Fragmentation Effects associated with W Production

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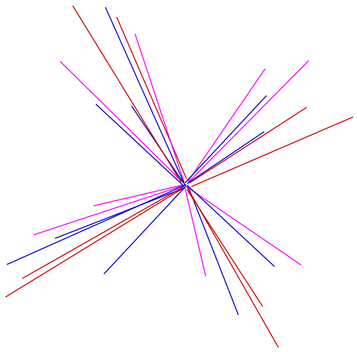
for the LEP collaborations

- Motivation
- Color Reconnection
- Bose-Einstein Correlations
- Summary

Motivation

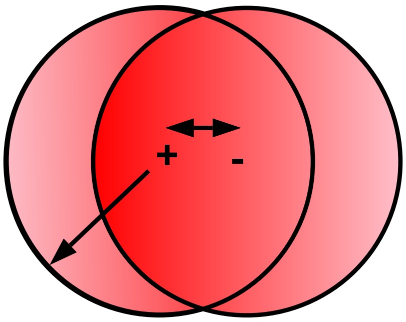
W bosons at LEP2 produced in pairs



- typical separation between W decay vertices $\approx$ 0.1 fm;
- hadronic scale about 1 fm

- space-time region of two $\mathrm{W} \rightarrow \mathrm{q\bar{q}}$ hadronisation overlap
  $\rightarrow$ NO independent decay of W bosons
- invariant mass might not add up to original W boson mass
  $\rightarrow$ impact on $\mathrm{M_W}$ measurement

separation between Ws 0.1fm



hadronisation size 0.5-1.0 fm

Possible Fragmentation Effects

1. **perturbative phase**

   color rearrangement of primary quarks

   negligible effect on $\mathrm{M_W}$ $\mathcal{O}(\sim 5\mathrm{MeV})$

2. **non-perturbative domain**

   soft gluon exchange during the hadronisation phase

   MC prediction on $\mathrm{M_W}$ shift up to $\mathcal{O}(\ 50\mathrm{MeV})$

3. **quantum mechanics (BEC)**

   symmetric two-boson wave function

   pion-pairs close in phase space enhanced

   MC prediction on $\mathrm{M_W}$ shift up to $\mathcal{O}(\ 50\mathrm{MeV})$

$\rightarrow$ significant shift of $\mathrm{M_W}$ in $\mathrm{W^+W^-} \rightarrow \mathrm{q\bar{q}q\bar{q}}$ events

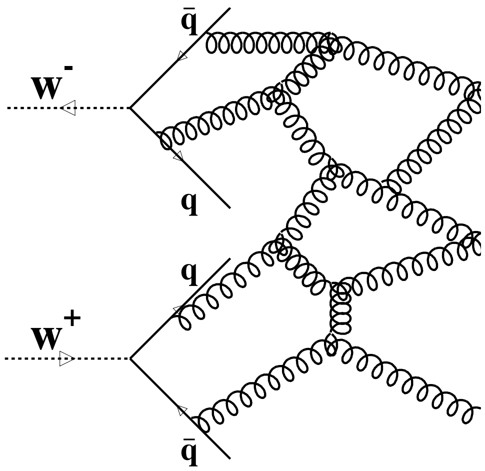
present experimental status:

$\mathrm{M_W(q\overline{q}q\overline{q})} - \mathrm{M_W(q\overline{q}\ell\overline{\nu}_\ell)} = 152 \pm 74\ \mathrm{MeV}/c^2$

(without syst. error for CR and BEC)

