Study of soft QCD phenomena and double parton interactions with ATLAS

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on behalf of the ATLAS Collaboration

Outline:

- first ATLAS measurement of double parton interaction
- strange hadrons in underlying event studies
- study of correlations between colour-adjacent hadrons
- measurement of properties of colour flux tube (in the framework of quantized fragmentation)

EUROPEAN PHYSICAL SOCIETY EPS HEP2025 MARSEILLE

07 11 JULY 2025

EPS-HEP CONFERENCE
07-11 JULY, 2025
PALAIS DU PHARO
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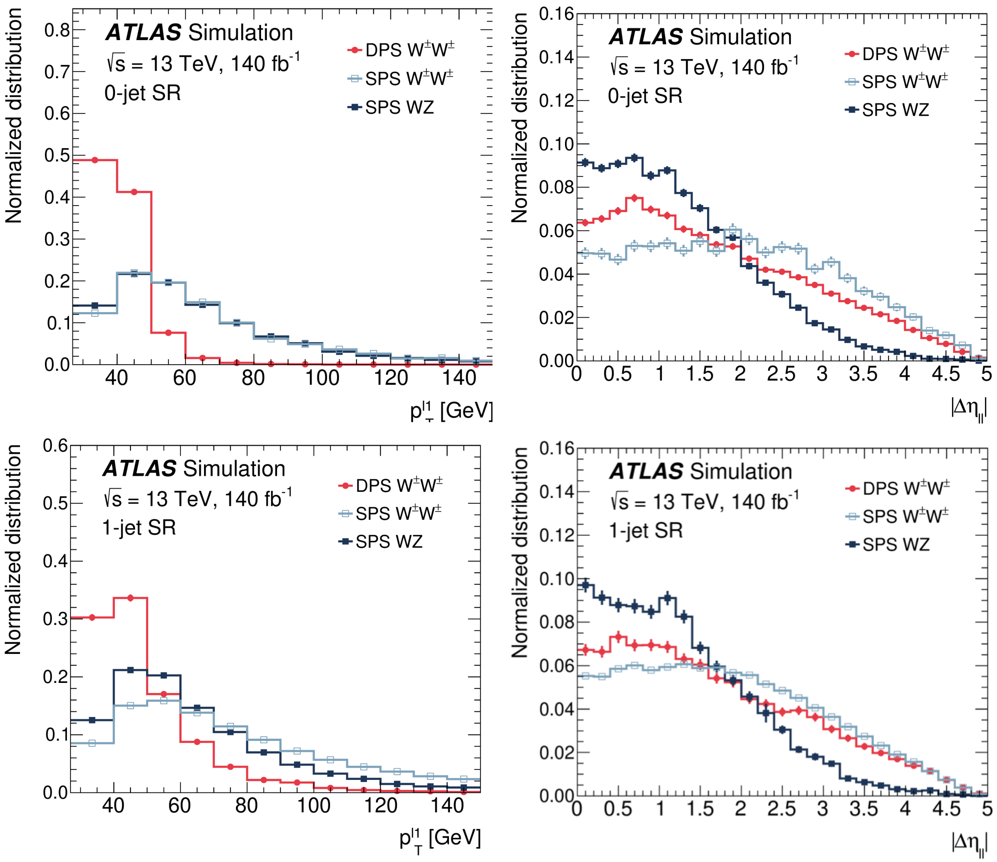
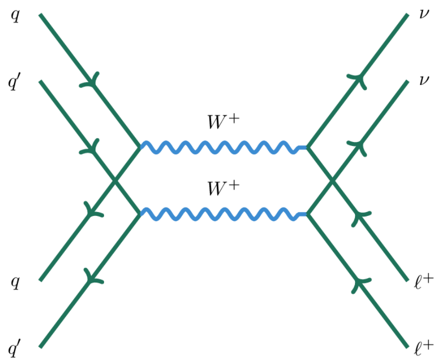
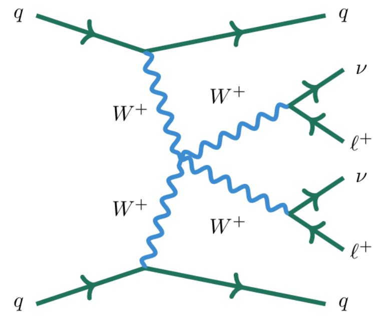
Observation of double parton scattering in same-sign W boson pair production in pp collisions at $\sqrt{s}$=13 TeV

Based on same-sign e/μ di-lepton signature





DPS



SPS

Discriminatory spectra in the signal region, for event selection containing 0 and 1 spectator jet .

WZ normalization constrained in control region with similar kinematic selection except requiring a third lepton (with opposite sign)

[arXiv:2505.08313, submitted to PLB]

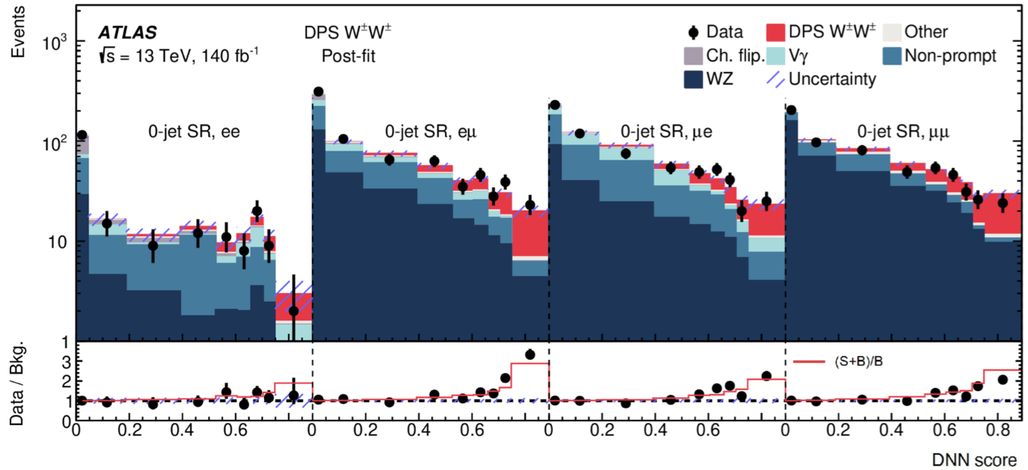
Observation of double parton scattering in same-sign W boson pair production in pp collisions at √s=13 TeV

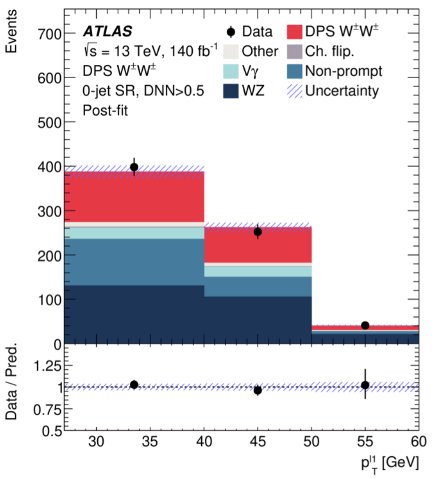
arXiv:2505.08313, submitted to PLB

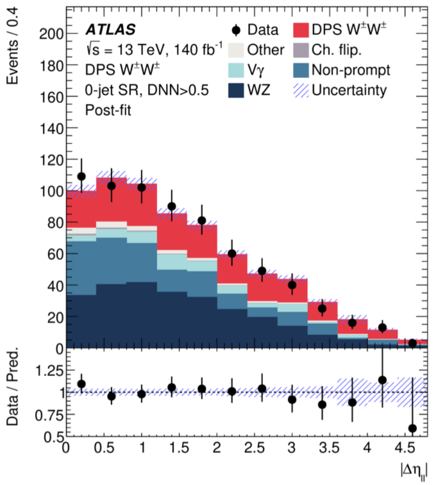
Deep neural networks trained on 8 kinematic variables using 3 hidden layers

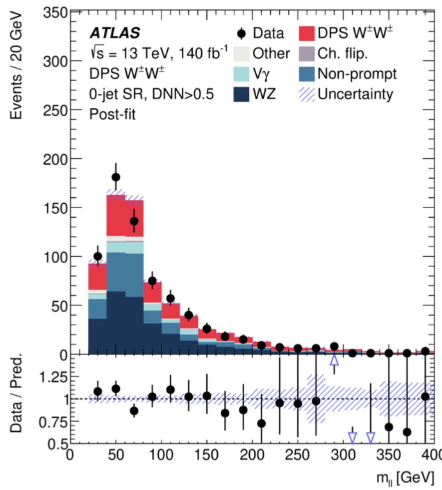
Non-prompt background estimated via data-driven fake-factor method

