BBSM Neutrino Course

Lecture XII

LMU

Spring 2020

It's neutrino, stupid!

$\boxed{\text{Colliders}}$

hadron

$p - p$

$p - \bar{p}$

lepton

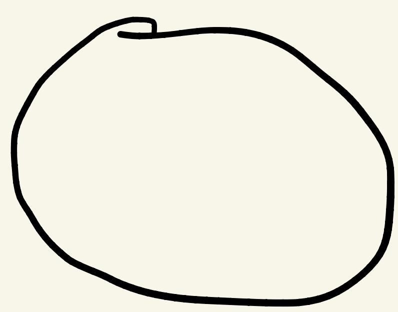
$e - \bar{e}$

$\boxed{\mu - \bar{\mu} \ ?!}$

Proposal

linear vs circular

hard to $E \uparrow$



$E \uparrow$

$$E_{loss} \propto a^2$$

$$a = m \frac{dp}{d\tau} = m\gamma \frac{dp}{dt}$$

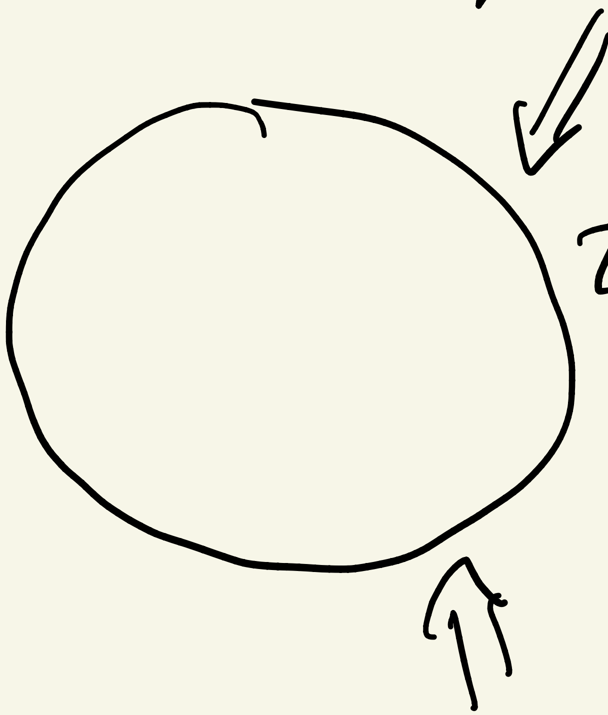
$$= m\gamma \frac{d}{dt}(\gamma m v)$$

$$\propto \gamma^2$$

$$\Rightarrow \boxed{E_{loss} \propto \gamma^4 = E/m^4}$$

$$\frac{E_{loss}\ e\text{-}\bar{e}}{E_{loss}\ p\text{-}\bar{p}} \simeq 10^{12}\ !$$

LEP Large Electron Positron



$$\boxed{E \simeq 209\ \text{GeV}}$$

LHC Large Hadron Collider

$$E = 13\ \text{TeV} \rightarrow 14\ \text{TeV}$$

LEP High precision SM

$$M_W,\ M_t \sim 1/10^3\ !$$

$$\Gamma_W,\ \Gamma_Z \leftarrow \#\nu$$

hadron colliders | lepton collider

$\parallel$ | $\parallel$

discovery | precision

$\boxed{E = 13\ \text{TeV}}$

$\xrightarrow{\quad}$ $\xleftarrow{\quad}$

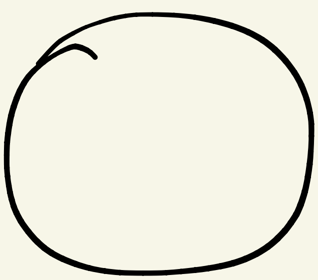
e $e(\bar{e})$ E uncertainty

$\boxed{100\ \text{GeV} - 5\ \text{TeV}}$

$\boxed{\text{Hadron}}$

$\boxed{\text{CERN}}$

SPS – super proton synchrotron



· 7km

300 GeV

W, Z in 83!

injection

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 M_W^2} \qquad \boxed{\underset{\text{em}}{e} = \underset{\text{weak}}{g} \sin\theta_W}$$

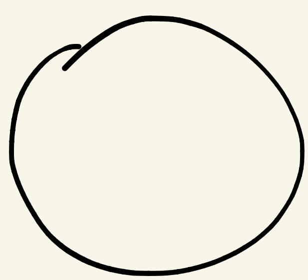
$$= \frac{e^2 \,(= 4\pi\alpha)}{8\,(\sin\theta_W M_W)^2} \qquad \theta_W \simeq 30^\circ$$

