LHC physics:

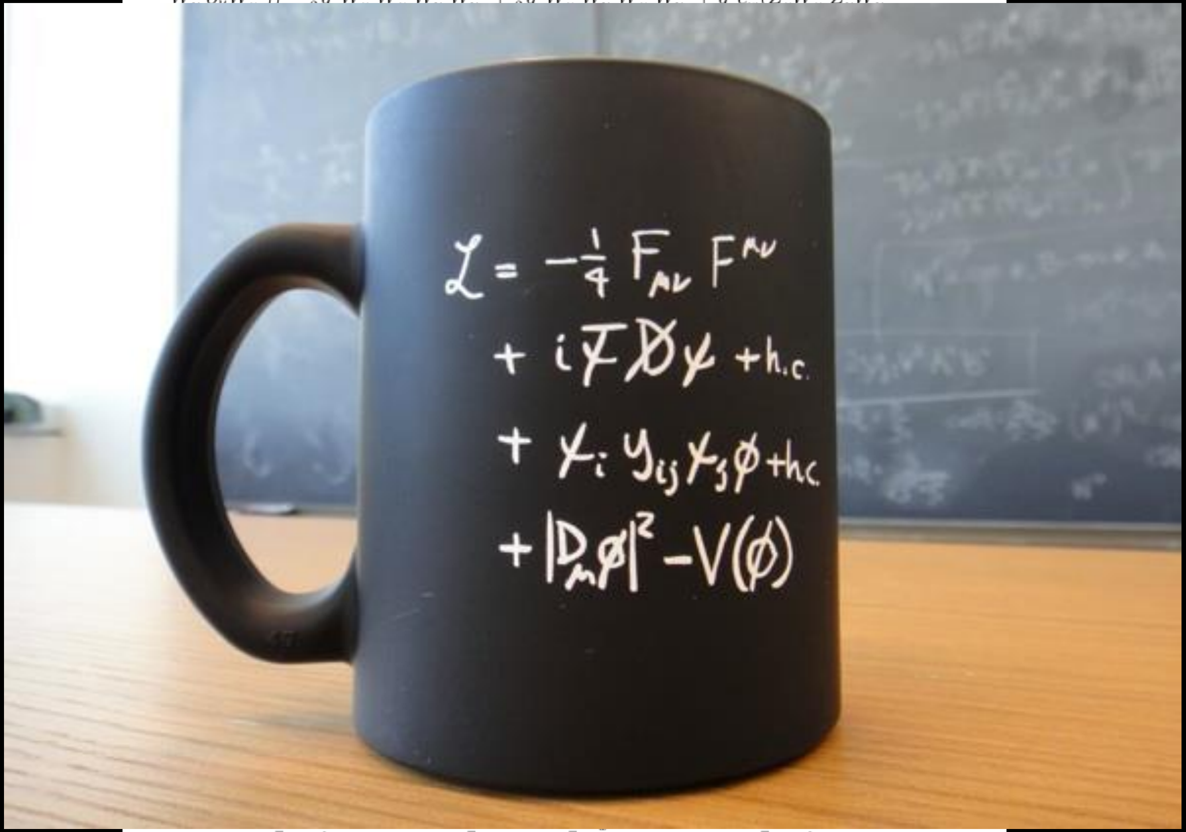
Interrogating the Standard Model of particle physics

See how in the LHC experimental lectures by Marco

GRASPA School 2015

The Standard Model Lagrangian:

$$\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) -$$
$$igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu -$$



$$\partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 -$$

accords (very) well with all measurements ever made in high-energy physics!

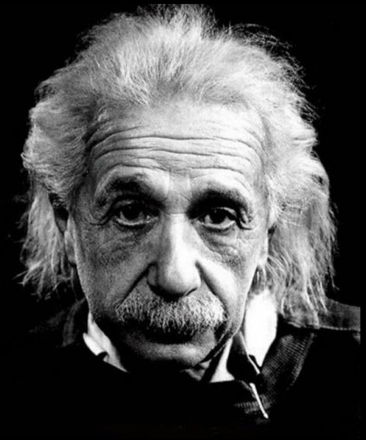
Outline:

- Lecture 1 :
  - *Why Nature needs a light Higgs boson?*
- Lecture 2 :
  - *Why a light Higgs boson is not the end?*

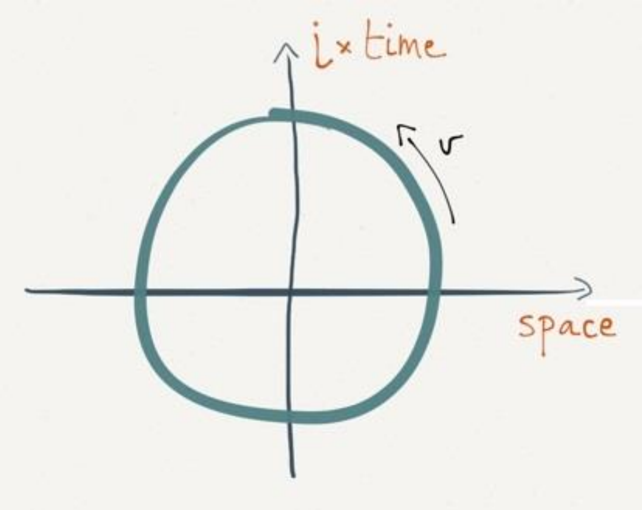
Lecture 0:

XXth century physics in a (hazel)nut-shell

Lessons from relativity



- *All inertial observers see the same physics:*
  - light speed $c < \infty$
  - *Lorentz symmetries = space-time "rotations"*



$$x^\mu \equiv (ct, \vec{x})$$
$$x^2 = \eta_{\mu\nu} x^\mu x^\nu = x^\mu x_\mu = \text{invariant}$$
$$\eta_{\mu\nu} = diag(1, -1, -1, -1)$$

- *Mass is just another form of energy:* $E = mc^2$

$$p^\mu = \left(\frac{E}{c}, \vec{p}\right) \rightarrow p^2 = \left(\frac{E^2}{c^2} - \vec{p}^2\right) = m^2 c^4$$

Lessons from quantum mechanics

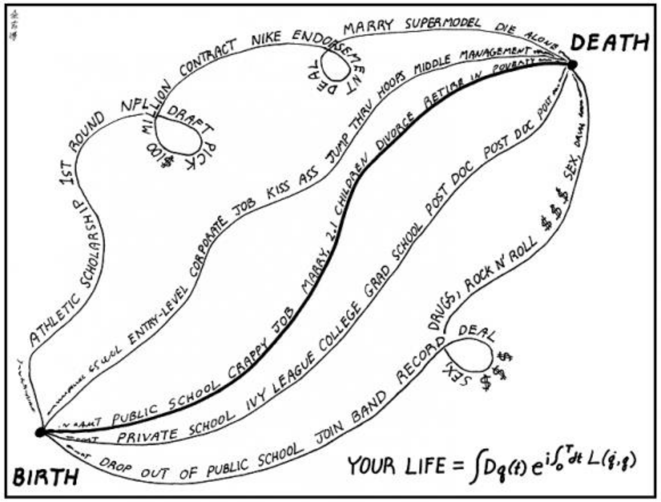
- *Determinism is not fundamental:* $\Delta x^{\mu} \times \Delta p_{\nu} \geq (\hbar/2)\delta^{\mu}_{\nu}$
  - *Nature is random → probability rules*
  - *The vacuum is not void, it fluctuates!*

- *Classical physics emerges from constructive interference of probability amplitudes:*

Feynman's path integral:

$$A = \int [Dq]\, exp\left[\frac{i}{\hbar} S[q(t), \dot{q}(t)]\right]$$

→ a rational for the least action principle!



The Path Integral Formulation of Your Life

Lessons from QM+relativity

- *number of particles in the system is no longer conserved:*

kinetic energy ↔ massive particles

→ particles = excitations (quanta) of fields

explaining why all electrons are the same

- *High-energy colliders are quantum "microscopes".*

A word on units

- [m],[g],[s] are not well suited units for fundamental particles

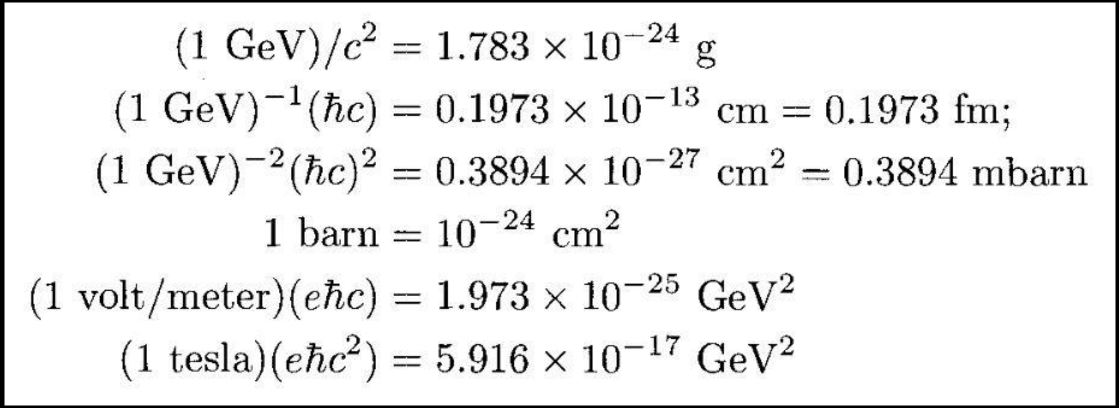
$$\Delta x \sim 10^{-18}\text{m},\ m_{proton} \sim 10^{-24}\text{g},\ \tau_{Higgs} \sim 10^{-22}\text{s},\ \ldots$$

- most phenomena are set by the particle's mass

→ *Can one measure length, time, energy, momentum in "units" of mass?*

$c = \hbar = 1$ [natural units]

$$E = mc^2 = m$$
$$L = \hbar/\text{mc} = 1/m$$
$$t = \hbar/E = 1/m$$
$$p = \hbar/L = m$$



$$(1\ \text{GeV})/c^2 = 1.783 \times 10^{-24}\ \text{g}$$
$$(1\ \text{GeV})^{-1}(\hbar c) = 0.1973 \times 10^{-13}\ \text{cm} = 0.1973\ \text{fm};$$
$$(1\ \text{GeV})^{-2}(\hbar c)^2 = 0.3894 \times 10^{-27}\ \text{cm}^2 = 0.3894\ \text{mbarn}$$
$$1\ \text{barn} = 10^{-24}\ \text{cm}^2$$
$$(1\ \text{volt/meter})(e\hbar c) = 1.973 \times 10^{-25}\ \text{GeV}^2$$
$$(1\ \text{tesla})(e\hbar c^2) = 5.916 \times 10^{-17}\ \text{GeV}^2$$

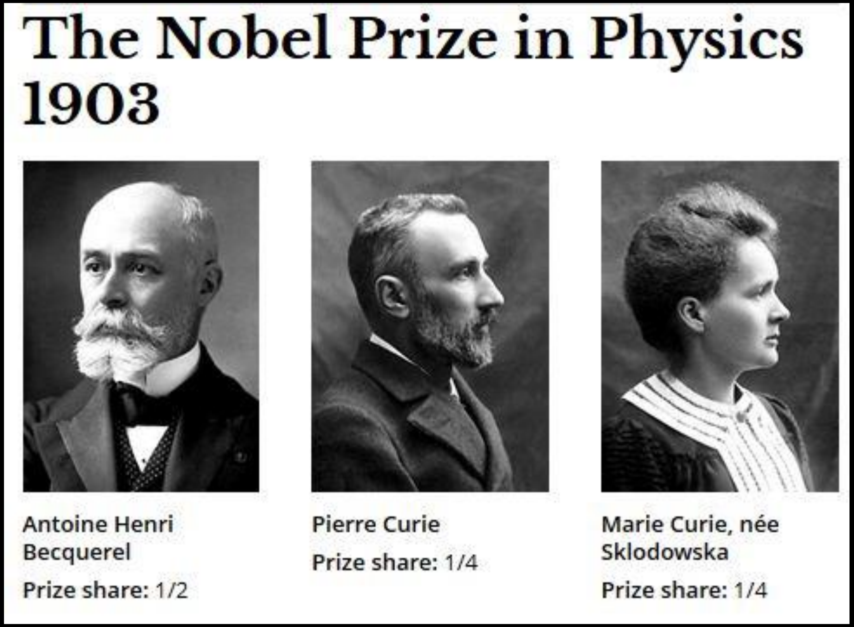
[length]=[time]=[energy]$^{-1}$=[momentum]$^{-1}$=[mass]$^{-1}$

Lecture 1:

What is Higgs good for?

