Non-perturbative models in Herwig & colour reconnection

Andrzej Siódmok

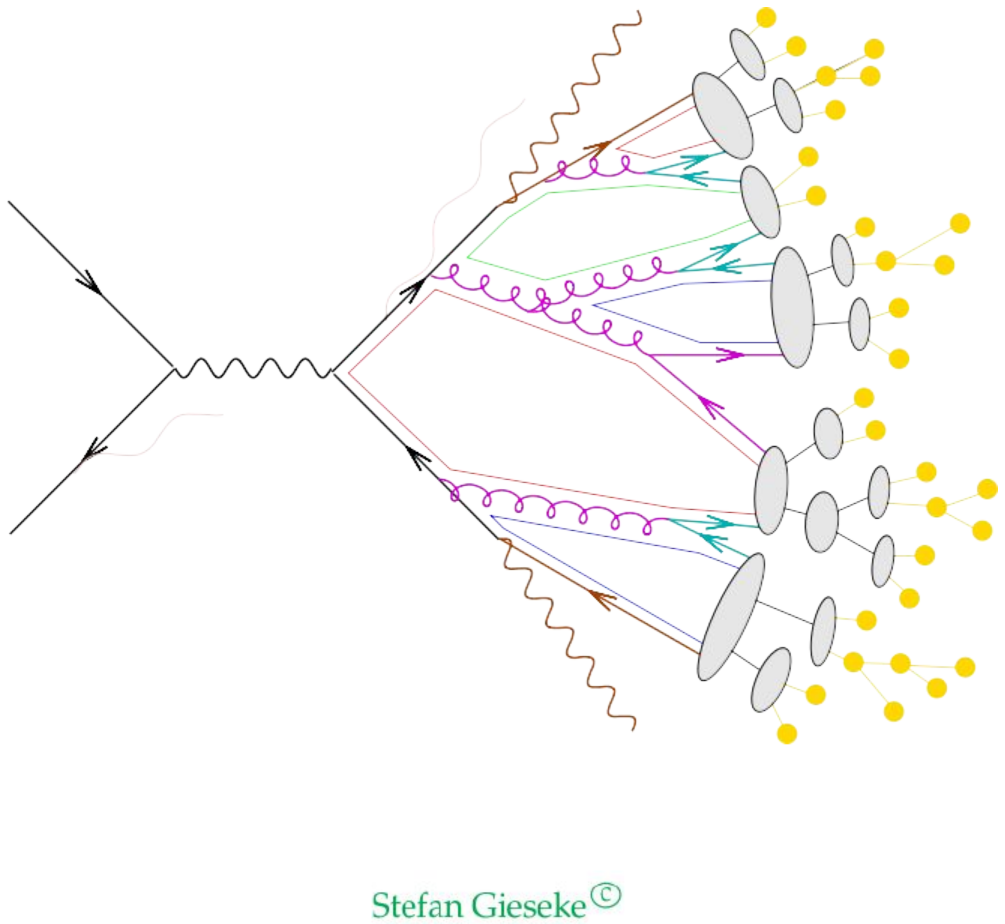
NARODOWE CENTRUM NAUKI

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

NAWA POLISH NATIONAL AGENCY FOR ACADEMIC EXCHANGE

MCnet

Lepton-Lepton collisions



Non-perturbative models

Cluster hadronization model:

- non perturbative gluon splitting
- colourless clusters
- cluster fission
- cluster → hadrons
- hadronic decays

Cluster hadronization model

The philosophy of the model:
use information from perturbative Parton Shower evolution for the input

Ref.TH.2620-CERN

PRECONFINEMENT AS A PROPERTY OF PERTURBATIVE QCD

D. Amati and G. Veneziano
CERN -- Geneva

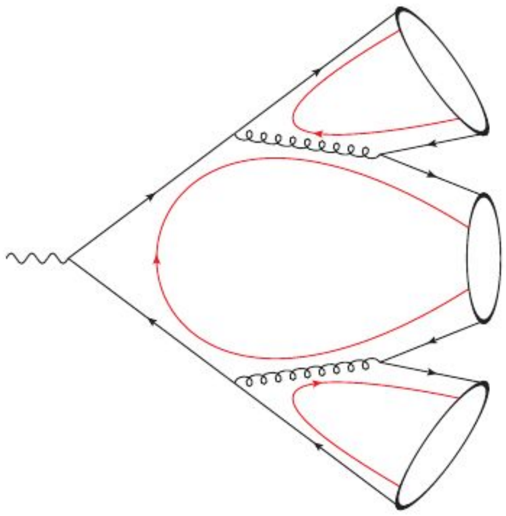
In these previous investigations little, if any, attention was paid to the way in which colour degrees of freedom evolve during the jet development. It is the purpose of this note to argue that quarks and gluons produced in this evolution from Q down to Q_0, become organized in lumps (clusters) of colour singlets with finite (i.e. Q-independent) masses of order Q_0 a phenomenon which we are tempted to call "preconfinement". We can then hope that confinement [occurring

Cluster hadronization model

[Webber NPB238(1984)492]

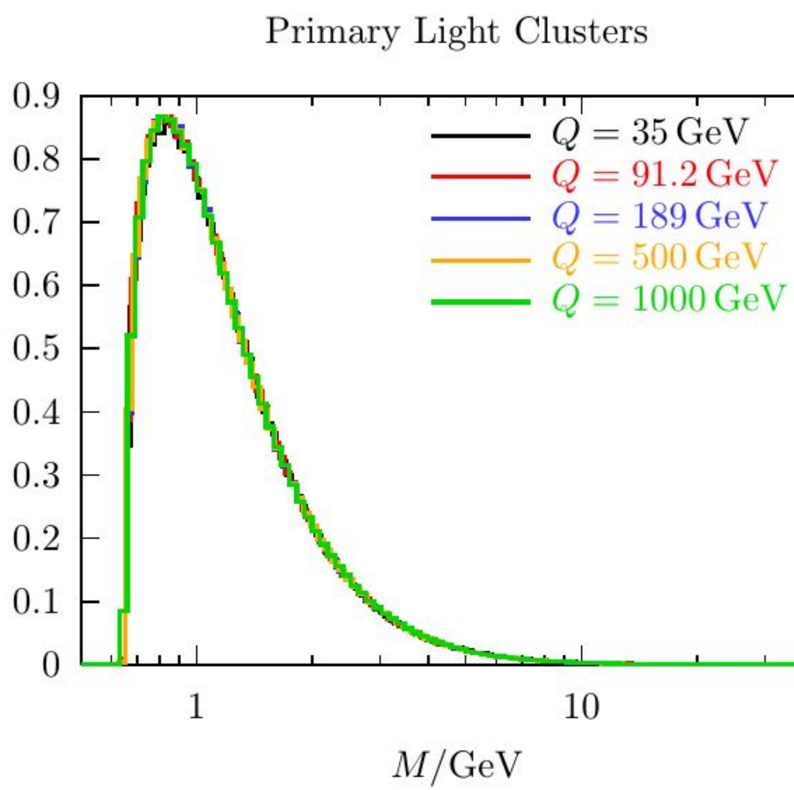
What if we have PS (more perturbative input before hadronization).
Can we get a simpler model?

Cluster Model:



- QCD parton showers provide *pre-confinement* of colour:
- Planar approximation: gluon = colour-anticolour pair
- colour-singlet pairs end up close in phase space and form highly excited hadronic states, the *clusters*
- Clusters ($\sim$ excited hadrons) decay into hadrons

Mass spectrum of primordial clusters independent of cm energy.



Peaked at low mass (1-10 GeV) typically decay into 2 hadrons. Project colour singlets onto continuum of high-mass mesonic resonances (clusters). Decay to lighter well-known resonances and stable hadrons.

Cluster hadronization in nutshell

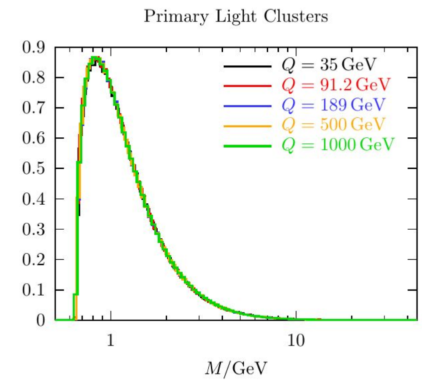
- Nonperturbative $g \longrightarrow q\bar{q}$ splitting $(q = uds)$ isotropically. Here, $m_g \approx 750\,\text{MeV} > 2m_q$.
- Cluster formation, universal spectrum
- Cluster fission, until

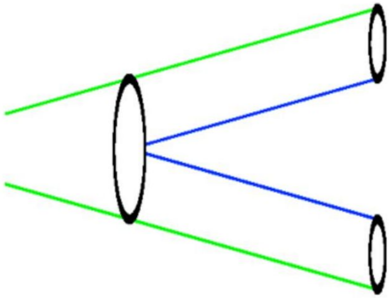
$$M^p < M^p_{\text{max}} + (m_1 + m_2)^p$$

where masses are chosen from

$$\begin{aligned} M_1 &= m_1 + (M - m_1 - m_q)\mathcal{R}_1^{1/P} \\ M_2 &= m_2 + (M - m_2 - m_q)\mathcal{R}_2^{1/P} \end{aligned}$$

with additional phase space contraints. Constituents keep moving in their original direction.



