Bose-Einstein Correlations in W^+W^- Events at LEP

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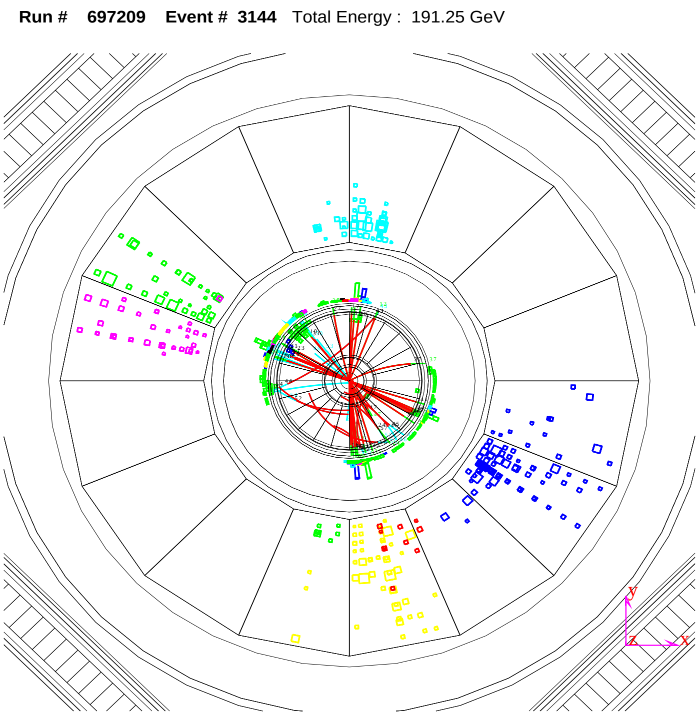
Introduction

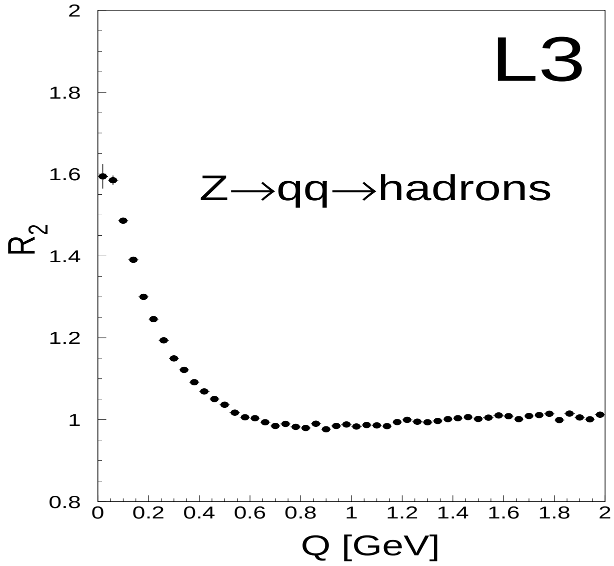


$$W^+W^- \to q_1\bar{q}_2q_3\bar{q}_4$$

Distance between W decay vertices $\sim$ 0.1 fm, whereas the hadronic scale $\sim$ 1 fm.
$\Rightarrow$ There may be inter-W correlations:

- Colour reconnection
- Inter-W Bose-Einstein correlations (BEC)

Bose-Einstein correlations?



where $\quad Q \equiv \sqrt{-(p_1 - p_2)^2} \quad$ and $\quad R_2 = \dfrac{\rho(Q)}{\rho_0(Q)}$

→ A well established effect at LEP I.

At LEP II, BEC in $e^+e^- \rightarrow W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$ can be divided into two types:

intra-W BEC: BEC between particles coming from the same W (do exist).
inter-W BEC: BEC between particles originating from different W's (may exist).

Inter-W BEC form a potential bias in the determination of the W-mass. The main question is therefore:

$\boxed{\text{DO INTER-W BEC EXIST ?}}$

Status of Analysis for BEC

- L3: 189 GeV data (prel.)
- DELPHI: 183, 189, 192, 196, 200 GeV data (prel.)
- ALEPH: 172, 183, 189 (publ.), 192, 196, 200, 202 GeV data (prel.)
- OPAL: 172, 183, 189 GeV data (prel.)

