— Bose Einstein Correlations — W final state interactions from OPAL

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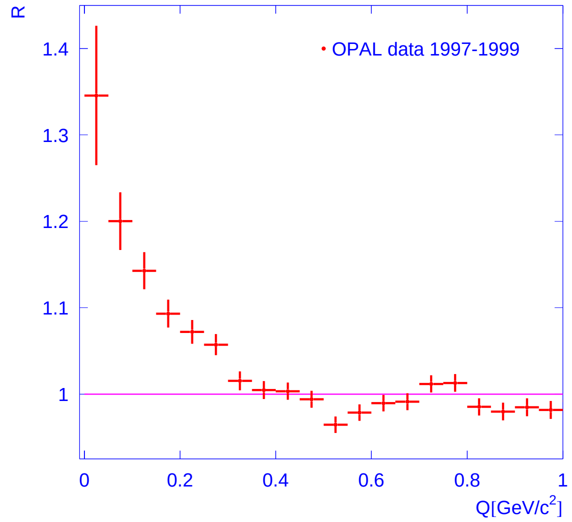
Introduction to Bose-Einstein Correlations

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 (e.g.: in $e^+e^- \rightarrow W^+W^-$)



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)?

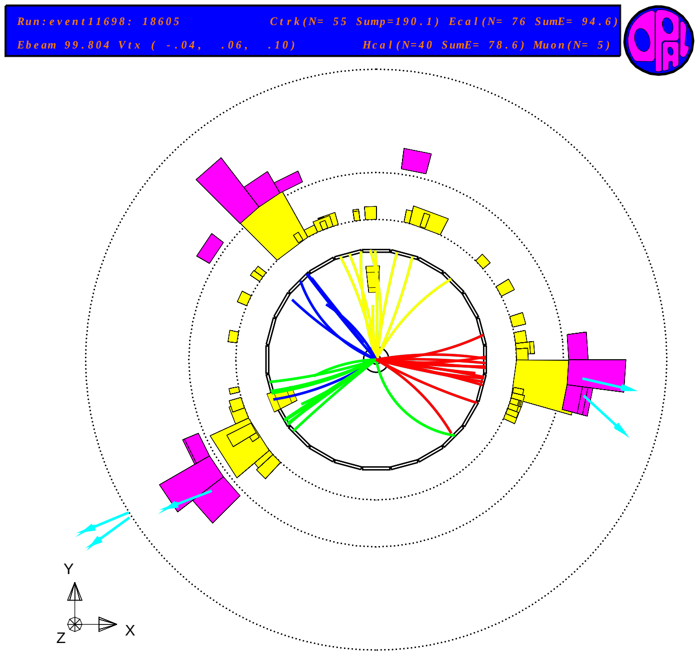
Consequence:

- 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:

$\Delta M_W^{\mathrm{BEC}}(4q) = 35$ MeV/c^2

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

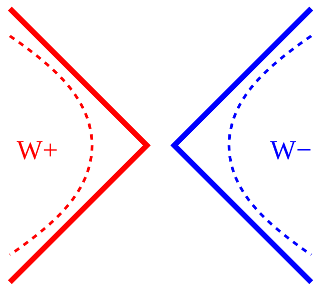


Space-time overlap:

- Typical separation of the two W decay vertices: 0.1 fm
- Scale of hadronization: O(fm)

String model (in absence of CR)

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:

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

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

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

Samples: WW→qqqq, qqlν

- 680 pb^{-1} @ 183–209 GeV

energy range [GeV]	WW→qqqq	WW→qqlν
183–192	1721	1720
196–200	1290	1300
> 200	1459	1513
all	4470	4533

WW→4q sample contain 15% background, mainly $Z^{0*}/\gamma \to$ 4 jets.
Reduced to 8% by tightening the standard OPAL WW selection.
WW→4q signal reduced: 17%
Bg subtracted with BEC MC.

