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QCD Interconnection Effects

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Introduction

(V.A. Khoze & TS, PRL72 (1994) 28, ZPC62 (1994) 281,
PLB328 (1994) 466, EPJC6 (1999) 271;
L. Lönnblad & TS, PLB351 (1995) 293, EPJC2 (1998) 165)

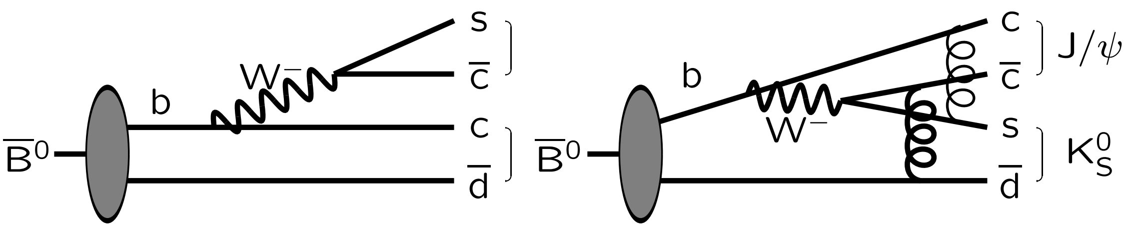
$\Gamma_{\mathrm{W}}, \Gamma_{\mathrm{Z}}, \Gamma_{\mathrm{t}} \approx 2$ GeV
$\Gamma_{\mathrm{h}} > 1.5$ GeV for $m_{\mathrm{h}} > 200$ GeV
$\Gamma_{\mathrm{SUSY}} \sim$ GeV (often)
Not too far from threshold:

$$\tau = \frac{1}{\Gamma} \approx \frac{0.2\,\mathrm{GeV\,fm}}{2\,\mathrm{GeV}} = 0.1\,\mathrm{fm} \ll r_{\mathrm{had}} \approx 1\,\mathrm{fm}$$

$\Rightarrow$ hadronic decay systems overlap,
between pairs of resonances (WW, ZZ, $\mathrm{t\bar{t}}$, ...)
$\Rightarrow$ cannot be considered separate systems!

Three main eras for interconnection:

1. Perturbative: suppressed for $\omega > \Gamma$ by propagators/timescales $\Rightarrow$ only soft gluons.
2. Nonperturbative, hadronization process: colour rearrangement.



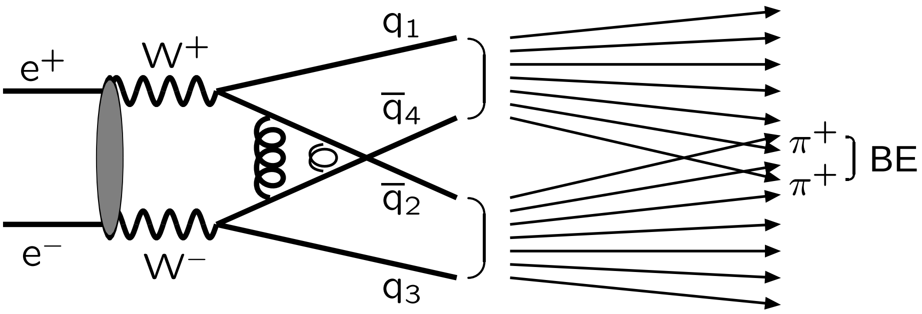
3. Nonperturbative, hadronic phase: e.g. Bose–Einstein.

Above topics among unsolved problems of strong interactions: confinement dynamics, $1/N_{\mathrm{C}}^2$ effects, QM interferences, ...:

- opportunity to study dynamics of unstable particles,
- new ways to probe confinement dynamics in space and time, *but*
- risk to limit/spoil precision mass measurements.

So far mainly studied for m_{W} at LEP2:

1. Perturbative: $\langle \delta m_{\mathrm{W}} \rangle \lesssim 5$ MeV.
2. Colour rearrangement: many models, conservatively $\langle \delta m_{\mathrm{W}} \rangle \lesssim 40$ MeV.