$$\Rightarrow \sin\theta_W M_W = 40\,\text{GeV}$$

$$\Rightarrow \boxed{M_W = 80\,\text{GeV}}$$

<u>Tevatron</u> (Fermilab) '96

$E \simeq \text{TeV}$



6 km

$\boxed{\text{top quark!}}$

$\boxed{m_t \simeq 175\,\text{GeV}}$

$\boxed{\text{SLAC}}$

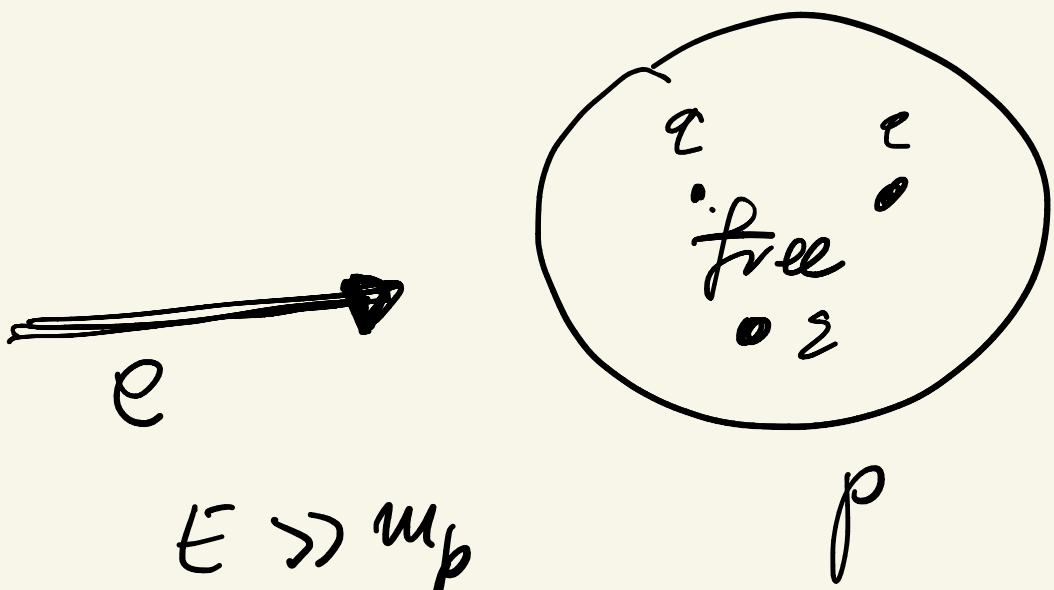
3 km

$e\text{-}\bar{e}$

- charm '74 $J/\psi = c\bar{c}$
- tau lepton '77
- **quarks**

$\boxed{\text{'67 - '68}}$

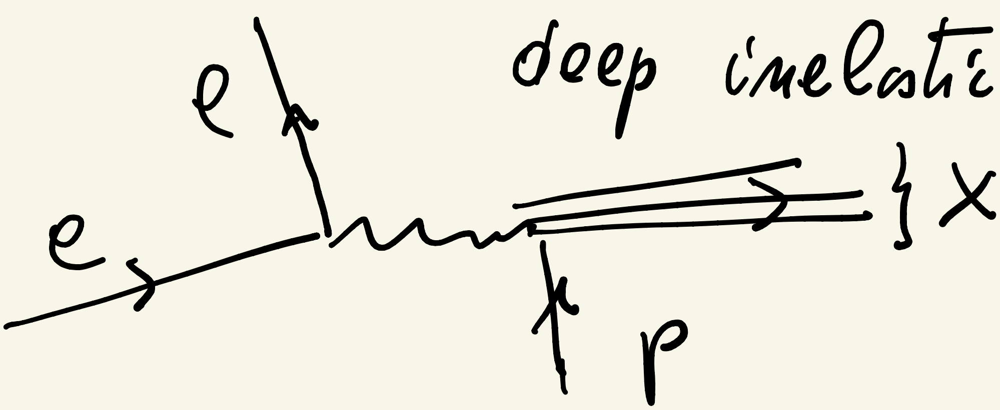
Kendall
Taylor
Friedman



$r \sim \frac{1}{E}$

$E \gg m_p$

deep inelastic scattering



Bjorken

nucleus

Marsden, Geiger – exp

explanation Rutherford

· quarks = confined

but

$e \rightarrow p \iff$ quarks are free

$E_e \gg m_p$

$\boxed{\text{Asymptotic freedom (AF)}}$

Gross, Wilczek,
Politzer '73
't Hooft '72

Coupling "constants" $\neq$ constant

$\Rightarrow \alpha(E)$ couplings "run" with E

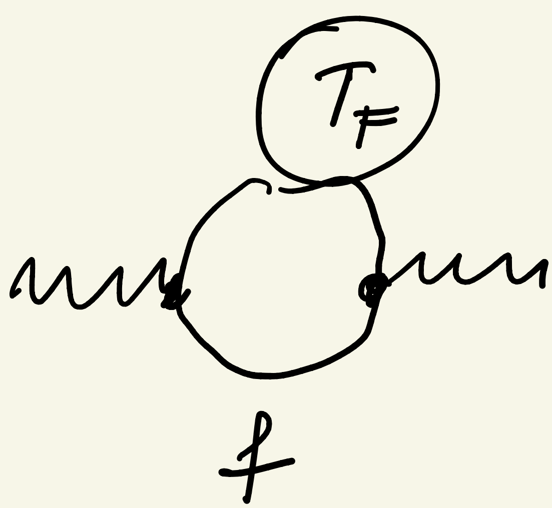
$$\boxed{\frac{1}{\alpha(E_2)} - \frac{1}{\alpha(E_1)} = \frac{b}{2\pi} \ln E_2/E_1}$$

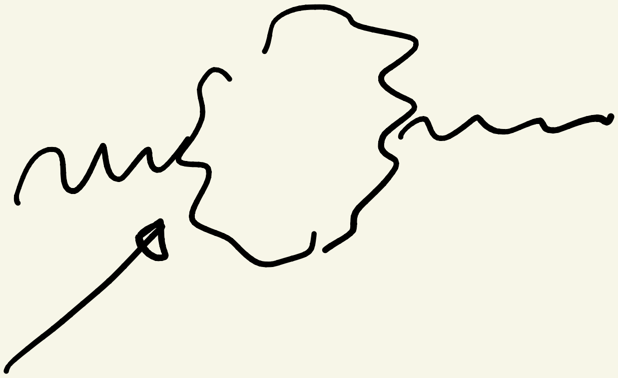
"crawling"

