Fermi – Dirac correlations in $Z^0 \to ppX$ at LEP

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- Introduction
- New results on Fermi-Dirac correlations
  - for $\bar{p}\bar{p}$ from DELPHI
  - for pp and $\bar{p}\bar{p}$ from ALEPH
- Bose-Einstein correlations for $K^0_S K^0_S$ from ALEPH
- Possible explanations for the observed R(m) dependence
  - using the Heisenberg uncertainty relation (G. Alexander et al.)
  - based on the Björken-Gottfried condition (A. Bialas, K. Zalewski)
- Conclusions

Introduction

Hanbury Brown-Twiss (HBT) interferometry

- identical particle interferometry usually identified with HBT (intensity interferometry)
- for some distributions of sources $\rho(x,t)$ interference pattern observed in momentum (wavelength) space

$$C_2(\vec{r}) = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle} \sim 1 + \cos\left(\vec{k} \cdot \Delta\vec{r}\right)$$

HBT in particle physics

- in particle physics :
  → symmetrisation (BEC) and antisymmetrisation (FDC) of total wave function
- in e^+e^- aplied to $\pi\pi$, KK, K^0K^0, $\Lambda\Lambda$, pp
- correlation function →

$$C_2(q_1,q_2) = C_2(Q) = \frac{\rho_2(Q)}{\rho_2(Q)^{REF}}, \qquad Q^2 = -(q_1 - q_2)^2$$

Goldhaber parametrisation

$$C_2(Q) = N(1 \pm \lambda\, e^{-Q^2 R^2})$$

BEC ($+$), FDC ($-$)

- R is the radius of a sphere describing source shape
- λ is chaocity parameter
  (0 – completely coherent source, 1 – entirely chaotic case)
- N – normalisation factor
- long range correlations' term sometimes added
- other parametrisations also used, e.g.

$$C_2(Q) \sim e^{-QR}$$

DELPHI analysis for antiprotons

DELPHI

DATA

$Z^0 \rightarrow$ hadrons

2.1 M events (the best ident. information)

180 K ev. with $\geq$ 2 protons

MC

JETSET 7.4 (no F-D corr. simulated)

6.2 M $Z^0 \rightarrow$ hadrons

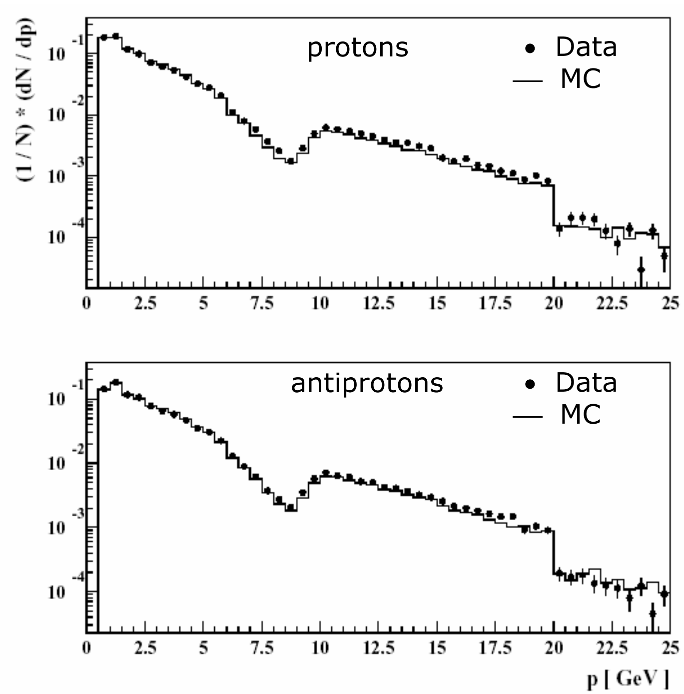
560 K ev. with $\geq$ 2 protons

Selection criteria

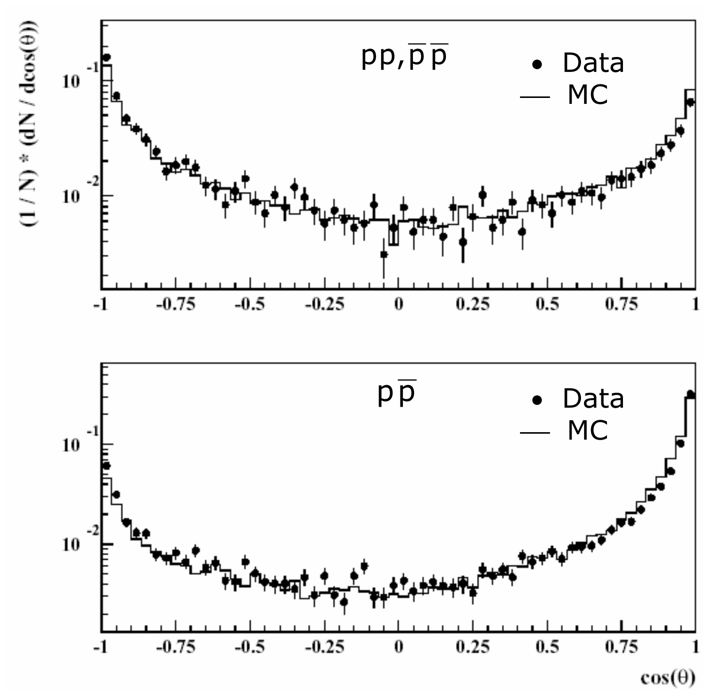
- Standard DELPHI hadronic event selection
- p_{LAB} > 0.7 GeV (good MC-data agreement)
- proton candidate's track measured in the silicon VD
- track well identified as a proton (combining RICH, dE/dx in TPC and VD)
- Λ^0 decay products excluded
- at least 1 pair (pp, $\bar{p}\bar{p}$, $p\bar{p}$) in the event

