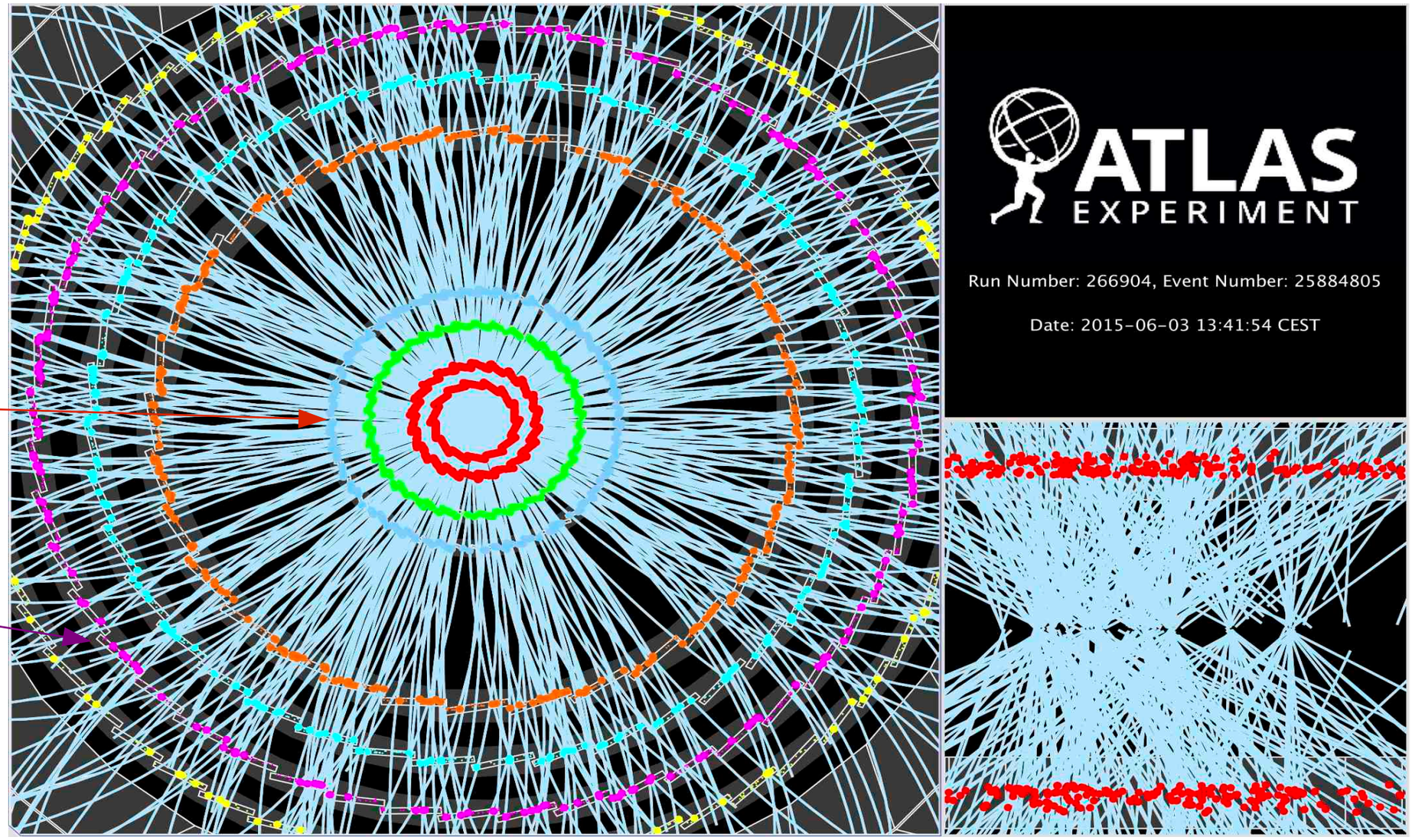
Measurement of the particle production properties in ATLAS

Alessia Bruni, INFN Bologna, on behalf of ATLAS collaboration

Low-x, 13-18th June 2017, Bisceglie, Italy

LHC pp events at high multiplicity



Most of QCD particle production cannot be calculated reliably using perturbative methods and is generally described by phenomenological models, usually implemented in MC generators

These models contains parameters, whose value and energy dependence is unknown and need to be tuned to the data

ATLAS results presented

- Underlying Event studies, results at √s=13 TeV, JHEP 03 (2017) 157

- Minimum Bias interactions, results at √s=13 TeV

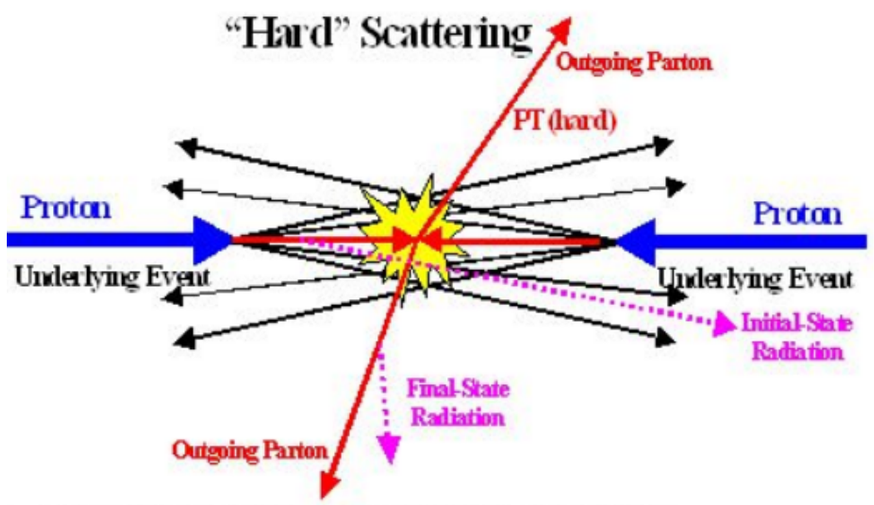
  Eur. Phys. J. C 76 (2016) 502, Phys. Lett. B758 (2016) 67

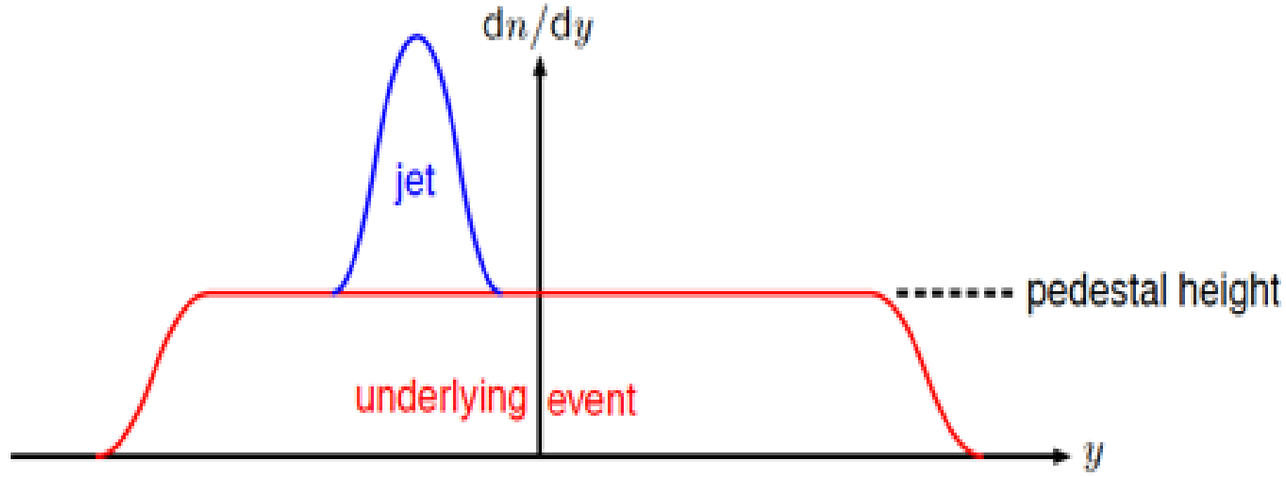
- Two-particle Bose-Einstein correlations in pp collisions at √s=0.9 and 7 TeV,

  Eur. Phys. J. C75 (2015) 466

- Testing new models of string fragmentation: hadronic chain analysis at √s=7 TeV, ATLAS STDM-2014-08 NEW

Underlying Event studies





The activity accompanying the hard scattering is defined as UE.
It includes beam-beam remnant interactions, multiple parton interactions (MPI), and initial and final state radiation.

UE not current calculable from first principles => measurements relevant:

- for better understanding of the mechanism involved
- for tuning of phenomenological model in in MC generators

Experimental studies of UE activity in different processes and energy shade light on process (in)dependence and energy evolution of UE

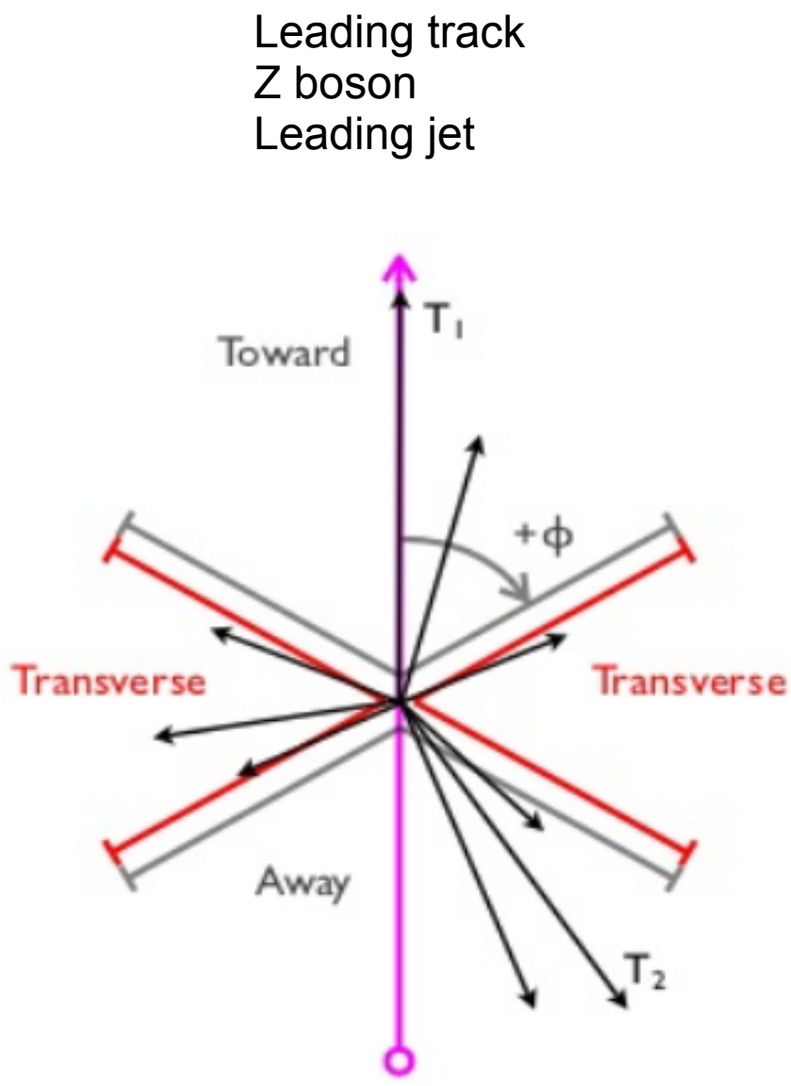
Underlying Event studies

Experimentally, 2 strategies:

1) investigate general properties of soft collisions, in minimum bias events, to have access to underlying event physics

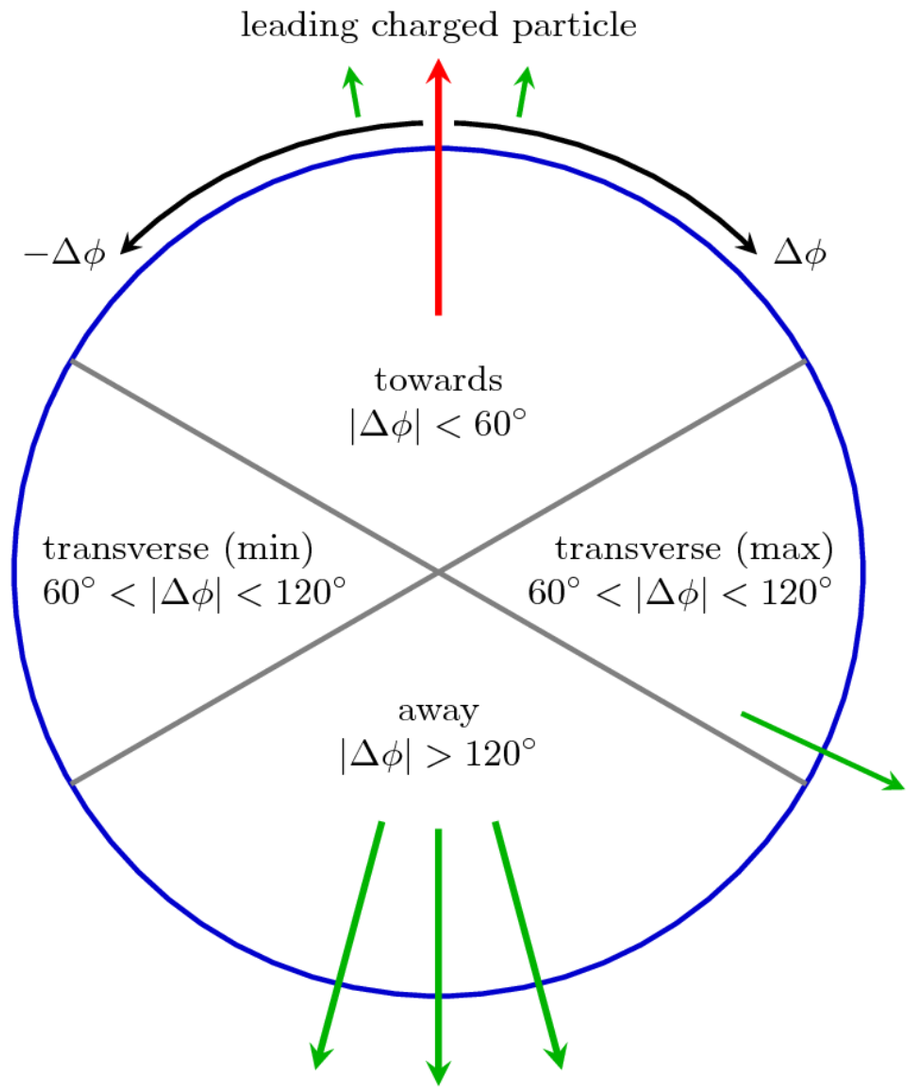
2) select reactions with a leading particle or jet, and on event-by-event bases, separate the phase space regions dominated from hard or soft contribution.

