UCLouvain
Institut de recherche en mathématique et physique
Centre de Cosmologie, Physique des Particules et Phénoménologie

Electroweak and Higgs phenomenology including EFT

Celine Degrande

Plan

- Electroweak interaction
  - Beta decay and Fermi theory
  - Parity violation
  - Weak algebra and neutral currents
  - Electroweak theory
- Spontaneous symmetry breaking
  - U(1)
  - SM
  - Fermions masses
- Effective field theory
  - Introduction
  - Non-interference and revival
  - CP example

Exercices in purple by hand and in MadGraph

Connection to pheno along the way

Questions

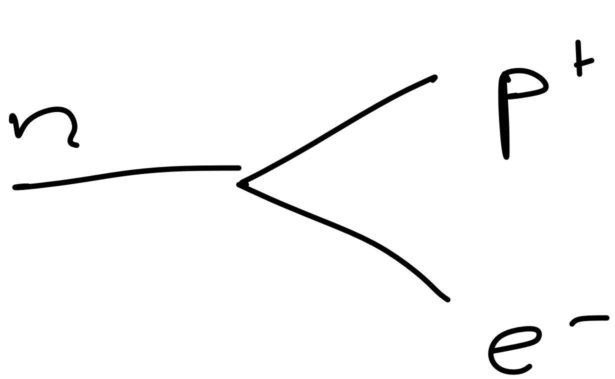
- Does the weak interaction explain why there are rocky planets?
- Is the proportionality of the Higgs to fermion couplings to their masses due to
  - Parity
  - Gauge invariance
  - Spontaneous symmetry breaking
- Why are they so many muons produced by cosmic rays in the atmosphere?

Questions

- Why is the proton stable and not the neutron?
- Why is neutrino detection due mainly to nucleons and not electrons?
- Can the W and Z masses being predicted from low energy data?

Electroweak interaction

Beta decay

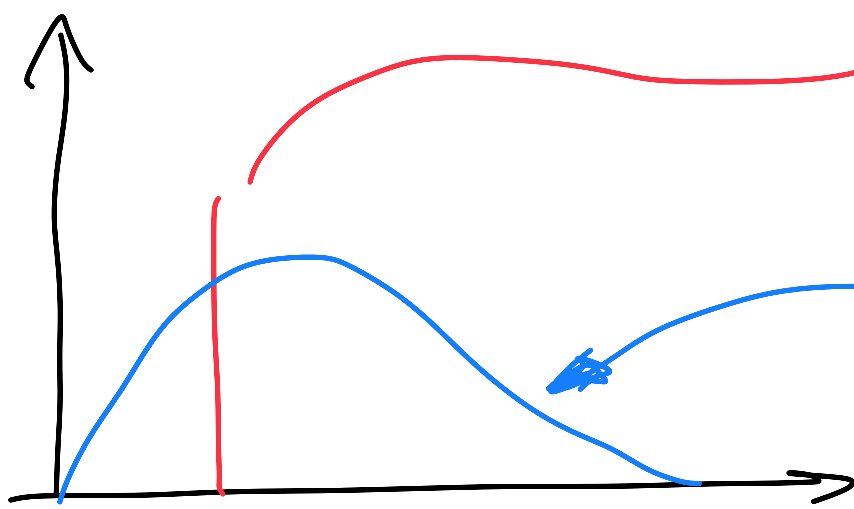


$1 \rightarrow 2$

Ex: $p_n = p_p + p_e$

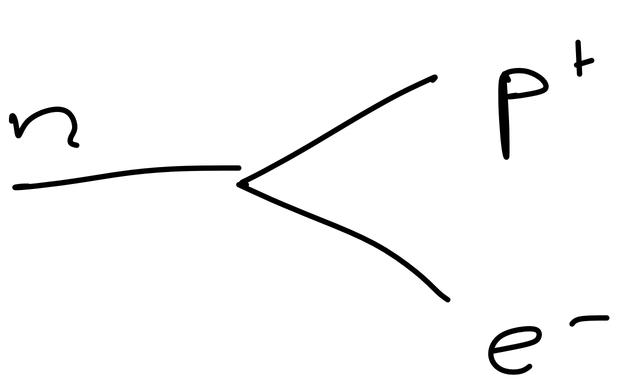
$$E_e^2 = \frac{(m_n^2 - m_p^2 + m_e)^2}{2 m_n} \longrightarrow m_e^2$$

$m_n \rightarrow m_p + m_e$



Pauli (1930) : + neutrino

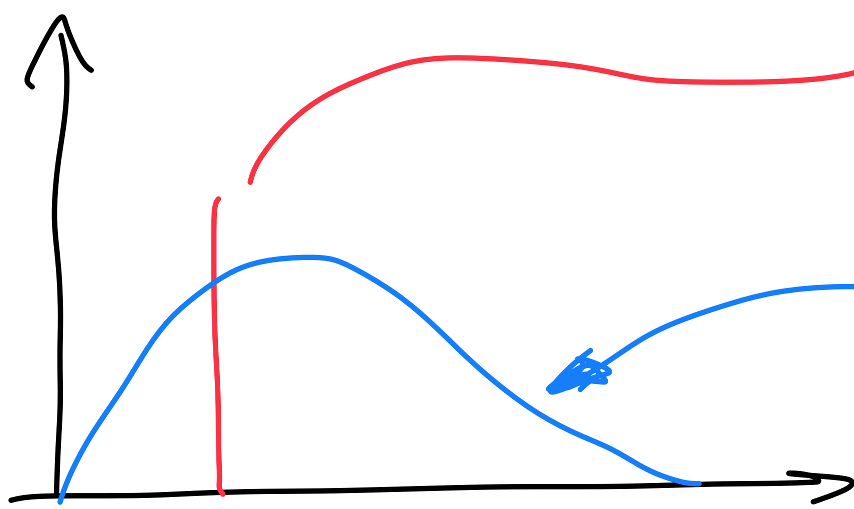
Beta decay



$1 \to 2$

Ex: $p_n = p_p + p_e$

$$E_e^2 = \frac{(m_n^2 - m_p^2 + m_e)^2}{2 m_n} \xrightarrow[m_n \to m_p + m_e]{} m_e^2$$



E and Spin conservation

Pauli (1930) : + neutrino

Fermi theory (1933)

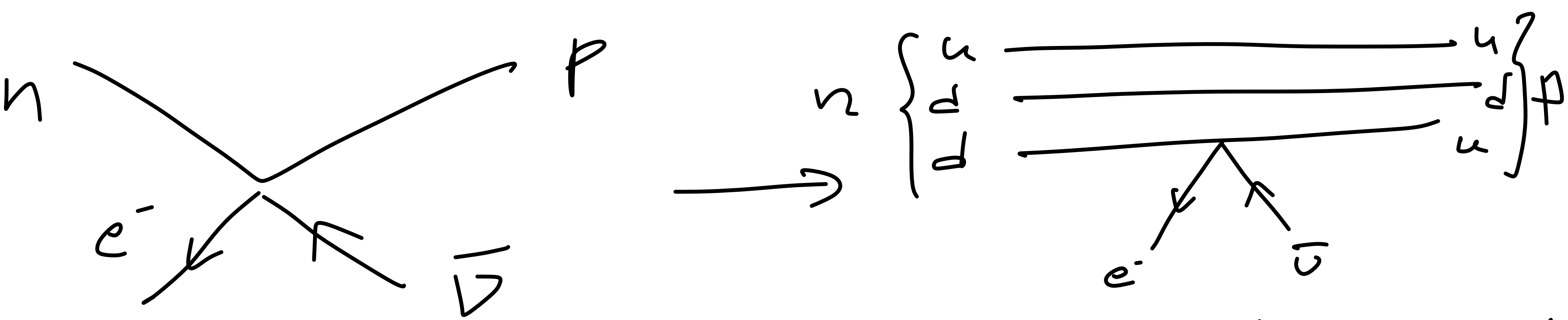
Current x current

$$\mathcal{L}_F \propto G_F \, J_{had}|_\mu \times J_{lep}^\mu$$

$$\bar{p}\,\Gamma_\mu\, n \qquad \bar{e}\,\Gamma^\mu\, \nu$$

$$\sim \gamma^\mu \qquad \sim \gamma^\mu$$

n destroyed and p, e, ν created



$$\mathcal{L}_F \propto G_F(\bar{u}\gamma^\mu d)\,(\bar{e}\gamma_\mu \nu)$$

Refused by Nature

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Fermi and dimension

$c = 1 = \hbar$

$$S = \int d^4x \, \mathcal{L}$$

S → Dimensionless

$[d^4x] = \frac{1}{\text{mass}^4}$

$[\mathcal{L}] = \text{mass}^4$

$$\mathcal{L}_{DIRAC} \ni \bar{\Psi} \not{\partial} \Psi \; , \; m \bar{\Psi} \Psi$$

