Weak Neutral Current

the discovery of the Z^0 boson.
and…future discoveries..

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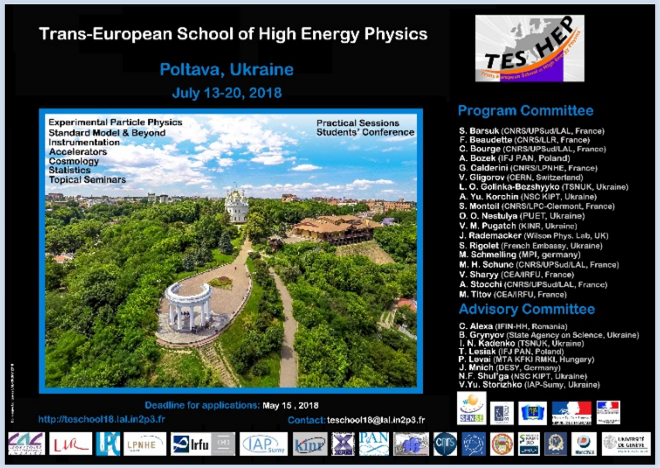


1 DISCOVERY of the Weak Neutral current in neutrino interactions - `70

Andante

2 WEAK NEUTRAL current IN THE '60/'70. THE FCNC PUZZLE

Allegro

3 STANDARD MODEL CONSTRUCTION – END OF THE `70.

Andante a piacere

4 THE DISCOVERY OF W, and Z^0 bosons at SPS at CERN by UA1 and UA2

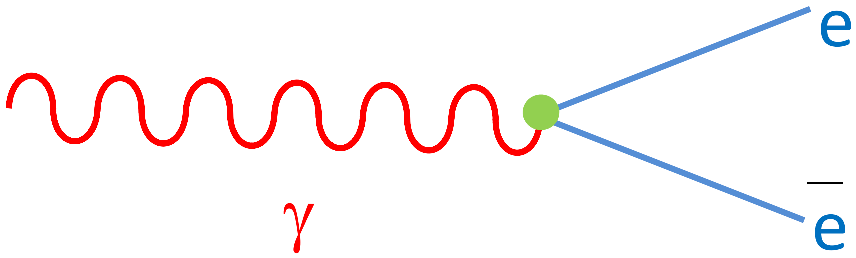
Presto accellerando

5 DETAILED STUDIES OF Z^0 BOSON at LEP. THE TRIUMPH of SM

Vivace animato

6 FCNC – a PRIVILIVIGIATE WAY FOR SEARCHING FOR NEW PHYSICS

Andante senza tempo



Charged fermions

$$e\,(\bar{e}_L\,\gamma_\mu A^\mu\,e_L)$$

Coupling : charge

Interaction : vector

field

Electromagnetic Interaction

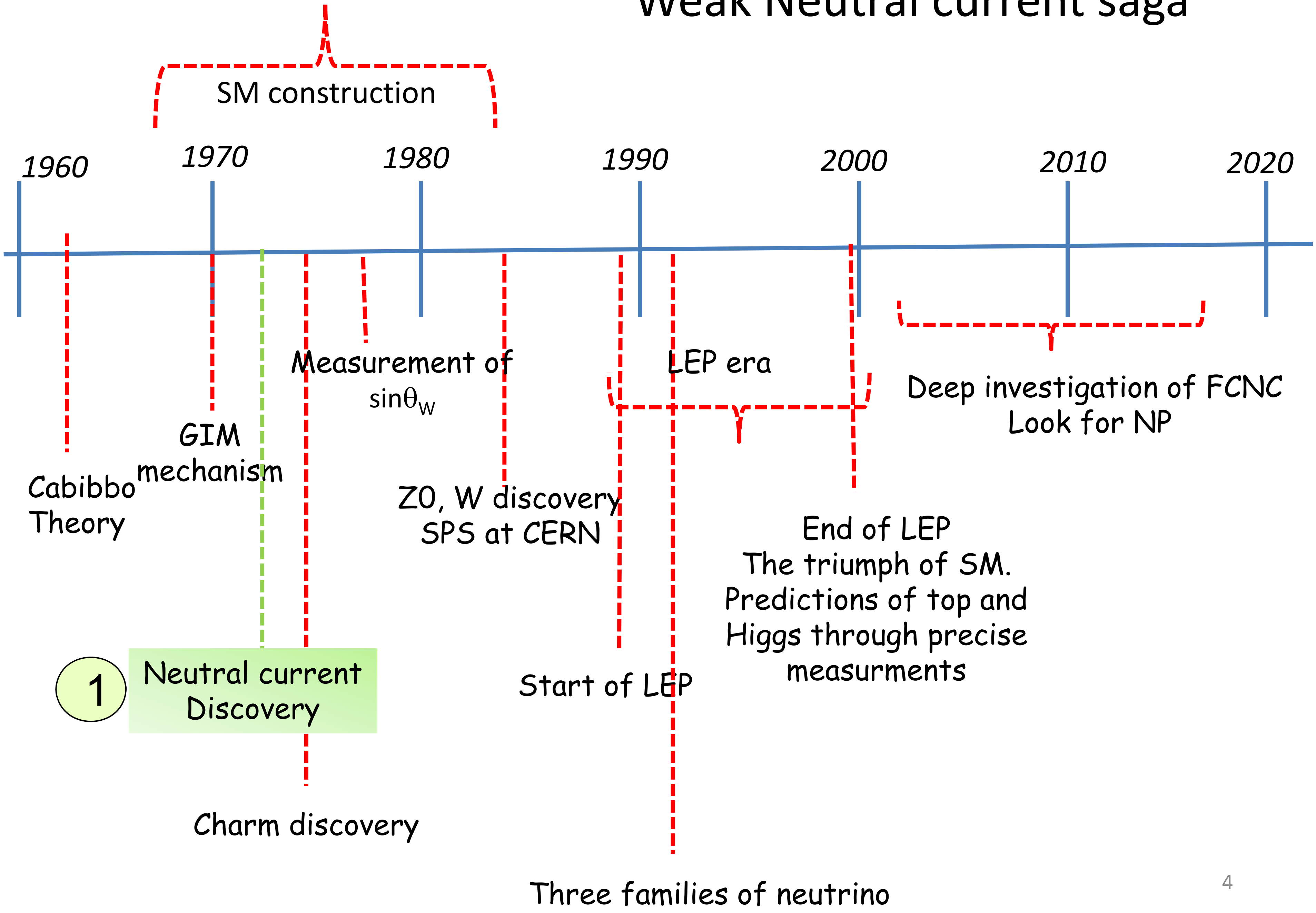
Neutral current

Photon SPIN $J^P = 1^-$, CHARGE = 0

Neutral current in the SM (see later…)

$$\Rightarrow \quad L_{NC} = \overline{\nu_L}\gamma_\mu\left[\frac{-e}{2\sin\theta_W\cos\theta_W}Z_0^\mu\right]\nu_L + \overline{e_L}\gamma_\mu\left[\frac{-e}{2\sin\theta_W\cos\theta_W}\left(-1+2\sin^2\theta_W\right)Z_0^\mu + eA^\mu\right]e_L$$
$$+\overline{e_R}\gamma_\mu\left[\frac{e}{2\sin\theta_W\cos\theta_W}\left(2\sin^2\theta_W\right)Z_0^\mu + eA^\mu\right]e_R$$

Weak Neutral current saga



1

The years `70

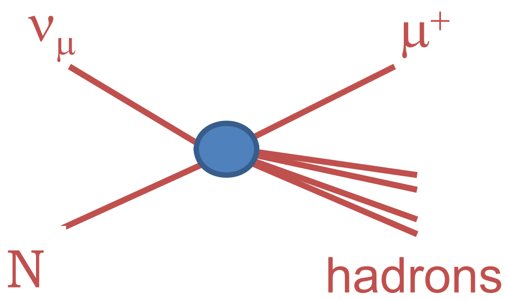
DISCOVERY OF WEAK neutral currents in NEUTRINO INTERECTIONS

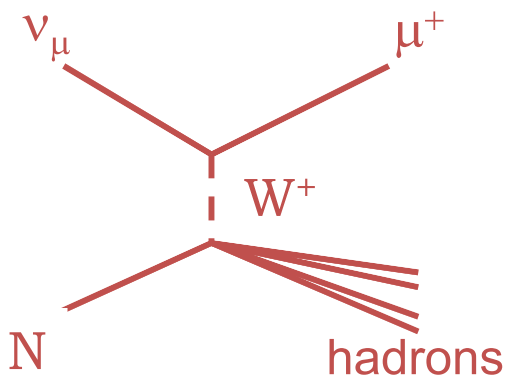
In the following I discuss neutrino interactions; There were studied/discovered before the Z^0 , W establishment, discovery… Often I'll use them in my graph

In effective / Fermi-like theory

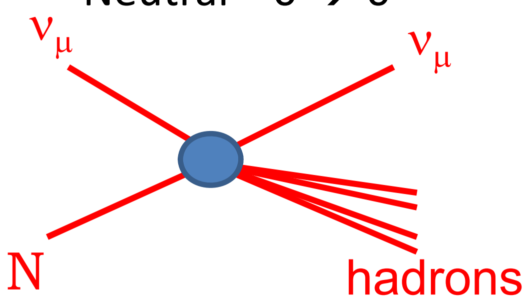
In SM with interaction bosons

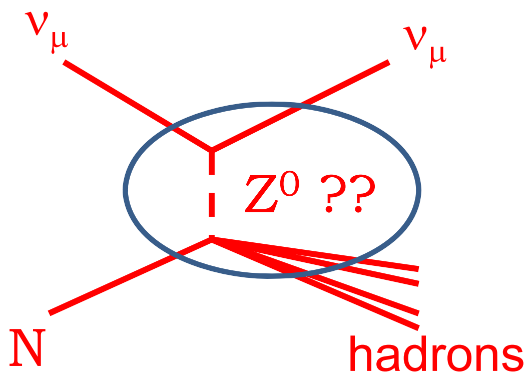
Charged 0 → +1



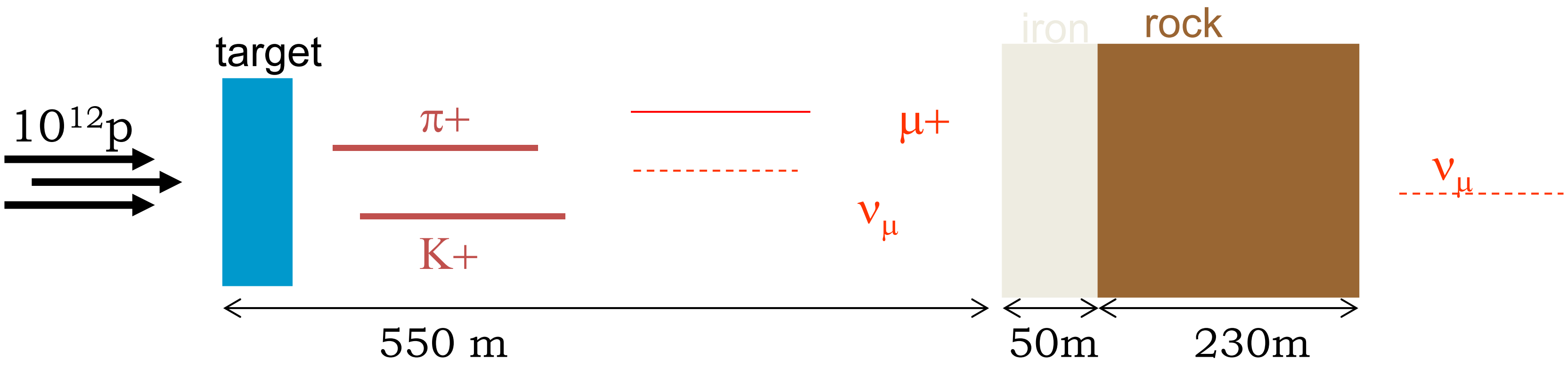


Neutral 0 → 0





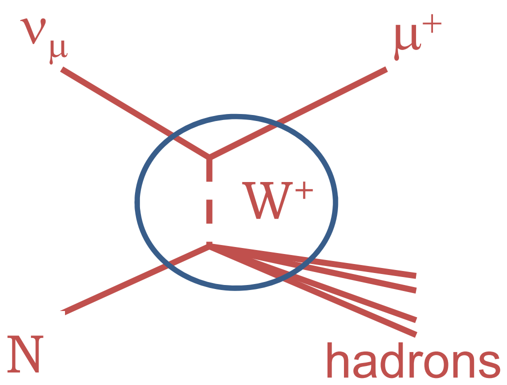
DISCOVERY OF WEAK NEUTRAL currents in NEUTRINO INTERECTIONS

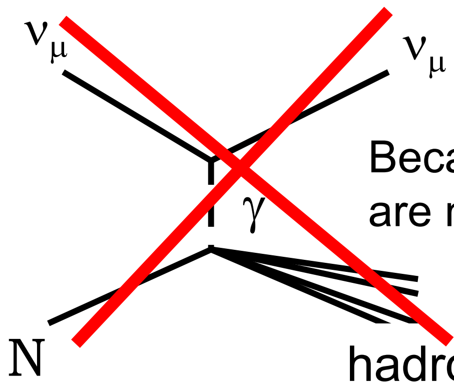


ν_μ N$\to$ μ X   charged current

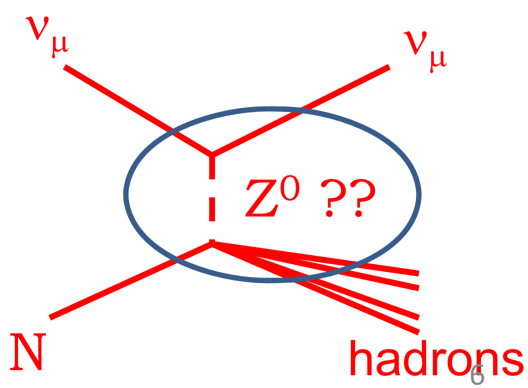
ν_μ N$\to$ ν_μ X   neutral current

n.b. Here for illustration we use already the Feynman diarams with W, Z… Consider that at that tim W, Z where not discovred yet





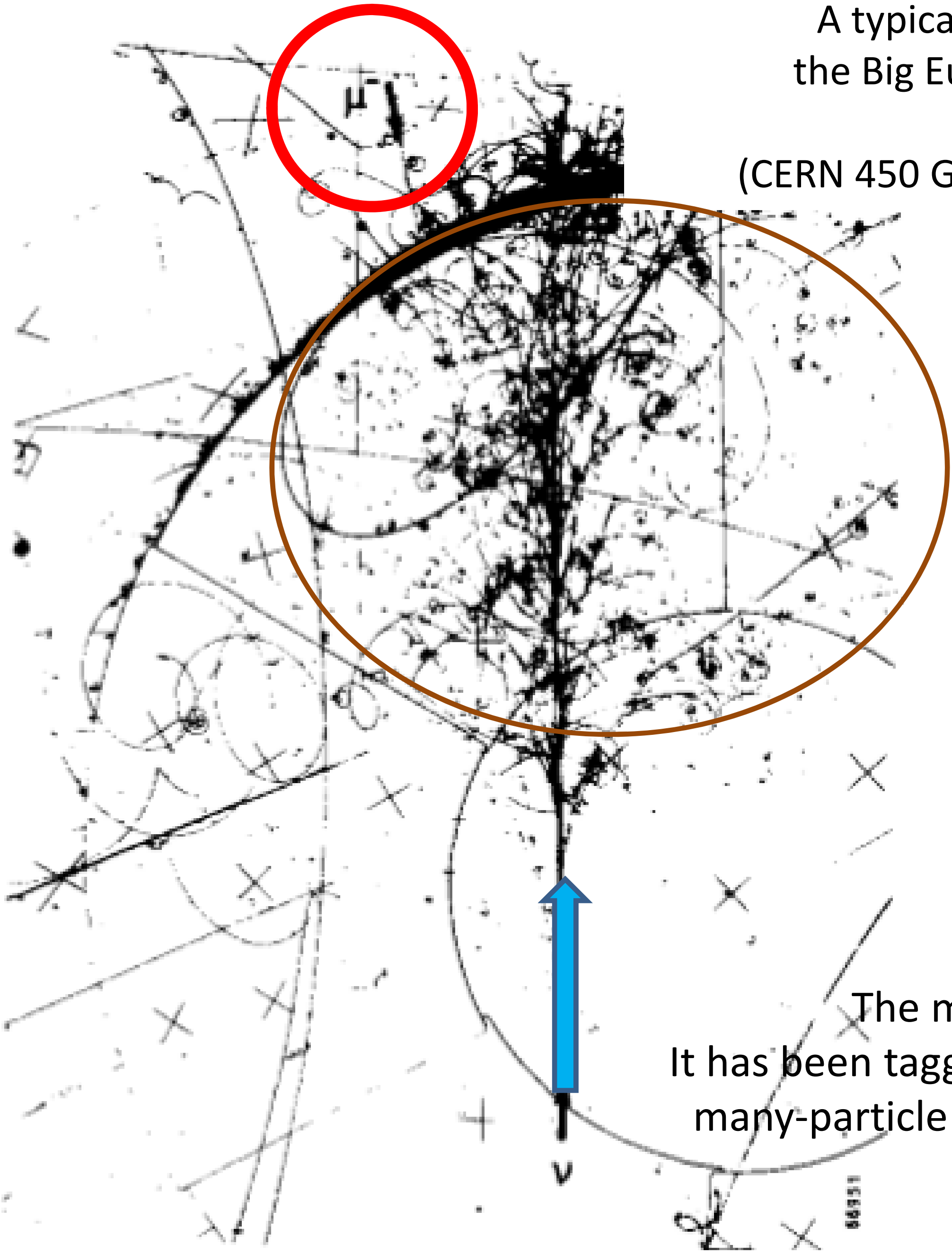
Because the ν are neutral…

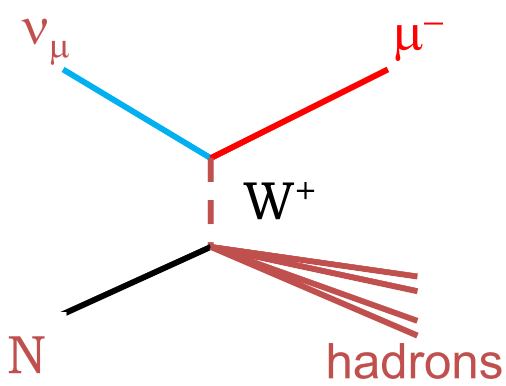


Gargamelle was a bubble chamber at CERN designed to detect neutrinos. It operated from 1970 to 1976 with a muon-neutrino beam produced by the CERN Proton Synchrotron, before moving to the Super Proton Synchrotron (SPS) until 1979.

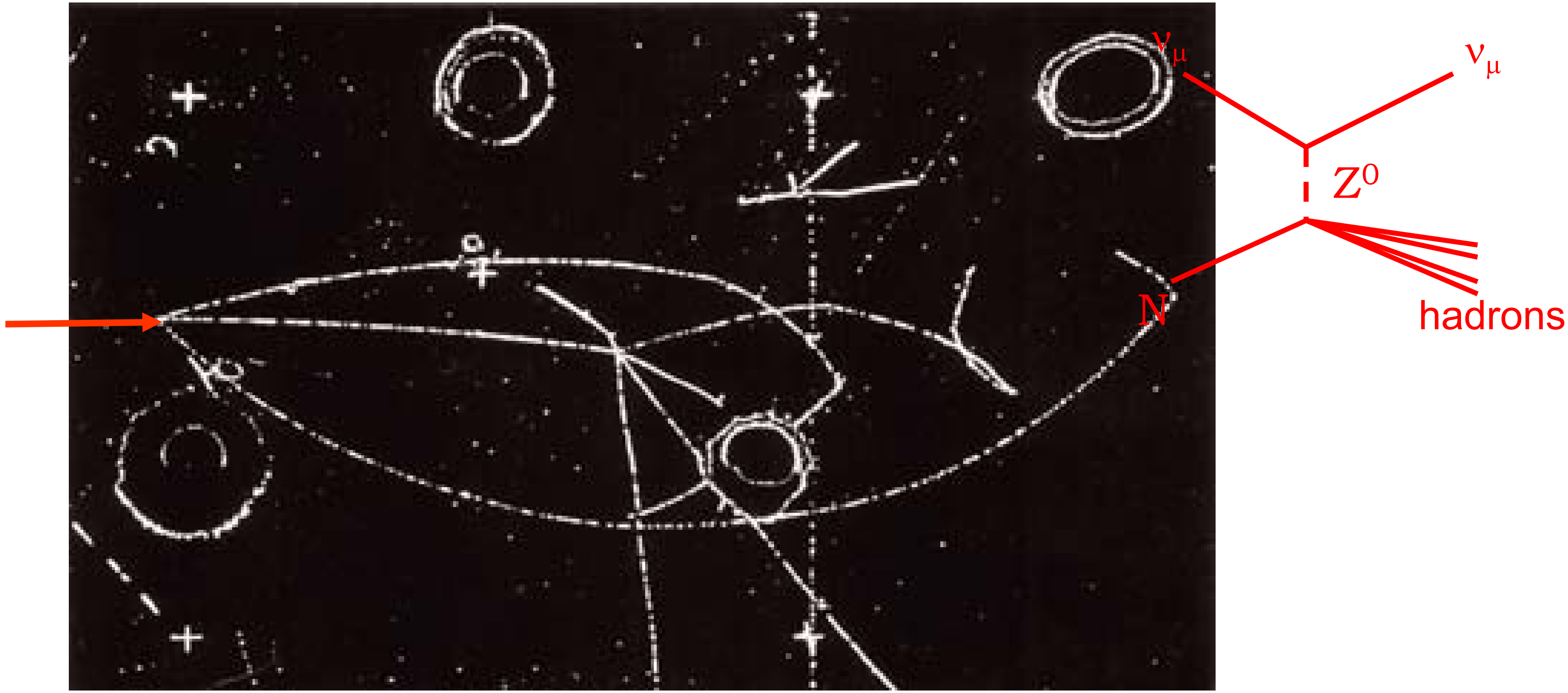
Gargamelle was 4.8 metres long and 2 metres in diameter. It weighed 1000 tonnes and held nearly 12 cubic metres of heavy-liquid freon (CF3Br).

A typical neutrino event as observed in
the Big European Bubble Chamber (BEBC)
filled with neon
(CERN 450 GeV Super Proton Synchrotron (SPS))



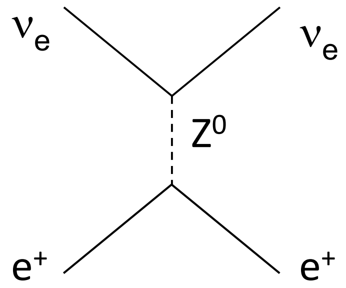


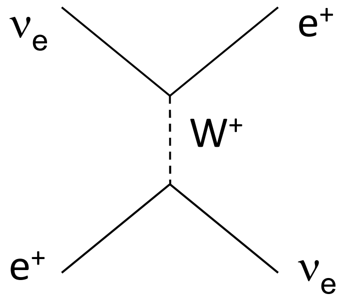
The muon can be seen on the left.
It has been tagged by an external muon identifier. The many-particle hadron shower is visible on the right.



hadronic neutral current event, where the interaction of the neutrino coming from the left produces three secondary particles, all clearly identifiable as hadrons, as they interact with other nuclei in the liquid. There is no charged lepton (muon or electron).

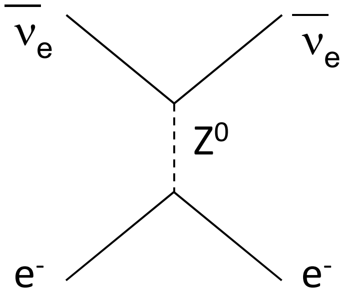
MORE diagrams concerning neutrino interaction with electrons

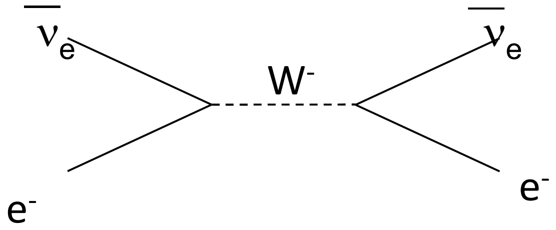




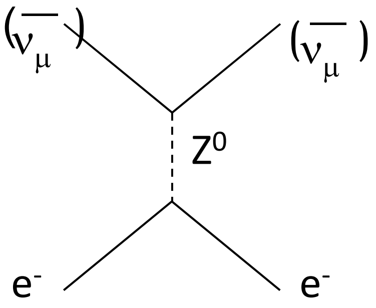
$\nu_e\ e^+ \rightarrow \nu_e\ e^+$

2 diagrams with W and Z





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



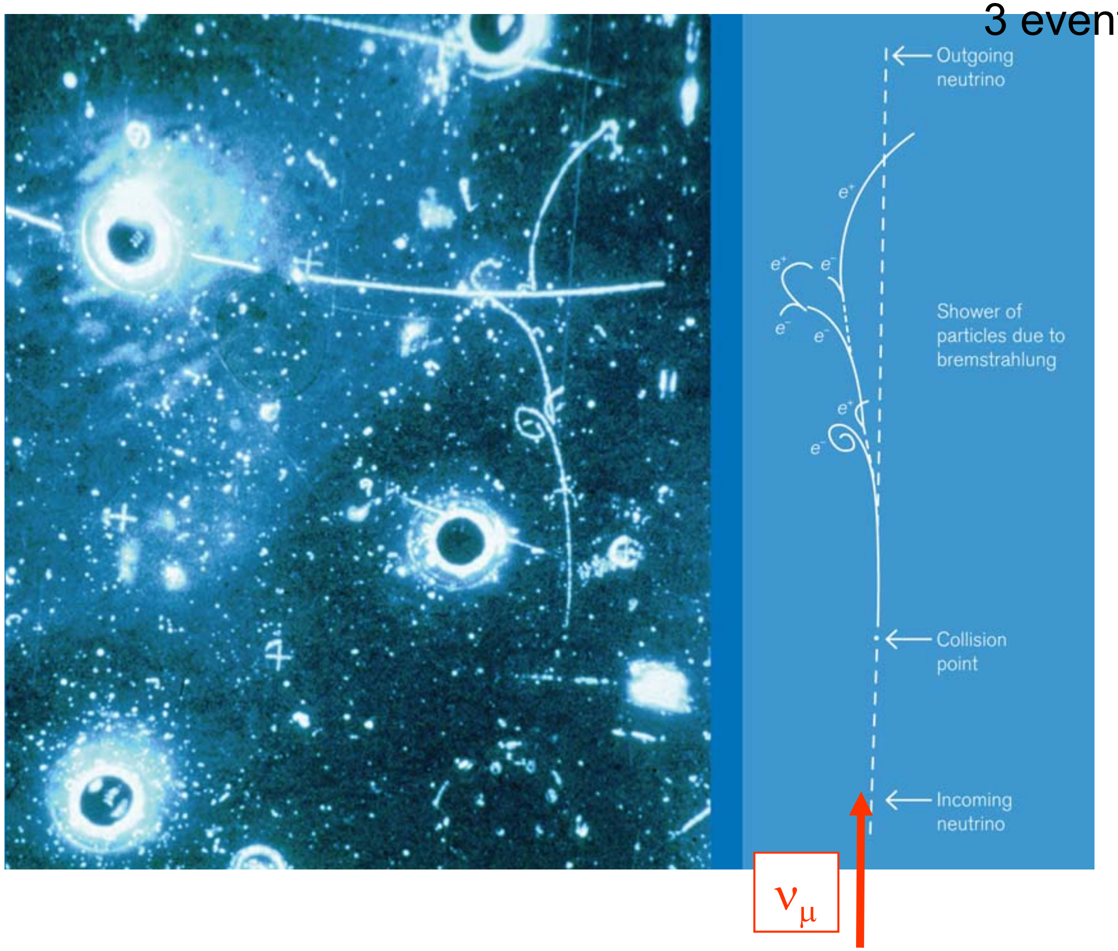
GOLDEN PLATED DIAGRAM!!

