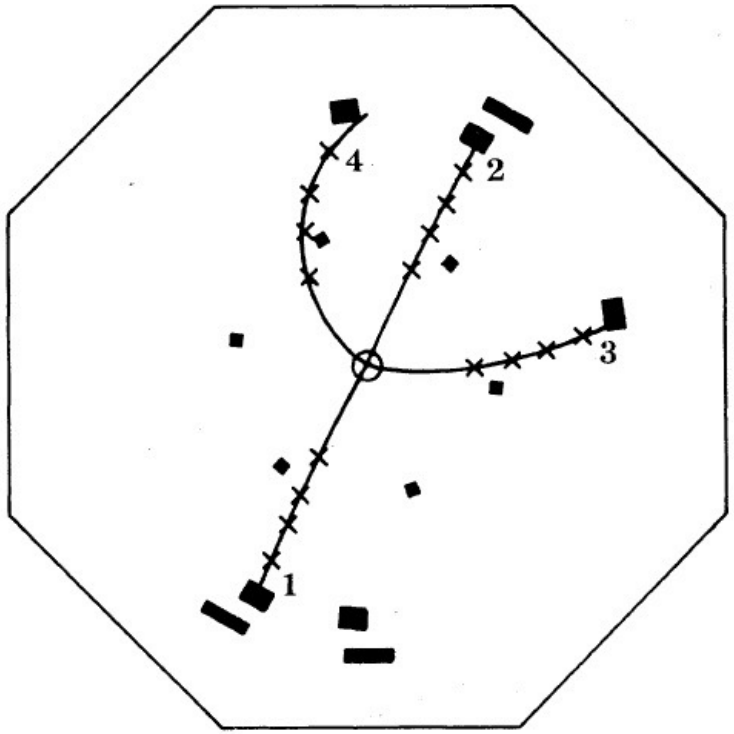
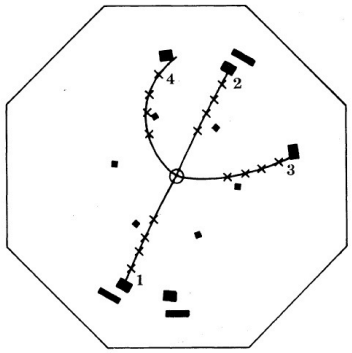
After the ψ



Symposium on the 50th Anniversary of the J/ψ

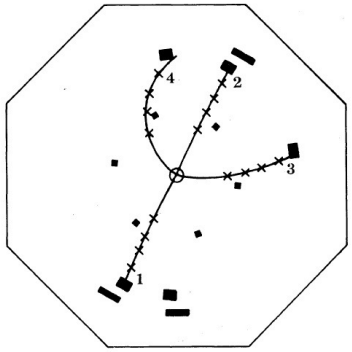
SLAC November 8, 2024

Gary Feldman



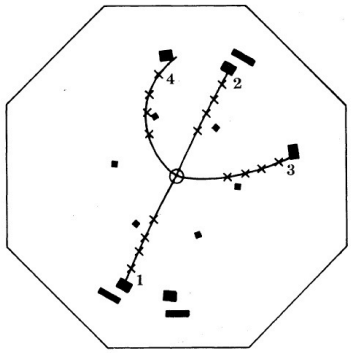
Overview

- For the most part, this talk is limited to the 38 papers that the SLAC-LBL group wrote in the three-year period November 1974 through October 1977.
- These 38 papers consisted of
  - 24 Physical Review Letters
  - 6 Physics Letters
  - 2 Physical Review D
- This was slightly more than 1 publication a month from a collaboration of (on average) 35 people.
- Less than half of these papers is covered in this talk.

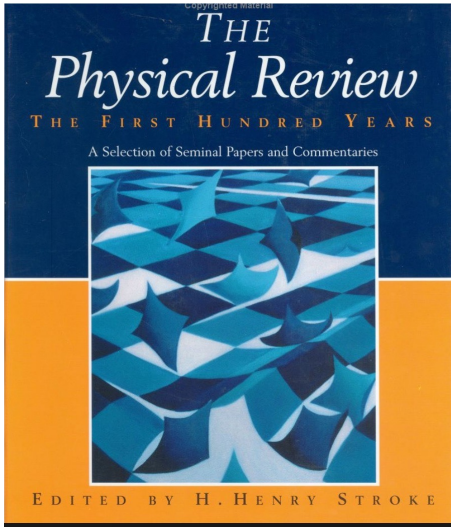


Lead Authors

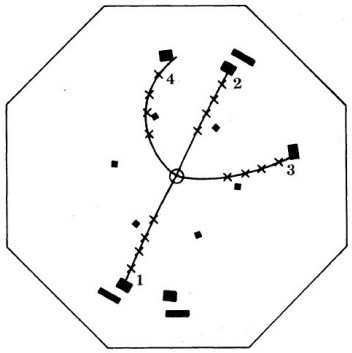
- For the first 8 papers, all of the names were in alphabetical order.
- But for the remaining 30 papers, the lead authors were listed first.
- This has not been done by other collaborations for good reasons.
- 33 different collaborators have been lead authors for a least one paper.
- More on this at the end of the talk.



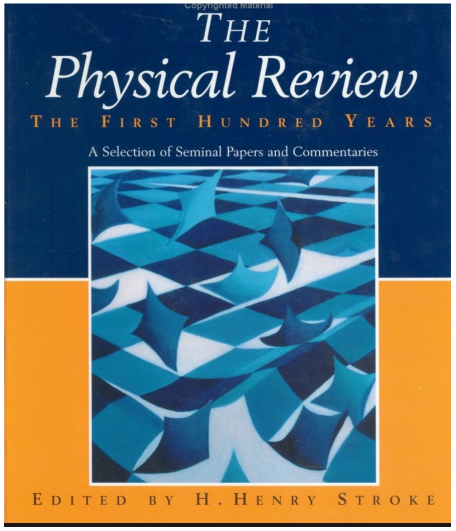
Topics



- In 1994 the American Physical Society published a collection of the most significant papers in the past 100 years.

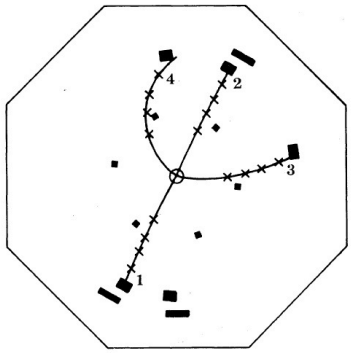


Topics

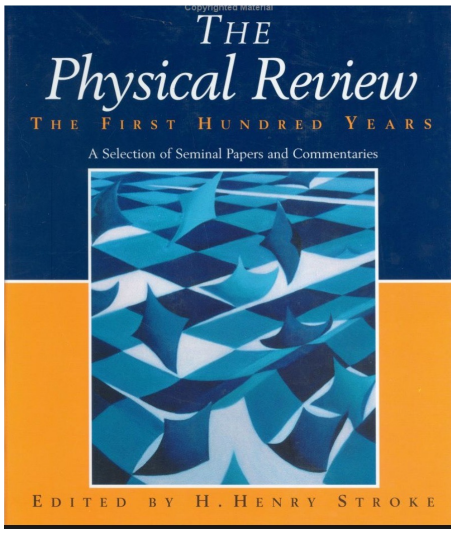


- In 1994 the American Physical Society published a collection of the most significant papers in the past 100 years.

