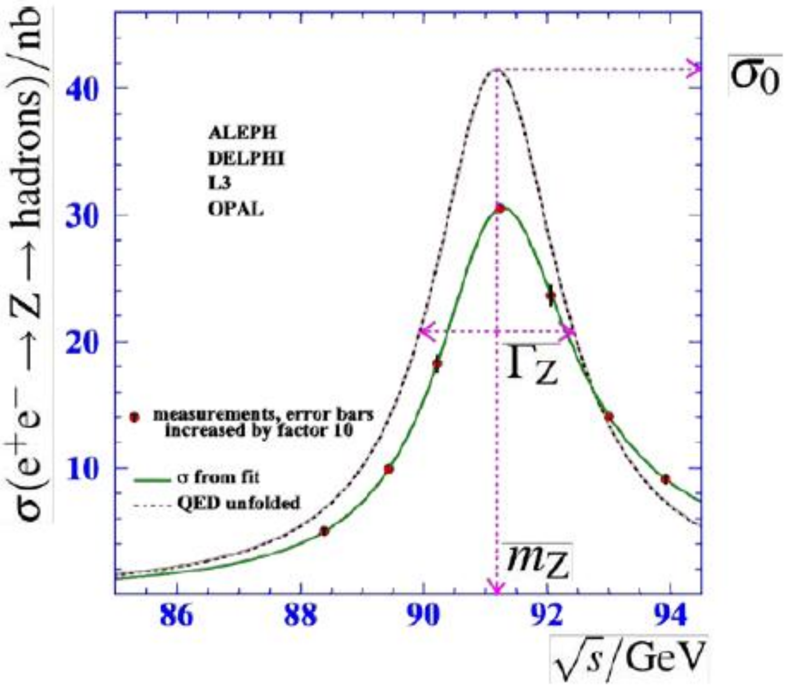
Elementary Particle Physics: theory and experiments

Precision Tests of the Standard Model



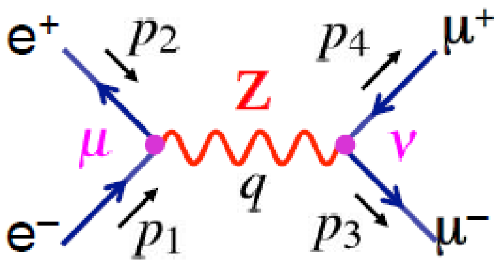
Follow the course/slides from M. A. Thomson lectures at Cambridge University

Prof. dr hab. Elżbieta Richter-Wąs

The Z Resonance

★ Want to calculate the cross-section for $e^+e^- \to Z \to \mu^+\mu^-$

- Feynman rules for the diagram below give:



e⁺e⁻ vertex: $\overline{v}(p_2)\cdot -ig_Z\gamma^\mu \frac{1}{2}(c_V^e - c_A^e\gamma^5)\cdot u(p_1)$

Z propagator: $\dfrac{-ig_{\mu\nu}}{q^2 - m_Z^2}$

μ⁺μ⁻ vertex: $\overline{u}(p_3)\cdot -ig_Z\gamma^\nu \frac{1}{2}(c_V^\mu - c_A^\mu\gamma^5)\cdot v(p_4)$

➡ $$-iM_{fi} = [\overline{v}(p_2)\cdot -ig_Z\gamma^\mu \tfrac{1}{2}(c_V^e - c_A^e\gamma^5)\cdot u(p_1)].\frac{-ig_{\mu\nu}}{q^2 - m_Z^2}.[\overline{u}(p_3)\cdot -ig_Z\gamma^\nu \tfrac{1}{2}(c_V^\mu - c_A^\mu\gamma^5)\cdot v(p_4)]$$

➡ $$M_{fi} = -\frac{g_Z^2}{q^2 - m_Z^2} g_{\mu\nu}[\overline{v}(p_2)\gamma^\mu \tfrac{1}{2}(c_V^e - c_A^e\gamma^5)\cdot u(p_1)].[\overline{u}(p_3)\gamma^\nu \tfrac{1}{2}(c_V^\mu - c_A^\mu\gamma^5)\cdot v(p_4)]$$

★ Convenient to work in terms of helicity states by explicitly using the Z coupling to LH and RH chiral states (ultra-relativistic limit so helicity = chirality)

$$\tfrac{1}{2}(c_V - c_A\gamma^5) = c_L\tfrac{1}{2}(1-\gamma^5) + c_R\tfrac{1}{2}(1+\gamma^5)$$

LH and RH projections operators

hence $c_V = (c_L + c_R), \;\; c_A = (c_L - c_R)$

and $\frac{1}{2}(c_V - c_A\gamma^5) \;=\; \frac{1}{2}(c_L + c_R - (c_L - c_R)\gamma^5)$

$= c_L\frac{1}{2}(1-\gamma^5) + c_R\frac{1}{2}(1+\gamma^5)$

with $c_L = \frac{1}{2}(c_V + c_A), \;\; c_R = \frac{1}{2}(c_V - c_A)$

★ Rewriting the matrix element in terms of LH and RH couplings:

$$M_{fi} = -\frac{g_Z^2}{q^2 - m_Z^2} g_{\mu\nu}[c_L^e \overline{v}(p_2)\gamma^\mu \tfrac{1}{2}(1-\gamma^5)u(p_1) + c_R^e \overline{v}(p_2)\gamma^\mu \tfrac{1}{2}(1+\gamma^5)u(p_1)]$$
$$\times[c_L^\mu \overline{u}(p_3)\gamma^\nu \tfrac{1}{2}(1-\gamma^5)v(p_4) + c_R^\mu \overline{u}(p_3)\gamma^\nu \tfrac{1}{2}(1+\gamma^5)v(p_4)]$$

★ Apply projection operators remembering that in the ultra-relativistic limit

$\frac{1}{2}(1-\gamma^5)u = u_\downarrow; \quad \frac{1}{2}(1+\gamma^5)u = u_\uparrow, \quad \frac{1}{2}(1-\gamma^5)v = v_\uparrow, \quad \frac{1}{2}(1+\gamma^5)v = v_\downarrow$

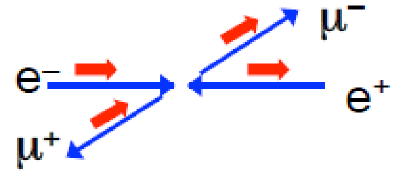
⇨
$$M_{fi} = -\frac{g_Z}{q^2 - m_Z^2} g_{\mu\nu}[c_L^e \overline{v}(p_2)\gamma^\mu u_\downarrow(p_1) + c_R^e \overline{v}(p_2)\gamma^\mu u_\uparrow(p_1)]$$
$$\times[c_L^\mu \overline{u}(p_3)\gamma^\nu v_\uparrow(p_4) + c_R^\mu \overline{u}(p_3)\gamma^\nu v_\downarrow(p_4)]$$

★ For a combination of **V** and **A** currents, $\overline{u}_\uparrow\gamma^\mu v_\uparrow = 0$ etc, gives four orthogonal contributions

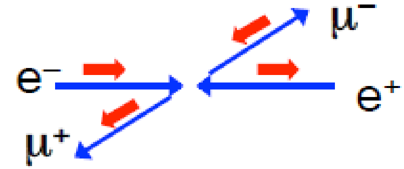
⇨
$$-\frac{g_Z^2}{q^2 - m_Z^2} g_{\mu\nu}[c_L^e \overline{v}_\uparrow(p_2)\gamma^\mu u_\downarrow(p_1) + c_R^e \overline{v}_\downarrow(p_2)\gamma^\mu u_\uparrow(p_1)]$$
$$\times[c_L^\mu \overline{u}_\downarrow(p_3)\gamma^\nu v_\uparrow(p_4) + c_R^\mu \overline{u}_\uparrow(p_3)\gamma^\nu v_\downarrow(p_4)]$$

★ **Sum of 4 terms**

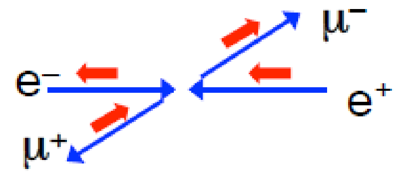
$$M_{RR} = -\frac{g_Z^2}{q^2 - m_Z^2} c_R^e c_R^\mu g_{\mu\nu} [\overline{v}_\downarrow(p_2)\gamma^\mu u_\uparrow(p_1)][\overline{u}_\uparrow(p_3)\gamma^\nu v_\downarrow(p_4)]$$



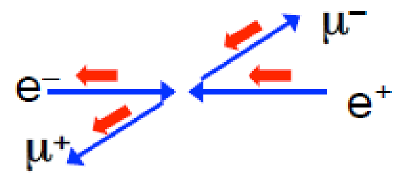
$$M_{RL} = -\frac{g_Z^2}{q^2 - m_Z^2} c_R^e c_L^\mu g_{\mu\nu} [\overline{v}_\downarrow(p_2)\gamma^\mu u_\uparrow(p_1)][\overline{u}_\downarrow(p_3)\gamma^\nu v_\uparrow(p_4)]$$



$$M_{LR} = -\frac{g_Z^2}{q^2 - m_Z^2} c_L^e c_R^\mu g_{\mu\nu} [\overline{v}_\uparrow(p_2)\gamma^\mu u_\downarrow(p_1)][\overline{u}_\uparrow(p_3)\gamma^\nu v_\downarrow(p_4)]$$



$$M_{LL} = -\frac{g_Z^2}{q^2 - m_Z^2} c_L^e c_L^\mu g_{\mu\nu} [\overline{v}_\uparrow(p_2)\gamma^\mu u_\downarrow(p_1)][\overline{u}_\downarrow(p_3)\gamma^\nu v_\uparrow(p_4)]$$