single proton purity ~85%
efficiency ~70%

proton-proton purity ~50%
antiproton-antiproton purity ~70%



good agreement data-MC observed



Event-mixing method

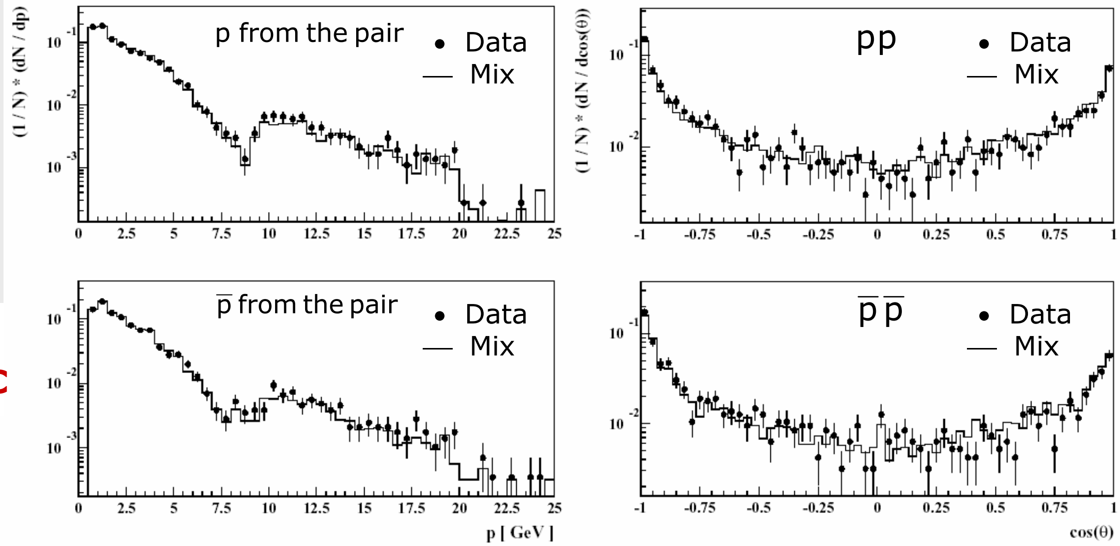
DELPHI

Mixing recipe

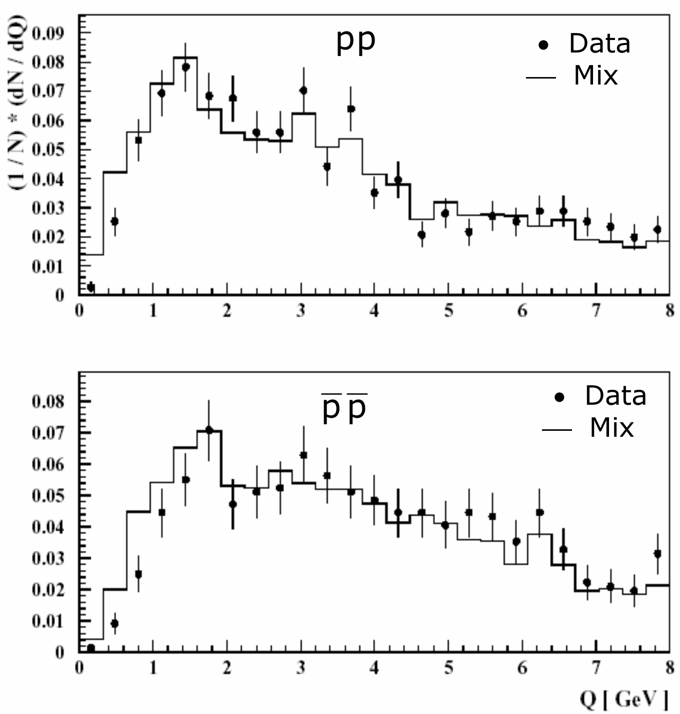
→ momentum vectors transformed to the thrust reference frame

→ for each $\bar{p}_1\bar{p}_2$ (p_1p_2), momentum vectors' pairs $\bar{p}_1\bar{p}_{MIX,2}$,$\bar{p}_{MIX,1}\bar{p}_2$ are constructed