- 4 SLAC-LBL papers were included:
  - The discovery of the ψ
  - The discovery of the D^0
  - The discovery of jets in e^+e^- annihilation
  - The discovery of the τ

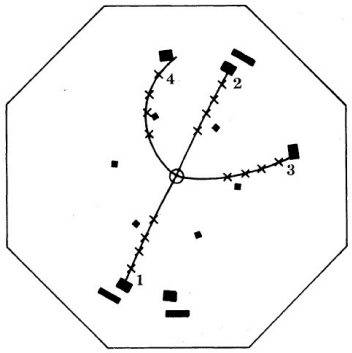


Topics



- In 1994 the American Physical Society published a collection of the most significant papers in the past 100 years.

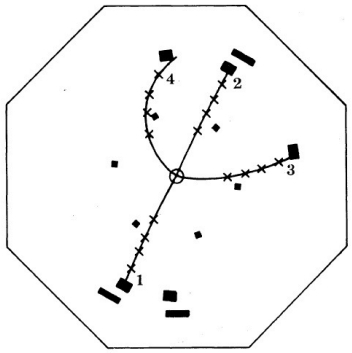
- 4 SLAC-LBL papers were included:
  - The discovery of the ψ — Charmonium
  - The discovery of the D^0 — Charm
  - The discovery of jets in e^+e^- annihilation — QCD
  - The discovery of the τ — τ Lepton



Charmonium

6. Decay of $\psi(3684)$ into $\psi(3095)$

- The purpose of this paper was to measure the branching ratios of $\psi' \to \psi$ decays.



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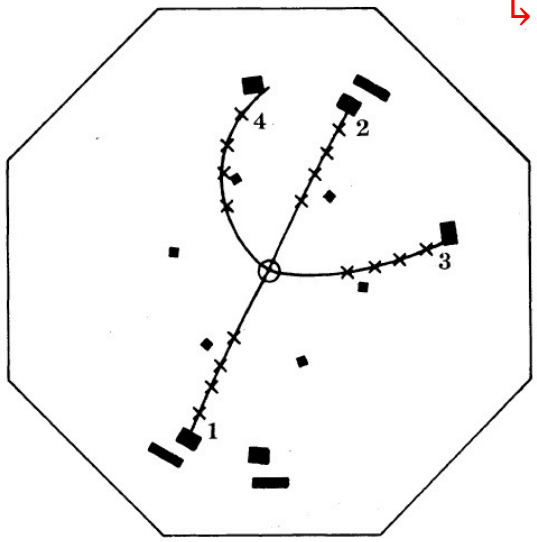
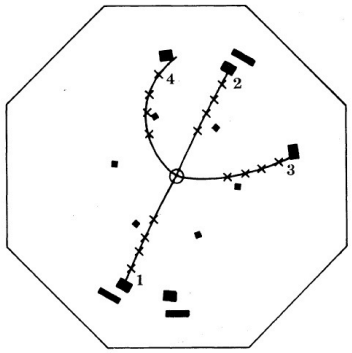
$\psi' \to \pi^+\pi^- \psi$

$\hookrightarrow e^+e^-$





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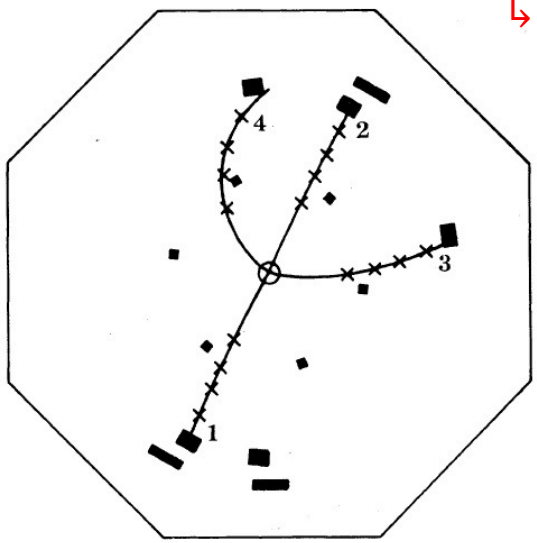
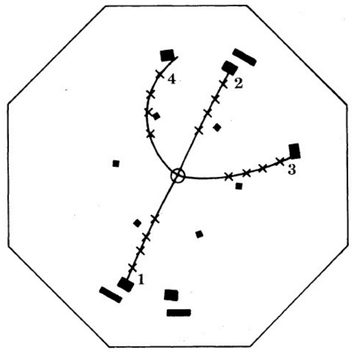


The referee for this paper said that this figure was unnecessary.



Charmonium
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$$\psi' \to \pi^+\pi^-\psi$$
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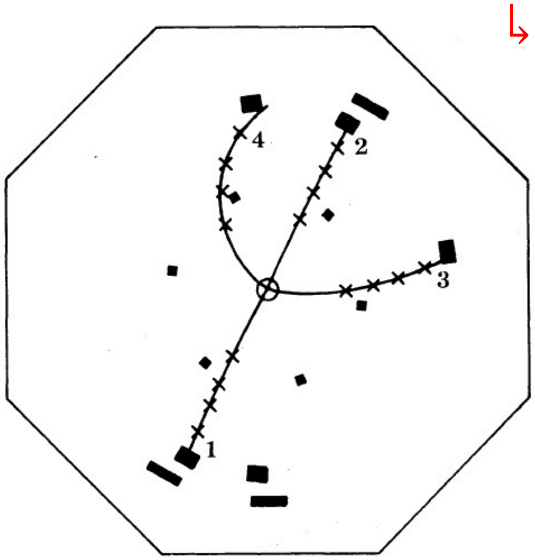
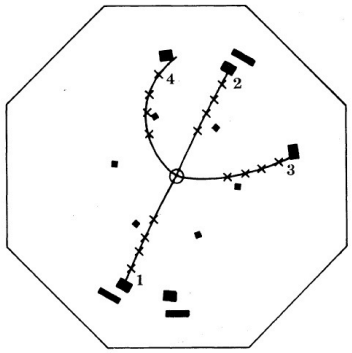


The referee for this paper said that this figure was unnecessary.

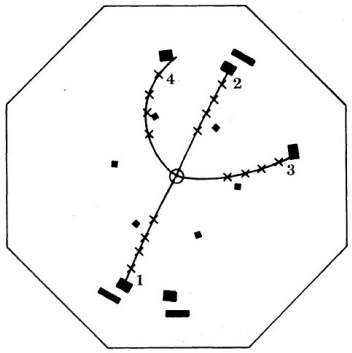
But the collaboration was convinced that the particle itself was telling us that we had selected the right name.

So, we published it and put it on T-shirts for wearing at the summer conferences.



Charmonium
24. Mesonic Decays of the $\psi(3095)$
Francois Vannucci

- Five more papers measuring branching ratios and determining quantum numbers of the ψ and ψ' followed.
- They culminated in a Physical Review D paper in 1977 that discussed 15 mesonic decays of the ψ and included an extended discussion of the evidence that the ψ was an SU(3) singlet and of the effects of the QZI rule.
- Fred Gilman was one of the authors of this paper.