Color Reconnection

- soft gluon exchange during hadronisation

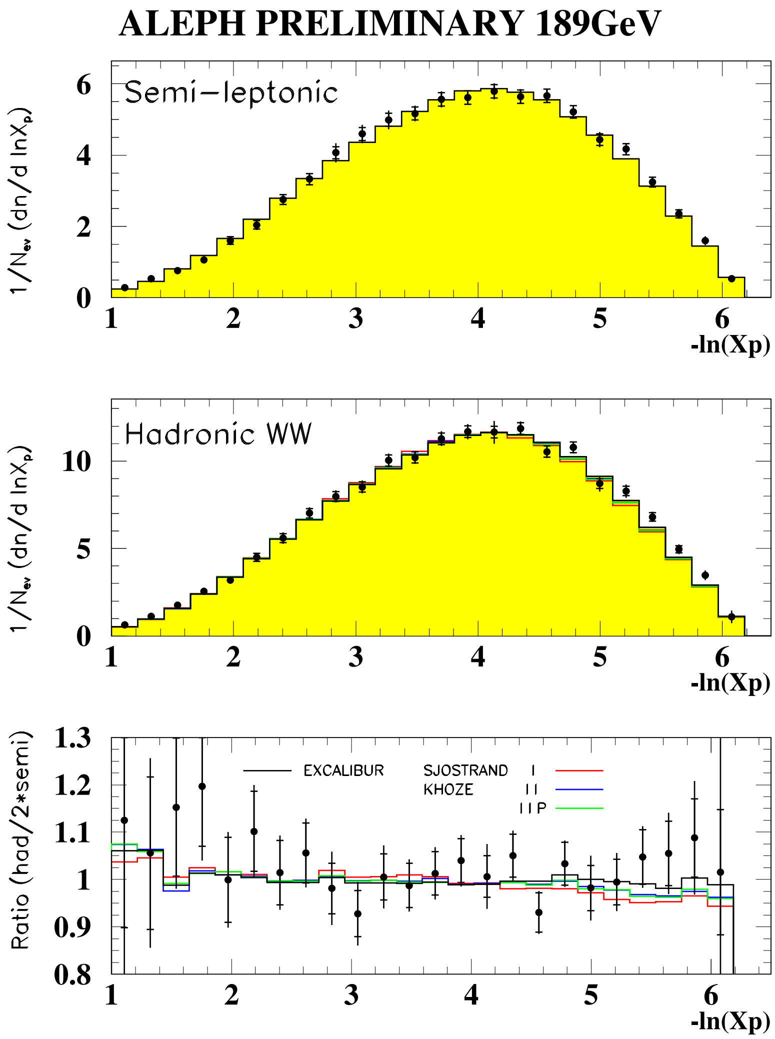


Signature: **depletion of charged multiplicity**
(between -0.3 and -0.1 units predicted by CR MC)

Experiment	Energy	$\Delta\langle n_{ch}\rangle = \langle n_{ch}^{4q}\rangle - 2\langle n_{ch}^{qq\ell\nu}\rangle$
ALEPH	189 GeV	$0.47 \pm 0.44 \pm 0.26$
L3	189 GeV	$-0.23 \pm 0.40 \pm 0.52$
OPAL	183 GeV	$0.7 \pm 0.8 \pm 0.6$
DELPHI	189 GeV	-0.92 ± 0.66
		$\langle n_{ch}^{4q}\rangle / 2\langle n_{ch}^{qq\ell\nu}\rangle$
DELPHI	189 GeV	$0.977 \pm 0.017 \pm 0.027$

Momentum distribution for all particles

CR affects low p spectra ($-\ln(x_p)$ with $x_p = \frac{2p}{\sqrt{s}}$)

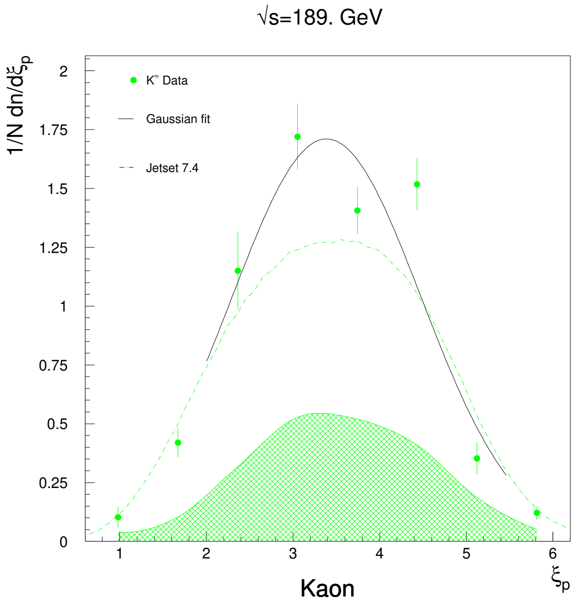


→ ratio between fully hadronic and semileptonic events not sensitive to different CR models

- similar analysis and results by DELPHI and OPAL

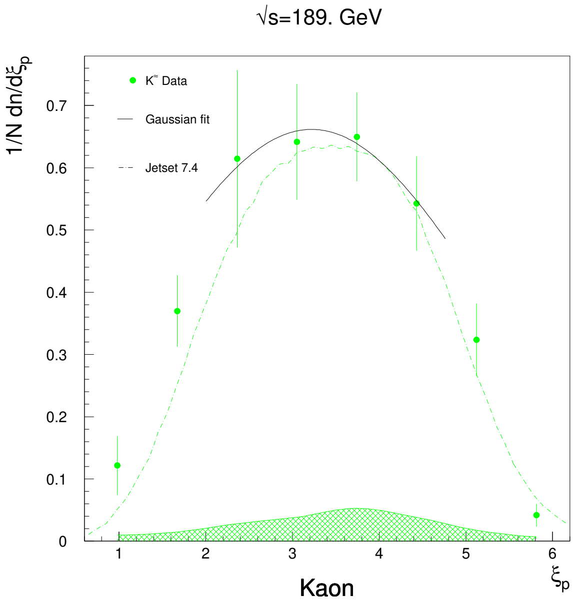
Momentum distribution for heavy particles

