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Evidence for planar events in e^+e^- annihilation at high energies

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Background

At this time (1979) the existence of quarks was largely accepted with evidence from:

- Deep inelastic scattering
- Measurement of cross-section of $e^+e^- \rightarrow$ hadrons
- Charmonium spectroscopy
- Jets in e^+e^- collisions

However only circumstantial evidence existed for gluons and a field theory description of strong interactions.

Search for an effect directly attributable to gluons…

- J. Ellis, M.K. Gaillard, G.G. Ross, Nucl. Phys. B 111, 253 (1976):

“Motivated by the approximate validity of the naive parton model and by asymptotic freedom, we suggest that hard gluon bremsstrahlung may be the dominant source of hadrons with large momenta transverse to the main jet axis. This process should give rise to three-jet final states”.

Abstract

Study of $e^+e^- \rightarrow$ hadrons at $\sqrt{s}$ = 13 - 31.6 GeV

Using TASSO detector at PETRA (e^+e^- collider at DESY, ran 1978 - 1986).

Results:

- p_T of jets increases strongly with $\sqrt{s}$
- Broadening of the jets is not uniform in azimuthal angle around the jet axis
- Planar events are observed with small p_T out of the plane.

Here p_T is momentum transverse to the jet axis, not the beam axis!

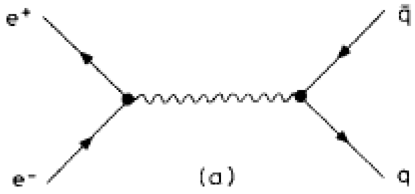
Conclusions:

- 3 basic particles in the final state
- Not consistent with $e^+e^- \rightarrow qq \rightarrow 2$ jets
- Consistent with $e^+e^- \rightarrow qqg \rightarrow 3$ jets

Introduction

Hadron production in e^+e^- annihilations conjectured to proceed by quark pair production followed by fragmentation.

- Produces 2 collinear jets
- Supported by data from SPEAR and DORIS (e^+e^- colliders with $\sqrt{s}$ ~ 3 GeV).



This study looks for deviations from this picture as expected from field theory (e.g. QCD).

Some deviation already observed in deep inelastic scattering and Y(1S) decays.

TASSO

“Large conventional solenoid filled with tracking chambers and time-of-flight counters. Particles are identified in two large hadron arms made of segmented Cerenkov counters with aerogel and two threshold gas counters in each segment, time-of-flight counters and range telescopes covering roughly 2 S.I. The finely segmented (towers) liquid argon counters are nearly complete and the last counters will be installed towards the end of the year. Muons are identified in 70% of 4π.”

Event selection

Track based analysis.

Trigger on track multiplicity.

Require a primary vertex in the “interaction volume” and some Σp thresholds.

- To reject beam gas events

“Further cuts on the event topology essentially eliminated $\gamma\gamma$ and $\tau\tau$ events.”

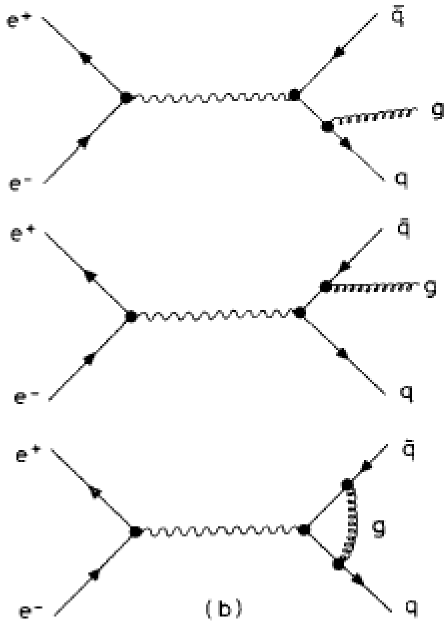
Some track quality criteria.

Photon conversion and Dalitz decay rejection.

Effects of cuts checked with MC; no bias.

Some phenomenology

In field theories of the strong interaction, field quanta are radiated and then hadronize:



3 experimental signatures:

(1) Broadening of the p_T distribution of the final state hadrons with increasing energy.

(2) Planar final states (momentum conservation).

