Particle Physics

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Timeline (Places: Europe & United States)

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

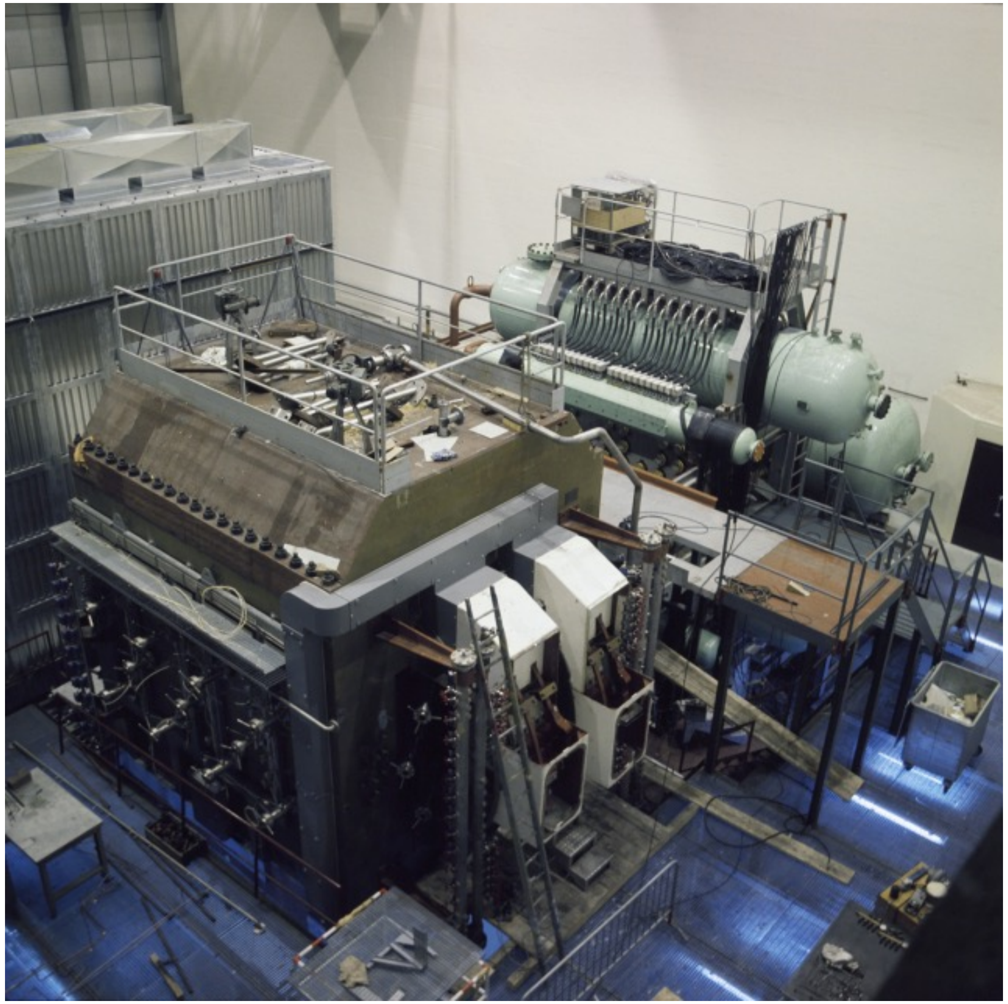
10 years

~20 years

10 years

Toni Baroncelli: Discoveries

The Bubble Chamber Gargamelle at CERN < History!



Gargamelle bubble chamber at CERN.

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)

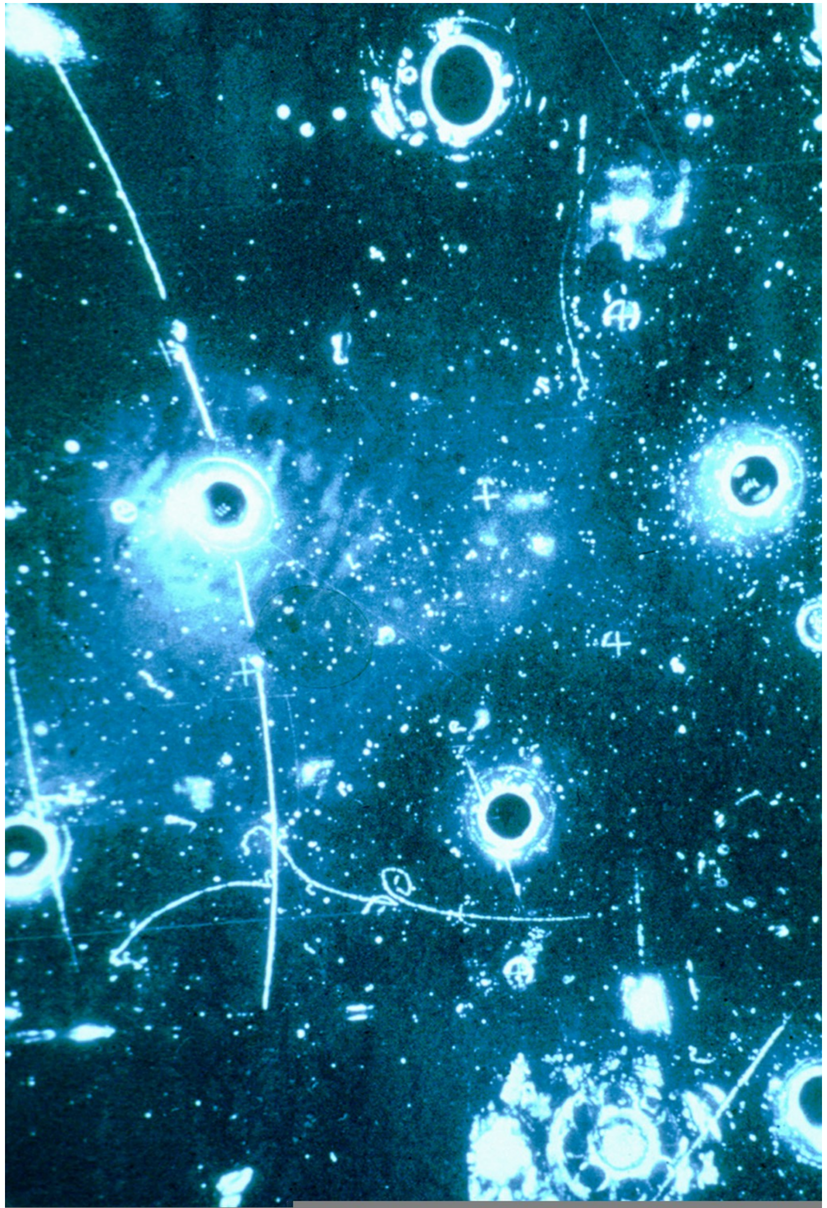
- designed to detect neutrinos & exposed to muon-neutrino beam

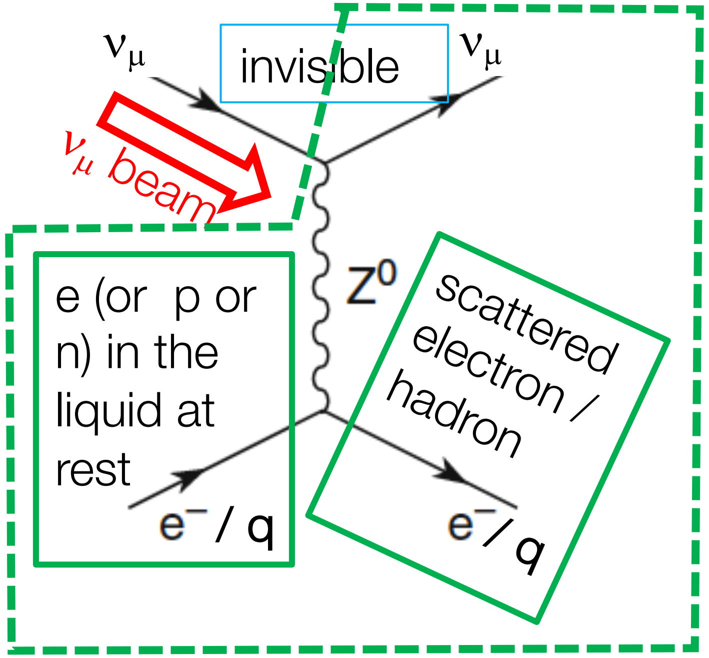
Neutrinos are not visible in detectors but the charged products of its interaction are visible. → indirect detection

- operated from 1970 to 1976

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

Neutral Currents and Gargamelle





$$\nu_\mu N \rightarrow \nu_\mu + hadrons$$

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

July 1973: first direct evidence of the

weak neutral current (NC)

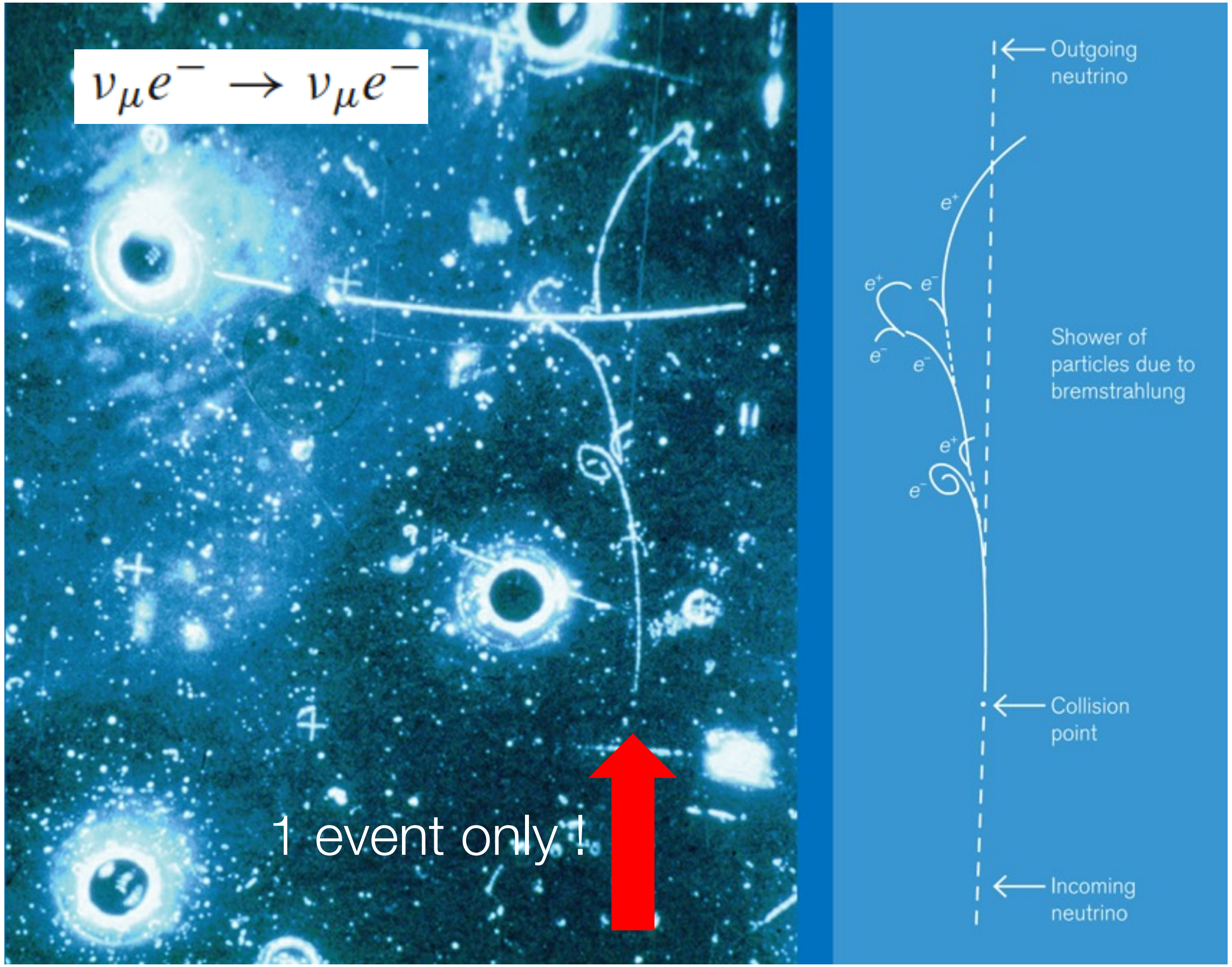
→ existence of a neutral particle to carry the weak fundamental force (the "Z").

Two types of events: interaction of the neutrino with

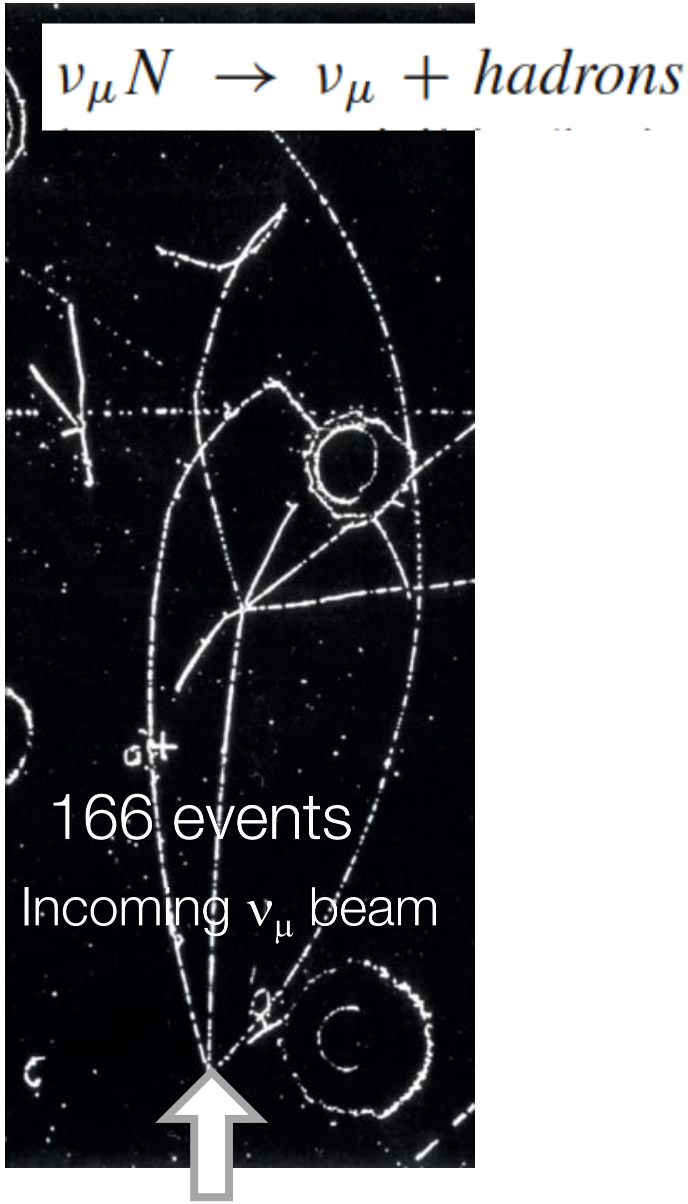
- an electron (1 event)
- a hadron (proton or neutron) 166 events

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)



Incoming ν_μ beam

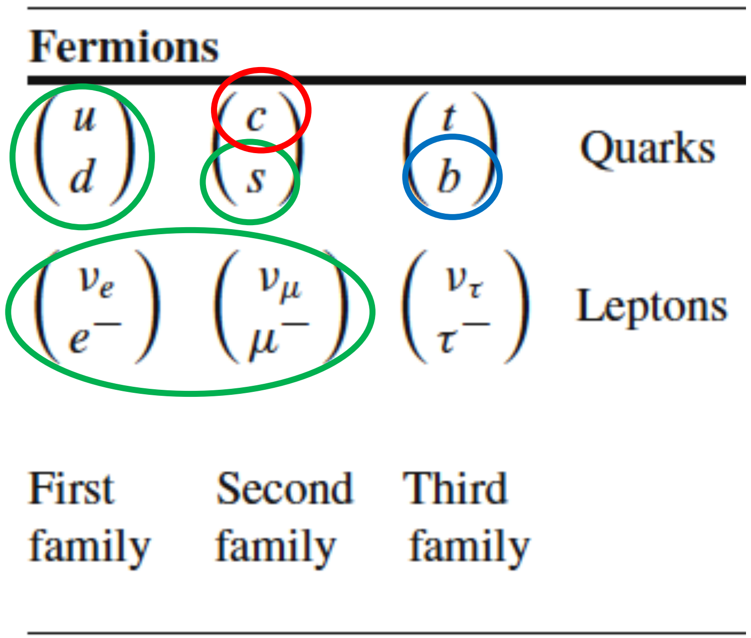


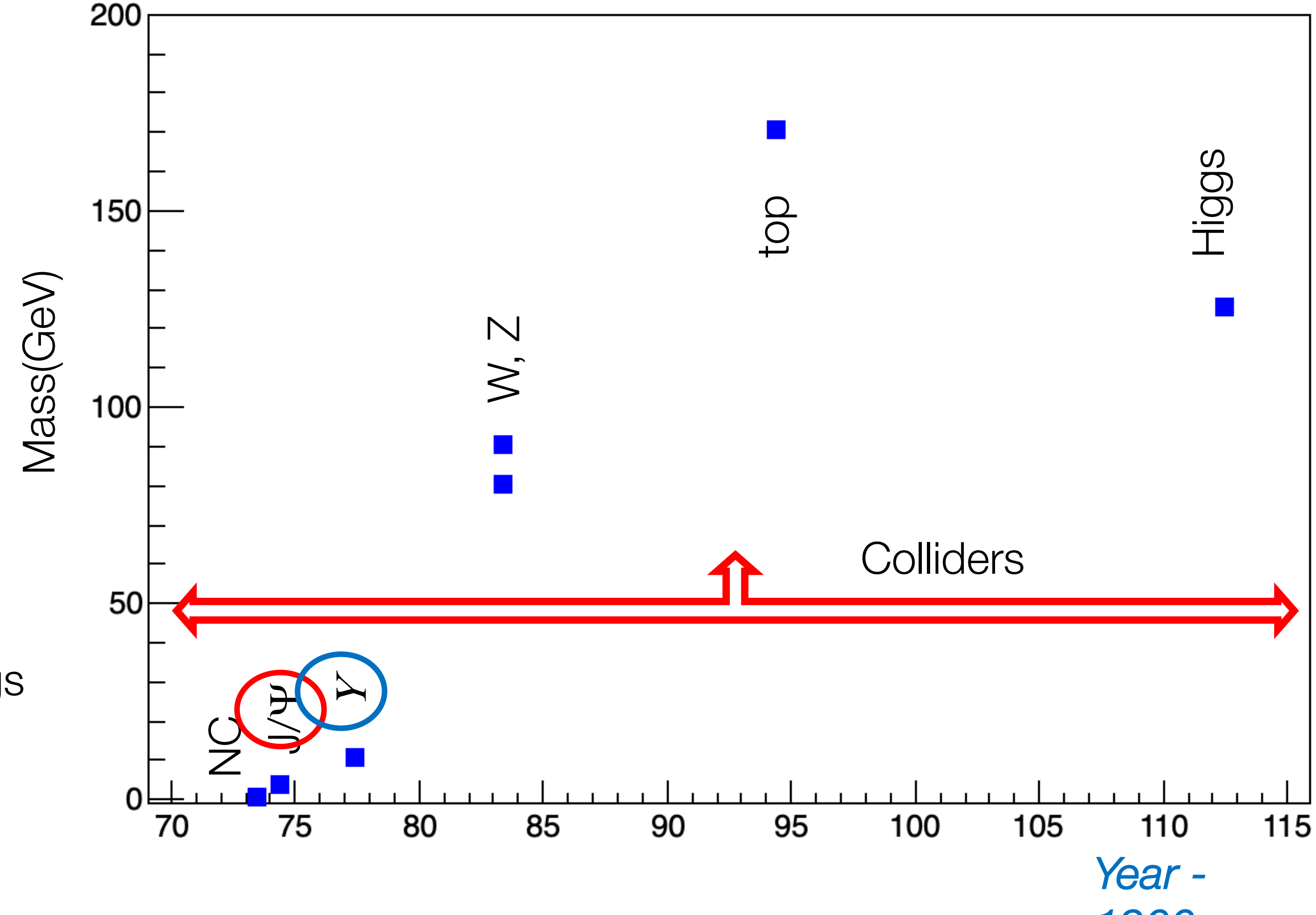
… More Quarks?

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





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

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

Two steps:

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

Elastic scattering, final state = initial state

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

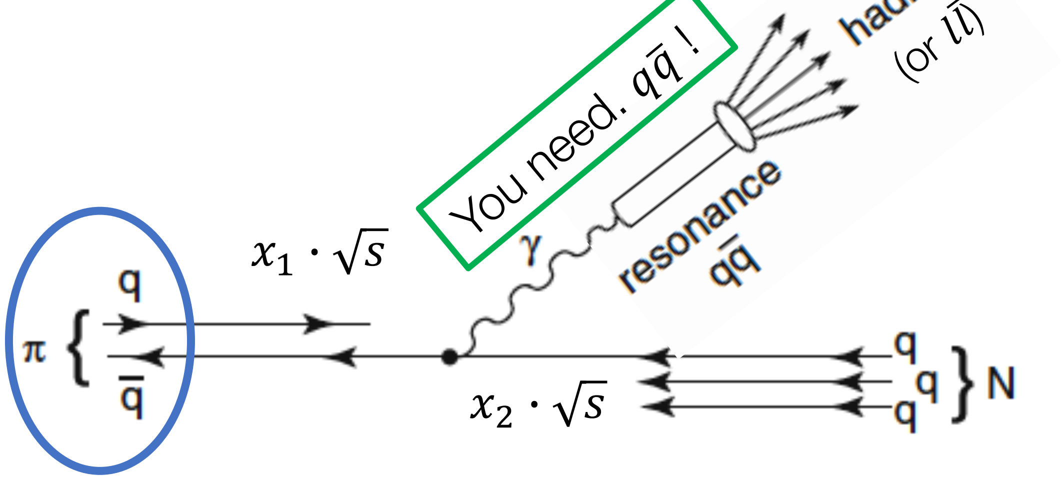
The cross section increases very rapidly if CMS energy ~ the mass of the resonance you search →

- 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	$e^+e^- \to J/\psi \to e^+e^-$, $\mu^+\mu^-$,hadrons	Cross section scan → resonance shape
BNL	$p + Be \to J\psi \to$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 → 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:

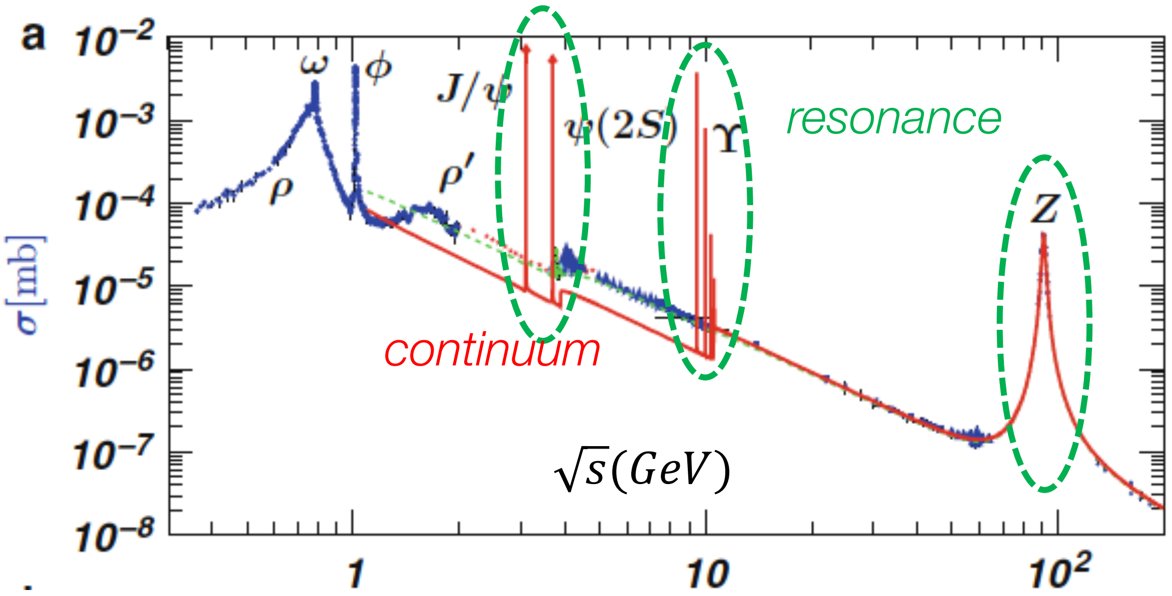
- the $\bar{q}$ is a valence quark carried by a pion beam
- In pp collisions → $\bar{q}$ from the sea.
- In $\bar{p}p$ collisions $\bar{q}$ is valence quark in the $\bar{p}$

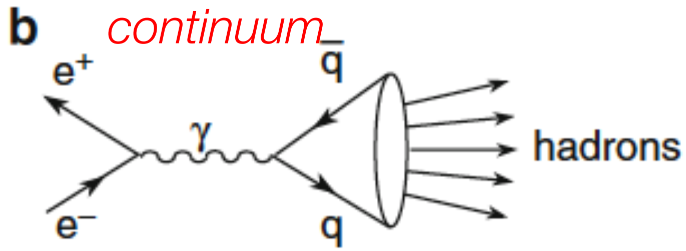
When the effective energy of the interaction $(x_1 + x_2) \cdot \sqrt{s}$ coincides with the mass of a resonance then the photon (mostly) couples directly to the resonant state.

