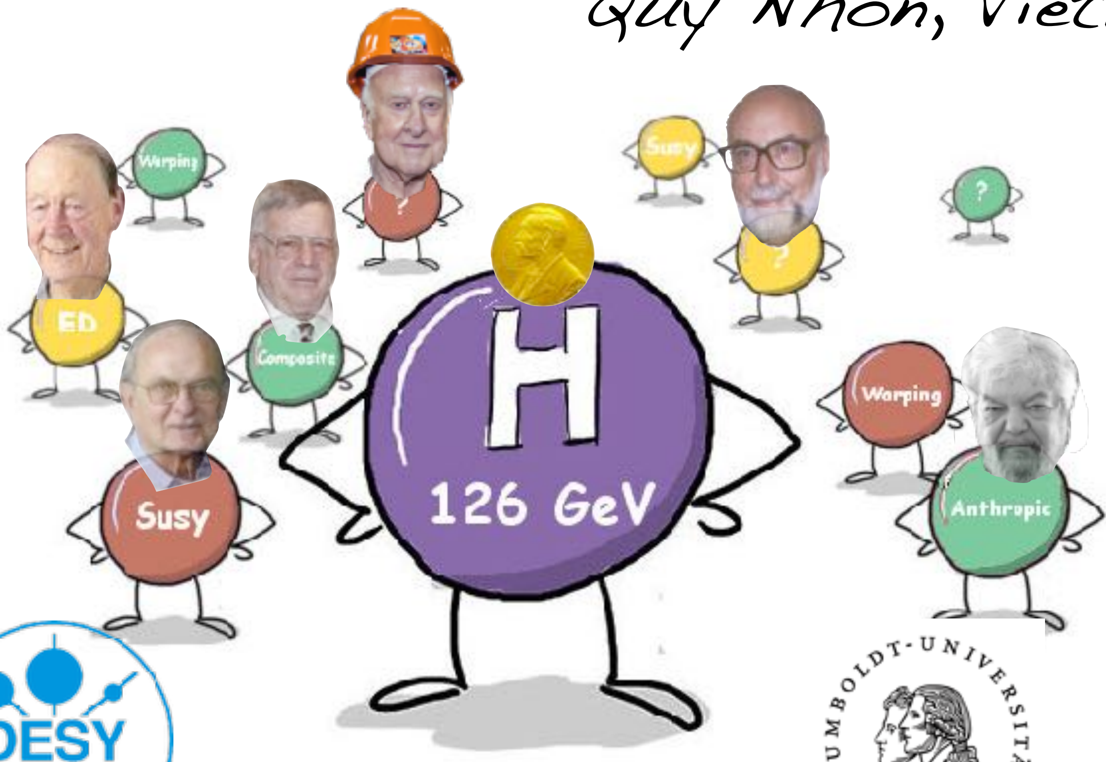
Higgs and BSM Physics

AEPSHEP 2018

Quy Nhon, Vietnam

Lecture 1/4



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Outline

▢ Lecture #1

- From Fermi theory to the Standard Model
- Chirality, fermion masses, spontaneous symmetry breaking
- Custodial symmetry
- Gauge boson masses, unitarity and the Higgs boson

▢ Lecture #2

- Higgs phenomenology (decay and production at colliders)
- Higgs quantum potential (vacuum (meta)stability, naturalness)
- Hierarchy problem

▢ Lecture #3

- Supersymmetry
- Composite Higgs
- Extra dimensions

▢ Lecture #4

- Connections particle physics-cosmology
- Quantum gravity: landscape vs swampland
- BSM searches beyond colliders: AMO, EDMs, nñ, GW, PBH

Some numerical values used in these lectures...

Fundamental constants

$$c \sim 3\times 10^{8}\,\mathrm{m.s^{-1}}$$
$$\hbar \sim 10^{-34}\,\mathrm{J.s}$$
$$e \sim 1.6\times 10^{-19}\,\mathrm{C}$$
$$G_N \sim 6.67\times 10^{-11}\,\mathrm{N.kg^{-2}.m^{2}}$$
$$k_B \sim 1.38\times 10^{-23}\,\mathrm{J.K^{-1}}$$

Natural units

$$1\,\mathrm{eV} = (6.6\times 10^{-16}\,\mathrm{s})^{-1} \quad 1\,\mathrm{eV} = (2.0\times 10^{-7}\,\mathrm{m})^{-1} \quad 1\,\mathrm{eV} = 1.8\times 10^{-36}\,\mathrm{kg} \quad 1\,\mathrm{eV} = 1.2\times 10^{4}\,\mathrm{K}$$

Mass spectrum

$$m_p = 938\,\mathrm{MeV} \quad m_n = 939\,\mathrm{MeV} \quad m_{\pi^\pm} = 139\,\mathrm{MeV} \quad m_{\pi^0} = 134\,\mathrm{MeV} \quad m_{K^\pm} = 494\,\mathrm{MeV} \quad m_{K^0} = 498\,\mathrm{MeV}$$

$$m_e = 511\,\mathrm{keV} \quad m_\mu = 106\,\mathrm{MeV} \quad m_\tau = 1.8\,\mathrm{GeV}$$

$$m_u = 2.3\,\mathrm{MeV} \quad m_d = 4.8\,\mathrm{MeV} \quad m_c = 1.3\,\mathrm{GeV} \quad m_s = 100\,\mathrm{MeV} \quad m_t = 173\,\mathrm{GeV} \quad m_b = 4.2\,\mathrm{GeV}$$

Astrophysics

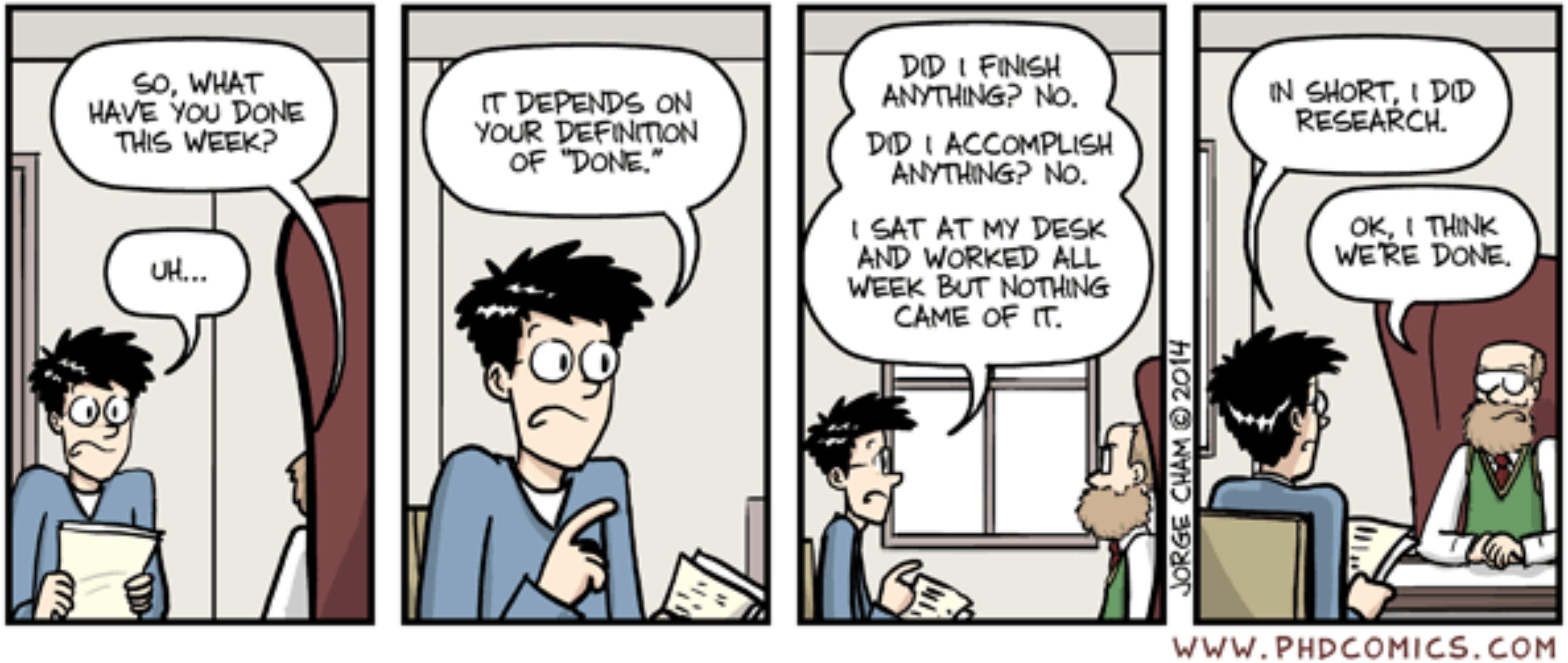
$$M_\odot = 2\times 10^{30}\,\mathrm{kg} \quad M_\oplus = 6.0\times 10^{24}\,\mathrm{kg} \quad M_\circ = 7.3\times 10^{22}\,\mathrm{kg}$$

$$\langle d_{\odot-\oplus}\rangle = 1.5\times 10^{6}\,\mathrm{km} \quad \langle d_{\oplus-\circ}\rangle = 3.8\times 10^{5}\,\mathrm{km}$$