(3) 3-jet events

(1) p_T distributions

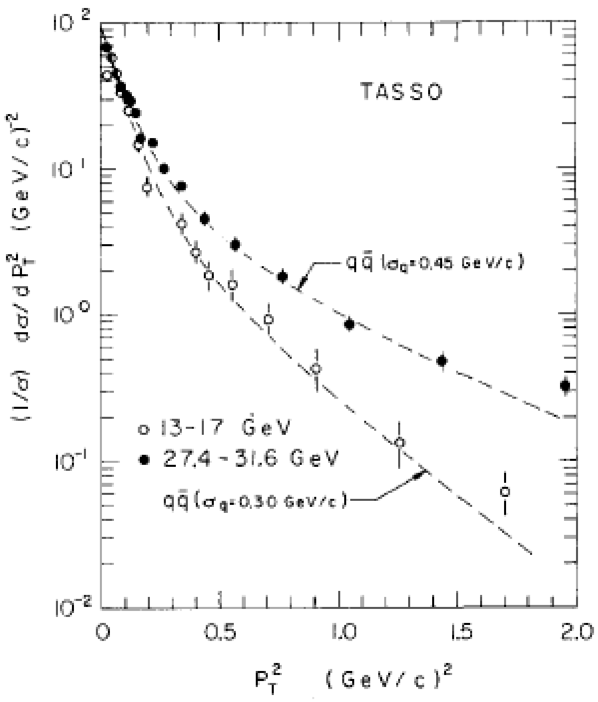
Look at low and high energy data separately.

Define a jet axis:

- Sphericity axis: minimises Σp_T
- Thrust axis: maximises $\Sigma p_{||}$
- No significant dependence on choice here, also checked with MC.

Plot normalised p_T distribution wrt sphericity axis:

- $d\sigma/dp_T^2$ doesn't drop as fast with increasing p_T for high energy data.
- Data are fitted using a qq fragmentation model (including c and b quarks).
- To fit the high energy data, the parameter determining the width of the p_T distribution must be increased.



Contradiction of $e^+e^- \rightarrow qq$ picture in which p_T distribution of final state hadrons is energy independent.

Agrees with field theory $e^+e^- \rightarrow qqg$

This effect could also be due to production of a new quark flavour: No other evidence for this.

(1) p_T distributions

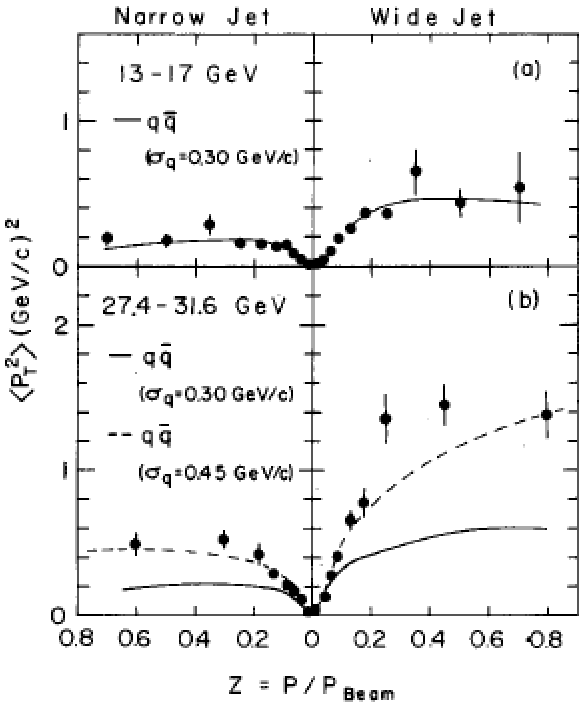
Split the event into two halves by a plane perpendicular to the jet axis (one jet in each half).

p_T of the wide jet increases more rapidly with energy than the p_T of the narrow jet.

- Consistent with emission of only one hard gluon (dominant in QCD).

Again, the p_T width parameter has to be increased to fit the high energy data.

Further support for $e^+e^- \rightarrow qqg$



(2) Event shape

So far evidence for gluon production is model dependent.

Now look at event shapes:

- $e^+e^- \rightarrow q\bar{q}$: Final state hadrons distributed with uniform azimuth around the quark/jet axis (not planar)
- $e^+e^- \rightarrow q\bar{q}g$: Planar configuration of hadrons; large p_T in the event plane, small p_T normal to the plane.

A significant excess of planar events would imply a 3rd particle in the final state in a model independent way.

Define a tensor from the hadron momenta

$$M_{\alpha\beta} = \sum_{j=1}^{N} p_{j\alpha} p_{j\beta} \qquad (\alpha, \beta = x, y, z),$$

where the sum is over all hadrons, and let $\mathbf{n}_1$, $\mathbf{n}_2$, $\mathbf{n}_3$ be the unit eigenvectors associated with the smallest, intermediate and largest eigenvalues respectively.

