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WW Interconnection Effects Well Above Threshold

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Introduction

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

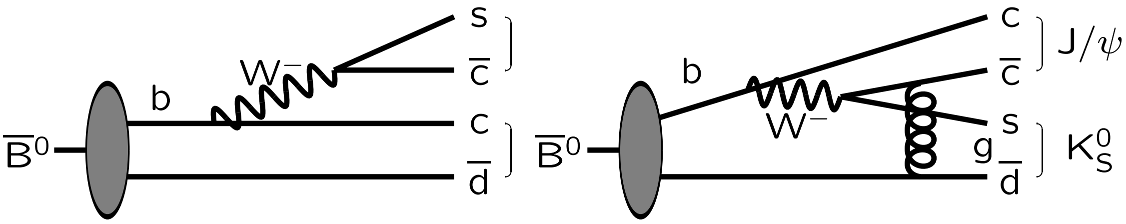
$\Gamma_{\mathrm{W}}, \Gamma_{\mathrm{Z}}, \Gamma_{\mathrm{t}} \approx 2$ GeV
$\Gamma_{\mathrm{h}} > 1.5$ GeV for $m_{\mathrm{h}} > 200$ GeV
$\Gamma_{\mathrm{SUSY}} \sim$ GeV (often)

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

$\Rightarrow$ hadronic decay systems overlap,
between pairs of resonances
$\Rightarrow$ 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.



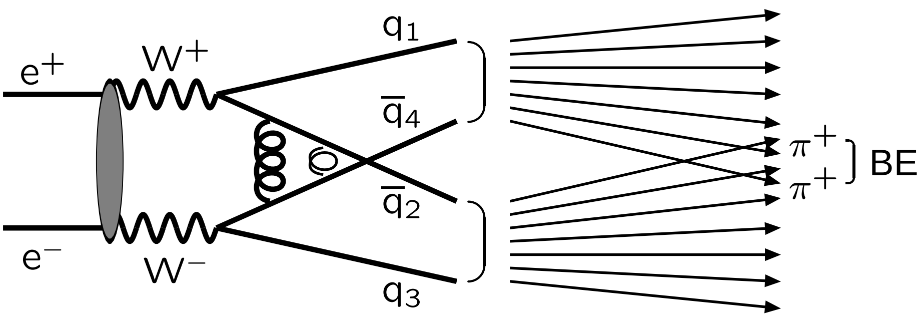
3. Nonperturbative, hadronic phase: Bose–Einstein.

Above topics among unsolved problems of strong interactions: confinement dynamics, $1/N_C^2$ effects, QM interferences, . . . :

- opportunity to study dynamics of unstable particles,
- opportunity to study QCD in new ways, *but*
- risk to limit/spoil precision mass measurements.

So far mainly studied for m_W at LEP2:

1. Perturbative: $\langle \delta m_W \rangle \lesssim 5$ MeV.
2. Colour rearrangement: many models, in general $\langle \delta m_W \rangle \lesssim 40$ MeV.

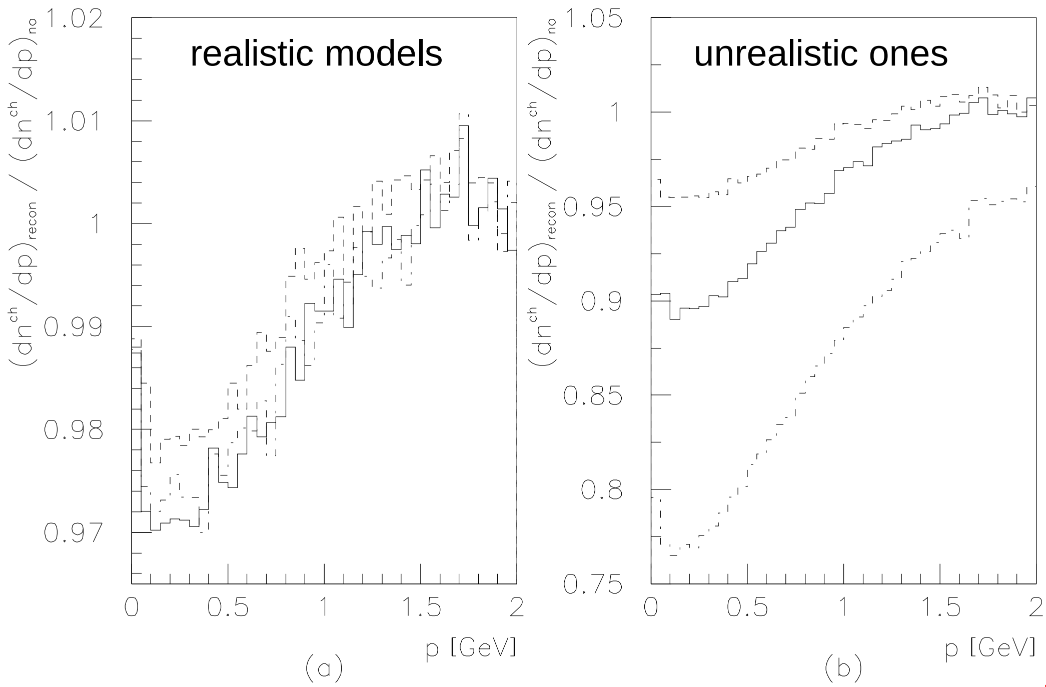


3. Bose-Einstein: symmetrization of unknown amplitude, wider spread 0–100 MeV among models, but realistically $\langle \delta m_W \rangle \lesssim 40$ MeV.

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

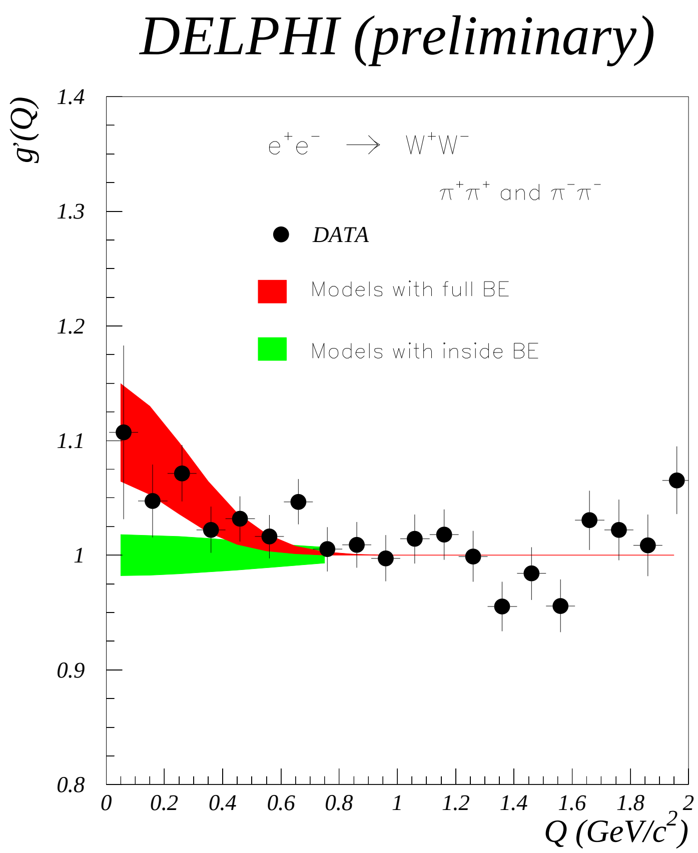
Connectometry – diagnosing interconnections:

Threshold: low-momentum particles depleted



$\sim 4\sigma$ ($\sim 2\sigma$) signal/experiment if 500 pb^{-1} at 172 (195) GeV. LEP1 Z^0 gives 'Z^0Z^0 no-reconnection' reference. (A) few alternatives.

BE:
first strong indication from DELPHI (Moriond 99)



Colour rearrangement models

Here we compare

- Scenario I: string $\approx$ elongated bag; reconnection probability $\propto$ space–time volume overlap of strings.
- Scenario II: string $\approx$ thin vortex line; reconnection occurs when cores of strings cross each other.
- Scenario II$'$: as above, but reconnection at a crossing only occurs when the total string length is reduced.
- “GH” (freely based on G. Gustafson & J. Häkkinen): do the reconnection that reduces the total string length most.
- intermediate: reconnect after showers at middle of each string.
- instantaneous: reconnect before showers at middle of each string (unrealistic!).

Only at most one colour reconnection.

Other models/programs not considered here:

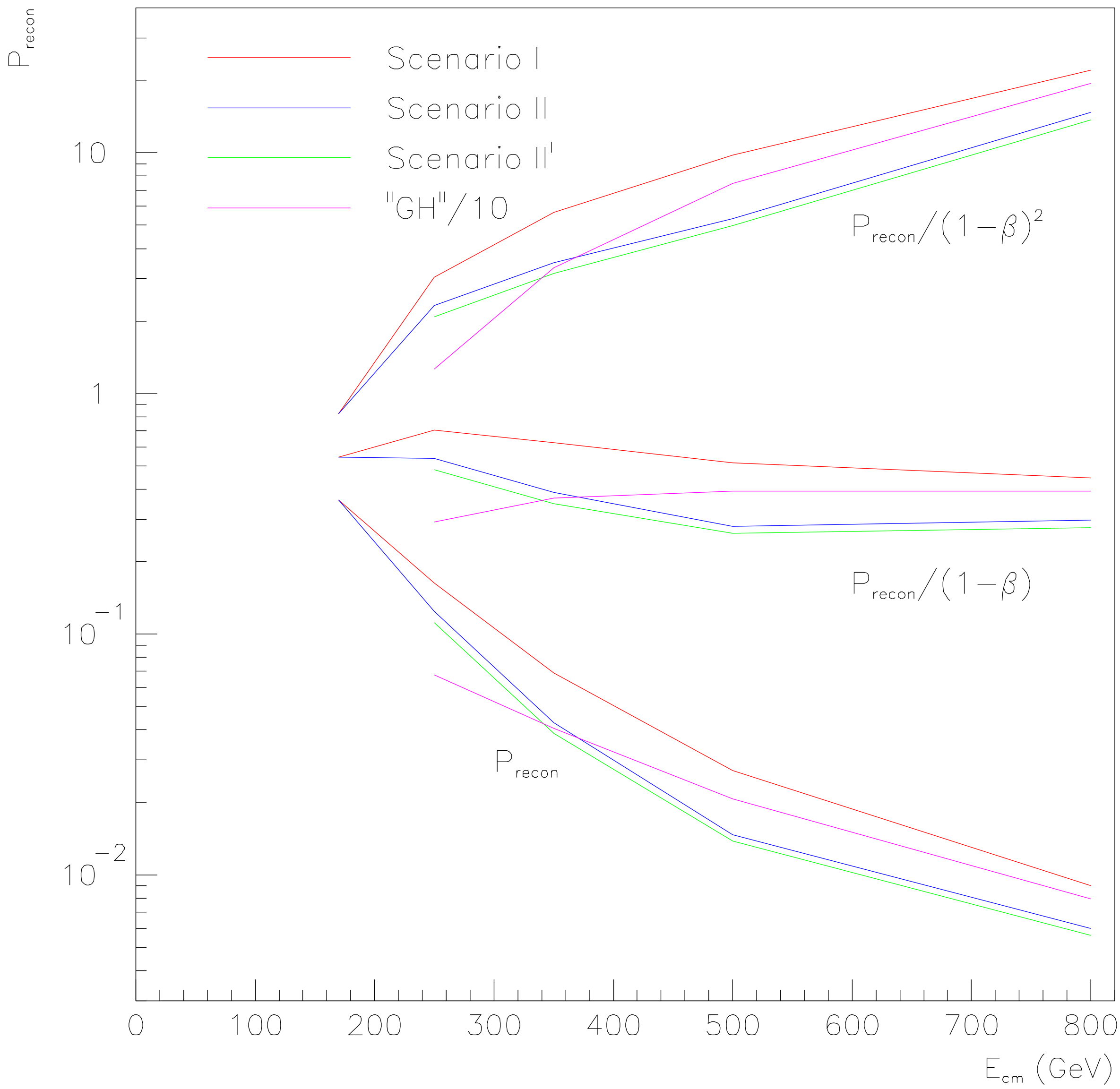
- L. Lönnblad (Ariadne)
- Š. Todorova–Nová
- B.R. Webber (Herwig)
- J. Ellis, K. Kinder-Geiger

Reconnection probabilities

(A.P. Chapovsky & V.A. Khoze, hep-ph/9902343:)

QED interconnection dampens roughly like $(1-\beta)^2$!