Discovery of radioactivty

- Earliest evidence by Becquerel in 1896 in Uranium salts:

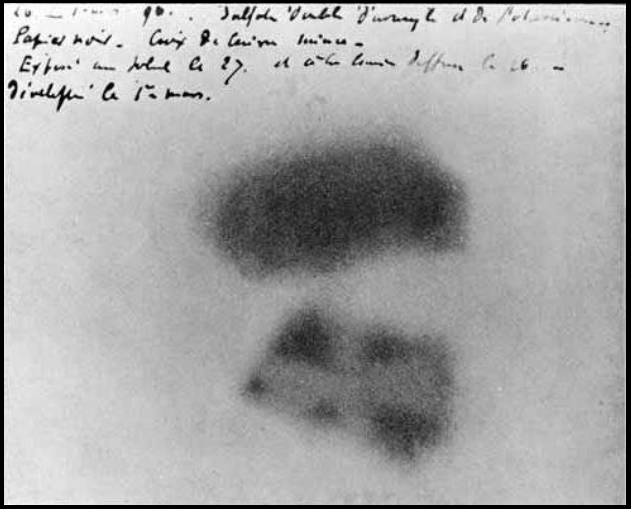


The Nobel Prize in Physics 1903

Antoine Henri Becquerel
Prize share: 1/2

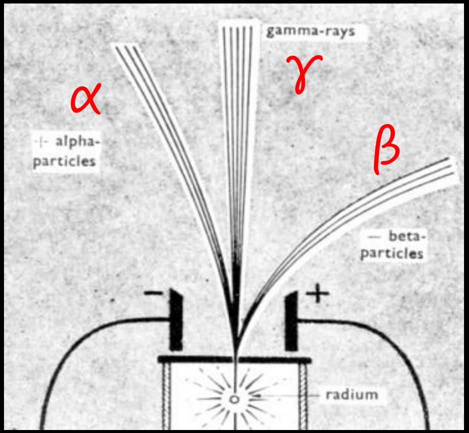
Pierre Curie
Prize share: 1/4

Marie Curie, née Sklodowska
Prize share: 1/4



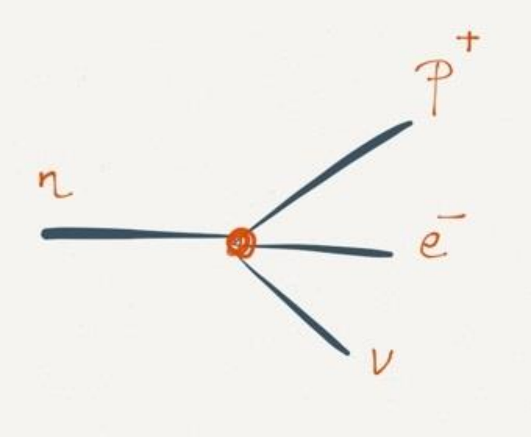
[Becquerel, 1896]

- Further studies by Rutherford/Villard quickly revealed 3 kinds of radioactivities: α,β,γ



Toward a theory of the weak interaction

- β-decay = nuclear transition+electron+antineutrino emission



Fermi "Weak" constant:

$G_F \approx 1.166 \times 10^{-5}$ GeV^{-2}

- 1934, Fermi proposed a first successful theory description, introducing a new fundamental (contact) interaction:

$$\frac{G_F}{\sqrt{2}} (\bar{n}\gamma^{\mu} p)_{V-A} \left(\bar{\nu}\gamma_{\mu} e\right)_{V-A} + h.c.$$

- 1940's, muon decay also described by Fermi theory

with $(\bar{n}\gamma^{\mu} p) \rightarrow \left(\bar{\mu}\gamma^{\mu}\nu_{\mu}\right)$ suggesting β-decay is universal!

(similarly to QED)

Toward a theory of the weak interaction

- Fermi's "Weak theory" worked well in describing low-energy nuclear processes known at the time:

  e.g. e⁻ nuclear capture, muon decay…

- But the theory is problematic at higher energies:

$$\sigma_{e\nu_\mu \to \mu\nu} \approx \frac{G_F^2 s}{4\pi} \xrightarrow[\sqrt{s}\to\infty]{} \infty$$

$\sqrt{s}$= center of mass E

- Unitary evolution in QM → cross-sections are bounded:

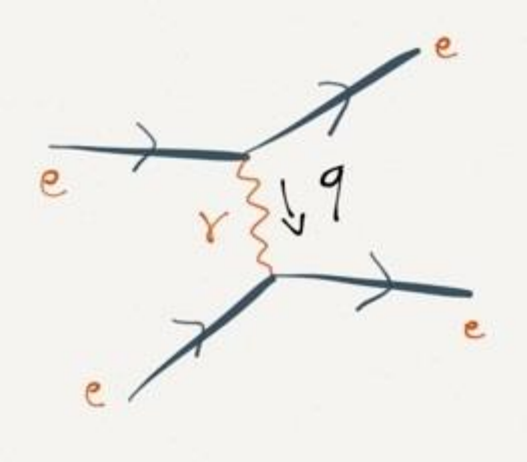
$$\text{any } \sigma \le \sum_J \frac{2\pi(2J+1)}{s} \approx \frac{2\pi}{s} + \text{higher partial-wave}$$

- QM → Fermi's theory **must** be modified below *E*~900GeV*!!*

Toward a theory of the weak interaction

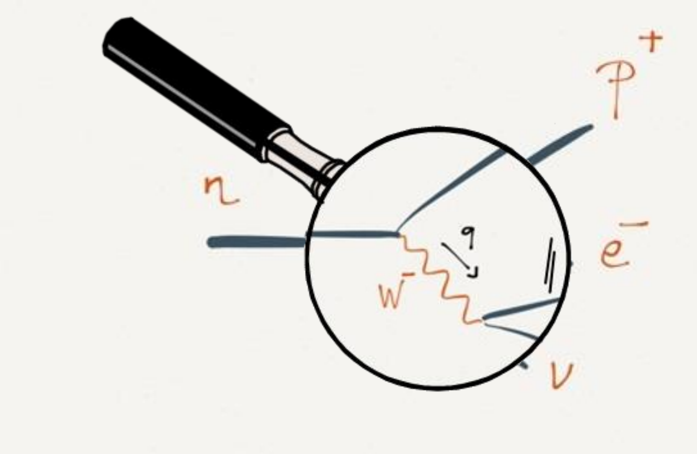
- Idea = mimic current-current interactions in QED:

[Schwinger, '57]



$$\approx i(\bar{e}\gamma^{\mu}e)\frac{4\pi\alpha}{\boxed{q^2}}(\bar{e}\gamma^{\mu}e) \quad = i\frac{J_{\mu}^{em}J_{em}^{\mu}}{q^2}$$

massless photon propagator
→ long-range force



$$= i(\bar{n}\gamma^{\mu}p)\boxed{\frac{G_F}{\sqrt{2}}\eta_{\mu\nu}}(\bar{\nu}\gamma^{\nu}e)$$

$$\frac{(\pi/2)\alpha_W}{q^2 - m_W^2}\left(\eta_{\mu\nu} - \boxed{\frac{q_{\mu}q_{\nu}}{m_W^2}}\right)$$

W longitudinal polarization
(see later)

Toward a theory of the weak interaction

- back to $\nu_\mu + e \to \mu + \nu$ scattering:

$$\sigma_{e\nu_\mu\to\mu\nu} = \frac{\pi\alpha_W^2 s}{8(s-m_W^2)^2}$$

low-energy regime, $s \ll m_W^2$:

$$\sigma_{e\nu_\mu\to\mu\nu} \approx \boxed{\frac{\pi\alpha_W^2 s}{8m_W^4}}\left[1+\mathcal{O}\left(\frac{s}{m_W^2}\right)\right]$$

$$\frac{G_F}{\sqrt{2}} \approx \frac{\pi\alpha_W}{2m_W^2}$$

it “matches”
Fermi’s theory

pushing QED analogy further:

$$\alpha_W \approx \alpha \approx \frac{1}{137} \to m_W \sim 40\text{GeV}$$

high-energy regime, $s \gg m_W^2$:

$$\sigma_{e\nu_\mu\to\mu\nu} \approx \boxed{\frac{\pi\alpha_W^2}{8s}}\left[1+\mathcal{O}\left(\frac{m_W^2}{s}\right)\right]$$

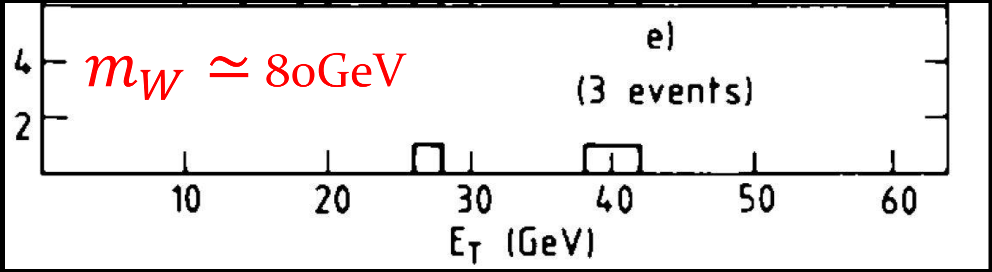
falls like $\sim \frac{1}{s}$

safe from unitarity problem!

meanwhile at the CERN SPS:*

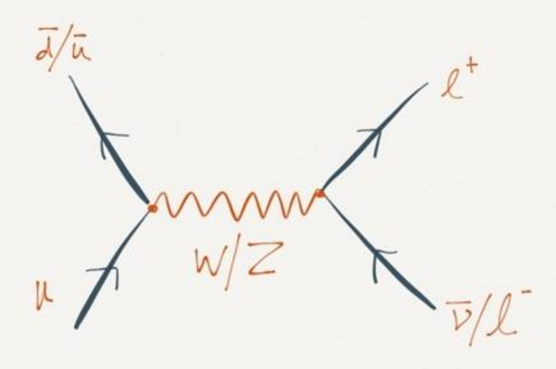
* $p\bar{p}$ collisions at $\sqrt{s}$=540GeV

W discovery at UA2, '83

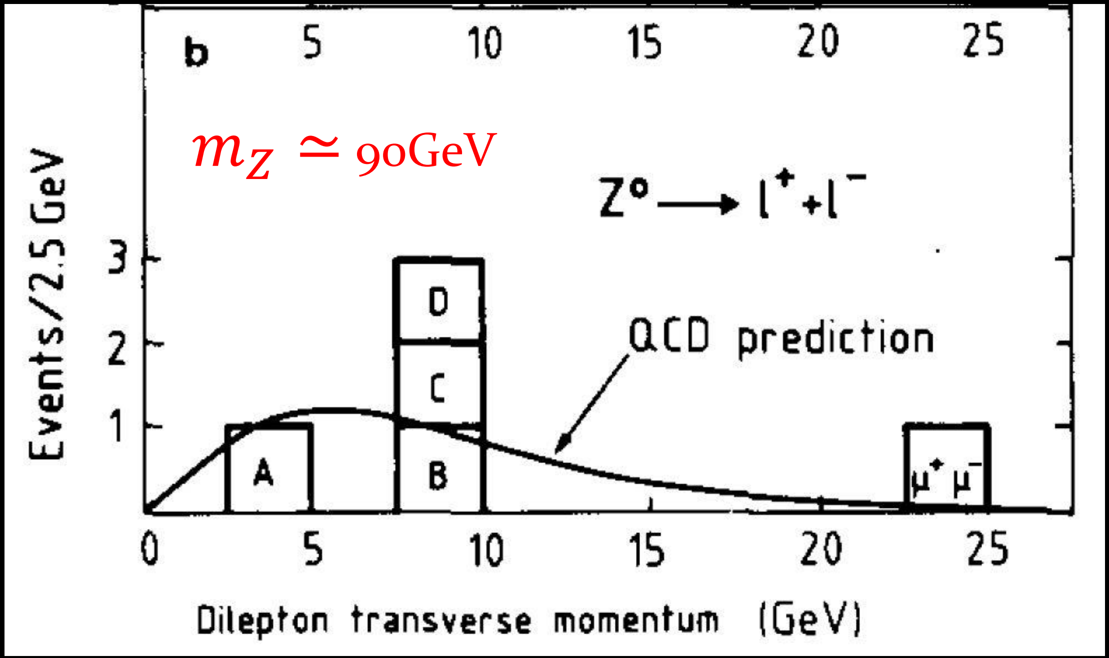


$m_W \simeq$ 80GeV

electrons recoiling against invisible ν's



Z discovery at UA1, '83



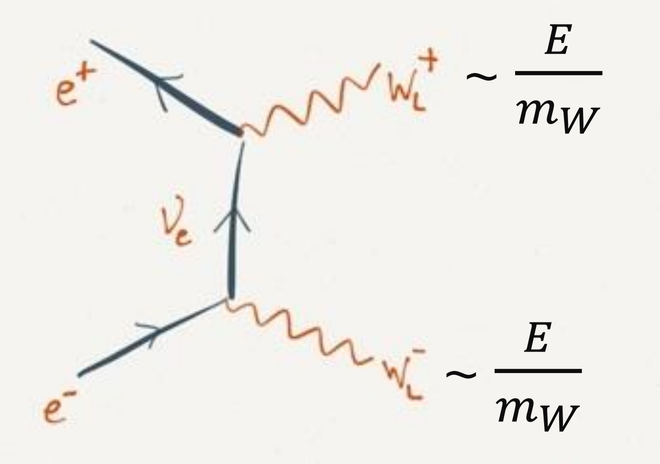
$m_Z \simeq$ 90GeV

Rubbia, Van der Meer, early '80's

$$\rightarrow \alpha_W \approx \frac{1}{35} \approx 4\alpha$$ weak force is not weak

Toward a theory of the weak interaction

- still problem with longitudinaly polarized W: $e^+e^- \to W_L^+W_L^-$



$$\underset{E \gg m_W}{\sim} \quad A_0 \frac{E^2}{m_W^2}$$

violate unitarity bound

polarization vectors for plane waves:

W rest frame: $p^\mu = (m_W, 0,0,0)$

3 indep. vectors satisfying $\epsilon_i^\mu p_\mu = 0$

$$\epsilon_1^\mu = (0,1,0,0)$$
$$\epsilon_2^\mu = (0,0,1,0)$$
$$\epsilon_3^\mu = (0,0,0,1)$$

$\xrightarrow{}$ z-boost

$$p^\mu = (E,0,0,p) \qquad (E^2 - p^2 = m_W^2)$$
$$\epsilon_1^\mu = (0,1,0,0)$$
$$\epsilon_2^\mu = (0,0,1,0)$$
$$\epsilon_3^\mu = \left(\frac{p}{m_W}, 0,0, \frac{E}{m_W}\right) \xrightarrow[E \gg m_W]{} \frac{p^\mu}{m_W} + \mathcal{O}^\mu\left(\frac{m_W}{E}\right)$$

Toward a theory of the weak interaction

- part of the solution involves introducing a neutral current:

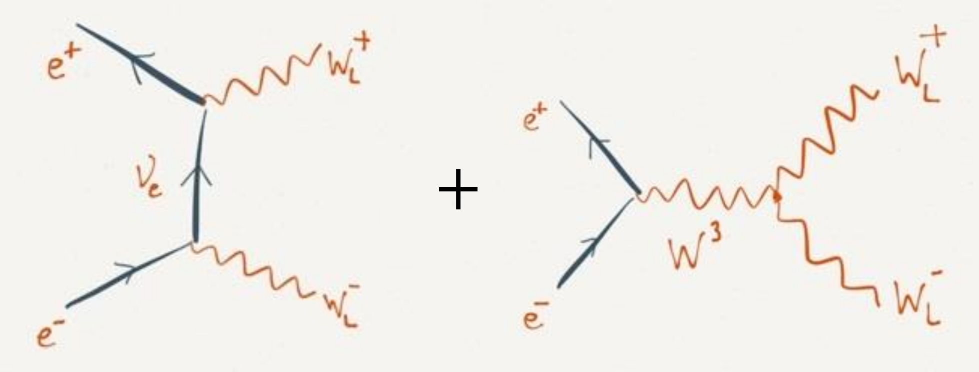
$$\mathcal{L}_{weak} \supset -\frac{g}{2\sqrt{2}}\left(J_+^\mu W_\mu^- + J_-^\mu W_\mu^+\right), \quad J_-^\mu = \bar{\nu}_e \gamma^\mu (1\text{-}\gamma_5) e + \cdots$$

define “weak charges” $Q_\pm \equiv \int d^3x\, J_\pm^0(x)$ → $\boxed{[Q_+, Q_-] = 2Q_3}$

$Q_3 = \int d^3x\, J_3^0(x)$,

$$J_3^\mu = \bar{e}\gamma^\mu(1\text{-}\gamma_5)e - \bar{\nu}_e\gamma^\mu(1-\gamma_5)\nu_e \neq J_{em}^\mu!$$

introduce associated mediator $\mathcal{L}_{weak} \rightarrow \mathcal{L}_{weak} - \frac{g}{2} J_3^\mu W_\mu^3$



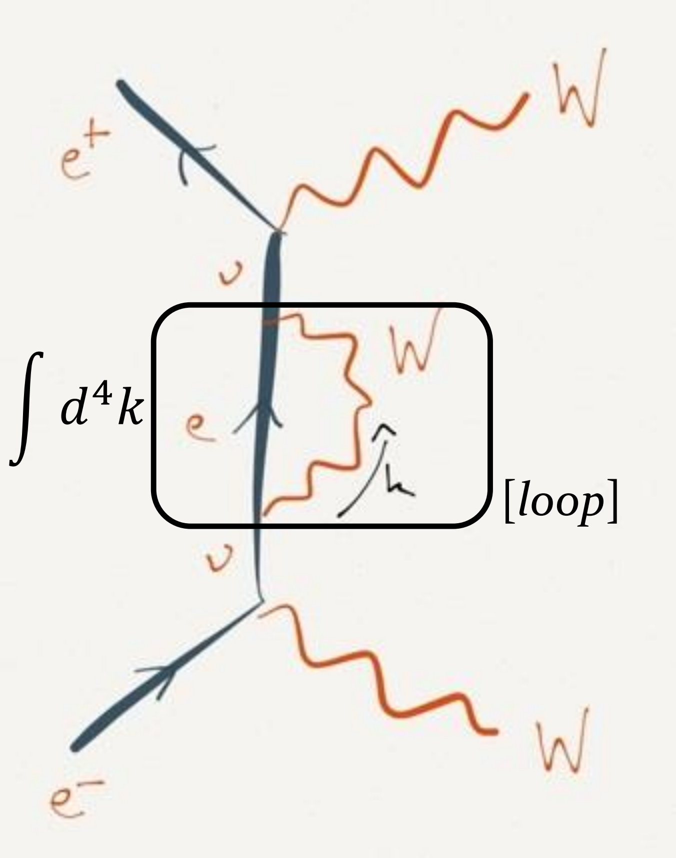
$$\underset{E \gg m_W}{\sim} A_0' \cancel{\frac{E^2}{m_W^2}}$$

SU(2)$_L$ isospin

unitarity saved

Towards a theory of weak interactions

- only classical so far, theory badly behaves at quantum level:



W propagator = $\frac{1}{k^2-m_W^2}\left(\eta_{\mu\nu} - \boxed{\frac{k_\mu k_\nu}{m_W^2}}\right)$

e propagator = $\frac{1}{k'^2-m_e^2}\left(k'_\mu\gamma^\mu + m_e\right)$

$k' = k - p$

$$\int d^4k\;[loop] \sim \int^{\Lambda^2} k^2 dk^2 \frac{k^2}{k^4} \approx \Lambda^2$$

→ *need gauge theories*

QED *interlude*

A gauge theory of electrodynamics

- QED $= U(1)$ locally invariant theory

$$\mathcal{L}_{Dirac} = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi \qquad \bar{\psi} = \psi^{\dagger}\gamma^{0}$$

global symmetry: $\psi \rightarrow e^{i\vartheta}\psi$, $\mathcal{L}_{Dirac} \rightarrow \mathcal{L}_{Dirac}$

Noether's theorem → conserved charge/current:

$$Q = \int d^3x\, J^0(x), \quad J^{\mu}(x) = \bar{\psi}\gamma^{\mu}\psi$$

declare local invariance: *(inspired by special relativity?)*

$\psi \rightarrow e^{i\vartheta(x)}\psi$ implies/dictates Q interactions through a long range force!!!

A gauge theory of electrodynamics

- **QED** $= U(1)$ locally invariant theory

local symmetry:

$$\psi \to e^{i\vartheta(x)}\psi$$

$$A_\mu \to A_\mu + e^{-1}\partial_\mu\vartheta$$

$$\mathcal{L}_{Dirac} = \bar{\psi}(i\gamma^\mu \boxed{\partial_\mu} - m)\psi$$

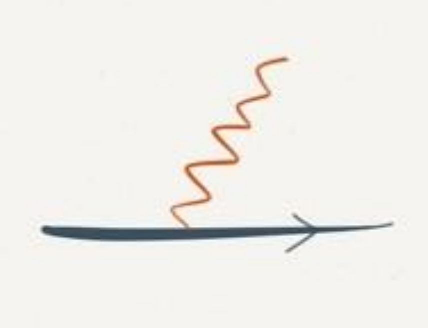
$$D_\mu \equiv \partial_\mu - ieA_\mu$$

$$\mathcal{L}_{QED} = \mathcal{L}_{Dirac} - \boxed{eJ^\mu A_\mu} - \boxed{\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}$$

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

current/photon interaction

kinetic term
photon propagation



A gauge theory of electrodynamics

- **QED** $= U(1)$ <u>locally</u> invariant theory $\qquad \psi \to e^{i\vartheta(x)}\psi$

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi - eJ^\mu A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

action:

$$S = \int d^4x\, \mathcal{L}(\varphi_i, \partial_\mu\varphi_i)$$

least action → *Euler-Lagrange equations:*

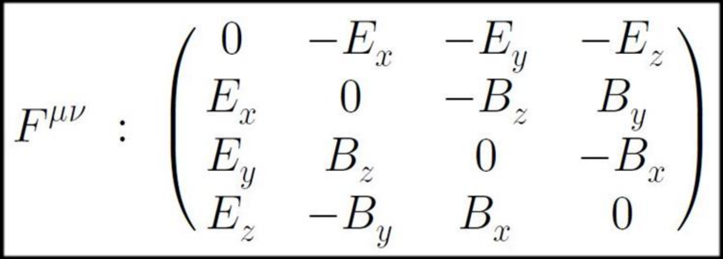
$$\delta S = 0 \quad \to \quad \partial_\mu\left(\frac{\partial\mathcal{L}}{\partial(\partial_\mu\varphi_i)}\right) - \frac{\partial\mathcal{L}}{\partial\varphi_i} = 0$$

EL eq. for A_μ:

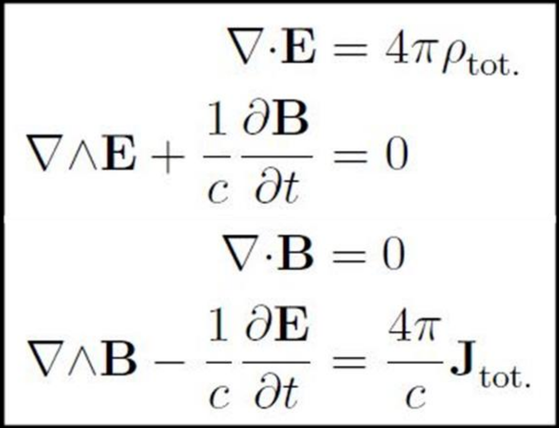
$$\boxed{\partial_\mu F^{\mu\nu} = eJ^\nu}$$

Maxwell's equations!

$$(\varepsilon^{\mu\nu\rho\sigma}\partial_\nu F_{\rho\sigma} = 0)$$



$$F^{\mu\nu} \; : \; \begin{pmatrix} 0 & -E_x & -E_y & -E_z \\ E_x & 0 & -B_z & B_y \\ E_y & B_z & 0 & -B_x \\ E_z & -B_y & B_x & 0 \end{pmatrix}$$



$$\nabla\cdot\mathbf{E} = 4\pi\rho_{\text{tot.}}$$

$$\nabla\wedge\mathbf{E} + \frac{1}{c}\frac{\partial\mathbf{B}}{\partial t} = 0$$

$$\nabla\cdot\mathbf{B} = 0$$

$$\nabla\wedge\mathbf{B} - \frac{1}{c}\frac{\partial\mathbf{E}}{\partial t} = \frac{4\pi}{c}\mathbf{J}_{\text{tot.}}$$

A gauge theory of electrodynamics

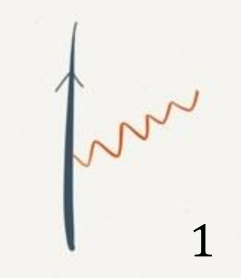
- QED is impressively predictive at quantum level:

e^- magnetic moment: $\vec{\mu} = g_e(\alpha)\frac{e}{2m}\vec{S}, \quad \alpha = \frac{e^2}{4\pi}$

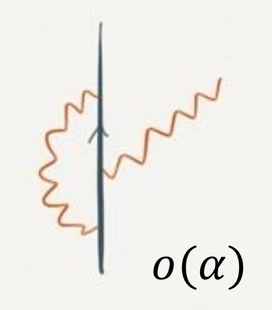
experimentally: $\frac{g_e}{2} \approx 1.00115965218076(76)$ [Gabrielse, '07]

theoretically:

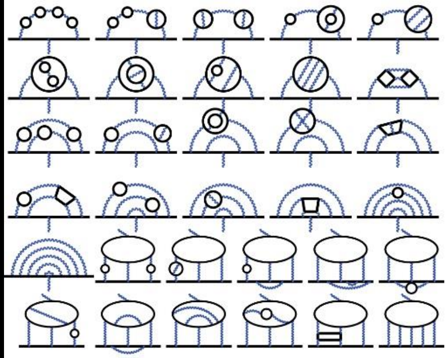
$\frac{g_e}{2} =$



$+$



$+ \cdots +$



$o(\alpha^4)$

$+ \cdots$

→ best determination of $\alpha^{-1} \approx 137.035999174(35)$

other independent measurements = testing QED at deep quantum level:

e.g. $R_\infty = \frac{\alpha^2 m}{4\pi} \rightarrow \alpha^{-1} \approx 137.03599878(91)$ $\approx 10^{-9}$ agreement!!

QED *lesson:*

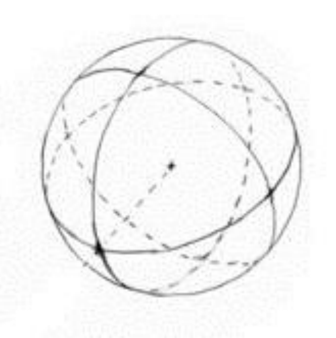
$\psi \rightarrow e^{i\vartheta(x)}\psi$ *local* invariance → extremely successful quantum theory of electrodynamics (tested at the 10^{-9} level!).

