Hadronization and Colour Reconnection models

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Parton Showers for future e^+e^- colliders
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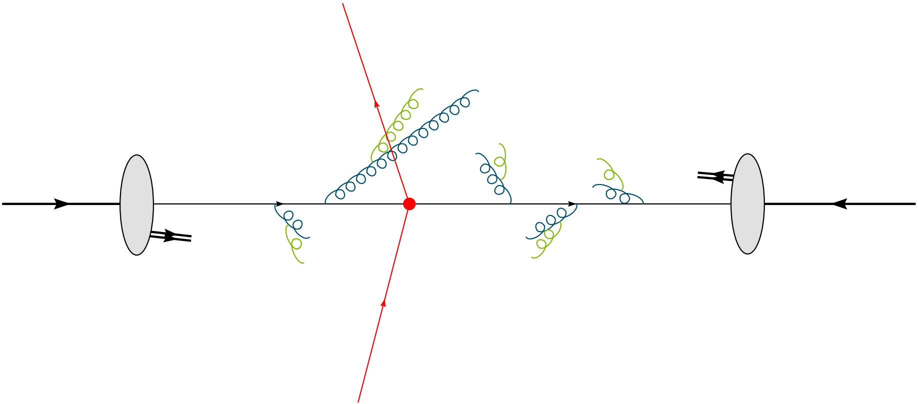
Karlsruhe Institute of Technology

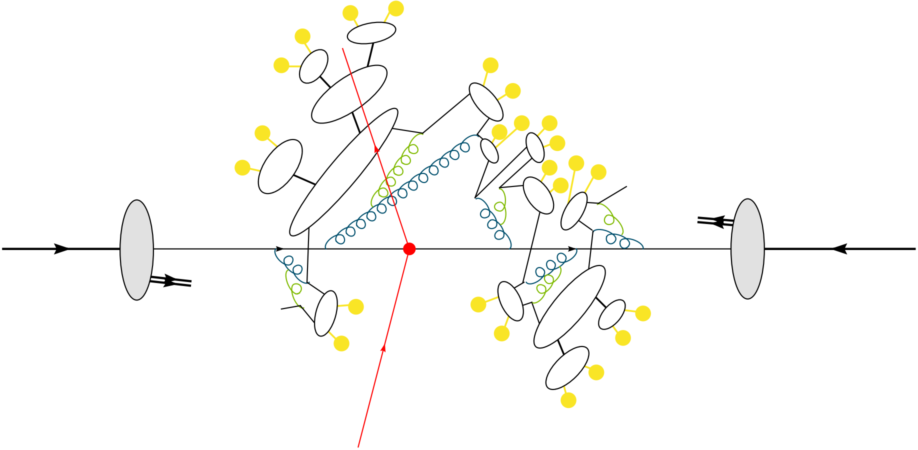
MCnet

Bundesministerium für Bildung und Forschung

pp Event Generator



pp Event Generator



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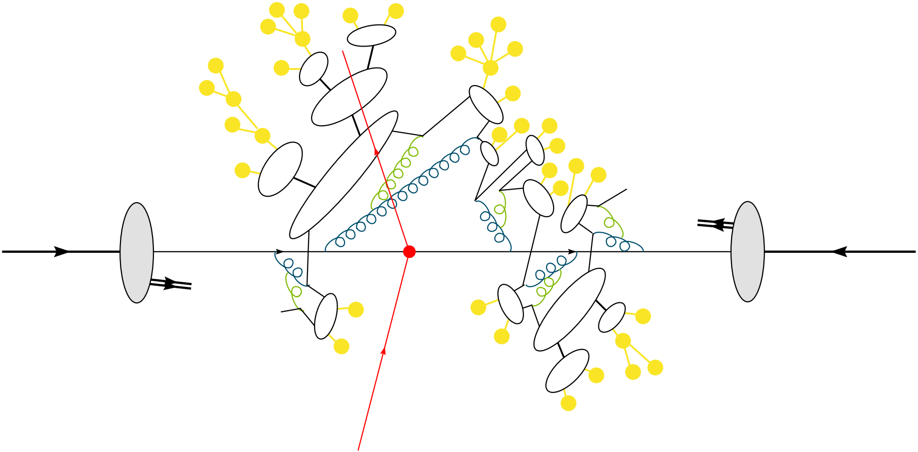
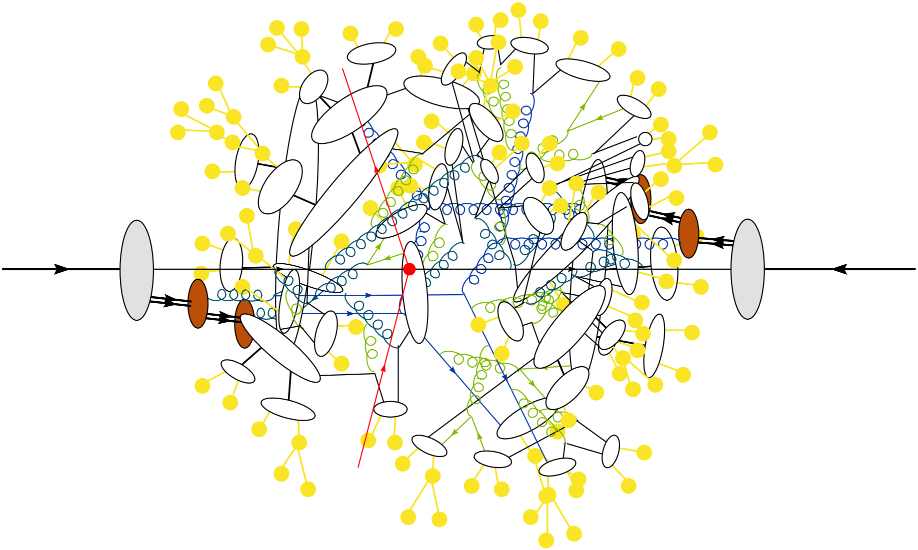


pp Event Generator



Soft models

Where do soft models affect observables at the final state?

- Multiple Parton Interactions (MPI) Modelling
- Colour Reconnection
- Hadronization
- Hadronic Decay

Momentum *and* colour structure from parton shower

Soft models

Where do soft models affect observables at the final state?

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Momentum *and* colour structure from parton shower

At e^+e^- collider

- obviously no MPI (exception “resolved” $\gamma\gamma$)
- role of CR? Jets in WW? Intra-jet?

Overview

Recap strings and clusters, similarities and differences

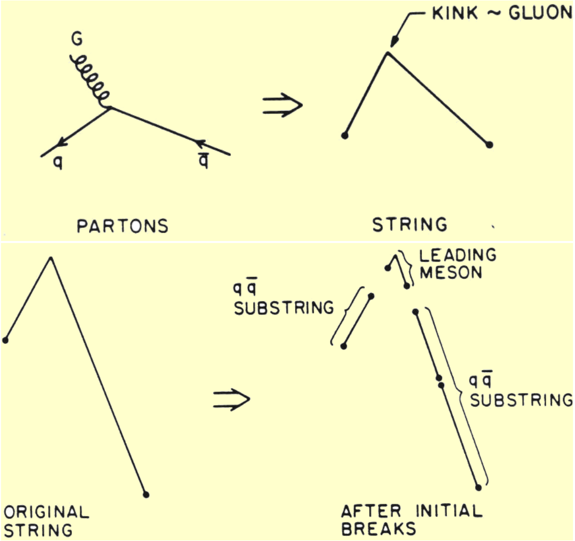
Recap developments of the past years, mainly MPI and CR

Newer ideas

Conclusions for e^+e^--colliders

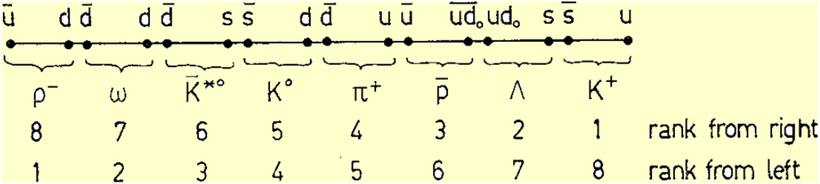
Lund string model

gluon = kink on string = motion pushed into the $q\bar{q}$ system.



