The discovery of the J/ψ

Andrea Giammanco

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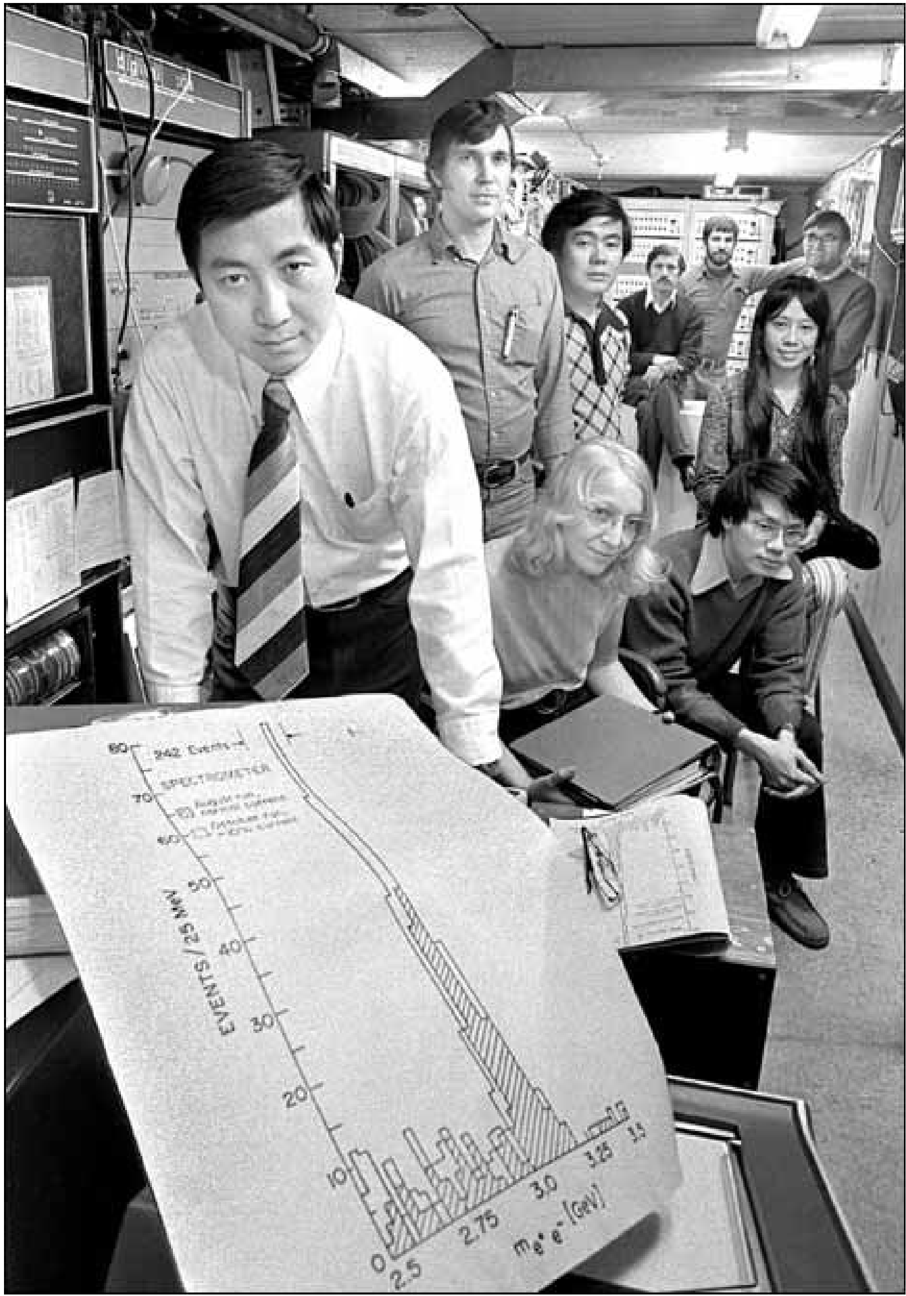
Physique des Particules Elementaires

http://cern.ch/andrea.giammanco/particules2009

Outline

- Status of knowledge in 1974
  - u,d,s quarks and Cabibbo angle
  - hypothesis of a 4^{th} quark
- The SLAC experiment
  - $R=\sigma(e^+e^- \to \text{had.})/\sigma(e^+e^- \to \mu^+\mu^-)$
  - The accelerator & the detector
  - Discovery of ψ and ψ'
- The Brookhaven experiment
  - $q\bar{q} \to e^+e^-$
  - Discovery of J
- Interpretation



Situation in 1974

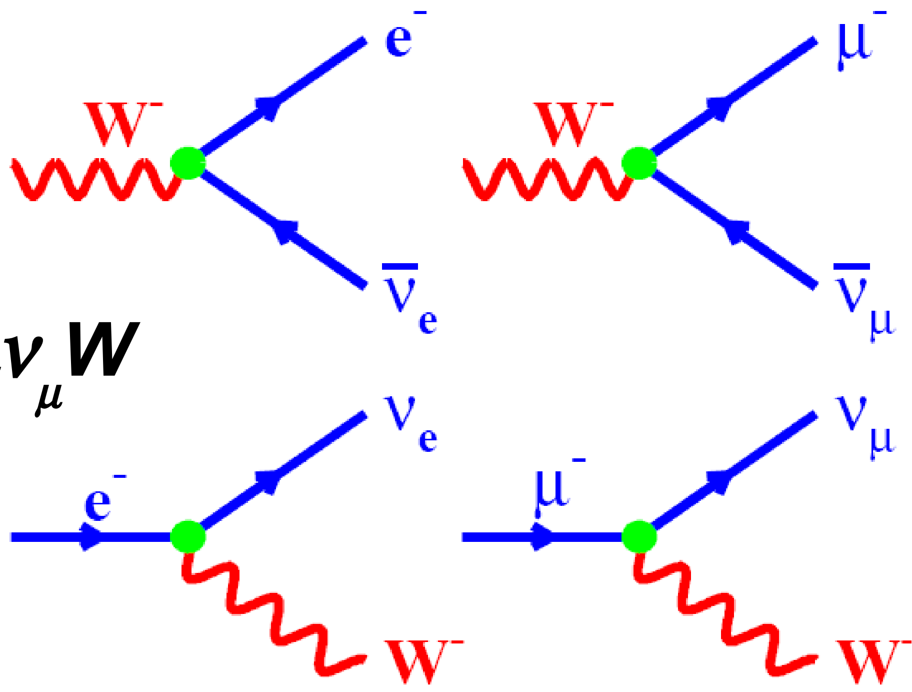
- Known leptons: e, μ, ν_e, ν_μ
  - Clearly divided in two generations (exact replicas apart from the mass)
- The quark model explained all the known hadrons as composed of u,d,s quarks
- The “partons” had been discovered in Deep Inelastic Scattering and QCD explained them as quarks (and gluons), valence+sea
- Electro-Weak Unification had been proposed
  - Taken seriously since the discovery of NCs in 1973

Leptonic weak interactions (CC)

- Leptons are represented in doublets

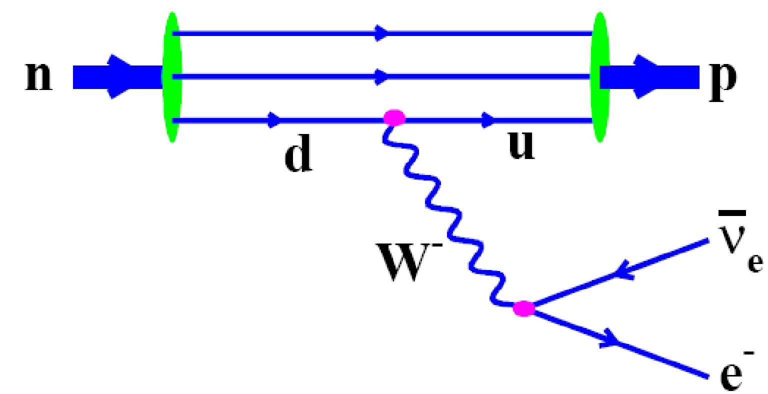
$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}, \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}$$

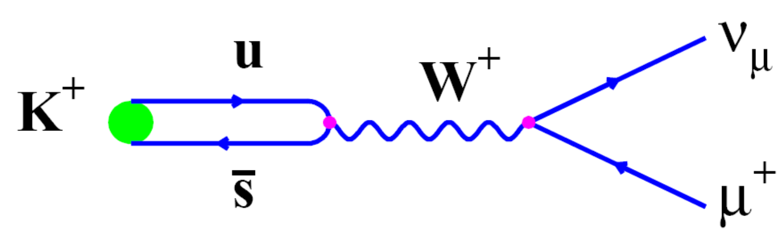
- W bosons only couple leptons of a same doublet:
  - $e\nu_e W$ and $\mu\nu_\mu W$
  - No $e\nu_\mu W$
- Universality:
  - Same strength for $e\nu_e W$ and $\mu\nu_\mu W$
  - Seen from pion decays
    - Homework! (Appendix)



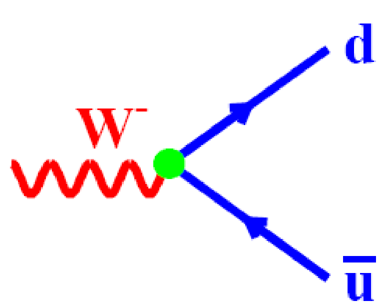
Hadronic weak interactions (CC)

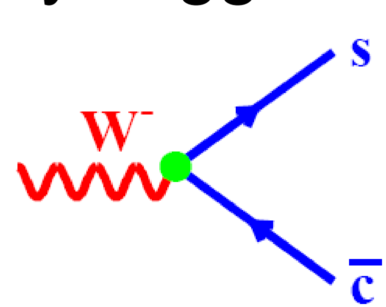
- But only 3 quarks were known at the time
- ***duW*** and ***suW*** both exist
  - Examples of ***duW***:
    - Neutron decay
    - Pion decay
  - Examples of s***uW***:
    - K decay (see figure)





- Analogy with leptons could already suggest a 4th quark





The Cabibbo angle

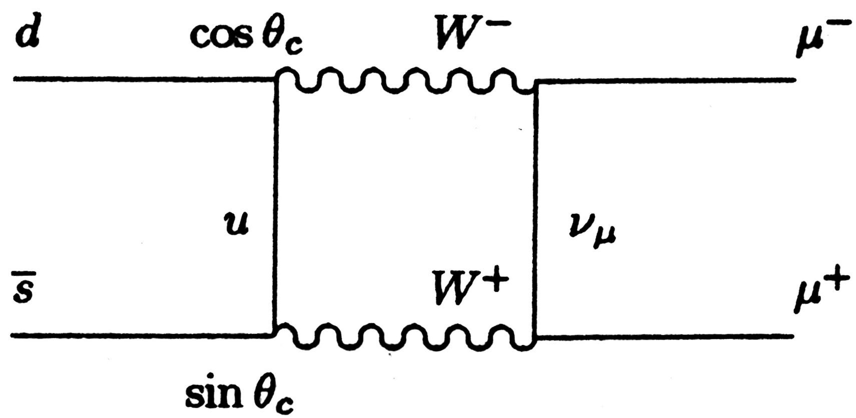
- The couplings $e\nu_e W$ and $\mu\nu_\mu W$ have the same strength, but the ***duW*** coupling is slightly smaller (~97%) as seen from neutron decay, ***suW*** is much smaller (~22%) as seen from the decays of S particles (K, Λ, Σ)
- Cabibbo noticed that it was sufficient to postulate a rotation between the Q=-1/3 quarks:

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix} .$$

Note: Kobayashi and Maskawa won Nobel Prize 2008 for having generalized this idea

- "Weak universality": $e\nu_e W = \mu\nu_\mu W = d'uW$ $(s'uW=0)$

Problem with the theory

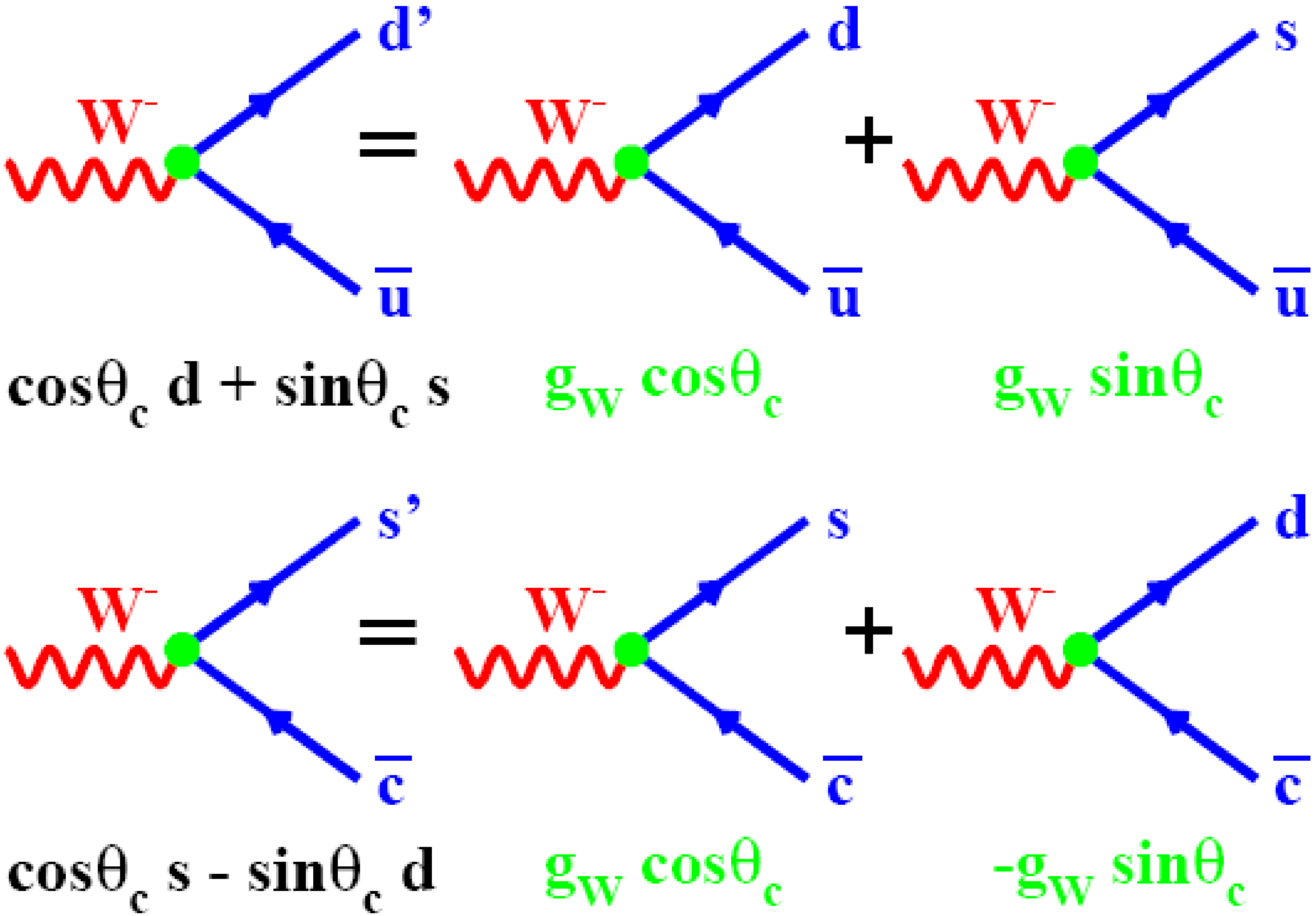


- $K^0(=d\bar{s}) \rightarrow \mu^+\mu^-$ is an example (not the only one) of a process which is observed to be much less frequent than expected by the Standard Model (under the assumption that only u,d,s exist)
- This kind of discrepancies were a big obstacle to the acceptation of the Standard Model

