Bose-Einstein Correlations in fully hadronic WW decays at LEP-2

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- Introduction to Bose-Einstein Correlations
- Methods to study BEC
- Results from ALEPH, DELPHI, L3 & OPAL
- Summary & Conclusion

Introduction to Bose-Einstein Correlations:

Identical bosons obey Bose-Einstein statistics:
Enhancement of identical bosons close in phase space

In e^+e^--annihilations BEC in charged particle pairs are unambiguously established in Z^0, W events

Main interest at LEP-2 ($e^+e^- \rightarrow W^+W^-$):

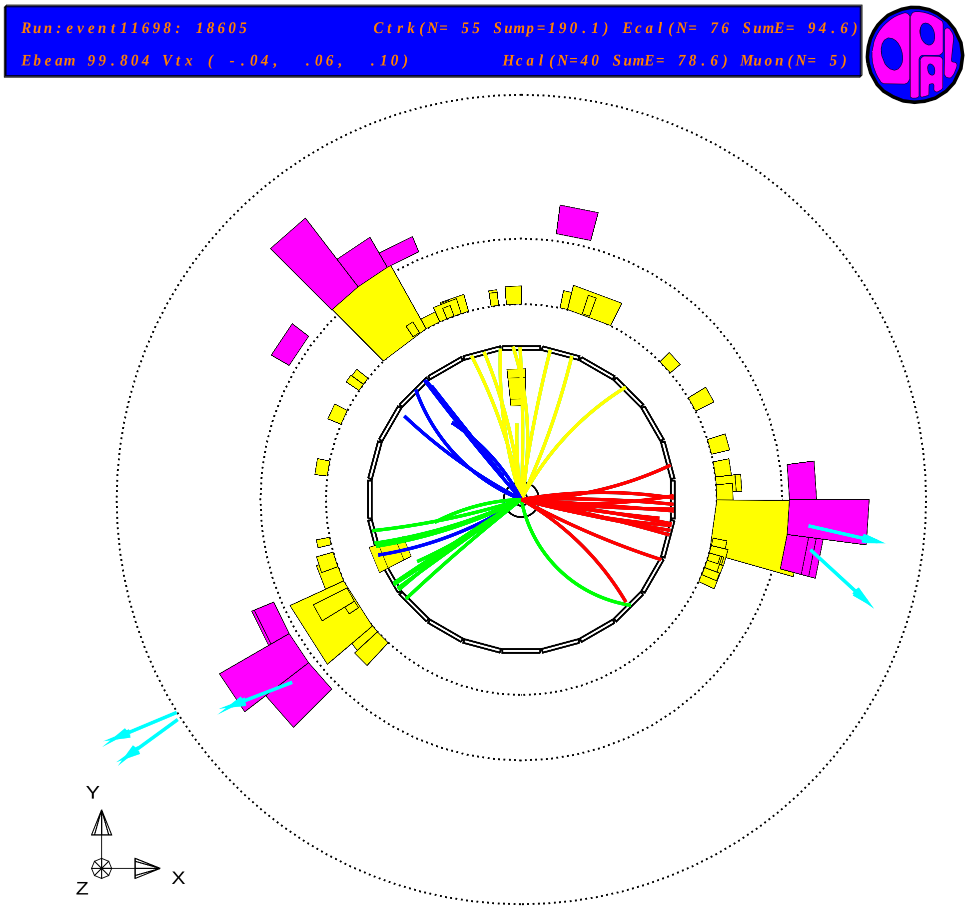
- Is there evidence for BEC between particles coming **from different W's** (inter-WW BEC)?

Consequence:

- Systematic uncertainty in the determination of the W mass in the 4-quark channel.
  Initial predictions for ΔM_W^{4q}: 0 – 100 MeV/c^2

Latest LEP W mass combination:
$\Delta M_W^{\mathrm{BEC}}(4q) = 25$ MeV/c^2

$W^+W^- \rightarrow q_1\overline{q_2}q_3\overline{q_4} \rightarrow$ **4 jets**

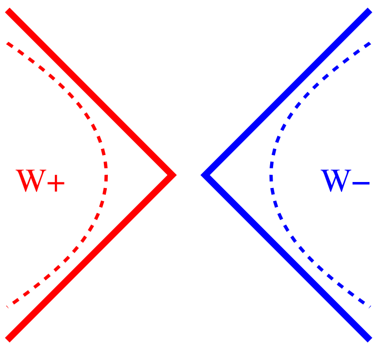


Space-time overlap:

- Typical separation of the two W decay vertices: 0.1 fm.
- Typical scale of hadronization: 0.5 – 1 fm.

