The Discovery of the Charm Quark at SLAC in 1974

A lecture based on personal experience

Vera G. Lüth

Professor Emerita at Stanford University

June 25, 2021

The Discovery of the Charm Quark in 1974

The Standard Model of Particle Physics

- Standard Model: 3 generations of quarks and leptons
- Quarks and leptons the building blocks of matter
- 3 Fundamental interactions (gravity not included)

Particle Storage Rings and Detectors of Novel Design and Performance

- Advantage of colliders over fixed target experiments – The SPEAR storage ring
- The SLAC-LBL Detector and event reconstruction– first puzzling results

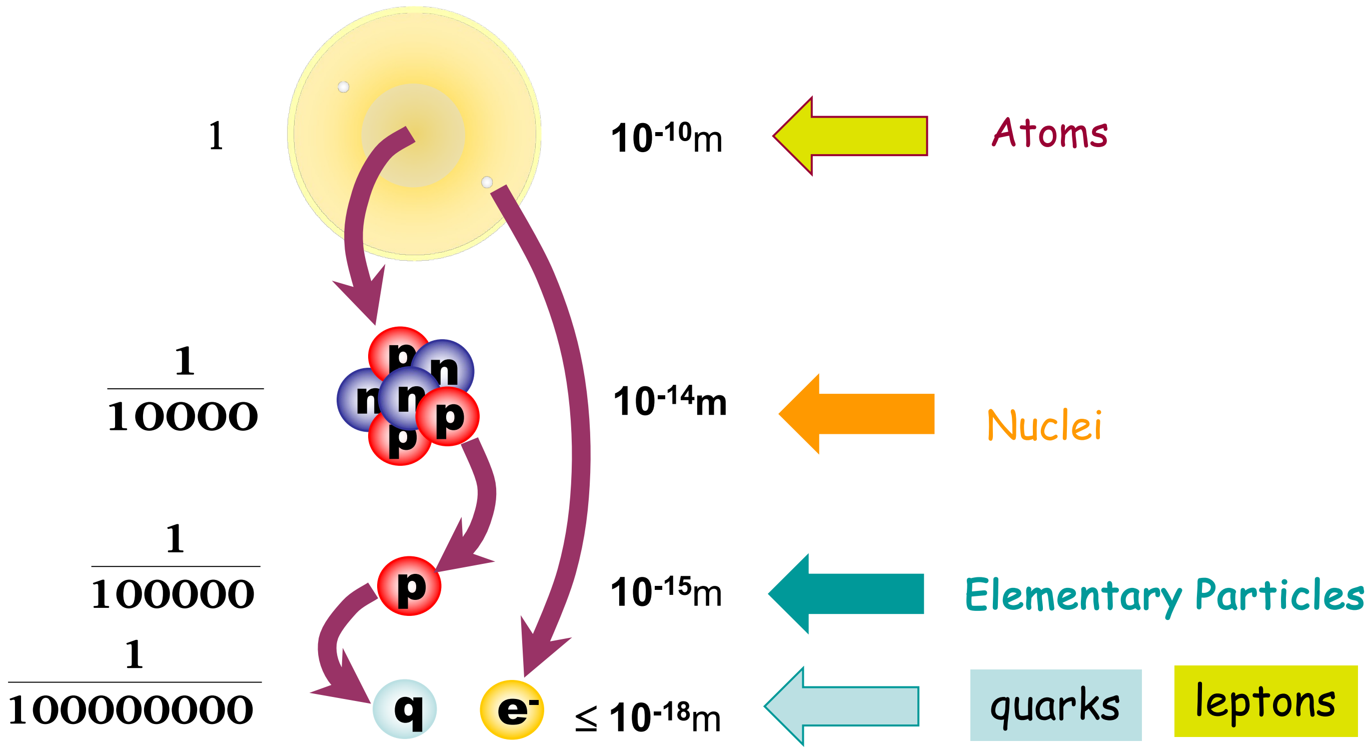
A very exciting **weekend** in November 1974

- First puzzling results – no **explanation found – so try again**
- Diligent set-up and recording of storage ring parameters and detector operations
- Fine tuning of energy settings revealed a huge rate increase near 3.1 GeV due to unknown resonance which we named Ψ (3105), decaying to hadrons, e^+e^-, and $\mu^+\mu^-$!
- Proton fixed target experiment at Brookhaven, led by Samuel C.C. Ting, had observed a very narrow peak indicating a new state decaying into e^+e^- pairs.

Discovery of other Charm Mesons

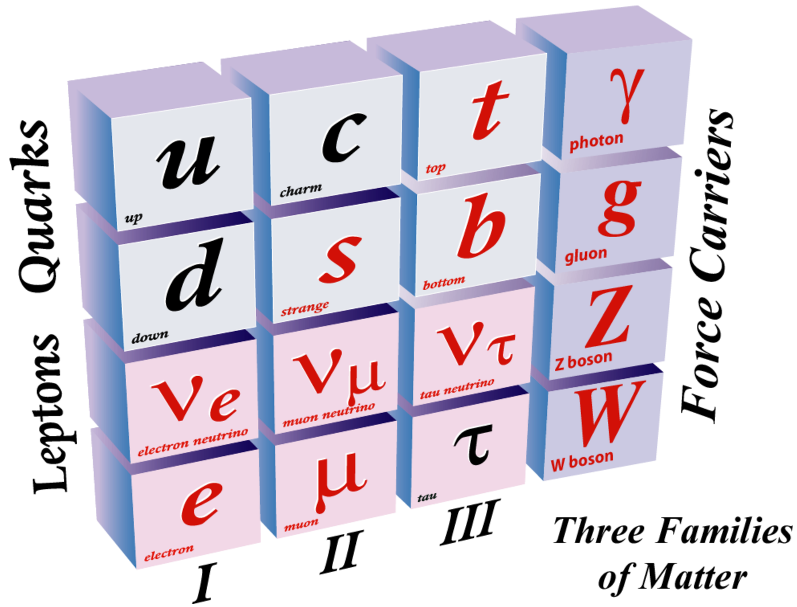
- SLAC-LBL discovered the spectroscopy of charmonium states and later charm mesons.
- The 1976 Nobel Prize was awarded to Burton Richter and Samuel C. C. Ting!

From Atoms to Quarks and Leptons



The Standard Model of Particle Physics

3 Generations of Quarks and Leptons



Baryons:

proton	(uud)
neutron	(udd)
Λ^+_c	(cud)

Mesons:

π^+, π^-	$(u\bar{d})$, $(\bar{u}d)$
K^0, $\bar{K}^0$	$(s\bar{d})$, $(\bar{s}d)$
D^+, D^-	$(c\bar{d})$, $(\bar{c}d)$
B^0, $\bar{B}^0$	$(\bar{b}d)$, $(b\bar{d})$
Ψ	$(c\bar{c})$

- 1st generation makes up stable matter: p, n, e-
- 2nd and 3rd generations existed in the early universe (and are produced in cosmic rays), they can now be created and studied at particle accelerators!
- For each quark and lepton there is an anti-quark and anti-lepton! And quarks come in 3 colors!

Quarks – Building Blocks of Hadrons

Gellman-Zweig, 1964

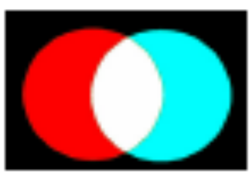
Quarks, spin 1/2, Q=+1/3, +2/3, come in three colors

red blue green

Anti-quarks: spin 1/2, Q =-1/3, -2/3, come in three anti-colors:

anti-red anti-blue anti-green

All known particles are color-less – for each particle, there is an anti-particle



Mesons: B=0 quark-antiquark
Spin 0,1,2,…

Baryons: B=+1 3 quarks: Spin 1/2; 3/2;
Anti-baryons: B= -1 3 anti-quarks
Spin ½, 3/2,

Leptons and Quark and Particles

Leptons spin 1/2	Charge	Mass (GeV)	Quarks	Charge	Mass (GeV)
e^-	-1	0.0005	d	- 1/3	0.005
ν_e	0	~0	u	2/3	0.002
μ^-	-1	0.106	s	- 1/3	0.1
ν_μ	0	~0	c	2/3	1.3
τ^-	-1	1.777	b	- 1/3	4.2
ν_τ	0	~0	t	2/3	173

A wide range of quark masses !
Their spectrum is not understood ??

Mesons		Quark	Mass	9
Symbol	Name	Contents	GeV	Spin
π^+	pion	$u\bar{d}$	0.14	0
K^-	Kaon	$s\bar{u}$	0.494	0
$\rho+$	rho	$u\bar{d}$	0.776	1
D^+	D plus	$c\bar{d}$	1.865	0
B^0	B zero	$\bar{b}d$	5.279	0
Ψ	Psi	$c\bar{c}$	3.095	1

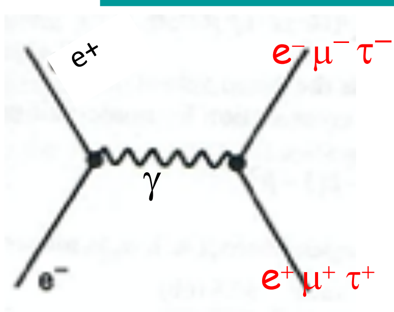
Baryons		Quark	Mass	
Symbol	Name	Contents	GeV	Spin
p	proton	uud	0.939	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	0.938	1/2
n	neutron	udd	0.94	1/2
Λ	lambda	sud	1.116	1/2
Λc	lambda-c	cud	2.286	1/2

Properties of the Interactions

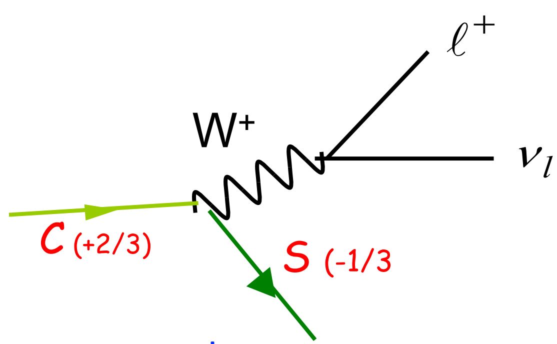
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

