Capitolo 11: Test del Modello Standard (LEP fase 2)

Corso di Fisica Nucleare e Subnucleare II

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A.A. 2012-2013

Divergenze nelle interazioni deboli

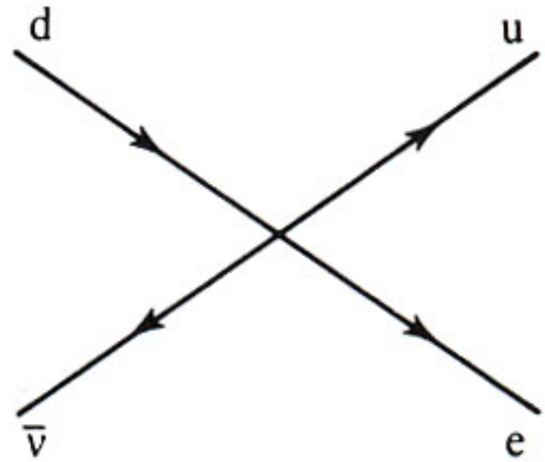
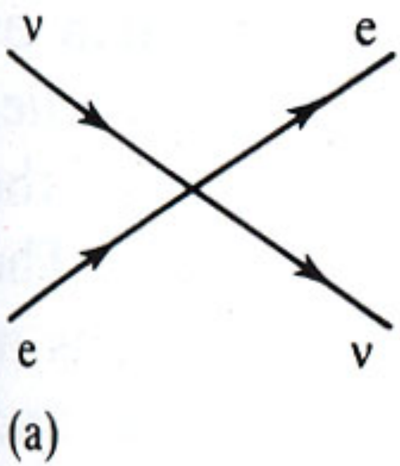


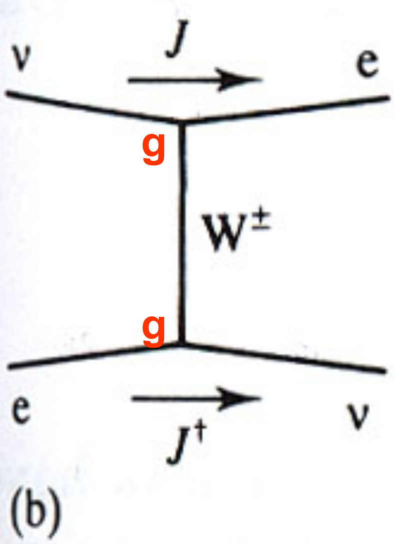
Figure 13.2
Quark level β decay process.



$$\nu_e + e^- \to e^- + \nu_e$$

$$\frac{d\sigma}{dq^2} = \frac{G^2}{\pi}$$

$$\sigma_{tot}(\nu e) = \frac{G^2}{\pi} q^2_{max} = \frac{2G^2 mE}{\pi} = \frac{G^2 s}{\pi}$$



Le divergenze sono "sistemate" dalla massa finita del W. Ce ne sono pero' altre per altri processi come per esempio $\nu\bar{\nu} \to WW$

Figure 13.3
(a) Point-like elastic ν_e–e scattering; (b) elastic ν_e–e scattering via $W^{\pm}$ exchange.

Divergenze nelle interazioni deboli

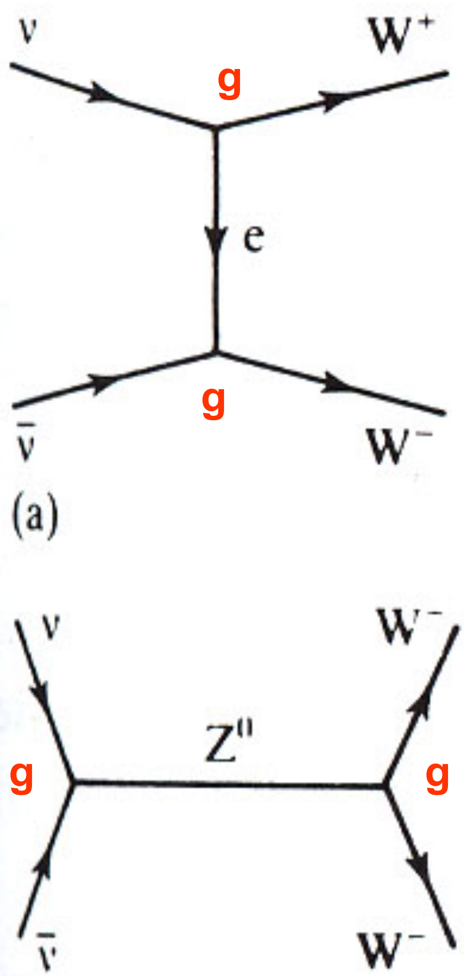


Figure 13.4
W-pair production in ν–ν̄ scattering (a) via electron exchange in the t channel and (b) via Z^0 exchange in the s channel.

Divergenze nelle interazioni deboli

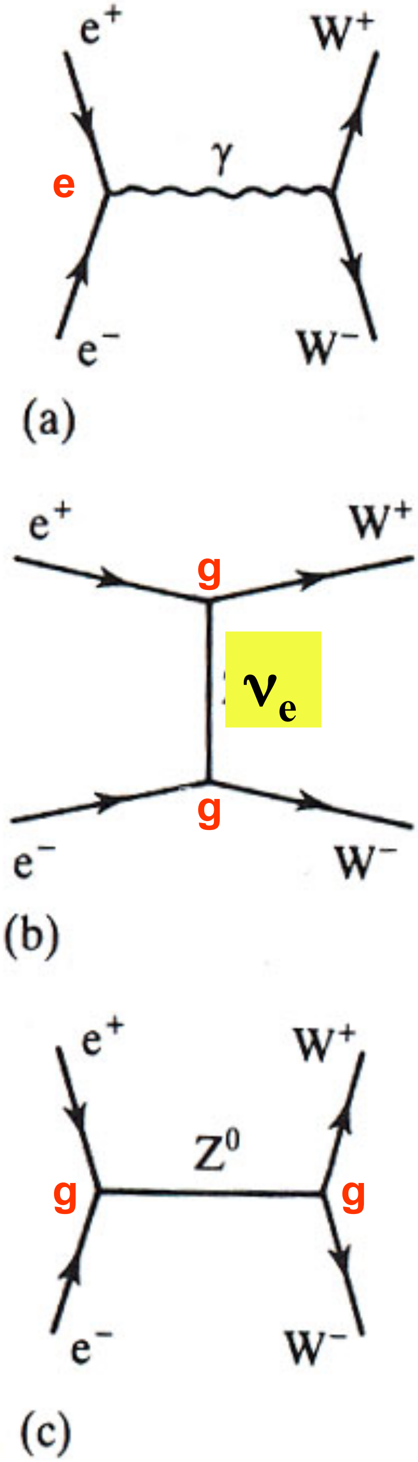
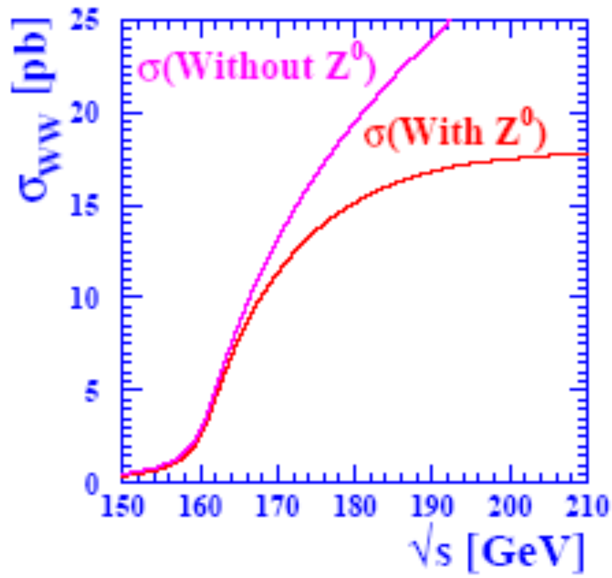
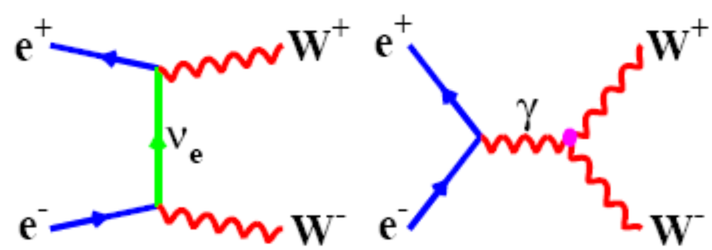


Figure 13.5
W-pair production in e^+–e^- scattering via (a) photon exchange in the s channel, (b) Z^0 exchange in the t channel and (c) Z^0 exchange in the s channel.





Divergence CURED by introducing Z^0

Extra Diagram

$e^+e^- \rightarrow W^+W^-$

Le divergenze sono risolte SE gli accoppiamenti dei γ, $W^{+(-)}$e Z^0 sono collegati : UNIFICAZIONE ELETTRODEBOLE !

Isospin e Ipercarica debole

Particle states	Antiparticle states
$u_L = \frac{1}{2}(1-\gamma^5)u$	$v_L = \frac{1}{2}(1+\gamma^5)v$
$u_R = \frac{1}{2}(1+\gamma^5)u$	$v_R = \frac{1}{2}(1-\gamma^5)v$
$\bar{u}_L = \bar{u}\frac{1}{2}(1+\gamma^5)$	$\bar{v}_L = \bar{v}\frac{1}{2}(1-\gamma^5)$
$\bar{u}_R = \bar{u}\frac{1}{2}(1-\gamma^5)$	$\bar{v}_R = \bar{v}\frac{1}{2}(1+\gamma^5)$

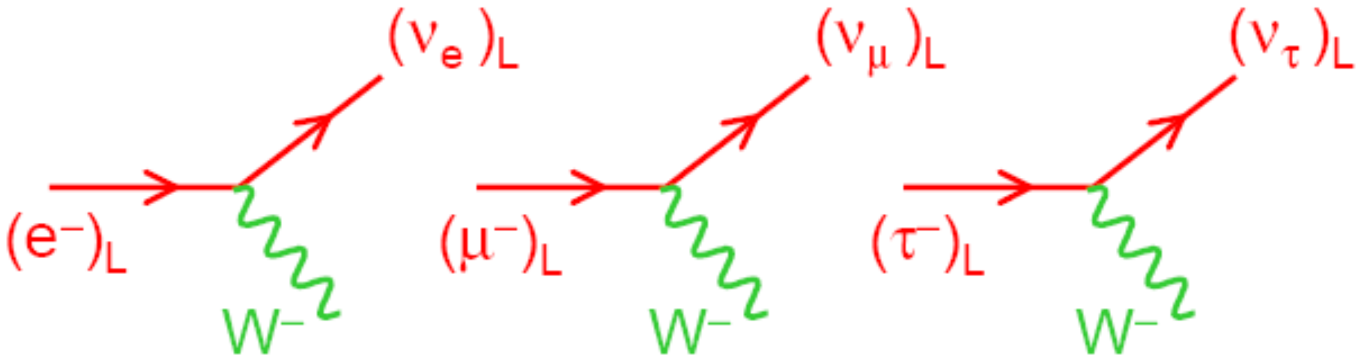
* The subscripts L and R correspond to helicity states −1 and +1 respectively.

