Bose-Einstein correlations in W decays at LEP

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Bose-Einstein Correlations (BEC)

- *enhancement in the production of multiple identical bosons due to amplitude symmetrization*
  - will only consider pairs in this talk
- BEC can be studied using the two-particle correlation function

$$R(p_1, p_2) = \frac{\rho(p_1, p_2)}{\rho_0(p_1, p_2)}$$

- need a «reference» ρ_0 with no BEC
  - unlike-sign charged pairs
  - event mixing
  - Monte Carlo with no BEC
- the effect is largest at small four-momentum difference

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

Introduction

BEC are well established in $Z \rightarrow qq$ decays at LEP1

- using $\pi^\pm\pi^\pm$, $K_s^0 K_s^0$, $K^\pm K^\pm$ pairs

BEC are also studied in $W \rightarrow qq$ decays at LEP2

→ *the subject of this talk!*

- analyses presented are for $\pi^\pm\pi^\pm$ pairs
- relevant to the W mass measurement

Only phenomenological models exist for BEC

- should symmetrize non-perturbative QCD amplitudes which are not known
- phenomenological parametrization

$$R(Q) \sim (1 + \lambda \exp(-r^2 Q^2))$$

for a BEC source of radius r and BE strength λ

BEC in WW events: status of analyses

Results in this talk are based on:

ALEPH

479 pb^{-1} @ 172-202 GeV (PREL.)

DELPHI

437 pb^{-1} @ 183-202 GeV (PREL.)

L3

177 pb^{-1} @ 189 GeV (PUBL.)

OPAL

250 pb^{-1} @ 172-189 GeV (PREL.)

Selection performance

Channel	Efficiency	Backgrounds
qqqq	70-90%	qq(15%), 4f(5%)
lνqq	50-75%	qq(3%), 4f(3%)

Typical event samples analysed

√s (GeV)	L (pb^{-1})	Nsel WW→qqqq	Nsel WW→lνqq
172	10	40	30
183	55	400	250
189	175	1300	800
192-202	230	1700	1100

BEC in WW events

«Intra-W» BEC observed!

- **BEC for pions from *the same* W**
  - a.k.a. «BEI» (BEC Inside a W)
  - present in any hadronic W decay

Do «Inter-W» BEC exist?

- **BEC for pions from *two different* W 's**
  - a.k.a. «BEB» (BEC Between W 's)
  - only relevant for $WW \to qqqq$ events
- **W decay products overlap in space-time**
  - distance between W decays ~ 0.1 fm
  - hadronisation scale ~ 1 fm
- **Many theoretical models for BEB**
  - most common are variants of JETSET LUBOEI
- **BEB may bias the W mass measurement**
  - models give contradictory predictions
  - systematic error ΔM_W is 25 MeV on M_W^{LEP}