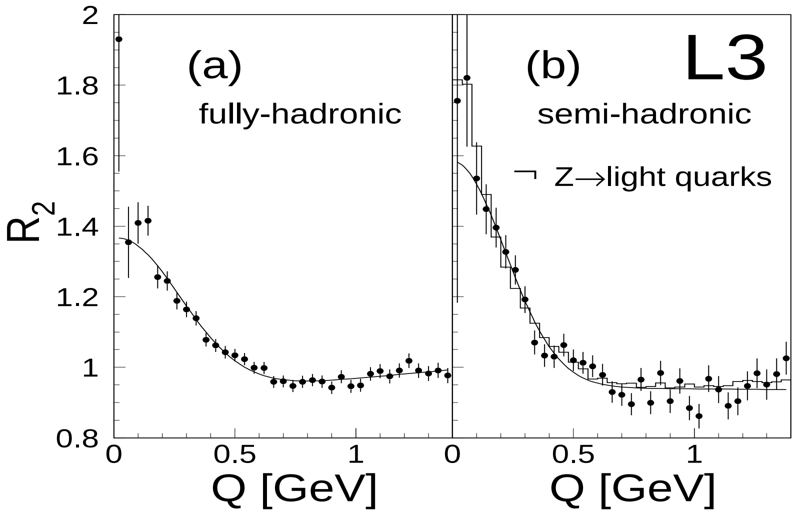
Typical number of W-pair events per experiment

$\sqrt{s}$ (GeV)	WW$\rightarrow$ $\mathrm{q_1\bar{q}_2q_3\bar{q}_4}$	WW$\rightarrow$ $\mathrm{q_1\bar{q}_2}\ell\nu_\ell$
172	60	40
183	450	300
189	1500	1000
192	270	180
196	660	440
200	750	500
202	330	220
total	4000	2700

L3 Analysis

Define the two-particle density: $\rho(p_1, p_2) = \frac{1}{N_{\mathrm{ev}}} \frac{\mathrm{d}n_{\mathrm{pairs}}}{\mathrm{d}Q}$

Intra-W BEC exist:



$$R_2 \equiv \frac{\rho(\pm,\pm)_{\mathrm{data}}}{\rho(\pm,\pm)_{\mathrm{MC,\,noBE}}}$$

and corrected for detector effects.

fit: $R_2(Q) = \gamma(1 + \delta Q)(1 + \lambda \exp(-R^2 Q^2))$

$\Rightarrow \lambda_{\mathrm{fully}} < \lambda_{\mathrm{semi}} \simeq \lambda_{\mathrm{Zudsc}}$

$\Rightarrow$ In agreement with no or weak inter-W BEC.

Study the (non-)existence of inter-W BEC directly:

If independent decay:

$$\rho^{\mathrm{WW}}(1,2) = \rho^{\mathrm{W}^+}(1,2) + \rho^{\mathrm{W}^-}(1,2) + 2\underbrace{\rho^{\mathrm{W}^+}(1)\rho^{\mathrm{W}^-}(2)}_{\downarrow\; 2\rho^{\mathrm{W}^+\mathrm{W}^-}_{\mathrm{mix}}}$$

$\rho^{\mathrm{W}^+\mathrm{W}^-}_{\mathrm{mix}}$ is obtained by pairing particles originating from two *different* semi-hadronic WW events.

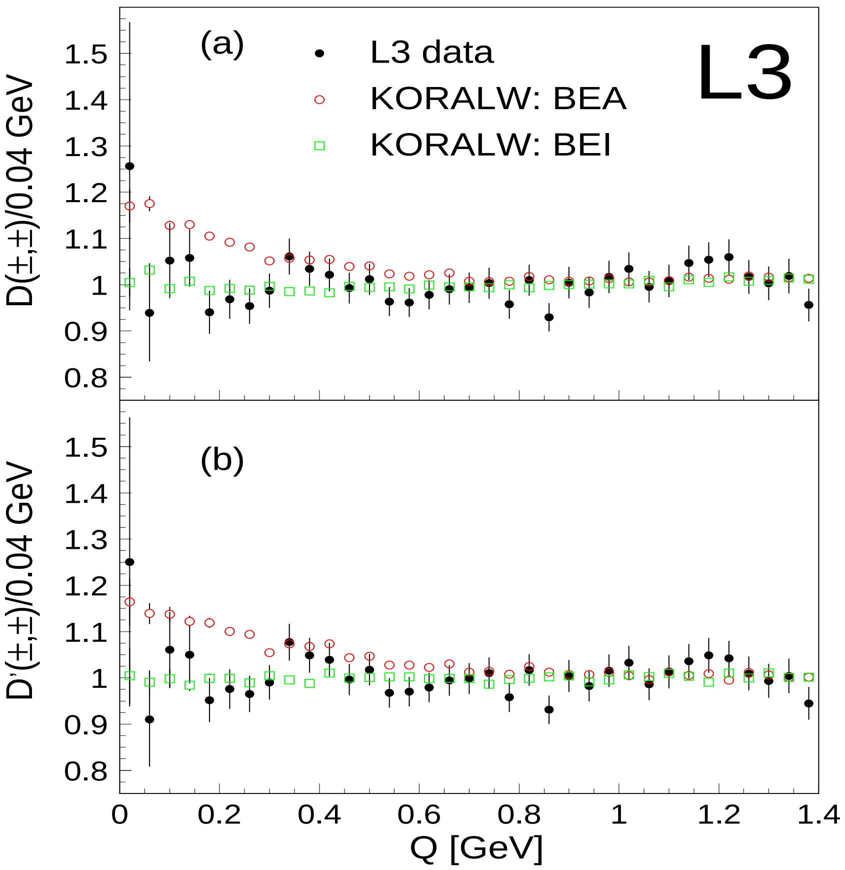
Define the ratio's:

$$D = \frac{\rho^{\mathrm{WW}}}{2\rho^{\mathrm{W}} + 2\rho^{\mathrm{W^+W^-}}_{\mathrm{mix}}} \quad \text{and} \quad D' = \frac{D_{\mathrm{data}}}{D_{\mathrm{MC,no\ BE}}}$$

$2\rho^{\mathrm{W}} + 2\rho^{\mathrm{W^+W^-}}_{\mathrm{mix}}$: two-particle density in fully-hadronic events that would occur if inter-W BEC did not exist.

$\Rightarrow$ look for a deviation from $D, D' = 1$

Results: BEA – BEC between all particles
BEI – only inside W's BEC

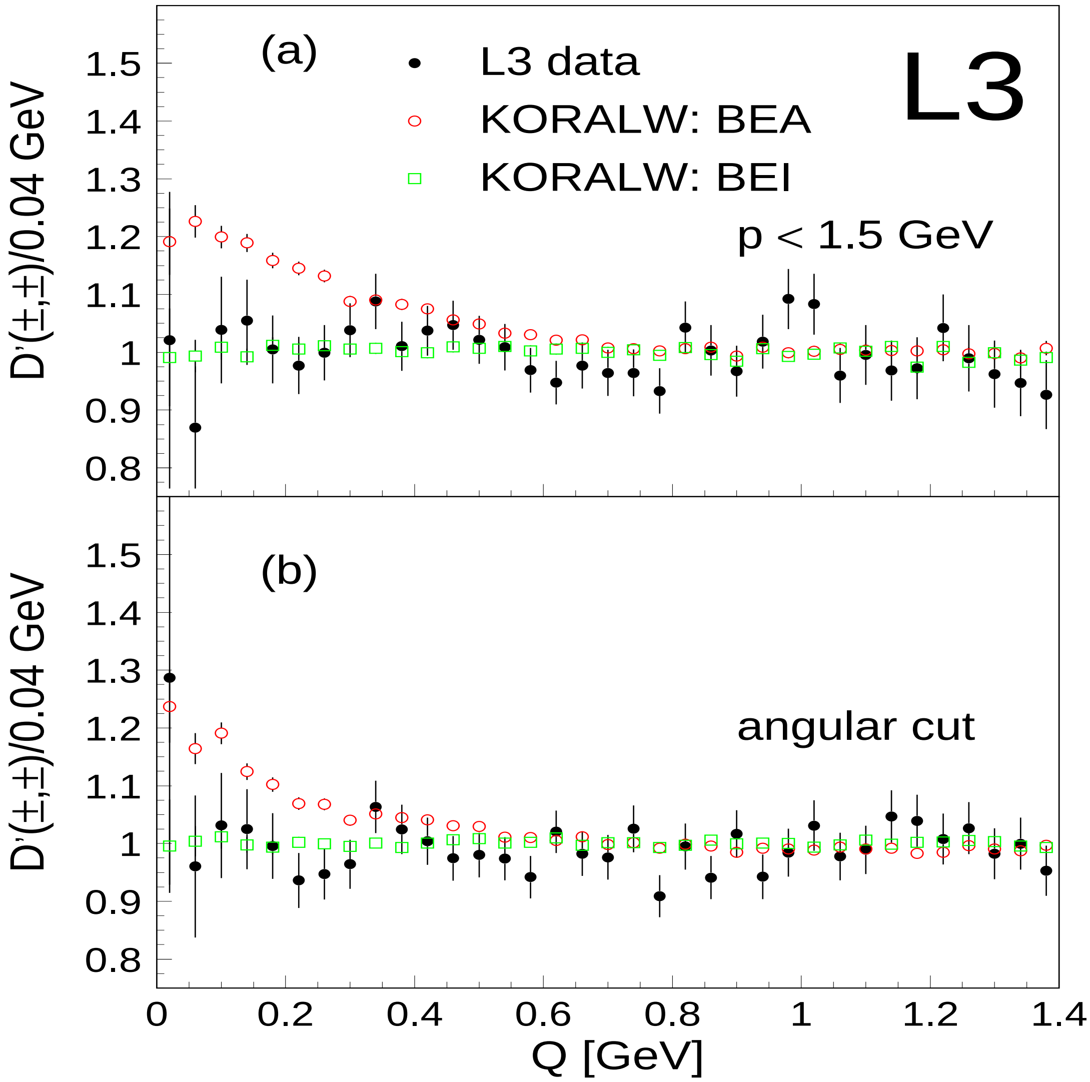


$D(\pm,\pm)$: strong enhancement in BEA; no enhancement in BEI and data

D': not very different

Fit: $D'(Q) = (1 + \epsilon Q)(1 + \Lambda \exp(-k^2 Q^2))$

$\Rightarrow \Lambda = -0.002 \pm 0.022(\text{stat}) \pm 0.015(\text{syst})$



Sensitivity analyses:

- $|\vec{p}_i| < 1.5$ GeV $\Rightarrow \Lambda = 0.024 \pm 0.034(\text{stat})$
- cut on angle between jets of different W's
  $\Rightarrow \Lambda = -0.019 \pm 0.029(\text{stat})$

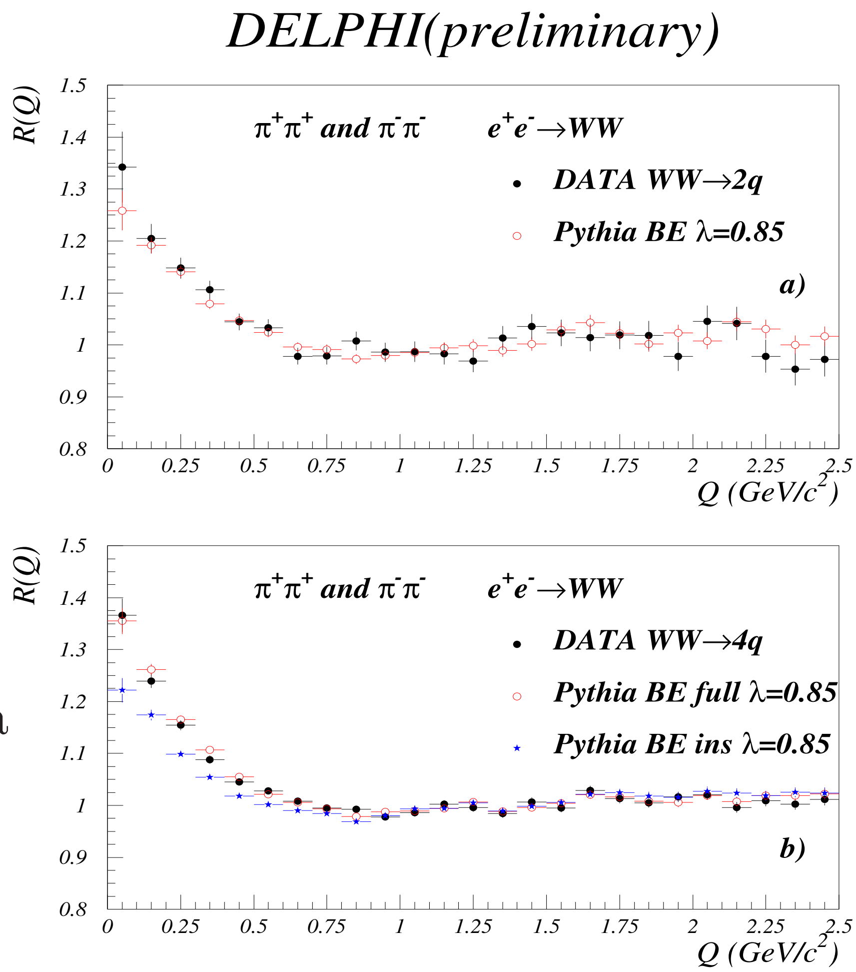
$\Rightarrow$ NO evidence for the existence of inter-W BEC:
BEA is excluded with $\sim 5.0\sigma$, BEI describes the data.

Delphi Analysis

$R_2(Q) = \frac{N^{\pm\pm}_{\text{data}}(Q)}{N^{\pm\pm}_{\text{MC, noBE}}(Q)}$ and corrected for detector effects:

$\text{WW} \rightarrow q_1\bar{q}_2\ell\nu_\ell$:

$\text{WW} \rightarrow q_1\bar{q}_2q_3\bar{q}_4$:
MC tuned to Z-data



$\Rightarrow$ BEA describes the data better than BEI at low Q

BEI is disfavoured by 2.9σ

Moreover:
$$\lambda_{\text{semi}} = 0.270 \pm 0.035 \pm 0.010$$
$$\lambda_{\text{fully}} = 0.302 \pm 0.021 \pm 0.019$$
$$\lambda_{'\text{Zudsc}'} = 0.309 \pm 0.008$$

