Experimental Tests of the Standard Model (1)

- **Measurements of the Weinberg angle**
- **$W^{\pm}$ and Z^0 discovery**
- Precision measurements of the Z^0
- Precision measurements of the W
- Discovery/measurements of the top
- Discovery of the Higgs

Neutral Current and measurements of the Weinberg angle

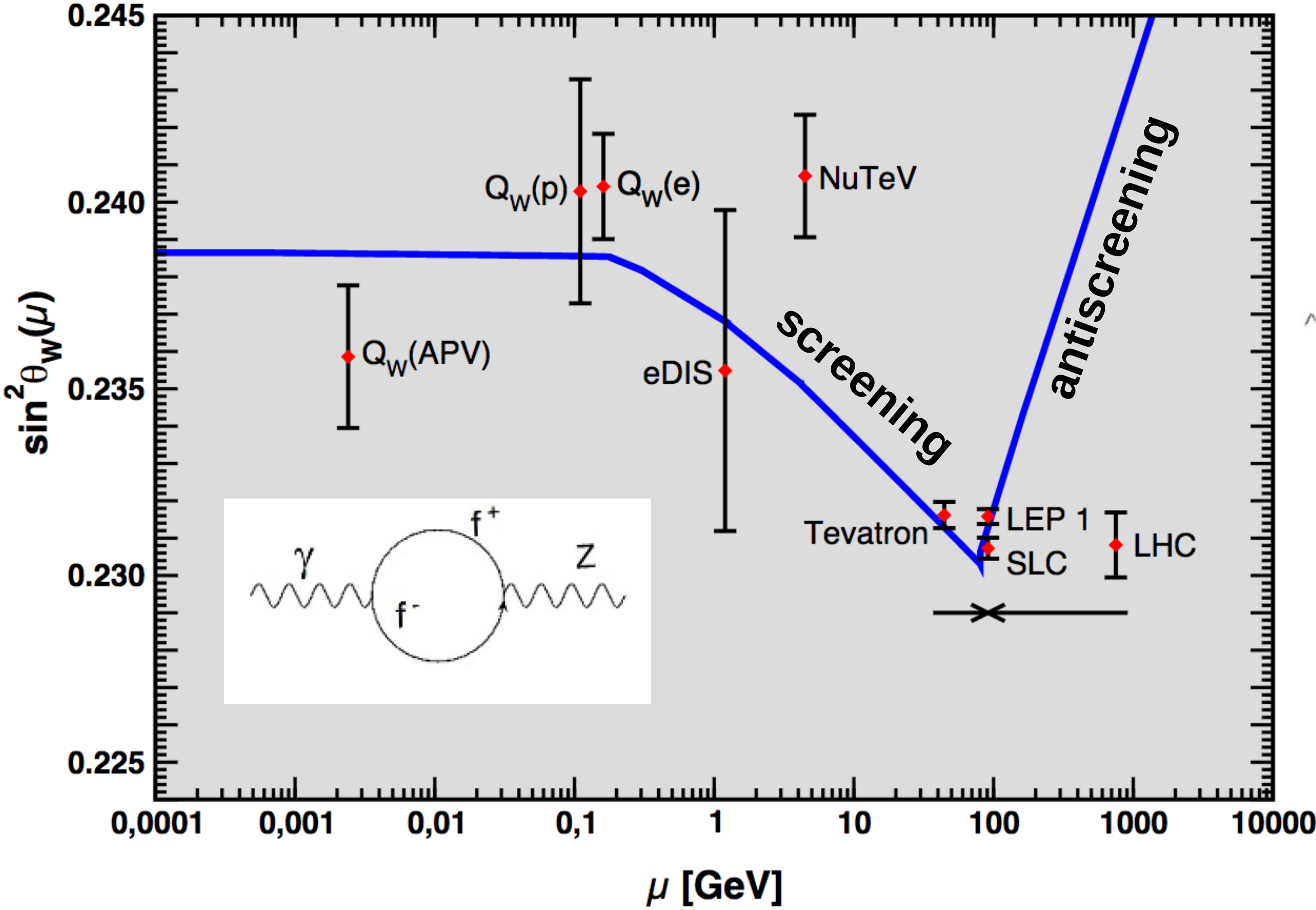
The unification of the electromagnetic and weak interaction is mainly evident in the neutral current processes, NC. In these processes we can measure the "weak charges" that in the unified theory are expressed as function of a single parameter: $\sin^2\theta_W$.

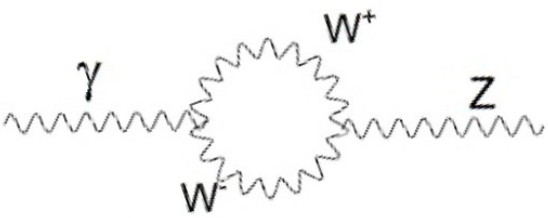
Its value should be the same independently from the type of measurement. In case of precise measurements, calculations must go beyond the **tree level**, including **radiative corrections** at the level needed to reach the required precision.

This has been verified in a wide range of energies and for many different couplings.

- Parity violation in atoms (energy scale = eV)
- Polarised electron diffusion (GeV)
- Forward-backward asymmetry in $e^+ e^- \rightarrow \mu^+\mu^-$ (from 10 GeV to 200 GeV)
- M_W/M_Z ratio (100 GeV)
- Diffusion of ν_μ on nuclei (several GeV)
- Diffusion of ν_μ on electrons (MeV)
    - we will discuss only this case

Neutral Current and measurements of the Weinberg angle





ν_μ Scattering– CHARM2

- The diffusion of neutrinos and antineutrinos on electrons is a purely leptonic process
- The cross section calculation is without theroretical uncertainties (present instead in diffusion from nuclei), but the cross sections are very small and so their measurement is difficult

- Weinberg angle measured from the cross section ratio of

$$\nu_\mu e^- \rightarrow \nu_\mu e^- \qquad \bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$$

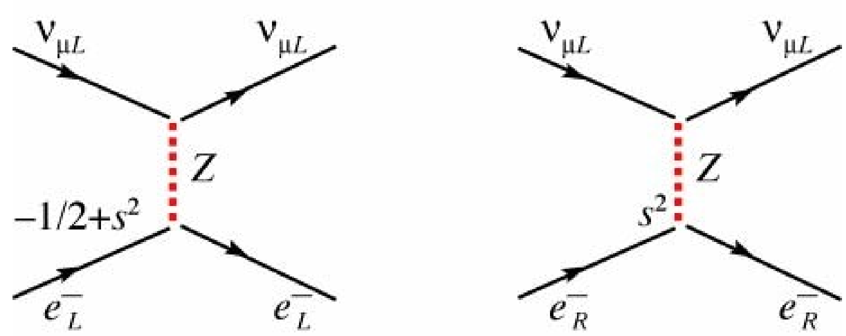
- The kinematics is such that the diffusion happens at small angles, the transfered momenta are $<< m_Z$ even if the neutrinos have energies of a hundred of GeV

$$\sigma \propto G_F^2 m_e E_\nu$$

$$\frac{\sigma(\nu_\mu e \rightarrow \nu_\mu e)}{\sigma(\nu_\mu N \rightarrow X)} \sim 10^{-4}$$

Cross Sections Ratio (1/2)

$\sigma(\nu_\mu e^- \rightarrow \nu_\mu e^-)$

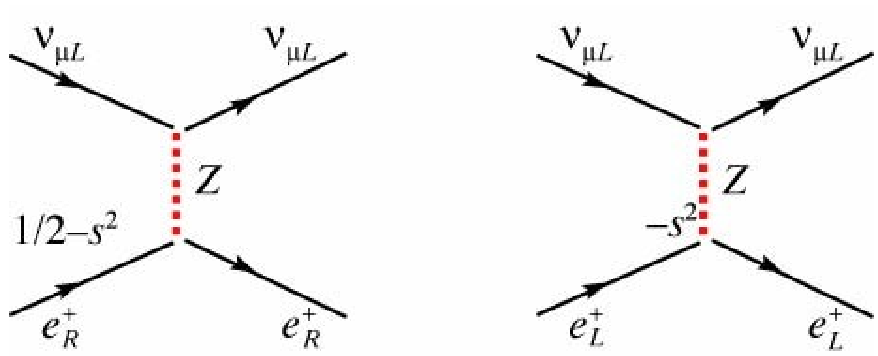


They can be distinguished measuring the helicities
→ we can sum their squared values

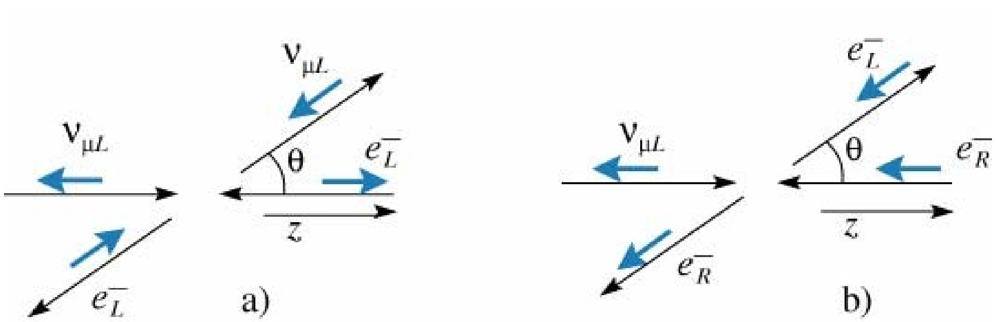
$\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$

CPT

$\nu_\mu e^+ \rightarrow \nu_\mu e^+$



$L+L \rightarrow L+L$

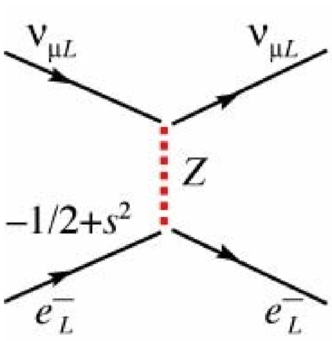


$L+R \rightarrow L+R$

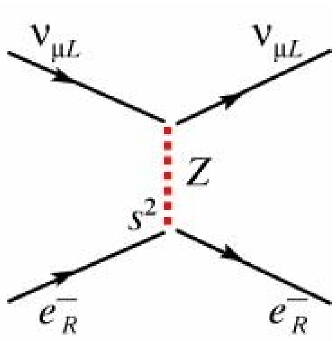
$J=0$, $J_z=0$ $\qquad$ $J=1$, $J_z=-1$, one over three

Cross sections Ratio (2/2)

L+L→ L+L

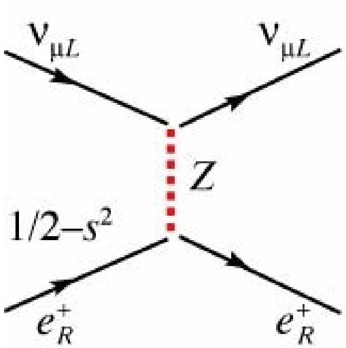


L+R→ L+R ⇒ 1/3

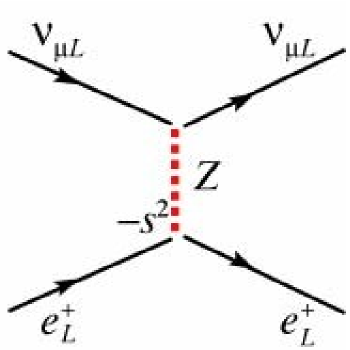


$$\sigma_{\nu_\mu e} \propto G_F^2 m_e E_\nu \left[\left(-\frac{1}{2} + \sin^2\theta_W \right)^2 + \frac{1}{3}\sin^4\theta_W \right]$$

L+R→ L+R ⇒ 1/3



L+L→ L+L



$$\sigma_{\bar\nu_\mu e} \propto G_F^2 m_e E_{\bar\nu} \left[\frac{1}{3}\left(-\frac{1}{2} + \sin^2\theta_W \right)^2 + \sin^4\theta_W \right]$$

$$R = \frac{\sigma_{\nu_\mu e}}{\sigma_{\bar\nu_\mu e}} = 3\,\frac{1 - 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W}{1 - 4\sin^2\theta_W + 16\sin^4\theta_W}$$

Measurement of the ratio of the fluxes

$$R = \frac{\sigma_{\nu_\mu e}}{\sigma_{\bar{\nu}_\mu e}} = 3\frac{1-4\sin^2\theta_W+\frac{16}{3}\sin^4\theta_W}{1-4\sin^2\theta_W+16\sin^4\theta_W}$$

- Neutrinos and antineutrinos are not monoenergetic. They have energy spectra slightly different
- The measured ratio is

$$R_{\text{exp}} = \frac{N(\nu_\mu e)}{N(\bar{\nu}_\mu e)} F$$

- It is necessary to measure independently the ratio of the beams: $F \equiv \frac{\int \Phi_{\bar{\nu}_\mu}(E_{\bar{\nu}}) E_{\bar{\nu}}\, d E_{\bar{\nu}}}{\int \Phi_{\nu_\mu}(E_\nu) E_\nu\, d E_\nu}$

The ratio was measured with four different methods, for cross-check

F known with a precision of ±2%

Goal of the experiment: $\Rightarrow \Delta\sin^2\theta_W = \pm\, 0.005$

Detector – the problem of the backgrounds

- The detector has to have a large sensitive mass, given the smallness of the cross sections: of the order of hundreds tons.
- The detector must visualise the tracks of the events and measure their energy. It must provide the target for neutrino interactions. In practise a "**fine grain calorimeter**" must be built.

