

Collider Physics: Discoveries

Discoveries

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Timeline (Places: Europe & United States)

What	Year	Where	Machine Type	Reaction / Signature
NC	1973	CERN	<i>Neutrino beam on Gargamelle Bubble chamber</i>	Neutral current events in ν interactions $\rightarrow \nu_W \rightarrow m_W, m_Z$
J/ Υ \rightarrow charm	1974	BNL	<i>p(30 GeV) on Be target</i>	$p + p \rightarrow e^+ + e^- + x$; invariant mass of e^+e^-
	1974	SLAC	<i>SPEAR(3 GeV e^+ + 3 GeV e^-)</i>	$e^+ + e^- \rightarrow$ hadrons or $\rightarrow \mu^+ + \mu^-$ Cross section scan measurement vs energy
	1974	Frascati	<i>Adone(~ 1.5 GeV e^+ + 1.5 GeV e^-)</i>	$e^+ + e^- \rightarrow$ hadrons $e^+ + e^- \rightarrow \mu^+ + \mu^-$ Cross section scan measurement vs energy
τ	1974	SLAC	<i>SPEAR(3 GeV e^+ + 3 GeV e^-)</i>	$e^+ + e^- \rightarrow \mu^+ + e^-$ (pair production of $\tau^+ \tau^-$)
$Y \rightarrow b$	1977	Fermilab	<i>p(400 GeV) on target</i>	Peak in the invariant mass of $\mu^+ + \mu^-$ pairs
$Y \rightarrow b$	1978	DESY	<i>DORIS(5 GeV e^+ + 5 GeV e^-)</i>	$e^+ + e^- \rightarrow$ hadrons Cross section scan measurement vs energy
W	1983	CERN	<i>Spp\bar{p}S (270 GeV $p + \bar{p}$)</i>	$u + \bar{d} \rightarrow W^- \rightarrow e^+ + \nu$ (8% BR)
Z	1983	CERN	<i>Spp\bar{p}S (270 GeV $p + \bar{p}$)</i>	$q + \bar{q} \rightarrow Z \rightarrow \mu^+ + \mu^-$ or $\rightarrow e^+ + e^-$
top	1994	Fermilab	<i>Tevatron (900 GeV $p + \bar{p}$)</i>	$t\bar{t} \rightarrow W^+W^-b\bar{b}$
Higgs	2012	CERN	<i>LHC (3.5/4.0 TeV $p + p$)</i>	$H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$; $H \rightarrow \gamma\gamma$; $H \rightarrow WW \rightarrow e\nu\mu\nu$

10 years

~ 20 years

10 years

... More Quarks?

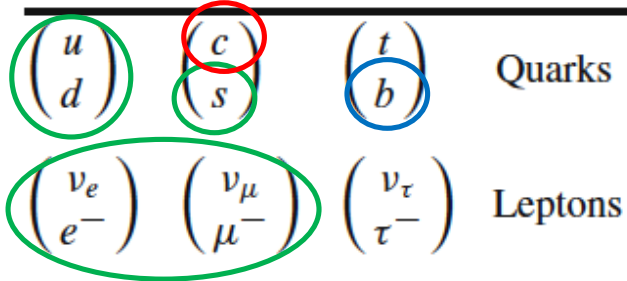
What was known @ beginning of 1970's:

- leptons e , μ , ν_e , ν_μ , and
- quarks: u , d , s

What was NOT known @ beginning of 1970's:

the structure in families

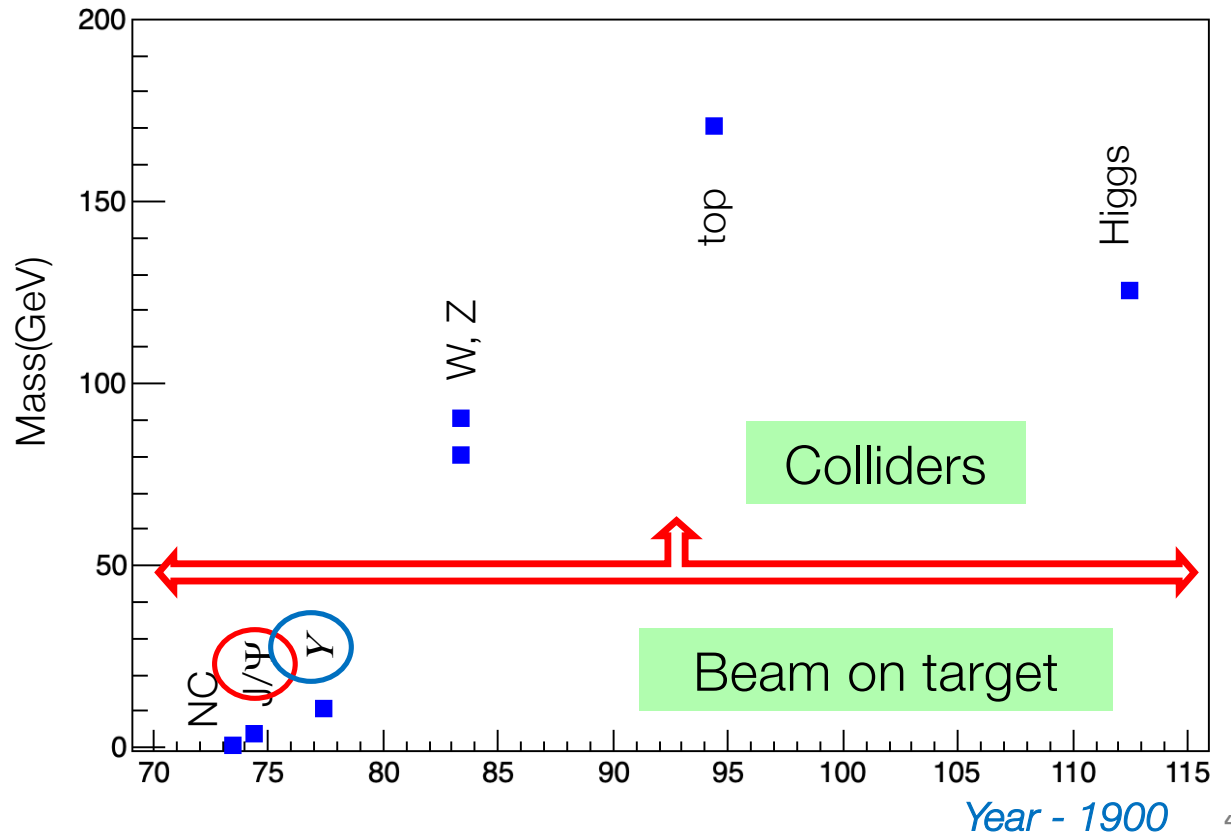
Fermions



First family Second family Third family

Suddenly in a few years many new things were discovered and the pattern of a more general and organised schema started to be visible

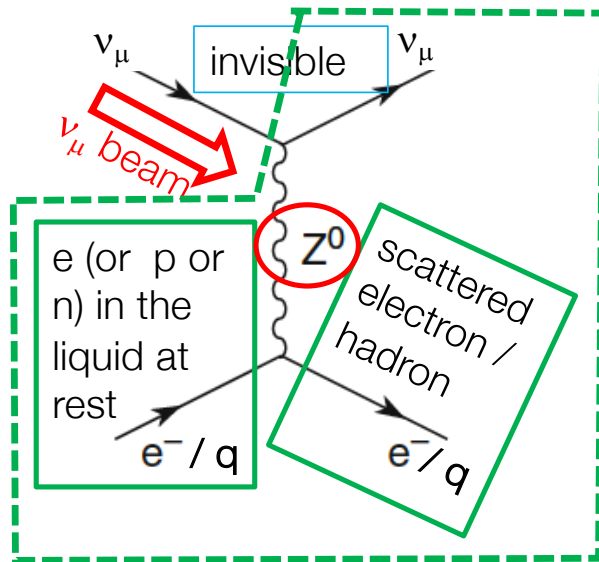
including Z & W Vector Bosons



The Bubble Chamber Gargamelle at CERN < History!

$$\nu_{\mu} N \rightarrow \nu_{\mu} + \text{hadrons}$$

$$\nu_{\mu} e^{-} \rightarrow \nu_{\mu} e^{-}$$



Gargamelle Bubble chamber@ CERN: detector filled with Freon (*) at a temperature close to the boiling point.

- charged particle generates a large number of visible bubbles
- A photographic camera can take (random) pictures
- sometime interactions are captured!
- Eye scan !!!!

Gargamelle (4.8 m in length, 2 m in diameter)

- designed to detect neutrinos & exposed to muon-neutrino beam

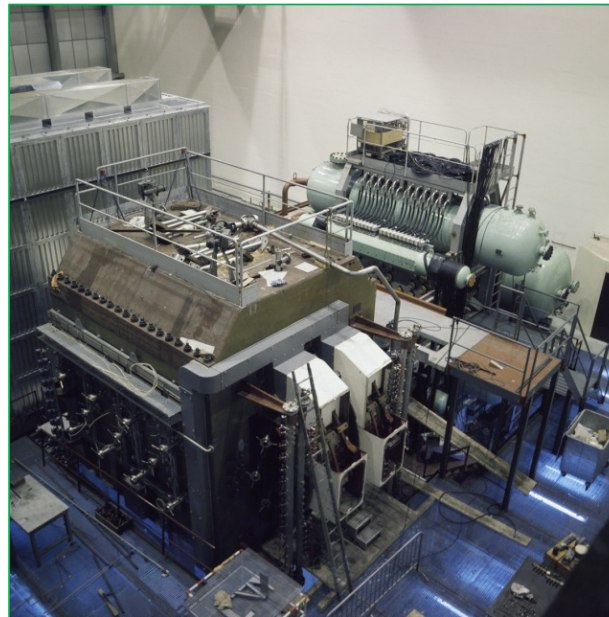
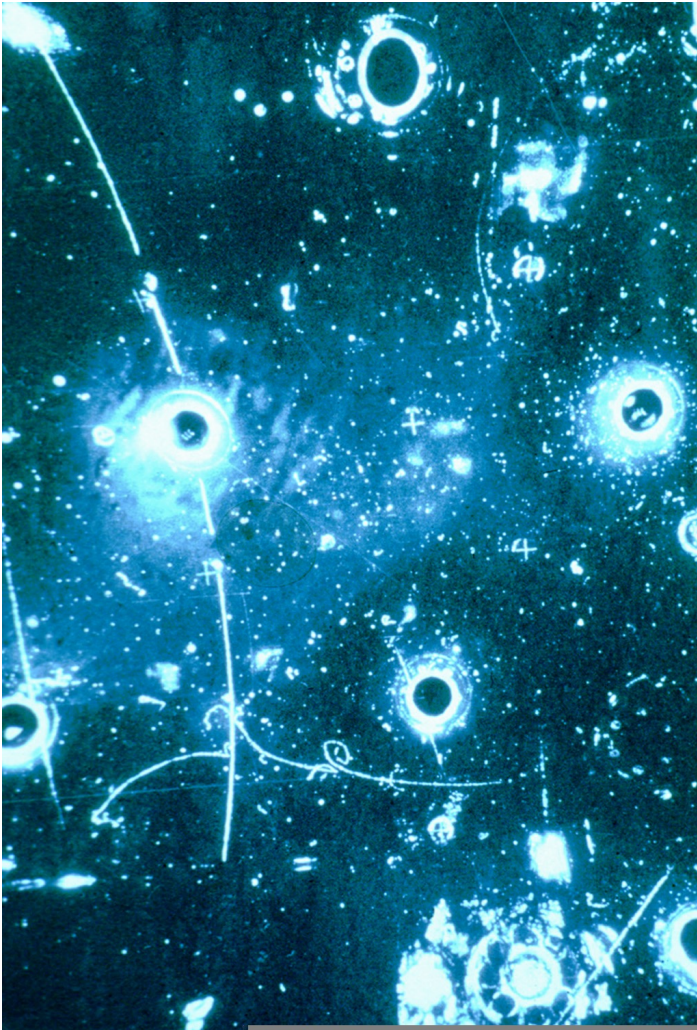
Neutrinos are not visible in detectors but the charged products of its interaction are visible. → indirect detection

- operated from 1970 to 1976

(*) Freon is a dense liquid → large amount of material → increased the probability of seeing neutrino interactions.

Z Boson → “Neutral Currents” at Gargamelle

Gargamelle bubble chamber at CERN.



$$\nu_{\mu} N \rightarrow \nu_{\mu} + \text{hadrons}$$

$$\nu_{\mu} e^{-} \rightarrow \nu_{\mu} e^{-}$$

July 1973: first direct evidence of the

weak neutral current (NC)
→ *indirect evidence of Z*

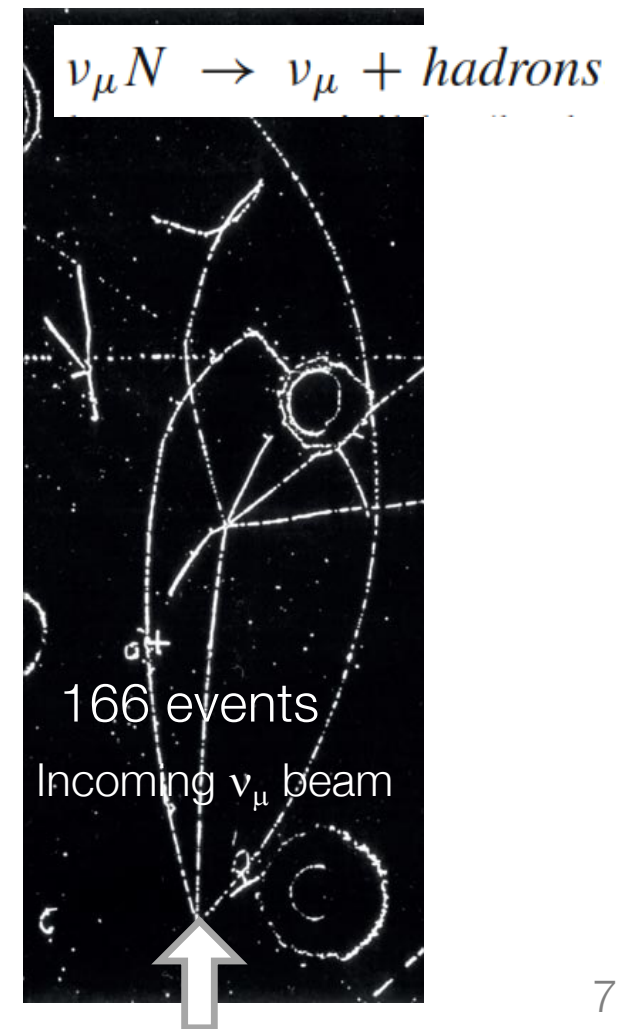
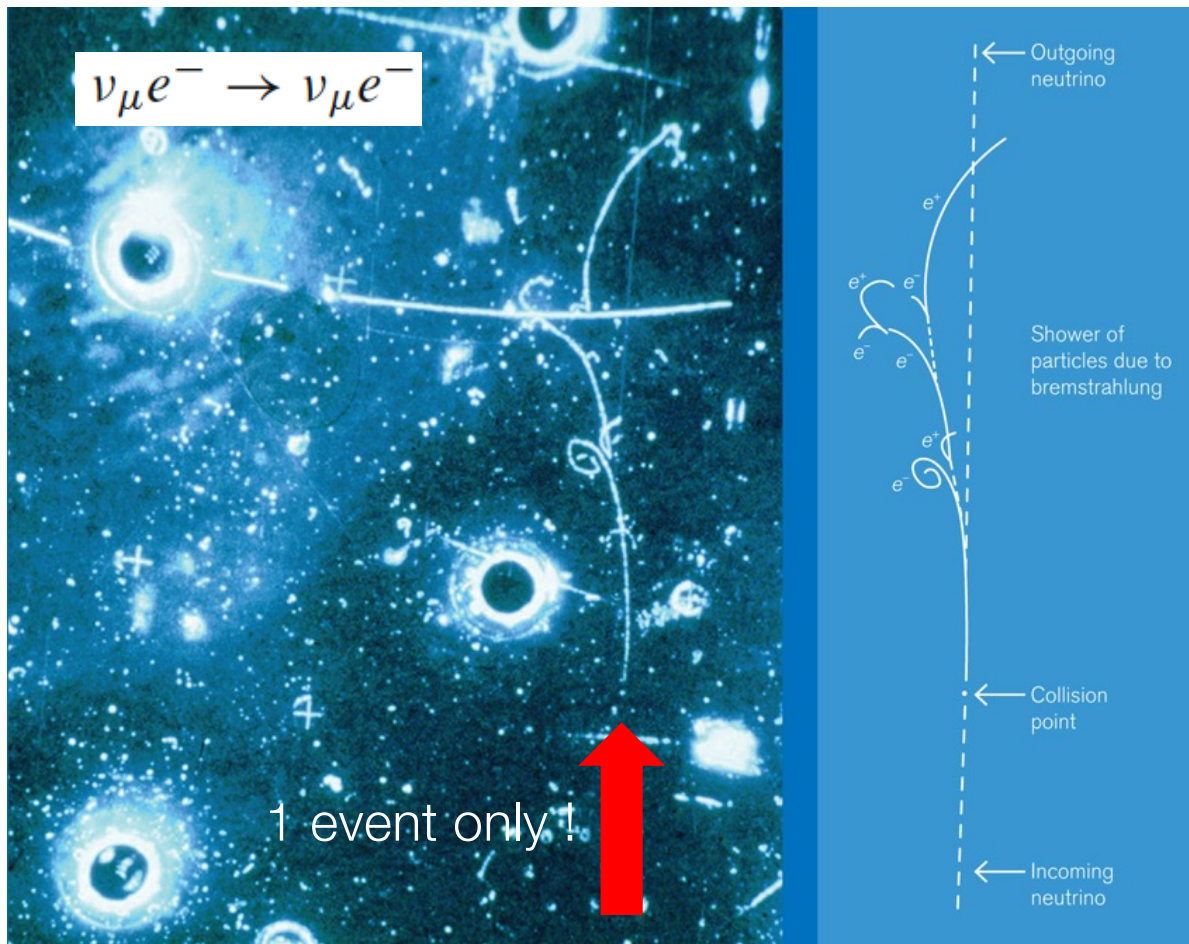
→ existence of a neutral particle that couples to neutrinos (to carry the weak fundamental force, the “Z”).

Two types of events: interaction of the neutrino with

- **an electron (1 event)**
- **a hadron** (proton or neutron) 166 events

Neutral current event: the neutrino enters invisibly, interacts, generates an isolated vertex (from which only hadrons/electrons are produced), and then moves on

Neutral Current Events in Gargamelle (1973)

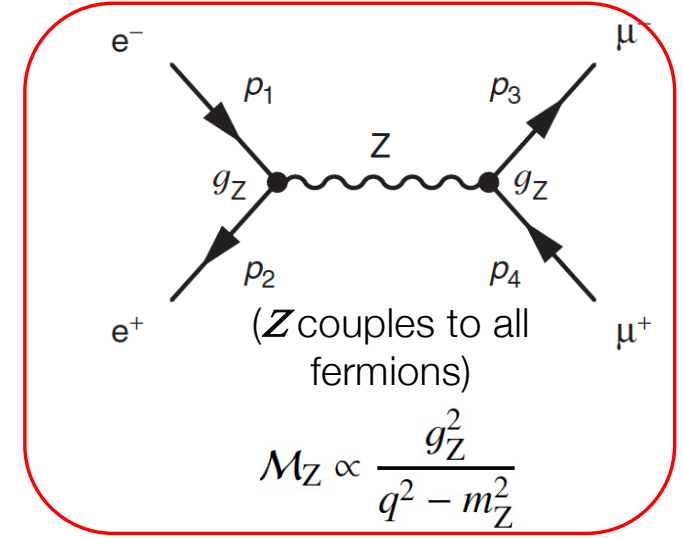
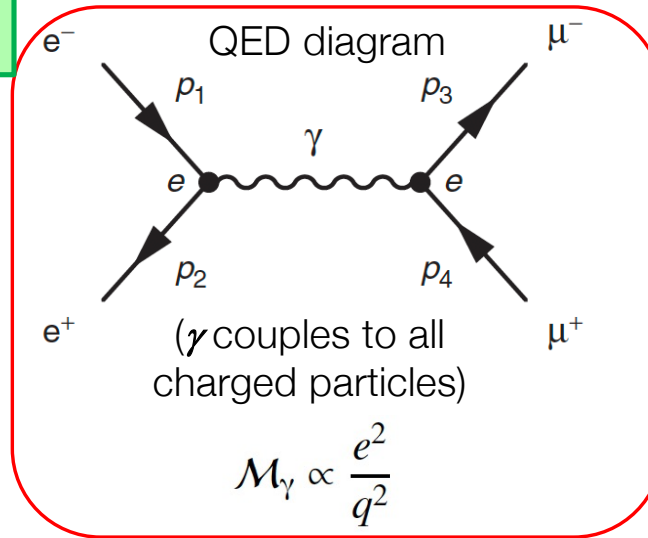


The Resonance Shape: Example Z Decay

Resonances → Unstable states

Main production modes (LO Feynman diagrams) for $e^+e^- \rightarrow \mu^+\mu^-$

- In the region $q^2 \ll m_Z^2 \rightarrow$ due to the Z mass in the propagator $\mathcal{M}_\gamma \gg \mathcal{M}_Z$;
- In the region $q^2 \gg m_Z^2 \rightarrow$ both terms contribute $\mathcal{M}_\gamma \approx \mathcal{M}_Z$;
- In the region $q^2 \approx m_Z^2 \rightarrow$ the Z propagator is such that $\mathcal{M}_Z \gg \mathcal{M}_\gamma$.



