Non-perturbative Corrections and Models

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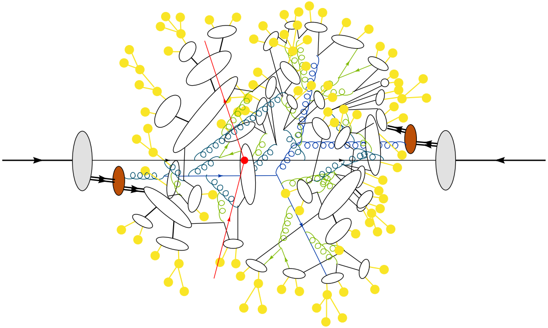
Motivation: Why do we need models?

QCD: quarks & gluons → observed hadrons



Monte Carlo Event Generator:

PDF

Hard interaction

Multi parton interactions

Diffraction

Parton shower

Hadronization

Colour reconnection

Decay

Motivation: From LEP to LHC

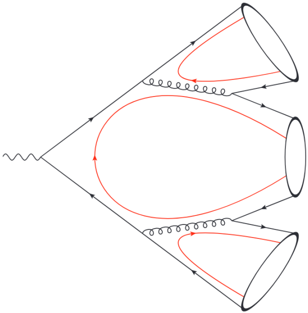
- LEP:
  - Hard process + Parton Shower + Hadronization
- LHC:
  - Tune hadronization model to LEP data
  - Add MPI
  - Add diffraction
  - Add colour reconnection
- Precision of LHC measurements often limited by non-perturbative components
- e.g. Daniel Samitz talk: $\Delta_m^{\mathrm{non-pert}} \neq 0$

This talk: **colour reconnection**

Outline

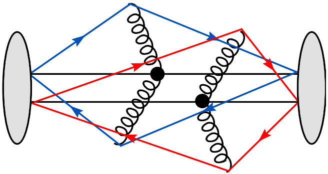
The cluster hadronization model

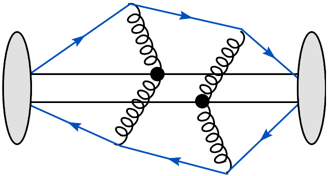
- Parton showers → colour preconfinement
- $N_c \to \infty$ limit: gluons= colour+ anticolour
- Colour connected partons → clusters
- Properties of cluster determined by its invariant mass
  $M^2 = (p_1 + p_2)^2$



Colour reconnection

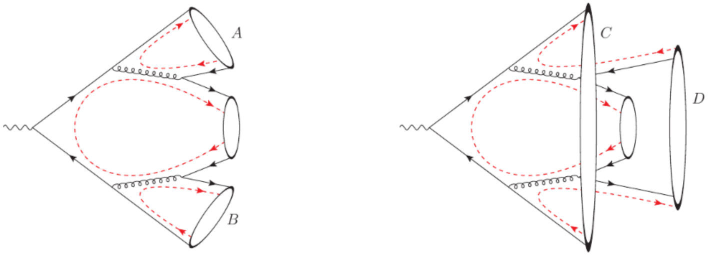
- Colour connection between different scattering centers unclear
- Expect further dynamics present responsible for colour exchange
- Encoded in forms of colour reconnection
- In Hadronization model: correspond to reduction of string length/cluster mass





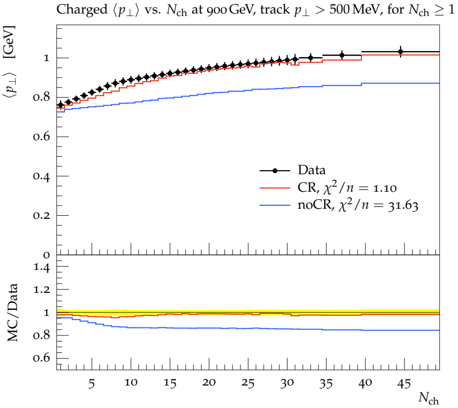
Colour reconnection model in Herwig

- Plain colour reconnection model [Röhr, Gieseke, Siodmok, EPJC C72 (2012)]
- If $M_C + M_D < M_A + M_B$ accept alternative cluster configuration with probability p_{reco}
- Important for hadron collision to restore colour pre-confinement (works pretty well at LEP)



Colour reconnection

- E.g. $\langle p_\perp \rangle$ vs. N_{ch}
- Necessary for the description of Minimum Bias (MB) and Underlying Event (UE) observables



