Particle Correlations at LEP

Review of selected experimental results of the four LEP collaborations

Introduction

- About Bose-Einstein Correlations

Particle Correlations in Z^0 Decays

- Bose-Einstein & Fermi-Dirac Correlations
- Genuine Multiparticle Correlations

Particle Correlations in W^+W^- Production

- Inter-WW Bose-Einstein Correlations

In Memory of
Bo Andersson

Thomas Kress
University of California, Riverside
OPAL Collaboration

XXXVIIth Rencontres de Moriond
QCD & High Energy Hadronic Interactions
Les Arc, France - March 19th, 2002

From HBT (1954) to GGLP (1960)

Hanbury Brown & Twiss

Determination of star radii with intensity interferometry

- Start with a symmetric 2-boson wave function
- Relation between space-time of source and correlation function C:

$$C(p_1,p_2) = \rho_2(p_1,p_2)/\{\rho_1(p_1)\cdot\rho_1(p_2)\} = 1+\Omega(\Delta p)^2$$

- Ω is the Fourier transform of the source intensity:

$$\Omega(\Delta p) = \left(\int f(x)^2 e^{i\Delta px} d^4x\right)/\left(\int f(x)^2 d^4x\right)$$

$$\rho_n(p_1,\ldots,p_n) = \frac{1}{\sigma_{tot}}\cdot\frac{d\sigma(\ldots)}{dp_1\ldots dp_n}$$

Goldhaber, Goldhaber, Lee & Pais

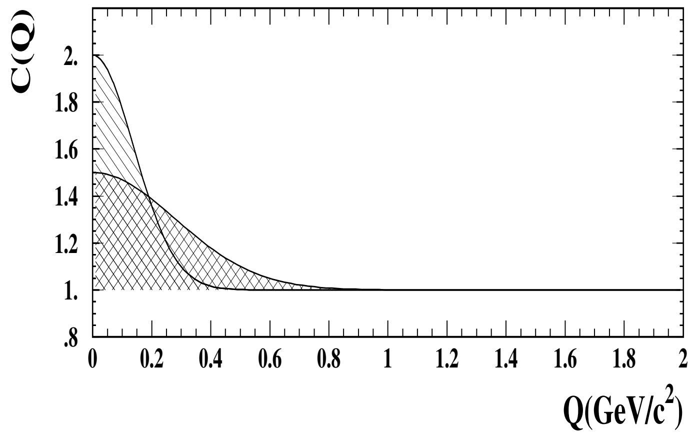
Enhancement of $\pi^+\pi^+$ (+ c.c.) pairs close in phase-space vs. $\pi^+\pi^-$ pairs

Spherical source with Gaussian density:

$$C(Q) = 1+\lambda e^{-Q^2R^2}$$

$$Q^2 = -\left(p_1^\mu - p_2^\mu\right)^2 = M_{12}^2 - 4m_\pi^2$$

R: source size, λ: strength parameter

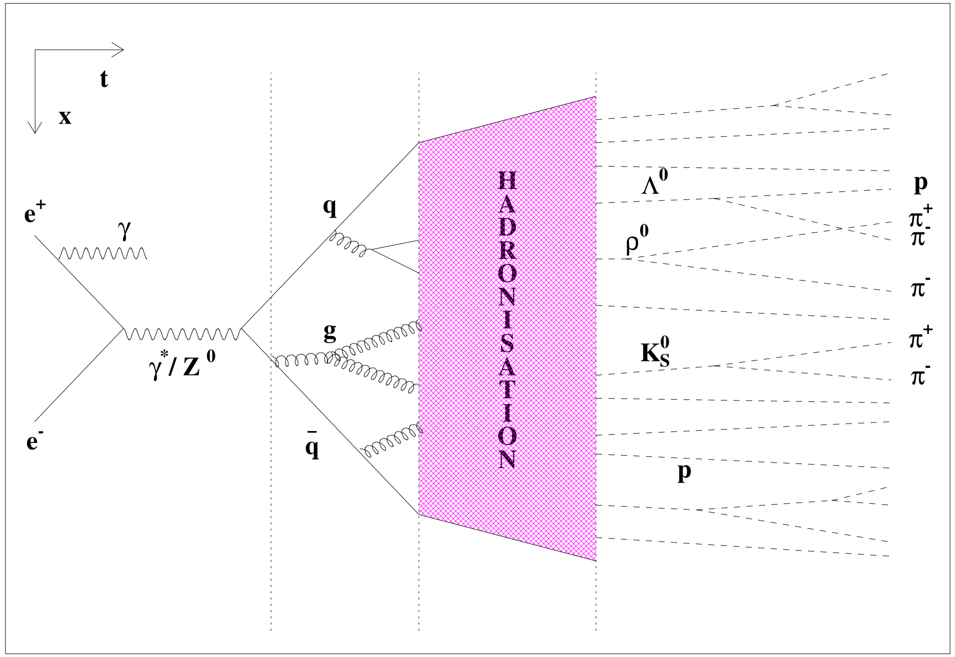


HBT vs. Hadron Production & LEP-1(1989-1995)

$$e^+e^- \to Z^0 \to q\bar{q} \to hadrons$$

Assumptions valid in astronomy
... but wrong in hadron production:

- Plane wave propagation
  ... only if no final-state interactions
- No coherence anywhere, anytime
  ... most particles from resonances
- No correlations between x and p
  ... strong (x,p)-correlations in the
  inside-outside cascade



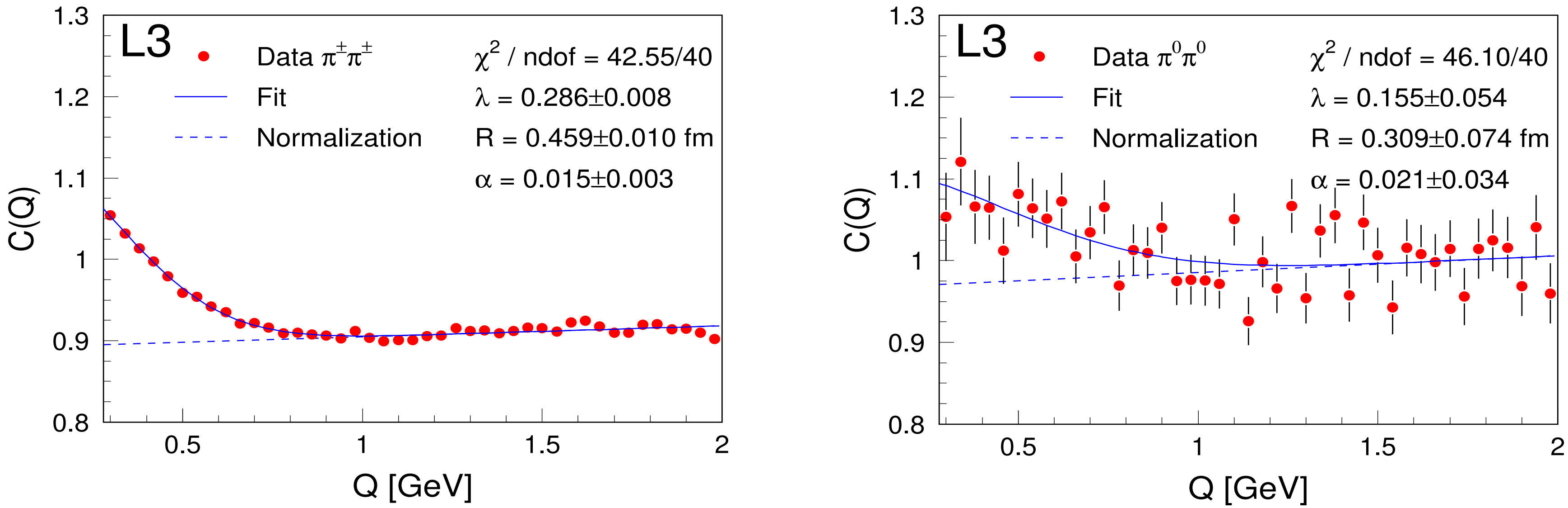
4 M hadronic Z per experiment

Final state particles (on average):

- 21 charged particles (17 π, 2 K, 1 p, ...)
- 21 photons (mostly from π^0)

Bose-Einstein Correlations in Pion Pairs

Phys. Lett. B (2001)



- Reference sample: $C(Q) = \rho_2^{BEC} / \rho_2^{no-BEC-MC}$

- BEC between charged pions clearly established at LEP

  Consistent results: source radius R = 0.5 ...1.0 fm (depending on reference sample)
  R significantly smaller than in nucleus or heavy ion reactions

- 1.5 σ-indication that R($\pi^0\pi^0$) is smaller than R($\pi^+\pi^+$,$\pi^-\pi^-$)

  Ambitious π^0 measurement; R difference qualitatively expected in Lund string model