- Big problem: the **backgrounds**. Two main types:
  - The muon neutrino beams contain an unavoidable contamination of electron neutrinos (1%):

$$\nu_e + N \rightarrow e + X$$

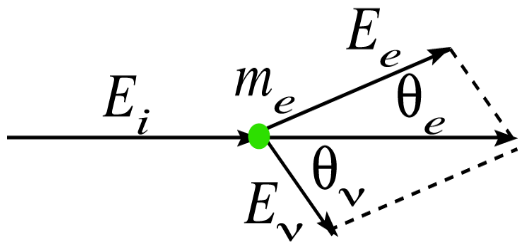
    the cross section is 10^4 times that of the elastic scattering. Consequently: S/N ~ 10^{-2}
  - The CC interactions are easily recognized (there is the penetrating muon). The NC generate problems:

$$\nu_\mu + N \rightarrow \nu_\mu + \pi^0 + X; \quad \pi^0 \rightarrow \gamma\gamma$$

    Sometimes the hadronic part (*X*) has not enough energy and escapes from the detection, sometimes one of the photons materialises in a positron-electron pair, that is confused with a single electron, simulating the signal.

Kinematics of the elastic scattering

- The searched signal is rather rare, its signature is only the presence of an electron. How to distinguish it from all the other backgrounds ? **Kinematics !!!**



The energies are very high: momentum ≈ energy

$$E_i + m_e = E_e + E_\nu$$

$$0 = E_\nu \sin\theta_\nu + E_e \sin\theta_e$$

$$E_i = E_\nu \cos\theta_\nu + E_e \cos\theta_e$$

$$E_i = E_\nu + E_e - E_\nu(1-\cos\theta_\nu) - E_e(1-\cos\theta_e)$$

$$E_i = E_i + m_e - E_\nu(1-\cos\theta_\nu) - E_e(1-\cos\theta_e)$$

$$E_e(1-\cos\theta_e) = m_e - E_\nu(1-\cos\theta_\nu) \leqslant m_e$$

$$1-\cos\theta_e \leqslant \frac{m_e}{E_e}$$

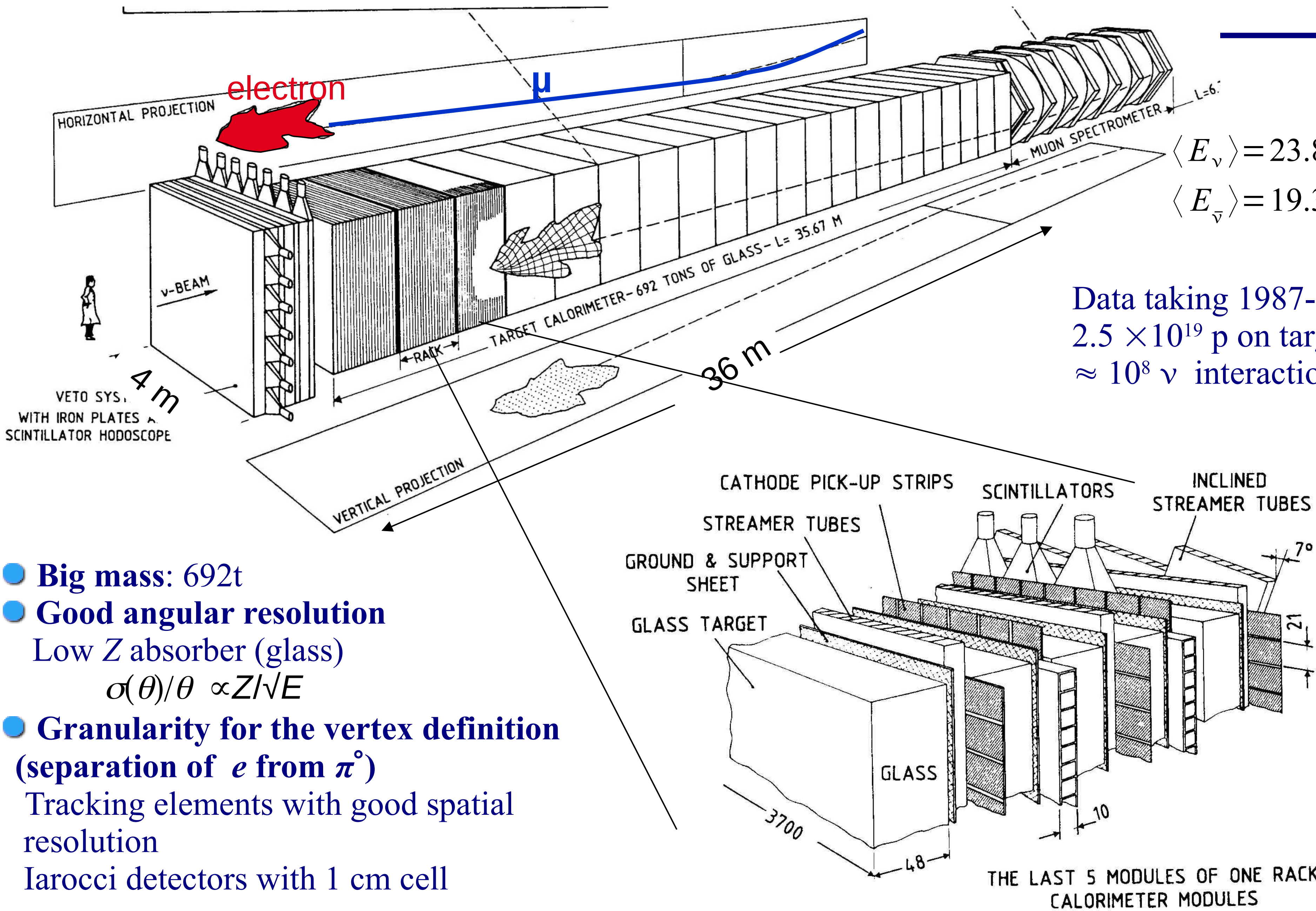
m_e/E_e is very small, then the cos is almost 1

$$1-\cos\theta_e \approx \frac{\theta_e^2}{2} \quad \Rightarrow \quad E_e\theta_e^2 \leqslant 2\, m_e$$

This is the fundamental kinematic variable to distinguish the signal from the background.

It is necessary to measure both well, especially the angle (it is squared).

CHARM2. The detector



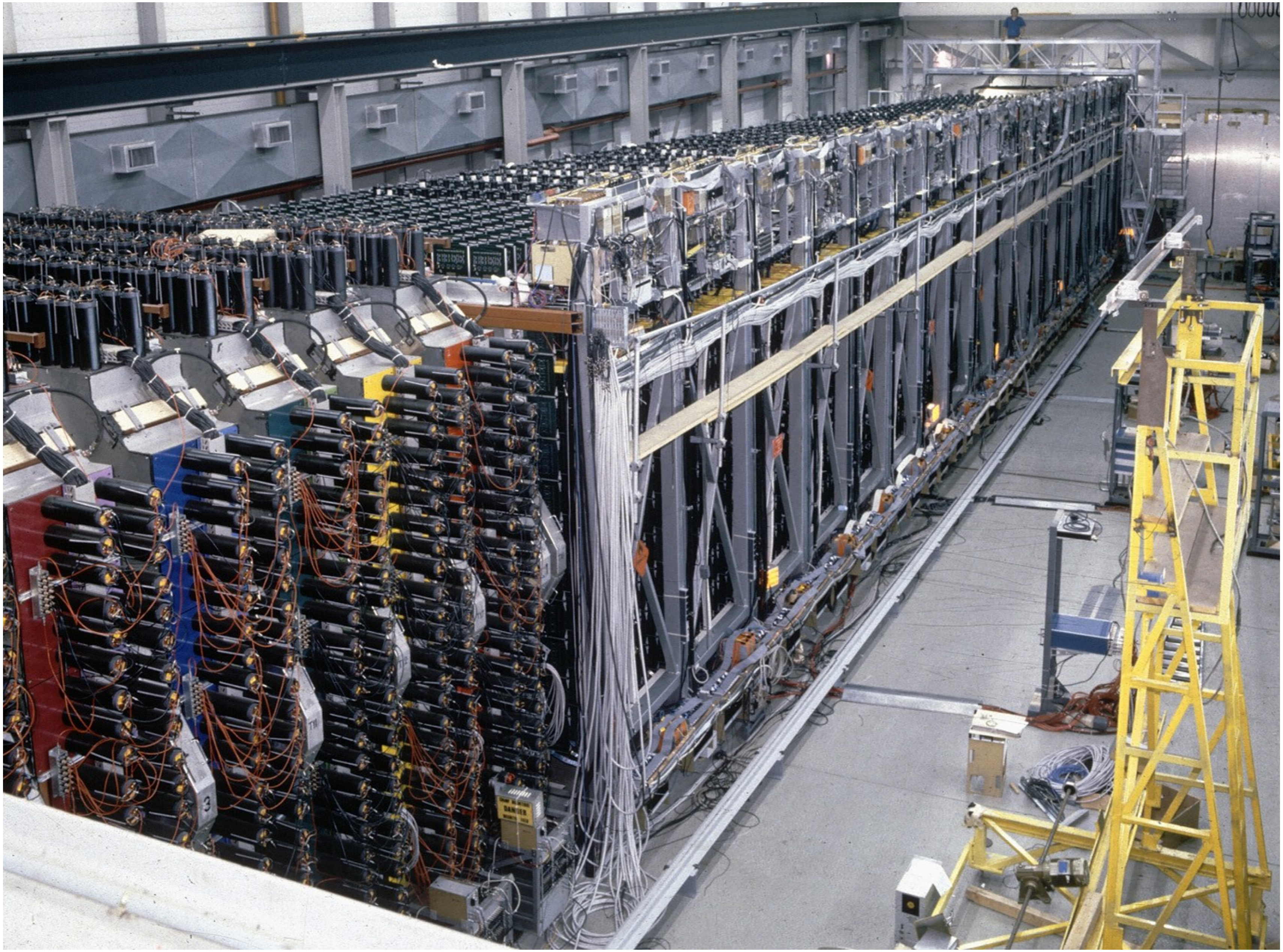
$\langle E_\nu \rangle = 23.8\,\text{GeV}$

$\langle E_{\bar{\nu}} \rangle = 19.3\,\text{GeV}$

Data taking 1987-1991
2.5×10^{19} p on target
$\approx 10^8\ \nu$ interactions

- **Big mass**: 692t
- **Good angular resolution**
  Low Z absorber (glass)
  $\sigma(\theta)/\theta \propto Z/\sqrt{E}$
- **Granularity for the vertex definition (separation of e from π°)**
  Tracking elements with good spatial resolution
  Iarocci detectors with 1 cm cell