$$b = \frac{11}{3} T_{GB} - \frac{2}{3} T_F - \frac{1}{3} T_S$$

T_{GB} = gauge boson, T_F = fermion, T_S = scalar

gauge boson $\downarrow$ positive



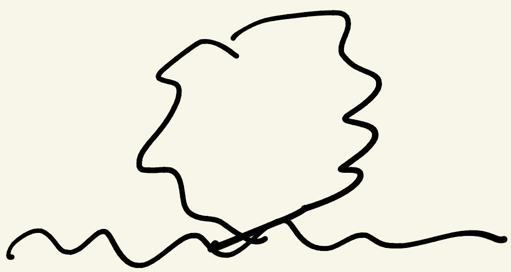


$= YM$

non-Abelian

f_{abc} $\quad [T_a, T_b] = i f_{abc} T_c$

$SU(2)$: $f_{abc} = \epsilon_{abc}$



$E \gg m_p$ — deep inelastic

$m_p \simeq \Lambda_{QCD}$ $\quad \boxed{E \to 20\,\text{GeV}}$

Λ_{QCD} = energy ∴ α_s = large

- $\alpha_s = \alpha_{QCD} = \alpha_3 \qquad SU(3)_c$

$$\boxed{\text{gauge theory} - \text{group } G}$$

$$\mathcal{L}_D = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi - m\bar{\Psi}\Psi$$

$$\Psi \to U\Psi \qquad U = e^{i\Theta_a T_a}$$

$$[T_a, T_b] = i f_{abc} T_c$$

$$UU^+ = 1$$

$$\Theta = \Theta(x) \Rightarrow D_\mu = \partial_\mu - ig\overbrace{A_\mu^a T_a}^{A^a}$$

$$D_\mu\Psi \to U D_\mu \Psi =$$

$$= U D_\mu U^+ U \Psi$$

$$[D_\mu, D_\nu] \to U[D_\mu, D_\nu]U^+$$

$$F_{\mu\nu} \propto [D_\mu, D_\nu] \qquad f_{abc} A_\mu^b A_\nu^c T_a$$

$$= \partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu]$$

QED: $A_\mu^a T_a \to A_\mu Q \Rightarrow$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\boxed{QCD = SU(3)_c}$$

$\boxed{AF}$ $\Rightarrow$ quarks $\to$ free at high E

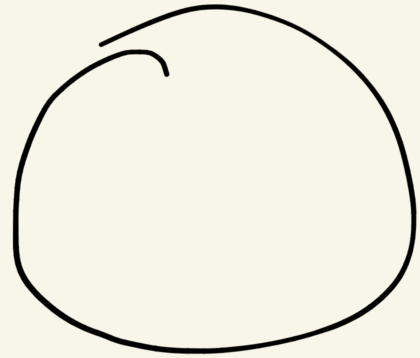
$E \simeq M_W$!

$$\alpha_{em} \simeq 1/120$$

$$\alpha_w = \alpha \simeq 1/30$$

$$\alpha_s \simeq 1/10$$

$\boxed{\mu-\bar{\mu} \text{ collider}}$



$\tau_\mu \simeq 10^{-6}$ sec

$m_\mu = 200\, m_e$

TeV

$$\frac{E_{\text{loss muon}}}{E_{\text{loss electron}}} \simeq 10^{-9}$$

$$\tau_\mu(E = \text{TeV}) = \left(\frac{\text{TeV}}{m_\mu}\right) 10^{-6}\ \text{sec}$$

$$\simeq 10^{-2}\ \text{sec}$$

$\boxed{\text{Luminosity}}$

$$\frac{dN}{dt} = L \cdot \sigma$$

$\frac{dN}{dt}$ = $\frac{\#\ \text{of events}}{\text{sec}}$

L = luminosity — machine

σ = physics cross section

SPS : 10^{30} $1/\mathrm{cm}^2\mathrm{sec}$

LEP, Tevatron : 10^{32} – " –

LHC : 10^{34} – " –

$\hookrightarrow 10^{35}$ final

$\boxed{\text{Higgs discovery}}$

$\boxed{\text{LEP}}$ Higgs particle

$$\boxed{h\left[g\frac{m_f}{M_W}\bar{f}f + g M_W W_\mu^+ W^{\mu-} + \frac{g}{\cos\theta_W} M_Z Z_\mu Z^\mu\right]}$$

$$W_\mu^\pm = \frac{(A_1 \mp i A_2)_\mu}{\sqrt{2}}$$

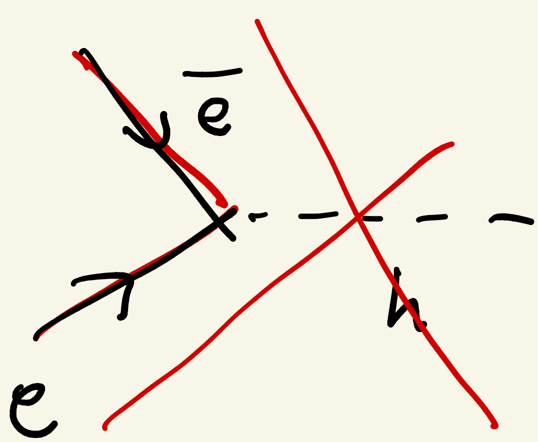
$$Z^\mu = -\cos\theta_W A_3^\mu + \sin\theta_W B^\mu$$

$$A^\mu = \sin\theta_W A_3^\mu + \cos\theta_W B^\mu$$

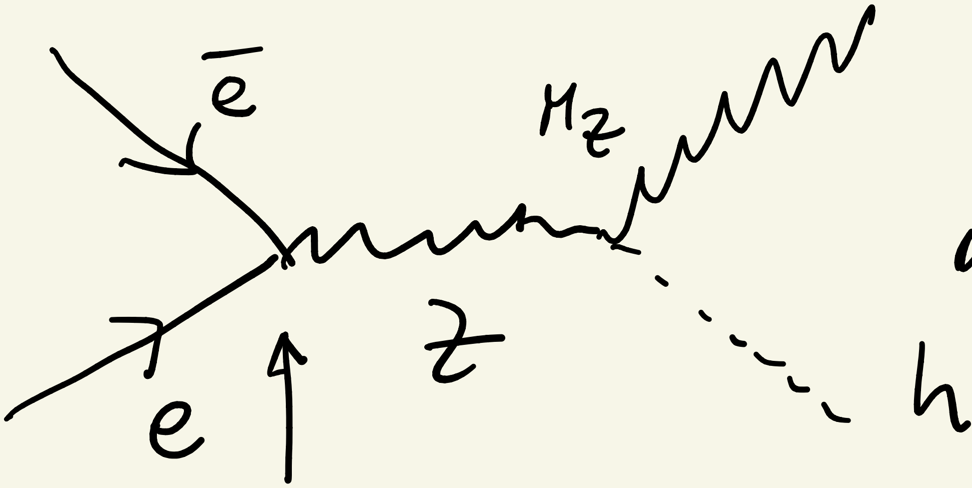
$$\tan\theta_W = g'/g \qquad \overset{g}{SU(2)_L} \times \overset{g'}{U(1)}$$

