Monte Carlos — Lecture III

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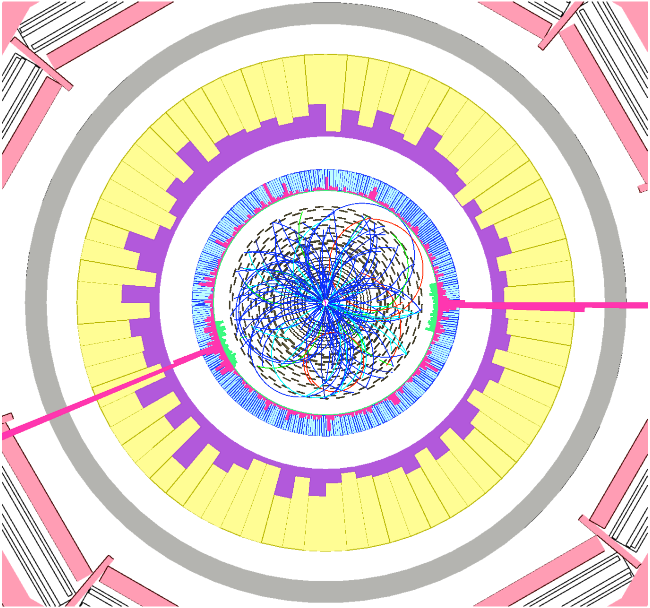
Outline

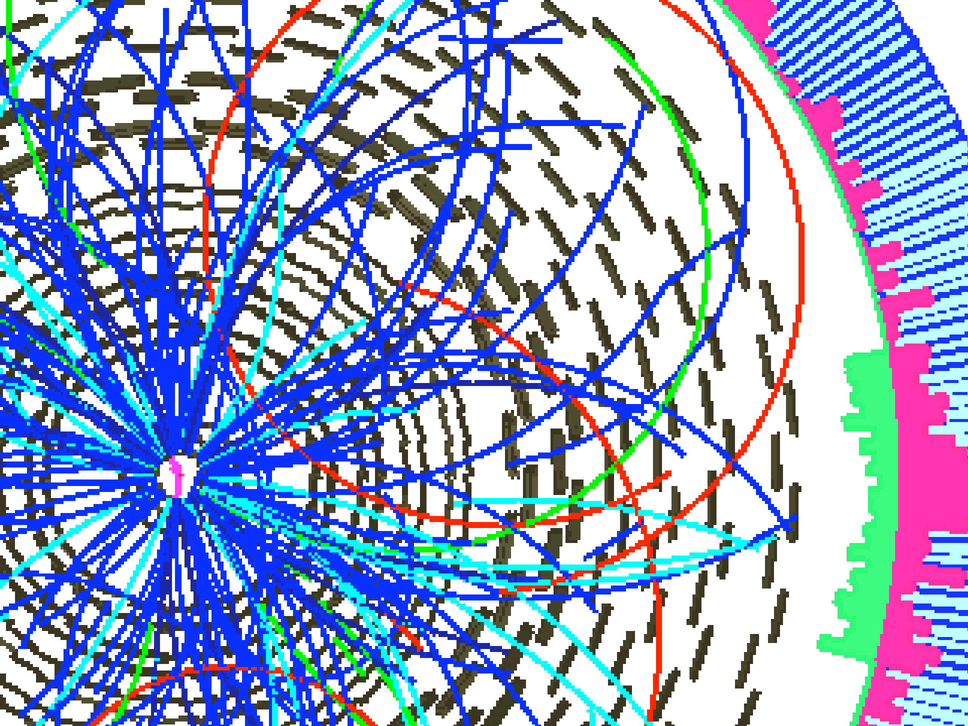
- Lecture I — Basics
  - Introduction
  - Monte Carlo techniques
- Lecture II — Perturbative physics
  - Hard scattering
  - Parton showers
- Lecture III — Non–perturbative physics
  - Hadronization
  - Hadronic decays
  - Comparison to data
- Lecture IV — Multiple Partonic Interactions
  - Minimum Bias/Underlying Event in data
  - Modelling

Outline Lecture III

- Hadronization
  - Confinement
  - Flux tube model
  - Independent fragmentation
  - Lund string model
  - Cluster hadronization model
- Hadronic decays
- Comparison to data

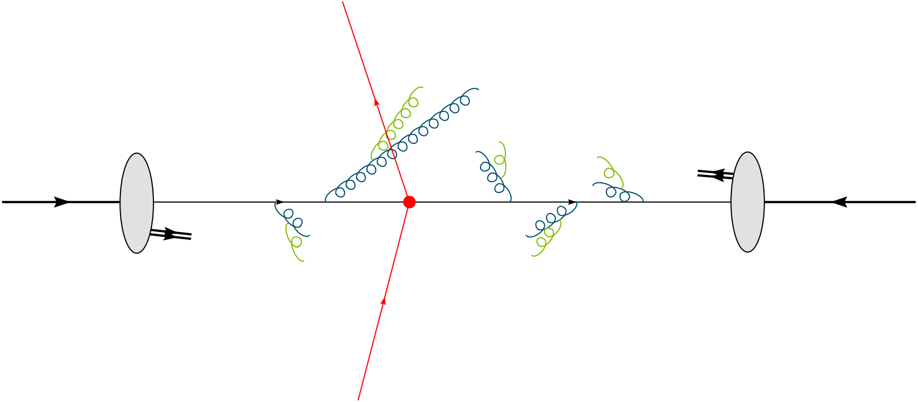
Can you spot the Higgs?



