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The GGLP Effect Alias Bose-Einstein Effect Alias H-BT Effect

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Round table discussion at *International Workshop on Correlations and Multiparticle Production*

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The GGLP effect alias Bose-Einstein effect alias H-BT effect

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What is clear is that we have been working on this effect for thirty years. What is not as clear is that we have come that much closer to a precise understanding of the effect.

In response to the convener of this roundtable discussion, I will present the historical development from the point of view of particle physics, as well as some results from e^+e^- interactions.

This subject has already been discussed in part in my talks at LESIP I [1] and LESIP II [2]. Other excellent reviews of the entire field have recently been given by Bill Zajc, Bengt Loerstad, Werner Hofmann, and a series of incisive papers by Mike Bowler[3].

The historical development from the particle physics point of view.

1959 The empirical observation. G. Goldhaber, et al.[4]

This was a $\bar{p}p$ propane bubble chamber experiment at the Bevatron, designed to look for the $\rho^0 \to \pi^+\pi^-$ decay. In this connection, we compared $\pi^+\pi^-$ mass distributions with the $\pi^\pm\pi^\pm$ distributions. While

* Round table discussion at CAMP, Marburg, Germany, May 14-16, 1990.

the statistical accuracy was not adequate to establish the existence of the ρ^0, we did observe a marked and very significant difference in angular opening angle for LIKE and UNLIKE pion pairs.

The lessons from this experiment are:

- Be sure to get enough statistics to achieve the desired goal!

- Be alert for unexpected (unexplained) effects!

1960 The interpretation of the empirical observation in terms of the symmetrization of the identical particle wave functions.

Gerson Goldhaber, Sulamith Goldhaber, Wonyong Lee, and Abraham Pais(5) were able to reproduce the empirical angular distribution by a detailed explicit multipion phase space calculation in which LIKE particle wave functions were symmetrized.

It must be remembered that this work was carried out **before** the detailed Monte Carlo phase space simulations were invented. We did not have LUND 6.3 available to carry out these integrations! All multiparticle integrals were numerically evaluated on a comparatively primitive computer (IBM 650). In fact, we had to invent our own Monte Carlo methods for these integrations.(5)

The result was clear. The effect could be interpreted as the consequence of the Bose-Einstein nature of LIKE pions. See Figure 1.

