Underlying-event properties and hadron production in ATLAS

Mario Campanelli (UCL)

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- Ordered hadron chains and coherent production
  Phys. Rev. D 96 (2017) 092008
- Charged particles distributions and the underlying event
  JHEP 03 (2017) 157

Hadron correlations

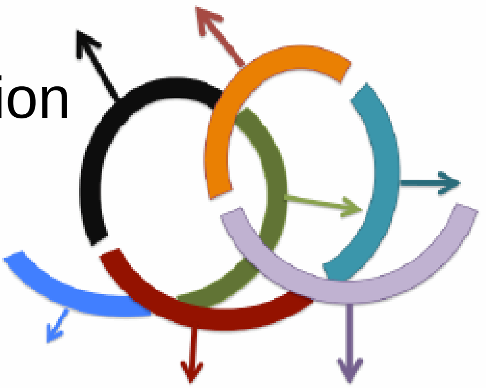
- Observed enhanced of same-sign hadron pairs observed in data, usually explained by Bose-Einstein correlations (not present for opposite sign), but MC models fail to properly describe them
- Recent theoretical work point to the fact that the enhancement can also be explained by quantising the fragmentation of a 3D string, as a consequence of coherent hadron emission.

String fragmentation

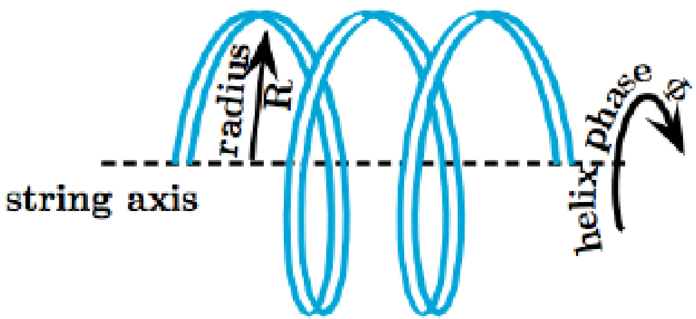
In 1d Lund model, strings are broken randomly to form hadron-antihadron pairs

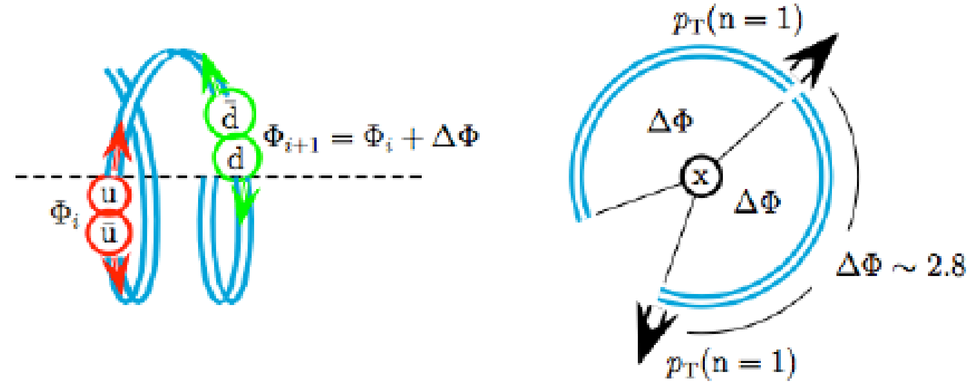
Helix string model (JHEP 09 (1009) 14,, Phys. ReV. D86, 034001(2012)) and quantised helix string model (Phys. Rev. D89, 015002 (2014)) show that the 3d extension of strings is a helix, whose breakdown into hadrons is quantised.

Like-sign and unlike-sign hadrons are correlated, but the different behaviour is explained by local charge conservation



Helicoidal string fragmentation in 3D





A 3D helicoidal string has energy scale k_R ~ 68 MeV and a phase Φ. It produces pion pairs at intervals ΔΦ ~ 2.8. Model predicts their transverse energy and relative opening angles, as well as threshold for momentum difference for each pair rank:

Pair rank difference r	1	2	3	4	5
Q expected [MeV]	266 ± 8	91 ± 3	236 ± 7	171 ± 5	178 ± 5

Testing the model

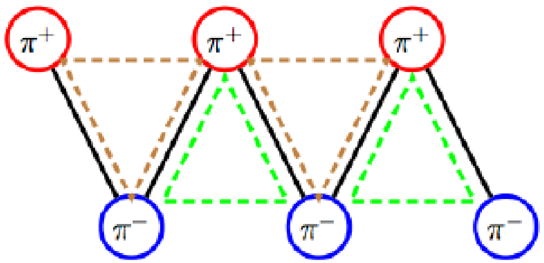
Measure correlations between hadron pairs and triplets

Adjacent pairs can be opposite sign only for rank 1, also same-sign for higher ranks

$$\Delta(Q) = \frac{1}{N_{ch}} \left[N(Q)^{OS} - N(Q)^{LS} \right]$$

For each particle, also find like-sign one with smallest Q, and define a triplet with the unlike sign particle (weighted by a factor ½) that minimises the triplet mass

$$\Delta_{3h}(Q) = \frac{1}{N_{ch}} \Sigma_{i=1}^{N_{ch}} w_i \left\{ \begin{array}{l} +\frac{1}{2}(Q_{min}^{+-}) \\ +\frac{1}{2}(Q_{max}^{+-}) \\ -1(Q^{++,--}) \end{array} \right\}$$

