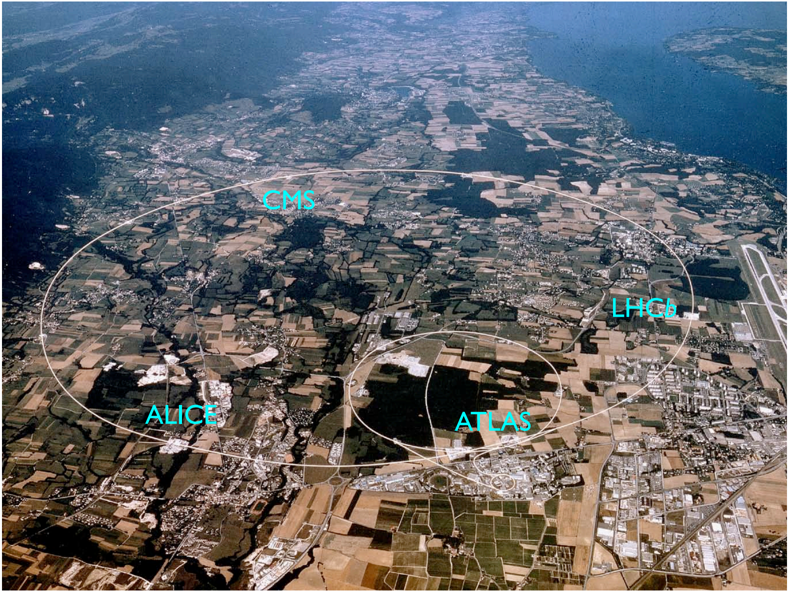
LAL Cours d'automne 2009

Potential Discoveries at the Large Hadron Collider

Chris Quigg

Fermilab

Large Hadron Collider: pp at $\sqrt{s} \rightarrow 14$ TeV



The importance of the 1-TeV scale

EW theory does not predict Higgs-boson mass,

but partial-wave unitarity defines tipping point

Gedanken experiment: high-energy scattering of

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

L: longitudinal, $1/\sqrt{2}$ for identical particles

The importance of the 1-TeV scale . .

In HE limit, s-wave amplitudes $\propto G_{\mathrm{F}} M_H^2$

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

Require that largest eigenvalue respect partial-wave unitarity condition $|a_0| \leq 1$

$$\Longrightarrow \quad M_H \leq \left(\frac{8\pi\sqrt{2}}{3 G_{\mathrm{F}}} \right)^{1/2} = 1 \text{ TeV}$$

condition for perturbative unitarity

The importance of the 1-TeV scale . . .

If the bound is respected

- weak interactions remain weak at all energies
- perturbation theory is everywhere reliable

If the bound is violated

- perturbation theory breaks down
- weak interactions among $W^{\pm}$, Z, H
  become strong on 1-TeV scale

New phenomena are to be found in the EW interactions at energies not much larger than 1 TeV

