Introduction to Particle Physics

- Chapter 12 -

Experimental evidence of the Standard Model

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Chapter summary:

- Discovery of the neutral currents in the bubble chamber at CERN
- Forward-backward asymmetry in the process $e^+e^- \rightarrow \mu^+\mu^-$
- W and Z production at the SPPS collider at CERN
- The e^+e^- collider LEP at CERN
- Measurement of the Z properties: mass, total and partial widths
- Measurement of the number of light neutrino families
- W pair production at LEP
- Measurement of the triple gauge boson vertex

Neutral currents

- The Standard Model predicts the existence of neutral weak currents (Z exchange) which have an intensity comparable to the charged currents
- Let's recall that the neutral currents were already searched in the K decays, like for instance:

$$K^+ \to \pi^+ e^+ e^- \qquad \text{or} \qquad K_L^0 \to \mu^+ \mu^-$$

we can think that the lepton pairs is originated from the decay of a virtual Z (but it is not so!)

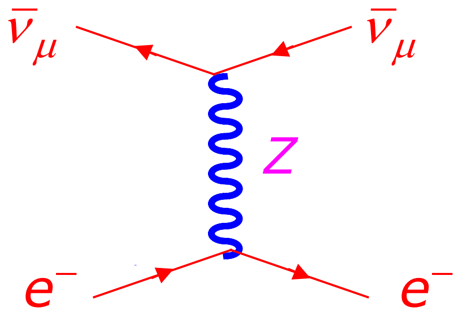
- Experimentally we observe that these decays are highly suppressed. At tree level we do not observe neutral current flavour changing
- The searches for neutral currents were almost abandoned, because if it is possible a Z exchange, it is also possible a photon exchange and the latter masks completely the Z exchange since the intensity of the e.m. interactions at low energy is much higher than the weak interactions one.
- The search for neutral currents had a new boost after the Standard Model prediction of their existence and by the work of Veltmann and 't Hooft that in 1970 proved that the theory was renormalizable.
- The only neutral current processes where it is possible to distinguish the Z exchange from the photon exchange are the neutrino interactions where the photon does not intervene.
- The discovery was done at CERN in 1973 by A.Lagarrigue and collaborators by using the bubble chamber Gargamelle filled with freon (CF_3Br). The chamber was exposed to neutrino and antineutrino beams obtained by in flight pion decays, so they contained mainly muon neutrinos
- The goal of the experiment was to find final states without muons, since muons are coming from charged current processes.
- The experiment proved the existence of the neutral currents, therefore of the Z, and permitted the very first measurement of the Weinberg angle: $\sin^2 q_W$ was between 0.3 and 0.4.

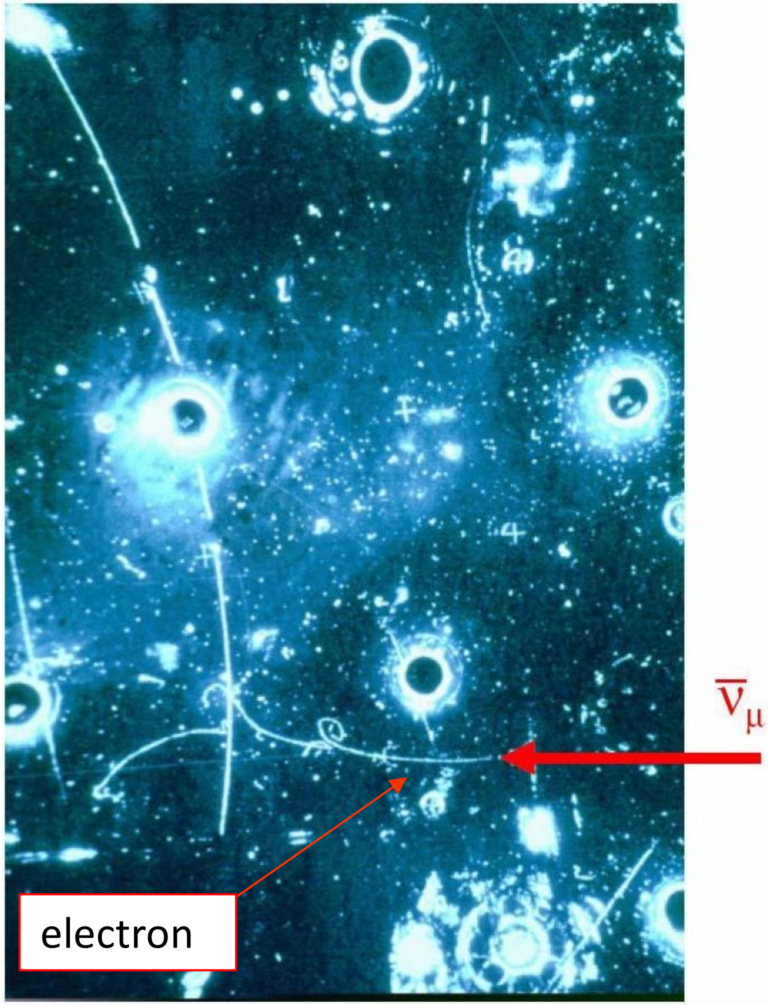
Neutral currents

- First event of neutral current: Gargamelle (1973)

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

This process can happen only through a Z exchange in the t channel.





- At CERN were observed 3 events of this type out of $1.4 \cdot 10^6$ beam pulses (accelerator cycles), with about 10^9 antineutrinos per cycle. The data taking lasted two years.
- The cross-section of the process is very small:

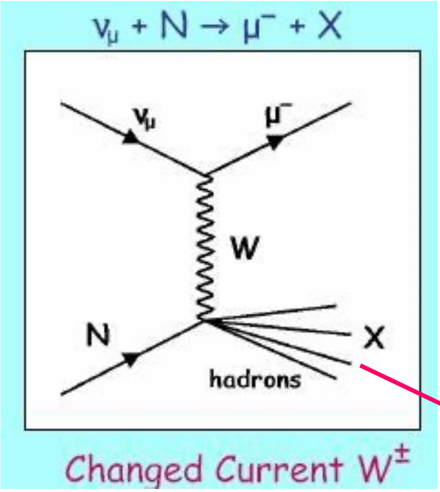
$$\frac{\sigma}{E_\nu} \approx 10^{-42} cm^2 \cdot GeV^{-1}$$

We observe an electron that start from "nothing" in the middle of the bubble chamber.

The eletctron is identified through its energy loss by bremsstrahlung (and the subsequent pair production by the photon)

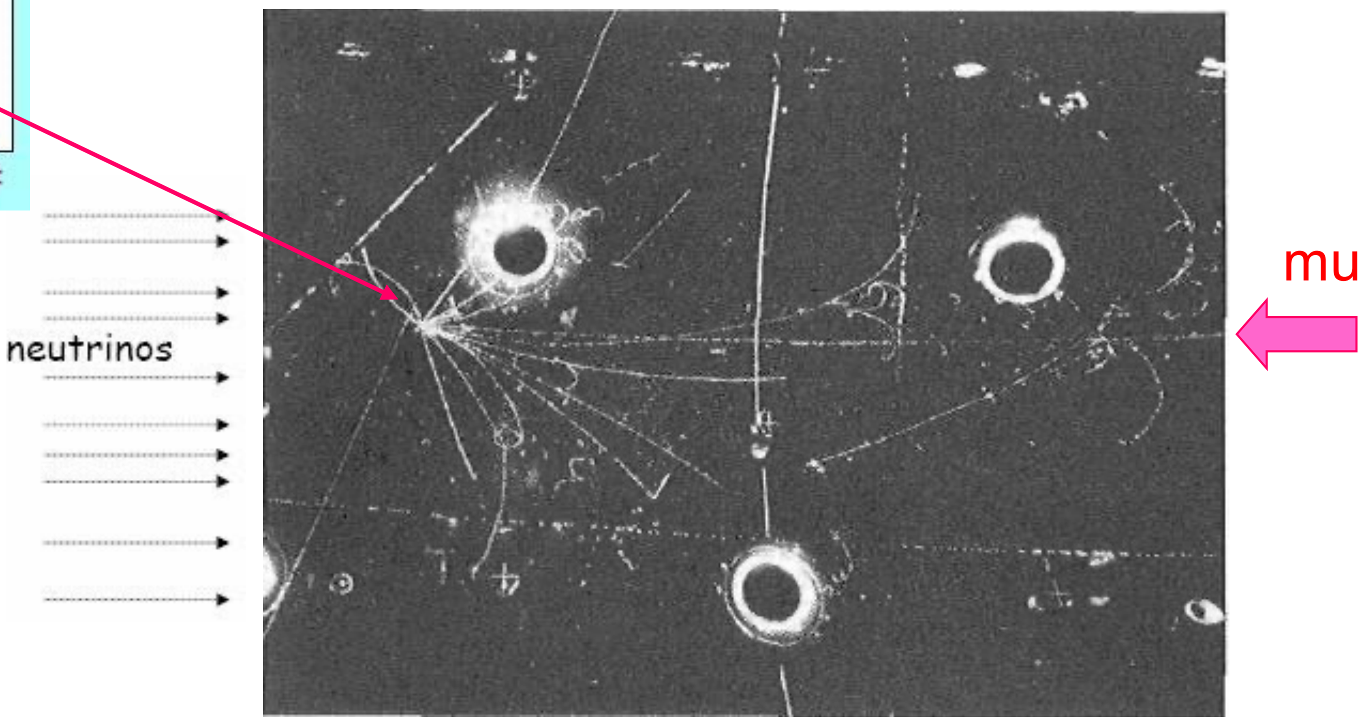
"hadronic" charge currents

- In the charged weak currents we have a W exchage. These are identified by the presence of a muon in the final state.
- The sign of the muon depends if the scattering is originated from a neutrino or an antineutrino.



$$\bar{\nu}_\mu + N \rightarrow \mu^+ + adroni$$

$$\nu_\mu + N \rightarrow \mu^- + adroni$$



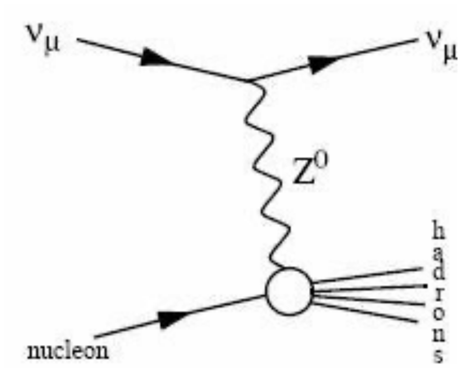
In the W coupling does not intervene the Weinberg angle, however it is important to measure these events along the neutral currents to get rid of some systematic errors in the neutral current cross-section measurement.