2-3 $\times$ larger effect for heavy particles predicted



DELPHI

momentum distribution for $K^{\pm}$ in $W^+W^- \rightarrow q\bar{q}q\bar{q}$ events and comparison with standard MC prediction



momentum distribution for $K^{\pm}$ in $W^+W^- \rightarrow q\bar{q}\ell\overline{\nu}_{\ell}$ events and comparison with standard MC prediction

note: $\xi_p = -\ln(x_p)$

1. comparison of heavy particle rate with standard MC

event type	particle	data	Jetset
$W^+W^- \to q\bar{q}q\bar{q}$	K^+	$4.59 \pm 0.26 \pm 0.12$	4.04
	p	$2.02 \pm 0.22 \pm 0.16$	1.89
$W^+W^- \to q\bar{q}\ell\bar{\nu}$	K^+	$2.12 \pm 0.21 \pm 0.17$	2.02
	p	$0.86 \pm 0.17 \pm 0.06$	0.95

$\rightarrow$ data consistent with standard MC prediction

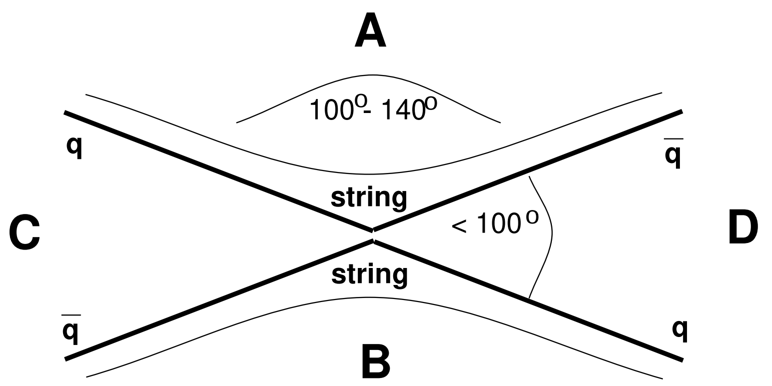
2. ratio between fully hadronic and semileptonic events

ratio $K^+(\frac{W^+W^- \to q\bar{q}q\bar{q}}{2 \cdot W^+W^- \to q\bar{q}\ell\bar{\nu}})$: 1.08 ± 0.12 (stat. only)

$\rightarrow$ ratio consistent with unity

Inter-Jet Particle- and Energy Flow

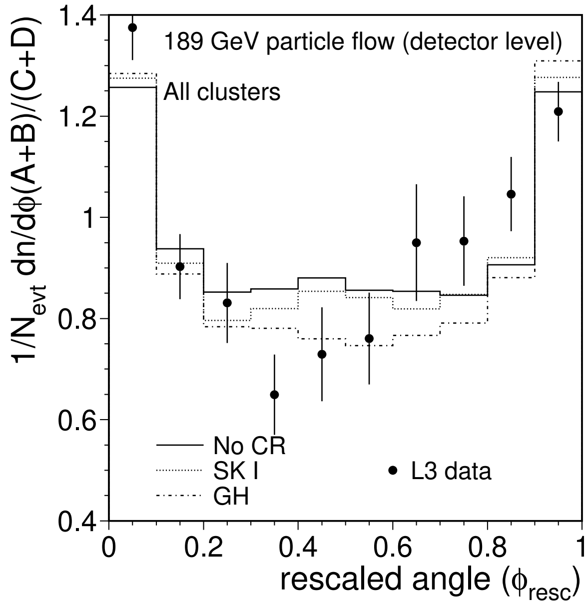
compare energy and Particle flow within W and between W