CHARM2. The detector



CHARM2: a muon event and an e event

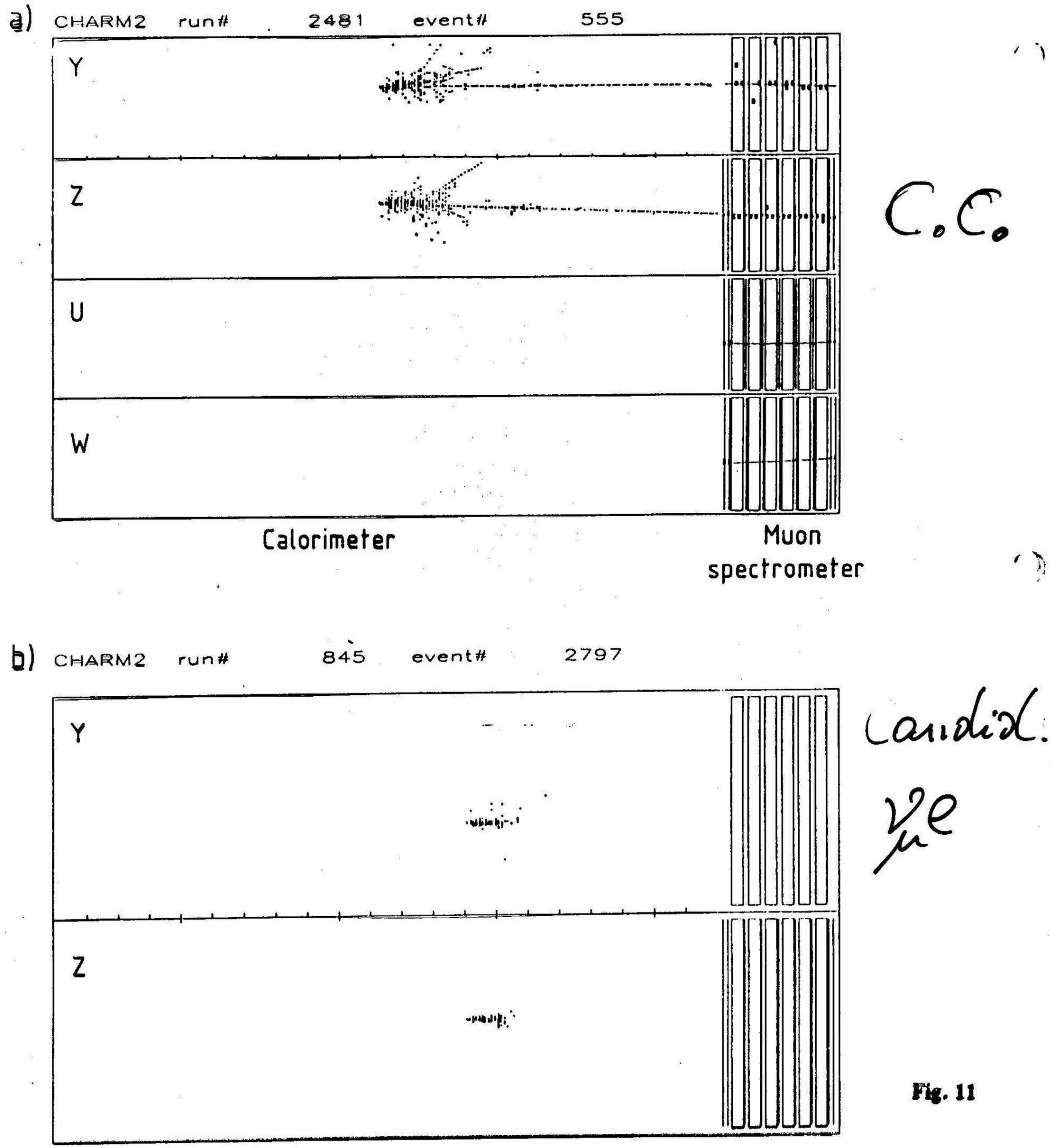
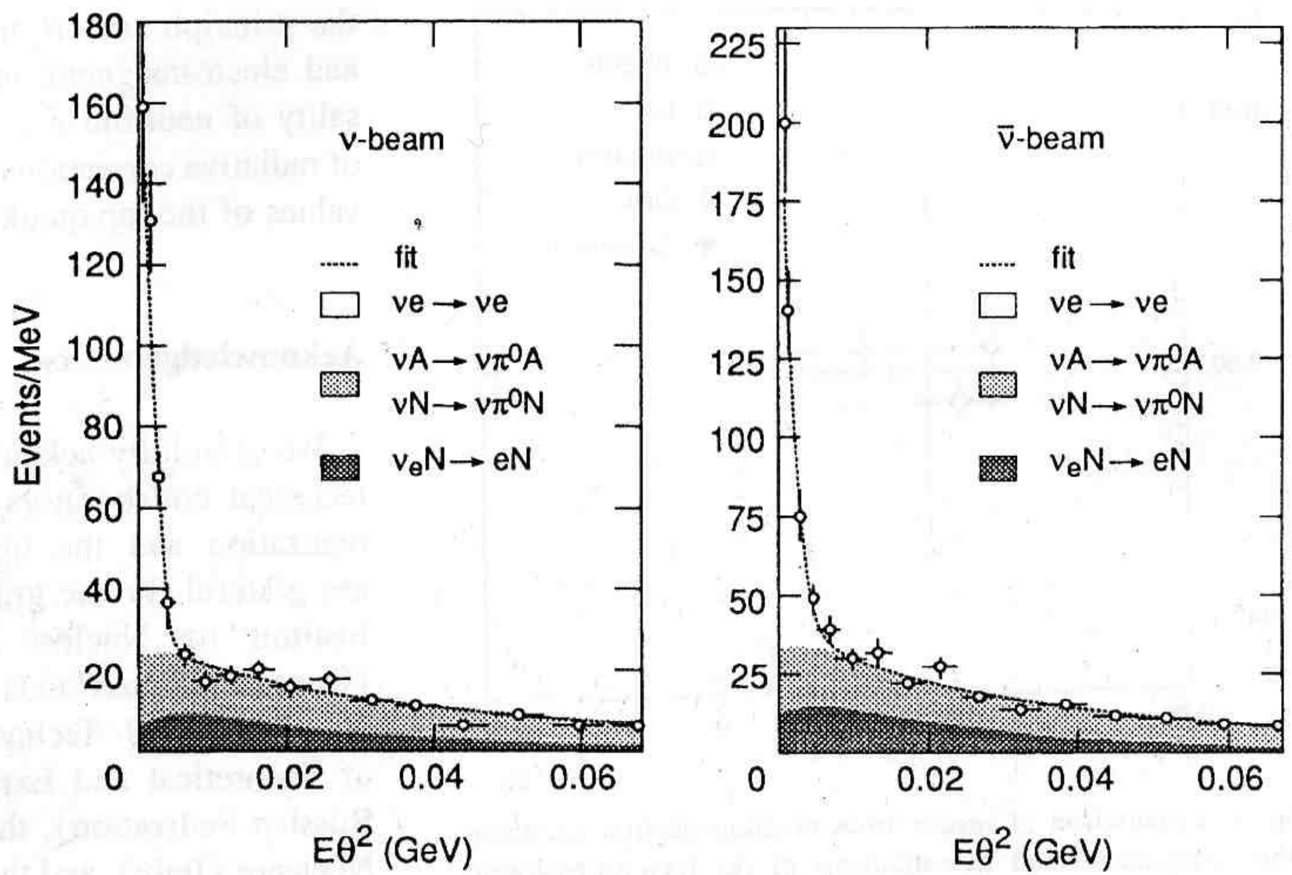


Fig. 11

CHARM2

- The main background is due to NC interactions with π° in the final state. The γ s from the π° decay give a shower as an electron. To distinguish between them one can use the energy deposit in the scintillator. In fact $\pi^\circ \rightarrow 2\gamma \rightarrow 4e$ and the scintillator sees 4 minimum ionizing particles instead of only one. But it is necessary to have seen the start of the shower.
- Selection of the events in the glass slabs before the scintillators
- The statistics is reduced but the signal/noise ratio is improved and it is possible to check how well the background is understood.



Final Result (1994)

$$\sin^2_{\nu e}\theta_W = 0.2324 \pm 0.0058\,(stat.) \pm 0.0059\,(syst.)$$

$W^{\pm}$ and Z^0 discovery

- Using data obtained with low energy measurements, the Standard Model prediction at tree level, of the masses of the intermediate vector bosons (IVB) is:

$$M_W = \left[\frac{\pi\alpha}{\sqrt{2}G\sin^2\theta_W}\right]^{1/2} = \frac{\sqrt{\pi\alpha/\sqrt{2}G}}{\sin\theta_W} = \frac{37.3GeV}{\sin\theta_W} = 77.8GeV \qquad (\sin^2\theta_W = 0.23)$$

$$M_Z = M_W/\cos\theta_W = 88.7GeV$$

- The radiative corrections determine the up shift of about 3 GeV for such predictions. As we will see the measured masses of the IVBs are:

$$M_W = 80.377 \pm 0.012 \quad GeV$$
$$M_Z = 91.1876 \pm 0.0021 \quad GeV$$

in very good agreement with the ‘fine structure’ of the theory predictions.

Resonant Creation of W and Z

- Both W and Z can be produced in resonance formation in a quark-antiquark collider
  But the quarks are not free $\Rightarrow$ proton-antiproton or proton-proton collider
  $\Rightarrow$ UA1 (CERN). Discovery in1983
- Z can be produced in resonance formation with an electron-positron collider
  $\Rightarrow$ precision studies at LEP (CERN) and SLC (SLAC) 1989-2000

- **Collisions quark-antiquark**

CM energy of the quarks $\sqrt{\hat{s}} = \sqrt{x_q x_{\bar{q}} s}$

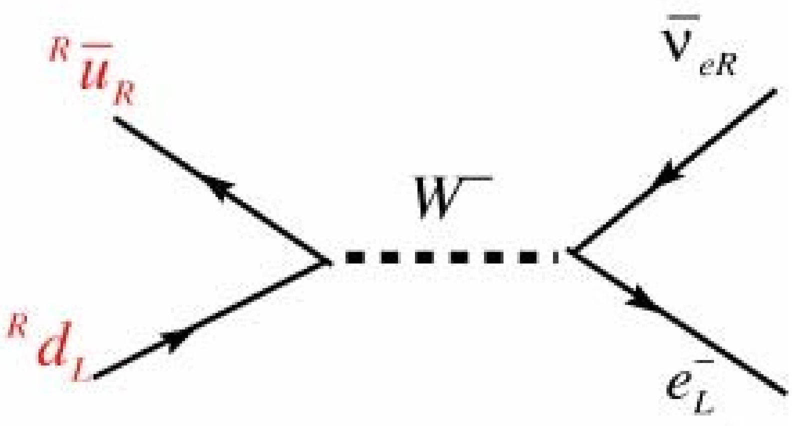
Main process to be observed

$$\bar{u} + d \rightarrow e^- + \bar{\nu}_e$$

They must have the same colour

They must have the same chirality

$$u + \bar{d} \rightarrow e^+ + \nu_e$$



Resonant Creation of W and Z

- For W $\quad \bar{u}+d\rightarrow e^{-}+\bar{\nu}_e$ $\quad$ Near the resonance $\Rightarrow$ Breit-Wigner (as for e^+e^-)

$$\sigma(\bar{u}d\rightarrow e^{-}\bar{\nu}_e)=\frac{1}{9}\frac{3\pi}{\hat{s}}\frac{\Gamma_{ud}\Gamma_{e\nu}}{(\sqrt{\hat{s}}-M_W)^2+(\Gamma_W/2)^2}$$

Probability that the colours are the same

$$\sigma_{max}(\bar{u}d\rightarrow e^{-}\bar{\nu}_e)=\sigma_{max}(\bar{d}u\rightarrow e^{+}\nu_e)=$$
$$=\frac{4\pi}{3}\frac{1}{M_W^2}\frac{\Gamma_{ud}\Gamma_{e\nu}}{\Gamma_W^2}=\frac{4\pi}{3}\frac{1}{81^2}\frac{0.640\times 0.225}{2.04^2}\times 388\left[\mu\,\mathrm{b/GeV^{-2}}\right]\approx 8.8\,\mathrm{nb}$$

Very small <<< $\sigma_{tot}\approx$ 100 mb. The weak interactions are weak!

