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Multiplicities and Correlations at LEP

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OUTLINE

- Introduction
- Multiplicity of unbiased gluon jets
- Two-particle Bose-Einstein and Fermi-Dirac correlations
- Genuine multiparticle correlations
- Bose-Einstein correlations in W-pair decays
- Summary and conclusions

Multiplicity densities and correlations

- Multiplicity, n, – important global variable in high-energy particle collisions
  - Characterises event
  - Derives other variables' spectra (dn/dy, dn/dp_T etc)
- Multiplicity density $\rho_n(p_1, ..., p_n) = \frac{1}{N_{\rm ev}} \frac{d\,n(p_1,...,p_n)}{d\,p_1 \cdots dp_n}$

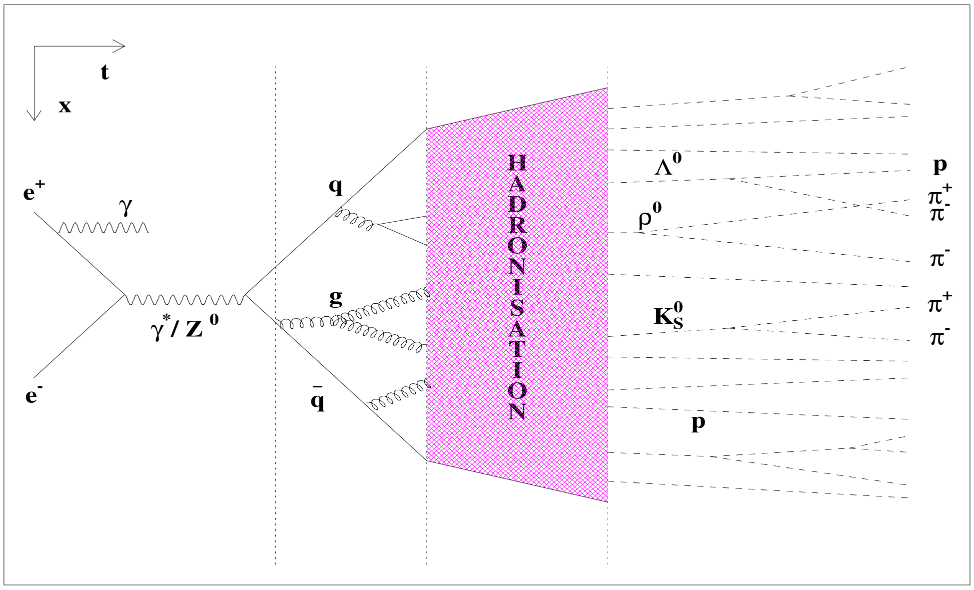
  inclusive distribution – probability density of n particles to have kinematic variable values p_1, p_2, ..., p_n, irrespective of the presence of any other particles
- Single-particle density $\rho_1(p_1)$
  - $\int \rho_1(p_1)\,dp_1 = \langle n \rangle$ – mean multiplicity
- Two-particle density $\rho_2(p_1, p_2)$
  - $\int \rho_2(p_1, p_2)\,dp_1\,dp_2 = \langle n\,(n-1) \rangle \equiv \langle n^{[2]} \rangle = f_2$

    second order factorial moment
- 2-particle, 2nd order, correlation funct. $C_2(p_1, p_2)$
  - $C_2(p_1, p_2) = \rho_2(p_1, p_2) - \rho_1(p_1)\,\rho_1(p_2)$
  - $k_2 = \langle n^{[2]} \rangle - \langle n \rangle^2$

    second order unnormalised cumulant
- Multi-particle densities, factorial moments, correlation functions, cumulants – by analogy

E.A. De Wolf, I.M. Dremin, W. Kittel, Phys. Reports 270 (96) 1

Hadron production in e^+e^- collision



Schematic stages of $e^+e^- \to$ *hadrons* process

- EW production of a $q\bar{q}$ pair

  Z^0/γ exchange; initial state bremsstrahlung

- pQCD gluon radiation, parton shower

  jet-level Matrix Element approach ⇒ Feynman diagrams

  jet-structural Parton Shower approach ⇒ pQCD LLA

- Non-perturbative colourless hadronisation

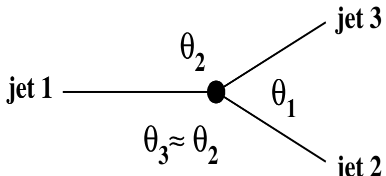
  Large α_s; String, cluster, etc. fragmentation MC models

