Gedanken Worlds without Higgs

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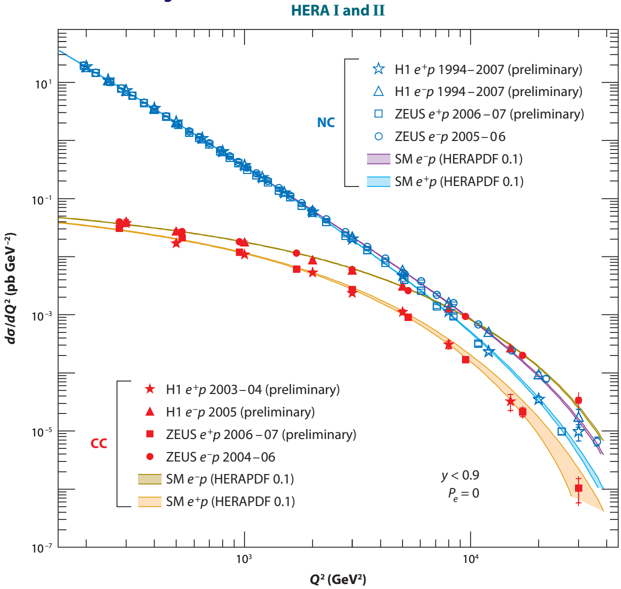
CQ & R. Shrock, *Phys. Rev. D* **79**, 096002 (2009) [arXiv:0901.3958]

CQ, *ARNPS* **59**, 505–555 (2009) [arXiv:0905.3187]

▸ *H*

Electroweak theory tests



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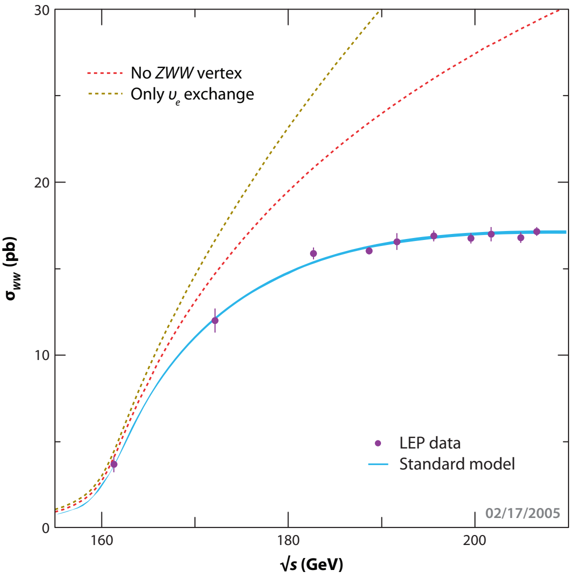

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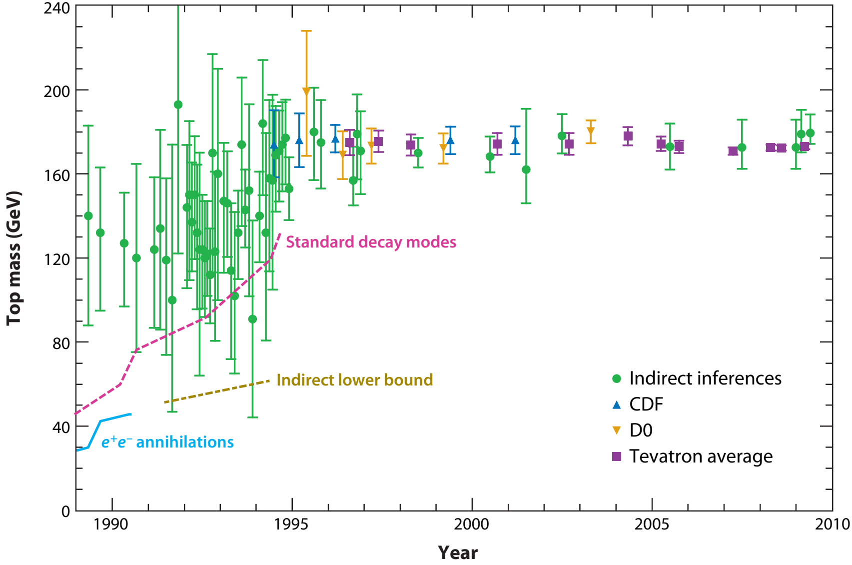

