Title: Standard Model Lecture

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Collection: Standard Model 2023/24

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Today: Z decay revisited

Input parameters $\{G_F, m_Z, \alpha\}$

Muon decay / E.F.T. example

e^+e^- vs pp scattering
(LEP) (LHC)

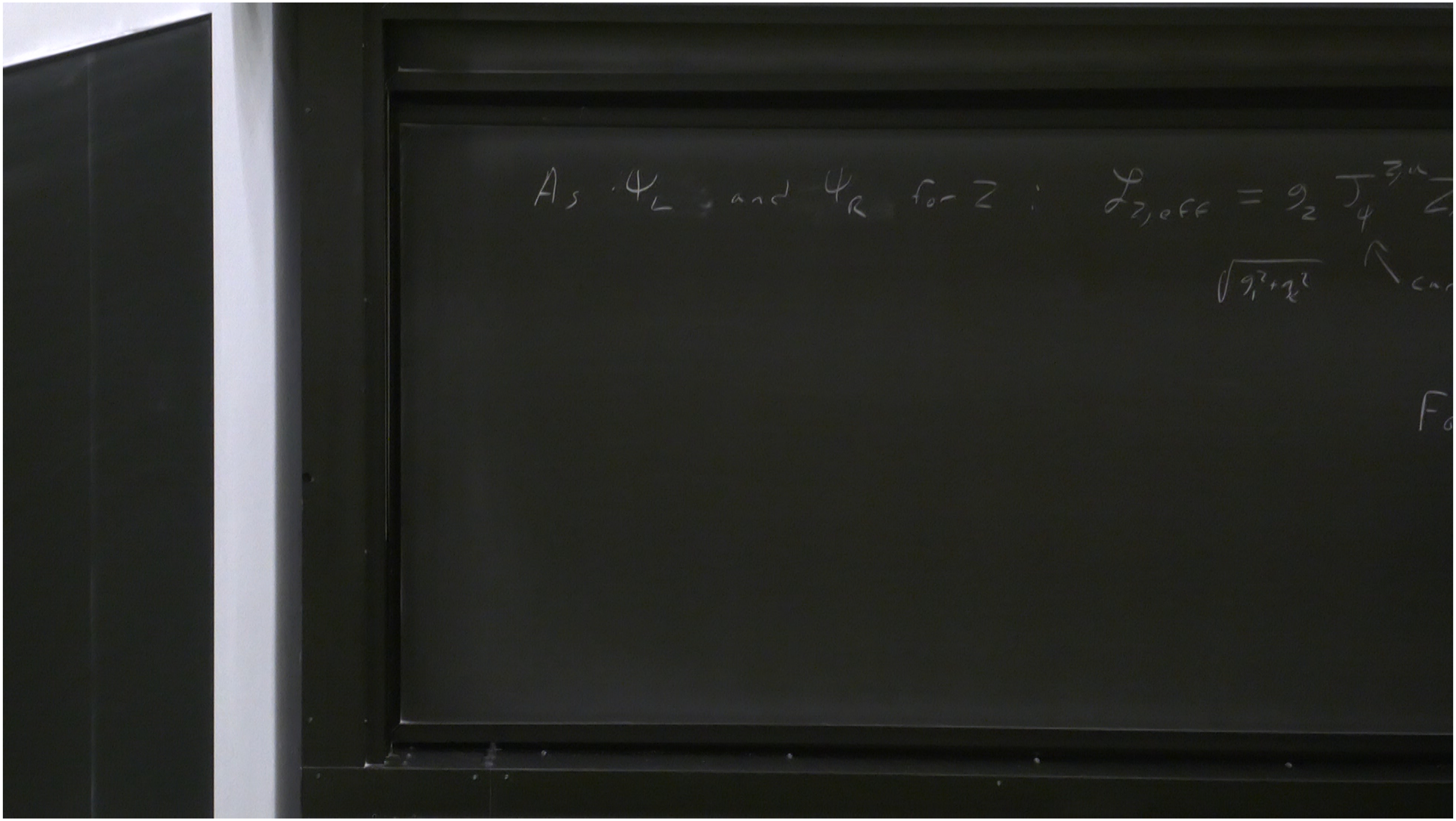