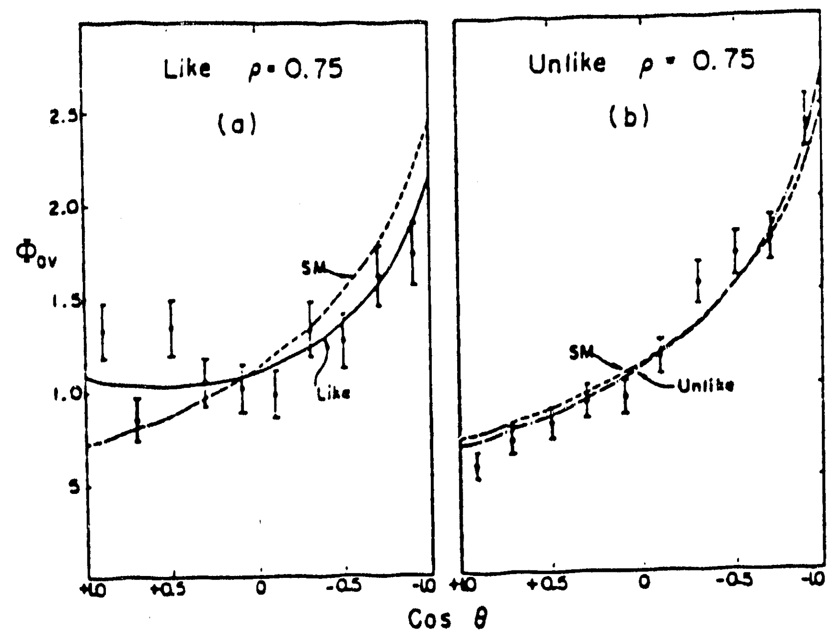

FIG. 6. The functions $\Phi_{av}(\cos\theta)$ computed at $\rho=0.75$ are compared with the experimental distribution of angles between pion pairs. Figures 6(a) and 6(b) give the distributions for like and unlike pions respectively. Also shown in each is the curve for $\Phi_{av}{}^{SM}(\cos\theta)$, the statistical distribution, without the effect of correlation functions. Here Φ_{av} represents an average of Φ_4, Φ_5, and Φ_6, weighted according to the individual charge channels. The experimental data comes from reference 1 (see also Table I, footnote a). Here ρ is in units of $\hbar/\mu_\pi c$.

Figure 1

The consequence of this analysis was the introduction of the expression:

$$R = 1 + e^{-r^2Q^2}$$

$$\text{where } Q^2 = -(p_1 - p_2)^2$$

$$= M_{12}^2 - (m_1 + m_2)^2$$

is the invariant four momentum difference of the two like pions, R is a "correlation function" and r represents the radius of some volume in four space. The numerical value we found to fit the data was $r \simeq 1.0$ fm. While one can argue that we should have used 3-momenta, the main justification for 4-momenta was that transformations and integrals were simpler with 4-vectors!

1960-1975 Many experimental confirmations of **the** effect in various particle physics experiments.(6)

- Biswas, et al. and M. Deutschman, V. Cocconi, D. Morrison, and others of CERN who carried out a major study on a variety of interactions.(6) An important result was the realization that the effect did not appear to come up to its maximal value, and that a factor λ was needed to fit the experimental data. This changed the expression for the correlation function to

$$R = 1 + \lambda\ e^{-r^2Q^2}$$

In the meantime, the new resonances (beyond the $\Delta(1236)$) were discovered. The $Y^*(1385) \equiv \Sigma(1385)$, the $K^*(890)$, the $\rho(770)$, $\omega(780)$, $\eta(550)$, f(1280), and many others.(7) These extremely important particle physics discoveries led to confusion about the interpretation of the effect." The effect was not really due to Bose-Einstein statistics; why not just a reflection of resonances?" Does this mean we discovered resonances - and did not know it? I am afraid not!

1970-1975 Can the effect become a precise tool in pion interferometry? Does the answer lie in the stars?

