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Like-Sign Particle Genuine Correlations in Hadronic Z Decays

Edward K. Sarkisyan-Grinbaum
CERN and Univ. Antwerpen
(for the OPAL Collaboration)

OUTLINE

- Introduction and motivation
- The method: **factorial cumulants**
- OPAL data
- Bose-Einstein correlation models
- Results: **all-charge vs. like-sign multiplets**
- Bose-Einstein correlations of $\pi^0\pi^0$ pairs

General motivation

- From global variables (averages) to local (in-cell) studies: **intermittency scaling $\leftrightarrow$ correlations**
- From correlation functions to factorial moments, cumulants: **a robust tool to search for multi-particle densities, genuine correlations**
- Bose-Einstein effects: **strong but qualitative** indications
- Local Parton-Hadron Duality (LPHD): does it hold?

Today's interest

- Heavy Ion physics: **large multiplicities and higher-order secondaries' correlations**
- W mass measurements at LEP, $e^+e^- \to W^+W^-$: **correlation and color reconnection** effects
- Bose-Eistein correlation BEC models: **different approaches**

Cumulants and correlations

- Divide a phase space into **M cells of equal size**
- Calculate **cell-averaged normalized cumulant moments**, cumulants, of order q:

$$\mathrm{K_q} = \frac{1}{\mathrm{M}} \sum_{\mathrm{m}=1}^{\mathrm{M}} \int_{\delta \mathrm{y}} \prod_{\mathrm{i}} \mathrm{dy_i} \frac{\mathrm{C_q(y_1, ..., y_2)}}{[\int_{\delta \mathrm{y}} \mathrm{dy} \rho_1(\mathrm{y})]^{\mathrm{q}}}$$

- $C_q(y_1, ..., y_2)$ – qth order correlation function
- For example,

$C_2(y_1, y_2) = \rho_2(y_1, y_2) - \rho_1(y_1)\rho_1(y_2)$

$C_3(y_1, y_2, y_3) = \rho_3(y_1, y_2, y_3) -$
$\sum_{(3)} \rho_1(y_1)\rho_2(y_2, y_3) + 2\rho_1(y_1)\rho_1(y_2)\rho_1(y_3)$

- **Cumulants calculated** according to:

$$\mathrm{K_q} = \frac{1}{\mathrm{M}} \sum_{\mathrm{m}=1}^{\mathrm{M}} \frac{\mathrm{k_q^{(m)}}}{\langle \mathrm{n_m} \rangle^{\mathrm{q}}}$$

- $k_q^{(m)}$ – **unnormalized** cumulants (Mueller moments),

e.g.: $k_2^{(m)} = \langle n_m^{[2]} \rangle - \langle n_m \rangle^2,$

$$k_3^{(m)} = \langle n_m^{[3]} \rangle - 3 \langle n_m^{[2]} \rangle \langle n_m \rangle + 2 \langle n_m \rangle^3$$

via unnormalized factorial moments,

$$n_m^{[q]} = \langle n_m (n_m - 1) \cdots (n_m - q + 1) \rangle$$

$\langle \cdot \rangle \equiv$ averaging over events

E.A. De Wolf, I.M. Dremin, W. Kittel, Phys. Reports 270 (1996) 1

Data selection

- **Multihadron events** from 1991–95 samples: about 4.1 million events
  - at least 5 "good" tracks
  - a momentum imbalance $< 0.4\sqrt{s}$
  - $E_{\rm tot} > 0.2\sqrt{s}$ (assumed pions)
  - $|\cos\theta_{\rm sph}| < 0.7$
- **After all cuts**: about 2.3 million events
- The variables used (w.r.t. sphericity axis):
  - Rapidity, $y = \ln\frac{E+p_\parallel}{E-p_\parallel}$, $-2.0 \leqslant y \leqslant 2.0$
  - Transverse momentum $-4.8 \leqslant \ln p_T^2 \leqslant 1.4$
  - Azimuthal angle, $0 \leqslant \phi < 2\pi$
- More **technical details** in:

  OPAL Collab., Eur. Phys. J. C 11 (1999) 239

  OPAL Collab., Phys. Lett. B 523 (2001) 35

Data correction

- Data correction factor

$$U_q(M) = K_q(M)_{gen}/K_q(M)_{det}$$

  - Generator level: JETSET 7.4/PYTHIA 6.1 events
    - *without* ISR
    - *with* $\tau > 3 \cdot 10^{-10}$ s (no K_0^S and Λ's)
    - *no* selection criteria passed
  - Detector level: JETSET 7.4/PYTHIA 6.1 samples
    - *through* OPAL detector simulator
    - *with* finite lifetimes
    - *with* ISR
    - *passing* the selection criteria

- Systematic uncertainties
  - $\sigma_{\rm stat}(U_q)$
  - track criteria changes
  - $|K_q(U_q) - K_q(U_q^{\rm BE})|$
  - $|K_q(U_q^{\rm all}) - K_q(U_q^{\rm ls})|$
  - **more details:**