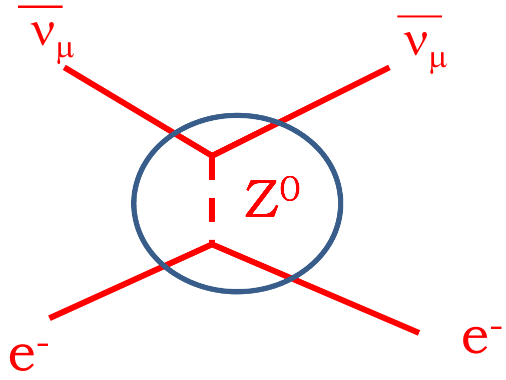
$\bar{\nu}_\mu\ e^- \rightarrow \bar{\nu}_\mu\ e^-$

No diagram with a W !
(would violate the leptonic number)

Gargamelle : Phys. Lett. B46, 138-140 (1973)

Over a total of 1.4 million pictures:
3 events (data taking : 2 ans)





GOLDEN PLATED EVENT
Almost background free !!

The electron is projected forward with an energy of 400 MeV at an angle of $1.5 \pm 1.5°$ to the beam

Kinematical analysis : direction close from the direction of the incoming ν beam

In 2009 EPS High Energy and Particle Physics Prize is this year awarded to the Gargamelle collaboration, for the "observation of the weak neutral current interaction" in 1973.

Papers signed by 55 physicists, from Aachen, Brussels, CERN, Paris, Milano, Orsay and London.

A. Pullia from CERN (now in Milano) and J.P. Vialle (Orsay)

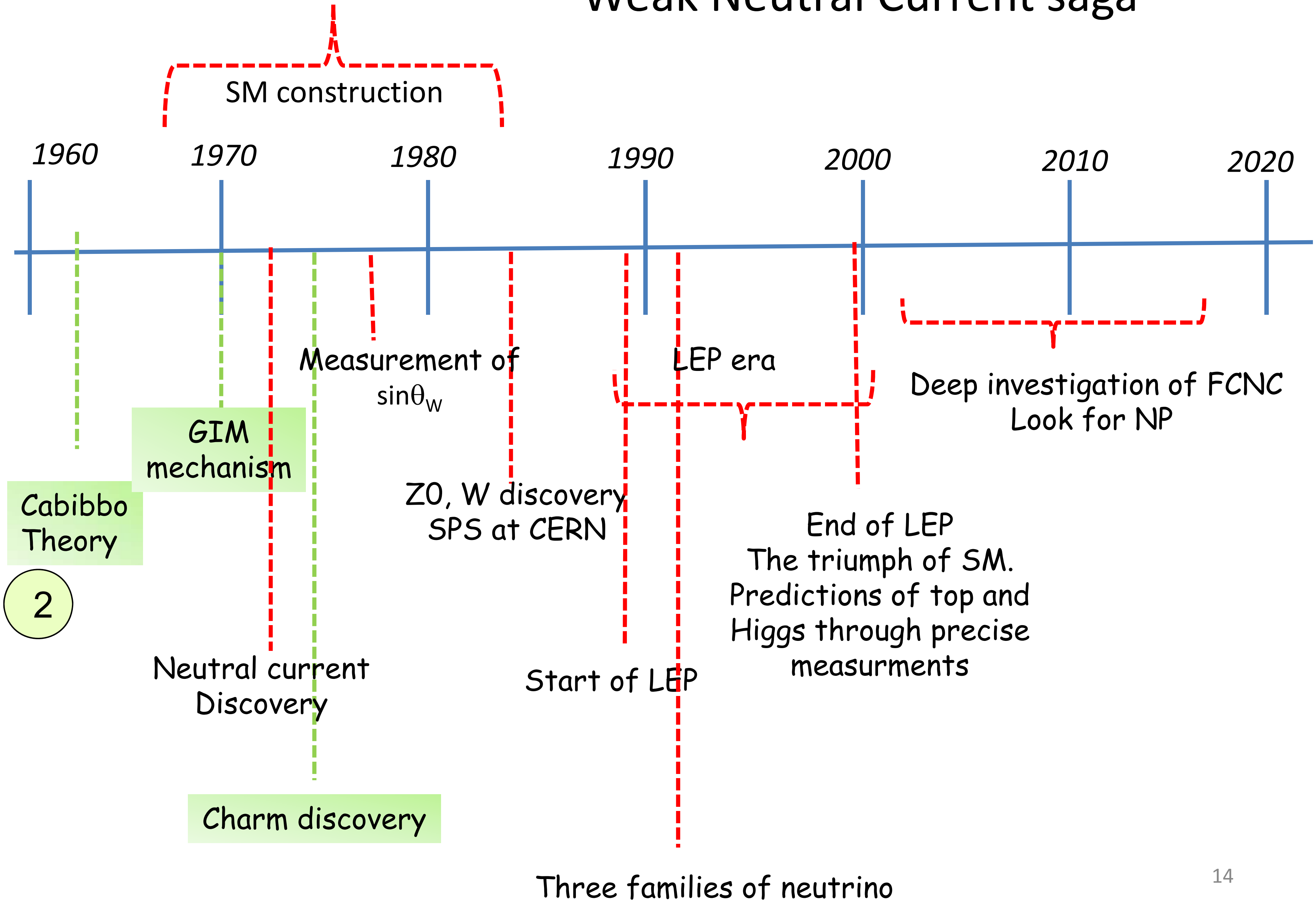
1

1st MESSAGE

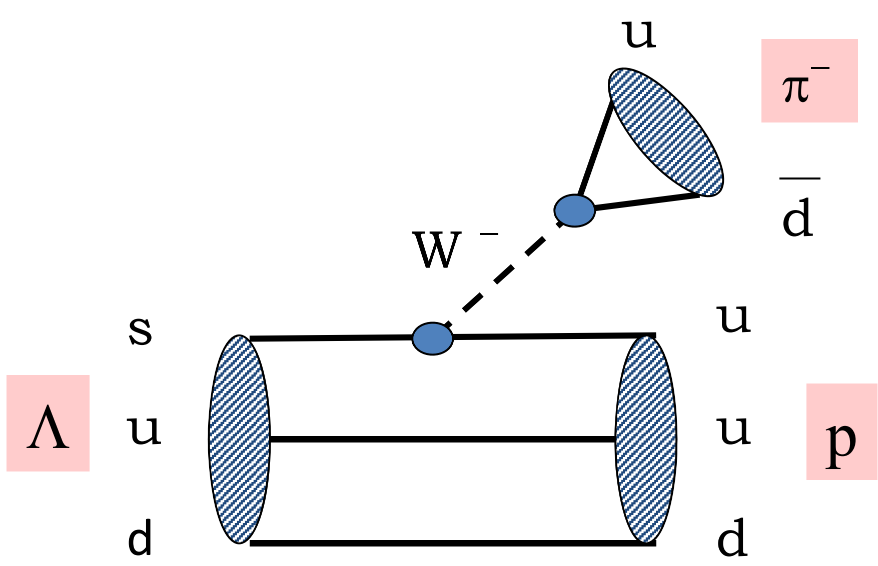
NEUTRAL WEAK CURRENTS EXIST

« eventually » brought
by a neutral boson … Z^0

Weak Neutral Current saga



In the following I still discuss « facts » which happened before the Z^0 , W establishment, discovery… I'll use them in my graph… and these type of graphs…



ALL THE SAME IN CASE YOU HAVE A NEUTRAL CURRENT

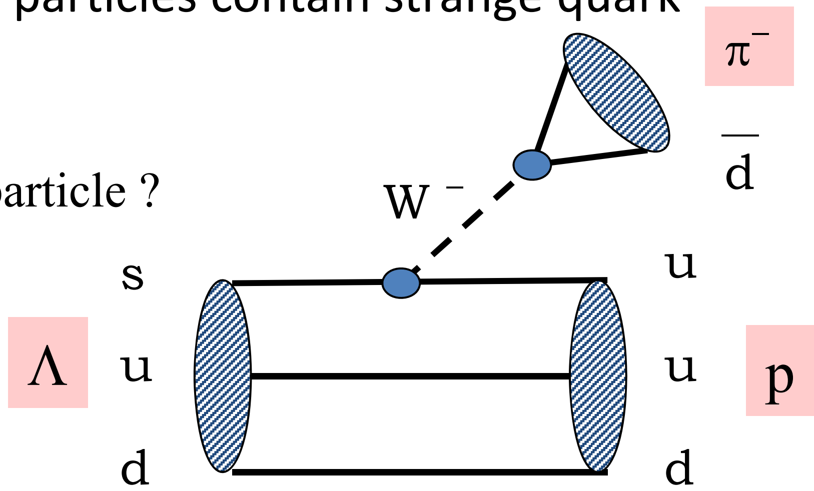
2

WEAK NEUTRAL CURRENTS. THE PUZZLE OF THE FCNC

years `60 – `70

Strange particles were discovered in the late ‘40 / early ’50
Today we know that strange particles contain strange quark

How do we see the decay of a strange particle ?



We have used a simplied vision which works well, called spectator model, were the heaviest quark decay first ! Doing some calculation we expect that the

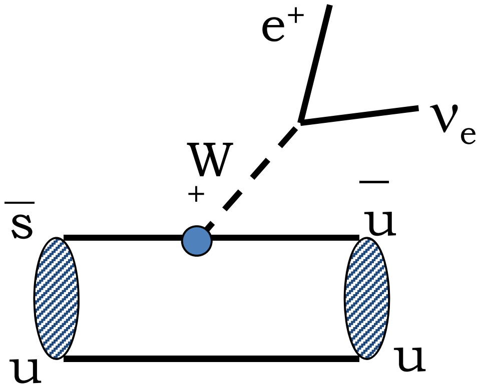
$$\Gamma \sim \frac{1}{\tau} = \frac{G_F^{\,2}\, m^5_{decay\ particle}}{192\,\pi^3}$$

Lifetime of heaviest particle is shorter that those of lighter particle

So strange particle are expected to have shorter lifetime than pions for example.

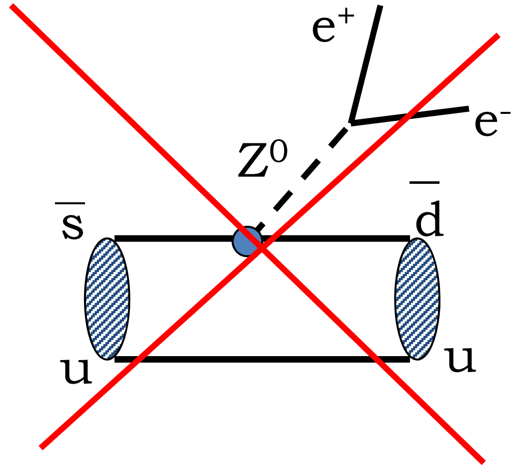
TWO « PUZZLING » FACTS

$\Delta S = 1$ transition.
Strangness changes 1 → 0



$K^+ \rightarrow \pi^0 e^+ \nu_e$

su transition/coupling



$K^+ \rightarrow \pi^+ e^+ e^-$

sd transition/coupling

1

When Lifetime was measured :

Strange particle have long lifetime of $\tau \sim 10^{-10}$ s (longer that $\tau(\pi) \sim 10^{-8}$ s ; $\tau(\mu) \sim 10^{-6}$ s)

The existence of neutral weak interaction and the existence of strange quarks implie naturally the possibilities of having s→d transitions…

2

But no observation of :

- $K^0 \rightarrow \mu^+ \mu^-$
- **$K^+ \rightarrow \pi^+ e^+ e^-$**
- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

No **Flavour Changing Neutral Currents (FCNC)**

- What can explain the lifetimes of the strange particles ~ 10^{-10} s? (π ~ 10^{-8} s)
  The transition rates $\Delta S=1$ are ~20 times smaller than $\Delta S=0$ rates

  What is the difference between weak processes with $\Delta S=1$ and $\Delta S=0$?

Cabibbo's hypothesis : the *d* and *s* quarks involved in the weak processes are mixed. The mixing angle is θ_c : the Cabibbo's angle.

Quarks are organized in doublets :

$$\begin{pmatrix} u \\ d_c \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta_c + s\sin\theta_c \end{pmatrix}$$

An additional parameter …

in which the components get transformed by weak interaction.

Cabibbo Theory :

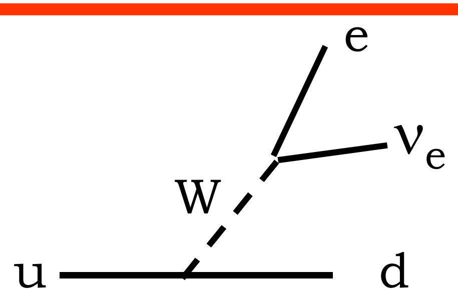
<u>The quarks *d* e *s* involved in weak processes are « rotated » by an angle</u>

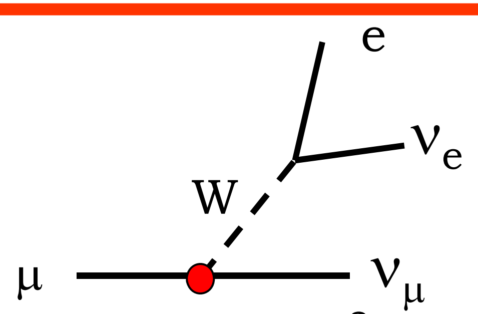
θ_c : the Cabibbo angle

$$\begin{pmatrix} u \\ d_c \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta_c + s\sin\theta_c \end{pmatrix}$$

Couplings : u d $G_F\cos\theta_c$ u s $G_F\sin\theta_c$

ΔS=0





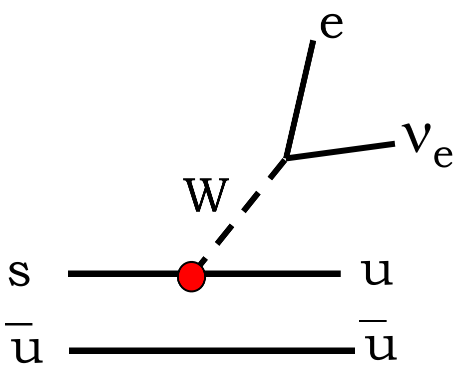
$G_\pi^2 =$ $G_n^2 =$ $G_\mu^2 \cos^2\theta_c$

$\pi^- \to \pi^0 e^- \bar{\nu}_e$ $p \to n\, e^+ \nu_e$ $\mu^- \to e^- \bar{\nu}_e\, \nu_\mu$

ΔS=1

$G_F^2 \sin^2\theta_c$

$K^- \to \pi^0 e^- \bar{\nu}_e$



Many measurements explained with :

$\sin\theta_c \sim 0.22$

Weak interaction among quarks

Non universal

θ_c **: the Cabibbo angle**

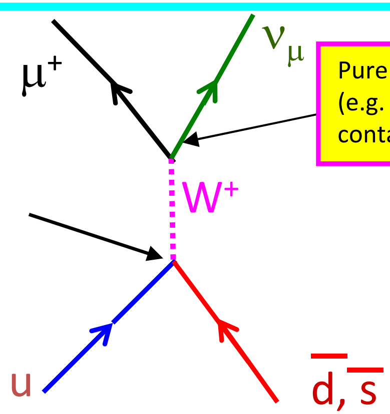
Cabibbo Theory :

The quarks d e s involved in weak processes are « rotated » by an angle

$$\begin{pmatrix} u \\ d_c \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta_c + s\sin\theta_c \end{pmatrix}$$

Couplings : u d $G_F\cos\theta_c$ u s $G_F\sin\theta_c$

$\Delta S=1$



Purely leptonic decays (e.g. muon decay) do not contain the Cabibbo factor:

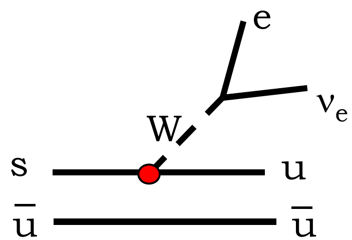
$\cos\theta_c$ or $\sin\theta_c$

$$\frac{\tau(K)}{\tau(\pi)} \quad \frac{BR(K^+\to\mu^+\nu)}{BR(\pi^+\to\mu^+\nu)} = \frac{\sin^2\theta_c}{\cos^2\theta_c}\left[\frac{m_K}{m_\pi}\right]\left[\frac{1-(m_\mu/m_K)^2}{1-(m_\mu/m_\pi)^2}\right]^2$$

$\tau(K)$: 1.2 10^{-8} s; $\tau(\pi)$: 2.6 10^{-8} s; $BR(K^+\to\mu^+\nu)$ (~0.63); $BR(\pi^+\to\mu^+\nu)$ (~1); mass factors: 8.5

$G_F^2 \sin^2\theta_c$

$K^- \to \pi^0 e^- \nu_e$



VOLUME 10, NUMBER 12 PHYSICAL REVIEW LETTERS 15 JUNE 1963

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

To determine θ, let us compare the rates for $K^+\to\mu^++\nu$ and $\pi^+\to\mu^++\nu$; we find

$$\Gamma(K^+\to\mu\nu)/\Gamma(\pi^+\to\mu\nu) = \tan^2\theta M_K(1-M_\mu^2/M_K^2)^2/M_\pi(1-M_\mu^2/M_\pi^2)^2. \quad (3)$$

From the experimental data, we then get[5,6]

$$\theta = 0.257. \quad (4)$$

For an independent determination of θ, let us consider $K^+\to\pi^0+e^++\nu$. The matrix element for this process can be connected to that for $\pi^+\to\pi^0+e^++\nu$, known from the conserved vector-current hypothesis (2nd assumption). From the rate[6] for $K^+\to\pi^0+e^++\nu$, we get

$$\theta = 0.26. \quad (5)$$

The two determinations coincide within experimental errors; in the following we use $\theta = 0.26$.

But the theory predicts flavour changing neutral transition : sd

$$u\bar{u} + d\bar{d}\cos^2\theta_c + s\bar{s}\sin^2\theta_c + \left(s\bar{d} + \bar{s}d\right)\cos\theta_c \sin\theta_c$$

1970 : Glashow, Iliopoulos et Maiani (GIM) proposed the introduction of **a fourth quark : the quark *c* (of charge 2/3)** :

$$\begin{pmatrix} c \\ s_c \end{pmatrix} = \begin{pmatrix} c \\ s\cos\theta_c - d\sin\theta_c \end{pmatrix}$$

Term added to the neutral coupling

$$c\bar{c} + s\bar{s}\cos^2\theta_c + d\bar{d}\sin^2\theta_c - \left(s\bar{d} + \bar{s}d\right)\cos\theta_c \sin\theta_c$$

$$\longrightarrow \quad u\bar{u} + c\bar{c} + \left(d\bar{d} + s\bar{s}\right)\cos^2\theta_c + \left(d\bar{d} + s\bar{s}\right)\sin^2\theta_c = u\bar{u} + c\bar{c} + d\bar{d} + s\bar{s}$$

1) Strange particles have a longer lifetime → introduction of Cabibbo theory.

2) The neutral current does not change flavour : absence of FCNC

→ prediction of the existence of the charm quark !

More formally. If we write the weak charged current

$$g_{aa} = 0$$
$$g_{ud} = (g/\sqrt{2})\cos\vartheta_C$$
$$g_{us} = (g/\sqrt{2})\sin\vartheta_C$$

$$j_\mu^{weak} = g_{ab}\overline{q_a}\gamma_\mu\frac{\left(1-\gamma^5\right)}{2}q_b = \overline{q_{aL}}\gamma_\mu q_{bL}$$

$$q_L = \begin{pmatrix} u \\ d\cos\vartheta_C + s\sin\vartheta_C \end{pmatrix}_L$$

$$j_\mu^+ = (g/\sqrt{2})(\overline{u},\overline{d}\cos\vartheta_C + \bar{s}\cos\vartheta_C)\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} u \\ d\cos\vartheta_C + s\sin\vartheta_C \end{pmatrix} =$$
$$= (g/\sqrt{2})\bar{u}d\cos\vartheta_C + (g/\sqrt{2})u\bar{s}\sin\vartheta_C$$

$$j_\mu^+ = \overline{q_L}\sigma_+ q_L \quad ; \quad \sigma_+ = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$$

The interaction comes from a gauge group. From the previous page it seems to be clear that for the weak interactions the group is the weak isospin. σ_{+-} are the matrices which increase(decrease) of one unity the weak isospin. But to form an algebra we also need σ_3

$$\begin{pmatrix} u \\ d\cos\vartheta_C + s\sin\vartheta_C \end{pmatrix}_L$$

$$j_\mu^0 = g(\overline{u}, \overline{d_C})\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} u \\ d_C \end{pmatrix} =$$

$$= u\overline{u} + d\overline{d}\cos^2\theta_c + s\overline{s}\sin^2\theta_c + \left(s\overline{d} + \overline{d}s\right)\cos\theta_c \sin\theta_c$$

FCNC

introducing $\begin{pmatrix} c \\ s_C = -d\sin\vartheta_C + s\cos\vartheta_C \end{pmatrix}_L$

Absence of FCNC

$$j_\mu^0 = g(\overline{u}, \overline{d_C})\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} u \\ d_C \end{pmatrix} + g(\overline{c}, \overline{s_C})\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} c \\ s_C \end{pmatrix} = u\overline{u} + d\overline{d} + s\overline{s} + c\overline{c}$$

$$j_\mu^0 = \overline{q_L}\sigma_3 q_L \quad ; \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

adding the charm in the charged currents

$$q = \begin{pmatrix} c \\ -d\sin\vartheta_C + s\cos\vartheta_C \end{pmatrix}$$

$$j_\mu^+ = (g/\sqrt{2})(\bar{c}, -\bar{d}\sin\vartheta_C + \bar{s}\cos\vartheta_C)\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} c \\ -d\sin\vartheta_C + s\cos\vartheta_C \end{pmatrix} =$$

$$= -(g/\sqrt{2})\bar{c}d\sin\vartheta_C + (g/\sqrt{2})c\bar{s}\cos\vartheta_C$$

$$j_\mu^+ = g/\sqrt{2}(\overline{u}, \overline{d_C})\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} u \\ d_C \end{pmatrix} + g/\sqrt{2}(\overline{c}, \overline{s_C})\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} c \\ s_C \end{pmatrix}$$

$$\rightarrow \quad \begin{pmatrix} d_C \\ s_C \end{pmatrix} = V\begin{pmatrix} d \\ s \end{pmatrix} \quad \textit{with} \quad V = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}$$

$$(\bar{u}, \bar{c})\gamma^\mu(1-\gamma_5)V\begin{pmatrix} d \\ s \end{pmatrix}$$

$$V = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}$$

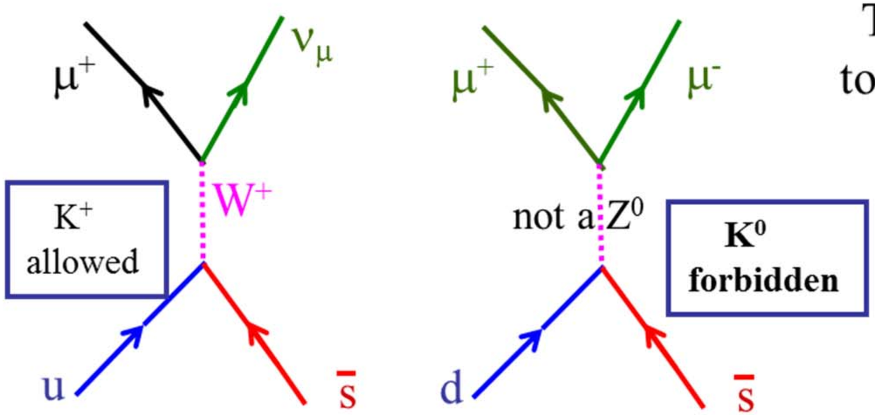
This rotation Matrix is The Cabibbo Matrix

FCNC : The GIM Mechanism (1970)

..Or the « charm discovery » by FCNC in Kaon system

1969-70 Glashow, Iliopoulos, Maiani (GIM) proposed a solution to the $K^0 \to \mu^+ \mu^-$ rate puzzle.

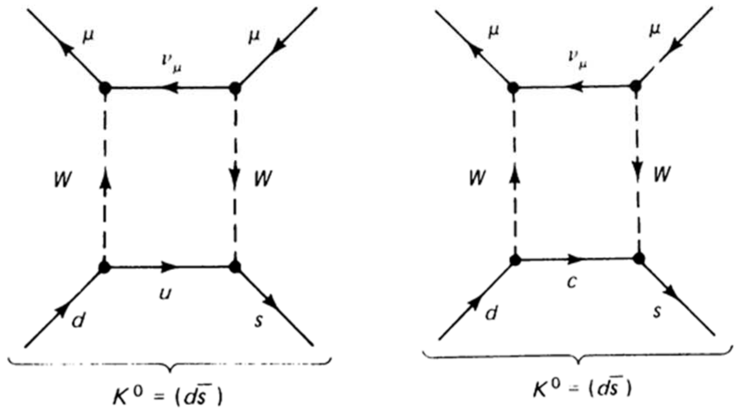
1st Order



The branching fraction for $K^0 \to \mu^+ \mu^-$ expected to be small as the first order diagram is forbidden

$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times10^{-9}}{0.64} \approx 10^{-8}$$

2nd Order



With only u quark the is an ultraviolet divergence

$$\approx (m_c^2 - m_u^2)\cos^2\vartheta_C \sin^2\vartheta_C$$

Prediction of the charm quark with mass ~ 1.5 GeV !

Directly observed in 1973

More details

These two diagrams cancel out the divergence

It remains a non zero contribution (which is infrared divergent) for momentum lower than the mc, which does not cancel out. The amount of cancellation depends on the mass of the new quark

$$\approx (m_c^2 - m_u^2)\cos^2\vartheta_C \sin^2\vartheta_C$$

For m_c=m_u It would be $BR(K^0 \to \mu^+\mu^-) = 0$

A quark mass of ≈1.5GeV is necessary to get good agreement with the experimental data.

First “evidence” for Charm quark! and the fact that m_c is such that was not yet observed…

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

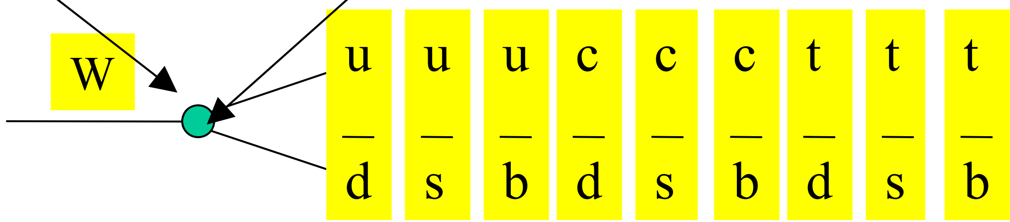
We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

2

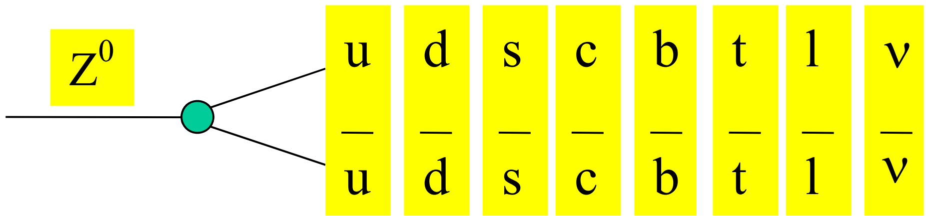
2nd MESSAGE

The coupling is not anymore universal

and this is codified in the CKM matrix.

