

Physics 56400

Introduction to Elementary Particle Physics I

Now in PowerPoint!

Lecture 19
Fall 2018 Semester
Prof. Matthew Jones

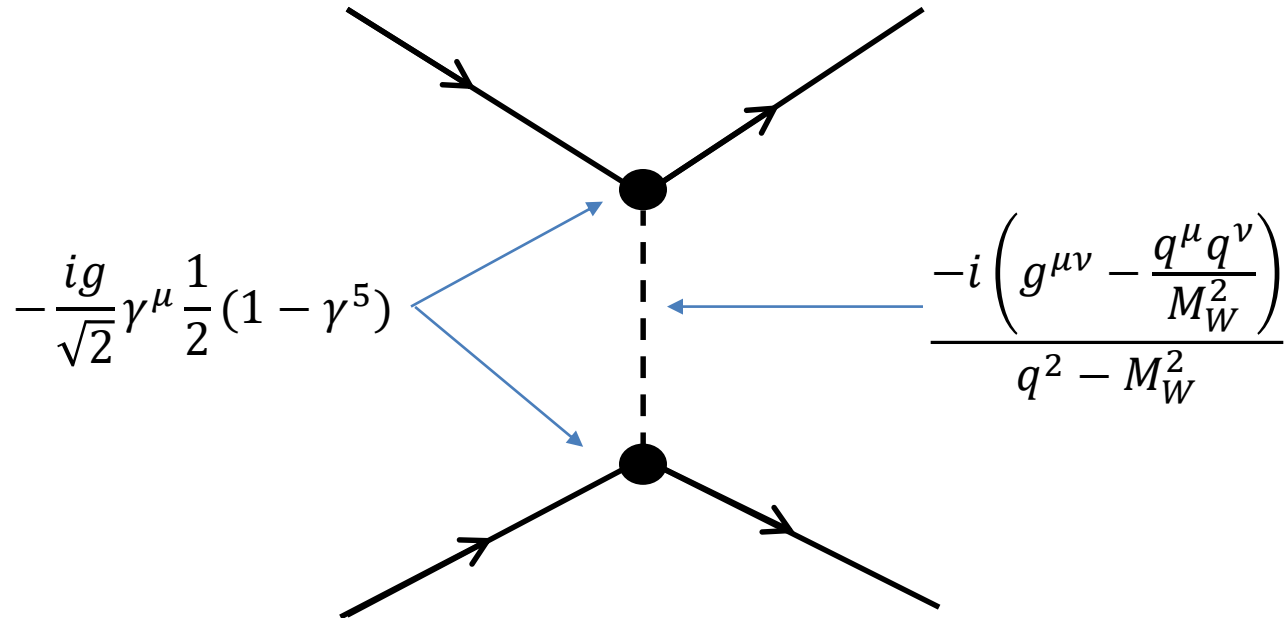
Summary of Tuesday's Lecture

- Weak interactions couple to fermion states with left-handed chirality
- This is a purely empirical observation, but consistent with all measurements
- Left-handed charged currents follow the form

$$J_e^\mu = \bar{u}_e \gamma^\mu \frac{1}{2} (1 - \gamma^5) v_{\nu_e}$$

- The Fermi 4-point interaction parameterized all the dynamics as a universal weak coupling with strength G_F
- Some cross sections calculated using the 4-point interaction violated unitarity at high energies
- This deficiency was mitigated by introducing a massive, charged, vector boson.

Charged Weak Current



$$\frac{-i \left(g^{\mu\nu} - \frac{q^\mu q^\nu}{M_W^2} \right)}{q^2 - M_W^2} \approx \frac{ig^{\mu\nu}}{M_W^2}$$

