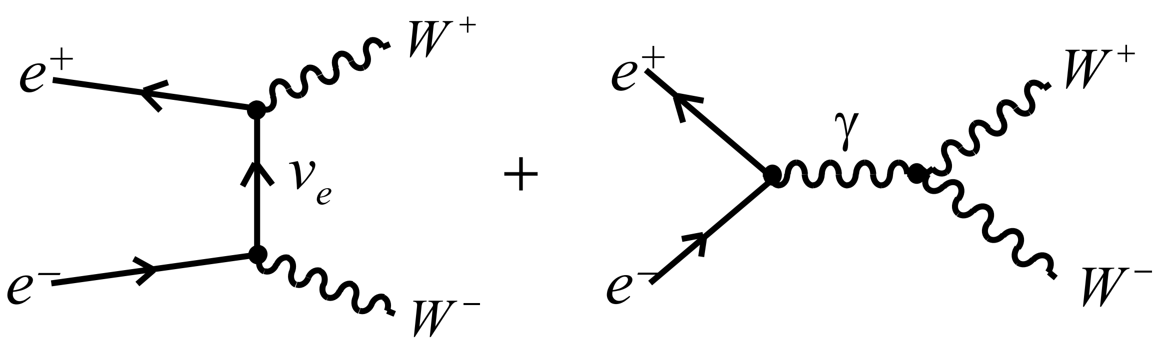
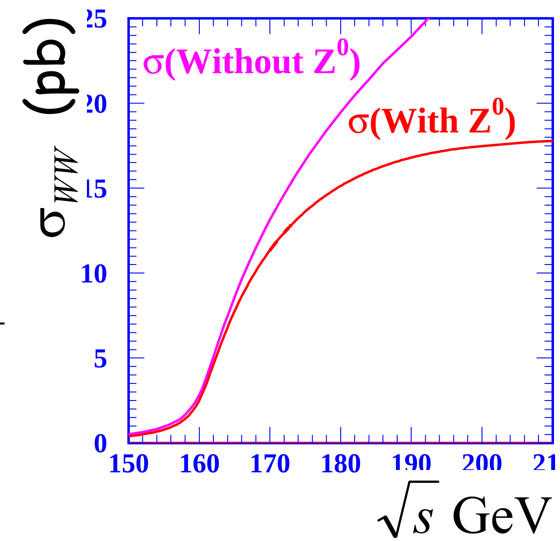
# Section IX
# Electroweak
# Unification

# Electroweak Unification

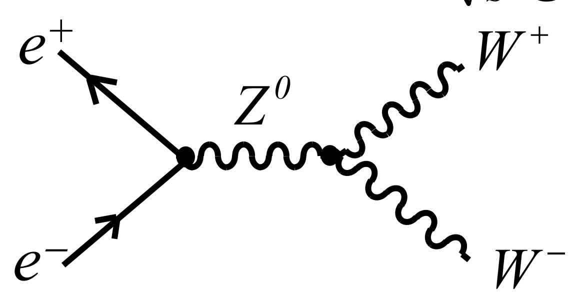
- Weak Charged Current interactions explained by $W^{\pm}$ exchange.
- W bosons are charged, $\therefore$ couple to photon.

Consider $e^+e^- \to W^+W^-$ 2 diagrams (+interference)




- Cross-section DIVERGES at high energy
- Divergence cured by introducing $Z^0$
- Extra diagram $e^+e^- \to W^+W^-$

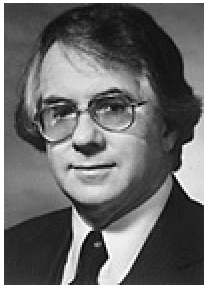



- Only works if $\gamma$, $W^{\pm}$, $Z^0$ couplings are related

$\Rightarrow$ ELECTROWEAK UNIFICATION

# The GWS Model

The Glashow, Weinberg and Salam model treats EM and WEAK interactions as different manifestations of a single UNIFIED ELECTROWEAK force (Nobel Prize 1979)



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 $W^\pm$, $Z^0$ and $\gamma$.

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

Physical fields: $W^+$, $Z^0$, $W^-$ and $A$ (photon)

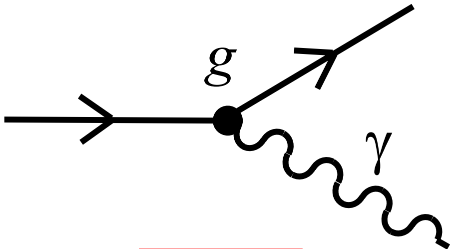
$$\boxed{\begin{aligned} Z^0 &= W^0 \cos\vartheta_W - B^0 \sin\vartheta_W \\ A &= W^0 \sin\vartheta_W + B^0 \cos\vartheta_W \end{aligned}}$$

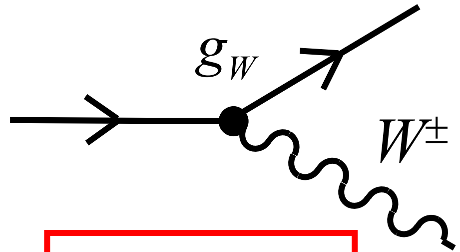
$\vartheta_W$ WEAK MIXING ANGLE

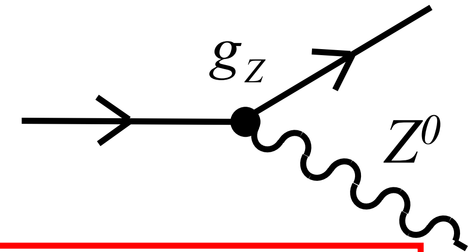
$W^\pm$, $Z^0$ "acquire" mass via the HIGGS MECHANISM.

The beauty of the GWS model is that it makes EXACT predictions of the $W^\pm$ and $Z^0$ masses and couplings with ONLY 3 free parameters.

Couplings given by $\alpha_{em}$ and $\vartheta_W$




$$\boxed{g \sim e} \qquad \alpha_{em} = \frac{e^2}{4\pi}$$

$$\boxed{g_W = \frac{e}{\sin\vartheta_W}} \qquad \boxed{g_Z = \frac{e}{\sin\vartheta_W \cos\vartheta_W}}$$

Masses given by $G_F$ and $\vartheta_W$

From Fermi theory
$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8M_W^2} = \frac{e^2}{8M_W^2 \sin^2\vartheta_W}$$

$$\boxed{M_{W^\pm} = \left(\frac{\sqrt{2}e^2}{8G_F \sin^2\vartheta_W}\right)^{1/2} \qquad M_Z = \frac{M_W}{\cos\vartheta_W}}$$

If we know $\{\alpha_{em}, G_F, \sin\vartheta_W\}$ (from experiment) everything else is FIXED.

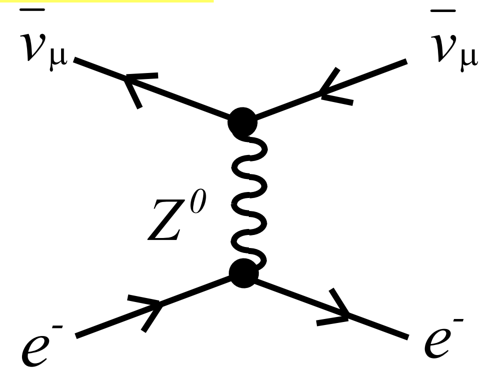
# Evidence for GWS Model

- Discovery of Neutral Currents (1973)

The process $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$ was observed.

ONLY possible Feynman diagram (no $W^\pm$ diagram)

Indirect evidence for $Z^0$




- Direct Observation of $W^\pm$ and $Z^0$ (1983)

First DIRECT observation in $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV via decays into leptons.

$$p\bar{p} \to W^\pm + X, \quad W^\pm \to e^\pm \nu_e,\ \mu^\pm \nu_\mu$$

$$p\bar{p} \to Z^0 + X, \quad Z^0 \to e^+ e^-,\ \mu^+ \mu^-$$

- Precision Measurements of the Standard Model (1989-2000 )

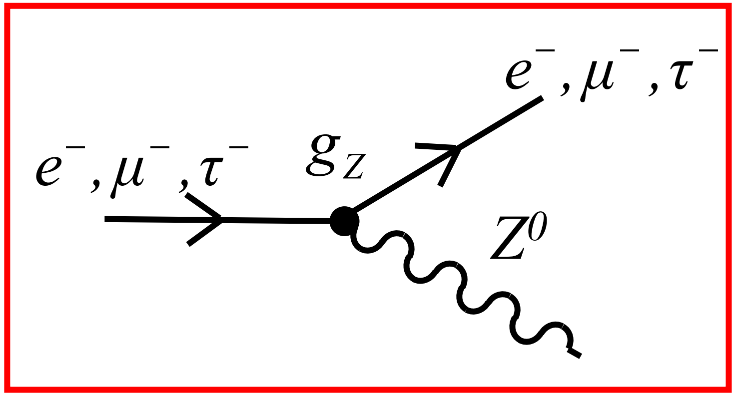
LEP $e^+e^-$ collider (see later) provided many precision measurements of the Standard Model.

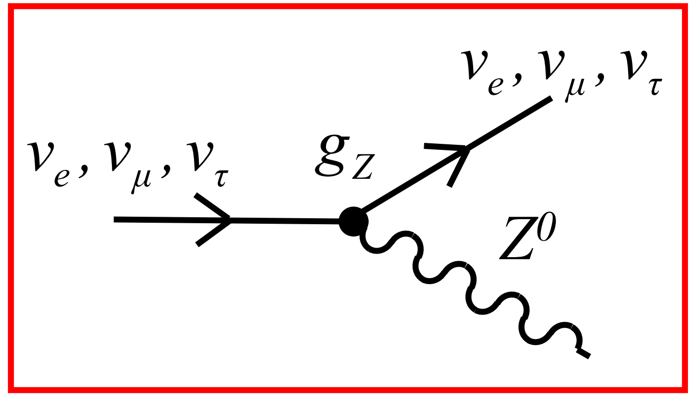
- Wide variety of different processes consistent with GWS model predictions and measure SAME VALUE of

$$\boxed{\sin^2\vartheta_W = 0.23113 \pm 0.00015} \qquad \vartheta_W \approx 29^\circ$$

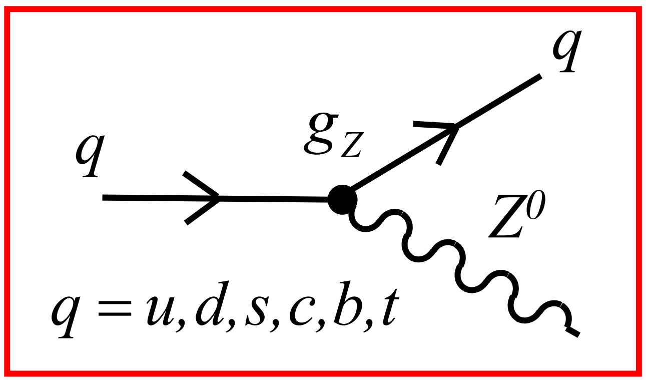
# The Weak NC Vertex

All weak neutral current interactions can be described by the $Z^0$ boson propagator and the weak vertices:




STANDARD MODEL WEAK NC LEPTON VERTEX

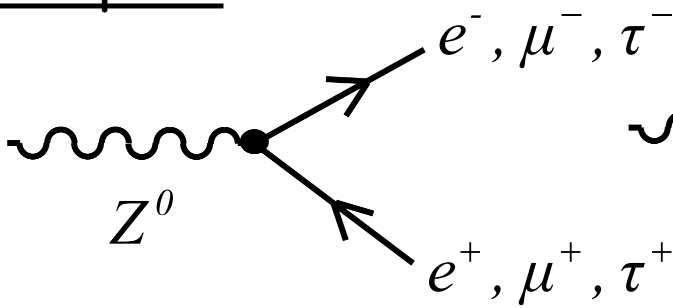


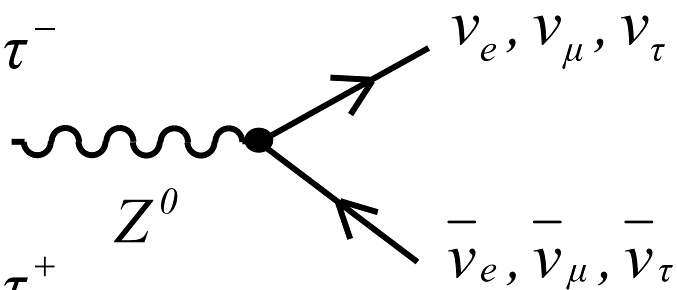

STANDARD MODEL WEAK NC QUARK VERTEX

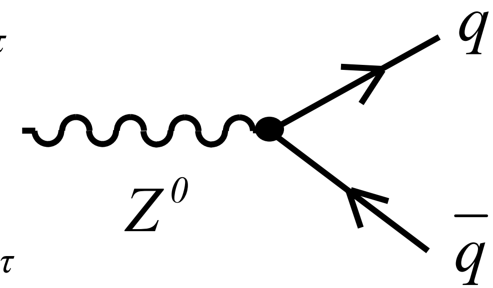
+antiparticles

- $Z^0$ NEVER changes type of particle
- $Z^0$ NEVER changes quark flavour
- $Z^0$ couplings are a MIXTURE of EM and WEAK couplings and therefore depend on $sin^2\vartheta_W$ (exact form treated in Part III Particles course)

## Examples:



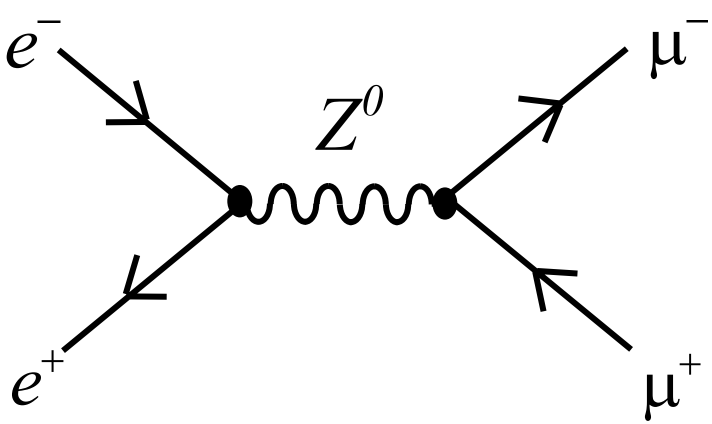



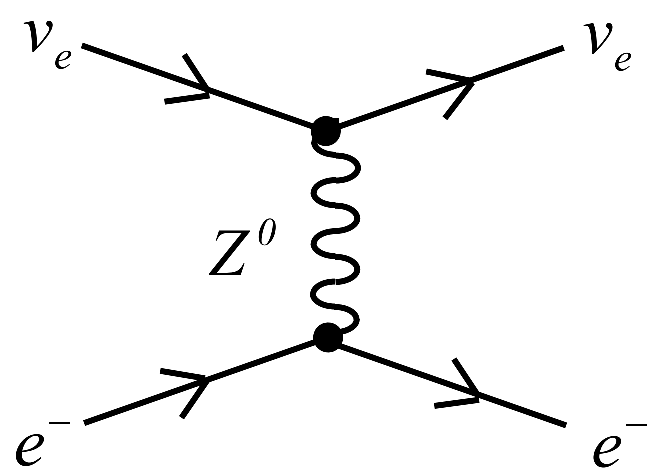




$$Z^0 \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$$

$$Z^0 \to \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau$$

$$Z^0 \to q\bar{q}$$



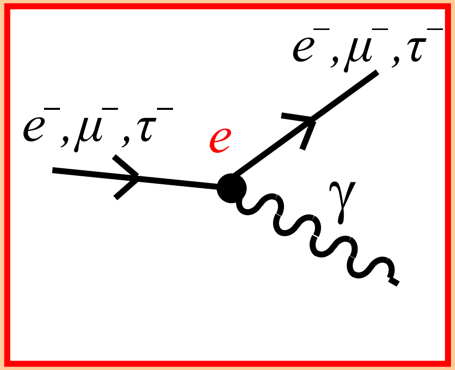



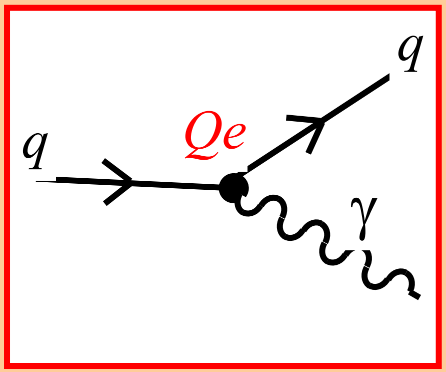

$$e^+e^- \to \mu^+\mu^-$$

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

# Summary of Standard Model Vertices

## ELECTROMAGNETIC (QED)



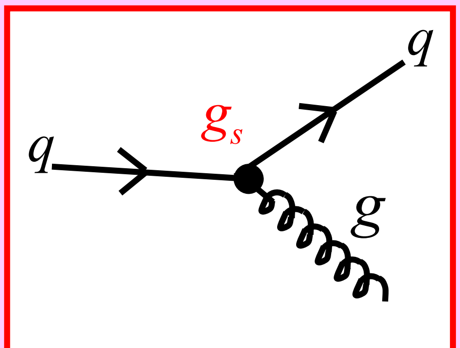




$$\alpha = \frac{e^2}{4\pi}$$

$$q = u,d,s,c,b,t$$

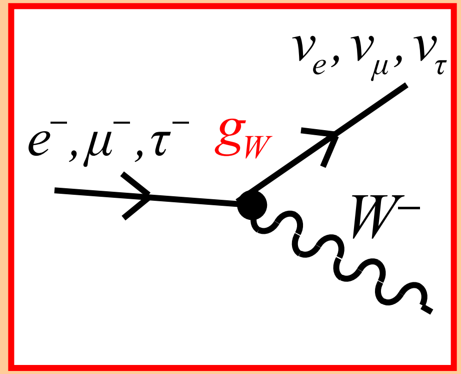
+antiparticles

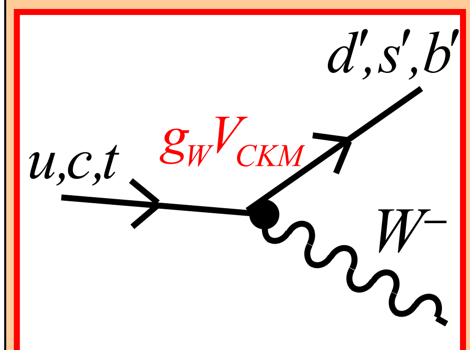
## STRONG (QCD)




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

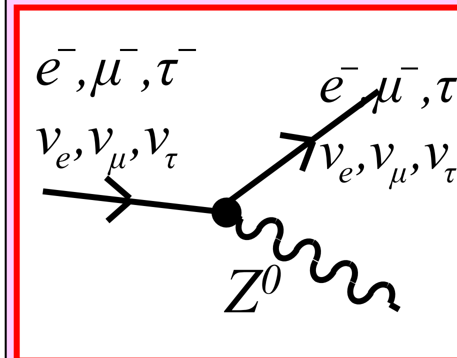
## WEAK CC

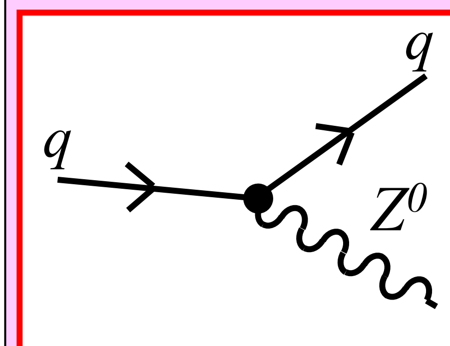



$$\alpha_W = \frac{g_W^2}{4\pi}$$

## WEAK NC



# Drawing Feynman Diagrams

A Feynman diagram is a pictorial representation of the matrix element describing particle decay or interaction

$$a \rightarrow b + c + \ldots \qquad\qquad a + b \rightarrow c + d$$

To draw a Feynman diagram and determine whether a process is allowed, follow the FIVE basic steps:

1. Write down the initial and final state particles and antiparticles and note the quark content of all hadrons.

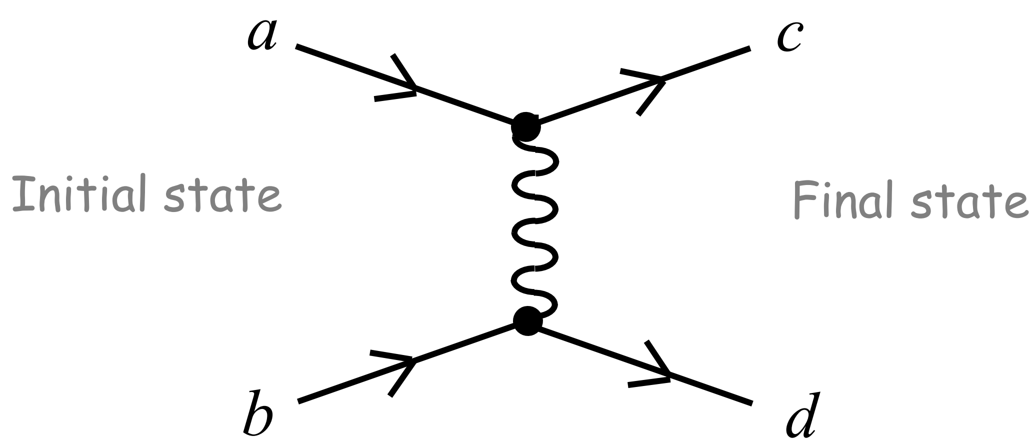
2. Draw the SIMPLEST Feynman diagram using the Standard Model vertices. Bearing in mind:
   - Similar diagrams for particles/antiparticles
   - NEVER have a vertex connecting a LEPTON to a QUARK
   - Only the WEAK CC vertex changes FLAVOUR

     within generations for leptons

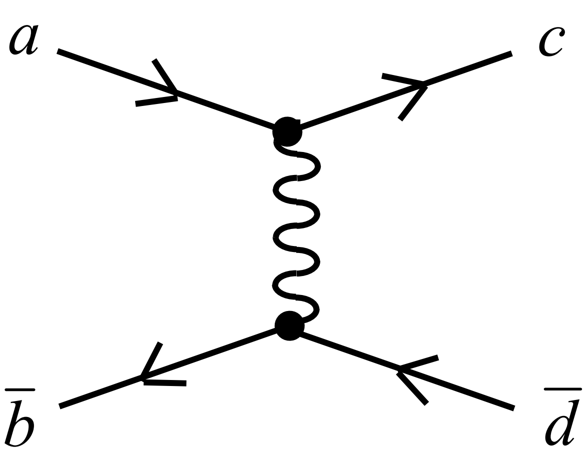
     within/between generations for quarks

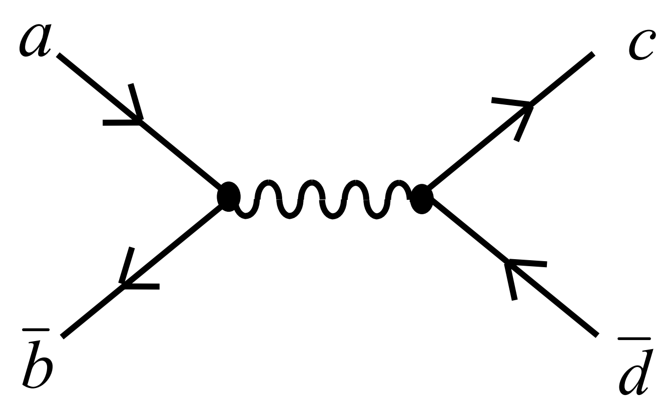
- Particle scattering

- If all particles (or all antiparticles), only SCATTERING diagrams involved e.g. $a+b \rightarrow c+d$




- If particles and antiparticles, can have SCATTERING and/or ANNIHILATION diagrams e.g. $a+\overline{b} \rightarrow c+\overline{d}$



3 Check that the whole system CONSERVES

- Energy, momentum (trivially satisfied for interactions)
- Charge
- Angular Momentum

4 Parity

- CONSERVED in EM/STRONG interaction
- CAN be violated in the WEAK interaction

5 Check SYMMETRY for IDENTICAL particles in the final state

- BOSONS $\psi(1,2) = +\psi(2,1)$
- FERMIONS $\psi(1,2) = -\psi(2,1)$

Finally, a process will occur (in order of preference) via the STRONG, EM and WEAK interaction if steps 1 - 5 are satisfied.

