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Institute for Theoretical Physics

Pinning Down A New Approach To Cluster Hadronization

Stefan Kiebacher with Stefan Gieseke and Simon Plätzer | Parton Showers and Resummation 2024 - Graz | July 4, 2024

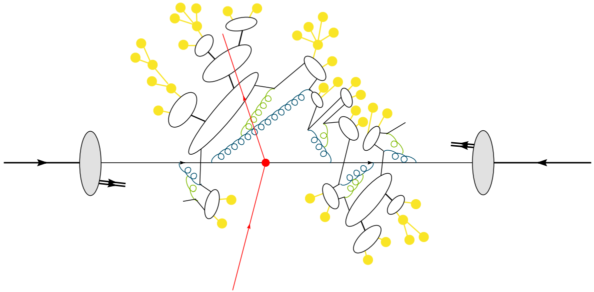
Introduction to Monte Carlo Event Generators

Monte Carlo event generators:

- Simulation of high energy particle collisions
- Different codes such as `Herwig`, `Sherpa` and `Pythia`

Stages of hadronization model in `Herwig`:

1. Gluon splitting to $q\bar{q}$
2. Primordial cluster formation
3. Colour Reconnection (CR)
4. Cluster Fission (CF)
5. Cluster Decay (CD)



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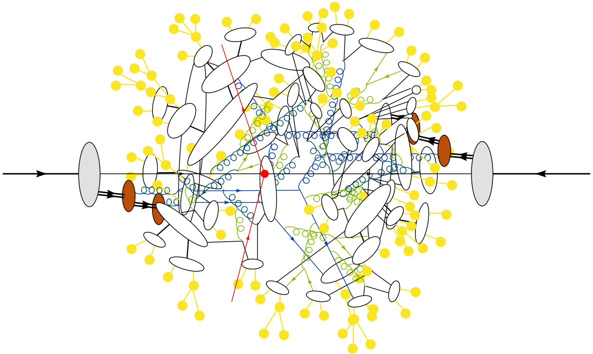

Cluster Hadronization

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- Cluster model [Marchesini and Webber 1984] is based on preconfinement [Amati and Veneziano 1979] was designed to be so simple to be easily excluded by data

  $\Rightarrow$ Still around and **unreasonably good** at describing data
- Many ad-hoc phenomenological modelling choices compared to Lund string model
- In the context of colour evolution it is not infra-red safe [Plätzer 2022]
- In the cluster model we need to impose kinematics. How can we test these imposed kinematics?

  $\rightarrow$ **Correlations of hadrons!**

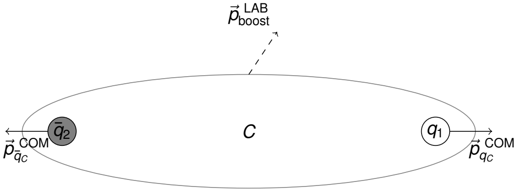
Outline:

- Describe the current cluster model
- Show the current failures of the cluster model in correlation data
- Present parts of a new cluster model, which show interesting features
- Show improvements/effects on observables at e^+e^- at different $\sqrt{s}$
- Show sensitivity of some observables to different parts of the cluster model

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 $M_1, M_2 \sim (M_1 M_2)^{\alpha}$ 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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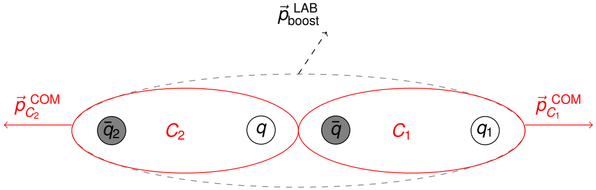
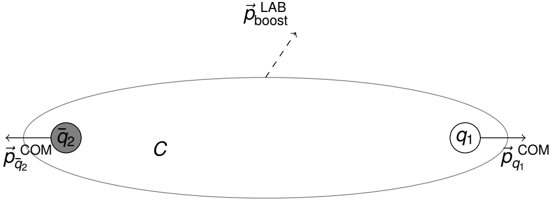


Cluster Decay (CD)

- 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 $B(q_1, (q, q')), \bar{B}'(\bar{q}_2, (\bar{q}, \bar{q}'))$
  3. The direction of decay is chosen isotropically in the cluster rest frame (except for b, c containing clusters)
- **Note:** High-mass clusters can produce **baryons**!



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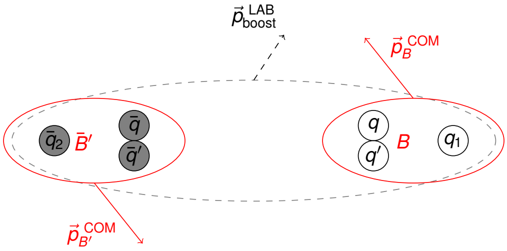


Baryon-Antibaryon Angular Correlations

- **Cluster Decay (CD)** baryons are responsible for unphysical far-side peak
- **Cluster Fission (CF)** baryons solve the unphysical far-side peak
- Switching CF baryons on and CD baryons off is not the full story:
  - Soft peak of p_T spectra not present [Adam et al. 2015]
  - At LEP meson in the middle $pM\bar{p}$ is ill-modelled [Abreu et al. 2000]

