Soft Models in Herwig

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and Hadronization Corrections
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Karlsruhe Institute of Technology

MCnet

Bundesministerium
für Bildung
und Forschung

TRR 257 - Particle Physics Phenomenology
after the Higgs Discovery

Soft models in Herwig

For this workshop: where do soft models affect observables that are determined perturbatively?

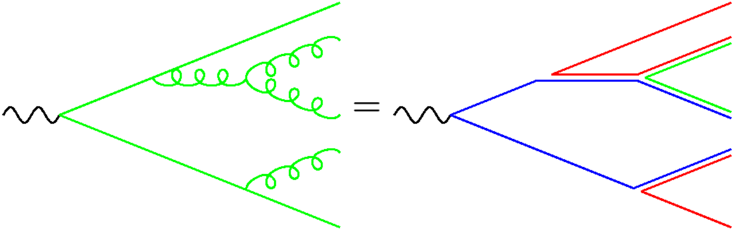
- Hadronization and Hadronic Decays
- Multiple Parton Interactions (MPI) Modelling
- Colour Reconnection
- Intrinsic $k_\perp$

All are in close *correspondence* with the parton shower.

One obvious but important omission: pdfs

Colour preconfinement

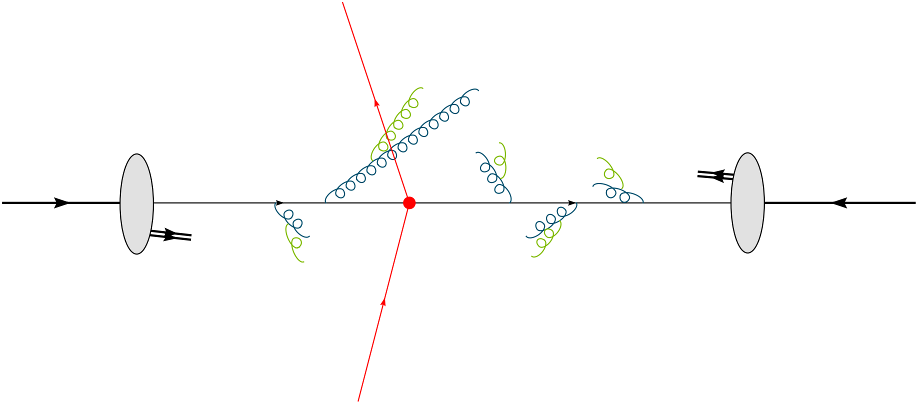
Large N_C limit ⟶ planar graphs dominate.
Gluon = colour — anticolour pair



Parton shower organises partons in colour space. Colour partners (=colour singlet pairs) end up close in phase space.

⟶ Cluster hadronization model

Cluster hadronization



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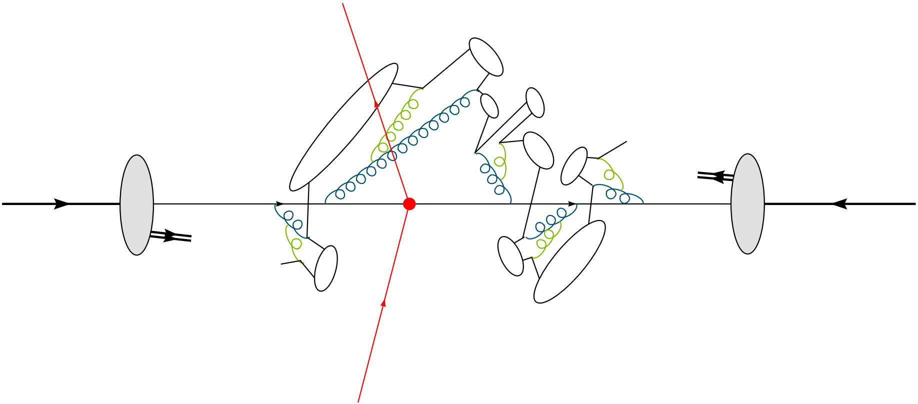