- Per Z $\quad \bar{u}+u\rightarrow e^{-}+e^{+} \qquad \bar{d}+d\rightarrow e^{-}+e^{+}$

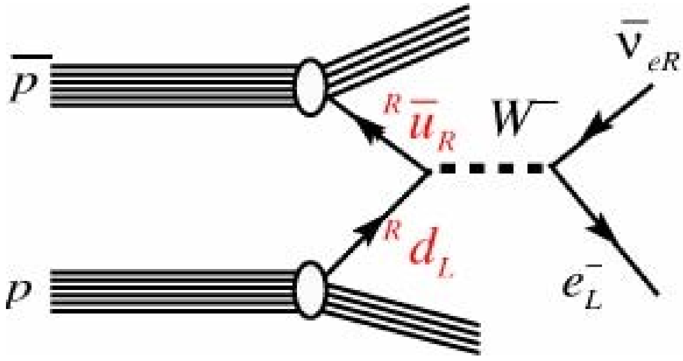
$$\sigma_{max}(\bar{u}u\rightarrow e^{-}e^{+})=\frac{4\pi}{3}\frac{1}{M_Z^2}\frac{\Gamma_{uu}\Gamma_{ee}}{\Gamma_Z^2}=\frac{4\pi}{3}\frac{1}{91^2}\frac{0.280\times 0.083}{2.42^2}\times 388\left[\mu\,\mathrm{b/GeV^{-2}}\right]\approx 0.8\,\mathrm{nb}$$

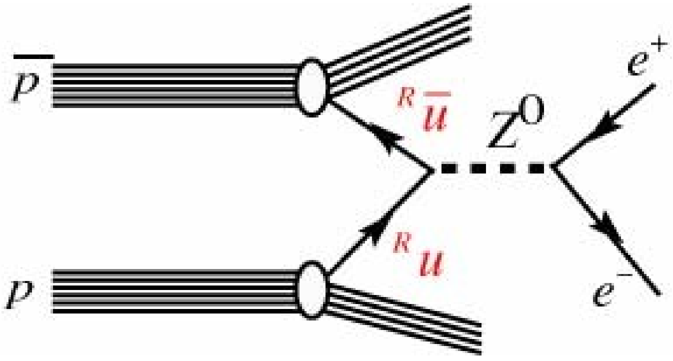
$$\sigma_{max}(\bar{d}d\rightarrow e^{-}e^{+})=\frac{4\pi}{3}\frac{1}{M_Z^2}\frac{\Gamma_{dd}\Gamma_{ee}}{\Gamma_Z^2}\approx 1\,\mathrm{nb}$$

An order of magnitude lower than for W

Cross Sections

Beam of p = broad band beam of *partons* (q, g, and some $\bar{q}$)
Beam of $\bar{p}$ = broad band beam of *partons* ($\bar{q}$, g, and some q)

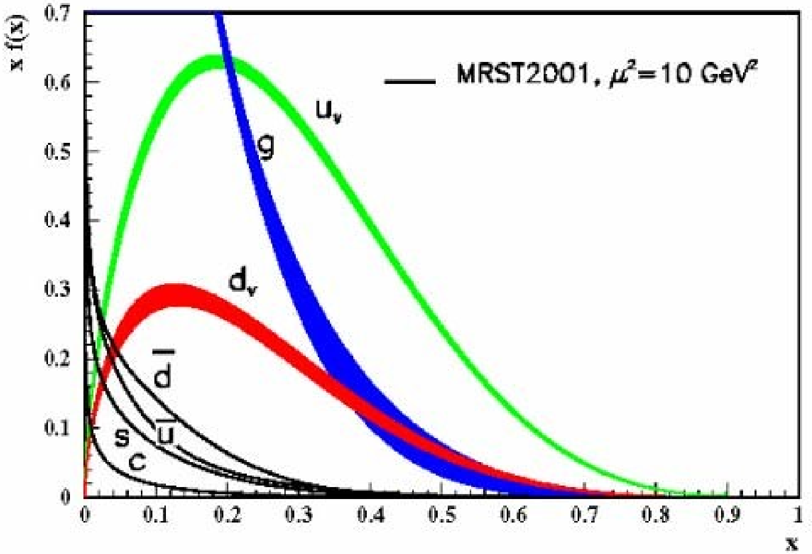




We consider the annihilation of a quark with a valence antiquark
if $\sqrt{s}$ = 630 GeV, the fraction of the momentum necessary for the resonance is:

$$\langle x \rangle \approx \frac{M_W}{\sqrt{s}} \approx \frac{M_Z}{\sqrt{s}} \approx 0.15$$

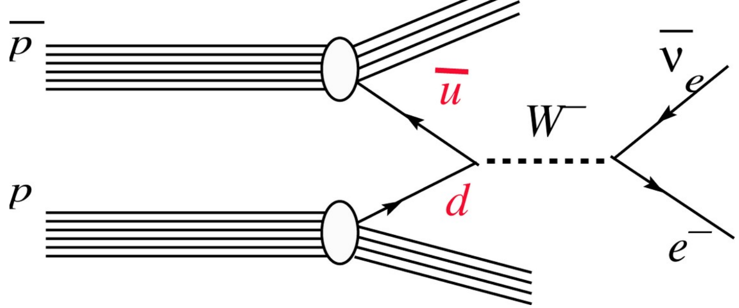
OK. There are a lot.



Production of *W* and *Z* from pp̄ collisions

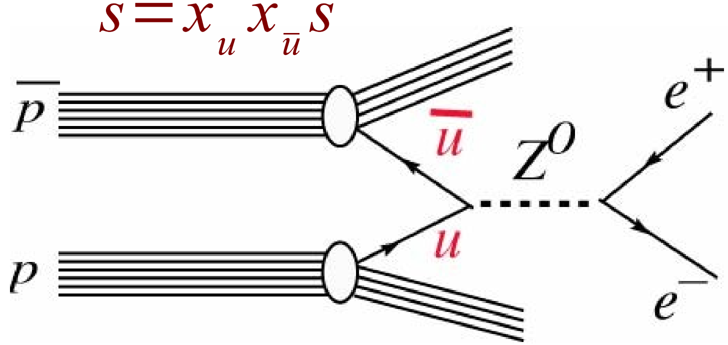
- The spread of the energies of the partons >> of the width of the *W* e *Z* resonances
- The reference system for the lab. is the cm of $\bar{p}p$, and not of $\bar{q}q$; this pair, and the *W* or *Z* produced have a longitudinal motion each time different

$$\hat{s} = x_d \, x_{\bar{u}} \, s$$



and a similar one from $\bar{d}u$

$$\hat{s} = x_u \, x_{\bar{u}} \, s$$



and a similar one from $\bar{d}d$

- Calculations of the cross section (taking into account QCD and structure function uncertainties) foresee at $\sqrt{s}$ = 630 GeV

$$\sigma(\bar{p}p \to W \to e\nu_e) = 530^{+170}_{-90}\ \text{pb}$$

$$\sigma(\bar{p}p \to Z \to e^+e^-) = 35^{+17}_{-10}\ \text{pb}$$

@ $\sqrt{s}$ = 630 GeV $\langle x \rangle = M_W/\sqrt{s} \approx 0.15$, valence quark much more than sea quark
q direction = p direction
$\bar{q}$ direction = $\bar{p}$ direction

An order of magnitude lower due to the fact that $M_Z > M_W$ and the weak charges

Cross sections grows rapidly with the energy and with it the possibility to have large longitudinal momentum of the boson

Resonant Creation of W and Z

In 1978 Cline, McIntire and Rubbia suggested to transform the proton accelerator SpS at CERN in a $p\bar{p}$ storage ring in which protons and antiprotons could circulate in opposite directons, in the same magnetic structure already existing using the CPT symmetry

The big problem solved by Rubbia and Van der Meer was the "cooling" of the particles bunches of the beams, that is to reduce them to enough small dimensions in the points of collision

In 1983 the reached luminosity was $\mathscr{L} = 10^{32}\ \text{m}^{-2}\ \text{s}^{-1}$, enough to discover W and Z

In 1983 W and Z were discovered

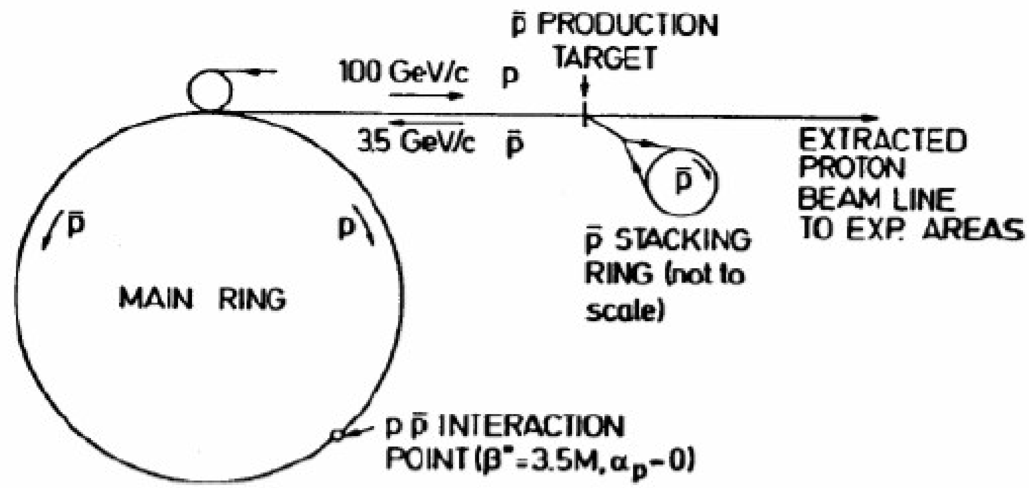


Fig. 5. General layout of the $p\bar{p}$ colliding scheme, from Ref. [9]. Protons (100 GeV/c) are periodically extracted in short bursts and produce 3.5 GeV/c antiprotons, which are accumulated and cooled in the small stacking ring. Then $\bar{p}$'s are reinjected in an RF bucket of the main ring and accelerated to top energy. They collide head on against a bunch filled with protons of equal energy and rotating in the opposite direction.

The signals

- The IVB production is a rare process 10^{-8} - 10^{-9} ($\sigma_{tot}(p\bar{p}) \approx 60$ mb $= 6\times10^{10}$ pb) [weak interaction is weak]
  The rejection power of the detectors has to be > 10^{10}
  More frequent final state are $q\bar{q}$

$$\sigma\times B(W\rightarrow q\,\bar{q})=3\,\sigma\times B(W\rightarrow l\,\nu_l)\quad 3=\text{colour numbers}$$

  Experimentally $q \rightarrow jet$
  Huge background from: $gg \rightarrow gg;\ gq \rightarrow gq;\ g\bar{q} \rightarrow g\bar{q};\ q\bar{q} \rightarrow q\bar{q};$

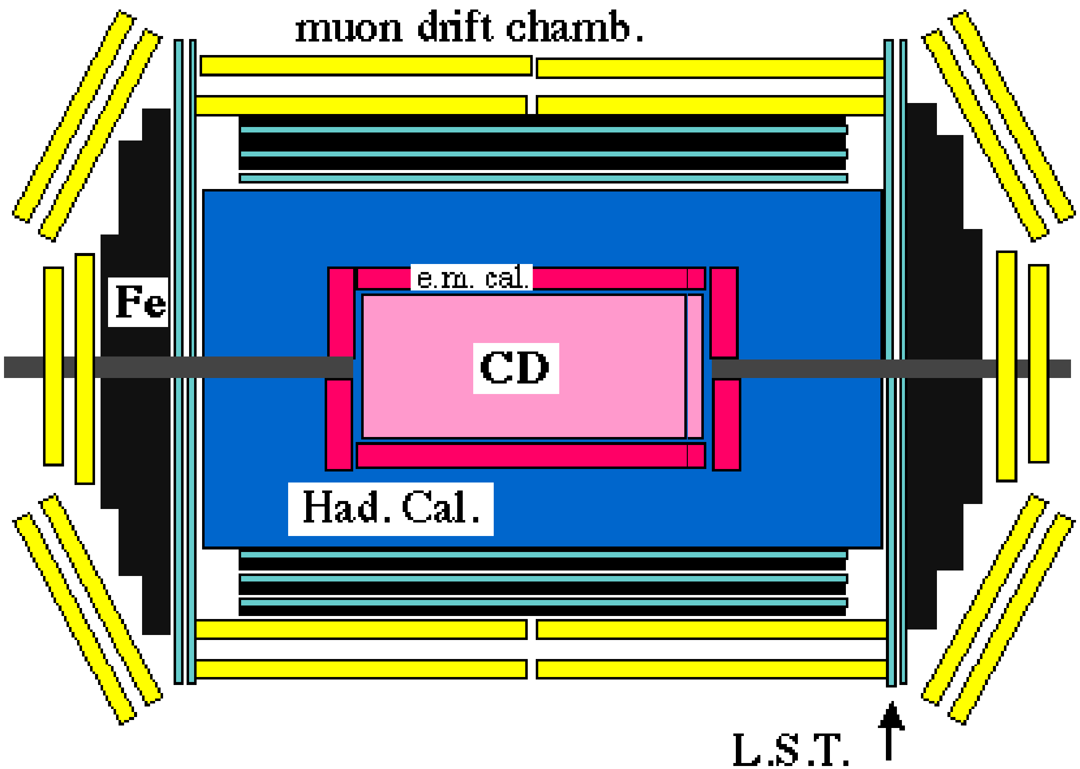
- Important measured kinematic quantity: ***trasverse momentum*** p_T = momentum component perpendicular to the beams

- The leptonic final states have a better S/N ratio

W	$\rightarrow e\ \nu_e$	**isolated e, high p_T**	} +
W	$\rightarrow \mu\ \nu_\mu$	**isolated μ , high p_T**	} +
Z	$\rightarrow e^-\ e^+$	**isolated 2e , high p_T**	
Z	$\rightarrow \mu^-\mu^+$	**isolated 2μ , high p_T**	