Remember: the L/R refer to the helicities of the initial/final state particles

★ **Fortunately we have calculated these terms before when considering** $e^+e^- \to \gamma \to \mu^+\mu^-$ **giving:**

$$[\overline{v}_\downarrow(p_2)\gamma^\mu u_\uparrow(p_1)][\overline{u}_\uparrow(p_3)\gamma^\nu v_\downarrow(p_4)] = s(1+\cos\theta)$$ **etc.**

★ Applying the QED results to the Z exchange with gives:

$$\frac{e^2}{q^2} \to \frac{g_Z^2}{q^2 - m_Z^2} c^e c^\mu$$

where $q^2 = s = 4E_e^2$

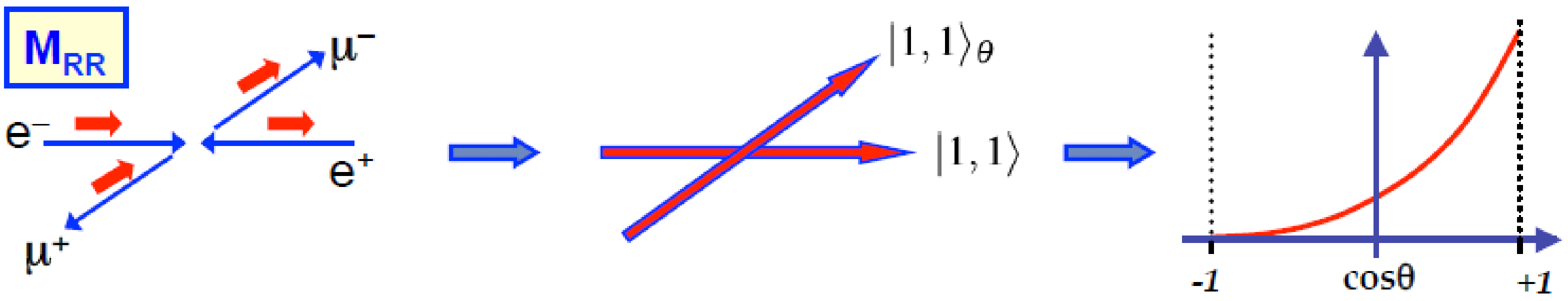
$$|M_{RR}|^2 = s^2 \left|\frac{g_Z^2}{s - m_Z^2}\right|^2 (c_R^e)^2 (c_R^\mu)^2 (1+\cos\theta)^2$$

$$|M_{RL}|^2 = s^2 \left|\frac{g_Z^2}{s - m_Z^2}\right|^2 (c_R^e)^2 (c_L^\mu)^2 (1-\cos\theta)^2$$

$$|M_{LR}|^2 = s^2 \left|\frac{g_Z^2}{s - m_Z^2}\right|^2 (c_L^e)^2 (c_R^\mu)^2 (1-\cos\theta)^2$$

$$|M_{LL}|^2 = s^2 \left|\frac{g_Z^2}{s - m_Z^2}\right|^2 (c_L^e)^2 (c_L^\mu)^2 (1+\cos\theta)^2$$

★ As before, the angular dependence of the matrix elements can be understood in terms of the spins of the incoming and outgoing particles e.g.



The Breit-Wigner Resonance

★ Need to consider carefully the propagator term $1/(s-m_Z^2)$ which diverges when the C.o.M. energy is equal to the rest mass of the Z boson

★ To do this need to account for the fact that the Z boson is an unstable particle

- For a stable particle at rest the time development of the wave-function is:

$$\psi \sim e^{-imt}$$

- For an unstable particle this must be modified to

$$\psi \sim e^{-imt}e^{-\Gamma t/2}$$

so that the particle probability decays away exponentially

$$\psi^*\psi \sim e^{-\Gamma t} = e^{-t/\tau} \quad \text{with} \quad \tau = \frac{1}{\Gamma_Z}$$

- Equivalent to making the replacement

$$m \rightarrow m - i\Gamma/2$$

★ In the Z boson propagator make the substitution:

$$m_Z \rightarrow m_Z - i\Gamma_Z/2$$

★ Which gives:

$$(s-m_Z^2) \longrightarrow [s-(m_Z - i\Gamma_Z/2)^2] = s - m_Z^2 + im_Z\Gamma_Z + \tfrac{1}{4}\Gamma_Z^2 \approx s - m_Z^2 + im_Z\Gamma_Z$$

where it has been assumed that $\Gamma_Z \ll m_Z$

★ Which gives

$$\left|\frac{1}{s-m_Z^2}\right|^2 \rightarrow \left|\frac{1}{s-m_Z^2+im_Z\Gamma_Z}\right|^2 = \frac{1}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}$$

- And the Matrix elements become

$$|M_{RR}|^2 = \frac{g_Z^4 s^2}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}(c_R^e)^2(c_R^\mu)^2(1+\cos\theta)^2 \qquad \text{etc.}$$

- In the limit where initial and final state particle mass can be neglected:

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}|M_{fi}|^2$$

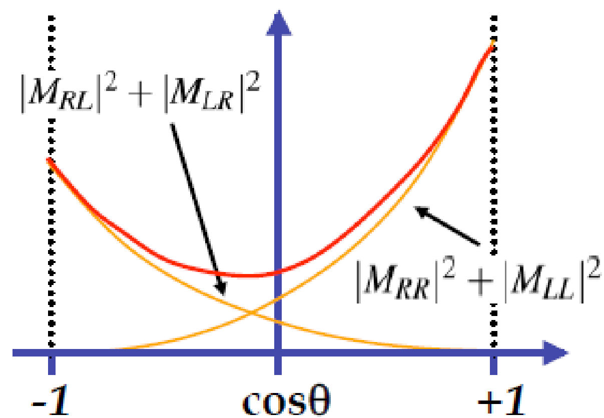
- Giving:

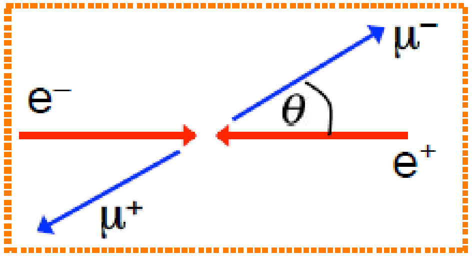
$$\frac{d\sigma_{RR}}{d\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}(c_R^e)^2(c_R^\mu)^2(1+\cos\theta)^2$$

$$\frac{d\sigma_{LL}}{d\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}(c_L^e)^2(c_L^\mu)^2(1+\cos\theta)^2$$

$$\frac{d\sigma_{LR}}{d\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}(c_L^e)^2(c_R^\mu)^2(1-\cos\theta)^2$$

$$\frac{d\sigma_{RL}}{d\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}(c_L^e)^2(c_R^\mu)^2(1-\cos\theta)^2$$





- Because $|M_{LL}|^2 + |M_{RR}|^2 \neq |M_{LR}|^2 + |M_{RL}|^2$, the differential cross section is asymmetric, i.e. parity violation (although not maximal as was the case for the W boson).

Cross section with unpolarised beams

★ To calculate the total cross section need to sum over all matrix elements and **average** over the **initial spin states**. Here, assuming unpolarized beams (i.e. both e^+ and both e^- spin states equally likely) there a four combinations of initial electron/positron spins, so

$$\langle |M_{fi}|^2 \rangle = \frac{1}{2} \cdot \frac{1}{2} \cdot (|M_{RR}|^2 + |M_{LL}|^2 + |M_{LR}|^2 + |M_{RL}|^2)$$

$$= \tfrac{1}{2} \cdot \tfrac{1}{2} \frac{g_Z^4 s^2}{(s-m_Z^2)^2 + m_Z^2 \Gamma_Z^2} \times \{ [(c_R^e)^2 (c_R^\mu)^2 + (c_L^e)^2 (c_L^2)^2](1+\cos\theta)^2 + [(c_L^e)^2 (c_R^\mu)^2 + (c_R^e)^2 (c_L^2)^2](1-\cos\theta)^2 \}$$

★ The part of the expression {…} can be rearranged:

$$\{\ldots\} = [(c_R^e)^2 + (c_L^e)^2][(c_R^\mu)^2 + (c_L^\mu)^2](1+\cos^2\theta) + 2[(c_R^e)^2 - (c_L^e)^2][(c_R^\mu)^2 - (c_L^\mu)^2]\cos\theta \qquad (1)$$

and using $c_V^2 + c_A^2 = 2(c_L^2 + c_R^2)$ and $c_V c_A = c_L^2 + c_R^2$

$$\{\ldots\} = \frac{1}{4}[(c_V^e)^2 + (c_A^e)^2][(c_V^\mu)^2 + (c_A^\mu)^2](1+\cos^2\theta) + 2 c_V^e c_A^e c_V^\mu c_A^\mu \cos\theta$$

★ Hence the complete expression for the unpolarized differential cross section is:

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\langle|M_{fi}|^2\rangle$$

$$= \frac{1}{64\pi^2}\cdot\frac{1}{4}\cdot\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}\times$$

$$\left\{\tfrac{1}{4}[(c_V^e)^2+(c_A^e)^2][(c_V^\mu)^2+(c_A^\mu)^2](1+\cos^2\theta)+2c_V^e c_A^e c_V^\mu c_A^\mu\cos\theta\right\}$$

★ Integrating over solid angle $d\Omega = d\phi d(\cos\theta) = 2\pi d(\cos\theta)$

$\int_{-1}^{+1}(1+\cos^2\theta)d(\cos\theta) = \int_{-1}^{+1}(1+x^2)dx = \frac{8}{3}$ and $\int_{-1}^{+1}\cos\theta d(\cos\theta) = 0$

$$\sigma_{e^+e^-\to Z\to\mu^+\mu^-} = \frac{1}{192\pi}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}\left[(c_V^e)^2+(c_A^e)^2\right]\left[(c_V^\mu)^2+(c_A^\mu)^2\right]$$