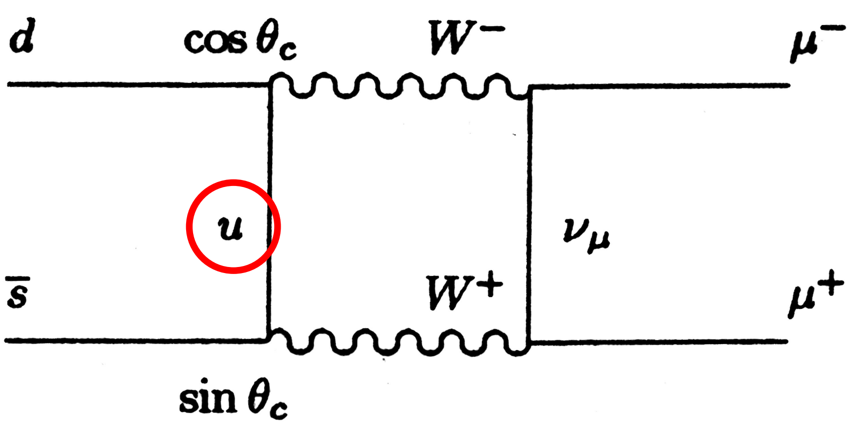
Eigenstates of different hamiltonians

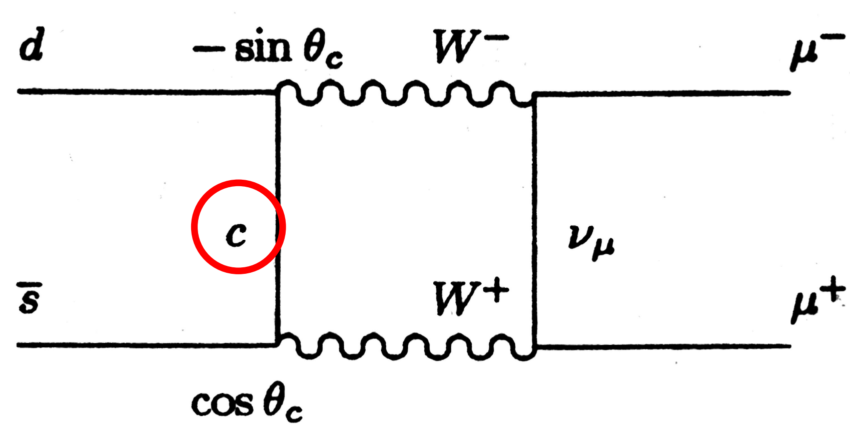
- Basic idea: the global hamiltonian (the operator whose eigenvalues are the allowed energies) is the sum of independent pieces, one per interaction
- The eigenstates of the strong and electromagnetic interactions are **u,d,s**
- The eigenstates of the weak interaction are **u,d',s'**
- Most of the creation processes for hadrons are mediated by strong force, less frequently by EM force, negligible contribution from weak force → almost always a $\mathbf{d\bar{d}}$ or $\mathbf{s\bar{s}}$ or $\mathbf{u\bar{u}}$ is created, not $\mathbf{d'\bar{d}'}$ or $\mathbf{s'\bar{s}'}$
- But if a particle has only weak decays, one has to write **|d›** or **|s›** as α **|d'› +** β **|s'›** and evolve the **|d'›** and **|s'›** components independently

Hadronic weak interactions (CC) with 4 quarks



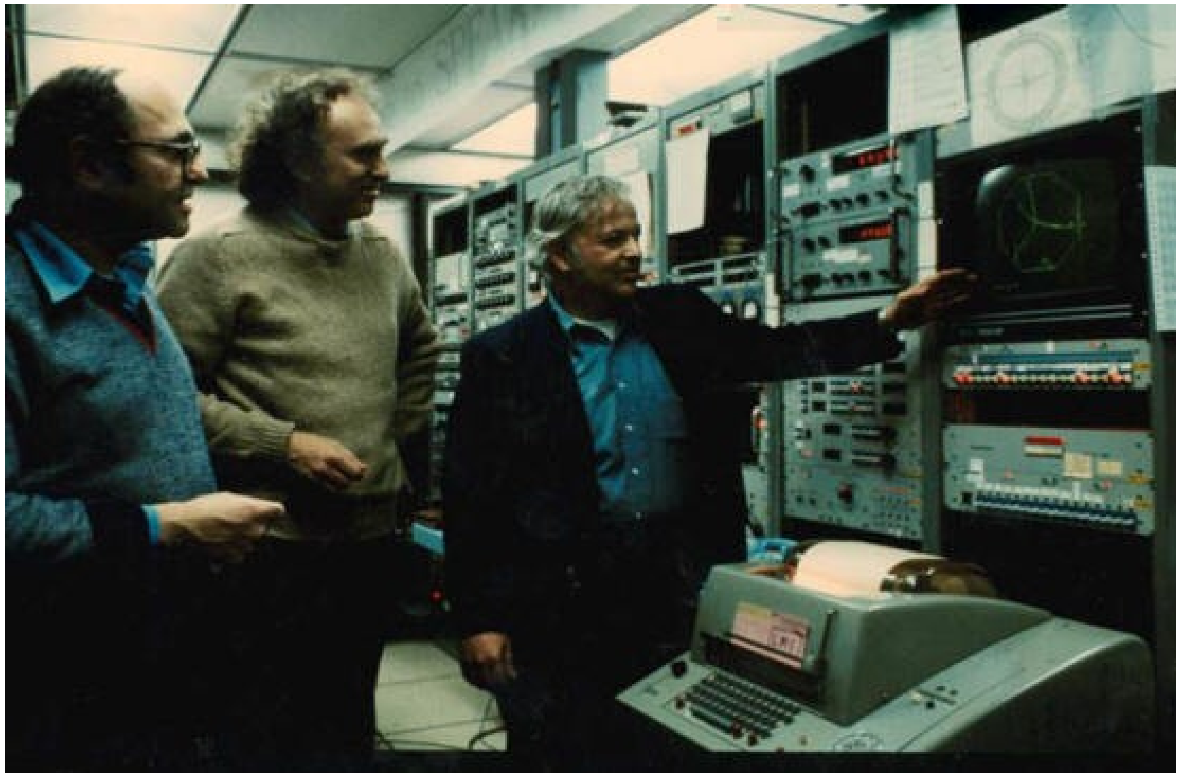
The GIM mechanism (Glashow/Iliopoulos/Maiani)





- An exact replica of the u quark provides the right cancellation between the two amplitudes
  - Question: why is the sign opposite?
  - Hint: write d and s in terms of d' and s'
- Note: cancellation is exact only if $m_u = m_c$
  - This way you could predict m_c

The SLAC experiment



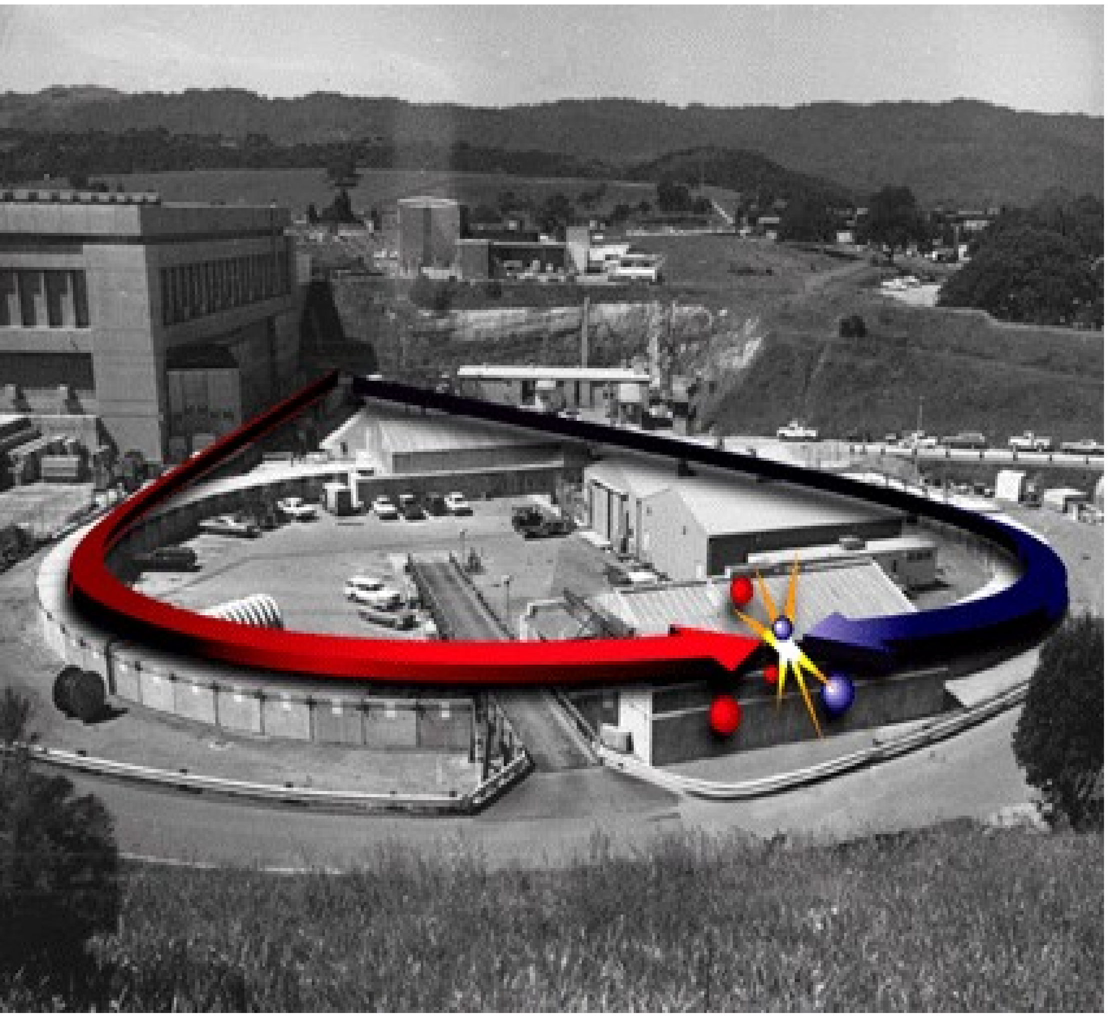
- I'm going to describe the experimental apparatus (accelerator and detector) which permitted the observation of the first hadron composed of “charm” quarks in e^+e^- collisions
- It was not intended for that!