Apparent divergence at $q^2 = m_Z^2$

$$\mathcal{M}_Z \propto \frac{g_Z^2}{q^2 - m_Z^2}$$

Need to account for the instability of the Z boson (the same for all unstable particles → Resonances);

→ lifetime Γ (width) = $1/\tau$ (lifetime)

$$\psi \propto e^{-imt} \rightarrow \psi \propto e^{-imt} e^{-\Gamma t/2}$$

It works: $\psi\psi^* =$ probability of finding a particle at time $t \rightarrow \psi\psi^* \propto e^{-t/\tau}$

The Breit-Wigner Resonance Formula (for the Z)

We accounted for decay by replacing

$$m \rightarrow m - i\Gamma/2$$

We use this replacement also in the propagator

$$m_Z \rightarrow m_Z - i\Gamma_Z/2$$

$$m_Z^2 \rightarrow (m_Z - i\Gamma_Z/2)^2 = m_Z^2 - im_Z\Gamma_Z - \frac{1}{4}\Gamma_Z^2$$

$$\frac{1}{q^2 - m_Z^2} \rightarrow \frac{1}{q^2 - m_Z^2 + im_Z\Gamma_Z}$$

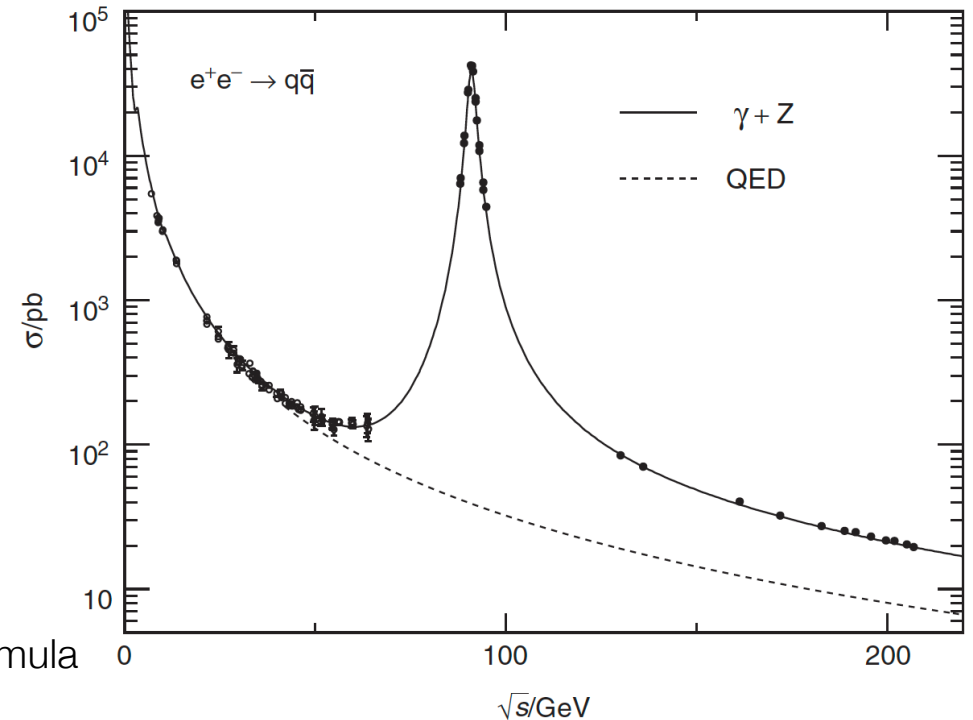
$$\Gamma_Z \ll m_Z \rightarrow \frac{1}{4}\Gamma_Z^2 \text{ small}$$

The cross section will be given by ($s = q^2$)

$$\sigma \propto |\mathcal{M}|^2 \propto \left| \frac{1}{s - m_Z^2 + im_Z\Gamma_Z} \right|^2 = \frac{1}{(s - m_Z^2)^2 + m_Z^2\Gamma_Z^2} \quad \text{Breit-Wigner formula}$$

More correct (any resonance):

$$\sigma(s) = \sigma_{\max} \frac{M_0^2\Gamma^2}{(s - M_0^2)^2 + M_0^2\Gamma^2} \quad \sigma_{\max} = \frac{4\pi (2J + 1) \text{BR}_{\text{in}} \text{BR}_{\text{out}}}{p^2 (2S_a + 1)(2S_b + 1)}$$



New (Resonant) States?: J/ψ ... and the heavier rest

Two steps:

Elastic scattering, final state = initial state

- Search for new quarks → a new hadronic resonance
- Understand which quarks compose it

$$\sigma_{el}(E; J) = 4\pi\lambda^2 \frac{(2J + 1)}{(2s_a + 1)(2s_b + 1)} \left[\frac{\Gamma^2/4}{(E_R - E)^2 + \Gamma^2/4} \right]$$

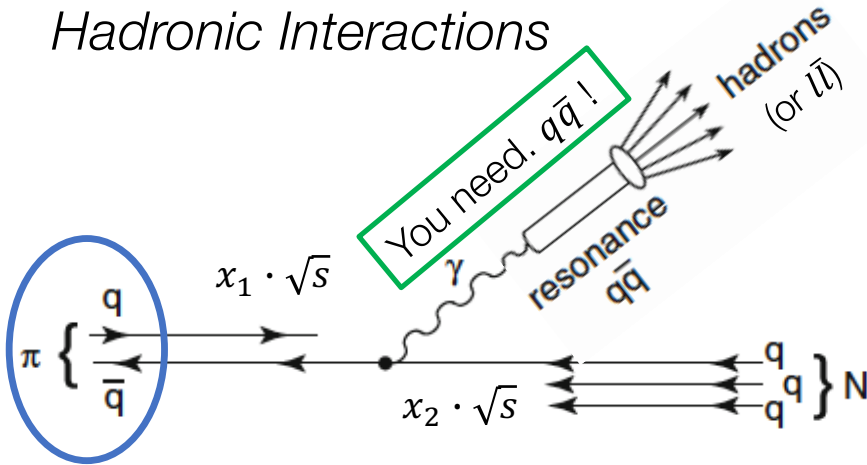
The cross section increases very rapidly if CMS energy ~ the mass of the resonance you search →

- Lepton (e^+e^-) collider with a variable beam energy do a scan → peak in the cross-section
- hadronic beam on a target you cannot do 'a scan'. However the x_1, x_2 distribution of the partons, will generate many 'effective' centre of mass energies; the invariant mass of the decay products will have a peak at the mass of the resonance.

Where	Reaction used	Method
SLAC	$e^+e^- \rightarrow J/\psi \rightarrow e^+e^-, \mu^+\mu^-, \text{hadrons}$	Cross section scan → resonance shape
BNL	$p + Be \rightarrow J\psi \rightarrow \text{hadrons}$	Peak in invariant mass

The J/Ψ Discovery in Hadronic Interactions (via Drell-Yan Processes)

Hadronic Interactions



Hadrons (or lepton pair) production in a πN collision:
quark-antiquark annihilates \rightarrow virtual photon which

- couples directly to the resonant state
- or gives rise to a lepton-antilepton pair or jet of hadrons ('continuum').

This process is generally known as 'Drell-Yan' mechanism.

There may be several cases:

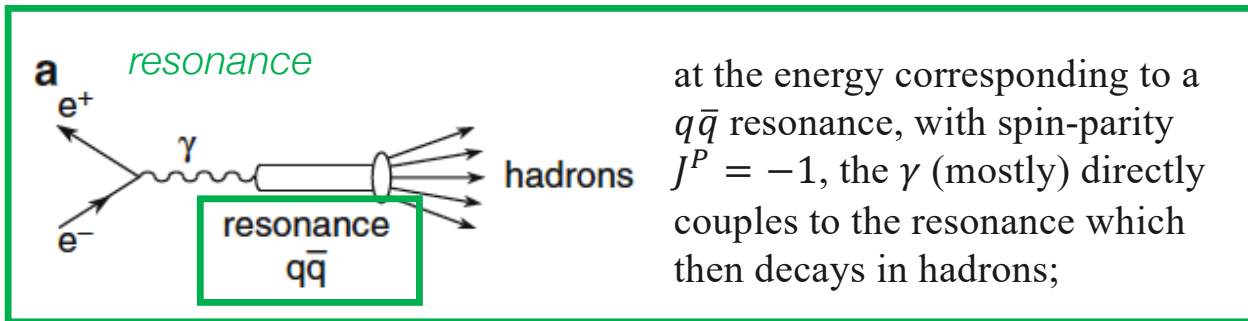
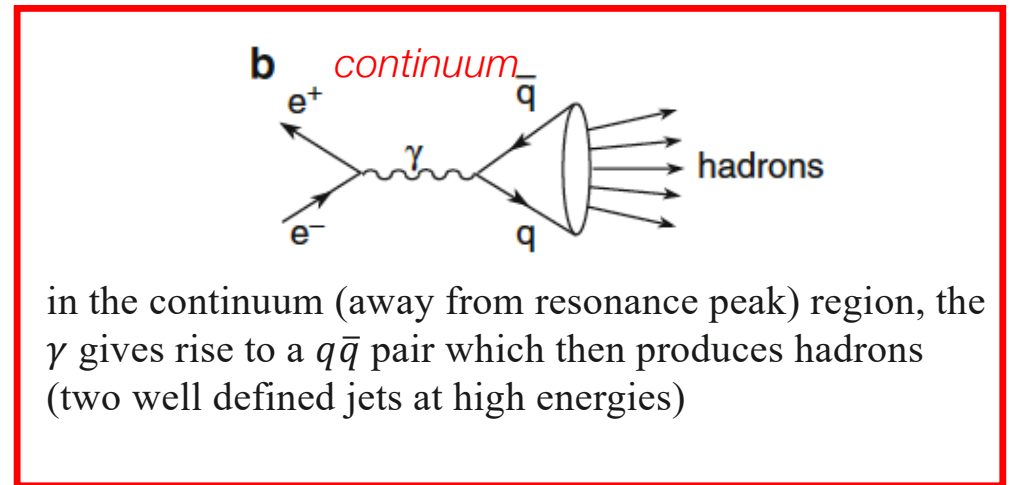
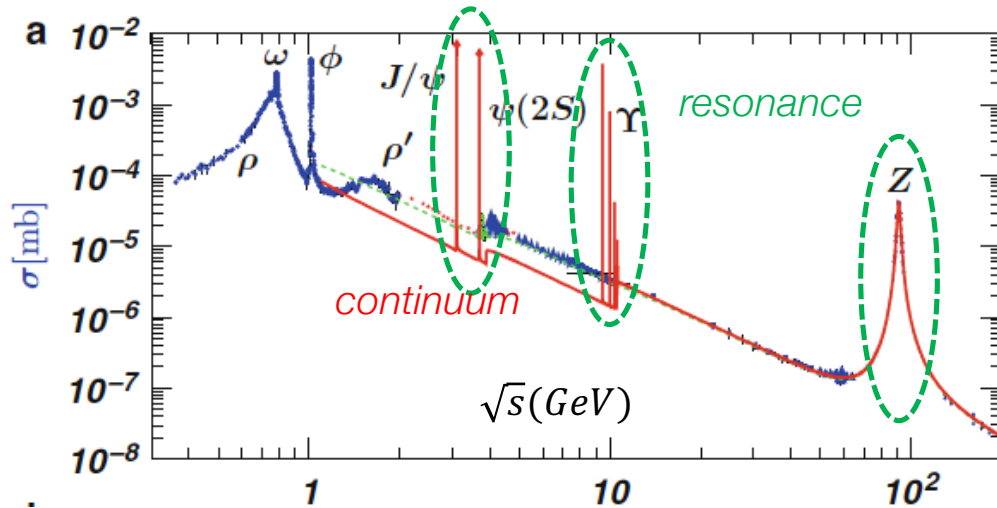
- the \bar{q} is a valence quark carried by a pion beam
- In pp collisions $\rightarrow \bar{q}$ from the sea.
- In $\bar{p}p$ collisions \bar{q} is valence quark in the \bar{p}

When the effective energy of the interaction $(x_1 + x_2) \cdot \sqrt{s}$ coincides with the mass of a resonance then the photon (mostly) couples directly to the resonant state.

The J/ψ Discovery in e^\pm Colliders

Width of the resonance invisible in this scale

Peaks = resonances



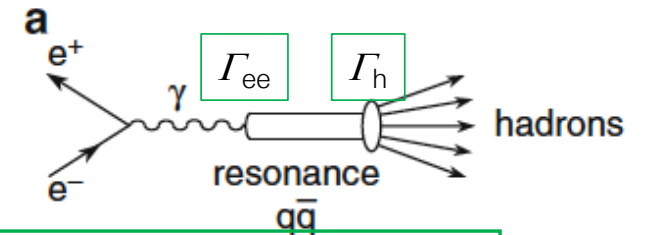
The 'new' (@1974) resonance:
 $J/\psi, c\bar{c}$ system

Cross Section Calculation in e^+e^- Interactions

$$\sigma_{el}(E; J) = 4\pi\lambda^2 \frac{(2J+1)}{(2s_a+1)(2s_b+1)} \left[\frac{\Gamma^2/4}{(E_R - E)^2 + \Gamma^2/4} \right]$$

elastic

Standard expression for the cross section close to the resonance mass



Resonant annihilation of an electron-positron pair and a decay into hadrons:

Γ^2 in the **numerator** $\rightarrow \Gamma_{ee}\Gamma_h$

- Γ_{ee} is width (BR), proportional to formation probability $e^+e^- \rightarrow resonance$
- Γ_h is width (BR), proportional to formation probability $resonance \rightarrow hadrons$

$$\Gamma = \Gamma_h + \Gamma_e + \Gamma_\mu \dots$$

Γ^2 In the **denominator** is the total resonance width in MeV ($\sim \Gamma_h$ in this case, Γ_{ee} is small).

$$\sigma_{had} = 4\pi\lambda^2 \frac{(2J+1)}{(2s_1+1)(2s_2+1)} \frac{\Gamma_{ee}\Gamma_h/4}{[(E - E_R)^2 + \Gamma^2/4]}$$

hadronic

$J=1, s_1=s_2=1/2$



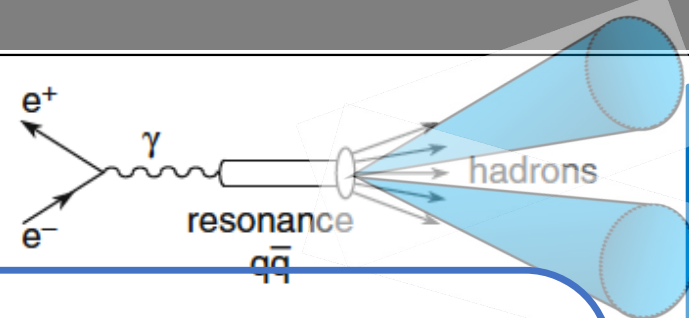
$$\sigma(e^+e^- \rightarrow J/\psi \rightarrow hadrons) = \frac{\pi\lambda^2(2J+1)\Gamma_{ee}\Gamma_h}{(2s_1+1)(2s_2+1)[(E - E_R)^2 + \Gamma^2/4]} = \frac{3\pi\lambda^2\Gamma_h\Gamma_{ee}}{4[(E - 3097)^2 + \Gamma^2/4]}$$

3097 MeV = $m_{J/\psi}$ mass

Resonance

Cross Section Calculation in e^+e^- Interactions

$$\sigma(e^+e^- \rightarrow J/\psi \rightarrow \text{hadrons}) = \frac{3\pi\lambda^2 \Gamma_h \Gamma_{ee}}{4[(E - 3097)^2 + \Gamma^2/4]}$$



In this expression:

- $\lambda = \frac{\hbar}{p}$ is the e^+e^- de Broglie wavelength in the centre of mass. In e^+e^- colliders beam energy $= \frac{\sqrt{s}}{2}$
at the J/ψ resonance $p = \frac{m_{J/\psi}}{2} = \frac{3097}{2} \text{ MeV} \rightarrow \lambda = 0.127 \text{ fm}$
- 3097 is the mass of the J/ψ
- Γ is the resonance total width = 93 KeV; $\frac{\Gamma_{ee}}{\Gamma} = 0.05$; $\frac{\Gamma_h}{\Gamma} = 0.88$

$$\sigma(e^+e^- \rightarrow J/\psi \rightarrow \text{hadrons}) = 3\pi\lambda^2 \left[\frac{\Gamma_{ee}\Gamma_h}{\Gamma^2} \right] = \boxed{0.07 \text{ mbarn.}}$$

This cross section is the resonant component only, the continuum em contribution, $e^+e^- \rightarrow \gamma \rightarrow \text{hadrons}$,

$$\sigma(e^+e^- \rightarrow \gamma \rightarrow q\bar{q} \rightarrow \text{hadrons}) = N_C \frac{4\pi\alpha_{EM}^2}{3} \frac{(\hbar c)^2}{s} \sum_{n=1}^{N_f} Q_n^2$$

has to be added. At 3 GeV this contribution amounts to $\sim 20 \text{ nb}$ ($\text{mb}/\text{nb} = 10^6$)

Resonance

Continuum

Cross Section in $e^+e^- \rightarrow e^+e^-, \mu^+\mu^-$

For $\sqrt{s} < 30 \text{ GeV}$ the $\mu^+ \mu^-$ production proceeds through the annihilation $e^+ + e^- \rightarrow \gamma$.

$$\sigma(e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-) = \frac{4\pi\alpha_{EM}^2 (\hbar c)^2}{3} \frac{1}{s} \simeq \frac{86.8 \text{ [nb]}}{s \text{ [GeV}^2\text{]}}$$

continuum

Continuum

Invariant mass reconstruction:

- Easier with leptons in the final state \rightarrow tracks
- Much better reconstructed than final state with quarks \rightarrow jets