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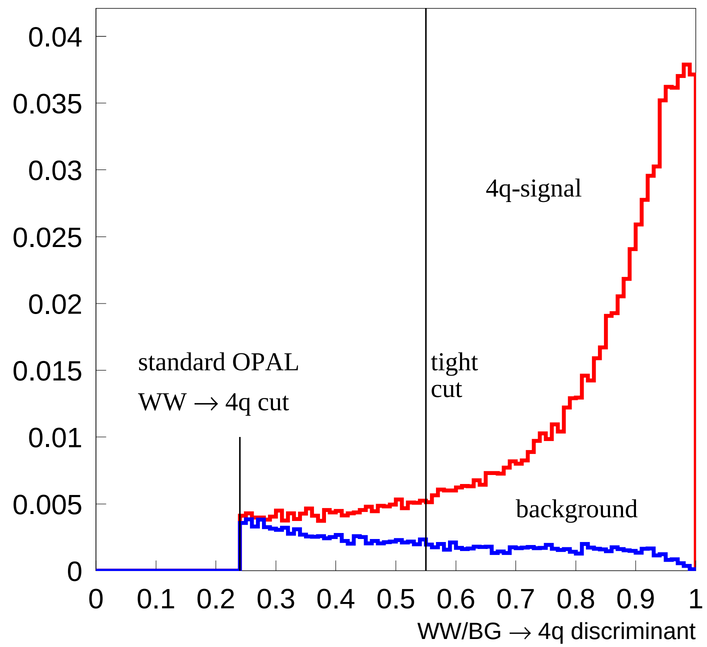

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MC implementation of BEC:

PYBOEI/PYTHIA reshuffles particle momenta after fragmentation to simulate BEC effect

option 1: full BEC (intra-W + inter-WW BEC)

option 2: only intra-W BEC, no inter-WW BEC

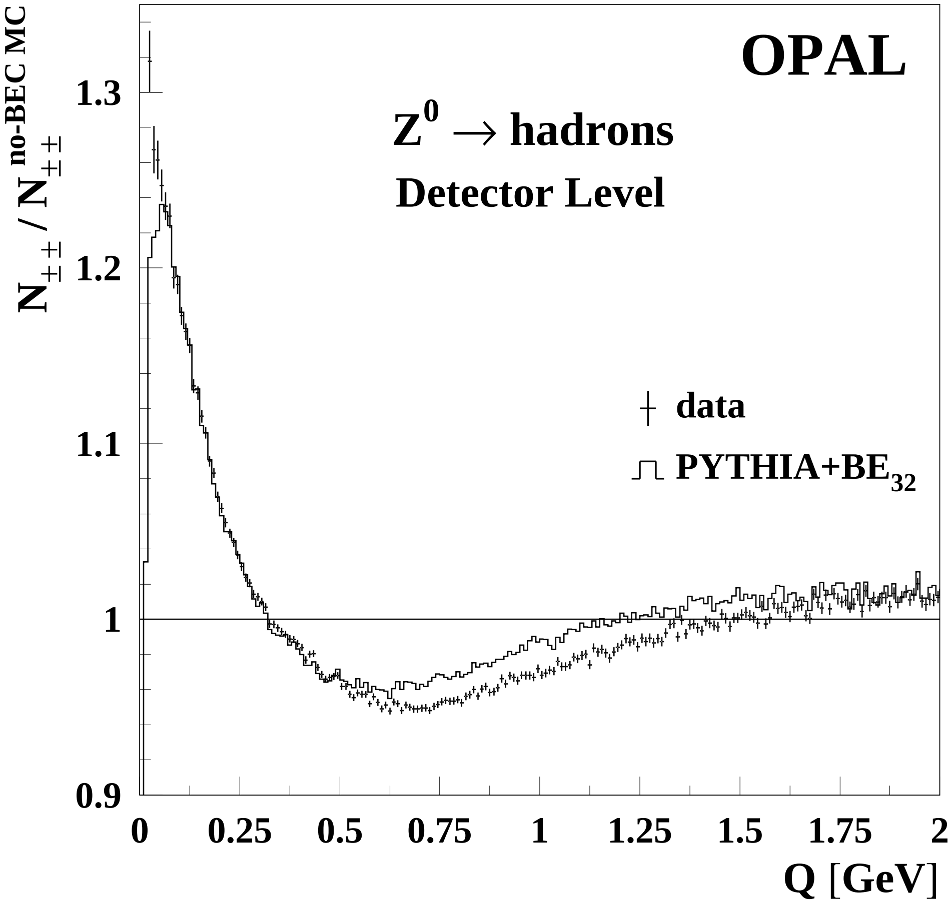
option 3: no BEC

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

MC Tuning

BEC parameters adjusted to Z^0 data to better than 2% per Q-bin, main QCD/frag. parameters retuned
(same χ^2/d.o.f. as for standard OPAL (`PYTHIA/JETSET`) tune).