The original motivation: R

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

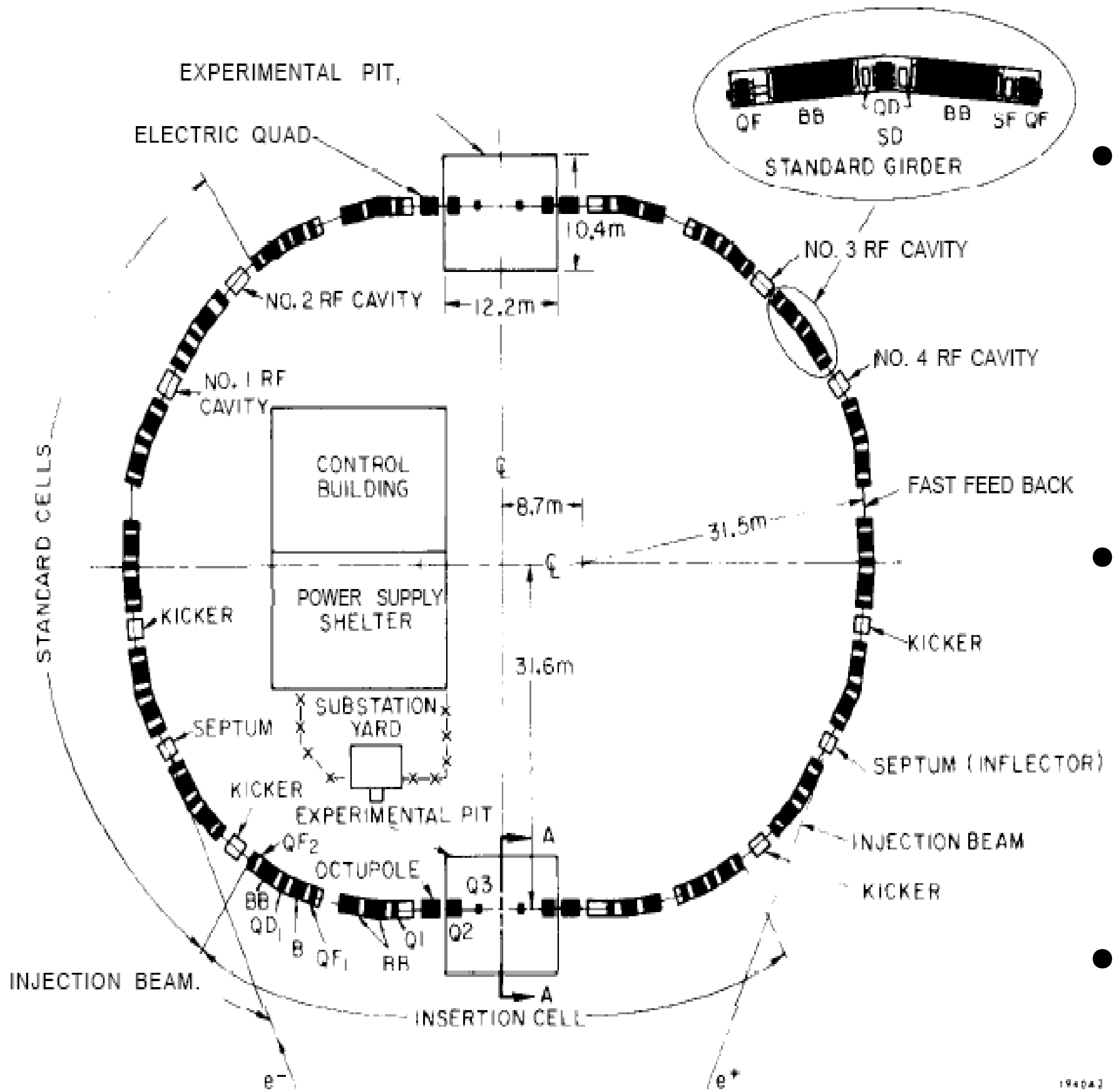
- In the quark model, the process $e^+e^- \to q\bar{q}$ is perfectly analogous to $e^+e^- \to \mu^+\mu^-$, the only differences being:
  - The electric charge (cross section prop.to Q^2)
  - Extra degree of freedom: number of colors (needed to explain the spin of the Δ(uuu); 3 colors)
- Standard Model: $3x[(-1/3)^2+(2/3)^2+(-1/3)^2] / 1^2 = 2$
- Other models: from 0.36 to 16 (or even more)

The accelerator SPEAR



- e^+e^- collider
- Opposite beams with equal energy: all the energy is available for particle creation
- Why not just shooting positrons against a target? (Lots of electrons in matter)
- Homework: calculate the energy needed for a reaction *ab*→*c*, when *b* is at rest, with m_c=3 GeV and m_a,m_b « m_c

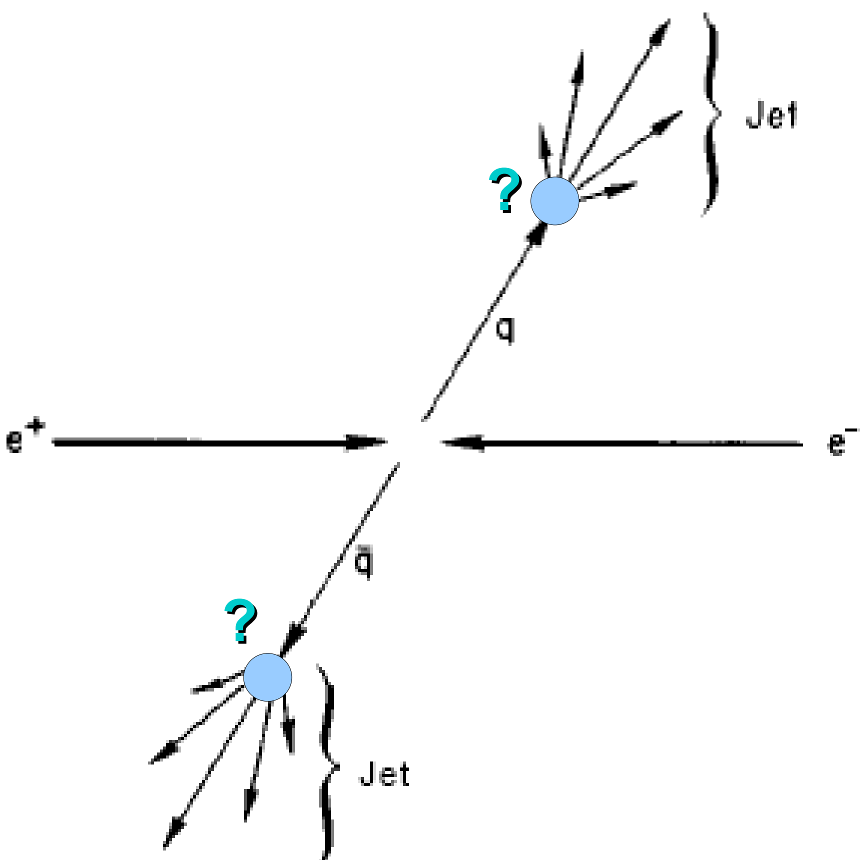
The ring

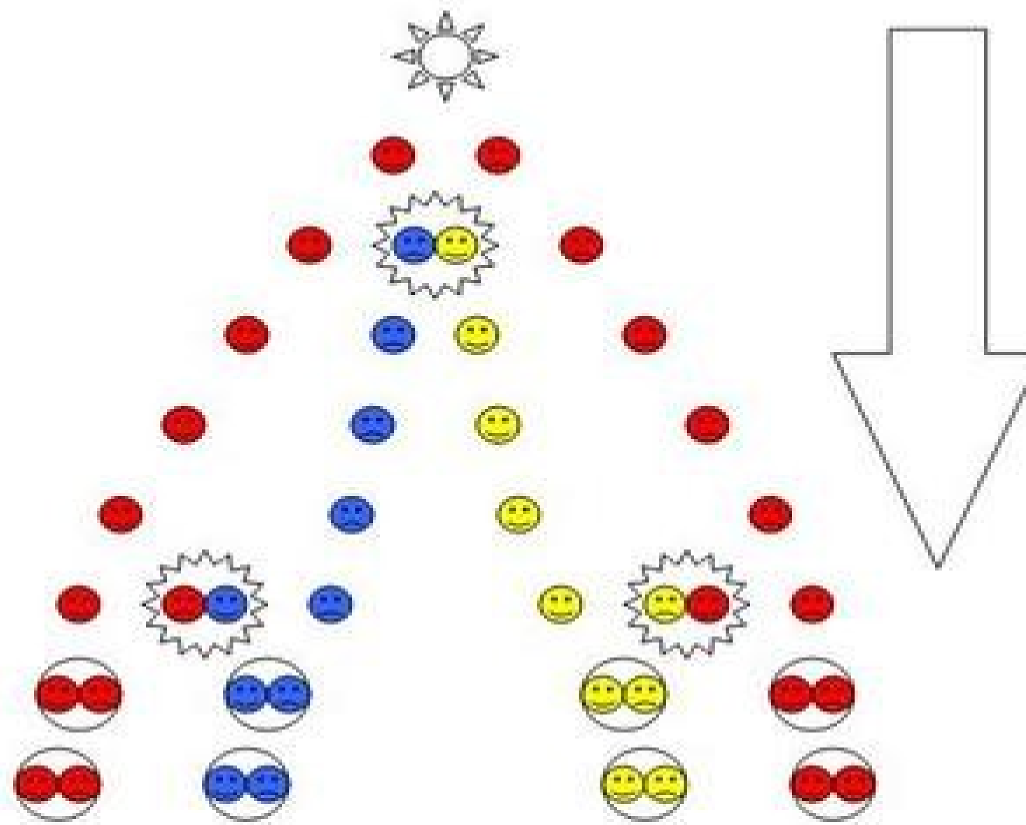


- RadioFrequency (RF) cavities: oscillating EM fields give an acceleration exactly when a bunch of particles is passing
- Magnetic dipoles: curvature (opposite for opposite charge, so a single ring is used for both e+ and e-)
- Quadrupoles, octupoles: they focus the beams

“Fragmentation” (also known as “hadronization”)

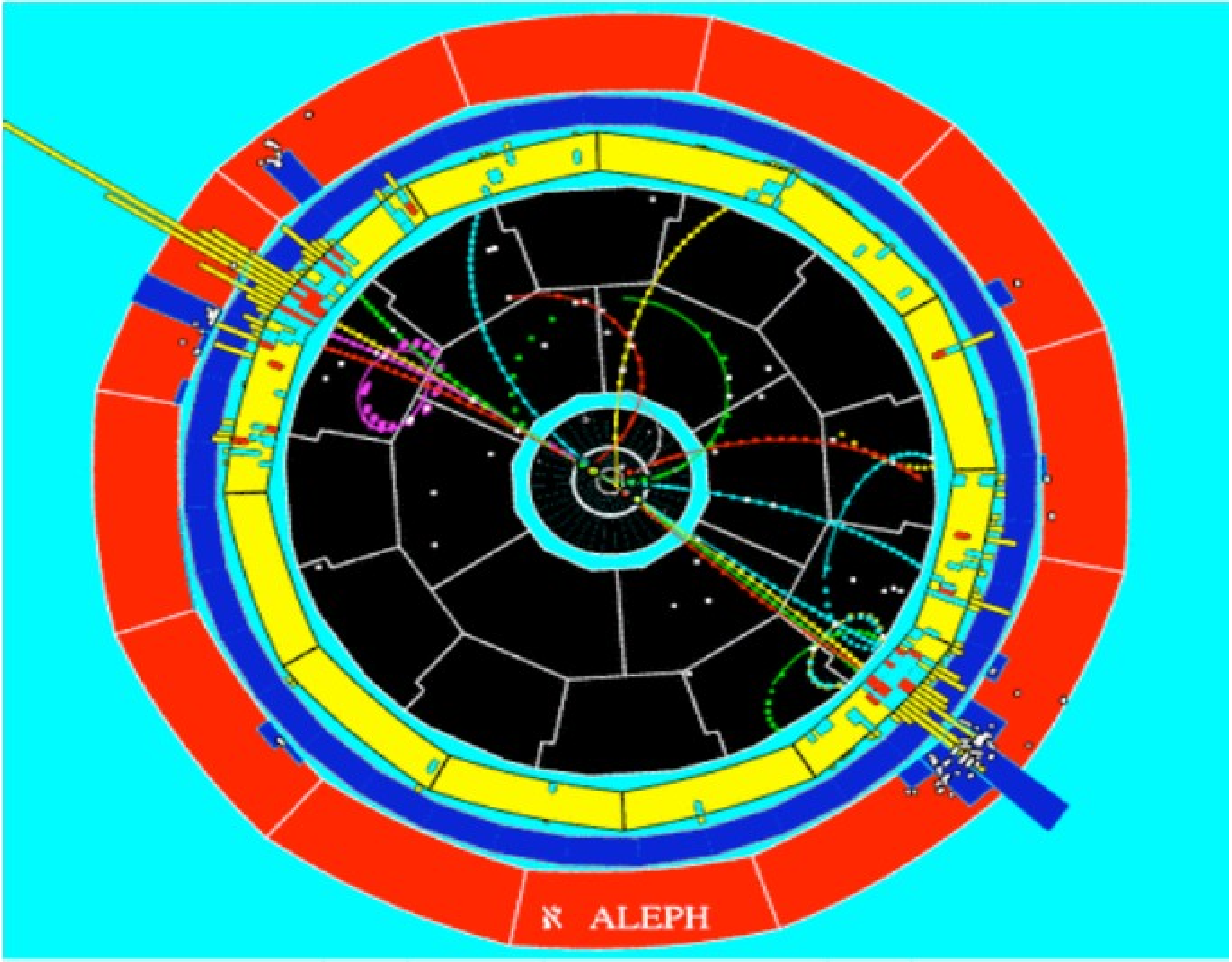
- As you know, you can't observe quarks directly
- QCD explanation: the attraction <u>increases</u> with r, so at some point the potential energy of the system is larger that $2m_q$