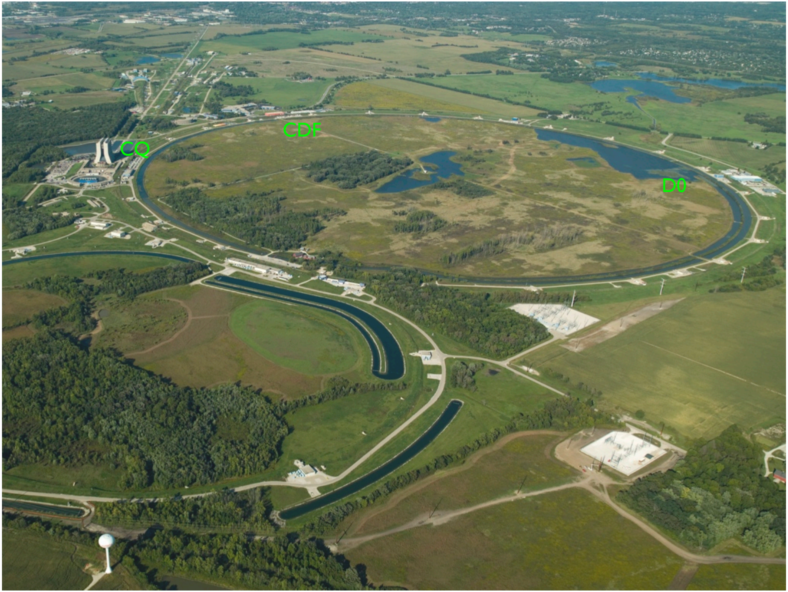
A Decade of Discovery Past

- ▷ Electroweak theory validated
- ▷ Higgs-boson influence observed
- ▷ Neutrino oscillations: $\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\mu/\nu_\tau$
- ▷ QCD
- ▷ Discovery of top quark
- ▷ Direct CP violation in $K \to \pi\pi$ decay
- ▷ B-meson decays violate CP
- ▷ Flat U, mostly dark matter & energy
- ▷ Detection of ν_τ interactions
- ▷ Constituents structureless at TeV scale

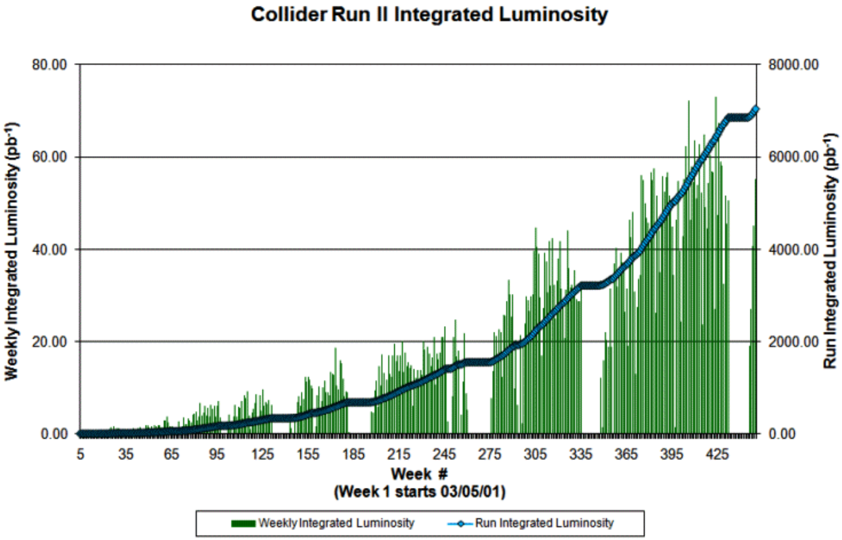
A Decade of Discovery Past

- ▷ Electroweak theory validated [Z, e^+e^-, $\bar{p}p$, νN, $\dots$]
- ▷ Higgs-boson influence observed [EW experiments]
- ▷ Neutrino oscillations: $\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\mu/\nu_\tau$ [$\nu_\odot$, ν_{atm}]
- ▷ QCD [heavy flavor, Z^0, $\bar{p}p$, νN, ep, lattice]
- ▷ Discovery of top quark [$\bar{p}p$]
- ▷ Direct CP violation in $K \to \pi\pi$ decay [fixed-target]
- ▷ B-meson decays violate CP [$e^+e^- \to B\bar{B}$]
- ▷ Flat U, mostly dark matter & energy [SN Ia, CMB, LSS]
- ▷ Detection of ν_τ interactions [fixed-target]
- ▷ Constituents structureless at TeV scale [mainly colliders]

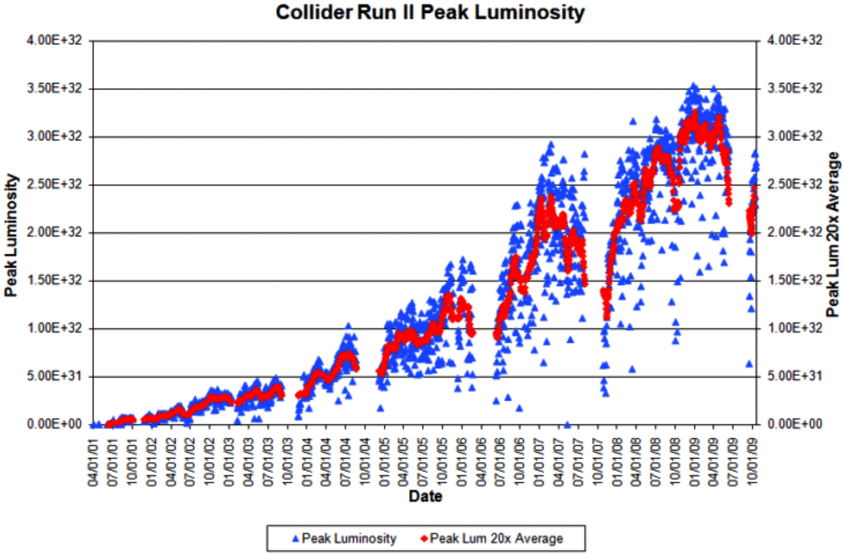
Tevatron: $\bar{p}p$ at $\sqrt{s} = 1.96$ TeV



