Particle Correlations at LEP

Review of selected experimental results of the LEP collaborations

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

HEP-MAD'01, First High-Energy Physics Conference in Madagascar

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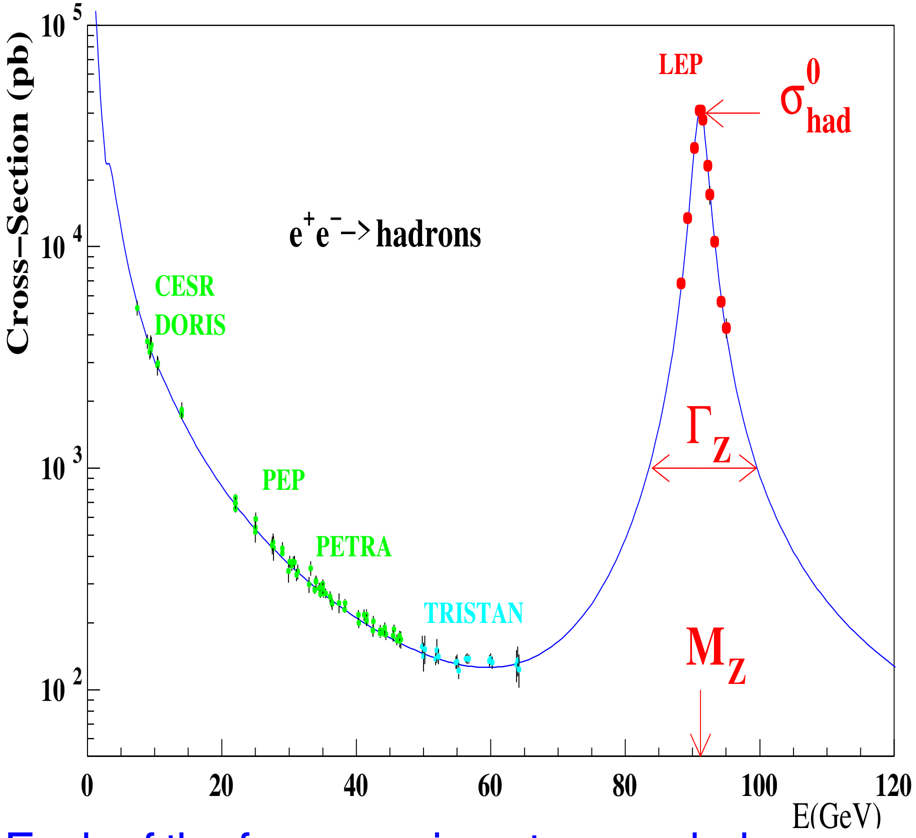
October 2001

LEP-1 (1989-1995) $e^+e^- \rightarrow Z^0 \rightarrow f\bar{f}$

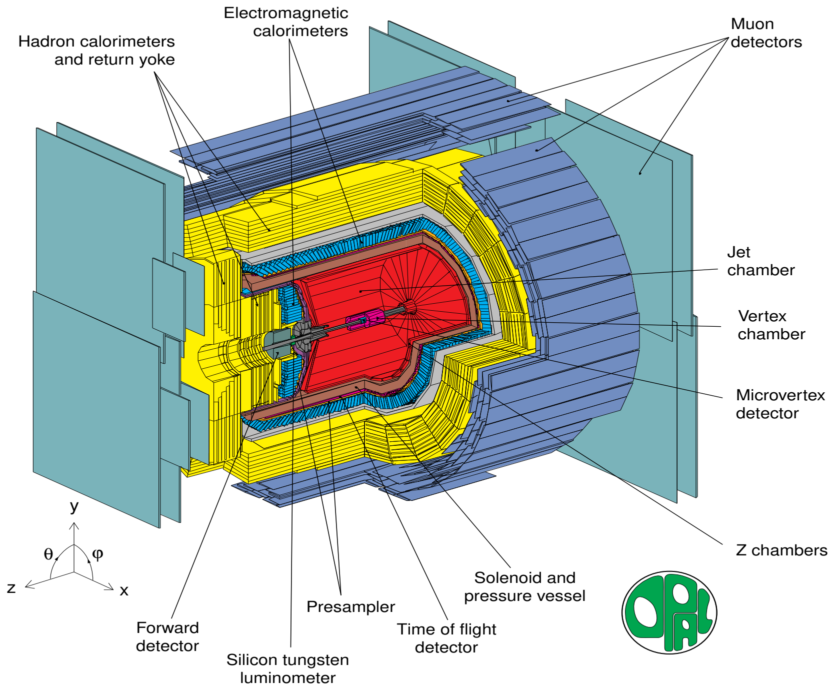
Data taken around the Z^0 resonance



Each of the four experiments recorded:

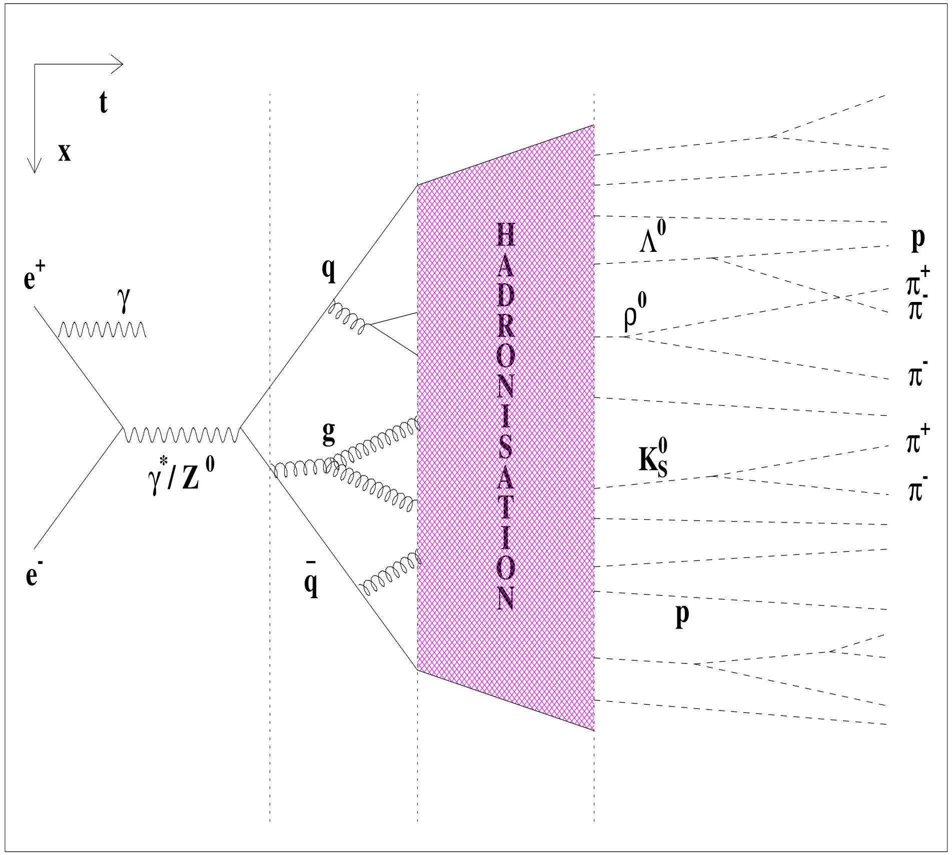
- A total integrated luminosity of 170 pb^{-1}
- More than 4 million hadronic Z^0 decays

One of the LEP detectors:



- Forward luminosity detectors
- Microvertex detector
- Tracking chambers with possibility of particle id
- Electromagnetic calorimeters
- Hadron calorimeters
- Muon detectors

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



Final state particles (on average):

- 21 charged particles (17 pions, 2 kaons, 1 proton)
- 21 photons (mostly from neutral pions)

Complementary information about QCD & dynamics of hadronization:

Global event properties

- Event shapes, jet rates, multiplicity, ...

Single-particle spectra

- Total & diff. rates, y-distribution, ...