The cast of characters changes. Enter particle physicists who have heard of Astronomy[8-11]. Flashback to 1956. Meanwhile, what have Hanbury-Brown and Twiss been doing? R. Hanbury-Brown has been thinking about how to measure stellar radii, or at least the angle θ subtended by nearby stars. He enlisted R. Q. Twiss to develop the mathematical theory of Intensity interference, or second-order interference[12]. What is more, they actually built the equipment to carry out the experiment. There is an interesting similarity to our experience. Skepticism that such an effect can exist! I quote from the very readable book by R. Hanbury-Brown[13],

> "Another stream of objections about photons were both instructive and entertaining. Our whole argument was based on the idea that the fluctuations in the outputs of two photoelectric detectors must be correlated when they are exposed to a plane wave of light. We had shown that this must be so by a semi-classical analysis in which light is treated as a classical wave and in this picture there is no need the worry about photons - the quantization is introduced by the discrete energy levels in the detector. However, if one must think of light in terms of photons then, if the two pictures are to give the same result, one must accept that the times of arrival of these photons at the two separated detectors are correlated - they

tend to arrive in pairs. Now, to a surprising number of people, this idea seemed not only heretical but patently absurd and they told us so in person, by letter, in publications, and by actually doing experiments which claimed to show that we were wrong. At the most basic level they asked how, if photons are emitted at random in a thermal source, can they appear in pairs at two detectors? At a more sophisticated level, the enraged physicist would brandish some sacred text, usually by Heitler, and point out that the number n of quanta in a beam of radiation and its phase ϕ are represented by non-commuting operators and that our analysis was invalidated by the uncertainty relation. "

Hanbury-Brown and Twiss developed a theory for intensity interferometry treating the stars in a first approximation as luminous disks. This led to the expression of

$$\Gamma^2(d) = [2\,J_1(x)/x]^2 \text{ where } x = \pi\theta d/\lambda.$$

Here Γ^2 is the "normalized correlation," $J_1(x)$ a Bessel function, λ the mean wave length of the light observed, d the distance between the two mirrors, and θ the resulting angle subtended by the star as approximated by a disk.

