8.882 LHC Physics

Experimental Methods and Measurements

Resonances: Production, Decay and Reconstruction

[Lecture 13, March 18, 2009]

Organizational Issues

Spring break

- next week: March 22-27, no lecture/recitation
- make sure project 1 is done by then

Project 1

- received the combined CERN people note: looks good, on first sight will evaluate for Monday after spring break
- will meet with Michael and Erik after lecture today

Project 2

- due April 9, Upsilon cross sections
- exact definitions are on the TWiki

Physics Colloquium Series

‘09

Spring

The Physics Colloquium Series

Thursday, March 19 at ***4:15 pm*** *in room* ***10-250***

Jeff Kimble

California Institute of Technology

"Quantum Networks"

For a full listing of this semester’s colloquia,
please visit our website at web.mit.edu/physics

Lecture Outline

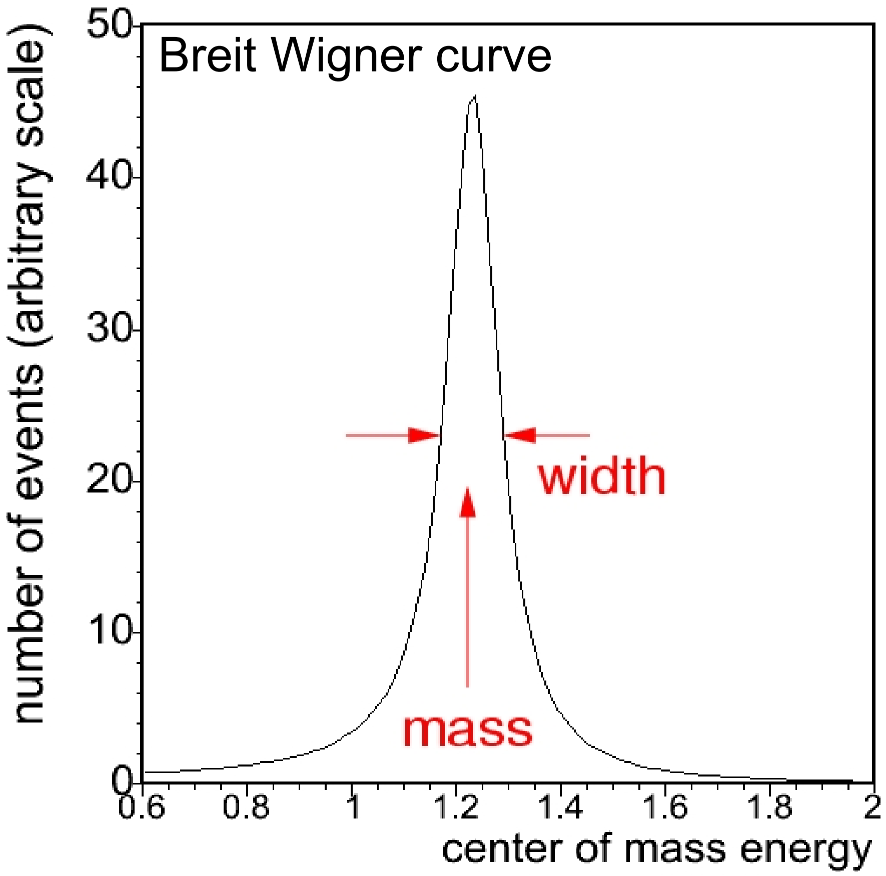
Resonances: Production, Decay and Reconstruction

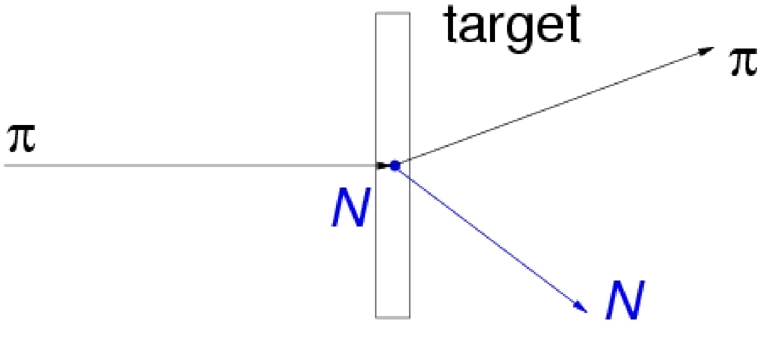
- resonances: an overview
- the *zoo of particles* and putting order into it
- production and decay
- vertex reconstruction
- reconstruct and selection of resonances

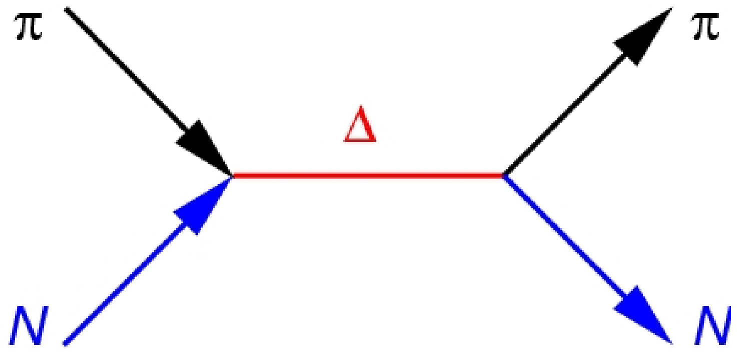
General Resonance Example

Take scattering experiment

- shoot pion on fixed target
- observe scattering rate depending on CM energy
- most likely creation: at Δ mass and around it







characteristics – mass and width

width = 1 / lifetime

Lifetime of Resonances

Resonance curve, Breit-Wigner: $f(E_{CM}) \propto \frac{1}{(E^2 - M^2)^2 + M^2\Gamma^2}$

Lifetime is defined by resonance width

- lifetime $\tau = 1/\Gamma \quad \rightarrow \quad$ *width* $\Gamma = 1/\tau$

Check whether this makes sense

- particle with super short lifetime has a huge width meaning that it “disappears”
- particle with a very long lifetime has a small width (very sharp peak)

What defines the lifetime of a particle?