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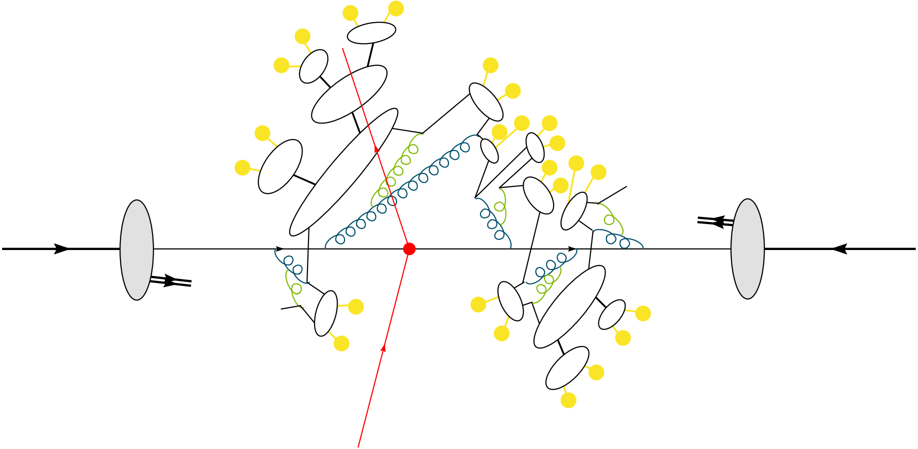
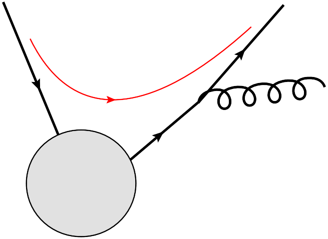


Cluster Hadronization

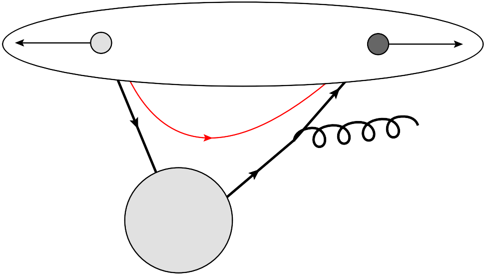


After parton shower, partons on constituent mass shell

Find colour singlets as 3-$\bar{3}$ pairs → cluster

Colour neighbours ∼ neighbours in momentum space

Cluster Hadronization



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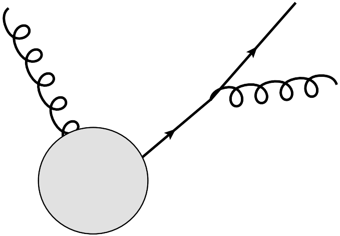
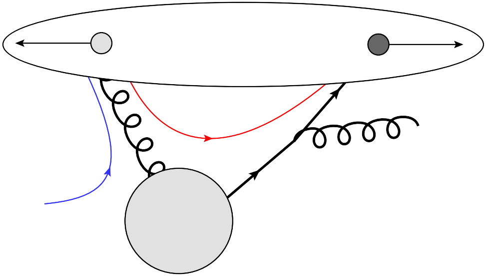
Cluster Hadronization



But gluons are $8 \sim 3\text{-}\bar{3}$!

Cluster Hadronization



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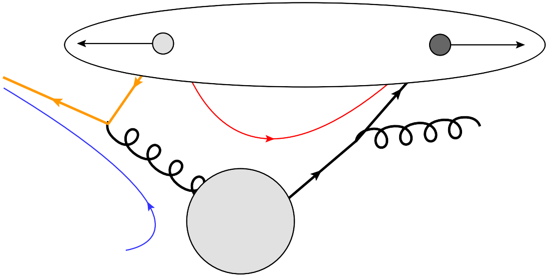
Cluster Hadronization



But gluons are $8 \sim 3\text{-}\bar{3}$!

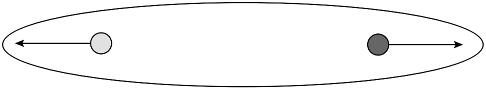
non-perturbative gluon splitting (isotropic)

