Angular Correlations of Baryons as a Probe for Colour Reconnection and Hadronization

Stefan Kiebacher in collaboration with Stefan Gieseke and Simon Plätzer | November 21, 2023

Introduction

Hadronization:

- Hadronization is the non-perturbative transition from partons to hadrons and relies on heavy modelling
- Two types of hadronization models: The Lund string model (used by `Pythia`) and the cluster model (used in `Sherpa` and `Herwig`)
- Baryons are not straightforward to produce in a hadronization model and are often badly modelled
  $\Rightarrow$ testing ground for Hadronization models

Open questions:

- How and with which kinematics are **Baryons** produced in high energy collisions?
- What knowledge can we extract from **Baryon** observables e.g. their **Angular Correlations**?

Sketch of Hadronization Model in Herwig

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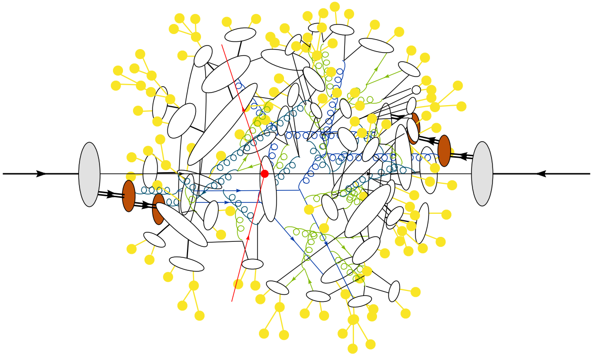
Stages of hadronization model in `Herwig`:

- Multiple Parton Interactions (MPIs)
- Primordial cluster formation
- Colour Reconnection (CR)
- Cluster Fission (CF)
- Cluster Decay (CD)
- Hadron Decay



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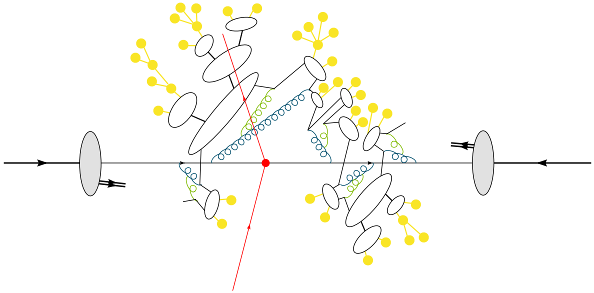
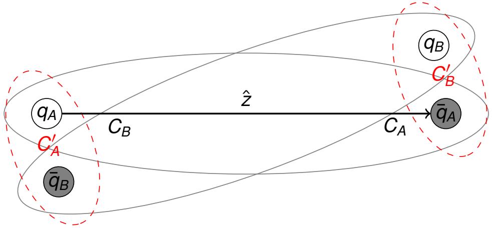


Colour Reconnection (CR)

- Select two clusters at random close in phase space
- Maximize closeness measure $y_{\text{sum}} = |y_{q_B}| + |y_{\bar{q}_B}|$ with respect to $\hat{z}$
- If $y_{q_B} > 0$ and $y_{\bar{q}_B} < 0$ for $y_{\text{sum}}^{\text{max}}$
  $\Rightarrow$ Mesonic Colour Reconnection (MCR) accepted with probability P_M



Colour Reconnection (CR)

- Select three clusters at random close in phase space
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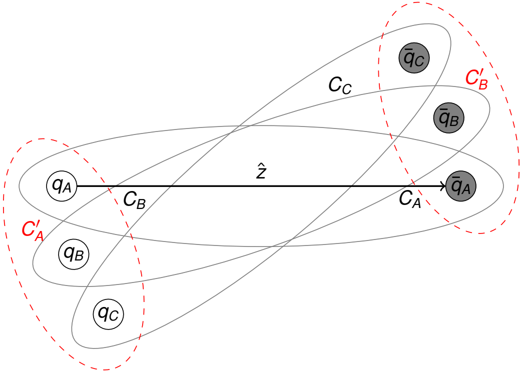
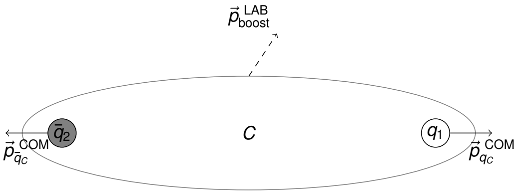
- If $y_{q_B} < 0$ and $y_{\bar{q}_B} > 0$ for $y_{\text{sum}}^{\text{max}}$
- Find next to maximal y_{sum} cluster to make baryon-antibaryon pair
  $\Rightarrow$ Baryonic Colour Reconnection (BCR) accepted with probability P_B [Gieseke, Kirchgaeßer, and Plätzer 2018]
- **Note:** Clusters can be light for Baryon Production However a lot of multiplicity is needed!



Cluster Fission (CF)

- Fission all clusters $M > M_{\max}(q_1, \bar{q}_2)$ above a threshold $M_{\max}(q_1, \bar{q}_2)$ **recursively**

1. Draw a light $q - \bar{q}$ pair from the vacuum with probability P_q (no diquarks currently allowed!)
2. Draw new masses M_1, M_2 for the fission products C_1, C_2
3. **Choose Direction** of decay $\Rightarrow$ Currently aligned with the original constituent momenta



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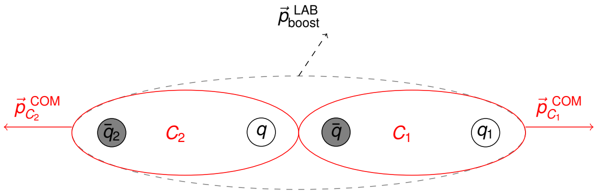

Cluster Decay (CD)

- Clusters decay to two hadrons
- Essentially the same as Cluster fission with a few differences:
  1. The masses are fixed by the hadron masses
  2. Mesonic clusters $C(q_1, \bar{q}_2)$ can decay to a baryon-antibaryon pair $B(q_1, (q, q')), \bar{B}'(\bar{q}_2, (\bar{q}, \bar{q}'))$
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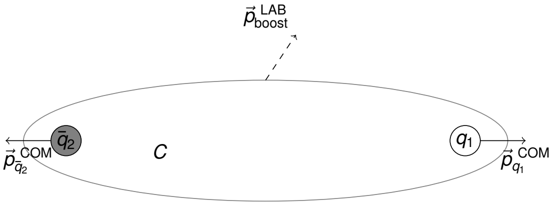
- **Note:** Not much multiplicity, but high-mass clusters are needed to produce **Baryons**!



