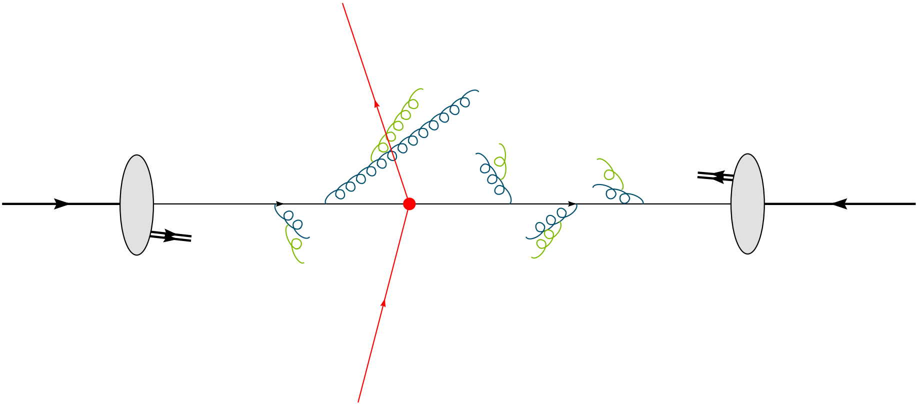
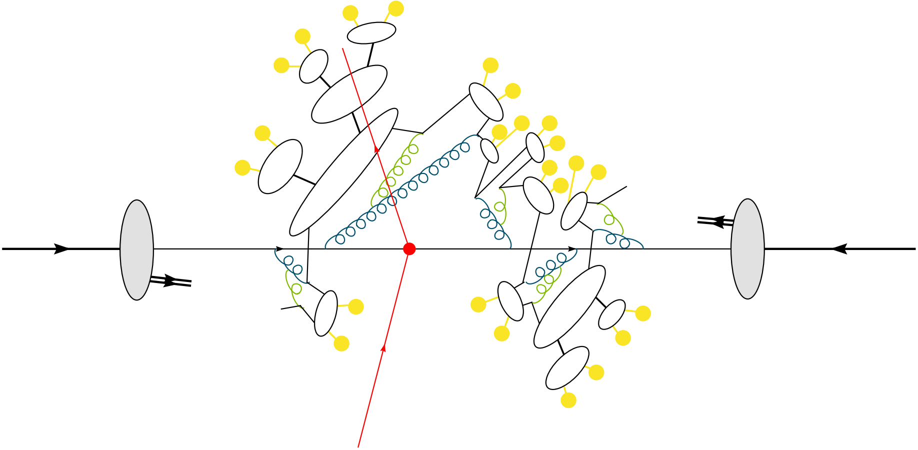
Hadronization

Parton shower



Parton shower ⟶ hadrons

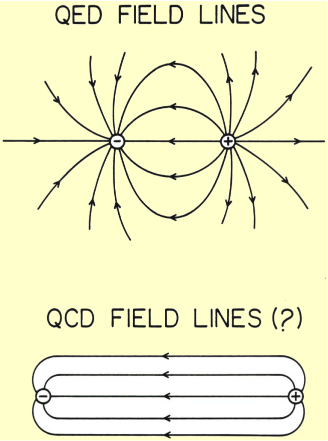


Parton shower $\longrightarrow$ hadrons

- Parton shower terminated at t_0 = lower end of PT.
- Can't measure quarks and gluons.
- Degrees of freedom in the detector are hadrons.
- Need a description of confinement.

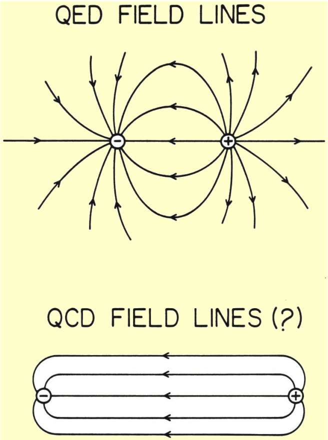
Physical input

Self coupling of gluons
$\leftrightarrow$ "attractive field lines"

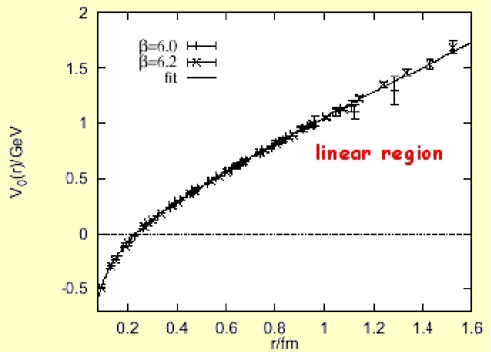


Physical input

Self coupling of gluons
↔ "attractive field lines"



Linear static potential $V(r) \approx \kappa r$.



Supported by lattice QCD,
hadron spectroscopy.

Hadronization models

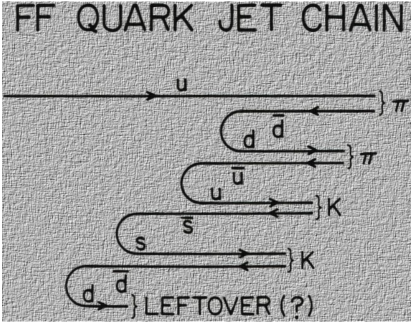
Older models:

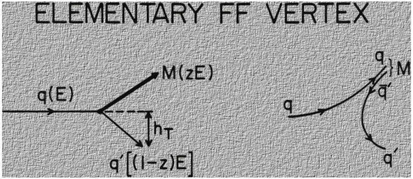
- Flux tube model.
- Independent fragmentation.

Today's models.

- Lund string model (Pythia).
- Cluster model (Herwig).

Independent fragmentation

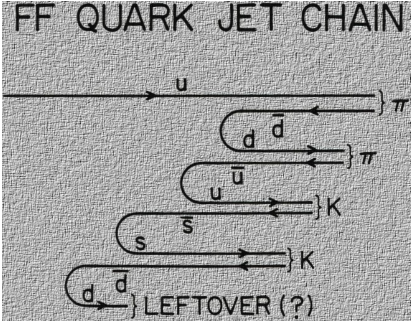


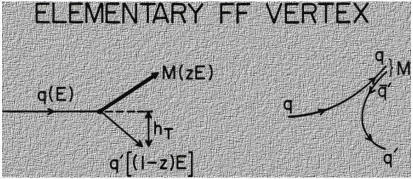


Feynman–Field fragmentation ('78).