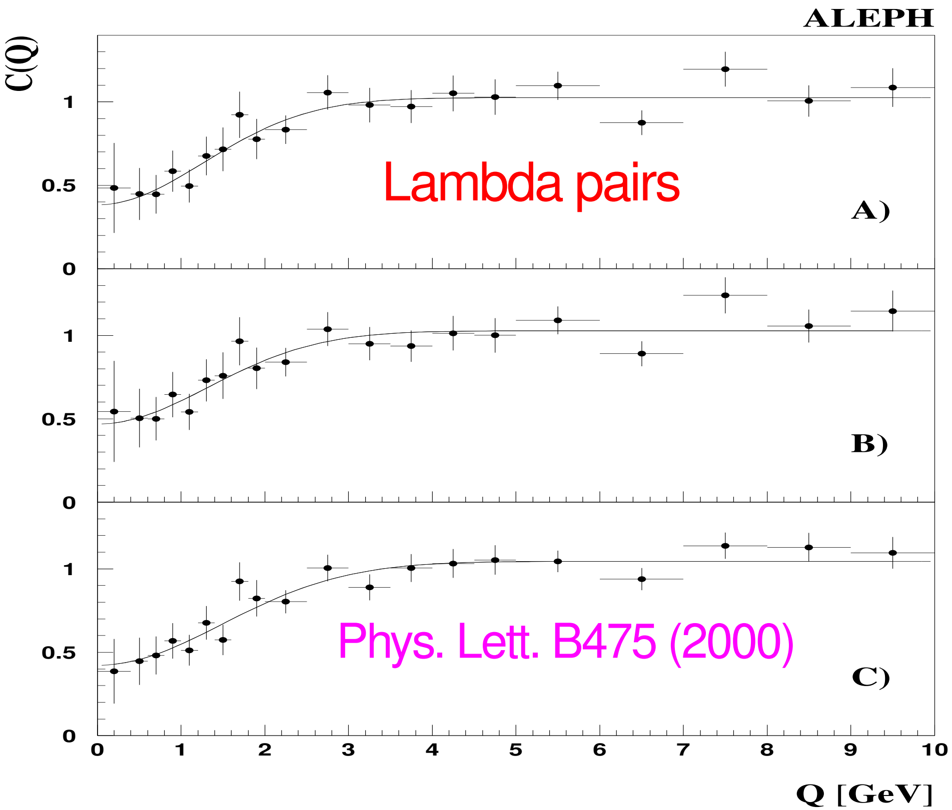
Fermi-Dirac Correlations of Baryon Pairs ?

Antisymmetric total wave function

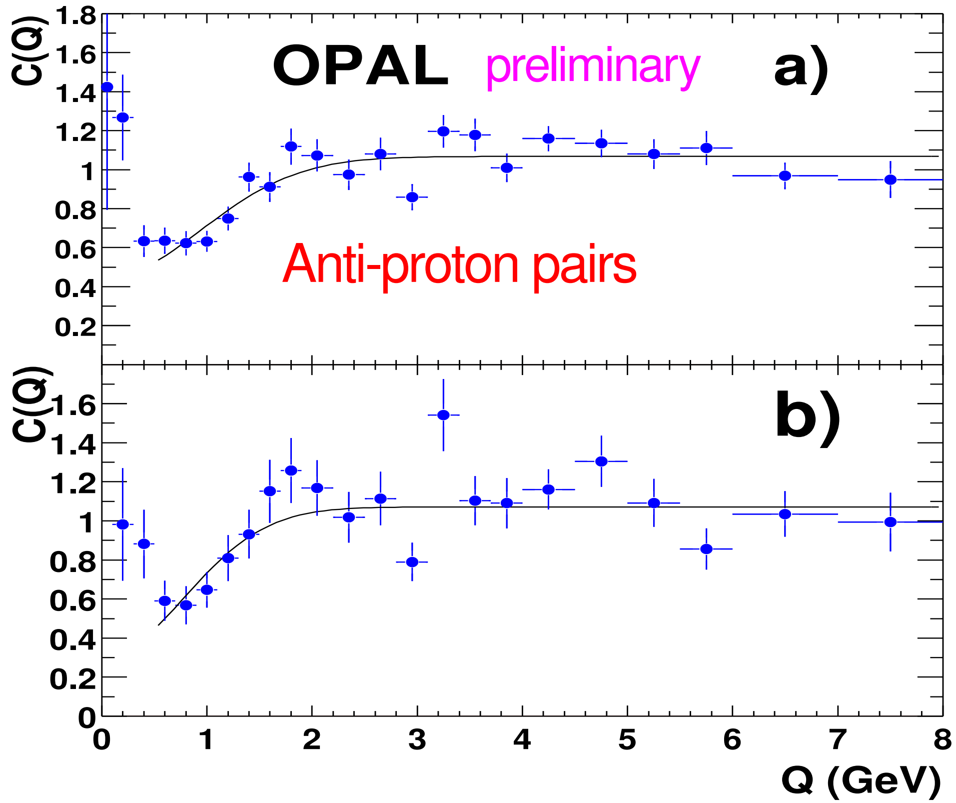
$\lambda = -0.5$ for stat. spin mixture & incoherent prod.