- time scale or strength of interaction it decays with
- strong interaction means *short lifetime* and *broad peak*
- weak interaction means *long lifetime* and *narrow peak*

Key Dates in Particle Discoveries

1897 electron: Thomson (cathode ray)

1911 atomic nucleus: Rutherford (gold foil experiment)

1918/9 proton: Rutherford (H nuclei observed in α on N_2)

1923 photon: Compton confirms quantum nature of *x* rays

1930 neutrino suggested by Pauli (α spectrum)

1930 positron suggested by Dirac (mathematical issue)

1931 neutron: Chadwick

1937 muon: at first confused with the pion

1946/47 muon is correctly identified and I.I.Rabi comments: ”who ordered that?”

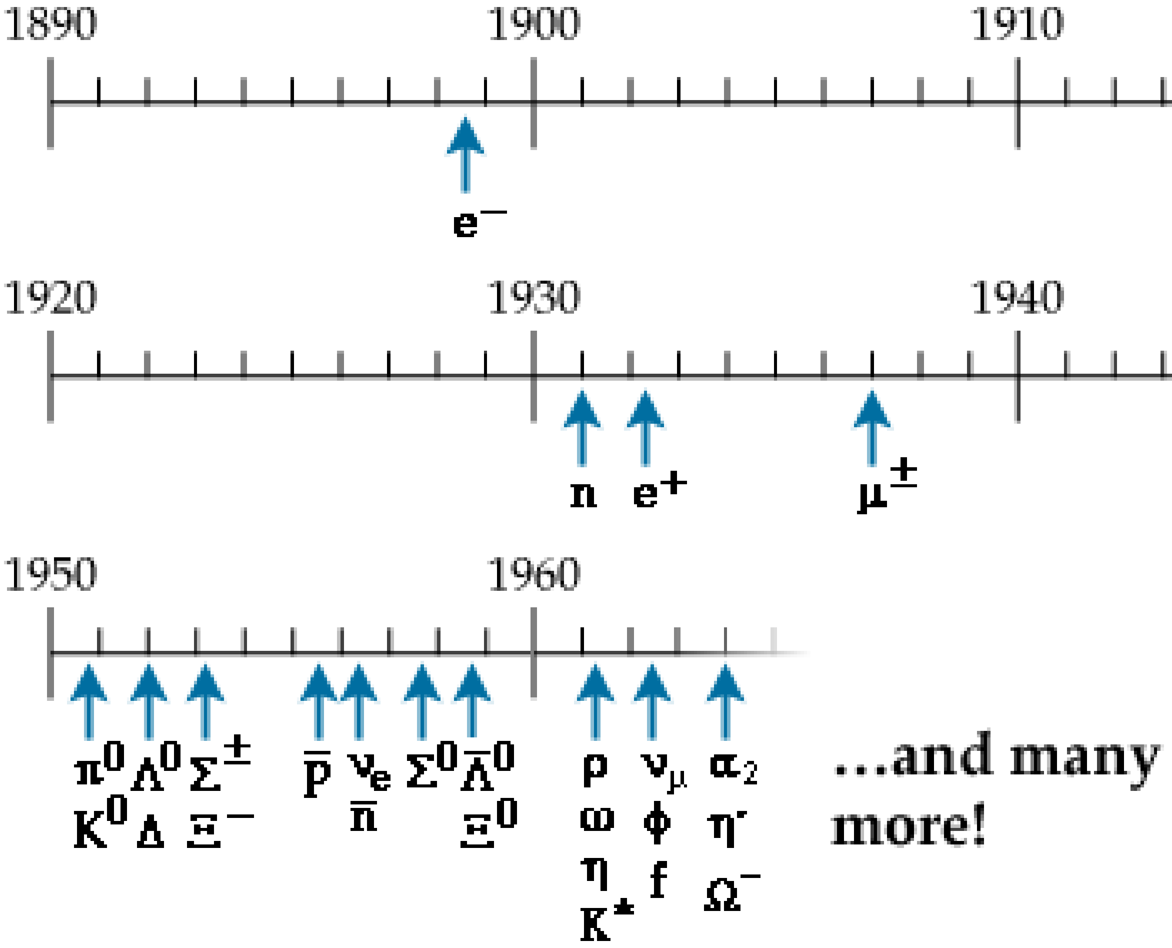
1947 charged pion in cosmic rays (interacts strongly)

1949 positive kaon

Key Dates in Particle Discoveries

1951 V like particles discovered: Λ^0, K^0

1952 Δ particles discovered (Δ^{++},Δ^{+},Δ^{0},Δ^{-})



The Stories

Neutrino story

- beta decay understood as: $n \rightarrow p + e^{-} + \bar{\nu}$
- neutrino was introduced to fix the energy balance

Pion story

- electron is held by EM force to nucleus (photon)
- force should hold neutrons and proton together (pion)
- uncertainty principle was used to explain reach of forces
  - photon is massless: infinitely far reach
  - pion has to be massive: force reach very limited
- discovered in 1947 in cosmic rays

The Stories

Muon story

- muon was found in comic rays shortly after Yukawa's pion prediction, and incorrectly identified as pion, mass too small though
- was finally correctly identified as the heavier brother of the electron but has no role in ordinary matter....