Experiments

The Experiments

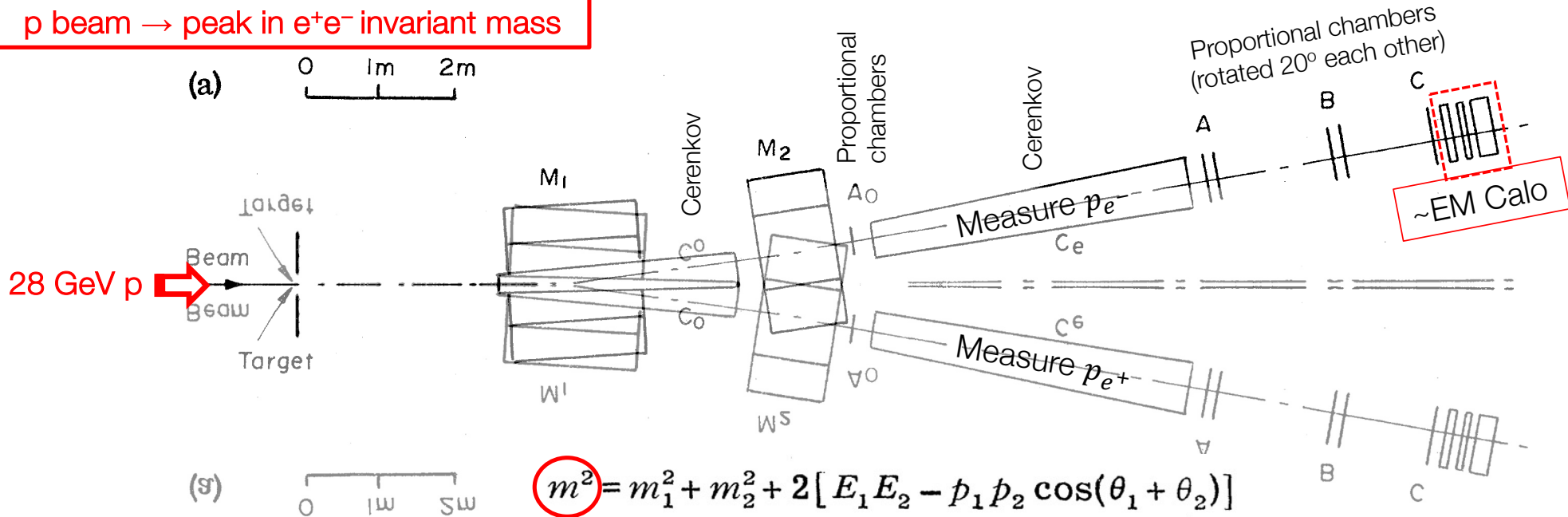
Ingredients to an Experiment

$(p + target)$ and $(e^+e^- colliders) \rightarrow e^+e^-, \mu^+\mu^-$

What you need	How you do it
Identify two electrons	Identify electrons = distinguish them from two 'any' charged tracks 1. \rightarrow look at the shower in EM Calorimeter, an electron is contained 2. \rightarrow the energy in EM Calorimeter \sim reconstructed momentum
measure the momentum of both electrons	1. \rightarrow well known magnetic field 2. \rightarrow tracking detector(s) 1. Inside magnetic field (large volume, difficult and expensive) 2. Before and after the magnetic field. In this case \rightarrow two arms
Identify two muons	Identify muons = distinguish them from two 'any' charged tracks 1. \rightarrow heavy material after trackers to filter all other charged particles 2. \rightarrow the energy in Calorimeters \sim compatible with a particle that doesn't shower
measure the momentum of both muons	1. \rightarrow well known magnetic field 2. \rightarrow tracking detector(s) 1. Inside magnetic field (large volume, difficult and expensive) 2. Before and after the magnetic field. In this case \rightarrow two arms
Two opposite charged particles	1. Radius of curvature of opposite sign

Ting's Experiment at Brookhaven → J discovery

p beam → peak in e⁺e⁻ invariant mass



$\Delta\theta = \pm 1^\circ; \Delta\phi = \pm 2^\circ; \text{Acceptance } \Delta m = 2\text{GeV}; 3 \text{ spectrometer settings} \rightarrow \text{study } m \text{ 1 to 5 GeV}$

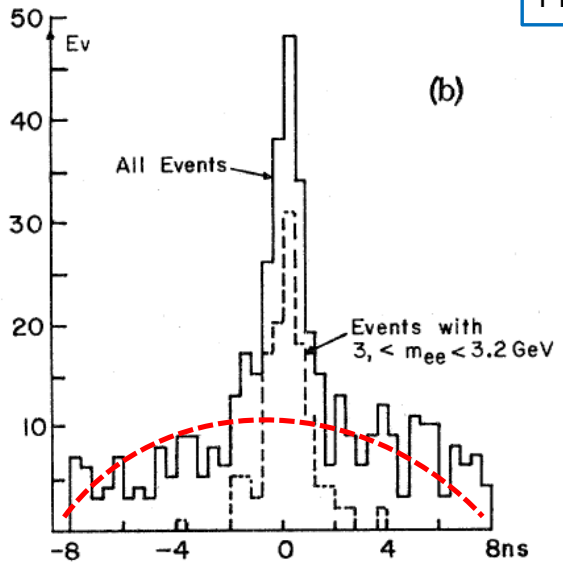
- two magnetic spectrometers for e⁺ and e⁻
- invariant mass resolution ~20 MeV for the e⁺e⁻ pair
- electrons and positrons identified using Cherenkov counters, time-of-flight information, and pulse height measurements.

Spectrometer → limited acceptance !

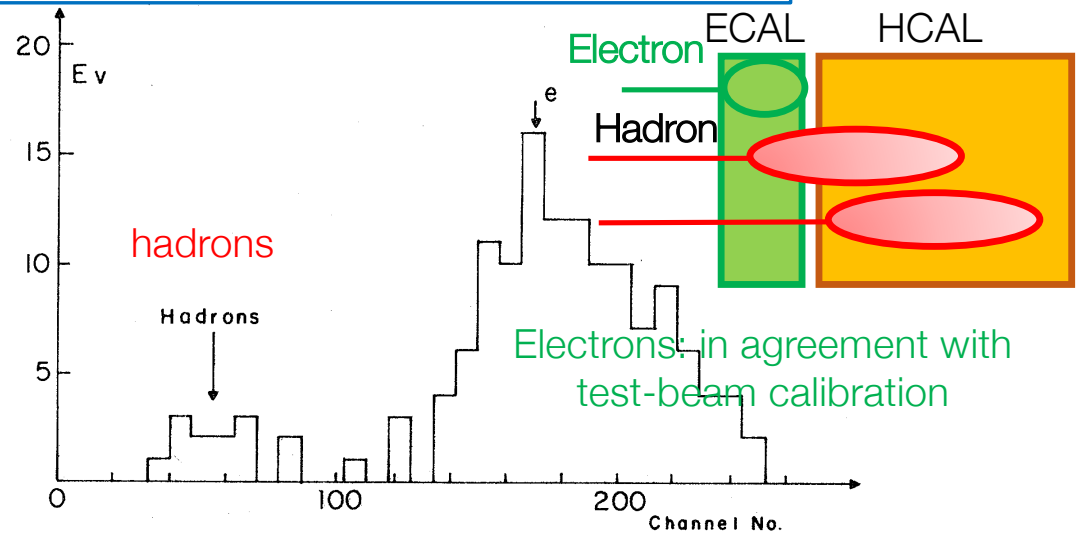
two banks of 25 lead glass counters of 3 X₀
each + one bank of lead-Lucite counters

The Discovery of the J

Hadron interactions → Peak in invariant mass distribution



Time of flight between e^+ and e^-



Pulse height spectrum of e^+ and e^- in lead-glass

e^+ and e^- from the J/Ψ decay arrive at the same time, $t_{e^+} - t_{e^-} \approx 0$ (time resolution).

- Peak $\sim 0 \rightarrow J/\Psi$ decay
- Remaining part accidentals

Electrons are more contained than hadrons \rightarrow
 Pulse height spectrum of electrons $>$
 Pulse height spectrum of hadrons

The Result: m_{ee} Invariant Mass Distribution

- Tracks in the two magnetic arms are reconstructed
- Events with wrong time-of-flight are rejected
- Events with hadron-like depositions in the lead glass are rejected
- Correct charges are selected

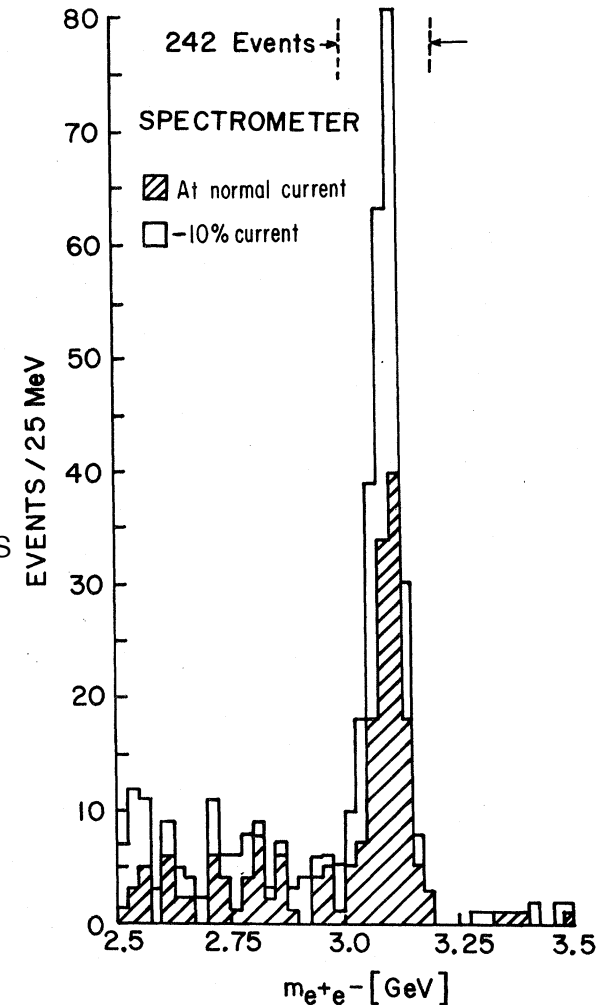
The resulting invariant mass distribution $m_{ee} \rightarrow$

A clear peak at ~ 3.1 GeV is observed,

the width of the peak is consistent with 0 width \rightarrow width is due to detector effects

A 10% reduction of the magnet currents \rightarrow larger acceptance \rightarrow more events
No effect is observed in the m_{ee}

The new particle was proposed the name "J"



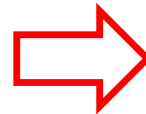
The MARK I Detector at SPEAR/SLAC

SLAC: e^+e^- collider CMS energies between 2.5 and 7.5 GeV

Increase of cross section

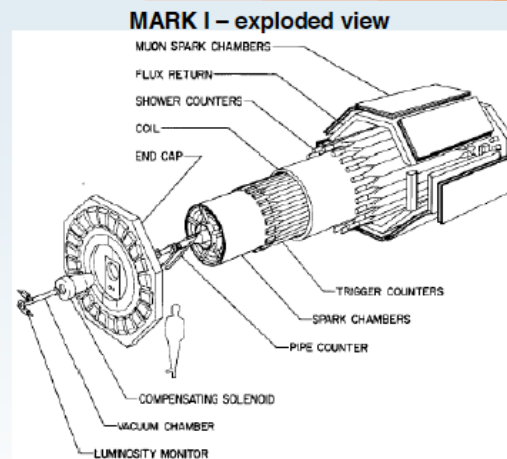
MARK I: a multipurpose large-solid-angle magnetic detector (~1970s)

- cylinder around the beam pipe
- detector-disks in the FW and BW direction
- 'ID' was a cylindrical spark chamber inside a solenoidal magnet of 4.6 kG.
- Time-of-flight counters for particle velocity measurements,
- shower counters for photon detection and electron identification,
- proportional counters inserted in iron absorber plates for muon identification.



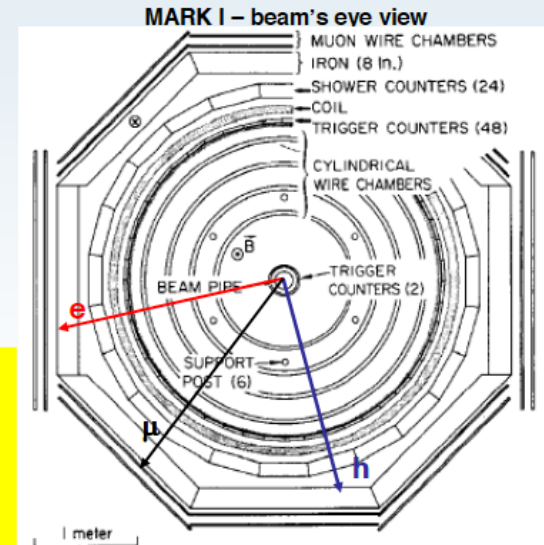
e^+e^- interactions → Vary beam energy → Scan in cms energy → Peak in cross section versus cms energy

MARK I – magnetic detector at SPEAR/SLAC



- **Tracking**
- Cylindrical magnet (5 KG / 20 m³)
- 16 cylindrical wire chambers
- **PID detectors**
- Trigger chambers (tof)
- Shower counters (e identification)
- Muon wire chambers

The "psion" family was discovered at SPEAR by using MARK I detector!



R.F. Schwitters et al., Ann. Rev. Nucl. Sci. 26 (1976) 89

The Discovery of the Ψ

Mark I:

energy scan (**200 MeV steps, no structure expected!**)
to study $e^+e^- \rightarrow \text{hadrons}$

→ 200 MeV is much larger than the J/Ψ width of ~ 100 KeV

The data:

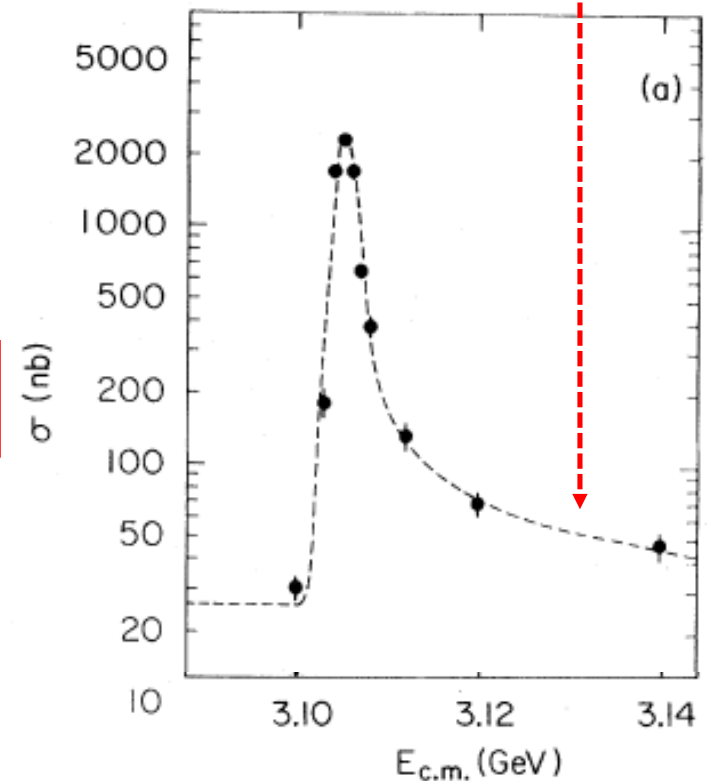
- \sim constant cross section BUT the value at 3.2 GeV \sim high
- in June 1974 additional data at 3.1 and 3.3 GeV \rightarrow irregularities at 3.1 GeV
- \rightarrow remeasure this region.

Scanning this region in very small energy steps revealed an enormous, narrow resonance.

The increase in the cross section at 3.2 GeV was due to the tail of the resonance

The anomalies at 3.1 GeV were caused by energy spread of the beam and by radiative corrections near the lower edge of the resonance, where the cross section was rising rapidly.

Dotted line is a calculation: expected shape of a δ -function peaking at 3.1 GeV, folded with beam energy spread and radiative processes



One 200 MeV step

The width of the J/ψ

Final states with e^+e^- and $\mu^+\mu^-$: the same pattern vs \sqrt{s} as that of hadronic final states but with less statistics

How to compute the width of that resonance?

The profile of $\sigma(s)$ is due to energy spread of the beam and by radiative corrections

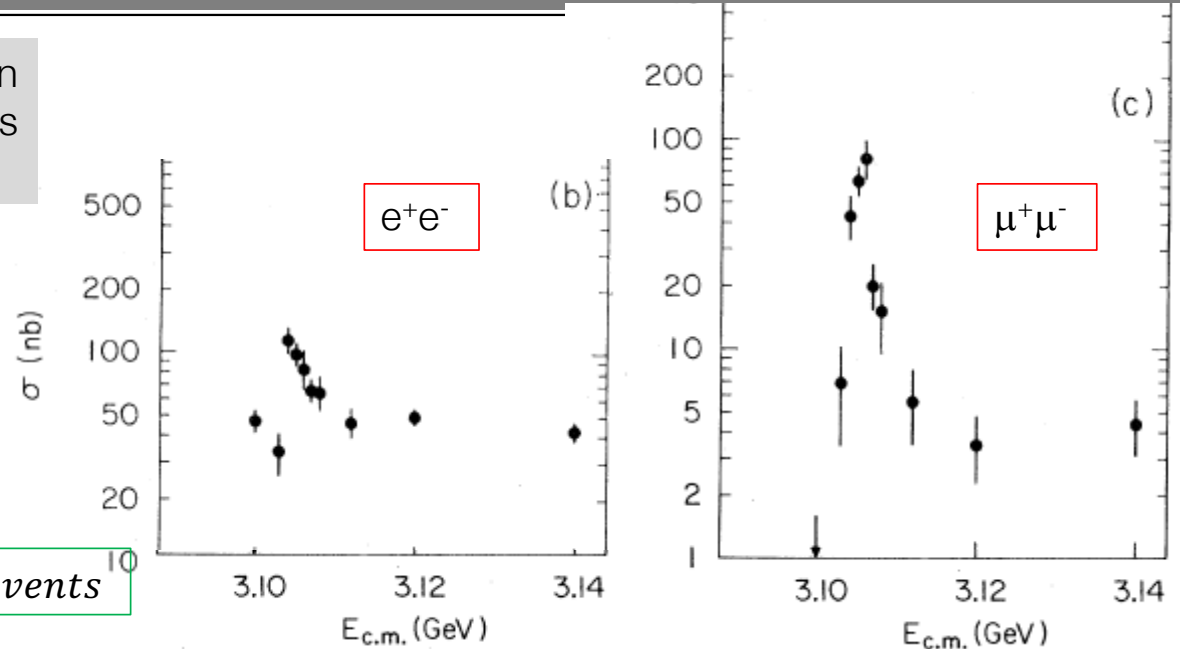
BUT: the area does not change and can be expressed as:

$$\Gamma_{ee}, \Gamma_{had} = \text{rate of events}$$

$$\sigma(e^+e^- \rightarrow J/\psi \rightarrow \text{hadrons}) = 3\pi\lambda^2 \left[\frac{\Gamma_{ee}\Gamma_h}{\Gamma^2} \right]$$

$$J/\psi \text{ resonance} \rightarrow \text{beam energy } p = \frac{m_{J/\psi}}{2} \rightarrow \lambda = 2\hbar/m_{J/\psi}$$

$$\text{Area} = \frac{6\pi^2\Gamma_{ee}\Gamma_{had}}{M_\psi^2\Gamma_{tot}}$$



The area under the resonance ~ 10 nb GeV.

$\Gamma_{had} \approx \Gamma_{tot}$, $M_\psi = 3.1$ GeV,

$\rightarrow \Gamma_{ee} \approx 5$ keV. (Later measurements: **total** width between 60 and 70 keV)

And of the Ψ'

Ten days after the first discovery, a second narrow resonance was found. The search continued, but no comparable resonances were found up to the maximum SPEAR energy of 7.4 GeV.

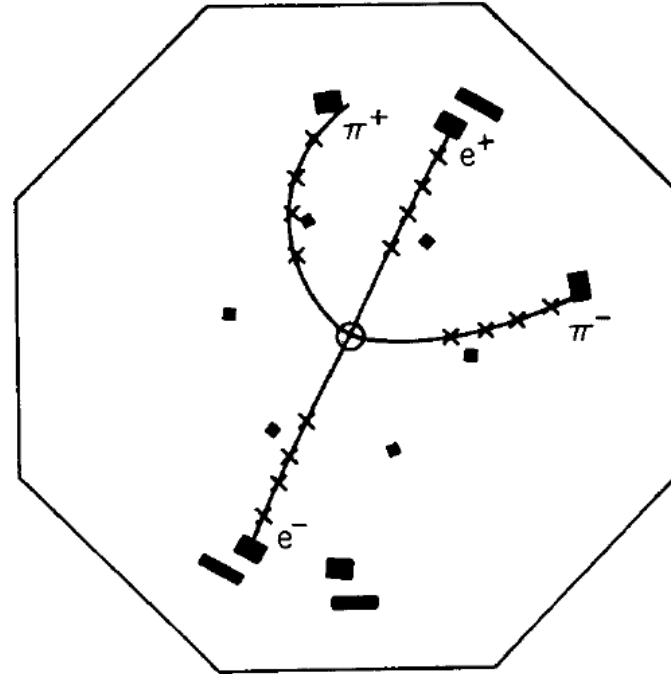


Figure 9.1. An example of the decay $\psi' \rightarrow \psi \pi^+ \pi^-$ observed by the SLAC-LBL Mark I Collaboration. The crosses indicate spark chamber hits. The outer dark rectangles show hits in the time-of-flight counters. Ref. 9.5.