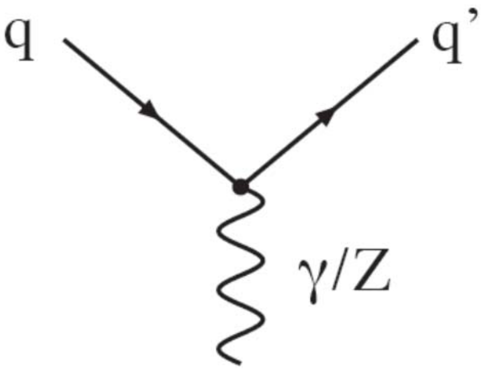


The neutral currents stay universal, in the mass basis :
<u>we do not need extra parameters for their complete description</u>



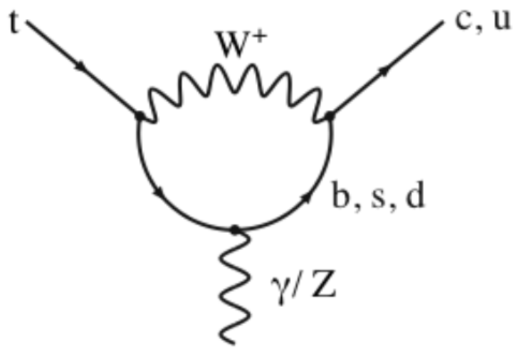
and this is completly included and comes out « naturally » from the Standard Model
(I'll not demonstrate during lecture, but is in Backup)

$u\bar{u}$ $d\bar{d}$ $s\bar{s}$ $c\bar{c}$ $b\bar{b}$ $t\bar{t}$



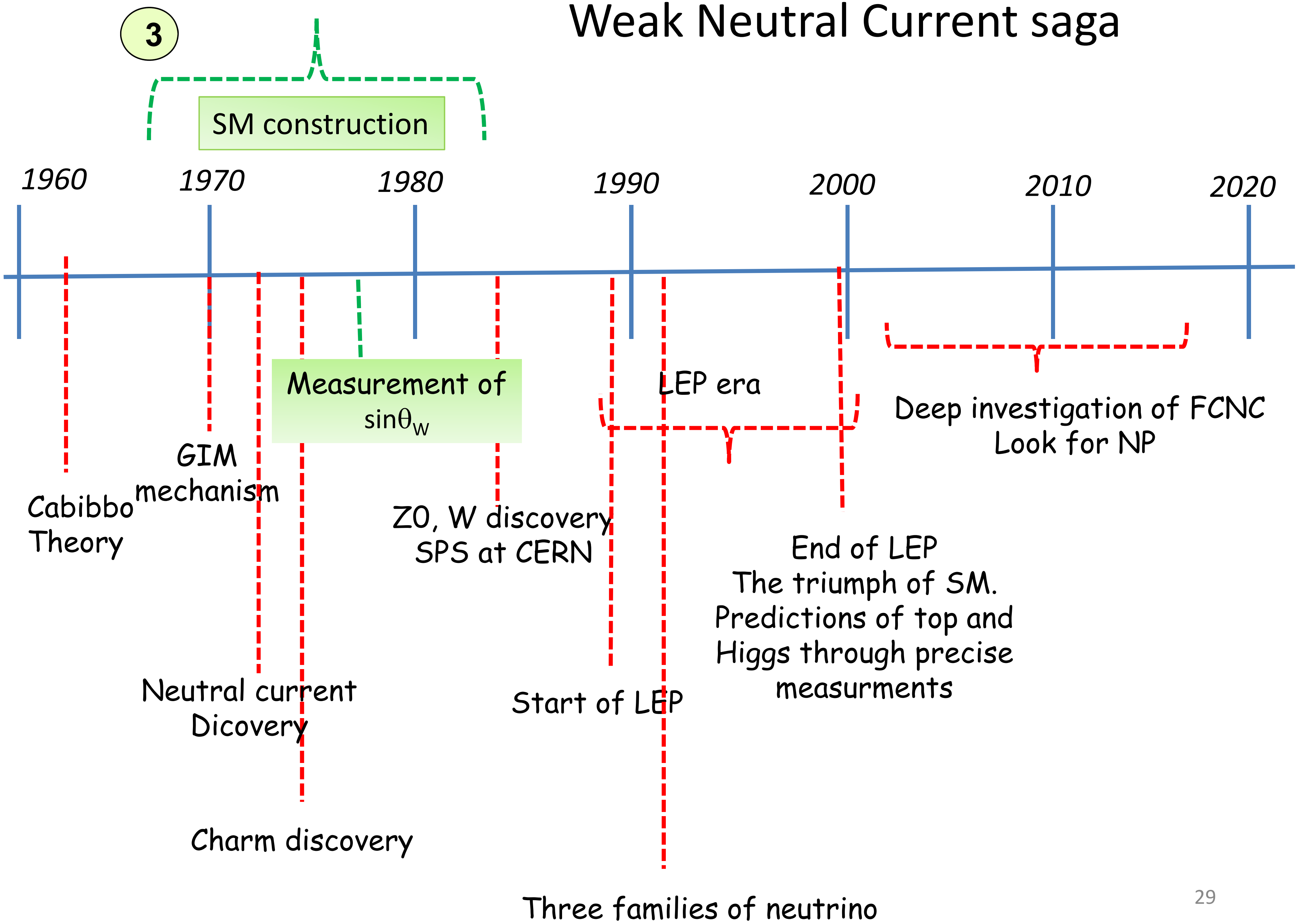
<u>NEUTRAL CURRENTS with Z0.</u>
DO NOT CHANGE THE FLAVOUR

$c\bar{u}$ $s\bar{d}$ $b\bar{s}$ $t\bar{c}$ $b\bar{b}$ $b\bar{d}$



<u>Flavour Changing Neutral Current (FCNC) occurs with W exchange.</u>
THEY ARE SUPPRESSED IN THE SM SINCE OCCURS AT SECOND ORDER.

Weak Neutral Current saga



3 The SM Construction

End of `70 years

In two pages since all is in the lectures of Sébastien Descotes-Genon

We have SU(2) et U(1) and so **4 field B_μ et $W^{1,2,3}_\mu$** and we have **2 coupling constants g et g'.**
In the Lagrangian we want to avoid for instance that neutrino have electromagnetic interaction…
For that we introduce the field Z_μ et A_μ as an orthogonal combination of W^3_μ et B_μ….

$$W_3^\mu = \cos\theta_W Z_0^\mu + \sin\theta_W A^\mu$$

$$B^\mu = -\sin\theta_W Z_0^\mu + \cos\theta_W A^\mu$$

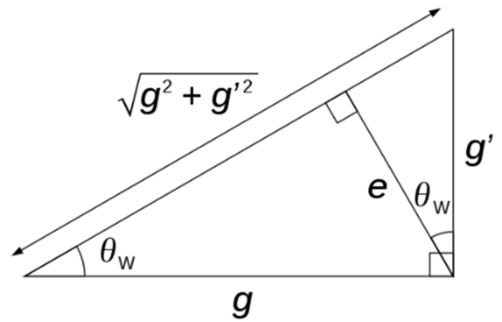
Now if we associate to the photon te field A^μ (the field Z^μ acts both to neutrinos and on charged particles) we find the relation of the electric charge as a fonction of g and g'

$$e \equiv \frac{gg'}{\sqrt{g'^2+g^2}}$$

We can also write

$$\sin\theta_W = \frac{g'}{\sqrt{g'^2+g^2}}$$

$$\cos\theta_W = \frac{g}{\sqrt{g'^2+g^2}}$$



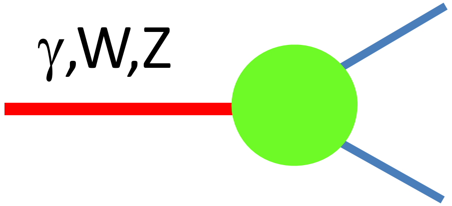
That implies

$$g = \frac{e}{\sin\theta_W}$$

$$g' = \frac{e}{\cos\theta_W}$$

The two constants g et g' can be written in terms of « e » and of the Weinberg θ_W.
ELECTROWEAK UNIFICATION

In term of **couplings**



When you calculate ..Γ,σ

W	$g^2/2 = e^2/2\sin^2\theta_W$	$-i\frac{g}{\sqrt{2}}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)$
γ	e^2	$-ie\,\gamma^\nu$ $e = g\sin\theta_W$
Z	$(g^2_V + g^2_A)\,(g/4\cos^2\theta_W)^2$	$-i\frac{e}{\sin\theta_W\cos\theta_W}\gamma^\nu\left(\frac{g_V - g_A\gamma_5}{2}\right)$

$g_V = T_3 - 2Q\sin^2\theta_W$ Vectorial constant

$g_A = T_3$ Axial constant

Very predictive !!
Let's me say the unexpected part of the SM…

$$\left(\frac{g_V - g_A\gamma_5}{2}\right) = \left(\frac{g_V + g_A}{2}\right)\left(\frac{1-\gamma_5}{2}\right) + \left(\frac{g_V - g_A}{2}\right)\left(\frac{1+\gamma_5}{2}\right)$$

+ propagator… $1/M^2_W$

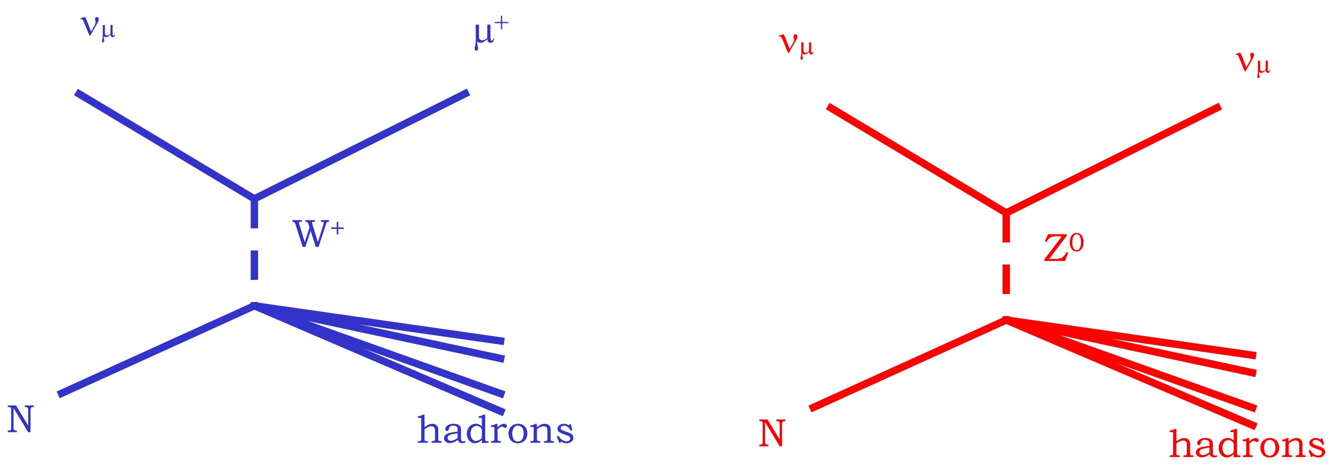
$1/M^2_Z$

DETERMINATION OF THE WEINBERG ANGLE FROM NEUTRINO SCATTERING and use of Neutral Current

Exemple again of Neutral current (NC) and Charge Currents (CC) , describing the diffusion of a muonic neutrinos on a Nucleus.

In case of CC the final state contain a muon + hadrons

in case of NC not… but only hadrons



$\nu_\mu N \rightarrow \nu_\mu X$ Neutral current

$\nu_\mu N \rightarrow \mu X$ Charge current

$\sigma(CC) \sim$ $e^2/2\sin^2\theta_W$

$\sigma(NC) \sim$ $(g^2_V + g^2_A)\,(g/4\cos^2\theta_W)^2$

A POSSIBLE OBSERVABLE : THE RATIO of the TWO CROSS SECTIONS which means being able to count the number of events having or not a muon in a final state..

$$\sigma(NC)/\,\sigma(CC) \sim f(\theta_W)$$

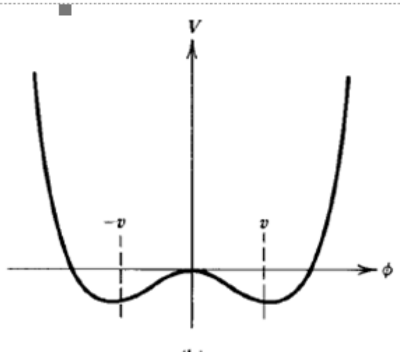
In PDG today

$\sin^2\theta = 0.23155(5)$

~1/4...

The SM Construction … continues…

FROM HIGGS MECHANISM



$$\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} \rightarrow \phi_0 = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}$$

v is the vaccum expectation value of the potential ϕ, namely the value of the potential in its fondamental state.

expanding

$$\phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+H(x)\end{pmatrix}$$

$$M_W = \frac{gv}{2} \qquad M_Z = \frac{\sqrt{g^2+g'^2}}{2}v \qquad M_\gamma = 0$$

$$M_Z = \frac{M_W}{\cos\theta_W}$$

ou $$\sin^2\theta_W = 1-\left(\frac{M_W}{M_Z}\right)^2$$

The value of the Z and W masses are linked through the Weinberg angle. It is a strong prediction of the SM !

ANY HINT ON THE W and Z masses ?

weak interaction Fermi EFFECTIVE theory

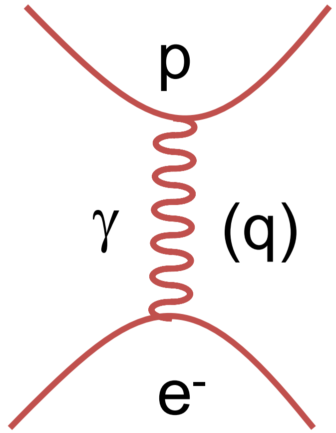
- 1932 : Fermi proposes a theory which is the analogous of electromagnetism to explain the β decay (by weak interaction)

QED :

$$M = \left(e\bar{u}_p \gamma^\mu u_p\right)\left(-\frac{1}{q^2}\right)\left(-e\bar{u}_e \gamma_\mu u_e\right)$$

$$M = -\frac{e^2}{q^2}\left(J_\mu\right)_p \left(J^\mu\right)_e$$

← J_μ current

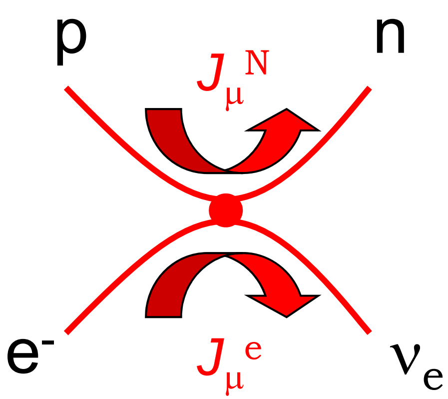


Fermi proposes for $n \to p\, e^- \nu_e$ and $p \to n\, e^+ \nu_e$ a local interaction :

$$G\left(\bar{u}_n \gamma^\mu u_p\right)\left(\bar{u}_{\nu_e} \gamma_\mu u_e\right)$$

[GeV^{-2}]

Local interaction (no $1/q^2$ term)



Through the analogy with electromagnetism, the G constant should be of GeV^{-2} dimension

From dimensional arguments $\Gamma \sim G^2 E^5$

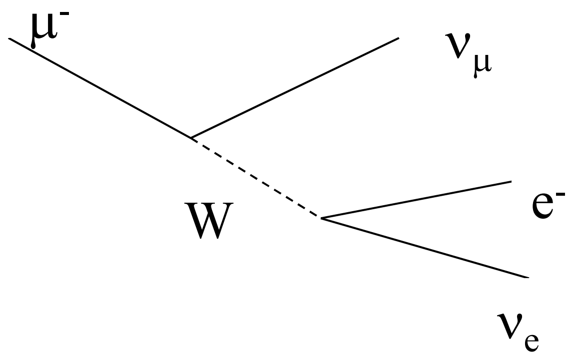
From precise muon lifetime

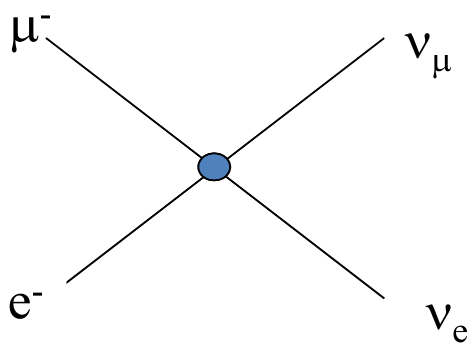
$$G_F = 1.16 \times 10^{-5}\, GeV^{-2}$$

From calculations :

$$\mu^- \rightarrow e^- \ \bar{\nu}_e \ \nu_\mu \qquad \Gamma_\mu = \frac{G_\mu^2 m_\mu^5}{192\pi^3}$$

$G \sim 10^{-5}/M^2_N$





$$M = \left(\frac{g}{\sqrt{2}} \bar{u}_{\nu_\mu} \gamma^\mu \frac{1}{2}(1-\gamma_5) u_\mu\right) \frac{1}{M_W^2 - q^2} \left(\frac{g}{\sqrt{2}} \bar{u}_e \gamma_\mu \frac{1}{2}(1-\gamma_5) u_{\nu_e}\right)$$

if $q^2 << M_W^2$ (which is the case for β decay for example)

$$M \sim \frac{g^2}{8M_W^2} \left(\bar{u}_{\nu_\mu} \gamma^\mu (1-\gamma_5) u_\mu\right)\left(\bar{u}_e \gamma_\mu (1-\gamma_5) u_{\nu_e}\right) \qquad M \sim \frac{G_F}{\sqrt{2}} \left(\bar{u}_{\nu_\mu} \gamma^\mu (1-\gamma_5) u_\mu\right)\left(\bar{u}_e \gamma_\mu (1-\gamma_5) u_{\nu_e}\right)$$

$$\frac{G}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

$$M_W = \left(\frac{\sqrt{2} g^2}{8 G_F} \right)^{1/2} = \left(\frac{\sqrt{2}\; 4\pi\alpha}{8 G_F \sin^2 \theta_W} \right)^{1/2}$$

$$= \left(\frac{\pi\alpha}{\sqrt{2} G_F} \right)^{1/2} \frac{1}{\sin\theta_W} = \frac{37.28}{\sin\theta_W} [GeV]$$

M_W ~78 GeV

The Masses of W and Z^0 are SM predictions

using the measured values of the couplings : α and $\mathbf{G_F}$ and $\mathbf{\sin\theta_W}$

$$M_Z = \frac{M_W}{\cos\theta_W}$$

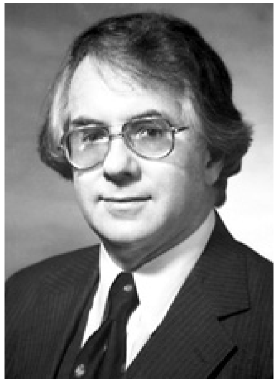
M_Z ~90 GeV

The Nobel Prize in Physics 1979

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

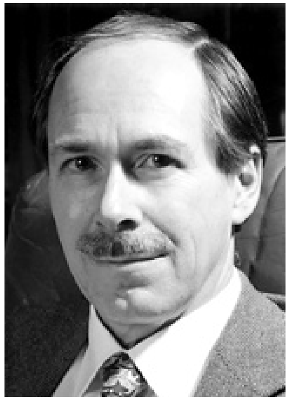

Abdus Salam

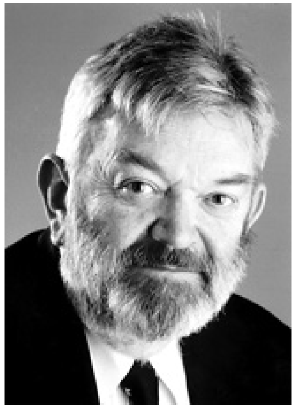

Steven Weinberg


Sheldon Lee Glashow

The Nobel Prize in Physics 1999

The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman *"for elucidating the quantum structure of electroweak interactions in physics"*


Gerardus 't Hooft


Martinus J.G. Veltman

The Nobel Prize in Physics 2008

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

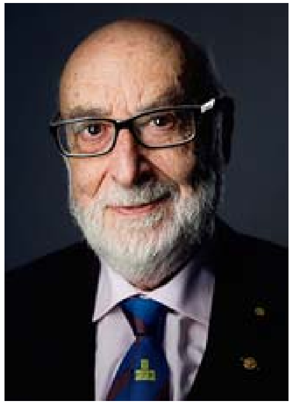
Yoichiro Nambu

Makoto Kobayashi

Toshihide Maskawa

The Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*



François Englert

Peter W. Higgs

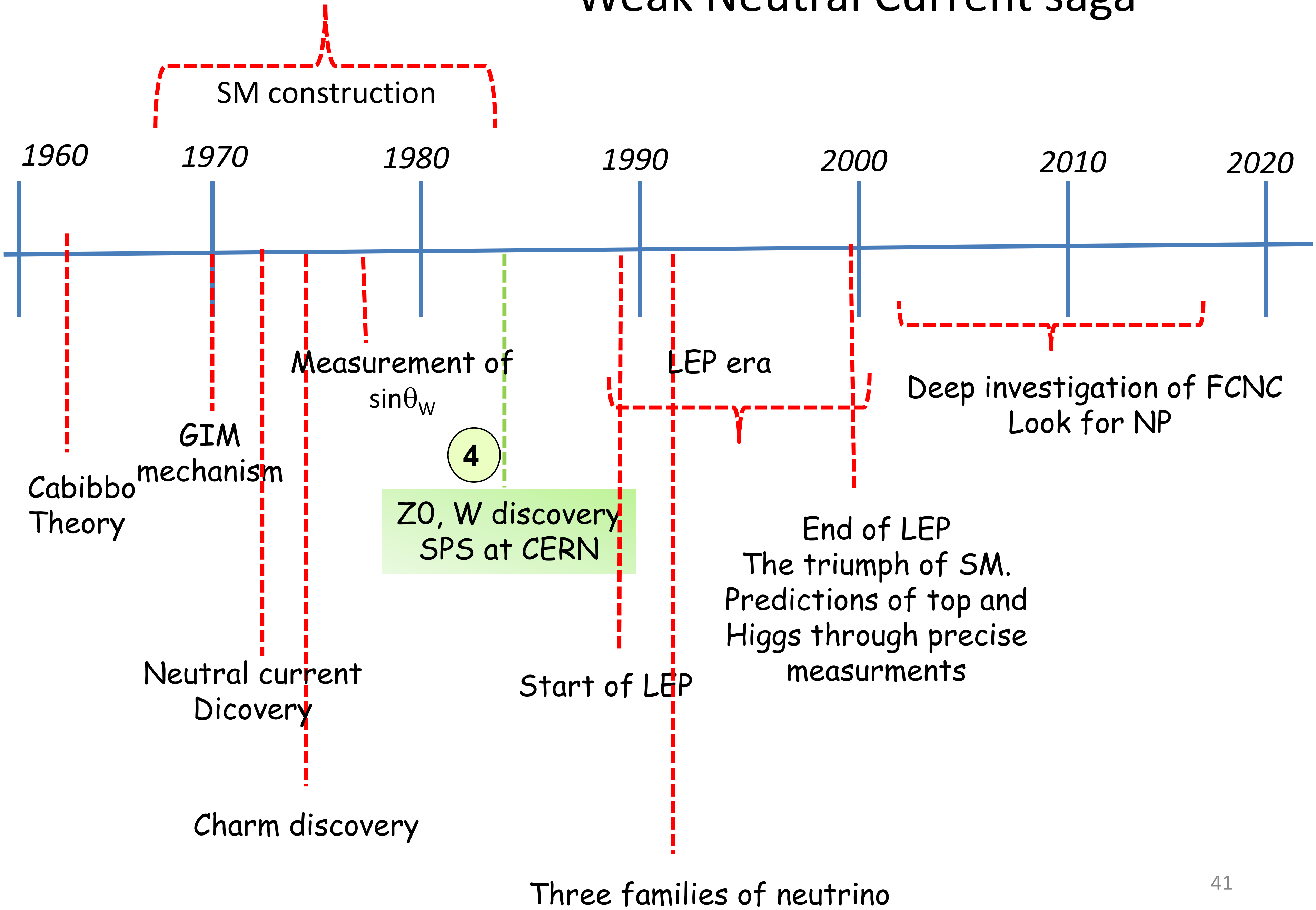
3

3rd MESSAGE

NEUTRAL CURRENTS ARE PERFECTLY CODED IN THE STANDARD MODEL

SM is very predictive in neutral current sector :
Coupling, Masses…

Weak Neutral Current saga

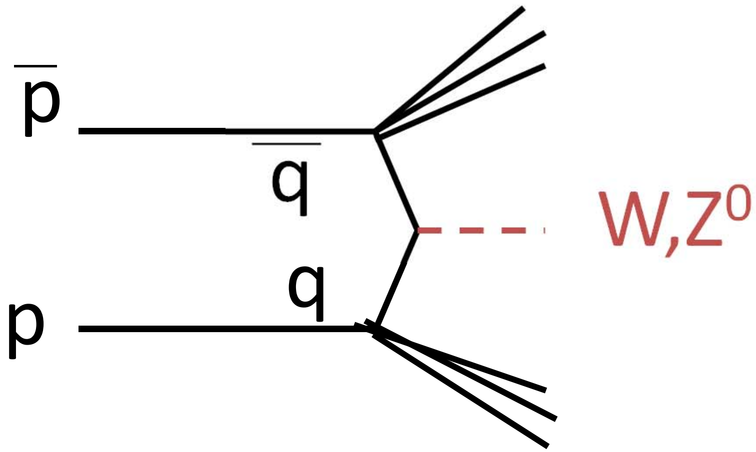


4

THE DISCOVERY OF W^{+-} and Z^0 bosons at SPS at CERN by UA1 and UA2 Coll.