The J/Ψ Discovery in $e^{\pm}$ Colliders

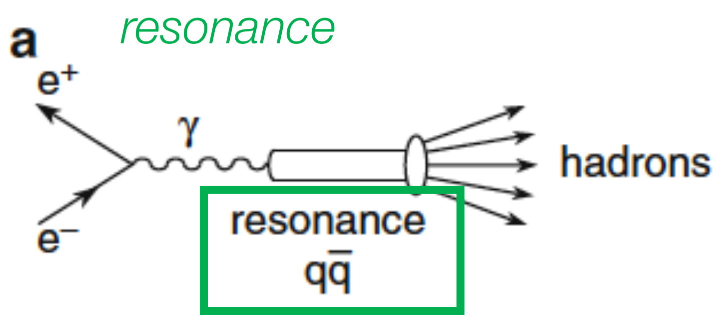
Width of the resonance invisible in this scale

Peaks = resonances





in the continuum region, the γ gives rise to a $q\bar{q}$ pair which then produces hadrons (two well defined jets at high energies)



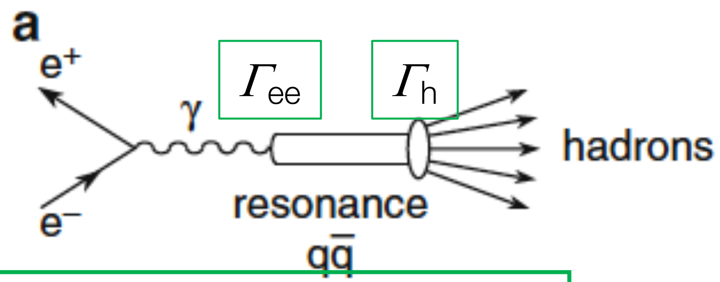
at the energy corresponding to a $q\bar{q}$ resonance, with spin-parity $J^P = -1$, the γ (mostly) directly couples to the resonance which then decays in hadrons;

The 'new' (@1974) resonance:
J/ψ, $c\bar{c}$ *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 → $\Gamma_{ee}\Gamma_h$

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

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

Γ^2 In the denominator is the total resonance width in MeV (~Γ_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*

⇩

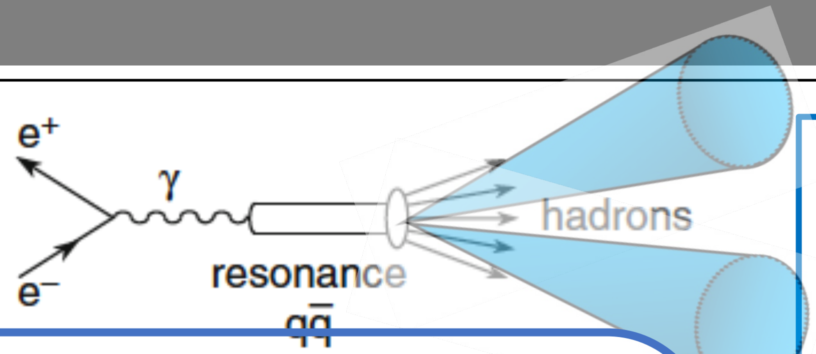
$$\sigma(e^+e^- \to J/\psi \to hadrons) = \frac{\pi\lambda\!\!\!^{-2}(2J+1)\Gamma_{ee}\Gamma_h}{(2s_1+1)(2s_2+1)[(E-E_R)^2+\Gamma^2/4]} = \frac{3\pi\lambda\!\!\!^{-2}\Gamma_h\Gamma_{ee}}{4[(E-3097)^2+\Gamma^2/4]}$$

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

Resonance

Cross Section Calculation in e^+e^- Interactions

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



Resonance

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 $p = \frac{m_{J/\psi}}{2} = \frac{3097}{2}\ MeV \to \lambda = 0.127\ fm$

- 3097 is the mass of the J/ψ
- Γ is the resonance total width =93 KeV; $\frac{\Gamma_{ee}}{\Gamma} = 0.05$; $\frac{\Gamma_h}{\Gamma} = 0.88$

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

Continuum

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

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

has to be added. At 3 GeV this contribution amounts to ~ 20 nb (mb/nb = 10^6)

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

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

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

continuum

Continuum

Invariant mass reconstruction:

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

The Experiments

Ingredients to an Experiment

$$p + target \rightarrow e^+e^-, \mu^+\mu^-$$

What you need	How you do it
Identify two electrons	Identify electrons = distinguish them from two ‘any’ charged tracks 1. → look at the shower in EM Calorimeter, an electron is contained 2. → the energy in EM Calorimeter ~ reconstructed momentum

measure the momentum of both electrons	1. → well known magnetic field
	2. → tracking detector(s)
	    1. Inside magnetic field (large volume, difficult and expensive)
	    2. Before and after the magnetic field. In this case → two arms

Identify two muons	Identify muons = distinguish them from two ‘any’ charged tracks 1. → heavy material after trackers to filter all other charged particles 2. → the energy in Calorimeters ~ compatible with a particle that doesn’t shower

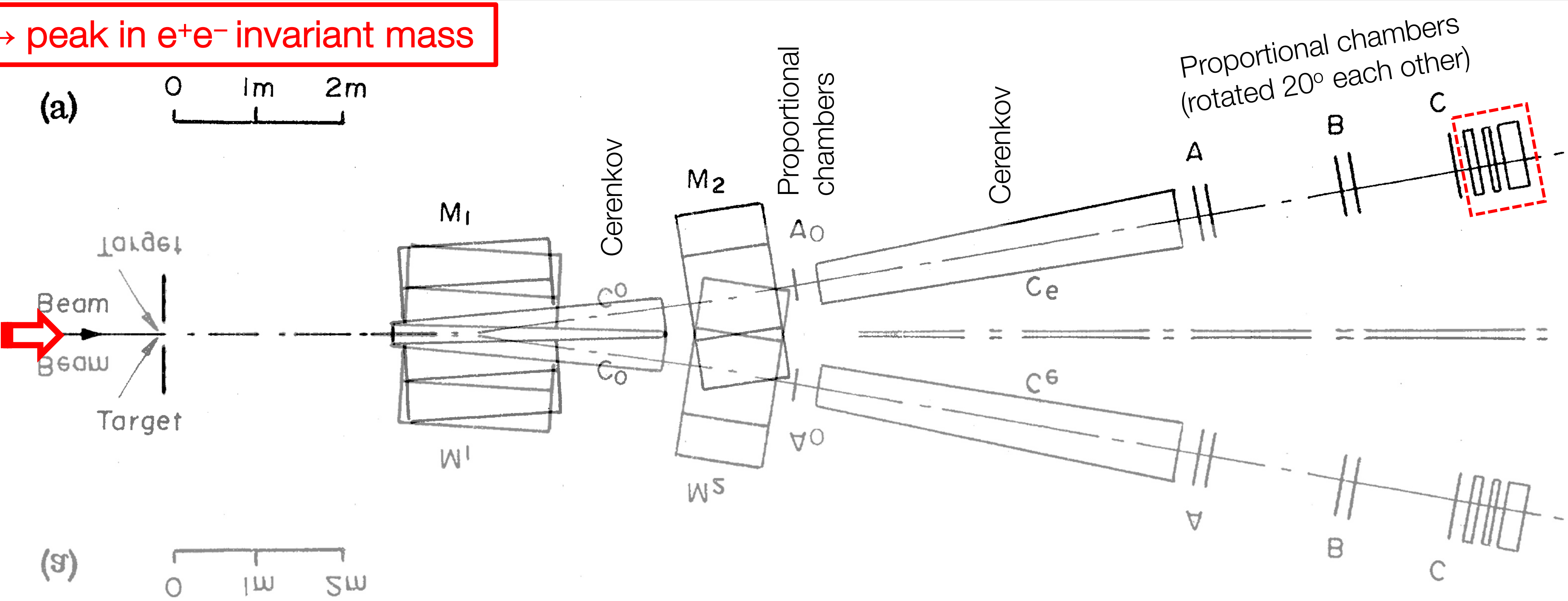
measure the momentum of both muons	1. → well known magnetic field
	2. → tracking detector(s)
	    1. Inside magnetic field (large volume, difficult and expensive)
	    2. Before and after the magnetic field. In this case → two arms

Two opposite charged particles	1. Radius of curvature of opposite sign

Ting's Experiment at Brookhaven

p beam → peak in e^+e^- invariant mass

28 GeV p



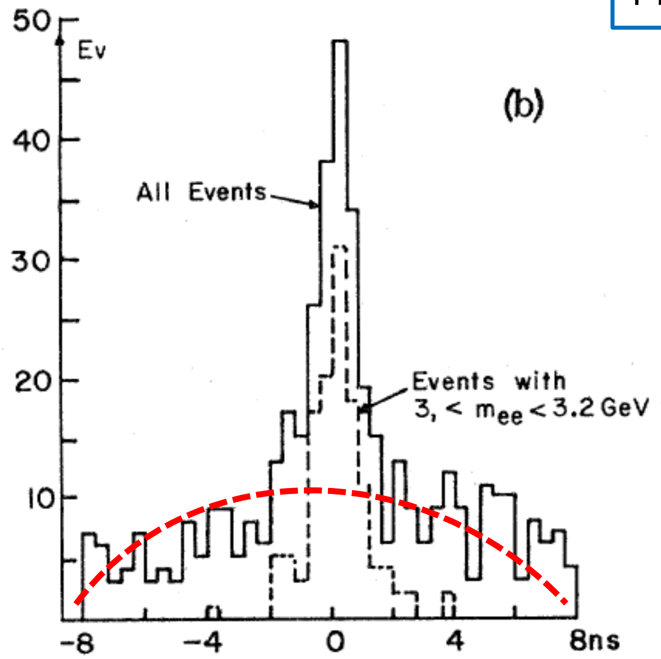
two banks of 25 lead glass counters of 3 X_0 each + one bank of lead-Lucite counters

$\Delta\theta = \pm 1°; \Delta\varphi = \pm 2°; Acceptance\ \Delta m = 2GeV; 3\ spectrometer\ settings \rightarrow \Delta m$ 1 to 5 GeV

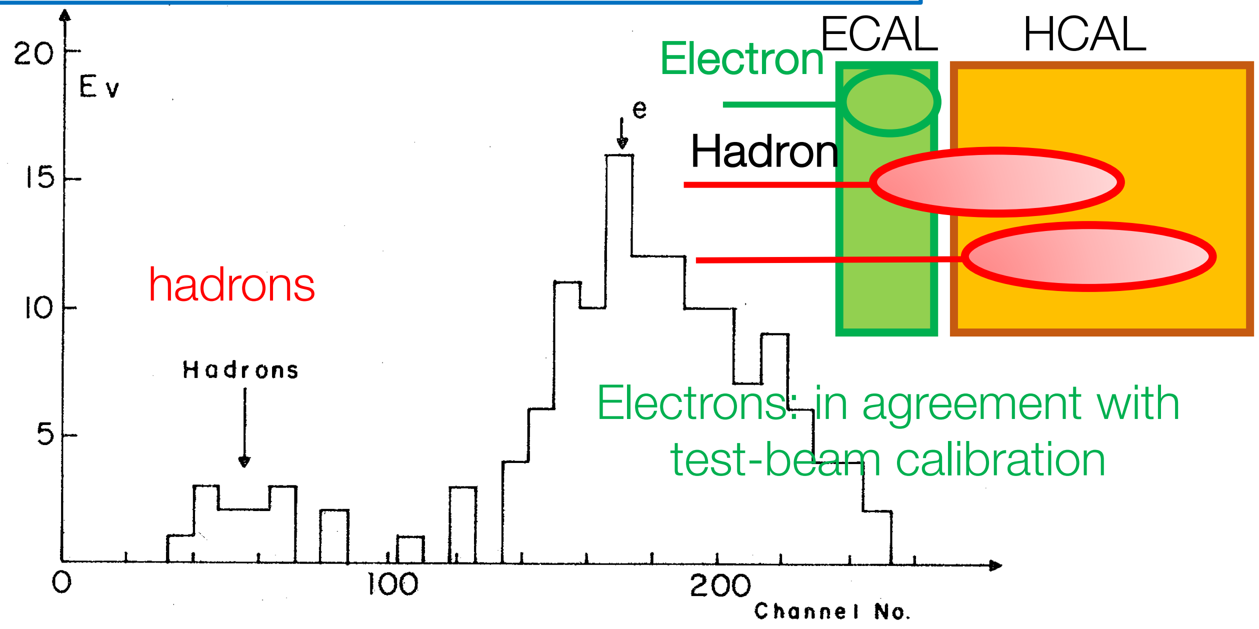
- two magnetic spectrometers for e^+ and e^-
- invariant mass resolution ~20 MeV for the e^+e^- pair
- electrons and positrons identified using Cherenkov counters, time-of-flight information, and pulse height measurements.

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 ~ 0 → J/Ψ decay
- Remaining part accidentals

Electrons are more contained that hadrons →
Pulse height spectrum of electrons >
Pulse height spectrum of hadrons

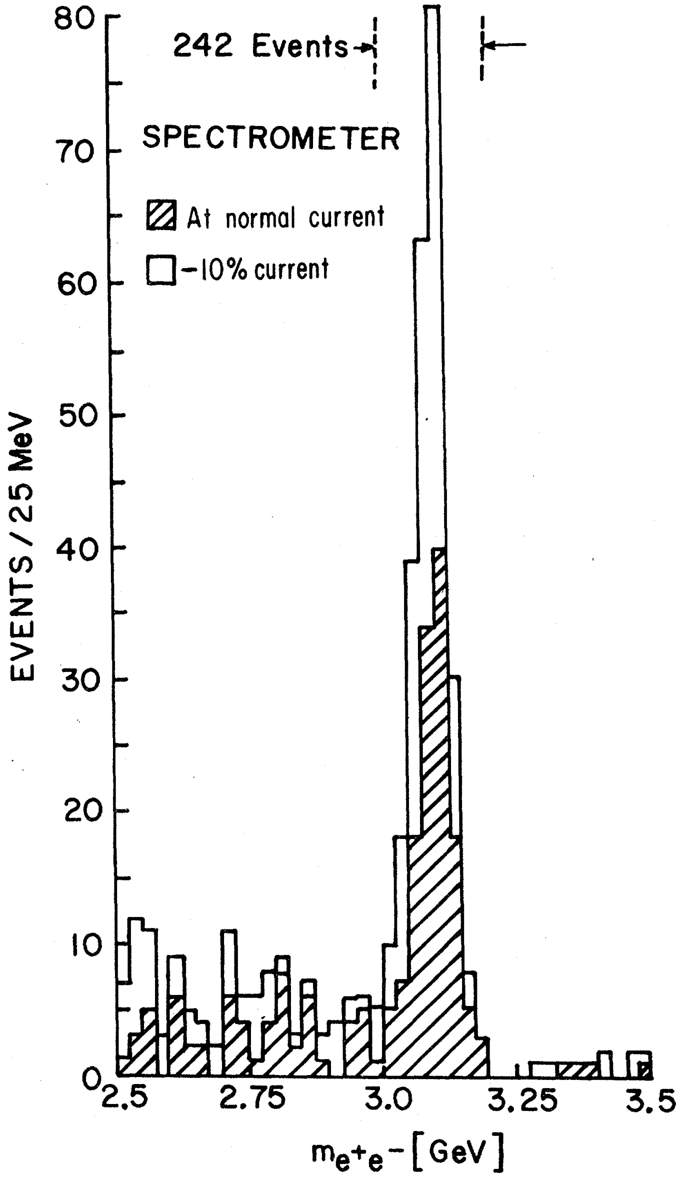
The Result: m_{ee} Invariant Mass Distribution

- 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} →

A clear peak at ~ 3.1 GeV is observed,

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



A 10% reduction of the magnet currents → larger acceptance → 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

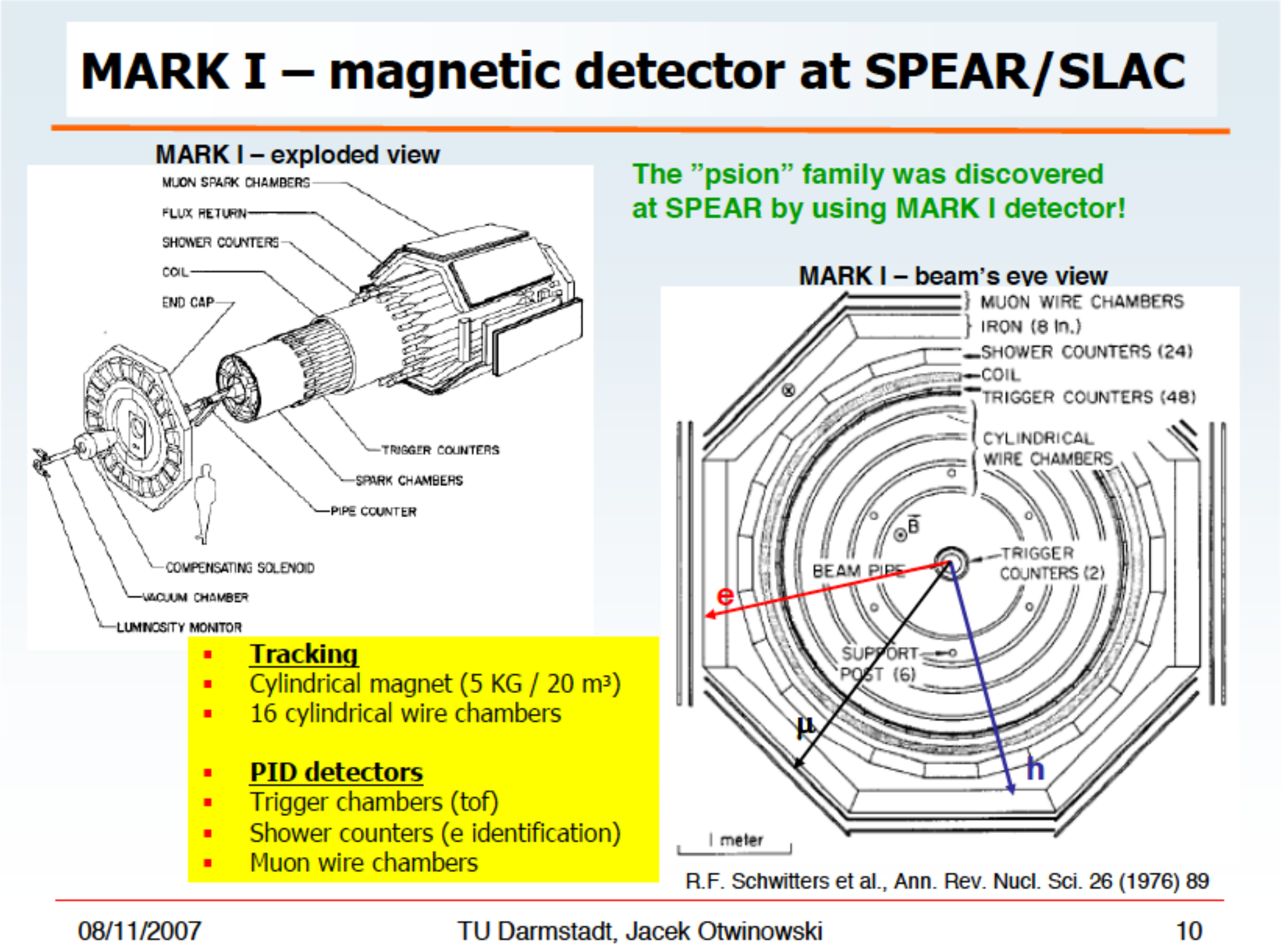
Increase of cross section

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

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.



The Discovery of the Ψ

Mark I:

energy scan (200 MeV steps, no structure expected!)

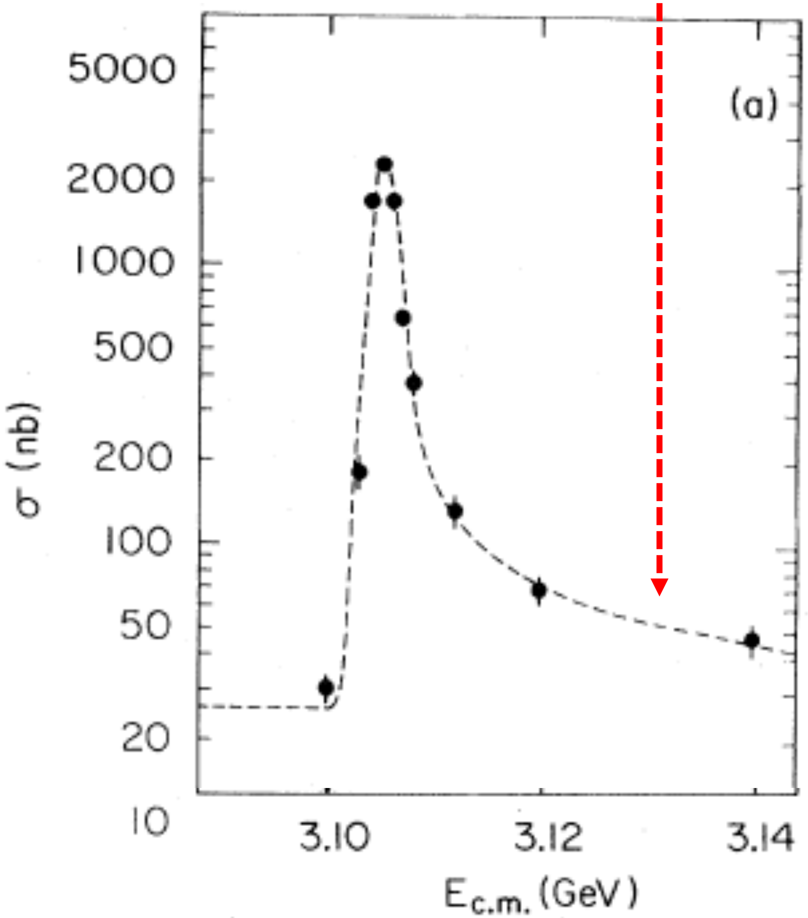
to study $e^+e^- \rightarrow hadrons$

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

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

The data:

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



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

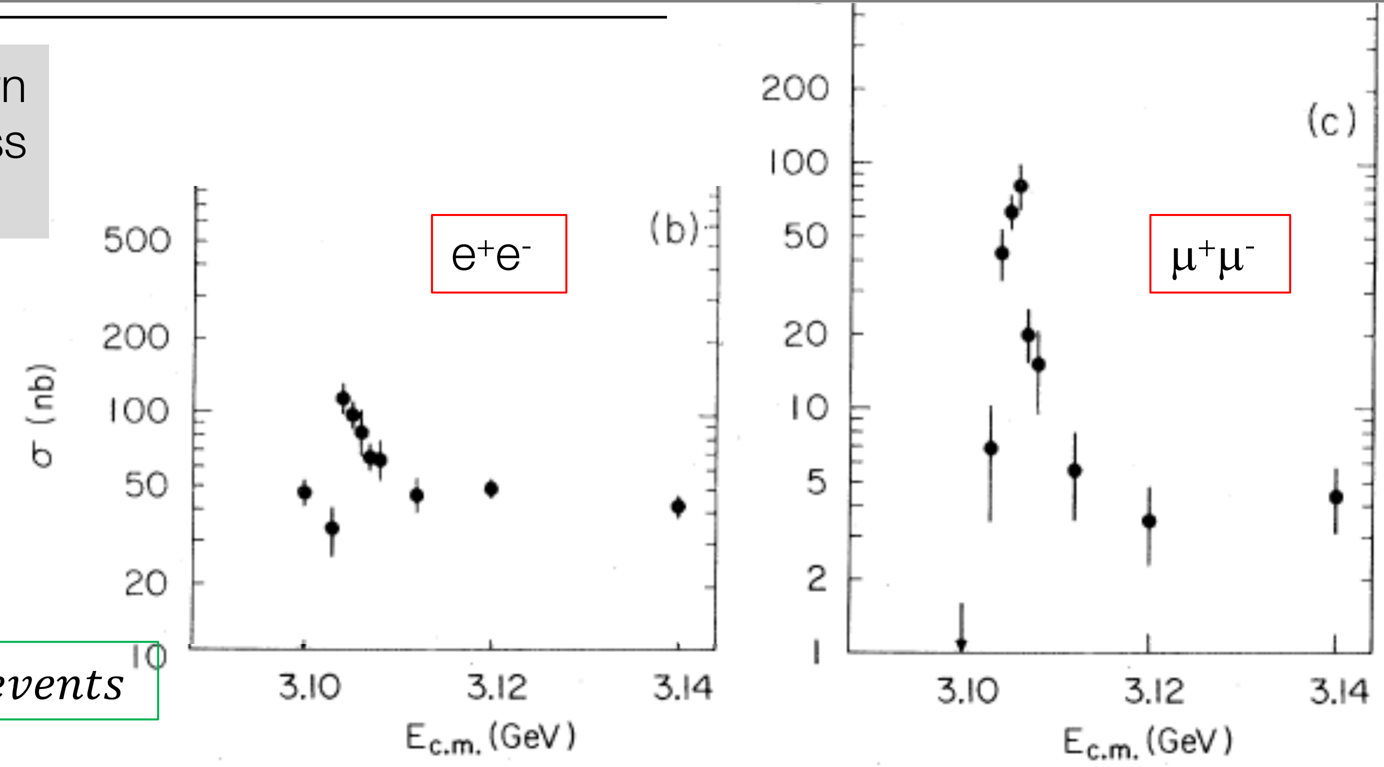
The increase in the cross section at 3.2 GeV was due to the tail of the resonance

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.

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:

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

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

J/ψ resonance → beam energy $p = \frac{m_{J/\psi}}{2} \to \lambda = 2\hbar/m_{J/\psi}$

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

The area under the resonance ~10 nb GeV.

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

→ $\Gamma_{ee} \approx$ 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.

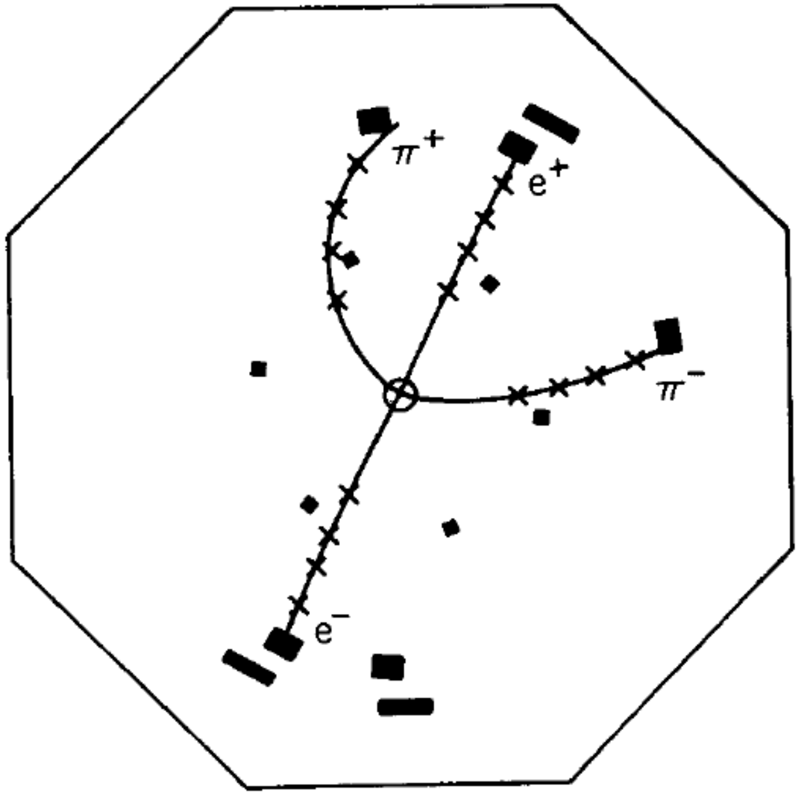


Figure 9.1. An example of the decay $\psi' \to \psi\pi^+\pi^-$ observed by the SLAC–LBL Mark I Collaboration. The crosses indicate spark chamber hits. The outer dark rectangles show hits in the time-of-flight counters. Ref. 9.5.

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

The Discovery of the τ Lepton

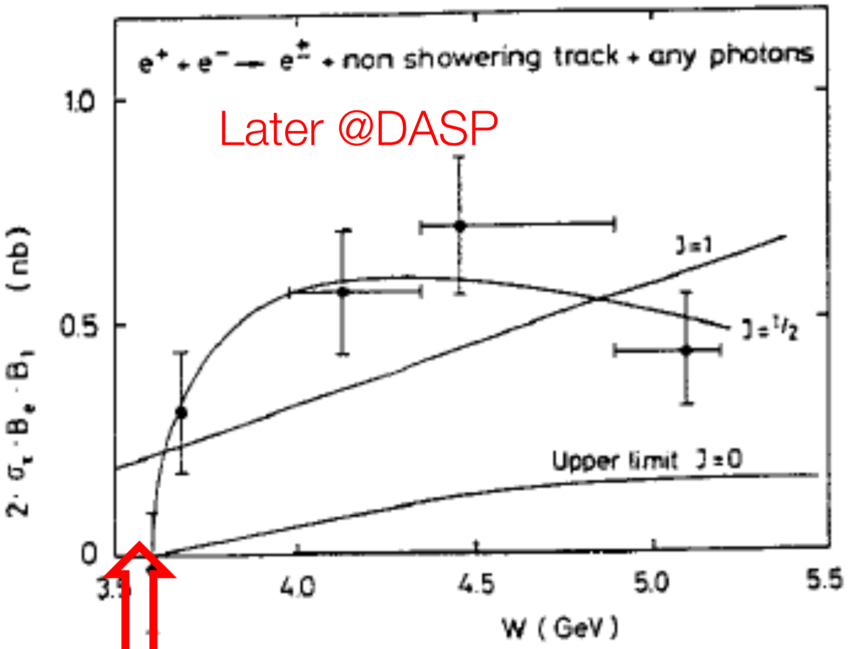
MARK I @ SLAC: while studying Ψ,Ψ' another discovery nearly as dramatic as that of the Ψ.