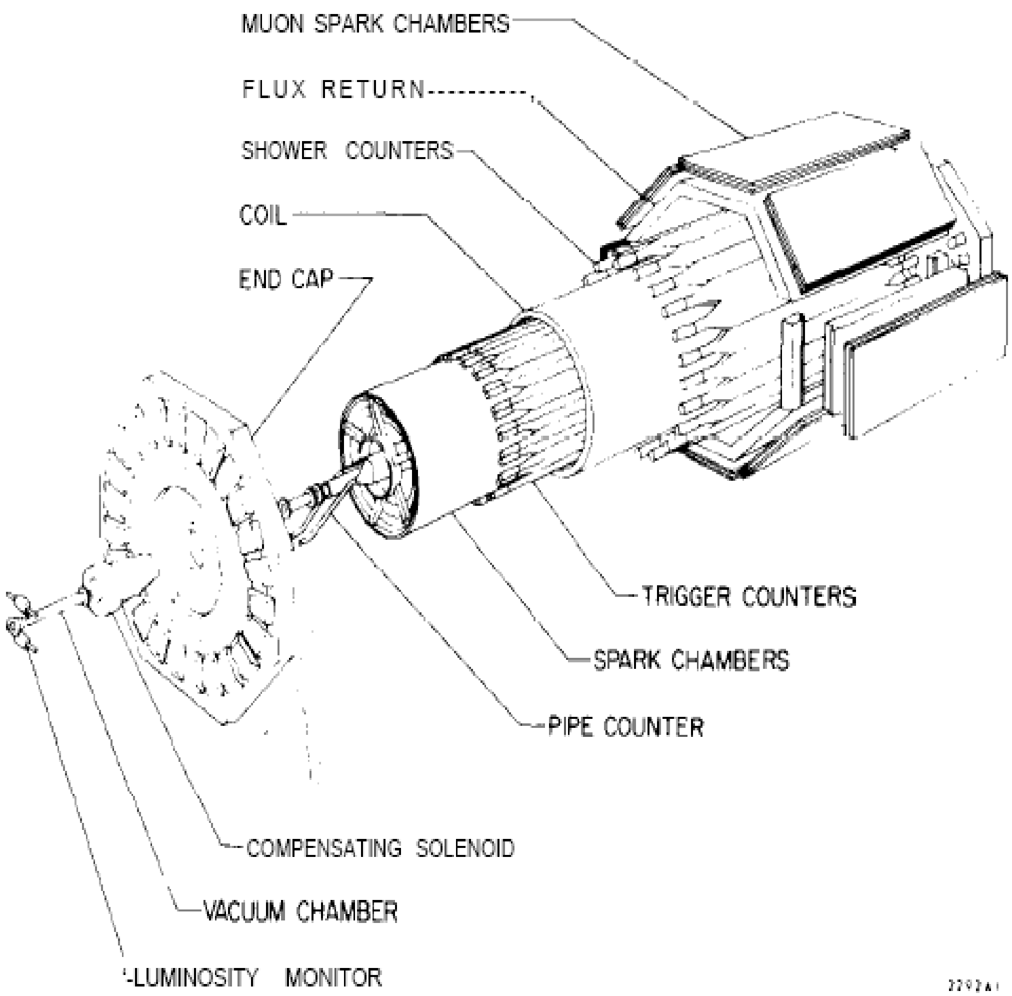


Credit for this picture: T.Dorigo

Typical result of a $q\bar{q}$ creation



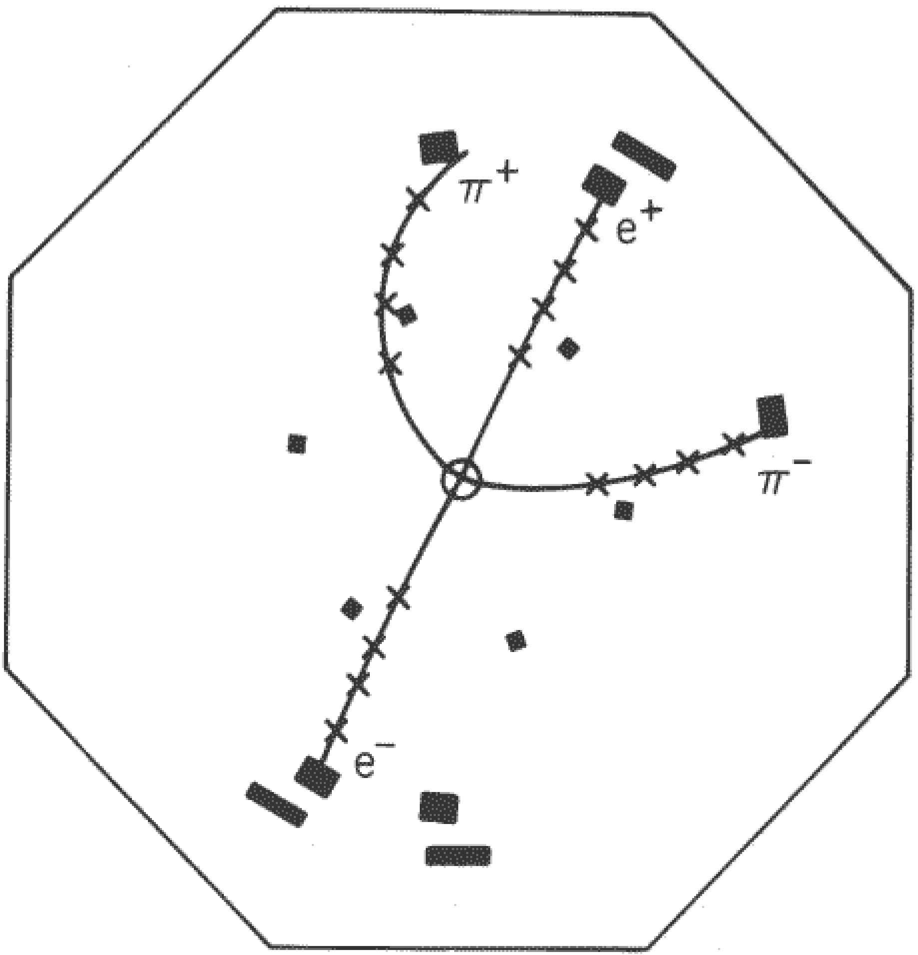
The MARK I detector



Note: this is an “exploded view”

- A very “modern” detector (most of the current detectors at colliders have the same general structure):
- “4π” acceptance
- Onion structure, with different specialized sub-detectors
- Tracking of charged particles
- Magnetic field (solenoidal) for momentum measurement
- Shower counters (for e,γ)
- Muon chambers

The tracking sub-detector

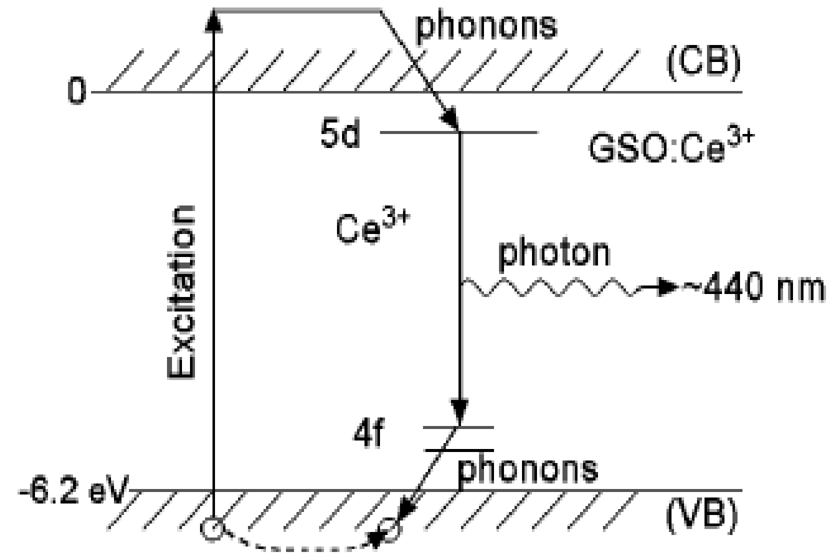


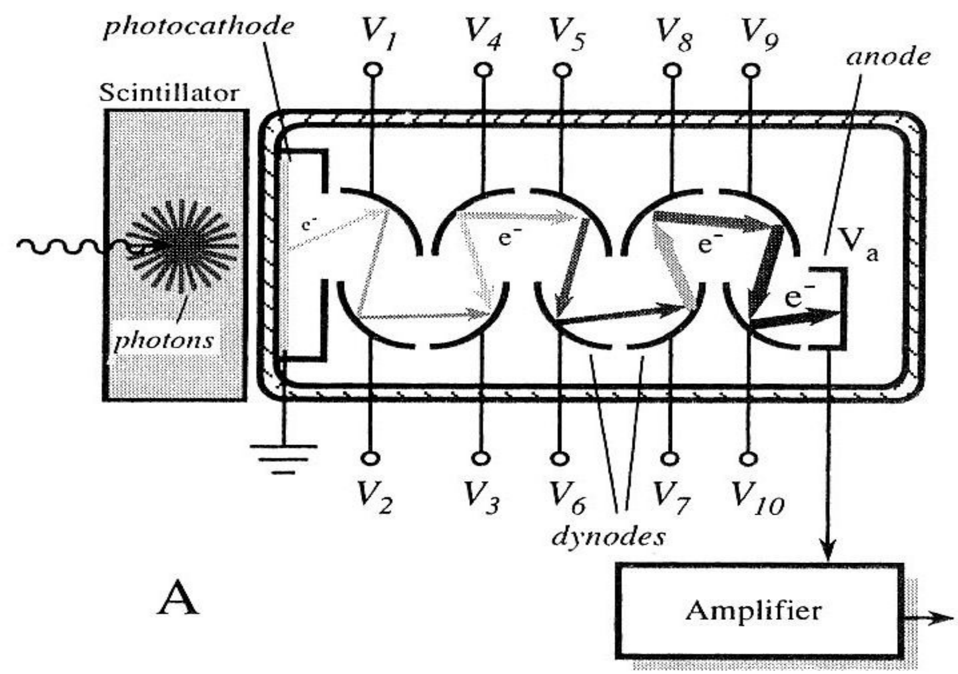
The lines come from a best fit to the sparks, plus the center of the detector as constraint

- **Spark chamber**: a volume filled with a gas, traversed by several wires at very high voltage
- A charged particle leaves a trail of ionized gas along its trajectory
- A **trigger** system (explained later) switches on the voltage to the wires, creating an intense electric field: the passage of the charged particle creates sparks along its trajectory
- Each spark → a voltage drop in the nearest wire; easy to digitalize and analyze offline

The trigger / time-of-flight detectors

- They were **scintillator detectors**
  - On the beam pipe, and between spark ch. and shower counters
- Very fast detectors:
  - Switch on the other detectors
  - Time-of-flight: T(ext.)-T(beam p.)
- A **scintillator** is a substance that absorbs the energy (released by ionization) of a traversing particle through molecular/reticular excitations and then, after a very short delay (~ ns), re-emits the energy as photons (fluorescence)
  - These photons are in turn detected by a **PhotoMultiplier**

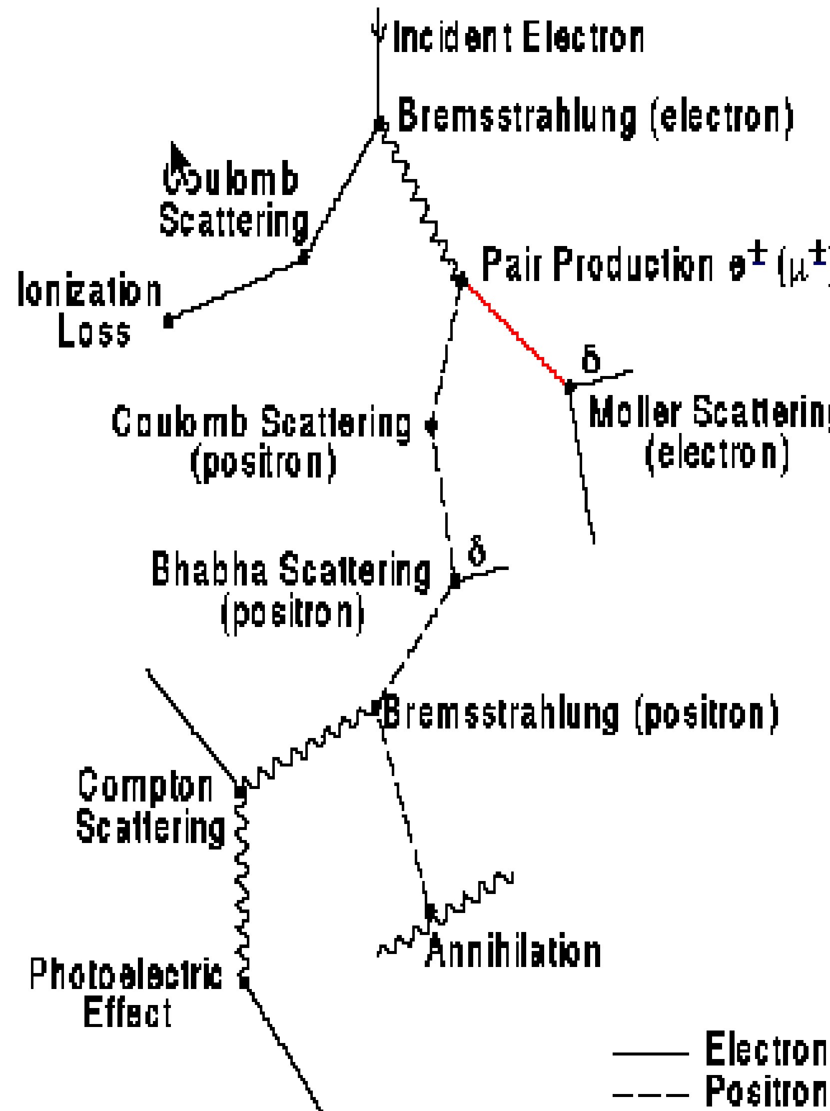




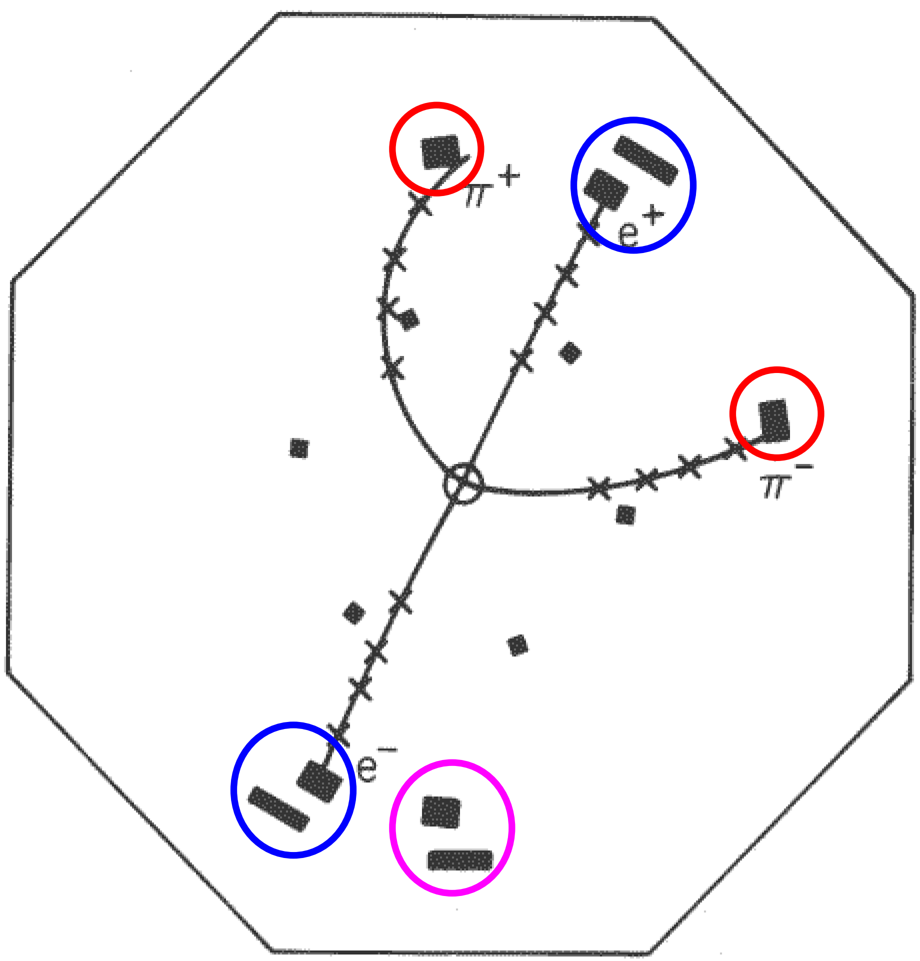
A

Electron identification detectors

- They were **shower counters**, made of a layer of **lead** followed by a **scintillator detector**
- Lead (Pb) has high Z; this means very high probability of interaction for photons and electrons
- Result is an "electromagnetic shower" (see figure)
- If the incident particle is a $e^+/e^-/\gamma$, at the exit of a lead layer you have many more $e^+/e^-/\gamma$: large cumulative signal in the scintillator detector
- Hadrons/muons: "simple" signal
  - Threshold set between e/γ and h/μ