$[\Psi] = \text{mass}^{3/2}$

EFT

$$\Rightarrow [\bar{\Psi}_1 \gamma_\mu \Psi_2 \bar{\Psi}_3 \gamma_\mu \Psi_4] = \text{mass}^6 \Rightarrow [G_F] = \text{mass}^{-2}$$

dimension > 4

Unitarity violation

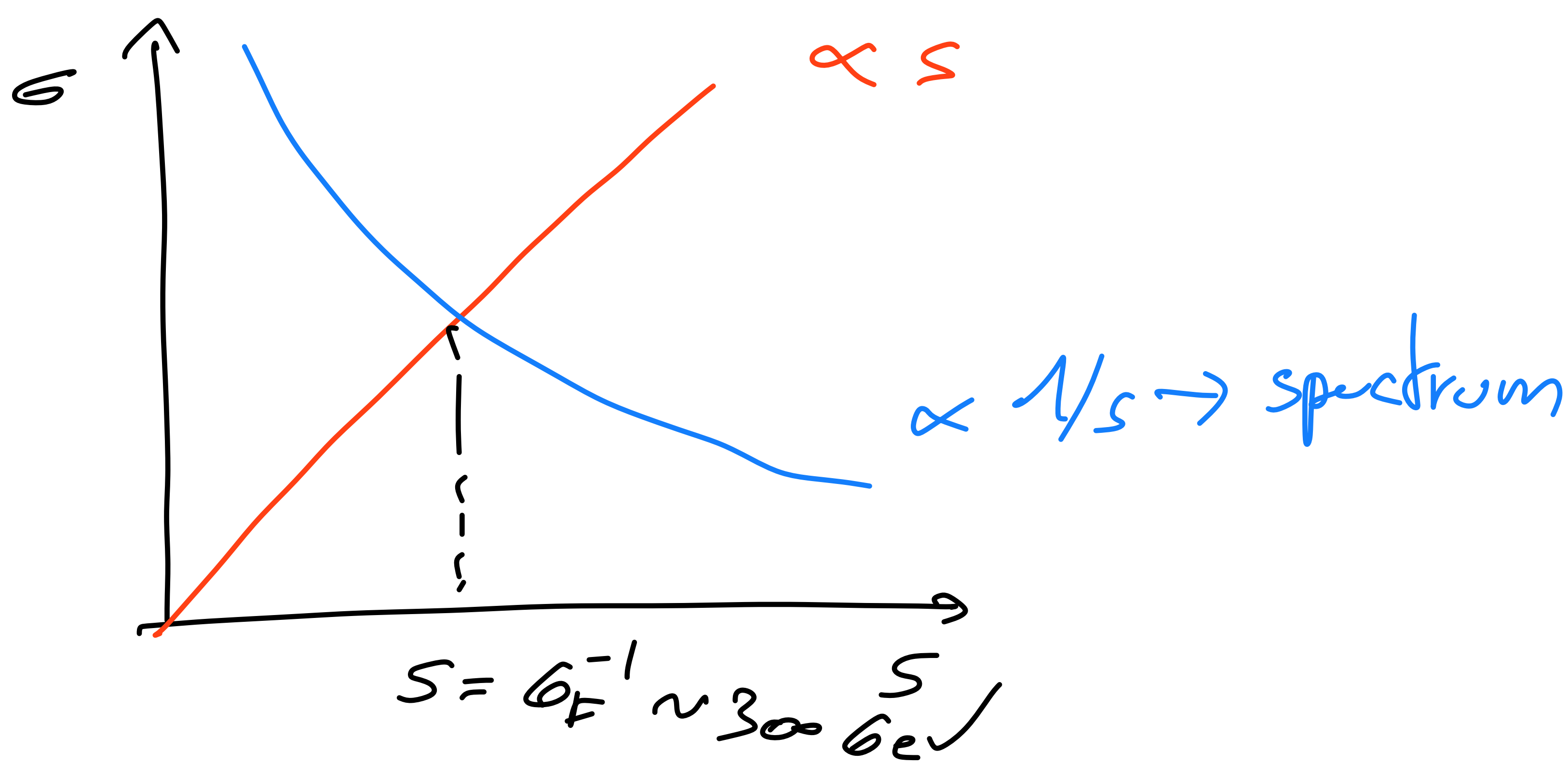
$$\sigma_{FERMI} \propto G_F^{\,2} \times s$$

$$[\;\;] = \frac{1}{\mathrm{mass}^2}$$

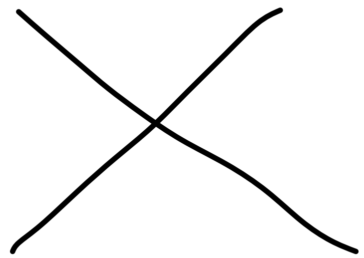
$s \rightarrow$ div

$\rightarrow$ Proba > 1

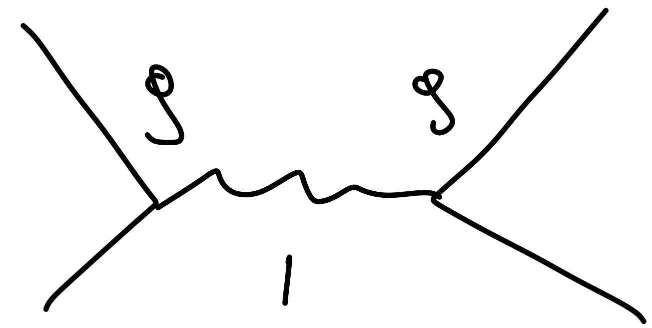
When?



Unitarity violation



4F but in QED

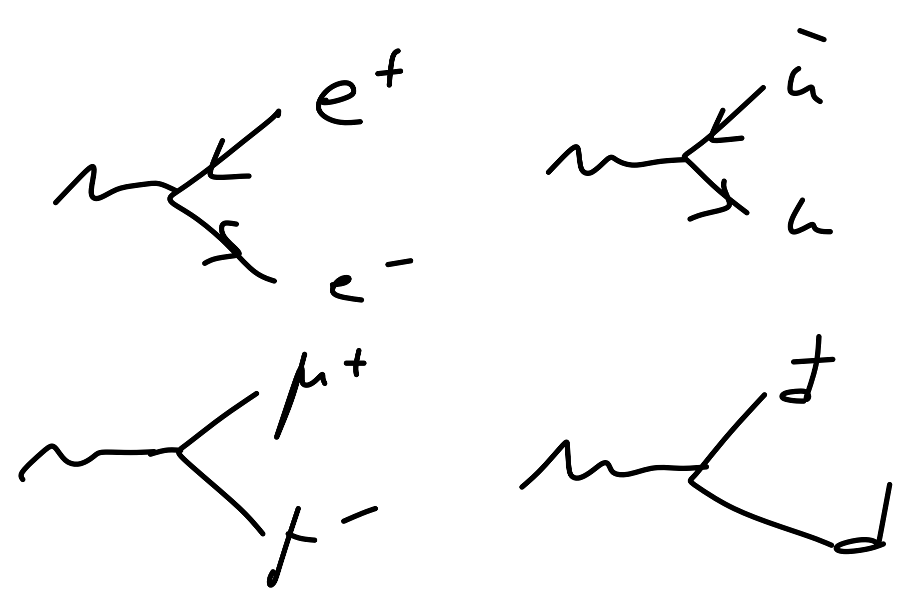


$$\frac{1}{p^2-m^2}$$

$$\frac{-g^2}{m^2} \sim G_F$$

$p^2 \ll m^2$

But in QED
- Always the same fermion
- Massless gauge boson



[no ν
$G_\nu = 0$]