Tevatron Performance



Tevatron Performance



Tentative Program

1. The Setting
    - Unanswered Questions in the Electroweak Theory
    - Why Electroweak Symmetry Breaking Matters
2. Early Running
    - Exploring the New Landscape
    - Physics Potential versus Energy
3. Discovery Opportunities within the Standard Model
4. Discovery Opportunities beyond the Standard Model

Lecture 1: The Setting

Unanswered Questions in the Electroweak Theory

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Key Words

electroweak symmetry breaking, Higgs boson, 1-TeV scale, Large Hadron Collider (LHC), hierarchy problem, extensions to the Standard Model

Abstract

This article is devoted to the status of the electroweak theory on the eve of experimentation at CERN's Large Hadron Collider (LHC). A compact summary of the logic and structure of the electroweak theory precedes an examination of what experimental tests have established so far. The outstanding unconfirmed prediction is the existence of the Higgs boson, a weakly interacting spin-zero agent of electroweak symmetry breaking and the giver of mass to the weak gauge bosons, the quarks, and the leptons. General arguments imply that the Higgs boson or other new physics is required on the 1-TeV energy scale.

Even if a "standard" Higgs boson is found, new physics will be implicated by many questions about the physical world that the Standard Model cannot answer. Some puzzles and possible resolutions are recalled. The LHC moves experiments squarely into the 1-TeV scale, where answers to important outstanding questions will be found.

505

Electroweak theory antecedents

Lessons from experiment and theory

- Parity-violating $V - A$ structure of charged current
- Cabibbo universality of leptonic and semileptonic processes
- Absence of strangeness-changing neutral currents
- Negligible neutrino masses; left-handed neutrinos
- Unitarity: four-fermion description breaks down at $\sqrt{s} \approx 620$ GeV $\quad \nu_\mu e \to \mu \nu_e$
- $\nu\bar{\nu} \to W^+W^-$: divergence problems of *ad hoc* intermediate vector boson theory

Electroweak theory consequences

- Weak neutral currents
- Need for charmed quark
- Existence and properties of $W^{\pm}$, Z^0
- No flavor-changing neutral currents at tree level
- No right-handed charged currents
- CKM Universality
- KM phase dominant source of CP violation
- Existence and properties of Higgs boson
- Higgs interactions determine fermion masses, *but . . .*
- (Massless neutrinos: no neutrino mixing)

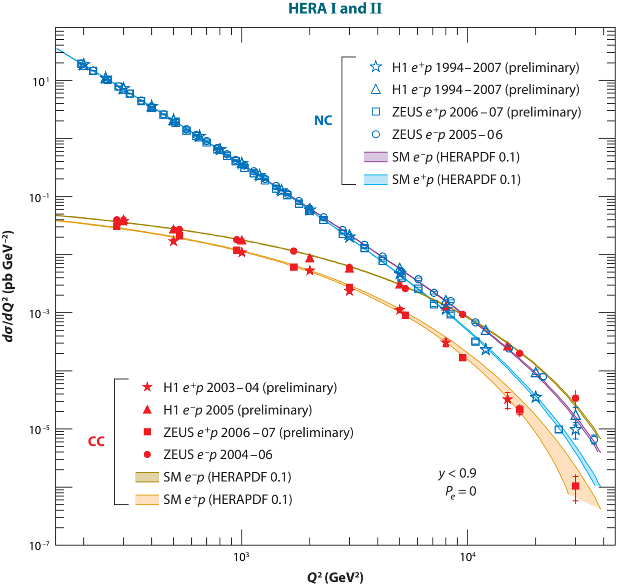
Electroweak theory tests: tree level

- $W^{\pm}$, Z^0 existence and properties verified
- Z-boson chiral couplings to quarks and leptons agree with $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ theory
- Third generation of quarks and leptons discovered
- Constraints on a fourth generation
- $M_{Z'} \gtrsim 789$ GeV (representative cases)
- $M_{W'} \gtrsim 1000$ GeV
- $M_{W_\mathrm{R}} \gtrsim 715$ GeV, $g_\mathrm{L} = g_\mathrm{R}$
- Strong suppression of FCNC:

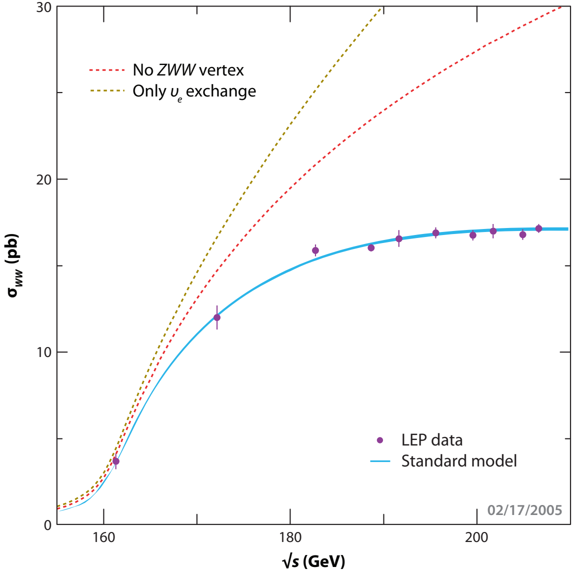
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10};$$

$$\text{SM expectation} = (0.85 \pm 0.07) \times 10^{-10}$$

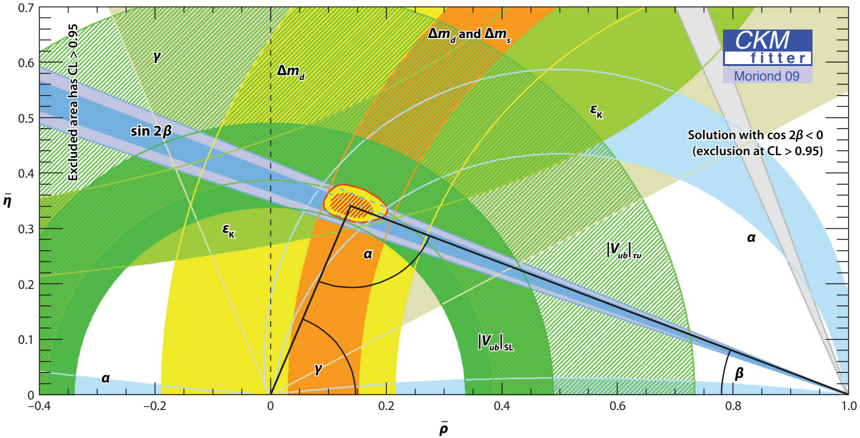
Electroweak theory tests: tree level



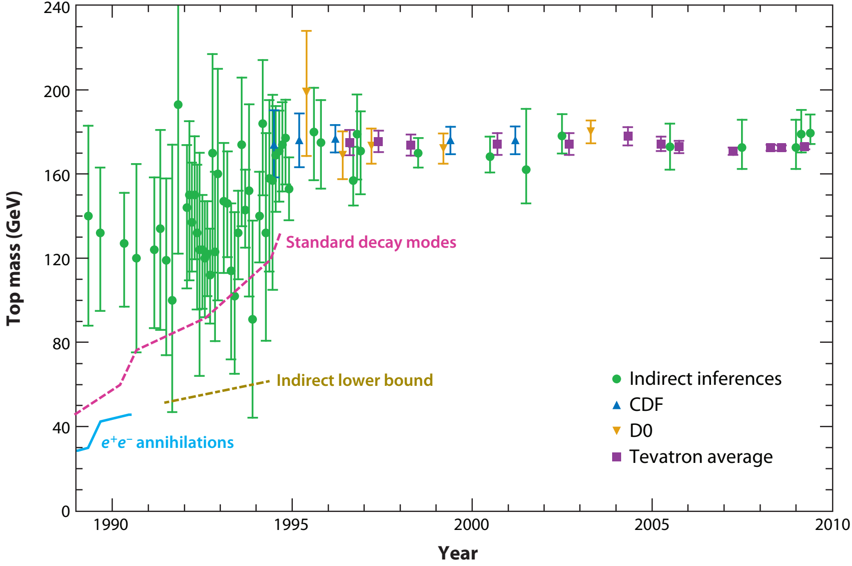
Electroweak theory tests: tree level



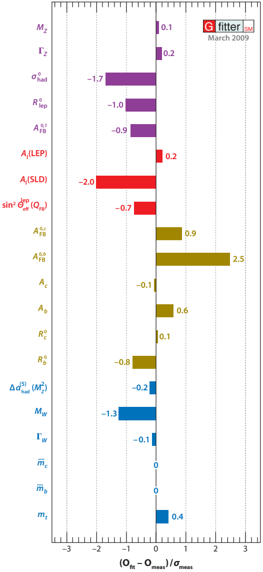
Electroweak theory tests: CKM paradigm



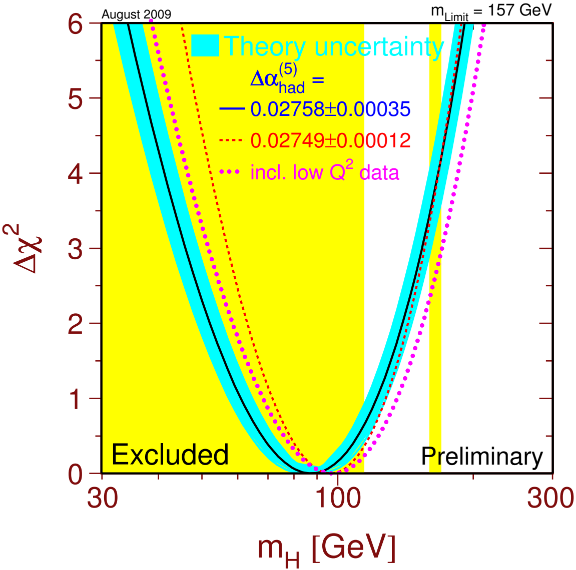