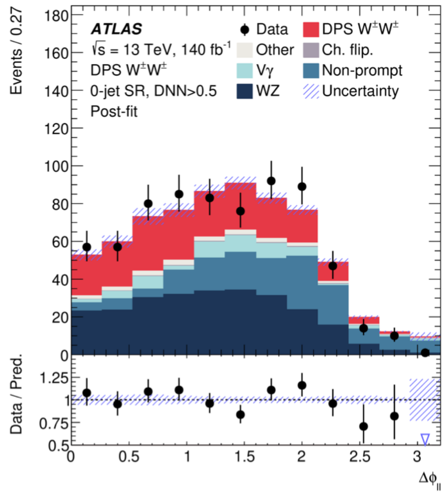
Post-fit data-MC conparison (0 spectator jet):











Observation of double parton scattering in same-sign W boson pair production in pp collisions at √s=13 TeV

arXiv:2505.08313, submitted to PLB

Measured fiducial cross-section

$$\sigma_{\text{fid}}^{\text{PYTHIA}} = 2.67\ \text{fb}$$

$$\sigma_{\text{fid}}^{\text{meas}} = \frac{N_{W^\pm W^\pm,\text{obs}}}{N_{W^\pm W^\pm,\text{PYTHIA reco}}} \cdot \sigma_{\text{fid}}^{\text{PYTHIA}} = \mu \cdot \sigma_{\text{fid}}^{\text{PYTHIA}}$$

$$= (1.72 \pm 0.24) \times 2.67\ \text{fb}$$

$$= 4.59 \pm 0.64\ \text{fb}$$

Source	Uncertainty [%]
Experimental	4.7
Electrons	0.4
Muons	0.8
Jets	3.1
$E_{\text{T}}^{\text{miss}}$	1.5
Flavor tagging	0.3
Non-prompt leptons	2.6
Charge flip	0.6
Pileup modeling	1.3
Luminosity	0.8
Modeling	1.5
DPS $W^\pm W^\pm$ scale	0.2
DPS $W^\pm W^\pm$ model	0.3
SPS $W^\pm W^\pm$ scale, PDF & α_S	0.2
WZ scale, PDF & α_S	0.8
WZ normalization	0.1
Other background normalizations	1.1
Model statistical	0.6
Experimental and modeling	5.0
Data statistical	13
Total	14

Observation of double parton scattering in same-sign W boson pair production in pp collisions at $\sqrt{s}$=13 TeV

$$\sigma_{eff} = \frac{1}{2} \times \frac{\boxed{\sigma_{W^+}\sigma_{W^+}} + \boxed{\sigma_{W^-}\sigma_{W^-}}}{\mu \cdot \boxed{\sigma^{DPS}_{W^\pm W^\pm}}} \times 4$$

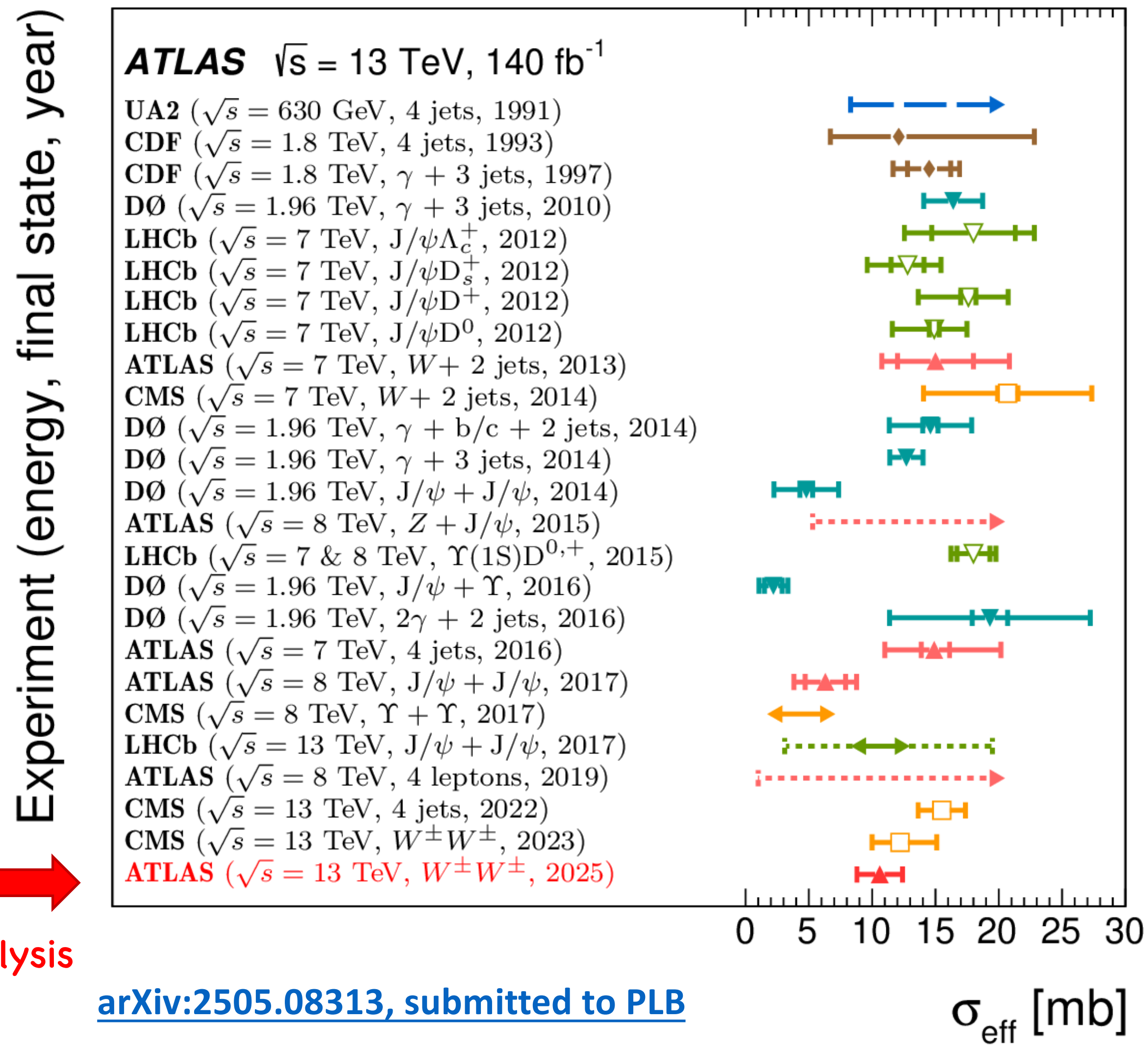
Estimated from the common fiducial region: 1 lep vs 2 lep

4 lepton channels: ee,em,me,mm

$$\boxed{\textbf{ATLAS}\ \sigma_{eff} = 10.8 \pm 1.8\ \text{mb}}$$

$$\textbf{CMS}\ \sigma_{eff} = 12.2^{+2.9}_{-2.2}\ \text{mb}$$

[Phys.Rev.Lett.131(2023)091803]



this analysis

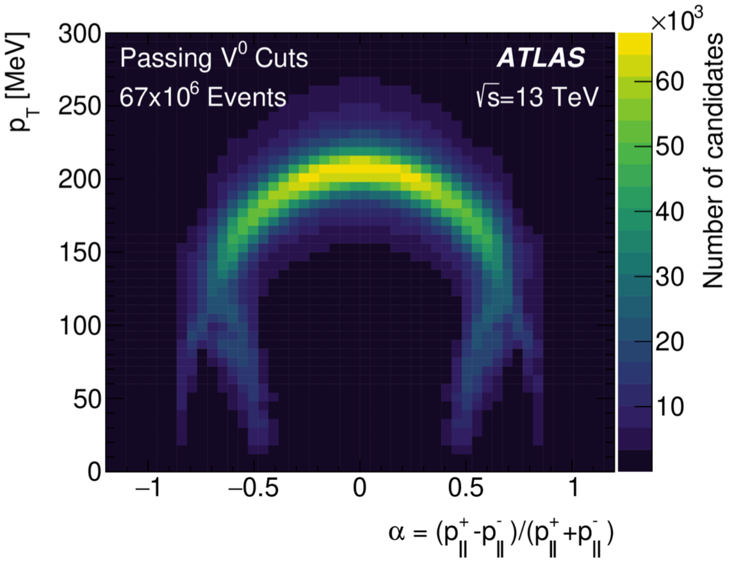
[arXiv:2505.08313, submitted to PLB](https://arxiv.org/abs/2505.08313)