$\bar{\psi} \not{D} \psi$

$D \to \partial_\mu - i g A_\mu$

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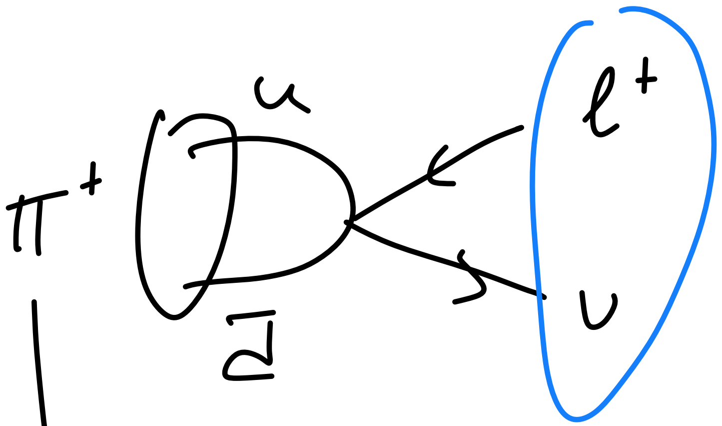
Pion decay



$$J_{lep\,\mu} \ni \bar{\nu}\gamma^\mu \ell$$

$$J^\mu_{had} \ni \pi^\pm$$

$$V \Longrightarrow J^{had}_\mu \sim f_\pi\, \partial_\mu \pi$$

$$[\ \ ] = \text{mass}$$

$$\mathcal{L}_{KG} \supset m^2 \phi^\dagger \phi$$

$$[\phi] = \text{mass}$$

$$\mathcal{L}_{FERMI} \supset G_F\, f_\pi\, \partial_\mu \pi^+\, \bar{\nu}\gamma^\mu \ell = G_F\, f_\pi\, \pi^+ \Big(\bar{\nu}\,\underbrace{\partial\!\!\!/\,\ell}_{m_\ell \ell} + \underbrace{(\partial_\mu \bar{\nu})\gamma^\mu \ell}_{0\cdot\bar{\nu}}\Big)$$

by part

Dirac

$$\mathcal{M} \propto G_F\ \pi\ m_e$$

Pion decay

$$\Gamma \propto G_F^2 f_\pi^2 m_\ell^2 m_\pi \underbrace{\left(1 - \frac{m_\ell^2}{m_\pi^2}\right)^2}_{\to\, 0 \text{ if } m_\ell \to m_\pi}$$

$[\Gamma] = \text{mass}$

$$\frac{\mathrm{Br}(\pi \to e\nu)}{\mathrm{Br}(\pi \to \mu\nu)} \simeq \frac{m_e^2}{m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2} \simeq 1.23\, 10^{-4}$$

Because V interaction

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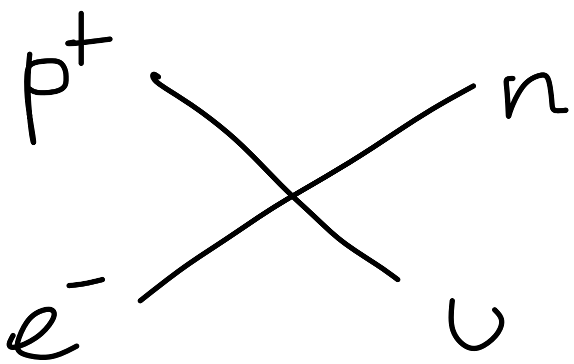
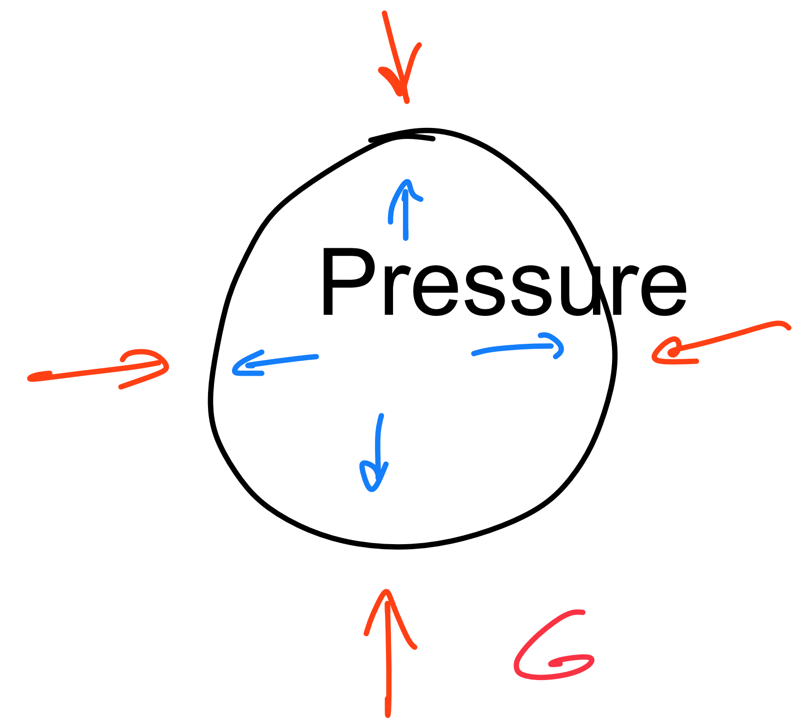
Inverse beta decay



$\longrightarrow$ star collapse

neutron star (fermi pressure)



produce neutrinos

Ex: momentum in CM

$$\Delta m = m_n - m_p$$

$$|\vec{p}_i| = \frac{m_n^2 - m_p^2}{2 m_n} \simeq \Delta m \simeq 1.3\ \mathrm{MeV}$$

$$1\ \mathrm{eV} \cong 10^4\ \mathrm{K} \implies 1.3\ \mathrm{MeV} \sim 10^{10}\ \mathrm{K}$$

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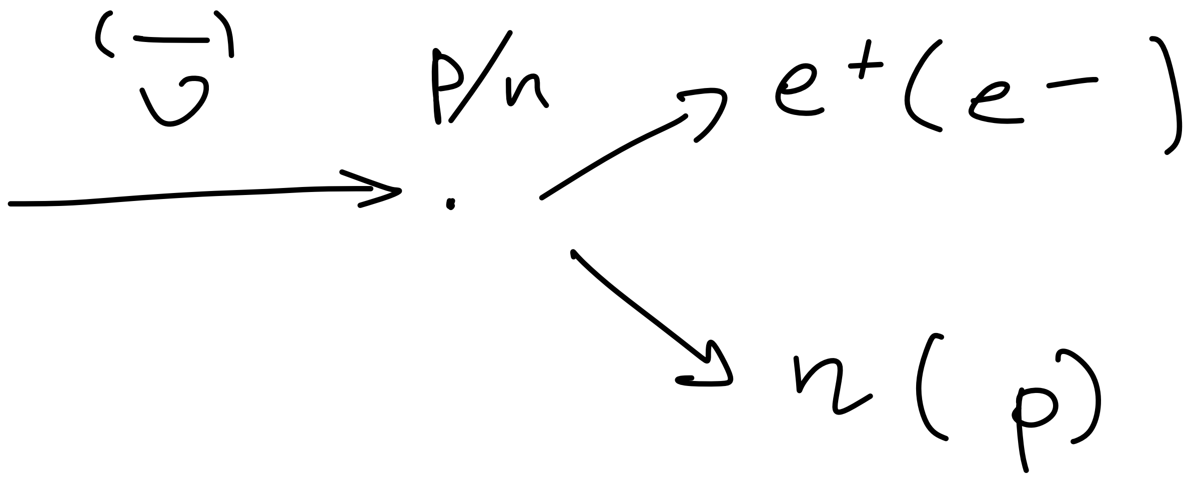
Neutrino detection