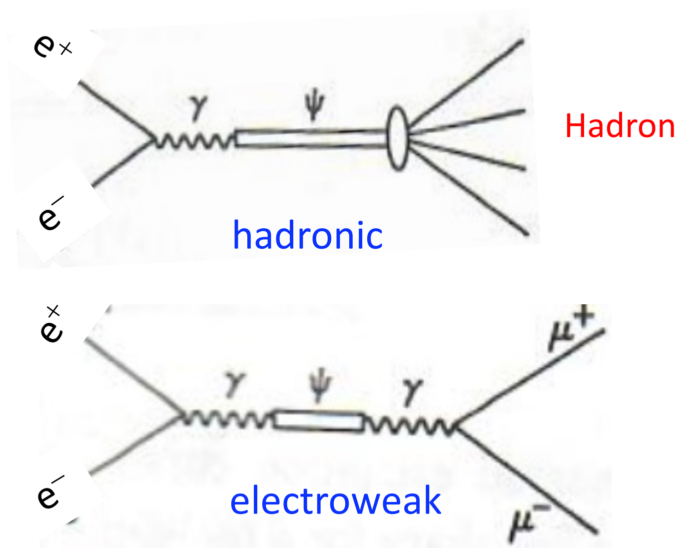
Einstein's Dream: Grand Unification of Forces: Achieved except for gravity!



electromagnetic

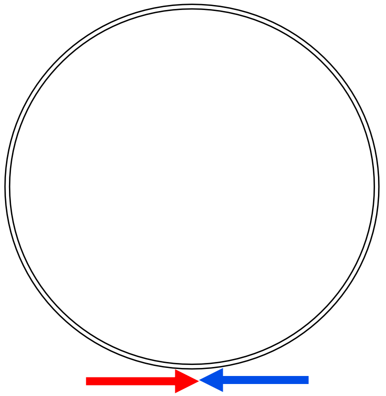


weak



Particle Collisions at Accelerators

Critical parameter for particle physics experiments
is the energy available to produce new particles,
i.e. center of mass energy !
Conservation of energy and momentum!



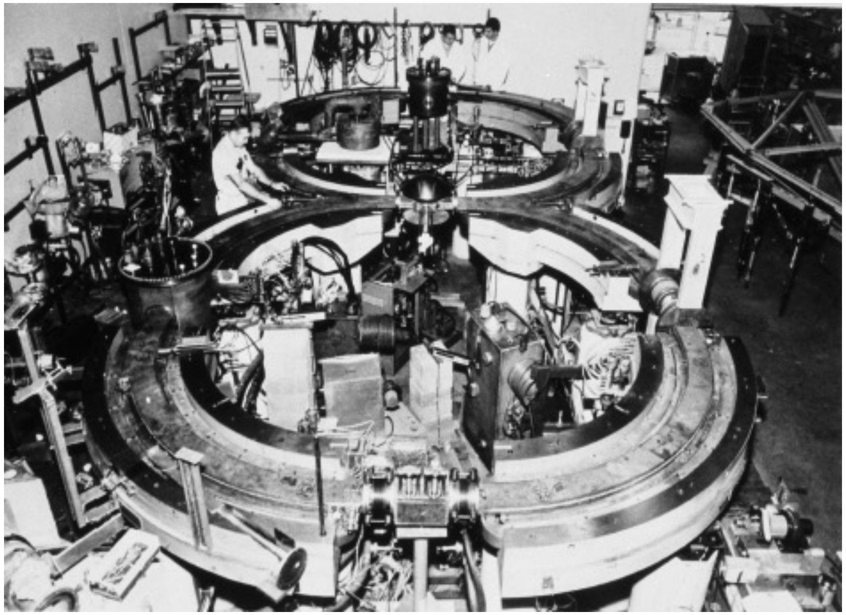
- Storage ring: e^+e^- collisions at $E_b = 5$ GeV
  total energy $W = E_1 + E_2 = 10$ GeV
- Fixed target: $W = \sqrt{2 m_e E_b}$

  to reach the same c.m. energy W = 10 GeV,
  we need E_b=100,000 GeV for e^+ beam hitting a stationary e^-
- The first e^+e^- small storage rings were designed and built in the early 1960s at Frascati and Stanford, storing (and also accelerating) counter-rotating beams of particles of opposite charge and equal energy in a single ring of magnets.
- Currently the LHC at CERN is colliding proton beams of 6500 GeV each in an underground tunnel of 27 km circumference.

The first e-e- collider at Stanford

In 1957 Gerald O'Neill of Princeton proposed to build an 8-shaped set of rings to store electrons and to collide the bunches at a single point. He was joined by Burton Richter – then a junior professor at Stanford - who had been studying e^+e^- pair production at Stanford's low energy electron linac.

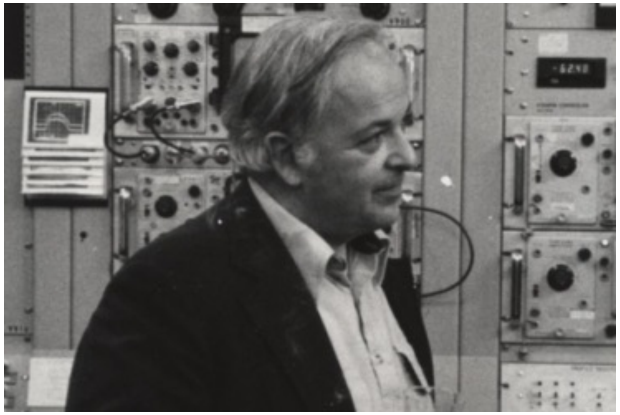
It took this small young team of physicists and technicians about 6 years to design and build these storage rings, and another two years to learn how to operate them and build a suitable detector for the produced particles.



This novel e^-e^- collider offered a c.m. energy 10 times larger than a single highest beam from the Stanford linac.

The measurements extended the proof of validity of QED by an order of magnitude, to 10^{-17}m !

SPEAR - A Challenging project - A Great Success



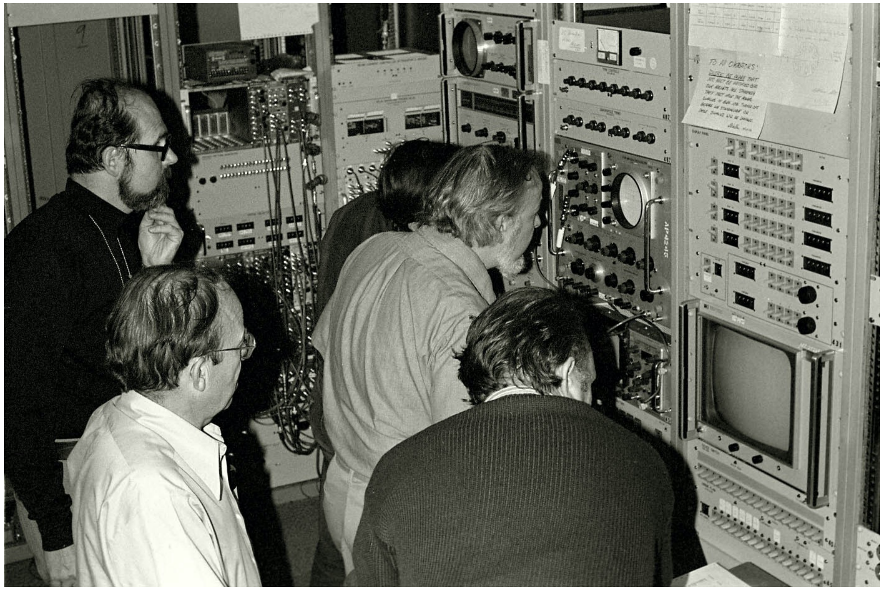
- Early discussion initiated by Burt Richter and Dave Ritson resulted in 1964/65 in a proposal for e^+e^- storage rings at SLAC.
- While awaiting approval, the design developed, based on extensive experience from low energy e^-e^- rings at Stanford.

- Construction started in 1970 without project approval from the AEC!
- A single ring, technically at the forefront:
  ultra-high vacuum → long beam lifetime
  small IP → high luminosity
  c.m. energy 2.6 – 8 GeV
- Civil engineering:
  placed on asphalt parking lot,
  enclosed by concrete shielding blocks!
- At a cost of ~ 6 Million $, a most productive particle physics project !

First colliding beams in April 1972 !!

SPEAR:

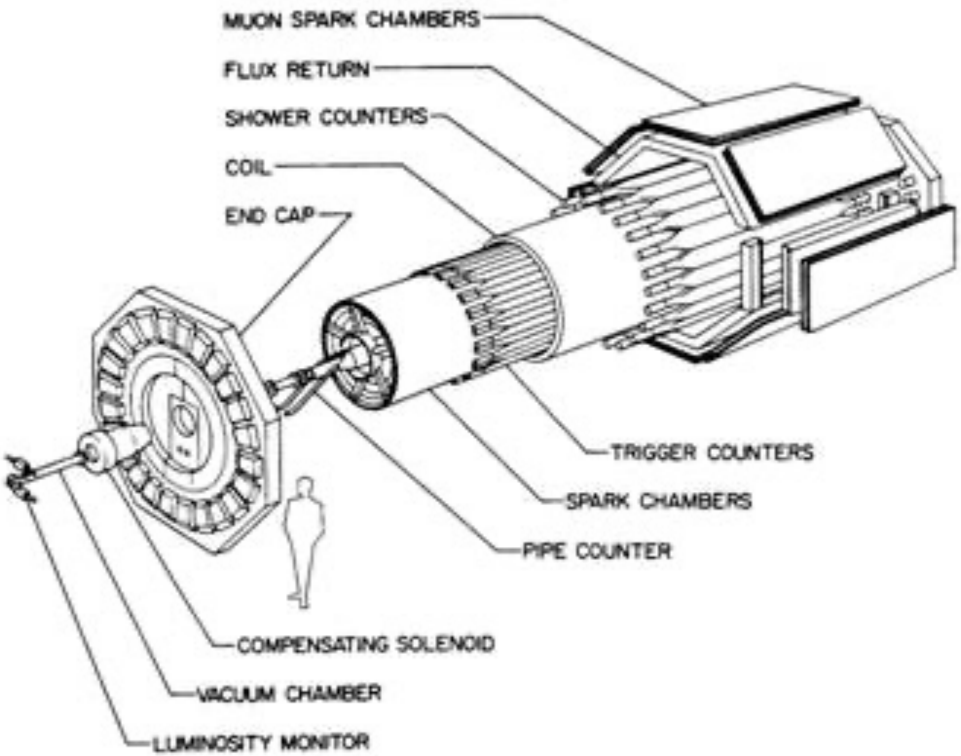
State of the art control system connected to powerful online computer



Leading scientists: W.K. Panofsky, Gerhard Fischer, Burton Richter

Rudy Larsen, Ewan Paterson, David Fryberger, Burton Richter

The SLAC-LBL Magnetic Detector – Mark I



The first cylindrical detector !!