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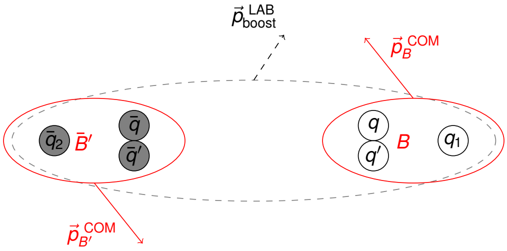


Baryon Angular Correlations

- Depletion of near-sided baryons only reproduced by **Baryonic Colour Reconnection (BCR)**
- **Cluster Decay (CD)** baryons are responsible for unphysical far-side peak
- BCR alone cannot produce enough baryons especially for low multiplicity events (e.g. at LEP)

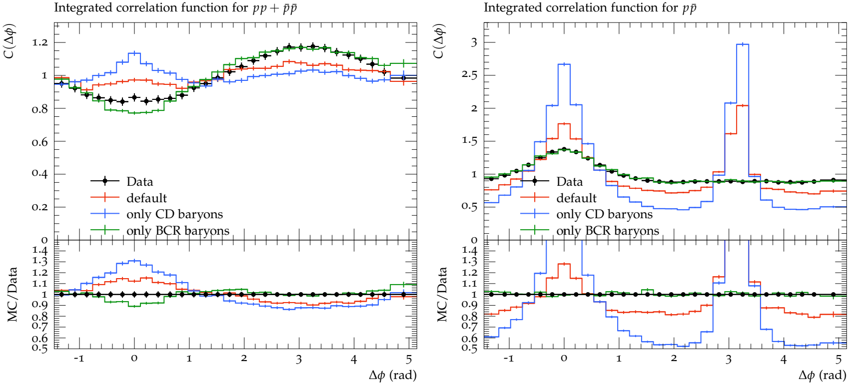
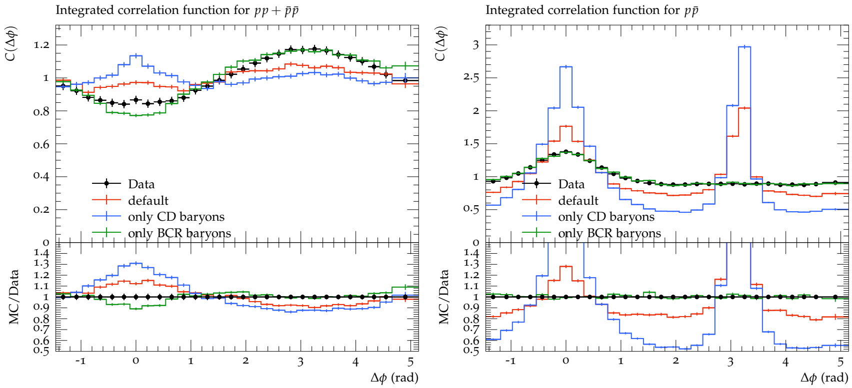


Figure: measured by ALICE [Adam et al. 2017]

Baryon Angular Correlations

Solutions:

1. Disable CD baryon production



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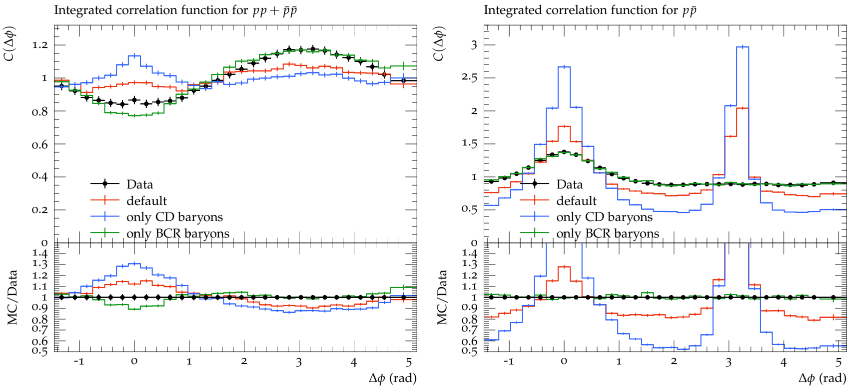

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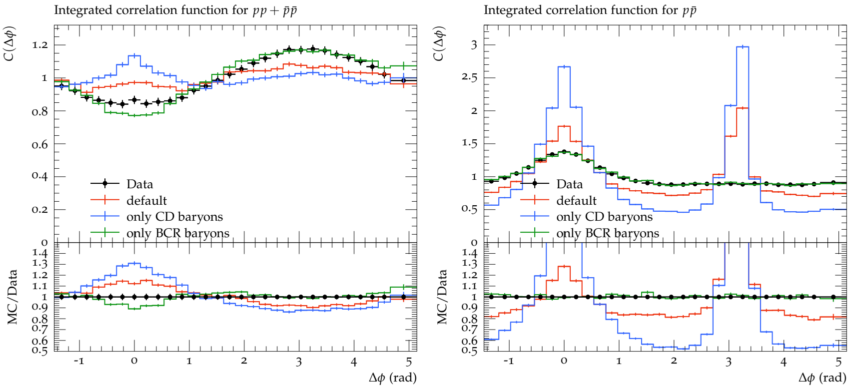

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Solutions:

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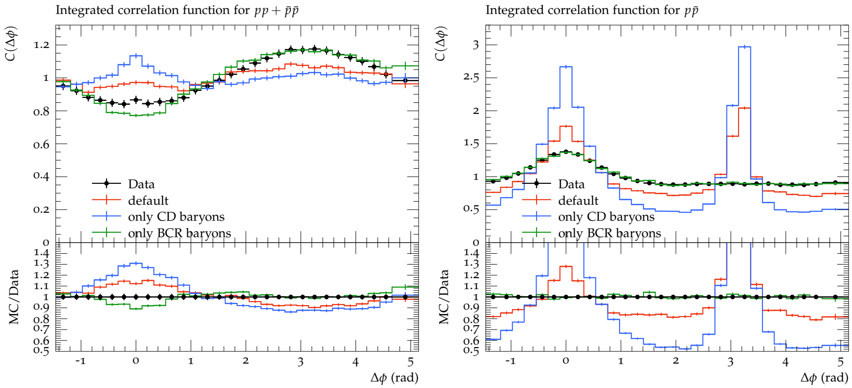
3. New Diquark Colour Reconnection algorithm



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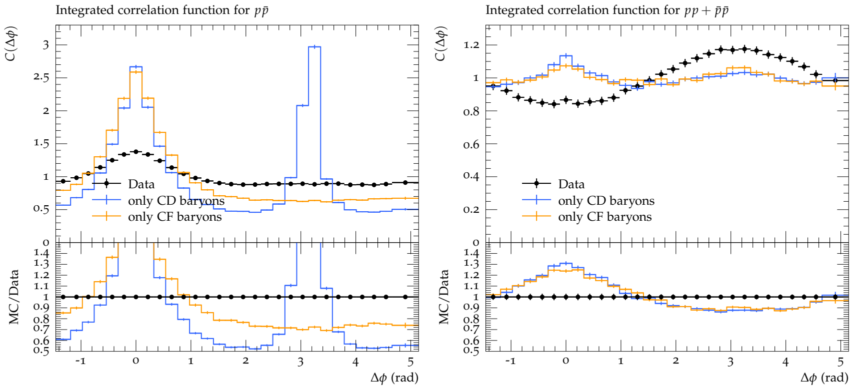
Cluster Fission (CF) vs Cluster Decay (CD) Baryons

- Near-side depletion not reproduced
  $\Rightarrow$ CD and CF are oblivious to other baryons
- Far-side peak is completely gone!