“hadronic” neutral currents

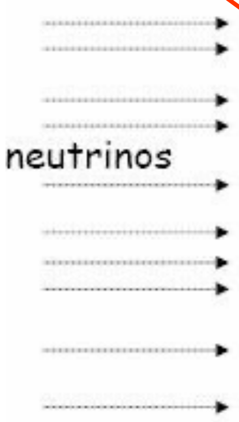
- In the same experiment were observed neutral currents through the scattering of a neutrino (or antineutrino) with a nucleon:

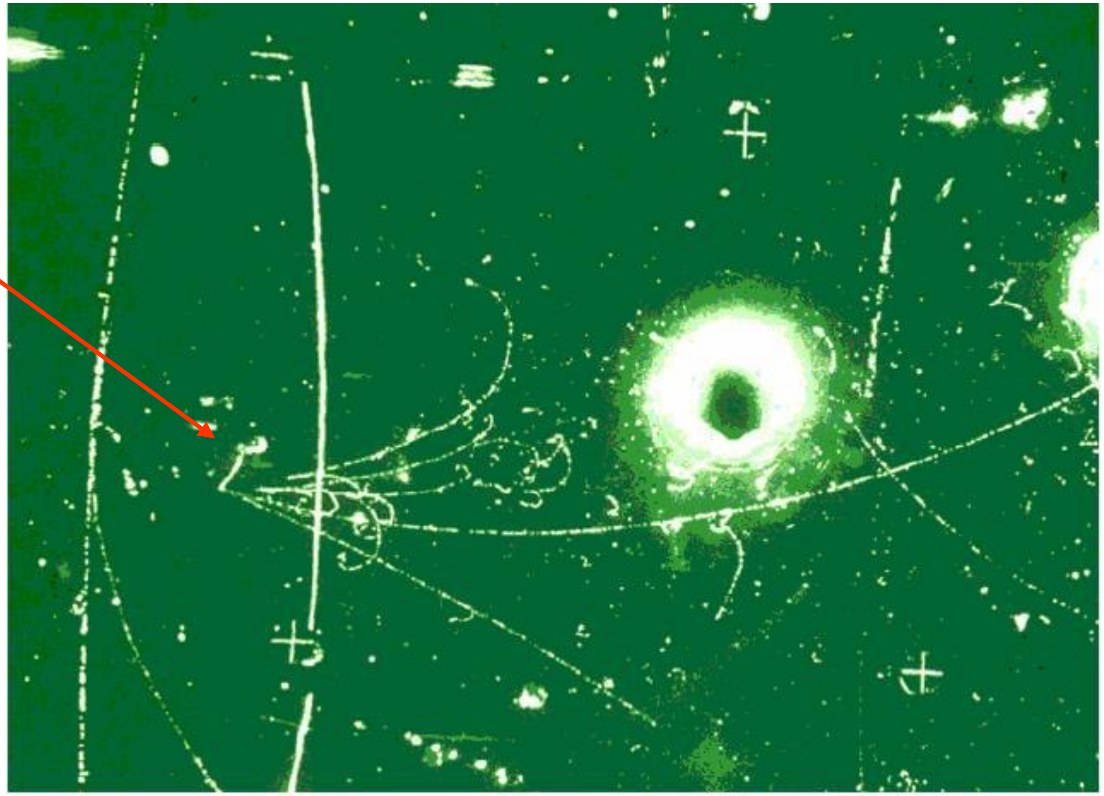
$$\nu_\mu + N \rightarrow \nu_\mu + adroni$$

$$\bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu + adroni$$



N.B. No muons in the final state





- The analysis was based on 83 thousand pictures of neutrino interactions and 207 thousand pictures of antineutrino events (in order to have the same statistical error). They had been found:

Neutrinos: 102 events of neutral currents and 428 events of charged currents

Antineutrinos: 64 events of neutral currents and 148 events of charged currents

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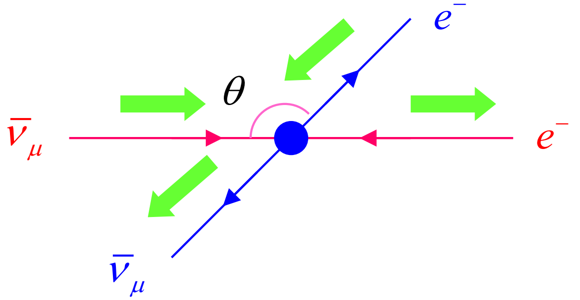
Neutrinos and antineutrinos interactions

- The neutrinos and antineutrinos cross-sections are difference due to their different helicity. Let's consider for instance the interaction with electrons or positrons. Let's suppose that the neutrinos have energy high enough (for instance higher than 1 GeV) that we can neglet the electron mass. In this condition also the electrons are lefthanded and the positrons righthanded.
- Let's analyse the scattering in the center of mass frame. We can have the following combinations:

$$\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$$



The initial state has Jz = 1

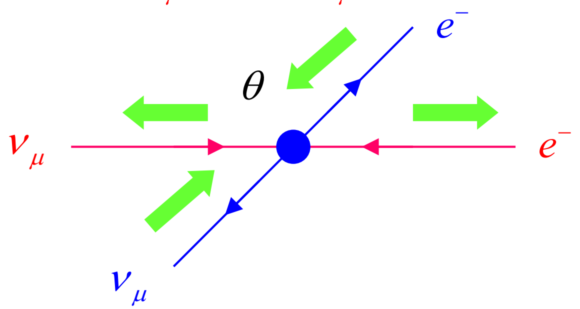
When ϑ=180, Jz=-1, therefore this configuration is not possible, so:

$$\frac{d\sigma}{d\Omega}(\bar{\nu}_\mu e^-) = \frac{d\sigma}{d\Omega}(\nu_\mu e^+) = \frac{G^2 s}{16\pi^2}(1+\cos\theta)^2 \quad \Rightarrow \sigma(\bar{\nu}_\mu e^-) = \sigma(\nu_\mu e^+) = \frac{G^2 s}{3\pi}$$

- The same is true for neutrino – positron scattering

- The total spin is 1, but only the projection Jz=1 contributes to the cross section, therefore we have a factor ⅓ with respect to the configuration with total spin equal to zero.

$$\nu_\mu + e^- \to \nu_\mu + e^-$$



The initial state has Jz = 0

In this case the differential cross section is isotropical, so:

$$\frac{d\sigma}{d\Omega}(\nu_\mu e^-) = \frac{d\sigma}{d\Omega}(\bar{\nu}_\mu e^+) = \frac{G^2 s}{4\pi^2} \quad \Rightarrow \sigma(\nu_\mu e^-) = \sigma(\bar{\nu}_\mu e^+) = \frac{G^2 s}{\pi} \approx \frac{2G^2 mE}{\pi}$$

- The same is true for antineutrino – positron scattering
- The same is true for antineutrino – positron scattering

$$\Rightarrow \frac{\sigma(\bar{\nu}_\mu e^-)}{\sigma(\nu_\mu e^-)} = \frac{\sigma(\nu_\mu e^+)}{\sigma(\bar{\nu}_\mu e^+)} = \frac{1}{3}$$

Measurement of $\sin\vartheta_W$

- From the comparison of the cross-sections of charged and neutral currents we can get $\sin\vartheta^2_W$
- Let's recall that the vectorial coupling of the Z with the fermions depends on $\sin\vartheta^2_W$:

$$C_V^f = I_3^f - 2Q^f \sin^2\theta_W \quad ; \quad C_A^f = I_3^f$$

- Experimentally we measure the ratio between the neutral and charged currents cross-section; in this way we don't need to know the neutrino flux that is the same in both cases.
- If we ignore the scattering on the antiquarks present in the sea (it is a correction of the order 10-20%), we have the following predictions:

$$R_\nu = \left(\frac{NC}{CC}\right)_\nu = \frac{1}{2} - \sin^2\theta_W + \frac{20}{27}\sin^4\theta_W$$

$$R_{\bar\nu} = \left(\frac{NC}{CC}\right)_{\bar\nu} = \frac{1}{2} - \sin^2\theta_W + \frac{20}{9}\sin^4\theta_W$$

- The Gargamelle data, once subtracted the background events (due for istance to the neutrons produced by neutrino interactions with the bubble chamber wall that interact afterward inside the bubble chamber faking a neutral current event), gave the result:

$$\sin^2\theta_W = 0.3 \div 0.4$$

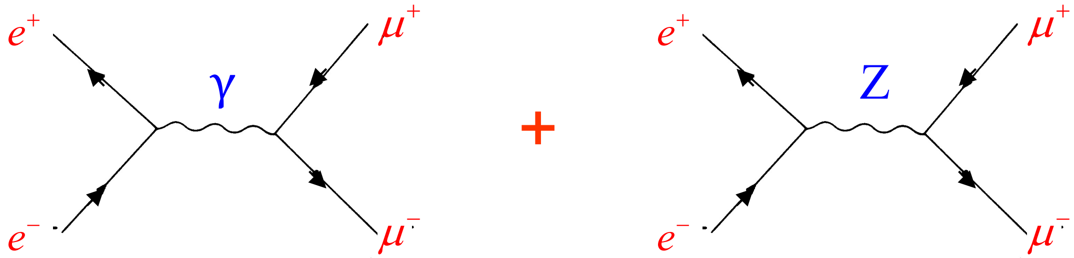
- Other neutrino experiments carried out in the following years, based on "electronic" detectors, measured the electron scattering that does not suffer about the nucleon composition, aive as a result:

$$\sin^2\theta_W = 0.231 \pm 0.010$$

- We will see that at LEP was reached a precision in the determination of $\sin\vartheta^2_W$ such to verify the radiative corrections of this parameter.

Asymmetries in the process $e^+e^- \rightarrow \mu^+\mu^-$

- The process $e^+e^- \rightarrow \mu^+\mu^-$ can be described, at tree level, by the following two Feynman diagrams:



- To compute the cross-section we need to sum the amplitudes of the two processes:

$$\sigma \propto \left|A_\gamma + A_Z\right|^2 = \left|A_\gamma\right|^2 + \left|A_Z\right|^2 + 2\,\mathrm{Re}\left(A_\gamma \cdot A_Z^*\right)$$

- This proces was studied in particular at the Petra collider at DESY (Hamburg) around 1980
- At a center of mass energy √s of 34 GeV, the values of the three terms are about:

$$\left|A_\gamma\right|^2 \approx 100\ \mathrm{p}b \quad ; \quad \left|A_Z\right|^2 \approx 0.15\ \mathrm{p}b\ ; \ 2\,\mathrm{Re}\left(A_\gamma \cdot A_Z^*\right) \approx 8\ \mathrm{p}b$$

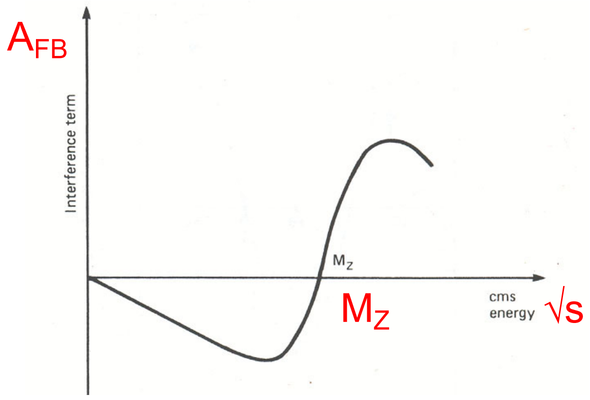
- As we see the interference term gives a sizeable contribution; it manifests as an energy dependent asymmetry in the differential cross-section of the process (we recall that the e.m. interactions do not violate parity while the weak interactions do).
- It is defined a forward-backward asymmetry in the following way:

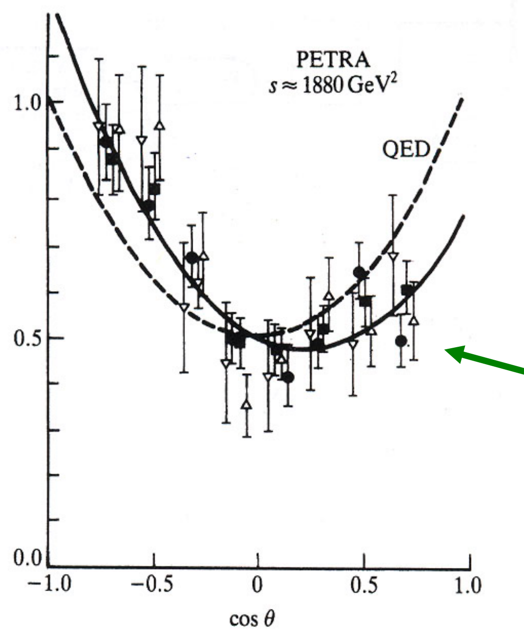
$$A(s) = \frac{N_F - N_B}{N_F + N_B}$$

where N_F and N_B are the number of events that have a positive muon in the forward or in the backward hemisphere (defined with respect to the positron line of flight)

Asymmetries in the process $e^+e^- \to \mu^+\mu^-$

The interference term, and then the forward-backward asymmetry, is a function of √s. At the Z mass the asymmetry is zero and then it changes sign.





- When √s << Mz , as it was at Petra, the forward-backward asymmetry has the following dependency on the Z coupling cnstants with the fermions:

$$A(s) = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = -\frac{3s}{4\sqrt{2}\pi\alpha} C_A^e C_A^\mu$$

Angular distribution of the process $e^+e^- \to \mu^+\mu^-$ at √s≈43 GeV. The best fit at the distribution give the asymmetry:

$$A(s) = \frac{N_F - N_B}{N_F + N_B} = -0.18 \pm 0.2$$

- The forward-backward asymmetry depends only on the axial coupling that does not contain the Weinberg angle (C_A=I_3). However from the cross-section measurements (total and/or differential) compared with the QED one (only photon exchange) it is possible to determine the Weinberg angle. From these data we get:

$$\sin^2\theta_W = 0.210 \pm 0.019\ \text{(stat.)} \pm 0.013\ \text{(syst.)}$$

- From this value of $\sin^2\vartheta_W$ and from M_Z measured in other experiment, we can derive C_A^2 (assuming lepton universality) and compare the result with the SM prediction (C_A=I_3=-1/2).

