Quantized fragmentation

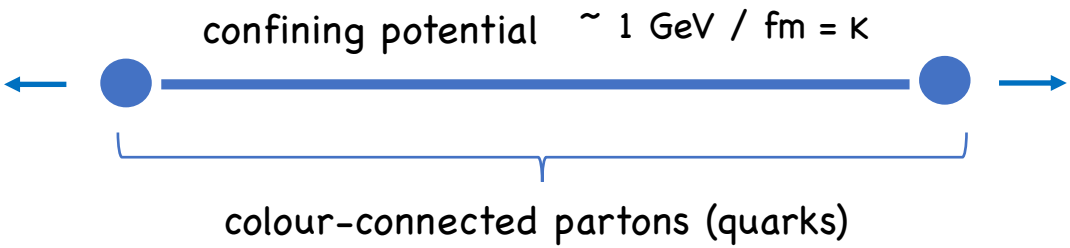
Šárka Todorova-Nová (IPNP Charles University, Prague)

Outline:

- hadron formation
- hadron mass spectra & quantum properties of the strong field
- correlations between colour-adjacent hadrons, phenomenology & measurements
- further studies

ICHEP 2024 | PRAGUE

Hadronization (terminology)

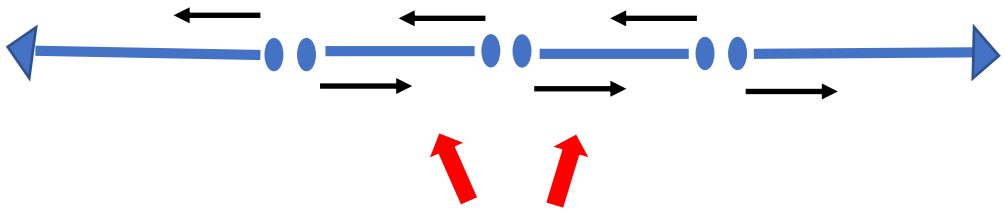


simplified picture of a chain of colour-connected gluons / QCD string

$$E_h = \kappa (x_i - x_{i+1})$$
$$p_h = \kappa c (t_i - t_{i+1})$$

$$E_h^2 - p_h^2 > 0 \quad \Leftrightarrow . \quad \Delta x^2 > (c \Delta t)^2$$

Hadron formation by gluon splitting $g \to q\bar{q}$ pair

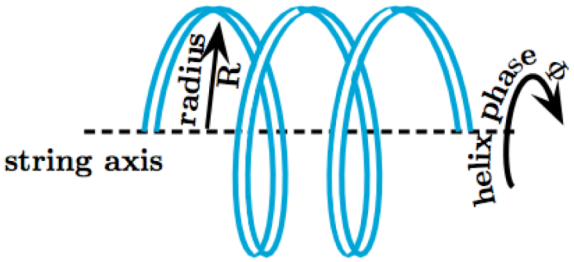


Colour-adjacent hadrons
(share break-up vertex)

PROBLEM : break-up points causally disconnected (by construction) – how the hadrons end up on the mass shell ?

1-dim QCD potential not suitable for a study of hadron formation
In practice:
hadron masses plugged in as external parameters, intrinsic p_t added by hand

Helical QCD string



Original idea of helical QCD string :
JHEP **09** (1998) 014

(causal constraint)

$$(x_1 - x_2)^2 <= c^2 (t_1 - t_2)^2$$

Hadron mass spectrum corresponds to a breaking of a helical string in regular phase intervals $\Delta\Phi$:

$$m_t = n \kappa R \Delta\Phi$$

Quantized fragmentation !

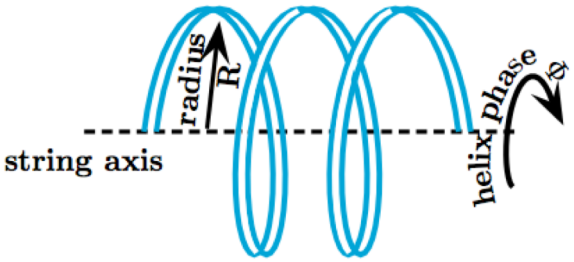
Phys.Rev.D89(2014) 015002

$\kappa\xi$ [MeV]	κ R [MeV]	$\Delta\Phi$
192.5 ± 0.5	68 ± 2	2.82 ± 0.06

meson	PDG mass [MeV]	model estimate [MeV]
π	135 - 140	137
η	548	565
η'	958	958

TABLE I. Best fit of the parameters of the pion ground state obtained from the mass spectrum of light pseudoscalar mesons. The η mass is reproduced within a 3% margin which serves as the base of uncertainty for $R, \Delta\Phi$ parameters.

Helical QCD string



Original idea of helical QCD string :
JHEP **09** (1998) 014

(causal constraint)

$$(x_1 - x_2)^2 <= c^2 (t_1 - t_2)^2$$

Hadron mass spectrum corresponds to a breaking of a helical string in regular phase intervals $\Delta\Phi$:

$$m_t = n \kappa R \Delta\Phi$$

Quantized fragmentation !

$\kappa\xi$ [MeV]	κ R [MeV]	$\Delta\Phi$
192.5 ± 0.5	68 ± 2	2.82 ± 0.06

meson	PDG mass [MeV]	model estimate [MeV]
π	135 - 140	137
η	548	565
η'	958	958

TABLE I. Best fit of the parameters of the pion ground state obtained from the mass spectrum of light pseudoscalar mesons. The η mass is reproduced within a 3% margin which serves as the base of uncertainty for $R, \Delta\Phi$ parameters.

helical string generates **mass (m)** as well as **intrinsic transverse momentum (p_t)**

$$m_t = \sqrt{m^2 + p_t^2}$$

=> both **m** & **p_t** become quantized

Phys.Rev.D89(2014) 015002

Quantized fragmentation: baryon production

- via gluon interaction across loops of helical string

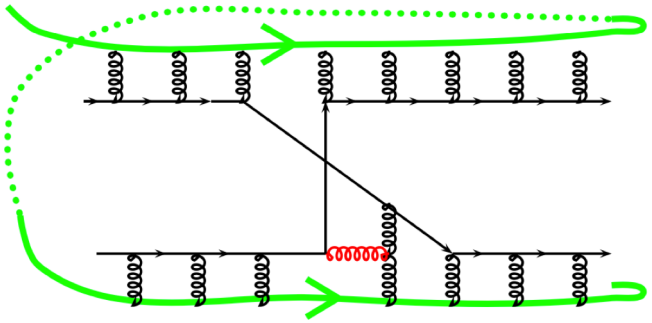
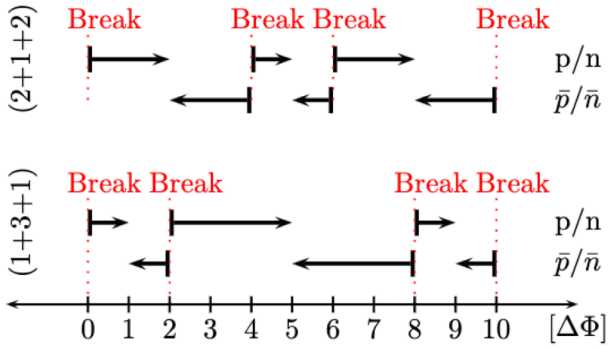
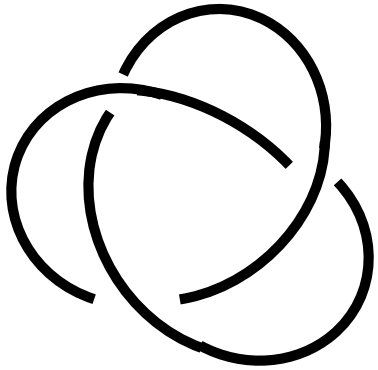


Figure 3: Schema of correlated(induced) string breakup across string loops. Green band indicates the color flow ordering of the gluon ladder. Excited gluon – which splits promptly into a $Q\bar{Q}$ pair – is marked in red.