Particle correlations & fluctuations

- Quantum mechanical correlations: Bose-Einstein & Fermi-Dirac statistics
- Genuine multiparticle correlations

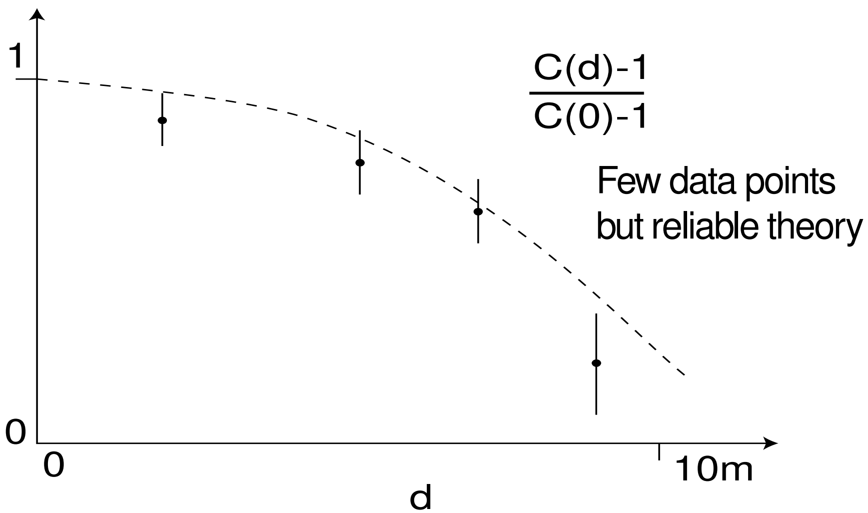
History of Bose-Einstein Correlations

Enhancement of identical particle pairs (e.g. $\pi^+\pi^+$, $\pi^-\pi^-$) close in phase space compared to $\pi^+\pi^-$-pairs Goldhaber, Goldhaber, Lee, Pais (1960)

Analogy in astronomy: determination of star radii with intensity interferometry

Hanbury Brown, Twiss (1954)

Measurement of angular diameter of Sirius



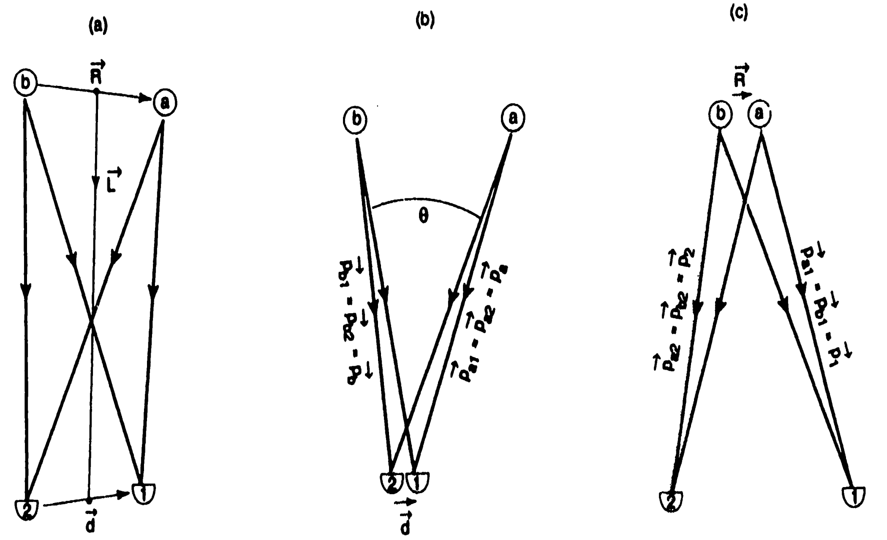


Figure 1: Measurement of the separation R of two sources a and b by correlating the intensities in detectors 1 and 2 at varying distances d. **a**: The general scheme. **b**: The specific situation in astronomy. **c**: The specific situation in particle physics.

Completely different relation of the dimensions in astronomy and particle physics

Relation between Space-Time of Source and Correlation Function for Identical Bosons

Start with symmetric two-boson wave function:

$$\Phi(p_1,p_2) = 1/\sqrt{2}\cdot\left\{e^{-ip_1x_1}\cdot e^{-ip_2x_2}+e^{-ip_1x_2}\cdot e^{-ip_2x_1}\right\}\cdot f(x_1)f(x_2)$$

Correlation function:

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

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

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

Normalized Fourier transform of the source intensity

Assumptions valid in astronomy: ..... they are wrong in hadron production

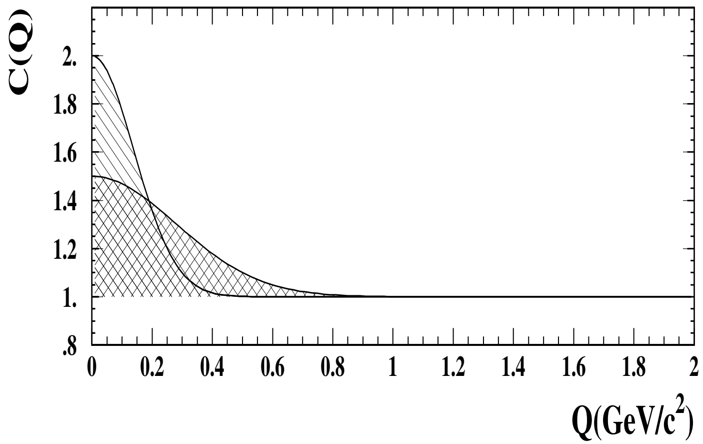
- Plane wave propagation ..... only if no final-state interactions
- No coherence anywhere, anytime ..... most pions originate from resonances
- No correlations between x and p .....(x,p)-correlations in inside-outside cascade

More Bose-Einstein Basics

GGLP: Gaussian source

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

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



R: source size

λ: strength parameter

In GGLP ansatz λ=1 for completely incoherent source

$$\rho_2(p_1, p_2) = \rho_2(Q) = \frac{1}{N_{events}} \frac{dn_{pairs}}{dQ}$$

$$C(Q) = \rho_2^{BEC} / \rho_2^{no-BEC}$$

Usually single-particle distributions in denominator of C are replaced by two-particle distribution of a reference without the BEC effect but with all other dynamical correlations

Some popular reference samples:

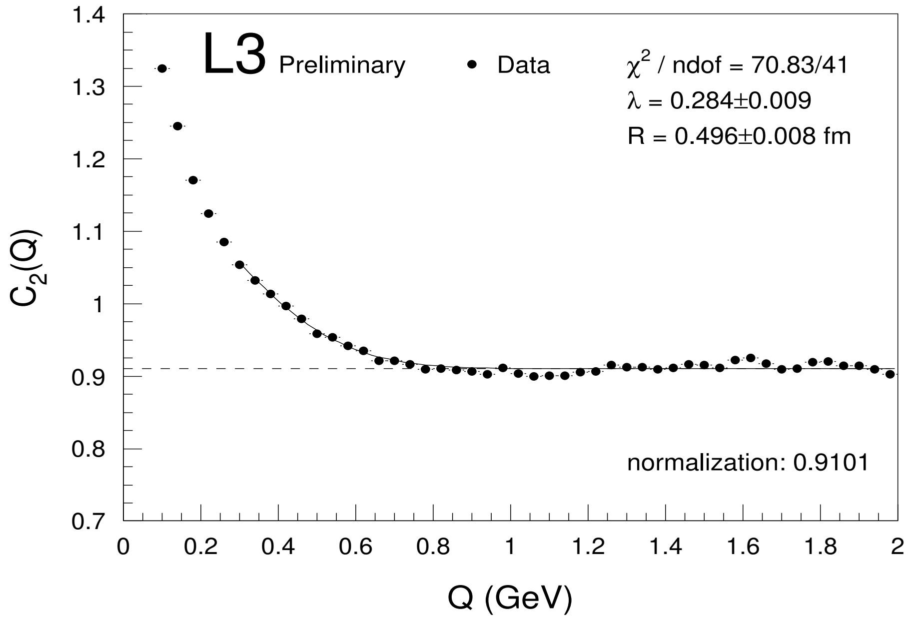
- MC without BEC
- Unlike-sign particle pairs
- Hemisphere mixing
- Event mixing