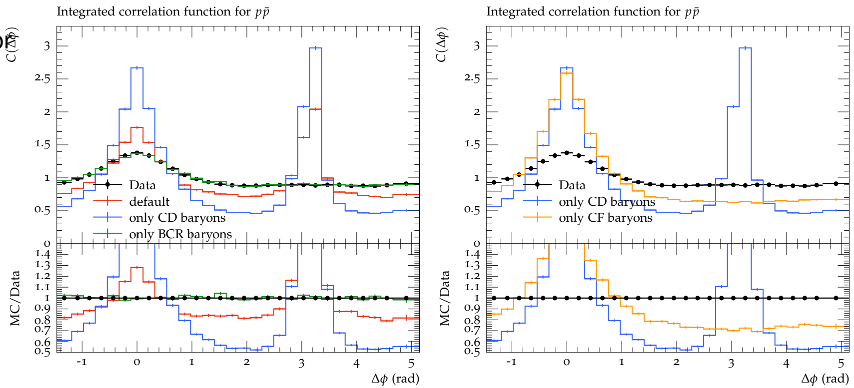


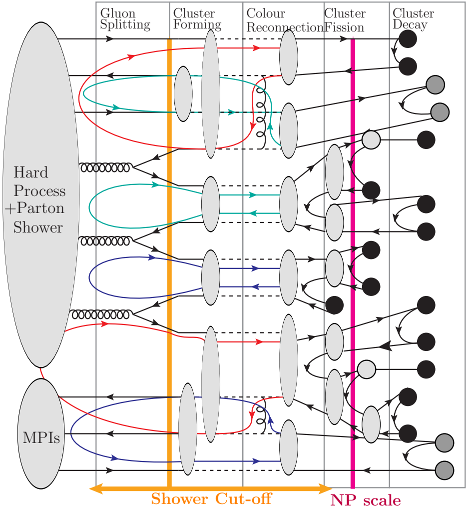
Figure: measured by ALICE [Adam et al. 2017]

Hadronization From Colour Evolution

Idea of colour evolution picture [Plätzer 2023]:

- **Shower Cut-off** is a factorization scale (see also [Hoang et al. 2024])
- Parton shower, Colour Reconnection and Hadronization (Cluster Fission) should be matched
- Final non-perturbative scale (**NP scale**) interfaces to the initial condition

Consequence: Cluster Fission is a perturbative process similar to the parton shower. Only Cluster Decay is non-perturbative (could be obtained from lattice QCD)



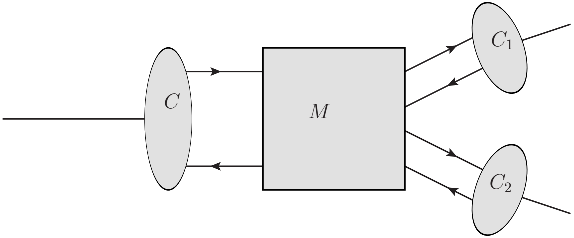
New Cluster Fission Kinematics

Consequence: CF is a partonic $2 \to 4$ process [Plätzer 2023]. CF should continue the "job" of the parton shower.

- Factorize the process $C(p_1, p_2) \to C_1(q_1, q), C_2(q_2, \bar{q})$ (see Jan Priedigkeit's Bachelor thesis Graz):

$$d\Gamma(C \to C_1, C_2) = \int d\Phi_4(P|q_1, q, \bar{q}, q_2)|\mathcal{M}(p_1, p_2 \to q_1, q, \bar{q}, q_2)|^2 \quad (1)$$

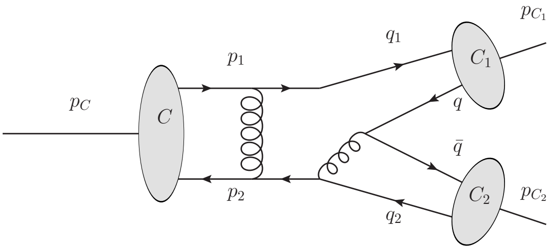
$$d\Gamma(C \to C_1, C_2) \propto \int dM_1^2 dM_2^2 d\Phi_2(P|Q_1, Q_2) d\Phi_2(Q_1|q_1, q) d\Phi_2(Q_2|q_2, \bar{q})|\mathcal{M}(p_1, p_2 \to q_1, q, \bar{q}, q_2)|^2 \quad (2)$$

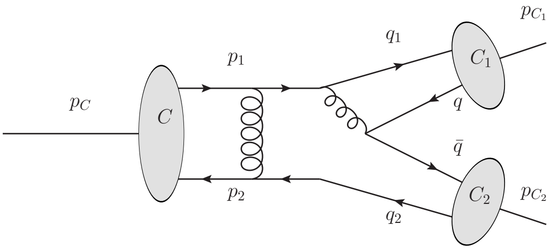


New Cluster Fission Kinematics

- Sample Masses M_1, M_2 from flat Phase Space weight
  $d\Phi_4 \propto dM_1 dM_2 \sqrt{\lambda(M, M_1, M_2)}\sqrt{\lambda(M_1, m_1, m)}\sqrt{\lambda(M_2, m_2, m)}/(M_1 M_2)$
- Importance sampling of soft $q\bar{q}$ emission diagram, which in the soft limit factorizes [Catani and Grazzini 2000]:

$$|\mathcal{M}(p_1, p_2 \to q_1, q, \bar{q}, q_2)|^2 \propto |\mathcal{M}(p_1, p_2 \to q_1, q_2)|^2 \frac{2(q_1 \cdot q_2)(q \cdot \bar{q}) + [q_1 \cdot (q - \bar{q})][q_2 \cdot (q - \bar{q})]}{2(q \cdot \bar{q})^2 [q_1 \cdot (q + \bar{q})][q_2 \cdot (q + \bar{q})]}$$