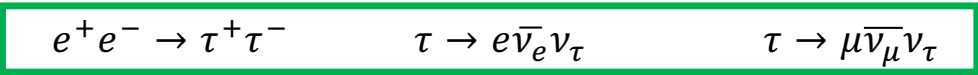
<http://crunch.ikp.physik.tu-darmstadt.de/nhc/pages/lectures/rhiseminar07-08/otwinowski.pdf>

The Discovery of the τ Lepton

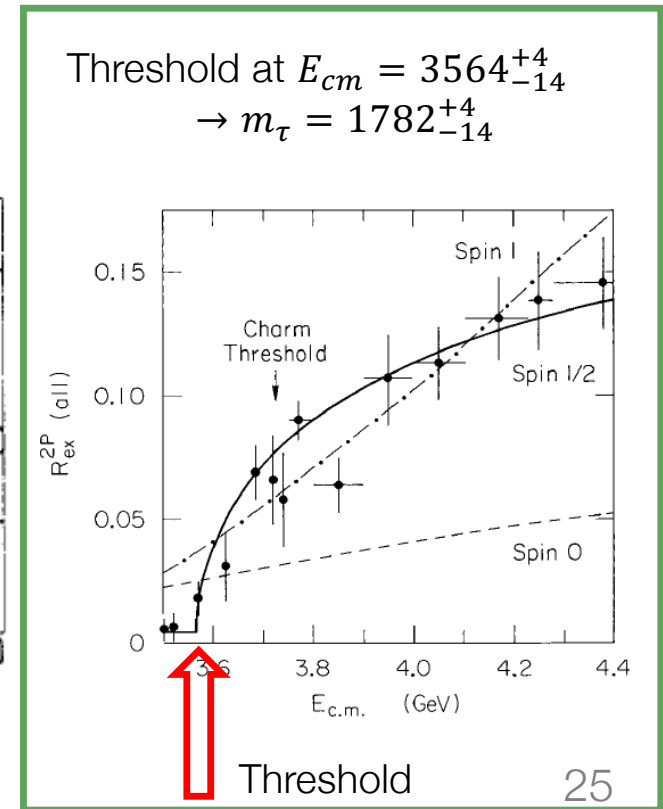
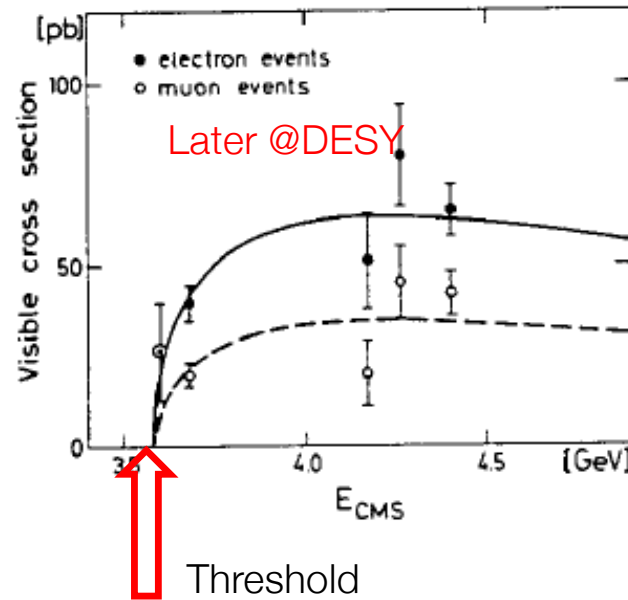
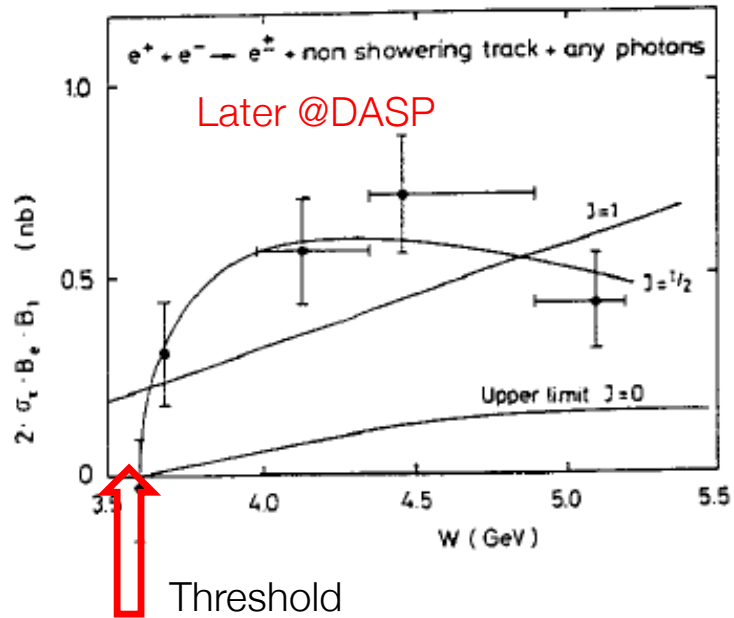
MARK I @ SLAC: while studying Ψ, Ψ' another discovery nearly as dramatic as that of the Ψ .

In 35,000 events, 24 events with a μ and an opposite sign e , no additional hadrons or photons.

These events were interpreted as the pair production of a new lepton, τ , followed by its leptonic decay. The leptonic decays were



$2 \times m_\tau \sim$ centre of mass energy where 'anomalous, events appear



The Fifth Quark, the “bottom”

The discovery of

- the $J/\psi \rightarrow$ charmed quark
- the τ and its neutrino suggested a new pair of quarks.

→ same techniques used to discover the charmed quark: e^+e^- annihilation and hadronic production of lepton pairs

Leon Lederman and his co-workers searched for peaks in the $\mu^+\mu^-$ spectrum at high energies by

- collisions of 400 GeV protons on nuclear targets at Fermilab
- double-arm spectrometer set to measure $\mu^+\mu^-$ pairs with invariant masses above 5 GeV with a resolution of 2%.
- Hadrons were eliminated by using long beryllium filters in each arm.

1977: a clear, **statistically significant $\mu^+\mu^-$ peak** was observed in the 9.5 GeV region with an **observed width of about 1.2 GeV (very large!!)**.

Later: the large peak was better described by two peaks at 9.44 and 10.17 GeV which were given the names Υ and Υ'

a repetition of the J/ψ and ψ' story

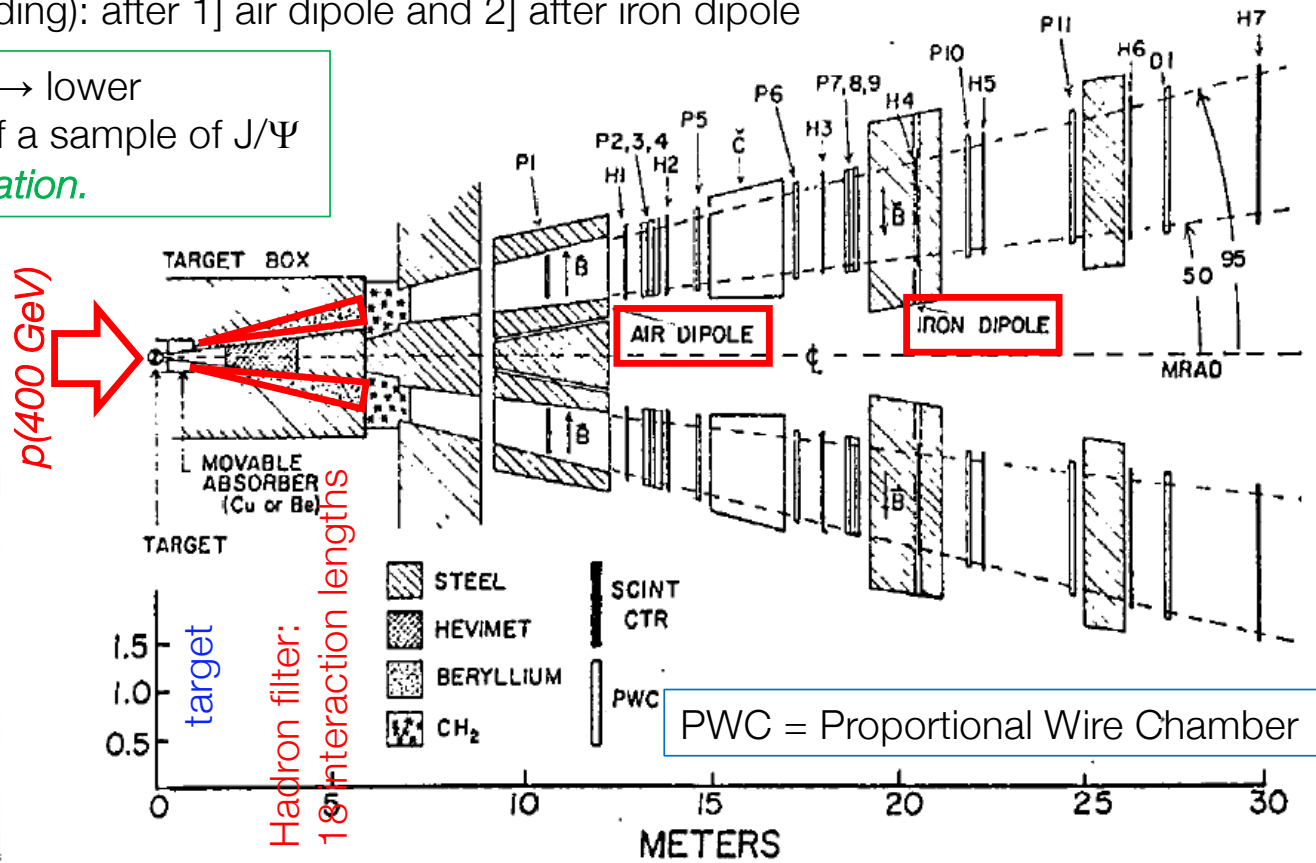
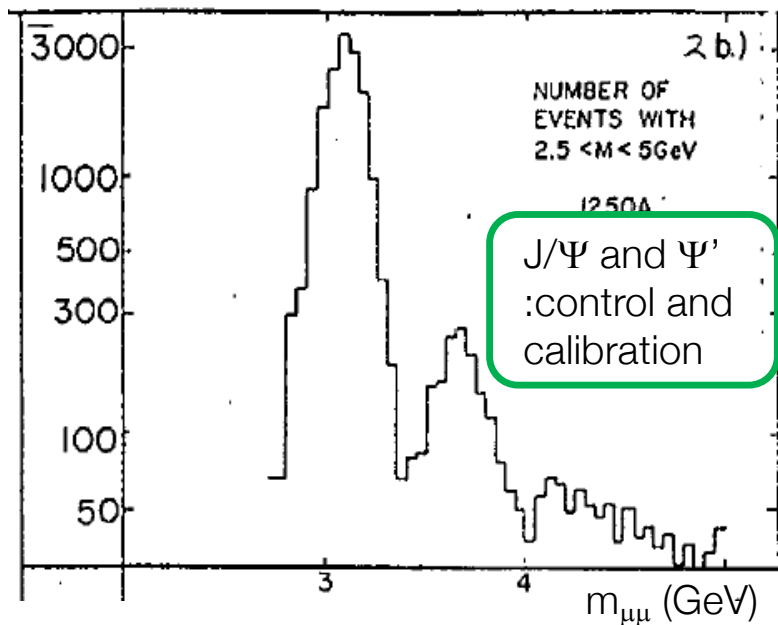
Fermions		
$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix} ?$ Quarks
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$ Leptons
First family	Second family	<u>Third family</u>

Discovered fermions

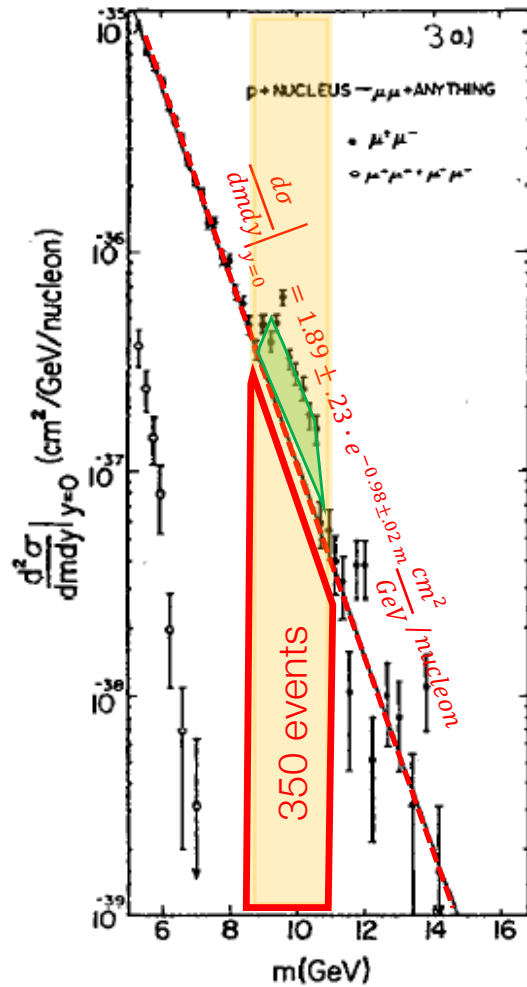
Fermilab: Dimuon Resonance at 9.5 GeV

- Hadron Filter to stop hadrons and leave only muons
- Wire chambers and scintillators to reconstruct the muon trajectory
- Muon momentum measured twice (bending): after 1] air dipole and 2] after iron dipole

dipoles at lower current → lower bending → lower momenta → lower masses → collection of a sample of J/Ψ and of Ψ' to be used as control and *calibration*.



The Upsilon at Fermilab



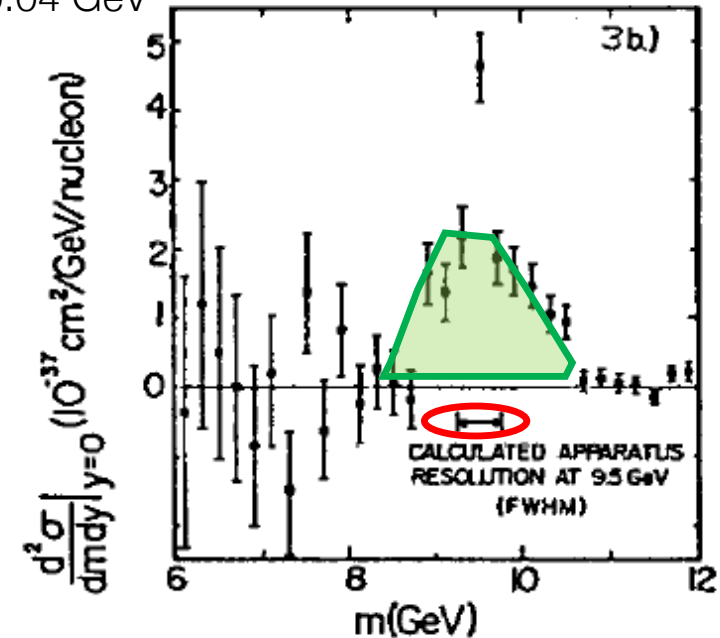
Increase of cross section

Later it was realised that the width of the excess had to be interpreted with

the superposition of two states:
the Υ and the Υ' .

These states were identified few months later at the DORIS accelerator in DESY

- A significant ‘bump’ excess is observed at ~ 9.5 GeV in mass
- Excluding the 8.8 to 10.6 GeV region \rightarrow the distribution = simple exponential f
- The exponential form has an integral of 350 events in the “excluded region” while data contain 770 events
- “The observed bump is *larger* than the mass resolution of 0.5 ± 0.1 GeV.
- Fitting the data minus the continuum fit with a simple gaussian gives:
Mass = 9.54 ± 0.04 GeV”



DORIS at DESY

May 1978 the PLUTO and DASP II detectors at the DORIS e^+e^- storage ring at DESY were able to observe the Υ at a mass

$$M_{\Upsilon} = 9.46 \pm 0.01 \text{ GeV}$$

As for the J/ψ ,

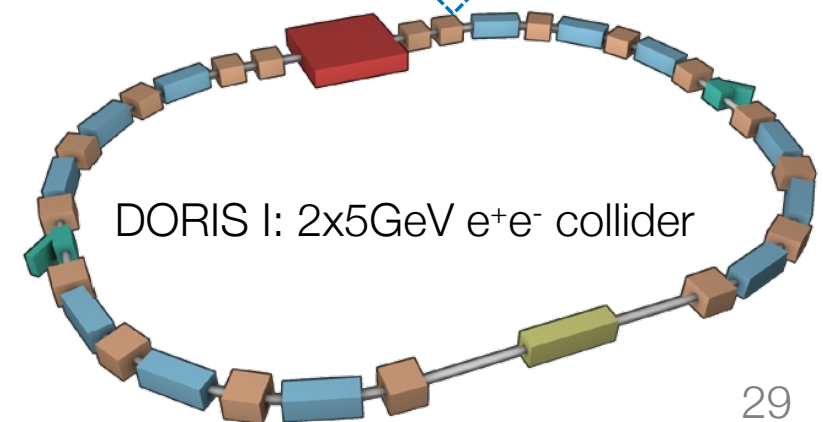
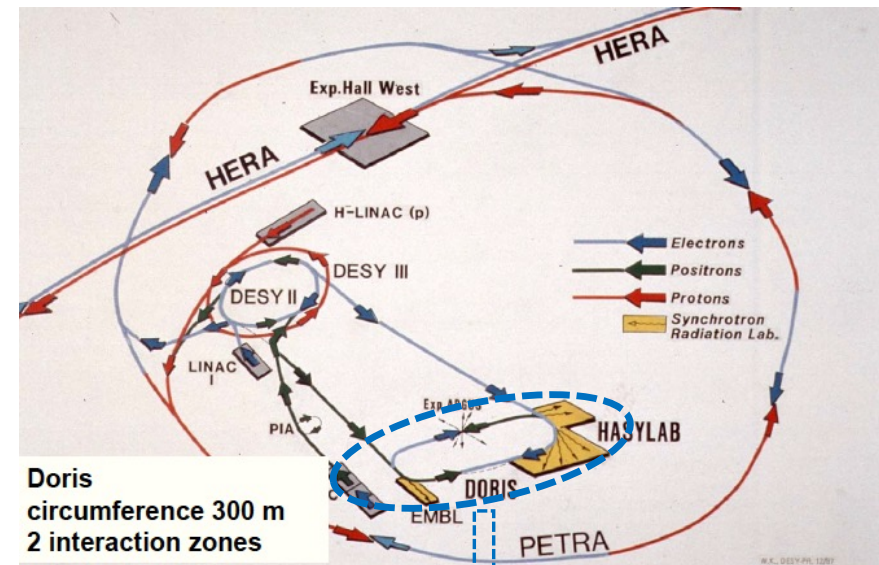
$$\Gamma_{\Upsilon \rightarrow e^+e^-} = 1.3 \pm 0.4 \text{ keV (area under the resonance)}$$