I will focus on the BEB analyses

ALEPH analyses

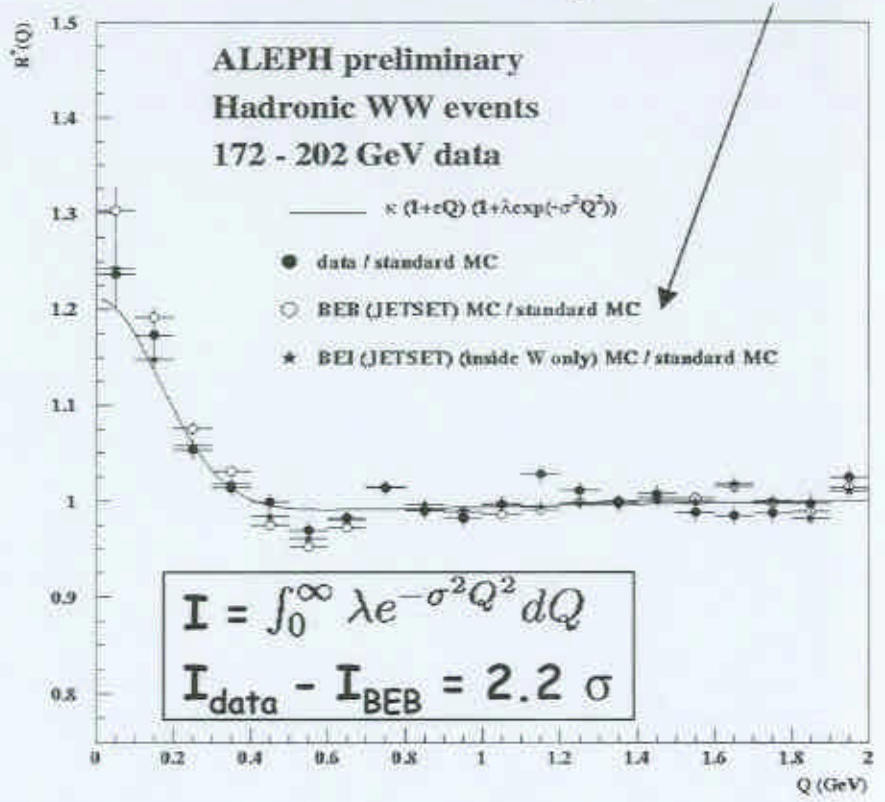
(1) Unlike-sign pair analysis

- unlike-sign pairs taken as reference ρ_0
- double ratio (over MC with no BEC) corrects for possible distortions:

$$R^*(Q) = \left(\frac{N_\pi^{++,--}(Q)}{N_\pi^{+-}(Q)}\right)^{\text{data}} \Big/ \left(\frac{N_\pi^{++,--}(Q)}{N_\pi^{+-}(Q)}\right)^{\text{MC}}_{\text{no BE}}$$

- MC prediction includes background

BEC models tuned using ALEPH Z data



Conclusions:

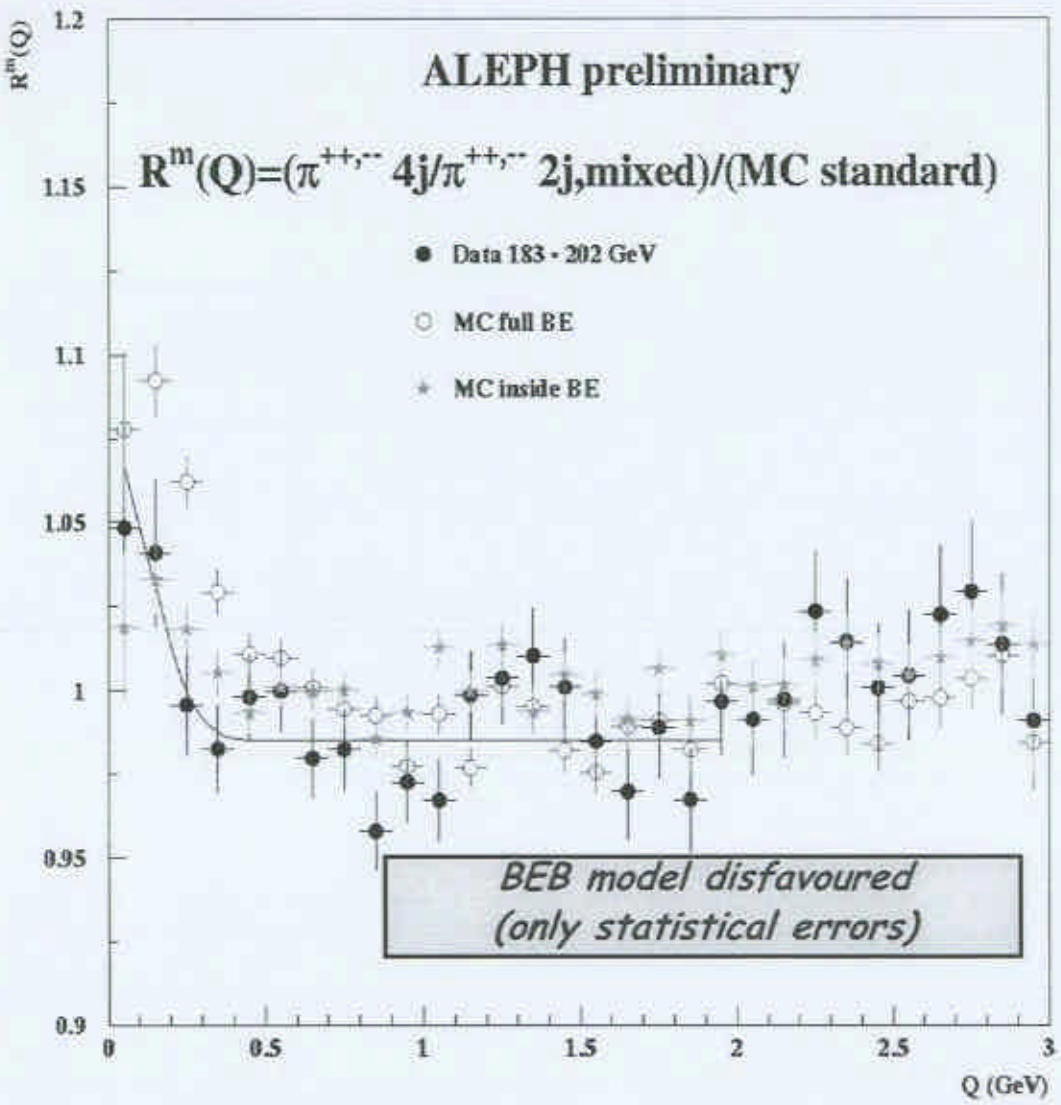
Data are compatible with the BEI model studied