All reference samples have their own specific problems

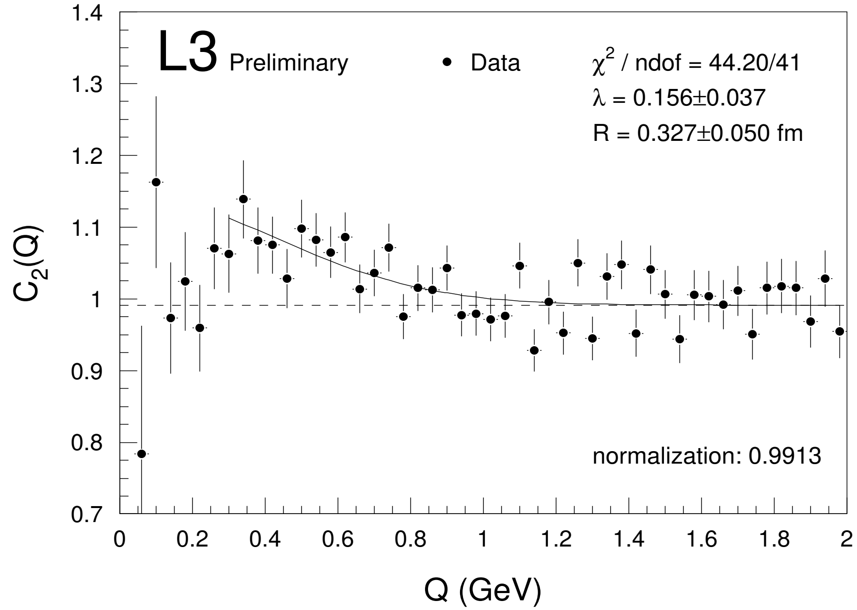
Note: there is no (hadron) world without BEC !

Bose-Einstein Correlations in Pion Pairs

$\pi^+\pi^+, \pi^-\pi^-$ pairs



$\pi^0\pi^0$ pairs



- BEC between charged pion pairs clearly established at LEP

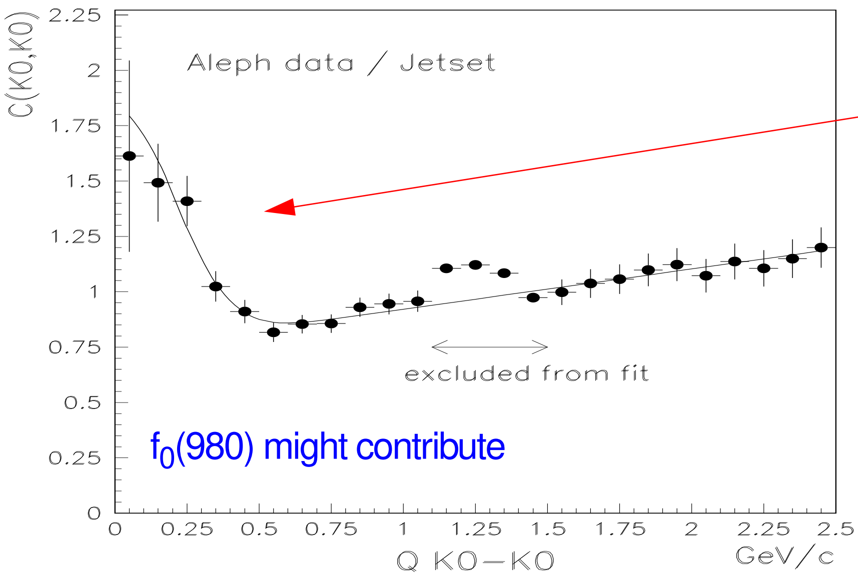
  Consistent results: source radius R = 0.5 ...1.0 fm (depending on reference sample)

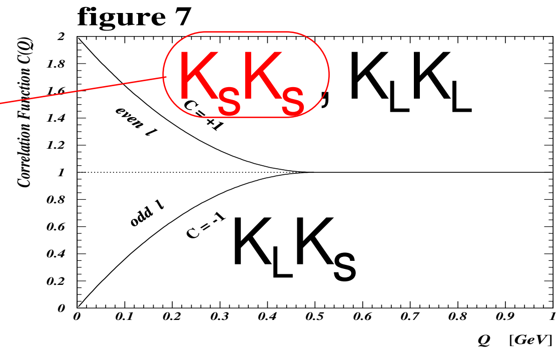
  R significantly smaller than in nucleus or heavy ion reactions

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

  Complicated measurement; qualitatively expected in Lund string model

Bose-Einstein Correlations in Kaon Pairs

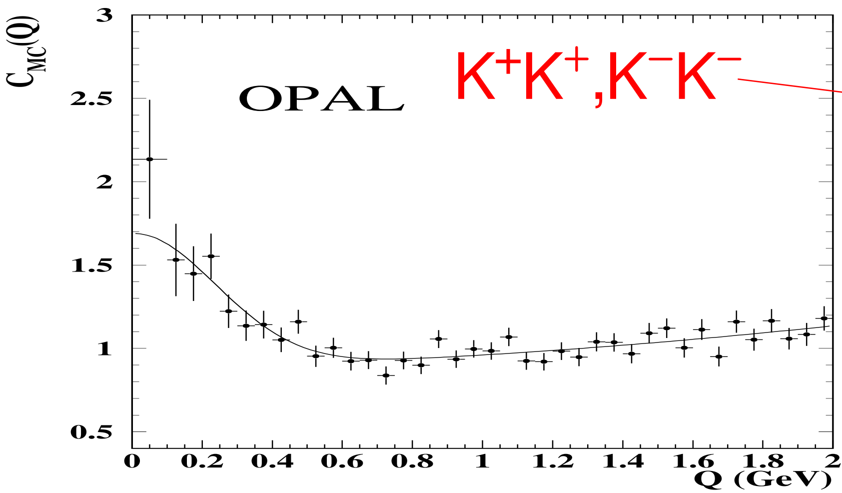


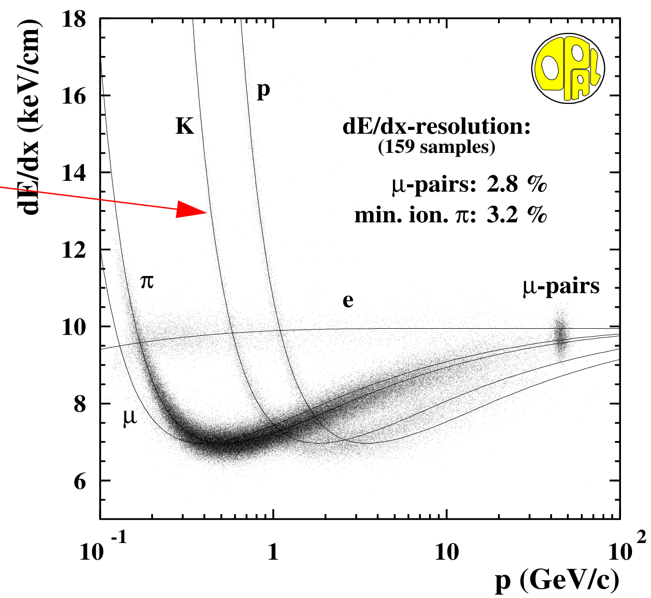


Classify K^0 pairs according to the C-parity of system

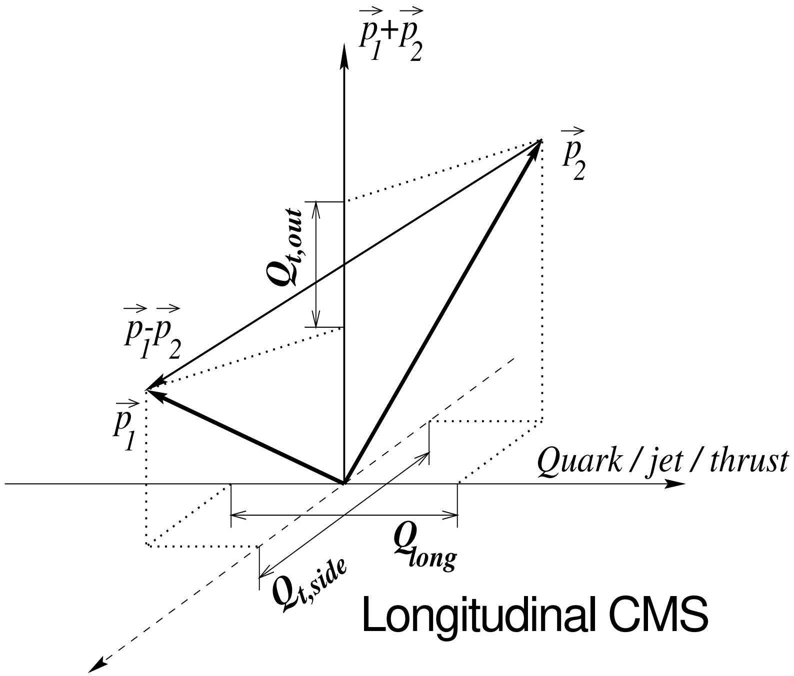
Alexander & Lipkin

K_S identification: cut in $\pi^+\pi^-$ invariant mass spectrum for candidates with a secondary vertex ($c\tau = 2.7$cm)