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

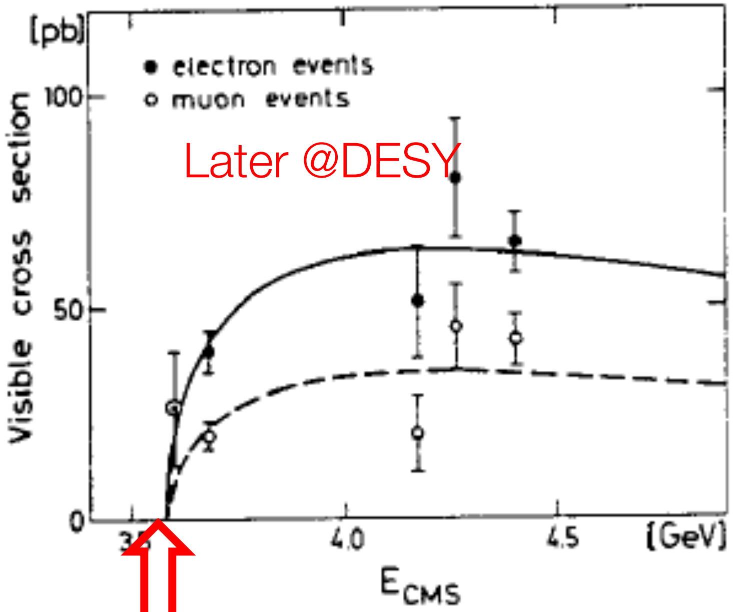
These events were interpreted as the pair production of a new lepton, τ , followed by its leptonic decay. The leptonic decays were

$$e^+e^- \to \tau^+\tau^- \qquad \tau \to e\bar{\nu}_e\nu_\tau \qquad \tau \to \mu\bar{\nu}_\mu\nu_\tau$$

2 x m_τ ~ centre of mass energy where ‘anomalous, events appear

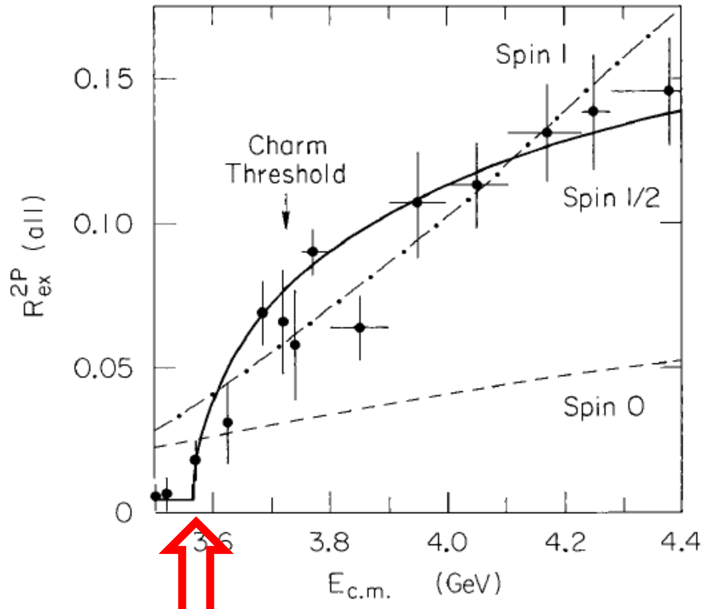


Threshold



Threshold

Threshold at $E_{cm} = 3564^{+4}_{-14}$
$\to m_\tau = 1782^{+4}_{-14}$



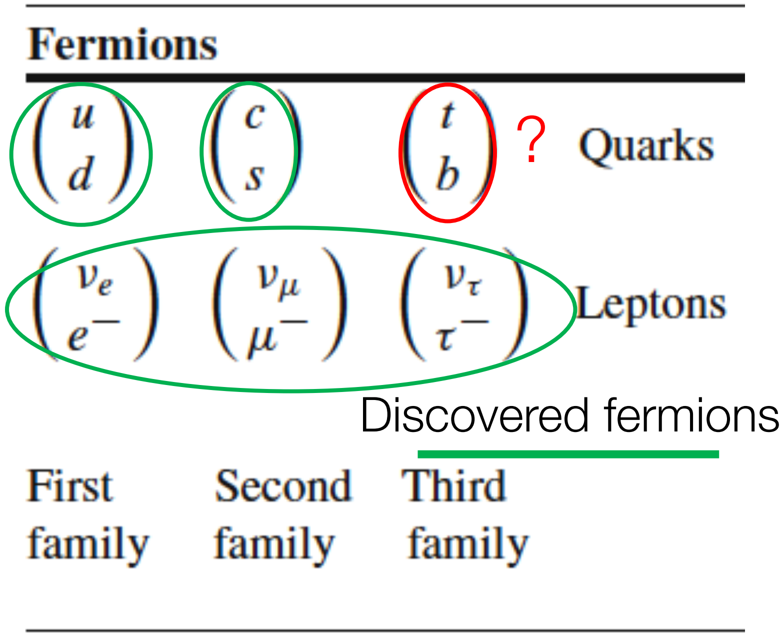
Threshold

The Fifth Quark, the “bottom”

The discovery of
- the J/ψ → 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!!).

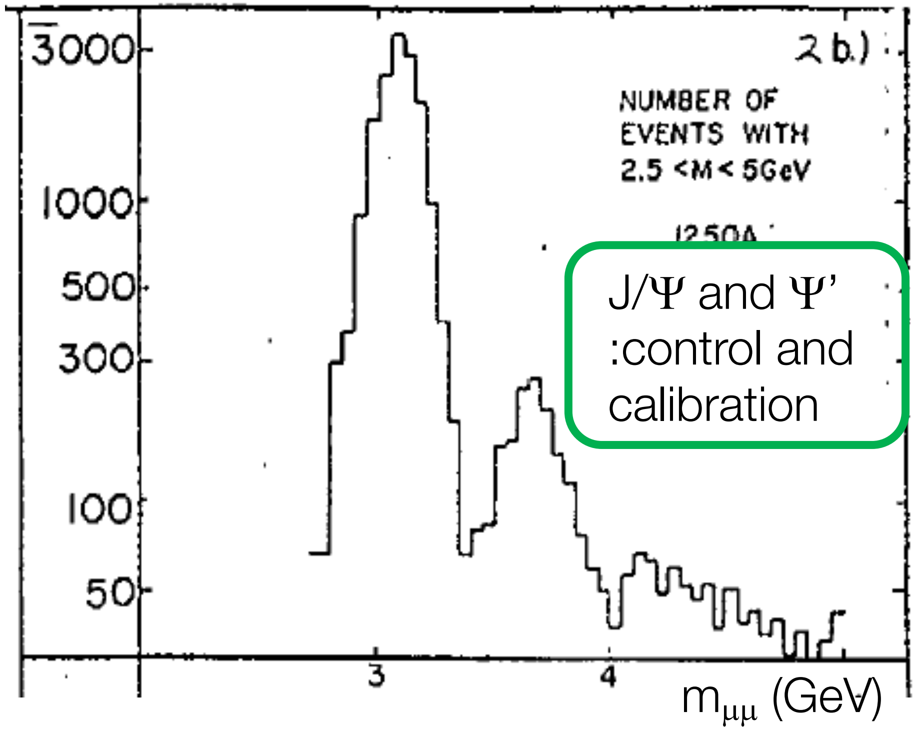
Later: the large peak was better described by two peaks at 9.44 and 10.17 GeV which were given the names ϒ and ϒ’

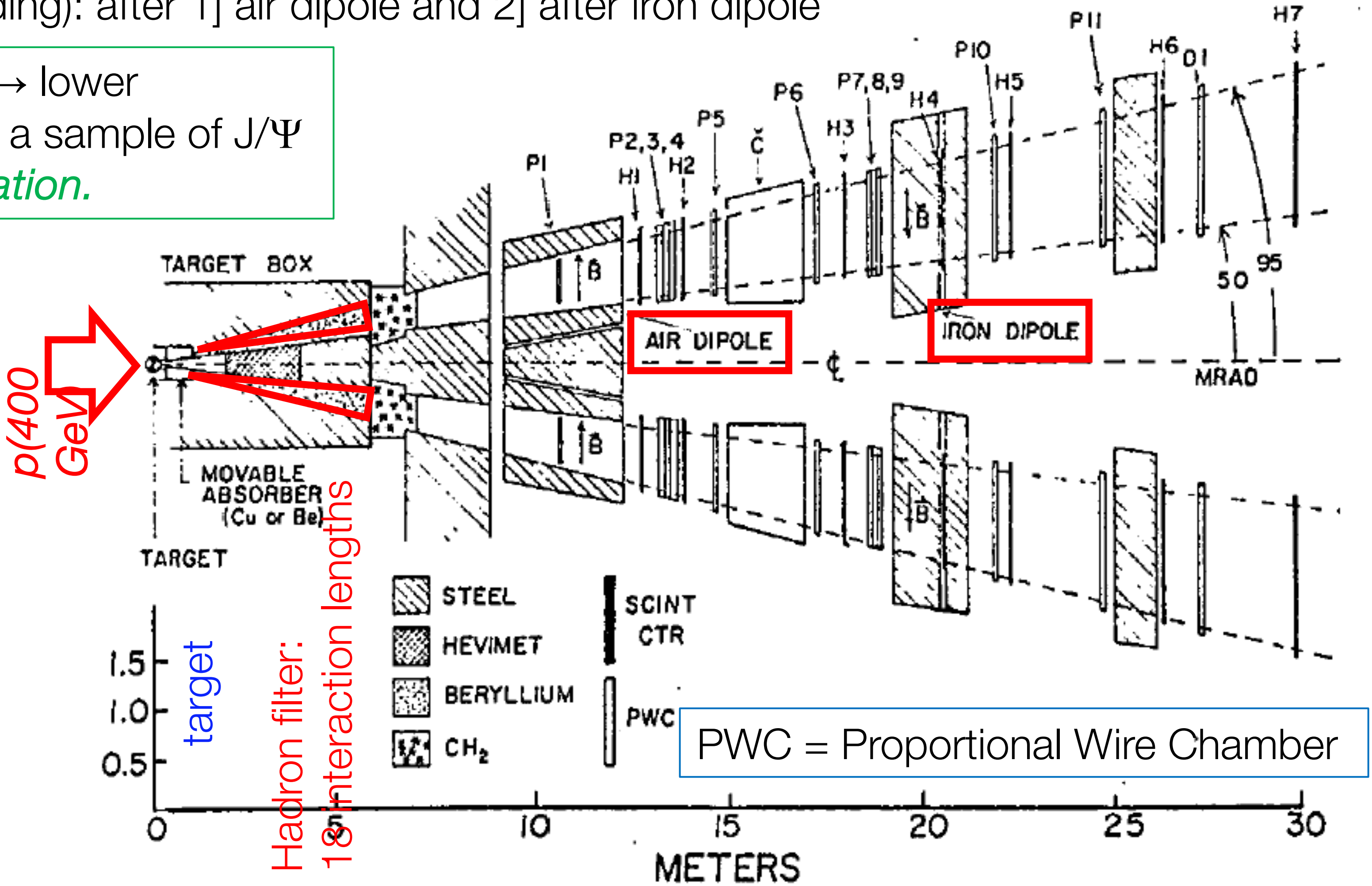
a repetition of the J/ψ and ψ’ story

Fermilab: Dimuon Resonance at 9.5 GeV

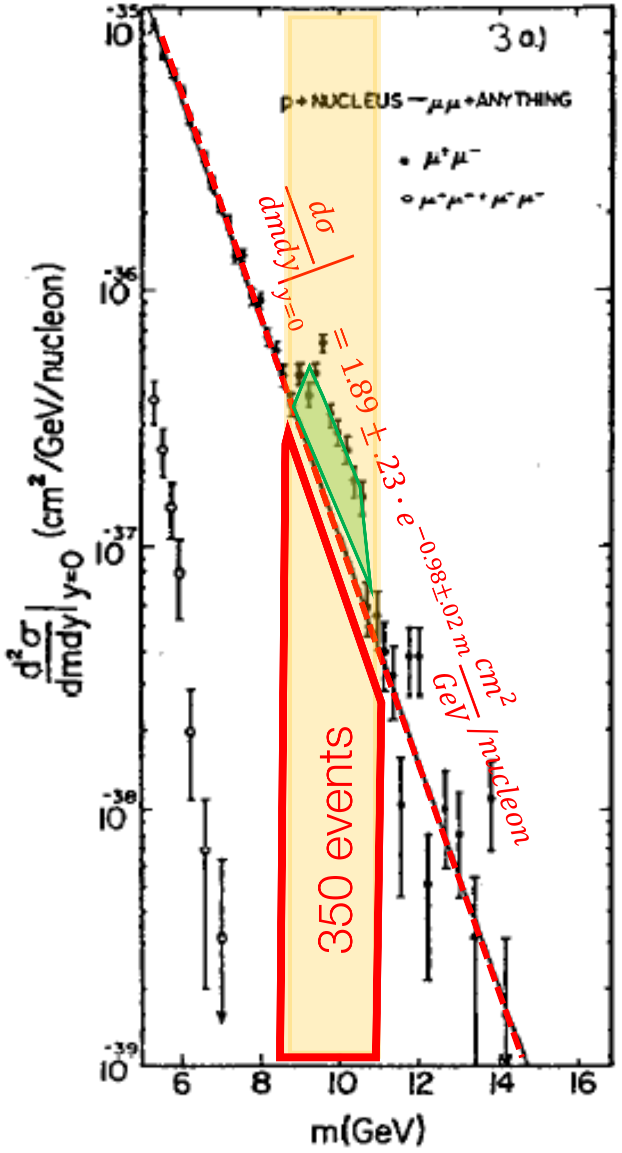
- Hadron Filter to stop hadrons and leave only muons
- Wire chambers and scintillators to reconstruct the muon trajectory
- Muon momentum measured twice (bending): after 1] air dipole and 2] after iron dipole

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



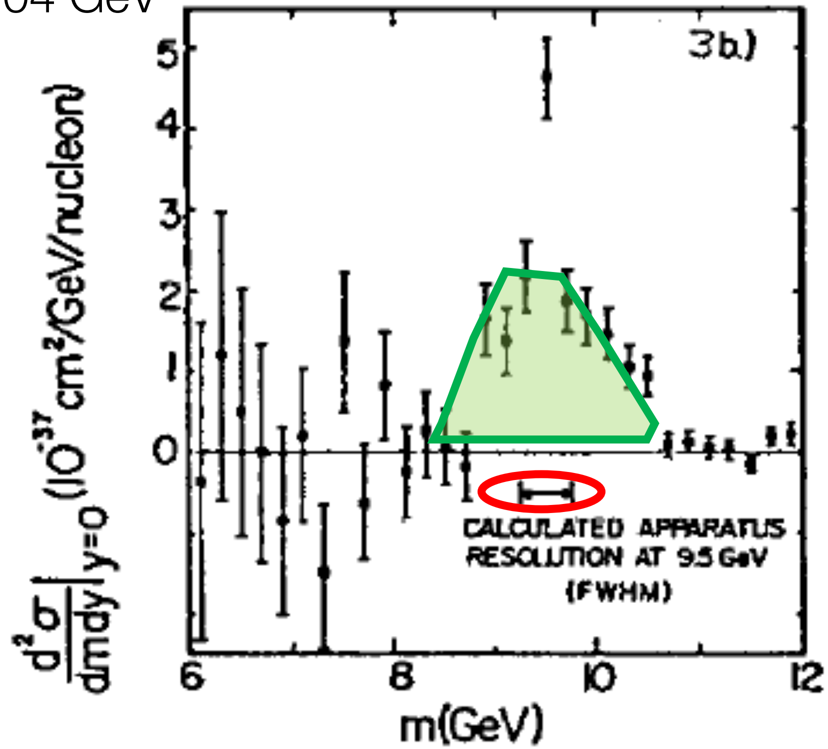
- A significant 'bump' excess is observed at ~9.5 GeV in mass
- Excluding the 8.8 to 10.6 GeV region → the distribution = simple exponential f
- The exponential form has an integral of 350 events in the "excluded region" while data contain 770 events
- "The observed bump is ***larger*** than the mass 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"

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



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

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

As for the J/ψ,

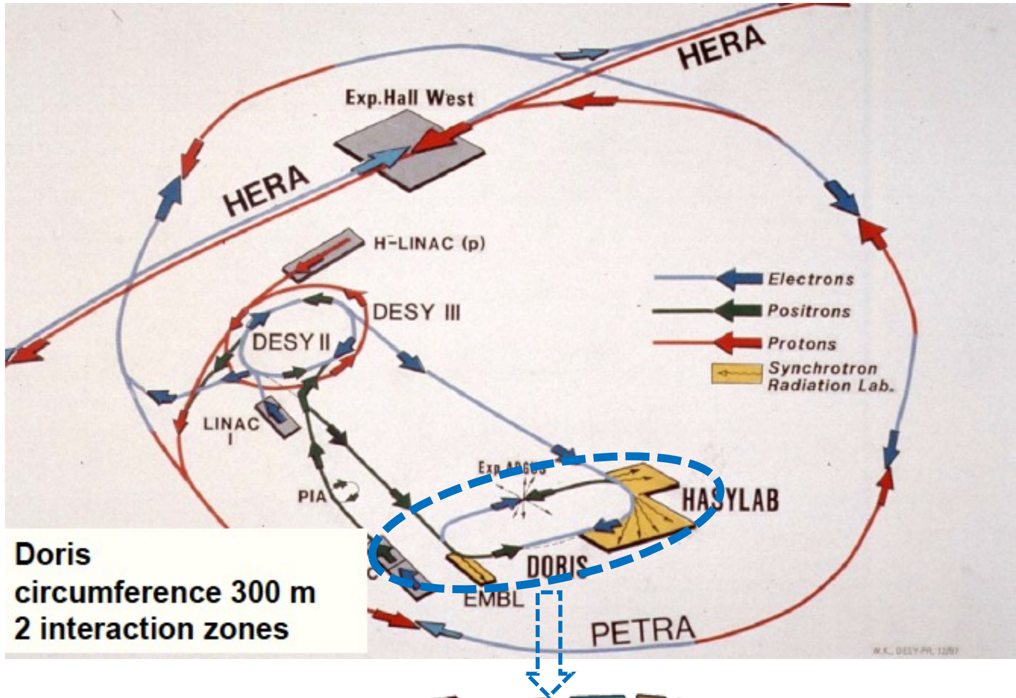
$$\Gamma_{\Upsilon} \rightarrow e^+e^- = 1.3 \pm 0.4\ \text{keV (area under the resonance)}$$

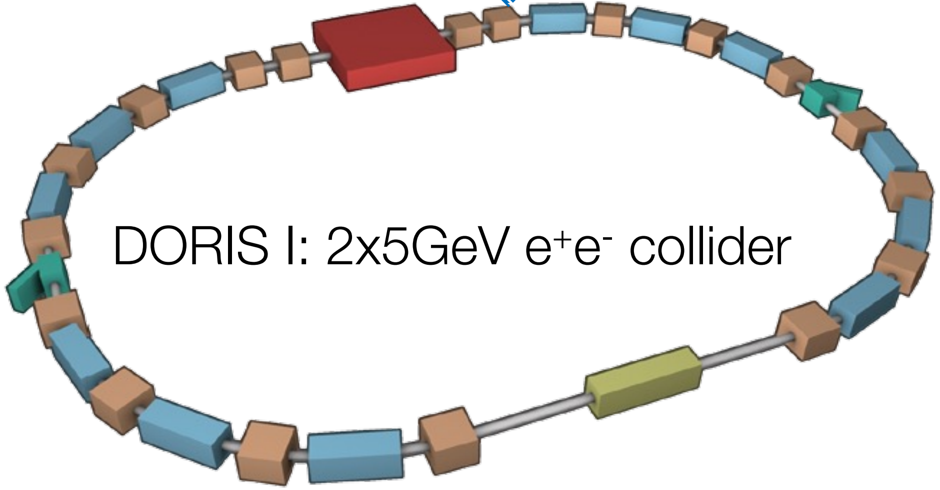
The comparison with models indicated that the new quark had

charge –1/3 (not +2/3)

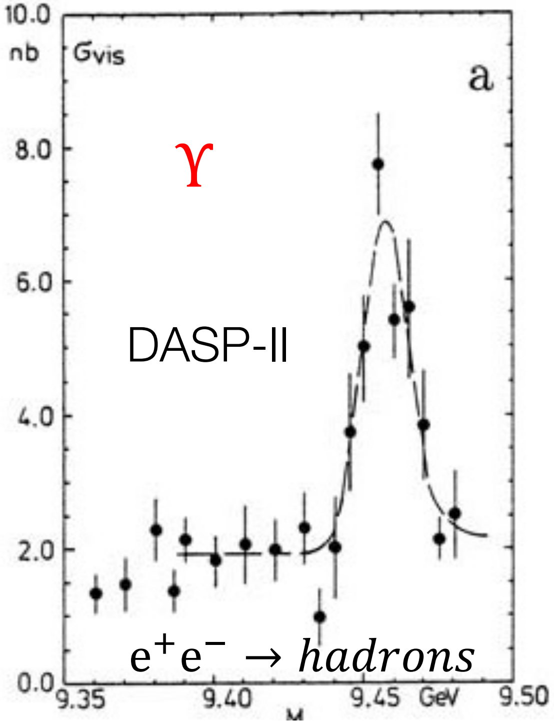
The new quark was called the "b" for "bottom": practice of writing the quark pairs (u, d) with the charge –1/3 and (c, s) below the charge 2/3 quark.

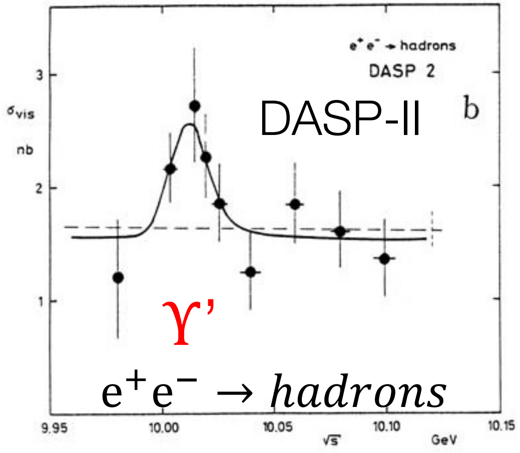
Thus the sixth quark was called "t" or "top" (before its discovery).

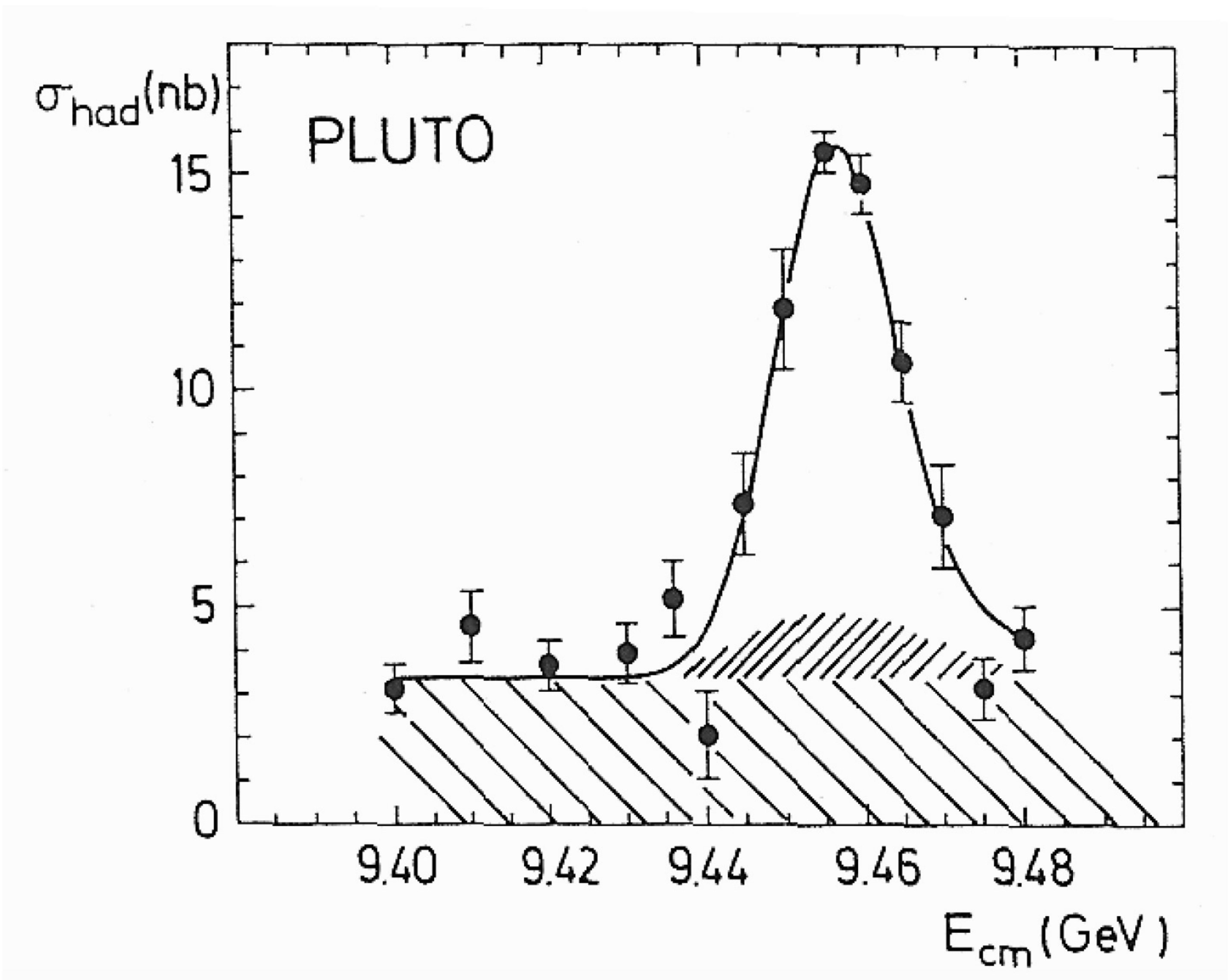




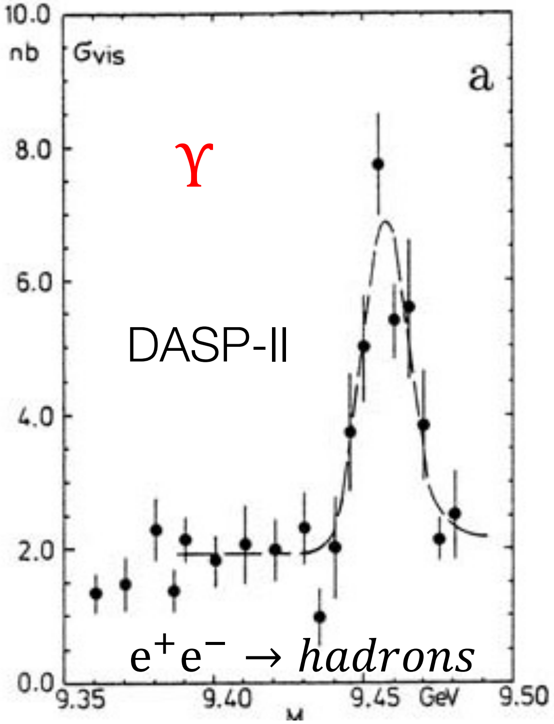
The Upsilon at DORIS





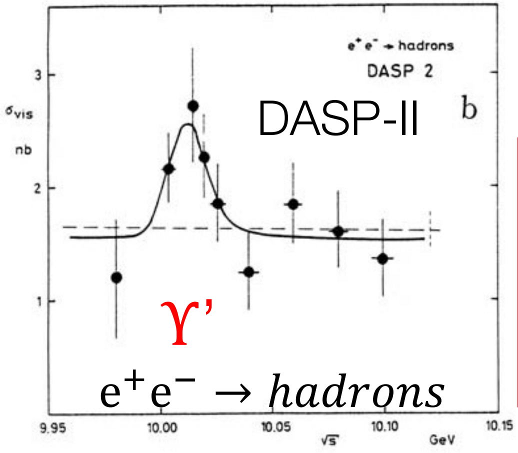


The Upsilon at DORIS

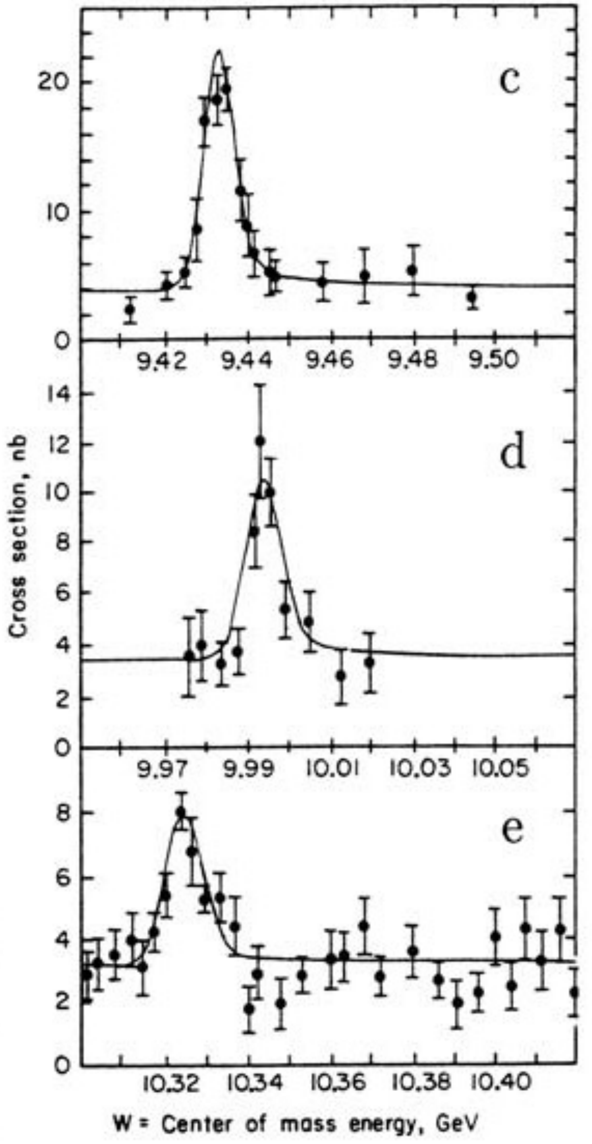


With the help of an energy upgrade, in May 1978 the PLUTO and DASP II detectors at the DORIS e^+e^- storage ring at DESY were able to observe the ϒ. The determination of the mass of the resonance was greatly improved: ***M_Υ = 9.46 ± 0.01 GeV***. Moreover, *the observed width was limited only by the 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±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

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

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

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

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

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

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

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

LEP & SPS & SppS and Fermilab: History

No need to have a narrow extracted beam !