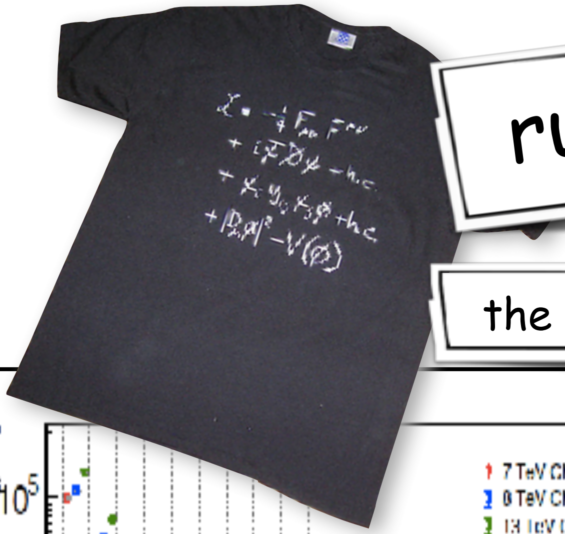
$$\langle T_\odot^{\mathrm{surface}}\rangle = 5778\,\mathrm{K}$$

Ask questions!

Your work, as students, is to question all what you are listening during the lectures...



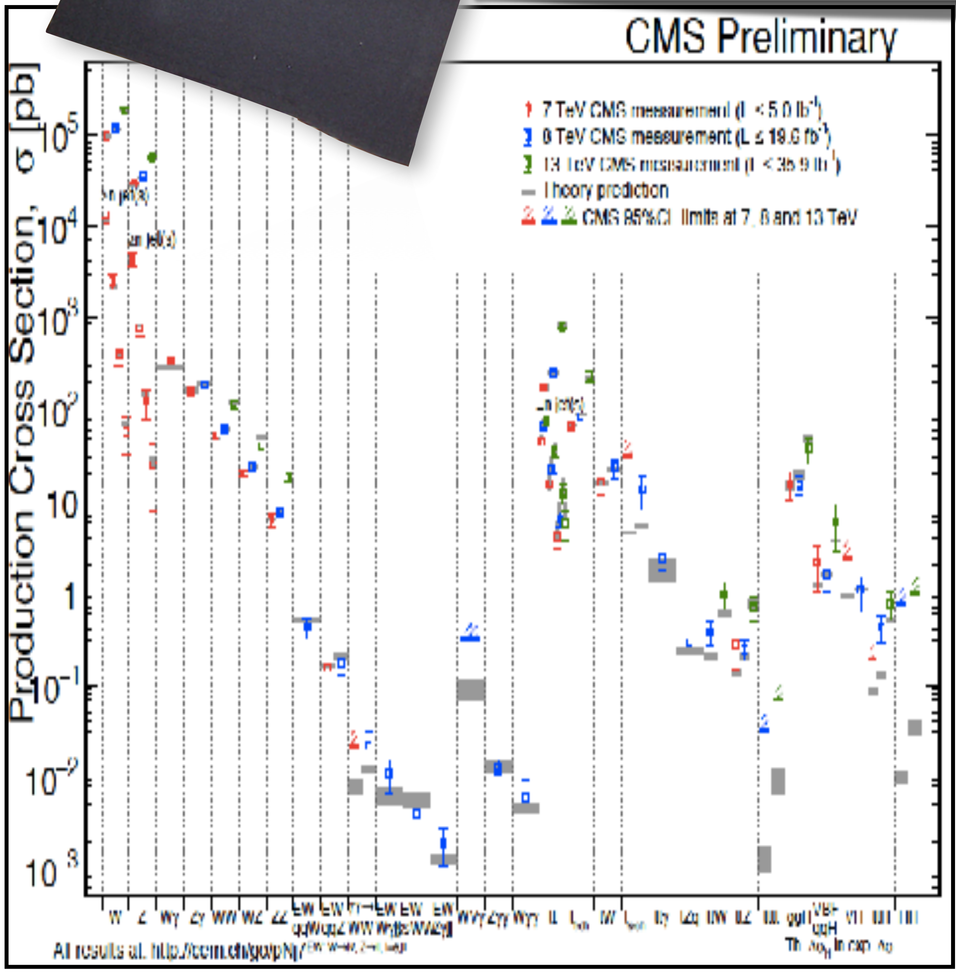
The SM and... the LHC data so far

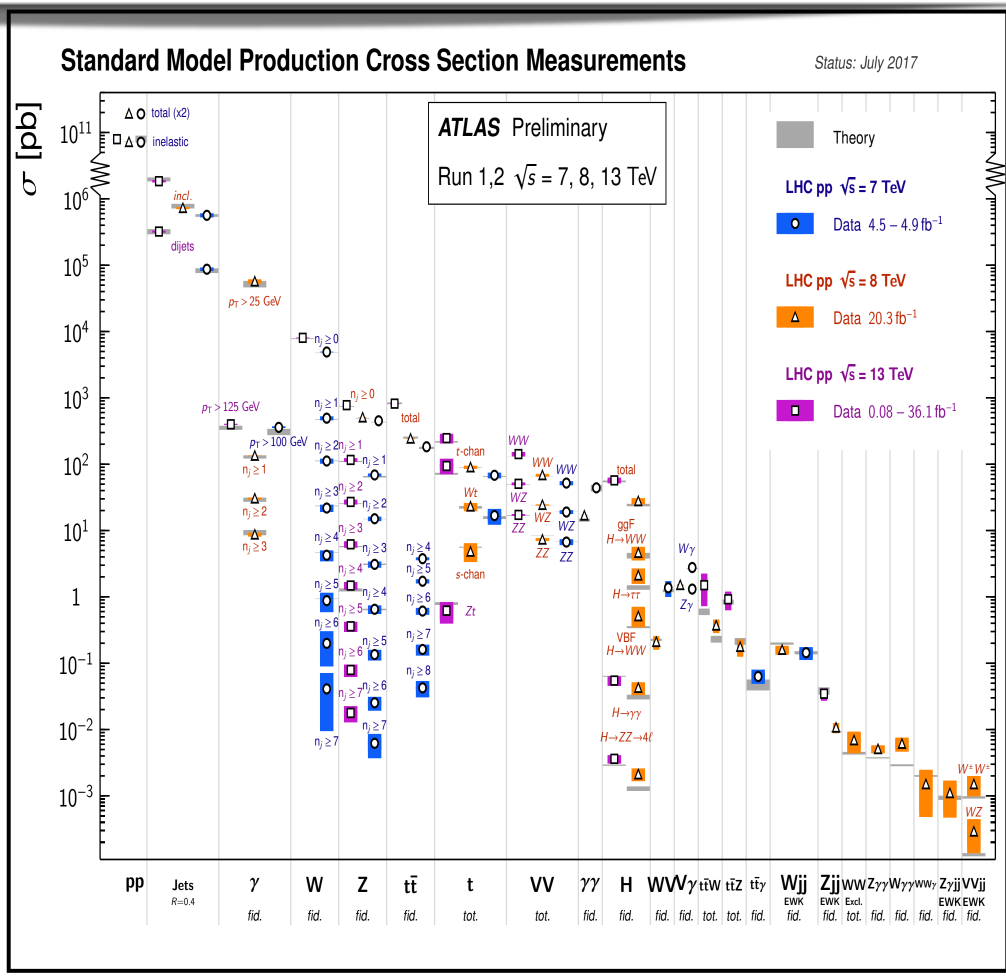


rules the world!