- Decay of unstable particles, resonances

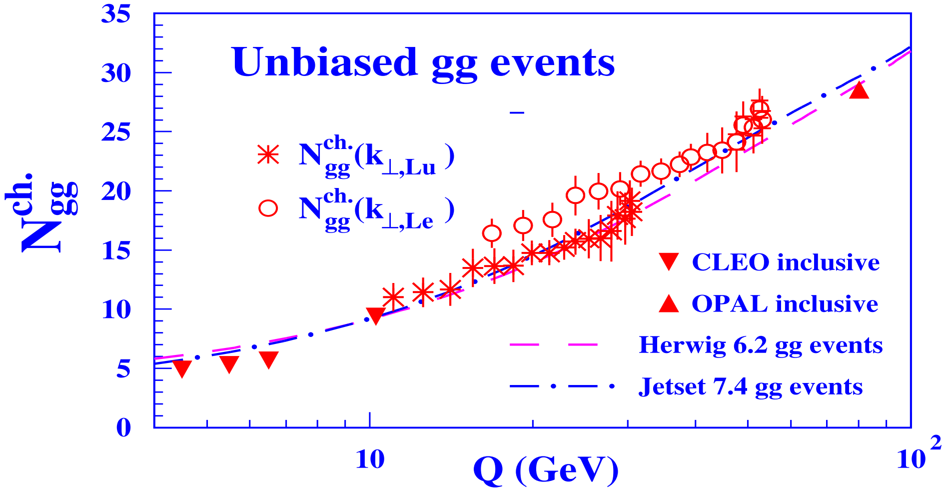
Advantages of e^+e^- annihilation to serve as QCD test

- Well-defined clean initial state
- Well-approximated energy and directions of primary partons
- Negligible background

Unbiased gluon jet multiplicity



3-jet $q\bar{q}g$ Y-event



OPAL Col., CERN-EP/2001-076 (EPJ C)

- No jet-def. algorithm dependence
  $\Rightarrow$ unbiased gluon jets in hemisphere
- Theory: $N_{q\bar{q}}$ from $q\bar{q}$ events,
  N_{gg} from gg events
- Exp.: $\frac{1}{2}N_{gg} = N_{q\bar{q}g} - N_{q\bar{q}}(L, k_\perp)$
  $L \sim \ln s,\ k_\perp \sim \ln p_\perp$
  $N_{q\bar{q}} = N_{q\bar{q}}(\sqrt{s}),\ \sqrt{s}(\mathrm{e}^+\mathrm{e}^-\to q\bar{q})$=10–200 GeV
- Y-event
  - 3 jets by adjusting y_{cut}
  - jet 1 –highest-energy jet
- $N_{q\bar{q}} \to N_{gg}(L, k_\perp)$ with 2 definitions
- $r^{(j)} \equiv (d^jN_g/d\varepsilon)/(d^jN_q/d\varepsilon),\ \varepsilon \sim \ln Q$
  $r^{(0)} < r^{(1)} < r^{(2)} \to 2.25,\ Q \to \infty$
- QCD colour factor from $N_{gg}(L)$ and $N_{q\bar{q}}(L)$
  C_A/C_F=2.232 ±0.008 ± 0.108 ± 0.082∼ 2.25 (pQCD)
  similar from DELPHI 2001-067 CONF 495 (prel.)
- General agreement with theory