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

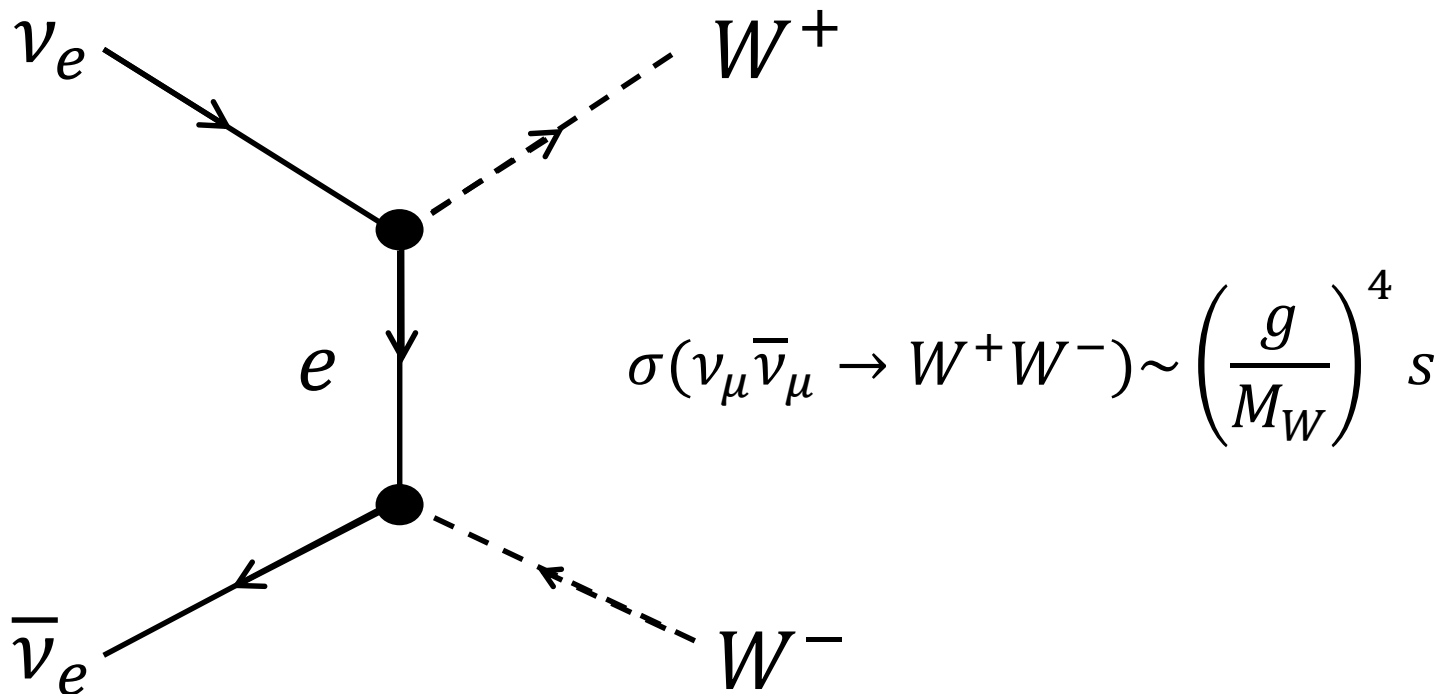
Family Structure of Matter

$$\begin{array}{ccc} \begin{pmatrix} u \\ d \end{pmatrix} & \begin{pmatrix} c \\ s \end{pmatrix} & \begin{pmatrix} t \\ b \end{pmatrix} \\ \begin{pmatrix} \nu_e \\ e \end{pmatrix} & \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} & \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \end{array}$$

- These are grouped into “weak isospin doublets”.
- The charged weak interaction couples within each doublet.
- This is like the idea of strong isospin (the strong interaction doesn’t distinguish based on electric charge)