- $N_{\pm\pm}$: number of like-sign pairs
- $N_{\pm\pm}^{\mathrm{no}-BECMC}$: number of like-sign pairs in standard OPAL MC w/o BEC
  - small discrepancy from multiplicity constraint in `PYBOEI/PYTHIA`



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

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

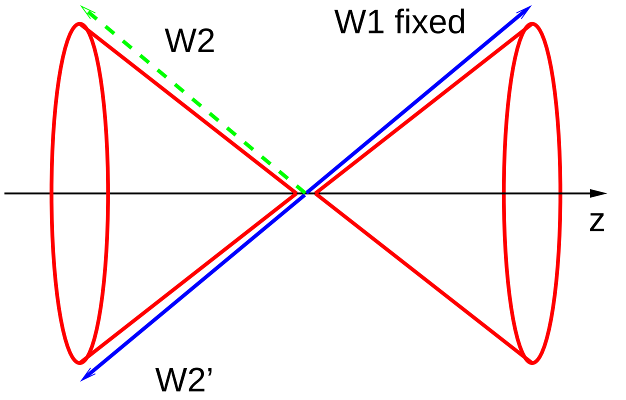
- WW $\to$ 4q: 4q sample
- W $\to$ 2q: qqlν sample without the leptonic part
- WW$_{mix}$: event made of 2 independent W $\to$ 2q events, use only pairs of particles from different W's

Construct BEC sensitive distributions:

E.g.: $\Delta\rho(Q) = \rho_2^{WW\to 4q}(Q) - 2\cdot\rho_2^{W\to 2q}(Q) - \rho_{mix}^{WW_{mix}}(Q)$

Event mixing technique

- Take semi-leptonic events and remove the leptonic part
- Take events that are in the same 'detector region'
  Same polar angle of W direction θ_W (sum over all selected tracks and clusters)
- W^+ with W^- (from lepton charge), same E_{cm} within 5 GeV
- Apply rotation procedure



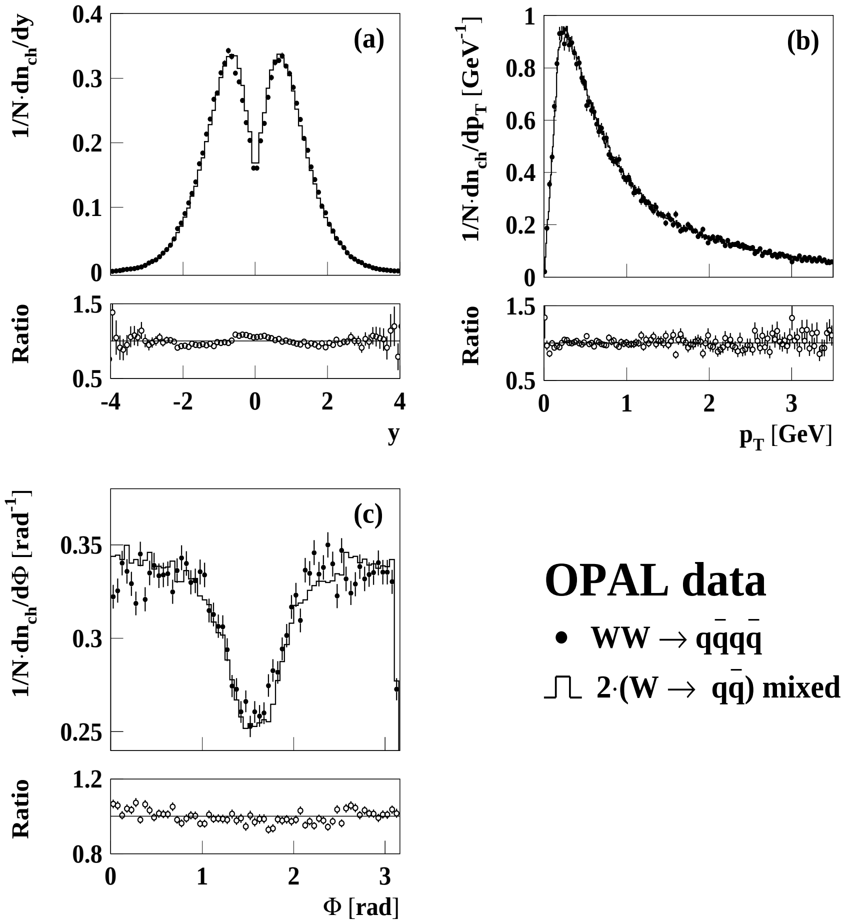
φ rotation for all particle momenta of one half event laying on the surface of a diabolo.
Flip to the opposite hemisphere if necessary.
Mixed events have to pass the 4q event selection (26% rejected).