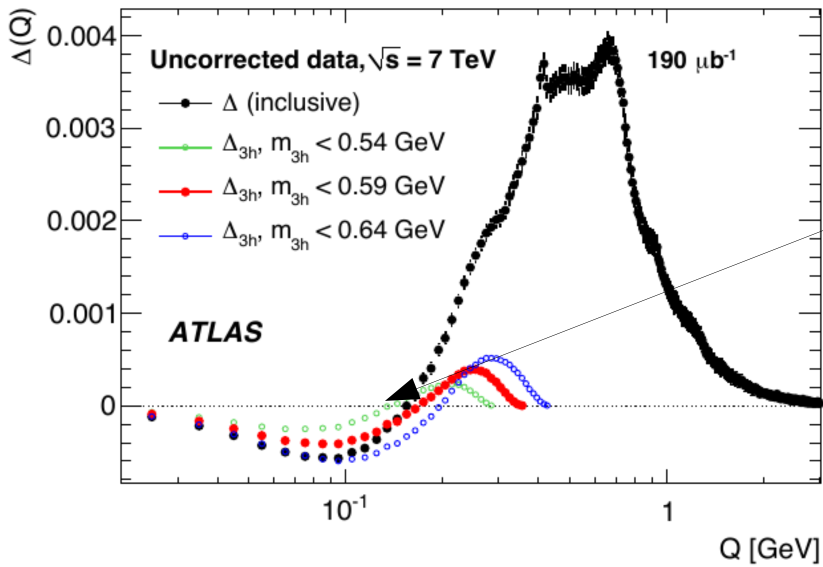


For triplets, also look at the Dalitz plot with variables

$$X = \sqrt{3}\, \frac{T_0 - T_2}{\Sigma_{i=0}^{2} T_i}, \qquad Y = \frac{3T_1}{\Sigma_{i=0}^{2} T_i} - 1,$$

Where T is the kinetic energy of the particle in the triplet rest frame

Correlation strengths

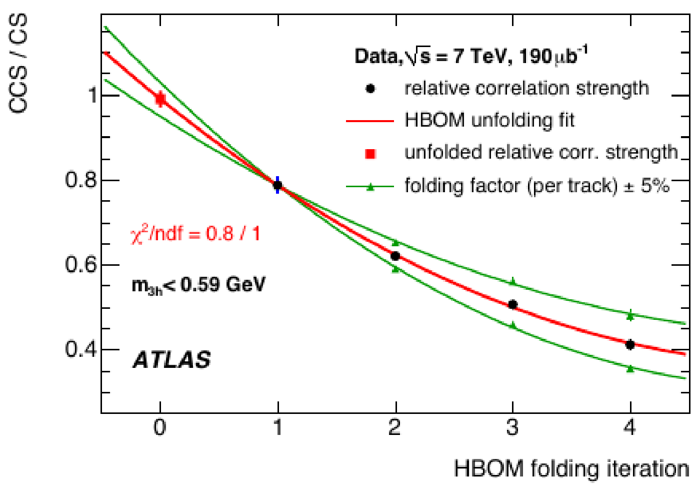


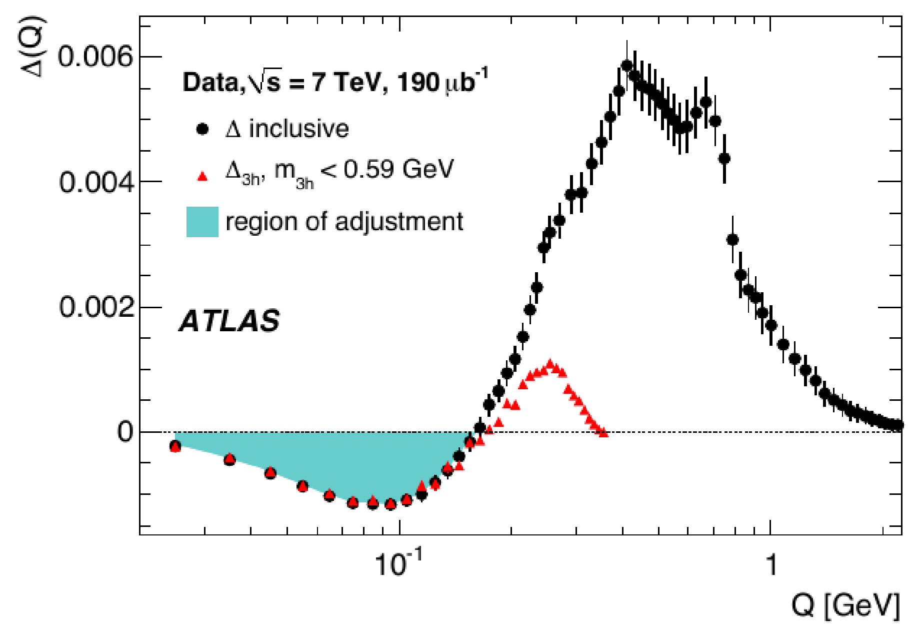
Evidence for same-sign enhancement in triplets, depending on 3h mass cutoff.