★ Note: the total cross section is proportional to the sums of the squares of the vector- and axial-vector couplings of the initial and final state fermions

$$(c_V^f)^2+(c_A^f)^2$$

Connection to the Breit-Wigner Formula

★ Can write the total cross section

$$\sigma_{e^+e^-\to Z\to\mu^+\mu^-} = \frac{1}{192\pi}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}\left[(c_V^e)^2+(c_A^e)^2\right]\left[(c_V^\mu)^2+(c_A^\mu)^2\right]$$

in terms of the Z boson decay rates (partial widths)

$$\Gamma(Z\to e^+e^-) = \frac{g_Z^2 m_Z}{48\pi}\left[(c_V^e)^2+(c_A^e)^2\right] \quad \text{and} \quad \Gamma(Z\to\mu^+\mu^-) = \frac{g_Z^2 m_Z}{48\pi}\left[(c_V^\mu)^2+(c_A^\mu)^2\right]$$

$$\Rightarrow \quad \sigma = \frac{12\pi}{m_Z^2}\frac{s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}\Gamma(Z\to e^+e^-)\Gamma(Z\to\mu^+\mu^-)$$

★ Writing the partial widths as $\Gamma_{ee}=\Gamma(Z\to e^+e^-)$ etc., the total cross section can be written

$$\sigma(e^+e^-\to Z\to f\bar{f}) = \frac{12\pi}{m_Z^2}\frac{s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}\Gamma_{ee}\Gamma_{ff} \qquad (2)$$

where f is the final state fermion flavour:

Electroweak Measurements at LEP

★ The Large Electron Positron (LEP) Collider at CERN (1989-2000) was designed to make precise measurements of the properties of the Z and W bosons.

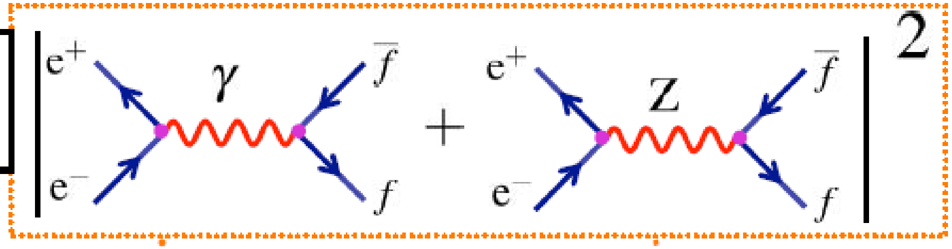
- 26 km circumference accelerator straddling French/Swiss boarder
- Electrons and positrons collided at 4 interaction points
- 4 large detector collaborations (each with 300-400 physicists):
  - ALEPH,
  - DELPHI,
  - L3,
  - OPAL

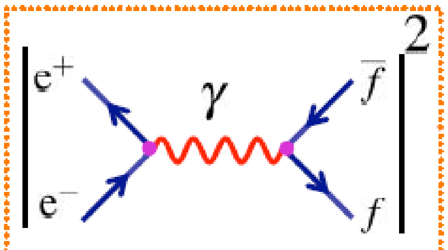
Basically a large Z and W factory:

- ★ 1989-1995: Electron-Positron collisions at $\sqrt{s}$ = 91.2 GeV
  - 17 Million Z bosons detected
- ★ 1996-2000: Electron-Positron collisions at $\sqrt{s}$ = 161-208 GeV
  - 30000 W^+W^- events detected

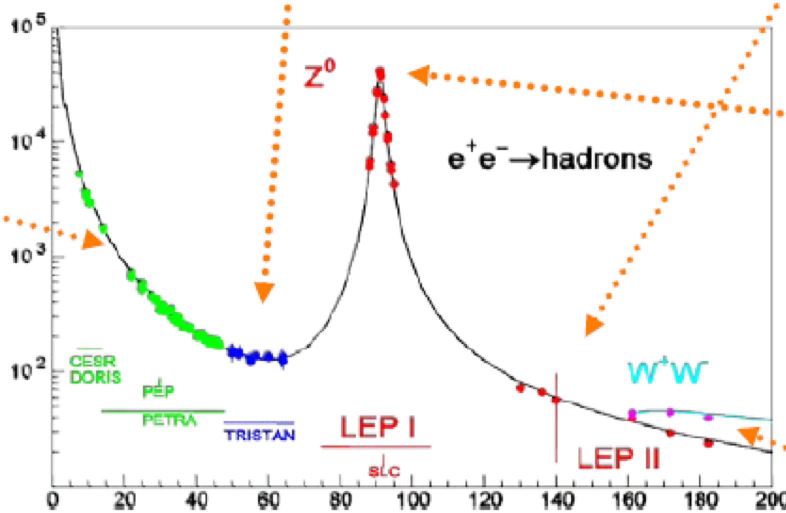
e^+e^- Annihilation in Feynman Diagrams

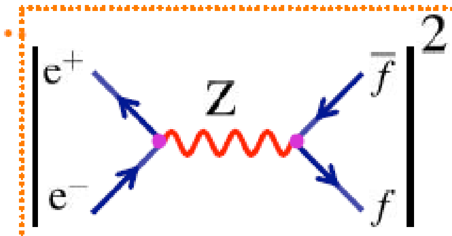
In general e^+e^- annihilation involves both photon and Z exchange : + interference





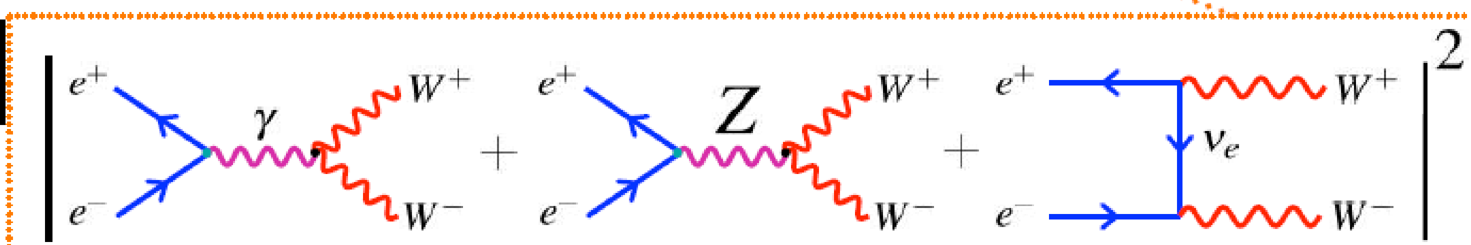
Well below Z: photon exchange dominant





At Z resonance: Z exchange dominant

High energies: WW production



Cross Section Measurements

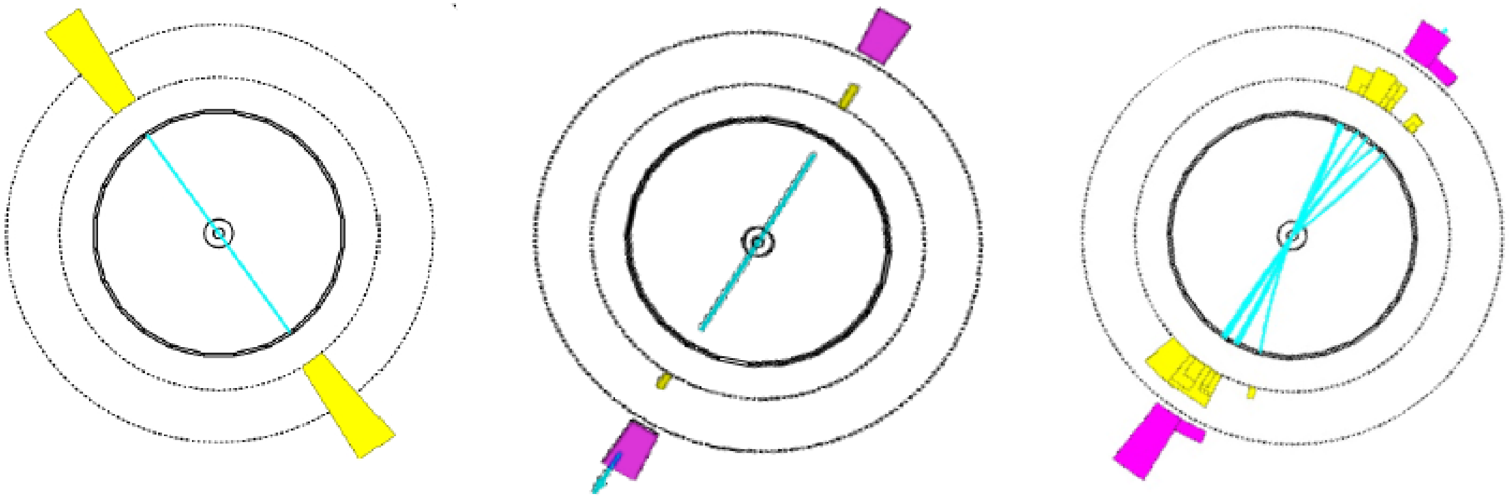
★ At Z resonance mainly observe four types of event:

$$e^+e^- \to Z \to e^+e^- \qquad e^+e^- \to Z \to \mu^+\mu^- \qquad e^+e^- \to Z \to \tau^+\tau^-$$

$$e^+e^- \to Z \to q\bar{q} \to \text{hadrons}$$

★ Each has a distinct topology in the detectors, e.g.

$$e^+e^- \to Z \to e^+e^- \qquad e^+e^- \to Z \to \mu^+\mu^- \qquad e^+e^- \to Z \to \text{hadrons}$$