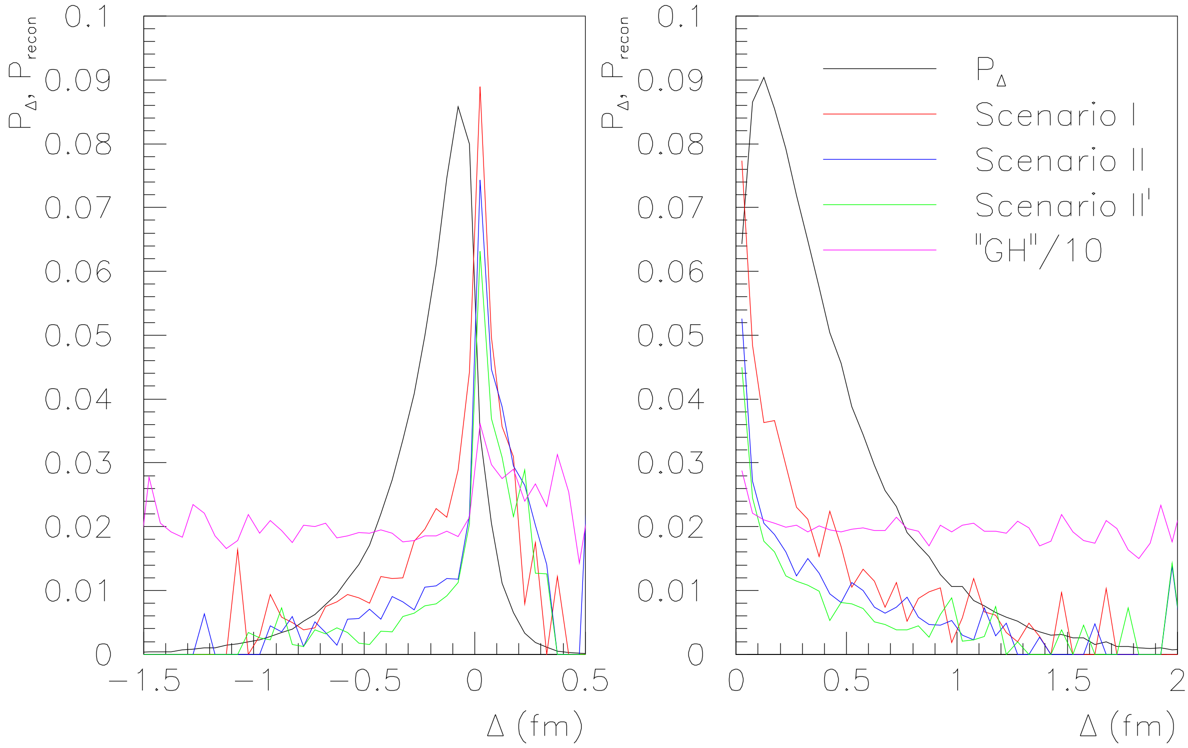
Nonperturbative models more like $(1-\beta)$:



Significant rôle played by ‘early’ W decays:

$\Delta = \text{sign}(\sqrt{|\Delta\tau^2|}, \Delta\tau^2), \qquad \Delta = \sqrt{\Delta t^2 + \Delta x^2}$

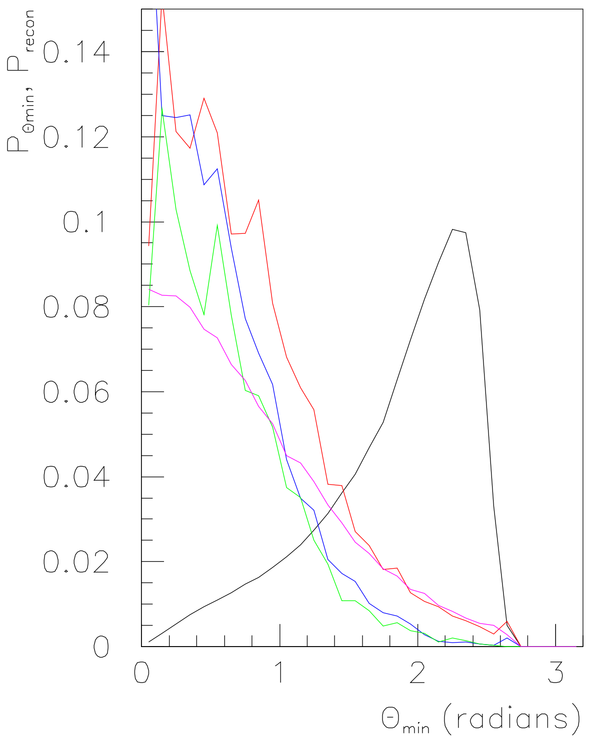
$\Delta\tau^2 = \Delta t^2 - \Delta x^2$



Also topology dependence:

$\theta_{\text{min}} = \min(\theta_{13}, \theta_{14}, \theta_{23}, \theta_{24})$

in $e^+e^- \to W^+W^- \to q_1\overline{q}_2q_3\overline{q}_4$

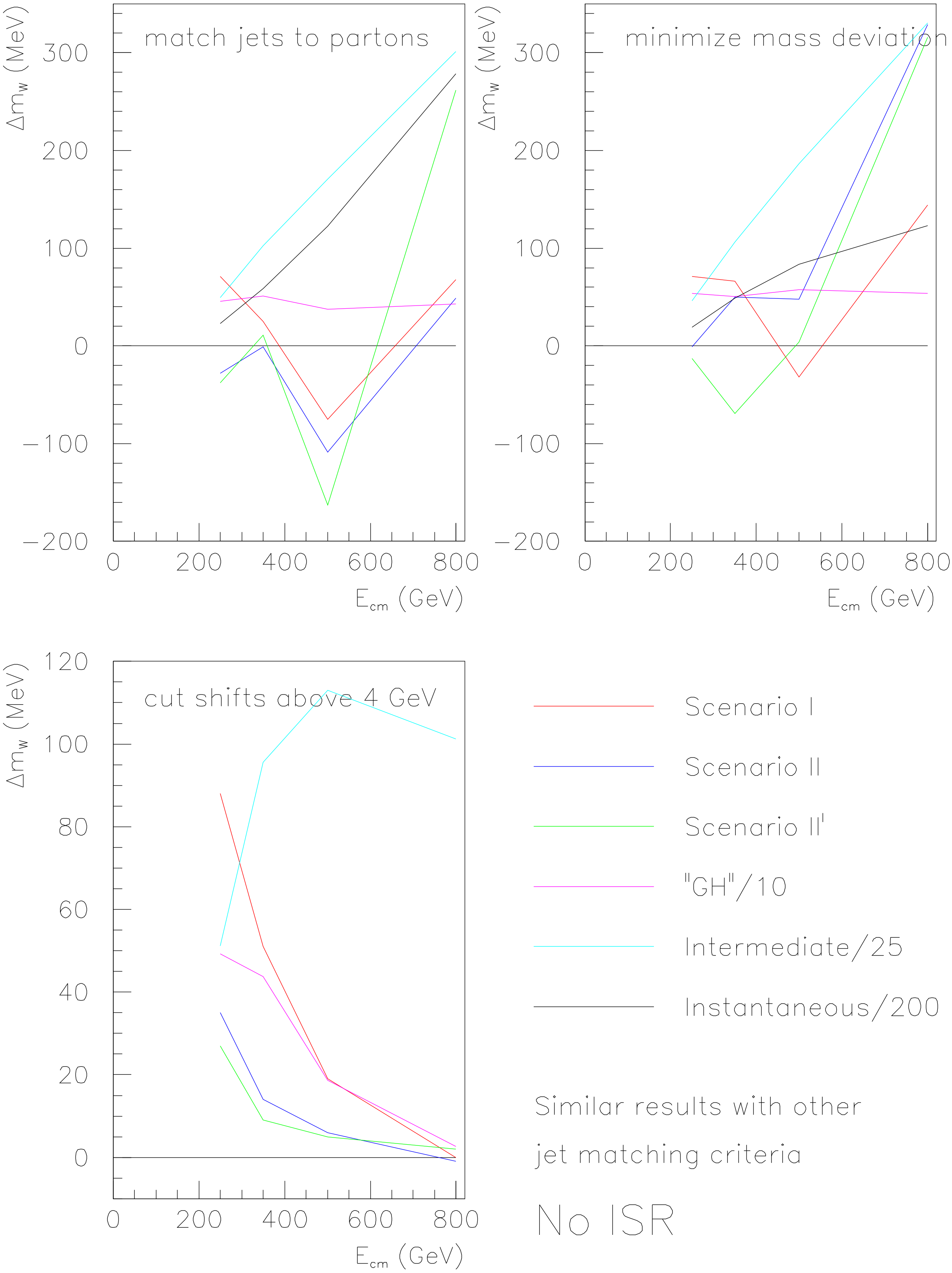


500 GeV, no ISR

Mass shifts

Search for 4 jets: $\theta_{\text{min}} = 0.5(E_{\text{cm}}/200\ \text{GeV})$, $E_{\text{min}} = 20$ GeV.

Main criterion: minimize $|m_{\text{jj}}^{(1)} - 80\ \text{GeV}| + |m_{\text{jj}}^{(2)} - 80\ \text{GeV}|$.

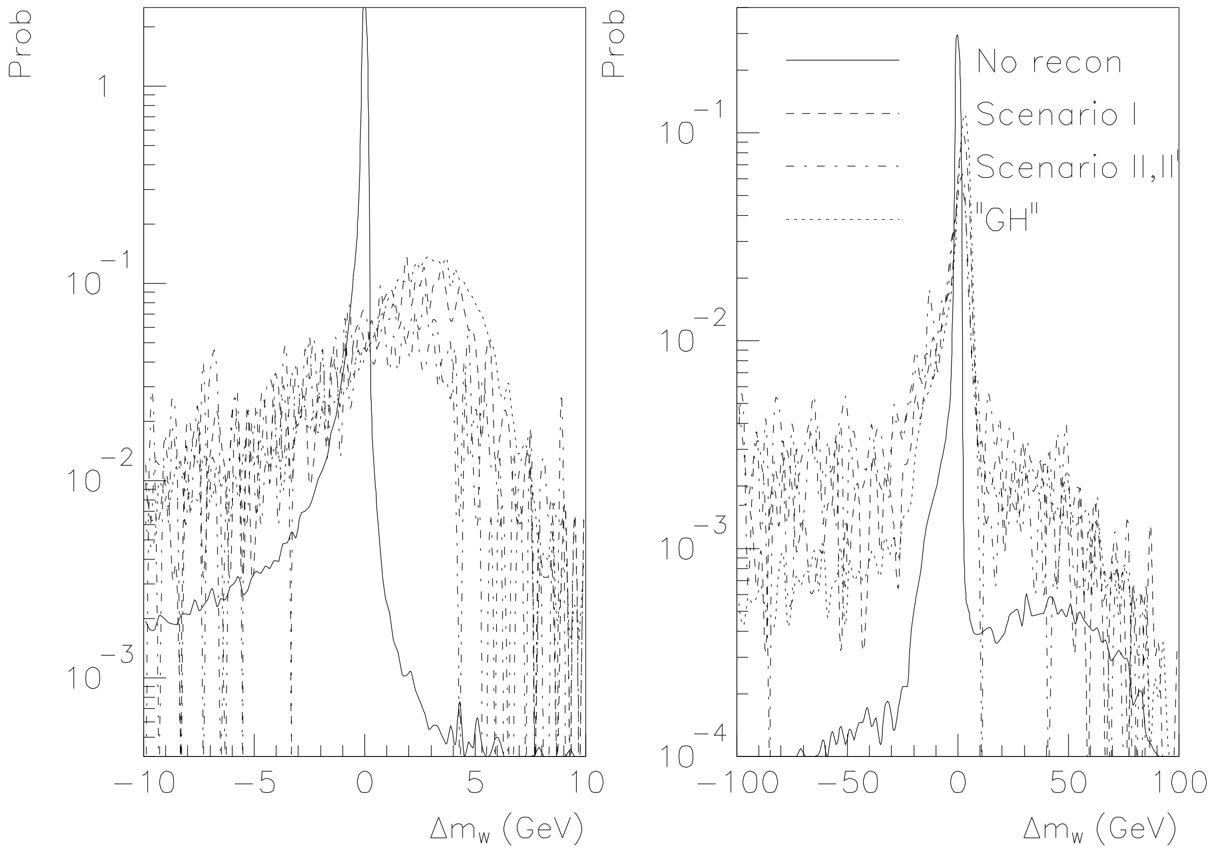


Similar results with other jet matching criteria

No ISR

Note big spread in mass shifts (at 500 GeV):

$$\Delta m_{\mathrm{W}} = \frac{m_{\mathrm{jj}}^{(1)} + m_{\mathrm{jj}}^{(2)}}{2} - \frac{m_{\mathrm{W}+} + m_{\mathrm{W}-}}{2}$$



Upwards: natural reconnection mass shift!

Downwards by "trigger bias": events with overlapping jets more likely to give reconnections *and* big mistakes in mass reconstruction.