EX: scan cross-section fermi for energies from 1 GeV to 100 GeV

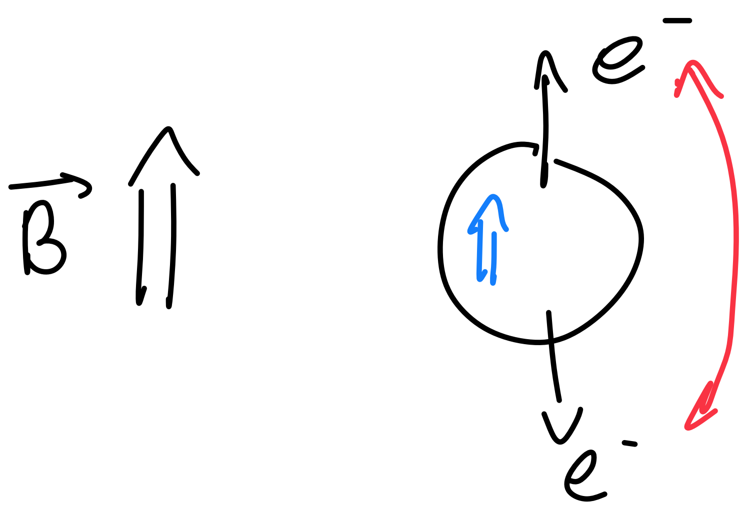
Same in the SM

Parity violation

$$\Gamma^\mu = \gamma^\mu \ ?$$

1956 Lee-Yang

Exp 1957 Wu



or

$$^{60}_{27}Co \longrightarrow {}^{60}_{28}Ni + e^- + \bar{\nu}_e$$
$$^{60}_{28}Ni \longrightarrow 2\gamma$$

$$\langle \vec{p}_e \cdot \vec{B} \rangle \neq 0 \implies \cancel{P}$$

Averaged value over the events

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Parity

$\vec{x} \longrightarrow -\vec{x}$ $t \longrightarrow t$

$\dot{\vec{x}} = \dfrac{\partial \vec{x}}{\partial t} \longrightarrow -\dot{\vec{x}}$ $\Longrightarrow$ $\vec{p} \longrightarrow -\vec{p}$

$\vec{E} \longrightarrow -\vec{E}$ Vector

$\vec{B} \longrightarrow +\vec{B}$ Axial vector or pseudo vector

$\mathcal{L}_{QED} \propto \underset{\hookrightarrow (\phi, \vec{A})}{A_\mu} \bar{\psi} \gamma^\mu \psi$ P-conserving

$A^\mu \longrightarrow A_\mu$

$\underset{\overset{\shortparallel}{J^\mu}}{\bar{\psi} \gamma^\mu \psi} \longrightarrow \bar{\psi} \gamma_\mu \psi$

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Parity

Axial vector   spin $\sim \vec{L} = \vec{r} \times \vec{p}$

Spin projector $s_\mu \gamma^\mu \gamma^5$

$s^2 = -1$

$s \cdot p = 0$

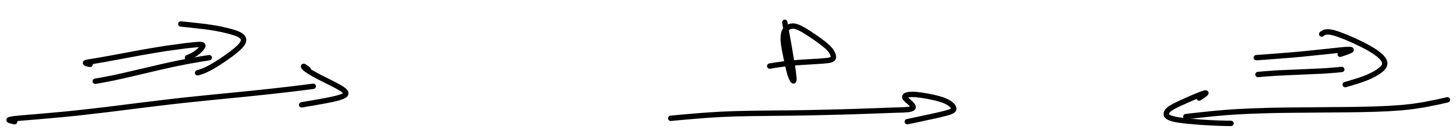
$\Downarrow$

$s = \frac{1}{m}\left(|\vec{p}|, \frac{E}{|\vec{p}|}\vec{p}\right)$

Helicity projector

$$P_\pm = \frac{1 \pm \not{s}\gamma^5}{2}$$

$m \to 0$ $\gamma_{R/L} \; \frac{1 \pm \gamma_5}{2} \longrightarrow$ Chirality projector



$\psi_L = \gamma_L \psi \longrightarrow \psi_R$

$\psi_R = \gamma_R \psi \longrightarrow \psi_L$

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Parity

$$J^\mu = \bar\psi \gamma^\mu \psi = \bar\psi \gamma^\mu (\gamma_L + \gamma_R) \psi$$
$$= \bar\psi_L \gamma^\mu \psi_L + \bar\psi_R \gamma^\mu \psi_R \xrightarrow{P} J_\mu$$

$$A^\mu = \bar\psi \gamma^\mu \gamma^5 \psi = \bar\psi \gamma^\mu (\gamma_R - \gamma_L) \psi$$
$$= \bar\psi_R \gamma^\mu \psi_R - \bar\psi_L \gamma^\mu \psi_L \xrightarrow{P} -A_\mu$$

Maximal violating interaction (1958)

Feynman Gell-Mann Marshak Sudarshan

Weak interaction with the left only

$V_\mu \to M_V$ $\qquad M_V \xrightarrow{P} M_V$

$A_\mu \to M_A$ $\qquad M_A \xrightarrow{P} -M_A$ $\qquad |M_A|^2 \xrightarrow{P} |M_A|^2$

Max if $\quad M_A = \pm M_V$

$$|M_V + M_A|^2 = |M_V|^2 + |M_A|^2 + 2\,\mathrm{Re}(M_V M_A^*)$$
$$\xrightarrow{P} |M_V|^2 + |M_A|^2 - 2\,\mathrm{Re}(M_V M_A^*)$$

Fermi summary

$$\mathcal{L}_F \propto G_F\, \bar{u}_L \gamma^\mu d_L\, \bar{\nu}_L \gamma_\mu \ell_L$$

Requests: pure left

massive Vector boson

changing particle flavour

$\hookrightarrow$ $e \leftrightarrow \nu$, $u \leftrightarrow d$

All the generations but only the leptons for now

Ex : $\sigma(e^- \mu^+ \to \nu_e \bar{\nu}_\mu)$ in Fermi and SM

at $s = 1, 5, 50, 500$

Weak group

$$\mathcal{L}_{FERMI} = -2\sqrt{2}\, G_F (\bar{\nu}_{\mu_L} \gamma^\alpha \mu_L)(\bar{e}_L \gamma_\alpha \nu_{e_L}) + \text{other flavours}$$

solution : $L_e = \begin{pmatrix} \nu_{e_L} \\ e_L \end{pmatrix}$, $L_\mu = \begin{pmatrix} \nu_{\mu_L} \\ \mu_L \end{pmatrix}$

$$\mathcal{L}_{FERMI} = -2\sqrt{2}\, G_F\, \bar{L}_\mu \gamma^\alpha T^- L_\mu \quad \bar{L}_e \gamma_\alpha T^+ L_e$$

$$T^- = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \qquad T^+ = (T^-)^\dagger = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