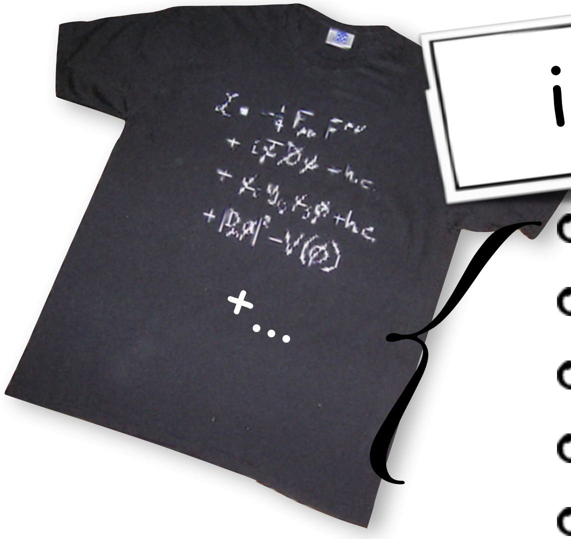
[and we, HEP practitioners, are all entitled for some royalties!]

the same set of eqs. describe phenomena over 15 orders of magnitude





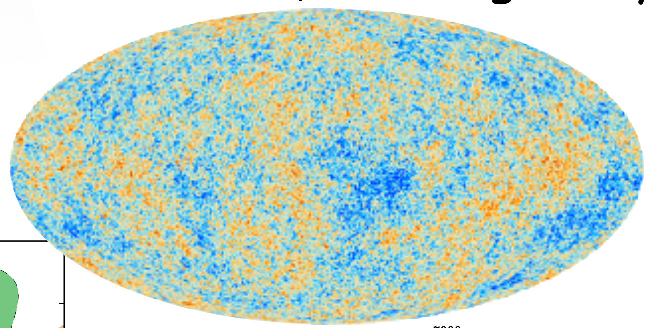
The SM and... the rest of the Universe

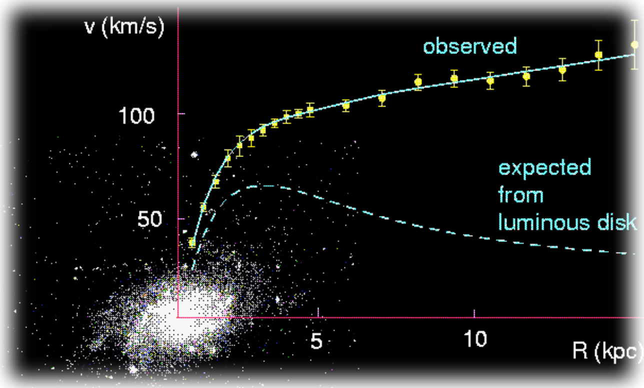


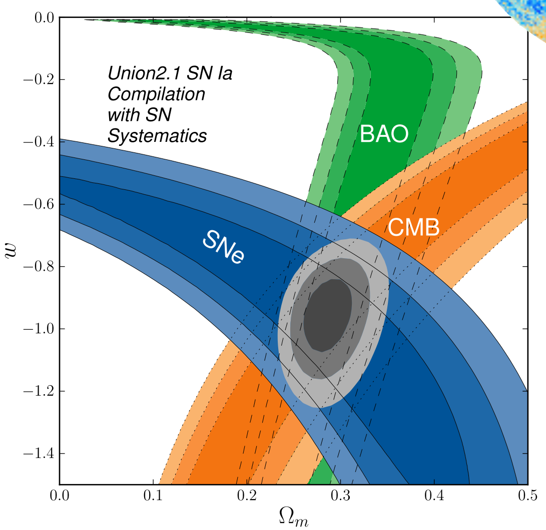
is not enough

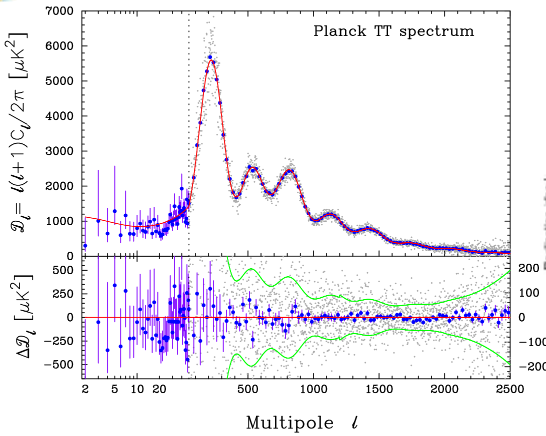
[and we all have to return our royalties!]

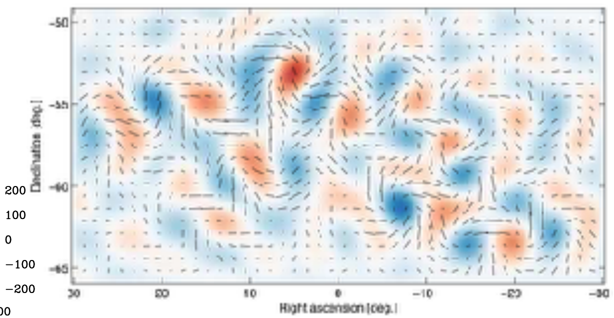
- neutrino masses
- matter-antimatter asymmetry
- Dark Matter
- Dark Energy
- Quantum gravity











Building the SM

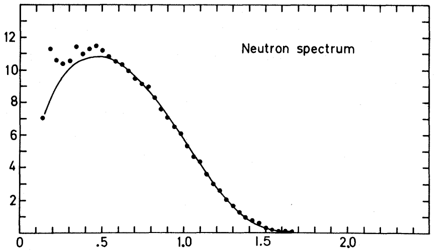
Beta decay & Fermi Theory

$${}^{40}_{19}\mathrm{K} \to {}^{40}_{20}\mathrm{Ca}^+ + e^- \qquad {}^{64}_{29}\mathrm{Cu} \to {}^{64}_{30}\mathrm{Zn}^+ + e^- \qquad {}^{3}_{1}\mathrm{H} \to {}^{3}_{2}\mathrm{He}^+ + e^-$$

- Two body decays: A→B+C

$$E_B = \frac{m_A^2 + m_B^2 - m_C^2}{2m_A} c^2 \qquad p = \frac{\sqrt{\lambda(m_A, m_B, m_C)}}{2m_A} c$$

$$\lambda(m_A, m_B, m_C) = (m_A + m_B + m_C)(m_A + m_B - m_C)(m_A - m_B + m_C)(m_A - m_B - m_C)$$



fixed energy of daughter particles (pure SR kinematics, independent of the dynamics)

⇛ non-conservation of energy?

Pauli '30: ∃ neutrino, very light since end-point of spectrum is close to 2-body decay limit

ν first observed in '53 by Cowan and Reines

- N-body decays: A→B_1+B_2+...+B_N

$$E_{B_1}^{\min} = m_{B_1} c^2 \qquad E_{B_1}^{\max} = \frac{m_A^2 + m_{B_1}^2 - (m_{B_2} + \ldots + m_{B_N})^2}{2m_A} c^2$$

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

Fermi theory '33

$$\mathcal{L} = G_{\mathcal{F}}(\bar{n}p)(\bar{\nu}_e e)$$

exp: $G_F = 1.166 \times 10^{-5}\ \mathrm{GeV}^{-2}$

Need to go beyond Fermi

How are we sure that muon and neutron decays proceed via the same interactions?

$\tau_\mu \approx 10^{-6}$s vs. $\tau_{neutron} \approx 900$s

$$\mathcal{L} = G_F\, \psi^4$$

$\mathcal{L}$: $[\text{mass}]^4$; G_F: $[\text{mass}]^{-2}$; ψ^4: $[\text{mass}]^{3/2\times 4}$

$$\Gamma \propto G_F^2 m^5$$

m: $[\text{mass}]$

for the muon, the relevant mass scale is the muon mass m_μ=105MeV: $\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3} \sim 10^{-19}\,\text{GeV}$

for the neutron, the relevant mass scale is (m_n-m_p)≈1.29MeV: $\Gamma_n = \mathcal{O}(1)\frac{G_F^2 \Delta m^5}{\pi^3} \sim 10^{-28}\,\text{GeV}$

ex: what about $\pi^\pm$ decay $\tau_\pi \approx 10^{-8}$s? Why $\frac{\Gamma(\pi^- \to e^- \bar\nu_e)}{\Gamma(\pi^- \to \mu^- \bar\nu_\mu)} \sim 10^{-4}$?