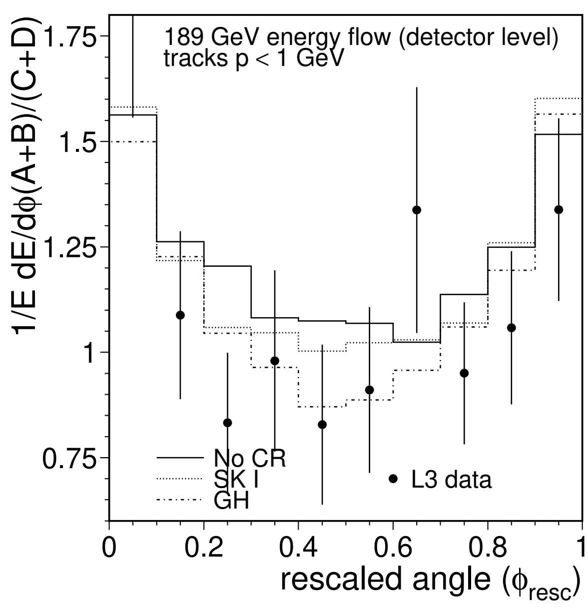


L3

- selection on topological criteria
- measure energy flow between Ws

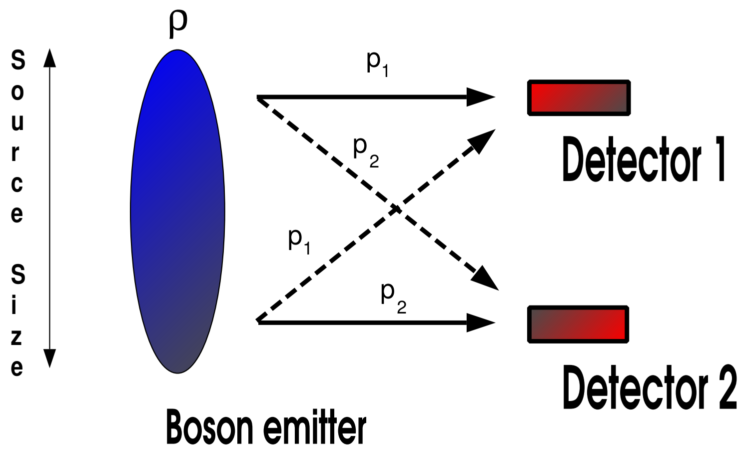
- rescale angle between jets and project momentum on jet-jet plane
- consider ratio between regions: (A +B) / (C +D)





Bose-Einstein Correlations

Quantum mechanical effect



Bosons $\longrightarrow$ symmetric wave function

correlation function: $C(Q) = 1 + \lambda e^{-Q^2 R_0^2}$

$Q = \sqrt{-(p_1 - p_2)^2}$: Lorentz invariant distance in phase-space

$0 < \lambda < 1$: strength of the correlations

$R_0\, \hbar\, c = R$: source size of pion emitter ($\sim$ 1 fm)

- pion pairs from **different** W bosons could exhibit BEC

$\longrightarrow$ distortion of momentum spectrum

BEC well established in Z^0 decays!

Simultaneous Fit by OPAL

Simultaneous fit of $C(Q)$ for following event classes:

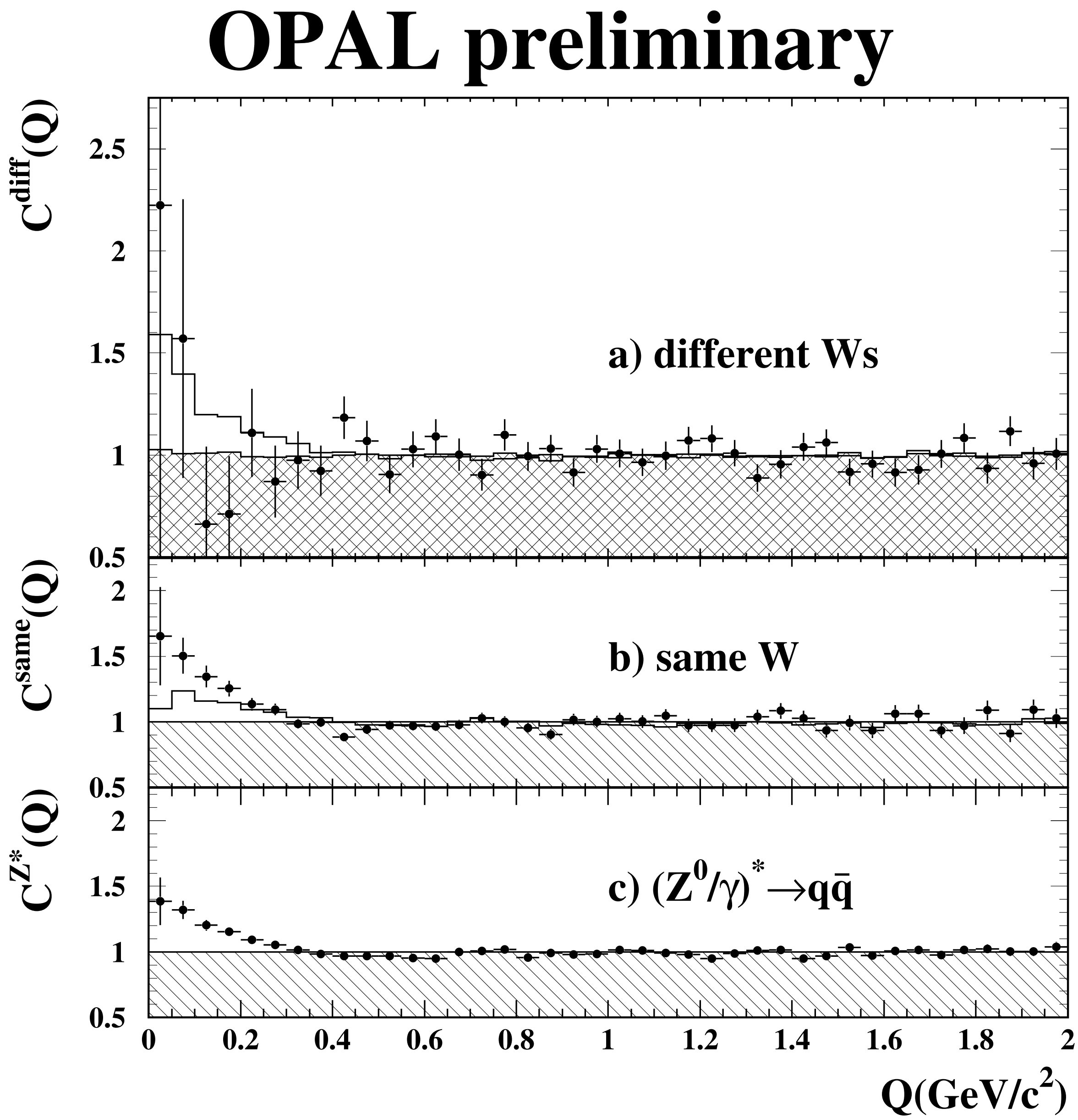
1. **fully hadronic W-pair events**
   $W^+W^- \rightarrow (q\bar{q})(q\bar{q})$: BEC in same and different W-bosons
2. **semileptonic W-pair events**
   $W^+W^- \rightarrow q\bar{q}l\bar{\nu}$: BEC in same W-boson

