

High Energy Physics

Lecture 6

Part 1:

More on the Passage of Particles through Matter

Part 2:

The UA1 Experiment — Discovery of W&Z

Primary and Secondary Ionization

- An electron ejected from an atom by a passing particle can itself cause ionization and hence produce a track called δ ray
- The number of δ rays per centimeter of path of a relativistic particle of charge ze is roughly proportional to z^2 (this is useful for particle identification in bubble chambers and in emulsions).
- The ionization caused by the passing particle is the **primary ionization**; the ionization caused by δ rays is **secondary ionization**.
- The amount of secondary ionization depends on the material; it can be up to 10 times the amount of primary ionization.
- **Empirical Rule**: the total number of ion pairs (primary + secondary) is independent of z and m and proportional to the energy loss; if the particle is stopped, then the number of ion pairs is proportional to the initial K.E.: **basis for energy measurement in calorimeters**.

Passage of electrons through matter

- 1.) The mass of the travelling particle is equal to the target mass. As a result large deflections are frequent. This leads to a large loss of intensity of a beam of electrons.
- 2.) Electrons are relativistic even at modest K.E.s ($\geq 50 \text{ keV}$)
- 3.) Because of the small mass of the electron, there is a large radiative energy loss. The radiative energy loss is dominant for K.E. above a few MeV.

$$-\frac{dE}{dx} = \left(-\frac{dE}{dx} \right)_{ion} + \left(-\frac{dE}{dx} \right)_{rad}$$

The energy loss by ionization is described by a formula similar to the Bethe-Bloch formula:

$$\left(-\frac{dT}{dx} \right)_{\text{ion}} = 4\pi (\alpha \hbar c)^2 \frac{N_A}{m_e A} \frac{z^2}{v^2} B$$

but now the stopping number B is different:

$$B = 2 \ln \frac{T}{I} + \ln \frac{\gamma + 1}{2} + f^\pm(\gamma)$$

$$T = \sqrt{(pc)^2 + (m_e c^2)^2} - m_e c^2; \quad \gamma = 1/\sqrt{1 - v^2/c^2}$$

$$|f^+(\gamma)| \leq 1 \quad (\text{for positron}) \quad |f^-(\gamma)| \leq 0.2 \quad (\text{for electron})$$

$$(-dT/dx) \propto 1/v^2$$

Radiative Energy Loss

When a charged particle is deflected from its path, then it is accelerated.

The acceleration of a particle of charge ze in the Coulomb field of a nucleus of charge Ze is proportional to zZe^2/m_e (assuming the nucleus mass is infinite).

By classical electrodynamics an accelerated charge emits e.m. radiation of an intensity that is proportional to the square of the acceleration, hence:

$$\frac{\text{Rad}^n \text{ intensity of proton}}{\text{Rad}^n \text{ intensity of electron}} = \left(\frac{m_e}{m_p} \right)^2 \sim 10^{-6}$$

The energy spectrum of the emitted photons is continuous and goes up to the K.E. of the electron.

The average rate of radiative energy loss is

$$\left(-\frac{dE}{dx} \right)_{rad} = N E \Phi_{rad}(Z, E)$$

where $N = N_A \rho / A$

is the number of electrons per cubic cm of the absorber, and

Φ_{rad} is the cross section for radiative interactions.

For $v/c \ll 1$: $\Phi_{rad} \propto Z^2$, *small*

For $v/c \sim 1$: $\Phi_{rad} \propto Z^2 \ln \frac{2E}{mc^2}$ (where $E = KE + mc^2$)

At very high energies $\Phi \sim \text{const.}$

therefore

$$\left(-\frac{dE}{dx} \right)_{rad} \propto E \quad \text{hence } E \approx E_0 \exp(-x/x_r)$$

i.e. after a distance of x_r the electron has lost $(1-1/e)$ or 0.63% of its initial energy.

The distance x_r is called **radiation length**.

Empirical rule:

$$\left(-\frac{dE}{dx} \right)_{rad} / \left(-\frac{dE}{dx} \right)_{ion} \approx \frac{EZ}{1600 mc^2}$$

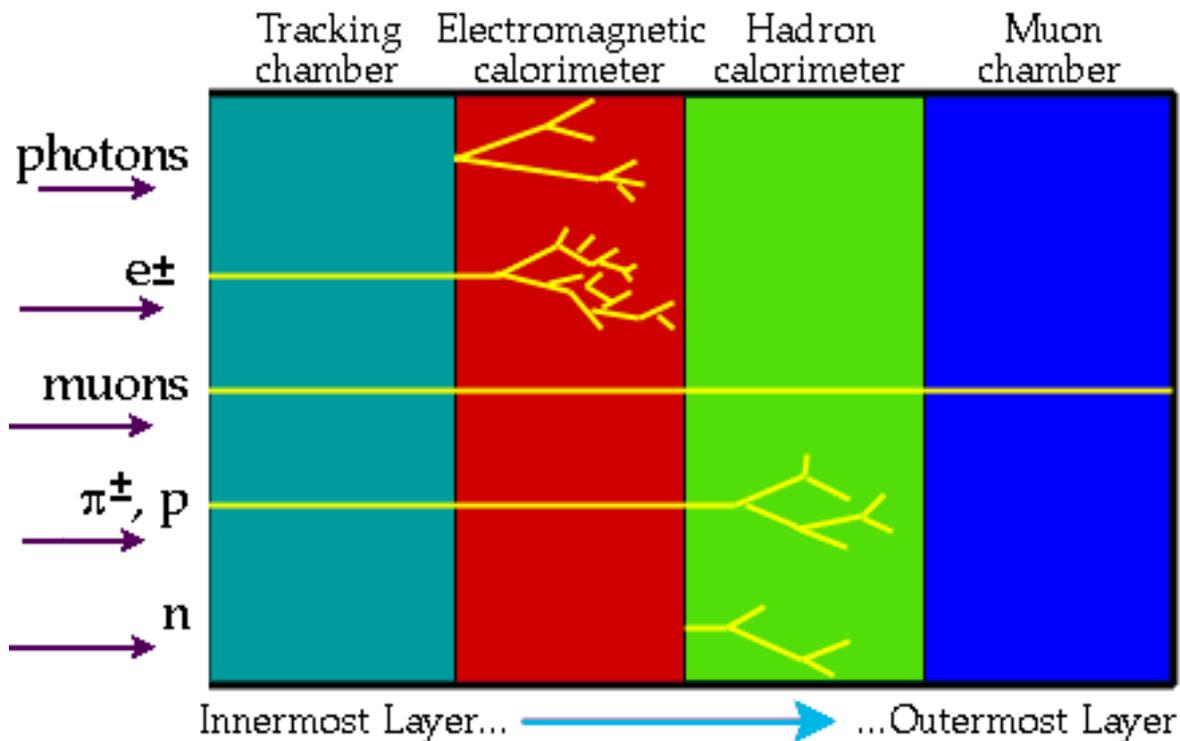
Critical Energy:

$$\frac{(-dE/dx)_{rad}}{(-dE/dx)_{ion}} = 1 \quad \text{for } E = E_{crit}$$

$$E_{crit} \propto mc^2 / Z$$

Substance	x_r g/cm ²	E_{crit} MeV
H ₂ (liq.)	63	400
C	44	100
Air	37	85
Pb	6.5	8

Schematic of energy loss of particles in detector components.



Only charged particles leave tracks in the tracking chamber.
Electrons and photons form showers in the e.m. calorimeter.
Charged hadrons leave tracks in the tracking chambers and in the e.m. calorimeter and produce showers in the hadronic calorimeter.
Only muons are not contained in the detectors, leaving tracks in all chambers.

The UA1 Experiment

*UA1: the Detector that Discovered the W
and Z Intermediate Vector Bosons*

The UA1 detector was built to discover the **W** and **Z** Intermediate Vector Bosons. There was indirect evidence that they do exist. The mass of the **W** boson was predicted to be about 80 GeV (*that is a mass greater than the mass of a copper atom*).

The Standard Model also predicted that the **W** boson could be produced in collisions of *u* quarks with anti-*d* quarks (or of *d* quarks with anti-*u* quarks):

$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ \nu \quad \text{or} \quad \bar{u} + d \rightarrow W^- \rightarrow e^- \bar{\nu}$$

The problem is that there are no free quarks: you can collide only *hadrons* to observe interactions between quarks. But in a hadron the quarks have only a fraction -- about 10 to 15% -- of the hadron momentum. So to have 80 GeV in the quark-antiquark centre-of-mass system you *must collide hadrons with a C.M. energy of about 500 GeV*.

You must collide hadrons containing quarks with hadrons containing antiquarks. Now, protons do contain quarks; there is also a “sea” of quark-antiquark pairs, but these have very low momenta, too low to produce W bosons.

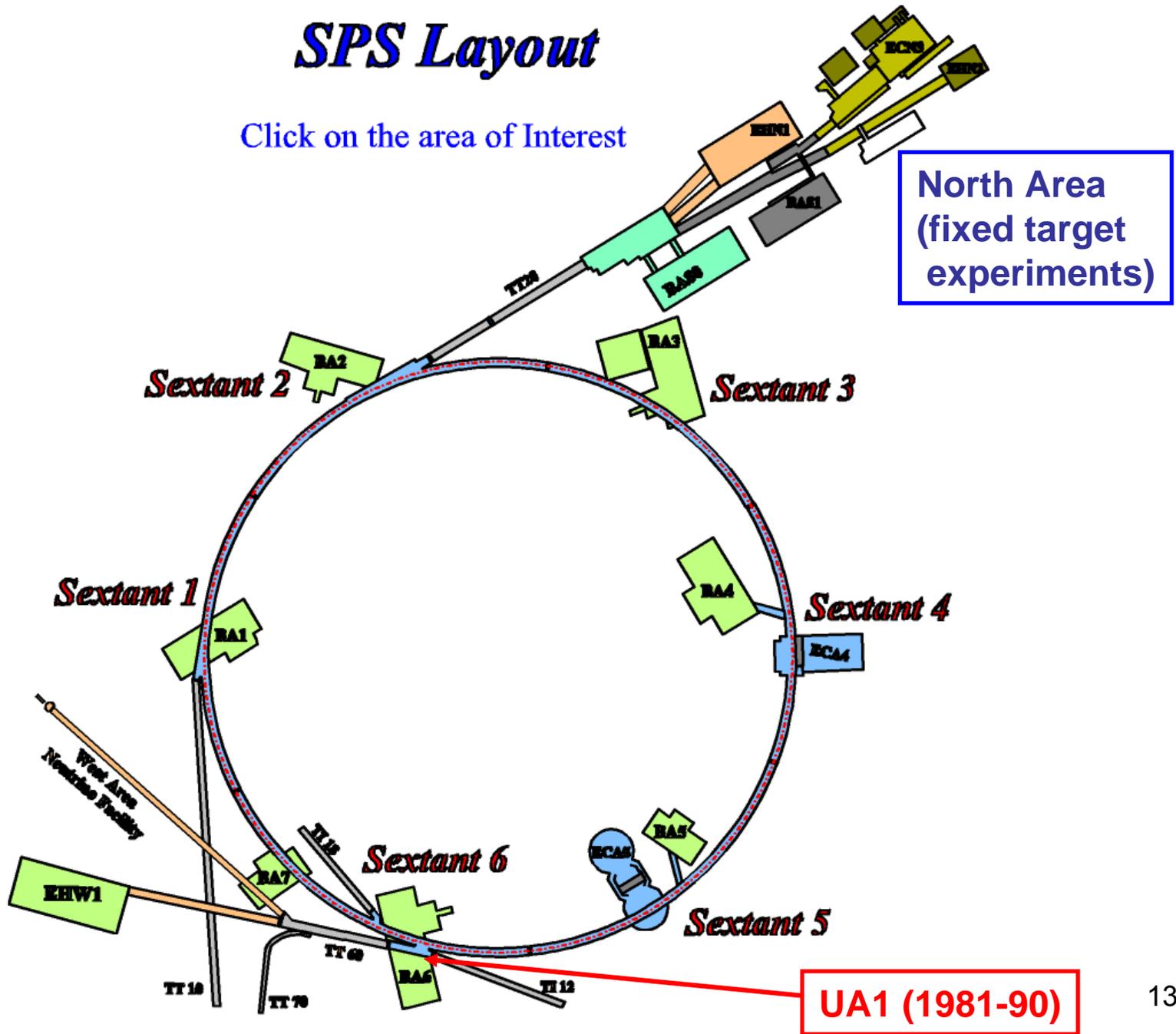
The solution of the problem was to make beams of antiprotons and collide the protons with the antiprotons.