- Near-side still overshoots the data



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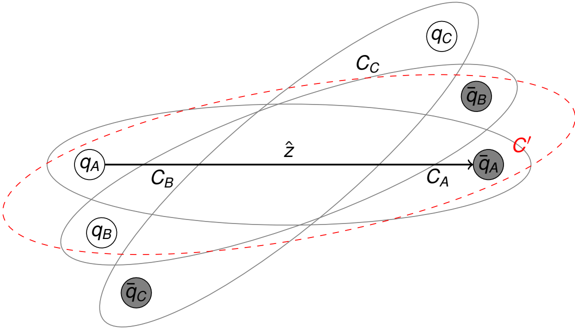
  $\Rightarrow$ Diquark Colour Reconnection (DCR) accepted with probability P_D if $M_{C'} > M_{\text{Baryon Pair}}^{\text{Lightest}}$
- **Note:** Mixed need for multiplicity and existing mass for producing baryons
- Similar to `Pythia`'s String Junction Colour Reconnections [Christiansen and Skands 2015]



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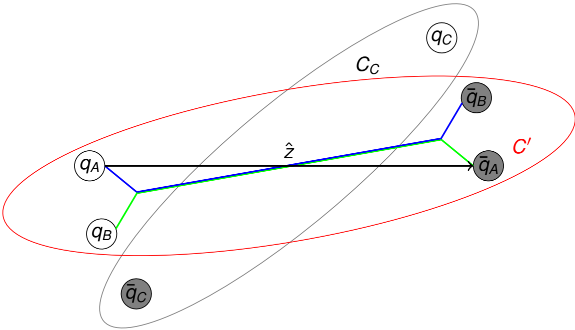
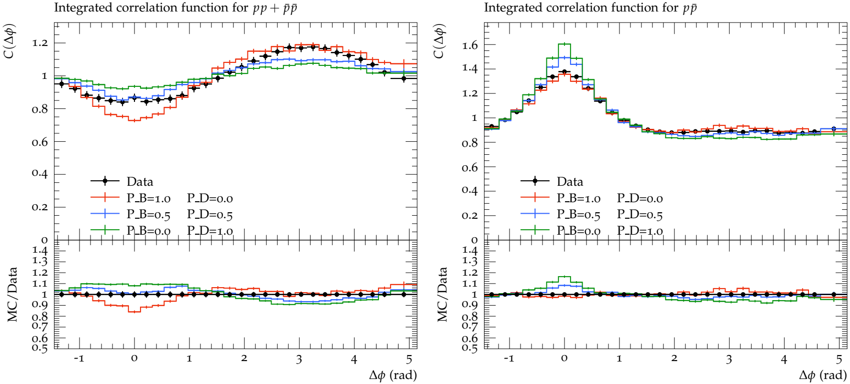


Diquark Colour Reconnection

- Purely Diquark-type CR with $P_D = 1$ has not enough depletion for *pp* correlations
- Near-sided peak reproduced!
- No far-sided peak for $p\bar{p}$ DCR and good phenomenology



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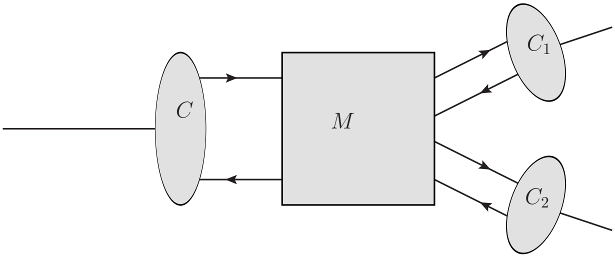
Revisiting Cluster Fission Kinematics

Idea: Cluster Fission is a partonic $2 \to 4$ process [Plätzer 2023].

- Factorize the process $C(p_i, p_j) \to C_1(q_i, q), C_2(q_j, \bar{q})$ (see Jan Priedigkeit's Bachelor thesis Graz):

$$d\Gamma(C \to C_1, C_2) = \int d^4\Phi_{q_i} d^4\Phi_q d^4\Phi_{\bar{q}} d^4\Phi_{q_j} (2\pi)^4 \delta^4(p_i + p_j - q_i - q - \bar{q} - q_j) |\mathcal{M}(p_i, p_j \to q_i, q, \bar{q}, q_j)|^2 \tag{1}$$

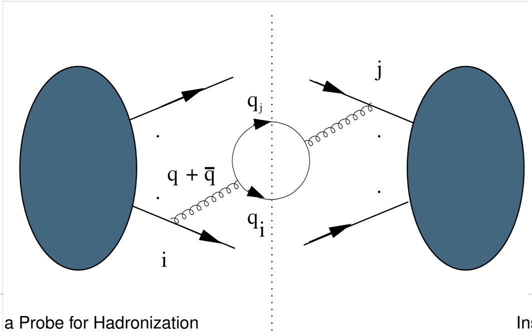
$$d\Gamma(C \to C_1, C_2) = \int dM_1 dM_2 d\Phi_2(P|Q_1, Q_2) d\Phi_2(Q_1|q_i, q) d\Phi_2(Q_2|q_j, \bar{q}) |\mathcal{M}(p_i, p_j \to q_i, q, \bar{q}, q_j)|^2 \tag{2}$$



Revisiting Cluster Fission Kinematics

- (Pre-)Sample Masses M_1, M_2 from flat Phase Space weight (Jan Priedigkeit's Bachelor thesis Graz)
  $d\Phi_4 \propto dM_1 dM_2 \sqrt{\lambda(M, M_1, M_2)}\sqrt{\lambda(M_1, m_1, m)}\sqrt{\lambda(M_2, m_2, m)}/(M_1 M_2)^2$
- Rejection sampling of soft $q\bar{q}$ emission diagram, which in the soft limit is given in [Catani and Grazzini 2000] by:

$$|\mathcal{M}(p_i, p_j \to q_i, q, \bar{q}, q_j)|^2 \propto \frac{2(q_i \cdot q_j)(q \cdot \bar{q}) + [q_i \cdot (q - \bar{q})][q_j \cdot (q - \bar{q})]}{2(q \cdot \bar{q})^2 [q_i \cdot (q + \bar{q})][q_j \cdot (q + \bar{q})]} \tag{3}$$



Summary and Outlook

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Summary:

- Used the angular correlations of baryons to examine the kinematics of the cluster model
- Found and fixed the far-sided peak of baryon-antibaryon correlations
- Developed new baryon production mechanism via Diquark CR

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Outlook for hadronization in `Herwig`:

- Dynamic gluon constituent masses (WIP by Daniel Samitz, S. Plätzer)
- Restructure the CF and CD to implement flexible kinematics (WIP with S. Plätzer, S. Gieseke)
- Make Colour Reconnection **dynamic** via soft gluon evolution [Gieseke, Kirchgaeßer, Plätzer, and Siodmok 2018; Plätzer 2023] (WIP with S. Plätzer, S. Gieseke) $\Rightarrow$ only 2 free parameters

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Long term goals for hadronization in `Herwig`:

- Make shower+hadronization model less sensitive on the shower cutoff
- Generalisation of Hadronization to dark hadrons (by Simon Plätzer, Dominic Stafford et al.)
- Convince experimentalists to get more (identified) particle correlation data (also for LEP), since important modelling input

Short summary

TLDL: Lots of construction sites in the Hadronization model in `Herwig` ...

References I

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Thank You For Your Attention!

Questions? Remarks? Comments?

