LHC studies of hadronization & string models

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I was asked to summarize existing and prospective LHC studies of hadronization and string models …

There is not really enough time to go into details of various measurements done in LHC experiments,
so I'll concentrate instead on where modeling goes wrong and what we can do about it
(a subjective and non-exhaustive point of view !)

Inclusive charged particle spectra

Short- and long-range correlations

Diffraction

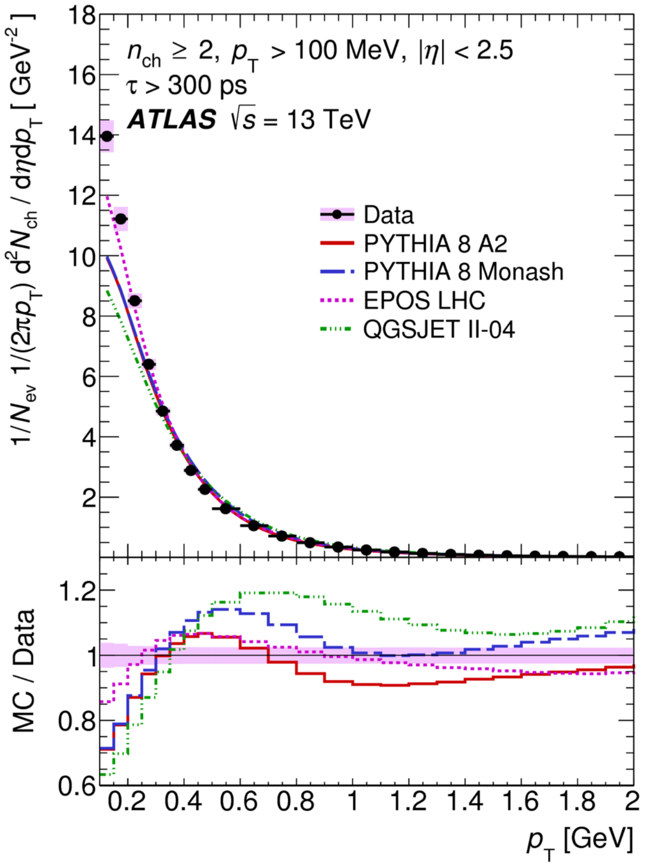
Underlying events

Jet quenching

Spectroscopy
Exotic hadrons

Jet substructure

Understanding of « simple » hadronic systems was never quite satisfactory ….
Example : inclusive p_T spectra



Minimum bias at LHC :

significant discrepancy at low p_T

Z^0 data from LEP :

dependence of p_T on x_p not understood

$p_{T,out}$ modeling inacceptable

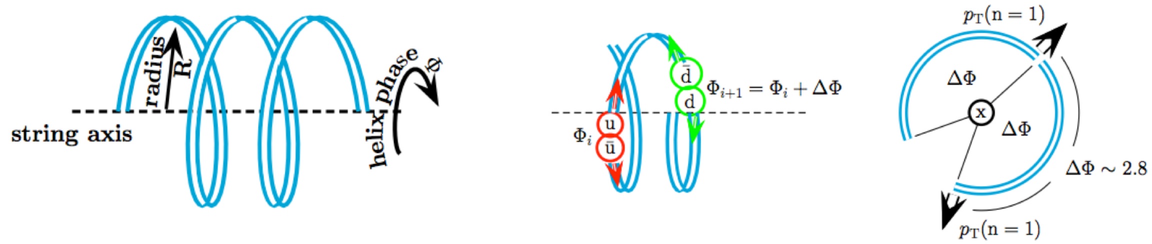
That's a problem we need to resolve

LEP (DELPHI »tuning » paper)

Table 8. χ^2/bin for the model/data comparisons of event shape and inclusive charged particle distributions. Only the p_t^{out} distributions are badly described by all models

	χ^2/bin				
	ARIADNE 4.06	JETSET 7.4 PS	JETSET 7.3 PS	HERWIG 5.8 C	JETSET 7.4 ME
$1-T$	0.67	0.98	1.14	8.44	27.23
M	1.41	1.99	2.34	21.50	11.83
m	1.28	3.43	4.10	38.17	18.89
O	0.58	7.78	7.62	1.33	6.24
S	1.07	2.29	2.28	4.32	3.52
A	1.57	5.57	5.53	7.56	13.32
P	0.91	2.25	1.97	2.29	6.17
C	1.00	1.86	2.09	12.48	25.77
D	1.55	3.36	3.58	8.84	29.62
M^2_{high}/E^2_{vis}	2.77	1.89	2.17	2.16	10.50
M^2_{low}/E^2_{vis}	0.65	0.77	0.60	1.40	4.90
M^2_{diff}/E^2_{vis}	4.45	0.37	0.34	1.25	3.76
B_{max}	2.31	1.67	2.42	25.78	10.18
B_{min}	9.77	1.92	1.13	70.14	13.39
B_{sum}	1.50	2.19	2.70	16.65	10.22
$B_{diff.}$	5.40	3.11	3.22	0.99	1.21
D_2^D	1.12	2.37	3.33	1.57	2.16
D_3^D	1.23	3.28	2.60	2.15	1.12
D_4^D	2.13	3.87	4.44	7.15	65.05
D_2^J	0.56	2.15	2.54	5.02	5.79
D_3^J	0.63	6.97	5.75	1.92	5.72
D_4^J	2.70	7.53	8.13	10.34	82.91
EEC	0.27	1.48	1.62	0.93	5.39
$AEEC$	2.11	9.28	9.84	11.26	11.05
p_t^{in} T $axis$	3.69	1.53	1.74	2.58	2.03
p_t^{out} T $axis$	17.27	26.48	26.68	11.79	28.84
y_T	1.11	1.07	1.43	9.09	40.95
p_t^{in} S $axis$	5.33	2.83	3.34	4.06	1.58
p_t^{out} S $axis$	14.01	20.78	21.74	7.51	21.39
y_S	1.38	0.93	1.44	1.57	11.63
x_p	2.22	0.98	1.76	3.76	3.55
ξ_p	1.30	0.99	0.95	3.41	2.48
p_t^{out} $vs.$ x_p	14.39	23.68	19.04	25.76	56.20
p_t $vs.$ x_p	11.00	4.48	5.32	19.12	25.41
all distrib.	3.62	5.32	5.40	10.62	16.05

Quantized fragmentation



Phenomenology

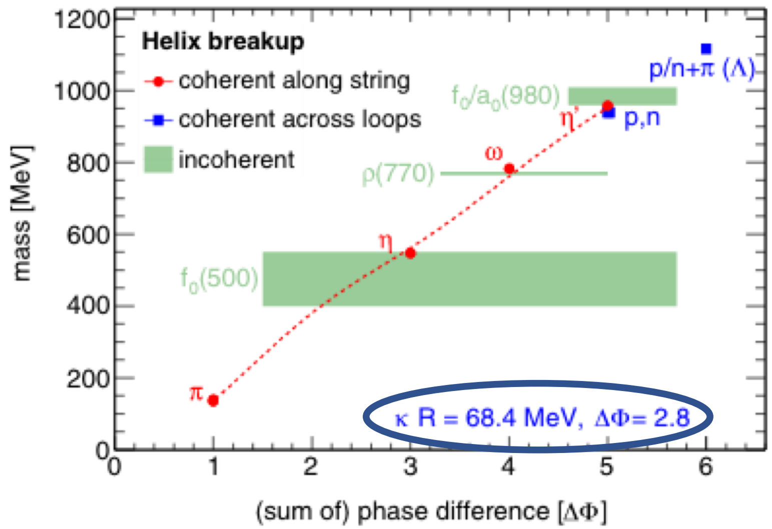
QCD confinement modeled by 3D string
Vortex translated into helical chain of gluons

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)

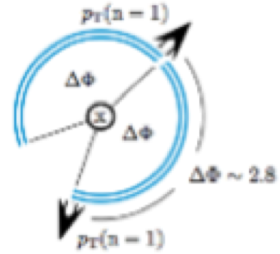


Production scenarios:

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)*

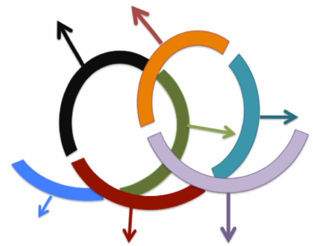
Phys.Rev.D96(2017)092008
arXiv:1709.07384[hep-ex]