$m_g > 2m_q$

kinematics from masses

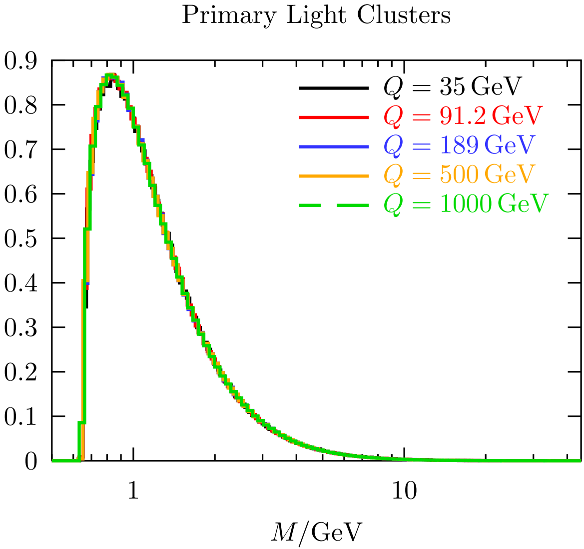
quarks and diquarks possible

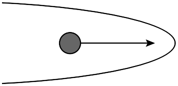
Cluster Hadronization



Cluster carries net momentum of its constituents
Spectrum determined by final state of parton shower
Independent of hard scales
Tail of *heavy clusters*, still large scale available

Cluster Hadronization

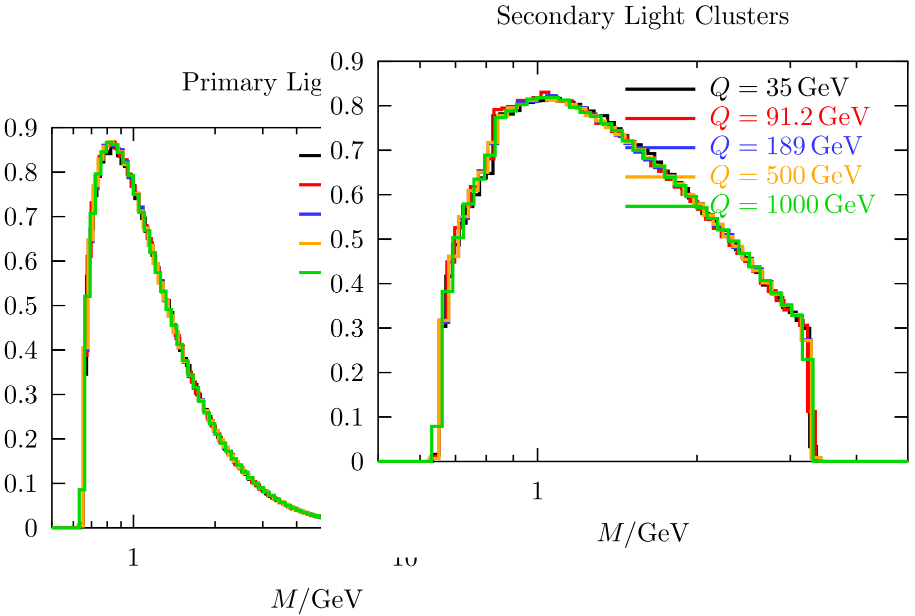




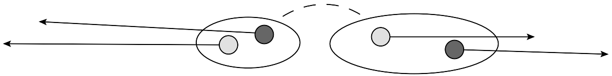
tuents
on shower

ble

Cluster Hadronization

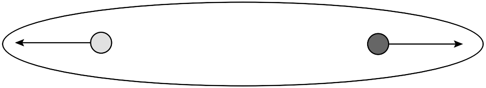


Cluster Hadronization



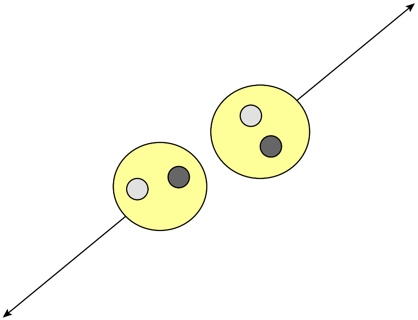
Binary fission along quarks' direction of motion
Flavour introduced in $q\bar{q}$ pairs
Baryons could be introduced via diquarks
Mass → multiplicity, momentum
Beam remnant clusters split off as very light clusters
→ *Kinematic triangle*

Cluster Hadronization



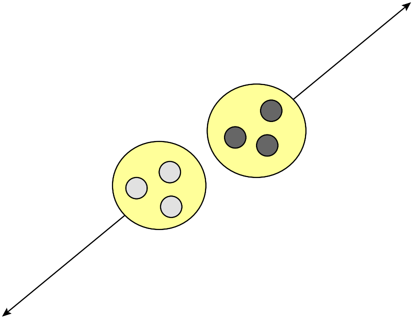
End up with fairly light clusters
too light? Decay into single hadron
Exchange momentum with neighbour

Cluster Hadronization



Decay isotropically into hadron pairs
Individual Hadrons get weight according to flavour multiplet,
CM momentum, spin multiplicity etc.

