Colour reconnections in the Herwig++ event generator

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Herwig++

Generator for lepton and hadron collisions.

- ▶ Successor of (Fortran-)HERWIG. [Marchesini, Webber '87]
- ▶ Major rewrite.

Actively developed multi-purpose event generators for LHC physics:

- ▶ Pythia8, Sherpa, Herwig++.

Herwig++

Main components:

- ► Matrix elements
- ► (alternatively: external matrix element generators via Les-Houches-Accord-Interface)
- ► Several processes accurate to NLO
- ► Parton showers
- ► Underlying event model
- ► Hadronization
- ► Hadron and tau decays

$\Rightarrow$ Comparison with detector-corrected data.

Contents

- Jet production in e^+e^- collisions
- Jet production in pp collisions
- Colour reconnection
- Results
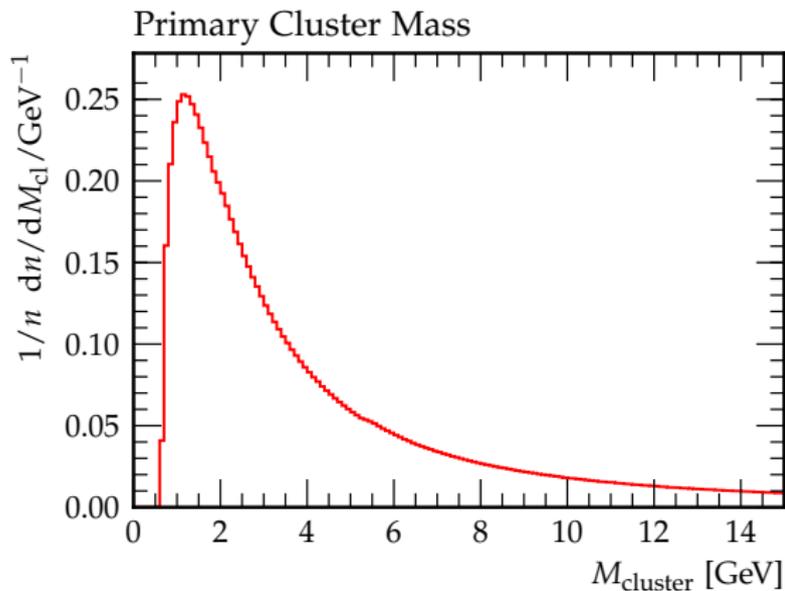
$e^+e^- \rightarrow$ jets

Monte Carlo simulation:

1. Sample $e^+e^- \rightarrow q\bar{q}$ according to cross section.
2. Parton shower: emission of coloured particles.
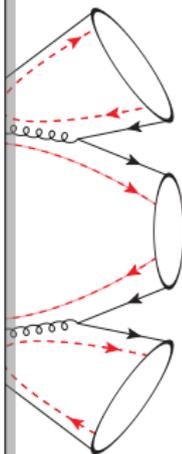3. Colour-neutral objects emerge naturally: clusters.