The years `80

- CERN 1983
- Proton -- anti-proton collider ($Sp\bar{p}S$)
- Centre-of-mass energy 540 GeV
- Innovative cooling of anti-proton beam



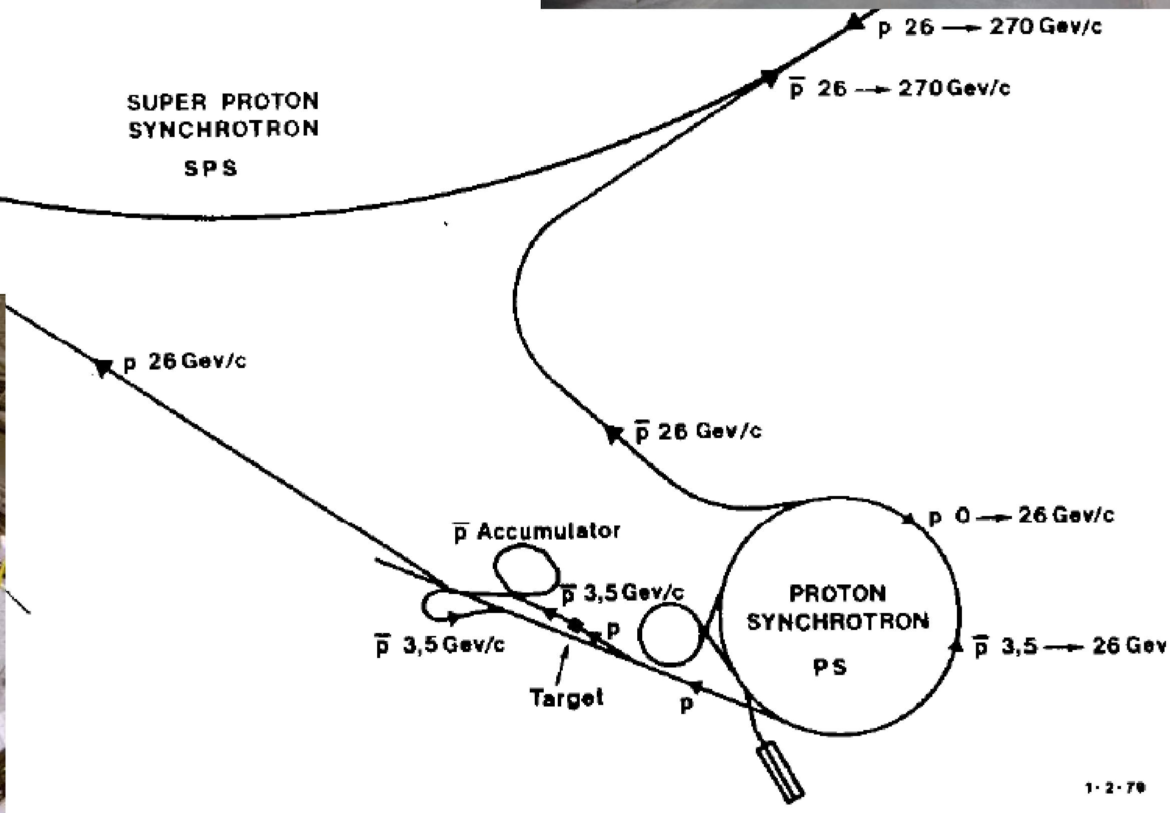
$u\bar{d} \rightarrow W^+$

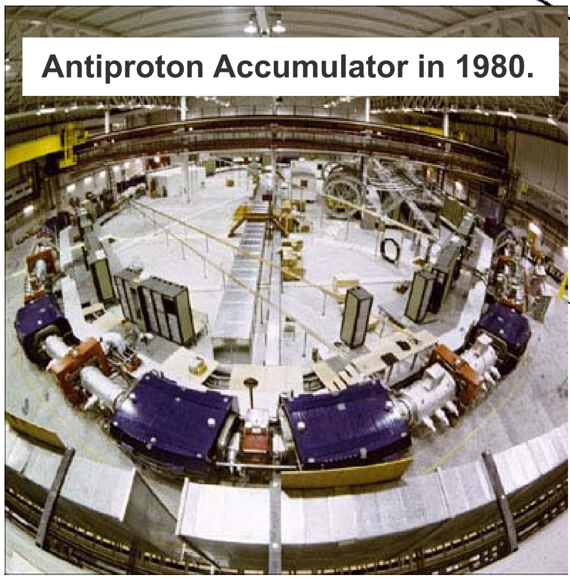
$u\bar{u}, d\bar{d} \rightarrow Z^0$

$p\,p \rightarrow W^+ X^-$ $\qquad W^+ \rightarrow l^+ \nu_l$

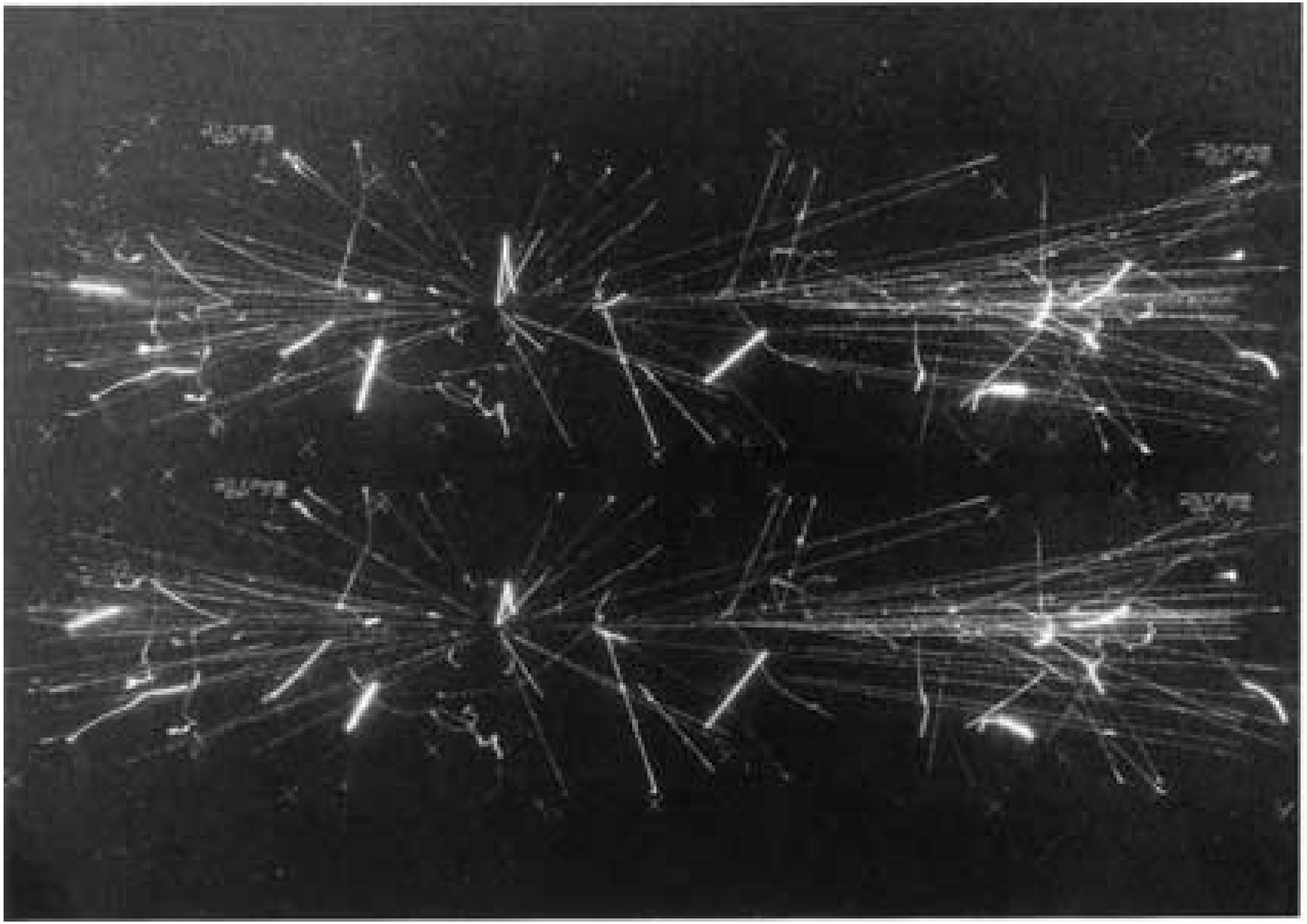
$p\,p \rightarrow Z^0\ X^0$ $\qquad Z^0 \rightarrow l^+ l^-$

The accelerator complex



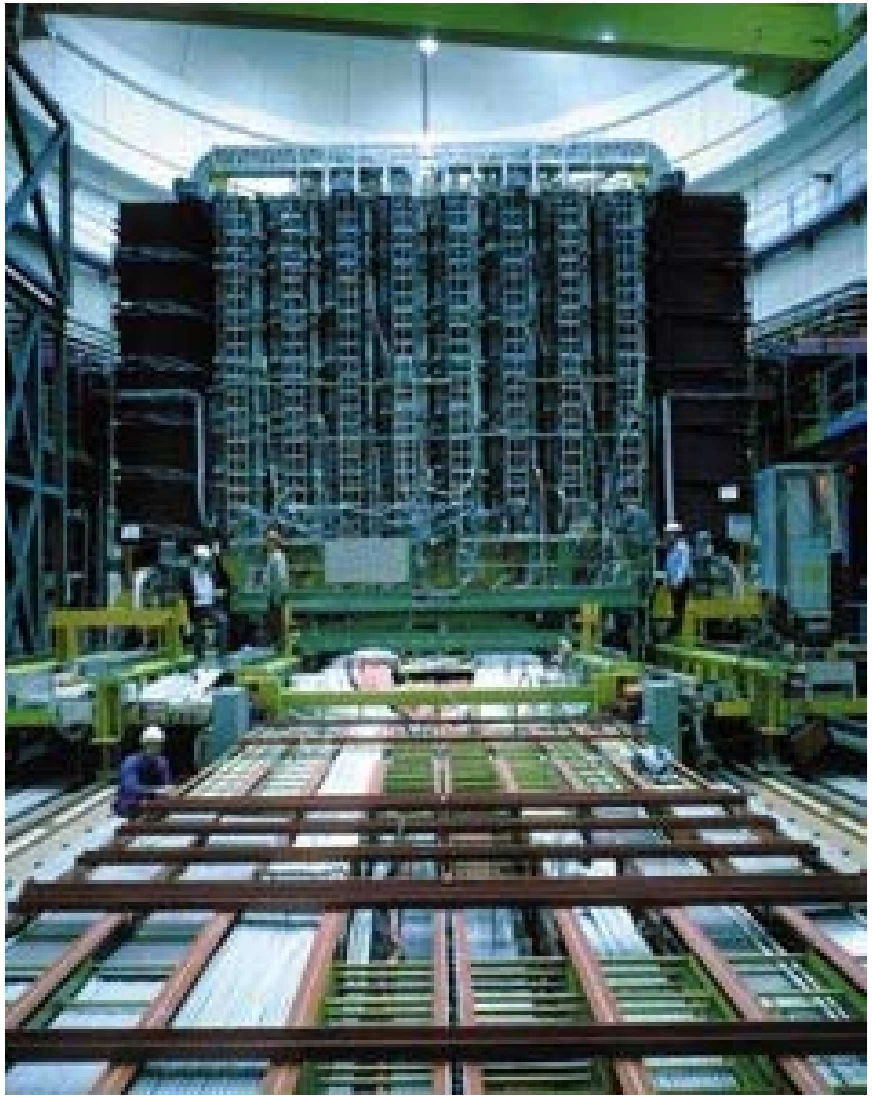

Antiproton Accumulator in 1980.

http://www.nobelprize.org/nobel_prizes/physics/laureates/1984/meer-lecture.pdf

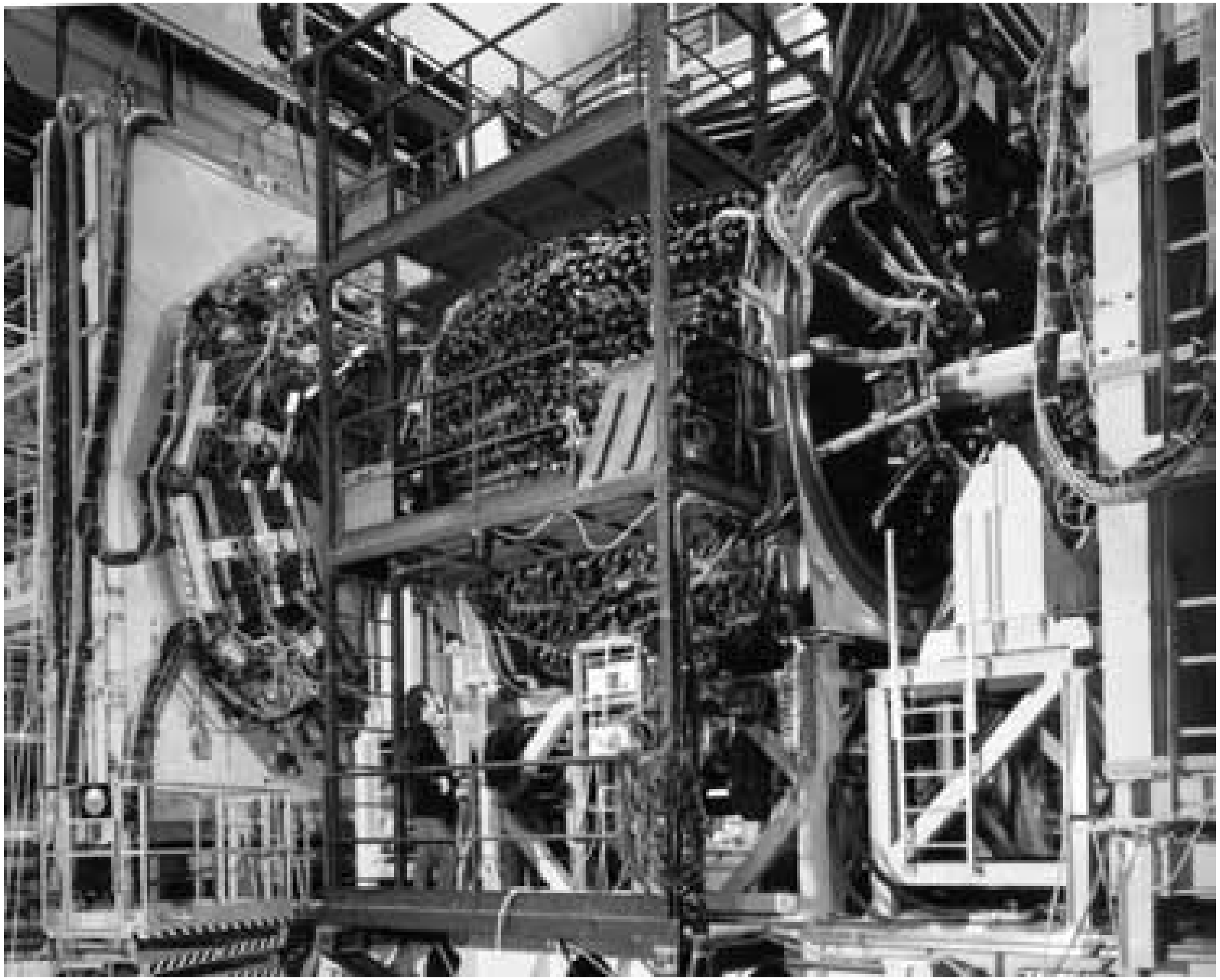


One of the first pictures of a 540 Ge V proton-antiproton collision, as recorded in the big streamer chambers of the UA5 experiment at the CERN SPS

UA1



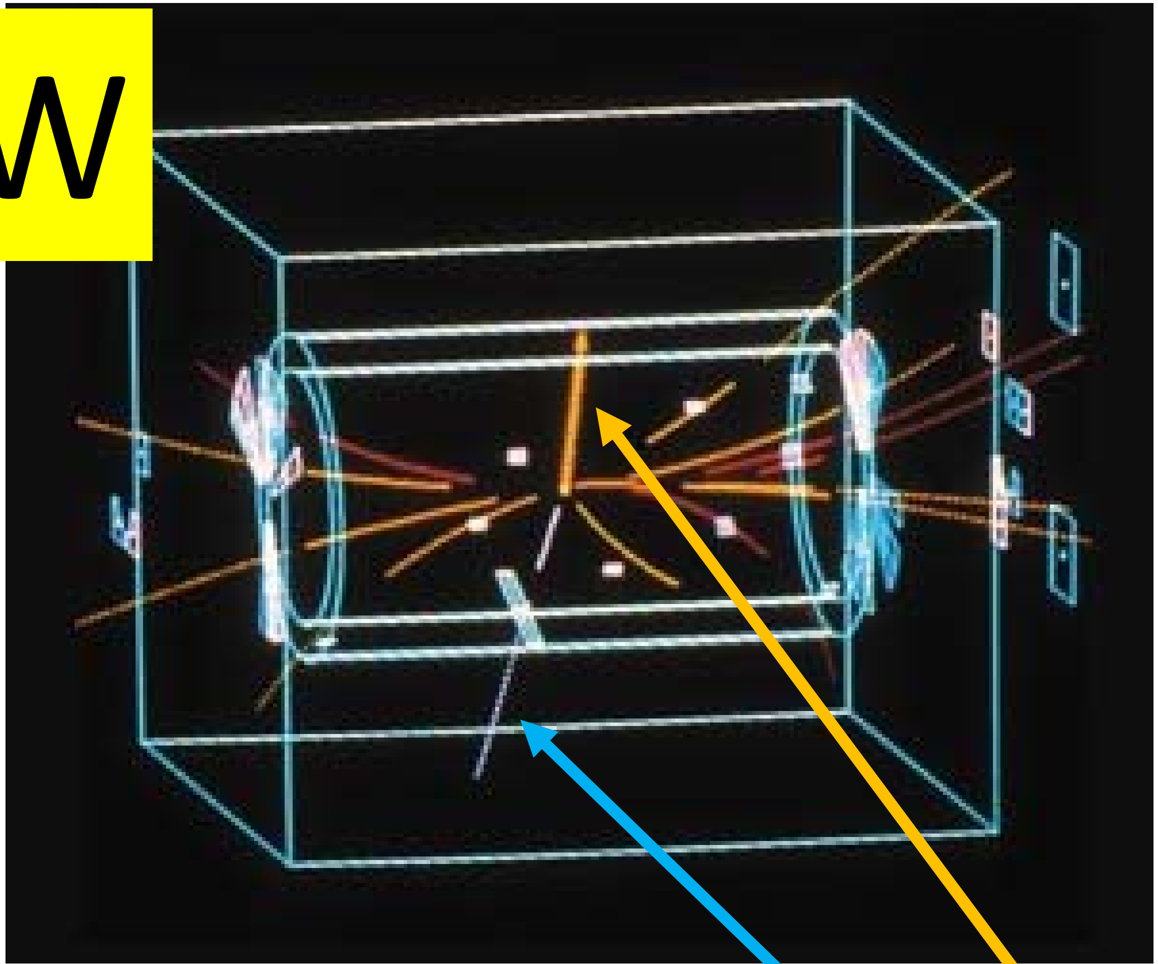
The UA1 detector, shown here in its "garage" position, was a multi-purpose detector. The main asset of the UA1 detector was a large-volume, high-resolution central tracking detector. It covered as large a solid angle as possible and could detect hadron jets, electrons and muons.



UA2

Particles emerging from the collisions are picked up in the inner vertex detector, equipped with interleaved proportional chambers and drift chambers. Surrounding this vertex detector are the central electromagnetic and hadronic calorimeters, segmented into 240 cells, each pointing towards the centre of the interaction region. Each of these cells is divided into electromagnetic (lead/scintillator) and hadronic (iron/scintillator) compartments.
During its initial runs in 1981 and 1982, the UA2 central calorimeter had a 'wedge' removed to accommodate a magnetic spectrometer which measured the level of neutral pion production.

W

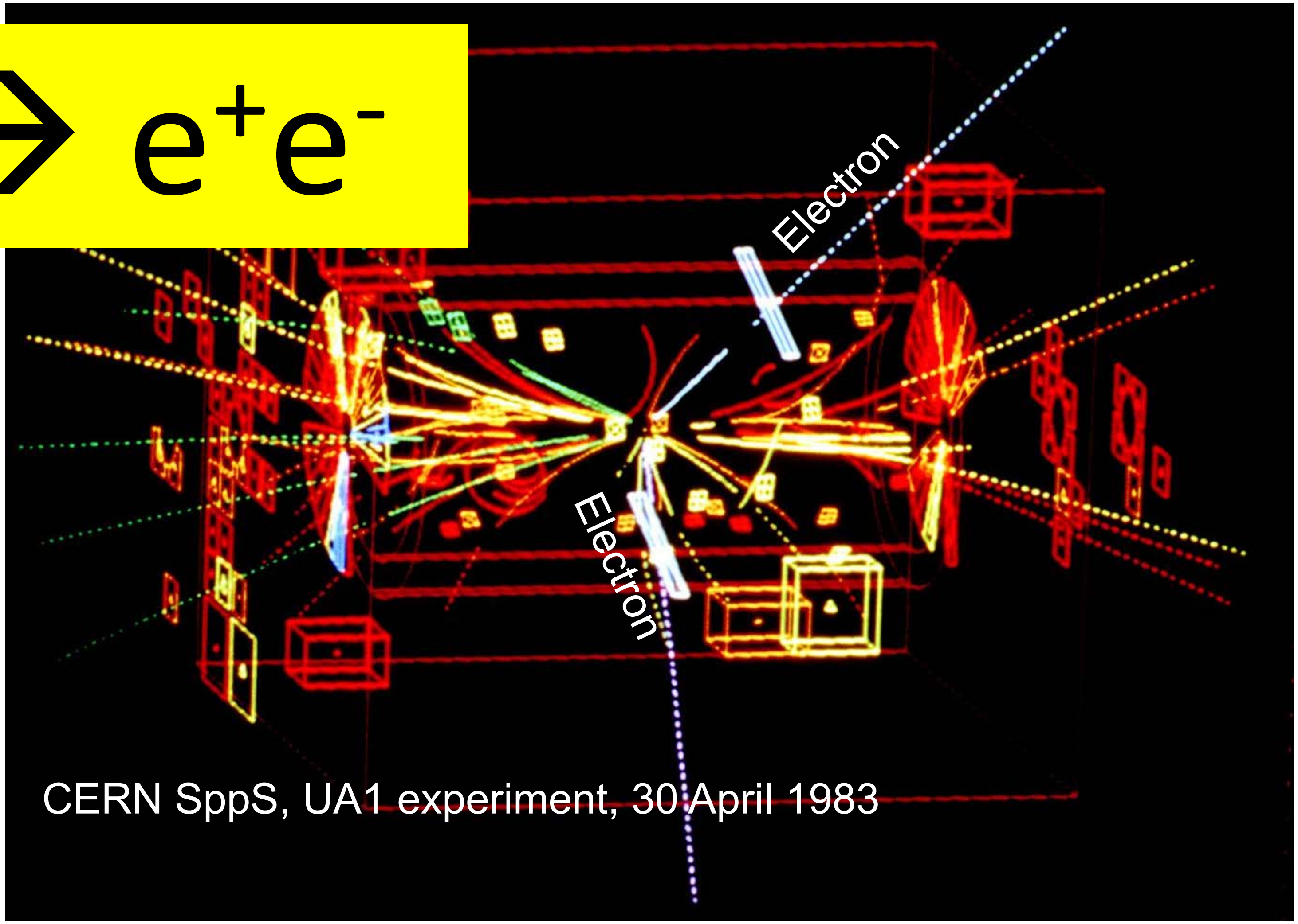


$W^- \rightarrow e^- \nu$

The decay of a W particle in the UA1 detector

showing the track of the high-energy electron towards the bottom. The yellow arrow marks the direction of the missing transverse energy and hence the path of the unseen neutrino.

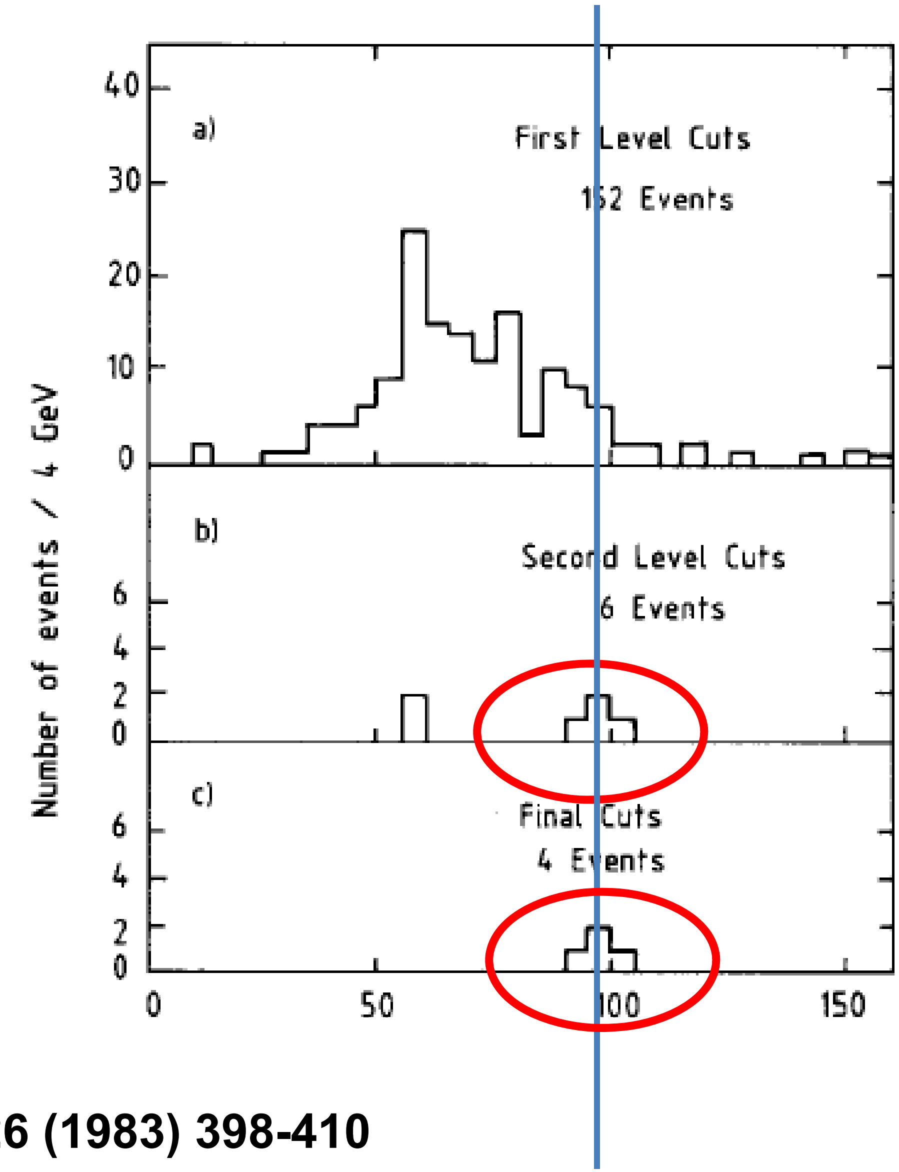
$Z \rightarrow e^+e^-$



One of the first Z particles observed in UA1.

The two white tracks (towards the top right and almost directly downwards) reveal the Z's decay into an electron-positron pair that deposit their energy in the electromagnetic calorimeter.

Z^0 discovery paper



UA1 collaboration

Received 6 June 1983

Phys.Lett. B126 (1983) 398-410

We report the observation of four electron–positron pairs and one muon pair which have the signature of a two-body decay of a particle of mass ~95 GeV/c^2. These events fit well the hypothesis that they are produced by the process $\bar{p} + p \rightarrow Z^0 + X$ (with $Z^0 \rightarrow \ell^+ + \ell^-$), where Z^0 is the Intermediate Vector Boson postulated by the electroweak theories as the mediator of weak neutral currents.

On 25 January 1983,
CERN called a press conference to announce the discovery of the W particles.

Carlo Rubbia and Simon Van der Meer received the Nobel Prize in 1984

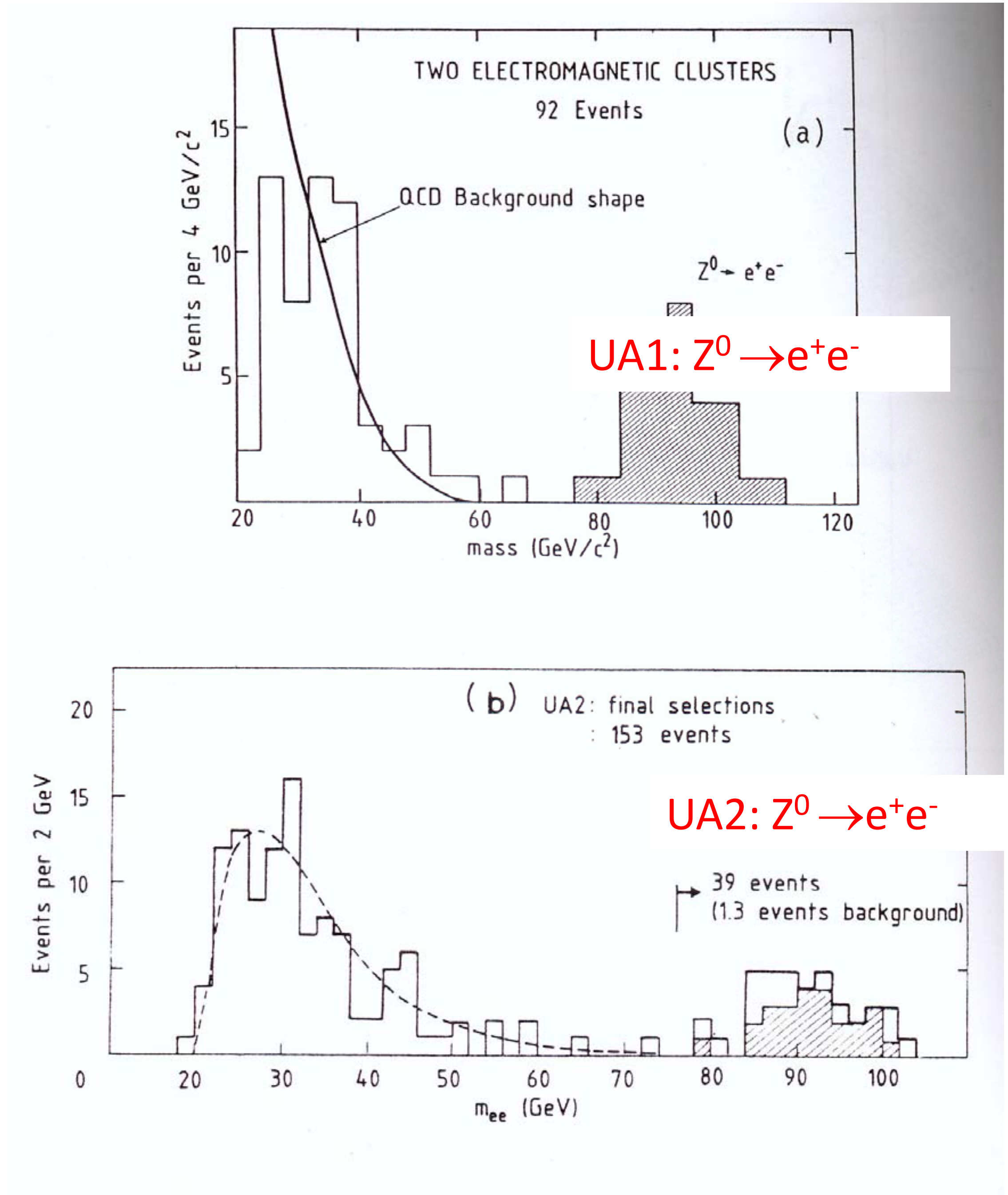
And the first mass measurements of $W^{\pm}$, Z^0

M_W = 81 ± 5 GeV

M_Z = 95.2 ± 2.5 GeV/c^2 (UA1)

= 91.9 ± 1.9 GeV/c^2 (UA2)

And later…


TWO ELECTROMAGNETIC CLUSTERS
92 Events
(a)
QCD Background shape
$Z^0 \to e^+e^-$
Events per 4 GeV/c²
mass (GeV/c²)
UA1: $Z^0 \to e^+e^-$
(b) UA2: final selections
: 153 events
39 events
(1.3 events background)
Events per 2 GeV
m_{ee} (GeV)
UA2: $Z^0 \to e^+e^-$

4

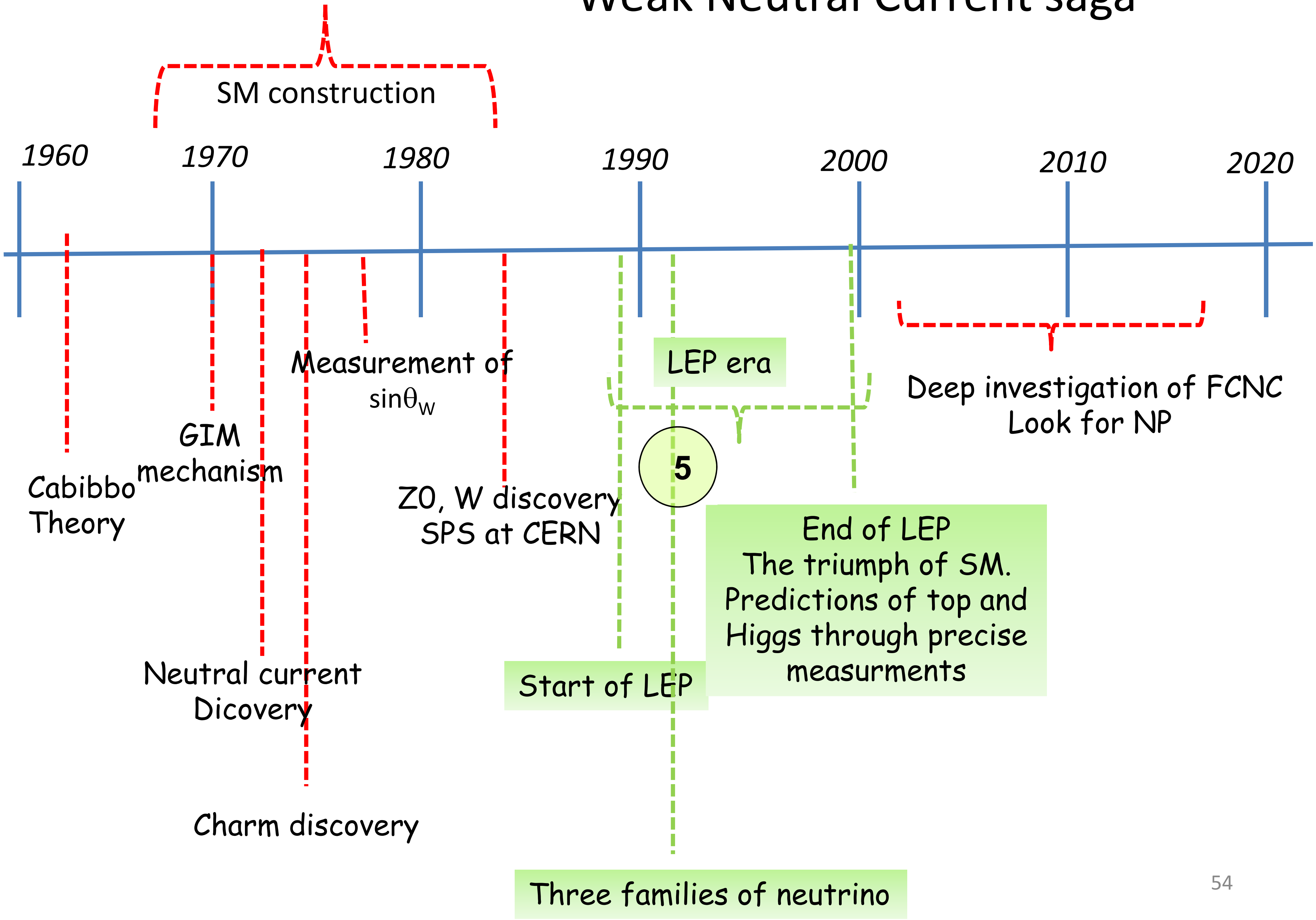
4th MESSAGE

Z^0 (and W) DISCOVERY

The Z^0 (and W) where discovered as real particles (peaks in invariant mass) at the expected masses.