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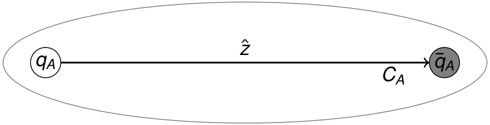

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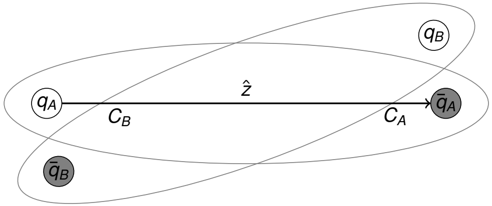

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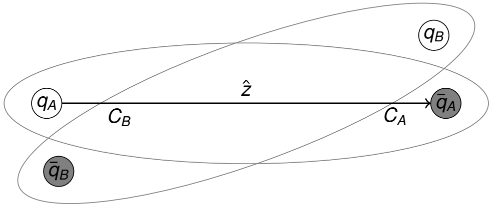

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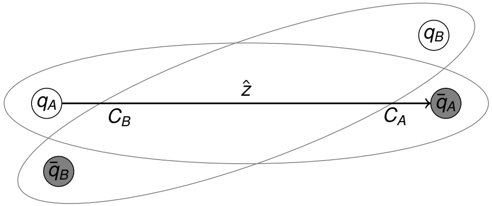

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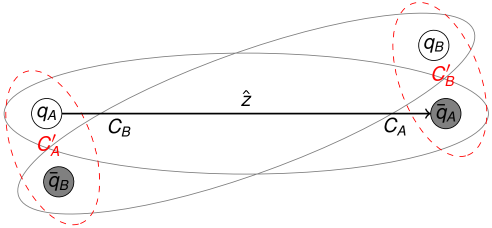

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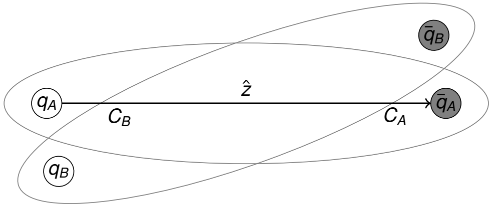

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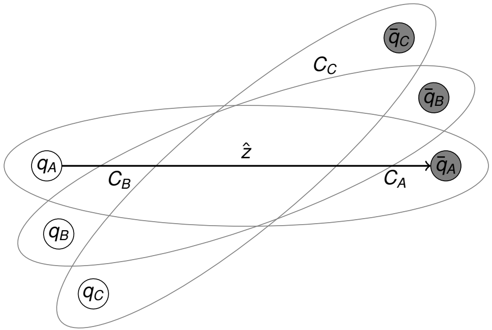

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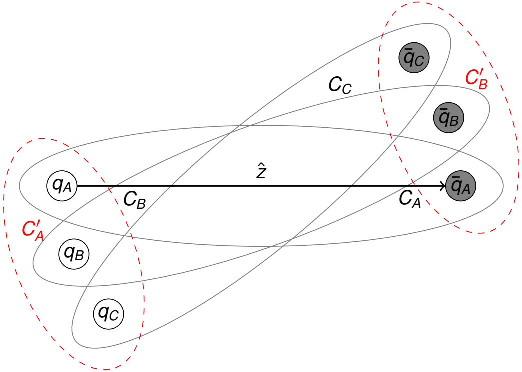

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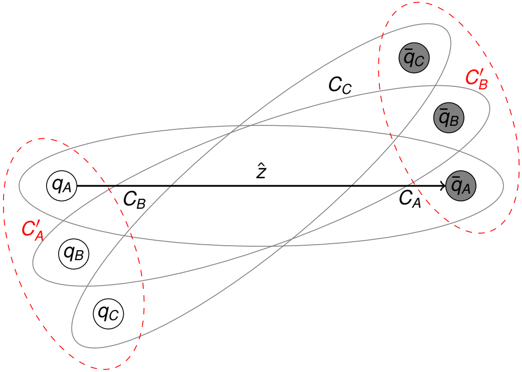

Backup: Colour Reconnection (CR)

- Boost in cluster rest frame
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- Compute $y_{\text{sum}} = |y_{q_B}| + |y_{\bar{q}_B}|$ with respect to $\hat{z}$
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- If $y_{q_B} < 0$ and $y_{\bar{q}_B} > 0$ for $y_{\text{sum}}^{\text{max}}$
- Find next to maximal y_{sum} cluster to make baryon-antibaryon pair
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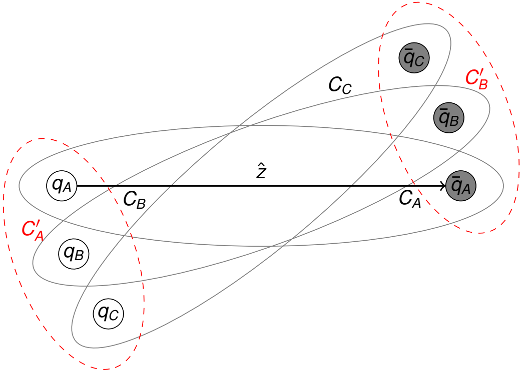

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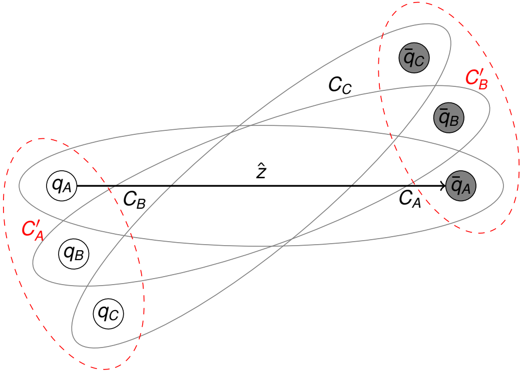
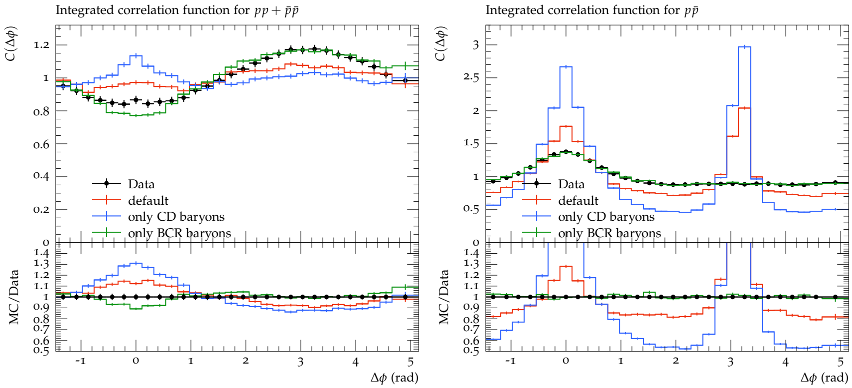
- **Note:** Clusters can be light for Baryon Production However a lot of multiplicity is needed!
- In fact BCR regulated the over-abundance of high multiplicity events [Gieseke, Kirchgaeßer, and Plätzer 2018]



Backup: Baryon Angular Correlations

- Depletion of near-sided baryons only reproduced by **Baryonic Colour Reconnection (BCR)**
- **Cluster Decay (CD)** baryons are giving opposite features to data
- Cluster Decay baryons are solely responsible for unphysical far-side peak
- BCR alone cannot produce enough baryons especially for low multiplicity events (e.g. at LEP)



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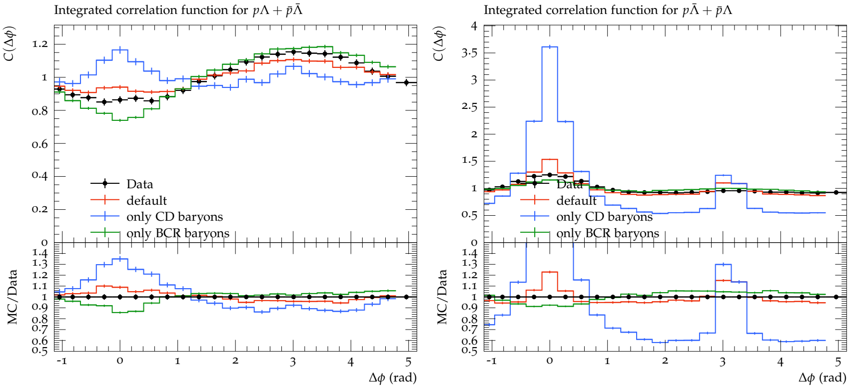