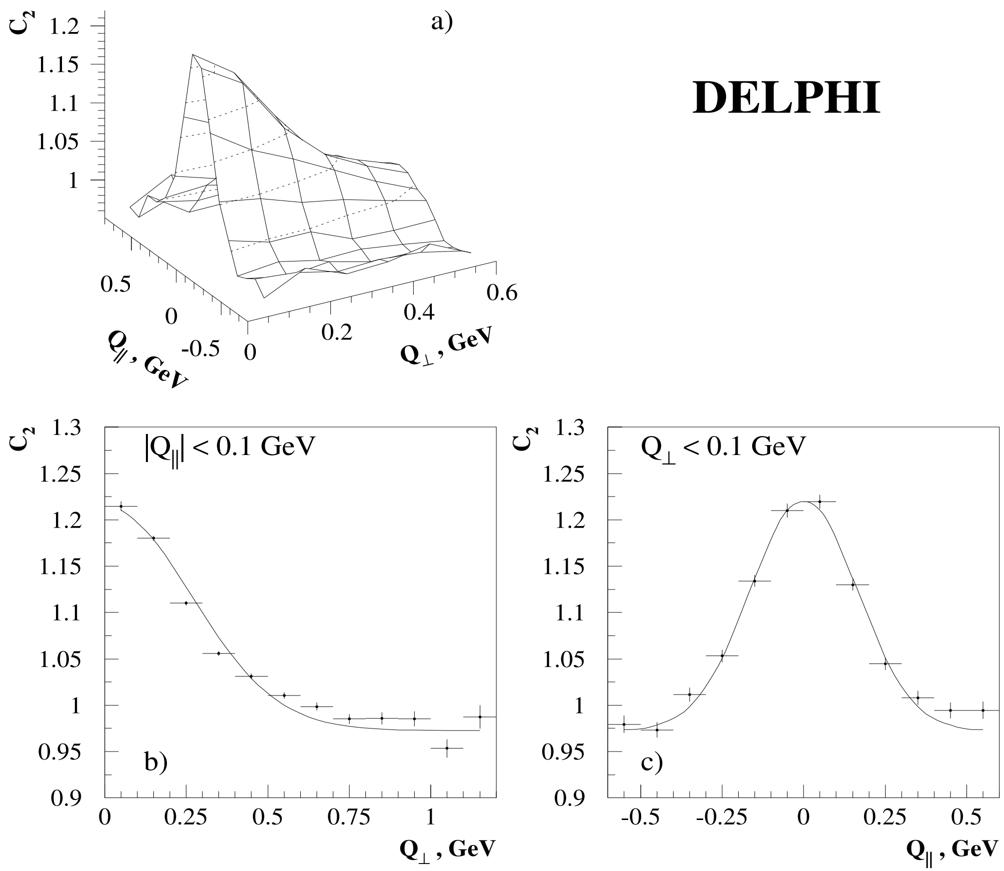
Two-dimensional Analysis of the Source



In the Lund/string picture for 2-jet events:

- Source is elongated along the direction of motion

  Andersson & Ringner (1998)



Consistent (DLO) results:

- $R_{transv.}/R_{long.} = 0.62 \ldots 0.81$

Source is not spherical

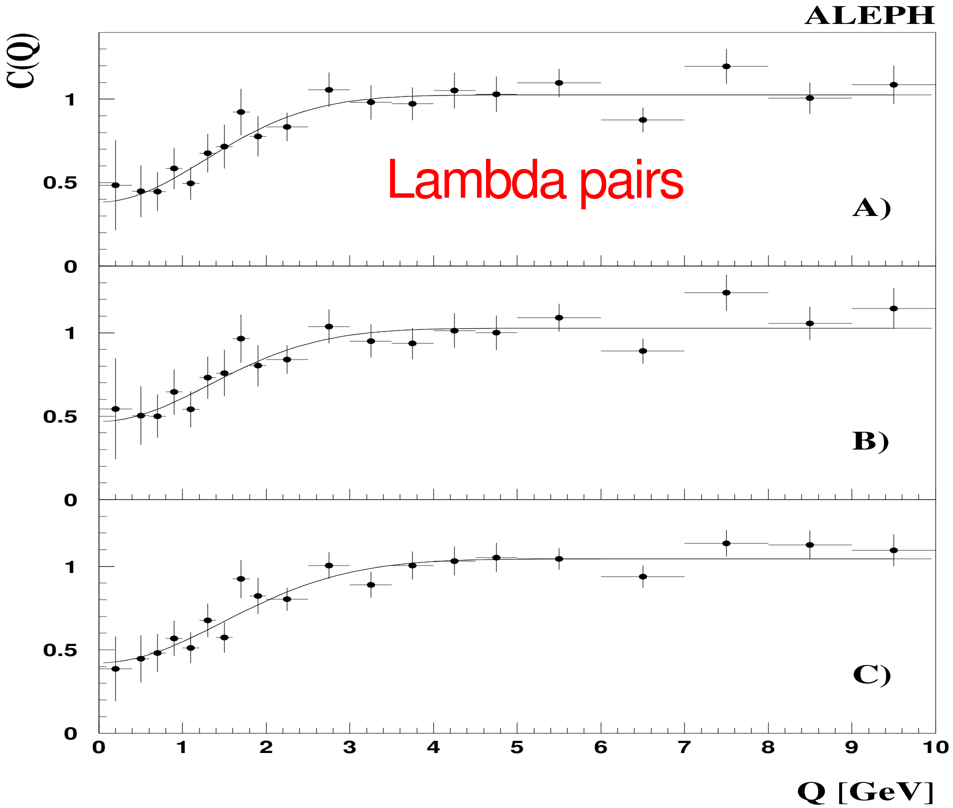
- Not implemented in PYTHIA+BEC

Fermi-Dirac Correlations of Baryon Pairs

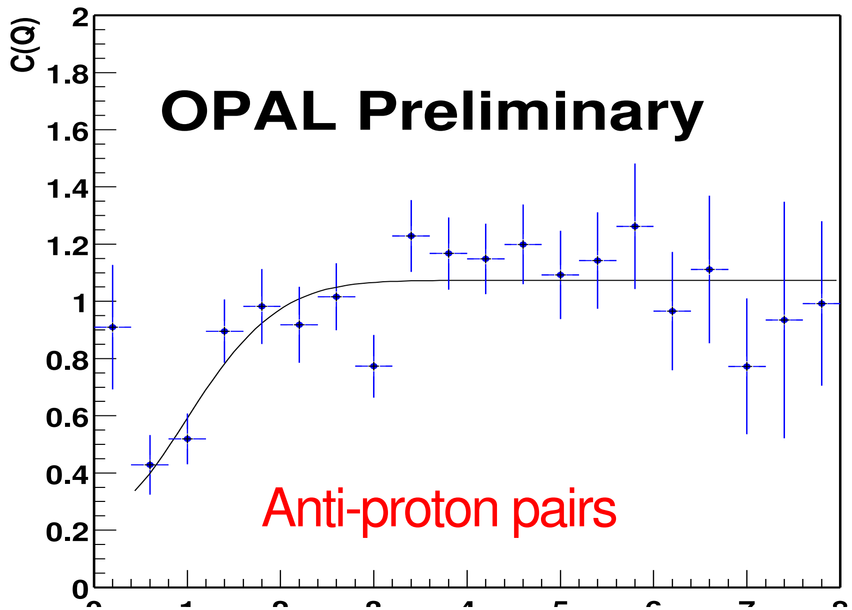
Antisymmetric spatial & spin wave function