Electroweak theory tests: loop level



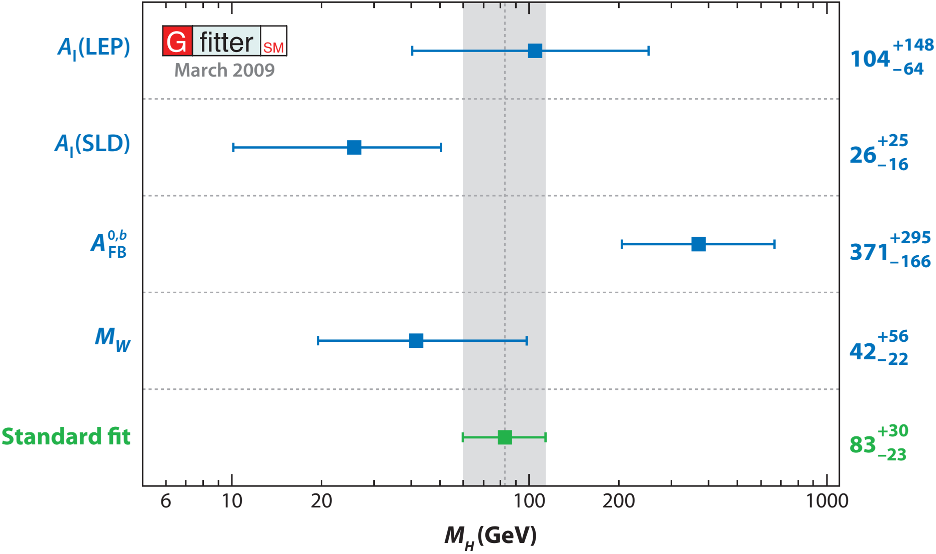
Electroweak theory tests: loop level



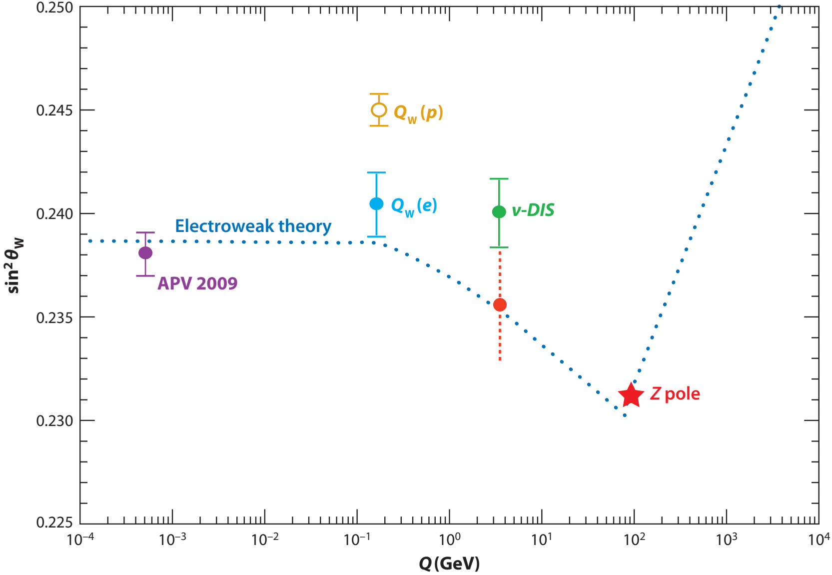
Electroweak theory tests: Higgs influence



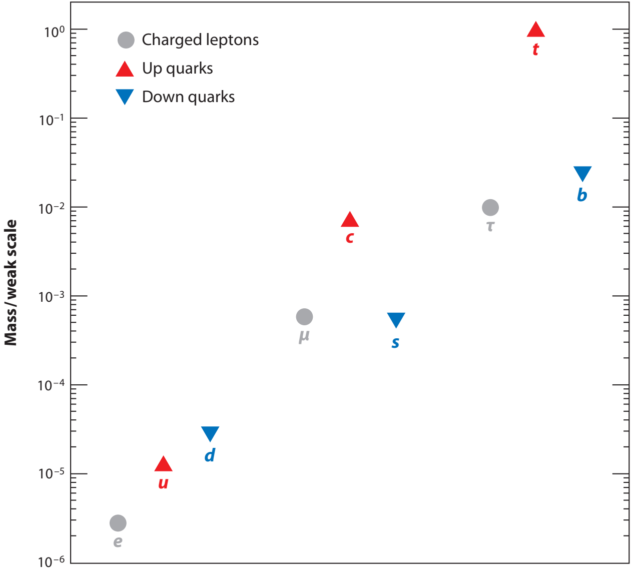
Electroweak theory tests: Higgs consistency?



Electroweak theory tests: low scales [Z']



Fermion Mass Generation



Electroweak theory successes

$\leadsto$ search for agent of EWSB

What the LHC *is not really* for . . .