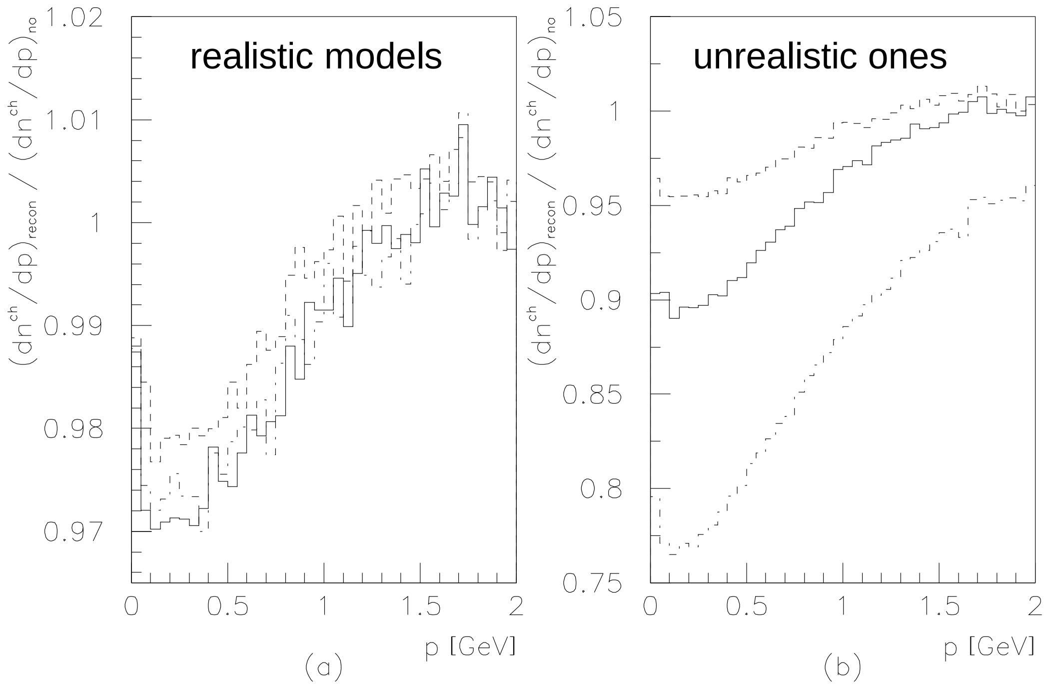


3. Bose-Einstein: symmetrization of unknown amplitude, wider spread among models, but again conservatively $\langle \delta m_{\mathrm{W}} \rangle \lesssim 40$ MeV.

In sum: $\langle \delta m_{\mathrm{W}} \rangle_{\mathrm{tot}} < m_{\pi}$, $\langle \delta m_{\mathrm{W}} \rangle_{\mathrm{tot}} / m_{\mathrm{W}} \lesssim 0.1\%$; a small number that becomes of interest only because we aim for high accuracy.

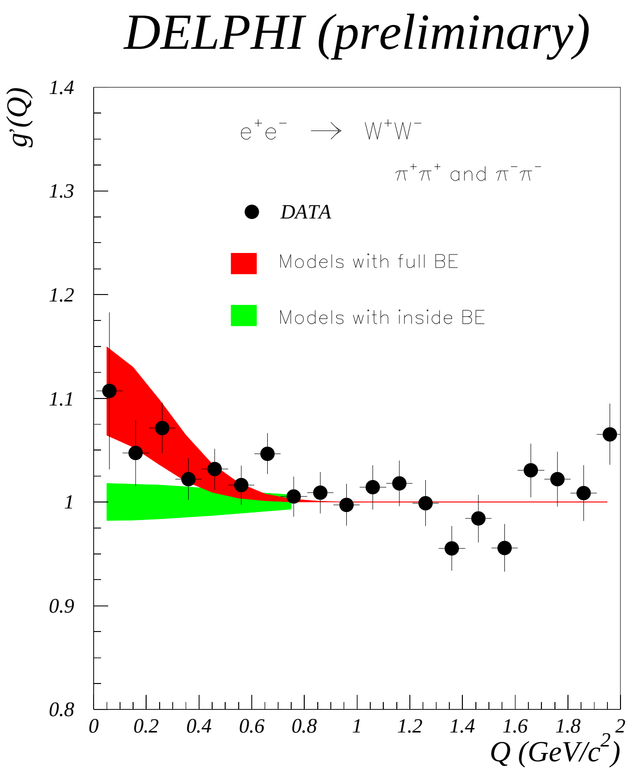
Connectometry

Threshold: low-momentum particles depleted



$\sim\ 4\sigma$ ($\sim\ 2\sigma$) signal/experiment if 500 pb^{-1} at 172 (195) GeV. (Hint in DELPHI data?)