$$C(Q)_{\mathrm{sel.}} = \Sigma_{i\ \mathrm{classes}}(C_i(Q) \cdot P_i(Q))$$

- $C_i(Q)$ BEC for 'pure' pion class i
  (same W-boson, different W-bosons)
- $P_i(Q)$ probability for a pion pair to come from process i
  (probability determined with Monte-Carlo)

simultaneous fit with C^{same} and C^{diff} as free parameters

Bin-by-Bin Separation



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Theoretical Information for C^{diff}

- C^{diff} statistically limited (less pairs close in phase space)
- use theoretical input for R^{diff}
- express R^{diff} as a function of
  1. R^{same}; source size within the same W
  2. separation of W decay vertices

$\rightarrow (R^{\text{diff}})^2 = (R^{\text{same}})^2 + 4\beta^2\gamma^2c^2\tau^2$

K. Fialkowski and R. Wit, *BE Effect in Monte-Carlo Generators*,hep-ph/9810492

Parameter	same W	diff W
R (fm)	$1.07 \pm 0.07 \pm 0.12$	$1.51 \pm 0.05 \pm 0.09$
λ	$0.69 \pm 0.12 \pm 0.06$	$0.05 \pm 0.67 \pm 0.35$

Parameter	$(Z^0/\gamma)^*$
R (fm)	$1.01 \pm 0.08 \pm 0.14$
λ	$0.43 \pm 0.06 \pm 0.08$

$\rightarrow$ no conclusion for C^{diff} possible

Subtraction Method by L3

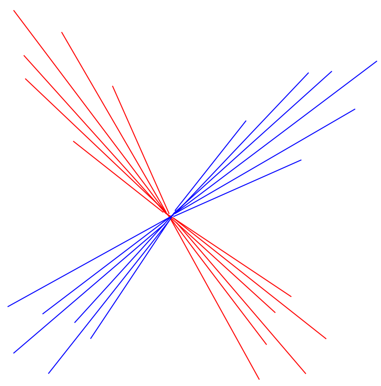
the contributions in $\mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$ events can be written as :

$$\rho(p_1,p_2)^{\mathrm{WW}} = \rho(p_1,p_2)^{\mathrm{W^-}} + \rho(p_1,p_2)^{\mathrm{W^+}} + 2\rho(p_1,p_2)^{\mathrm{WW}}_{\mathrm{mixed}}$$

$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
BEC for	BEC for	BEC for	BEC for
$\mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$	$\mathrm{W^-} \to \mathrm{\bar{q}q}$	$\mathrm{W^+} \to \mathrm{\bar{q}q}$	pairs from different Ws

with $\rho(p_1,p_2) = \frac{1}{N_{\mathrm{ev}}}\frac{\mathrm{d}n_{\mathrm{pairs}}}{\mathrm{d}Q}$

- $\rho(p_1,p_2)^{\mathrm{W^-}} = \rho(p_1,p_2)^{\mathrm{W^+}} = \rho(p_1,p_2)^{\mathrm{W}}$:
  two-particle density from same W



- $\rho(p_1,p_2)^{\mathrm{WW}}_{\mathrm{mixed}}$:
  two particle density, using particles from different Ws