The essence of their equipment consisted of two roughly paraboloid mirrors, each of which focused the light from a star onto a photomultiplier tube. Figure 2 shows such a mirror. An essential feature of the device is the "correlator. " An electronic circuit that receives the signals from both mirrors and "multiplies them." A technique that allows to distinguish between noise and correlated signals. An interesting feature is that the mirrors need

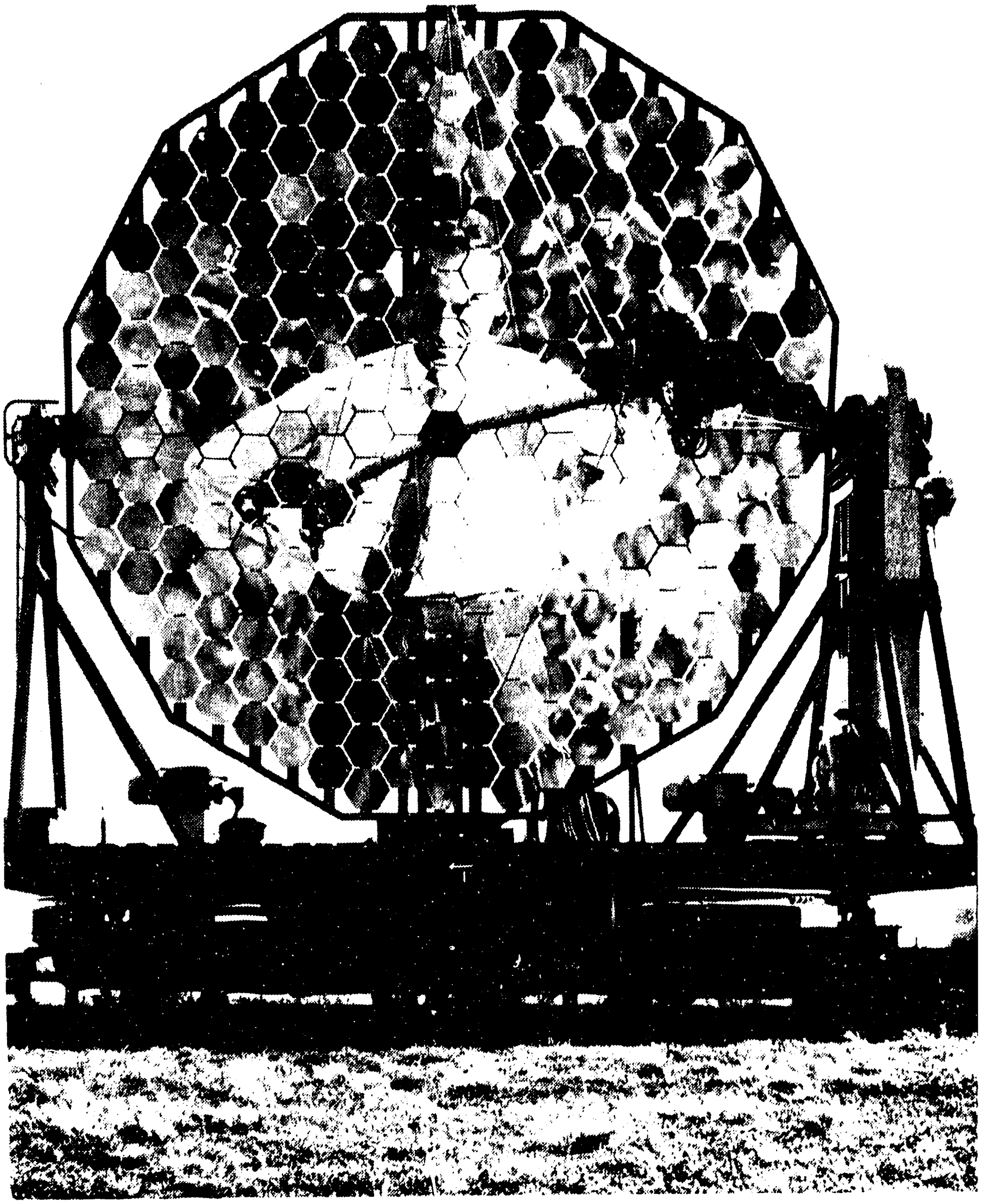

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Figure 2

not be of the usual high optical quality associated with telescope mirrors. To quote:

> "It took us six months to realize that although we should certainly need two very large telescopes, they could be extremely crude by astronomical standards. Their function would simply be to collect the light from the star like rain in a bucket and pour it on to the detector there was no need to form a conventional image. In practice this meant that the whole problem was transformed into one of reasonable cost since our telescopes need only be like the paraboloids used for radio-astronomy, but with light-reflecting surfaces. The necessary precision of these surfaces would be governed by the maximum permissible field of view and not, as at radio wavelengths, by the beamwidth; for bright stars a field of view of several minutes of arc would be tolerable and this could be achieved with the sort of structures which were used by radio-astronomers for microwaves."

Figure 4 gives a photograph and a sketch of the complete interferometer at Narrabri in Australia. Figures 4 and 5 show examples of the Interference distributions and the measured angles θ subtended by the various stars. The awareness by particle physicists (8-11) of the work by Hanbury-Brown and Twiss on stellar interferometry led to attempts and suggestions to place "pion interferometry" on a more respectable footing.

Summary of Further Developments

~ 1975 - 1982 M. Deutschman et al. <u>CERN</u>

- λ as an empirical parameter.
- Event Mixing for reference samples.

