Bose –Einstein Correlations at LEP & HERA

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- *Introduction, terminology*
- *Q2 dependence of Bose–Einstein (BE) correlations (ZEUS)*
- *BE correlations in two dimensions (ZEUS / LEP)*
- *correlations of charged and neutral pions (L3)*
- *genuine 3–particle correlations in Z decay (L3)*
- *correlations of particles from independent overlapping sources (L3,DELPHI,ALEPH)*
- *modelling ....*

Enhanced production of 'close' bosonic pairs /multiplets ...
....due to quantum–mechanical interference (BE symmetrization)

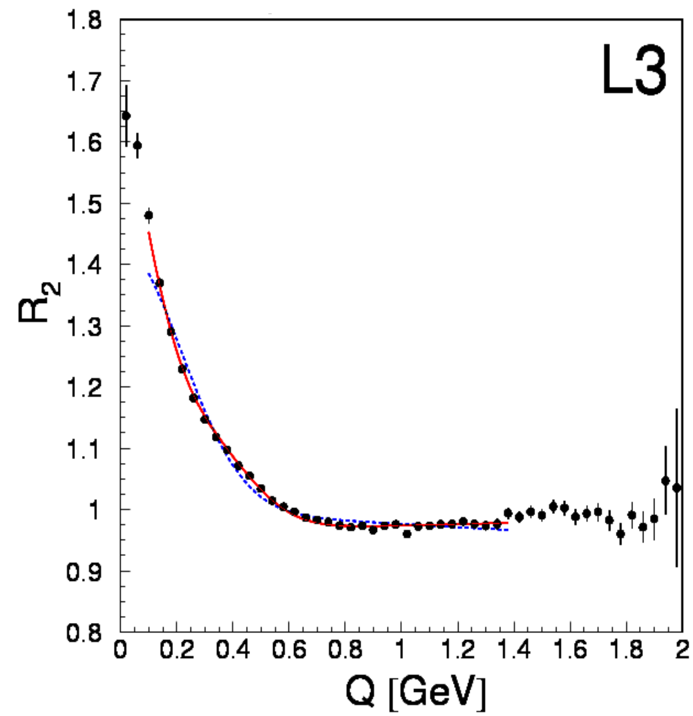
Well established property of hadron production in high–energy interactions:

n–particle density : $\rho(Q) = \dfrac{1}{N_{ev}} \dfrac{d\,N(multiplets)}{dQ}$

n–particle momentum transfer:

$$Q^2 = M^2 - n^2 m^2$$

m (M) mass of the hadron (multiplet)



Correlation function defined with respect to uncorrelated reference sample (MC , mixed tracks from diff.events, unlike–sign spectra)

$$R_2(Q) = \rho(Q) / \rho_{ref}(Q)$$

Depends on many factors:

- *Track selection*
- *Amount of secondary tracks*
- *(Mis)identification of particles*
- *Detector acceptance*
- *Particles from decay of (long–lived) resonances*
- *Event topology*

Interpretation : historically (Goldhaber et al.,1959) treated in close analogy with Hanbury Brown–Twiss (HBT) effect (intensity interferometry in astronomy)

Static, unifom, incoherently emitting source $\Rightarrow$ $R(Q) \sim 1 + \left| \int dx\, f(x) \exp(i\, \Delta p \cdot x) \right|^2$

Additional assumption about shape of the source defines the shape of the correlation function (gaussian source ~ gaussian enhancement)

fit $R(Q) = 1 + \lambda * \exp\{-(Q\, r)^2\}$ => "radius" r

=> "chaoticity" parameter λ

Particle Correlations & HBT –a valid analogy ?

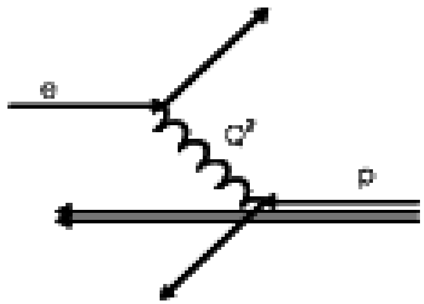
Astronomy :

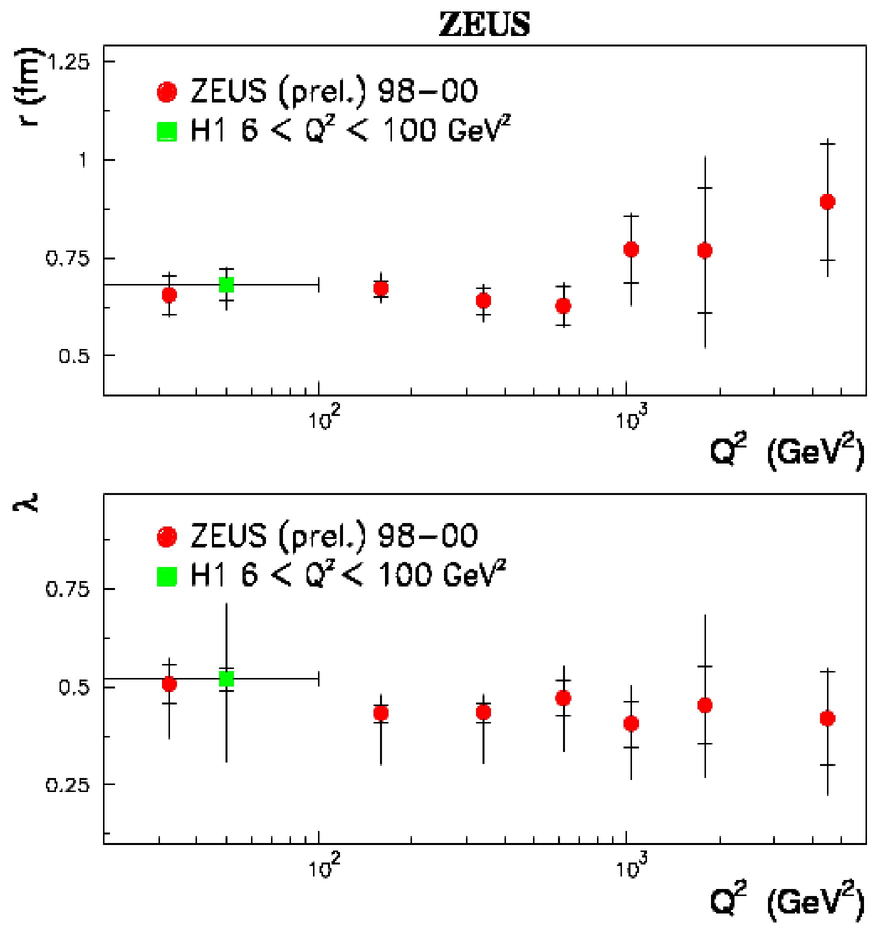
- Static source , often with simple geometrical shape
- Spectrum uncorrelated with position within the source
- Typically observed in a narrow spectral band