The comparison with models indicated that the new quark had

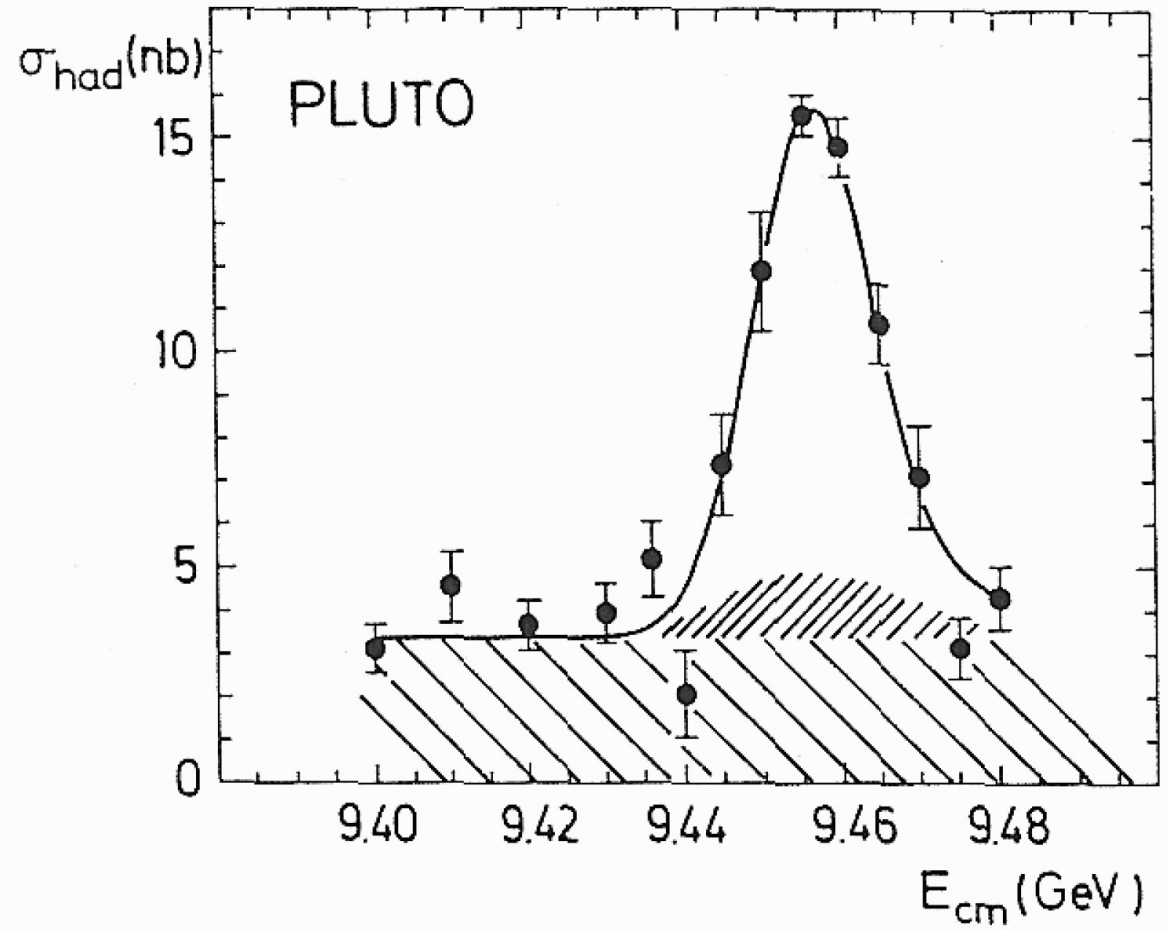
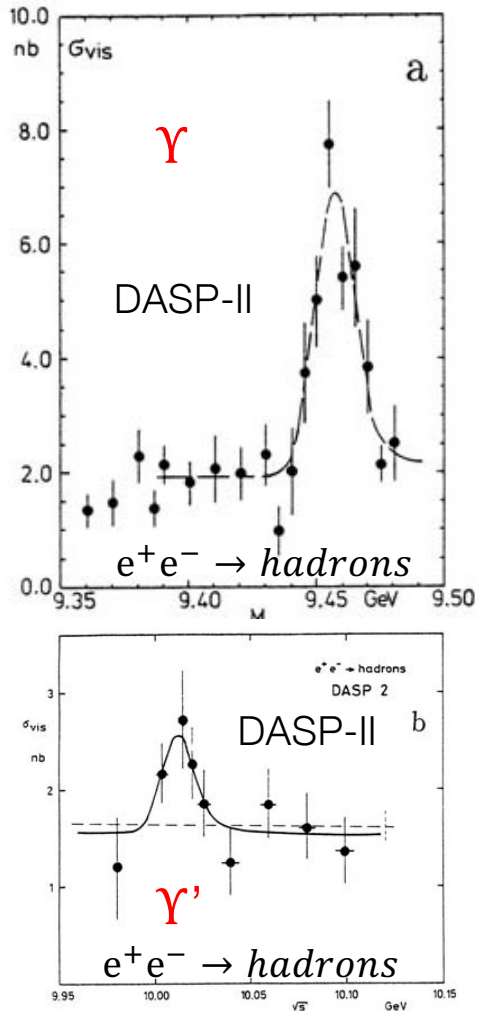
charge $-1/3$ (not $+2/3$)

The new quark was called the “b” for “bottom”: practice of writing the quark pairs (u, d) with the charge $-1/3$ and (c, s) below the charge $2/3$ quark.

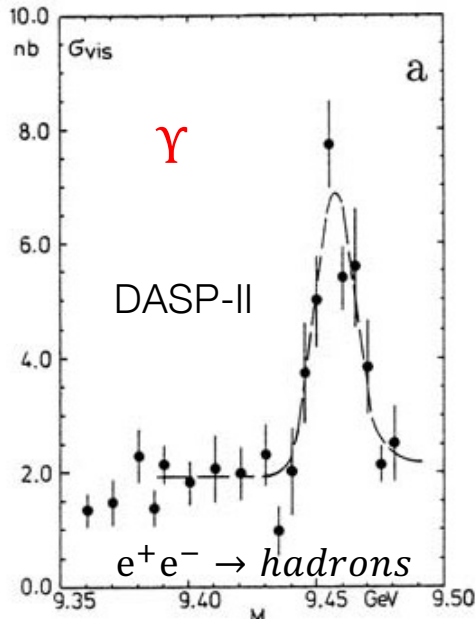
Thus the sixth quark was called “t” or “top” (before its discovery).



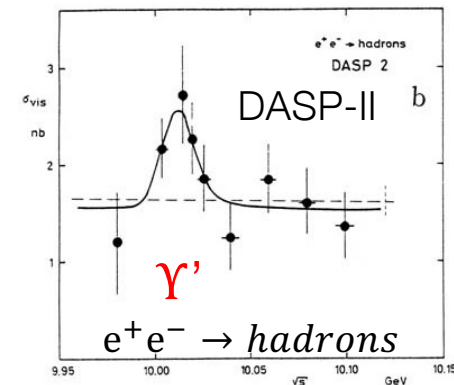
The Upsilon at DORIS



The Upsilon at DORIS

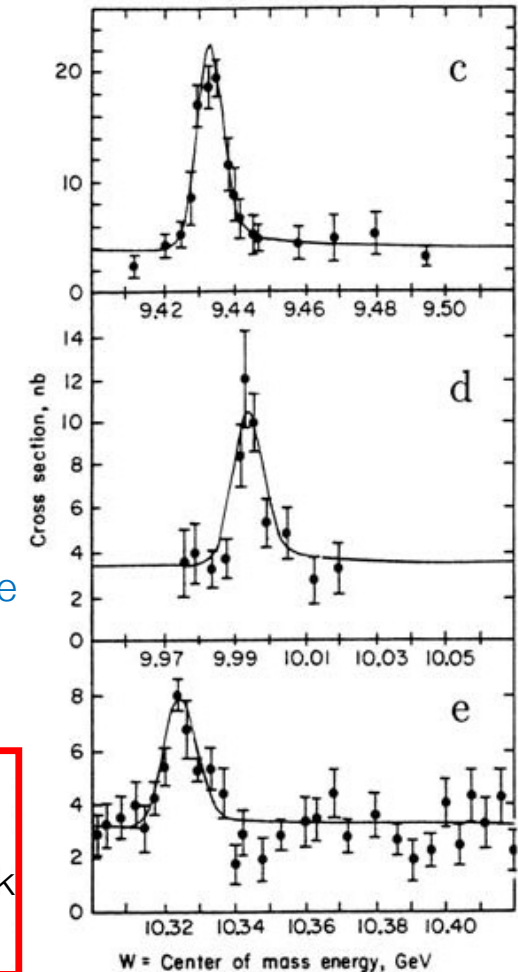


With the help of an energy upgrade, in May 1978 the PLUTO and DASP II detectors at the DORIS e^+e^- storage ring at DESY were able to observe the Υ . The determination of the mass of the resonance was greatly improved: $M_\Upsilon = 9.46 \pm 0.01$ GeV. Moreover, *the observed width was limited only by the energy spread of the beams*, so that it was less than 1/100 as much as that observed in hadronic production.



Just as for the J/ψ , it was possible to derive the partial width for $\Gamma_\Upsilon \rightarrow e^+e^-$ from the area under the resonance curve, with the result $\Gamma_\Upsilon \rightarrow e^+e^- = 1.3 \pm 0.4$ keV. Using model calculations derived from the ψ system, it was possible to predict Γ_Υ for the cases of charge $-1/3$ and $+2/3$. The comparison indicated that the new quark had charge $-1/3$ rather than $+2/3$.

The new quark was called the “b” for “bottom,” reflecting the practice of writing the quark pairs (u, d) and (c, s) with the charge $-1/3$ below the charge $2/3$ quark. Thus the sixth quark was called “t” or “top” (before its discovery).



Preparing the Discovery of the W and of the Z

Neutral Currents (exchange of Z boson) discovered in 1973 at CERN (Bubble Chamber Gargamelle)
 → search for the W and Z bosons, predicted by the SM.

In the SM

$$m_{W^\pm}, m_Z = f(\sin^2 \theta_W)$$

$$m_W^2 = \frac{\pi \cdot \alpha}{\sqrt{2} \cdot \sin^2 \theta_W \cdot G_F} \quad m_Z^2 = m_W^2 / \cos^2 \theta_W$$

In 1973 NC were discovered and in 1976 the value of $\sin^2 \theta_W = 0.3 \pm 0.1$ was obtained

$$m_W = \frac{37 \text{ GeV}}{\sin \theta} \approx 68 \pm 40 \text{ GeV}; \quad m_Z = \frac{73 \text{ GeV}}{\cos \theta} \approx 80 \pm 25 \text{ GeV}$$

Large masses → design of the accelerator and of the detector.

$$R^\nu = \frac{\sigma_{\text{NC}}^\nu}{\sigma_{\text{CC}}^\nu}$$

$$R_{\text{exp}}^\nu$$

$$R_{\text{theory}}^\nu(\sin^2 \theta_W)$$

$$\sin^2 \theta_W \sim 0.2-0.3$$

$$\sigma = \frac{G_F^2}{\pi(\hbar c)^4} \cdot \frac{M_W^2 c^4}{s + M_W^2 c^4} \cdot s$$

For $\sin^2 \theta_W = 0.23$ (the value known today) you get $m_W = 80 \text{ GeV}$ and $m_Z = 91 \text{ GeV}$

LEP & SPS & SppS and Fermilab: History

Situation in late 70s @CERN:

No need to have a narrow extracted beam !

1. A proton accelerator was under construction at CERN (SPS) (*one proton beam for extraction*)
2. A new e^+e^- accelerator was under project: the *Large Electron-Positron* Collider (LEP). This machine was ideal to measure the properties of W and Z bosons (~10 to 15 years for design + construction + *digging 27Km tunnel*)

CERN felt it could not wait for the construction of LEP.

In 1976 Carlo Rubbia and colleagues proposed to modify the SPS proton accelerator into a $p\bar{p}$ collider (SppS).

(A similar proposal also at Fermilab but was rejected)

The SppS was in operation in 1983

To convert the SPS to a $p\bar{p}$ collider with 540 GeV c.m.s:

1. the antiproton beam was needed. *Invention of the “stochastic cooling” of particles by Simon van der Meer in 1968-1972.*
2. Since the protons and antiprotons are of opposite charge, but of same energy E, they can circulate in the same magnetic field in opposite directions → only a single vacuum chamber

Emittance ϵ and the \bar{p}

The β function, describes the envelope of the single-particle trajectories.

$$x(s) = \sqrt{\epsilon} \cdot \sqrt{\beta(s)} \cdot \cos(\psi(s) + \phi)$$

- s is the position along the trajectory
- $\psi(s)$ and ϕ are the amplitude in position s and ϕ its initial condition

ϵ is an invariant and describes the space occupied by the particle in the transverse two-dimensional phase space $[x, x']$.

Two important quantities that describe the beam can be introduced using the expression above:

Beam size, width:

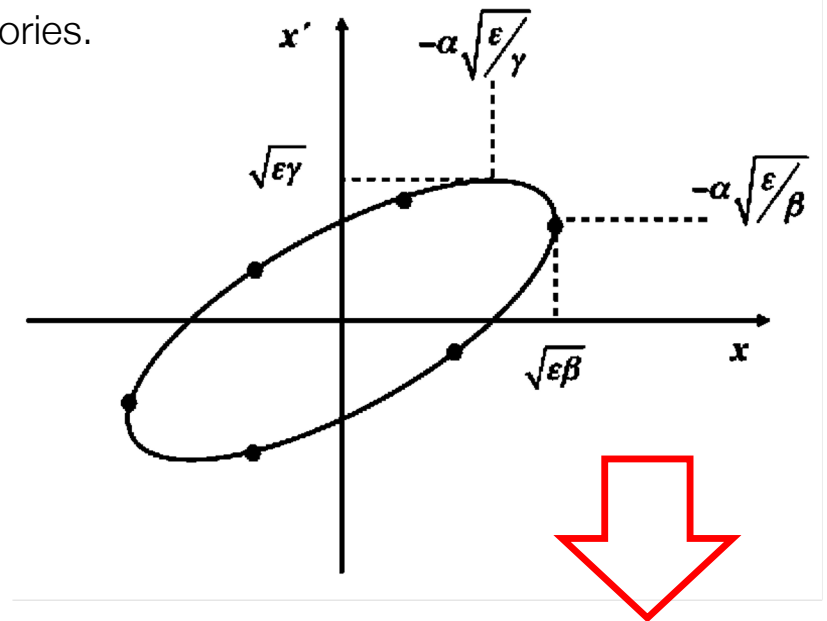
Beam divergence:

Product:

$$\sigma(s) = \sqrt{\epsilon \cdot \beta(s)}$$

$$\theta(s) = \sqrt{\epsilon / \beta(s)}$$

$$\sigma(s) \cdot \theta(s) = \epsilon$$

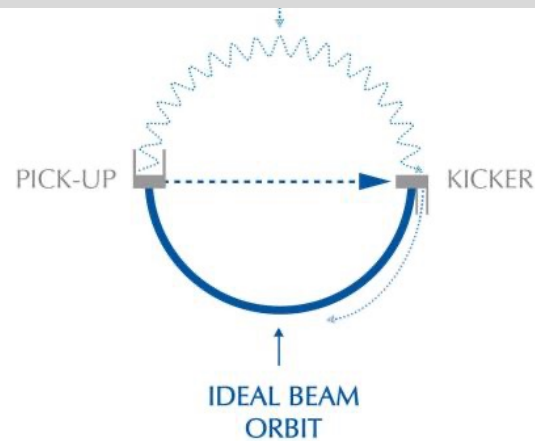


This means that emittance cannot be changed once the optics of the machine is defined: it is a property of the beam, and cannot be changed.

A narrow beam is divergent, a collimated beam is more spread

Stochastic Cooling

Main SpS problem : the production and storage of $3 \cdot 10^{10}$ \bar{p} each day into a few bunches
Small angular and momentum dispersion



Gases:

heat ~ disorder

→ “cooling” means reduction of disorder in the beam.

→ Dump oscillations of particles in a beam to a smaller size

Stochastic cooling = iterative process

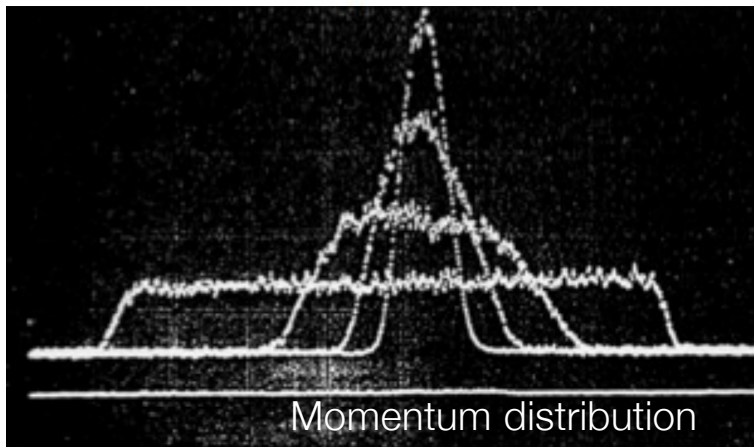
- pick-up: measures the deviation of a bunch of particles with respect to the ‘ideal’ orbit.
- sends a signal to the kicker which applies an electric field to this same bunch to correct the deviation measured

AA (Antiproton Accumulator)

Momentum cooling in ICE of 5×10^7 particles.

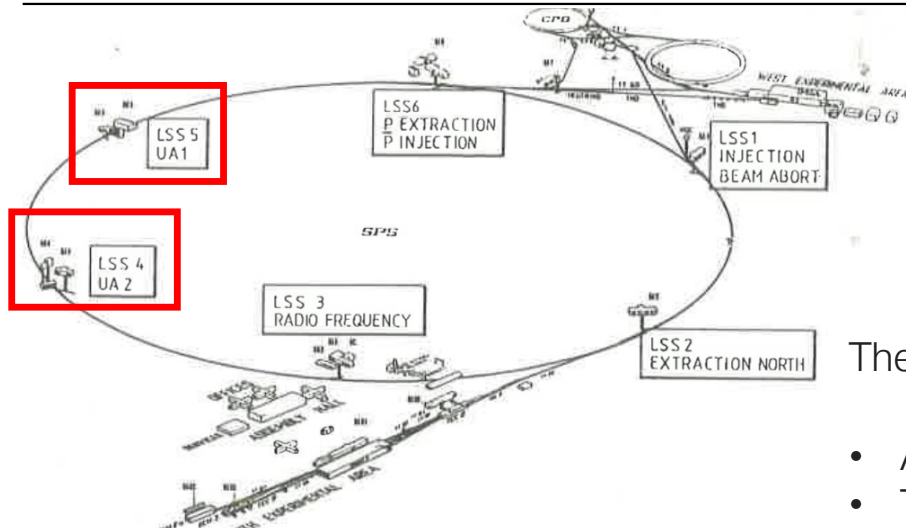
Momentum distribution after 0, 1, 2 and 4 minutes.

The relative momentum spread reduces from 3.5×10^{-3} to 5.0×10^{-4}



From the SPS to the SppS

SPS → one beam → extraction
SppS → storage ring where two beams circulate for hours.



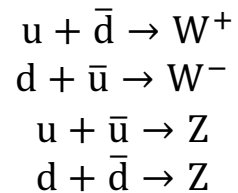
The following modifications were done on the SPS:

- A new beam line to transfer \bar{p} from the PS to the SPS
- The injection system in the SPS from 14 GeV/c to 26 GeV/c

- The design vacuum of $2 \cdot 10^{-7}$ Torr was adequate for the SPS, beam accelerated to 450 GeV and extracted ~soon
- The SppS had to keep beams for 15 to 20 hours, the vacuum reduced by 3 orders of magnitude.
- The RF system had to undergo modifications for simultaneous accelerations of protons and antiprotons. (collisions at the centre of the detectors)
- Construction of huge experimental areas for experiments (UA1 and UA2).
- The beam abort system had to be moved to make place for the experiments.