It is a tremendous triumph of our vision of weak interactions (unified with electromagnetism) carried by intermediate bosons

Weak Neutral Current saga



The years `90

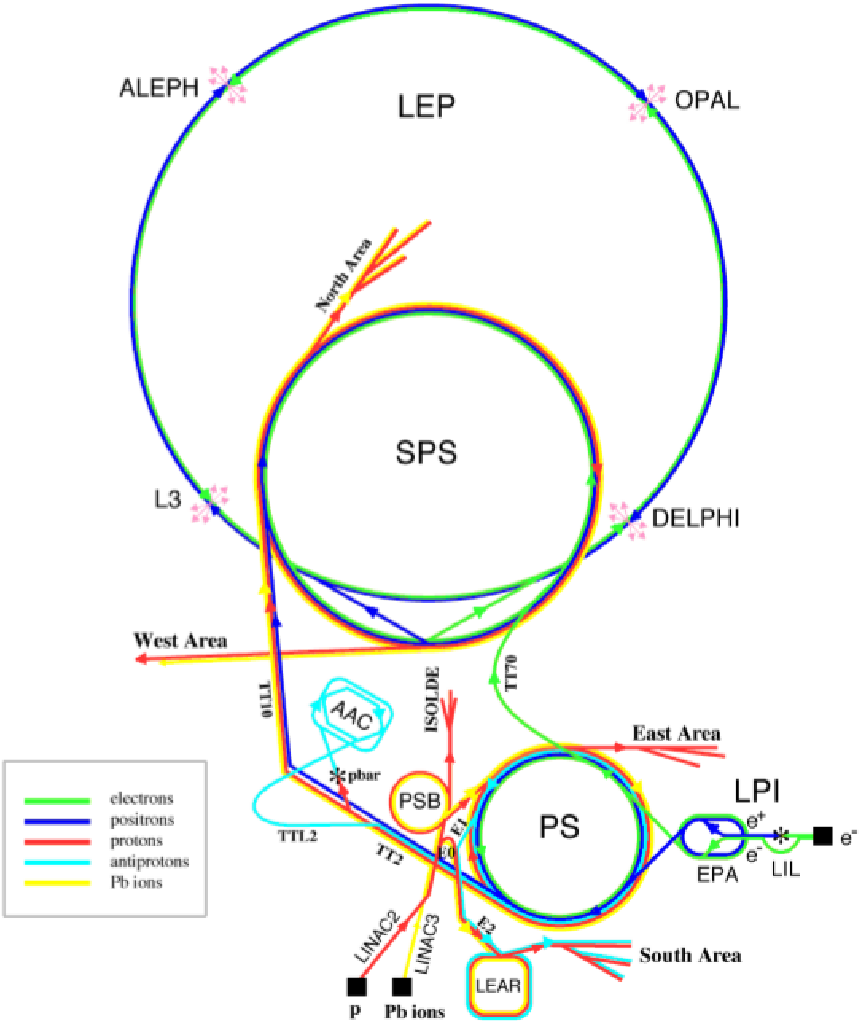
5

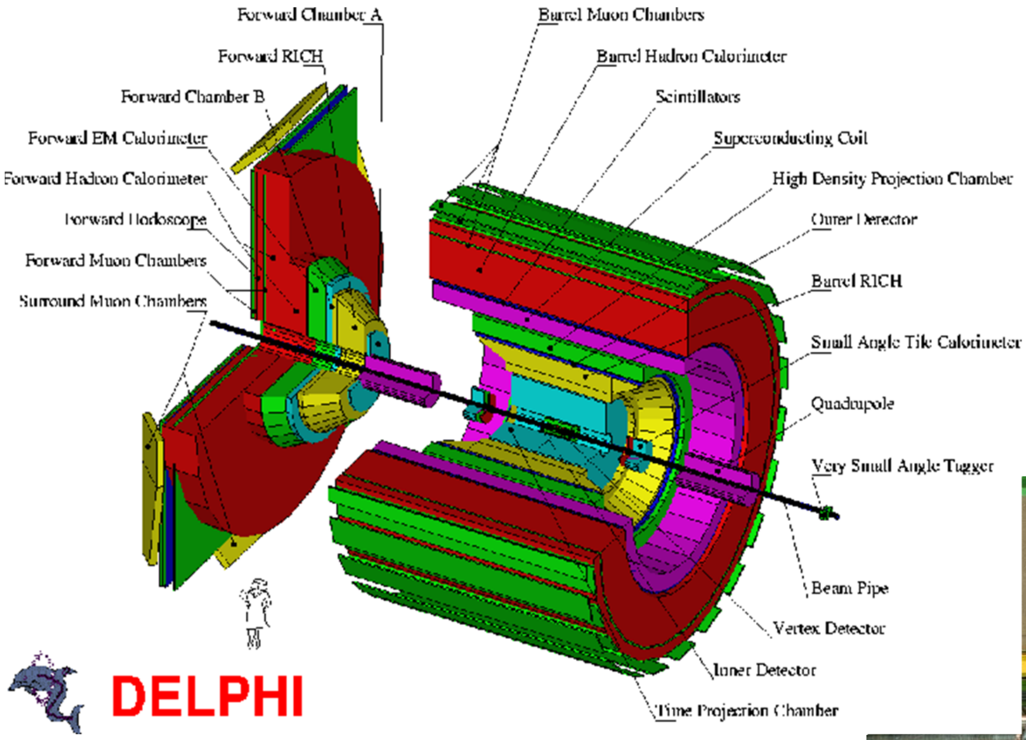
DETAILED STUDIES OF THE Z^0 BOSON at LEP !

The TRIUMPH of the STANDARD MODEL

Large Electron–Positron Collider (**LEP**) at CERN.
LEP collided electrons with positrons

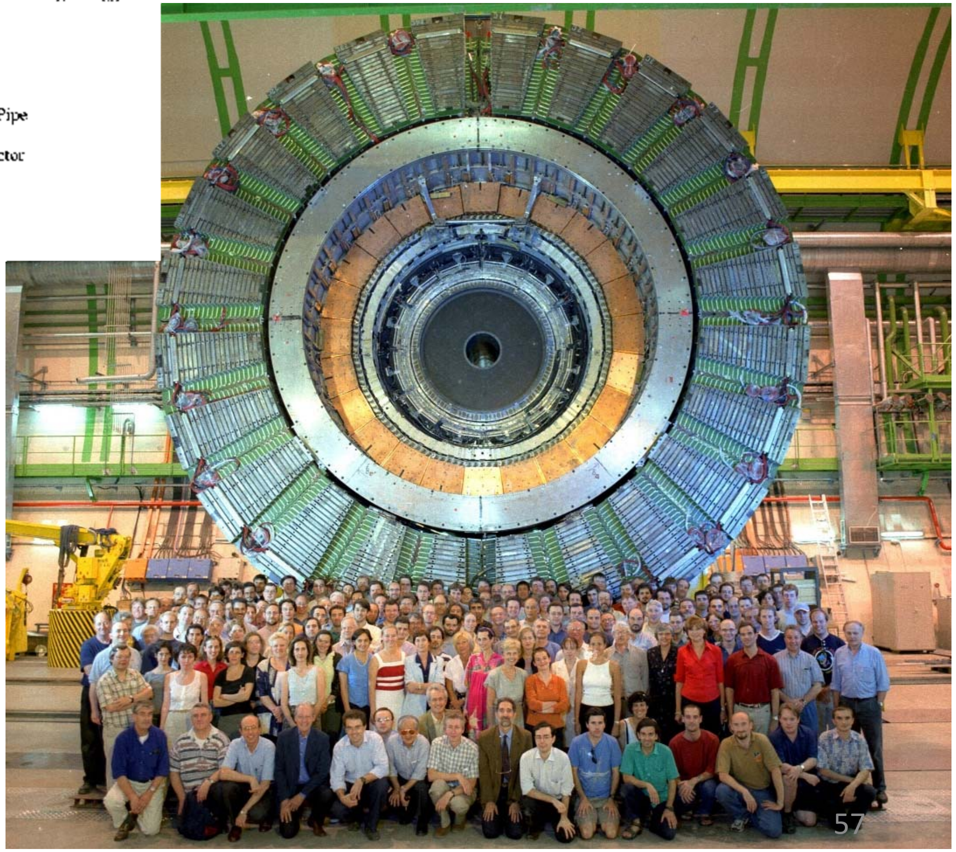
- Large Electron-Positron (LEP) collider:
  - Used from 1989 till 2000
  - 2000 onwards: Large Hadron Collider (LHC)
  - 26.67 km circumference, 40 m to 150 m below the surface (inclination of 1.4%) due to the geological composition of the ground
  - Synchrotron with e^+e^- collisions
  - Center-of-mass energy went from 91 GeV (1989-1995) to 209 GeV (2000)
    → increase in energy for analysis of $W^\pm$
    → production cross-section of $W^\pm$ increases with energy up to 200 GeV



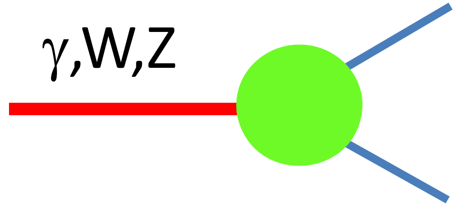


As an example

DELPHI DETECTOR



In term of **couplings**



When you calculate ..Γ,σ

W	$g^2/2 = e^2/2\sin^2\theta_W$	$-i\frac{g}{\sqrt{2}}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)$
γ	e^2	$-ie\,\gamma^\nu$ $e = g\sin\theta_W$
Z	$(g^2_V + g^2_A)\,(g/4\cos^2\theta_W)^2$	$-i\frac{e}{\sin\theta_W\cos\theta_W}\gamma^\nu\left(\frac{g_V - g_A\gamma_5}{2}\right)$

$g_V = T_3 - 2Q\sin^2\theta_W$ Vectorial constant

$g_A = T_3$ Axial constant

Very predictive !!
Let's me say the unexpected part of the SM…

$$\left(\frac{g_V - g_A\gamma_5}{2}\right) = \left(\frac{g_V + g_A}{2}\right)\left(\frac{1-\gamma_5}{2}\right) + \left(\frac{g_V - g_A}{2}\right)\left(\frac{1+\gamma_5}{2}\right)$$

+ propagator… $1/M^2_W$

$1/M^2_Z$

Z production

$$\frac{d\Gamma}{d\Omega} = \frac{1}{64\pi^2 M_Z}\sum |T_{if}|^2$$

$$\frac{d\sigma}{d\Omega} = \sigma_{(a+b\to R\to 1+2)}(\sqrt{s}) = \frac{4\pi}{(p^*)^2}\frac{2J+1}{(2s_a+1)(2s_b+1)}\frac{(\Gamma_{in}\Gamma_{out})/4}{(\sqrt{s}-m_R)^2+\Gamma^2/4}$$

At pole :

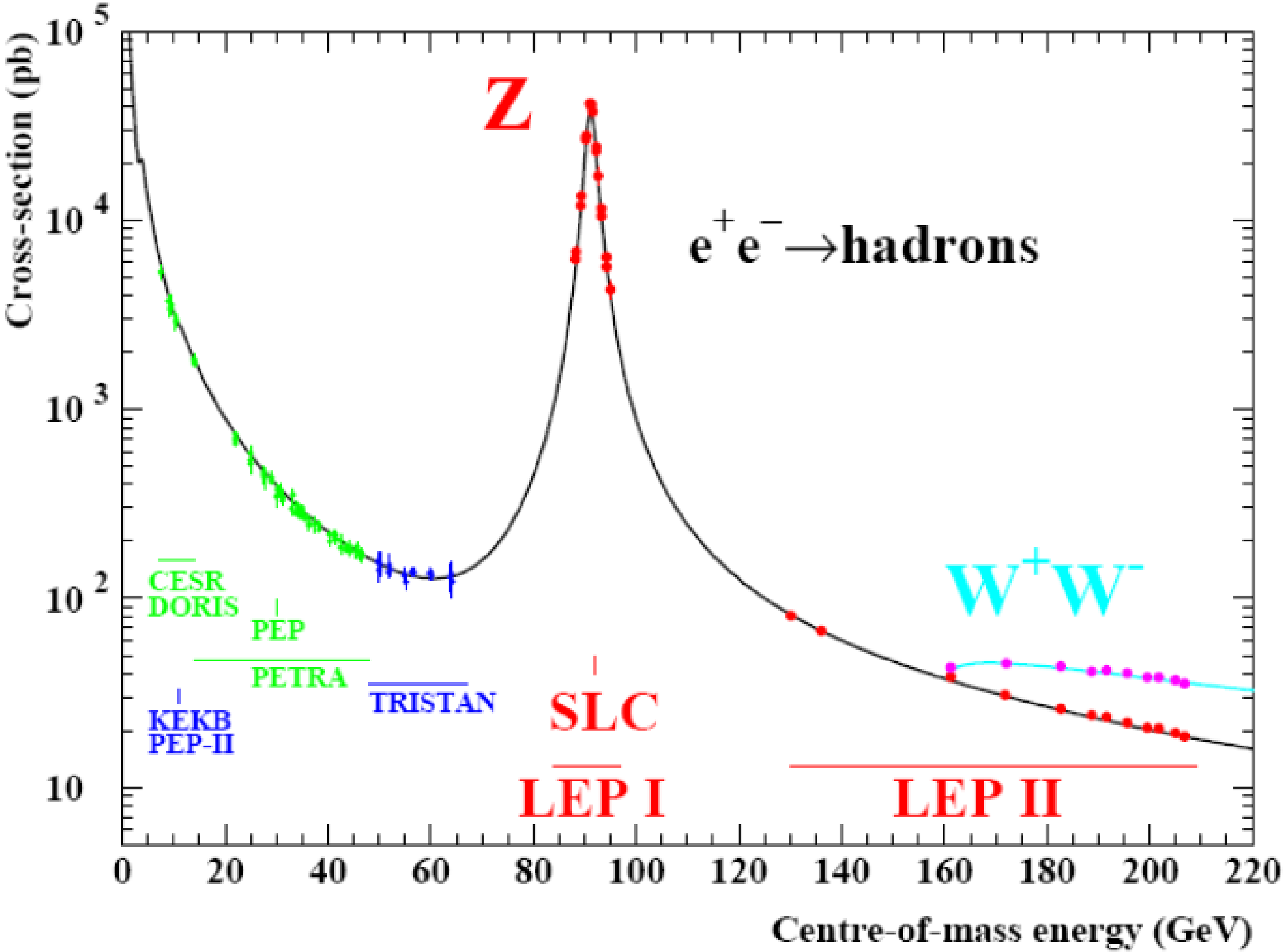
$$\sigma(\mathrm{s{=}M}_Z, f\bar{f}) = 12\pi\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{M_Z^2\Gamma^2}$$

$$\sigma_{tot}(\sqrt{\mathrm{s}}\mathrm{=M}_Z) = 12\pi\frac{\Gamma_{ee}}{M_Z^2\Gamma} \approx \frac{12\pi}{30}\frac{1}{M_Z^2}$$

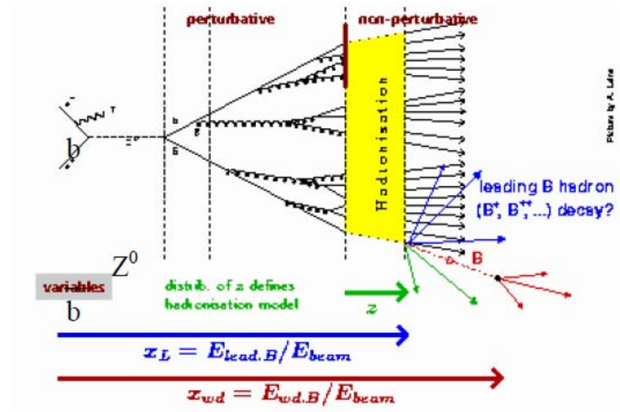
$$\sigma_{tot}(\mathrm{s{=}M}_Z) \approx \frac{12\pi}{30M_Z^2}(hc)^2 = 1.4\times10^{-4}\times0.389\ mbarn \approx 5\times10^{-2}\mu barn \sim 50nbarn$$

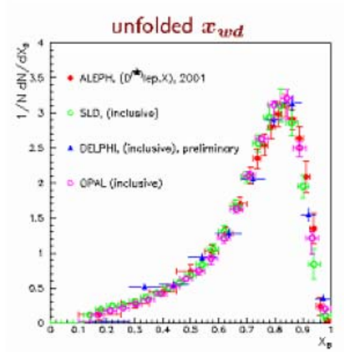
Compared with $\sigma_{\mu\mu}^{QED} = \frac{4\pi\alpha^2}{3s} = \frac{86.8nb}{s[GeV]}$

At Z^0 pole/peak the weak cross section is 200 times larger than electomagnetism cross section !

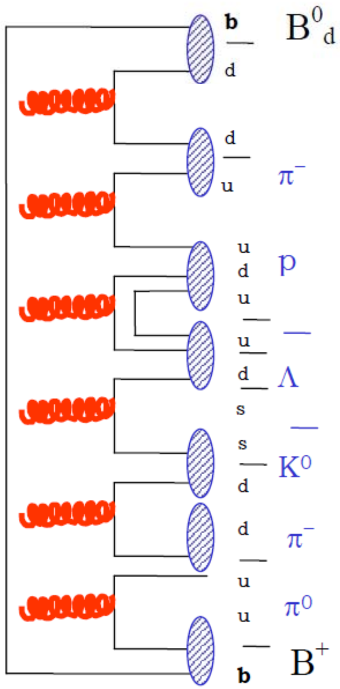

Cross-section (pb)
Z
$e^+e^- \rightarrow$ hadrons
W^+W^-
CESR
DORIS
PEP
PETRA
TRISTAN
KEKB
PEP-II
SLC
LEP I
LEP II
Centre-of-mass energy (GeV)