# Examples:

1. $\pi^- + p \rightarrow K^0 + \Lambda$

2. $\nu_\tau + e^- \rightarrow \nu_\tau + e^-$   $\bar{\nu}_\tau + \tau^- \rightarrow \bar{\nu}_\tau + \tau^-$

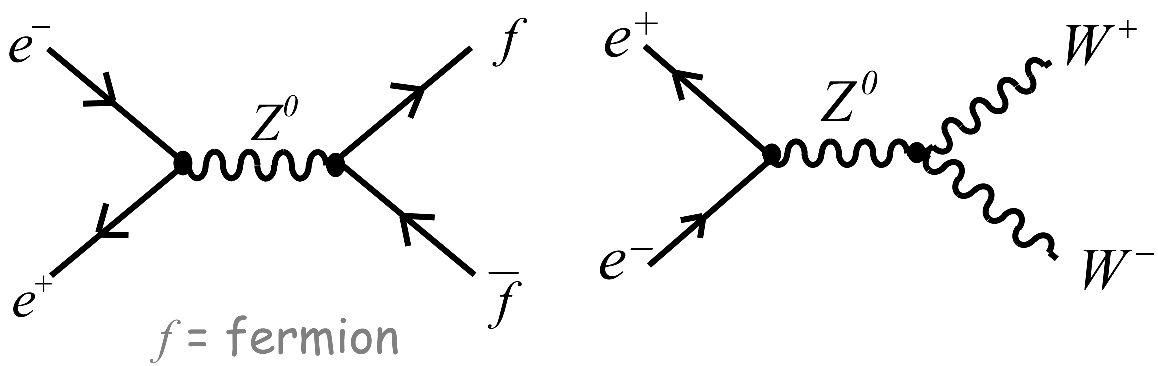
3. $D^+ \rightarrow K^- \pi^+ \pi^+$

4. $\Xi^0 \rightarrow \Sigma^- e^+ \nu_e$

# Experimental Tests of the Standard Model

The Large Electron Positron (LEP) collider at CERN provided precision measurements of the Standard Model (1989-2000).

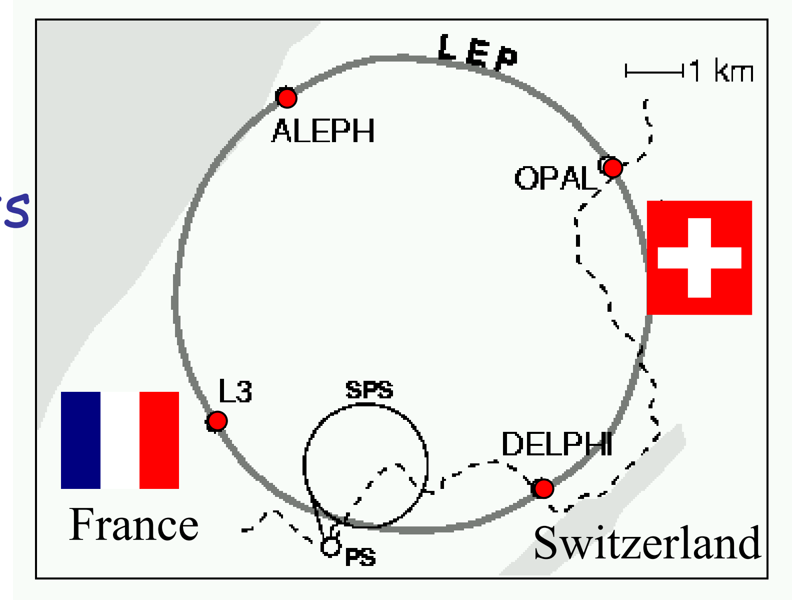
Designed as a $Z^0$ and $W^{\pm}$ boson factory

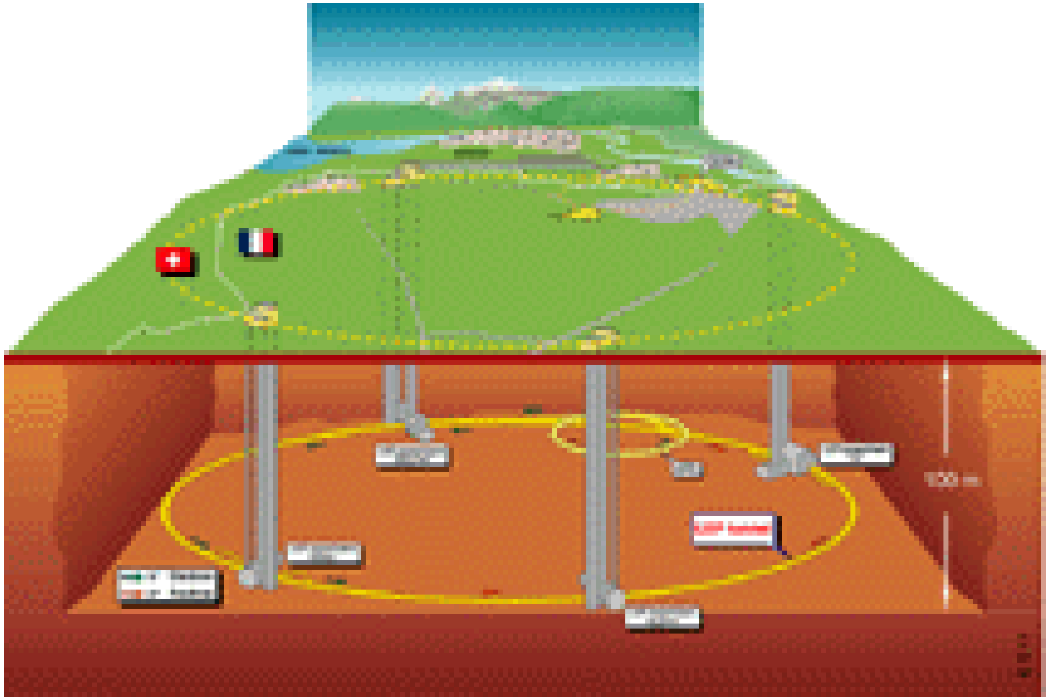


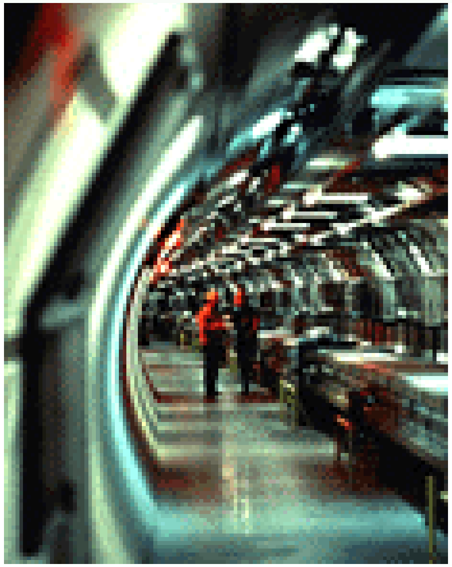

Precise measurements of the properties of $Z^0$ and $W^{\pm}$ bosons provide the most stringent test of our current understanding of particle physics.

# LEP

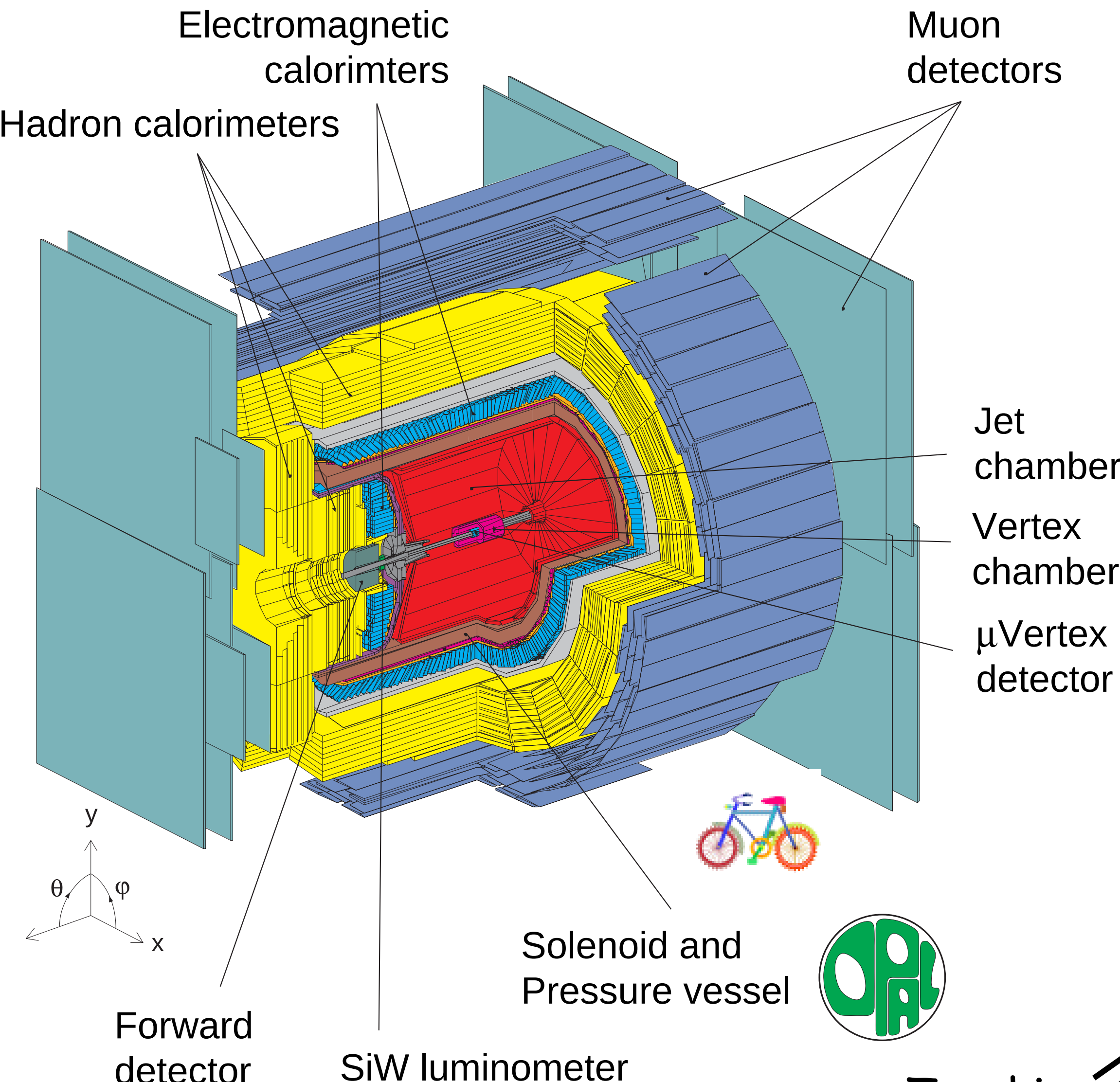
- LEP is the highest energy $e^+e^-$ collider ever built: $\sqrt{s} = 90 - 200\ \text{GeV}$
- Large = 27 km circumference
- 4 experiments combined:
  16,000,000 $Z^0$ and 30,000 $W^\pm$ events