The BEB model considered is disfavoured by 2.2σ

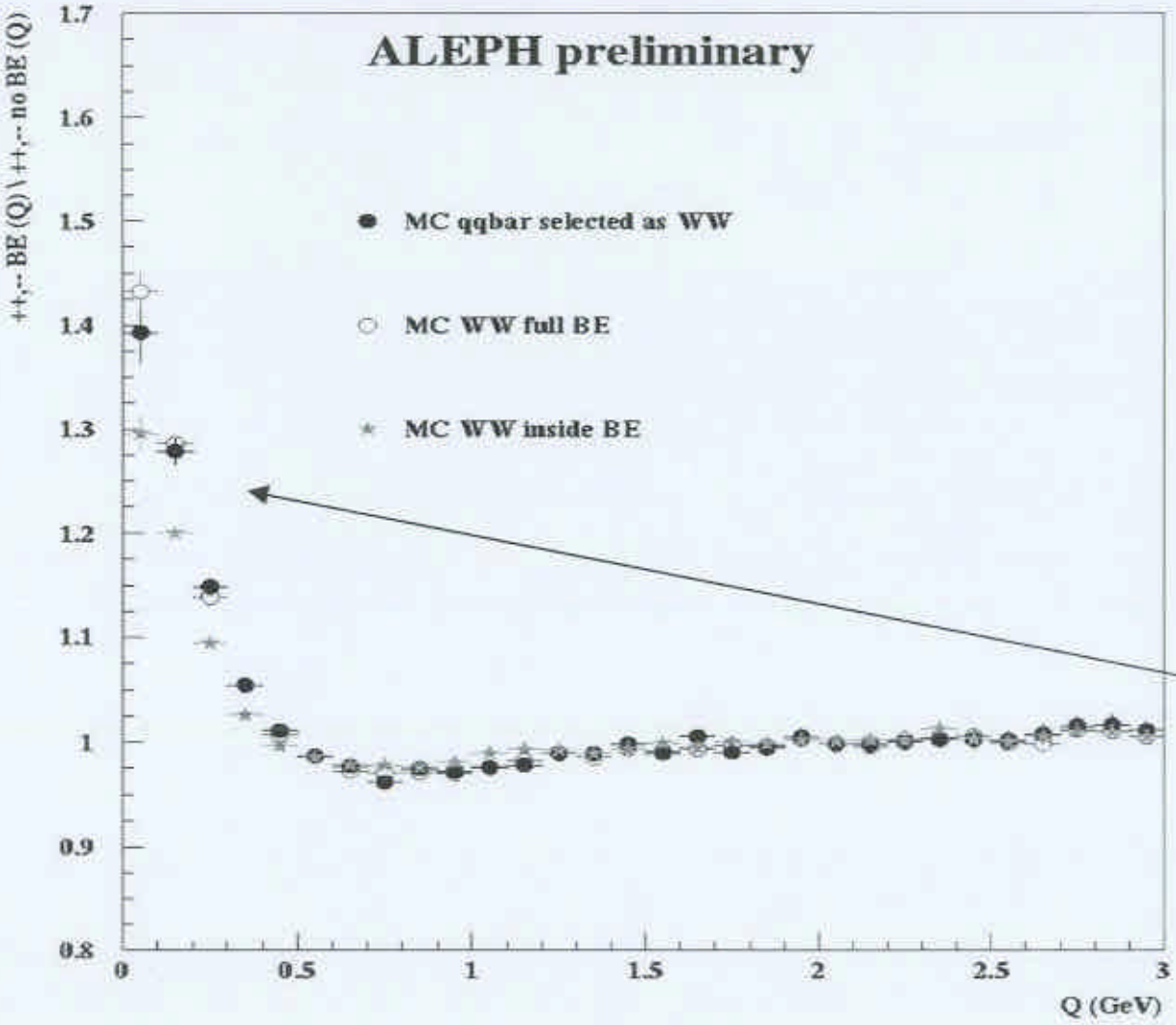
(2) Mixed-reference analysis

- pairs from mixed lνqq events taken as reference ρ_0
- double ratio (over MC with no BEC) corrects for possible distortions:

$$R^m(Q) = \frac{\left(N^{++,--}_{\text{Sel. 4q}} \,/\, N^{++,--}_{\text{Mixed}}\right)^{\text{data}}}{\left(N^{++,--}_{\text{Sel. 4q}} \,/\, N^{++,--}_{\text{Mixed}}\right)^{\text{MC(WW+qq̄), no BEC}}}$$



2 π's in WW→qqqq events, either from the same W (with BEI) or from different W 's (without BEB): estimated from 2 mixed WW→lνqq events



Background MC with BEC
is included
in all MC predictions
entering $R^m(Q)$.

