Can quantized fragmentation replace colour reconnection models ?

Šárka Todorova-Nová, Charles University, Prague

Outline of the talk

- (very) brief history of colour reconnection models

  (« change of colour flow »)
- observables sensitive to colour flow
- quantized fragmentation

  (recap from last year + new ATLAS data ☺)
- $<p_T>(N_{ch})$ in modeling

ISMD 2022

What is colour reconnection ? PYTHIA manual :

Colour Reconnection

The colour flows in the separate subprocesses defined in the multiparton-interactions scenario are tied together via the assignment of colour flow in the beam remnant. This is not an unambiguous procedure, and currently two different methods are implemented. In the first model the colour flow is reconstructed by how a PS could have constructed the configuration. In the second model, the full QCD colour calculation is taken into account, however the dynamical effects are modeled loosely, only an overall saturation is taken into account. The idea is to later account for other dynamical effects through colour reconnections.

A simple "minimal" procedure of colour flow only via the beam remnants does not result in a scenario in agreement with data, however, notably not a sufficiently steep rise of *<pT>(n_ch)*. The true origin of this behaviour and the correct mechanism to reproduce it remains one of the big unsolved issues at the borderline between perturbative and nonperturbative QCD. Since no final answer is known, several models are implemented. The different models also rely on the two different colour assignments in the beam remnant. There are two, somewhat motivated, models implemented: the original PYTHIA scheme and a new scheme that tries to incorporate more of the colour knowledge from QCD.

The original PYTHIA scheme relies on the PS-like colour configuration of the beam remnant. This is combined with an additional step, wherein the gluons of a lower-*pT* MPI system are merged with the ones in a higher-pT MPI. A more detailed description of the merging can be found below. Relative to the other models it tests fewer reconnection possibilities, and therefore tends to be reasonably fast.

The new scheme [Chr14a]relies on the full QCD colour configuration in the beam remnant. This is followed up by a colour reconnection, where the potential string energy is minimized (ie. the *lambda* measure is minimized). The QCD colour rules are also incorporated in the colour reconnection, and determine the probability that a reconnection is allowed. The model also allows the creation of junction structures.

In addition to the two models described above, a simple model is implemented, wherein gluons can be moved from one location to another so as to reduce the total string length. This is one out of a range of simple models developed to study potential colour reconnection effects

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The MPI-based scheme

A simple « minimal » colour flow via the beam remnants …. does not agree with data … notably, the steep rise of $\langle p_T\rangle(N_{ch})$. The true origin of this behaviour and the correct mechanism to reproduce it remains one of the big unsolved issues …. Since no final answer is known, several … somewhat motivated … models are implemented

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History of colour reconnection (highly subjective!)

- Question about possible final state interaction between overlapping hadronic sources arised in connection with W mass measurement at LEP2, in fully hadronic WW events

- »Experimental « modeling included extreme models of reconnection at the level of hard scattering (large effects)– combined with experimental measurements of particle flow between jets (small differences) -> systematic uncertainty on reconstructed W mass

- most of models assume partons »close enough » in phase space interact forming a more « compact » configuration (shorter strings, for example) -> higher boost -> higher pT

- models enjoy increasing popularity at hadron colliders ever since it was shown they can reproduce the multiplicity dependence of $<p_T>$

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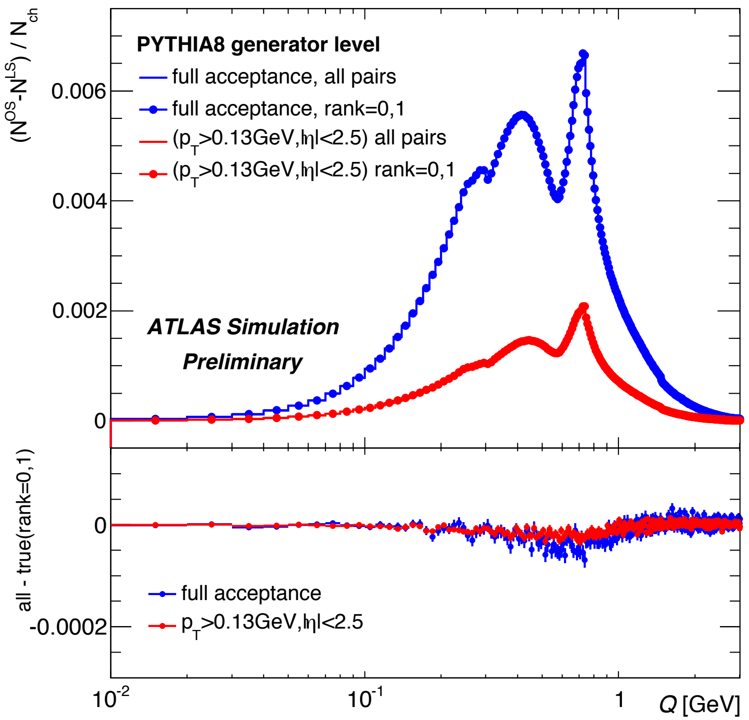
Tampering with «natural » colour flow can be counter-productive if not under control

Observable sensitive to colour flow



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

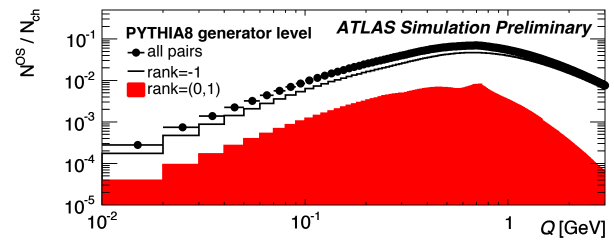
$$Q(p_i, p_j) = \sqrt{-(p_i - p_j)^2}$$

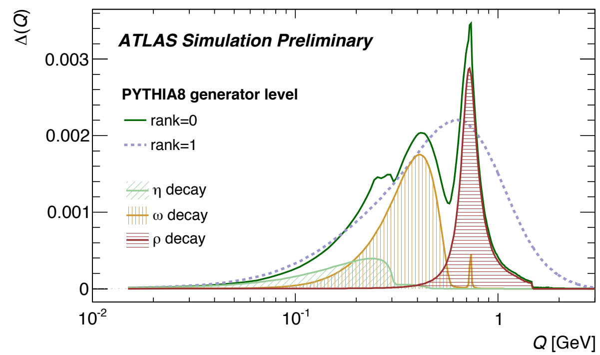
all particles assigned pion mass

Rank describes the ordering of hadrons along the colour flow.

