Studying particle production in small systems through correlation measurements in ALICE

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for the ALICE Collaboration

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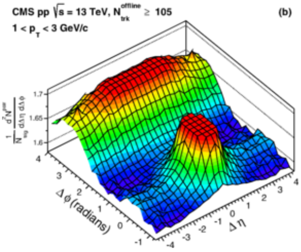
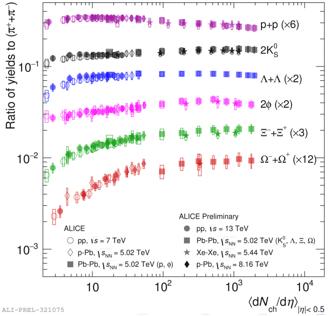
Observation: Collective effects in small systems

- Several observables indicate there are collective effects in small systems such as high-multiplicity pp and p-Pb collisions, particularly
  - Near-side ridge in angular correlations
  - Strangeness enhancement
- In Pb-Pb collisions these effects are attributed to the formation of a QGP
- What is their origin in small systems?

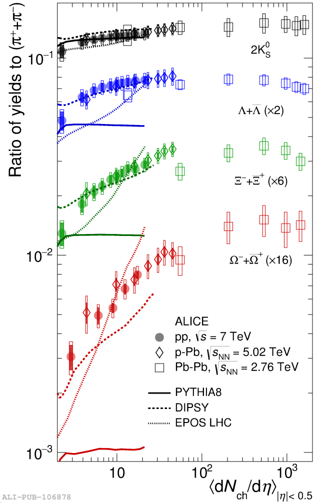


CMS Collaboration. *Phys. Rev. Lett.* **116** (2016) 172302



Phenomenological models

- PYTHIA: QCD-based initial stage + hadronisation based on $q\bar{q}$ breakings
- PHOJET: QCD-based + Pomeron chain fragementation
- EPOS: core-corona model
- PYTHIA and PHOJET have local baryon and strangeness conservation, EPOS does not
- Ongoing work to incorporate collective effects in PYTHIA (rope hadronisation / string shoving)

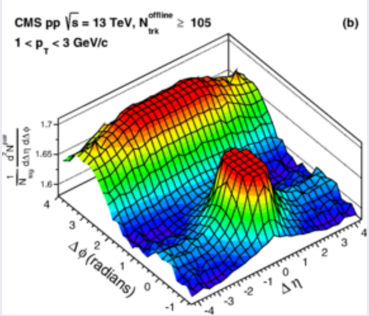


ALICE Collaboration. *Nature Phys.* 13 (2017) 535-539

Way to test these models: angular correlations

- These probe the distribution of particle pairs in an event
- Give information about baryon, meson, and strangeness production
- Provide information whether quarks are produced early or late in the event

- Provide information about diffusion, local or global correlations
- Can be divided into charge correlated and uncorrelated effects; can be separated by subtracting same-sign from opposite-sign correlations



CMS Collaboration. *Phys. Rev. Lett.* **116** (2016) 172302

Particle selection

Correlations between the following particles have been studied:

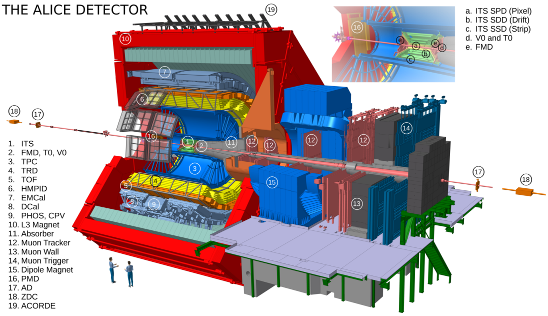
- Pions and kaons to probe meson production, minijet formation, and the underlying event
- Protons and Λ baryons ($\Lambda = uds$) to probe baryon production
- Ξ baryons ($\Xi^- = dss$), kaons, and Λ baryons to study strangeness production