- $q\bar{q}$ pairs created from vacuum to dress bare quarks.
- Fragmentation function $f_{q\to h}(z)$ = density of momentum fraction z carried away by hadron h from quark q.
- Gaussian $p_\perp$ distribution.

Independent fragmentation





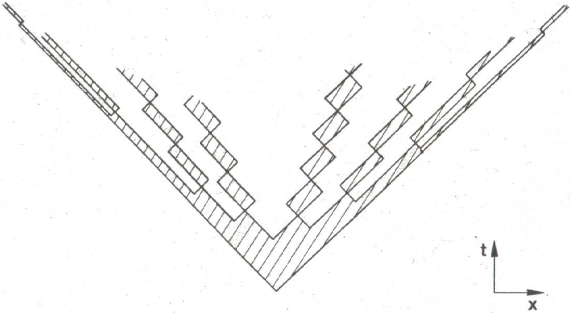
Feynman–Field fragmentation ('78).

- $q\bar{q}$ pairs created from vacuum to dress bare quarks.
- Fragmentation function $f_{q\to h}(z)$ = density of momentum fraction z carried away by hadron h from quark q.
- Gaussian $p_\perp$ distribution.
- Problems:
  - "last quark".
  - not Lorentz invariant.
  - infrared safety.
  - …
- Good at that time.
- Still usefull for inclusive descriptions.

Lund string model

String energy $\sim$ intense chromomagnetic field.
$\longrightarrow$ Additional $q\bar{q}$ pairs created by QM tunneling.

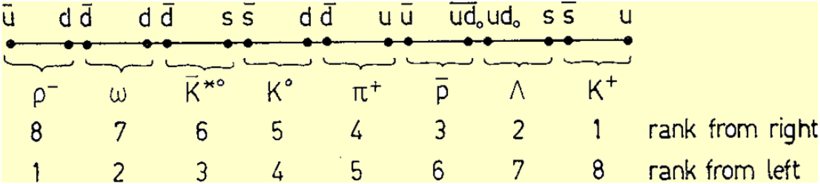
$$\frac{\mathrm{dProb}}{\mathrm{d}x\mathrm{d}t} \sim \exp\left(-\pi m_q^2/\kappa\right) \qquad \kappa \sim 1\,\mathrm{GeV}\,.$$



String breaking expected long before yoyo point.

Lund string model

Ajacent breaks form hadrons.



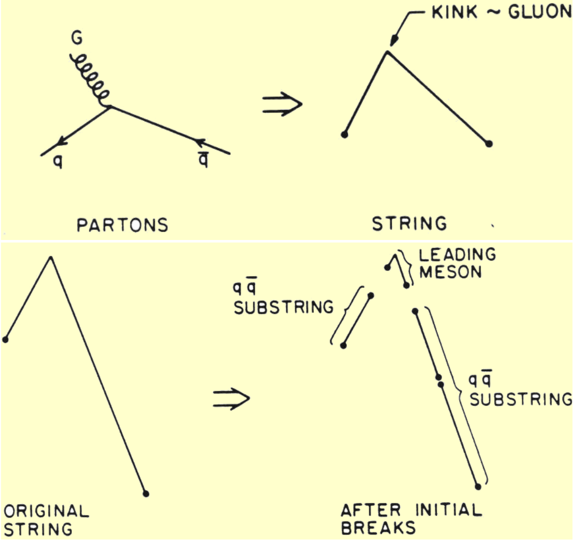
Works in both directions (symmetry).
Lund symmetric fragmentation function

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

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

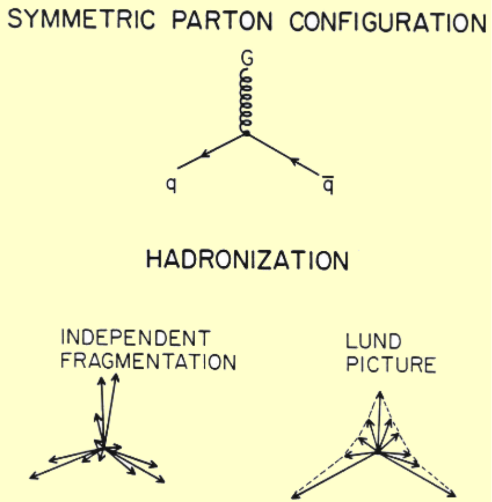
Lund string model

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



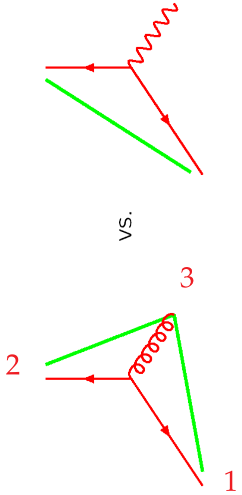
Lund string model

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

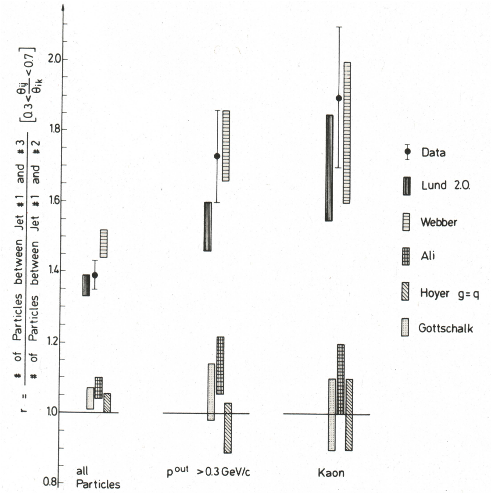


Lund string model

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



"String effect"



Lund string model

Some remarks:

- Originally invented without parton showers in mind.

Lund string model

Some remarks:

- Originally invented without parton showers in mind.
- Stong physical motivation.
- Very successful desription of data.
- Universal desription of data
  (fit at e^+e^-, transfer to hadron-hadron).
- Many parameters, ~ 1 per hadron.
- Too easy to hide errors in perturbative description?