OS
opposite
sign

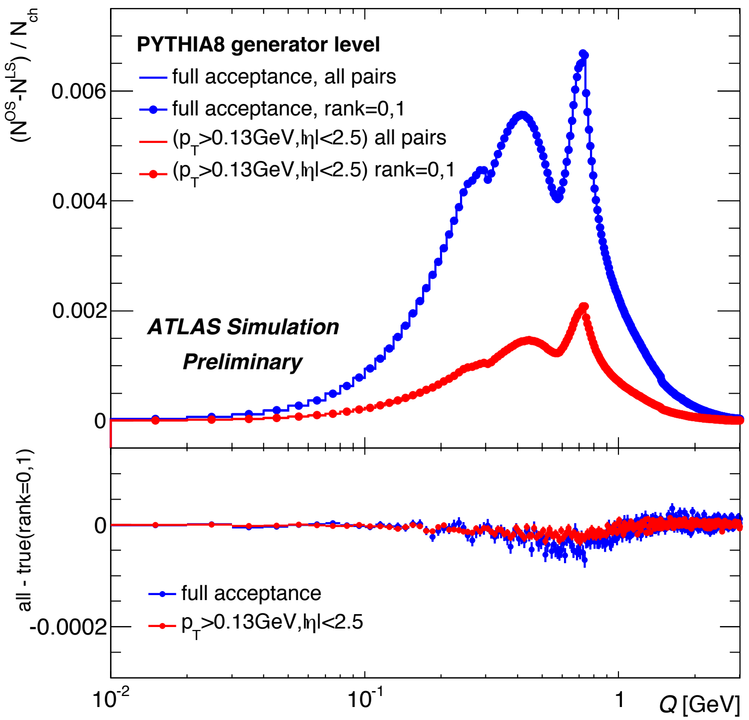
Pair rank difference r	1	2	3	4	5
Q expected [MeV]	266 ± 8	91 ± 3	236 ± 7	171 ± 5	178 ± 5

LS
like-sign

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

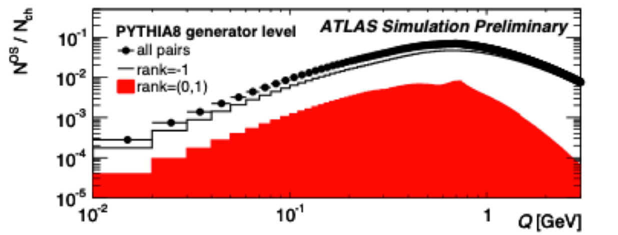


$$\Delta(Q) = \frac{1}{N_{ch}} \left[\, N(Q)^{OS} - N(Q)^{LS} \,\right]$$

4-momentum difference

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

(all particles assigned pion mass)

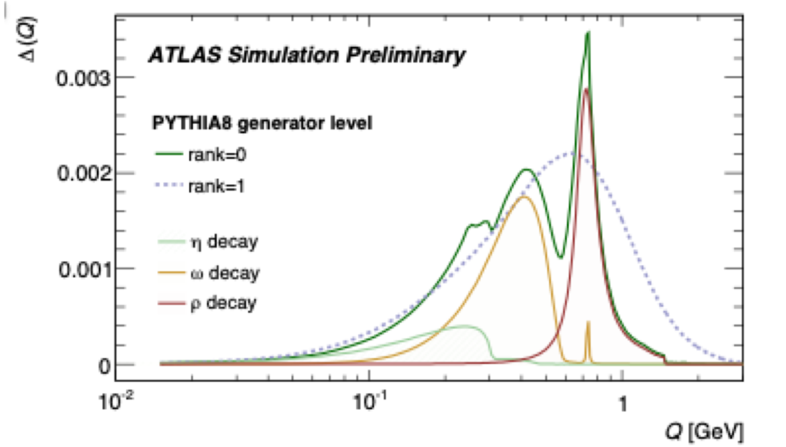


Hadron pairs classified by **rank difference** (shortened to « rank »)

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



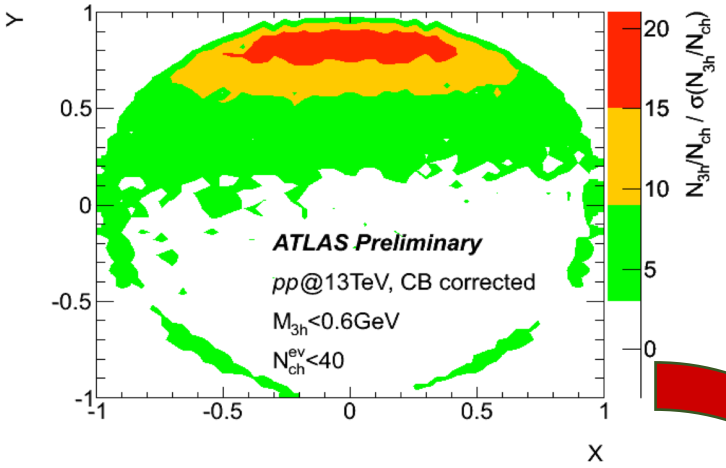
Pairs : rank = 0 decays,

rank = 1 colour-adjacent hadrons (sharing common string breakup)

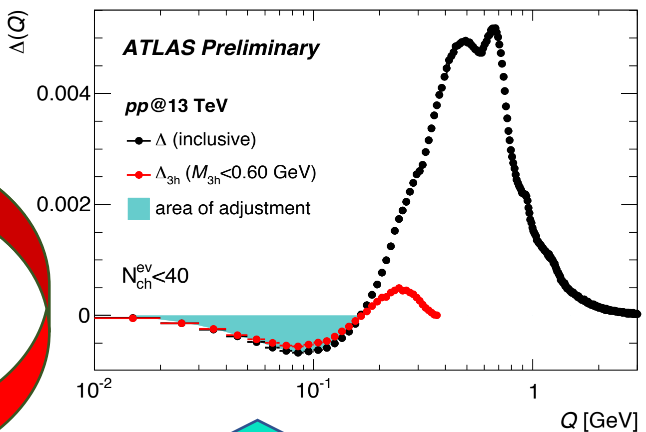
rank = -1 if hadrons coming from different sources

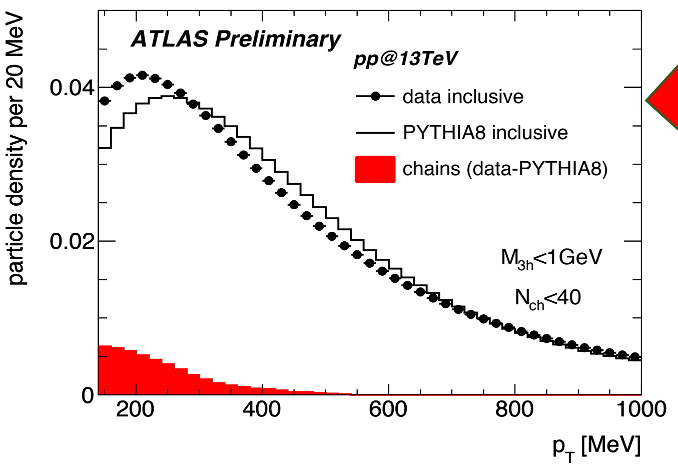
ATLAS-CONF-2022-055

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



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





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

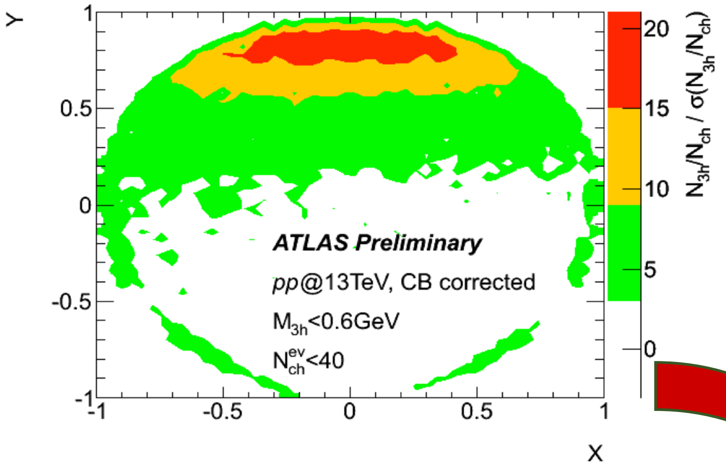
Data consistent with model expectations :

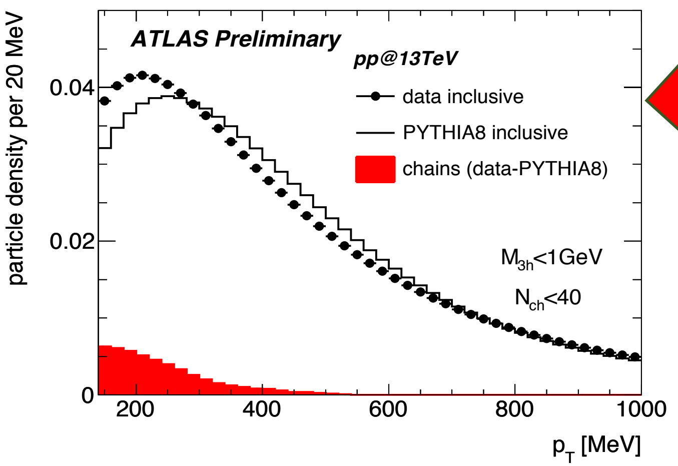
- *excess in mass-minimized charge-ordered triplet chains observed (Dalitz plot)*
- *associated with the source of anomalous production of close LS pairs (Δ vs. Δ_{3h})*
- *associated with the modification of inclusive low p_T spectra*

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

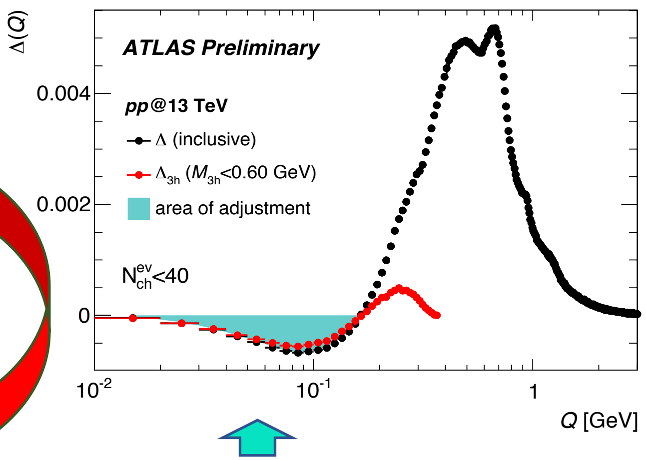
Model independent measurement (MIM) of link between 1-,2-,3-particle distributions

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





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



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.