Expected Topologies

There are \bar{q} in $\bar{p} \rightarrow$ the production proceeds via valence quarks only:



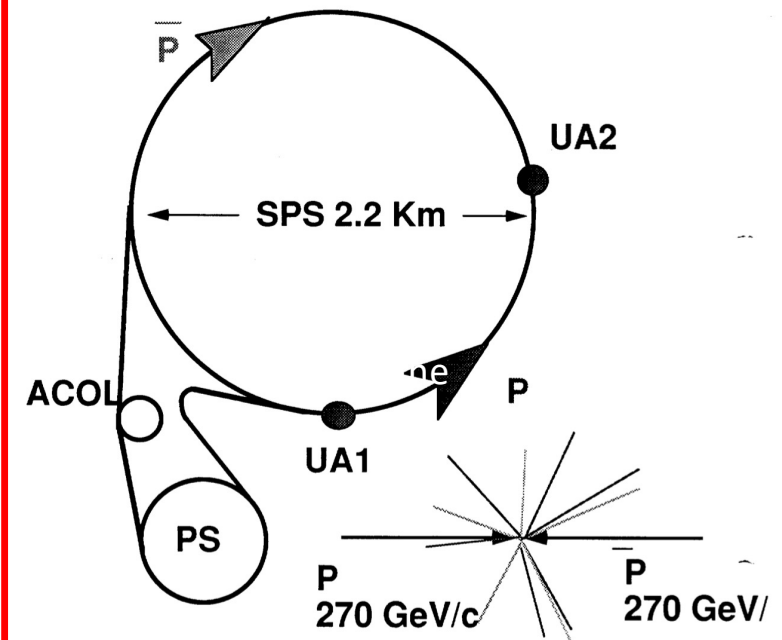
(SM expected) decay modes were:

- **Leptonic** (only decays to e, μ were used):
 1. $W^\pm \rightarrow l^\pm + \nu_l$ ($l = e, \mu, \tau$) one lepton + missing energy, unbalanced event, **cross section \mathcal{O} 1 nb per leptonic species,**
 $\sigma_{\text{tot}} \approx 4 \cdot 10^7 \text{ nb}$
 2. $Z \rightarrow l^+l^-$ ($l = e, \mu, \tau$) two opposite sign, same flavour leptons, balanced event **cross section \mathcal{O} 0.1 nb per leptonic species,**
 $\sigma_{\text{tot}} \approx 4 \cdot 10^6 \text{ nb}$
 3. $Z \rightarrow \nu_l \bar{\nu}_l$ ($l = e, \mu, \tau$) invisible decay \rightarrow *unmeasurable!*
- **Hadronic**

$$W \rightarrow qq' \rightarrow \text{hadrons} \rightarrow 2 \text{ jets}$$

$$Z \rightarrow q\bar{q} \rightarrow \text{hadrons} \rightarrow 2 \text{ jets}$$

CERN SppS Collider



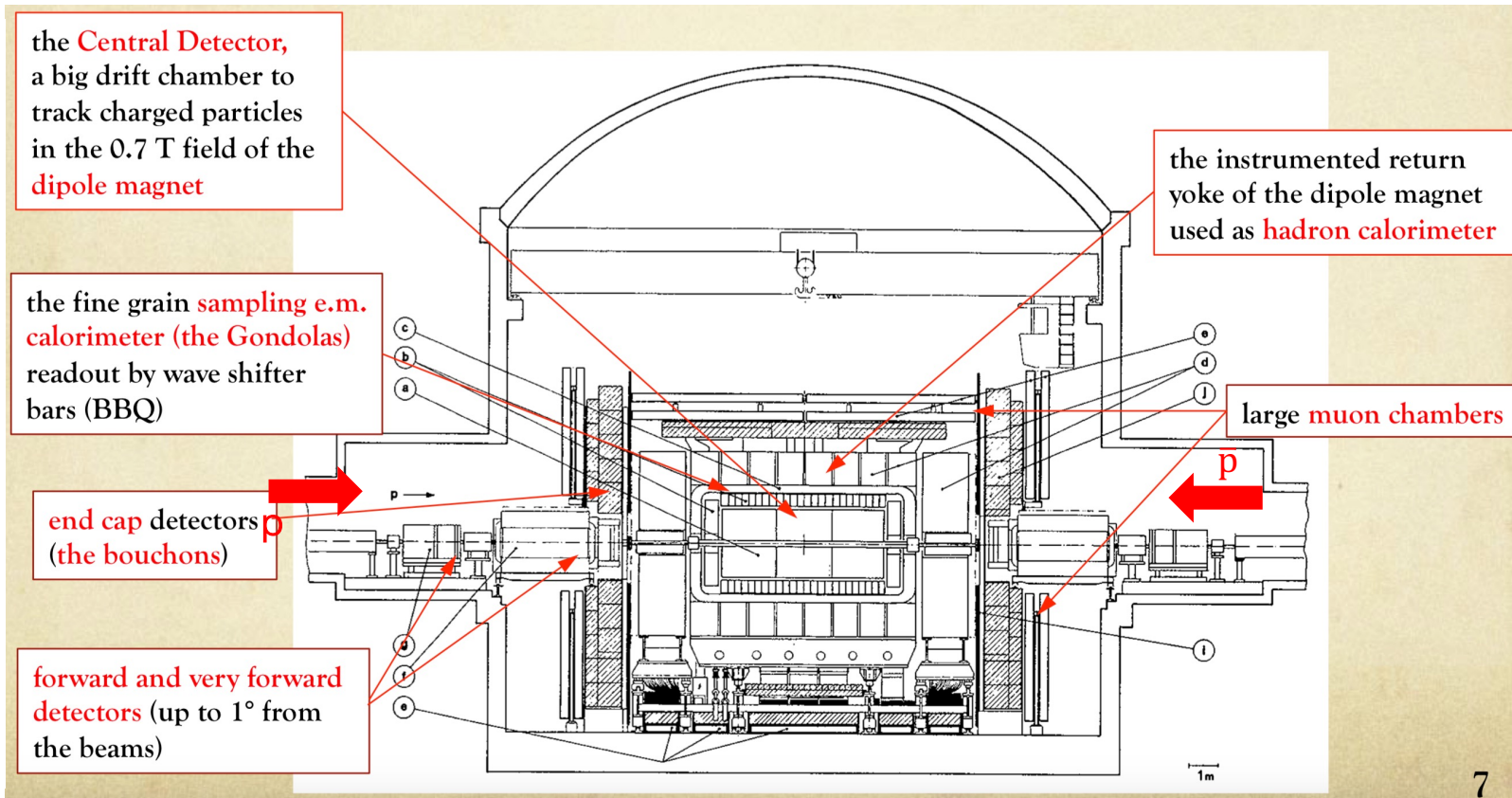
The SppS brought into collision
270 GeV p and 270 GeV \bar{p} in 1983

The UA1 Experiment

Z and W give a very small signal compared to a very large background.
muons and neutrinos from the W and Z decays have very high transverse momenta: $p_T \approx m_W/2$ much larger than that of background muons.

The UA-1 detector:

- 0.7 T uniform magnetic field
- a high quality drift chamber inside.
- electromagnetic and hadronic calorimeters.
- The discrimination between electrons and hadrons with many X_0 segmented into layers \rightarrow shape of shower
- Muon chambers after calorimeters



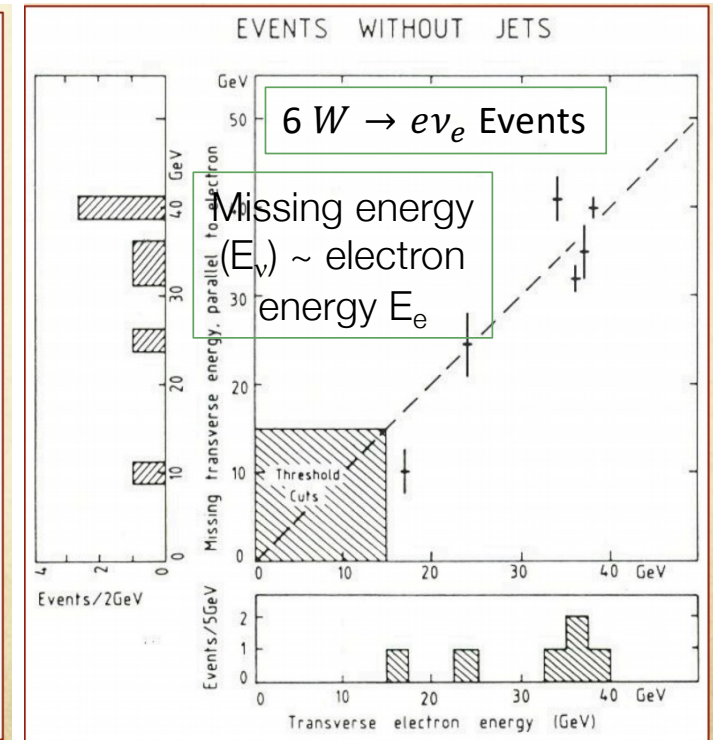
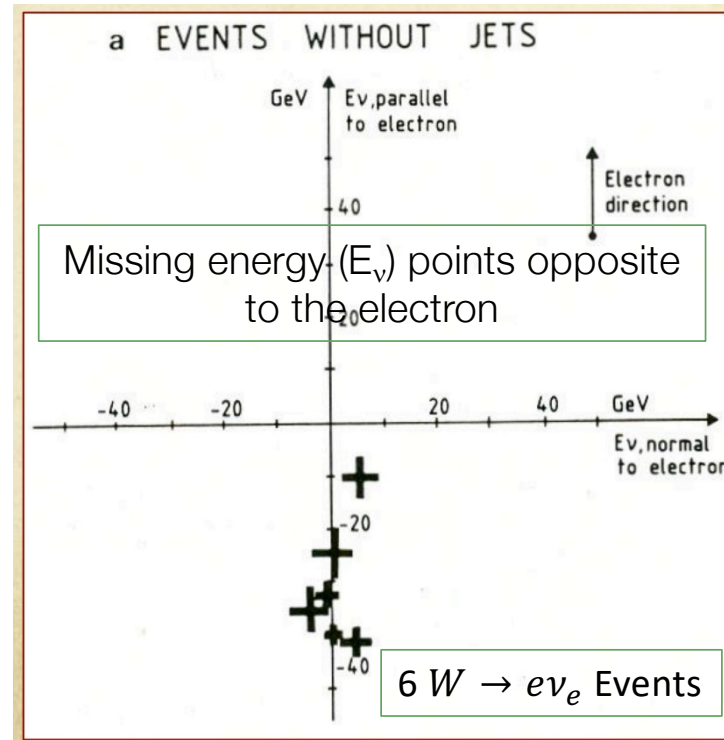
The UA1 Results: $6 W \rightarrow e\nu_e$ Events

Selection of $W^- \rightarrow e^- + \nu_\mu$ (cuts-flow)

1. A track with $p_T > 7$ GeV/c associated to an em shower (1106 events)
2. Isolation: Σ Other charged tracks < 2 GeV/c transverse momenta (276 events)
3. Shower vertex in em calorimeters must agree with the impact of the track (167 events)
4. The energy deposition E_c in the hadronic calorimeters in the direction of the extrapolated track must not exceed 600 MeV to select contained electrons (72 events)
5. E_{em} and p_T of the charged track must agree within 3σ (39 events).

→ 6 events with no jet and missing energy + events with jets and no missing energy

The kinematics of the events indicates $m_W = 81 \pm 5$ GeV. Number of events if agreement with expected σ 39



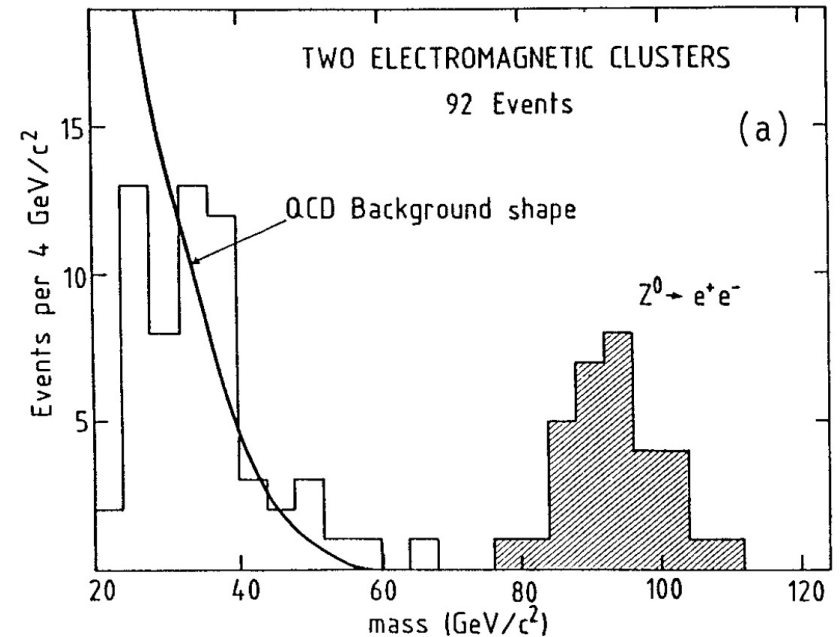
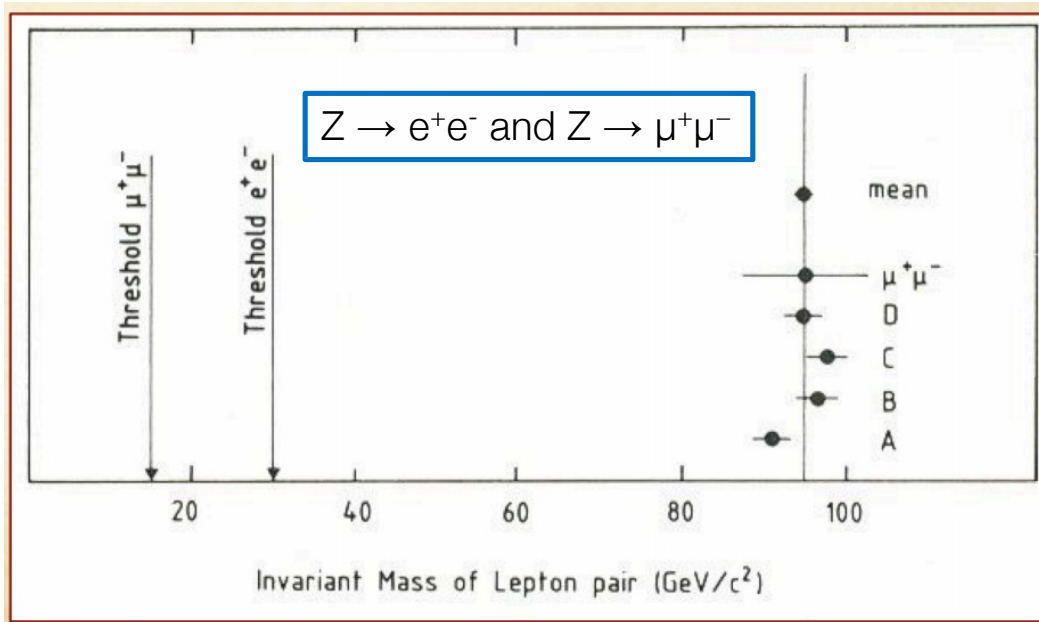
The UA1 Results: $Z \rightarrow \ell^+ \ell^-$ Events

Z decays $\rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ were discovered later

- Cross section for Z production is ~ 10 times smaller than that for W's
- the branching ratios $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ are expected to be only 3% each, while $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ should be 8% each.

However, the signature of two leptons with large invariant mass was very clear, and only a few events were necessary to establish the existence of the Z with a mass consistent with the theoretical expectation

Results for the decay $Z \rightarrow e^+e^-$ obtained by the UA-1 and UA-2 Collaborations are shown below



Lego Plots of $Z \rightarrow e^+ e^-$ Events from UA1

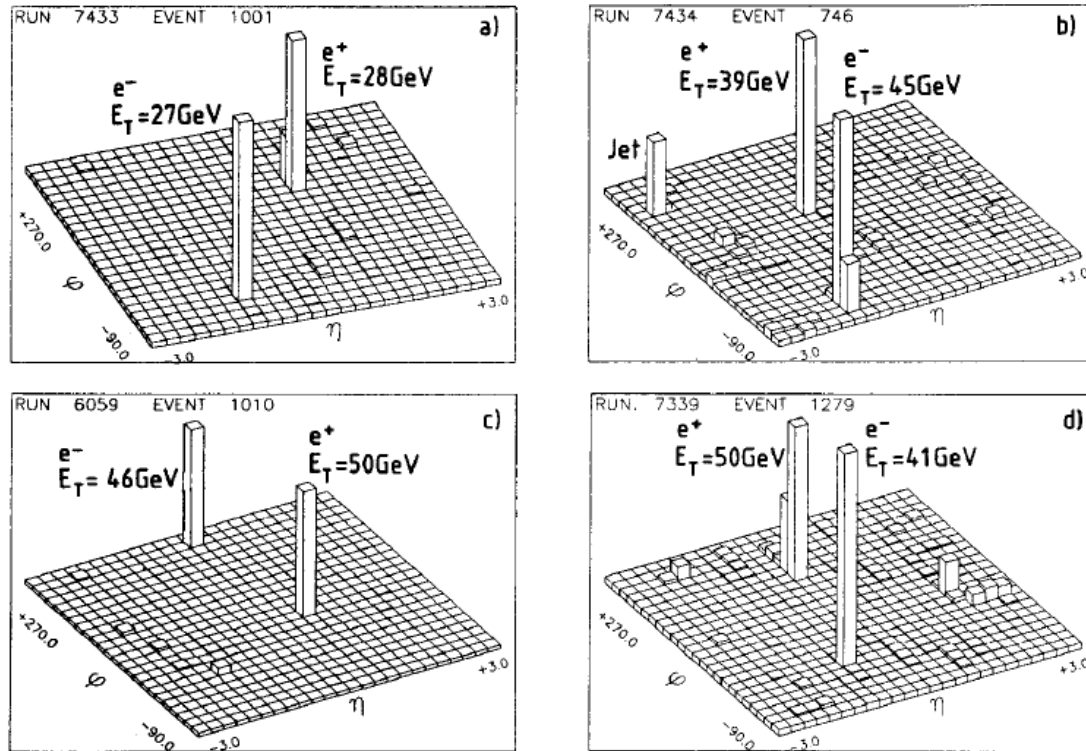


Figure 12.3. Lego plots for four UA-1 events that were candidates for $Z^0 \rightarrow e^+ e^-$. The plots show the location of energy deposition in ϕ , the azimuthal angle, and $\eta = -\ln \tan(\theta/2)$, the pseudorapidity. The isolated towers of energy indicate the cleanliness of the events (Ref. 12.8).

UA2 Results

The UA1 and the UA2 experiments had many things in common; they were both operating on the same accelerator and both had the same objective (to discover the W and Z bosons). The main difference was the detector design; UA1 was a multipurpose detector, while UA2 had a more limited scope. UA2 was optimized for the detection of electrons from W and Z decays. The emphasis was on a highly granular calorimeter with spherical projective geometry, which also was well adapted to the detection of hadronic jets. Charged particle tracking was performed in the central detector, and energy measurements were performed in the calorimeters. Unlike UA1, UA2 had no muon detector.

On 22 January 1983, the UA2 collaboration announced the recording of four candidates for a W boson decaying to electrons. This brought the combined number of candidate events seen by UA1 and UA2 up to 10.

The quest for the Z boson took longer. The experiments therefore needed to collect several times the data collected in the 1982 run.

On 1 June 1983, the formal announcement of the discovery of the Z boson was made at CERN.