Analysis details

Definitions

- Correlation function: $\mathbb{C}(\Delta\eta, \Delta\varphi) = \frac{1}{N_{\text{pairs}}} \frac{\mathrm{d}^2 N_{\text{pairs}}}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\varphi}$, number of pairs is normalised to unity
- Per-trigger yield: $\mathbb{Y}(\Delta y, \Delta\varphi) = \frac{1}{N_{\text{trig}}} \frac{\mathrm{d}^2 N_{\text{trig}-\text{assoc pairs}}}{\mathrm{d}\Delta y \mathrm{d}\Delta\varphi}$, normalised to number of triggers
- Balance function: $\mathbb{B}(\Delta y, \Delta\varphi) = \frac{1}{2}\left(\mathbb{Y}_{(+,-)} + \mathbb{Y}_{(-,+)} - \mathbb{Y}_{(+,+)} - \mathbb{Y}_{(-,-)}\right)$
- In practice, one uses event mixing to cancel out detector inefficiency effects from the correlation function

Detectors and data set



Track selection:

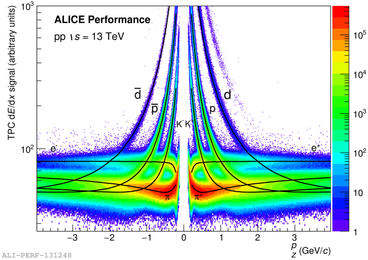
- $|\eta| < 0.8$ (all analyses)
- $|y| < 0.5$ (balance functions)

pp collision results at 5.02, 7, and 13 TeV are shown (depending on the analysis)

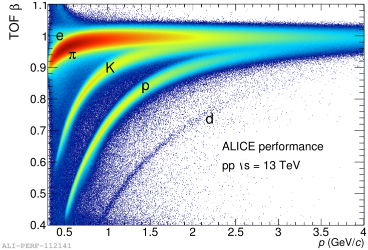
- Inner Tracking System (ITS) + Time Projection Chamber (TPC)
  - Tracking, vertexing, triggering
- TPC + Time-Of-Flight (TOF):
  - Particle identification
- VZERO detectors:
  - Centrality / multiplicity determination

Particle identification

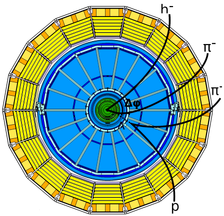
TPC:



TOF:



- Pions, kaons, and protons: PID of the TPC and TOF detectors
- Λ and Ξ baryons: Reconstruction of their daughter tracks. Decay topologies:
  - $\Lambda \rightarrow \mathrm{p} + \pi^-$
  - $\Xi^- \rightarrow \Lambda + \pi^-$



Results, $\mathrm{h}-\mathrm{h}$ correlation functions

Definitions

- Correlation function: $\mathbb{C}(\Delta\eta,\Delta\varphi)=\frac{1}{N_{\mathrm{pairs}}}\frac{\mathrm{d}^2N_{\mathrm{pairs}}}{\mathrm{d}\Delta\eta\mathrm{d}\Delta\varphi}$, number of pairs is normalised to unity
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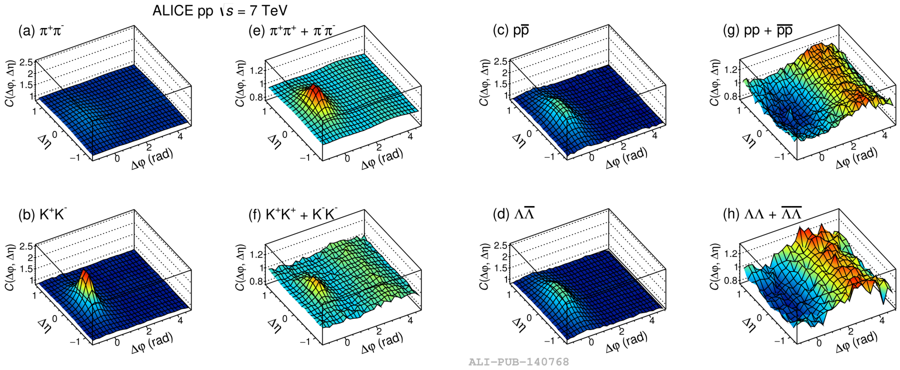
- Balance function: $\mathbb{B}(\Delta y,\Delta\varphi)=\frac{1}{2}\left(\mathbb{Y}_{(+,-)}+\mathbb{Y}_{(-,+)}-\mathbb{Y}_{(+,+)}-\mathbb{Y}_{(-,-)}\right)$