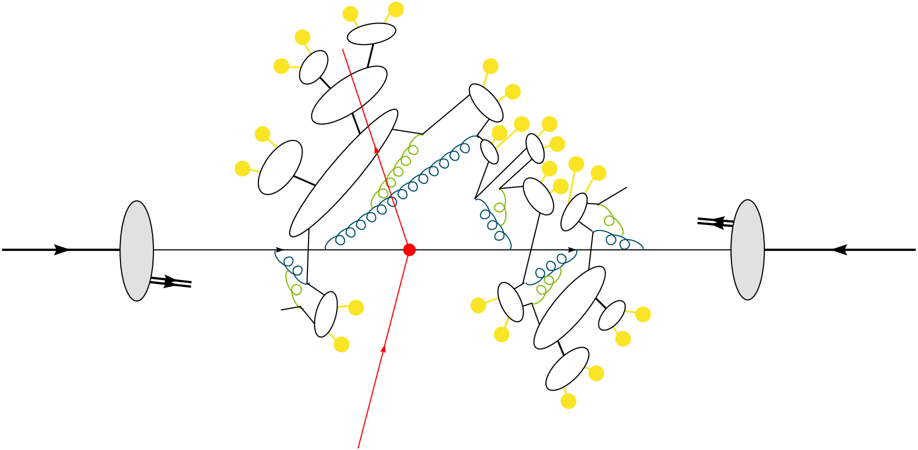


Hadronization

Parton shower



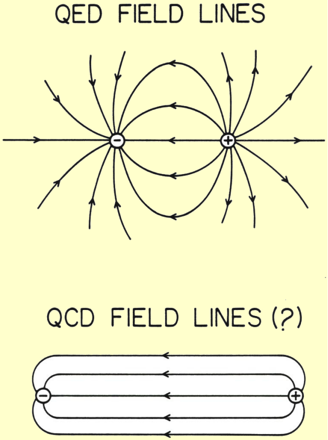
Parton shower ⟶ hadrons



Parton shower $\longrightarrow$ hadrons

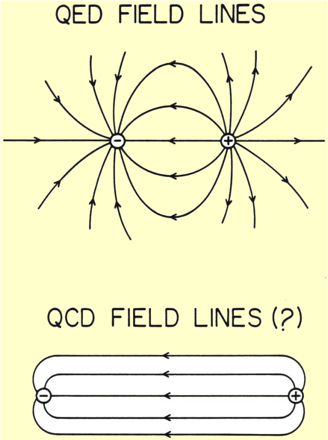
- Parton shower terminated at t_0 = lower end of PT.
- Can't measure quarks and gluons.
- Degrees of freedom in the detector are hadrons.
- Need a description of confinement.

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

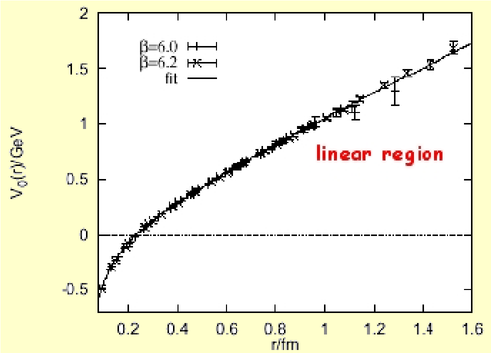


Physical input

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



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



Supported by lattice QCD,
hadron spectroscopy.

Hadronization models

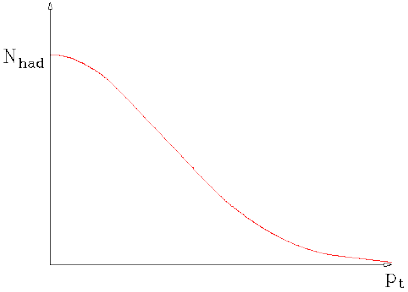
Older models:

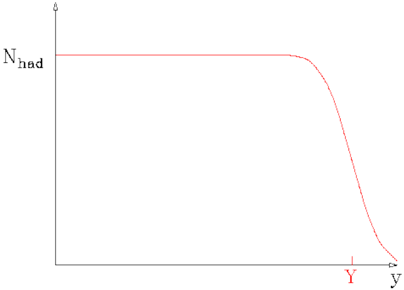
- Flux tube model.
- Independent fragmentation.

Today's models.

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

$e^+e^- \to$ hadrons: hadrons in "flux tube".
Limited $p_\perp$, flat in y.





Suggests simple model for jet mass (Feynman, '72).

Flux tube model

Estimate hadronization corrections to perturbative quantities.
Jet Energy and momentum:

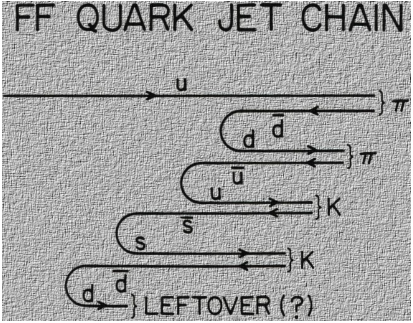
$$E = \int_0^Y \mathrm{d}y \mathrm{d}^2 p_\perp \, \rho(p_\perp) p_\perp \cosh y = \lambda \sinh Y$$

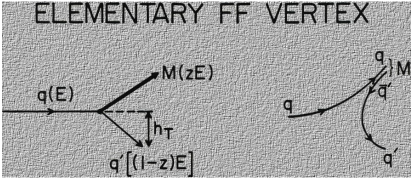
$$P = \int_0^Y \mathrm{d}y \mathrm{d}^2 p_\perp \, \rho(p_\perp) p_\perp \sinh y = \lambda (\cosh Y - 1) \approx E - \lambda$$

$$\langle p_\perp \rangle = \int \mathrm{d}^2 p_\perp \, \rho(p_\perp) p_\perp = \lambda \ .$$

Motion inside confined hadrons, estimate
$\langle p_\perp \rangle \sim 1/R_{\mathrm{had}} \sim m_{\mathrm{had}} \sim 1\,\mathrm{GeV}$.

$\Longrightarrow$ Jets acquire non–perturbative mass $M^2 \sim E^2 - P^2 \sim 2\lambda E$.
Large hadronization correction, $O(10\,\mathrm{GeV})$ for $O(100\,\mathrm{GeV})$ jet.

