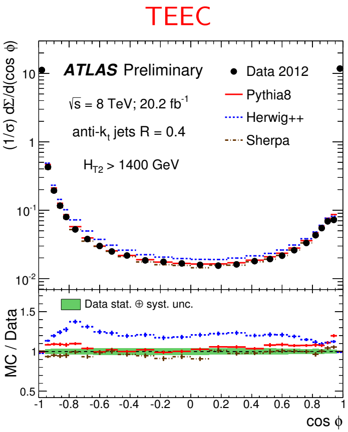
Experimental uncertainties:

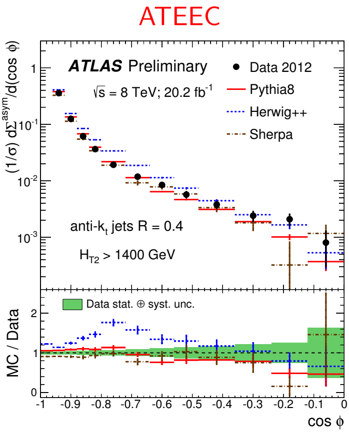
JES and JER: amount to 2% and 1%. Full set of 67 nuisance parameters

Monte Carlo modeling: dominant source of the uncertainty 5%. Different generators used in the unfolding

Other uncertainties: jet angular resolution, jet cleaning, data mismodelling

Results



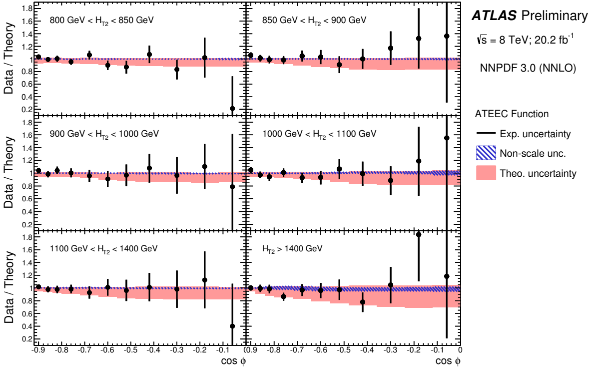


- TEEC $\cos\phi$ topologies $\rightarrow$ back-to-back (-1), wide angle gluon radiation (0), jet self-correlation (1)
- Good modeling by PYTHIA 8 and SHERPA, significant mis-modelling by HERWIG++

Theoretical NLO predictions

- Evaluated using NLOJET++
- Dominant uncertainty due to choice of renormalization and factorization scales: up to 20%
- Other contributions: PDF (NMHT 2014, CT14, NNPDF 3.0, HERAPDF 2.0), α_s in PDFS, non-perturbative corrections

ATEEC



Test of asymptotic freedom and α_s global fit

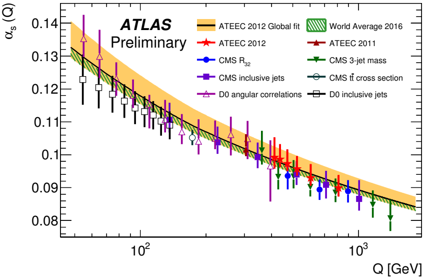
- $\alpha_s(Q^2)$ extracted in 6 $H_\mathrm{T}/2$ bins as well as in a global fit
- $\chi^2/N_{dof} = 60.3/65$ for global fit, showing very good quality
- Using nuisance parameters to include experimental and theoretical uncertainties
- Largest uncertainty due to scale variation 7% (TEEC) and 5% (ATEEC)

TEEC:

$$\alpha_s(m_Z) = 0.1162 \pm 0.0008\ \text{(exp.)}\ \pm 0.0007\ \text{(corr.)}\ {}^{+0.0076}_{-0.0061}\ \text{(scale)} \pm 0.0018\ \text{(PDF)} \pm 0.0003\ \text{(NP)}$$

ATEEC:

$$\alpha_s(m_Z) = 0.1196 \pm 0.0013\ \text{(exp.)}\ \pm 0.0003\ \text{(corr.)}\ {}^{+0.0061}_{-0.0013}\ \text{(scale)} \pm 0.0017\ \text{(PDF)} \pm 0.0004\ \text{(NP)}$$