Outline

Perturbative colour evolution

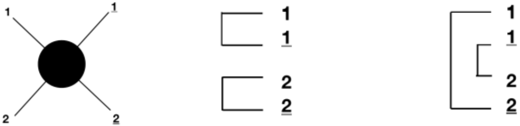
- QCD scattering apmplitudes are vectors in (spin) and colour space

$$|\mathcal{M}\rangle = \sum_{\sigma} \mathcal{M}_{\sigma} |\sigma\rangle$$

- In colour flow basis we can describe colour flow from one leg to another

$$|\sigma\rangle = \left| \begin{matrix} 1 & \cdots & n \\ \sigma(1) & \cdots & \sigma(n) \end{matrix} \right\rangle = \delta^{1}_{\sigma(1)} \cdots \delta^{n}_{\sigma(n)} \, .$$

- E.g. system with 4 legs (2 quarks and 2 antiquarks)



$$\left| \begin{matrix} \bar{1} & \bar{2} \\ 1 & 2 \end{matrix} \right\rangle = |12\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad |21\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

[Plätzer, EPJC 74 (2014) 6], [Martinez, De Angelis, Forshaw, Plätzer, JHEP 1805 (2018) 044]

Perturbative colour evolution

- Bare amplitude can be related to the renormalized amplitude as

$$|\mathcal{M}(\{p\},\mu^2)\rangle = \mathbf{Z}^{-1}(\{p\},\mu^2,\epsilon)|\tilde{\mathcal{M}}(\{p\},\epsilon)\rangle \ ,$$

- Structure of **Z** governed by RGE

$$\mu^2\frac{\mathrm{d}}{\mathrm{d}\mu^2}|\mathcal{M}(\{p\},\mu^2)\rangle = \Gamma(\{p\},\mu^2)|\mathcal{M}(\{p\},\mu^2)\rangle$$

with the soft-anomalous dimension

$$\Gamma(\{p\},\mu^2) = -\mathbf{Z}^{-1}(\{p\},\mu^2,\epsilon)\mu^2\frac{\partial}{\partial\mu^2}\mathbf{Z}(\{p\},\mu^2,\epsilon).$$

Perturbative colour evolution

- Evolution equation can be solved by

$$|\mathcal{M}(\{p\},\mu^2)\rangle = \mathbf{U}(\{p\},\mu^2,\{M_{ij}^2\})|\mathcal{H}(\{p\},Q^2,\{M_{ij}^2\})\rangle,$$

where

$$\mathbf{U} = \exp\left(\int_{\mu^2}^{M_{\alpha\beta}^2} \frac{\mathrm{d}q^2}{q^2} \Gamma(p,q^2)\right)$$

$\rightarrow$ Final colour structure depends on soft anomalous dimension

Perturbative colour evolution

- Soft-anomalous dimension [Becher, Neubert, Phys. Rev. Lett. 102 (2009)]

$$\Gamma(\{p\},\mu^2) = \sum_{i\neq j}(-\mathbf{T}_i\cdot\mathbf{T}_j)\gamma_{\text{cusp}}\ \ln\left(\frac{-s_{ij}}{\mu^2}\right) + \sum_i \gamma_i$$

- At 1-loop: $\gamma_{\text{cusp}} = \alpha_s/2\pi$
- Neglect γ^i (no effect on colour structure)
- The evolution operator then becomes

$$\begin{aligned}\mathbf{U}\left(\{p\},\mu^2,\{M_{ij}^2\}\right) &= \exp\left(-\sum_{i\neq j}\int_{\mu^2}^{M_{ij}^2}\frac{\mathrm{d}q^2}{q^2}(-\mathbf{T}_i\cdot\mathbf{T}_j)\gamma_{\text{cusp}}\ \left(\ln\frac{2p_i\cdot p_j}{q^2} - i\pi\right)\right)\\ &= \exp\left(\sum_{i\neq j}\mathbf{T}_i\cdot\mathbf{T}_j\frac{\alpha_s}{2\pi}\left(\frac{1}{2}\ln^2\frac{M_{ij}^2}{\mu^2} - i\pi\ln\frac{M_{ij}^2}{\mu^2}\right)\right)\end{aligned}$$

Perturbative colour evolution

- Evolve a given colour flow $|\tau\rangle$ and project onto different flows

$$\mathcal{A}_{\tau\to\sigma} = \langle\sigma|\mathbf{U}\left(\{p\},\mu^2,\{M_{ij}^2\}\right)|\tau\rangle \; .$$

- We can then define a *reconnection probability*

$$P_{\tau\to\sigma} = \frac{|\mathcal{A}_{\tau\to\sigma}|^2}{\sum_\rho |\mathcal{A}_{\tau\to\rho}|^2} \; ,$$