Alexander & Lipkin (1995)

Reference samples: A): MC; B,C): mixing techniques

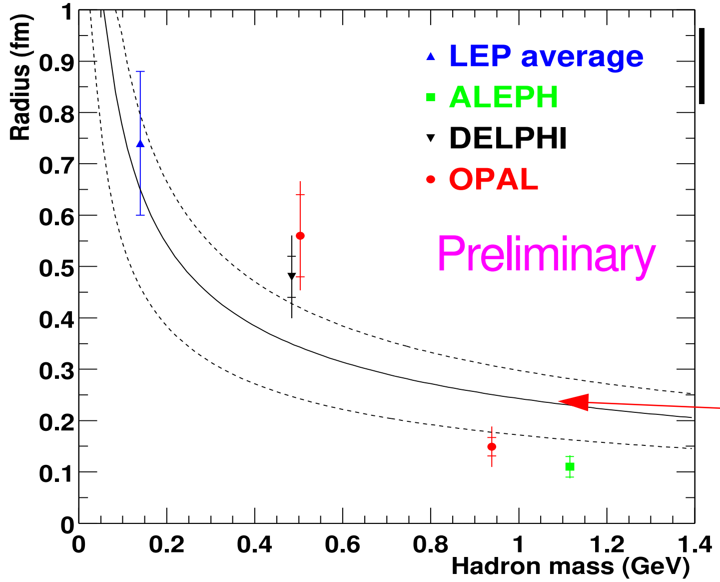


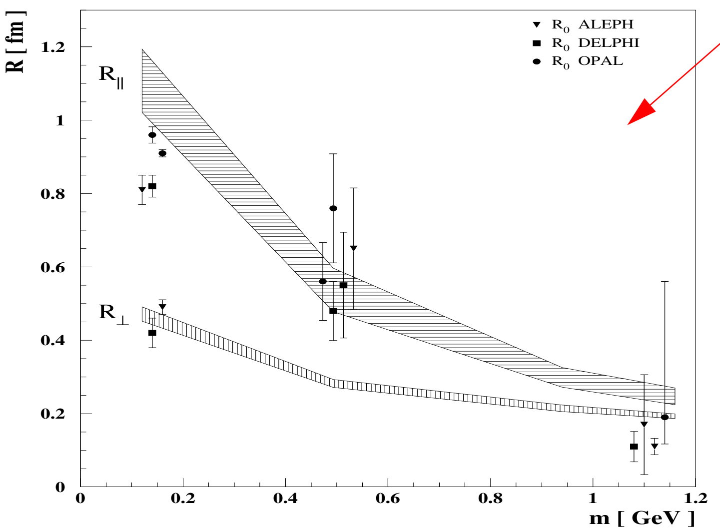
Reference samples: a):MC; b):event mixing



- Checks with $\bar{p}\bar{\Lambda}$-pairs in progress
- Rise in first Q bins: no obvious experimental problem; $\bar{p}\bar{p}$-FSI ?

Dependence of Source Size on Hadron Mass





$R_\pi > R_K > R_{p,\Lambda}$ hierarchy observed
using F.-D. hypothesis for p, Λ

Opposite trend expected in Lund string model

In qualitative agreement with models based on:

- Heisenberg uncertainty principle $\Delta t=10^{-24}$s, $\Delta r=R$

  Alexander, Cohen & Levin (1999)

- Bjorken-Gottfried conjecture $$p^\mu = \frac{M_\perp}{\sqrt{t^2 - z^2}} \cdot x^\mu$$

  Implements (x,p)-correlation expected from relativity
  Inside-outside cascade: fast particles produced last

  Measured R does not represent the source size

  Bialas, Kucharczyk, Palla, Zalewski (1999, 2000)