Nucleons (proton, neutron)can be described as 2 loop states (n=5). Topological trefoils (simplest non-trivial knots)

Phys.Rev.D104(2021) 034012

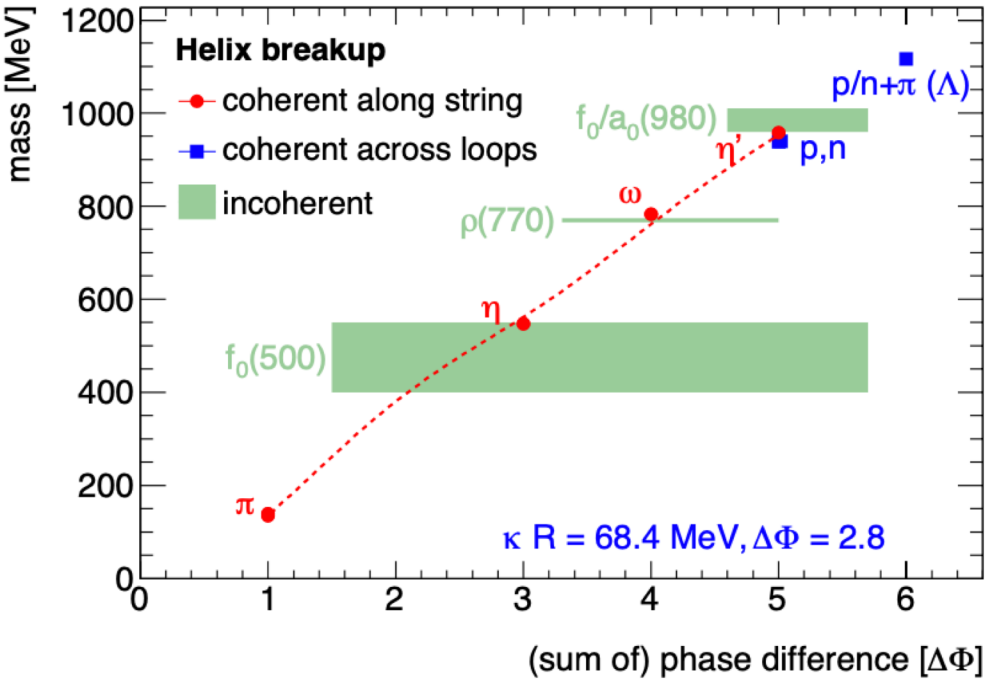
Quantized fragmentation of helical QCD string : hadron mass spectra

Various hadron production scenarii:

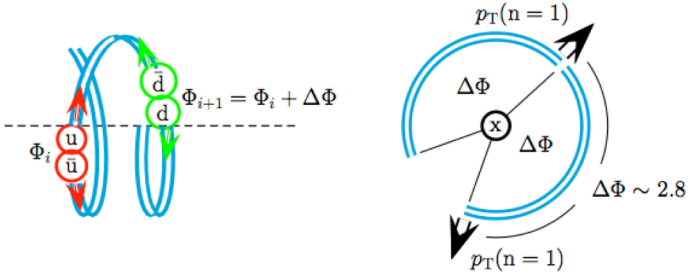
- causal constraint/information running along string
  π (n=1), η(n=3), η′(n=5), ω(n=4), ρ(n=4), …)
- wide / non-resonant f_0 states
- gluon interaction along string (baryons, …)

Nearly complete set of light hadrons described by simple helical string source with help of only 2 parameters (κR, ΔΦ)

Possibly the data can be described by a helical string with low density of gluons (perhaps as few as two gluons per ΔΦ)

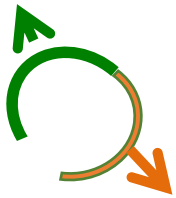


Quantized fragmentation of helical QCD string : correlation of adjacent hadrons

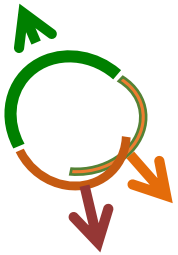


With help of κR and ΔΦ, intrinsic momenta of direct hadrons, as well as their correlations in the transverse plane, can be calculated

Predictions:

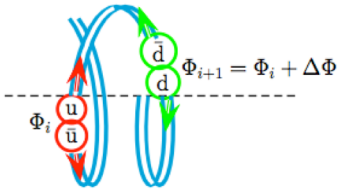


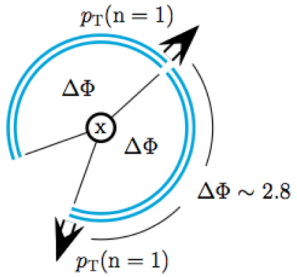
Expecting quantum threshold in production of color-adjacent (opposite-sign, OS) pion pairs



Expecting signature of close like-sign (LS) pion pairs

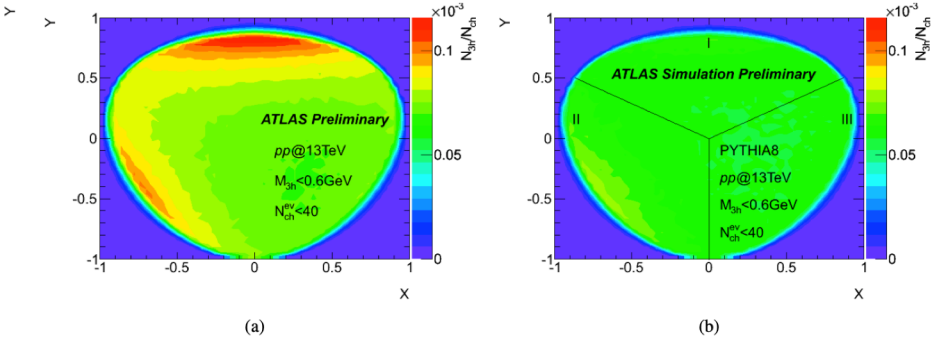
Quantized fragmentation of helical QCD string : correlation of adjacent hadrons



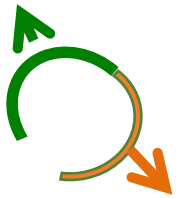


With help of κR and ΔΦ, intrinsic momenta of direct hadrons, as well as their correlations in the transverse plane, can be calculated

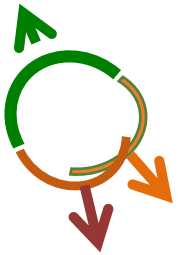
$$X = \sqrt{3}\frac{T_0 - T_2}{\Sigma T};\ Y = \frac{3T_1}{\Sigma T} - 1;$$



Predictions:

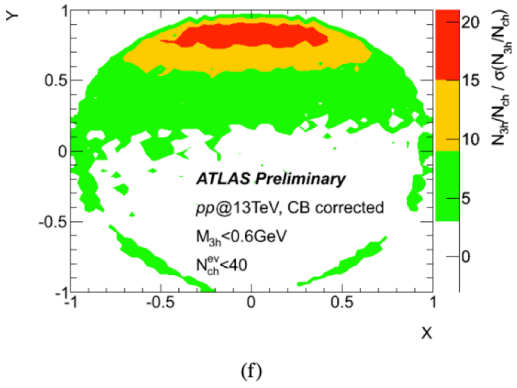


Expecting quantum threshold in production of color-adjacent (opposite-sign, OS) pion pairs

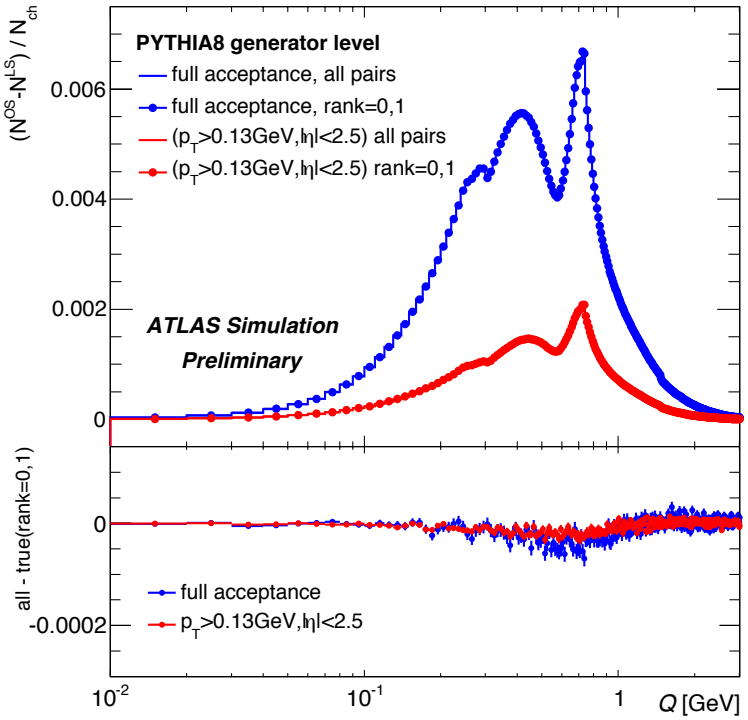


Expecting signature of close like-sign (LS) pion pairs

Confirmed by measurements – the anomalous production of close like-sign pion pairs is associated with signal in form of charge-ordered pion triplets



Observable sensitive to colour flow



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

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:

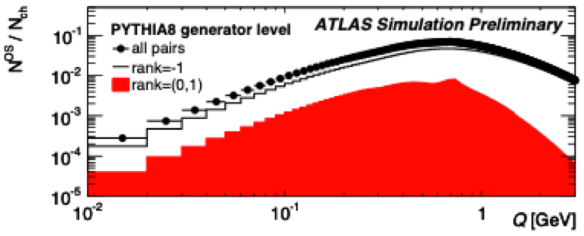
- a unique reflection of the dynamics of hadronization
- experimentally robust