$e^+e^- \to$ jets

Monte Carlo s

1. Sample e⁺
   to cross s

2. Parton sh
   coloured

3. Colour-ne
   naturally:

Primary Cluster Mass
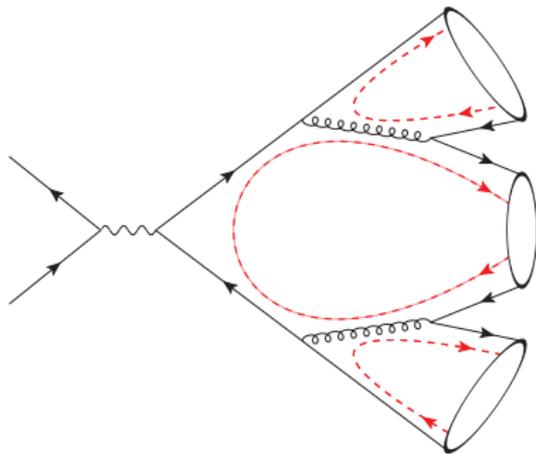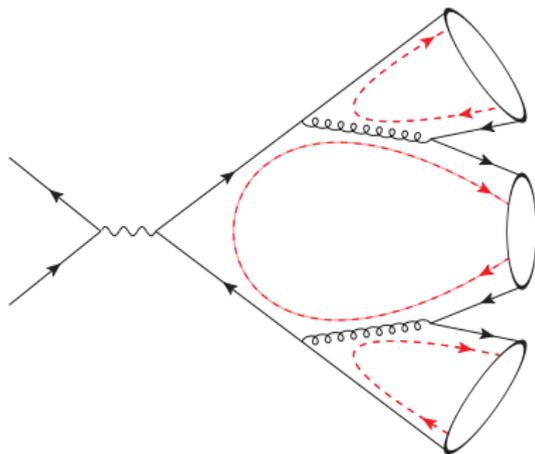
- ▶ Peaks just beyond the threshold.
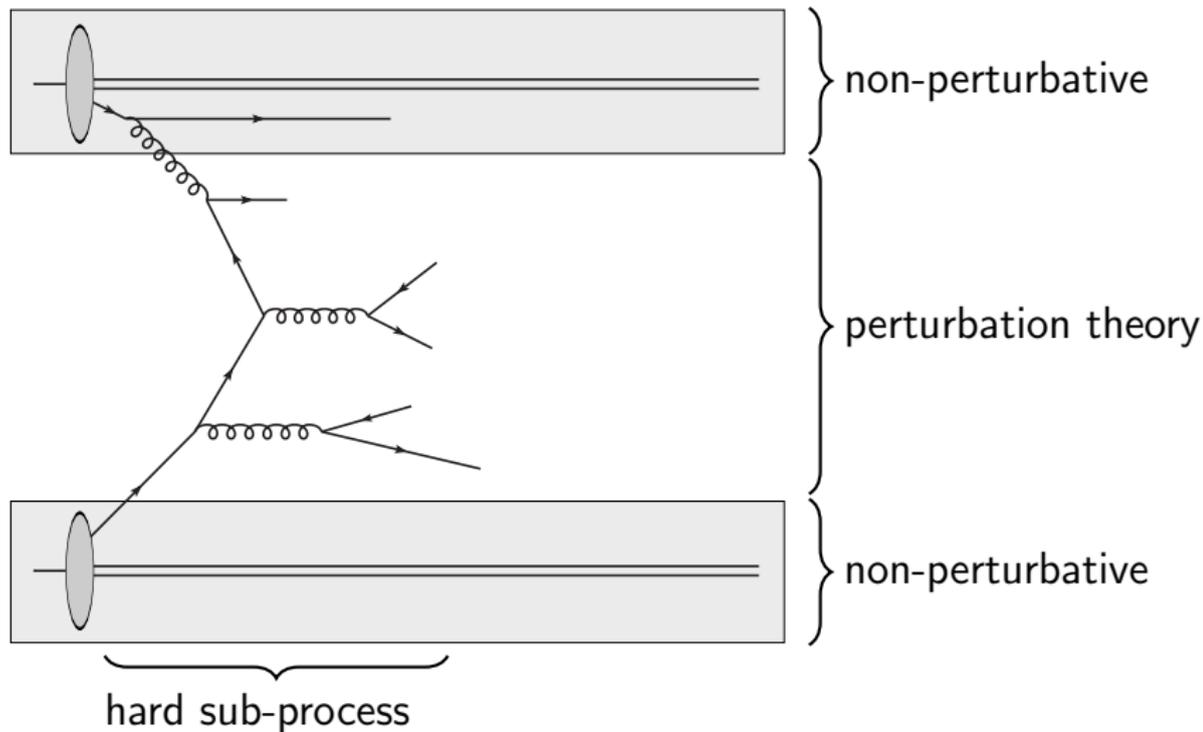- ▶ Clusters $\hat{=}$ "excited hadrons"
- ▶ Pre-confinement
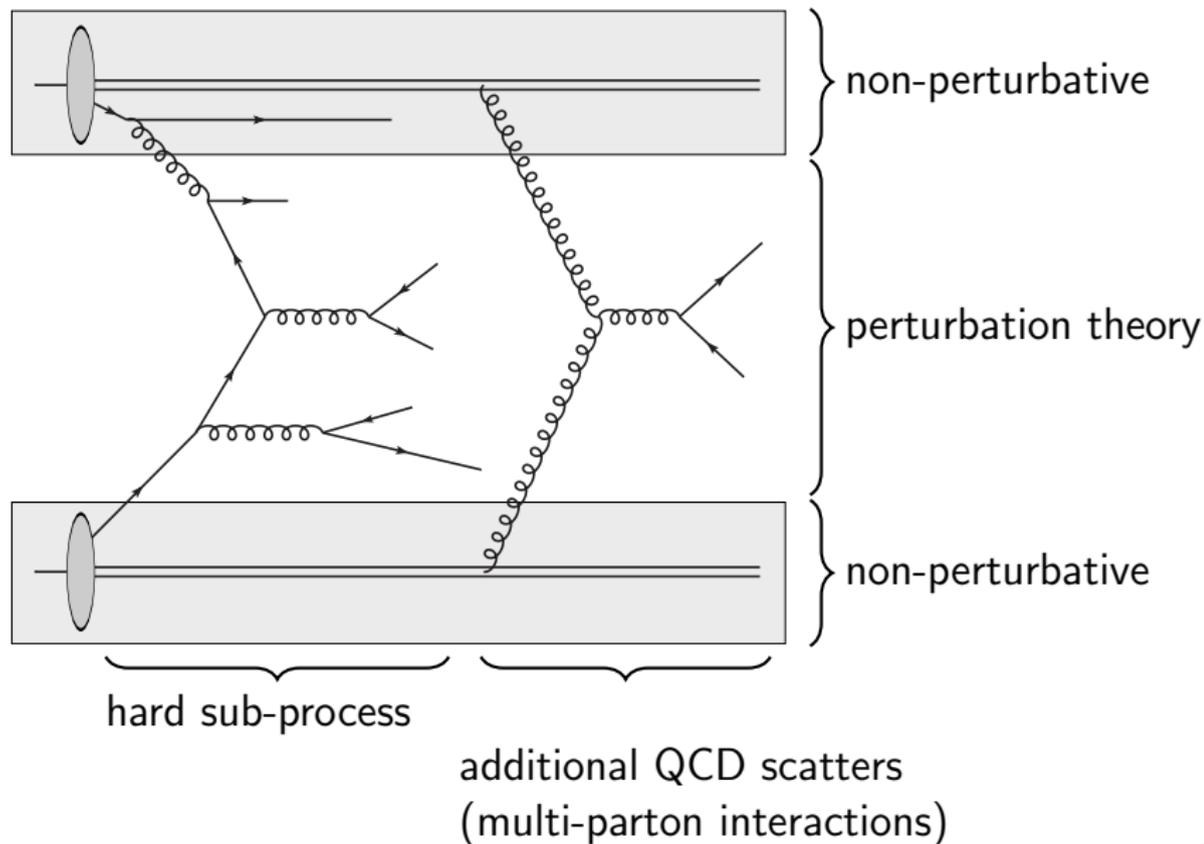
$e^+e^- \rightarrow$ jets

