Helix string fragmentation and charged particle correlations

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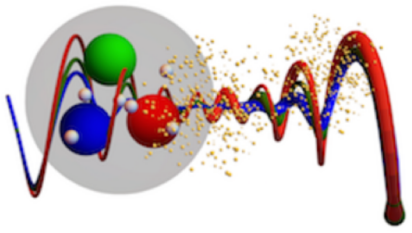
on behalf of the ATLAS Collaboration

Outline of the talk

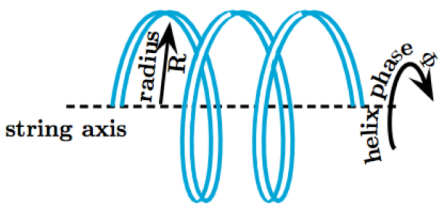
- a short introduction to the quantized fragmentation of a helical QCD string
- anomalous production of like-sign pions (better known as Handbury-Brown-Twiss or Bose-Einstein effect)
- a selection of recent experimental results

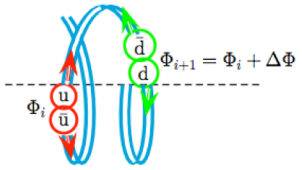


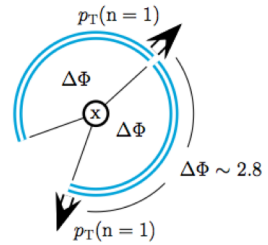
13th International workshop on Multiple Partonic Interactions at the LHC

Quantized fragmentation

Phenomenology







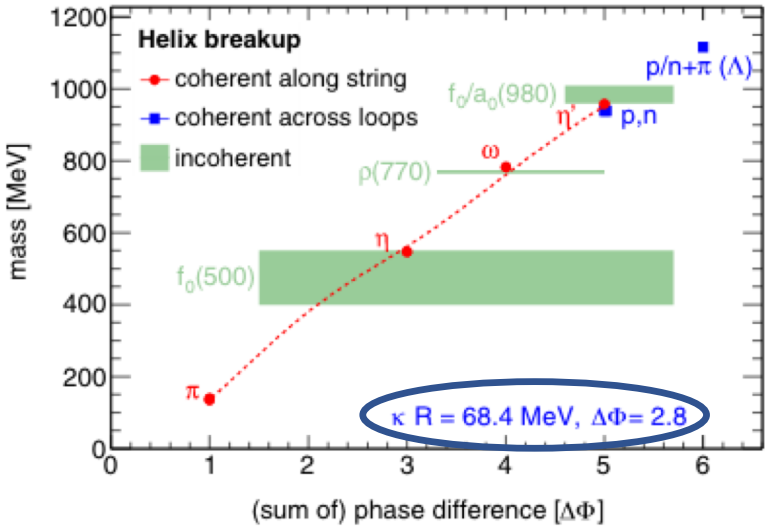
QCD confinement modeled by 3D string
Vortex translated into helical chain of gluons

Requirement of causal cross-talk between break-up vertices reveals a quantization scheme : hadrons correspond to string pieces carrying multiple of ΔΦ (~2.8 rad) of helix phase.

Quantization proceeds in m_t = n κR ΔΦ rather than mass alone. Non-trivial quantized correlations in the transverse plane (w.r.t. string axis). Sparsely populated QCD vacuum ?

More information to be found in : JHEP09(1998)014, Phys.Rev.D89(2014)015002

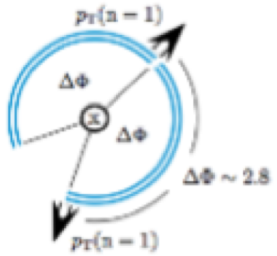
Phys. Rev. D 104, 034012 (2021)



Production scenarios:
induced gluon splitting with information running along string (π,η,η',ω,…)
induced gluon splitting across string loops (p,n,Λ,…)
« incoherent » (similar to standard Lund) - wide resonances (f_0, ρ, …)

$m_t = \sqrt{m^2+p_t^2}$, κ string tension

Quantized fragmentation and anomalous production of like-sign(LS) hadrons pairs



- *transverse sector of string entirely constrained*
- *intrinsic momenta of direct hadrons predicted*
- *correlations between direct (adjacent) hadrons (in string transverse plane) predicted*

For the specific case of a chain of direct charged pions, their momentum difference can be calculated as a function of their rank difference :

***(rank** describes the ordering of hadrons along the colour flow)*

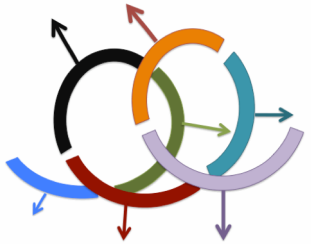
OS
opposite
sign

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

LS
like-sign

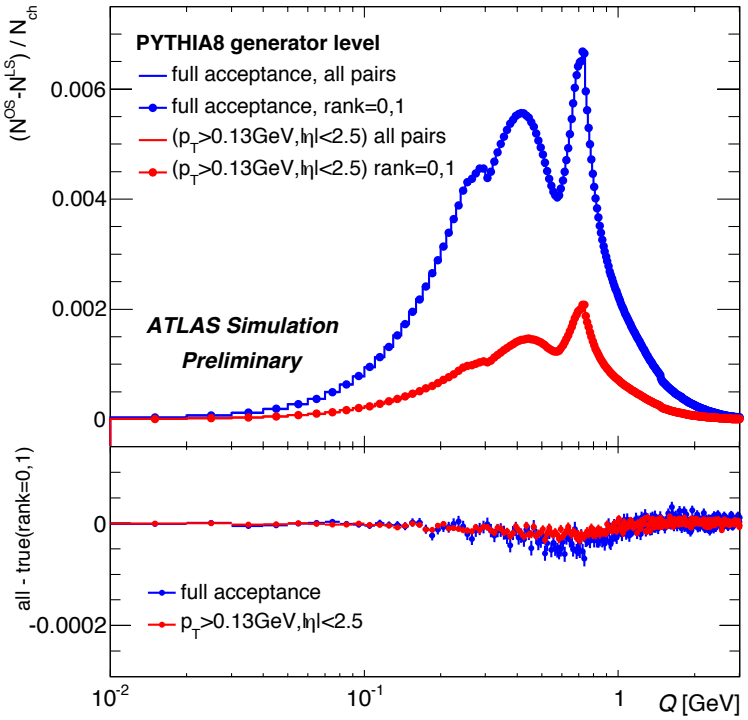
Phys.Rev.D96(2017)092008

Q(r=1) >> Q(r=2) creates asymmetry in production of LS and OS sign pairs
(local charge conservation forbids creation of LS pairs with r=1)



Also, a chain of n direct pions should have the minimal possible mass , locally.

Observable sensitive to colour flow

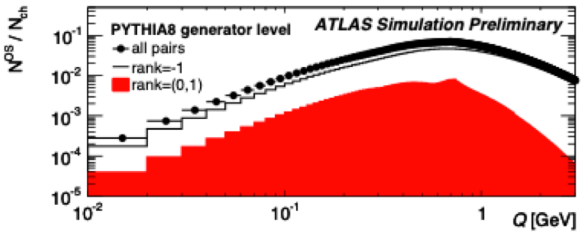


$$\Delta(Q) = \frac{1}{N_{ch}} [\, N(Q)^{OS} - N(Q)^{LS} \,]$$

4-momentum difference

$$Q(p_i, p_j) = \sqrt{-(p_i - p_j)^2}$$

(all particles assigned pion mass)

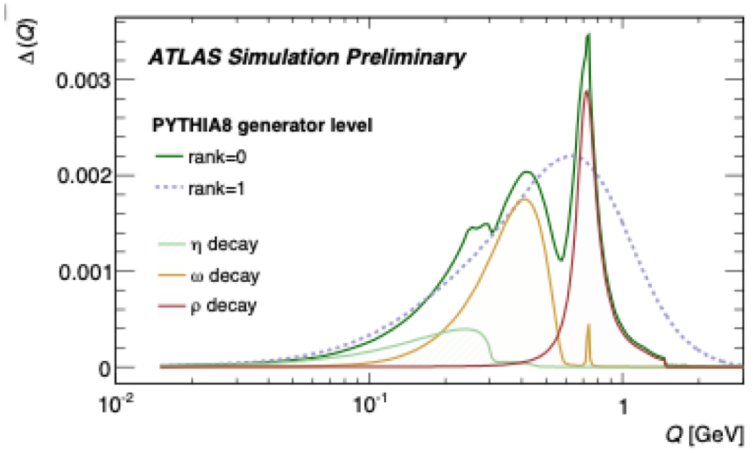


Hadron pairs classified by **rank difference** (shortened to « rank »)

Decay products inherit rank from parent resonance

Δ(Q) extracts signature of rank=0,1 pairs:

- a unique reflection of the dynamics of hadronization
- experimentally robust



Pairs : rank = 0 decays,
rank = 1 colour-adjacent hadrons
(sharing common string breakup)
rank = -1 if hadrons coming from different sources