Quantify by defining Correlation Strength and Chain Correlation Strength:

$$CS = -\int_{\Delta<0} \Delta(Q)\,\mathrm{d}Q.$$

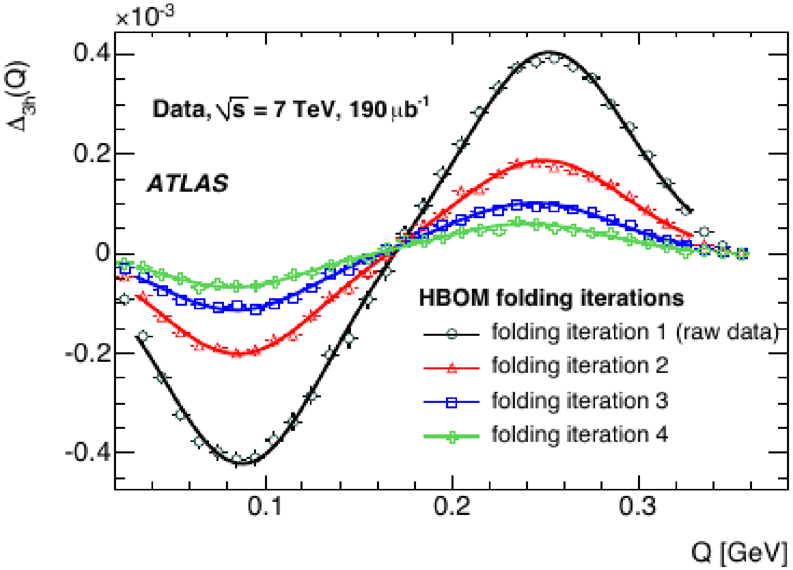
$$CCS\,(m_{3h}^{\rm cut}) = -\int_{\Delta_{3h}<0} \Delta_{3h}(Q)\,\mathrm{d}Q, \qquad \text{for } m_{3h} < m_{3h}^{\rm cut}.$$

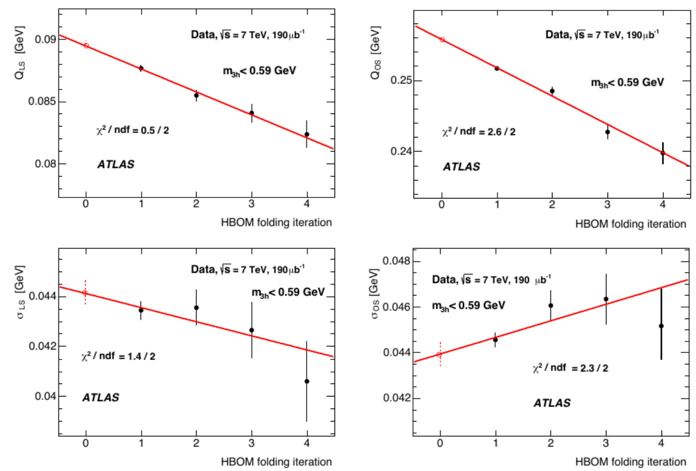




Data from the 2010 ATLAS low-mu sample; the measured value of CCS/CS corrected for detector effects by doing 3 iterations of folding through detector simulation, and extrapolating back the fitted functional form once more wrt the measured data point

3-particle correlations





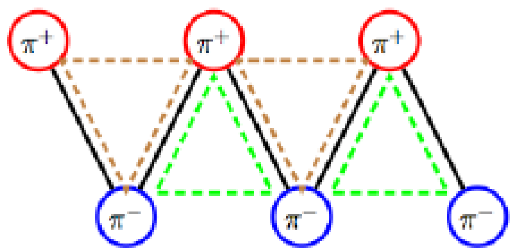
Parameter	m_{3h}^{cut} [MeV]				QCD helix model
	580	590	600	591(best estimate)	predictions [MeV]
	$\pm\sigma(stat)$			$\pm\sigma(stat) \pm \sigma(rec)$	
Q_{LS}	86.6 ± 0.4	89.4 ± 0.4	92.2 ± 0.4	89.7 ± 0.4 ± 1.2	91 ± 3
σ_{LS}	41.4 ± 0.6	44.1 ± 0.6	46.5 ± 0.7	44.3 ± 0.6 ± 2.0	-
Q_{OS}	248.3 ± 0.5	255.8 ± 0.5	262.9 ± 0.5	256.4 ± 0.5 ± 1.8	266 ± 8
σ_{OS}	40.9 ± 0.5	43.9 ± 0.6	46.5 ± 0.7	44.2 ± 0.6 ± 1.5	-