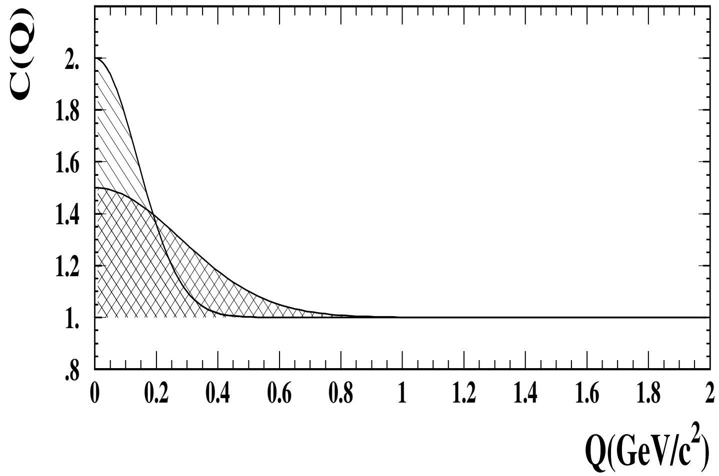
BEC function of identical hadrons

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

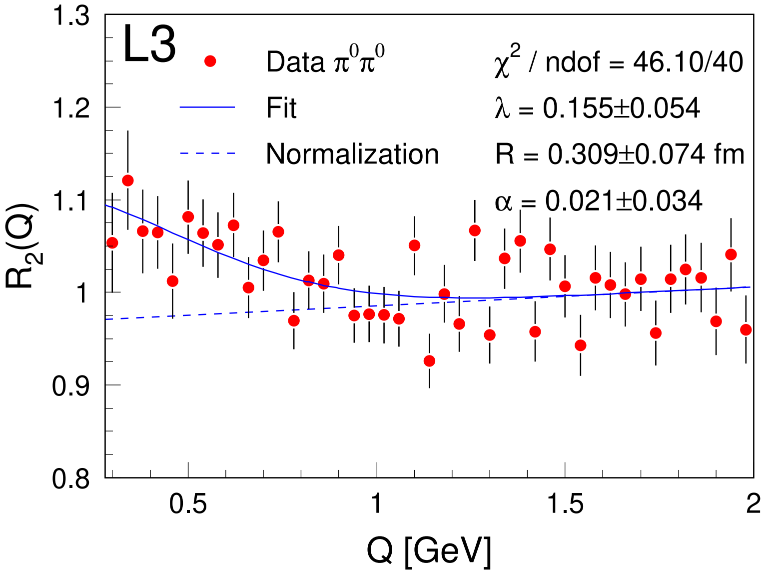
$$C(p_1, p_2) = \frac{\rho_2(p_1, p_2)}{\rho_1(p_1)\rho_1(p_2)}$$