- Find the Higgs boson,
  the Holy Grail of particle physics,
  the source of all mass in the Universe.
- Celebrate.
- Then particle physics will be over.

We are not ticking off items on a shopping list . . .

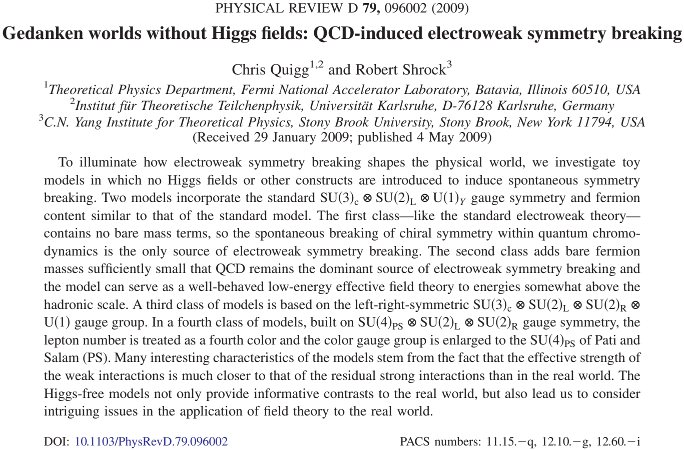
We are exploring a vast new terrain
. . . and reaching the Fermi scale

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

Lecture 1: The Setting
Why EWSB Matters



PHYSICAL REVIEW D **79,** 096002 (2009)