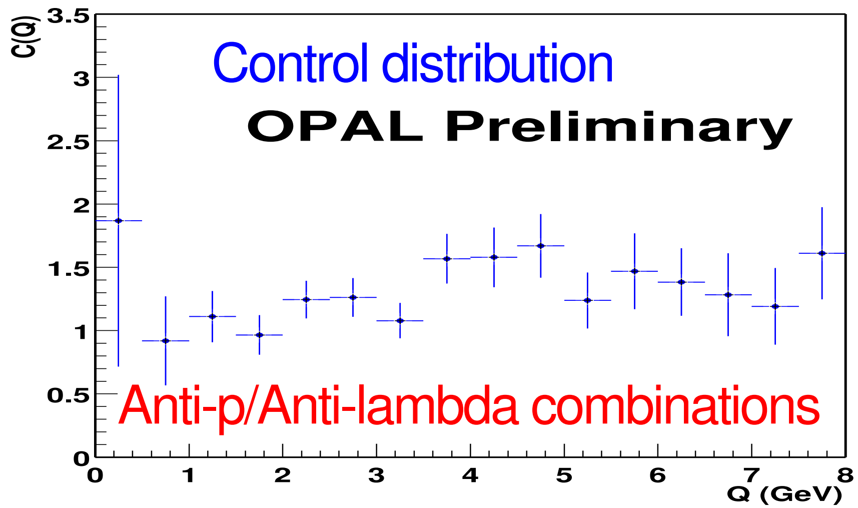
- λ= -0.5 for incoherent source without FSI

Alexander & Lipkin (1995)

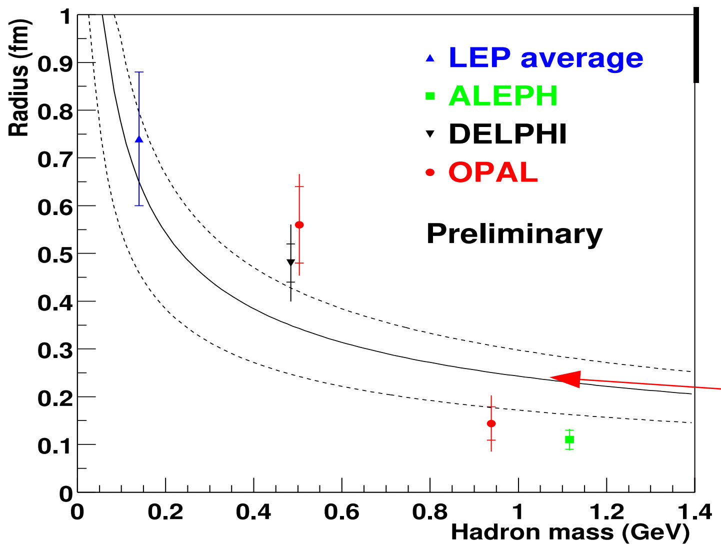


Reference samples: A): MC; B,C): mixing techniques





Dependence of Source Size on Hadron Mass



$R_\pi > R_K > R_{p,\Lambda}$ hierarchy observed

Opposite relation in Lund/string model

In qualitative agreement with models based on:

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

  Virial theorem + LPHD + QCD potential

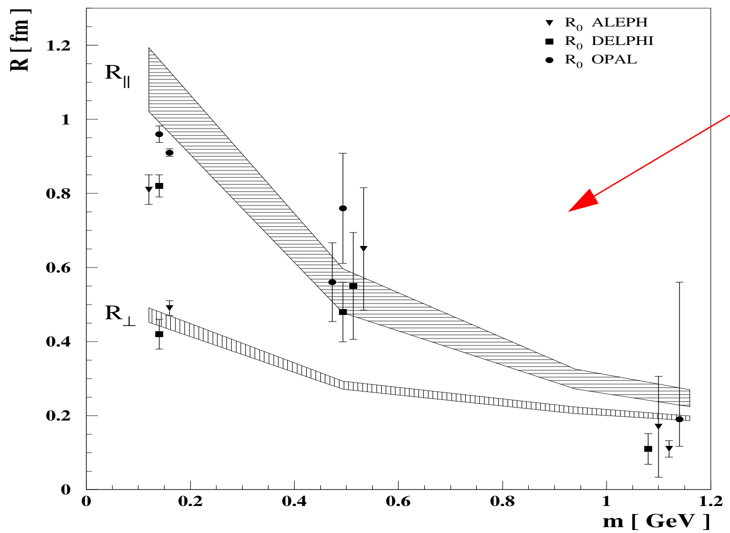
  Alexander, Cohen & Levin (1999)

- 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

  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

Genuine Multiparticle Correlations

See e.g. De Wolf, Dremin, Kittel (1995)

- Powerful tools to measure n-particle correlations:

  Factorial moments, cumulants, correlation integrals

- n-particle density $\rho_n(1, \ldots, n)$ contains correlations from all orders
- Cluster expansion in cumulant correlation functions $C_q(1, \ldots, q)$:

$$\rho_1(1) = C_1(1)$$
$$\rho_2(1, 2) = C_1(1)C_1(2) + C_2(1, 2)$$
$$\rho_3(1, 2, 3) = C_1(1)C_1(2)C_1(3) + C_1(1)C_2(2, 3) + \ldots + C_3(1, 2, 3)$$
$$\rho_4(1, 2, 3, 4) = \ldots$$

- C_q from inversion; C_q vanish when one of the arguments becomes statistically independent of the others
- Genuine correlation of order q if C_q not zero

