Colour Flux Studies in Quark and Gluon Fragmentation in the DELPHI Experiment

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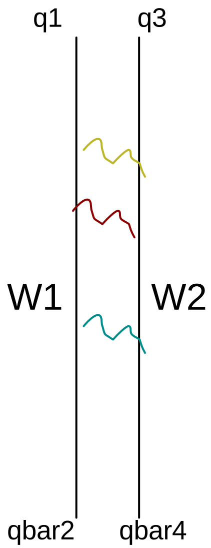
1. Investigation of Colour Reconnection in WW Events with the DELPHI detector at LEP-2 (Eur. Phys. J. C51 (2007) 249)
2. Bose-Einstein Correlations in WW Events at LEP-2
(Eur. Phys. J. C44 (2005) 161)
3. **Study of Leading Hadrons in Gluon and Quark Fragmentation**
(Phys. Lett. B643 (2006) 147)

1. Colour reconnection (CR) in WW events



$e^+e^- \rightarrow W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$, 189 - 209 GeV, 550 pb^{-1}

Interconnection effects between the fragmentation products of the two W-Bosons expected, lifetime ($\tau_W \approx 0.1$ fm/c) is much smaller than typical hadronisation times.

Colour Reconnection: exchange of coloured gluons between partons which originate from the different colour strings; Original singlets q1-qbar2, q3-qbar4 may be transmuted into new singlets.

On pertubative level effect is expected to be small,

But it may be large at hadronisation level (many soft gluons sharing space-time).

Two methods to evaluate the recombination probability per event:

1.The Particle Flow Method

A+C: Inside-W-region **(intra W)**,
B+D: Between-W-region **(inter W)**
Expected: CR decreases particle production Inside-W and increases them Between-W region

Required: only 4 jet events -> **1343 selected Events)**

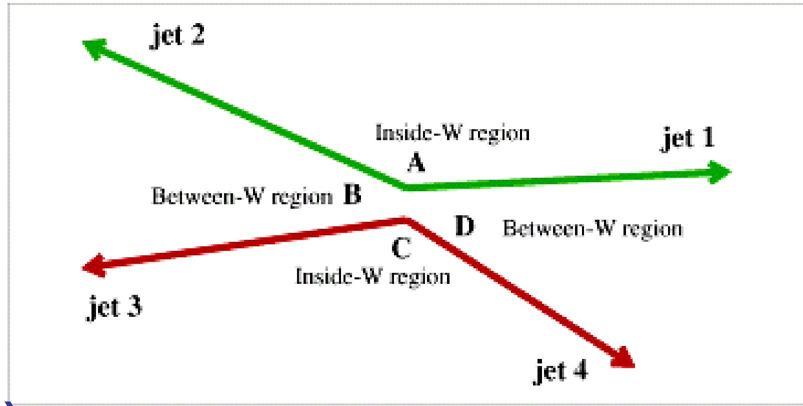


Figure 3: Schematic drawing of the angular selection.

$$R_N = \frac{\frac{1}{N_{\rm event}} \int_{0.2}^{0.8} \frac{{\rm d}n}{{\rm d}\phi_r} ({\rm intra-W}) {\rm d}\phi_r}{\frac{1}{N_{\rm event}} \int_{0.2}^{0.8} \frac{{\rm d}n}{{\rm d}\phi_r} ({\rm inter-W}) {\rm d}\phi_r} .$$

Monte Carlo Model mainly used in this study: $P_{reco}(\kappa) = 1 - e^{-\kappa V_{overlap}}$

"SK-1" (Sjoestrand-Khoze model 1) implemented at fragmentation with PYTHIA.

T. Sjoestrand and V.A, Khoze, Z.Phys. C62, (1994) 281.

Semi-leptonic events $WW \rightarrow q\bar{q}\, l\bar{\nu}$ used to built R_{mix} to check the Monte Carlo

Comparison with a combination of all LEP2-measurements:

(A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model", CERN-PH/2004-069, arXiv:hep-ex/0412015 v2 11 Jan 2005)

Results DELPHI, ($\sqrt{s}$=183-209 GeV)

$\langle R_{data} \rangle$ = 0.979 ± 0.032(stat) ± 0.035(syst)

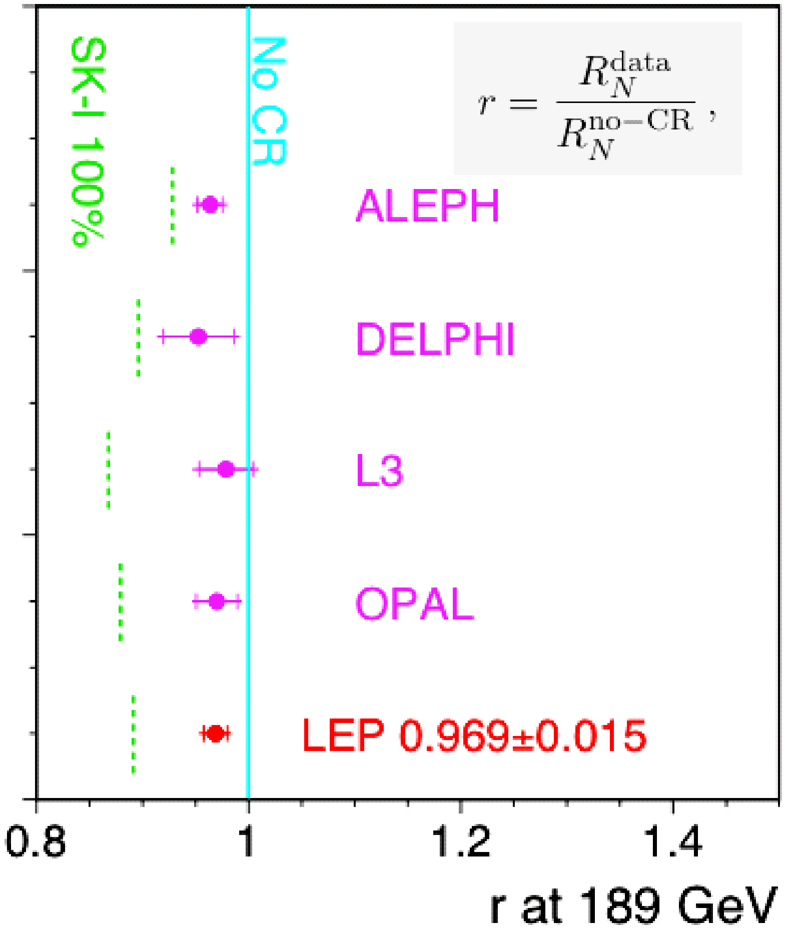
$$r^{\mathrm{data}}_{\mathrm{no\,CR}} = \frac{\langle R \rangle_{\mathrm{data}}}{R_{\mathrm{no\,CR}}} = 0.944 \pm 0.031(\mathrm{stat}) \pm 0.034(\mathrm{syst})$$

$$\delta r = \frac{\langle R_{\mathrm{data}} \rangle - R_{\mathrm{no\,CR}}}{R_{\mathrm{CR}} - R_{\mathrm{no\,CR}}} = 0.49 \pm 0.27(\mathrm{stat}) \pm 0.29(\mathrm{syst}),$$

Final combined result with MW Estimator Analysis:

$$\kappa_{\mathrm{SK-I}} = 2.2^{+2.5}_{-1.3}$$

$0.31 < P_{reco} < 0.68$, at 68% confidence level, best value at 0.52



2. Bose-Einstein (BE) Correlatrons in W^+W^- events at LEP-2

•If interconnection effects (CR) show up already at parton level, there is no reason, why particles should separate again at hadron level.

• W- lifetime ($\tau_W \approx 0.1$ fm/c) is much smaller than the typical hadronisation time $\rightarrow$ correlations, in particular Bose-Einstein correlations between hadrons originating from the two different colour strings spanned by the W^+ and W^- could/should exist

$$\Delta\rho = \rho^{WW}(1,2) - 2\rho^{W}(1,2) - 2\,\rho^{W}(1)\,\rho^{W}(2)$$

$\Delta\rho=0$, if no inter-W correlations

$$\Delta\rho(Q) = \rho^{WW}(Q) - 2\rho^{W}(Q) - 2\rho^{ww}_{mix}(Q), \qquad Q = \sqrt{-(p_1 - p_2)^2}$$

$2\rho^{WW}_{mix}(Q)$ mixed from semileptonic events

$\rho^{W}(Q)$ from semileptonic events

$$\delta_I(Q) = \frac{\Delta\rho(Q)}{2\rho^{ww}_{mix}(Q)}$$

genuine normalised inter-W correlations

Result: fit to $\delta_I(Q) = \Lambda_I e^{-RQ}(1 + \epsilon_d RQ) + \delta_N\left(1 + \frac{\rho^W(Q)}{\rho^{WW}_{mix}(Q)}\right),$

MC with full inter-W BE correlations (BEA):

[redacted]

$\Lambda_{I_{BEA}}(+,-) = 0.30 \pm 0.03(\text{stat}).$

Data:

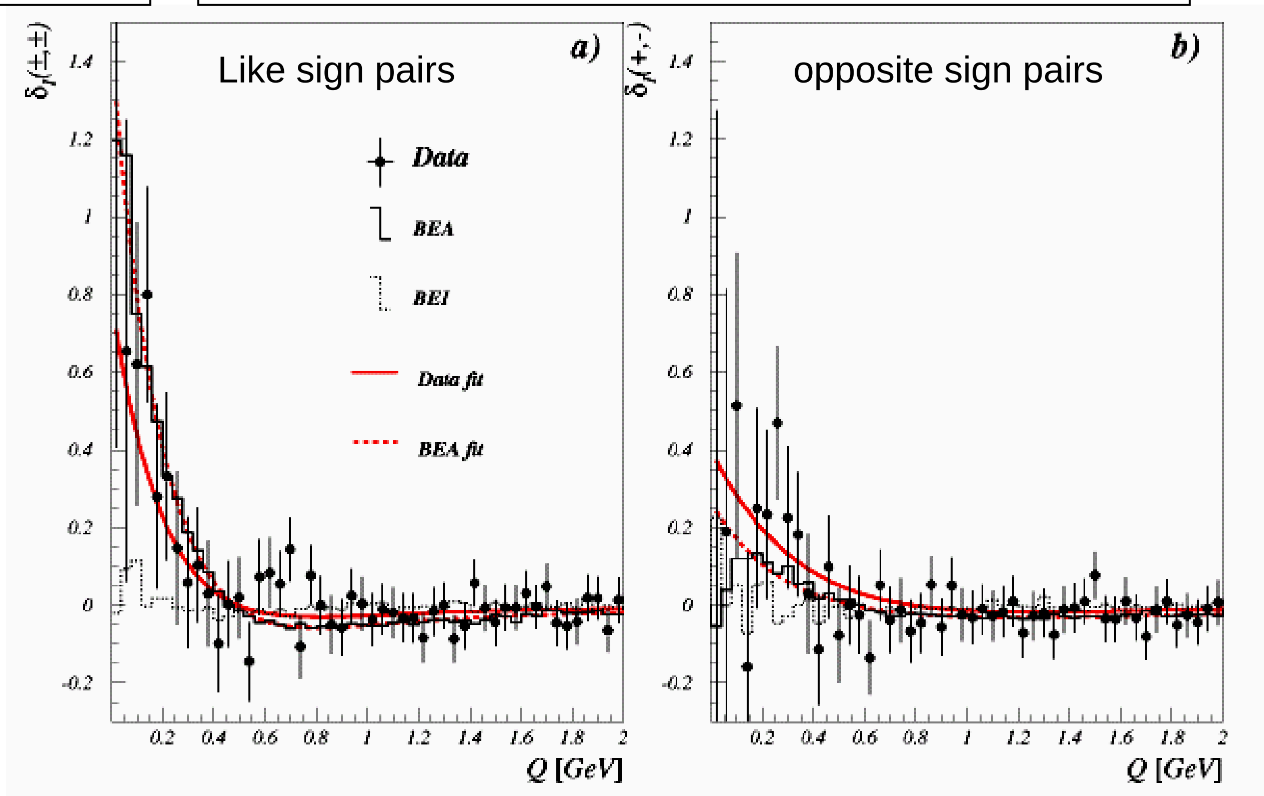
$\Lambda_I(\pm,\pm) = 0.82 \pm 0.29(\text{stat}) \pm 0.17(\text{syst}),$

$\Lambda_I(+,-) = 0.40 \pm 0.18(\text{stat}) \pm 0.22(\text{syst})$

Data: 550 pb^{-1}, 189 to 209 GeV, 3252 fully hadronic and 2567 semi-leptonic events

BEA: Monte Carlo sample including full intra and inter-W Bose-Einstein correlations with the algorithm “BE32”,

BEI: Only intra-W (same-W) Bose-Einstein correlations are taken into account

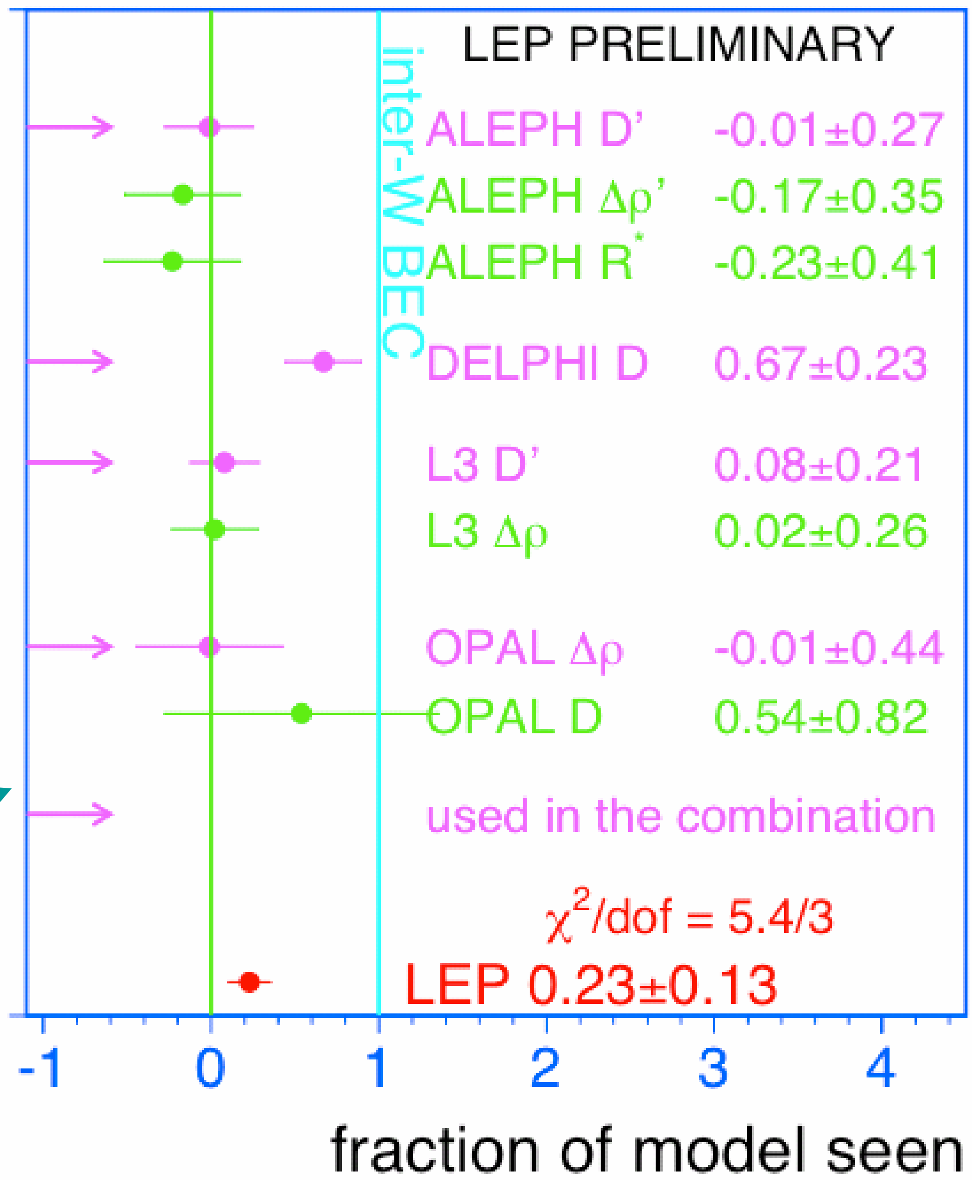


DELPHI: indication for inter-W BE correlations with 2.4 σ

However:

Other LEP-2 Experiments?

A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model", CERN-PH/2004-069, arXiv:hep-ex/0412015 v2 11 Jan 2005



If “inter-string” Bose-Einstein correlations are diminished (or even absent):

Quantum mechanical effect: What is wrong with the basic assumptions ?

Chaoticity, Symmetrisation of the wave function for Bosons from different strings?

- **Bo Anderson: “Bose-Einstein correlations and colour strings”** Andersson and Hofmann, Phys. Lett. 169B, 364 (1986), Andersson and Ringner, Nucl. Phys. B513, 627, (1998), J. Häkkinen and M. Ringnér, Eur. Phys. J. C5, 275 (1998)

- **Symmetrisation only within one colour string**

- **Based on this model J. Häkkinen and M. Ringnér predicted ano 1998: “there are no Bose-Einstein correlations between bosons coming from different W’s” !!**

A "side-step": Are inter-string Bose-Einstein correlations also generally diminished (or even absent)?

Second order genuine correlation function: $\mathbf{C(p_1,p_2)=\rho(p_1,p_2) - \rho(p_1)\,\rho(p_2)}$,

Superposition of **N statistically independent sources (strings)**, completely overlapping in phase-space:

single particle distribution: $\mathbf{\rho(p)= N\cdot\rho^I(p)}$

$$\mathbf{C(p_1,p_2) = N\cdot C^I(p_1,p_2)}$$

Normalized Cumulant: $\mathbf{K(p_1,p_2) = C(p_1,p_2)/\,\rho(p_1)\cdot\rho(p_2)}$

$$\mathbf{K(p_1,p_2) = N^{-1}\cdot C^I(p_1,p_2)\,/\rho^I(p_1)\cdot\rho^I(p_2) = \underline{\underline{N^{-1}}}K^I(p_1,p_2)}$$

hadron-hadron and heavy-ion reactions: strength of BEC decreases with increasing multiplicities $\propto$ Nr. of Strings? // Heavy-ion reactions at very high multiplicity: BEC increase again,coalescence, percolation of strings?