Lund string model

Ajacent breaks form hadrons.



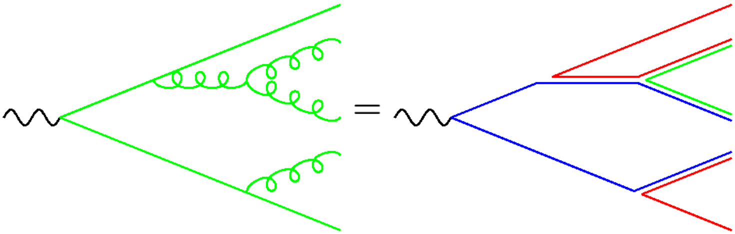
Works in both directions (symmetry).
Lund symmetric fragmentation function

$$f(z, p_\perp) \sim \frac{1}{z}(1-z)^a \exp\left(-\frac{b(m_h^2 + p_\perp^2)}{z}\right)$$

a, b, m_h^2 main adjustable parameters.
Note: diquarks $\to$ baryons.

Colour preconfinement

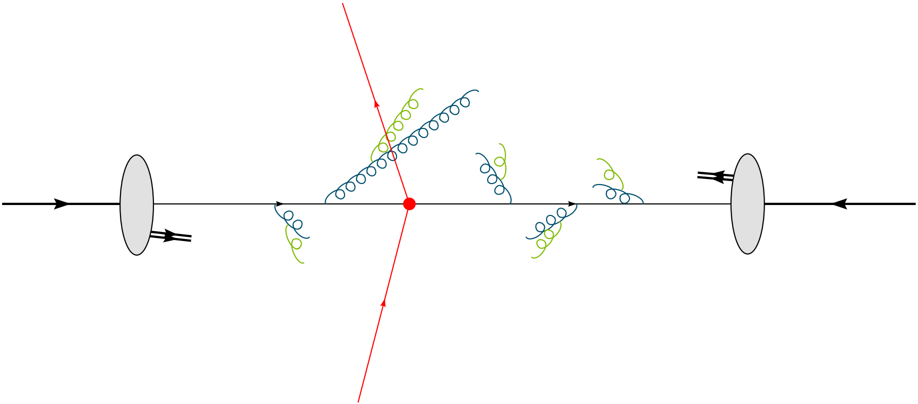
Large N_C limit $\longrightarrow$ planar graphs dominate.
Gluon = colour — anticolour pair



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

$\longrightarrow$ Input for hadronization model

Cluster hadronization



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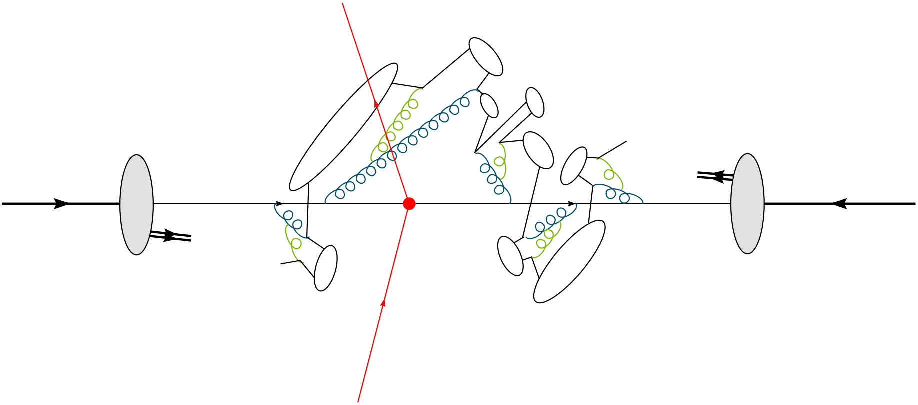
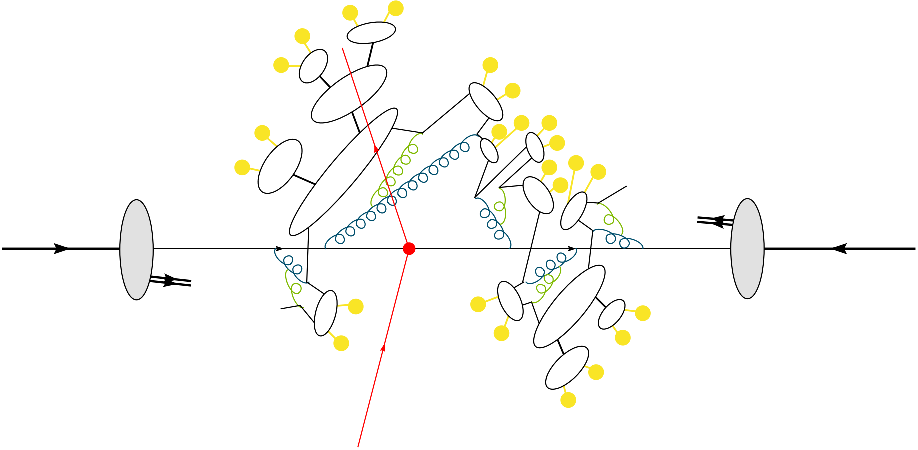
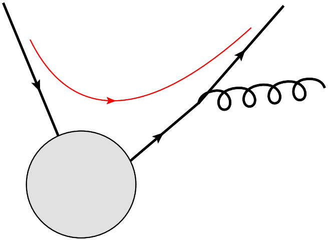


Cluster hadronization

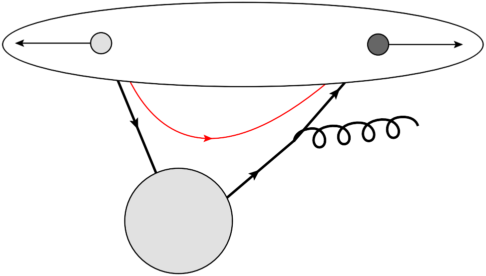


Cluster Hadronization



After parton shower, partons on constituent mass shell
Find colour singlets as 3-$\bar{3}$ pairs $\rightarrow$ cluster
Colour neighbours $\sim$ neighbours in momentum space

Cluster Hadronization



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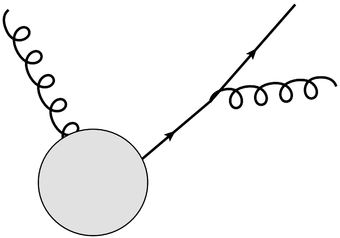
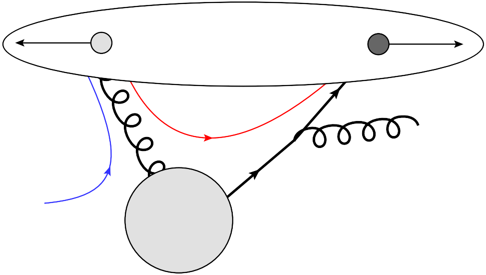


But gluons are $8 \sim 3\text{-}\bar{3}$!