Example

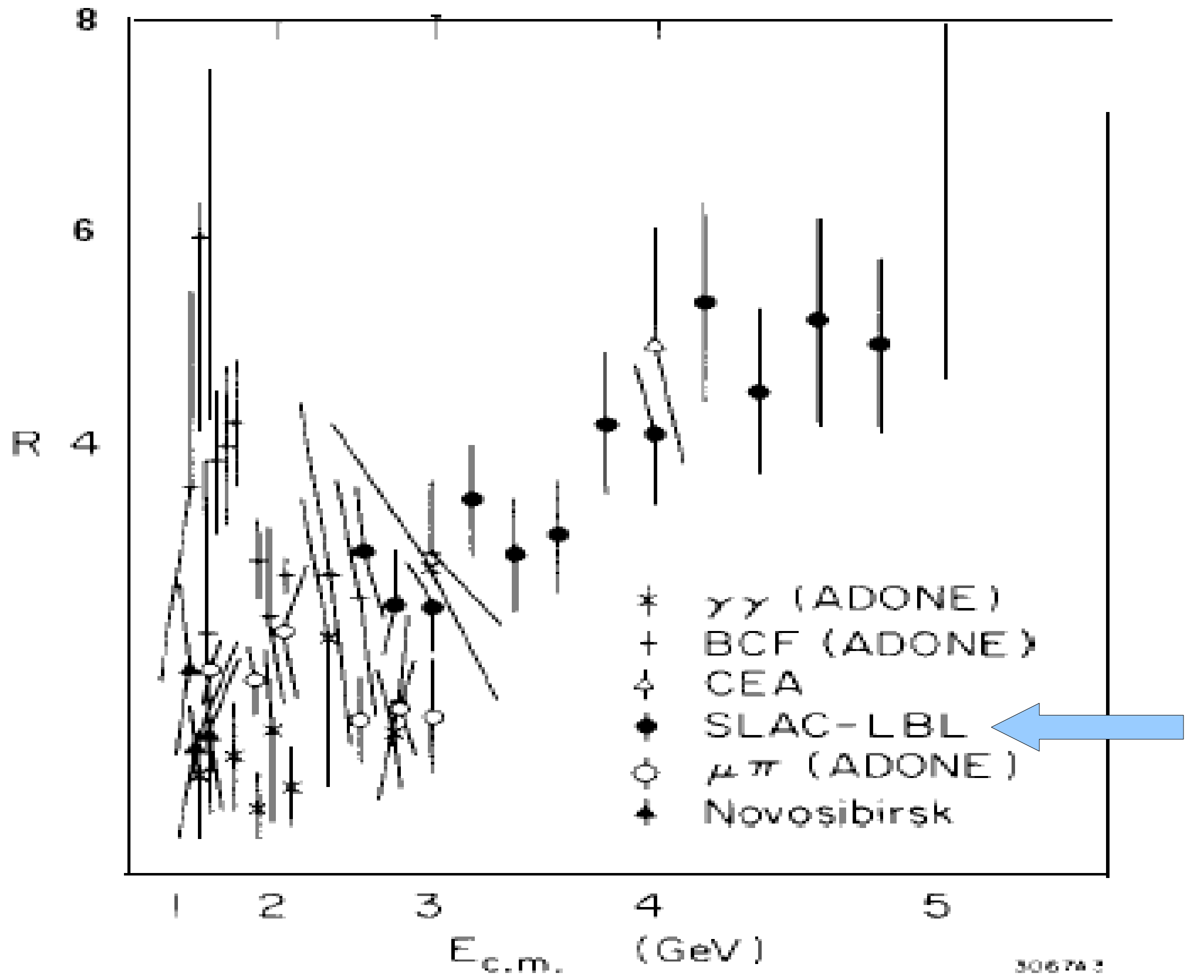


- Electron:
  - Track in spark chamber
  - Signal in 1st scintillator (trigger)
  - Signal in 2nd scintillator (shower)
- Photon:
  - No track
  - Signal in 1st scintillator (trigger)
  - Signal in 2nd scintillator (shower)
- Other:
  - Track in spark chamber
  - Signal in 1st scintillator (trigger)
  - Below the threshold in 2nd scint.

Muon identification

- “Muon chambers”: **proportional gas counters** alternated with iron layers
- Before arriving there, a particle had to traverse the return coil of the solenoid: iron, 20 cm thick
- Hadrons undergo nuclear interactions, muons do not
- Electrons and photons are stopped even before (due to the lead of the shower counters)
- So, if a particle gives a signal in <u>all</u> the muon chambers, it is almost certainly a muon
- Background: the rare “punch-through” hadrons and some (uninteresting) $\pi/K \to \mu\nu$

Early results on R

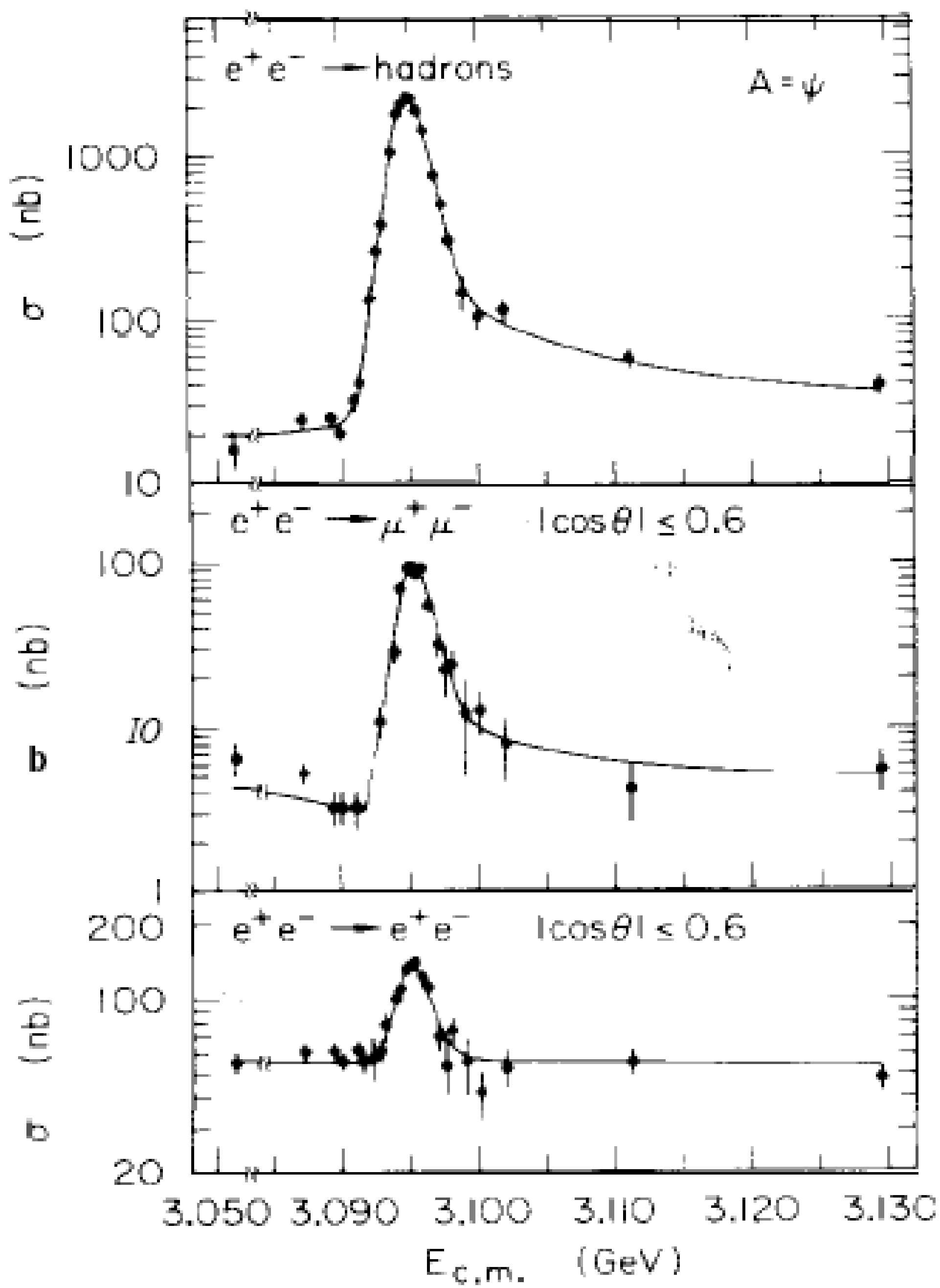


The low-energy data (E<3 GeV) were consistent with R=2, while the high-energy data indicated R>2 (inconsistent with Standard Model). The first MARK I data joined smoothly both regions.

The mystery of the unstable cross section

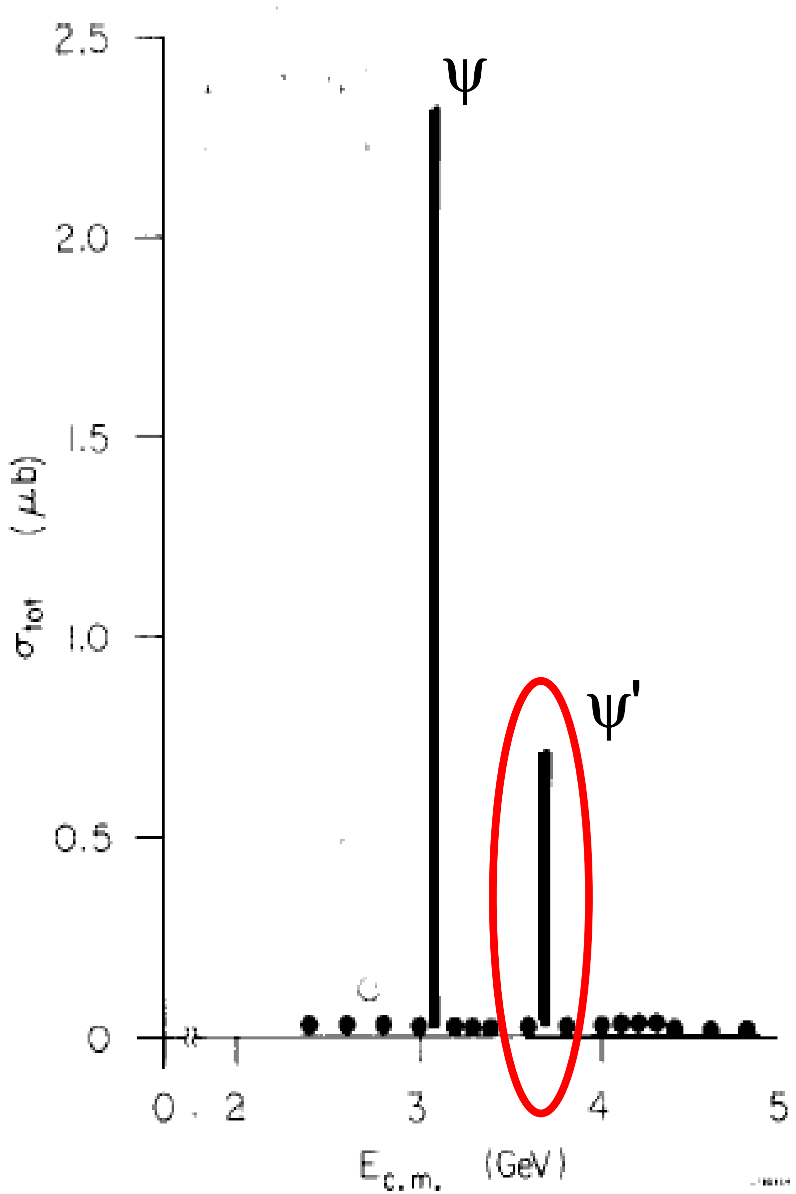
- The region of the rise (3-4 GeV) was measured with particular attention: SPEAR was operated with energy steps of 0.2 GeV (3.0, 3.2, 3.4, ...)
- Everything was ok, apart from a slight anomaly at 3.2 GeV: total cross section seemed a bit too high
- It was decided to check also at 3.1 and 3.3 GeV
- And at 3.1 GeV things went crazy
  - Cross section was huge
  - And it was changing from run to run!
  - (Now we know that it was due to the imprecision in the beam energy, in a region of fast rise of the cross section)

