Colour Reconnection
and Its Effect on Precise Measurements at the LHC

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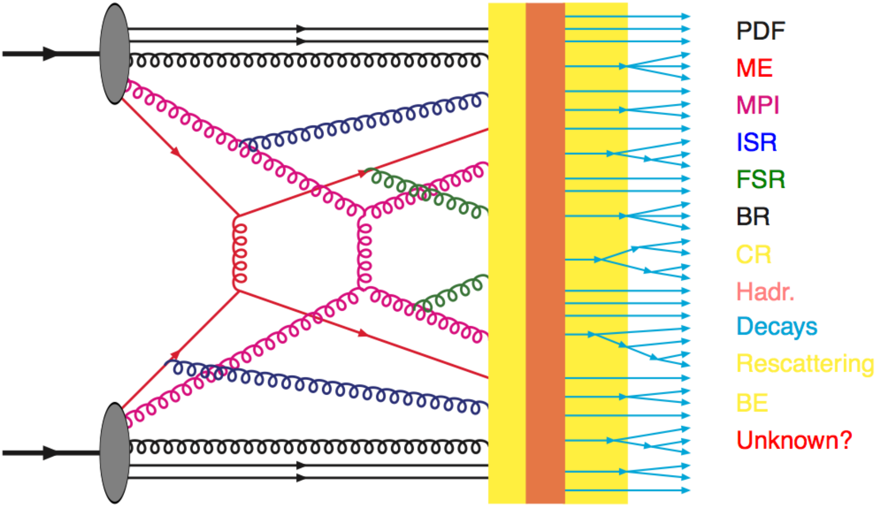
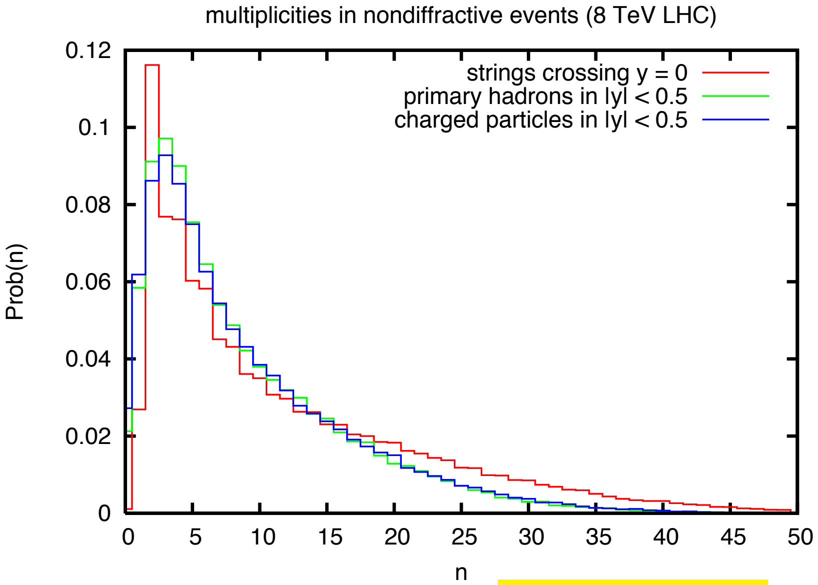
The Structure of an Event

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

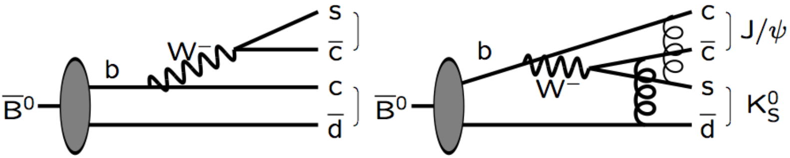


The Density of Particle Production



String width $\sim$ hadronic width $\Rightarrow$ **Overlap factor $\sim$ 10!**

Colour operators in B decay $\Rightarrow$ some η_c:
A. Ali, J.G. Körner, G. Kramer, J. Willrodt, Z. Phys. **C1** (1979) 269