Table 13.2
Weak isospin and weak hypercharge assignments for fermions

	I	I_3	Q	Y
ν_e, ν_μ, ν_τ	$\frac{1}{2}$	$+\frac{1}{2}$	0	-1
e_L^-, μ_L^-, τ_L^-	$\frac{1}{2}$	$-\frac{1}{2}$	-1	-1
e_R^-, μ_R^-, τ_R^-	0	0	-1	-2
u_L, c_L, t_L	$\frac{1}{2}$	$+\frac{1}{2}$	$+\frac{2}{3}$	$+\frac{1}{3}$
d'_L, s'_L, b'_L	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{3}$	$+\frac{1}{3}$
u_R, c_R, t_R	0	0	$+\frac{2}{3}$	$+\frac{4}{3}$
d'_R, s'_R, b'_R	0	0	$-\frac{1}{3}$	$-\frac{2}{3}$

Le Interazioni Deboli : Riassunto

- **Nel settore dei leptoni abbiamo solo:**



$\Rightarrow$ **E' naturale organizzare I leptoni in DOPPIETTI di particelle levogire :**

$$\begin{array}{l} I_W^3 = +1/2 : \\ I_W^3 = -1/2 : \end{array} \quad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \qquad I_W = 1/2$$

ed in SINGOLETTI di particelle destrogire :

$$I_W^3 = 0 : \qquad (e^-)_R \quad (\mu^-)_R \quad (\tau^-)_R \qquad I_W = 0$$

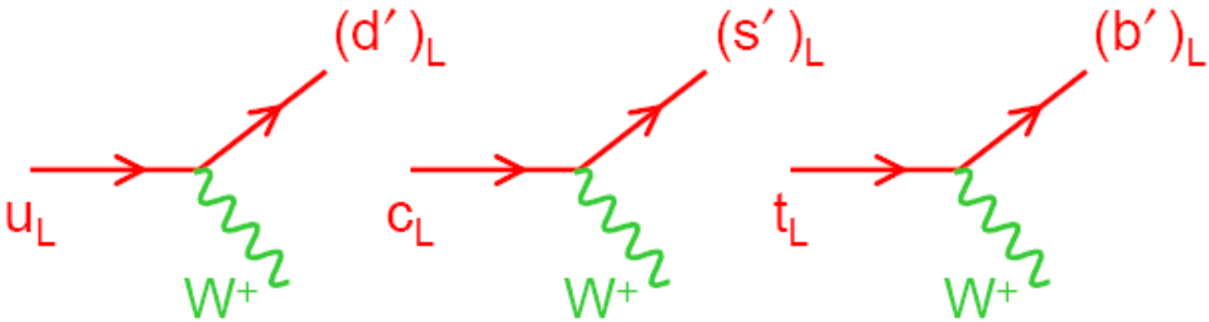
Abbiamo quindi Multipletti di Isospin Debole :

$$\left(I_W, I_W^3\right)$$

(nothing to do with ordinary spin or flavour isospin ...

... just common SU(2) mathematics)

Analogamente per il settore dei quark avremo:



(d´, s´, b´ are the CKM-rotated weak eigenstates)

Si formano DOPPIETTI di quark levogiri :

$$I_W^3 = +1/2: \quad I_W^3 = -1/2: \qquad \begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L \qquad I_W = 1/2$$

e SINGOLETTI di quark destrogiri :

$$I_W^3 = 0: \qquad \begin{matrix} (u)_R & (c)_R & (t)_R \\ (d')_R & (s')_R & (b')_R \end{matrix} \qquad I_W = 0$$

- Turn this into a gauge theory by requiring invariance under <u>local</u> SU(2) phase transformations:

$$\psi \to \psi' = e^{i\boldsymbol{\tau}.\mathbf{W}(x)}\psi$$

where: $\boldsymbol{\tau} = (\tau_1, \tau_2, \tau_3)$ are the Pauli matrices

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

and $\mathbf{W}(x) = (W_1(x), W_2(x), W_3(x))$

Corresponds to invariance under rotations in “weak isospin” space about a direction varying with position and time

- Requires the introduction of 3 gauge fields

$$W_1^\mu, W_2^\mu, W_3^\mu$$

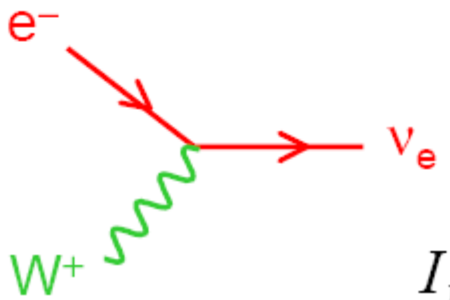
and the resulting gauge invariance leads to conservation of weak isospin

$$\left.\begin{aligned} W^+ &= \frac{1}{\sqrt{2}}\left(W_1^\mu + iW_2^\mu\right) \\ W^0 &= W_3 \\ W^- &= \frac{1}{\sqrt{2}}\left(W_1^\mu - iW_2^\mu\right) \end{aligned}\right\}$$

form a multiplet with $I_W = 1$

- W^+ and W^- can be identified with the charged $W^{\pm}$ bosons

e.g.



$$e^- + W^+ \rightarrow \nu_e$$

$$I_W^3: \quad -\tfrac{1}{2} + 1 \rightarrow +\tfrac{1}{2}$$

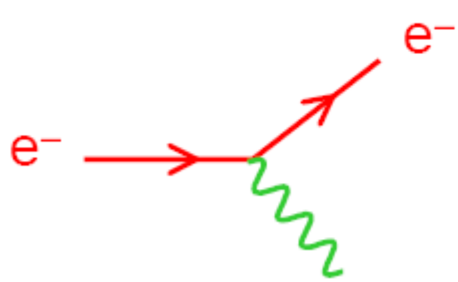
- W_3 must mediate interactions like

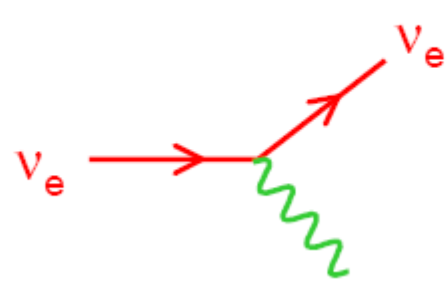
$$e^- + W_3 \rightarrow e^-$$

$$I_W^3: \quad -\tfrac{1}{2} + 0 \rightarrow -\tfrac{1}{2}$$

$\Longrightarrow$ corresponds to a neutral gauge boson W^0

i.e. SU(2) gauge invariance requires the existence of weak neutral currents





- Tempting to identify $W_3 \equiv Z^0$

But: $W^{\pm}$ and Z^0 have different masses

$\Longrightarrow$ can't belong to same SU(2) multiplet

- **But**: there is another neutral gauge boson, the photon, with the same quantum numbers as the Z^0

$\Longrightarrow$ W_3 could be a mixture of Z^0 and γ

→ **unification of EM and weak forces**

- In the Standard Model:

$$W_3^\mu = \cos\theta_W . Z^\mu + \sin\theta_W . A^\mu$$

where θ_W is the Weinberg angle

has to be determined from experiment :

$$\sin^2\theta_W \approx 0.23$$

- The combination orthogonal to W_3 is

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

In the Standard Model, B^μ is the gauge boson associated with a local U(1) phase invariance

$$\psi \to \psi' = e^{ig'\theta(x)}\psi$$

where U(1) = group of all 1x1 unitary matrices:

$$U = \left(e^{i\phi}\right) \qquad U^+U = I$$

- Hence, overall, the electroweak sector of the SM is invariant under two independent symmetries:

$$\mathrm{SU(2)} \quad \otimes \quad \mathrm{U(1)}$$

$$W^+, W^-, W_3 \qquad\qquad B$$

mix to form Z^0 and γ

- Interactions of $W^\pm$, Z^0 and γ are completely specified, and find

$$\boxed{g_\mathrm{W} \sin\theta_\mathrm{W} = g_\mathrm{Z} \cos\theta_\mathrm{W} \sin\theta_\mathrm{W} = e}$$

photon coupling

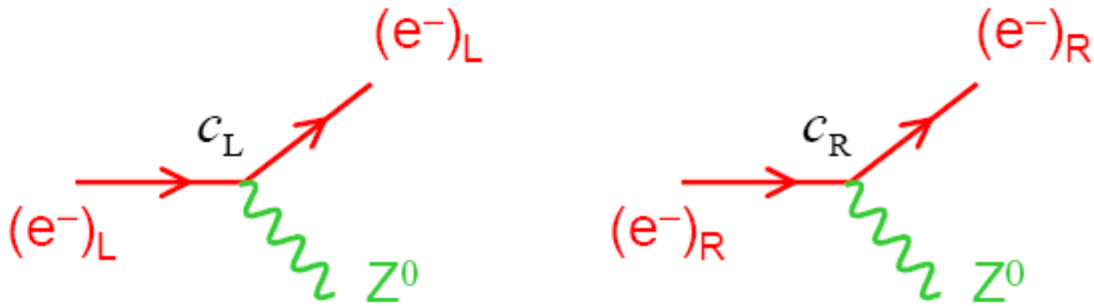
Hence $W^\pm$, Z^0 and γ interaction strengths are all of similar size

in fact $W^\pm$, Z^0 are stronger: $\quad \dfrac{g_\mathrm{W}^2}{4\pi} \approx \dfrac{1}{29} \qquad \dfrac{g_\mathrm{Z}^2}{4\pi} \approx \dfrac{1}{22} \qquad \dfrac{e^2}{4\pi} \approx \dfrac{1}{137}$

"Weak" interactions only <u>appear</u> weak at low energies because of large W, Z mass

$\longrightarrow$ propagator $\quad \dfrac{1}{q^2 - m_\mathrm{W}^2} \approx \dfrac{-1}{m_\mathrm{W}^2} \quad$ (small)

- Left- and right-handed components interact with Z^0 with strengths c_L and c_R :



For a particle of charge Q, weak isospin I_W^3 :

$$c_L = I_W^3 - Q\sin^2\theta_W$$
$$c_R = \qquad - Q\sin^2\theta_W$$

Weak bit of Z (i.e. W^0) couples to <u>left</u>-<u>handed</u> <u>particles</u> <u>only</u>

(with strength prop to weak isospin I_W^3)

EM bit of Z (i.e. B^μ) couples <u>equally</u> to left- and right-handed

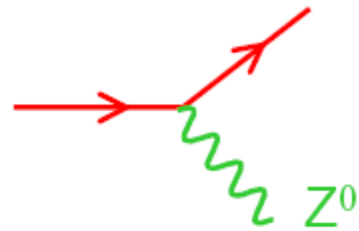
(with strength prop to electric charge Q)

- Overall interaction contains factor

$$c_L(1-\gamma^5)+c_R(1+\gamma^5)=(c_L+c_R)-(c_L-c_R)\gamma^5$$
$$\equiv c_V - c_A\gamma^5$$

- Vertex factor for Z^0 is:

$$-i\frac{g_Z}{2}\gamma^{\mu}\left(c_V - c_A\gamma^5\right)$$



where

$$\left.\begin{aligned} c_V &= c_L + c_R \\ c_A &= c_L - c_R \end{aligned}\right\}$$

vector and axial vector coupling constants

- For $\sin^2\theta_W = 0.23$:

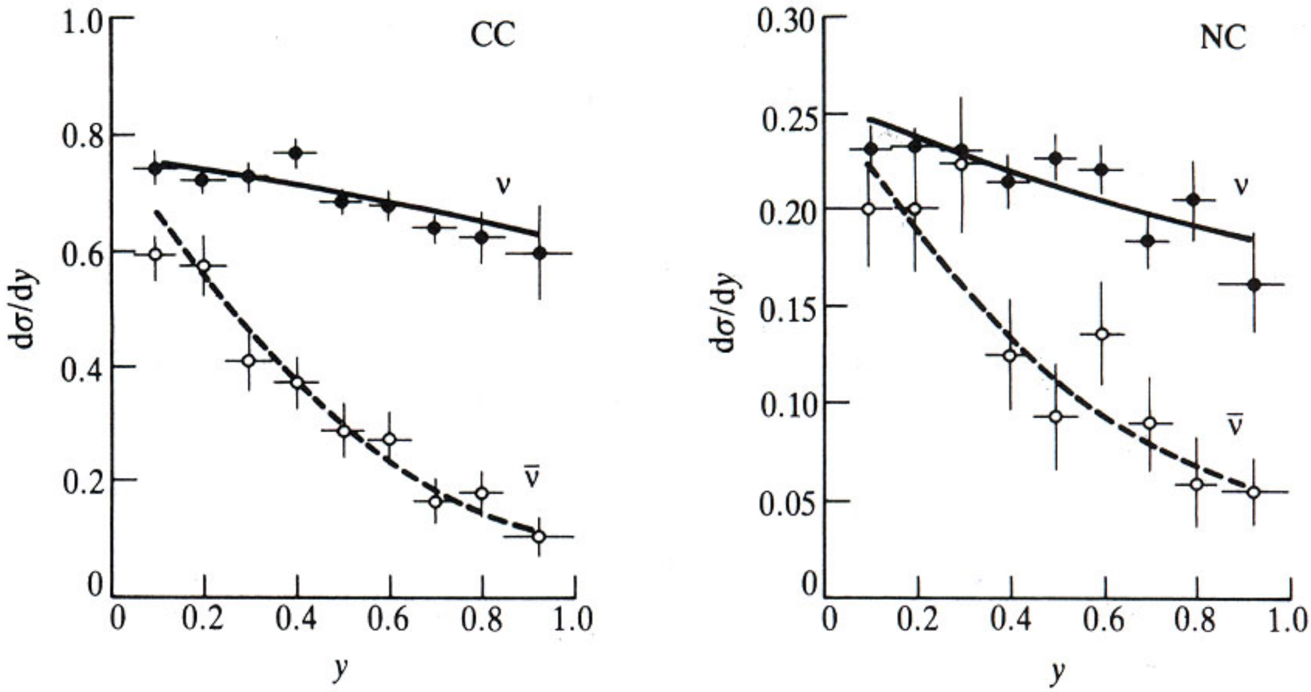
fermion	Q	I_W^3	c_L	c_R	c_V	c_A
ν_e, ν_μ, ν_τ	0	$+\frac{1}{2}$	$\frac{1}{2}$	0	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-, τ^-	-1	$-\frac{1}{2}$	-0.27	0.23	-0.04	$-\frac{1}{2}$
u, c, t	$+\frac{2}{3}$	$+\frac{1}{2}$	0.35	-0.15	$+0.19$	$\frac{1}{2}$
d', s', b'	$-\frac{1}{3}$	$-\frac{1}{2}$	-0.42	0.08	-0.35	$-\frac{1}{2}$