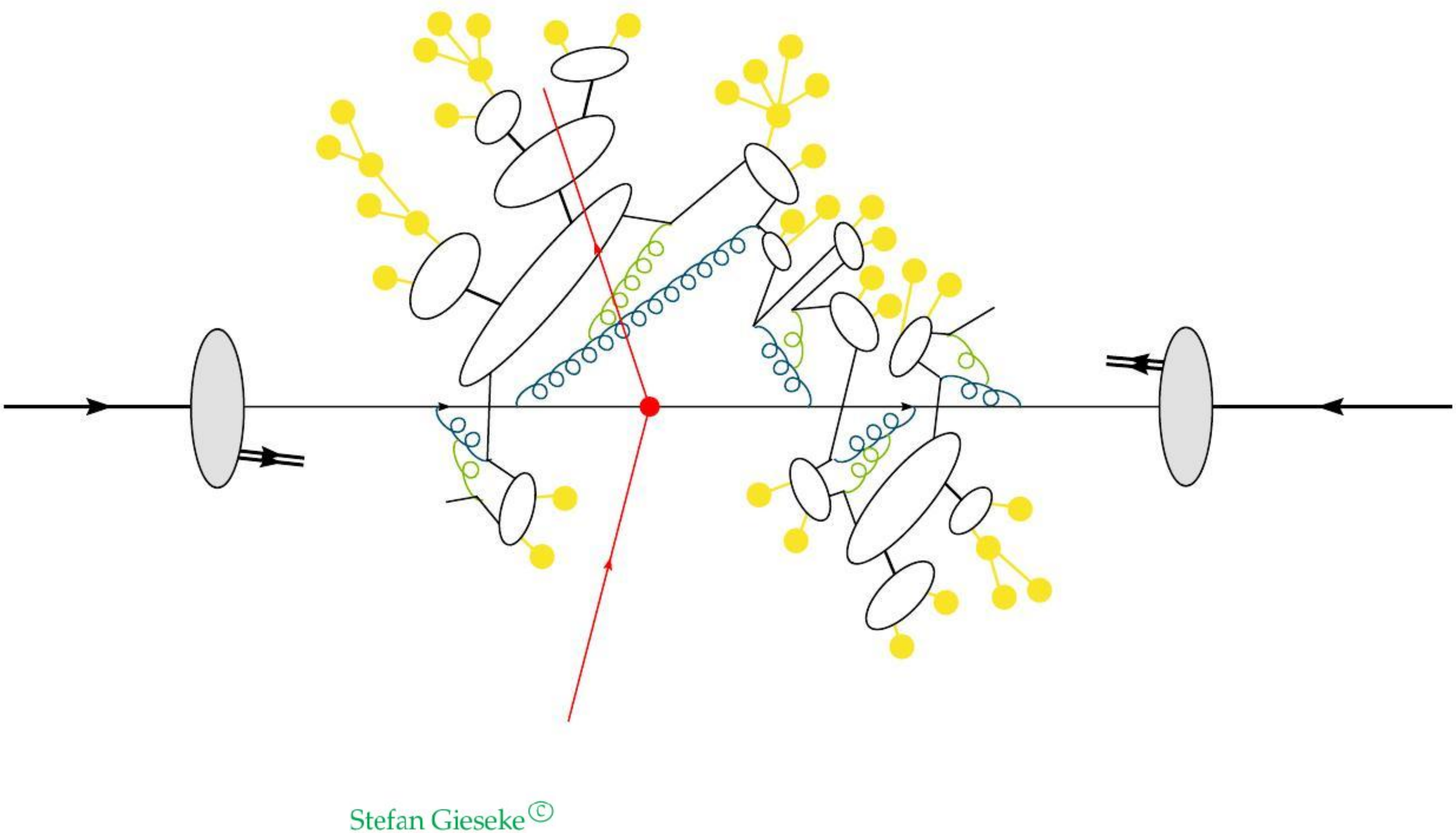


- Cluster Decay extract q or diquark pair from vacuum and form hadrons which are selected from all the possible hadrons with the appropriate flavour based on the available phase space, spin.

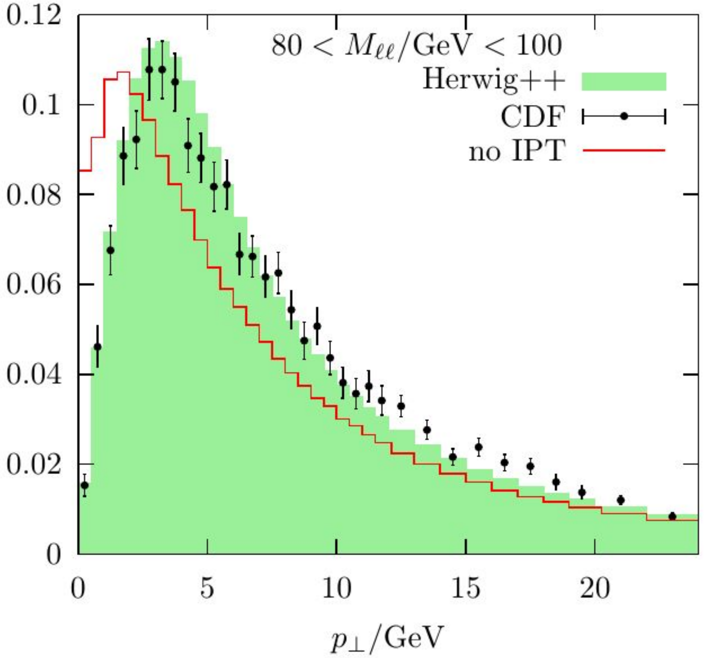
Interesting problems/observations:

- ~15% of primary clusters get split but ~50% of hadrons come from them - space for improvements?
- Adjust the model to new developments in Parton Shower (for example subleading colour)

Hadron-Hadron collisions



Parton Showers Intrinsic Kt



- Radiation it is not enough
- We need additional Gaussian smeared intrinsic momentum.
- But there are two problems:
  - for example: Herwig++ for TVT ($\sqrt{S} = 1800$ GeV): $< k_T >= 2.1$ GeV. Is to big! $0.3 - 0.5\ GeV$ based solely on a proton size and the uncertainty rule
  - No predictive power! - dependend on central energy of the beam. $\sqrt{S} = 62$ GeV $< k_T >= 0.9$ GeV

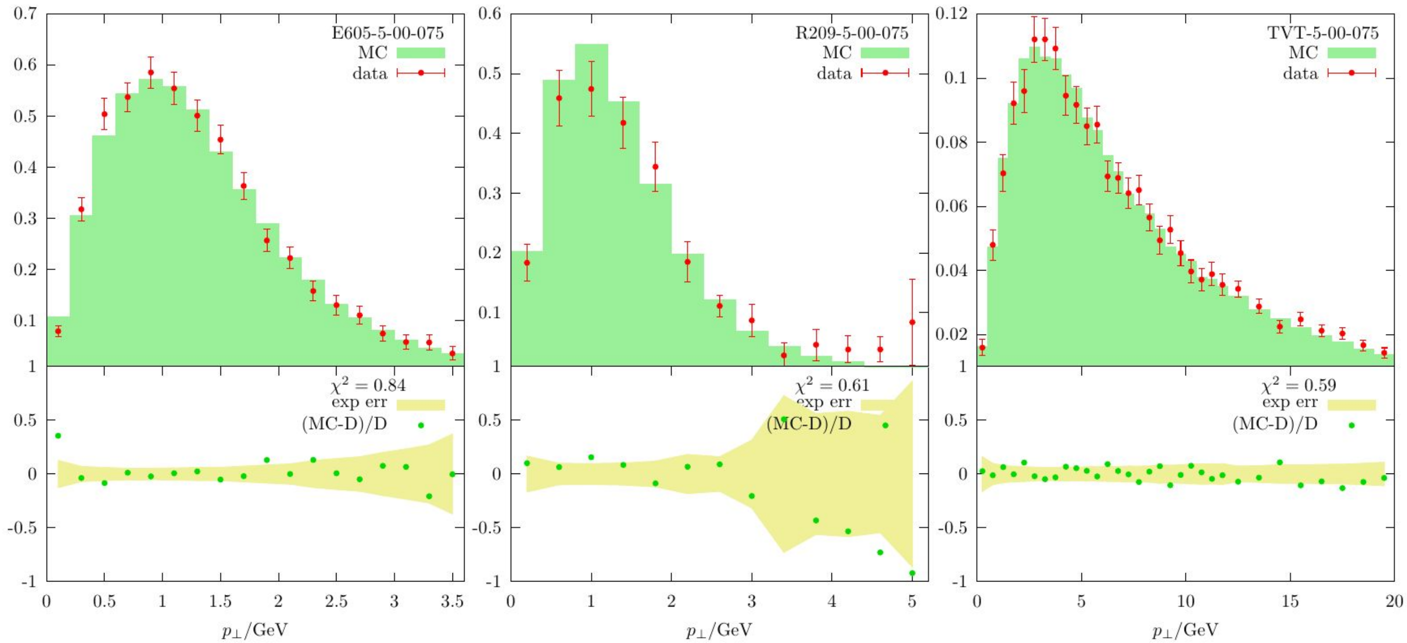
A model of non-perturbative gluon emission in an initial state parton shower

[S. Gieseke, M. H. Seymour, AS JHEP 0806:001,2008]

The idea

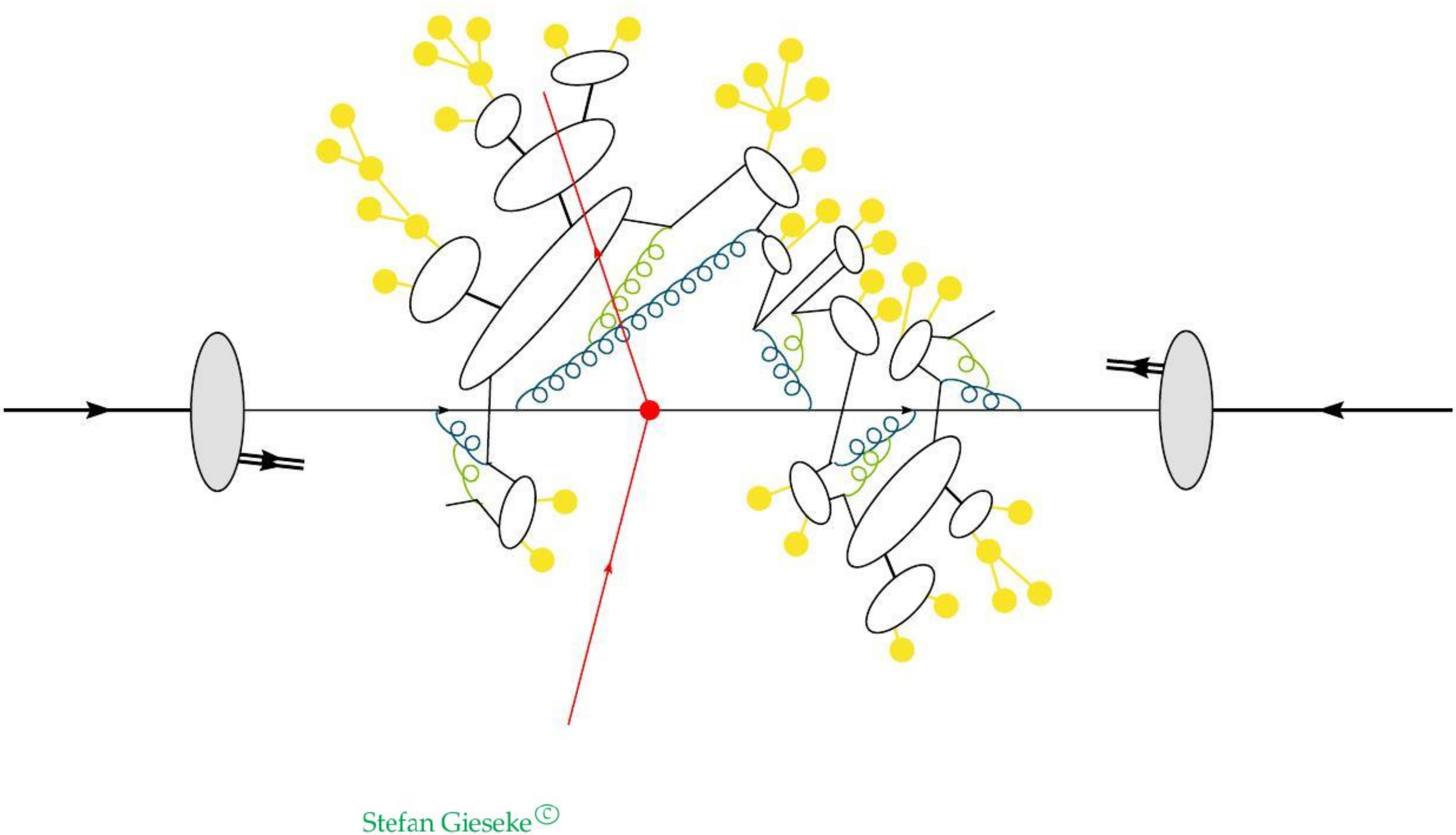
- Idea: Introduce addition soft radiation in each steep of PS evolution (below cut-off).
- Energy dependence: By construction the amount of such non-perturbative smearing grows with the length of the perturbative evolution ladder.
- How?: Additional sudakov form factor

$\sqrt{S} = 38.8$ GeV Fermilab E605 | $\sqrt{S} = 62$ GeV CERN-R209 | $\sqrt{S} = 1.8$ TeV Tevatron-CDF