Good agreement with model predictions for same sign and opposite sign

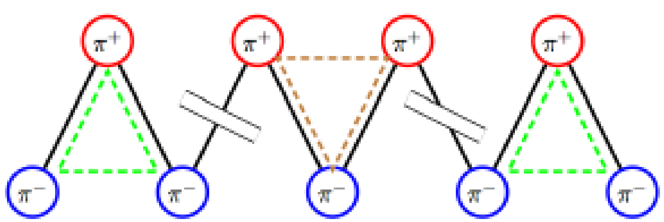
Subtracting 3h contribution

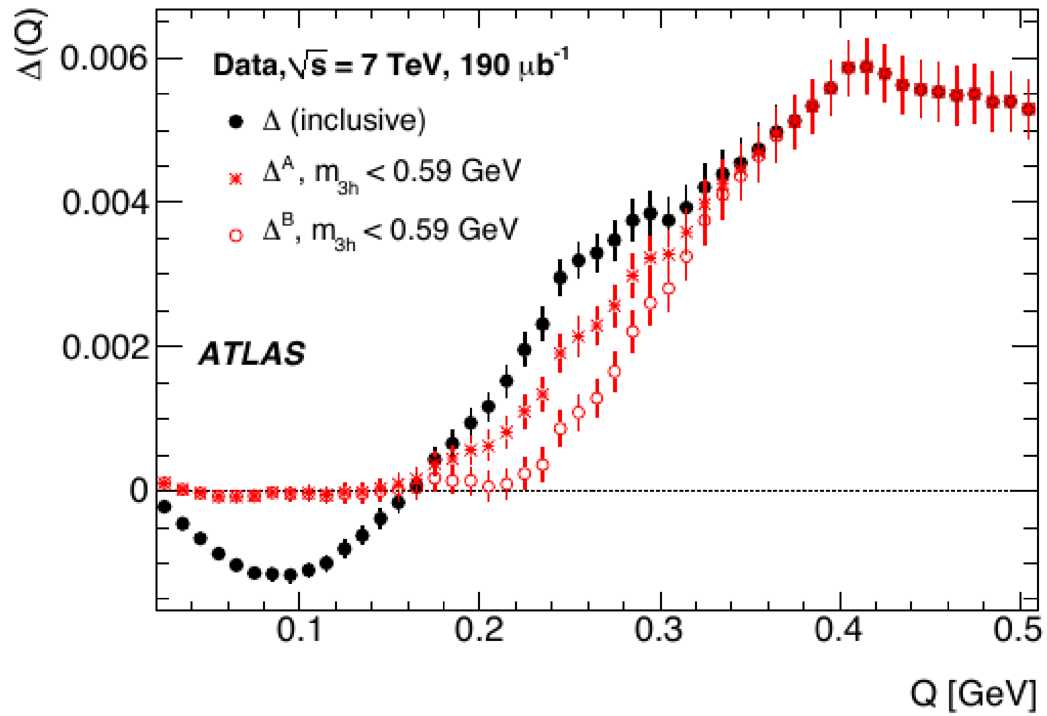
$$\Delta^{A}(Q) = \Delta(Q) - \Delta_{3h}(Q),$$
$$\Delta^{B}(Q) = \Delta(Q) - \Delta_{3h}(Q) - f_{OS}(Q; Q_{OS}, \sigma_{OS}).$$

A: $\Delta_{3h} = \{0.5(Q^{+-}_{min}), 0.5(Q^{+-}_{max}), -1(Q^{++,--})\}$



B: $\Delta_{3h} = \{1(Q^{+-}_{min}), 1(Q^{+-}_{max}), -1(Q^{++,--})\}$

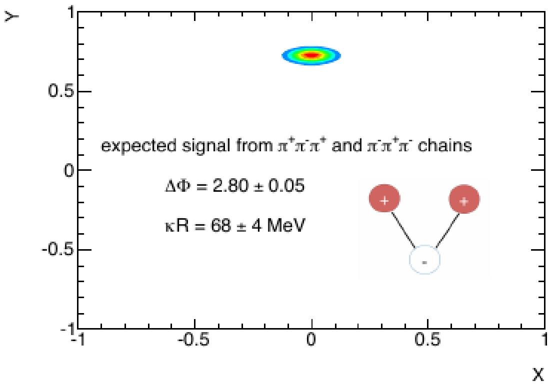


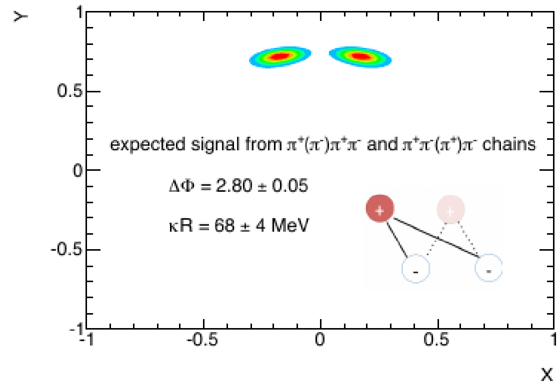


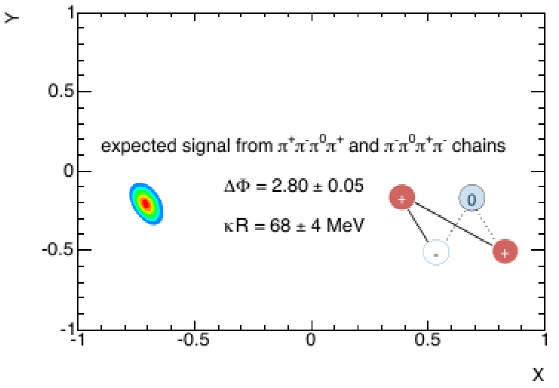
Δ_{3h} definition corresponds to long uninterrupted chain (hypothesis A)
An estimate for disconnected triplets is obtained by rescaling of positive part of Δ_{3h}
(after subtraction of random combinations)