W and Z discoveries

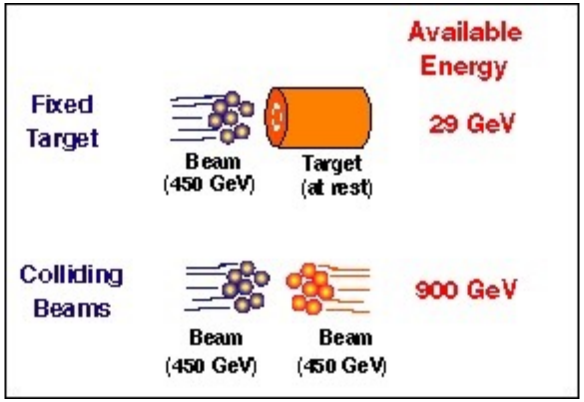
• The neutral current discovery was a great evidence in favor of the Standard Model; since in 1978 Glashow, Weimberg and Salam got a Nobel prize for the SM foundation.

• **However the definite proof in favor of the Model would have been the discovery of the W and Z.**

• Let's recall what were the mass values expected for these particles after the neutral current discovery:

$$M_W = \sqrt{\frac{g^2\sqrt{2}}{8G}} \approx \frac{37.4}{\sin\theta_W} = \frac{37.4}{\sqrt{0.23}} \approx 78 \text{ GeV} \quad ; \quad M_Z = \frac{M_W}{\cos\theta_W} \approx 89 \text{ GeV}$$

• In 1976 started to work at CERN the SPS, a proton accelerator with energy up to 450 GeV. However the center of mass energy was not sufficient to produce the W or Z. (At Fermilab in the same years there was another accelerator slightly more powerful (500 GeV) but still not sufficient).



• Rubbia proposed to transform the SPS in a proton-antiproton collider likewise an e^+e^- collider. The proposal did not receive very much consensus because there was no way to accumulate enough antiproton to ensure a sufficient luminosity to produce the W and the Z in a reasonable amount of time.

• The problem was solved by Simon van der Meer who proposed (invented) the stocastic cooling to reduce the emittance of the antiprotons in order to increase the luminosity.

• In 1978 was launched the project SppS (270 + 270 GeV).

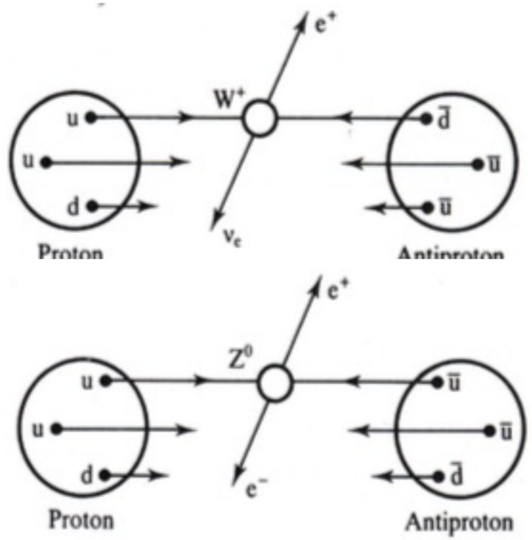
• In 1982-83 were produced the first W and Z found by the detector UA1 (Rubbia) and UA2.

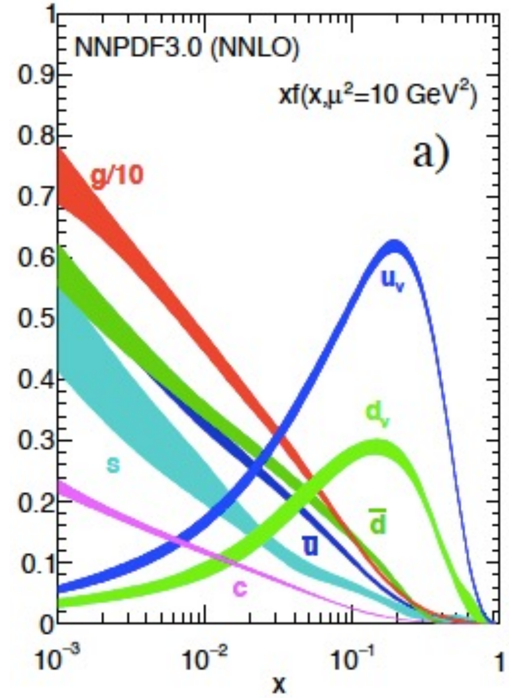
• **1984: Nobel prize to Rubbia and van der Meer**

W and Z discoveries

- Proton and antiproton are not elementary particles but they are composed system; besides the valence quarks, there also quarks and antiquarks belonging to the sea and the gluons.
- The collision takes place between a parton of the proton and a parton of the antiproton. The partons do not have a fixed momentum but we are dealing with a probability distribution that the parton carries a given fraction of the proton momentum.
- As a consequence also the center of mass energy is not defined; moreover the center of mass is not at rest in the Lab frame but it moves along the beam direction. The transvers moment is null (infinite momentum frame approximation).
- In average the parton center of mass energy is about 1/6 of the collider energy (roughly 50% of momentum is carried by quarks and 50% by gluons and in average a valence quark has 1/3 of the quark momentum share, so it gives 1/6 as we see in the graph). Since the collider center of mass energy was 540 GeV, it gives 90 GeV that was sufficient to produce a W or a Z.
- However to compute the parton luminosity we have to know the pdf of the partons inside the proton shown in the picture, but in 1982 they were not known very precisely, so the theoretical prediction about the cross-section production of W and Z at the SppS were affected by a big systematic error due to the pdf knowledge.
- In any case a very plausible calculation gave for the cross-sections:

$$\sigma_{W^\pm} \approx 4 \text{ nb} \quad ; \quad \sigma_Z \approx 2 \text{ nb}$$



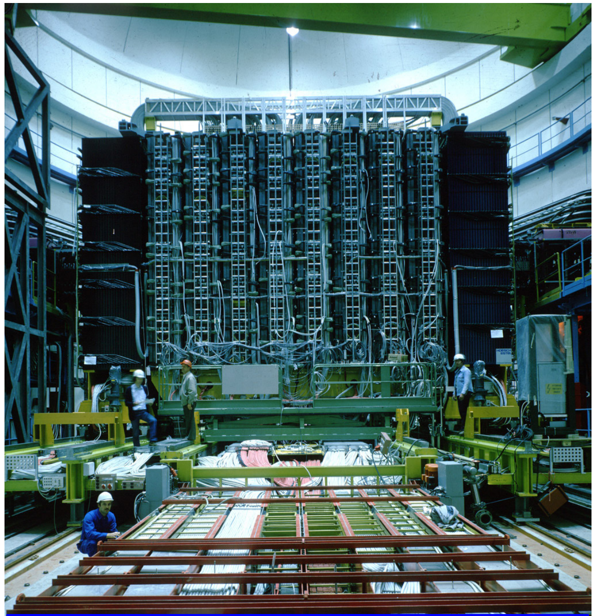


W discovery in 1982

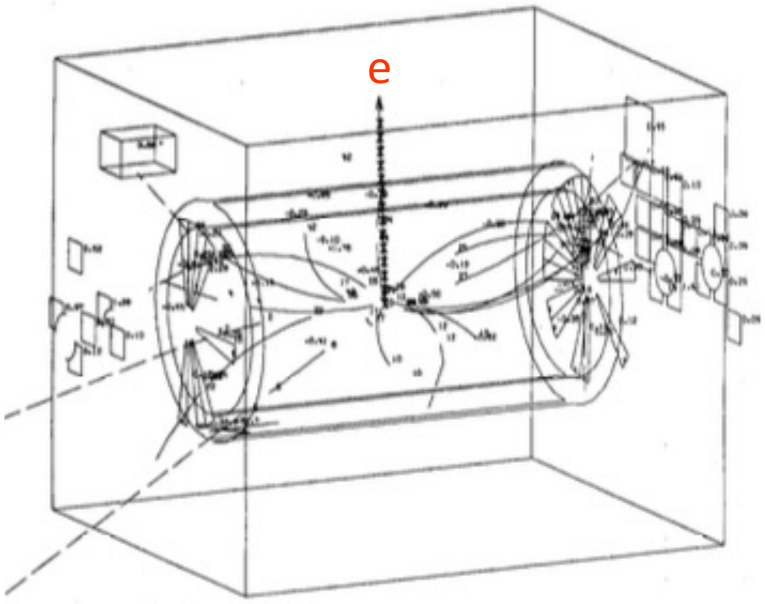
- The SppS was equipped with two detectors: UA1 (C.Rubbia) and UA2 (P.Darriulat).
- UA1 had a dipolar magnetic field that allowed to measure the charged tracks momentum in the central chamber, electromagnetic and hadron calorimeters surrounded by muon chamber to measure muons.
- In November-December 1982 UA1 (as well as UA2) collected an integrated luminosity of 18 nb^{-1}, corresponding roughly to 10^9 proton-antiproton collisions at $\sqrt{s}$=540 GeV.
- They were found 6 events of the type: $p\bar{p} \rightarrow W + \text{anything}$

$$W \rightarrow e + \nu$$

- The event topology consisted in one isolated electron with a high transverse momentum (with respect to the beam axis) in addition to a big missing transverse momentum (due to the neutrino).



UA1 detector (C.Rubbia)



- The clear experimental signature, with a little background, allowed to measure the W mass even with the very few events available:

$$M_W = 81 \pm 5\ GeV$$

- The analysis of the events with a muon and UA2 experiment confirmed this result.

PDG 2016: $M_W = (80.385 \pm 0.015)$ GeV

$$\Gamma_W = (2.085 \pm 0.042)\ \text{GeV}$$

Z discovery in 1983

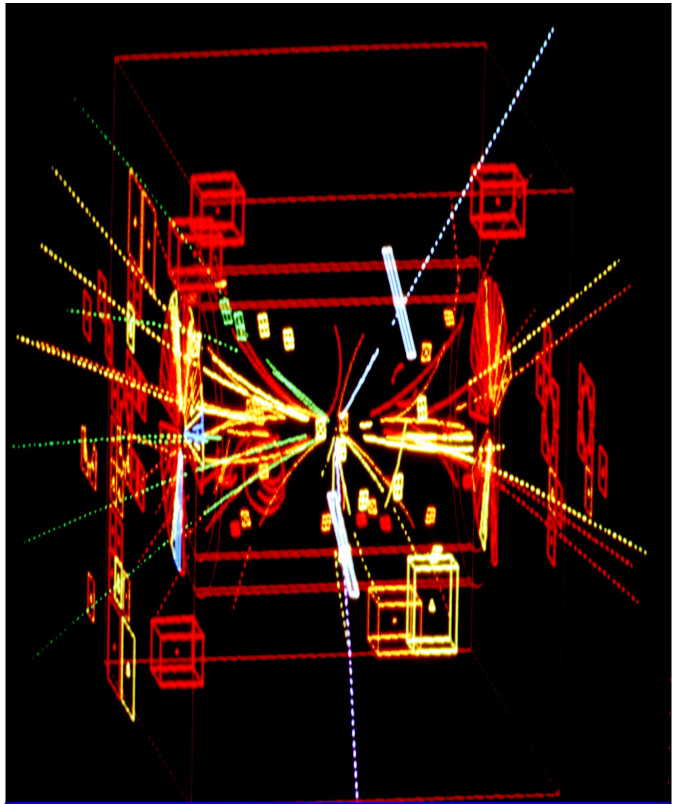
- In 1983 the detectors UA1 and UA2 observed a few Z decays:

$$p\bar{p} \to Z + \text{anything}$$

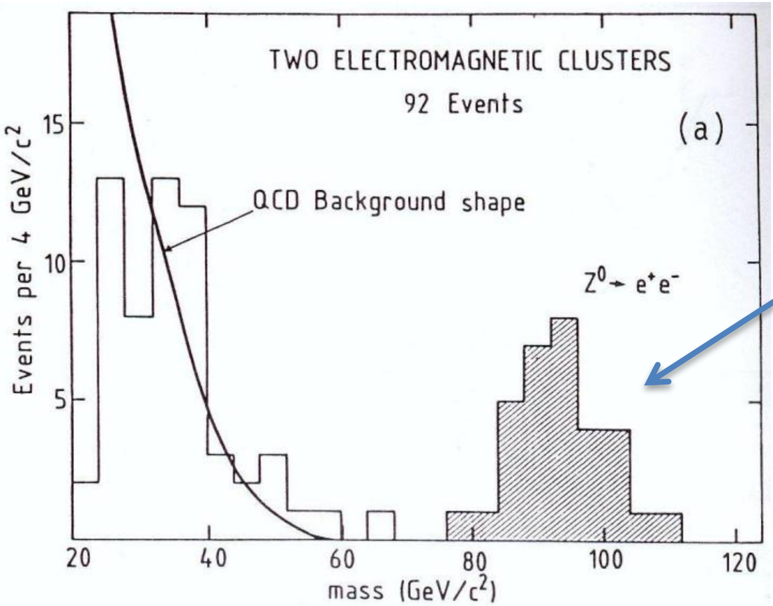
$$Z \to e^+e^- \quad \text{or} \quad \mu^+\mu^-$$