Gedanken worlds without Higgs fields: QCD-induced electroweak symmetry breaking

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To illuminate how electroweak symmetry breaking shapes the physical world, we investigate toy models in which no Higgs fields or other constructs are introduced to induce spontaneous symmetry breaking. Two models incorporate the standard $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ gauge symmetry and fermion content similar to that of the standard model. The first class—like the standard electroweak theory—contains no bare mass terms, so the spontaneous breaking of chiral symmetry within quantum chromodynamics is the only source of electroweak symmetry breaking. The second class adds bare fermion masses sufficiently small that QCD remains the dominant source of electroweak symmetry breaking and the model can serve as a well-behaved low-energy effective field theory to energies somewhat above the hadronic scale. A third class of models is based on the left-right-symmetric $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)$ gauge group. In a fourth class of models, built on $\mathrm{SU}(4)_{PS} \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$ gauge symmetry, the lepton number is treated as a fourth color and the color gauge group is enlarged to the $\mathrm{SU}(4)_{PS}$ of Pati and Salam (PS). Many interesting characteristics of the models stem from the fact that the effective strength of the weak interactions is much closer to that of the residual strong interactions than in the real world. The Higgs-free models not only provide informative contrasts to the real world, but also lead us to consider intriguing issues in the application of field theory to the real world.

DOI: 10.1103/PhysRevD.79.096002 PACS numbers: 11.15.−q, 12.10.−g, 12.60.−i

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!
$\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$

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

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

(treat $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ as perturbation)

Nucleon mass little changed:

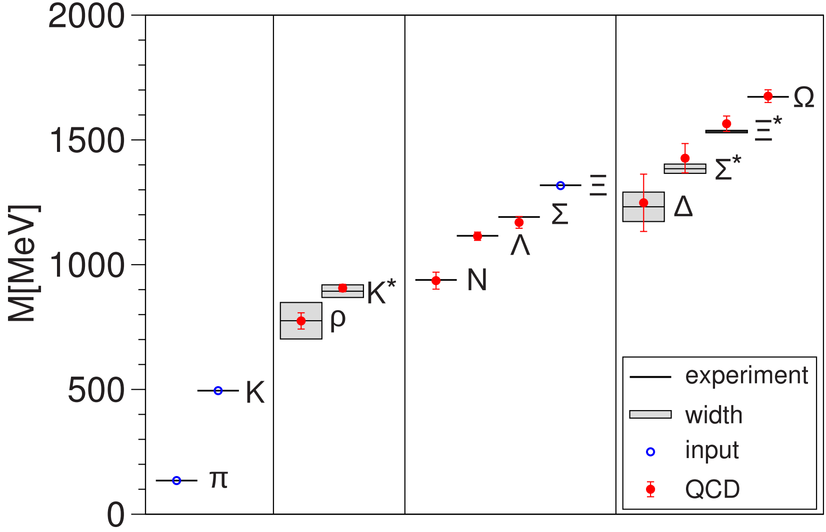
$$M_p = C \cdot \Lambda_{\mathrm{QCD}} + \dots$$

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

Small contribution from virtual strange quarks

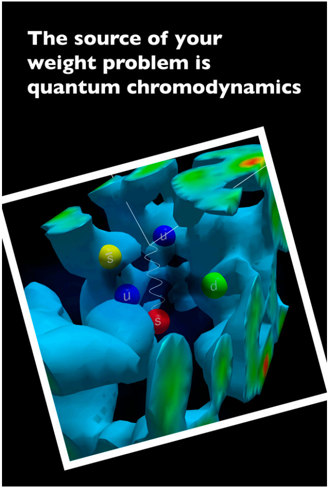
M_N decreases by $< 10\%$ in chiral limit: $939 \rightsquigarrow 870$ MeV

Hadron Masses from Lattice QCD: $M = E_0/c^2$



BMW, *Science* **322,** 1224 (2008)

QCD accounts for (most) visible mass in Universe



(*not* the Higgs boson)