Particle physics:

- Rapidly expanding system (fireball in heavy ion collisions, well structured jets in e+e–); different event topologies integrated over
- Strong correlations between momenta of particles and their production point within the system
- Integrated over the momentum phase space

BE correlations in DIS





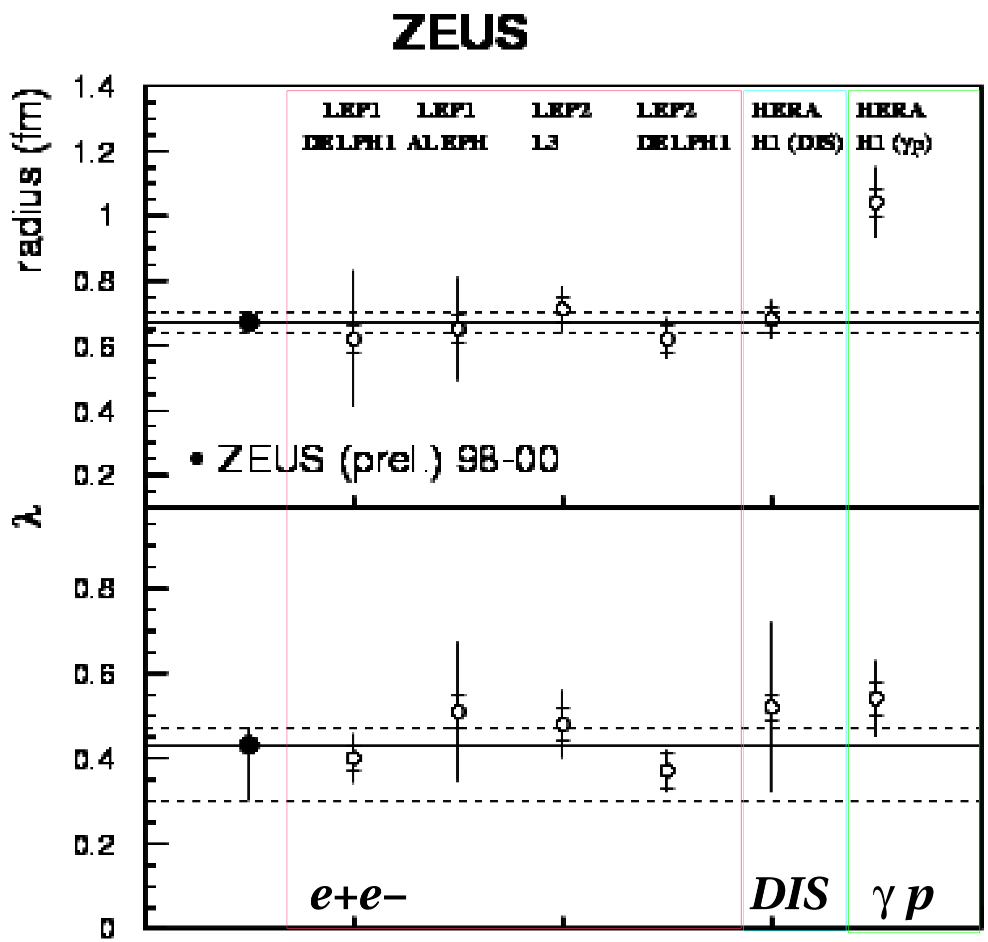
- DIS selection
- data 1998–2000 , 83 pb^{-1}
- reference sample :
  unlike–sign pairs
- gaussian fit

No significant dependence of BE correlations on Q2 observed

BE correlations in DIS

Fitted parameters of the correlation function consistent with LEP measurements

⇒ BE correlations are a universal hadronization phenomenon, not sensitive to the hard scattering process

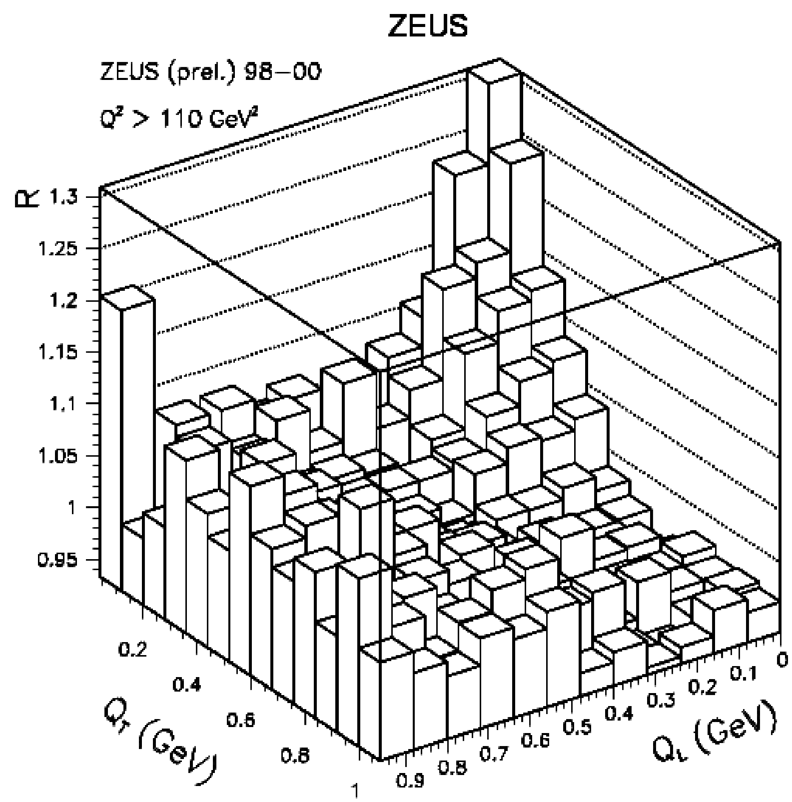


2–dimensional correlation function in DIS at HERA

– *measured in LCMS (longitudinal rest frame of the particle pair)*
– *fitted by*

$$R(Q) \sim 1+\lambda * \exp\{-(Q_L^2 R_L^2 + Q_T^2 R_T^2)\}$$

$$r_T / r_L = 0.67 \pm 0.08 \text{ (stat.)}$$



Result compatible with LEP
(DELPHI 2–jet 0.62 ± 0.02 ,
L3 incl. 0.73 ± 0.02 , OPAL)