String model

2 independent strings:



If BEC affect particles from different W's (inter–WW BEC) a transfer of particles and/or momentum can disturb the W mass determination from the invariant 2-jet mass.

Inter-WW BEC extraction methods:

- BEC effects are studied in terms of 4-momentum differences

$$Q^2 = -(p_1 - p_2)^2$$

- BEC traditionally studied with two-particle correlation function:

$$\rho(p_1, p_2) = \frac{1}{N_{ev.}} \frac{\mathrm{d}n_{\mathrm{pairs}}}{\mathrm{d}Q} \qquad R(p_1, p_2) = \frac{\rho(p_1, p_2)}{\rho_0(p_1, p_2)}$$

- ρ_0: reference without BEC
  - unlike sign charged particle pairs
  - Monte Carlo without BEC
  - 'mixed' events
- phenom. parametrization: $R(Q) \approx (1 + \lambda \cdot \exp(-r^2 Q^2))$
  - r: source radius
  - λ: BEC strength

Selected WW samples
WW$\longrightarrow$qqqq, qqlν, lνlν:

ALEPH	479 pb^{-1} @ 172–202 GeV
DELPHI	531 pb^{-1} @ 189–206 GeV
L3	627 pb^{-1} @ 189–208 GeV
OPAL	250 pb^{-1} @ 172–189 GeV

WW$\longrightarrow$4q sample contain 10-20% background, mainly $Z^{0*}/\gamma \rightarrow$ 4 jets.
Subtracted with BEC MC.

MC implementation of BEC:

`PYBOEI/PYTHIA` reshuffles particle momenta after fragmentation to simulate BE effect

option 1: full BEC, intra + inter BEC
option 2: only intra-W BEC, no inter-WW BEC
option 3: no BEC

`PYBOEI/PYTHIA` parameters tuned to Z^0 data.
Tested on WW$\longrightarrow$qqlν

Analysis à la Chekanov, De Wolf, Kittel

Eur.Phys.J C6(1999) 403 & hep-ph/0101243

Access to inter–WW BEC directly from data.
In the absence of inter–WW correlations the 2-particle density ρ for like sign and unlike sign pairs can be written as

$$\boxed{\rho^{WW\to 4q} = 2\cdot\rho^{W\to 2q} + \rho^{WW_{mix}}}$$

- WW $\longrightarrow$ 4q: 4q sample
- W $\longrightarrow$ 2q: qqlν sample without the leptonic part
- WW$_{mix}$: event made of 2 independent W $\longrightarrow$ 2q events, use only pairs of particles from different W's

Sensitive test distributions:

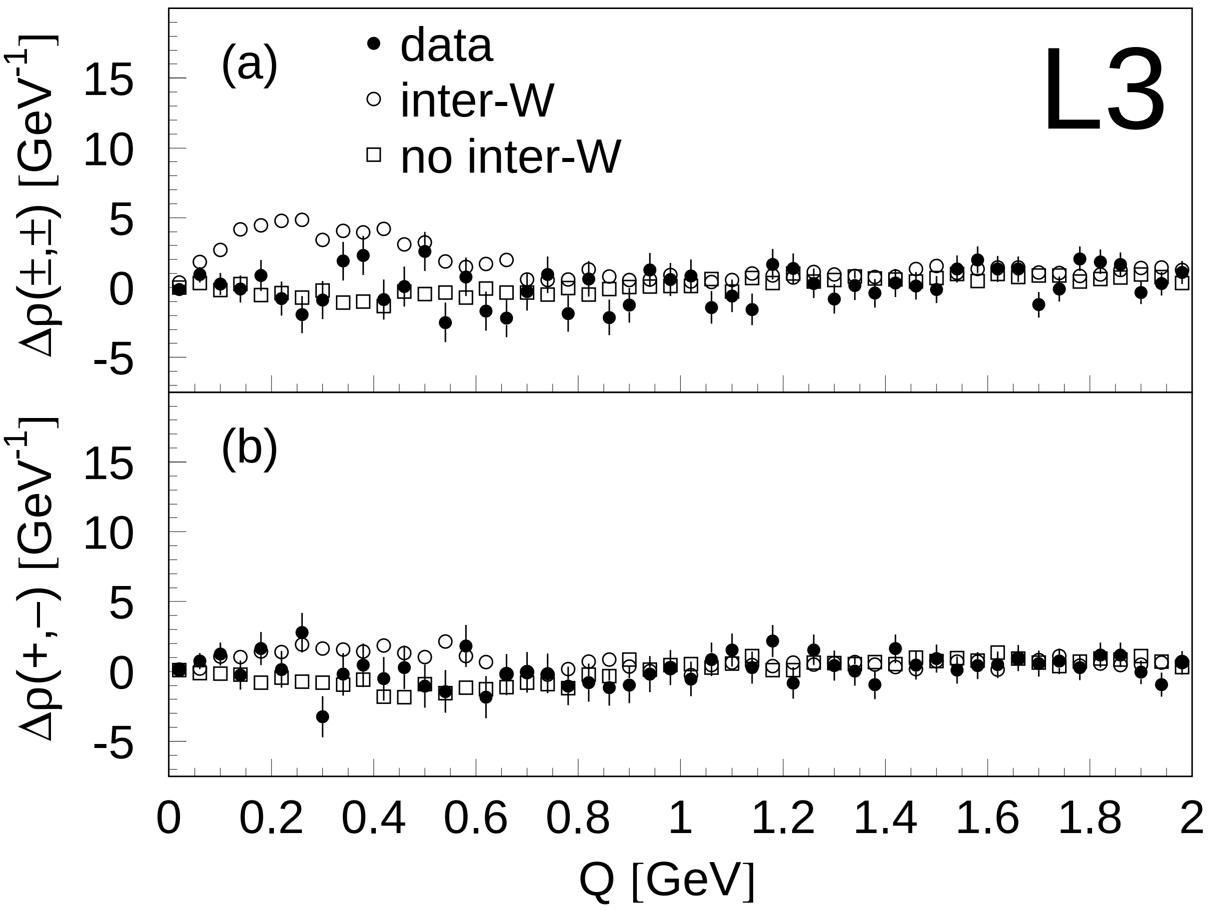
$$\boxed{\Delta\rho = \rho^{WW\to 4q} - 2\cdot\rho^{W\to 2q} - \rho^{WW_{mix}}}$$

$$\boxed{D(Q) = \frac{\rho^{WW\to 4q}}{2\cdot\rho^{W\to 2q}+\rho^{WW_{mix}}}} \qquad \boxed{D'(Q) = \frac{D(Q)}{D(Q)_{\mathrm{MC,w/o\,inter-WW\,BEC}}}}$$

If inter-WW BEC do not exist
$\Delta\rho(\mathrm{Q}) = 0$
$\mathrm{D(Q)} = \mathrm{D'(Q)} = 1$

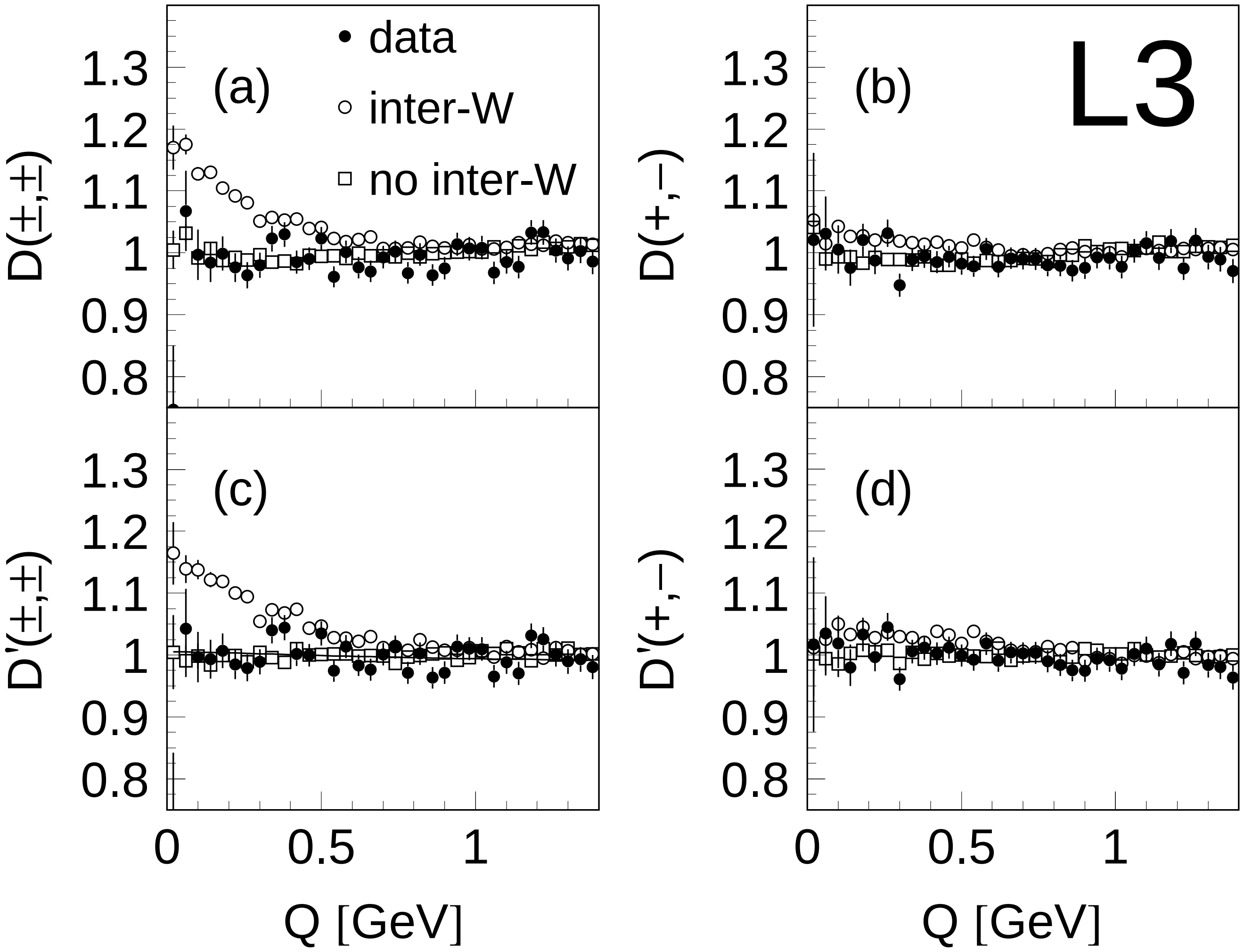
$\mathrm{L3}$ results (I):