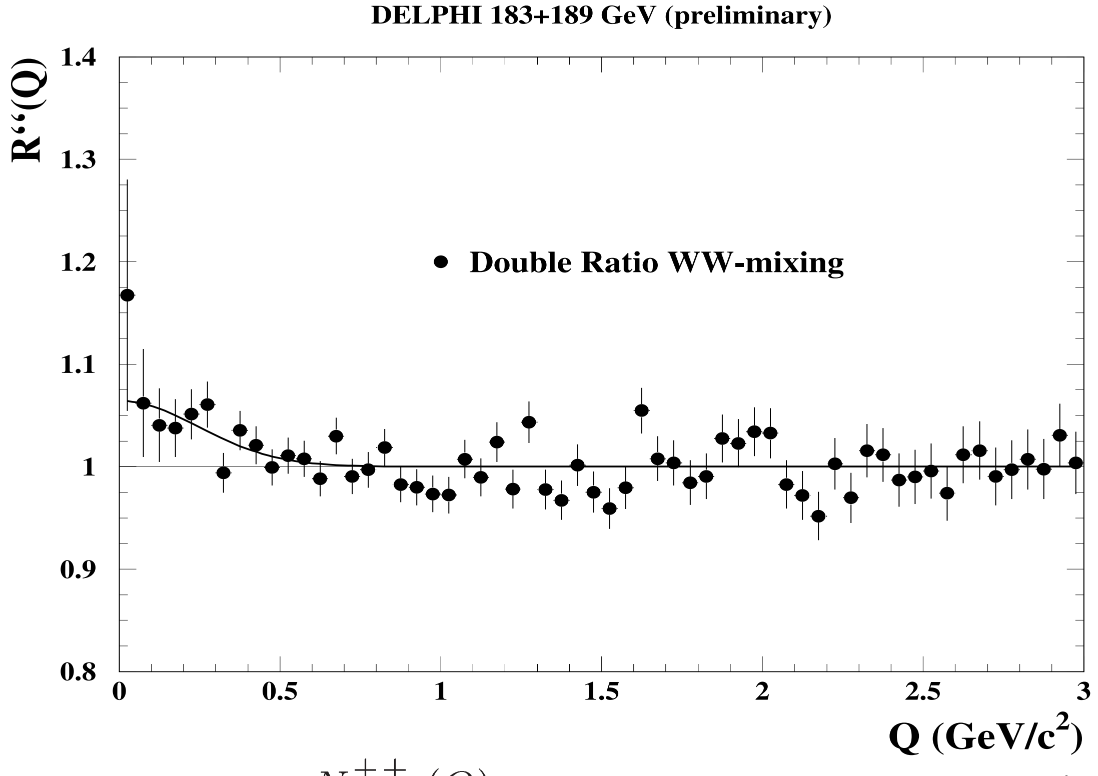
$\Rightarrow$ Indication for the existence of inter-W BEC.

This indication is confirmed by:

Making $R(Q)^{\rm constr} \equiv \frac{\left[N^{\pm\pm}_{\rm semi}+N^{\pm\pm}_{\rm mix}\right]_{\rm data}}{\left[N^{\pm\pm}_{\rm semi}+N^{\pm\pm}_{\rm mix}\right]_{\rm MC,\,noBE}}$, thus no inter-W BEC, where $N^{\pm\pm}_{\rm mix}$ from $\rm WW \rightarrow q_1\bar{q}_2\ell\nu_\ell$ events, gives:

$$\lambda_{\rm constr} = 0.214 \pm 0.029 \pm 0.008$$
$$\Rightarrow \Delta\lambda = 0.088 \pm 0.036 \pm 0.015 \quad \Rightarrow 2.4\sigma \text{ effect.}$$

Moreover, the subset of 183 and 189 GeV data shows:



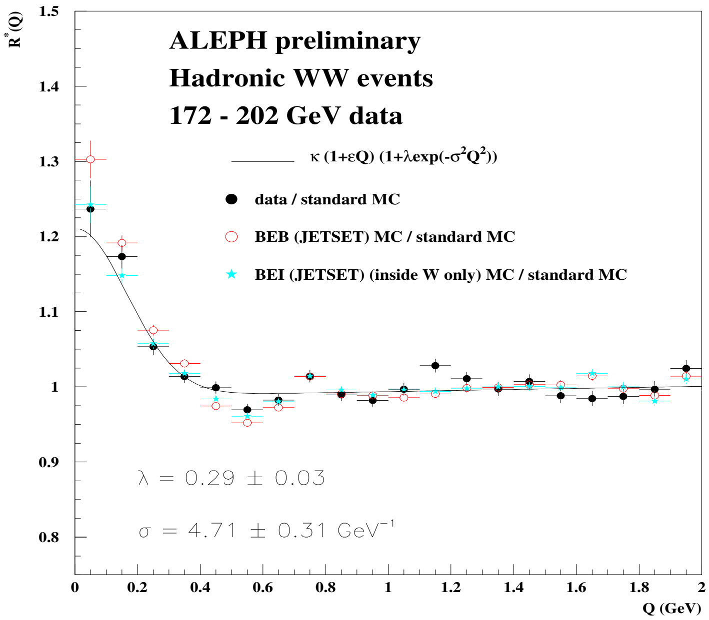
$$R'(Q) \equiv \frac{N^{\pm\pm}_{\rm fully}(Q)}{2N^{\pm\pm}_{\rm semi}+N^{\pm\pm}_{\rm mix}(Q)} \quad \text{and} \quad R''(Q) \equiv \frac{R'(Q)_{\rm data}}{R'(Q)_{\rm MC,\,noBE}}$$