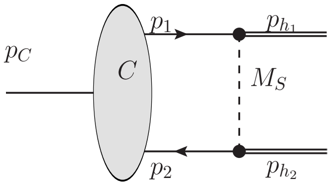


New Cluster Decay Kinematics

- Idea: Again describe cluster decay by an "effective" matrix element
- Which matrix element? $\Rightarrow$ t-channel like to preserve local parton-hadron duality
- Avoid hard transition from CF $\rightarrow$ CD

$$|\mathcal{M}_{\mathrm{CD}}(p_1, p_2 \rightarrow p_{h_1}, p_{h_2})|^2 \propto \frac{1}{[(p_1 - p_3)^2 - M_S^2]^2} \propto \frac{1}{[A - \cos(\theta)]^2},$$

$$\text{with } A > 1 \text{ if } M_S = \max\{(m_1 - m_{h_1}), (m_2 - m_{h_2})\}$$



Di-hadron mass spectra

- Observable probes final cluster mass distribution $m_{h_1 h_2}$ for $z \lesssim 1$
- Default gives unphysical plateau
- Mass phase space resolves the behaviour
- Cluster Decay (CD) has impact
- Missing resonance due to hard cutoff for CF

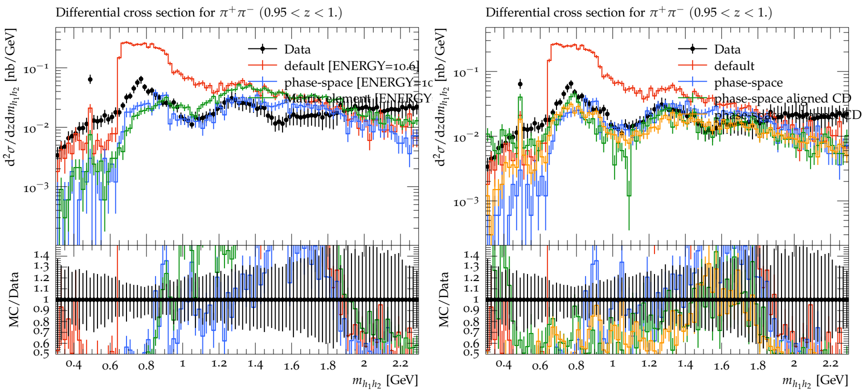


Figure: measured by BELLE [Seidl et al. 2017a]

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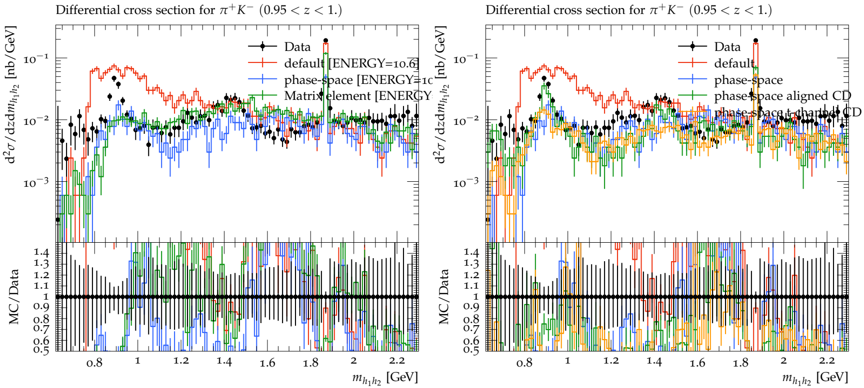

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pT in/out spectra

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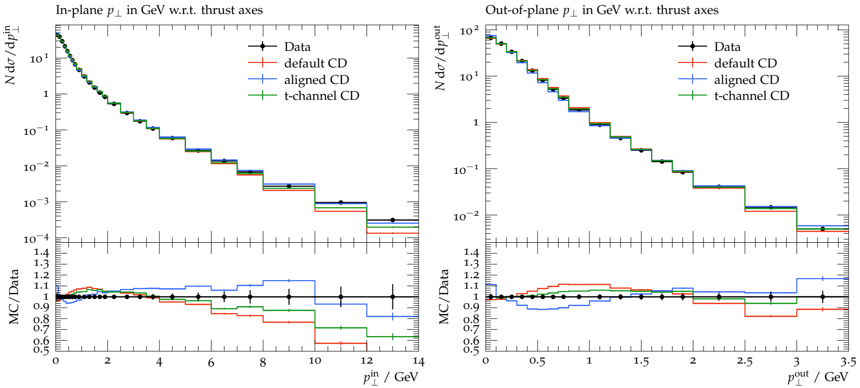
- LEP at the Z pole
- Default isotropic CD spits multiplicity in/out of plane
- Aligned CD overcorrects for this
- t-channel CD gives most reasonable prediction