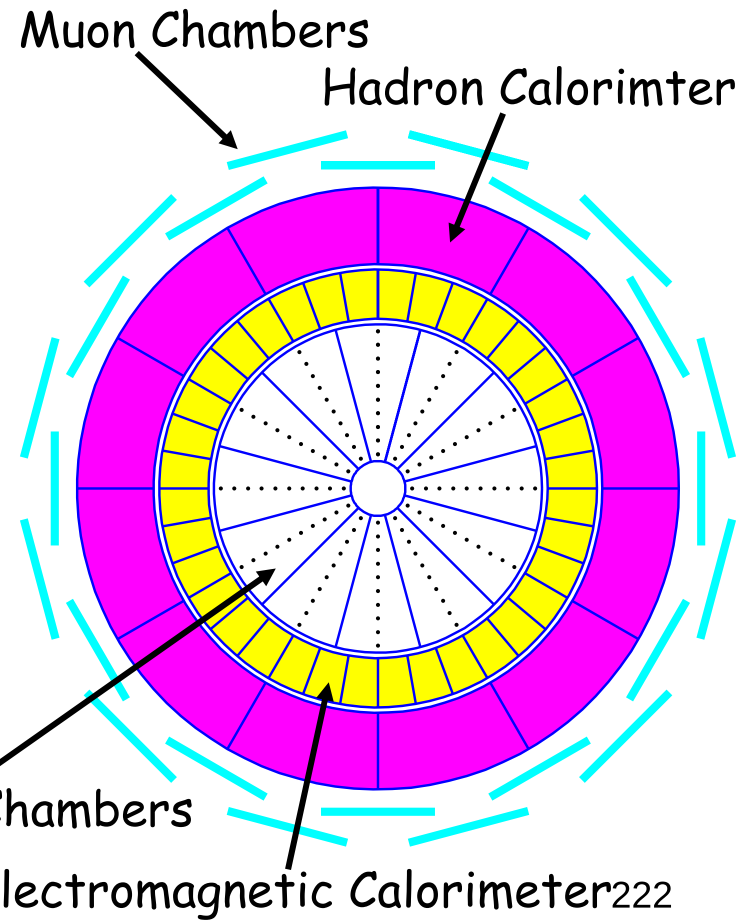


# A LEP Detector: OPAL

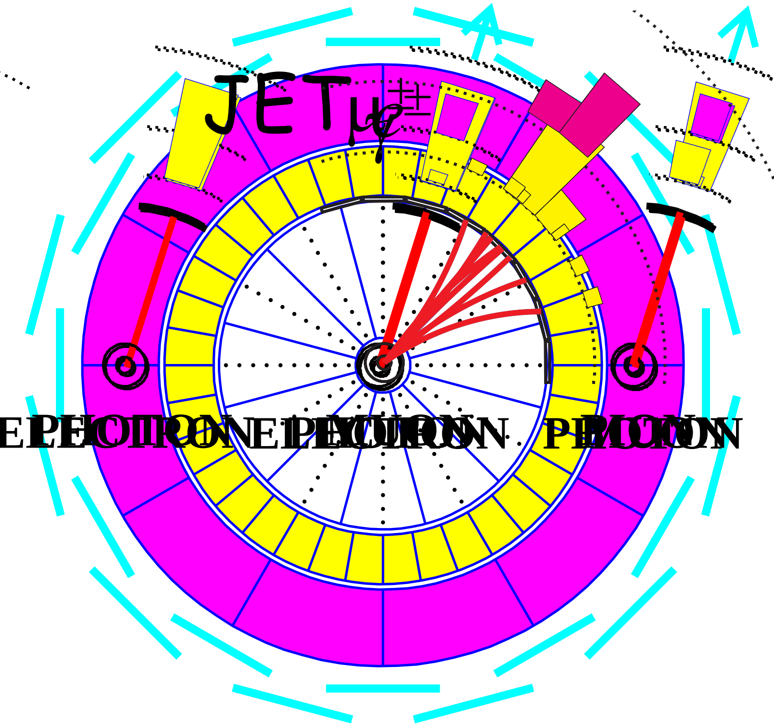



OPAL was one of the 4 experiments at LEP.

Size = 12 m x 12m x 15m



# Particle Identification




Different particles leave different signals in the various detector components allowing almost unambiguous identification.

$e^{\pm}$ : EM energy + track

$\gamma$ : EM energy, no track

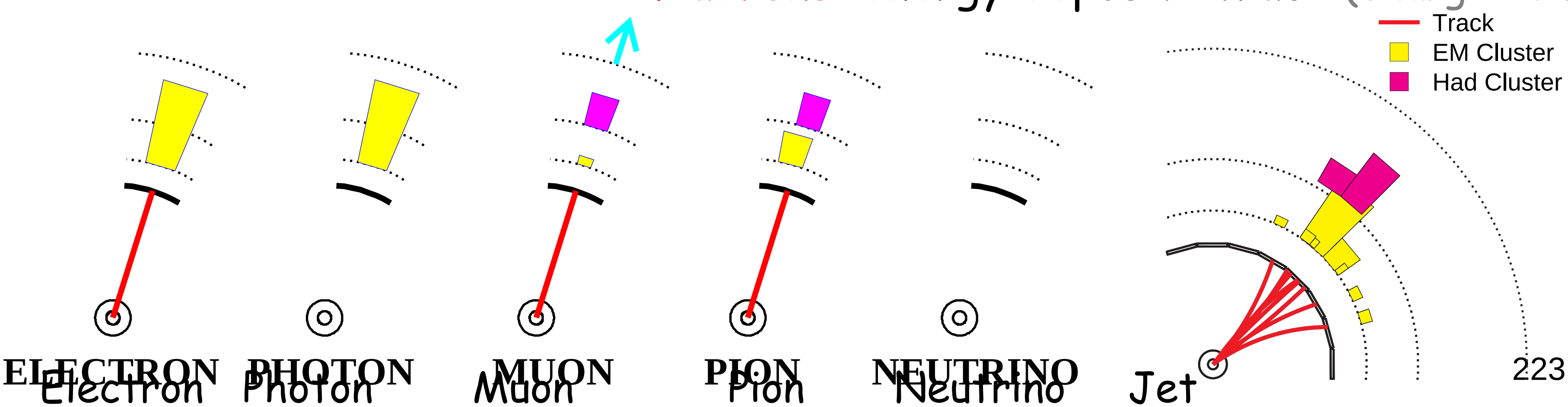
$\mu^{\pm}$ : track + small energy deposit + muon

$\tau^{\pm}$ : decay, observe decay products

$\nu$ : not detected

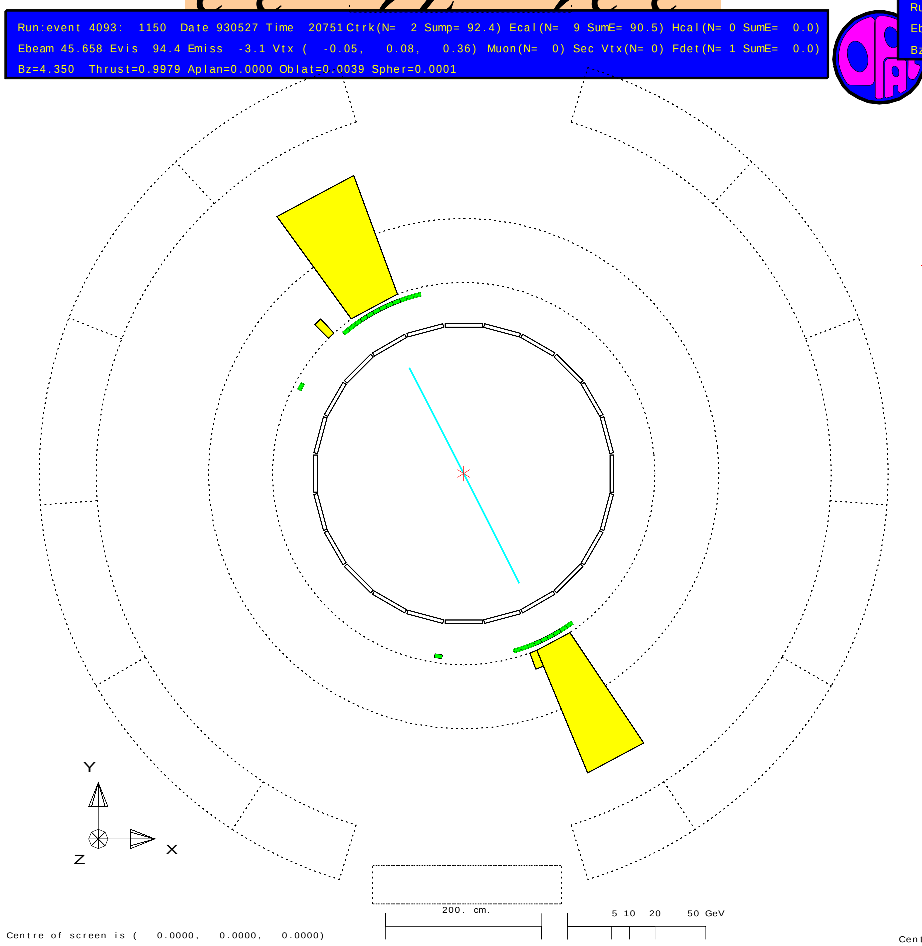
Quarks: seen as jets of hadrons

Hadrons: energy deposit+ track (charged only)

