Colour Reconnection and Its Effect on Precise Measurements at the LHC

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The Structure of an Event

An event consists of many different physics steps, which have to be modelled by event generators:

PDF
ME
MPI
ISR
FSR
BR
CR
Hadr.
Decays
Rescattering
BE
Unknown?
The Density of Particle Production

multiplicities in nondiffractive events (8 TeV LHC)

strings crossing $y = 0$
primary hadrons in $|y| < 0.5$
charged particles in $|y| < 0.5$

String width $\sim$ hadronic width $\Rightarrow$ Overlap factor $\sim 10!$
Reconnection in B decays

Colour operators in B decay $\Rightarrow$ some $\eta_c$:

$B \to J/\psi \to \mu^+\mu^-$ good way to find B mesons:
. . . soon confirmed by experiment

$g^* \to c\bar{c} \to J/\psi$ production mechanism in pp ("colour octet")
more complicated to test (at the time, later "confirmed")
Reconnection at SppS


\[ \langle p_\perp \rangle(n_{ch}) \text{ sensitive to colour flow.} \]

\[ \text{long strings to remnants} \Rightarrow \text{comparable } n_{ch}/\text{interaction} \Rightarrow \langle p_\perp \rangle(n_{ch}) \sim \text{flat.} \]

\[ \text{shorter extra strings for each consecutive interaction} \Rightarrow \langle p_\perp \rangle(n_{ch}) \text{ rising.} \]

**FIG. 27.** Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings only; dotted line, $gg$ scatterings with “maximal” string length; solid line $gg$ scatterings with “minimal” string length.
Interconnection at LEP 2

\[ e^+e^- \rightarrow W^+W^- \rightarrow q_1\bar{q}_2 q_3\bar{q}_4 \] reconnection limits \( m_W \) precision!

- **perturbative** \( \langle \delta M_W \rangle \lesssim 5 \text{ MeV} \) : negligible!
  (killed by dampening from off-shell \( W \) propagators)
- **nonperturbative** \( \langle \delta M_W \rangle \sim 40 \text{ MeV} \) : inconclusive.
  (but more extreme models from other authors ruled out)
- **Bose-Einstein** \( \langle \delta M_W \rangle \lesssim 100 \text{ MeV} \) : full effect ruled out.
  (but models with \( \sim 40 \text{ MeV} \) barely acceptable)

Colour rearrangement studied in several models, e.g.

**Scenario II: vortex lines.**
Analogy: type II superconductor.
Strings can reconnect only if central cores cross.

**Scenario I: elongated bags.**
Analogy: type I superconductor.
Reconnection proportional to space–time overlap.

In both cases favour reconnections that reduce total string length.

(schematic only; nothing to scale)
Multiple colour charges extracted from beams by MPIs:

Ambiguities from $N_C = 3$ and spatial correlations?
$N_C = \infty$ builds too high remnant charge (forward particle flow)!
Random walk in colour space, with restoring force?
Junction topologies when $\geq 2$ valence quarks kicked out!
Reconnection at the LHC

\[ \langle p_\perp \rangle (n_{\text{ch}}) \] effect alive and kicking:

Reconnection important also for other generators, e.g. Herwig++
Colour rearrangement models for the LHC

Space–time models too complicated
⇒ simplified (in PYTHIA)

Common aspect: reduce string length
\[ \lambda = \sum \ln \left( \frac{m_{ij}^2}{m_0^2} \right) \sim \text{multiplicity} \]

Ingelman, Rathsman: reduce \( \sum m_{ij}^2 \);

Generalized Area Law

In total 12 scenarios in PYTHIA 6, mainly annealing:

- \( P_{\text{reconnect}} = 1 - (1 - \chi)^{n_{\text{MPI}}} \) with \( \chi \) strength parameter.
- Random assignment by \( P_{\text{reconnect}} \) for each string piece.
- Choose new combinations that reduce \( \lambda \) (with restrictions).

PYTHIA 8 still only primitive:
let each MPI either form a separate system, or attach its partons to a higher-\( p_\perp \) MPI where it gives minimal \( \lambda \) increase.

Much room for improvement.
MC: close to pole mass, in the sense of Breit–Wigner mass peak.
\( t, W, Z: c\tau \approx 0.1 \text{ fm} < r_p \).

At the Tevatron: \( m_t = 173.20 \pm 0.51 \pm 0.71 \text{ GeV} = \text{PMAS}(6,1) \)
At the LHC (CMS): \( m_t = 173.54 \pm 0.33 \pm 0.96 \text{ GeV} = 6:m0 \)?
The Mass of Unstable Coloured Particles

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Now severely limited by colour reconnection uncertainty
Studies for the Tevatron.

Green bands: old virtuality-ordered showers.

Blue bands: new $p_{\perp}$-ordered showers.

In total $\pm 1.0$ GeV, whereof $\pm 0.7$ GeV perturbative, and $\pm 0.5$ GeV nonperturbative.

(M. Sandhoff and P. Z. Skands, FERMILAB-CONF-05-518-T;)
Kinematics dependence of mass determinations

Dependence of Top Mass on Event Kinematics

- First top mass measurement binned in kinematic observables.
- Additional validation for the top mass measurements.
- With the current precision, no mis-modelling effect due to
  - color reconnection, ISR/FSR, b-quark kinematics, difference between pole or MS^~ masses.

E. Yazgan
(Moriond 2013)
Semileptonic top decay.

Find jets with anti-$k_\perp$,
$R = 0.5$, $p_{\perp \text{min}} = 20$ GeV.

Request $n_{\text{jet}} \geq 4$.

Find two jets closest to $m_W$.

Kill if $|m_{12} - m_W| > 5$ GeV.

Find third jet closest to $m_t$.

Kill if $|m_{123} - m_t| > 20$ GeV.

t/W decay after $\rightarrow$ before CR:
$\langle \delta n_{\text{ch}} \rangle = -0.26 \pm 0.09$
$\langle \delta m_t \rangle = +0.060 \pm 0.020$ GeV

t/W decay after $\rightarrow$ no CR:
$\langle \delta n_{\text{ch}} \rangle = +36.44 \pm 0.09$
$\langle \delta m_t \rangle = +0.149 \pm 0.020$ GeV
Transverse boosts ⇒
≈ collective particle velocity.
More common with reconnection.

A. Ortiz Velasquez et al.,
Summary and Outlook

- Reconnection well established, from $B \rightarrow J/\psi$ to $\langle p_\perp \rangle (n_{ch})$.
- Missed chance for clean tests at LEP 2.
- Multitude of algorithms for $\textsc{Pythia}$ 6 $\Rightarrow$ uncertainty band.
- Predict (possibility of) significant effects on $m_t$.
- To do: develop new reconnection algorithms in Pythia8.
- Want more detailed understanding of space–time picture combined with colour algebra.
- High string density will preclude any definitive answers?
- Breakthrough from new precision differential data?
- Far future: high-luminosity $e^+e^-$ collider?

Addendum: new CMS PAS TOP-13-007, "Study of the underlying event, b-quark fragmentation and hadronization properties in $t\bar{t}$ events" shows colour reconnection impact on underlying activity as function of $p_\perp$ and $\phi$. 
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Let’s aim for more than a flying circus . . .