Fit: $R''(Q) = 1 + \Lambda \exp(-k^2Q^2)$

$$\Rightarrow \Lambda = 0.064 \pm 0.040 \quad \Rightarrow 1.6\sigma \text{ effect.}$$

Aleph Analysis

$$R_2(Q) = \left(\frac{N^{\pm\pm}(Q)}{N^{+-}(Q)}\right)^{\text{data}} \Bigg/ \left(\frac{N^{\pm\pm}(Q)}{N^{+-}(Q)}\right)^{\text{MC, noBE}}$$



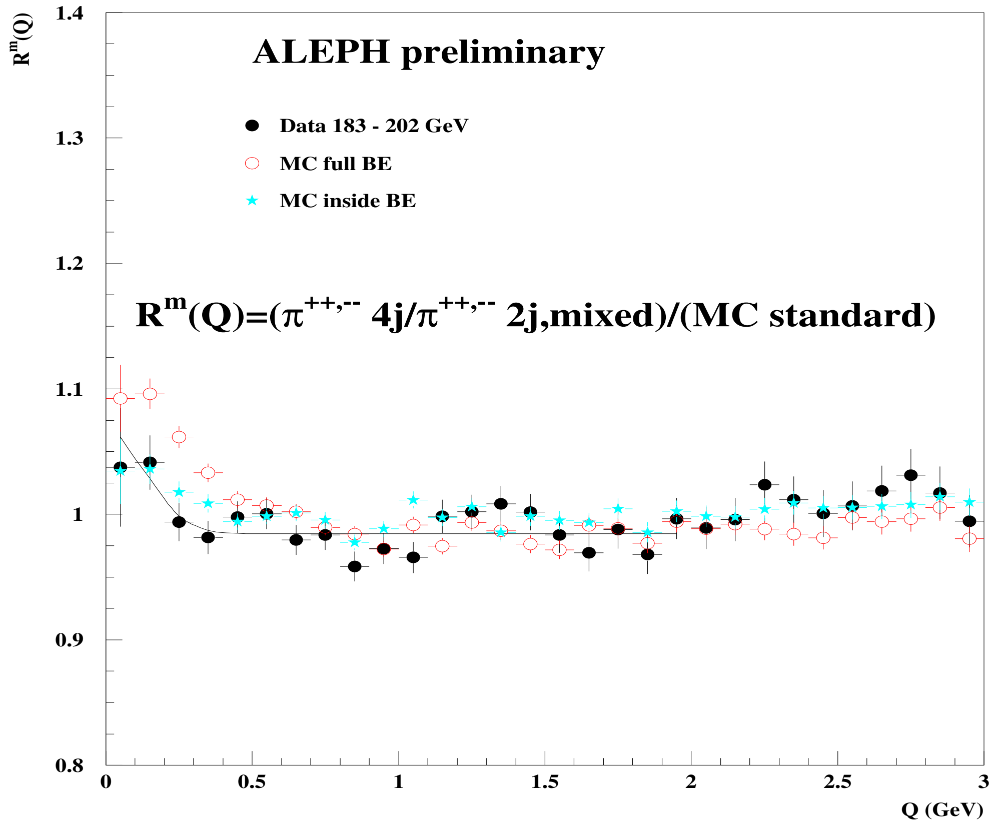
A MC with BEC (BE_3 scheme) is tuned to the Z data; Pure Z$\longrightarrow$ 'udsc' events are extracted in data and MC.

MC corrected for remaining data/MC discrepancies via: $\frac{R_2(Q)^{\text{Zudsc}}_{\text{data}}}{R_2(Q)^{\text{Zudsc}}_{\text{MC}}}$; Thus: $R_2(Q)^{\text{Zudsc}}_{\text{MC}} \equiv R_2(Q)^{\text{Zudsc}}_{\text{data}}$.

BEC in Z$\longrightarrow$ 'udsc' events appear to reproduce the BEC in WW $\rightarrow q_1\bar{q}_2\ell\nu_\ell$ events.