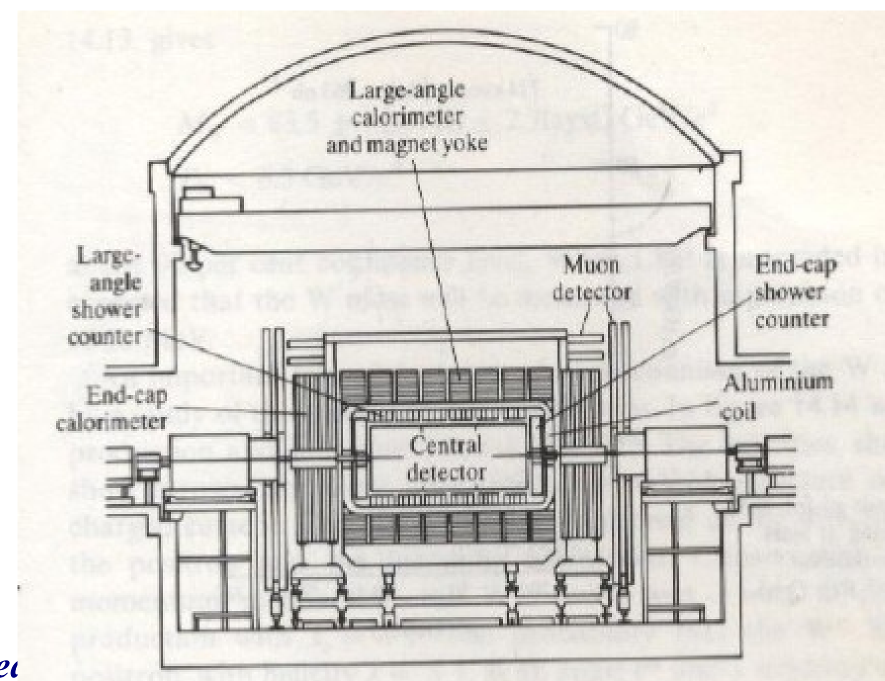
ν at high **p_T = high missing p_T**
Hermetic detector (UA1 able to measure missing p_T with a precision of about some GeV)

Identification and measurement of leptons and hadrons

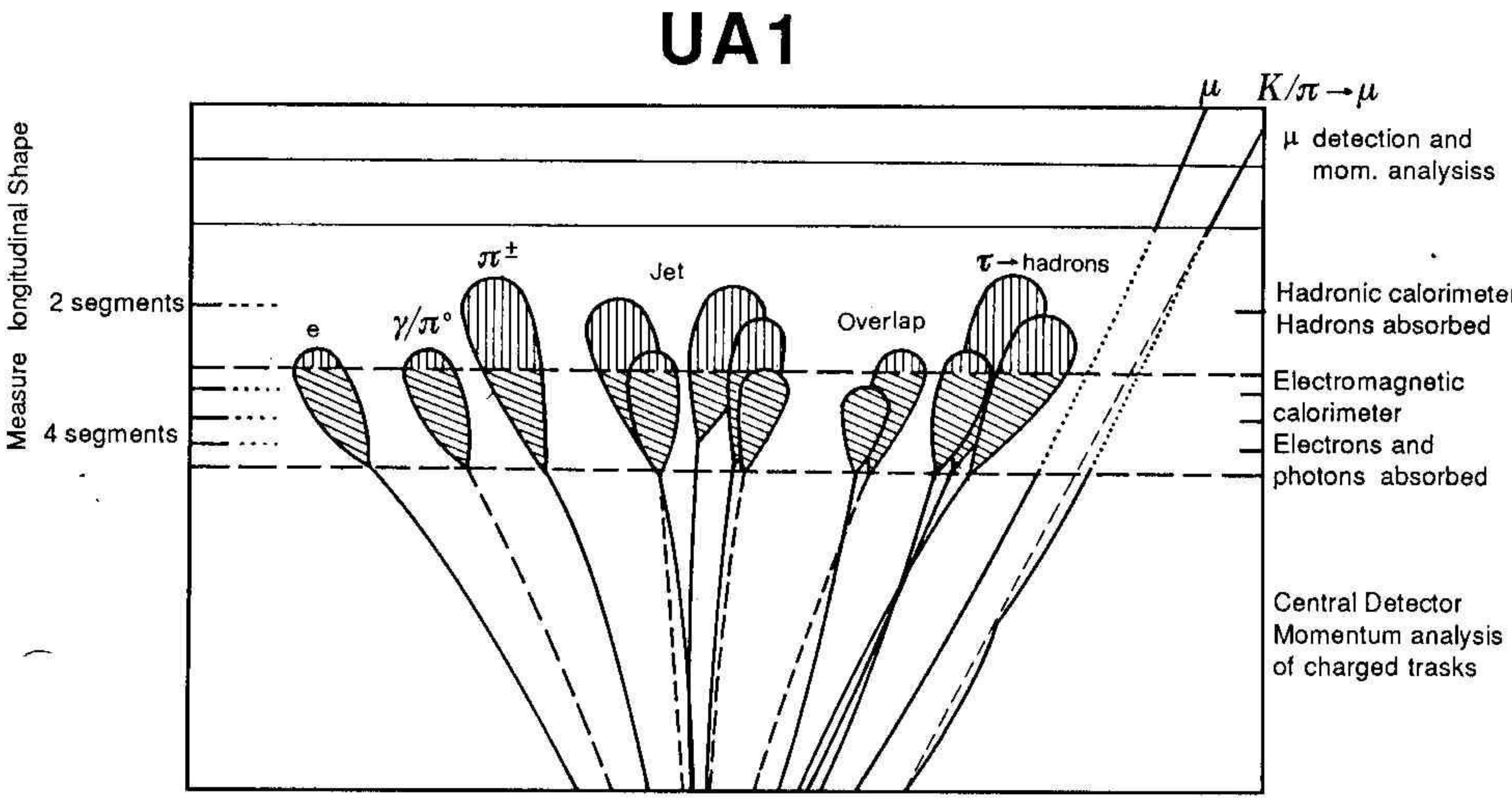


CD. Central Detectors tracking in a B field perpendicular to the beams. Momentum measurement
EM Calorimeter. Measurement of the electron energy
Hadronic Calorimeter. Identification of hadrons and energy measurement
Fe filters with tracking, external chambers for μ
Transversal Hermeticity. Transverse missing momentum = neutrino

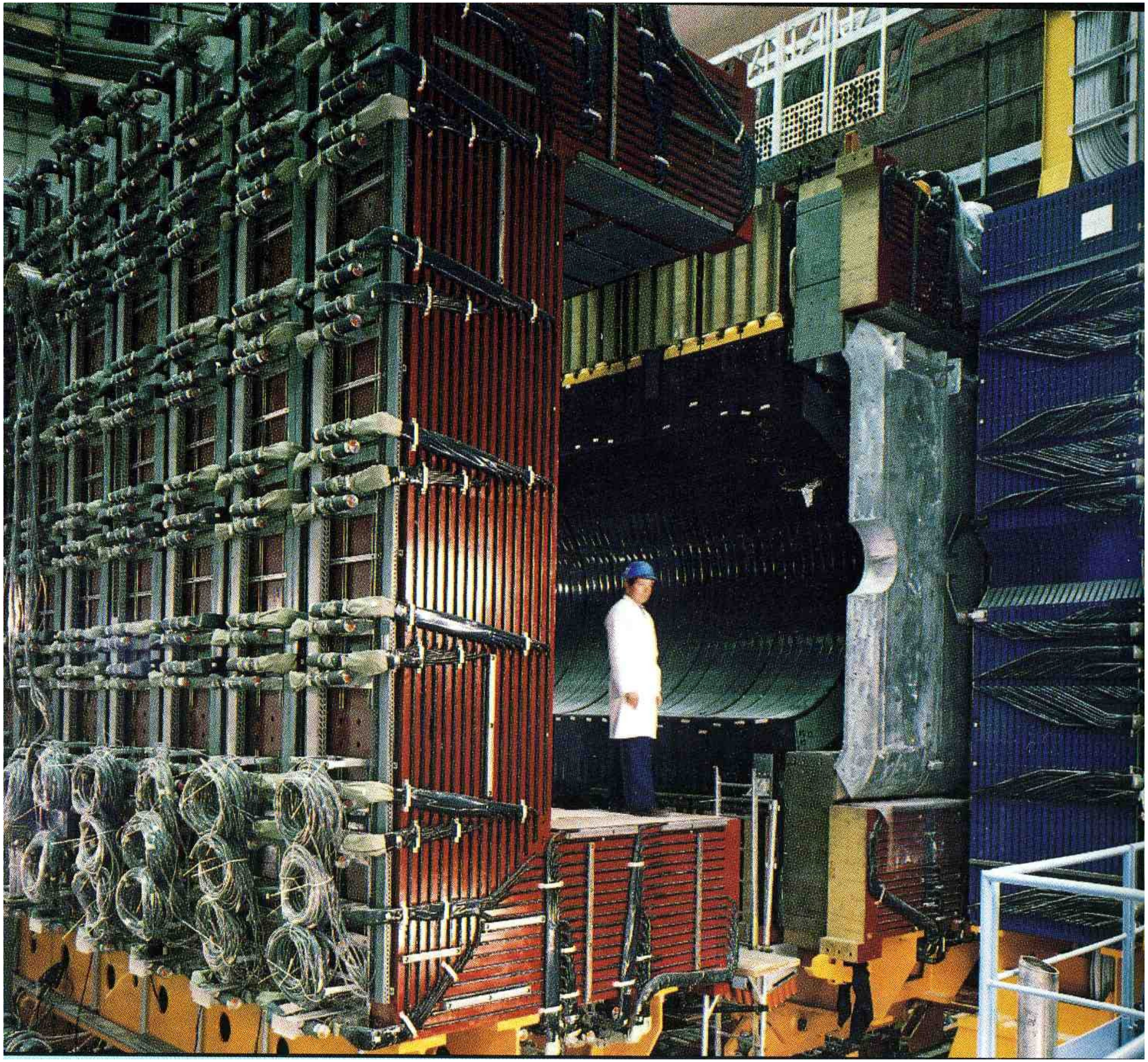
UA1



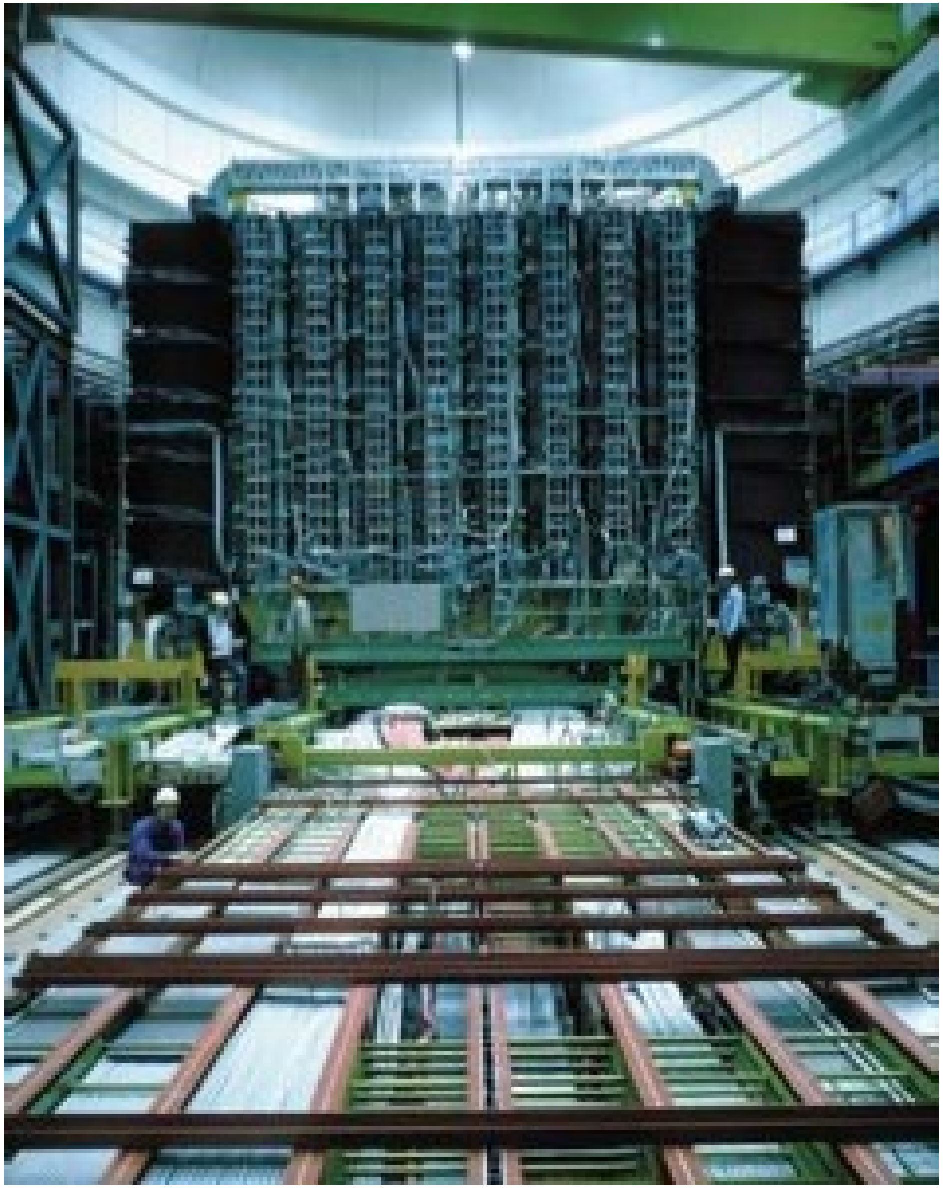
Identification and measurement of leptons and hadrons