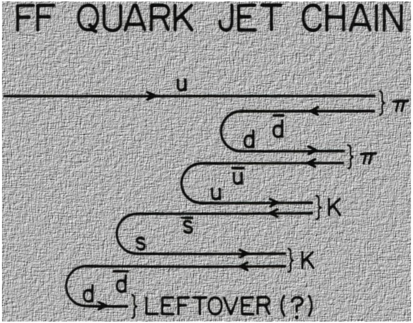


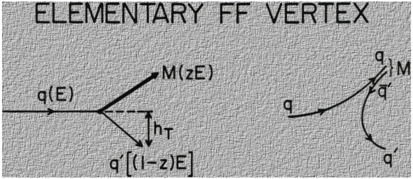


Feynman–Field fragmentation ('78).

- $q\bar{q}$ 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





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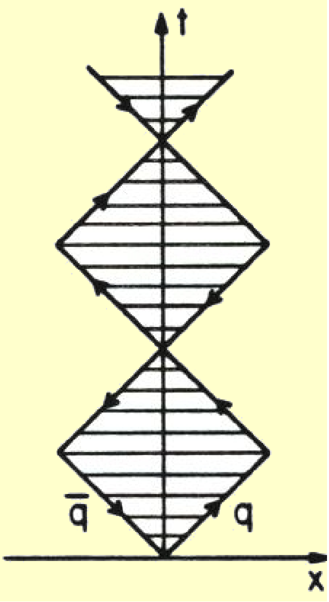
- $q\bar{q}$ pairs created from vacuum to dress bare quarks.
- Fragmentation function $f_{q\to h}(z)$ = density of momentum fraction z carried away by hadron h from quark q.
- Gaussian $p_\perp$ distribution.
- Problems:
  - "last quark".
  - not Lorentz invariant.
  - infrared safety.
  - …
- Good at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

Lund string model

String model of mesons.
$L = 0$ mesons move in yoyo modes.
Area law: $m^2 \sim$ area.



Lund string model

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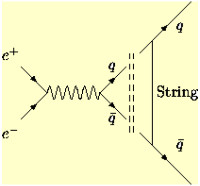
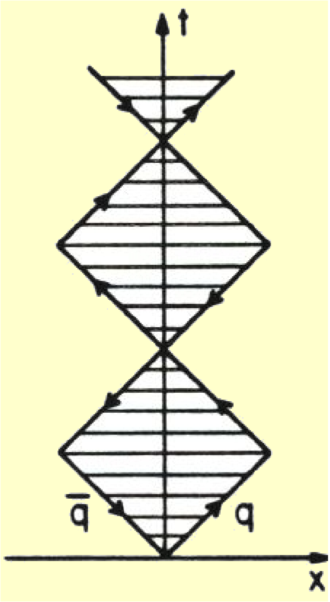
Area law: $m^2 \sim$ area.
Simple model for particle production in e^+e^- annihilation:



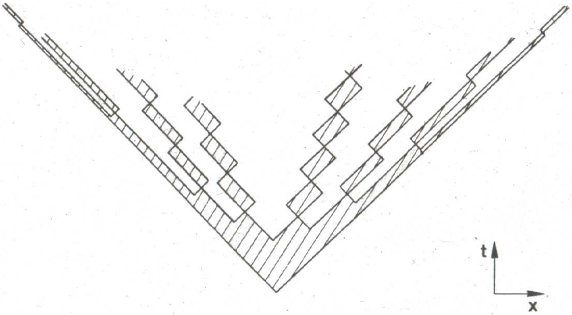
$q\bar{q}$ pair as pointlike source of string.



Lund string model

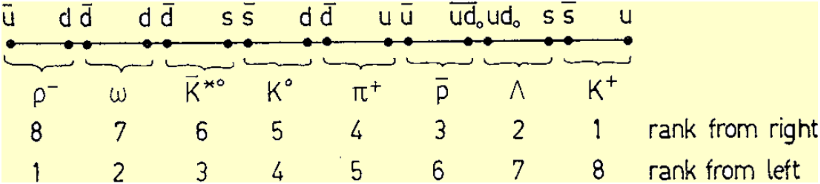
String energy $\sim$ intense chromomagnetic field.
$\longrightarrow$ Additional $q\bar{q}$ pairs created by QM tunneling.

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



String breaking expected long before yoyo point.

Ajacent breaks form hadrons.



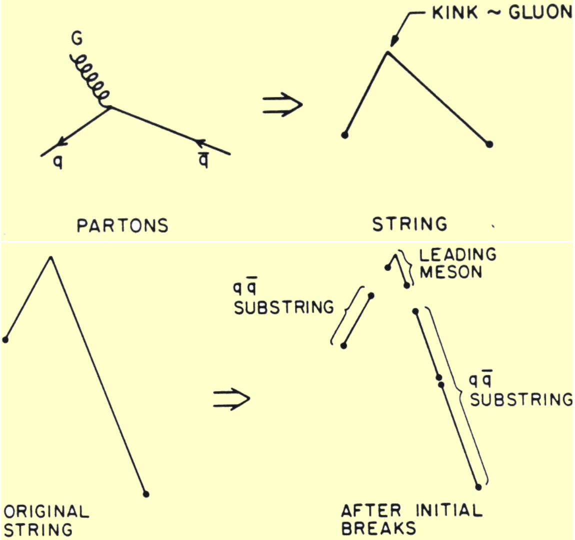
Works in both directions (symmetry).
Lund symmetric fragmentation function

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

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.



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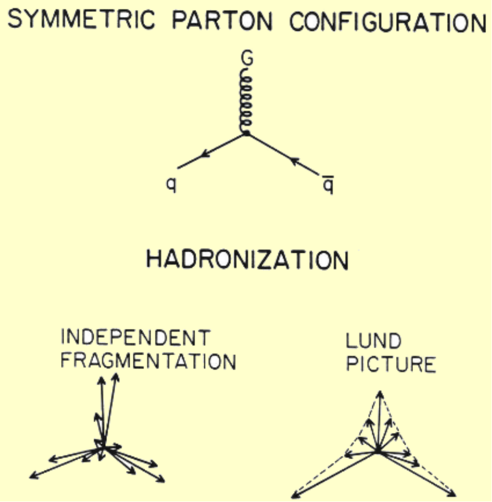