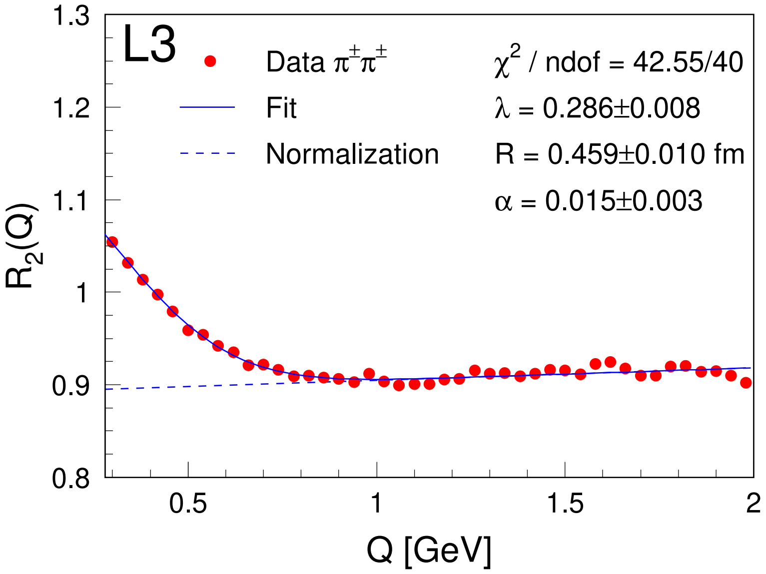
- In experiment,

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

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

$\pi^0\pi^0$ vs. $\pi^\pm\pi^\pm$ BEC

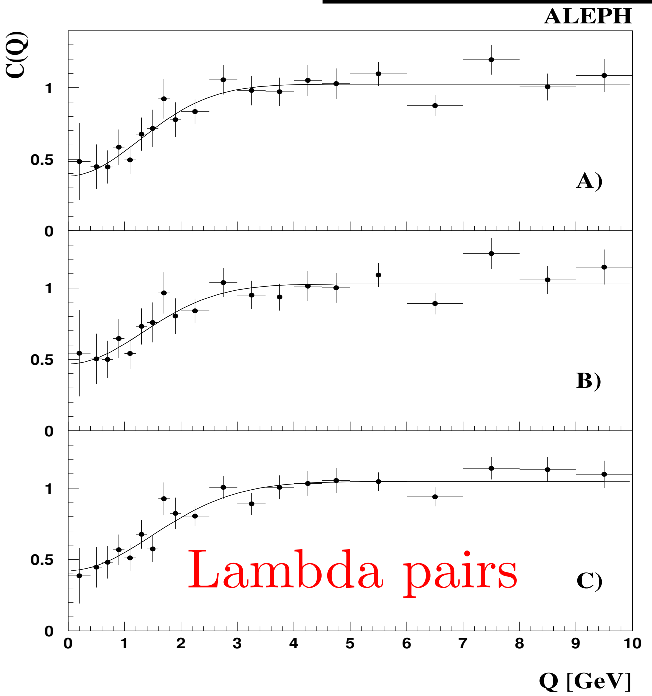


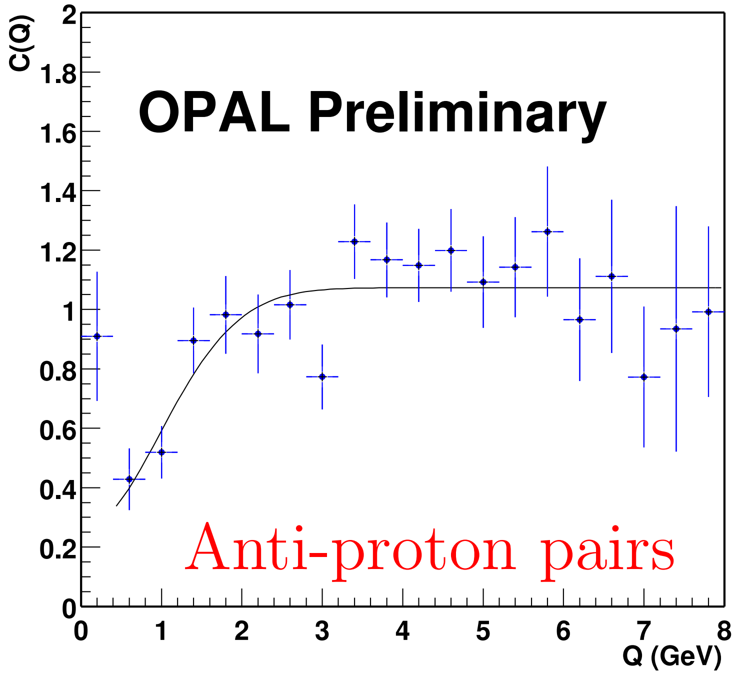


L3 Col., Phys. Lett. B524 (2002) 55

- BEC of charged pion pairs: well established at LEP
- Radius $R = 0.5 \ldots 1.0$ [depends on ref. sample]
- $R_2(Q) = \frac{\rho(Q)}{\rho_0(Q)} \propto (1 + \lambda\, e^{-Q^2 R^2})(1 + \alpha Q)$
- similar analysis framework for charged and neutral pions
- $R(\pi^0\pi^0) < R(\pi^\pm\pi^\pm)$ [with 2σ evidence] – qualitatively expected in Lund string model

Fermi-Dirac Correlations





ALEPH Col., Phys.Lett. B475 (2000) 395 OPAL Col., Phys. Note PN486 (2001)

- Antisymmetric final state $\Rightarrow$ decrease of C(Q) as $Q \to 0$

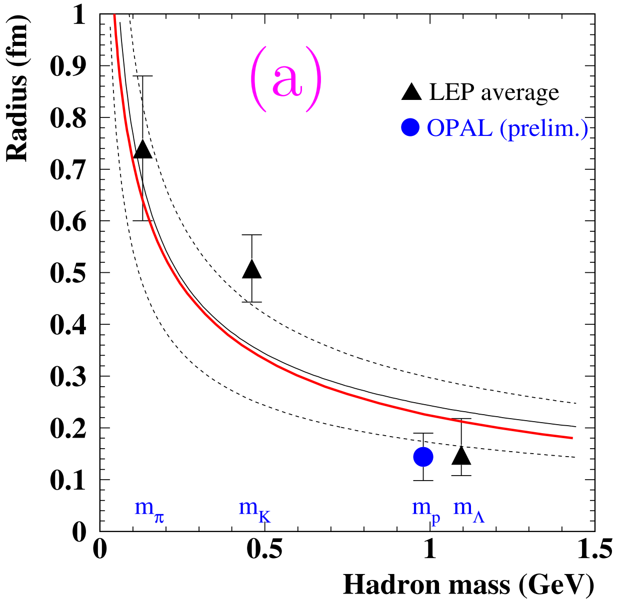
  $\lambda = -0.5$ for incoherent source G. Alexander, H.J. Lipkin (1995)

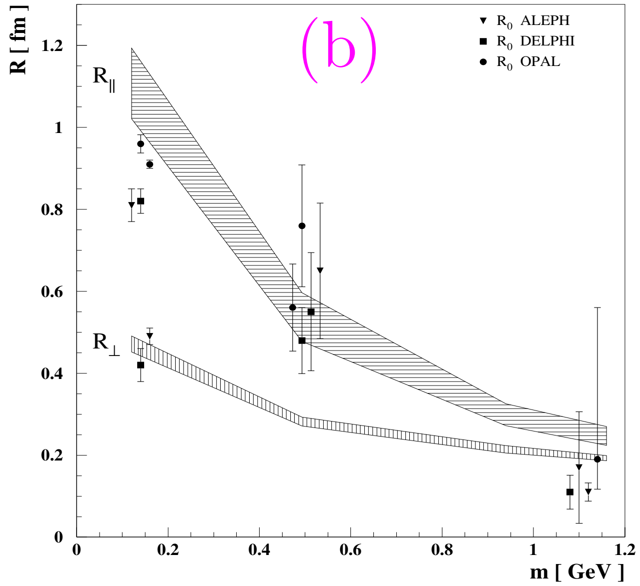
- ALEPH Ref. sample: A) MC, B & C) MIXing techniques

$\mathrm{R}(\Lambda\Lambda/\overline{\Lambda}\,\overline{\Lambda}) \sim 0.11\text{-}0.17$ fm, similar to that of OPAL (96), DELPHI (98,prel.)