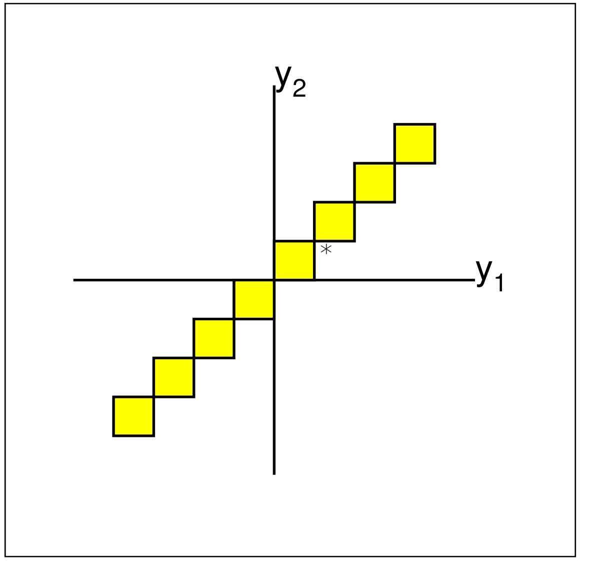
Cell-Averaged Factorial Cumulants

- Divide phase space Ω in M non-overlapping cells Ω_m

  E.g. bins in rapidity y wrt sphericity axis

- Integrate over the cells Ω_m and average

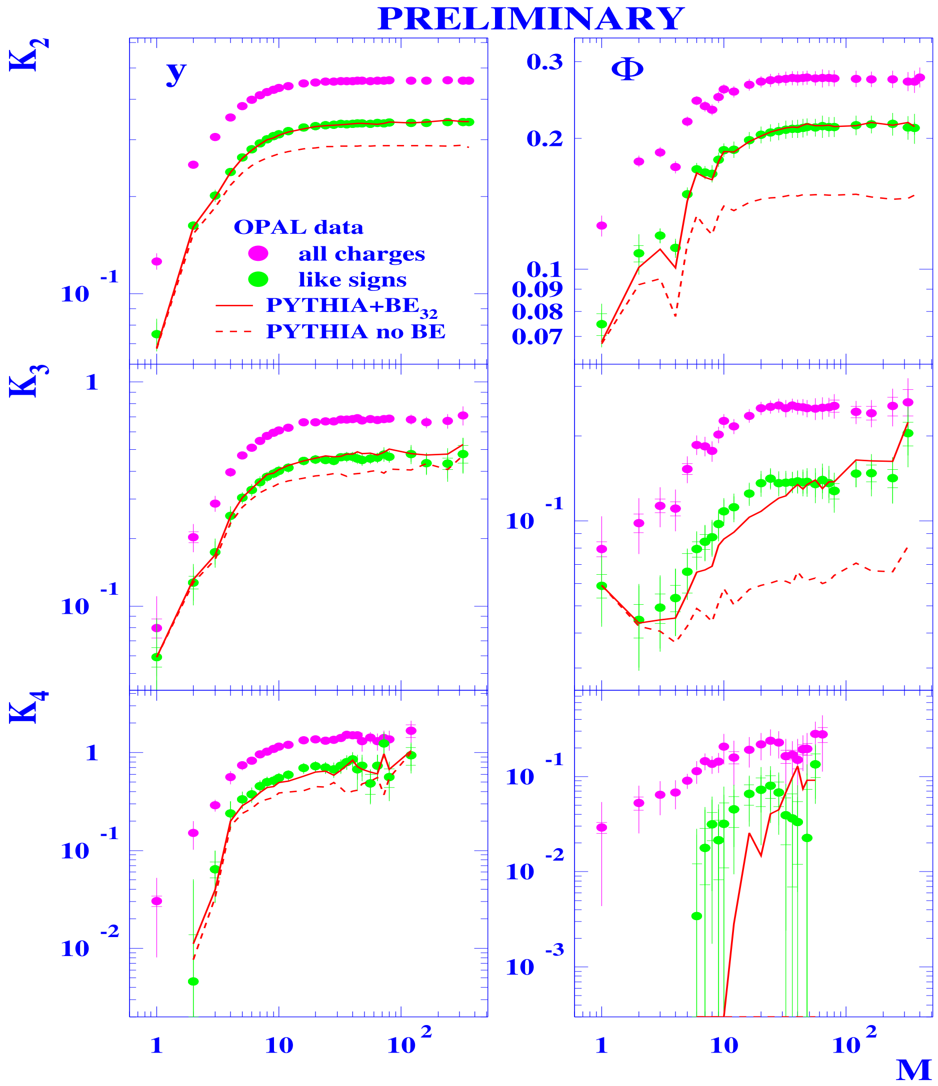
- K_q (M) gives information about correlation range

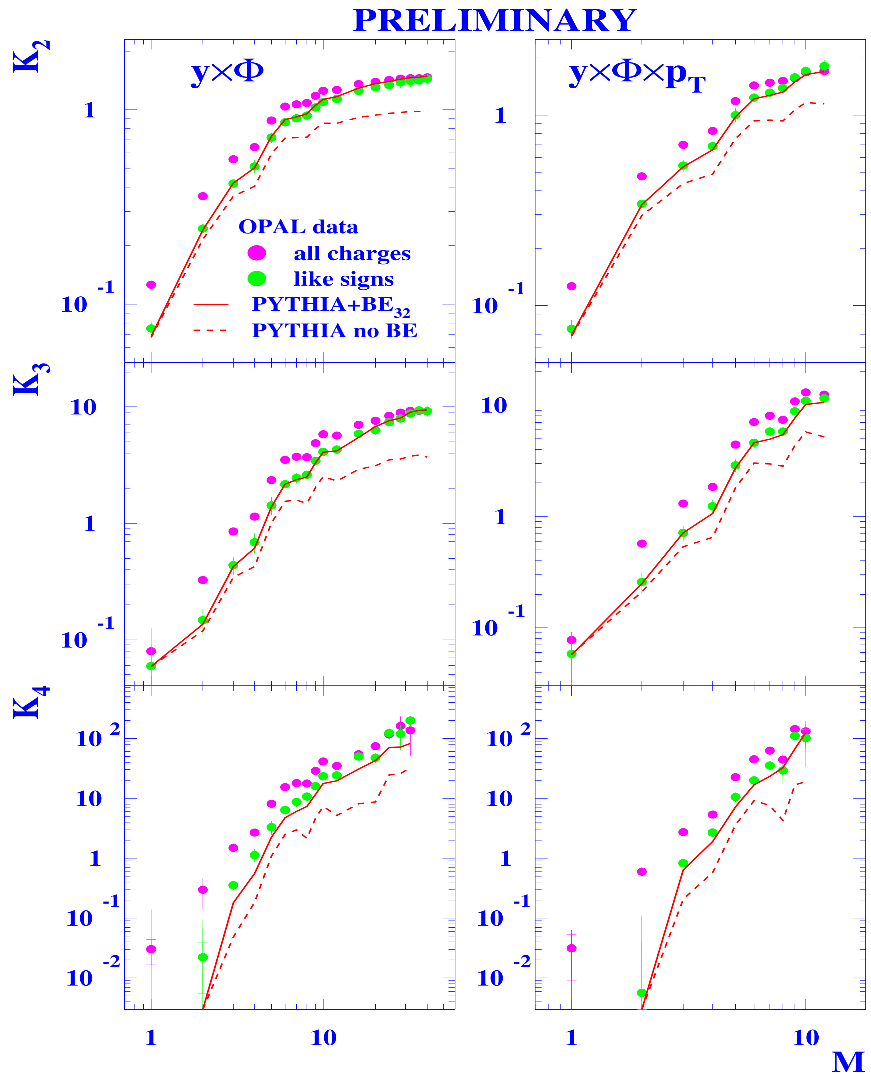


$$K_q = \frac{1}{M} \sum_{m=1}^{M} \frac{\int_{\Omega_m} C_q(y_1,\ldots,y_q)\,dy_1\ldots dy_q}{\left(\int_{\Omega_m} \rho_1(y)\,dy\right)^q}$$

Lower order correlations and Poissonian noise removed by construction

2-, 3- & 4-Particle Genuine Correlations



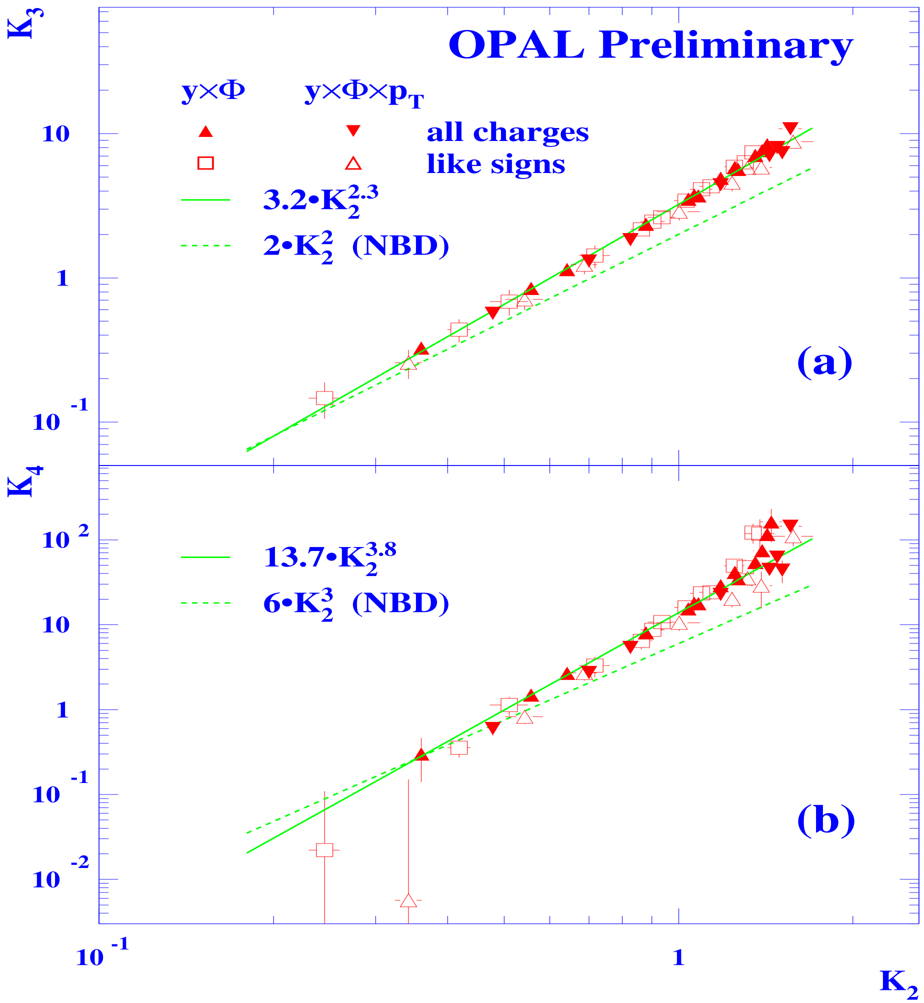


Results from Cumulants

- Strong genuine correlations up to 4th order for both all-charge and like-sign multiplets observed
- In 2D and 3D, one observes that the rise of the cumulants for all-charge multiplets is increasingly driven by that of like-sign multiplets as the phase space cells become small which points to the influence of BEC
- PYTHIA Monte Carlo without BEC, tuned to event shapes and single-particle spectra, fails to describe the observations