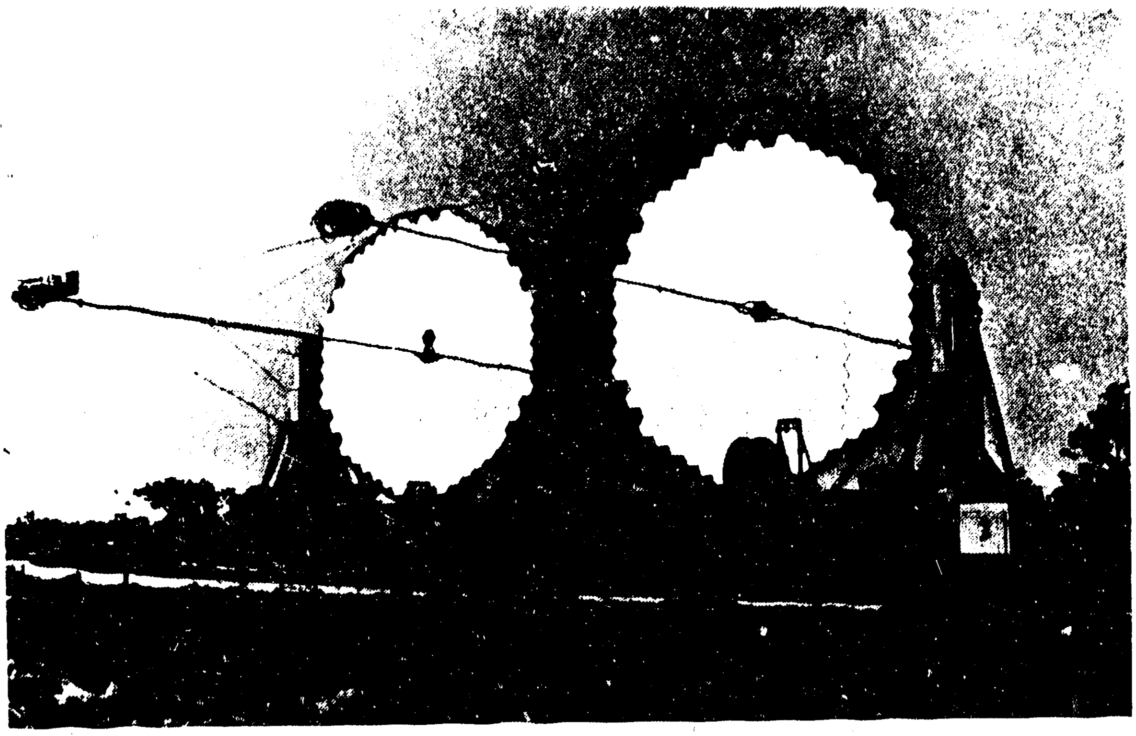

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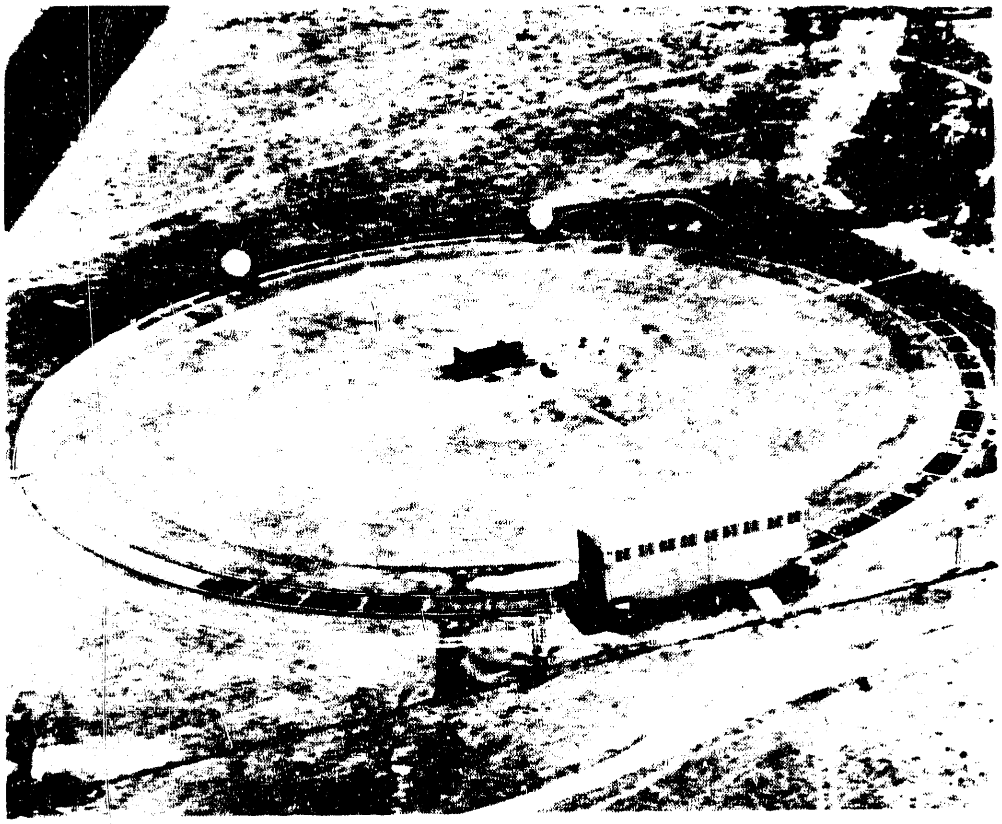
Figure 3