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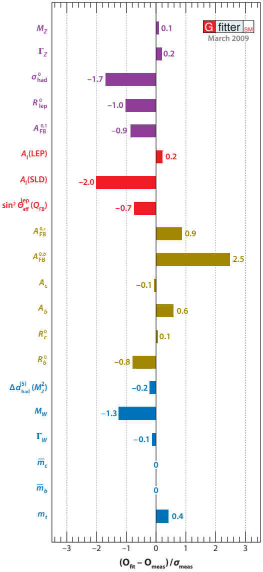

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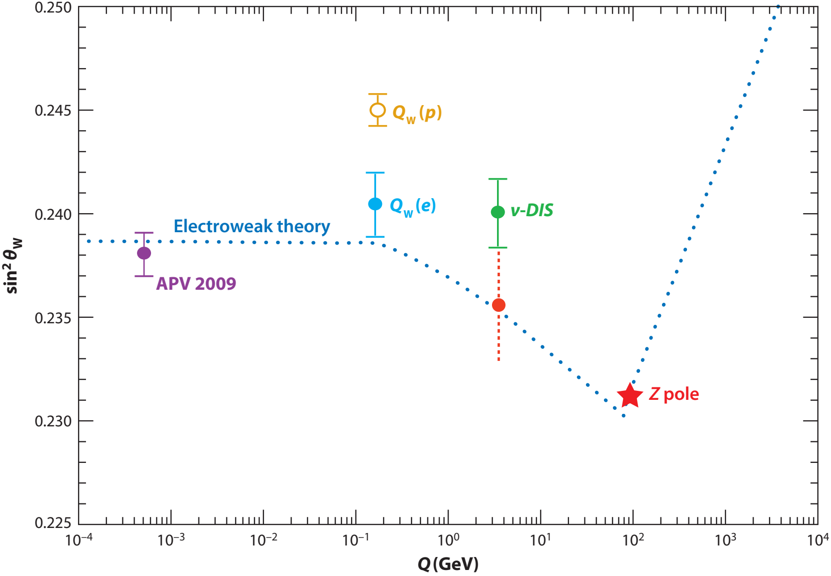

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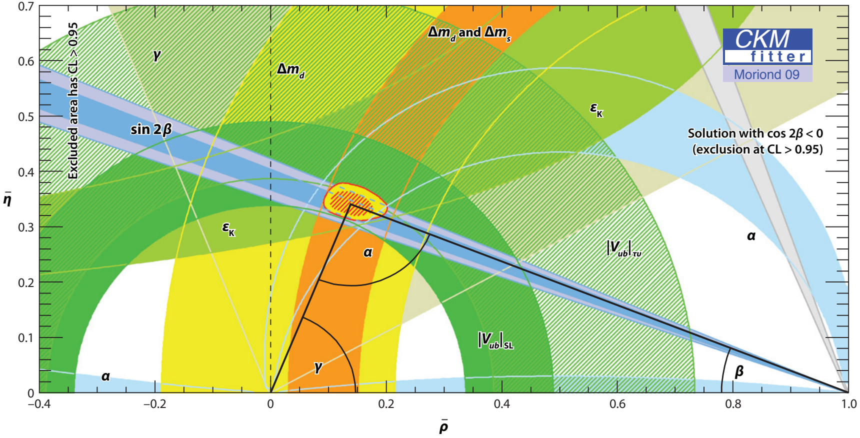

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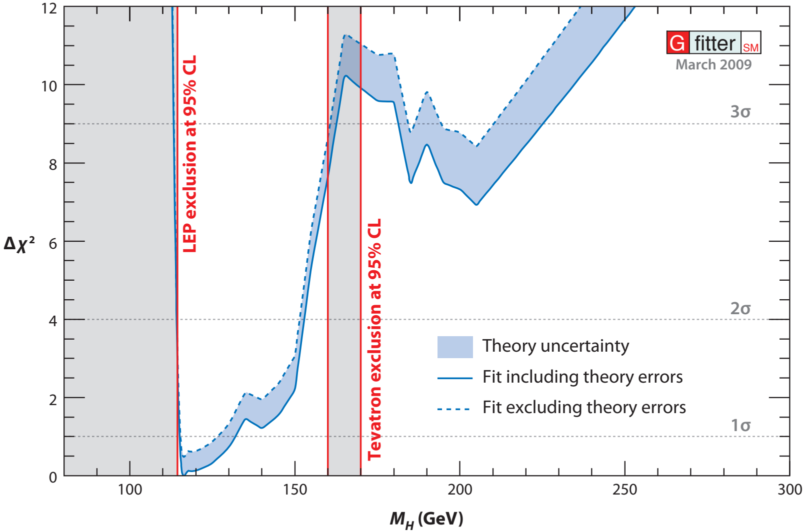
Electroweak theory projection