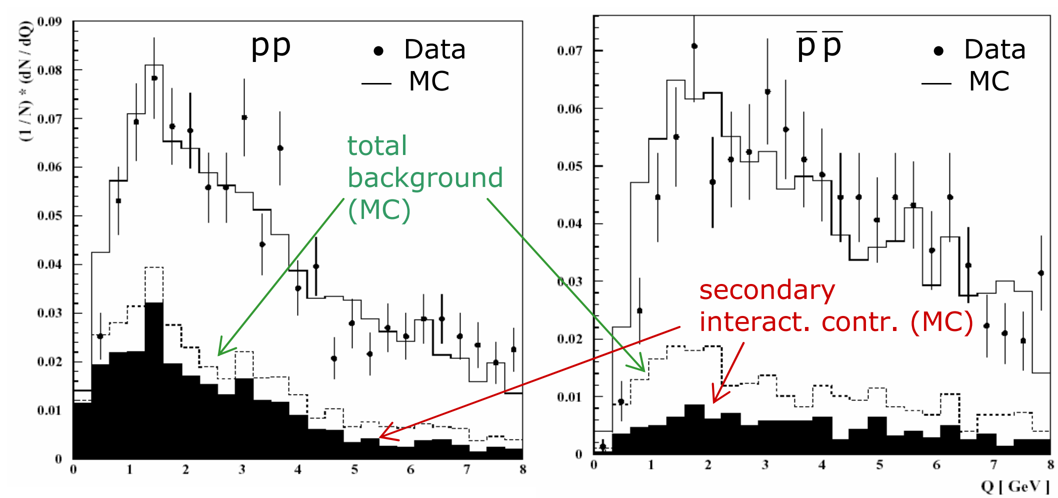
good agreement data-mix



Q distributions in Data vs Mix and MC



more backgrd in pp (sec. int.) → the main result for $\bar{p}\bar{p}$



Correlation radius

DELPHI

Correlation function

$$C_2(Q) = \frac{N(Q)^{DATA}}{N(Q)^{REF}}, \quad REF = mix, MC, unlike$$

double ratio needed

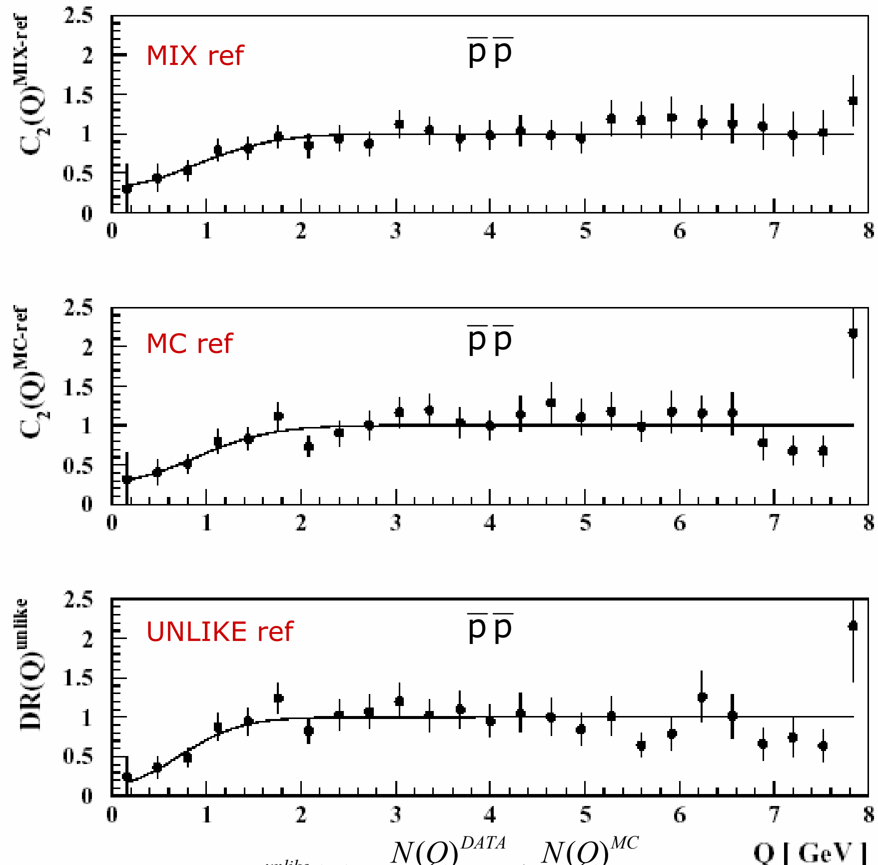
Goldhaber parametrisation

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

- double ratio used (whenever appropriate)
- the main result for $\bar{p}\bar{p}$, mixed-ref.
- others samples used for x-checks and syst. error determination

List of systematic errors

systematic error source	ΔR	Δλ
identification ; $XPRNET \in (0.90-0.97)$	0.017	0.141
opening angle $\theta > 2^\circ$	0.008	0.023
background subtraction	0.004	0.052
different reference samples	0.013	0.068
double ratio	0.002	0.011
$C_2(Q)$ parametrisation	0.011	0.022
fit range ; $Q_{MAX} \in (6.0-9.0)\,GeV$	0.003	0.005
Q bin size ; $\Delta Q \in (0.25-0.35)\,GeV$	0.011	0.063
total systematic error	0.028	0.180



$$R^{unlike}(Q) = \frac{N(Q)^{DATA}}{N(Q)^{DATA}_{unlike}} \Big/ \frac{N(Q)^{MC}}{N(Q)^{MC}_{unlike}}$$

$$R = 0.16 \pm 0.04(stat) \pm 0.03(syst) \quad fm,$$
$$\lambda = 0.67^{+0.19}_{-0.17}(stat) \pm 0.18(syst)$$

MIX

ALEPH analysis for (anti)protons

ALEPH preliminary

DATA

3.9 M $Z^0 \to$ hadrons

MC

JETSET 7.4 (no B-E or F-D corr.)