Traditionally azimuthal plane of the event is segmented into distinct regions with respect to the leading particle or jet (toward, away and transverse) that have different sensitivity to UE



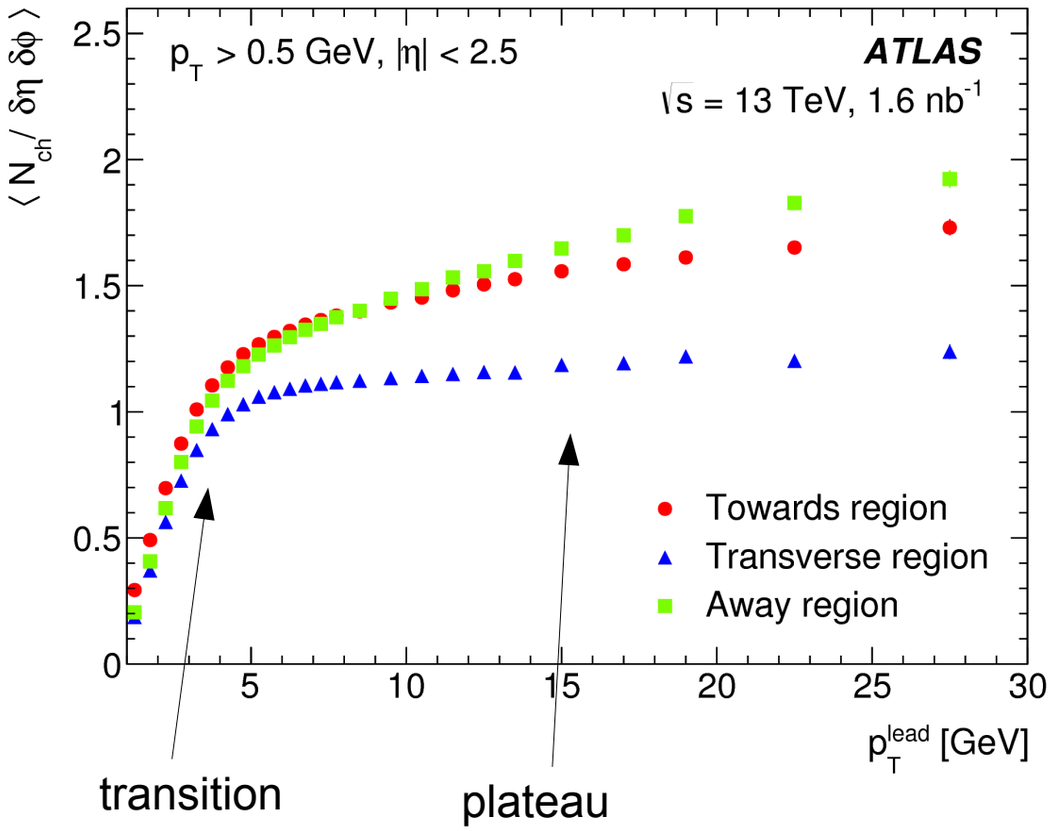
UE at 13 TeV - JHEP 03 (2017) 157

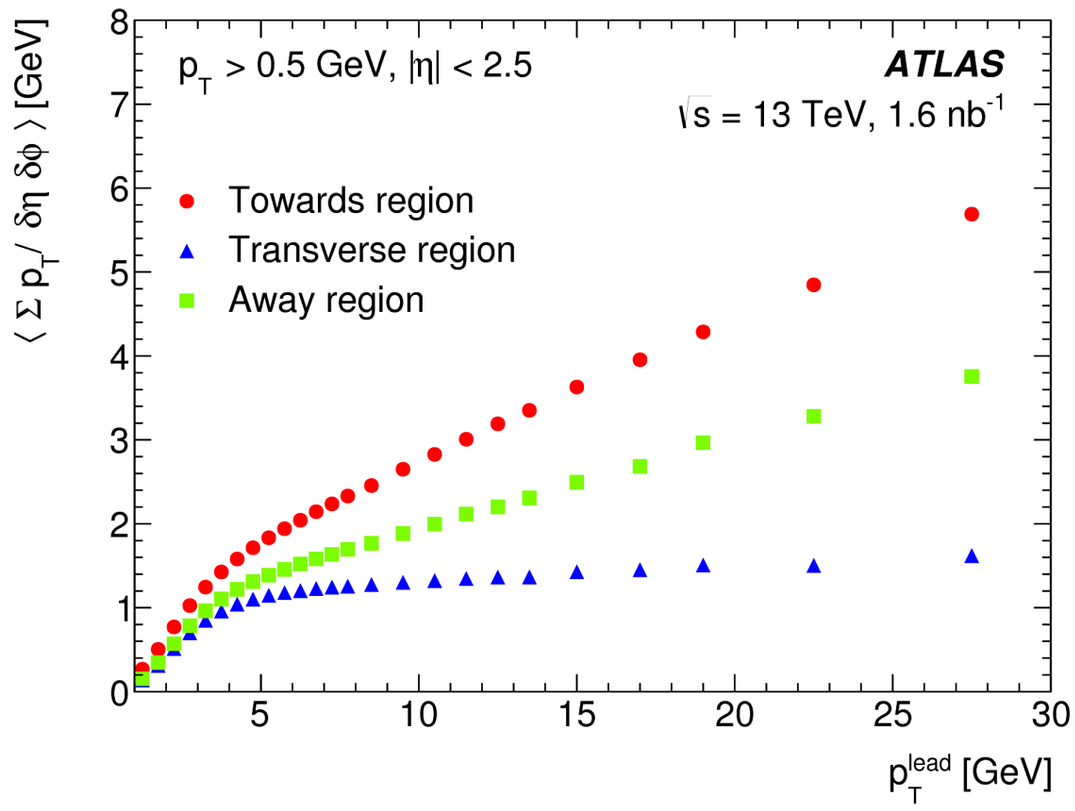
- Int lumi 1.6 nb^{-1}
- Track based analysis, observables from primary charged particles with $|\eta|<2.5$, $p_T>500$ MeV (strange barions excluded with lifetime cut $30<\tau<300$ ps)
- Regions defined in azimuthal angle with respect to the leading (highest p_T, $p_T>1$ GeV) charged particle: toward, transverse and away region
- Hard process contamination studied defining trans-min and -max regions: trans-min is relatively insensitive to wide angle emissions from hard process
- Angular distribution of energy and particle flows are studied



UE – 13 TeV results

JHEP 03 (2017) 157





- Mean η–φ densities of charged-particle multiplicities n_{ch} and $\sum p_T$ as a function of the of p_T the leading charged particle, for the transverse, towards, and away azimuthal
- Smooth transition at p_T^{lead} ~5 GeV from minimum bias interaction and hard scattering
- Pedestal effect in the transverse region for n_{ch} and mean $\sum p_T$

UE – N_{ch} and Σp_T densities in transverse region for different energies $\sqrt{s}$=0.9 TeV, 7 TeV, 13 TeV

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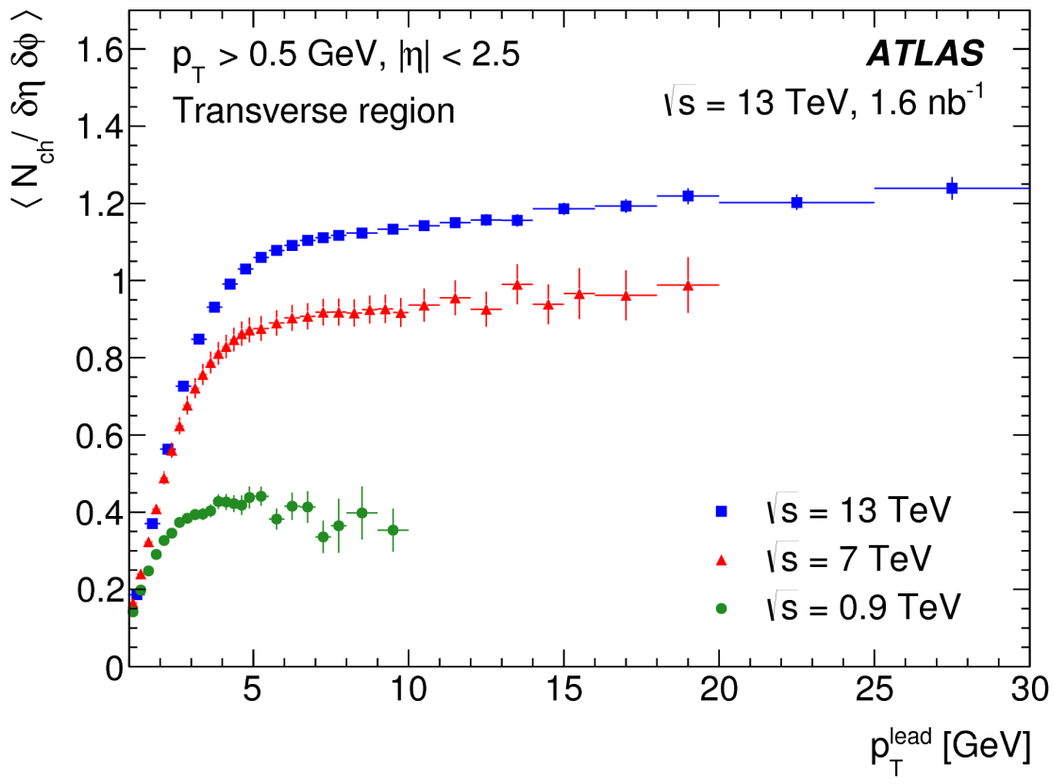

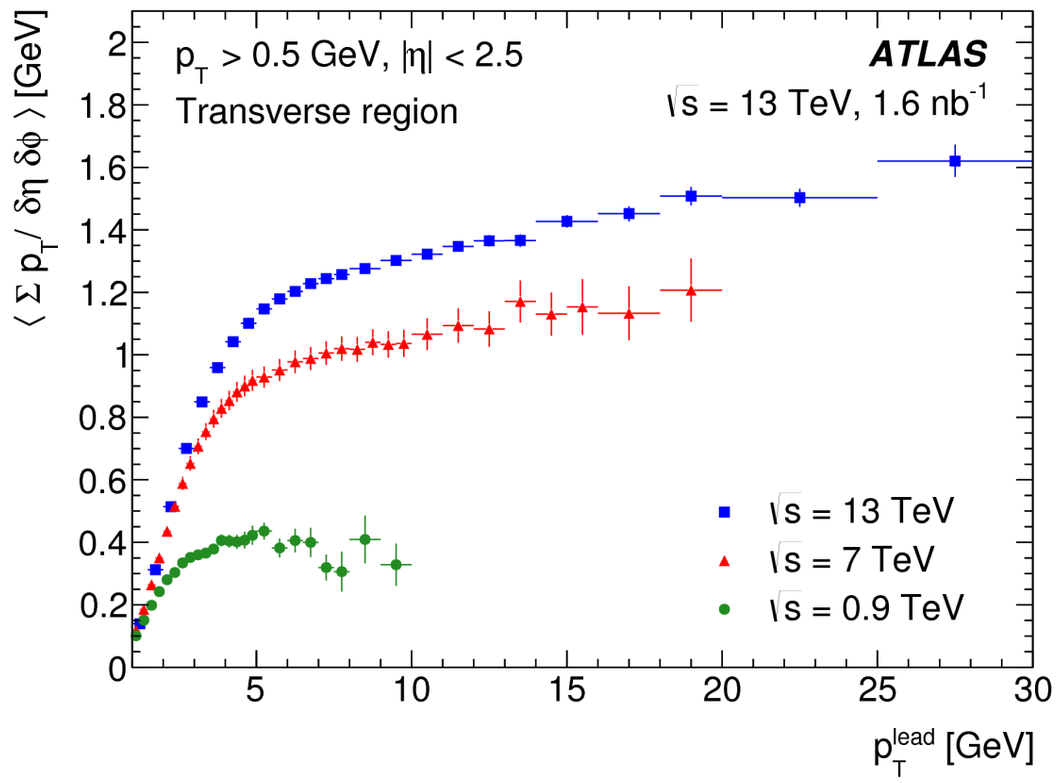

- UE studied for different energies, $\sqrt{s}$=0.9 TeV, 7 TeV, 13 TeV
- Smooth transition from minimum bias interaction and hard scattering at all energies
- UE increases of 20% from $\sqrt{s}$=7 TeV to 13 TeV pp collisions

UE – MC comparison and tuning

- The data of the analysis were carefully compared to MC predictions using the generators PYTHIA 8; HERWIG 7 and EPOS
- The scattering subprocesses contributing most to the UE observables is non diffractive inelastic scattering
- For each generator, the set of parameters optimized for the description of the data are called tunes. Tunes optimized at $\sqrt{s}$=7 TeV are compared to 13 TeV data