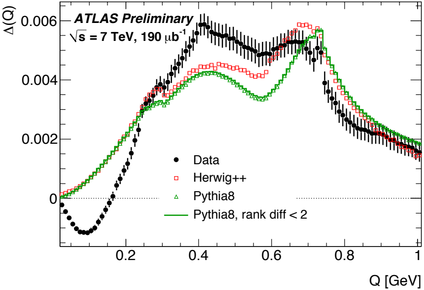
Hadronic chains

Define two-particle correlation

$$\Delta(Q) = \frac{1}{N_{ch}}(N(Q)^{+-} - N(Q)^{++/--})$$

as an average difference of unlike-sign and like-sign pairs, depends on momentum difference $Q = \sqrt{-(p_i - p_j)^2}$

Enhanced production of ++/−− over +− not described by MC ($Q < 200\,\text{MeV}$)



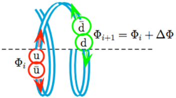
Novel approach to measure $\Delta_{3\mathrm{h}}(Q)$:

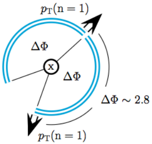
- $\Delta(Q)$ for particles contained in three-hadron chains ($\pi^+\pi^-\pi^+$ or $\pi^-\pi^+\pi^-$)
- Powerful probe of the correlation between particles
- What fraction of the $\Delta(Q)$ explained by low-$m_{3\mathrm{h}}$ chains?
  - Helix string model - essentially all, $\Delta_{3\mathrm{h}}(Q) \sim \Delta(Q)$ for $Q < 200\,\text{MeV}$
  - Standard Lund model - only a small fraction

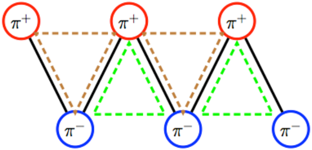
Motivation for the observable

Predictions of quantized model of helical string fragmentation (arXiv:1309.6761):

- Ground-state hadrons are emitted in preferred directions to each other $\Delta\phi \sim 2.8$ (almost back-to back)
- Small chain mass, $m_{3\mathrm{h}} < 0.6\,\mathrm{GeV}$, when 3 hadrons produced in 'near' string fragments with rank $r = 1, 2$ (ordering along the string)
- Implies $Q(+-) = 266\,\mathrm{MeV}$, $Q(--/++) = 91\,\mathrm{MeV}$ for particles with $r = 1, 2$ $\rightarrow$ Threshold behavior for unlike-sign pairs should be visible in $\Delta_{3\mathrm{h}}(Q)$

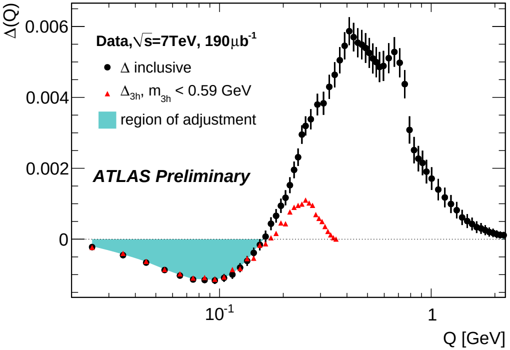






An algorithm developed to uniquely assign particles into chains to access $r = 1, 2$ by minimizing chain Q and $m_{3\mathrm{h}}$ $\rightarrow$ Rivet routine provided

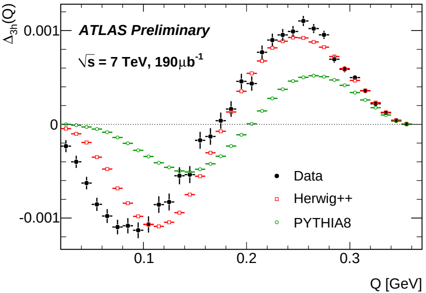
Event selection and results



- $7\mu\mathrm{b}^{-1}$ of 7 TeV data selected with minimum bias trigger
- Low-p_T tracking with $p_\mathrm{T} > 100\,\mathrm{MeV}$, $|\eta| < 2.5$
- HBOM semi data-driven unfolding
- $\Delta(Q)$ is a ratio $\rightarrow$ reduced uncertainties
- Sensitive to track reconstruction at small opening angle, low-Q