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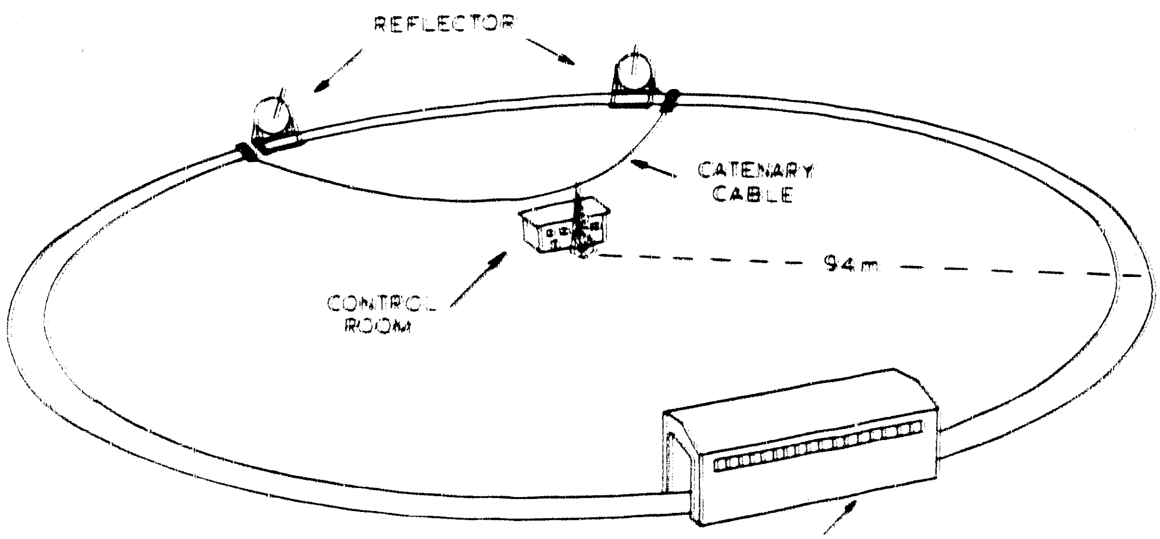
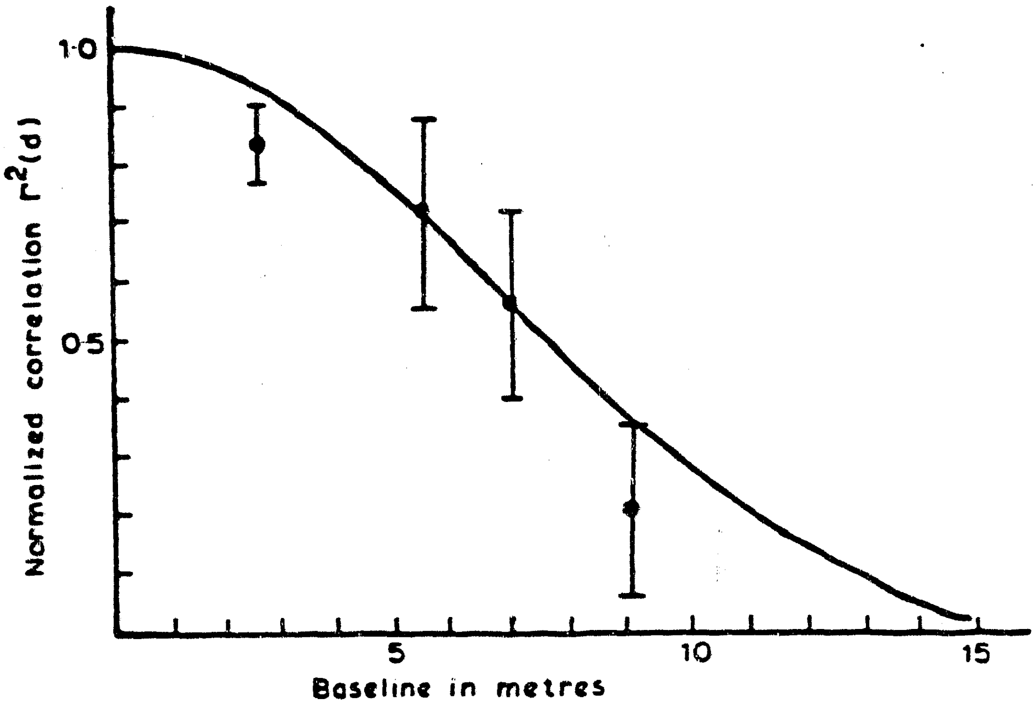