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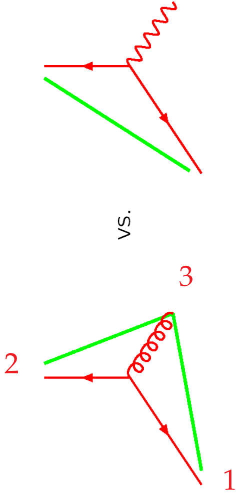
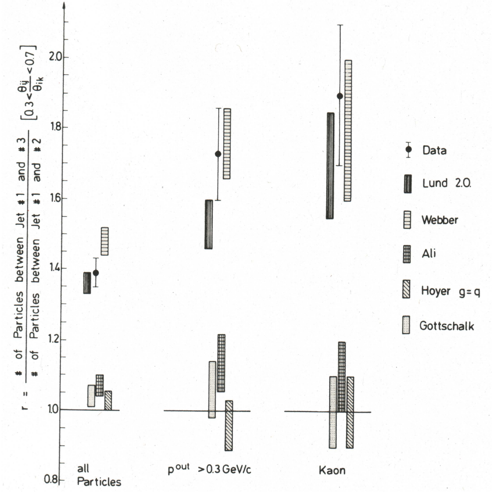


"String effect"



Some remarks:

- Originally invented without parton showers in mind.

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- 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

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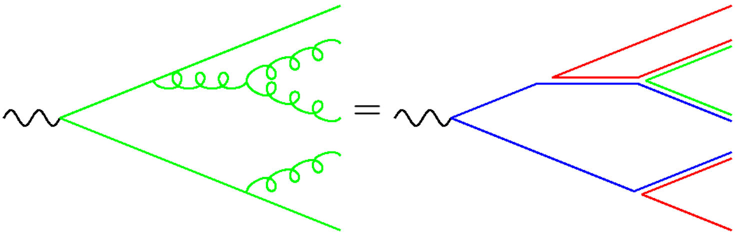
  (fit at e^+e^-, transfer to hadron-hadron).
- Many parameters, ~ 1 per hadron.
- Too easy to hide errors in perturbative description?

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

Colour preconfinement

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



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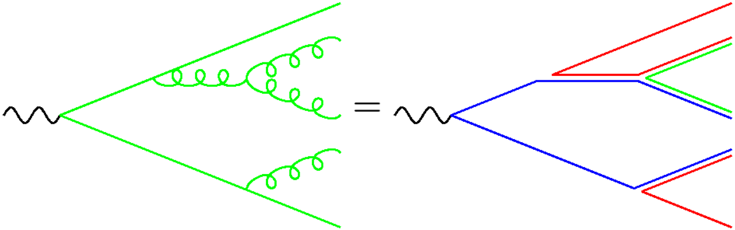
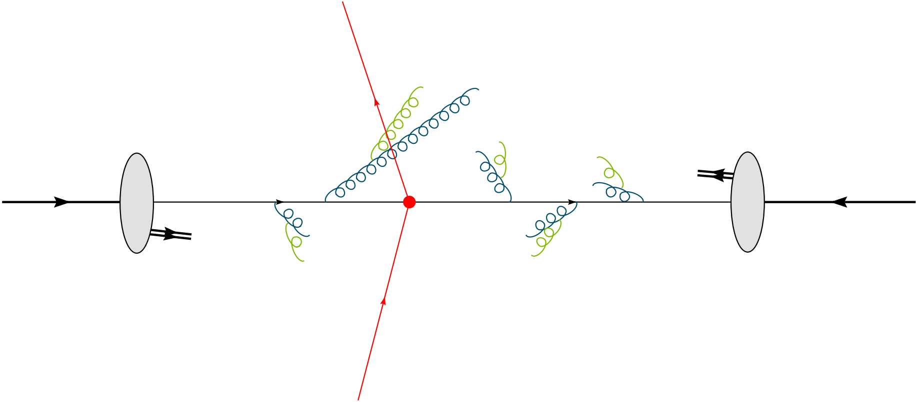


Parton shower organises partons in colour space. Colour partners (=colour singlet pairs) end up close in phase space.

$\longrightarrow$ Cluster hadronization model

Cluster hadronization



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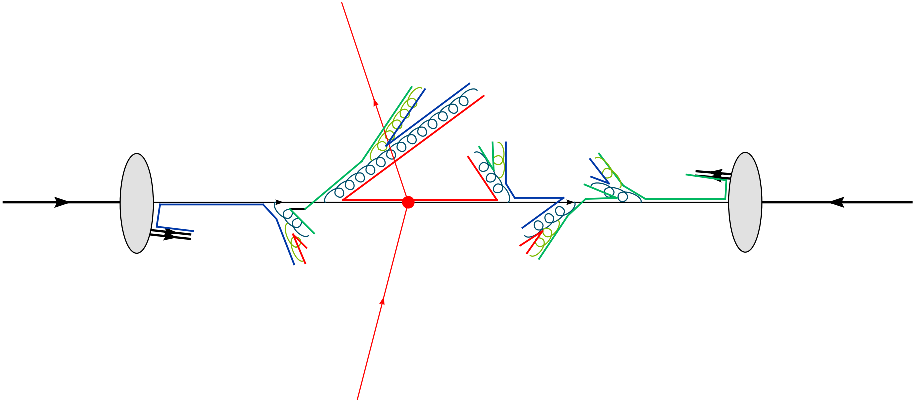

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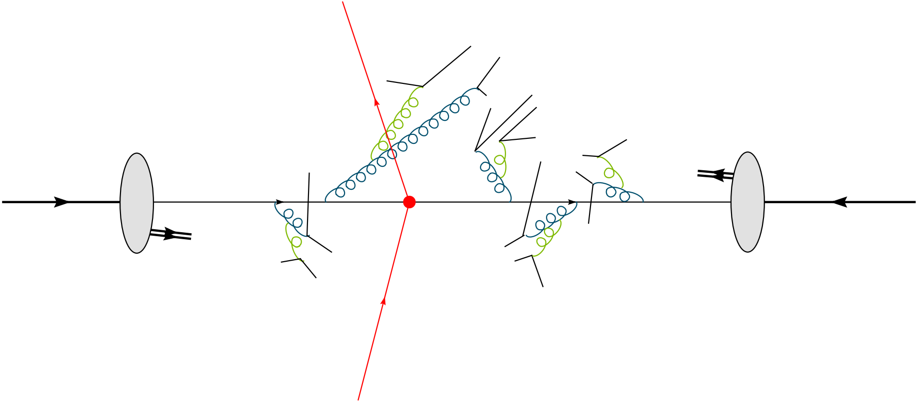