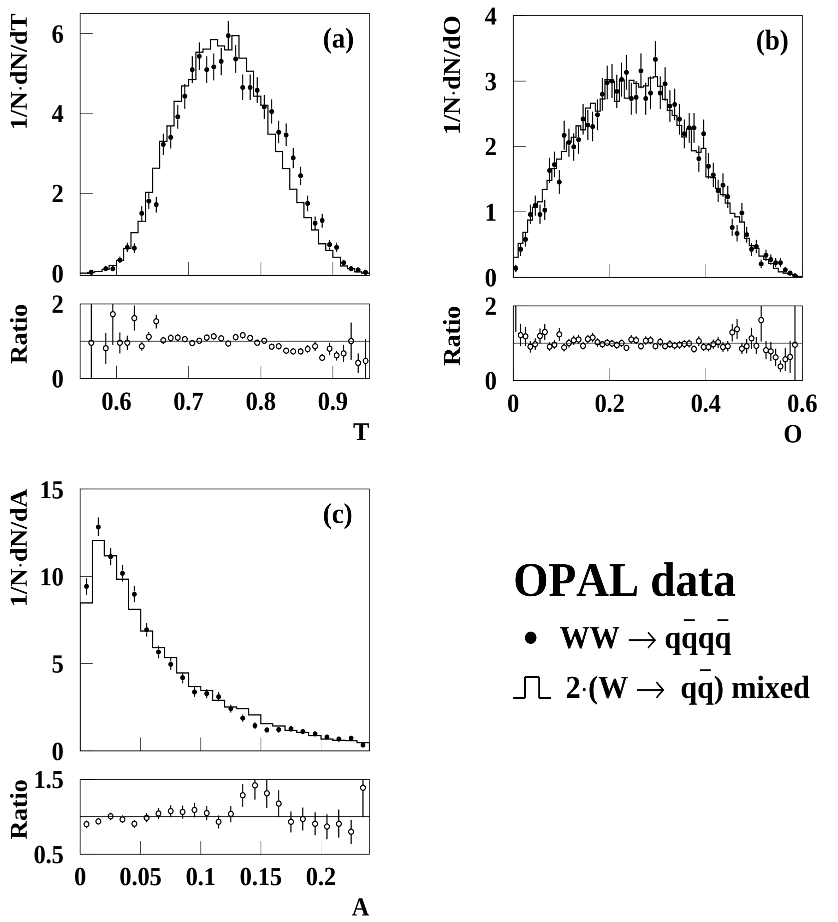
Check with event shapes and single particle spectra (MC without correlations)

Check mixing

Left: Single particle spectra: a) rapidity b) p_T, c) azimuthal angle Φ

Right: Event shape distributions: a) Thrust b) Oblateness c) aplanarity





Sensitive test distributions

- $\Delta\rho(Q) = \rho_2^{WW\to 4q}(Q) - 2\cdot\rho_2^{W\to 2q}(Q) - \rho_{mix}^{WW_{mix}}(Q)$
- $J = \int_0^{Q_{max}} \Delta\rho(Q)\mathrm{d}Q$ (bin-to-bin statistical fluctuations are reduced)
- $\delta_I(Q) = \Delta\rho(Q)/\rho_{mix}^{WW_{mix}}(Q)$ (inter-source correlation function)
- $D(Q) = \frac{\rho_2^{WW\to 4q}}{2\cdot\rho_2^{W\to 2q} + \rho_{mix}^{WW_{mix}}}$

To disentangle BEC from other possible correlation effects:

- $\delta\rho(Q) = \Delta\rho(\pm,\pm) - \Delta\rho(+,-)$
- $\Delta_I(Q) = \delta_I(\pm,\pm) - \delta_I(+,-)$
- $d(Q) = D(\pm,\pm)/D(+,-)$
- $D'(Q) = \frac{D(Q)}{D(Q)_{\mathrm{MC,w/o\,inter-WW\,BEC}}}$

If inter-WW BEC do not exist:

$\Delta\rho$(Q) = $\delta\rho$(Q) = J = 0

D(Q) = D'(Q) = d(Q) = 1

Uncertainties

Systematic errors:

- Track selection
- Background in WW→qqlν by leaving out τ events
- Event selection for WW→qqqq, likelihood weight variation
- Monte Carlo correction for $Z^{0*}/\gamma \rightarrow$ 4 jets
- Event mixing procedure (vary angle and energy matching)