Monte Carlo simulation:

1. Sample $e^+e^- \rightarrow q\bar{q}$ according to cross section.
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3. Colour-neutral objects emerge naturally: clusters.

$\Rightarrow$ Clusters decay into hadrons.

A *pp* event in Herwig++
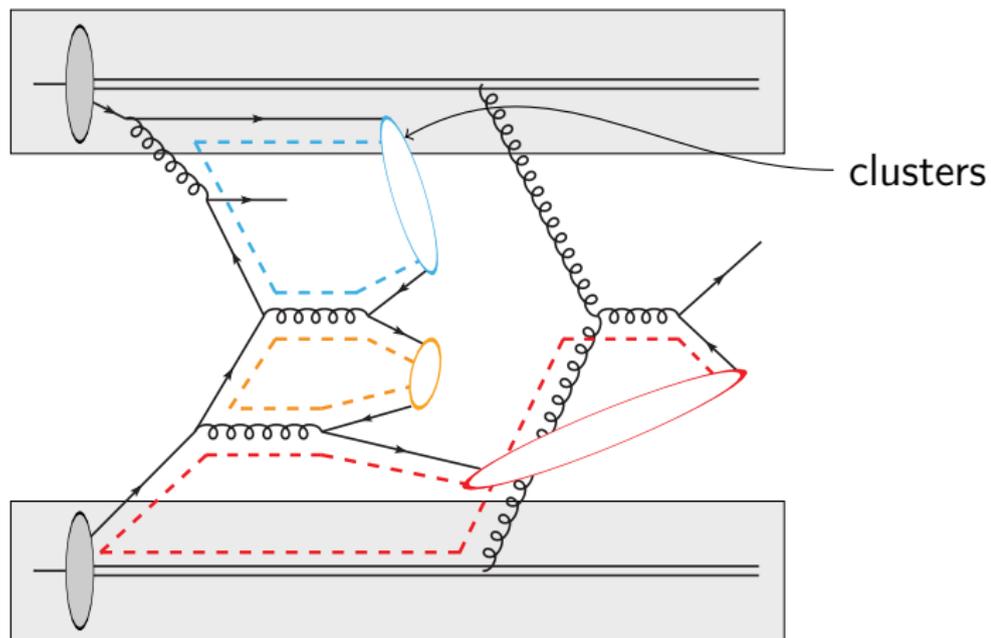

non-perturbative

perturbation theory

non-perturbative

hard sub-process

A *pp* event in Herwig++

non-perturbative

perturbation theory

non-perturbative

hard sub-process

additional QCD scatters
(multi-parton interactions)