- centered on the beam pipe
- multilayer, uniform coverage
- 70% solid angle coverage
- electronic tracking devices in co-axial magnetic field,
- Particle ID: e,μ,p,K, photons

This became the prototype of all future detectors at colliding beams !!

Conceived by Rudy Larsen - Burt Richter

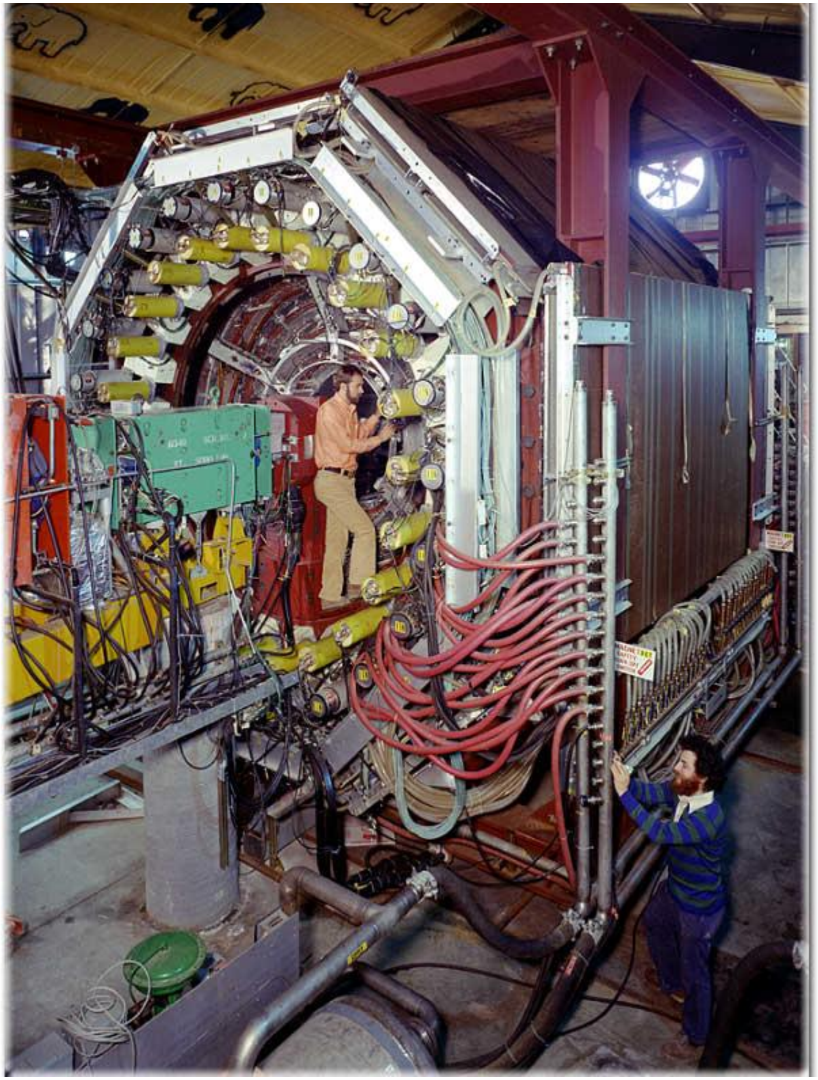
Designed and built by SLAC-LBL Collaboration

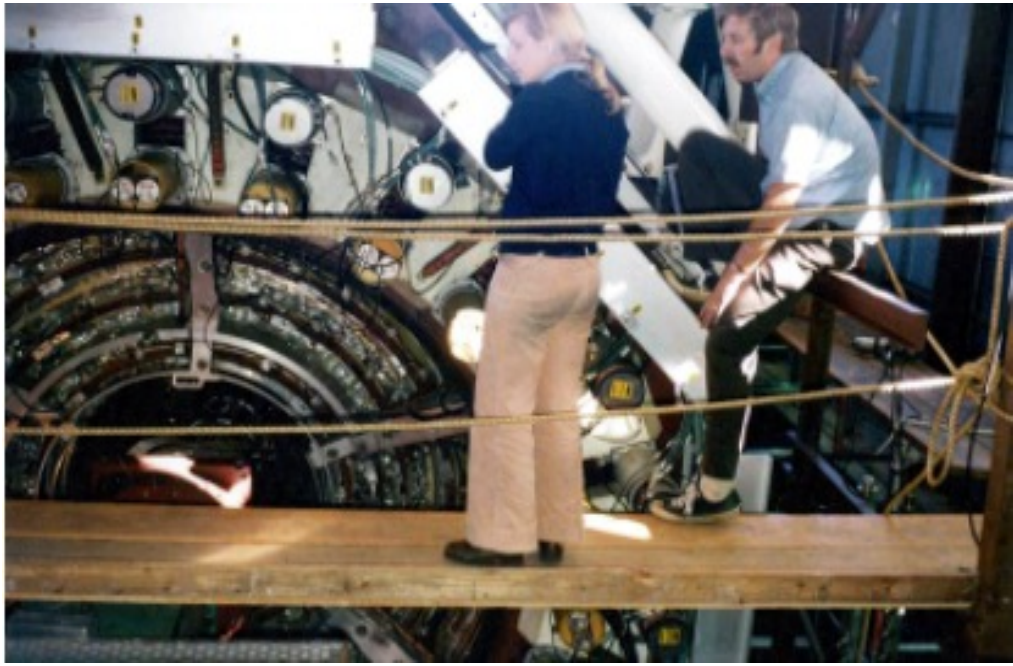
SLAC: beams and inner core components
electronics, trigger, online software

LBL: Photon counters,
offline software and simulation

Ready for colliding beams in early 1973 !

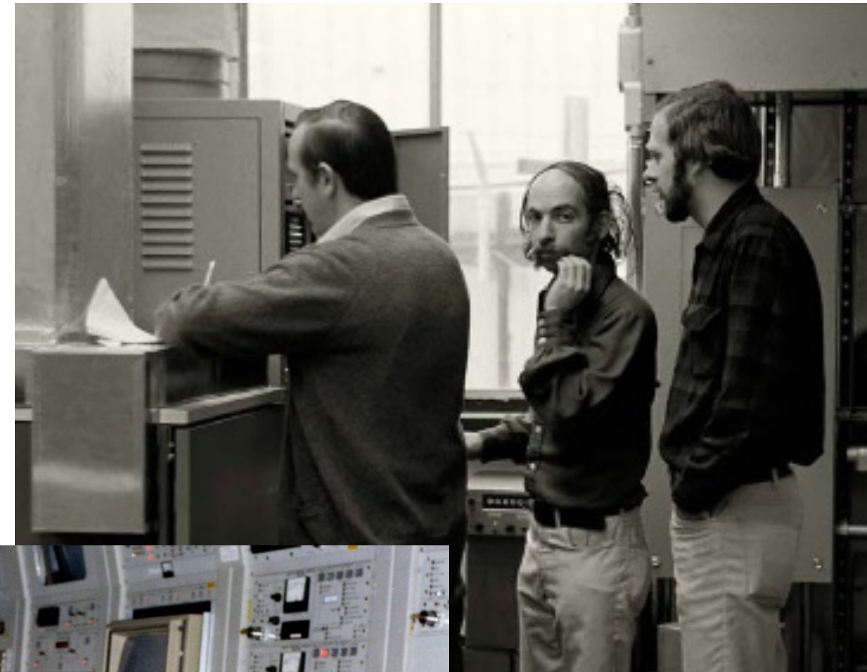
The SLAC – LBL Detector





The maintenance crew:
Charles Morehouse and Vera Lüth

Detector and SPEAR Control System

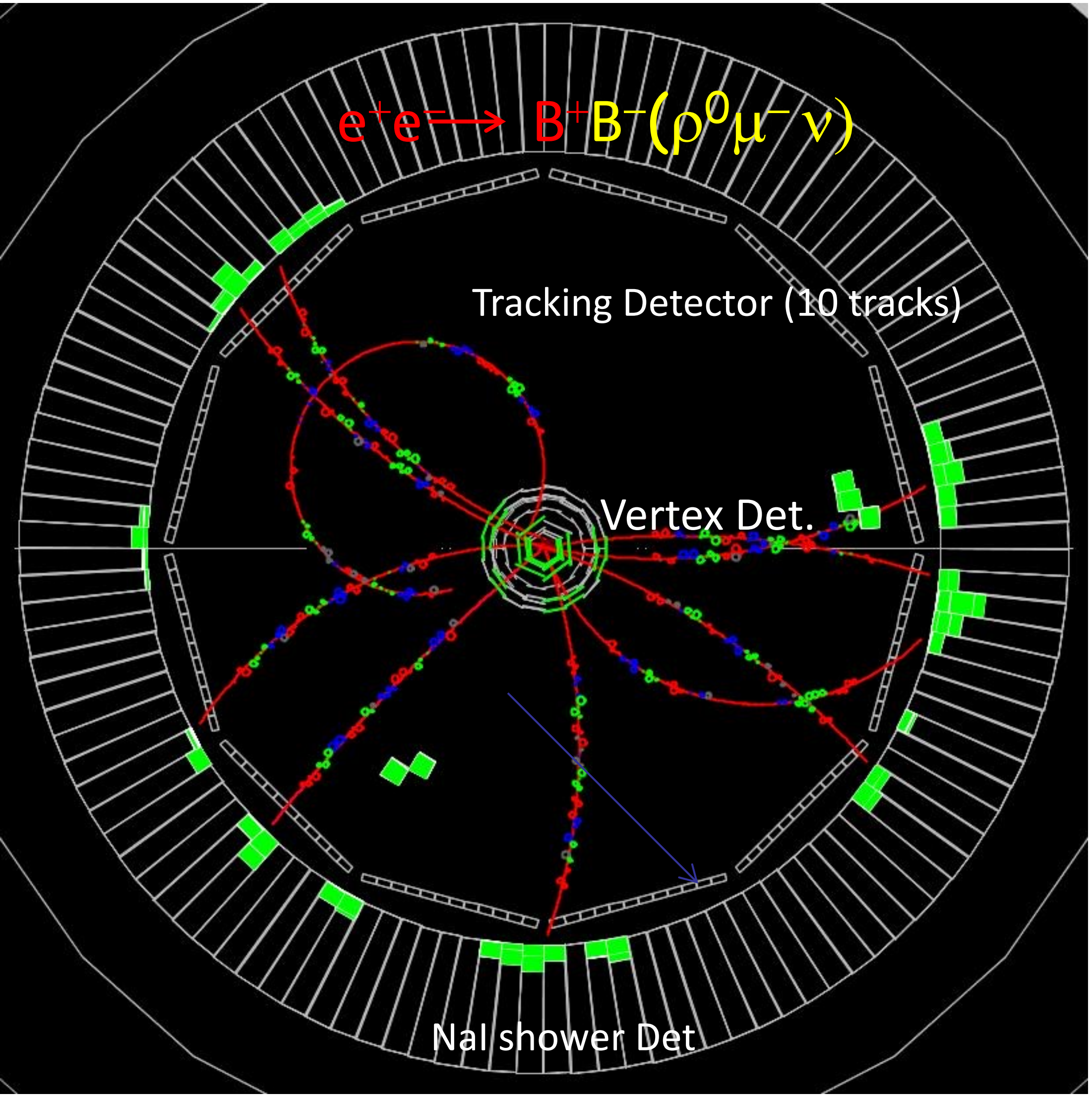


Marty and Harvey at the Mark I controls

Ken Underwood at the SPEAR controls

Adam, Marty, and Roy puzzling over a problem with the XEROX Sigma V online computer