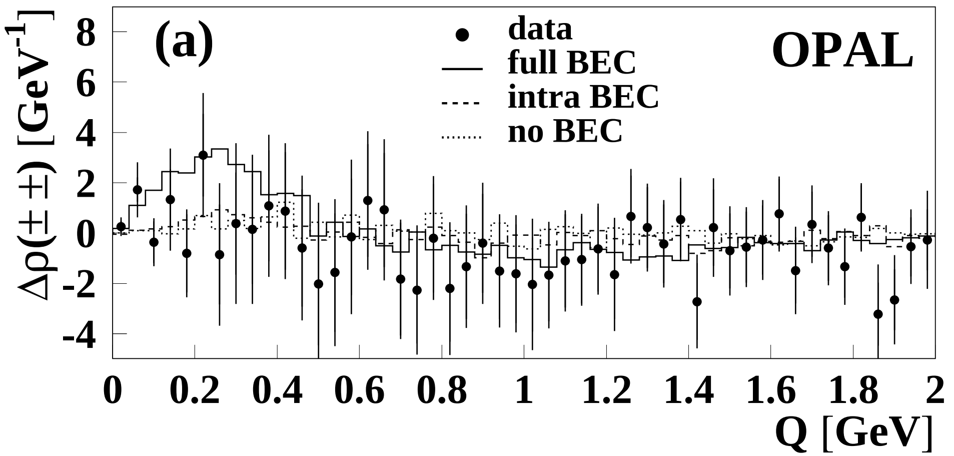
Colour reconnection:

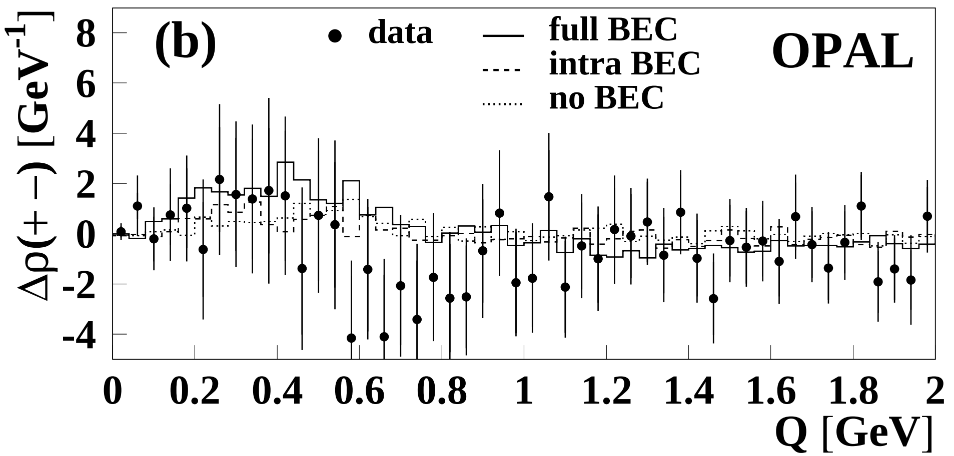
- negligible when $\rho^{WW\rightarrow 4q}$ scaled to have the same mean particle pair multiplicity as $\rho^{WW_{mix}}$

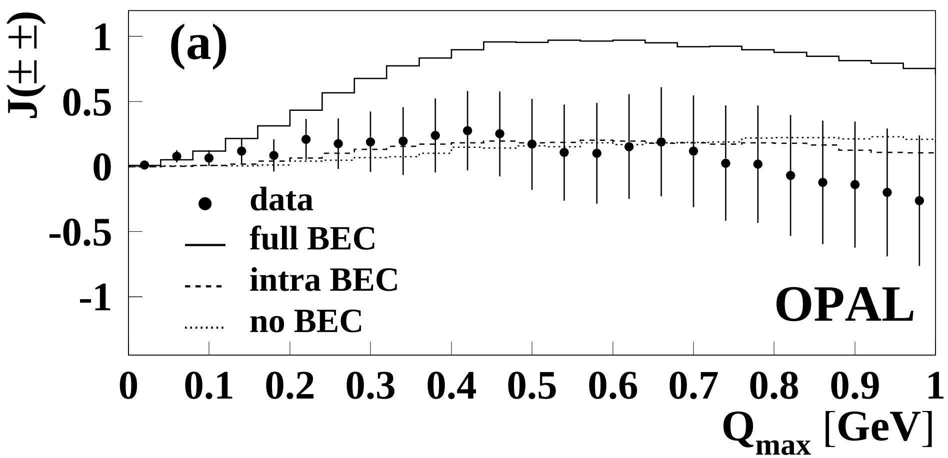
Statistical errors:

- Statistical sampling technique instead of conventional error propagation to account for bin-to-bin correlations. Using the full covariance matrix.