Cluster Hadronization



Baryon pairs possible
usually appear from clusters with 1 or 2 diquarks
could also emerge in pairs from mesonic clusters

Hadronization

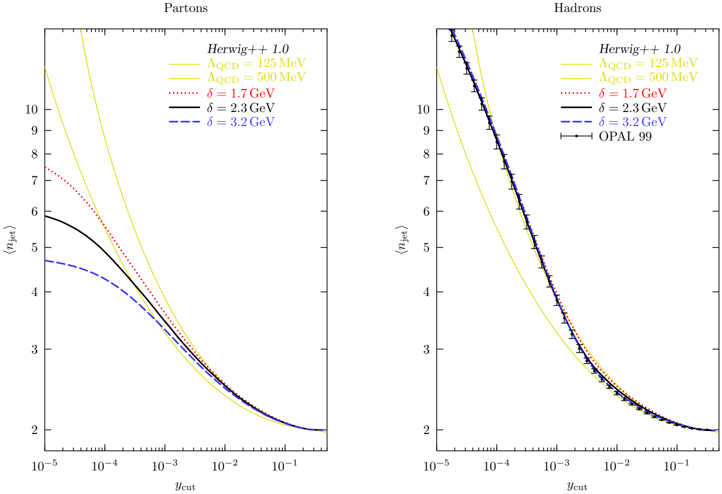
UV cutoff of hadronizaiton is IR cutoff of parton shower.
Some kind of factorization.

- Assignment of colour lines, leading $1/N_C$ expansion.
  First insight from colour evolution of soft gluons?
  More updates from parton showers at non-leading colour.
- Colour reconnection models alter the picture. See later.
- Gluon splitting, m_g-dependence (+kinematic details?)
- Fission dynamics, now binary. Choice of phase space.
  Non-binary, i.e. $2 \to N$ fission, relation to soft UE?
  Non-perturbative $p_\perp$.
- Choice of hadrons and masses in cluster decay

After tuning (ideal world):
$\approx$ independence of PS cutoff scale μ^2

μ^2-dependence (here: δ)

Smooth interplay between shower and hadronization.

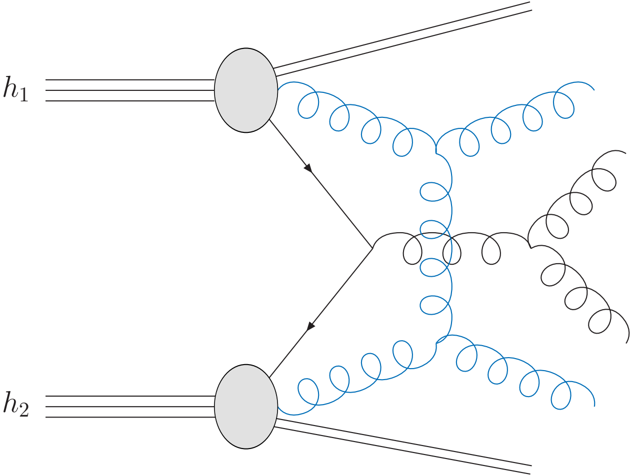


UV behaviour of Hadronization could be derived from PS.

[SG, A. Ribon, M. Seymour, P. Stephens, B.R. Webber, JHEP 0402 (2004) 005]

MPI/Eikonal model basics

Mulitple hard and soft interactions



Eikonal model basics

Starting point: hard inclusive jet cross section.

$$\sigma^{\rm inc}(s;p_t^{\rm min}) = \sum_{i,j} \int_{{p_t^{\rm min}}^2} {\rm d}p_t^2 f_{i/h_1}(x_1,\mu^2) \otimes \frac{{\rm d}\hat{\sigma}_{i,j}}{{\rm d}p_t^2} \otimes f_{j/h_2}(x_2,\mu^2)\,,$$

$\sigma^{\rm inc} > \sigma_{\rm tot}$ eventually (for moderately small $p_t^{\rm min}$).