$$J_L^\mu = \sum_\ell \bar{L}_\ell \gamma^\alpha T^- L_\ell$$

$$\mathcal{L}_{FERMI} = -2\sqrt{2}\, G_F\, J_L^\mu \quad J^\dagger_{\mu L}$$

Weak group

In QED $\quad \psi \to e^{iq\theta(x)}\,\psi$

$$\partial_\mu \longrightarrow D_\mu = \partial_\mu - i\underset{\downarrow}{q} A_\mu$$

charge replaced by $T^{\pm}$

Do not commute: non abelian

symmetry group close under anticommutation

$$[T^+, T^-] = -2\,T^3 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} = -2\begin{pmatrix} 1/2 & 0 \\ 0 & -1/2 \end{pmatrix}$$

$$T^1 = \frac{T^+ + T^-}{2} = 1/2\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$T^2 = i\,\frac{(T^+ - T^-)}{2} = 1/2\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$\Downarrow$$

$$[T^i, T^j] = i\,\varepsilon^{ijk}\,T^k$$

$SU(2)$: $U = e^{i\vec{\alpha}\cdot\vec{T}}$

$\det U = 1$

$\Updownarrow$

$\mathrm{Tr}(T^i) = 0$

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Neutral currents and right leptons

changed currents and group $\Longrightarrow$ neutral currents

$$J_3^\alpha = J_{NC}^\alpha = \bar{L}_\ell \gamma^\alpha T^3 L_\ell = \underbrace{\bar{\nu}_{\ell L} \gamma^\alpha \nu_{\ell L}}_{\text{Not EM}} - \bar{\ell}_L \gamma^\alpha \ell_L$$

Not EM

$Q(\nu) = 0$

No charged currents with the right fermions

$\nu_R , \ell_R \sim 1_{SU(2)}$ $\qquad Tr(1 \times 1) = 0$

$= 0$

$m\bar{\psi}\psi = m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$

Not invariant under SU(2)

Electroweak group

$+\ U(1)_Y \neq EM \longrightarrow [Q, T^a]$

All particles in an SU(2) multiplet have the same charge

$$\psi \longrightarrow e^{ig_2 \vec{\alpha}(x)\cdot\vec{T} + ig_1 Y\theta(x)}\,\psi$$

$$D_\alpha = \partial_\alpha - ig_2 \vec{W}_\alpha\cdot\vec{T} - ig_1 Y B_\alpha$$

$$B_\mu \longrightarrow B_\mu + \partial_\mu \theta(x)$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

Invariant

$$\vec{W}_\mu \longrightarrow \vec{W}_\mu + \partial_\mu \vec{\alpha}(x) + g_2 (\underbrace{\vec{W}_\mu \times \vec{\alpha}}_{\epsilon^{ijk} W_\mu^j \alpha^k})$$

$$\bar{\psi}\,\cancel{D}\,\psi$$

$$\downarrow$$

$$[\ ,\ ]$$

$\boxed{\text{Non Abelian}}$

$$T^i W_{\mu\nu}^i = \partial_\mu W_\nu^i T^i - \partial_\nu W_\mu^i T^i - ig_2 [W_\mu^j T^j, W_\nu^k T^k]$$

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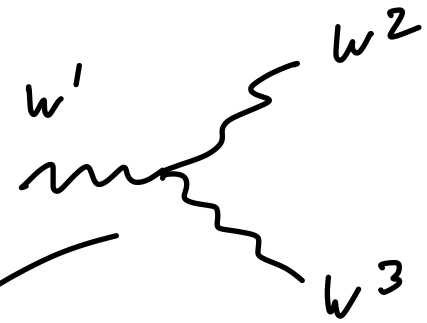
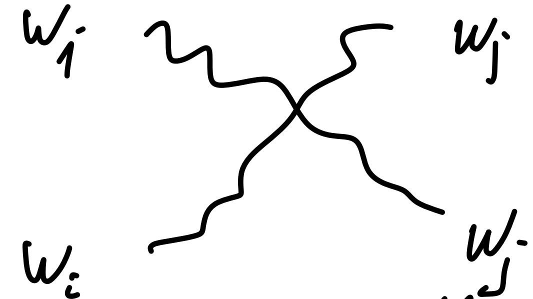
Pheno of non abelian gauge theory

$W^i_{\mu\nu} W^{\mu\nu}_i \ni$



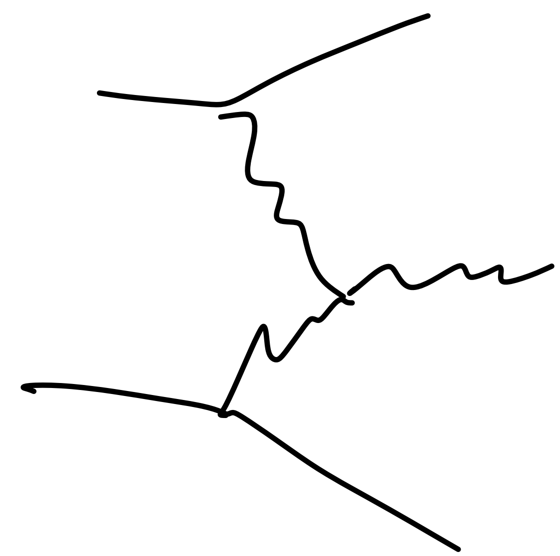
$\propto p^\mu \eta^{\alpha\beta}, g_2$



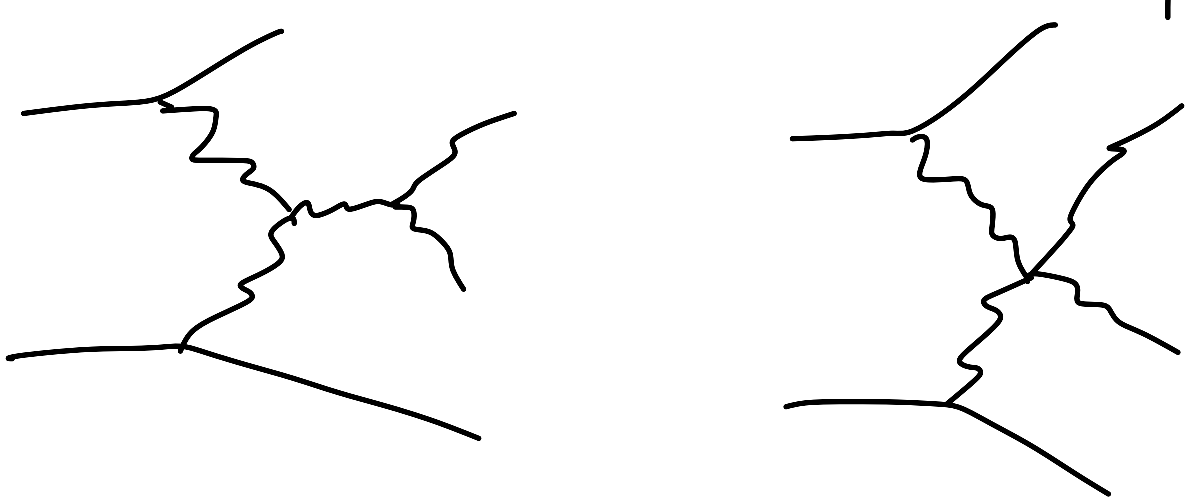
$\propto \eta^{\mu\nu} \eta^{\alpha\beta}, g_2^2$