There are of course no antiprotons in any ordinary matter. So the first step in producing W bosons is to produce antiproton beams of sufficient intensity and get them to collide with proton beams. This was achieved at CERN by a team led by **Simon van der Meer**.

The second problem was to design and build a detector capable of observing the reactions characteristic of W production. This was achieved by a team of physicists led by **Carlo Rubbia** who built the **UA1** detector.

SPS Layout

Click on the area of Interest

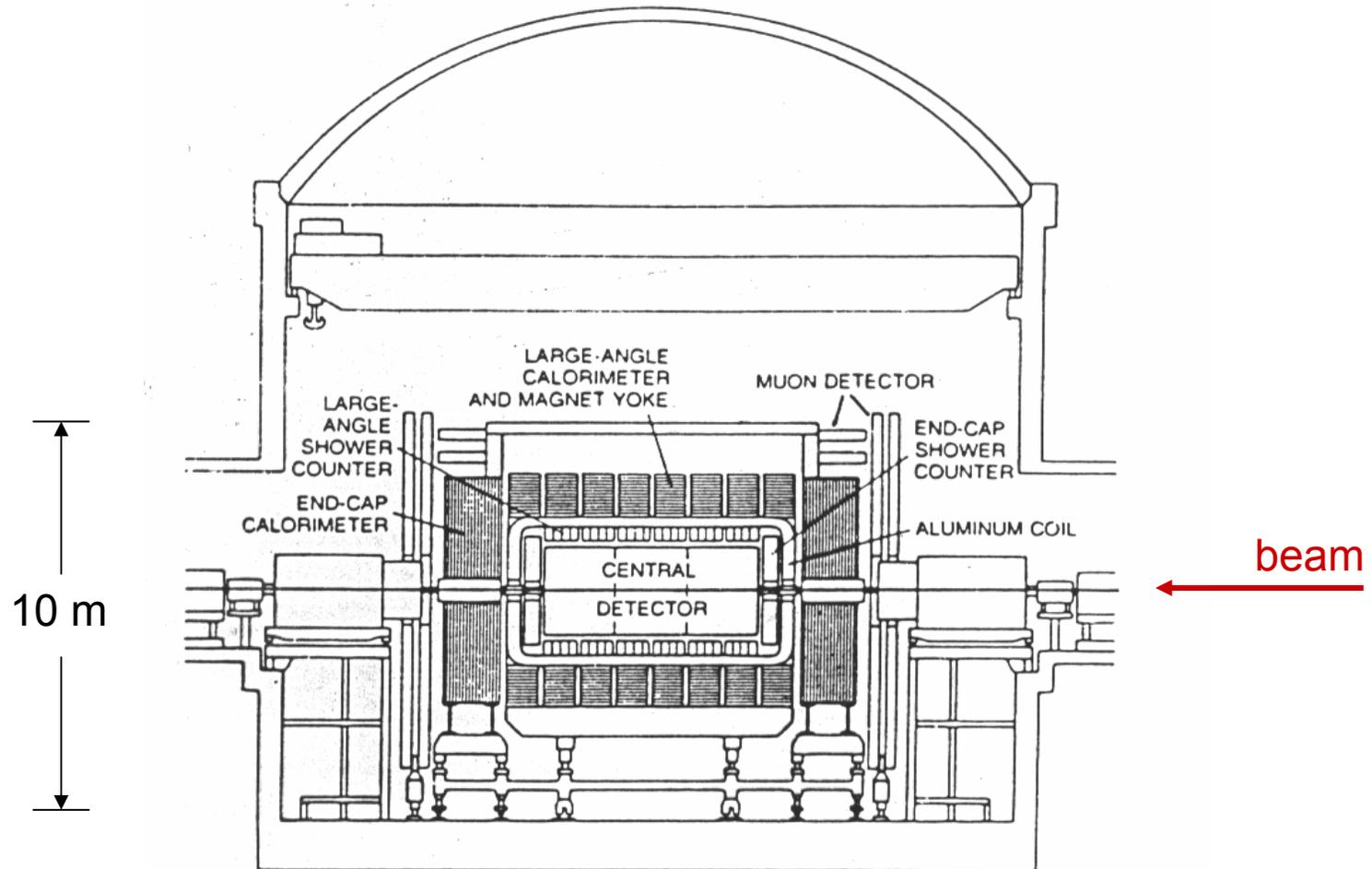


The UA1 Detector

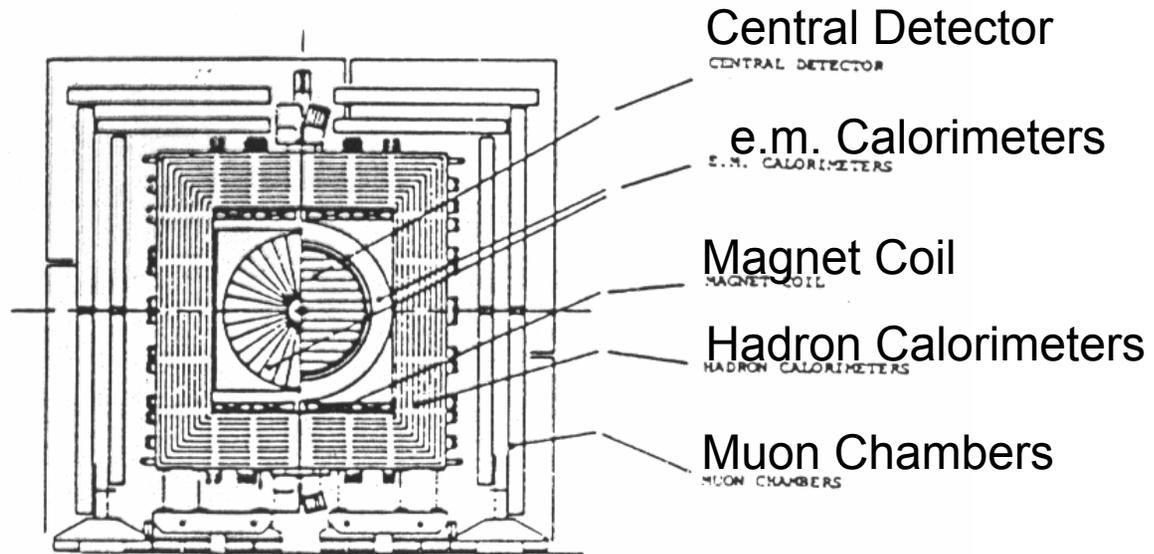
- The UA1 detector is a transverse dipole magnet which produces a uniform field of 0.7 T over a volume of $7 \times 3.5 \times 3.5 \text{ m}^3$.