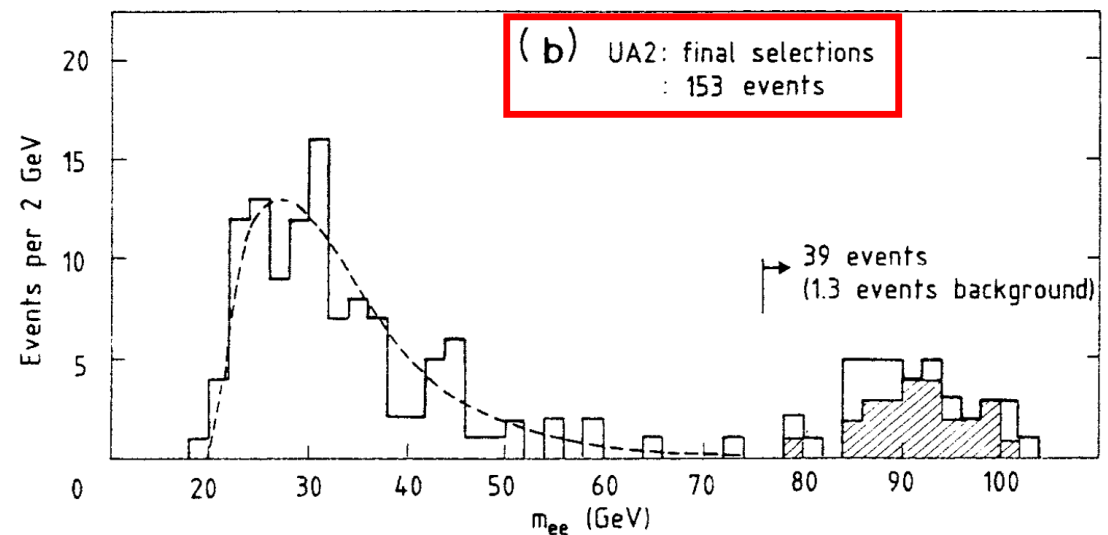
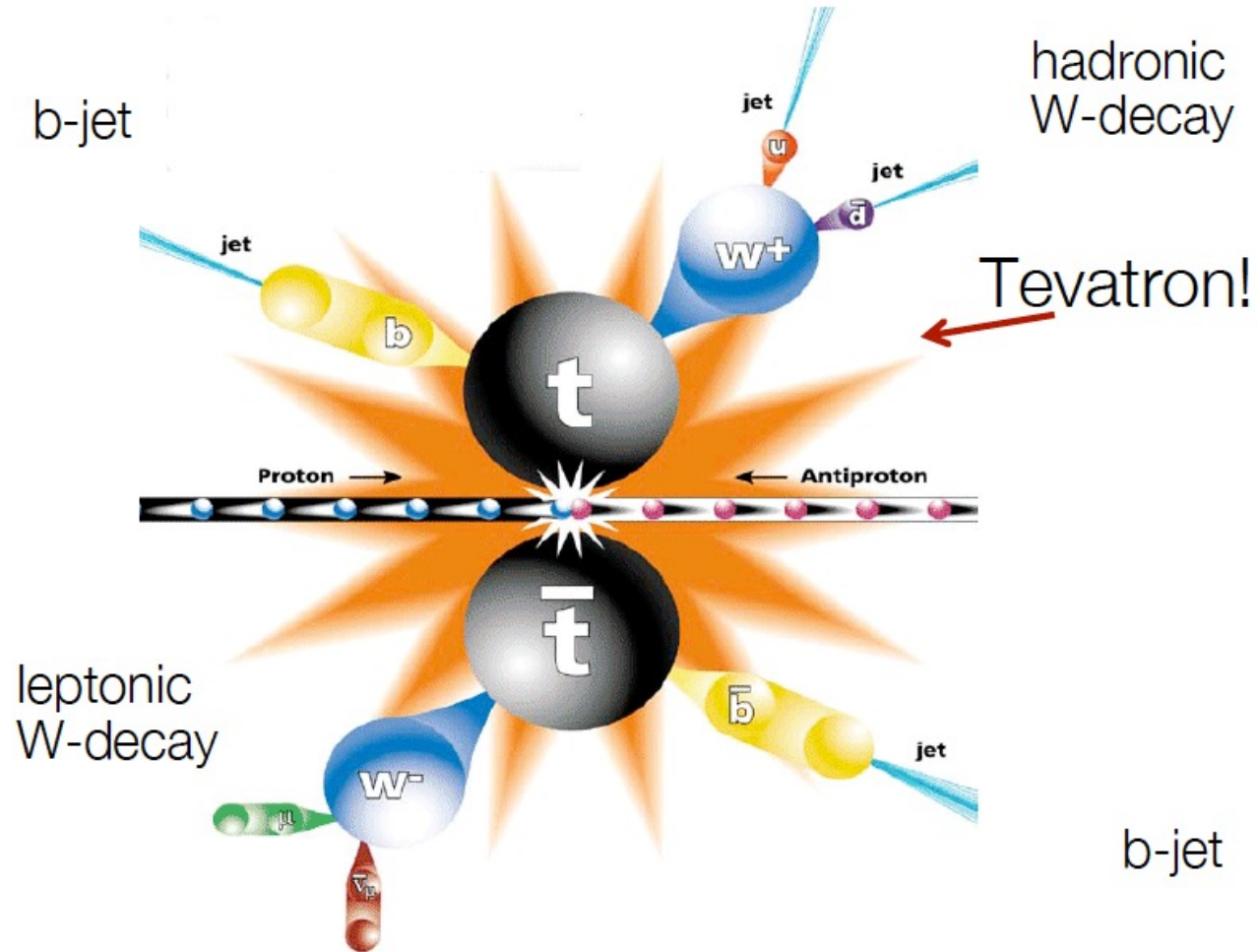


Figure 12.5. (a) The invariant mass distribution for e^+e^- pairs identified through electromagnetic calorimetry in the UA-1 detector. (Figure supplied by UA-1 Collaboration) (b) The analogous plot for the UA-2 data (Ref. 12.12). In both data sets, the Z appears well-separated from the lower mass background.

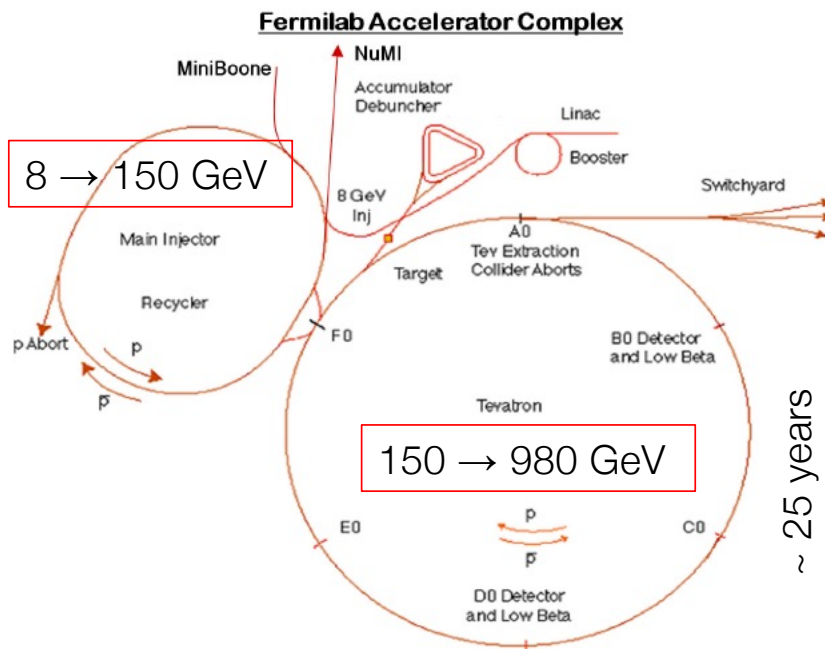
The Discovery of the Top



The Discovery of the top. The Tevatron

The Tevatron:

- proton-antiproton collider
- 1-km radius synchrotron, with superconducting magnets
- beam accelerated from 150 to 980 GeV two interaction points for the CDF and D0 detectors.



Timeline:

- 1976 Initial proposal of a $p\bar{p}$ collider at *Fermilab* by transforming an existing accelerator into a storage ring → accumulation and cooling of antiprotons.
- 1978 *Fermilab* decided the construction of the accelerator. Design goals were: a luminosity of $11 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$ at $\sqrt{s}=1.8$ TeV.
- 1981 Tevatron starts as fixed target accelerator
- 1985 Tevatron operates as a $p\bar{p}$ collider, first collisions, experiments in construction
- 1987-1989 first ~test run of the Tevatron, 5 pb⁻¹ of data collected
- 1992-96 Run Ia & Run Ib → upgrade of the collider to a luminosity of $5 \cdot 10^{31} \text{cm}^{-2} \text{s}^{-1}$, 180pb⁻¹ collected
- 1995 Discovery of the Top
- 2001-2011 RunII top luminosity $5 \cdot 10^{32} \text{cm}^{-2} \text{s}^{-1}$

Introduction: the top Quark

The top quark is

- the heaviest known elementary particle
- Completes the third family of quarks
- its lifetime which is too short to build hadronic bound states.

The large value of the top quark mass indicates a strong Yukawa coupling to the Higgs, → could provide special insights in our understanding of electroweak symmetry breaking.

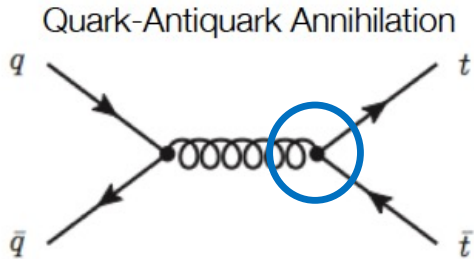
Together with the W boson mass, it constrains the Higgs boson mass through global electroweak fits.

The top was discovered in 1995 at the Tevatron.

Different periods of data taking at the Tevatron

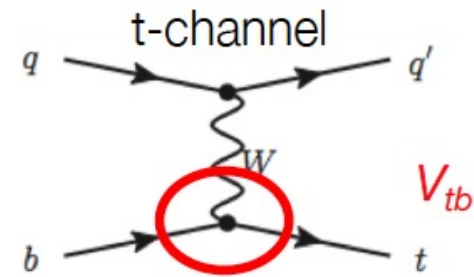
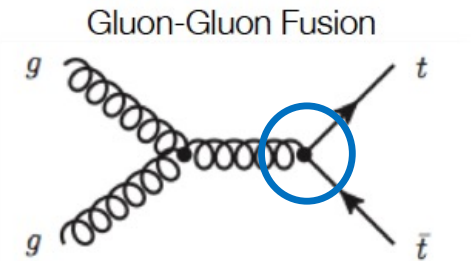
	Run Ia	Run Ib	Run II	
Energy (center-of-mass)	1800	1800	1960	GeV
Protons/bunch	1.2	2.3	2.9	$\times 10^{11}$
Antiprotons/bunch	3.1	5.5	8.1	$\times 10^{10}$
Bunches/beam	6	6	36	
Total Antiprotons	19	33	290	$\times 10^{10}$
Proton emittance (rms, normalized)	3.3	3.8	3.0	π mm-mrad
Antiproton emittance (rms, normalized)	2	2.1	1.5	π mm-mrad
β^*	35	35	28	cm
Luminosity (Typical Peak)	5.4	16	340	$\times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$
Luminosity (Design Goal)	5	10	200	$\times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$

top Production and Decay



The **primary mode**, in which a $t\bar{t}$ pair is produced from a $g t\bar{t}$ vertex via the **strong interaction**, was used by the D0 and CDF collaborations to **discover the top quark in 1995**.

One pair of tops produced



The **second production mode** of top quarks is the **ew** production of a single top quark from a Wtb vertex.

- Cross section ~ half that of $t\bar{t}$ pairs
- signal-to-background ratio is much worse

One top produced

$$\begin{aligned}
 \text{A. } t\bar{t} &\rightarrow W^+ b W^- \bar{b} \rightarrow q \bar{q}' b q'' \bar{q}''' \bar{b}, & (45.7\%) \\
 \text{B. } t\bar{t} &\rightarrow W^+ b W^- \bar{b} \rightarrow q \bar{q}' b \ell^- \bar{\nu}_\ell \bar{b} + \ell^+ \nu_\ell b q'' \bar{q}''' \bar{b}, & (43.8\%) \\
 \text{C. } t\bar{t} &\rightarrow W^+ b W^- \bar{b} \rightarrow \ell^+ \nu_\ell b \ell'^- \bar{\nu}_{\ell'} \bar{b}. & (10.5\%)
 \end{aligned}$$

Always 2 b-jets

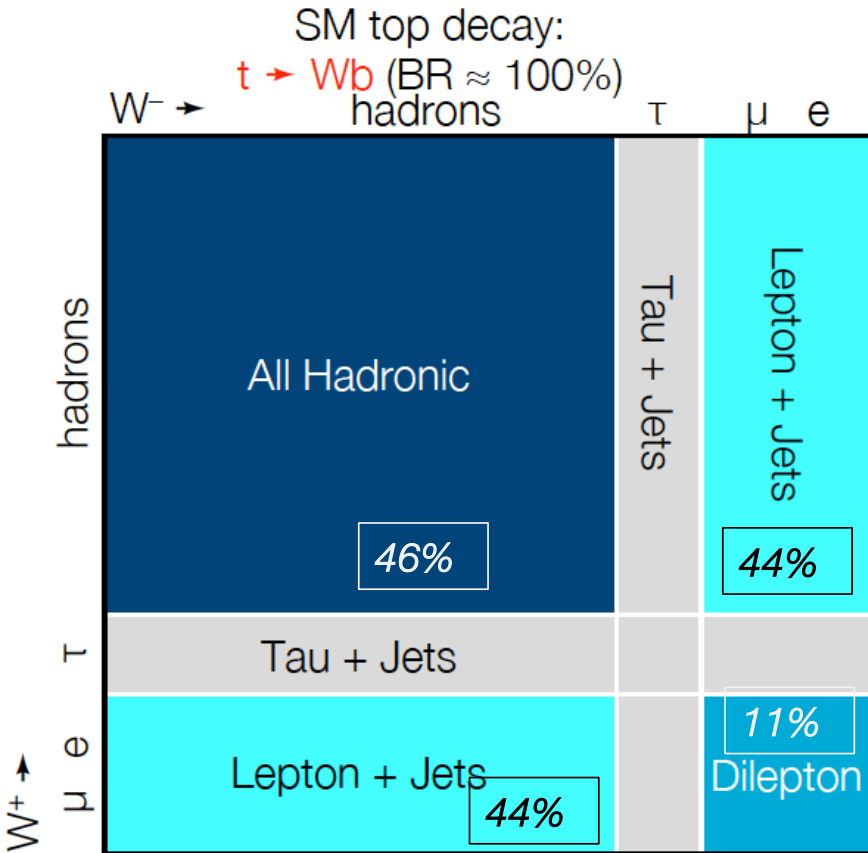


SM: ~100% $t \rightarrow Wb$

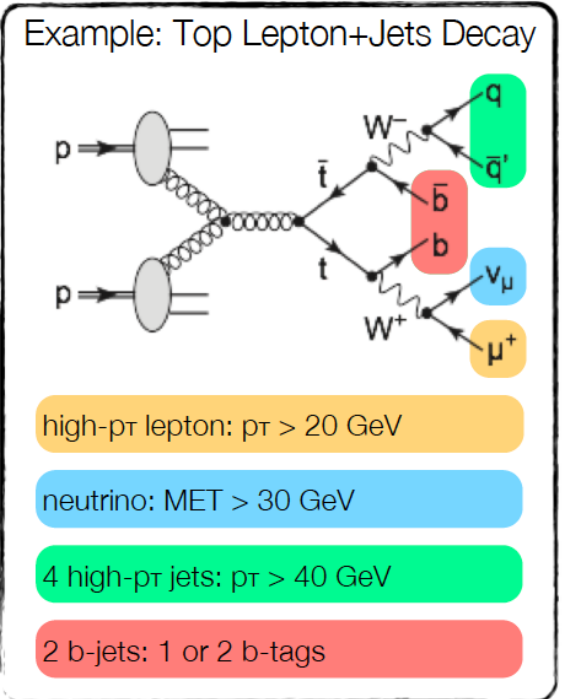
	$W^- \rightarrow$	hadrons	τ	μ	e
hadrons	A	All Hadronic	Tau + Jets	Lepton + Jets	
τ		Tau + Jets		B	
μ		Lepton + Jets	B	C	
e				Dilepton	

Topologies in $t\bar{t}$ Decays

- These events always contain two b quarks



- The W decays characterise the topology of the event:
 - All hadronic** \rightarrow 6 jets (2 b jets) with large QCD background. Problem is **jet-pairing**, many possible combinations (W mass as constraint...)
 - Lepton + jets** \rightarrow lepton, neutrino + 4 jets; lepton and missing energy suppress QCD background. 4 jets, pairing problem even if less than in the full hadronic case
 - Di-lepton** \rightarrow 2 leptons, 2 neutrinos 2 b jets; clean, little background but (10% BR) + ambiguities due to **2 neutrinos**



How to Recognise a “b” Jet? → b-Tagging

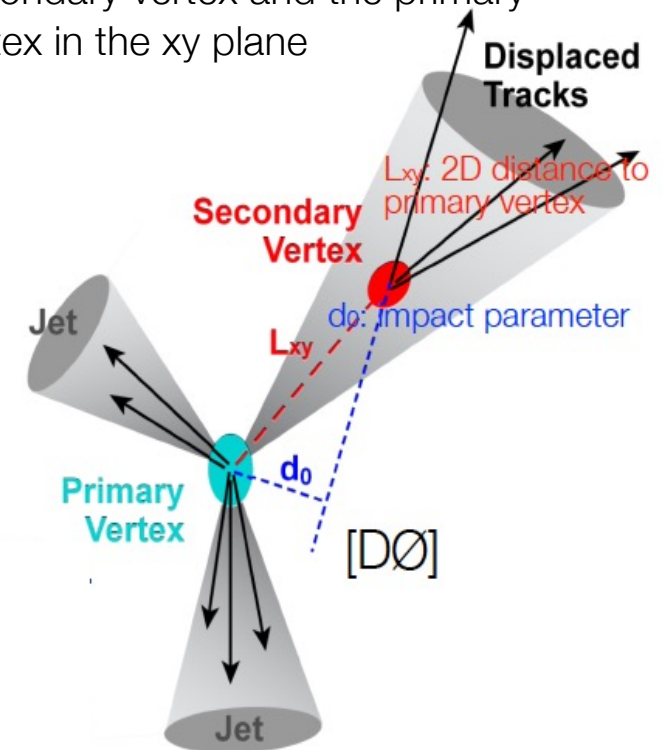
Heavy flavour hadrons (→ “b hadrons”) are unstable (life-time $\sim 1.5 \times 10^{-12}$ s) and decay after a measurable path (mm’s).