- *event topology*: two isolated charged leptons with high p_T, opposed electric charge and no missing momentum (no neutrinos).
- *background* : almost negligeable
- N.B. The Z experimental signature is "easier" than the one of the W, but its cross-section is smaller than the W's one, that's why it has been observed first the W and then the Z. Moreover:

$$\text{B.R. } Z \to \ell^+\ell^- = 3.4\% \quad ; \quad \text{B.R. W} \to \ell\nu = 10.7\%$$



Z→$\mu^+\mu^-$ in UA1: computer reconstruction



The Z peak is "around" 90 GeV. From the fit we get:

$$M_Z = 95.6 \pm 1.4 \pm 2.9 \ \ GeV$$

PDG 2016: $M_Z = (91.1876 \ \pm \ 0.0021)$ GeV

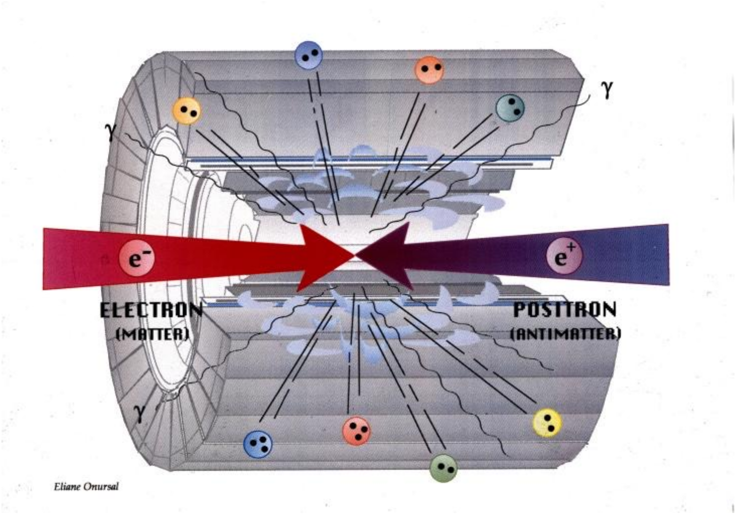
$\Gamma_Z = (2.4952 \pm 0.0023)$ GeV

The LEP

- In 1981 the CERN decided to built the largest accelerator in the world: the LEP. It was an electron-positron collider with a circumference 27 km long.
- In 1983 begins the tunnel excavation. The gallery has a diameter of 3.8 m and it is located at about 100 m underground.
- In 1988 the tunnel was completed. At that time it was the longest tunnel in Europe, surpassed now by the train tunnel under the English Channel (La Manica).

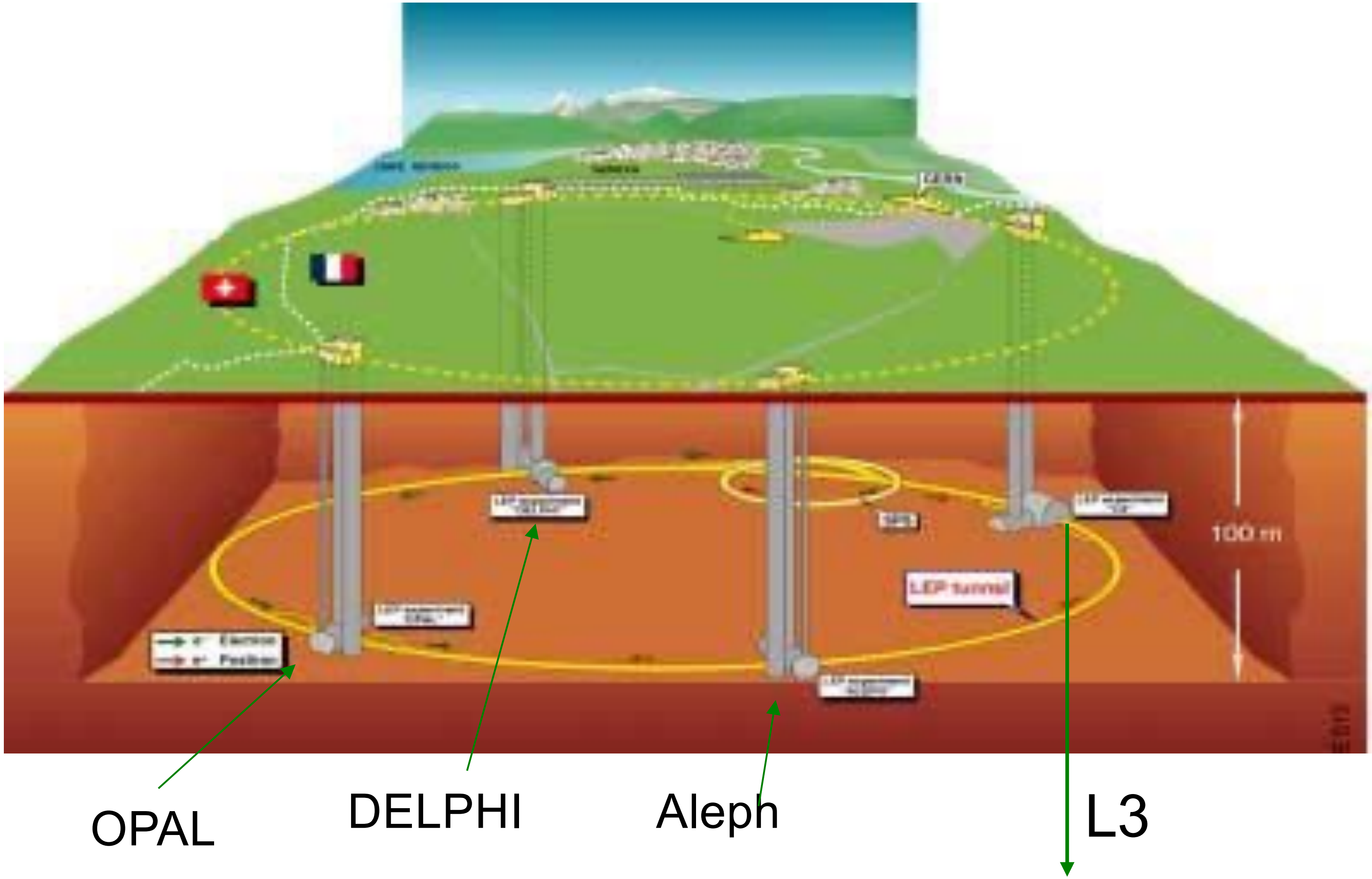
- The electrons, contrary to the protons, are elementary particles, therefore the electron-positron interaction is by far cleaner than the proton-antiproton interaction. The initial state is perfectly known and the Standard Model predictions can be verified with higher accuracy.

- The LEP scientific goal were (taken from my thesis [1988]):
  - Higgs boson discovery;
  - quark top discovery and measurement of the topponium energy levels;
  - Supersymmetric particles discovery;
  - Measurement of the Z mass with an error of 50 MeV;
  - precision measurement of the Standard Model parameters;
  - measurement of the number of light neutrino families;
  - Lep2: measurement of the W mass and check of the triple gauge boson coupling.