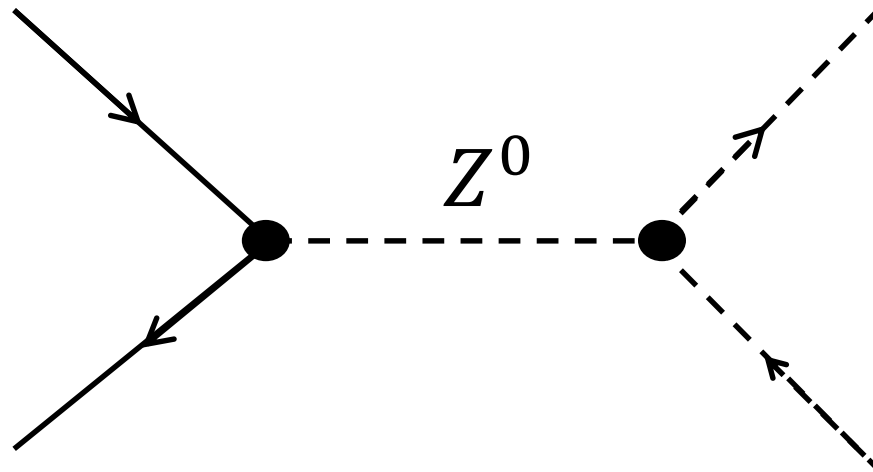
Charged Weak Current

- Introducing the W boson avoided unitarity violation in $\nu_e \bar{\nu}_e \rightarrow \mu^+ \mu^-$
- But it persists in the process $\nu_\mu \bar{\nu}_\mu \rightarrow W^+ W^-$



Weak Neutral Currents

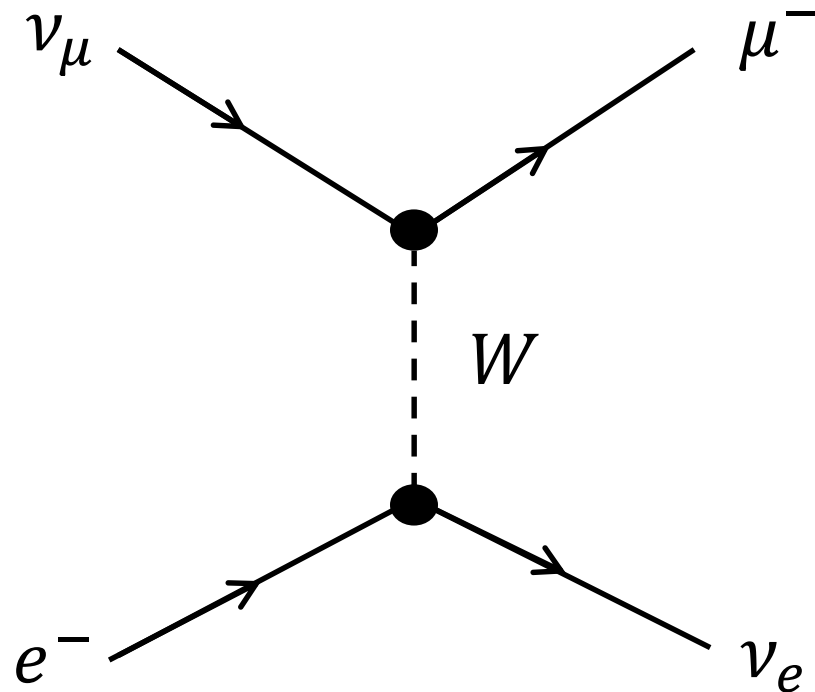
- To fix the problem with unitarity, another vector boson was introduced that would cancel the bad behavior in the amplitude:



- Its mass would be about the same as the W and its couplings to fermions and W 's would be highly constrained.