The BEC enhancement in the qq background to WW→qqqq events looks like BEB!

L3 analysis

Mixed lνqq events are taken as reference ρ_0

If the two W's decay independently:

$$\rho_2^{\mathrm{WW}}(p_1,p_2) = 2\rho_2^{\mathrm{W}}(p_1,p_2) + 2\rho_1^{\mathrm{W}}(p_1)\,\rho_1^{\mathrm{W}}(p_2)$$

any 2 π's in WW→qqqq

2 π's from the same W: estimated from WW→lνqq events

2 π's from different W 's: estimate $\rho_{\mathrm{mix}}{}^{\mathrm{WW}}$ built by mixing 2 WW→lνqq events

Background (from MC with BEC) is subtracted from the data

The following single and double ratios are defined:

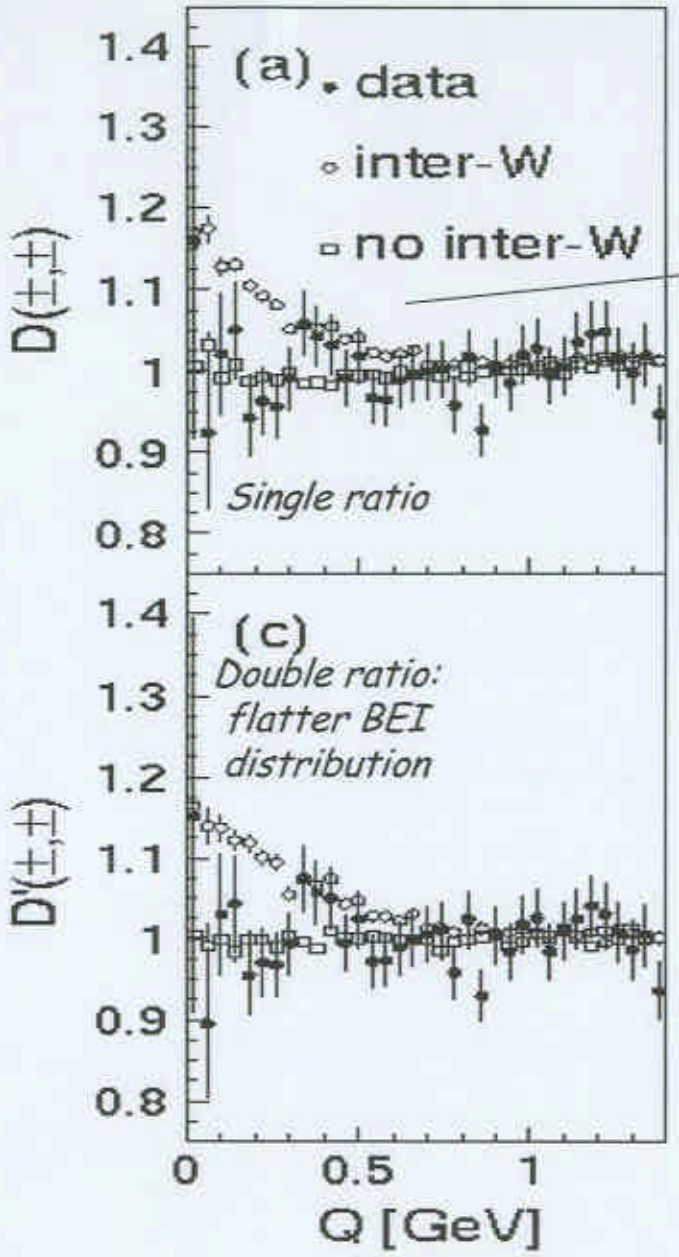
$$D(Q) = \frac{\rho_2^{\mathrm{WW}}(Q)}{2\rho_2^{\mathrm{W}}(Q) + 2\rho_{\mathrm{mix}}^{\mathrm{WW}}(Q)}$$