- At the centre of the detector is a cylindrical drift chamber (CD) of length 5.8 m and diameter 2.3 m, which yields a bubble-chamber quality picture of each *pp* interaction in addition to measuring the momenta and specific ionizations of all charged tracks.
- The central section of the electromagnetic and hadronic calorimeters has been used to identify electrons over a pseudorapidity interval $|\eta| < 3$ with full azimuthal coverage.

Note: **pseudorapidity** is defined by $\eta = -\ln(\tan \theta/2)$

Central elevation of the UA1 detector.



Cross Section through the UA1 Detector



XBL 832-8020

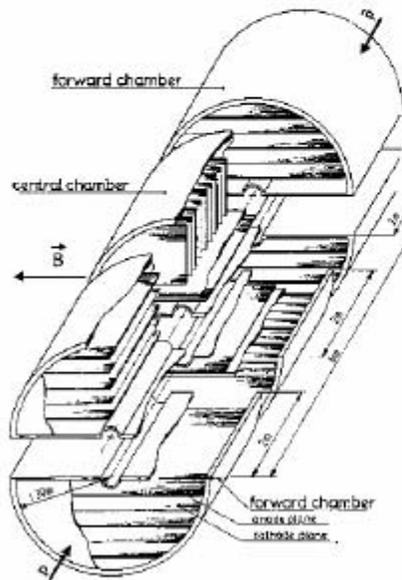
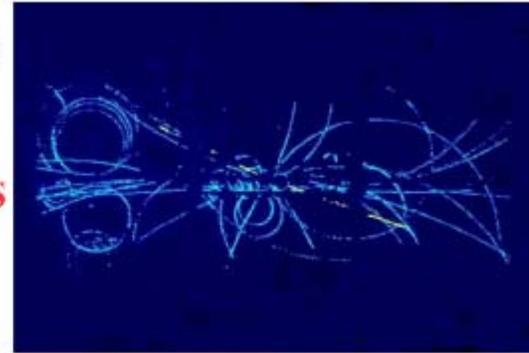
The proton-antiproton collider

Fast decisions, fast realization

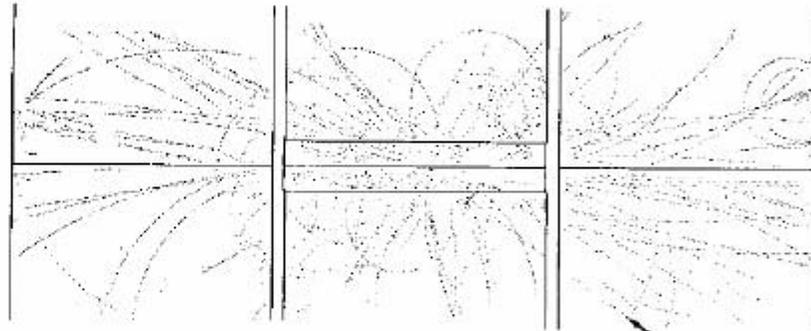
A great machine with great detectors

Hermeticity, redundancy, innovative techniques

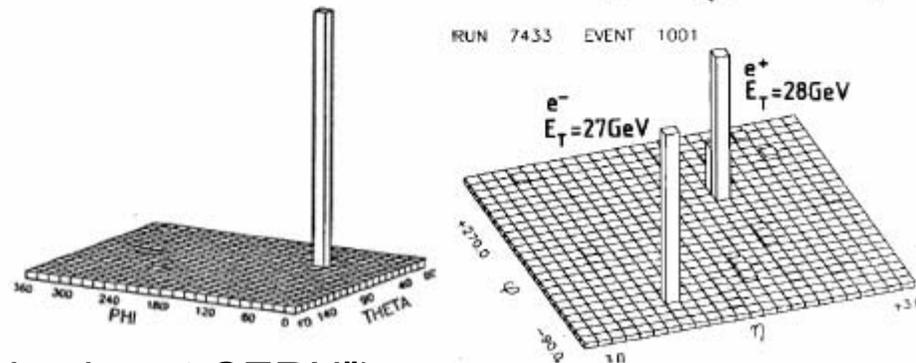
La physique au rendez-vous



EVENT 2958. 1278.