$\mathrm{B} \to \mathrm{J}/\psi \to \mu^+\mu^-$ good way to find B mesons:
H. Fritzsch, Phys. Lett. **B86** (1979) 164, 343
. . . soon confirmed by experiment

$\mathrm{g}^* \to \mathrm{c}\overline{\mathrm{c}} \to \mathrm{J}/\psi$ production mechanism in pp ("colour octet")
H. Fritzsch, Phys. Lett. **B67** (1977) 217
more complicated to test (at the time, later "confirmed")

Reconnection at Sp$\bar{\text{p}}$S

T.S. and M. van Zijl,
Phys.Rev. **D36** (1987) 2019

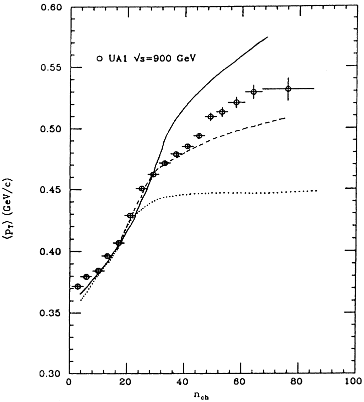
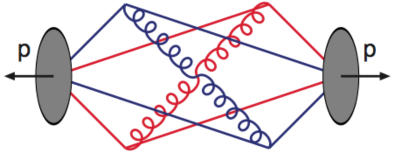
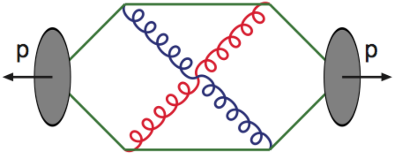


FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings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

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



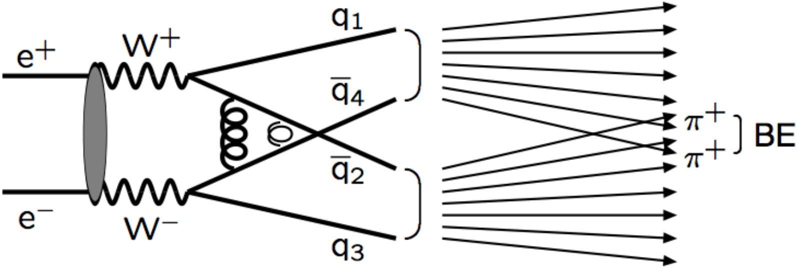
long strings to remnants
$\Rightarrow$ comparable n_{ch}/interaction
$\Rightarrow \langle p_\perp \rangle (n_{ch}) \sim$ flat.



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

Interconnection at LEP 2

$e^+e^- \to W^+W^- \to q_1\overline{q}_2\, q_3\overline{q}_4$ reconnection limits m_W precision!



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

V.A. Khoze & TS, PRL 72 (1994) 28; L. Lönnblad & TS, EPJ C6 (1999) 271

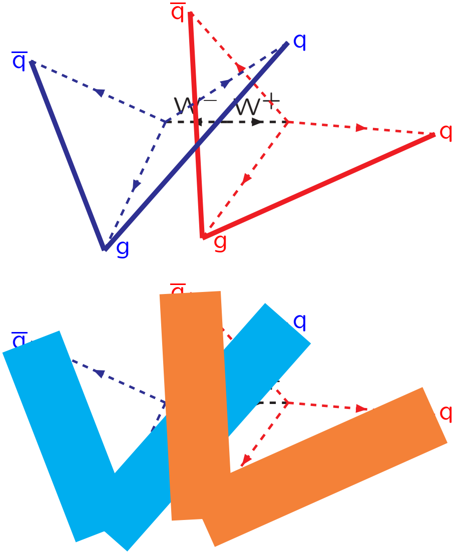
Colour rearrangement models for LEP 2

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.