The same MC reproduces the BEC in WW $\rightarrow q\bar{q}q\bar{q}$ events assuming NO inter-W correlations.
A model allowing inter-W BEC is disfavoured by 2.2σ

Moreover, analysis 'a là' Delphi gives:

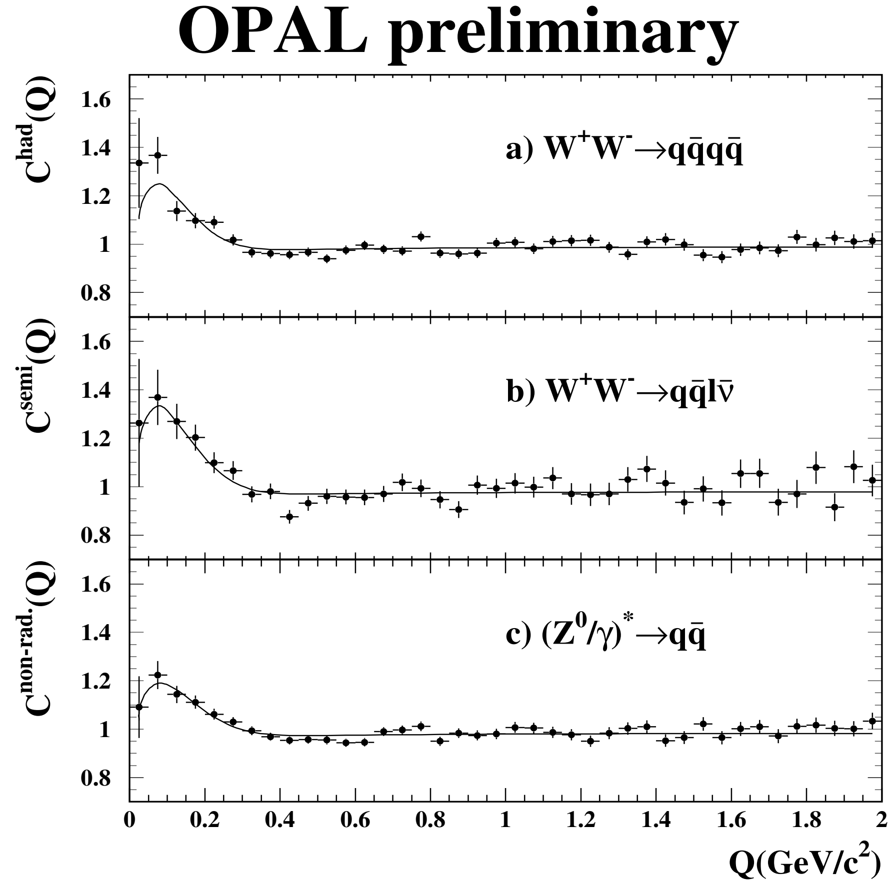


$$R^{\mathrm{m}} \equiv \frac{\left[N^{\pm\pm}_{\mathrm{fully}}/N^{\pm\pm}_{\mathrm{mix}}\right]_{\mathrm{data}}}{\left[N^{\pm\pm}_{\mathrm{fully}}/N^{\pm\pm}_{\mathrm{mix}}\right]_{\mathrm{MC,\ noBE}}}$$

Note: enhancement in BEI is caused by $q\bar{q}$ background.

$\Rightarrow$ Good agreement between DATA and JETSET BEI
$\Rightarrow$ BEA (i.e. with inter-W BEC) is disfavoured

Opal Analysis



The different processes: $(\mathrm{Z}/\gamma)^* \rightarrow \mathrm{q}\bar{\mathrm{q}}$, $\mathrm{W}^+\mathrm{W}^- \rightarrow \mathrm{q}_1\bar{\mathrm{q}}_2\mathrm{q}_3\bar{\mathrm{q}}_4$ and $\mathrm{W}^+\mathrm{W}^- \rightarrow \mathrm{q}_1\bar{\mathrm{q}}_2\ell\nu_\ell$ may have different BEC.