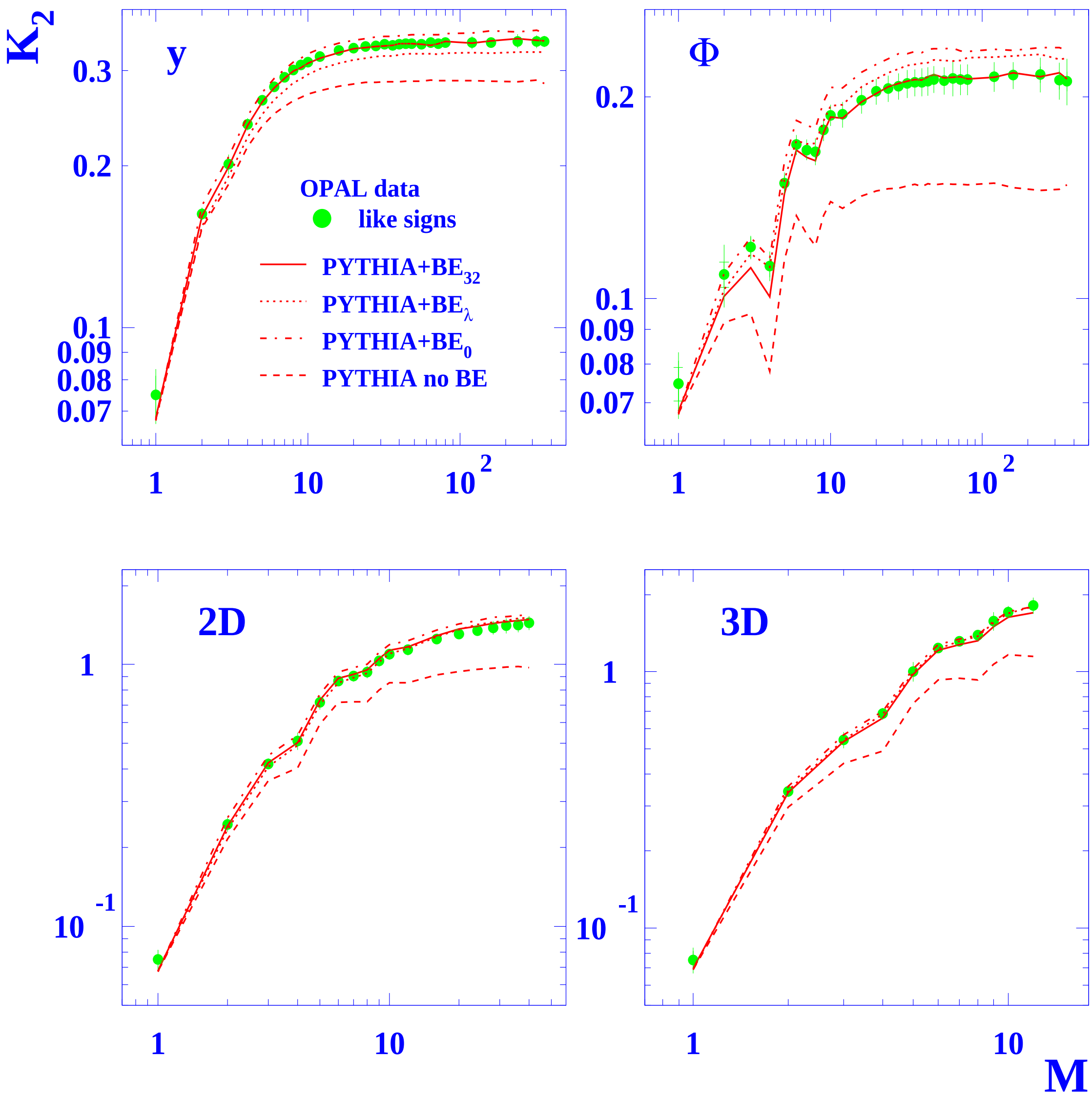
    OPAL Collab., Phys. Lett. B 523 (2001) 35

BEC models

- No rigorous method for BEC in event generators
- PYTHIA algorithm **PYBOEI**
  - ∘ BEC as local shifts of particle momenta among pairs of identical particles
  - ∘ Methods differ only in how $(E,\vec{p})$ conservation is ensured
  - ∘ Enhancement factor $g_2(Q) = 1 + \lambda\, e^{-Q^2 R^2}$
    $Q^2 = -(p_1 - p_2)^2$
- BE$_0$: $\vec{p}$ conserved exactly, E conserved via global rescaling of final state momenta
- BE$_{32}$ is based on the ansatz
  $$f_2(Q) = 1 + \lambda\, e^{-Q^2 R^2} \;\; (\equiv g_2(Q)) \times (1 + \alpha\, \lambda\, e^{-Q^2 R^2/9}) \times (1 - \lambda\, e^{-Q^2 R^2/4})$$
  (α - free parameter)
  to mimic pair-weights' oscillations below and above unity.
- BE$_\lambda$: reshufting among "close-by" particles only and use $g_2(Q)$
- **Higher-order correlations** could be introduced