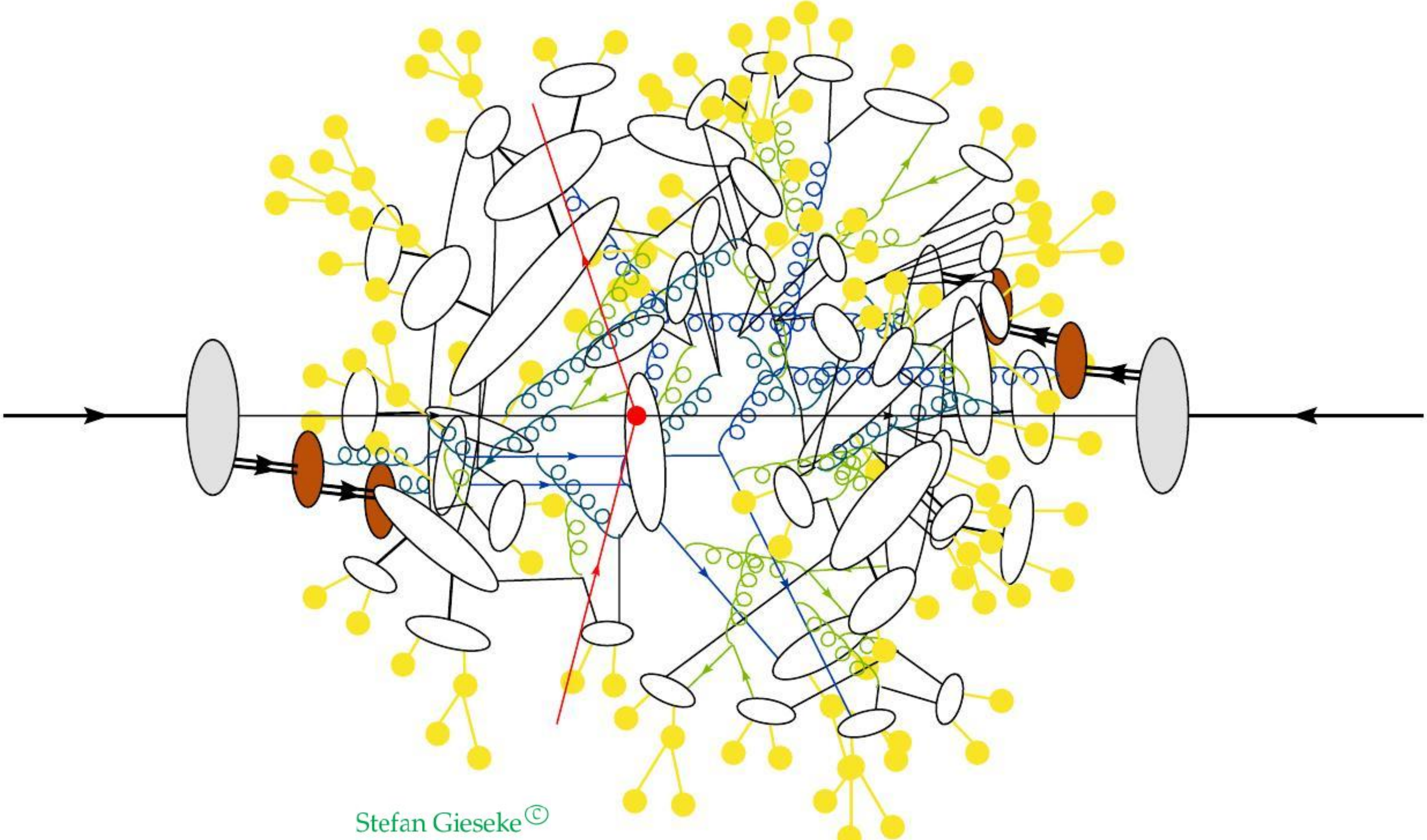


intrinsic k⊥ fixed at 0.4 GeV

hadron-hadron collisions

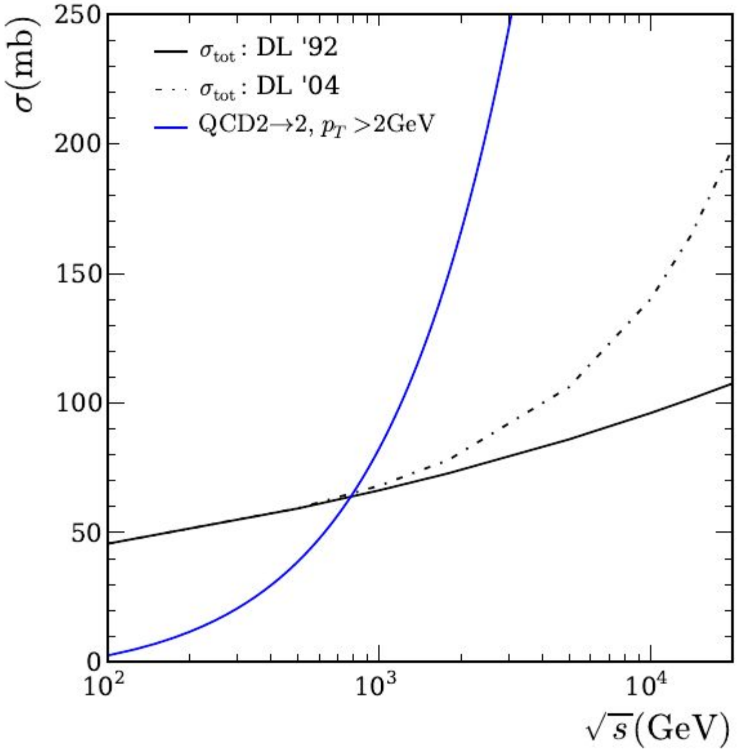


hadron-hadron collisions



Inclusive hard jet cross section in pQCD:

$$\sigma^{\text{inc}}(s, p_t^{\text{min}}) = \sum_{i,j} \int_{p_t^{\text{min}2}} \mathrm{d}p_t^2 \int \mathrm{d}x_1 \mathrm{d}x_2 \; f_i(x_1, Q^2)\, f_j(x_2, Q^2) \; \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$



$\sigma^{\text{inc}} > \sigma_{\text{tot}}$ eventually

Interpretation:

- σ^{inc} counts all partonic scatters in a single *pp* collision
- more than a single interaction

$$\sigma^{\text{inc}} = \langle n_{\text{dijets}} \rangle \sigma_{\text{inel}}$$

MPI Eikonal model basics – Overlap function

Assumptions:

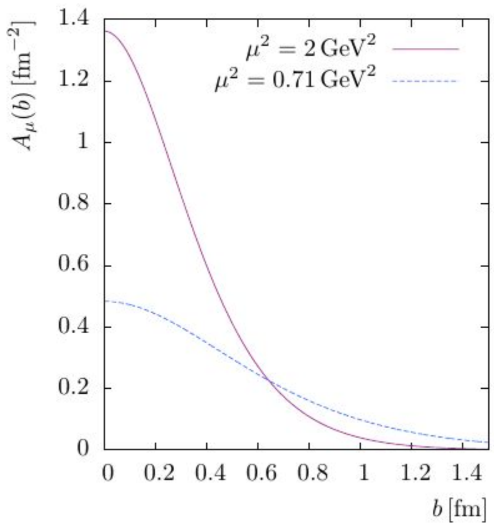
- the distribution of partons in hadrons factorizes with respect to the b and x dependence ⇒ average number of parton collisions:

$$
\begin{aligned}
\bar{n}(\vec{b}, s) &= L_{\text{partons}}(x_1, x_2, \vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&\quad \times D_{i/A}(x_1, p_t^2, |\vec{b}'|) D_{j/B}(x_2, p_t^2, |\vec{b} - \vec{b}'|) \\
&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&\quad \times f_{i/A}(x_1, p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2, p_t^2) G_B(|\vec{b} - \vec{b}'|) \\
&= A(\vec{b}) \sigma^{\text{inc}}(s; p_t^{\text{min}}) \,.
\end{aligned}
$$

- at fixed impact parameter b, individual scatterings are independent (leads to the Poisson distribution)

MPI model in Herwig in nutshell

Matter distribution (μ^2)

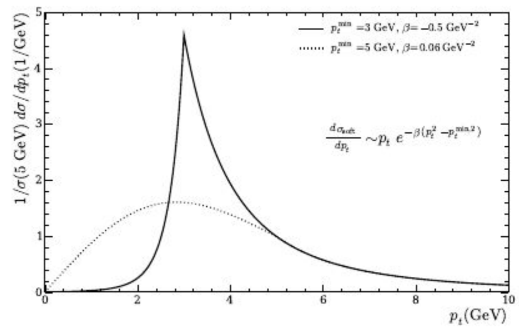


Based on electromagnetic form factor

(radius of the proton free parameter)

[Bähr, Gieseke, Seymour, JHEP 0807:076]
[Bähr, Butterworth, Seymour, JHEP 0901:065]

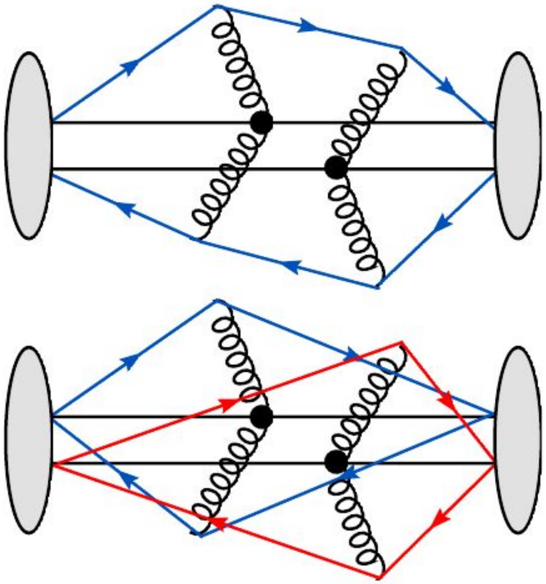
Extension to soft MPI ($p_t < p_t^{\min}$)



Gaussian extension below $p_t^{\min}$

Energy dependent $p_t^{\min}$

Colour structure (p_{reco}, p_{CD})



Possibility of change of color structure (color reconnection)

[Gieseke, Röhr, AS, EPJC 72 (2012)]

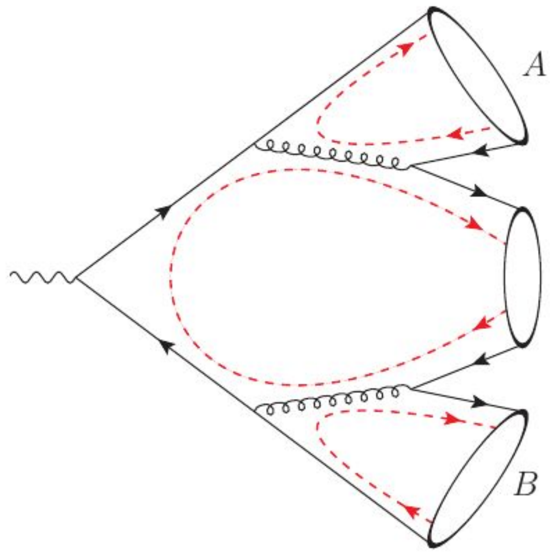
The least understood part of modeling

Main parameters:

- μ^2 - inverse hadron radius squared (parametrization of overlap function)
- $p_t^{\min}$ - transition scale between soft and hard components $\Rightarrow p_t^{\min} = p_{t,0}^{\min}\left(\frac{\sqrt{s}}{E_0}\right)^b$
- p_{reco} - colour reconnection

Colour Reconnection [CR] in Herwig in nutshell

Cluster hadronization [Webber, Nucl. Phys. B238 (1984) 492]



- perturbative QCD provides *preconfinement* [Amati, Veneziano, Phys. Lett. B83 (1979) 87]
- colour-singlet pairs end up close in phase space and form highly excited hadronic states, the *clusters*
- i.e. small cluster masses $M_{\mathrm{cl}} \gtrsim M_{\mathrm{parton}\,1} + M_{\mathrm{parton}\,2}$

Colour Reconnection [CR] in Herwig in nutshell

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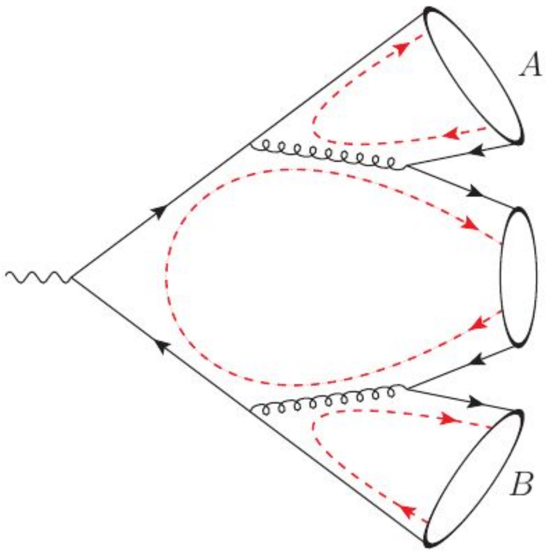

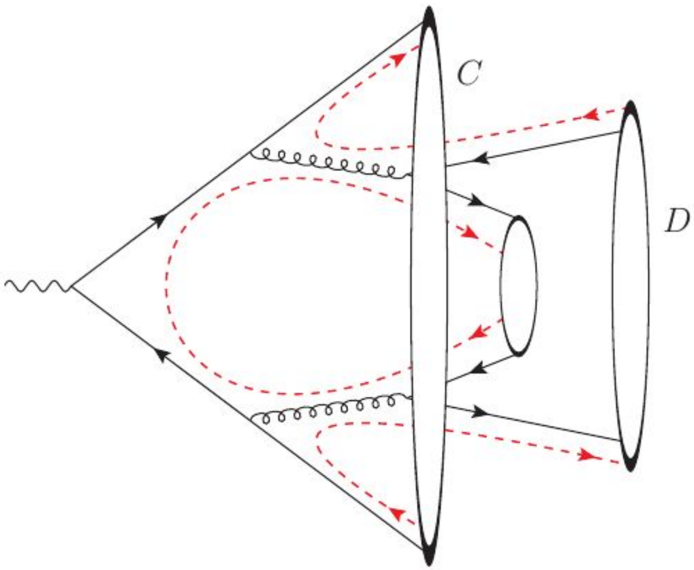

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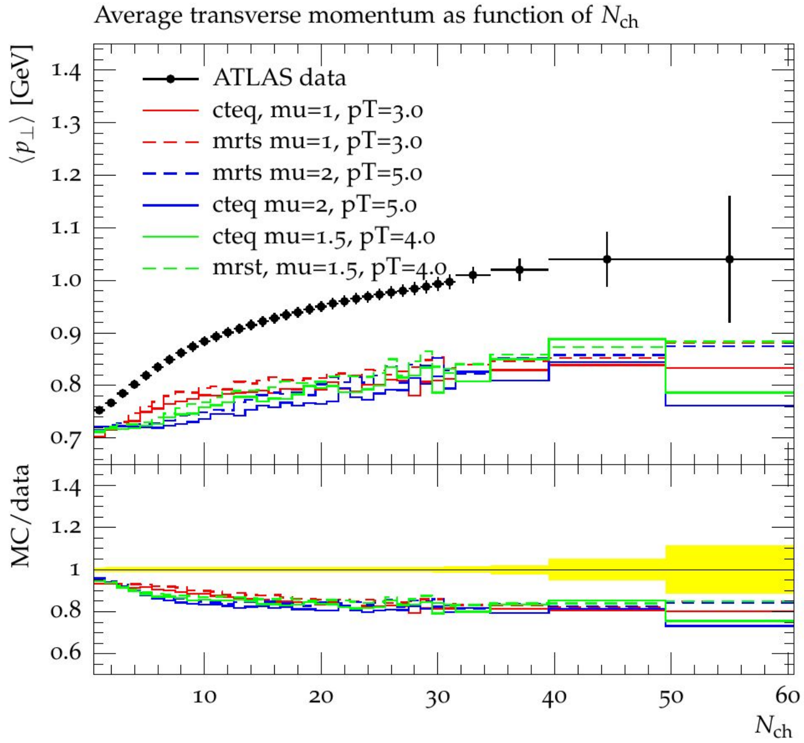
- i.e. small cluster masses $M_{\rm cl} \gtrsim M_{\rm parton\,1} + M_{\rm parton\,2}$

- improved description of soft events/UE at hadron colliders: manually reduce cluster masses
- if $M_C + M_D < M_A + M_B$ accept alternative clustering with probability $p_{\rm reco}$ (model parameter)

Colour Reconnection [CR] in Herwig in nutshell

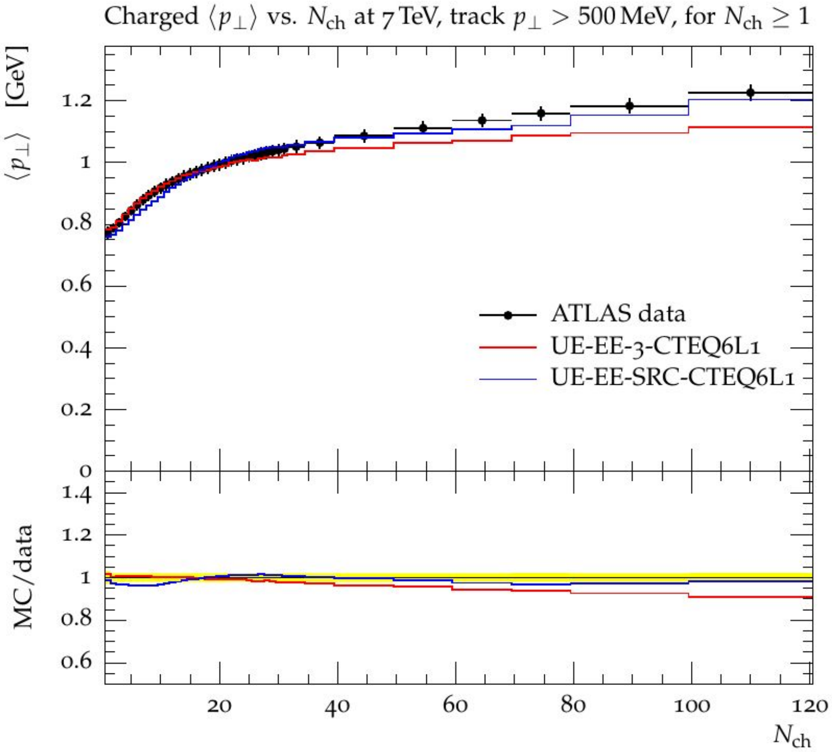
Without CR



Plain CR model

- problem: not deterministic

With CR



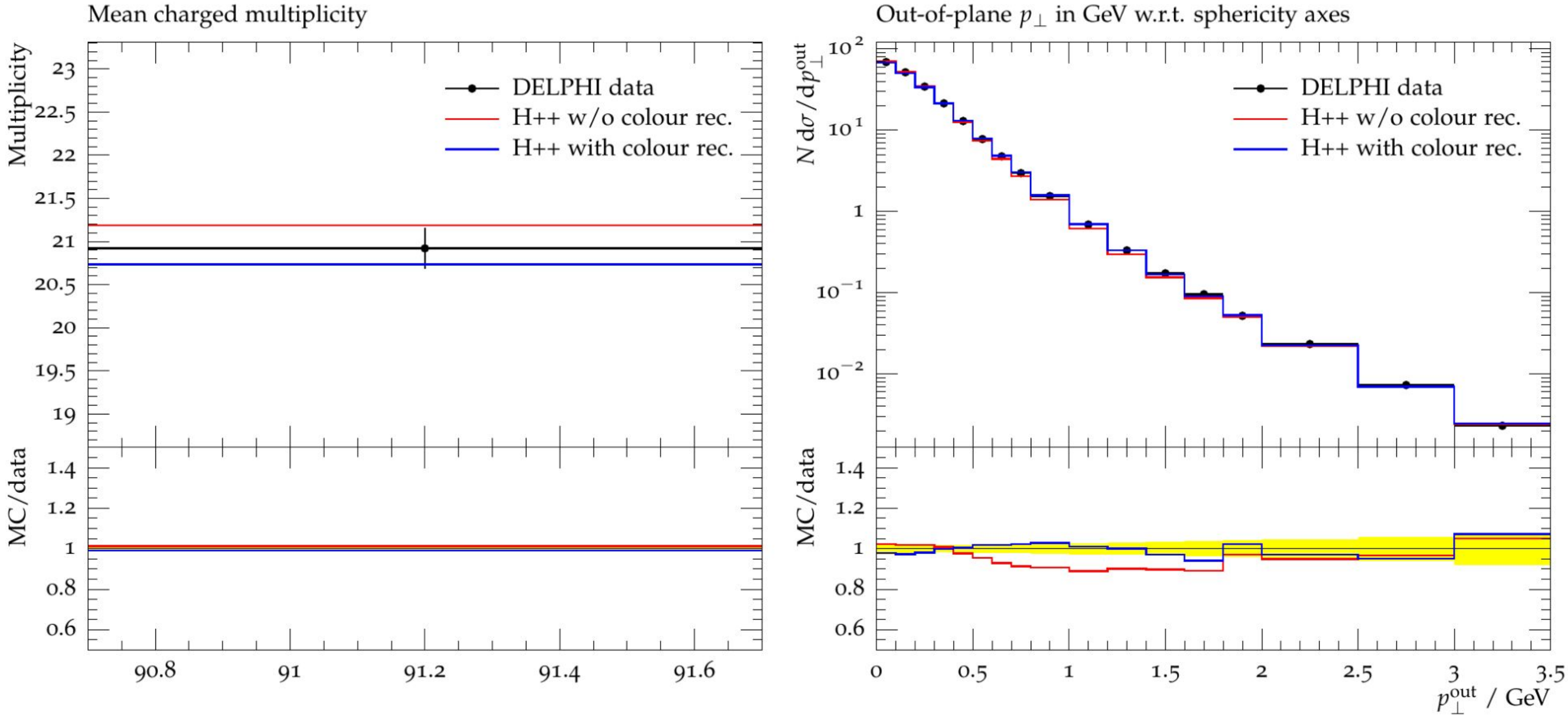
Statistical CR model

Reduce sum of (squared) cluster masses

$$\lambda \equiv \sum_{i \in \{\text{clusters}\}} m_i^2 ,$$

using a simulated annealing algorithm

Check against LEP data



Agreement on same level as w/o CR model.