Event Reconstruction (BABAR Experiment)

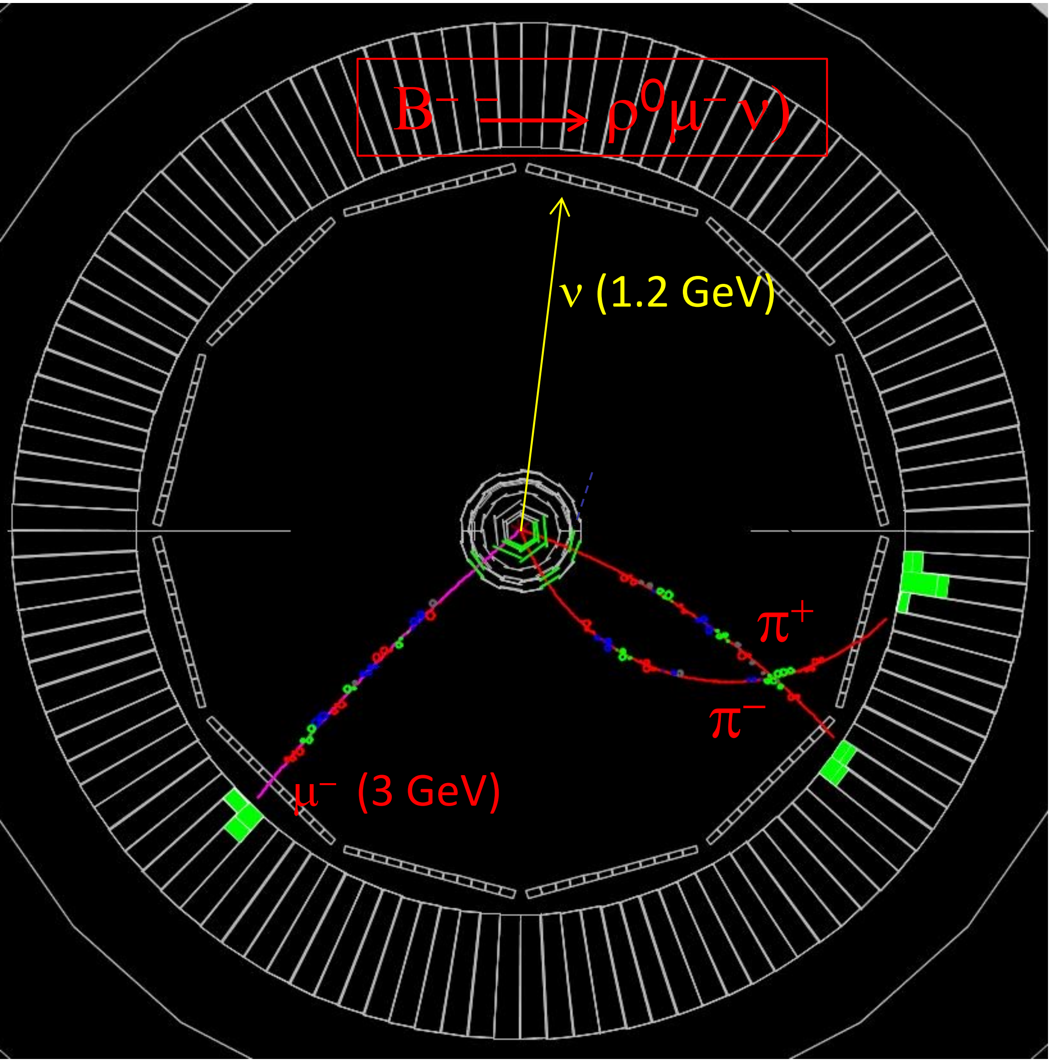


Cylindrical Geometry, centered on beam pipe

Figure: Projection on the plane transverse to the beams

- Charged particle tracks induce signals in cylindrical wire chamber and Si strips vertex detector
- Transverse momenta from curvatures in magnetic field
- Electrons and photons deposit energy in CsI crystals
- Muons penetrate layers of dense material on the outside
- Presence of neutrinos derived from missing energy and momentum in the whole event

Event Reconstruction (BABAR Experiment)



- BABAR and also Belle analyze pair production of B mesons at fixed energy: $e^+ e^- \longrightarrow B\,\bar{B}$
- Detection of one semileptonic B decay, by fully reconstructing the other B decay (7 of 10 tracks, no photons)
- 3 remaining tracks: 1 muon, and 2 low energy pions, no photons, and 1.2 GeV missing energy and momentum.
- Strong reduction in backgrounds, leads to much reduced systematic uncertainties!

Initial Physics Program: $e^-e^+ \longrightarrow$ hadrons

- Primary focus was on the production of hadrons by e+e- annihilation as a function of c.m. energy.

  Measurements reported in terms of the ratio

$$R = \frac{\text{cross section for } e^+e^- \rightarrow \text{hadrons}}{\text{cross section for } e^+e^- \rightarrow \mu^+\mu^-}$$

- At ICHEP 1974 in London 1st results from SPEAR were compared with earlier results from ADONE (Frascati) and CEA (Cambridge U.S.)
- Very puzzling result! The expected value is

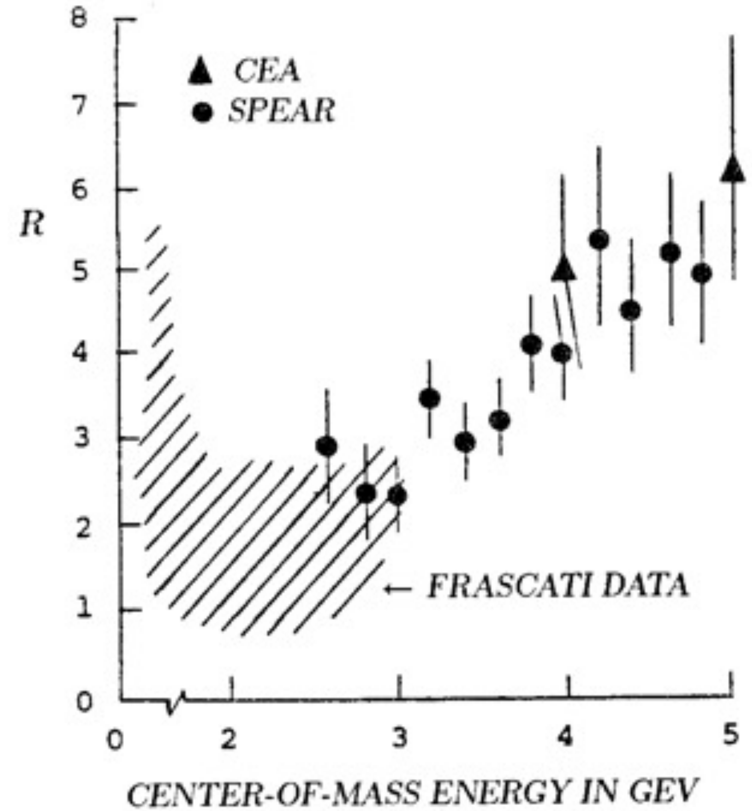
  $R = \Sigma_i\, q_i^2$ q : charge of quark

  i.e. depends on the number and type of quarks!

  Thus $R = 2$ for uds quarks with 3 colors

  $R = 3\ 1/3$ for udsc quarks with 3 colors

- Variety of explanations by theorists – none convincing !



R appeared to be rising linearly as a function of E_{cm} !!

1974: Further Investigation of R Measurements

- In June 1974, just before the shutdown to upgrade SPEAR to higher energies, additional data were recorded by Mark I:
  3.1, 3.2, 3.3, 4.1, 4.2. and 4.3 GeV.