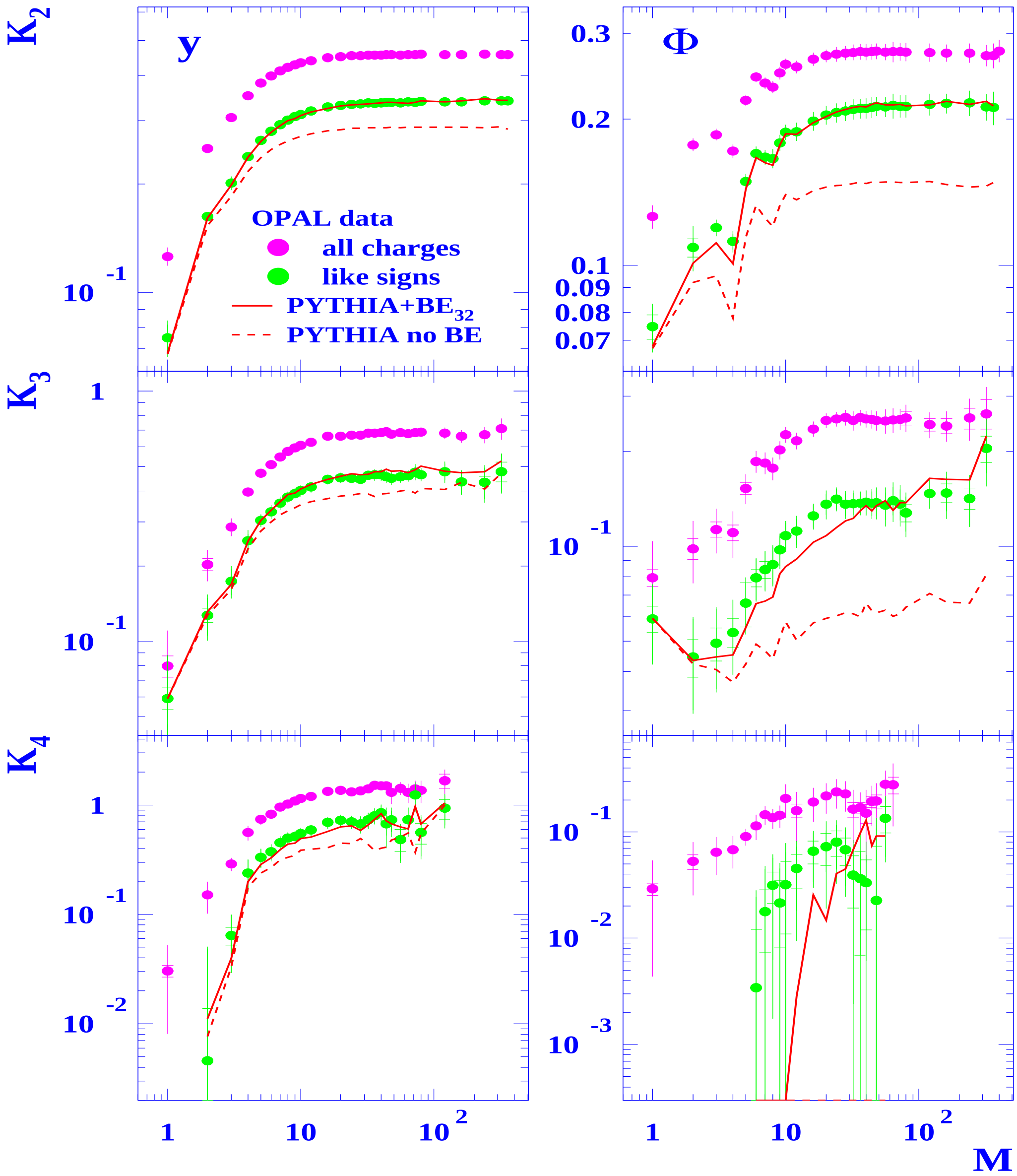
L. Lönbland, T. Sjöstrand, Eur. Phys. J. C 2 (1998) 165