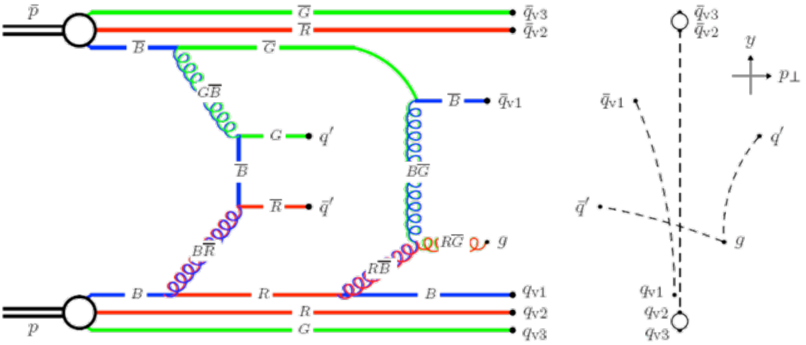
In both cases favour reconnections that reduce total string length.



(schematic only; nothing to scale)

Colour assignment at hadron colliders

Multiple colour charges extracted from beams by MPIs:



Ambiguities from $N_C = 3$ and spatial correlations?

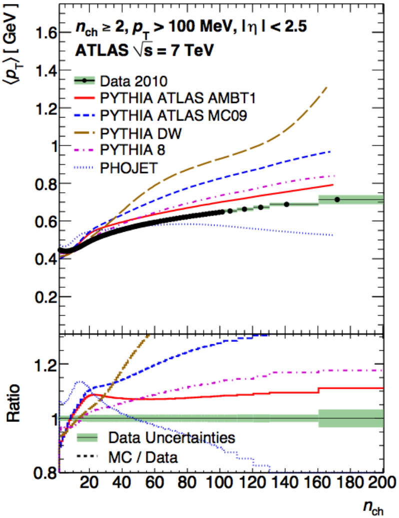
$N_C = \infty$ builds too high remnant charge (forward particle flow)!

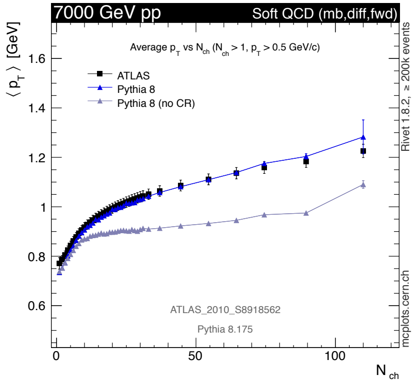
Random walk in colour space, with restoring force?

Junction topologies when ≥ 2 valence quarks kicked out!

Reconnection at the LHC

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





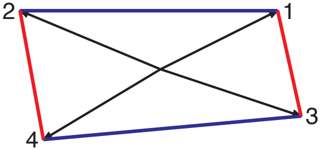
Reconnection important also for other generators, e.g. Herwig++

Colour rearrangement models for the LHC

Space–time models too complicated
$\Rightarrow$ simplified (in PYTHIA)

Common aspect: reduce string length
$\lambda = \sum \ln(m_{ij}^2/m_0^2) \sim$ multiplicity

Ingelman, Rathsman: reduce $\sum m_{ij}^2$;
Generalized Area Law



$m_{13}m_{24} < m_{12}m_{34}$

In total 12 scenarios in PYTHIA 6, mainly annealing:

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

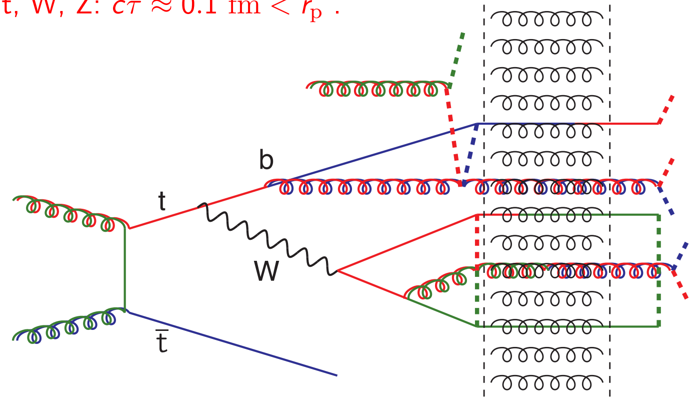
PYTHIA 8 still only primitive:
let each MPI either form a separate system, or attach its partons to a higher-$p_\perp$ MPI where it gives minimal λ increase.