Cluster Hadronization



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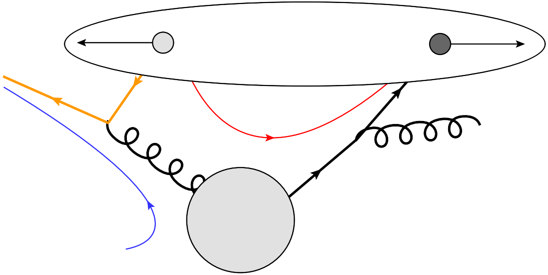
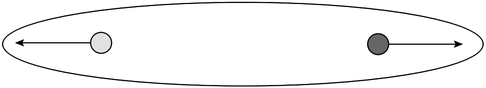


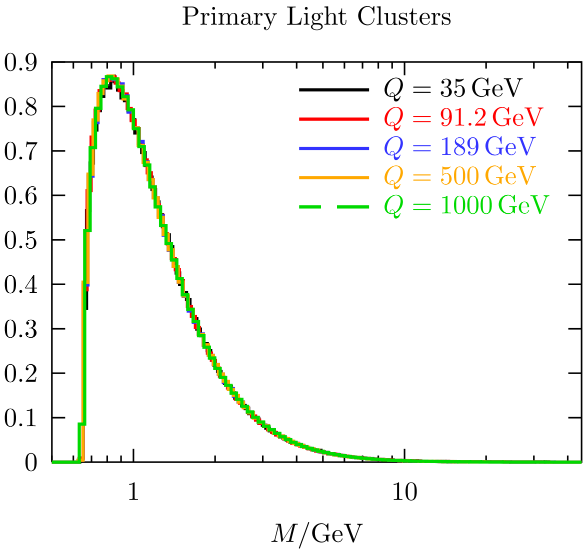
But gluons are $8 \sim 3\text{-}\bar{3}$!
non-perturbative gluon splitting (isotropic)
$m_g > 2m_q$
kinematics from masses
quarks and diquarks possible

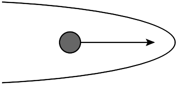
Cluster Hadronization



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





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on shower

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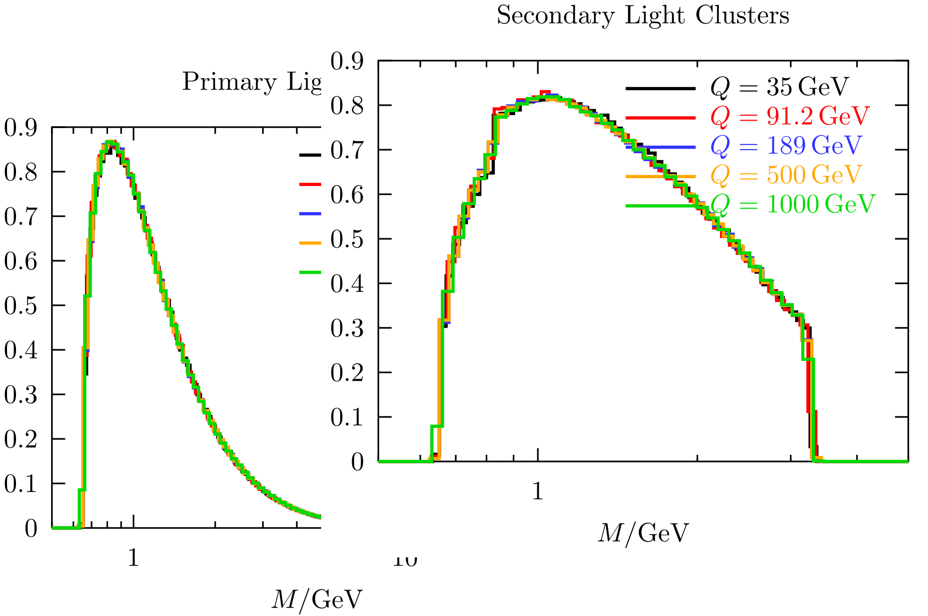
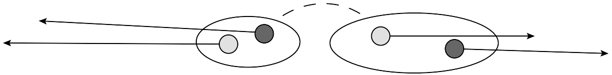
Cluster Hadronization

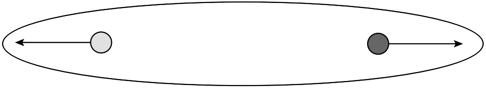


Cluster Hadronization



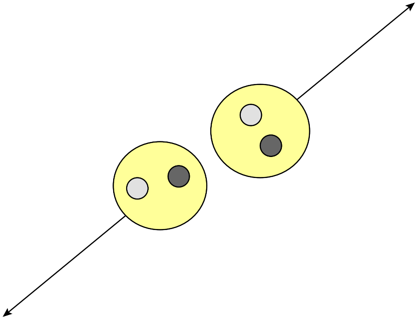
Binary fission along quarks' direction of motion
Flavour introduced in $q\bar{q}$ pairs
Baryons could be introduced via diquarks
Mass $\rightarrow$ multiplicity, momentum
Beam remnant clusters split off as very light clusters
$\rightarrow$ *Kinematic triangle*

Cluster Hadronization



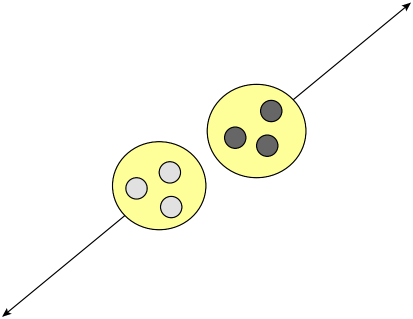
End up with fairly light clusters
too light? Decay into single hadron
Exchange momentum with neighbour

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

Strings vs clusters

Similarities

- Build on structure of partonic final state → momentum, colour, flavour.
- Both keep the bulk momentum flow of jets intact
- Trade Energy with multiplicity, → heavy particles, baryons
- Introduce some soft smearing of transverse momentum

Main difference

- strings treated as a whole
- clusters undergo binary fission, binary decay into hadrons

Some LEP results

Works quite well for a vast number of observables

- Nch
- Event shapes
- Spectra of identified particles (some better, some worse)
- Jets
- B fragmentation

Works quite well, particularly considering "charged" only. Also over larger energy ranges. Mostly pions.

Identified particle spectra often more difficult while averages right.

Hadronization

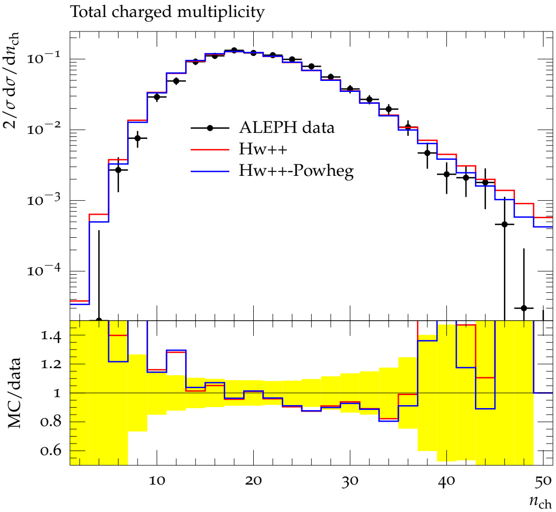
UV cutoff of hadronization is IR cutoff of parton shower.
Some kind of factorization.