What about weak scattering process, e.g. $e\nu_e \to e\nu_e$?

$$\sigma \propto G_F^2 E^2$$

σ: $[\text{mass}]^{-2}$; G_F^2: $[\text{mass}]^{-2\times 2}$; E^2: $[\text{mass}]^2$

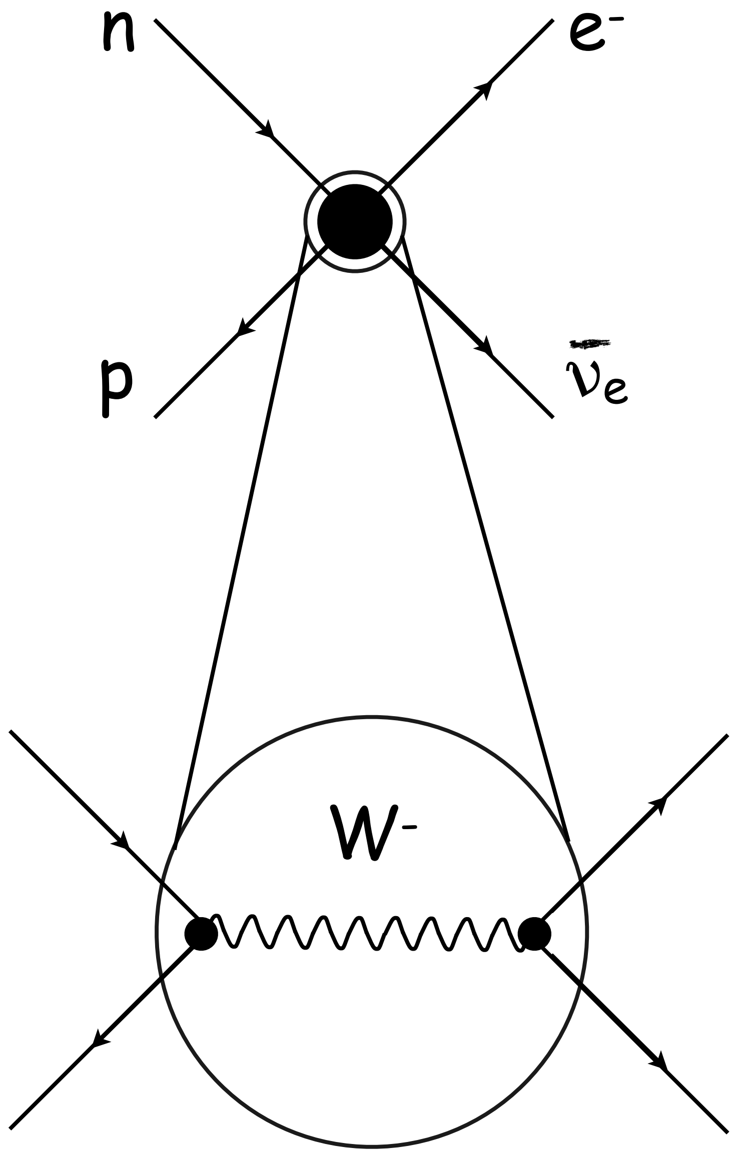
non conservation of probability
(non-unitary theory)
inconsistent at energy above 300GeV

Why Gauge Theories?

What about weak scattering process, e.g. $e\nu_e \to e\nu_e$?

$$\sigma \propto G_F^2 E^2$$

$[\text{mass}]^{-2}$ $[\text{mass}]^{-2\times 2}$ $[\text{mass}]^{2}$



Gauge theory

$$\sigma \propto g^4 \frac{E^2}{m_W^2\,(E^2+m_W^2)}$$

- match with Fermi theory at low energy $G_{\mathcal{F}} = \frac{\sqrt{2}g^2}{8m_W^2}$

  (we say that the Fermi theory is an **effective theory** of the weak gauge theory at low energy)

- good high energy behaviour

exp. m_W=80.4 GeV
➲ g ≈0.6, ie, same order as e=0.3
unification EM & weak interactions

From Gauge Theory back to Fermi

We can derive the Fermi current-current contact interactions by "integrating out" the gauge bosons, i.e., by replacing in the Lagrangian the W by their equation of motion. Here is a simple derivation (a better one taking into account the gauge kinetic term and the proper form of the fermionic current will be presented in the lecture, for the moment, take it as a heuristic derivation)

$$\mathcal{L} = -m_W^2 W_\mu^+ W_\nu^- \eta^{\mu\nu} + g W_\mu^+ J_\nu^- \eta^{\mu\nu} + g W_\nu^- J_\nu^+ \eta^{\mu\nu}$$

$$J^{+\mu} = \bar{n}\gamma^\mu p + \bar{e}\gamma^\mu \nu_e + \bar{\mu}\gamma^\mu \nu_\mu + \dots \qquad \text{and} \qquad J^{-\mu} = \left(J^{+\mu}\right)^*$$

The equation of motion for the gauge fields: $\frac{\partial \mathcal{L}}{\partial W_\mu^+} = 0 \qquad \Rightarrow \qquad W_\mu^- = \frac{g}{m_W^2} J_\mu^-$

Plugging back in the original Lagrangian, we obtain an effective Lagrangian (valid below the mass of the gauge bosons):

$$\mathcal{L} = \frac{g^2}{m_W^2} J_\mu^+ J_\nu^- \eta^{\mu\nu}$$

Which is the Fermi current-current interaction. The Fermi constant is given by $G_F = \frac{g^2}{m_W^2}$

(the correct expression involves a different normalisation factor)

In the current-current product, the term $(\bar{n}\gamma^\mu p)(\bar{\nu}_e \gamma^\nu e)\eta_{\mu\nu}$ is responsible for beta decay, while the term $(\bar{\mu}\gamma^\mu \nu_\mu)(\bar{\nu}_e \gamma^\nu e)\eta_{\mu\nu}$ is responsible for muon decay. Both decays are controlled by the same coupling, as indicated by the measurements of the lifetimes of the muon and neutron.

Why non-abelian Gauge Theories?

EM = exchange of photon = U(1) gauge symmetry

EM U(1) $\phi \to e^{i\alpha}\phi$ but $\partial_\mu \phi \to e^{i\alpha}\left(\partial_\mu \phi\right) + \underbrace{i(\partial_\mu \alpha)}\,\phi$

≠0 if local transformations

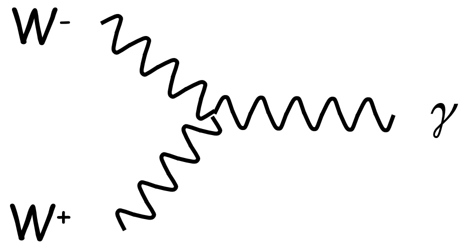
EM field and covariant derivative $\partial_\mu \phi + ieA_\mu \phi \to e^{i\alpha}(\partial_\mu \phi + ieA_\mu \phi)$

if $A_\mu \to A_\mu - \frac{1}{e}\partial_\mu \alpha$

the EM field keeps track of the phase in different points of the space-time

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

photon do not interact with itself because it doesn't carry an electric charge
W carries an electric charge since it mediates charged current interactions
W interacts with the photon ☛ non-abelian interactions