Extract BEC for pions from different W bosons

$$\Delta\rho(\pm,\pm) = \rho(\pm,\pm)^{\mathrm{WW}} - 2\rho(\pm,\pm)^{\mathrm{W}} - 2\rho(\pm,\pm)^{\mathrm{WW}}_{\mathrm{mixed}}$$

for like-charged pairs, sensitive to BEC, CR, energy conservation

$$\Delta\rho(+-) = \rho(+-)^{\mathrm{WW}} - 2\rho(+-)^{\mathrm{W}} - 2\rho(+-)^{\mathrm{WW}}_{\mathrm{mixed}}$$

for unlike-charged pairs, sensitive to CR, energy conservation

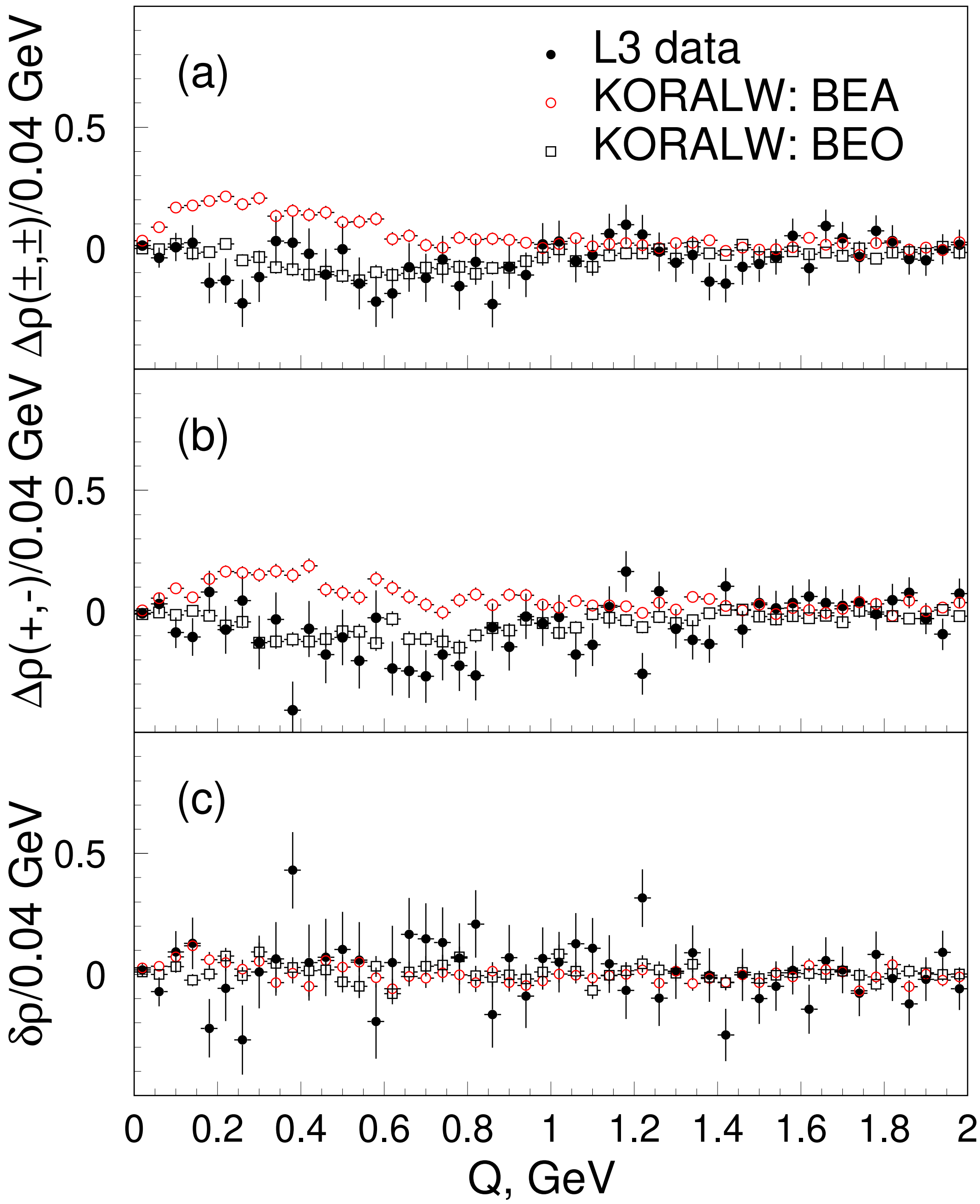
$\delta\rho = \Delta\rho(\pm,\pm) - \Delta\rho(+-) \rightarrow$ **sensitive to BEC**

	χ^2/d.o.f.	C.L. (%) $0 < Q < 0.6$ GeV/c^2
BEA : BEC between all paricles		
$\Delta\rho(\pm,\pm)$, BEA	101.6/14	$2.3 \cdot 10^{-13}$
$\Delta\rho(+,-)$, BEA	68.3/14	$3.1 \cdot 10^{-6}$
$\delta\rho$, BEA	21.8/14	8.3
BEO : no BEC simulation		
$\Delta\rho(\pm,\pm)$, BEO	38.7/49	39.2
$\Delta\rho(+,-)$, BEO	18.7/14	43.8
$\delta\rho$, BEO	20.9/14	10.4