Generator	Tune	Data used	Results
PYTHIA 8	A14	ATLAS UE, optimized to several UE and jet radiation observables, emphasis on high scale	Good description, undershoots data in low multiplicity events
PYTHIA 8	A2	ATLAS, Minimum Bias, 7 TeV	Good description of MB and transverse energy flow, overshoots data in high multiplicity events
PYTHIA 8	Monash	ATLAS+CMS+SPS+Tevatron to constrain energy scaling	Excellent description of ATLAS MB at 7,8,13 TeV
HERWIG 7	UE-MMHT	Tevatron and LHC data	Largest variations as a function of n_{CH}
EPOS	LHC	Soft QCD/cosmic-ray air shower MC Based on an implementation of Gribov-Regge model	Good description of MB but lacks of hard scattering conmponent

UE – N_{ch}, Σp_T densities in transverse min. region

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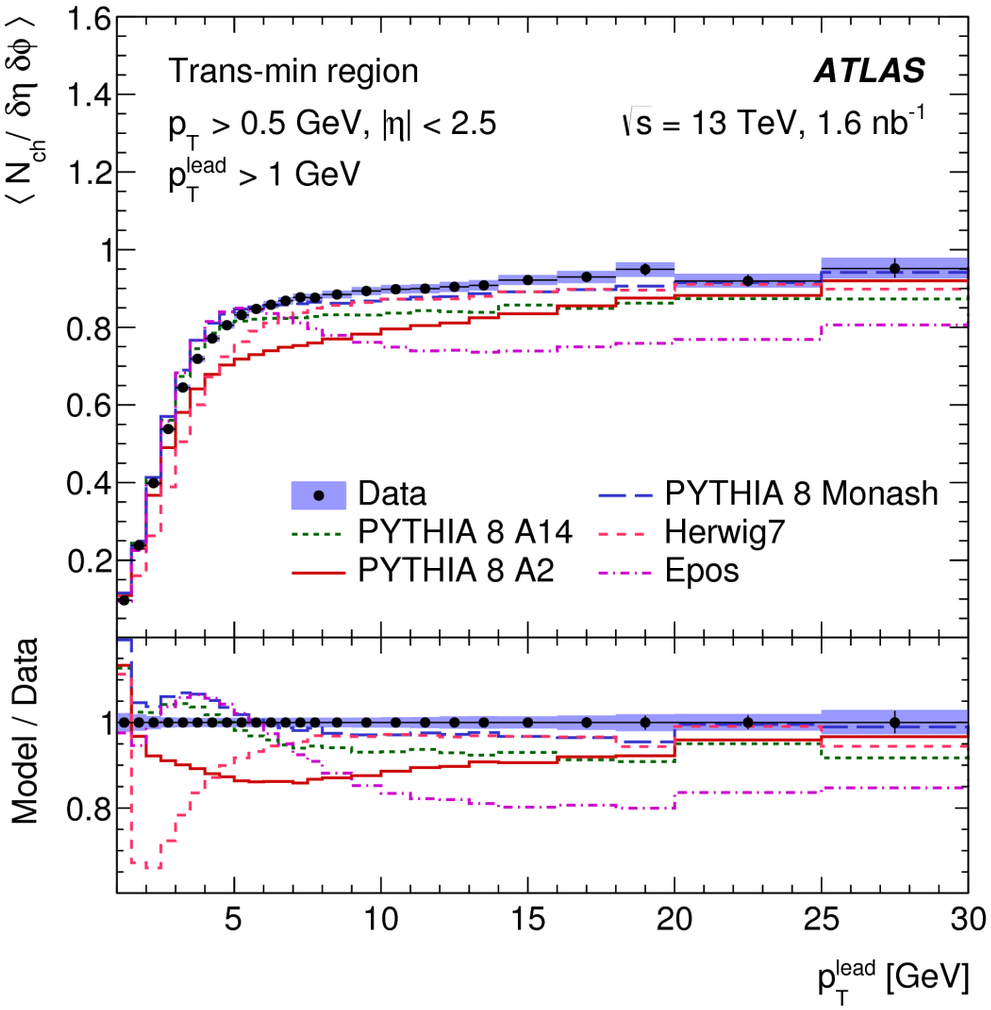
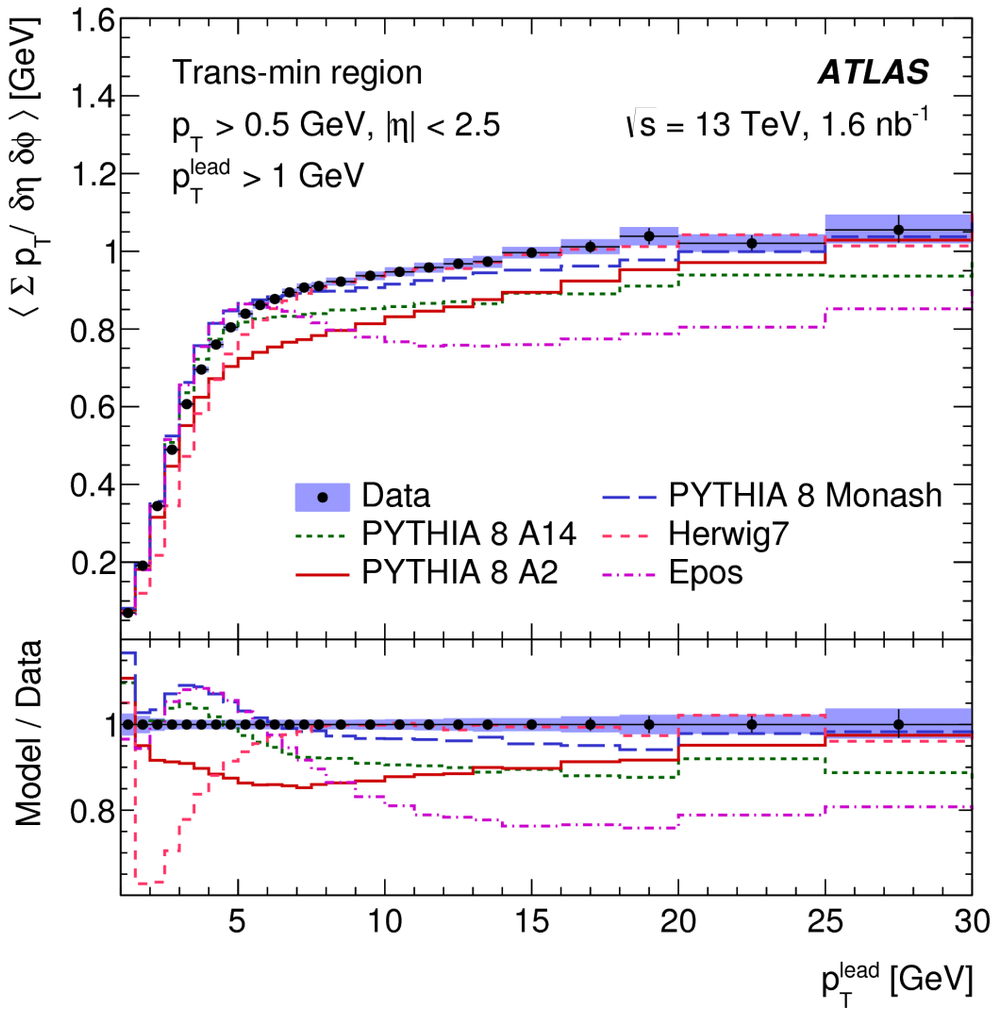
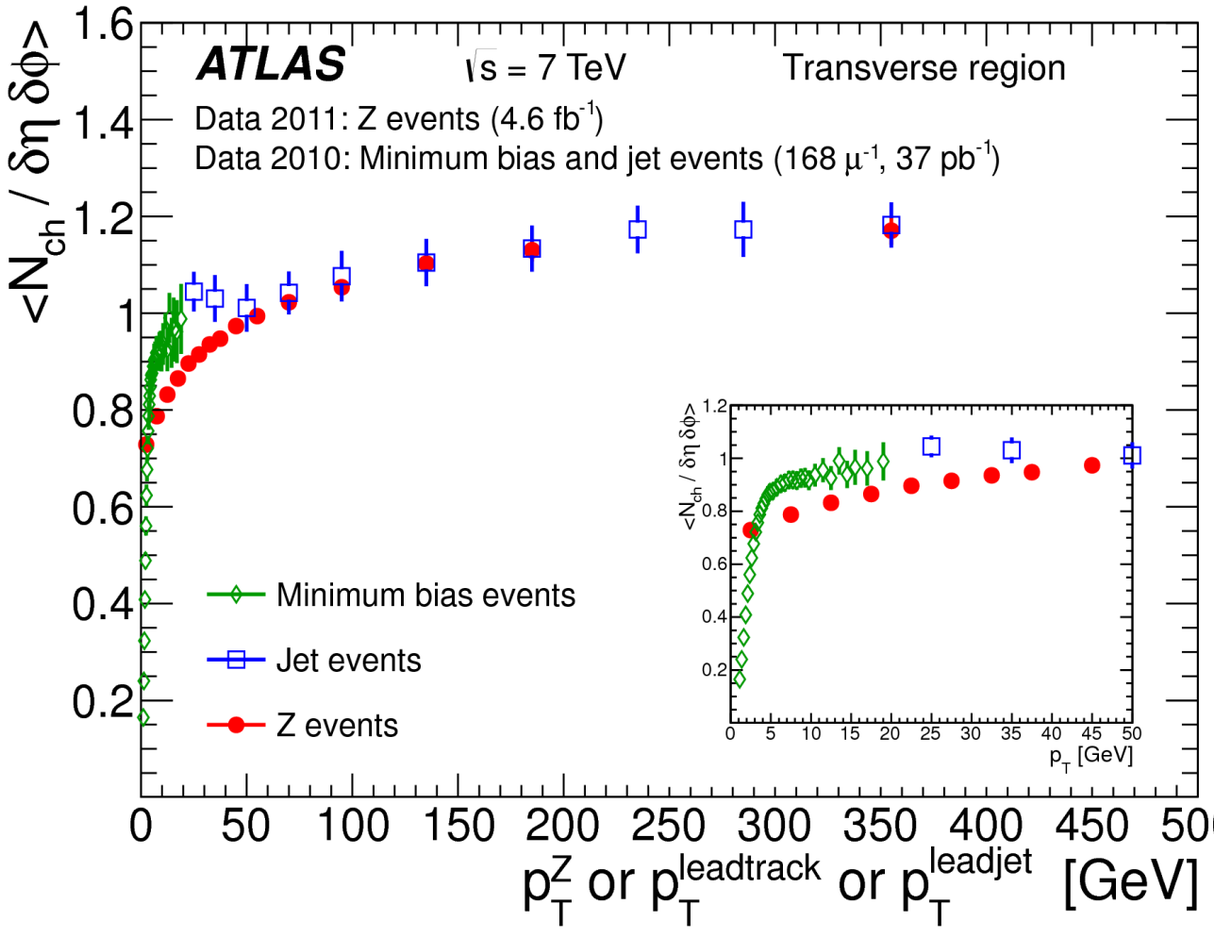


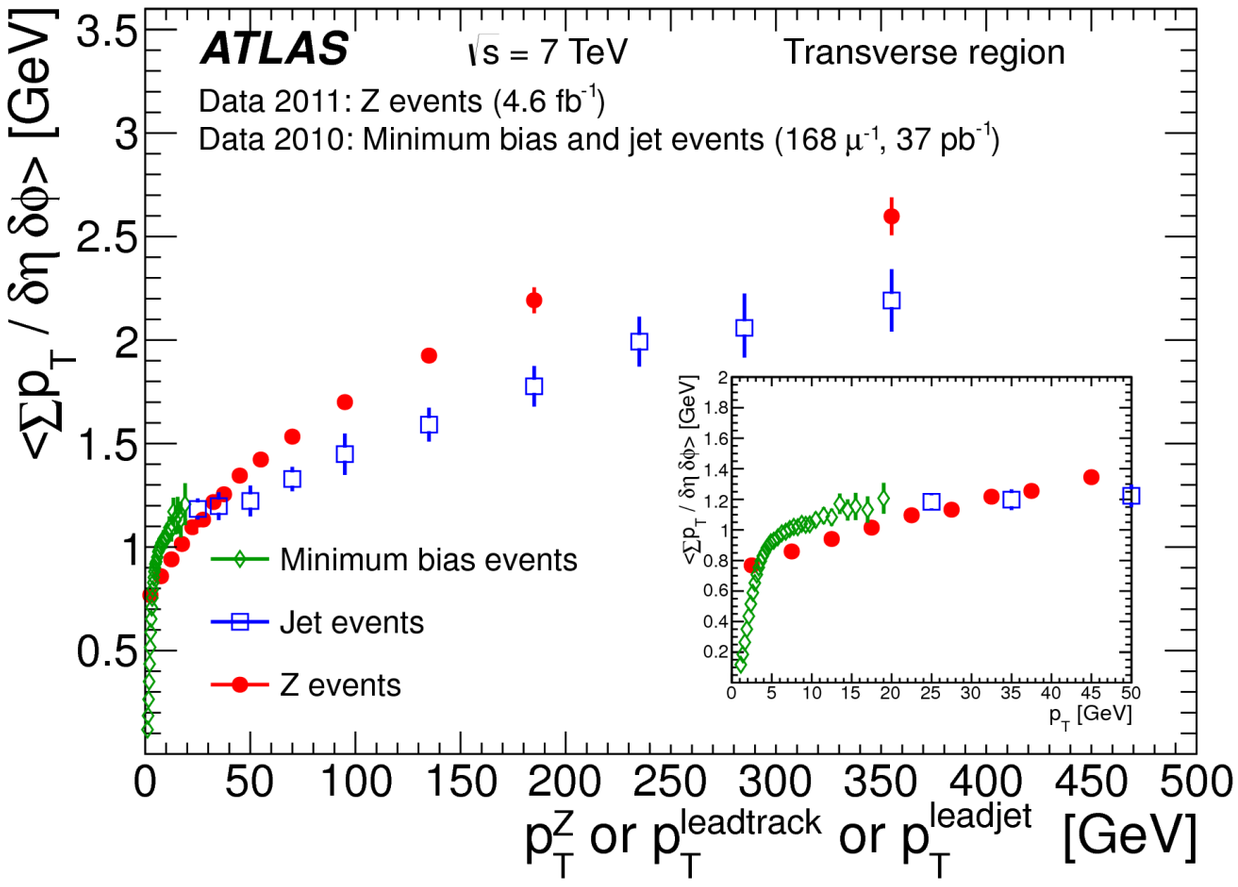


- For most observable, MC models describe data within 5% accuracy
- But data uncertainty requires <1% precision
- Evidence of mismodelling, i.e. in the transition from mimimum bias and hard scattering (i.e. EPOS describes minimum bias but lacks of had scattering)
- This study provides relevant data for MC tuning for LHC Run 2 and beyond