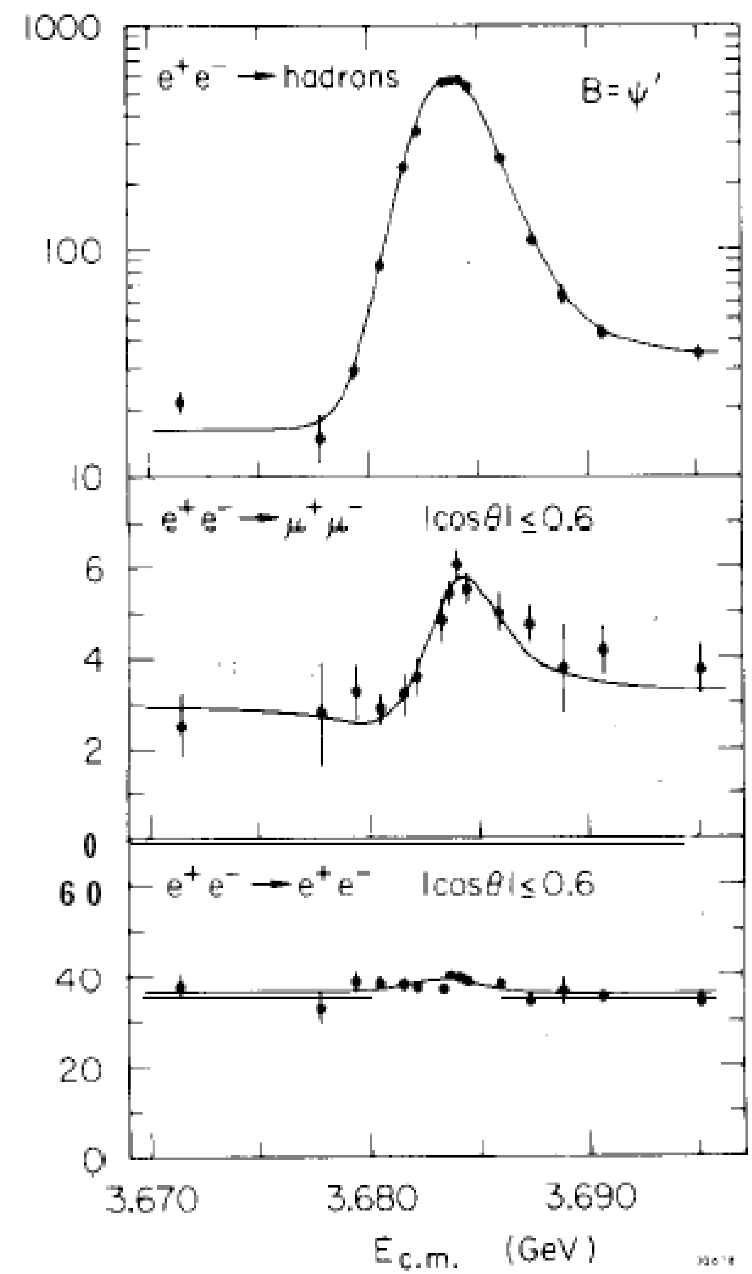
Energy scan around 3.1 GeV



- Measurement was repeated with a fine scan of the energy
- A very precise magnetometer was used, this time, to measure the beam energy with a precision of ±0.1%
  - Question: how does it work?
- A clockwork mechanism automatically increased the energy by 1 MeV every two minutes
- This was sufficient to show a clear peak; a slower scan with higher statistics was performed around this peak (see figure)

And it was not the end of the story



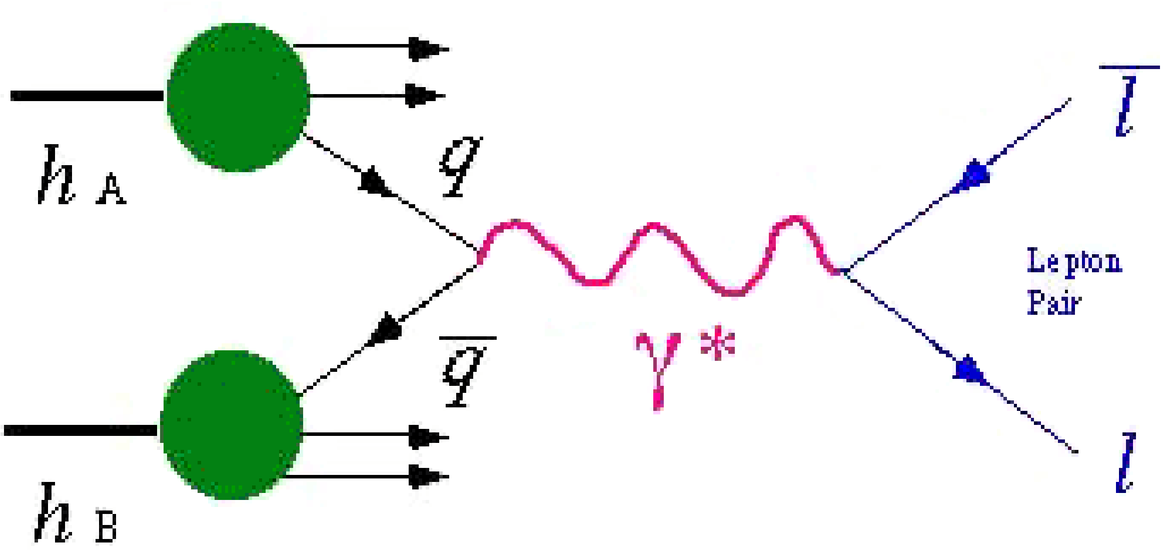


Other resonances were discovered later

The Brookhaven experiment

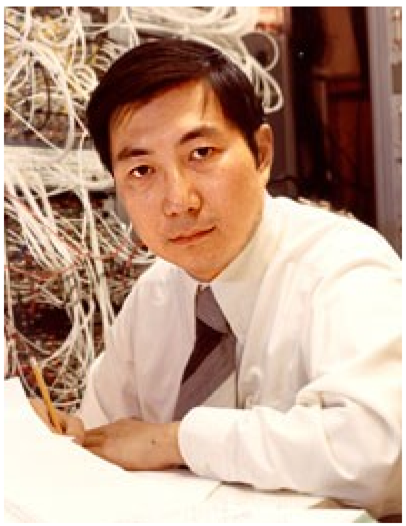
- Also this was not looking for the charm quark
- But it was looking for generic new hadronic resonances (composed of the usual u,d,s)
- More traditional for the time:
  - Proton beam
  - Fixed target (mostly Be, also Cu & Pt)
  - Small angular acceptance
  - Very specialized detector for only one final state: electron pairs

The Drell-Yan process



- Instead of the virtual photon, you may have a neutral "resonance" (short-lived particle)
- In the parton model, the initial particles are $q\bar{q}$ and the antiquark comes from the "Dirac sea"
- You have also other particles in the final state

Ting's official proposal for the new experiment with Brookhaven's beam



The best way to search for vector mesons is through production experiments of the type $p + p \rightarrow V^0 + X$, $V^0 \rightarrow e^+e^-$. The reasons are:

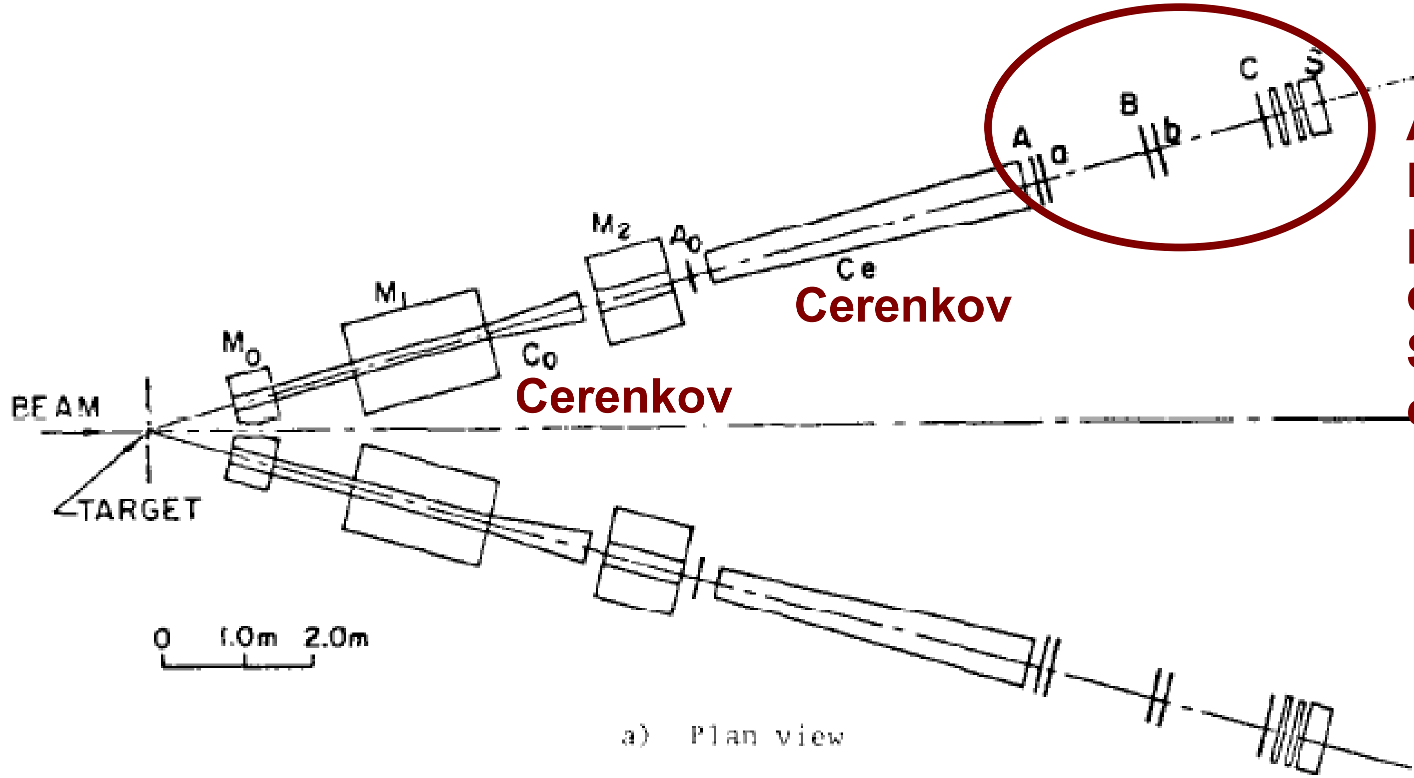
(a) The V^0 are produced via strong interactions, thus a high production cross section.

(b) One can use a high intensity, high duty cycle extracted beam.

(c) An e^+e^- enhancement limits the quantum number to 1^-, thus enabling us to avoid measurements of angular distribution of decay products.

Contrary to popular belief, the e^+e^- storage ring is not the best place to look for vector mesons. In the e^+e^- storage ring, the energy is well-defined. A systematic search for heavier mesons requires a continuous variation and monitoring of the energy of the two colliding beams—a difficult task requiring almost infinite machine time. Storage ring is best suited to perform detailed studies of vector meson parameters once they have been found.