7 TeV results, h − h correlation functions



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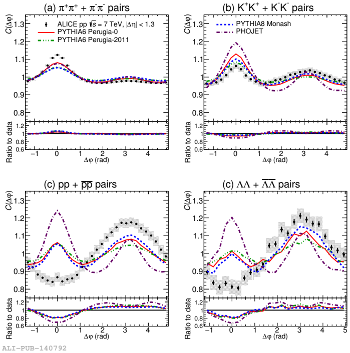
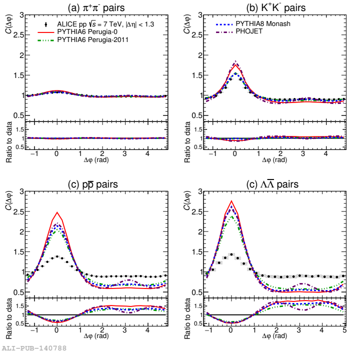
13 TeV results are similar both qualitatively and quantitatively

Projections and model comparisons





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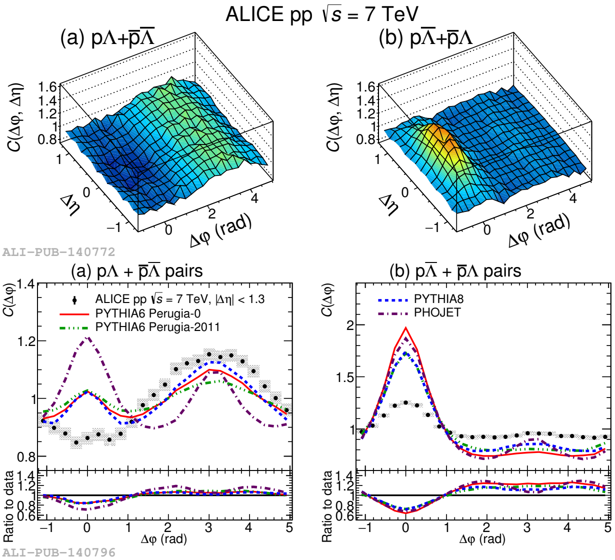
- $\pi\pi$ + KK: Well understood; minijet correlations, resonance decays, and Bose-Einstein effects
- pp + $\Lambda\Lambda$: Anti-correlations not understood, production of two baryons close in phase space is disfavoured

$p - \Lambda$ correlations



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- Anti-correlations present also for correlations between different baryonic species
- Neither of the correlations are reproduced by PYTHIA or PHOJET

Results, balance functions

Definitions

- Correlation function: $\mathbb{C}(\Delta\eta, \Delta\varphi) = \frac{1}{N_{\mathrm{pairs}}} \frac{\mathrm{d}^2 N_{\mathrm{pairs}}}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\varphi}$, number of pairs is normalised to unity
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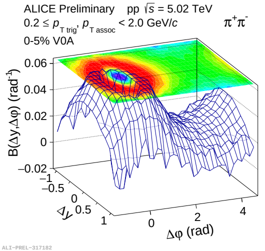
- Balance function:
$\mathbb{B}(\Delta y, \Delta\varphi) = \frac{1}{2}\left(\mathbb{Y}_{(+,-)} + \mathbb{Y}_{(-,+)} - \mathbb{Y}_{(+,+)} - \mathbb{Y}_{(-,-)}\right)$