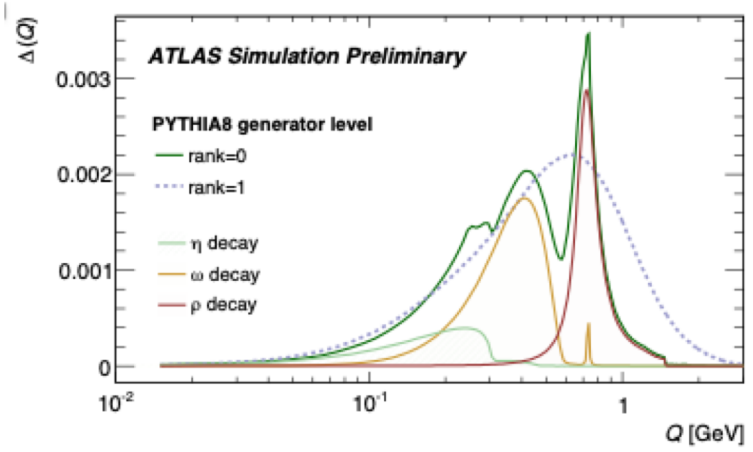
Pairs : rank = 0 decays,
rank = 1 colour-adjacent hadrons
(sharing common string breakup)
rank = -1 if hadrons coming from different sources

4-momentum difference

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

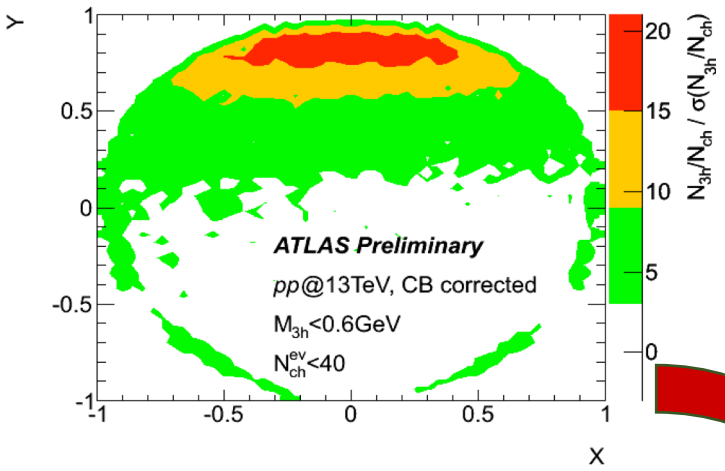
(all particles assigned pion mass)



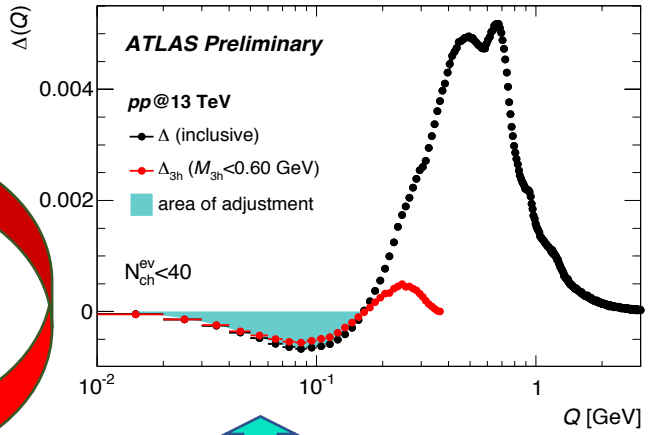


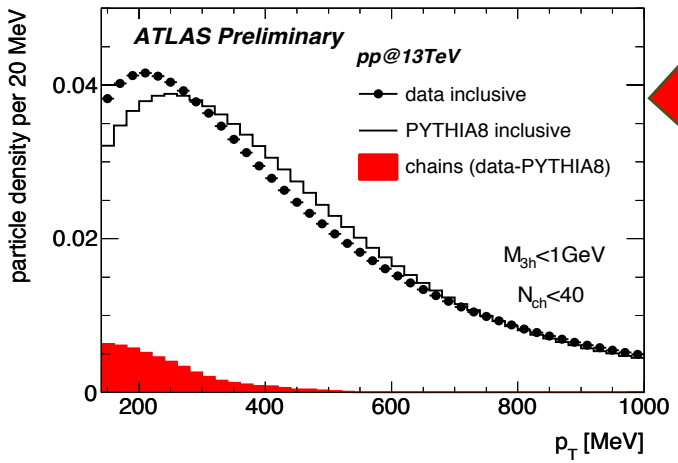
ATLAS-CONF-2022-055

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



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





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 :

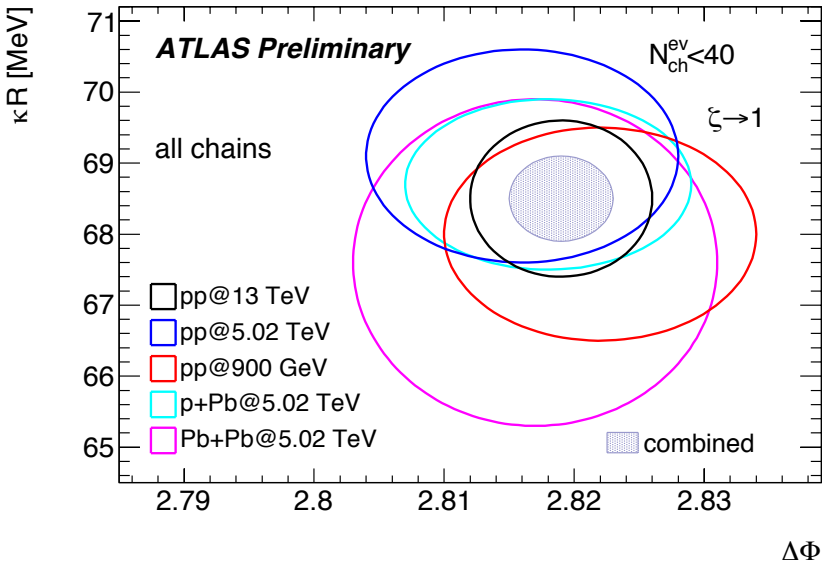
- *excess in mass-minimized charge-ordered triplet chains observed (Dalitz plot)*
- *associated with the source of anomalous production of close LS pairs (Δ vs. Δ_{3h})*
- *associated with the modification of inclusive low p_T spectra*

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

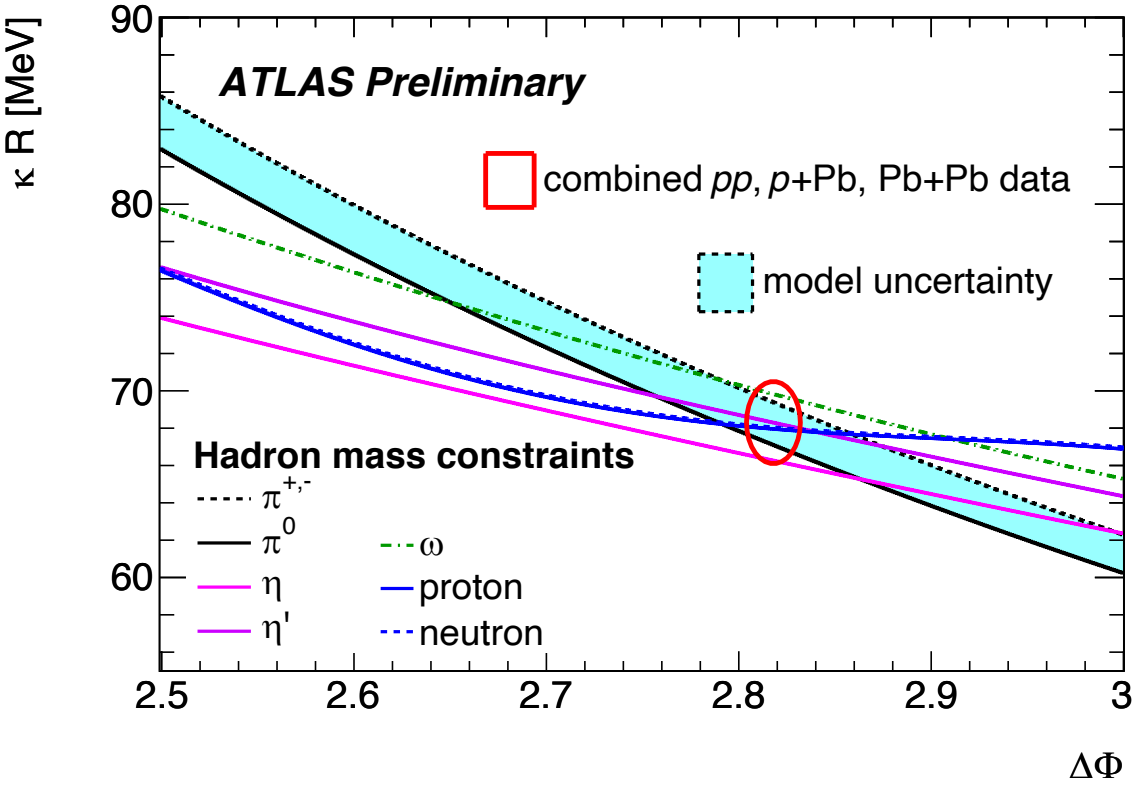
ATLAS-CONF-2022-055

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

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).