Lund string model

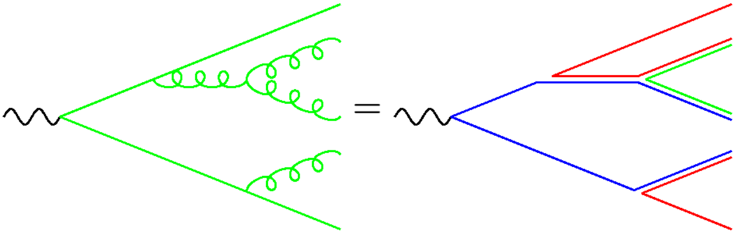
Some remarks:

- Originally invented without parton showers in mind.
- Stong physical motivation.
- Very successful desription of data.
- Universal desription of data
  (fit at e^+e^-, transfer to hadron-hadron).
- Many parameters, ~ 1 per hadron.
- Too easy to hide errors in perturbative description?

$\longrightarrow$ try to use more QCD information/intuition.

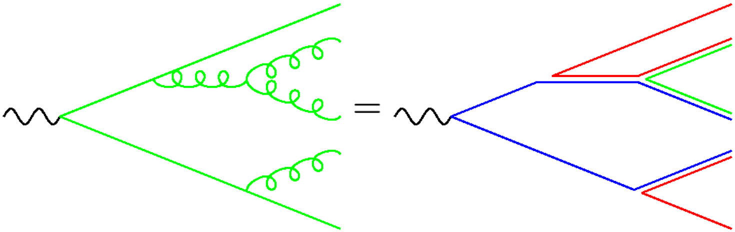
Colour preconfinement

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



Colour preconfinement

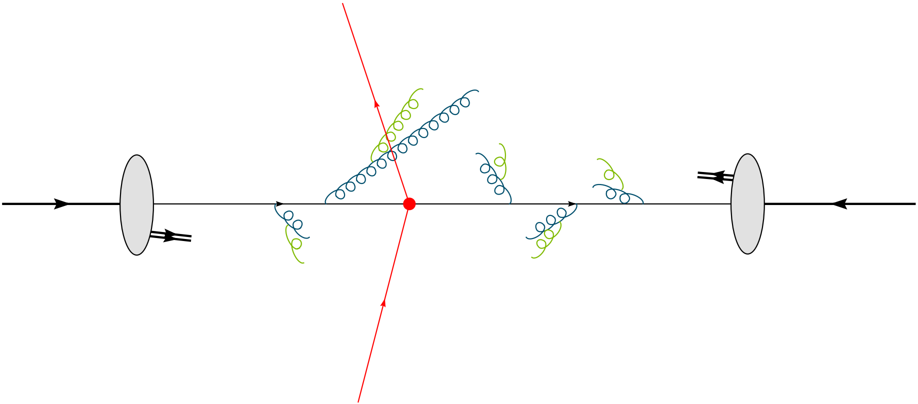
Large N_C limit $\longrightarrow$ planar graphs dominate.
Gluon = colour — anticolourpair



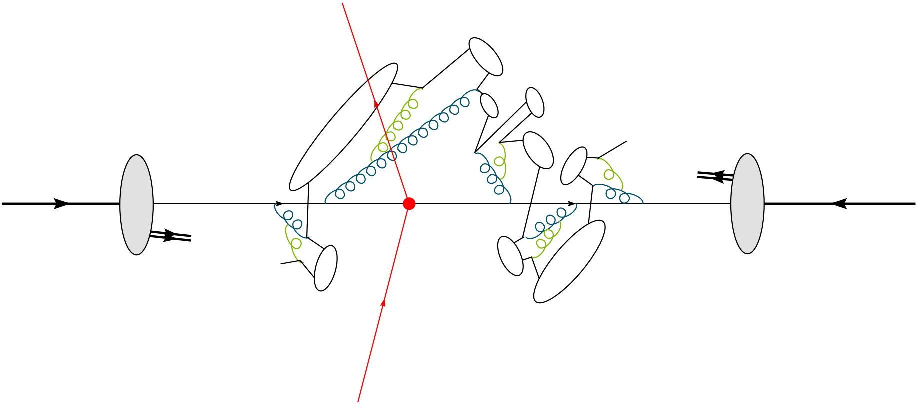
Parton shower organises partons in colour space. Colour partners (=colour singlet pairs) end up close in phase space.

$\longrightarrow$ Cluster hadronization model

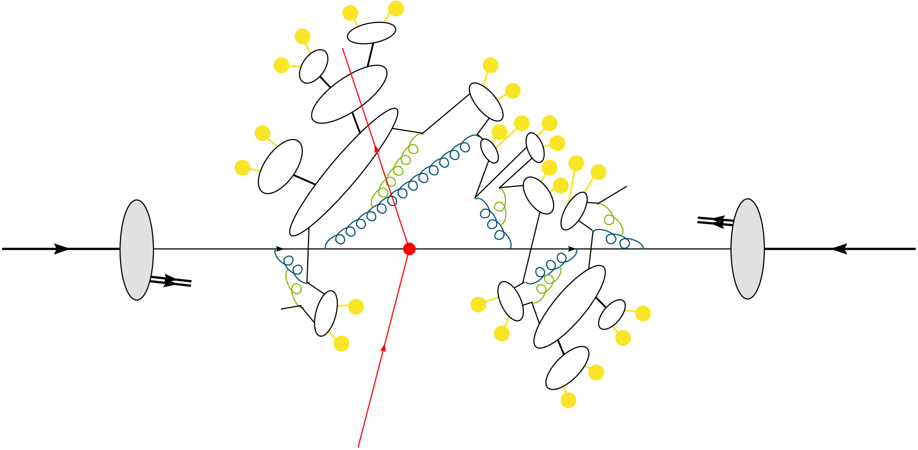
Cluster hadronization



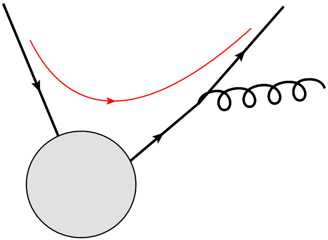
Cluster hadronization



Cluster hadronization

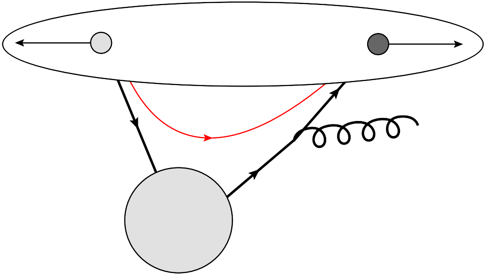


Cluster Hadronization



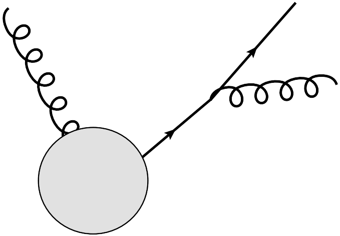
After parton shower, partons on constituent mass shell
Find colour singlets as 3-$\bar{3}$ pairs $\rightarrow$ cluster
Colour neighbours $\sim$ neighbours in momentum space