- OPAL $\mathrm{R}(\overline{\mathrm{p}}\,\overline{\mathrm{p}}) = 0.142 \pm 0.035 \pm 0.047$ fm (prelim.)
  - ◦ No obvious experimental problem in first Q bin $\Rightarrow$ physics (?)

Two-particle correlation source size vs. hadron mass





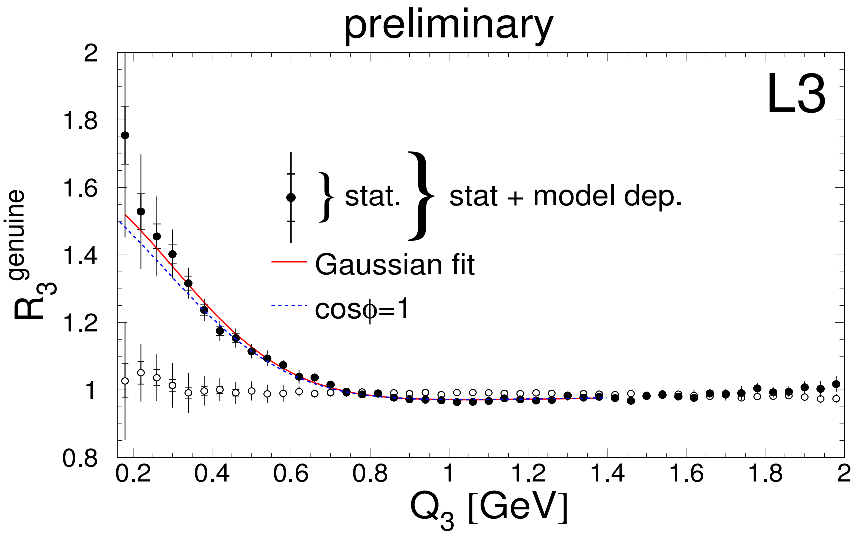
- $R_\pi > R_K > R_{p,\Lambda}$ hierarchy observed
- Not expected in Lund string model
- In qualitative agreement with models based on

(a) Heisenberg uncertainty principle [$\Delta t = (1 \pm 0.5) \times 10^{-24}$s], Virial theorem + LPHD + QCD potential – G.Alexander, I.Cohen, E.Levin (1999)

(b) Bjorken-Gottfried conjecture: $R(M)$ - from (x,p)-relations – A.Białas et al. (1999)

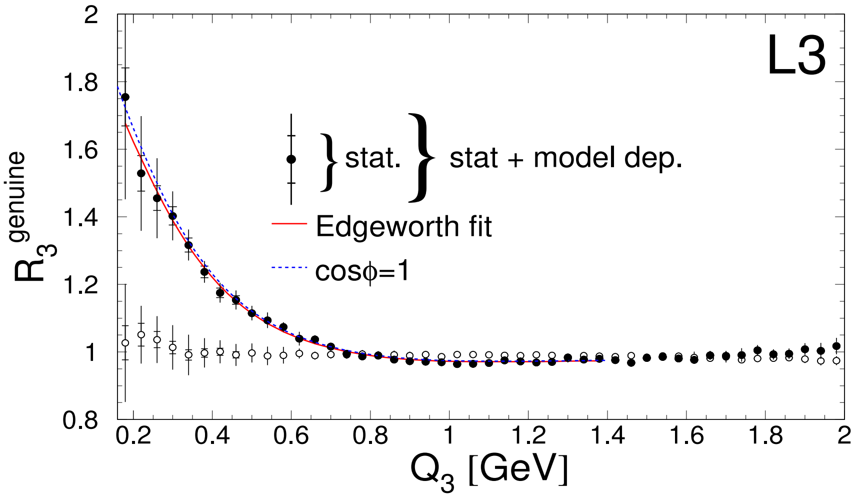
- Problem with energy density at high mass, 10–100 GeV/fm^3.
  Is R an 'emitter radius'?