These measurements suggest anomalous production of close LS pions is a pure hadronization effect

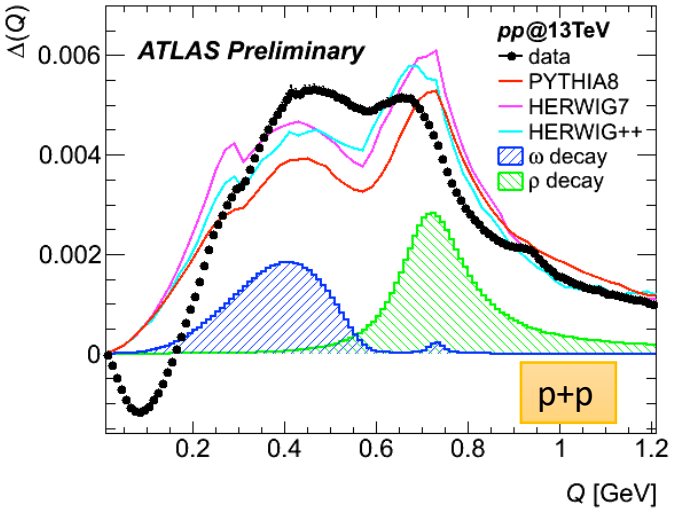
ATLAS-CONF-2022-055

What's next ?

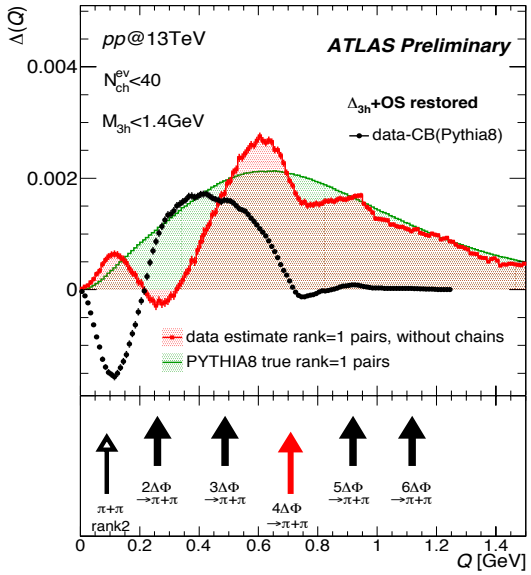
Correlations along colour flow
(= dynamics of hadronization)
described poorly by conventional models

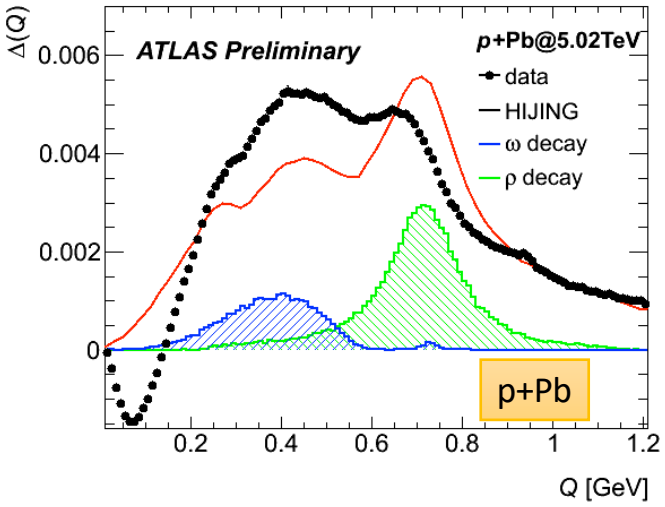
Problem : all models fail in a similar way ☹

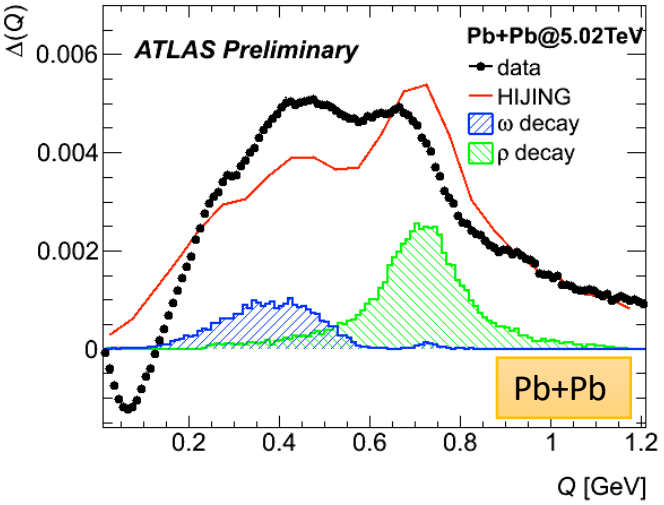
Difference between data and MC
reveals resonant spectrum of
unbound adjacent pairs



ATLAS-CONF-2022-055



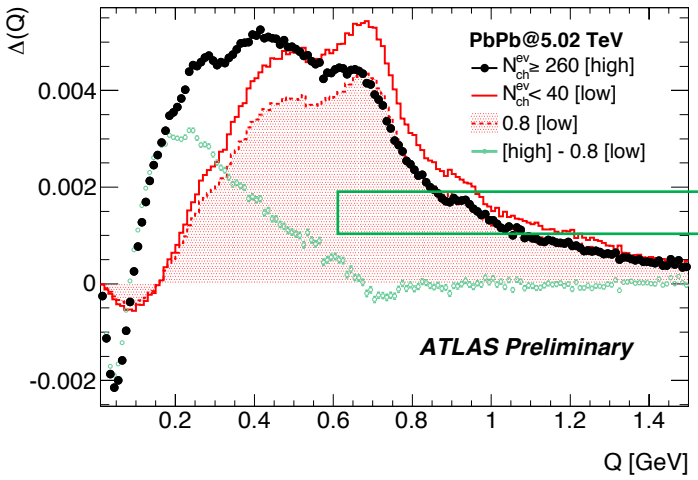


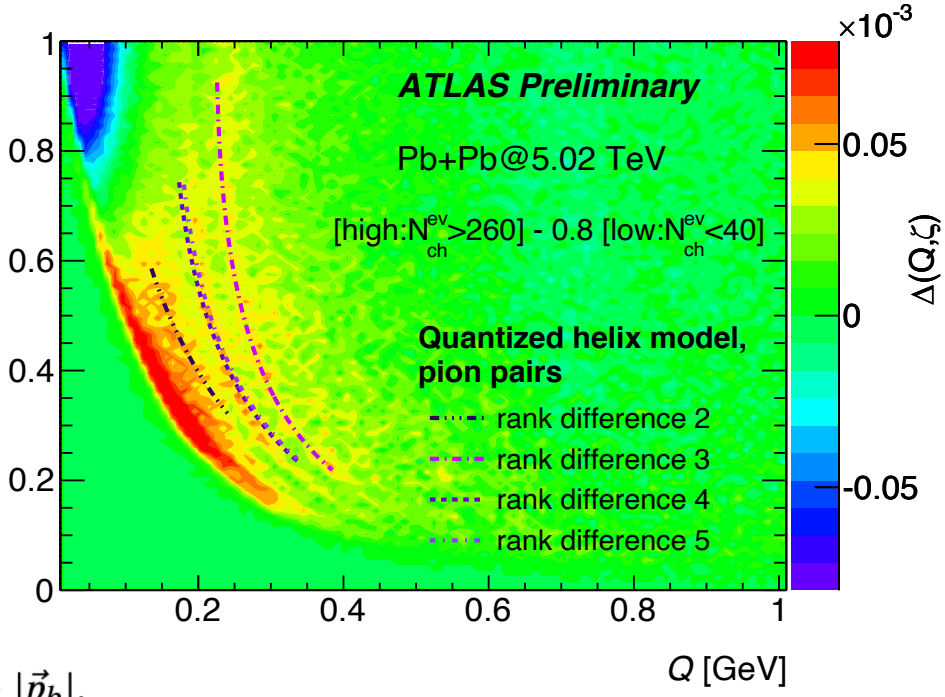


What's next ? signature of chains of direct pions found in Pb+Pb (first observation)

[ATLAS-CONF-2022-055]

thanks to complementary observable ζ disentangling longitudinal & transverse sector





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

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

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

This (hadronization) signature may carry the long range correlations ! Study of heavy ion remnant in multiplicity range beyond pp

What's next ? integrate strange hadrons in the quantization scheme

2-loop state attributed to nucleons.
What about the 1-loop state ?

$\Delta\Phi < \pi$ ... closed loop needs more than 2 quanta?
n = 3 state

Interaction across loop may create closed loop
or correlated of 3 pions

Kaon ?