RUN 7433 EVENT 1001



(From D. Treille, "50 years of physics at CERN")

Computer reconstruction of tracks in the UA1 Central Drift Chamber:



The calorimeters were highly segmented in azimuth ϕ and in polar angle θ . Instead of the polar angle one prefers to use the pseudo-rapidity $\eta = -\ln(\tan(\theta/2))$.

The energies deposited in the calorimeter cells are displayed event by event in the (η, ϕ) plane. In some events one observes a spectacular concentration of energy in just a single cell: the signal of a charged particle of very high energy if it is matched to a high-energy track in the CD. The transverse momentum of such an event may be unbalanced. The imbalance of the transverse momentum is precisely measured. If it is approximately “back-to-back” with the high-energy calorimeter signal, then it can be interpreted as a neutrino, and that makes it a candidate W boson event.

If two high-energy electrons are seen which travel approximately “back-to-back”, then this is a candidate Z boson event.

In the **SppS** the protons and antiprotons were travelling in 4 bunches about 50 cm long. They were made to cross at the centres of the detectors **UA1** and **UA2**. The intensity was such that there was usually one ***p-anti p*** collision per crossing.

In a 30 day data taking run about 10^9 collisions were registered by UA1. A fast electronic trigger flagged 10^5 of these as containing a high-energy electron.

The further analysis was done off-line. Looking for events with a transverse energy > 15 GeV in the e.m. calorimeter, the number of candidate events was reduced to **28 000**.

For these events the CD information was processed: *this is slow!* Looking for matches of CD tracks with H.E. e.m. calorimeter deposits and with tracks pointing to the interaction vertex, **2125** events were selected.

The final step of the analysis was a visual inspection of the events on a computer graphics device (“Megatek”). This left 6 events compatible with a W boson of about the right mass: the value obtained from these 6 events was

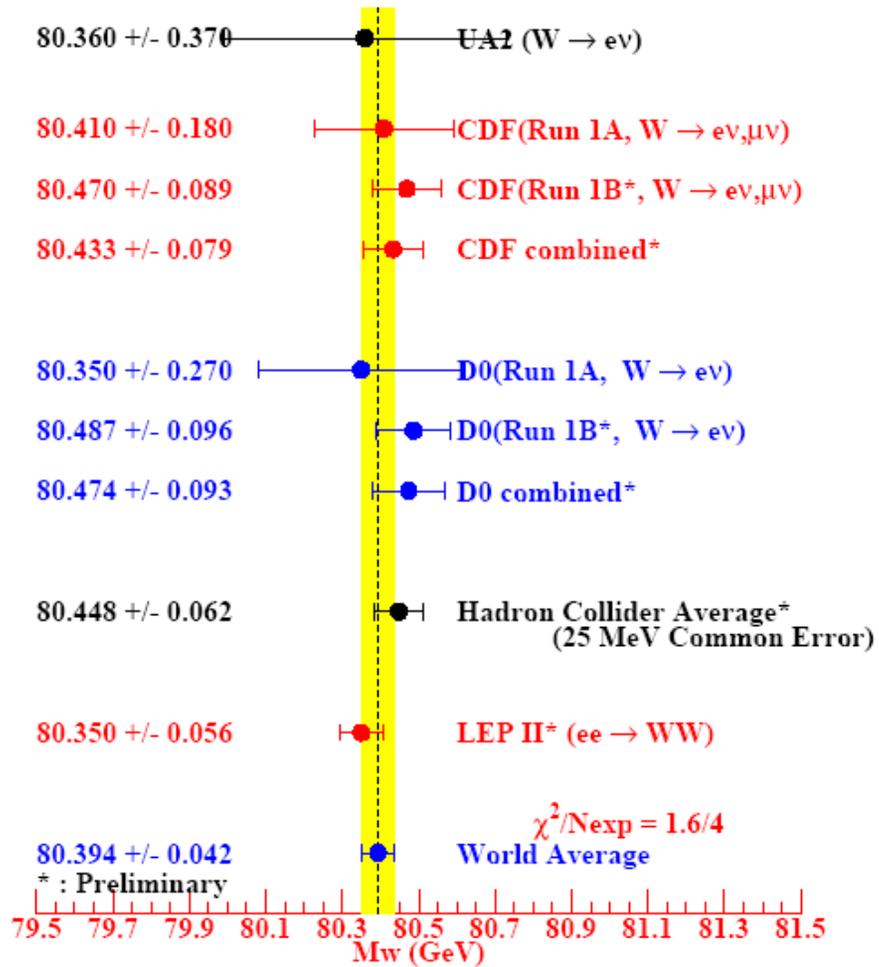
$$M_W = 81 \pm 5 \text{ GeV}$$

Today (autumn 2005) the World Average from all experiments which have measured the W mass is