Much room for improvement.

The Mass of Unstable Coloured Particles

MC: close to pole mass, in the sense of Breit–Wigner mass peak.

t, W, Z: $c\tau \approx 0.1\ \mathrm{fm} < r_\mathrm{p}$.



At the Tevatron: $m_\mathrm{t} = 173.20 \pm 0.51 \pm 0.71$ GeV = `PMAS(6,1)`

At the LHC (CMS): $m_\mathrm{t} = 173.54 \pm 0.33 \pm 0.96$ GeV = `6:m0` ?

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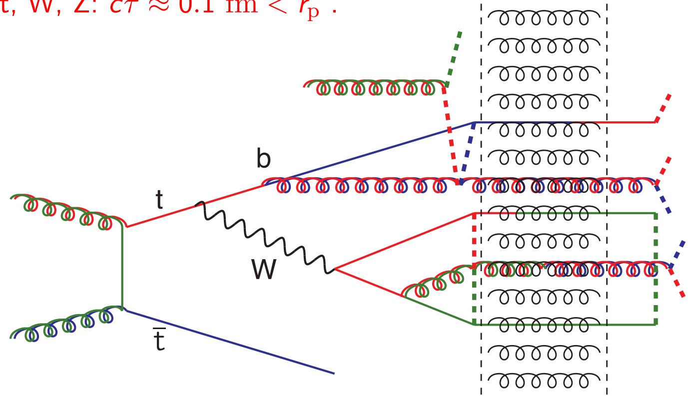

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Now severely limited by colour reconnection uncertainty

Top mass shift in PYTHIA 6

Studies for the Tevatron.

Green bands: old virtuality-ordered showers.

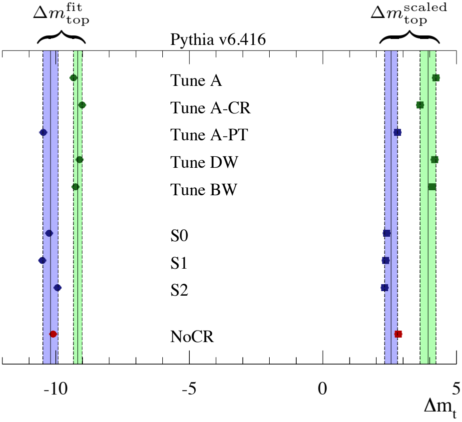
Blue bands: new $p_\perp$-ordered showers.

In total ± 1.0 GeV,

whereof ± 0.7 GeV perturbative,

and ± 0.5 GeV nonperturbative.

Fit $\rightarrow$ scaled: Jet Energy Scaling.



(M.Sandhoff and P.Z Skands, FERMILAB-CONF-05-518-T;)
D. Wicke and P.Z. Skands, EPJ C52 (2007) 133, Nuovo Cim. B123 (2008) S1

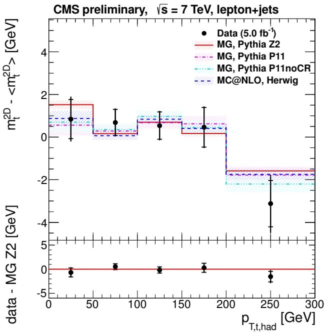
Kinematics dependence of mass determinations

Dependence of Top Mass on Event Kinematics

CMS-PAS-TOP-12-029

NEW

	Fig.	Observable
color recon.	1	$\Delta R_{q\bar{q}}$
	2	$\Delta\phi_{q\bar{q}}$
	3	$p_{T,t,had}$
	4	$\lvert\eta_{t,had}\rvert$
ISR/FSR	5	H_T
	6	$m_{t\bar{t}}$
	7	$p_{T,t\bar{t}}$
	8	Jet multiplicity
b-quark kin.	9	$p_{T,b,had}$
	10	$\lvert\eta_{b,had}\rvert$
	11	$\Delta R_{b\bar{b}}$
	12	$\Delta\phi_{b\bar{b}}$