$W^+ W^- \gamma$ since $Q(W^+) = 1$

DIBOSON



VBF



VBS

Z-A mixing

$$\mathcal{L} \ni \bar{L}\not{D} L + \bar{\nu}_R \not{D} \nu_R + \bar{l}_R \not{D} l_R$$

$$= \bar{L}\not{\partial} L + \bar{\nu}_R \not{\partial} \nu_R + \bar{l}_R \not{\partial} l_R - i\sqrt{2}\, g_2 \bar{L} \not{W}^+ T^- L$$

$$- i\sqrt{2}\, g_2 \bar{L} \not{W}^- T^+ L$$

$$- i g_2 \bar{L} \not{W}_3 T^3 L - i g_1 \bar{L} Y_L \not{B} L - i g_1 Y_{\nu_R} \bar{\nu}_R \not{B} \nu_R$$

$$- i g_1 Y_{l_R} \bar{l}_R \not{B} l_R$$

$\mathcal{L}_{NC}$ "

$$W^+ = \frac{W_1 - i W_2}{\sqrt{2}} \qquad W^- = \frac{W_1 + i W_2}{\sqrt{2}}$$

$$\begin{pmatrix} W_3 \\ B \end{pmatrix} = \begin{pmatrix} c_w & s_w \\ -s_w & c_w \end{pmatrix} \begin{pmatrix} Z \\ A \end{pmatrix} \xrightarrow[s.t.]{c_w,\, s_w} \mathcal{L}_{NC} \ni i e Q_F A_\mu \bar{F} \gamma^\mu F$$

VECTOR

$$\left.\begin{matrix} Q(\nu) = 0 \\ Q(e) = -1 \end{matrix}\right\} \Longrightarrow \begin{matrix} e = g_2 s_w = g_1 c_w \\ Y_L = -1/2 \end{matrix}$$

$$Q = T^3 + Y$$

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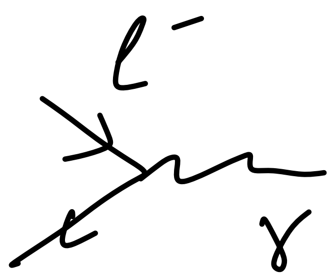
FFV

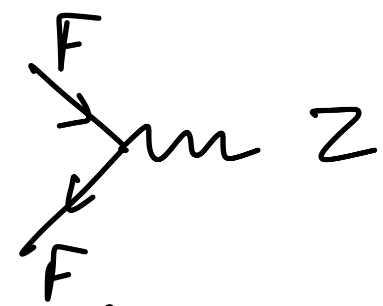
$\Rightarrow$ $Y_{\nu_R} = 0 \rightarrow$ Not interacting, not in the SM

$Y_{e_R} = -1$

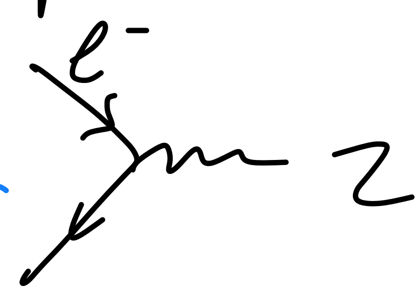
$$\mathcal{L}_{NC} = \sum_{F=\nu_R, e_R, L} \left\{ -ie Q_F A_\mu \bar{F}\gamma^\mu F - i\frac{e}{s_w c_w} Z_\mu (T^3 - s_w^2 Q) \right\}$$



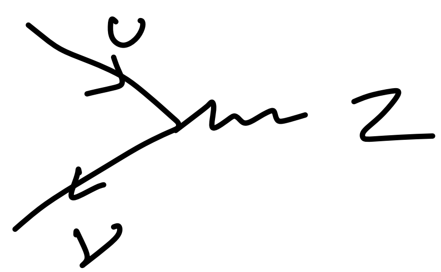
$iq_e \gamma^\mu$



$$\frac{ie}{s_w c_w}(T^3 - s_w^2 Q)\gamma^\mu$$



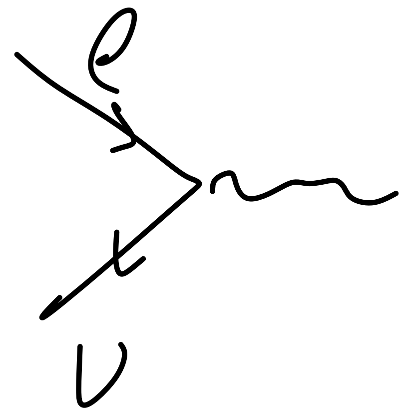
$$\frac{ie}{s_w c_w}\left[(-1/2 - s_w^2)\gamma^\mu\gamma_L + (-s_w^2)\gamma^\mu\gamma_R\right]$$



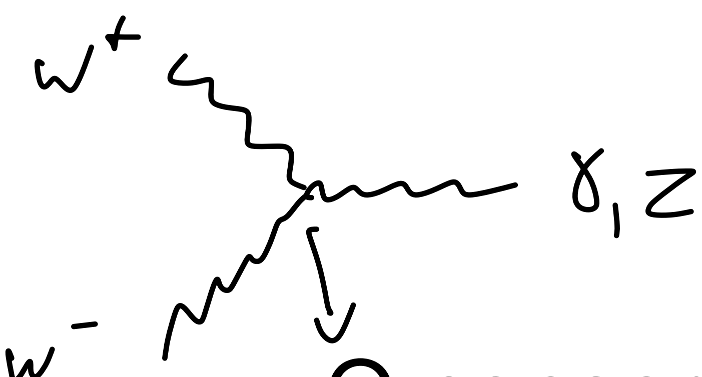
$$\frac{ie}{s_w c_w} \quad \frac{1}{2}\gamma^\mu\gamma_L$$

no γ_R!