M.A. Braun, F.del Moral and C. Pajares, Eur. Phys. J. C21 (2001) 557; See also discussion in "Soft Multihadron Dynamics", W. Kittel and E.A. De Wolf World Scientific 2005, section 11.2.2, pg. 531 and references therein

3. Leading Hadrons in Gluon and Quark Fragmentation

- Exists the process of the **direct neutralisation of the Gluon colour octet field by an other Gluon** by creating a 2-Gluon system ?
- Creation of Glueballs ? Predicted by QCD !
- **Investigate the „Gluon-corner“ in 3-jet Events!**

P. Minkowski and W. Ochs, Phys. Lett. B485 (2000) 139.

P.Roy and K. Sridhar, JHEP07 (1999) 013

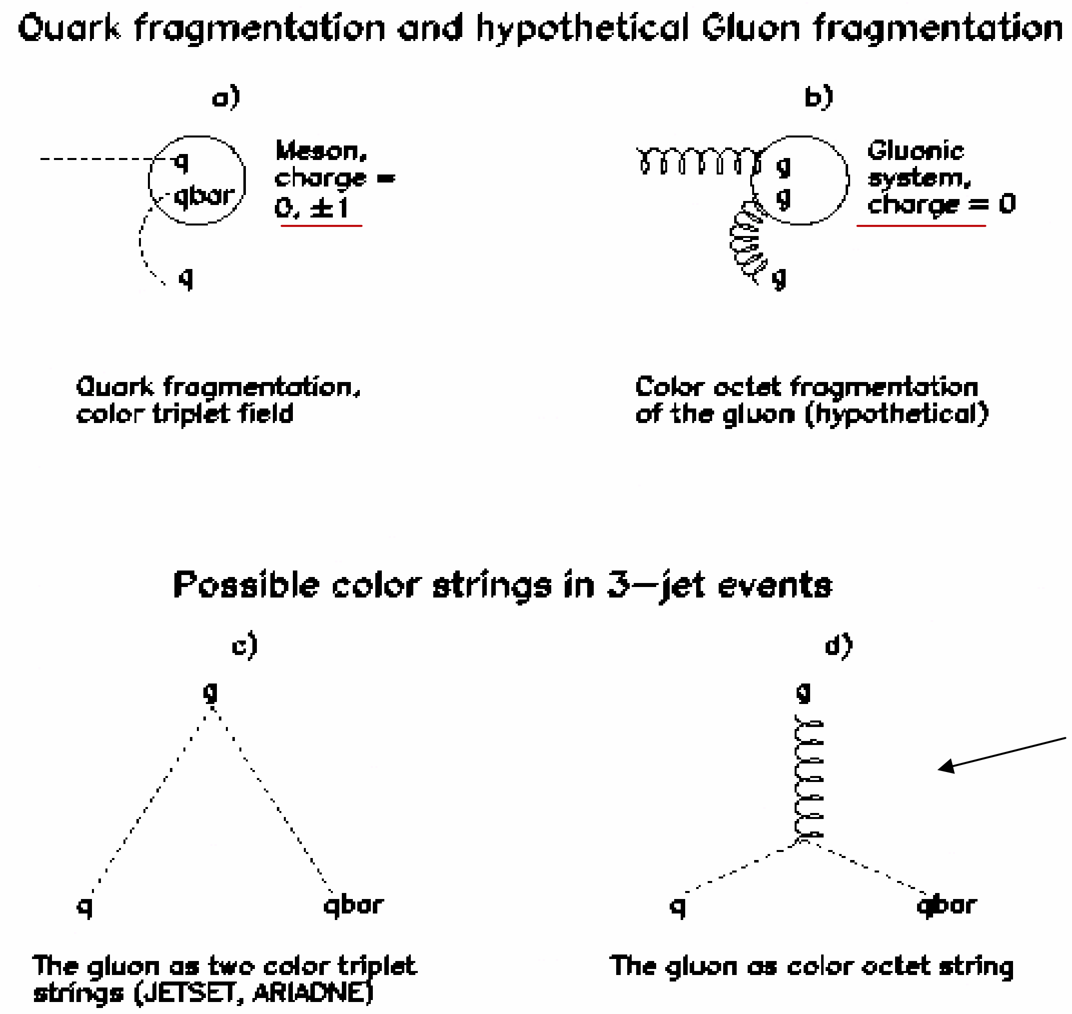
H. Spiesberger and P.M. Zerwas, Phys. Lett. B481 (2000) 236,

H. Fritsch and P. Minkowski, Nuovo Cimento 30A (1975)

I. Montvay, Phys. Lett. B84 (1979) 331,

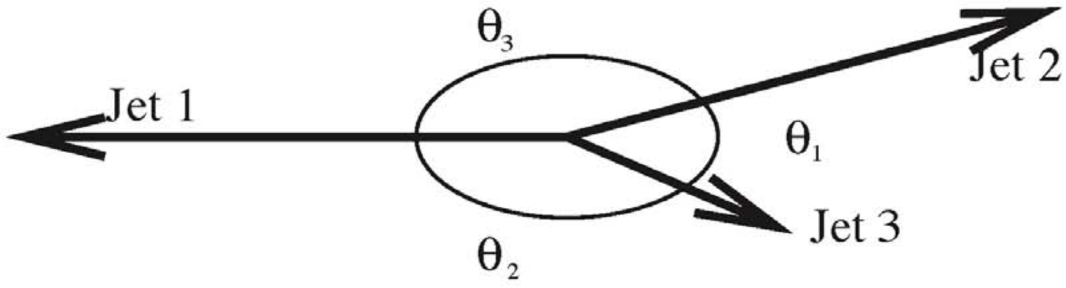
C. Peterson and T.F. Walsh, Phys. Lett. B91 (1980) 455,

Strategy: compare measured 3-jet events with the LUND-STRING Model (JETSET/ARIADNE)



This mechanism is different from colour recombination!

Data Selection



- LEP-I hadronic Z-decays
- Select three-jet events
- Durham algorithm, $y_{\text{cut}} = 0.015$
- $\theta_2, \theta_3 = 135^\circ \pm 35^\circ$

$\rightarrow$ 314000 events

- $E(\text{jet } 1) \geq E(\text{jet } 2) \geq E(\text{jet } 3)$

- Implicit jet assumptions: **Sample1**
  - Jet 1: $\geq 90\%$ quark contribution
  - Jet 3: $\sim 70\%$ gluon contribution
- Alternatively: b-tagging **Sample2**
  - Positive b-tag on jet 1 and 2
  - Negative b-tag on jet 3
  - Jet 3: Gluon contribution $\sim 90\%$

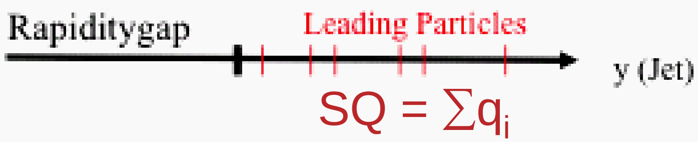
Rapidity gap: All charged particles in jet $y \geq \Delta y = 1.5$

Monte Carlo Event Samples

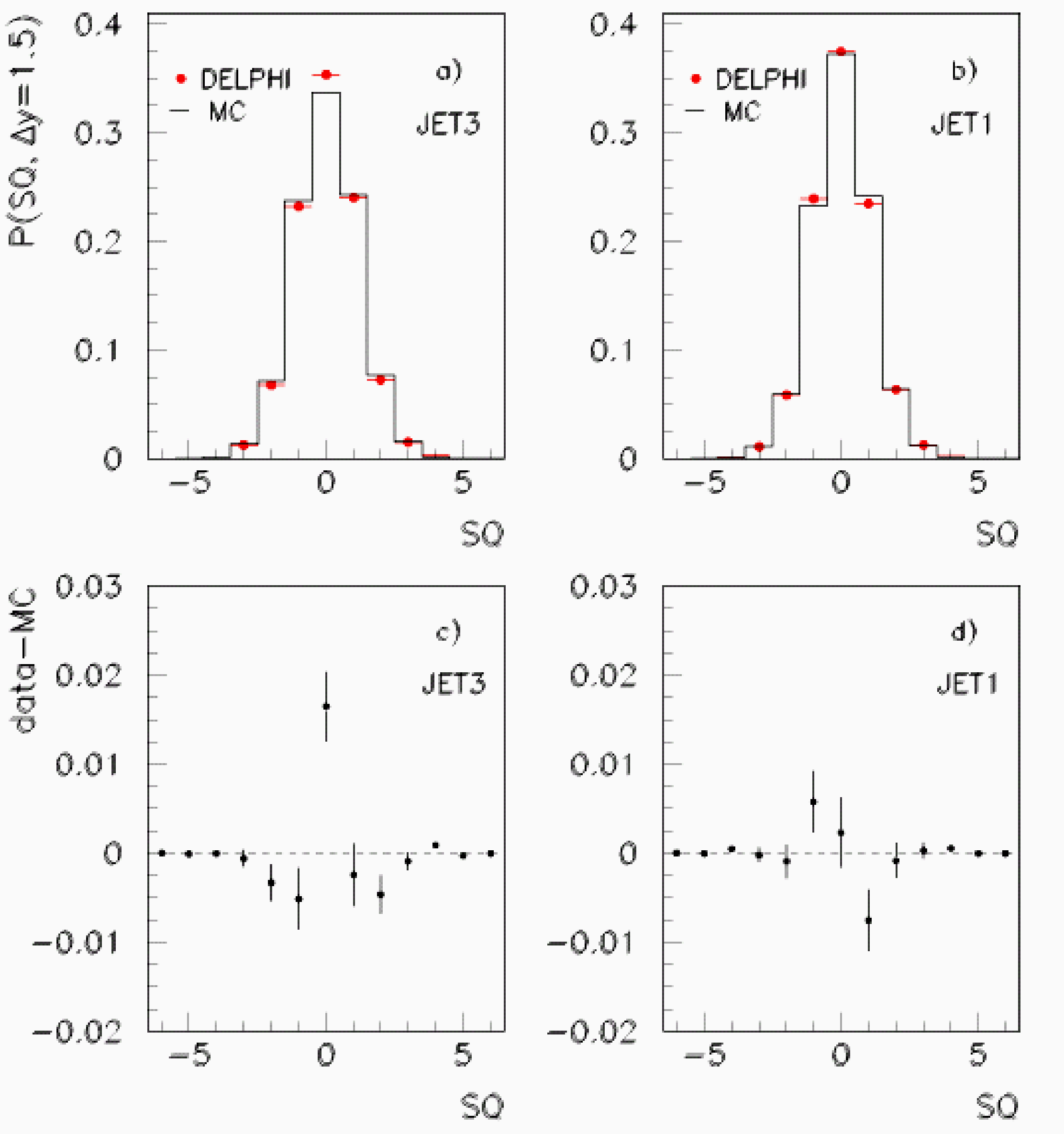
- Colour octet neutralisation not implemented in MC simulations
- Comparison Data - Monte Carlo: More neutral leading systems in gluon jets due to colour octet neutralisation expected
- Monte Carlo events processed with full detector simulation
- Problem: Bose-Einstein correlation
  - Pulls identical Mesons closer together → Charge compensation disturbed
  - Implementation of BE in MC sophisticated, magnitude of disturbance unknown
  - Counted towards systematic error
- Studied Monte Carlo event samples:
  - JETSET with Bose-Einstein correlations (Model 1)
  - JETSET without Bose-Einstein correlations (Model 2)
  - ARIADNE without Bose-Einstein correlations (Model 3)