6.5 M $Z^0 \to$ hadrons

Data selection

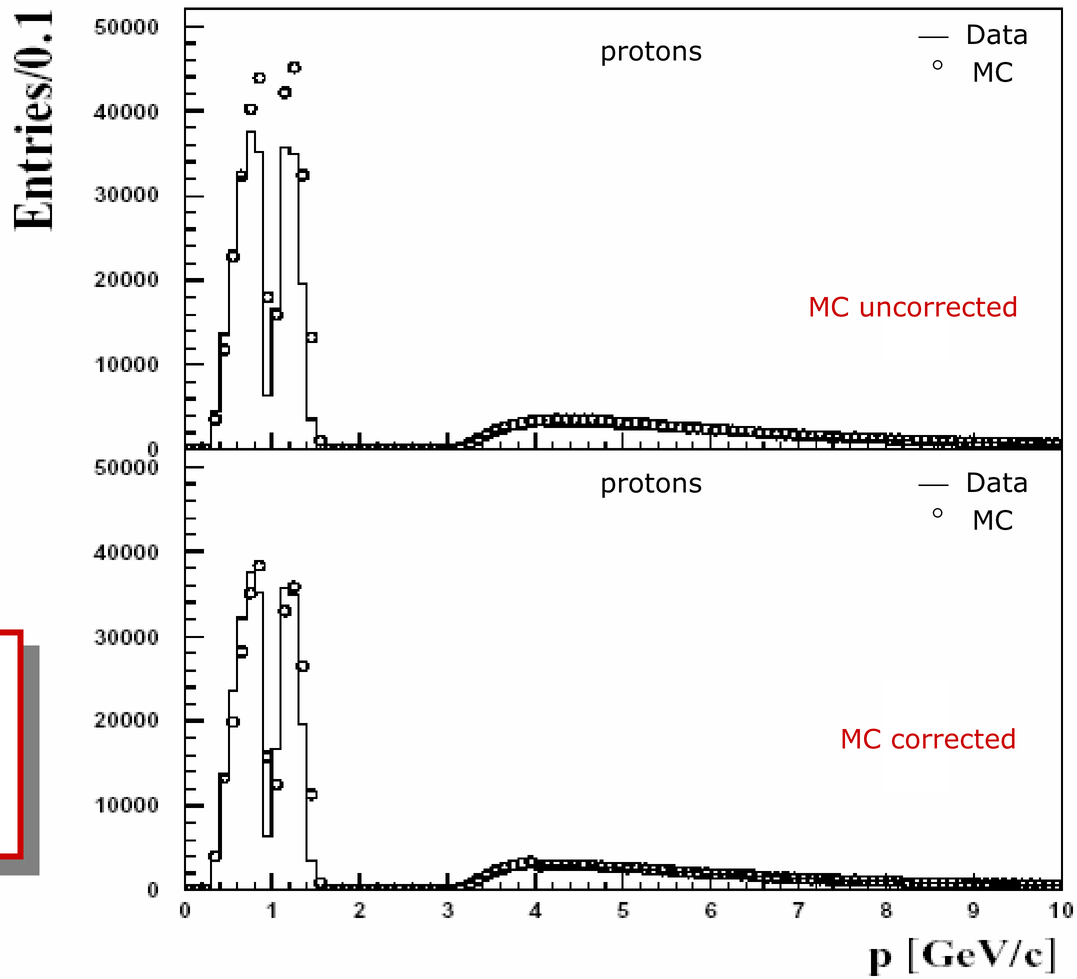
- number of charged tracks > 5
- $E_{tot} > 0.1\ \sqrt{s}$
- $p_{LAB} > 0.4$ GeV
- four TPC hits
- impact parameter in $z < 10$ cm
- impact parameter in $R\phi < 2$ cm
- $|\cos\theta| < 0.95$

→ **corrections for 0.5 < p < 1.3 GeV (to have agreement data-MC)**

→ **only protons from primary vertex (by using χ^2 criterium)**

Identification

- p, $\overline{p}$ identification → dE/dx
- $1.3 < p_{LAB} < 3.0$ GeV excluded



single proton purity ~70%
(anti)proton-(anti)proton purity ~74% (0-5 GeV)