Higgs Production / Decay

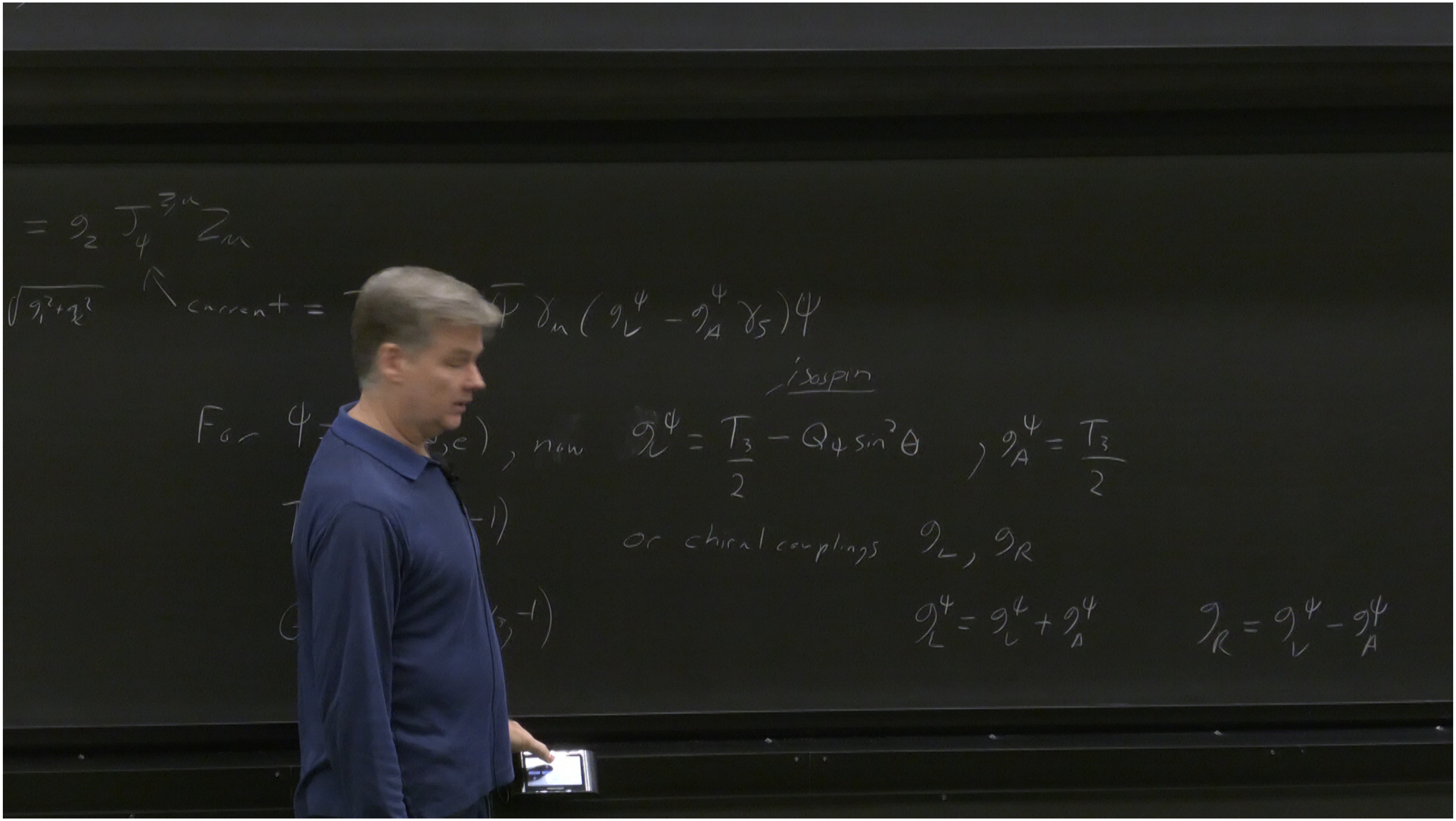
Z Decay Detail $\bar{\psi} i \not{D} \psi \to -\bar{\psi}(T_3^{\psi} - \sin^2\theta Q_{\psi})\gamma_\mu \psi Z^\mu \sqrt{g_1^2+g_2^2}$

for: $\mathcal{L}_{SM} \supseteq \bar{Q}_L i\not{D} Q_L + \bar{u}_R i\not{D} u_R + \bar{d}_R i\not{D} d_R + \bar{L}_L i\not{D}$