Analysis:

The sum of charges in the leading system with a rapidity gap (sample1)



$$P(SQ, \Delta y) = \frac{N(SQ, \Delta y)}{N(\Delta y)}$$

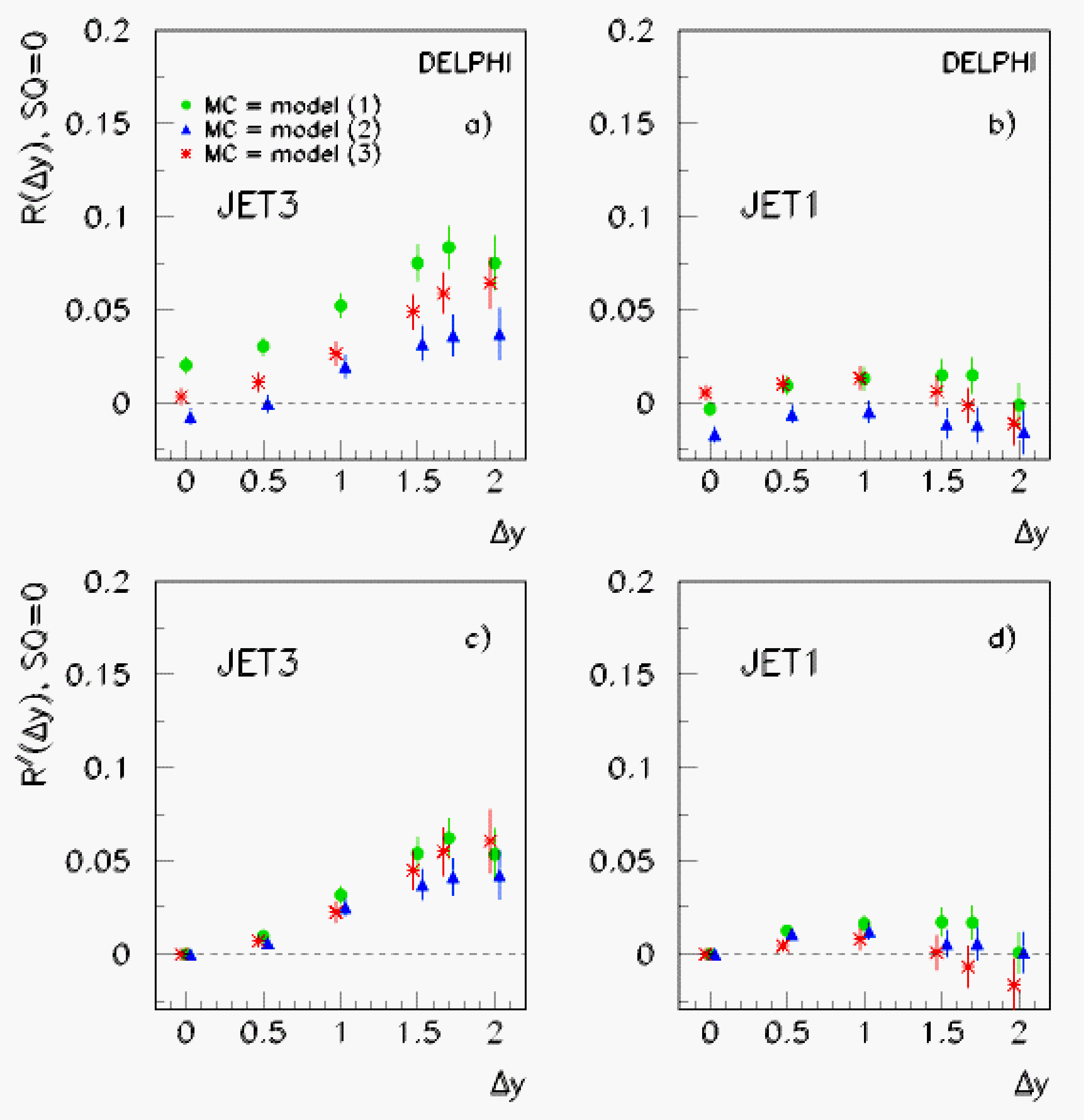


Dependence on the size of the gap

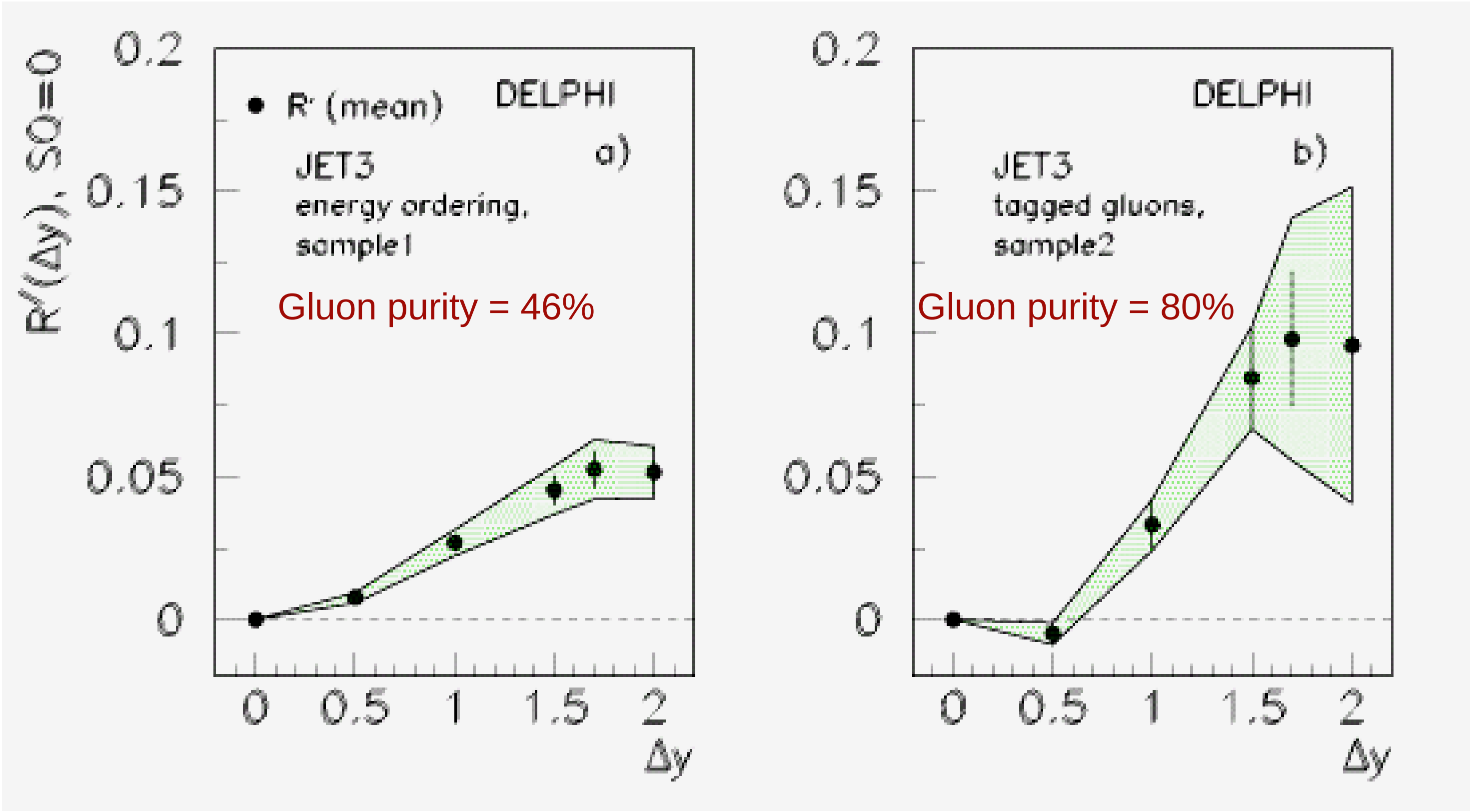
$$R(\Delta y) = \frac{P(0,\Delta y)_{data} - P(0,\Delta y)_{MC}}{P(0,\Delta y)_{MC}}$$