Interpretation: $\sigma^{\rm inc}$ counts *all* partonic scatters that happen during a single *pp* collision ⇒ more than a single interaction.

$$\sigma^{\rm inc} = \bar{n}\sigma_{\rm inel}\,.$$

Eikonal model basics

Use eikonal approximation (= independent scatters). Leads to Poisson distribution of number m of additional scatters,

$$P_m(\vec{b},s) = \frac{\bar{n}(\vec{b},s)^m}{m!} \mathrm{e}^{-\bar{n}(\vec{b},s)} \ .$$

Then we get σ_{inel}:

$$\sigma_{\mathrm{inel}} = \int \mathrm{d}^2\vec{b} \sum_{m=1}^{\infty} P_m(\vec{b},s) = \int \mathrm{d}^2\vec{b} \left(1 - \mathrm{e}^{-\bar{n}(\vec{b},s)}\right) \ .$$

Cf. σ_{inel} from scattering theory in eikonal approx. with scattering amplitude $a(\vec{b},s) = \frac{1}{2i}(\mathrm{e}^{-\chi(\vec{b},s)} - 1)$

$$\sigma_{\mathrm{inel}} = \int \mathrm{d}^2\vec{b} \left(1 - \mathrm{e}^{-2\chi(\vec{b},s)}\right) \qquad \Rightarrow \qquad \chi(\vec{b},s) = \tfrac{1}{2}\bar{n}(\vec{b},s) \ .$$

$\chi(\vec{b},s)$ is called *eikonal* function.

Eikonal model basics

Calculation of $\bar{n}(\vec{b},s)$ from parton model assumptions:

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

Eikonal model basics

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&\qquad \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}$$

$$\Rightarrow \quad \chi(\vec{b},s) = \tfrac{1}{2}\bar{n}(\vec{b},s) = \tfrac{1}{2}A(\vec{b})\sigma^{\text{inc}}(s;p_t^{\text{min}}) \ .$$

Overlap function

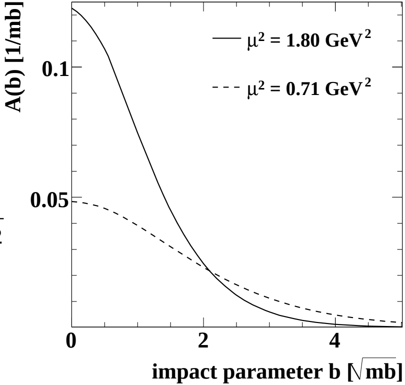
$$A(b) = \int \mathrm{d}^2\vec{b}' G_A(|\vec{b}'|) G_B(|\vec{b}-\vec{b}'|)$$

$G(\vec{b})$ from electromagnetic FF:

$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{\mathrm{d}^2\vec{k}}{(2\pi)^2} \frac{\mathrm{e}^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

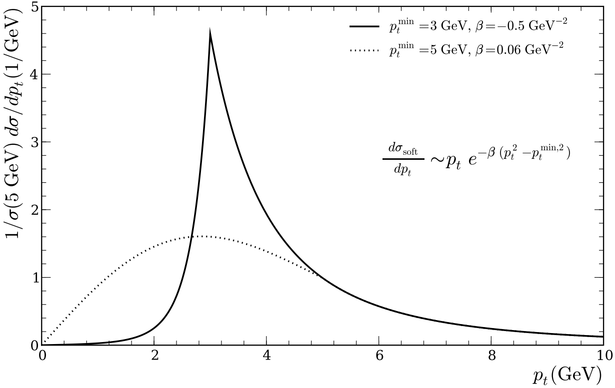
But μ^2 *not fixed* to the *electromagnetic* $0.71\,\mathrm{GeV}^2$.
Free for colour charges.

⇒ Two main parameters: $\mu^2, p_t^{\mathrm{min}}$.



Extending into the soft region

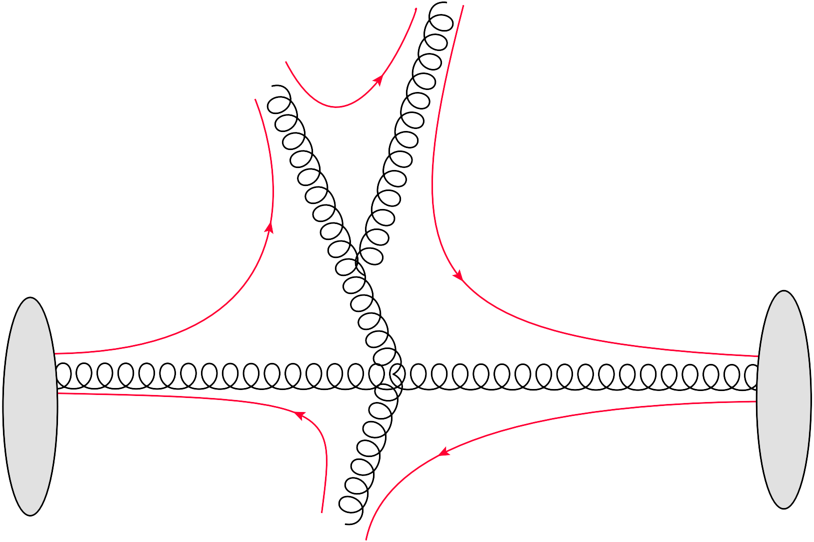
Continuation of the differential cross section into the soft region $p_t < p_t^{\min}$ (here: p_t integral kept fixed)