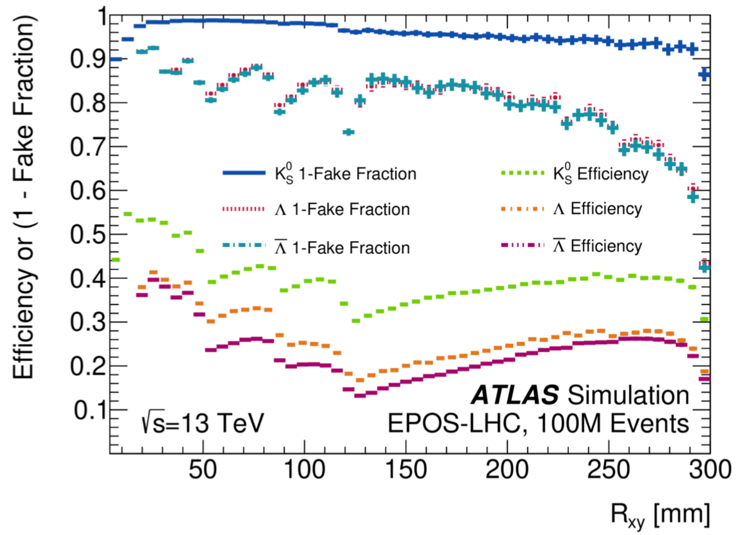
Underlying event studies with strange hadrons in pp collisions at $\sqrt{s}$=13 TeV

Eur. Phys. J. C84(2024)1335, arXiv:2405.05048

- analysis of minimum bias data (low pile-up)
- additional tracking iteration to reconstruct tracks originating at higher radii
- non-identified tracks (p_T > 500 MeV) used to reconstruct secondary vertices consistent with the K_S^0, Λ decay

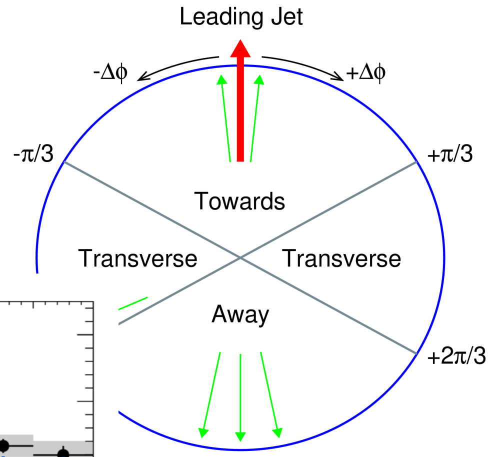
	K_S^0	$\Lambda, \bar{\Lambda}$
$\|\eta\|$	< 1.0	< 1.0
p_T	> 400 MeV	> 750 MeV
$\cos\theta$	> 0.9990	> 0.9998
R_{xy}	4 mm $< R_{xy} \leq$ 300 mm	15 mm $< R_{xy} \leq$ 300 mm
$M_{V^0}^{err}$	< 15 MeV	< 5 MeV
M_{V^0}	$\|M_{V^0} - M_{K_S^0}\| < 20$ MeV	$\|M_{V^0} - M_\Lambda\| < 7$ MeV

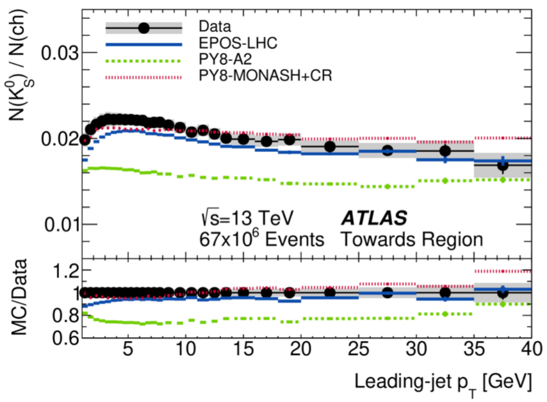


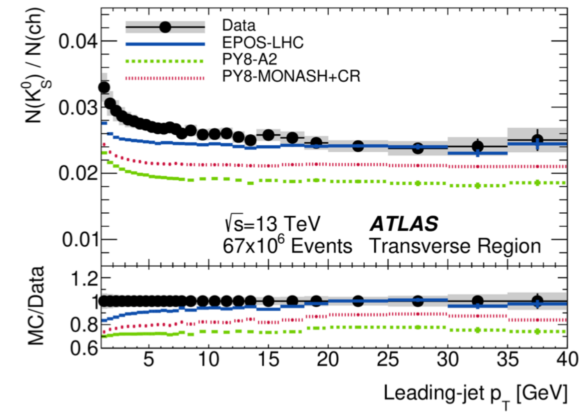


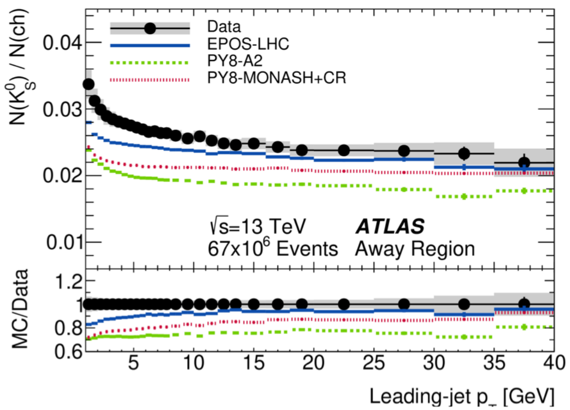
Underlying event studies with strange hadrons in pp collisions

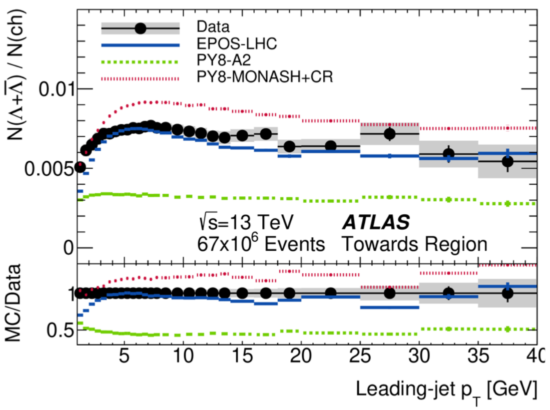
[Eur. Phys. J. C84(2024)1335, arXiv:2405.05048]