Situation in late 70s @CERN:

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

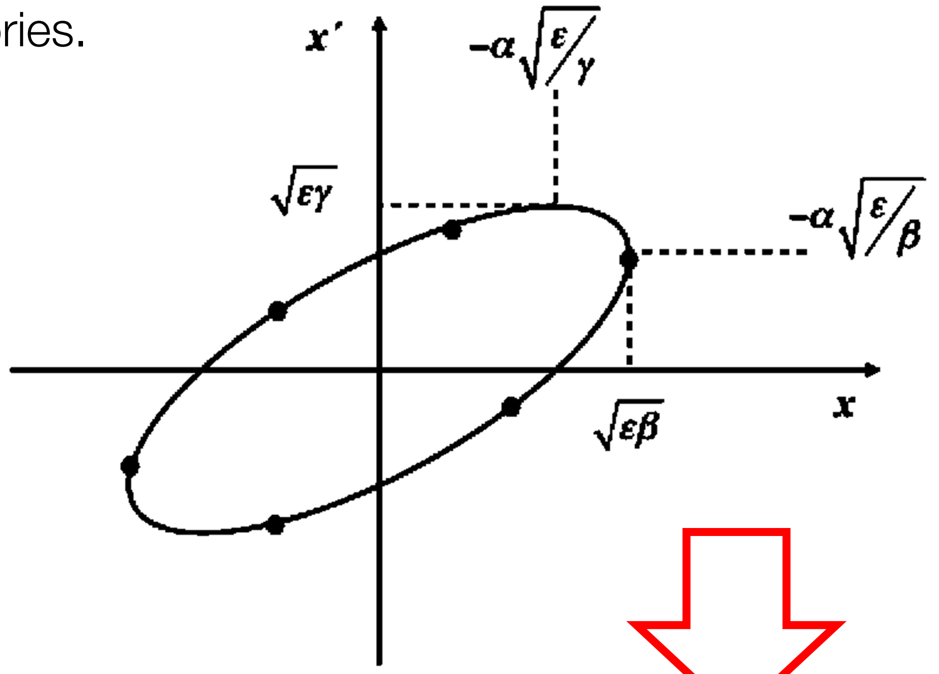
Emittance ε and the $\bar{p}$

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

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

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

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

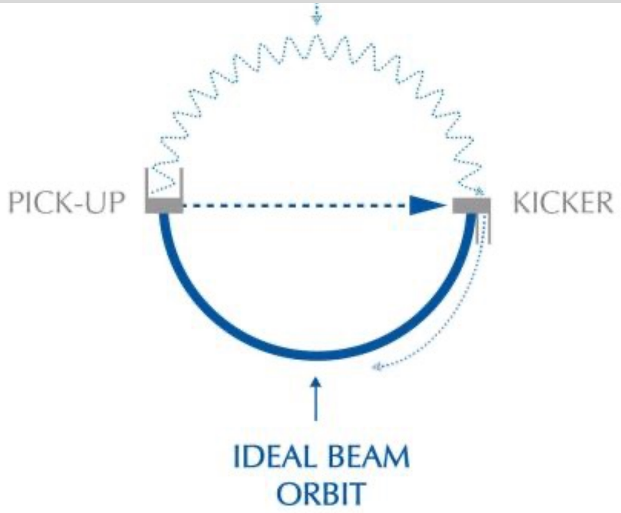
This means that emittance cannot be changed once the optics of the machine is defined: it is a property of the beam, and cannot be changed.

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

Toni Baroncelli: Discoveries

Stochastic Cooling

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



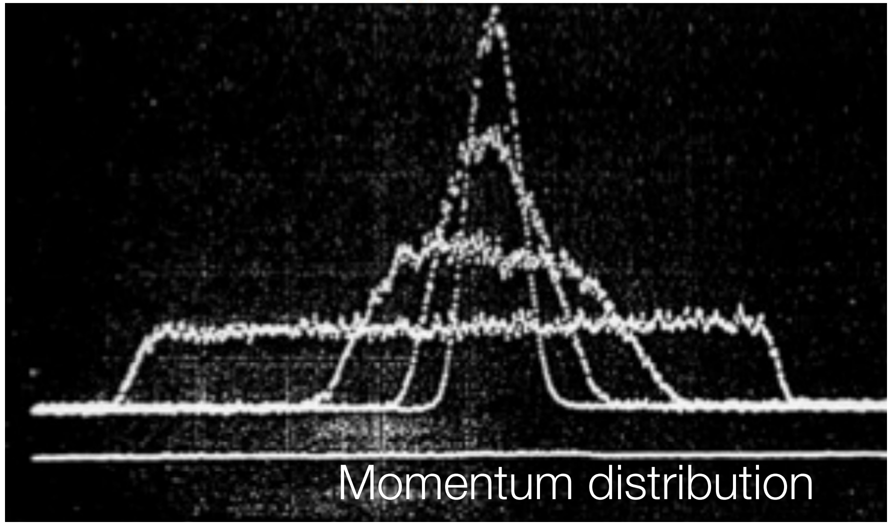
Gases:

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

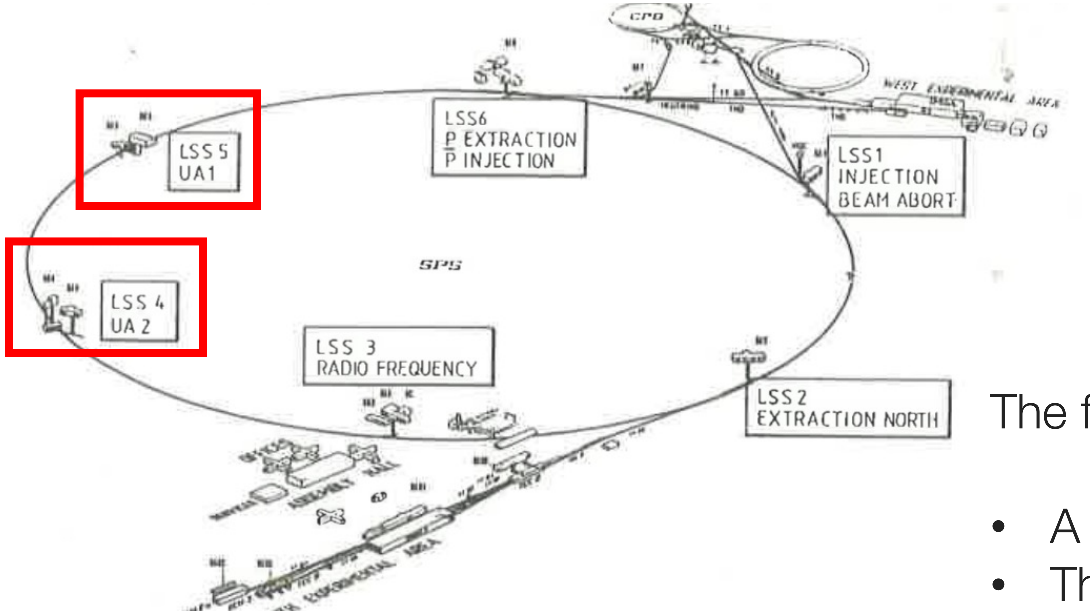
- pick-up: measures the deviation of a bunch of particles with respect to the 'ideal' orbit.
- sends a signal to the kicker which applies an electric field to this same bunch to correct the deviation measured

AA (Antiproton Accumulator)



Momentum cooling in ICE of $5\text{x}10^{7}$ particles.
Momentum distribution after 0, 1, 2 and 4 minutes.
The relative momentum spread reduces from $3.5\text{x}10^{-3}$ to $5.0\text{x}10^{-4}$

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 $\bar{p}$ → the production proceeds via valence quarks only:

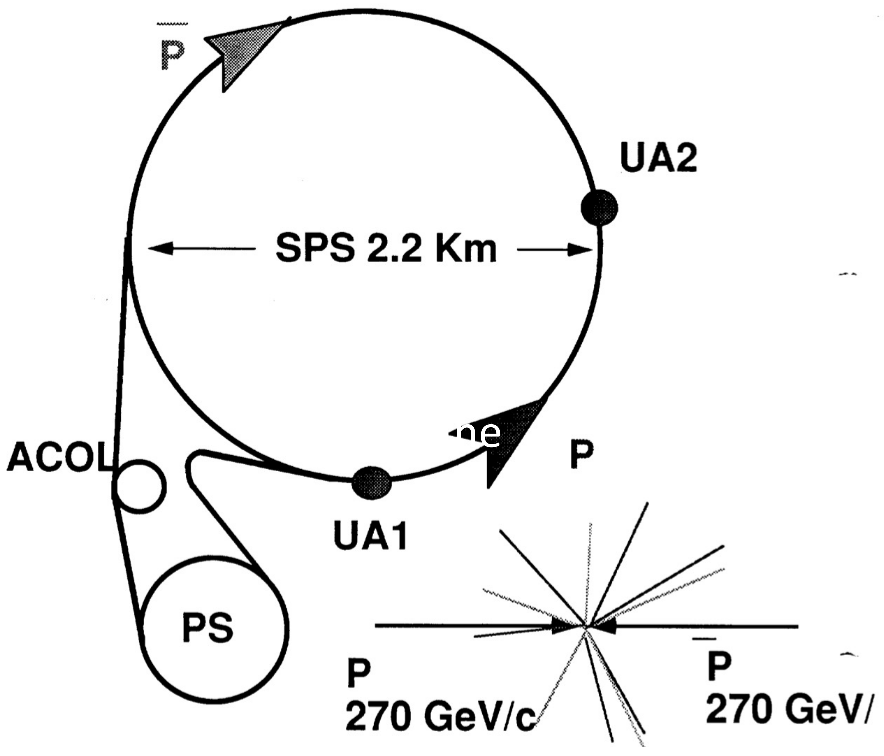
$$u + \bar{d} \rightarrow W^+$$
$$d + \bar{u} \rightarrow W^-$$
$$u + \bar{u} \rightarrow Z$$
$$d + \bar{d} \rightarrow Z$$

(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, un-balanced event, cross section $\mathcal{O}$ 1 nb per leptonic spieces, $\sigma_{tot} \approx 4 \cdot 10^7$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 spieces, $\sigma_{tot} \approx 4 \cdot 10^6$nb
  3. $Z \rightarrow \nu_l \bar{\nu}_l$ $(l = e, \mu, \tau)$ invisible decay → *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



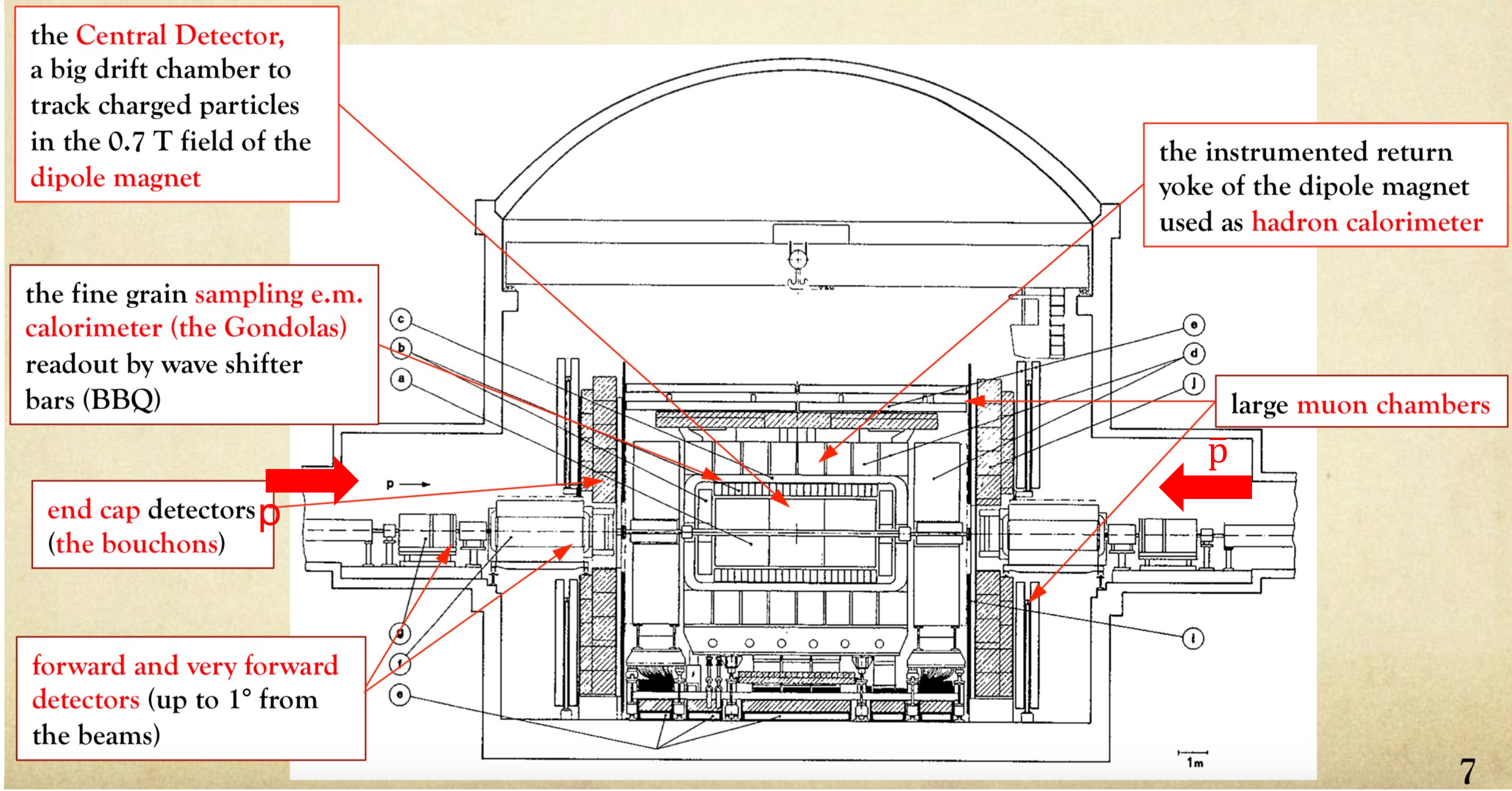
The SppS brought into collision 270 GeV p and 270 GeV $\bar{p}$ in 1983

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:

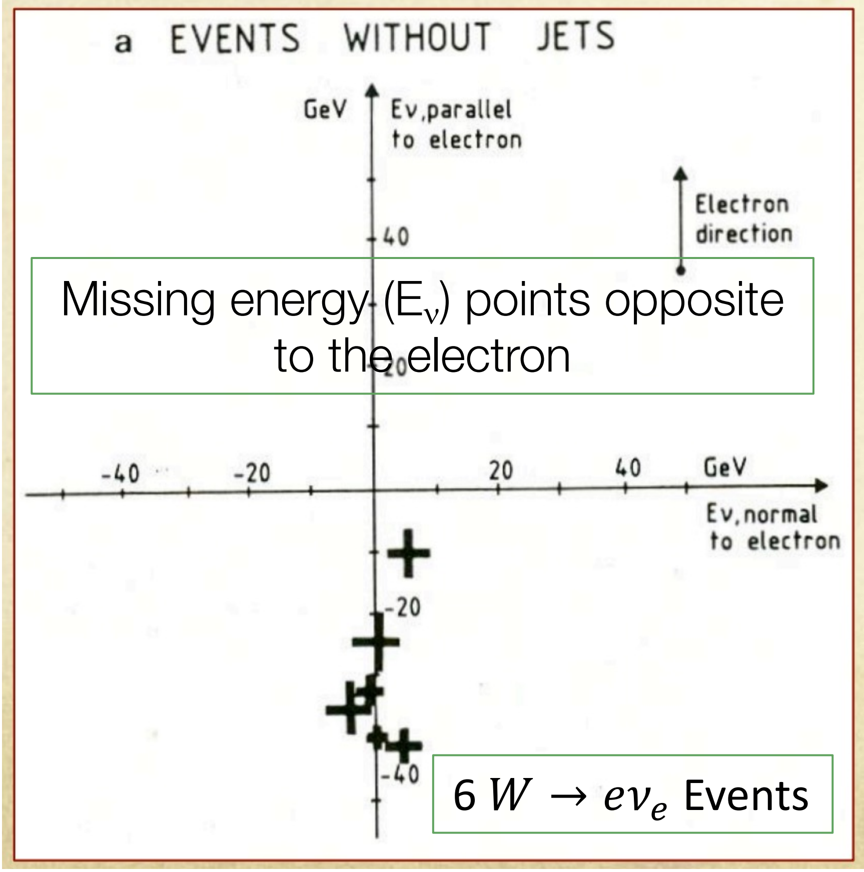
- 0.7 T uniform magnetic field
- a high quality drift chamber inside.
- electromagnetic and hadronic calorimeters.
- The discrimination between electrons and hadrons with many X_0 segmented into layers → shape of shower
- Muon chambers after calorimeters

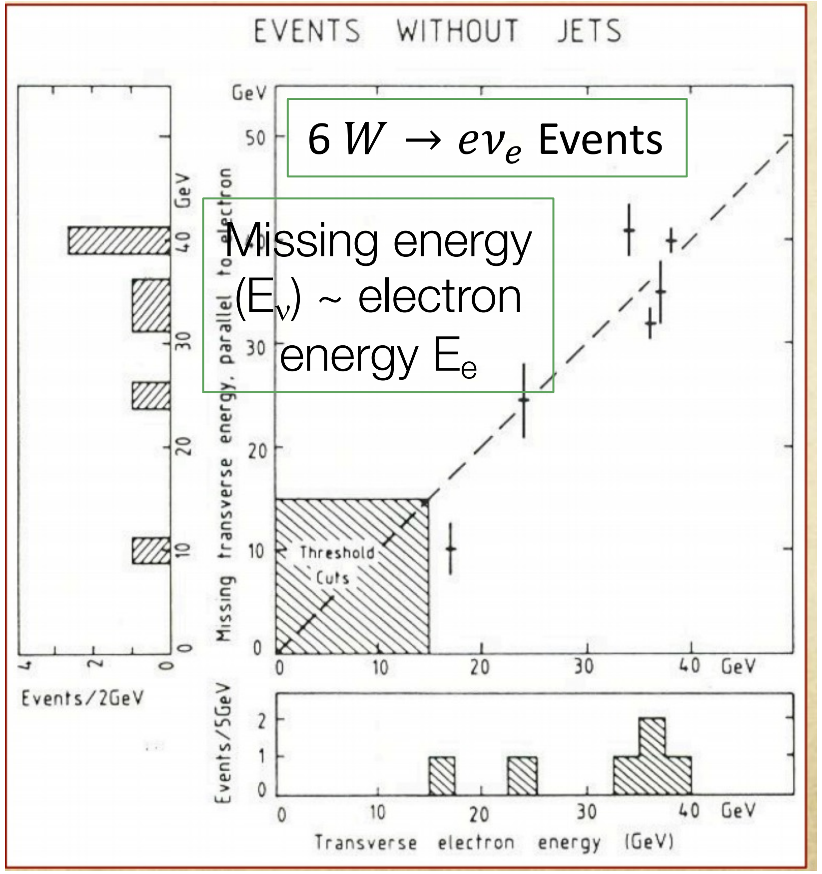


The UA1 Results: 6 $W \to e\nu_e$ Events

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

1. A track with $p_T > 7$ GeV/c associated to an em shower (1106 events)
2. Other charged tracks, give < 2 GeV/c of 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

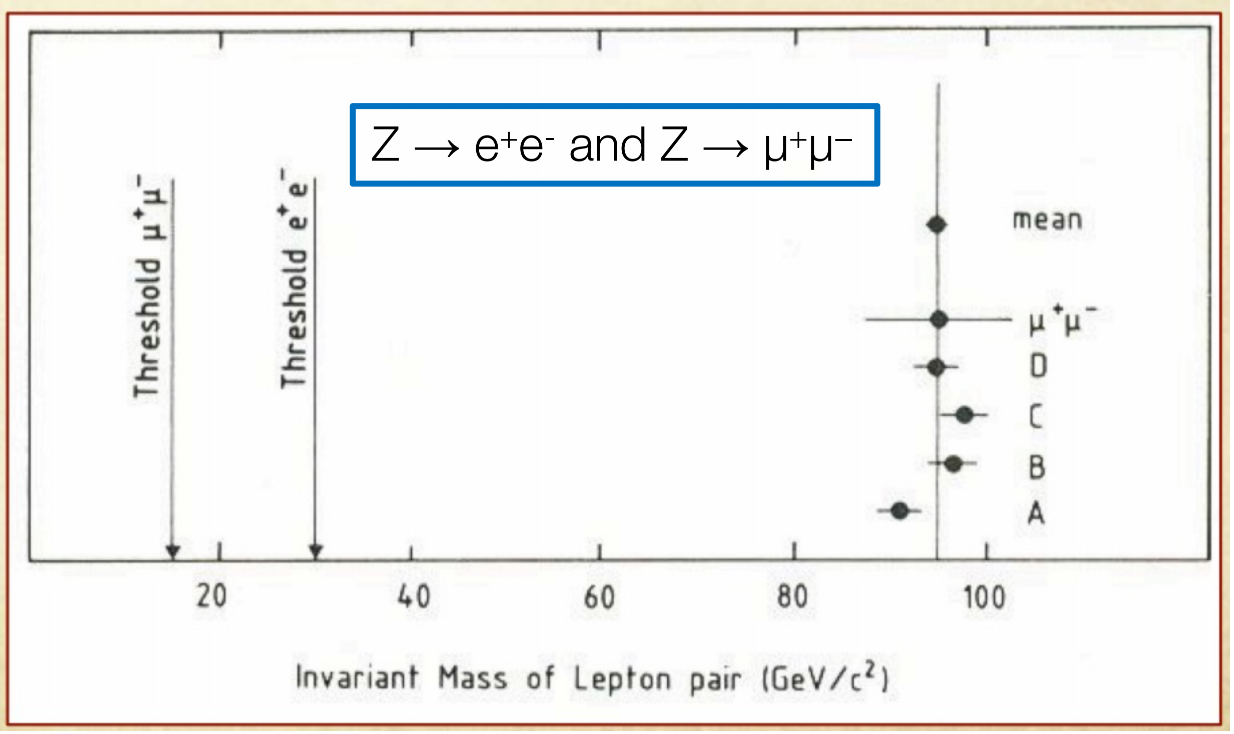
The UA1 Results: 5 $Z \to \ell^+\ell^-$ Events

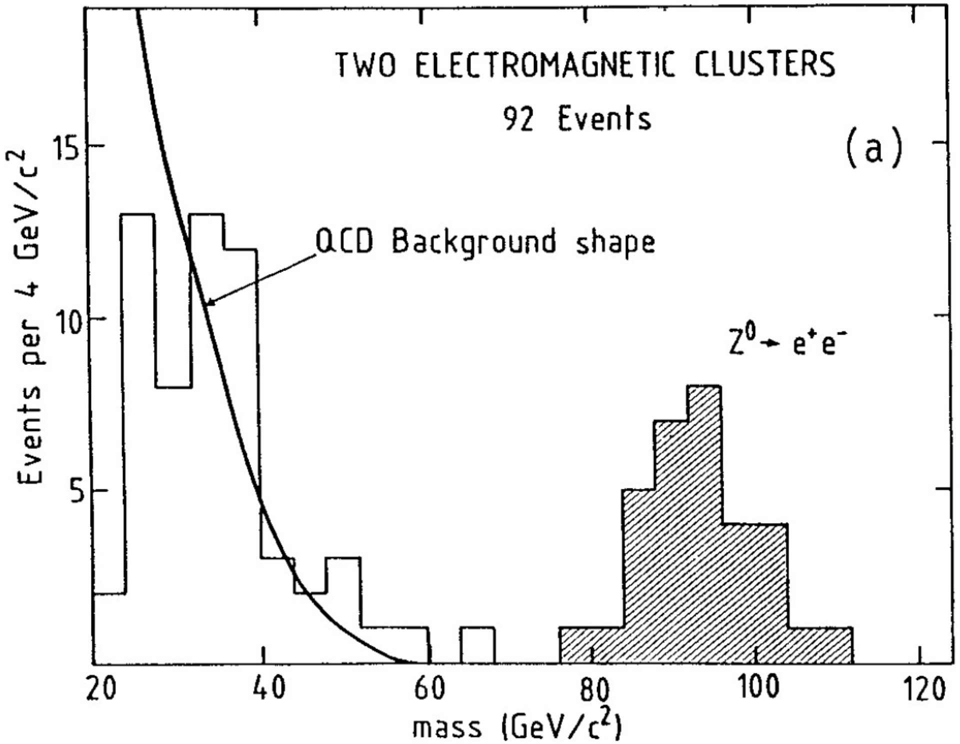
Z decays → e^+e^- and Z → $\mu^+\mu^-$ were discovered later

- Cross section for Z production is ~ 10 times smaller than that for W's
- the branching ratios Z → e+e– and Z → μ+μ– are expected to be only 3% each, while W → eν and W → μν should be 8% each.