UE – N_{ch} and p_T sum in transverse region for different leading objects: Z boson, Jets, tracks

Eur.Phys.J.C 74(2014)3195





ATLAS measurements.: Z boson Eur. Phys. J. C (2014) 74:3195, Leading jets Eur.Phys.J. C74 (2014) 2965, Phys. Rev. D 86 (2012) 072004 and leading tracks, JHEP 03 (2017) 157

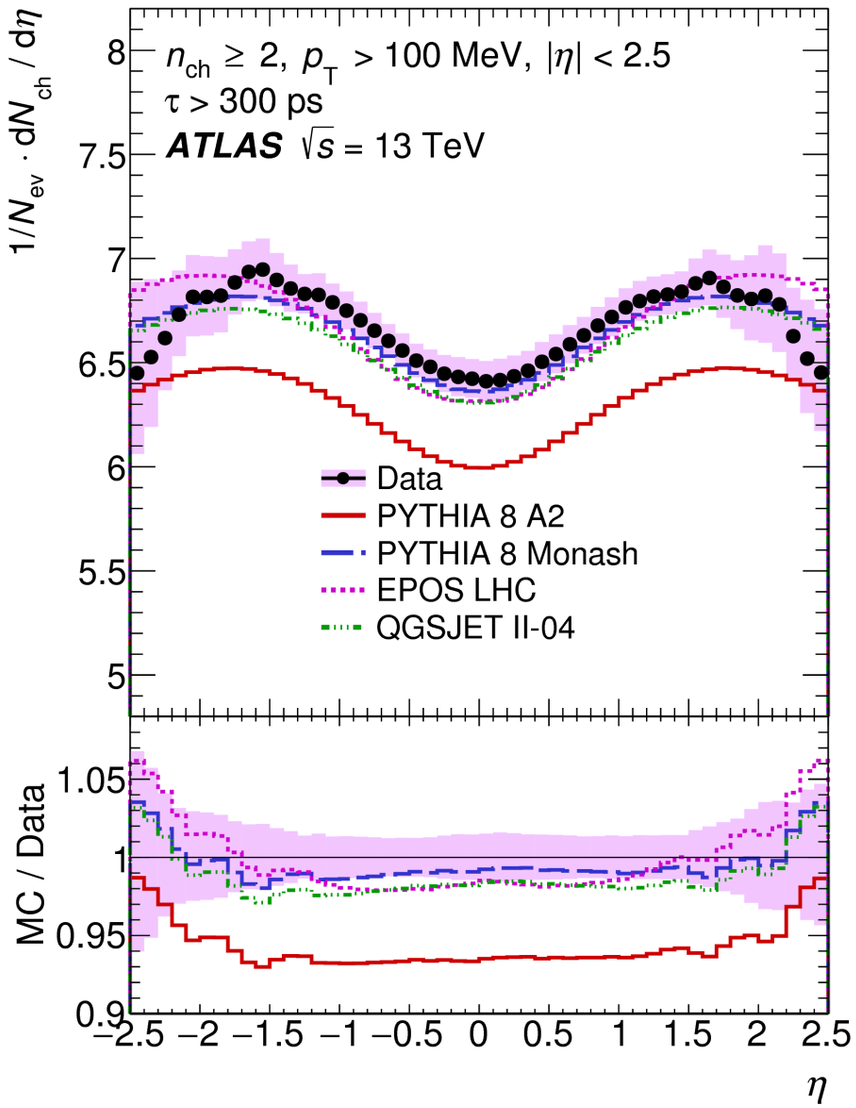
- Both N_{CH} and p_T sum increase to a plateau for $p_T^{leading} > 6$ GeV, pattern compatible with the impact parameter picture of pp collisions
- Consistent UE activity across processes within known selection bias

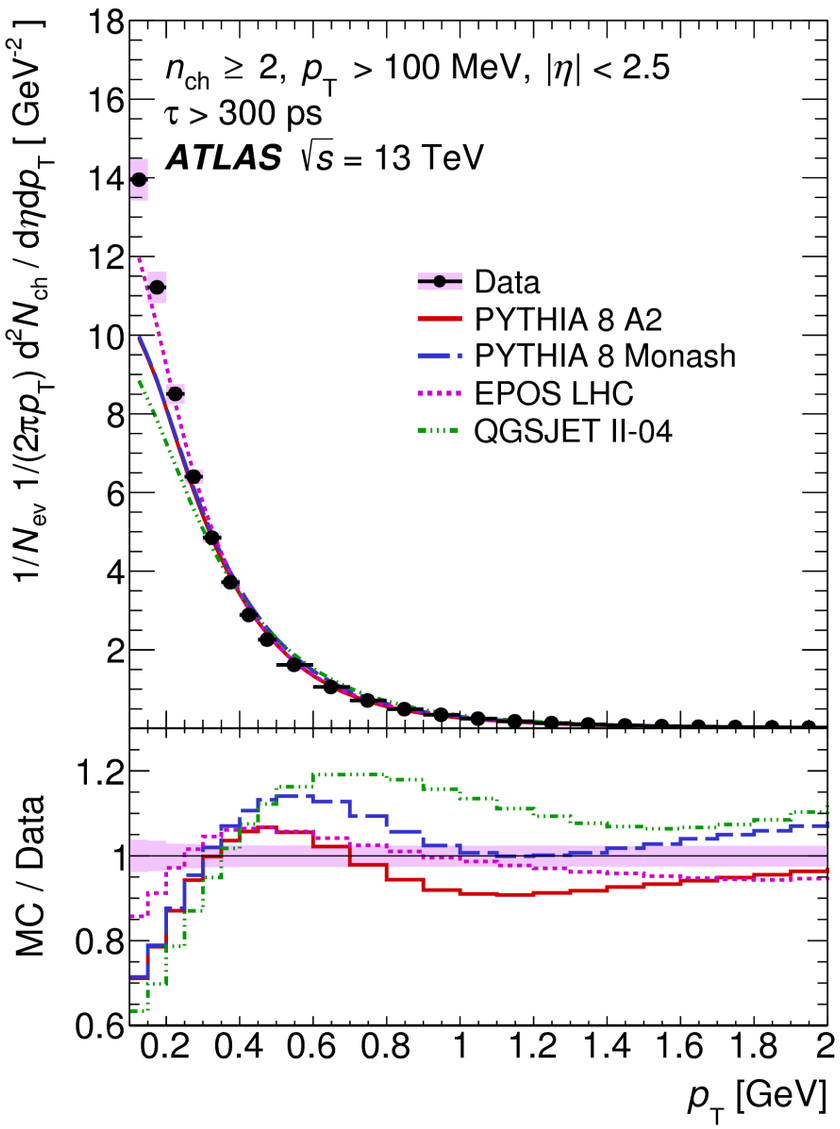
Minimum bias - multiplicity of charged particles vs η and p_T

- Measurement of utmost importance for precise understanding of LHC data, used to model pile-up collisions. Tracks studied for p_T> 100 GeV
- Strategy:
  - collect minimum bias data in low pile-up runs
  - study n_{ch}, dn_{ch}/dp_T $dn_{ch}/d\eta$, in comparison with tuned models