It should be possible to test the hypothesis
experimentally : if kaon is a n=3 state,
m_t (K) = 3 KR $\Delta\Phi$ ~ 580 MeV
p_t (K) ~ 300 MeV ?

K* : n=5 ? p_t (K*) ~ 350 MeV ?

Φ (1020) : n=6 ? p_t (Φ) ~ 540 MeV ?

Complication : predictions for the intrinsic transverse momentum, w.r.t. string axis
not the laboratory frame p_T
... and direct hadrons only

TO DO

To summarize :

- there is a relatively simple quantization scheme describing the mass spectra of light (direct) hadrons, their intrinsic transverse momentum as well as dynamic correlations along the colour flow – not reflected by hadronization models yet

- supported by the experimental measurements and observations by ATLAS – it would be good to have inputs from other collaborations

- the importance of understanding of the colour flow not emphasized enough : a lot of effort goes into colour reconnections studies, but these do not resolve problems of colour flow [related]

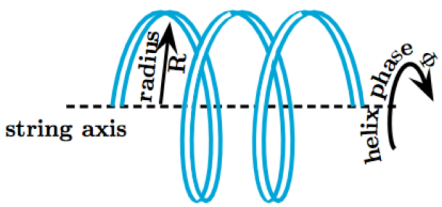
- the concept of helical QCD string was introduced in order to stabilize the end of parton cascade. That may well be the net result of the data-driven model building once the quantum thresholds are properly understood and implemented.

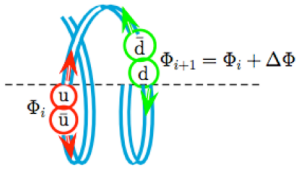
Thanks for your attention !

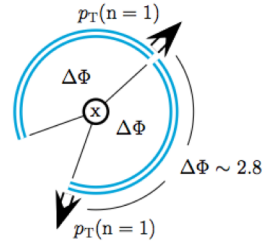
Backup slides

Quantized fragmentation

Phenomenology







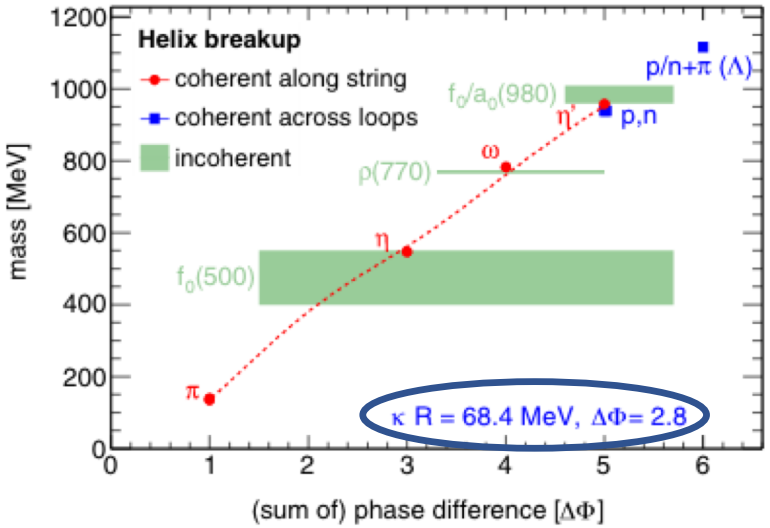
QCD confinement modeled by 3D string
Vortex translated into helical chain of gluons

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

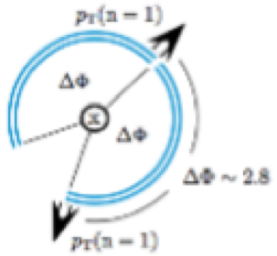
Phys. Rev. D 104, 034012 (2021)



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)*

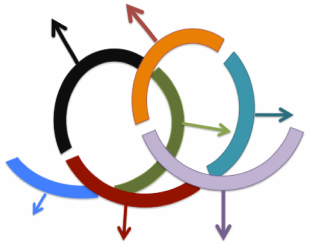
OS
opposite
sign

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

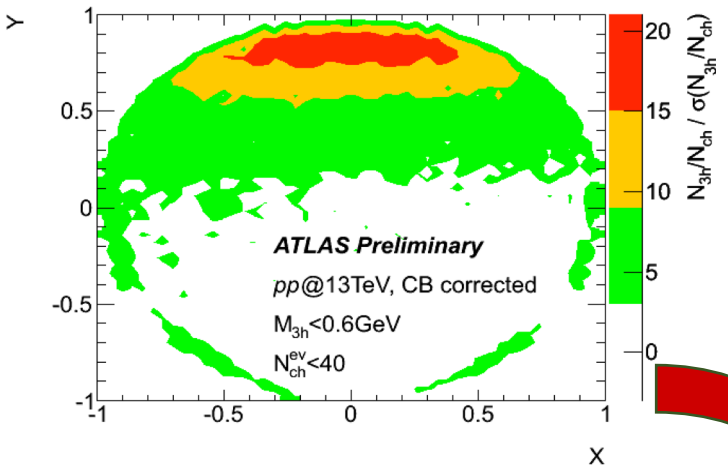
Phys.Rev.D96(2017)092008

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)

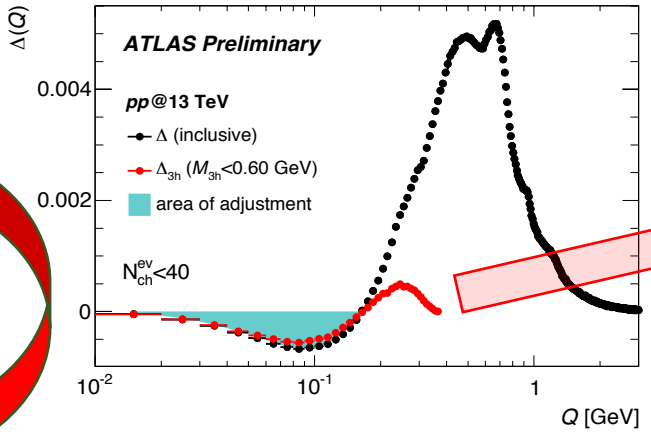


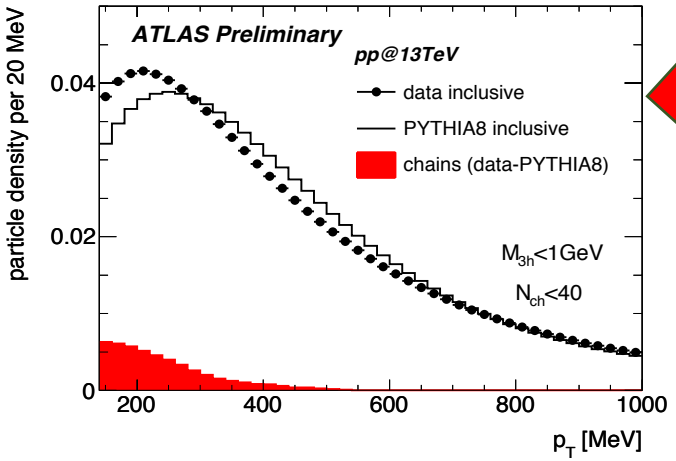
Also, a chain of n direct pions should have the minimal possible mass , locally.

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



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





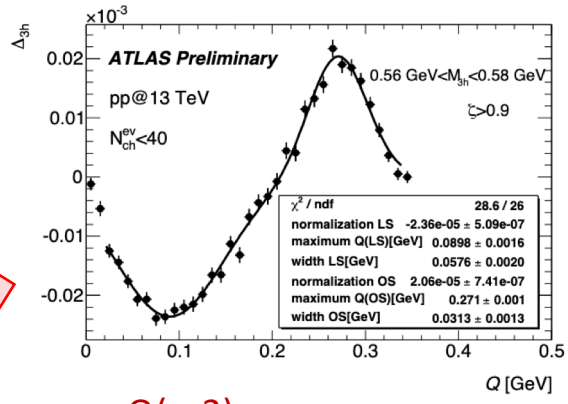
Signature of quantized fragmentation in 1-,2-,3-particle distributions

Model independent measurement

ATLAS-CONF-2022-055

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)