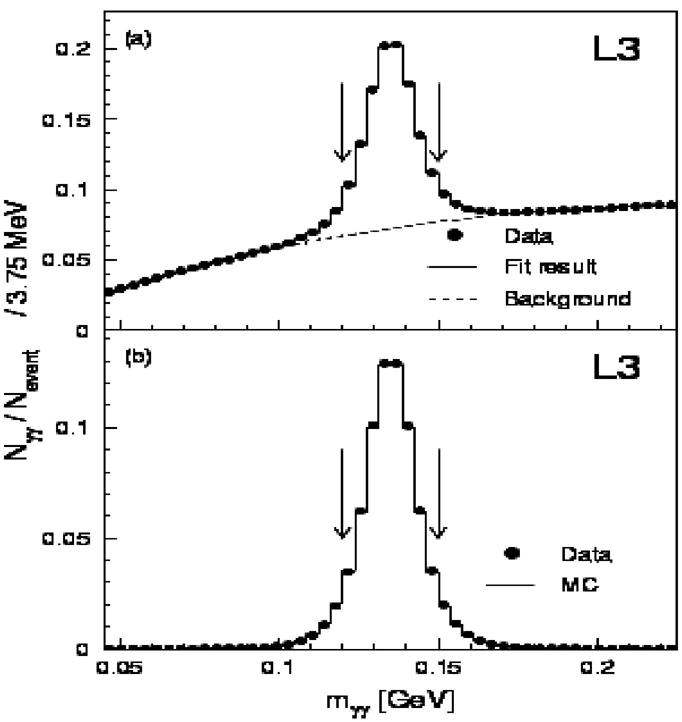
'Elongation' of the source

(fits well the string picture of hadronization in e+e–/ ep interactions)

BE correlations of Neutral and Charged Pions in Hadronic Z0 Decays

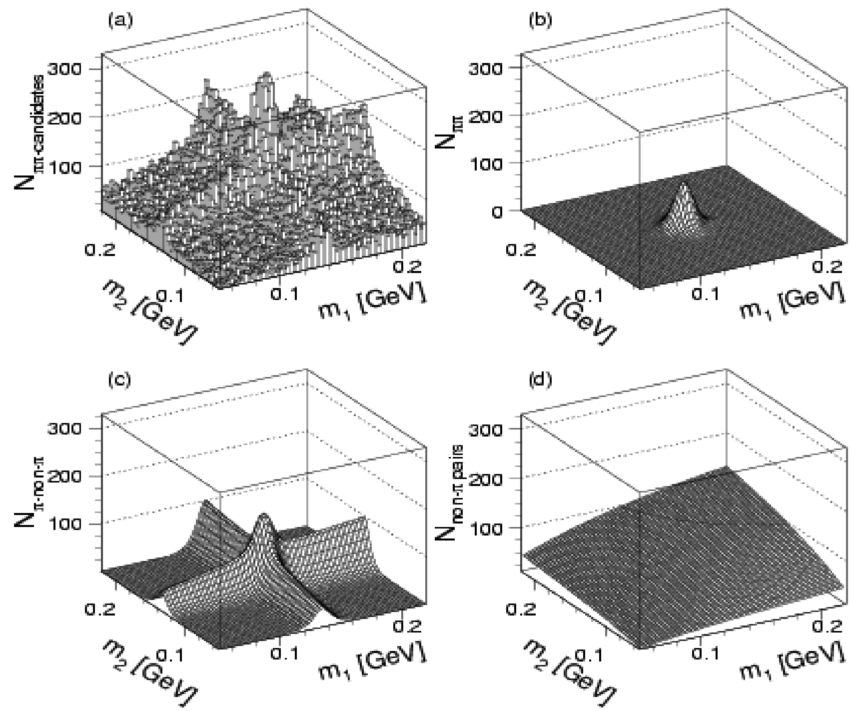
$\pi0\ \pi0$ *reconstruction – a true challenge !*

$\gamma\gamma$ pairs



0.2 GeV < E($\gamma\gamma$) < 6 GeV

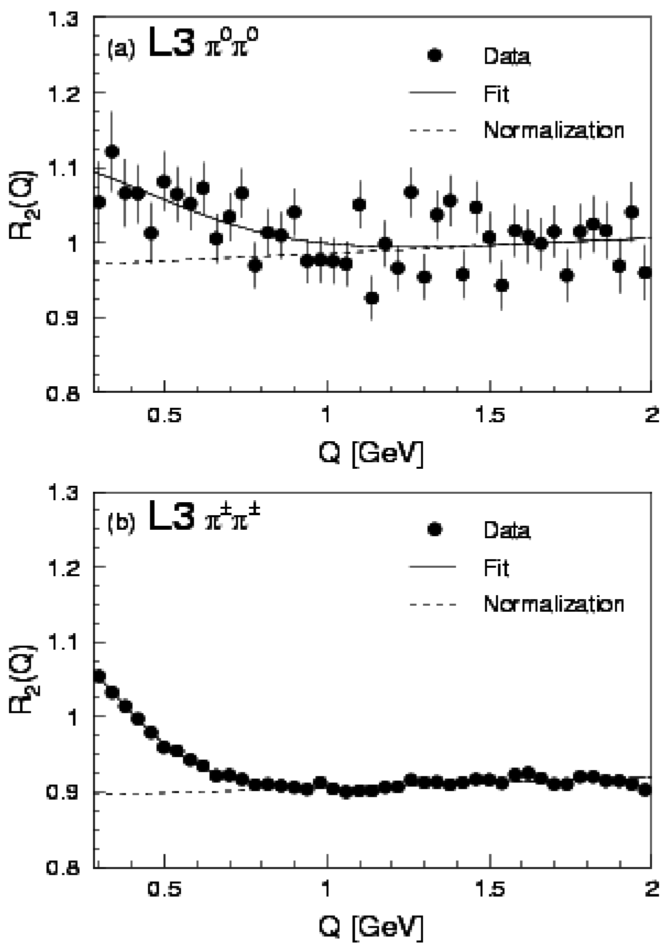
$\pi0\ \pi0$ *pairs (fit per bin in Q)*



Reconstruction efficiency: $\pi0$ *~ 17 % (purity 54 %)*

0.3 GeV < Q < 2 GeV : $\pi0\ \pi0$ ~ 1–4 %

BE correlations of Neutral and Charged Pions in Hadronic Z0 Decays



– Q spectra corrected by MC
– reference sample MC without BE
– charged pion selection cuts as for neutral pions