Strange particles

- in cosmic rays a whole bunch of unnecessary particles started popping up: K^+, K^-, K_L, K_S
- in strong interactions they appeared in conjunction with other new particles: Λ, Σ, Ξ
- they were considered to be strange and strange quantum number followed: strangeness has to be conserved

Ordering the Zoo

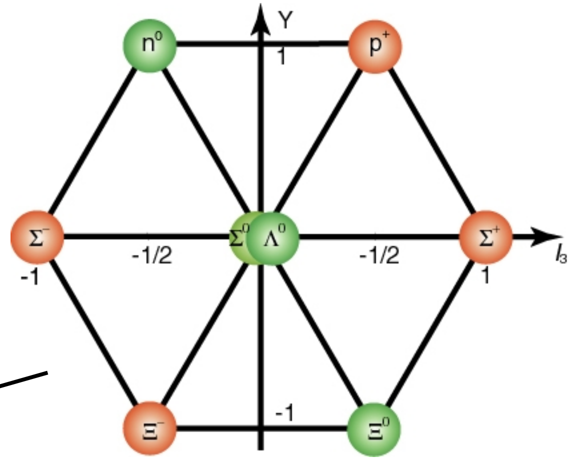
By the sixties over 100 particles (resonances) were known, categorizing scheme(s) became necessary

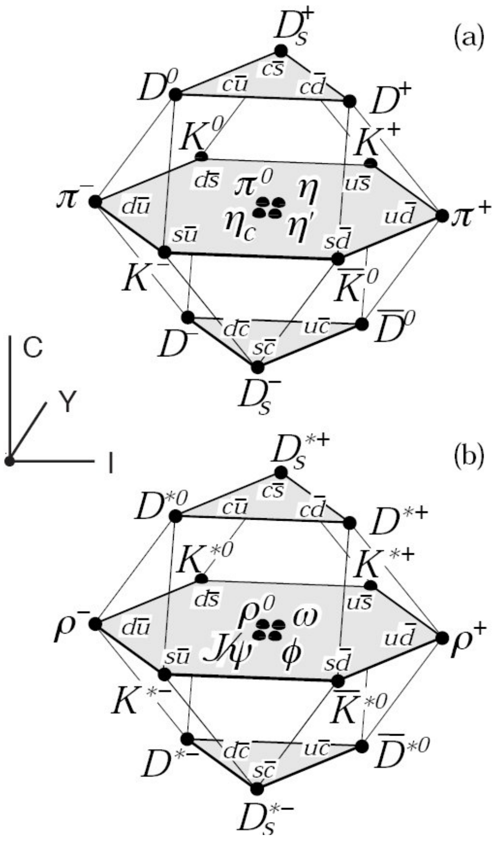
- according to mass, did not really work
  - photons: massless
  - leptons: lightweight (electron, neutrino, muon)
  - mesons: middle weights (pion, kaon)
  - baryons: heavyweights (proton,neutron, Λ, Σ, Ξ)
- the eightfold way
  - 1960/1 Murray Gell-Mann and Yuval Ne'eman arranged particles in patterns
  - number eight is one of the recurring schemes and gives it its name
  - 1964 Gell-Mann and George Zweig propose that only three quarks could construct all particles u (2/3), d (-1/3), s (-1/3) following an $SU(3)$ symmetry group (later more $SU(N)$)

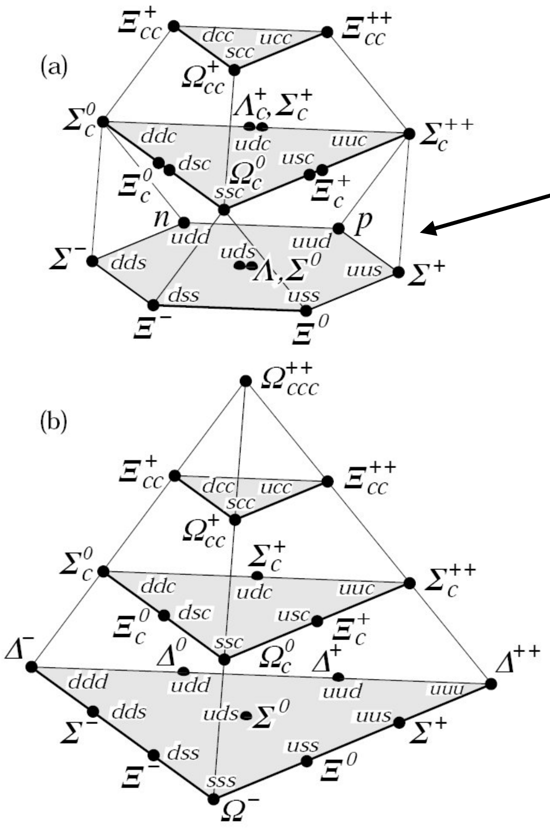
The Eightfold Way

Neutron and proton form part of the octoplet which gave the theory its name (8 particles)