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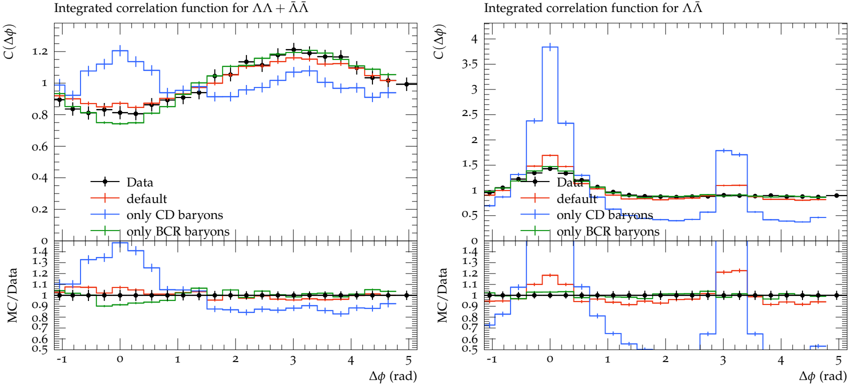
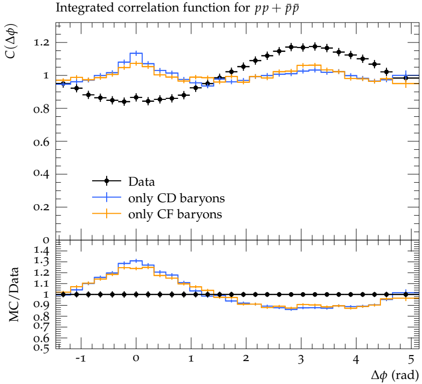
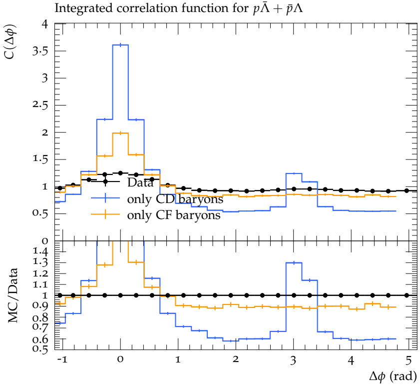


Backup: Cluster Fission vs Cluster Decay Baryons

- CD baryon mechanism vs new Cluster Fission (CF) mechanism
- Near-side depletion not reproduced

  ⇒ CD and CF are oblivious to other baryons





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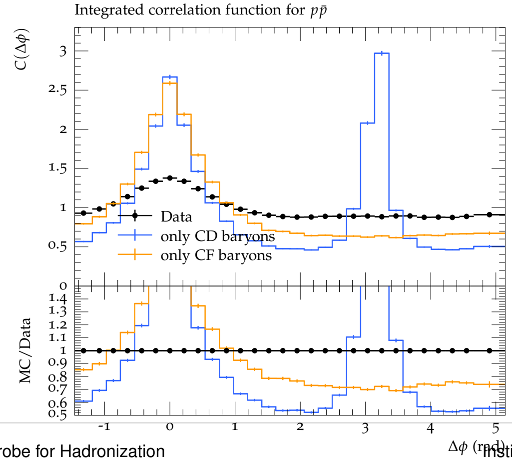

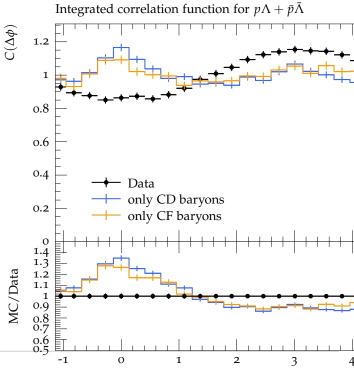

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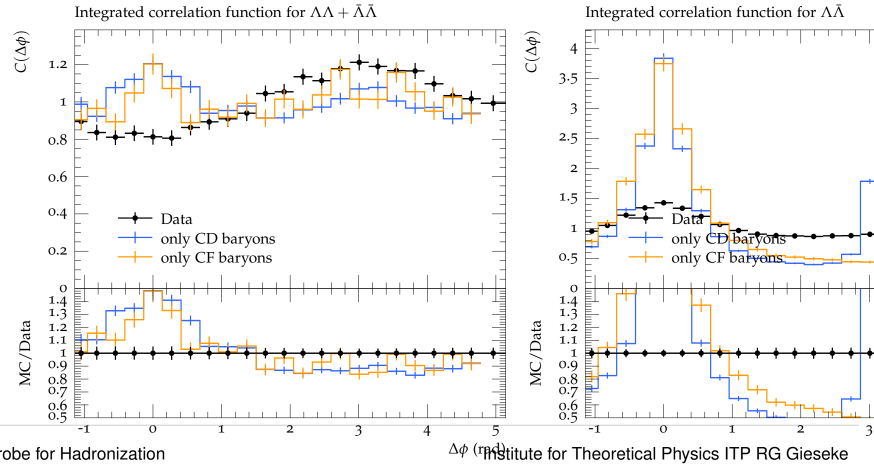
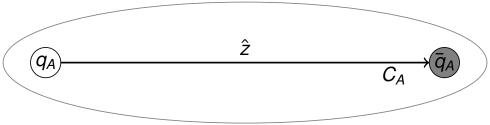


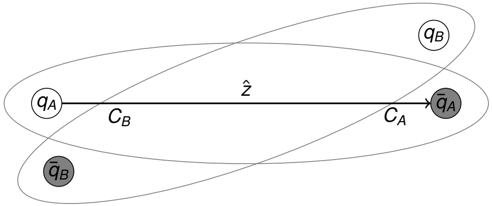
Backup: Diquark Colour Reconnection Algorithm

- Boost in cluster rest frame



Backup: Diquark Colour Reconnection Algorithm

- Boost in cluster rest frame
- Select next cluster at random



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- Compute $y_{\text{sum}} = |y_{q_B}| + |y_{\bar{q}_B}|$ with respect to $\hat{z}$
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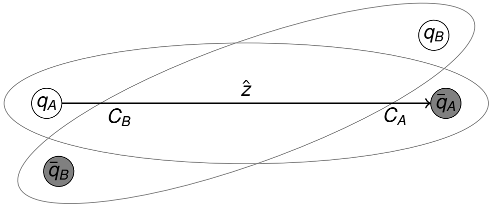

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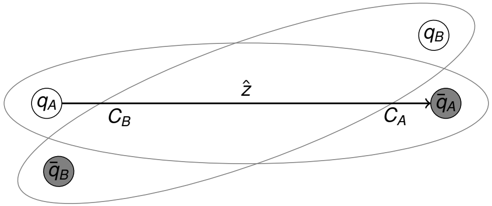

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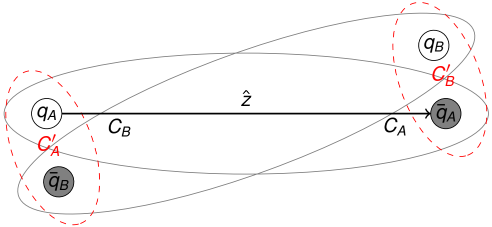
  $\Rightarrow$ Mesonic Colour Reconnection
  accepted with probability P_M



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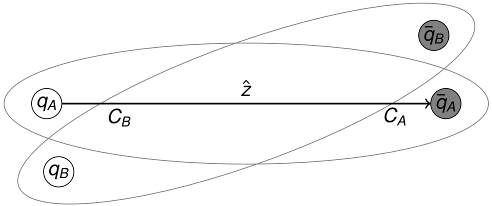