W coupling only to $\bar{Q}_L i\not{D} Q_L + \bar{L}_L i\not{D} L_L$

Z coupling both ψ_L, ψ_R fields


As ψL and ψR for Z :
ℒZ,eff = gZ Jψ3,μ
√(g1² + g2²)


$= g_2 J_\psi^{3\mu} Z_\mu$
$\sqrt{g_1^2+g_2^2}$
current $=$ $\bar\psi \gamma_\mu (g_V^\psi - g_A^\psi \gamma_5)\psi$
isospin
For ψ $e)$, now $g_V^\psi = \frac{T_3}{2} - Q_\psi \sin^2\theta$, $g_A^\psi = \frac{T_3}{2}$
or chiral couplings g_L, g_R
$g_L^\psi = g_V^\psi + g_A^\psi$
$g_R = g_V^\psi - g_A^\psi$

Decay

$$\mathcal{L}^{\psi}_{Z,\text{eff}} = g_Z J_\psi^{Z\mu} Z_\mu$$

$\sqrt{g_1^2+g_2^2}$ current $= J_\psi^{Z,\mu} = \bar{\psi}\gamma_\mu (g_V^\psi - g_A^\psi \gamma_5)\psi$

isospin

For $\psi = (u,\nu,d,e)$, now $g_V^\psi = \frac{T_3}{2} - Q_\psi \sin^2\theta$, $g_A^\psi = \frac{T_3}{2}$