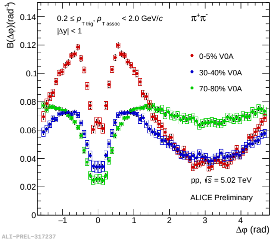
Results, balance functions

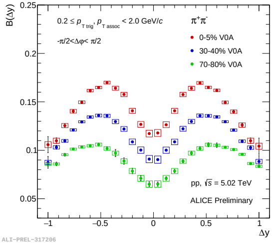
2D balance functions (top: pions, bottom: protons):

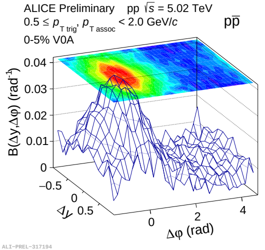
Projections onto $\Delta\varphi$:

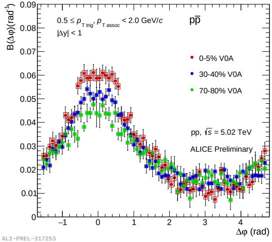
Projections onto Δy:

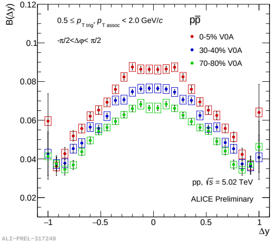




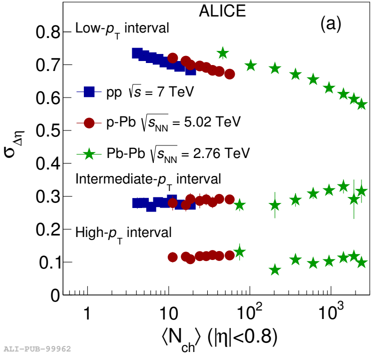








Narrowing of the balance function



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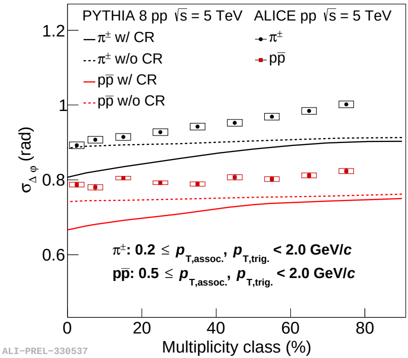
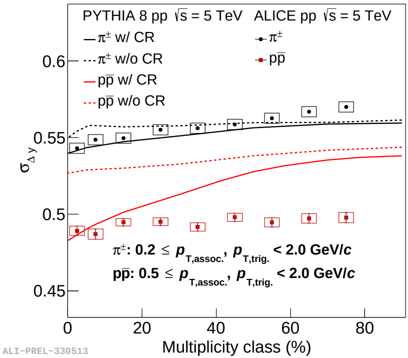
- In Pb-Pb collisions, this is due to increased radial flow $\Longrightarrow$ collective effect
- Not expected in small systems (no QGP), so probably has different origin, maybe colour reconnection (CR)?
- If radial flow: should be stronger for heavier particles (protons)

Balance function width for identified hadrons

Width in $\Delta\varphi$:



Width in Δy:



- No significant narrowing for protons, as opposed to CR
- Balance function probably not solely driven by CR, nor radial flow