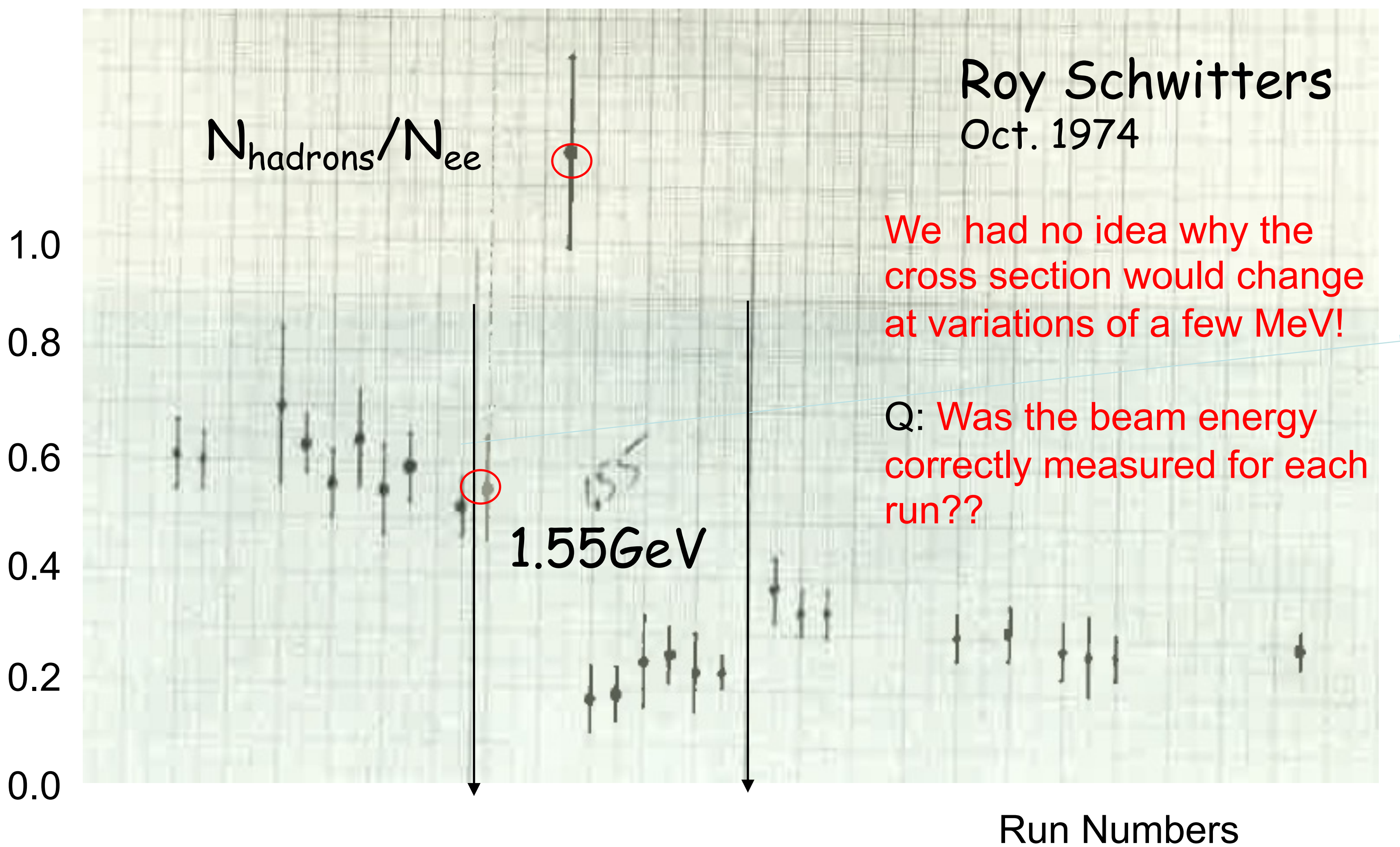
- Several of us, led by Roy Schwitters, looked at the new data.
  Near 3.1 GeV, 2 runs at the same nominal energy indicated inconsistent values of R ! → Next slide

- Suspecting software problems, we used the first video display at SLAC connected to the IBM mainframe to classify event pictures!
  We did not find anything wrong with the analysis.

- On November 8th, Gerson Goldhaber and Francois Vannucci reported independently an enhanced rate of kaons in the runs with higher cross sections – this turned out to be fluctuations!!

- This finally convinced Burton to defer the planned higher energy run and allow us "to waste a weekend to find the reason for these anomalies!"

Reanalysis of June 1974 Data



We had no idea why the cross section would change at variations of a few MeV!

Q: Was the beam energy correctly measured for each run??

The Weekend Nov. 9th -11th at SPEAR

- Harvey Lynch prepared the Run Plan for this weekend to make sure we would not waste it!
  - Assure the proper operation of the detector and data taking

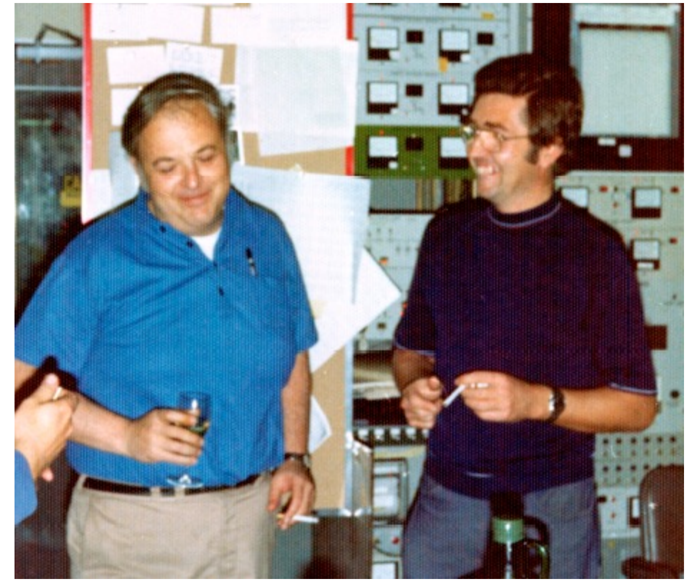
    First data at E_{cm}=2.4 GeV to confirm proper operation of detector
  - Establish good data at 3.0 GeV
  - Proceed with search for critical energy range, 3.1 GeV and above
- Special attention to the SPEAR energy setting
  - Record and monitor the magnetic field of the storage ring by a flip coil reading for an external magnet connected to the same power supply.
  - Fine tune by adjusting the RF frequency (phase) which impacts the beam energy and orbit. Orbit scans are critical !
  - The natural energy spread of the beams is ~0.04
- It took a while to get things going – for both SPEAR and Mark I

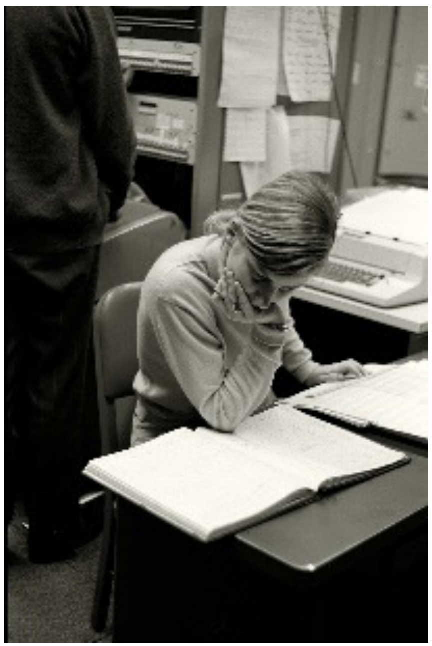
The Weekend Nov. 9th -11th at SPEAR

Date-Time		Run#	E_{cm}	# had	# e+e-	Rx	counting
11/09	8:00	1452	3.120	22	37	0.59	scan
11/09	21:00	1455	3.000	16	61	0.27	scan
11/09	23.15	1456	3.120	74	170	0.44	scan
11/10	11:31	1461	3.104	354	53	6.68	offline
11/10	16:50	1468	3.105	2090	188	11.12	offline
11/11	7:30	1475	3.105	1362	126	10.81	offline

- On Sunday, the data tapes were sent for processing on the IBM 168.
- As the energy setting was fine tuned, both the hadron and e+e- event rates began to rise near 3.105 GeV,
  up to ~100 times for hadrons and ~10 times for e+e- final states
- The news spread quickly and in the afternoon, it got crowded in the CR, the phone started ringing, the first champagne bottle corks popped!
- Gerson Goldhaber and others started drafting the PRL paper!
- The $\Psi(3105)$ was born! The $\Psi' \longrightarrow \Psi\pi^+\pi^-$ decay justified its given name!

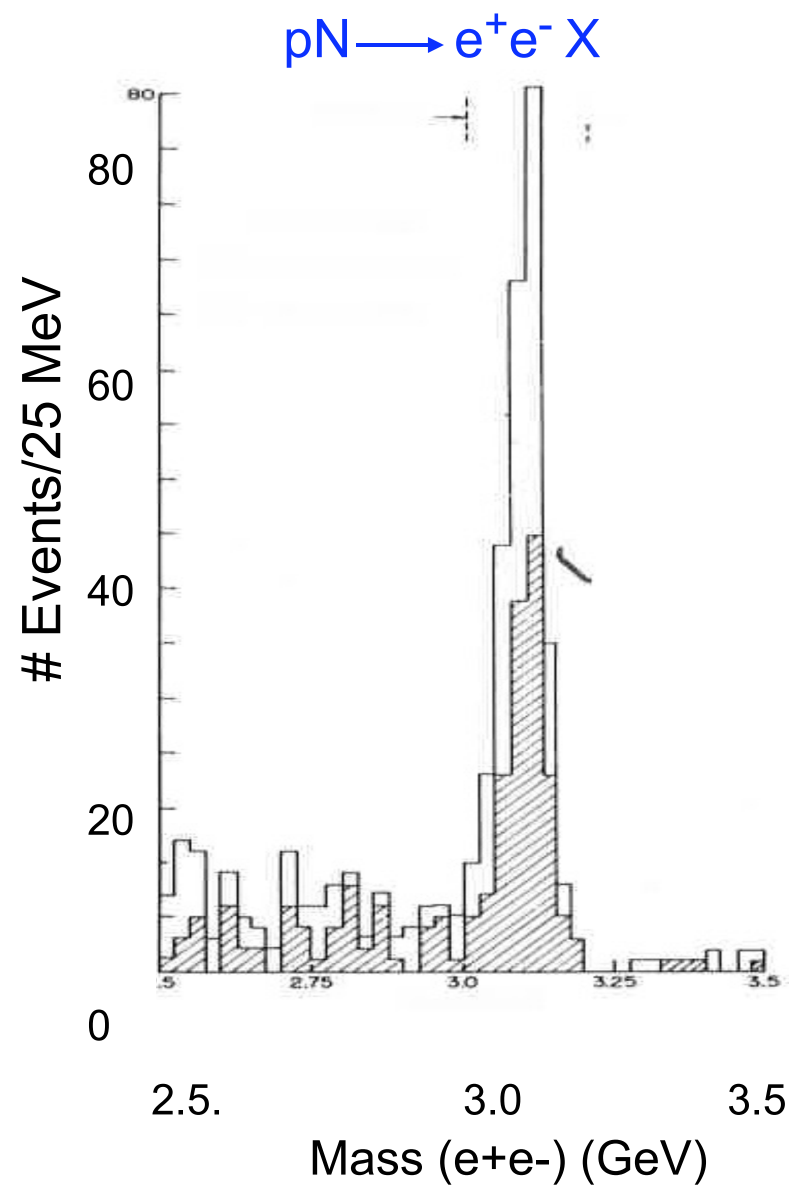
Sunday, Nov.10th





Surprise on Monday, Nov. 11th

- Sam Ting - Professor at MIT - was on his way to SLAC on this Sunday to attend the PAC on Monday. Upon arrival at SFO he received a call from his MIT colleagues who had received the news from SPEAR!
- Sam spent most of the night on the phone with his colleagues at MIT, completing their paper, and also with DESY and Frascati!
- Monday morning Roy, Marty, and I were editing our latest paper draft, when Pief summoned Roy to his office. Roy returned, white as a sheet, and announced that "Sam has the same thing".
- At an ad-hoc seminar at noon, Roy described the experiment and showed our data and Sam sketched the experiment and results on the black board and took the next flight back to Boston!