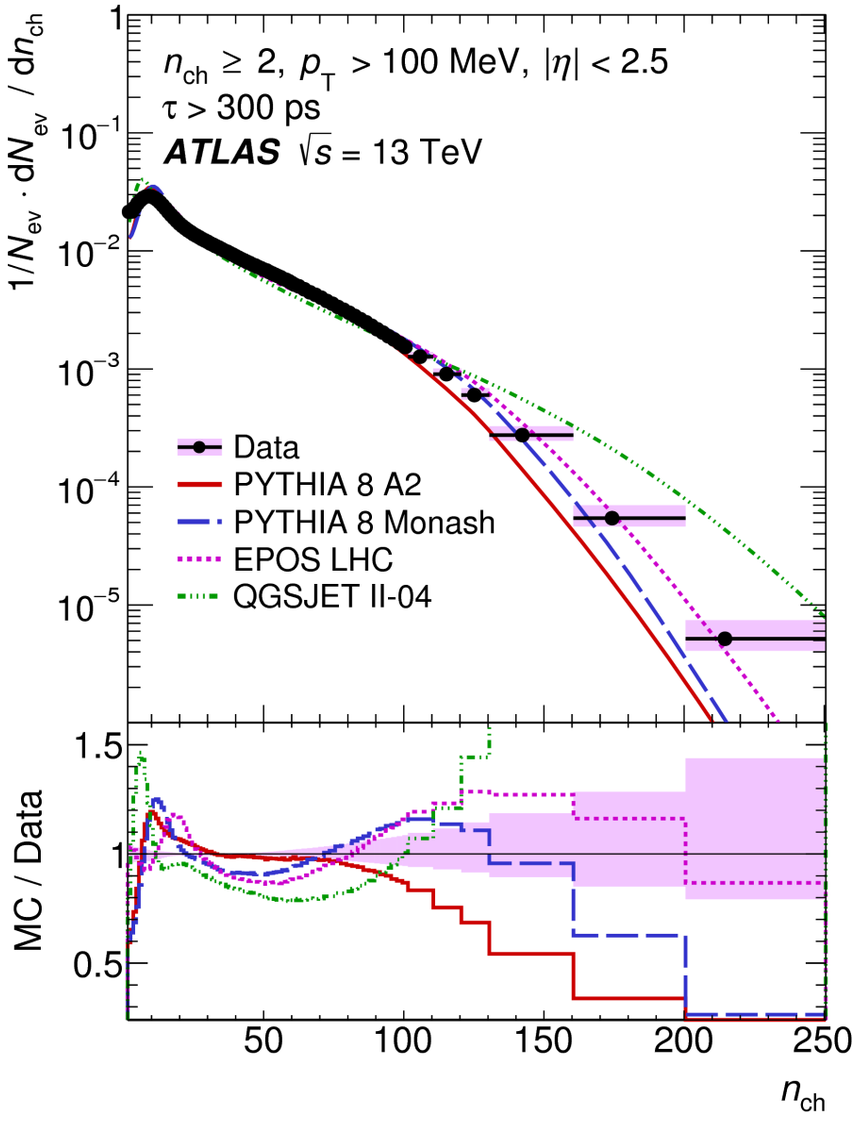
13 TeV, low p_T

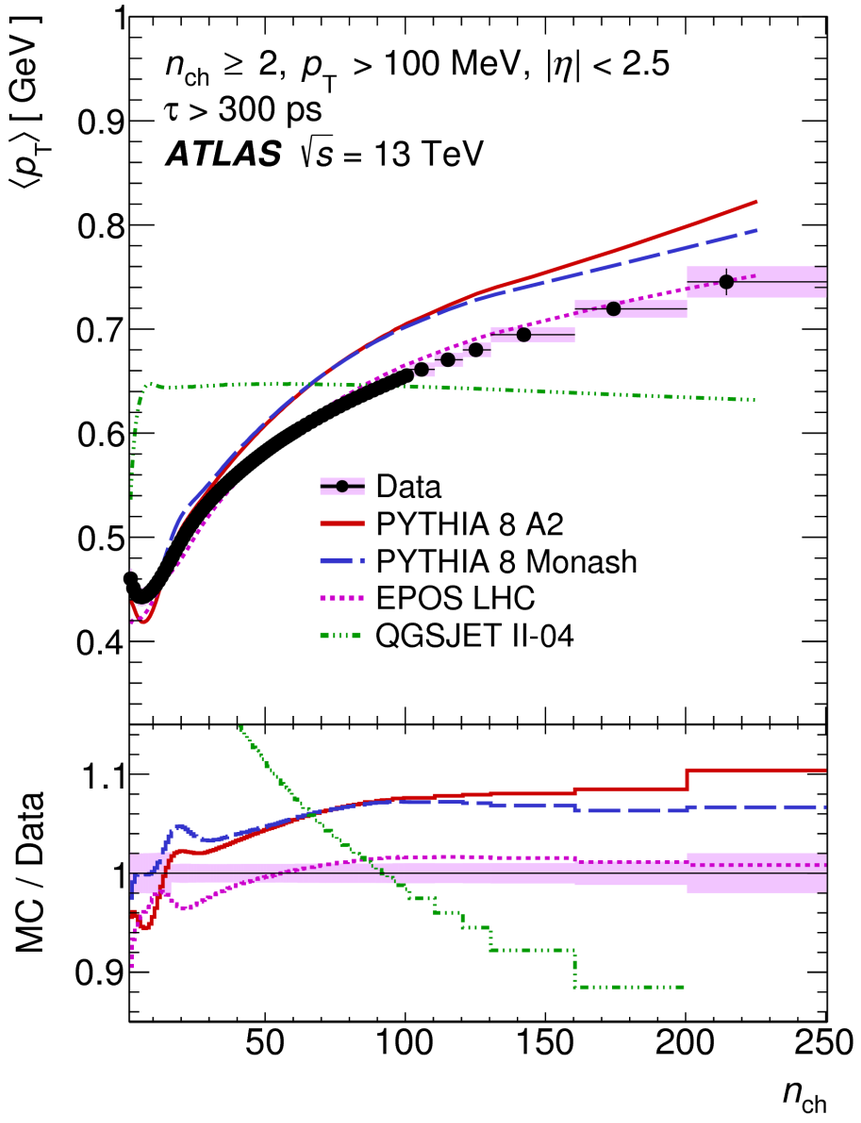
EPJ C76 (2016) 502





Minimum bias – multiplicity of charged particles and mean p_T vs n_{ch}





13 TeV – low p_T

EPJ C76 (2016) 502

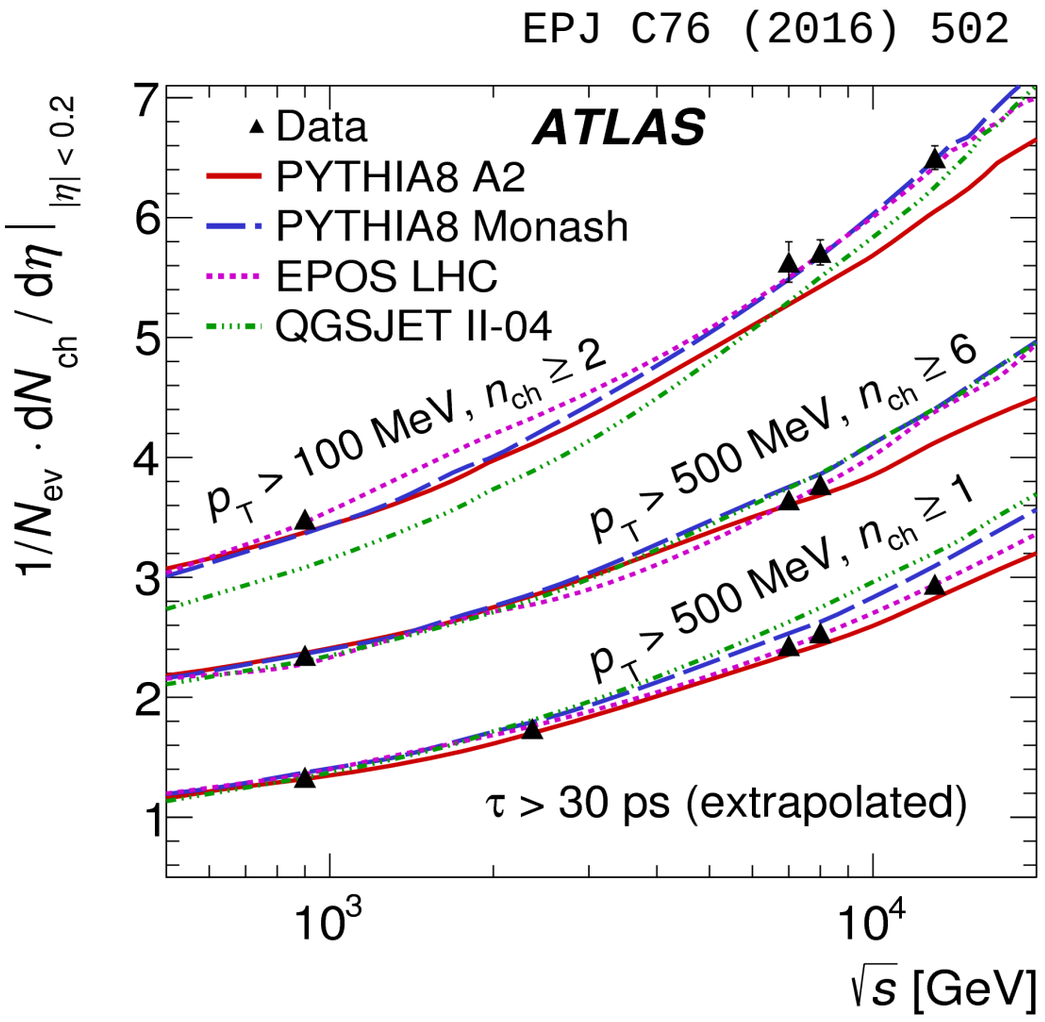
low-p_T version of the 'original' MinBias analysis at 13 TeV

EPOS reproduces the data the best, PYTHIA 8 provides a reasonable description

Minimum Bias:

- Very essential measurements for experiments
- Some tuning needed for low momentum tracks

Minimum bias – energy dependence of charged multiplicity



N_{ch} energy dependence studied

for p_T down up to 100 MeV up to

$\sqrt{s}$=13 TeV

At 13 TeV, charged multiplicity per unit of **η ~6 for** p_T >100 MeV

<N_{ch}> increased by a factor ~2 when $\sqrt{s}$ increases by a factor 14, from $\sqrt{s}$=0.9 to 13 TeV.

Energy dependence reproduced by various MC models, big success for MC

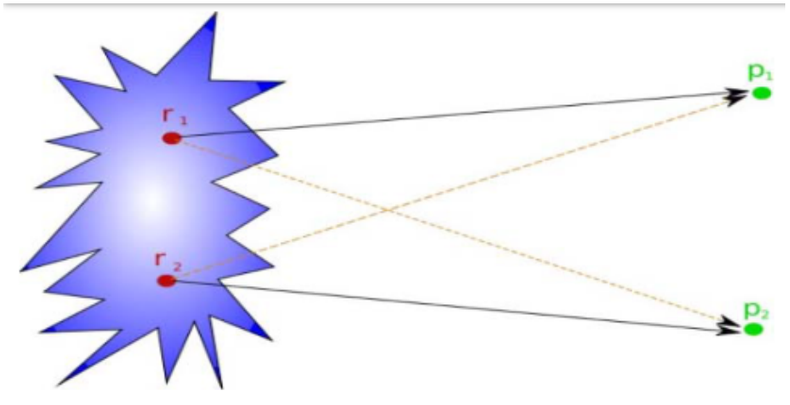
Two particle correlation in mimimum bias events

1) Studies of Bose-Einstein correlation Eur. Phys. J. C75 (2015) 466

2) Models based to QCD string fragmentation scenario, a recent study of the ATLAS coll. ATLAS STDM-2014-08 NEW

For the model, see also Sharka Todorova, "Quantization of the QCD string with a helical structure, arXiv:1309.6761, Phys.Rev.D89(2014) 015002"

Particle correlation - Bose-Einstein correlations



Eur. Phys. J. C75 (2015) 466

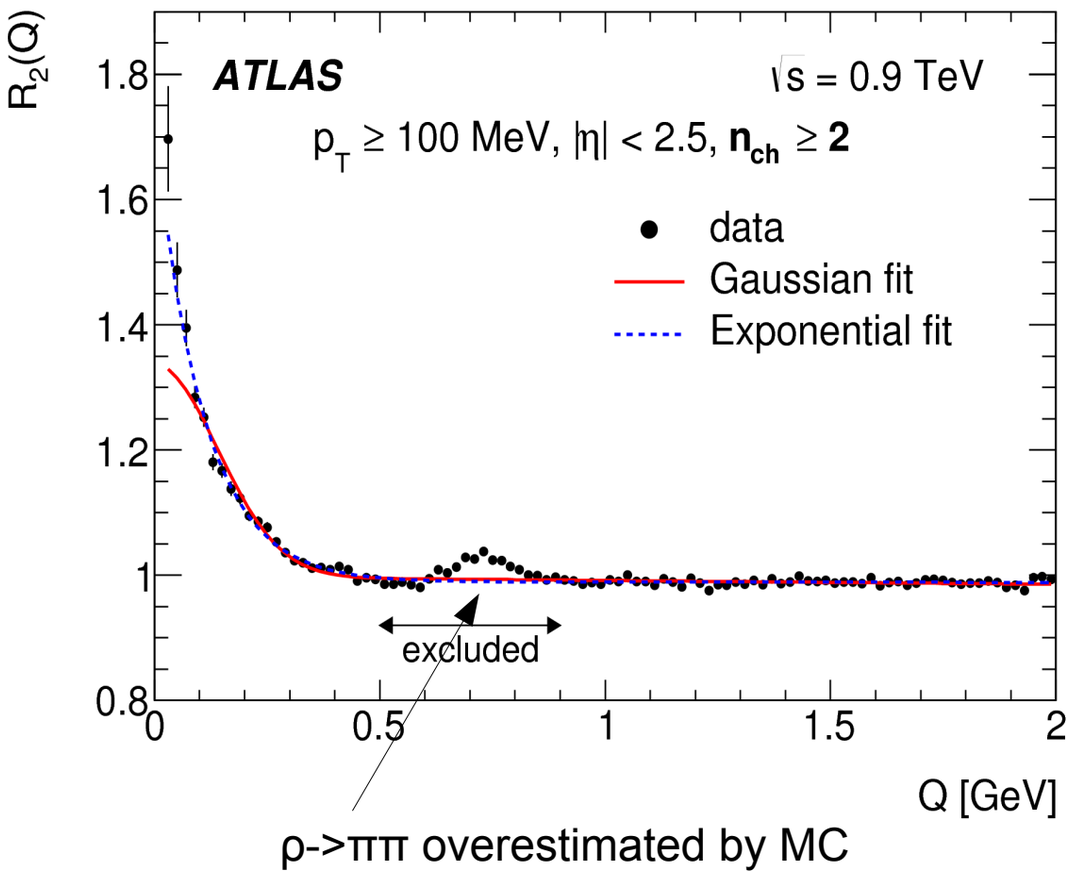
BEC effect = higher emission probability of two identical bosons with very similar momenta

- 2 particle correlation function

$$C_2(p_1,p_2) = \frac{\rho(p_1,p_2)}{\rho_0(p_1,p_2)}$$

Probability to observe 2 particles with momenta p1 and p2

Probability to observe one particle with momenta p1 or p2



- R double ratio of correlation functions

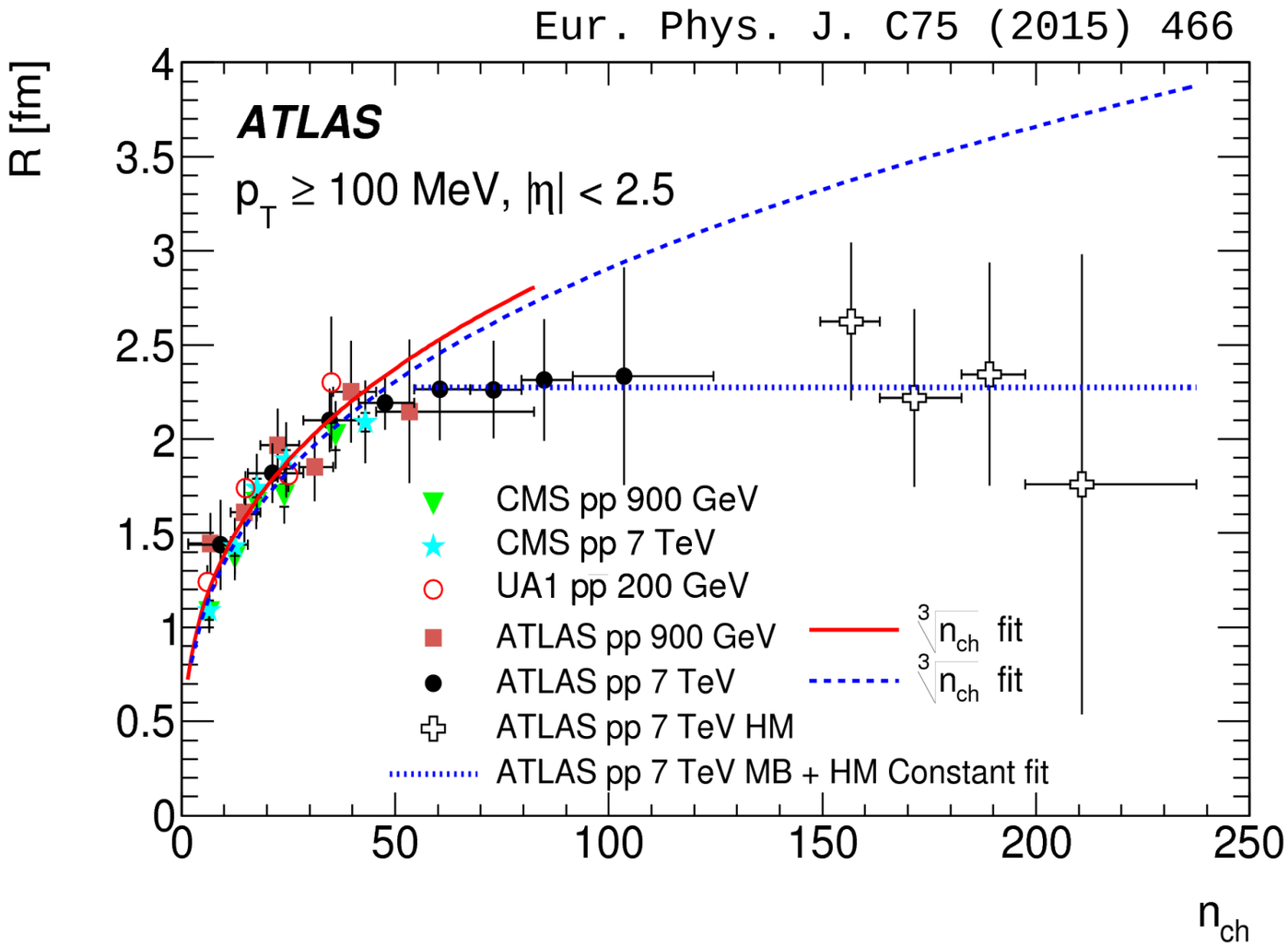
$$R_2(Q) = \frac{C_2(Q)}{C_2^{MC}(Q)} = \frac{\rho(++,--)}{\rho(+-)} \Big/ \frac{\rho^{MC}(++,--)}{\rho^{MC}(+-)}$$

R is a measurement of emitting source effective radius. R studied as a function of:

- Q, the 4-momentum difference of the 2 particles
- Multiplicity n_{ch}

Bose Einstein correlation – R vs n_{ch}

R, effective size of the source of emitting particle, vs multiplicity



R increases with multiplicity up to n_{ch}~50, independently form √s, indicating an increase of the size of emitting source

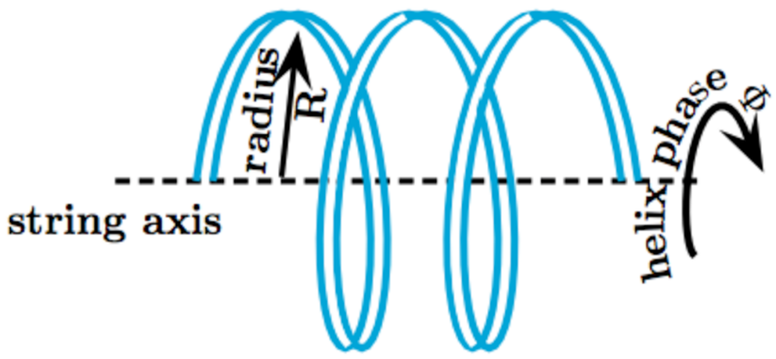
For larger multiplicity, there is a saturation effect of R indicating a constant size of the emitting source

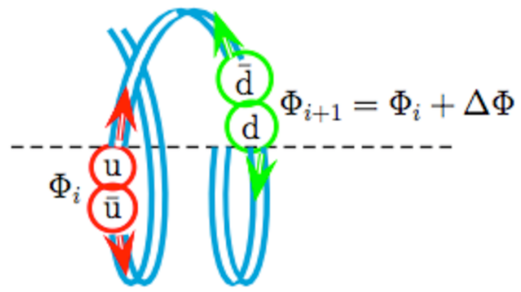
This is predicted by Pomeron-based models as consequence of overlap of colliding protons

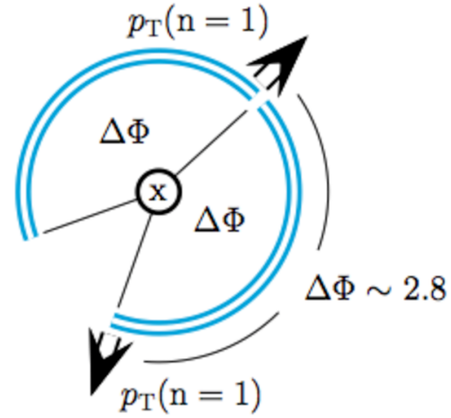
Analysis of momentum difference between charged hadron at LHC and QCD string fragmentation models

Quark confinement: for large charge separation, QCD field lines seem to be compressed to tubelike regions => QCD field approximated by strings

- Lund fragmentation model: 1D string
- Quantized string fragmentation models: 3D string with helicity conservation in gluon emission => helix shaped string. An effective quantization is imposed







Observables are related to string parameters: the quantized helix phase $\mathbf{\Delta \Phi}$ and the transverse shape of string R radiuns and string tension k (~1 GeV/fm)

$$E_T(n) = n\kappa R\ \mathbf{\Delta \Phi} \qquad p_T(n) = 2\kappa R\ |\sin(n\mathbf{\Delta \Phi}/2)|,)$$

- Pseudoscalar meson (π, η, η')can be seen as string pieces fragmenting in ground state hadrons with n=1,3,5.
- Their mass spectrum is used to extract the helical QCD field parameter

Quantized helix string models - predictions

- Ordered hadrons chains:

  QCD string breaks into a chain of ground state hadrons (pions); the order of pions along the string is called rank (r). Hadrons with rank difference 1 are called adjacent hadrons.

- The 4-momentum difference Q between hadrons within a chain is expected to be asymmetric, due to the local charge conservation, between pair of pions with equal sign charge (r=2,4...) or opposite sign (r=3,4..),

equal sign charge

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

opposite sign charge

- The region where Q is low is expected to be populated by pions of equal sign charge
- A quantum threshold is expected in 4-momentum difference Q in the production of adjacent hadrons

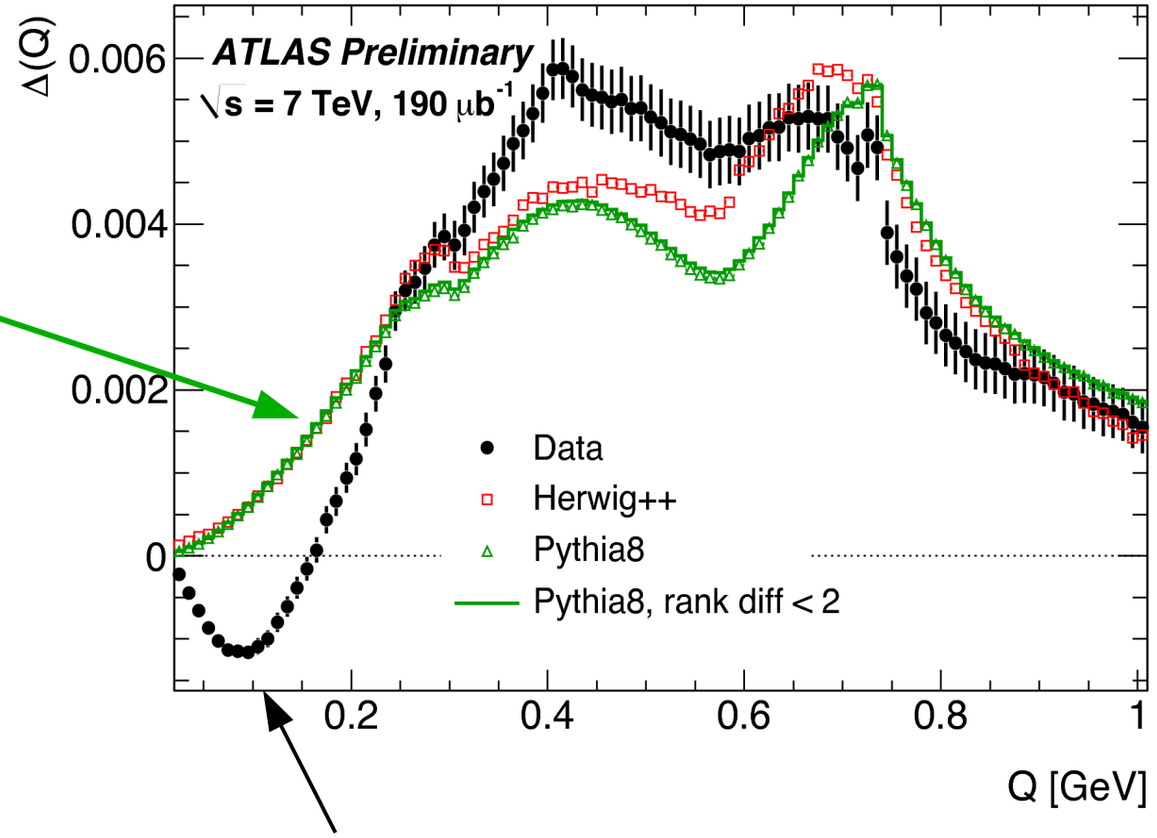
Study of the ordered hadron chains: analysis strategy-1

A correlation function **Δ(Q)** is defined as function of inclusive spectrum of opposite-sign or like-sign pairs $N(Q)^{+-}$, as a function of Q, the difference in 4-momentum of particles

$$\Delta(Q) = \frac{1}{N_{\mathrm{ch}}} [\, N(Q)^{+-} - N(Q)^{++,--} \,],$$

- Property of correlation function checked in MC
  I.e. in PYTHIA the subtraction of inclusive pair distributions give the same results as the extraction of true adjacent pairs
  =>correlation function effectively removes background from random combinations

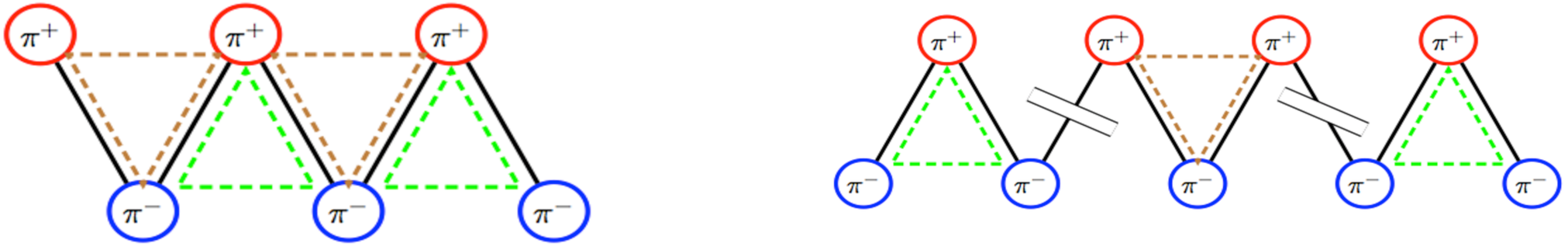
- the shape of inclusive correlations at low Q matches the expected signal from chains of ground pions, let's try to isolate the source of the signal.



Data show signal at low Q

Study of the ordered hadron chains: analysis strategy-2

- The shortest chains of hadrons sensitive to the dynamical properties of QCD field are chains of 3 charged hadrons



- It is experimentally impossible to to assess the exact rank ordering of particle => using the minimization of the mass of chains of hadrons

The method is the following:

1) Each particle is paired with the like sign particle minimizing the pair momentum difference Q
2) Each pair is completed with an opposite charged particle minimizing the triplet mass, assuming all particles are pions
3) ... some refinement of the chains is applied. The final number of chains = number of charged particles

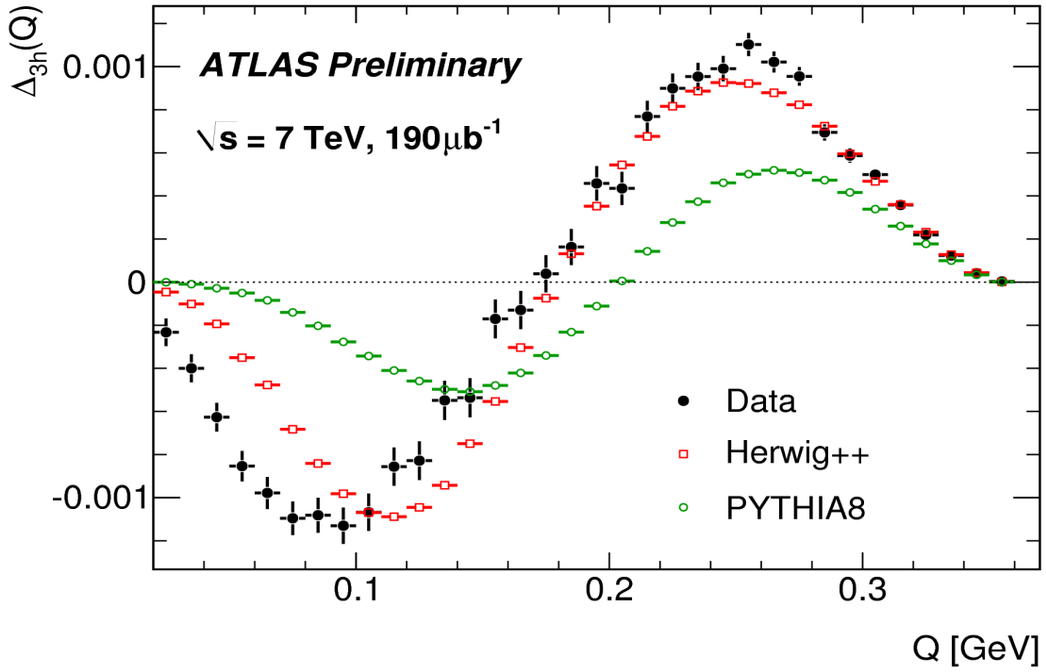
Study of the ordered hadron chains: analysis strategy-2

- A correlation function for triplets of hadrons is introduced Δ_{3h}

$$\Delta_{3h}(Q) = \frac{1}{N_{ch}} \Sigma_{i=1}^{N_{ch}} w_i \left\{ \begin{array}{l} +\frac{1}{2}\ (Q = Q_i^{+-\mathrm{min}}) \\ +\frac{1}{2}\ (Q = Q_i^{+-\mathrm{max}}) \\ -1\ (Q = Q_i^{++,--}) \end{array} \right\}, \quad w_i \neq 0,$$

Data from minimum bias analysis at $\sqrt{s}$=7 TeV, already used for the Bose-Einstein corr. analysis