→ *Could weak interactions inherit the powerful features of QED? Could one build a gauge theory of the weak interaction?*

A gauge theory of weak interactions

- *what's needed?* [not U(1)^3]
  - 3 conserved currents → SU(2) local symmetry

$$[\sigma_i, \sigma_j] = 2\varepsilon_{ijk}\sigma_k$$ like spin → "isospin"



lepton doublet: $L = \begin{pmatrix} \nu_l \\ l^- \end{pmatrix} \begin{matrix} \uparrow \text{ up} \\ \downarrow \text{ down} \end{matrix}$ ~ *"isospinor"*

$$\sigma_1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$
$$\sigma_2 = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$
$$\sigma_3 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

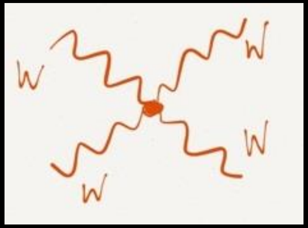
impose local SU(2) invariance: $L \to e^{i\sigma_a \vartheta^a(x)/2} L$

$$\mathcal{L}_{weak} = i\bar{L}\gamma^\mu\left(\partial_\mu - \boxed{ig\frac{\sigma_a}{2}W_\mu^a}\right)L - \frac{1}{4}\boxed{W_{\mu\nu}^a W_a^{\mu\nu}}$$

$$W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g\varepsilon_{ijk}W_\mu^j W_\nu^k$$

charged ($\bar{L}\sigma_\pm L$)
& neutral ($\bar{L}\sigma_3 L$) current
Interactions with $W_\mu^{\pm,3}$

$W_\mu^{\pm,3}$ propagation



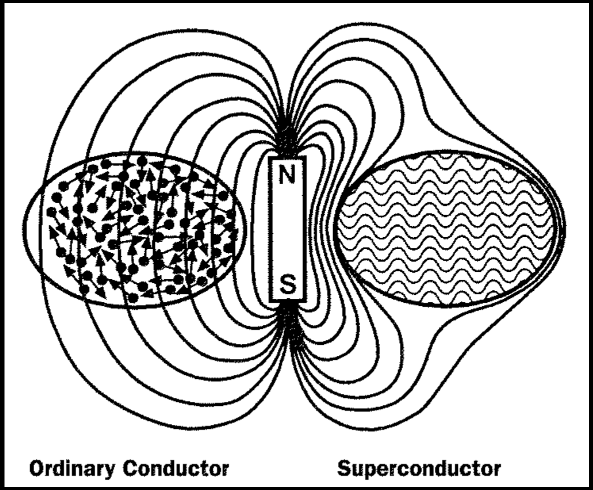
A gauge theory of weak interactions

- *what's also needed?*
  - $m_W \approx$ o(100GeV) ← *Problem!! gauge theories only describe <u>massless</u> force carriers*

e.g. U(1) : $m^2 A_\mu A^\mu \to m^2 (A_\mu - \frac{1}{e}\partial_\mu \vartheta)(A^\mu - \frac{1}{e}\partial^\mu \vartheta) \neq m^2 A_\mu A^\mu$

Solution: break the symmetry in the vacuum! [Y. Nambu, '60]

introduce a vacuum condensate $\langle 0|\varphi|0\rangle \equiv v \neq 0$



dynamics ($\mathcal{L}_{weak}$) invariant, field configurations are not!

relativistic analogue of Cooper pair condensate

$\langle e^- e^- \rangle \neq 0 \to m_{photon} \neq 0$

→ Meissner effect

A gauge theory of weak interactions

- *what's also needed?*
  - $m_W \approx$ o(100GeV)

introduce:

$$\Sigma(x) \equiv \mathscr{v} \times exp\left[\frac{i\sigma_a \chi^a(x)}{\mathscr{v}}\right]$$

$$\mathcal{L}_{weak} \to \mathcal{L}_{weak} + \frac{1}{4}\boxed{Tr[D_\mu \Sigma^\dagger D^\mu \Sigma]}$$

$$\Sigma^\dagger \Sigma = 1, \ \ \langle \Sigma \rangle = \mathscr{v}$$

$$\Sigma \to e^{i\sigma_a \vartheta^a(x)/2}\Sigma$$

$$D_\mu \Sigma = \partial_\mu \Sigma - ig\frac{\sigma_a}{2}W_\mu^a \Sigma$$

$$\chi^a \to \chi^a + \frac{\mathscr{v}}{2}\vartheta^a$$

in unitary gauge

$\vartheta^a = 2\chi^a/\mathscr{v}$

$\Sigma = 1$

$$= \frac{1}{2}m_W^2 W_\mu^a W_a^\mu, \quad m_W = g\mathscr{v}/2$$

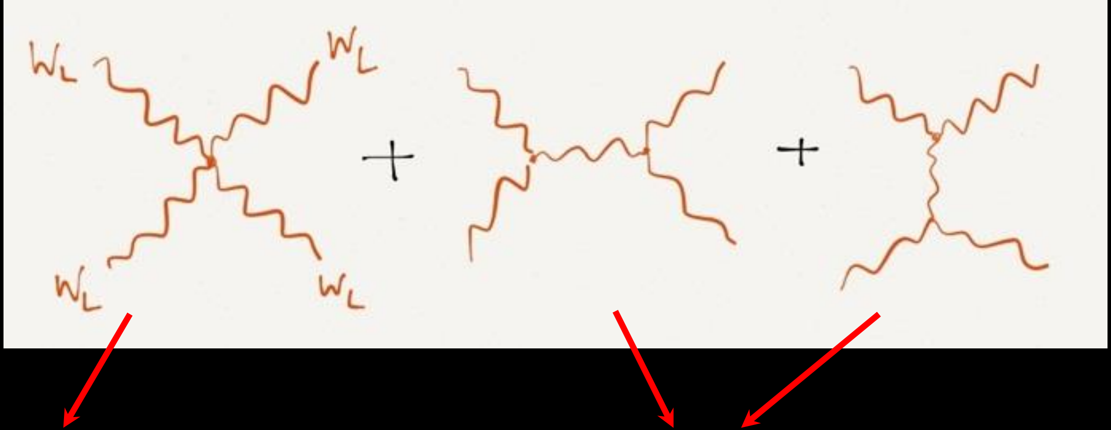
The vaccum condensate $\mathscr{v}$ breaks spontaneously SU(2) gauge invariance

$\to m_W \sim \mathcal{O}(\mathscr{v})$ & $\chi^a =$ *longitudinal* W_μ^a

A gauge theory of weak interactions

- *This theory explains pages of particle physics data, but is still not consistent with unitarity at high E's:*

$\mathcal{A}_{W_L^+W_L^-\to W_L^+W_L^-} =$



$\approx \frac{g^2E^2}{m_W^2}$

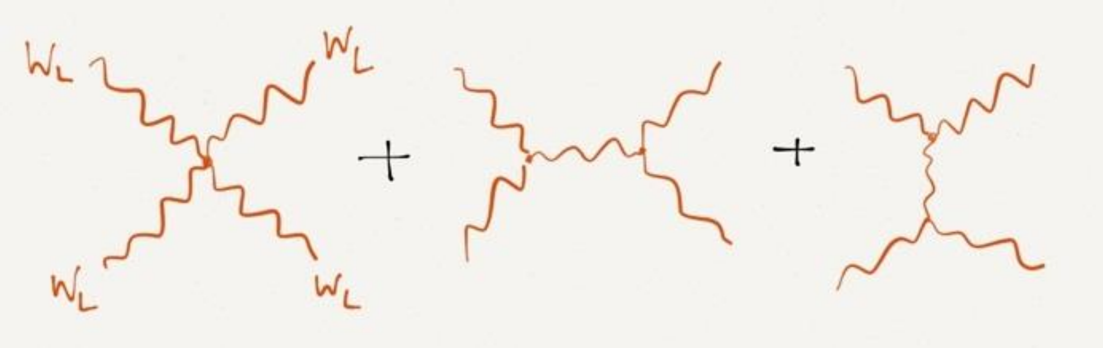
$$\sim \mathcal{O}\left(\xcancel{\frac{E^4}{m_W^4}}\right) + \mathcal{O}\left(\frac{E^2}{m_W^2}\right) + \cdots \qquad \sim \mathcal{O}\left(\xcancel{\frac{E^4}{m_W^4}}\right) + \mathcal{O}\left(\frac{E^2}{m_W^2}\right) + \cdots$$

→ *something new must happen before* $E \approx \mathcal{O}(4\pi v) \approx$ TeV *!!*
in order to restore unitarity

A gauge theory of weak interactions

- *This theory explains pages of particle physics data, but is still not consistent with unitarity at high E's:*

$\mathcal{A}_{W_L^+W_L^-\to W_L^+W_L^-} =$



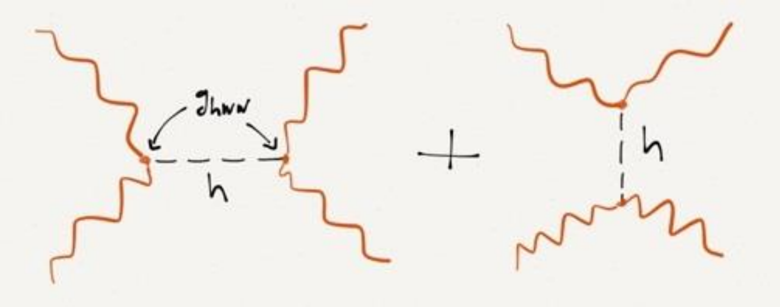
$\approx \frac{g^2E^2}{m_W^2}$

simplest (weakly coupled) solution:

add a scalar particle h

$m_h < \mathcal{O}(\text{TeV})$

$g_{hWW} = \frac{gm_w}{2}a$

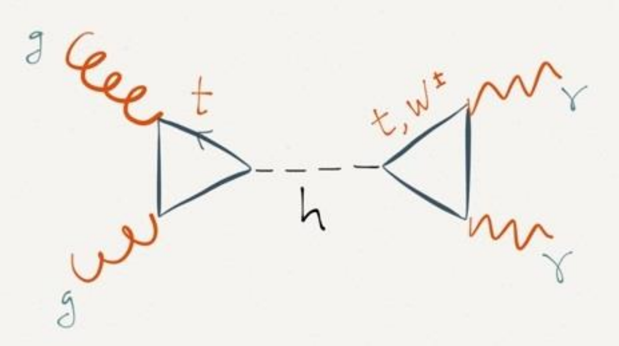


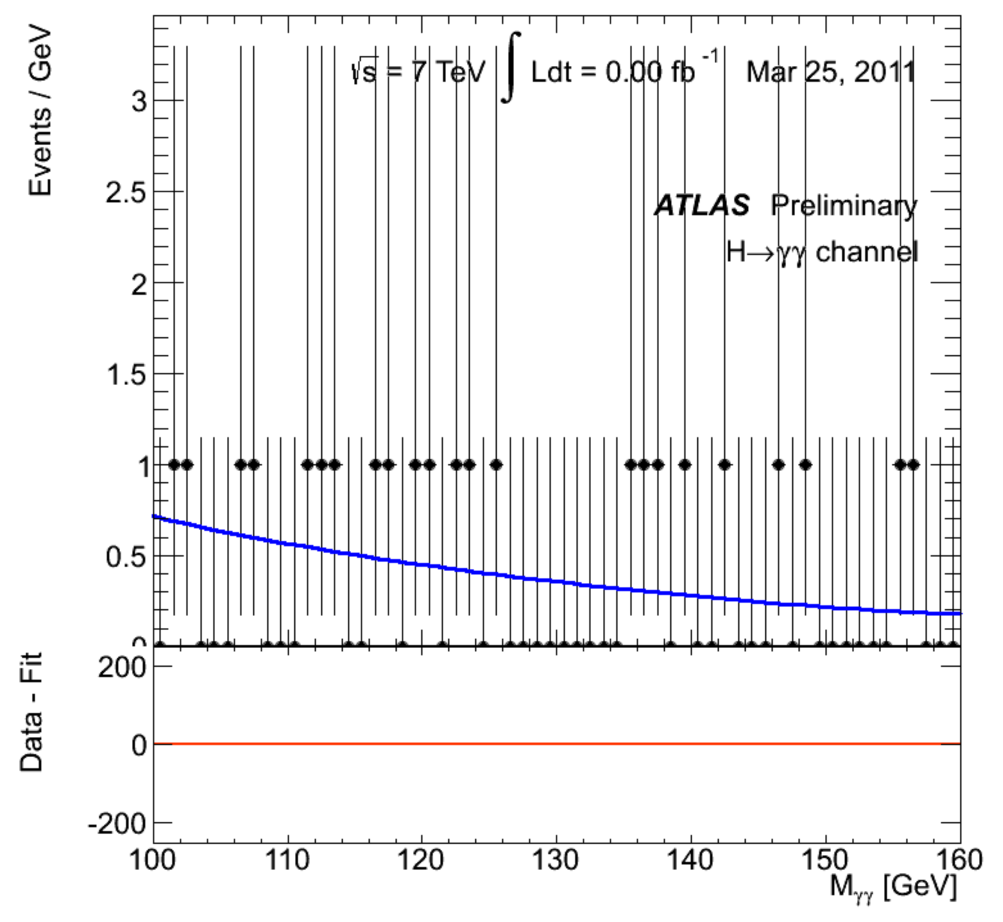
$\approx -\frac{g^2E^2}{m_W^2}a^2$

if $a \approx 1$, consistent theory up to $E \approx \frac{4\pi v}{\sqrt{|1-a^2|}} \gg$ TeV

→ h = "a" Higgs boson

meanwhile at the CERN LHC:





On July 4th, 2012 at CERN:
ATLAS/CMS announces to the world they've found a Higgs-like particle

$m_h \approx 125\text{GeV}$

$h \to WW^*, ZZ^*$ also observed

$|a - 1| \lesssim 20\%$

The Higgs mechanism

- What if $a = b = 1$ exactly? Theory consistent up to $E \to \infty$

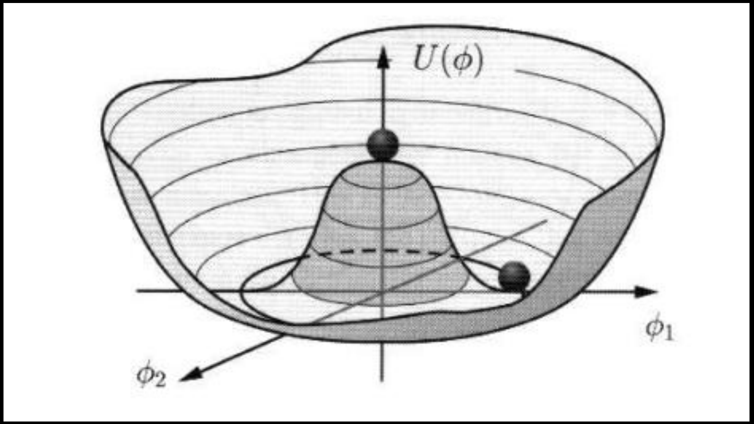
$$\mathcal{L} = \mathcal{L}_{weak} + \frac{1}{4} Tr\left[D_\mu \Sigma^\dagger D^\mu \Sigma\right]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$

$$+\frac{1}{2}\partial_\mu h \partial^\mu h - \frac{m_h^2}{2} h^2 + \cdots$$

$$\longrightarrow \mathcal{L}_{weak} + D_\mu H^\dagger D^\mu H - V(H^\dagger H),$$

$$H = e^{\frac{i\sigma_a \chi^a(x)}{v}} \begin{pmatrix} 0 \\ \frac{v + h(x)}{\sqrt{2}} \end{pmatrix}$$

$$V(H^\dagger H) = m^2 H^\dagger H + \lambda (H^\dagger H)^2$$



if $m^2 < 0, \lambda > 0$ SU(2) broken by the vacuum:

$$v = \sqrt{-m^2/\lambda}$$

This is the so called Higgs mechanism

$$m_h^2 = 2\lambda v^2$$

Higgs, Englert, Brout ‘64

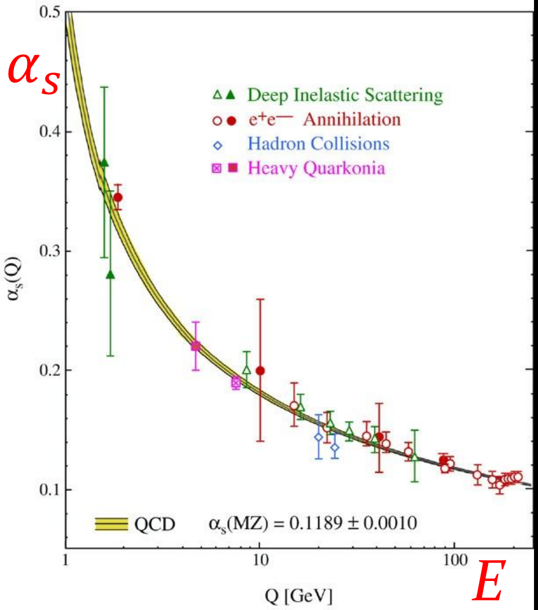
QCD interlude

QCD crash course

- Quantum ChromoDynamics = SU(3) gauge theory
  - quarks carry color charge, force carrier = *massless gluons*

$$\mathcal{L}_{QCD} = i\bar{q}\gamma^{\mu}\left(\partial_{\mu} - i g_s T^A G^A_{\mu}\right)q - \frac{1}{4} G^A_{\mu\nu} G^{\mu\nu}_A$$