Cluster Hadronization



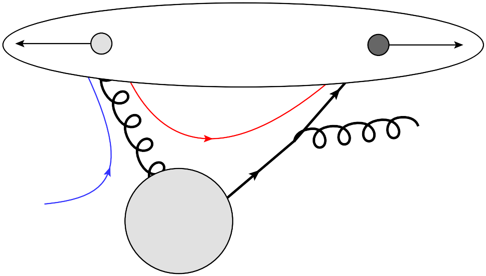
After parton shower, partons on constituent mass shell
Find colour singlets as 3-$\bar{3}$ pairs $\rightarrow$ cluster
Colour neighbours $\sim$ neighbours in momentum space

Cluster Hadronization



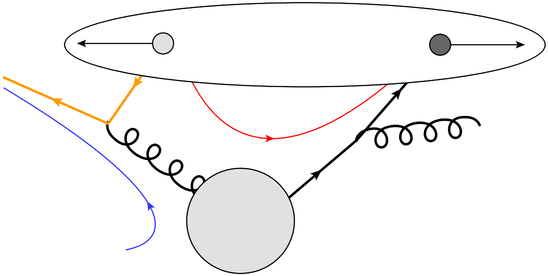
But gluons are not just 3 or $\bar{3}$!

Cluster Hadronization



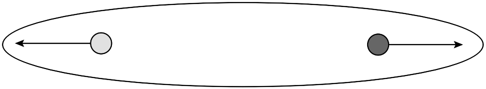
But gluons are not just 3 or $\bar{3}$!

Cluster Hadronization



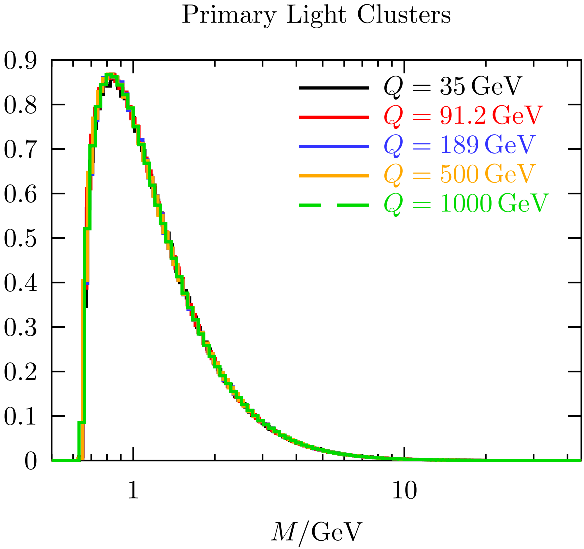
But gluons are not just 3 or $\bar{3}$!
non-perturbative gluon splitting
$m_g > 2m_q$
kinematics from masses
quarks and diquarks possible

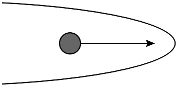
Cluster Hadronization



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

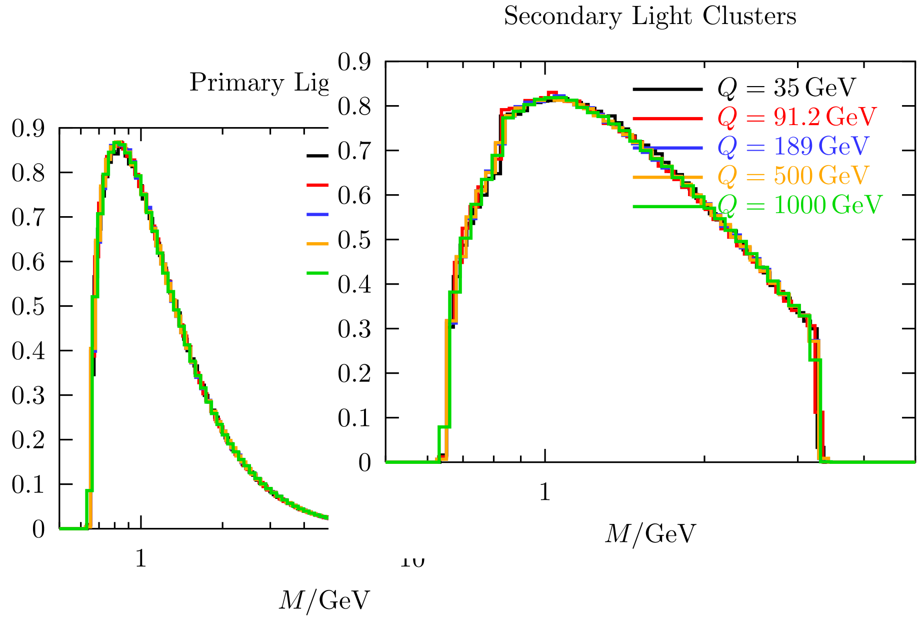




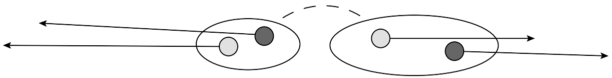
tuents
on shower

ble

Cluster Hadronization

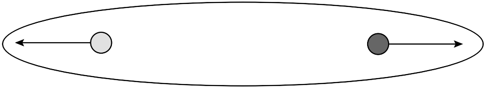


Cluster Hadronization



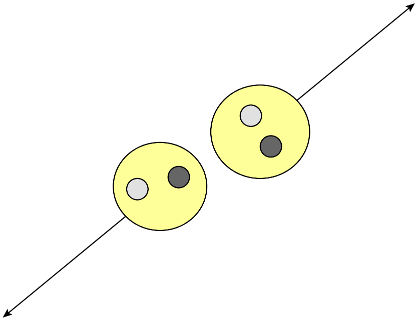
Binary fission along quarks' direction of motion
Flavour introduced in $q\bar{q}$ pairs
Mass $\rightarrow$ multiplicity, momentum
Beam remnant clusters split off as very light clusters