A *pp* event in Herwig++

clusters

A *pp* event in Herwig++

clusters

decay to hadrons

fission of *heavy* clusters

A *pp* event in Herwig++

Non-perturbative colour connections guesswork!
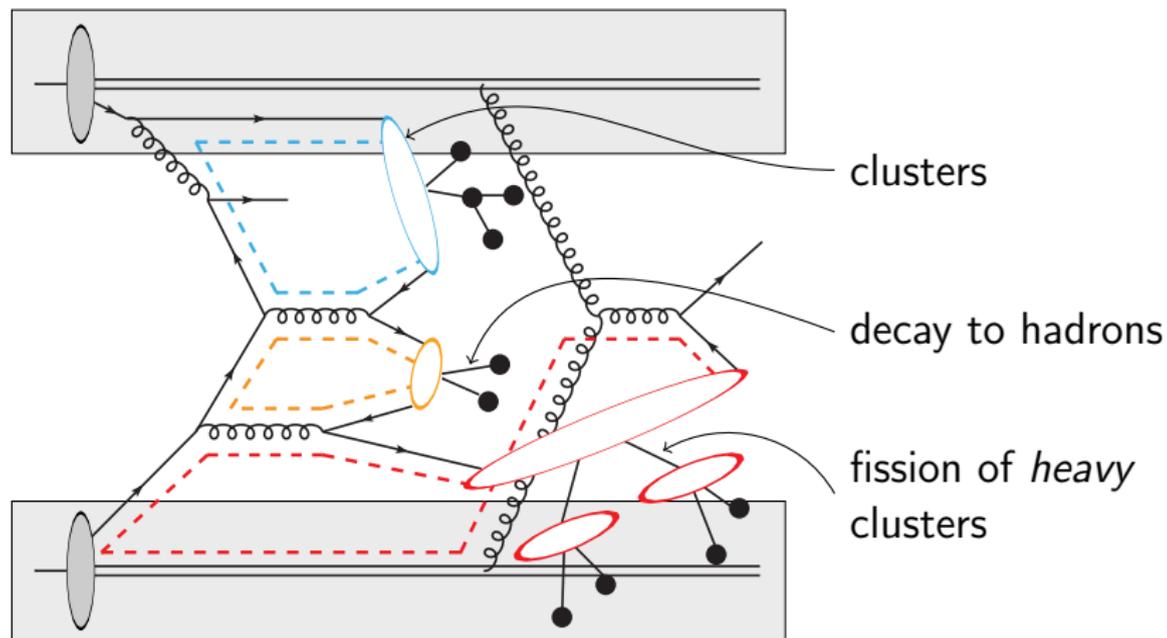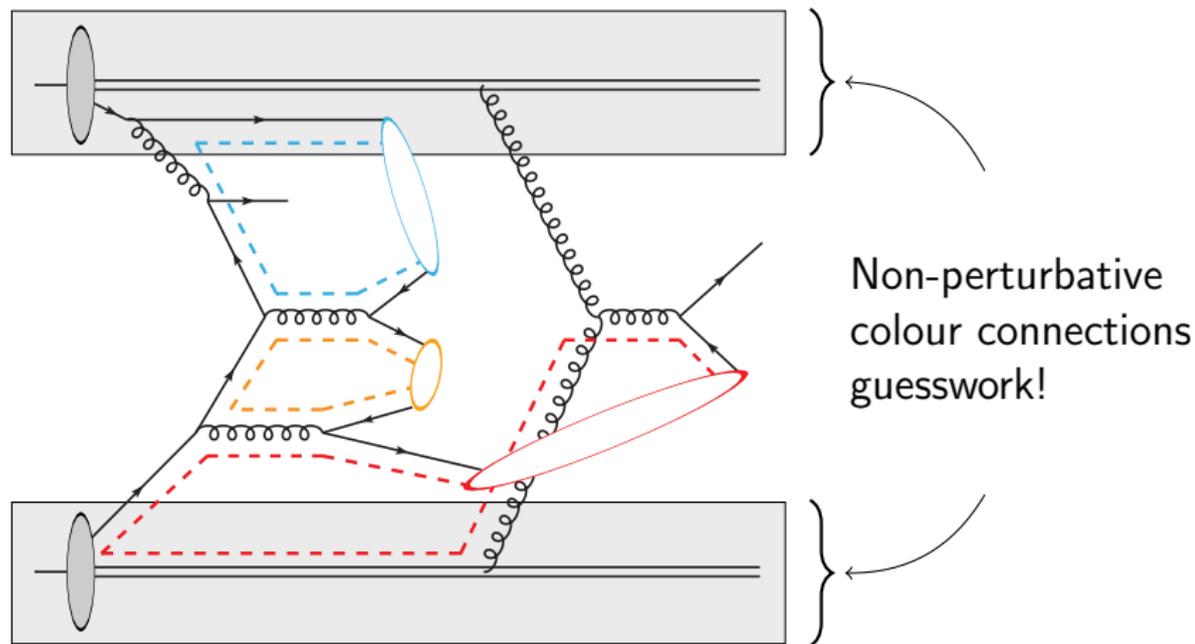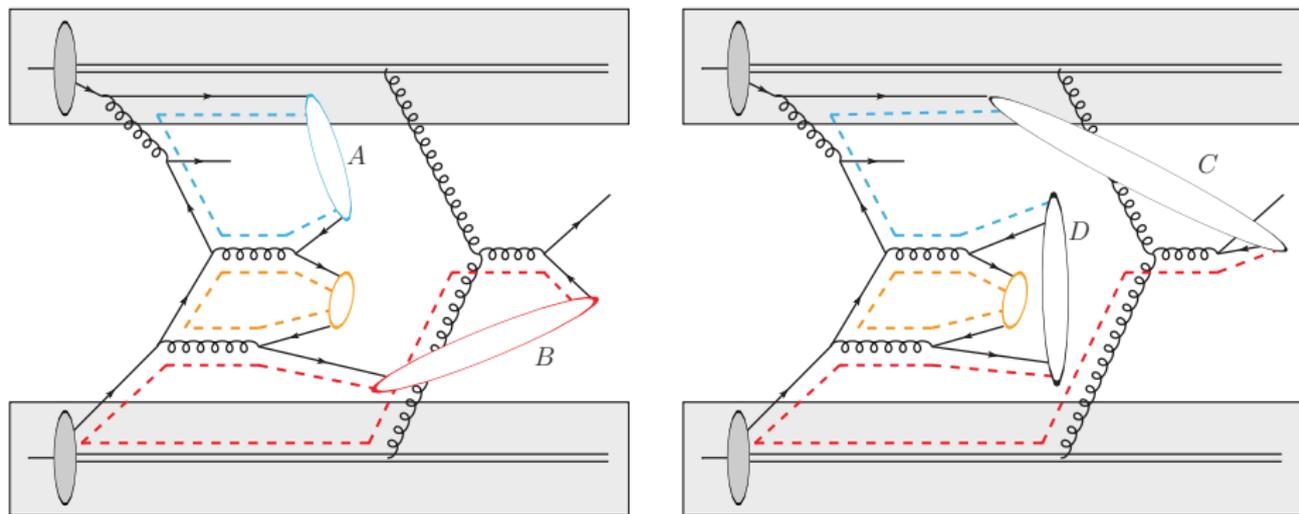
- ▶ ⇒ *Not assessable* whether hadron multiplicities and momenta correct.
- ▶ Repair possible errors: *colour reconnection* model.