Rapid Publication in PRL

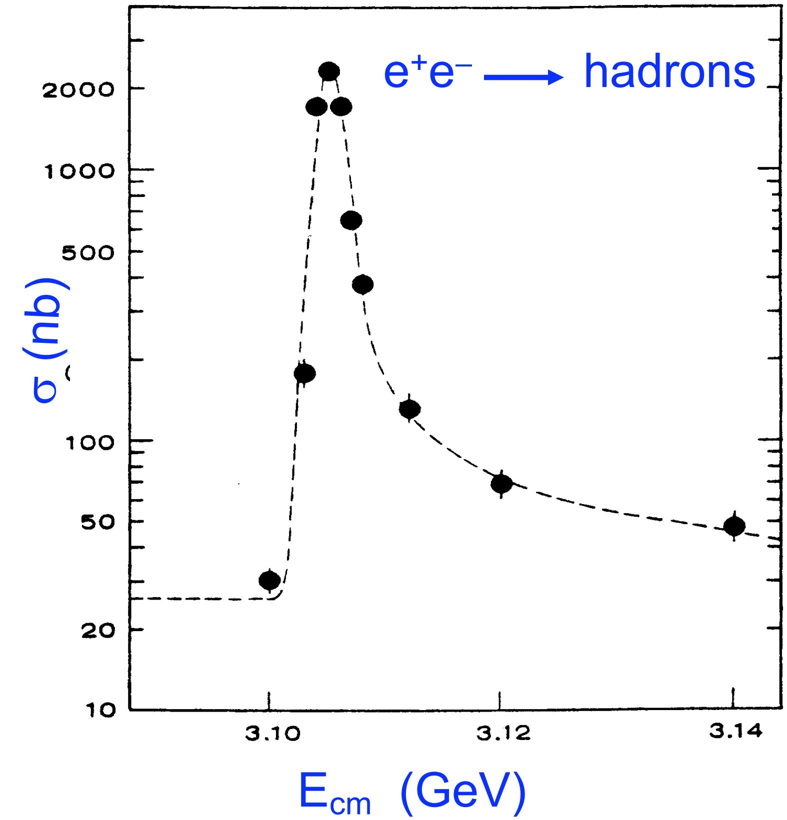
Discovery of a Narrow Resonance in e+e- Annihilation
Submitted on Nov. 13th, published on Dec.3rd, 1974

We have observed a very sharp peak in the cross section for $e^+e^- \longrightarrow$ hadrons, e^+e^- and possibly $\mu^+\mu^-$ at the cm energy of 3.105 +/- 0.003 GeV. The upper limit to the full width at half maximum is 1.9 MeV.

Discovery of a Narrow Resonance in e^+e^- Annihilation
J. E. Augustin et al., PRL. 33 (1974) 1406

Experimental Observation of a Heavy Particle J
J.J. Aubert et al., PRL 33 (1974) 1404

Preliminary Results of Frascati (ADONE) on the Nature of a New 3.1 GeV Particle Produced in e+e- Annihilation
C. Bacci et al., PRL. 33 (1974) 1408



Precision scan of the $\Psi(3105)$

Mass: 3.105+/- 0.003 GeV
Width: < 1.9 MeV

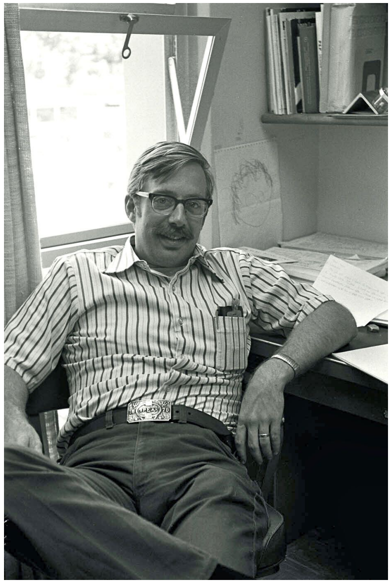
Search for Other Narrow Resonances

- Now, the obvious question was: Are there other narrow resonances??
- Marty Breidenbach and Terry Goldman concocted a positronium model of the Ψ, resulting in a prediction for the 1st radial excitation at 3.7 GeV!
- The SPEAR control was changed to allow smaller steps in beam energy.
- To get instant feedback on the event rates, we connected to the IBM mainframe to reconstruct the events in real time!
- In the early hours of Nov. 21st, the scan was started at E_{cm}= 3.8 GeV.
  - The c.m. energy was increased in steps of 2 MeV every 3 minutes, and the results were recorded online.
  - After about 50 steps a significant signature was observed!

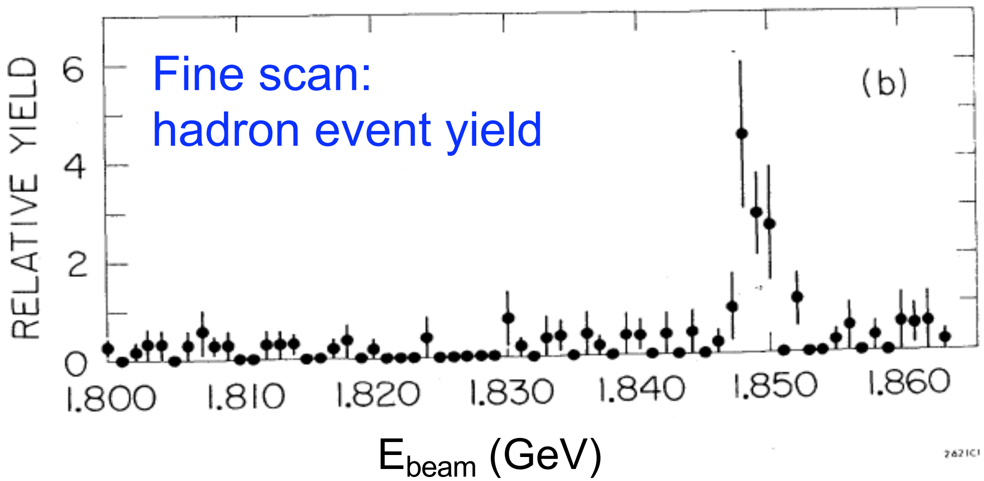
Chuck Morehouse welcomed it as the “SON of GLORY”!

The continuation of this scan to 5.9 GeV did not reveal any other state, however, we missed the Ψ(3777) and states above 4 GeV!

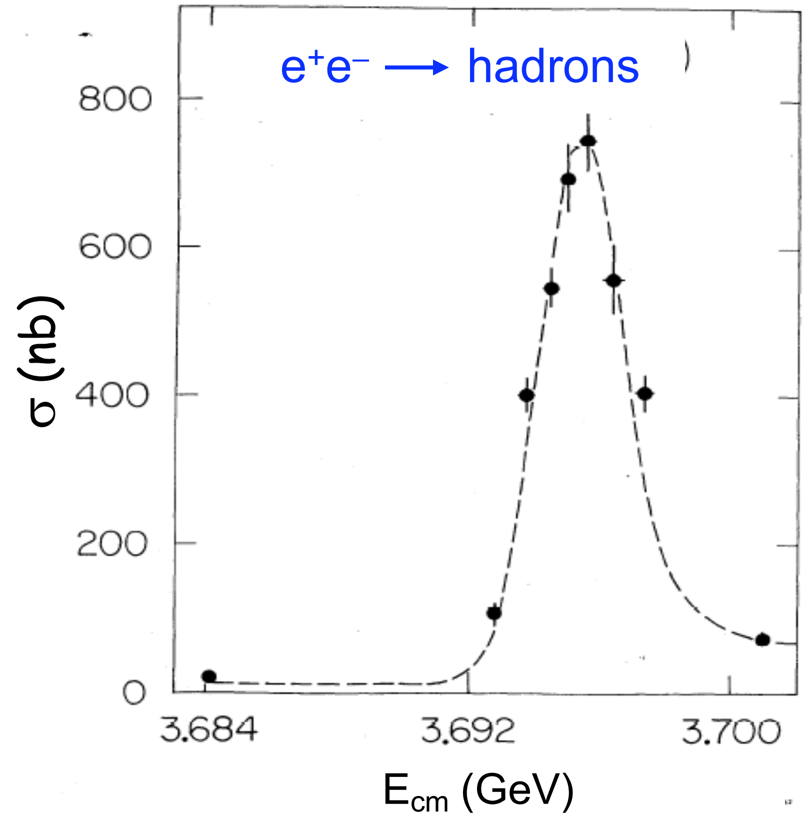
Chuck Morehouse



Search for Other Narrow Resonances



The scan was stopped to map out the shape of the resonance with higher statistics.
Based on experience with the Ψ (3105) efficiency corrections, luminosity, acceptance were implemented.



Precision scan of the Ψ'(3695)

Mass: 3.695 +/- 0.004 GeV
Width: < 2.7 MeV

Discovery of a 2nd Narrow Resonance in e+e- Annihilation
G.S. Abrams et al., PRL 33 (1974) 1453

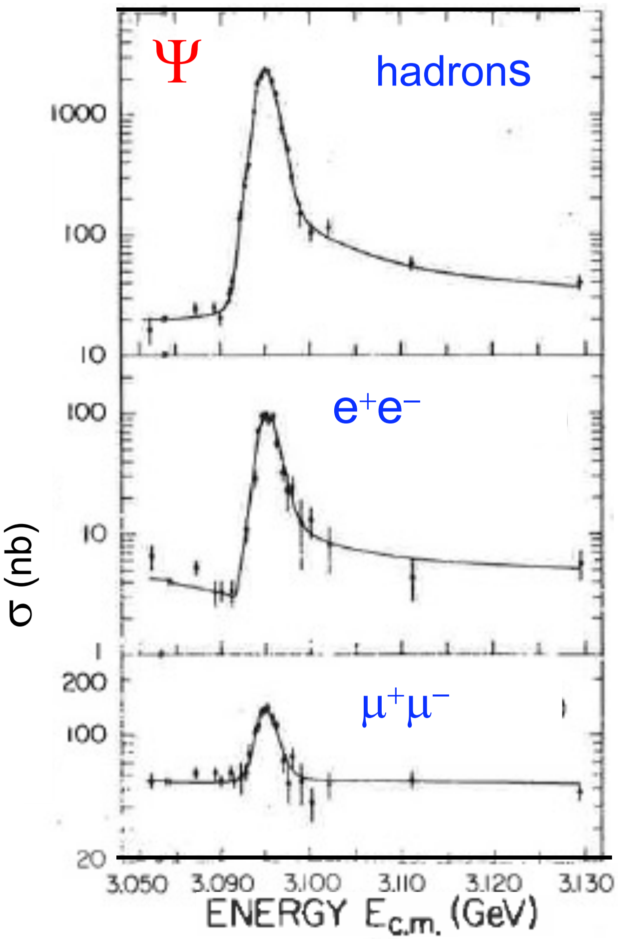
The Non-Observation of Heavier J Particles
J.J. Aubert, PRL 33 (1974) 1624