Different multiplets put all together





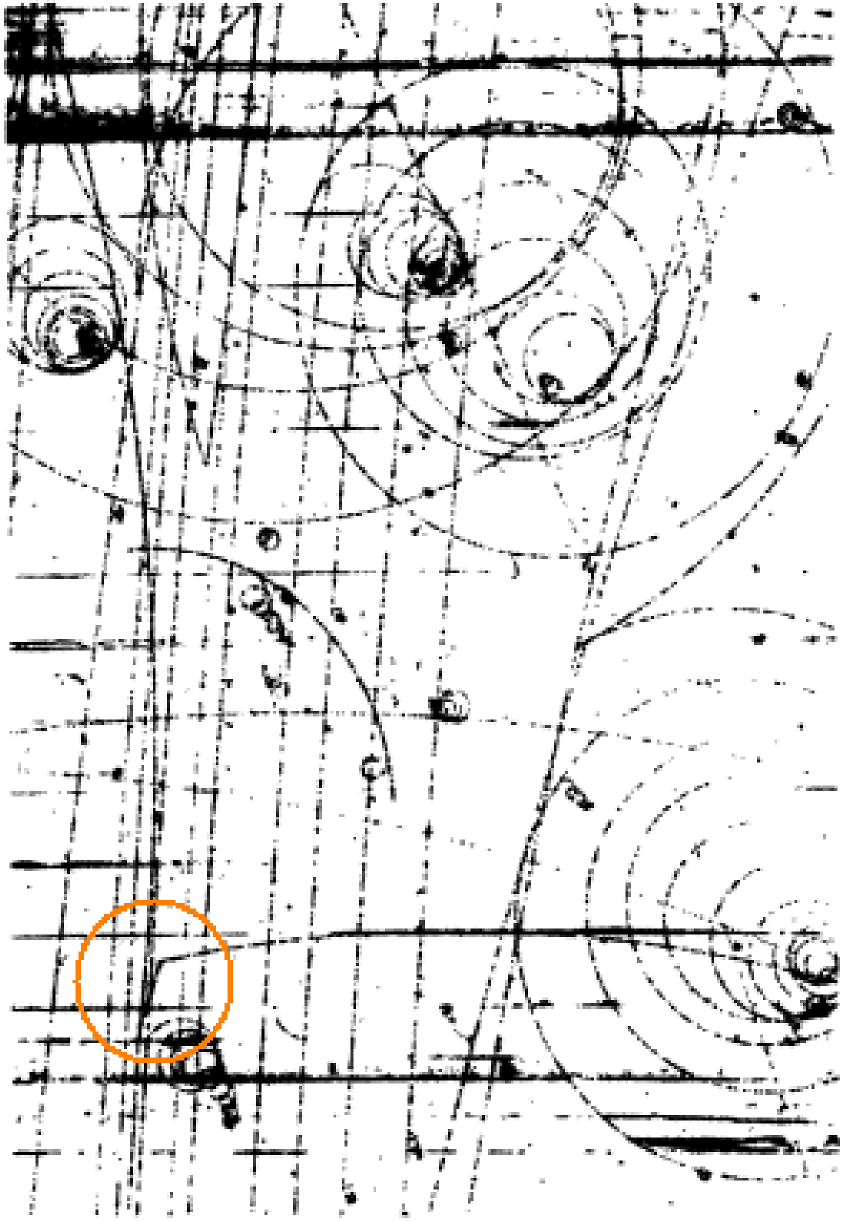


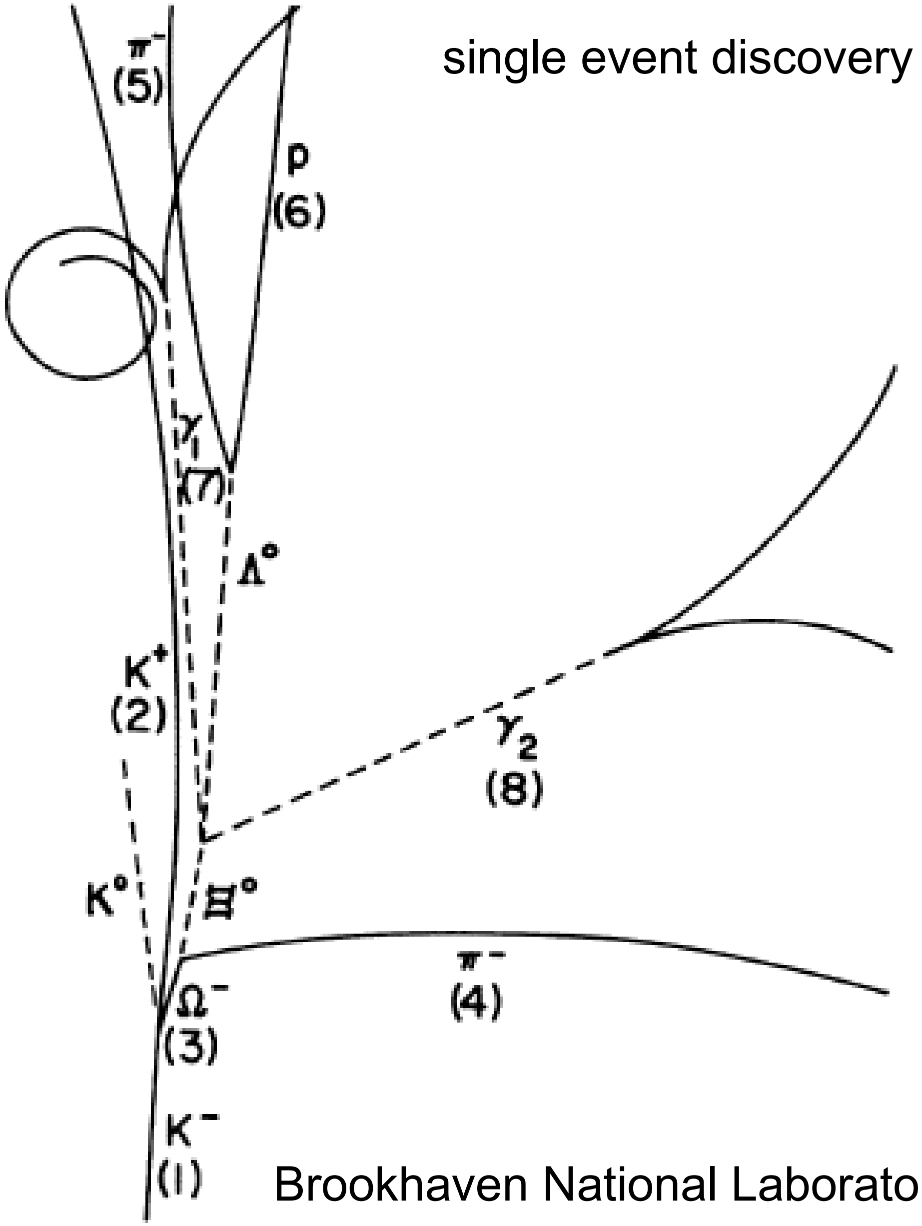
The Eightfold Masterpiece

“The esoteric world of theoretical physics went into spasms of enthusiasm last week when Brookhaven National Laboratory announced the identification of a new elementary particle. It is not the biggest particle known or the smallest, and it lives only one ten-billionth of a second. But physicists all over the world were stirred up because it has almost precisely the mass that was predicted for it by long-range theory. It was rather as if Columbus, sailing across the Atlantic, had really found Japan just where he thought it would be...”