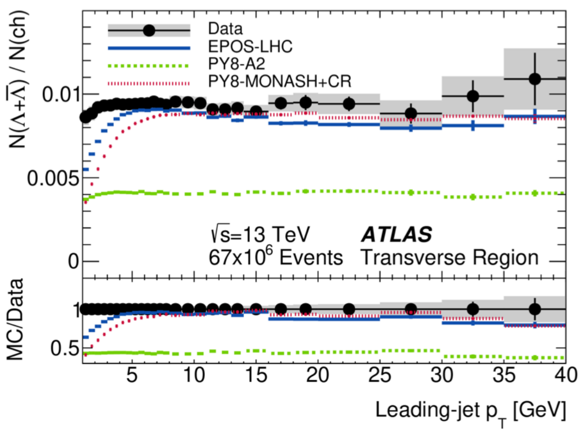


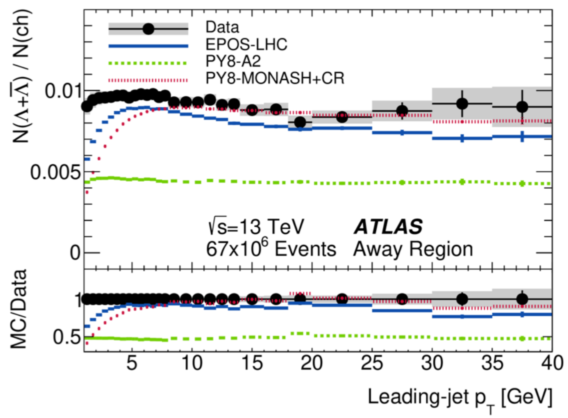


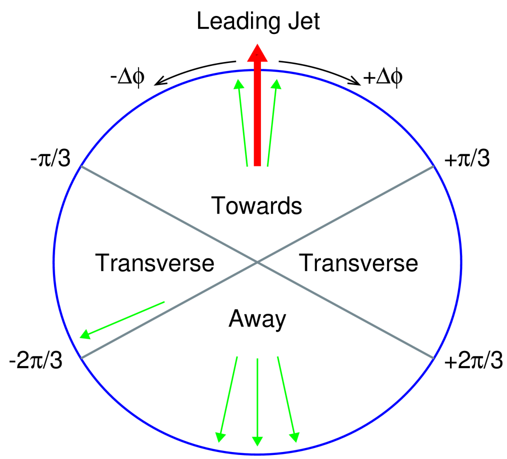










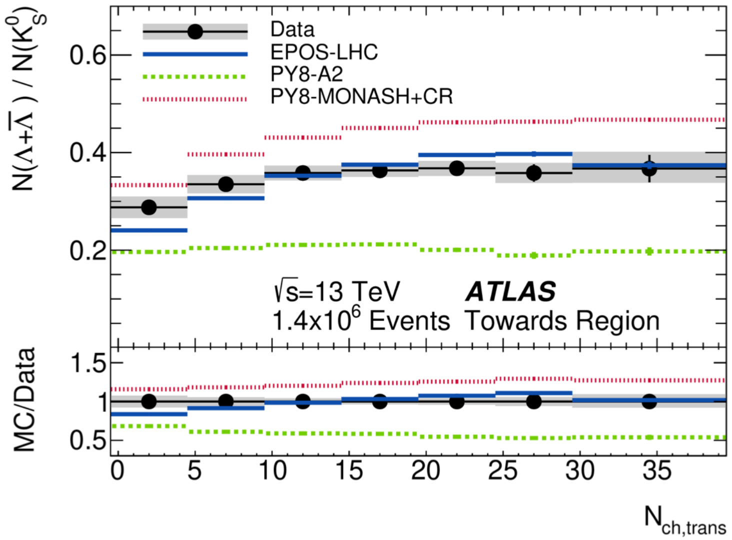


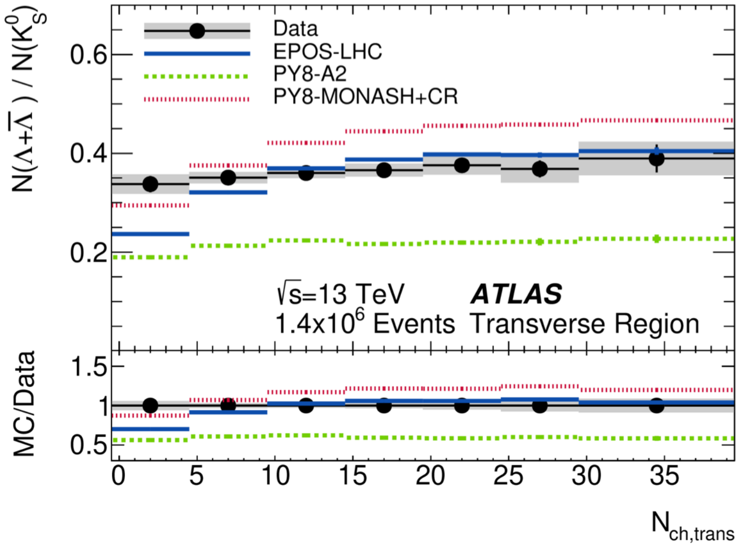
Underlying event studies with strange hadrons in pp collisions at $\sqrt{s}$=13 TeV

Eur. Phys. J. C84(2024)1335, arXiv:2405.05048

relative yields of ($\Lambda + \Lambda$) to K_s^0 as a function of $N_{ch,trans}$

data show somewhat weaker dependence in comparison with models, described better by EPOS





Study of ordered hadron chains in proton-proton, proton-lead and lead-lead collisions

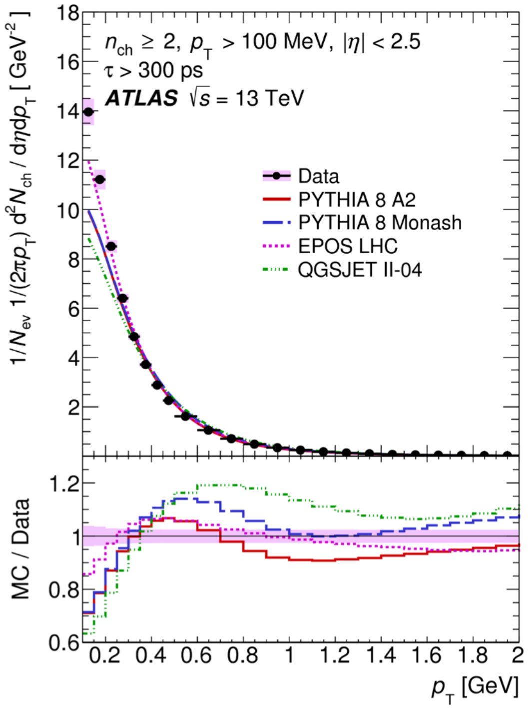
ATLAS-CONF-2022-055

- minimum bias event selection, p_T > 100 MeV
- focused on signature of colour-connected hadrons
  (g -> q $\bar{q}$) (sharing a common gluon ancestor)
- a fresh look at some of most visible differences between data and hadronization models

low pT single particle inclusive spectra

Eur. Phys. J. C 76 (2016) 502

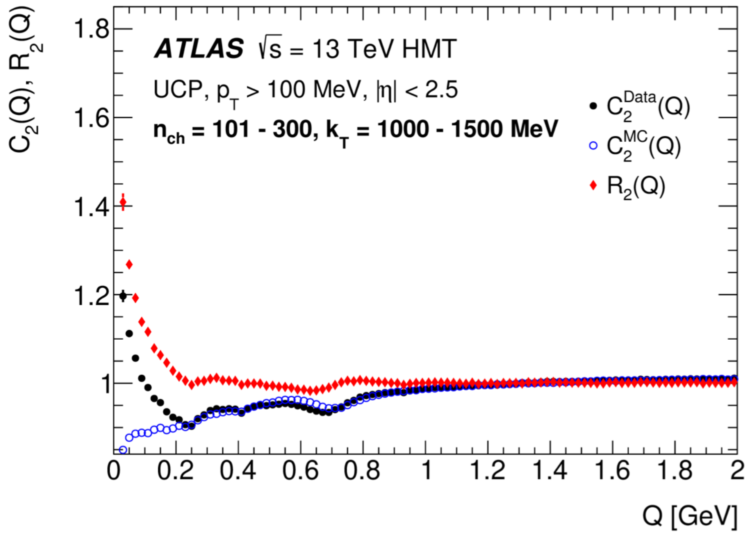
arXiv:1606.01133



excess of like-sign particle pairs (BEC, HBT, femtoscopy)

Eur. Phys. J. C 82 (2022) 608

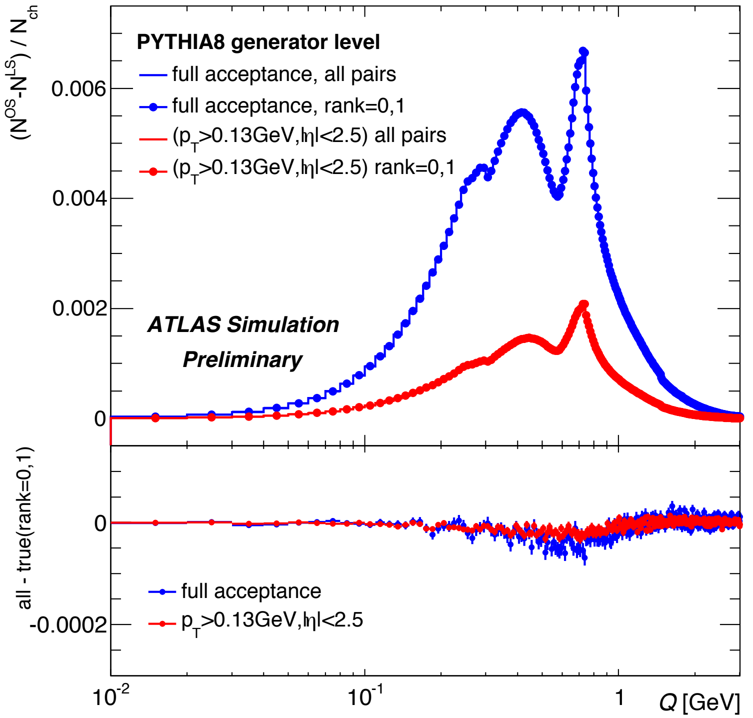
arXiv:2202.02218



Study of ordered hadron chains in proton-proton, proton-lead and lead-lead collisions

Observable sensitive to colour flow dynamics:

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



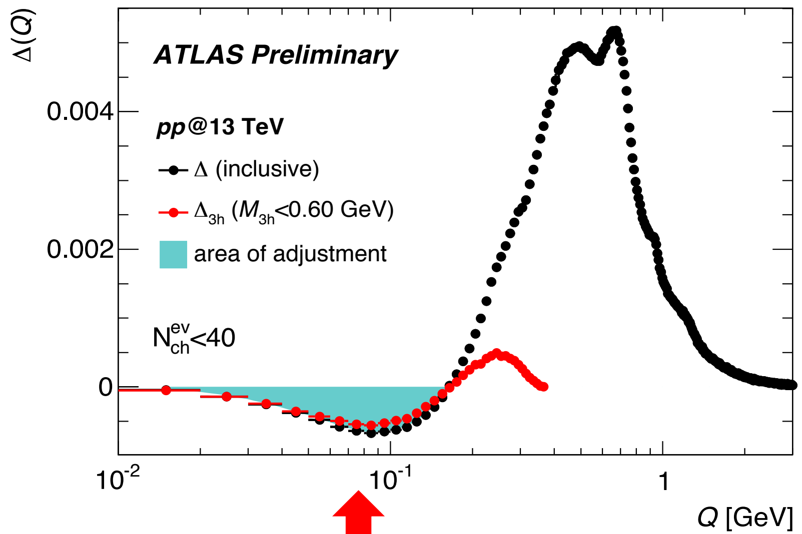
4-momentum difference

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

(all particles assigned pion mass)