Charmonium
Spectroscopic Notation

- For clarity, I am going to use spectroscopic notation:

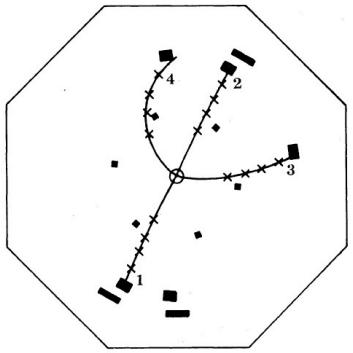
Number of radial nodes + 1

Spin multiplicity
1 or 3 for mesons

Orbital angular momentum
S, P, D …

$$\psi = 1^3S_1$$

Total angular momentum

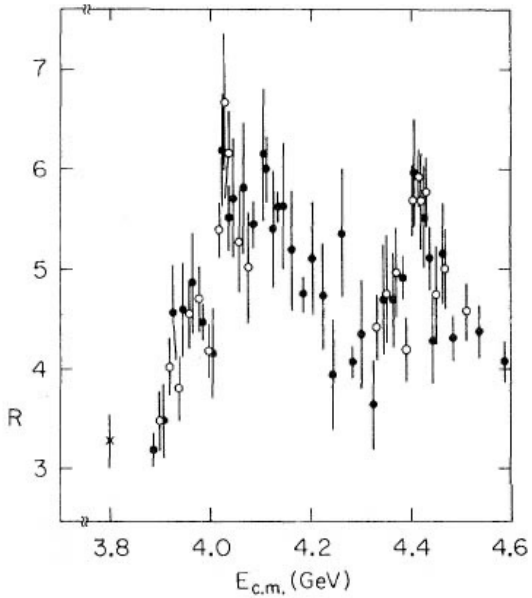


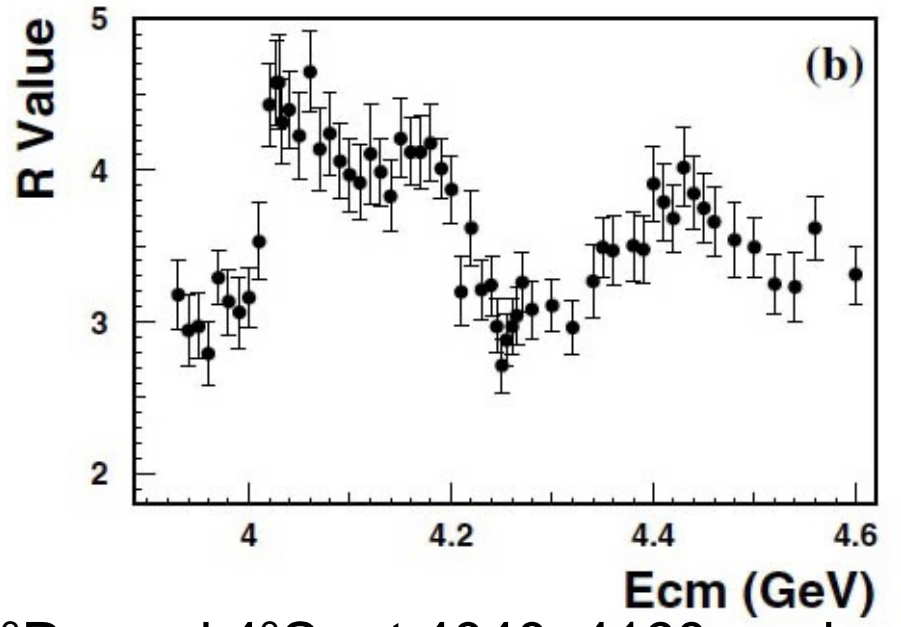
Charmonium

17. Observation of a Resonance at 4.4 GeV and Additional Structure near 4.1 GeV in e^+e^- Annihilation

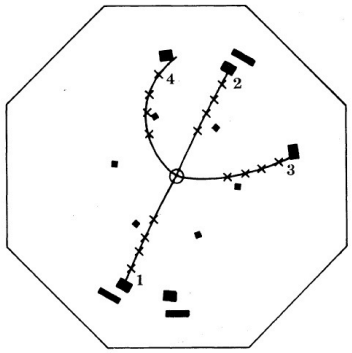
Jim Siegrist

- Below are plots from this paper (left) and from the Beijing Electron-Positron Collider 25 years later (right).





There are three states here: 3^3S_1, 2^3D_1, and 4^3S_1 at 4040, 4160, and 4415 GeV, with interference between the first two filling the gap between them.



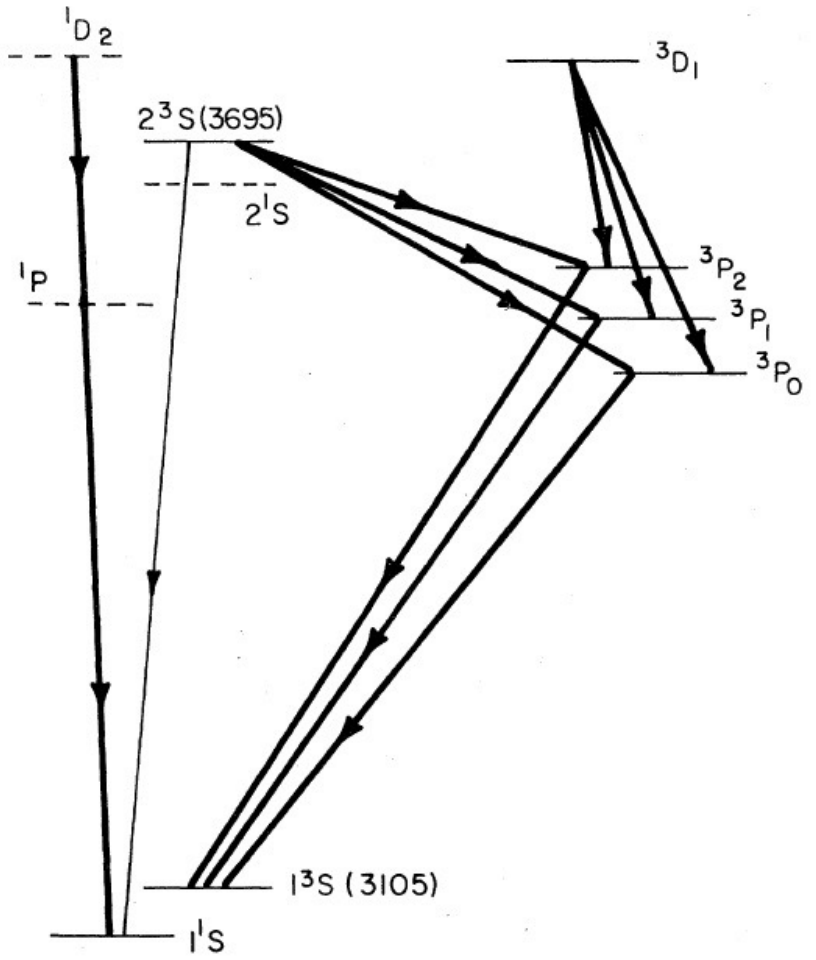
Charmonium

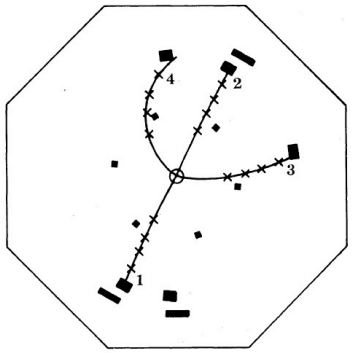
Theoretical Predictions in Less than a Month After the ψ' Discovery