K_2: Like-sign pairs



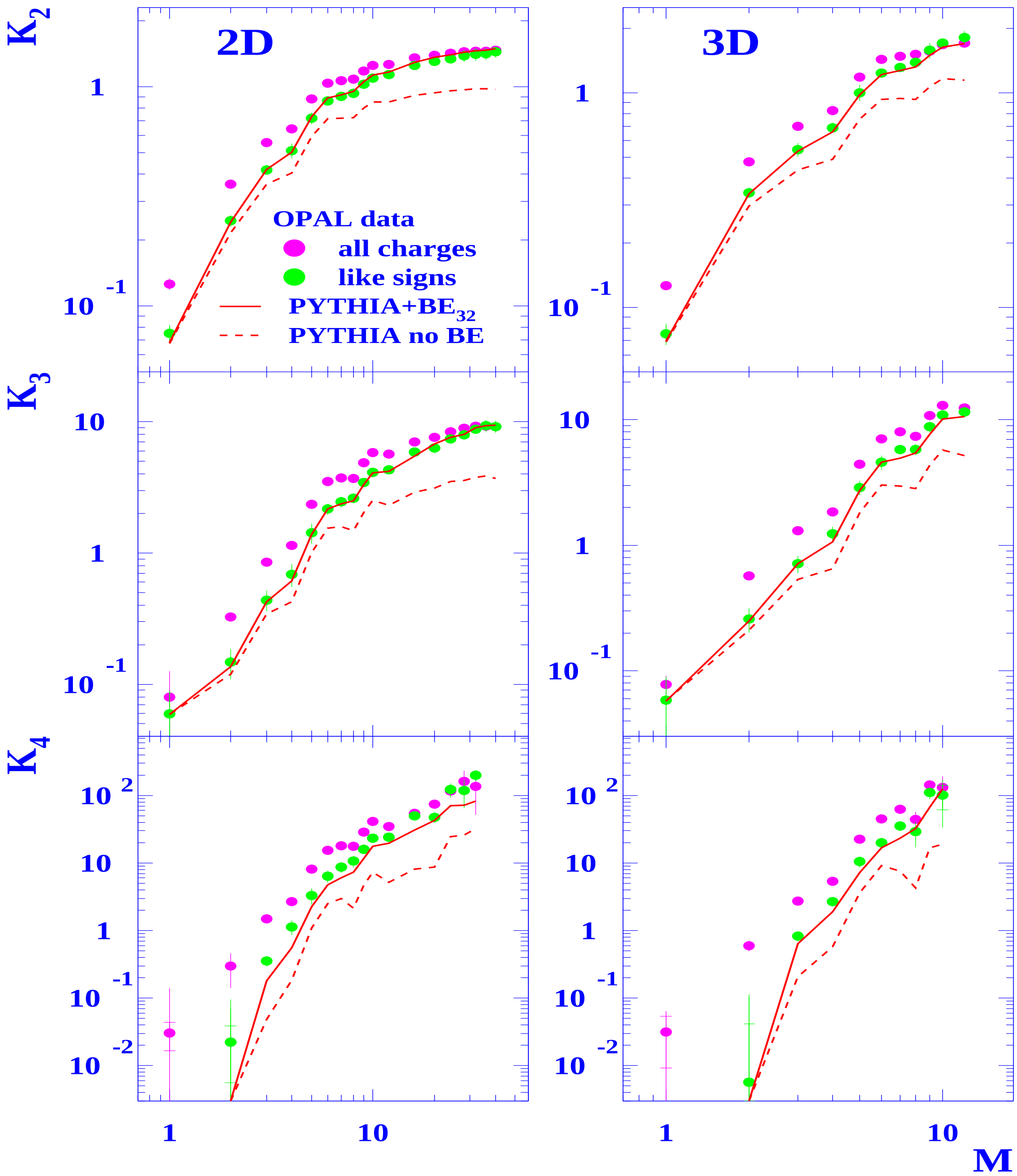
- BE_{32} **parameters** adjusted to this data
  $\lambda = 1.5$, $R = 0.76$ fm
- Model without BEC fails, BEC needed
- BEC model **reproduces** 1D to 3D Ks

One-dimensional y-, Φ-cumulants



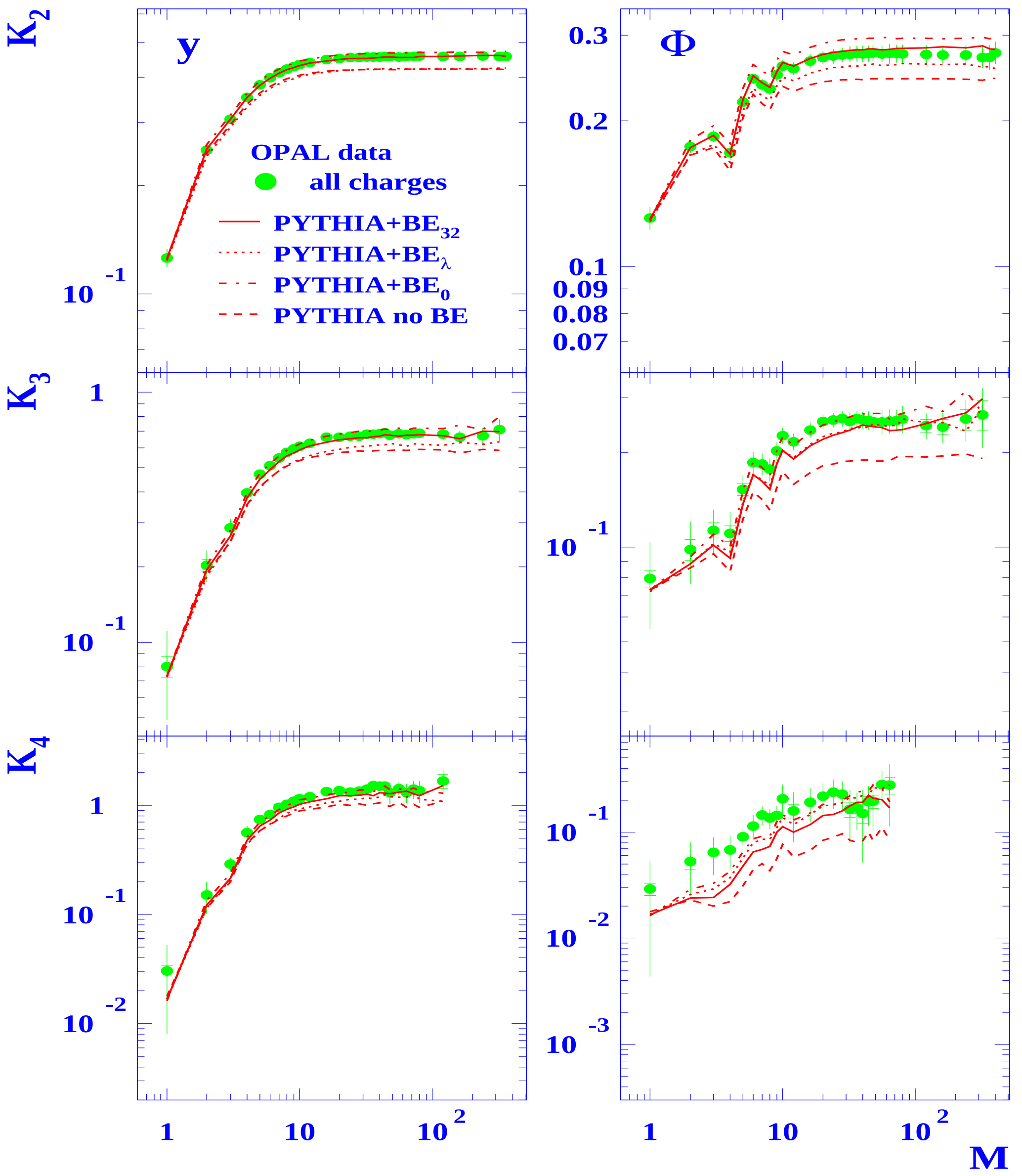
- **Genuine multi**-particle correlations observed
- 1D Ks increase with M, **saturate** as $1/M \to 0$
  $\Rightarrow$ hard gluon jet emission
- **Like-sign** Ks increase faster, derive all charge Ks as $1/M \to 0$ (small size cells)
- No-BEC model fails, BEC **clearly** needed
- Model **adjusted** to like-sign Ks