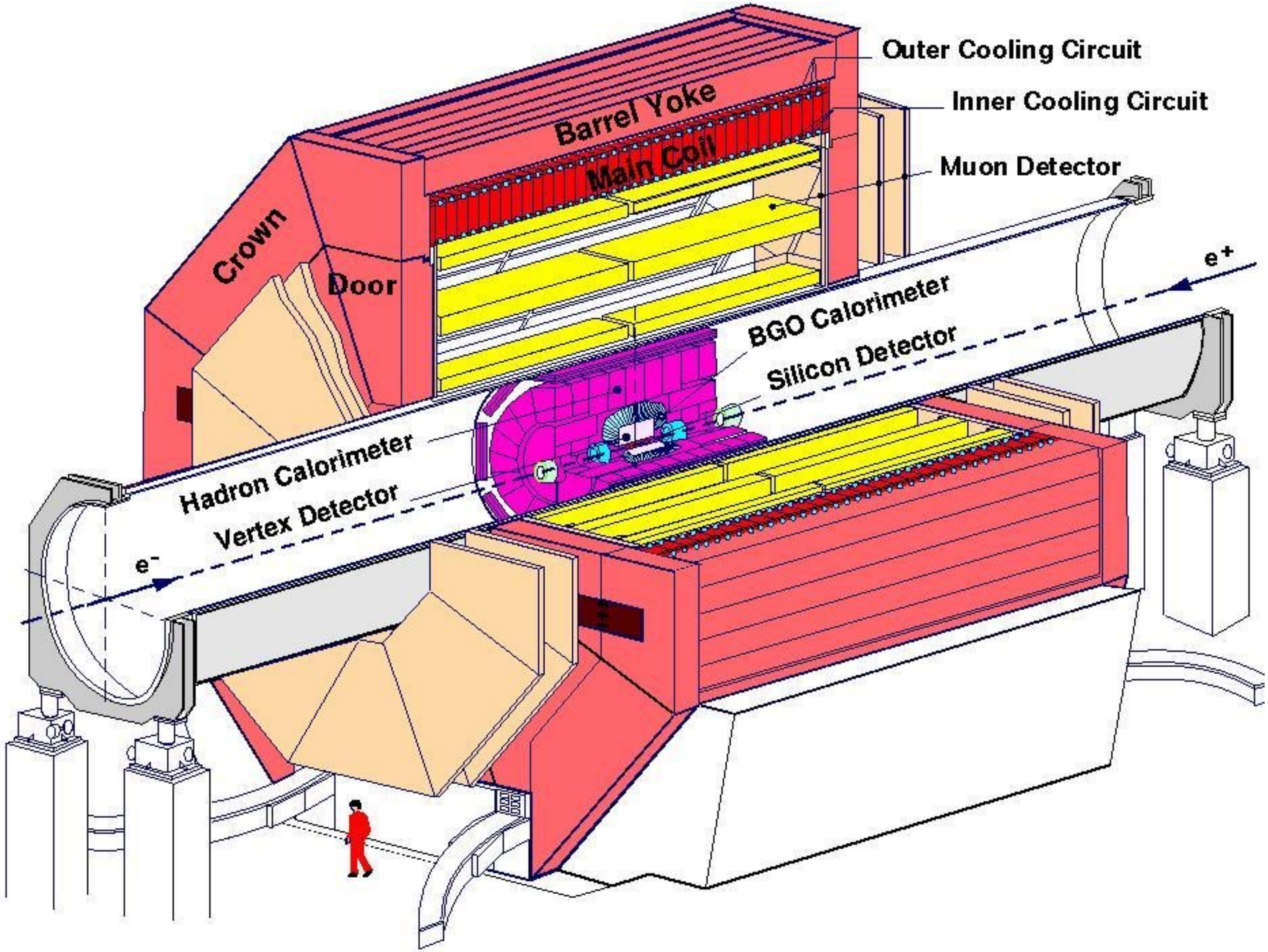


The center of mass energy is all available to create new particles: $E=mc^2$

LEP and the experiments



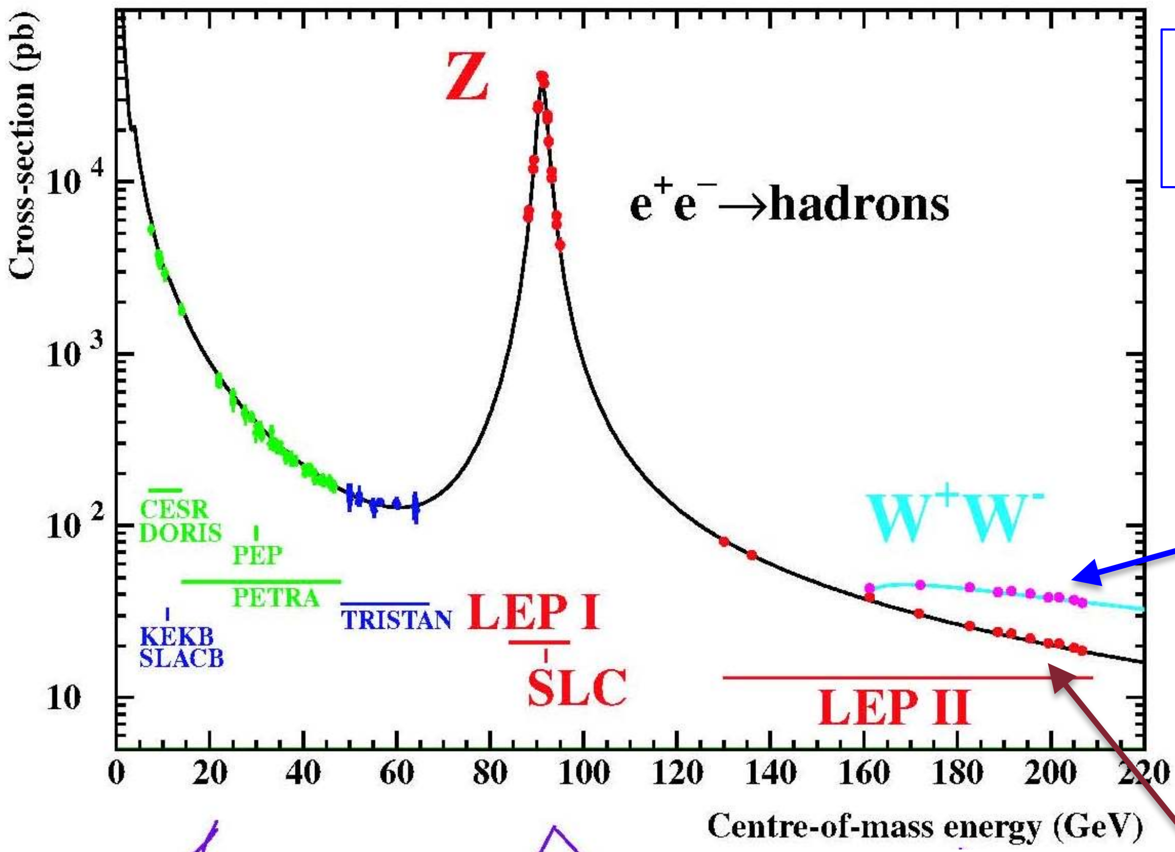
The L3 detector

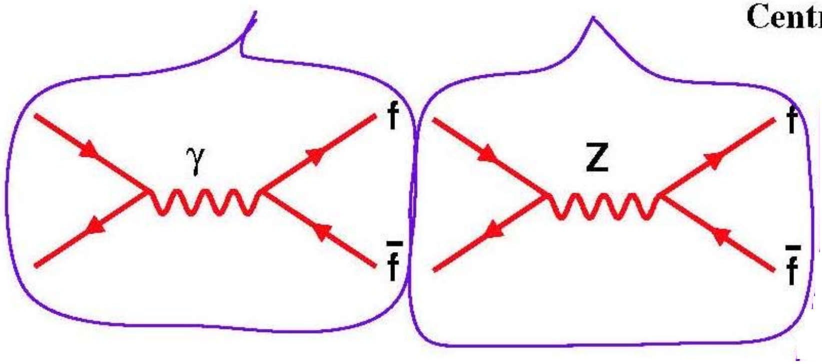


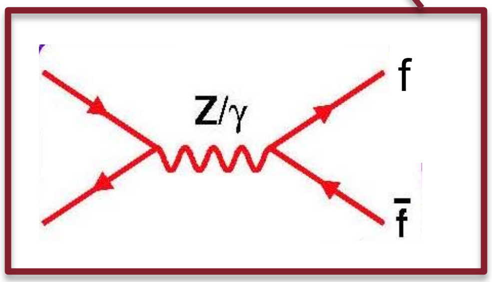
Cross-section as a function of √s

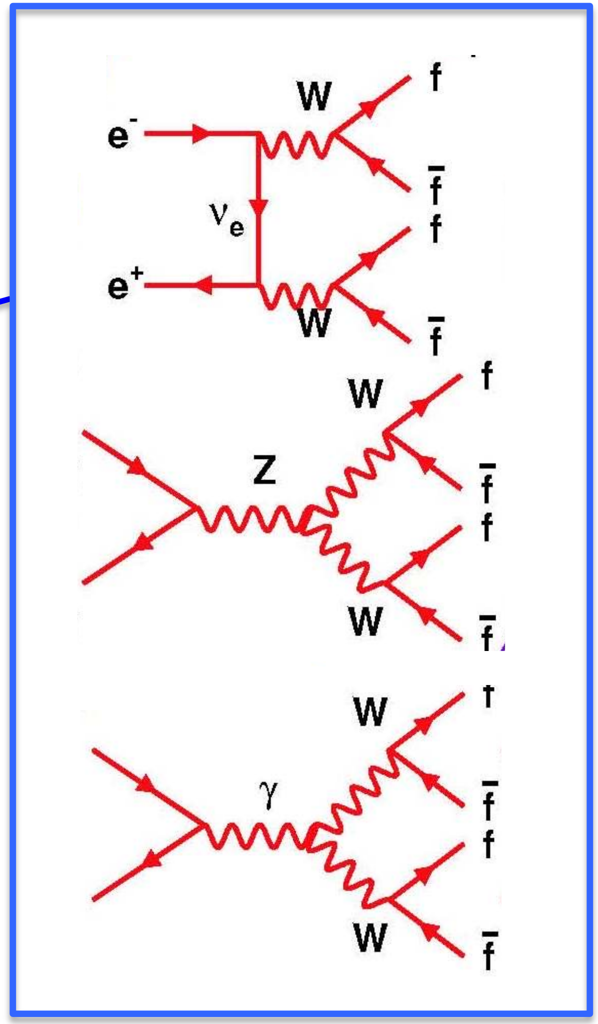
LEP collected 4.5 million Z,

12 thousand WW per experiment



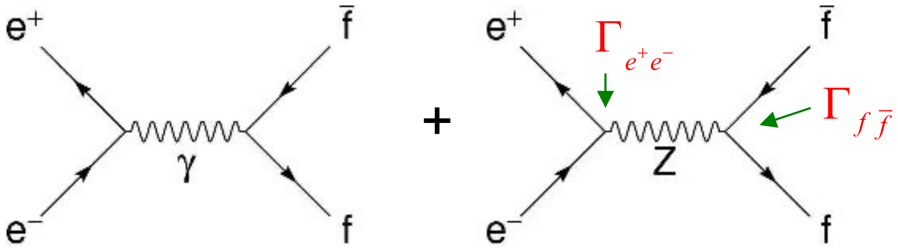






$e^+e^- \rightarrow f\bar{f}$ at $\sqrt{s} \approx M_Z$

- Tree level Feynman diagrams of the process $e^+e^- \rightarrow \mu^+\mu^-$:



$$\sigma \propto |A_\gamma + A_Z|^2 = |A_\gamma|^2 + |A_Z|^2 + 2\,\mathrm{Re}(A_\gamma \cdot A_Z^*)$$

- At $\sqrt{s} \approx M_Z$ the photon contribution and the intereference term are only a few per cent of the total cross-section of the process. The photon exchange can be computed theoretically with great precision (QED) while for the interference term is assumed as valid the Standard Model to carry on the calculation. The Z exchange is parameterized in a model independent way in order not to rely on the Standard Model:

$$\sigma_{q\bar{q}} = \frac{12\pi}{M_Z^2} \frac{s\Gamma_{e^+e^-}\Gamma_{q\bar{q}}}{(s - M_Z^2)^2 + \frac{s^2\Gamma_Z^2}{M_Z^2}}$$

- Γ_Z is the Z total width = 2.4952±0.0023 GeV
- Γ_{ff} is the partial width of the Z decay in the channel $f\bar{f}$

$$\Gamma(Z \rightarrow l^+l^-) = 2\frac{GM_Z^3}{\sqrt{2}\cdot 12\pi}\left[(C_V^l)^2 + (C_A^l)^2\right]$$

The Z couplings C_V and C_A enter in the partial widths

$$\Gamma(Z \rightarrow q\bar{q}) = 6\frac{GM_Z^3}{\sqrt{2}\cdot 12\pi}\left[(C_V^l)^2 + (C_A^l)^2\right]$$

(The factor 3 is due to colour)

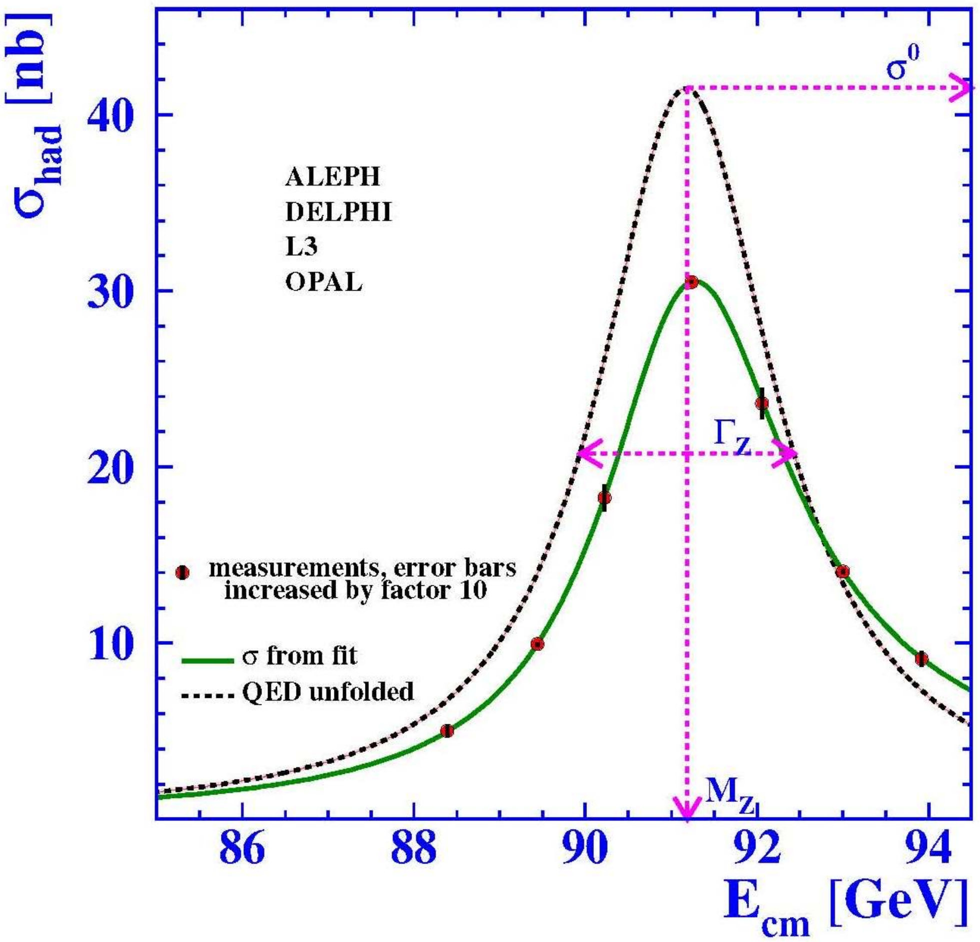
$$\Gamma_Z = \Gamma_{\text{charged leptons}} + \Gamma_{\text{hadrons}} + N_\nu \cdot \Gamma_{\nu\bar{\nu}}$$