Results: $\Delta\rho$, J



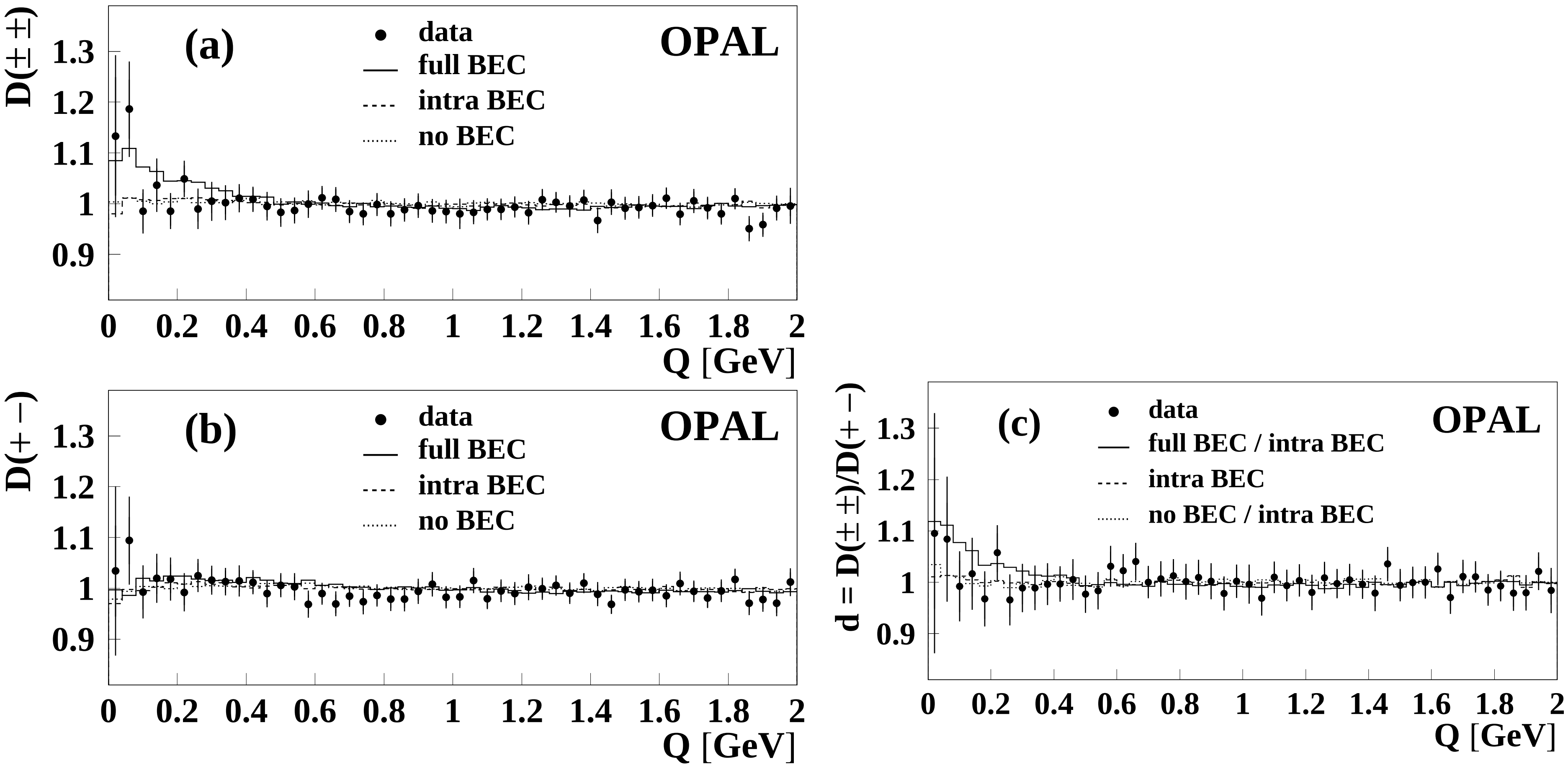




$$
\begin{aligned}
\text{data}: J(Q_{max} = 0.48\ \text{GeV}) &= 0.17 \pm 0.26(\text{stat}) \pm 0.23(\text{syst}) \\
\text{full BEC}: J(Q_{max} = 0.48\ \text{GeV}) &= 0.95 \pm 0.09(\text{stat})
\end{aligned}
$$