Colour Reconnection from Soft Gluon Evolution

[Gieseke, Kirchgaesser, Plätzer, Siodmok – JHEP 11 (2018) 149]

Idea: smooth extension of perturbative colour evolution to non-perturbative region

Formalism: QCD amplitudes and colour flow basis [see Simon's talk]

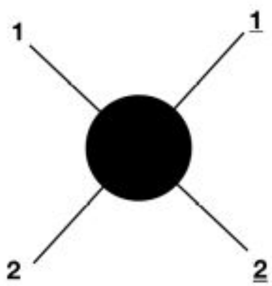
QCD amplitudes can be decomposed in a basis of contributing colour/spin structures

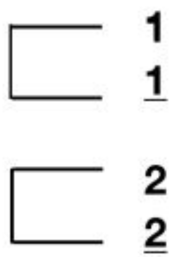
$$|\mathcal{M}\rangle = \sum_\sigma \mathcal{M}_\sigma |\sigma\rangle$$

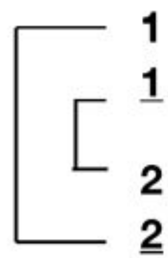
we are mainly interested in the colour structure → we use colour flow basis

$$|\sigma\rangle = \left| \begin{matrix} 1 & \cdots & n \\ \sigma(1) & \cdots & \sigma(n) \end{matrix} \right\rangle = \delta^{\alpha_1}_{\bar{\alpha}_{\sigma(1)}} \cdots \delta^{\alpha_n}_{\bar{\alpha}_{\sigma(n)}}$$

2 cluster (4 legs) example







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

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

Colour Reconnection from Soft Gluon Evolution

Idea: Extend perturbative colour evolution to non-perturbative regime

Evolution of colour flow

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

Reconnection probability

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

where

$$\mathbf{U}\left(\{p\},\mu^2,\{M_{ij}^2\}\right) = \exp\left(\sum_{i\neq j}\mathbf{T}_i\cdot\mathbf{T}_j\frac{\alpha_s}{2\pi}\left(\frac{1}{2}\ln^2\frac{M_{ij}^2}{\mu^2} - i\pi\ln\frac{M_{ij}^2}{\mu^2}\right)\right)$$

Example: Two cluster evolution (analytical insight)

Evolution of a single state $|12\rangle$:

$$|\tau\rangle = U|12\rangle = \begin{pmatrix} U_{11} & U_{21} \\ U_{12} & U_{22}\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix} = U_{11}|12\rangle + U_{12}|21\rangle$$

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

Investigate different limits →

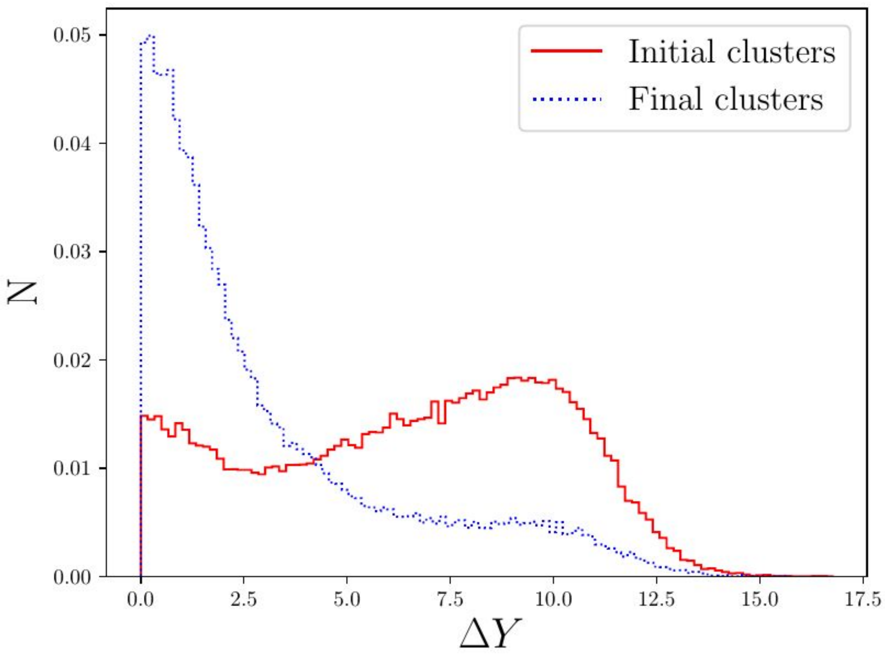
$p_{T2} \sim p_{T3}$ and $\Delta Y = y_3 - y_2 \sim 0$

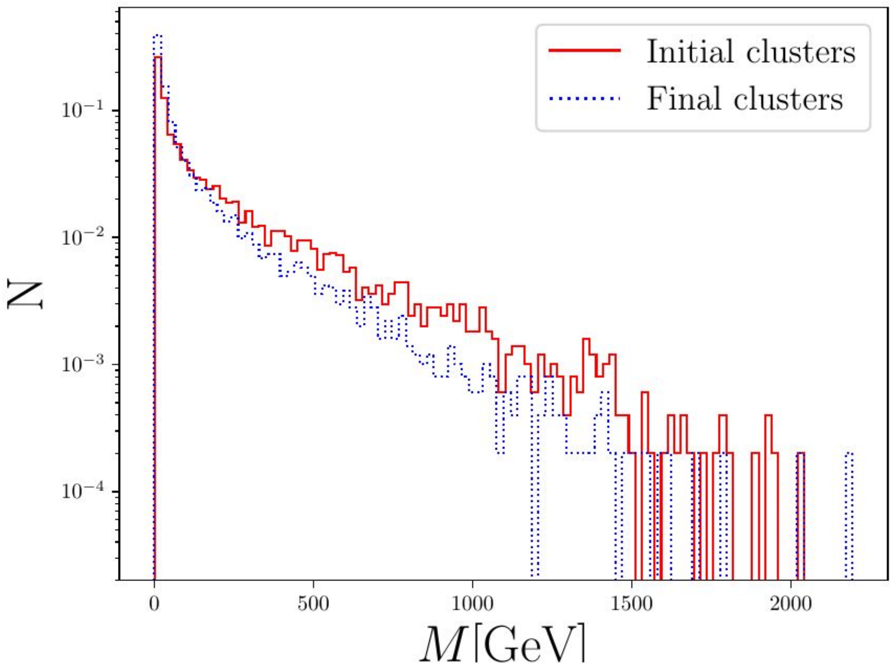
(initial partons in clusters close in rapidity)

Prob. minimal → preconfiment

Colour Reconnection from Soft Gluon Evolution

Numerical results 5 clusters





Connects quarks which are closer in spacetime [Preconfiment]

Reduces invariant cluster masses [main aim of plain CR]

Summary:

- Idea: smooth extension of perturbative colour evolution to non-perturbative region
- Analytical insight into colour reconnection from soft gluon evolution: 2 clusters case.
- Toy Monte Carlo for full colour flow evolution for up to 5 clusters (limitation exp of big matrix)
- Strong support for geometrical/kinematical models

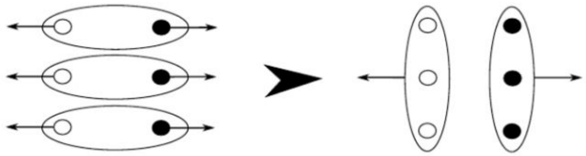
Baryonic Colour Reconnection

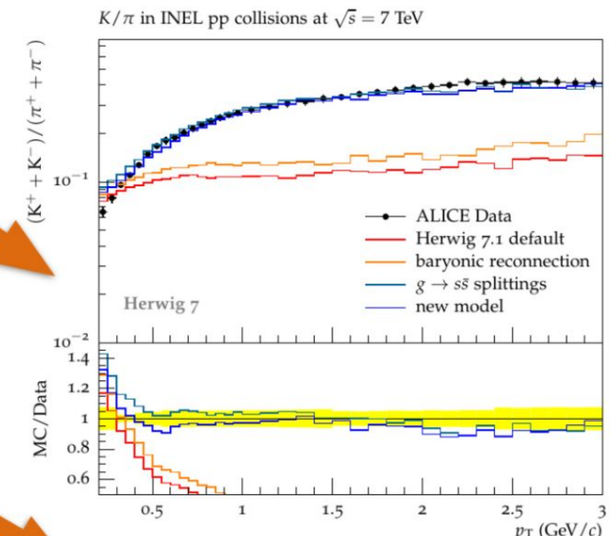
[Gieseke, Kirchgaeßer, Plätzer EPJC 78 (2018) no.2, 99]

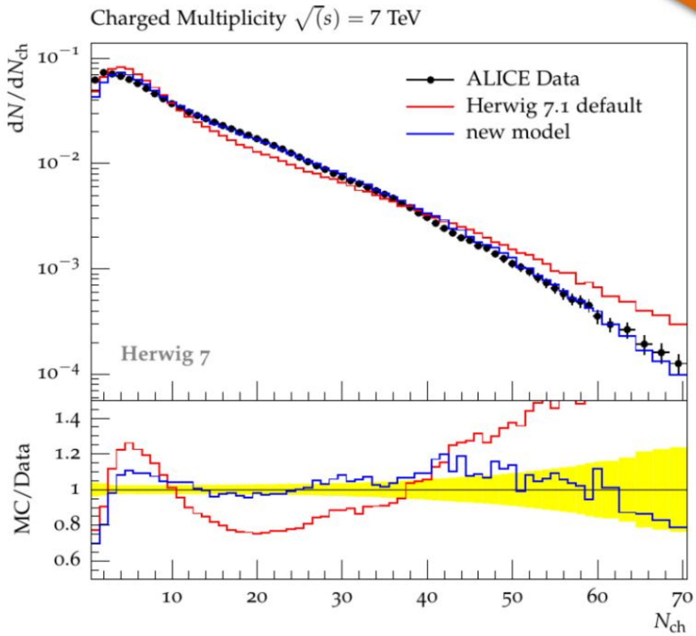
Idea:

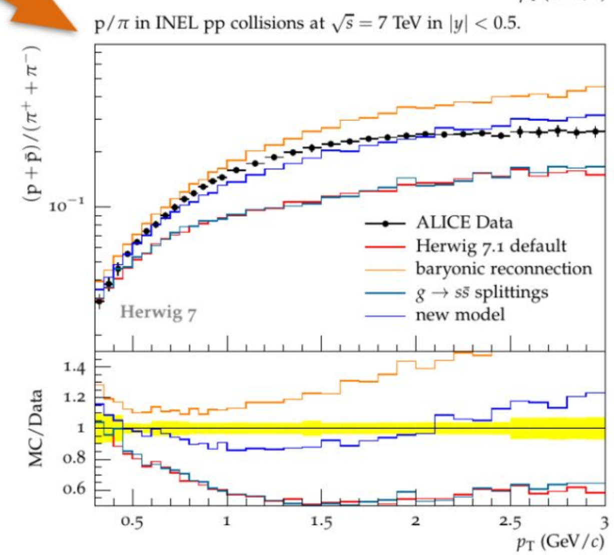
– Allow gluon to strange-pairs

– Allow recombination of mesonic to baryonic clusters with probability derived in proximity in momentum space.