$y \times \Phi$ and $y \times \Phi \times \ln p_T$ cumulants



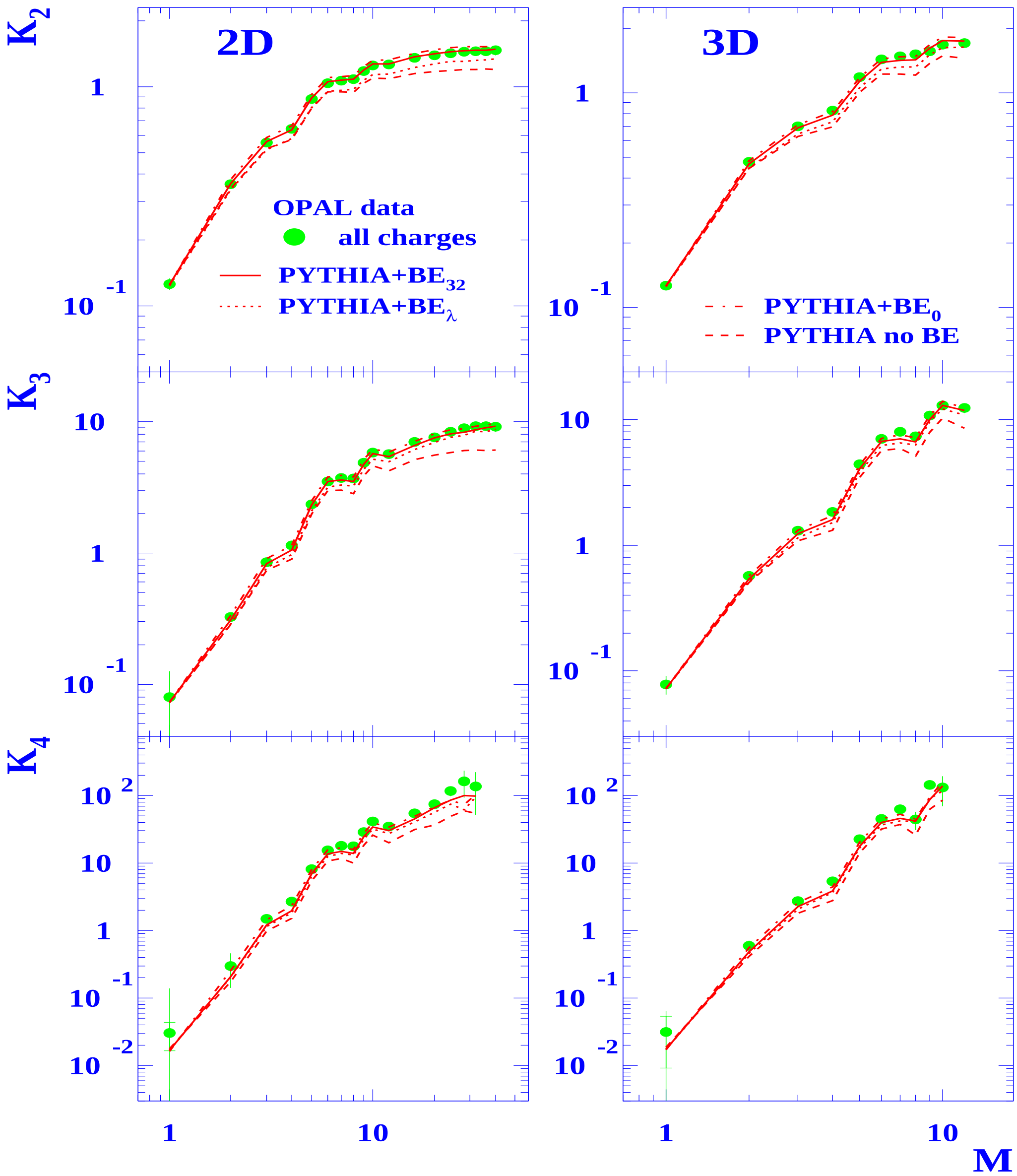
- **Genuine multi**-particle correlations observed
- No **sturation** at small cell-size ($1/\mathrm{M} \to 0$)
- **Like-sign** Ks increase faster, approach all charge Ks as $1/\mathrm{M} \to 0$
- No-BEC model fails, BEC needed!
- BEC model **reproduces** 1D to 3D Ks
- Pair-wise BEC account for higher order Ks (?)