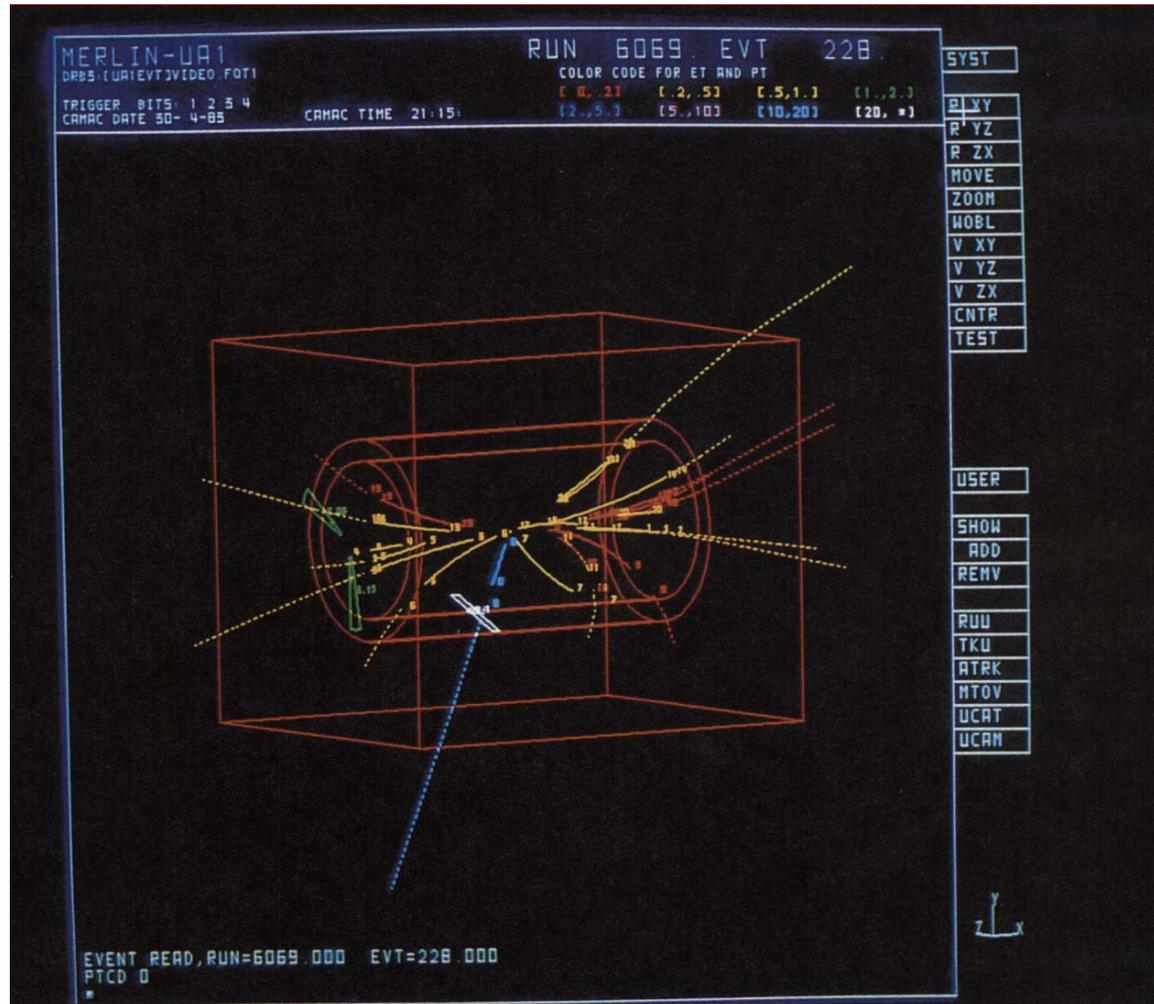
$$M_W = 80.425 \pm 0.038 \text{ GeV}$$

Update from Particle Data Tables 2006:

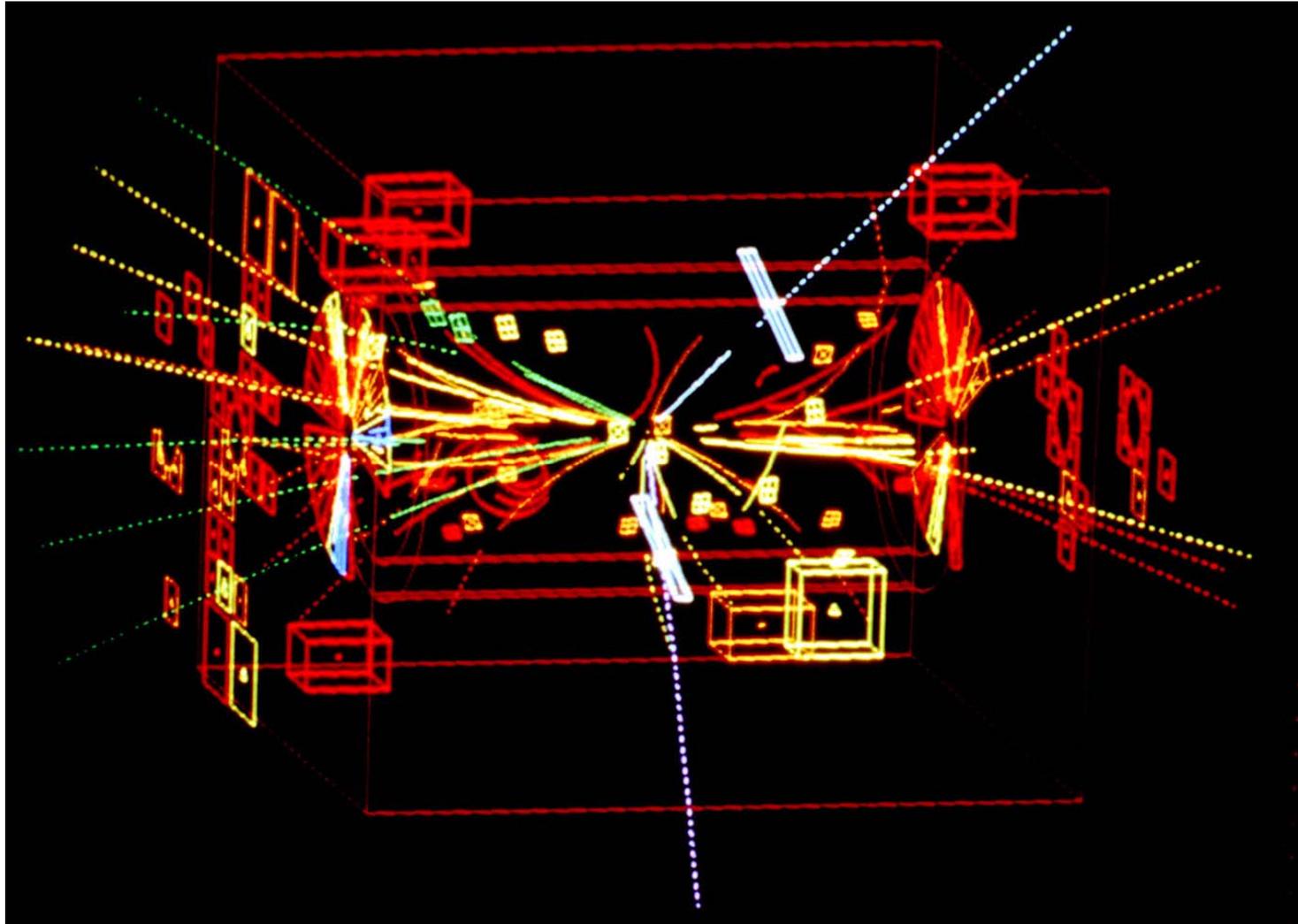
$$M_W = 80.403 \pm 0.029 \text{ GeV}$$



Computer reconstruction of a W event seen by the UA1 detector. The straight blue line indicates a very high energy electron; the computed transverse momentum is balanced by an invisible particle – the neutrino from the decay of the W boson.



Computer reconstruction of the first observed Z boson event. The two white lines indicate the very high energy electrons from the decay of the Z boson.





Carlo Rubbia (left) and Simon van der Meer celebrating their Nobel prize for the discovery of the **W** and **Z** bosons.

Carlo Rubbia



Also in the picture is
Herwig Schopper,
CERN Director General
at the time of the discovery
of the W and Z.