and

$$D'(Q) = \frac{D(Q)}{D_{\mathrm{MC,\,noBE}}(Q)}$$

BEI MC is used in the double ratio

D = D' = 1
if inter-W BEC do not exist



The D'(Q) distribution is fitted using

$$D'(Q) = (1 + \varepsilon Q)\,(1 + \Lambda \exp(-k^2 Q^2))$$

BEB distribution shows an enhancement

BEI distribution is expected to be flat (no inter-W BEC)

Data agree with BEI

$\Lambda = 0$
if inter-W BEC do not exist

Results for BEC strength parameter Λ :

Λ (data) = 0.001 ± 0.026 (stat.) ± 0.015 (syst.)

Λ (BEB MC) = 0.127 ± 0.007 (stat. only)

Conclusions:

Data compatible with intra-W BEC (Λ~0)

BEB model considered is disfavoured by >4σ

Mixed-method analysis

- MC with no BEC taken as reference ρ_0 to build $R_{4q}(Q)$ for $WW \rightarrow 4q$ events

$$R_{4q}(Q) = \frac{[\rho_{4q}(Q)]^{\text{data}}}{[\rho_{4q}(Q)]^{\text{MC no BEC}}}$$

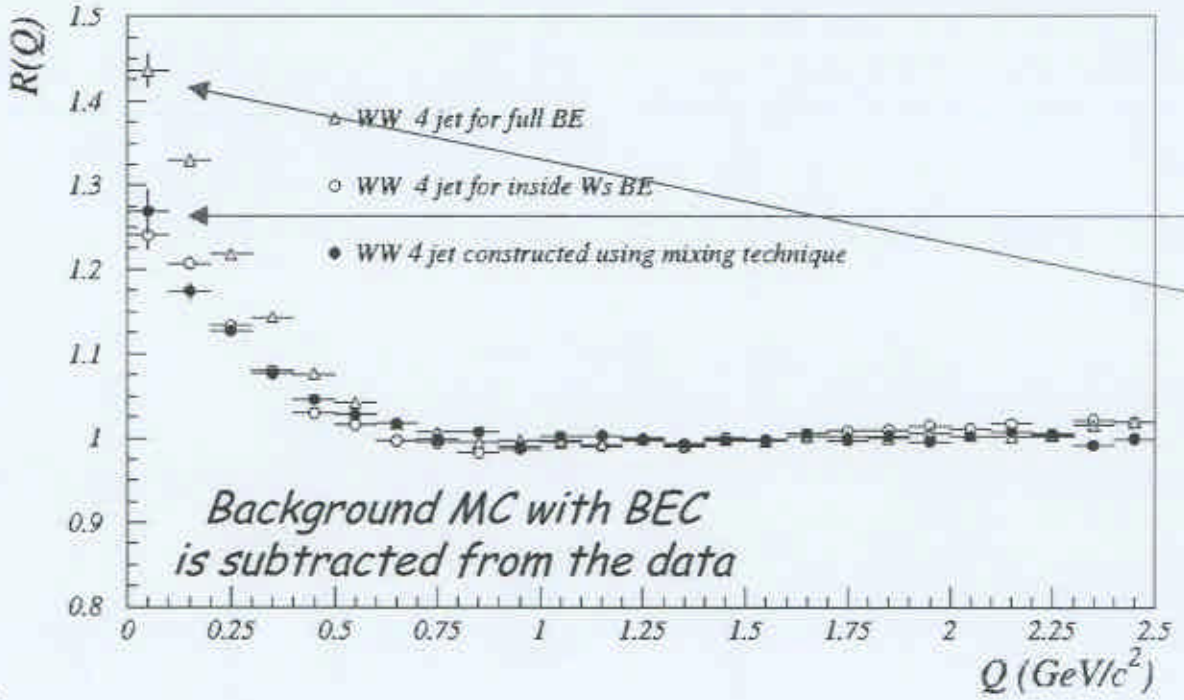
More details about Delphi analyses were given in Nelli Pukhaeva 's talk.