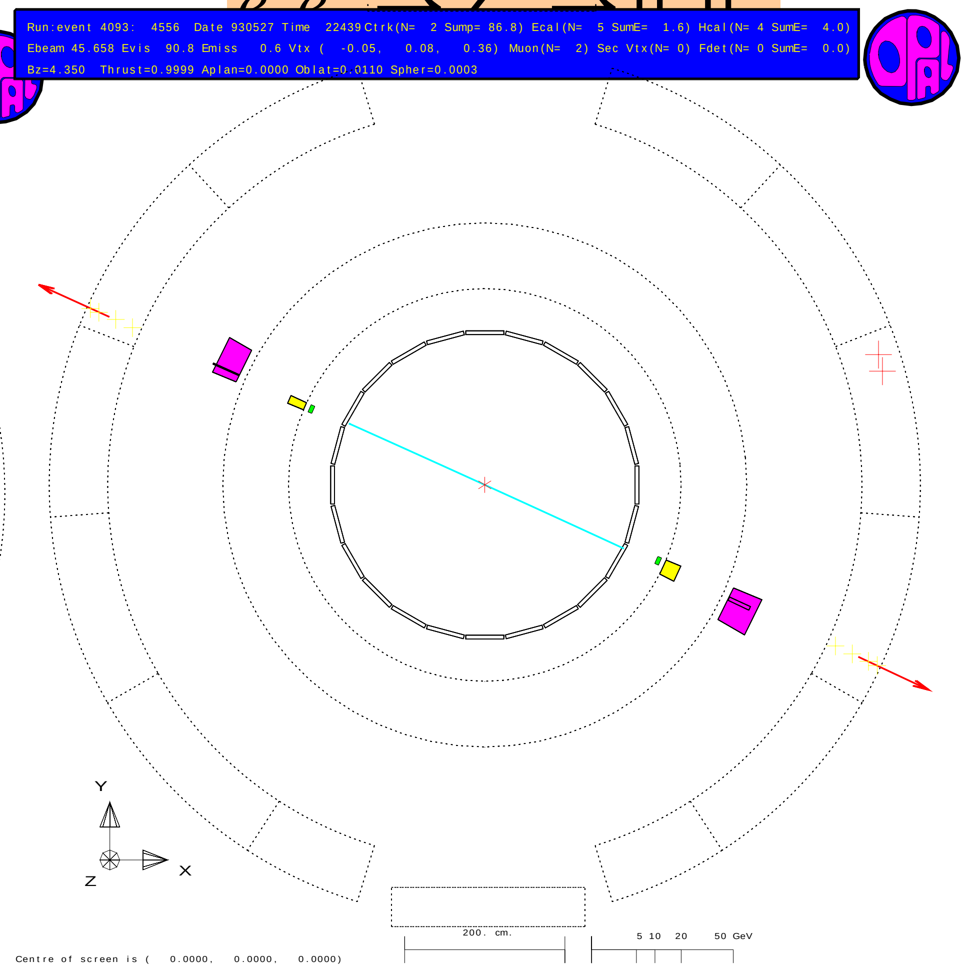


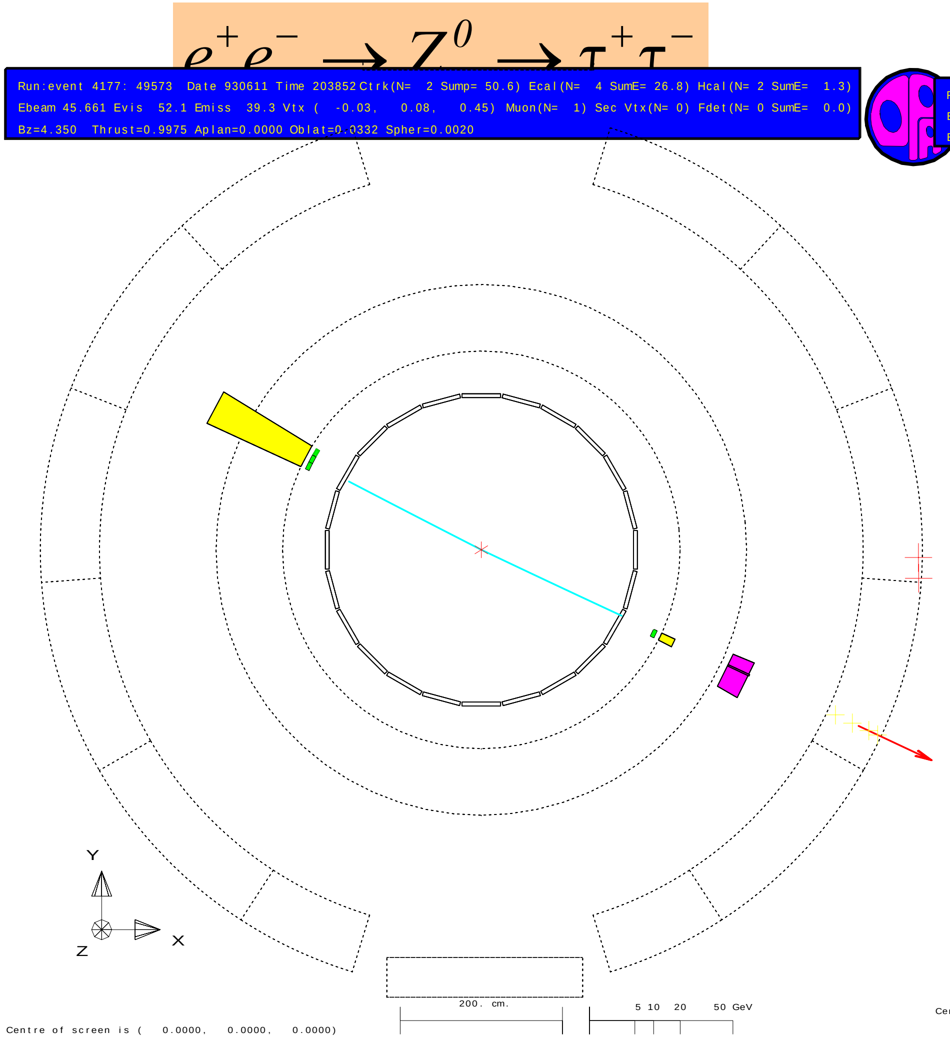
# Typical $e^+e^- \to Z^0$ Events

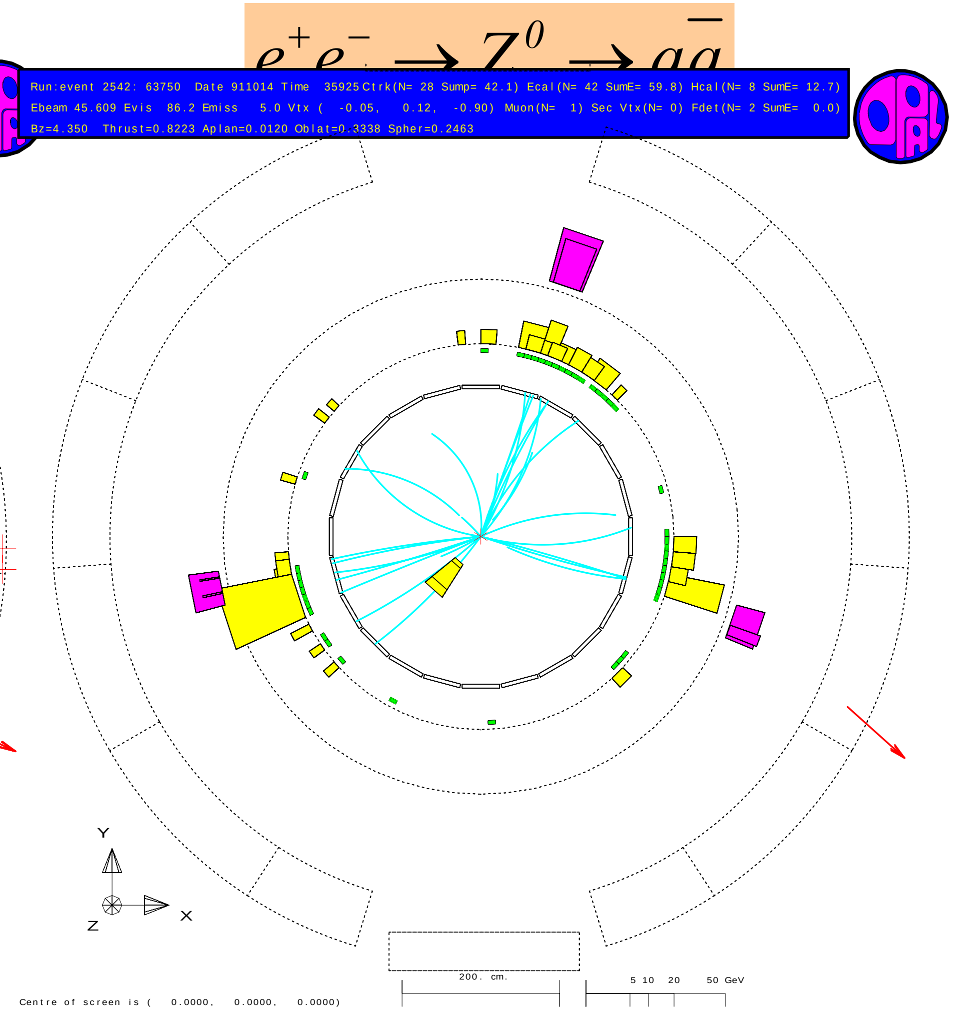
$e^+e^- \to Z^0 \to e^+e^-$




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





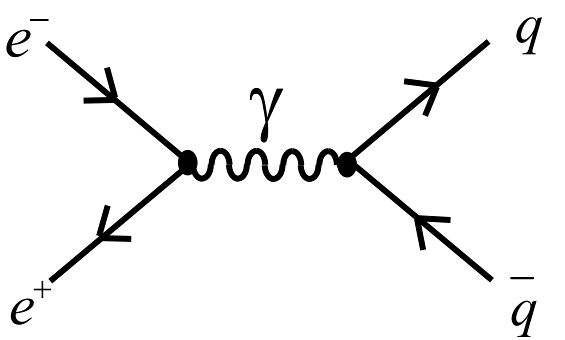

In the $e^+e^- \to Z^0 \to \tau^+\tau^-$ event, the tau leptons decay within the detector (lifetime ~ $10^{-13}$ s).

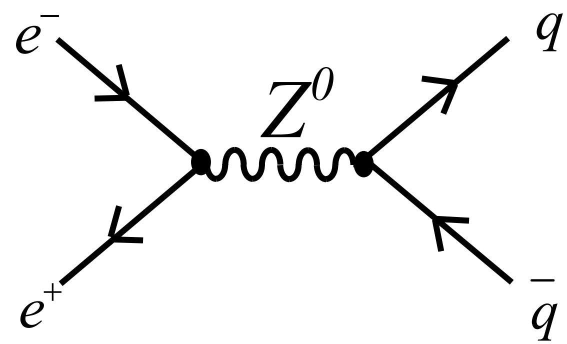
Here, $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ and $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$

# The $Z^0$ Resonance

Consider the process of $e^+e^- \to q\bar{q}$

- Previously, $\sqrt{s} < 50\,\mathrm{GeV}$, only considered an intermediate photon
- At higher energies also have the $Z^0$ exchange diagram (plus $Z^0\gamma$ interference)



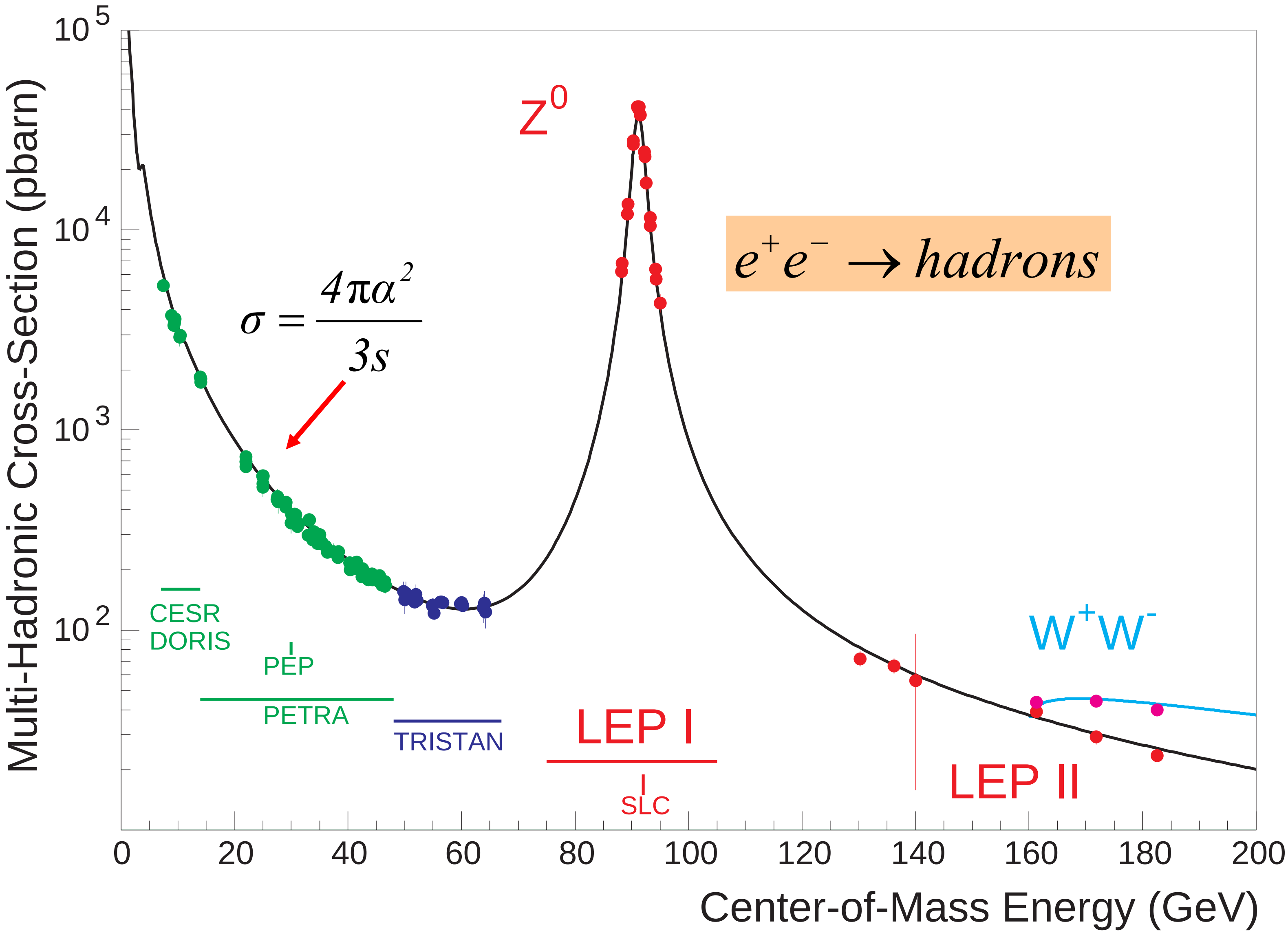

$$\sigma(e^+e^- \to \gamma \to q\bar{q}) = \frac{4\pi\alpha^2}{3s}$$

(see page 92)

- The $Z^0$ is a decaying intermediate massive states (lifetime ~ $10^{-25}$ s)

  $\Rightarrow$ BREIT-WIGNER RESONANCE

- At $\sqrt{s} \sim M_Z$ the $Z^0$ diagram dominates.