E. Eichten et al., PRL 34, 369

Also

T. Appelquist et al., PRL 34, 369



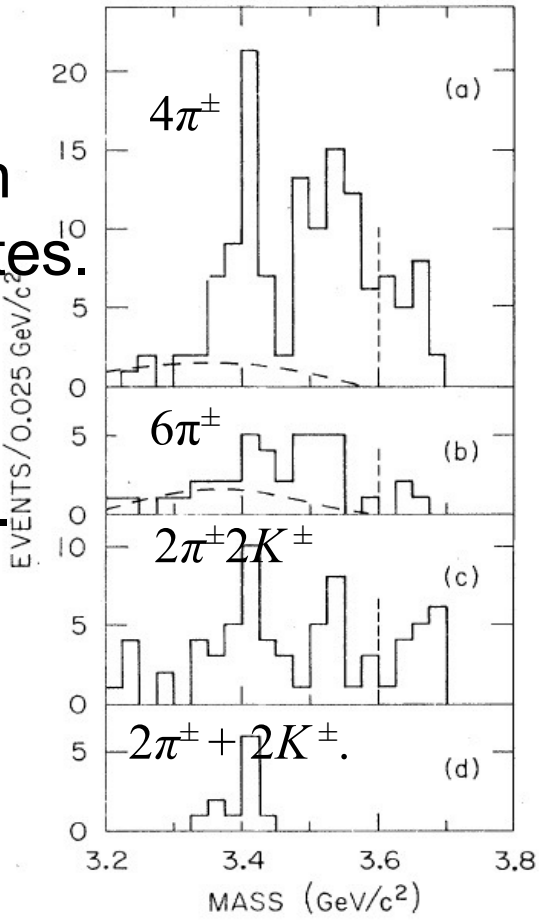


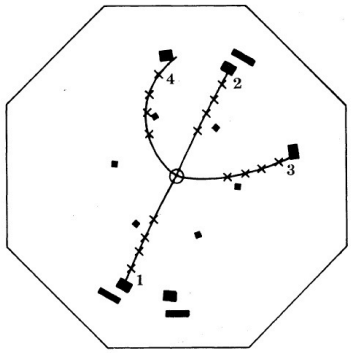
Charmonium

10. $\psi(3684)$ Radiative Decays to High-Mass States

Gary Feldman, Bernard Jean-Marie,
Bernard Sadoulet, and Francois Vannucci

- $\psi' \to \gamma(^3P_x) \to (2\pi^{\pm}, 4\pi^{\pm}, 6\pi^{\pm}, 2\pi^{\pm}2K^{\pm}, \text{and } 2K^{\pm})$
- At least two states at 3.41 and 3.53 GeV, with the possibility that 3.53 structure was two states.
- Competition from DESY: $\psi' \to \gamma(3Px) \to \gamma\psi$ at 3.26 or 3.52 Gev. W. Braunschweig et al., PL 57B, 407. Submitted 11 days before ours.
- Another naming kerfuffle: The DESY group suggested P_c. We suggested χ (chi). The PDG went with χ.



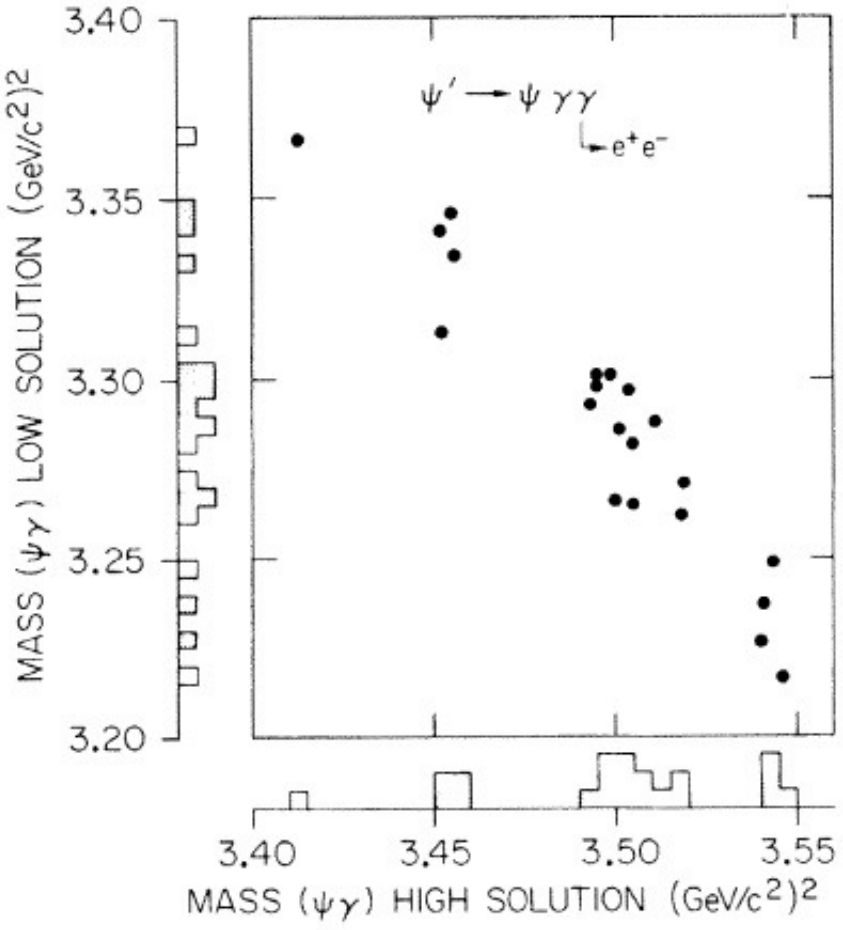


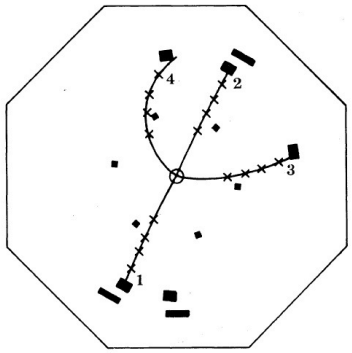
Charmonium

21. Radiative Decays of ψ(3095) and (3684)

Scott Whitaker and Bill Tanenbaum

- About a year later, there was enough data to see the full radiative decays: $\psi' \to \gamma(^3P_x) \to \gamma\psi$.
- Three clusters are clearly visible.
- The data in the vertical direction are broader due to Doppler broadening.



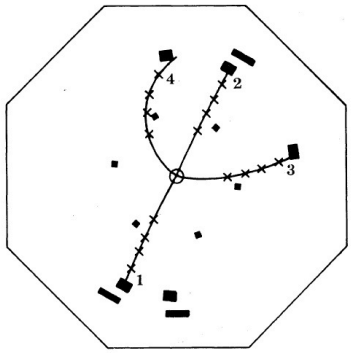


Charmonium

31. Radiative Decays of the $\psi(3684)$ into High-Mass States

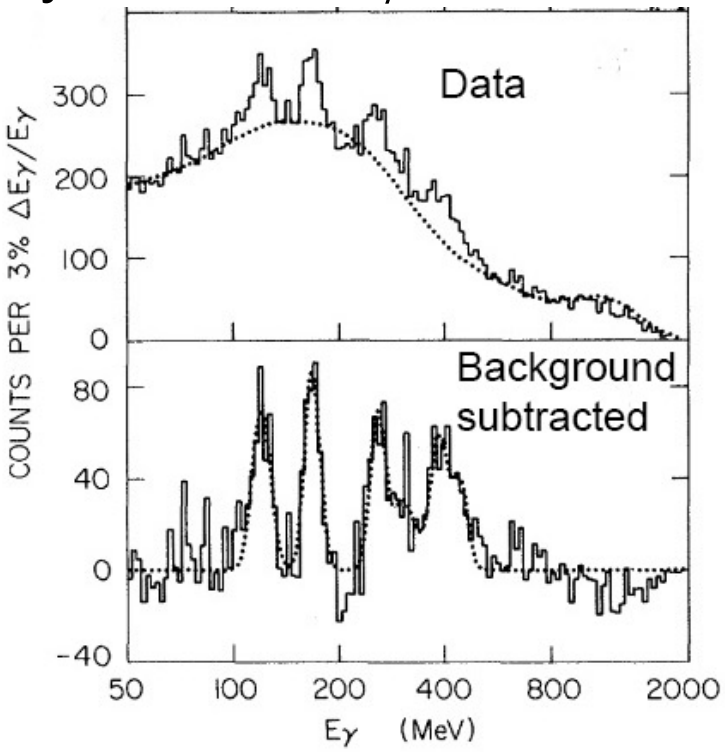
Bill Tanenbaum, George Trilling, and Scott Whitaker

- This was a beautifully written Physical Review D paper putting all of the χ state data and analysis together.
- The final masses differ from the present PDG values only by 2, 6, and 3 MeV, respectively.