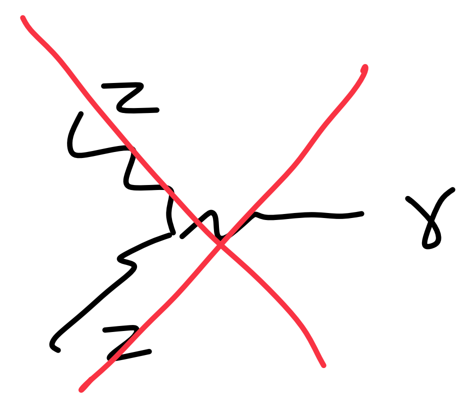
More electroweak interactions



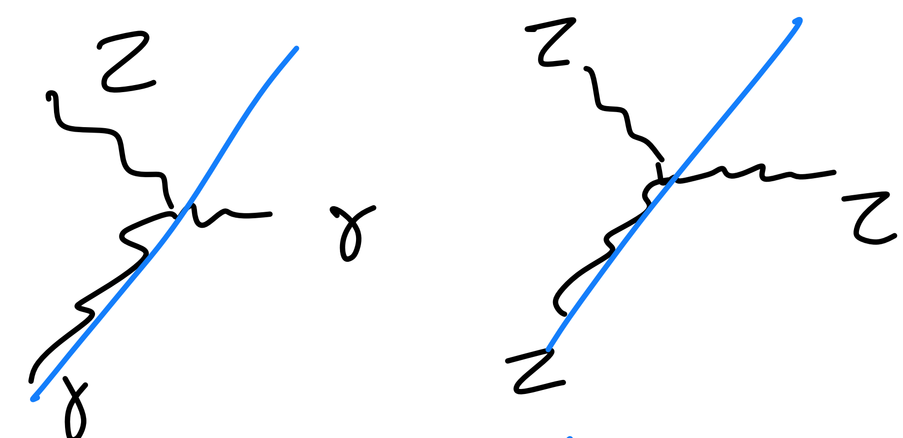
$$\frac{ie}{s_W}\gamma_\mu \gamma_L$$



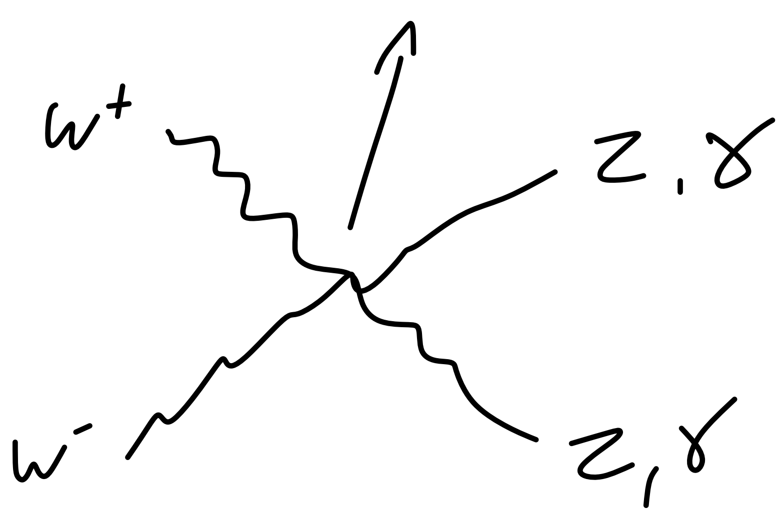
Q conserved

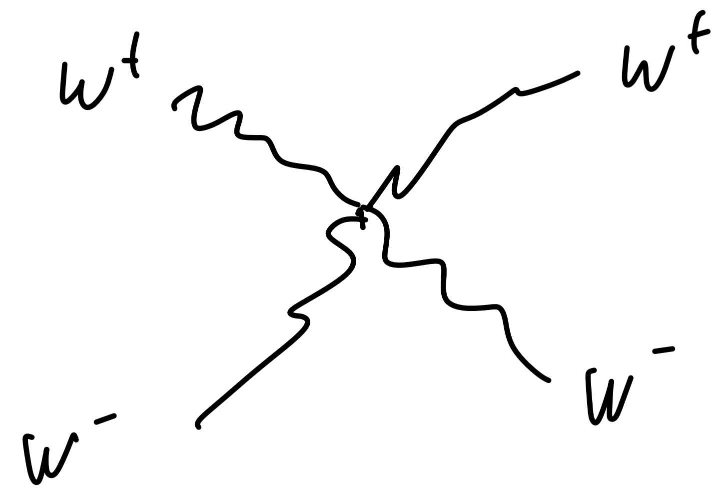


$Q_Z = 0$



Z-γ is abelian

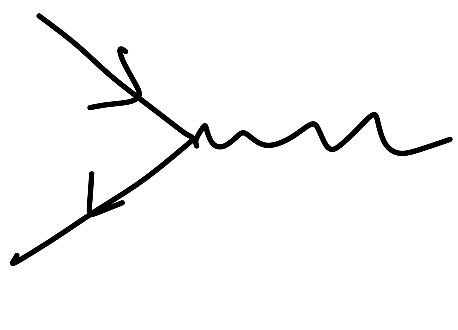




no Z-γ only in the SM!

Z production

e^- q



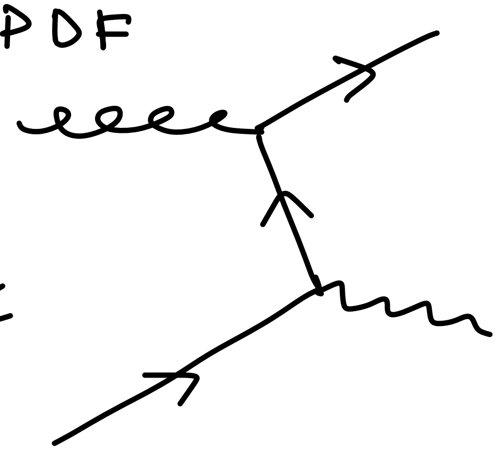
e^+ $\bar{q}$

LEP

LHC
TEVATRON

PDF

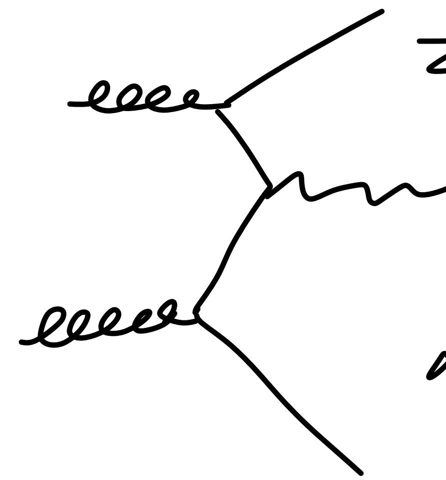
g
$\downarrow$
LHC



q

$Z+j$

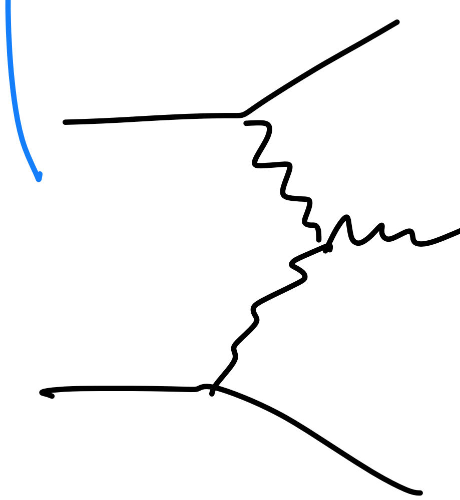
Strong
Zjj



Z

$\alpha_s^2 \alpha$

large bkg



α^3
EW
Zjj

- $\dfrac{\sigma(Zj)}{\sigma(Z)}\left(p_T^j\right)$ ⚠ IR

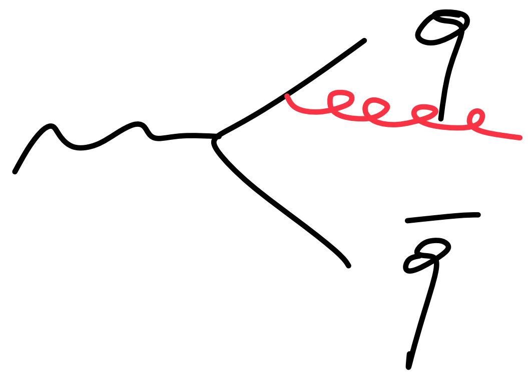
rapidity gap,
large m_{jj},
...

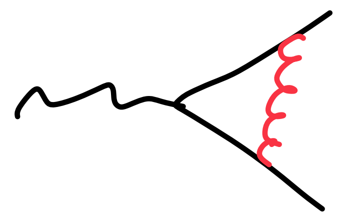
- $\dfrac{\sigma^{EW}(Zjj)}{\sigma^{QCD}(Zjj)}$ → find cut to improve

NLO : ? Mixed EW / QCD

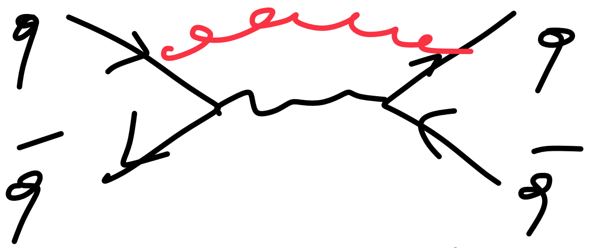
- $\sigma(pp \to Z \to \ell\ell) / \sigma(pp \to \ell\ell)$ + ≠ in distributions