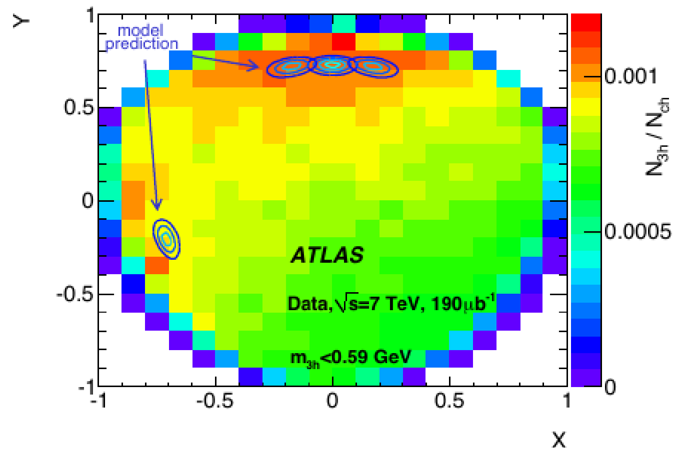
Subtracted result point to the existence of quantum threshold in adjacent pair production

Dalitz plot results









String parameters ΔΦ and κR are smeared by 2% and 6%, respectively. The maximal enhancement in the data corresponds to the expected location of the signal from the chain of three ground-state pions, with some indication for a possible presence of quadruplet chains: the wide “shoulder” of the signal in region can be interpreted as a signature of a quadruplet chain with a missing middle particle.

Summary of correlation measurement

- The quantised helical QCD string fragmentation model offer a good description of the observed data
- Enhanced production of like-sign pairs corresponds to coherent emission of ground-state hadron chains: 90 ± 3 MeV (91 ± 3 model expectation)
- QCD string properties: k_R = 68 ± 3 MeV (68 ± 2 exp.), $\Delta\Phi$ = 2.80 ± 0.01 (2.82 ± 0.06 model expectations)
- Quantum threshold in production of adjacent pairs: 266 ± 8 MeV (265.6 ± 9 model expectations)
- Properties of hadronic ground state:
  - E_T = 192 ± 9 MeV (192.5 ± 0.5 exp.)
  - P_T = 135 ± 6 MeV (136 exp.)
  - M = 136 ± 6 MeV (137 exp.) → Pion

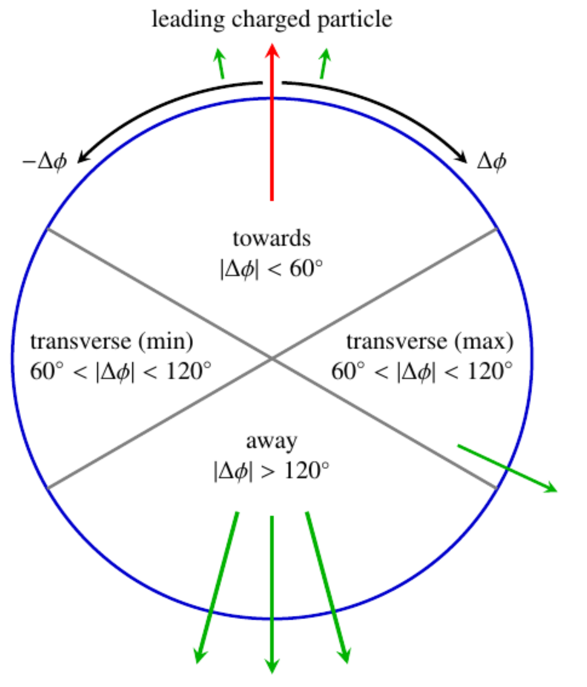
Underlying event studies with charged particle distributions

First ATLAS Run-2 measurement of charged particle distribution in Minimum Bias events

Idea, pioneered by CDF, is to divide the detector into three regions according to angular distance wrt leading track.

Expect more activity in torwards and away regions, less in transverse regions

Define transverse max and min on event-by-event basis, trans-diff difference between the two.



Measurement on 16/nb of low-mu pp collisions

Kinematic region:

p_T lead > 1 GeV; p_T track > 0.5 GeV; $|\eta| < 2.5$

Observables and models

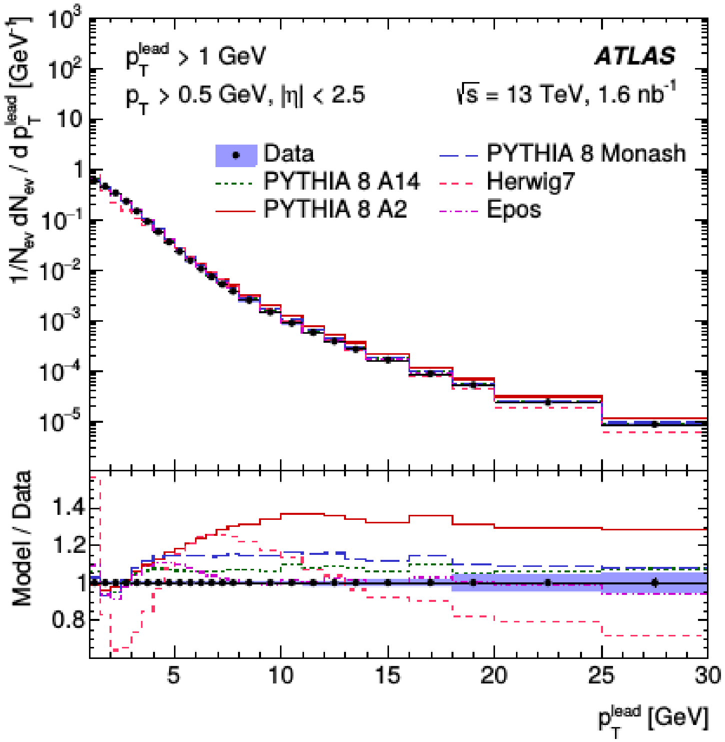
Measured observables:

Symbol	Description
BINNED VARIABLES	
p_T^{lead}	Transverse momentum of the leading charged particle
N_{ch}(transverse)	Number of charged particles in the transverse region
$\lvert\Delta\phi\rvert$	Absolute difference in particle azimuthal angle from the leading charged particle
AVERAGED VARIABLES	
$\langle N_{ch}/\delta\eta\delta\phi\rangle$	Mean number of charged particles per unit η–ϕ (in radians)
$\langle\sum p_T/\delta\eta\delta\phi\rangle$	Mean scalar p_T sum of charged particles per unit η–ϕ (in radians)
$\langle$mean $p_T\rangle$	Mean per-event average p_T of charged particles ($\geq$ 1 charged particle required)

Models tested:

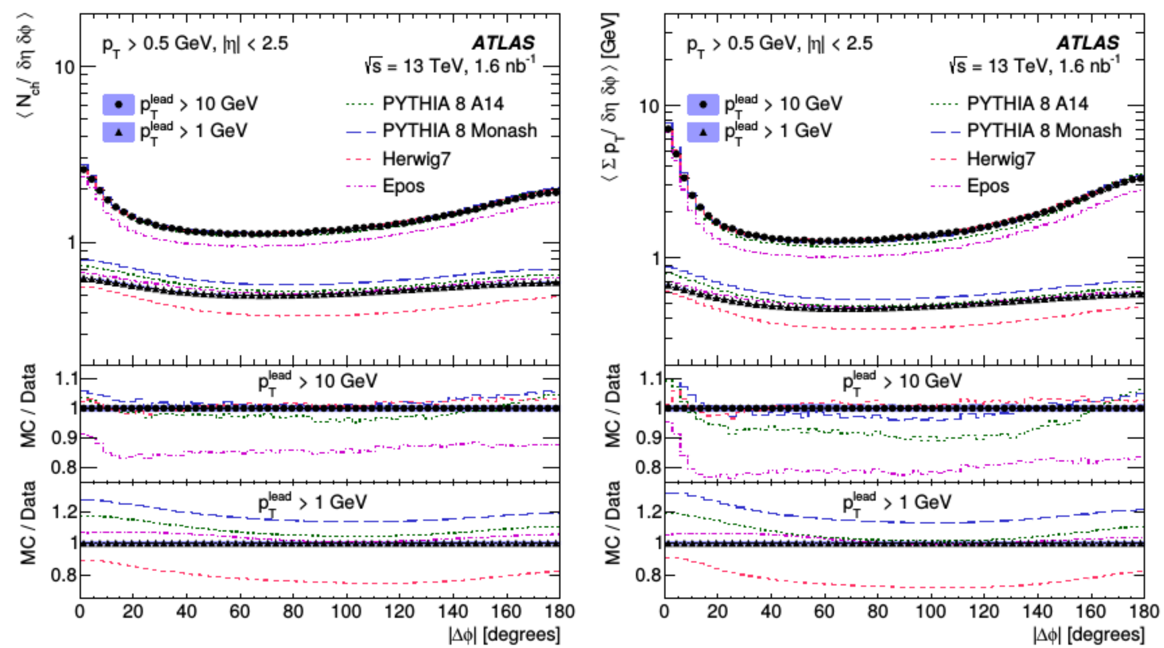
Generator	Version	Tune	PDF	Focus	From
PYTHIA 8	8.185	A2	MSTW2008 LO	MB	ATLAS
PYTHIA 8	8.185	A14	NNPDF2.3 LO	UE	ATLAS
PYTHIA 8	8.186	Monash	NNPDF2.3 LO	MB/UE	Authors
HERWIG 7	7.0.1	UE-MMHT	MMHT2014 LO	UE/DPS	Authors
EPOS	3.4	LHC	—	MB	Authors