[ATLAS-CONF-2022-055]

Excess of LS pairs seen as a depletion in Δ(Q)

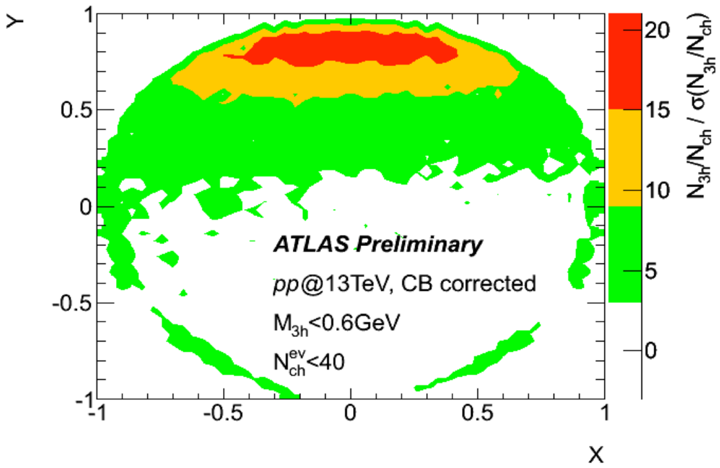


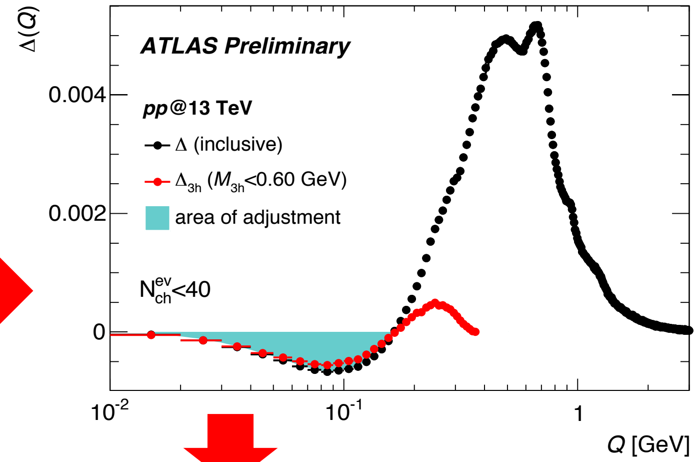
… coincides with the excess of charge-ordered , mass-minimized particle TRIPLETS

-> hadronic chains

Study of ordered hadron chains in proton-proton, proton-lead and lead-lead collisions

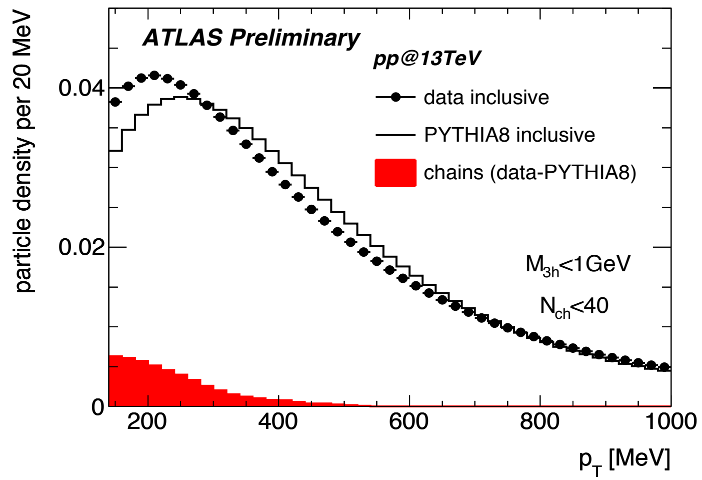
ATLAS-CONF-2022-055





Highly significant excess in chain signature generates excess of LS pairs AND a modification of inclusive p_T spectra

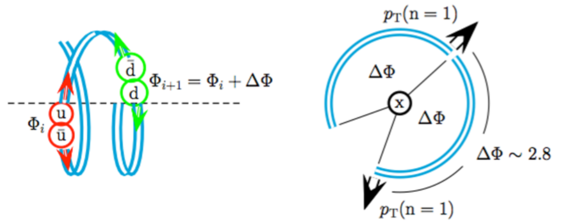
$$X = \sqrt{3}\frac{T_0 - T_2}{\Sigma T};\ Y = \frac{3T_1}{\Sigma T} - 1;$$



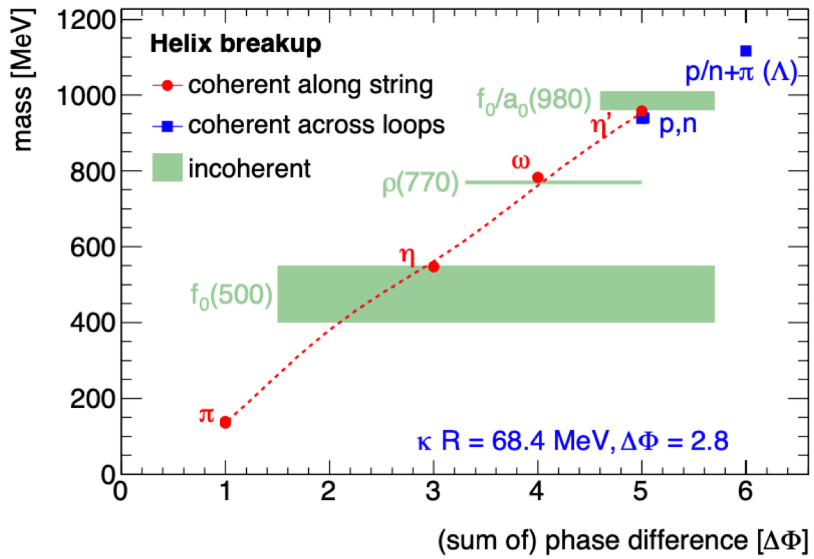
$$\Delta_{3h}(Q) = \frac{1}{N_{ch}} \Sigma_{i=1}^{N_{ch}} w_i \left\{ \begin{array}{l} +\frac{1}{2}\ \delta(Q - Q_i^{+-\mathrm{min}}) \\ +\frac{1}{2}\ \delta(Q - Q_i^{+-\mathrm{max}}) \\ -1\ \delta(Q - Q_i^{++,--}) \end{array} \right\}$$

Model independent measurement comparing 1-,2-,3-particle distributions : experimentally robust

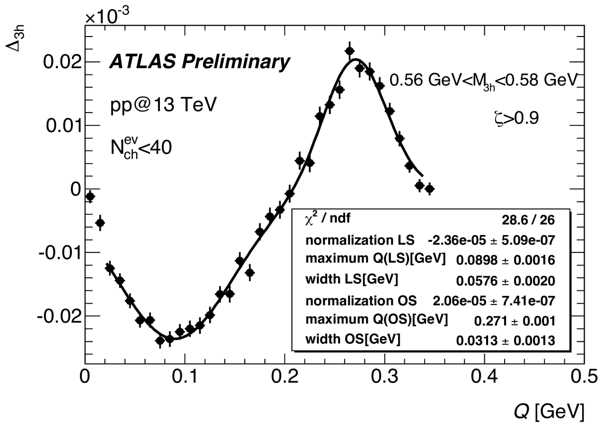
To complete the picture : hadron chain signature introduced to test predictions of the model of quantized fragmentation of helical QCD string



Discrete mass spectra of light hadrons described by simple helical string source with help of only 2 parameters (κR, ΔΦ)

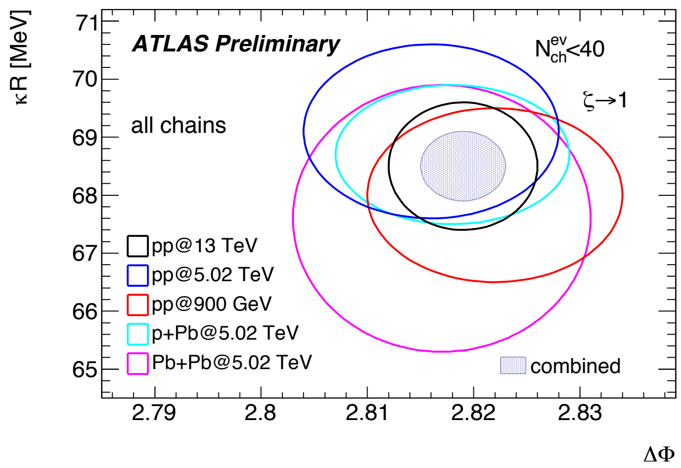


Phys.Rev.D104(2021) 034012



Triplet chains associated with the signature of a chain of direct pions

Resonant behaviour of (colour connected) hadrons allows to extract parameters of the generating QCD string