- $\mathbf{n}_3$ is the jet axis
- $\mathbf{n}_2$-$\mathbf{n}_3$ plane is the event plane
- $\mathbf{n}_1$ is normal to the event plane

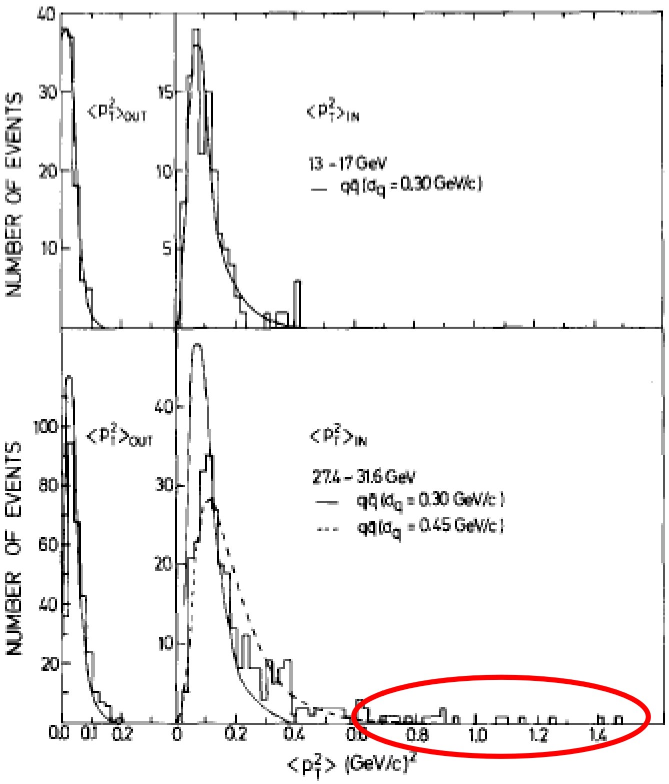
(2) Event shape

From $M_{\alpha\beta}$, the average p_T in and normal to the event plane can be defined:

$$\langle p_T^2 \rangle_{in} = \frac{1}{N} \sum_{j=1}^{N} (p_j \cdot \hat{n}_2)^2 \qquad \langle p_T^2 \rangle_{out} = \frac{1}{N} \sum_{j=1}^{N} (p_j \cdot \hat{n}_1)^2$$

Plot these variables for low and high energy data separately:

- Little difference in $\langle p_T^2 \rangle_{out}$ between low and high energy, agrees with qq fragmentation model.
- Significant difference in $\langle p_T^2 \rangle_{in}$ distribution between low and high energy, with large tail at high energy.
- The tail is not reproducible by the qq model.



Data contains an excess of planar events not described by the qq model, independent of the average p_T of that model.

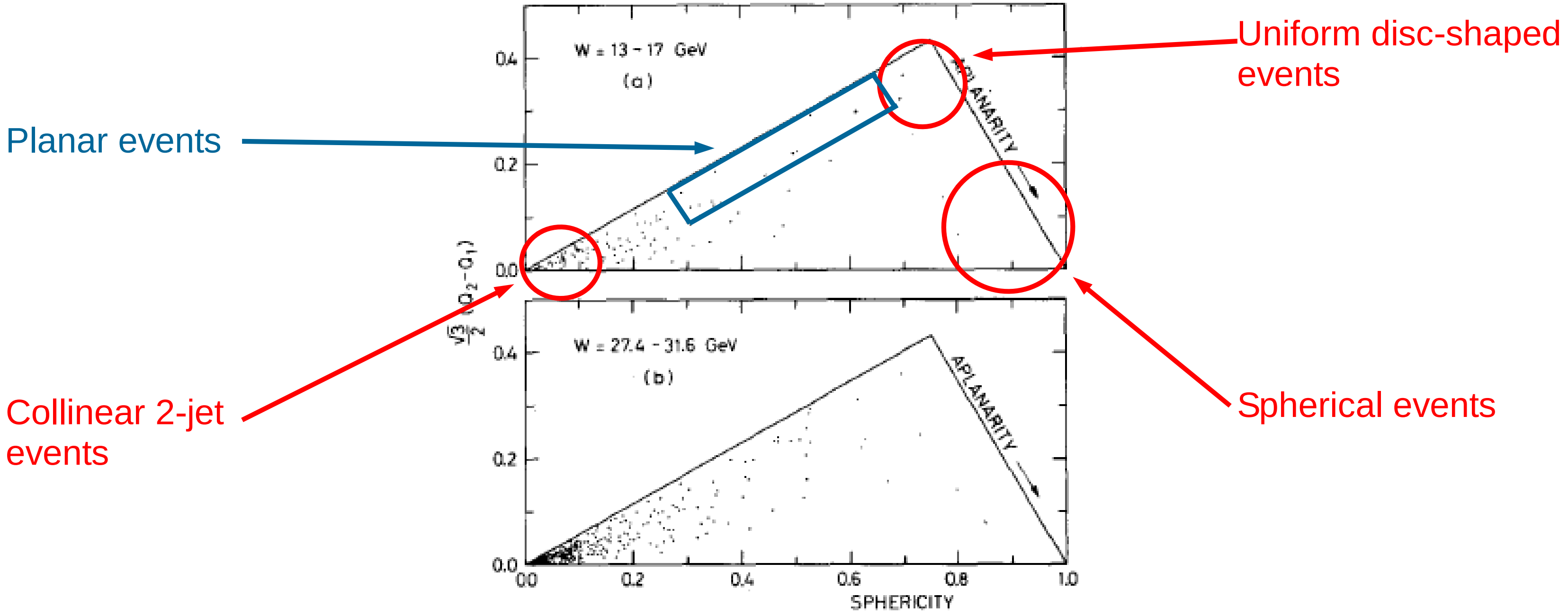
(2) Event shape: Aplanarity & Sphericity