Multi-Hadronic Cross-Section (pbarn)
$10^5$
$10^4$
$10^3$
$10^2$
$Z^0$
$e^+e^- \rightarrow hadrons$
$\sigma = \frac{4\pi\alpha^2}{3s}$
CESR
DORIS
PEP
PETRA
TRISTAN
LEP I
SLC
LEP II
$W^+W^-$
0
20
40
60
80
100
120
140
160
180
200
Center-of-Mass Energy (GeV)

BREIT-WIGNER formula for $e^+e^- \rightarrow Z^0 \rightarrow f\bar{f}$ (where $f\bar{f}$ is ANY fermion-antifermion pair)

Centre-of-mass energy $\sqrt{s} = E_{CM} = E_{e^-} + E_{e^+}$

$$\boxed{\sigma\left(e^+e^- \rightarrow Z^0 \rightarrow f\bar{f}\right) = \frac{g\pi}{E_e^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\left(E_{CM} - M_Z\right)^2 + \Gamma_Z^2/4}}$$

with $g = \dfrac{2J_Z + 1}{\left(2J_{e^-} + 1\right)\left(2J_{e^+} + 1\right)} = \dfrac{3}{4}$ $\qquad J_Z = 1;\ J_{e^\pm} = 1/2$

giving

$$\sigma\left(e^+e^- \rightarrow Z^0 \rightarrow f\bar{f}\right) = \frac{3\pi}{4E_e^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\left(\sqrt{s} - M_Z\right)^2 + \Gamma_Z^2/4} = \underline{\frac{3\pi}{s}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\left(\sqrt{s} - M_Z\right)^2 + \Gamma_Z^2/4}}$$

- $\Gamma_Z$ is the TOTAL DECAY WIDTH, i.e. the sum over the partial widths for different decay modes.

$$\boxed{\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{q\bar{q}} + \Gamma_{\nu\bar{\nu}}}$$

At the peak of the resonance $\sqrt{s} = M_Z$ :

$$\boxed{\sigma\left(e^+e^- \to Z^0 \to f\bar{f}\right) = \frac{12\pi}{M_Z^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}}$$

Hence, for ALL fermion/antifermion pairs in the final state

$$\boxed{\sigma\left(e^+e^- \to Z^0 \to anything\right) = \frac{12\pi}{M_Z^2}\frac{\Gamma_{ee}}{\Gamma_Z}} \qquad \Gamma_{f\bar{f}} = \Gamma_Z$$

Compare to the QED cross-section at $\sqrt{s} = M_Z$ $\quad \sigma_{QED} = \dfrac{4\pi\alpha^2}{3s}$

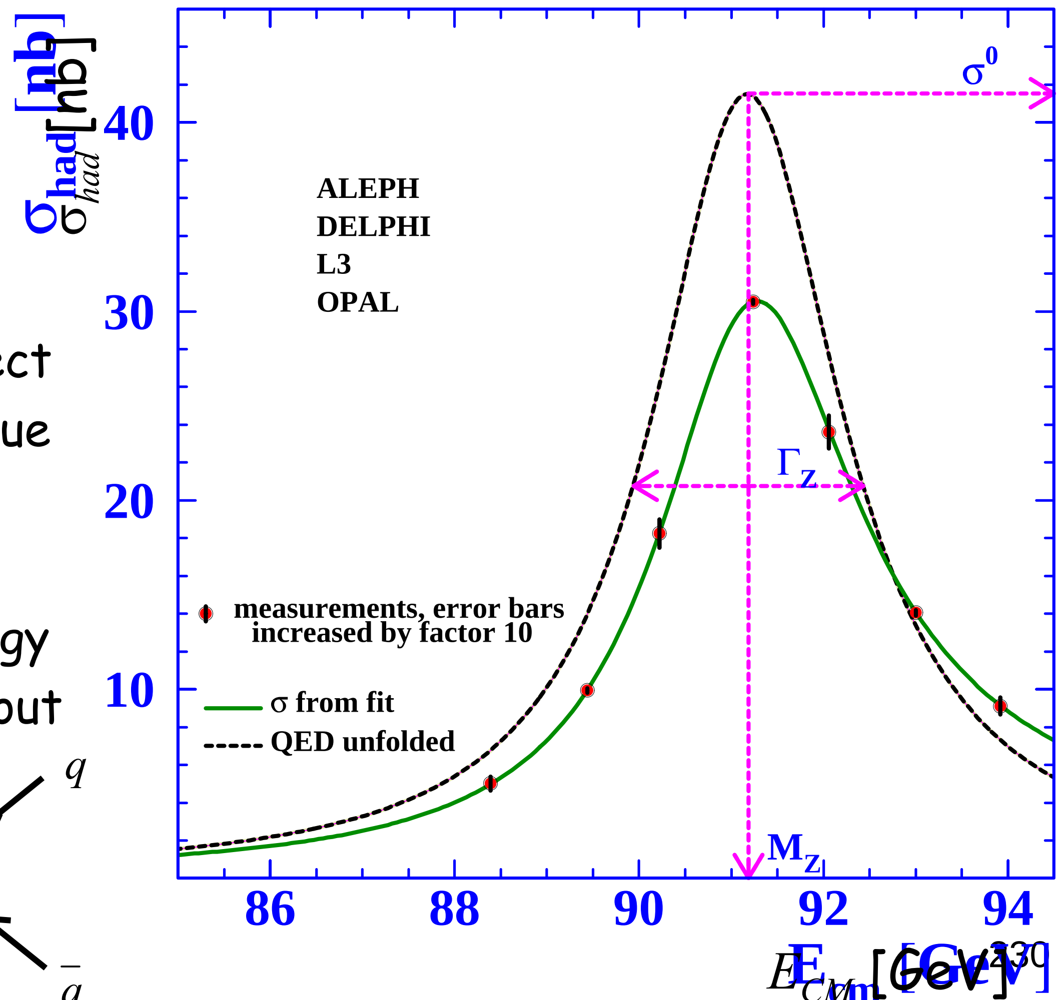
$$\frac{\sigma\left(e^+e^- \to Z^0 \to anything\right)}{\sigma_{QED}} = \frac{9}{\alpha^2}\frac{\Gamma_{ee}}{\Gamma_Z} \approx 5700$$

$\Gamma_{ee} = 85\ \text{MeV}$
$\Gamma_Z = 2.5\ \text{GeV}$
$\alpha = 1/137$

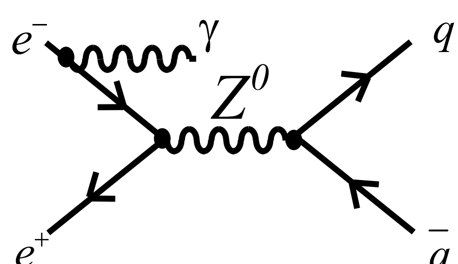
# Measurement of $M_Z$ and $\Gamma_Z$

- Run LEP at various centre-of-mass energies ($\sqrt{s}$) close to the peak of the $Z^0$ resonance and measure $\sigma\left(e^+e^- \to q\bar{q}\right)$
- Determine the parameters of the resonance:

| | |
|---|---|
| Mass of the $Z^0$, | $M_Z$ |
| Total decay width, | $\Gamma_Z$ |
| Peak cross-section, | $\sigma^0$ |




One subtle feature: need to correct measurements for QED effects due to radiation from the $e^+e^-$ beams. This radiation has the effect of reducing the centre-of-mass energy of the $e^+e^-$ collision which smears out the resonance.



## $M_Z$ measured with precision 2 parts in $10^5$

- To achieve this required a detailed understanding of the accelerator and astrophysics! Tidal distortions of the Earth by the Moon cause the rock surrounding LEP to be distorted. The nominal radius of LEP changes by 0.15 mm compared to radius of 4.3 km. This is enough to change the centre-of-mass energy !

- Also need a train timetable ! Leakage currents from the TGV rail via lake Geneva follow the path of least resistance…using LEP as a conductor.

Accounting for these effects (and many others):

$$\boxed{\begin{aligned} M_Z &= (91.1875 \pm 0.0021)\,\mathrm{GeV} \\ \Gamma_Z &= (2.4952 \pm 0.0023)\,\mathrm{GeV} \\ \sigma^0_{q\bar{q}} &= (41.540 \pm 0.037)\,\mathrm{nb} \end{aligned}}$$

# Number of Generations

- Currently know of THREE generations of fermions. $\begin{pmatrix} u & e^- \\ d & \nu_e \end{pmatrix}$ $\begin{pmatrix} c & \mu^- \\ s & \nu_\mu \end{pmatrix}$ $\begin{pmatrix} t & \tau^- \\ b & \nu_\tau \end{pmatrix}$

  Masses of quarks and leptons INCREASE with generation. Neutrinos are ~ massless (?)

- Could there be more generations ? e.g. $\begin{pmatrix} t' & L \\ b' & \nu_L \end{pmatrix}$

- The $Z^0$ boson couples to ALL fermions, including neutrinos. Therefore, the total decay width, $\Gamma_Z$, has contributions from all fermions with $m_f < M_Z/2$

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{q\bar{q}} + \Gamma_{\nu\bar{\nu}}$$

with
$$\Gamma_{\nu\bar{\nu}} = \Gamma_{\nu_e\bar{\nu}_e} + \Gamma_{\nu_\mu\bar{\nu}_\mu} + \Gamma_{\nu_\tau\bar{\nu}_\tau}$$

- If there were a FOURTH generation, it seems likely that the neutrino would be light, and, if so would be produced at LEP

$$e^+e^- \rightarrow Z^0 \rightarrow \nu_L\bar{\nu}_L$$

- The neutrinos would not be observed directly, but could infer their presence from the effect on the $Z^0$ resonance curve.

At the peak of the $Z^0$ resonance $\sqrt{s} = M_Z$

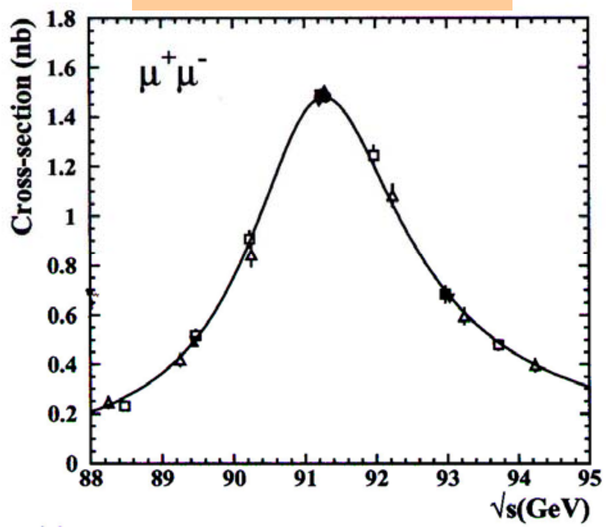
$$\sigma^0_{f\bar{f}} = \frac{12\pi}{M_Z^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$$

A FOURTH generation neutrino would INCREASE the $Z^0$ decay rate and thus INCREASE $\Gamma_Z$. As a result a DECREASE in the measured peak cross-sections for the VISIBLE final states would be observed.