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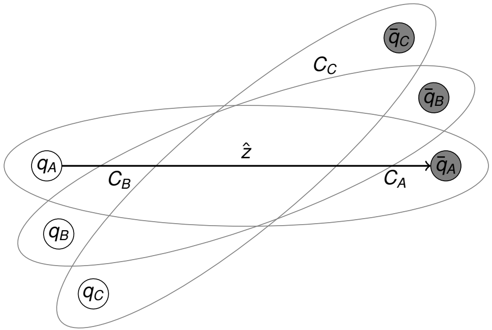

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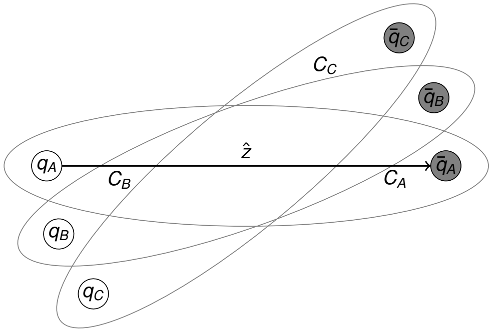

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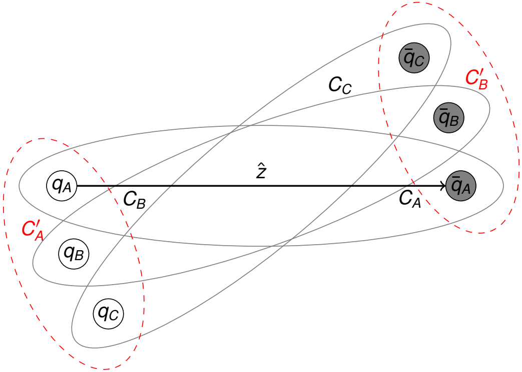
  $\Rightarrow$ Baryonic Colour Reconnection (BCR) accepted with probability P_B



Backup: Diquark Colour Reconnection Algorithm

Karlsruhe Institute of Technology

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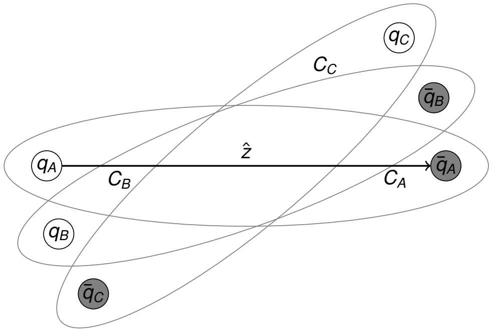

Backup: Diquark Colour Reconnection Algorithm

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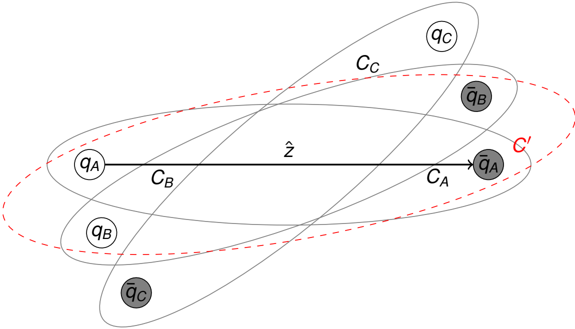
  $\Rightarrow$ Diquark Colour Reconnection (DCR) accepted with probability P_D



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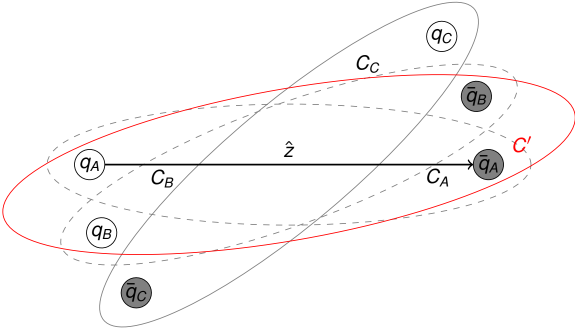
  $\Rightarrow$ Diquark Colour Reconnection (DCR)
  accepted with probability P_D if $M_{C'} > M_{\text{Baryon Pair}}^{\text{Lightest}}$



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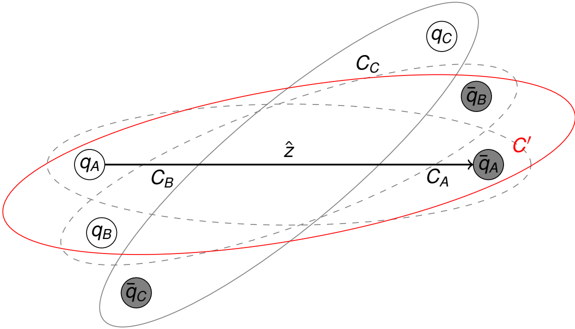
- **Note:** Mixed need for multiplicity and existing mass for producing baryons



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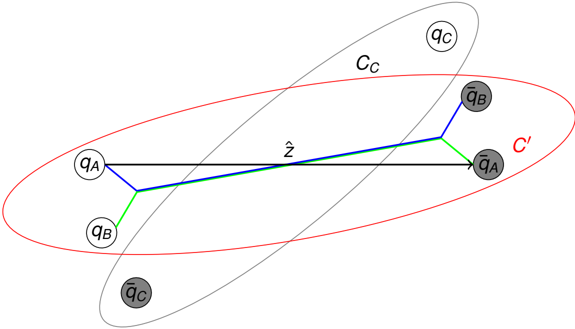
- **Note:** Mixed need for multiplicity and existing mass for producing baryons
- Similar to `Pythia`'s String Junction Colour Reconnections [Christiansen and Skands 2015]



Preliminary: New Cluster Fission Kinematics applied

- BELLE data for di-hadron mass spectrum improve for large z with Preliminary results

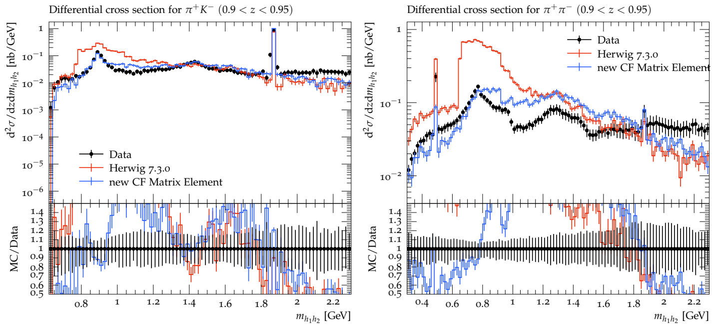
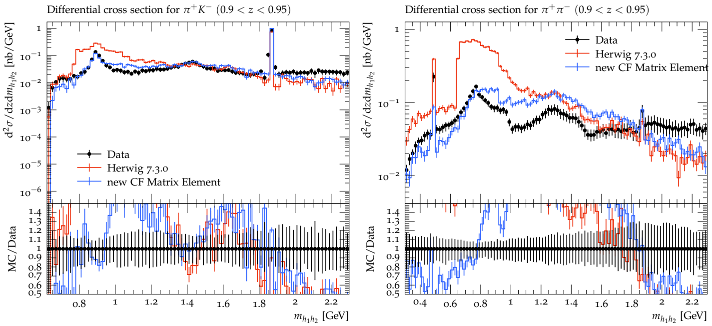