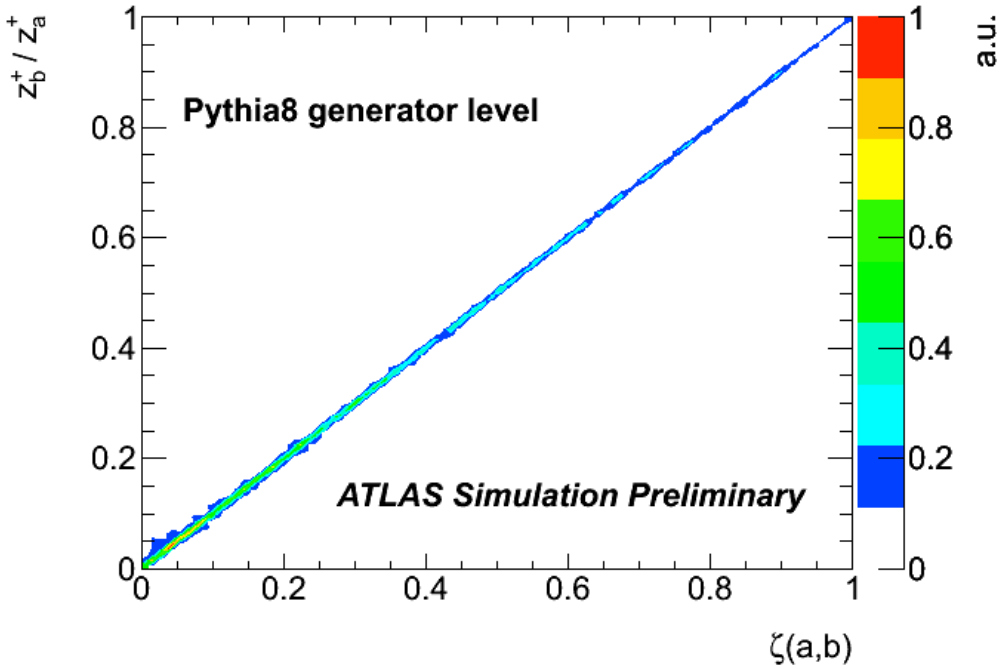
=> independent measurement of string parameters κR, ΔΦ

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)

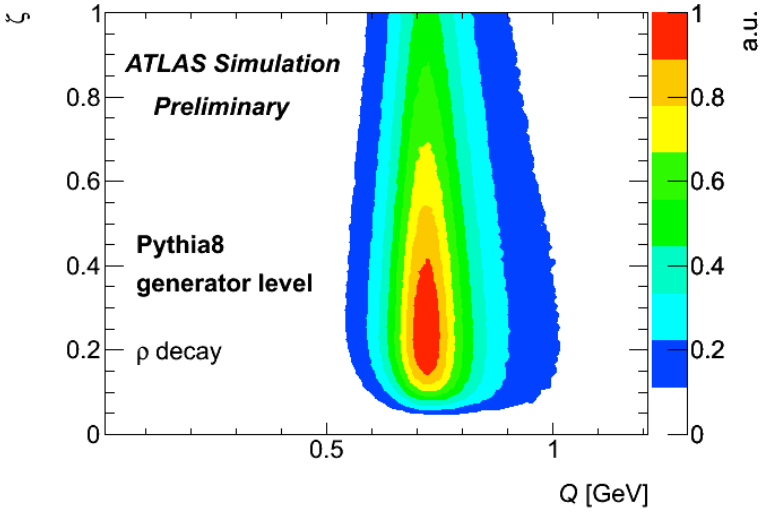
$$Q^2(p_a, p_b) = (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t,a}^2(\frac{z_b^+}{z_a^+} - 1) + m_{t,b}^2(\frac{z_a^+}{z_b^+} - 1).$$

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

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

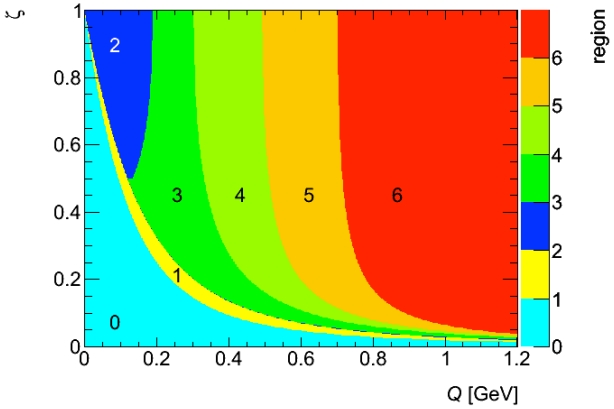


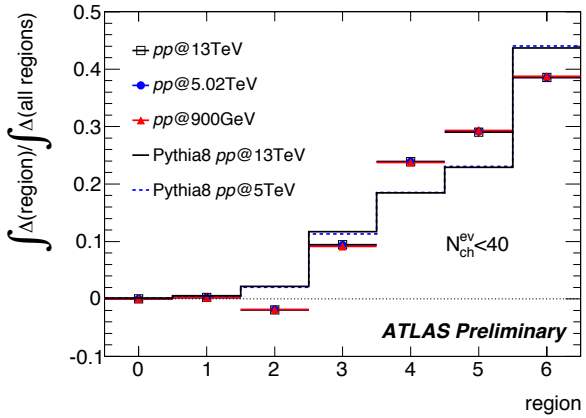
Allows to distinguish between rank 0 and rank 1 contributions

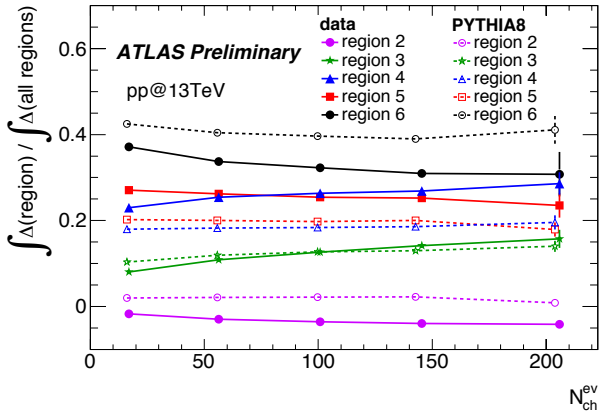


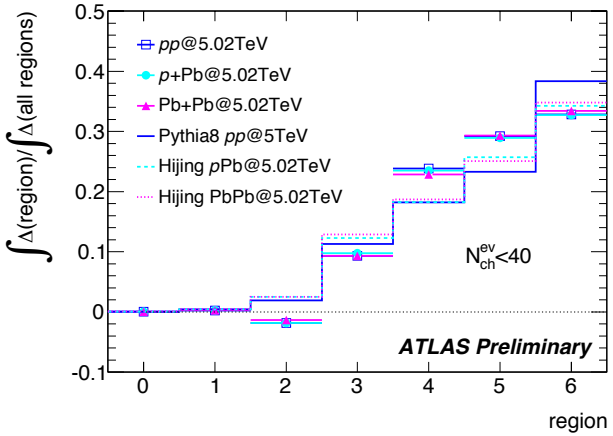
[ATLAS-CONF-2022-055]

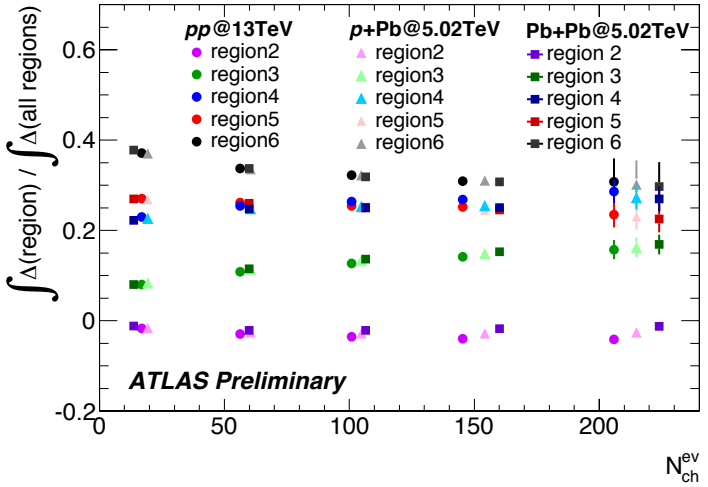
Quantification of Δ(Q,ζ)