Mixed events analysis à la Chekanov, De Wolf, Kittel



- inter-WW BEC MC:
  Enhancement of like sign pairs in the small Q region.
  Unlike sign pairs artificially disturbed by the MC model.

L3 results (II):

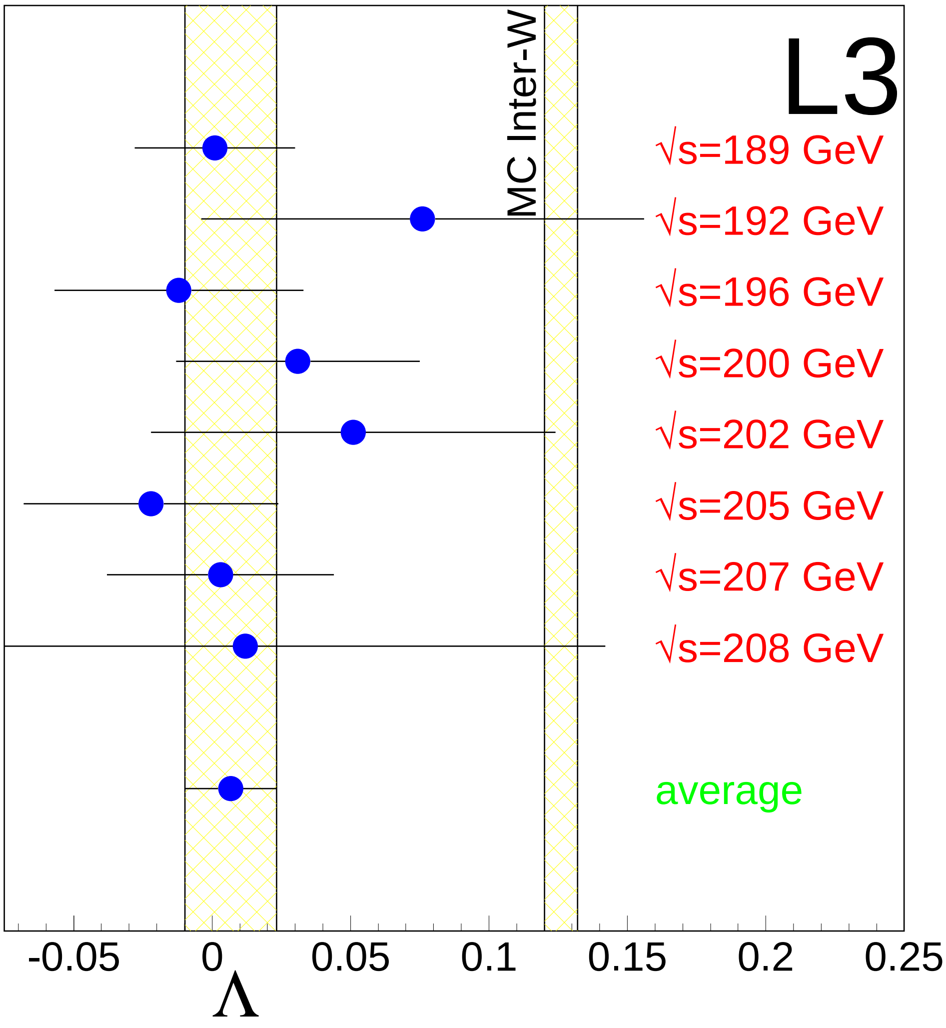


Data compatible with no inter-WW BEC scenario

$\longrightarrow$ quantify the exclusion of inter-WW BEC

$\mathrm{L3}$ **results (III):**

Empirical fit: $D'(Q) = (1 + \epsilon Q)(1 + \Lambda \cdot \exp(-\sigma^2 Q^2))$



$$\Lambda^{\mathrm{inter-WW\,BE}} = 0.126 \pm 0.008(\mathrm{stat.})$$
$$\Lambda^{\mathrm{data}} = 0.008 \pm 0.018(\mathrm{st.}) \pm 0.016(\mathrm{sy.})$$

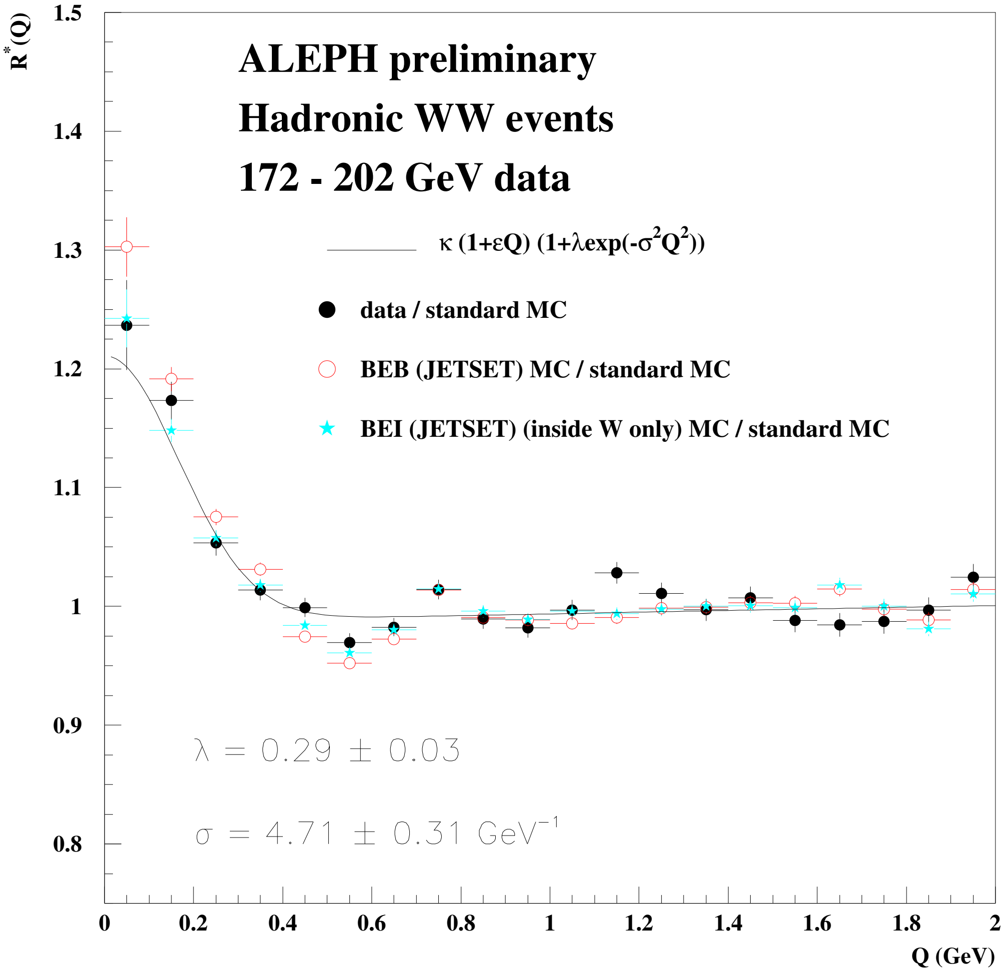
No evidence for inter-WW BEC.
Inter-WW BEC MC is disfavoured with 4.7σ.