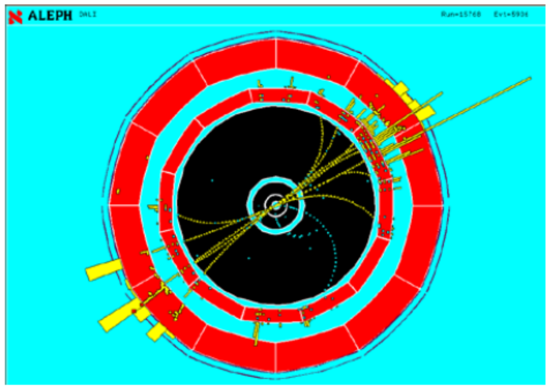
Event topology at LEP





E_b ~ 0.7 E_{beam}



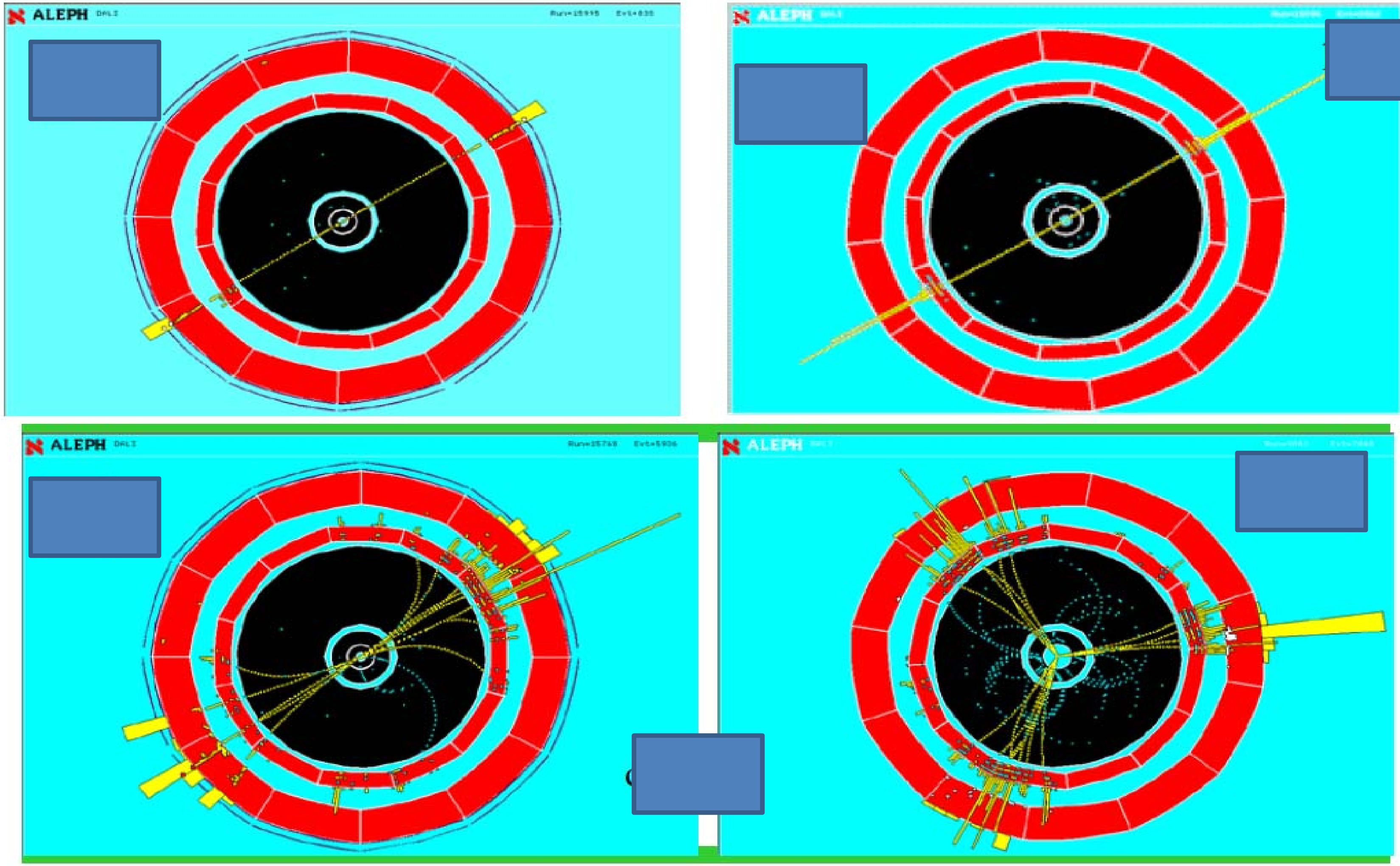


Independent fragmentation

ex: $B^0{}_d B^+$

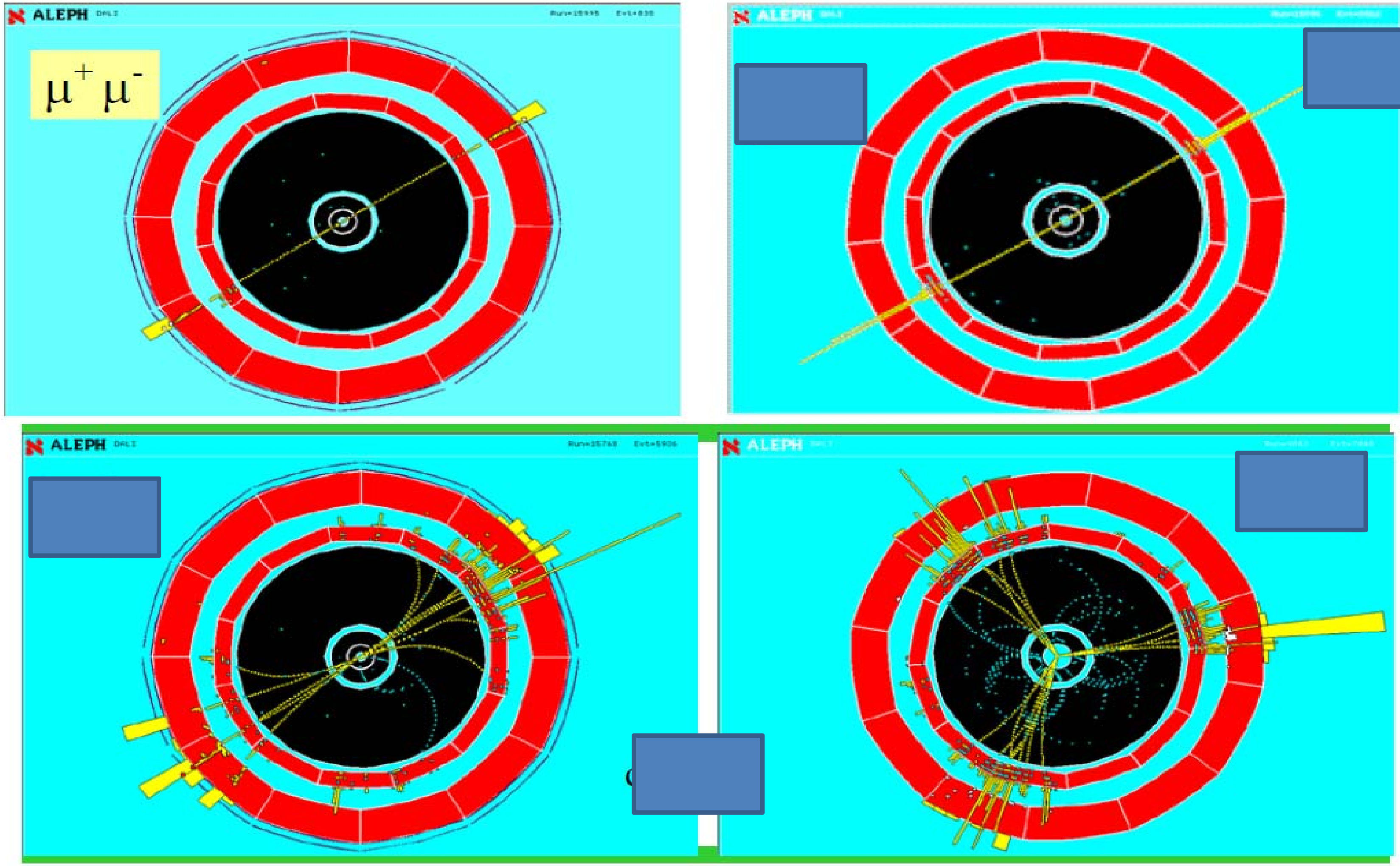
événements LEP

$Z^0 \rightarrow f\,f$



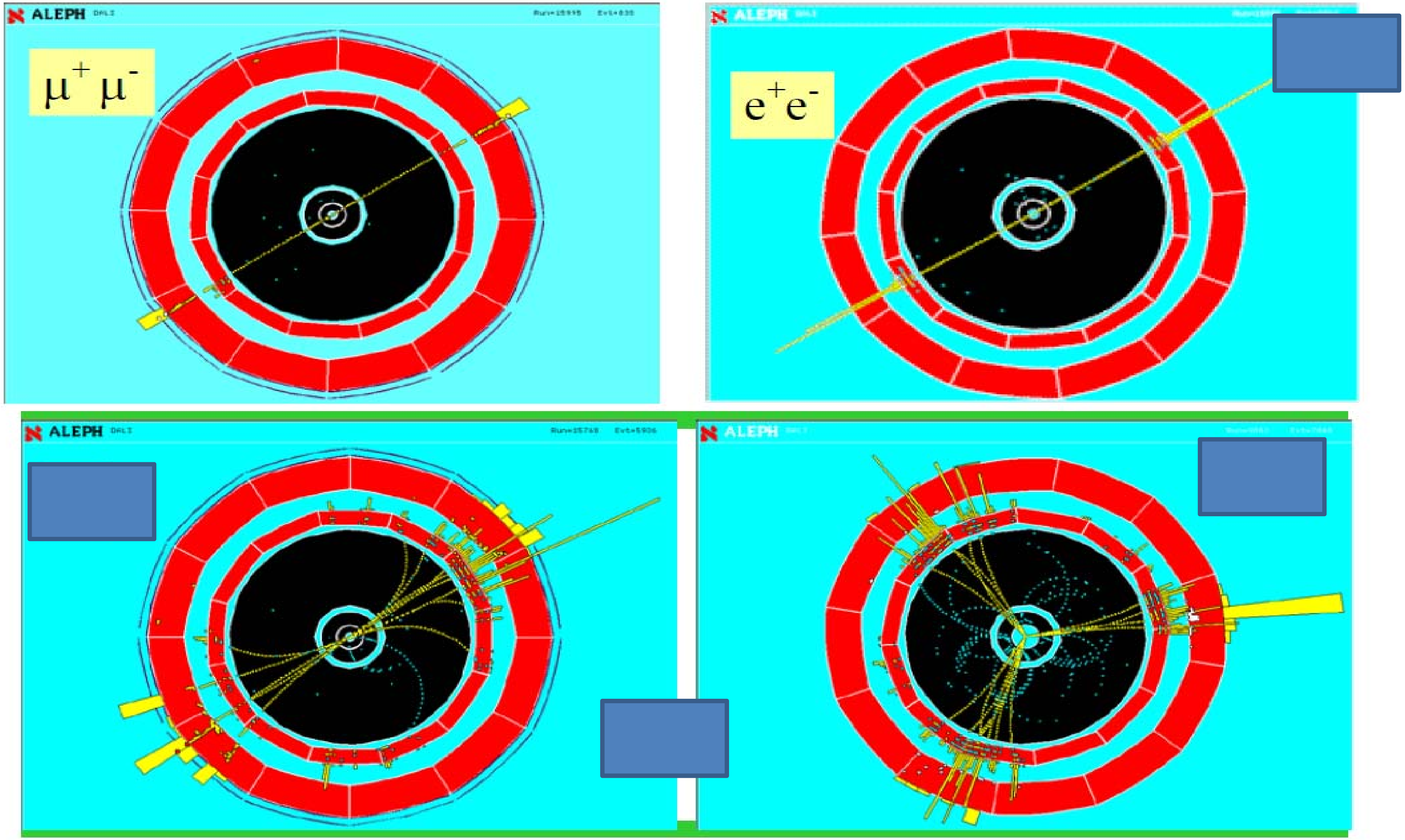
événements LEP

$Z^0 \rightarrow f\, f$



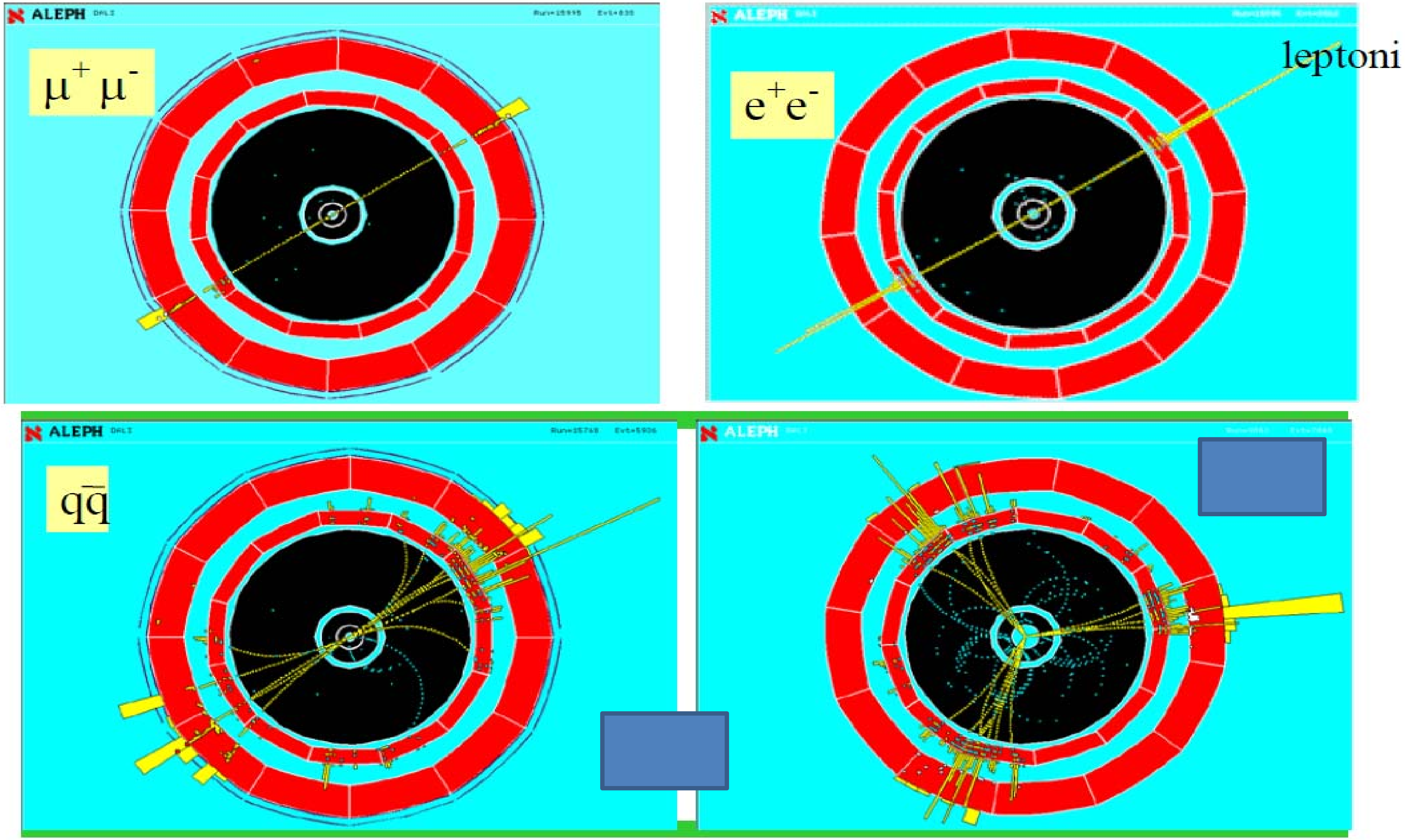
événements LEP

$Z^0 \rightarrow f\,f$



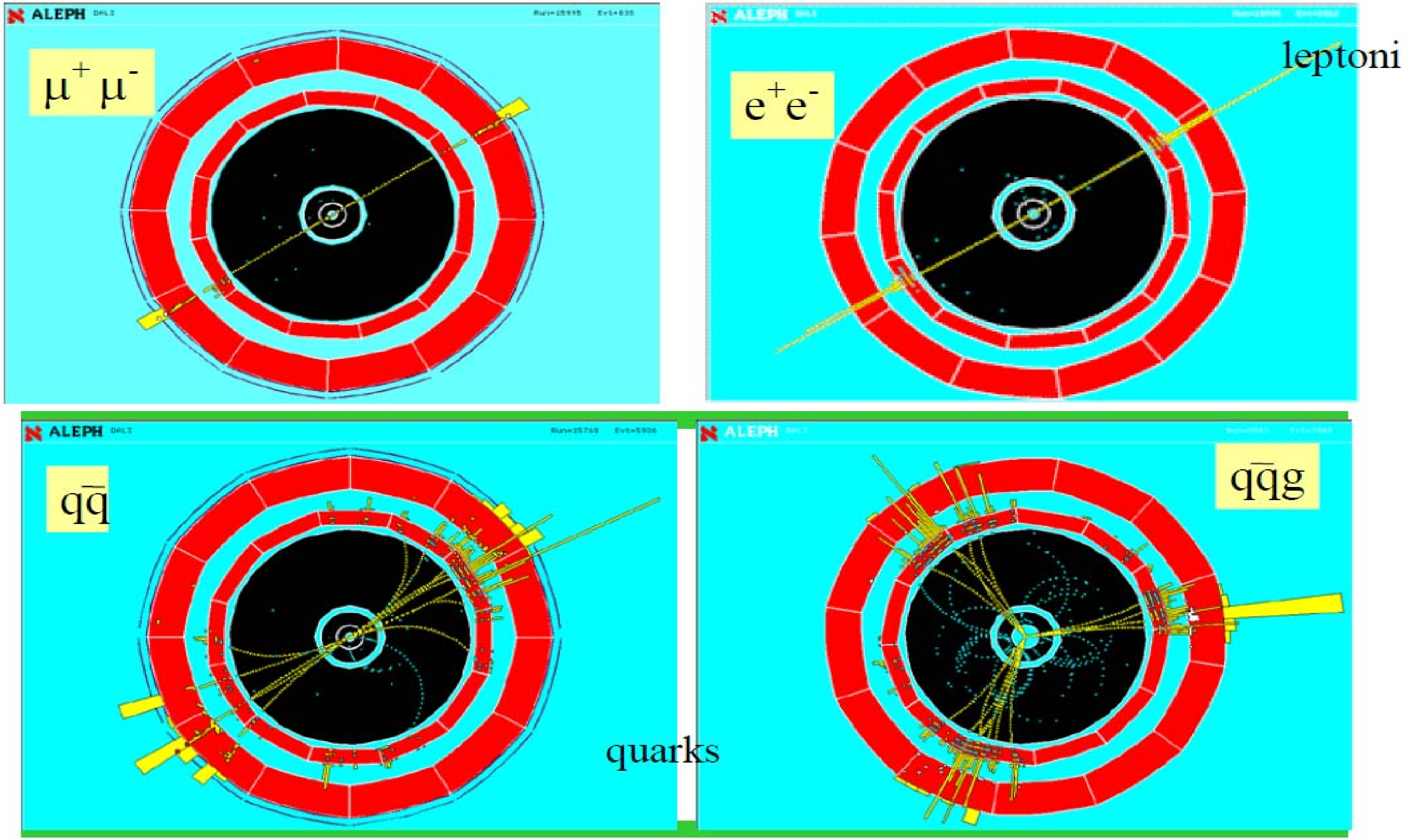
événements LEP

$Z^0 \rightarrow f\,f$

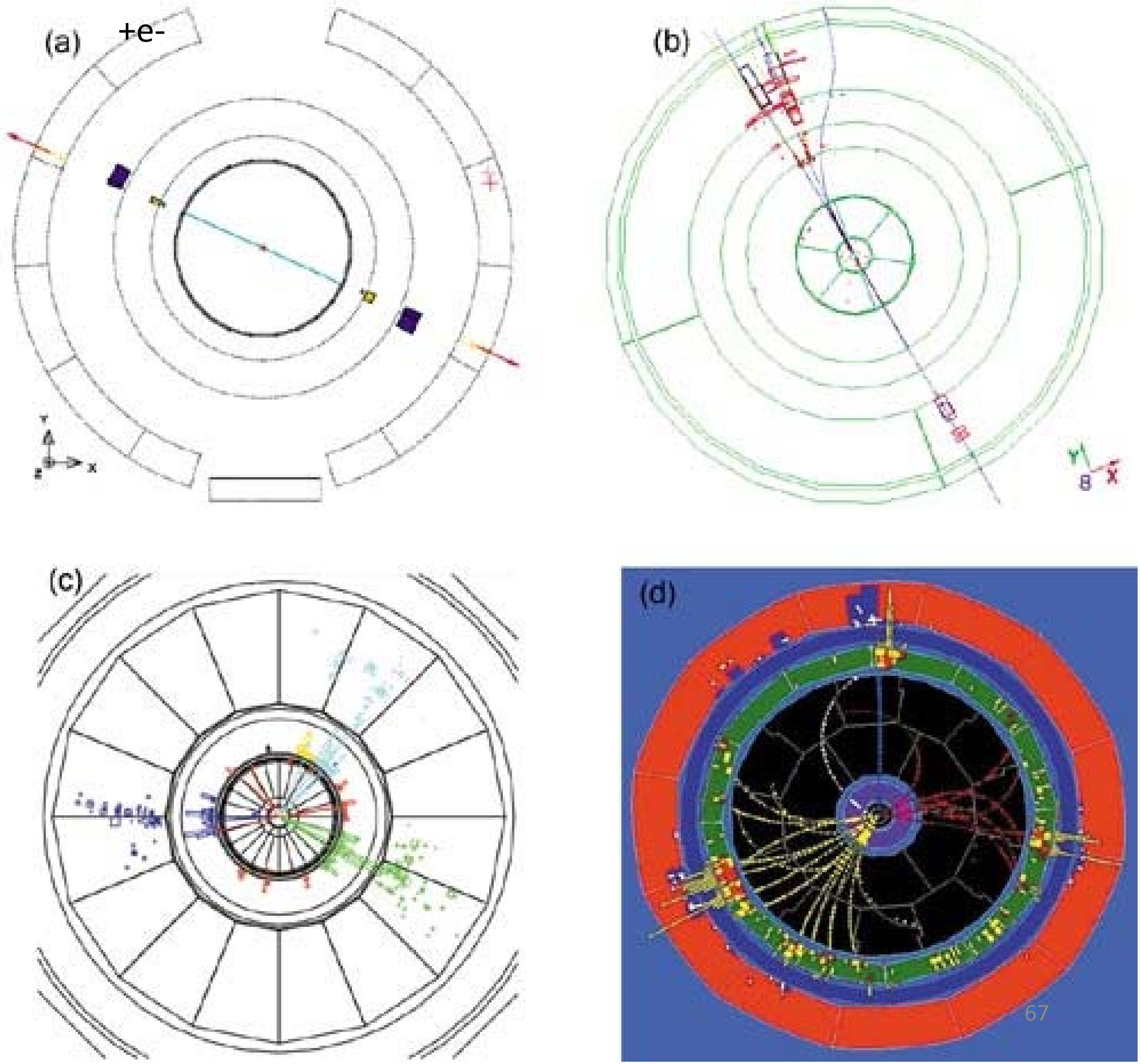


événements LEP

$Z^0 \rightarrow f \bar{f}$



SUMMARY



Z decay

fermion	Q	T_3	g_v	g_a	g_v/g_a
ν	0	½	½	½	1
e,μ,τ	-1	-½	$-1/2+2\sin^2\theta_w$ (~0.04)	-½	$1-4\sin^2\theta_w$
u,c,t	2/3	½	$½-4/3\sin^2\theta_w$ (~0.19)	½	$1-8/3\sin^2\theta_w$
d,s,b	-1/3	-½	$-1/2+2/3\sin^2\theta_w$ (~-0.35)	-½	$1+4/3\sin^2\theta_w$

Using

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}, M_Z = \frac{M_W}{\cos\theta_W}$$

we obtain

$$\Gamma(Z \to f\bar{f}) = C\frac{G_F}{6\pi\sqrt{2}}(g_a^2 + g_V^2)M_Z^3$$

and so

$$\Gamma(Z \to f\bar{f}) = C\frac{G_F}{6\pi\sqrt{2}}g_a^2(1+\frac{g_V^2}{g_a^2})M_Z^3$$

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{G_F}{12\pi\sqrt{2}}M_Z^3$$

$$\Gamma(Z \to l^+l^-) = \frac{1}{2}\frac{G_F}{12\pi\sqrt{2}}M_Z^3[(1-4\sin^2\theta_W)^2+1]$$

$$\Gamma(Z \to u\bar{u}) = \frac{3}{2}\frac{G_F}{12\pi\sqrt{2}}M_Z^3[(1-\frac{8}{3}\sin^2\theta_W)^2+1] \quad \text{quarks u,c,t}$$

$$\Gamma(Z \to d\bar{d}) = \frac{3}{2}\frac{G_F}{12\pi\sqrt{2}}M_Z^3[(1-\frac{4}{3}\sin^2\theta_W)^2+1] \quad \text{quark d,s,b}$$

and finally for all the fermions kinematically accessible (all but top quarks)

$$\Gamma(TOT) = \frac{G_F}{8\pi\sqrt{2}}M_Z^3[14-\frac{80}{3}\sin^2\theta_W+\frac{320}{9}\sin^4\theta_W]$$

Using

$G_F = 1.16637 \times 10^{-5}\, GeV^{-2}$

$\sin^2\theta_W = 0.23138 \pm 0.00013$ (EWWG 2007)

$M_Z = 91.1875 \pm 0.0021$ (EWWG final)

We obtain

$$\Gamma(Z \to \nu\bar{\nu}) = 166 MeV$$

$$\Gamma(Z \to l^+l^-) = \frac{1}{2}\Gamma(Z \to \nu\bar{\nu}) \times 1.0055 = 83 MeV$$

$$\Gamma(Z \to u\bar{u}) = \frac{3}{2}\Gamma(Z \to \nu\bar{\nu}) \times 1.1467 = 285 MeV$$

$$\Gamma(Z \to d\bar{d}) = \frac{3}{2}\Gamma(Z \to \nu\bar{\nu}) \times 1.4782 = 368 MeV$$

$$\Gamma(TOT) = \frac{3}{2}\Gamma(Z \to \nu\bar{\nu}) \times 9.73 = 2.42 GeV \quad (2.4952 \pm 0.0023\text{GeV EWWG final})$$

Z0 prefers neutrinos to charged leptons

Z0 prefers d-type quark to up-down-quark

And for branching fraction we find

$Br(Z \to \nu\bar{\nu}) = 6.8\%$ and in total 20.5% PDG2006 $(20.00 \pm 0.06)\%$

$Br(Z \to l^+l^-) = 3.4\%$ PDG2006 (3.3658 ± 0.005)

$Br(Z \to u\bar{u}) = 11.8\%$

$Br(Z \to d\bar{d}) = 15.2\%$

$Br(Z \to hadrons) = 69.1\%$ PDG2006 $(69.91 \pm 0.06)\%$

NEUTRINO FAMILY COUNTING

Each neutrino would contribute to the total width of Z0 by 7%. So the measurement of The invisible width is a good way of determining the number of neutrino families with mass $<M_Z/2$

1) $$\sigma^0_{HAD} = 12\pi \frac{\Gamma_{ee}\Gamma_{Had}}{M_Z^2\,\Gamma_Z^2}$$

$$M_Z = 91{,}171 \pm 0.030 \pm 0.030 \text{ GeV}$$
$$\Gamma_Z = 2{,}511 \pm 0.065 \text{ GeV}$$
$$\sigma^0 = 41.6 \pm 0.7 \pm 1.1 \text{ nb}$$

↓

$$\Gamma_\ell\,\Gamma_H$$

2)

$$\Gamma_\ell/\Gamma_H = 0.0489 \pm 0.023$$

1) + 2) → Γ_ℓ and Γ_H

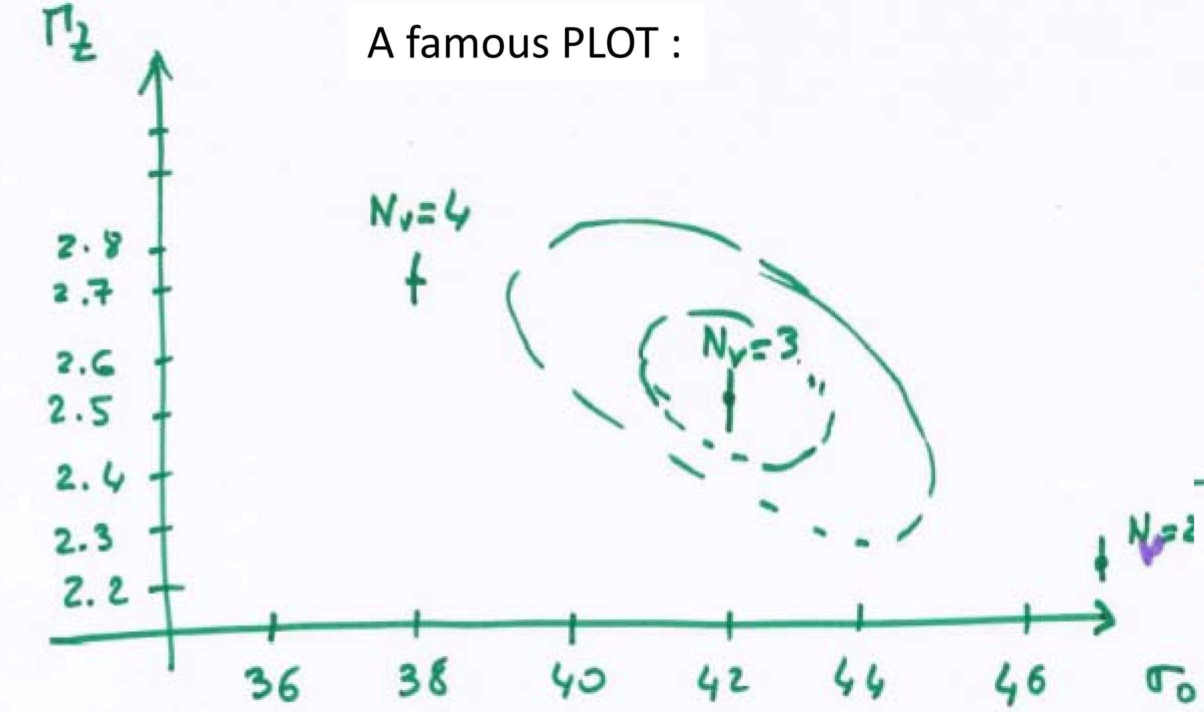
Using

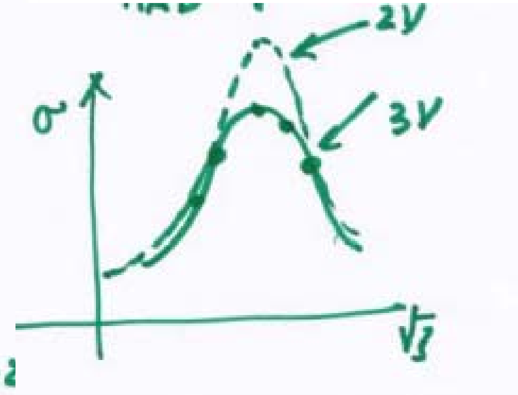
$$\Gamma_Z = \Gamma_H + \Gamma_e + \Gamma_\mu + \Gamma_\tau + \Gamma_{INV} \stackrel{\psi}{=}$$
$$= \Gamma_H + 3\Gamma_\ell + \Gamma_{INV}$$

SM Predictions with 3 neutrino

$$\Gamma_\ell = 85{,}1 \pm 2{,}9 \text{ MeV} \longrightarrow 83{,}9 \pm 0.8 \text{ MeV}$$
$$\Gamma_H = 1741 \pm 61 \text{ MeV} \longrightarrow 1747 \pm 28 \text{ MeV}$$
$$\Gamma_{INV} = 515 \pm 54 \text{ MeV} \longrightarrow 500 \pm 5 \text{ MeV}$$

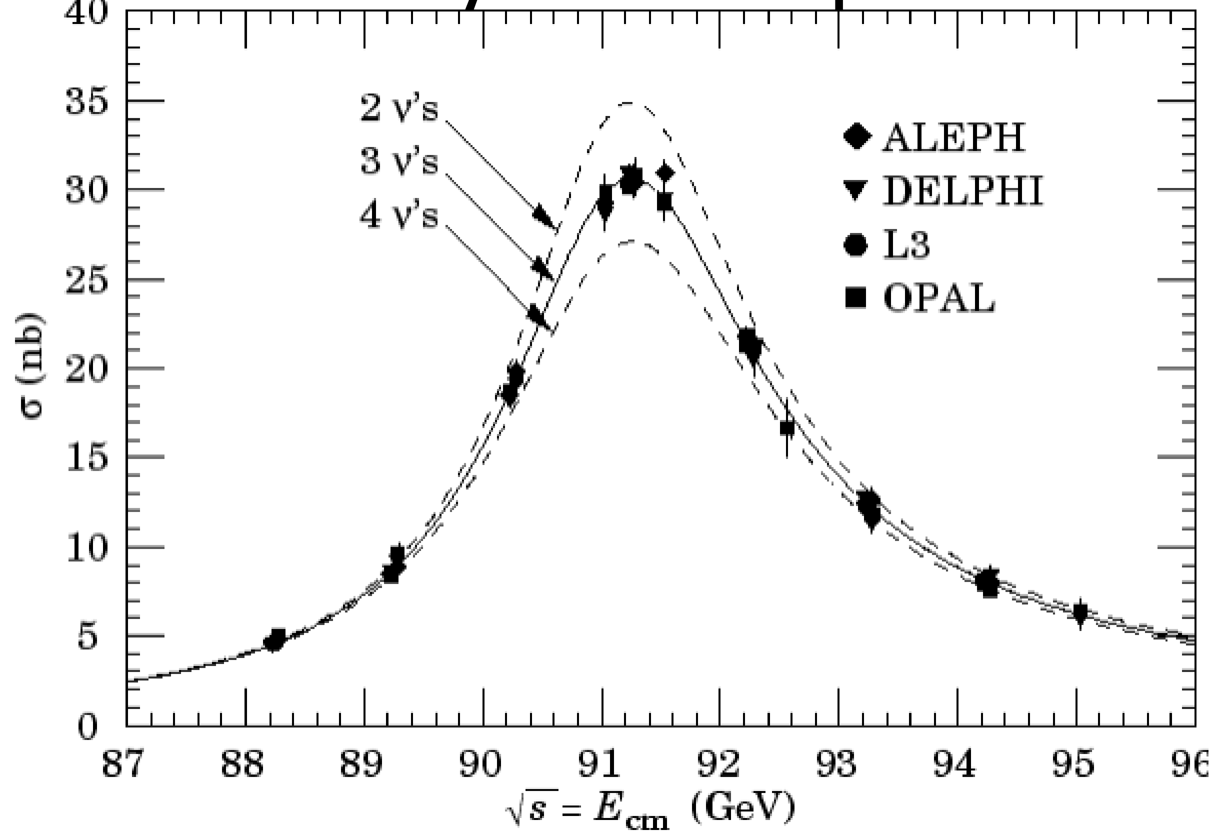
A famous PLOT :





si $N_\nu \uparrow$ $\Gamma_Z \uparrow$ $\sigma^0_{HAD} \downarrow$

The very famous plots !!