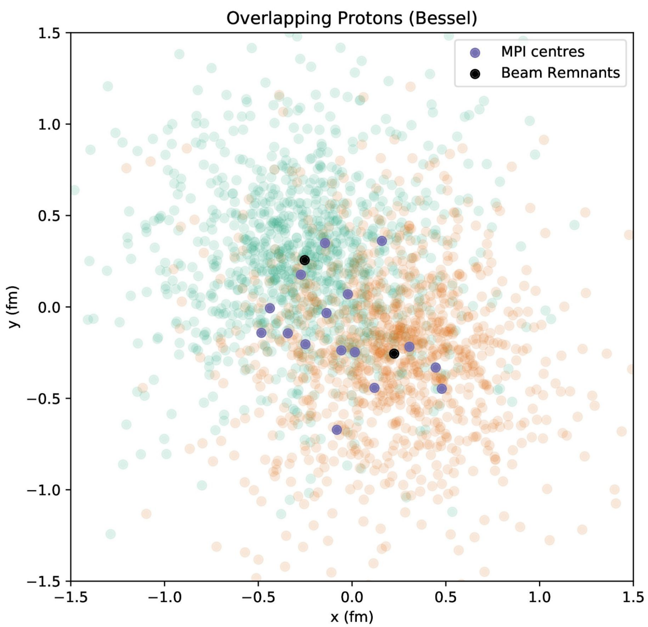
[ALICE, EPJ C75 (2015) 226]

Space-time Colour Reconnection

[J. Bellm, C. Duncan, S. Gieseke, M. Myska *Eur.Phys.J.C* 79 (2019) 12]

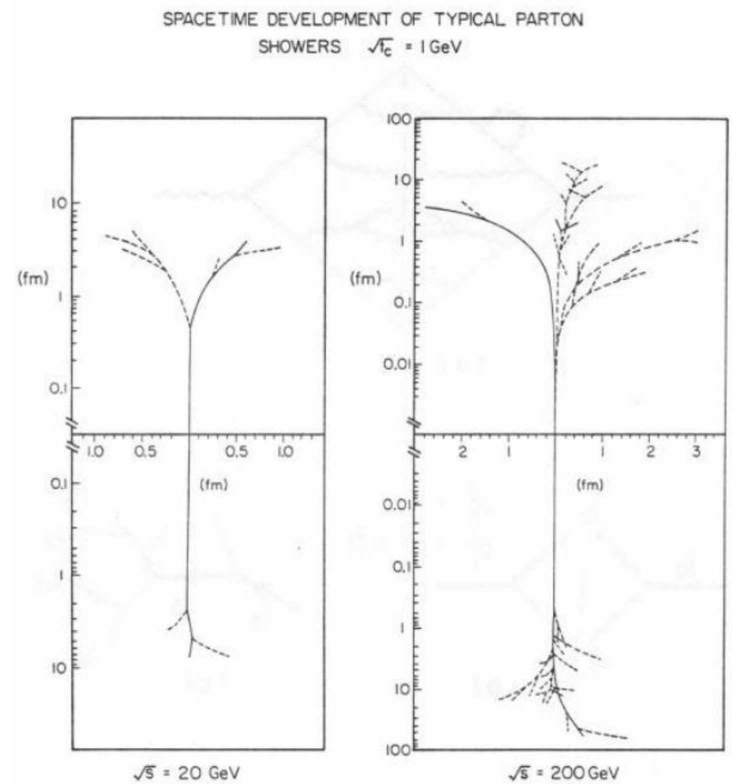
Space-time Coordinate of MPI centres

Electromagnetic Form Factor



$$A(b) = \int \mathrm{d}^2 b' G(b') G(b - b')$$

Space-time Coordinate of MPI centres



G. C. Fox, S. Wolfram,
A Model for Parton Showers in QCD
Nucl. Phys. B168 (1980) 285

- Fortran Herwig-like algorithm
- minimum virtuality v mean lifetime: $\tau_{0,p} = \frac{\hbar m_p}{\nu^2}$.

Space-time Colour Reconnection

- We introduce a boost-invariant distance measure:

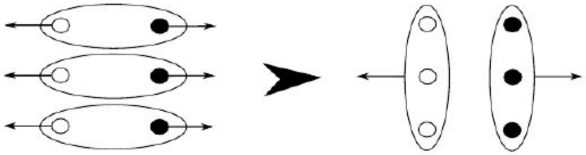
$$R_{ij}^2 = \frac{\Delta r_{ij}^2}{d_0^2} + \Delta y_{ij}^2, \text{where } \Delta r_{ij}^2 = (\vec{x}_{\perp,i} - \vec{x}_{\perp,j})^2$$

d_0 is the characteristic length scale for CR, a tuneable parameter

- This is inspired by conventional jet algorithms, where we replace the azimuthal separation with transverse separation.
- Similar strategy as in the plain CR base on the cluster. Try to reconnect if

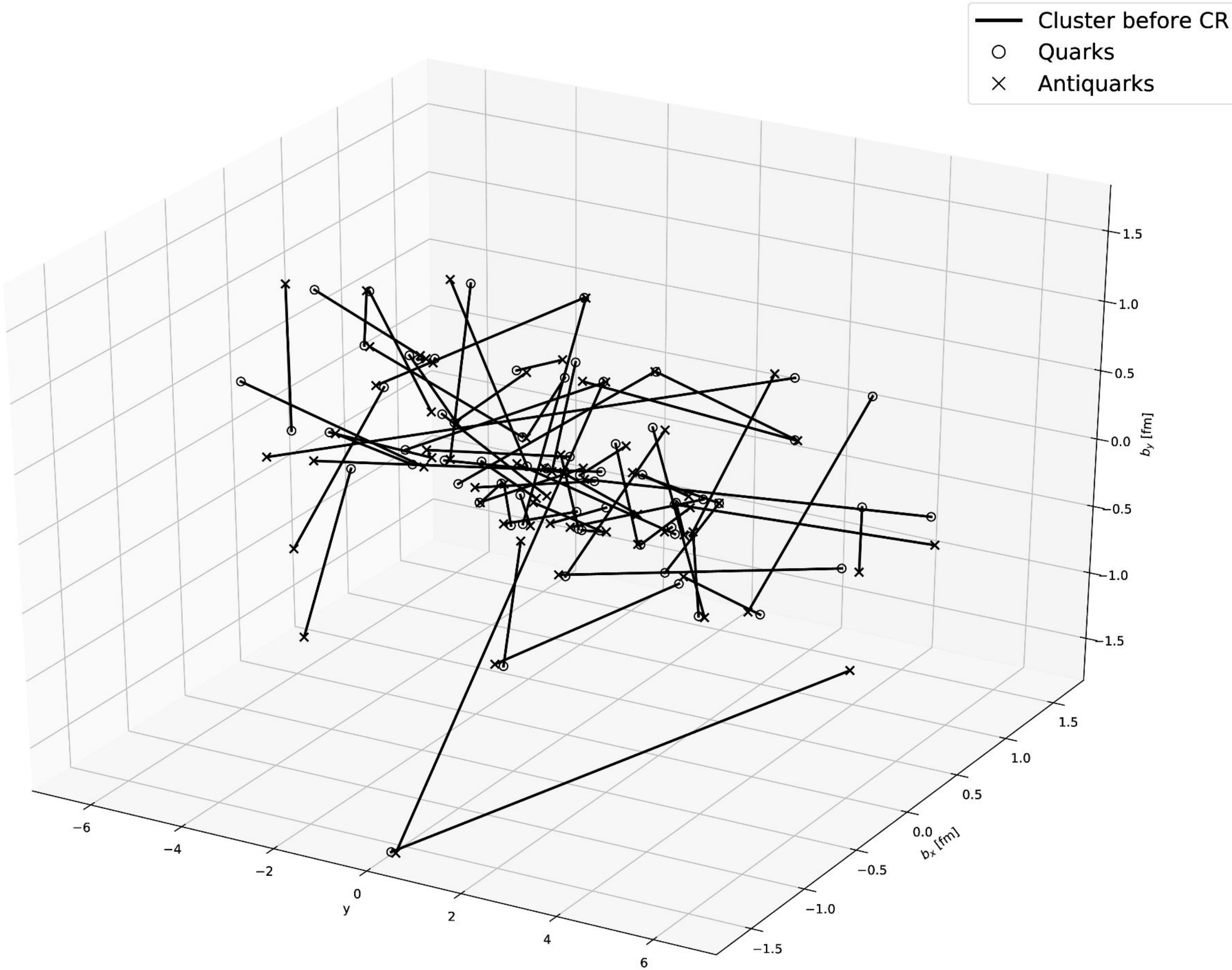
$$R_{q'} + R_{q'} < R_q + R_{q''}$$

- Baryonic spacetime colour reconnection

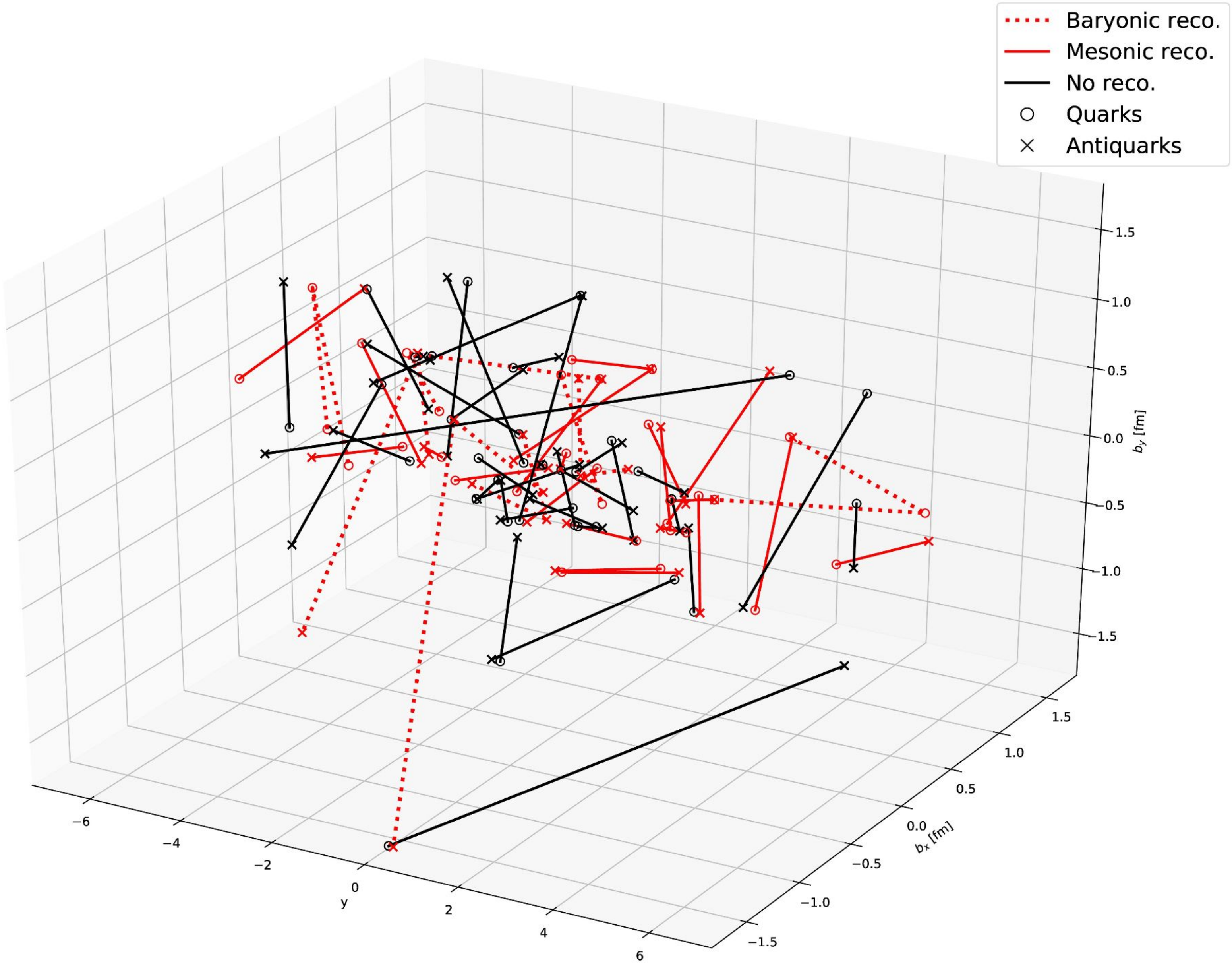


$$R_{q,qq} + R_{\bar{q},\bar{q}\bar{q}} < R_{q,\bar{q}} + R_{qq,\bar{q}\bar{q}}$$