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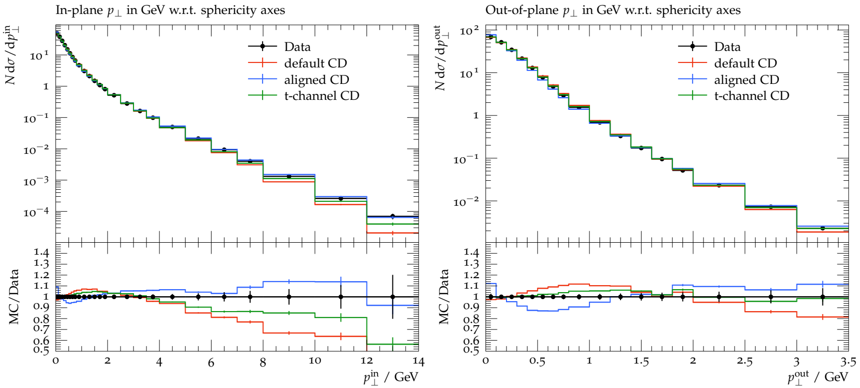

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Generalized Angularities

- LEP at the Z pole
- Generalized angularities $\lambda_\beta^\alpha = \sum_{i \in \text{jet}} z_i^\beta \theta_{i,\text{jet}}^\alpha$ with $z_i = \frac{E_i}{E_{\text{vis}}}$

  [Gras et al. 2017; Larkoski, Moult, and Neill 2014]
- Discriminative power between CF and CD

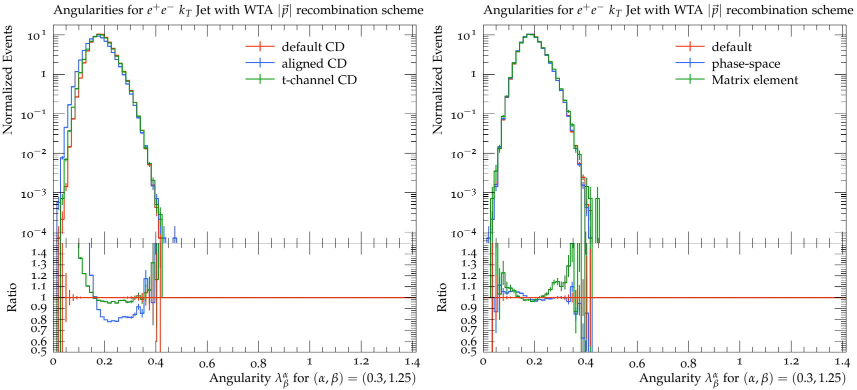

Figure: Generalized angularities $\alpha = 0.3$, $\beta = 1.25$

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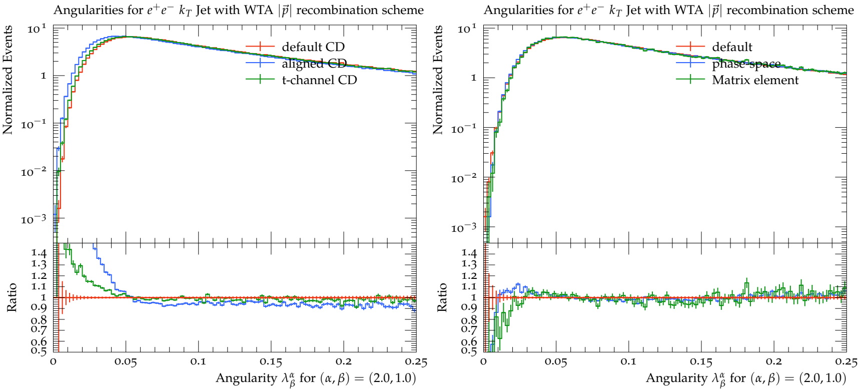

Figure: Generalized angularities $\alpha = 2, \beta = 1$

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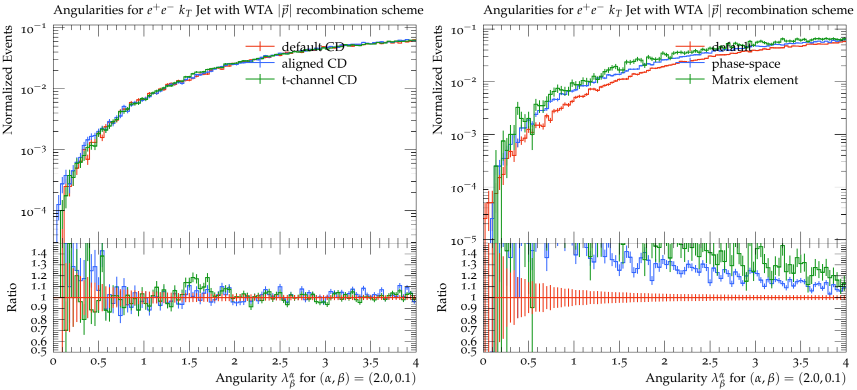

Figure: Generalized angularities $\alpha = 2, \beta = 0.1$

Energy-weighted Correlations

- LEP at the Z pole
- Energy-weighted correlations $EEC^{\gamma}(\rho) = \frac{1}{N_\gamma} \sum_{i<j\in \text{jet}} (E_i E_j)^{\gamma} \delta(\Delta R_{ij} - \rho)$ with $N_\gamma = \sum_{i<j\in \text{jet}} (E_i E_j)^{\gamma}$
- Discriminative power between CF and CD