- Note that, for neutrinos:

$$c_L = \tfrac{1}{2} \qquad c_R = 0 \qquad\qquad c_V = c_A = \tfrac{1}{2}$$

$\Longrightarrow$ coupling to Z^0 is V–A, just as for $W^\pm$

$\Longrightarrow$ $\boxed{\text{still only left-handed neutrinos}}$



Fermion f	I_3^f	Q^f	c_A^f	c_V^f
ν_e, ν_μ, ν_τ	$+\frac{1}{2}$	0	$\frac{1}{2}$	$\frac{1}{2}$
e_L^-, μ_L^-, τ_L^-	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	$-\frac{1}{2} + 2\sin^2\theta_W$
u_L, c_L, t_L	$+\frac{1}{2}$	$+\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$
d'_L, s'_L, b'_L	$-\frac{1}{2}$	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$
e_R^-, μ_R^-, τ_R^-	0	-1	0	$2\sin^2\theta_W$
u_R, c_R, t_R	0	$+\frac{2}{3}$	0	$-\frac{4}{3}\sin^2\theta_W$
d'_R, s'_R, b'_R	0	$-\frac{1}{3}$	0	$\frac{2}{3}\sin^2\theta_W$

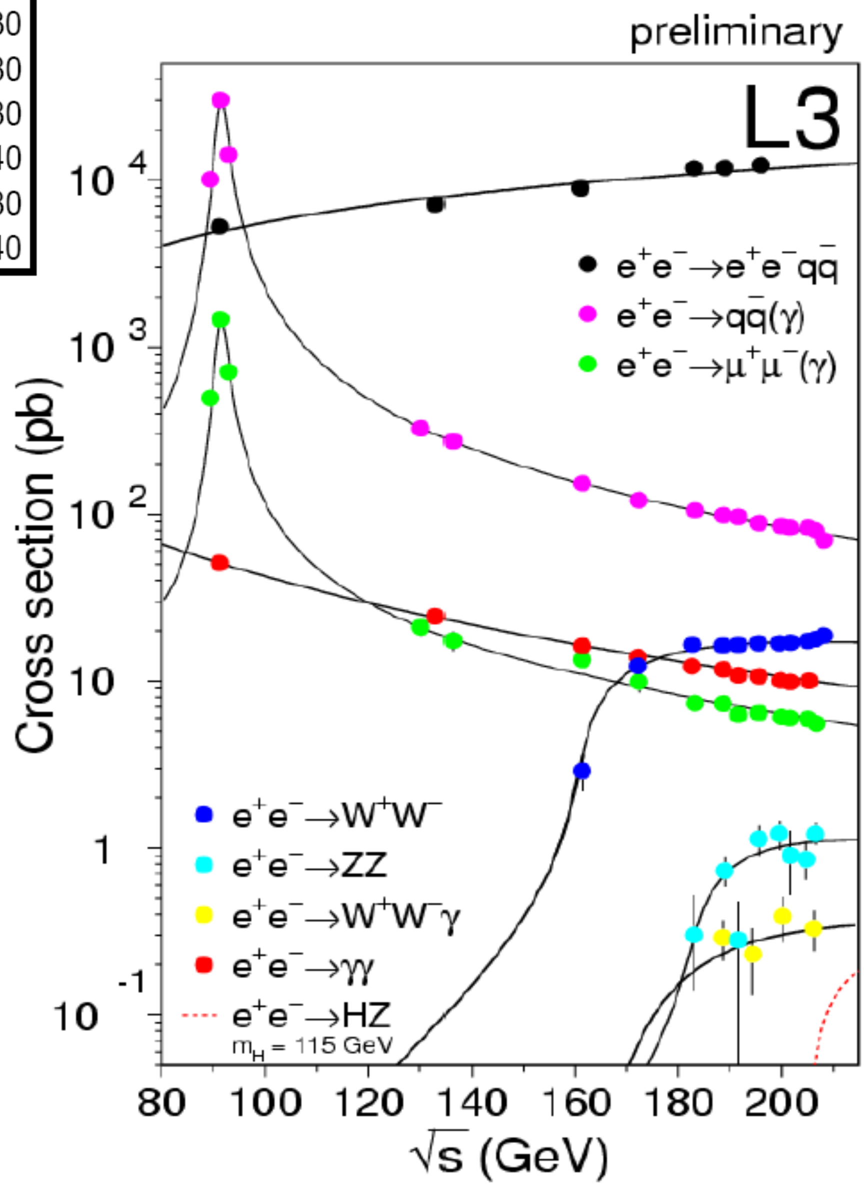
Accoppiamenti vettoriali e assiali dei fermioni allo Z come predetti dal Modello Standard.

Le coppie WW e ZZ a LEP fase II

Sezioni d' urto e Luminosita' integrate a LEP II

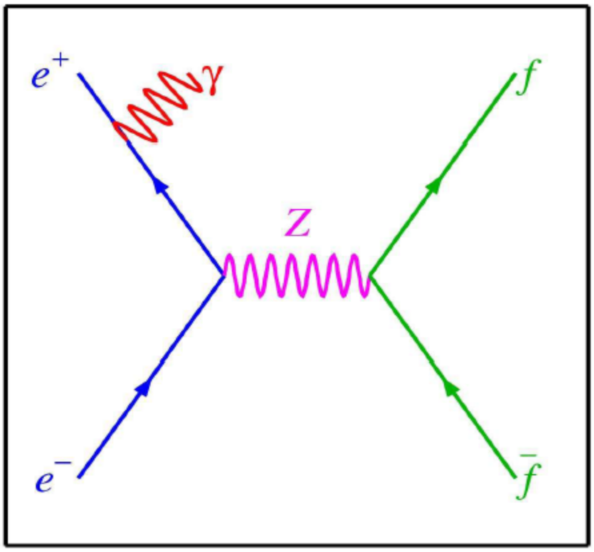
Year	Energy (GeV)	Integrated Lumi (pb^{-1})
1995	130	3
	136	3
1996	161	10
	172	10
1997	130	2
	136	2
	183	50
1998	189	170
1999	192	30
	196	80
	200	80
	202	40
2000	205	80
	207	140

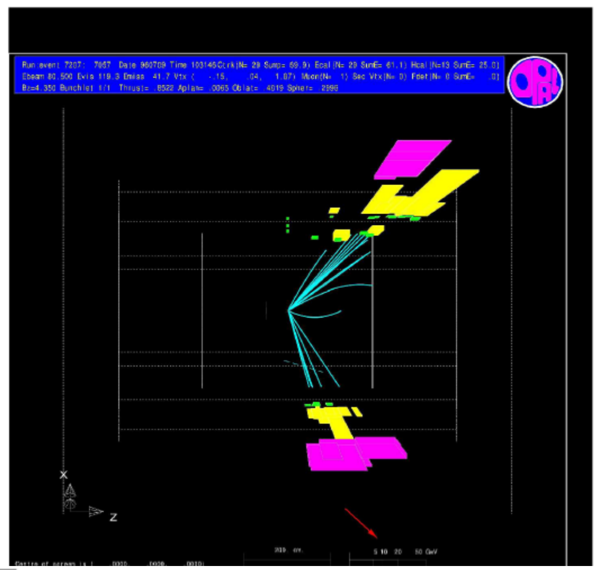
Sebbene la statistica sia molto inferiore a quella di LEP I, le sezione d' urto sono tipicamente 3 ordini di grandezza piu' piccole, lo spettro di argomenti di fisica e' molto ricco. Affrontiamo tra questi la produzione di coppie W e la ricerca del bosone di Higgs.

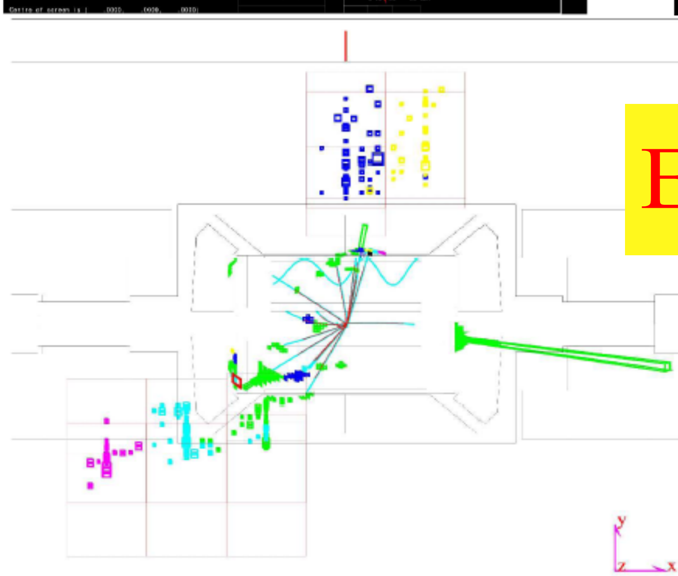


Maggio 2013

Ritorno radiativo allo Z

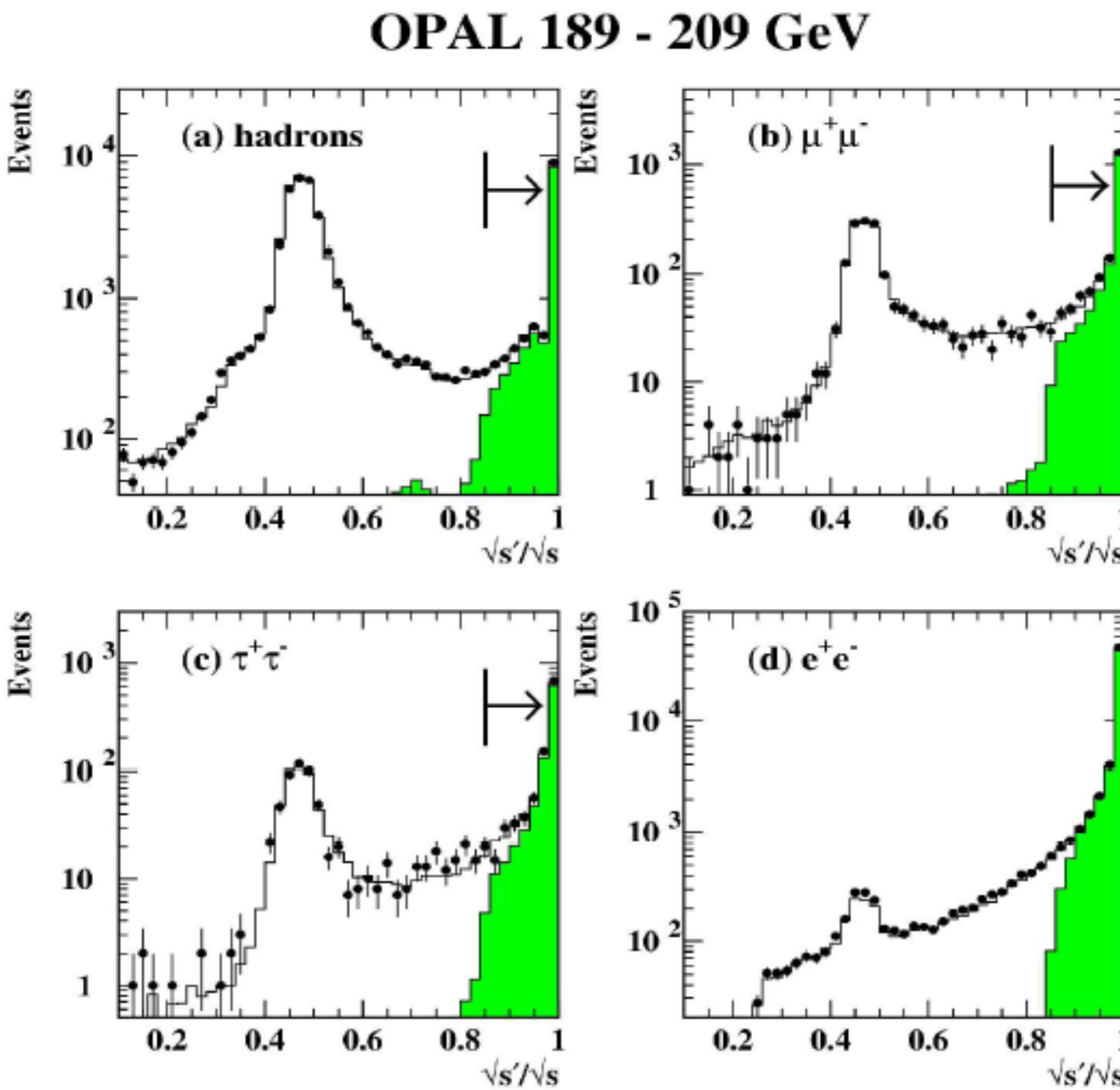






$$E_\gamma \approx \sqrt{s} - M_Z$$

Effective C.M. Energy



Dove $\sqrt{s'}$ e' dato dalla massa combinata delle coppie dei fermioni.