Time magazine article: Feb 28, 1964

The Eightfold Masterpiece





single event discovery

Brookhaven National Laboratory

Resonance Decays

Table of different decays

Decay type	Mediator	Typical decay time
strong force	gluon	1.00E-023
electromagnetic force	photon	1.00E-016
weak force	intermediate vector boson	1.00E-013

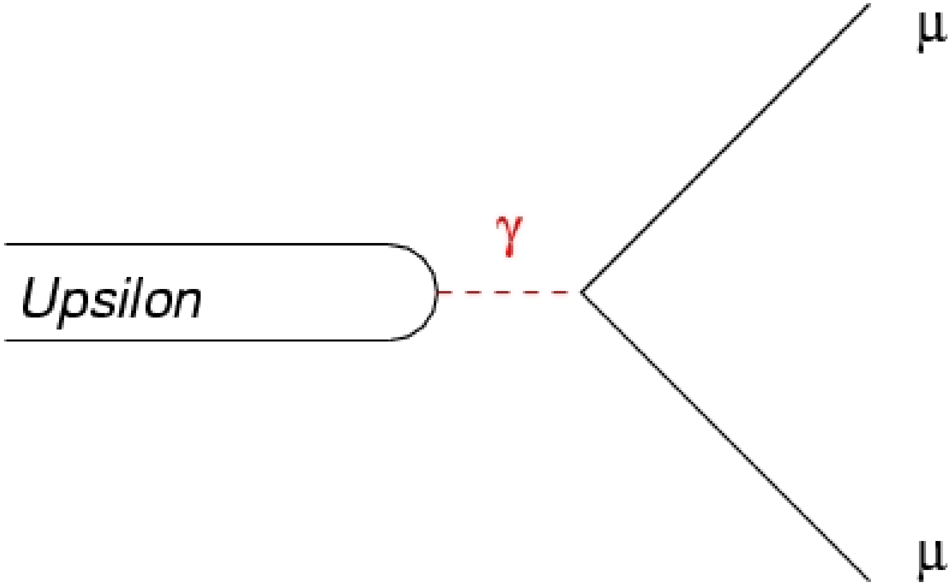
Practicalities

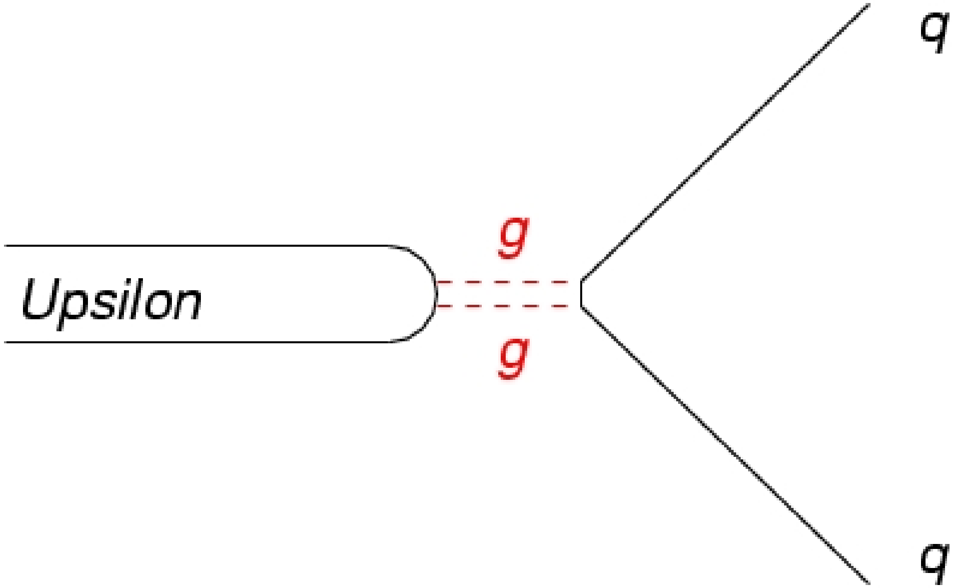
- strong force gives very fast decay: no measurable lifetime but the particle width can be measured
- electromagnetic decays: no measurable lifetime nor width
- weak decays: lifetimes measurable [10-500µm] but no measurable width
- many details in decays: conservation laws, quantum numbers: angular momentum, spin, ...

Upsilon Decay

Upsilon is a bottomonium

- quark-anti quark decays via 2 gluons or electromagnetically (short decay governs lifetime)
- decay to leptons is electromagnetic
- rest is hadronic and messy
- also radiative decay (photon gets emitted)





Reconstruction of Resonances

Preferred scenario

- use decays with charged tracks
- tracker gives most precise determination of momentum
- leptons in decay help a lot to clean up (clear signature)
- vertex determination helps a lot
  - in some cases cleans up with lots of background: longer lived particles like *B* and *D* mesons which have displaced vertex
  - improves the momentum resolution further
- can add photons and neutral pions but very difficult for hadron collider environment or worse heavy ion collisions
- excellent opportunity for BaBar and Belle at the *Upsilon(4S)* where only direct decay products are registered