Figure: Thrust $T > 0.8$, $\vec{p}_1 \cdot \vec{p}_2 > 0$ and $z = \frac{2(E_1+E_2)}{\sqrt{s}}$ [Seidl et al. 2017]

Preliminary: New Cluster Fission Kinematics applied

- BELLE data for di-hadron mass spectrum improve for large z with Preliminary results
- However still very inefficient rejection sampling for large mass clusters (LEP manageable; LHC way too slow)



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Backup: Spectra of Protons

- Proton p_T-spectra are badly modelled

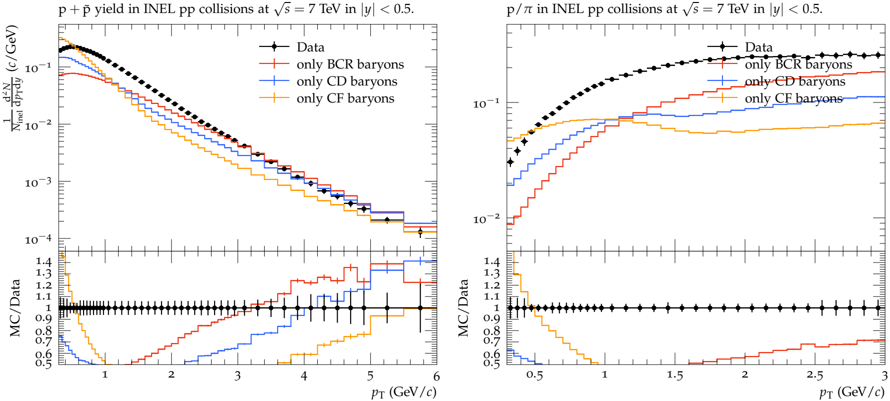

Figure: Compare p_T- spectra of p for only BCR, only CD or only CF baryon mechanisms [Adam et al. 2015]

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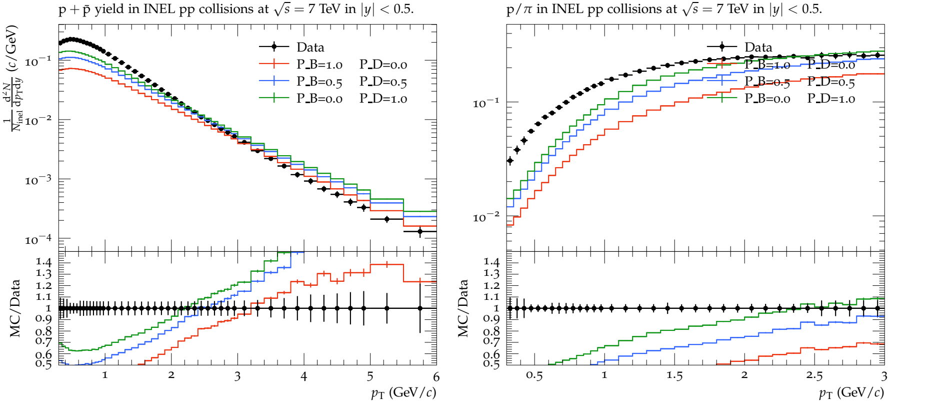

Figure: Compare p_T- spectra of p for only new DCR baryon mechanism with different probabilities [Adam et al. 2015]

Backup: Tuning

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Strategy:

1. Perform a dedicated tune to LEP multiplicities, event shapes and momentum spectra for CF, CR parameters

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Possible solutions: Use of a different "Loss function" than regular χ^2 e.g. $\chi^2 \rightarrow \frac{\chi^2}{1+\chi^2}$ or $\mathtt{tanh}(\chi^2)$

Backup: Cluster Fission Details

- A cluster of mass M is fissioned if $M^{\mathrm{Cl_{pow}}} \geq \mathrm{Cl}_{\mathrm{max}}^{\mathrm{Cl_{pow}}} + (m_1 + m_2)^{\mathrm{Cl_{pow}}}$, where m_1, m_2 are the masses of the constituents of the cluster
- Currently masses are sampled as follows, where $r_1, r_2 \in [0, 1]$ are uniform random numbers [Bahr et al. 2008]:

$$M_1 = m_1 + (M - m_1 - m_q) r_1^{\frac{1}{P_{\mathrm{split}}}} \tag{4}$$

$$M_2 = m_2 + (M - m_2 - m_q) r_2^{\frac{1}{P_{\mathrm{split}}}} \tag{5}$$

- Reject samples if $M_1 + M_2 > M$
- Problems: huge dependence on parameters $\mathrm{Cl}_{\mathrm{max}}$ and especially P_{split}
- Work in progress: Sample masses according to phase space

Backup: Angular Correlations

- The shown plots are showing correlations integrated in $\Delta\eta$ up to $\Delta\eta_{\text{max}} = 1.3$
- The angular correlations are measured via the event mixing [Adam et al. 2017]:

$$C_i(\Delta\phi, \Delta\eta) = \frac{S(\Delta\phi, \Delta\eta)}{B(\Delta\phi, \Delta\eta)} \tag{6}$$

$$S_i(\Delta\phi, \Delta\eta) = \frac{1}{N_{\text{pairs}}^{\text{same}}} \frac{d^2 N_{\text{pairs}}^{\text{same}}}{d\Delta\eta d\Delta\phi} \tag{7}$$

$$B_i(\Delta\phi, \Delta\eta) = \frac{1}{N_{\text{pairs}}^{\text{mixed}}} \frac{d^2 N_{\text{pairs}}^{\text{mixed}}}{d\Delta\eta d\Delta\phi} \tag{8}$$

$$C_i(\Delta\phi) = \int_0^{\Delta\eta_{\text{max}}} C_i(\Delta\phi, \Delta\eta) d\Delta\eta \tag{9}$$

Spectra of Protons

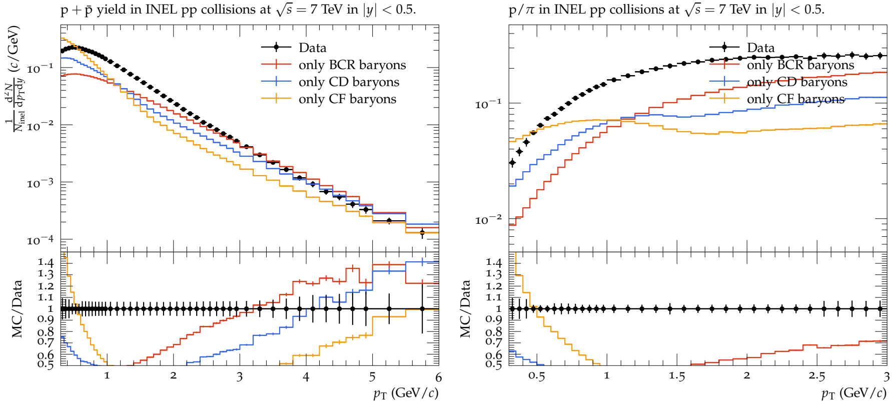

Figure: Compare p_T- spectra of p for only BCR, only CD or only CF baryon mechanisms [Adam et al. 2015]