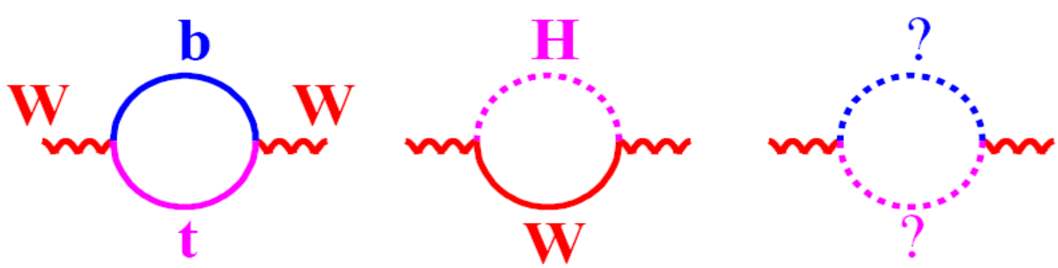
Esempio: le correzioni radiative e M_W

Confrontiamo il valore di $M_W(\alpha; M_Z; G_F)$ *all'ordine piu' basso con le misure sperimentali.*

- ★ PREDICT $M_W = 80.937\ \mathrm{GeV}$
- ★ MEASURE $M_W = 80.426 \pm 0.034\ \mathrm{GeV}$

➔ **Lowest order prediction is <u>inconsistent</u> with the measurement**

➔ **Need to include higher order diagrams - radiative corrections !**



$$M_{top}^2 \qquad \ln(m_H) \qquad ?$$

$$M_W{}^2 \sin^2\theta_W = \frac{\pi\alpha_{em}}{\sqrt{2}G_\mu}(1+\Delta r)$$

where $\Delta r = A M_{top}^2 + B \ln(m_H)$

and where A and B are calculable constants.

By making precise measurements we are sensitive to particles which are not being produced directly - thus placing constraints on possible new particles/physics beyond the Standard Model.

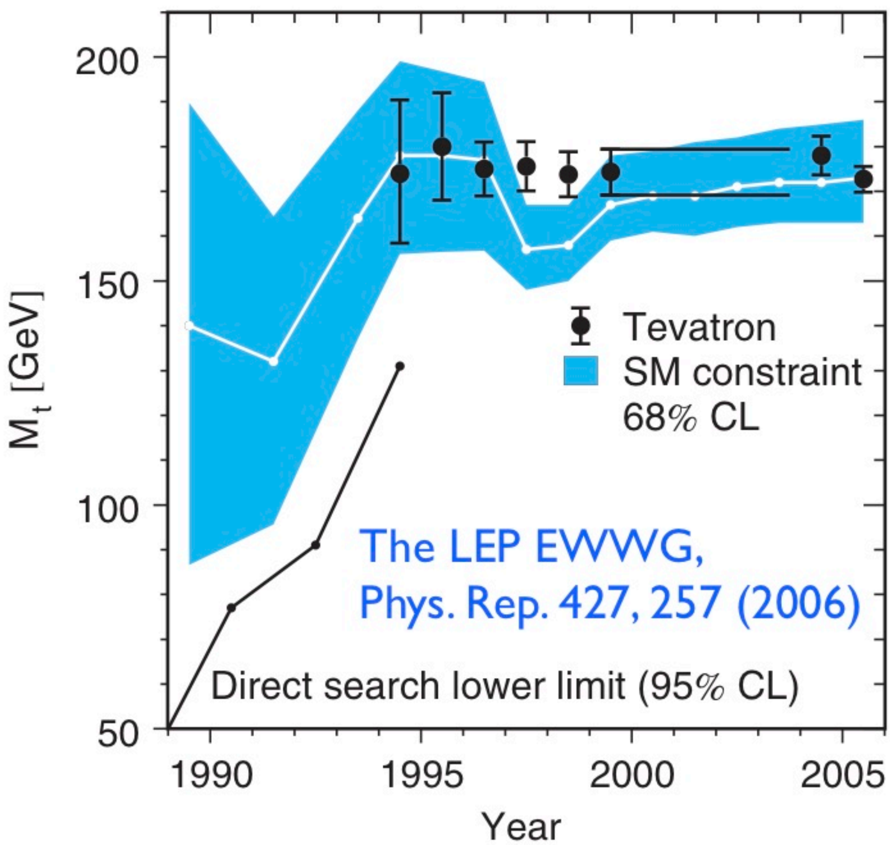
For example:

★ In 1994 precise measurements gave a prediction of the (then undiscovered) top-quark mass:

$M_{top}^{\mathbf{pred}} = 175 \pm 20$ GeV

★ Later in 1994 it was discovered:

$M_{top} = 174.1 \pm 5.4$ GeV



La figura mostra l'evoluzione delle misure dirette e indirette, dal fit elettrodebole , della massa del quark top all'aumentare negli anni della precisione delle misure dei dati.

The Top Quark

leptons — **Charge**

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix} \quad \begin{matrix} -1 \\ 0 \end{matrix}$$

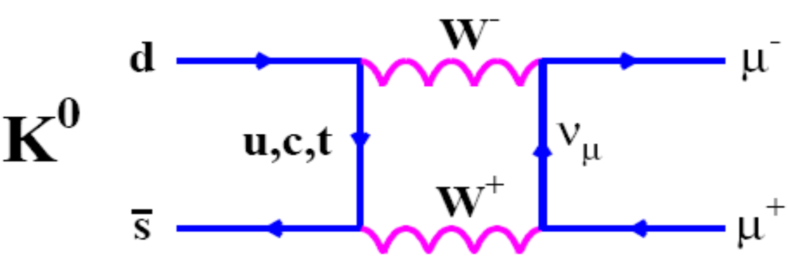
quarks — e.g. proton (uud)

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{matrix} +\frac{2}{3} \\ -\frac{1}{3} \end{matrix}$$

+ anti-particles

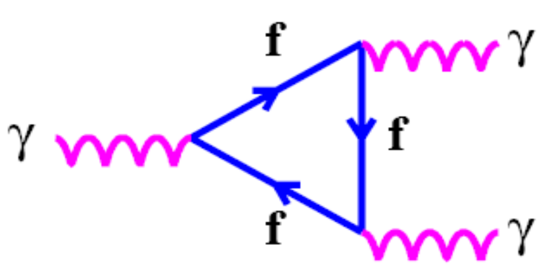
The existence of the TOP QUARK is predicted by the Standard Model and is required to explain a number of observations:

Example: absence of the decay $K^0 \to \mu^+\mu^-$



In the Standard Model the top quark cancels the contributions from the u and c quarks

Example: Electro-magnetic anomalies



This triangle diagram leads to infinities in the theory unless

$$\sum_f Q_f = 0$$

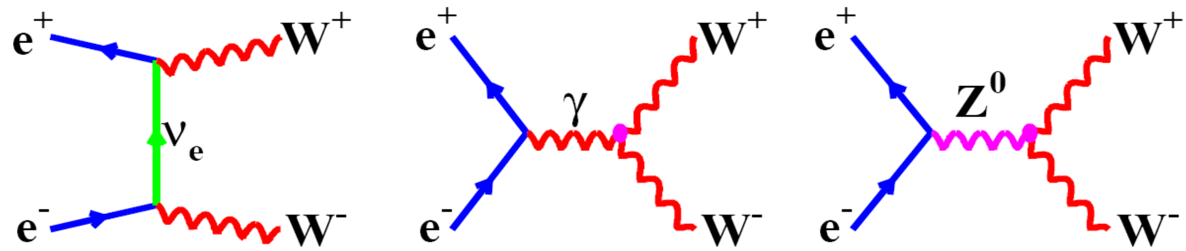
where the sum is over all fermions (and colours)

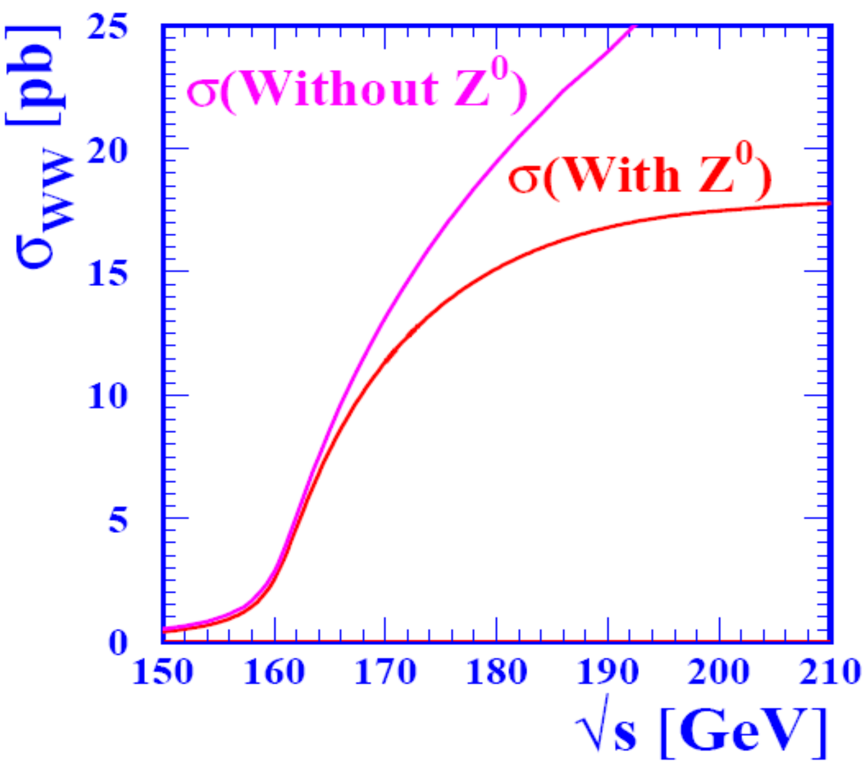
$$\sum_f Q_f = [3 \times (-1)] + [3 \times 0] + [3 \times 3 \times \tfrac{2}{3}] + [3 \times 3 \times (-\tfrac{1}{3})] = 0$$

$\mathbf{W^+W^-}$ at LEP

- ★ e^+e^- collisions Ws produced in pairs.
- ★ In Standard Model 3 possible diagrams for