Reconstructing Upsilon to Di-Muon

Sketch of reconstruction

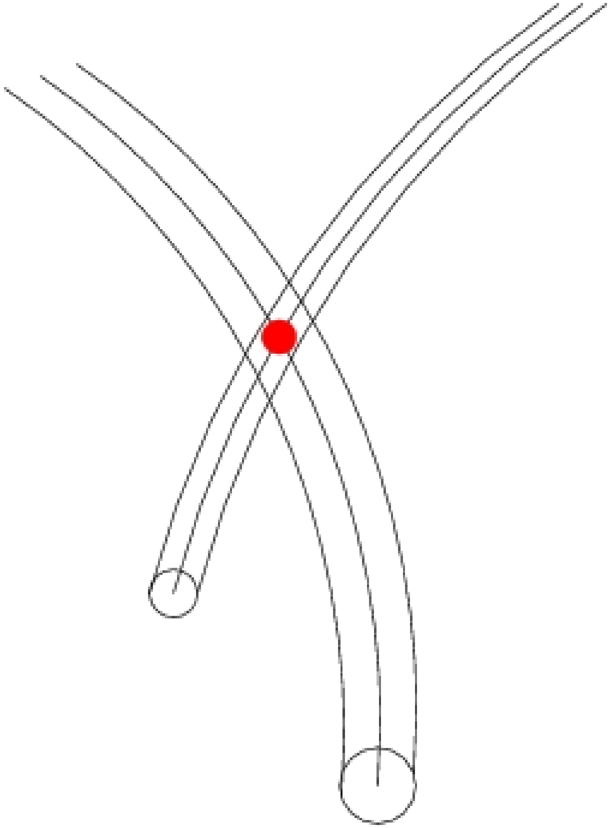
- find all muons and require good track quality
- use opposite side muon pairs and calculate mass
- select within reasonable window (pretty large)
- perform a full 3 dimensional vertex fit of the two muons forcing them to intersect in one point
  - for straight lines: always works in 2 dimensions (*xy*-plane)
  - to good approximation: require *z* coordinate to match up
  - obviously: the tracks are helices and its is a bit more complicated but not too much
- make selection based on vertex fit
  - require good fit quality (chi2 or probability)
  - require high transverse momentum (depends on measurement)
  - Upsilon is prompt: no displacement expected

Vertex Fit

Tracks are helices together with uncertainties: they for kind of tubes of most likely particle position

Adjust helix within uncertainties

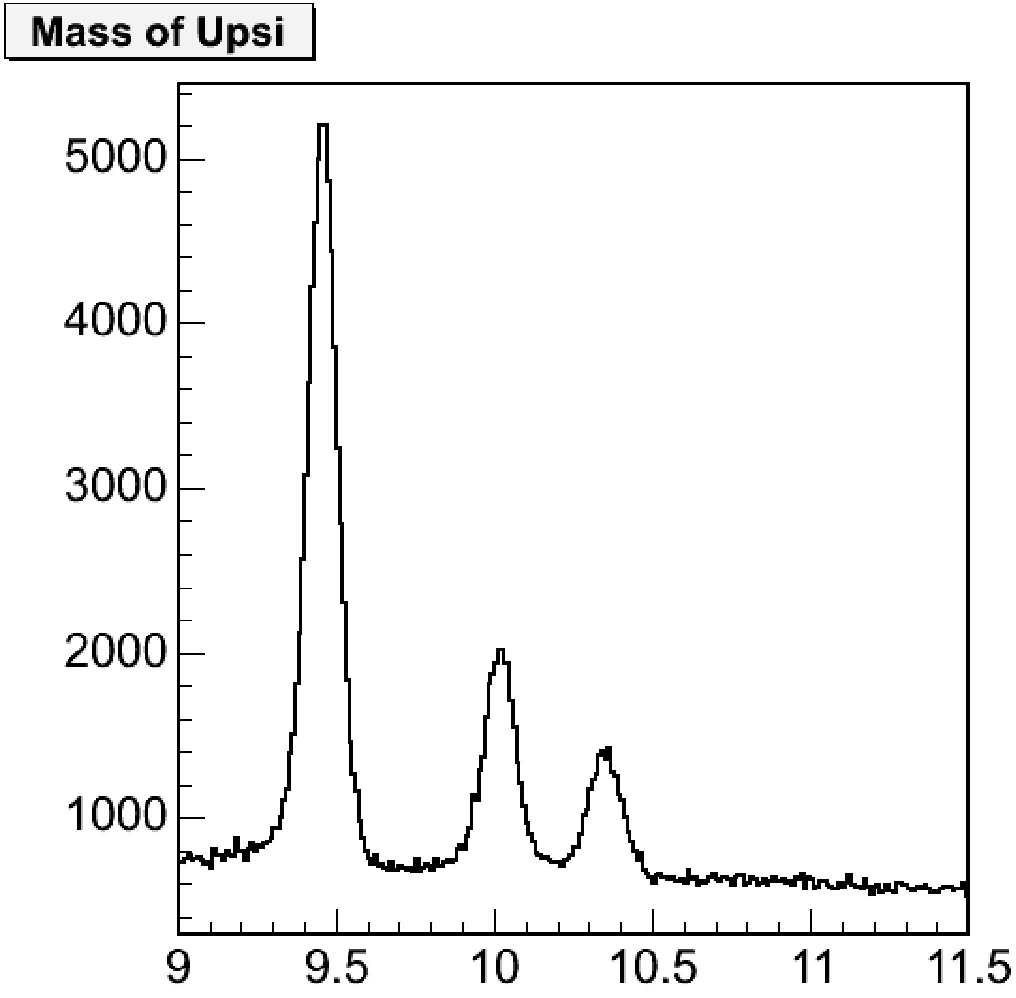
- intersect them exactly in one position
- if assumption correct momenta are more precise
- process is linearized based on the track parameters and the covariance matrix
- iterative process completely corrects for linearization
- converges after few steps (2,3)