Colour reconnection (CR)

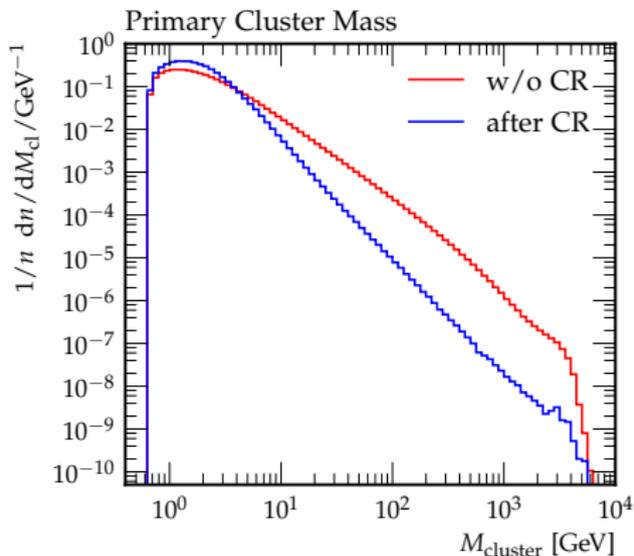*Idea*: Try to restore pre-confinement in *pp* collisions.

Allow alternative clusters C and D if
$$M_C + M_D < M_A + M_B.$$

- ► Detailed discussion of two CR algorithms in
  [Gieseke, CR, Siódmok, arXiv:1206.0041] .

Invariant mass of clusters

- Shift to 'physical' masses, $\mathcal{O}(m_{\text{hadrons}})$.
- CR substitutes *really heavy* clusters by lighter ones.

LHC data: minimum bias

MB trigger: Selects events with minimal requirements.

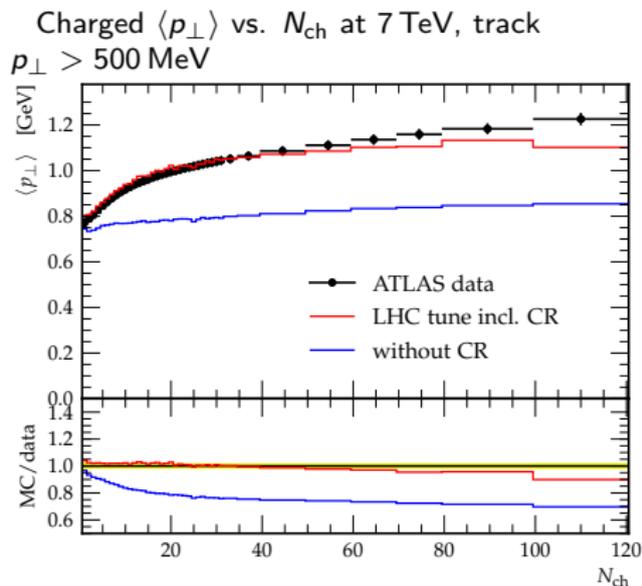- Dominant contribution to σ_{tot} at the LHC: events *without* hard jets.
- Pile-up
    - Additional *pp* coll. in the same bunch crossing.
    - Usually soft.
    - Impedes e.g. *W* mass measurement.
- Good understanding of MB events vital.

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Charged $\langle p_\perp \rangle$ vs. N_{ch} at 7 TeV, track $p_\perp > 500$ MeV

- ATLAS data
- LHC tune incl. CR
- without CR

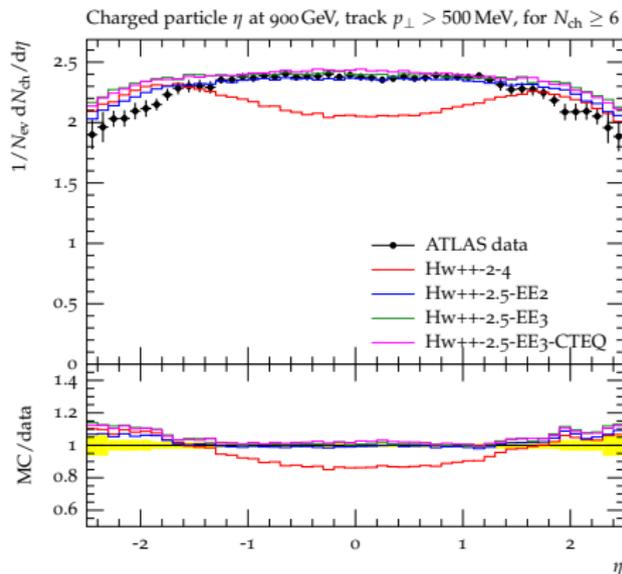$\Rightarrow$ Colour reconnection important.