BE:
first strong
indication
from DELPHI
(Moriond 99)
but not
agreement
between
LEP groups



LEP2-energy LC runs

(G. Wilson, talk in session P4:) 100 fb^{-1} $\mathrm{W}^+\mathrm{W}^-$ threshold scan (with polarization):
$\Delta m_{\mathrm{W}} \sim 7$ MeV
with negligible interconnection uncertainty.

So shift emphasis from m_{W} to understanding of physics of hadronic cross-talk!

High-statistics run, e.g. 50 fb^{-1} at $\sim$175 GeV (neglecting systematic errors):

- $\sim 40\sigma$ for low-momentum particle depletion.
- A few other (potential) interconnection signals: alignment along string directions, azimuthal anisotropies, ...
- Excellent possibilities for BE.
- $\Delta(\langle m_{\mathrm{W}}\rangle_{\mathrm{hadronic}} - \langle m_{\mathrm{W}}\rangle_{\mathrm{semileptonic}}) = \sqrt{2} \times 36\ \mathrm{MeV}/\sqrt{100} = 5\ \mathrm{MeV}$.

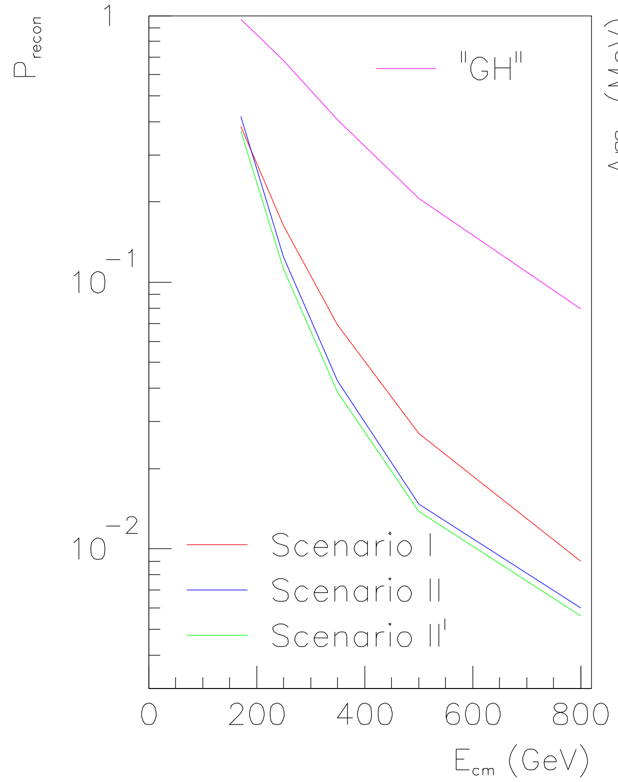
Above $\mathrm{Z}^0\mathrm{Z}^0$ threshold: single-Z^0 from LEP1 (or LC run at Z^0) provides a unique '$\mathrm{Z}^0\mathrm{Z}^0$ no-reconnection' reference.

High-luminosity LEP2-energy runs — if performed — excellent to *establish* signal.
To explore *character* of effects, energy dependence could give further leverage!