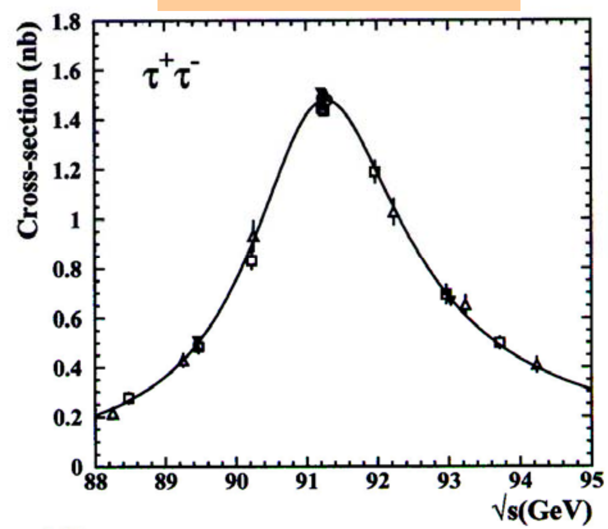
➢ Measure the $e^+e^- \to Z^0 \to f\bar{f}$ cross-sections for all visible decay modes (i.e. all fermions apart from $\nu\bar{\nu}$)

<u>Examples:</u>

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




$e^+e^- \to \tau^+\tau^-$



- Have already measured $M_Z$ and $\Gamma_Z$ from the shape of the Breit-Wigner resonance. Therefore, obtain $\Gamma_{f\bar{f}}$ from the peak cross-sections in each decay mode using

$$\sigma^0_{f\bar{f}} = \frac{12\pi}{M_Z^2} \frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$$

Note, obtain $\Gamma_{ee}$ from

$$\sigma^0_{ee} = \frac{12\pi}{M_Z^2} \frac{\Gamma_{ee}^2}{\Gamma_Z^2}$$

- Can relate the partial widths to the measured TOTAL width (from the resonance curve)

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{q\bar{q}} + N_\nu \Gamma_{\nu\bar{\nu}}$$

where $N_\nu$ is the NUMBER OF NEUTRINO SPECIES and $\Gamma_{\nu\nu}$ is the partial width for a single neutrino species.

The difference between the measured value of $\Gamma_Z$ and the sum of the partial widths for visible final states gives the INVISIBLE WIDTH $N_\nu \Gamma_{\nu\bar{\nu}}$

| | |
|---|---|
| $\Gamma_Z$ | $2494 \pm 4.1$ MeV |
| $\Gamma_{ee}$ | $83.7 \pm 0.2$ MeV |
| $\Gamma_{\mu\mu}$ | $84.0 \pm 0.3$ MeV |
| $\Gamma_{\tau\tau}$ | $83.9 \pm 0.4$ MeV |
| $\Gamma_{q\bar{q}}$ | $1745.3 \pm 3.5$ MeV |
| $N_\nu \Gamma_{\nu\bar{\nu}}$ | $497.3 \pm 3.5$ MeV |

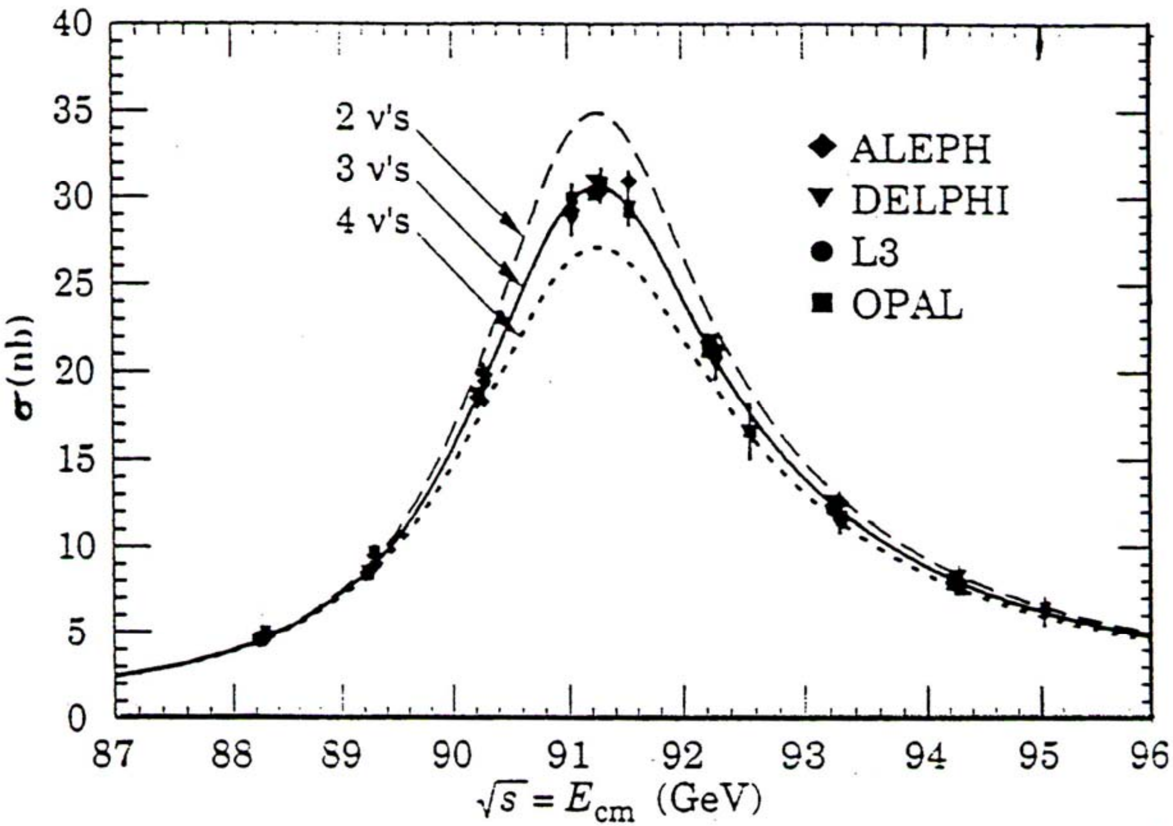
In the Standard Model, calculate $\Gamma_{\nu\bar{\nu}} = 167\ \text{MeV}$

Therefore $$N_\nu = \frac{497.3 \pm 3.5}{167} = \underline{2.98 \pm 0.02}$$

$\Rightarrow$ THREE generations of light neutrinos $\quad m_\nu < M_Z/2$

Most likely that

ONLY 3 GENERATIONS OF QUARKS AND LEPTONS EXIST

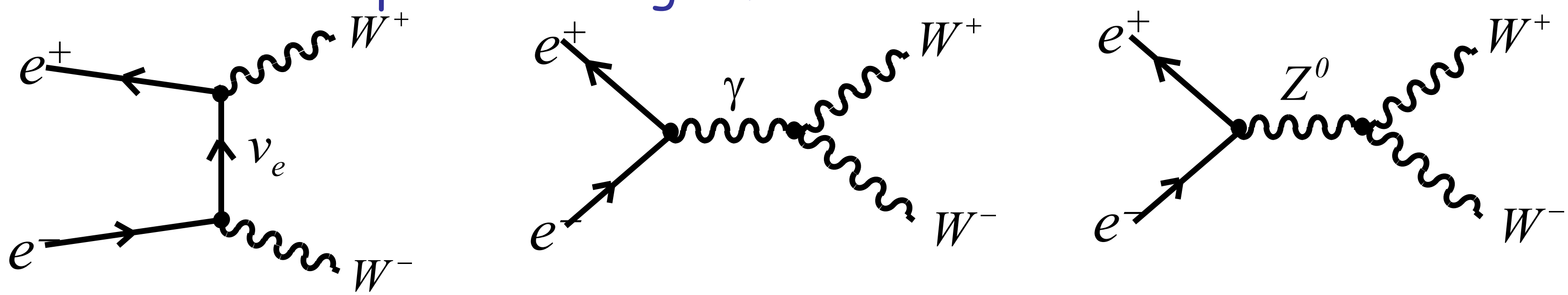



In addition:

- $\Gamma_{ee}, \Gamma_{\mu\mu}, \Gamma_{\tau\tau}$ are consistent $\Rightarrow$ universality of the lepton couplings to the $Z^0$
- $\Gamma_{q\bar{q}}$ is consistent with the expected value which assumes 3 COLOURS – yet more evidence for colour

# $W^+W^-$ at LEP

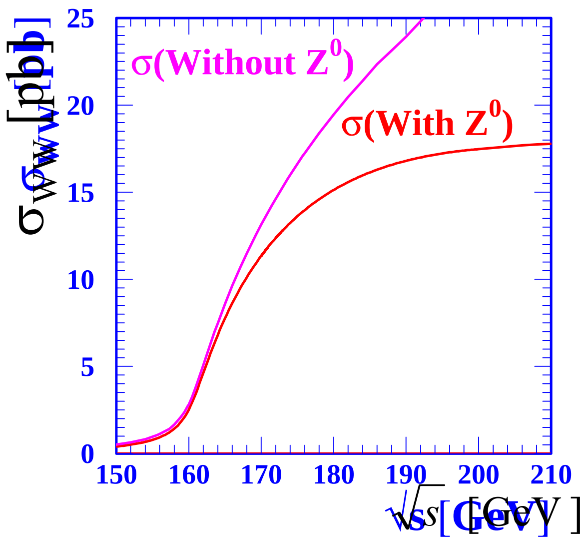
- $e^+e^-$ collisions W bosons are produced in pairs.
- Standard Model 3 possible diagrams:

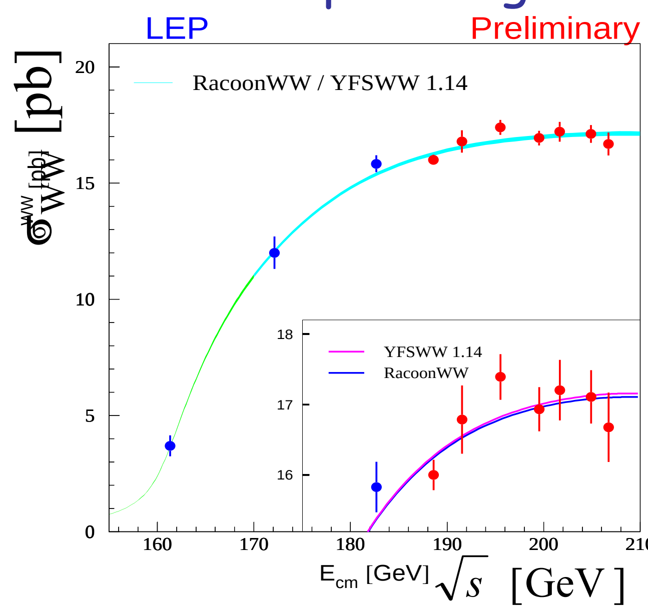



- LEP operated above the threshold for $W^+W^-$ production (1996-2000)

$$\sqrt{s} > 2M_W$$

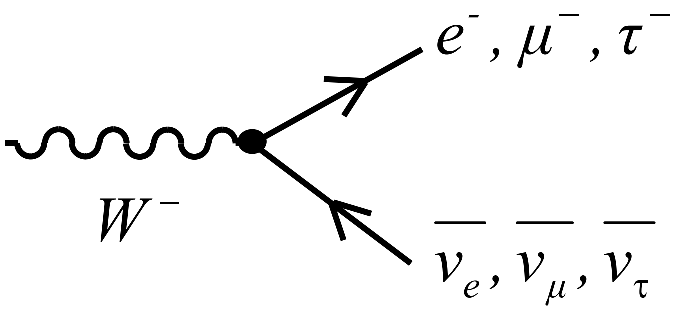
- Cross-section sensitive to the presence of the Triple Gauge Boson vertex $Z^0W^+W^-$

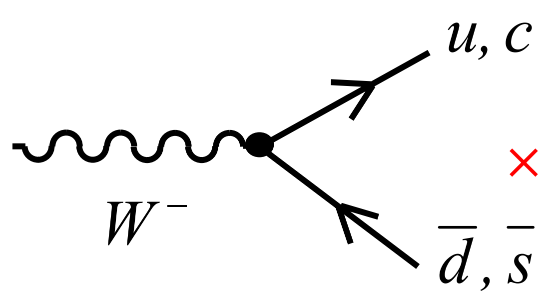


# $W^+W^-$ Decay at LEP

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




$M_W < m_t$

×3 FOR COLOUR

EXPECT (assuming 3 colours):