$T_3^\psi = \frac{1}{2}(1,1,-1,-1)$

or chiral couplings g_L, g_R

$Q_\psi = (2/3, 0, -1/3, -1)$

$g_L^\psi = g_V^\psi + g_A^\psi$ $g_R = g_V^\psi - g_A^\psi$

$(g_{\text{eff}}^{L,\psi})^2 + (g_{\text{eff}}^{R,\psi})^2$

As Ψ_L and Ψ_R for Z : $\mathcal{L}_{Z,eff} = \bar{g}_2 \, J_\psi^{Z,\mu} Z_\mu$

$\sqrt{\bar{g}_1^2+\bar{g}_2^2}$

current $= J_\psi^{Z,\mu} = \bar{\Psi}$

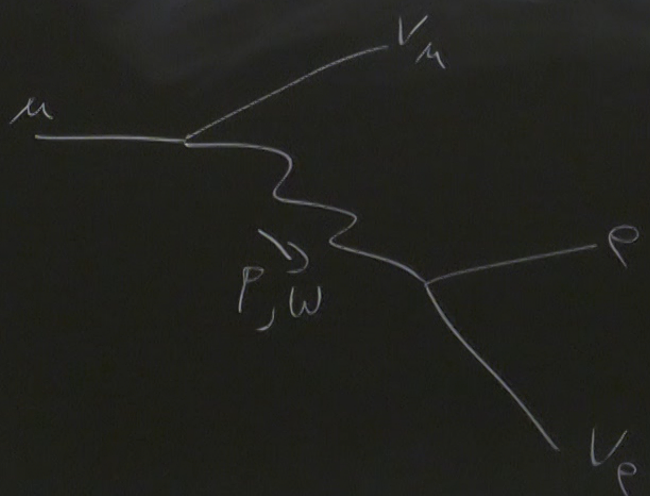
For $\psi = (u, \nu, d, e)$,

$T_3^\psi = \frac{1}{2}(1, 1, -1, -1)$

$Q_\psi = (2/3, 0, -1/3, -$

Input Parameters $(\hat{G}_F, \hat{m}_Z, \hat{\alpha}_{ew})$

Define $\hat{G}_F$ $\quad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$



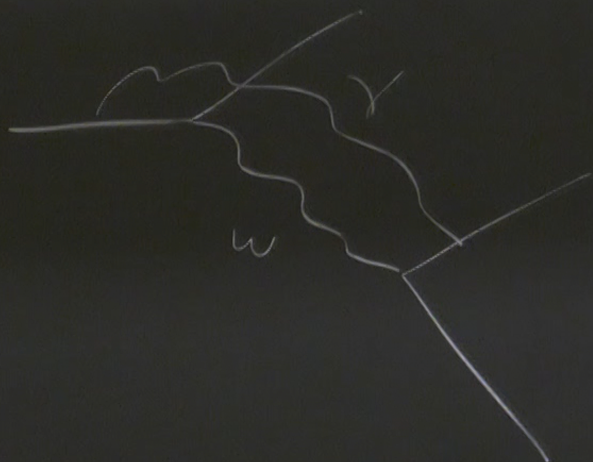
$$iA = -\frac{g_2^2}{2}\left(\bar{\Psi}\gamma_\mu P_L \Psi\right)\left(\bar{\Psi}\gamma_\nu P_L \Psi\right)\left(\frac{-i\,g_{\mu\nu}}{p^2 - m_W^2}\right)$$

, Feynman gauge $\xi = 1$

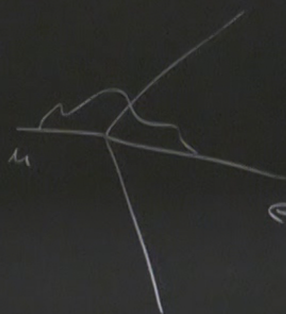
$$\frac{\cancel{(\xi - 1)\,k^\mu k^\nu}}{}$$

$$\Gamma_{\mu\,\text{decay}} = \frac{g_2^4\, m_\mu^5}{(32)(192\pi^3)}\,\frac{1}{(p^2 - m_W^2)^2}$$

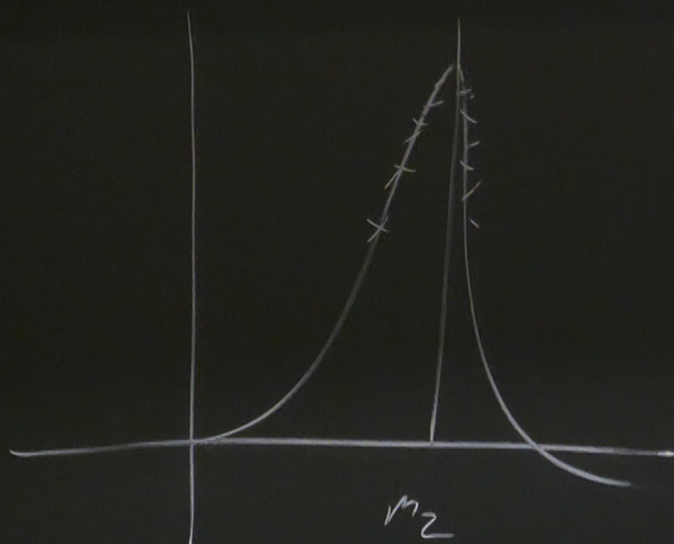
$\approx m_W^2$



expand $\Rightarrow$



1 loop $\rightarrow$ $-\frac{\alpha_{ew}}{4\pi}\left(\pi^2 - \frac{25}{4}\right)$



$$\sigma^2_{\bar\psi\psi} = \sigma^{\text{peak}}_{\bar\psi\psi}\,\frac{s\,\Gamma_Z^2}{(s-m_Z^2)^2+s^2\Gamma_Z^2/m_Z^2}$$

$$m_Z^2 = \frac{(g_1^2+g_2^2)v^2}{4}$$

Expand $-\frac{g_2^2 i}{2}\frac{1}{m_W^2} = -\frac{i g_2^2}{2}\frac{4}{g_2^2 v^2}$ Key Benefit - expand before <u>Integrating</u>

$$= -\frac{i 2}{v^2}$$

$$-\frac{2}{v^2} = -\frac{4}{\sqrt{2}}\hat{G}_F$$

$$iA = -\frac{g_2^2}{2}\left(\bar{\Psi}\gamma_\mu P_L \Psi\right)\left(\bar{\Psi}\gamma_\nu P_L \Psi\right)\left(\frac{-i g_{\mu\nu}}{p^2 - m_W^2}\right)$$