Correlation radius

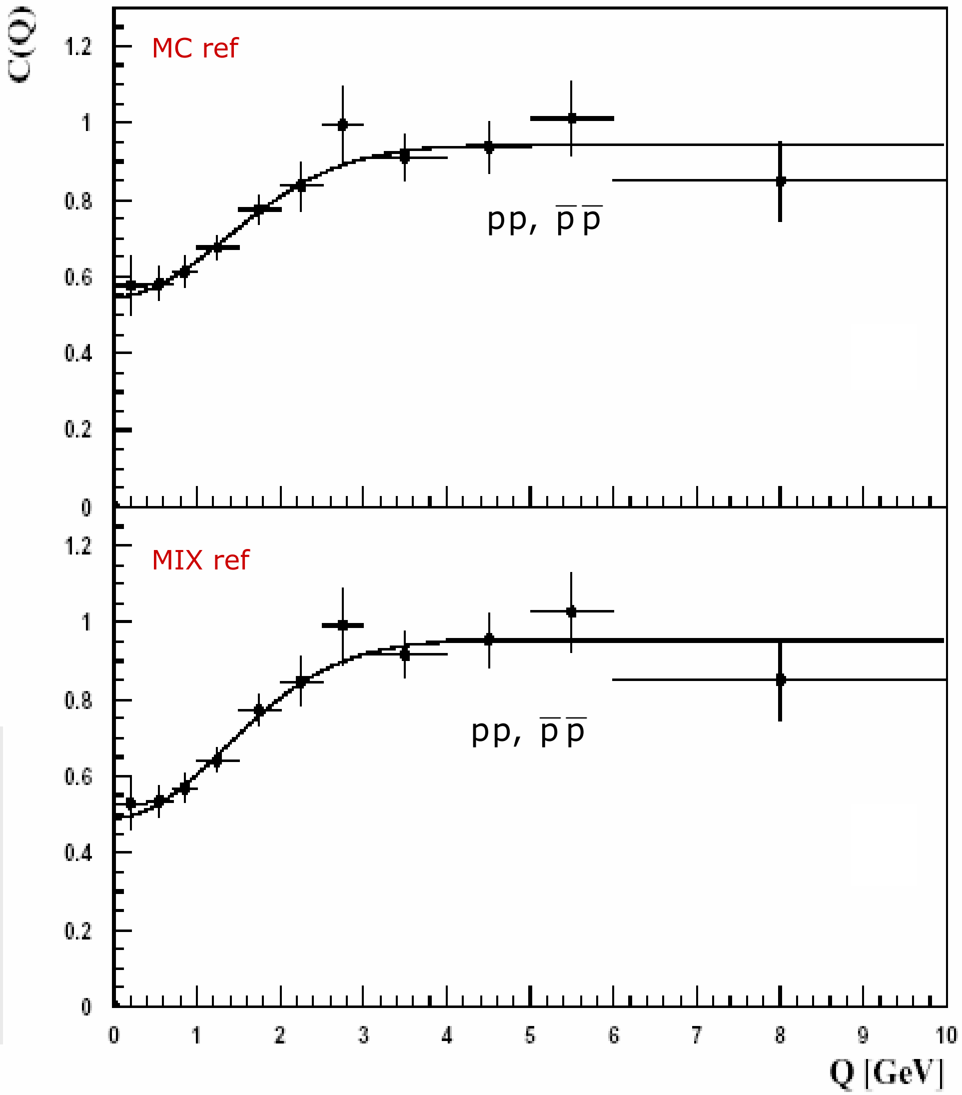
ALEPH preliminary

Goldhaber parametrisation

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

$$R = 0.10 \pm 0.02(stat) \pm 0.02(syst) \quad fm,$$
$$\lambda = 0.46 \pm 0.04(stat) \pm 0.11(syst)$$

MIX



Main contributions to systematics

- Coulomb corrections (Gamov fact., 12% corr. in the 1st bin)
- different reference sample
- reweighting MC

Summary for pp analyses

	R [fm]	λ	ref. sample	
ALEPH	$0.10 \pm 0.02(stat) \pm 0.02(syst)$	$0.46 \pm 0.04(stat) \pm 0.11(syst)$	mix	$pp, \bar{p}\bar{p}$
DELPHI	$0.16 \pm 0.04(stat) \pm 0.03(syst)$	$0.67^{+0.19}_{-0.17}(stat) \pm 0.18(syst)$	mix	$\bar{p}\bar{p}$
OPAL	$0.14 \pm 0.04(stat) \pm 0.05(syst)$	$0.76 \pm 0.16(stat) \pm 0.29(syst)$	MC	$\bar{p}\bar{p}$