More Z production + decay

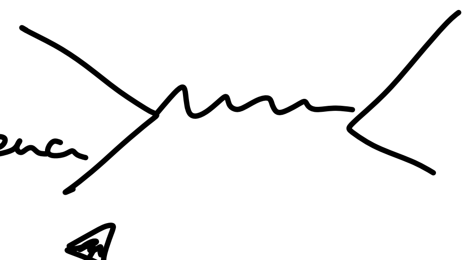




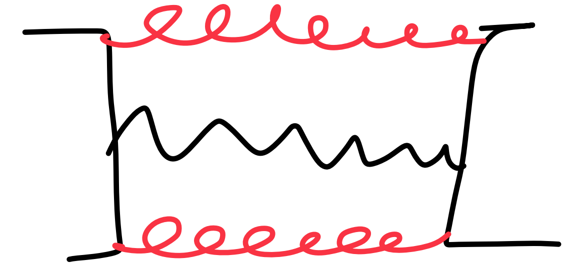
$1+\frac{\alpha_s}{\pi}$

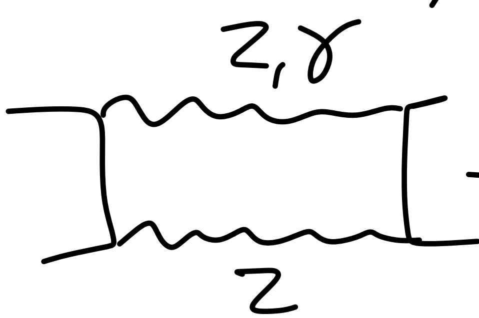


no interference

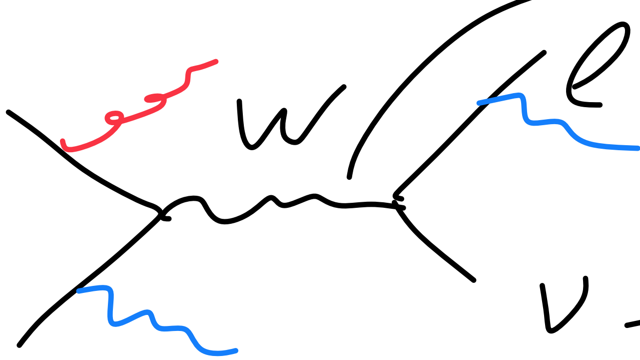


only with





$\times\alpha \to 1\%$



$\nu \to$ MET

Mass : BW template

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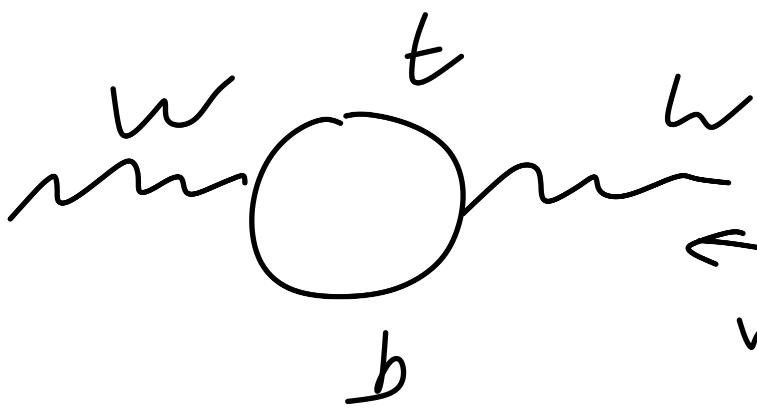
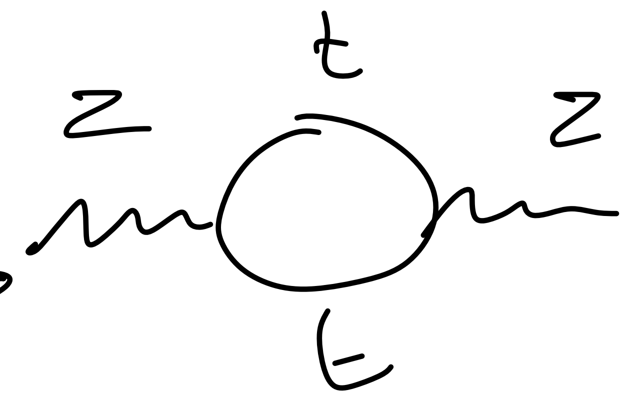
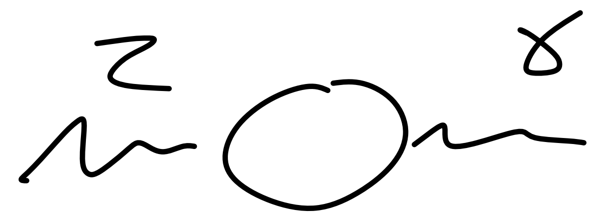
Electroweak precision tests





mass relation

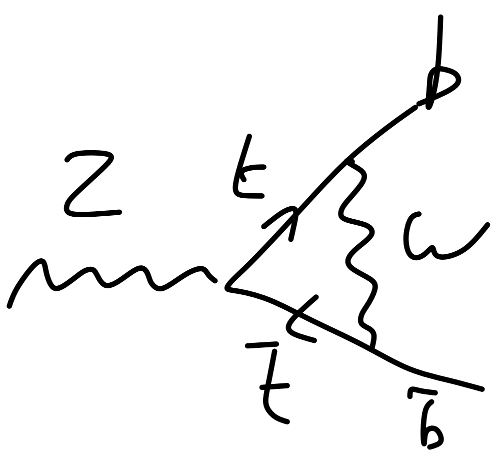
ρ



change mixing

m_t from LEP!

corr $\propto m_t^2$



$\longrightarrow$ 1‰ + $N_\nu \simeq 3$

C. Degrande

Exercises

$\underbrace{\sigma(pp \to Z) \quad + \text{ scale variation}}_{\text{TH ERROR}}$

@ LO, NLO

- Discuss shape uncertainties at LO?
- Fixed order vs Parton shower
- Number of jets

WW scattering

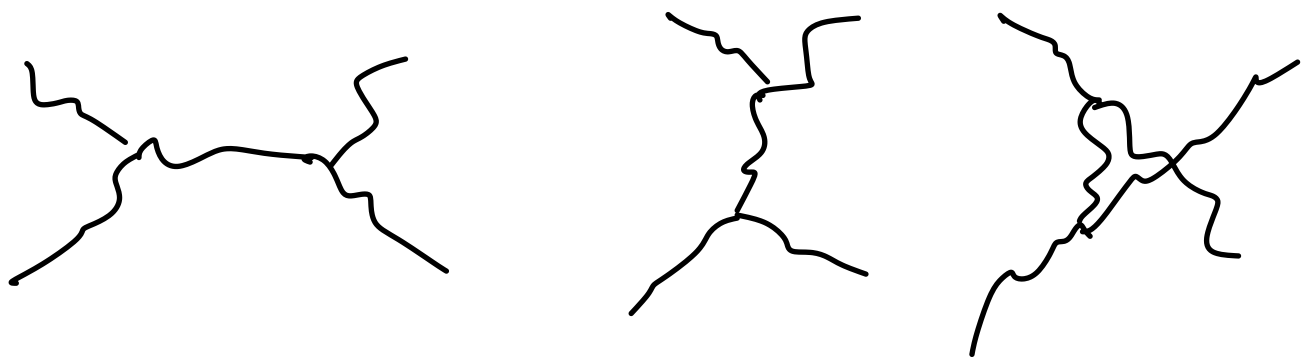
$W_L \, W_L \to W_L \, W_L$

$p^\mu = (E, 0, 0, p) \quad \epsilon_\pm = \frac{(0, 1, \pm i, 0)}{\sqrt{2}}$

$\epsilon_L = \frac{1}{m}(p, 0, 0, E)$

↳ longitudinal, only if massive
otherwise transverse only

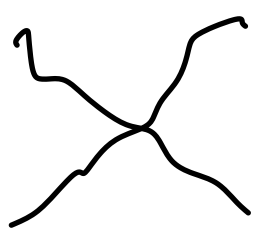
3 pt only



$$|M_1 + M_2|^2 \propto \frac{(s^2 + 4ts + t^2)}{m_W^4}$$

$$\Rightarrow \sigma \sim s \qquad \left(\sigma \sim \frac{|M|^2}{s}\right)$$

3 pt and 4 pt



$$|M_1 + M_2 + M_3| \propto \frac{(-s-t)}{m_W^2}$$

$\sigma \sim$ const

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