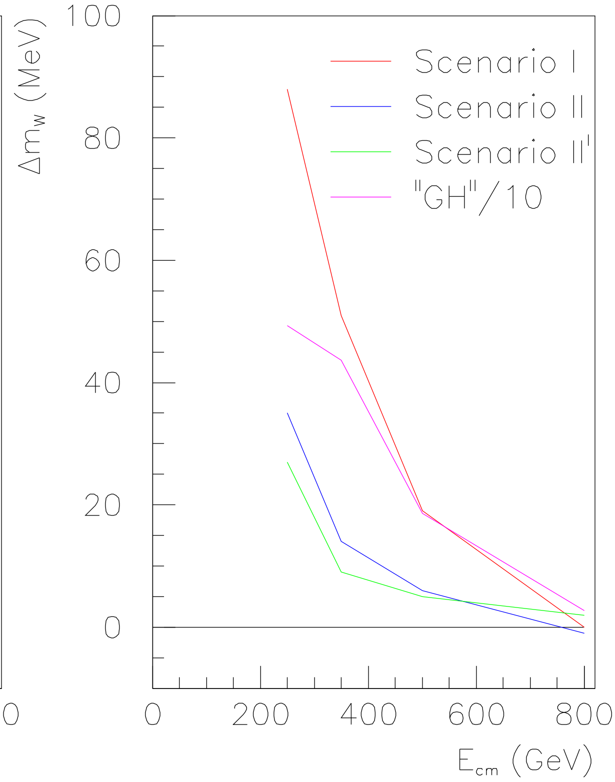
Colour rearrangement rates

QED interconnection dampens $\propto (1-\beta)^2$.
(A.P. Chapovsky & V.A. Khoze, hep-ph/9902343)

Nonperturbative models more like $(1-\beta)$:



Mass shift in peak region also dampens:



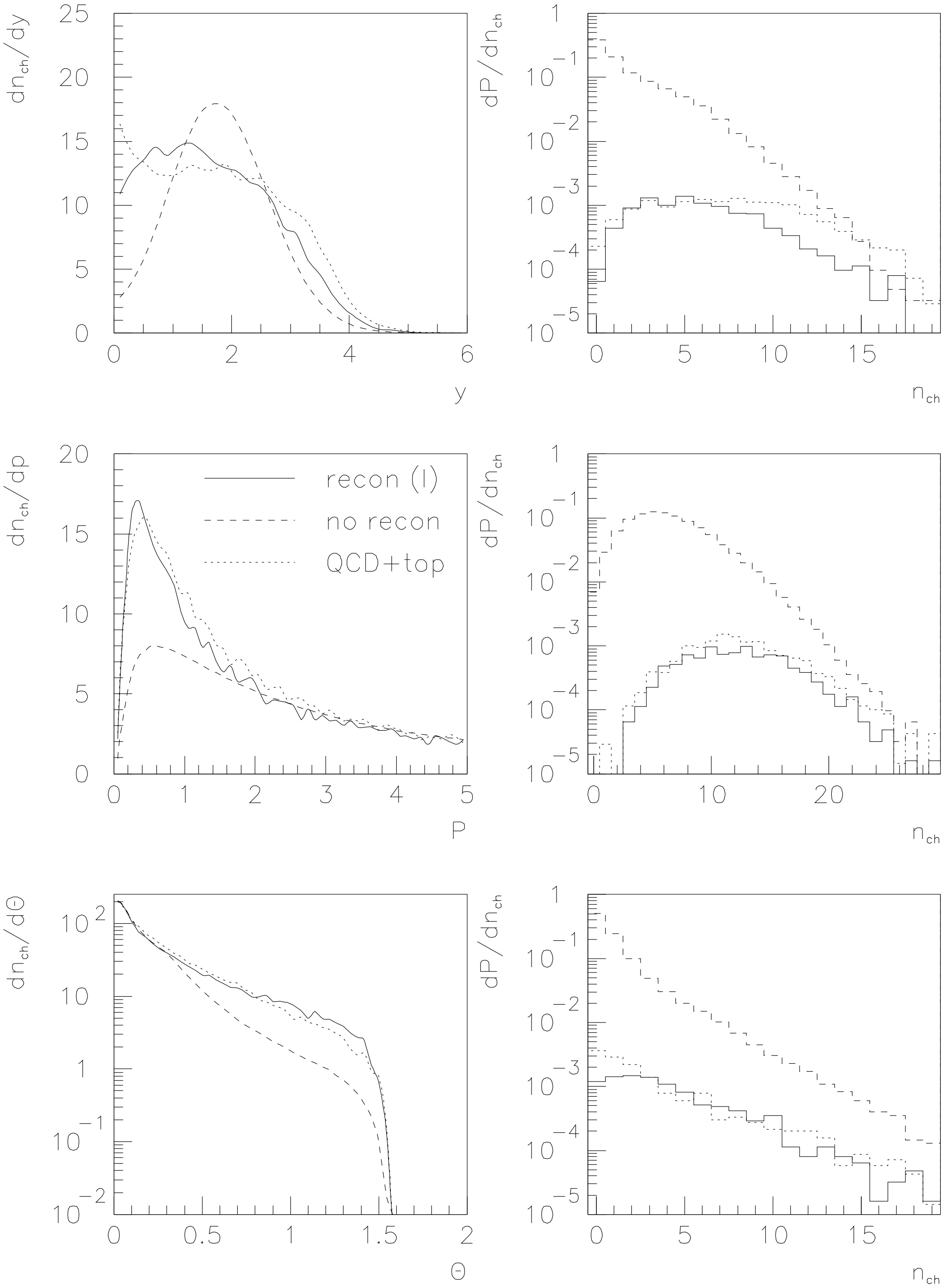
Search for 4 jets: $\theta_{\text{min}} = 0.5(E_{\text{cm}}/200\text{ GeV})$, $E_{\text{min}} = 20$ GeV.
Main criterion: minimize $|m_{\text{jj}}^{(1)} - 80\text{ GeV}| + |m_{\text{jj}}^{(2)} - 80\text{ GeV}|$.
Remove shifts above 4 GeV $\approx$ cut wings of mass distribution.
ISR effects not included here, but does not change picture.