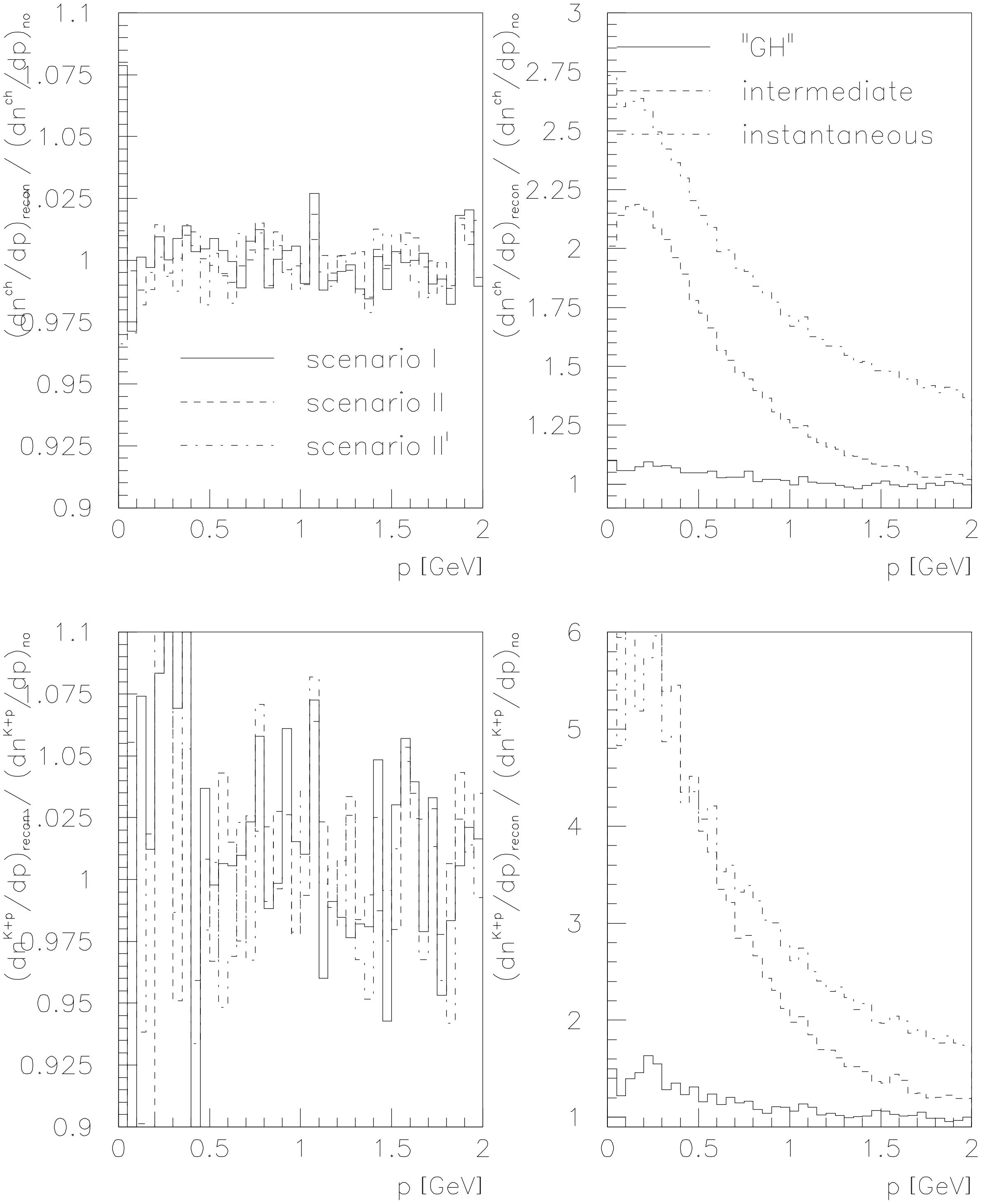
Crude (non-Gaussian tails!) run error estimate:

$$\sigma(m_{\mathrm{W}}) \approx \frac{\sigma(\Delta m_{\mathrm{W}})}{\sqrt{n_{\mathrm{ev}}}} \approx \frac{13 \text{ GeV}}{\sqrt{100000}} \approx 40 \text{ MeV}$$

Multiply by $\sqrt{2}$ for difference scenarios.

Inclusive signals

Now expect *enhancement* at low p:



Looks tough!