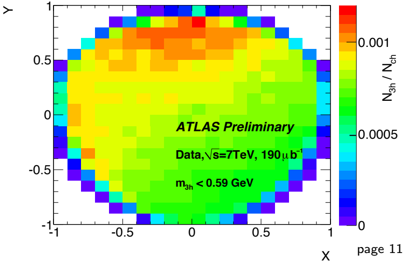
- Measured $\Delta_{3\mathrm{h}}(Q)$ for chains with $m_{3\mathrm{h}} < 0.59\,\mathrm{GeV}$
- Mass cut fixed so that $\int \Delta_{3\mathrm{h}}(Q) = \int \Delta(Q)$ for $\Delta(Q) < 1$ and $\Delta_{3h}(Q) < 1$
- Low-mass hadron chains explain the shape $\Delta(Q)$ at low-Q entirely

Properties of 3h chains

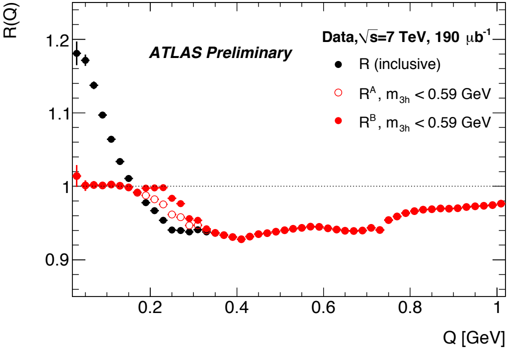


- Extracted position of like-sign ($Q \sim 90\,\text{MeV}$) and unlike-sign ($Q \sim 250\,\text{MeV}$) peaks in $\Delta_{3h}(Q)$ compatible with the helix-like fragmentation prediction
- MC generators fail to describe $\Delta_{3h}(Q)$

- Distinct polarization patterns seen in data, not contained in the generators
- $X = \sqrt{3}\frac{T_0 - T_2}{\sum T_i}$ $\quad Y = \frac{3T_1}{\sum T_i} - 1$ with T_i kinetic energies of pions in the chain



Contribution of 3h chains to $R(Q)$



- At low Q, 3h chains are not only at the origin of $\Delta(Q)$ but also of $R(Q)$

$$R(Q) = N(Q)^{++/--}/N(Q)^{+-}$$

- The enhancement in 2-particle correlation traditionally attributed to Bose-Einstein interference can be viewed as a production of low-mass chains in the helix model

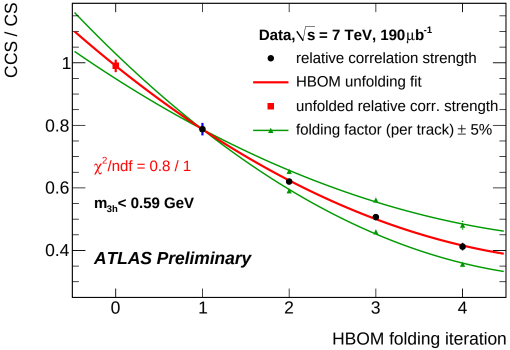
Summary

- Jet energy-energy correlations distribution used to extract $\alpha_s(M_Z)$ at the M_Z scale with a precision of 5% and 7%
- In good agreement with previous measurements

- Tree-hadron chains are used to probe details of hadronization
- Indication of helix-like string behaviour
- Unfolded distributions and Rivet routine available to model builders for further interpretation