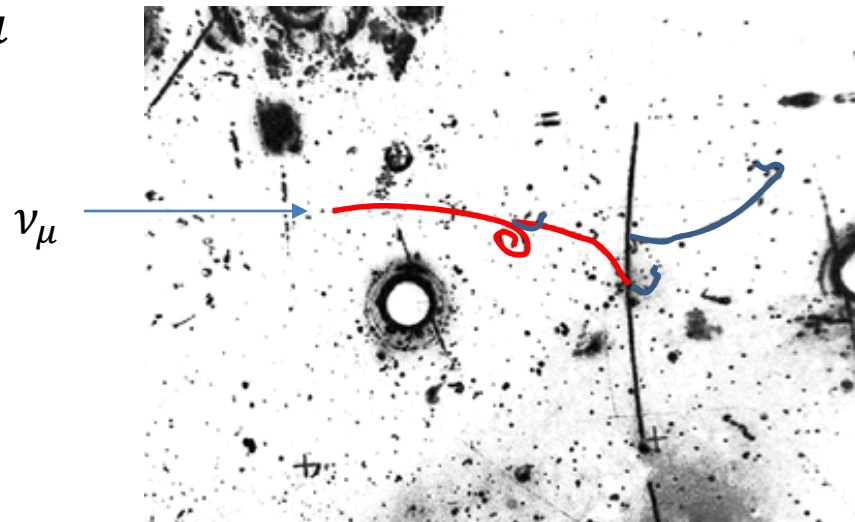
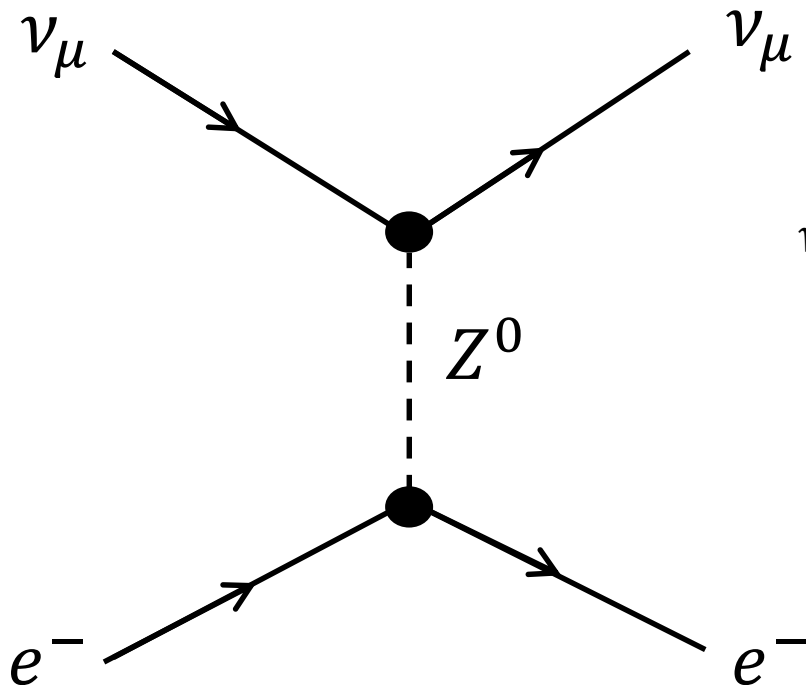
Evidence for Weak Neutral Currents

- If the weak interaction only involved charged currents, then neutrino scattering would have to change the lepton charge:



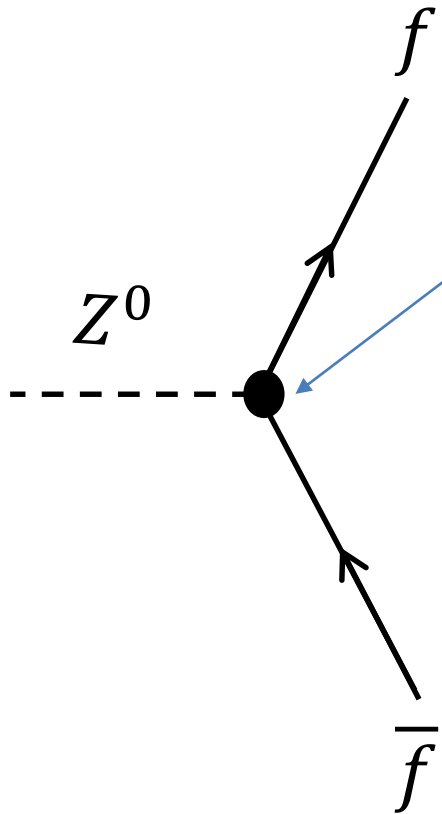
Evidence for Weak Neutral Currents

- But, weak neutral currents would allow elastic neutrino-electron scattering:



CERN, 1973

Weak Neutral Currents



$$-\frac{ig'}{2} \gamma^\mu (c_V - c_A \gamma^5)$$

Axial coupling:

$$c_A = I_3$$

Vector coupling:

$$c_V = I_3 - 2Q_f \sin^2 \theta_W$$

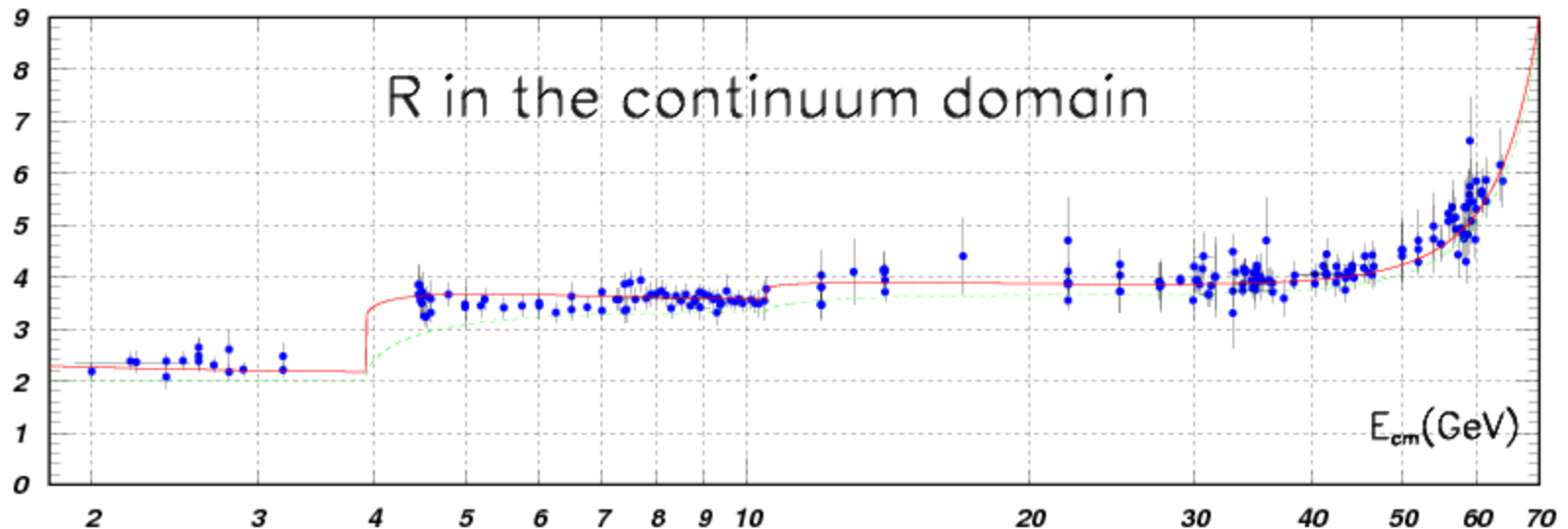
$$g \sin \theta_W = g' \cos \theta_W = e$$

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

(this follows from the unification of electromagnetic and weak interactions via the Higgs mechanism.)

Evidence for the Z Boson

- Elastic neutrino scattering
- “R” ratio at e^+e^- colliders:



- Forward-backward asymmetries in e^+e^- collisions

Forward-Backward Asymmetries

- Pure quantum electrodynamics:

$$\frac{d\sigma}{d\Omega} = n_c Q_f^2 \frac{\alpha^2}{4s} (1 + \cos^2 \theta)$$

- Forward/backward cross-section:

$$\sigma_F = 2\pi \int_0^1 \frac{d\sigma}{d\Omega} d(\cos \theta) = n_c Q_f^2 \frac{2\pi\alpha^2}{3s}$$

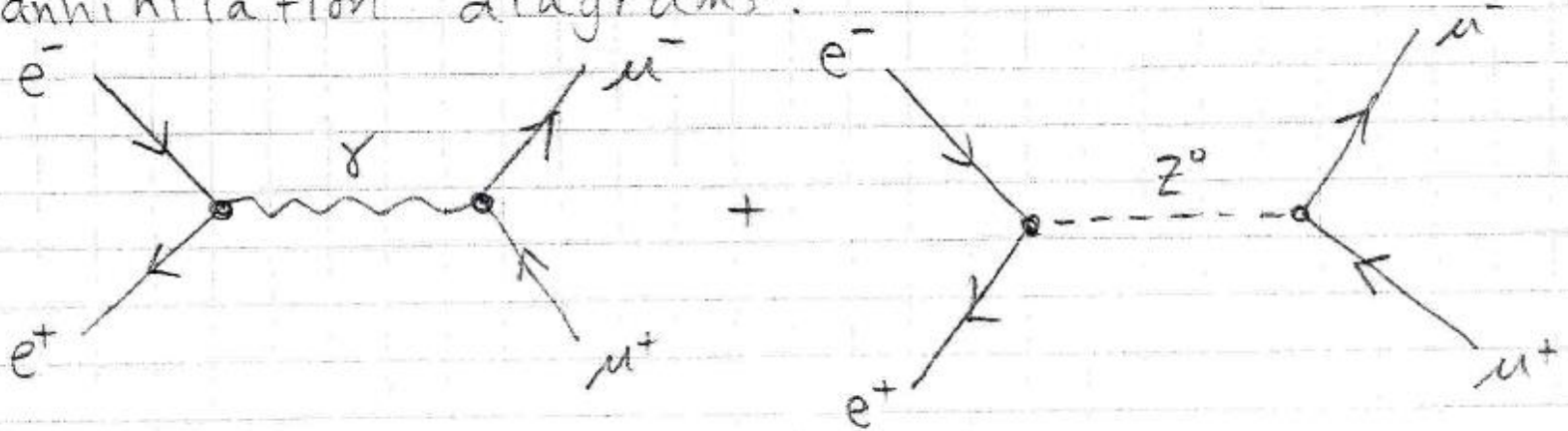
$$\sigma_B = 2\pi \int_{-1}^0 \frac{d\sigma}{d\Omega} d(\cos \theta) = n_c Q_f^2 \frac{2\pi\alpha^2}{3s}$$