Fit:

	λ	*r (fm)*
$\pi0\ \pi0$	$0.155\pm 0.054\pm 0.072$	$0.309\pm 0.074\pm 0.07$
$\pi\pm\pi\pm$	$0.286\pm 0.008\pm 0.025$	$0.459\pm 0.010\pm 0.01$

Parameter r larger for charged pions (in qualitative agreement with expectations of string fragmentation model)

Correlations weaker for neutral pions – due to the larger fraction of resonance decays ?

Genuine 3–particle BE correlations in Hadronic Z0 Decays

Z0 inclusive sample

3–particle correlation function

$$R_3(Q_3) = \rho_3 / \rho_0$$

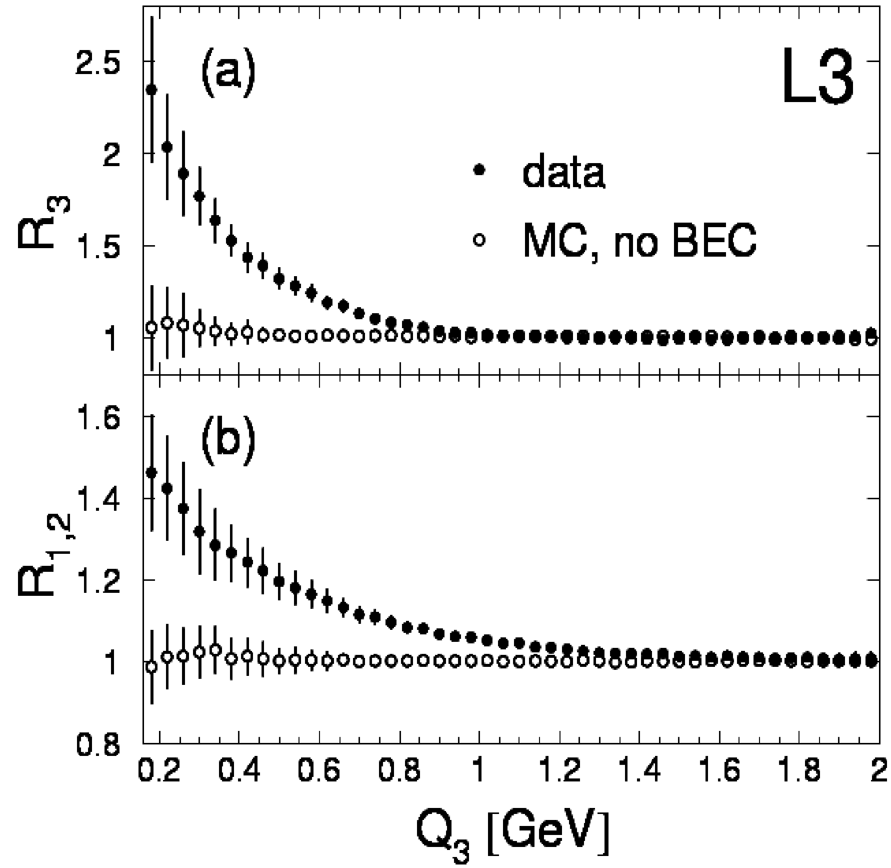
contribution from 2–particle correlations

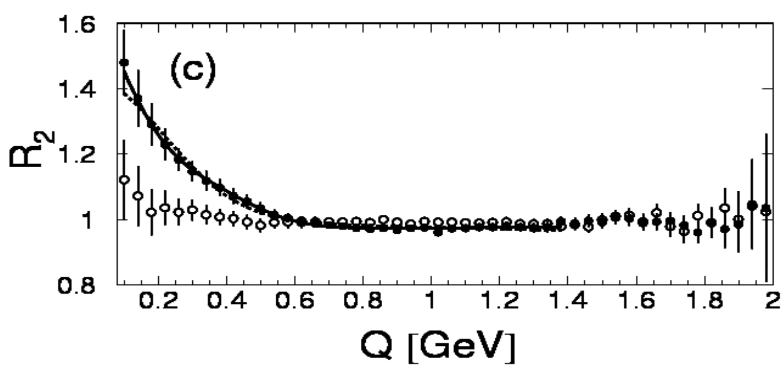
$$R_{1,2}(Q_3) = (\Sigma \rho_1 \rho_2) / \rho_0 - 2$$

2–particle correlation function

$$R_2(Q) = \rho_2 / \rho_0$$

$\rho_1 \rho_2$, ρ_0 *constructed by mixing tracks from different events*





– MC corrections for mixing, detector effects, acceptancy, efficiency, pion purity applied

– corrected for Coulomb repulsion

Genuine 3–particle BE correlations versus expectations

Genuine 3–particle correlations:

$$R_3^{Genuine} = R_3 - R_{1,2} + 1$$

Expectations:

If there are no correlations between momentum of emitted particle and its position within the source (not fulfilled in particle physics) :