$$D_\mu = \partial_\mu - i g T_a A_\mu^a - i g' \frac{Y}{2} B_\mu$$

$$\frac{Y}{2} = (Q - T_3)$$



but $\frac{m_e}{M_W} \simeq 10^{-5}$ $(g=1)$



$g = O(1)$

$M_Z = 90\,\text{GeV}$

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

$m_h + M_Z \simeq 215\,\text{GeV}$

$\boxed{E_{LEP} = 209\,\text{GeV}}$

just (barely) missed!

Tevatron $\quad p - \bar{p}$

quarks
glue

proton

gluons

$\underbrace{SU(3)}$

$D_\mu = \partial_\mu - g_s A_\mu^\alpha T^\alpha$

$\alpha = 1, \ldots, 8$

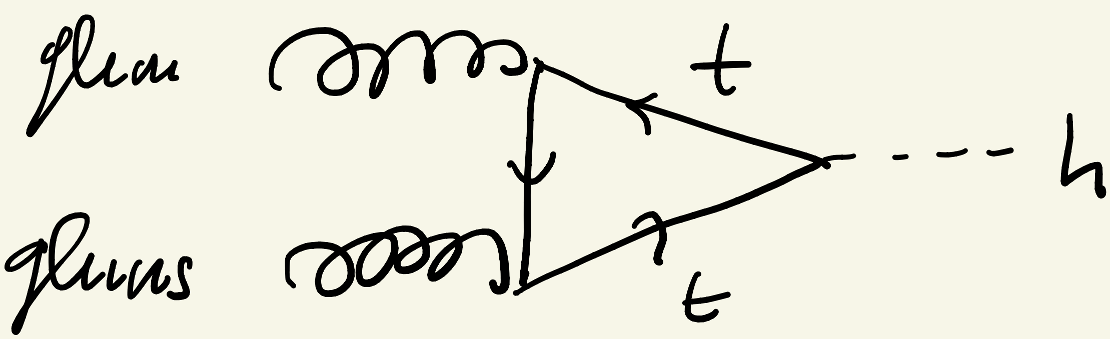
$m_{glue} = 0$ (gluon)

$m_A = 0$ (photon)

<u>but</u> h does not couple to A, gluon!

<u>caveat</u> loops!