  - unlike EW, QCD is weakening at high energy



→ asymptotic freedom

Gross, Politzer, Wilczek ‘73

- quarks bound in hadrons ~Λ_{QCD}~200MeV
- rational for the parton model for hadron collisions at $E \gg \Lambda_{QCD}$

EW symmetry breaking from QCD

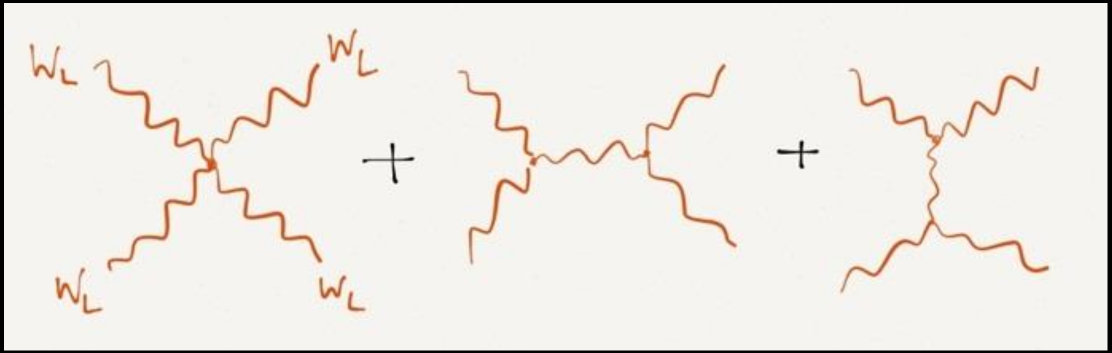
- Quantum ChromoDynamics = SU(3) gauge theory
  - quarks carry color charge, force carrier = *massless gluons*

$$\mathcal{L}_{QCD} = i\bar{q}\gamma^{\mu}(\partial_{\mu} - ig_s T^A G_{\mu}^A)q - \frac{1}{4}G_{\mu\nu}^A G_A^{\mu\nu}$$

  - *for* $E \lesssim$ GeV, quark fluctuations “freeze” in the vacuum:

$\langle \overline{q_L} q_R \rangle \sim \Lambda_{QCD}^3$ carries weak charge → breaks SU(2)

even if $v \rightarrow 0$, $m_W \approx \Lambda_{QCD}$



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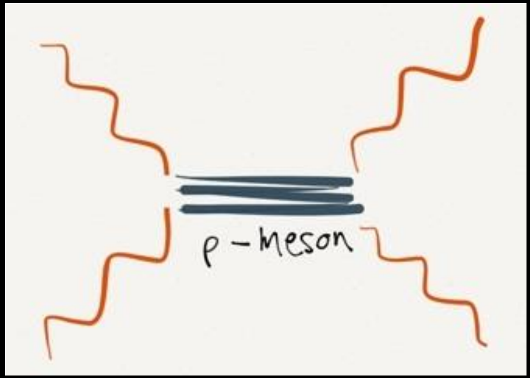


what restores unitarity above Λ_{QCD}*?*

spin-1 QCD resonances!

QCD *lesson:*

Strong interactions can solve the apparent unitarity violation in longitudinal W scattering

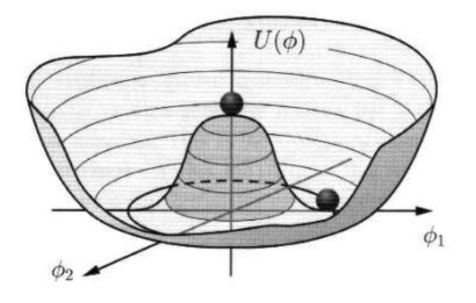
→ *Higgs-less theories like technicolor (i.e. more energetic version of QCD) was also a possibility, as good as a light Higgs scalar,*

but Nature did not choose this…

Lecture 2:

What is lying behind/beyond the Higgs?

The Higgs mechanism

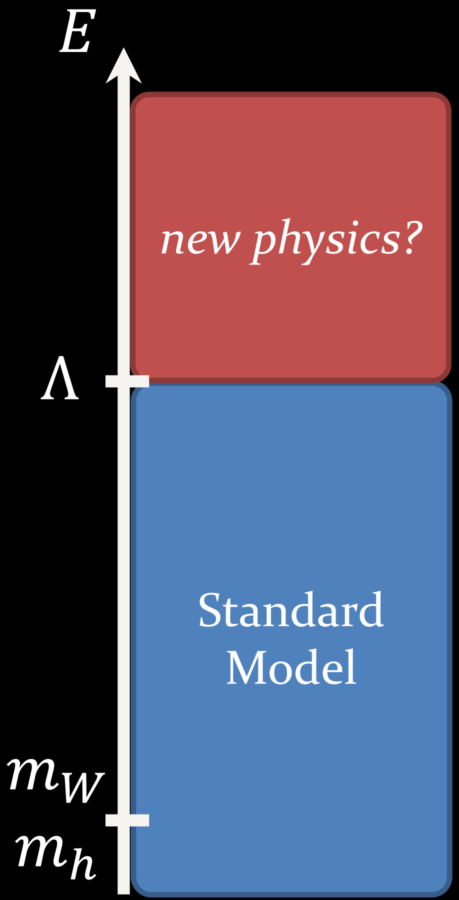


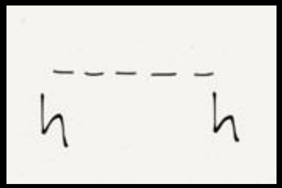
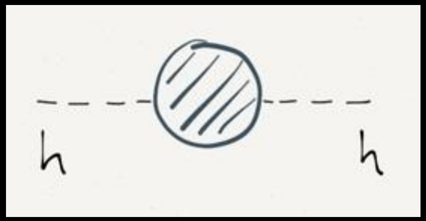
- Virtues of the Higgs mechanism:
  - Simple description of weak boson masses:
    it provides 3longitudinal W + unitarization scalar
  - Theory of Weak interactions consistent at all energies

- Short-comings of the Higgs mechanism:
  - Mere description of the breaking, not an explanation
    what makes $m^2 < 0$?
  - Higgs scalar is very sensitive to unknown physics in the UV

→ *severe "hierarchy problem"*

The Hierarchy problem



$m^2_{h\ \text{measured}} =$  $+$ 

classical mass

quantum correction
new physics at $E \approx \Lambda$

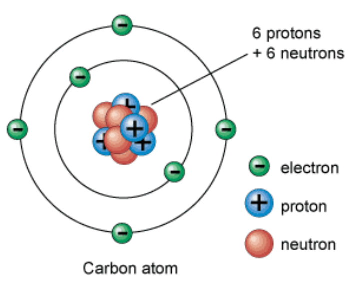
$$(125\text{GeV})^2 = \sim -\mathcal{O}(\Lambda^2) \qquad \sim \frac{\alpha_{new}}{4\pi}\Lambda^2$$

if there is any new dynamics at energies $\Lambda \gg m_h$ which couples to h, its quantum fluctuations will destabilize m_h , unless the (unobservable) classical mass is chosen so to almost exactly cancel this large correction.

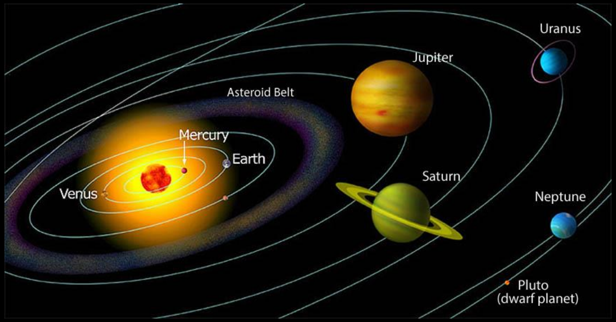
Hierarchy problem → short/long distance fine-tuning!

UV physics is irrelevant for IR physics

One does not need to tweak atomic physics:



in order to understand Kepler's laws:



Short distance dynamics "factors out" from long distance one in physical observables → theories are only effective descriptions

$$\mathcal{O}_{full}(E \ll \Lambda) = \mathcal{O}_{long}(E) \times \left[1 + o\left(\frac{E}{\Lambda}\right)^{n>0}\right]$$

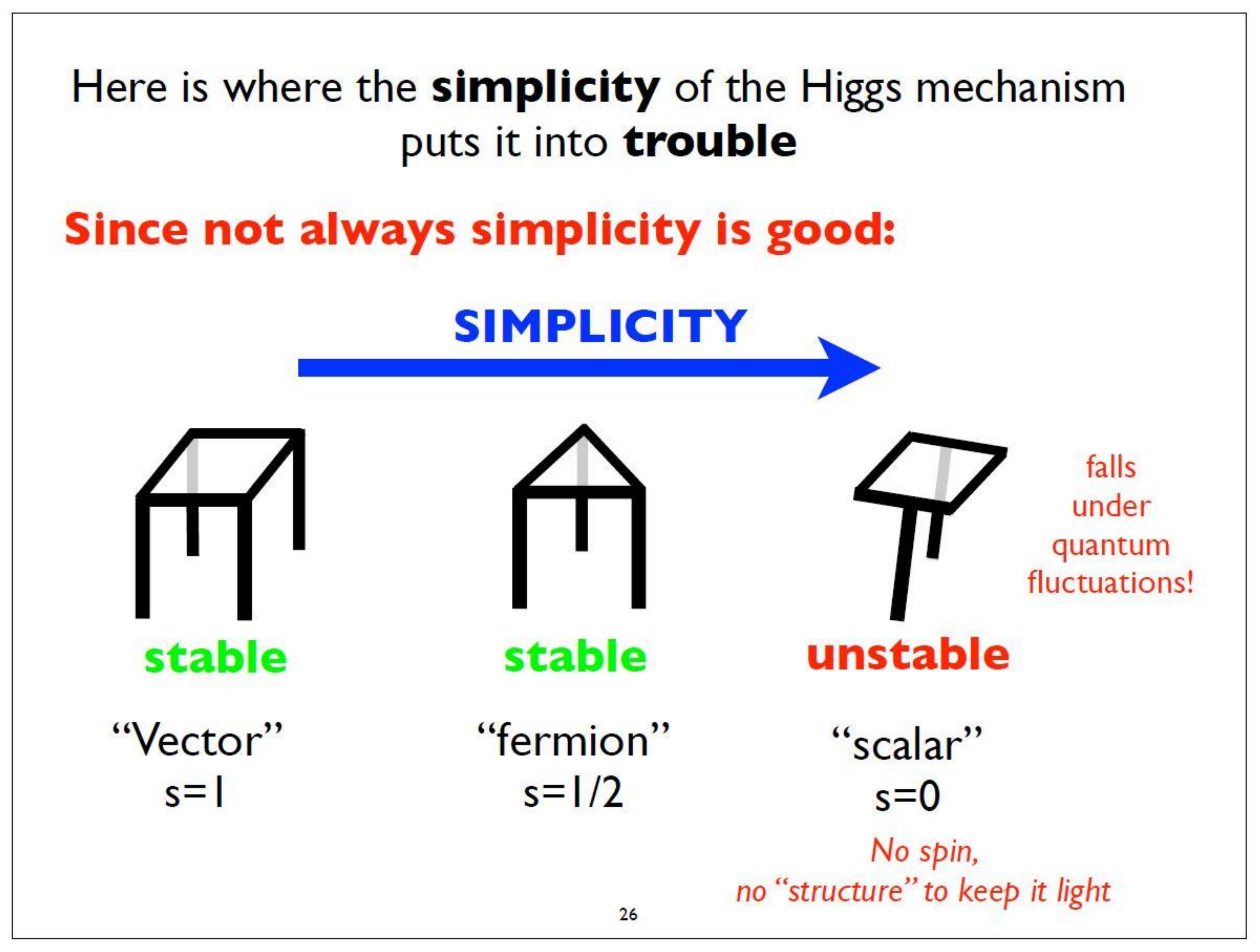
Only scalar masses are UV sensitive

	# of physical polarizations for massless excitations		**# of physical polarizations for massive excitations**
vector (spin 1)	2	≠	3
spinor (spin ½)	2	≠	4*
scalar (spin 0)	1	=	1

Gauge boson and fermion* masses are stable under quantum fluctuations at the shortest distance because massless and massive states propagate different degrees of freedom.