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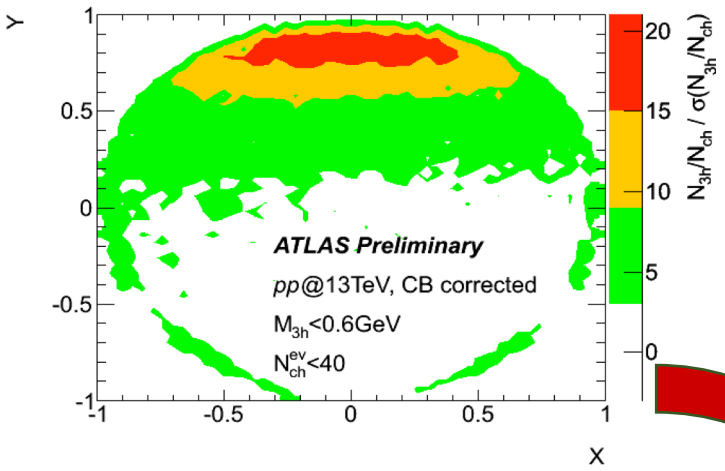
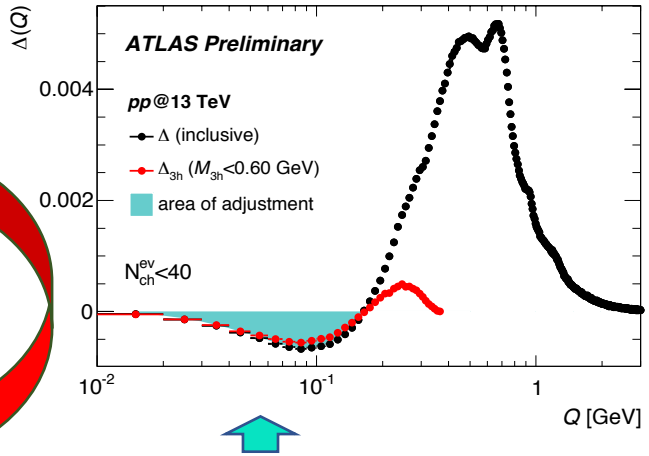
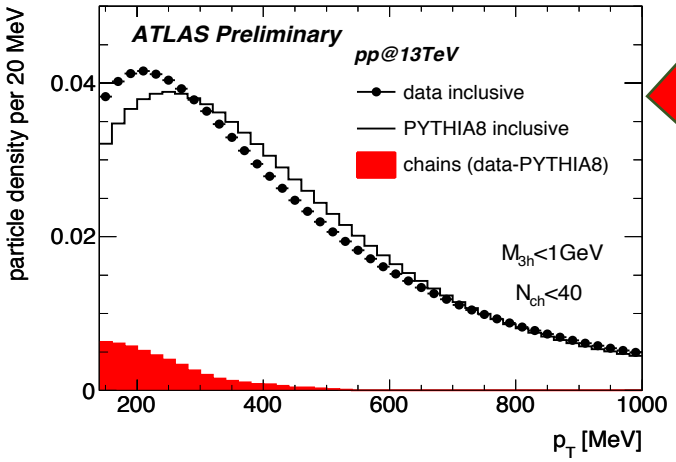
$$X = \sqrt{3}\frac{T_0 - T_2}{\Sigma T};\ Y = \frac{3T_1}{\Sigma T} - 1;$$



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





Negative part of Δ(Q) marks the anomalous production of LS pairs, traditionally attributed to Bose-Einstein interference (also called HBT effect).

Better understood as a signature of quantized fragmentation.

Quantized fragmentation and anomalous production of LS hadrons pairs

Data consistent with model expectations :

- *excess in mass-minimized charge-ordered triplet chains observed (Dalitz plot)*
- *associated with the source of anomalous production of close LS pairs (Δ vs. Δ_{3h})*
- *associated with the modification of inclusive low p_T spectra*

(quantized fragmentation predicts intrinsic p_t of a direct pion ~130 MeV)

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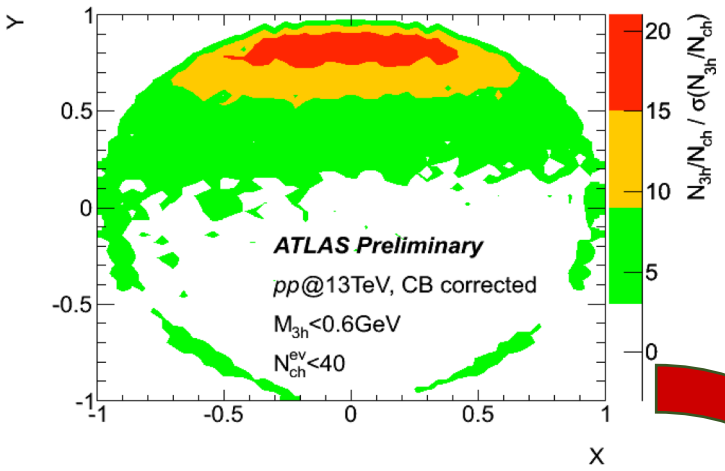
Model independent measurement (MIM) of link between 1-,2-,3-particle distributions

$$X = \sqrt{3}\frac{T_0 - T_2}{\Sigma T};\ Y = \frac{3T_1}{\Sigma T} - 1;$$



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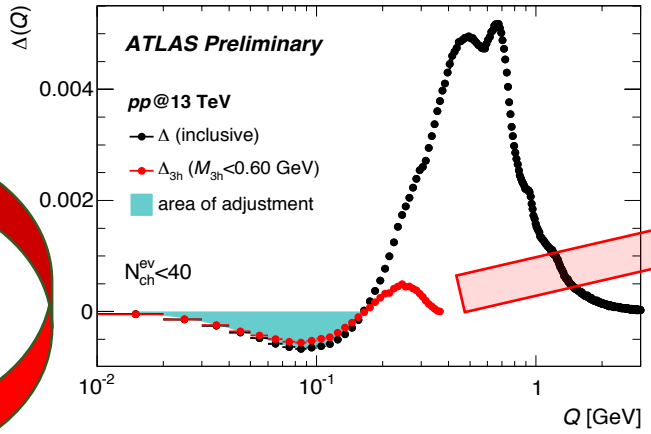

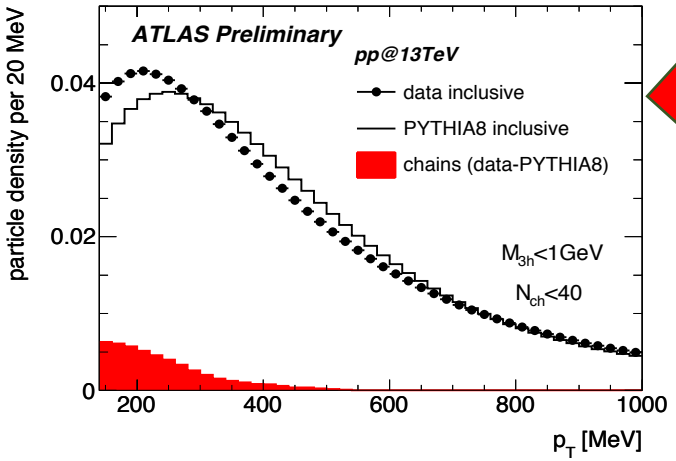

Signature of quantized fragmentation in 1-,2-,3-particle distributions

Model independent measurement

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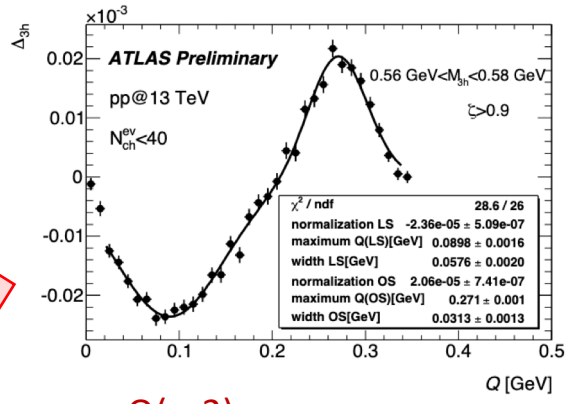
Quantized fragmentation and anomalous production of LS hadrons pairs

Q(r=1)