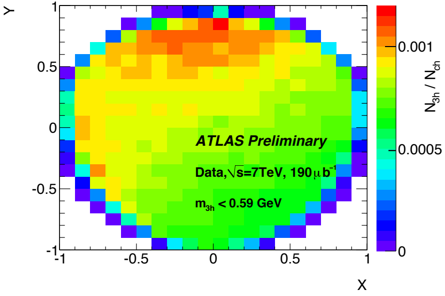
Backup

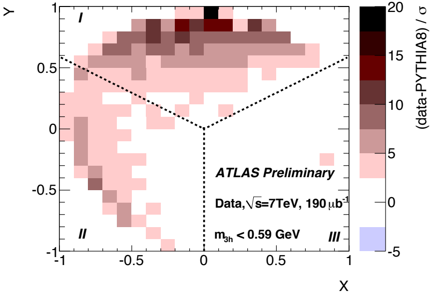
HBOM Method



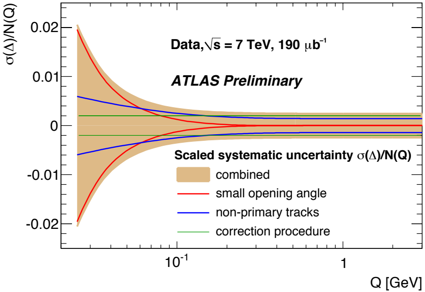
$$CCS/CS \equiv \int_{\Delta_{3\mathrm{h}}(Q)<1} \Delta_{3\mathrm{h}}(Q) / \int_{\Delta(Q)<1} \Delta(Q)$$

Three-body Dalitz diagram



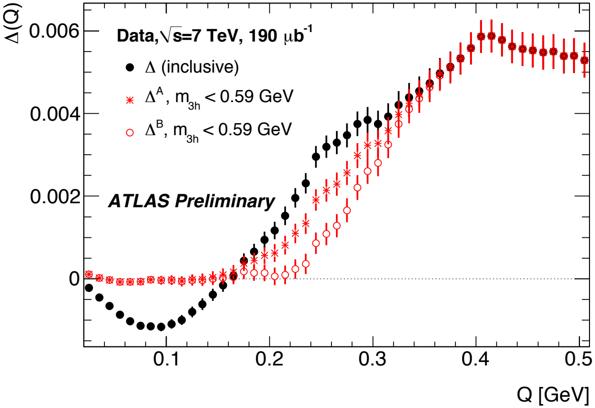


Event selection and uncertainties



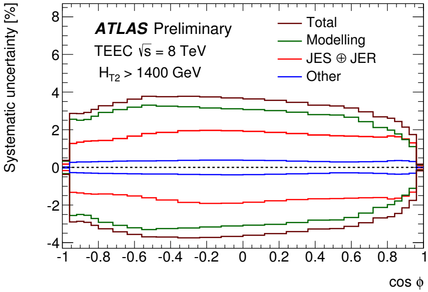
- Systematic uncertainties due to material modelling in the inner tracker
- Reduced sensitivity to uncertainties thanks to ratio in $\Delta(Q)$
- Important to understand track reconstruction at small opening angle, low-Q

Contribution of 3h chains to $\Delta(Q)$

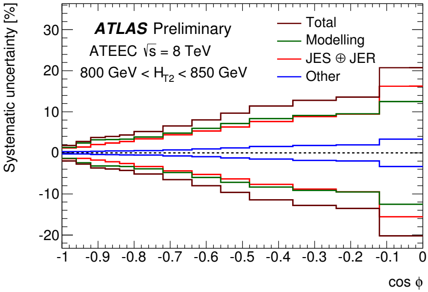


Systematic uncertainties TEEC and ATEEC

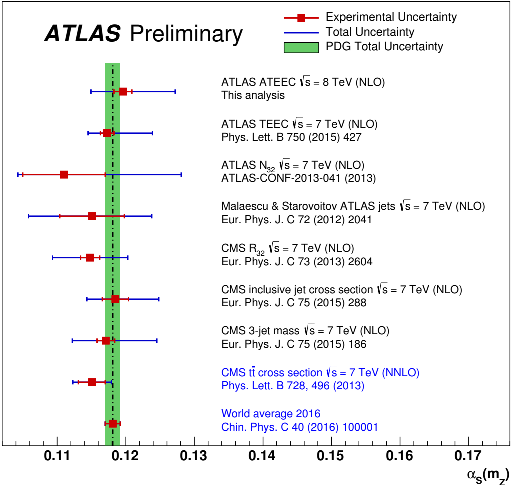
TEEC



ATEEC



Comparison of $\alpha_s(M_Z)$ other experiments



Interupted and uninterupted chains