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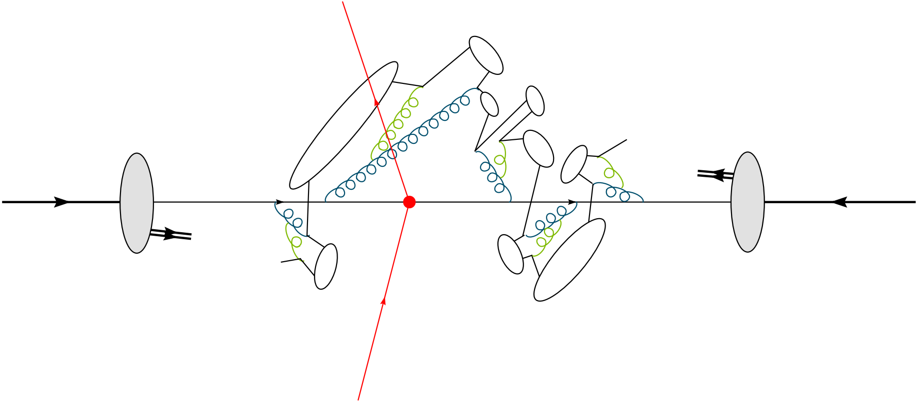
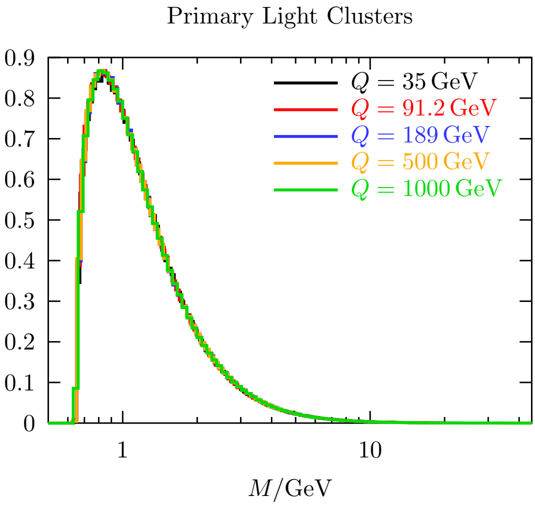


Primary cluster mass spectrum independent of production mechanism. Peaked at some low mass.



Cluster hadronization

Primary cluster mass spectrum independent of production mechanism. Peaked at some low mass.

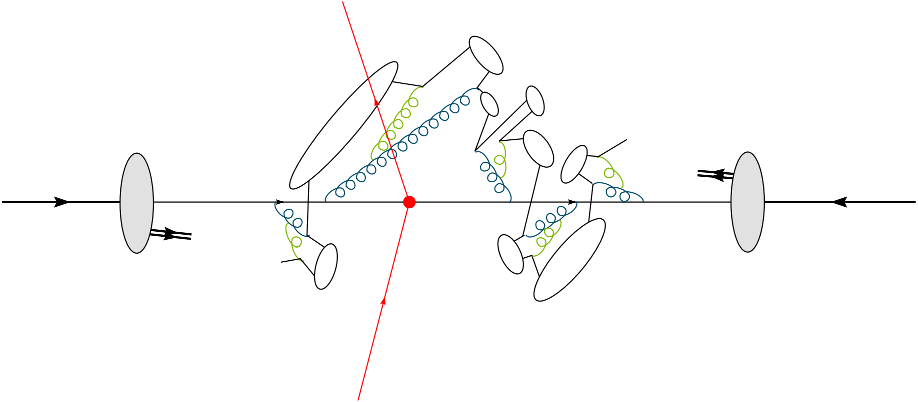
Cluster = continuum of high mass resonances.
Decay into well–known lighter mass resonances
= discrete spectrum of hadrons.

No spin information carried over, i.e. only phase space.

Suppression of heavier particles
(particularly baryons, can be problematic).

Cluster spectrum determined entirely by parton shower, i.e. perturbation theory. Hence, t_0 crucial parameter.

Cluster hadronization



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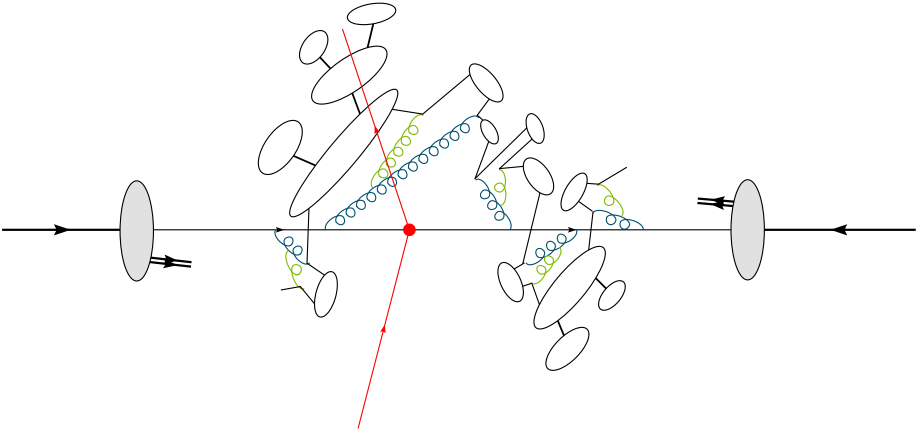
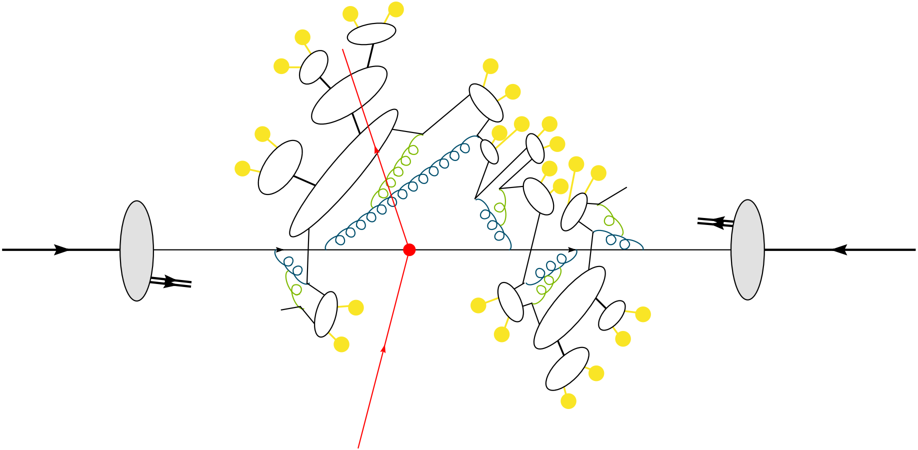