- Forward-backward asymmetry:

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = 0 \quad (\text{in pure QED})$$

Forward-Backward Asymmetries

If the Z^0 couples to e^+e^- then there should be interference between Z^0 and γ annihilation diagrams:



$$\mathcal{M} = \mathcal{M}_\gamma + \mathcal{M}_Z$$

$$|\mathcal{M}|^2 = |\mathcal{M}_\gamma|^2 + |\mathcal{M}_Z|^2 + 2\text{Re}(\mathcal{M}_\gamma^* \mathcal{M}_Z)$$

Left-Right Couplings

- The chiral decomposition of the Z coupling can be written in terms of separate coupling constants for right- and left-handed chiral fermions:

$$-\frac{ig}{\cos \theta_W} \gamma^\mu \frac{1}{2} (c_V + c_A \gamma^5) = -\frac{ig}{\cos \theta_W} \gamma^\mu \left(c_L \frac{1}{2} (1 - \gamma^5) + c_R \frac{1}{2} (1 + \gamma^5) \right)$$

$$c_L = \frac{1}{2} (c_V + c_A)$$

$$c_R = \frac{1}{2} (c_V - c_A)$$

- This is the same vertex factor as in QED when we set $c_A = 0$ in which case the photon couples equally to left- and right-handed fermions.

Left-Right Couplings

- Consider $e^+e^- \rightarrow \mu^+\mu^-$ in which both the e^- and μ^- have left-handed chirality:

$$\begin{aligned} -i\mathcal{M} &= \left(\frac{ie^2}{q^2} + \frac{ig^2}{4\cos^2\theta_W} \frac{c_L^e c_L^\mu}{q^2 - M_Z^2} \right) \times \bar{v}_L(p_2) \gamma^\mu u_R(p_1) \bar{u}_L(k_1) \gamma_\mu v_R(k_2) \\ &= \frac{ie^2}{s} (1 + r c_L^e c_L^\mu) \bar{v}_L(p_2) \gamma^\mu u_R(p_1) \bar{u}_L(k_1) \gamma_\mu v_R(k_2) \end{aligned}$$

$$r = \frac{g^2}{4\cos^2\theta_W} \cdot \frac{1}{s - M_Z^2} \cdot \frac{s}{e^2} = \frac{\sqrt{2}M_Z^2 G_F}{s - M_Z^2} \left(\frac{s}{e^2} \right)$$

- Taking into account the finite width of the Z resonance,

$$r = \frac{\sqrt{2}M_Z^2 G_F}{s - M_Z^2 + i\Gamma_Z M_Z} \left(\frac{s}{e^2} \right)$$

Left-Right Couplings

- Differential cross section:

$$|\mathcal{M}_{LL}|^2 = \frac{e^4}{s^2} |1 + r c_L^e c_L^\mu|^2 (1 + \cos \theta)^2$$

- Likewise,

$$|\mathcal{M}_{RR}|^2 = \frac{e^4}{s^2} |1 + r c_R^e c_R^\mu|^2 (1 + \cos \theta)^2$$