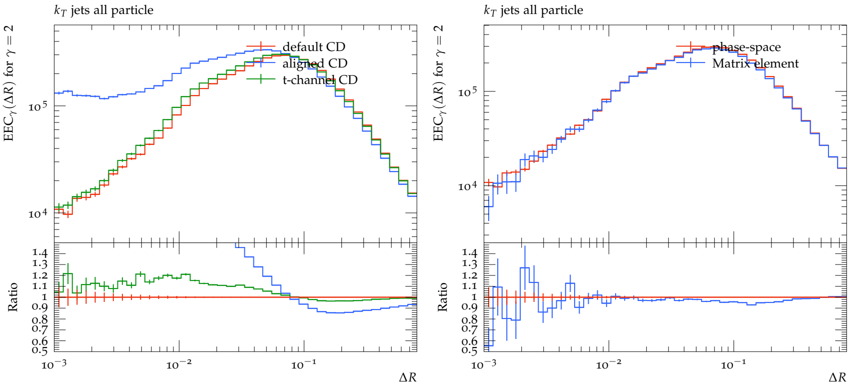

Figure: Correlations for $\gamma = 2.0$

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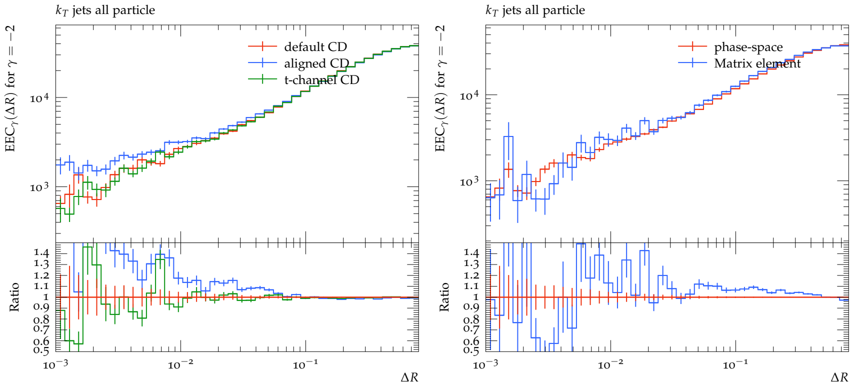

Figure: Correlations for $\gamma = -2.0$ $\Rightarrow$ "Infrared dangerous"

Summary and Outlook

Summary:

- Found shortcomings of the kinematics of the cluster model in the correlations
- Try to address these issues with a new cluster hadronization model, motivated by colour evolution
- Found observables which may be able to discriminate between different stages of hadronization

Outlook for hadronization in `Herwig`:

- Examine the model with a dynamic CF threshold as is the default in `Herwig 7.3.x` [Bewick et al. 2023]
- Merge our work with dynamic gluon constituent masses and cluster fission [Hoang et al. 2024]
- Make Colour Reconnection **dynamic** via soft gluon evolution [Gieseke et al. 2018; Plätzer 2023] (WIP with S. Plätzer, S. Gieseke)

Thank You For Your Attention!

Questions? Remarks? Comments?

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Backup: Meson in the middle

- If we only consider baryon production due to CF we ill-model rapidity rank structure

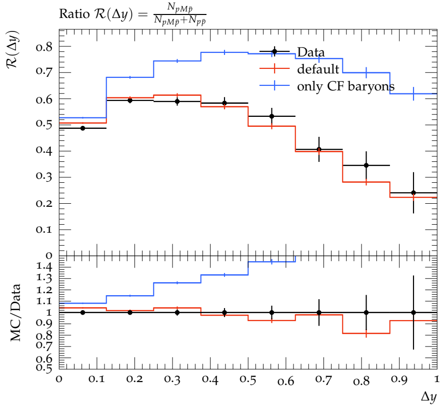

Figure: Rapidity rank structure by DELPHI only CD or only CF baryon mechanisms [Abreu et al. 2000]

Backup: Spectra of Protons

- Proton p_T-spectra are badly modelled

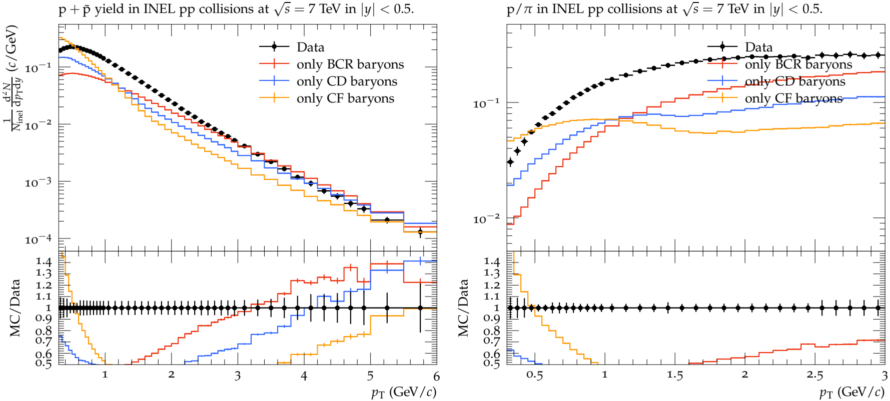

Figure: Compare p_T- spectra of p for only BCR, only CD or only CF baryon mechanisms [Adam et al. 2015]