$\rightsquigarrow$ search for agent of EWSB

SM shortcomings

- No explanation of Higgs potential
- No prediction for M_H
- Doesn't predict fermion masses & mixings
- M_H unstable to quantum corrections
- No explanation of charge quantization
- Doesn't account for three generations
- Vacuum energy problem
- Beyond scope: dark matter, matter asymmetry, etc.

$\rightsquigarrow$ imagine more complete, predictive extensions

Challenge: Understanding the Everyday World

What would the world be like, without a (Higgs) mechanism to hide electroweak symmetry and give masses to the quarks and leptons?

(No EWSB agent at $v \approx 246$ GeV)

Consider effects of all SM interactions!

$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

Modified Standard Model: No Higgs Sector: $\overline{\text{SM}}_1$

$\mathbf{SU(3)_c} \otimes \text{SU(2)}_\text{L} \otimes \text{U(1)}_Y$ with massless u, d, e, ν

(treat $\text{SU(2)}_\text{L} \otimes \text{U(1)}_Y$ as perturbation)

Nucleon mass little changed:

$$M_p = C \cdot \Lambda_{\text{QCD}} + \ldots$$

$$3\,\frac{m_u + m_d}{2} = (7.5 \text{ to } 15) \text{ MeV}$$

Small contribution from virtual strange quarks

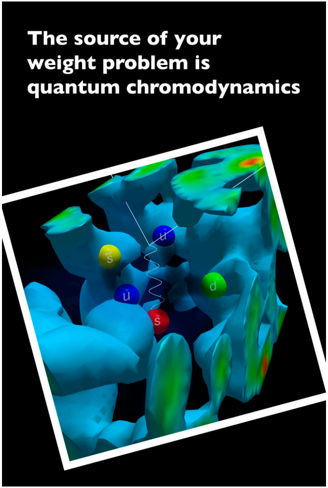
M_N decreases by $< 10\%$ in chiral limit: $939 \rightsquigarrow 870$ MeV

QCD accounts for (most) visible mass in Universe

Ab Initio Determination of Light Hadron Masses

S. Dürr,[1] Z. Fodor,[1,2,3] J. Frison,[4] C. Hoelbling,[2,3,4] R. Hoffmann,[2] S. D. Katz,[2,3] S. Krieg,[2] T. Kurth,[2] L. Lellouch,[4] T. Lippert,[2,5] K. K. Szabo,[2] G. Vulvert[4]

More than 99% of the mass of the visible universe is made up of protons and neutrons. Both particles are much heavier than their quark and gluon constituents, and the Standard Model of particle physics should explain this difference. We present a full ab initio calculation of the masses of protons, neutrons, and other light hadrons, using lattice quantum chromodynamics.



(*not* the Higgs boson)

Modified Standard Model: No Higgs Sector: $\overline{\mathrm{SM}}_1$

QCD has exact $\mathrm{SU(2)_L} \otimes \mathrm{SU(2)_R}$ chiral symmetry.

At an energy scale $\sim \Lambda_{\mathrm{QCD}}$, strong interactions become strong, fermion condensates $\langle \bar{q}q \rangle$ appear, and

$$\mathrm{SU(2)_L} \otimes \mathrm{SU(2)_R} \to \mathrm{SU(2)_V}$$

$\rightsquigarrow$ 3 Goldstone bosons, one for each broken generator:
3 massless pions (Nambu)

Fermion condensate . . .