Major shift in strategy of model development

« conventional » approach:

- *build a model*
- *tune parameters*
- *If discrepancy, add more parameters*

Here we propose:

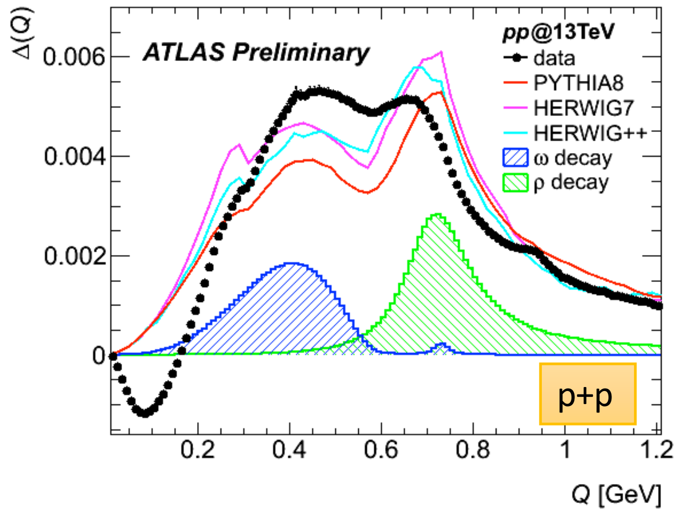
- *find a (model inspired) link between various discrepancies*
- *reduce number of model parameters (hadron masses, intrinsic p_t, correlations)*
- *measure the remaining »parameters » (κR, ΔΦ)*

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

Further colour-flow sensitive measurements by ATLAS

Correlations along colour flow
(= 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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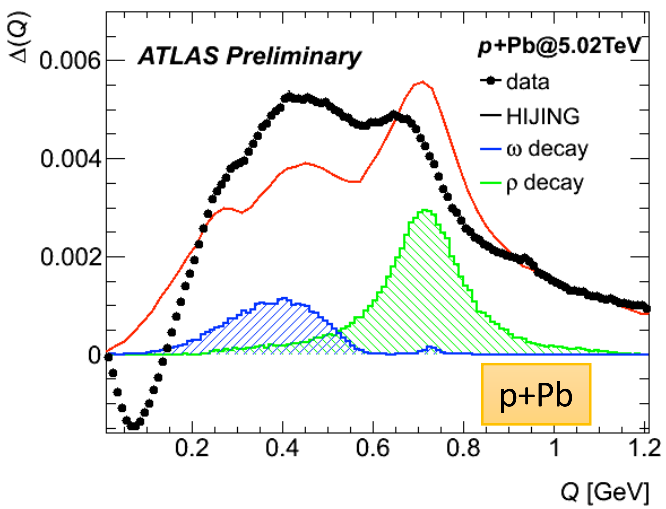
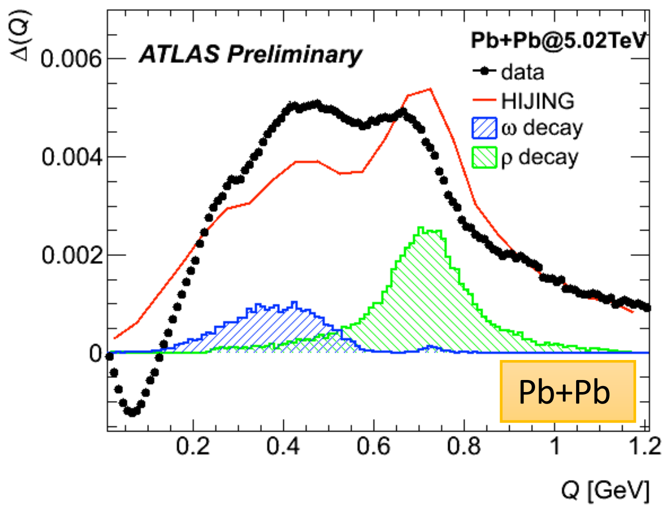




And even bigger problem potentially : the weight given to various color-reconnection models in LHC tunes :

Parameter	A3 value	A2 value	Monash value
MultipartonInteractions:pT0Ref	2.45	1.90	2.28
MultipartonInteractions:ecmPow	0.21	0.30	0.215
MultipartonInteractions:coreRadius	0.55	-	-
MultipartonInteractions:coreFraction	0.90	-	-
MultipartonInteractions:a1	-	0.03	-
MultipartonInteractions:expPow	-	-	1.85
BeamRemnants:reconnectRange	1.8	2.28	1.8
Diffraction:PomFluxEpsilon	0.07 (0.085)	-	-
Diffraction:PomFluxAlphaPrime	0.25 (0.25)	-	-

ATL-PHYS-PUB-2016-017

CMS-GEN-17-002, arXiv:2205.02905v2 [hep-ex]

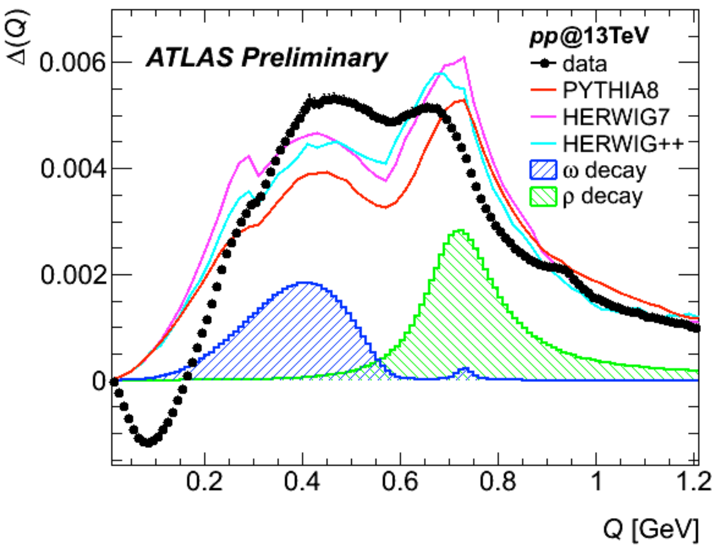
Table 2: The MPI and CR parameter ranges used in the tuning procedure.

PYTHIA 8 parameter	Min–Max
MPI parameters	
`MultipartonInteractions:pT0Ref`	1.0—3.0
`MultipartonInteractions:ecmPow`	0.0—0.3
`MultipartonInteractions:coreRadius`	0.2—0.8
`MultipartonInteractions:coreFraction`	0.2—0.8
QCD-inspired model	
`ColourReconnection:m0`	0.1—4.0
`ColourReconnection:junctionCorrection`	0.01—10
`ColourReconnection:timeDilationPar`	0—60
Gluon-move model	
`ColourReconnection:m2lambda`	0.2—8.0
`ColourReconnection:fracGluon`	0.8—1.0

Soft QCD tunes concentrate on multi-parton interactions.

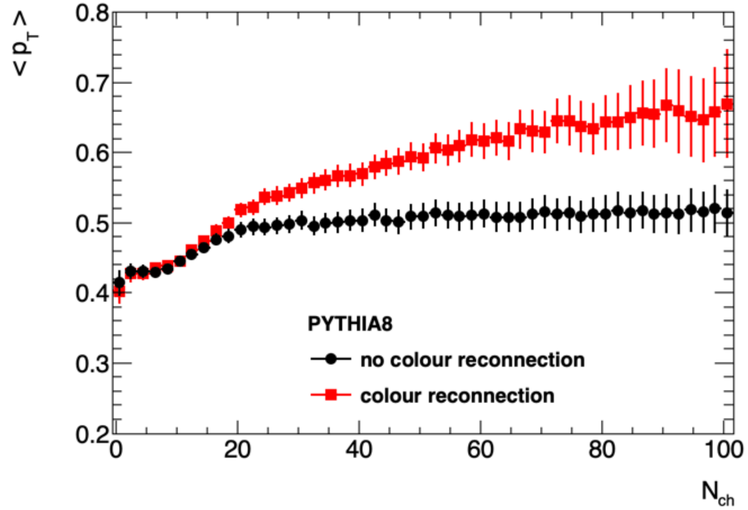
Driven by the need to describe <p_T> (N_{ch}) , colour reconnection models modify « natural » (QCD driven) colour flow of partons.

Is the colour flow described better by colour reconnection models ?