- *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)

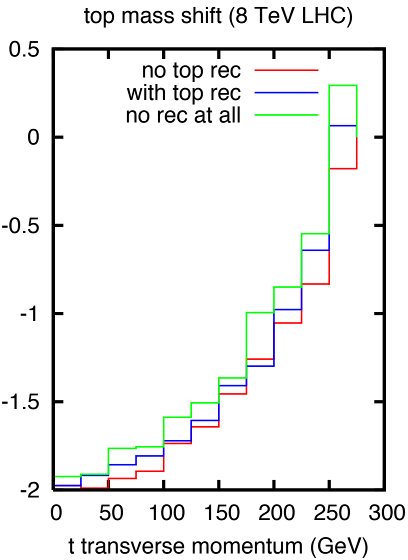
1(

Top mass shift in PYTHIA 8

- Semileptonic top decay.
- Find jets with anti-$k_{\perp}$, $R = 0.5$, $p_{\perp\mathrm{min}} = 20$ GeV.
- Request $n_{\mathrm{jet}} \geq 4$.
- Find two jets closest to m_{W}.
- Kill if $|m_{12} - m_{\mathrm{W}}| > 5$ GeV.
- Find third jet closest to m_{t}.
- Kill if $|m_{123} - m_{\mathrm{t}}| > 20$ GeV.

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

t/W decay after → no CR:
$\langle \delta n_{\mathrm{ch}} \rangle = +36.44 \pm 0.09$
$\langle \delta m_{\mathrm{t}} \rangle = +0.149 \pm 0.020$ GeV

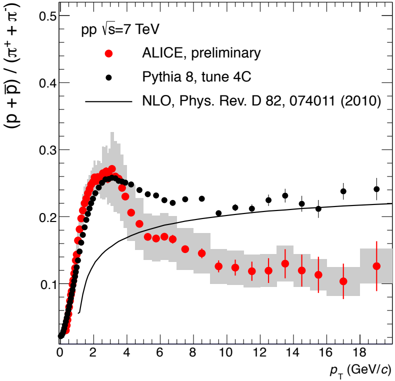


Reconnection and collective flow

Transverse boosts ⇒

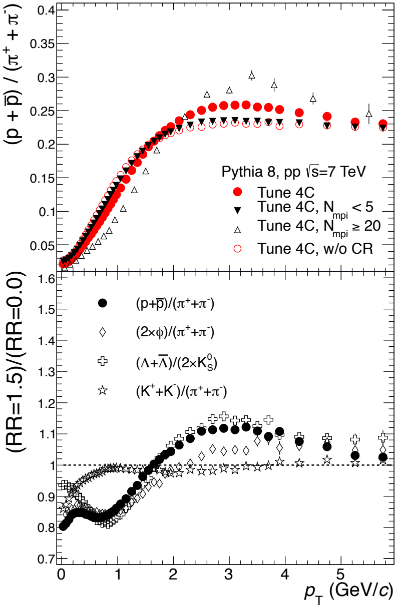
∼ collective particle vecocity.

More common with reconnection.



A. Ortiz Velasquez et al.,

Phys. Rev. Lett. 111 (2013) 042001



Summary and Outlook

- Reconnection well established, from $\mathrm{B} \to \mathrm{J}/\psi$ to $\langle p_{\perp} \rangle (n_{\mathrm{ch}})$.
- Missed chance for clean tests at LEP 2.
- Multitude of algorithms for 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 $\mathrm{e}^{+}\mathrm{e}^{-}$ collider?

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Addendum: new CMS PAS TOP-13-007, “Study of the underlying event, b-quark fragmentation and hadronization properties in $\mathrm{t\bar{t}}$ events” shows colour reconnection impact on underlying activity as function of $p_{\perp\mathrm{t\bar{t}}}$ and $\phi_{\mathrm{t\bar{t}}}$.

Let's aim for more than a flying circus . . .