links left-handed, right-handed fermions

$$\langle \bar{q}q \rangle = \langle \bar{q}_{\mathrm{R}} q_{\mathrm{L}} + \bar{q}_{\mathrm{L}} q_{\mathrm{R}} \rangle$$

$$1 = \tfrac{1}{2}(1+\gamma_5) + \tfrac{1}{2}(1-\gamma_5)$$

$$\mathsf{Q}^a_{\mathrm{L}} = \begin{pmatrix} u^a \\ d^a \end{pmatrix}_{\mathrm{L}} \qquad u^a_{\mathrm{R}} \quad d^a_{\mathrm{R}}$$

$$(\mathrm{SU(3)_c}, \mathrm{SU(2)_L})_Y\text{:}\ (\mathbf{3},\mathbf{2})_{1/3} \qquad (\mathbf{3},\mathbf{1})_{4/3} \quad (\mathbf{3},\mathbf{1})_{-2/3}$$

transforms as $\mathrm{SU(2)_L}$ doublet with $|Y| = 1$

Induced breaking of $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y \to \mathrm{U(1)_{em}}$

Broken generators: 3 axial currents; couplings to π: $\bar{f}_\pi$

Turn on $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$*:*

Weak bosons couple to axial currents, acquire mass $\sim g\bar{f}_\pi$

$$g \approx 0.65,\ g' \approx 0.34,\ f_\pi = 92.4\ \mathrm{MeV} \rightsquigarrow \bar{f}_\pi \approx 87\ \mathrm{MeV}$$

$$\mathcal{M}^2 = \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g'^2 \end{pmatrix} \frac{\bar{f}_\pi^2}{4} \qquad (w_1, w_2, w_3, \mathcal{A})$$

same structure as standard EW theory

Induced breaking of $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$

Diagonalize:

$$\begin{aligned} \overline{M}_W^2 &= g^2 \bar{f}_\pi^2/4 \\ \overline{M}_Z^2 &= (g^2 + g'^2)\bar{f}_\pi^2/4 \\ \overline{M}_A^2 &= 0 \end{aligned}$$

$$\overline{M}_Z^2/\overline{M}_W^2 = (g^2 + g'^2)/g^2 = 1/\cos^2\theta_W$$

NGBs become longitudinal components of weak bosons.

$\overline{M}_W \approx 28$ MeV $\qquad \overline{M}_Z \approx 32$ MeV

($M_W \approx 80$ GeV $\qquad M_Z \approx 91$ GeV)

No fermion masses . . .

(Possible division of labor)

Inspiration for Technicolor $\rightsquigarrow$ *Extended Technicolor . . .*

Higher scales? $uu \to X^{4/3} \to e^+ d^c$ mixes p, e^+

$$\varepsilon \equiv \mathcal{M}(p \leftrightarrow e^+) \approx \frac{4\pi\alpha_{\mathrm{U}}}{M_X^2} \Lambda_{\mathrm{QCD}}^3 \approx 10^{-36}\ \mathrm{GeV}$$

(e^+, p) mass matrix

$$\mathrm{M} = \begin{pmatrix} 0 & \varepsilon \\ \varepsilon^* & M_p \end{pmatrix}$$

$$\rightsquigarrow m_e = |\varepsilon|^2 / M_p \approx 10^{-72}\ \mathrm{GeV}$$

Electroweak scale

EW theory: *choose* $v = (G_F\sqrt{2})^{-1/2} \approx 246$ GeV

$\overline{\text{SM}}$: *predict*

$$\overline{G}_F = 1/(\bar{f}_\pi^2\sqrt{2}) \approx 93.25\ \text{GeV}^{-2} \approx 8 \times 10^6\ G_F$$

Cross sections, decay rates $\times(\overline{G}_F/G_F)^2 \approx 6.4 \times 10^{13}$

$$\text{Real world: } \sigma(\nu_e n \to e^- p) \approx 10^{-38}\ \text{cm}^{-2}$$

$$\rightsquigarrow \overline{\text{SM}}\text{: } \bar{\sigma}(\nu_e n \to e^- p) \approx \text{ few mb}$$

Weak interaction strength $\sim$ residual strong interactions

$\overline{\mathrm{SM}}_1$: Hadron Spectrum

Pions absent (became longitudinal $W^{\pm}$, Z^0)

ρ, ω, a_1 "as usual," but

$$\rho^0 \to W^+ W^-$$
$$\rho^+ \to W^+ Z$$
$$\omega \to W^+ W^- Z$$

$M_\Delta > M_N; \quad \Delta \to N(W^{\pm}, Z, \gamma)$

Nucleon mass little changed: look in detail

Nucleon masses . . .