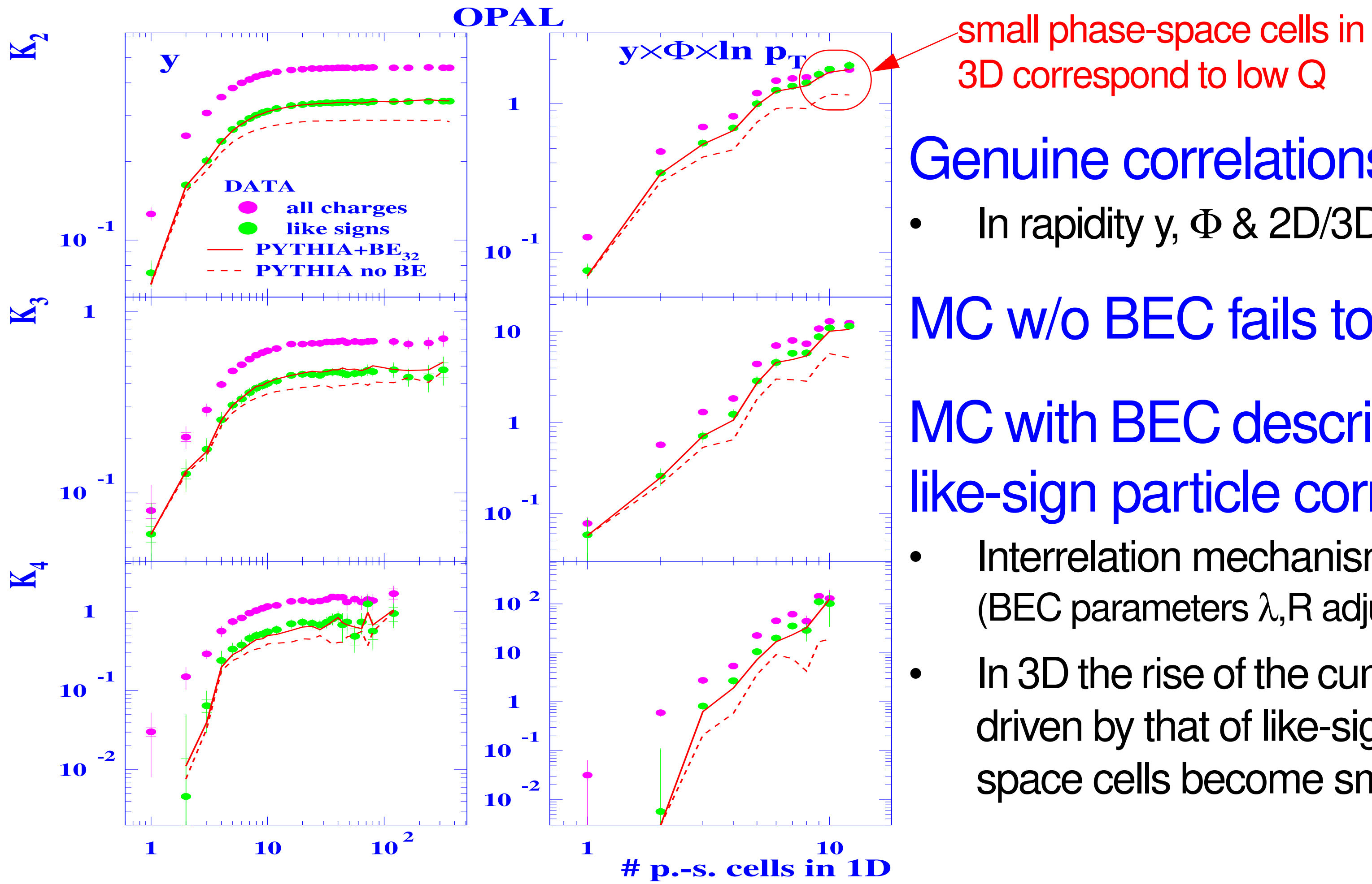
Problem if R is interpreted as emitter radius:

Enormous energy density for high mass: 10-100 GeV/fm^3

2-, 3- & 4-Particle Genuine Correlations

Measured by cell-averaged cumulants K_n (related to multiplicity factorial moments)

Lower order particle & random correlations removed by construction Phys. Lett. B523 (2001)



Genuine correlations up to 4th order

- In rapidity y, Φ & 2D/3D wrt sphericity axis

MC w/o BEC fails to describe K_n

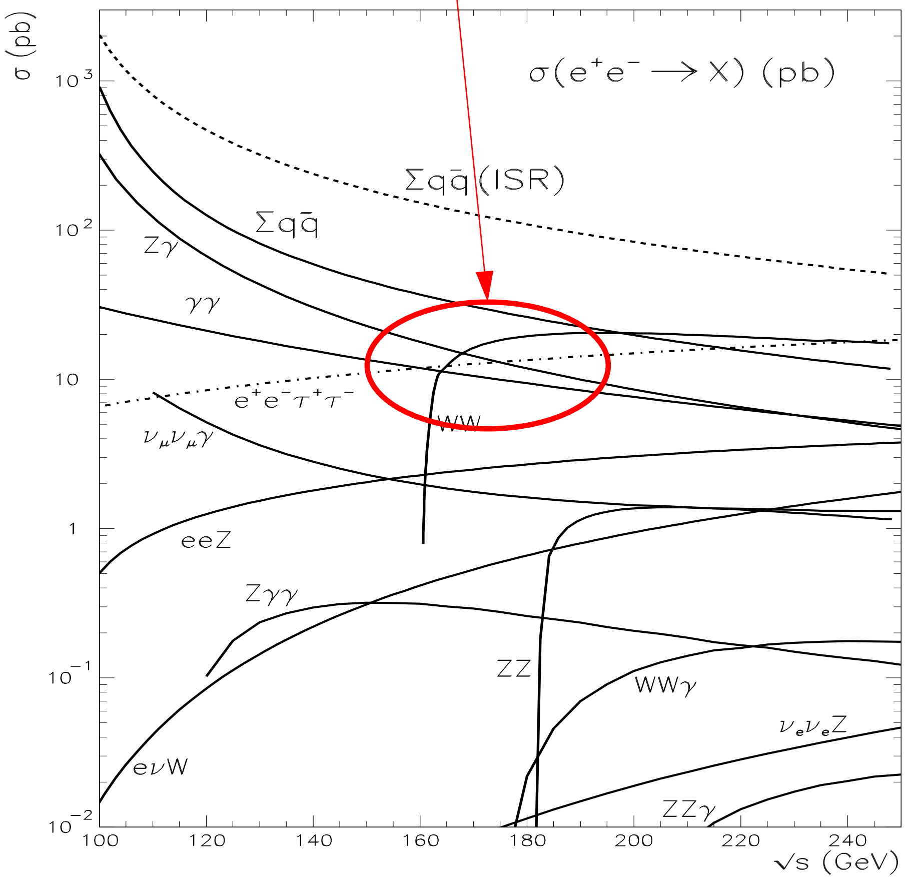
MC with BEC describes all-charge & like-sign particle correlations