But average and width of mass shifts of all events do not die out! (Not shown.)
Thus, with increasing energy:
hadronic cross-talk occurs in fewer events,
but the effect in these is more dramatic.

Reconnection signals

Inclusive enhancement at low p appears too small for reliable detection at high energies.

Turn to exclusive signals, e.g. at 500 GeV

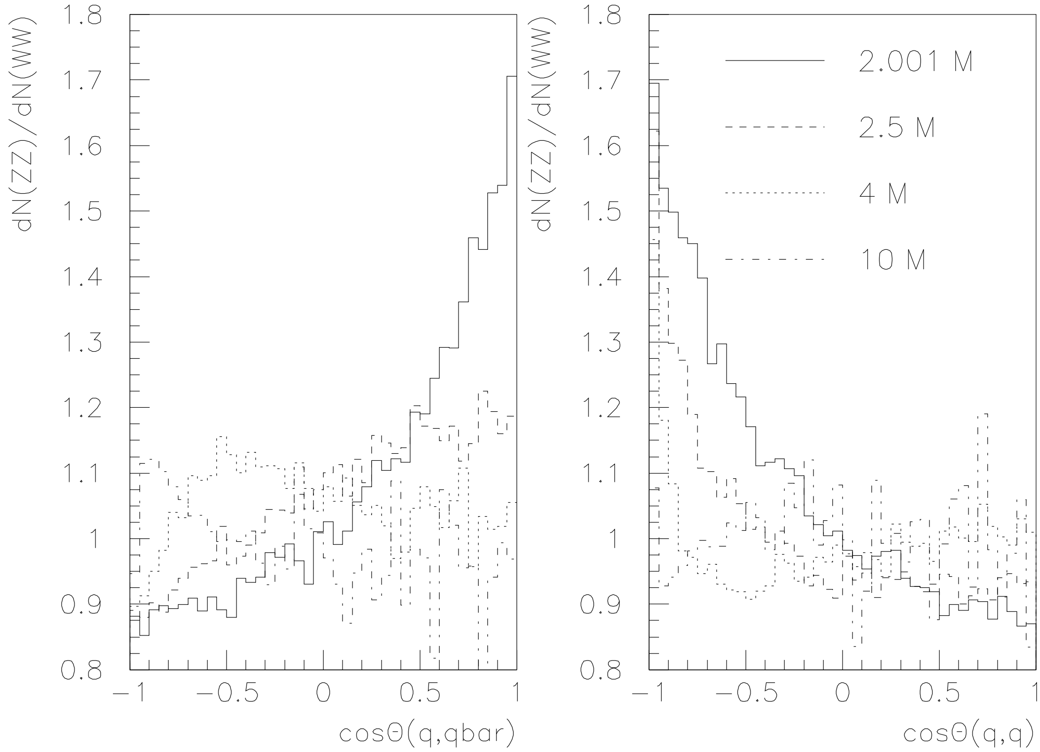


for scenario I, with some model dependence.

$Z^0 Z^0$ vs. $W^+ W^-$

Z^0 mass and properties known $\Rightarrow$ $Z^0 Z^0$ excellent hunting ground for interconnection.

Ratio of angular distributions:



Why are $Z^0 Z^0$ and $W^+ W^-$ different?

1. Feynman graphs, mix vector/axial.
2. Higher mass $\Rightarrow$ Z slower at fixed E_{cm}.
3. Larger width $\Rightarrow$ Z decay vertices closer.