Space-time Colour Reconnection

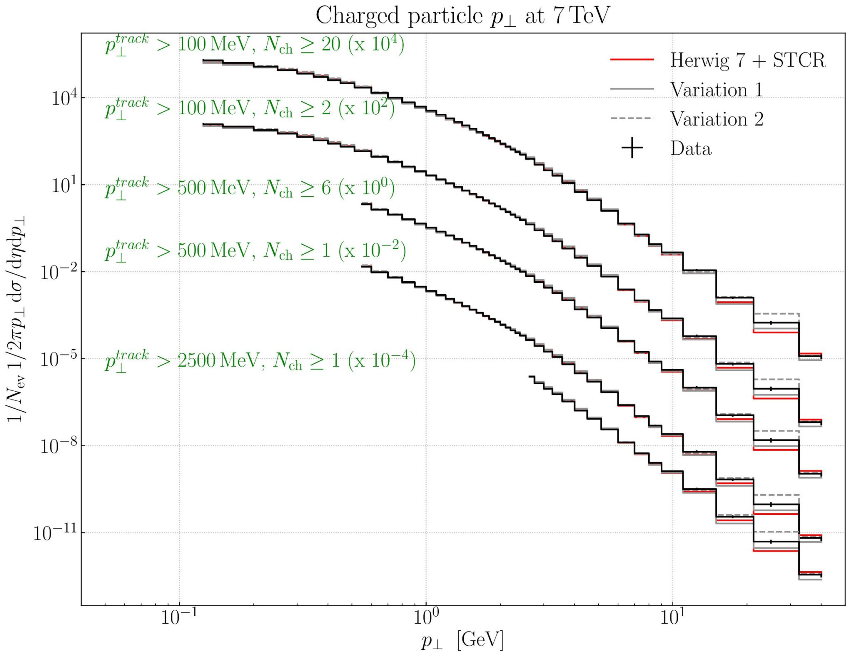


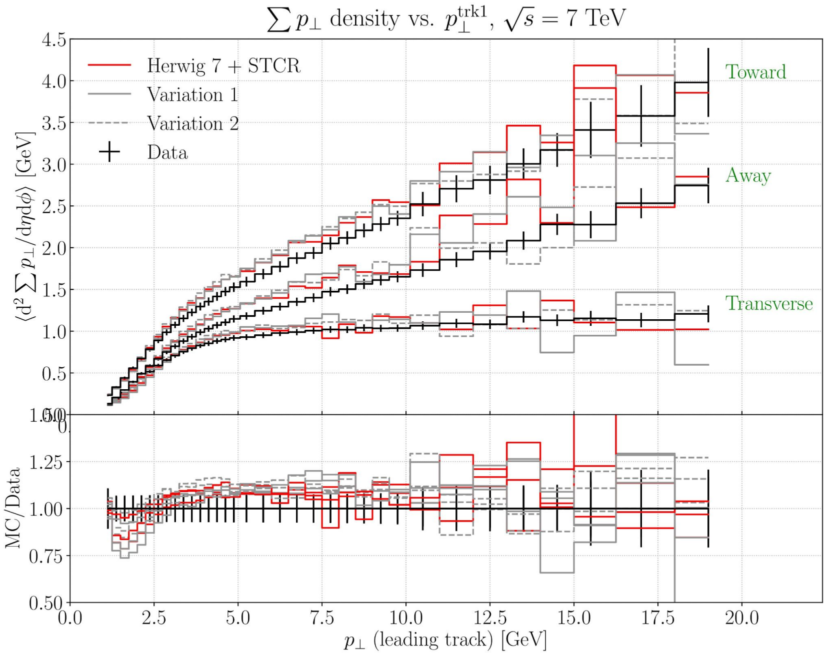
Space-time Colour Reconnection



Space-time Colour Reconnection

Good agreement with Minimum Bias and Underlaying Event data





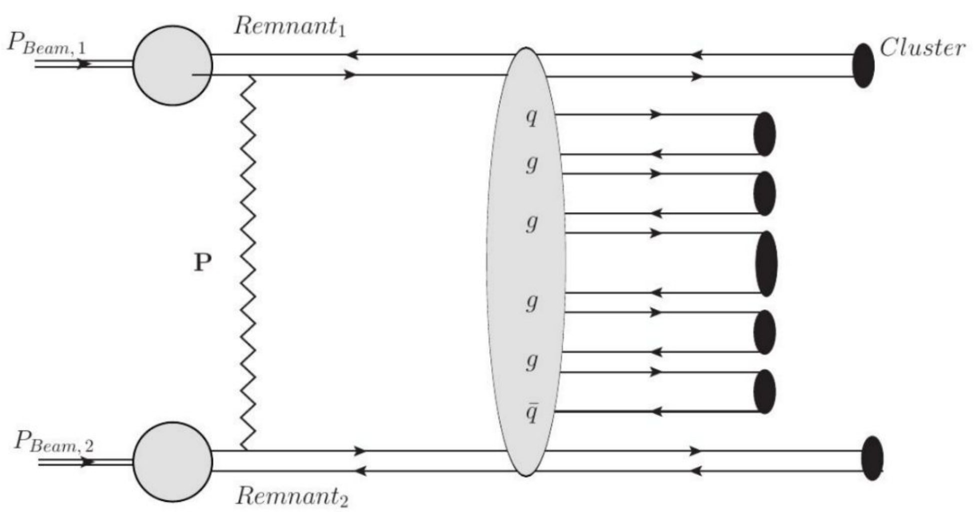
Summary:

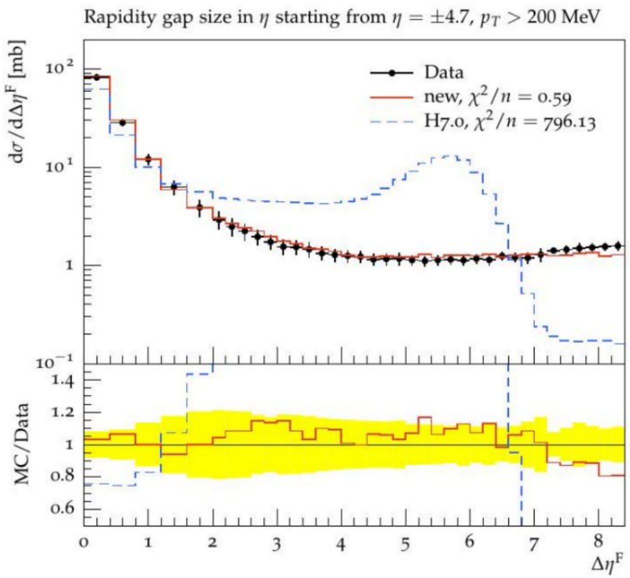
- Space-time model position of MPI and Parton Shower
- Base for the Heavy Ion collision simulation and rescattering
- Reasonable description of the data
- Hadronization of very dense systems (CMS ridge)?

New soft MPI model

Soft Physics

- Inclusion of diffractive topologies
- New soft peripheral MPI model
- The rapidity bump disappears

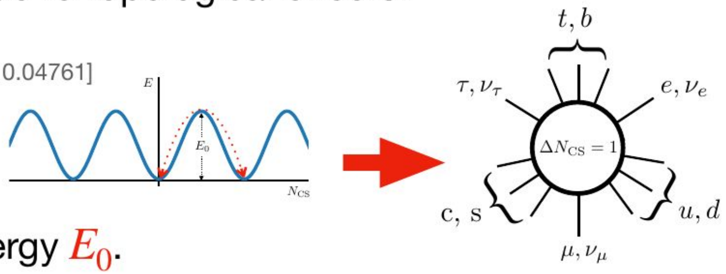




[S. Gieseke, F. Loshaj, P. Kirchgaeßer Eur.Phys.J. C78 (2018) no.2, 99]

[J. Bellm S. Gieseke P. Kirchgaesser JHEP 0901:065]

- Herwig 7 contains simulations of non-perturbative phenomena due to topological effects.
  - e.g. **Electroweak Sphalerons:** [e.g. Papaefstathiou, Plätzer, Sakurai, arXiv:1910.04761]



    ➡ Change in Chern-Simons number.

    ➡ Large number of gauge/Higgs bosons above threshold energy E_0.

    ➡ $q + q \to 7\bar{q} + 3\bar{\ell} + n_B W/Z/\gamma/H.$

  - e.g. **QCD Instantons:** [e.g. Khoze, Krauss, Schott, arXiv:1911.09726, Amoroso, Kar, Schott, arXiv:2012.09120]

    ➡ e.g. Change in topological charge gives "soft bombs":

    ➡ $$g + g \to n_g g + \sum_{f=1}^{N_f} (q_{Rf} + \bar{q}_{Lf}).$$

    ➡ Could contribute to scattering processes in QCD.

    ➡ **Colour flow, colour reconnection, helicity, hadronization**: important questions to be investigated!

[Cormier, Jin, Kirchgaesser, Papaefstathiou, Plätzer, in preparation]

Conclusion

1. **Taming the accuracy of event generators.**
   Better control of perturbative corrections ("NLO revolution") → more often LHC measurements are limited by non-perturbative components (hadronization or multiparton interactions):

   - W mass measurement using a new method [Freytsis at al. JHEP 1902 (2019) 003]
   - extraction of the strong coupling in [M. Johnson, D. Maître, Phys.Rev. D97 (2018) no.5, 054013].
   - the top mass [S. Argyropoulos, T. Sjöstrand, JHEP 1411 (2014) 043]
     precision dominated by colour reconnection [see talk by S. Amoros].