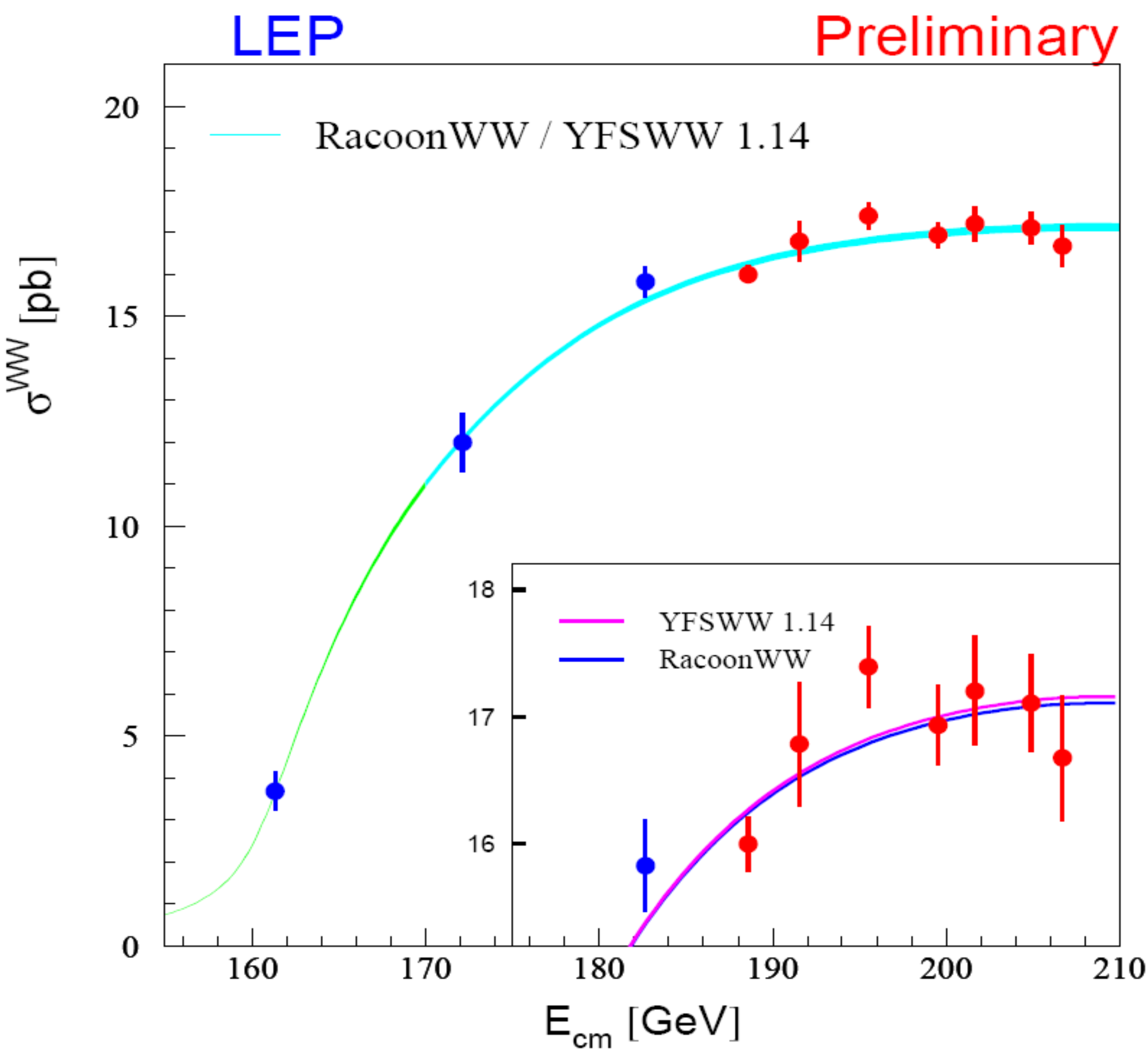
$$e^+e^- \rightarrow W^+W^-$$





Cross section sensitive to presence of the Triple Gauge Boson vertex $Z^0W^+W^-$

1996-2000, LEP operated above the threshold for W^+W^- production $\sqrt{s} > 2M_W$



Cross section agrees with Standard Model prediction. Confirmation of the existence of the $Z^0W^+W^-$ vertex

W^+W^- Decay at LEP

In Standard Model: $W^{\pm}\ell\nu$ and $W^{\pm}q\bar{q}$ couplings are equal.

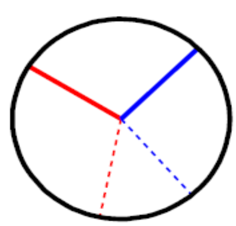
			3 TIMES		
e	μ	τ	u	c	$\cancel{t}$
ν_e	ν_μ	ν_τ	d	s	$\cancel{b}$

EXPECT (assuming 3 COLOURS)

- ★ $Br(W^{\pm} \to q\bar{q}) = \frac{2}{3}$
- ★ $Br(W^{\pm} \to \ell\nu) = \frac{1}{3}$

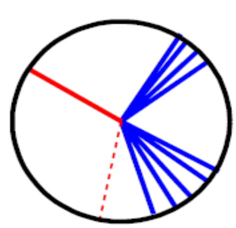
QCD corrections $\sim (1 + \alpha_s/\pi)$ ➜
$Br(W^{\pm} \to q\bar{q}) = 0.675$