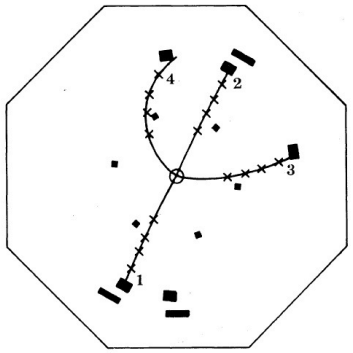


Charmonium
Other SPEAR Interaction Region

- In 1977, a San Diego, Maryland, Pavia, Princeton, SLAC, and Stanford collaboration combined sodium iodide crystals from two experiments to measure the γ rays from the ψ'.



C. J. Biddick et al., PRL 38, 1324



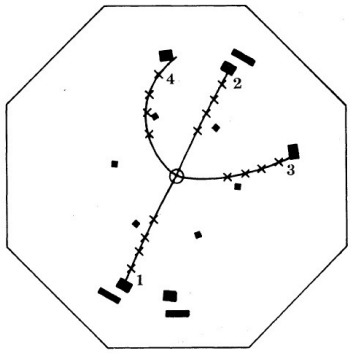
Charmonium

Other States Below the ψ'

- 1^1S_0: Simultaneously, at the Mark II and the Crystal Ball from radiative decay from the ψ'
  - T. M. Himel et al., PRL 45, 1146 (1978)
  - R. Partridge et al., PRL 45, 1150 (1978)

- 2^1S_0: The Crystal Ball from radiative decay from the ψ'
  - C. Edwards et al., PRL 48, 70 (1982

- 1^1P_1: At CERN from $\bar{p}p \rightarrow \psi + 1^1P_1$
  - C. Baglin et al., PL 171B, 135 (1986)

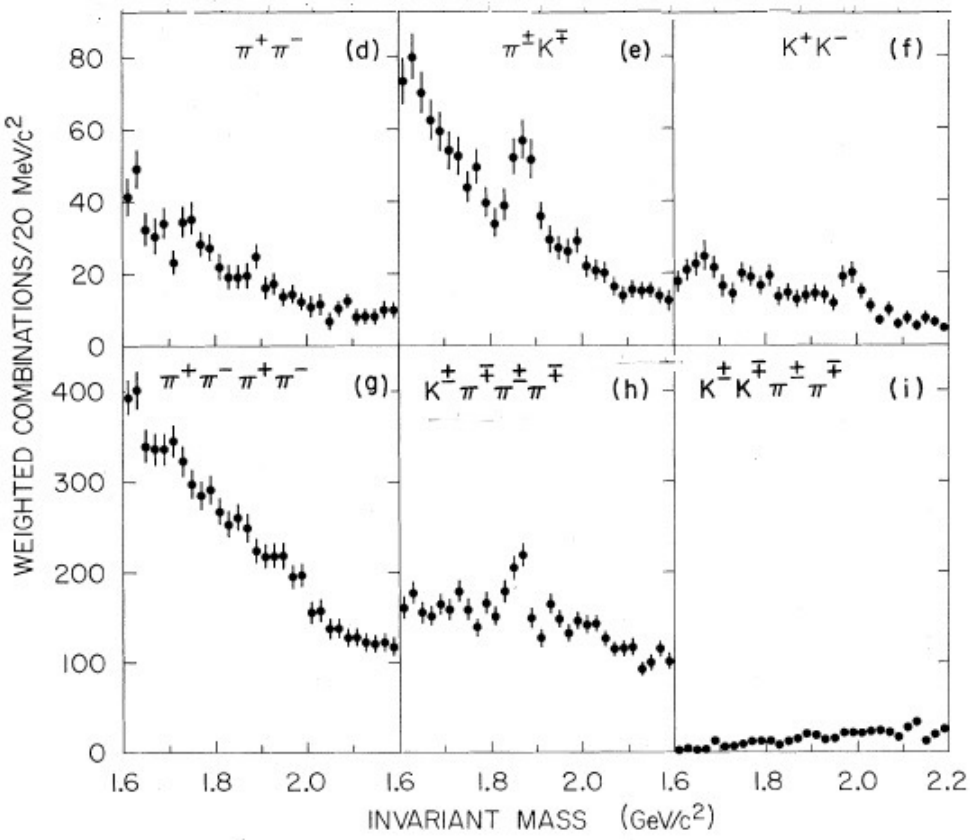


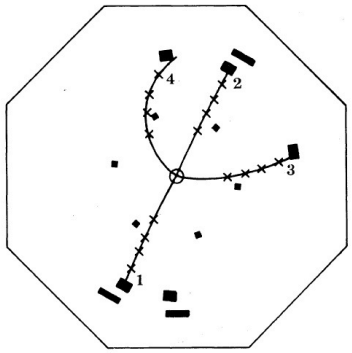
Charm

18. Observation in e^+e^- Annihilation of a Narrow State at 1865 MeV/c^2 Decaying into $K\pi$ and $K\pi\pi\pi$

Gerson Goldhaber and Francois Pierre

- This is the discovery of the D^0.
- Why did it take until 1976?
- A better time-of-flight system was needed to help with K-π separation.



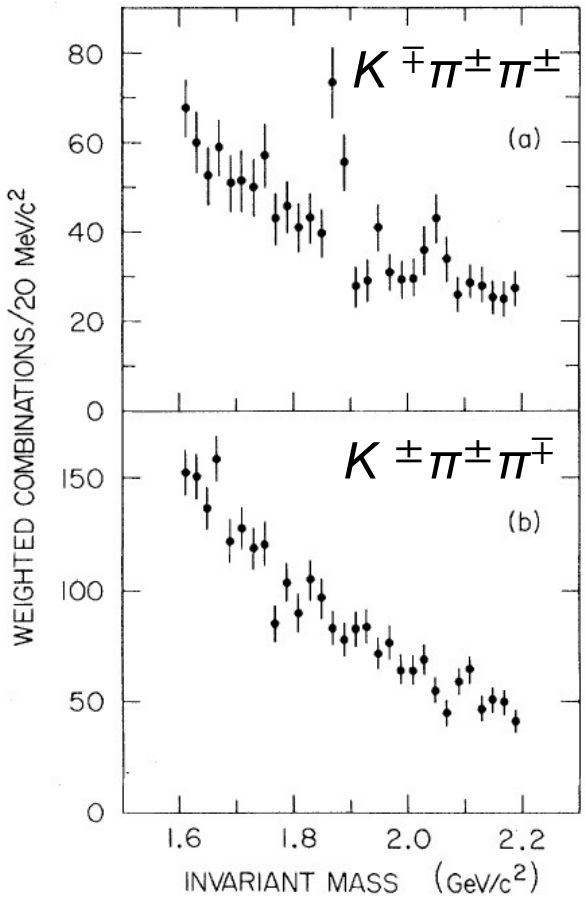


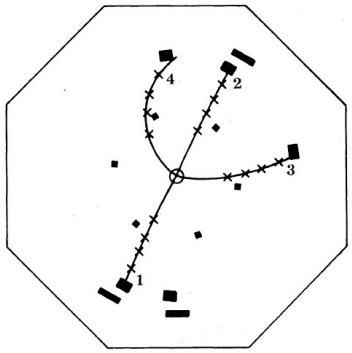
Charm

20. Observation of a Narrow Charged State at 1876 MeV/c^2 Decaying to an Exotic Combination of $K\pi\pi$

Ida Peruzzi, Marcello Piccolo, Gary Feldman,
H. K. Nguyen, and James Wiss

- This is the discovery of the D^+.