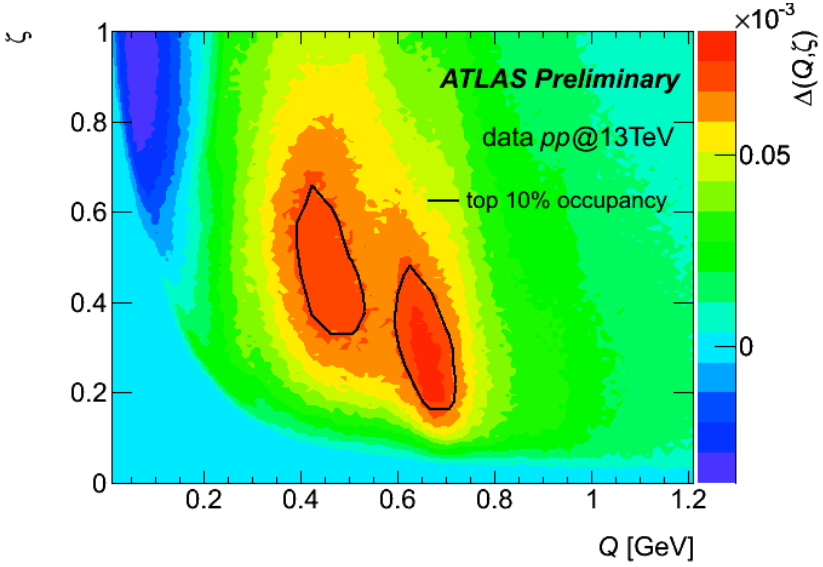


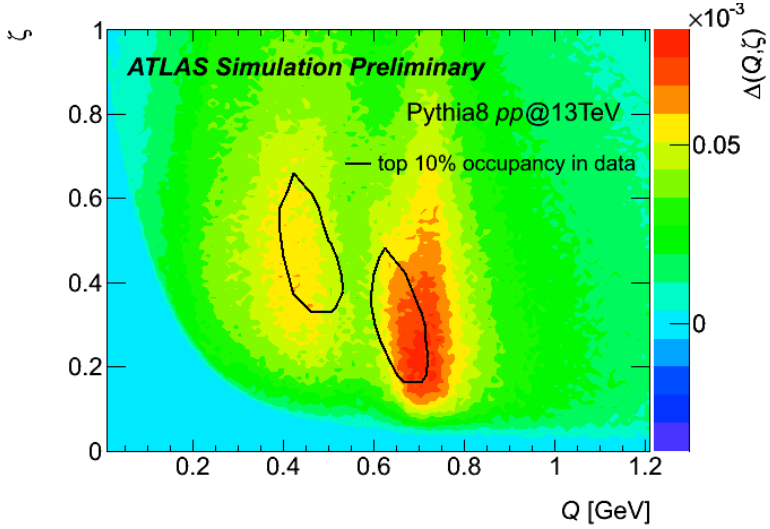
Now I am making case for quantized fragmentation to be at the origin of MC-data discrepancies in colour flow

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

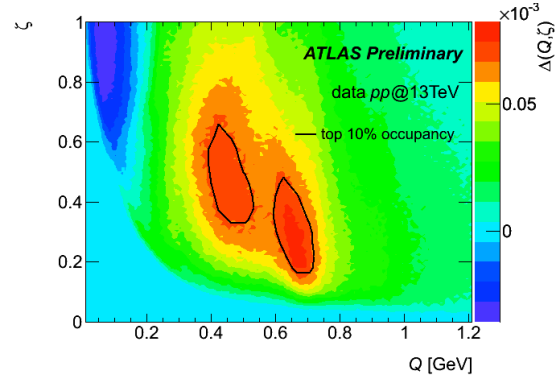
ATLAS-CONF-2022-055

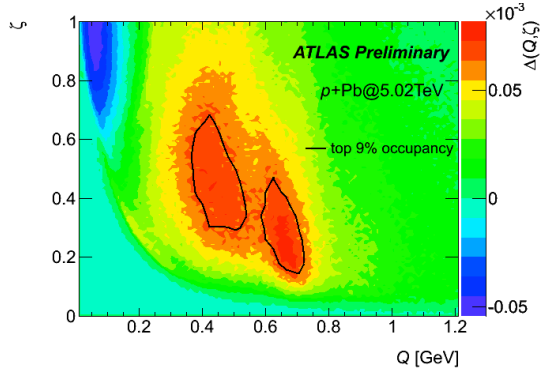
pp

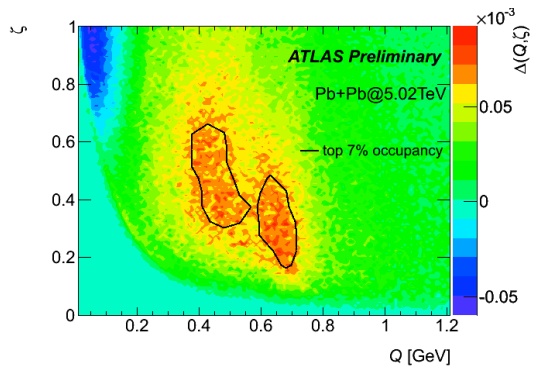
p+Pb

Pb+Pb

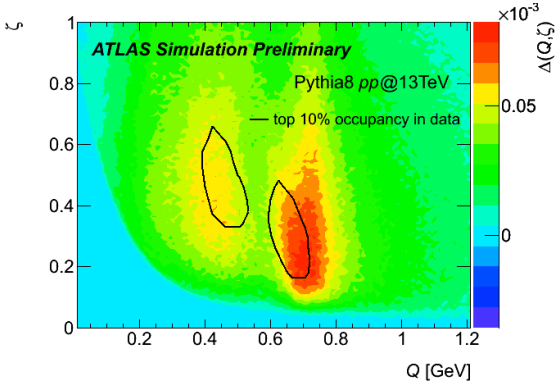
DATA

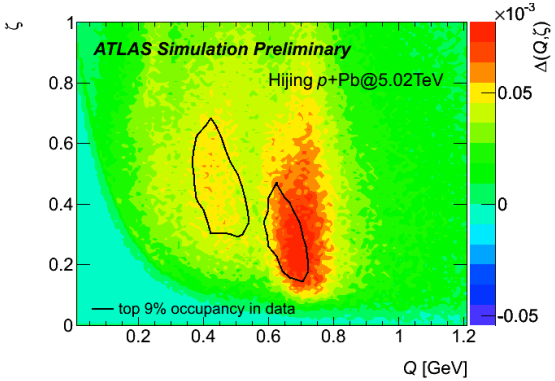


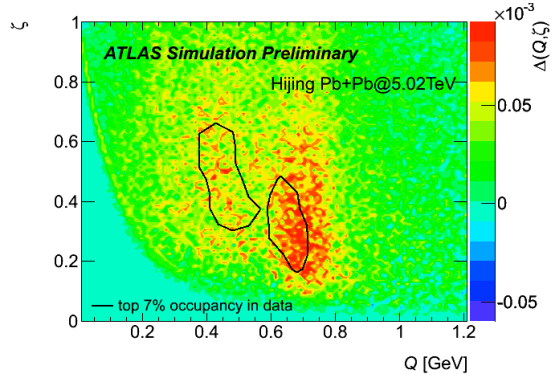




MODELS

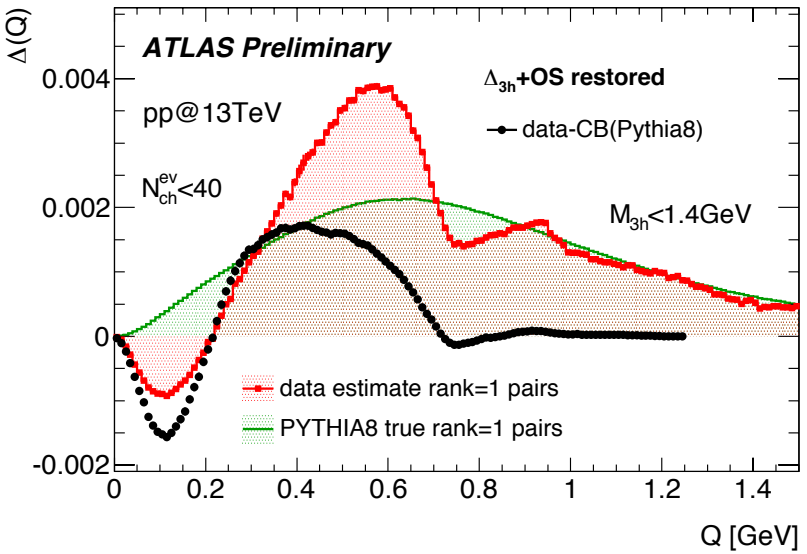






Now I am making case for quantized fragmentation to be at the origin of MC-data discrepancies in colour flow

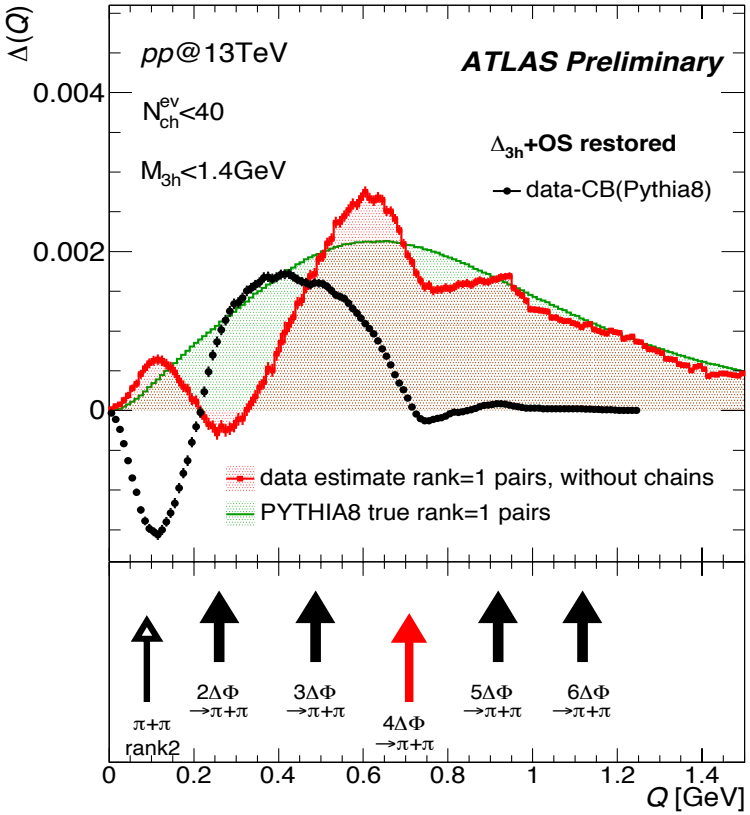
In model-dependent approach, it is assumed that Pythia describes hadron content and decays of resonances correctly , rank 1 estimate is obtained by subtraction of MC decays from measured Δ(Q)