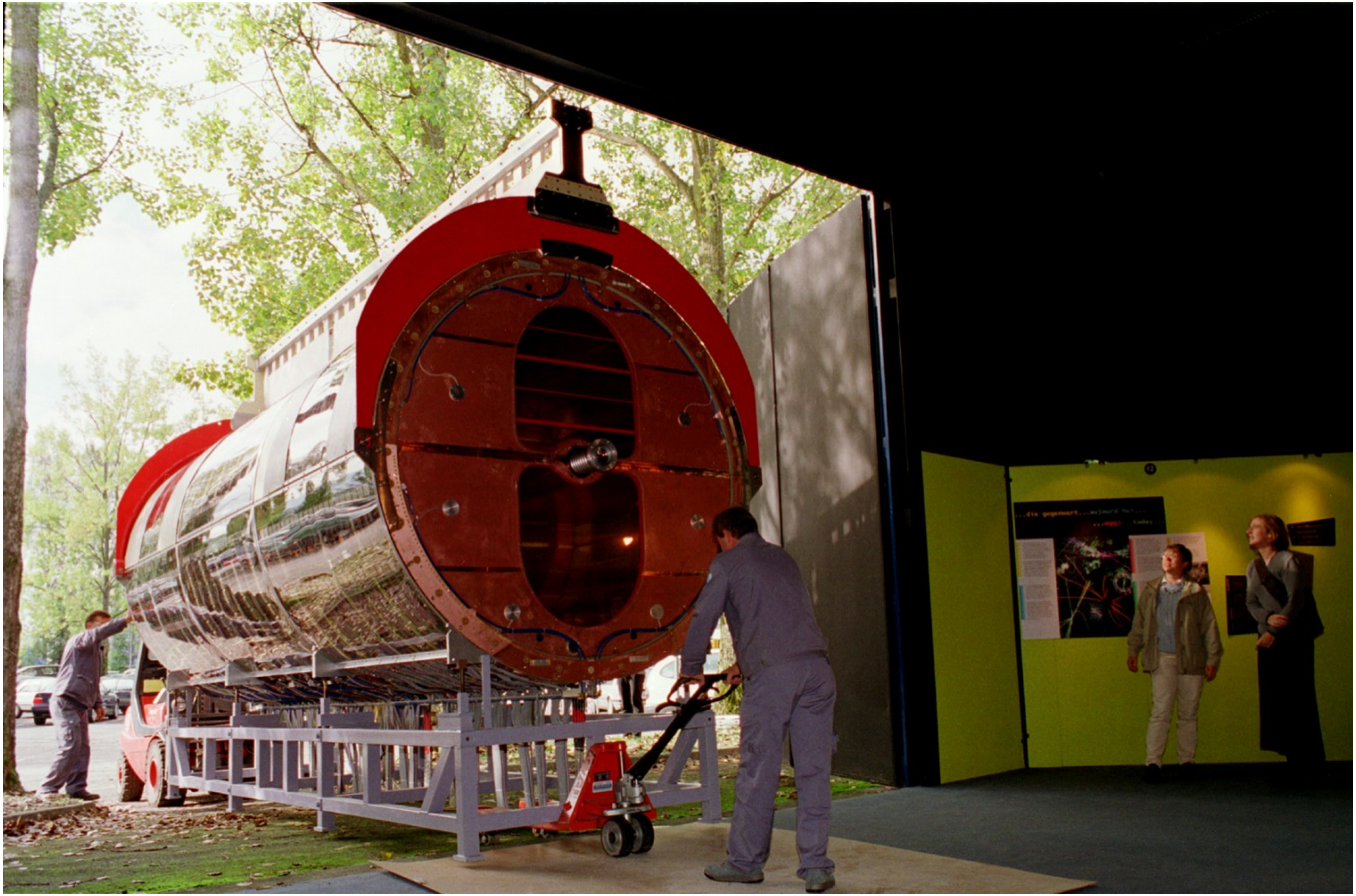
building of UA1



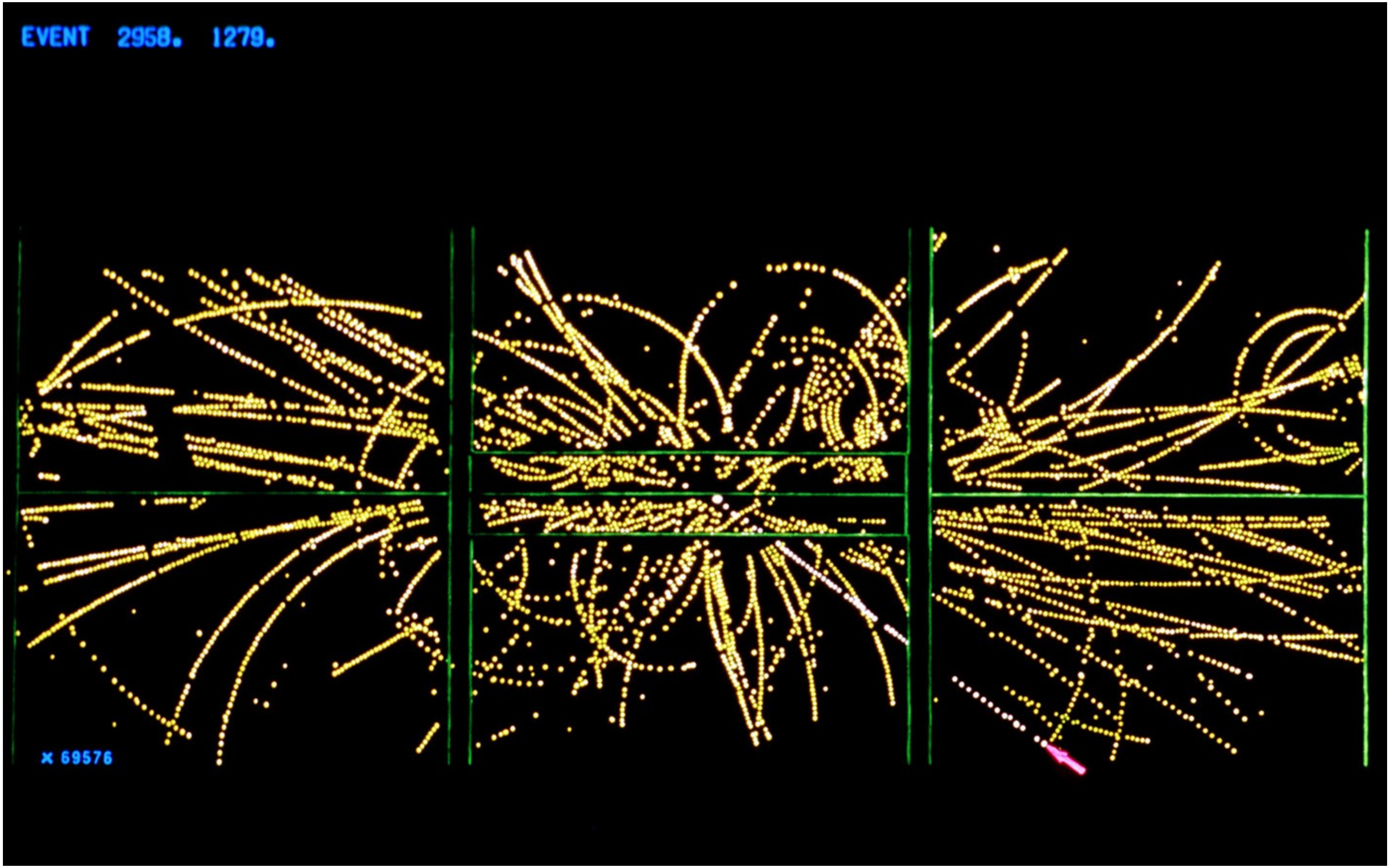
building of UA1



UA1. The central detector to the museum

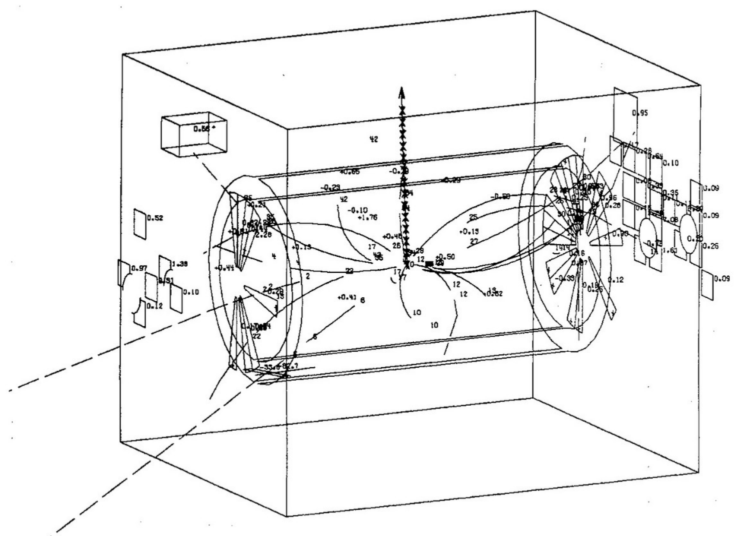


UA1. The first W



$W \rightarrow e\nu$

$W^- \rightarrow e\bar{\nu}$



Cutting the traces with $p_T < 1$ GeV cleans completely the event, only the electron and the “neutrino” survive

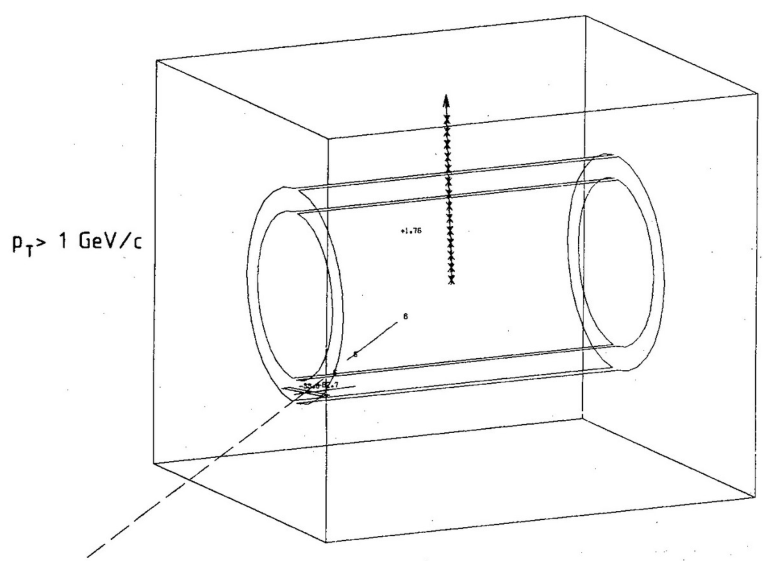
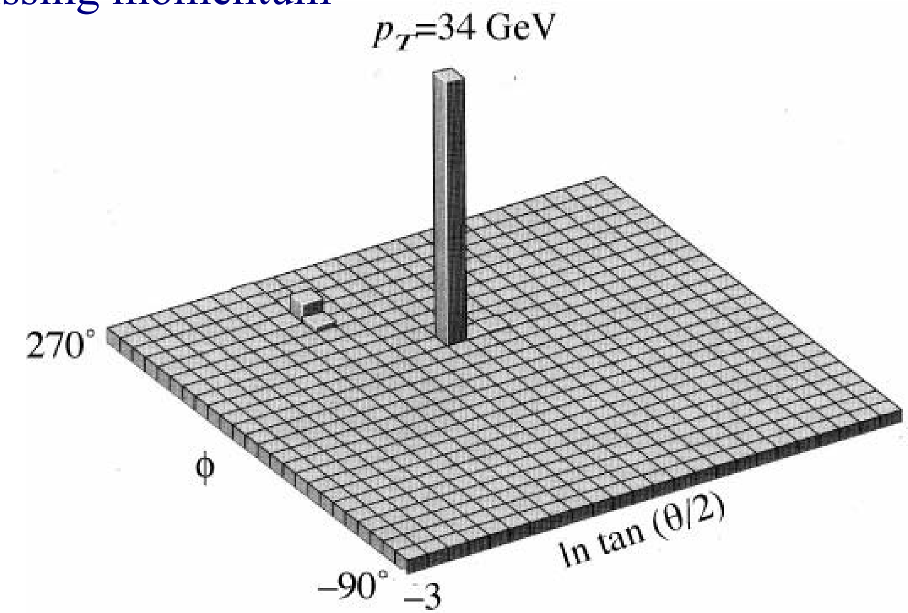


Fig. 16b. The same as picture (a), except that now only particles with $p_T > 1$ GeV/c and calorimeters with $E_T > 1$ GeV are shown.