Cluster Hadronization



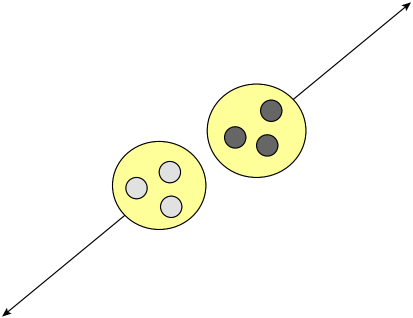
End up with fairly light clusters
too light? Decay into single hadron
Exchange momentum with neighbour

Cluster Hadronization



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

Cluster Hadronization



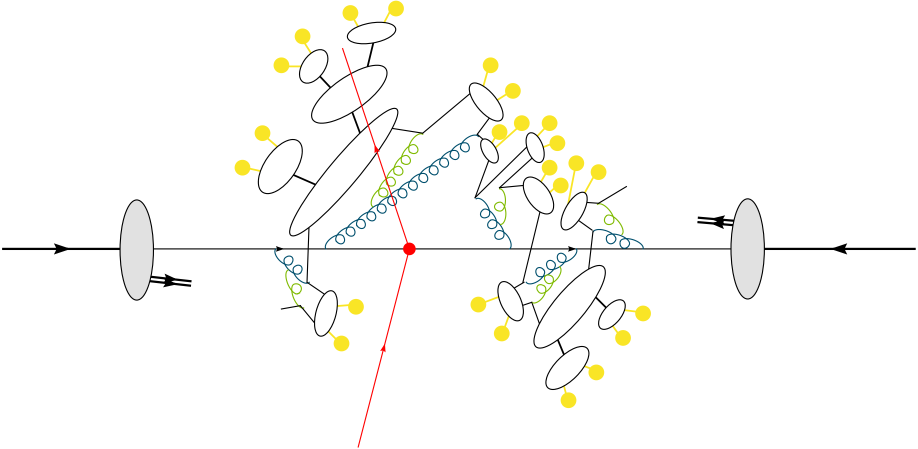
Baryon pairs possible
usually appear from clusters with 1 or 2 diquarks
could also emerge in pairs from mesonic clusters

Hadronization

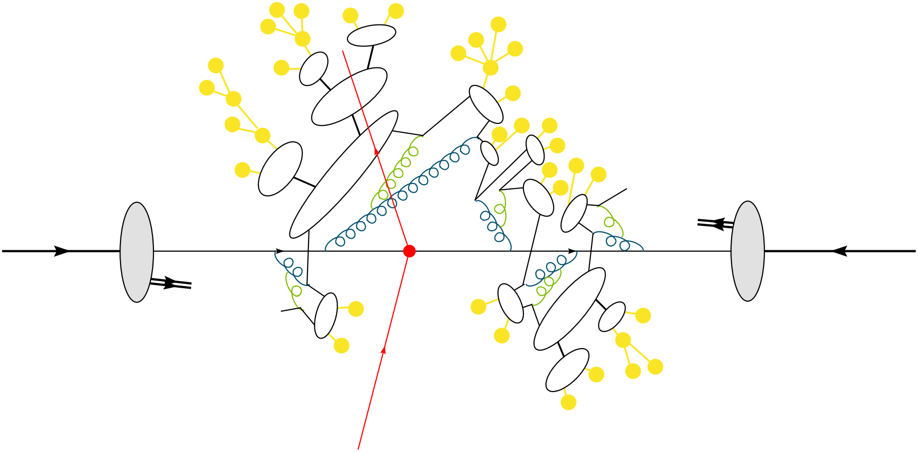
- Only string and cluster models used in recent MC programs.
  Independent fragmentation only for inclusive observables.
- Strings started non–perturbatively,
  improved by parton shower.
- Cluster model started mostly on perturbative side,
  improved by string like cluster fission.

Hadronic Decays

Hadronic decays



Hadronic decays



Hadronic decays

Many aspects:

$$
\begin{aligned}
B^{*0} \to \gamma B^0 \\
\hookrightarrow \bar{B}^0 \\
\hookrightarrow e^- \bar{\nu}_e D^{*+} \\
\hookrightarrow \pi^+ D^0 \\
\hookrightarrow K^- \rho^+ \\
\hookrightarrow \pi^+ \pi^0 \\
\hookrightarrow e^+ e^- \gamma
\end{aligned}
$$

Hadronic decays

Many aspects:

$$B^{*0} \to \gamma B^0$$
$$\hookrightarrow \bar{B}^0$$
$$\hookrightarrow e^- \bar{\nu}_e D^{*+}$$
$$\hookrightarrow \pi^+ D^0$$
$$\hookrightarrow K^- \rho^+$$
$$\hookrightarrow \pi^+ \pi^0$$
$$\hookrightarrow e^+ e^- \gamma$$

EM decay.

Hadronic decays

Many aspects:

$$
\begin{aligned}
B^{*0} &\to \gamma B^0 \\
&\quad \hookrightarrow \bar{B}^0 \\
&\qquad \hookrightarrow e^- \bar{\nu}_e D^{*+} \\
&\qquad\qquad \hookrightarrow \pi^+ D^0 \\
&\qquad\qquad\qquad \hookrightarrow K^- \rho^+ \\
&\qquad\qquad\qquad\qquad \hookrightarrow \pi^+ \pi^0 \\
&\qquad\qquad\qquad\qquad\qquad \hookrightarrow e^+ e^- \gamma
\end{aligned}
$$

Weak mixing.

Hadronic decays

Many aspects:

$$
\begin{aligned}
B^{*0} \to \gamma B^0 \\
\hookrightarrow \bar{B}^0 \\
\hookrightarrow e^- \bar{\nu}_e D^{*+} \\
\hookrightarrow \pi^+ D^0 \\
\hookrightarrow K^- \rho^+ \\
\hookrightarrow \pi^+ \pi^0 \\
\hookrightarrow e^+ e^- \gamma
\end{aligned}
$$

Weak decay.