**Carlo Rubbia and Simon
van der Meer shared the 1983
Nobel Prize in physics for the
discovery of the W and Z bosons.**

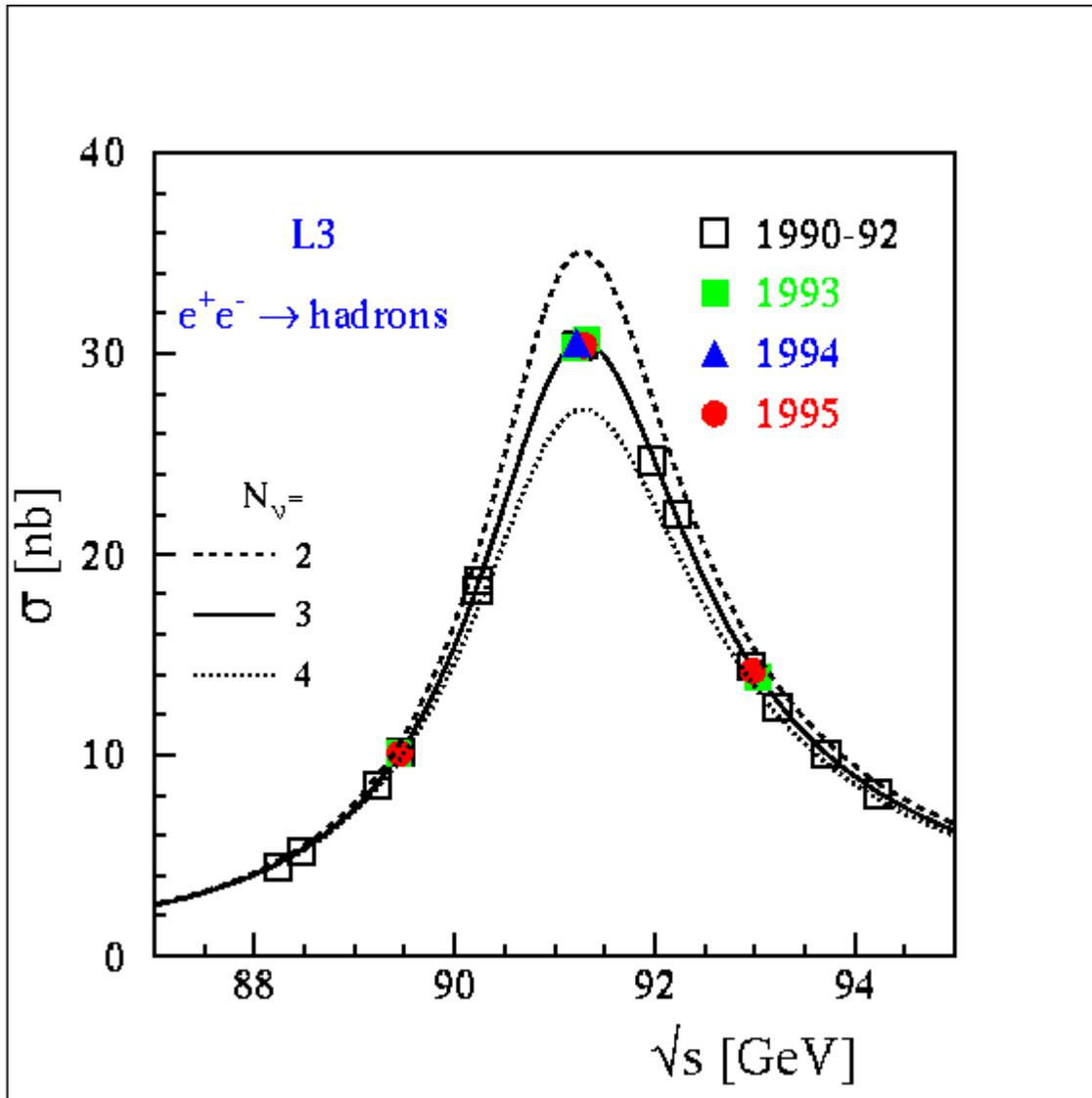
Physics after UA1 and UA2

After the shutdown of the proton-antiproton collider HE physics at CERN moved to the Large Electron-Positron collider (LEP) with four experiments: ALEPH, DELPHI, OPAL and L3.

For a number of years they were precision measurements of the Z boson peak. The most important outcome of this work was that there were only **three generations of fundamental particles** with a light neutrino.

To come to this conclusion interpreting the experimental data required highly sophisticated precision calculations Standard Model pioneered in this country by a group at JINR (D.Yu. Bardin *et al.*).

Z boson peak measured by the L3 collaboration at CERN

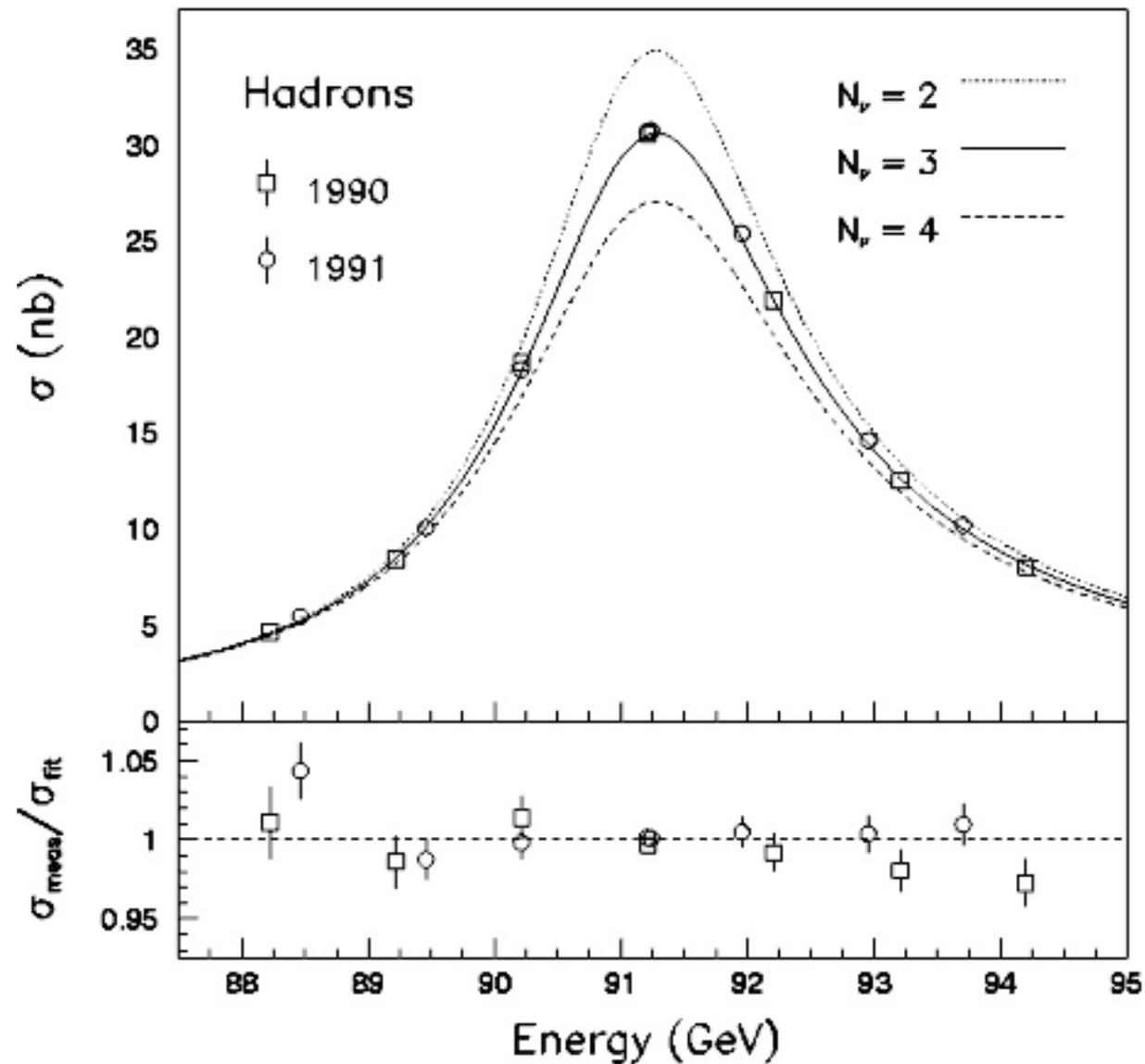


World average of
Z boson mass and
width (in GeV)
(from PDT 2004):

$$M_Z = 91.1876(21) \text{ GeV}$$

$$\Gamma_Z = 2.4952(23) \text{ GeV}$$

Note that only the $N_\nu = 3$
hypothesis agrees with
the data.



Throughout the 1990s proton-antiproton collisions continued to be studied on the Tevatron at the Fermi National Laboratory in Batavia near Chicago.

The most momentous discovery of that work was the identification of the top quark with a mass of 175 GeV.