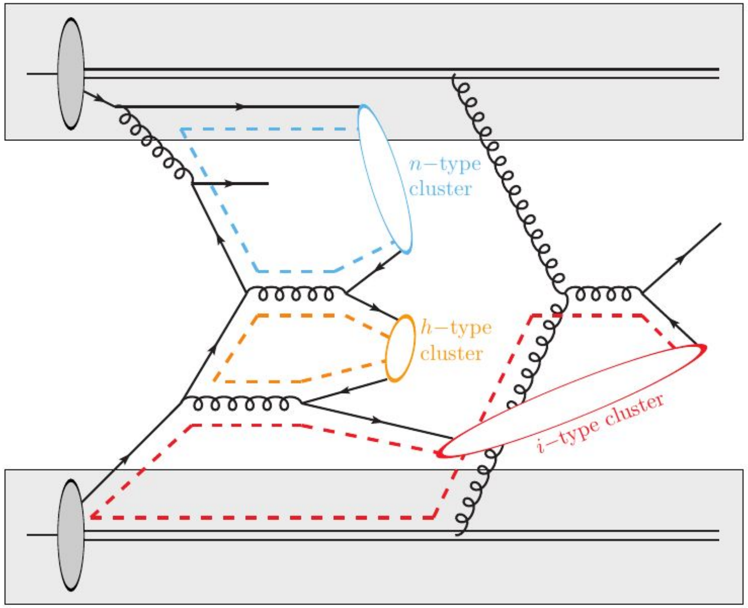
2. **A lot of progress in development the NP models in Herwig including MPI and CR.**

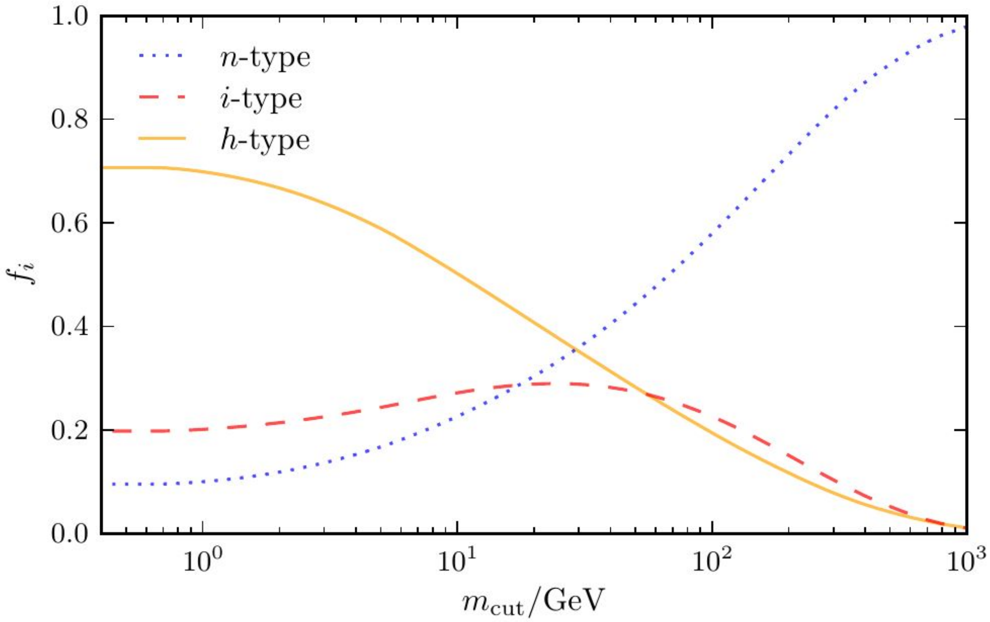
3. **Stay tune for more.**

Backup

Backup

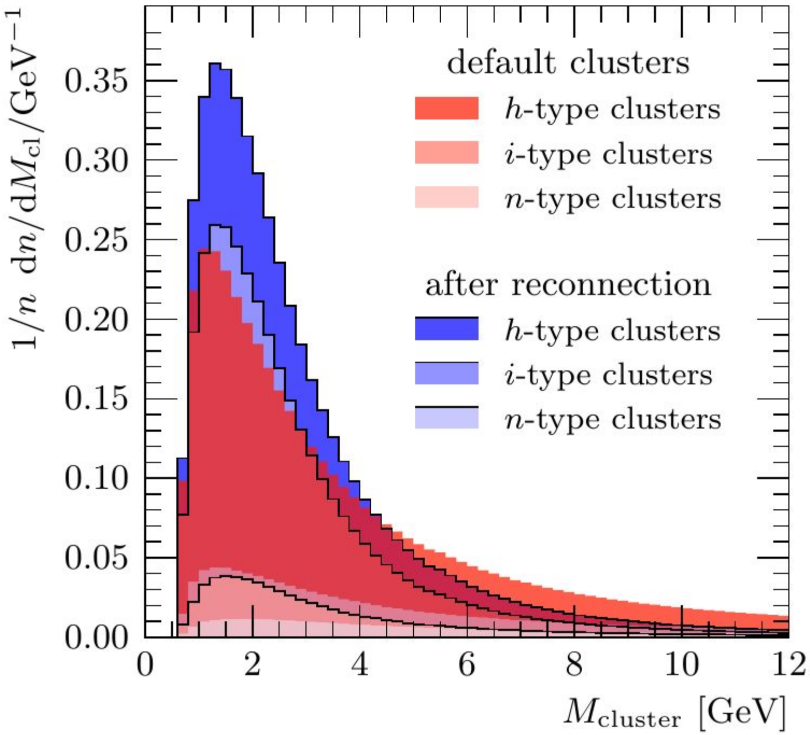
$$f_a(m_{cut}) \equiv N_a(m_{cut}) / \sum_{b=h,i,n} N_b(m_{cut}) = \frac{N_a(m_{cut})}{N_{cl}}\,, \tag{1}$$



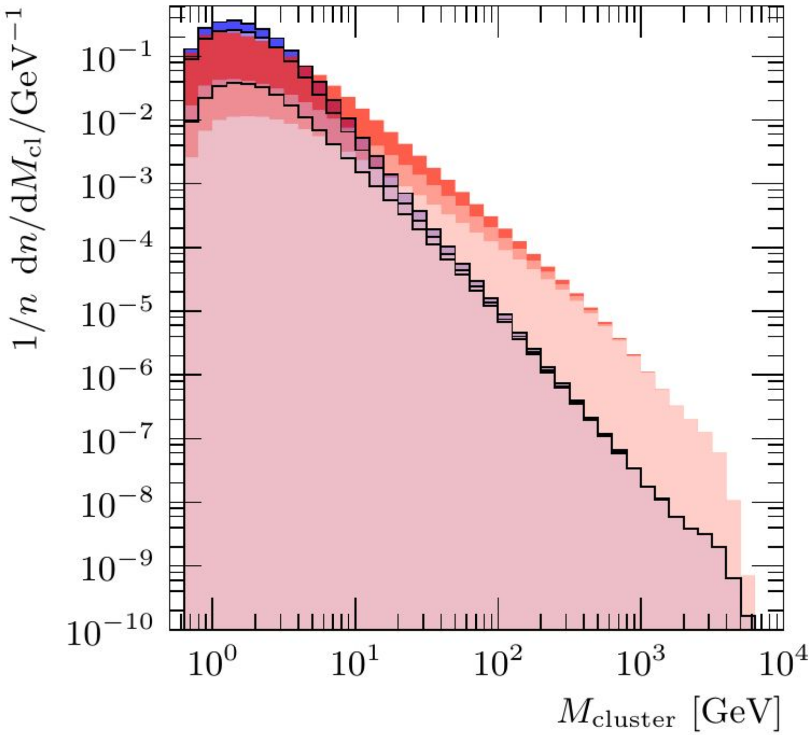


Since these n-clusters can lie at very different rapidities (the extreme case being the two opposite beam remnants), the strings or clusters spanned between them can have very large invariant masses (though normally low p⊥), and give rise to large amounts of (soft) particle production.

Backup

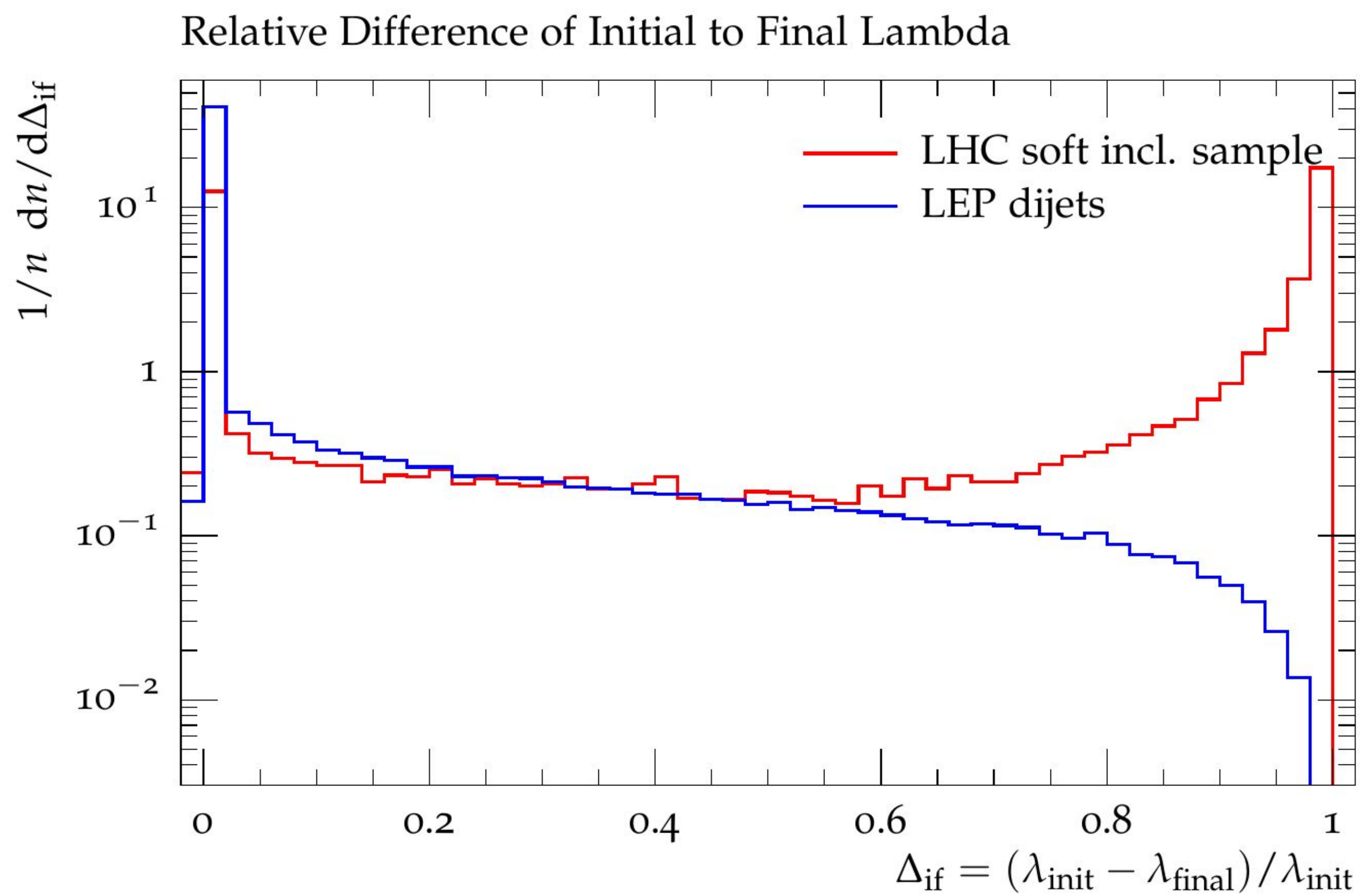


default clusters
h-type clusters
i-type clusters
n-type clusters
after reconnection
h-type clusters
i-type clusters
n-type clusters
$1/n\ \mathrm{d}n/\mathrm{d}M_{\mathrm{cl}}/\mathrm{GeV}^{-1}$
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0
2
4
6
8
10
12
M_{cluster} [GeV]



$1/n\ \mathrm{d}n/\mathrm{d}M_{\mathrm{cl}}/\mathrm{GeV}^{-1}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
M_{cluster} [GeV]

$$\lambda \equiv \sum_{i \in \{\text{clusters}\}} m_i^2$$



observe extreme decrease of λ in hadron collisions only

$\Rightarrow$ almost no colour reconnection at LEP!