Subtract the offset (due to the Bose-Einstein correlations)

$$R'(\Delta y) = R(\Delta y) - R(0)$$



The dependence on the Gluon purity



Pure Gluon Jets, Δy=1.5 : R'g(1.5) = 0.102 ± 0.011(stat) ± 0.026

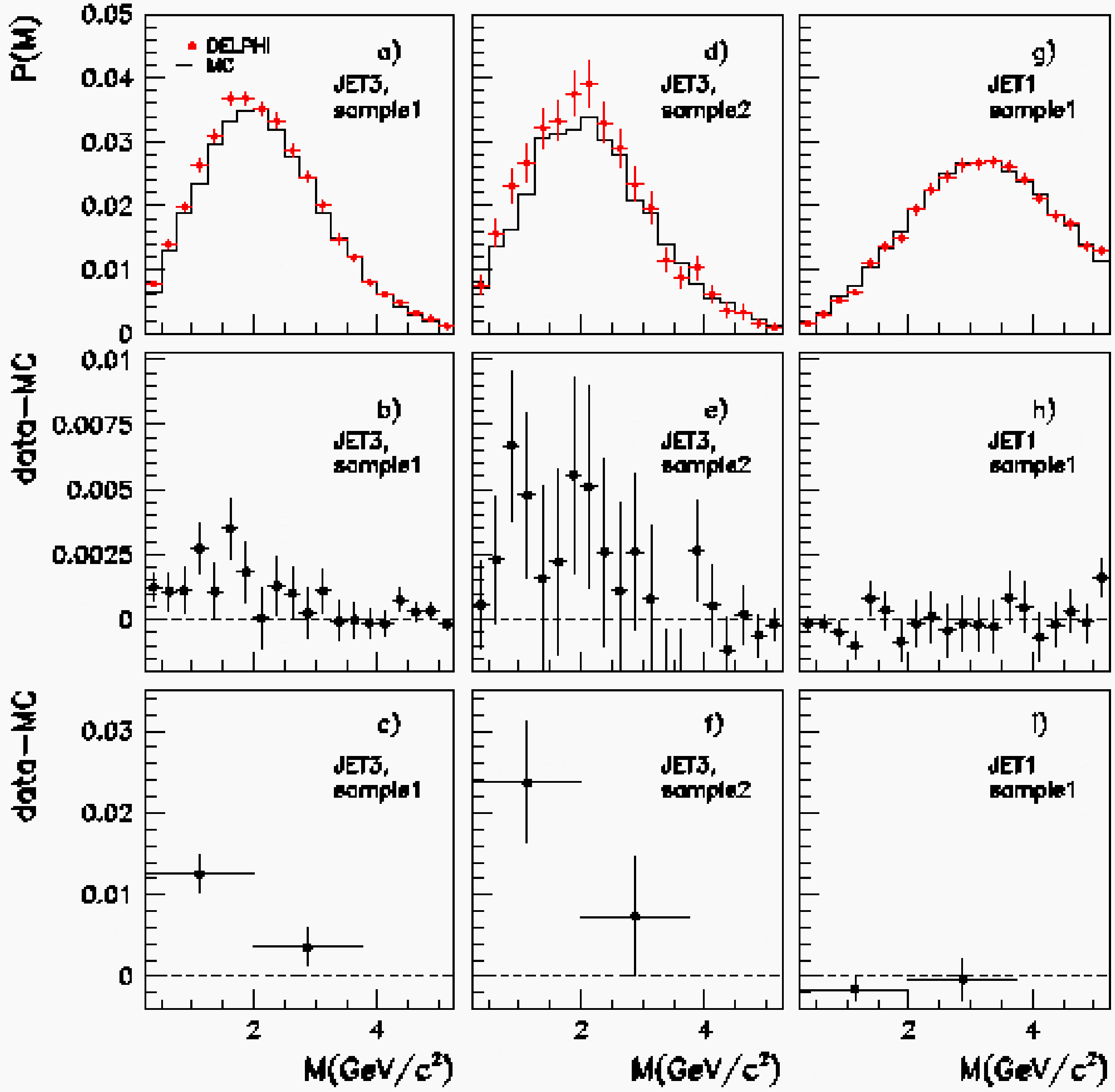
Pure Gluon Jets without any gap or charge-selection: A possible octet neutralisation occurs with a probability of about 1/2 %.

Mass spectra

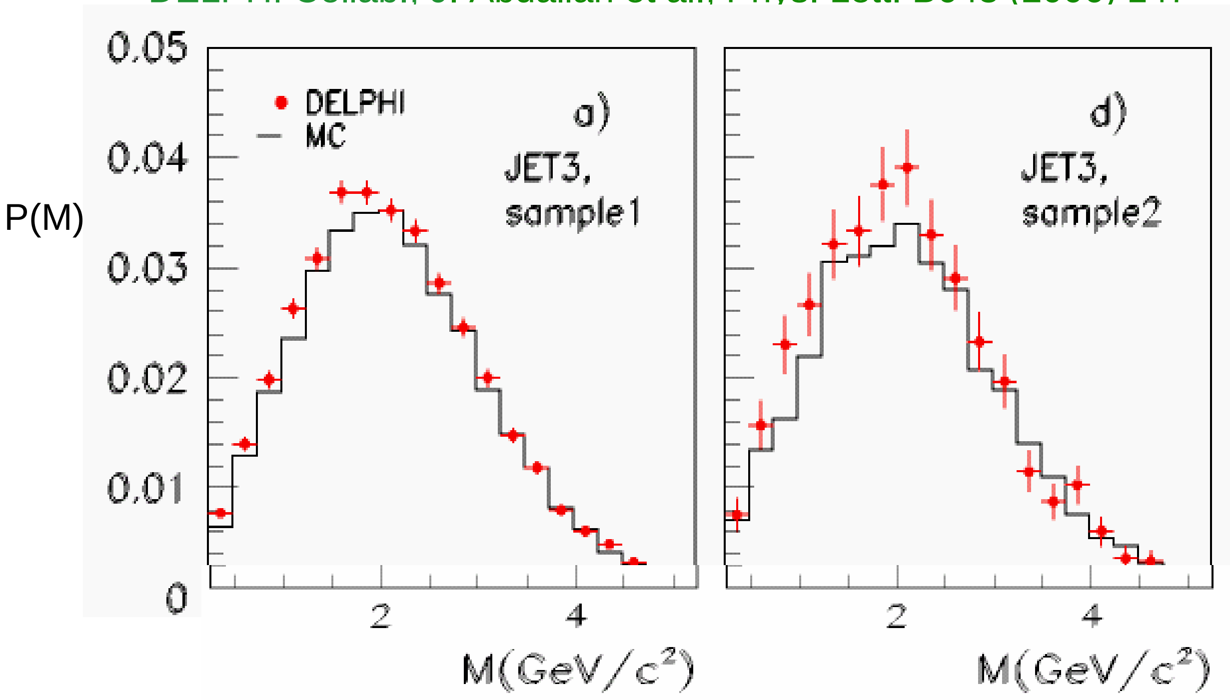
Including charged (p>0.2GeV/c) and neutral particles (mainly γ's), E>0.5 GeV), Δy=1.5

$$P(M) = \frac{N(M, SQ=0, \Delta y)}{N(\Delta y)}$$

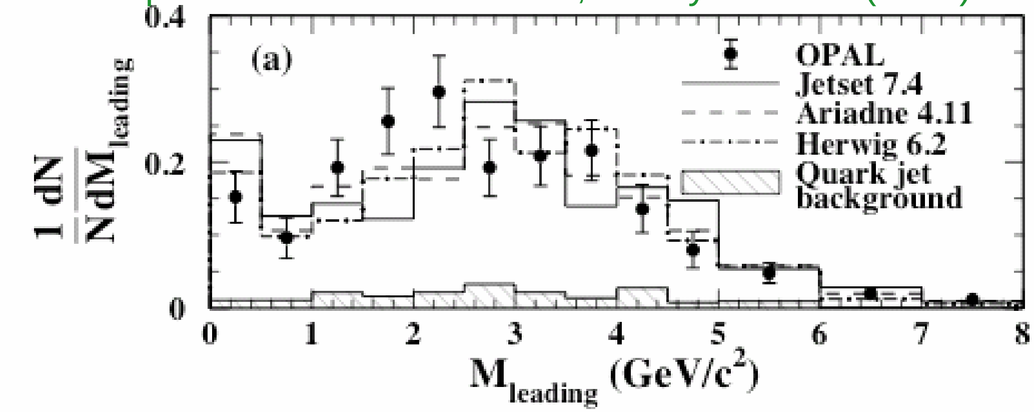
- **Where in the mass spectrum is the excess of neutral systems located ?**



DELPHI Collab., J. Abdallah et al., Phys. Lett. B643 (2006) 147



Opal Coll. G. Abbiendi et al.,Eu.Phys. J. C35 (2004) 293



Also Aleph has seen such an excess in the mass spectrum ! See talk of. G. Rudolph, this workshop.

Summary, main achievements from colour flux studies:

1. $e^+e^- \rightarrow W^+W^- \rightarrow q_1q_2q_3q_4$

•Signal for Colour reconnection in fully hadronic WW decay present (DELPHI), but less than 2σ; all LEP experiments together show a weak signal with 2σ .

•Bose-Einstein correlation between the decay products of the different W's seem to be diminished or absent (all LEP-2 experiments),

• If symmetrisation occurs in each string separately - **a tool to study the string-structure in hadron-hadron and heavy-ion reactions (percolation of strings)**

2. $e^+e^- \rightarrow q\bar{q}g$, study of leading particles in Gluon jets

•Gluon jets produce more neutral leading systems than predicted by string models (Jetset, Ariadne) $\leftarrow$ predicted, if gluon fragments also as a **colour octet field** !

•Concentration of the excess **at low invariant mass** could be a **signal for gluonic states (Glueballs), as predicted by QCD**. **Further investigations of Gluon-jets!**

The End of talk, Trento 30’

GLUEBALLS ?