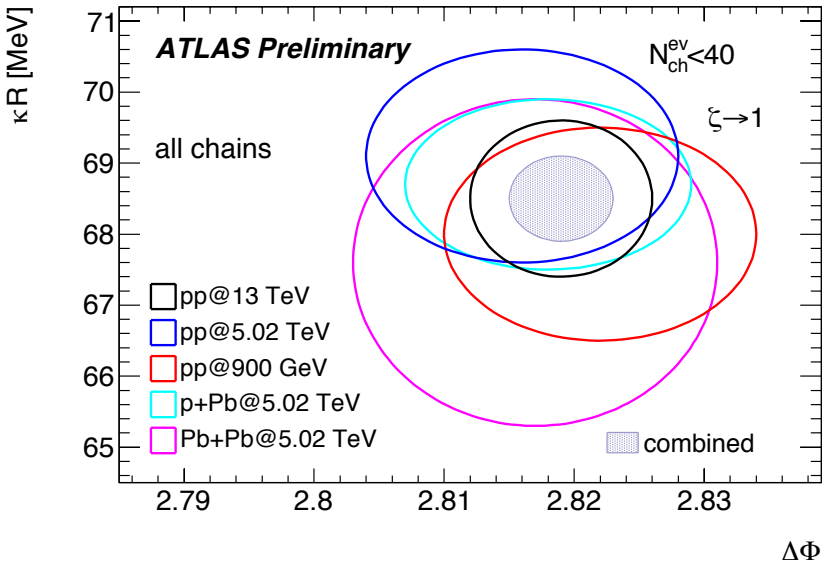


Q(r=2)

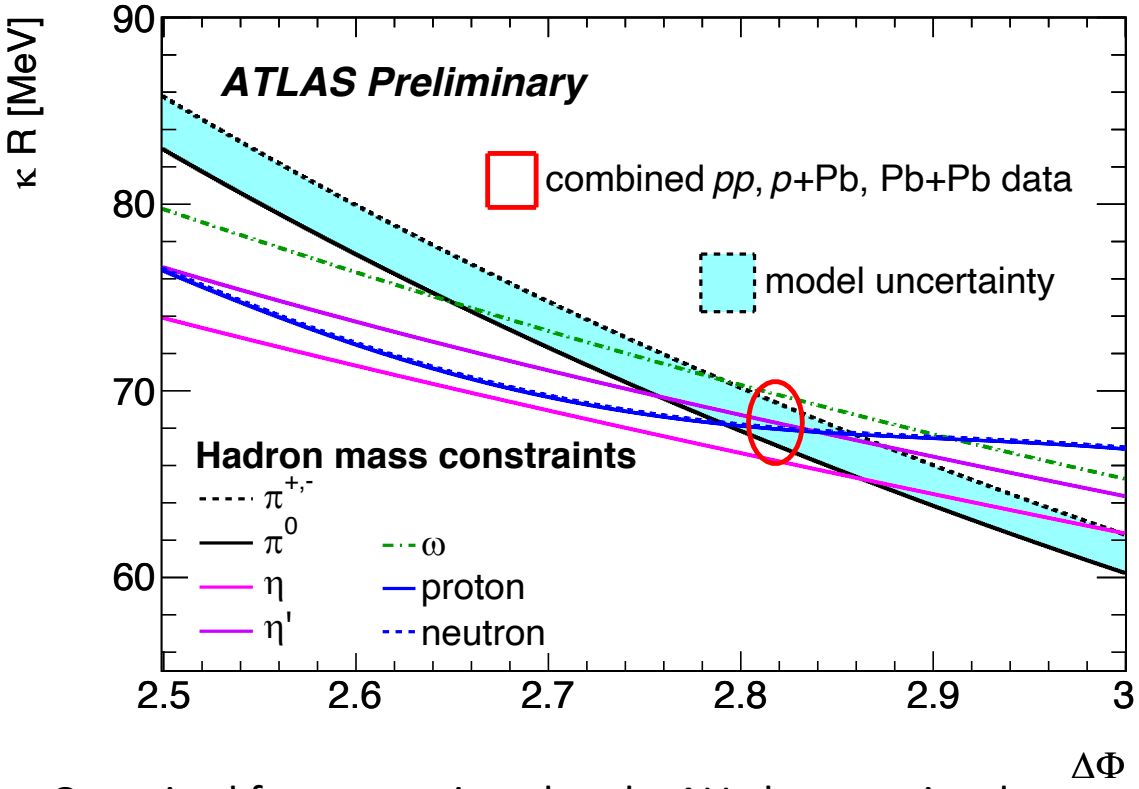
Charge-ordered triplets +-+, -+-
2xOS pairs (rank 1)
LS pair (rank 2)

=> independent measurement of string parameters κR, ΔΦ

Measurement of quantized string parameters from hadron correlations, pp+pPb+PbPb combination



Excellent agreement between pp data at various collision energies.
Excellent agreement between pp and HI data.



Quantized fragmentation absorbs ALL data previously associated with Bose-Einstein interference (HBT).

Anomalous production of close LS pions is purely hadronization effect.

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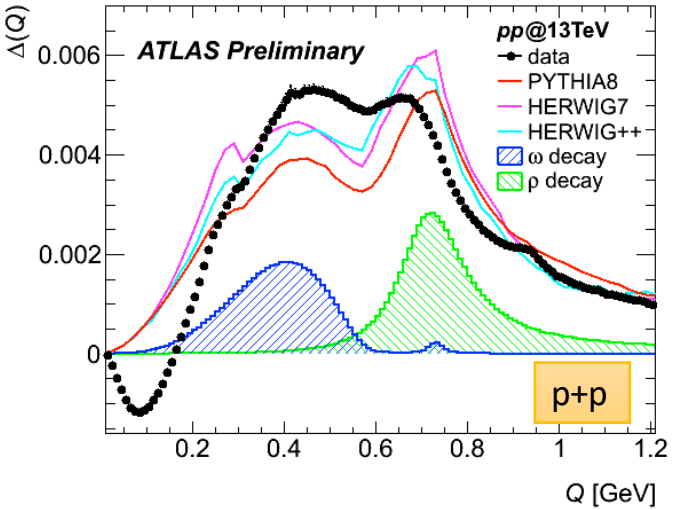
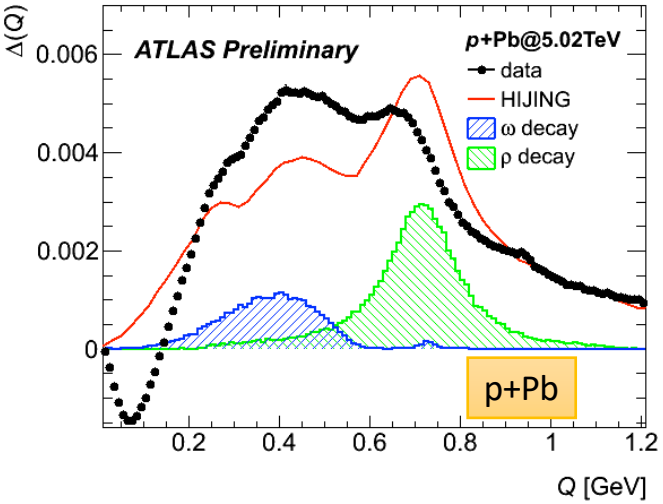
Further colour-flow sensitive measurements by ATLAS

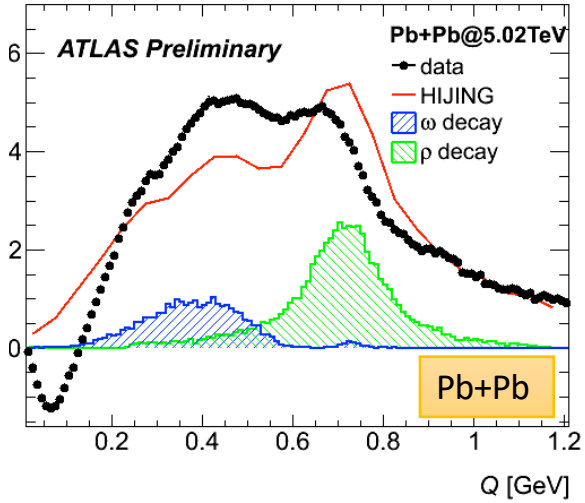
Correlations between colour-adjacent hadrons
(= dynamics of hadronization)
described poorly by conventional models

Problem : the modeling does not allow
to evaluate the hadronization systematics ….
models fail in similar way



pp and HI data very similar
(universality of hadronization
- best seen as f(N_{ch}) – not shown)





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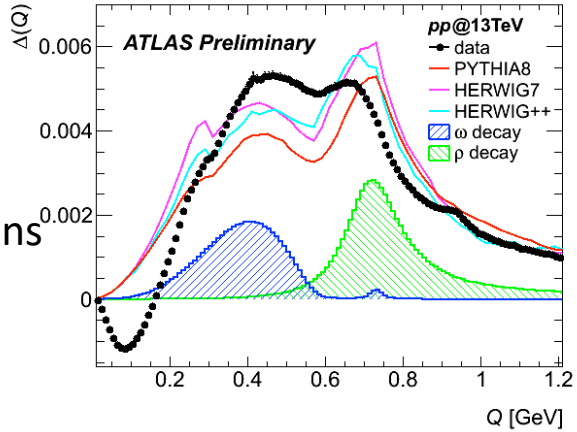
Further colour-flow sensitive measurements by ATLAS