Extra parameters σ_{soft} and μ^2_{soft} fixed from data.

[M. Bähr, SG, M.H. Seymour, JHEP 0807 (2008) 076]

Colour correlations in hadronic collisions



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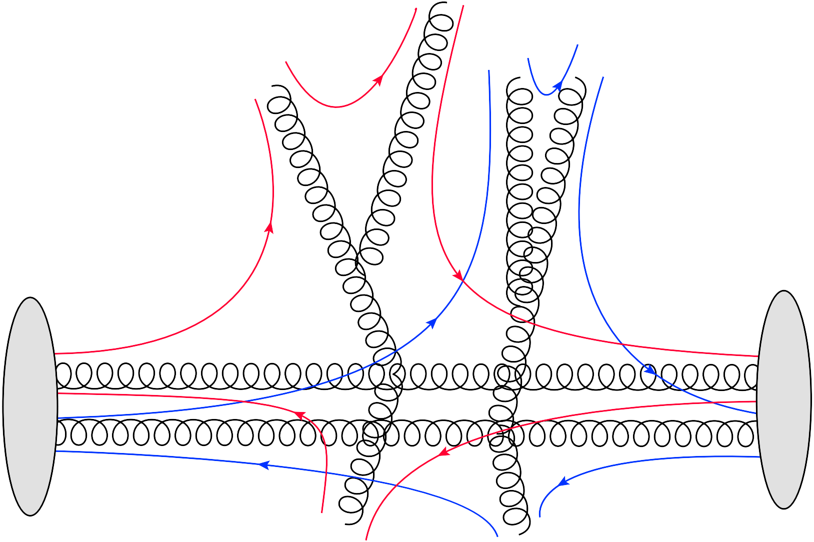

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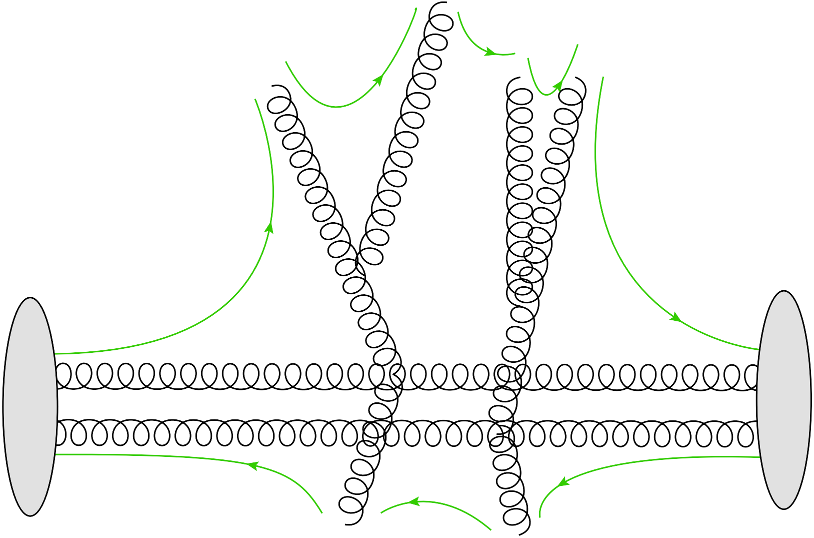
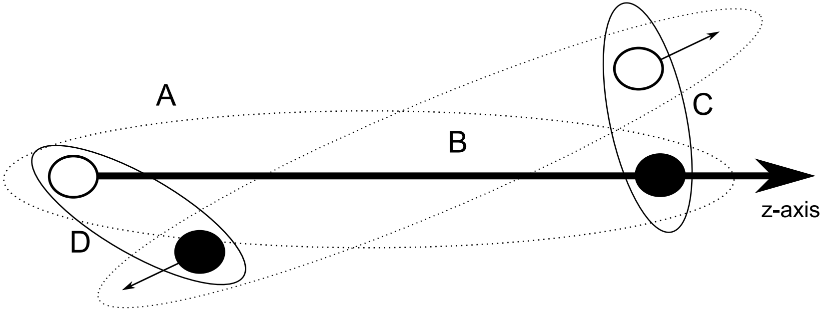


Rapididy based colour reconnection

“Closeness” of quarks not based on invariant mass but on proximity in momentum space.