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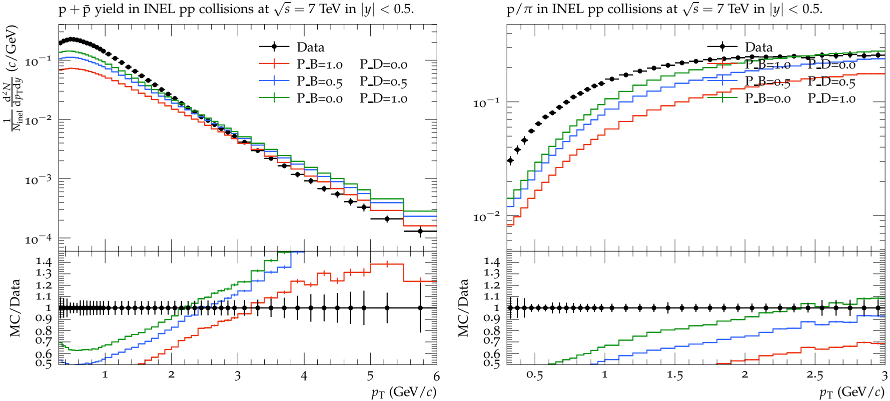

Figure: Compare p_T- spectra of p for only new DCR baryon mechanism with different probabilities [Adam et al. 2015]

Backup: Cluster Fission vs Cluster Decay Baryons

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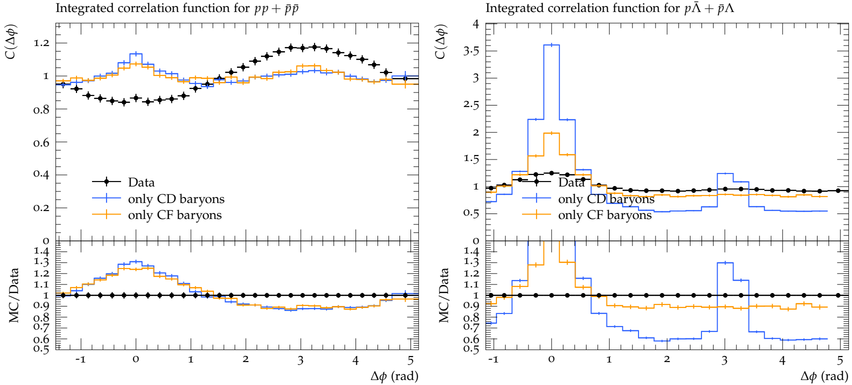
- CD baryon mechanism vs new Cluster Fission (CF) mechanism
- Near-side depletion not reproduced

  $\Rightarrow$ CD and CF are oblivious to other baryons



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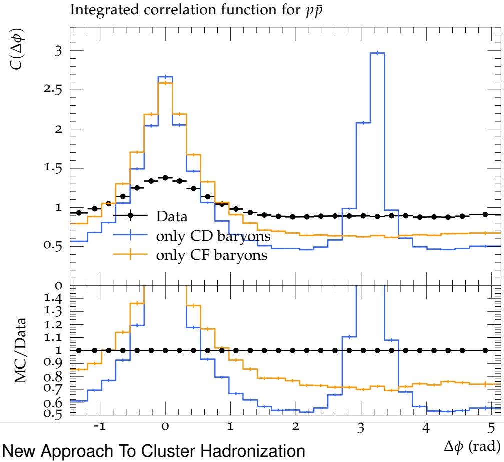

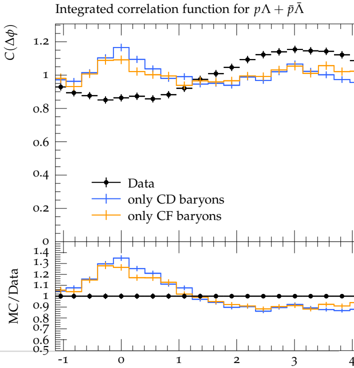

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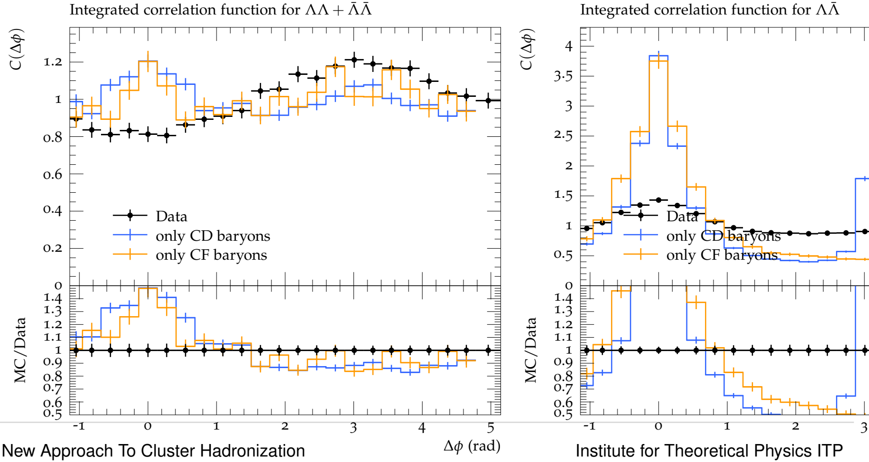

Preliminary: New Cluster Fission Kinematics applied

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

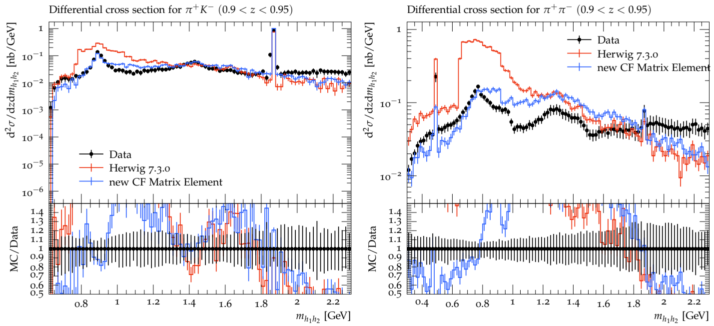

Figure: Thrust $T > 0.8$, $\vec{p}_1 \cdot \vec{p}_2 > 0$ and $z = \frac{2(E_1+E_2)}{\sqrt{s}}$ [Seidl et al. 2017b]