ALEPH results (I):

Reference ρ_0: unlike sign particle pairs

- double ratio (corrects for possible distortions)

$$R^*(Q) = \left(\frac{\rho^{++,--}(Q)}{\rho^{+-}(Q)}\right)^{\mathrm{data}} \Big/ \left(\frac{\rho^{++,--}(Q)}{\rho^{+-}(Q)}\right)^{\mathrm{MC(WW+q\overline{q}(bg))}}_{\mathrm{w/o\,BEC}}$$

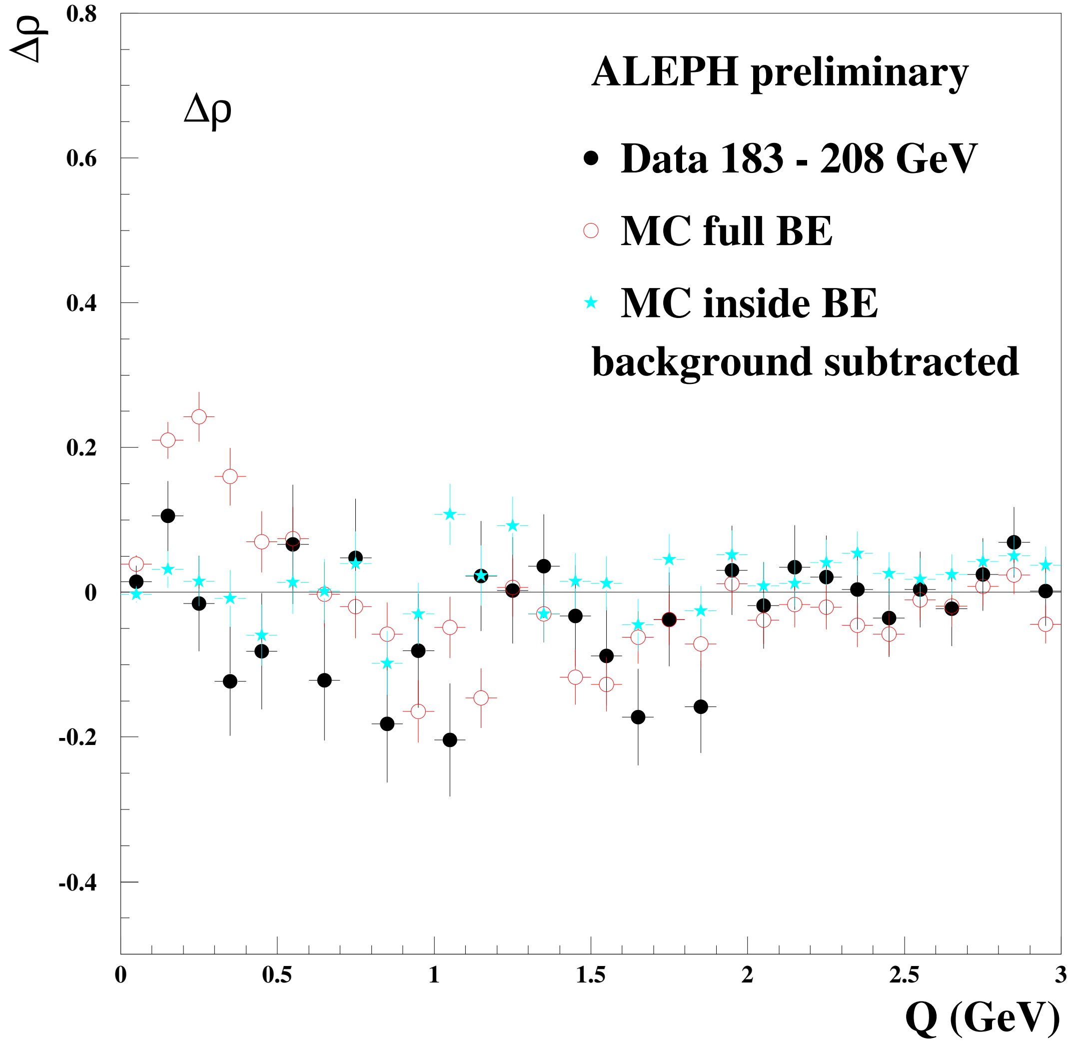


Data compatible with only intra-W BE.
Inter-WW BEC (BEB) scenario disfavored with 2.2σ

Aleph results (II):