$\rightarrow$ $\Delta\rho(\pm,\pm)$ and $\delta\rho$ show no excess for low Q

$\rightarrow$ $\Delta\rho(\pm,\pm)$ and $\Delta\rho(+,-)$ exclude LUBOEI (BEA) model

Distributions



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BEC approaches by ALEPH and DELPHI

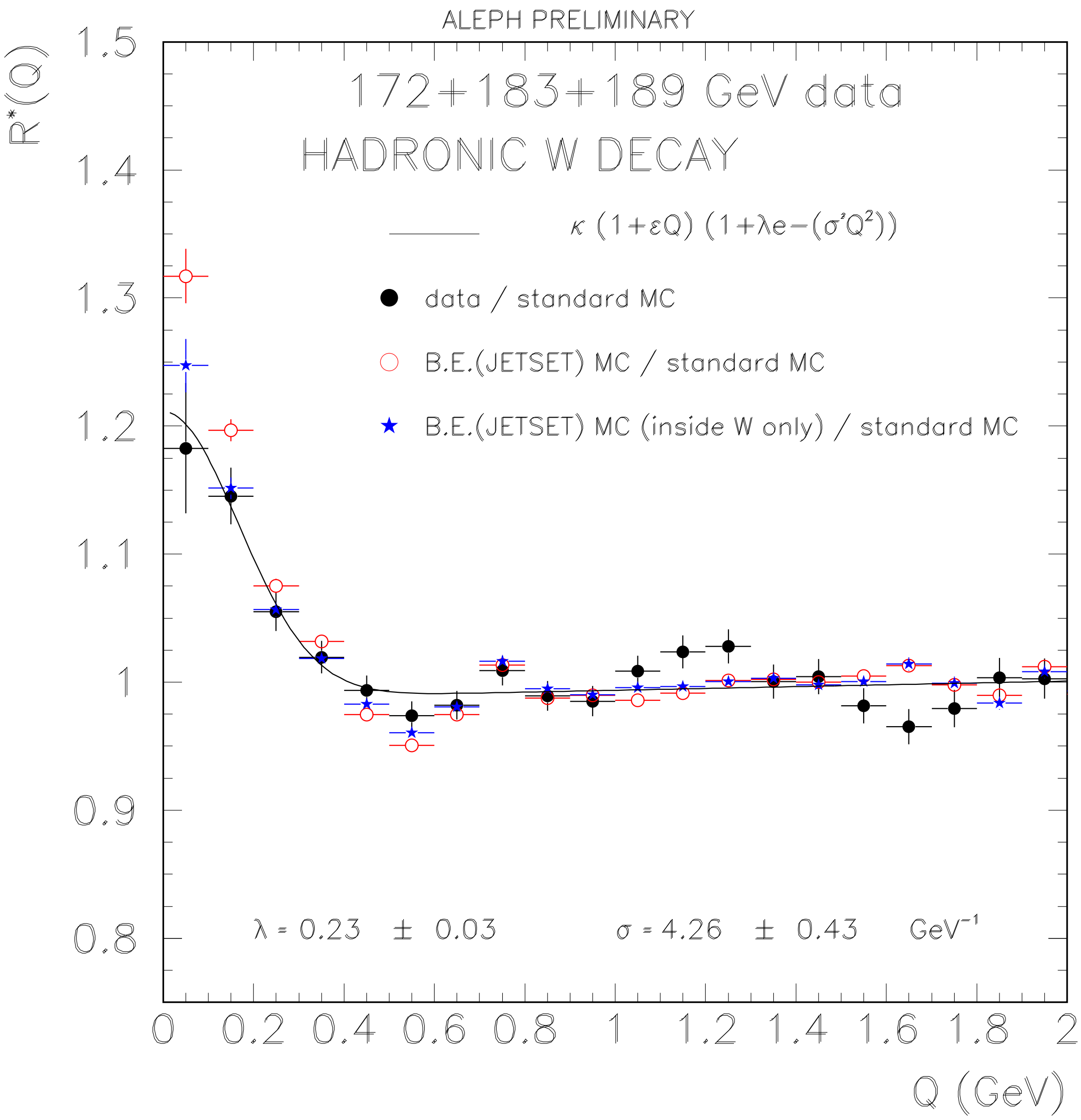
- ALEPH:
  - tune BEC MC at Z^0 data
  - compare $W^+W^- \to q\bar{q}q\bar{q}$ distribution with different MC BEC scenarios
  - exclude MC with BEC between different W bosons by 2.7σ
- DELPHI:
  - build $W^+W^- \to q\bar{q}q\bar{q}$ events out of two $W^+W^- \to q\bar{q}\ell\overline{\nu}_\ell$ events
  - comparison with $W^+W^- \to q\bar{q}q\bar{q}$ events
  - variable Δ sensitive to BEC between pions from different Ws $\Delta = 7.3 \pm 2.5$(stat.)± 1.8(syst.)$\%$ $\to$ 2.2 σ