  PYTHIA+BEC MC provides a reasonable description of the data for like-sign and for all-charge multiplets

Further Results from Cumulants



- K_q obey hierarchical relation

  Higher order (3-, 4-) correlations linked to 2-particle correlations

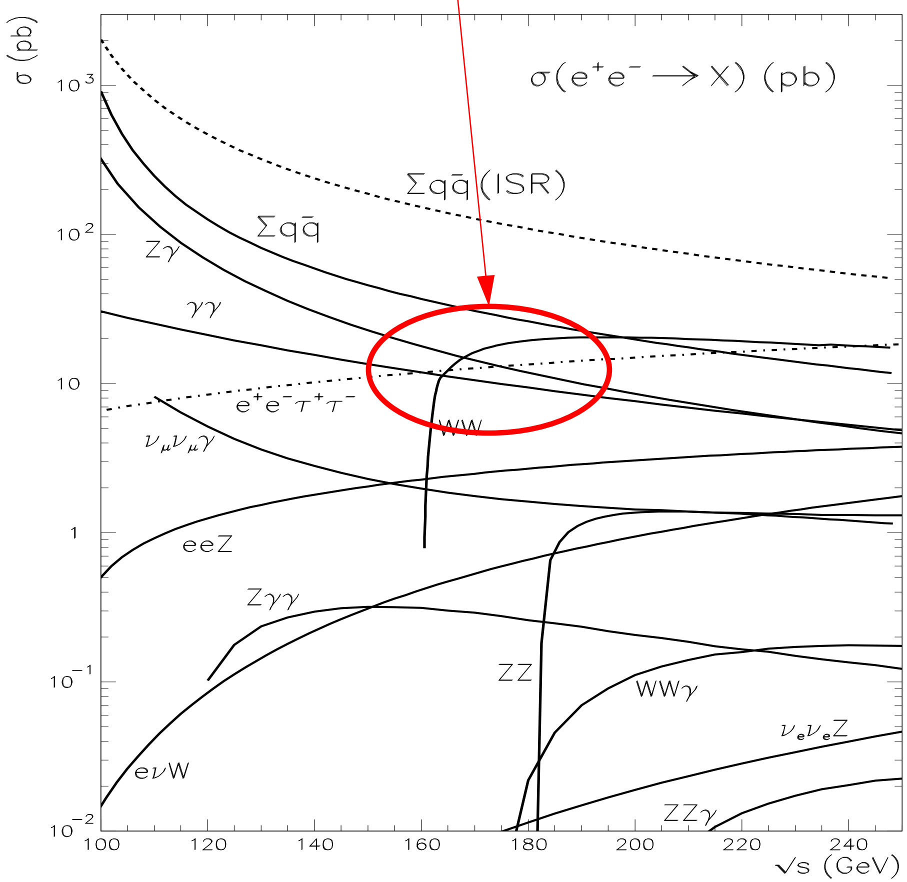
  Conjectured in various branches of many-body physics

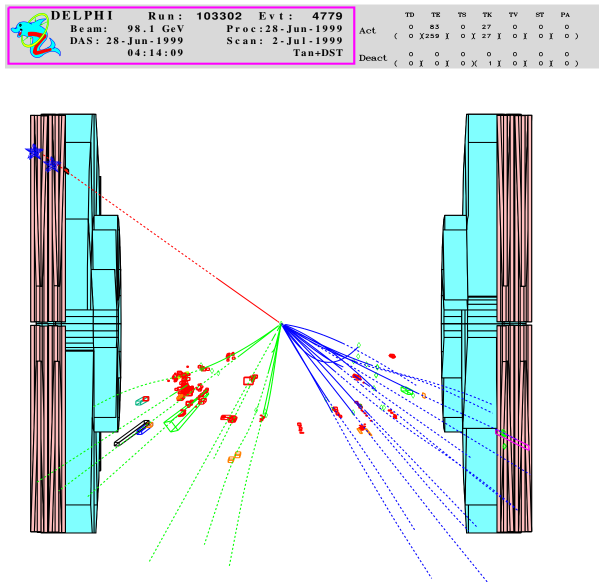
  Could explain why BEC-MC (only 2-particle correlations implemented) describes 3- & 4-particle correlations

LEP-2 (1997-2000)

Data taken above W^+W^- threshold

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





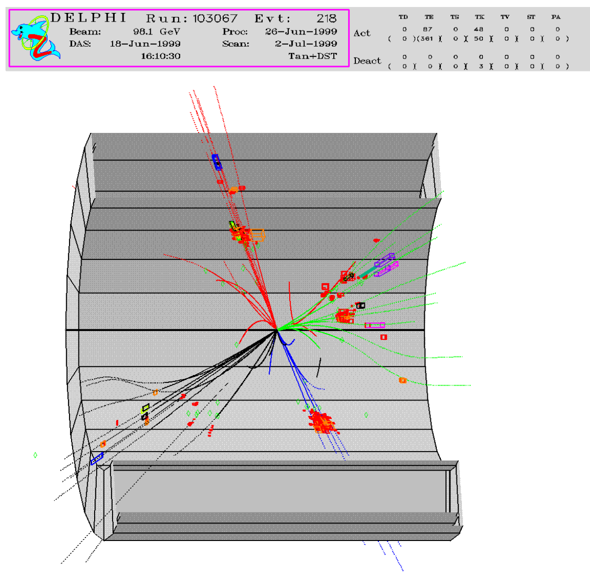
qqlν channel

(l=e,μ,τ)

BR: 43.8%

~4000 events/collab.

Low backgrounds



qqqq channel

BR: 45.6%

~5000 events/collab.

Significant BG:

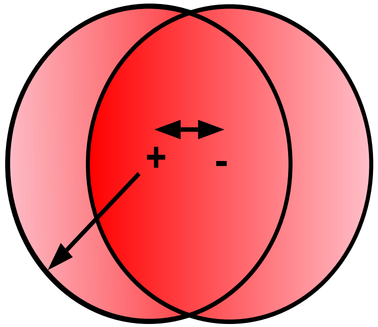
~10 -15% Z^0

~ 5 -10% Z^0Z^0

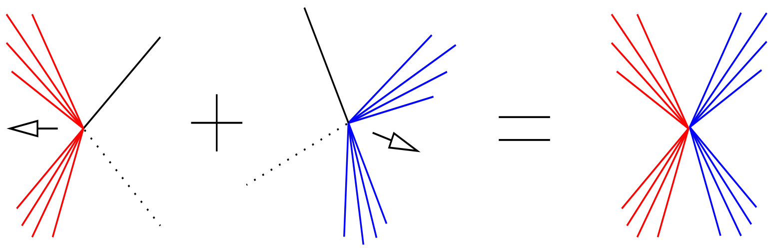
Do Inter-WW BE Correlations Exist ?