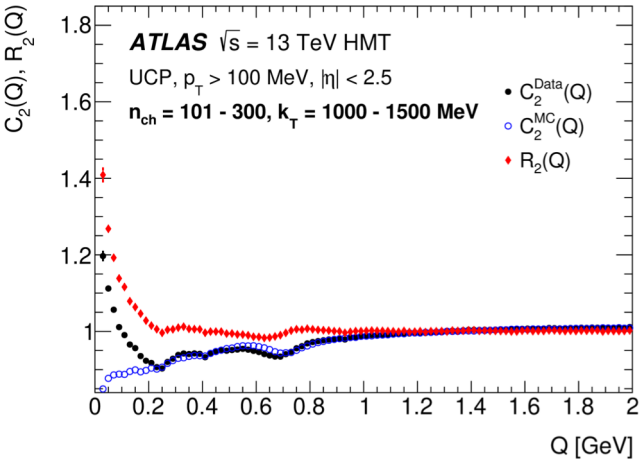
[ATLAS-CONF-2022-055]

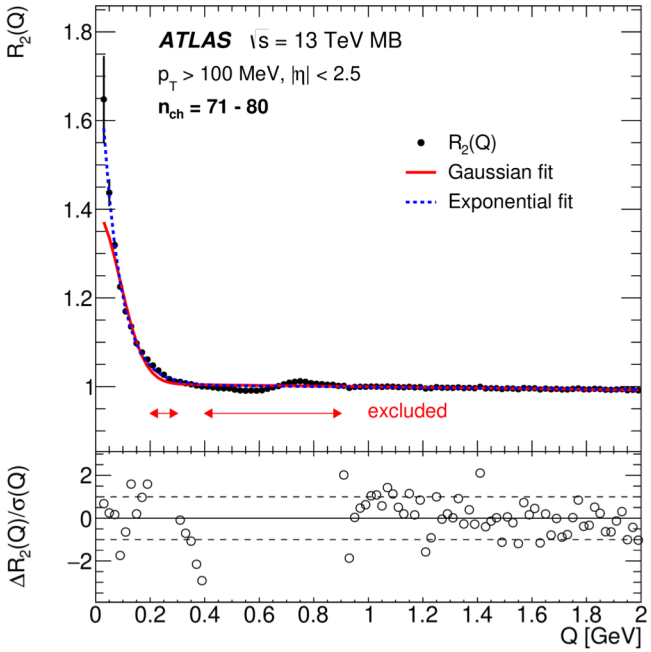


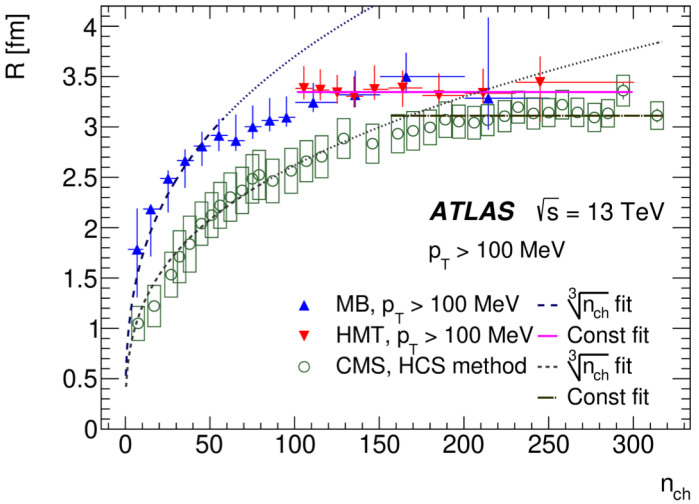
Problem : the modeling does not allow to evaluate the hadronization systematics: models fail in similar way

Immediate impact on « traditional » measurement of « Bose-Einstein » correlations

Correlation function is model dependent & there are no models which describe the data sufficiently well - no "absolute" measurement possible







[Eur.Phys.J.C82(2022)608]

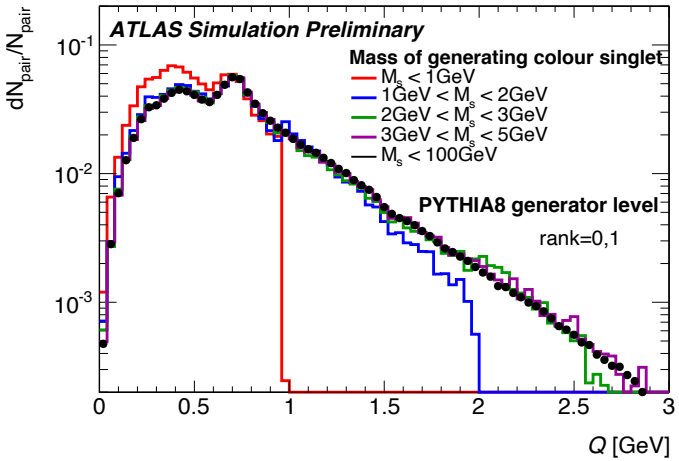
$C_2 = N^{++,--} / N^{+-}$

$R_2 = C_2$ (data) / C_2 (MC)

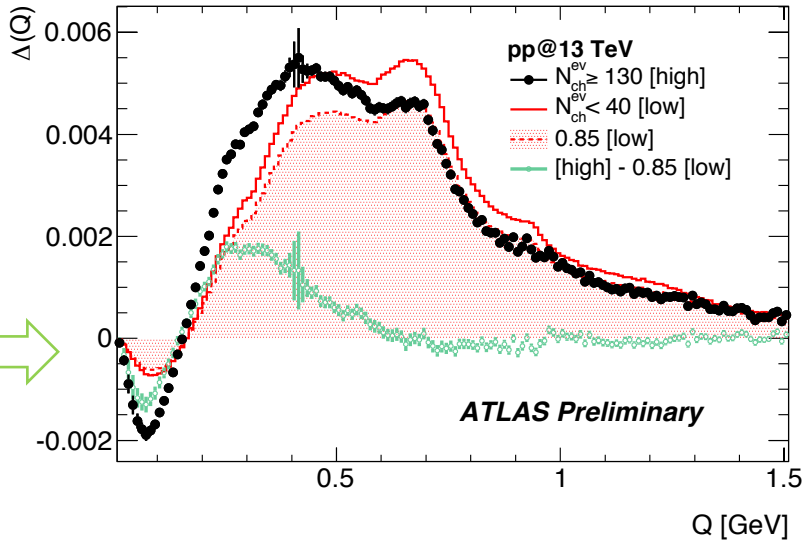
Further colour-flow sensitive measurements by ATLAS

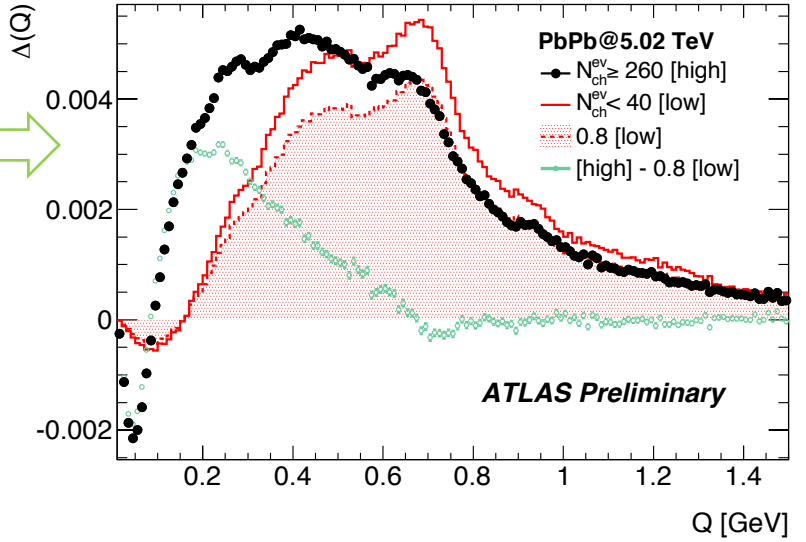
Of particular interest for studies of underlying event:
study of mass spectrum of hadron sources

(1) Generator-level study:



(2) Data show growing presence of very light hadron sources with increasing particle multiplicity.
Possibly signature of hadronization of wounded nucleons.
Differs between pp and HI.