Scalar particles are too simple to enjoy this property.

** Majorana fermions are the exception, but they can't carry any charge.*



Here is where the **simplicity** of the Higgs mechanism puts it into **trouble**

Since not always simplicity is good:

SIMPLICITY

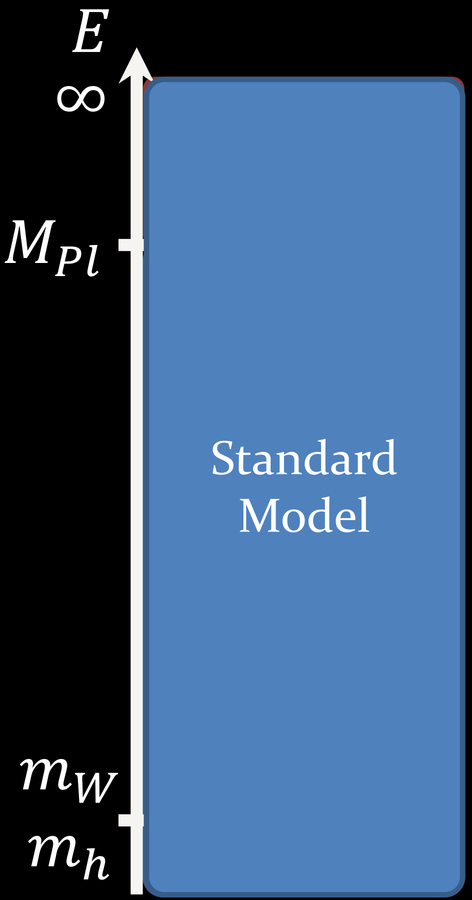
falls under quantum fluctuations!

stable	**stable**	**unstable**
“Vector” s=1	“fermion” s=1/2	“scalar” s=0

No spin,
no “structure” to keep it light

Alex Pomarol, ESHEP 2014

Is there another scale above m_W?



→ *no hierarchy, no problem*

but we actually do know
of two scales beyond the SM:

- Gravity: $G_N = M_{Pl}^{-2}, \; M_{Pl} \approx 10^{19}\text{GeV}$
- QED* Landau pole:

$$\Lambda_Y \sim m_W e^{\frac{2\pi\alpha_Y^{-1}(m_W)}{b_Y}} \approx 10^{41}\text{GeV}$$

if $\Lambda \approx M_{Pl}$, humongous fine-tuning needed,
as precise as 1/10³²!!

---

* actually hypercharge

A layman fine-tuning analogue

There are two possibilities:

1) A few Avogadro numbers ~10^{23} of air molecules conspire to all move upwards in order to balance the Earth's gravitational pull…

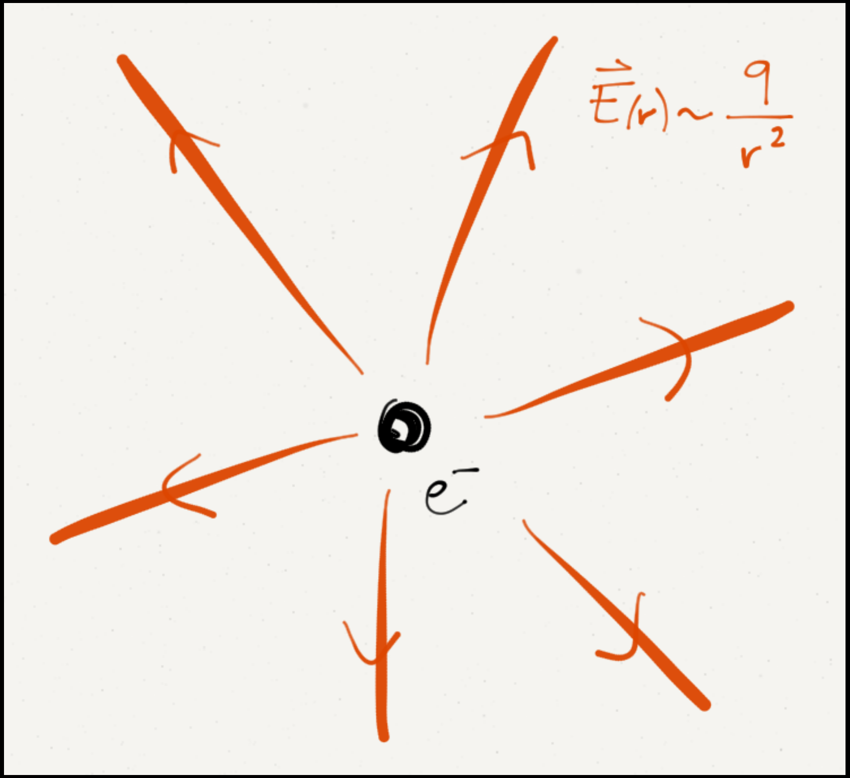
2) There is a trick! Some mechanical structure is hidden and explain the stability

Which would you think is right?

→ What is the structure stabilizing the Higgs mass?

A less pedestrian fine-tuning analogue

→ electron mass in classical physics: $m_e = m_0 + \Delta$



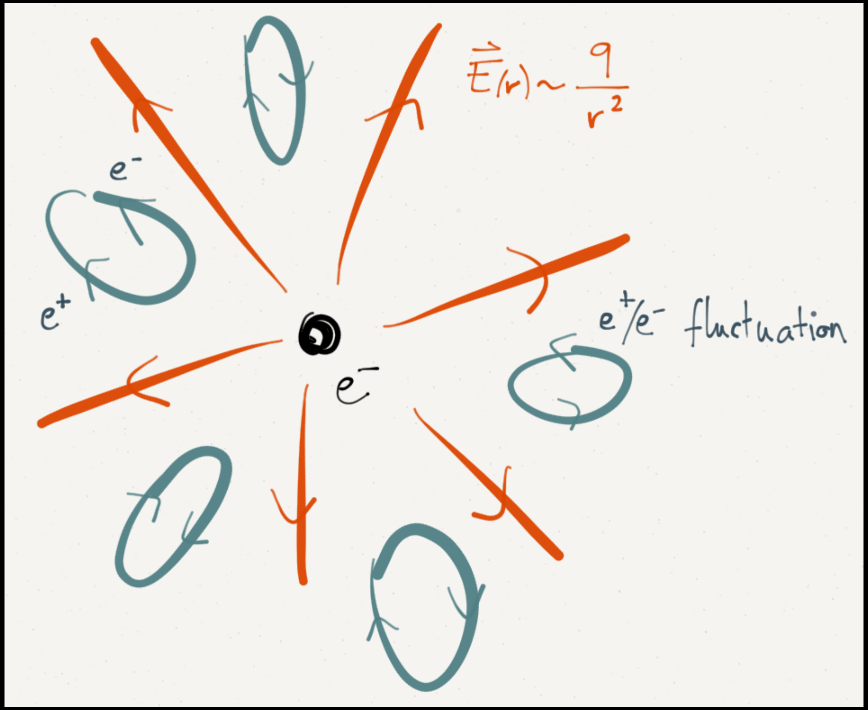
$$\Delta \approx q \int d^3\vec{r}\, \vec{E}(r)^2$$

$$\approx 4\pi q \int_{\frac{1}{\Lambda}}^{\infty} \frac{r^2 dr}{r^4} \propto \Lambda$$

→ there should be something new around $E \sim \mathcal{O}(m_e)$ to avoid large tuning

A less pedestrian fine-tuning analogue

→ electron mass in classical physics: $m_e = m_0 + \Delta$



At $E \approx 2m_e$ or $r \approx 10^{-13}$m
two new phenomena emerge:
quantum fluctuations + positron

↓

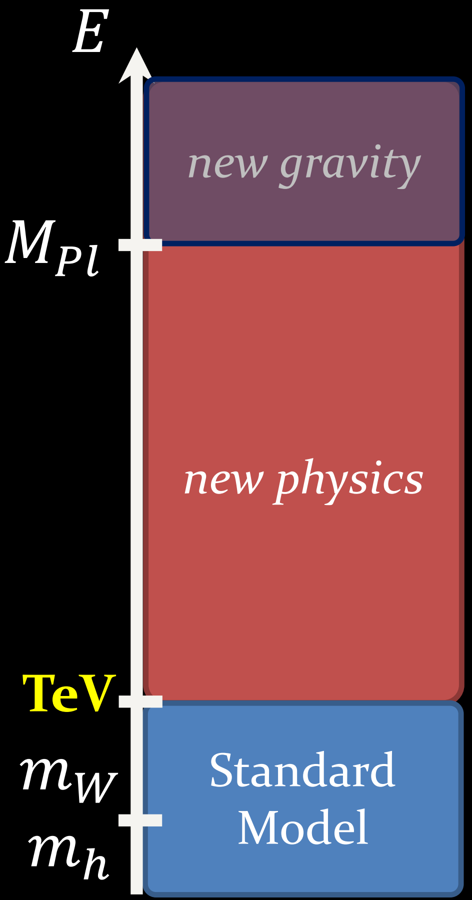
electron/positron pair fluctuations screen out the ("valence") electron from its electric field for $r \lesssim m_e^{-1}$

↙

thus stabilizing the electron mass:

$$\Delta \approx m_e \log \Lambda/m_e$$

TeV scale new physics from Naturalness



At what energy this structure should emerge?

No fine-tuning if $\frac{\alpha_{new}}{4\pi}\Lambda^2 \sim \mathcal{O}(m_h^2)$

$\rightarrow$ Λ~TeV *within LHC reach!*

what kind of structure?

technical naturalness:

m_h^2 is stable under quantum corrections if the theory enjoys a new symmetry when $m_h \rightarrow 0$.

't hooft, '79

Which symmetry to protect m_h?

- how to forbid $m^2 H^\dagger H$?
  - can't be a new "charge" : $H \to e^{iX} H$
  - shift symmetry: $H \to H + c$ → H = Goldstone boson
  - "spin trick": link H to s≠0 field whose mass is protected

spin = good quantum number under Lorentz symmetries relating fields of different spin → extend space-time

s=1:

extradimensions

$$A_M = \begin{pmatrix} A_\mu \\ H \end{pmatrix}$$

s=1/2:

supersymmetry

$$\Phi = \begin{pmatrix} H \\ \psi_H \end{pmatrix}$$

Extradimensions

- we only experience 3+1 dimensions, thus:
  - extradimensions are small
  - they are large, but we are confined on a 3+1 subspace

→ *how can we see them?*

- Gravity cannot be confined:

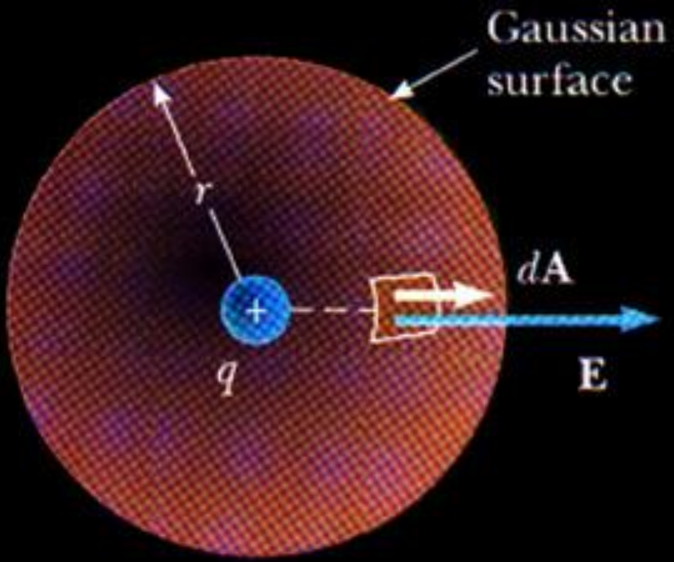
Gauss' theorem:

$$\int \vec{g}(x).\, d\vec{S} = -4\pi G_N M$$

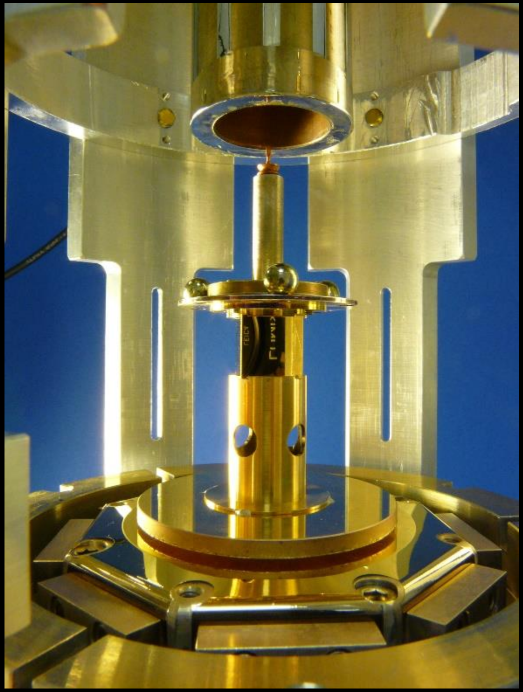
$$\vec{g}(r < \boxed{L}) \sim \frac{G_N M}{r^{2+\boxed{n}}}$$