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Charged particle η at 900 GeV, track $p_\perp > 500$ MeV, for $N_{\text{ch}} \geq 6$

ATLAS data
Hw++-2-4
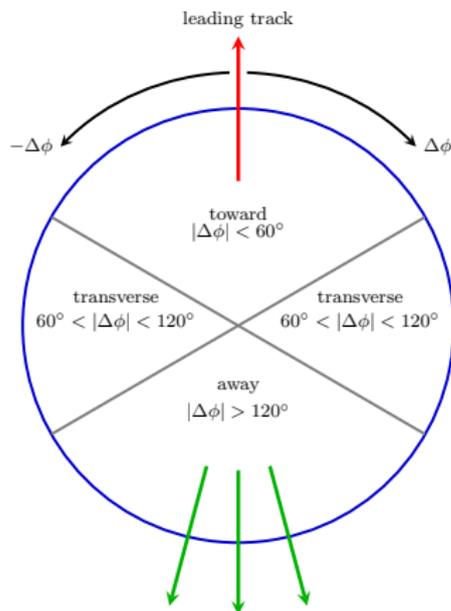Hw++-2.5-EE2
Hw++-2.5-EE3
Hw++-2.5-EE3-CTEQ

$\Rightarrow$ Colour reconnection important.

LHC data: underlying event

Irreducible background to hard jets in hadron collisions.

- ▶ Additional partonic scatters.
- ▶ UE affects e.g. jet mass and substructure.
- ▶ "Transverse region" most sensitive to UE.

leading track

$-\Delta\phi$ $\Delta\phi$

toward
$|\Delta\phi| < 60°$

transverse
$60° < |\Delta\phi| < 120°$

transverse
$60° < |\Delta\phi| < 120°$

away
$|\Delta\phi| > 120°$

from [**Atlas**, Phys. Rev. D **83** (2011) 112001]

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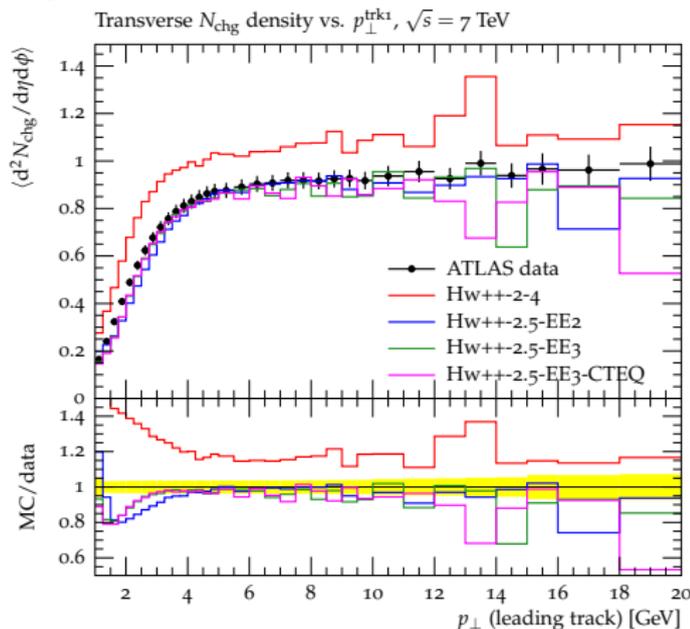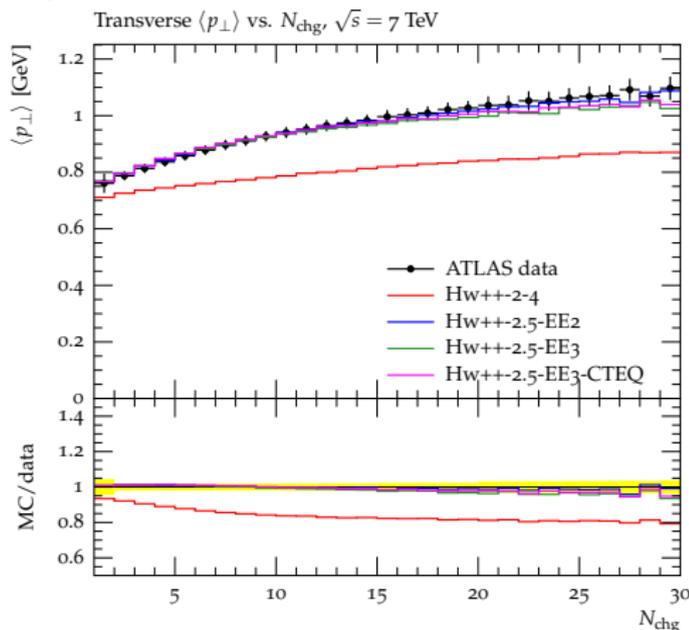- ▶ "Transverse region" most sensitive to UE.

⇒ Colour reconnection important.

LHC data: underlying event

Irreducible background to hard jets in hadron collisions.

Transverse $\langle p_\perp \rangle$ vs. N_{chg}, $\sqrt{s} = 7$ TeV

- ▶ Additional partonic scatters.
- ▶ UE affects e.g. jet mass and substructure.
- ▶ "Transverse region" most sensitive to UE.