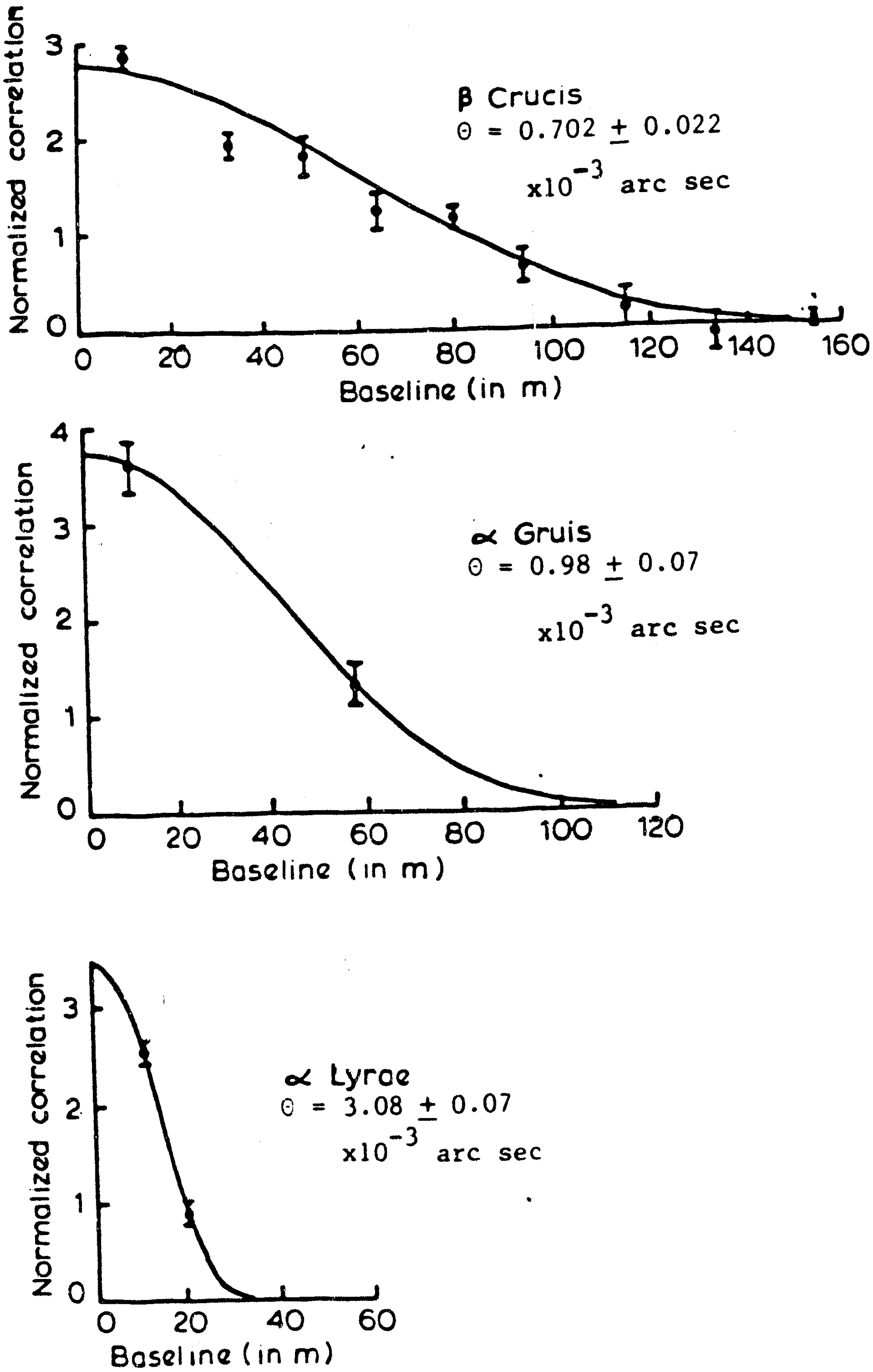
Figure 4



Correlation versus baseline for Sirius. The full line shows the theoretical variation of $\Gamma^2(d)$ the normalized correlation for an angular diameter of $6{\cdot}9 \times 10^{-3}$ seconds of arc. The points show the experimental results together with their probable errors. From Hanbury Brown and Twiss (1958 b).

Figure 5

Measurement at Jordell Bank.



Correlation versus baseline measured for three stars of different angular size. The full lines were fitted to the points as described in the text. From Hanbury Brown, Davis, Allen and Rome (1967).

Figure 6

1977 G. N. Fowler and R. M. Weiner

also A. Giovannini and G. Veneziano

λ is Chaos/Coherence Parameter

$\lambda = 1$ Chaotic Source

$\lambda = 0$ Pion Laser

1977 P. Grassberger

Effect of resonances.

Pion carried by "long lived" resonance. eg. ω^0

$$L = \beta\gamma c\tau$$

$$= \frac{\langle p \rangle}{M} c\tau \qquad \tau = \frac{\hbar}{\Gamma}$$

$$= \frac{\langle p \rangle}{M\Gamma} \hbar$$

$$= \frac{\langle p \rangle}{M\Gamma} \; 197 \text{ MeV fm}$$

Typical values

Res:	ρ	K^*	ω^0	η
L fm	2	4	20	400

Typical Radius observed : 0.7 fm

For Particles:

	D^0	D^+	B
$L \simeq c\tau$	10^{11} fm	3×10^{11} fm	3×10^{11} fm

Thus resonances, and certainly particles.
should reduce λ

1986 B. Andersson and W. Hofmann

also M. Bowler

Introduction into Lund model of 2 pion symmetrization.
Interchange on color string

1987 M. Suzuki $\pi\pi$ final state interaction are expected to reduce λ by 20%.