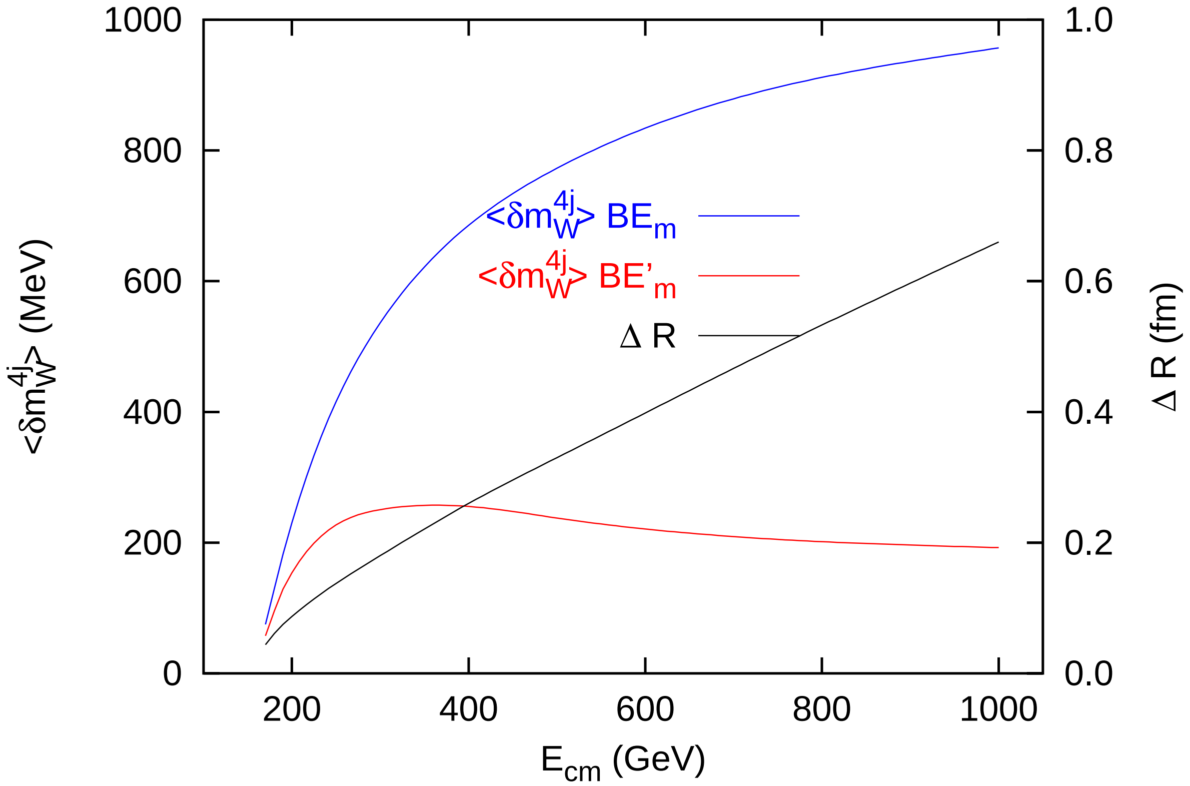
Thus more reconnections for $Z^0 Z^0$.
Scenario II at 500 GeV: P_{recon} is 3.2% for ZZ and 1.5% for WW. $\sigma_{\mathrm{ZZ}}/\sigma_{\mathrm{WW}} \approx 1/6$.
$Z^0 Z^0$ interesting in its own right,
but comparisons with $W^+ W^-$ nontrivial.

Bose–Einstein

BE ≈ symmetrization of *unknown* amplitude.
Many models have been proposed.

Our approach is based on a *local* reweighting among almost equivalent global configurations, by a shift of momenta within pairs. Several variants.