★ To work out cross sections, first count events of each type

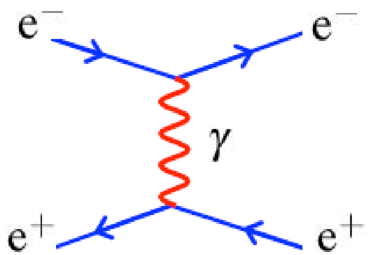
★ Then need to know "integrated luminosity" of colliding beams, i.e. the relation between cross-section and expected number of interactions

$$N_{\text{events}} = \mathscr{L}\sigma$$

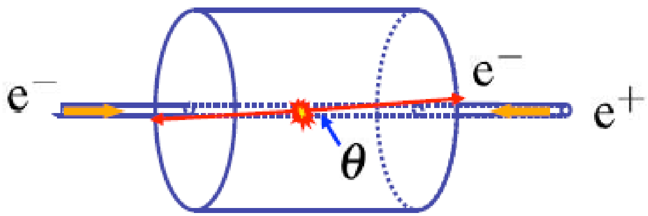
★ To calculate the integrated luminosity need to know numbers of electrons and positrons in the colliding beams and the exact beam profile

- very difficult to achieve with precision of better than 10%

★ Instead "normalise" using another type of event:



- Use the QED Bhabha scattering process
- QED, so cross section can be calculated very precisely
- Very large cross section – small statistical errors
- Reaction is very forward peaked – i.e. the electron tends not to get deflected much



$$\frac{d\sigma}{d\Omega} \propto \frac{1}{q^4} \propto \frac{1}{\sin^4 \theta/2} \Rightarrow \frac{d\sigma}{d\theta} \propto \frac{1}{\theta^3}$$

Photon propagator

- Count events where the electron is scattered in the very forward direction

$$N_{\text{Bhabha}} = \mathscr{L}\sigma_{\text{Bhabha}} \Rightarrow \mathscr{L}$$

σ_{Bhabha} known from QED calc.

★ Hence all other cross sections can be expressed as

$$\sigma_i = \frac{N_i}{N_{\text{Bhabha}}}\sigma_{\text{Bhabha}}$$

⇒ Cross section measurements Involve just event counting !

Measurements of the Z line-shape

- Measurements of the Z resonance lineshape determine:
  - m_Z : peak of the resonance
  - Γ_Z : FWHM of resonance
  - Γ_f : Partial decay widths
  - N_ν : Number of light neutrino generations
- Measure cross sections to different final states versus C.o.M. energy $\sqrt{s}$
- Starting from

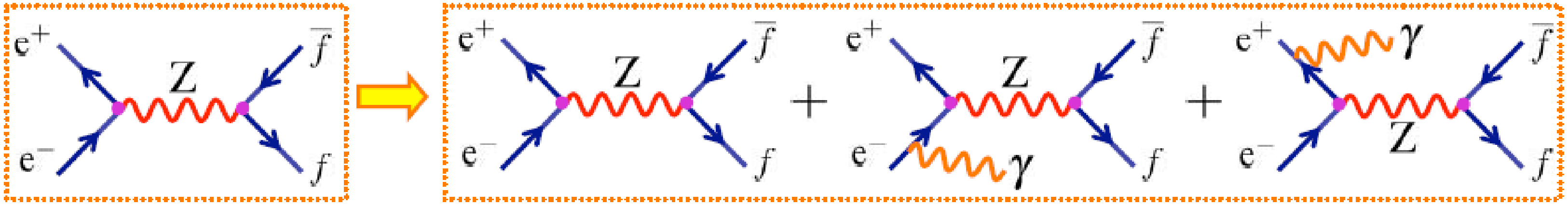
$$\sigma(e^+e^- \to Z \to f\bar{f}) = \frac{12\pi}{m_Z^2}\frac{s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}\Gamma_{ee}\Gamma_{ff} \qquad (3)$$

maximum cross section occurs at $\sqrt{s} = m_Z$ with peak cross section equal to

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

- Cross section falls to half peak value at $\sqrt{s} \approx m_z \pm \frac{\Gamma_Z}{2}$ which can be seen immediately from eqn. (3)
- Hence $\Gamma_Z = \frac{\hbar}{\tau_Z} = \text{FWHM of resonance}$

- In practise, it is not that simple, QED corrections distort the measured line-shape
- One particularly important correction: initial state radiation (ISR)



- Initial state radiation reduces the centre-of-mass energy of the e^+e^- collision

$e^+ \xrightarrow{E} \quad \xleftarrow{E} e^- \qquad \sqrt{s} = 2E$

becomes

$\xrightarrow{E} \quad \xleftarrow{E - E_\gamma} \qquad \sqrt{s}' \approx 2E(1 - \frac{E_\gamma}{2E})$

- Measured cross section can be written:

$$\sigma_{\text{meas}}(E) = \int \sigma(E')f(E',E)\text{d}E'$$

Probability of e+e- colliding with C.o.M. energy E' when C.o.M energy before radiation is E

- Fortunately can calculate $f(E',E)$ very precisely, just QED, and can then obtain Z line-shape from measured cross section

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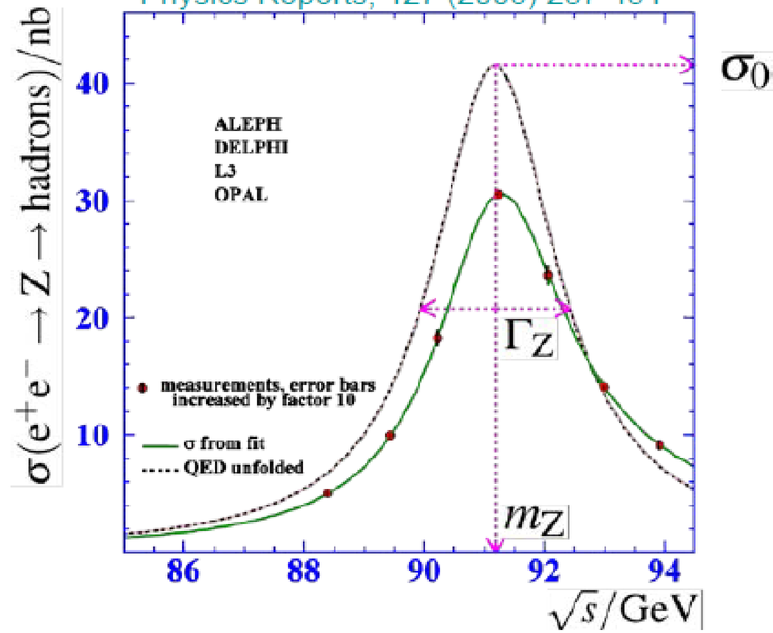


★ In principle the measurement of m_Z and Γ_Z is rather simple: run accelerator at different energies, measure cross sections, account for ISR, then find peak and FWHM

$$m_Z = 91.1875 \pm 0.0021\,\mathrm{GeV} \qquad \Gamma_Z = 2.4952 \pm 0.0023\,\mathrm{GeV}$$

★ 0.002 % measurement of m_Z !

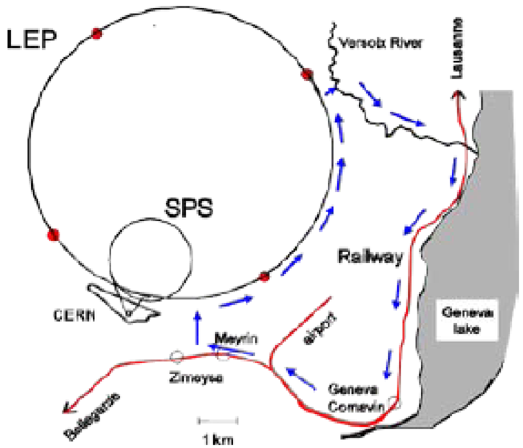
★ To achieve this level of precision – need to know energy of the colliding beams to better than 0.002 % : sensitive to unusual systematic effects…

Moon:

- As the moon orbits the Earth it distorts the rock in the Geneva area very slightly !
- The nominal radius of the accelerator of **4.3 km** varies by **±0.15 mm**
- Changes beam energy by **~10 MeV** : need to correct for tidal effects !

Trains:

- Leakage currents from the TGV railway line return to Earth following the path of least resistance.
- Travelling via the Versoix river and using the LEP ring as a conductor.
- Each time a TGV train passed by, a small current circulated LEP slightly changing the magnetic field in the accelerator
- LEP beam energy changes by ~10 MeV



Number of generations

★ Total decay width measured from Z line-shape: $\Gamma_Z = 2.4952 \pm 0.0023\,\text{GeV}$

★ If there were an additional 4th generation would expect $Z \to \nu_4 \bar{\nu}_4$ decays even if the charged leptons and fermions were too heavy (i.e. > $m_Z/2$)

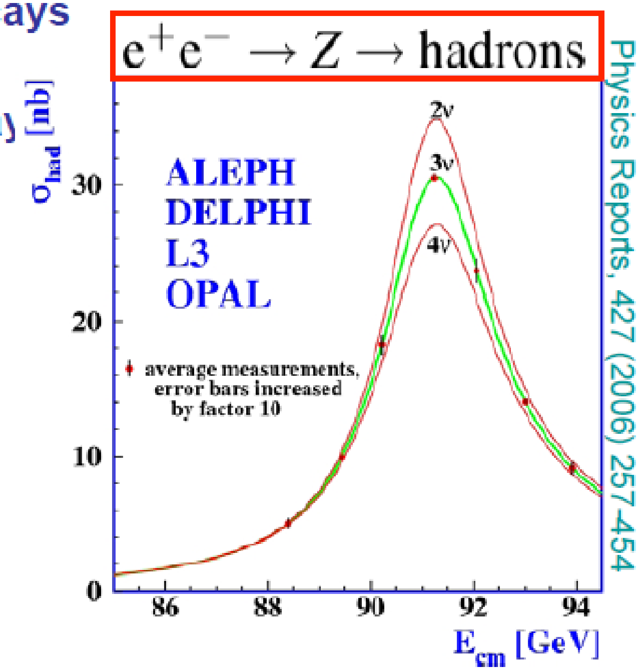
★ Total decay width is the sum of the partial widths:

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\text{hadrons}} + \Gamma_{\nu_1\nu_1} + \Gamma_{\nu_2\nu_2} + \Gamma_{\nu_3\nu_3} + ?$$

★ Although don't observe neutrinos, $Z \to \nu\bar{\nu}$ decays affect the Z resonance shape for all final states

★ For all other final states can determine partial decay widths from peak cross sections:

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



★ Assuming lepton universality:

$$\Gamma_Z = 3\Gamma_{\ell\ell} + \Gamma_{\text{hadrons}} + N_\nu \Gamma_{\nu\nu}$$

- Γ_Z: measured from Z lineshape
- $\Gamma_{\ell\ell}$, Γ_{hadrons}: measured from peak cross sections
- $\Gamma_{\nu\nu}$: calculated

⇨ $N_\nu = 2.9840 \pm 0.0082$

★ **ONLY 3 GENERATIONS** (unless a new 4th generation neutrino has very large mass)

Forward-Backward Asymmetry

★ The expression for the differential cross section:

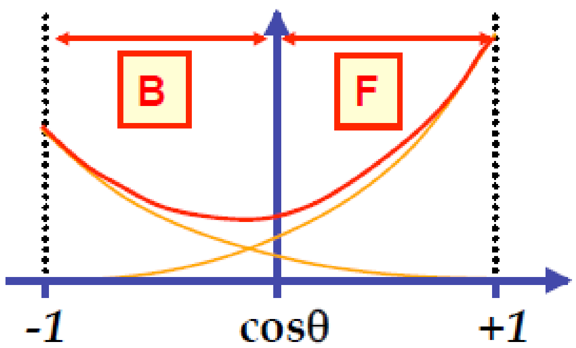
$$\langle|M_{fi}|\rangle^2 \propto [(c_L^e)^2+(c_R^e)^2][(c_L^\mu)^2+(c_R^\mu)^2](1+\cos^2\theta)+[(c_L^e)^2-(c_R^e)^2][(c_L^\mu)^2-(c_R^\mu)^2]\cos\theta$$

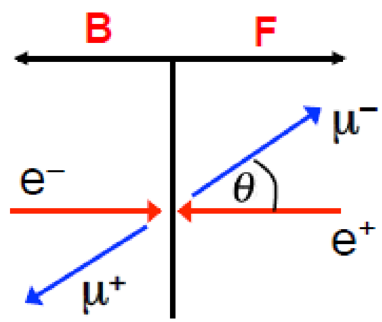
★ The differential cross sections is therefore of the form:

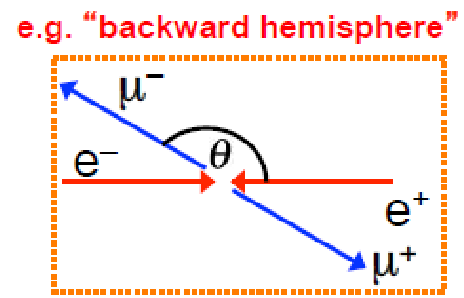
$$\frac{d\sigma}{d\Omega} = \kappa \times [A(1+\cos^2\theta)+B\cos\theta] \qquad \begin{cases} A = [(c_L^e)^2+(c_R^e)^2][(c_L^\mu)^2+(c_R^\mu)^2] \\ B = [(c_L^e)^2-(c_R^e)^2][(c_L^\mu)^2-(c_R^\mu)^2] \end{cases}$$

★ Define the **FORWARD** and **BACKWARD** cross sections in terms of angle incoming electron and out-going particle

$$\sigma_F \equiv \int_0^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta \qquad \sigma_B \equiv \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\, d\cos\theta$$

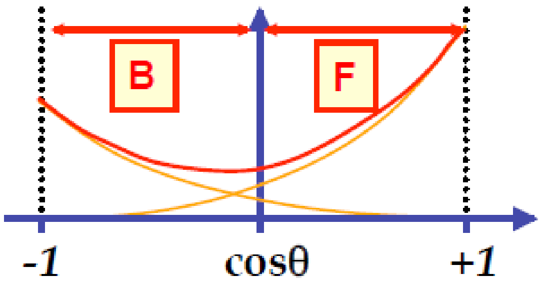






★ The level of asymmetry about cosθ=0 is expressed in terms of the Forward-Backward Asymmetry

$$A_{\rm FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



• Integrating equation (1):

$$\sigma_F = \kappa \int_0^1 [A(1+\cos^2\theta) + B\cos\theta] \mathrm{d}\cos\theta = \kappa \int_0^1 [A(1+x^2) + Bx] \mathrm{d}x = \kappa \left(\frac{4}{3}A + \frac{1}{2}B\right)$$

$$\sigma_B = \kappa \int_{-1}^0 [A(1+\cos^2\theta) + B\cos\theta] \mathrm{d}\cos\theta = \kappa \int_{-1}^0 [A(1+x^2) + Bx] \mathrm{d}x = \kappa \left(\frac{4}{3}A - \frac{1}{2}B\right)$$

★ Which gives:

$$A_{\rm FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{B}{(8/3)A} = \frac{3}{4}\left[\frac{(c_L^e)^2 - (c_R^e)^2}{(c_L^e)^2 + (c_R^e)^2}\right] \cdot \left[\frac{(c_L^\mu)^2 - (c_R^\mu)^2}{(c_L^\mu)^2 + (c_R^\mu)^2}\right]$$

★ This can be written as

$$A_{\rm FB} = \frac{3}{4}A_e A_\mu$$

with

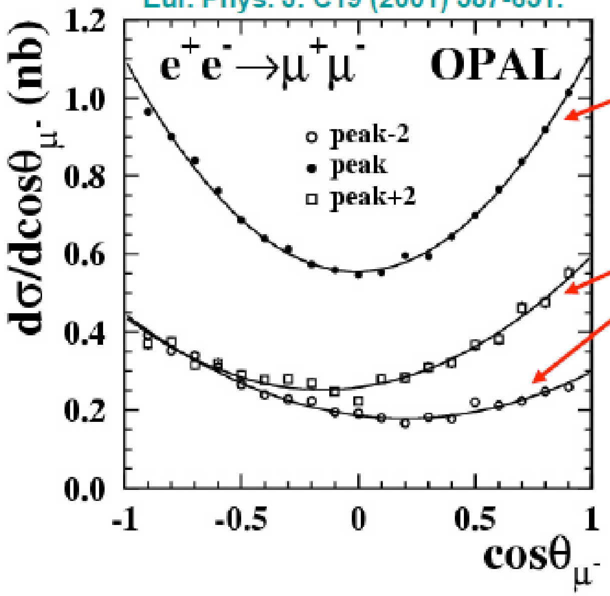
$$A_f \equiv \frac{(c_L^e)^2 - (c_R^e)^2}{(c_L^e)^2 + (c_R^e)^2} = \frac{2c_V^f c_A^f}{(c_V^f)^2 + (c_A^f)^2} \qquad (4)$$

★ Observe a non-zero asymmetry because the couplings of the Z to LH and RH particles are different. Contrast with QED where the couplings to LH and RH particles are the same (parity is conserved) and the interaction is FB symmetric

Measured Forward-Backward Asymmetries

★ Forward-backward asymmetries can only be measured for final states where the charge of the fermion can be determined, e.g. $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$

OPAL Collaboration, Eur. Phys. J. C19 (2001) 587-651.



Because $\sin^2\theta_W \approx 0.25$, the value of A_{FB} for leptons is almost zero

For data above and below the peak of the Z resonance interference with $e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-$ leads to a larger asymmetry

★ LEP data combined:

$$A_{FB}^{0,e} = 0.0145 \pm 0.0025$$

$$A_{FB}^{0,\mu} = 0.0169 \pm 0.0013$$

$$A_{FB}^{0,\tau} = 0.0188 \pm 0.0017$$

★ To relate these measurements to the couplings uses $A_{\mathrm{FB}} = \frac{3}{4} A_e A_\mu$

★ In all cases asymmetries depend on A_e

★ To obtain A_e could use $A_{FB}^{0,e} = \frac{3}{4} A_e^2$ (also see Appendix II for A_{LR})

Determination of the Weak Mixing Angle

★ From LEP : $A_{FB}^{0,f} = \frac{3}{4} A_e A_f$

★ From SLC : $A_{LR} = A_e$

$\Big\} \; A_e, A_\mu, A_\tau, \ldots$

Putting everything together ⇨

$$A_e = 0.1514 \pm 0.0019$$
$$A_\mu = 0.1456 \pm 0.0091$$
$$A_\tau = 0.1449 \pm 0.0040$$

includes results from other measurements

with $$A_f \equiv \frac{2 c_V^f c_A^f}{(c_V^f)^2 + (c_A^f)^2} = 2 \frac{c_V / c_A}{1 + (c_V / c_A)^2}$$

★ Measured asymmetries give ratio of vector to axial-vector Z coupings.