Distribution of momentum difference between colour-adjacent hadron pairs is limited by the mass of the source but otherwise pretty stable (there is no or very little difference in Δ shape below Q~1.5GeV for. sources with masses above 2 GeV)
=> evolution of shape signals variation of low mass sources

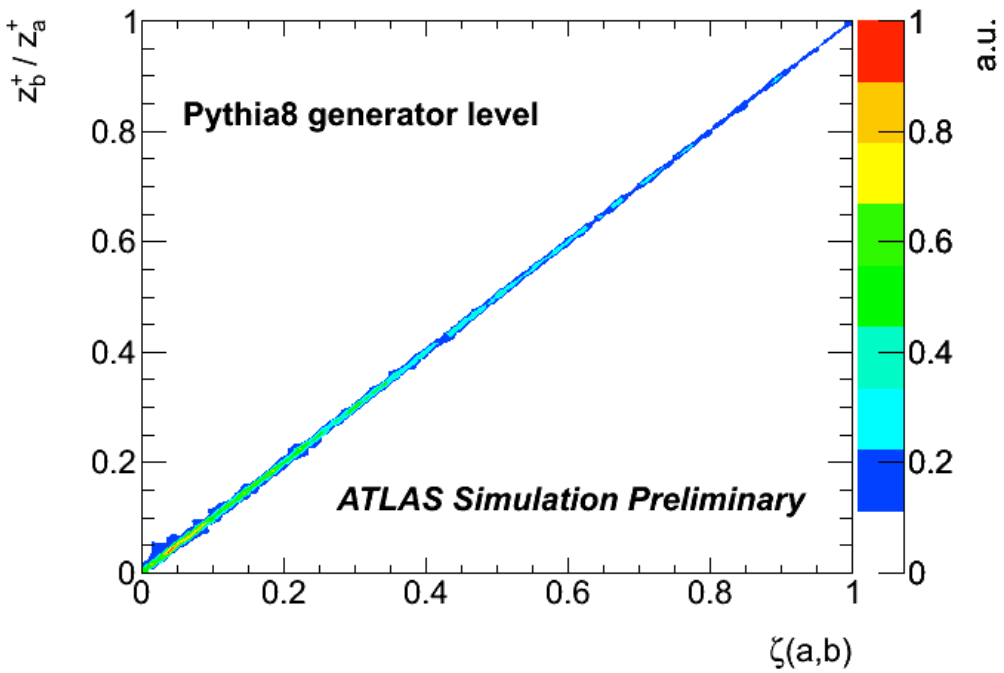
[ATLAS-CONF-2022-055]

More information (about colour flow) can be obtained with help of other sensitive observables.
Example : Observable sensitive to local evolution of fragmentation function (for colour-adjacent hadrons)

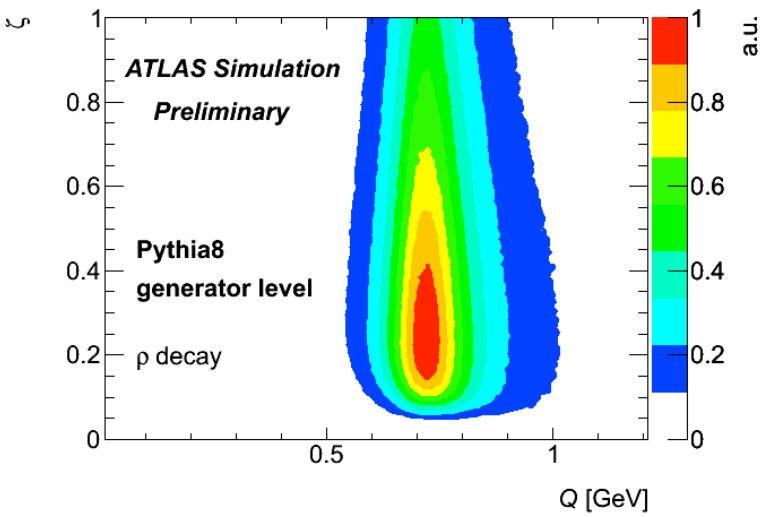
$$Q^2(p_a, p_b) = (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t,a}^2(\frac{z_b^+}{z_a^+} - 1) + m_{t,b}^2(\frac{z_a^+}{z_b^+} - 1).$$

$$Q^2 \sim (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t_a}^2(\zeta(p_a, p_b) - 1) + m_{t_b}^2(1/\zeta(p_a, p_b) - 1), \quad \text{for } |\vec{p}_a| > |\vec{p}_b|.$$

$$\zeta(\vec{p}_i, \vec{p}_j) = min(\frac{|\vec{p}_j|}{|\vec{p}_i|}, \frac{|\vec{p}_i|}{|\vec{p}_j|})$$



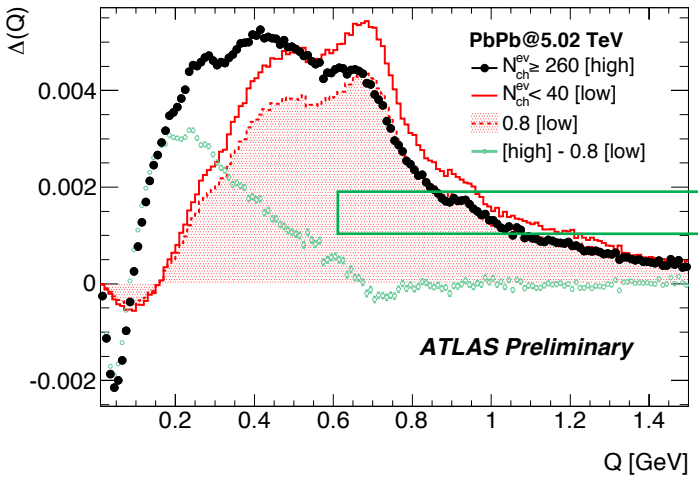
Allows to distinguish between rank 0 and rank 1 contributions

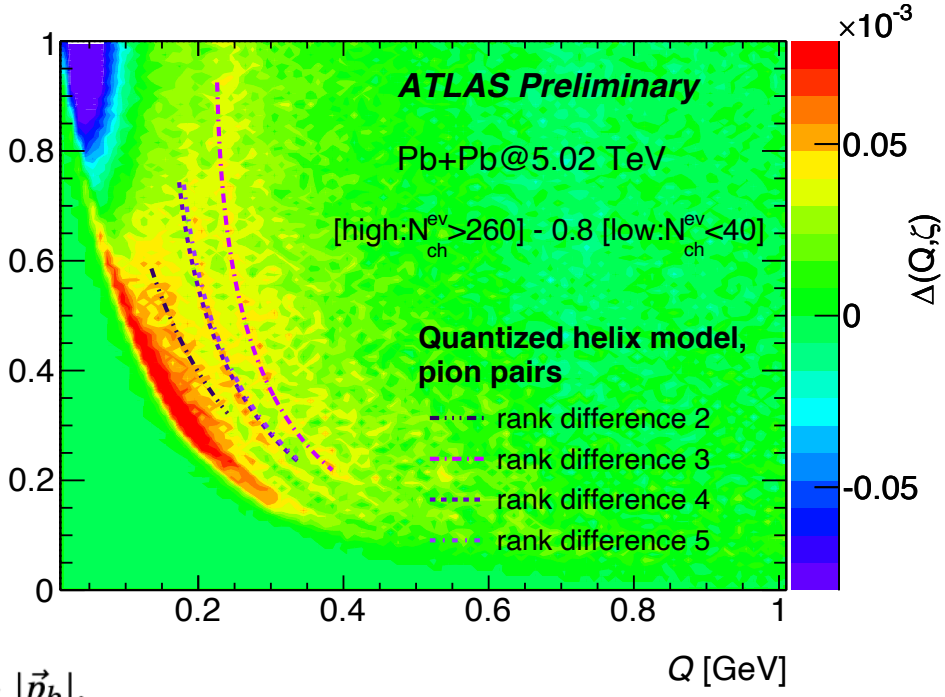


[ATLAS-CONF-2022-055]

Quantized fragmentation, signature of long chains found in Pb+Pb (first observation)

[ATLAS-CONF-2022-055]





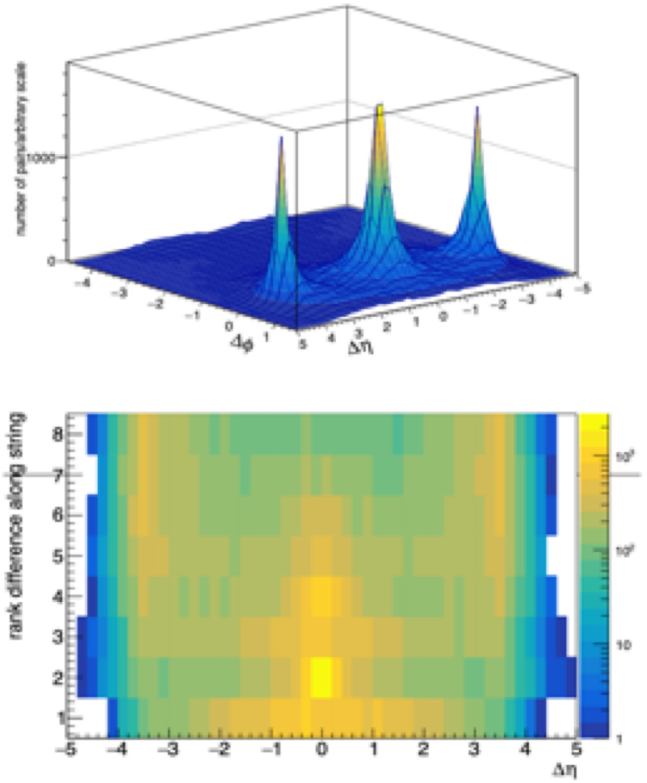
$$Q^2 \sim (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t_a}^2(\zeta(p_a, p_b) - 1) + m_{t_b}^2(1/\zeta(p_a, p_b) - 1), \quad \text{for } |\vec{p}_a| > |\vec{p}_b|.$$