Decay products inherit rank from parent resonance

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





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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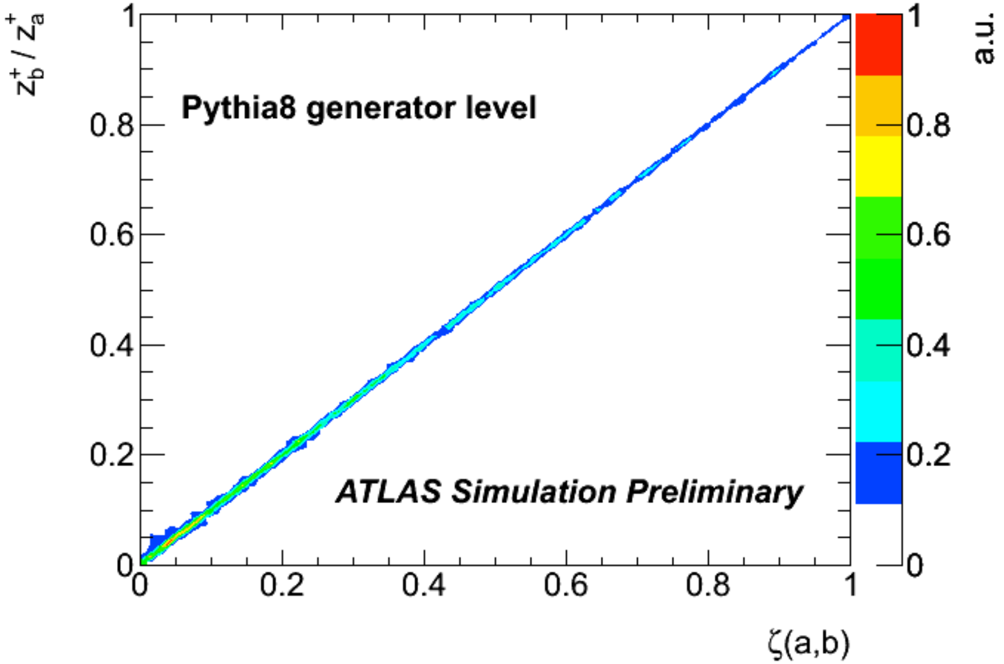
Observable sensitive to local evolution of fragmentation function :

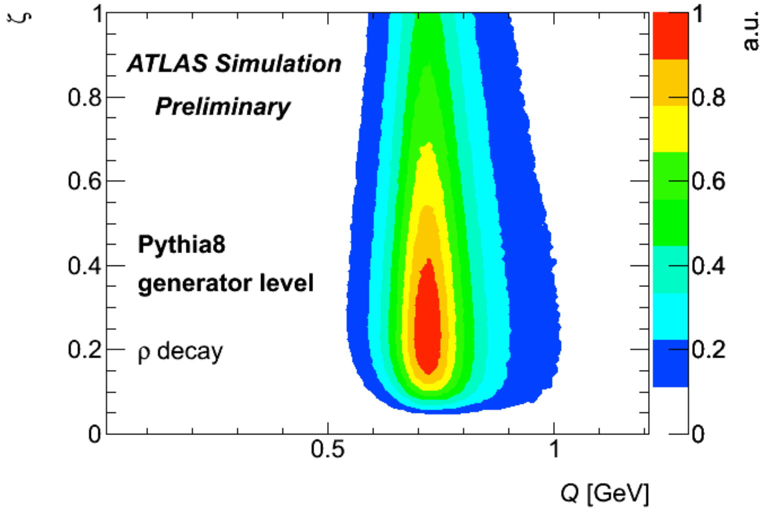
$$Q^2(p_a, p_b) \quad = \quad (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t,a}^2(\frac{z_b^+}{z_a^+} - 1) + m_{t,b}^2(\frac{z_a^+}{z_b^+} - 1).$$

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

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

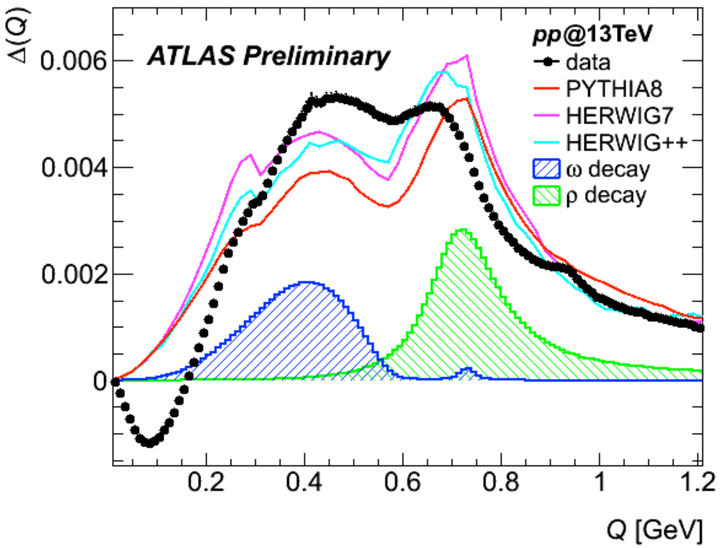


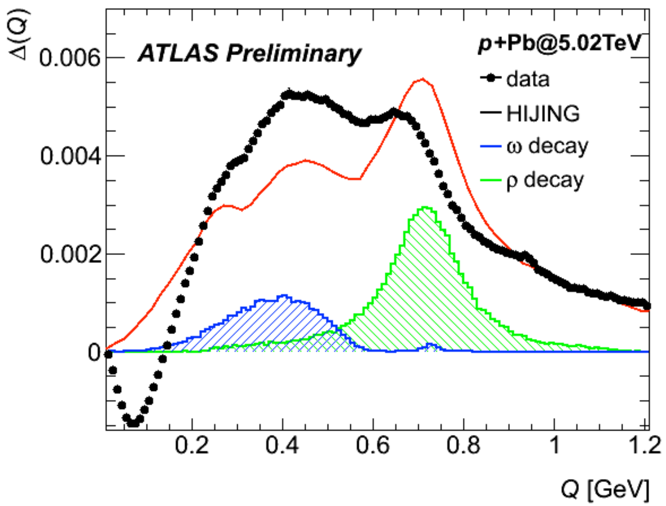
Allows to distinguish between rank 0 and rank 1 contributions

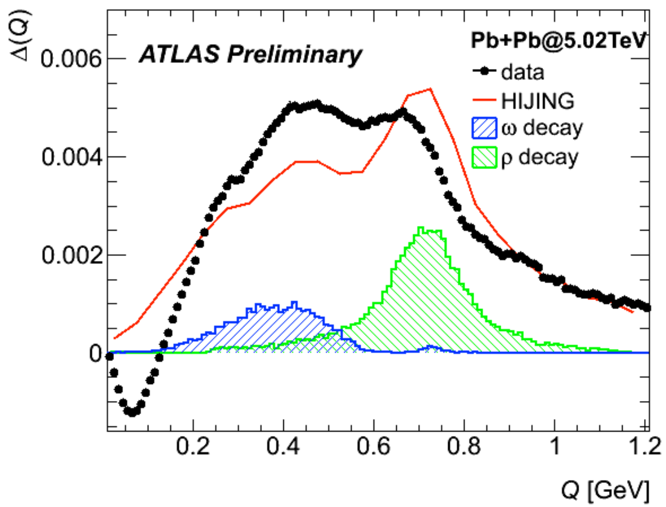


Correlations along colour flow
(= dynamics of hadronization)
described poorly by conventional models

<u>Alarming</u> : the modeling does not allow
to evaluate the hadronization systematics ….