$\to$ contradiction between measurements

Summary and Conclusion

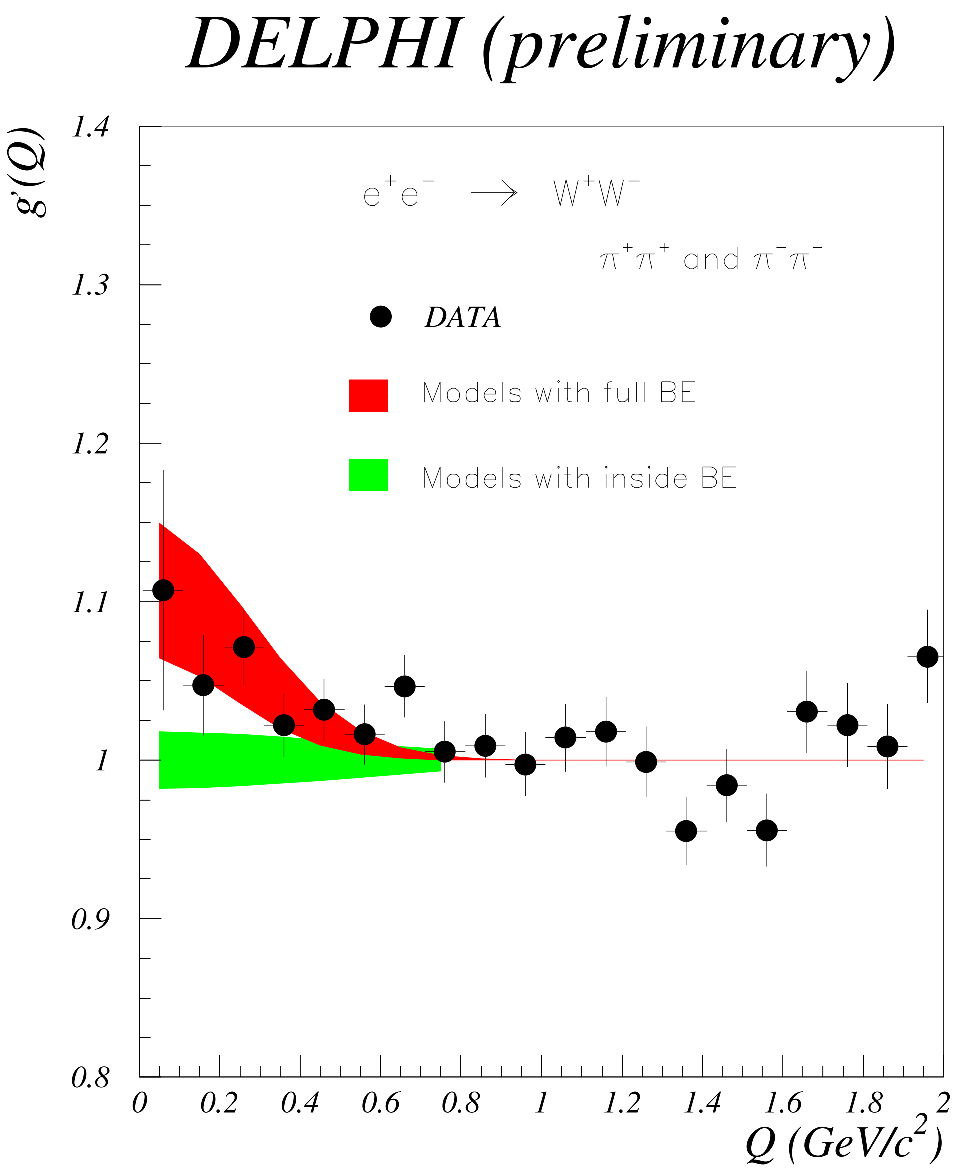
- Fragmentation effects could bias $\mathrm{M_W}$
- Color Reconnection
  - charged multiplicity consistent with standard MC
  - momentum distribution consistent with standard MC
  - energy and particle flow analysis looks promising
- Bose-Einstein Correlations
  - 4 experiments - 4 methods
  - no consistent picture and no conclusive answer yet
  - more experimental effort necessary to understand BEC
  - LUBOEI model possibly excluded by L3
- CR and BEC still important point for $\mathrm{M_W}$ measurement

BEC at ALEPH



ALEPH PRELIMINARY
172+183+189 GeV data
HADRONIC W DECAY
κ (1+εQ) (1+λe−(σ²Q²))
data / standard MC
B.E.(JETSET) MC / standard MC
B.E.(JETSET) MC (inside W only) / standard MC
λ = 0.23 ± 0.03
σ = 4.26 ± 0.43 GeV⁻¹
R*(Q)
Q (GeV)
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

BEC at DELPHI



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