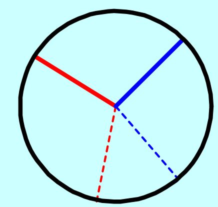
Branching fractions

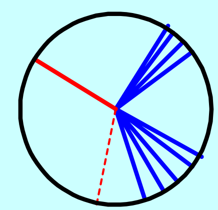
$$B\left(W^{\pm} \rightarrow q\bar{q}\right) = \frac{6}{9} = \frac{2}{3}$$

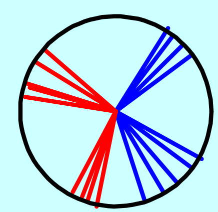
$$B\left(W^{\pm} \rightarrow \ell\nu\right) = \frac{3}{9} = \frac{1}{3}$$

QCD corrections ~ $\left(1 + \alpha_s/\pi\right)$

$$\Rightarrow B\left(W^{\pm} \rightarrow q\bar{q}\right) = \underline{0.675}$$

$W^+W^- \rightarrow \ell\nu\ell\nu$ WW→lνlν  10.5% 10.5 %

$W^+W^- \rightarrow q\bar{q}\ell\nu$ WW→$q\bar{q}$lν  43.9% 43.9 %

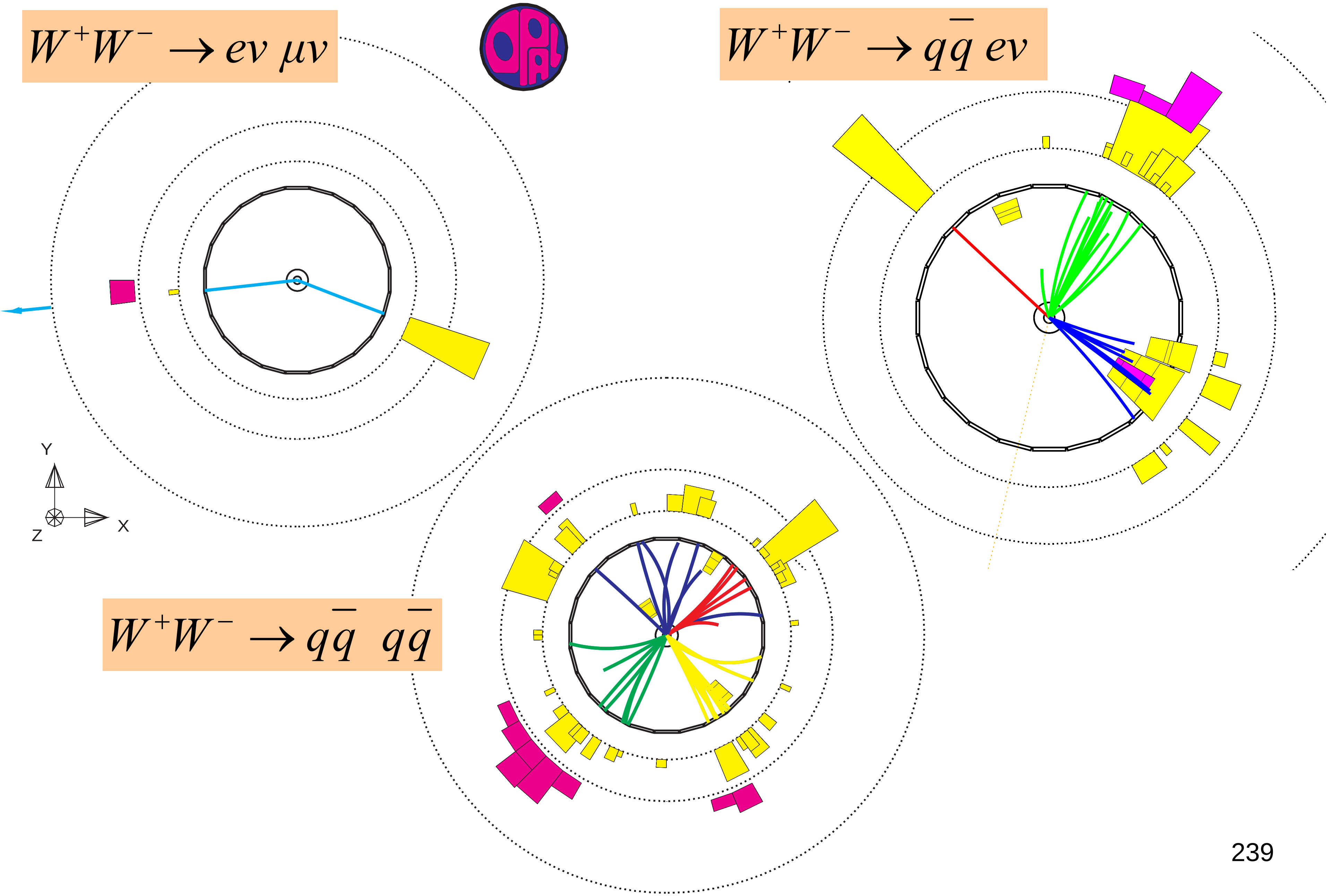
$W^+W^- \rightarrow q\bar{q}q\bar{q}$ WW→$q\bar{q}q\bar{q}$  45.6% 45.6 %

# $W^+W^-$ Events in OPAL

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

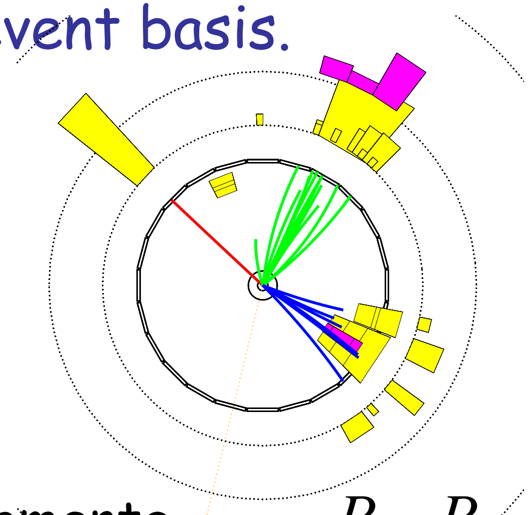
$W^+W^- \to q\bar{q}\ e\nu$

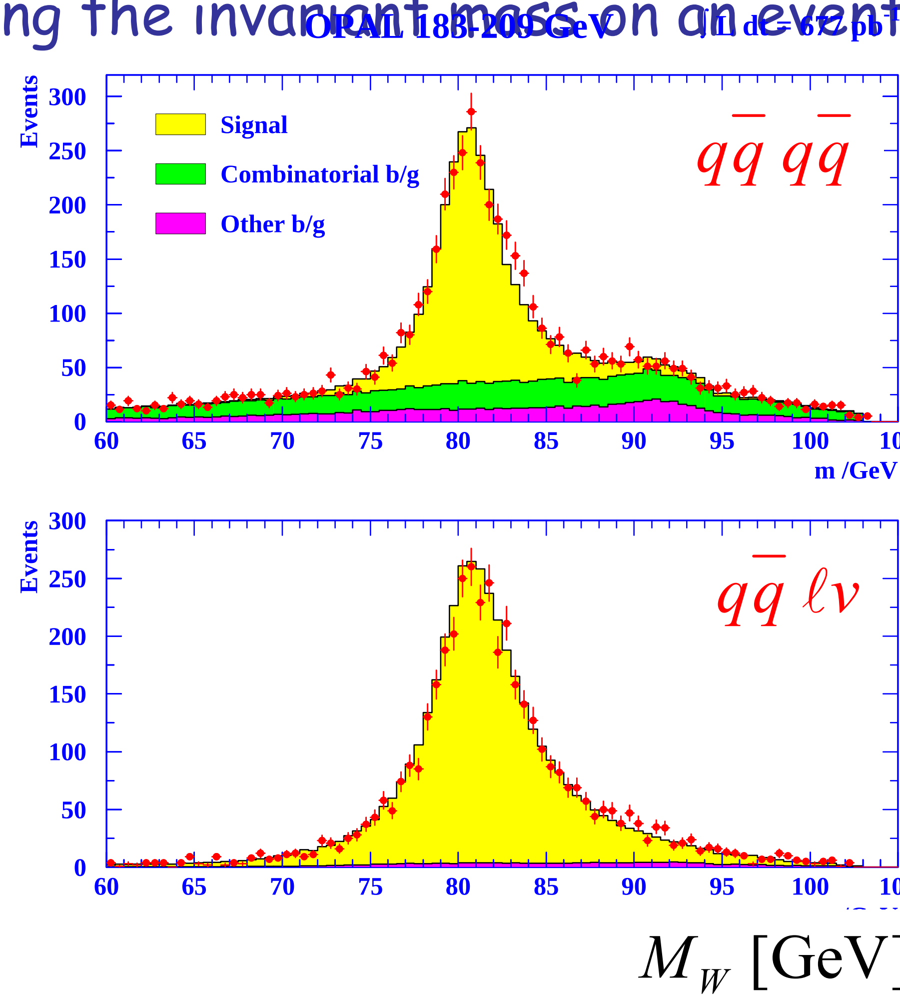
$W^+W^- \to q\bar{q}\ \ q\bar{q}$



# Measurement of $M_W$ and $\Gamma_W$

- Unlike $e^+e^- \to Z^0$, W boson production at LEP is NOT a resonant process
- $M_W$ measured by reconstructing the invariant mass on an event-by-event basis.






4-momenta $P_{q1}, P_{q2}, P_e, P_\nu$

$$M_W = \frac{1}{2}\left(M_{q\bar{q}} + M_{\ell\nu}\right)$$

$$\boxed{\begin{aligned} M_W &= (80.423 \pm 0.038)\,\mathrm{GeV} \\ \Gamma_W &= (2.12 \pm 0.11)\,\mathrm{GeV} \end{aligned}}$$

# W Boson Decay Width

In the Standard Model, the W boson decay width is given by

$$\boxed{\Gamma_W = \frac{g_W^2 M_W}{48\pi} = \frac{G_F M_W^3}{6\sqrt{2}\pi}}$$

μ-decay: $G_F = 1.166\times10^{-5}\ \mathrm{GeV}^{-2}$ LEP: $M_W = (80.423 \pm 0.038)\,\mathrm{GeV}.$

Therefore, predict partial width: $\Rightarrow$ $\Gamma(W^- \to e^-\bar{\nu}_e) = 227\ \mathrm{MeV}$

Total width is the sum over all partial widths:

$$W^- \to e^-\bar{\nu}_e,\ \mu^-\bar{\nu}_\mu,\ \tau^-\bar{\nu}_\tau$$

$$W^- \to d\bar{u},\ s\bar{c}$$ ×3 FOR COLOUR

IF the W coupling to leptons and quarks is EQUAL, and there are 3 colours:

$$\Gamma = \sum_i \Gamma_i = (3 + 2\times3)\,\Gamma(W^- \to e^-\bar{\nu}_e) \approx 2.1\,\mathrm{GeV}$$

Compare with measured value (LEP): $\Gamma_W = (2.12 \pm 0.11)\,\mathrm{GeV}$

- Universal coupling constant
- Yet more evidence for colour !

# Summary

Now have 5 precise measurements of fundamental parameters of the Standard Model

$$\alpha_{em} = 1/(137.03599976 \pm 0.00000050)$$
$$G_F = (1.16632 \pm 0.00002) \times 10^{-5}\ \mathrm{GeV}^{-2}$$
$$M_W = (80.423 \pm 0.038)\,\mathrm{GeV}$$
$$M_Z = (91.1875 \pm 0.0021)\,\mathrm{GeV}$$
$$sin^2\vartheta_W = 0.23143 \pm 0.00015$$

(at $q^2$=0)

In the Standard Model, ONLY 3 are independent.

Their consistency is an incredibly powerful test of the Standard Model of Electroweak Interactions !