Results consistent within errors

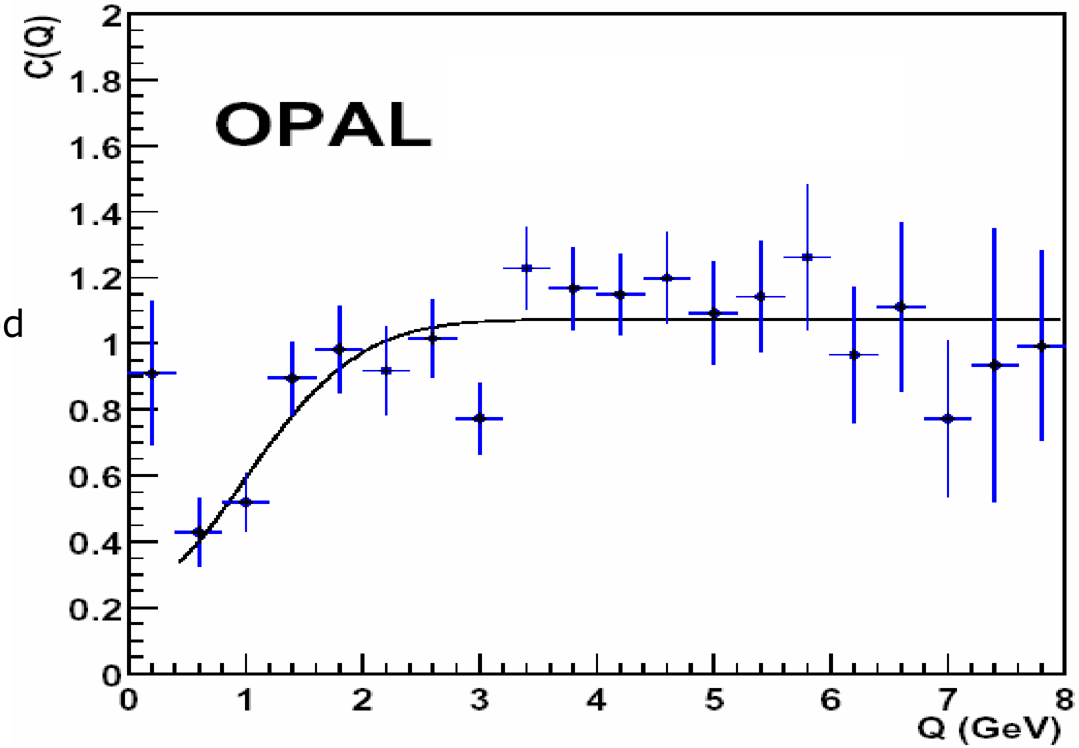
OPAL Coll.,
CERN-EP/2001, OPAL-PN486

→ Event-mixing ref.,

→ MC ref.,

→ UNLIKE ref. samples studied

- **MC for the main result**



ALEPH analysis for $K^0_S K^0_S$

ALEPH preliminary

Data selection

- pion's momentum > 0.15 GeV
- both tracks from the same secondary vertex
- χ^2 test of energy-momentum conservation
- cuts on the impact parameter of the sec. tracks from V^0
- $K^0 \rightarrow \pi\pi$ accepted if χ^2 for pion hypothesis > 0.005

kaon-kaon purity ~96%
efficiency ~27%

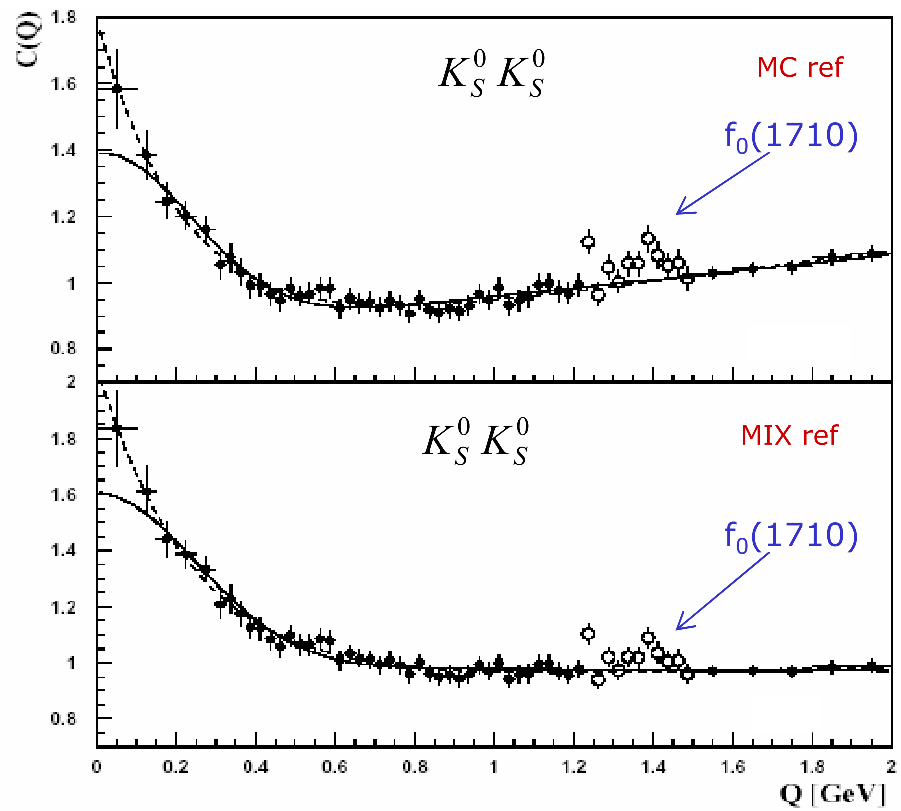
216 K ev. with 2 kaons

→ enhancement seen at Q < 0.5 GeV

→ rise of C(Q) for Q > 0.8 GeV in MC-ref (imperfect MC simulation)

→ region of $f_0(1710)$ excluded from the fit

$f_0(980) \rightarrow K^0_S K^0_S$ signal included in MC replaced by contr. from Breit-Wigner distr.