$WW \to l\nu l\nu$



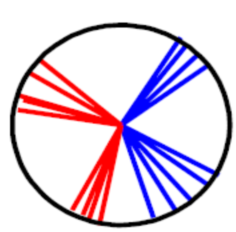
10.5 %

$WW \to qql\nu$



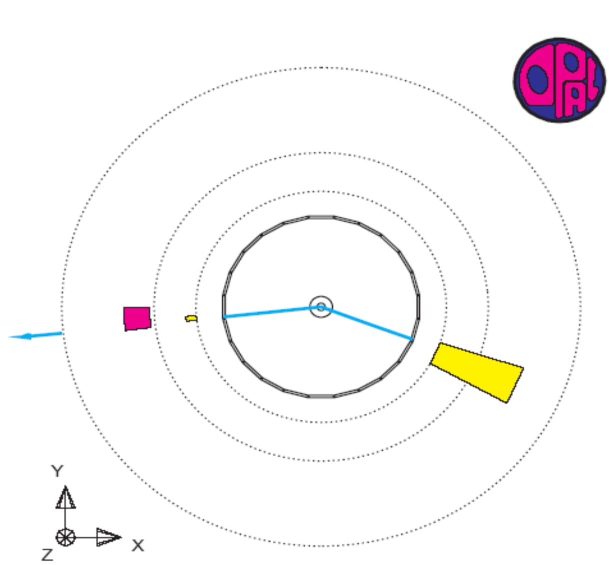
43.9 %

$WW \to qqqq$

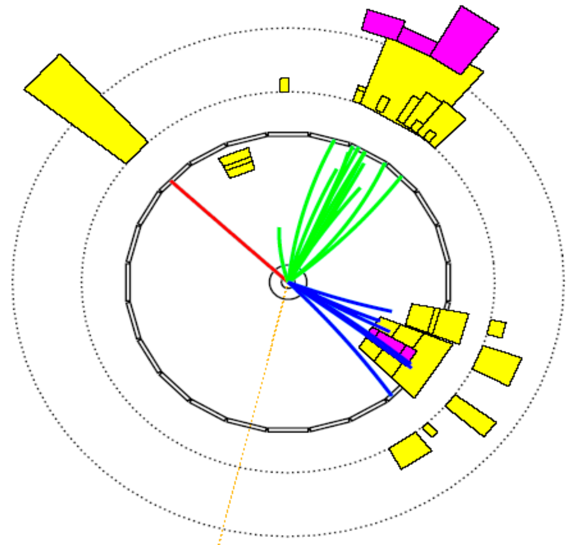


45.6 %

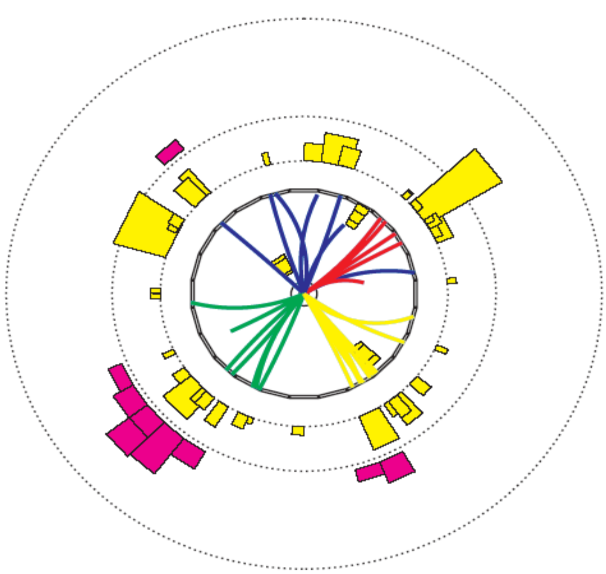
W^+W^- Events in OPAL



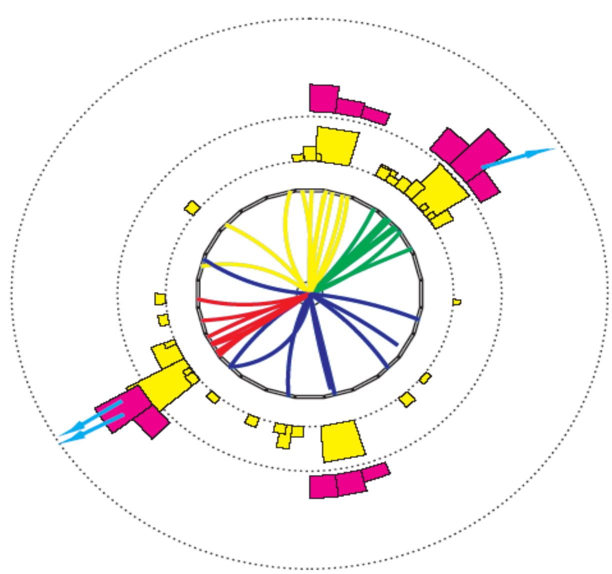
$W^+W^- \rightarrow e\nu\mu\nu$



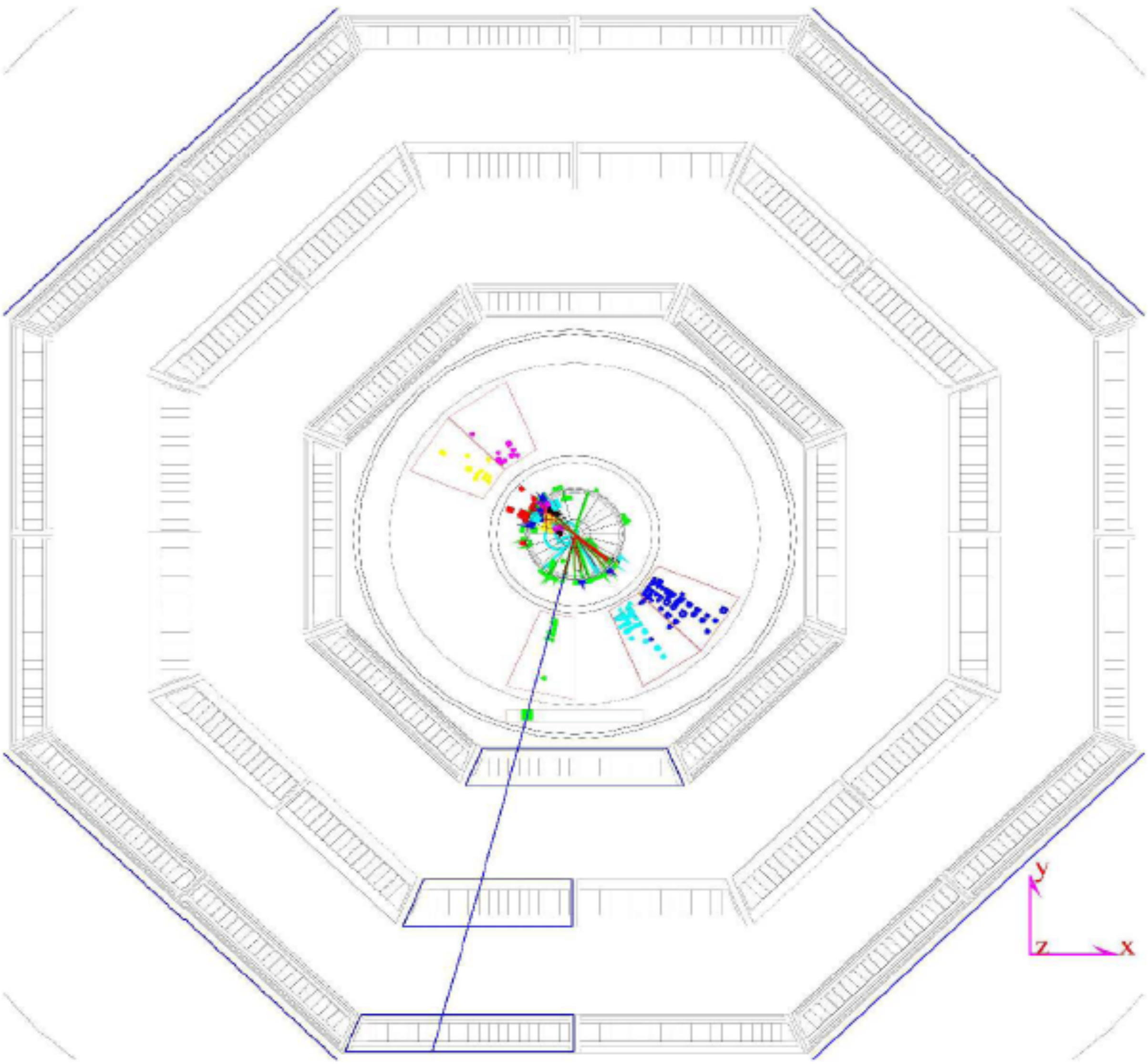
$W^+W^- \rightarrow q\bar{q}e\nu$



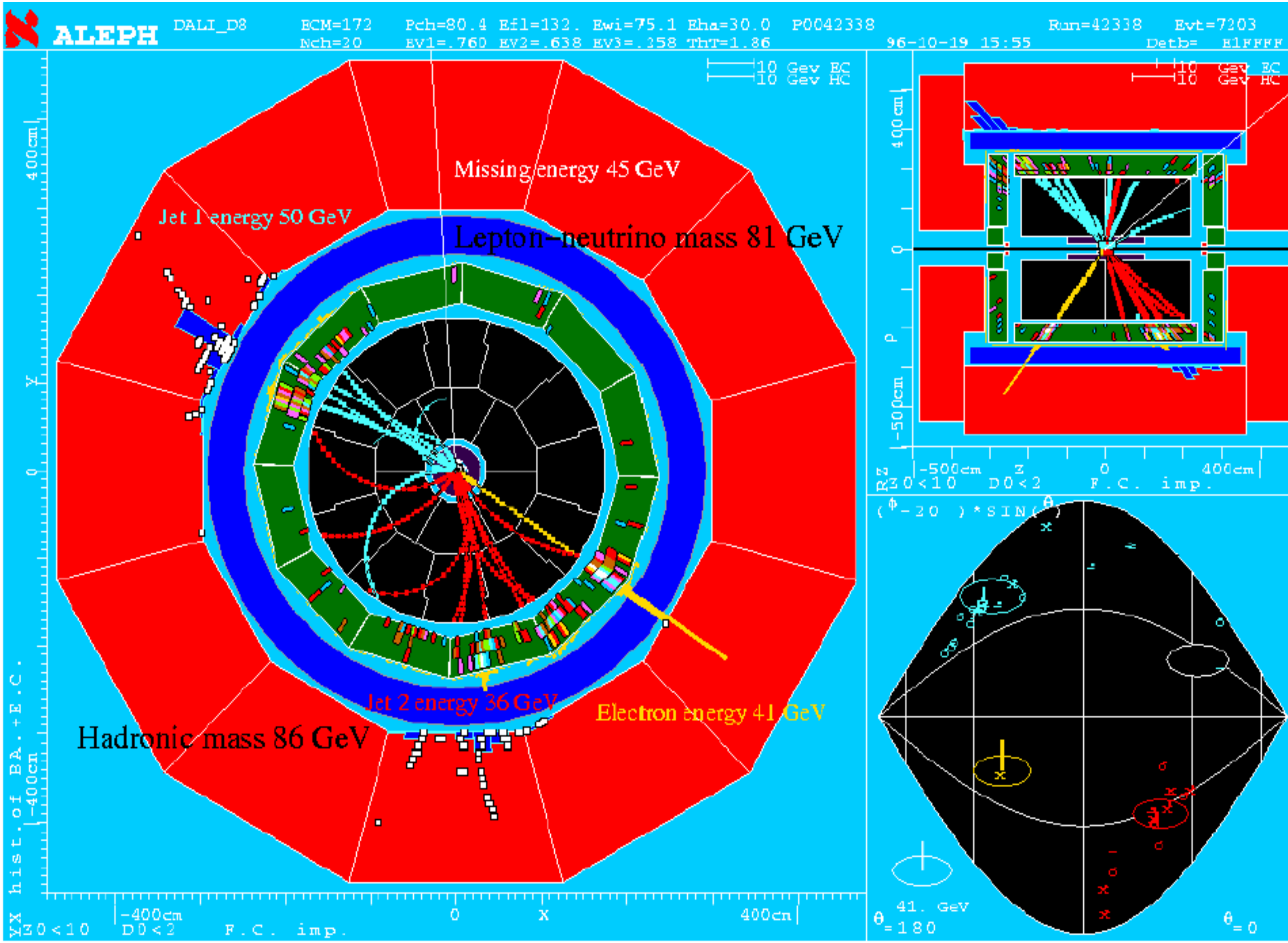
$W^+W^- \rightarrow q\bar{q}q\bar{q}$



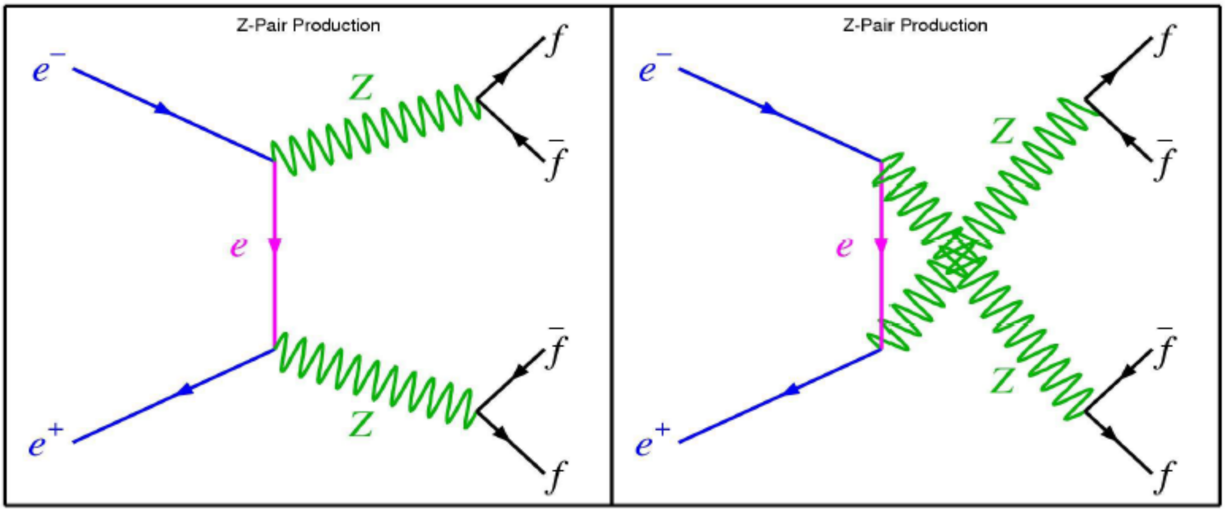
$W^+W^- \rightarrow q\bar{q}q\bar{q}$

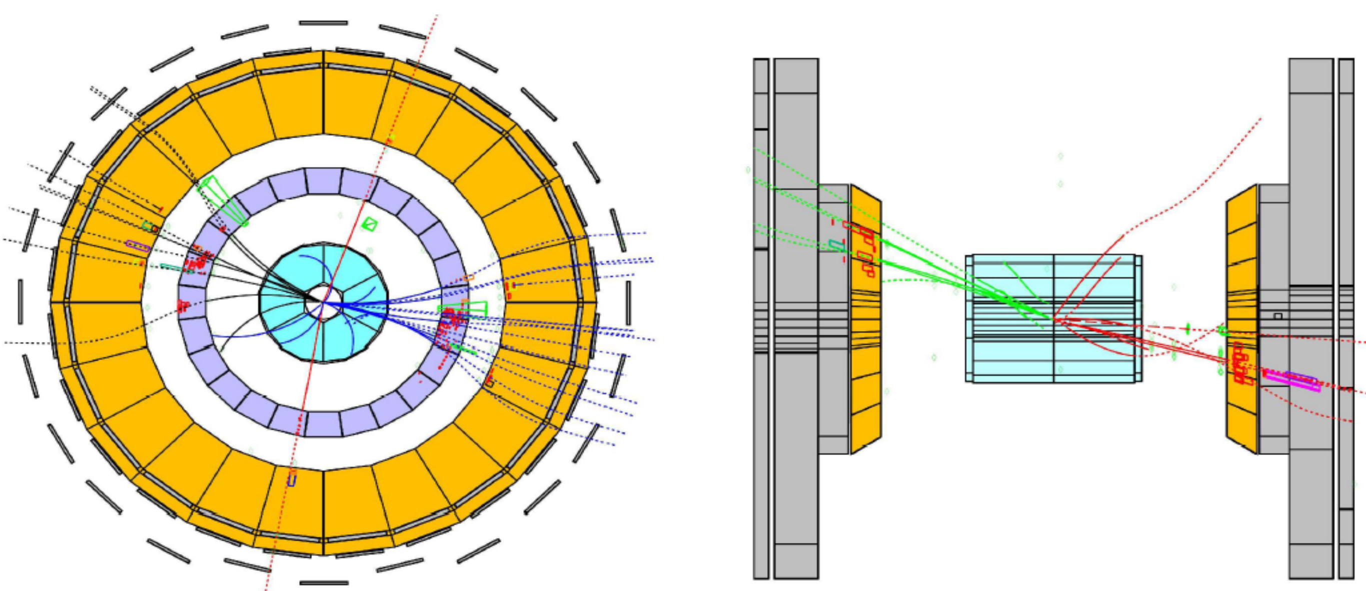


Transverse Imbalance :	.3665		Longitudinal Imbalance :	.3354	
Thrust :	.7432	Major :	.4897	Minor :	.3135
Event DAQ Time :	980824 53636				


ALEPH
DALI_D8
ECM=172 Nch=20
Pch=80.4 Efl=132. Ewi=75.1 Eha=30.0 P0042338
EV1=.760 EV2=.638 EV3=.358 ThT=1.86
Run=42338 Evt=7203
96-10-19 15:55
Detb= E1FFFF
10 Gev EC
10 Gev HC
Missing energy 45 GeV
Jet 1 energy 50 GeV
Lepton–neutrino mass 81 GeV
Jet 2 energy 36 GeV
Electron energy 41 GeV
Hadronic mass 86 GeV
YX hist. of BA.+E.C.
Z0<10 D0<2 F.C. imp.
-400cm 0 X 400cm
RZ Z0<10 D0<2 F.C. imp.
-500cm Z 0 400cm
41. GeV

Produzione di coppie di Z

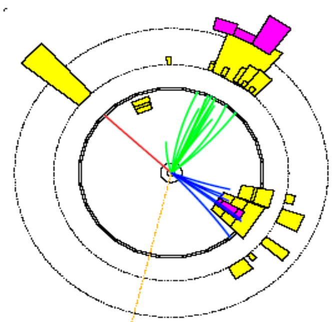




Un candidato ZZ di DELPHI

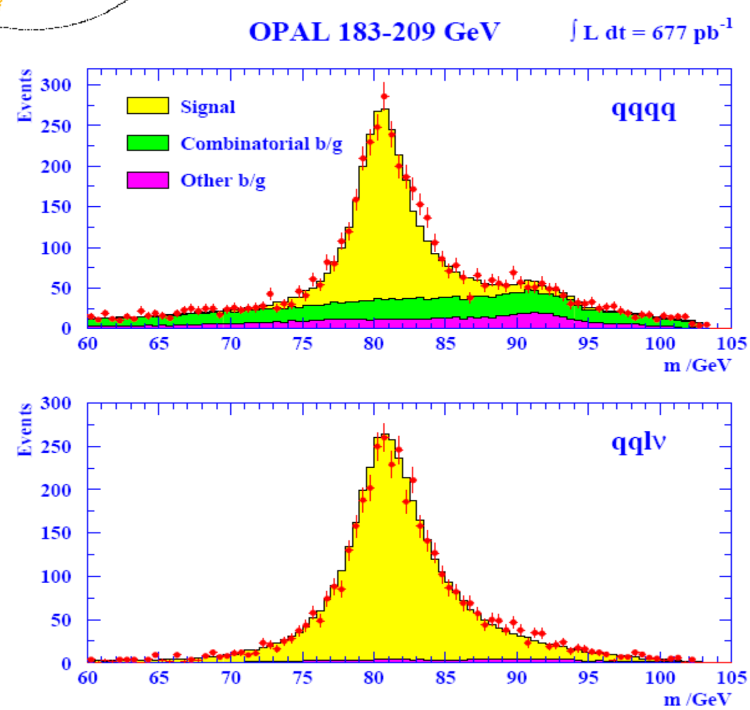
W-Boson Mass and Width

- ★ Unlike $e^+e^- \to Z^0$, W boson production at LEP is not a resonant process
- ★ M_W measured differently.
- ★ Reconstruct invariant mass distribution.
- ★ Use measured lepton/jet momenta and energies to estimate M_W on an event-by-event basis