- 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

How well does it work?

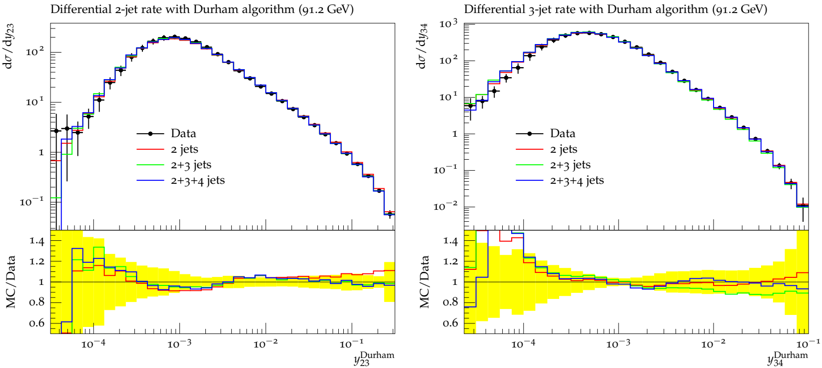
N_{ch} at LEP. Crucial for t_0 (Herwig++ 2.5.2)



*Hw++-Powheg = Matchbox multiplicative matching

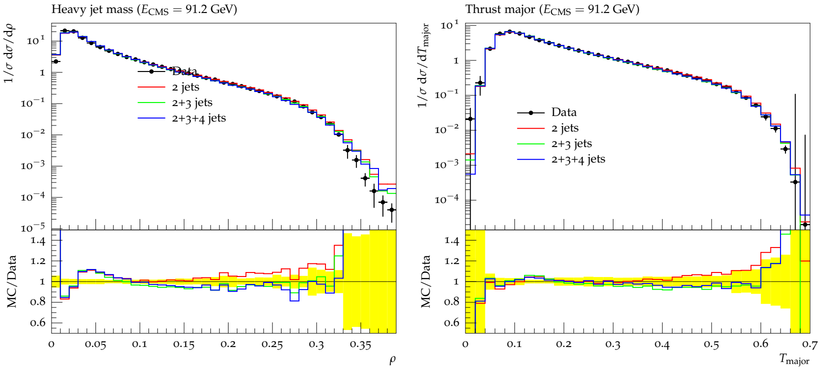
How well does it work?

Differential Jet Rates at LEP (Herwig++ pre-3.0).
Dipole shower + some merging



How well does it work?

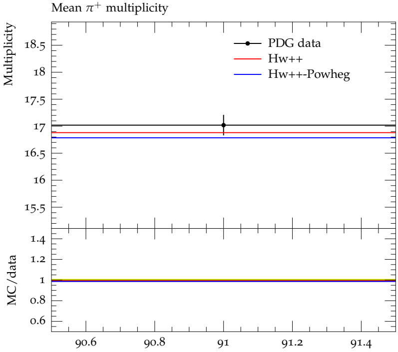
Event Shapes at LEP (Herwig++ pre-3.0).
Dipole shower + some merging

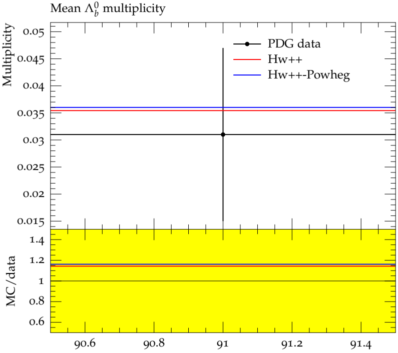


Parton showers do very well, today!

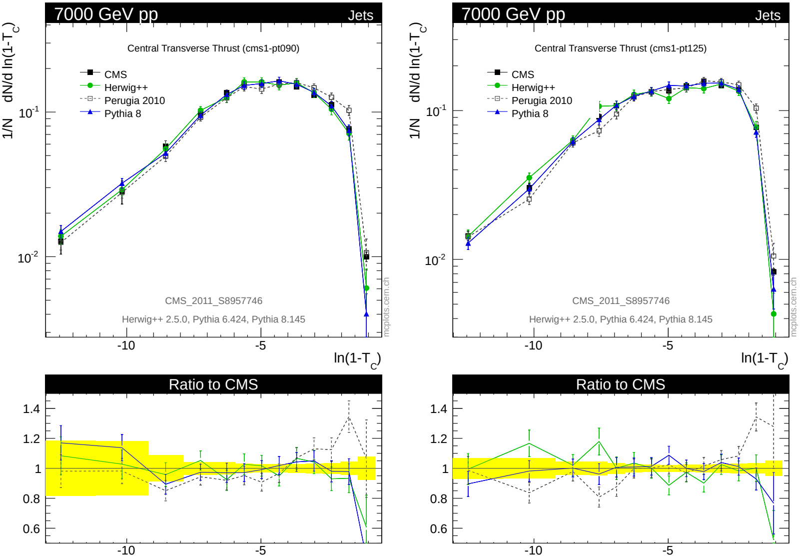
How well does it work?

Hadron Multiplicities at LEP (e.g. π^+, Λ_b^0).



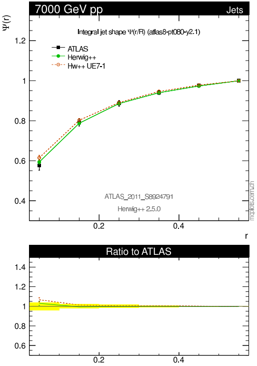


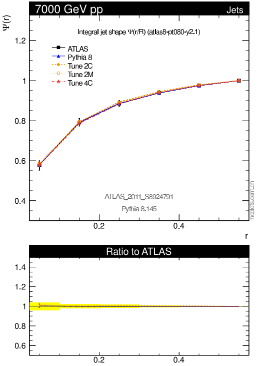
Transverse thrust

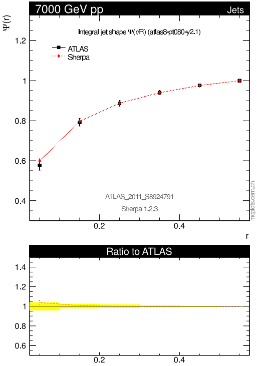


Integral jet shapes

harder, more forward ($80 < p_T/\text{GeV} < 110; 1.2 < |y| < 2.1$)

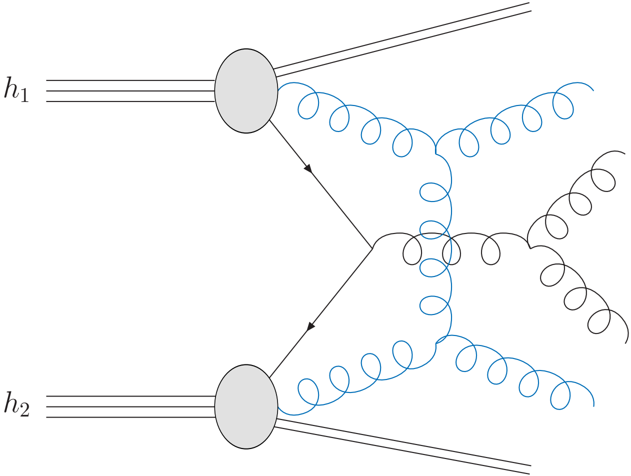






MPI/Eikonal model basics

Mulitple hard and soft interactions



Eikonal model basics

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

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

Then we get $\sigma_{\rm inel}$:

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

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

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

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

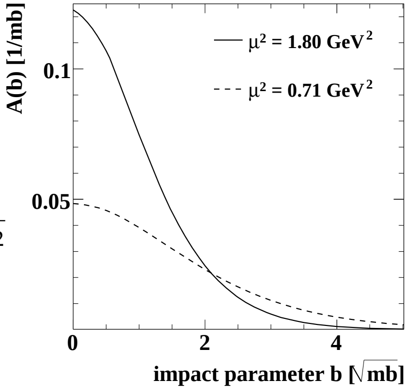
Overlap function

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

$G(\vec{b})$ 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.