"Obvious" that proton should outweigh neutron

. . . but false in real world: $M_n - M_p \approx 1.293$ MeV

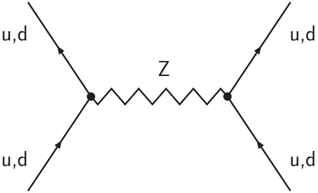
Real-world contributions,

$$\begin{aligned} M_n - M_p &= (m_d - m_u)\cancel{(m_d - m_u)} - \tfrac{1}{3}\left(\delta m_q + \delta M_C + \delta M \right. \\ &\rightsquigarrow -1.7 \text{ MeV} \end{aligned}$$

. . . but weak contributions enter.

Weak contributions are not negligible

$$\overline{M}_n - \overline{M}_p\Big|_{\text{weak}} \propto dd - uu$$



$$\begin{aligned}\overline{M}_n - \overline{M}_p\Big|_{\text{weak}} &= \frac{\overline{G}_{\text{F}}\Lambda_{\text{h}}^3\sqrt{2}}{3}x_{\text{W}}(1-2x_{\text{W}}) \approx \frac{\overline{G}_{\text{F}}\Lambda_{\text{h}}^3\sqrt{2}}{24} \\ &= \frac{\Lambda_{\text{h}}^3}{3\bar{f}_\pi^2}x_{\text{W}}(1-2x_{\text{W}}) \approx \frac{\Lambda_{\text{h}}^3}{24\bar{f}_\pi^2} > 0\end{aligned}$$

$x_{\text{W}} = sin^2\theta_{\text{W}} \approx \frac{1}{4}$

perhaps a few MeV?

Bending the rules . . .

$$\overline{M}_n - \overline{M}_p\big|_{\text{weak}} \text{ doesn't depend on } g$$

(in point-coupling limit)

$$\overline{M}_n - \overline{M}_p\big|_{\text{em}} \propto \alpha \propto g^2 x_{\text{W}}$$

Amusing that (for fixed x_{W})
increasing or decreasing g
increases or decreases em with respect to weak

Consequences for β decay

Scale decay rate $\Gamma \sim \overline{G}_F^2 |\overline{\Delta M}|^5 / 192\pi^3$ (rapid!)

$$\bar{\tau}_\mu \longrightarrow 10^{-19} \text{ s}$$

$$n \longrightarrow pe^- \bar{\nu}_e \text{ or } p \longrightarrow ne^+ \nu_e$$

Example: $\left|\overline{M}_n - \overline{M}_p\right| = M_n - M_p \rightsquigarrow \bar{\tau}_N \approx 14$ ps

No Hydrogen Atom?

Neutron could be lightest nucleus

Strong coupling in $\overline{\text{SM}}$

In SM, Higgs boson regulates high-energy behavior

Gedanken experiment: scattering of

$$W_L^+ W_L^- \quad \frac{Z_L^0 Z_L^0}{\sqrt{2}} \quad \frac{HH}{\sqrt{2}} \quad HZ_L^0$$

In high-energy limit, s-wave amplitudes

$$\lim_{s \gg M_H^2} (a_0) \to \frac{-G_{\mathrm{F}} M_H^2}{4\pi\sqrt{2}} \cdot \begin{bmatrix} 1 & 1/\sqrt{8} & 1/\sqrt{8} & 0 \\ 1/\sqrt{8} & 3/4 & 1/4 & 0 \\ 1/\sqrt{8} & 1/4 & 3/4 & 0 \\ 0 & 0 & 0 & 1/2 \end{bmatrix} .$$

Strong coupling in $\overline{\text{SM}}$

In *standard model*, $|a_0| \leq 1$ yields

$$M_H \leq \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} = 4v\sqrt{\pi/3} = 1 \text{ TeV}$$

In $\overline{\text{SM}}_1$ *Gedanken* world,

$$\overline{M}_H \leq \left(\frac{8\pi\sqrt{2}}{3\overline{G}_F}\right)^{1/2} = 4\bar{f}_\pi\sqrt{\pi/3} \approx 350 \text{ MeV}$$

violated because no Higgs boson $\rightsquigarrow$ strong scattering

Strong coupling in $\overline{\mathrm{SM}}$

SM with (very) heavy Higgs boson:

s-wave W^+W^-, Z^0Z^0 scattering as $s \gg M_W^2, M_Z^2$:

$$a_0 = \frac{s}{32\pi v^2}\begin{bmatrix} 1 & \sqrt{2} \\ \sqrt{2} & 0 \end{bmatrix}$$