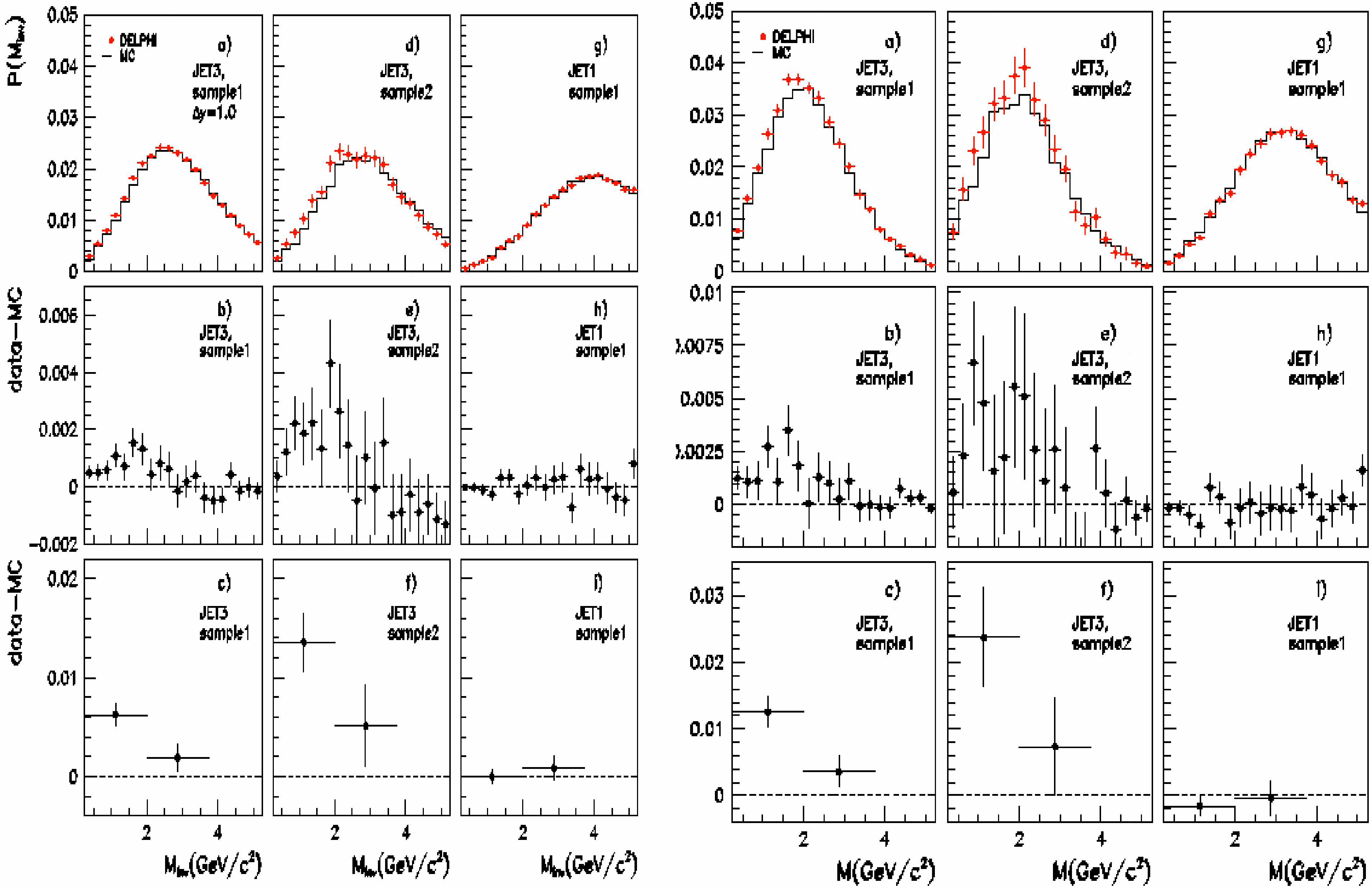
		$f_0(400-1200)^1$
	$a_0(980)^2$	$f_0(980)^2$
		$f_0(1370)^1$
$K_0^*(1430)^2$	$a_0(1490)^3$	$f_0(1500)^2$
		$f_0(1750)^3$
$K_0^*(1950)^3$		$f_0(2100)^3$

Table 7: The scalar mesons and their interpretation: ^{1}: generated by t-channel exchanges. ^{2}: The 1^3P_0 ground state scalar meson nonet. ^{3}: The 2^3P_0 first radially excited scalar meson nonet.

E. Klempt, PSI Zuoz Summer School, Phenomenology of Gauge Interactions, 2000, arXiv: hep-ex/0101031 v1, Jan.2001

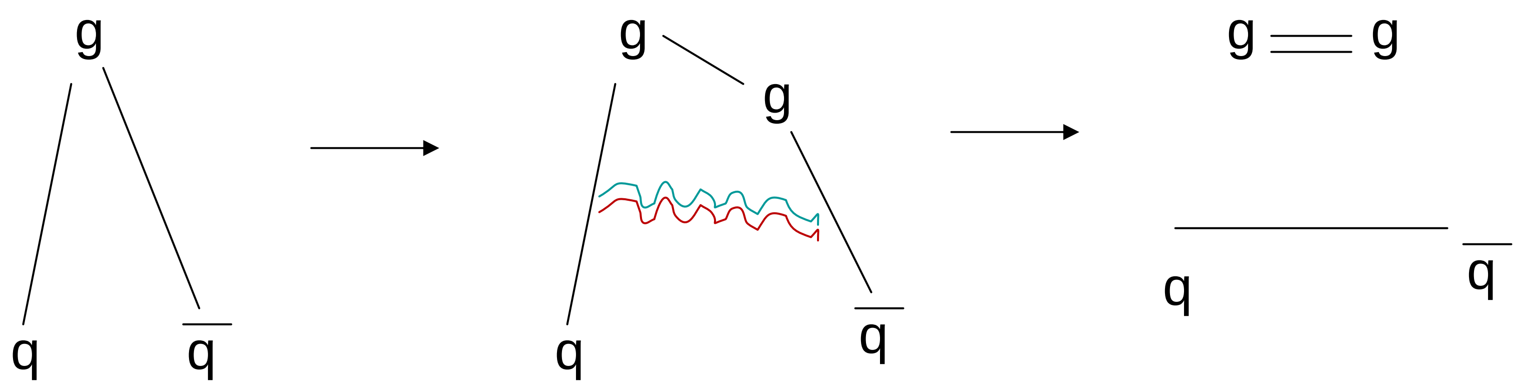
P. Minkowski and W. Ochs, Proc. of the Ringberg Workshop on New Trends in HERA, Sept. 2003, arXiv: hep-ph/0401167, 22.Jan. 2004

Δy=1.0   Δy=1.5



DELPHI
MC
JET3, sample1
Δy=1.0
JET3, sample2
JET1 sample1
P(Mkk)
data−MC
M(GeV/c²)

Colour Reconnection in Gluon Jets



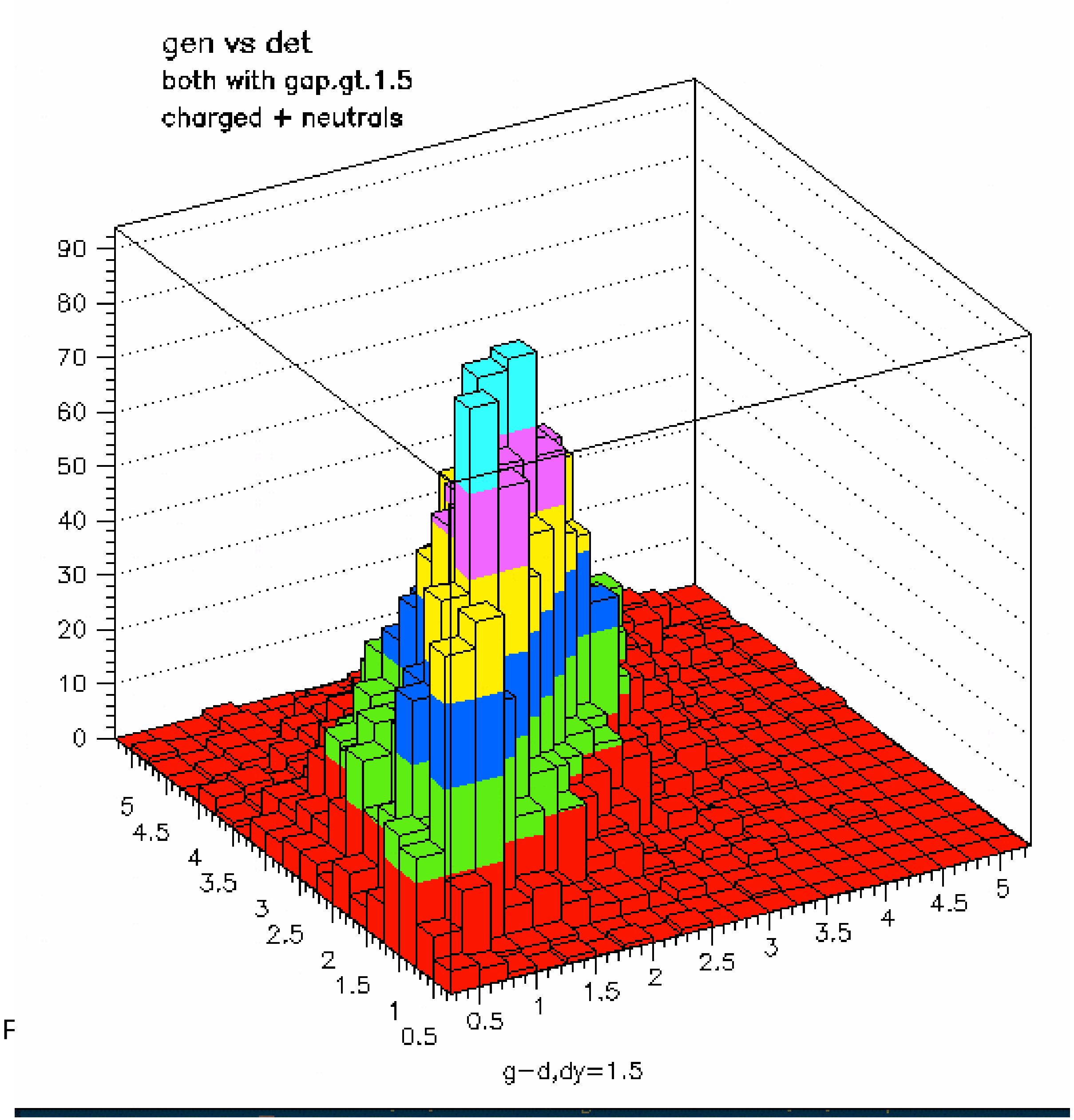
- In reconnection scenarios, you assume there is only the traditional kind of Lund string, that breaks by the production of q qbar pairs. In an event such as q-g-g-qbar the strings are drawn exactly as indicated by hyphens. By the exchange of another gluon, colours can then be rearranged into q-qbar plus g=g, where the = indicates that you have two normal Lund strings spanned between the two gluons, each between the colour of one gluon and the anticolour of the other. In the limit of small masses, this may then collapse to a glueball state. Torbjorn Sjoestrand