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)

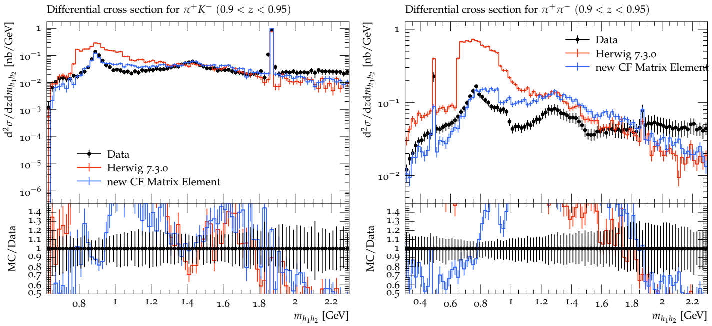

Figure: Thrust $T > 0.8$, $\vec{p}_1 \cdot \vec{p}_2 > 0$ and $z = \frac{2(E_1+E_2)}{\sqrt{s}}$ [Seidl et al. 2017b]

Backup: Tuning

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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 $\tanh(\chi^2)$

Backup: Cluster Fission Details

- A cluster of mass M is fissioned if $M^{\mathrm{Cl}_{\mathrm{pow}}} \geq \mathrm{Cl}_{\mathrm{max}}^{\mathrm{Cl}_{\mathrm{pow}}} + (m_1 + m_2)^{\mathrm{Cl}_{\mathrm{pow}}}$, 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]:

$$M_1 = m_1 + (M - m_1 - m_q) r_1^{\frac{1}{P_{\mathrm{split}}}} \tag{3}$$

$$M_2 = m_2 + (M - m_2 - m_q) r_2^{\frac{1}{P_{\mathrm{split}}}} \tag{4}$$

- 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]:

$$C_i(\Delta\phi, \Delta\eta) = \frac{S(\Delta\phi, \Delta\eta)}{B(\Delta\phi, \Delta\eta)} \tag{5}$$

$$S_i(\Delta\phi, \Delta\eta) = \frac{1}{N_{\text{pairs}}^{\text{same}}} \frac{d^2 N_{\text{pairs}}^{\text{same}}}{d\Delta\eta d\Delta\phi} \tag{6}$$

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

$$C_i(\Delta\phi) = \int_0^{\Delta\eta_{\text{max}}} C_i(\Delta\phi, \Delta\eta) d\Delta\eta \tag{8}$$

Spectra of Protons

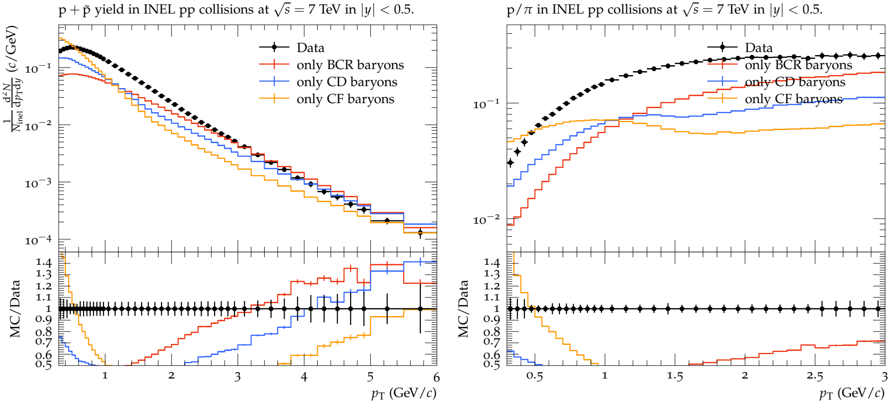

Figure: Compare p_T- spectra of p for only BCR, only CD or only CF baryon mechanisms [Adam et al. 2015]

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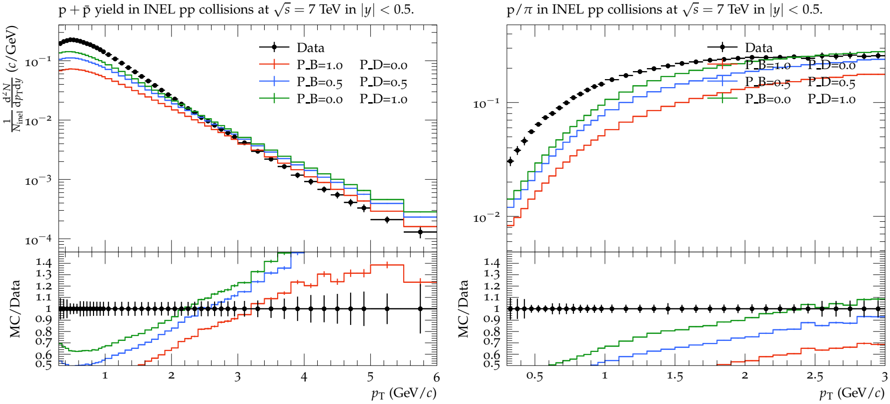