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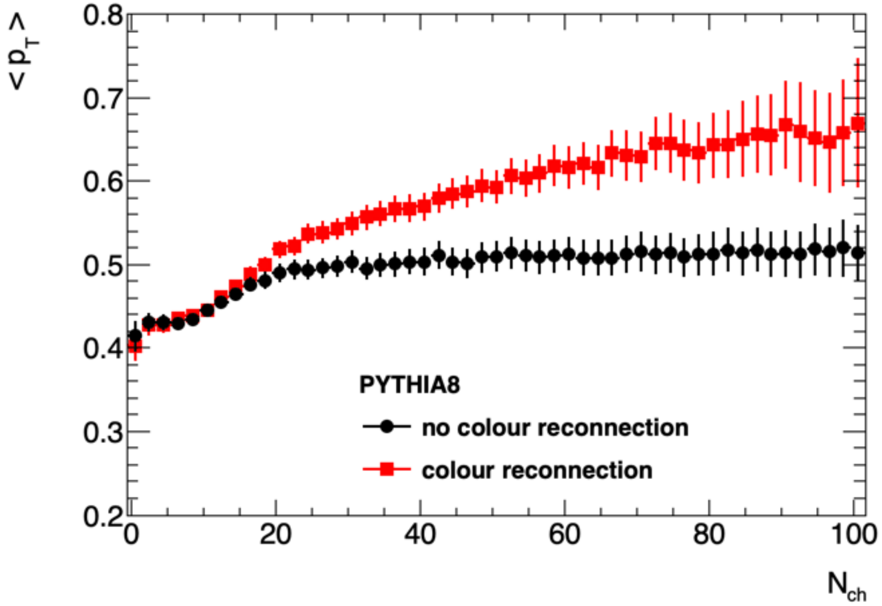
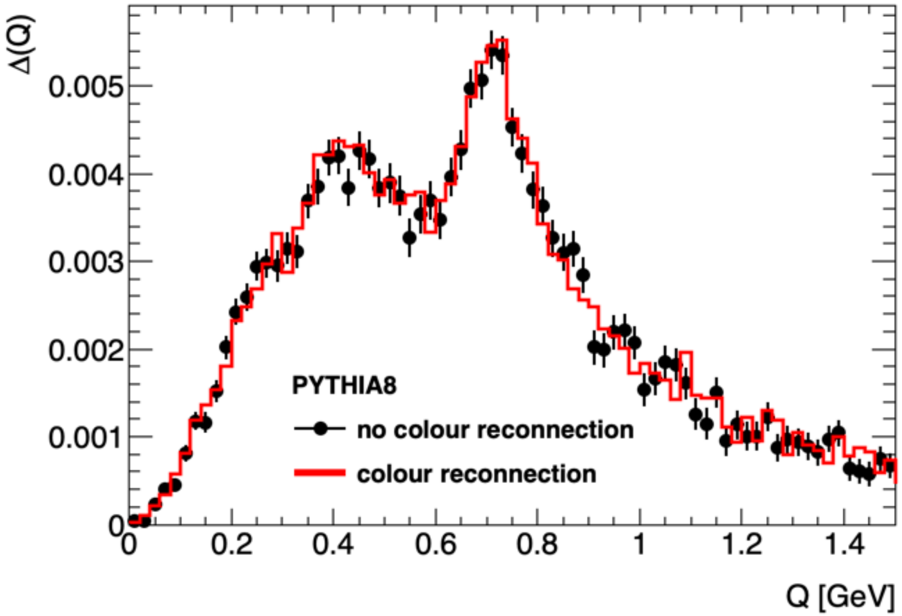
Is the colour flow described better by colour reconnection models ?



Not at all …

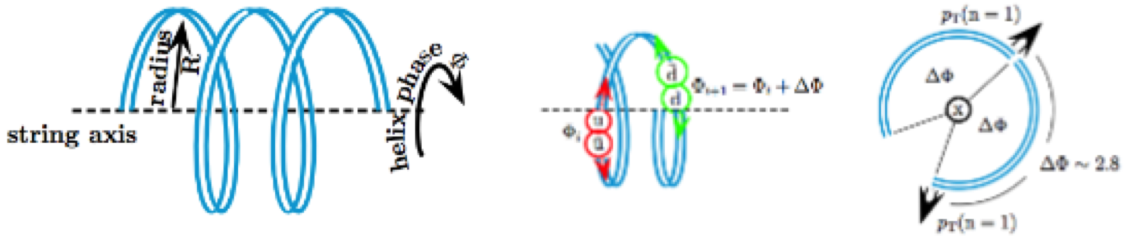


Precisely the situation one would prefer to avoid :
QCD predictions compromised for partial gain
in one observable …

<u>Quantized fragmentation</u> *(extract from poster, recap of presentation at ISMD 2021)*

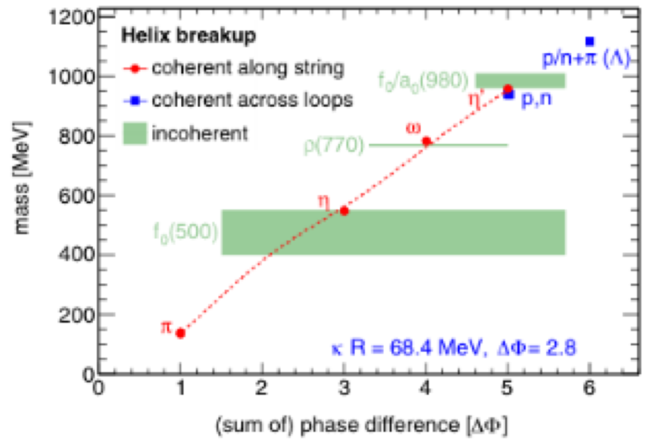
Phenomenology

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.

PHYS. REV. D **104**, 034012 (2021)



Quantization proceeds in $m_t = n\ \kappa R\ \Delta\Phi$ 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

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, …)

Quantized fragmentation and anomalous production of 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 pions, their momentum difference can be calculated as a function of their rank difference :

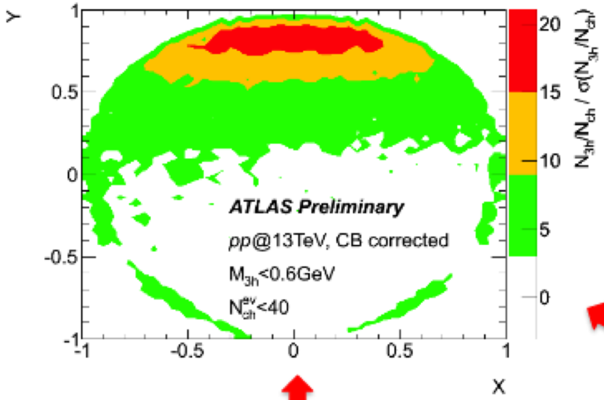
Phys.Rev.D96(2017)092008
arXiv:1709.07384[hep-ex]

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

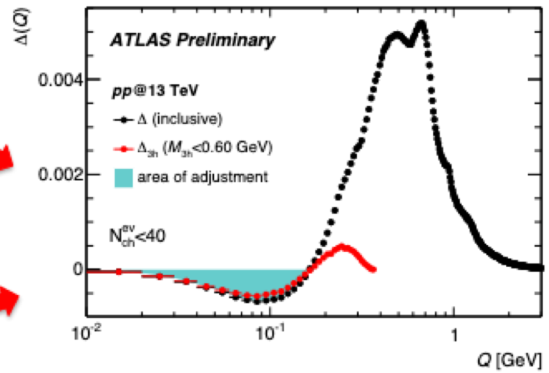
Also, a chain of n direct pions should have the minimal possible mass , locally.