$$h \bar{t} t \left(g \frac{m_t}{M_W} = 1 \right)$$



$\Uparrow$

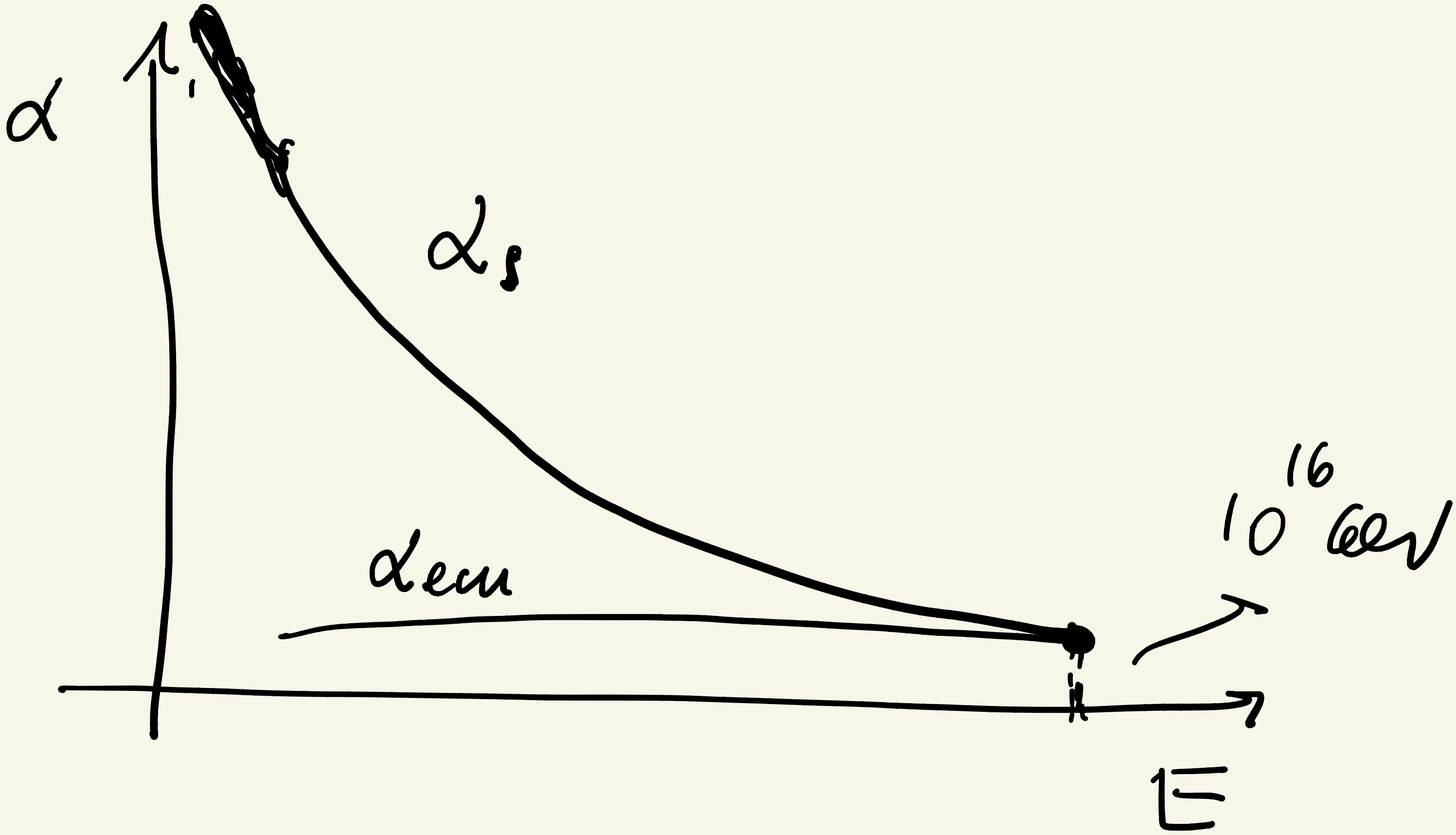
gluon fusion

main Higgs production @ LHC

$$\frac{dN}{dt} = L \cdot \sigma$$

Tevatron just missed!

$$L_{LHC} = 100\ L_{Tevatron}$$



$$\frac{1}{\alpha(E_2)} - \frac{1}{\alpha(E_1)} = \frac{b}{2\pi} \ln E_2/E_1$$

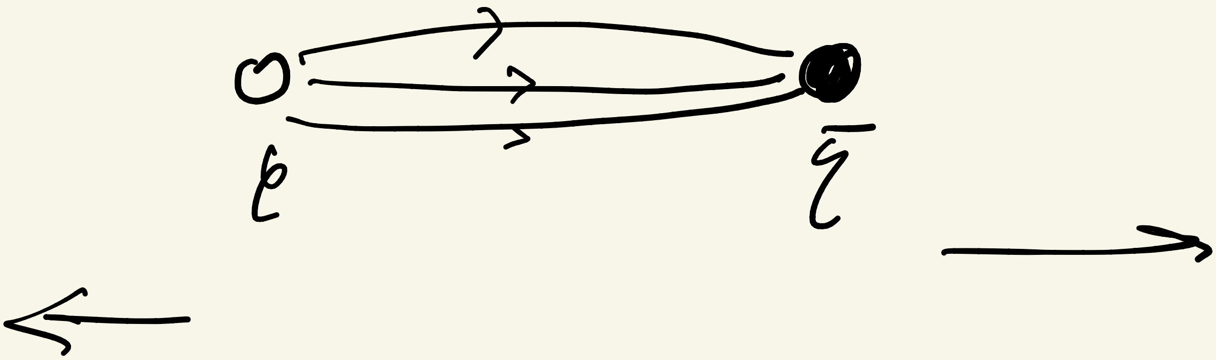
$$b = \frac{11}{3}(g.b) - \frac{2}{3}(f) - \frac{1}{3}(s)$$

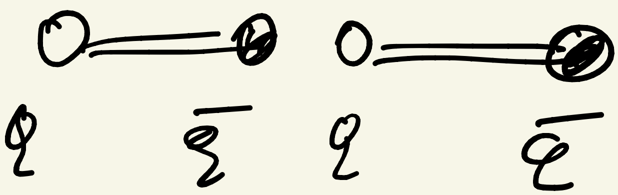
$\updownarrow$

$b > 0$ non-Abelian nature

$$\boxed{\begin{array}{c} \alpha_s \longrightarrow \infty \\ E \to 0 \end{array}}$$

$$V_{QCD}(r) \simeq r \,, \quad \text{large } r$$





favored

<u>Theory of physical phenomena</u>

1/28

<u>Dirac</u> – linear eq for $E \gg m_e$

$\Downarrow$

spin $\to$ $\boxed{\text{positron}}$ '31

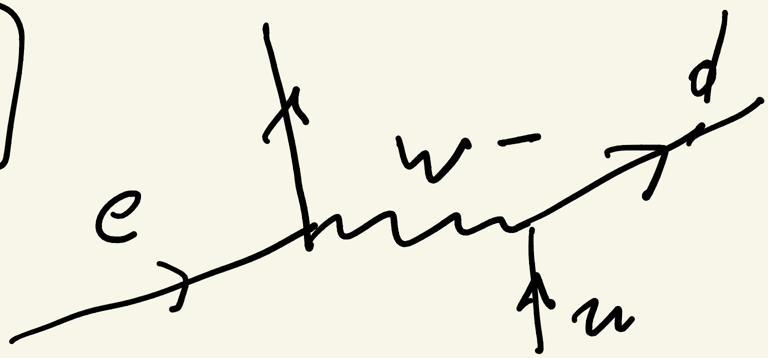
- **Newton** $\Rightarrow$ univ. theory of gravity

- Einstein $\quad T_{\mu\nu}$ - gen. of mass

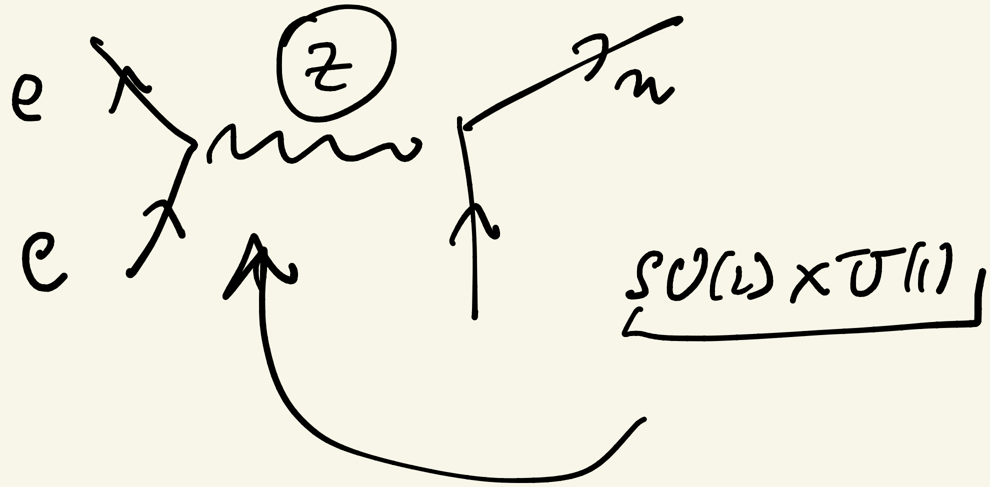
$T_{00} = \rho$ (mass density)

$$\boxed{\begin{aligned} \Box h_{\mu\nu} &\propto T_{\mu\nu} \\ \Box A_\mu &\propto j_\mu \end{aligned}}$$