Cluster hadronization



Cluster hadronization in a nutshell

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

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

  where masses are chosen from

  $$M_i = \left[\left(M^P - (m_i + m_3)^P\right) r_i + (m_i + m_3)^P\right]^{1/P},$$

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

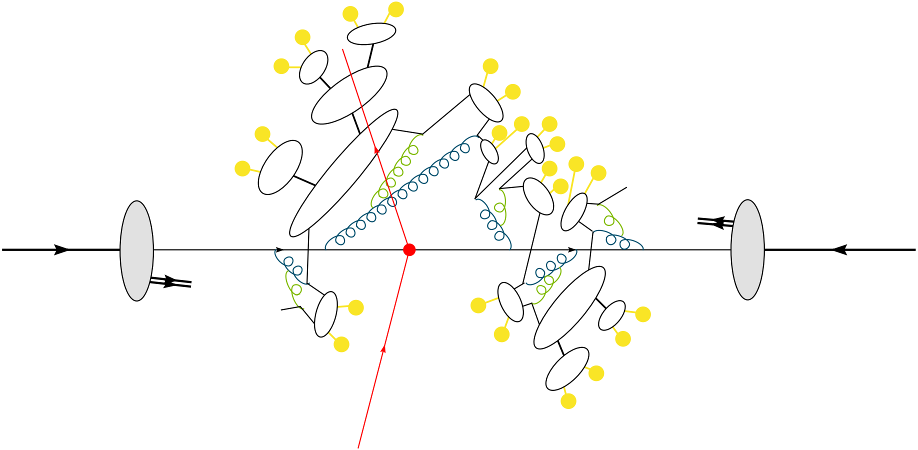
  $$P(a_{i,q}, b_{q,j}|i,j) = \frac{W(a_{i,q}, b_{q,j}|i,j)}{\sum_{M/B} W(c_{i,q'}, d_{q',j}|i,j)}.$$

Hadronization

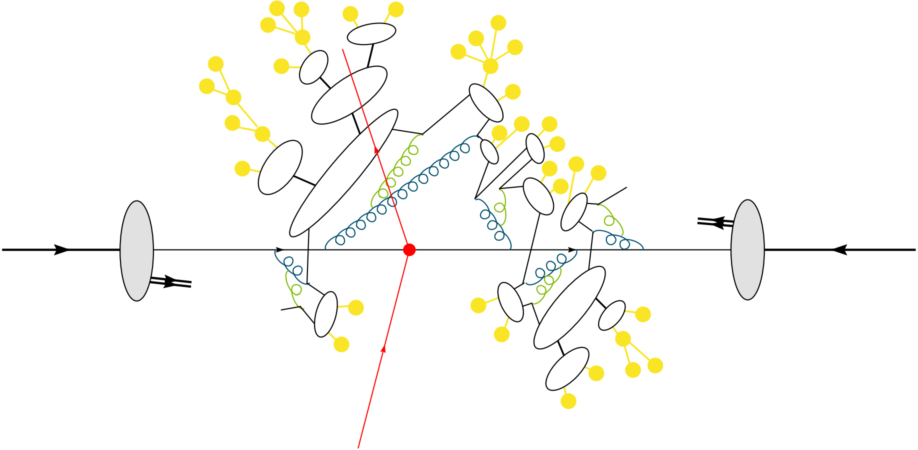
- Only string and cluster models used in recent MC programs.
  Independent fragmentation only for inclusive observables.
- Strings started non–perturbatively,
  improved by parton shower.
- Cluster model started mostly on perturbative side,
  improved by string like cluster fission.

Hadronic Decays

Hadronic decays



Hadronic decays



Hadronic decays

Many aspects:

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

EM decay.

Hadronic decays

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$$

Weak mixing.

Hadronic decays

Many aspects:

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Weak decay.

Hadronic decays

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Strong decay.

Hadronic decays

Many aspects:

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\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:

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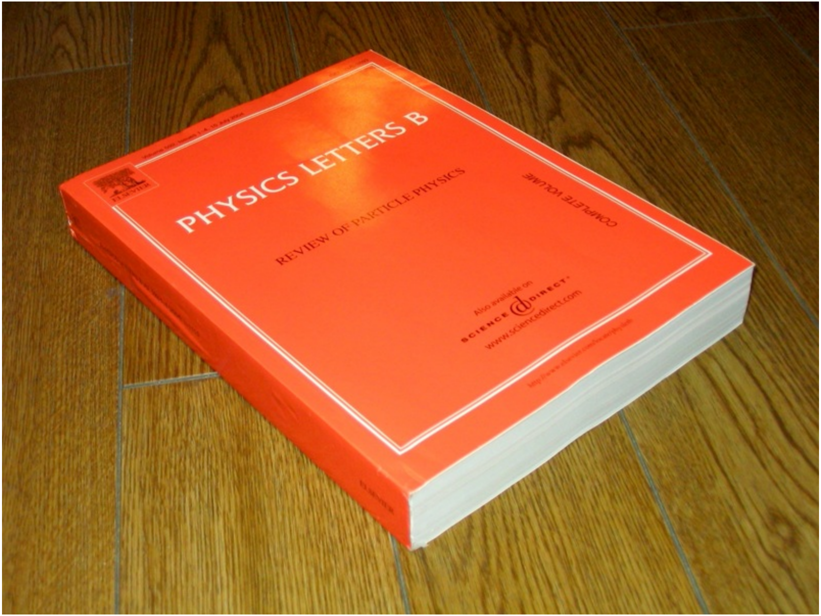
\end{aligned}
$$