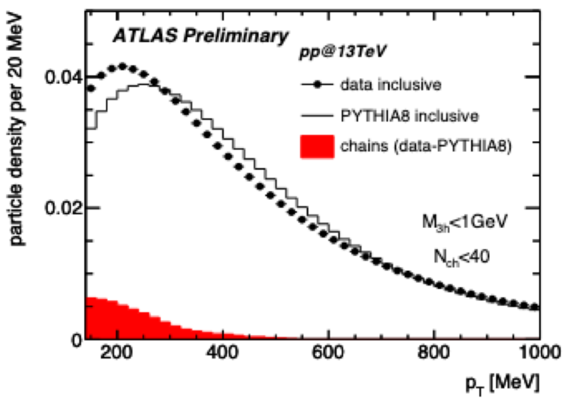
Quantized fragmentation and anomalous production of LS hadrons pairs

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



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





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

Model independent measurement

Quantized fragmentation and anomalous production of LS hadrons pairs

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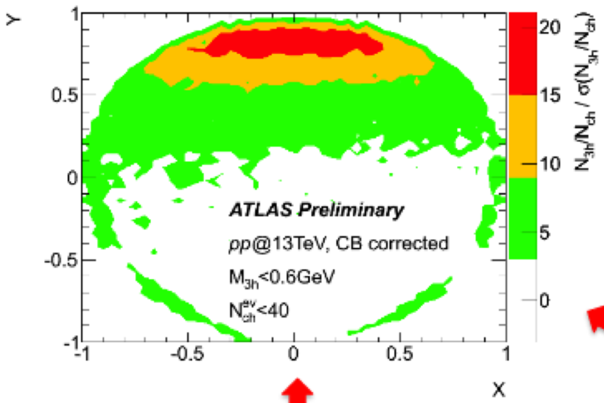

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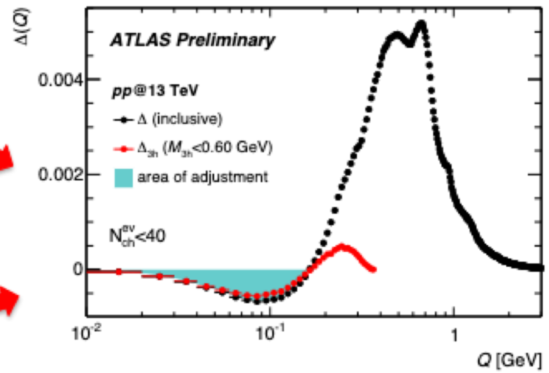
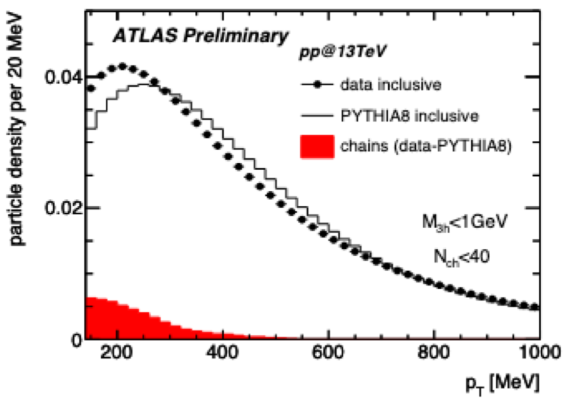
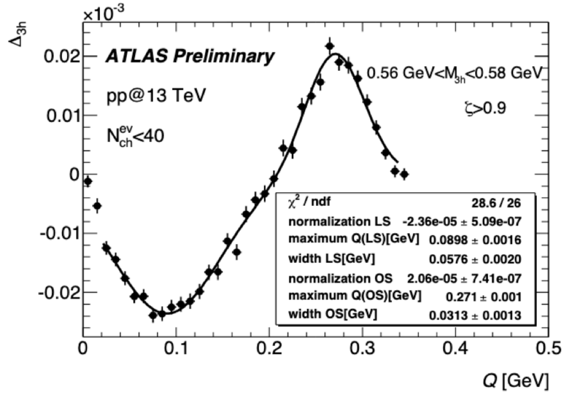




Signature of quantized fragmentation in 1-,2-,3-particle distributions

Model independent measurement

Q(r=1)

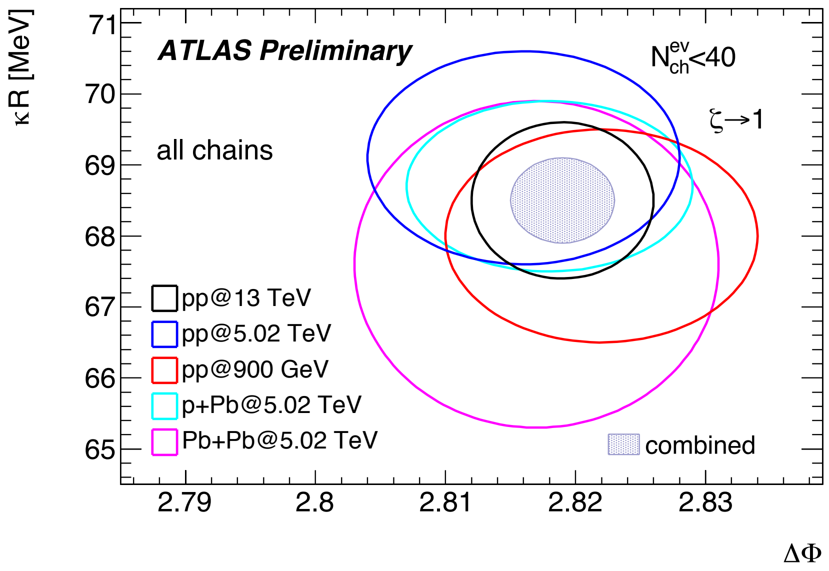


Q(r=2)

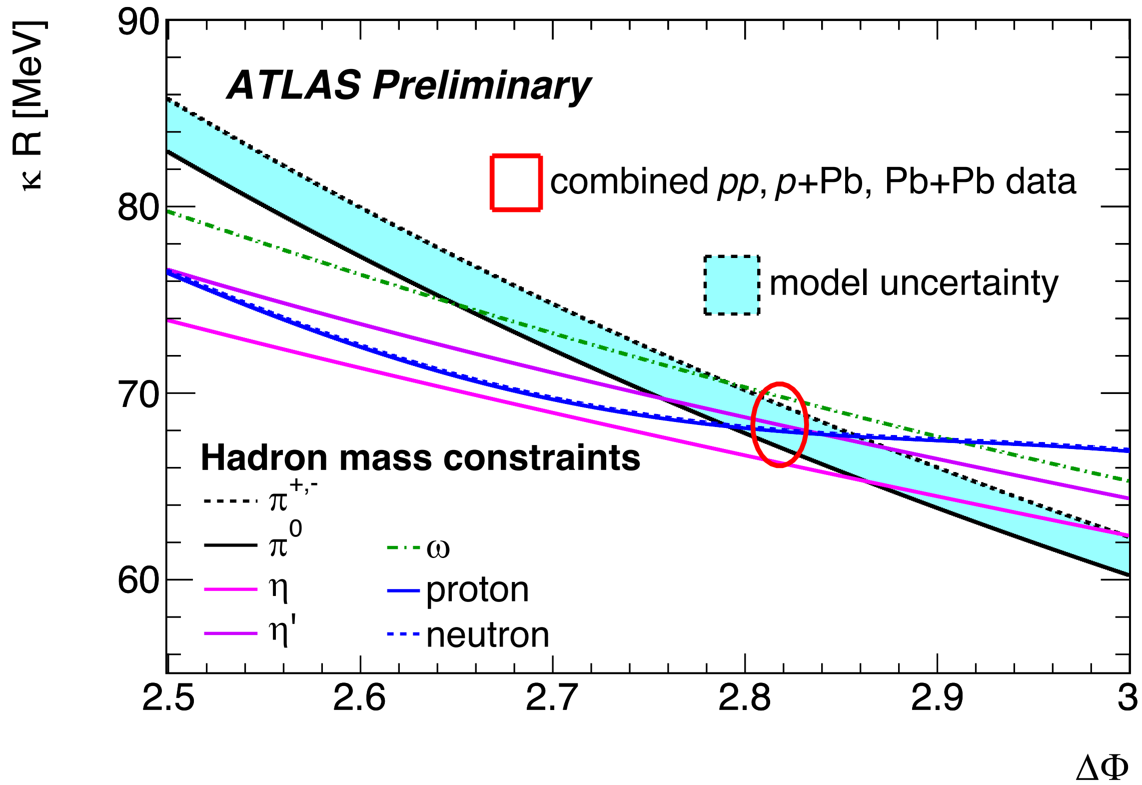
Charge-ordered triplets +-+, -+-
2xOS pairs (rank 1)
LS pair (rank 2)