- $\boxed{\text{SM}}$



weak



$$\frac{g Z_\mu}{\cos\theta_W} \bar{f} \gamma^\mu \left[T_3 - Q \sin^2\theta_W \right] f$$

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seesaw mechanism

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad \because \quad m_\nu \leq 10^{-6} m_e$$

$$e_R, \ \nu_R = C \bar{N}_L^T$$

$$\Downarrow$$

$$\boxed{\begin{gathered} M_\nu = - M_D^T \frac{1}{M_N} M_D \\ \Leftrightarrow \quad \nu^T C \nu = \text{Majorana} \\ \Downarrow \\ \Delta L = 2 \end{gathered}}$$

- $$\theta_{\nu N} = \frac{1}{M_N} M_D$$

  how to produce N with small $\theta_{\nu N}$?

- $$M_D = i \sqrt{M_N}\, O \sqrt{M_\nu}$$

  $$O^T O = 1 \,, \quad O \in \mathbb{C}$$

$$\boxed{\text{Imagine}}$$

- N has new gauge int.

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_L \qquad\qquad \begin{pmatrix}N\\ e\end{pmatrix}_R \Longleftrightarrow \begin{pmatrix}\nu\\ e\end{pmatrix}_R$$

$$e_R$$

$$\underbrace{e_L + e_R}_{\text{photon}}$$

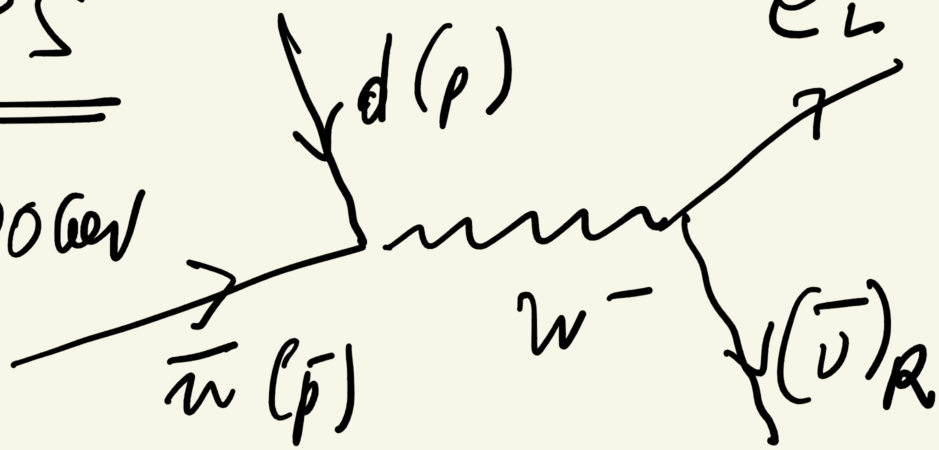
$$e_L^c \equiv C\bar{e}_R^{\,T}$$

<u>means</u>

$$\frac{g}{\sqrt{2}}\,\bar{\nu}_L \gamma_\mu e_L W^+_{\mu L} \Longleftrightarrow \frac{g}{\sqrt{2}}\,\bar{N}_R \gamma^\mu e_R W^+_{\mu R}$$

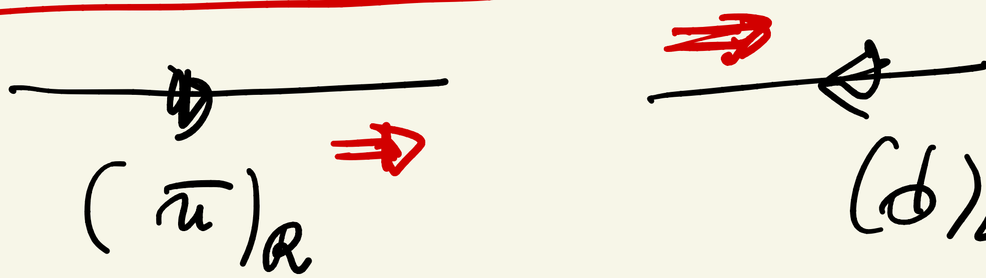
SPS

$E = 300\,\text{GeV}$



$$\boxed{m_u \simeq m_d \simeq \text{MeV} = 0}$$

$h\, d_L = -\frac{1}{2} d_L$



$h\, \bar{u}_R = +\frac{1}{2} \bar{u}_R$

z axis

$$\boxed{S_z(W) = -1}$$

$$\frac{d\Gamma}{d\Omega} \propto (1 + \cos\theta)^2$$

$\boxed{\text{electron}}$

DISCOVERY of W!