Charm

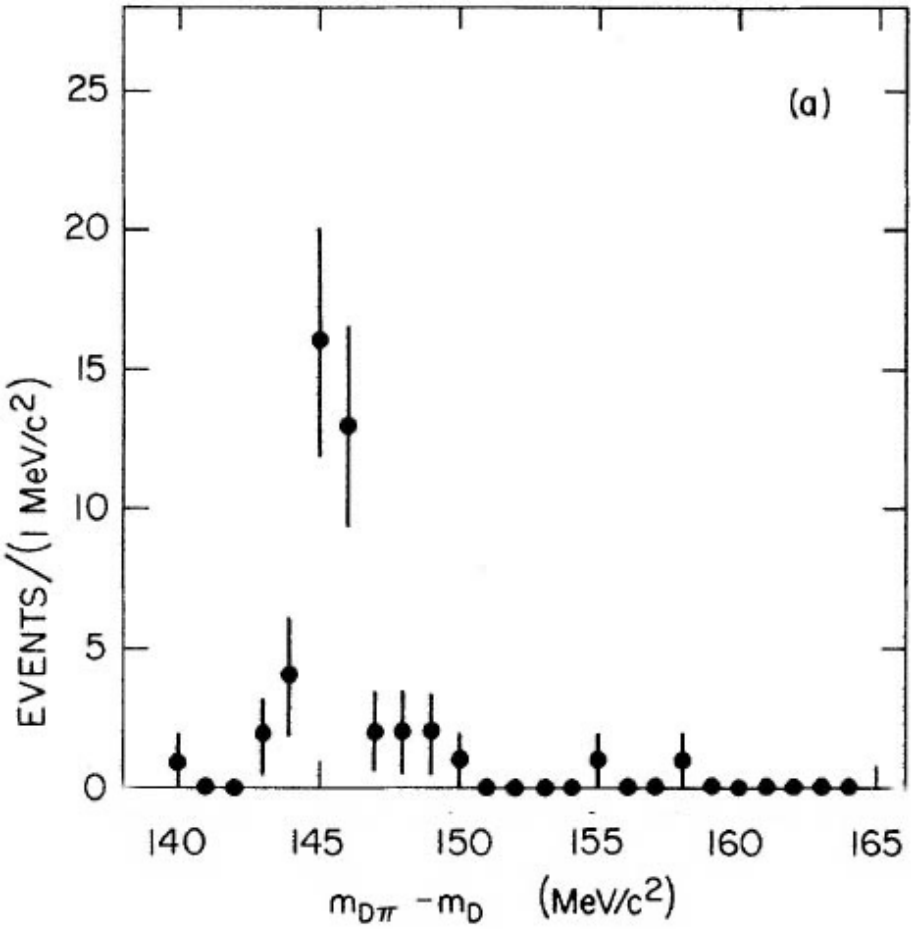
25. Observation of the Decay $D^{*+} \rightarrow D^0\pi^+$

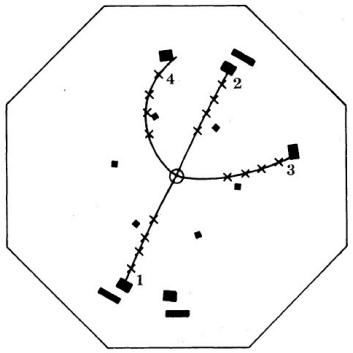
Gary Feldman, Ida Peruzzi, and Marcello Piccolo

- And this is the discovery of the D*+.

$$D^{*+} \rightarrow D^0\,\pi^+$$
$$\hookrightarrow K^+\,\pi^-$$

- Only a Q value of 5 MeV





Charm

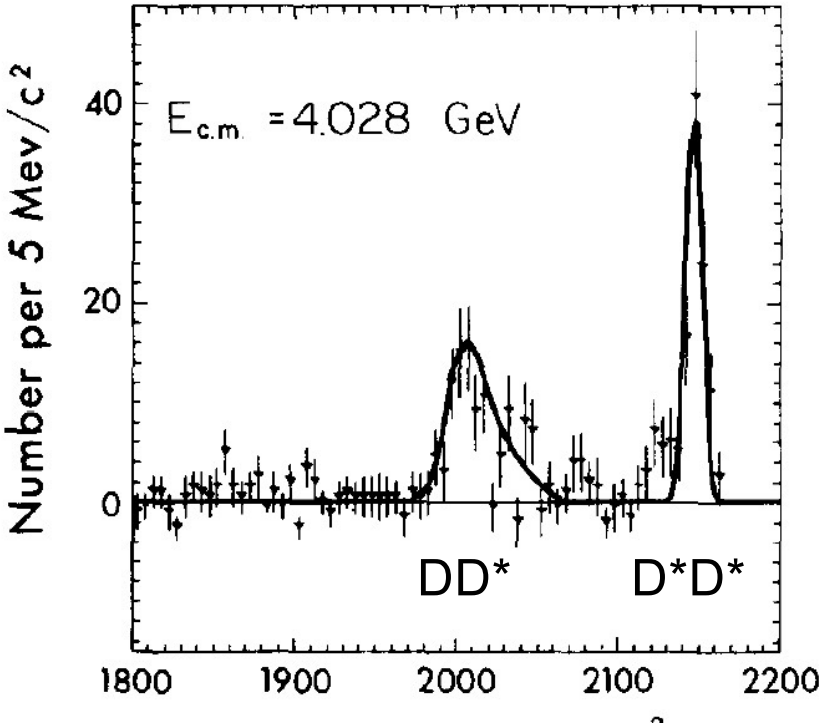
26. Spin Analysis of Charmed Mesons Produced in e^+e^- Annihilation

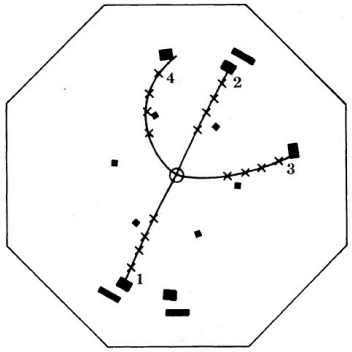
H. K. Nguyen and James Wiss

30. D and D^* Meson Production near 4 GeV in e^+e^- Annihilation

Gerson Goldhaber and James Wiss

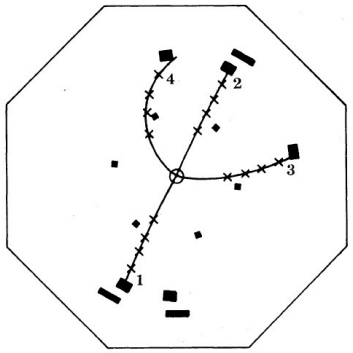
- The D^{*0} was first detected in the mass recoiling against D^0 mesons.