Example: colour evolution for two clusters

- Start evolution with initial colour flow $|12\rangle$

$$|\tau\rangle = U|12\rangle = U_{11}|12\rangle + U_{12}|21\rangle$$

- Project out all possible colour flows

$$\langle 12|\tau\rangle = U_{11}\langle 12|12\rangle + U_{12}\langle 12|21\rangle$$

$$\langle 21|\tau\rangle = U_{11}\langle 21|12\rangle + U_{12}\langle 21|21\rangle$$

where

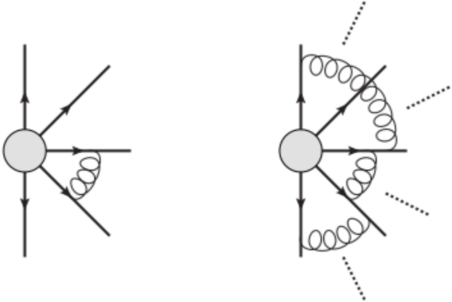
$$\langle\sigma|\tau\rangle = N_C^{m-\#\text{transpositions}(\sigma,\tau)}$$

Probability for alternative colour flow

$$\mathcal{P} = \frac{|\langle 21|\tau\rangle|^2}{|\langle 12|\tau\rangle|^2 + |\langle 21|\tau\rangle|^2}$$

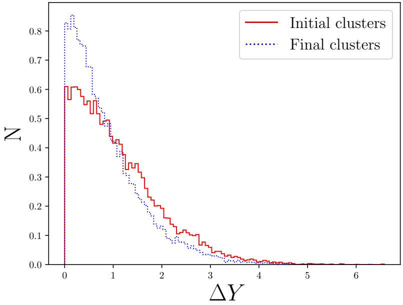
Strategy

- Consider soft gluon exchanges between all legs
- Evolve colour structure to decide which quarks to connect
- Arrive at different input for hadronization models

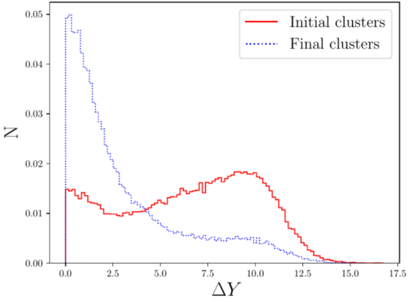


Numerical results

- Toy Monte Carlo to study colour evolution of up to 5 clusters ($\rightarrow$ 120 possible colour flows)
- Use different quark kinematics:
  - RAMBO phase space
  - Multiperipheral phase space (UA5)



RAMBO



UA5

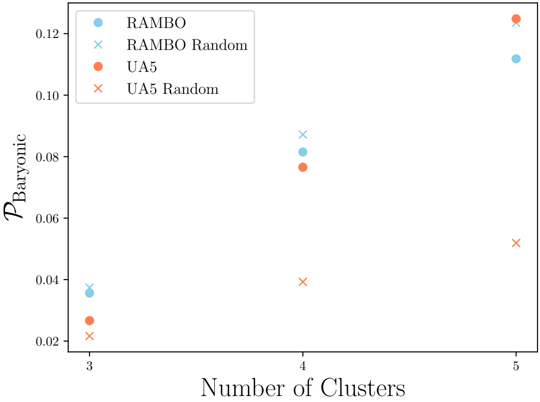
Baryonic colour reconnection

- Motivation: MC underestimate baryons at the LHC
- Improved description with baryonic colour reconnection
  [Gieseke, PK, Plätzer, EPJC 78 (2018) 99]
- Amplitude for evolution into a baryonic state

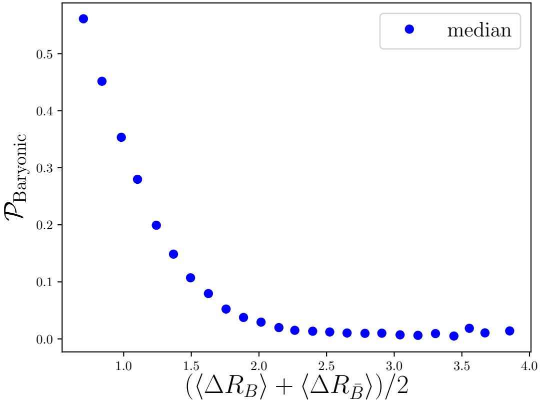
$$\mathcal{A}_{\tau \to B_{ijk} \otimes \tilde{\sigma}_{ijk}} = \langle B_{ijk}| \otimes \langle \tilde{\sigma}_{ijk}| \mathbf{U} \left(\{p\}, \mu^2, \{M_{ij}^2\} \right) |\tau\rangle \ ,$$

- Calculate probability for a baryonic configuration

Numerical results



Numerical results



Summary

- Colour reconnection important for description of observables, especially MB and UE
- Perturbative approach to colour reconneciton
- Toy Monte Carlo for full colour flow evolution for up to 5 clusters
- Find strong support for geometrical models
- More details in [Gieseke, PK, Plätzer,Siodmok, JHEP 1811 (2018) 149]