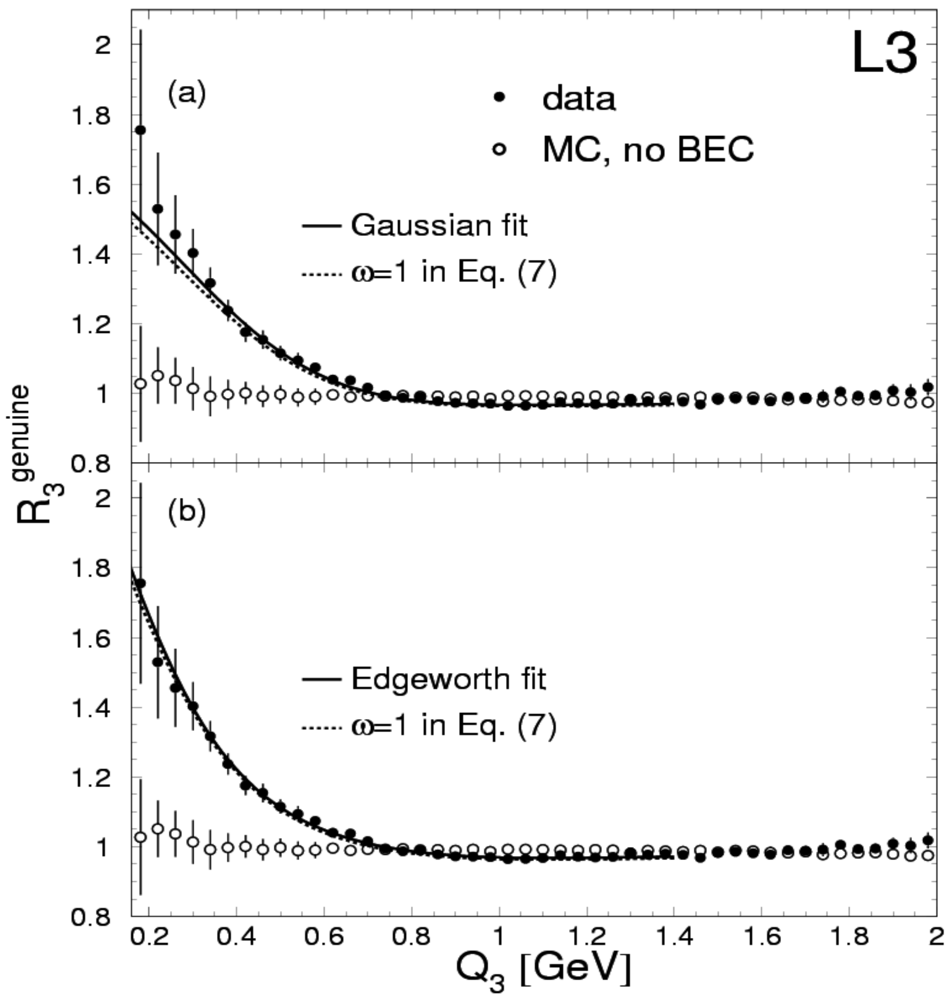
$$R_3^{Genuine} = 1 + 2\,\omega \sqrt{\Pi\,(R_2\,(Q_{ij}) - 1)}\ ,$$

where $\omega = \cos(\Sigma\,\phi)$ *(phase)*

incoherent emission

$\Leftrightarrow$ *randomization of phases*

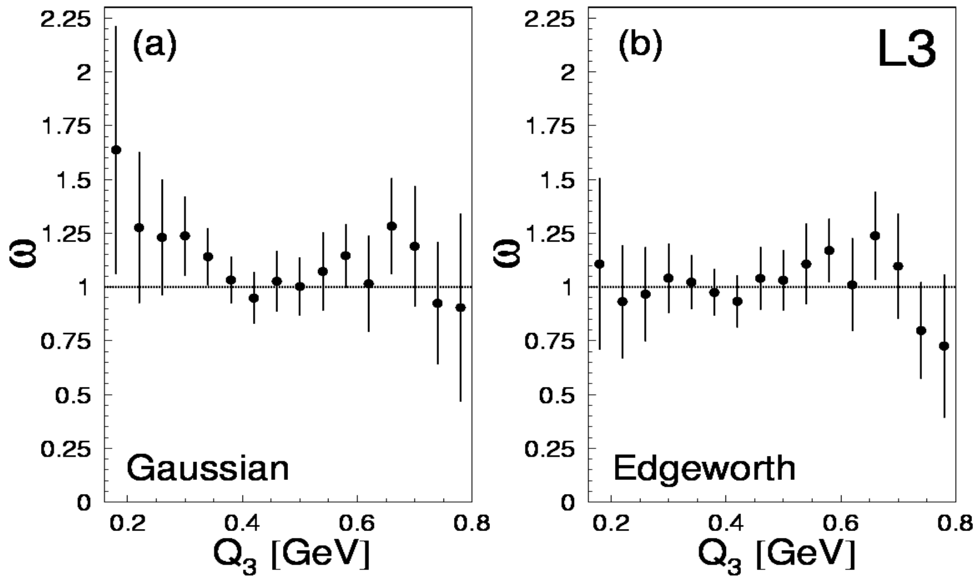
$\Leftrightarrow\ \omega = 1$



Genuine 3–particle BE correlations & (in)coherence ; discussion

Compare with other measurements:

e+e−(L3)			$\omega \approx 1$
hh	*(UA1)*		$\omega > 1$ (!)
	(NA22)		$\omega \approx 1$
AA	*(NA44)*	*SPb*	$\omega = 0.2 \pm 0.2$
		PbPb	$\omega = 0.85 \pm 0.22$
	(WA98)	*PbPb*	$\omega = 0.61 \pm 0.18$



?? e+e− incoherent , AA coherent ??

Alternative explanation :