Richter Group Leaves the SLAC-LBL Collaboration

- Sometime around the first part of 1977, Burt Richter pulled his group off the SLAC-LBL collaboration to concentrate work on building the Mark II detector.
  - The Mark II would be a much superior detector.
  - There was probably nothing significant left to be discovered.
- He was wrong on the latter, and later he privately told me that he had make a mistake in withdrawing his group.

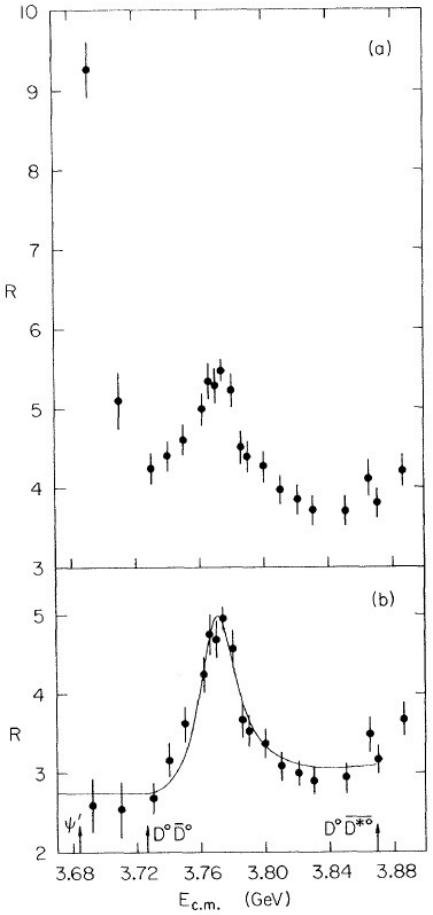


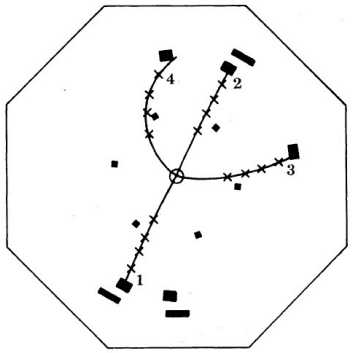
Back to Charmonium

28. Observation of a Resonance in e^+e^- Annihilation Just Above Charm Threshold

Petros Rapidis, Bruno Gobbi, and Dieter Lüke

- Ken Lane urged us to search for the 1^3D_1 state.
  - It was supposed to mix with the tail of the ψ' and be just over the charm pair threshold.
- We found it at 3772 MeV, just 20 MeV above the $D\bar{D}$ threshold.
- It decays to $D\bar{D}$ 93% of the time.
- Three additional papers in this time period used this state to study D decays.



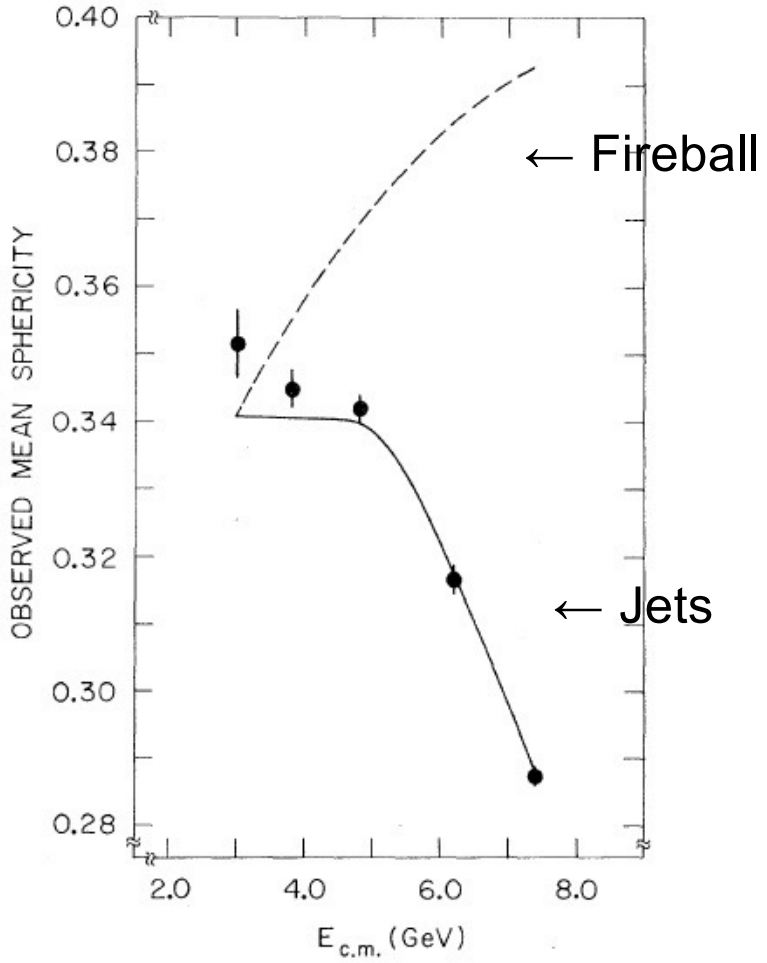


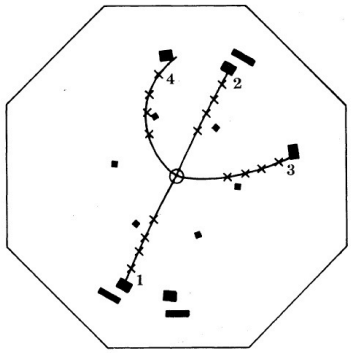
QCD

14. Evidence for Jet Structure in Hadron Production by e^+e^- Annihilation

Gail Hanson

- In 1970, Bj Bjorken and Stan Brodsky (PRD 1, 1416 (1970) wrote a paper saying that we do not know whether $e^+e^- \rightarrow$ hadrons will be jet-like or fireball-like and suggested a test parameter that we named sphericity.
- Gail Hanson followed this proscription to get these data:



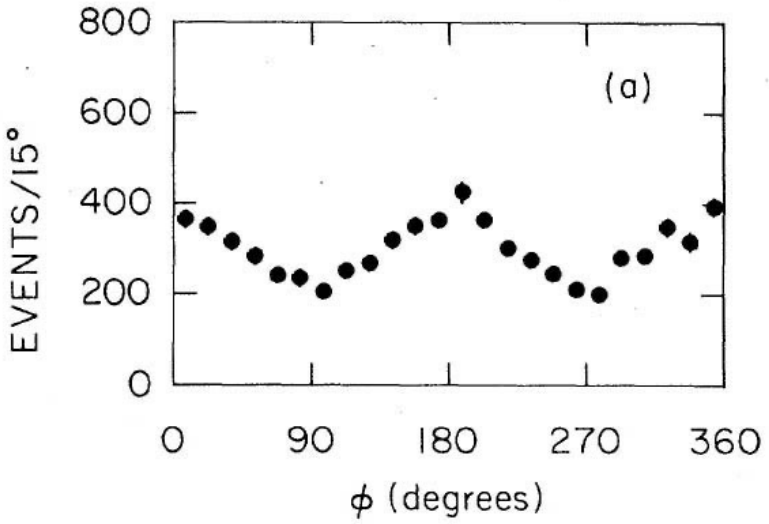


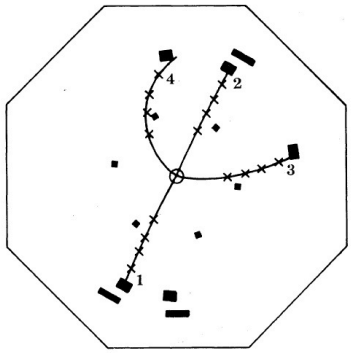
QCD

11. Azimuthal Asymmetry in Inclusive Hadron Production by e^+e^- Annihilation

Roy Schwitters and Francois Pierre

- Gail Hansom was surprised that data at 7.6 GeV showed an azimuthal asymmetry.
- When Roy Schwitters saw these data, he knew immediately that the beam was becoming polarized.
- Although the hadrons being produced were mostly mesons, the polarization indicated the origin was a pair of spin 1/2 particles.