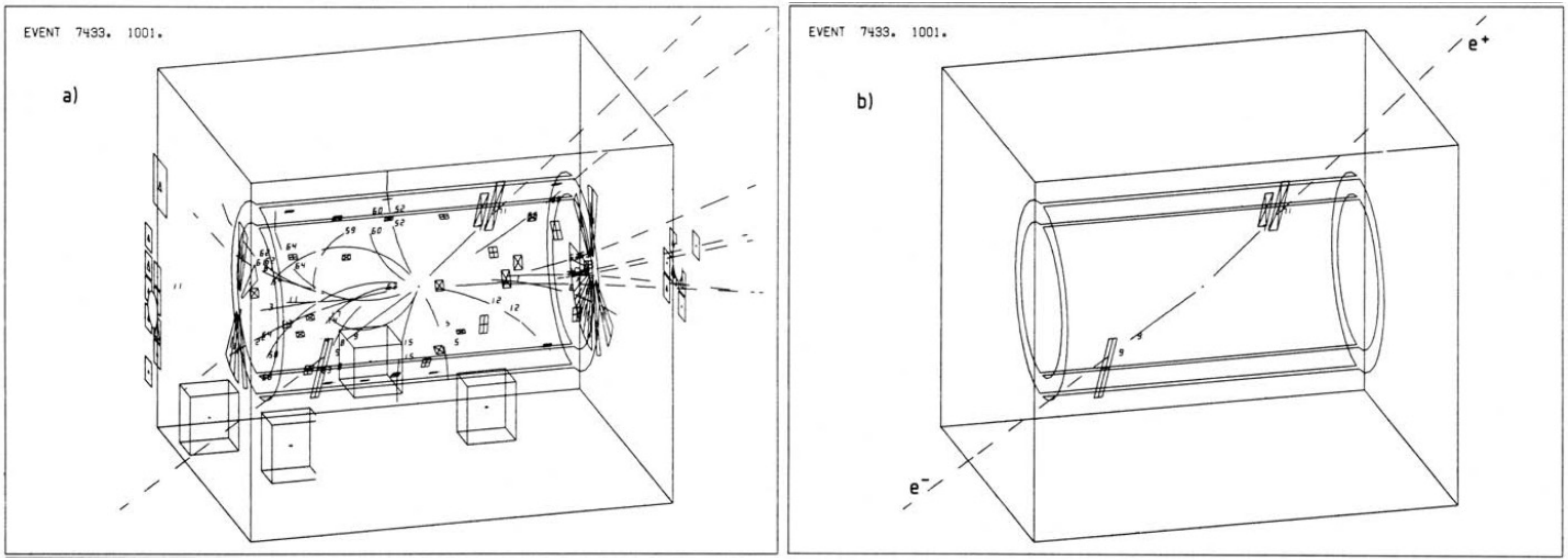
However, the signature of two leptons with large invariant mass was very clear, and only a few events were necessary to establish the existence of the Z with a mass consistent with the theoretical expectation

Results for the decay Z → e+e– obtained by the UA-1 and UA-2 Collaborations are shown below





UA1 Events Displayed



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

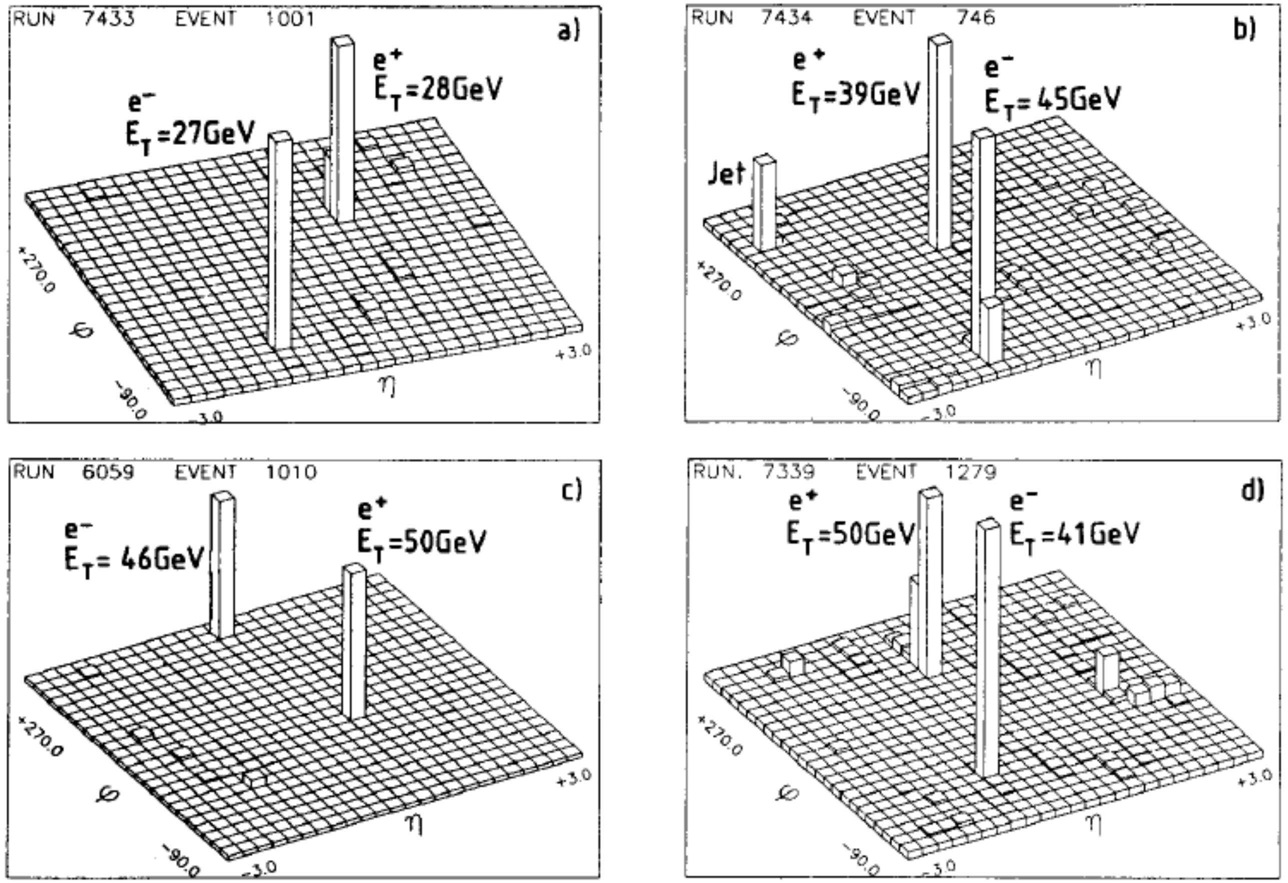


Figure 12.3. Lego plots for four UA-1 events that were candidates for $Z^0 \rightarrow e^+e^-$. The plots show the location of energy deposition in ϕ, the azimuthal angle, and $\eta = -\ln\tan(\theta/2)$, the pseudorapidity. The isolated towers of energy indicate the cleanliness of the events (Ref. 12.8).

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.

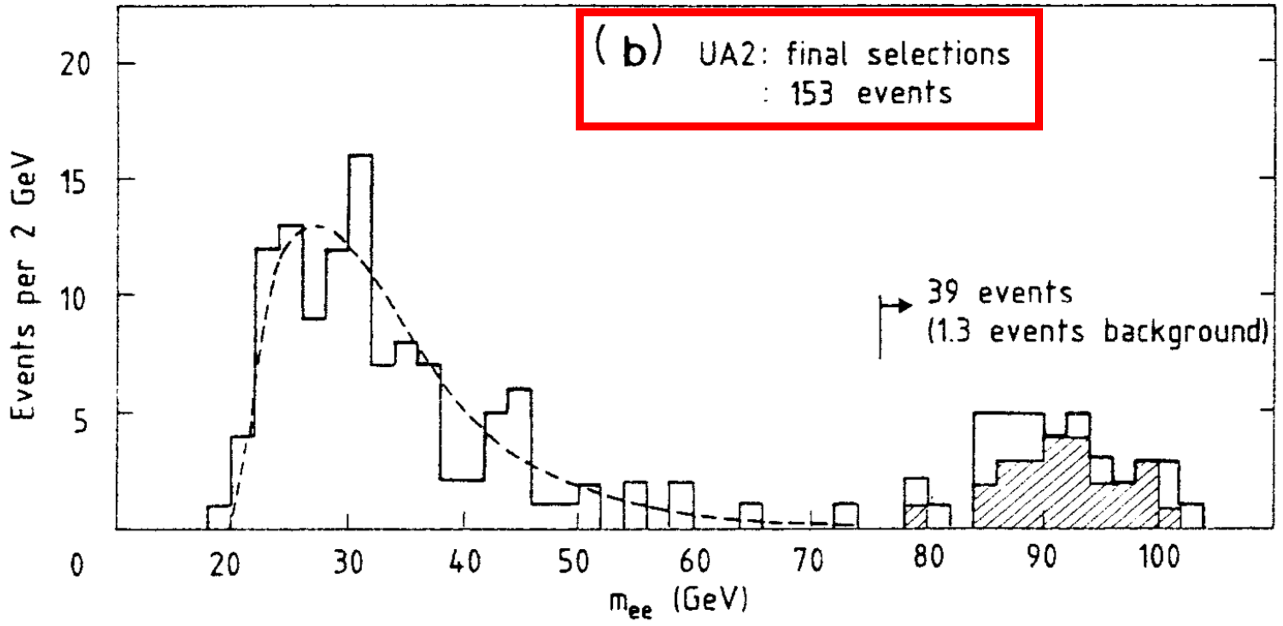
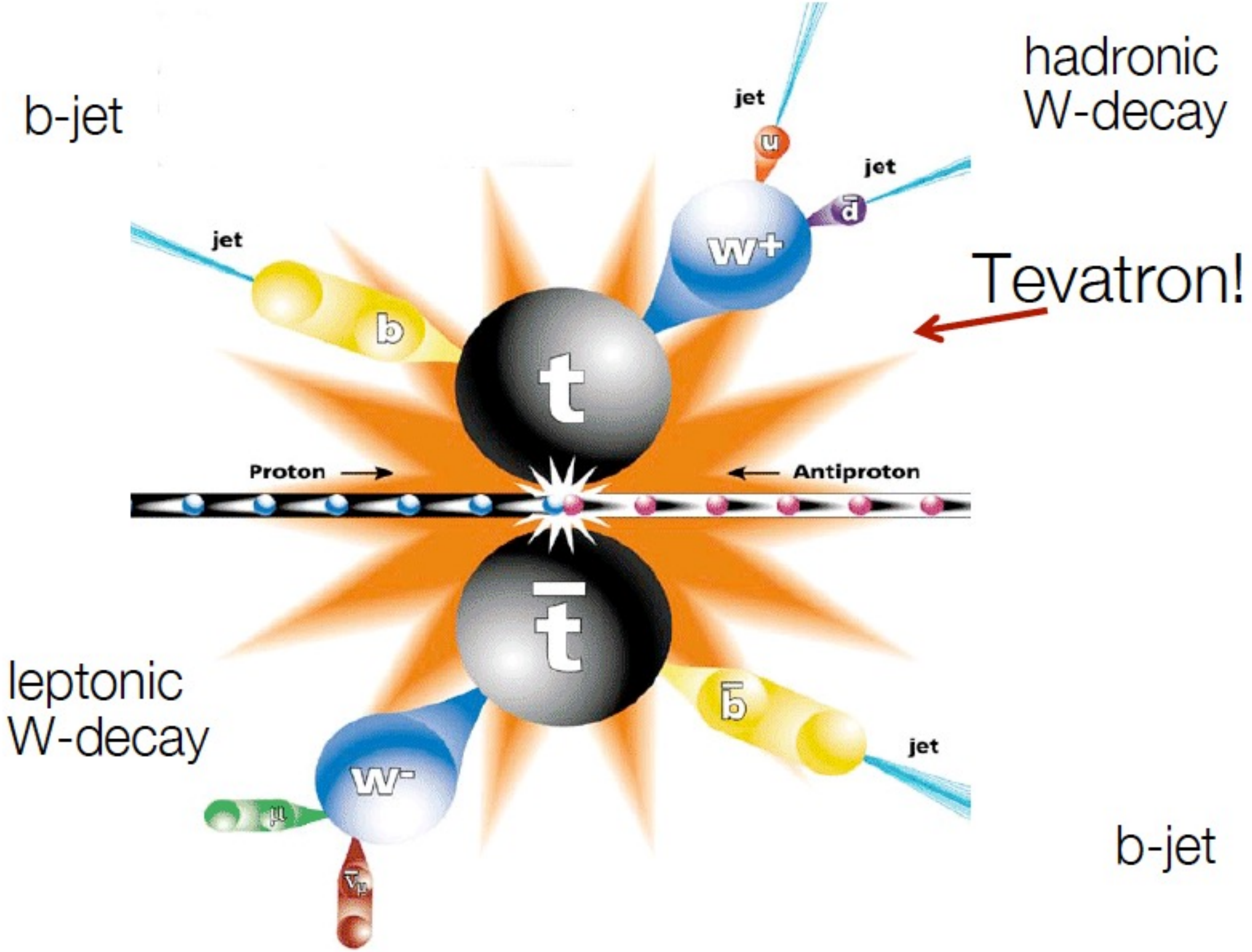


Figure 12.5. (a) The invariant mass distribution for e^+e^- pairs identified through electromagnetic calorimetry in the UA-1 detector. (Figure supplied by UA-1 Collaboration) (b) The analogous plot for the UA-2 data (Ref. 12.12). In both data sets, the Z appears well-separated from the lower mass background.

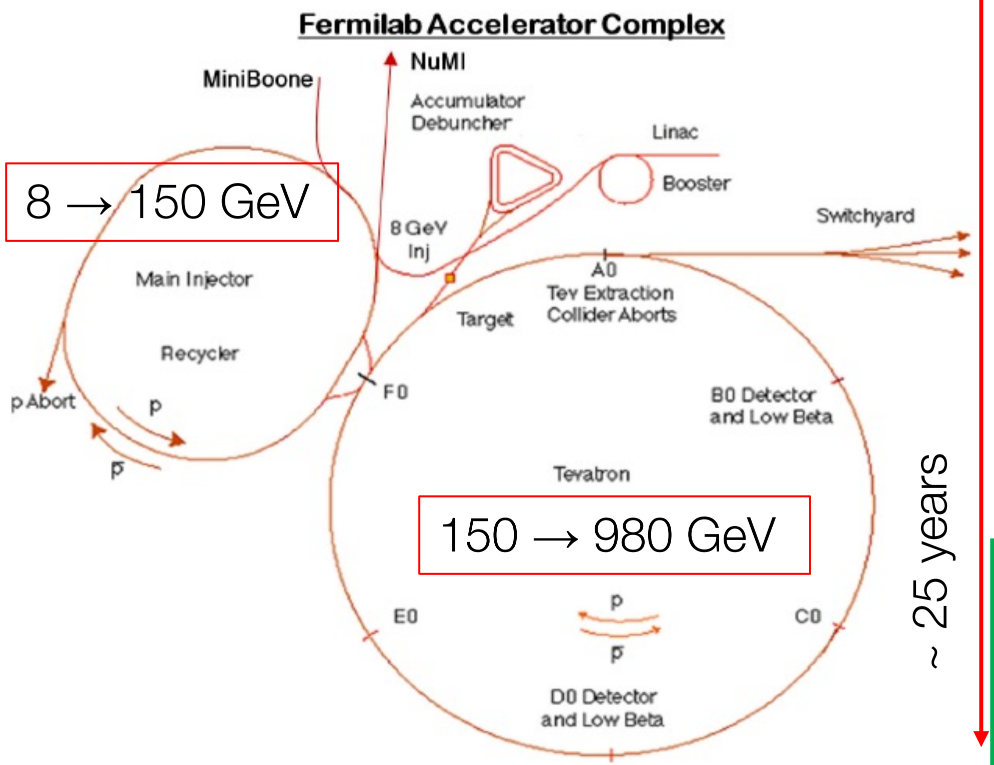
The Discovery of the Top



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.



~ 25 years

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 $11 \cdot 10^{30} cm^{-2} s^{-1}$ at √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 $5 \cdot 10^{31} cm^{-2} s^{-1}$, 180pb^{-1} collected
- 1995 Discovery of the Top
- 2001-2011 RunII top luminosity $5 \cdot 10^{32} cm^{-2} s^{-1}$

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.

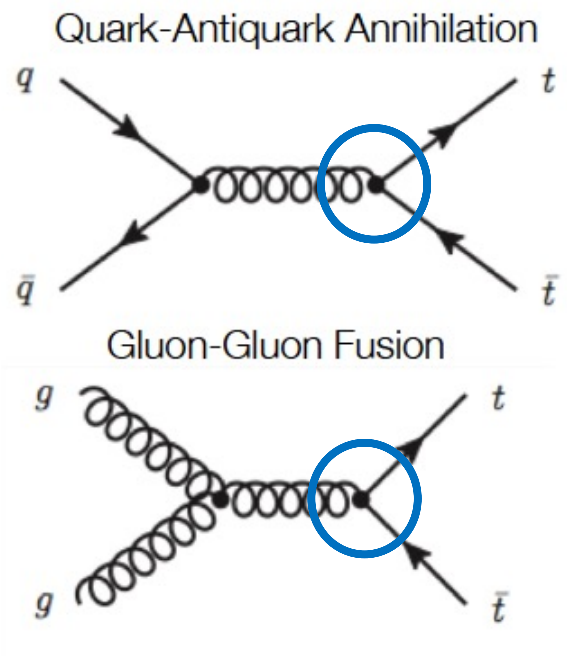
The large value of the top quark mass indicates a strong Yukawa coupling to the Higgs, → could provide special insights in our understanding of electroweak symmetry breaking.
Together with the W boson mass, it constrains the Higgs boson mass through global electroweak fits.

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	$\times 10^{30}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$
Luminosity (Design Goal)	5	10	200	$\times 10^{30}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$

top Production and Decay



The primary mode, in which a $t\bar{t}$ pair is produced from a $gt\bar{t}$ 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

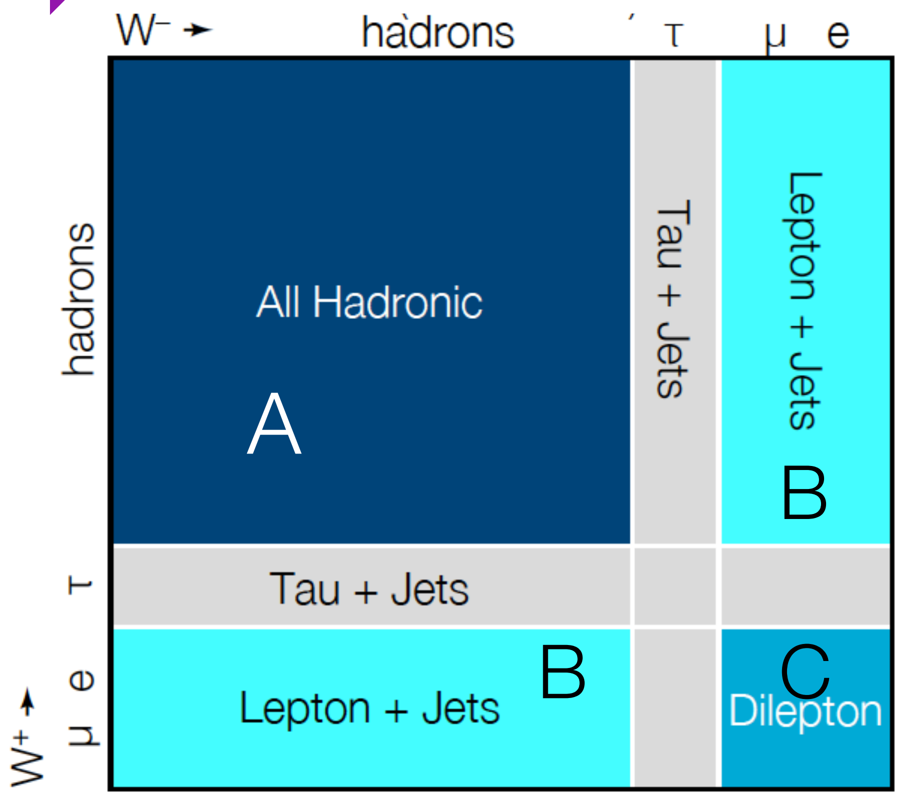
A. $t\bar{t} \rightarrow W^+ b\, W^- \bar{b} \rightarrow q\bar{q}'\, b\, q''\bar{q}'''\bar{b}$, (45.7%)

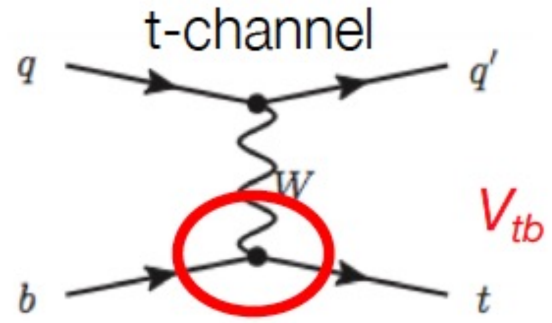
B. $t\bar{t} \rightarrow W^+ b\, W^- \bar{b} \rightarrow q\bar{q}'\, b\, \ell^- \bar{\nu}_\ell \bar{b} + \ell^+ \nu_\ell\, b\, q''\bar{q}'''\bar{b}$, (43.8%)

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

SM: ~100% $t \rightarrow Wb$



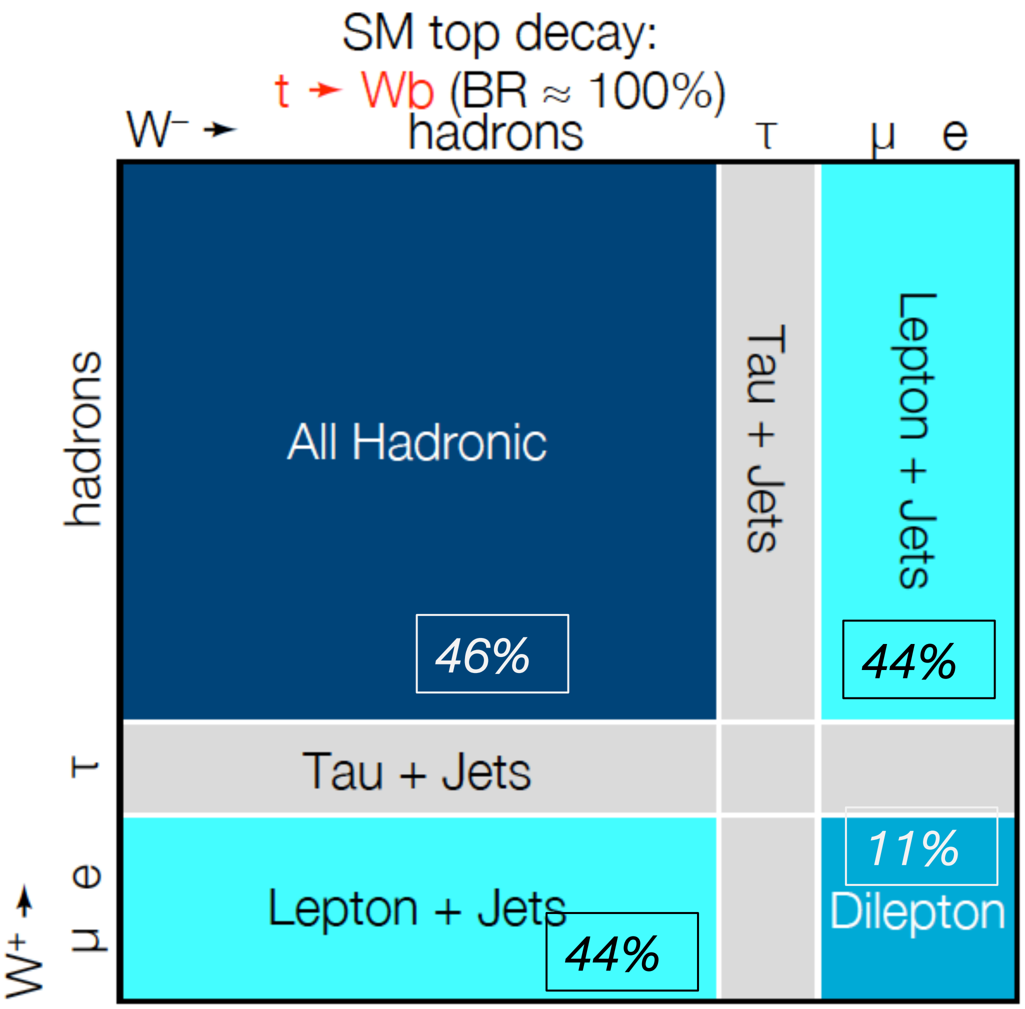


One top produced

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

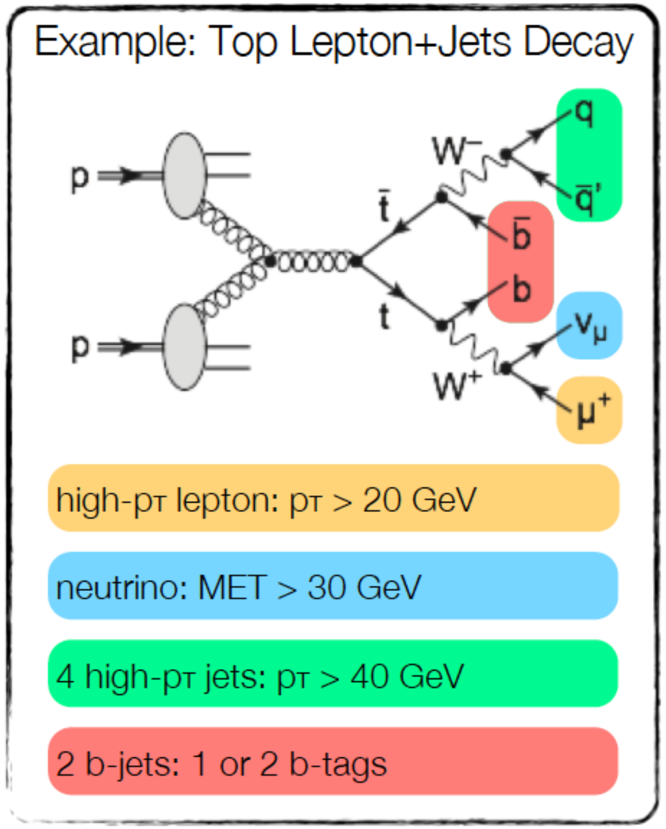
- Cross section ~ half that of $t\bar{t}$ pairs
- signal-to-background ratio is much worse

Topologies in $t\bar{t}$ Decays



- These events always contain two b quarks

- The W decays characterise the topology of the event:
  - **All hadronic** → 6 jets (2 b jets) with large QCD background. Problem is jet-pairing, many possible combinations (W mass as constraint…)
  - **Lepton + jets** → 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** → 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

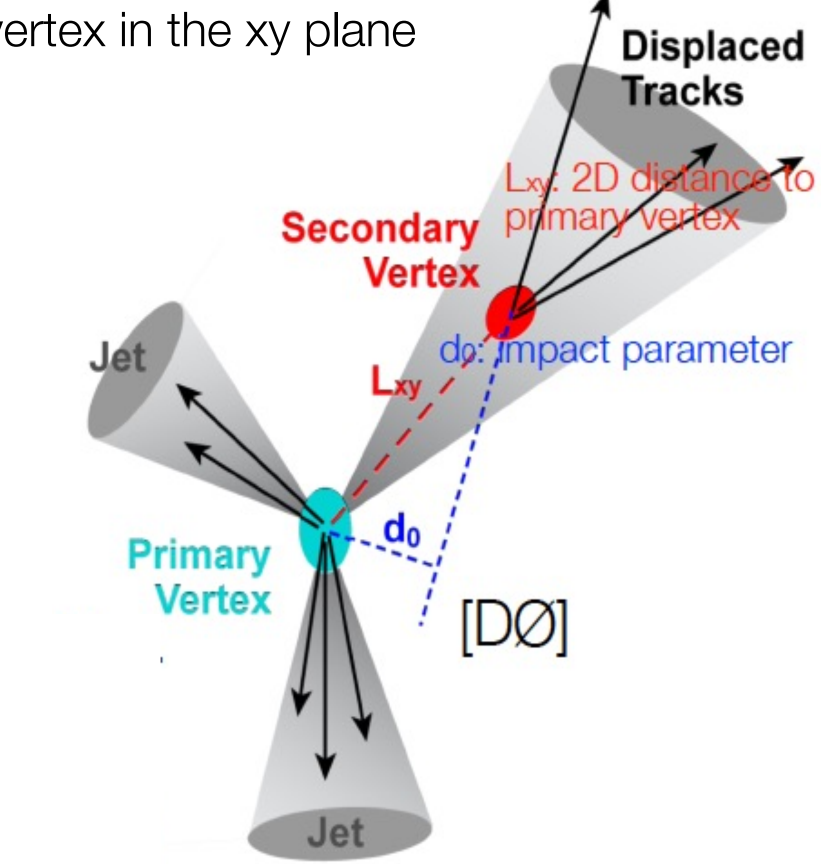
Heavy flavour hadrons (→"b hadrons") are unstable (life-time ~ 1.5 x 10^{-12} s) and decay after a measurable path (mm's).