size of extra dimensions

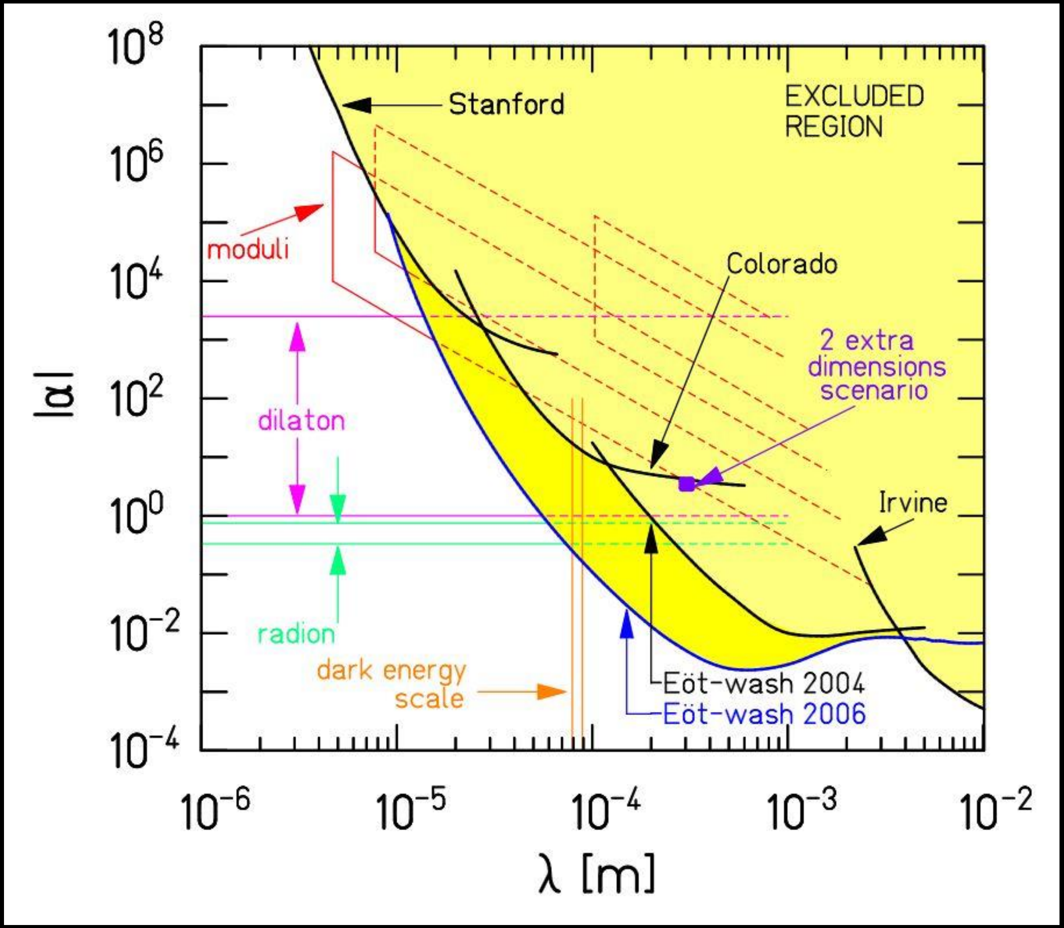
# of extra space dimensions



Short range test of Newton's Law



$$V(r) = \frac{G_N m_1 m_2}{r}(1 + \alpha e^{-r/\lambda})$$



Eöt-Wash experiment, '07

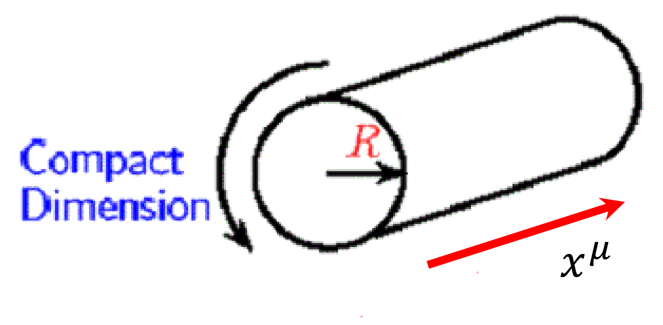
No deviation to inverse square law observed down to $\lambda \approx 56\mu m$

$\rightarrow\ R \lesssim 40\mu m$

Fields in extradimensions

- 5d example:

$$x^M = (x^\mu, y),$$
$$p^M = (p^\mu, p_5)$$



- if $0 \leq y \leq L \rightarrow p_5 = n/L$ quantized ~ 4d mass

5d momentum conservation: $p^M p_M = p^2 - p_5^2 = 0 \;\rightarrow\; p^2 = 0 + n/L^2 \equiv m_n^2$

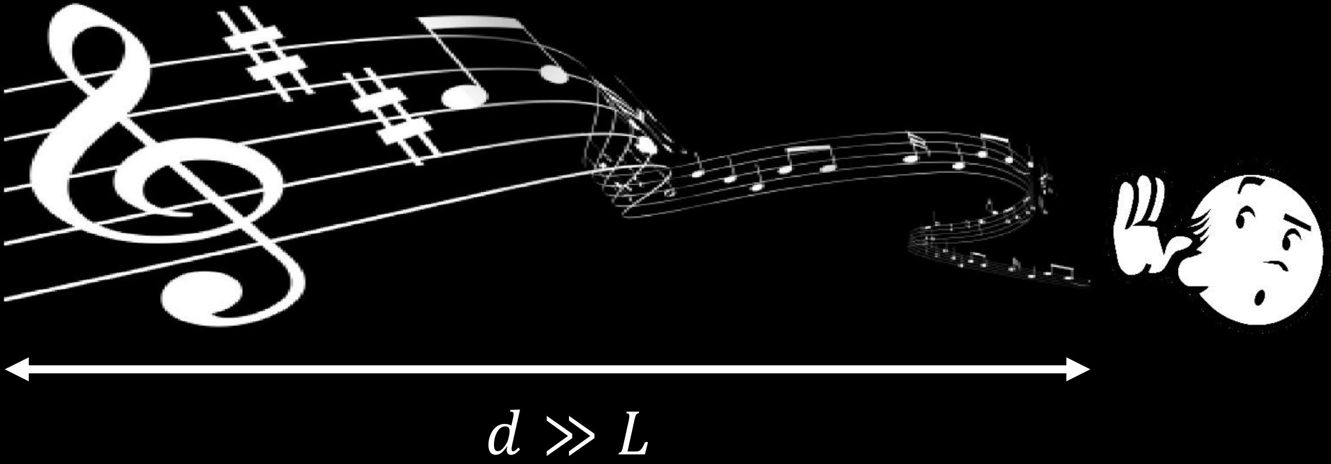
- for $r \gg L$ $(E \ll 1/L)$, massless 5d field describes a tower of massive 4d Kaluza-Klein fields:

5d "wave-function"

$$\phi(x,y) = \sum_{n=0}^{\infty} \phi_n(x) \boxed{f_n(y)}$$

Kaluza, Klein, 1920's

KK states = signature of extradimensions



How to tell ***from afar*** *that sounds originate from an extended object?*

check the spectrum!

→ only $f \approx n/L$ harmonics propagate over long distances

Fields in extradimensions

- compact y breaks 5d space-time symmetries → 4d:
  - y-translation breaking → 5d mass is not "conserved"

massless 5d field = Σ massive 4d fields

  - $x^\mu y$-rotation breaking → 5d spin is not "conserved"

$A_M = (A_\mu, A_5)$ 5d spin 1 = 4d spin 1 + spin 0

- For $E \gg 1/L$, 5d symmetries are restored

→ scalar mass protected by 5d gauge symmetry

$m_h \sim 1/L$ → $L \sim \mathcal{O}(\mathrm{TeV}^{-1})$

Supersymmetry

- Extended space-time w/ “fermionic dimensions”:

Superspace: $X = (\boxed{x^{\mu}}, \boxed{\theta^{\alpha}})$ $\alpha = 1, \ldots, 4$

4d coordinates

fermionic coordinate
θ^{α} = (Majorana) spinor

$\{\theta, \theta\} = 0 \rightarrow \theta^2 = 0$
Only one step in θ is allowed

$$\{\mathcal{Q}_{\alpha}, \mathcal{Q}_{\beta}\} = 2(\gamma^{\mu}\gamma_0\gamma_2)_{\alpha\beta}\mathcal{P}_{\mu}$$

two steps in θ = translation

Superfields in Superspace

- Susy[scalar]~spinor, $\mathcal{Q}_\alpha \phi \sim \psi_\alpha$ → spin is not “conserved”:

$$\Phi(X) = \Phi(x, \theta) = \phi(x) + \bar{\theta}\psi(x)$$

- $[\mathcal{Q}_\alpha, \mathcal{P}_\mu] = 0$ → mass is still conserved $m_\phi = m_\psi$!

→ *scalars inherit protection from fermions*

Supersymmetry is broken

- By Susy, all fermions have a degenerate scalar partners:

$$\Phi_{electron}(X) = \boxed{\tilde{e}(x)} + \bar{\theta}\psi_e(x)$$

NOT observed, although it carries EW charge

- Supersymmetry has to be broken at some scale Λ_{SUSY}:

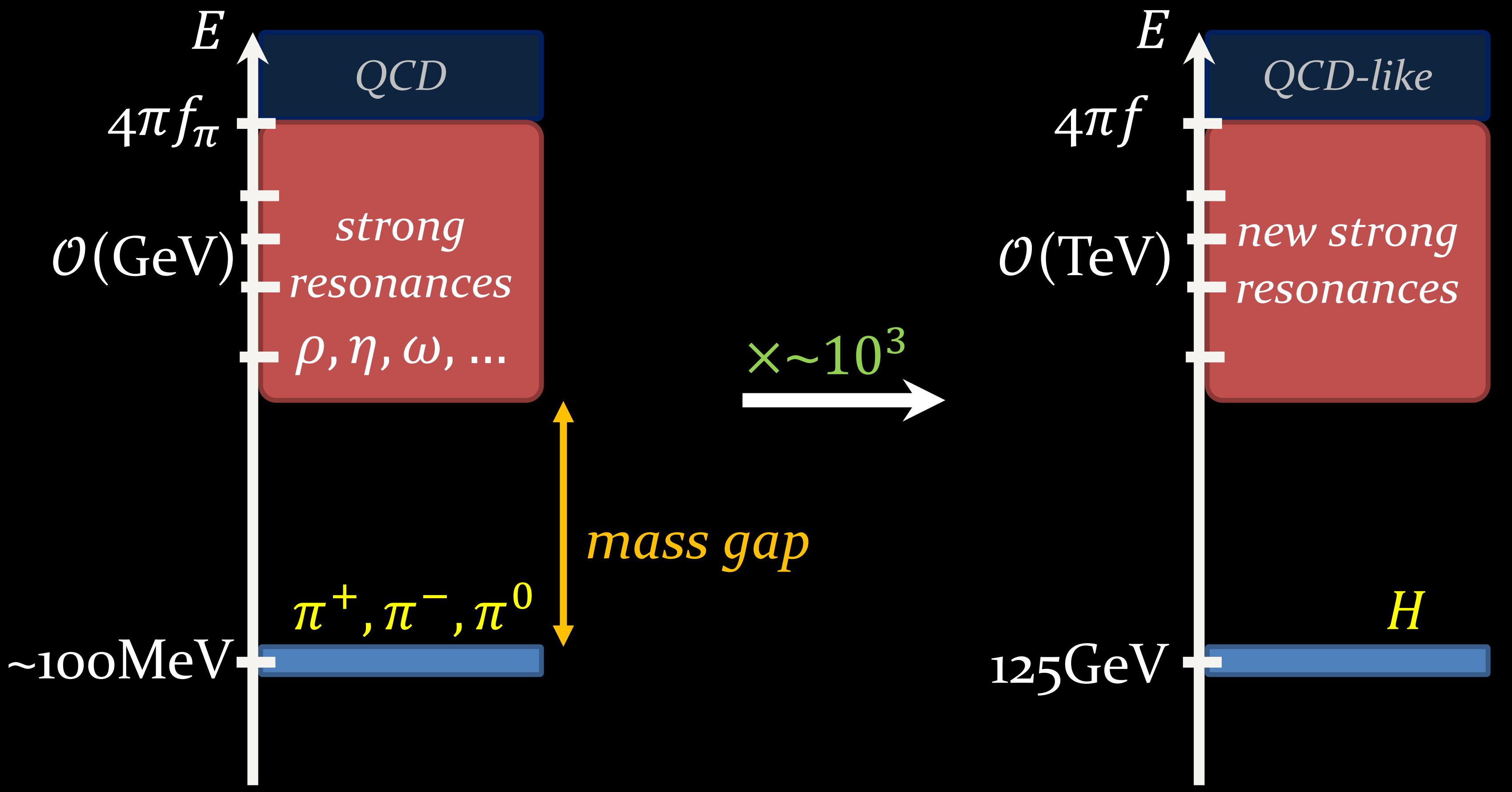
$$m_{\tilde{e}} \sim \Lambda_{\mathrm{SUSY}} \gg m_e$$

- Higgs mass is no longer fully protected:

$$m_h \sim \Lambda_{\mathrm{SUSY}} \rightarrow \Lambda_{\mathrm{SUSY}} \sim \mathcal{O}(\mathrm{TeV})$$

Higgs as a pseudo Goldstone boson

- more mundane option: *stay in 4d, once again mimick QCD*



Higgs as a pseudo Goldstone boson

- Light π's thanks to chiral symmetry breaking: $q = u, d$

$$\mathcal{L}_{QCD} = i\overline{q_L}\gamma^\mu D_\mu q_L + i\overline{q_R}\gamma^\mu D_\mu q_R - \frac{1}{4}G^A_{\mu\nu}G^{\mu\nu}_A - \overline{q_L}\, m_q\, q_R + h.c.$$

global symmetry: $SU(2)_L \times SU(2)_R$, $q_{L,R} \rightarrow \mathcal{U}_{L,R} q_{L,R}$

- $g_s \rightarrow o(4\pi) \rightarrow \langle\overline{q_L} q_R\rangle \sim \Lambda^3_{QCD}$

symmetry breaks: $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$

$q_{L,R} \rightarrow \mathcal{U}\, q_{L,R}$

- Goldstone theorem:

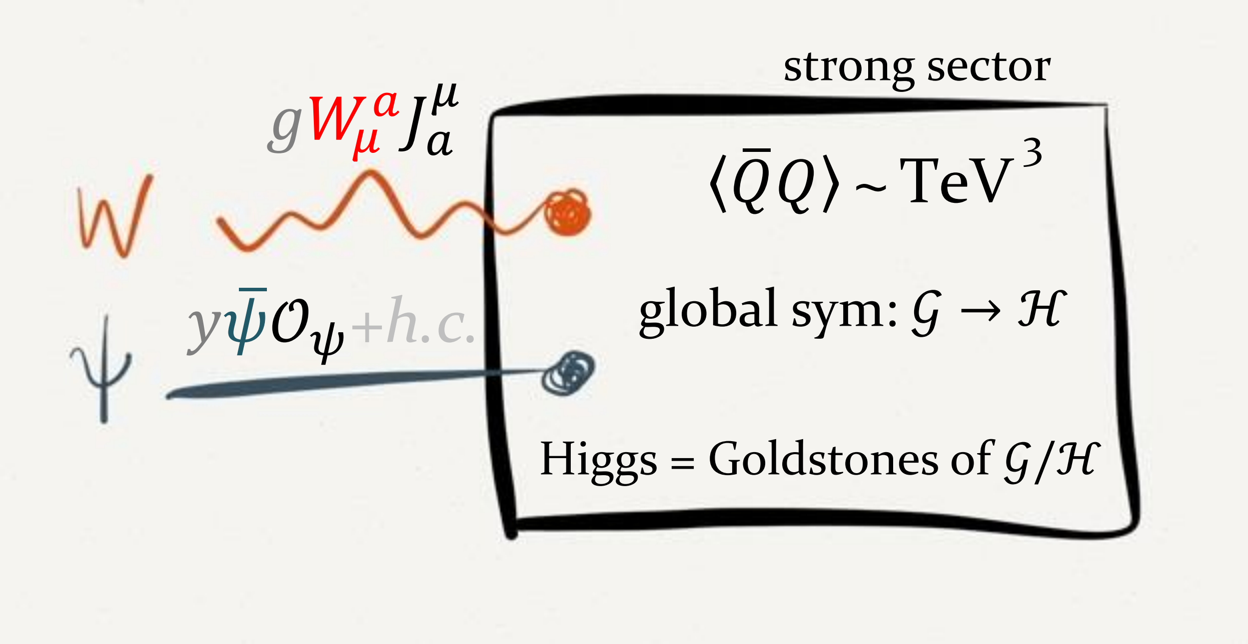
"global continuous symmetry broken in the vacuum → massless scalar"

$\pi^{\pm,0}$ = 3 *massless Goldstone bosons of* $SU(2)^2/SU(2)$

$$\rightarrow m^2_\pi \approx \frac{(m_u+m_d)\Lambda^3_{QCD}}{f^2_\pi}$$

Higgs as a pseudo Goldstone boson

- Add a new strong force (SU(N)?) with "techni-quarks" Q



$gW_\mu^a J_a^\mu$

$y\bar{\psi}\mathcal{O}_\psi + h.c.$

strong sector

$\langle \bar{Q}Q \rangle \sim \text{TeV}^3$

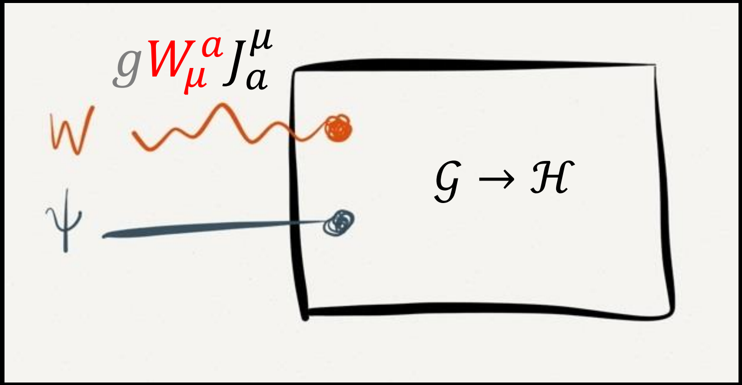
global sym: $\mathcal{G} \to \mathcal{H}$

Higgs = Goldstones of $\mathcal{G}/\mathcal{H}$

- *global symmetry breaking $\mathcal{G} \to \mathcal{H}$ at scale $f \sim$* TeV
- unbroken $\mathcal{H}$ must contain SU(2)
- g, y breaks $\mathcal{G}$ explicitly → $m_h = m_h(g, y)$ and naturally small!

Higgs as a pseudo Goldstone boson

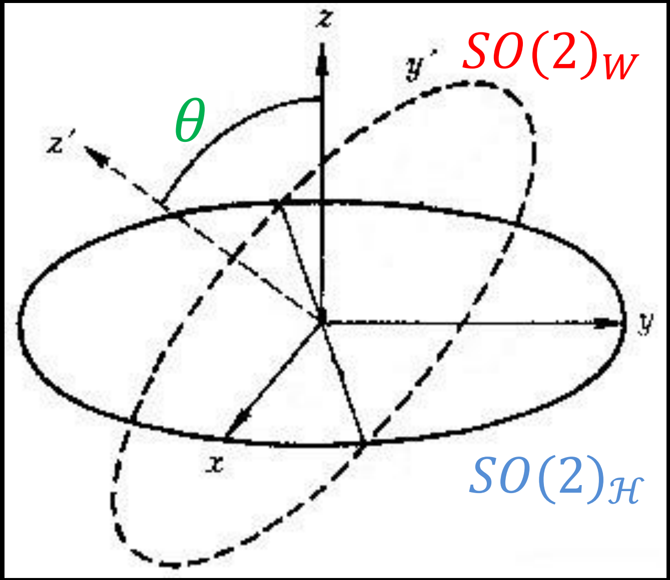
- EW symmetry breaking/m_W from vacuum misalignment:



if the SU(2) associated with J_μ^a is not aligned with the SU(2) in $\mathcal{H}$, then $\mathcal{G} \to \mathcal{H}$ breaking induces EW gauge symmetry breaking.

$SO(3) \to SO(2)$ analogue:

$$v = f \sin\theta$$



Time to wrap up!

Conclusions 1

- Despite ~100yrs of progress, we still do not know the complete mechanism driving the weak force.

- Since Fermi, unitarity clearly indicated a scale below which the theory must be modified (in the form of introducing new particles)

- After the discovery of the Higgs boson, this is no longer the case. The Standard Model is consistent potentially up to the Planck scale, where gravity has to be modified.

Conclusions 2

- Yet, in the SM, the Higgs boson is much lighter only at the price of a $1/10^{32}$ fine-tuning miracle.

- A naturally light Higgs boson requires to extend the theory beyond the SM at E~TeV.

- Two well motivated avenues:

  1. Extend space-time | 2. Add new forces

- All solutions predict new particles w/in LHC reach

Do not hesitate:

LHsea

more

Space-time symmetries crash course

- *Poincaré group = Lorentz $SO(3,1)$ symmetry + translations*

Symmetries → Generators

Rotations → angular momentum $\mathcal{J}_i$

Boosts → $\mathcal{K}_i$

Translations → energy/momentum $\mathcal{P}_\mu$

$$[\mathcal{J}_i, \mathcal{J}_j] = i\varepsilon_{ijk}\,\mathcal{J}_k$$

$$[\mathcal{K}_i, \mathcal{K}_j] = -i\varepsilon_{ijk}\,\mathcal{J}_k$$

$$[\mathcal{J}_i, \mathcal{K}_j] = i\varepsilon_{ijk}\,\mathcal{K}_k$$

$$[\mathcal{J}_i, \mathcal{P}_j] = i\varepsilon_{ijk}\,\mathcal{P}_k$$

$$[\mathcal{K}_i, \mathcal{P}_j] = -i\delta_{ij}\,\mathcal{P}_0$$

$$[\mathcal{P}_0, \mathcal{J}_i] = 0,\ [\mathcal{P}_0, \mathcal{K}_i] = i\mathcal{P}_i$$

Representations characterized by two invariants: *mass, spin*

- *Physical particles are representations of Poincaré group:*

e.g. ϕ=scalar, V^μ=vector, $T^{\mu\nu}$=tensor,… + ψ=spinor

s=0 *s=1* *s=2* *s=1/2*

Spinor crash course

- $[\mathcal{J}_m + i\mathcal{K}_m , \mathcal{J}_n - i\mathcal{K}_n] = 0 \quad \rightarrow \quad SO(3{,}1) \approx SU(2)_L \times SU(2)_R$

$SU(2)_{L,R}$ representations labelled by $j_{L,R}$ =0,1/2,1,3/2,…

$(j_L, j_R) =$ (0,0) scalar
(1/2,0) left-handed spinor
(0,1/2) right-handed spinor
(1/2,1/2) vector
…

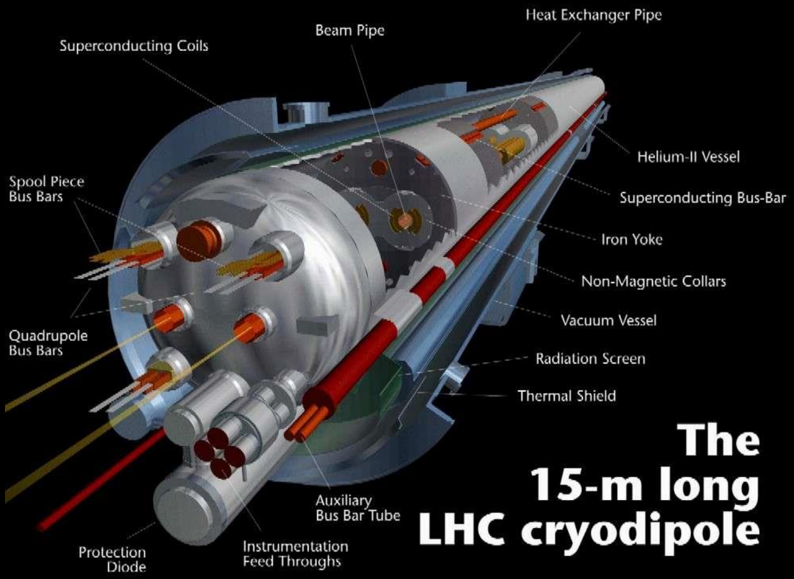
Dirac spinor = (1/2,0) + (0,1/2)

it is not "fundamental", but reducible
(1/2,0) and (0,1/2) can a priori have different interactions

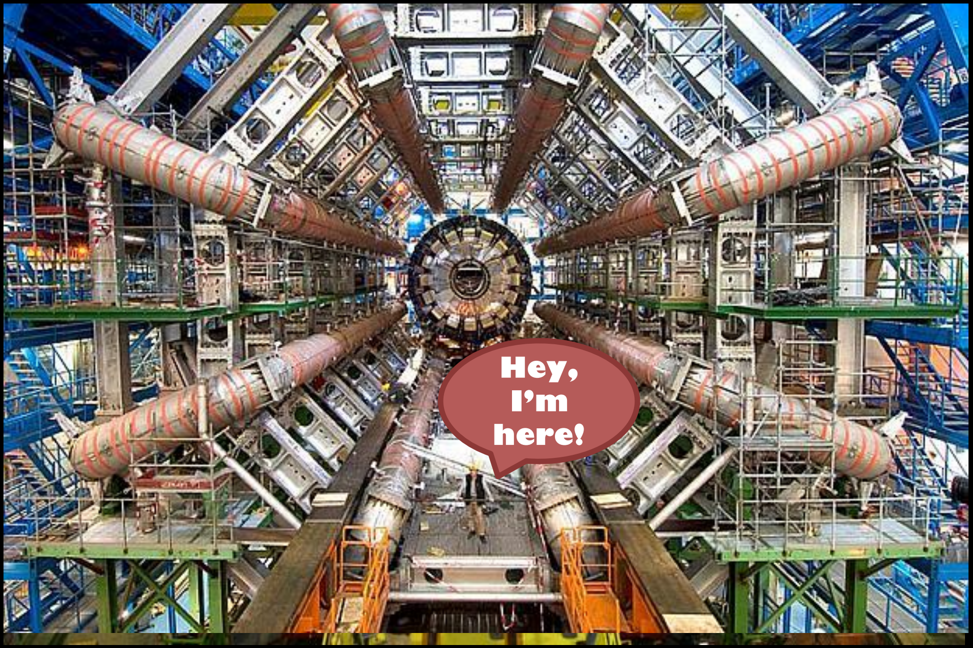
Majorana spinor = (1/2,0) + $(1/2,0)^c$ *for neutral fermions only*

LHC

Large Hadron Collider



The 15-m long LHC cryodipole



How large is large?

- total cost ~ 9 billion € (~1/5 of French public debt yearly interest)
- size: → ring ~ 27km | $-z$ ~ 100m
  - → detectors ~ $25\times50\ \pi m^3$ [ATLAS]
- beam pipe:
  - → T ~ 1.9K (~30% colder than the Universe sparsest regions)
  - → B field ~ 8.4T (~300 000 Earth's magnetic field)
  - → current ~ 12kA (~40 000 common light bulb current)
- beam:
  - → proton/proton (occasionaly lead)
  - → quasi-luminal speed: γ ~ 7000 (~10^4 laps/♥-beat*!!!*)
  - → kinetic energy ~ 7×2=14TeV (TeV = 10^{12} eV)
- collisions:
  - → 6×10^8/s
  - → ~GB/s of data, of which only ~100MB/s recorded

Why is LHC so large?

quantum mechanics: $\Delta x \times \Delta p \geq \hbar/2$

We want to probe Δx~$10^{-18/-19}$m ~ $L_{proton}/10^3$,
where weak force separates from QED,

→ E~pc > 100GeV/1TeV

(~10TeV needed because protons are composite.)

High energies → long accelerators (magnet limited)
+ big calorimeter to stop outgoing particles.