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

MPI at low $p_\perp$

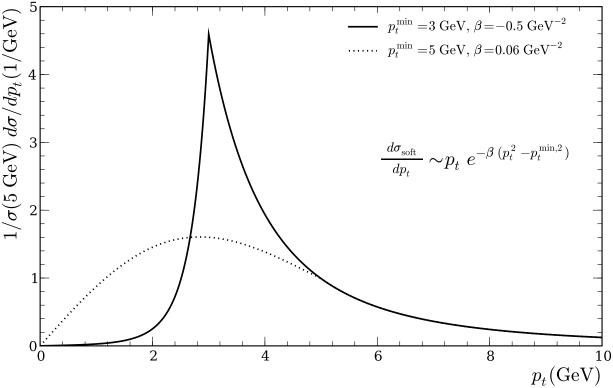
Pythia: "freezing" of hard $\sim 1/p_\perp^4$ spectrum at low $p_\perp$ as model for soft MPI.

Herwig: transition from hard to soft MPI at $p_\perp^{\rm min}$.

Sherpa: BFKL ladders

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]

Soft particle production model in Herwig

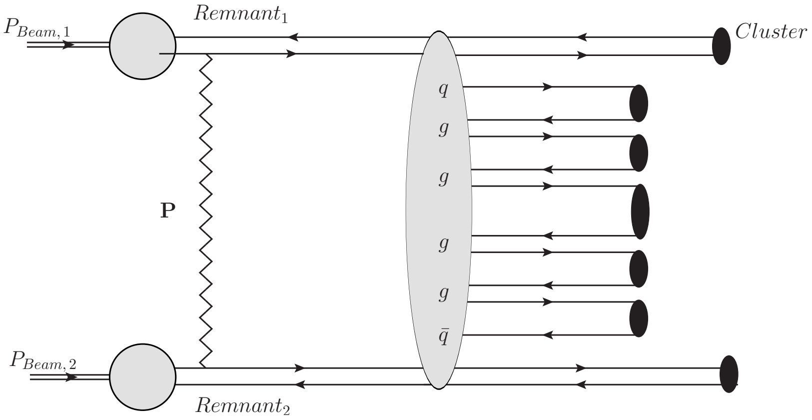
- #ladders = N_{soft} (MPI).
- N particles from Poissonian, width $\langle N \rangle$.
- $\sim$ flat in y
- $p_\perp$ from Gaussian acc to soft MPI model.
- particles are q, g, see figure.
  Symmetrically produced from both remnants.
- Colour connections between neighboured particles.

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

[J. Bellm, SG, P. Kirchgaeßer, EPJ C80 (2020) 5, 469]

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]

[J. Bellm, SG, P. Kirchgaeßer, EPJ C80 (2020) 5, 469]

Energy evolution

Some parameters $\sqrt{s}$ dependent.

$$p_\perp^{\min} = p_{\perp,0}^{\min} \left(\frac{\sqrt{s} + m_0}{E_0} \right)^b \qquad \longrightarrow \qquad p_{\perp,0}, b$$

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

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

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

Diffractive final states

Strictly low mass diffraction only. Allow M^2 large nonetheless.

M^2 power-like, t exponential (Regge).

$$pp \to \text{(baryonic cluster)} + p \; .$$

Hadronic content from cluster fission/decay $C \to hh \ldots$
Cluster may be quite light. If very light, use directly

$$pp \to N^* + p \; .$$

Also double diffraction implemented.

$$pp \to \text{(cluster)} + \text{(cluster)} \qquad pp \to N^* + N^* \; .$$

Technically: new MEs for diffractive processes set up.

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

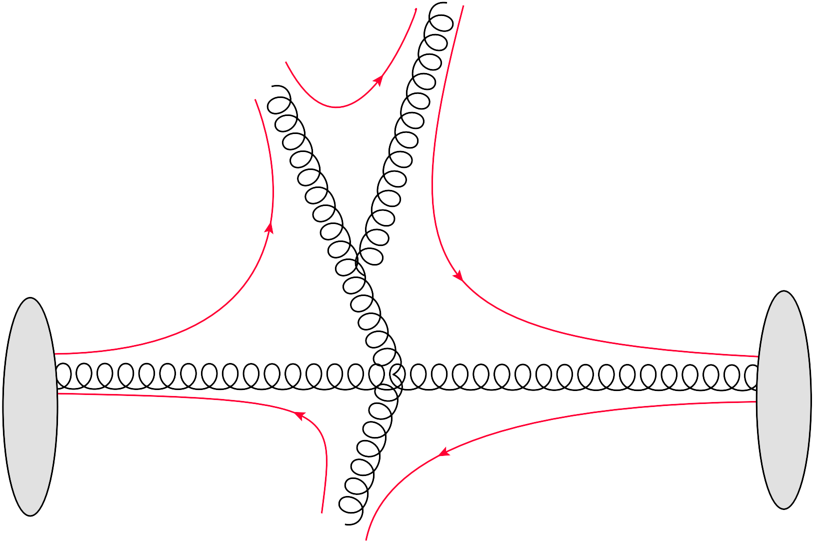
$$(p_{\perp,0}^{\rm min}, b) \to p_\perp^{\rm min}(\sqrt{s}), \quad \mu^2, \quad p_{\rm reco} \; .$$