data is 2.2 σ below the full BEC in `PYBOEI/PYTHIA`

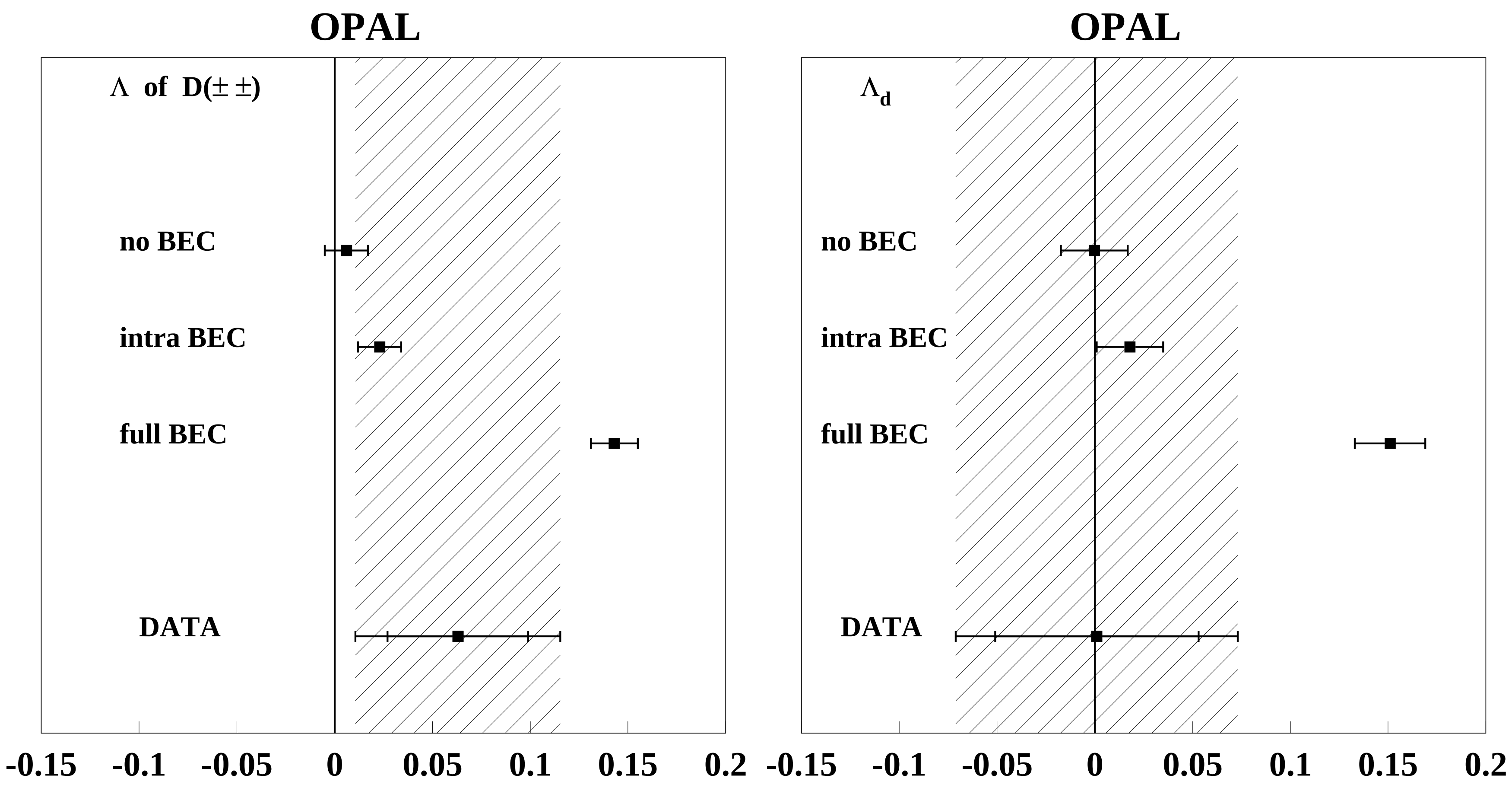
Results: D(Q), d(Q)



fit empirical parametrization: $f(Q) = N(1 + \delta \cdot Q)(1 + \Lambda \cdot \exp(-Q/R))$

(R determined by fit to full BEC)

Fit to D(Q) and d(Q)



Λ(data) = 0.063±0.036(stat)±0.038(syst)