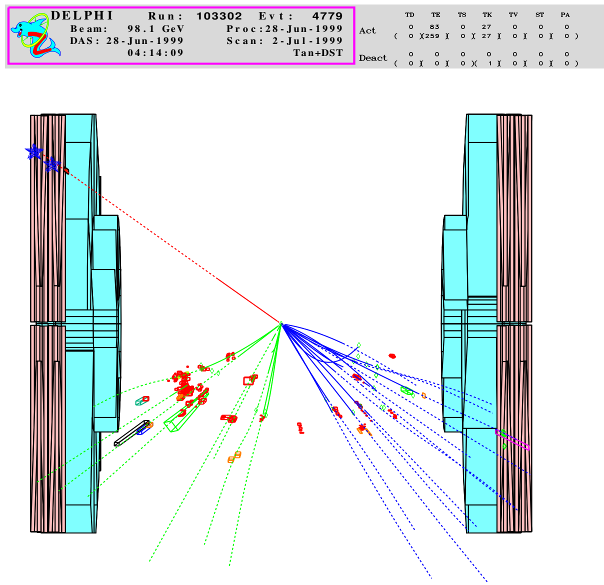
- Interrelation mechanism ?
  (BEC parameters λ,R adjusted only on K_2)
- In 3D the rise of the cumulants is increasingly driven by that of like-sign multiplets as phase space cells become smaller, pointing to BEC

LEP-2 (1997-2000)

Data taken above W^+W^- threshold

$$e^+ + e^- \rightarrow W^+W^- \rightarrow f\bar{f}f\bar{f}$$





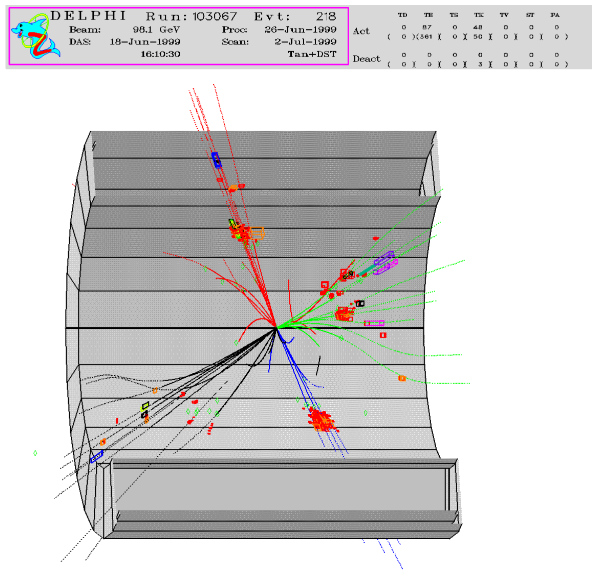
qqlυ channel

(l=e,μ,τ)

BR: 43.8%

~4000 events/collab.

Low background



qqqq channel

BR: 45.6%

~5000 events/collab.