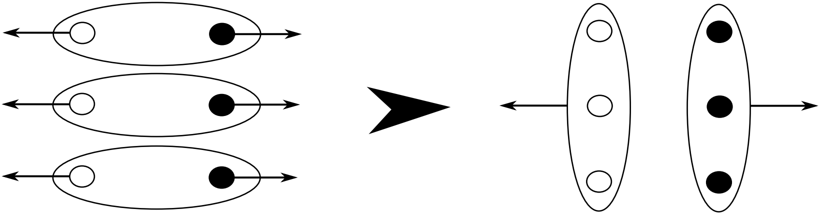
Consider other quarks’ movement based on their rapidity in reference clusters’ CM frame.

[SG, C. Röhr, A. Siodmok, EPJC72 (2012) 2225]

[SG, P. Kirchgaeßer, S. Plätzer, EPJC78 (2018) 99]

Rapididy based colour reconnection

Colour singlets not only from $q\bar{q}$ but also from qqq states



But, baryonic clusters would typically be much heavier

$$M_{ijk} + M_{lmn} > M_{il} + M_{jm} + M_{kn}$$

would always/often be reconnected into mesonic clusters.

[SG, C. Röhr, A. Siodmok, EPJC72 (2012) 2225]

[SG, P. Kirchgaeßer, S. Plätzer, EPJC78 (2018) 99]

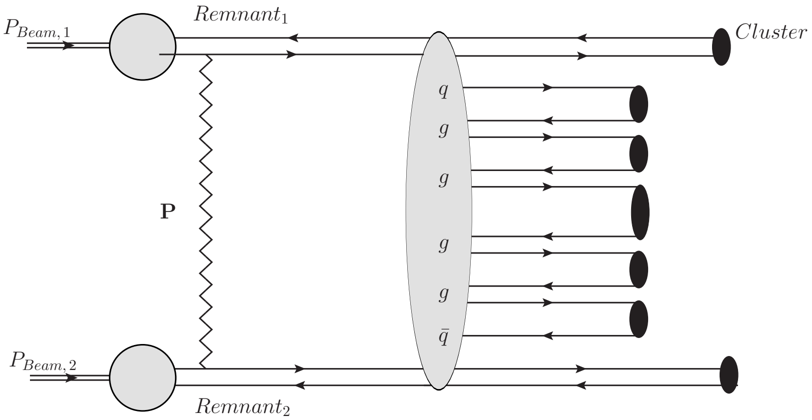
Soft particle production model in Herwig

- #ladders = N_{soft} (MPI).
- N particles from Poissonian, width $\langle N \rangle$.
  Model parameter $1/\ln C \equiv n_{\text{ladder}} \to$ tuned.
- $\sim$ flat in y
- $p_\perp$ from Gaussian acc to soft MPI model.
- particles are q, g, see figure.
  Symmetrically produced from both remnants.
- Colour connections between neighboured particles.

[SG, F. Loshaj, P. Kirchgaeßer, EPJ C77 (2017) 156]

Soft particle production model in Herwig

Single soft ladder with MinBias initiating process.



Further hard/soft MPI scatters possible.

[SG, F. Loshaj, P. Kirchgaeßer, EPJ C77 (2017) 156]

Energy evolution

Some parameters $\sqrt{s}$ dependent.

$$p_\perp^{\min} = p_{\perp,0}^{\min}\left(\frac{\sqrt{s}}{E_0}\right)^b \qquad \longrightarrow \qquad p_{\perp,0}, b$$

$p_{\perp,0} \sim 3.5\,\mathrm{GeV}$, $b \sim 0.4$.

$$\langle n_{\text{ladder}}\rangle = N_0\left(\frac{s}{1\,\mathrm{TeV}^2}\right)^a \log\frac{s}{m_p^2} \qquad \longrightarrow \qquad N_0, a$$

$N_0 \sim 1$, $a \sim -0.08$.