DELPHI analyses

- Compare to $R_{4q}(Q)^{\text{mix}}$ built from lvqq data

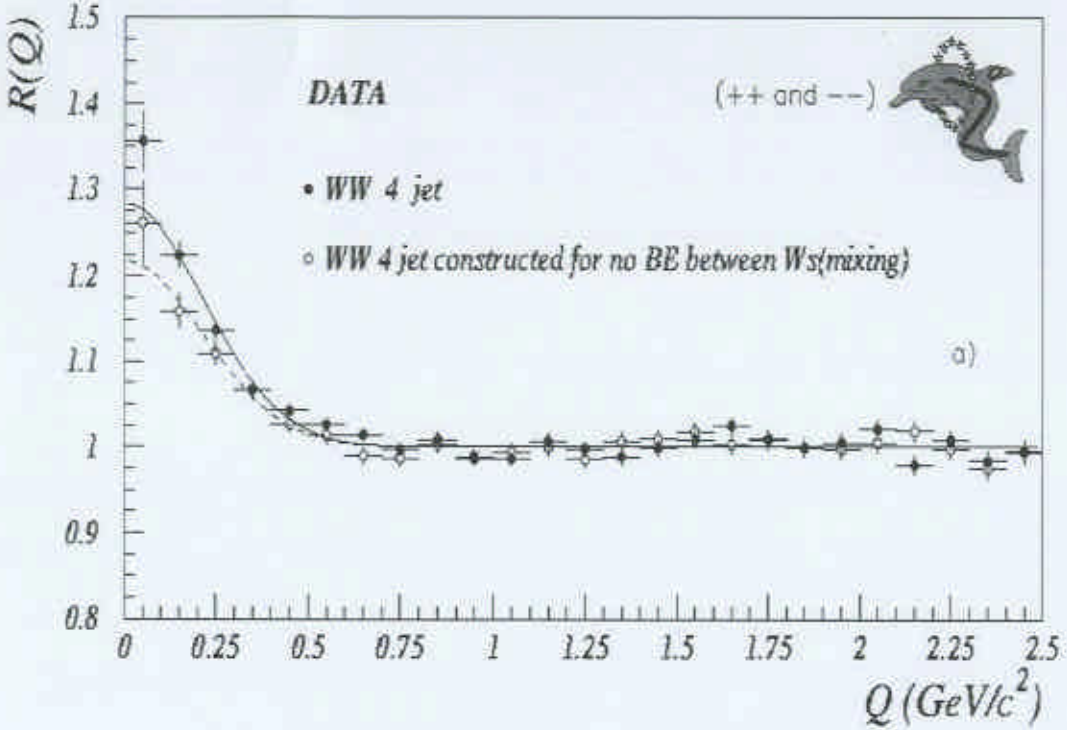
$$R_{4q}(Q)^{\text{mix}} = \frac{[\rho_{2q}(Q) + \rho_{\text{mix}}(Q)]^{\text{data}}}{[\rho_{2q}(Q) + \rho_{\text{mix}}(Q)]^{\text{MC no BEC}}}$$

If BEB do not exist, $R_{4q}(Q) = R_{4q}(Q)^{\text{mix}}$



This assumption is tested using the BEI MC, $R_{4q}(Q)^{\text{BEI}} \sim R_{4q}(Q)^{\text{mix}}$