=> κR, ΔΦ independent measurement of string parameters

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



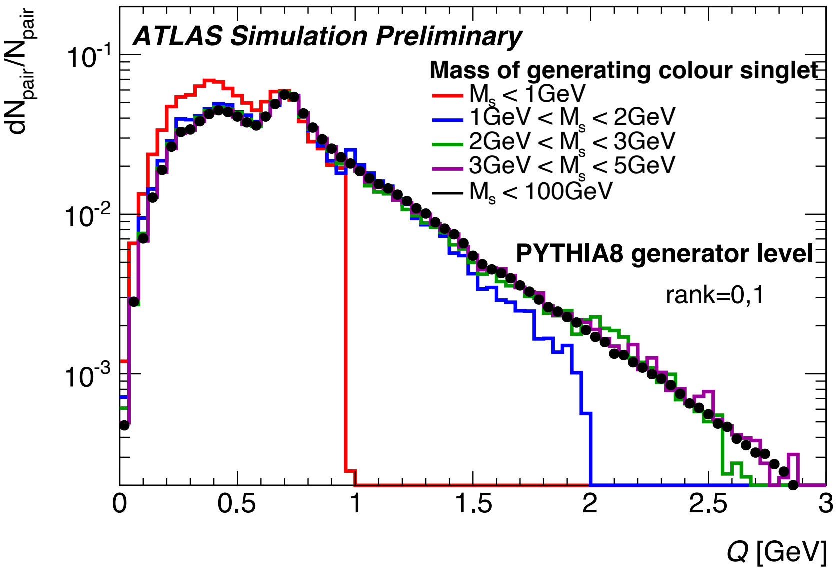
Excellent agreement between pp data at various collision energies.
Excellent agreement between pp and HI data.

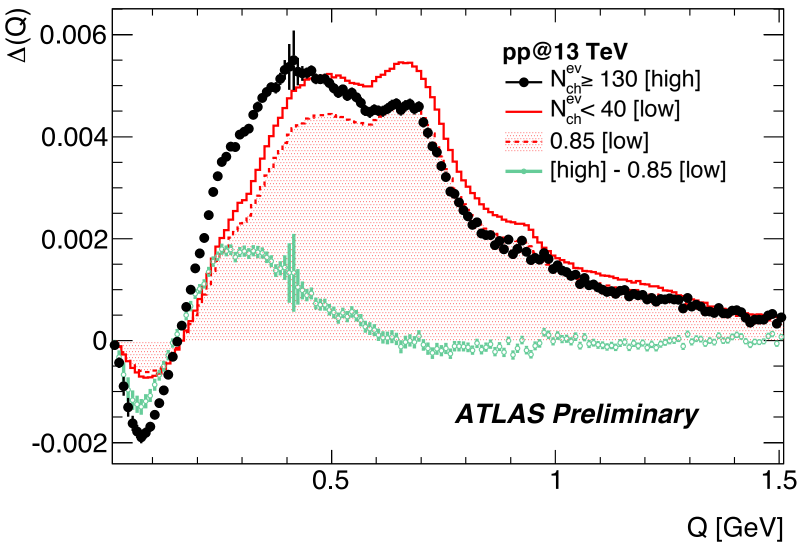


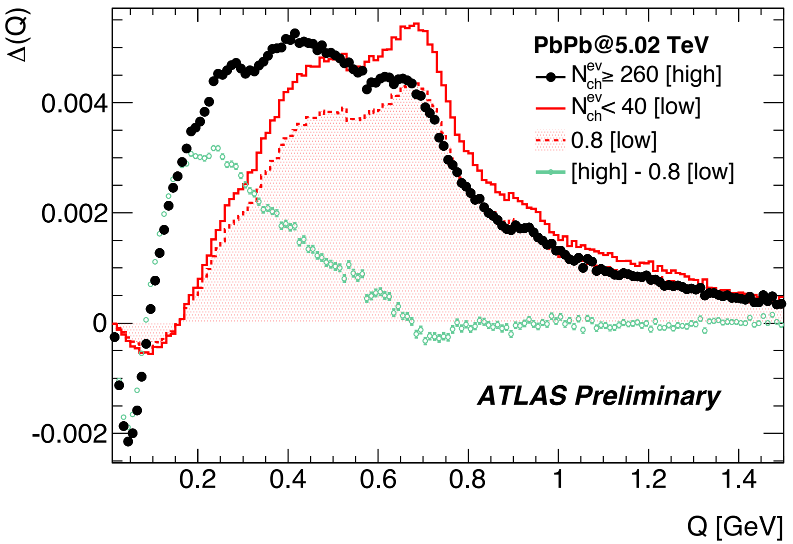
Quantized fragmentation absorbs ALL data previously associated with Bose-Einstein interference (HBT).

Anomalous production of close LS hadrons is purely hadronization effect.