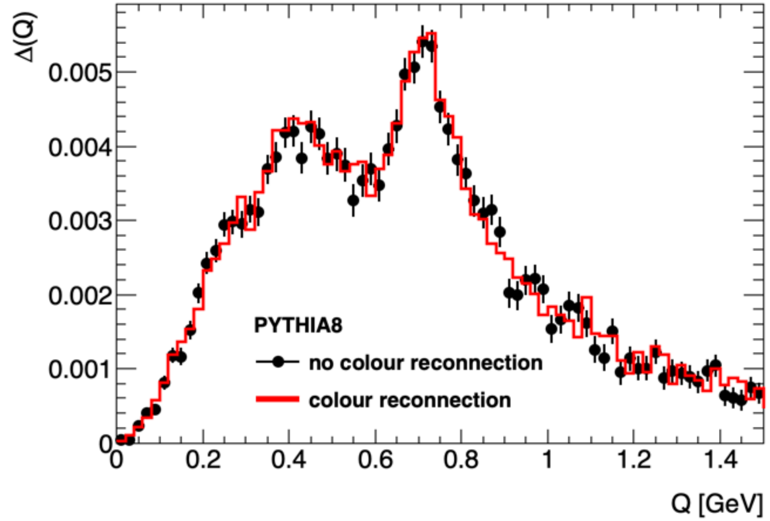


« generic « colour reconnection model

(default Pythia 8, pp 5)



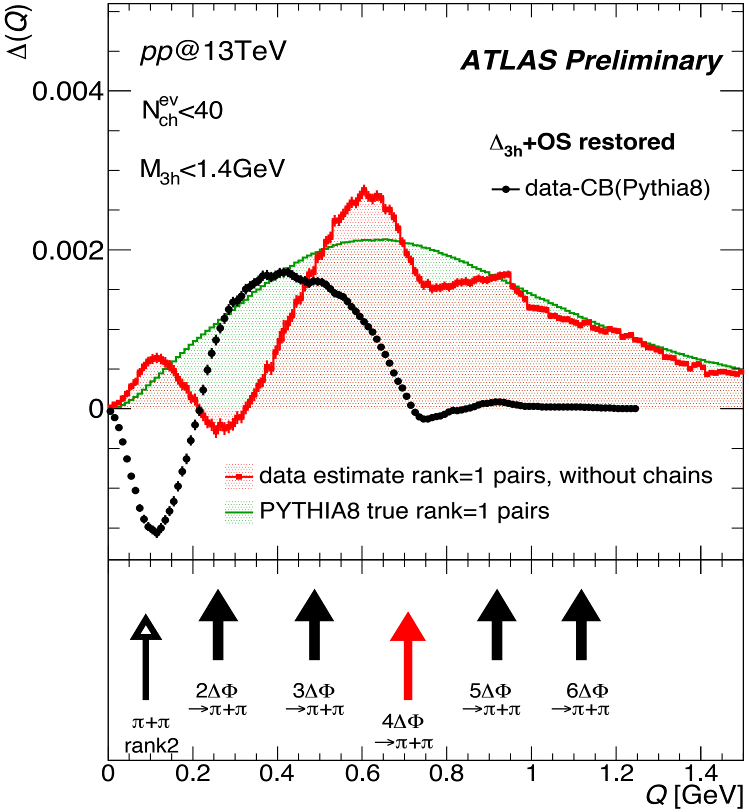
Not at all …



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

Quantized fragmentation may 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

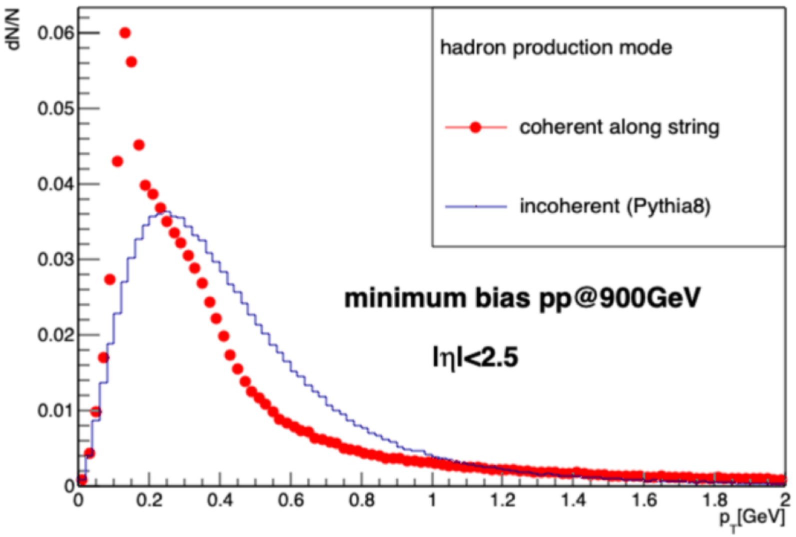
Curiously, 4 ΔΦ -> π+ π is missing …

Hypothesis : unbound state integrated with ρ(770) shape

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

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

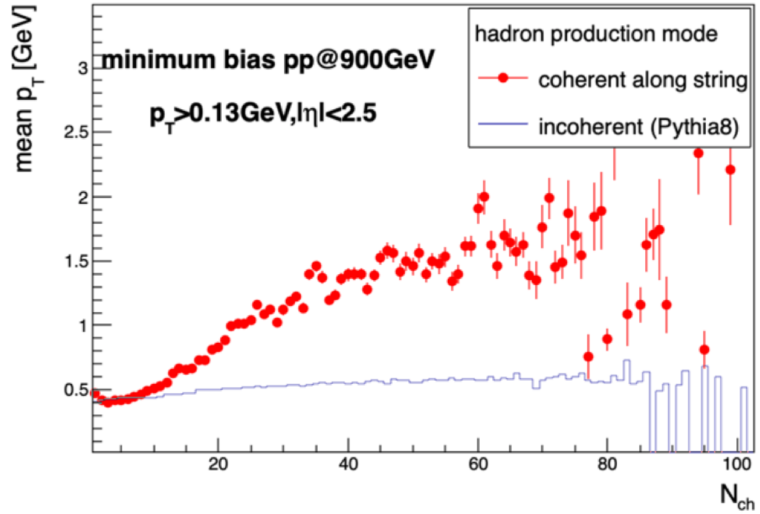


WORK IN PROGRESS

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

And finally : does quantized fragmentation impact $<p_T>(N_{ch})$?

!!!! 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:

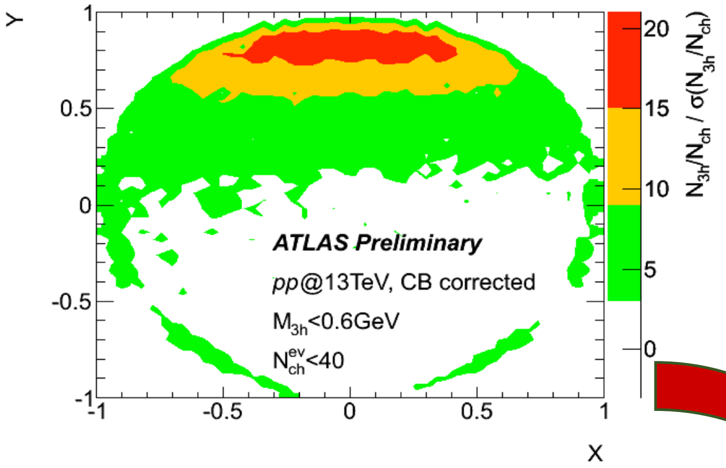
- *currently used hadronization models not precise enough, even for simple systems (single string)*
- *recent ATLAS results indicate that causal approach to the description of confining field quite efficiently resolves a number of long-standing issues in the hadronization.*
  (hadron mass spectrum / pT spectra / particle correlations / … the list is growing)
- *quantum effects essential for the understanding : seems to be related to a finite number of gluons in the QCD vacuum – the measurement of natural cutoffs in the particle production (low p_T, Q) within the reach of LHC (minbias with p_T -> 50MeV requires lowering of B field in trackers)*
- *new observables sensitive to colour flow (and local variations of fragmentation function) have been deployed by ATLAS*
- *next step requires study of fragmentation function for 3dim (helical) QCD string : alternatively, the problem can be reformulated into generation of full parton shower, down to »effective » gluon content (there are no infrared nor collinear divergencies in the nature). That's what the helical string was originally about …*

Big apology to everybody whose studies should have been quoted here and were not because of time or of my own ignorance – please complain loudly !