The prediction for the BEB model is much higher



$R_{4q}(Q)$ and $R_{4q}(Q)^{mix}$ distributions fitted simultaneously with

$$R(Q) = \gamma(1 + \delta Q)\left(1 + \lambda e^{-r^2Q^2}\right)$$

with same γ, δ, r but different λ_{4q} and λ_{4q}^{mix}

If BEB do not exist,
$\Delta\lambda^{mix} = \lambda_{4q} - \lambda_{4q}^{mix} = 0$

Results from mixed method:

$\Delta\lambda^{mix} = \lambda_{4q} - \lambda_{4q}^{mix} = 0.062 \pm 0.025 \pm 0.021$

Similar results from «linear scenario»

$\Delta\lambda^{linear} = \lambda_{4q} - \lambda_{4q}^{linear} = 0.077 \pm 0.026 \pm 0.020$

Conclusions:

Data support inter-W BEC at the level of ~ 2σ

The BEI model considered is disfavoured

OPAL analysis

Unlike-sign pairs taken as reference ρ_0

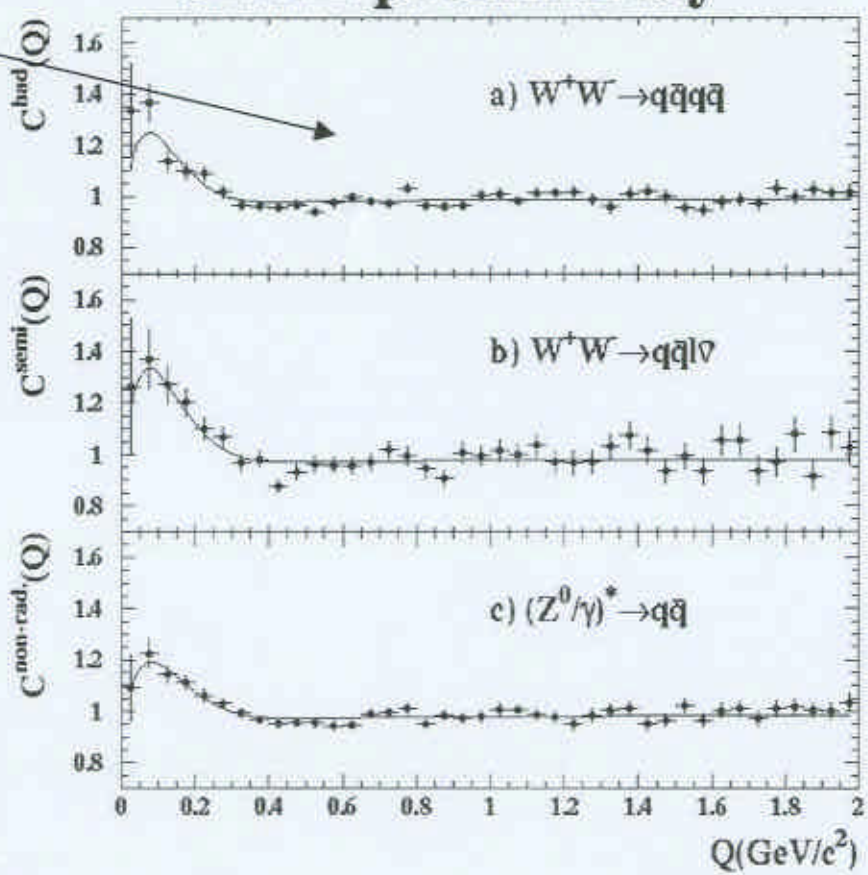
- double ratio $C(Q)$ is used, (data)/(MC with no BEC)

$C(Q)$ distributions studied for 3 sample

- $WW \rightarrow qqqq$
- $WW \rightarrow l\nu qq$
- high-energy qq events

Deconvolute as sum of 3 contributions (with probabilities given by the MC):

- $C^{same}(Q)$ for BEC in the same W
- $C^{diff}(Q)$ for BEC between different W 's
- $C^{Z^*}(Q)$ for BEC in qq events
  - slight differences if selected as qq, $qqqq$ or $l\nu qq$