, Feynman gauge $\xi = 1$

$\cancel{(\xi - 1) k^\mu k^\nu}$

$$\mathcal{L}^{eff}_{G_F} \equiv -\frac{4\hat{G}_F}{\sqrt{2}} (\bar{\Psi} \gamma_\mu P_L \Psi)(\bar{\Psi} \gamma_\mu P_L \Psi)$$

Expand

$$(\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e} \gamma_\mu P_L \nu_e)$$

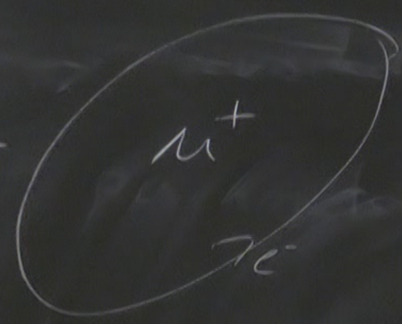
this case μ decay

$$\frac{m_\mu}{m_W} \simeq 10^{-6} \qquad \frac{1}{(m_\mu^2 - m_W^2)^2} = \frac{1}{m_W^4}\left(1 + \overbrace{2\frac{m_\mu^2}{m_W^2}}^{\sim 10^{-6}} + \cdots\right)$$

Input Parameters $(\hat{G}_F, \hat{m}_Z, \hat{\alpha}_{ew})$

$$iA = -\frac{g_2^2}{2}(\bar{\Psi}$$

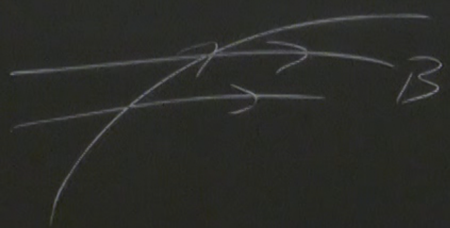
Muonium



Zeeman spin orbit

$\Rightarrow m_e/m_\mu$

IF $m_e \to m_\mu$ use $\Gamma_{\mu\,\text{decay}} \to \nu$



$$F = Q(\vec{E} + \vec{v} \times \vec{B})$$

$$F = ma$$

$$\frac{m_e}{Q_e} = \vec{E} + \vec{v} \times \vec{B}$$

Oil drop experiments

Always a combination of Exp results

$$\bar{\psi} i \not{D} \psi \to -\bar{\psi} (T_3^{\psi} - \sin^2\theta\, Q_\psi)\gamma_\mu \psi Z^\mu \sqrt{g_1^2+g_2^2}$$

$$\bar{Q}_L i\not{\partial} Q_L + \bar{u}_R i\not{\partial} u_R + \bar{d}_R i\not{\partial} d_r + \bar{L}_L i\not{\partial} L_L + \bar{e}_R i\not{\partial} e_R$$

$$\bar{Q}_L i\not{\partial} Q_L + \bar{L}_L i\not{\partial} L_L$$

ψ_L, ψ_R fields

$e^+e^- \to Z \to \bar{\psi}\psi$

"LEP"

$pp \xrightarrow{h} \bar{f}f$

<u>Hadron</u> is a bound state of QCD

$1, 8 \leftarrow r\bar{b}$ overlaps

$$\bar{\psi}_j^{\alpha}\, i g_2 (T^A)_{\alpha}^{\beta}\, \psi^j_{\beta}\, A_A$$

$\beta, \alpha = 1, 2, 3$

3 types colour — red, green, blue

3 types anticolour $\overline{\text{red}}$, $\overline{\text{green}}$, $\overline{\text{blue}}$