Genuine 3-pion BEC



$R^G = 0.66 \pm 0.03 \pm 0.05$ fm

$\lambda^G = 0.50 \pm 0.03 \pm 0.06$



$R^E = 0.72 \pm 0.04 \pm 0.05$ fm

$\lambda^E = 0.72 \pm 0.04 \pm 0.07$

(ext. for non-Gauss. source, uses Hermite polynomials)

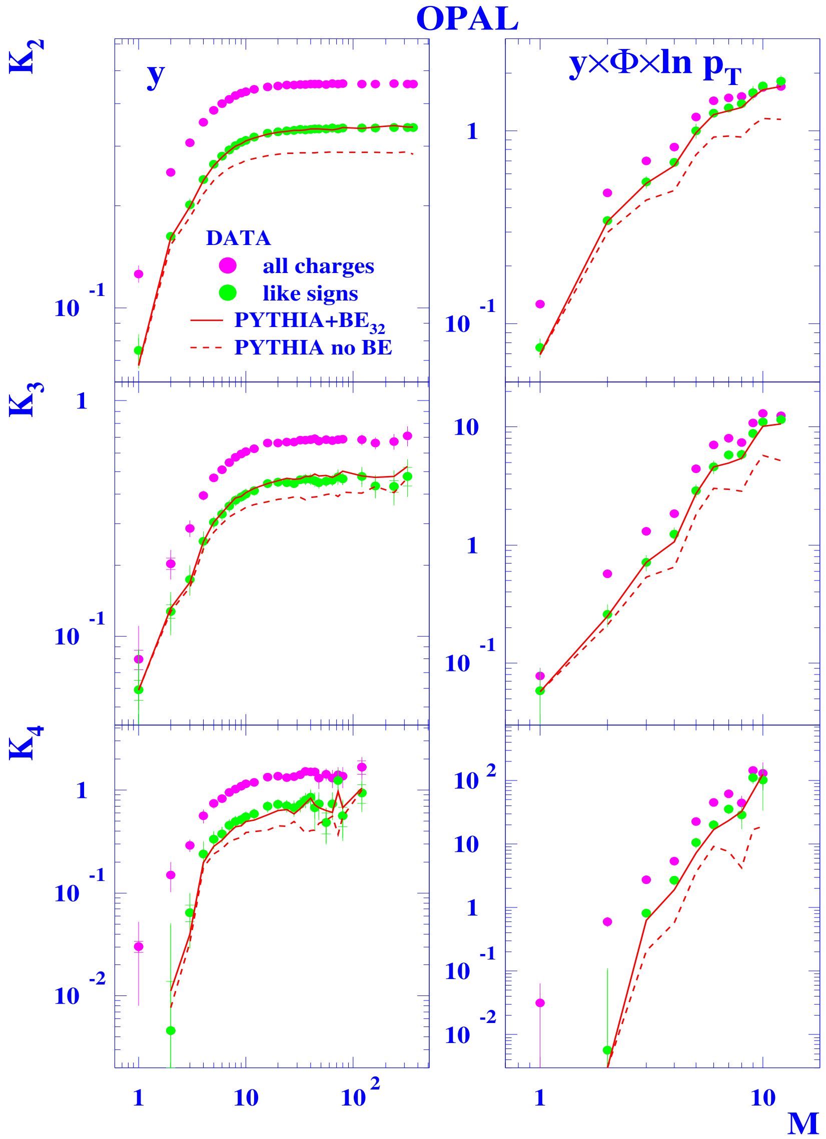
L3 Col., Note 2738 (2002)

- $R_3^{\rm genuine}(Q_3) = R_3(Q_3) - R_3^{\rm non-genuine}[\equiv R_{1,2}](Q_3) + 1$

  $Q_3^2 = Q_{12}^2 + Q_{23}^2 + Q_{13}^2 = M_{123}^2 - 9m^2$
- Incoherent hadroproduction $\Rightarrow \cos\Phi = 1$

  Complete incoherency $\Rightarrow \lambda = 1$
- R^G and λ^G consistent within LEP
- $(\mathrm{R}^E, \lambda^E) > (\mathrm{R}^G, \lambda^G)$
- $\cos\Phi = \dfrac{R_3^{\rm genuine}(Q_3) - 1}{2\sqrt{(R_2(Q_{12})-1)(R_2(Q_{23})-1)(R_2(Q_{13})-1)}}$
- Consistent with incoherent particle production