Significant bkg:

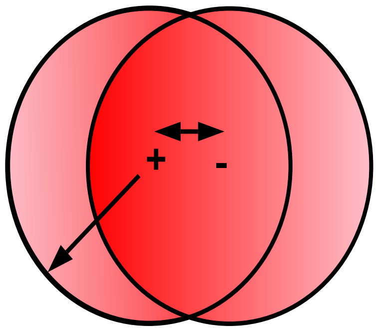
~10 -15% Z^0

~ 5 -10% Z^0Z^0

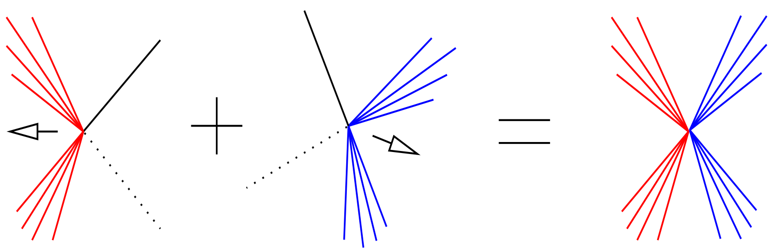
Do Inter-WW BE Correlations Exist ?

$W^+W^- \rightarrow q\bar{q}q\bar{q}$

Separation between W's: 0.1fm



Hadronization size: 0.5 to several fm



4q: qqqq events

2q: qqlν events without leptonic part

mix: two independent 2q events; use only pairs of particles from different W's

Overlap in PS: Inter-WW BEC possible

Cross-talk between W's: particle/momentum transfer

Significant uncertainty in W mass determination from the invariant jet-jet mass; initial predictions: $\Delta M_W = 0 - 100$ MeV

BEC within a W similar (udsc) as in Z decays

Access to Inter-WW BEC directly from data

- MC subtraction of 10 -15% 4-jet bkg from Z^0 subtle
- Mixing method: Chekanov, De Wolf & Kittel (1999)

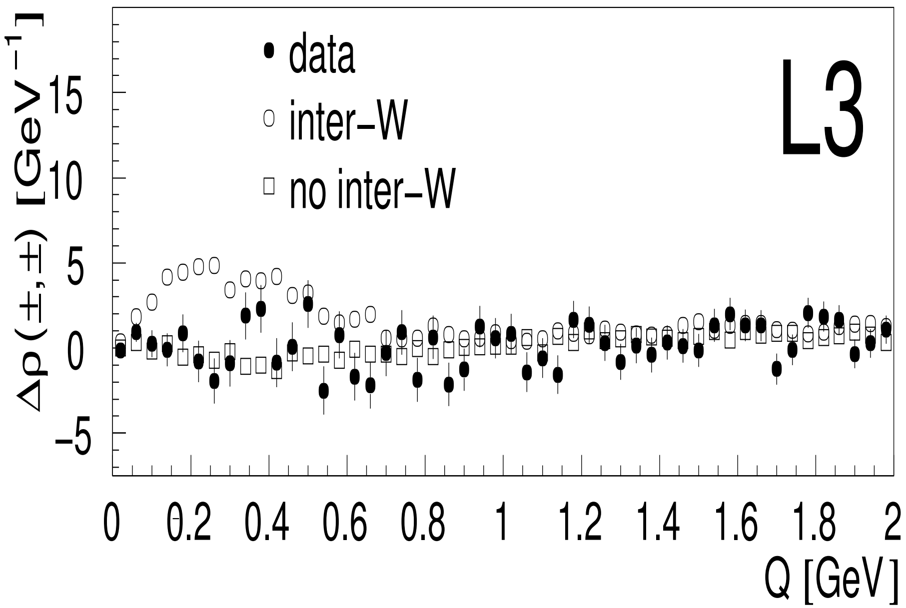
$$\Delta\rho = \rho_2^{WW \rightarrow 4q} - \left(2\rho_2^{W \rightarrow 2q} + \rho_2^{WW_{mix}}\right)$$

faked 4q event

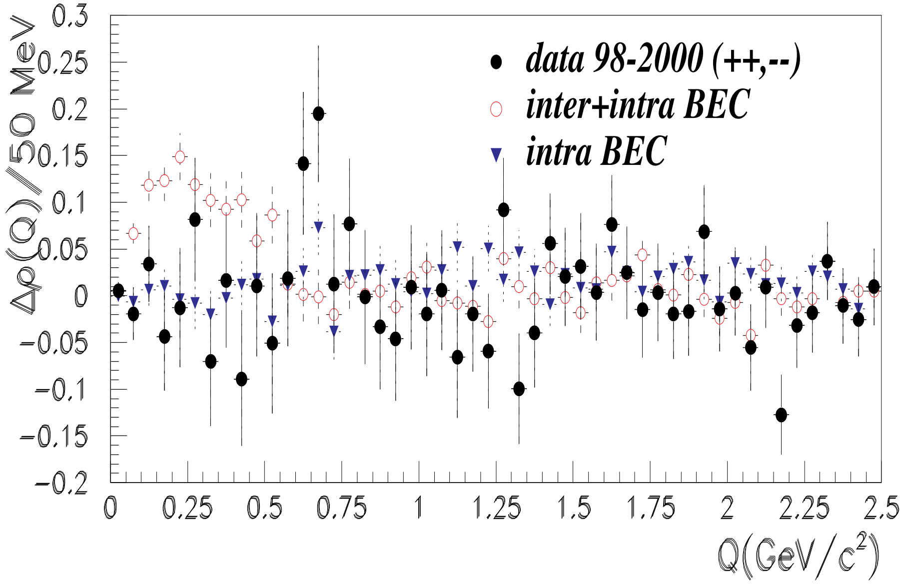
$\Delta\rho = 0$ in the absence of <u>any</u> Inter-WW correlation