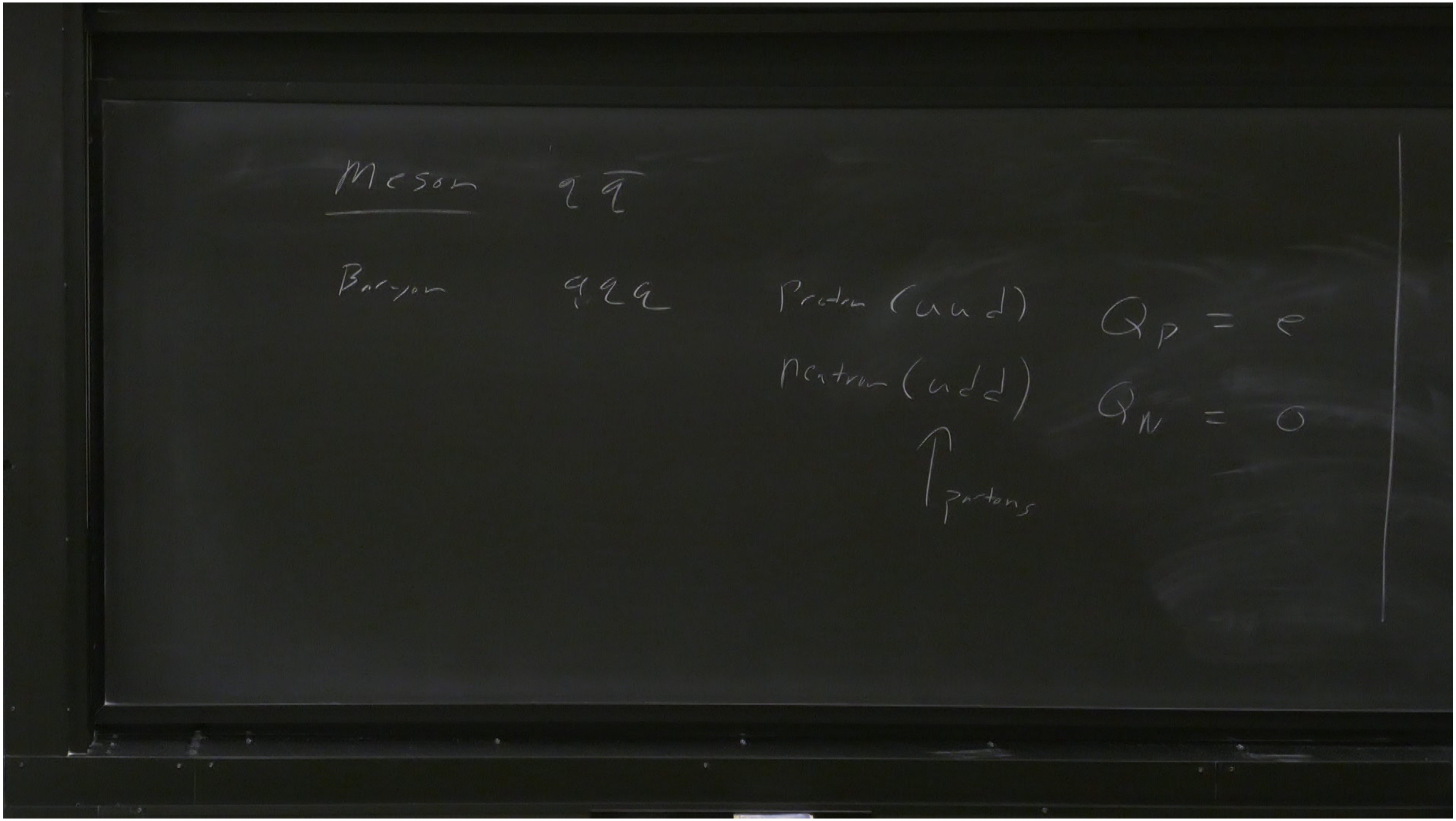
$$= J_\psi^{Z,\mu} = \bar{\psi}\gamma_\mu(g_V^\psi - g_A^\psi\gamma_5)\psi$$

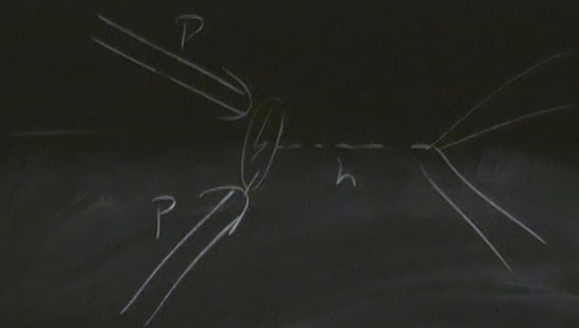
isospin

$$\psi = (u,\nu,d,e), \text{ now } g_V^\psi = \frac{T_3}{2} - Q_\psi \sin^2\theta, \quad g_A^\psi = \frac{T_3}{2}$$

$$T_3^\psi = \frac{1}{2}(1,1,-1,-1) \qquad \text{or chiral couplings } g_L, g_R$$