- But,

$$|\mathcal{M}_{LR}|^2 = \frac{e^4}{s^2} |1 + r c_L^e c_R^\mu|^2 (1 - \cos \theta)^2$$

$$|\mathcal{M}_{RL}|^2 = \frac{e^4}{s^2} |1 + r c_R^e c_L^\mu|^2 (1 - \cos \theta)^2$$

Left-Right Couplings

- Differential cross sections:

$$\frac{d\sigma}{d\Omega}(e_L^- e_R^+ \rightarrow \mu_L^- \mu_R^+) = \frac{\alpha^2}{4s} (1 + \cos \theta)^2 |1 + r c_L^e c_L^\mu|^2$$

$$\frac{d\sigma}{d\Omega}(e_L^- e_R^+ \rightarrow \mu_R^- \mu_L^+) = \frac{\alpha^2}{4s} (1 - \cos \theta)^2 |1 + r c_L^e c_R^\mu|^2$$

etc...

- Average over incident helicity, sum over final state helicity:

$$\frac{d\sigma}{d\Omega}(e^- e^+ \rightarrow \mu^- \mu^+) = \frac{\alpha^2}{4s} (A_0(1 + \cos^2 \theta) + A_1 \cos \theta)$$

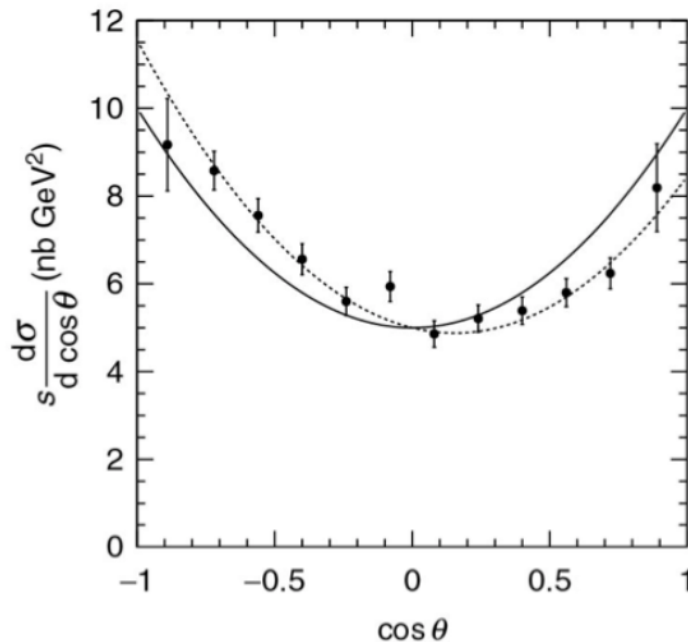
- Forward-backward asymmetry:

$$A_{FB} = \frac{3 A_1}{4 A_0}$$

- Remember that this depends on r which is a function of s .

Forward-Backward Asymmetry

- The influence of the Z^0 was apparent even at energies much less than M_Z :