Largest eigenvalue: $a_0^{\max} = s/16\pi v^2$

$$|a_0| \le 1 \Rightarrow \sqrt{s^\star} = 4\sqrt{\pi}v \approx 1.74\ \mathrm{TeV}$$

$$\boxed{\overline{\mathrm{SM}}\text{: } \sqrt{s^\star} = 4\sqrt{\pi}\bar{f}_\pi \approx 620\ \mathrm{MeV}}$$

$\overline{\mathrm{SM}}$ becomes strongly coupled on the hadronic scale

Strong coupling in $\overline{\text{SM}}$

As in standard model . . .

$I = 0$, $J = 0$ and $I = 1$, $J = 1$: attractive
$I = 2$, $J = 0$: repulsive

As partial-wave amplitudes approach bounds,
WW, WZ, ZZ resonances form,
multiple production of W and Z

in emulation of $\pi\pi$ scattering approaching 1 GeV

Detailed projections depend on unitarization protocol

What about atoms?

Suppose some light elements produced in BBN survive

Massless $e \Longrightarrow \infty$ Bohr radius

No meaningful atoms

No valence bonding

No integrity of matter, no stable structures

▸ $\overline{\text{SM}}m$

Strong-interaction symmetries

- ▷ Strong CP problem: $\mathcal{L}_\theta = \frac{\theta g_s^2}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\,\mu\nu}$
  can be tuned away if at least one $m_q = 0$

- ▷ Real world: strong interactions respect P & C
  Gedanken world: long-range "strong" interactions from W, Z exchange (no pions) so P & C are violated

Look more closely at NN interaction in $\overline{\mathrm{SM}}_1$

Nuclear force in the *Gedanken* world

- Size of hadrons:
  $1/m_\pi \approx 1.4$ fm in real world
  $1/\overline{M}_W \approx 7$ fm in $\overline{\text{SM}}_1$

- π-exchange in real world

$$A(N_1 N_2 \to N_3 N_4) \sim \frac{g_{\pi NN}^2}{m_\pi^2} \qquad g_{\pi NN} \approx 14$$

W-exchange in *Gedanken* world

$$\overline{A}(N_1 N_2 \to N_3 N_4) \sim \frac{g^2}{8\overline{M}_W^2} \sim \frac{1}{2\bar{f}_\pi^2}$$

▸ $\overline{\text{SM}}m$

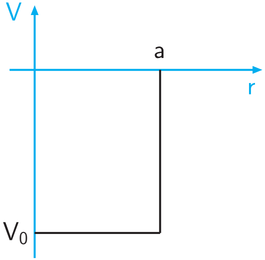
Nuclear force in the *Gedanken* world

▷ *NN* scattering amplitude smaller in $\overline{\mathrm{SM}}_1$:

$$\bar{A}/A = \frac{m_\pi^2}{2\bar{f}_\pi^2 g_{\pi NN}^2} = 0.0065$$

but (as we saw) 5× longer range

▷ Bound states as $\xi = 2\mu V_0 a^2/\hbar^2\pi^2 \sim O(1)$



(μ: reduced mass)

$$\frac{\bar{\xi}}{\xi} = \frac{m_\pi^2}{2\bar{f}_\pi^2 g_{\pi NN}^2} \cdot \frac{m_\pi^2}{\overline{M}_W^2} \approx \frac{1}{6}$$

Not $\ll 1$

EWSB with $n_g > 1$ fermion generations: $\overline{\mathrm{SM}}_{n_g}$

Spontaneously broken $\mathrm{SU}(n_g)_\mathrm{L} \otimes \mathrm{SU}(n_g)_\mathrm{R} \to \mathrm{SU}(n_g)_\mathrm{V}$

$$
\begin{aligned}
|\Pi^+\rangle &= \frac{1}{\sqrt{n_g}} \sum_{i=1}^{n_g} |u_i \bar{d}_i\rangle \\
|\Pi^0\rangle &= \frac{1}{\sqrt{2n_g}} \sum_{i=1}^{n_g} |(u_i \bar{u}_i - d_i \bar{d}_i)\rangle \\
|\Pi^-\rangle &= \frac{1}{\sqrt{n_g}} \sum_{i=1}^{n_g} |d_i \bar{u}_i\rangle .
\end{aligned}
$$