$\Rightarrow$ Colour reconnection important.

Conclusions

- Complete theory of hadron collisions not understood.
- Compose multiple partonic scatters $\Rightarrow$ high-mass clusters.
- Need colour reconnection to restore pre-confinement from perturbative QCD.
- (Diffraction-suppressed) minimum-bias and underlying-event data better described.
- In Herwig++ as of version 2.5
- Gieseke, Röhr, Siódmok '12 (arXiv:1206.0041)

Outlook

- Complete minimum-bias model: need diffraction model.
- Study impact on top mass measurement.
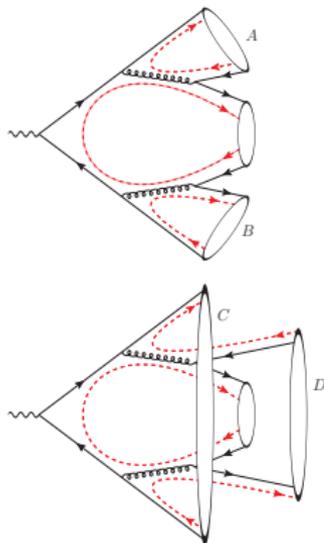
backup slides

Reduce sum of (squared) cluster masses,

$$\lambda \equiv \sum_{i \in \{\text{clusters}\}} m_i^2 \,,$$
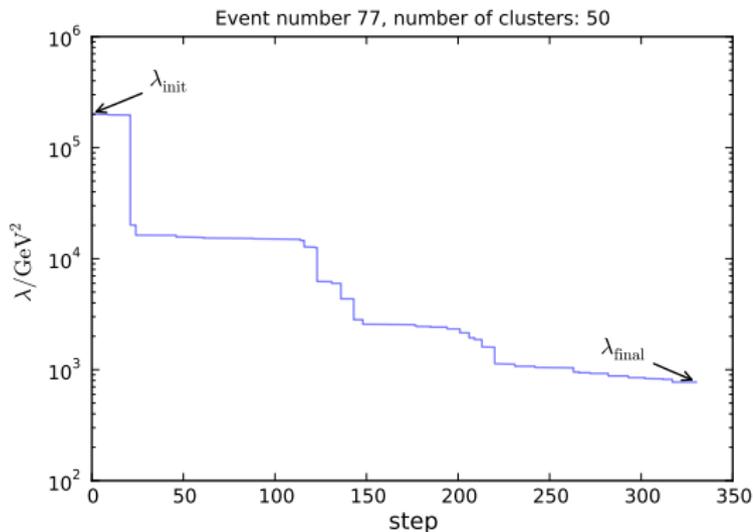
using a simulated annealing algorithm:

- try random swaps $(A, B \to C, D)$
  - always accept the steps that reduce λ
  - accept 'bad' steps $(\lambda_2 > \lambda_1)$ with Boltzmann probability,

$$p = \exp\left[-(\lambda_2 - \lambda_1)/T\right]$$

- $T_{\text{start}} \sim \text{median}\{|\Delta\lambda|, \text{a few dry-run swaps}\}$
- gradually decrease T
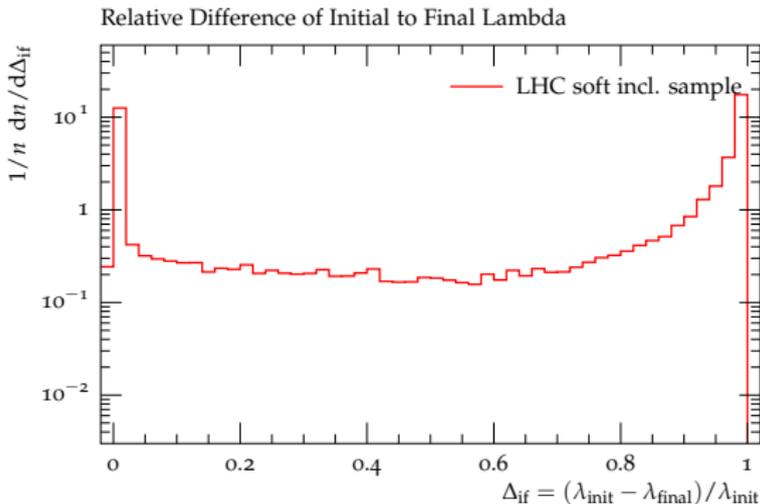
Event number 77, number of clusters: 50

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

- CR breaks up **very** heavy clusters
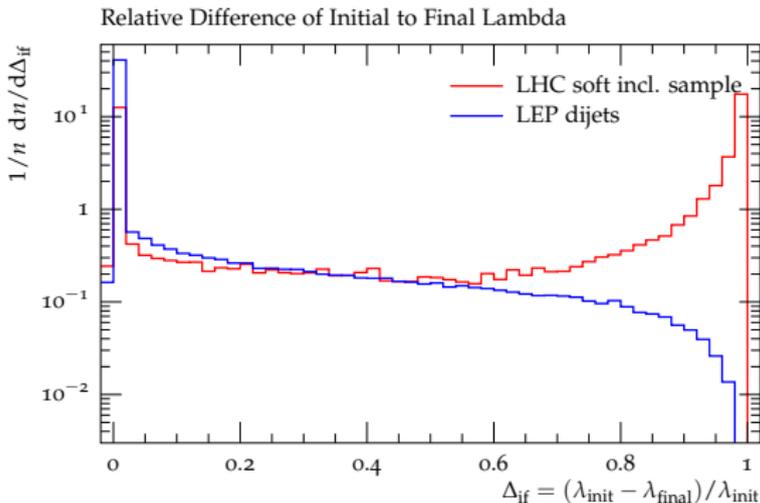- λ often reduced by large factor