In electromagnetic calorimeters a *W* appears as a localized energy deposit in a direction opposite to the missing momentum



The central tracking detector immersed in a magnetic field measures the sign of the charge and the momentum

The EM calorimeters measure the *e* energy

One knows that it is an electron because $E = p$

The hermiticity of the detector in the transverse direction permits the calculation of the “missing p_T” = p_T of the ν

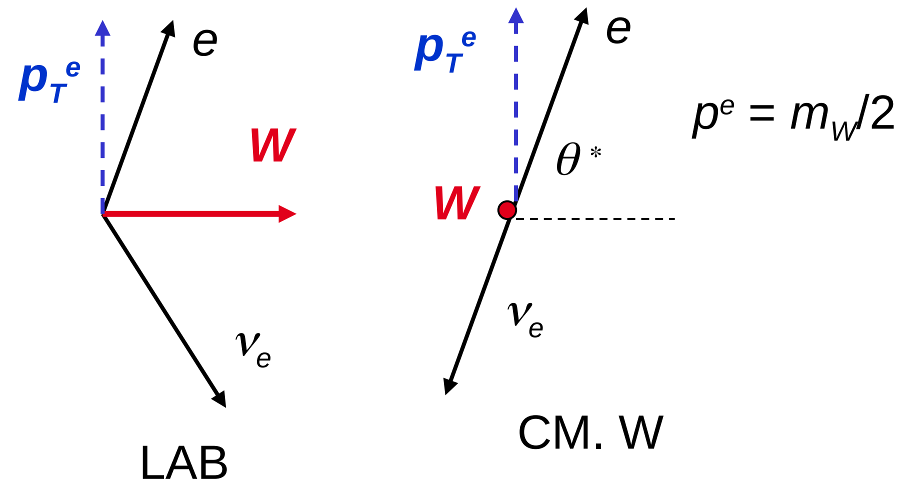
Measurement of M_W

$W \rightarrow l\, \nu_l$

Trasverse momentum of q and $\bar{q}$ is small, then also that of the W.

Ignoring it:

p_T^e is the same in the two ref. frame = $(m_W/2)\sin\theta^*$



Angular distribution in the CM is known

$$\frac{dn}{d\theta^*} \xrightarrow{\text{coordinate transf.}} \frac{dn}{dp_T} = \frac{dn}{d\theta^*}\frac{d\theta^*}{dp_T}$$

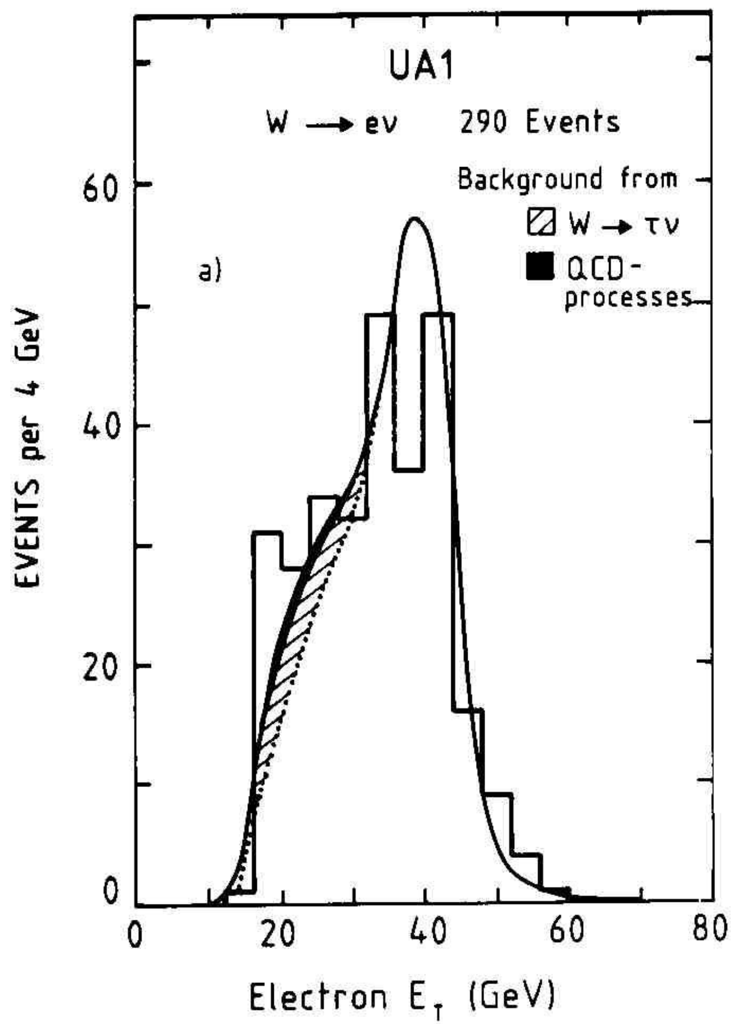
$$\frac{dn}{dp_T} = \frac{1}{\sqrt{\left(\frac{m_W}{2}\right)^2 - p_T^2}}\frac{dn}{d\theta^*}$$

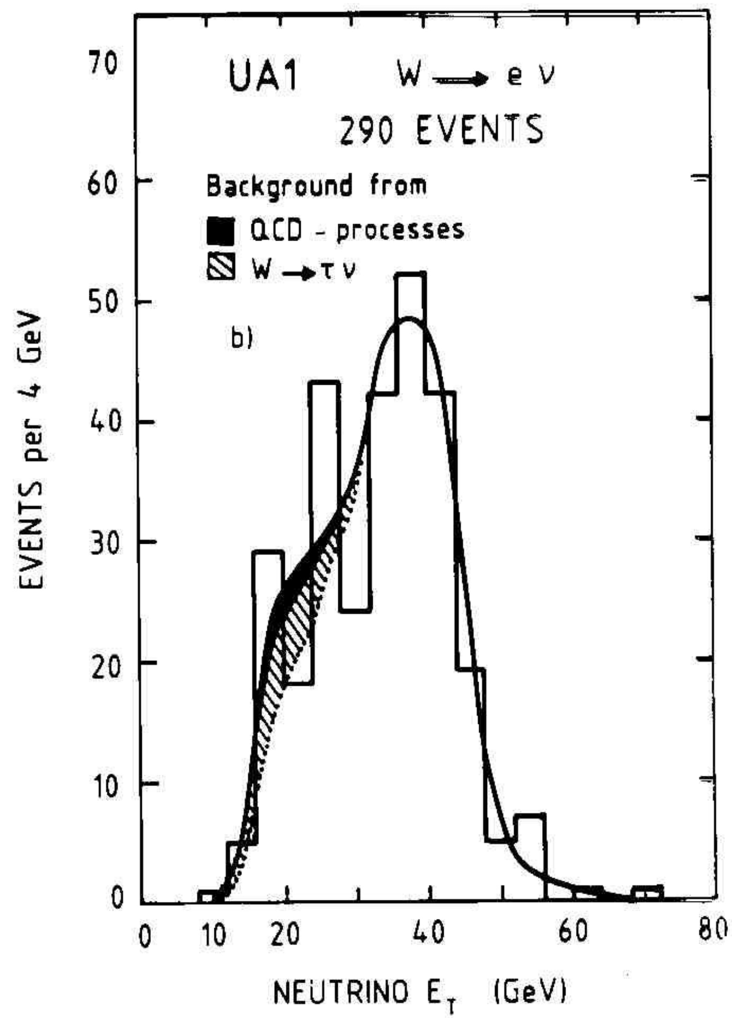
"Jacobian" peak for $p_T^e = m_W/2$

"Jacobian" peak for $p_T^{missing} = m_W/2$

The transverse momentum of the W ($p_T^W \neq 0$) broadens the peak, but does not cancel it. The measurement of the m_W is based on the measurement of the energy of the peak and of its falling front

Distribution of the transverse energies



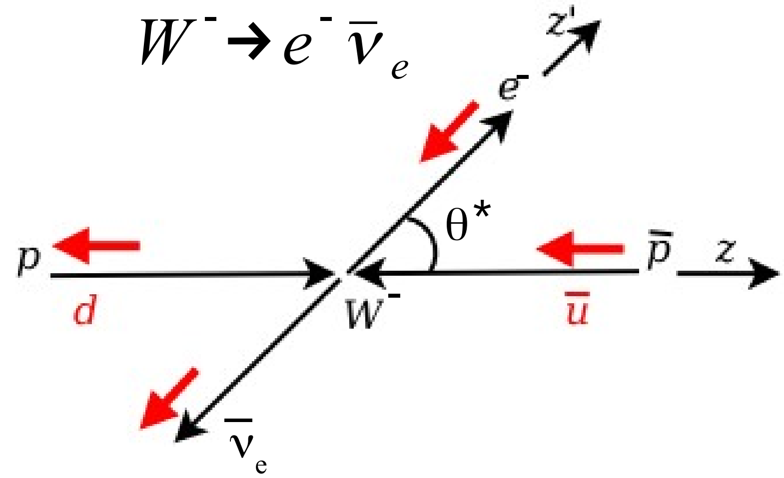


UA1 M_W= 82.7±1.0(stat)±2.7(syst) GeV Γ_W< 5.4 GeV

UA2 M_W= 80.2±0.8(stat)±1.3(syst) GeV Γ_W< 7 GeV

Spin and polarization of the W

In the c.m. reference frame of the *W* the electron energy $>> m_e$.
chirality ≈ helicity
$V\text{–}A \Rightarrow W$ is coupled only with **fermions with helicity –**
antifermions with helicity +



Tot. Ang. Mom. $J = S_W = 1$

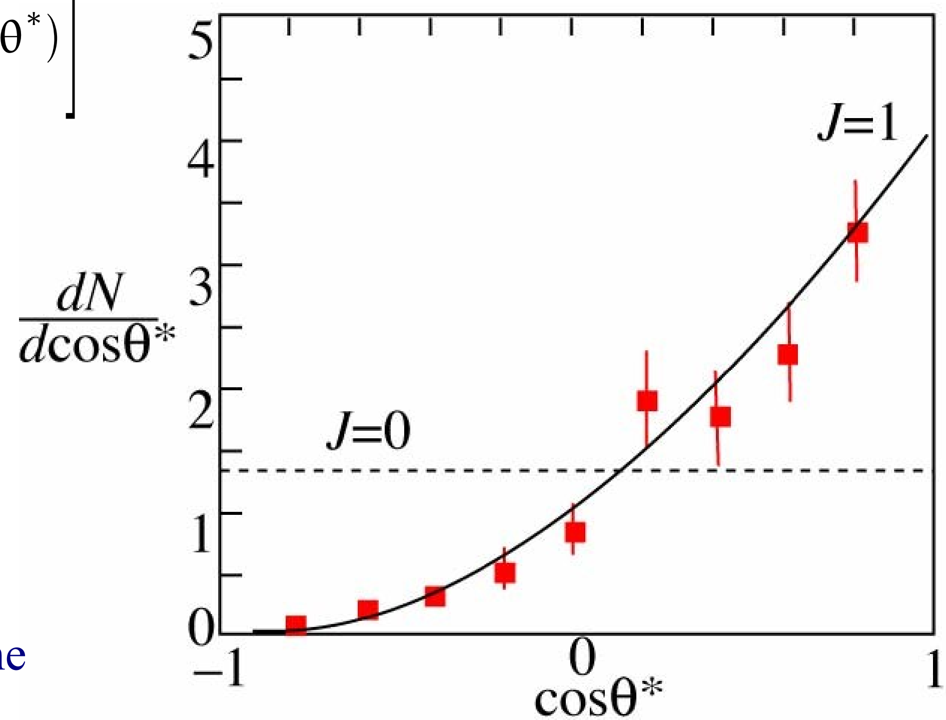
J_z (iniz.) = $\lambda = -1$

$J_{z'}$ (fin.) = $\lambda' = -1$

$$\frac{d\sigma}{d\Omega} \propto \left[d^1_{-1,-1} \right]^2 = \left[\frac{1}{2}(1+\cos\theta^*) \right]^2$$