Measurement of the Z mass (line shape)

$$\sigma_{q\bar{q}} = \frac{12\pi}{M_Z^2} \frac{s\Gamma_{e^+e^-}\Gamma_{q\bar{q}}}{\left(s - M_Z^2\right)^2 + \frac{s^2\Gamma_Z^2}{M_Z^2}}$$

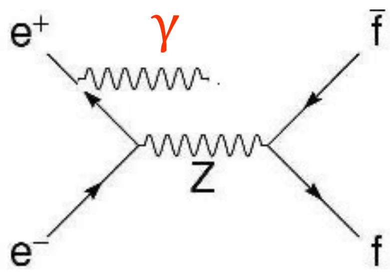
- The cross-section has a strong dependen on the center of mass energy. The strategy to measure the Z mass consisted to mesure the hadronic cross-section at a few energies around the peak and then make a fit.
- The dominant systematic error on the Z mass was due to the knowledge of the beam energy.
- In an e^+e^- collider the center of mass energy is known with great precision. In 1989 the LEP accelerator physicists thought that was possible to measure the beam energy with a precision such to have an error on the Z mass about 50 MeV. Afterward they applied several "tricks" to improve the measurement by an order of magnitude. The final result permitted to measure the Z mass with an error of 2 MeV.
- The fit has to take into account the QED radiation emitted by the inital state (the electron or the positron emits a photon before colliding) that reduces the effective center of mass energy.

$$M_Z = 91.1875 \pm 0.0021 \text{ GeV}$$

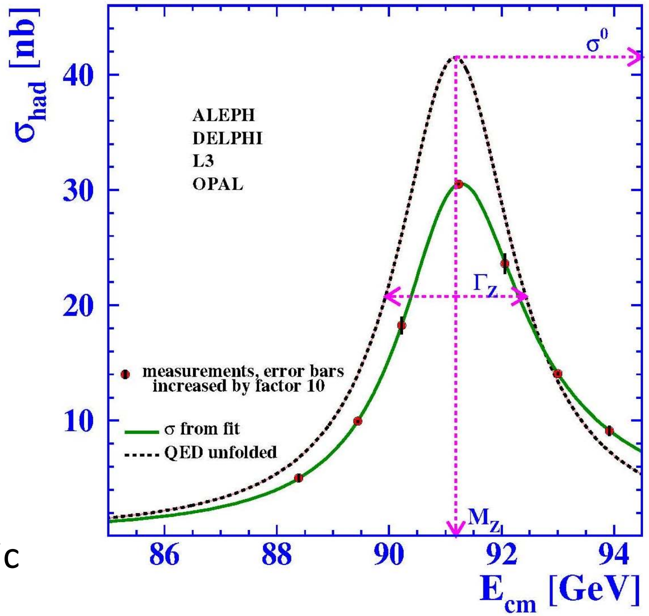


$$\frac{\Delta M_Z}{M_Z} = \pm 2.3 \cdot 10^{-5}$$

Mesurement of the Z partial widths



The emission of a photon from the inital state lower the effective center of mass energy. This effect is taken into account in the fit by a "radiator" function (it is a pure QED effect and can be computed with great precision).



$$\sigma_{q\bar{q}} = \frac{12\pi}{M_Z^2} \frac{s\Gamma_{e^+e^-}\Gamma_{q\bar{q}}}{\left(s-M_Z^2\right)^2 + \frac{s^2\Gamma_Z^2}{M_Z^2}} \quad \xrightarrow{s=M_Z^2} \quad \sigma^0_{q\bar{q}} = \frac{12\pi}{M_Z^2}\frac{\Gamma_{e^+e^-}\Gamma_{q\bar{q}}}{\Gamma_Z^2}$$

- To measure the partial widths of the Z decays in the various fermionic channels, we need to measure the cross-section at the peak:
- We select the following channels:

$$Z \to q\bar{q}$$
$$Z \to \mu^+\mu^-$$
$$Z \to \tau^+\tau^-$$
$$Z \to e^+e^-$$

1. Peak cross-section;
2. Partial width;
3. Z couplings

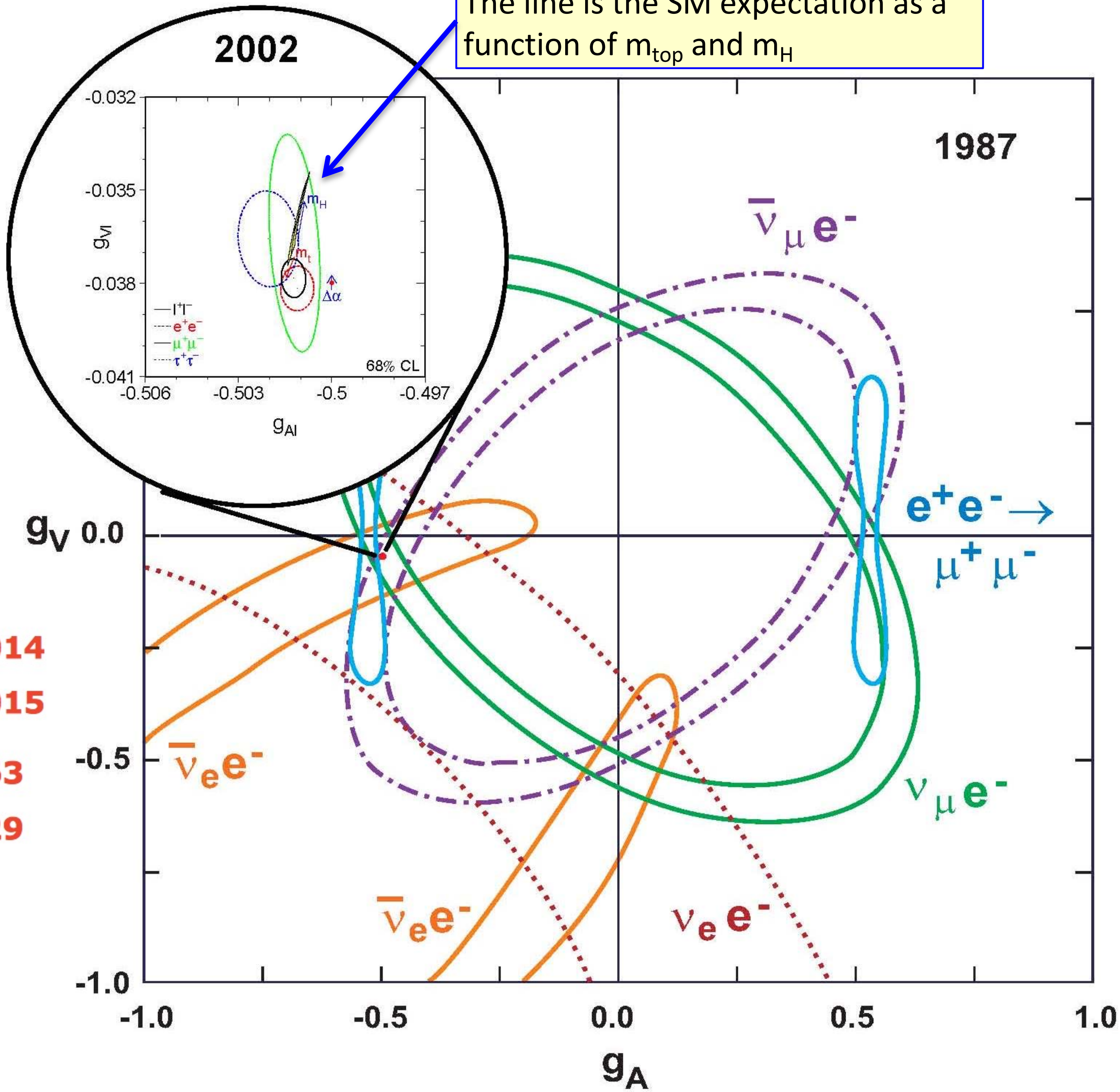
- N.B. The total width Γ_Z is the same in all channels; from a channel to the other does not change the resonance shape but only the peak value;
- N.B. the electron channel is more complicated because there is also the photon exchange in the t channel;
- N.B. in the hadron channel it is possible to distinguish the b quark from its impact paramenter (B_0 mesons live long enough); therefore we can measure the partial width also in the $b\bar{b}$ channel.

Mesurement of C_V and C_A (g_V and g_A)

The measurement of the Z couplings before LEP did not have enough precision to make stringent tests of the Standard Model, for instance they could not disantangle the sign of the couplings, we need the asymmetries to do it.

C_V=-0.03783(41)
C_A=-0.50123(26)

The line is the SM expectation as a function of m_{top} and m_H

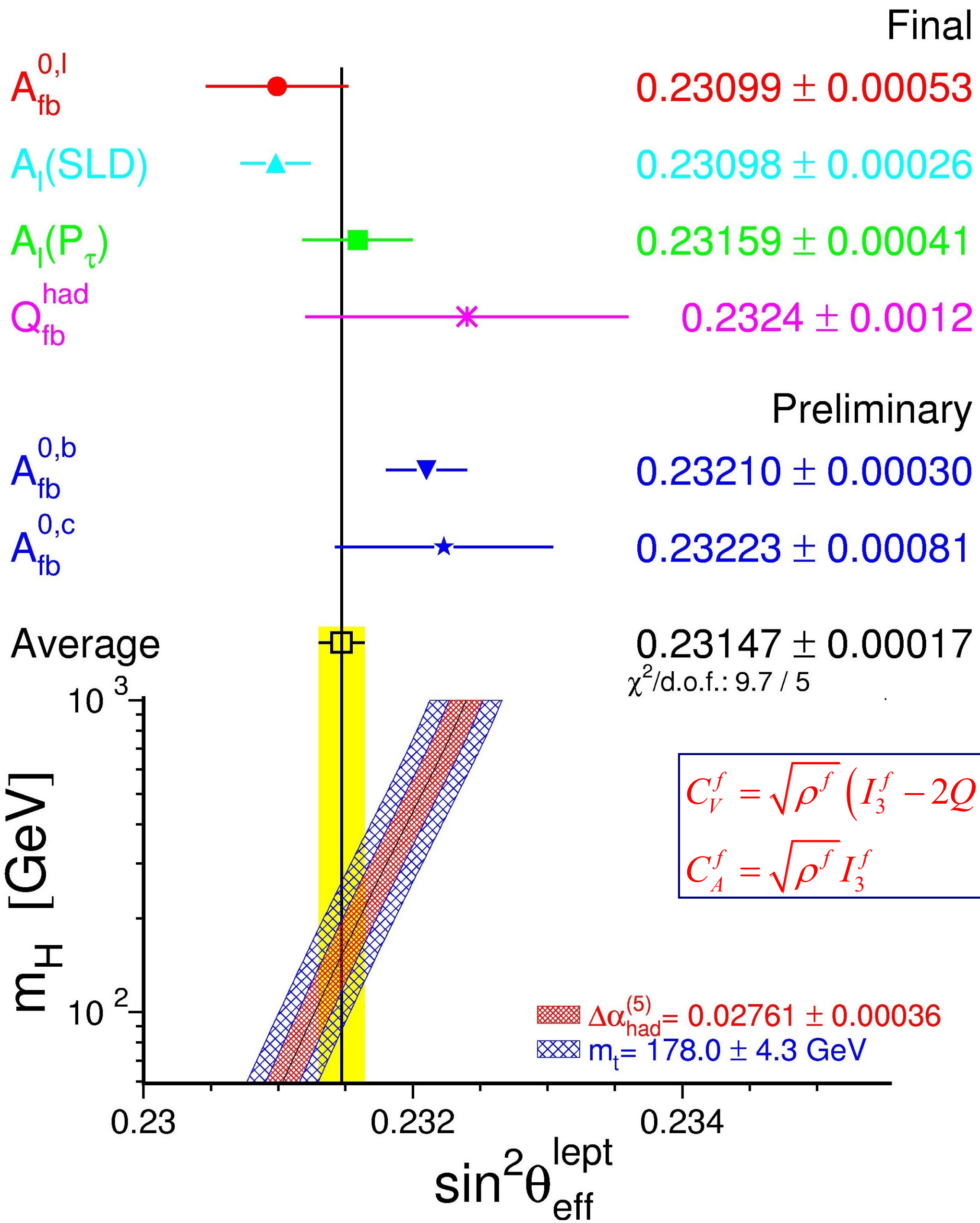


- **Lepton coupling to the Z**
  Ratios of coupling constants:

g_A^μ/g_A^e	=	1.0002	±	0.0014
g_A^τ/g_A^e	=	1.0019	±	0.0015
g_V^μ/g_V^e	=	0.962	±	0.063
g_V^τ/g_V^e	=	0.958	±	0.029

Lepton universality is verified at the per mill level.