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



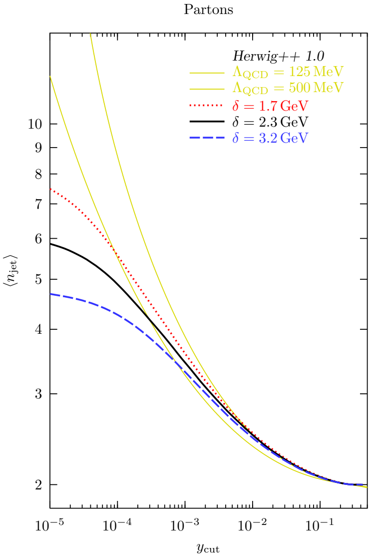
A few plots

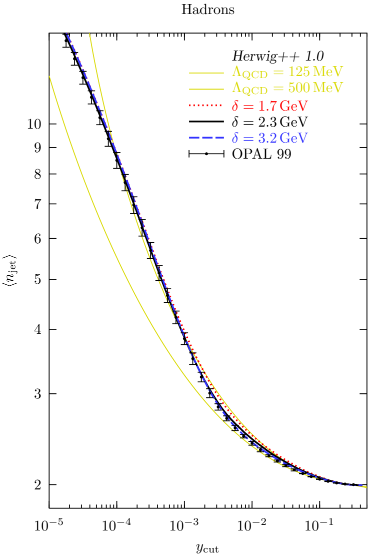
How well does it work?

- $e^+e^- \to$ hadrons, mostly at LEP.
- Jet shapes, jet rates, event shapes, identified particles…
- 'Tuning' of parameters.
- Want to get *everything* right with *one* parameter set.
- Compare to literally 100s of plots.

How well does it work?

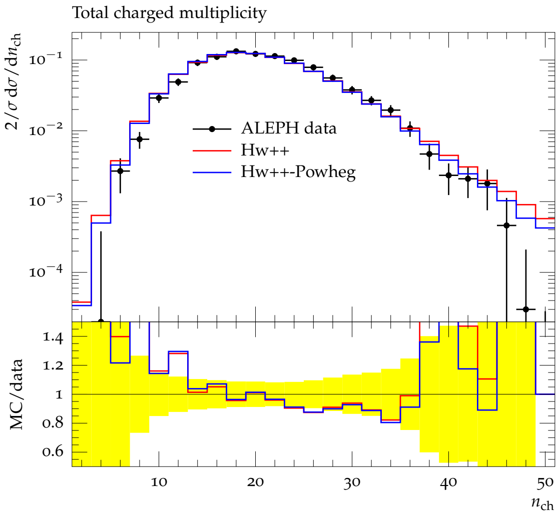
Smooth interplay between shower and hadronization.





How well does it work?

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

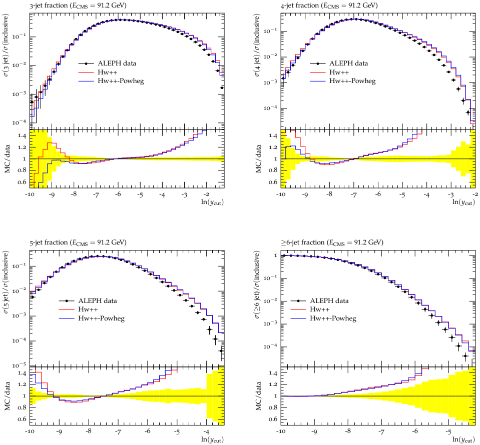


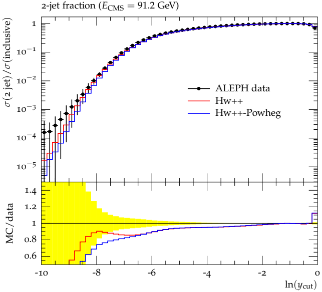
How well does it work?

Jet rates at LEP.

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

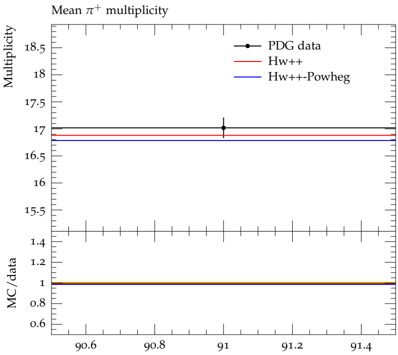
(Herwig++ 2.5.2)

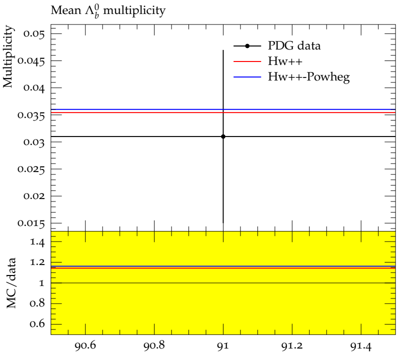




How well does it work?

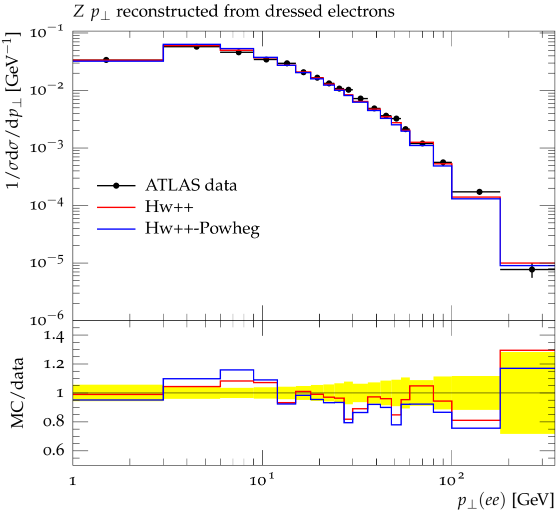
Hadron Multiplicities at LEP (e.g. π^+, Λ_b^0).