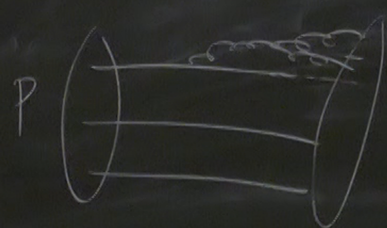
$$Q_\psi = (2/3, 0, -1/3, -1) \qquad g_L^\psi = g_V^\psi + g_A^\psi \qquad g_R = g_V^\psi - g_A^\psi$$


Meson $q\bar{q}$
Baryon qqq
Proton (uud)
neutron (udd)
partons
$Q_p = e$
$Q_N = 0$



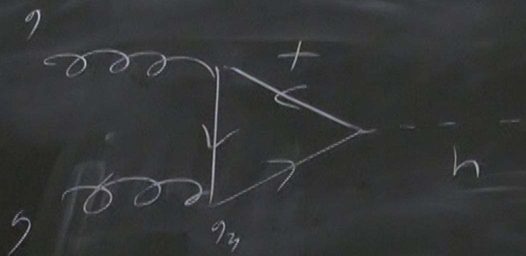
$$\sigma(P,P) = \int dx^1\, f_p^1(x_1,\mu) \int dx^2\, f_p^2(x_2,\mu)\, \sigma(12 \rightarrow \text{final state})$$

parton
distribution
function



$P_1 = x_1\, P_{\text{proton}}$

$P_2 = x_2\, P_{\text{proton}}$



gluon fusion

$$\Gamma(h \to gg) = \frac{\alpha_s^2 G_F}{64\sqrt{2}\pi^2} m_h^2 \left| \sum_\psi F_{1/2}(\tau_\psi) \right|^2$$

$\dots$ m_t, m_h $\quad \tau_\psi = 4m_\psi^2/m_h^2$

$$) = \frac{\alpha_s^2 G_F}{64\sqrt{2}\pi^2} m_h^2 \left| \sum_{\psi} F_{1/2}(\tau_\psi) \right|^2$$

$$F^{\psi}_{1/2} = -2\tau_\psi - 2\tau_\psi(1-\tau_\psi)\Big\{ \text{ar} \ldots$$

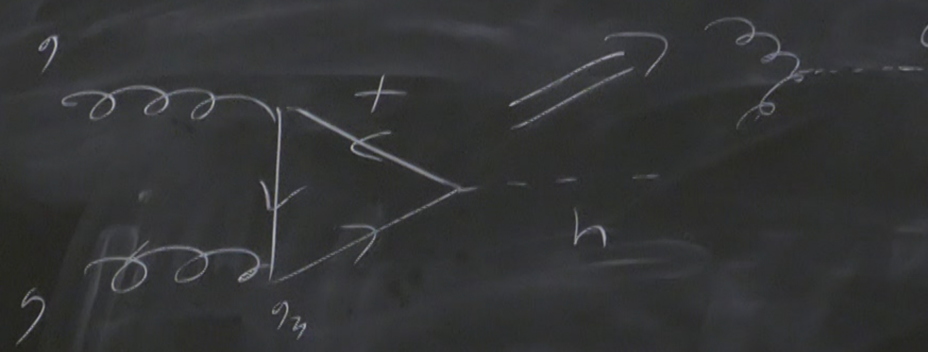
$$- \frac{1}{4} (\ldots$$

$$m_t, m_h \qquad \tau_\psi = 4m_\psi^2/m_h^2$$

$$\Rightarrow -2$$

top $\tau > 1$ $\quad m_t = 173\,\text{GeV}$

$m_h = 125\,\text{GeV}$



$c\, G_A^{\mu\nu} G^A_{\mu\nu} \frac{h}{v}$ ← dim 5

$$\Gamma(h\to gg) = \frac{\alpha_s^2 G_F}{64\sqrt{2}\pi^2} m_h^2 \Big| \sum_q F_{1/2}($$

gluon fusion

m_t, m_h

top $\tau > 1$ $\quad m_t =$

$m_h =$