Integrated distributions

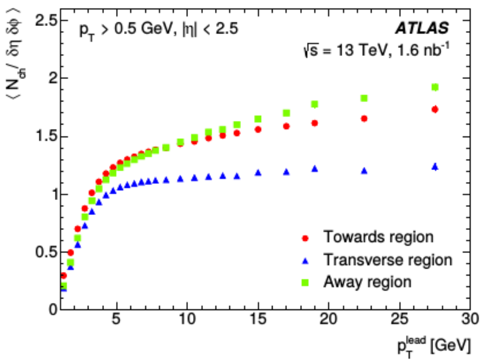


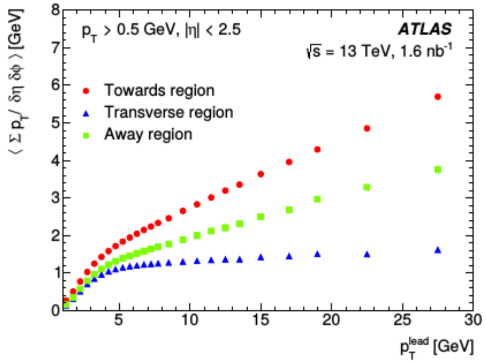
Charged multiplicity vs leading p_T

Charged multiplicity and p_T sums vs $|\Delta\Phi|$



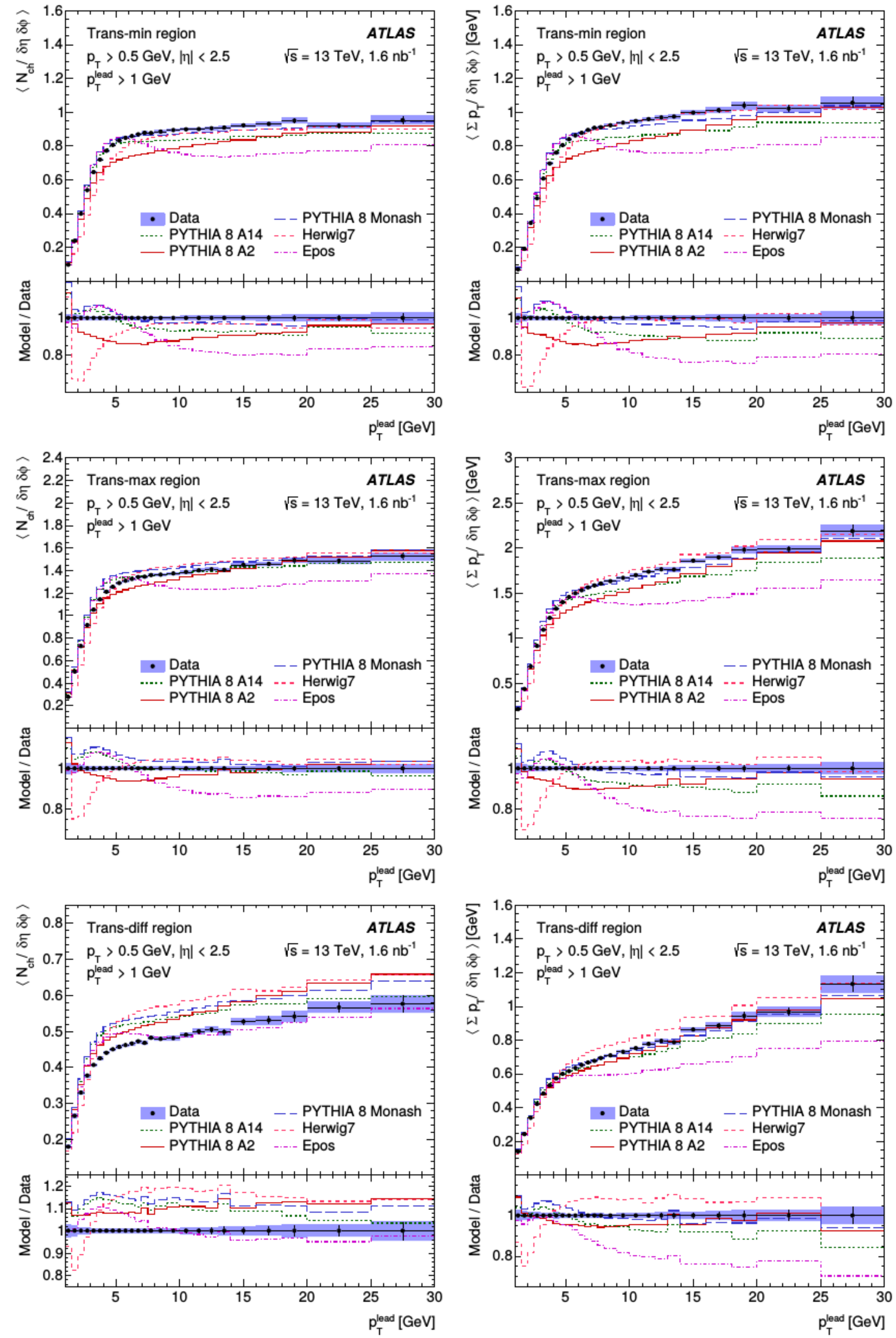
Different regions





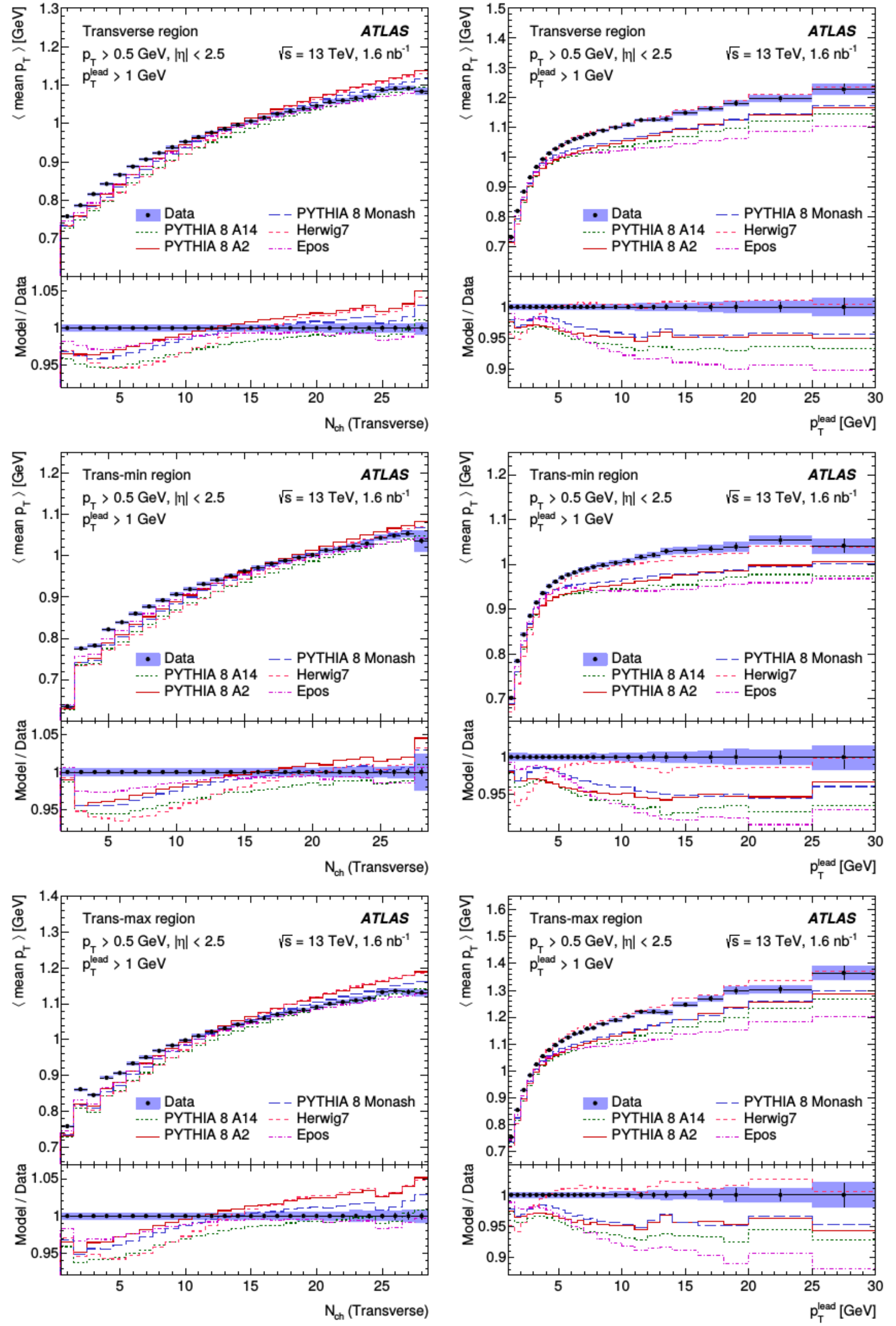
As expected, activity decreases between towards/away/transverse region.

In general, Pythia tunes give better agreement than Herwig, Epos quite bad apart from charged multiplicity in trans-diff region

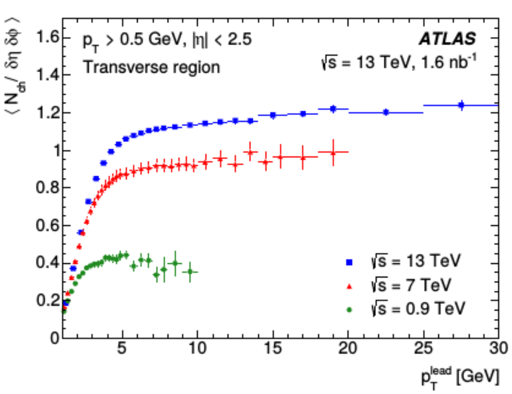


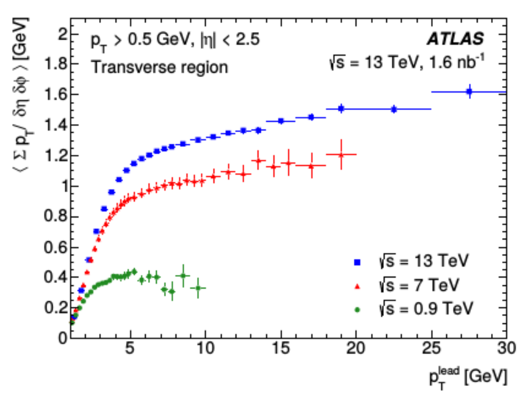
Mean pT distributions

Agreement with Herwig seems better than the other generators in <p_T> vs $p_T$lead distributions: agreement with data is at 1% level, apart in the region of $p_T$lead < 5 GeV, where the Herwig model is not expected to work.



Dependence on E(CM):





UE grows by a factor of 2 between 0.9 and 7 TeV, by 20% from 7 to 13 TeV

Conclusions

- The properties of hadron pairs and triples show that same-sign enhancement can be quantitatively explained with high accuracy by a quantised 3D helicoidal string model.
- The study of underlying event at 13 TeV explores correlations between $p_T$lead, $\langle p_T \rangle$ and multiplicity in the various azimuthal regions. A 20% increase in underlying event is observed from 7 to 13 TeV.
- Uncertainties on these measurements are sub-%, smaller than differences between MonteCarlo models, O(5%).
- These experimental results put strong quantitative limits on soft-QCD models.