★ In SM these are related to the weak mixing angle

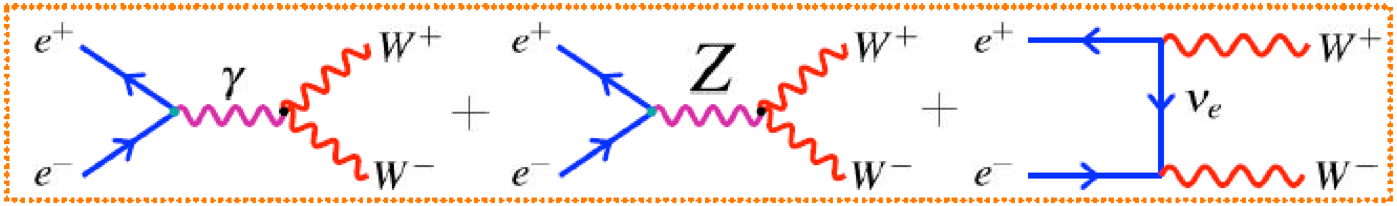
$$\frac{c_V}{c_A} = \frac{I_W^3 - 2Q \sin^2\theta_W}{I_W^3} = 1 - \frac{2Q}{I_3} \sin^2\theta_W = 1 - 4|Q| \sin^2\theta_W$$

★ Asymmetry measurements give precise determination of $\sin^2\theta_W$

$$\sin^2\theta_W = 0.23154 \pm 0.00016$$

W^+W^- Production

- From 1995-2000 LEP operated above the threshold for W-pair production
- Three diagrams "CC03" are involved

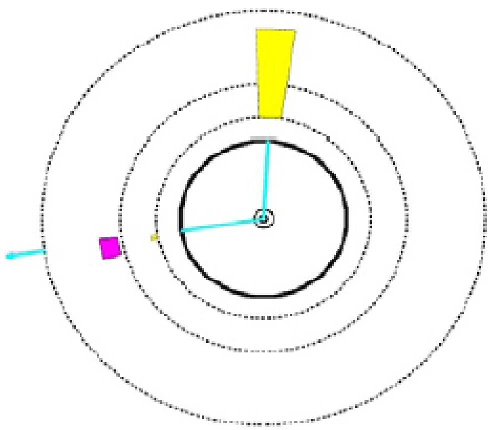


- W bosons decay either to leptons or hadrons with branching fractions:

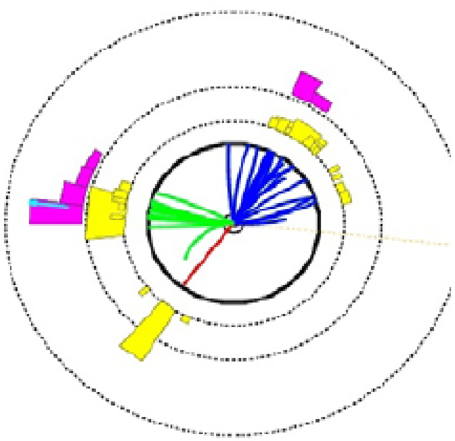
$$Br(W^- \to \text{hadrons}) \approx 0.67 \qquad Br(W^- \to e^-\bar{\nu}_e) \approx 0.11$$

$$Br(W^- \to \mu^-\bar{\nu}_\mu) \approx 0.11 \qquad Br(W^- \to \tau^-\bar{\nu}_\tau) \approx 0.11$$

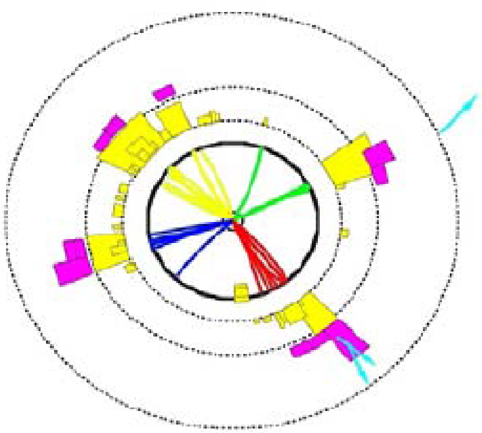
- Gives rise to three distinct topologies



$W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$



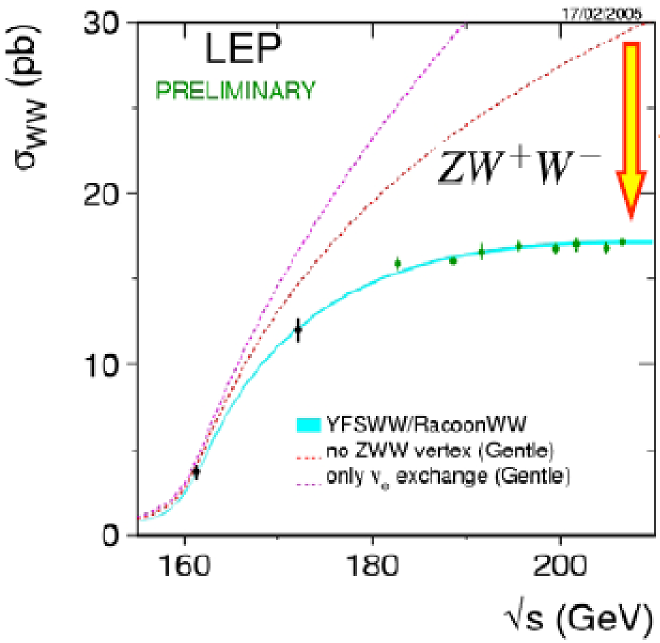
$W^+W^- \to q\bar{q}\ell\nu$



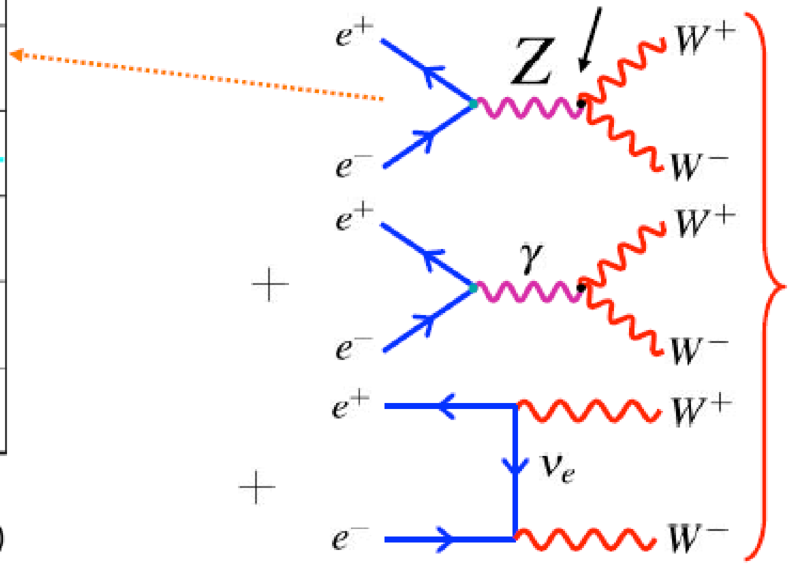
$W^+W^- \to q\bar{q}q\bar{q}$

$e^+e^- \to W^+ W^-$ Cross Section

- ★ Measure cross sections by **counting events** and normalising to low angle Bhabha scattering events



- ★ Data consistent with SM expectation
- ★ Provides a direct test of ZW^+W^- vertex



- ★ Recall that without the Z diagram the cross section violates unitarity
- ★ Presence of Z fixes this problem

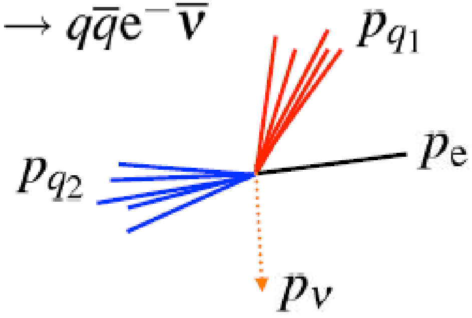
W-mass and W-width

★ Unlike $e^+e^- \rightarrow Z$, the process $e^+e^- \rightarrow W^+W^-$ is not a resonant process

⇨ **Different method to measure W-boson Mass**

• Measure energy and momenta of particles produced in the W boson decays, e.g.

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

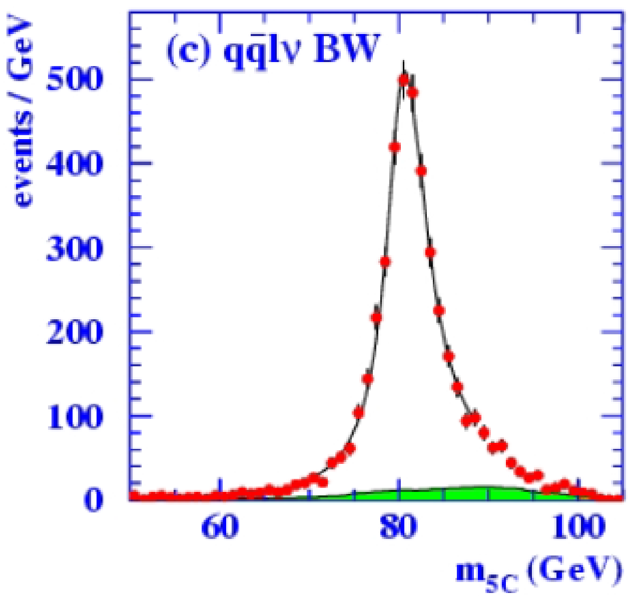


▪ Neutrino four-momentum from energy-momentum conservation !

$$p_{q_1} + p_{q_2} + p_e + p_\nu = (\sqrt{s}, 0)$$

▪ Reconstruct masses of two W bosons

$$M_+^2 = E^2 - \vec{p}^2 = (p_{q_1} + p_{q_2})^2$$
$$M_-^2 = E^2 - \vec{p}^2 = (p_e + p_\nu)^2$$



$$\approx \frac{1}{2}(M_+ + M_-)$$

★ Peak of reconstructed mass distribution gives

$$m_W = 80.376 \pm 0.033\,\mathrm{GeV}$$

★ Width of reconstructed mass distribution gives:

$$\Gamma_W = 2.196 \pm 0.083\,\mathrm{GeV}$$

Does not include measurements from Tevatron at Fermilab

Does not include measurements ATLAS at LHC

The Higgs mechanism

★ The Higgs mechanism provides a way of giving the gauge bosons mass

The Higgs Mechanism

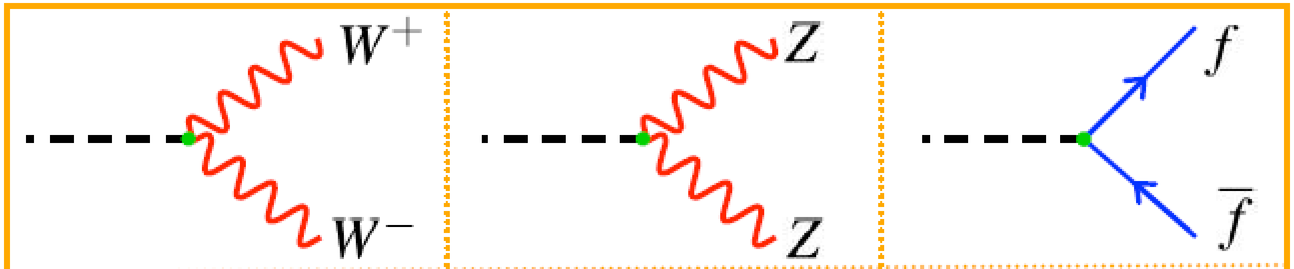
★ Propose a scalar (spin 0) field with a non-zero vacuum expectation value (VEV)

> Massless Gauge Bosons propagating through the vacuum with a non-zero Higgs VEV correspond to massive particles.