Hadronic decays

Many aspects:

$$
\begin{aligned}
B^{*0} \to \gamma B^0 & \\
&\hookrightarrow \bar{B}^0 \\
&\quad\hookrightarrow e^- \bar{\nu}_e D^{*+} \\
&\qquad\hookrightarrow \pi^+ D^0 \\
&\qquad\quad\hookrightarrow K^- \rho^+ \\
&\qquad\qquad\hookrightarrow \pi^+ \pi^0 \\
&\qquad\qquad\quad\hookrightarrow e^+ e^- \gamma
\end{aligned}
$$

Strong decay.

Hadronic decays

Many aspects:

$$
\begin{aligned}
B^{*0} \to \gamma B^0 & \\
& \hookrightarrow \bar{B}^0 \\
& \qquad \hookrightarrow e^- \bar{\nu}_e D^{*+} \\
& \qquad\qquad \hookrightarrow \pi^+ D^0 \\
& \qquad\qquad\qquad \hookrightarrow K^- \rho^+ \\
& \qquad\qquad\qquad\qquad \hookrightarrow \pi^+ \pi^0 \\
& \qquad\qquad\qquad\qquad\qquad \hookrightarrow e^+ e^- \gamma
\end{aligned}
$$

Weak decay, ρ^+ mass smeared.

Hadronic decays

Many aspects:

$$B^{*0} \to \gamma B^0$$
$$\hookrightarrow \bar{B}^0$$
$$\hookrightarrow e^- \bar{\nu}_e D^{*+}$$
$$\hookrightarrow \pi^+ D^0$$
$$\hookrightarrow K^- \rho^+$$
$$\hookrightarrow \pi^+ \pi^0$$
$$\hookrightarrow e^+ e^- \gamma$$

ρ^+ polarized, angular correlations.

Hadronic decays

Many aspects:

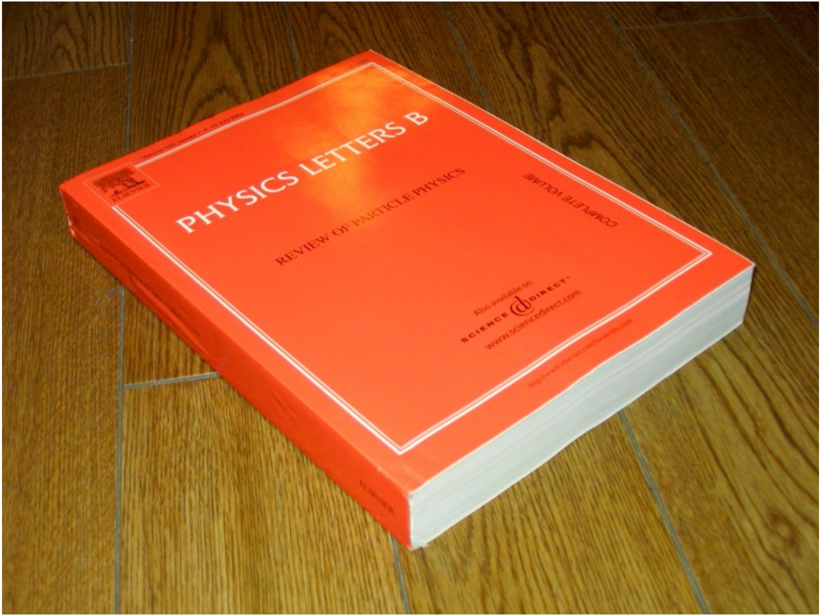
$$
\begin{aligned}
B^{*0} &\to \gamma B^0 \\
&\quad \hookrightarrow \bar{B}^0 \\
&\quad\quad \hookrightarrow e^- \bar{\nu}_e D^{*+} \\
&\quad\quad\quad \hookrightarrow \pi^+ D^0 \\
&\quad\quad\quad\quad \hookrightarrow K^- \rho^+ \\
&\quad\quad\quad\quad\quad \hookrightarrow \pi^+ \pi^0 \\
&\quad\quad\quad\quad\quad\quad \hookrightarrow e^+ e^- \gamma
\end{aligned}
$$

Dalitz decay, m_{ee} peaked.

Hadronic decays

Tedious.
100s of different particles, 1000s of decay modes, phenomenological matrix elements with parametrized form factors…

Hadronic decays



A few plots

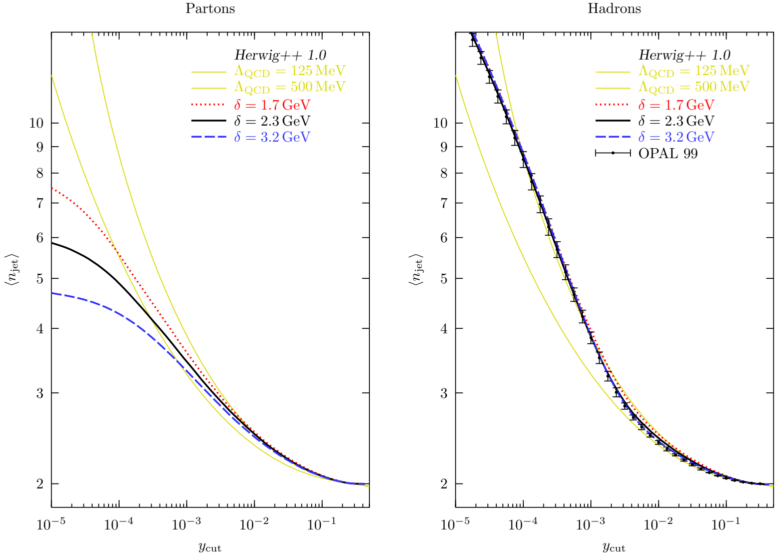
How well does it work?

- $e^+e^- \to$ hadrons, mostly at LEP.
- Jet shapes, jet rates, event shapes, identified particles…
- 'Tuning' of parameters.
- Use *all* analyses available in Rivet.
- Want to get *everything* right with *one* parameter set.
- Compare to literally $\approx$ 20000 plots.

- Check out `http://herwig.hepforge.org` ($\to$ Plots) for many more and comparisons with the latest release.