6. Studies with the detector response matrix

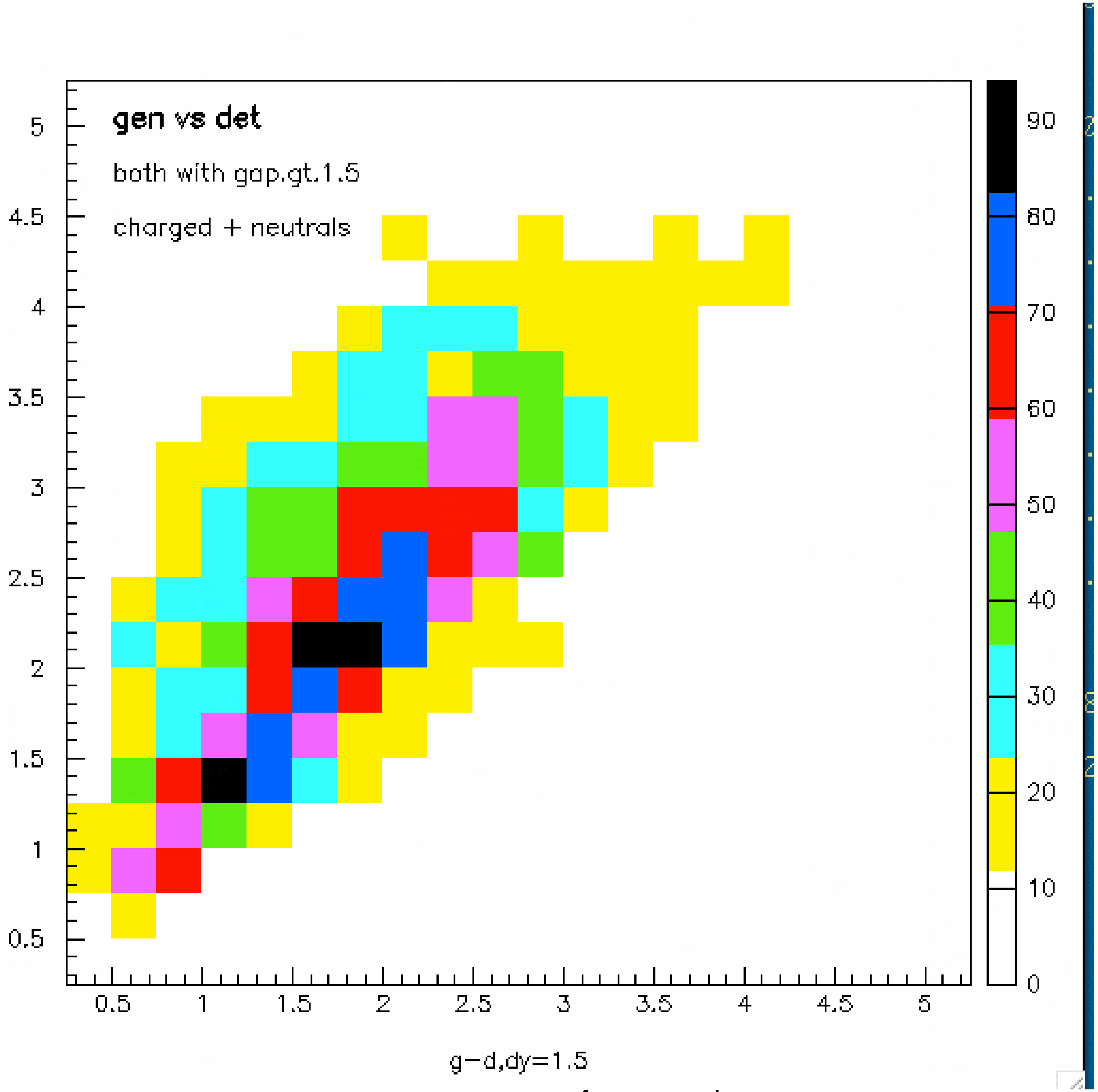
- All comparisons are done on detector level
- Systematic shifts of mass spectra with neutrals expected: Due to the loss of neutrals (mainly γ's), the measured spectra are shifted to lower mass values by 0.3-0.5 GeV/c^2
- Study with the detector response matrix with the SVD (Singular Value Decomposition) Approach

A.Höcker and V. Kartvelishvili, “The SVD Approach to Data Unfolding“, MC-TH-95/15, LAL-95/55, arch-ive/9509307, August 1995