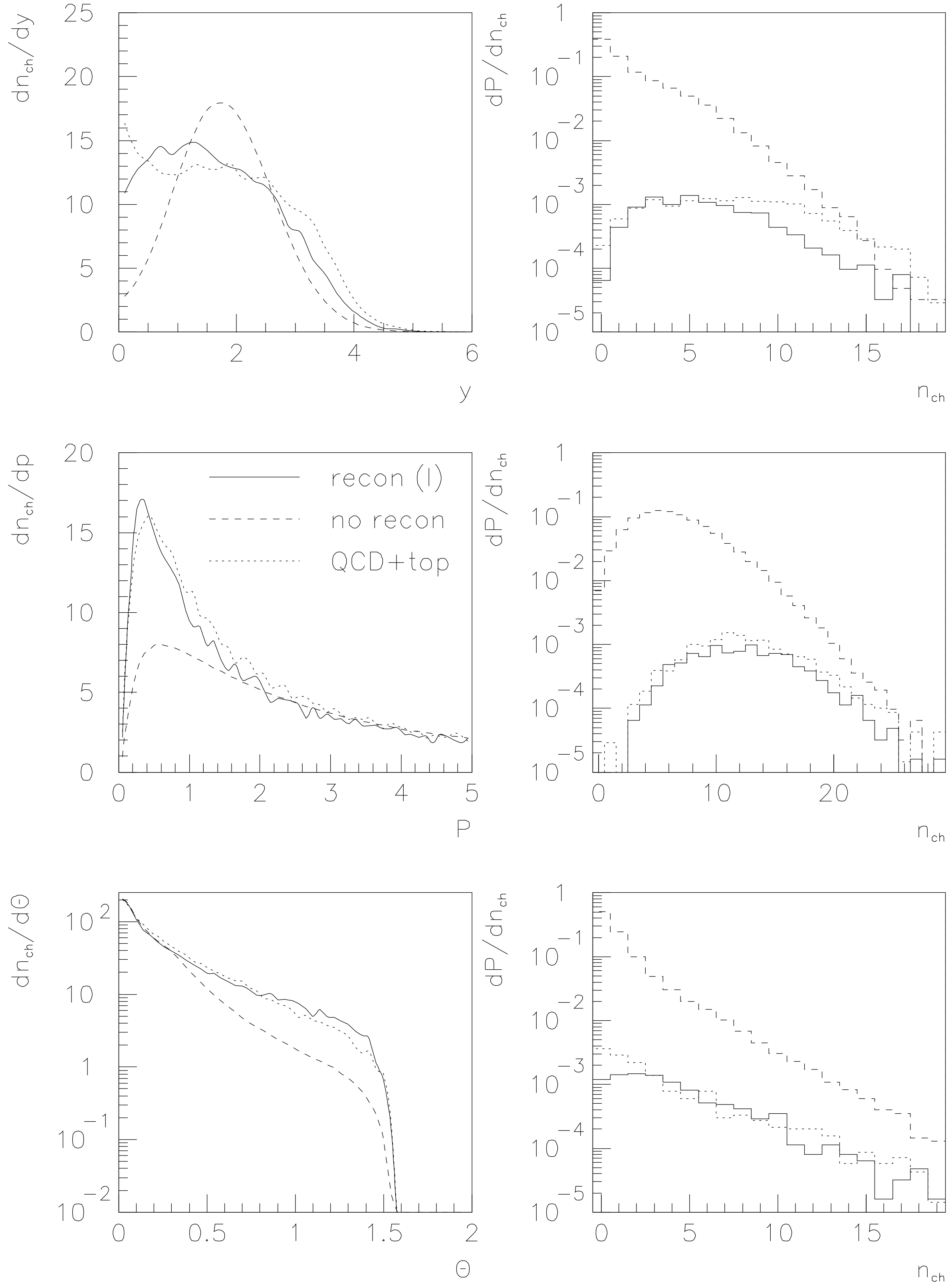
Exclusive signals

Reconnection $\Rightarrow$ more particles in the central region (i.e. regions between the two W's).

Procedure (at 500 GeV):

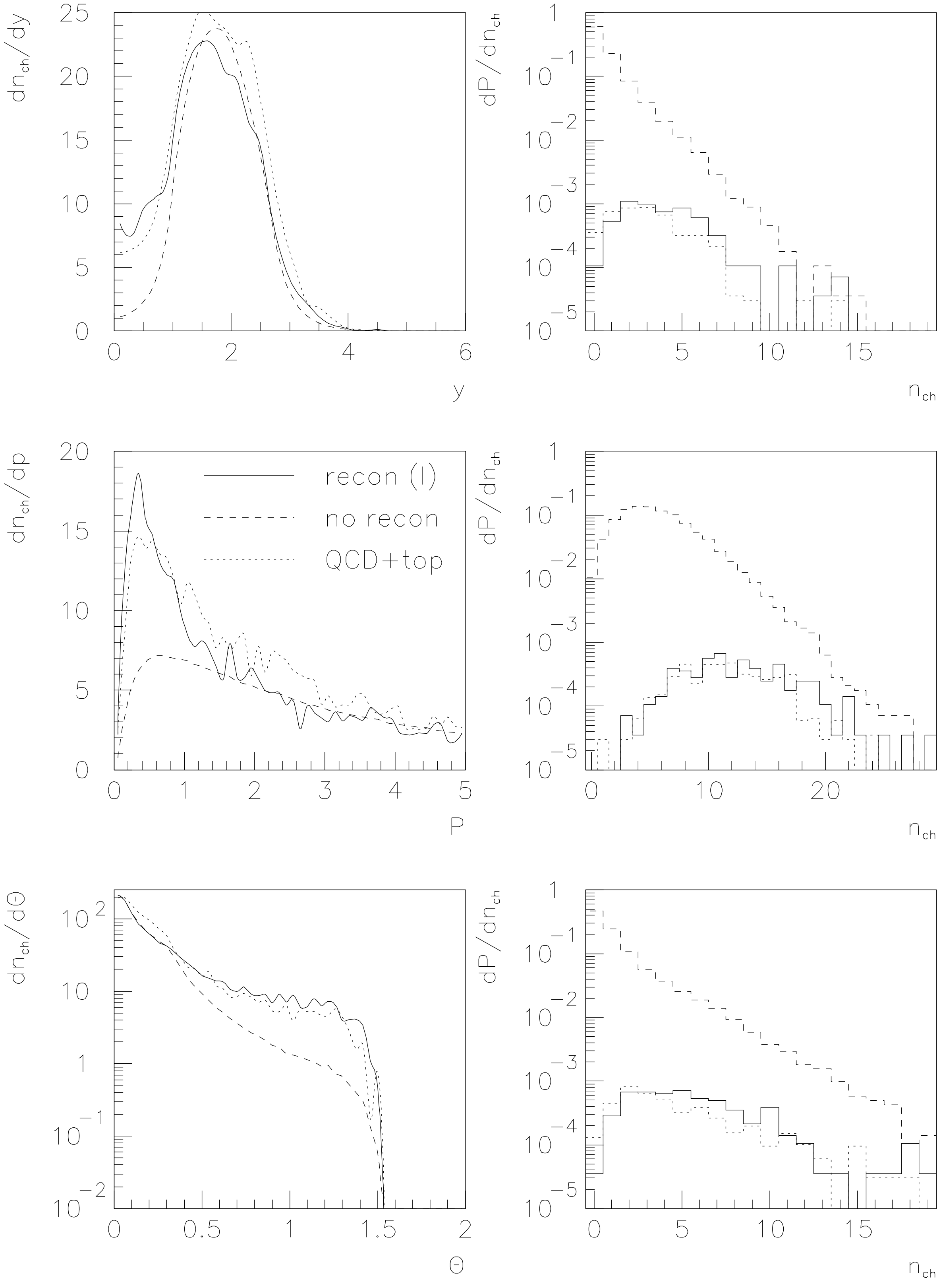
1. Orient event along linearized sphericity axis.
2. Reconstruct $\geq$ 4 jets with PYCLUS, $d_{\text{join}} = 12.5$ GeV, and reject events with ≥ 5 jets.
3. Reconstruct the invariant mass in each hemisphere and require both to be in the range $70 \text{ GeV} < m_{\text{hem}} < 90 \text{ GeV}$.
   (Retains $\sim$63% of WW,
   $\sim$1.0% of QCD+top background)
4. Calculate the total charged multiplicity n_{ch} in
   (a) the region $|y| < 0.5$ (Gustafson et al.);
   (b) the region $|p| < 1$ GeV; and
   (c) everywhere, excluding cones around each of the four jets, with cone opening angle defined to the other jet in the same hemisphere.
5. Repeat (4) for events where all $|y_{\text{jet}}| > 1$.
   (Retains $\sim$28% of WW,
   $\sim$0.14% of QCD+top background)

Scenario I results, point (4):



. . . and slightly worse for scenarios II and II′;
better for "GH", intermediate, instantaneous.