Mixed events analysis à la Chekanov, De Wolf, Kittel (all data $\geq$ 183 GeV) :

$$\Delta\rho(Q) = (\rho_{4\mathrm{q}} - \rho_{\mathrm{mixed}})^{\mathrm{data}} - (\rho_{4\mathrm{q}} - \rho_{\mathrm{mixed}})^{\mathrm{MC(WW)}}_{\mathrm{w/o\,BEC}}$$

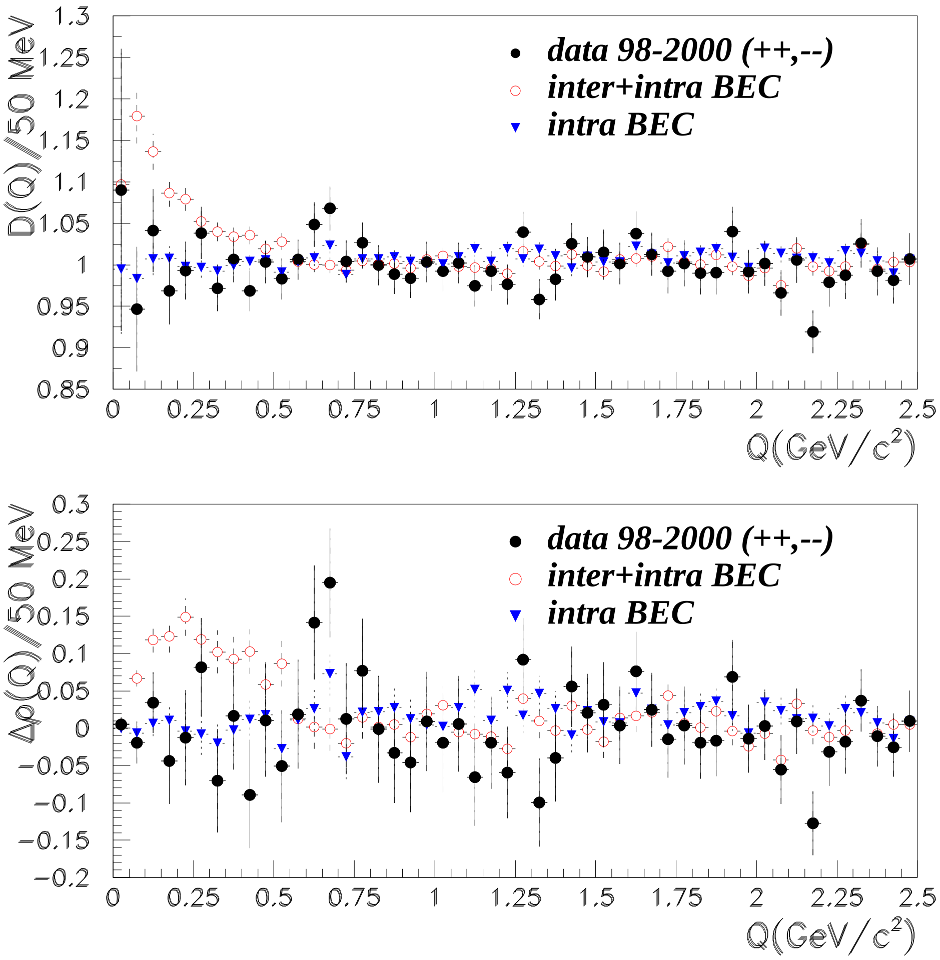


Data clearly prefer no inter-WW BEC (inside BE)

DELPHI **results:**

Mixed events analysis à la Chekanov, De Wolf, Kittel

- Empirical fit $D(Q) = N(1 + \epsilon Q)(1 + \Lambda \cdot \exp(-\sigma Q))$
- fix σ to 1.01 fm (fit result for full BE MC)



$$\Lambda^{\text{intra + inter BEC}} = 0.24 \pm 0.03(\text{stat.only})$$
$$\Lambda^{\text{data}} = -0.037 \pm 0.055(\text{stat.}) \pm 0.055(\text{syst.})$$

No evidence for inter-WW BEC.
Inter-WW BEC MC is disfavoured with 3.2σ.