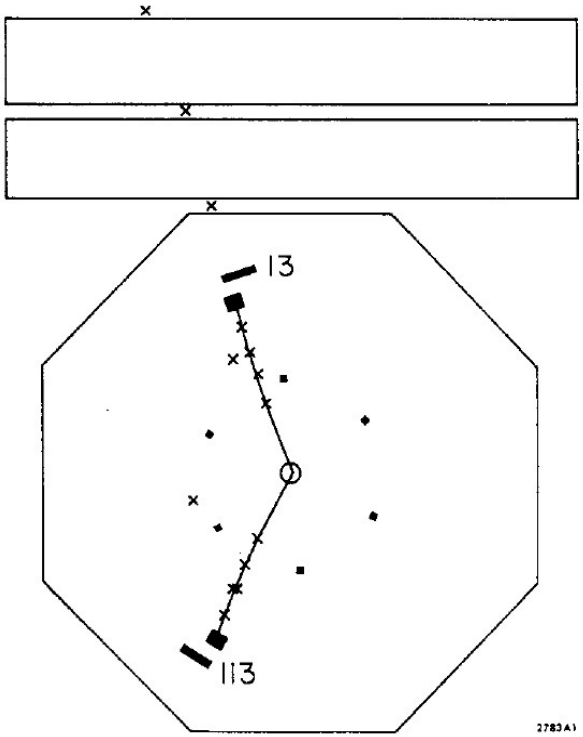


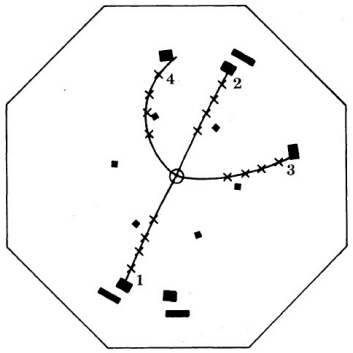
τ Lepton

12. Evidence for Anomalous Lepton Production in e^+e^- Annihilation

Martin Perl

- Martin Perl expressed interest in searching for a heavy lepton in the 1971 SLAC-LBL proposal.
- A heavy lepton should have sizable decays into $\tau \to e\nu\bar{\nu}$ *and* $\tau \to \mu\nu\bar{\nu}$. Thus, an event with one *e*, one *μ,* and missing energy would be unconventional.





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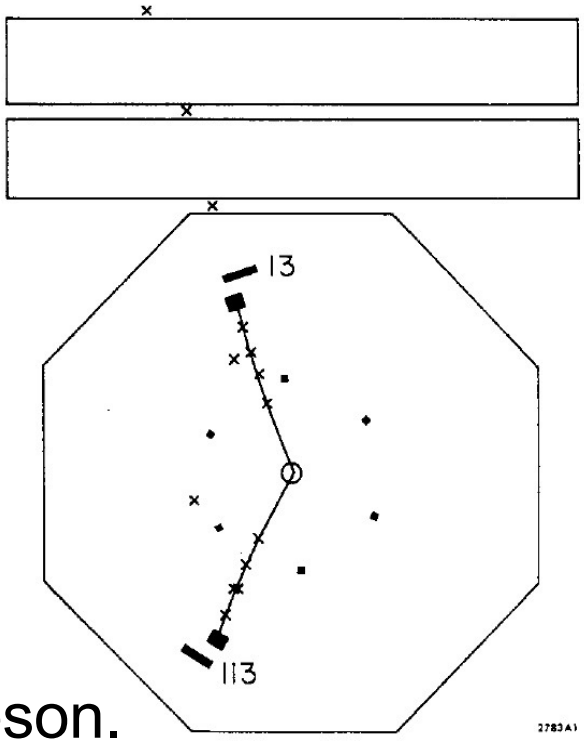
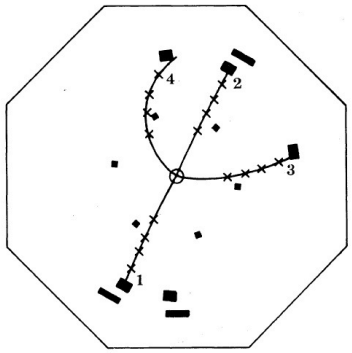
- There were 26 of these events with an estimated background of 4.7 events from misidentifications, an 8 σ effect.
- There was insufficient data to determine whether this was a new lepton or new meson.





τ Lepton

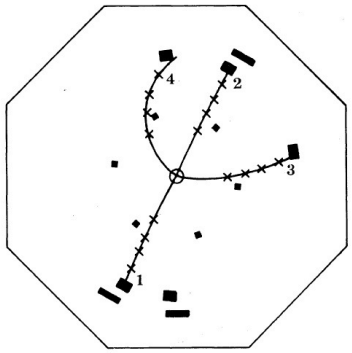
19. Properties of Anomalous $e\mu$ Events Produced in e^+e^- Annihilation

Martin Perl and Gary Feldman

34. Properties of the Proposed τ Lepton

Martin Perl and Gary Feldman

- A year later: Data favor a heavy lepton with a mass between 1.6 and 2.0 GeV.
- Another year later: All data favor a third sequential lepton:
  - Rate of production
  - Branching ratios
  - V – A coupling
- Named τ from the Greek word τριτον, meaning "third in a sequence."



Lead Authors Redux

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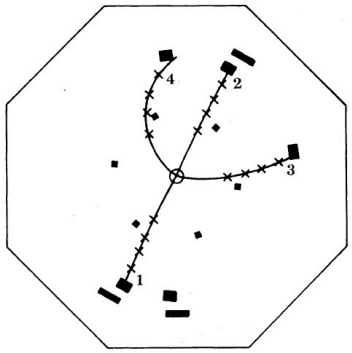

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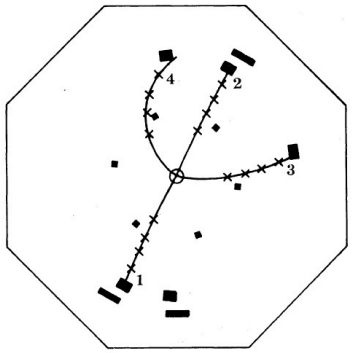

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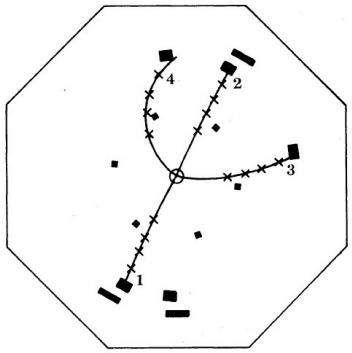

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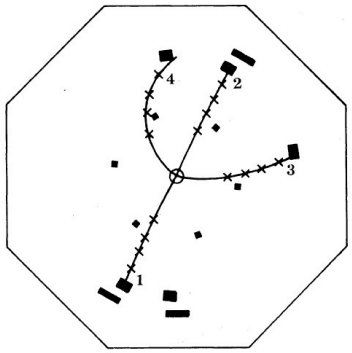
Would these prizes have been given if we did not have lead authors?



Questions and Comments