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

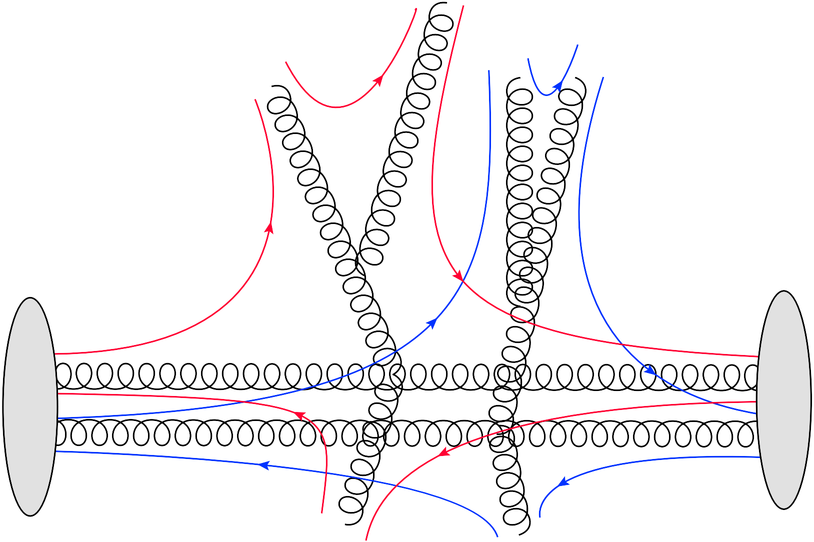
$$n_{\rm ladder} \; .$$

Good description of most UE and Min Bias data

Colour correlations in hadronic collisions



Colour correlations in hadronic collisions



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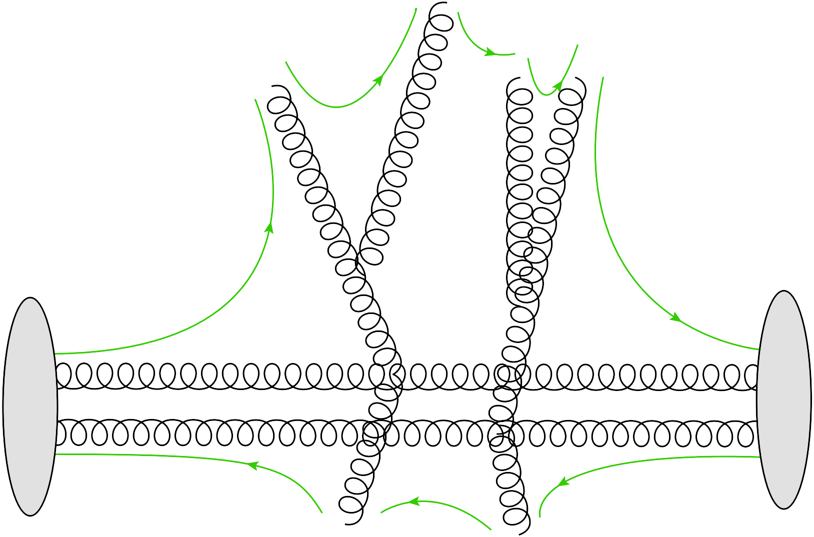
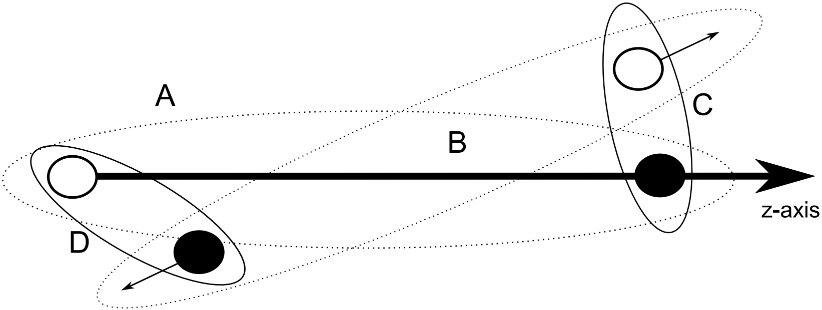


Rapididy based colour reconnection

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



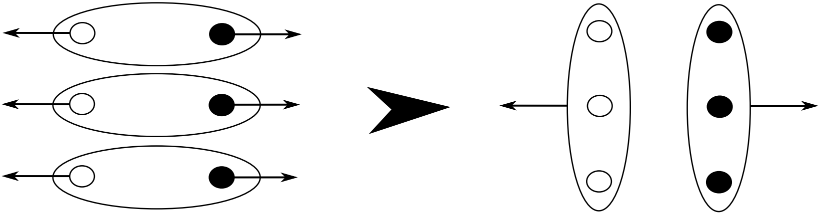
Consider other quarks' movement based on their rapidity in reference clusters' CM frame.

[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]

Colour Reconnection

Different models for "colour distance"

- Δy, ΔR, also with transverse component

[Bellm, Duncan, SG, Myska, Siodmok, EPJC79 (2019) 12, 1003]

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

- Different models for minimization of colour distance, combinatiorial, Metropolis.

[Sandhoff, Skands, 2005]

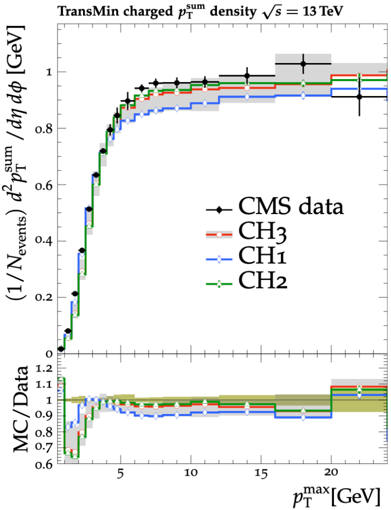
[SG, C. Röhr, A. Siodmok, EPJC72 (2012) 2225]

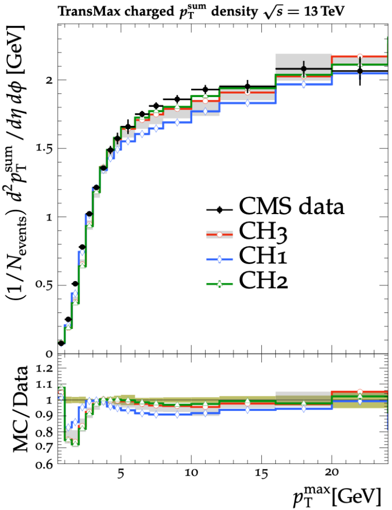
Perturbative support of phenomenological approach from soft gluons

[SG, Kirchgaeßer, Plätzer, Siodmok, JHEP 11 (2018) 149]

Colour Reconnection, particularly with the formation of Baryons, seems to be key for our understanding of particle production and correlations.

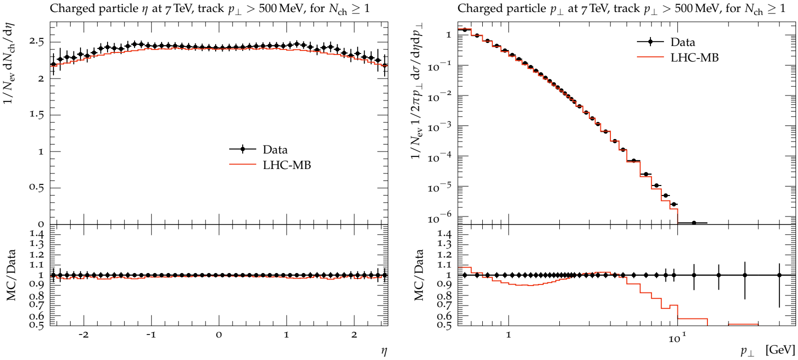
Underlying Event (CMS tunes)





[CMS H7 tunes, EPJC 81 (2021) 312]

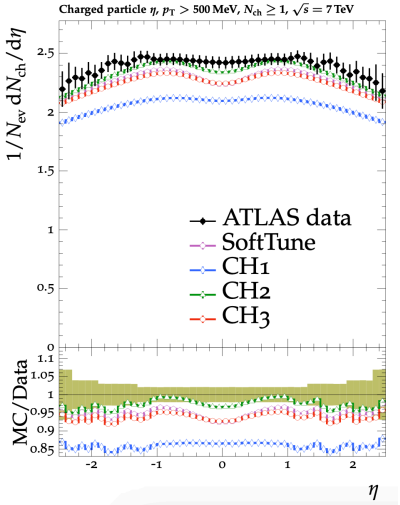
Example: Min Bias observables

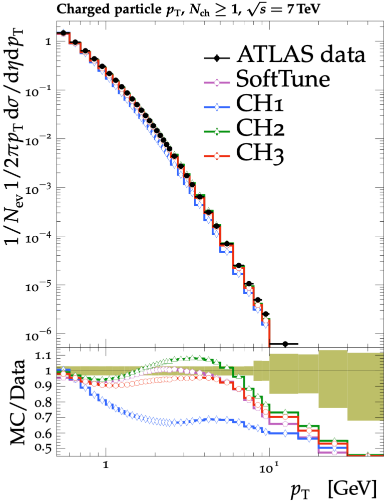


[ATLAS, New J.Phys. 13 (2011) 053033; Herwig 7.2.2]