Theoretical mass shifts — no reconstruction:



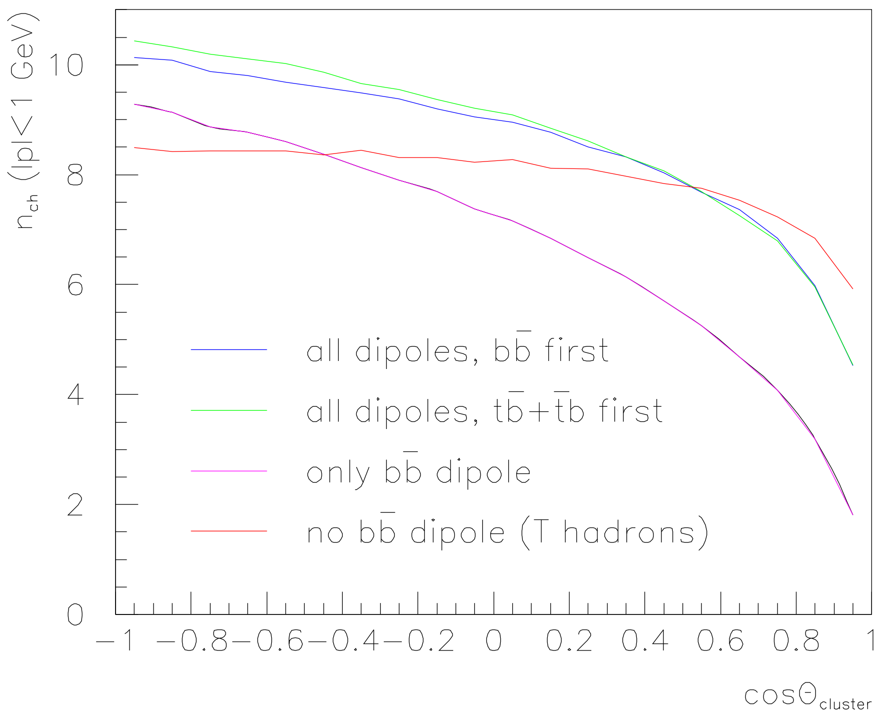
Conclusions of studies for LEP2:

- Significant spread of $\langle \delta m_{\mathrm{W}} \rangle$ between models — signal of BE ≠ known mass correction.
- Size of $\langle \delta m_{\mathrm{W}} \rangle$ markedly reduced by experimental procedure (even sign shift possible).

Top events

$t\bar{t}$ systems are colour connected: even
$e^+e^- \to t\bar{t} \to bW^+\bar{b}W^- \to b\bar{b}\ell^+\nu_\ell\ell'^-\bar{\nu}'_\ell$
contains nontrivial interconnection effects!

Hadronic multiplicity as function of $\theta_{b\bar{b}}$:



$m_t = 174$ GeV

$E_{cm} = 360$ GeV

$\Delta E = 12$ GeV

$= E_{cm} - 2m_t$

Curves: various scenarios for QCD radiation from $\widehat{tb}$, $\widehat{\bar{t}\bar{b}}$ and $\widehat{b\bar{b}}$ colour dipoles, realistically

$$\mathcal{I} \propto \frac{\omega^2}{\Gamma_t^2 + \omega^2}\left(\widehat{tb} + \widehat{\bar{t}\bar{b}}\right) + \frac{\Gamma_t^2}{\Gamma_t^2 + \omega^2}\widehat{b\bar{b}}$$

To unrealistic: $\langle\delta m_t\rangle = 100 - 500$ MeV.
Between realistic: $\langle\delta m_t\rangle \approx 30$ MeV.
Add W hadronic decays, $t\bar{t} \to b\bar{b}q_1\bar{q}_2q_3\bar{q}_4$:
$\langle\delta m_t\rangle \gtrsim 100$ MeV?

Summary

- LEP2 may clarify Bose–Einstein situation and provide some hadronic cross-talk hints.
- High-luminosity LEP2-energy LC run best way to establish colour rearrangement.
- Both colour rearrangement and BE effects (may) remain significant over the full LC energy range.
- The fraction of the (appreciably) affected events goes down with energy but the effect per such event comes up.
- It appears feasible to reduce WW/ZZ "interconnection noise" to harmless levels at high energies, by simple proper cuts.
- It should be possible (but not easy) to dig out a colour rearrangement signal also at high energies, with optimized cuts.
- $\mathrm{Z}^0\mathrm{Z}^0$ events should display about twice as large interconnection effects as $\mathrm{W}^+\mathrm{W}^-$.
- Single-Z^0 calibration makes $\mathrm{Z}^0\mathrm{Z}^0$ unique.
- Direct reconstruction of m_{t} uncertain by $\gtrsim 100$ MeV?
- Not yet a clean handle on how to distinguish models (for reconnections or BE).

The work continues . . .

. . . and so does the excitement!