Experimental Results on Inter-WW BEC

L3 preliminary



DELPHI preliminary



Similar results from ALEPH

No evidence for Inter-WW BEC

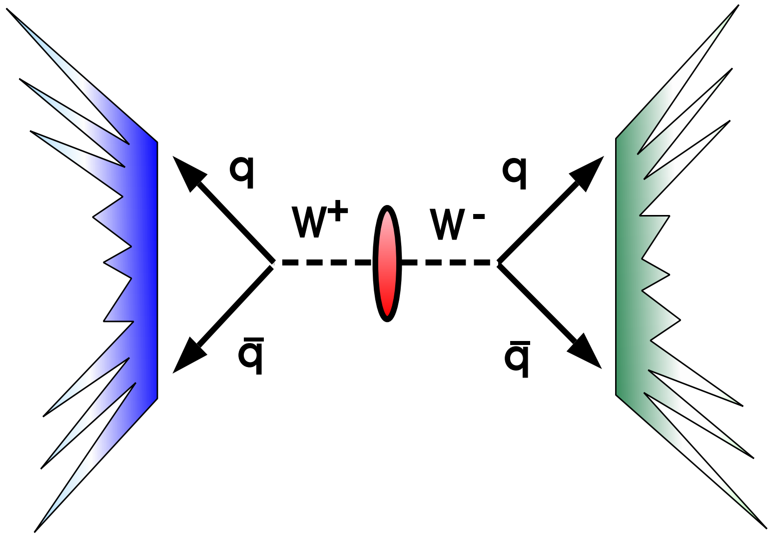
- LUBOEI/PYTHIA model which describes BEC between W's with same R and λ as within single W is disfavoured

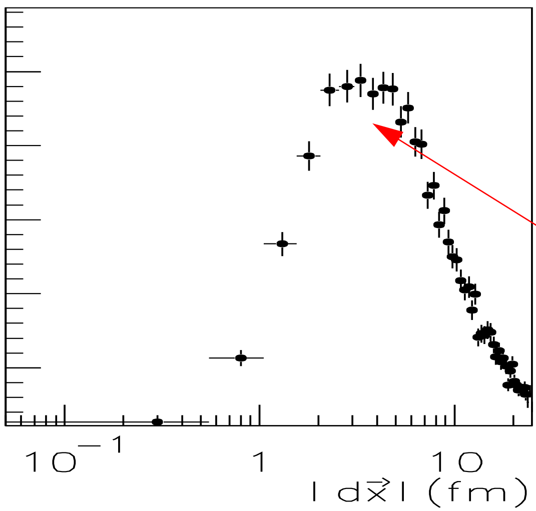
LEP combination in preparation

LEP experiments are preparing final publications with new MC tunings and more accurate background subtraction

- BEC-MC tuned on inclusive Z events over-estimates BEC for (bgk relevant) 4-jet events
- Expected that significance for absence of Inter-WW BEC will decrease somewhat

Why are there no Inter-WW BEC ? Speculations only ...





Todorova-Nova, Rames (1997)

Lund string model Andersson et al.

- Observed BEC effects in e^+e^- can be explained with a coherent particle production in string

  R is related to distance in string where momentum distributions of particles still overlap

- In the absence of colour reconnection, no cross-talk between independent strings possible

However, a new preliminary L3 result on 3-particle BEC at the Z is consistent with fully incoherent pion production

Extra (incoherent) HBT correl.? De Wolf (2001)

- (In string model), space-time difference for pairs with particles from different W's is several fm
- Correl. would manifest at lowest Q bins (Fourier) which are not evaluable with low LEP-2 statistics

A Kind of a Summary

G. Goldhaber about BEC (1990):

- What is clear is that we have been working on this effect for 30 years.
- What is not as clear is that we have come much closer to a precise understanding of the effect.

K. Zalewski about Goldhaber's statement (2000):

- What would be his statement now ?
- What is clear is that he would have changed 30 years to 40 years.
- What is not as clear is that he would have considered any other changes necessary.

A complementary & more optimistic view:

- The study of particle correlations gives important information about the dynamics of hadron production.