Parametrisation

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

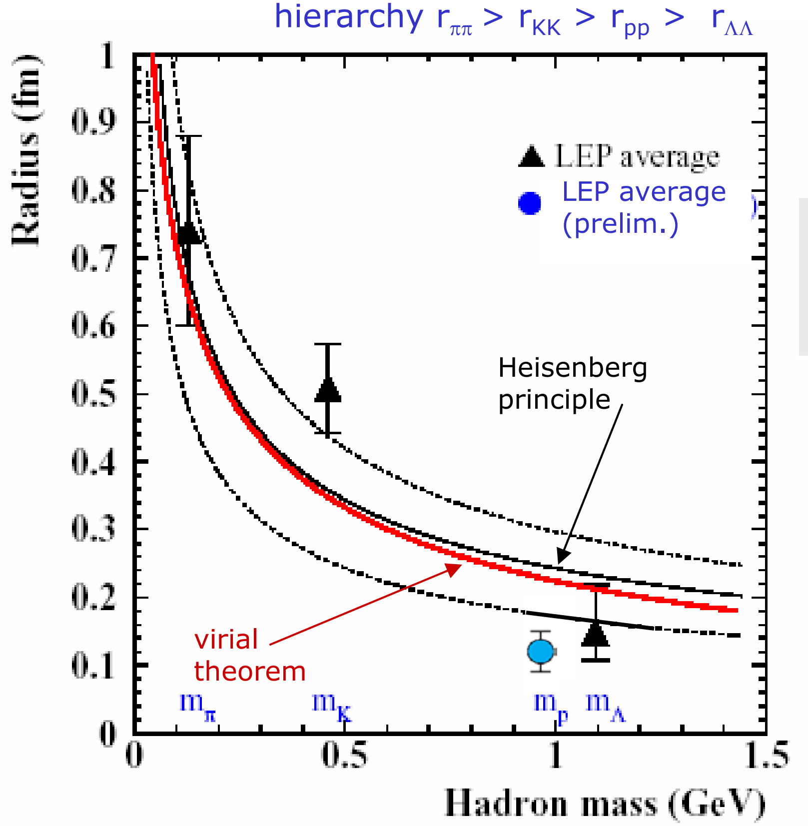
$$R = 0.57 \pm 0.04(stat) \pm 0.06(syst) \quad fm,$$
$$\lambda = 0.63 \pm 0.06(stat) \pm 0.06(syst)$$

MIX, Gaussian-like par., α = 0.005 ± 0.03

Models based on Heisenberg principle

G. Alexander, I. Cohen, E. Levin,
Phys. Lett. **B452** (1999) 159.

hierarchy $r_{\pi\pi} > r_{KK} > r_{pp} > r_{\Lambda\Lambda}$



- heavier particles are emitted first
- Δt does not depend on the mass
- ΔE depends only on kinetic energy
- $\Delta r \sim r$

from the Heisenberg uncertainty principle

$$r(m) = \frac{\hbar c / \sqrt{\hbar / \Delta t}}{\sqrt{m}} = \frac{c\sqrt{\hbar \Delta t}}{\sqrt{m}}$$

$$fit: \quad r(m) = A/\sqrt{m}, \quad A = 0.243 \; fm\, GeV^{1/2}, \quad \Delta t = 10^{-24} \text{ sec}$$

upper dashed curve: $\Delta t = 1.5 \times 10^{-24}$ sec

lower dashed curve: $\Delta t = 0.5 \times 10^{-24}$ sec

QCD model using virial theorem

$$r^2 \left\langle \vec{r} \cdot \vec{\nabla} V(r) \right\rangle \sim \frac{(\hbar c)^2}{m}$$

general QCD potential $$V(r) = \kappa r - \frac{4}{3}\frac{\alpha_s \hbar c}{r}$$

$$\kappa = 0.14\, GeV, \quad \alpha_s = 2\pi \ln(2 + 1.87/r))$$

Model based on Björken-Gottfried condition

A. Bialas, K. Zalewski,
Acta Phys. Polon. **B30** (1999) 359.

Björken-Gottfried condition

$$p_\mu = \lambda x_\mu \qquad \tau_0^2 = t^2 - z^2 \qquad p_\mu = \frac{M_\perp}{\tau_0} x_\mu$$

source function

$$S(P,X) = W(\vec{P},\vec{X})\,\delta(X_0 = 0) = F(\tau) S_\parallel S_\perp$$

$$S_\parallel = \exp\left[\frac{1}{2\delta_\parallel^2}\left(P_+ - \frac{M_\perp}{\tau}X_+\right)\left(P_- - \frac{M_\perp}{\tau}X_-\right)\right],$$

$$S_\perp \sim \exp\left[-\frac{1}{2\delta_\perp^2}\left(\vec{P}_\perp - \frac{M_\perp}{\tau}X_-\right)^2\right]$$

$$X_\pm = t \pm z,\quad P_\pm = P_0 \pm P_z,\quad M_\perp^2 = P_+ P_-,\quad \tau = X_+ X_-$$