Standard particle production observables
MPI and NP models tuned to these

Example: Min Bias observables





[Same data, CMS tune]

Standard particle production observables

MPI and NP models tuned to these

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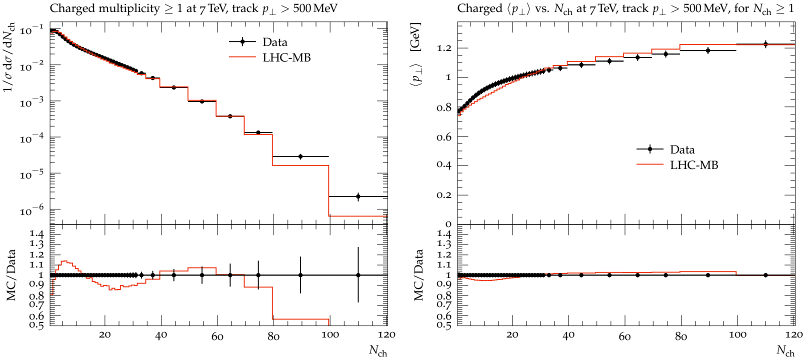

[ATLAS, New J.Phys. 13 (2011) 053033; Herwig 7.2.2]

Standard particle production observables
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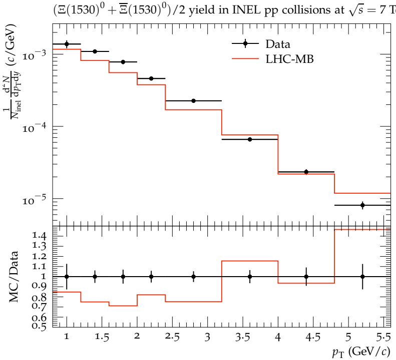
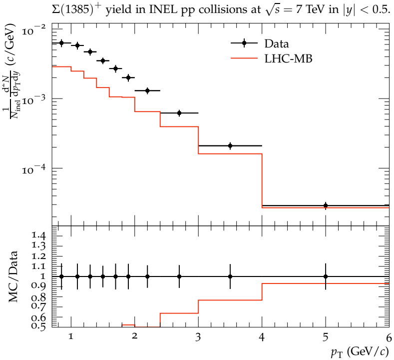
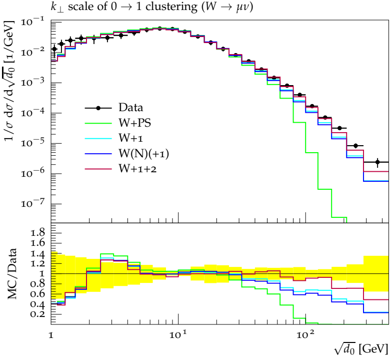


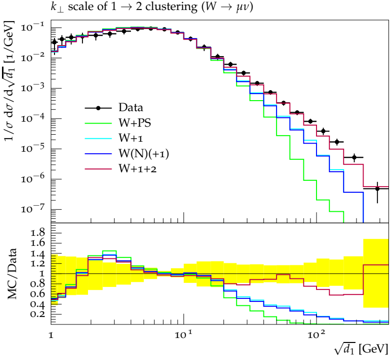


[ALICE, EPJ C75 (2015) 1,1; Herwig 7.2.2]

Identified particles, baryons in particular, harder to describe

W+jets. Note residual MPI/hadronization dependance.





[J. Bellm, S. Plätzer, SG, PhD thesis Bellm, KIT]

MPI/Hadronization on.

$W+1, W+1+2$: LO merging with 1(2) jets.
$W(N)+1$: 0j NLO with 0j+1j LO

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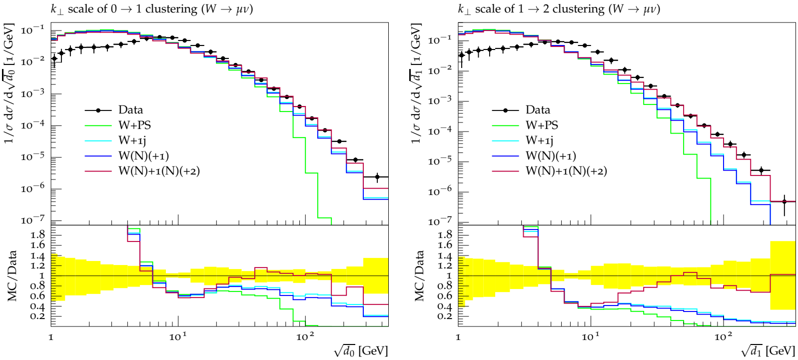

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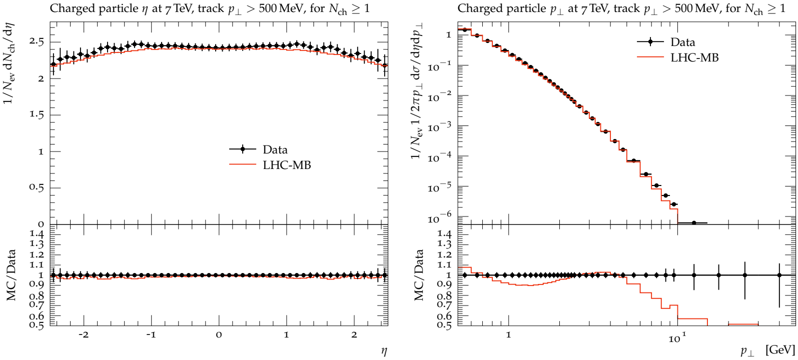

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Standard particle production observables
MPI and NP models tuned to these

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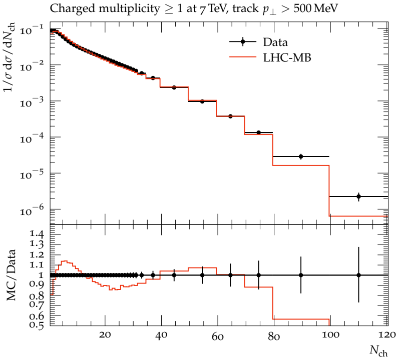

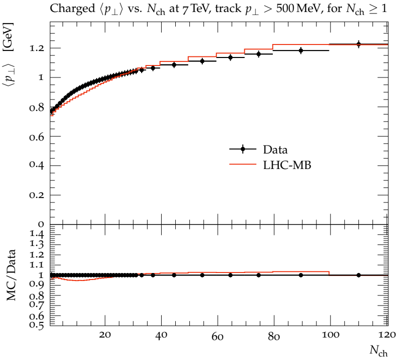

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Standard particle production observables
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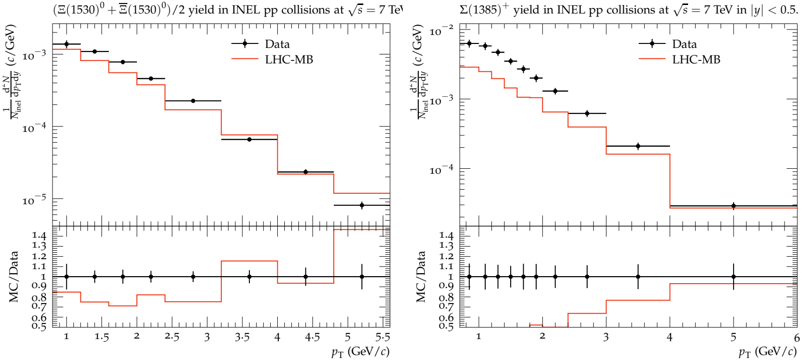


[ALICE, EPJ C75 (2015) 1,1; Herwig 7.2.2]

Identified particles, baryons in particular, harder to describe
$\rightarrow$ probably not "just" tuning?