High-order genuine correlations
1D and 3D cumulants

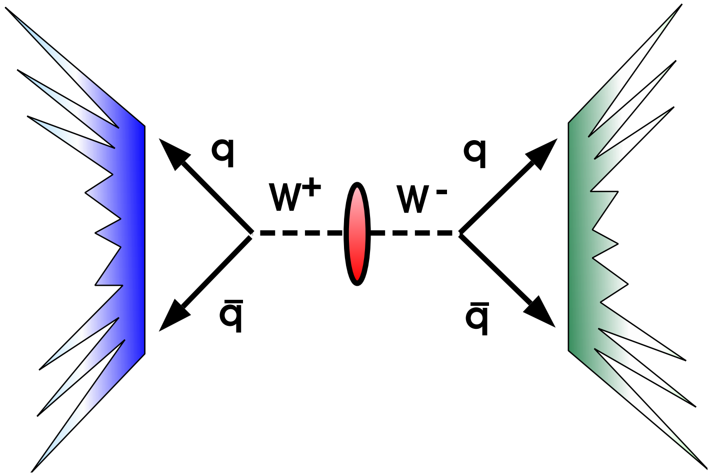


OPAL Collab., G. Abbiendi et al., Phys. Lett. B523 (2001) 35

- Genuine 2-, 3-, 4-particle correlations observed
- Model without BEC fails, BEC clearly needed
- Like-sign cumulants increase faster, derive 'all charged' at small bins
- BEC model simultaneously reproduces 1D to 3D Ks
- Pair-wise adjusted BEC account for higher-order Ks (?)
- Model adjusted to like-sign Ks reproduces all-charge Ks

W-pair decay and BEC

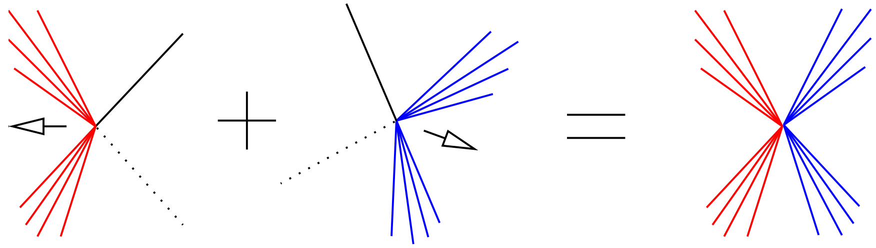
$e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$



- Separation of W decays ~ 0.1 fm
  Hadronisation scale $\sim 0.5 - 1$ fm
  $\Rightarrow$ PS overlap, inter-W BEC possible
- ΔM_{W} initial predictions: $0 - 100$ MeV
- $R_2(Q)$: strong BEC model dependence
- More robust variable/method needed

Mixing method and new variables

S.Chekanov, E.A.DeWolf, W.Kittel (99)



- Access to inter-W BEC from data
  - 10-15% Z-background, MC subtraction
  - 4q: $q\bar{q}q\bar{q}$ events; 2q: $q\bar{q}l\nu$ without l, ν

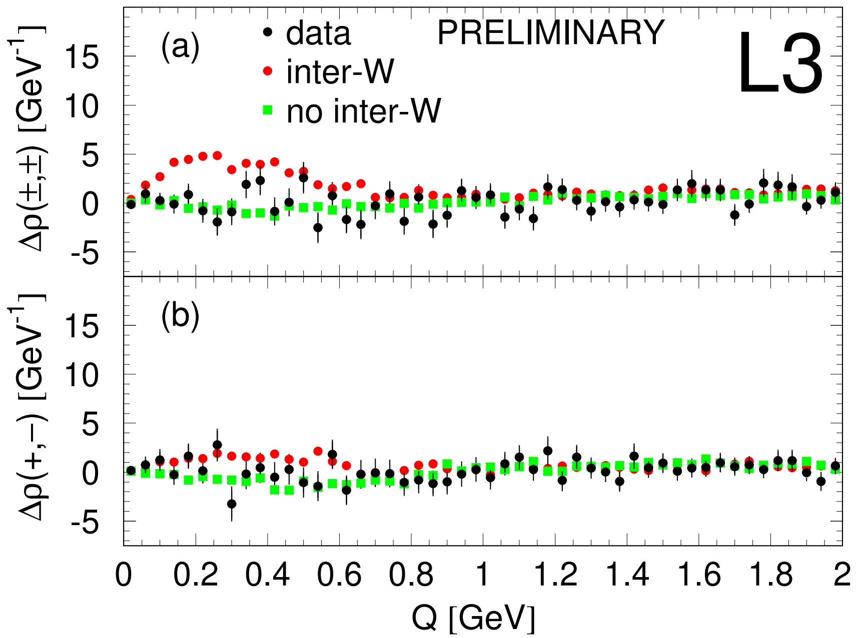
    mix: 2q with pairs from different Ws
  - $\Delta\rho$ & D as funct. of Q

$$\Delta\rho = \rho_2^{WW\to 4q} - \underbrace{(2\rho_2^{W\to 2q} + \rho_2^{\mathrm{mix}})}_{\text{faked 4q events}}$$