One-dimensional y-, Φ-cumulants: all charges



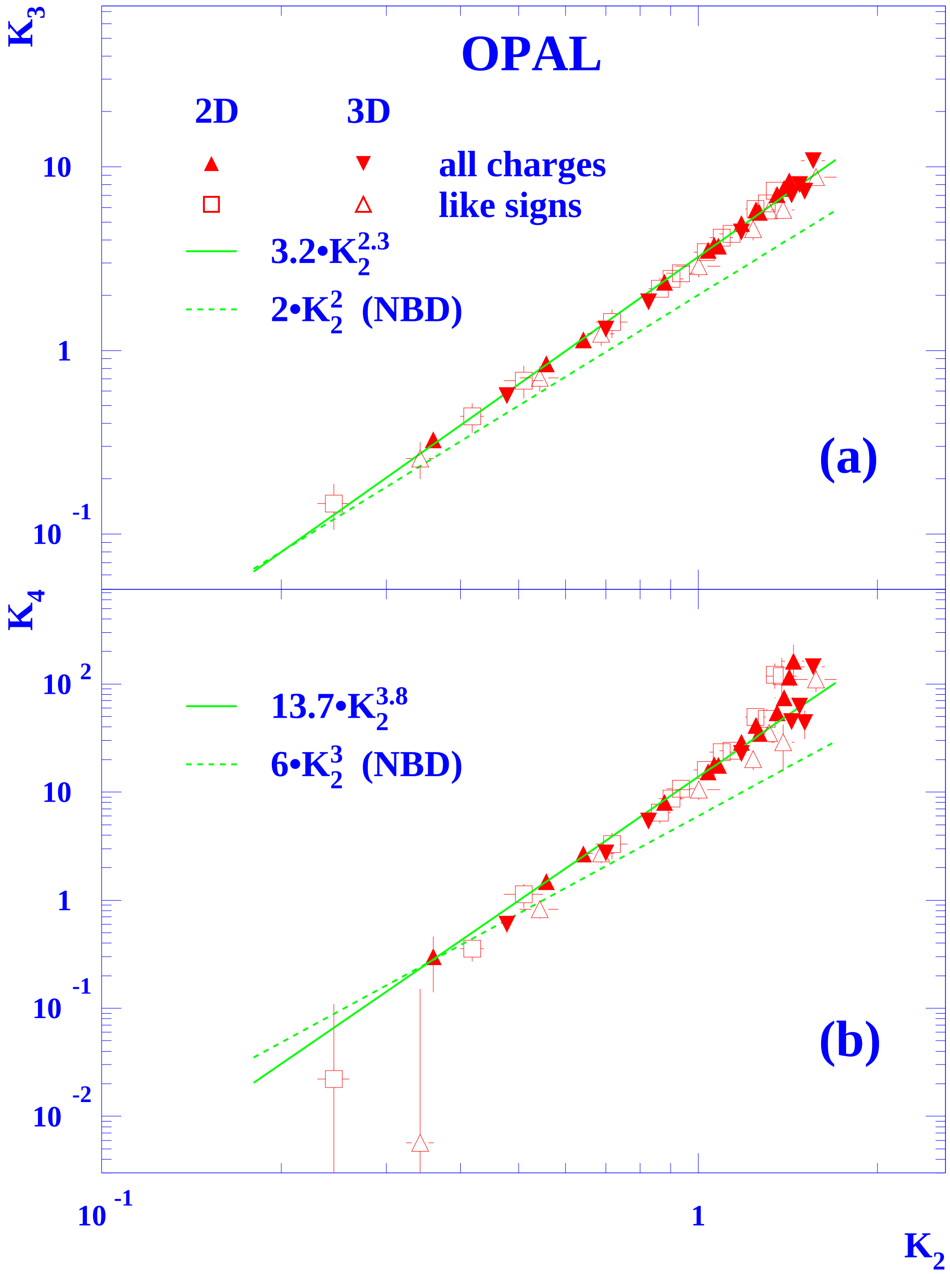
- Model without BEC **fails**
- Model adjusted to like-sign Ks reproduces all-charge Ks
- **BEC-type correlations** were missed
- 2-particle BEC account for high-order Ks (?)