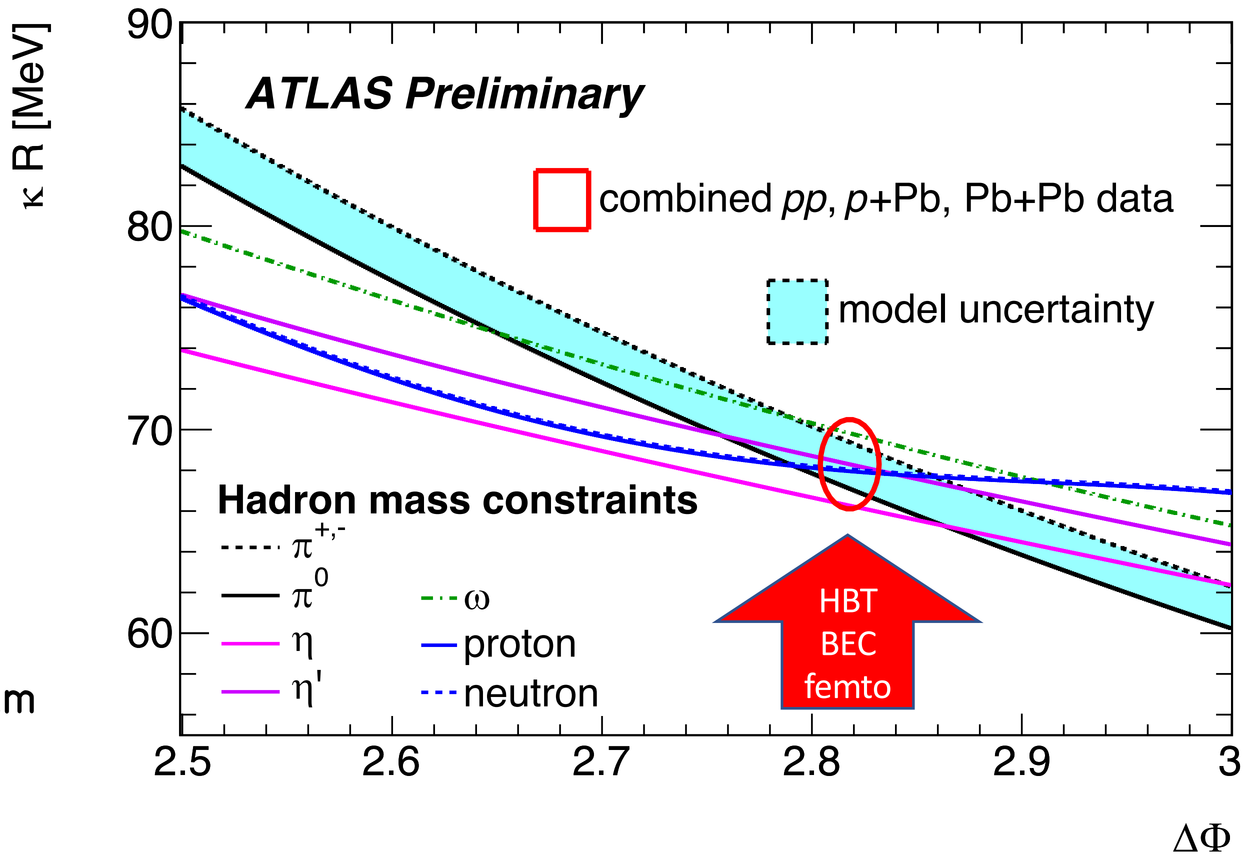
ATLAS-CONF-2022-055

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

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

Excellent agreement between string parameter values obtained from correlations and from discrete hadron mass spectrum

$$\kappa R = (68.5^{+2.0}_{-2.2})\ \text{MeV},$$
$$\Delta\Phi = 2.819^{+0.013}_{-0.014}.$$

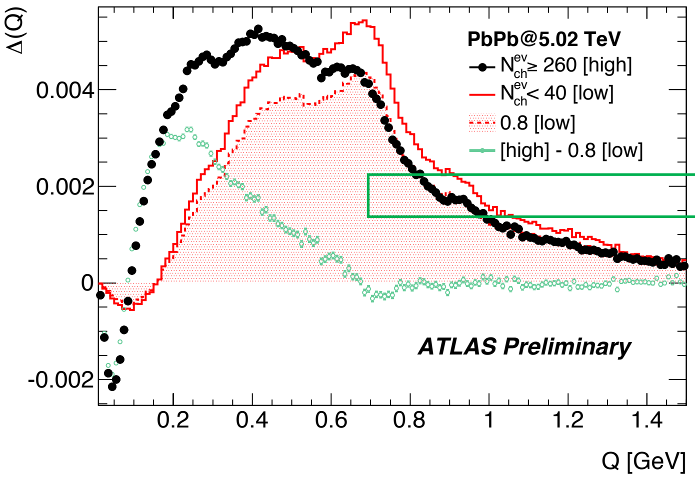


ATLAS-CONF-2022-055

Study of ordered hadron chains in lead-lead collisions

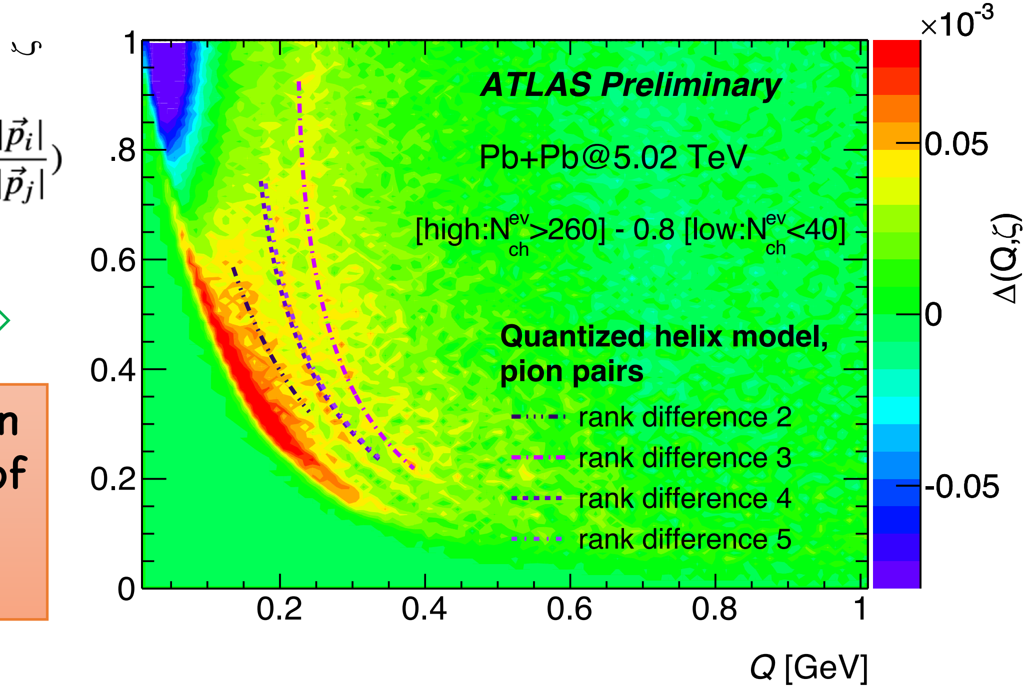
[ATLAS-CONF-2022-055]

thanks to complementary observable ζ disentangling longitudinal & transverse string sector



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

first observation of a signature of long chains of direct pions



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

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

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

To summarize :

- First observation of double parton scattering in W±W± in ATLAS
  - the measured fiducial cross-section times leptonic BR is 4.59±0.64 fb
  - the estimated DPS effective cross-section is 10.8±1.8 mb
- strange hadron production studied as a function of underlying event selection
- study of ordered hadron chains finds the source of so called Bose-Einstein correlations and establishes the link of causality across data-MC differences

- experimental evidence suggests we are dealing with quantum effects in the hadronization (primarily affecting opposite-sign colour-connected hadrons)

- measurements are consistent with expectations of the model of quantized fragmentation of helical QCD string. Proton-proton and heavy ion data from Run2 are combined in the measurement of string parameters:

$$\kappa R = (68.5^{+2.0}_{-2.2})\ \mathrm{MeV}, \qquad \Delta\Phi = 2.819^{+0.013}_{-0.014}.$$

$$m_t^{thr} = \kappa R\, \Delta\Phi = (192.8\ \pm\ 6.0)\ \mathrm{MeV}$$ smallest hadron-building block

$$m^{thr}(n=1) = \kappa R \sqrt{\Delta\Phi^2 - (2\sin\frac{\Delta\Phi}{2})^2} = (137.6\ \pm\ 4.2)\ \mathrm{MeV}$$ a pion !