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

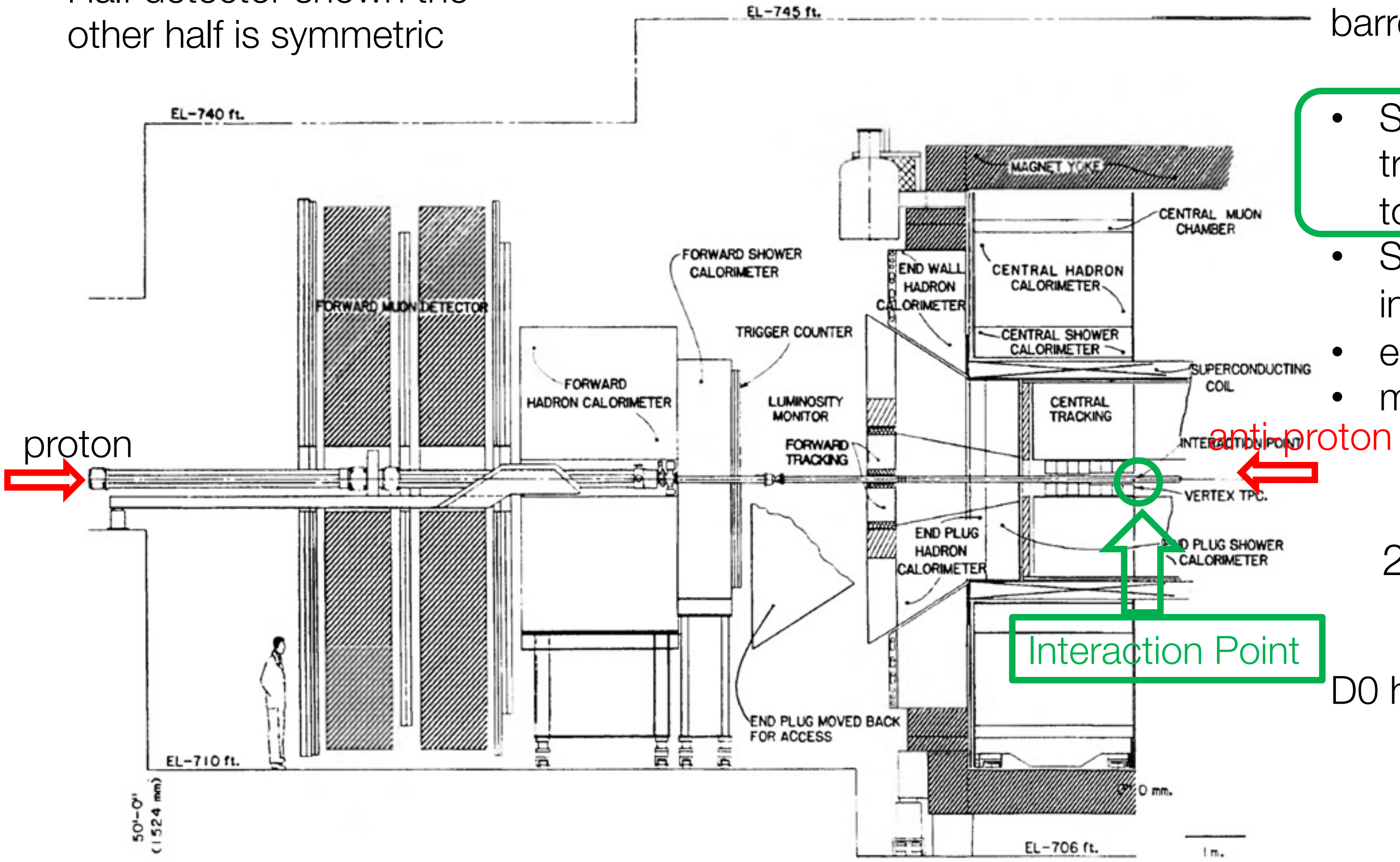
- d_0 track based indicator distance of minimum approach to the primary vertex
- *Lxy* distance between the secondary vertex and the primary vertex in the xy plane



Second approach: leptonic decay of the b-hadron →
b decay to lν+X → ~soft lepton close to a jet

The Experiments: CDF & D0

Half detector shown the other half is symmetric



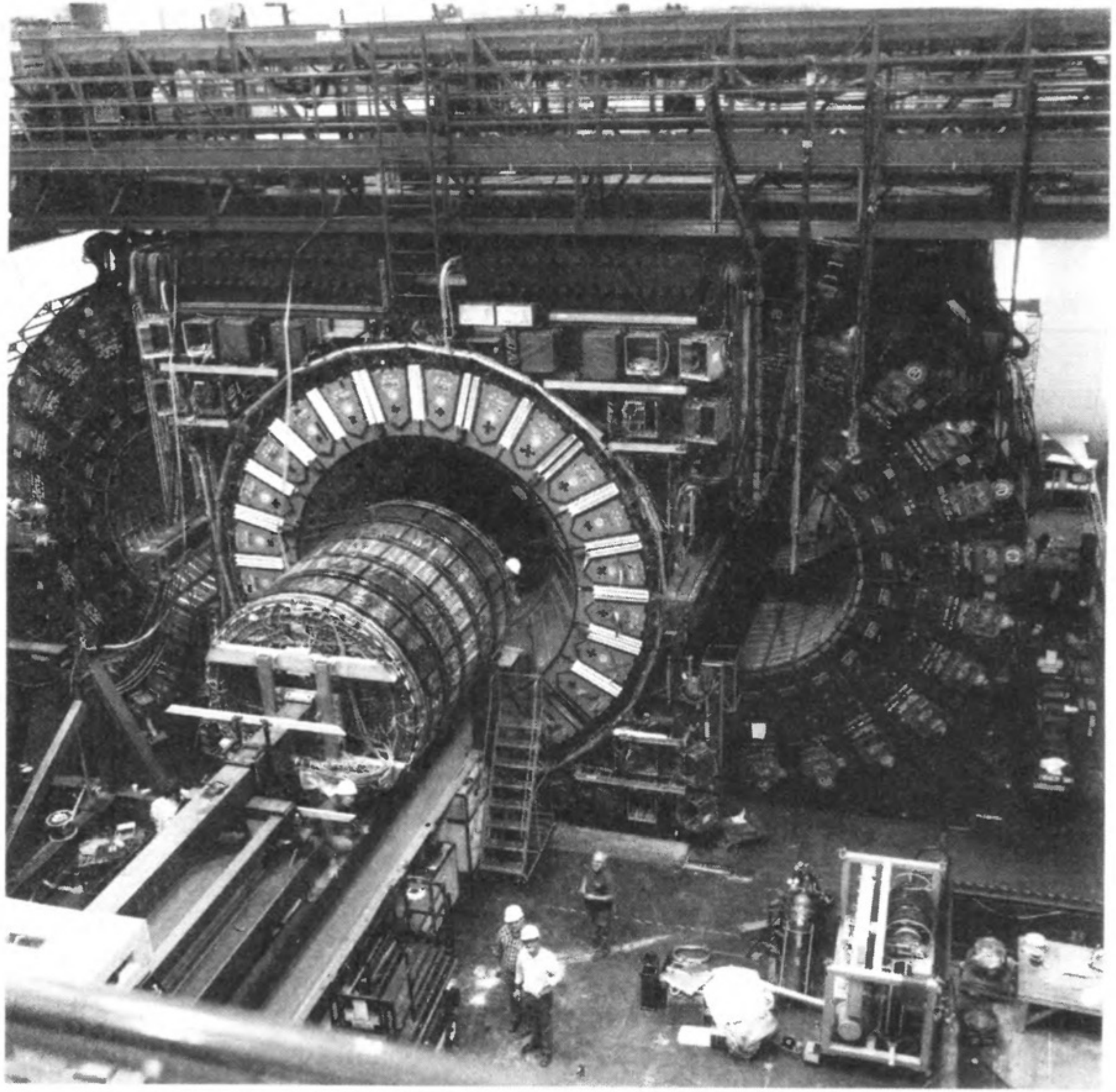
Already a ~ large modern detector: barrel part + forward/backward disks

- 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

The Discovery of the top in CDF



CDF during installation

A. $t\bar{t} \to W^+ b W^- \bar{b} \to q \bar{q}' b q'' \bar{q}''' \bar{b},$ (45.7%)
B. $t\bar{t} \to W^+ b W^- \bar{b} \to q \bar{q}' b \ell^- \bar{\nu}_\ell \bar{b} + \ell^+ \nu_\ell b q'' \bar{q}''' \bar{b},$ (43.8%)
C. $t\bar{t} \to W^+ b W^- \bar{b} \to \ell^+ \nu_\ell b \ell'^- \bar{\nu}_{\ell'} \bar{b}.$ (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
$1 \times W \to l\nu \ (l = e, \mu)$	$2 \times W \to l\nu \ (l = e, \mu)$
$p_T^l > 20\ GeV$	$p_T^l > 20\ GeV$
$\geq 3\ jets\ (of\ which\ 2b)$	2 jets (from b-decay)
(1 secondary vertex) OR (1 soft lepton from b-decay p_T> 2 GeV)	$E_T^{miss} > 25\ GeV$
	$75\ GeV < m_{ee,\mu\mu} < 105\ GeV$

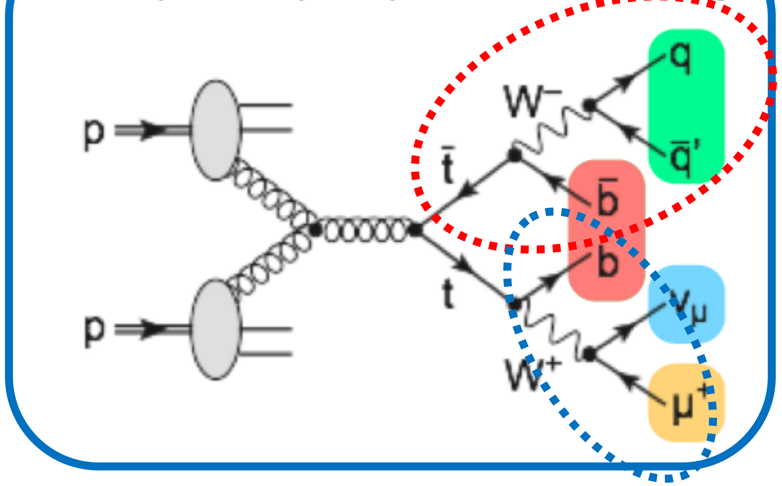
Top Mass using Lepton + Jets (2 methods)

1

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

- m_W = invariant mass of jet_q and $jet_{\overline{q'}}$
- 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 $W + jet_{\bar{b}}$

Example: Top Lepton+Jets Decay



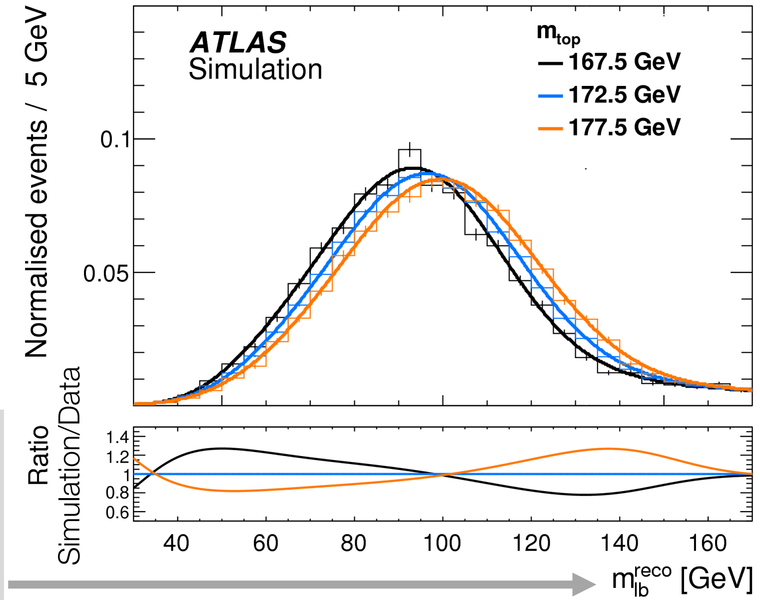
m_{lb}^{reco} = invariant mass of lepton + jet_b

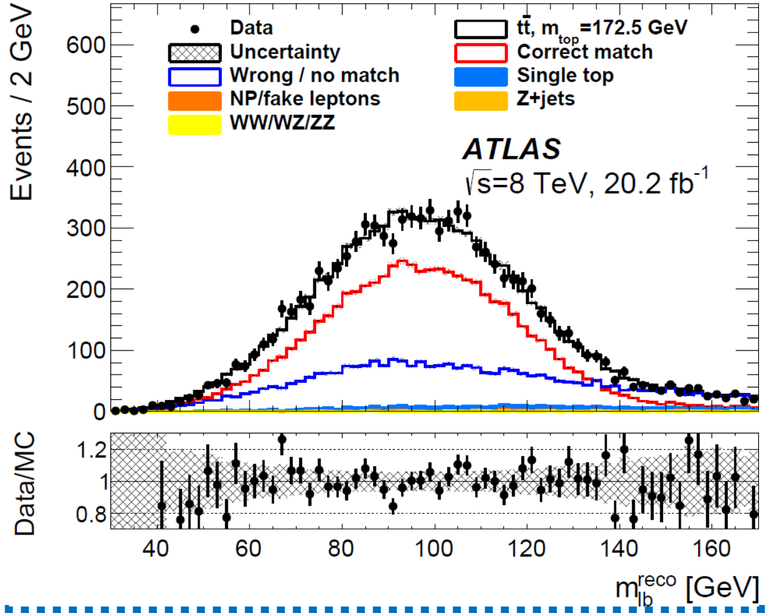
(ν_l non included $\rightarrow m_{lb}^{reco} < m_{top}$)

2

Template method: USE SIMULATED EVENTS! → 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 → m_{top}

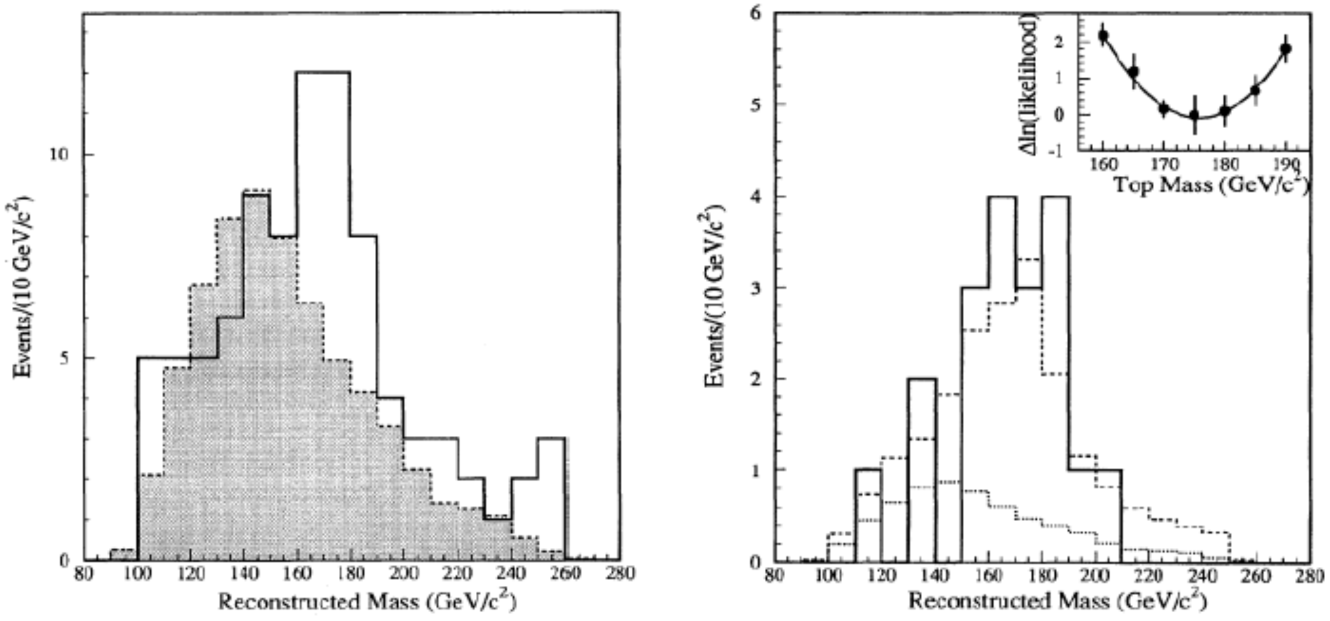




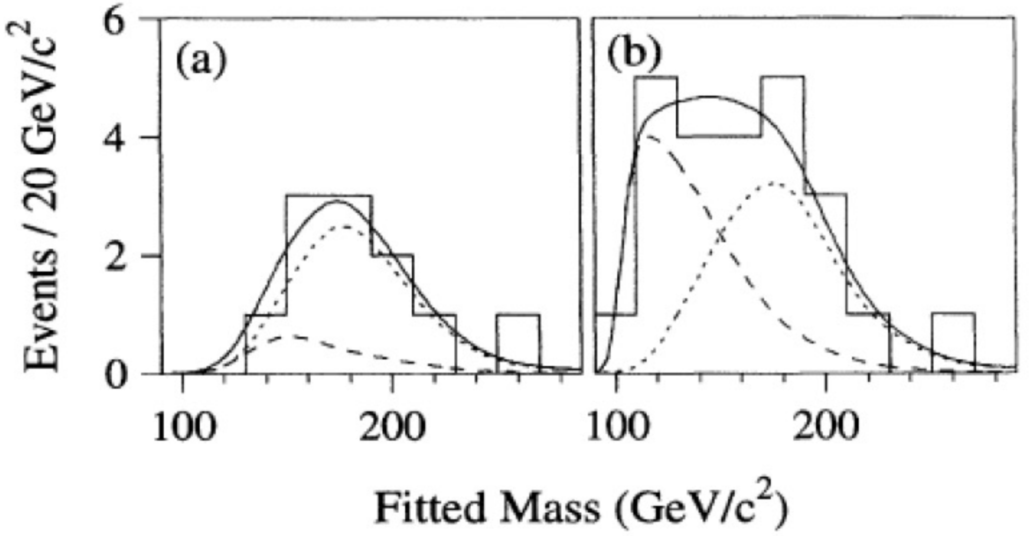
Discovery of the top at CDF & D0

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

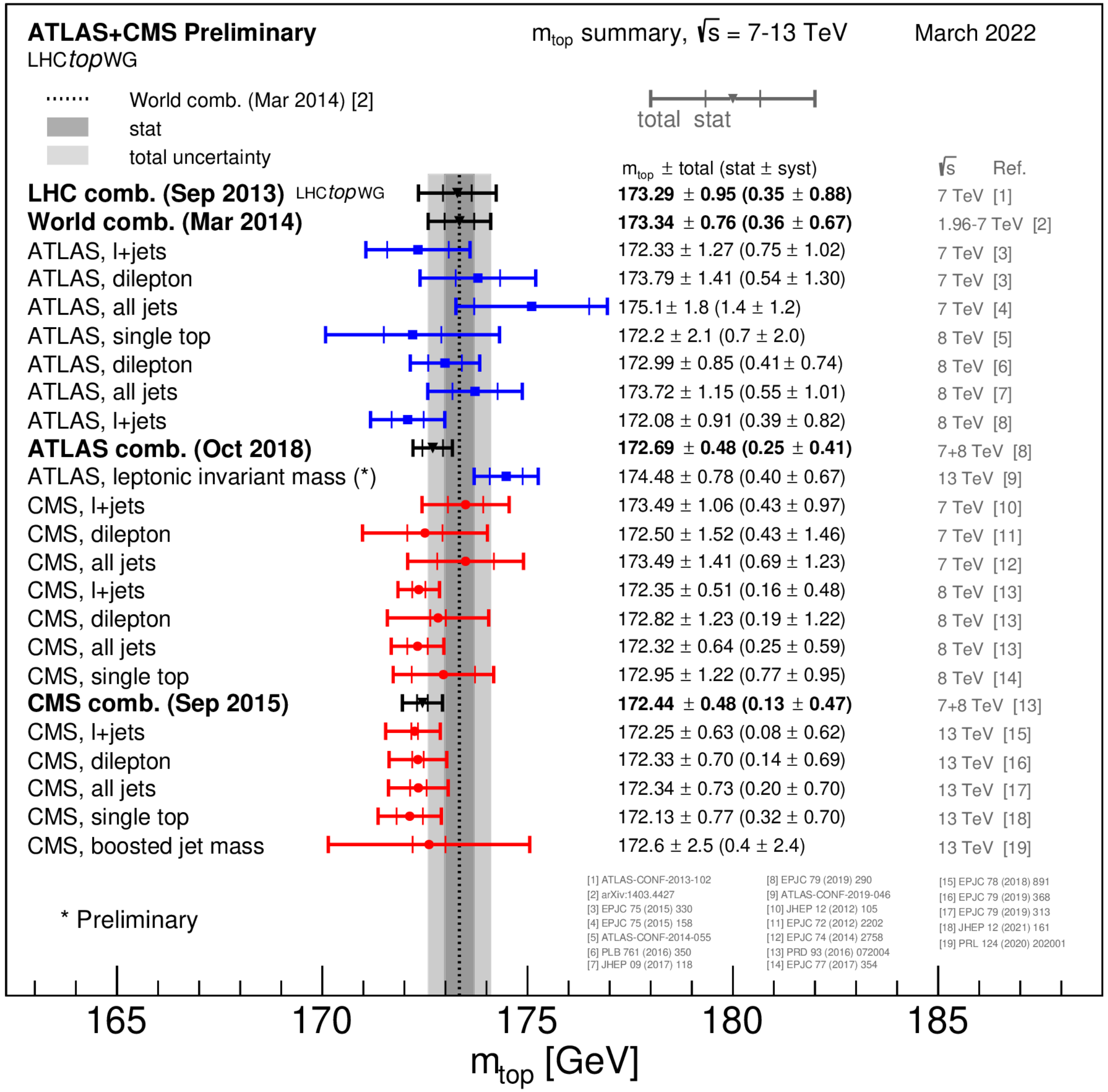
CDF



D0

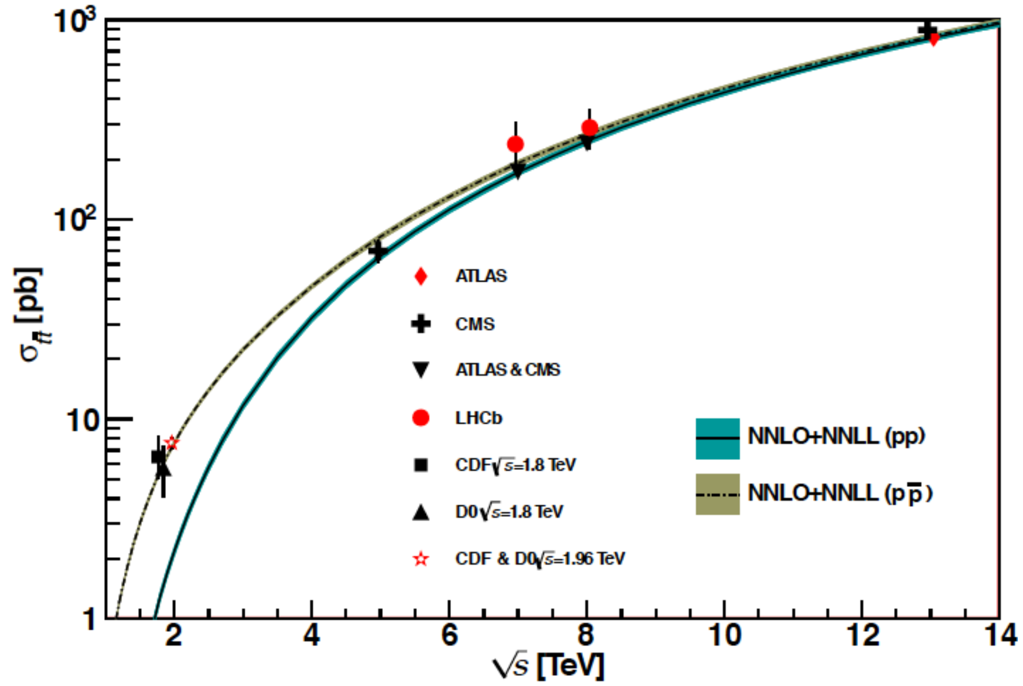


The Evolution of m_t from Tevatron to LHC



Important improvements with time (and going to LHC):

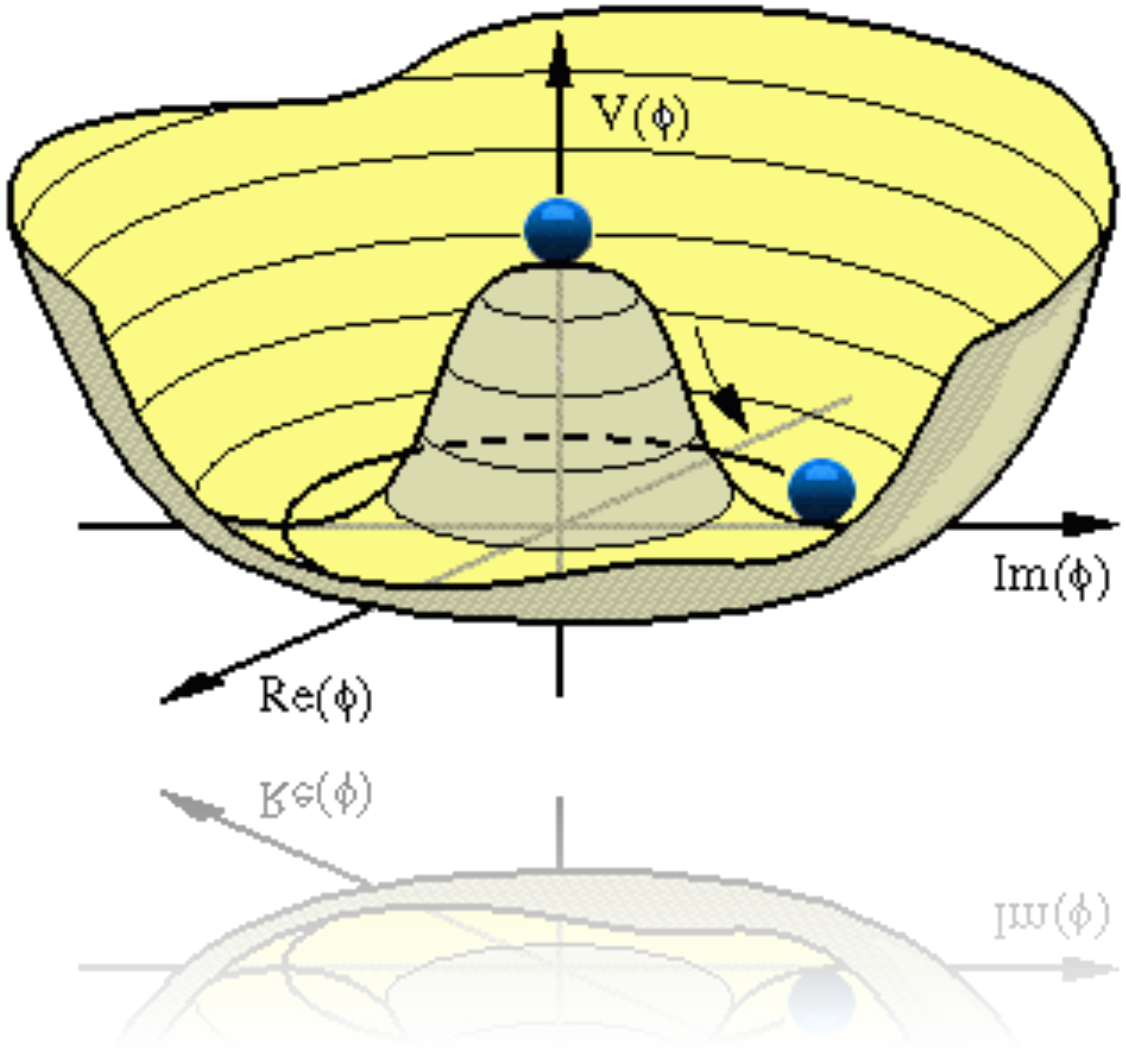
- $m_t = 174.30 \pm 0.35 \pm 0.54\ (CDF + D0)$
- $\rightarrow m_t = 173.34 \pm 0.36 \pm 0.67\ (CDF + D0 + LHC)$