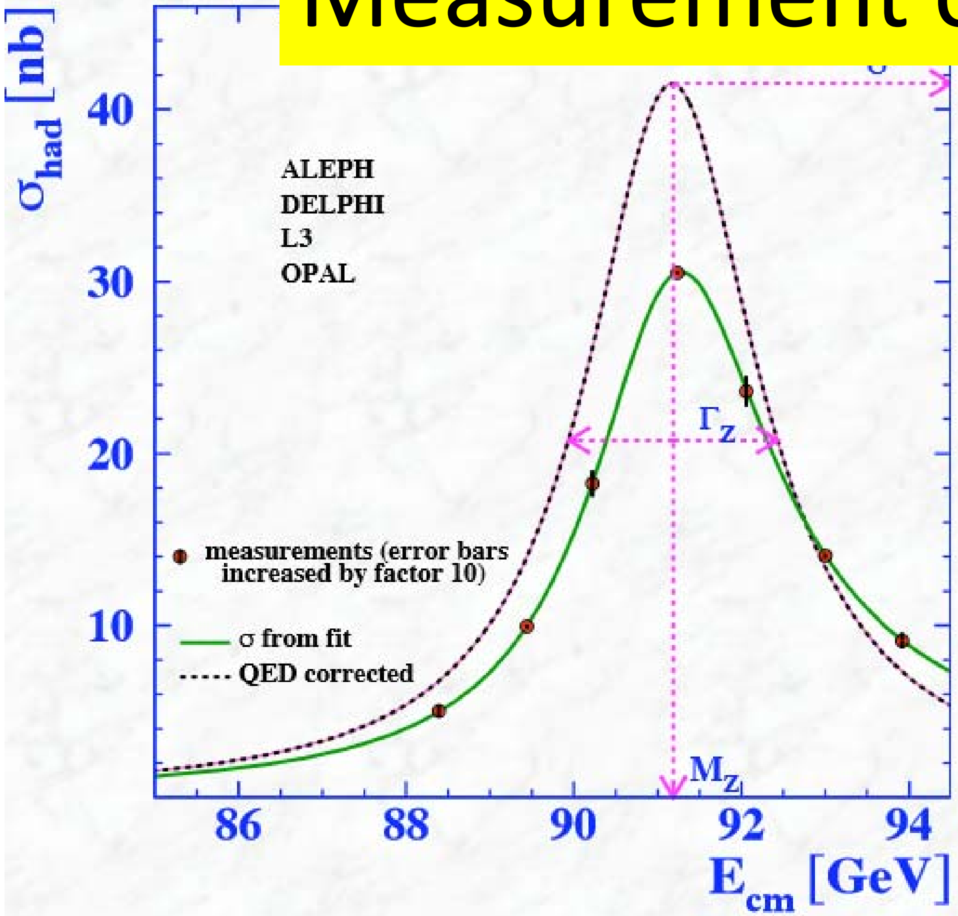


FROM FIRST MEASUREMENT $N_\nu = 2.94 \pm 0.11$

TO A PRECISE MEASURMENT $N_\nu = 2.984 \pm 0.0082$

RESULT compatible with 3 families of neutrino with mass < $M_Z/2$

Measurement of the mass of Z^0



$$\sigma(s) = 12\pi \frac{\Gamma_e \Gamma_\mu}{M_Z^2} \cdot \frac{s}{(s-M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$

Peak: $\sigma_0 = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_\mu}{\Gamma_Z^2}$

- Position of maximum → M_Z
- Full width at half maximum → Γ_Z
- Peak cross section σ_0 → $\Gamma_e \Gamma_\mu$

Radiative corrections (photon radiation) important

LEP 1 Phase 1989-1995

- **15 million Z's**
- **M_Z = 91187.5±2.1 MeV**

Precision of 2 10^{-5} !

- **Γ_Z=2495.2±2.3 MeV**

REMEMBER…

$$M_W = \left(\frac{\sqrt{2}g^2}{8G_F}\right)^{1/2} = \left(\frac{\sqrt{2}\,4\pi\alpha}{8G_F \sin^2\theta_W}\right)^{1/2}$$

$$= \left(\frac{\pi\alpha}{\sqrt{2}G_F}\right)^{1/2} \frac{1}{\sin\theta_W} = \frac{37.28}{\sin\theta_W}[GeV]$$

$M_W \sim 78$ GeV

And the measured masses

$$M_Z = \frac{M_W}{\cos\theta_W}$$

$M_Z = 91{,}1875 \pm 0.0021$ GeV

$M_Z \sim 90$ GeV

$M_W = 80{,}398 \pm 0{,}025$ GeV

NOT BAD.. !!!.....

BUT…

COMPARISON BETWEEN MEASUREMENTS AND PREDICTIONS …

We have to do better predictions….

For instance we take here the value of the Weinberg angle mesured in neutrino diffiusion (measurement which is independent on W and Z mass).

$$\sin^2 \theta_W = 0.2255 \pm 0.0021$$

$$M_W = 78.51 \pm 0.36 \quad GeV$$
$$M_Z = 89.21 \pm 0.29 \quad GeV$$

Predicted mass

M_Z = 91,1875±0.0021 GeV

M_W=80.398 ±0.025 GeV

Measured masses

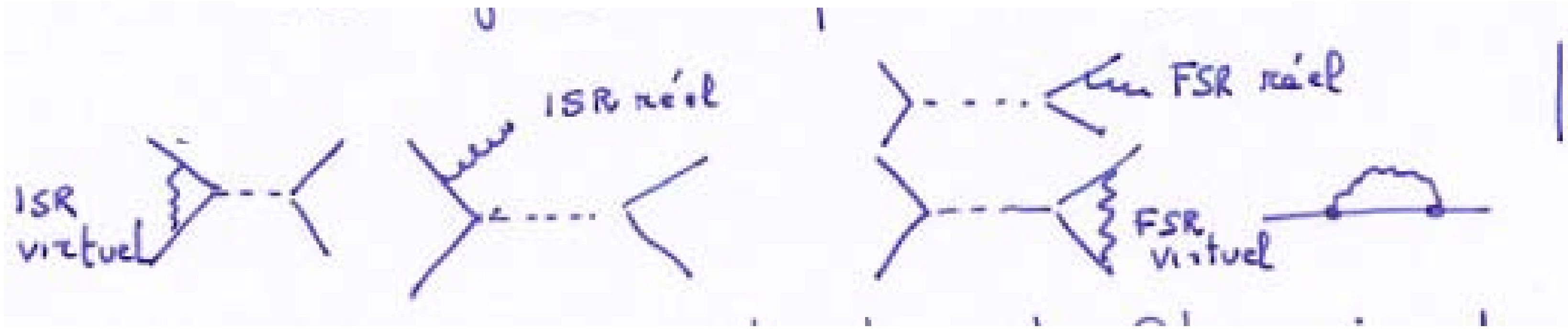
$$\Delta M_W = M_W^{Predicted} - M_W^{Measured} = -1.88$$ Corresponding to 5.2σ

$$\Delta M_Z = M_Z^{Predicted} - M_Z^{Measured} = -1.98$$ Corresponding to -6.8σ

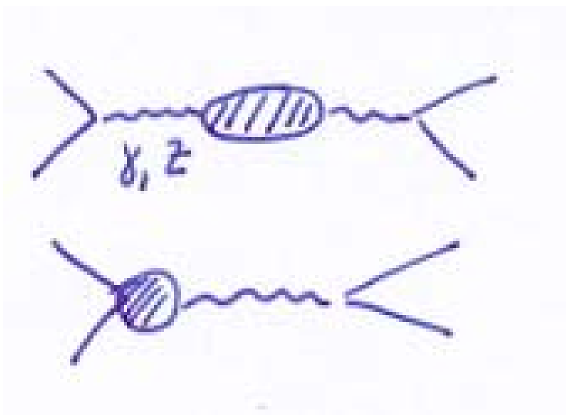
???

It is due to the radiative corrections

Electromagnitic radiative corrections



But also **weak radiative corrections**… correcting the propagator, the vertexes…



Exemple with M_W

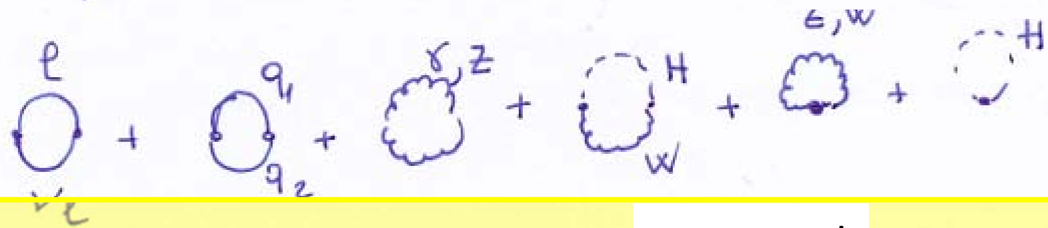
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2(1-\Delta r)} = \frac{\pi\alpha}{2M_W^2\sin^2\theta_W(1-\Delta r)}$$

$e = g\sin\theta_W$

$$M_W = \frac{37,280}{\sin\theta_W}\frac{1}{\sqrt{1-\Delta r}}$$

$\Delta r \cong 0.0465$

$\Delta r =$



predicted

$M_W = 80,40 \pm 0.37\ GeV/c^2$

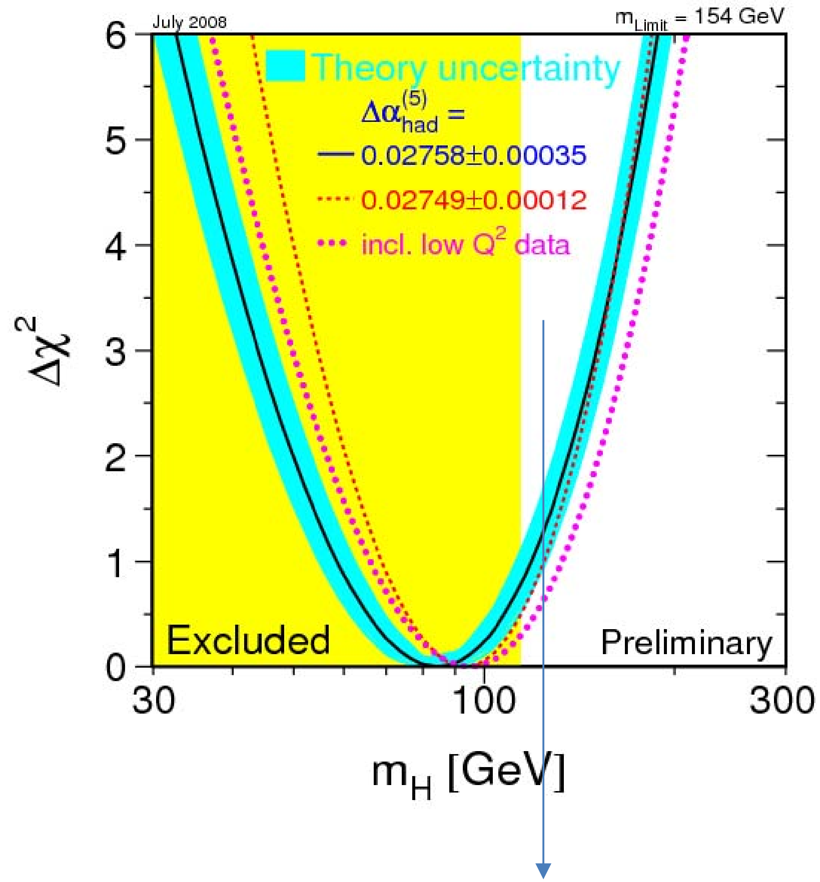
measured

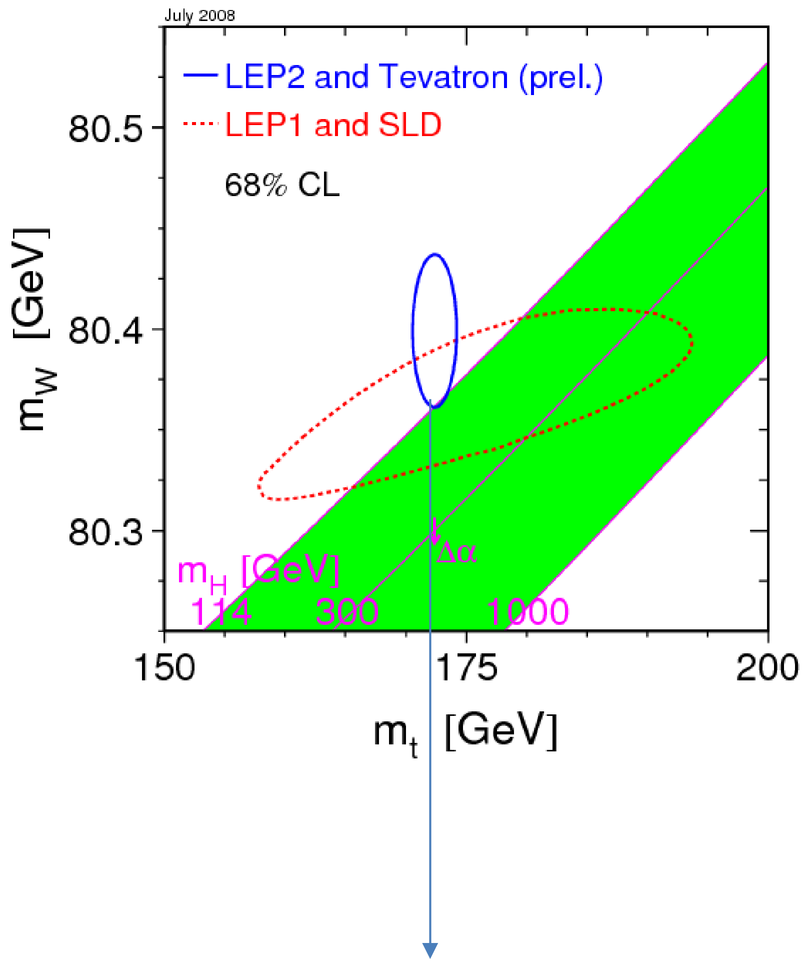
M_W=80.398 ±0.025 GeV

(Before was 78,51 ±0.36 GeV)

So the masses of the W and Z are sensitive
to all the particles in the loops… top quark, Higgs…

Using all the electroweak measurements we got





M(Higgs) = 125.6 ± 0.4 GeV

M(top) = 172.4 ± 1.2 GeV

5

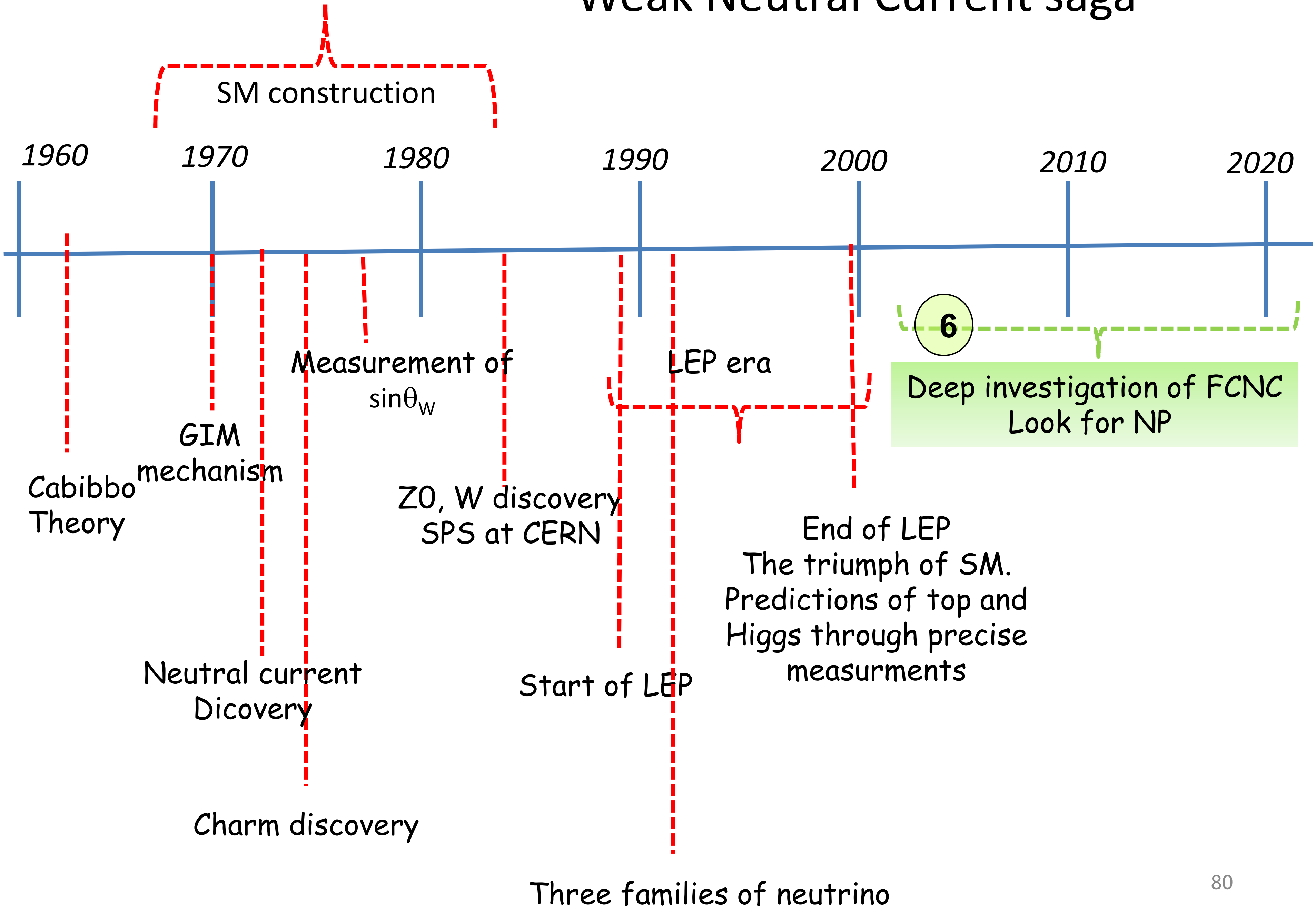
5th MESSAGE

SM TRIUMPH

SM and in particular neutral sector (Z^0) has been studied at high precision (~per mill) and did not show sofar any deviations.

So precise that we have seen radiative corrections... testing deeply the gauge structure of SM and opening the possibility of testing New Physics.

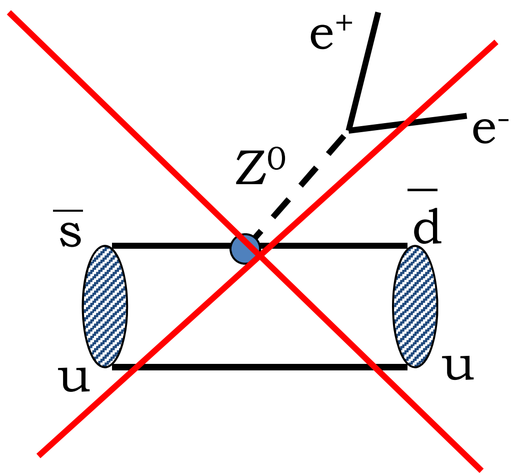
Weak Neutral Current saga



6

The years `NOW

FCNC – a PRIVILIVIGIATE WAY FOR SEARCHING FOR NEW PHYSICS

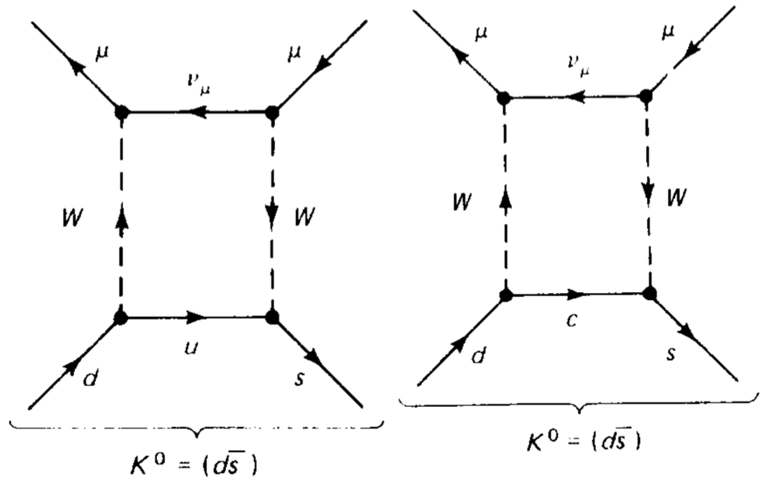


$K^+ \to \pi^+ e^+ e^-$

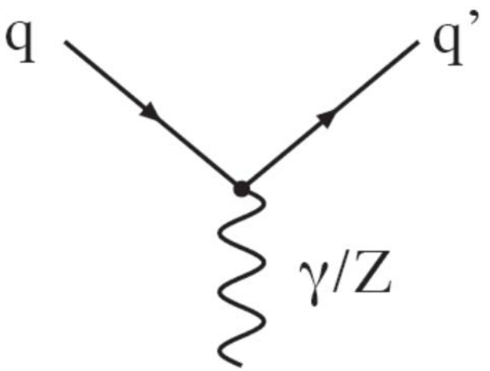
But **particle beyond the SM** could evenutally not share this ! Z^0 could be an **exotic Z^0**…

In general FCNC are rares since they pass through loops… second order effects

$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times10^{-9}}{0.64} \approx 10^{-8}$$

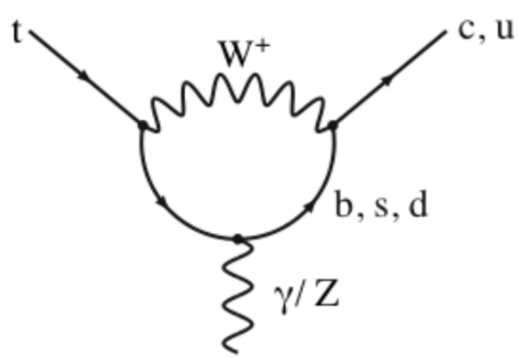


$u\bar{u}$ $d\bar{d}$ $s\bar{s}$ $c\bar{c}$ $b\bar{b}$ $t\bar{t}$



NEUTRAL CURRENTS with Z0.
DO NOT CHANGE THE FLAVOUR

$c\bar{u}$ $s\bar{d}$ $b\bar{s}$ $t\bar{c}$ $b\bar{b}$ $b\bar{d}$



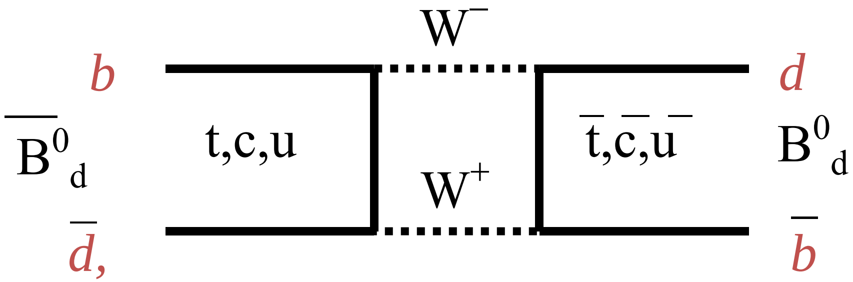
Flavour Changing Neutral Current (FCNC) occurs with W exchange.
THEY ARE SUPPRESSED IN THE SM SINCE OCCURS AT SECOND ORDER.

Example for B oscillations (FCNC-ΔB=2)

FCNC porcesses are ideal place to look for NP effects because they are suppressed in SM

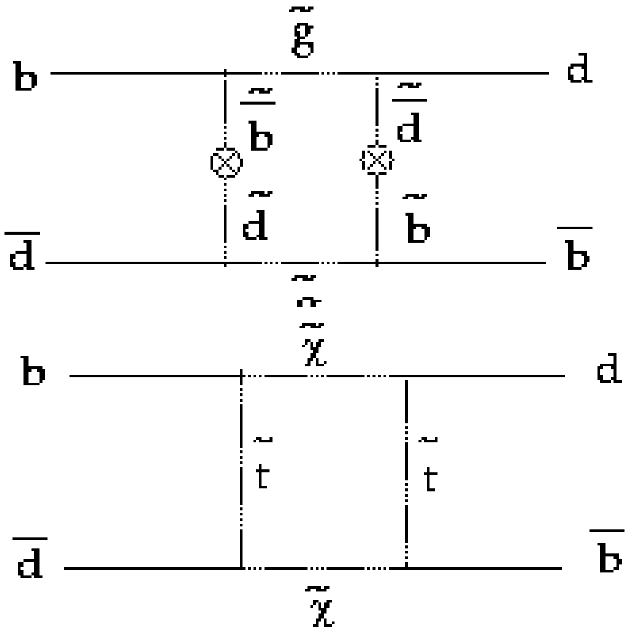
Precise measurements are needed.
Effects goes $1/\Lambda^2$

SM

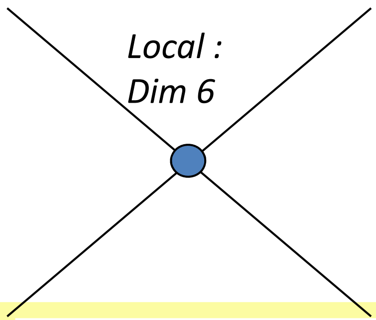


$$\frac{\left|V^*_{tb}V_{tq}\right|}{M_W^2}$$

BSM



$$\frac{\left|\delta_{bq}\right|}{\Lambda^2_{eff}}$$

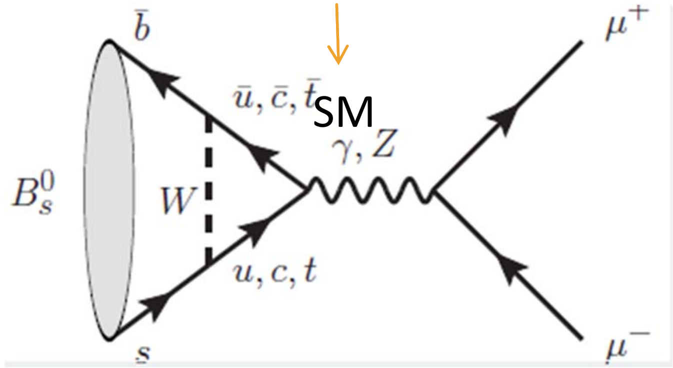


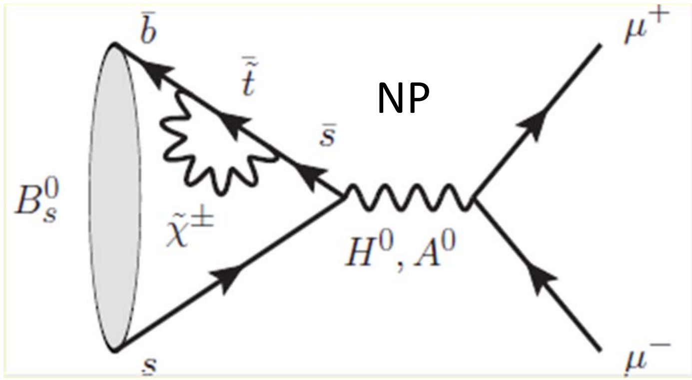
In the language of
The EFT, the operators
have dimension 6
→ $1/\Lambda^2$

The measurements (in this case Δm_d)
are modified wrt the predictions of the SM by the presence of BSM particles.
modifications are important if couplings are larger and/or NP masses are lighter

$B_s \to \mu^+\mu^-$

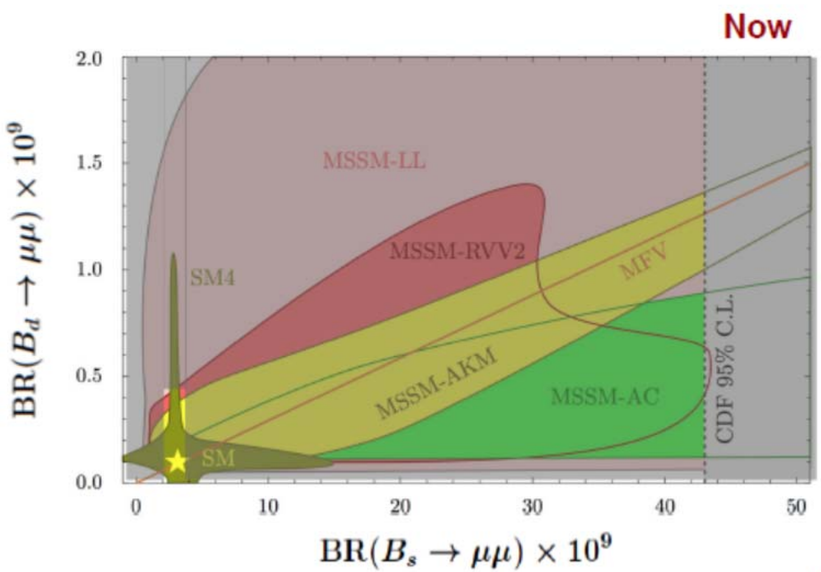
- Very small branching ratio, but very well predicted in the Standard model: $(3.54 \pm 0.30) \times 10^{-9}$.