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

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

Access to Inter-WW BEC directly from data

(MC subtraction of 10 -15% 4-jet-like BG from Z^0 subtle)

Mixing method: Chekanov, De Wolf & Kittel (1999)

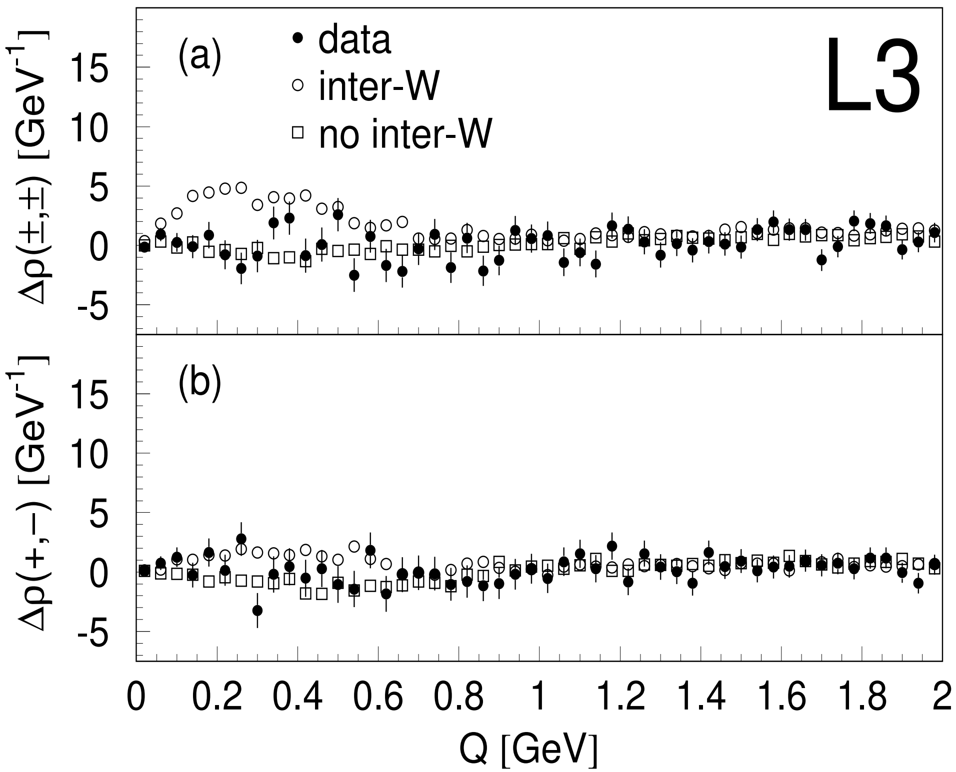
In the absence of any Inter-WW correlation:

$\Delta\rho = 0$

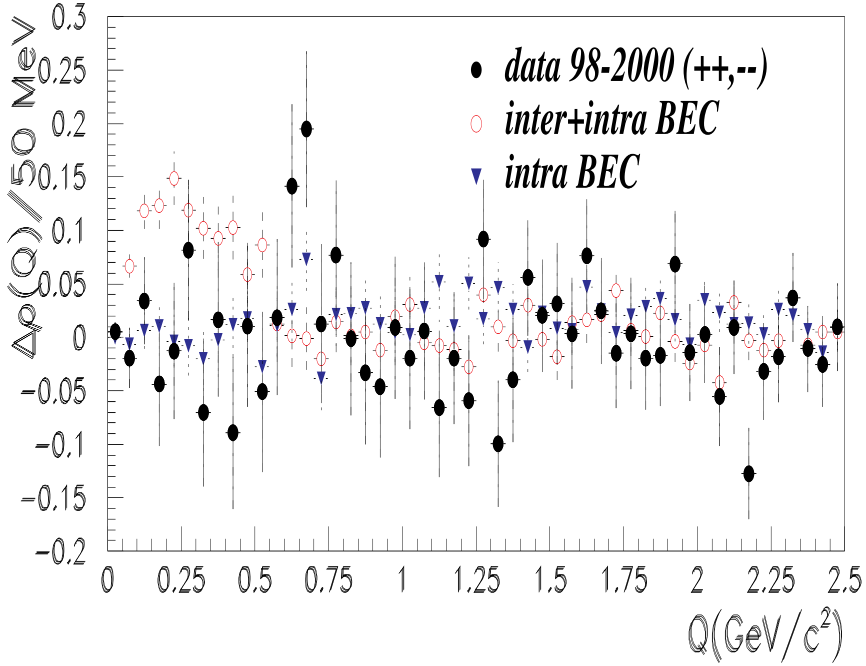
$$\Delta\rho = \rho_2^{WW \rightarrow 4q} - \underbrace{\left(2\rho_2^{W \rightarrow 2q} + \rho_2^{WW_{mix}}\right)}_{\text{faked 4q event}}$$

Experimental Results on Inter-WW BEC

L3 preliminary



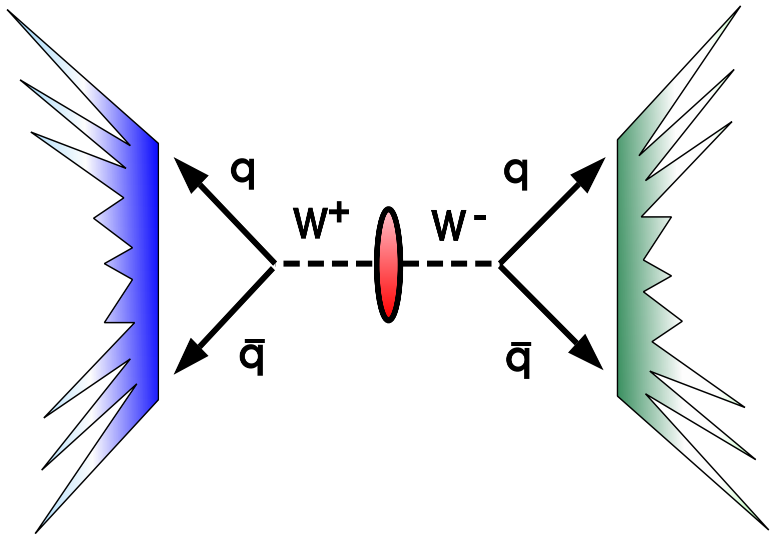
DELPHI preliminary



- No evidence for Inter-WW BEC
- LUBOEI model (within PYTHIA) which describes BEC between W's with same R and λ as within a single W is strongly disfavoured

Why are there no Inter-WW BEC ?

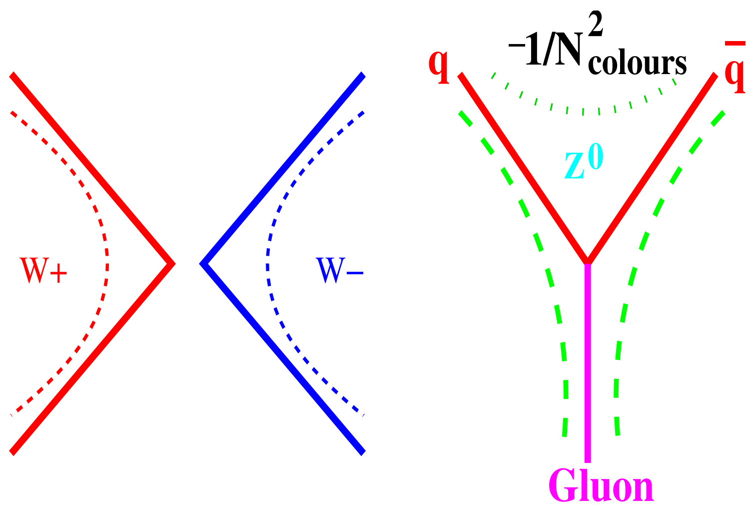
Speculations only ...



Lund string model (Andersson et al.):

- Observed BEC effects in e^+e^- can be explained with coherent particle production in string
- In absence of colour reconnection no cross-talk between independent strings possible

In progress: studies with high statistics Y-events at the Z^0



Implications for Heavy Ion collisions:

- Since in HI collisions particles are likely to originate from different strings (if strings exist) no strong BEC expected
- However the observed BEC effects in HI are sizable
- Completely different hadronization dynamics ?

Summary

- Particle correlation studies provide important information about hadronization dynamics
- Existence of Bose-Einstein correlations for pion and kaon pairs is clearly established at LEP
- Fermi-Dirac(-like) effects for baryons observed

  Is the depletion really due to quantum statistics ?
- Cumulants are a powerful tool to compare Monte Carlo models with the data
- 2-, 3- & 4-particle correlations are reasonably well described if MC model contains BEC

  Higher order correlations are linked to 2-particle correlations
- No evidence for Inter-WW BEC
- The Lund string model is able to qualitatively explain most of the observed features

  However fails to reproduce the observed R(m) hierachy
- Interesting results expected from RHIC & LHC

Another Summary

G. Goldhaber about BEC (1990):

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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 under-
standing of the effect.
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What would be Goldhaber's statement now ?

- What is clear is that he would have changed 30 years to 41 years.
- What is not as clear is that he would have considered any other changes necessary.

From K. Zalewski's Very Brief Review of BEC (2000)