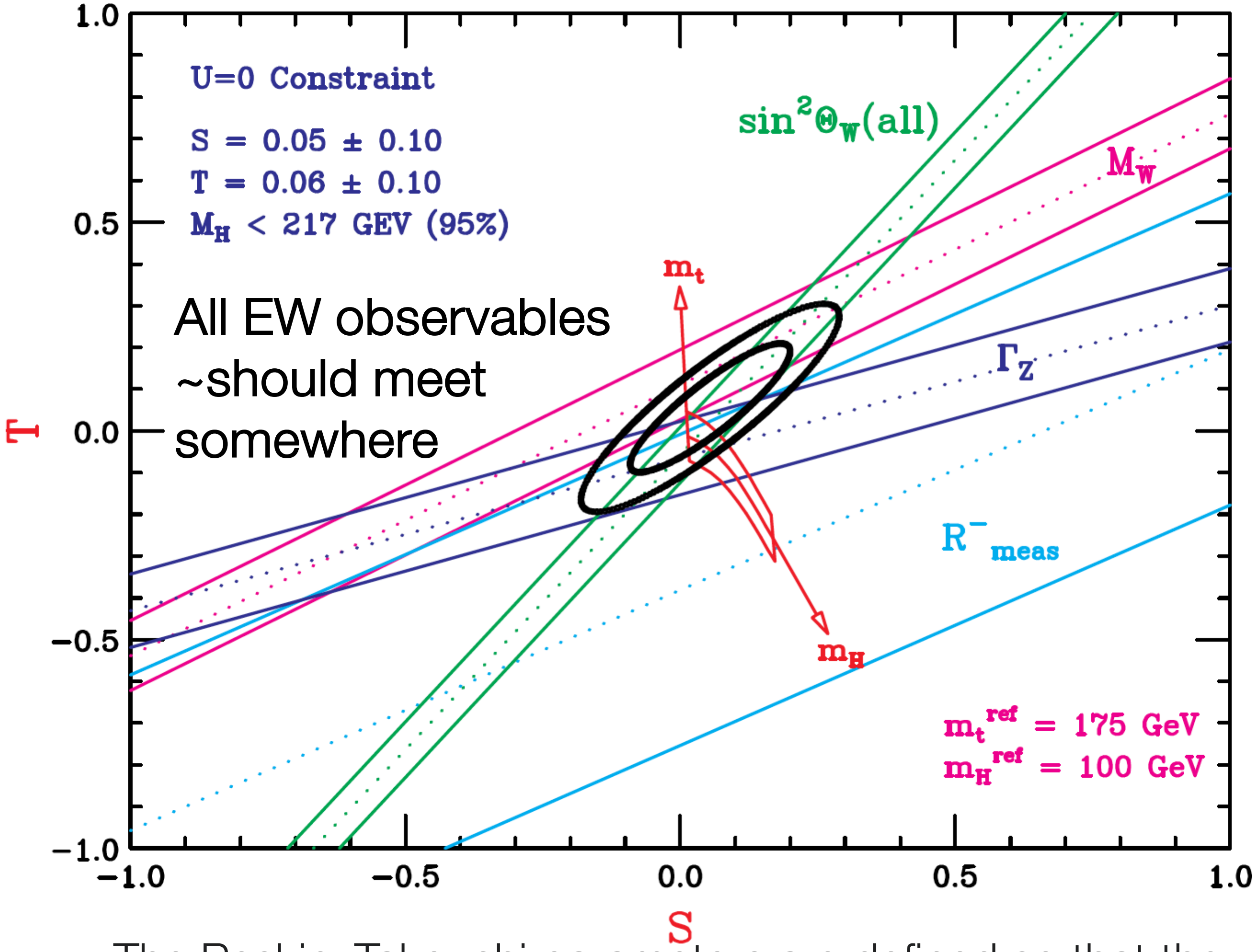
The σ_{tt} was measured from ~2 TeV to 13 TeV and found to be in agreement with SM predictions

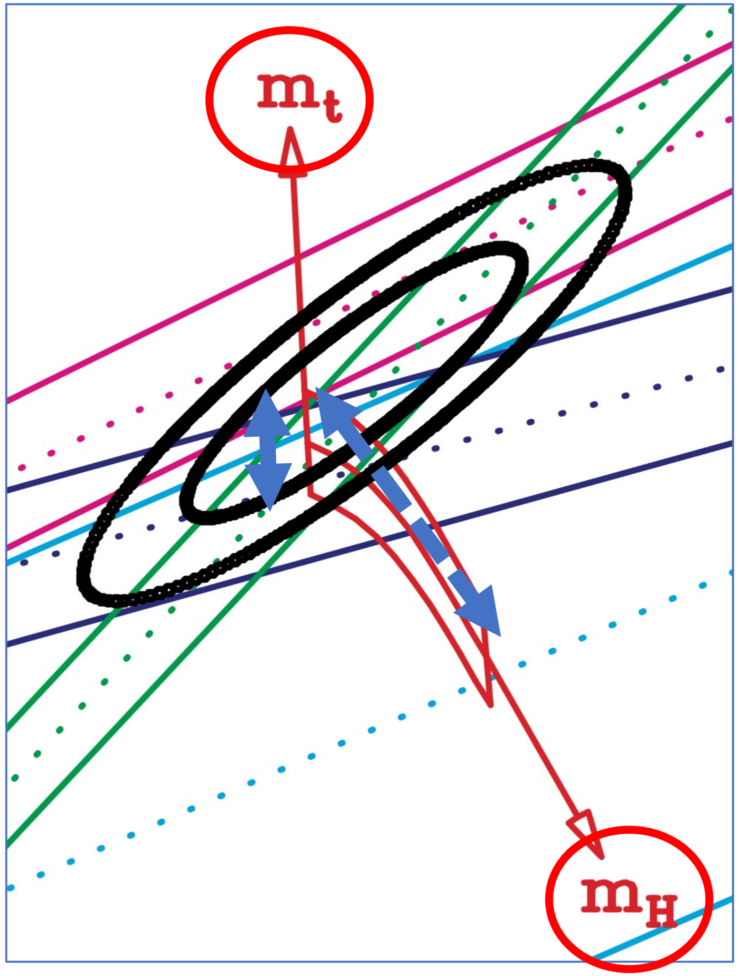
Higgs Searches at LEP

The Higgs, the (once!) missing piece of the Standard Model



ST Parameters

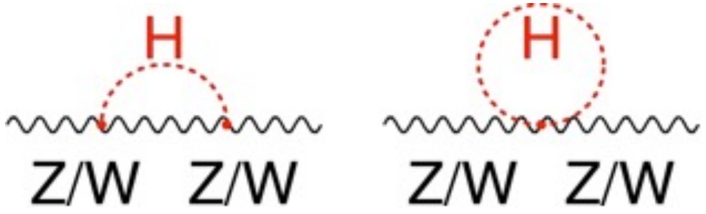




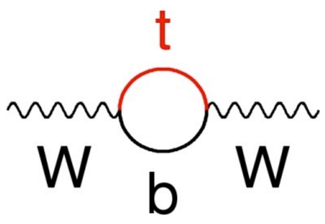
S, T, Peskin–Takeuchi parameterise potential new physics contributions to EW radiative corrections.

The Peskin–Takeuchi parameters are defined so that they are all *equal to zero for the Standard Model*. These parameters are then extracted from a global fit to the high-precision EW data from collider experiments (mostly the data from the CERN LEP collider) and atomic parity violation.

Indications from EW measurements



$\sim \log(m_H)$



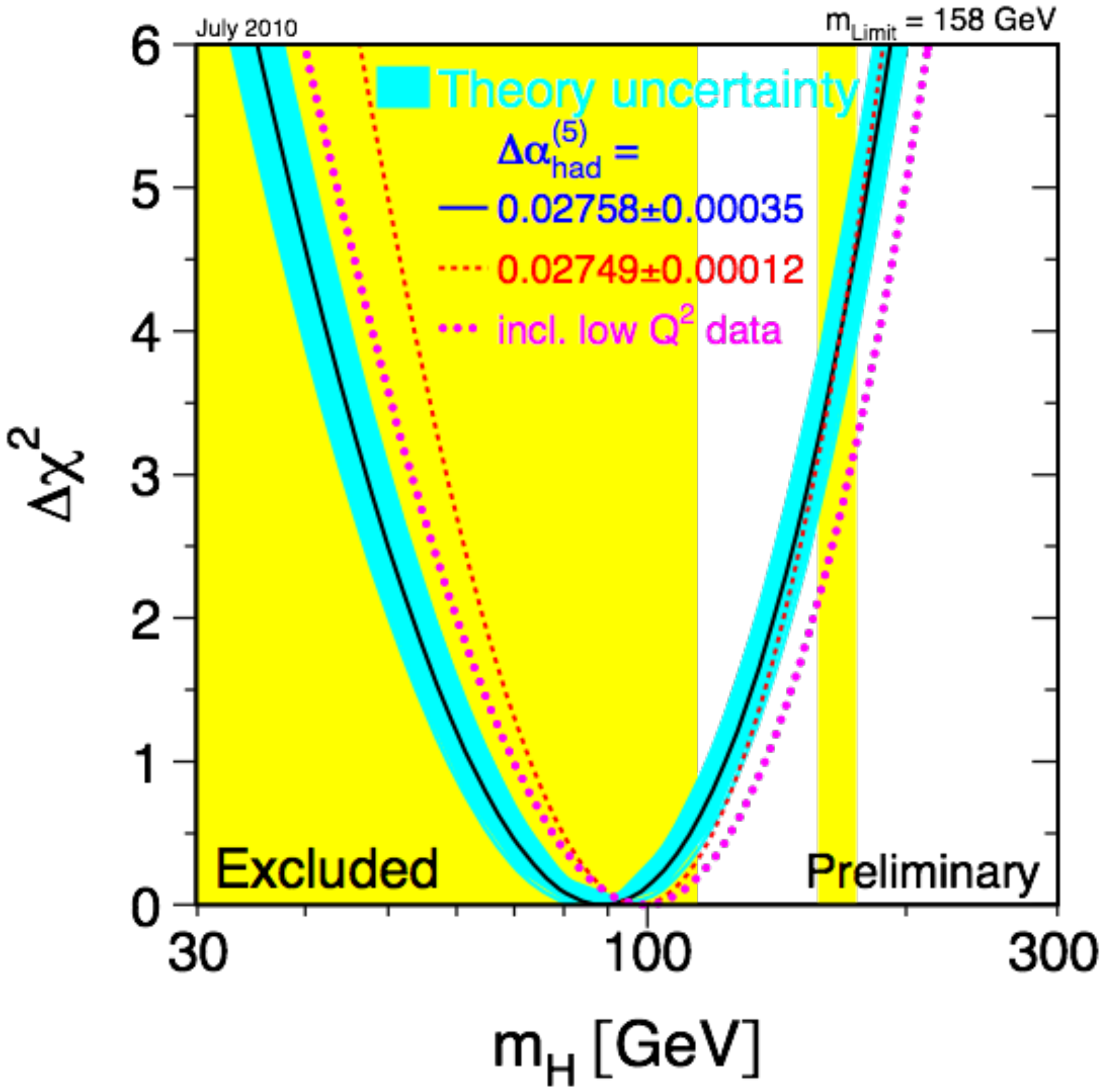
$\sim m_q^2$

EW-Fits:

M

M_H = 89 GeV

M_H < 158 GeV @ 95% CL



Where to Search for the Higgs Boson?

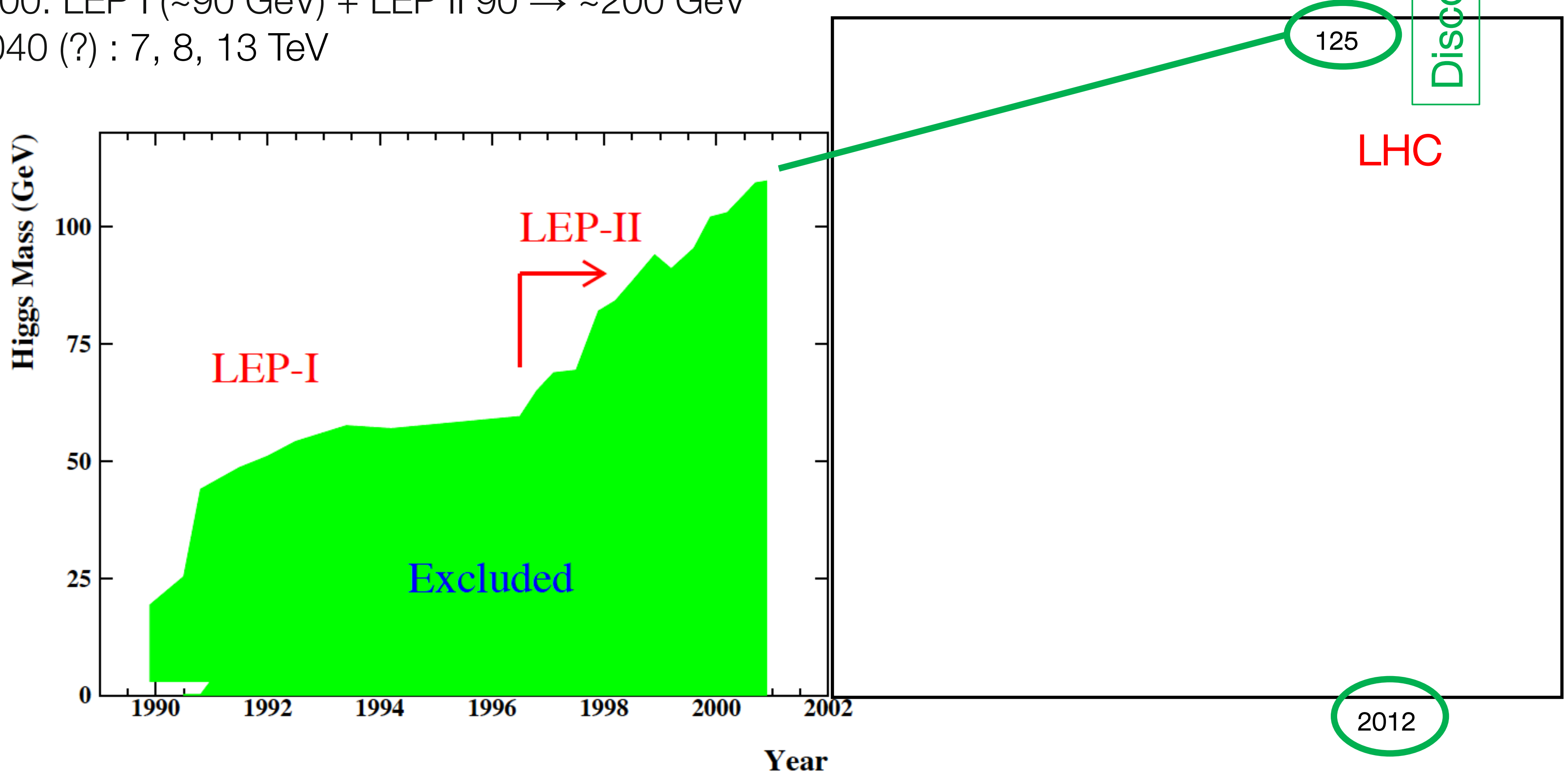
Higgs Mass not predicted by the SM.

$\sigma(E_{cms}, m_H)$: $\uparrow$ $if\, E_{cms}$ $\uparrow$

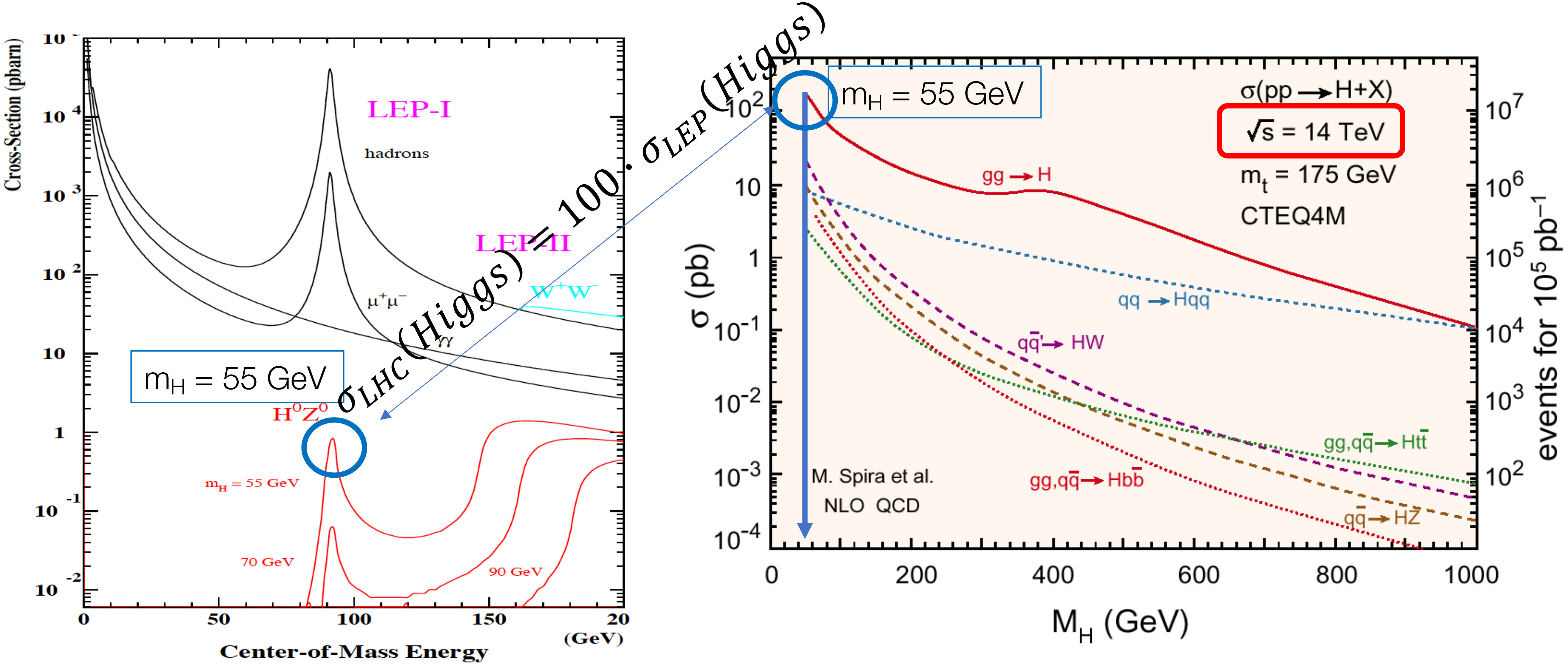
$\sigma(E_{cms}, m_H)$: $\downarrow$ $if\, m_H$ $\uparrow$

LEP 1990 → 2000: LEP I (~90 GeV) + LEP II 90 → ~200 GeV

LHC 2010 → 2040 (?) : 7, 8, 13 TeV



Where to Search for the Higgs Boson?



LEP, "Large Electron Positron" collider

LHC, "Large Hadron Collider"

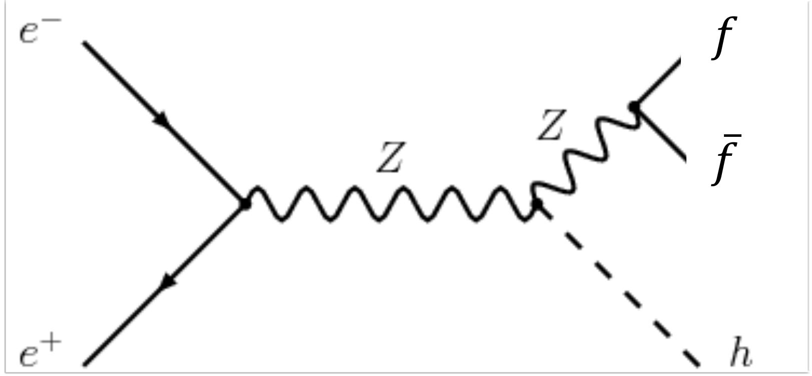
$$\sigma_{LHC}(Higgs) = 100 \cdot \sigma_{LEP}(Higgs)$$

Variable cms energy: 90 → 200 GeV

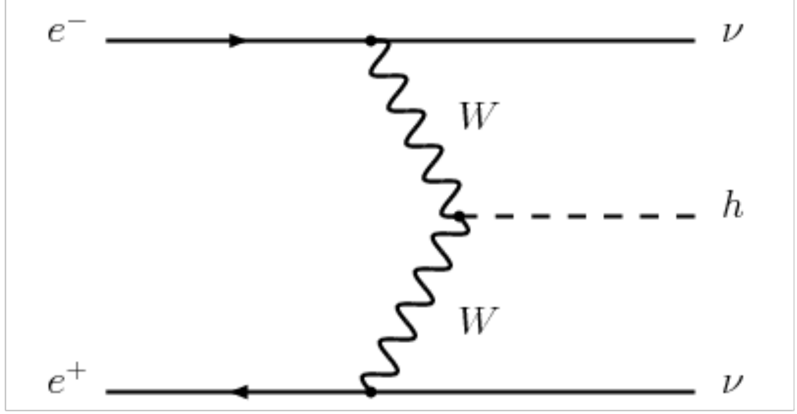
Higgs Production at LEP (e^+e^- Collider)

Production of Higgses at LEP:

- The *Higgsstrahlung* mechanism
- The *WW fusion* diagram (& ZZ fusion mechanism)



Higgsstrahlung



WW fusion

$\sigma_{Higgsstrahalung}$ $\gg\gg$ $\sigma_{WW\ fusion}$

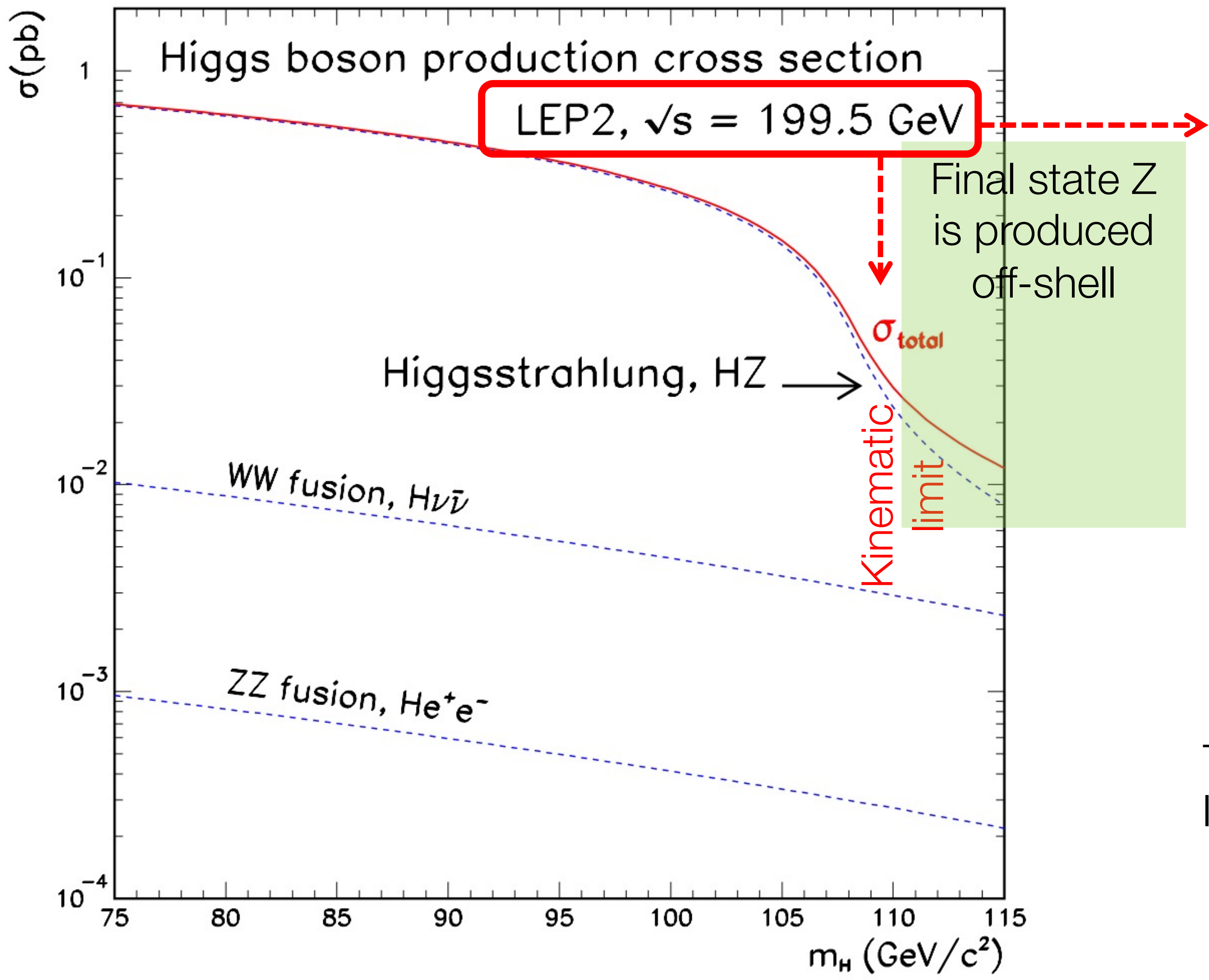
$\sigma_{Higgsstrahalung}$: kinematic limit: cms energy used to produce m_Z and $m_H \rightarrow m_H^{max} = \sqrt{s} - m_Z$ (…some margin by the tail of the Breit-Wigner distribution)

$\sigma_{WW\ fusion}$: can produce H up to $\sqrt{s}$ however small cross section limits drastically the statistics

Period	Energy (GeV)	Luminosity (pb^{-1})
1995	130/136	6.2
1996	161	12.1
1996	172	11.3
1997	183	63.8
1998	189	196.4
1999	192	30.

$m_H^{max} = 98\ GeV$

Higgs Production at LEP



Cross section

$$e^+e^- \to H + anything$$

@Cms energy of 199.5 GeV.