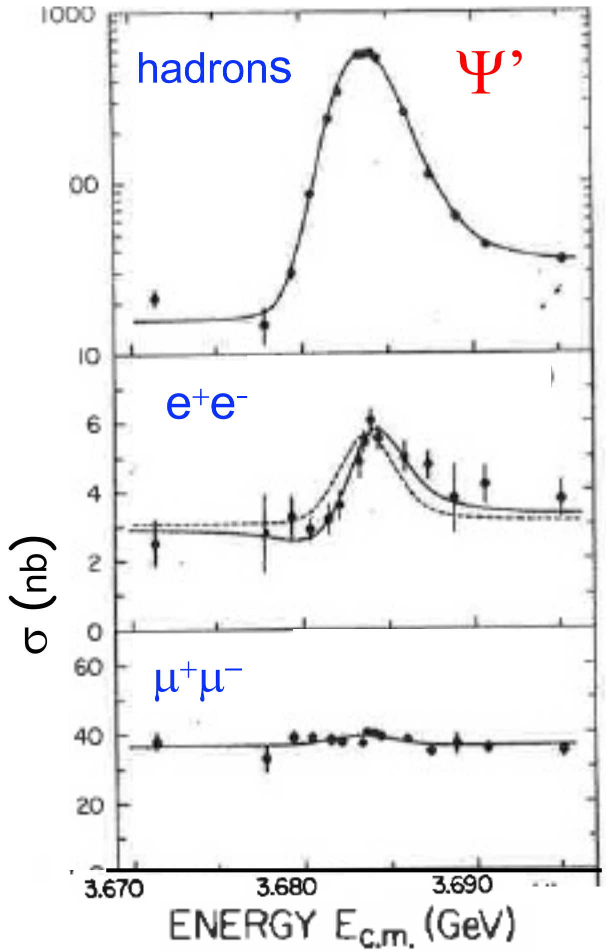
Quantum Numbers and Decay Width of Ψ and Ψ'

Following the discovery of Ψ and Ψ' extensive measurements as a function of E_{cm} were used to determine the mass and decay widths. New calibrations led to 10 MeV lower masses !

Ψ Boyarski et al, PRL 34, 1357

Mass	3.095 +/- 0.004 GeV
$\Gamma_{ee} = \Gamma_{\mu\mu}$	4.8 +/- 0.6 keV
Γ_h	59 +/- 14 keV
Γ_{tot}	69 +/- 15 keV





Ψ' Lüth et al, PRL 35, 1124

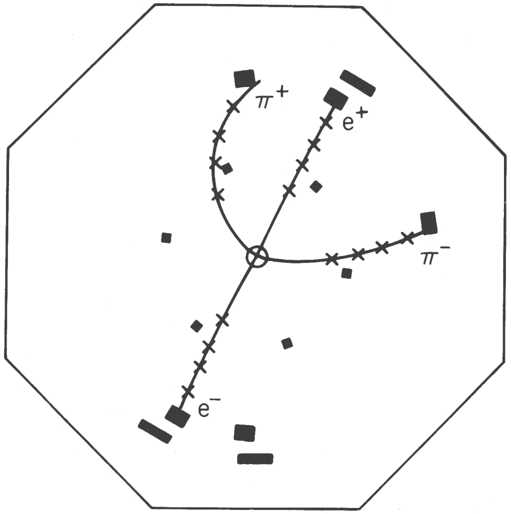
Mass	3,685 +/- 0.005 GeV
$\Gamma_{ee} = \Gamma_{\mu\mu}$	2.1 +/- 0.3 keV
Γ_h	224 +/- 56 keV
Γ_{tot}	228 +/- 56 keV

Adam Boyarski

Harvey Lynch

Discovery of Charmonium States

Mesons composed of $c\bar{c}$ quark pairs with $J^{PC} = 1^{--}$

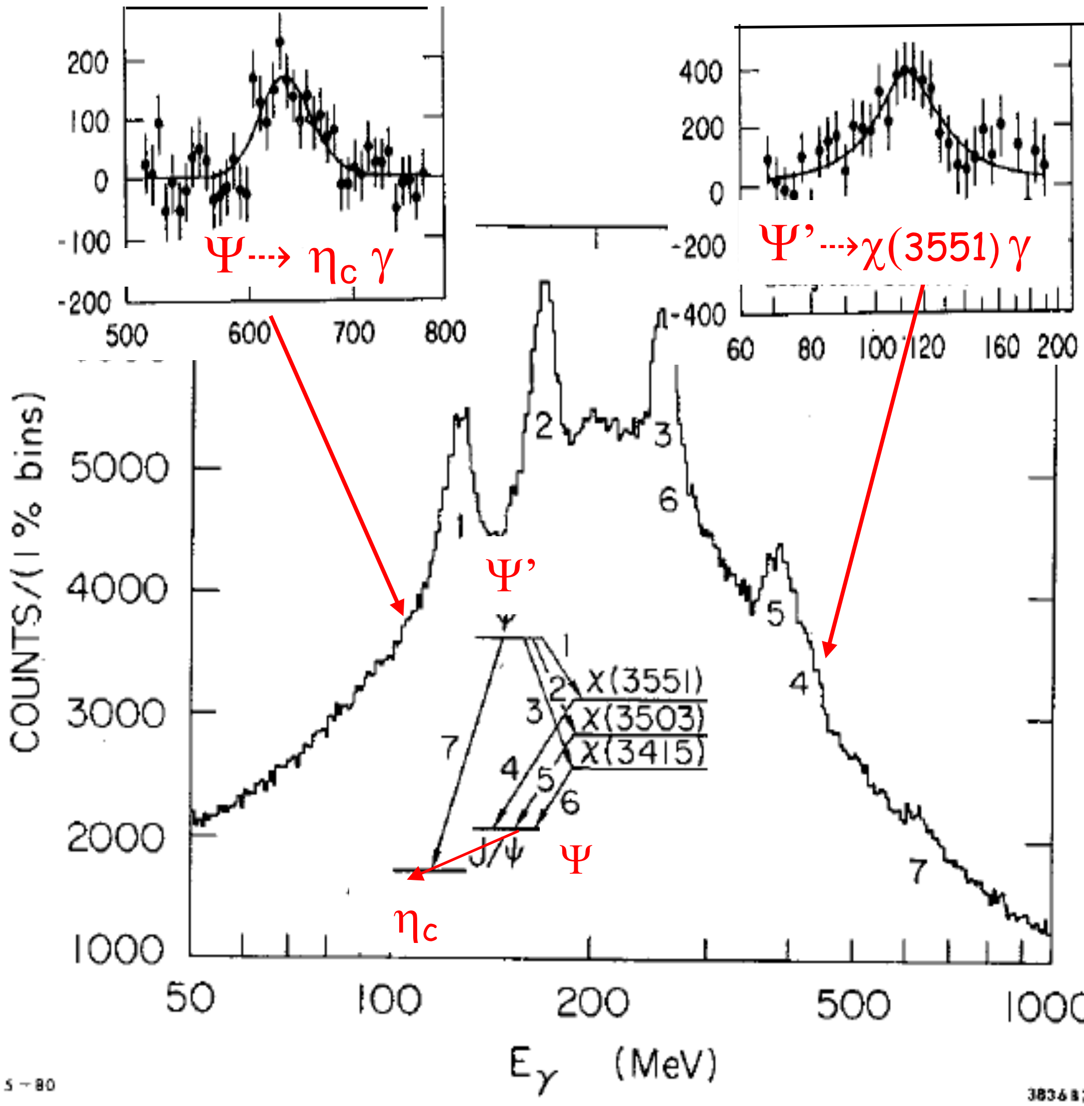


$\Psi' \rightarrow \Psi(\rightarrow e^+e^-)\ \pi^+\pi^-$

- Great effort to detect and study decays of $J^{PC} = 1^{--}$ states like Ψ, Ψ', Ψ'' and others, decaying to leptons, hadrons and γ

- Radiative transitions to new states
  $e^+e^- \rightarrow \Psi' \rightarrow \chi_1\gamma,\ \chi_1 \rightarrow \chi_2\ \gamma,$

Crystal Ball: PRL 45 (1980) 1150



Discovery of Open Charm

- As early as 1964 , Bjorken and Glashow postulated the existence of a 4th quark, based on SU(4) symmetry. They predicted meson multiplets and their decay modes: Phys. Lett. 11, 255

- As charmonium states were commonly interpreted as $c\bar{c}$ states, i.e. "hidden charm", open charm states ($c\bar{q}$) states with $\bar{q}=\bar{u},\bar{d},\bar{s}$ should exist.

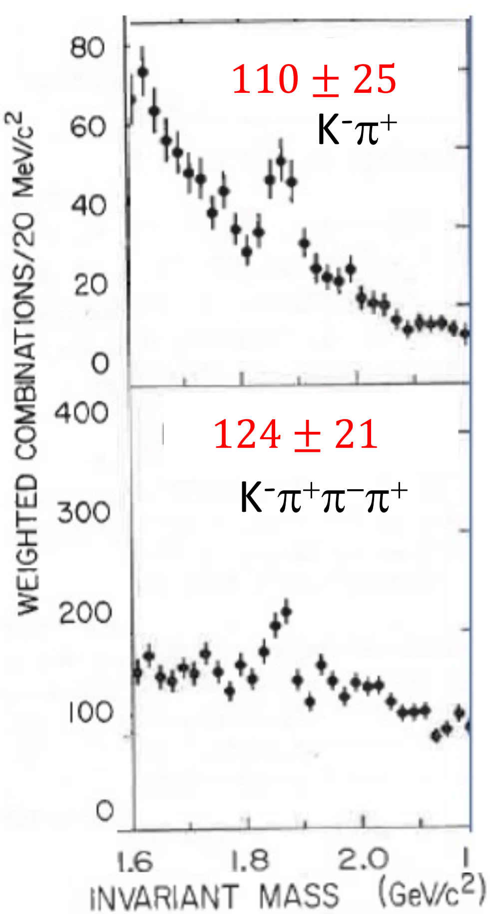
- In 1975, Mary K. Gaillard, Ben W. Lee and Jonathan Rosner derived estimates of the masses of charm mesons and decay modes, and lifetimes, Rev. Mod. Phys. 47, 277.