$y\times\Phi$ and $y\times\Phi\times\ln p_T$ cumulants: all charges



- Model without BEC **fails**, **BE-type** correlations were missed
- Model adjusted to *like-sign* Ks reproduces *all charge* Ks from 1D to 3D
- **Small 3D** cell-size: *multi*-boson correlations

Interdependence of correlations
Ochs-Wosiek type relation



- Hierarchy between cumulants, $K_2 \leftrightarrow K_3$, $K_2 \leftrightarrow K_4$
  $\Rightarrow$ Same mechanism for $K_2 \rightarrow K_3 \rightarrow K_4$?
- Same for like-sign and all-charged multiplets
- MD deviates from NBD in small bins

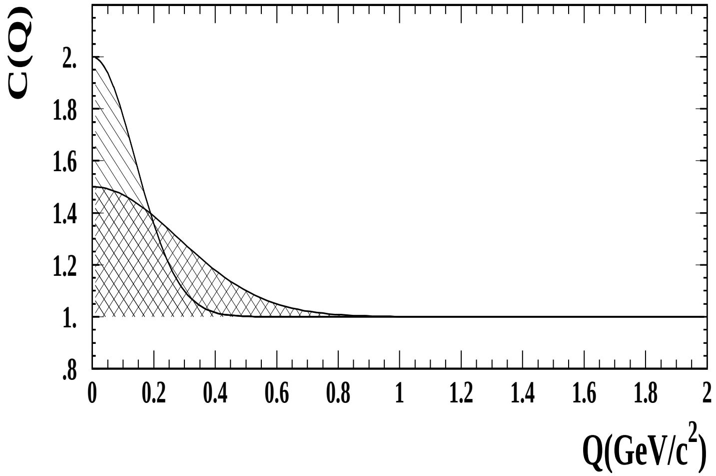
BEC function of identical hadrons

Gaussian source

G.Goldhaber, S.Goldhaber, W.-Y.Lee, A.Pais (1960)

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

$$Q^2 = -(p_1 - p_2)^2 = M_{12}^2 - 4m^2$$



- R – source size
- λ – strength length

  GGLP ansatz: $\lambda = 1$ for completely incoherent sources

Measurement method

$$C(p_1, p_2) = \frac{\rho_2(p_1, p_2)}{\rho_1(p_1)\rho_1(p_2)}$$

- In experiment,

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

- No-BEC reference sample
  - MC without BEC
  - Unlike-sign pairs
  - Event mixing
  - Hemisphere mixing

π_0s and π_0-pairs selection

- π_0s reconstructed from photon pirs in EM calorimeter
  - variables: E_γ, E_{clust}, θ_{clust}, E_{trk}, θ_{trk}
  - likelihood ratio of MC to measured photon candidates for a weight function w_i(variables)
  - Photon pair probability $P = w_i \times w_j$
    Background: (i) wrong pairing of 2 correctly reconstructed photons,
    (ii) pairs of two fake photons,
    (iii) pairs of 1 correct and 1 fake photons

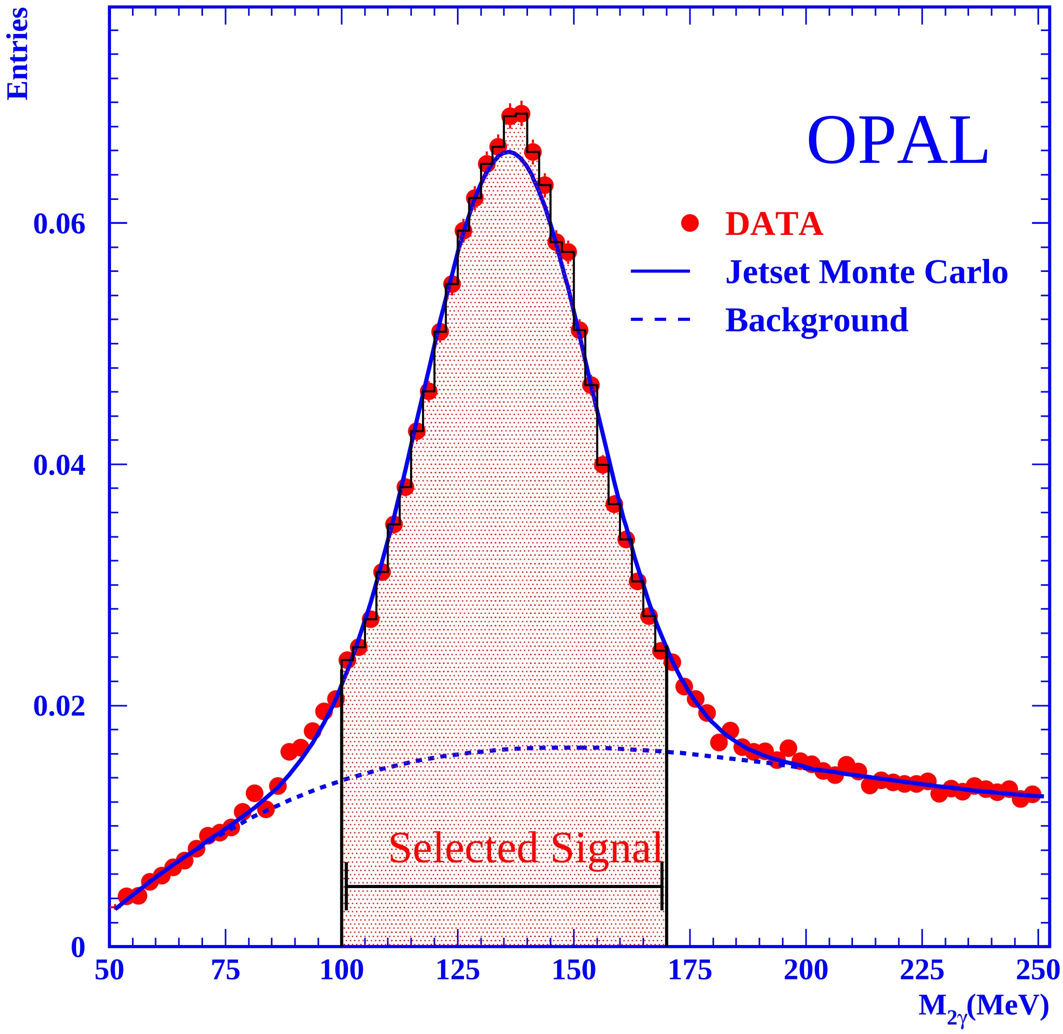
  P>0.2 removes 60% bkgd. with loss in effic. 8%