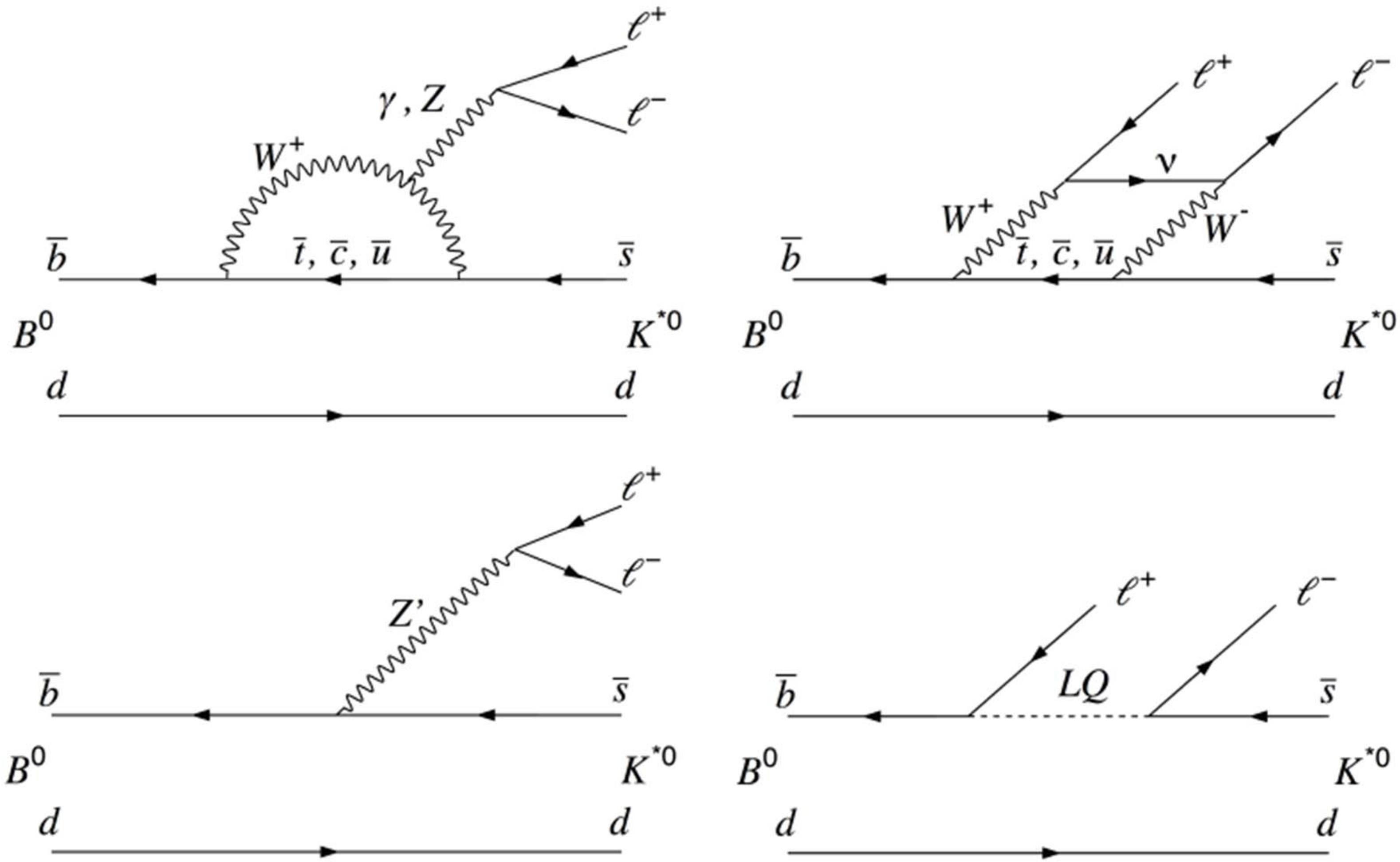


- But possibly enhanced by ***new physics***.

BUT RECENT RESULTS..

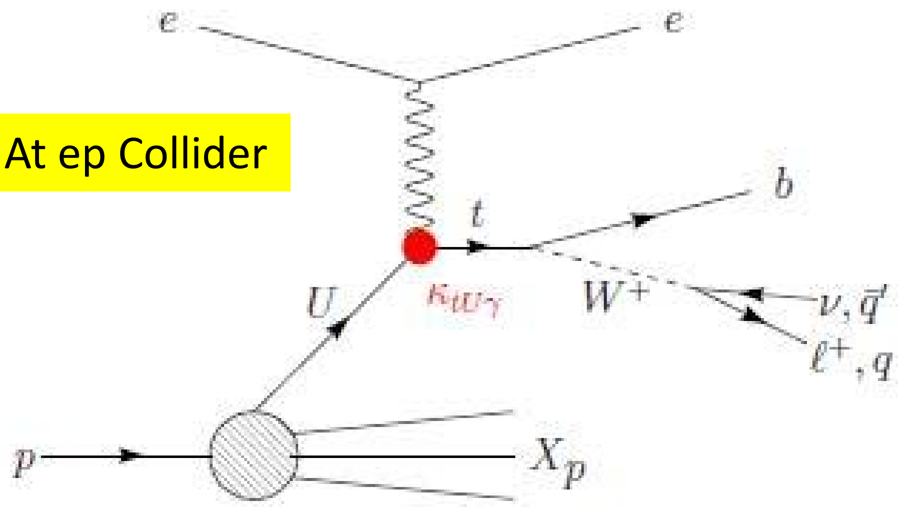


Other possibilities studying radiative b to s transitions…

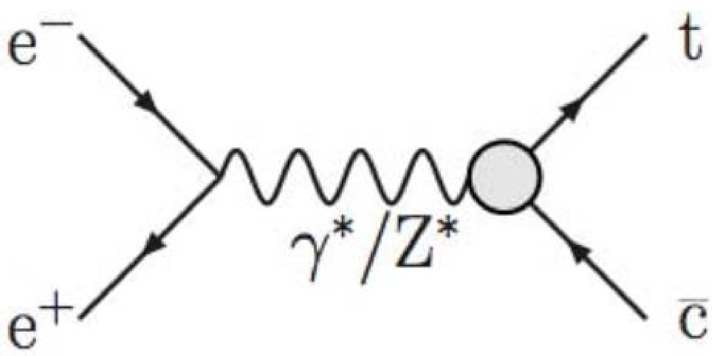


Of course there are a lot of direct searches for direct FCNC

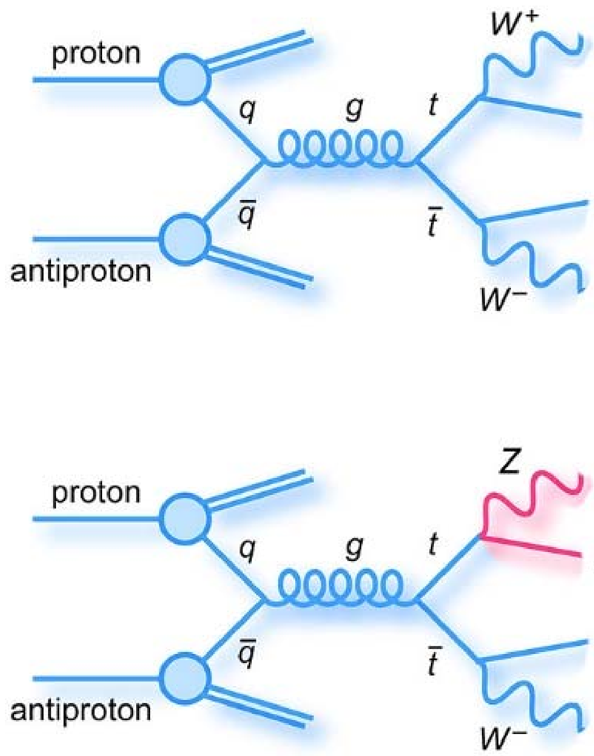
At ep Collider



At e+e- Collider



At pp Collider



AND SOFAR...

SM RESISTED TO ALL THE ATTACKS...

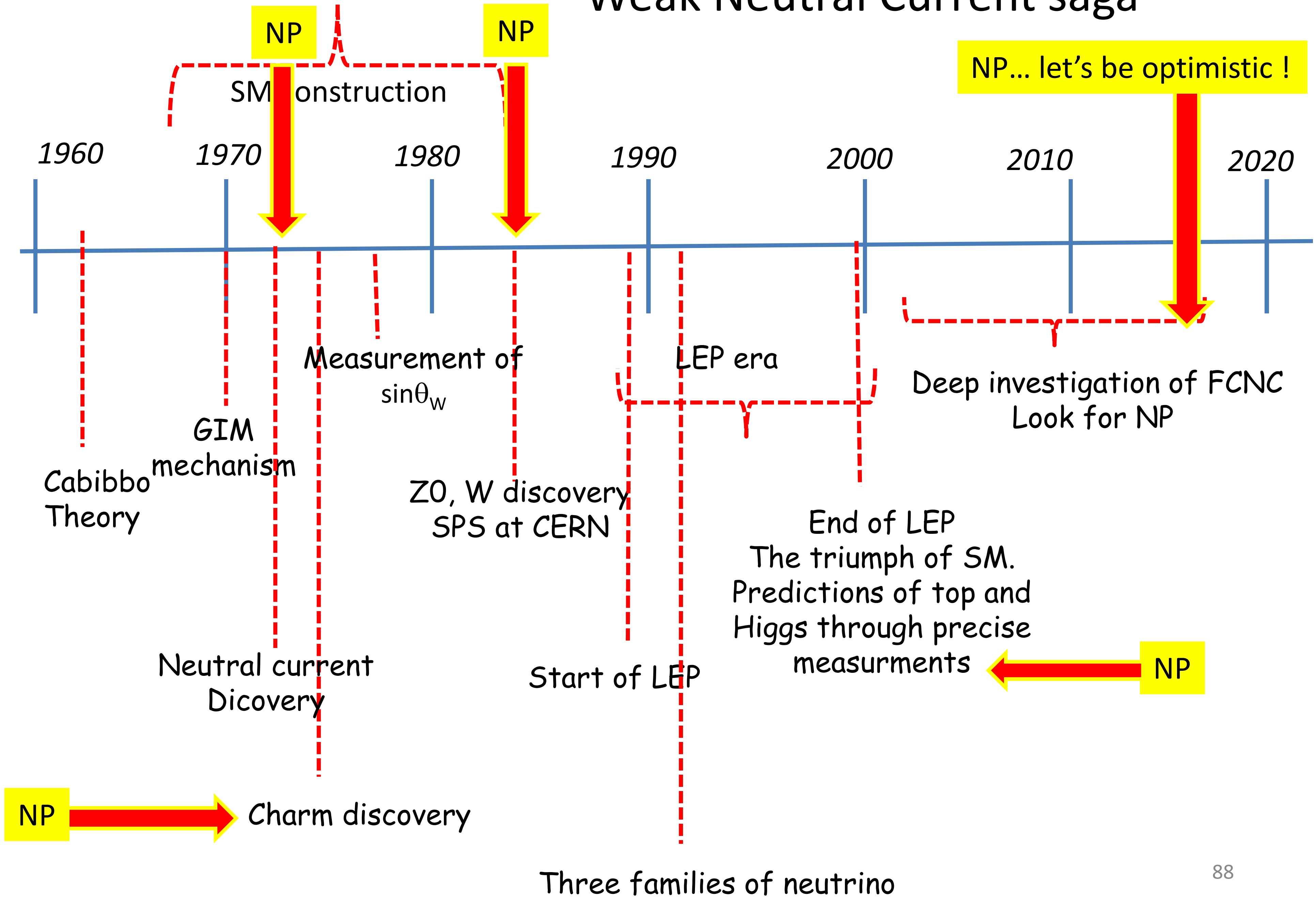
All the measured quantities involving FCNC agree rather well with SM predictions !!

very large effects are excluded.
so the extentions of the SM should be « corrections » to SM

$$\frac{|\delta_{bq}|}{\Lambda_{eff}^2}$$

BUT IT IS NOT THE END OF THE STORY :
Couplings of NP small or NP at high masses

Weak Neutral Current saga



BACKUP

The Standard Model

in the

fermion sector

Flavour Physics in the *Standard Model* (SM) in the quark sector:

10 free parameters

~ half of the *Standard Model*

6 quarks masses

4 CKM parameters

In the Standard Model, charged weak interactions among quarks are codified in a 3 X 3 unitarity matrix : the **CKM Matrix**.

The existence of this matrix conveys the fact that the quarks which participate to weak processes are a linear combination of mass eigenstates

The fermion sector is poorly constrained by SM + Higgs Mechanism

mass hierarchy and CKM parameters

The Standard Model is based on the following gauge symmetry

$$SU(2)_L \times U(1)_Y$$

Weak Isospin (symbol L because only the LEFT states are involved)

Weak Hypercharge :

(LEFT and RIGHT states)

			I	I_3	Q	Y
Leptons	doublet L	ν_e	½	½	0	-1
		e_L^-	½	-½	-1	-1
	singlet R	e_R^-	0	0	-1	-2
quarks	doublet L	u_L	½	½	2/3	1/3
		d_L	½	-½	-1/3	1/3
	singlet R	u_R	0	0	2/3	4/3
	singlet R	d_R	0	0	-1/3	-2/3

Idem for the other families

Short digression on the mass

$$E^2 = \vec{p}^{\,2} + m^2 \quad \rightarrow \quad \partial^\mu \partial_\mu + m^2\phi = 0 \quad \leftrightarrow \quad L = \partial^\mu \phi \partial_\mu \phi - \frac{1}{2} m^2 \phi^2 = 0$$

$$(i\gamma^\mu \partial_\mu - m) = 0 \quad \leftrightarrow \quad L = i\overline{\psi}\gamma_\mu \partial^\mu \psi - m\overline{\psi}\psi$$

$$m\overline{\psi}\psi \quad = m\overline{\psi}(P_L + P_R)\psi = m\overline{\psi}(P_L P_L + P_R P_R)\psi =$$

$$= m[(\overline{\psi}P_L)(P_L\psi) + (\overline{\psi}P_R)(P_R\psi)]\psi \qquad = m\left(\overline{\psi}_R \psi_L + \overline{\psi}_L \psi_R\right)$$

The mass should appear in a LEFT-RIGHT coupling

ψ_R : SU(2) singlet

ψ_L : SU(2) doublet

The mass terms are not gauge invariant under

$SU(2)_L \times U(1)_Y$

ψ_R (I=0,Y=-2) leptoni_R

(I=0,Y=-2/3) quark d_R

(I=0,Y=4/3) quark u_R

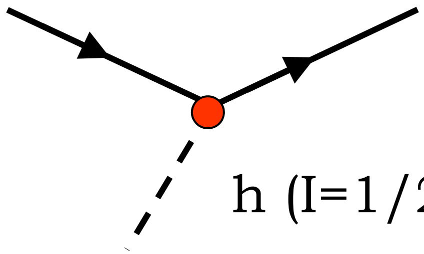
ψ_L (I=1,Y=-1) leptoni_L

(I=1,Y=1/3) quark d_L

(I=1,Y=1/3) quark u_L

Adding a doublet

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad I = \frac{1}{2} \quad Y = 1$$



h (I=1/2,Y=1)

Yukawa interaction : $\overline{\psi}_L \phi \psi_R$

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$$

$$g_e(\overline{\psi}_L \phi \psi_R + \phi^+ \overline{\psi}_R \psi_L)$$

(le deuxieme terme est l'hermitien conjuge du premier)

After SSB

$$\frac{g_e v}{\sqrt{2}}(\overline{\psi}_L \psi_R + \overline{\psi}_R \psi_L) + \frac{g_e}{\sqrt{2}}(\overline{\psi}_L \psi_R + \overline{\psi}_R \psi_L)H$$

$$m_e = \frac{g_e v}{\sqrt{2}}$$

$$g_e = \frac{\sqrt{2} m_e}{v}$$

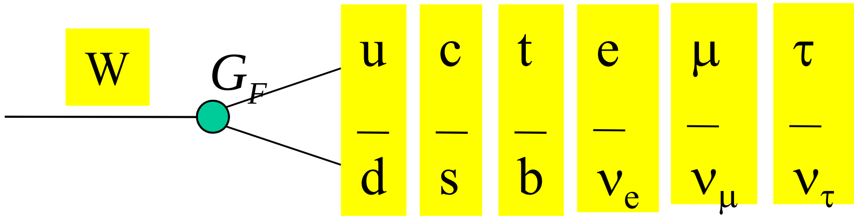
v/sqrt(2) ~natural mass (g~1)

$$m_e \overline{e}e + \frac{m_e}{v}\overline{e}eH$$

$$\frac{g_e}{\sqrt{2}} = \frac{m_e}{v}$$ couplage Hee

$$L_W = \frac{g}{2}\overline{Q}^{Int.}_{L_i}\gamma^\mu \sigma^a Q^{Int.}_{L_i} W^a_\mu \qquad a = 1,2,3 \qquad Q^{Int.}_{L_i} = \begin{pmatrix} u_{L_i} \\ d_{L_i} \end{pmatrix} \quad L^{Int.}_{L_i} = \begin{pmatrix} \nu_{L_i} \\ l_{L_i} \end{pmatrix}$$

$$\overline{Q}^{Int.}_{L_i} Q^{Int.}_{L_i} = \overline{Q}^{Int.}_{L_i} 1_{ij} Q^{Int.}_{L_j} \quad \text{universality of gauge interactions}$$



The SM quantum numbers are I_3 and Y
→ The gauge interactions are

Flavour blind

In this basis the Yukawa interactions has the following form :

$$L_Y = Y^d_{ij}\overline{Q}^{Int.}_{L_i}\phi d^{Int.}_{R_j} + Y^u_{ij}\overline{Q}^{Int.}_{L_i}\tilde{\phi} u^{Int.}_{R_j} + Y^l_{ij}\overline{L}^{Int.}_{L_i}\phi l^{Int.}_{R_j}$$

$$SSB^* \rightarrow <\phi^0> = v/\sqrt{2}; \mathrm{Re}(\phi^0) \rightarrow (v + H^0)/\sqrt{2}$$

With: $\tilde{\phi} = i\sigma_2 \phi^* = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}\phi^*$

To be manifestly invariant under SU(2)

Y_{ij} complex

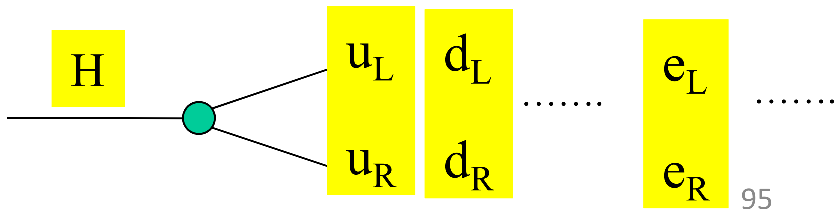
Two matrices are needed to give a mass term to the **u-type** and **d-type quarks**

....

$$L_M = M^d_{ij}\overline{d}^{Int.}_{L_j} d^{Int.}_{R_j} + M^u_{ij}\overline{u}^{Int.}_{L_j} u^{Int.}_{R_j} + M^l_{ij}\overline{l}^{Int.}_{L_j} l^{Int.}_{R_j}$$

We made the choice of having the Mass Interaction diagonal

where $M^f = (v/\sqrt{2})Y^f$



* SSB=Spontaneous Symmetry Breaking

To have mass matrices diagonal and real, we have defined: $M^{f}(diag) = V_L^{f} M^{f} V_R^{f\dagger}$

The mass eigenstates are:

$$d_{L_i} = (V_L^{d})_{ij}\, d_{L_j}^{Int.} \quad ; \quad d_{R_i} = (V_R^{d})_{ij}\, d_{R_j}^{Int.}$$

$$u_{L_i} = (V_L^{u})_{ij}\, u_{L_j}^{Int.} \quad ; \quad u_{R_i} = (V_R^{u})_{ij}\, u_{R_j}^{Int.}$$

$$l_{L_i} = (V_L^{d})_{ij}\, l_{L_j}^{Int.} \quad ; \quad l_{R_i} = (V_R^{d})_{ij}\, l_{R_j}^{Int.}$$

$$\nu_{L_i} = (V_L^{l})_{ij}\, \nu_{L_j}^{Int.} \qquad \nu_{L_i} \ \text{arbitrary} \quad (\text{assuming} \quad \nu \quad \text{massless})$$

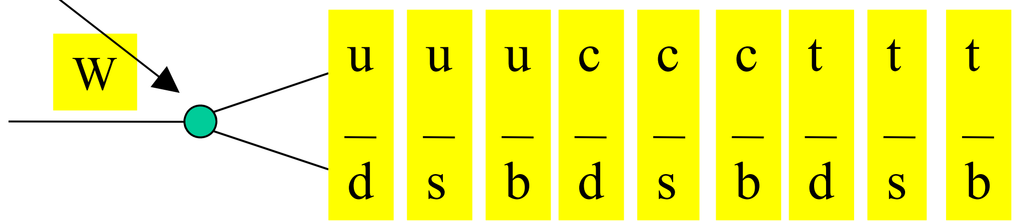
In this basis the Lagrangian for the gauge interaction is:

$$L_W = \frac{g}{2} \bar{u}_{L_i} \gamma^{\mu} (V_L^{u} V_L^{d\dagger}) d_{L_j} W_{\mu}^{a} + h.c.$$

The coupling is not anymore universal

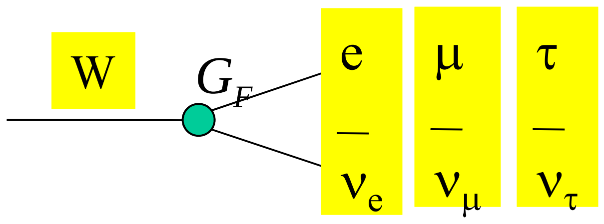
$$V(CKM) = (V_L^{u} V_L^{d\dagger})$$

Unitary matrix



If a similar procedure is applied to the lepton sector

$$V(leptons) = (V_L^{\nu} V_L^{l\dagger}) = (V_L^{l} V_L^{l\dagger}) = 1$$



Since the neutrino are (were) massless the matrix which change the basis from int-> mass is in principle arbitary

We can always choose $V_L^{\nu} = V_L^{l}$

Now the neutrino have a mass, it exists a similar matrix in the lepton sector with mixing a CP violation

For the Z^0

Facultatif

$$L_W = \frac{g}{2}\overline{Q}^{Int.}_{L_i}\gamma^\mu\sigma^a Q^{Int.}_{L_i}W^a_\mu \qquad a=1,2,3$$

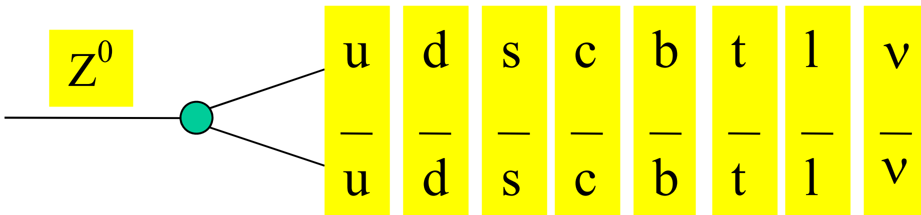
$$-L_B = g'\left[\frac{1}{6}\overline{Q}^{Int.}_{L_i}\gamma^\mu 1_{ij} Q^{Int.}_{L_j} + \frac{2}{3}\overline{u}^{Int.}_{R_i}\gamma^\mu 1_{ij} u^{Int.}_{R_j} - \frac{1}{3}\overline{d}^{Int.}_{R_i}\gamma^\mu 1_{ij} d^{Int.}_{R_j}\right]B_\mu$$

for the Z^0 $\quad Z^\mu = \cos\vartheta_W W_3^\mu - \sin\vartheta_W B^\mu \;;\; \tan\vartheta_W = g'/g$

in the mass basis (example for d_L)

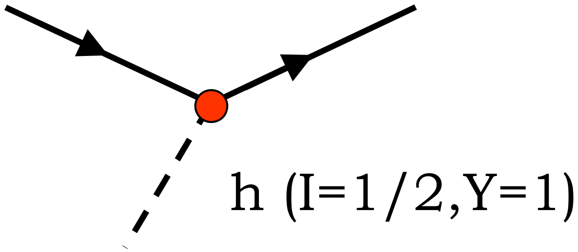
$$-L_Z = \frac{g}{\cos\vartheta_W}\left(-\frac{1}{2}+\frac{1}{3}\sin^2\vartheta_W\right)\overline{d}_{L_i}\gamma^\mu (V^\dagger_{dL}V_{dL}) d_{L_i} Z_\mu = \frac{g}{\cos\vartheta_W}\left(-\frac{1}{2}+\frac{1}{3}\sin^2\vartheta_W\right)\overline{d}_{L_i}\gamma^\mu d_{L_i} Z_\mu$$

The neutral currents stay universal, in the mass basis :
<u>we do not need extra parameters for their complete description</u>

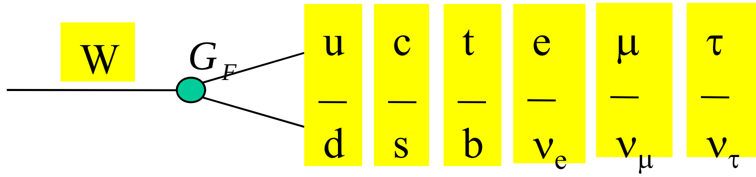


SUMMARY

The mass is a LEFT-RIGHT coupling and has to respect the gauge invariance $SU(2)_L \times U(1)_Y$



$$\overline{\psi}_L \phi \psi_R \qquad \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad I = \frac{1}{2} \quad Y = 1$$



$$M^D = \begin{pmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{pmatrix} \qquad M^U = \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix}$$

9+9 Complex parameters

$$M^{D,U}_{DIAG} = V^{D,U}_L M^{D,U} (V^{D,U}_R)^+$$

$$M^D_{DIAG} = \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} \qquad M^U_{DIAG} = \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix}$$

$$\mathbf{V(CKM)} = V^U_L (V^D_L)^+ = \begin{pmatrix} \text{4 parameters} \\ \lambda, A, \rho, \eta \end{pmatrix}$$

$$L_M = M^d_{ij} \overline{d}^{Int.}_{L_j} d^{Int.}_{R_j} + M^u_{ij} \overline{u}^{Int.}_{L_j} u^{Int.}_{R_j} + M^l_{ij} \overline{l}^{Int.}_{L_j} l^{Int.}_{R_j}$$

To have mass matrices diagonal and real, we have defined: $M^f(diag) = V^f_L M^f V^{f\dagger}_R$

The mass eigenstates are:

$$d_{L_i} = (V^d_L)_{ij} d^{Int.}_{L_j} \quad ; \quad d_{R_i} = (V^d_R)_{ij} d^{Int.}_{R_j}$$

The Lagrangian for the gauge interaction is:

$$L_W = \frac{g}{2} \overline{u}_{L_i} \gamma^\mu (V^u_L V^{d\dagger}_L) d_{L_j} W^a_\mu + h.c.$$