$$\boxed{\Gamma_W \simeq \alpha_W M_W}$$

$$W^- \to \begin{cases} \bar{u}\, d \\ e\, \bar{\nu} \end{cases}$$

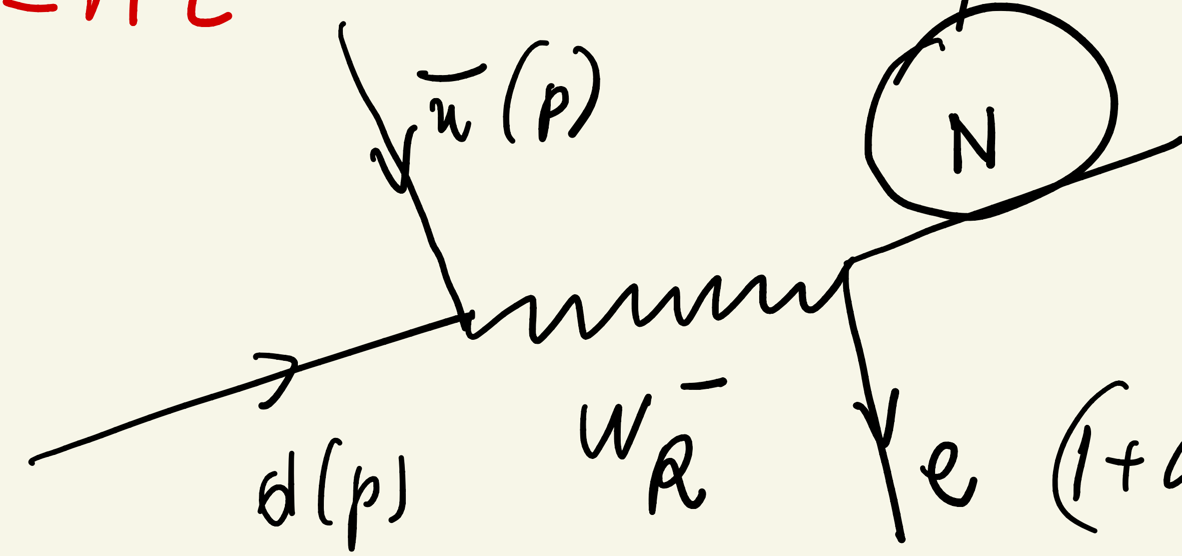
$\alpha_W \simeq 1/30$

$M_W = 80\ \mathrm{GeV}$

$$\boxed{\Gamma_W (\mathrm{exp}) \simeq 2\ \mathrm{GeV}}$$

LHC

Majorana lepton



$(1+\cos\theta)^2$

$$\boxed{m_N \ll M_{W_R}}$$

$$\boxed{N = \text{Majorana}}$$

$$\underbrace{\nu_L^T C \nu_L}_{\text{Lorentz inv.}}$$

$$\downarrow$$

$$\underbrace{N_R^T C N_R}_{\text{Lorentz inv.}}$$

$$\overline{e_R}\,\gamma^\mu N_R\, W_{R\mu}^- + \underbrace{\overline{N_R}\,\gamma^\mu e_R\, W_{R\mu}^+}$$

$$\boxed{\overline{N_R}\,\gamma^\mu e_R = \overline{(e^c)_L}\,\gamma^\mu (N^c)_L} \quad (\pm)$$

Proof:

RHS

$$\Downarrow$$

$$\boxed{(\psi^c)_L \equiv C\,\overline{\psi_R}^T}$$

$$\overline{e^c}_L \gamma^\mu N^c_L \equiv \overline{C \overline{e_R}^T} \gamma^\mu C \overline{N_R}^T$$

$$= \left[C(e_R^\dagger \gamma^0)^T\right]^\dagger \gamma^0 \gamma^\mu C \overline{N_R}^T$$

$$= (C \gamma_0 e_R^*)^\dagger \gamma^0 \gamma^\mu C \overline{N_R}^T$$

$$= e_R^T \gamma_0 C^\dagger \gamma^0 \gamma^\mu C \overline{N_R}^T$$

$$\boxed{\begin{aligned} C^\dagger &= C^T \\ &= -C \end{aligned}}$$

$C \equiv i\gamma_2\gamma_0$

$$= e_R^T \underbrace{(-C^T)\gamma^\mu C}_{\equiv\ \gamma_\mu^T \text{ (def. of } C)} \overline{N_R}^T$$

$$= e_R^T (\gamma^\mu)^T \overline{N_R}^T = -\overline{N_R} \gamma^\mu e_R$$

QED

$\Downarrow$

$$\overline{e_R}\gamma^\mu N_R W^-_{\mu R} + (-)\overline{e^c_L}\gamma^\mu N^c_L W^+_{\mu R}$$

$$\boxed{\begin{aligned} N_M &= N_L + C\overline{N_R}^T \\ N_M &= N_M^c \end{aligned}}$$

$$\overline{e_R}\gamma^\mu N_R W^+_{\mu R} - \overline{e^c_L}\gamma^\mu N_L W_{\mu R}$$

R $\Downarrow$ L

Γ does not depend on whether $L(R)$

$\Downarrow$

$$\Gamma(N \to e + W_R^+) = \Gamma(N \to e^c + W_R^-)$$

LHC

N = Majorana

Keung, GS, '83

• $M_D^T = M$ Unique (*)

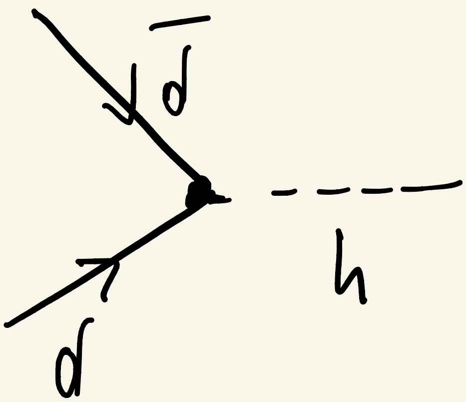
untangle seesaw

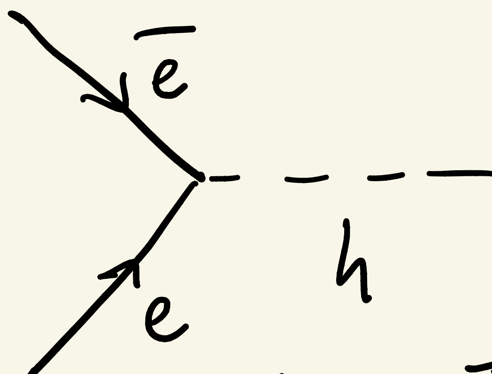
Prove: $M_D = f(M_\nu, M_N)$ (**)