➡ $\vec{p}_{q_1}, \vec{p}_{q_2}, \vec{p}_e, \vec{p}_\nu$

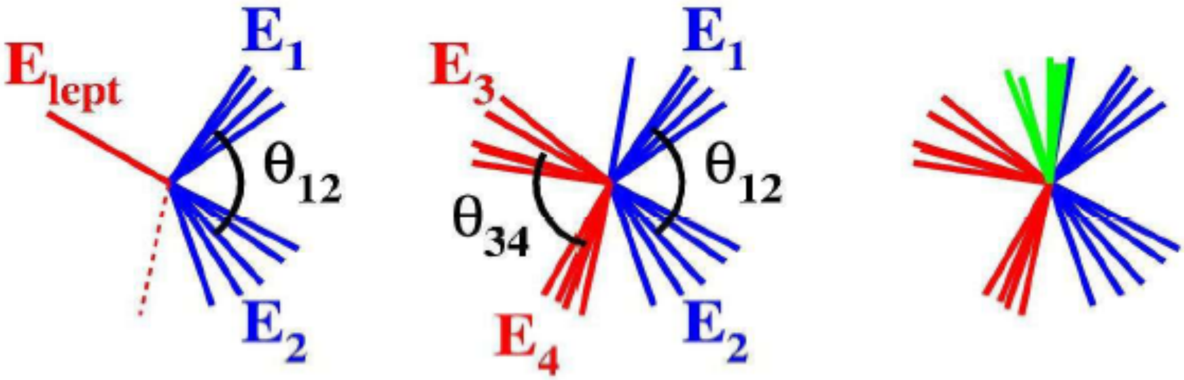
➡ $M_W = \frac{1}{2}(M_{q\bar{q}} + M_{ln})$

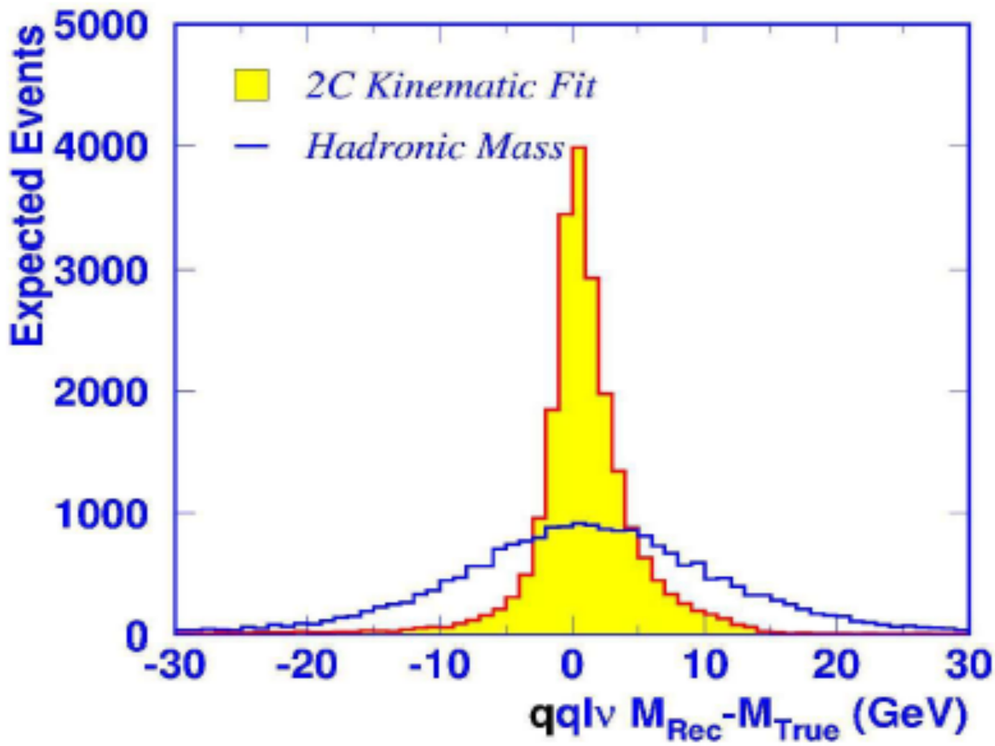


$$\Gamma_W = 2.12 \pm 0.11 \text{ GeV}$$

$$M_W = 80.423 \pm 0.038 \text{ GeV}$$

Risoluzione in massa per il W



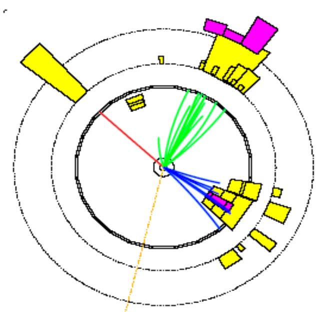


Kinematic fit: E and $\vec{p}$ conservation,
possibly $M_{12} = M_{34}$

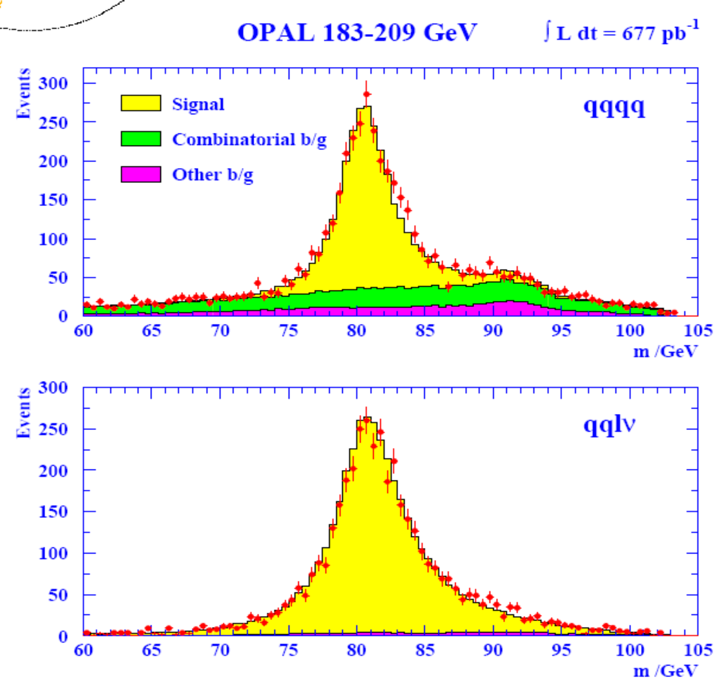
$$\boxed{\delta M_W / M_W \approx \delta E_{beam} / E_{beam}}$$

W-Boson Mass and Width

- ★ Unlike $e^+e^- \rightarrow Z^0$, W boson production at LEP is not a resonant process
- ★ M_W measured differently.
- ★ Reconstruct invariant mass distribution.
- ★ Use measured lepton/jet momenta and energies to estimate M_W on an event-by-event basis



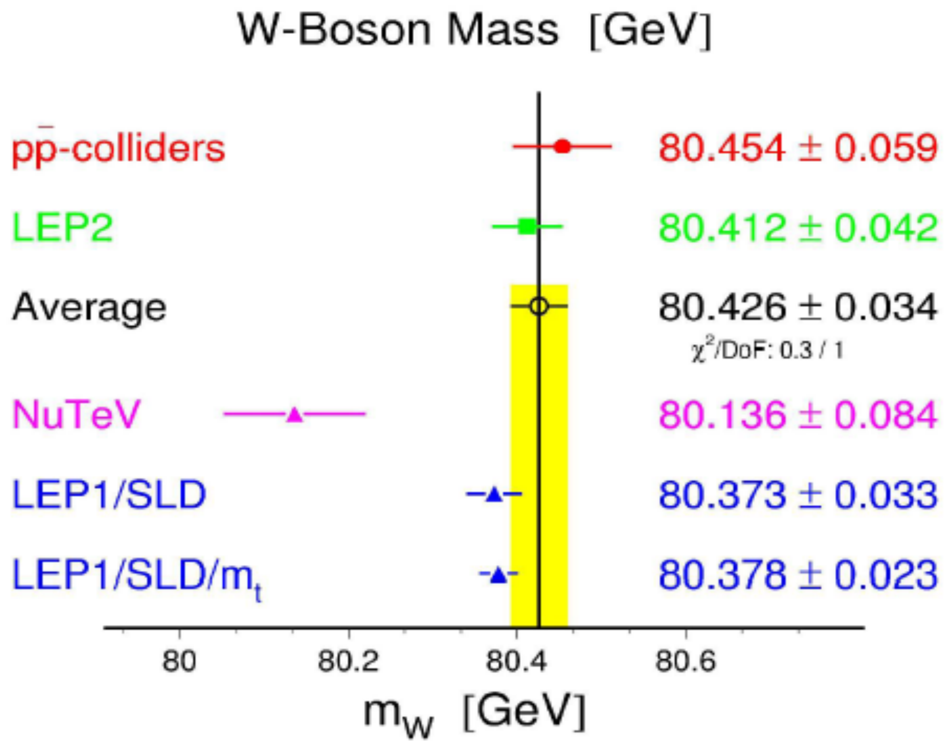
- ➜ $\vec{p}_{q_1}, \vec{p}_{q_2}, \vec{p}_e, \vec{p}_\nu$
- ➜ $M_W = \frac{1}{2}(M_{q\bar{q}} + M_{ln})$

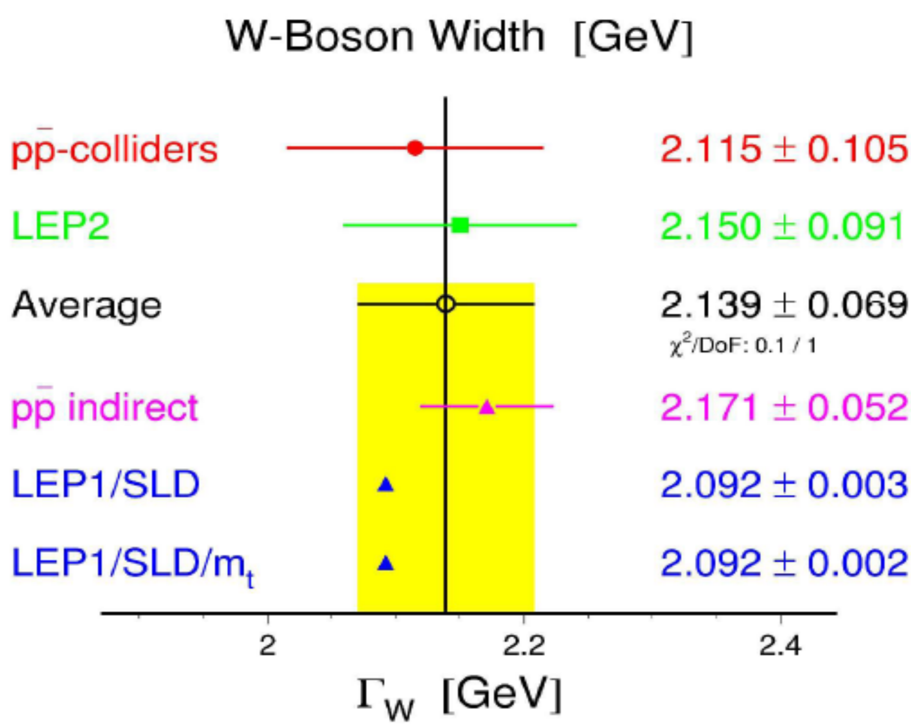


$$\Gamma_W = 2.12 \pm 0.11 \text{ GeV}$$

$$M_W = 80.423 \pm 0.038 \text{ GeV}$$

Risultati per la Massa e la Larghezza del W





W-Boson Decay Width

Nel Modello Standard Γ_W e' data da:

$$\Gamma(W^- \to e^-\overline{\nu}_e) = \frac{g_w^2 M_W}{48\pi} = \frac{G_F M_W{}^3}{6\sqrt{2}\pi}$$

From μ-decay : $G_F = 1.166 \times 10^{-5}\,\mathrm{GeV}^{-2}$.

From LEP measure : $Mw = 80.423 \pm 0.038\,\mathrm{GeV}$.