Measurement of $\sin^2\vartheta_{eff}$



$$C_V^f = \sqrt{\rho^f}\left(I_3^f - 2Q\sin^2\theta_{eff}^f\right)$$

$$C_A^f = \sqrt{\rho^f}\, I_3^f$$

- **Asymmetries at Z pole**
  - **forward-backward**
  - **left-right (SLD)**
  - **tau polarisation**

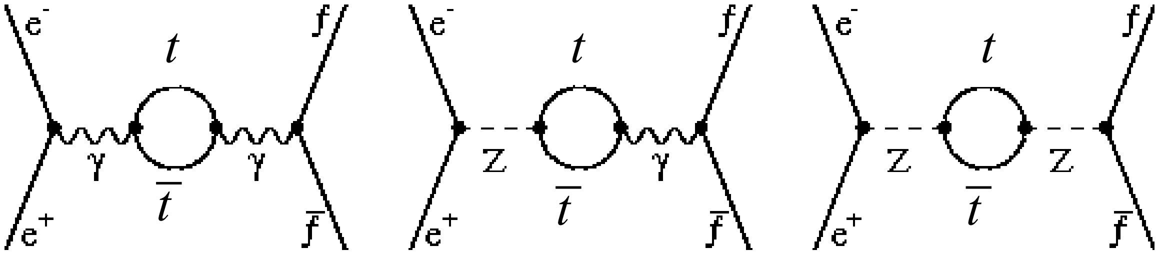
$\sin^2\vartheta_{eff}$ is a renormalized value of $\sin^2\vartheta_W$. The tree level prediction of the SM is not sufficient to have an agreement with real data.

From the measured values of various asymmetries we can get the value of the Weinberg angle.

The radiative corrections depend of the top mass and Higgs mass, therefore with a comparison with the measured value we can make a prediction on these two parameters.

From this kind of measurements it has been possible to foresee the value of the top mass and to put constraints on the Higgs mass.

Prediction of the top mass at LEP

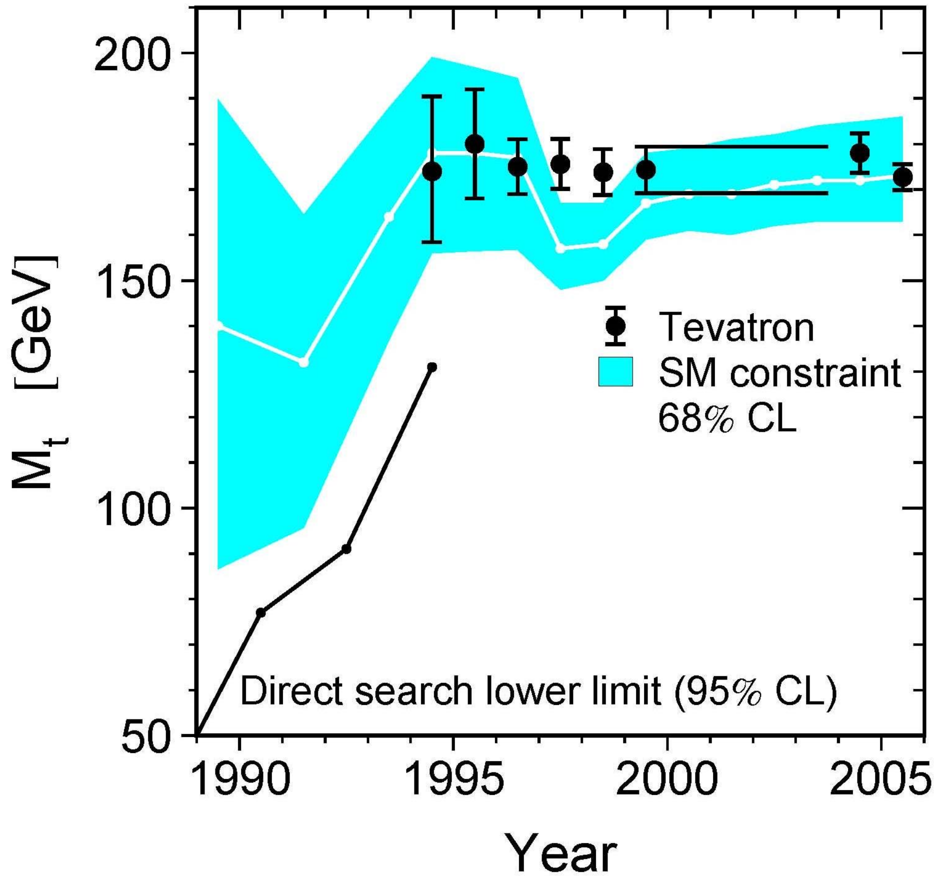


propagator corrections

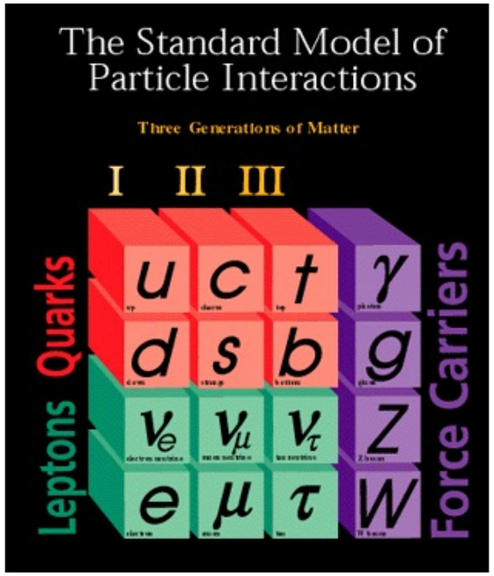
- The top could not be produced at LEP because its mass was too high. However it enters in the virtual loop, therefore it has been possible to set limits on its mass through the comparison of the theoretical predictions (that include the top mass) with experimental measurements.

- The LEP prediction are in agreement with direct measurement of the top mass done at the Tevatron (Fermilab) once the top was discovered in 1994.

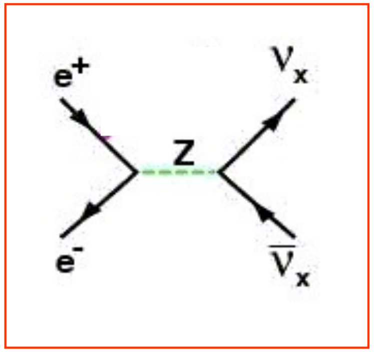
The radiative corrections are function of m_t^2



Measur. of the numb. of light neutrinos

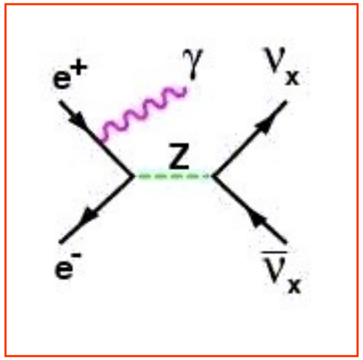


- The number of lepton families is not foreseen in the Standard Model but it has to be determined experimentally.
- Before LEP functioning a fourth family of leptons was not excluded by the available data.
- In every family is a present a neutrino, massless or in any case with a negliable mass; therefore the LEP strategy was to look for the presence of a fourth light neutrino (where light means of mass less half of the m_Z).
- If the forth neutrino were identified it would have been the first hint of a fourth lepton family.



- Therefore the goal was to measure the Z partial width in the neutrino channel and from this deduce the number of light neutrinos.
- Let's recall the fact that the neutrinos are not "seen" in the LEP detector, so we need a "trick" to perform the measurement.

$$\Gamma_Z = \Gamma_{\text{leptoni carichi}} + \Gamma_{\text{adroni}} + N_\nu \cdot \Gamma_{\nu\bar{\nu}}$$



- There were two kind of measurement of the so called invisible width (Γ_{inv}): an indirect measurement where $\Gamma_{inv\ i}$is obtained as a difference by subtracting to Γ_Z the "visible" partial width, and a direct measurement where it was detected the photon emitted from the initial state; in this case the event signature was a single photon with energy around 1 GeV.

N_ν: results

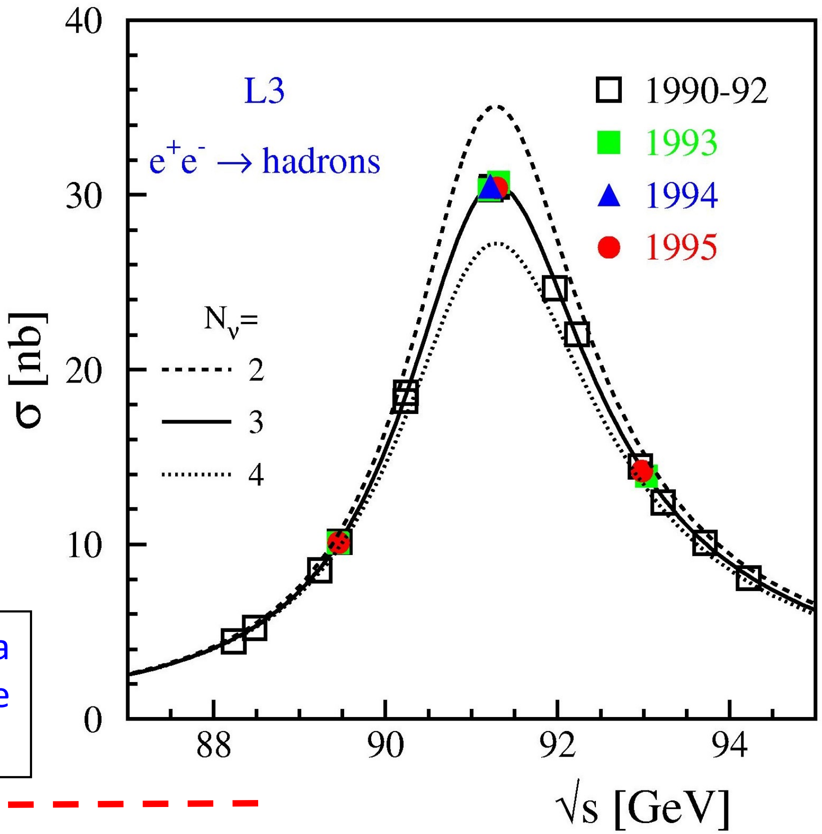
Indirect measurement:

$$N_\nu = 2.9841 \pm 0.0083$$

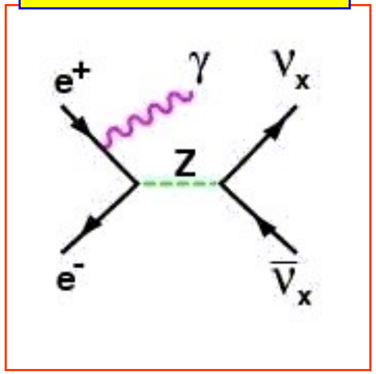
It is a very precise measurement that excludes the presence of a fourth neutrino family (unless this has a structure completely different from the previous three, like a very heavy neutrino).

N.B. The Z partial width into a neutrino pair is obtained from a SM computation.