source density matrix

$$\rho(q,q') = \int d^4X\, e^{iQX} S(P,X)$$

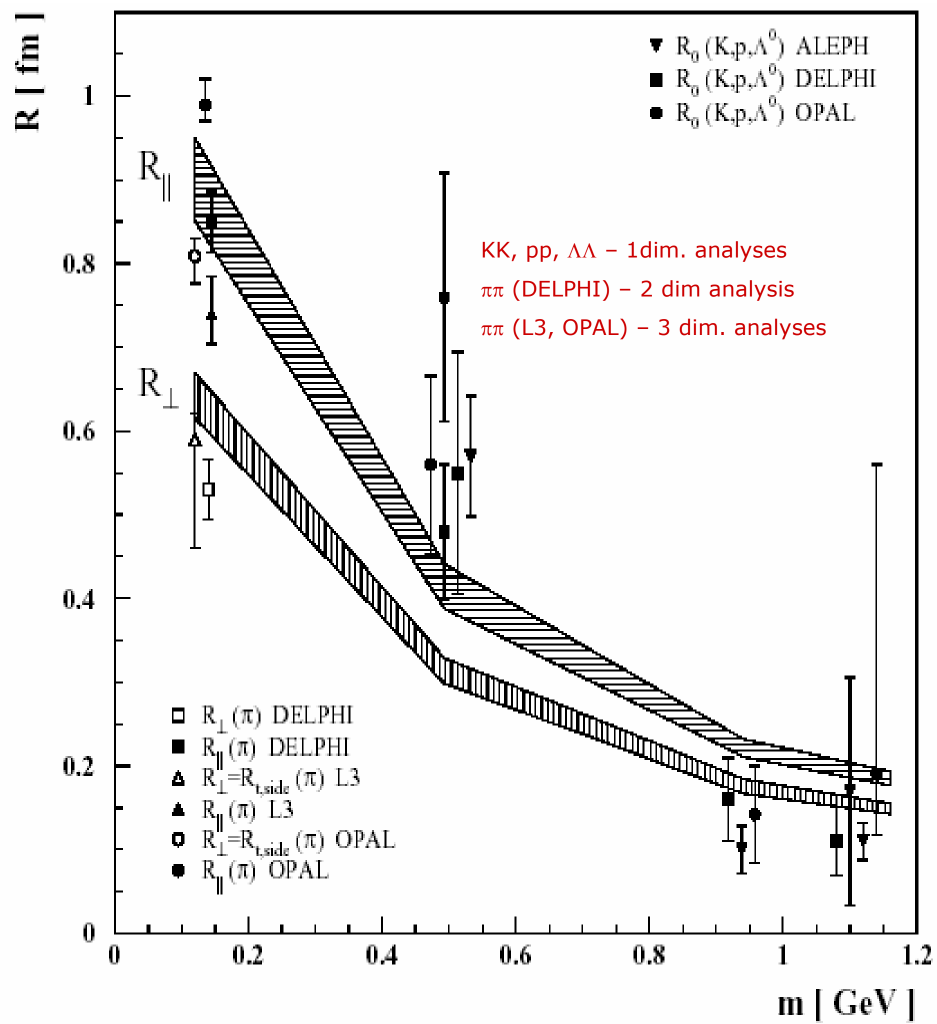
$$P = (q+q')/2, \qquad Q = q - q'$$

one-particle distribution

$$\rho(p) \equiv \frac{dn}{dy\, d^2 p_\perp} \sim r_\perp^2 \delta_\perp^2 \exp\left[\frac{m_\perp^2}{\delta_\parallel^2}\right] K_0\left(\frac{m_\perp^2}{\delta_\parallel^2}\right) \exp\left[-\frac{q_\perp^2}{2\Delta^2}\right]$$

Model based on Björken-Gottfried condition (cont.)

A. Bialas, M. Kucharczyk, H. Palka, K. Zalewski,
Phys. Rev. **D62** (2000) 114007.
Acta. Phys. Polon., **B32** (2001) 2901.



Free parameters

- $F(\tau) \rightarrow \tau = 0.9$ fm
- $\delta_{||}$, $\delta_{\perp}$ parametrise the correlation range
- $\nu^2 = r^2 / \tau^2$
- Δ represents width of Gaussian-like distr. of $p_{\perp}$

ν	$\delta_{\perp} = \delta_{\parallel}$ [GeV]	Δ [GeV]
0.94	0.233	0.421

x-p correlations → apparent source

$$\frac{1}{R_{HBT}} \approx \frac{1}{R} + \frac{M_{\perp}^2}{\tau_0^2 \delta^2} \quad \Rightarrow \quad R_{HBT} < R$$

all particles emitted at the same radius

Summary and conclusions

- **New measurements of the hadronic source radius by Fermi-Dirac correlations:**

  $\rightarrow$ **ALEPH :** **R = 0.10 ± 0.02 ± 0.02 fm**

  $\rightarrow$ **DELPHI :** **R = 0.16 ± 0.04 ± 0.03 fm**

- **New result for $K^0_S K^0_S$:** **R = 0.57 ± 0.04 ± 0.06 fm** **(BEC, ALEPH)**

- **Together with the previous ALEPH, DELPHI, L3, OPAL measurements the R(m) is established**

- **Do we measure the real radius or apparent?**
  (the real radius $R_p \sim 0.1$ fm implies the enormous energy density > 100 GeV / fm^3)

- **The model based on Heisenberg relations and virial theorem gives acceptable description of R(m)**

- **Quantum-mechanical approach based on the Björken-Gottfried condition explains the mass dependence and longitudinal elongation of the source and allows to extract the information of space-time evolution of the hadronic source**