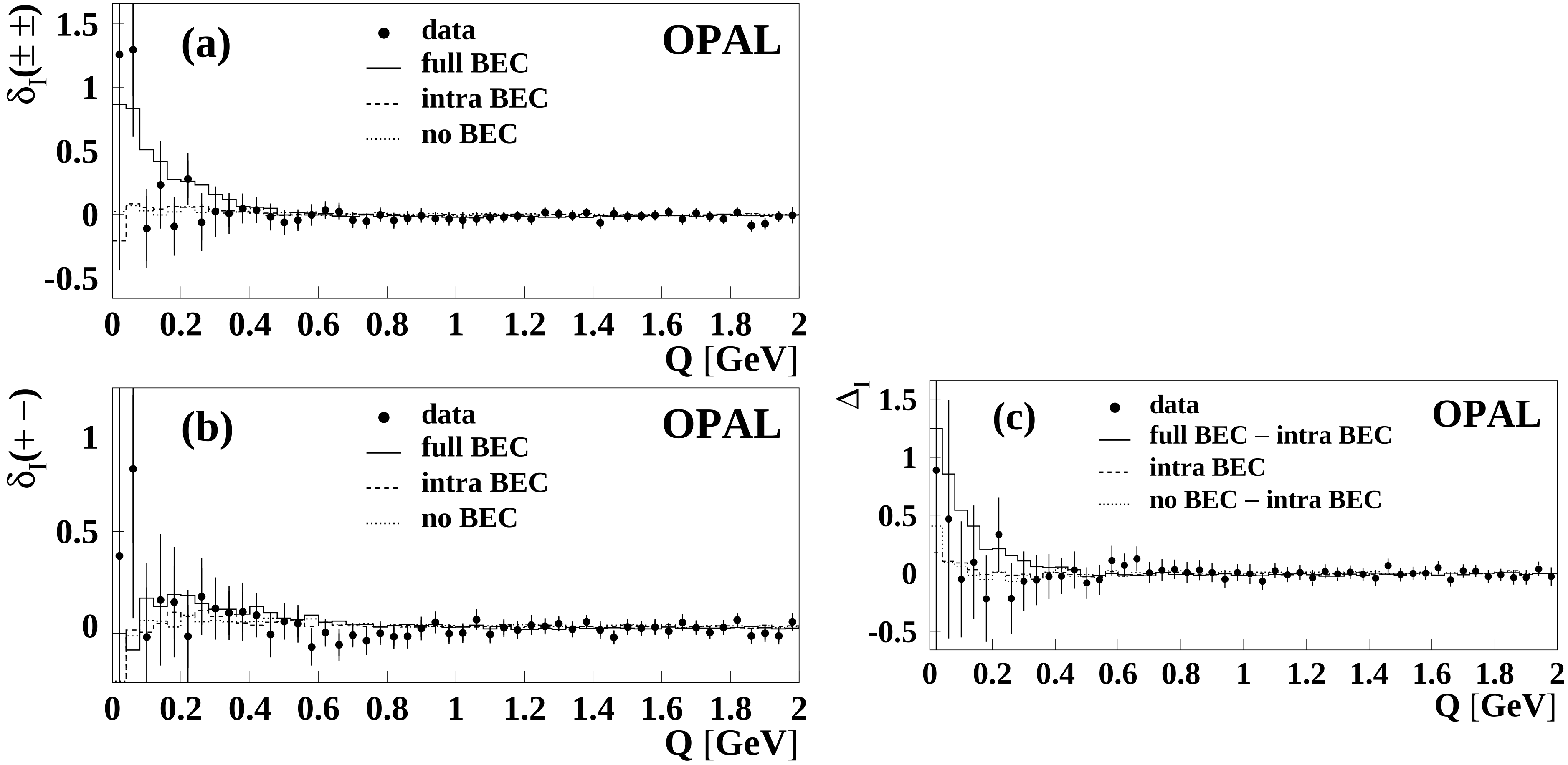
Λ(full BEC) = 0.143±0.012(stat)

Λ_d(data) = 0.001±0.052(stat) ± 0.050(syst)

Λ_d(full BEC) = 0.151±0.018(stat)

measured values of Λ and Λ_d differ from full-BEC by 1.5 and 2.1 standard deviations, resp.

Others: $\delta_I(Q)$, $\Delta_I(Q)$



$\Rightarrow$ No hint for full-BEC in data

Sensitivity

Compare the difference between the predictions of the full-BEC and intra-W-BEC, scaled by the total uncertainty of the measurement from data.

$\Rightarrow$ comparable power:

- J: 2.2
- Λ: 2.3
- Λ': 2.0
- Λ_d: 1.8

For the purpose of setting a limit on the amount of inter-WW BEC to be considered as a systematic uncertainty for the W mass, take the measured data plus one σ as a bound on the fraction of the full-BEC `PYBOEI/PYTHIA` prediction consistent with data.

- J: 44%
- Λ: 77%
- Λ': 84%
- Λ_d: 41%

Conclusion & Outlook

- Within the data statistics available no inter-WW BEC have been observed by the OPAL experiment
- Inter-WW BEC effects of the size predicted by `PYBOEI/PYTHIA` are disfavoured
- However, limited statistics do not permit them to be completely excluded

Outlook:
Combination of the data from all four LEP experiments will be required to draw a firm conclusion on the existence or absence of inter-WW BEC.

Model independent limits for inter-WW BEC using the combined LEP data.
W mass uncertainty < 20 MeV/c^2?