$$\Longleftrightarrow \quad O = \text{fixed}$$

$$M_D = i\sqrt{M_N}\, O \sqrt{M_\nu}$$

$$\boxed{\text{Compute } M_D} \; !$$





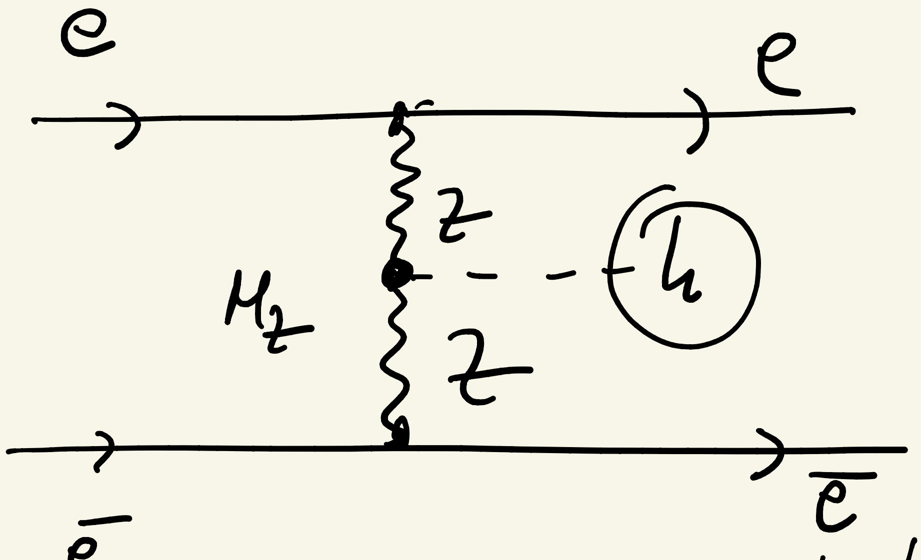
$$g\frac{m_d}{M_W} = 10^{-4} \qquad\qquad g\frac{m_e}{M_W} = 10^{-5}$$

$$\sigma(h) \simeq 10^{-8} \ldots \qquad\qquad \sigma(h) \simeq 10^{-10}$$

$$\frac{dN}{dt} = L \cdot \sigma \longleftarrow \text{small}$$

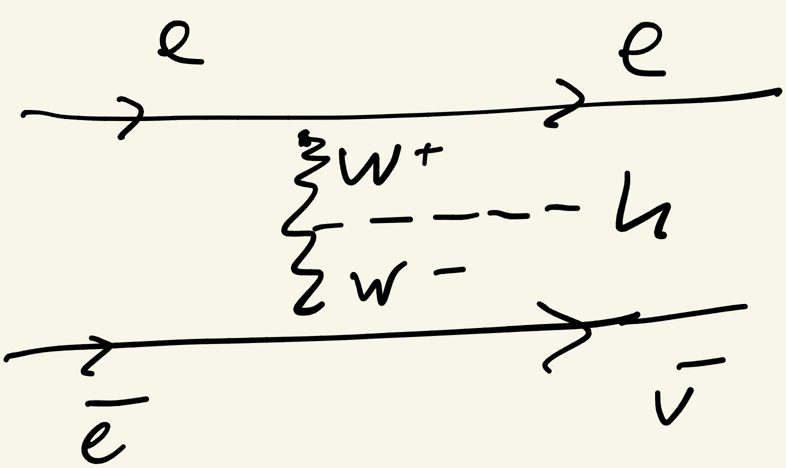
not so small

$\boxed{\text{Answer}}$ $\boxed{\text{Yes, it is } \underline{\text{so}} \text{ small}}$



$$g\, M_Z\, Z_\mu Z^\mu h$$

$\boxed{\text{Still } \sigma \text{ is too small!}}$



$\boxed{\text{help!}}$

$$h f \bar{f} \quad g \frac{m_f}{M_W}$$

$$h \to f \bar{f} \propto m_f^2$$

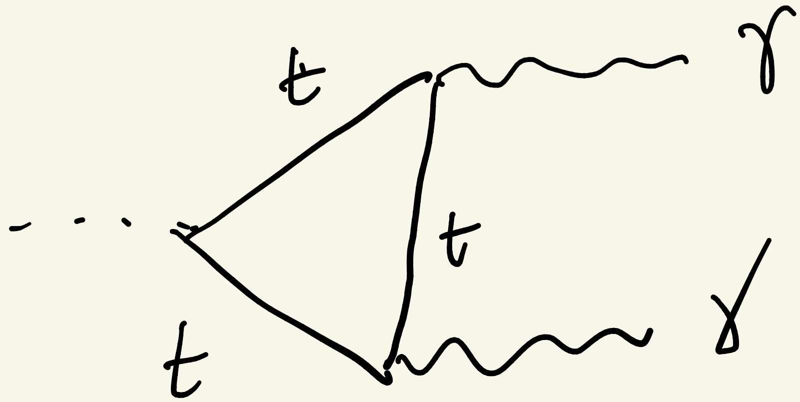
$\underline{\text{LHC}}$ $\underline{\underline{\text{ur}}}$ hope to check Higgs mechanism for 1st

$$h \Rightarrow b\bar{b} \quad W^+W^{-*}$$
$$\tau\bar{\tau} \quad ZZ^*$$

$\boxed{\text{discovery}}$ $(h \to \gamma\gamma)$ $BR \simeq 10^{-3}$

July 2012

62.5 GeV 62.5 GeV



$h \to b\bar{b}, \; t\bar{t}, \; W^+W^-, \; ZZ$

$\tau\bar{\tau}$