So far…

We find that for many observables we get a reasonable answer

Only looking at any *charged particles*

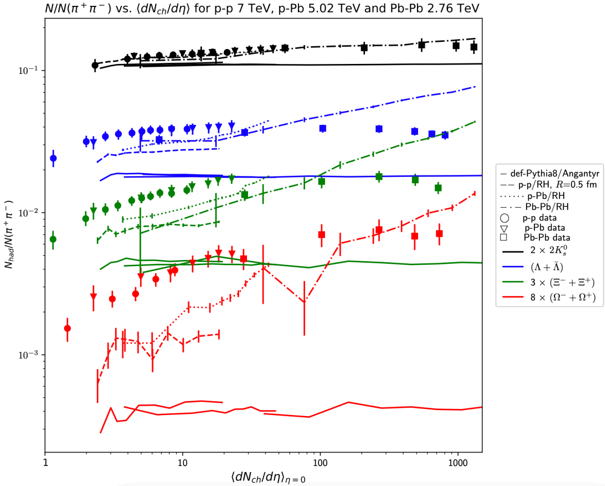
General activity from soft particles reflected

High $p_\perp$ observables decouple where expected (not shown)

How about more details?

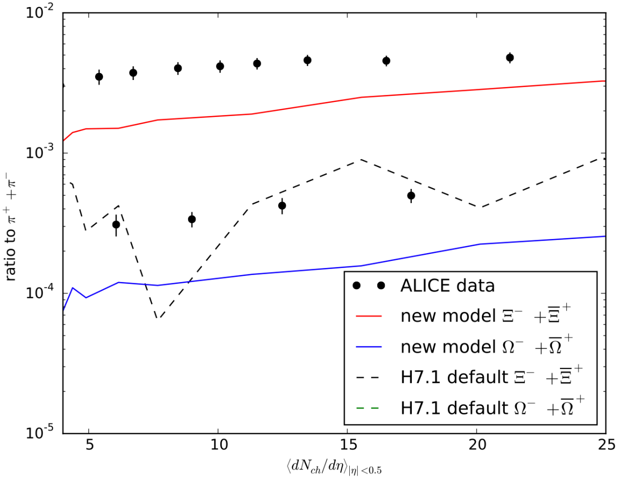
Colour Ropes in string fragmentation

Idea: strings close → new colour configurations → higher string tension → enhancement of heavy particle production



[Bierlich, Chakraborty, Gustafson, Lönnblad, 2205.11170]

Strange Baryons in Herwig

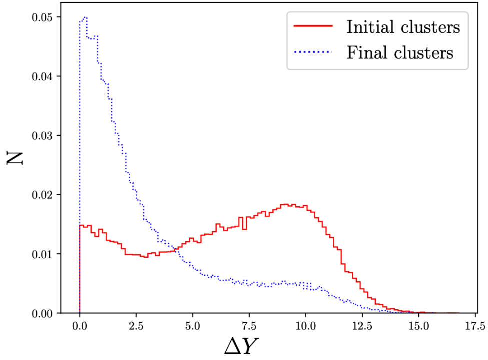


[SG, P. Kirchgaeßer, S. Plätzer, EPJC78 (2018) 99]

Colour reconnection from soft gluon evolution

CR could be initiated by soft gluon exchange =
colour-anticolour exchange in the fundamental representation.

- Evolution of multiple clusters in colour space
- project on colour singlet states
- phase space dependent weights
- preconfinement evident



[SG, Kirchgaeßer, Plätzer, Siodmok, JHEP 11 (2018) 149]

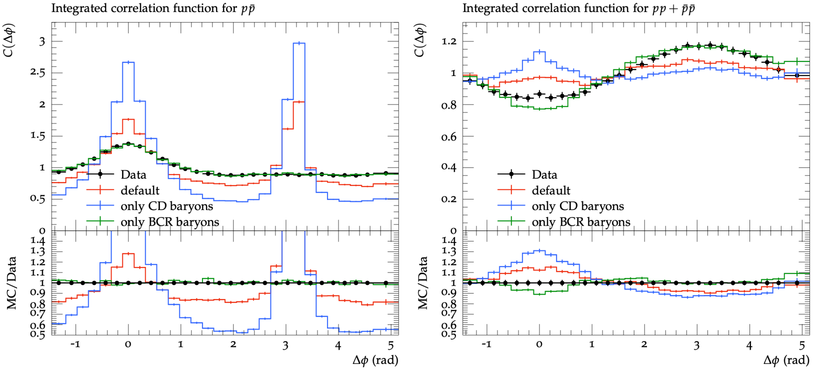
Cluster fission dynamics

Still only longitudinal splitting in $C \to CC$ phase space.

Demand smooth connection to parton shower μ^2 = UV cutoff for hadronization $\to$ real sensitivity to "soft" regions in event shapes etc. [Plätzer, Samitz, *to appear*]

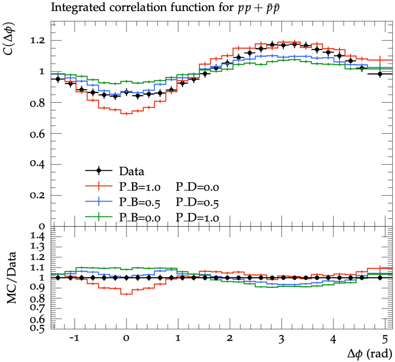
Demand smooth interpolation from perturbative to non-perturbative physics.
Currently under study [SG, S. Kiebacher, S. Plätzer, *in progress*]

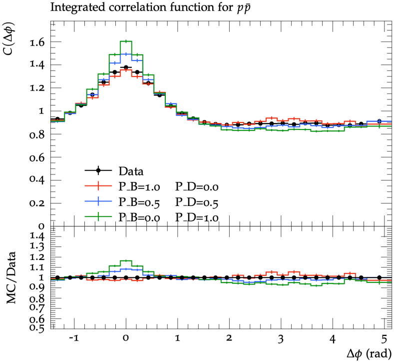
Two particle correlations



Cluster Decay correlations as expected
No strong correlations from CR.

Two particle correlations





Balance of diquark-pair and baryonic clusters.

Conclusion

- Non-perturbative models determine many details of particle production
- Many observables only look into averaged quantities
- Detailed observations demand refinements
- Models not always universal (re-tuning)

- New insights from theoretical considerations
- Disentangle hard and soft regions

FCC will give the opportunity to understand hadronization at a different level.