The *Higgsstrahlung* cross section drops rapidly when

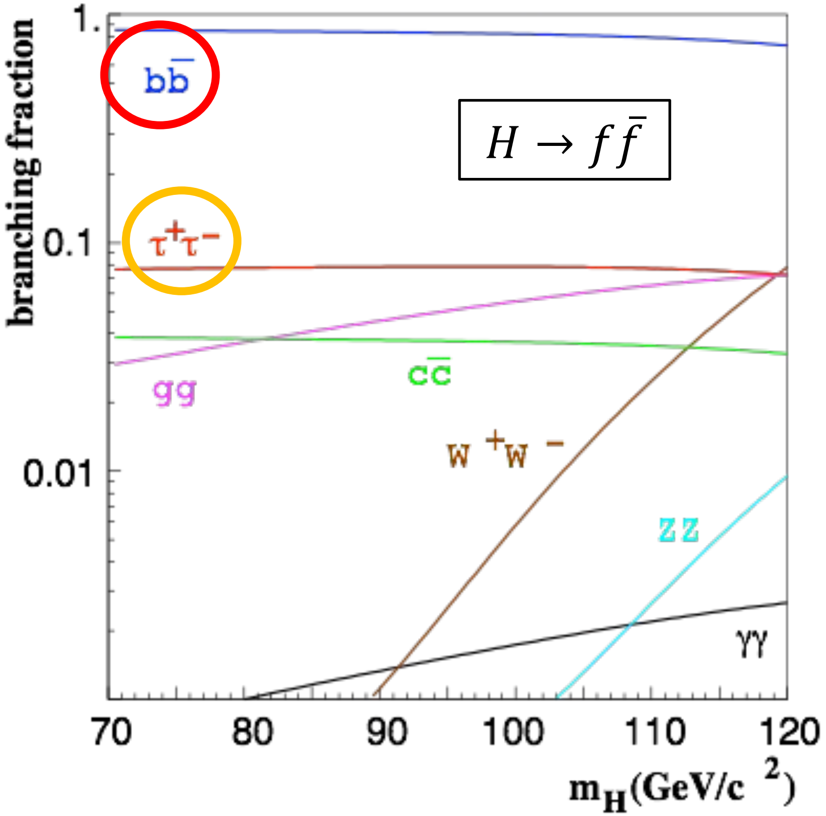
$$m_H = \sqrt{s} - m_Z$$

The two other mechanisms are not kinematically limited, but are statistically limited

Higgs Decay

The H couples to pairs of fermions with a strength proportional to the mass of the fermion itself

The H → decays to the heaviest kinematically accessible pair of $f\bar{f}$



Topologies		Rates	Backgrounds
$H \to b\bar{b}$ $Z \to q\bar{q}$	4-jets	51%	WW → qqqq ZZ → qqqq QCD 4-jets
$H \to b\bar{b}$ $Z \to \nu\bar{\nu}$	missing energy	15%	WW → qqlν ZZ → bbνν
$H \to b\bar{b}$ $Z \to \tau^+\tau^-$	τ-channel	2.4%	WW → qqτν ZZ → bbττ ZZ → qqττ QCD low mult. jets
$H \to \tau^+\tau^-$ $Z \to q\bar{q}$	τ-channel	5.1%	
$H \to b\bar{b}$ $Z \to e^+e^-$ $\mu^+\mu^-$	lepton channel	4.9%	ZZ → bbee ZZ → bbμμ

Analysis Strategy of the Higgs Search

The ~largest accessible Higgs mass at LEP was ~115 GeV @ LEP cms 200 GeV

Analysis strategy: compromise between
- of statistics and → (small) signal is hidden by a large background → almost invisible
- Need to reduce background → (even smaller) signal is ~insignificant over a ~reduced background

. The searches at LEP was driven by Z decay channels (since $H \to b\bar{b}$)

- the four-jet final state $(H \to b\bar{b})(Z \to q\bar{q})$ Including one very special case… $(H \to b\bar{b})(Z \to b\bar{b})$
- the missing energy final state $(H \to b\bar{b})(Z \to \nu\bar{\nu})$
- the leptonic final state $(H \to b\bar{b})(Z \to l^+l^-)$ where ℓ denotes an electron or a muon,
- and the tau lepton final states $(H \to b\bar{b})(Z \to \tau^+\tau^-)$ and $(H \to \tau^+\tau^-)(Z \to q\bar{q})$

Two approaches:
- Selection cuts based on kinematical variables and topologies
- MVA analysis → use global variables & neural networks → one indicator per each event to distinguish signal and background (more efficient)

Looking for an Higgs Boson: how?

Excess of events at an unknown Mass !

Analysis Strategy for one final state topology:

Choose a mass & optimise selection as much signal (S) and as little background (B) as possible. *Use MC*

Count selected events in data → $N_{selected}$
Calculate background events (simulation) $N_{background}$

$$\frac{N_{selected} - N_{background}}{\sqrt{N_{background}}}$$

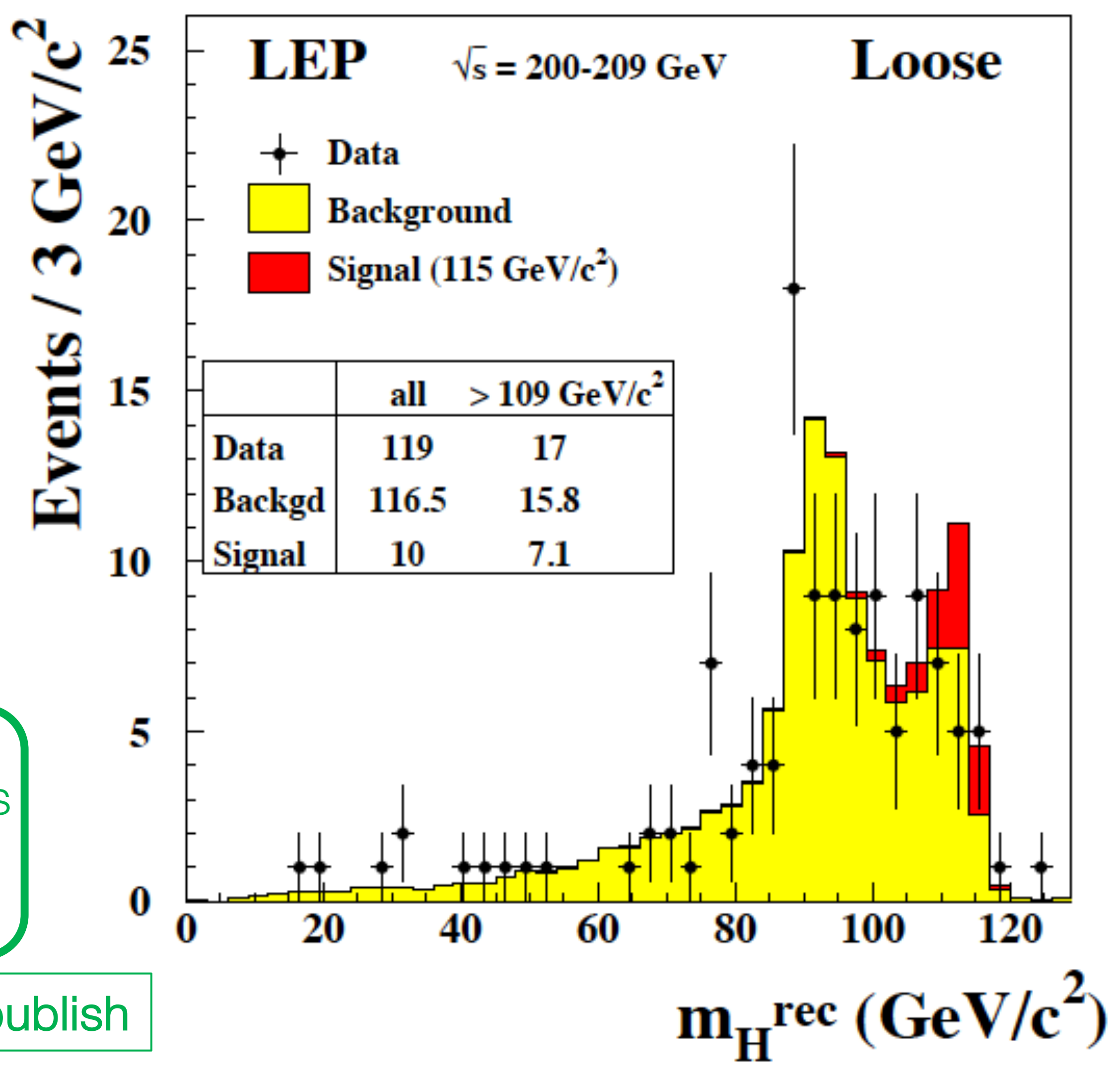
< 3?
Another mass

between 3 and 5?

Do more analysis and collect more statistics

≥ 5 ?
Significant excess
Discovery

Do a seminar & publish



	all	> 109 GeV/c²
Data	119	17
Backgd	116.5	15.8
Signal	10	7.1

Combining Different Channels

Higgs search at LEP = small signal + large background → two ways to increase statistics:

- Combine different experiments → 4 experiments → statistical significance of signal increases by $\sqrt{4} = 2$
- Combine different channels of the same experiment (= one final-state and one centre-of-mass energy)

Characterise each event with:

- m_h^{rec} the reconstructed Higgs boson mass, and a
- *G*(many event variables): **how "Higgs-like" is the sample:**
  - G < 0 or G << 0 → likely it is Higgs (one choice, it could be the opposite, G>0)
  - G > 0 or G >> 0 → likely it is background (one choice, it could be the opposite, G<0)

The ***distribution of data*** in the plane (m_h^{rec},G) is interpreted

In two hypothetical scenarios:

- The distribution contains background only $\mathcal{L}_b$
- The distribution contains signal plus background $\mathcal{L}_{s+b}$

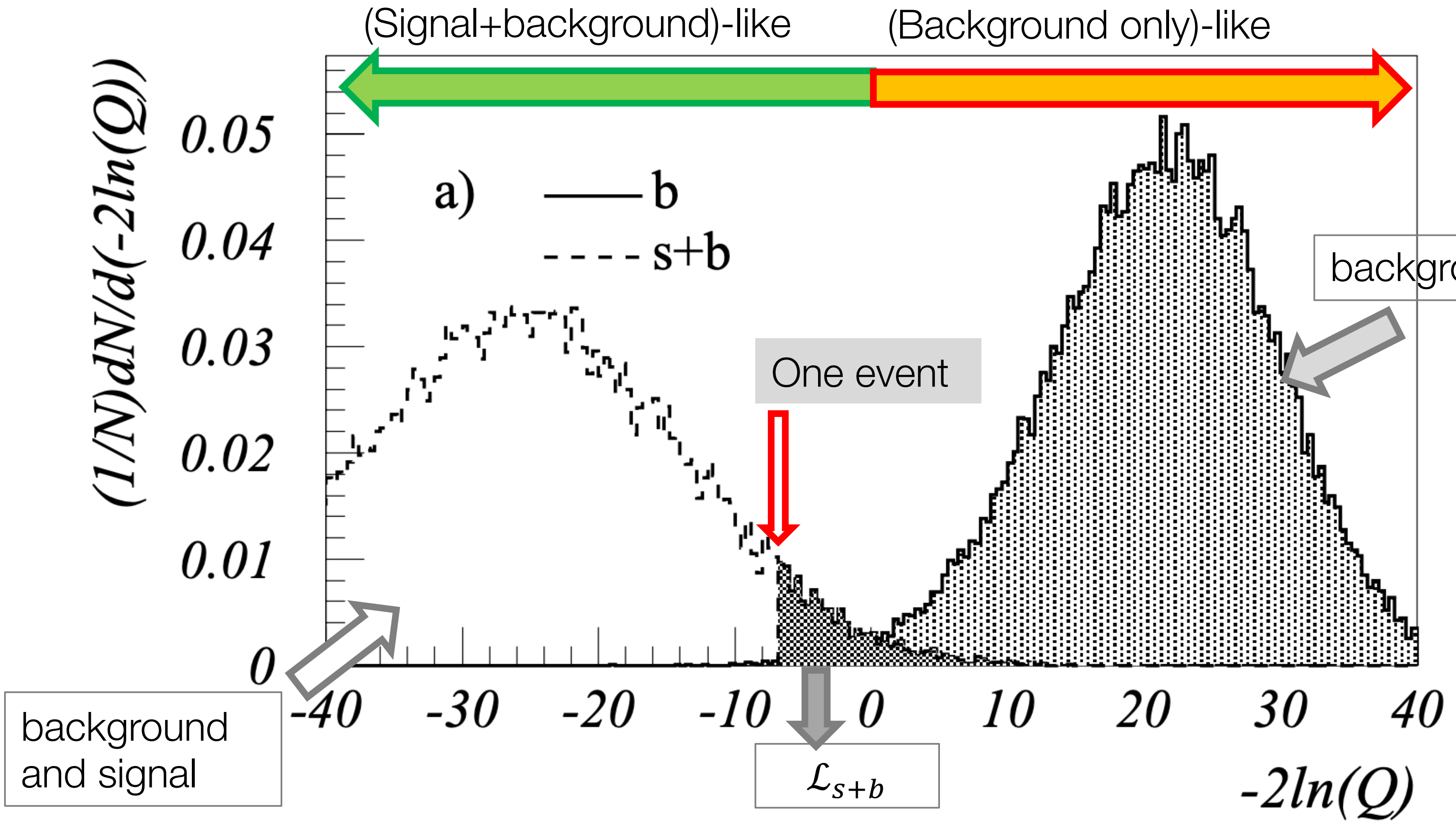
In a search experiment one very good indicator is the likelihood ratio

$$Q = \mathcal{L}_{s+b} / \mathcal{L}_b \quad (use \ -2\ln(Q))$$

Statistical Analysis

One cannot tell on an event-by-event basis whether one event is signal or background → statistical analysis.

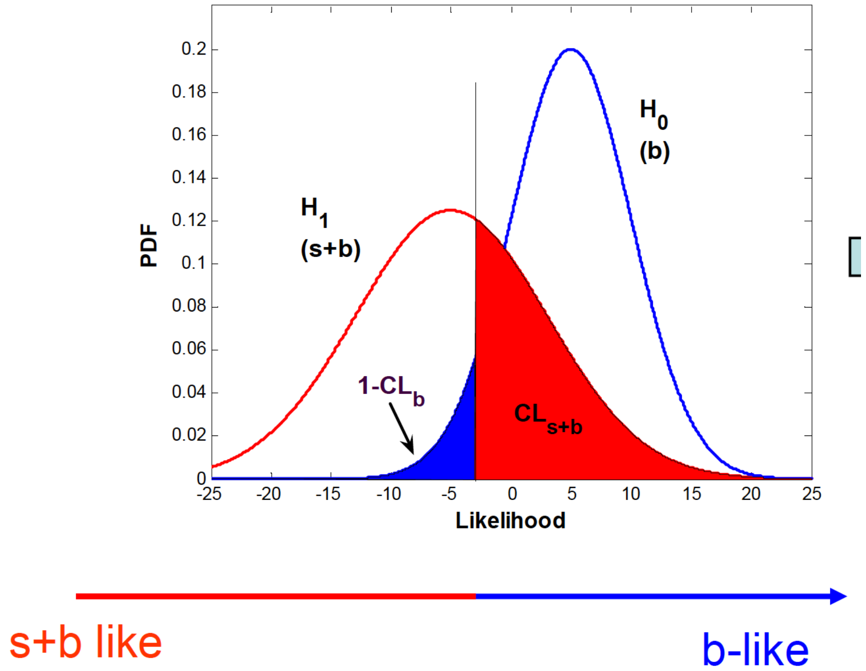
$$Q = \mathcal{L}_{s+b} / \mathcal{L}_b$$

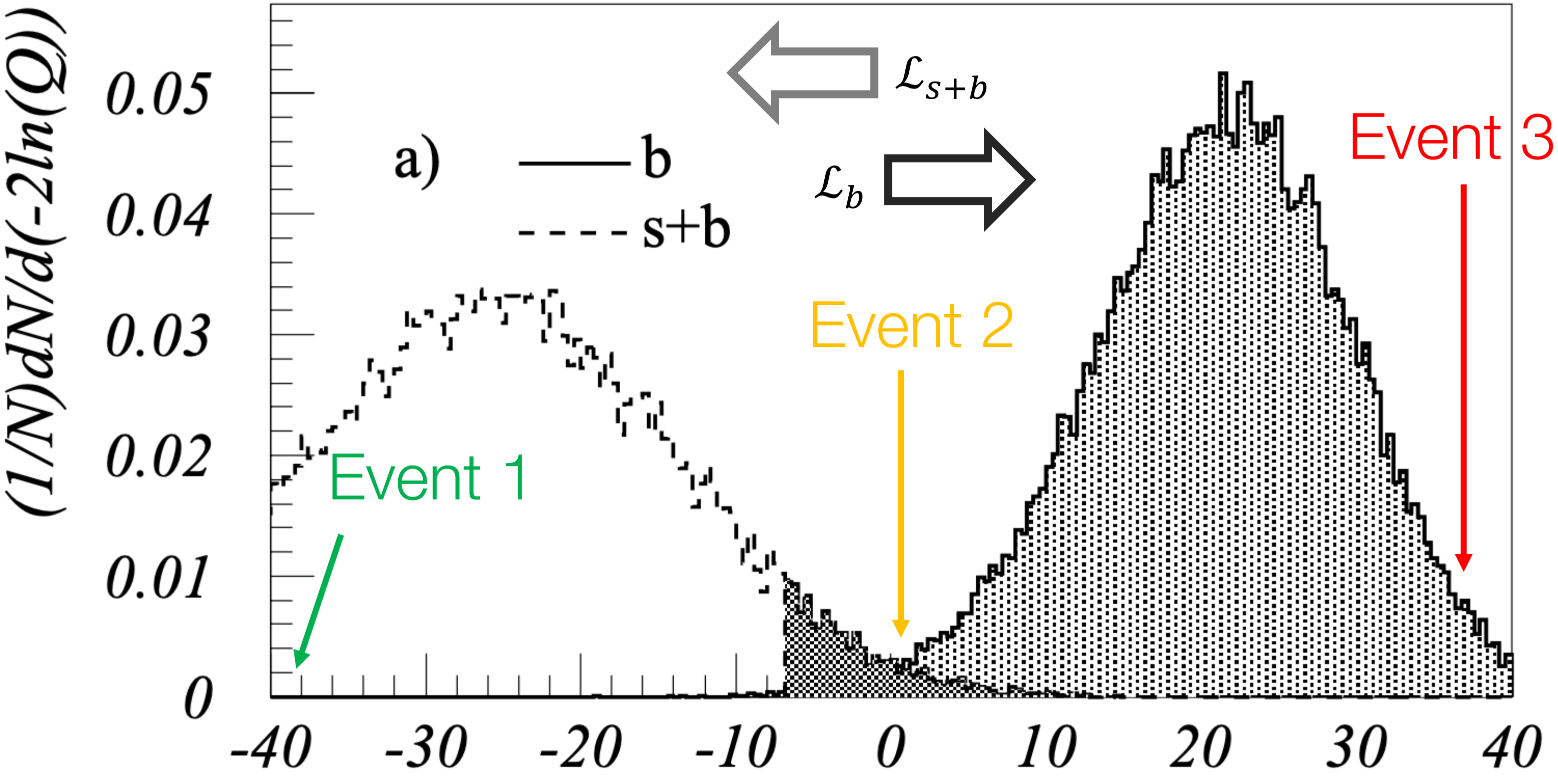


For each event compute

- $\mathcal{L}_b$ is the fraction of the *b* distribution "less background like" than *Q*
- $\mathcal{L}_{s+b}$ is the fraction of the *s+b* distribution "more signal + background like" than *Q*

Statistical Analysis



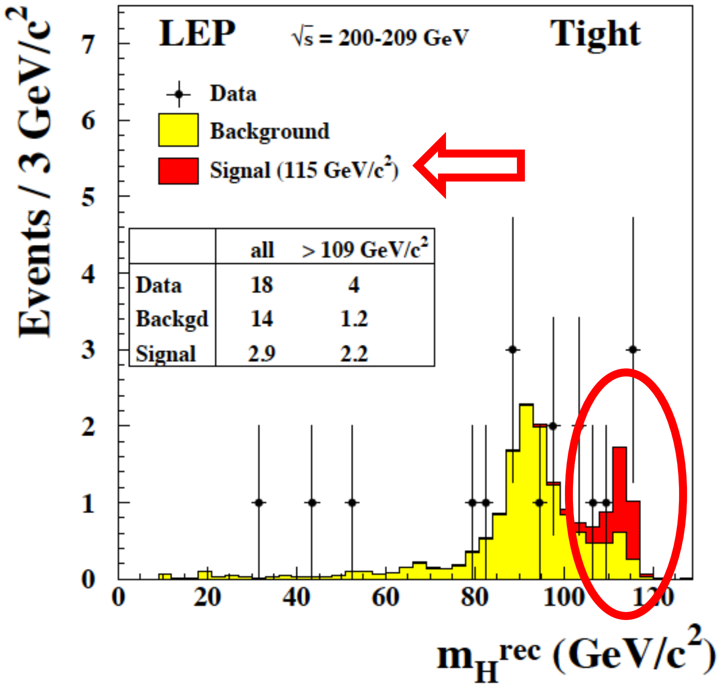


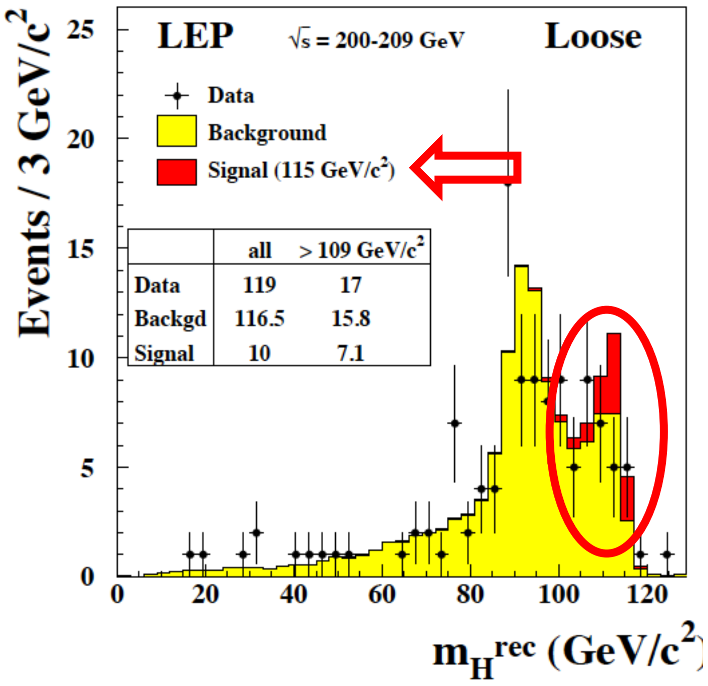
$$\mathcal{L}_b = \int_{-\infty}^{measurement} background(x)\, dx$$

$$\mathcal{L}_{s+b} = \int_{measurement}^{+\infty} [background(x) + signal(x)]\, dx$$

Event	1	2	3
$\mathcal{L}_b$	Very small	Small	large
$\mathcal{L}_{s+b}$	Large	Small	Very small
$\mathcal{L}_{s+b}/\mathcal{L}_b$	Very large	~ 1	Very small

The Result: m_h^{rec} of Different Experiments





Loose

	Experiment	E_{cm}(GeV)	Final state topology	$m_{\mathrm{H}}^{\mathrm{rec}}$ (GeV/c^2)	$\ln(1+s/b)$ at 115 GeV/c^2
1	ALEPH	206.6	Four-jet	114.1	1.76
2	ALEPH	206.6	Four-jet	114.4	1.44
3	ALEPH	206.4	Four-jet	109.9	0.59
4	L3	206.4	Missing energy	115.0	0.53
5	ALEPH	205.1	Leptonic	117.3	0.49
6	ALEPH	208.0	Tau	115.2	0.45
7	OPAL	206.4	Four-jet	111.2	0.43
8	ALEPH	206.4	Four-jet	114.4	0.41
9	L3	206.4	Four-jet	108.3	0.30
10	DELPHI	206.6	Four-jet	110.7	0.28
11	ALEPH	207.4	Four-jet	102.8	0.27
12	DELPHI	206.6	Four-jet	97.4	0.23
13	OPAL	201.5	Missing energy	108.2	0.22
14	L3	206.4	Missing energy	110.1	0.21
15	ALEPH	206.5	Four-jet	114.2	0.19
16	DELPHI	206.6	Four-jet	108.2	0.19
17	L3	206.6	Four-jet	109.6	0.18

Distributions m_{H}^{rec} for two different signal purities.

Monte Carlo predictions:

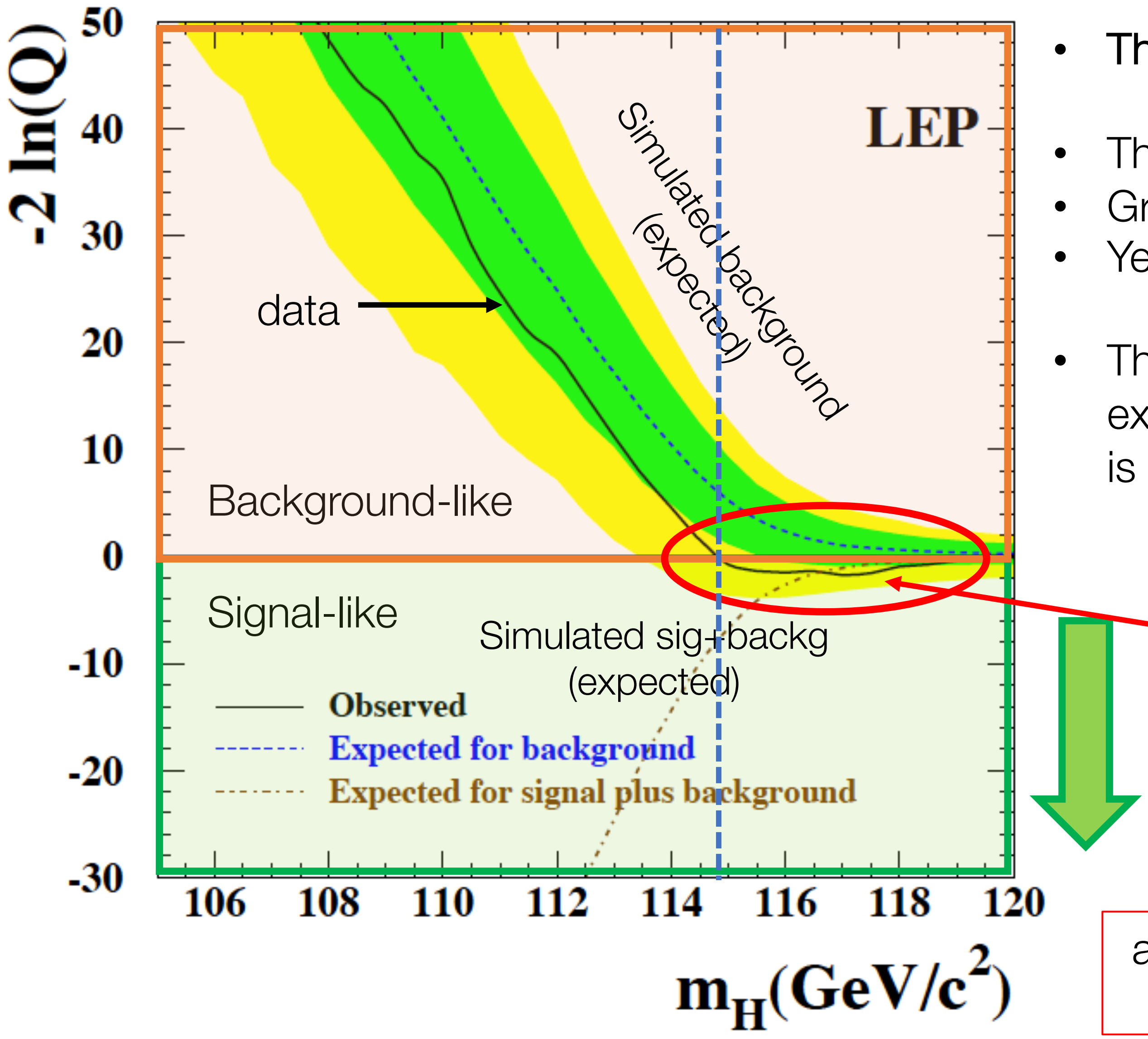
- yellow for the background
- red for an Higgs boson of mass 115 GeV.

The points with error bars show the data.

LEP final result:

- 17 candidate events
- 15.8 background events expected
- 7.1 expected signal events for m_h = 115 GeV

The Upper Limit of m_h^{rec}



- The solid curve represents the observation
- The dashed curve background expectation;
- Green band 68% probability around <background>
- Yellow band 95% probability around <background>
- The dash-dotted curve signal plus background expectation (when the signal mass given on the abscissa is tested).

Broad region of data just below 0 → no significant signal detected

Very negative values of -2ln(Q) would indicate the very likely presence of a signal

a lower bound of 114.4 GeV/c^2 is set on the mass of the SM Higgs boson at the 95% confidence level.

Discoveries

End of Discoveries

Particle Physics
Toni Baroncelli
Haiping Peng
USTC

The Combination Mechanism (ADLO)

For each given channel and bin in the (m_h^{rec},G) plane, the experiments give

- the number of selected data events,
- the number of expected background events, and
- the number of expected signal events for a set of hypothetical Higgs boson masses.

The expected signal and background estimates make use of detailed Monte Carlo simulations by the four experiments: all known experimental features, the centre-of-mass energies, integrated luminosities of the data samples, cross-sections and decay branching ratios for the signal and background processes, selection efficiencies and experimental resolutions with possible non-Gaussian contributions.