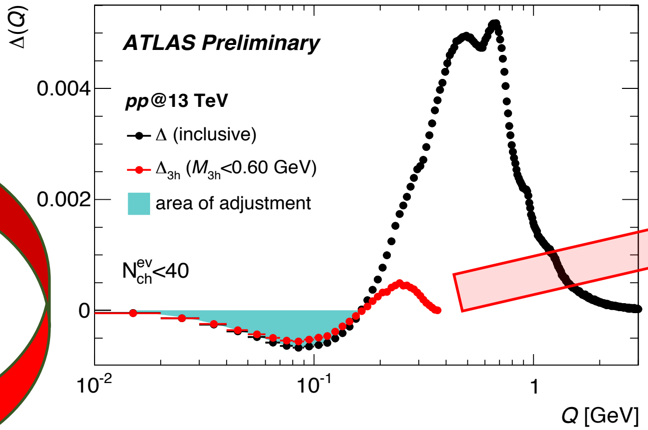
Backup slides

Quantized fragmentation and anomalous production of LS hadrons pairs

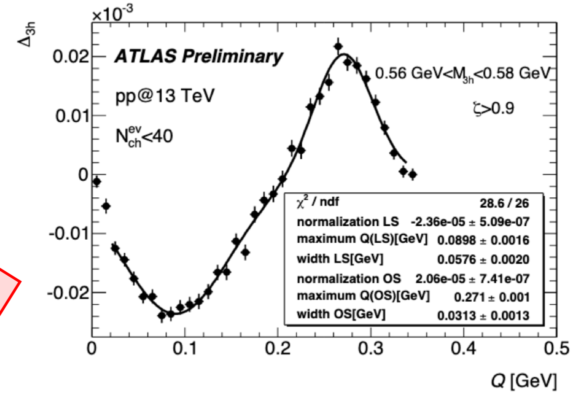
$$X = \sqrt{3}\frac{T_0 - T_2}{\Sigma T}; \; Y = \frac{3T_1}{\Sigma T} - 1;$$



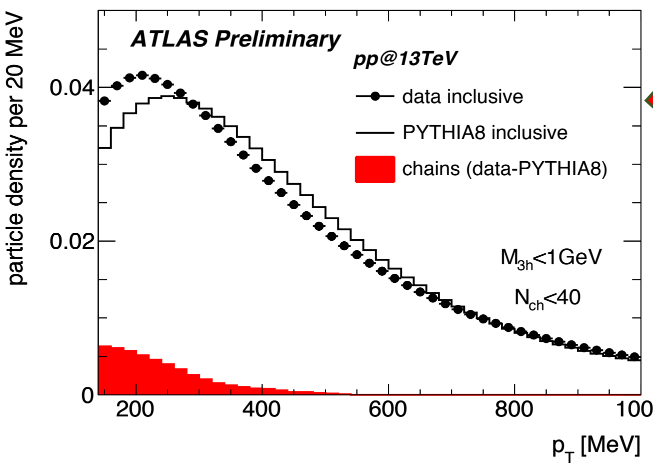
$$\Delta_{3h}(Q) = \frac{1}{N_{ch}}\Sigma_{i=1}^{N_{ch}} w_i \begin{Bmatrix} +\frac{1}{2}\,\delta(Q-Q_i^{+-\min}) \\ +\frac{1}{2}\,\delta(Q-Q_i^{+-\max}) \\ -1\,\delta(Q-Q_i^{++,--}) \end{Bmatrix}$$



Q(r=1)



Q(r=2)



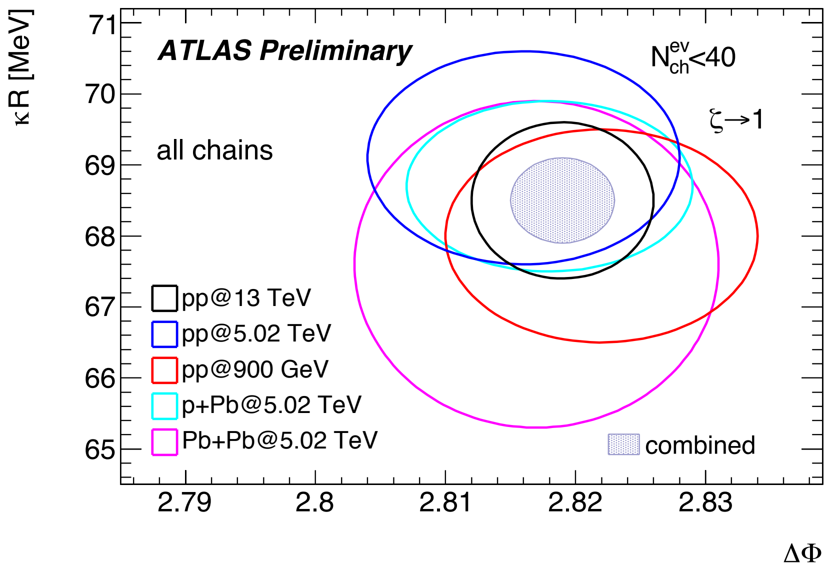
Signature of quantized fragmentation in 1-,2-,3-particle distributions

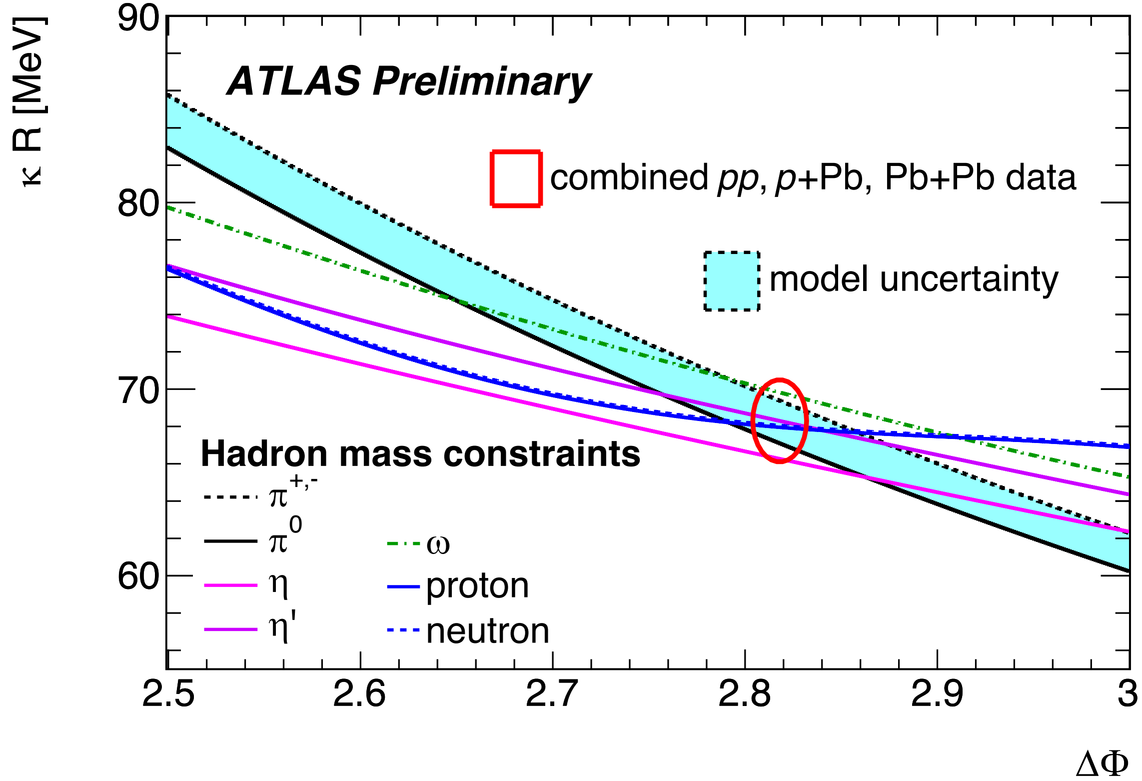
Model independent measurement

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.

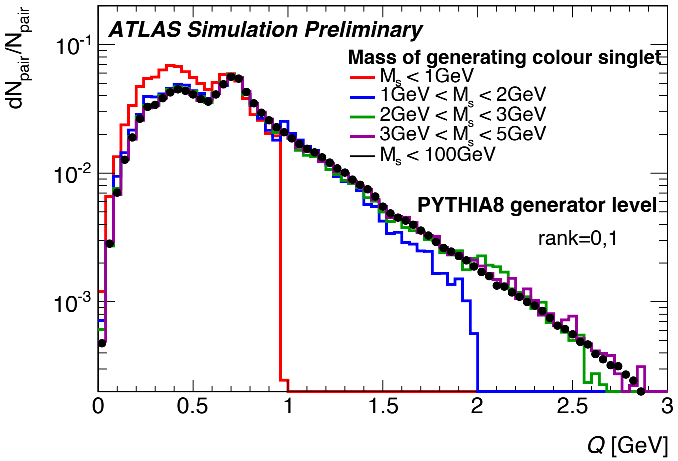
Quantized fragmentation absorbs ALL data previously associated with Bose-Einstein interference (HBT).

Anomalous production of close LS hadrons is purely hadronization effect.