First approach: hadronic decay of the b-hadron →

1. charged tracks do not extrapolate back to the primary vertex
2. A secondary vertex detached from the primary vertex is present in the event

The topology close to the primary vertex has to be studied → vertex detector

- d_0 track based indicator distance of minimum approach to the primary vertex
- L_{xy} distance between the secondary vertex and the primary vertex in the xy plane

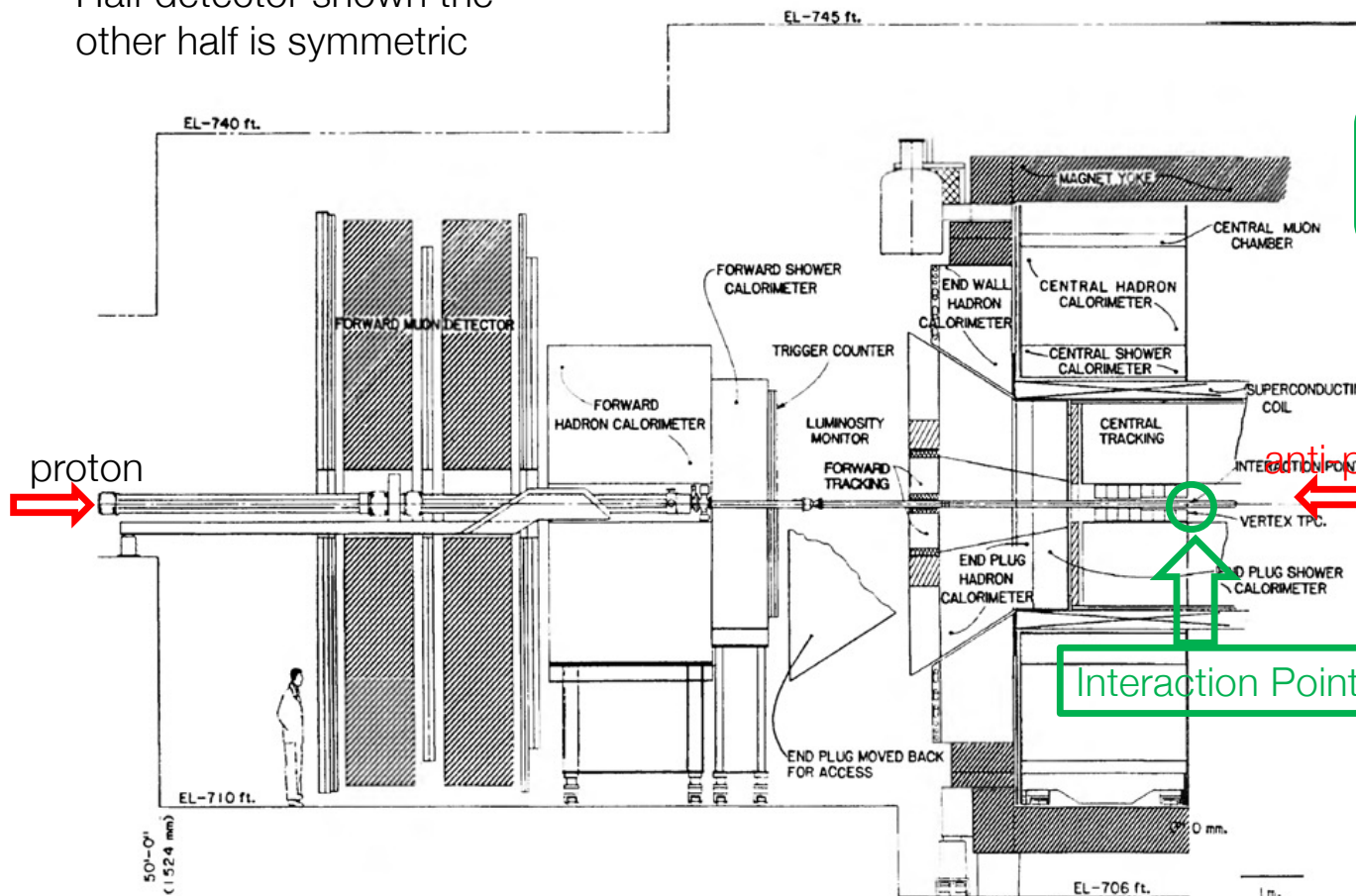


Second approach: leptonic decay of the b-hadron →
b decay to $lv+X$ → \sim soft lepton close to a jet

The Experiments: CDF & D0

Half detector shown the other half is symmetric

Already a ~ large modern detector:
barrel part + forward/backward disks



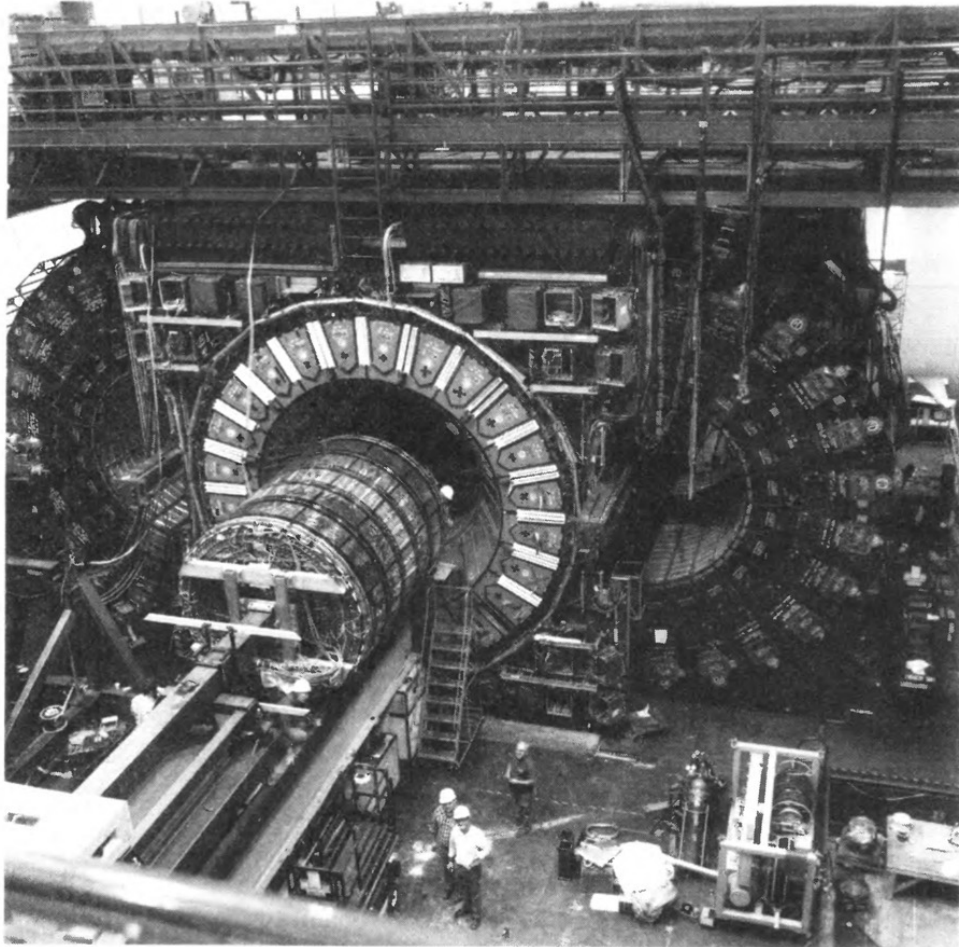
- Silicon strip detector to measure tracks close to the interaction point to identify secondary vertices
- Superconducting solenoid + tracker inside
- em and had calorimeters
- muon chambers

26 m long and 10 m high

D0 had a similar structure

Interaction Point

The Discovery of the top in CDF



Toni Baronecelli: Introduction to Accelerators

← CDF during installation

- | | | |
|----|--|---------|
| A. | $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q\bar{q}' b q'' \bar{q}''' \bar{b},$ | (45.7%) |
| B. | $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q\bar{q}' b \ell^- \bar{\nu}_\ell \bar{b} + \ell^+ \nu_\ell b q'' \bar{q}''' \bar{b},$ | (43.8%) |
| C. | $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow \ell^+ \nu_\ell b \ell'^- \bar{\nu}_{\ell'} \bar{b}.$ | (10.5%) |

Always 2 b-jets

A: all hadronic, B: lepton + jets, C: leptons

Selections (optimise $S/\sqrt{S+B}$)

A: Lepton + jets	B: Di-lepton
$1 \times W \rightarrow l\nu (l = e, \mu)$	$2 \times W \rightarrow l\nu (l = e, \mu)$
$p_T^l > 20 \text{ GeV}$	$p_T^l > 20 \text{ GeV}$
$\geq 3 \text{ jets (of which } 2b)$	2 jets (from b-decay)
(1 secondary vertex)	$E_T^{\text{miss}} > 25 \text{ GeV}$
OR (1 soft lepton from b-decay $p_T > 2 \text{ GeV}$)	$75 \text{ GeV} < m_{ee, \mu\mu} < 105 \text{ GeV}$

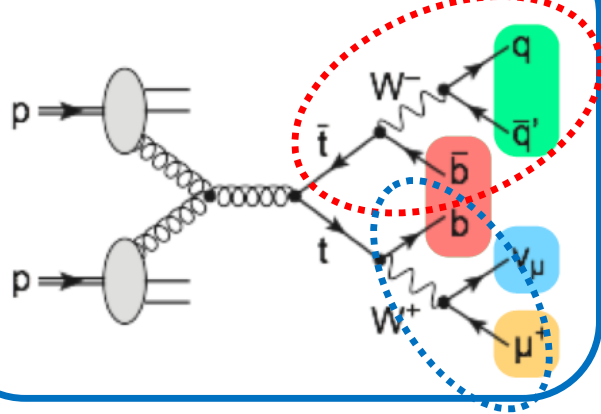
Top Mass using Lepton + Jets (2 methods)

Direct m_{top} reconstruction in the $l+jets$ channel: take the hadronic side ('jet side') and compute

- m_W = invariant mass of jet_q and $jet_{\bar{q}}$
- JES = Jet Energy Scale: scale factor which multiplies the jet energy. You look for the JES which gives the best reconstruction of m_W
- M_{top} = invariant mass of reconstructed hadronically decaying $W + jet_{\bar{b}}$

1

Example: Top Lepton+Jets Decay

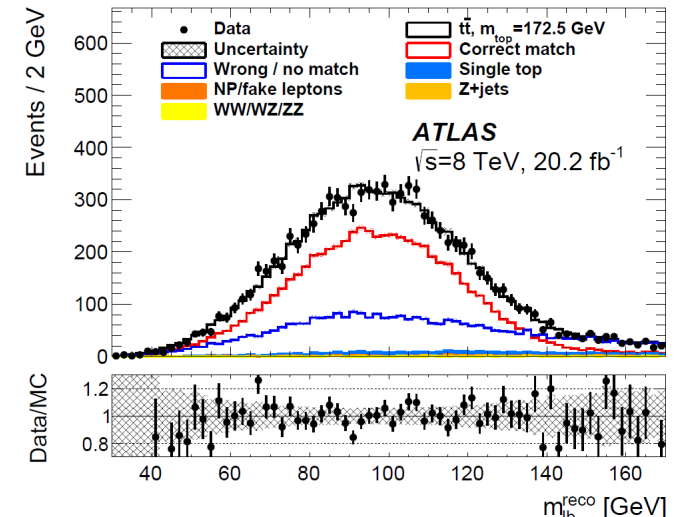
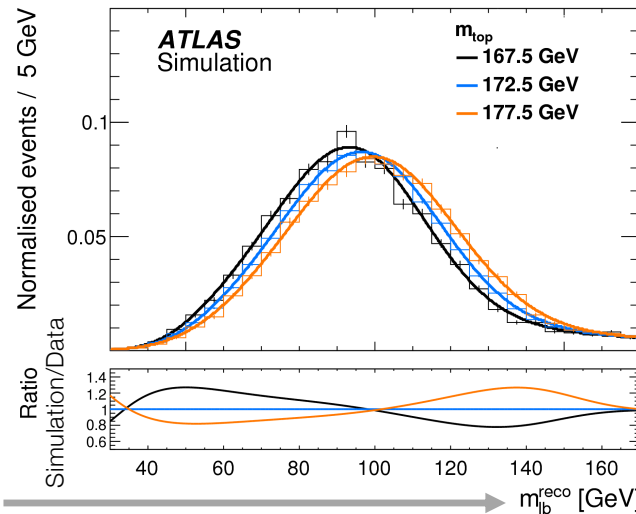


$m_{lb}^{reco} = \text{invariant mass of lepton} + jet_b$
 (ν_l non included $\rightarrow m_{lb}^{reco} < m_{top}$)

Template method: USE SIMULATED EVENTS! \rightarrow generate

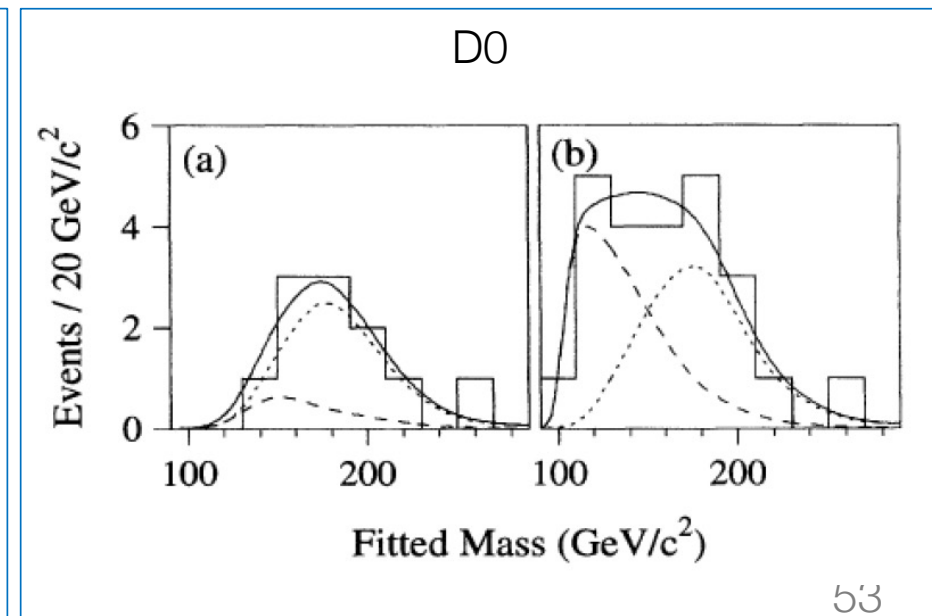
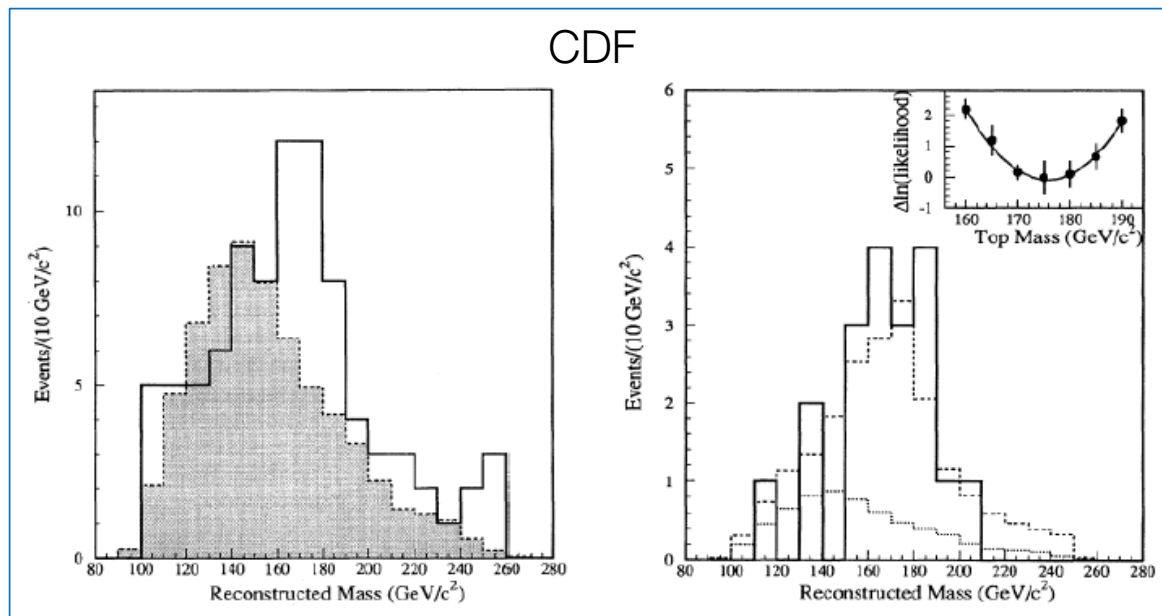
- Many samples of tt events with m_{top} varying in small steps
- Take one observable with memory of m_{top} and compare with data
- Best agreement $\rightarrow m_{top}$

2

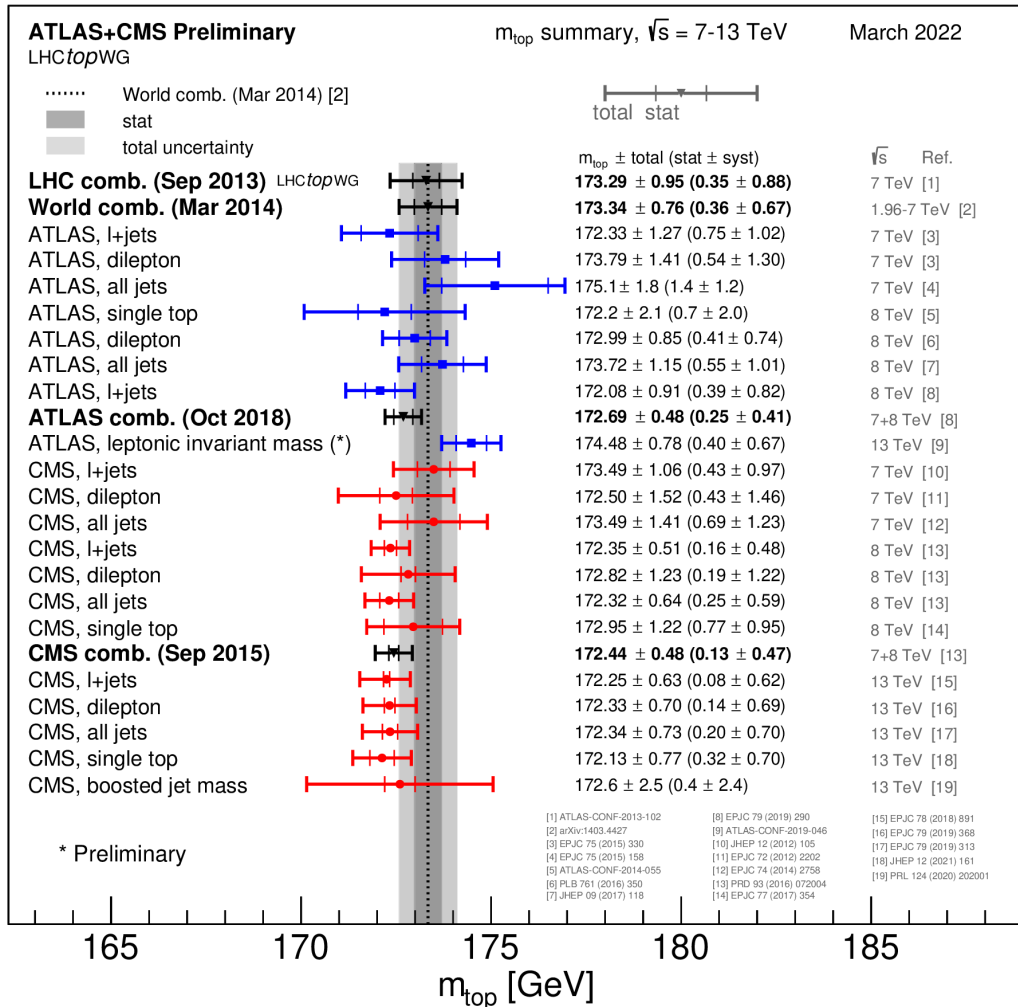


Discovery of the top at CDF & D0

Year	Number Selected Events (CDF+D0)		top mass (GeV)
	A: Lepton + jets	B: Di-lepton	
1994 (evidence)	86 (background:37)	12 (background:2.5)	$174 \pm 10^{+13}_{-12}$
1995 (discovery)	signal incompatible with background: CDF 4.9σ D0 4.6σ		CDF: $174 \pm 8 \pm 10$ D0: $199 \pm 22^{+19}_{-21}$

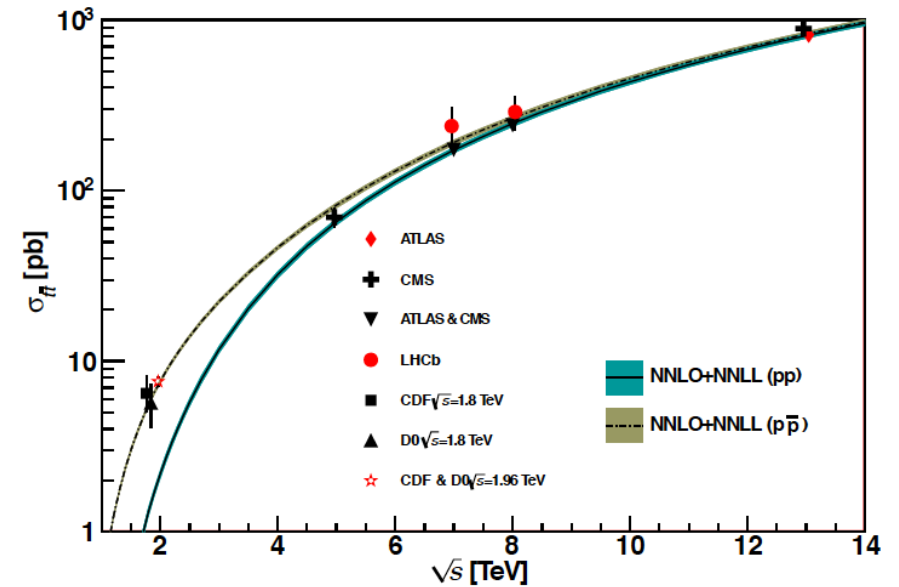


The Evolution of m_t from Tevatron to LHC



Important improvements with time (and going to LHC):

- $m_t = 174.30 \pm 0.35 \pm 0.54$ (CDF + D0)
- $\rightarrow m_t = 173.34 \pm 0.36 \pm 0.67$ (CDF + D0 + LHC)



The σ_{tt} was measured from ~ 2 TeV to 13 TeV and found to be in agreement with SM predictions 54