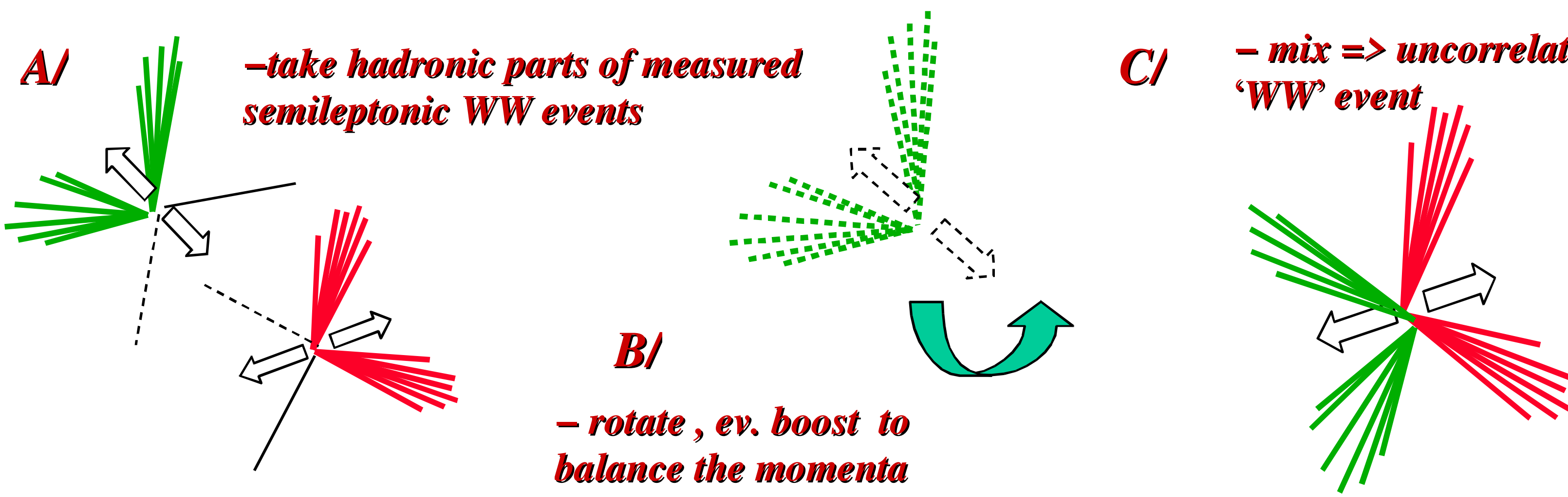
a/ $\omega = 1$ an inherent feature of correlations (yet to be explained)
b/ diluted in SPb due to the overlap of independent sources (strings)
c/ enhanced again in PbPb due to larger interaction of sources
(Braun, Moral, Pajares : percolation)

Measurement of inter –W Correlations in e+e– –> W+W– events at LEP

\+ *hadronically decaying W+W–bosons = overlapping sources*

++ *mixing of hadronic Ws from semileptonic WW events => an ideal reference sample*

(Eur.Phys.J.C6 (1999) 403)



– experimentally robust (data compared with data)

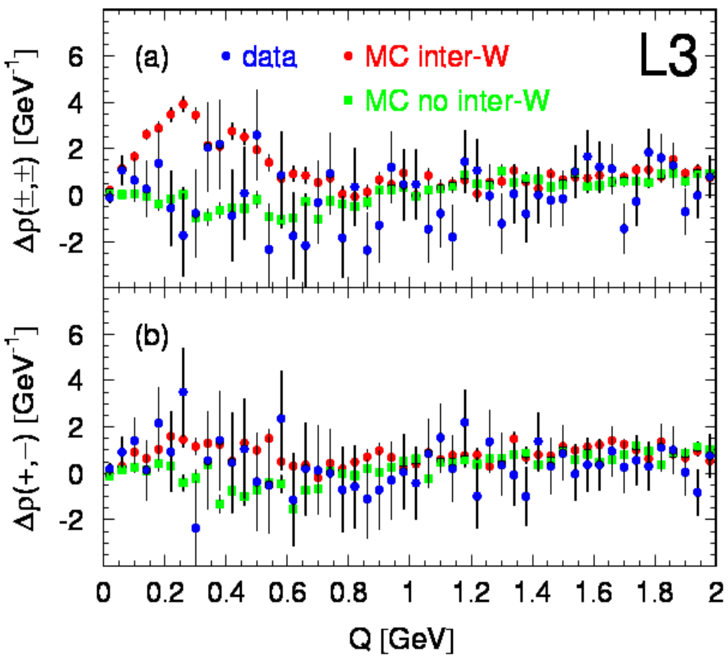
– model independent (except for background subtraction)

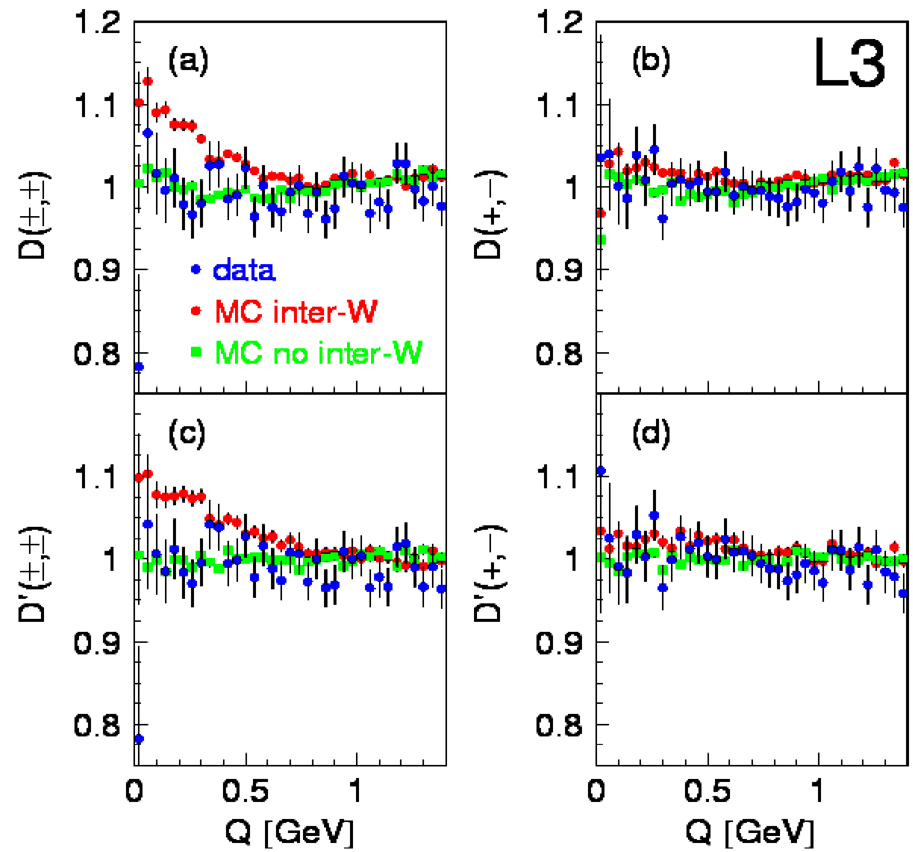
ABSOLUTE MEASUREMENT OF THE INTER–W CORRELATIONS !