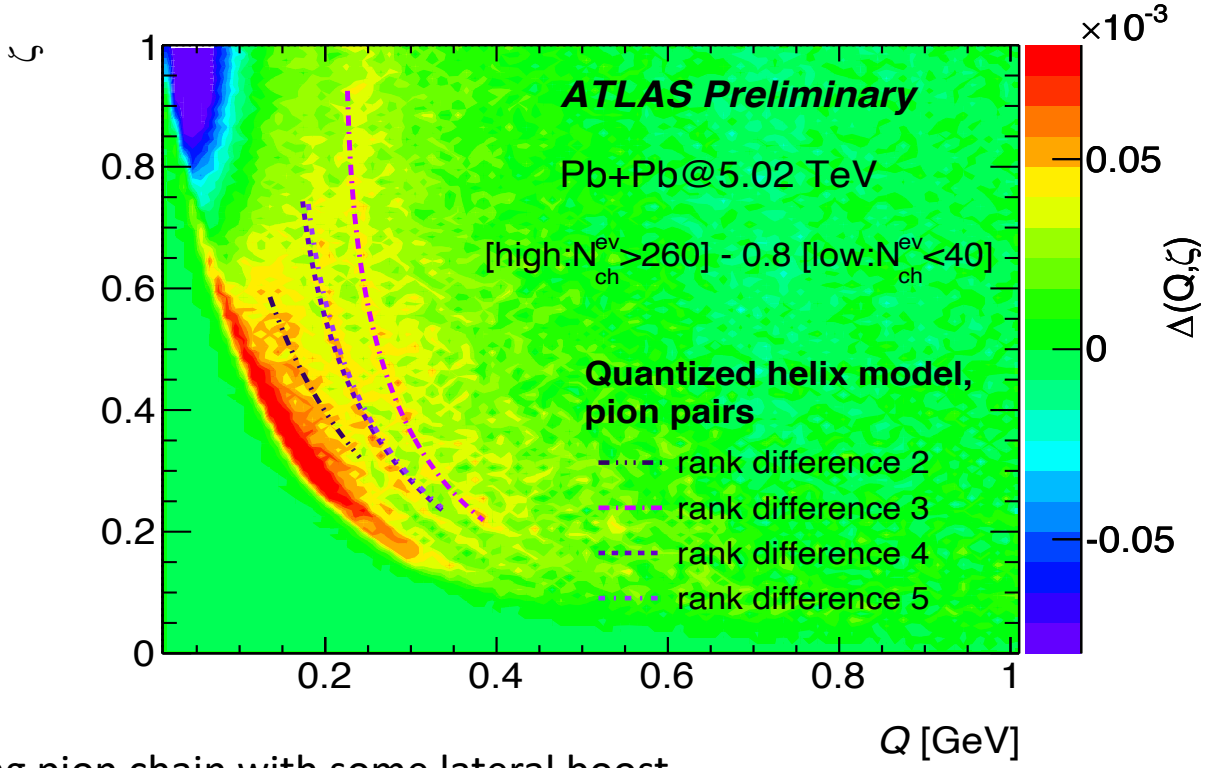
Pair rank difference r	1	2	3	4	5
Q expected [MeV]	266 ± 8	91 ± 3	236 ± 7	171 ± 5	178 ± 5

Observation of long pion chains demonstrates the predictive power of the model and validates the whole framework

Long pion chains from quantized fragmentation can carry long range correlations

arXiv:1801.10232[hep-ph]





Long pion chain with some lateral boost is generating a ridge-like signal

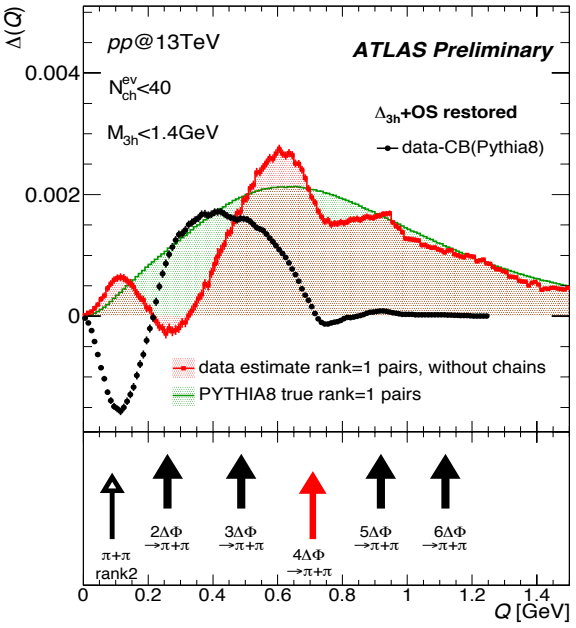
[ATLAS-CONF-2022-055]

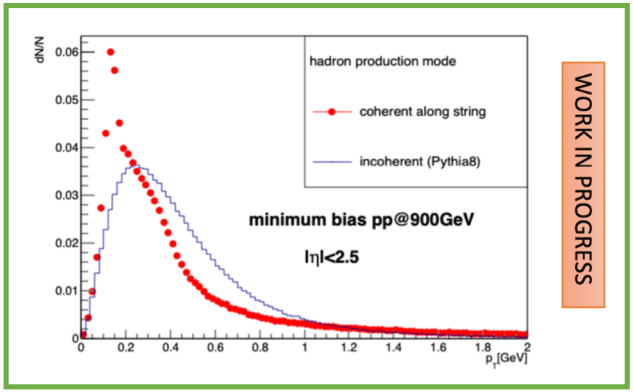
… material for future conferences ☺

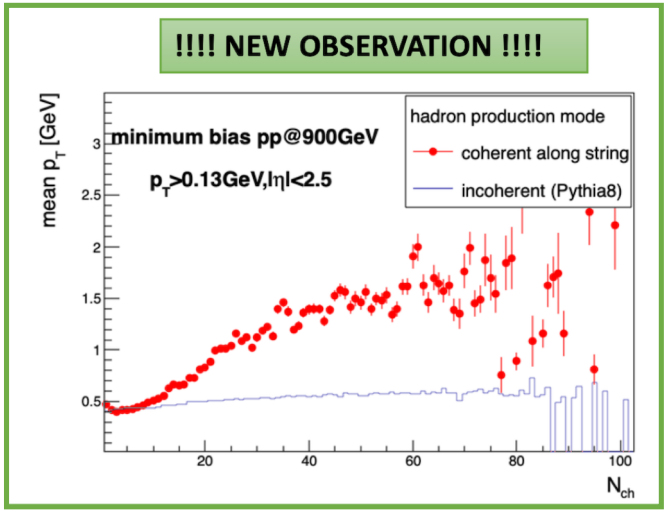
Of special interest for the study of MPI and UE : **quantized fragmentation has a significant impact on the evolution of $\langle p_T \rangle$ (N_{ch}), can possibly replace colour-reconnection models (?)**

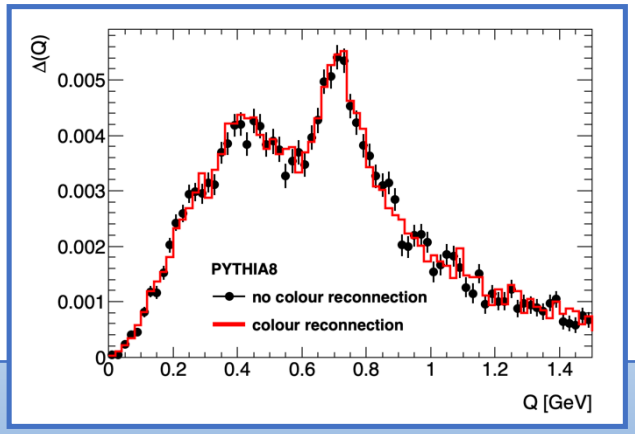
Talk at ISMD2002: exploring extreme helix scenarios

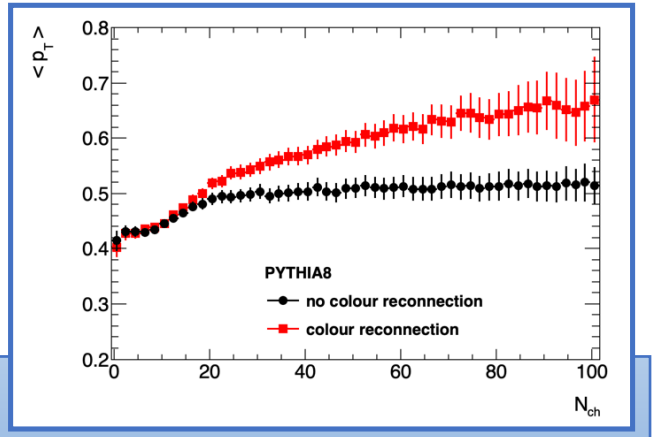
[ATLAS-CONF-2022-055]











Colour reconnection (here Pythia8 4C tune)
modifies colour flow but does not fix problems in colour flow sensitive observable !!!