Now normalise the eigenvalues of $M_{\alpha\beta}$ to the total momentum and define aplanarity and sphericity:

$$A = \tfrac{3}{2}\,Q_1 = \tfrac{3}{2}\,\langle p_T^2\rangle_{out}/\langle p^2\rangle\,,$$

$$S = \tfrac{3}{2}\,(Q_1 + Q_2) = \tfrac{3}{2}\,\langle p_T^2\rangle/\langle p^2\rangle\,.$$

such that *A* is large in events with a large fraction of momentum normal to the event plane, and *S* is large in events with a large fraction of momentum in the $\mathbf{n}_1$-$\mathbf{n}_2$ plane.



(2) Event shape: Aplanarity & Sphericity

Collinear events dominate, more so at high energies.

- Reject these and select planar events: A < 0.04, S > 0.25
- At low energy: 6 planar events; 3.5 expected from qq
- At high energy: 18 planar events; 4.5 expected from qq

Randomise the data to destroy any natural correlations:

- Rotate all tracks by a random angle around the sphericity axis (preserving p_T and $p_{||}$ of the tracks)
- Invert the sign of $p_{||}$ of random tracks
- Gives 6 (4) “accidentally planar events” at low (high) energy

I think this means the background at high energy is taken to be 4.5 ± 4 (?):

- A ~3.5σ excess at high energy (?).

"Thus at the higher energies there is an excess of planar events well above the level predicted from statistical fluctuations of the qq jets".

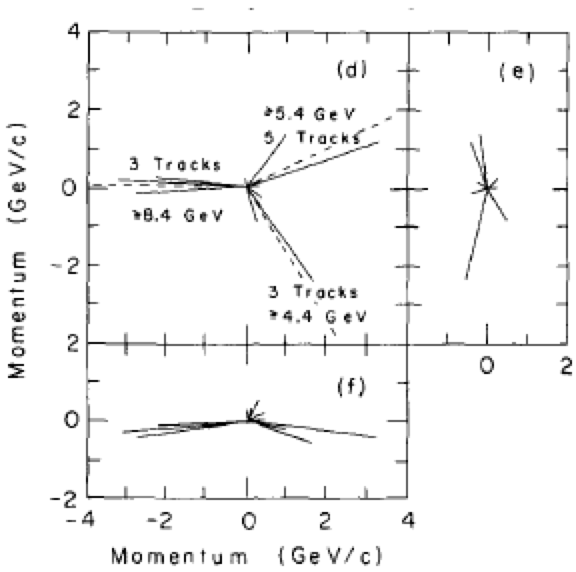
3 basic final state particles, each fragmenting to hadrons, consistent with $e^+e^- \rightarrow qqg$

(3) 3-jet events

Check: if planar events are due to $e^+e^- \rightarrow qqg$, some fraction of the events should display a 3-jet structure.

"All the coplanar events gave a good fit to the three-jet hypothesis."

The average p_T of the hadrons wrt to the jet axis to which they are assigned is ~0.3 GeV/c, as observed in 2-jet events.



Summary

Three experimental signatures of hard gluon radiation were identified and observed:

- Broadening of jets with rising energy, occuring predominantly in one of the jets and in the event plane.
- Significant excess of planar events at high energies with respect to expection from qq → hadrons.
- The planar events are consistent with a 3-jet topology.

"The data are most naturally explained by hard noncollinear bremsstrahlung $e^+e^- \rightarrow qqg$"

The first direct evidence for the existence of gluons.