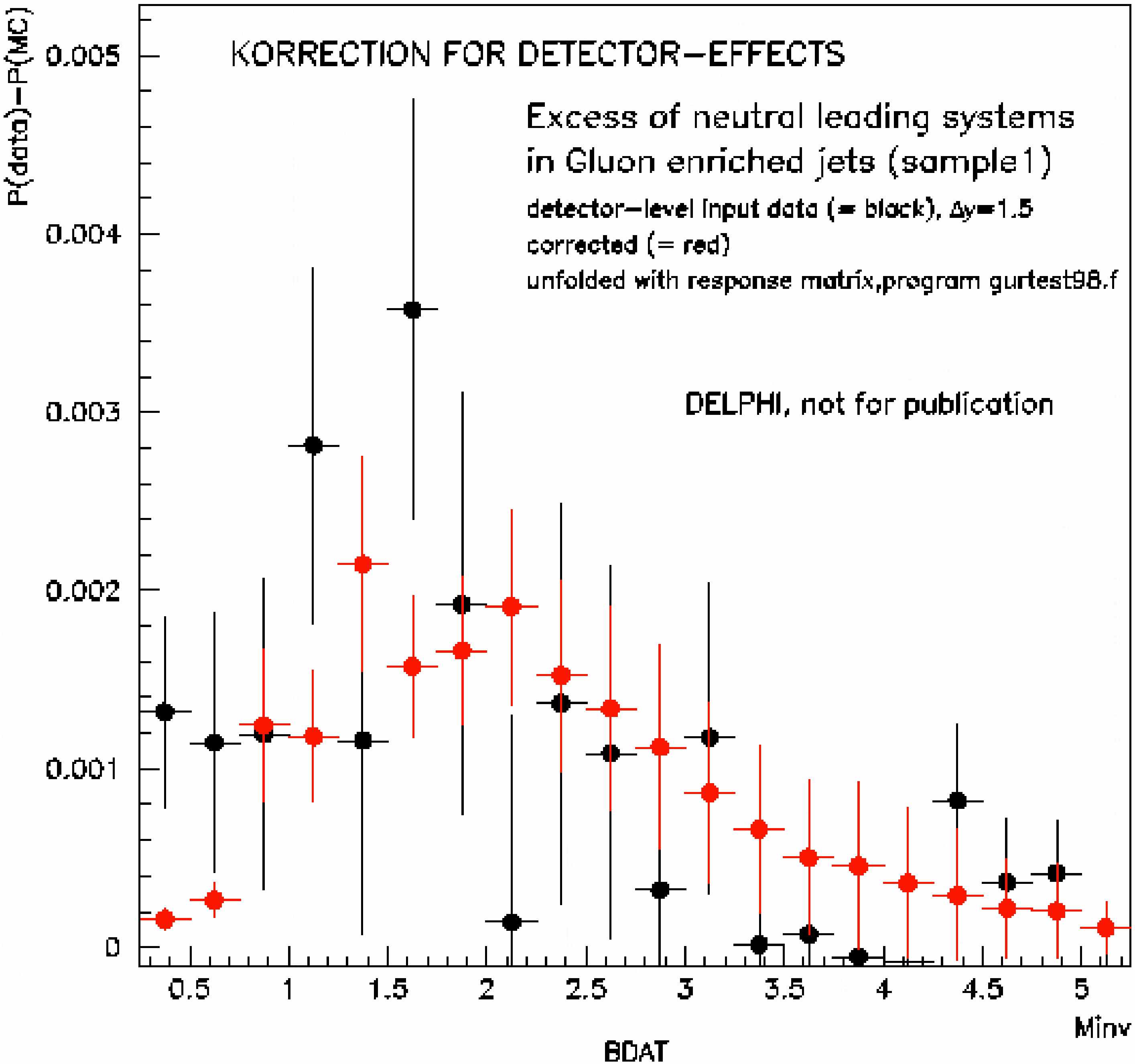
The detector response matrix



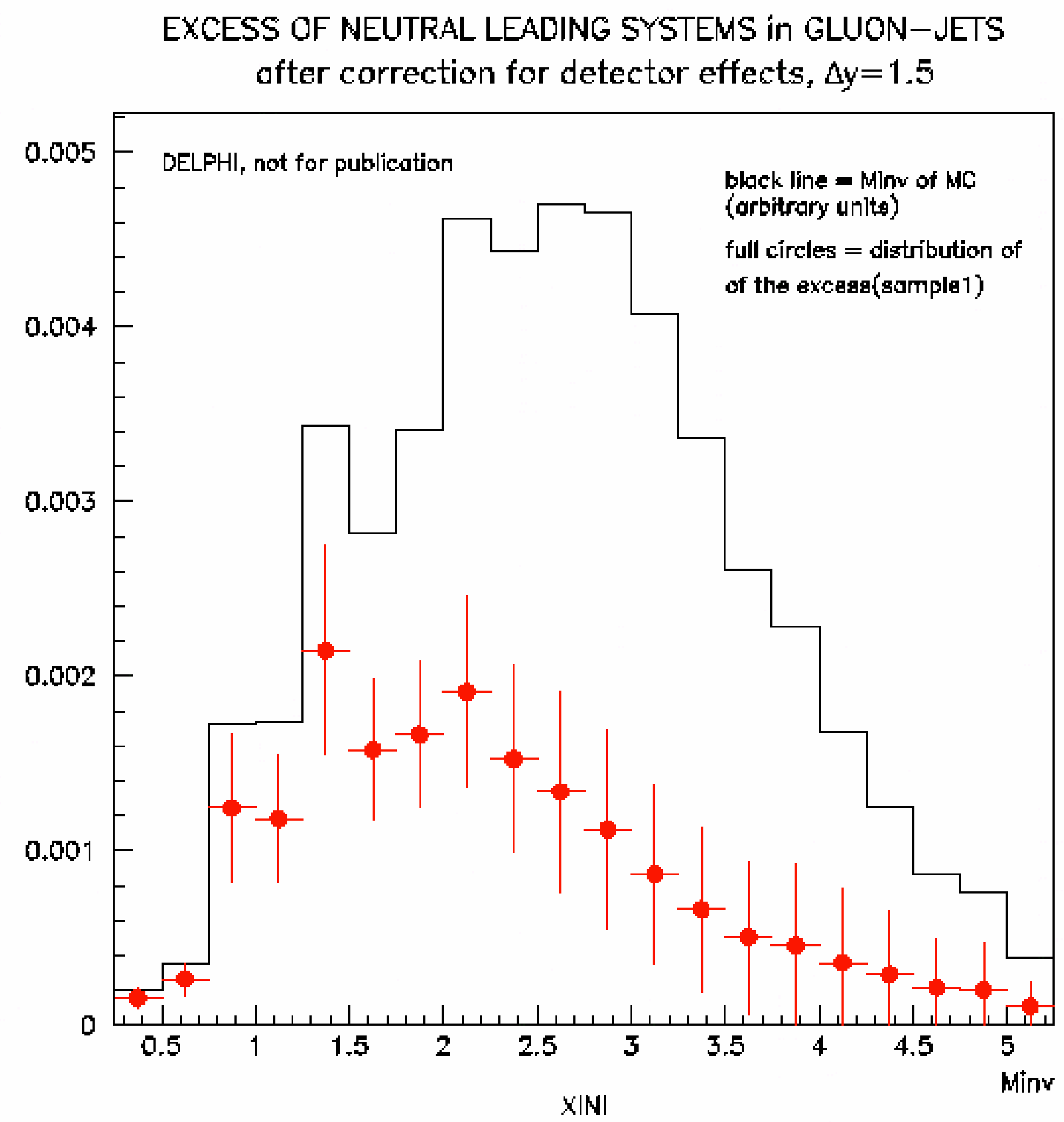
The detector response matrix



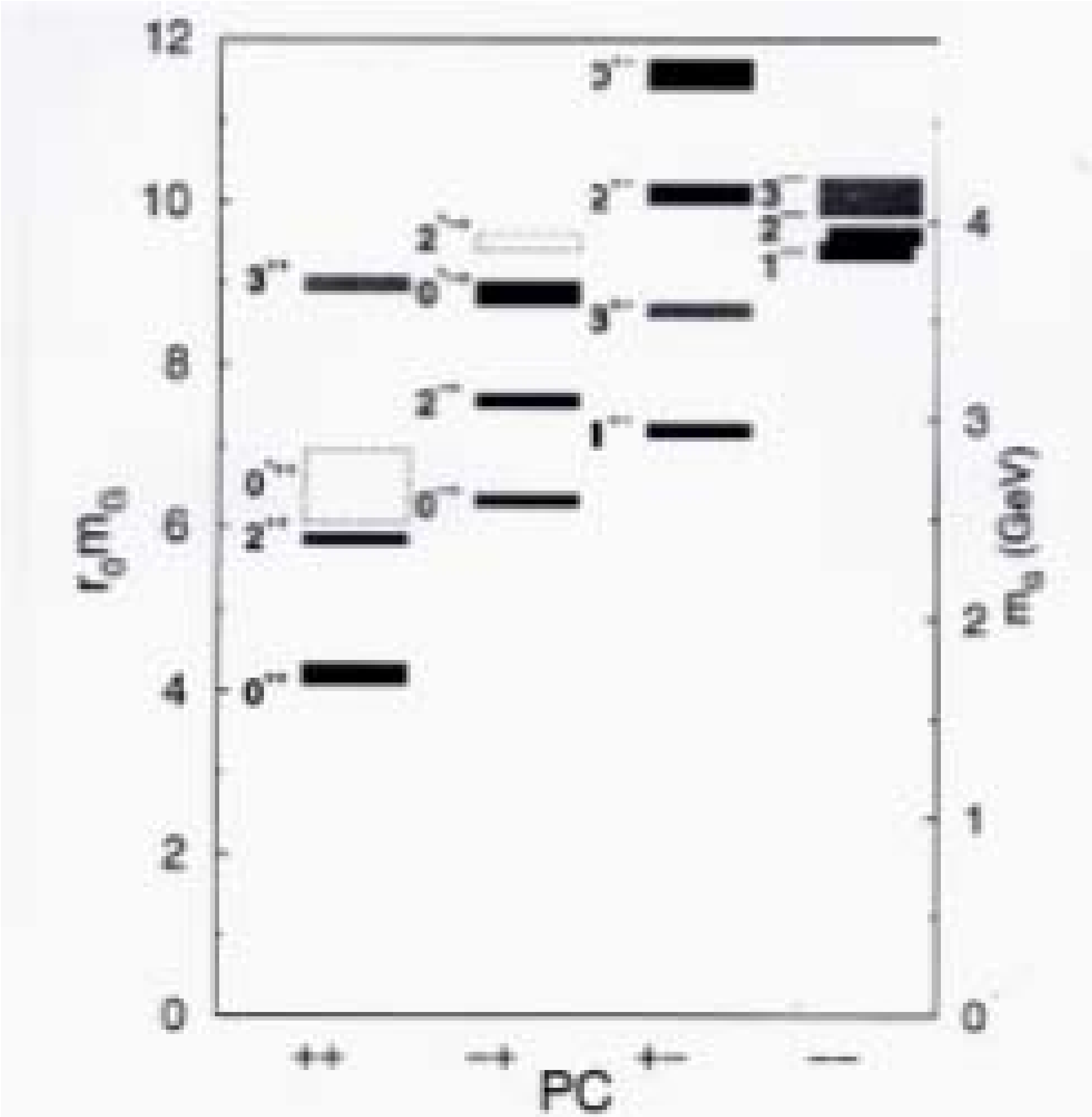
fragmentation


KORRECTION FOR DETECTOR–EFFECTS
Excess of neutral leading systems
in Gluon enriched jets (sample1)
detector–level input data (= black), Δy=1.5
corrected (= red)
unfolded with response matrix,program gurtest98.f
DELPHI, not for publication
P(data)–P(MC)
0.005
0.004
0.003
0.002
0.001
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Minv
BDAT

Tre



EXCESS OF NEUTRAL LEADING SYSTEMS in GLUON–JETS
after correction for detector effects, Δy=1.5
DELPHI, not for publication
black line = Minv of MC
(arbitrary units)
full circles = distribution of
of the excess(sample1)
0.005
0.004
0.003
0.002
0.001
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Minv
XINI



Results from Lattice Calculations

See E. Klempt,
PSI ZUOZ Summer School.
Phenomenology of Gauge
Intertactions, 13.-19. 8. 2000,
hep-ex/0101031

- The experimental detection of Glueballs which are an early prediction of QCD is of primary interest.
- The present study gives evidence for the existence of octet neutralization of the gluon field and the possibility that new information on gluonic systems can be obtained from the comparative study of the leading particle systems in quark and gluon jets.
- This is especially important for future studies with much better statistics at LHC where gluon jets will be produced frequently.

Summary

The DELPHI collaboration has investigated the leading systems of gluon and quark jets, defined by a rapidity gap, in e+e- reactions at an energy of 91.2 GeV.

One observes for (enriched) gluon jets a higher rate of neutral leading systems than predicted by string models (JETSET, ARIADNE).

At a rapidity gap of 1.5 and in pure gluon jets, this excess has been estimated to be about 10% with a significance of 3.6σ.

It is expected to be of the order of 0.5% in pure gluon jets without any charge or gap selection

On contrary, quark jets do not show any excess.

Invariant mass spectra, which include charged and neutral particles show clearly, that the excess is concentrated at low $M_{inv} \leq 2$ GeV/c^2.

The observed excess, its increase with gap-size and gluon purity is in agreement with expectations, if the hitherto unobserved but predicted process of octet neutralization of the gluon field takes place in nature;

Its concentration at low invariant mass could be a signal of gluonic states, predicted by QCD.

A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model", CERN-PH/2004-069, arXiv:hep-ex/0412015 v2 11 Jan 2005