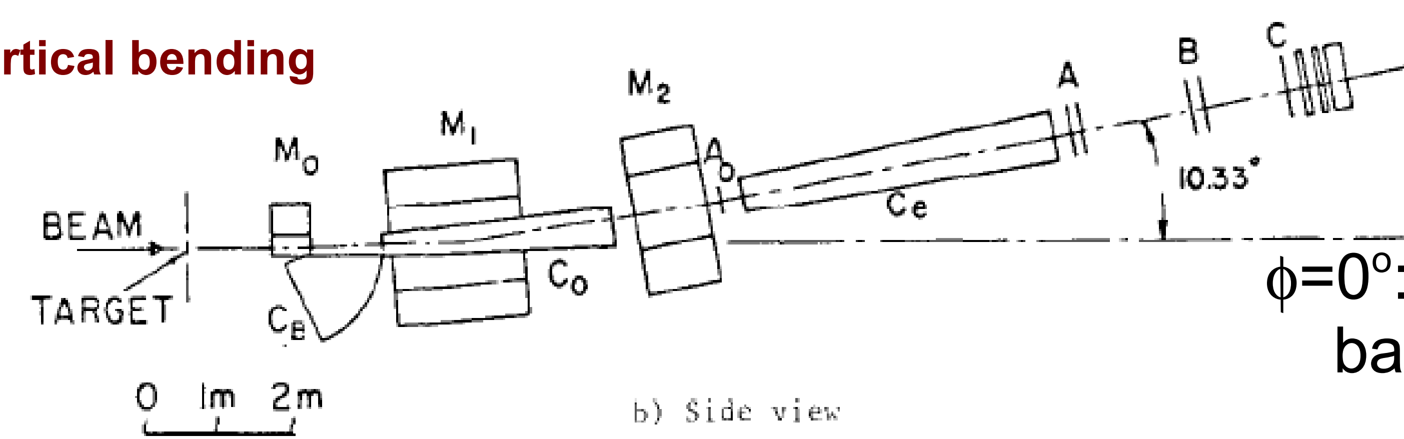
The Brookhaven detector



a) Plan view

A,B,C: Multiwire proportional chambers, S: shower counter

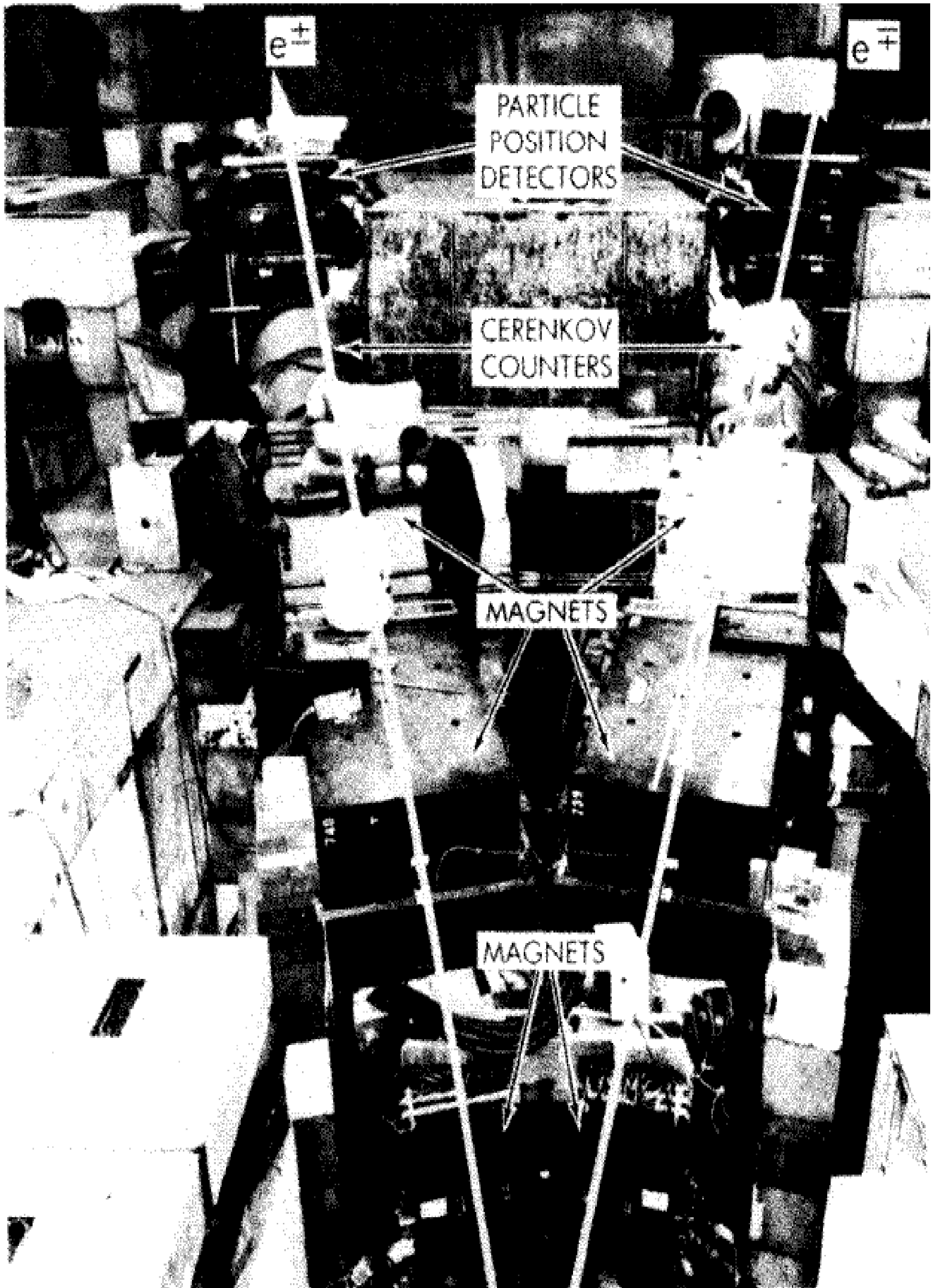
Magnets: vertical bending



b) Side view

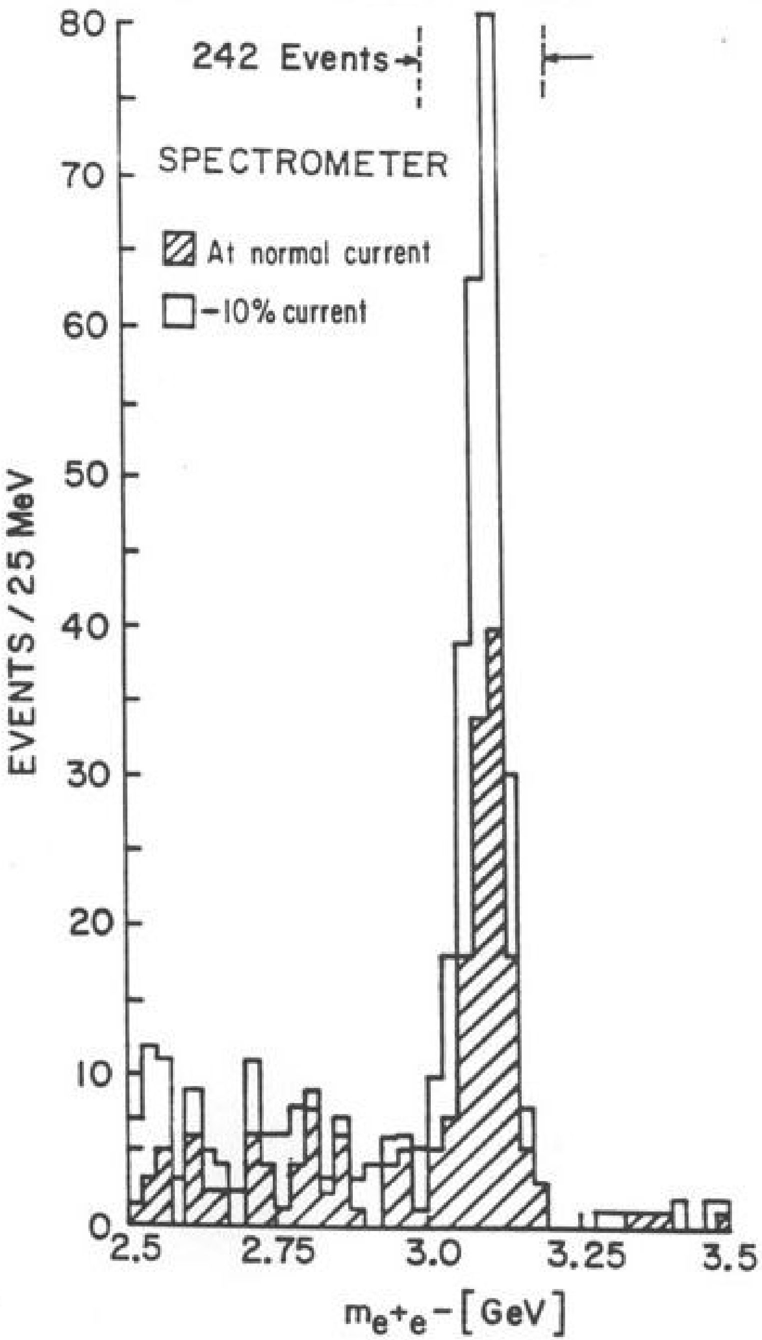
ϕ=0°: very high background

Sub-detectors



- **Cerenkov counters**: hadron rejection; 8 photoelectrons for a single electron, 16 for an electron pair ($\gamma \rightarrow e^+e^-$, background)
  - They are fast detectors, enabling to measure the time difference between the electrons in the two arms, thus rejecting accidental combinations
- **Multi-wire proportional chambers**: precise reconstruction of the trajectory → good angular resolution; multi-track events are rejected
- **Shower counters:** further electron/hadron discrimination

The J particle

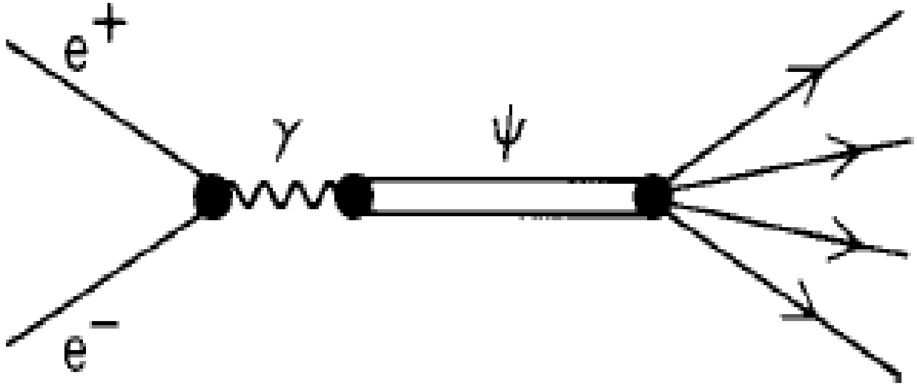


- $M_{ab} = 2\, p_a p_b\, [1 - \cos(\theta_a - \theta_b)]$ in the approx. of massless final particles (good for electrons at high p). $M_{ee} = 2\, p^2\, [1 - \cos 2\theta]$
- There are two histograms here, because they checked that the peak didn't depend on experimental settings (in this case, the magnet current – or, equivalently, p)
- Checks on accidental combinations:
  - signal is proportional to the beam intensity, accidental combinations are proportional to the square of the beam intensity; so, by variating the intensity one can estimate the amount of this background
  - they variated also the target thickness; question: doubling or halving the thickness, what do you learn?

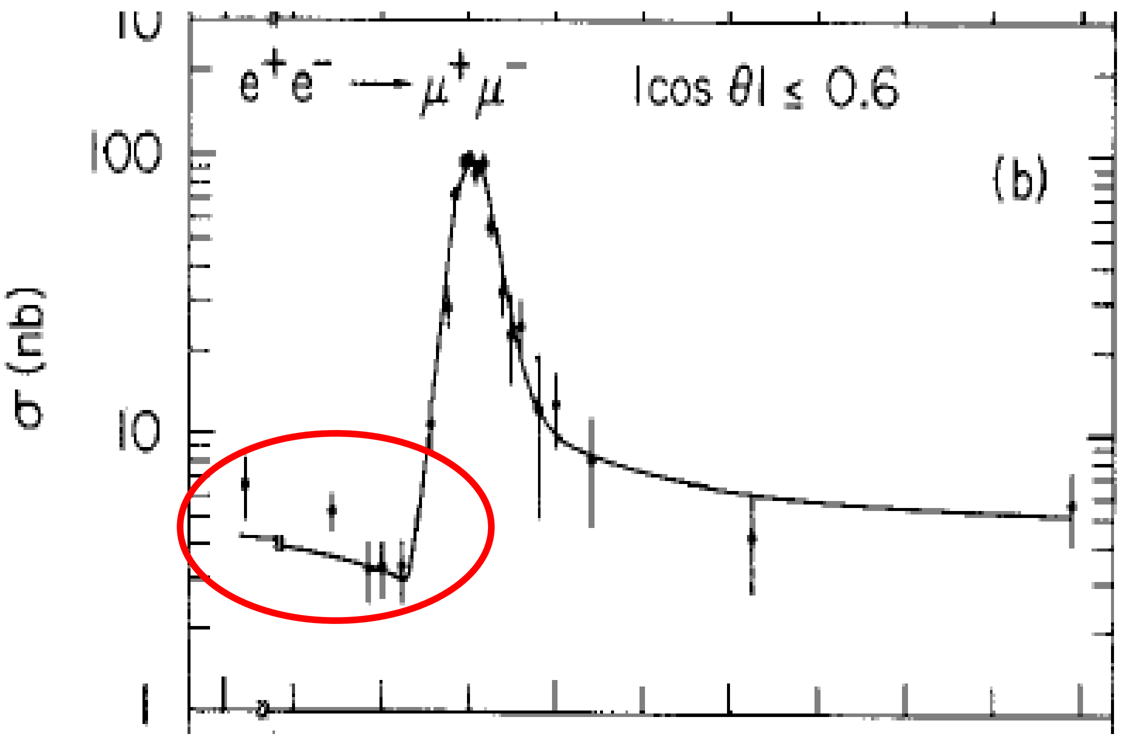
Ok, so you have a new particle. But what is it?