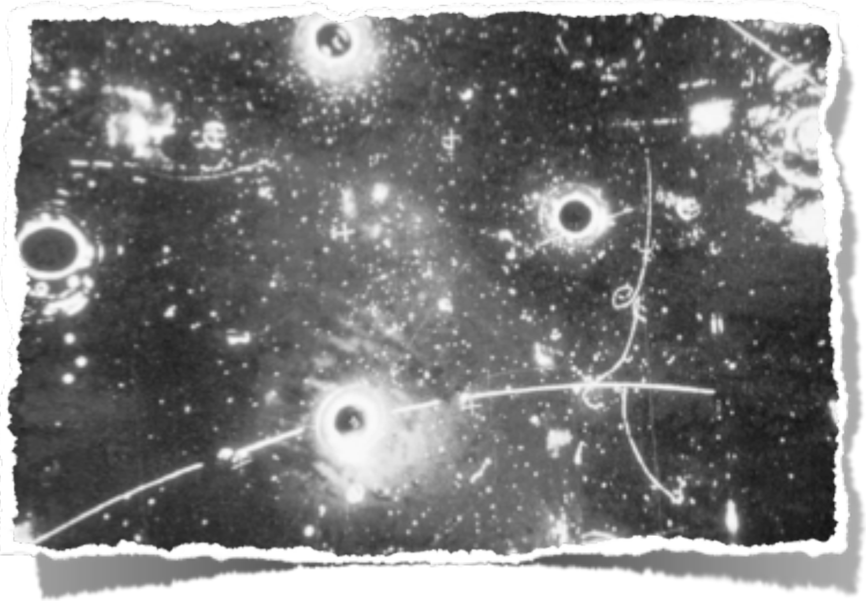


The Standard Model

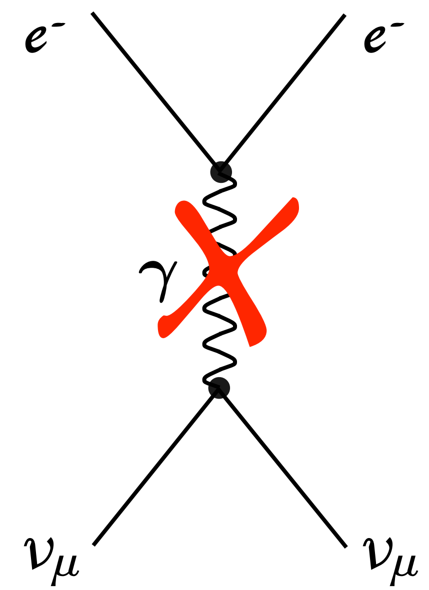
the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

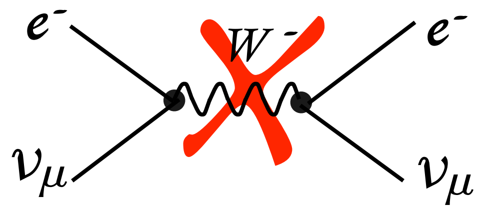
$SU(3)_C \times SU(2)_L \times U(1)_Y$

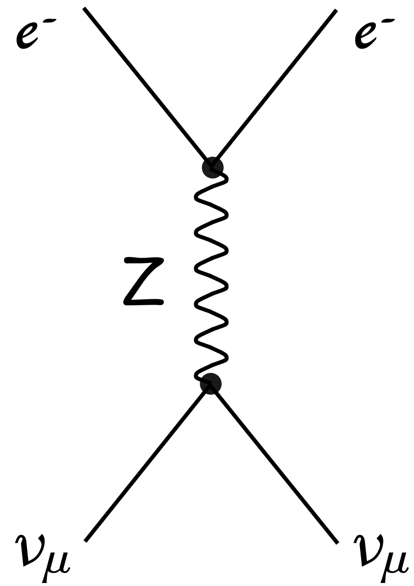
$\nu_\mu e^- \to \nu_\mu e^-$



[Gargamelle collaboration, '73]





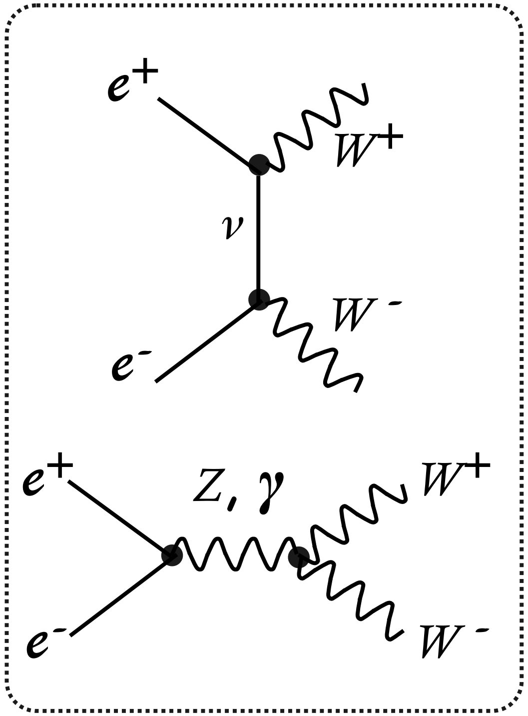


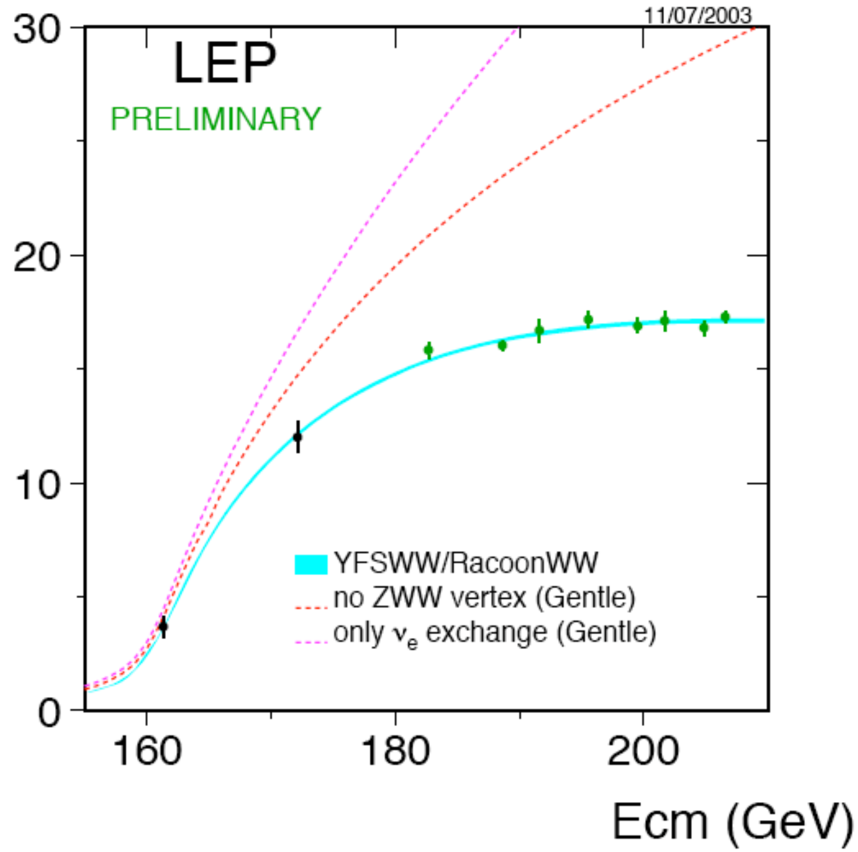
Gauge Theory as a Dynamical Principle

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$

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





The SM and the Mass Problem

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$

the masses of the quarks, leptons and gauge bosons don't obey the full gauge invariance

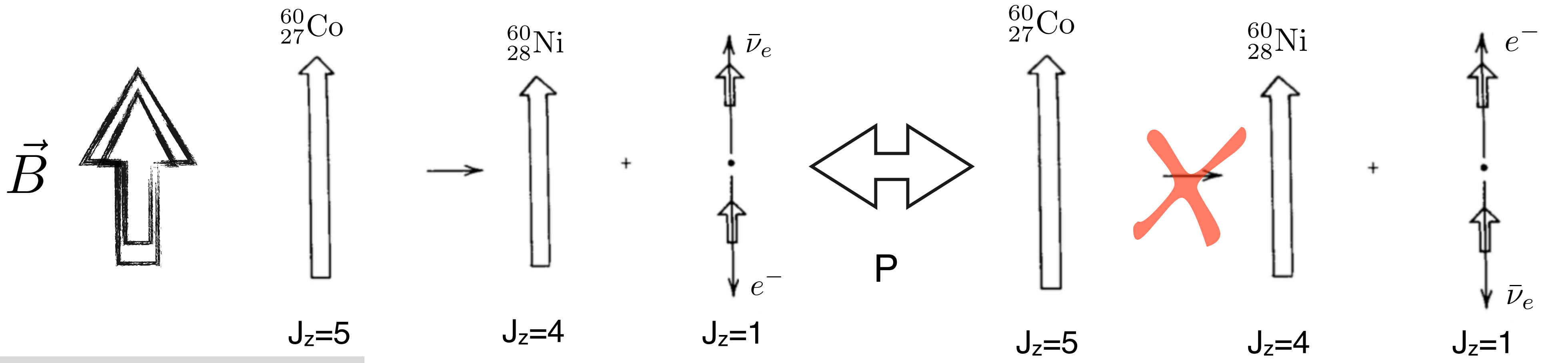
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$ is a doublet of $SU(2)_L$ but $m_{\nu_e} \ll m_e$

a mass term for the gauge field isn't invariant under gauge transformation $\delta A^a_\mu = \partial_\mu \epsilon^a + g f^{abc} A^b_\mu \epsilon^c$