OPAL **results (I):**

Reference ρ_0: unlike sign pairs

– double ratio R(Q): (data / MC without BEC)

- R(Q) studied for 3 samples at LEP-2 energies:
  – WW $\rightarrow$ qqqq
  – WW $\rightarrow$ qqlν
  – Z^{0*} $\rightarrow$ qq
  all three samples contain contributions from the others

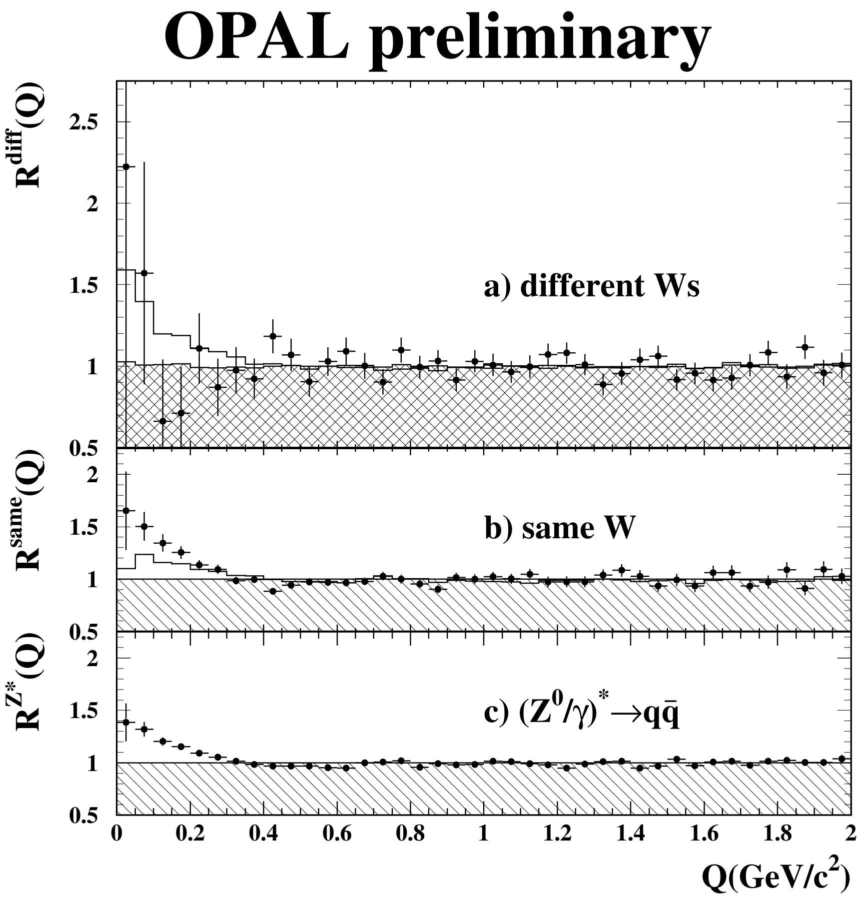
- Deconvolute to three pure contributions:
  – R$^{\text{same}}$(Q) for intra-W BEC
  – R$^{\text{diff}}$(Q) for inter-WW BEC
  – R$^{Z^*}$(Q) for BEC in qq events

OPAL **results (II):**

Simultaneous fit to $R^{\text{same}}(Q)$, $R^{\text{diff}}(Q)$, $R^{Z^*}(Q)$:

$$R(Q) = N(1 + \mathcal{P}_\pi(Q) \cdot \lambda \cdot \exp(-\sigma^2 Q^2))$$

$\lambda^{\text{diff}} = 0$, if inter-WW BEC do not exist



$$\lambda^{\text{same}} = 0.69 \pm 0.12(\text{stat.}) \pm 0.06(\text{syst.})$$
$$\lambda^{Z^*} = 0.43 \pm 0.06(\text{stat.}) \pm 0.08(\text{syst.})$$
$$\lambda^{\text{diff}} = 0.05 \pm 0.67(\text{stat.}) \pm 0.35(\text{syst.})$$

Within errors, data (172-189 GeV) compatible with both no inter-WW BEC and inter-WW BEC

Publication using the mixing method is in preparation.

Conclusion & Outlook:

Inter-WW BEC not observed by the LEP experiments.

$\hookrightarrow$ Now a consistent picture compared to Osaka 2000

Why does ADLO not observe inter-WW BEC?

Hypotheses:

1. Inter-WW BEC do not exist:
   Consistent with the Lund string model picture in WW
   The strings from the two W's are independent
2. Inter-WW BEC do exist:
   Incoherent emission from two independent sources
   as in astronomy (Hanbury-Brown Twiss)
   BUT: Correlations are too short ranged in Q to be observed.
   Larger R?
   Non spherical sources? (see Z^0 analyses) $\Rightarrow$
   The space-time overlap of the two W system is smaller than expected.

– What about heavy-ion collisions?

Outlook:

ADLO combination with mixing method in progress $\Rightarrow$
Model independent limits for inter-WW BEC using the combined data.
W mass uncertainty < 20 MeV/c^2?