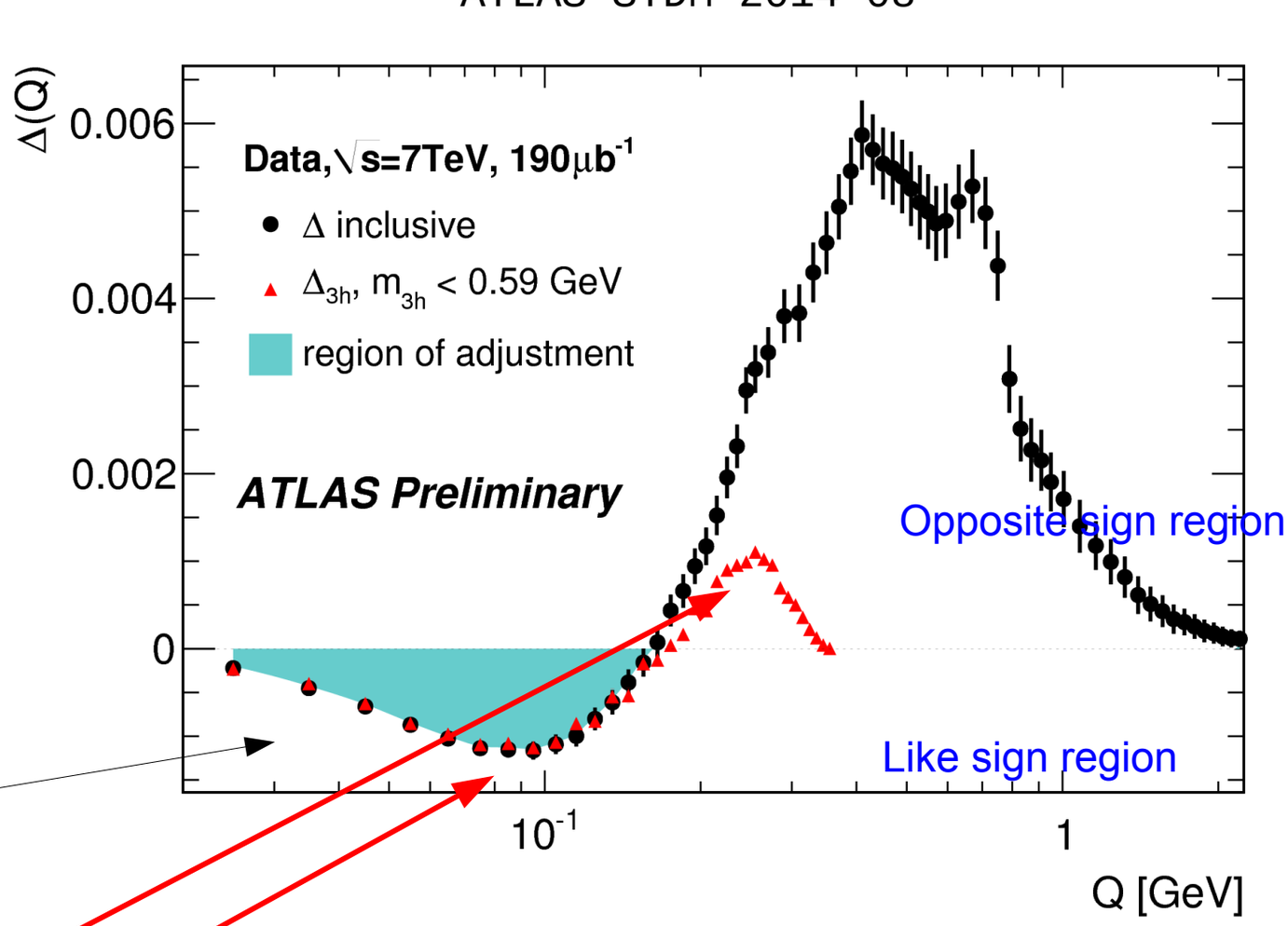
Data compared to PYTHA and Herwig MC. MCs have no correlation beyond local charge and momentum conservation in the string breakup



Study of the ordered hadron chains: results

Correlation function vs 4-momentum difference Q between charged hadrons

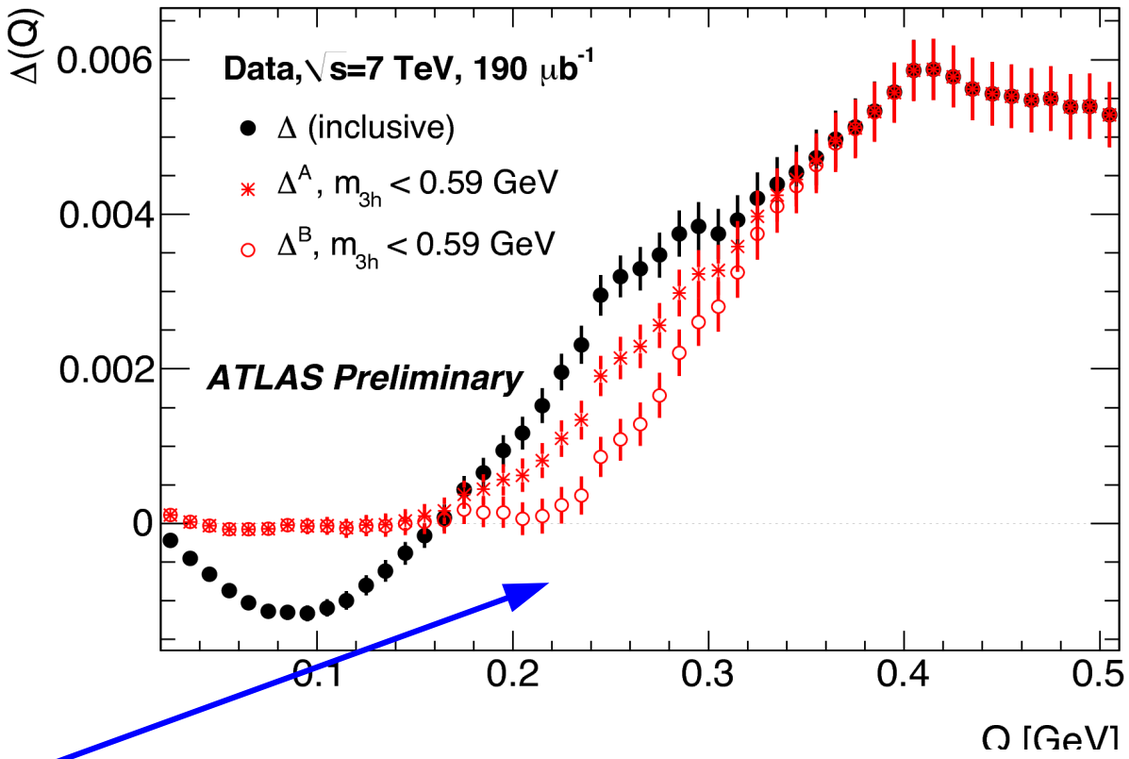
- Inclusive 2-particle correlation function **Δ(Q)** is compared to the correlation of exclusive 3-hadron chains Δ_{3h}
- The 3-hadron chain contribution is adjusted to the distribution for a cut M^{cut}_{3h}=590 MeV , in agreement with the model
- Enhanced like-sign production at low Q can be entirely attributed to ordered 3-hadron chains
- 3-hadron chains Δ_{3h} is asymmetric with peaks in agreement with model predictions, at 91 MeV (like sign) and 266 MeV (opposite sign)



Observed correlations in particle production reflect pattern of coherent emission from a helical QCD string

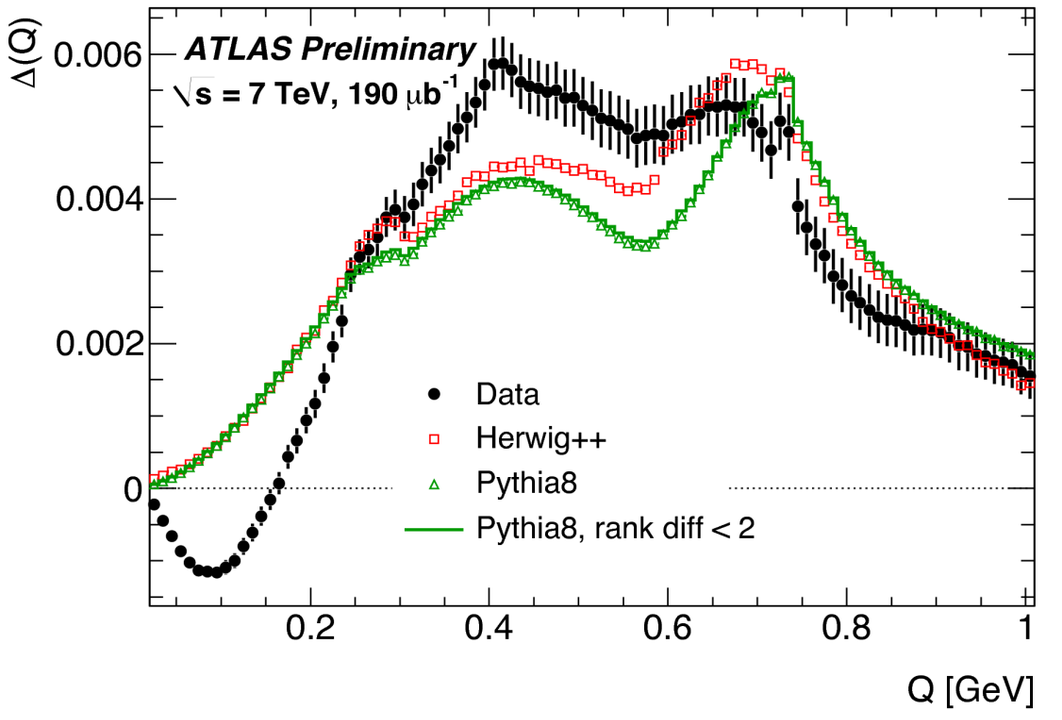
Study of the ordered hadron chains: results

- After the subtraction of the 3-hadron chains from the inclusive correlation Δ(Q), there are no adjacent pairs visible up to a threshold, which depends on the length of the correlated hadron chains



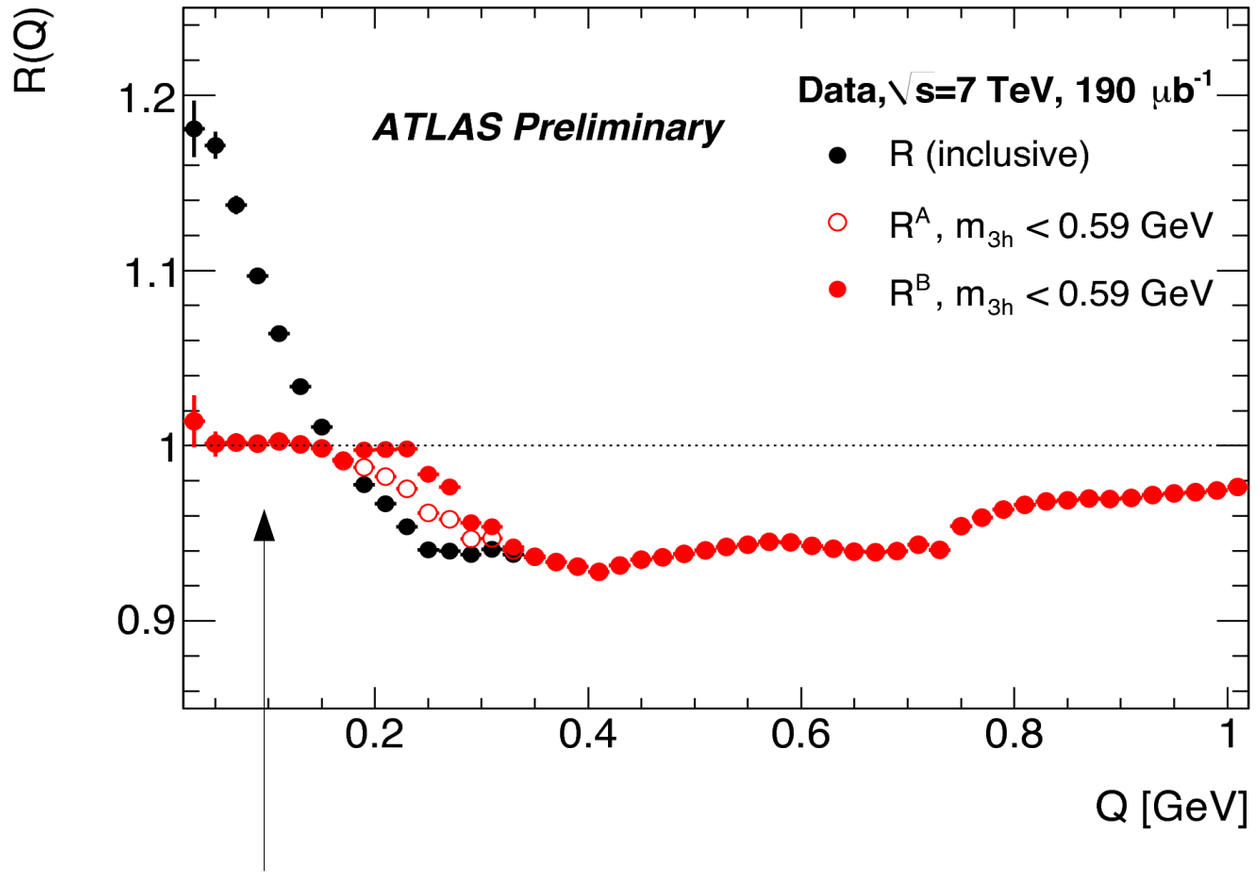
- The threshold effect ~ 0.25 GeV is predicted by the quantized model of fragmentation of a helical QCD string

- MC have no threshold effect



Study of the ordered hadron chains: results Bose-Einstein correlation

- Ratio of inclusive like-sign and opposite-sign pair spectra inclusive and after the subtraction of the 3-hadron chains (for chains of different lenght) investigated



- Enhanced production of pairs of like-sign charged hadrons is traditionally attributed to the Bose-Einstein effect originating in the symmetrization of the quantum-mechanical amplitude with respect to the exchange of identical bosons

Bose-Einstein effect region.