Figure: Compare p_T- spectra of p for only new DCR baryon mechanism with different probabilities [Adam et al. 2015]

Spectra of Strange Baryons

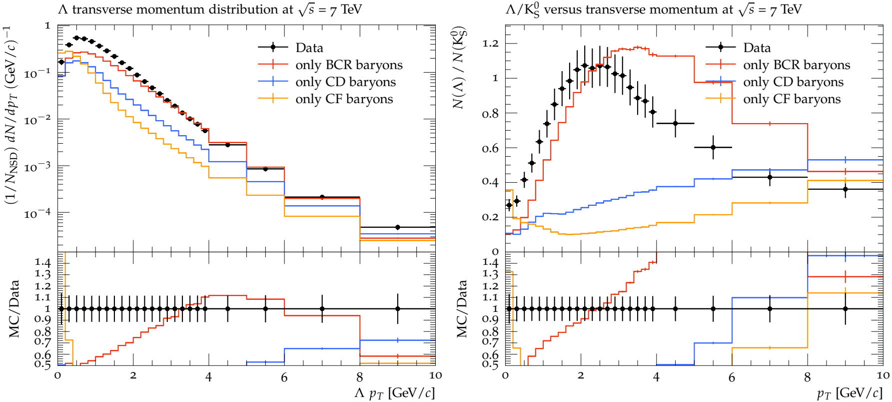

Figure: Compare p_T- spectra of Λ, Ξ for only BCR, only CD or only CF baryon mechanisms [Khachatryan et al. 2011]

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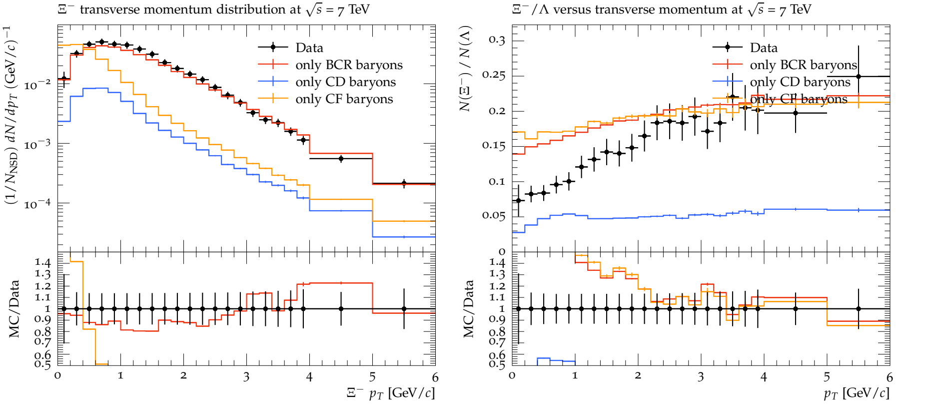

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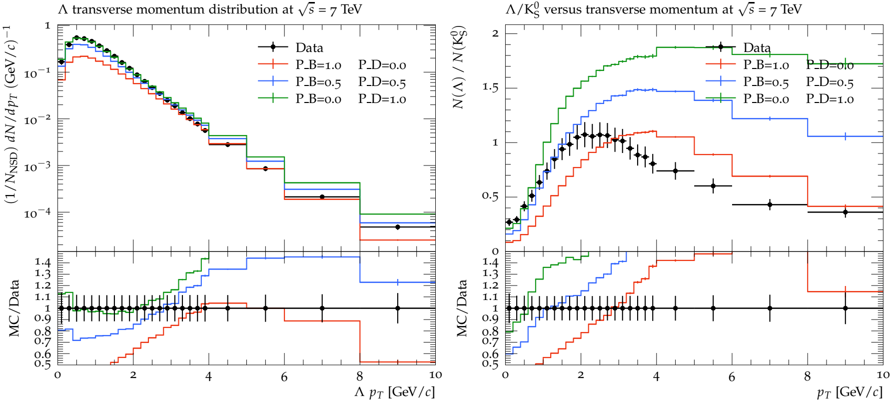

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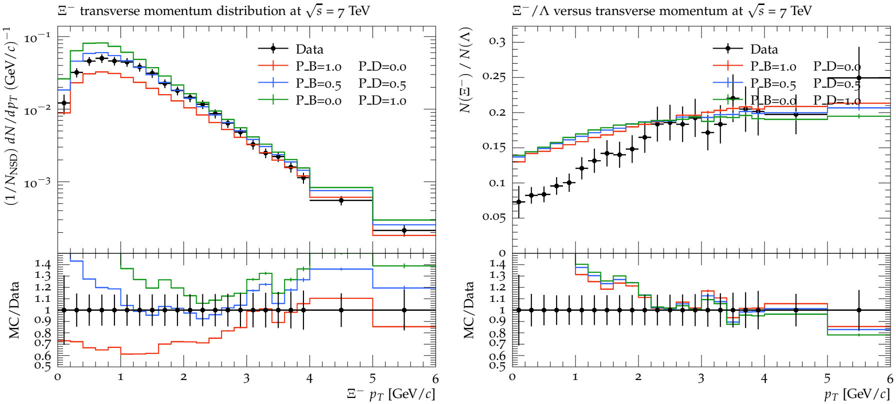

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Consistent Two Particle Boost

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- 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 $\Lambda^{\nu}{}_{\mu}$