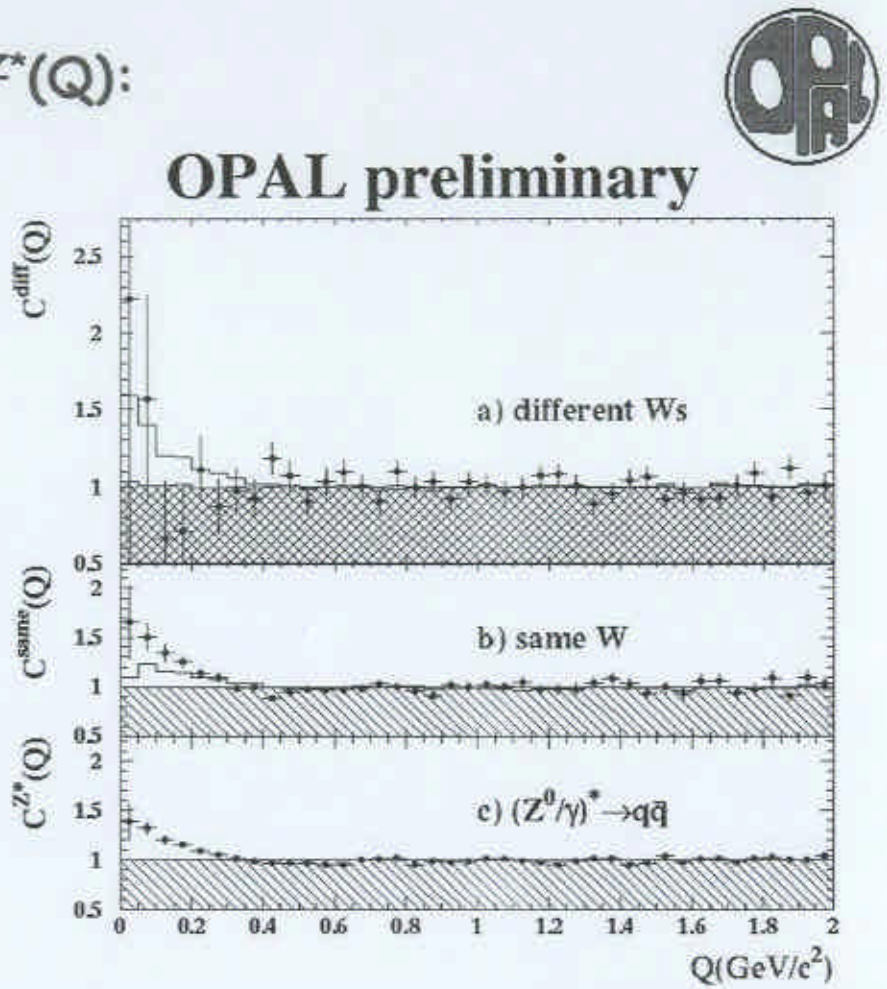
Simultaneous fits to $C^{same}(Q)$, $C^{diff}(Q)$, $C^{Z^*}(Q)$:

$C(Q) = N\,(1 + f_\pi(Q)\,\lambda \exp(-Q^2R^2))$

If inter-W BEC do not exist, $\lambda^{diff} = 0$

3 scenarios considered for source size R

- same $R^{diff} = R^{same} = R^{Z^*}$
  λ^{same}=0.70±0.10, λ^{diff}=-0.14±0.36
- independently variable R^{diff}, R^{same}, R^{Z^*}
  λ^{same}=0.62±0.10, λ^{diff}=2.85±1.70
- impose $(R^{diff})^2 = (R^{same})^2 + (\text{W motion})^2$
  λ^{same}=0.69±0.12±0.06, λ^{diff}= 0.05±0.67±0.35



Conclusions:

Data compatible with no-BEB hypothesis (λ^{diff}~0)

Not established whether inter-W BEC exist or not

Conclusions?

Different methods...
...with different results!

ALEPH (172-202 prel.)

Inter-W BEC are
disfavoured *(~ 2.2σ, prel.)*

DELPHI (172-202 prel.)

Inter-W BEC are
favoured *(~ 2σ, prel.)*

L3 (189 publ.)

Inter-W BEC are
disfavoured *(~ 4σ)*

OPAL (172-189 prel.)

Inter-W BEC are
neither favoured nor disfavoured

Still a lot to understand!
BEC uncertainty on M_W measurement:
ΔM_W^{LEP} = 25 MeV