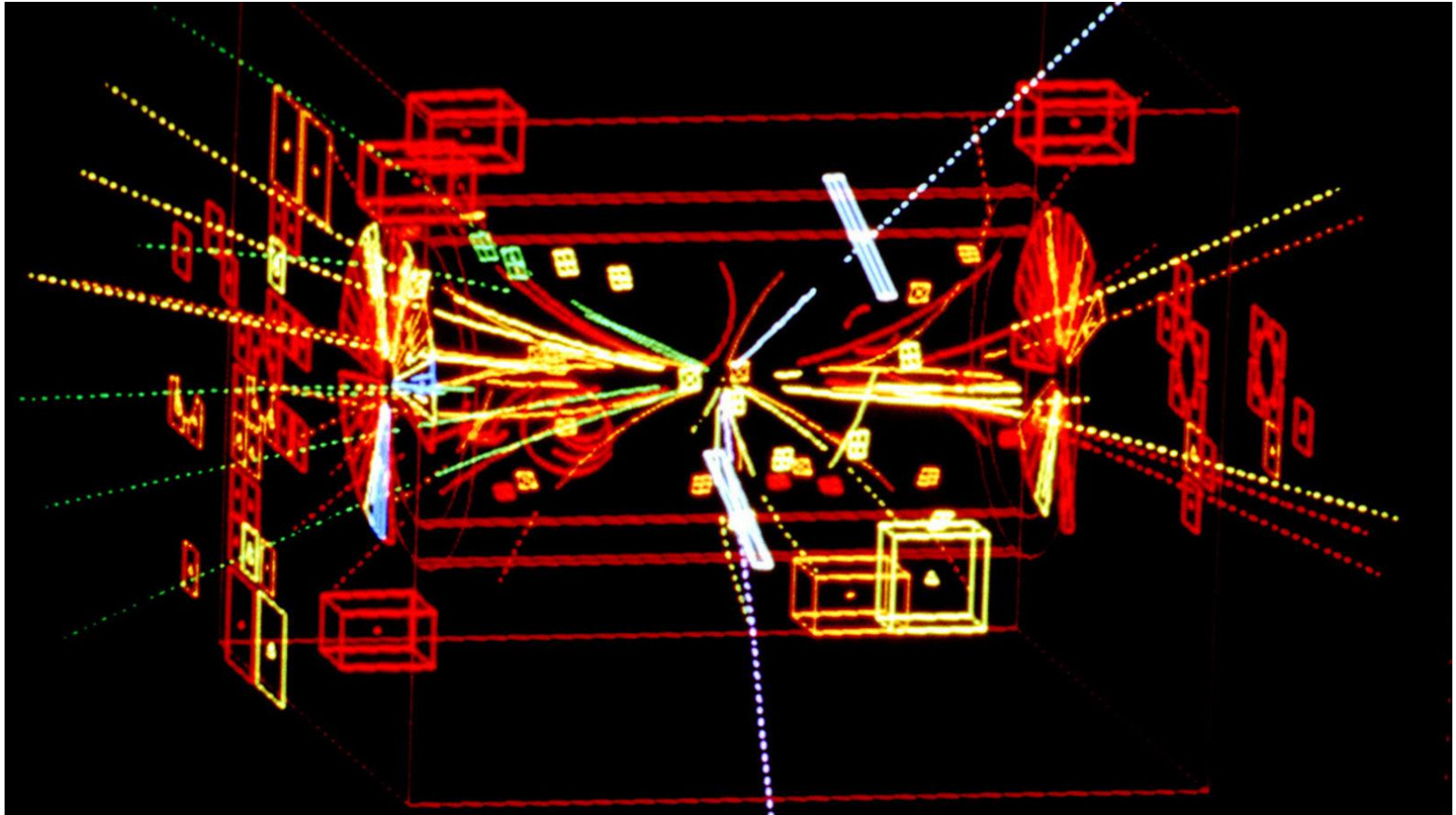
Results from the JADE experiment
 $\sqrt{s} = 34.4 \text{ GeV}$

Analysis of the interference effects
suggested that $M_Z \approx 90 \text{ GeV}$.

Direct Production of W and Z

- In the early 1980's, e^+e^- colliders did not have sufficient energy to produce Z's directly.
- e^+e^- can only produce W^+W^- in pairs, so they certainly didn't have enough energy to produce them.
- It was proposed to turn the CERN SPS into a proton-anti-proton collider
 - Doubles center-of-mass energy for $u\bar{u}, d\bar{d} \rightarrow Z^0$
 - Can produce single W's via $u\bar{d} \rightarrow W^+$ and $\bar{u}d \rightarrow W^-$
 - Technical challenges associated with colliding anti-protons

Observation of W and Z



UA1 experiment at the Sp $\bar{p}$ S
June 1, 1983

Construction of LEP (and SLC)

- Precision studies of the electroweak sector of the standard model motivated building high-energy e^+e^- colliders
- SLAC Linear Collider (SLC):
 - $\sqrt{s} = 91$ GeV collisions (just sufficient to produce Z)
 - Highly polarized electron beam
- Large Electron Positron (LEP) Collider:
 - LEP1 : $\sqrt{s} \approx 91$ GeV
 - LEP1.5: $\sqrt{s} = 130/136$ GeV
 - LEP2: $\sqrt{s} = 161, 172, 183, 189$ GeV (above W^+W^- threshold)