Summary:

- *recent ATLAS results indicate that causal approach to the description of confining field quite efficiently resolves a number of long-standing issues in the hadronization.*
  (hadron mass spectrum / pT spectra / particle correlations / … the list is growing)

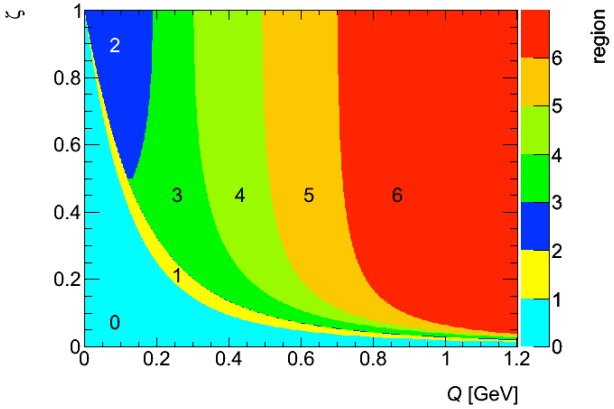
- *new observables sensitive to colour flow and local variations of fragmentation function are deployed by ATLAS which allow to combine hadronization measurements from pp and HI samples*

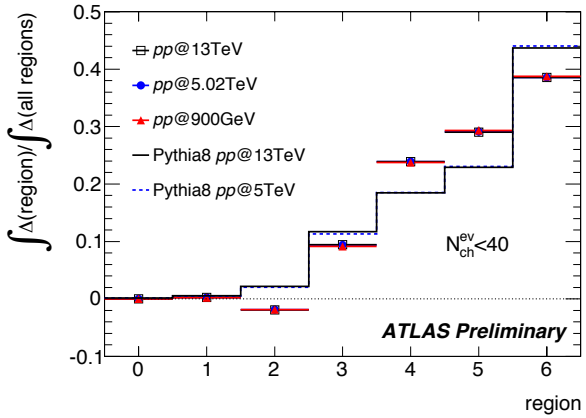
- *properties of QCD field in transverse plane (helical string shape) were measured using particle correlations : very good agreement with values derived from hadron mass spectrum*

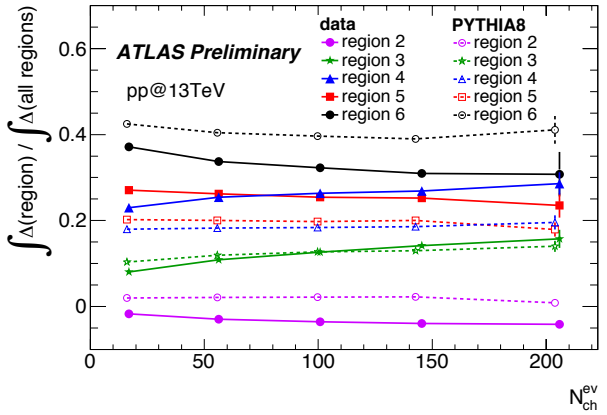
- *so called Bose-Einstein effect (an anomalous production of close like-sign pions) is a side-effect of a helical ordering of colour-adjacent hadrons*

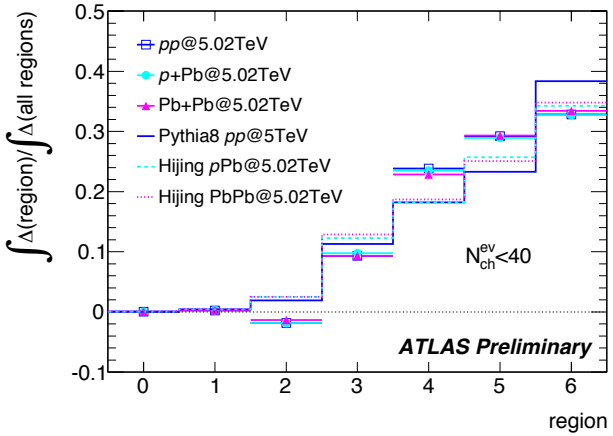
Backup slides

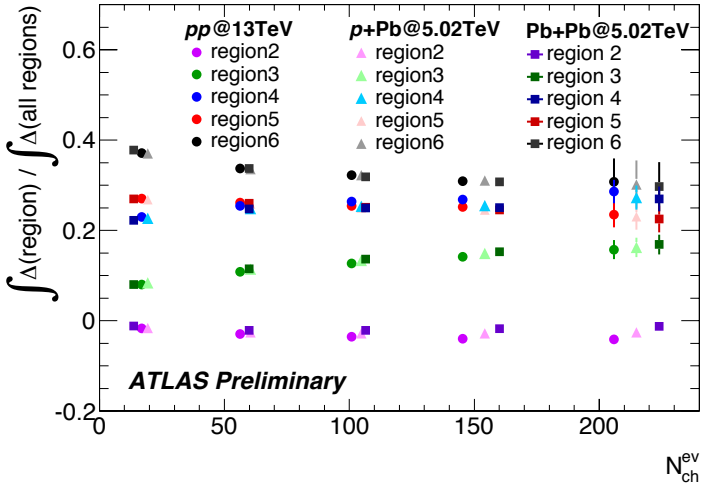
Quantification of Δ(Q,ζ)









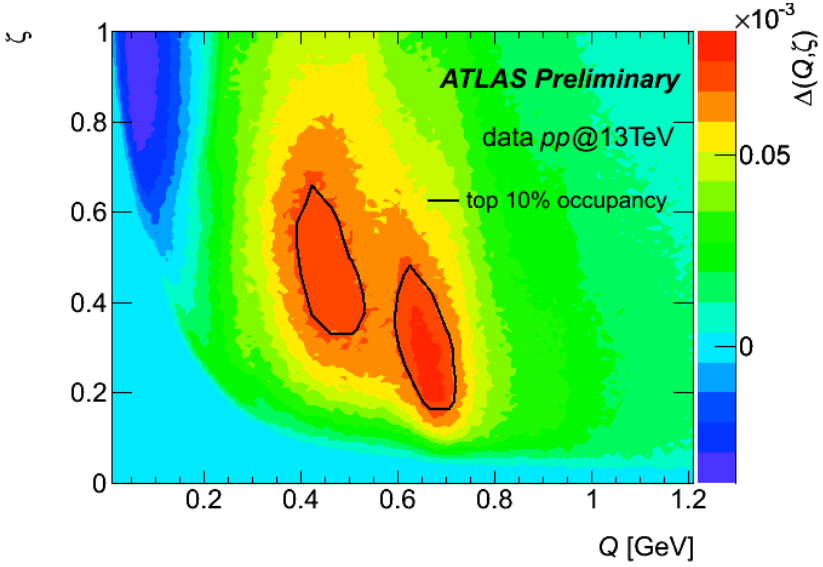


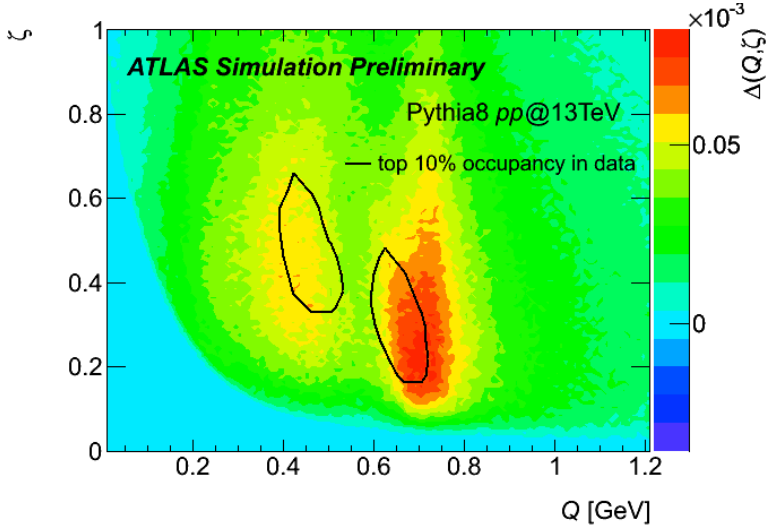
Now I am making case for quantized fragmentation to be at the origin of MC-data discrepancies in colour flow

In model-independent approach, Δ is studied in (Q, ζ) plane

Leaving aside the anomalous production of LS hadrons, the excess in data comes from « running » components centered approximately at ζ ~ 1/2 and ζ ~ 1/3 (suggesting 2+1 , resp. 3+1 hadron quantum content)

=> Consistent conclusion : difference due to quantized correlated adjacent hadron pairs





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In model-independent approach, Δ is studied in (Q, ζ) plane