3 of $(4n_g^2 - 1)$ NGBs

$\overline{M}_W^2 = n_g\, g^2 \bar{f}_\pi^2/4 \quad \overline{M}_Z^2 = n_g (g^2 + g'^2)\bar{f}_\pi^2/4 \quad \overline{G}_\mathrm{F} \propto 1/n_g$

so $\sqrt{s^\star} = 4\sqrt{\pi n_g}\bar{f}_\pi \approx 620\,\sqrt{n_g}$ MeV

Meson spectrum in $\overline{\mathrm{SM}}_{n_g}$

n_g^2 NGBs each with charge ± 1

$\sim$ real-world $\pi^{\pm}$ $(n_g = 1)$; & $K^{\pm}$, $D^{\pm}$, $D_s^{\pm}$ $(n_g = 2)$

$2n_g(n_g - 1)$ charge-zero NGBs with flavor

$\sim K^0, \bar{K}^0$, and $D^0, \bar{D}^0$ $(n_g = 2)$

$2n_g - 1$ self-conjugate flavor-nonsinglet NGBs

$\sim \pi^0$ $(n_g = 1)$; & η and η_c $(n_g = 2)$

After EWSB, $4n_g^2 - 4$ NGBs

$\rightsquigarrow$ very large hadrons, very long range nuclear forces

Goldberger–Treiman: $|g_A|\, M_N = f_\pi g_{\pi NN}$

Baryon spectrum in $\overline{\mathrm{SM}}_{n_g}$

Similar to real-world spectrum . . . (weak decays)

$$\mathbf{n_q} \otimes \mathbf{n_q} \otimes \mathbf{n_q} = S_3 \oplus M_1 \oplus M_2 \oplus A_3$$

$$\begin{aligned} \dim(S_3) &= \frac{n_q(n_q+1)(n_q+2)}{3!} \\ \dim(M) &= \frac{n_q(n_q^2-1)}{3} \\ \dim(A_3) &= \binom{n_q}{3} \end{aligned}$$

$SU(2n_g)_{\text{flavor}}$ symmetry exact

equal masses within multiplets

Massless fermion pathologies . . .

Vacuum readily breaks down to e^+e^- plasma

. . . persists with GUT-induced tiny masses

"hard" fermion masses: explicit $\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_Y$ breaking

NGBs $\longrightarrow$ pNGBs

$$\mathrm{SM}m\text{: } a_J(f\bar{f} \to W_L^+ W_L^-) \propto G_\mathrm{F}\, m_f\, E_\mathrm{cm}$$

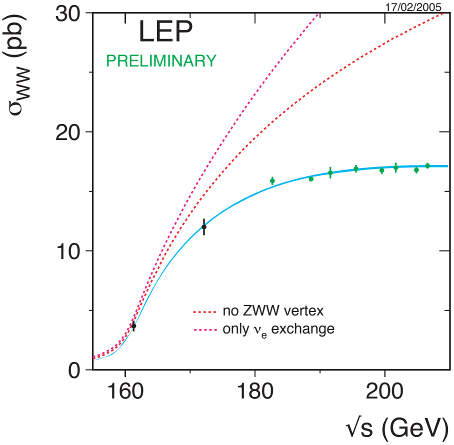
saturate p.w. unitarity at

$$\sqrt{s_f} \simeq \frac{4\pi\sqrt{2}}{\sqrt{3\eta_f}\, G_\mathrm{F}\, m_f} = \frac{8\pi v^2}{\sqrt{3\eta_f}\, m_f}$$

$\eta_f = 1(N_\mathrm{c})$ for leptons (quarks)

Hard electron mass: $\sqrt{s_e} \approx 1.7 \times 10^9$ GeV ...