Study of mass spectrum of hadron sources

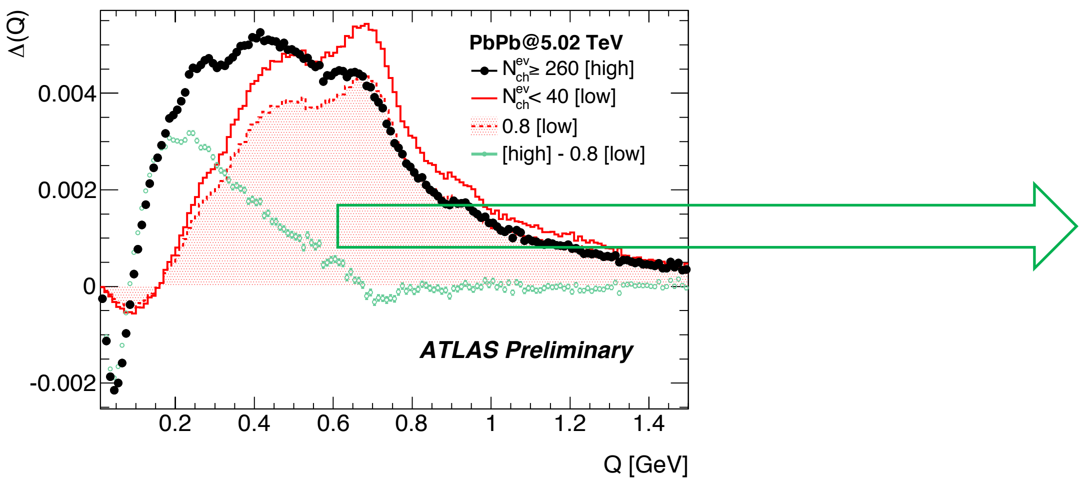


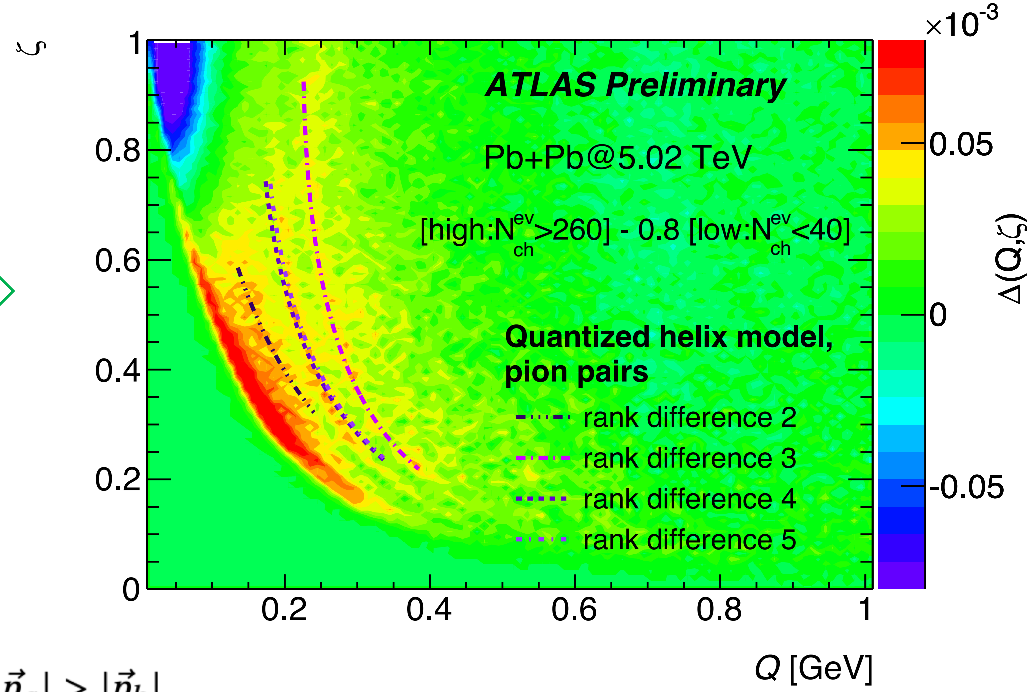




Distribution of momentum difference between colour-adjacent hadron pairs is obviously limited by the mass of the source but otherwise pretty stable
(there is no or very little difference in Δ shape below Q~1.5GeV for. sources with masses above 2 GeV)

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





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

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 demostrates 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]

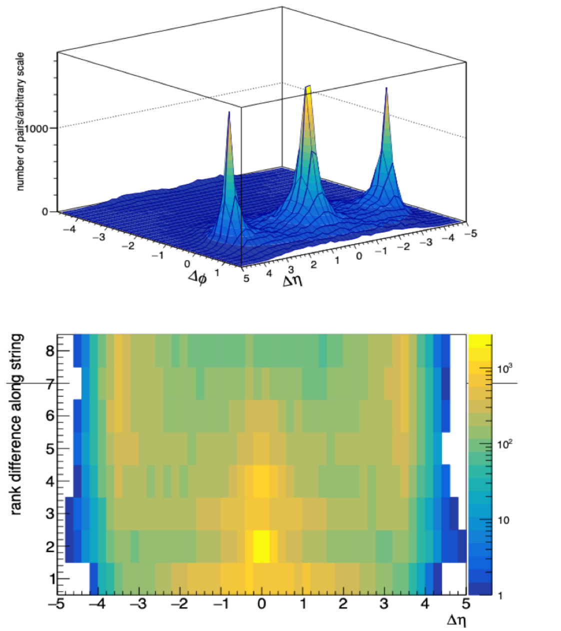
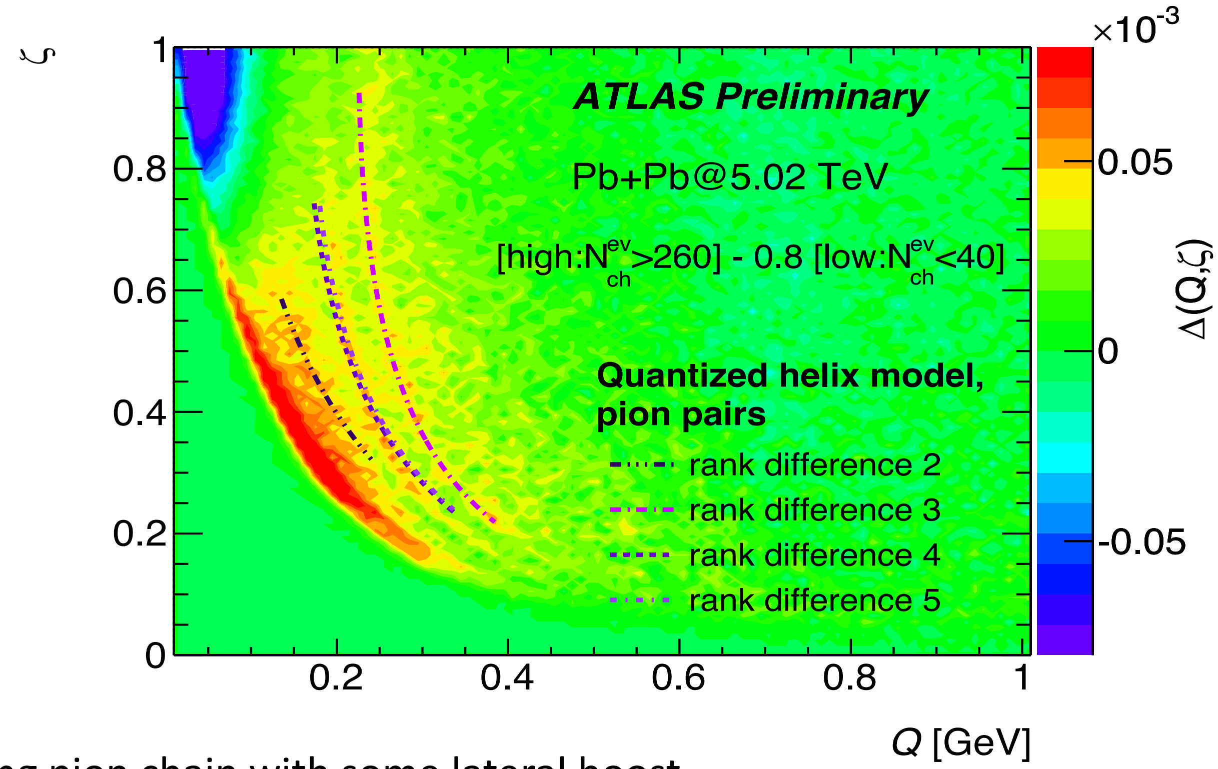


FIG. 13. Top: The emergence of a ridge-like structure in the fragmentation of a helical string with a lateral boost. The narrow helix radius (0.07 fm) implies a small intrinsic momentum (∼140 MeV) of hadrons and thus smaller smearing in the boosted direction. The recoiling system is not shown. Bottom: The rank dependence of the ridge structure shown above. Higher eta difference is effectively dominated by pairs with larger rank distance (the distribution is truncated) but the adjacent hadrons may have a large pseudorapidity difference as well.