Parameters and tuning

Diffraction plus MPI incl new soft model.

Diffractive cross sections adjusted to data.

Tuning to Min Bias data: $\eta, p_\perp$ for various $N_{\rm ch}$, $\langle p_\perp \rangle (N_{\rm ch})$.

Usual MPI parameters

$$(p_{\perp,0}^{\rm min}, b) \to p_\perp^{\rm min}(\sqrt{s}), \quad \mu^2, \quad p_{\rm reco}\ .$$

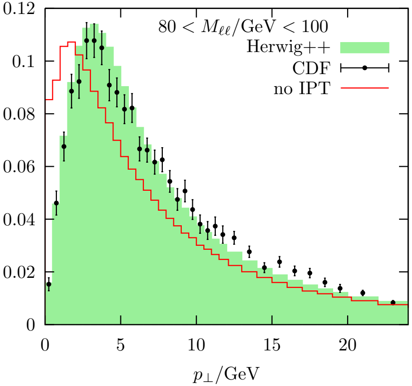
One additional parameter
("gluons per unit rapidity" in soft ladder)

$$n_{\rm ladder}\ .$$

Good description of most UE and Min Bias data

Nonperturbative issues (Drell Yan)

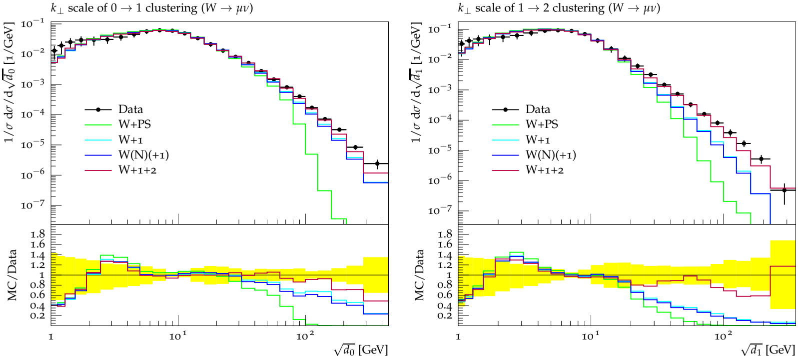
- Primordial $k_\perp$ from soft, non–perturbative(?) gluons.
- Gaussian smearing. Default: $\langle p_\perp \rangle = 2.1\,\mathrm{GeV}$!
- Could be modeled by soft, non–perturbative gluon emissions.



[SG, M. Seymour, A. Siodmok,JHEP 0806 (2008) 001]

Unitarized Matching/Merging

W+jets. Note residual MPI/hadronization dependance.

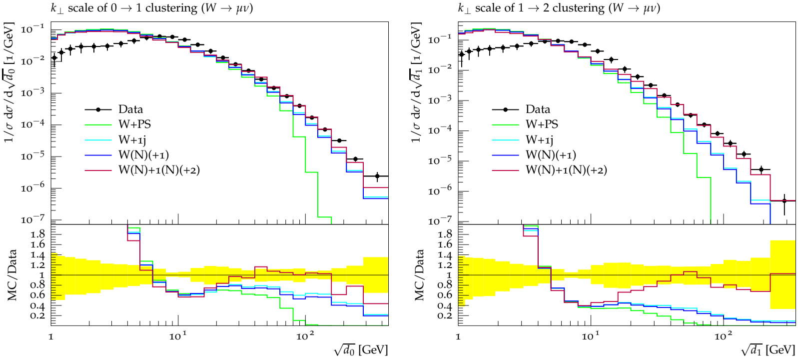


[J. Bellm, SG, S. Plätzer]

MPI/Hadronization on.
$W+1, W+1+2$: LO merging with 1(2) jets.
$W(N)+1$: 0j NLO with 0j+1j LO (“matching through merging”).

Unitarized Matching/Merging

W+jets. Note residual hadronization dependance.



[J. Bellm, SG, S. Plätzer]

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For this workshop: where do soft models affect observables that are determined perturbatively?

- Hadronization and Hadronic Decays
  UV scale of Hadronization = IR scale of PS.
- Multiple Parton Interactions (MPI) Modelling
  Strong influence at low $p_\perp$. Systematics less clear.
- Colour Reconnection
  More important for identified particles than for jets.
- Intrinsic $k_\perp$
  Obviously matters at low $k_\perp$