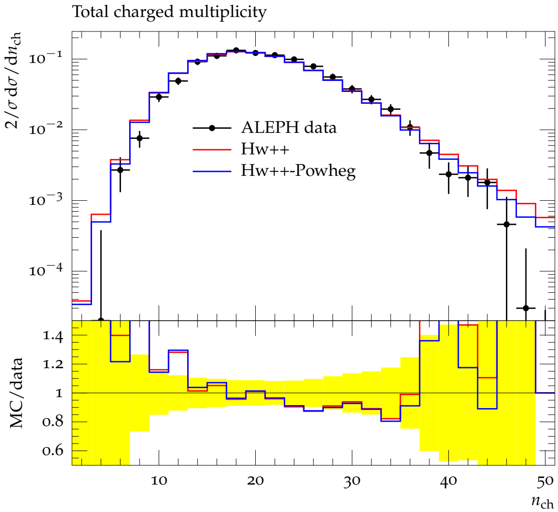
How well does it work?

Smooth interplay between shower and hadronization.



How well does it work?

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

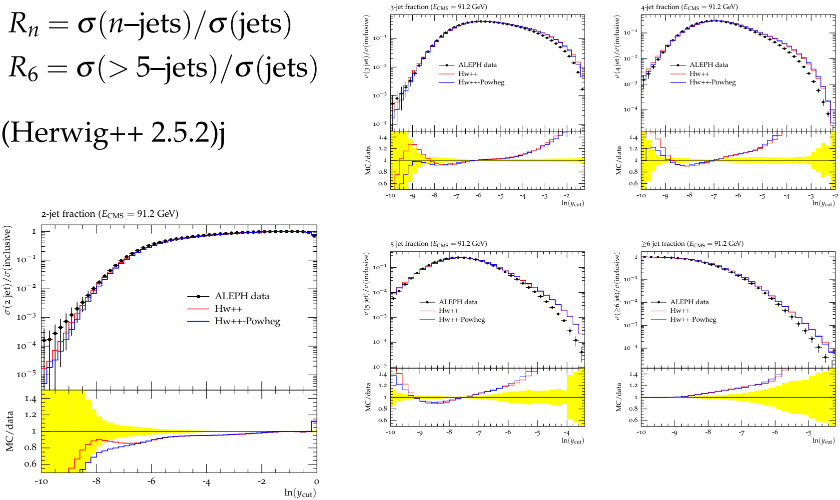


How well does it work?

Jet rates at LEP.

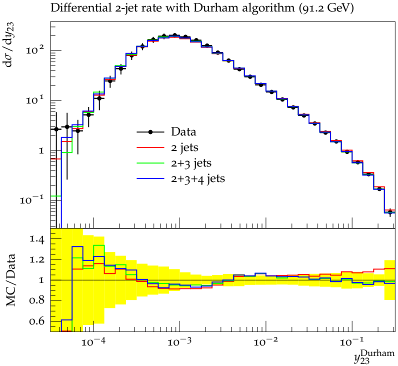
$$R_n = \sigma(n\text{–jets})/\sigma(\text{jets})$$
$$R_6 = \sigma(> 5\text{–jets})/\sigma(\text{jets})$$

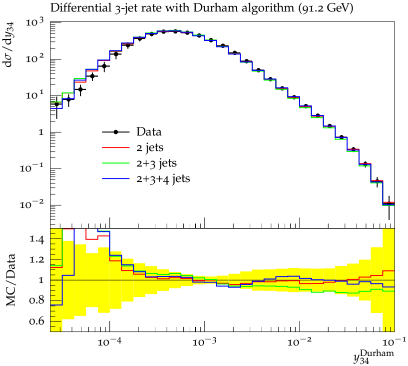
(Herwig++ 2.5.2)j



How well does it work?

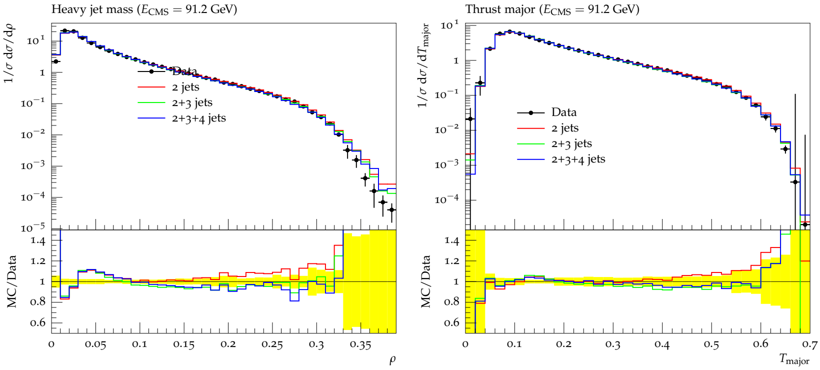
Differential Jet Rates at LEP (Herwig++ pre-3.0).
Dipole shower + some merging





How well does it work?

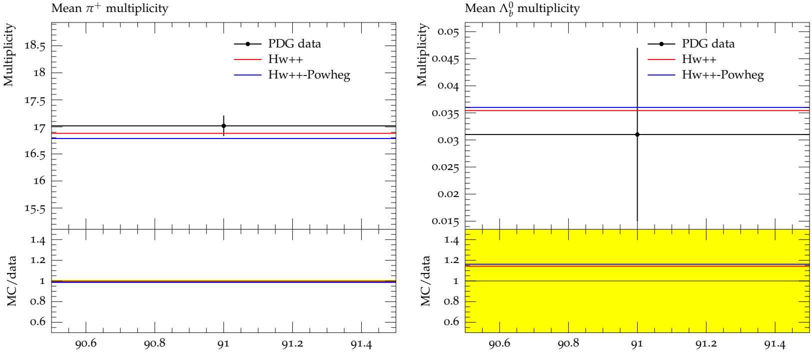
Event Shapes at LEP (Herwig++ pre-3.0).
Dipole shower + some merging



Parton showers do very well, today!

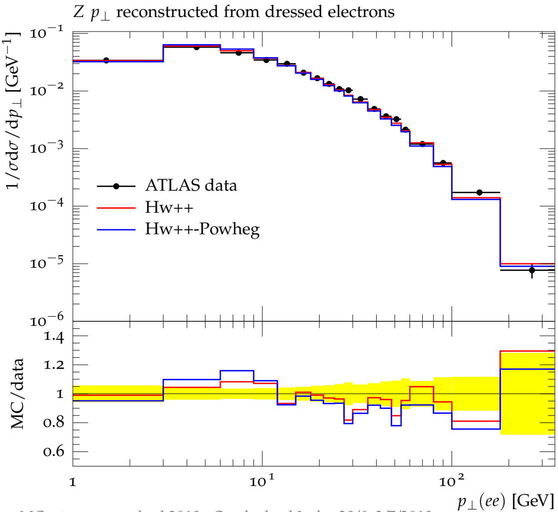
How well does it work?