Scenario I results, point (5):

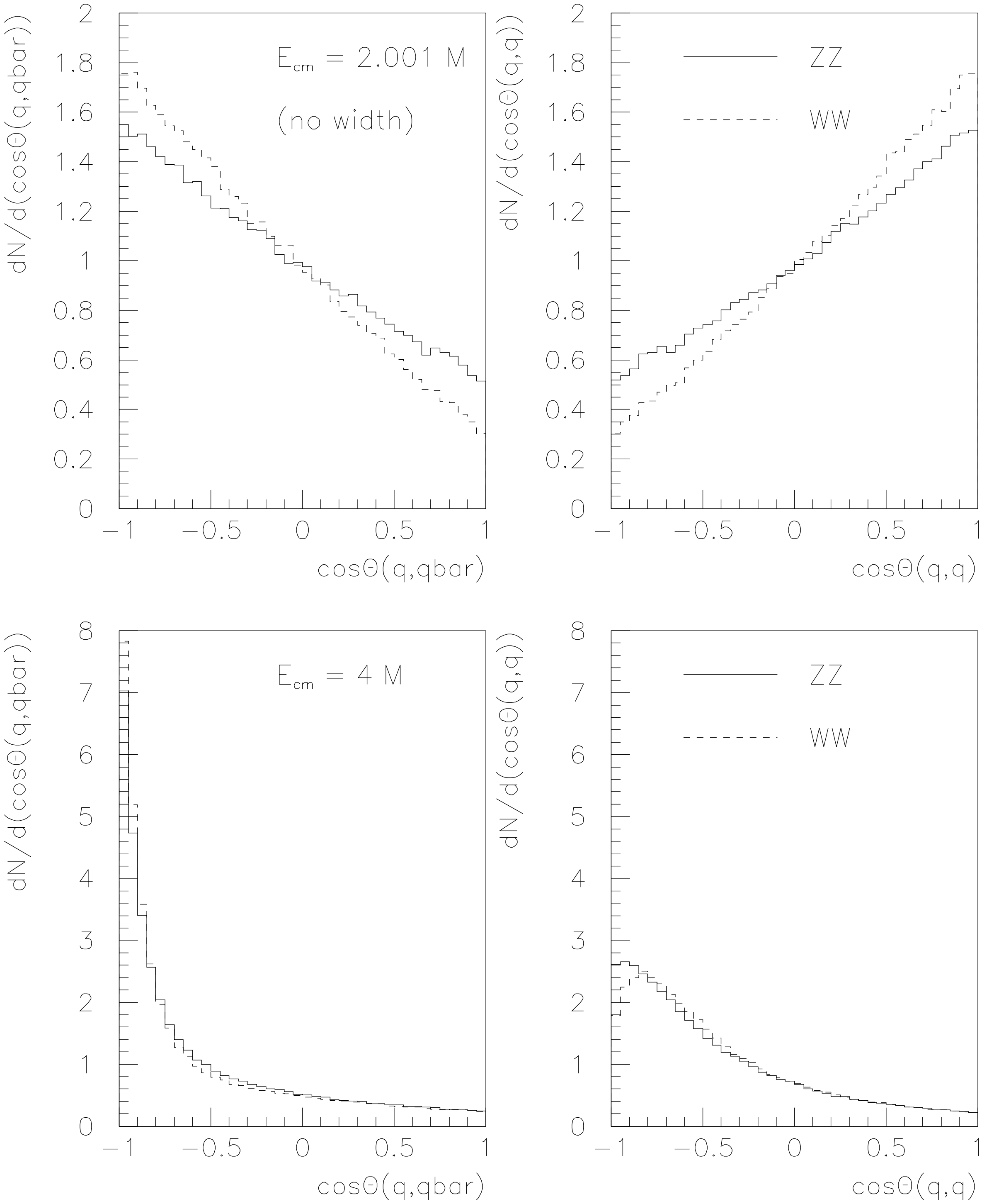


does clear up background for m_{W};
but no success for reconnection hunting.

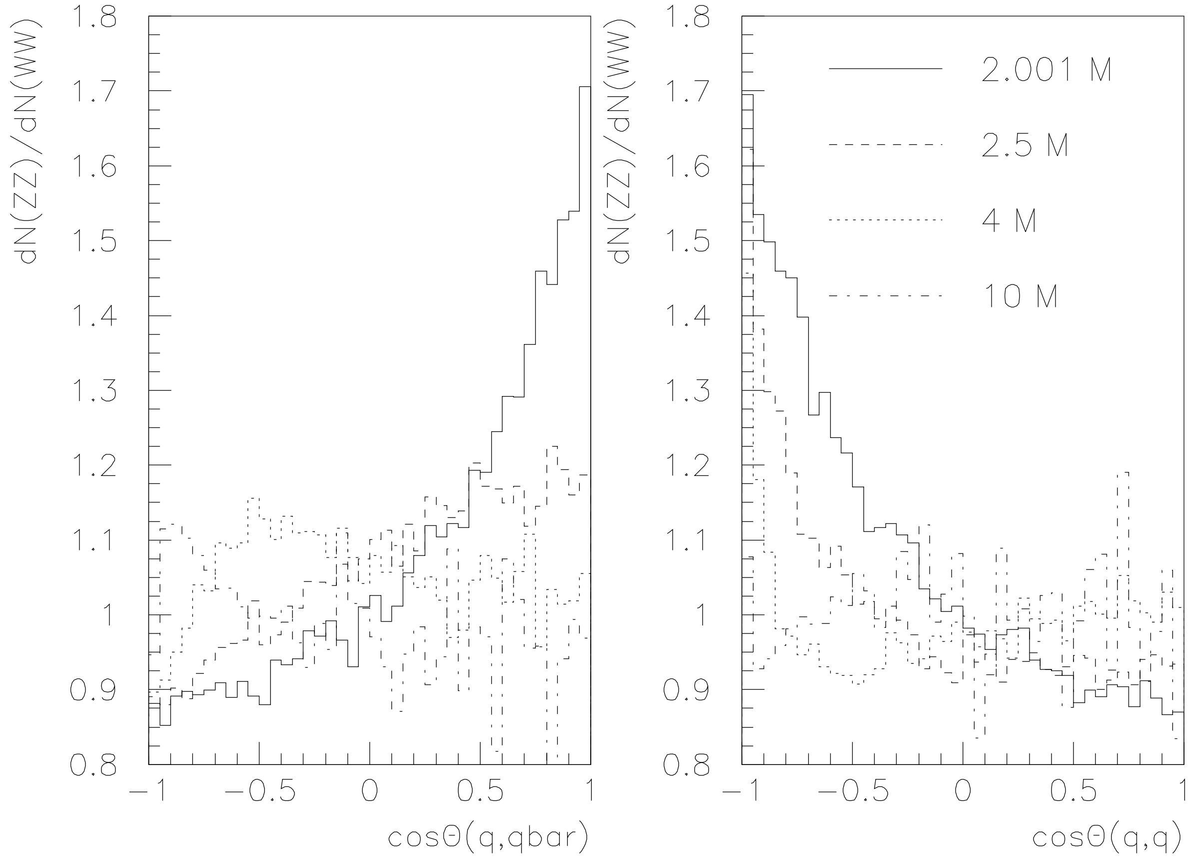
Z^0Z^0 vs. W^+W^-

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

Compare Z^0Z^0/W^+W^- angular distribution between $q/\overline{q}$'s from *different* bosons:



Ratio normally close to unity:



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

1. Feynman graphs not all same:
   $e^+e^- \to \gamma^*/Z^* \to W^+W^-$ absent for Z^0Z^0.
2. Another mix vector/axial couplings.
3. Higher mass $\Rightarrow$ Z slower at fixed E_{cm}.
4. Larger width $\Rightarrow$ Z decay vertices closer.

Thus in general:

- More reconnections for Z^0Z^0.
  Scenario II at 500 GeV: P_{recon} is 3.2% for ZZ and 1.5% for WW. $\sigma_{ZZ}/\sigma_{WW} \approx 1/6$.
- Z^0Z^0 moderately good calibration for M_W.

Bose–Einstein models

BE $\approx$ symmetrization of *unknown* amplitude.

Many models. Our approach:

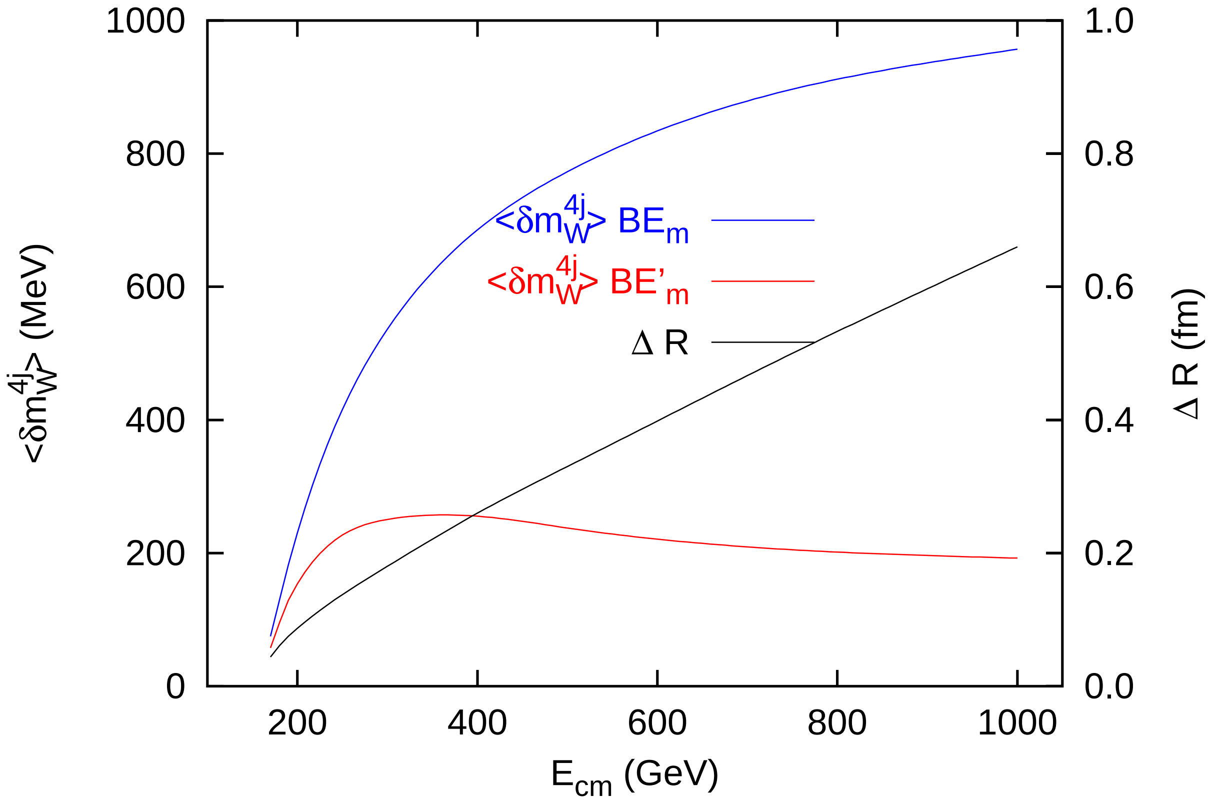
- reject interpretation as *global* weight;
- replace *local* reweighting among almost equivalent global configurations by a shift of momenta within pairs;
- perform shift so as to reproduce given input shape, e.g. $f_2(Q) = 1 + \lambda \exp(-Q^2R^2)$, in limit of starting from a sparse population isotropic in phase space.

Problem: how conserve both energy and momentum?

- BE_0: original global rescaling, requiring inconvenient subtraction.
- BE_3: shift nearby pairs closer and further-away (identical) ones apart, $f_2(Q) =$ $(1+\lambda \exp(-Q^2R^2))(1+\alpha\lambda \exp(-Q^2R^2/9))$, with $\alpha \approx -0.2$ determined event-by-event by energy conservation.
- BE_{32} modified form of above with $f_2(0) = 1 + \lambda$.

- BE_m: shift apart a nearby (in mass) pair of non-identical particles for each identical pair pulled closer.
- BE'_m: $R \to R + \Delta R$ for pairs from different W's, $\Delta R = |x_{\mathrm{W}+} - x_{\mathrm{W}-}|$.

Theoretical mass shifts — no reconstruction:



Conclusions of (previous) studies:

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

Further studies clearly warranted!

Summary

- LEP2 may clarify Bose–Einstein situation.
- Both colour rearrangement and BE effects (may) remain significant over the full LC energy range.
- The fraction of (significantly) affected events goes down with energy but the effect per event comes up.
- It appears feasible to reduce interconnection “background”, by suitable cuts, to harmless levels for m_{W} determinations.
- The possibility to dig out a colour rearrangement signal not yet established, but should be doable with the right cuts.
- $\mathrm{Z}^0\mathrm{Z}^0$ events should display larger effects than $\mathrm{W}^+\mathrm{W}^-$ ones, by about a factor of two.
- How do we distinguish models (for reconnections and for BE)?

The work continues . . .

. . . and so does the excitement!