Quantifying the effect of colour reconnection

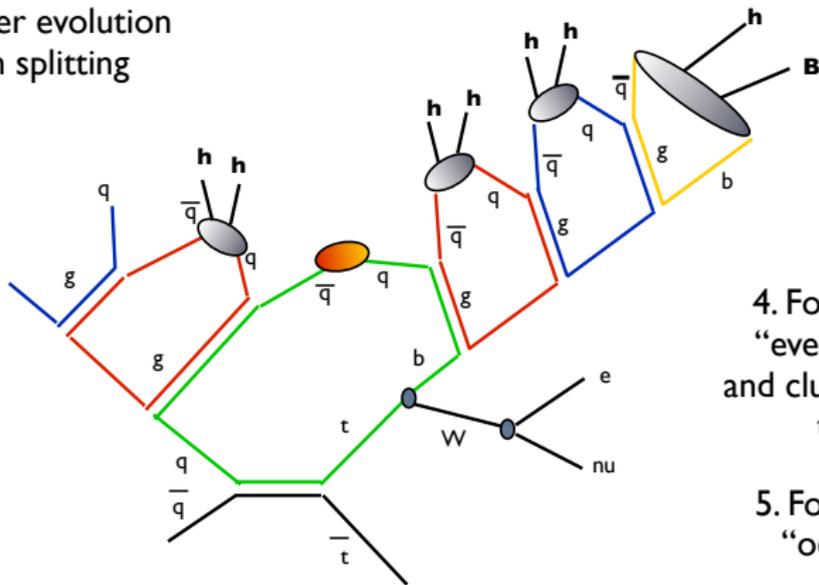$$\lambda \equiv \sum_{i \in \{\text{clusters}\}} m_i^2$$

Relative Difference of Initial to Final Lambda

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

Relative Difference of Initial to Final Lambda

LHC soft incl. sample
LEP dijets

$1/n \; \mathrm{d}n/\mathrm{d}\Delta_{if}$

$\Delta_{if} = (\lambda_{\text{init}} - \lambda_{\text{final}})/\lambda_{\text{init}}$

observe extreme decrease of λ in hadron collisions only
$\Rightarrow$ almost no colour reconnection at LEP!
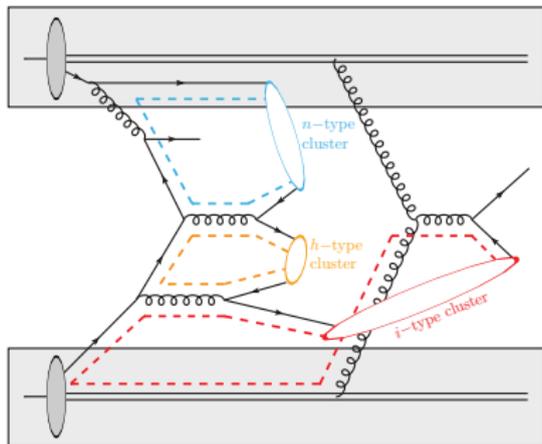
1. Hard Process
2. Shower evolution
3. Gluon splitting

4. Formation of "even" clusters and cluster decay to hadrons
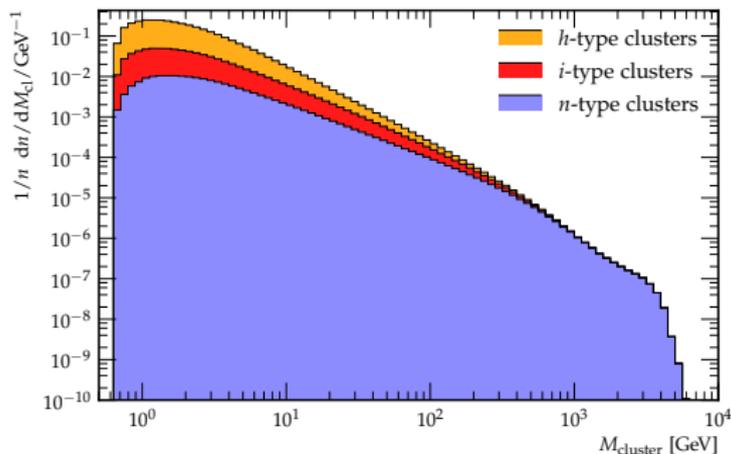
5. Formation of "odd" cluster

from [M. Mangano, LHC top WG meeting, 19 July '12]

- *h*-type clusters: within a single subprocess
- *i*-type clusters: interconnecting subprocesses
- *n*-type clusters: containing a non-perturbative parton

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