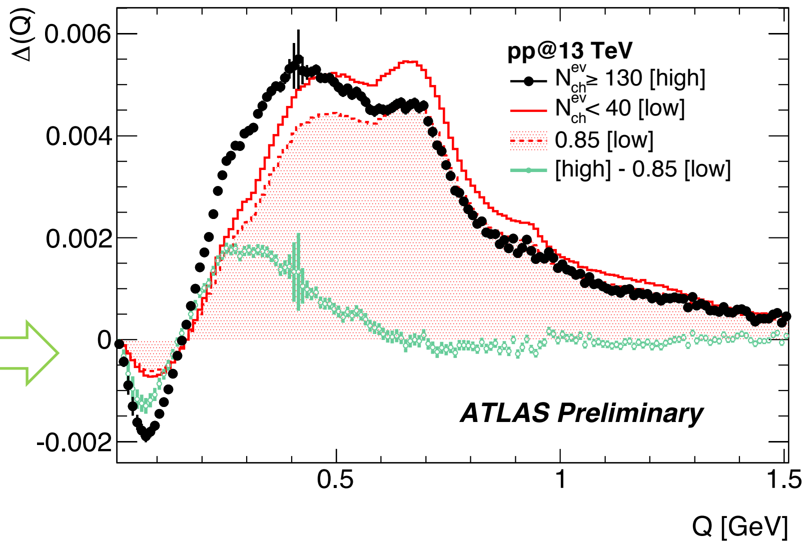
Further colour-flow sensitive measurements by ATLAS

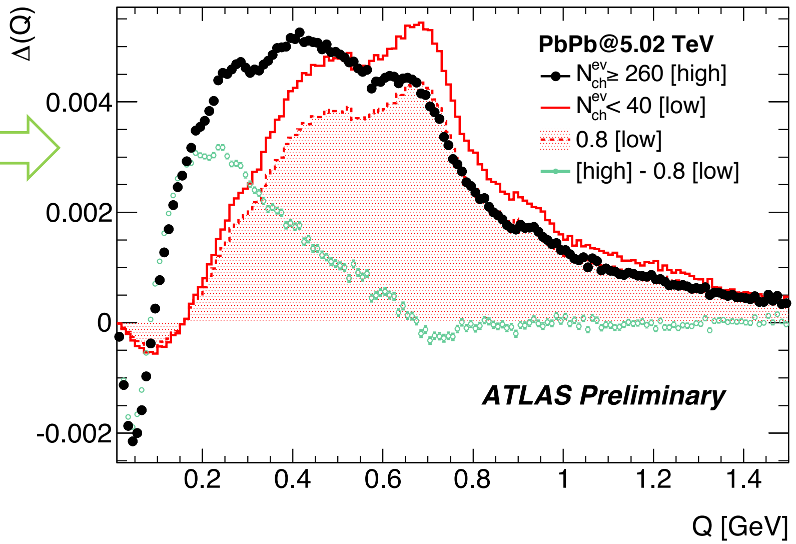
Of particular interest for diffractive studies :
study of mass spectrum of hadron sources

(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.





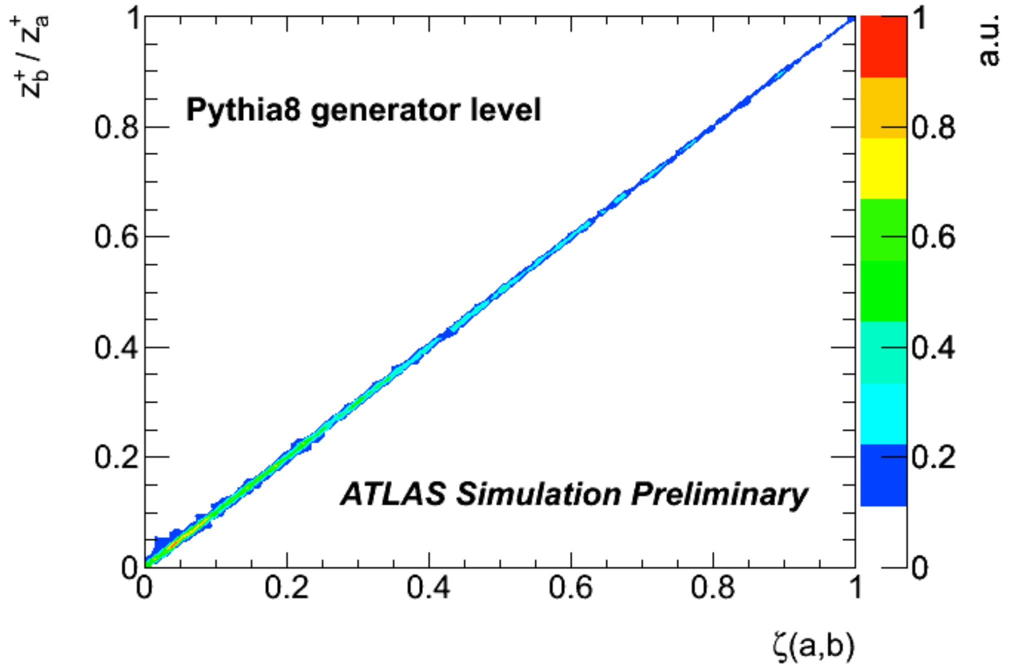
Distribution of momentum difference between colour-adjacent hadron pairs is limited by the mass of the source but otherwise pretty stable (there is no or very little difference in Δ shape below Q~1.5GeV for. sources with masses above 2 GeV)
=> evolution of shape signals variation of low mass sources

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

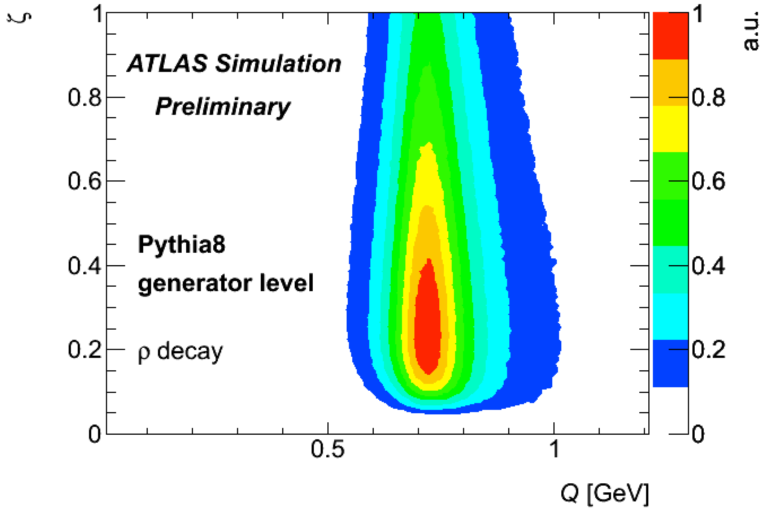
$$Q^2(p_a, p_b) \;=\; (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t,a}^2(\frac{z_b^+}{z_a^+} - 1) + m_{t,b}^2(\frac{z_a^+}{z_b^+} - 1).$$

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

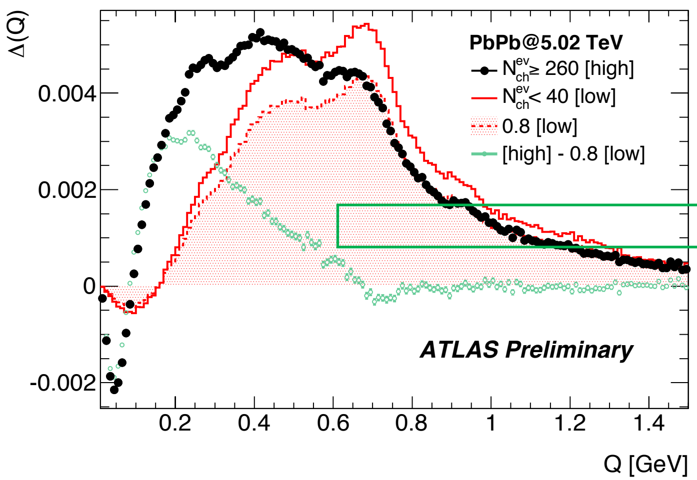
$$Q^2 \sim (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t_a}^2(\zeta(p_a, p_b) - 1) + m_{t_b}^2(1/\zeta(p_a, p_b) - 1), \;\; \text{for } |\vec{p}_a| > |\vec{p}_b|.$$

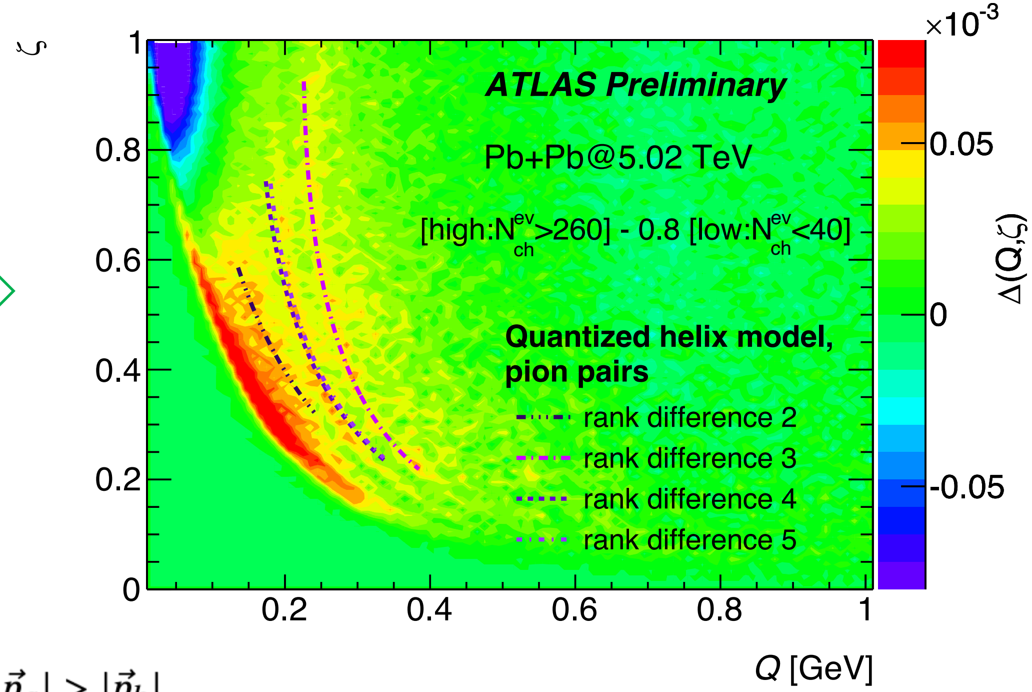


Allows to distinguish between rank 0 and rank 1 contributions



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





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

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]