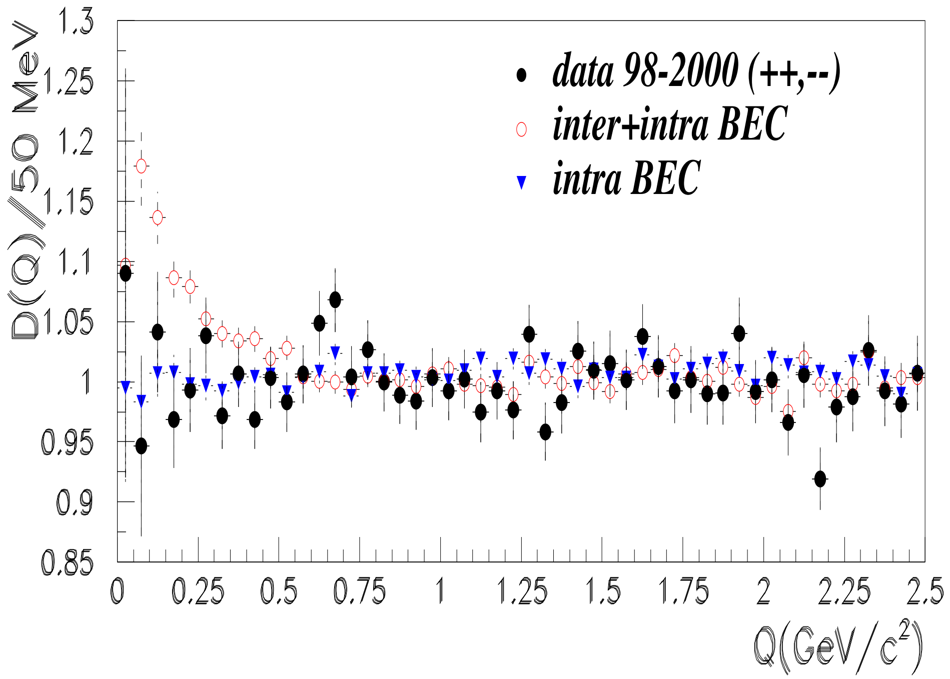
$$D(Q) = \rho_2^{WW\to 4q}/[\text{faked 4q}]$$

- No inter-W: $\Delta\rho = 0\,,\ D = 1$

BEC in W-pair decays: $\Delta\rho$ results



L3 Note 2674 (2001)



DELPHI 2001-060 CONF 488 (2001)

- Inter-W BEC with same λ and R as within a W (*intra*-W) strongly disfavoured
- $D(Q) = \frac{\rho_2^{WW}(Q)}{2\rho_2^W(Q)+\rho^{\rm mix}(Q)} = N(1+\delta Q)(1+\Lambda e^{-rQ})$

L3 (prelim.): $\Lambda = 0.008 \pm 0.018 \pm 0.016$, DELPHI (prel.): $\Lambda = -0.037 \pm 0.055 \pm 0.055$

$\Delta\rho$, D analyses $\Rightarrow$ No evidence for *inter*-W BEC

SUMMARY and OUTLOOK

- At LEP, multiplicity and correlation studies provided detailed information about hadron production

- Unbiased gluon jet multiplicity
  - Good agreement with pQCD predictions
  - Measurements consistent with $C_{\mathrm{A}}/C_{\mathrm{F}} = 2.25$

- Two-particle correlations at LEP1
  - ◦ Bose-Einstein correlations of neutral pions
  - ◦ Fermi-Dirac correlations of anti-protons
    - Spin statistics plays a role
  - ◦ Mass dependence of emitter size
    - A decrease observed, $\mathrm{R}_{\pi} > \mathrm{R}_{\mathrm{K}} > \mathrm{R}_{\mathrm{p},\Lambda}$
    - Is it emitter size that is measured?

- Multi-particle correlations at LEP1
  - ◦ 3-particle Bose-Einstein correlations
    - Non-Gaussian vs. Gaussian source
    - Completely incoherent particle production (?)
  - ◦ High-order correlations in terms of cumulants
    - BEC is a necessary ingredient
    - Order hierarchy between correlations

SUMMARY and OUTLOOK (cont'd)

- Bose-Einstein correlations at LEP2, W-pairs
  - New variables and mixing technique
    - No evidence for *inter*-W BEC correlations
      Multiparticle correlations, cumulants to be used (?)
    - W mass measurement uncertainty $\sim$ 20 MeV
      LEP combination in progress

- A lot of interesting analyses done, more is ongoing and even more is expected to be done

- Not shown in this report (sorry, no time)
  Momentum distributions, angular correlations, intermittency, BEC elongation, kaon pair correltaions, $\mathrm{H_q}$ moments, rapidity and p_T dependence of pairs, colour reconnection effects...

THANKS TO ALL WHO HELPED!