To summarize :

- First observation of double parton scattering in W±W± in ATLAS
  - the measured fiducial cross-section times leptonic BR is 4.59±0.64 fb
  - the estimated … 8 mb
- strange hadro… ing event selection
- study of c… ed Bose-Einstein correlatio… -MC differences
- experiment… um effects in the hadronizat… r-connected hadrons).
- measurements a… he model of quantized fragmentation of helical QCD … on-proton and heavy ion data from Run2 are combined in the measurement of string parameters:

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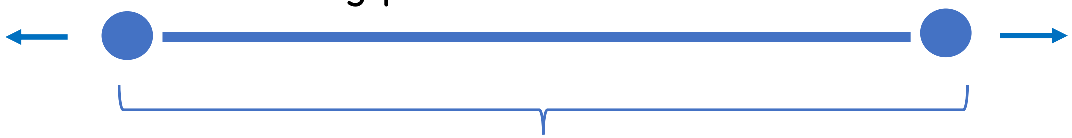
Backup slides

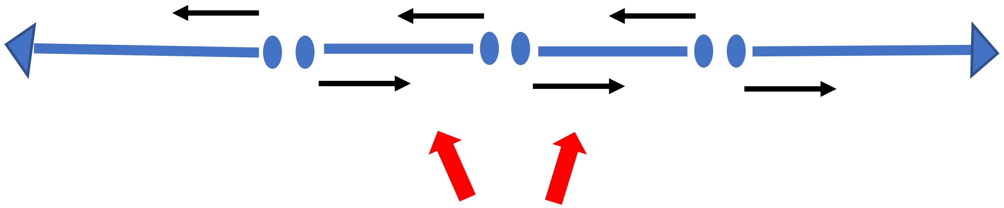
Hadronization (terminology)

confining potential ~ 1 GeV / fm = κ



colour-connected partons (quarks)

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



Colour-adjacent hadrons
(share break-up vertex)

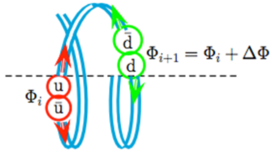
simplified picture of a chain of colour-connected gluons / QCD string

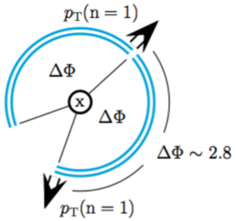
$$E_h = \kappa \, (x_i - x_{i+1})$$
$$p_h = \kappa \, c \, (t_i - t_{i+1})$$
$$E_h^2 - p_h^2 > 0 \quad \Leftrightarrow. \quad \Delta x^2 > (c \, \Delta t)^2$$

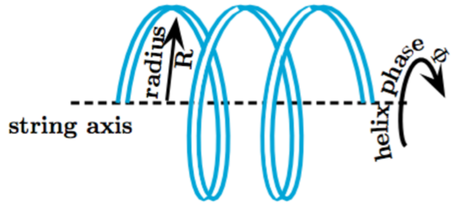
PROBLEM : break-up points causally disconnected (by construction) – how the hadrons end up on the mass shell ?

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

To complete the picture : hadron chain signature introduced to test predictions of the model of quantized fragmentation of helical QCD string





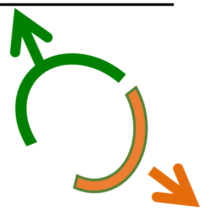


Nearly complete set of light hadrons described by simple helical string source with help of only 2 parameters (κR, ΔΦ)

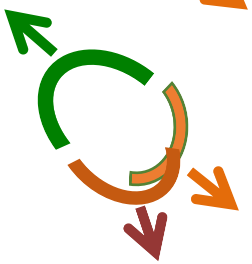
Various hadron production scenarii:

- 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, …)

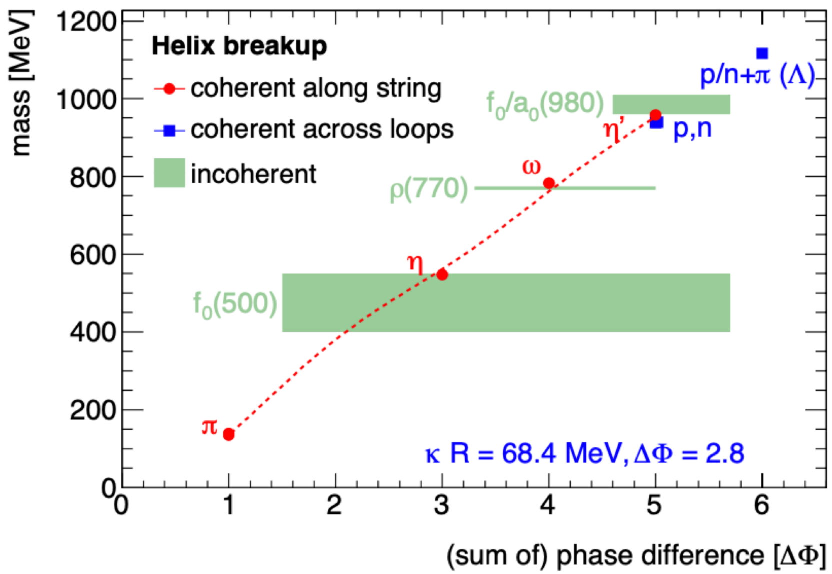
Predictions:



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

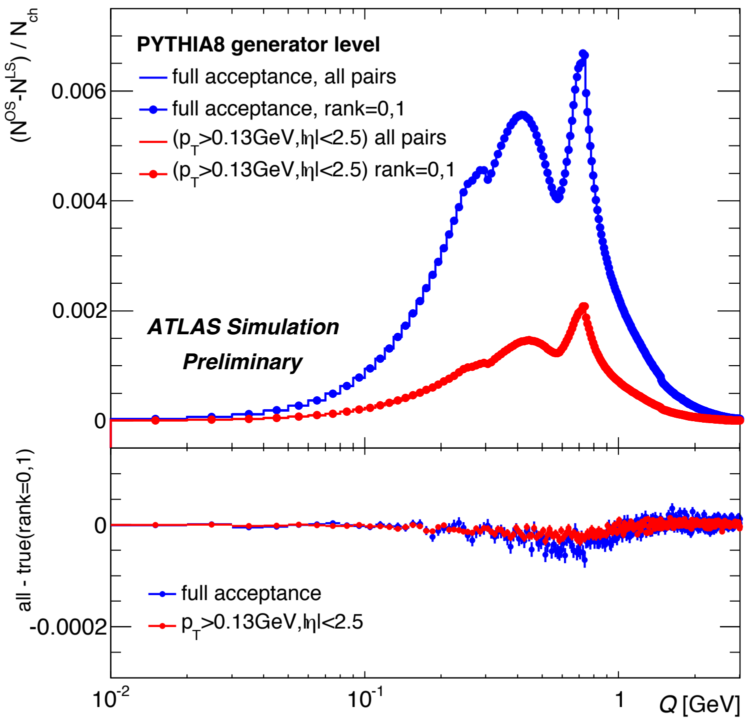


Expecting signature of close like-sign (LS) pion pairs



Phys.Rev.D104(2021) 034012

Observable sensitive to colour flow



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

4-momentum difference

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

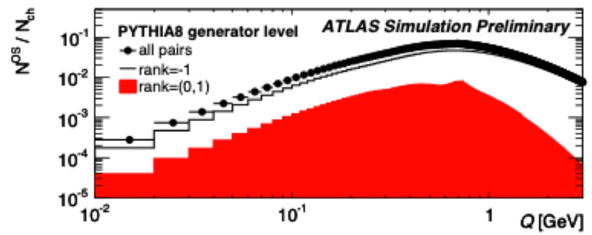
(all particles assigned pion mass)

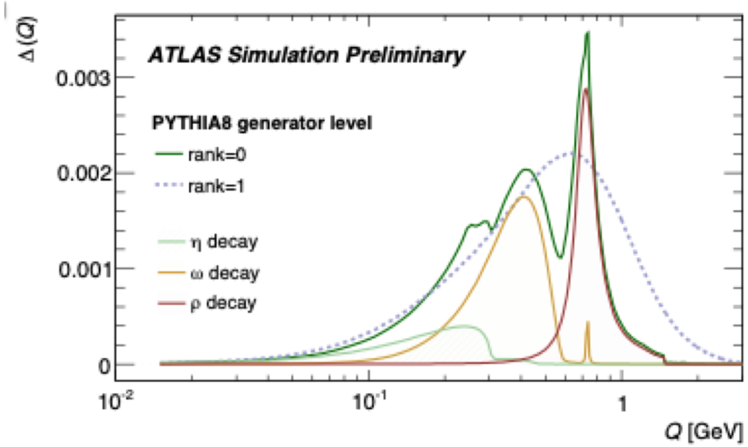
Hadron pairs classified by **rank difference** (shortened to « rank »)