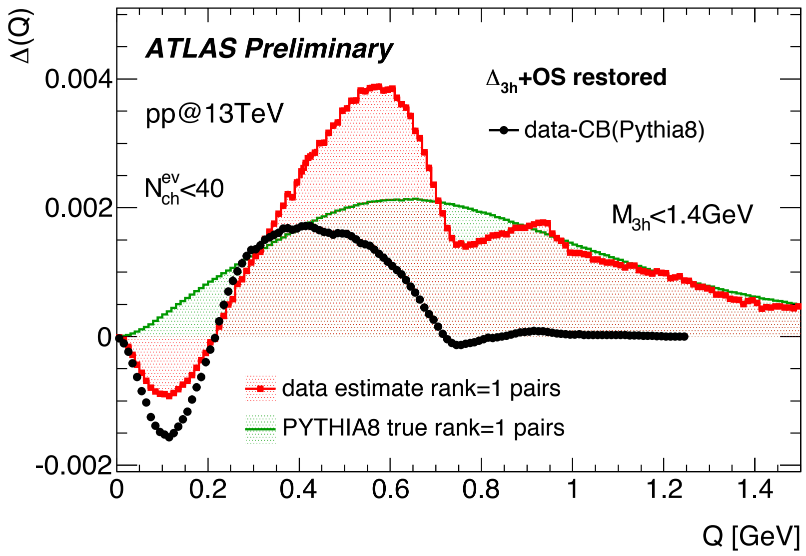


Long pion chain with some lateral boost is generating a ridge-like signal

… material for future conferences ☺

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.

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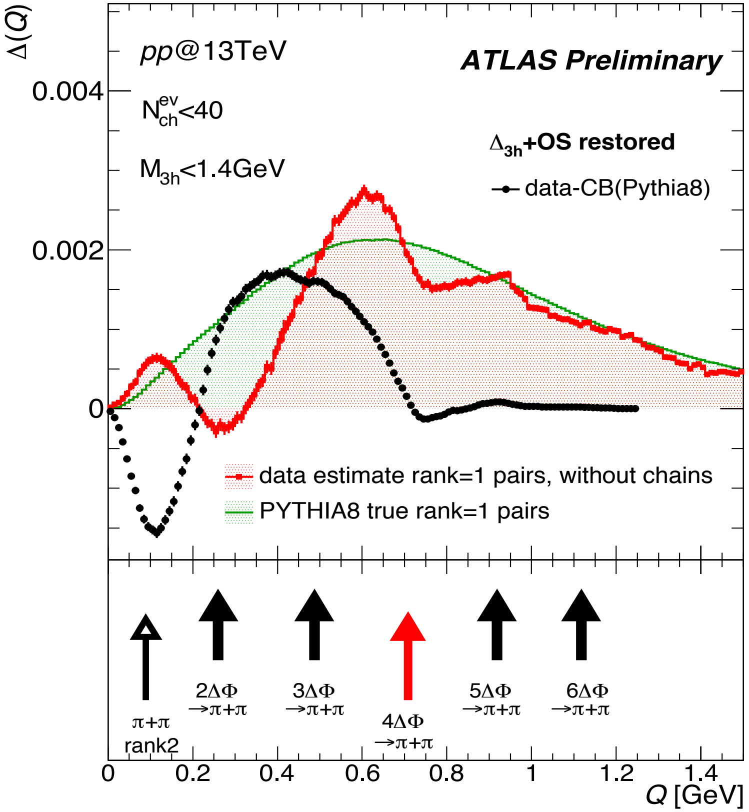


Measured contribution from chains associated with anomalous production of LS hadrons is subtracted as well.

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

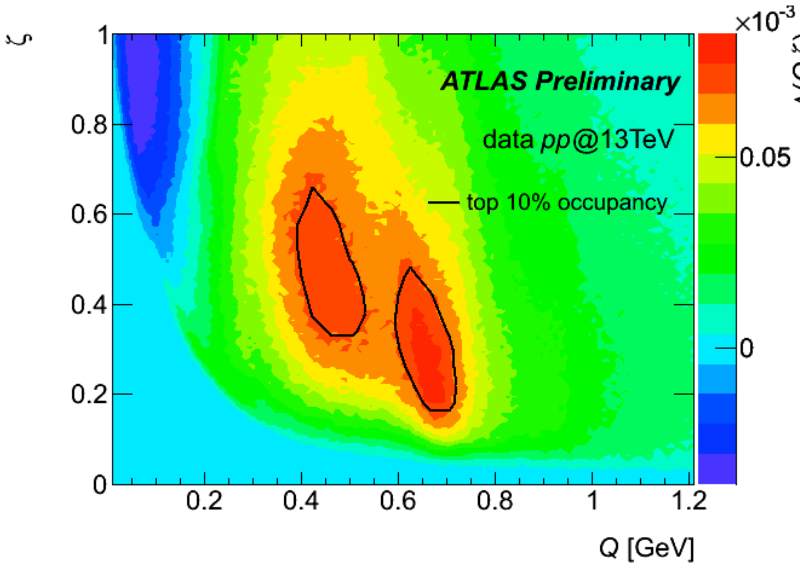
Experimental evidence supports that : ρ mass and width measurements differ in τ decays and hadroproduction

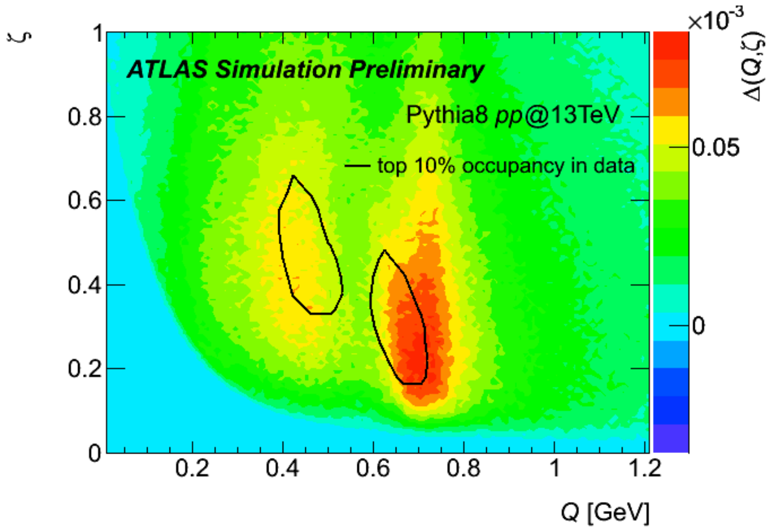
Now I am making case for quantized fragmentation to be at the origin of MC-data discrepancies in colour flow