⇒ spontaneous breaking of gauge symmetry ⇐

SM is a Chiral Theory

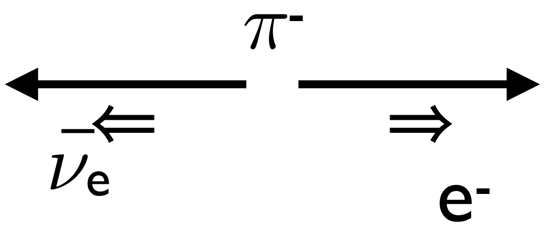
Weak interactions maximally violates P



$^{60}_{27}\mathrm{Co} \to {}^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e$

only LH e⁻ produced

TH: Yang&Lee '56. EXP: Wu '57



Conservation of momentum and spin imposes to have a RH e⁻

Weak decays proceed only w/ LH e⁻
So the amplitude is prop. to m_e

$$\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} \propto \frac{m_e^2}{m_\mu^2} \sim 2 \times 10^{-5} \sim 10^{-4}_{\text{obs}}$$

Extra phase-space factor

Fermion Masses

SM is a chiral theory (≠ QED that is vector-like)

$m_e \bar{e}_L e_R + h.c.$ is not gauge invariant

The SM Lagrangian doesn't not contain fermion mass terms
fermion masses are emergent quantities
that originate from interactions with Higgs vev

$$y_{ij} \bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}} \bar{f}_{L_i} f_{R_j} + \frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

Fermion Masses

In SM, the Yukawa interactions are the only source of the fermion masses

$$y_{ij}\bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}} \bar{f}_{L_i} f_{R_j} + \frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

mass   higgs-fermion interactions

both matrices are simultaneously diagonalizable

⇩ ⇩ ⇩

no tree-level Flavor Changing Current induced by the Higgs

Not true anymore if the SM fermions mix with vector-like partners(*) or for non-SM Yukawa

$$y_{ij}\left(1 + c_{ij}\frac{|H|^2}{f^2}\right)\bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}}\left(1 + c_{ij}\frac{v^2}{2f^2}\right)\bar{f}_{L_i} f_{R_j} + \left(1 + 3c_{ij}\frac{v^2}{2f^2}\right)\frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

Look for SM forbidden Flavor Violating decays $h \to \mu\tau$ and $h \to e\tau$

(look also at $t \to hc$ ATLAS '14)

- weak indirect constrained by flavor data ($\mu \to e\gamma$): BR<10%
- ATLAS and CMS have the sensitivity to set bounds O(1%)
- ILC/CLIC/FCC-ee can certainly do much better

Blankenburg, Ellis, Isidori '12

Harnik et al '12

Davidson, Verdier '12

CMS-PAS-HIG-2014-005

(*) e.g. Buras, Grojean, Pokorski, Ziegler '11

Fermion Masses

In SM, the Yukawa interactions are the only source of the fermion masses

$$y_{ij}\bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}} \bar{f}_{L_i} f_{R_j} + \frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

mass — higgs-fermion interactions

both matrices are simultaneously diagonalizable

no tree-level Flavor Changing Current induced by the Higgs

Quark mixings

$$\mathcal{L}_{Yuk} \;=\; \lambda^L_{ij}(\bar{L}^i_L \phi^c) l^j_R + \lambda^U_{ij}(\bar{Q}^i_{L,\alpha}\phi) u^j_{R,\alpha} + \lambda^D_{ij}(\bar{Q}^i_{L,\alpha}\phi^c) d^j_{R,\alpha} + cc$$

$$\mathcal{L}_L^\dagger \left(\frac{v}{\sqrt{2}}\lambda^L\right)\mathcal{L}_R = \begin{pmatrix} m_e & & \\ & m_\mu & \\ & & m_\tau \end{pmatrix}$$

$$\mathcal{U}_L^\dagger \left(\frac{-v}{\sqrt{2}}\lambda^U\right)\mathcal{U}_R = \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix}$$

$$\mathcal{D}_L^\dagger \left(\frac{v}{\sqrt{2}}\lambda^D\right)\mathcal{D}_R = \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_{Yuk\,quad} = & - \left(\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L\right) \begin{pmatrix} m_e & & \\ & m_\mu & \\ & & m_\tau \end{pmatrix} \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix} \\ & - \left(\bar{u}_{L,\alpha}, \bar{c}_{L,\alpha}, \bar{t}_{L,\alpha}\right) \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} \begin{pmatrix} u_{R,\alpha} \\ c_{R,\alpha} \\ t_{R,\alpha} \end{pmatrix} \\ & - \left(\bar{d}_{L,\alpha}, \bar{s}_{L,\alpha}, \bar{b}_{L,\alpha}\right) \mathcal{V}^\dagger_{KM} \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} \begin{pmatrix} d_{R,\alpha} \\ s_{R,\alpha} \\ b_{R,\alpha} \end{pmatrix} \\ & + \; cc \end{aligned}$$

$$\mathcal{V}_{KM} = \mathcal{D}^\dagger_L \mathcal{U}_L$$

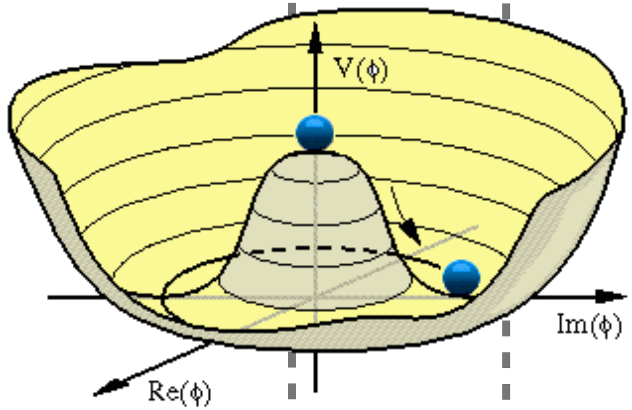
Spontaneous Symmetry Breaking

Symmetry of the Lagrangian

$SU(2)_L \times U(1)_Y$

Higgs Doublet

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$



Symmetry of the Vacuum

$U(1)_{e.m.}$

Vacuum Expectation Value

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad \text{with} \quad v \approx 246 \text{ GeV}$$

$$D_\mu H = \partial_\mu H - \frac{i}{2} \begin{pmatrix} gW^3_\mu + g'B_\mu & \sqrt{2}gW^+_\mu \\ \sqrt{2}gW^-_\mu & -gW^3_\mu + g'B_\mu \end{pmatrix} H \quad \text{with} \quad \mathrm{W}^\pm_\mu = \frac{1}{\sqrt{2}}\left(\mathrm{W}^1_\mu \mp \mathrm{W}^2_\mu\right)$$

$$|D_\mu H|^2 = \frac{1}{4}\, g^2 v^2\, W^+_\mu W^{-\,\mu} + \frac{1}{8}\left(W^3_\mu\, B_\mu\right) \begin{pmatrix} g^2v^2 & -gg'v^2 \\ -gg'v^2 & g'^2v^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

- Gauge boson spectrum
  - electrically charged bosons $\quad M_W^2 = \frac{1}{4} g^2 v^2$
  - electrically neutral bosons $\quad Z_\mu = cW^3_\mu - sB_\mu$, $\quad \gamma_\mu = sW^3_\mu + cB_\mu$

Weak mixing angle

$$c = \frac{g}{\sqrt{g^2+g'^2}} \qquad s = \frac{g'}{\sqrt{g^2+g'^2}}$$

$$M_Z^2 = \frac{1}{4}(g^2 + g'^2)v^2$$

$$M_\gamma = 0$$

Interactions Fermions-Gauge Bosons

Gauge invariance says:

$$\mathcal{L} = gW^3_\mu \left(\sum_i T_{3L\,i}\; \bar{\psi}_i \bar{\sigma}^\mu \psi_i \right) + g' B_\mu \left(\sum_i y_i\; \bar{\psi}_i \bar{\sigma}^\mu \psi_i \right)$$