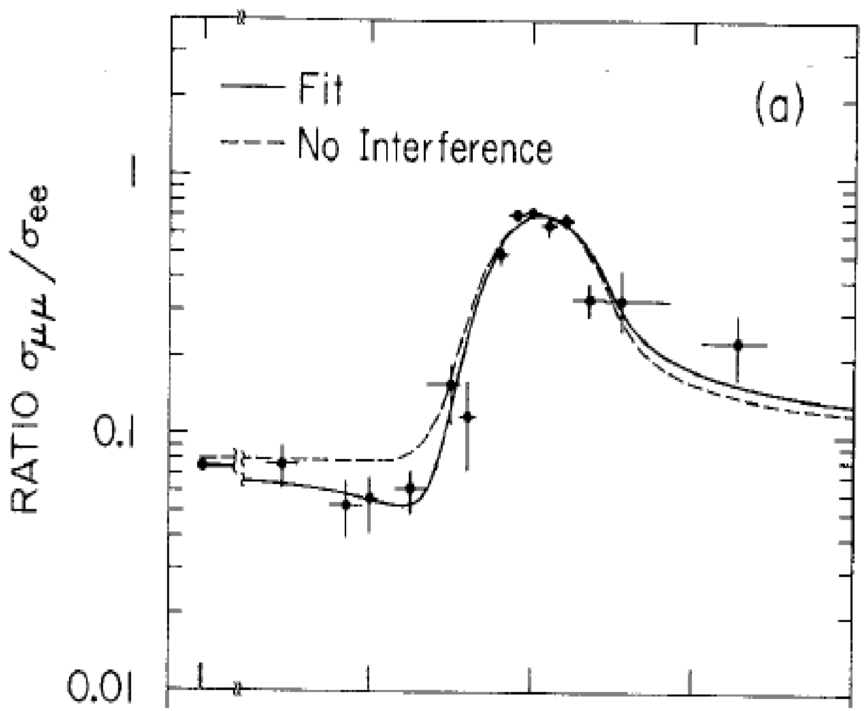
- Textbooks and lessons (including this one) risk to give the false impression that the correct interpretation was immediately found at the time
- But usually you need to know a lot of properties of a particle before guessing how it fits into one or more models
- The simple presence of a resonance doesn't tell you much
  - ...but the presence of *two* identical resonances suggested that, whatever they were, they were composite
- The most economical explanation in the context of the SM was that this resonance was the Z boson, predicted by the Electro-Weak unification and responsible of NC interactions
  - (Note that, in some non-SM theories, W and Z are composite)

J^{PC}: spin, parity, charge conjugation



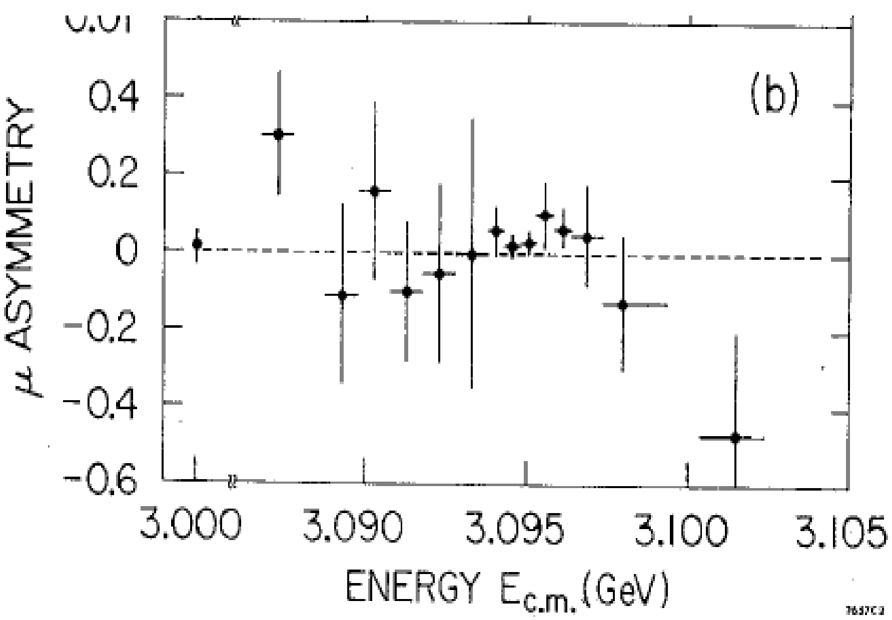
If this diagram exists, the J/ψ has the quantum numbers of the photon (1^{--}).
In this case, you expect an interference between $e^+e^- \to \gamma \to J/\psi \to \mu^+\mu^-$ and the normal (direct) $e^+e^- \to \gamma \to \mu^+\mu^-$.
There is indeed evidence of an interference effect (see figures).

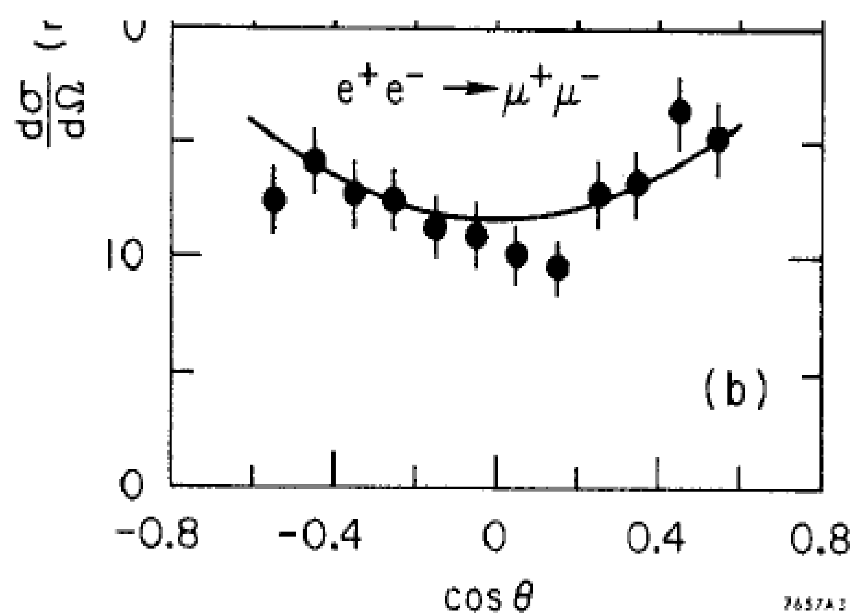




How do you know that it is not a Z?

- P conserved ↔ Forward/Backward symmetry; the Z would cause an asymmetry (weak interactions violate P)



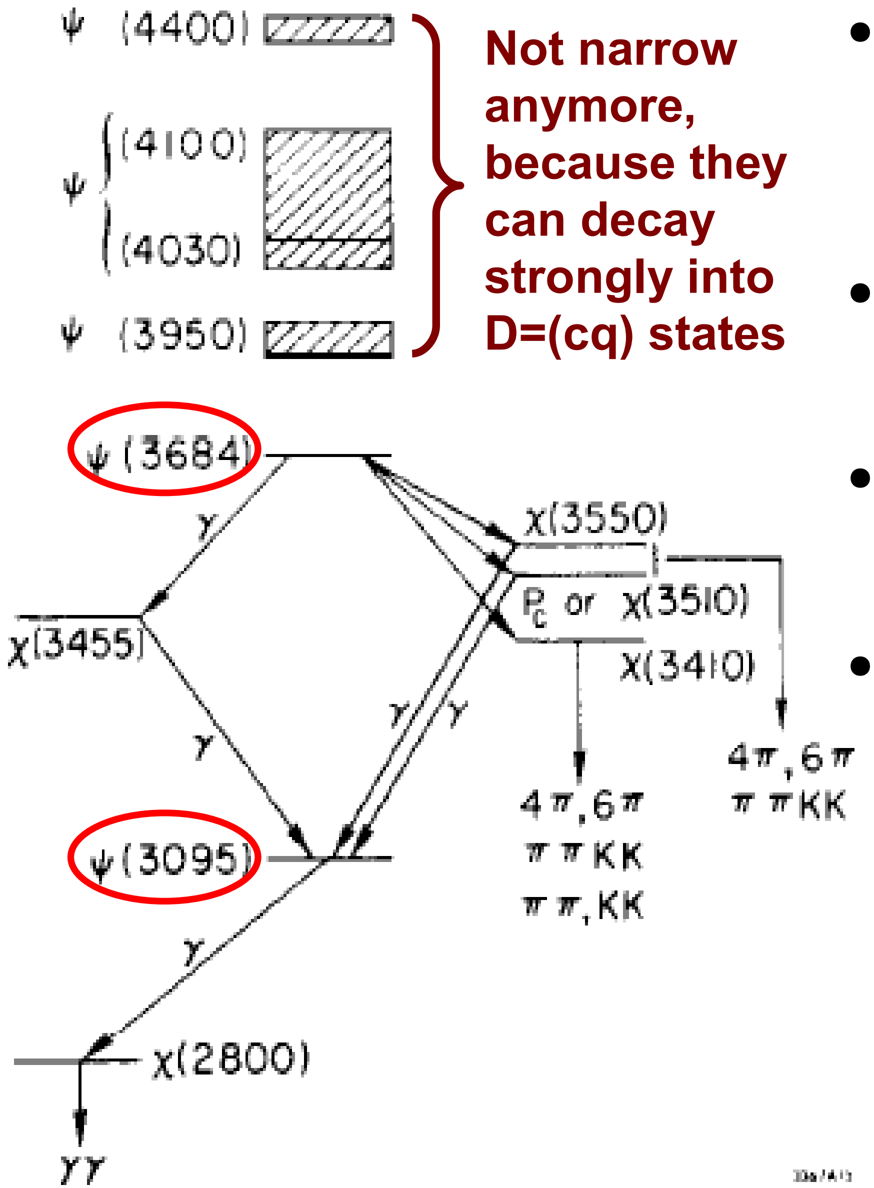


Fit curve: 1+cos²θ

Why is the width so small?

- For decays involving quark anti-quark annihilation the initial and final states are connected by gluons
- Since gluons carry color and J/ψ is colorless there must be more than one gluon involved in the decay
- But C(J/ψ)=C(γ)= -1, while C(2g)=+1; you need at least 3g
- So, amplitude depends on $\boldsymbol{\alpha_s^3}$
- The value of α_s depends on energy
  - in the J/ψ system (since it is heavy), $\alpha_s < 1$
- This is also why the leptonic branching ratios are not negligible compared to the hadronic decays: the strong interaction is so suppressed to become of the same order of magnitude of the EM interaction

The "charmonium" spectrum



- The "positronium" is a hydrogen-like bound e^+e^- system, whose spectroscopy tells a lot about QED
- Similarly, the "quarkonia" composed of equal quarks tell a lot about QCD
- Heavy quarks make the calculation easier (non relativistic:Schroedinger eq.)
- Indeed, it was not by chance that ψ' was discovered so soon after ψ : one member of the collaboration proposed to scan around 3.7 GeV, after a quick calculation with some simplifying assumption on the potential V(r)

Historical note

- The charm quark was a typical theory success, being predicted before observation
- ...although very few really knew about that at the time (not the experimenters!)
- It would have been discovered much earlier, if more people had taken the GIM article seriously
  - The ISR accelerator (at CERN) produced a lot of J/ψ's, but its detectors were not designed for muon or electron pairs
  - The ADONE accelerator (in Italy, very similar to SPEAR) ran at 3.0 GeV; the day after the SLAC/Brookhaven announcement, they made a run at 3.1 GeV and confirmed the discovery
  - An experiment for $q\bar{q}\rightarrow\mu^{+}\mu^{-}$, but with poor momentum resolution, had noticed a “shoulder” ~3 GeV

Bibliography

- Textbooks:
  - Perkins, “Introduction to High Energy Physics”
  - Cahn, Goldhaber, “The experimental foundations of Particle Physics”
- Richter's and Ting's Nobel Lectures:
  - http://nobelprize.org/nobel_prizes/physics/laureates/1976/

Appendix: homeworks

Homework: test weak universality

- You observe the decays $\pi^+ \to \mu^+ \nu_\mu$ and $\pi^+ \to e^+ \nu_e$
- You see that the ratio electrons/muons is 1.28×10^{-4}
- You know that:
  - the pion has spin 0, the leptons have spin 1/2
  - the weak interaction involves only left-handed particles
- Goal: demonstrate that the couplings $e\nu_e W$ and $\mu\nu_\mu W$ have the same value
- Hints: first, demonstrate that, if $m_\mu = m_e = 0$, both decays are forbidden; second, consider the allowed phase space

Homework: extract the Cabibbo angle

- Goal: extract the Cabibbo angle by comparing the decays of charged kaons and pions into muons
  - Assume universality
  - Bonus: extract the error on the angle, too
- Hints:
  - $\pi^+ = (u\bar{d})$, $K^+ = (u\bar{s})$
  - To take into account *non-perturbative effects*, you have to multiply the widths by the "**form factors**" f_K and f_π
  - From the PDG (http://pdg.lbl.gov/) take:
    - The **form factors**, the **lifetimes**, the **branching ratios** and the **masses** of all the particles involved

Homework: how to decide the opening angle θ

- Proton beam at Brookhaven: 28 GeV
- Naif expectation: high mass → high momenta of the decay products → large angles
- Goal: show that the maximum angle does not depend on M_J
- Hints:
  - The resonance (whatever it is) is almost at rest in the center of mass of the proton-Berillium system
  - Assume, for simplicity, that its decay products are emitted at 90^o with respect to the incoming particles (in the center of mass)
    - This last assumption is valid only for a fraction of the decays
    - Bonus: assume isotropic decay (in the c.m.) and angular acceptance $\Delta\theta=\pm 2^o$ and calculate the fraction of detectable electrons. (Superbonus: use the real angular distribution...)

Homework: the Breit-Wigner formula

$$\sigma_{(n,f)} = \frac{\lambda^2}{4\pi} \cdot \frac{2I_C + 1}{2(2I_A + 1)} \cdot \frac{\Gamma_n \Gamma_f}{(E - E_0)^2 - \left(\frac{\Gamma}{2}\right)^2}$$

- Special case of the Cauchy distribution
- <u>Goal</u>: show that its Fourier transform gives the exponential decay law
  - Narrow resonance ↔ long lifetime
- I_A: spin of the incoming particles, I_C: spin of the resonance, Γ_n,Γ_f: widths of the decays when only these initial and final state are considered
- Bonus: derive all the normalization factors, as in Perkins, chapter 2, sec.2.11

How to measure the width of a very narrow resonance

- In both the SLAC and Brookhaven experiments, the observed width of the distribution was equal to the experimental resolution: the natural width Γ was much smaller!
- Trick: consider $\sigma_0=\sigma(E=E_0=M_\psi)$ and do some easy algebra
  - $\sigma_0(e^+e^-\rightarrow J/\psi\rightarrow l^+l^-)\sim\Gamma(e^+e^-)\Gamma(l^+l^-)/\Gamma^2$
  - $\sigma_0(e^+e^-\rightarrow J/\psi\rightarrow \text{had.})\sim\Gamma(e^+e^-)\Gamma(\text{hadrons})/\Gamma^2$
  - Assume lepton universality: $\Gamma(e^+e^-)=\Gamma(\mu^+\mu^-)=\Gamma(l^+l^-)$
  - Assume no other decays exist: $\Gamma=2\Gamma(l^+l^-)+\Gamma(\text{hadrons})$
  - Measure $BR(l^+l^-)=[\# \, l^+l^-]/[\# \, \text{tot}]$; remember: $BR(l^+l^-)=\Gamma(l^+l^-)/\Gamma$; substitute everywhere, and obtain:
  - Area = $\int\sigma(E)dE = 6\pi^2 BR(J/\psi\rightarrow e^+e^-)BR(J/\psi\rightarrow \text{had})\Gamma/M_\psi^2$