★ The Higgs is electrically neutral but carries weak hypercharge of 1/2
★ The photon does not couple to the Higgs field and remains massless
★ The W bosons and the Z couple to weak hypercharge and become massive

★ The Higgs mechanism results in absolute predictions for masses of gauge bosons
★ In the SM, fermion masses are also ascribed to interactions with the Higgs field
 - however, here no prediction of the masses – just put in by hand

Feynman Vertex factors:



$ig_W m_W g^{\mu\nu}$	$ig_Z m_Z g^{\mu\nu}$	$-i\dfrac{g_W}{2m_W} m_f$

★ **Within the SM of Electroweak unification with the Higgs mechanism:**

Relations between standard model parameters

$$m_W = \left(\frac{\pi \alpha_{em}}{\sqrt{2} G_F} \right)^{\frac{1}{2}} \frac{1}{\sin \theta_W}$$

$$m_Z = \frac{m_W}{\cos \theta_W}$$

★ **Hence, if you know any three of :** $\alpha_{em}, G_F, m_W, m_Z, \sin\theta_W$ **predict the other two.**

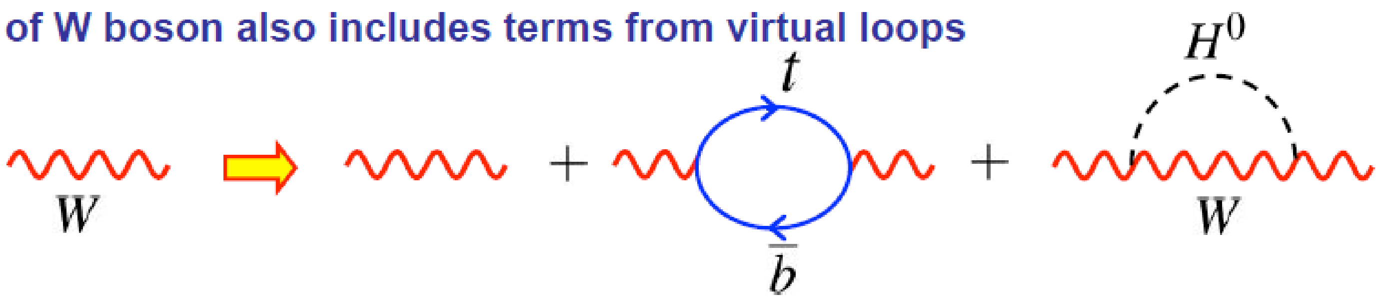
Precision Tests of the Standard Model

★ From LEP and elsewhere have precise measurements – can test predictions of the Standard Model !

- e.g. predict: $m_W = m_Z \cos\theta_W$ measure $m_Z = 91.1875 \pm 0.0021\,\mathrm{GeV}$, $\sin^2\theta_W = 0.23154 \pm 0.00016$
- Therefore expect: $m_W = 79.946 \pm 0.008\,\mathrm{GeV}$ but measure $m_W = 80.376 \pm 0.033\,\mathrm{GeV}$

★ Close, but not quite right – but have only considered lowest order diagrams

★ Mass of W boson also includes terms from virtual loops



$$m_W = m_W^0 + a m_t^2 + b \ln\left(\frac{m_H}{m_W}\right)$$

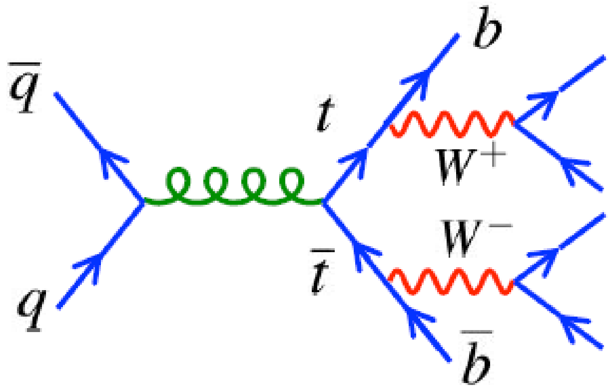
★ Above "discrepancy" due to these virtual loops, i.e. by making very high precision measurements become sensitive to the masses of particles inside the virtual loops !

The Top quark

★ From virtual loop corrections and precise LEP data can predict the top quark mass:

$$m_t^{\text{loop}} = 173 \pm 11\,\text{GeV}$$

★ In 1994 top quark observed at the Tevatron proton anti-proton collider at Fermilab – with the predicted mass !



★ The top quark almost exclusively decays to a bottom quark since

$$|V_{tb}|^2 \gg |V_{td}|^2 + |V_{ts}|^2$$

★ Complicated final state topologies:

$$t\bar{t} \to b\bar{b}q\bar{q}q\bar{q} \to 6\text{ jets}$$

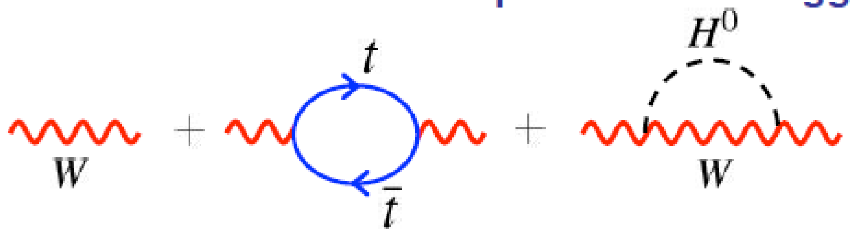
$$t\bar{t} \to b\bar{b}q\bar{q}\ell\nu \to 4\text{ jets} + \ell + \nu$$

$$t\bar{t} \to b\bar{b}\ell\nu\ell\nu \to 2\text{ jets} + 2\ell + 2\nu$$

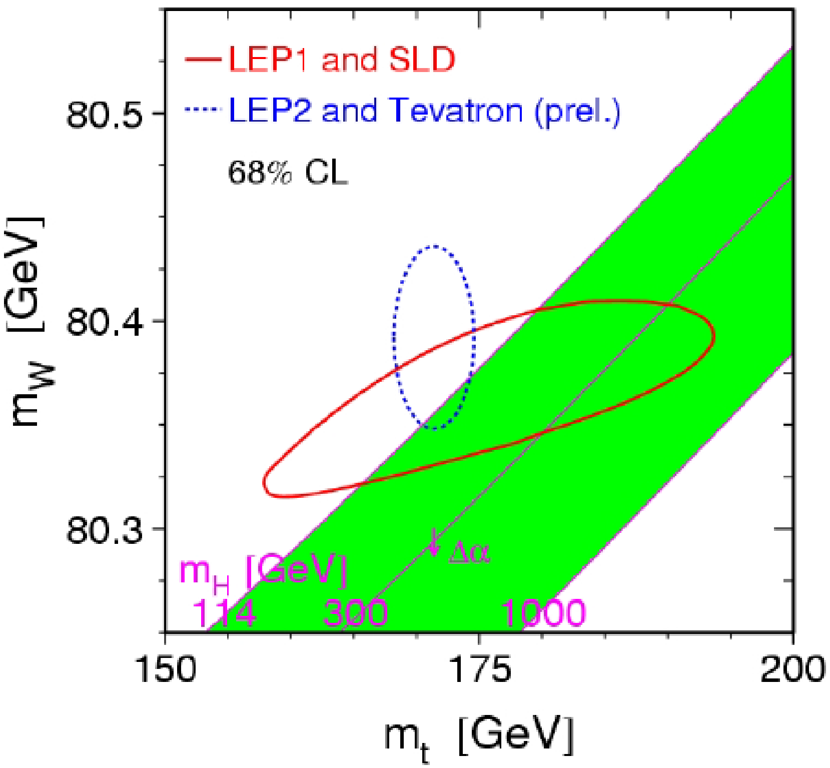
★ Mass determined by direct reconstruction (see W boson mass)

$$m_t^{\text{meas}} = 174.2 \pm 3.3\,\text{GeV}$$

★ But the W mass also depends on the Higgs mass (albeit only logarithmically)



$$m_W = m_W^0 + a m_t^2 + b \ln\left(\frac{m_H}{m_W}\right)$$



★ Measurements are sufficiently precise to have some sensitivity to the Higgs mass

★ Direct and indirect values of the top and W mass can be compared to prediction for different Higgs mass