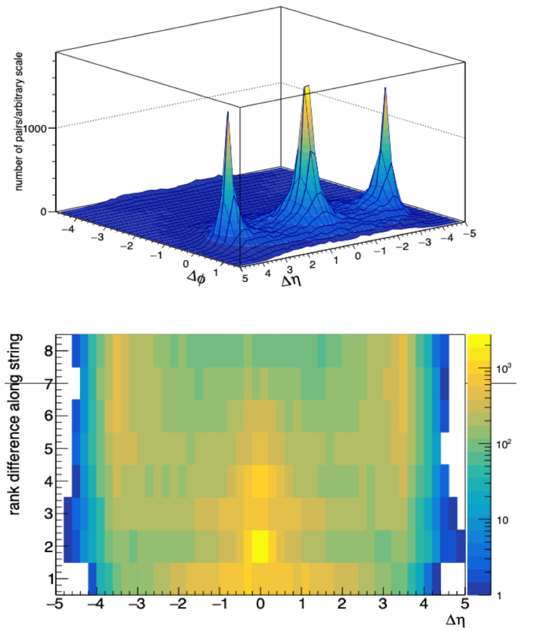
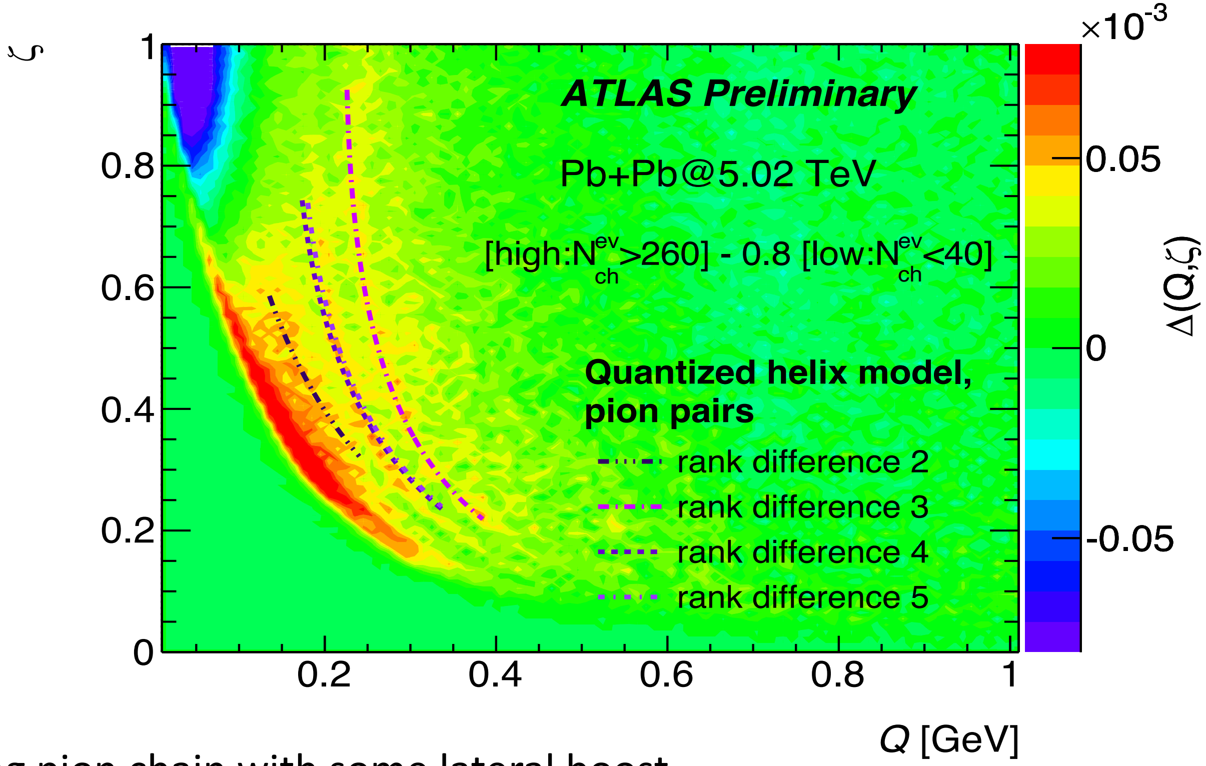


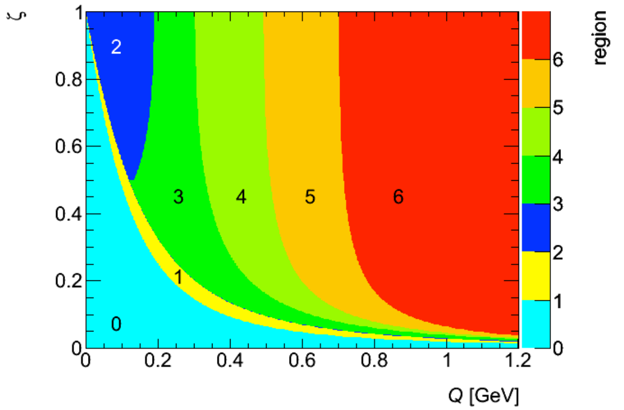
FIG. 13. Top: The emergence of a ridge-like structure in the fragmentation of a helical string with a lateral boost. The narrow helix radius (0.07 fm) implies a small intrinsic momentum (∼140 MeV) of hadrons and thus smaller smearing in the boosted direction. The recoiling system is not shown. Bottom: 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.

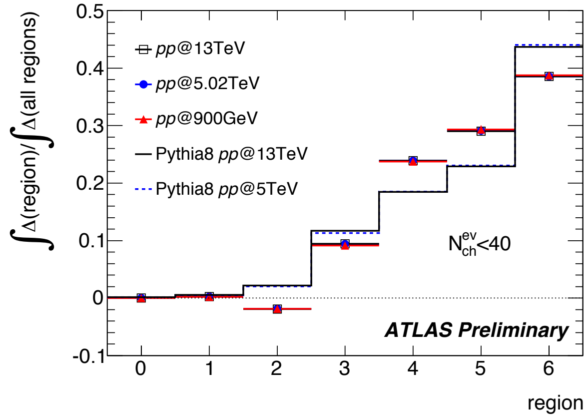


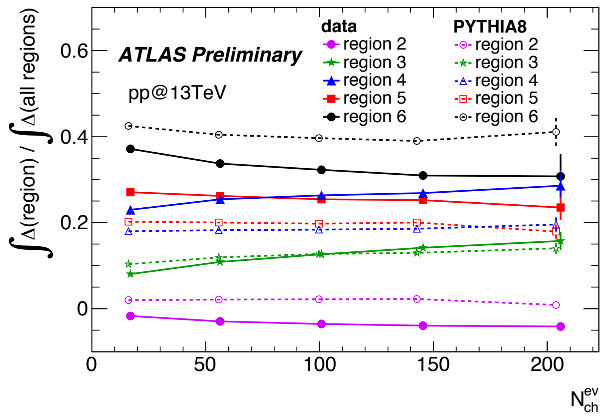
Long pion chain with some lateral boost is generating a ridge-like signal

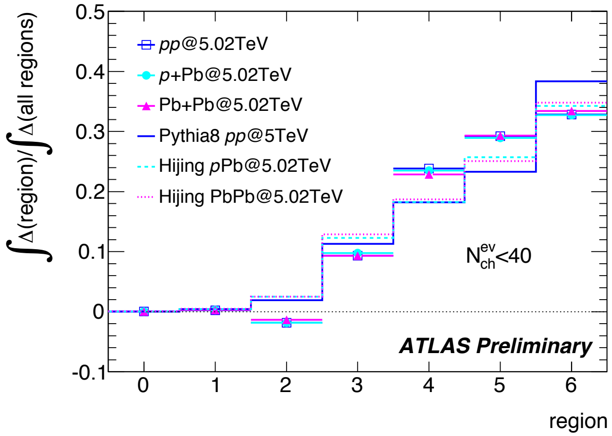
… material for future conferences ☺

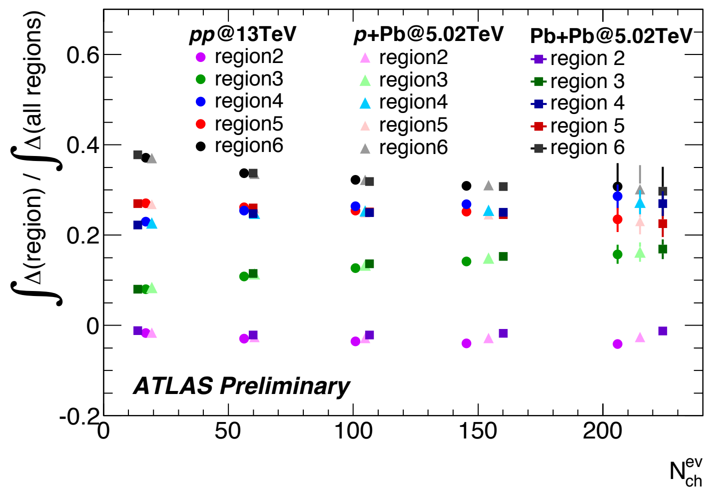
Quantification of Δ(Q,ζ)