Spectra of Protons

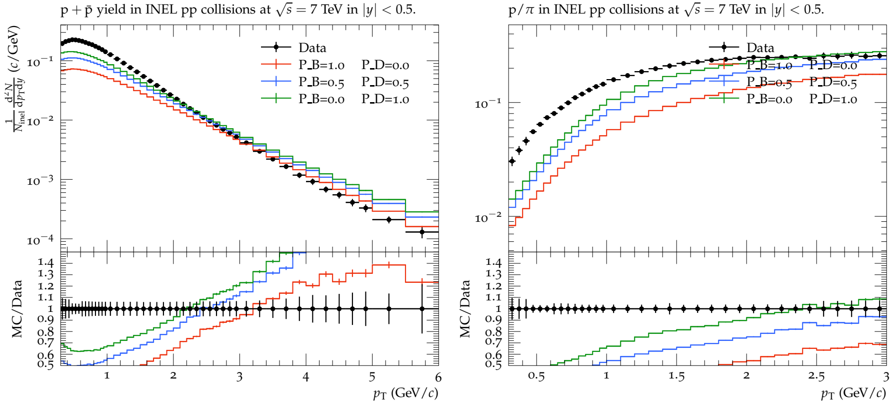

Figure: Compare p_T- spectra of p for only new DCR baryon mechanism with different probabilities [Adam et al. 2015]

Spectra of Strange Baryons

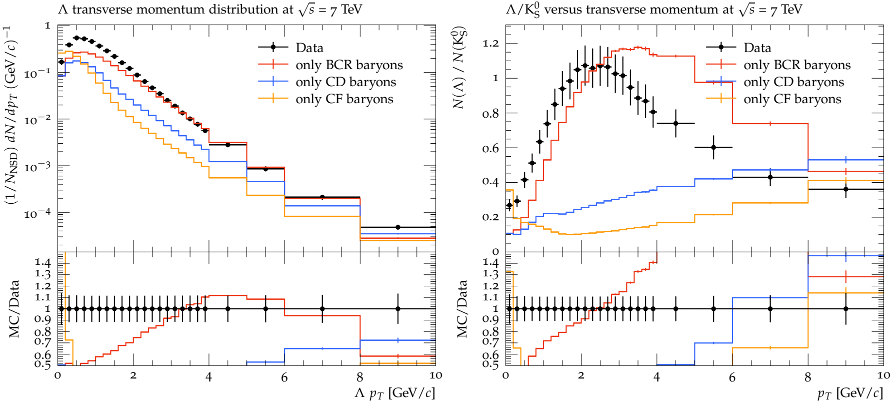

Figure: Compare p_T- spectra of Λ, Ξ for only BCR, only CD or only CF baryon mechanisms [Khachatryan et al. 2011]

Spectra of Strange Baryons

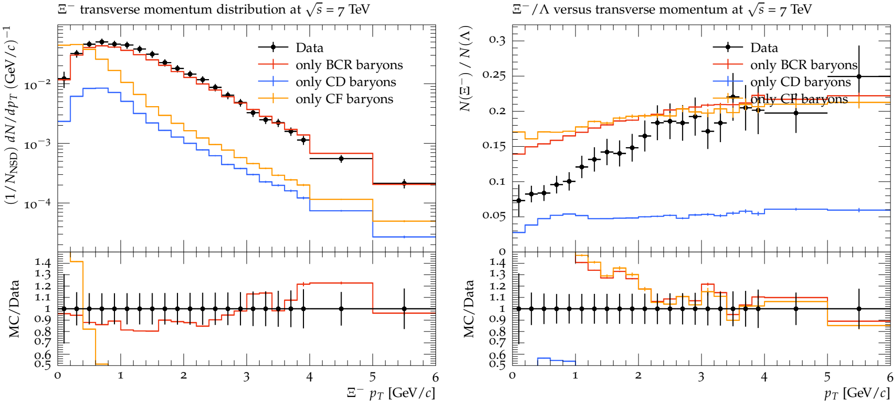

Figure: Compare p_T- spectra of Λ, Ξ for only BCR, only CD or only CF baryon mechanisms [Khachatryan et al. 2011]

Spectra of Strange Baryons

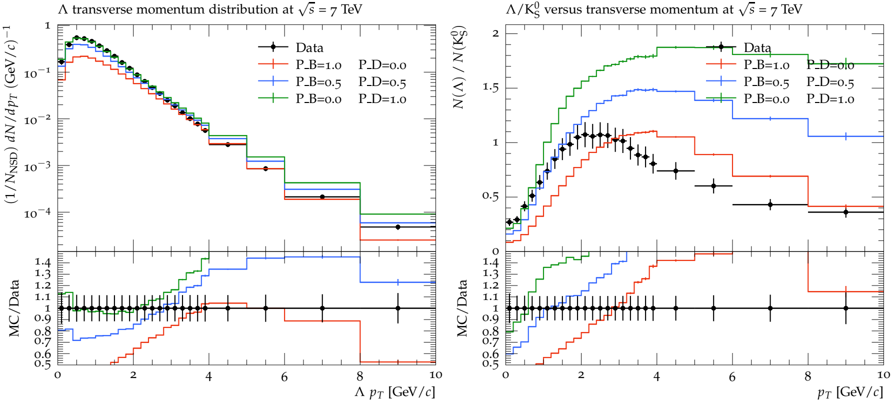

Figure: Compare p_T- spectra of Λ, Ξ baryons for only new DCR baryon mechanism with different probabilities [Khachatryan et al. 2011]

Spectra of Strange Baryons

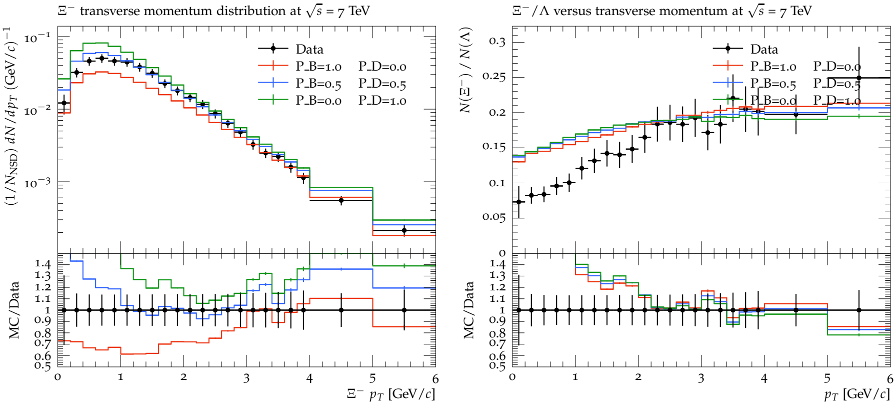

Figure: Compare p_T- spectra of Λ, Ξ baryons for only new DCR baryon mechanism with different probabilities [Khachatryan et al. 2011]

Consistent Two Particle Boost

- If we boost a two particle system $P = (p_i + p_j)$ into its rest frame $\hat{P} = (\hat{p}_i + \hat{p}_j)$ one needs to be careful to tranform the relative momentum correctly $\hat{P}_{\text{rel}} = (\hat{p}_i - \hat{p}_j)$
- The naive transformation would be to just use $\Lambda_{(-P)}$, but this would give in general $\hat{P}_{\text{rel}} = (\hat{p}_i - \hat{p}_j + 2k)$, because $\Lambda\hat{p}_i = p_i + k$ and $\Lambda\hat{p}_j = p_j - k$.
- Intuitively the momentum P is completely oblivious to its components and therefore Λ must depend on both the consituents p_i, p_j
- Want a Lorentz Tranformation (matrix or tensor) $\Lambda(p_i, p_j|\hat{p}_i, \hat{p}_j)$ such that $\Lambda\hat{p}_i = p_i$ and $\Lambda\hat{p}_j = p_j$
- Found solution for $\Lambda(p_i, p_j|\hat{p}_i, \hat{p}_j)$, but numerically not very easy
- Work in Progress: Tensor for this trafo $\Lambda^{\nu}{}_{\mu}$