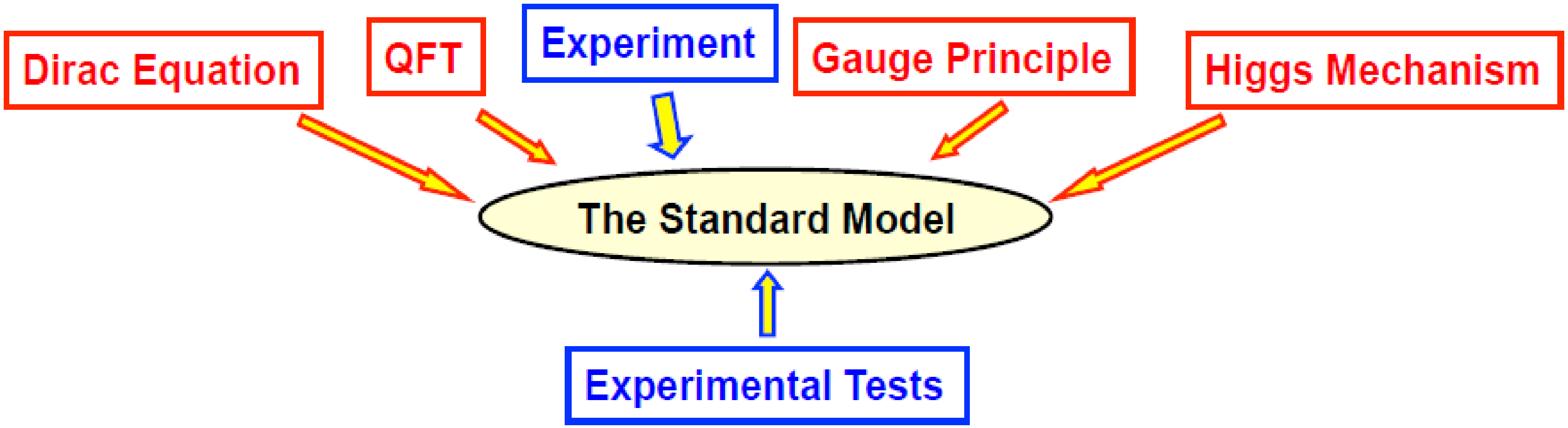
- **Direct:** W and top masses from direct reconstruction
- **Indirect:** from SM interpretation of Z mass, θ_W etc. and

★ Data favour a light Higgs:

$$m_H < 200\,\text{GeV}$$

Summary

- The Standard Model of Particle Physics is one of the great scientific triumphs of the late 20th century
- Developed through close interplay of experiment and theory



- Modern experimental particle physics provides many precise measurements. and the **Standard Model** successfully describes all current data !
- Despite its great success, we should not forget that it is just a model; a collection of beautiful theoretical ideas cobbled together to fit with experimental data.
- There are many issues / open questions…

Appendix I: Non-relativistic Breit-Wigner

★ For energies close to the peak of the resonance, can write $\sqrt{s} = m_Z + \Delta$

$$s = m_Z^2 + 2m_Z\Delta + \Delta^2 \approx m_Z^2 + 2m_Z\Delta \qquad \text{for} \quad \Delta \ll m_Z$$

so with this approximation

$$\begin{aligned}(s - m_Z^2)^2 + m_Z^2\Gamma_Z^2 \approx (2m_Z\Delta)^2 + m_Z^2\Gamma_Z^2 &= 4m_Z^2(\Delta + \tfrac{1}{4}\Gamma_Z^2) \\ &= 4m_Z^2[(\sqrt{s} - m_Z)^2 + \tfrac{1}{4}\Gamma_Z^2]\end{aligned}$$

★ Giving: $\sigma(e^+e^- \to Z \to f\bar{f}) \approx \dfrac{3\pi}{m_Z^4} \dfrac{s}{(\sqrt{s} - m_Z)^2 + \frac{1}{4}\Gamma_Z^2} \Gamma_e\Gamma_f$

★ Which can be written:

$$\sigma(E) = \frac{g\lambda_e^2}{4\pi} \frac{\Gamma_i\Gamma_f}{(E - E_0)^2 + \frac{1}{4}\Gamma^2} \qquad (3)$$

Γ_i, Γ_f : are the partial decay widths of the initial and final states

E, E_0 : are the centre-of-mass energy and the energy of the resonance

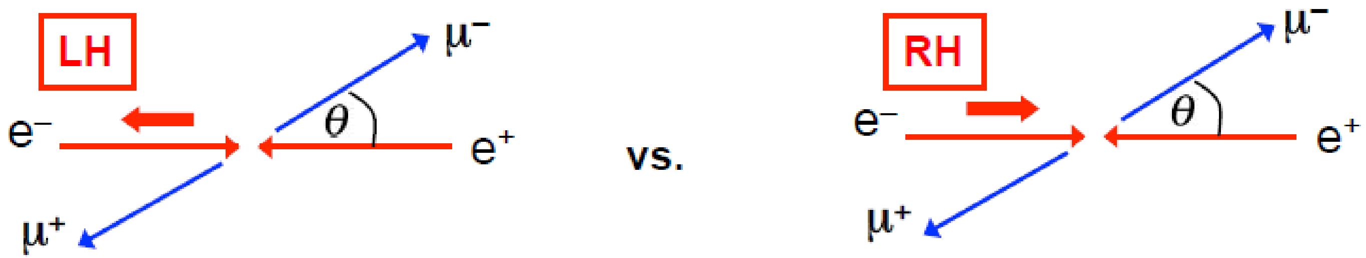
$g = \dfrac{(2J_Z+1)}{(2S_e+1)(2S_e+1)}$ is the spin counting factor $g = \dfrac{3}{2\times 2}$

$\lambda_e = \dfrac{2\pi}{E}$: is the Compton wavelength (natural units) in the C.o.M of either initial particle

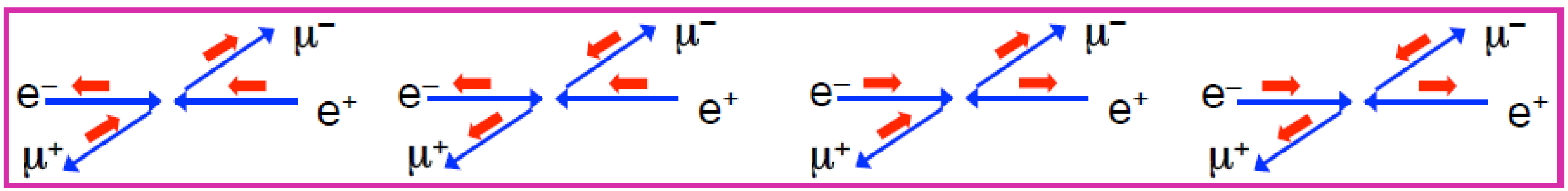
Appendix II: Left-Right Asymmetry, A_L, A_R

★ At an e^+e^- linear collider it is possible to produce polarized electron beams e.g. SLC linear collider at SLAC (California), 1989-2000

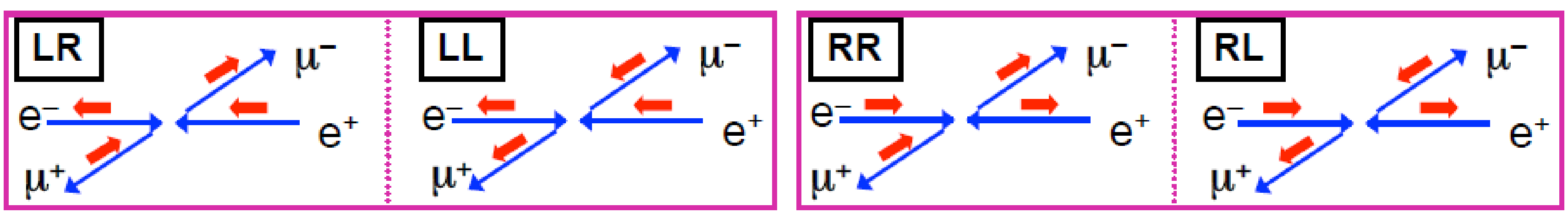
★ Measure cross section for any process for LH and RH electrons separately



- At LEP measure total cross section: sum of 4 helicity combinations:



- At SLC, by choosing the polarization of the electron beam are able to measure cross sections separately for LH / RH electrons



★ Averaging over the two possible polarization states of the positron for a given electron polarization:

$$\langle|M_L|\rangle^2 = \frac{1}{2}(|M_{LL}|^2 + |M_{LR}|^2) \qquad \langle|M_R|\rangle^2 = \frac{1}{2}(|M_{RL}|^2 + |M_{RR}|^2)$$

$$\Rightarrow \quad \boxed{\sigma_L = \frac{1}{2}(\sigma_{LR} + \sigma_{LL})} \qquad \boxed{\sigma_R = \frac{1}{2}(\sigma_{RR} + \sigma_{RL})}$$

★ Define cross section asymmetry:

$$\boxed{A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}}$$

★ Integrating the expressions on page 494 gives:

$$\sigma_{LL} \propto (c_L^e)^2(c_L^\mu)^2 \quad \sigma_{LR} \propto (c_L^e)^2(c_R^\mu)^2 \quad \sigma_{RL} \propto (c_R^e)^2(c_L^\mu)^2 \quad \sigma_{RR} \propto (c_R^e)^2(c_R^\mu)^2$$

$$\Rightarrow \quad \sigma_L \propto (c_L^e)^2[(c_L^\mu)^2 + (c_R^\mu)^2] \qquad \sigma_R \propto (c_R^e)^2[(c_L^\mu)^2 + (c_R^\mu)^2]$$

$$\boxed{A_{LR} = \frac{(c_L^e)^2 - (c_R^e)^2}{(c_L^e)^2 + (c_R^e)^2} = A_e}$$

★ Hence the Left-Right asymmetry for any cross section depends only on the couplings of the electron