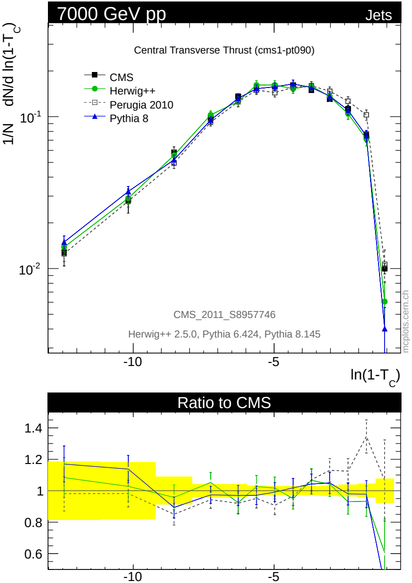


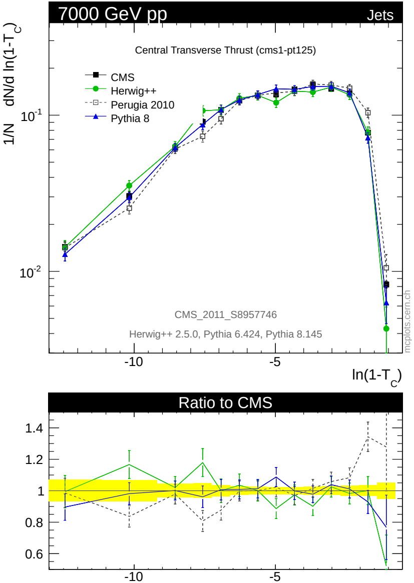
How well does it work?

$p_\perp(Z^0) \to$ intrinsic $k_\perp$ (LHC 7 TeV).



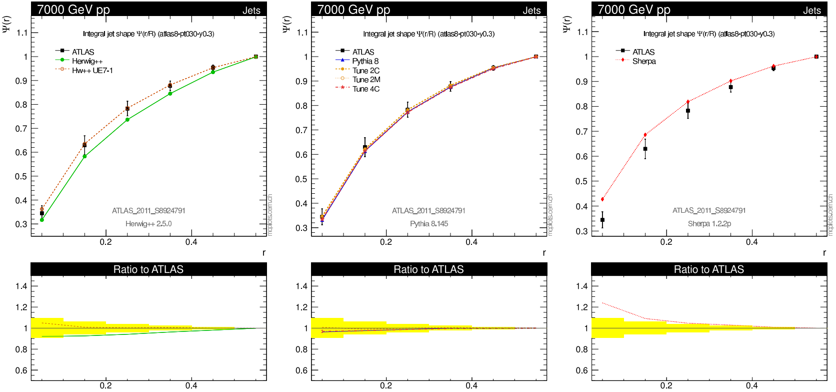
Transverse thrust





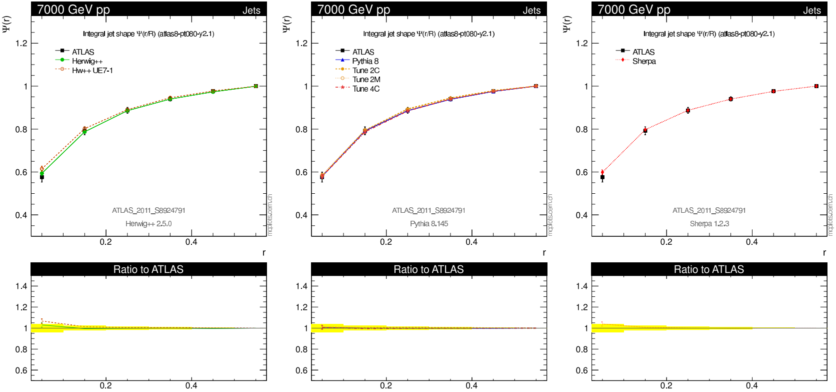
Integral jet shapes

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



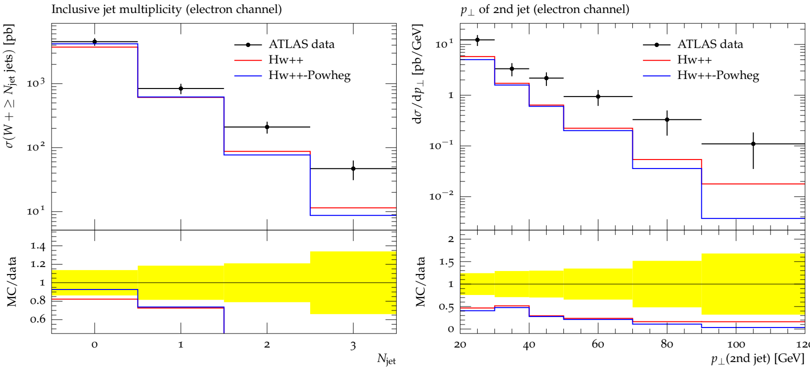
Integral jet shapes

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



Limits of parton shower

$W + $jets, LHC 7 TeV.



Higher jets not covered by parton shower only → matching.

Outline Lecture III

- Hadronization
  - Confinement
  - Flux tube model
  - Independent fragmentation
  - Lund string model
  - Cluster hadronization model
- Hadronic decays
- Comparison to data

Outline

- Lecture I — Basics
  - Introduction
  - Monte Carlo techniques
- Lecture II — Perturbative physics
  - Hard scattering
  - Parton showers
- Lecture III — Non–perturbative physics
  - Hadronization
  - Hadronic decays
  - Comparison to data
- Lecture IV — Multiple Partonic Interactions
  - Minimum Bias/Underlying Event in data
  - Modelling