If *V+A:*

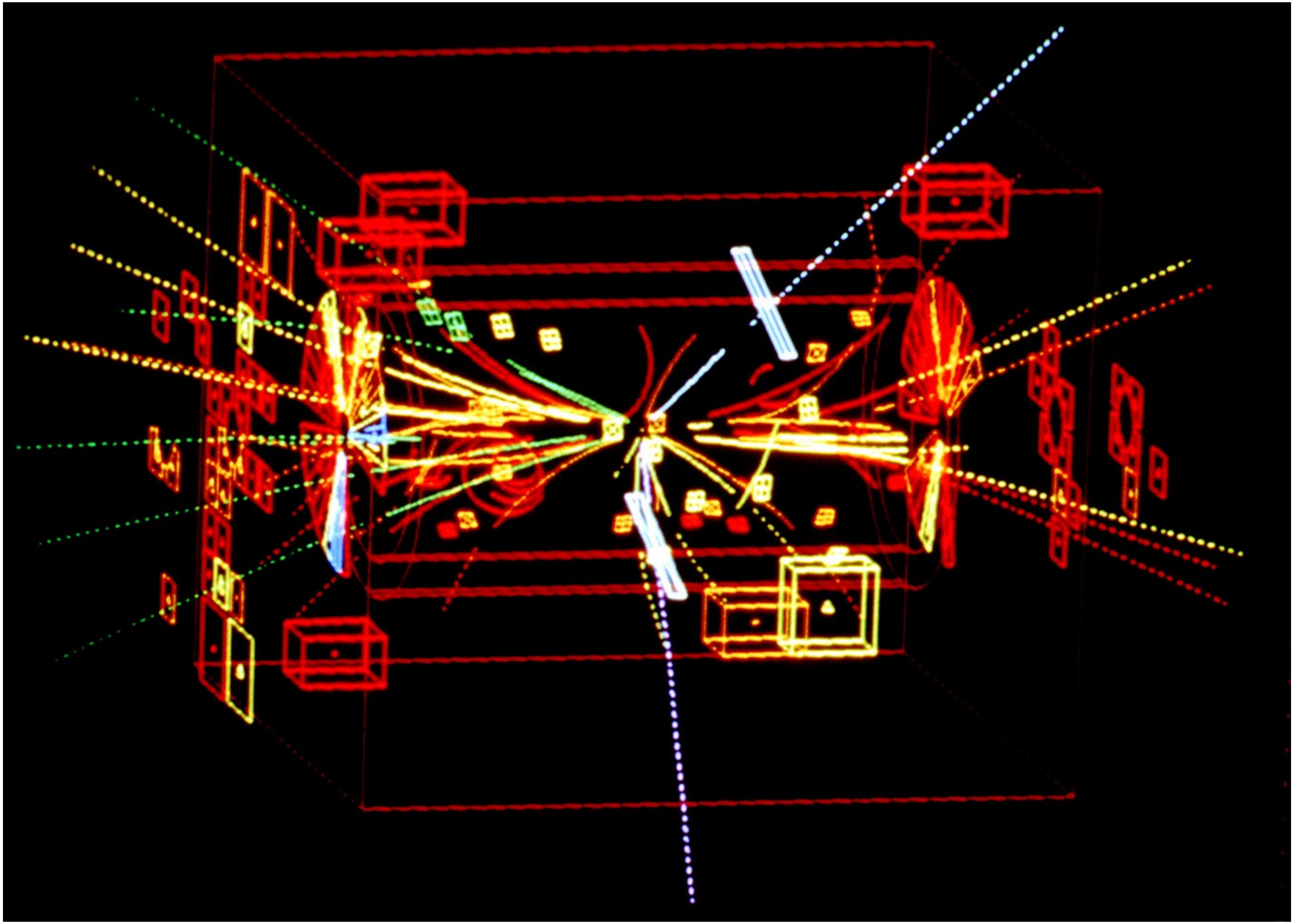
$$\frac{d\sigma}{d\Omega} \propto \left[d^1_{-1,-1} \right]^2 = \left[\pm\frac{1}{2}(1+\cos\theta^*) \right]^2$$



To distinguish between *V–A* and *V+A* are necessary measurements of the electron polarization

The forward-backward asymmetry is a consequence of the violation of the parity

UA1. The first Z



$Z \rightarrow e^+ e^-$

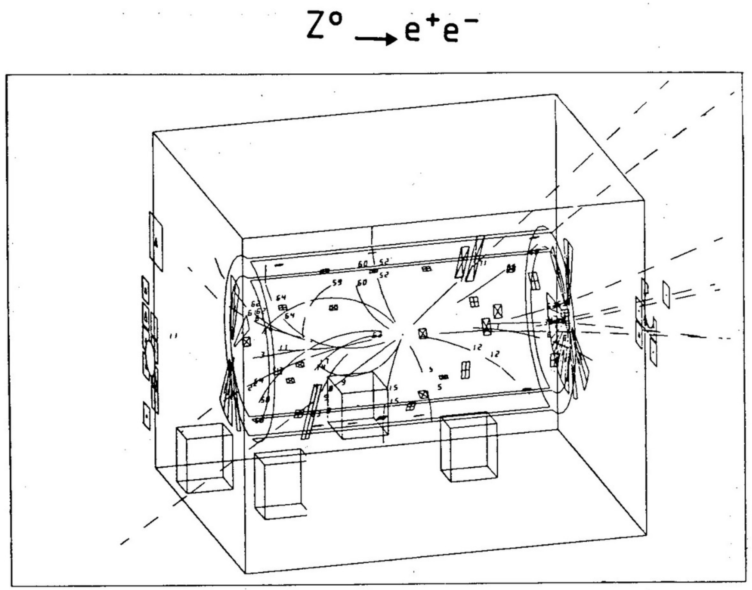
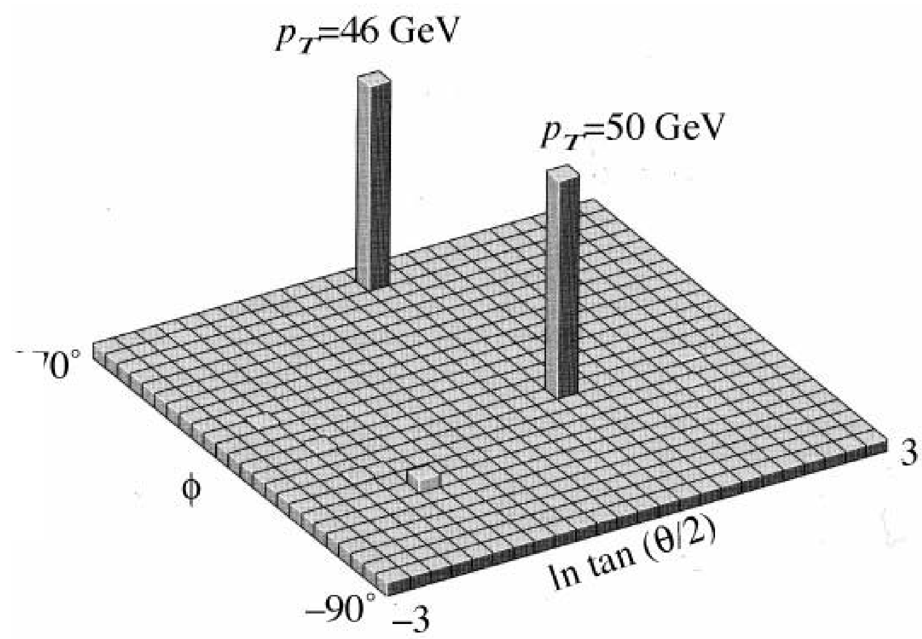


Fig. 25. Event display. All reconstructed vertex-associated tracks and all calorimeter hits are displayed.

In the electromagnetic calorimeters a Z appears as two localized energy deposit in two opposite directions



Cutting the traces with $p_T < 1$ GeV cleans completely the event, only the electron and the positron survive

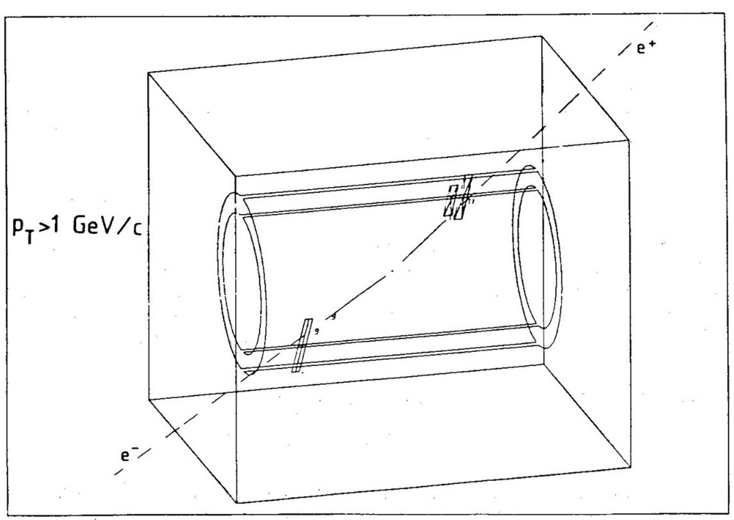


Fig. 26. The same as Fig. 25, but thresholds are raised to p_T>2 GeV/c for charged tracks and E_T>2 GeV for calorimeter hits. We remark that only the electron pair survives these mild cuts.

The central tracking detector immersed in a magnetic field measures the sign of the charge and the momentum

The EM calorimeters measure the e energy

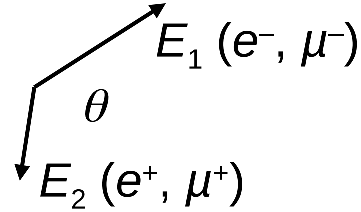
One knows that it is an electron because $E = p$

Measurement of M_Z

$$Z^0 \to e^+ e^-$$

$$m^2 = (E_1 + E_2)^2 - (\boldsymbol{p_1} + \boldsymbol{p_2})^2 = E_1^2 + E_2^2 + 2E_1E_2 - p_1^2 - p_2^2 - 2p_1p_2\cos\theta \simeq 2E_1E_2(1-\cos\theta)$$

$$m^2 \simeq 4E_1E_2\sin^2\theta/2 \qquad \frac{\sigma(m^2)}{m^2} = \sqrt{\left(\frac{\sigma(E_1)}{E_1}\right)^2 + \left(\frac{\sigma(E_2)}{E_2}\right)^2 + \left(\frac{\sigma(\theta)}{tg\,\theta/2}\right)^2}$$



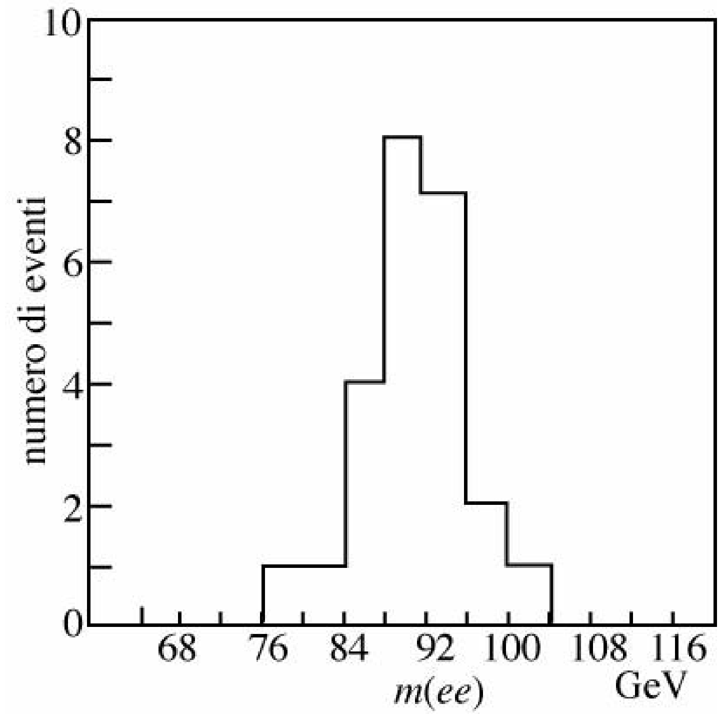
θ is in general large → $tg\theta/2 \approx 1$ usually $\sigma(\theta) \sim 10^{-2}$ → $\sigma(\theta)/tg\theta/2$ not so important

The uncertainty on the electron energies is the dominat one (calorimeter)

$$\frac{\sigma(E)}{E} = \frac{20\,\%}{\sqrt{E}}$$

$$\frac{\sigma(m^2)}{m^2} = \sqrt{2}\,\frac{\sigma(E)}{E} \approx 4-6\,\%$$

$$\frac{\sigma(m)}{m} = \frac{1}{2}\,\frac{\sigma(m^2)}{m^2} \approx 2-3\,\%$$



statistical error: **$\sigma(m) \approx$ 2-3 GeV**

energy scale error ≈3.1 GeV (UA1); **1.7 GeV** (UA2)

UA1 (24 $Z \to ee$) **M_Z=93.1±1.0(stat)±3.1(syst) GeV**

UA2 **M_Z=91.5±1.2(stat)±1.7(syst) GeV**