Find a coherent explanation within the helical QCD string model

Summary

LHC is a good place to study QCD phenomenology

Underlying Event studied at 13 TeV:

1) current models typically describes data to 5% accuracy, compared with data uncertainty of <1%
2) Study provides important data for the tuning of MC generators for LHC Run 2, and for the development of a nucleon collision model capable of describing both hard and soft scattering at multiple CM energies

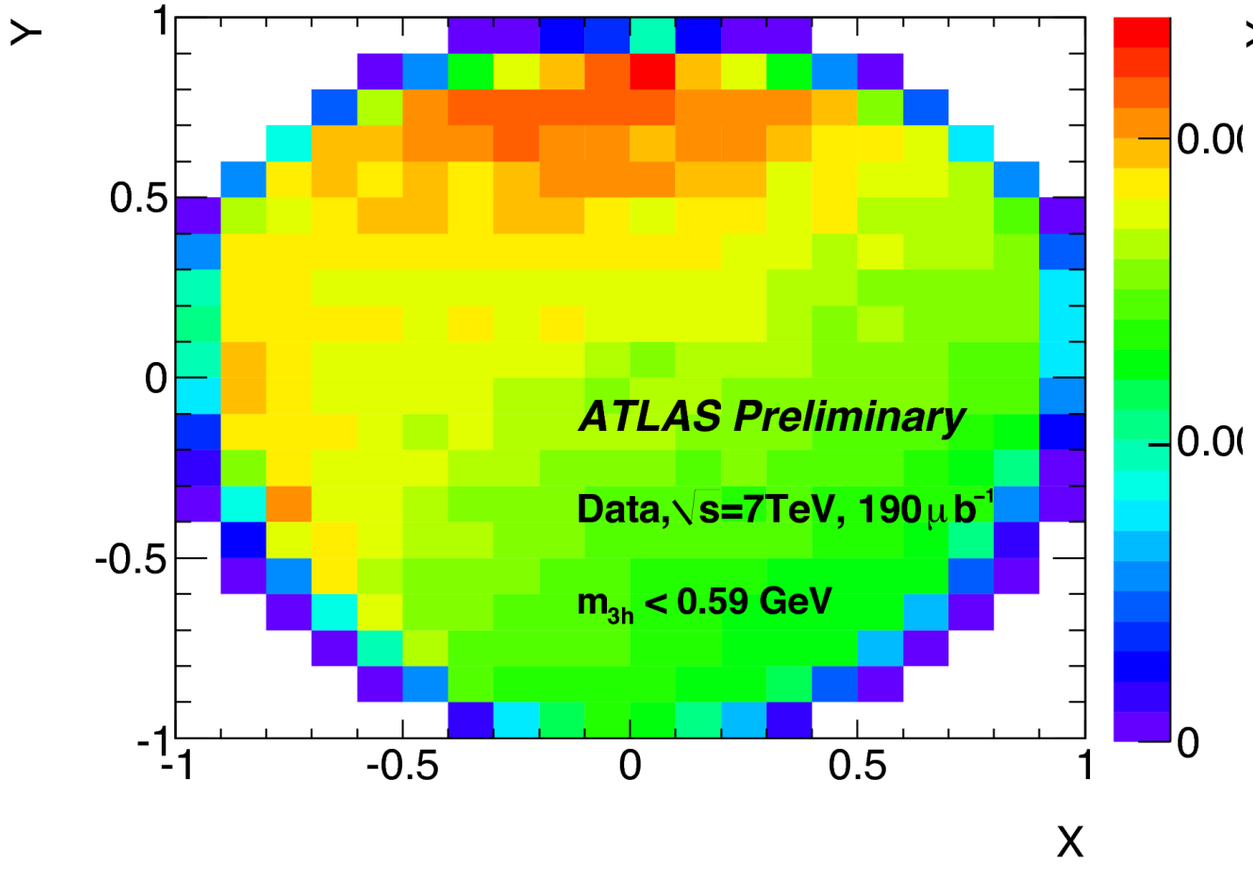
Minimum bias at 13 TeV: studied for tracks at low p_T>100 MeV

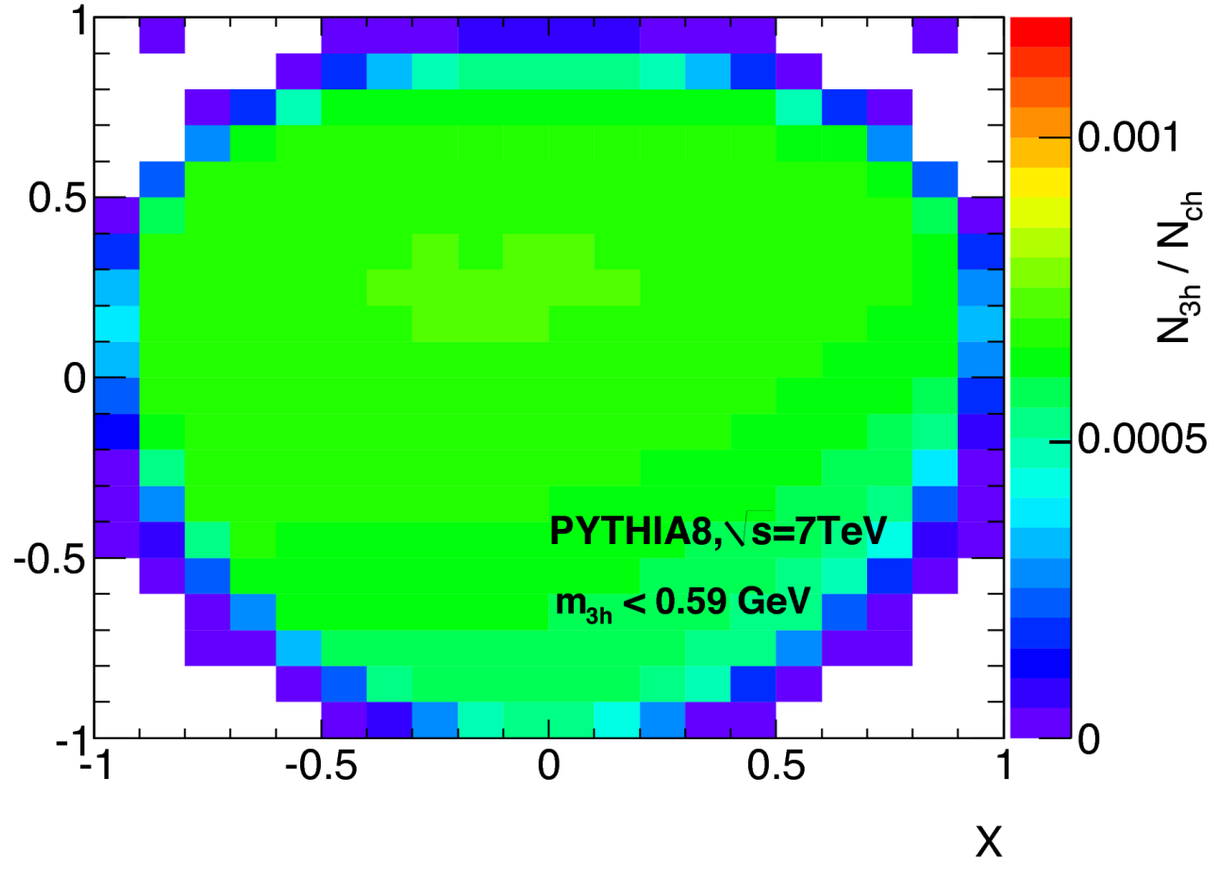
Particle correlation studies:

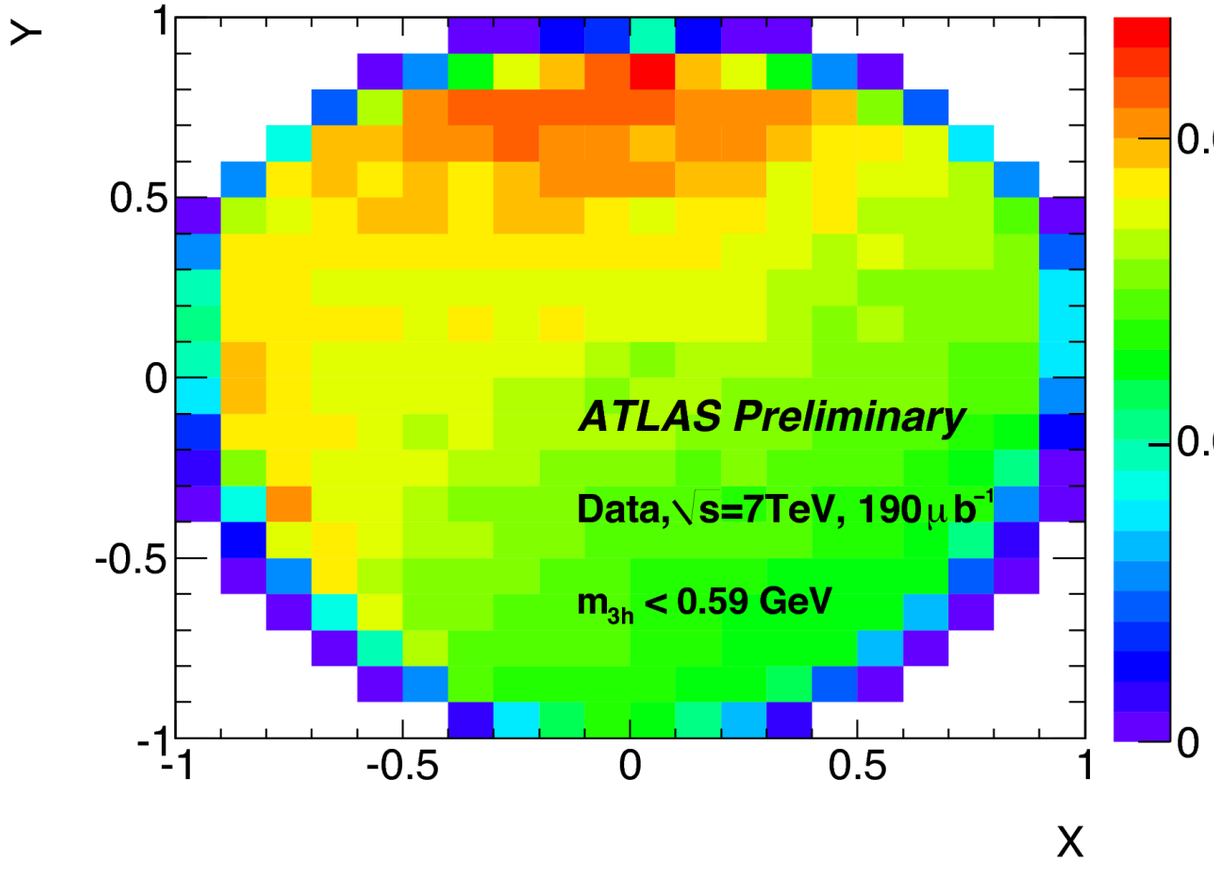
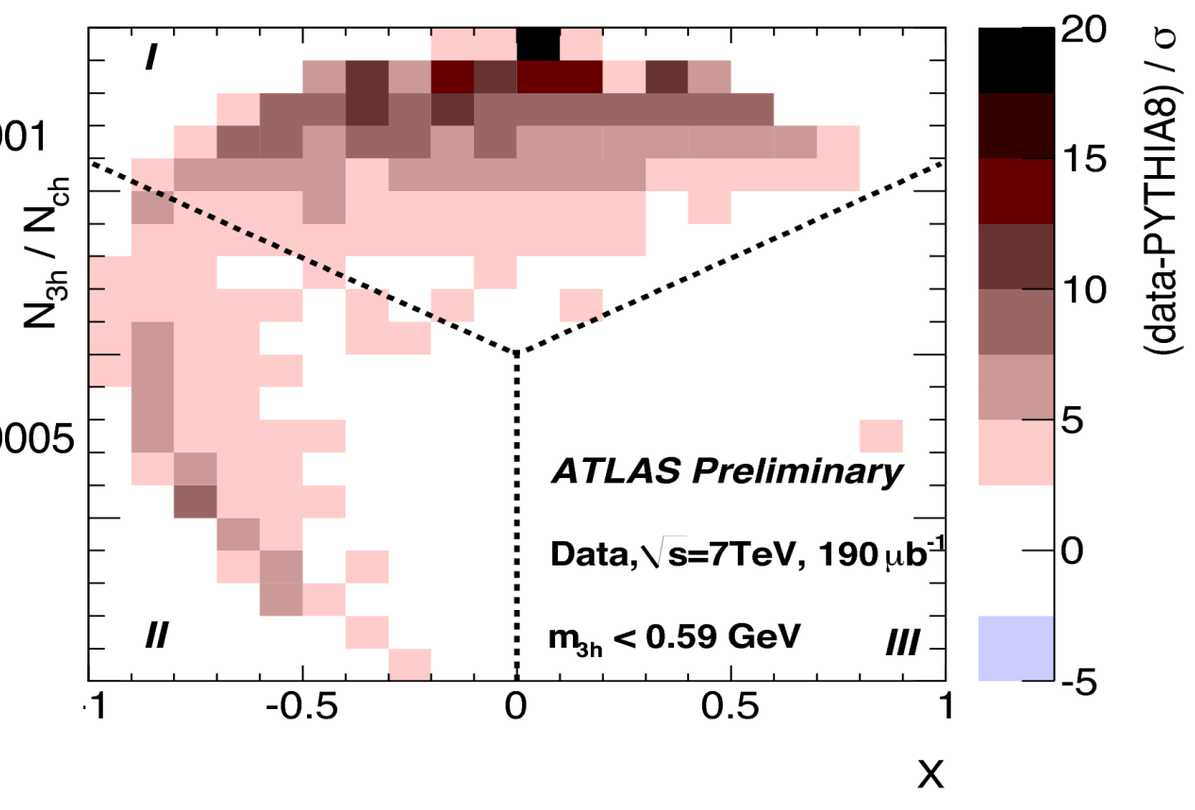
1. Bose Einstein Correlations of same sign particles - saturation effect in the effective radius of particle source observed for large n_{ch}
2. Study of ordered hadron chains support model of quantized fragmentation of a QCD string with helical structure: this model emerge as a powerful concept unifying previously disconnected aspects of hadron production

Back-up slide: Ordered chains, Dalitz plots

- a complementary cross-check of the presence of true ordered chains is done by looking at the 3-body decay (Dalitz plot), which shows enhancement in the data w.r.t. the MC as predicted by the model of helical string fragmentation
- Dalitz plot showing the chains originating from a decay of a single direct hadron in data e MC





Back-up slide: Ordered chains, Dalitz plots

Dalitz plot showing the chains originating from a decay of a single direct hadron in data and significance of the shape difference of the Dalitz plot filled with the polarization pattern of chains with mass below 0.59 GeV, between the data and the PYTHIA 8 MC