- π_0 pair selection
  - purity ≈40% → large bkg to be MC-subtr.
  - 4.5π_0 candidates per event → 6 pairings *with* 1.5 true π_0 pais in average
  - π_0 selection criteria tightened
    * $E_\pi > 1.2$ GeV
    * $P > 0.6$
    * no 2π_0s' events ($\sim$ 10%)
  - χ_2-minimizing for $M_{ij}^2 = M_{\pi_0}^2$

OPAL Physics Note 513 (September 5, 2002)

Two-photon distribution

Preliminary



- Events with **exactly** two π_0s contribute
- Average signal **purity** $\sim 80\%$
- Background: 2nd-order polynomial from data (side bands of the peak) or MC

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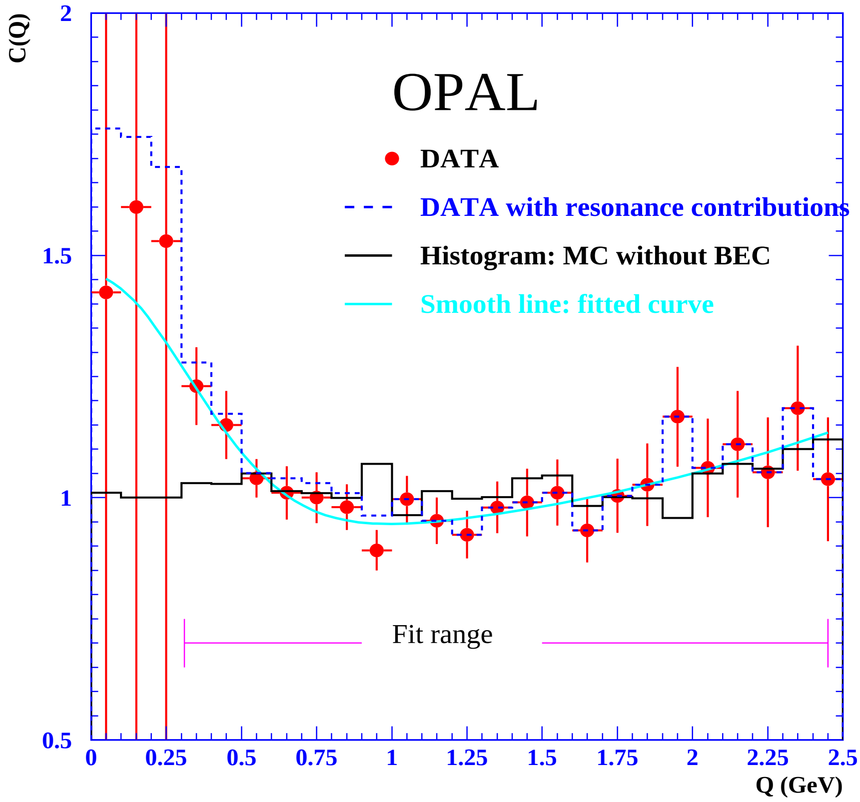
$\pi^0\pi^0$ BEC

Preliminary



OPAL Physics Note 513 (Sept. 5, 2002)

- BEC of charged pion pairs: well established at LEP
- Radius $R = 0.5 \ldots 1.0$ [depends on ref. sample]
- $C(Q) = \frac{\rho(Q)}{\rho_0(Q)} \propto (1 + \lambda\, e^{-Q^2 R^2})(1 + \alpha Q + \varepsilon Q^2)$
- $C(Q) = [\rho^m(Q) - \rho^b(Q)]/[\rho_0^m(Q) - \rho_0^b(Q)]$
- ρ_0 from **mixing** method
- $\lambda = 0.40 \pm 0.12 \pm 0.23$, $R = 0.60 \pm 0.09 \pm 0.19$ fm
- $R(\pi^0\pi^0) \approx R(\pi^\pm\pi^\pm) = 0.74 \pm 0.01 \pm 0.14$ (LEP av.)
- BEC of π^0s originate: **from strong decays**, not from prompt π^0s (string break-ups, cluster decays)