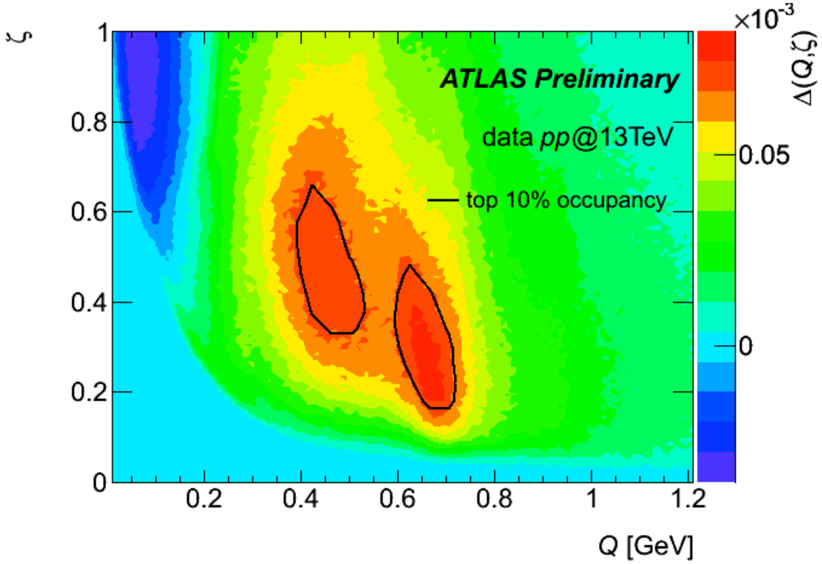


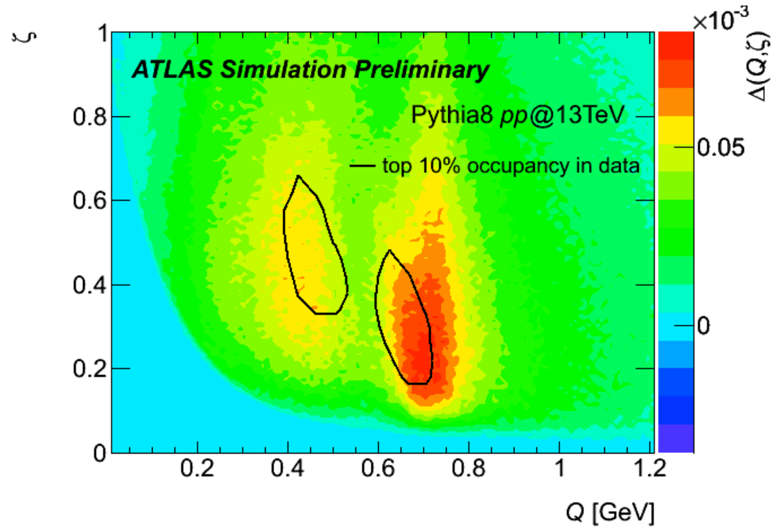
Now I am making case for quantized fragmentation to be at the origin of MC-data discrepancies in colour flow

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

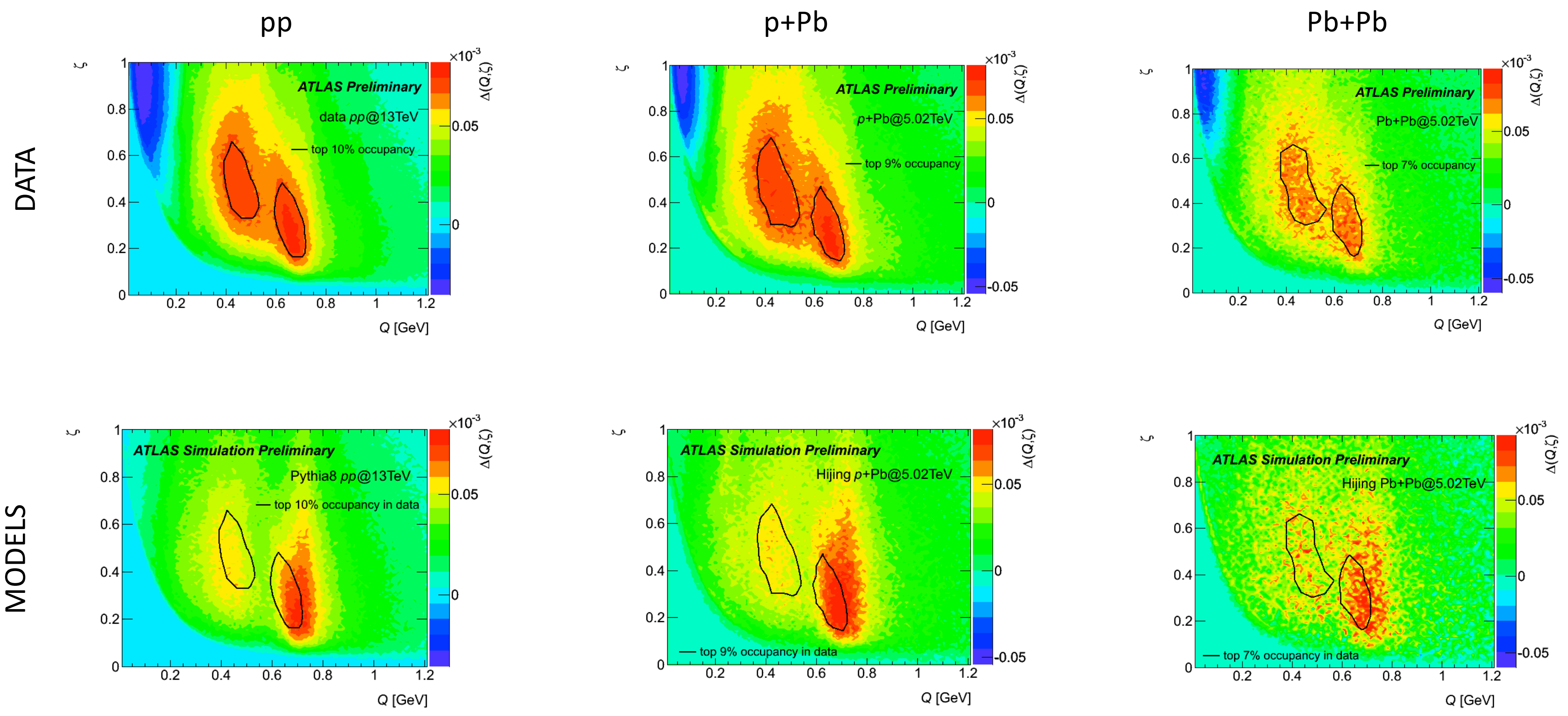




Now I am making case for quantized fragmentation to be at the origin of MC-data discrepancies in colour flow

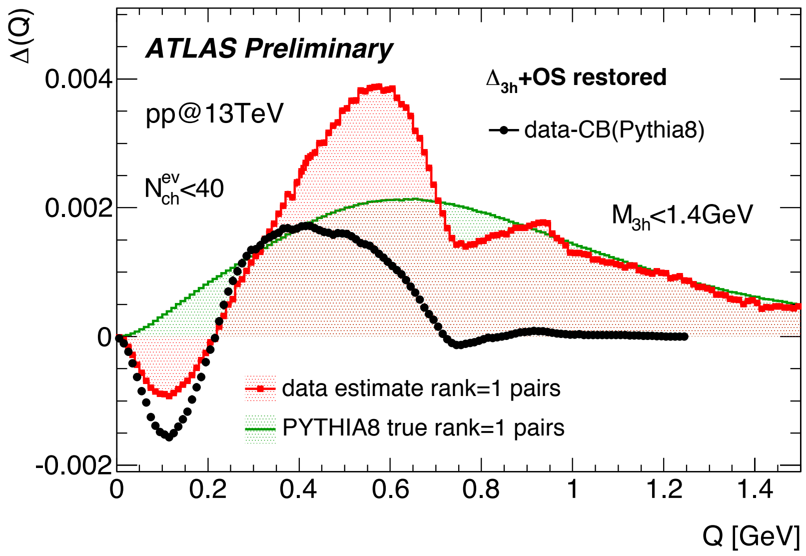
In model-independent approach, Δ is studied in (Q, ζ) plane

ATLAS-CONF-2022-055



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.