Going to the mass eigenstate basis:

$$Z_\mu = cW^3_\mu - sB_\mu \qquad c = \frac{g}{\sqrt{g^2+g'^2}}$$

with

$$\gamma_\mu = sW^3_\mu + cB_\mu \qquad s = \frac{g'}{\sqrt{g^2+g'^2}}$$

$$Q = T_{3L} + Y$$

$$\mathcal{L} = \sqrt{g^2+g'^2}\, Z_\mu \left(\sum_i (T_{3L\,i} - s^2 Q_i)\; \bar{\psi}_i \bar{\sigma}^\mu \psi_i \right) + \frac{gg'}{\sqrt{g^2+g'^2}} \gamma_\mu \left(\sum_i Q_i\; \bar{\psi}_i \bar{\sigma}^\mu \psi_i \right)$$

protected by $U(1)_{em}$ gauge invariance
⇛ no correction

not protected by gauge invariance
corrected by radiative corrections + new physics

electric charge

$$e = \frac{gg'}{\sqrt{g^2+g'^2}} = sg = cg'$$

Custodial Symmetry

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_w} = \frac{\frac{1}{4}g^2v^2}{\frac{1}{4}(g^2+g'^2)v^2\frac{g^2}{g^2+g'^2}} = 1$$

- Consequence of an approximate global symmetry of the Higgs sector

$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$ Higgs doublet = 4 real scalar fields

$V(H) = \lambda\left(H^\dagger H - \frac{v^2}{2}\right)^2$ is invariant under the rotation of the four real components

$$SO(4) \sim SU(2)_L \times SU(2)_R$$

$SU(2)_R$ ↓

$SU(2)_L$ → $\left(i\sigma^2 H^\star \quad H\right) = \Phi$

2x2 matrix

$$\Phi^\dagger\Phi = H^\dagger H \begin{pmatrix} 1 & \\ & 1 \end{pmatrix}$$

$$V(H) = \frac{\lambda}{4}\left(\mathrm{tr}\Phi^\dagger\Phi - \mathrm{v}^2\right)^2$$

explicitly invariant under $SU(2)_L \times SU(2)_R$

Custodial Symmetry

Higgs vev

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \qquad \langle \Phi \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 1 & \\ & 1 \end{pmatrix}$$

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

unbroken symmetry in the broken phase

$$(W^1_\mu, W^2_\mu, W^3_\mu) \quad \text{transforms as a triplet}$$

$$(Z_\mu \, \gamma_\mu) \begin{pmatrix} M_Z^2 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} Z^\mu \\ \gamma^\mu \end{pmatrix} = (W^3_\mu \, B_\mu) \begin{pmatrix} c^2 M_Z^2 & -csM_Z^2 \\ -csM_Z^2 & s^2 M_Z^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

The $SU(2)_V$ symmetry imposes the same mass term for all W^i thus $c^2 M_Z^2 = M_W^2$

$\rho = 1$

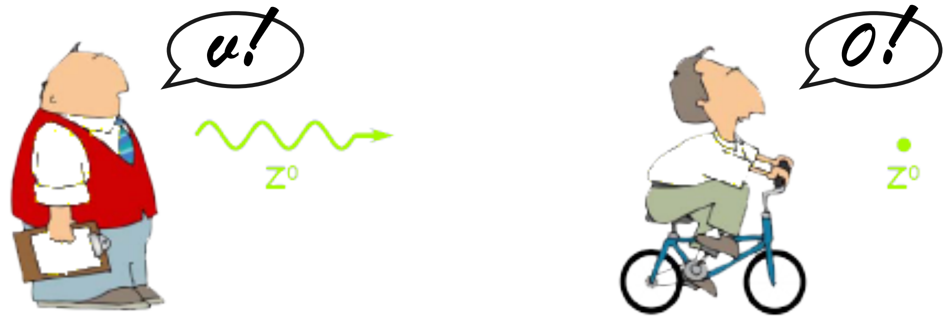
The hypercharge gauge coupling and the Yukawa couplings break the custodial $SU(2)_V$, which will generate a (small) deviation to $\rho = 1$ at the quantum level.

The longitudinal polarization of massive W, Z

a massless particle is never at rest: always possible to distinguish (and eliminate!) the longitudinal polarization

3=2+1

Guralnik et al '64



the longitudinal polarization is physical for a massive spin-1 particle

(pictures: courtesy of G. Giudice)

symmetry breaking: new phase with more degrees of freedom

$$\epsilon_{\parallel} = \left(\frac{|\vec{p}|}{M}, \frac{E}{M} \frac{\vec{p}}{|\vec{p}|} \right)$$ polarization vector grows with the energy

The longitudinal polarization of W, Z

Indeed a massive spin 1 particle has 3 physical polarizations:

$$A_\mu = \epsilon_\mu \; e^{ik_\mu x^\mu}$$

$$\epsilon^\mu \epsilon_\mu = -1 \qquad k^\mu \epsilon_\mu = 0$$

$$k^\mu = (E, 0, 0, k)$$

with $k_\mu k^\mu = E^2 - k^2 = M^2$

- 2 transverse: $\begin{cases} \epsilon_1^\mu = (0, 1, 0, 0) \\ \epsilon_2^\mu = (0, 0, 1, 0) \end{cases}$

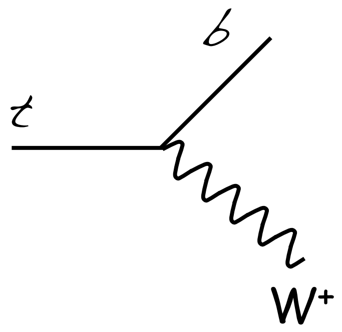
- 1 longitudinal: $\epsilon_\parallel^\mu = (\frac{k}{M}, 0, 0, \frac{E}{M}) \approx \frac{k^\mu}{M} + \mathcal{O}(\frac{E}{M})$

(in the R-ξ gauge, the time-like polarization ($\epsilon^\mu \epsilon_\mu = 1 \quad k^\mu \epsilon_\mu = M$) is arbitrarily massive and decouple)

in the particle rest-frame, no distinction between L and T polarizations
in a frame where the particle carries a lot of kinetic energy, the L polarization "dominates"

The BEH mechanism: "V_L=Goldstone bosons"

At high energy, the physics of the gauge bosons becomes simple



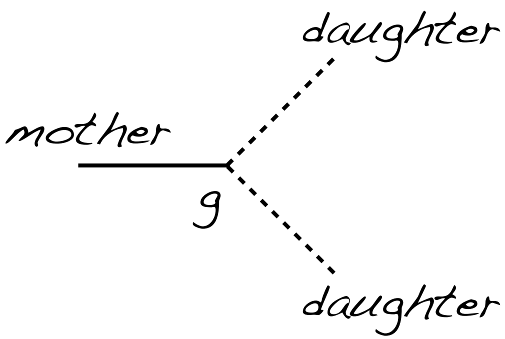
$$\Gamma(t \to b W_L) = \frac{g^2}{64\pi} \frac{m_t^2}{m_W^2} \frac{(m_t^2 - m_W^2)^2}{m_t^3}$$

$$\Gamma(t \to b W_T) = \frac{g^2}{64\pi} \frac{2(m_t^2 - m_W^2)^2}{m_t^3}$$

- at threshold ($m_t \sim m_W$) democratic decay
- at high energy ($m_t \gg m_W$) W_L dominates the decay

At high energy, the dominant degrees of freedom are W_L

~~ why you should be stunned by this result: ~~



we expect: (dimensional analysis) $\Gamma \sim g^2\, m_{\text{mother}}$

instead $\Gamma \propto m_{\text{mother}}^3$ means $g \propto m$ like the Higgs couplings!

very efficient way to get energy from the mother particle $\tau \ll \tau_{\text{naive}}$

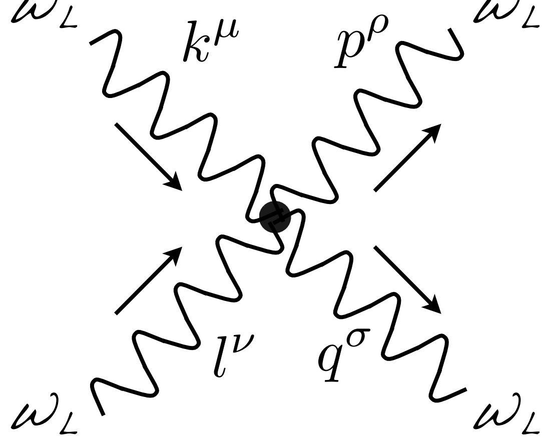
Goldstone equivalence theorem
$W^\pm_L, Z_L \approx SO(4)/SO(3)$

This is the physics that was understood at LEP
The pending question was then: is there something else?
That was the job of the LHC

Call for extra degrees of freedom

NO LOSE THEOREM

Bad high-energy behaviour for the scattering of the longitudinal polarizations



$$\mathcal{A} = \epsilon^\mu_\parallel(k)\epsilon^\nu_\parallel(l)g^2\left(2\eta_{\mu\rho}\eta_{\nu\sigma} - \eta_{\mu\nu}\eta_{\rho\sigma} - \eta_{\mu\sigma}\eta_{\nu\rho}\right)\epsilon^\rho_\parallel(p)\epsilon^\sigma_\parallel(q)$$

$$\mathcal{A} = g^2\frac{E^4}{4M_W^4}$$

violations of perturbative unitarity around E ~ M/√g (actually M/g)

Extra degrees of freedom are needed to have a good description of the W and Z masses at higher energies

numerically: E ~ 3 TeV ⬅ the LHC was sure to discover something!