Results, $\Xi - \mathrm{h}$ correlations

Definitions

- Correlation function: $\mathbb{C}(\Delta\eta, \Delta\varphi) = \frac{1}{N_{\mathrm{pairs}}} \frac{\mathrm{d}^2 N_{\mathrm{pairs}}}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\varphi}$, number of pairs is normalised to unity
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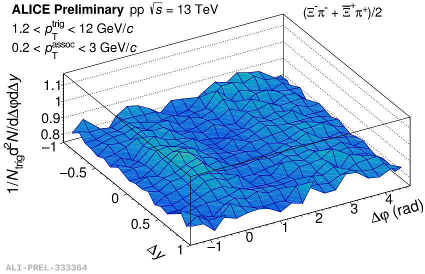
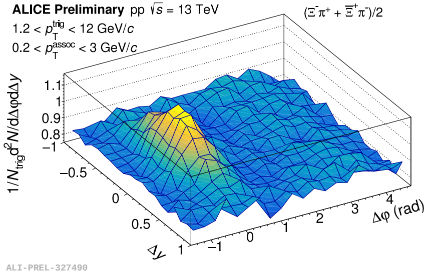
- Balance function:
  $\mathbb{B}(\Delta y, \Delta\varphi) = \frac{1}{2}\left(\mathbb{Y}_{(+,-)} + \mathbb{Y}_{(-,+)} - \mathbb{Y}_{(+,+)} - \mathbb{Y}_{(-,-)}\right)$

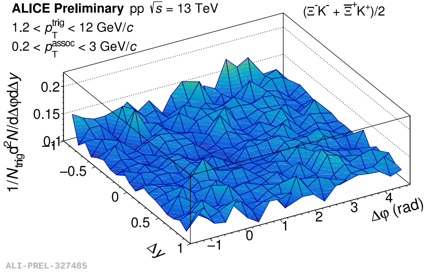
Results, $\Xi - \pi$ and $\Xi - \mathrm{K}$ correlations

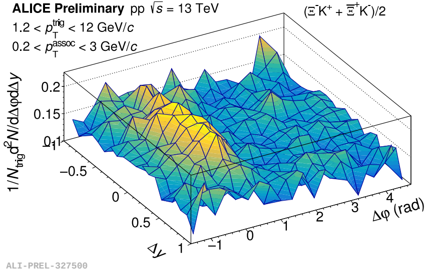
Same sign:



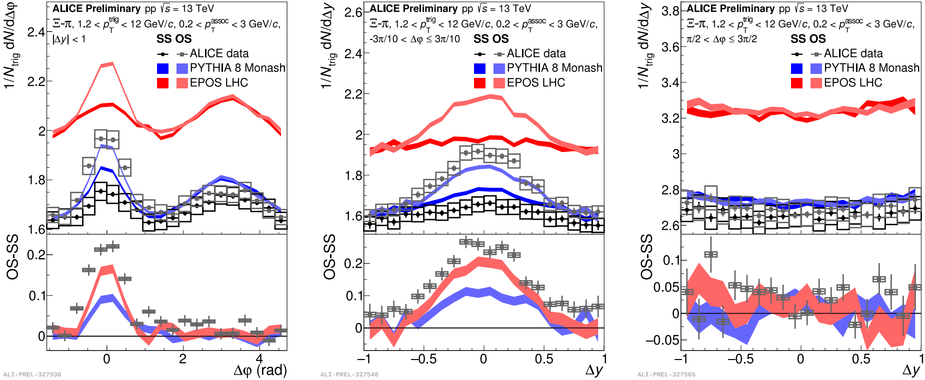
Opposite sign:





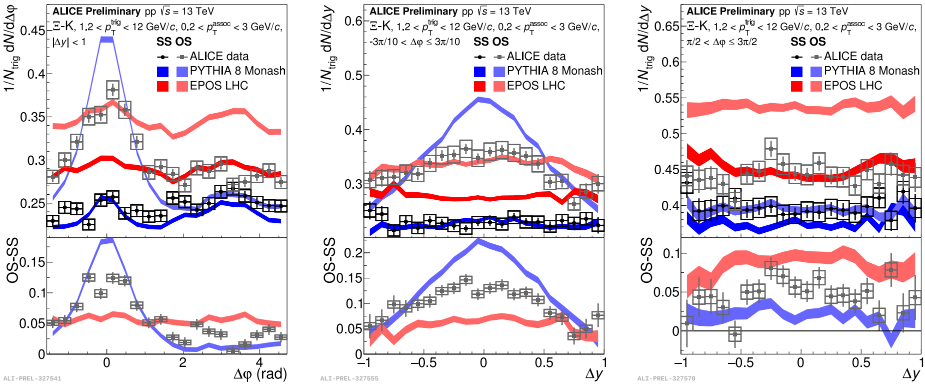


Projections and model comparions, $\Xi - \pi$ correlations



- Mostly due to minijet correlations, quite well described by both models
- Balance function (lower panels) underestimated by PYTHIA