- Their improved estimates of the D meson mass of 1.8 – 1.9 GeV, were well matched to the rise in the ratio R near 4 GeV for $D\bar{D}$ pair production in e+e- annihilations!

- At a conference in Madison in April 1976, S. Glashow urged G. Goldhaber to reexamine an earlier search for the decay $D^0 \to K^-\pi^+$ which had not revealed a signal.

Observation of D^0 and $\bar{D}^0$ Mesons - 1976

Our efforts to find these states had been unsuccessful until May 1976, when it was realized that the Mark I identification of $K^{\mp}$ or $\pi^{\mp}$ was rather poor!

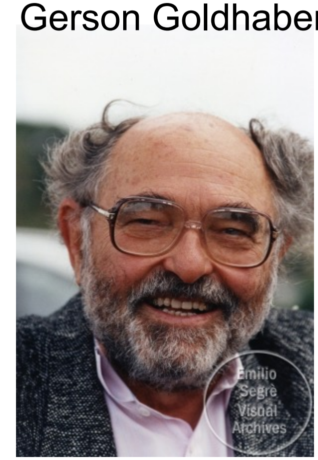


- Francois Pierre and Gerson Goldhaber studied the decays (and their charge conjugates)
  $D^0(c\bar{u}) \rightarrow K^-(s\bar{u})\,\pi^+$ $\quad D^0(c\bar{u}) \rightarrow K^-(s\bar{u})\,\pi^+\pi^-\pi^+$
  in interactions $e^+e^- \rightarrow D^0\,\bar{D}^0\,X$ at E_{cm}=3.9 – 4.6 GeV
- With improved the PID measurements, and following a suggestion by Jonathan Dorfan, they assigned weights to each pair of tracks to suppress decays with poor PID.
- This resulted in clear evidence for both decays!
  Mass: 1865 ± 15 MeV
  Width: ≤ 40MeV
- The recoil spectra suggested associate production with particles of equal or higher mass! As predicted !

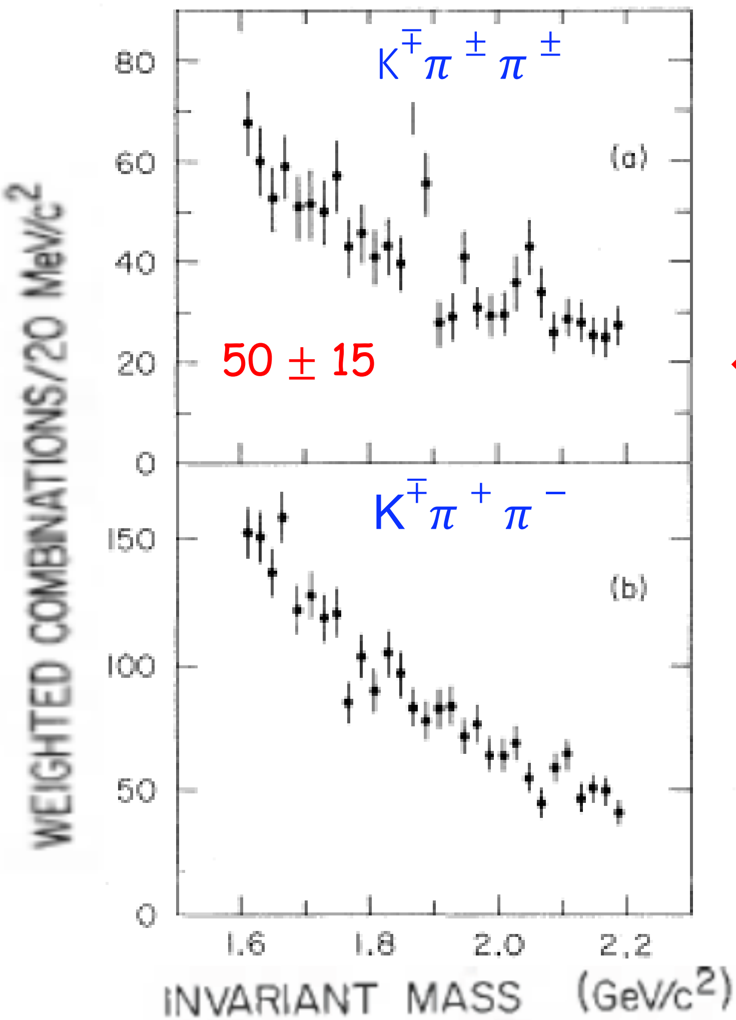
PRL 37 (1976) 255

Francois Pierre

Gerson Goldhaber



Charged Charm Mesons - 1976



- A similar approach was used by Ida Peruzzi and Marcello Piccolo observing decays of a charged charm meson with an exotic decay via a K^{*0} !

  $D^+(c\bar{d}) \rightarrow K^{*0}(s\bar{d})\ \pi^+$ with $K^{*0}(s\bar{d}) \rightarrow K^-(s\bar{u})\ \pi^+(u\bar{d})$

  in interactions $e^+e^- \rightarrow D^+D^-X$ at 4.03 GeV

- Again, weights used to suppress decays with poor PID resulted in clear evidence for these decays!

  Mass: 1867 ± 15 MeV

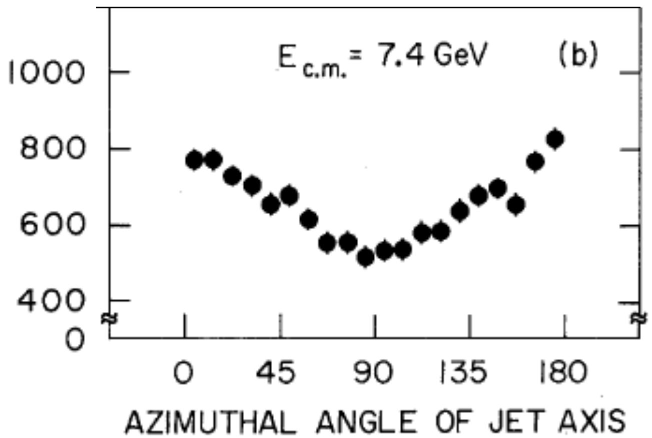
  Width: ≤ 40 MeV

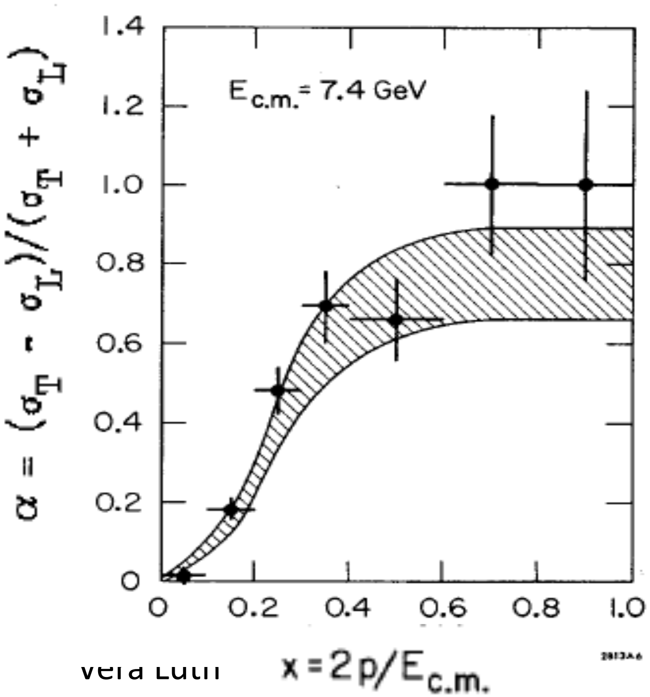
PRL 37 (1976) 569

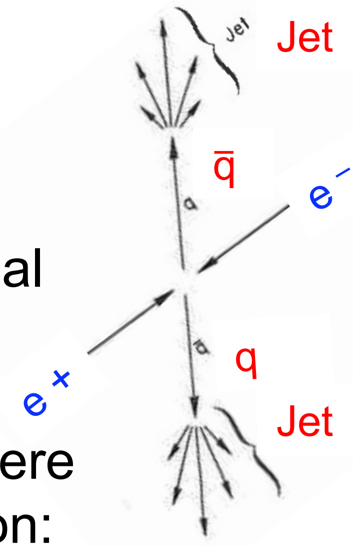
Ida Peruzzi

Marcello Piccolo

Hadron Production e^+e^- Annihilation







- In the SM, hadrons are produced from $q\bar{q}$ pairs created via the virtual intermediate photon
- Two studies were performed at E_{cm}= 7.4 GeV where the beams were polarized in the transverse direction:
  - a) selecting the hadron with the highest momentum in the event,
  - b) a novel algorithm to find the axis that minimizes the sum of the squares of the transverse momenta of all final state particles.
- Both methods show the azimuthal asymmetries identical to $\mu^+\mu^-$ pairs, as expected for intermediate spin 1/2 quark pairs.

Gail Hanson

Schwitters et al. PRL 35 (1975) 1320
Hanson et al. PRL 35 (1975) 1609

End of Mark I Party 1976

Harvey Lynch, Chuck Morehouse and the SPEAR operators, wearing their specially crafted belts !

The SLAC – LBL Collaboration 1973-1976

I had the luck and privilege to be a junior member of the SLAC-LBL Collaboration in those years when under outstanding leadership this most amazing experiment collected data at a unique collider !

J.-E. Augustin,[†] A. M. Boyarski, M. Breidenbach, F. Bulos,
J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson,
B. Jean-Marie,[†] R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon,
C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis,
R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci[†]

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg,
G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,[‡]
G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse

Sources of Information:

Burton Richter: Nobel Lecture and Oral History recorded at Stanford 1996

Gerson Goldhaber: Adventures of Experimental Physics, Vol. 5, 131 (1976)

Photographs by Harvey Lynch and Vera Lüth

The SLAC Archivist Dorothy Leung

Many conversations and interactions with colleagues and friends

1976 Nobel Prize

"for their pioneering work in the discovery of a heavy elementary particle of a new kind"

2 years after the November Revolution

Burton Richter

Samuel C. C. Ting