Therefore predict partial width

$$\Rightarrow \quad \Gamma(W^- \to e^-\overline{\nu}_e) = 227\,\mathrm{MeV}$$

Total width is the sum over all partial widths:

$$\begin{aligned} W^- &\to e^-\overline{\nu}_e \\ W^- &\to \mu^-\overline{\nu}_\mu \\ W^- &\to \tau^-\overline{\nu}_\tau \\ W^- &\to d\bar{u} \\ W^- &\to s\bar{c} \end{aligned}$$

Di conseguenza, SE l'accoppiamneto del W ai leptoni e ai quark e' lo stesso e ci sono 3 colori. Ci aspettiamo:

$$\begin{aligned} \Gamma &= \sum_i \Gamma_i = (3 + 2 \times 3)\Gamma(W^- \to e^-\overline{\nu}_e) \\ &\approx 2.1\,\mathrm{GeV} \end{aligned}$$

Il valore misurato a LEP e': Γ_W = 2.150 ± 0.091 GeV

- **L' intensita' dell'accoppiamento del W e' Universale;**
- **Un'altra evidenza dell' esistenza del colore.**

Riassunto alla "Bignami" del Modello Standard

- **G**lashow (1961), **W**einberg (1967) and **S**alam (1968) model treats EM and WEAK interactions as different manifestations of a UNIFIED force.
  - It is somewhat *ad hoc*
  - But gives concrete predictions - i.e. a testable theory
  - provides perfect description of precise data

- "Basic idea" - start with 4 massless bosons, $\{W^+, W^0, W^-\}$ and B^0. The neutral bosons mix to give physical BOSONs, (the particles we see), *i.e.* the $W^{\pm}$, $\mathbf{Z^0}$ and γ.

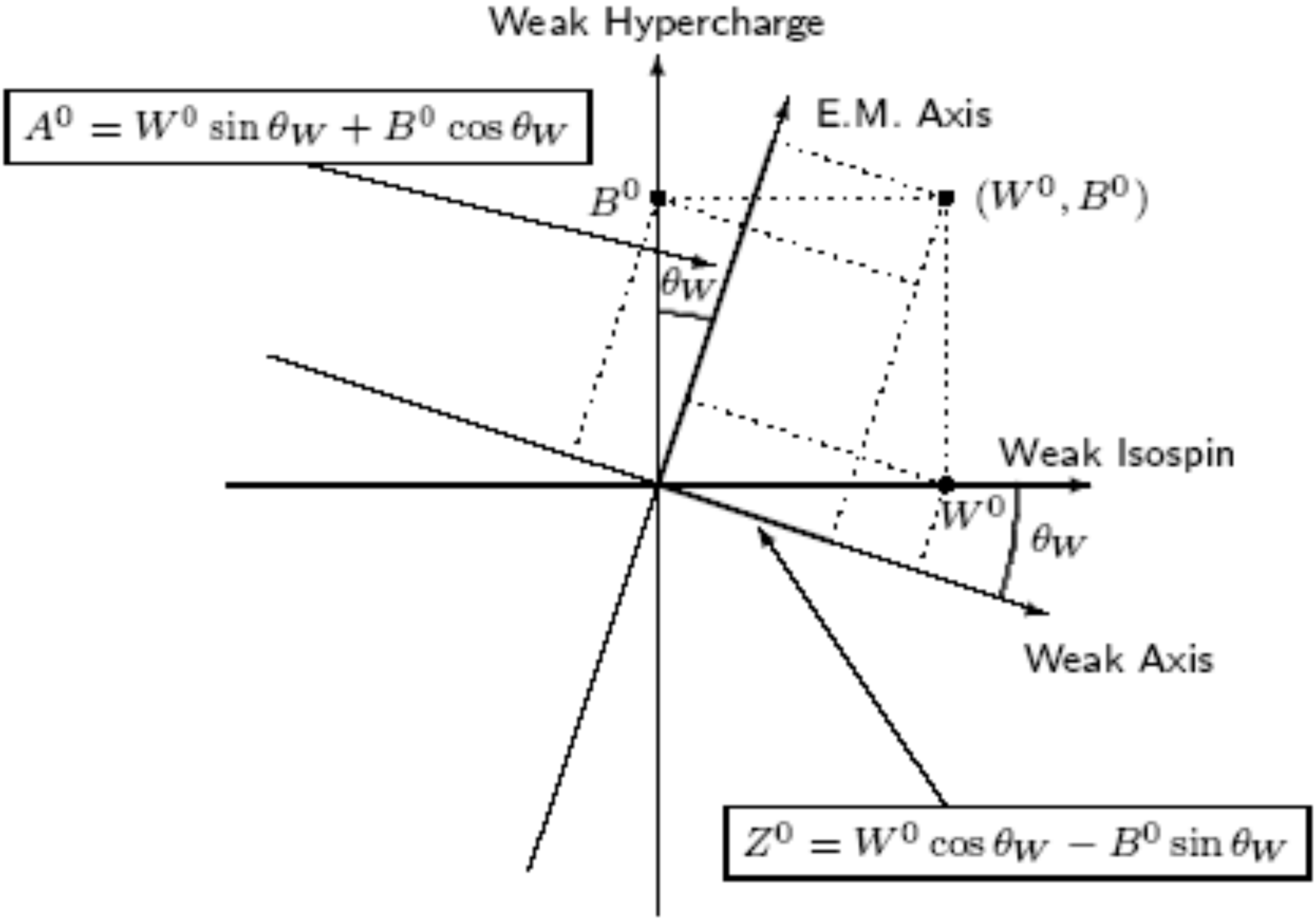
$$\begin{pmatrix} W^+ \\ W^0 \\ W^- \end{pmatrix}, B \rightarrow \begin{pmatrix} W^+ \\ Z^0 \\ W^- \end{pmatrix}, \gamma$$

Physical Fields : W^+, W^+ Z^0, A (photon)

$$\begin{aligned} \mathrm{Z}^0 &= W^0 \cos\theta_W - B\sin\theta_W \\ A &= W^0 \sin\theta_W + B\cos\theta_W \end{aligned}$$

$$e = g\sin\theta_w \qquad M_{Z^0} = \frac{M_W}{\cos\theta_W}$$

θ_W : **Angolo di mixing debole**



★ $\mathbf{W}^{\pm}$ and $\mathbf{Z}^0$ 'acquire' mass via the HIGGS MECHANISM

The beauty of the model is that it makes exact predictions:

★ Weak coupling constant: $e = g\sin\theta_w$

★ The mass of the $\mathbf{Z}^0$ boson

$$M_{\mathbf{Z^0}} = \frac{M_{\mathbf{W}}}{\cos\theta_W}$$

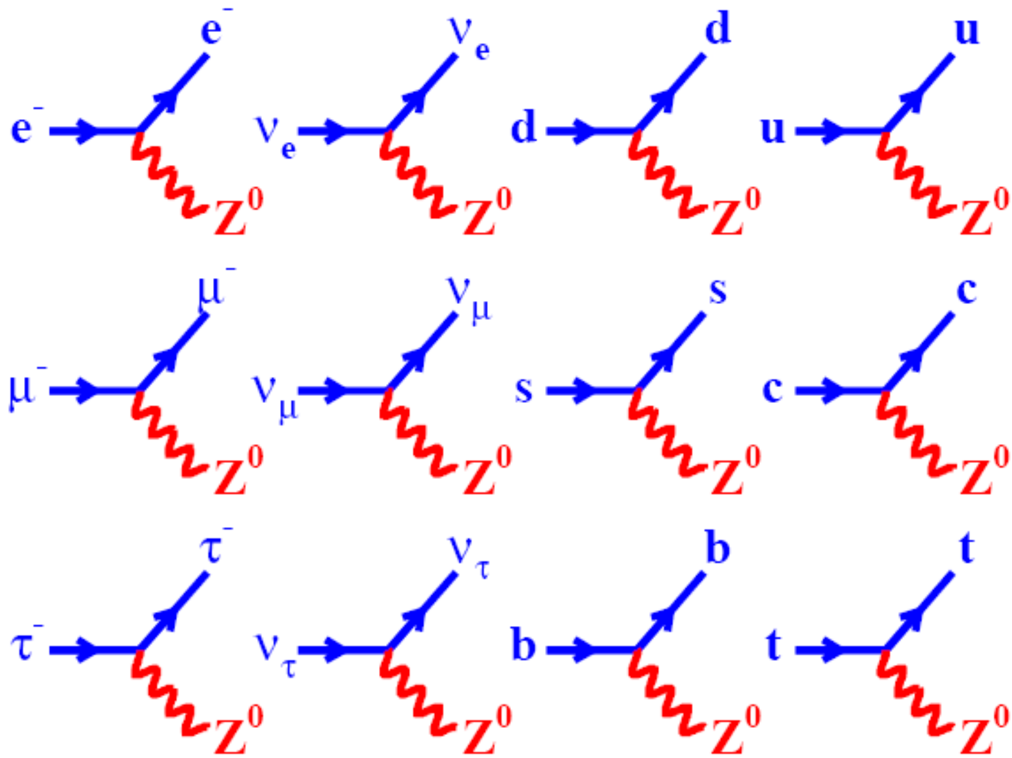
★ The couplings of the $\mathbf{Z}^0$ boson

★ ONLY 3 free parameters !

IF we know $\{\alpha_{em}, G_{\mathbf{F}}, \sin\theta_W\}$ everything else is FIXED, i.e. predict $M_{\mathbf{W}}$, $M_{\mathbf{Z^0}}$, couplings, etc.

Z^0 Neutral Current

★ WEAK Neutral Current (NC) interactions are mediated by the Z^0 boson.



WEAK NC NEVER changes flavour

Z^0 couplings are a "MIXTURE" of weak and electro-magnetic couplings

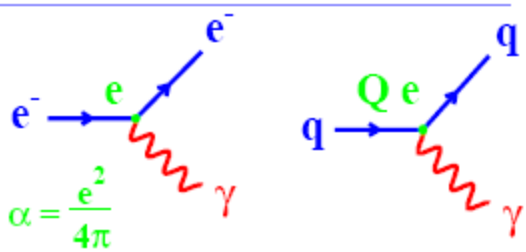
WEAK NC couplings therefore depend on $\sin^2\theta_W$

Z^0 couplings are a mixture of EM (VECTOR) and WEAK (VECTOR—AXIAL-VECTOR) couplings

$$\frac{g}{\cos\theta_W}\frac{1}{2}\gamma^\mu(C_V - C_A\gamma^5)$$

Summary of Standard Model Vertices

ELECTROMAGNETIC (QED)

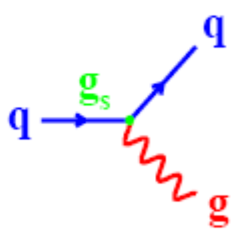


$$\alpha = \frac{e^2}{4\pi}$$

Couples to CHARGE

Does NOT change FLAVOUR

STRONG (QCD)

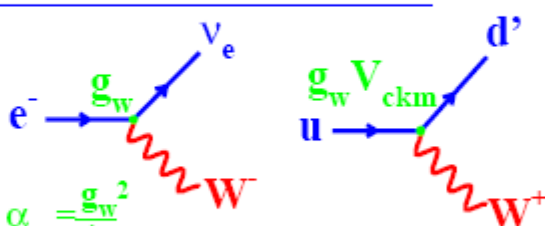


$$\alpha_s = \frac{g_s^2}{4\pi}$$

Couples to COLOUR

Does NOT change FLAVOUR

WEAK Charged Current

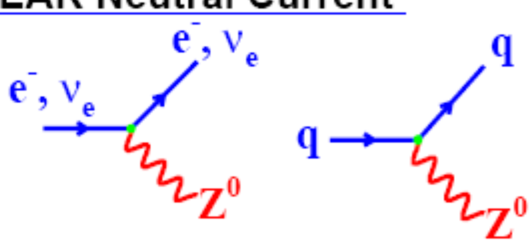


$$\alpha_W = \frac{g_W^2}{4\pi}$$

Changes FLAVOUR

For QUARKS: coupling BETWEEN generations

WEAK Neutral Current



Does NOT change FLAVOUR

Summary

★ **Abbiamo ora 5 misure precise di alcuni dei parametri fondamentali del Modello Standard.**

- ★ α_{em}
- ★ $G_F = (1.16632 \pm 0.00002) \times 10^{-5}\ \mathrm{GeV}^{-2}$
- ★ $M_W = (80.423 \pm 0.038)\ \mathrm{GeV}$
- ★ $M_{Z^0} = (91.1875 \pm 0.0021)\ \mathrm{GeV}$
- ★ $\sin^2\theta_W = 0.23143 \pm 0.00015$

Nel Modello Standard, SOLO 3 sono INDIPENDENTI !
La loro consistenza e' un test di una potenza straordinaria per
IL MODELLO STANDARD
DELLE INTERAZIONI ELETTRODEBOLI !

ESEMPIO: M_W

Nel Modello standard si puo' predire M_W usando la teoria perdurbativa all'ordine piu' basso:

$$G_\mu = \frac{\pi \alpha_{em}}{\sqrt{2}\sin^2\theta_W}\frac{1}{M_W{}^2}$$

$$\sin^2\theta_W = 1 - \frac{M_W{}^2}{M_{Z^0}{}^2}$$

Il Modello Standard fornisce anche " una finestra " :
" on physics Beyond the Standard Model "

Bibliografia

P. Wells: Appendice 6