Measurement of inter –W Correlations in e+e– –> W+W– events at LEP

Comparing 2–particle densities in hadronic and 'mixed' WW events:

$$\Delta\rho = \rho^{WW}(hadr.) - \rho^{WW}(mixed)$$
$$D = \rho^{WW}(hadr.) / \rho^{WW}(mixed)$$
$$D' = D(data) / D(MC)$$





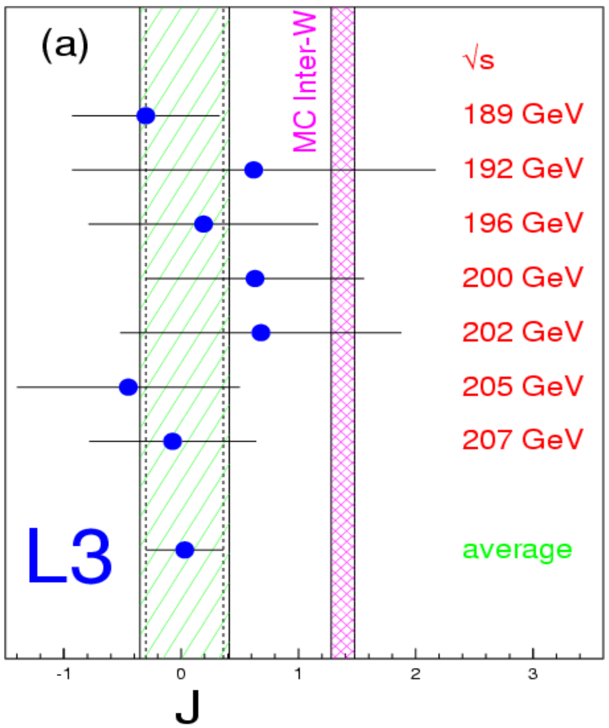
Measurement of inter –W Correlations in e+e– –> W+W– events at LEP

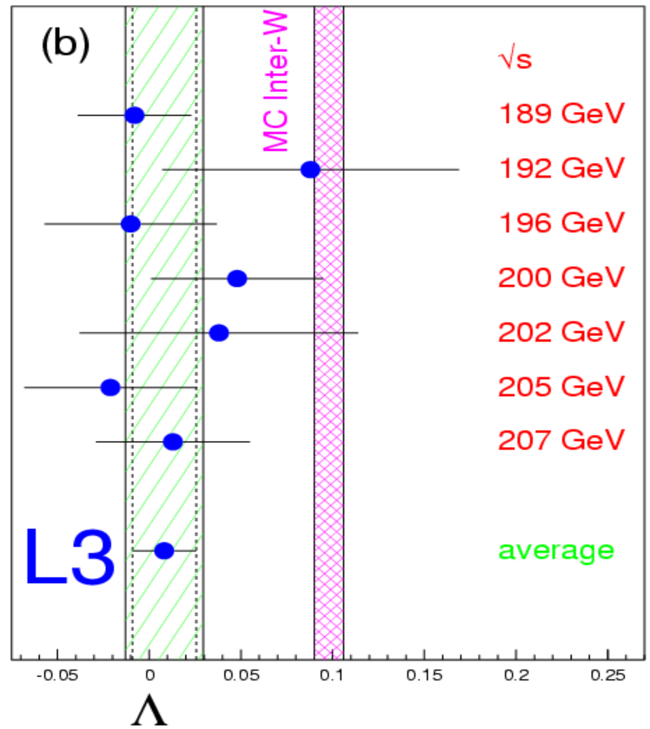
Final L3 results in numbers :

$\Delta\rho$ integrated in range 0.–0.68 GeV:

$J(\pm,\pm) = 0.03 \pm 0.33 \pm 0.15$

$J(+,-) = 0.01 \pm 0.36 \pm 0.16$





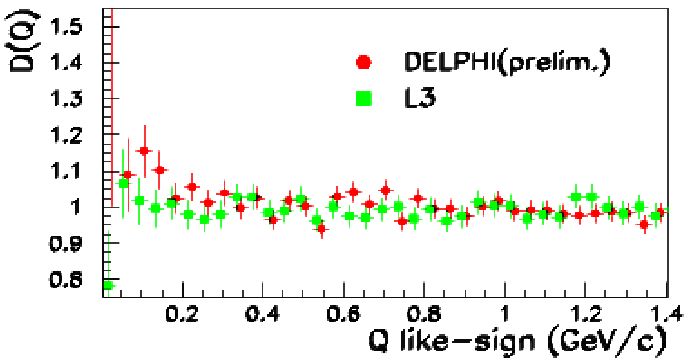
D' fitted in range 0.–1.4 GeV by

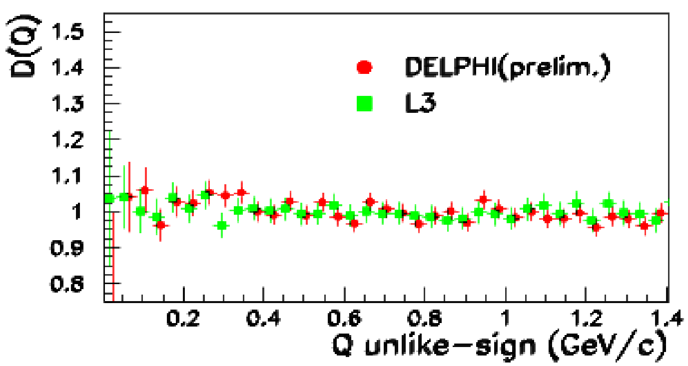
$D' = (1+ \delta Q)\,(1 + \Lambda \exp(-k^2 Q^2))$

$\Lambda(\pm,\pm) = 0.008 \pm 0.018 \pm 0.012$

Measurement of inter –W Correlations in e+e– –> W+W– events at LEP

Add DELPHI data (preliminary) :



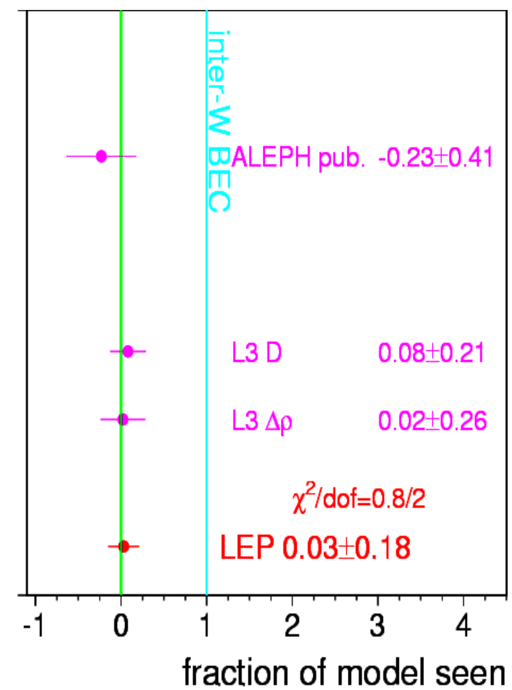


DELPHI versus L3 ?
data not inconsistent ...