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

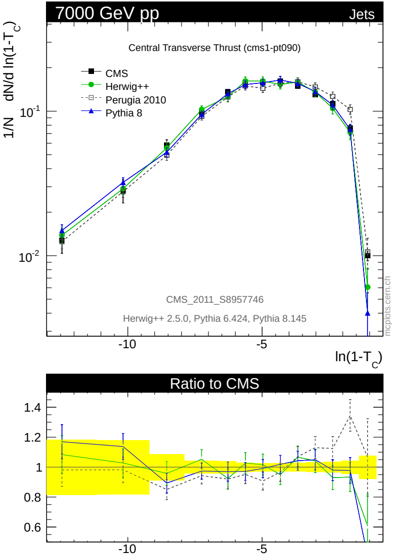


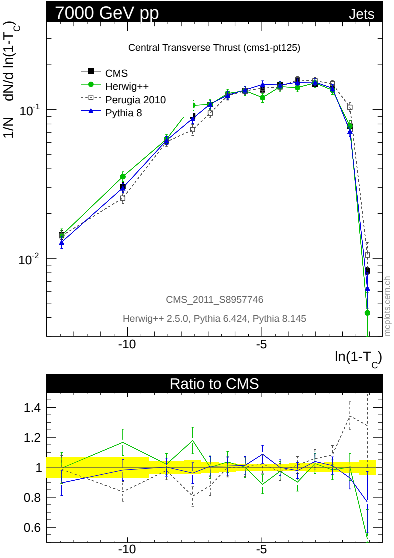
How well does it work?

$p_\perp(Z^0) \to$ intrinsic $k_\perp$ (LHC 7 TeV).
See also in context of matching/marging.



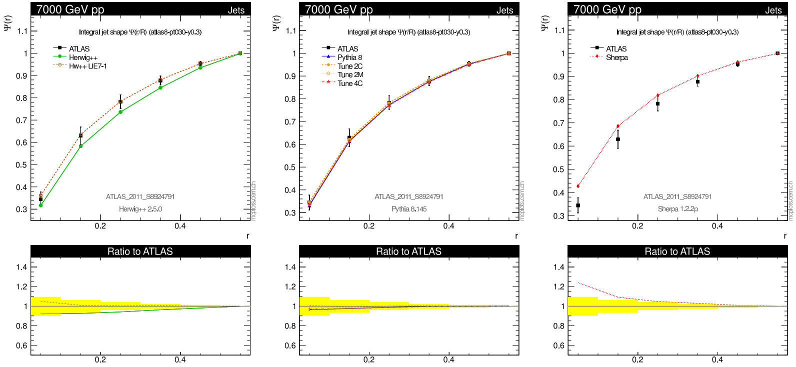
Transverse thrust





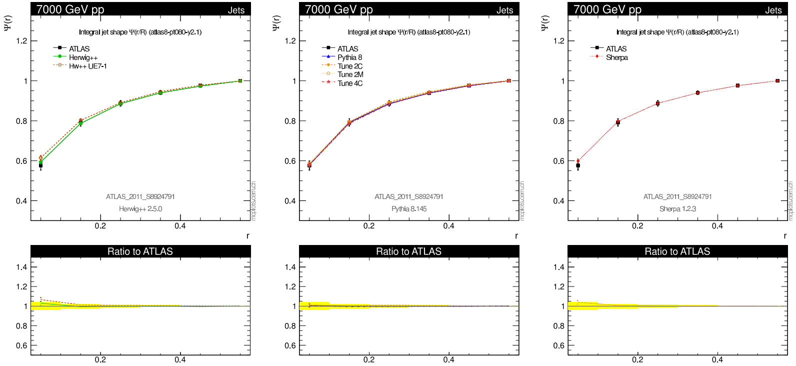
Integral jet shapes

not too hard, central $(30 < p_T/\mathrm{GeV} < 40; 0 < |y| < 0.3)$



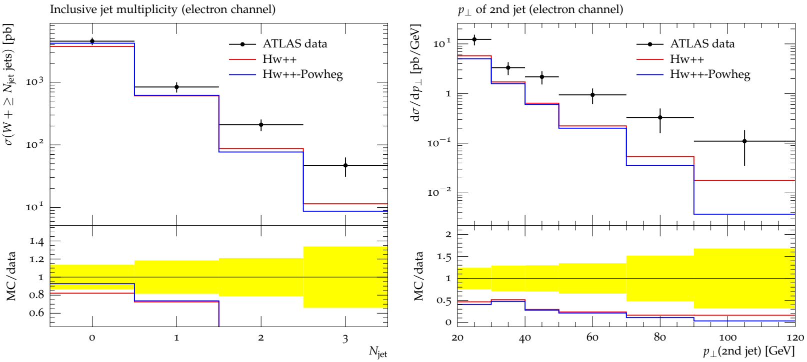
Integral jet shapes

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



Limits of parton showers

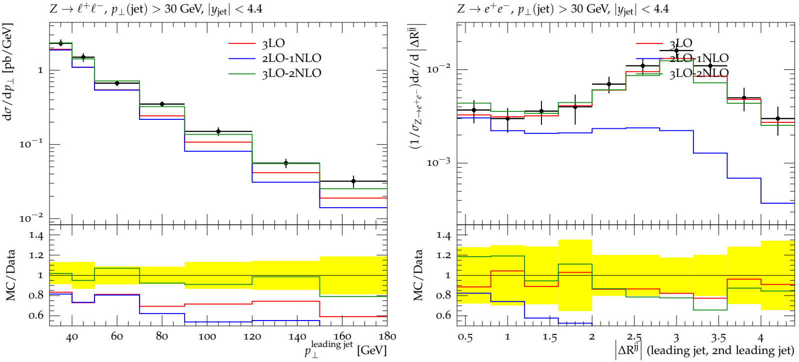
$W + \text{jets}$, LHC 7 TeV.



Higher jets not covered by parton shower only → merging.

Unitarized Matching/Merging

Preliminary example: Z production, jet-jet correlation.



[J. Bellm, KIT]

3LO-2NLO = Z+0, 1, 2 (tree) and Z+0,1 NLO (virtual).