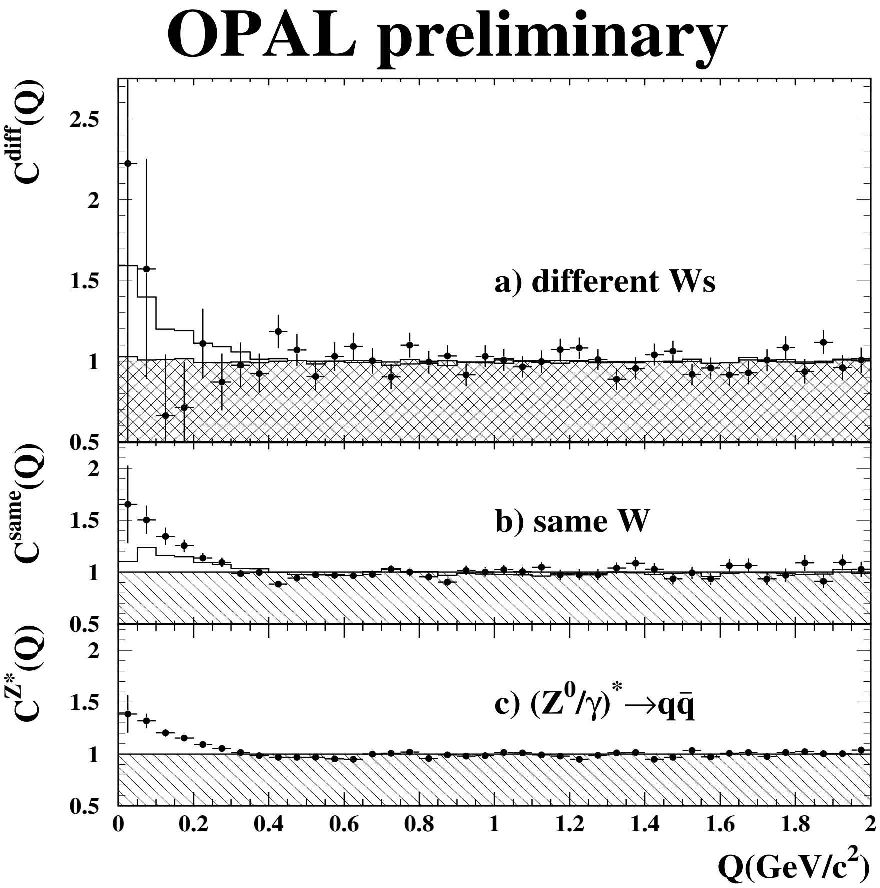
$\Rightarrow$ Rewrite the BEC-function,

$$C(Q) \equiv \left(\frac{N^{\pm\pm}(Q)}{N^{+-}(Q)}\right)^{\mathrm{data}} \Bigg/ \left(\frac{N^{\pm\pm}(Q)}{N^{+-}(Q)}\right)^{\mathrm{MC,\,noBE}},$$

as a combination of contributions from the various pure pion classes.

E.g. for $\mathrm{W}^+\mathrm{W}^- \rightarrow \mathrm{q}_1\bar{\mathrm{q}}_2\mathrm{q}_3\bar{\mathrm{q}}_4$:

$$C^{\mathrm{had}}(Q) = P^{\mathrm{same}}_{\mathrm{had}}(Q)C^{\mathrm{same}}(Q) + P^{\mathrm{Z}^*}_{\mathrm{had}}(Q)C^{\mathrm{Z}^*}(Q) + \left(1 - P^{\mathrm{same}}_{\mathrm{had}}(Q) - P^{\mathrm{Z}^*}_{\mathrm{had}}(Q)\right) C^{\mathrm{diff}}(Q)$$



Results simultaneous fit: "$3\times$" $N(1+f_\pi(Q)\lambda\exp(-Q^2R^2))$

- common source size R

$\lambda^{\rm same} = 0.70 \pm 0.10$; $R^{\rm same} = 1.04 \pm 0.05$ fm
$\lambda^{\rm diff} = -0.14 \pm 0.36$; $R^{\rm diff} = 1.04 \pm 0.05$ fm

- R is allowed to vary for each class

$\lambda^{\rm same} = 0.62 \pm 0.10$; $R^{\rm same} = 1.03 \pm 0.07$ fm
$\lambda^{\rm diff} = 2.85 \pm 1.70$; $R^{\rm diff} = 3.24 \pm 1.18$ fm

- Impose $(R^{\rm diff})^2 = (R^{\rm same})^2 + 4\beta^2\gamma^2\tau^2$

$\lambda^{\rm same} = 0.69 \pm 0.12 \pm 0.06$; $R^{\rm same} = 1.07 \pm 0.07 \pm 0.12$ fm
$\lambda^{\rm diff} = 0.05 \pm 0.67 \pm 0.35$; $R^{\rm diff} = 1.51 \pm 0.05 \pm 0.09$ fm

$\Rightarrow$ No evidence for the existence of inter-W BEC.

Conclusions

- L3: 189 GeV data.
  Inter-W BEC DISFAVOURED $\Rightarrow$ 5.0σ (prel.)
- Delphi: 183+189+192+196+200 GeV data.
  Inter-W BEC FAVOURED $\Rightarrow$ 2.4σ (prel.)
- Aleph: 172+183+189+192+196+200+202 data.
  Inter-W BEC DISFAVOURED $\Rightarrow$ 2.2σ (prel.)
- Opal: 172+183+189 data.
  Inter-W BEC DISFAVOURED (prel.)

$\star$ Opposite conclusion from Delphi and L3/Aleph

$\star$ Very different methods and variables