Projections and model comparions, $\Xi - K$ correlations



- Near-side peak more smeared out and away-side correlation difference stronger in data than in PYTHIA, but not nearly as much as in EPOS
- Indicates some collective mechanism not described well by either model

Conclusions

- Correlations dominated by minijet production are well-understood and reproduced by PYTHIA, in particular:
  - Meson-meson correlations
  - $\Xi - \pi$ correlations
- Many other results are not yet understood:
  - Baryon-baryon correlations, particularly near-side anti-correlations for same-sign baryons
  - Absence of narrowing in $\mathrm{p} - \mathrm{p}$ balance functions
  - Smearing of $\Xi - \mathrm{K}$ correlations – seems to have some collective origin, but these are not nearly as smeared out as in EPOS, disfavouring this particular core-corona approach

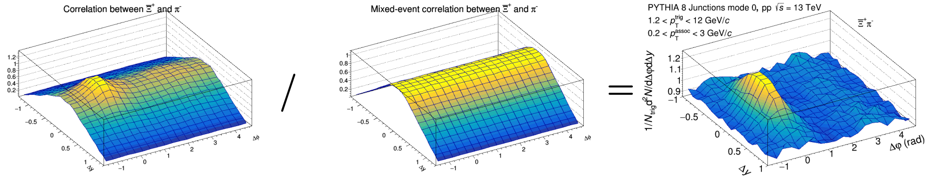
Outlook

- Planned measurements in ALICE:
  - More baryon and strange hadron correlation measurements (particularly $\mathrm{p}-\Xi$, $\Xi-\Lambda$, $\mathrm{p}-\Omega$; $\Omega^{-}=sss$), for $\Xi-\mathrm{h}$ correlations also multiplicity dependent
  - $\mathrm{K}-\mathrm{K}$ balance functions to fill the gap, and balance functions for cross-correlations ($\mathrm{K}-\pi$, $\mathrm{K}-\mathrm{p}$, etc.)
  - Extensions to p-Pb collisions and comparisons across systems
- Ongoing theoretical development:
  - Incorporation of colour ropes (Angantyr) or string shoving in PYTHIA
  - Further work on EPOS3, which is not yet publicly available (this is an improvement over EPOS LHC, including a microcanonical description)

Backup

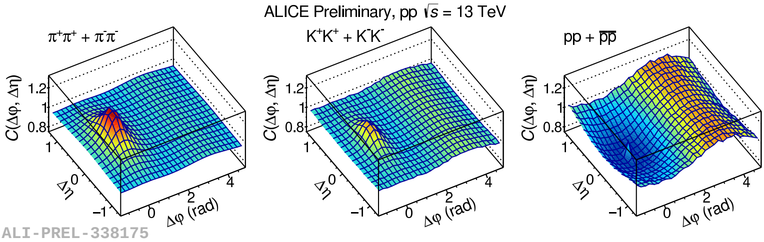
Event mixing

- For a finite detector volume, the shape of the correlation function will be convoluted by the acceptance window
- This may be further altered by detector inefficiencies
- Solution: divide by a mixed-event correlation function, which only follows the background shape
- Done by mixing tracks with similar number of tracks and collision vertex, otherwise the shape will not be the same as for the signal