Gauge cancellation need not imply renormalizable theory



Hard top mass: $\sqrt{s_t} \approx 3$ TeV

Add explicit fermion masses to $\overline{\mathrm{SM}}$: $\rightsquigarrow \overline{\mathrm{SM}}m$

$a_J(f\bar{f} \to W_L^+ W_L^-)$ unitarity respected up to

$$\sqrt{s^\star} = 4\sqrt{\pi n_g}\bar{f}_\pi \approx 620\sqrt{n_g}\ \text{MeV}$$

(condition from WW scattering)

$$\rightsquigarrow m_f \lesssim \frac{2\sqrt{\pi n_g}\bar{f}_\pi}{\sqrt{3\eta_f}} \approx \begin{cases} 126\sqrt{n_g}\ \text{MeV (leptons)} \\ 73\sqrt{n_g}\ \text{MeV (quarks)} \end{cases}$$

would accommodate real-world e, u, d masses

▸ LR ▸ Summary

Extension to $N_c > 3$

EWSB scale is related to QCD confinement scale in $\overline{\text{SM}}$

Examine N_c scaling laws, $N_c \to \infty$ limit

QCD: hold $g_3^2 N_c =$ constant as $N_c \to \infty$

Anomaly freedom fixes quark charges:

$$Q_u = Q_d + 1 = \tfrac{1}{2}\left[1 - (2Q_e + 1)/N_c\right]$$

$SU(2)_L \otimes U(1)_Y$: $g^2 N_c$, $g'^2 N_c$, $e^2 N_c \to$ fixed as $N_c \to \infty$

...compensates $f_\pi \propto \sqrt{N_c}$

$\overline{M}_W$ independent of N_c, so $\overline{G}_F \propto 1/\sqrt{N_c}$

SM as low-energy limit of . . .

LR-symmetric $\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{SU(2)_R} \otimes \mathrm{U(1)}_{B-L}$

$$Q = I_{3\mathrm{L}} + I_{3\mathrm{R}} + \tfrac{1}{2}(B - L)$$

Real world (?), $\mathrm{SU(2)_R} \otimes \mathrm{U(1)}_{B-L} \to \mathrm{U(1)}_Y$

Gedanken world:

QCD breaks $\mathrm{SU(2)_L} \otimes \mathrm{SU(2)_R} \otimes \mathrm{U(1)}_{B-L}$

$\to \mathrm{SU(2)_V} \otimes \mathrm{U(1)}_{B-L}$

At $\Lambda_\mathrm{V} \approx 10^{-24}\Lambda_\mathrm{QCD}$, $\mathrm{SU(2)_V}$ confines leptons,

leaves $\mathrm{U(1)}_{B-L}$ long-range force (not em)

Summary

SM as low-energy limit of . . .

Pati-Salam $\mathrm{SU}(4)_{\mathrm{PS}} \otimes \mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{SU}(2)_{\mathrm{R}}$

lepton number as fourth color; charge quantization

Real world (?), broken to $\mathrm{SU}(3)_{\mathrm{c}} \otimes \mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{U}(1)_{Y}$

Gedanken world:

$\mathrm{SU}(4)_{\mathrm{PS}}$ breaks $\mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{SU}(2)_{\mathrm{R}} \to \mathrm{SU}(2)_{\mathrm{V}}$

At $\Lambda_{\mathrm{V}} \approx 10^{-21}\Lambda_{\mathrm{PS}}$, $\mathrm{SU}(2)_{\mathrm{V}}$ produces V-glueballs;

no residual long-range force!

"EWSB" doesn't lead to low-energy electromagnetism

In summary . . .

- $\overline{\mathsf{SM}}$: QCD-induced $\mathsf{SU(2)_L \otimes U(1)}_Y \to \mathsf{U(1)_{em}}$
- No fermion masses; division of labor?
- No physical pions in $\overline{\mathsf{SM}}_1$
- No quark masses: might proton outweigh neutron?
- Infinitesimal m_e: integrity of matter compromised
- $\overline{\mathsf{SM}}$ exhibits strong W, Z dynamics below 1 GeV
- $\overline{M}_W \approx 30$ MeV in *Gedanken* world
- $\overline{G}_\mathsf{F} \sim 10^7\, G_\mathsf{F}$: accelerates β decay
- Weak, hadronic int. comparable; nuclear forces
- Infinitesimal m_ℓ: vacuum breakdown, e^+e^- plasma
- $\overline{\mathsf{SM}}m$: effective theory through hadronic scale

Outlook

How different a world, without a Higgs mechanism:
preparation for interpreting experimental insights

$\overline{\text{SM}}$, $\overline{\text{SM}}m$: explicit theoretical laboratories
complement to studies that retain Higgs, vary v
(very intricate alternative realities)

Fresh look at the way we have understood the real world
(possibly > 1 source of SSB, "hard" fermion masses)

How might EWSB deviate from the Higgs mechanism?