Difference between size of the effect in (±,±) and (+,–) spectra < 1 σ (in both experiments)

$\delta M(W) < 20$ MeV
(currently 35 MeV)

More to come (ALEPH, OPAL) ....



Modelling of BE Correlations in e+e−/ e p collisions

Current situation is not satisfactory ... *generated data simply adjusted to the observed spectra, often using brute force*

Techniques : *SHIFTING of particles in the final state – introduces an artificial energy / momentum transfer in the event*

WEIGHTING of events – based on the fit to the data rather than quantum mechanics (space–time properties of the system and p / x correlations ignored)

e+e– collisions are the simplest and cleanest environment, yet the experimentalists lack the tools necessary for interpretation of the correlation data within a consistent framework ....

..... *the task is highly non–trivial : make a step from*

(semi)classical modelling of the hadronization

towards

quantum–mechanical description

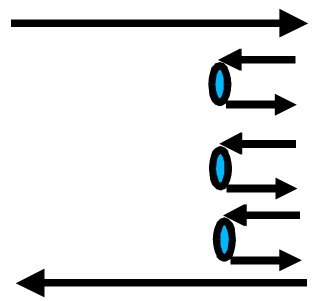
Modelling of BE Correlations in e+e−/ e p collisions

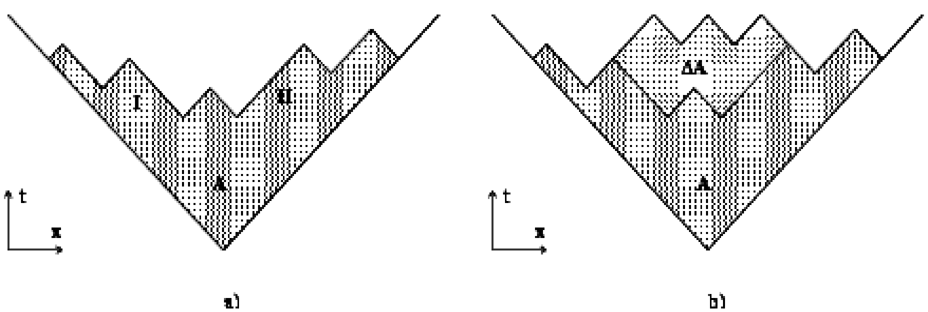
* *The quantum–mechanical frame for the fragmentation of the Lund string developed by Bo Andersson and coll.*
(Phys.Lett.B169(1986), Phys.Lett.B421(1998))

Bo Andersson,
1937–2002

$$\boxed{M \sim \exp\{(i\kappa - b/2)A\}}$$

String tension *String area*
Fragmentation parameter





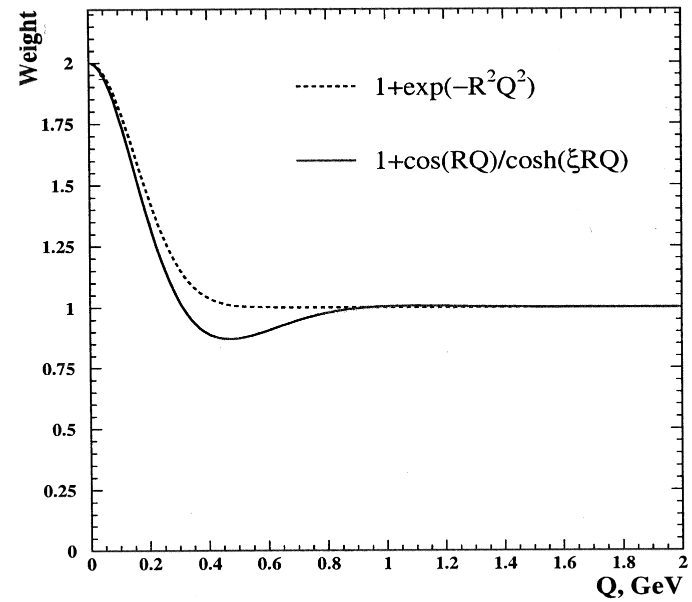
$$|M_1+M_2|^2 \sim (M_1^2+M_2^2)\ *$$
$$\{1 + \cos(\kappa\,\Delta A) / \cosh(b\,\Delta A/2)\}$$

Correlations enter here !
Fully predicted !

Modelling of BE Correlations in e+e–/ e p collisions

Kartvelishvili, Kvatadze : Phys.Lett. B 514 (2001) 7

– *free inspiration by Lund BE model*
– *adopt the functional form of BE weights:*
  – *presence of negative weigths cures many of traditional problems in BE reweighting (weights centered around 1, multiplicity and factorization properties not affected)*
– *predict only small effect on reconstruction of W mass (< 13 MeV)*
– *not tested against the data (yet)*



HOWEVER :

Calculation of string area difference for each pair of identical bosons replaced by a multiplicative constant .....

=> the physical content is gone ...

Summary :

- *BE correlations are a universal property of hadronization, insensitive to the initial hard process*
- *Elongation of the source (assymetry between longitudinal / transverse correlation function) observed in e+e–/ep collisions*
- *Comparison of correlations of neutral pions and of charged pions suggest s larger effective source size for latter*
- *Genuine 3–particle correlations measured ; their relation to 2–particle correlations investigated ; (in)coherence issues discussed*
- *Measurement of correlations between particles from overlapping hadronic sources (WW) in progress ; more to come*

- *Modelling : does not keep pace with the experiment, but gets a boost from QM reformulation of the Lund fragmentation model ; to be followed !*

It's time to move beyond HBT !
Stellar interferometry has done so a long time ago ...