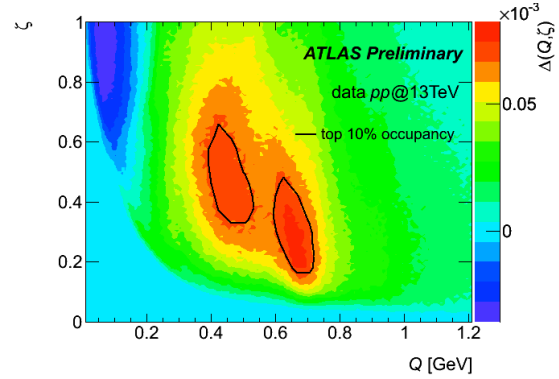
ATLAS-CONF-2022-055

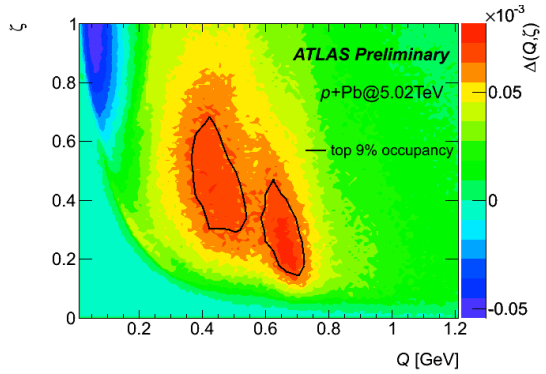
pp

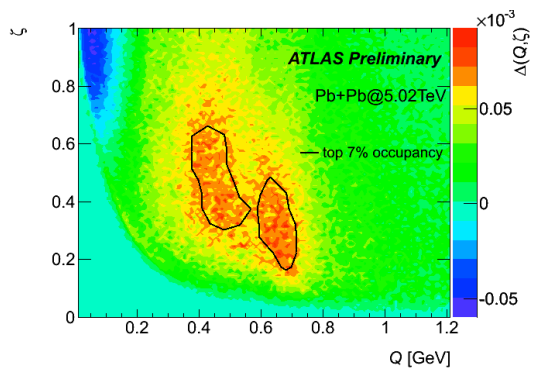
p+Pb

Pb+Pb

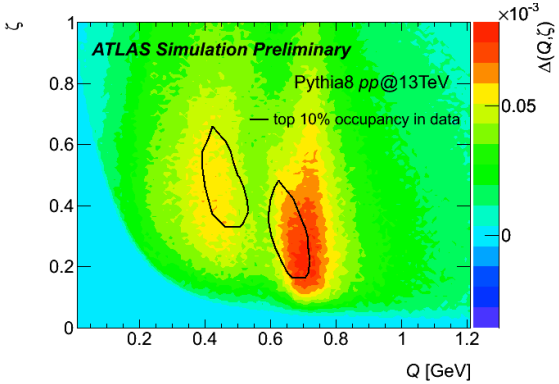
DATA

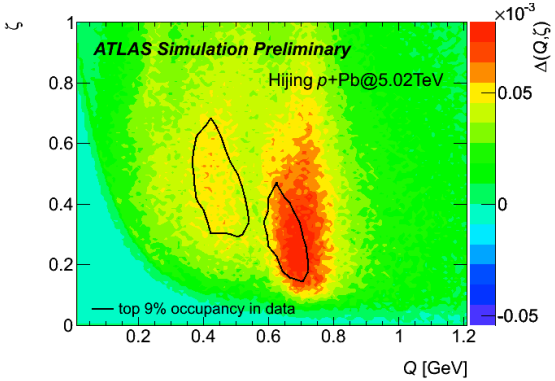


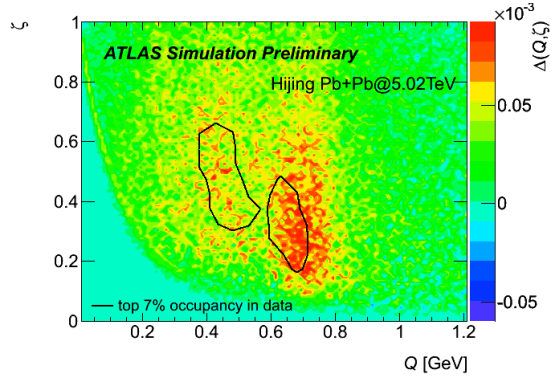




MODELS

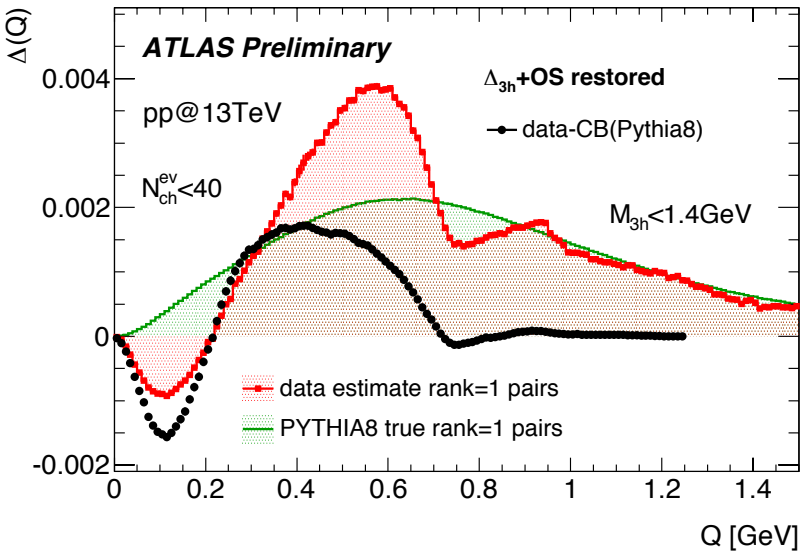






Now I am making case for quantized fragmentation to be at the origin of MC-data discrepancies in colour flow

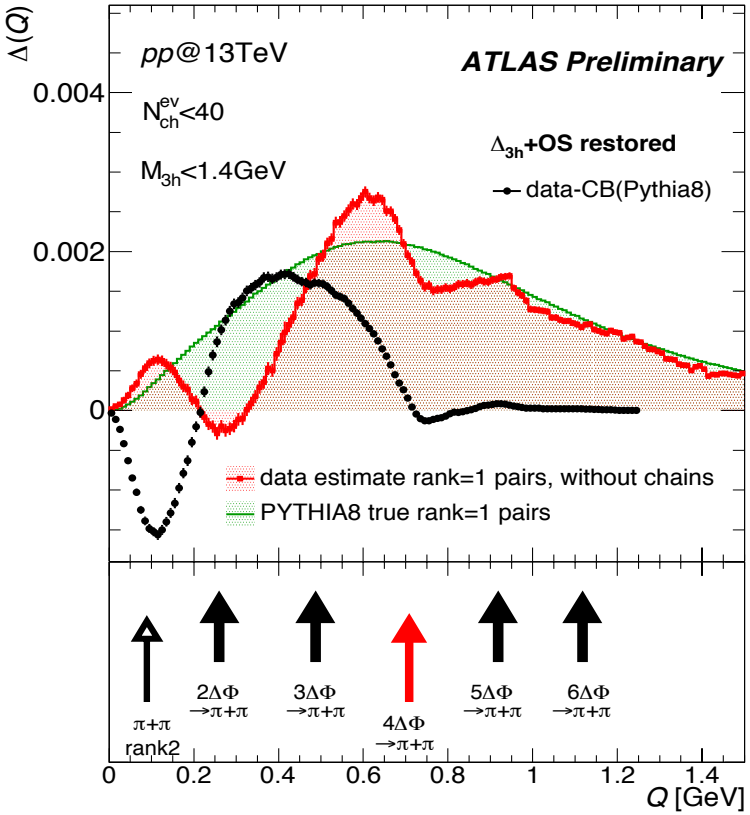
In model-dependent approach, it is assumed that Pythia describes hadron content and decays of resonances correctly , rank 1 estimate is obtained by subtraction of MC decays from measured Δ(Q)



Clear modulation observed in data : colour-adjacent hadrons are correlated
The signal of hadron triplets associated with anomalous production of LS hadrons (presumably, rank 1 and rank 2 pairs) roughly describes the low Q spectrum.

Now I am making case for quantized fragmentation to be at the origin of MC-data discrepancies in colour flow

In model-dependent approach, it is assumed that Pythia describes hadron content and decays of resonances correctly , rank 1 estimate is obtained by subtraction of MC decays from measured Δ(Q)



Measured contribution from chains associated with anomalous production of LS hadrons is subtracted as well.

Modulation of rank 1 distribution approximately follows the predictions of quantized fragmentation for
(n quanta) -> π+ π

Curiously, 4 ΔΦ -> π+ π is missing …

Hypothesis : unbound state integrated with ρ(770) shape

Experimental evidence supports that : ρ mass and width measurements differ in τ decays and hadroproduction