What is the SM Higgs?

A single scalar degree of freedom that couples to the mass of the particles

$\Sigma = e^{i\pi^a \sigma^2/v}$ parametrises the coset SO(4)/SO(3)

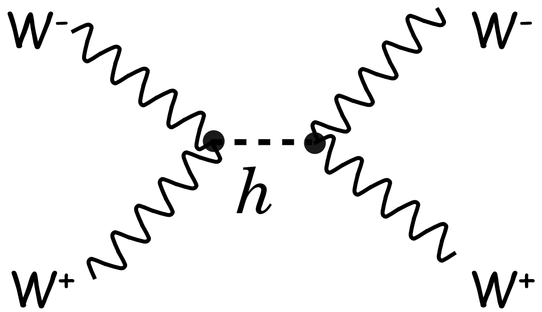
$$\mathcal{L} = \frac{v^2}{4} \mathrm{Tr}\, D_\mu \Sigma^\dagger D^\mu \Sigma$$

$\Sigma = \mathbb{1}$ $\longrightarrow$ $m_W^2 W_\mu^+ W_\mu^+ + \frac{1}{2} m_Z Z_\mu Z^\mu$

$g = g' = 0$ $\longrightarrow$ $\frac{1}{2}(\partial\pi)^2 + \frac{1}{v^2}\partial^2\pi^4 + \ldots$

$$\mathcal{L}_{\mathrm{EWSB}} = m_W^2 W_\mu^+ W_\mu^+ \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_\psi \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s - m_h^2}\right)$$

growth cancelled for
a = 1
restoration of
perturbative unitarity

What is the Higgs the name of?

A single scalar degree of freedom that couples to the mass of the particles

$$\mathcal{L}_{\rm EWSB} = m_W^2 W_\mu^+ W_\mu^+ \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_\psi \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right)$$

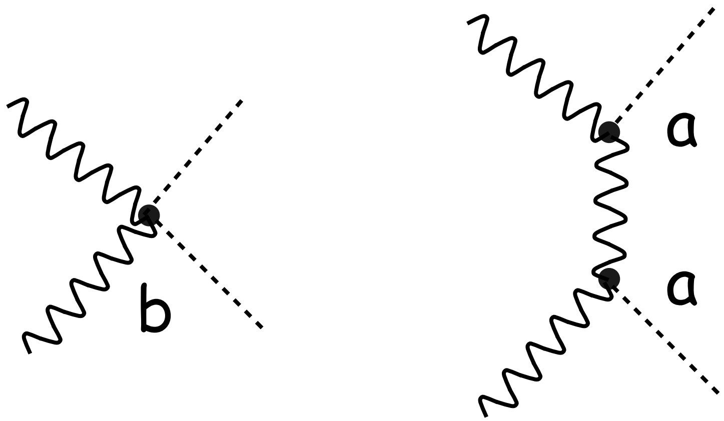
'a', 'b' and 'c' are arbitrary free couplings

For a=1: perturbative unitarity in elastic channels WW → WW

For b = a^2: perturbative unitarity in inelastic channels WW → hh

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10



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For b = a²: perturbative unitarity in inelastic channels WW → hh

For ac=1: perturbative unitarity in inelastic WW → $\psi\ \psi$

Cornwall, Levin, Tiktopoulos '73

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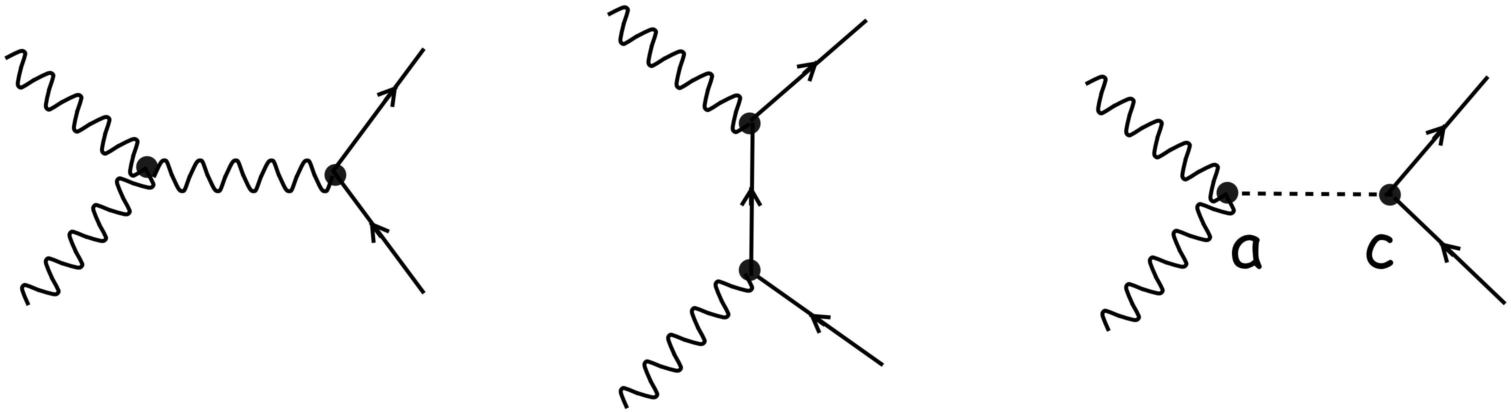

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For a=1: perturbative unitarity in elastic channels WW $\to$ WW

For b = a^2: perturbative unitarity in inelastic channels WW $\to$ hh

For ac=1: perturbative unitarity in inelastic WW $\to$ $\psi\,\psi$

Cornwall, Levin, Tiktopoulos '73

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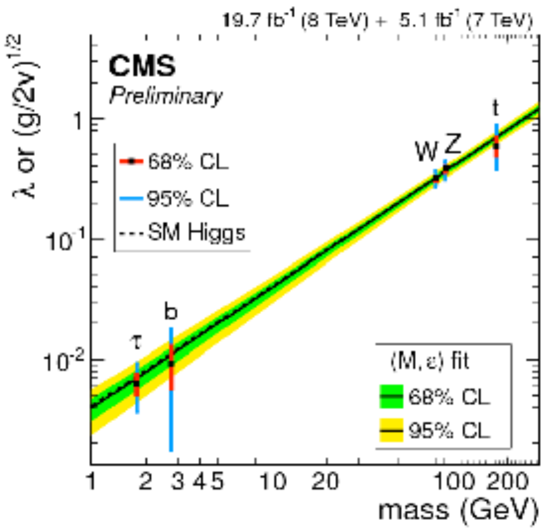

CMS PAS-HIG-14-009

Higgs couplings
are proportional
to the masses of the particles

$$\lambda_\psi \propto \frac{m_\psi}{v}, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

HEP with a Higgs boson

The Higgs discovery has been an important milestone for HEP
but it hasn't taught us much about **BSM** yet

typical Higgs coupling deformation: $\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_*^2\, v^2}{\Lambda^2_{\rm BSM}}$

current (and future) LHC sensitivity
O(10-20)% ⇔ Λ_{BSM} > 500(g_*/g_{SM}) GeV

not doing better than direct searches unless in the case of strongly coupled new physics
(notable exceptions: New Physics breaks some structural features of the SM
e.g. flavor number violation as in h→$\mu\tau$)

Higgs precision program is very much wanted
to probe BSM physics