Conclusions on the Effect From e^+e^- Experiments

We have carried out four distinct experiments with e^+e^- interactions, in the Mark II detector. Juricic, et al.(14)

We can describe these 4 Data Sets, which differ in energy and production mechanisms as:

- SPEAR J/ψ – 3 Gluon annihilation, E = 3.1 GeV.
  Below charm threshold.
- SPEAR $q\bar{q}$ - Beginning of JET production, E = 4 - 6.5 GeV.
  Above charm production threshold.
- PEP $q\bar{q}$ - 2 and 3 JET production, E = 29 GeV.
  Above charm and bottom production threshold.
- PEP $\gamma\gamma$ – VDM and hard scattering, $<E> \simeq 5$ GeV.
  Mostly below charm threshold.

From these we observed the following:

- $r \simeq 0.7$ fm is nearly the same in all four cases.

From this we conclude that here r is a measure of the size of the **local region** rather than the **entire** source size.

- λ is nearly maximal ≈ 1 in the two cases below charm threshold.
  Thus resonance effects are not observed. Would increase λ by ~50% for the ρ, K^* ω^0, η etc. **if we correct for it**

- Also the final state interaction effect predicted by M. Suzuki is not observed.
  Would increase λ by ~20% **if corrected for.**
- The reduced value of λ ($\approx$ 0.6 - 0.5) observed for the SPEAR $q\bar{q}$ and PEP $q\bar{q}$ data sets can be explained by the onset of charm and charm + bottom, respectively.
- Thus there is apparently no room for the reduction of λ due to coherence effects.

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