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

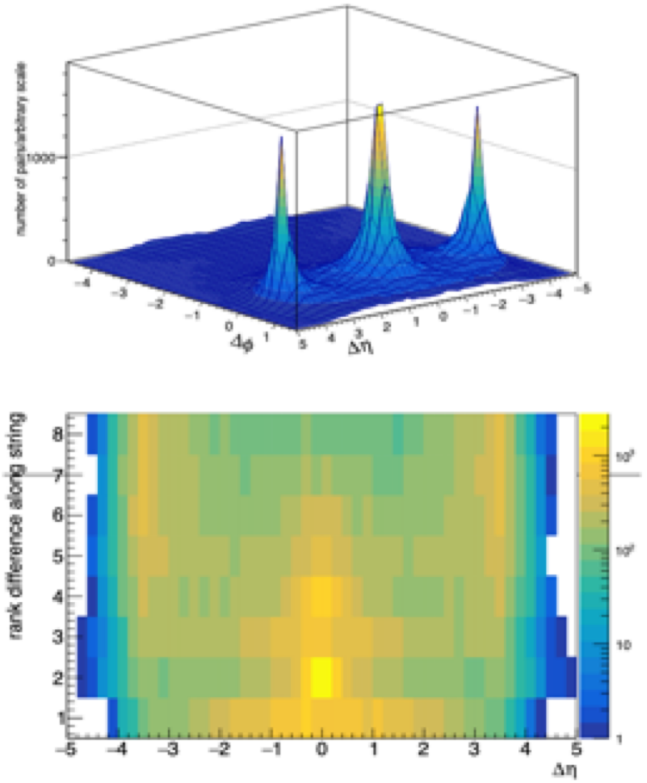
Curiously, 4 ΔΦ -> π+ π is missing …

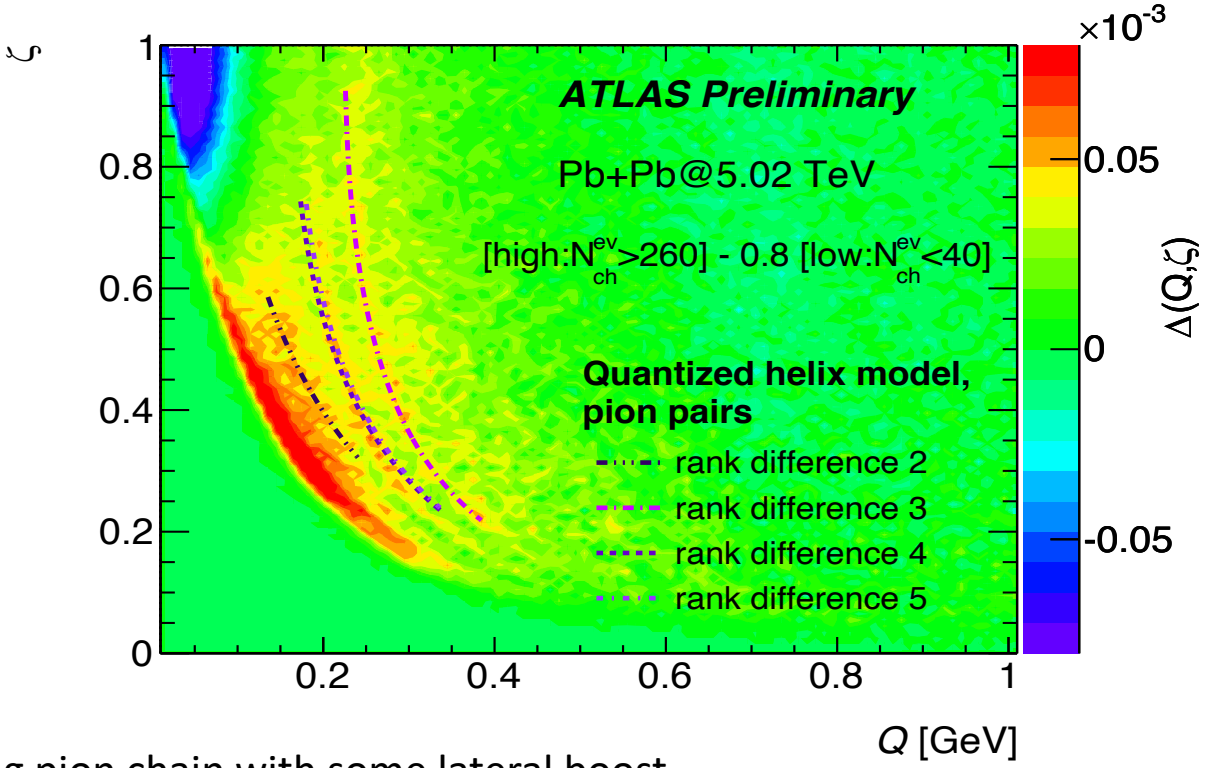
Hypothesis : unbound state integrated with ρ(770) shape

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

Long pion chains from quantized fragmentation can carry long range correlations

arXiv:1801.10232[hep-ph]





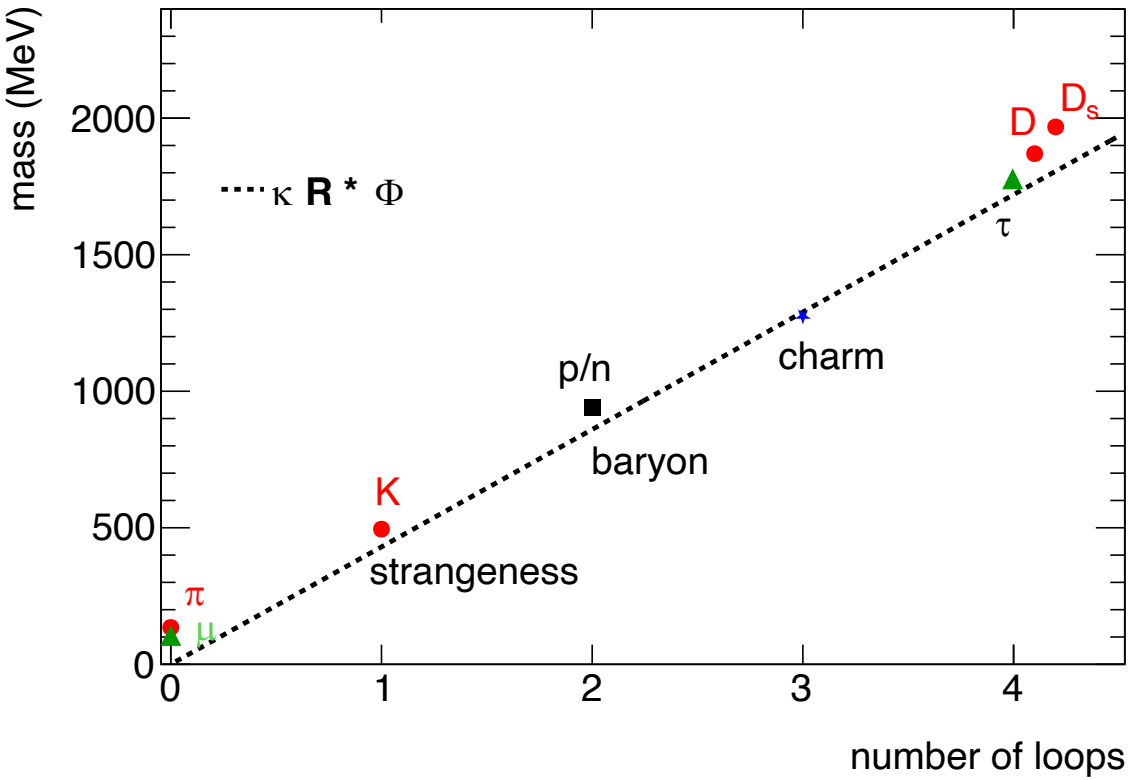
Long pion chain with some lateral boost is generating a ridge-like signal

[ATLAS-CONF-2022-055]

… material for future conferences ☺

Quantized fragmentation of helical QCD string : Beyond Standard Model

Number of string loops seems to correlate with the emergence of new quantum numbers



(bottom n=10)