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

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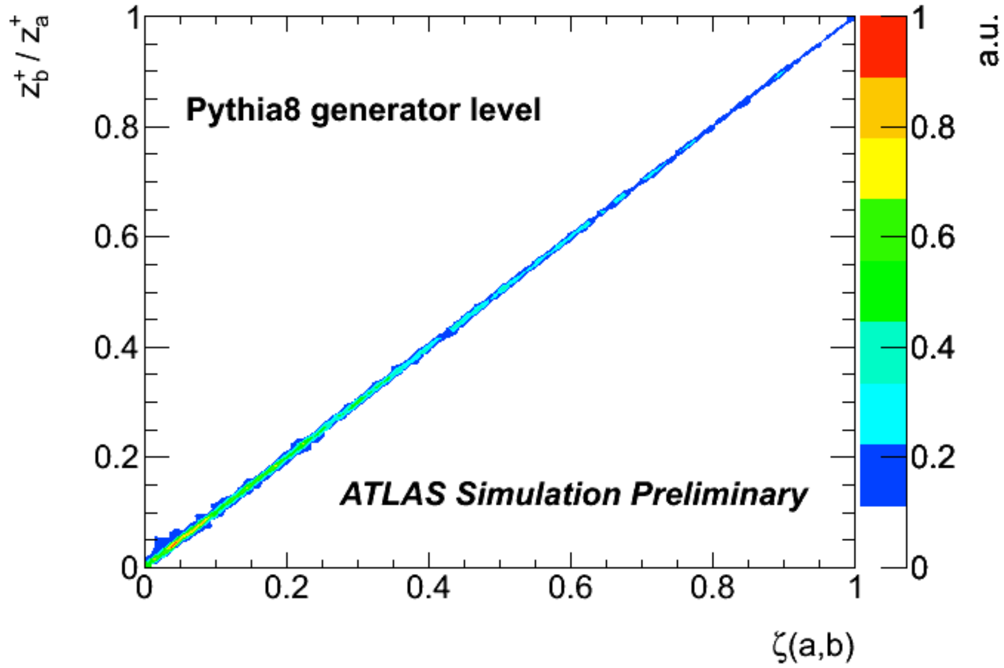
More information (about colour flow) can be obtained with help of other sensitive observables.
Example : <u>Observable sensitive to local evolution of fragmentation function</u> (for colour-adjacent hadrons)

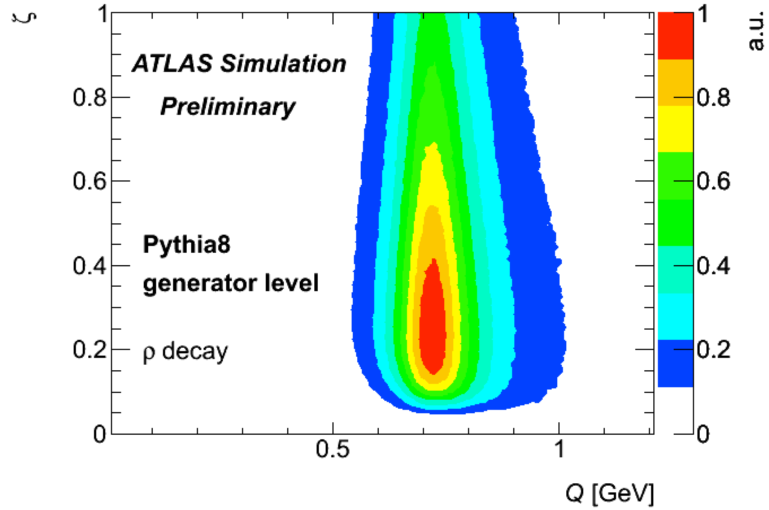
$$Q^2(p_a,p_b) \;=\; (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t,a}^2(\frac{z_b^+}{z_a^+} - 1) + m_{t,b}^2(\frac{z_a^+}{z_b^+} - 1).$$

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

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



Allows to distinguish between rank 0 and rank 1 contributions



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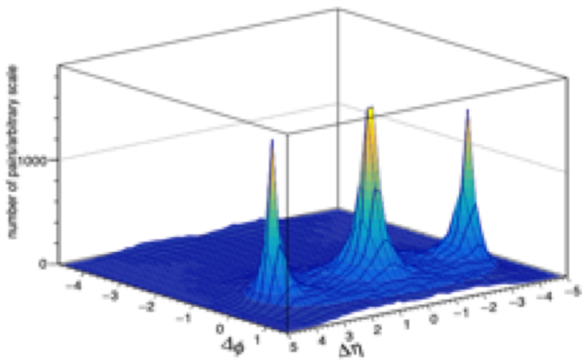
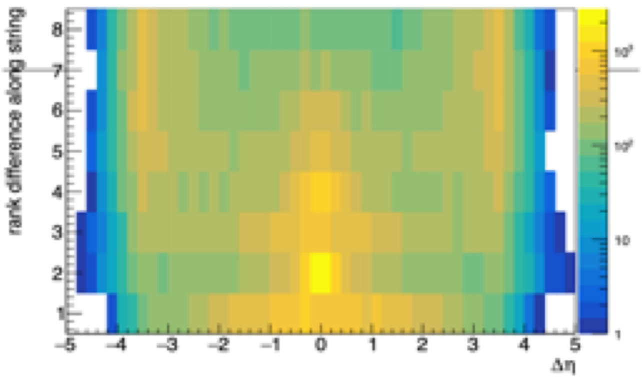
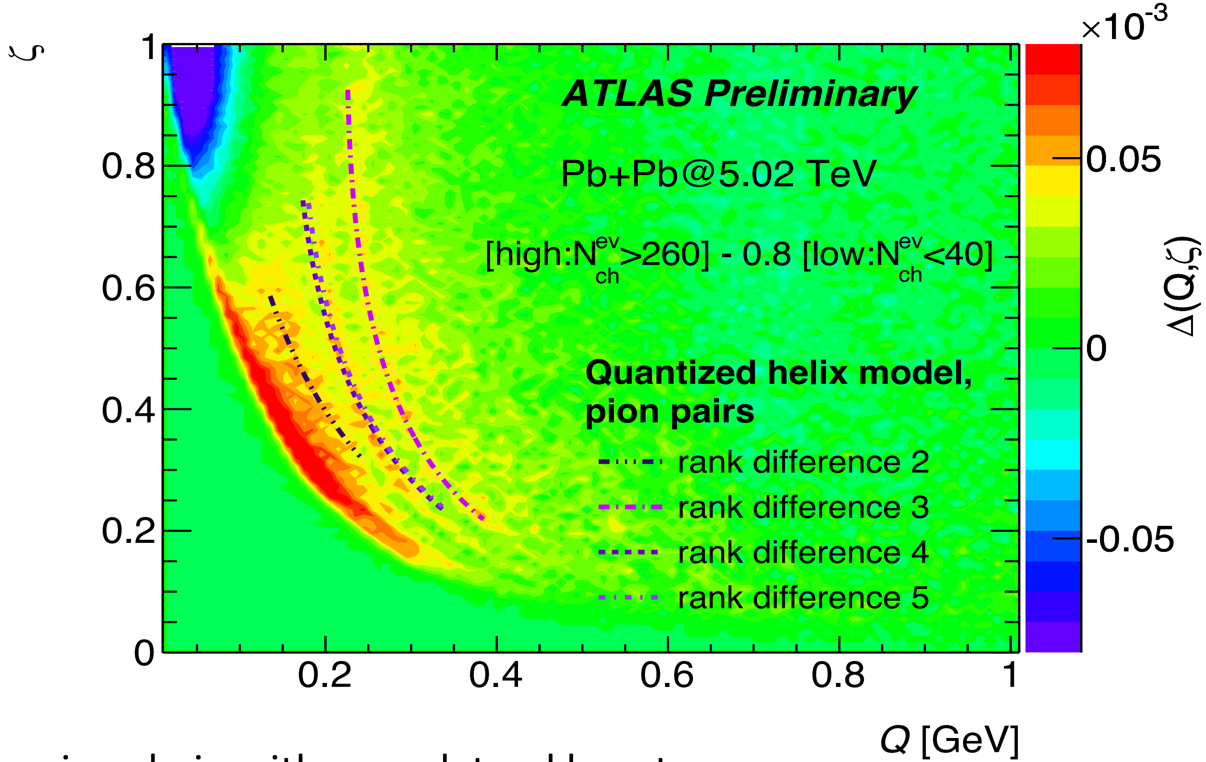
Long pion chains from quantized fragmentation can carry long range correlations

arXiv:1801.10232[hep-ph]







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

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… material for future conferences ☺