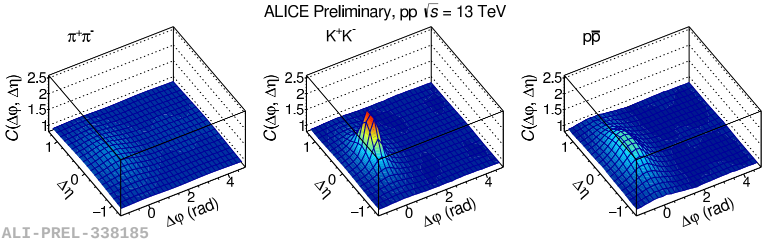


Results for $\mathrm{h} - \mathrm{h}$ correlations at 13 TeV

Same sign:

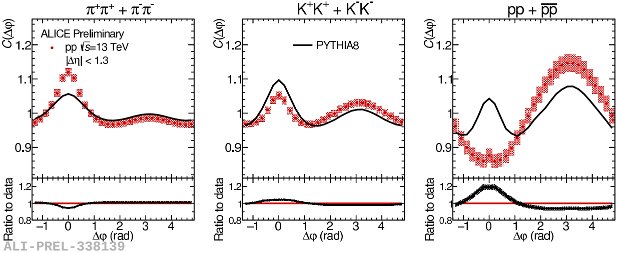


Opposite sign:

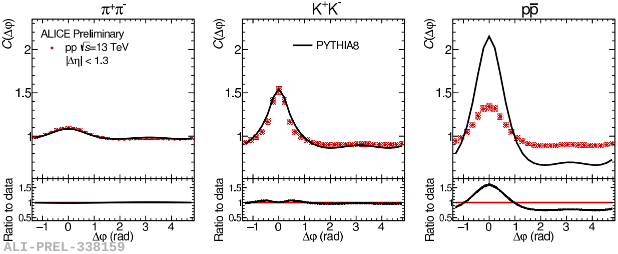


Projections and model comparisons, 13 TeV

Same sign:



Opposite sign:



Radial flow

- For an expanding fluid, such as a QGP, radial particle velocities will be boosted, so a larger boost is expected for high-multiplicity events
- Since $\mathbf{p} = \gamma \mathbf{v}$, the *momentum* boost will be larger for heavier particles $\Longrightarrow$ mass ordering
- Consequence: depletion of low-p_{T} particles with increasing multiplicity
- Moreover, the particles become more collimated, reducing the balance function width

Colour reconnection

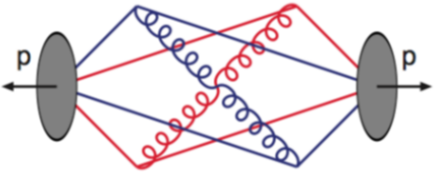
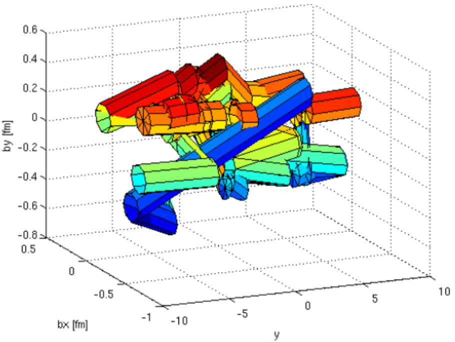


Figure credit: Torbjörn Sjöstrand

- With CR, different colour interactions between partons interfere $\Longrightarrow$ strings tend to cluster, shorter strings overall
- Consequence: fewer partons, especially at high multiplicity
- Total energy does not decrease, so the p_{T} spectrum becomes harder with increasing multiplicity
- Exactly what happens in radial flow, effect on balance functions is similar

Rope hadronisation

- In this model, colur strings are clustered into ropes
- Makes it easier to form multistrange hadrons (the relatively rare *s* quarks more easily cluster together)
- Larger multiplicity $\implies$ more ropes $\implies$ strangeness enhancement
- Originally implemented in the DIPSY model, now incorporated in an extension to PYTHIA



C. Bierlich. *QCD Challenges at the LHC: from pp to AA.* [Conference presentation]. Taxco, Mexico. (2016).