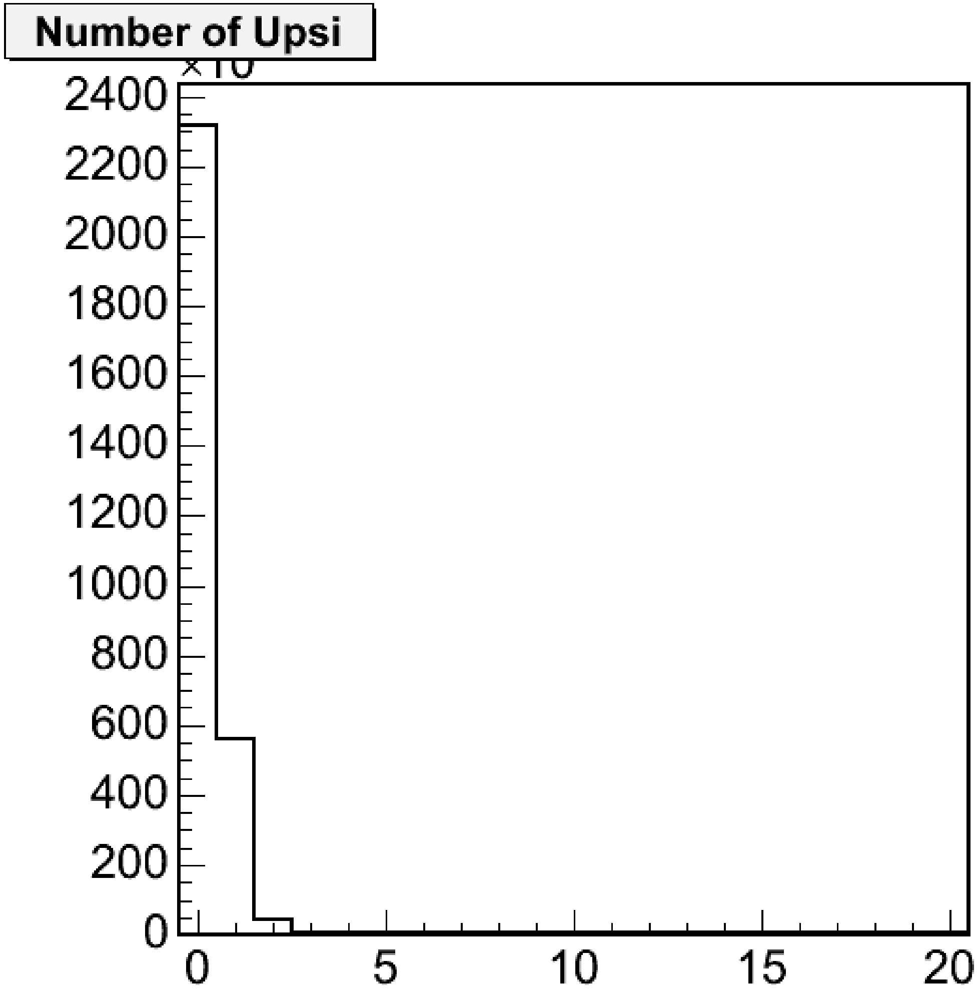


Other constraints

- mass of sub resonance, pointing

Some Quantities of Upsilon Sample

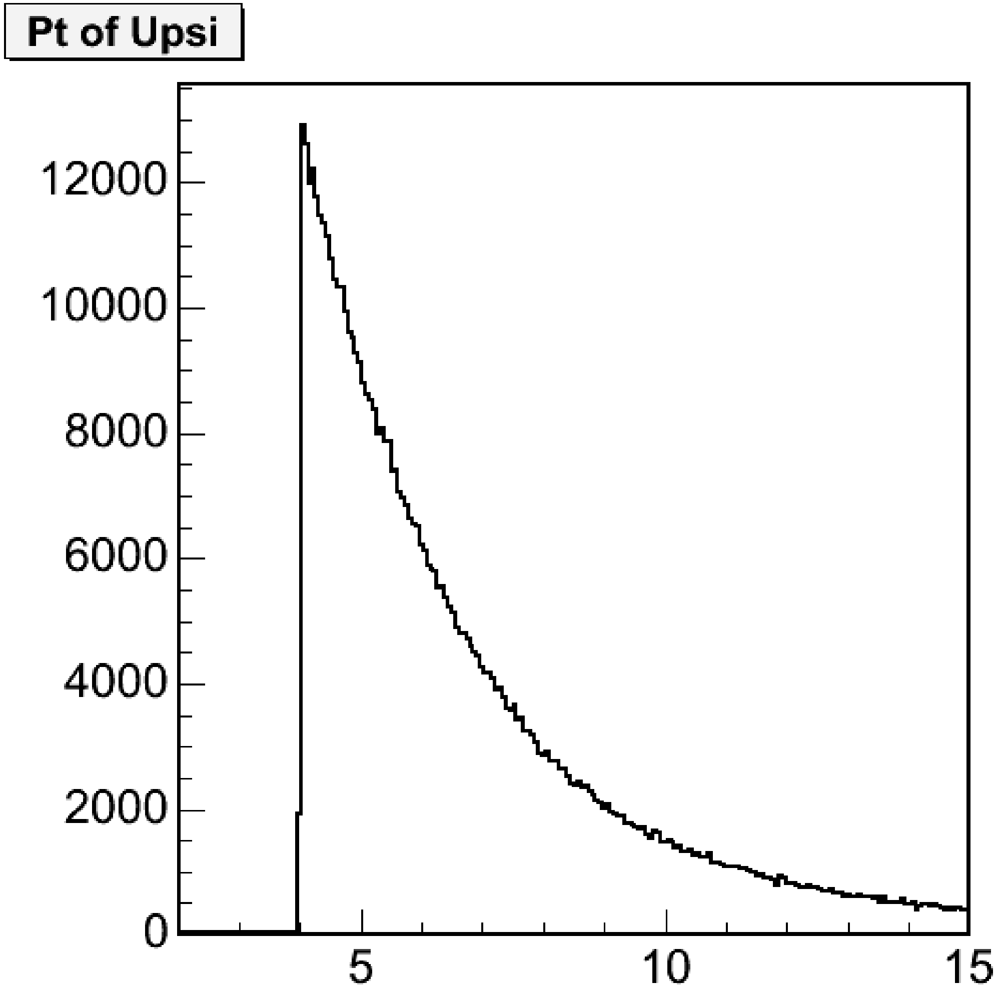


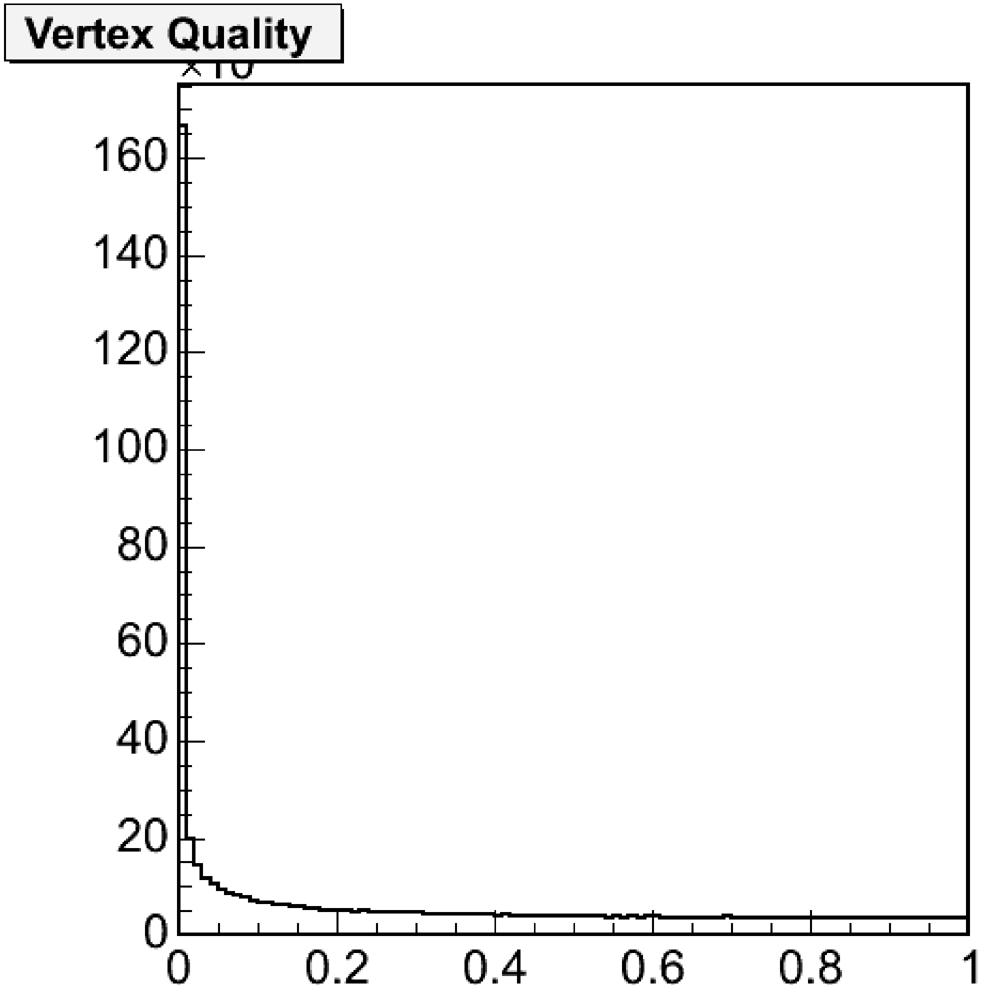


Three states visible: 2 and 3 close, work at fit model

Per event mostly just one candidate (good)

Some Quantities of Upsilon Sample





Analysis has 4 GeV cutoff (not needed?!)

Probability spikes at zero: mis-reconstruction

Analysis Outline

Perform a cross section measurement

- cross section:

$$\sigma = \frac{N_{\text{signal}}}{\mathcal{L}} = \frac{N_{\text{measured}}/\varepsilon_{\text{MC}}}{\mathcal{L}}$$

- number of signal events depends on kinematic phase space allowed for the decay

Kinematic phase space we should consider

- it should be well matched with what the detector covers, otherwise extrapolation is large and introduces uncertainty
- consider: $|\eta|$ and p_T of the *Upsilon*
- no lowest transverse momentum needed: $p_T > 0$ GeV
  - Upsilon decaying at rest: two muons with ≈5 GeV, seems fine
  - muon acceptance and efficiency from Monte Carlo
- match good tracking coverage: $|\eta|<1.0$ seems reasonable

Analysis Extensions

Differential cross sections

- spectrum of the transverse momentum is very interesting
  - depends on the detailed production mechanism
  - color singlet and color octet production have different total cross sections and spectra in p_T
- propose a differential cross section versus p_T
- carefully implement sideband subtraction
- full correction for each p_T bin

Relative cross sections

- form ratios of cross sections (σ_{1S} / σ_{2S} *etc.*)
- some systematic uncertainties will reduce significantly

Conclusion

Resonances are another word for a particle

- they appear as a spike in the mass distribution
- follow a Breit-Wigner distribution
- depending on decay mechanism: broad or narrow
- longer lived particles have long lifetime and small decay width (spiky), spike width given by the detector resolution
- shorter lived particles have short lifetime and large decay width, spike depends on the details of the decay, usually in keV range for EM decay and in MeV range for strong decays

Ordering the Zoo the eightfold way

- big days of the quark model

Assignment is out there... April 9

Next Lecture

Search Strategies and Observations