N.B. N_ν does not need to be an integer. For istance a massive fourth neutrino (with m < ½ m_Z) would contribute less to the width because of the phase space effect



$$e^+e^- \to \nu\bar{\nu}\gamma$$



Direct measurement:

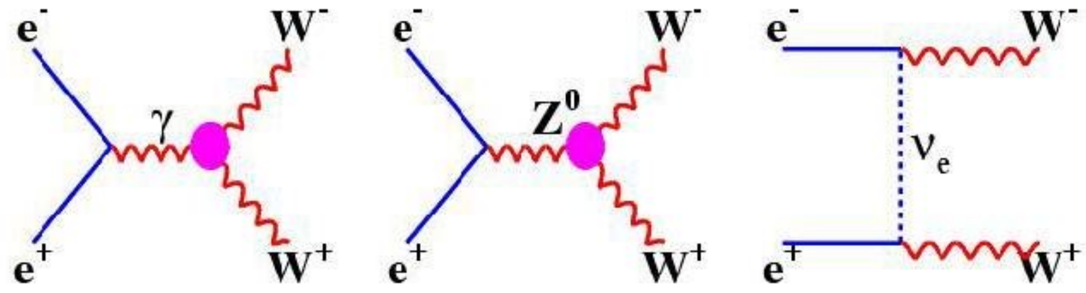
- However in the indirect measurement the number of neutrinos is obtained as a difference, therefore if it was found a number different from three, we would have not been sure that we were in the presence of a fourth neutrino or some other effect. A direct measurement was needed:

L3 has found at LEP phase-1 702 single photon events (to be compared with 5 milions Z decays) where the photon energy was greater than 1 GeV.

L3: N_ν=2.98±0.10

Measurement of the W mass

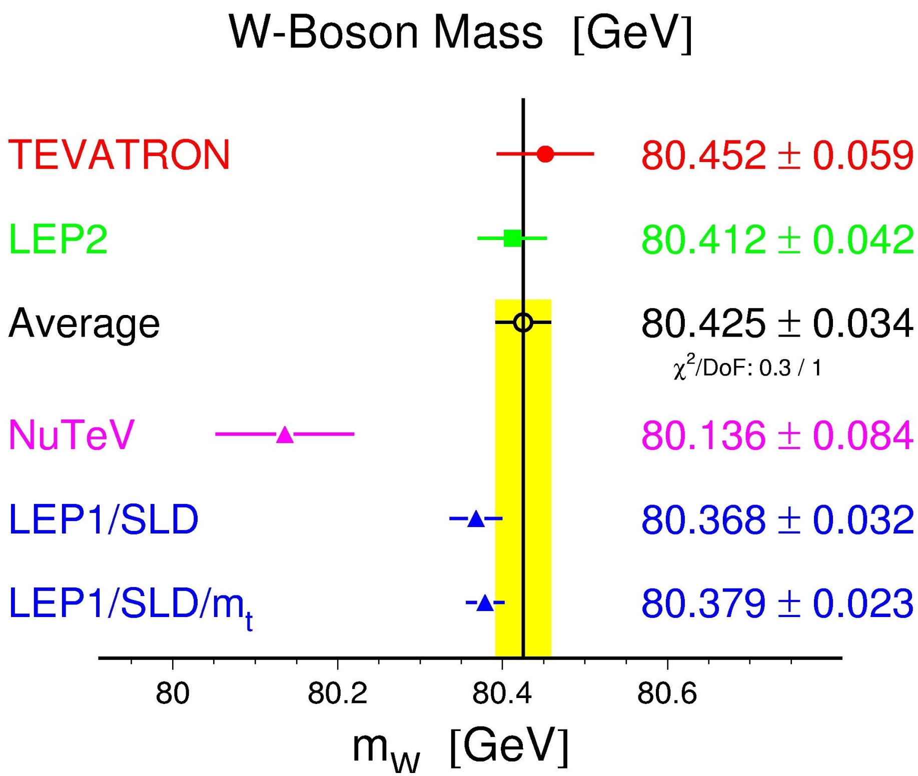
- At LEP phase 2 the center of mass energy reached 208 GeV. This permitted to produce W pairs. It has been possible to measure the mass with high precision and to measure its couplings with the fermions.



- The mass has been measured using a tecnique of invariant mass with a few constraints given by the knowledge of the center of mass energy. However the error is not comparable with the one obtained for the Z mass.

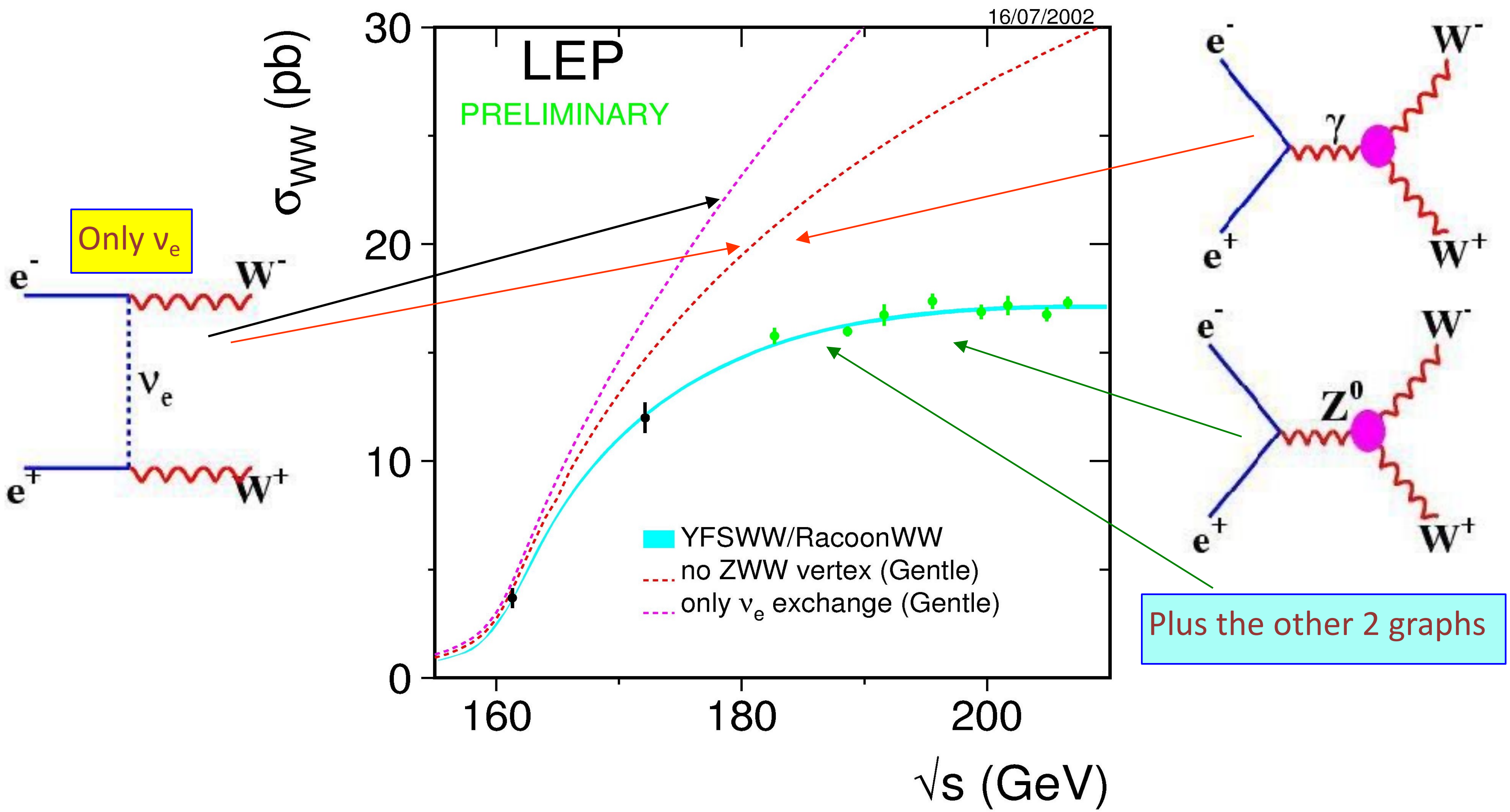
- The precision on M_W obtained at LEP2 is comparable with the one obtained at Tevatron.

- Moreover the indirect measurement of M_w done at LEP1 through the radiative corrections of the Z measurement is in agreement with the direct measure of the mass.



Triple gauge boson coupling

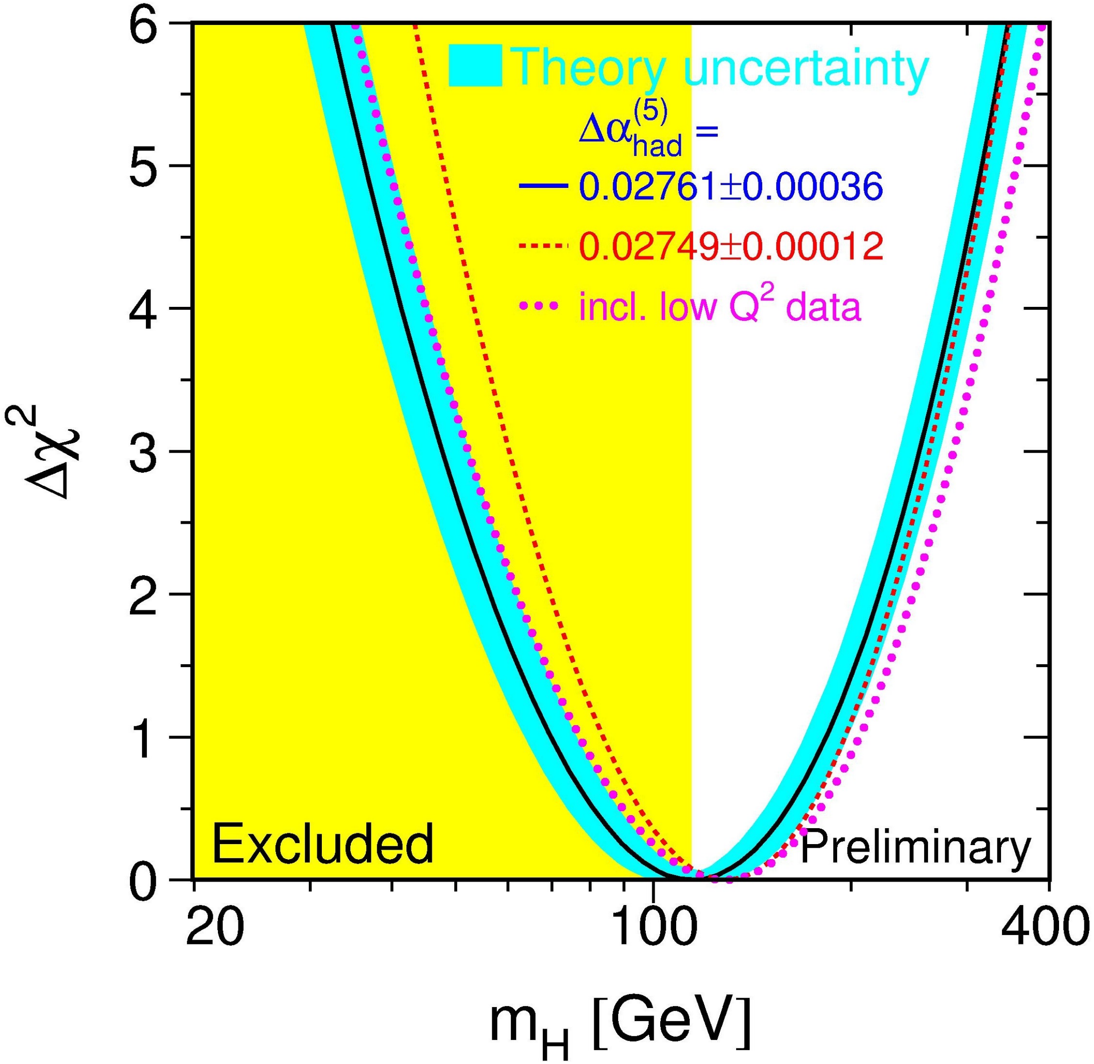
- At LEP2 it has been possible to verify the existence of the coupling with 3 or 4 gauge bosons foreseen by the Standard Model ($SU(2)_L$ is a non abelian symmetry group).



- The cross-section measurement of the W production as a function of $\sqrt{s}$ shows that the data are correctly described only if we consider also the vertex ZWW foreseen in the SM.

Prediction on the Higgs mass

- The success obtained at LEP to predict the top mass with an error of 5-6 MeV through the radiative correction can not be repeated for the Higgs boson mass because the radiative corrections depend on the log of Higgs mass, therefore the sensitivity is very low:



- **95% CL upper limit:**

m_H < 260 GeV

... waiting for LHC ...

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End of chapter 12