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





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

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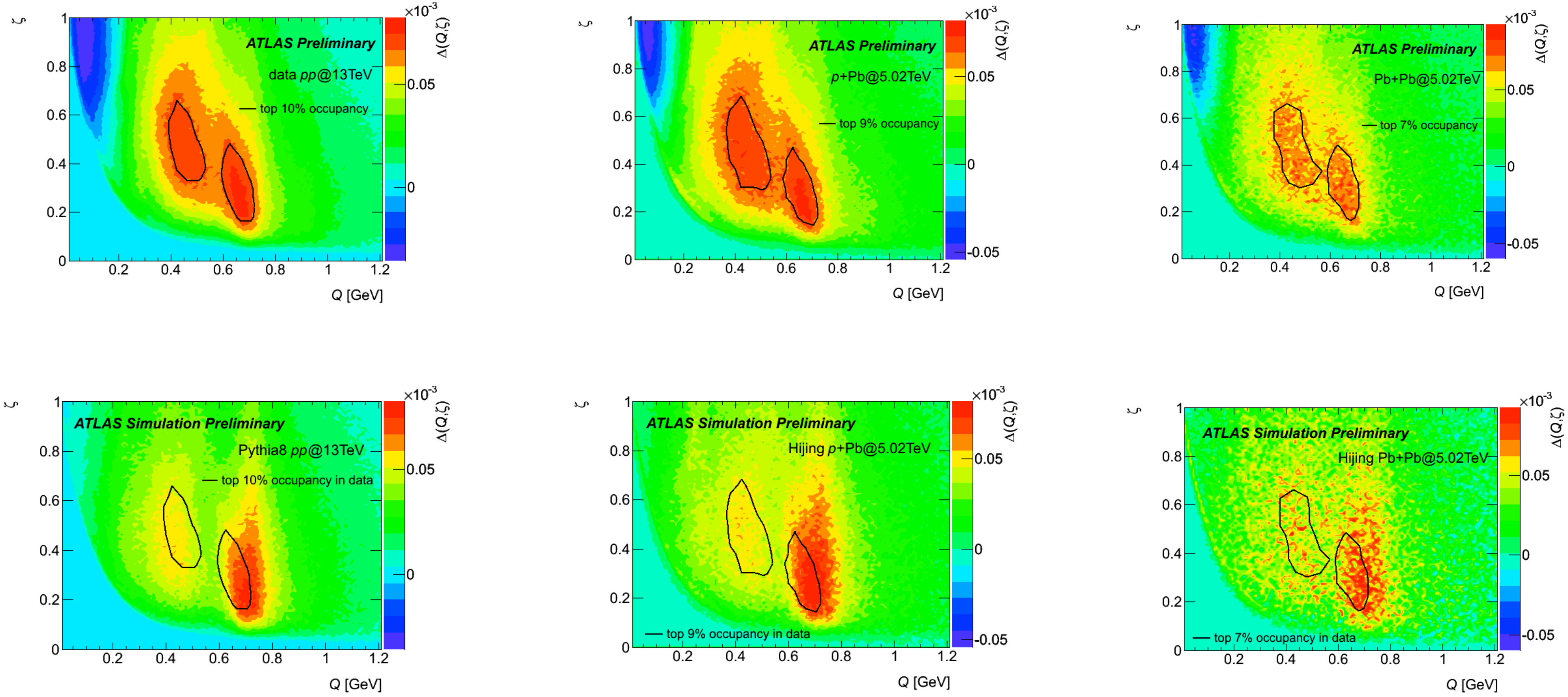
pp | p+Pb | Pb+Pb

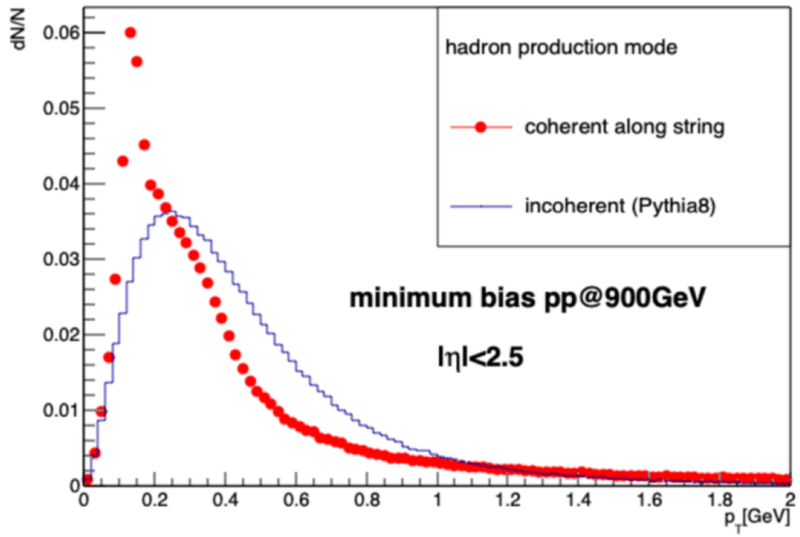
DATA

MODELS



Slide extracted from MC study of quantized fragmentation in view of special ATLAS run with low magnetic field

« extreme « scenarios : fully coherent vs. fully incoherent

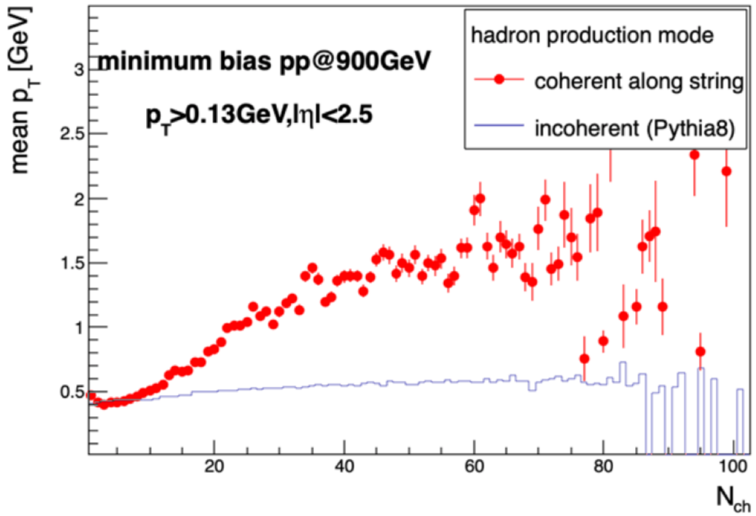


WORK IN PROGRESS

- ***In both scenarios, ~99% of all hadrons (eta filtered) within acceptance for p_T>50 MeV***

And finally : does quantized fragmentation impact $\langle p_T \rangle (N_{ch})$?

!!!! NEW OBSERVATION !!!!



- ***increase of average p_T with multiplicity for coherent hadron production***
- ***considered to be a proof of colour reconnection in conventional modelling***
- ***another opportunity to reduce the number of independent model parameters***

Summary

- ✓ *correlations between colour-adjacent hadrons measured (pure hadronization)*
- *differences between data and conventional models (in colour flow sensitive observable)*

  NOT cured by colour-reconnection models

  acting on distribution of masses of hadronizing colour singlets
- ✓ *experimental evidence points towards quantum effects in the fragmentation function*
- ✓ *quantized fragmentation seems to capture essential features of hadron formation*

  -> (light) hadrons mass spectra (with precision of few %)

  -> short-range correlations (traditionally attributed to HBT/Bose-Einstein interference)
- ✓ *new experimental evidence (supporting quantized fragmentation):*

  --> long range correlations (signature of long pion chains)

  --> modification of inclusive p_T spectra related to short-range correlations

  --> very good agreement between pp/pP/PbPb (universality of hadronization)

- *« Is there screwiness at the end of parton cascades ? « JHEP09(1998)04*

YES, THERE IS !

- *« Can quantized fragmentation replace colour reconnection models ? »*

PROBABLY

-> more work is needed to measure parameters related to
the (longitudinal) evolution of QCD field

-> in parallel, modify parton shower to take into account quantum effects
and natural cutoffs -> full description of the (effective) final gluon configuration

MANY THANKS FOR YOUR ATTENTION

Backup slides

Quantification of Δ(Q,ζ)