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

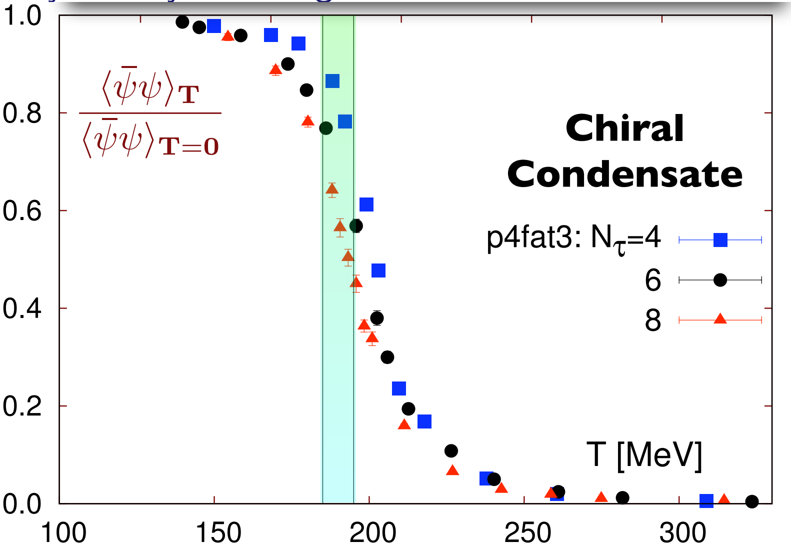
QCD has exact $\mathsf{SU(2)_L} \otimes \mathsf{SU(2)_R}$ chiral symmetry.

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

$$\mathsf{SU(2)_L} \otimes \mathsf{SU(2)_R} \longrightarrow \mathsf{SU(2)_V}$$

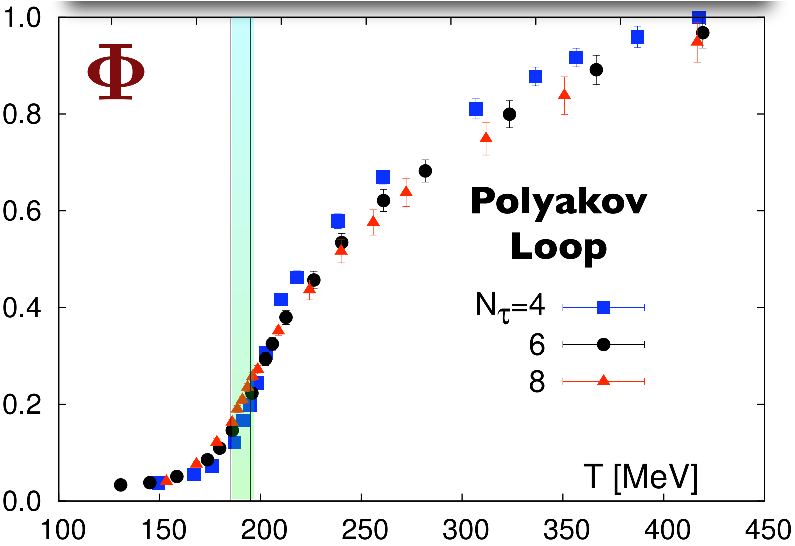
$\rightsquigarrow$ 3 Goldstone bosons, one for each broken generator:
3 massless pions (Nambu)

Chiral Symmetry Breaking on the Lattice



Weise lecture for review and lattice QCD references

Deconfinement on the Lattice



A. Polyakov, *Phys. Lett.* **B72,** 477 (1978)

Fermion condensate . . .

links left-handed, right-handed fermions

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

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

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

$$(\mathsf{SU}(3)_\mathsf{c}, \mathsf{SU}(2)_\mathsf{L})_Y\!: \; (\mathbf{3},\mathbf{2})_{1/3} \qquad (\mathbf{3},\mathbf{1})_{4/3} \qquad (\mathbf{3},\mathbf{1})_{-2/3}$$

transforms as $\mathsf{SU}(2)_\mathsf{L}$ 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.

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

$$(M_W \approx 80\ \text{GeV} \qquad M_Z \approx 91\ \text{GeV})$$

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$$(M_W \approx 80 \text{ GeV} \qquad M_Z \approx 91 \text{ GeV})$$

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

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

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

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

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

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

Weak interaction strength ∼ residual strong interactions

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

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

ρ, ω, a_1 “as usual,” but

$$\begin{aligned} \rho^0 &\to W^+W^- \\ \rho^+ &\to W^+Z \\ \omega &\to W^+W^-Z \end{aligned}$$

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

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,

$$M_n - M_p \;=\; (m_d - m_u) - \tfrac{1}{3}\,(\delta m_q + \delta M_{\mathrm{C}} + \delta M_{\mathrm{M}})$$

. . . but weak contributions enter.

Nucleon masses . . .

"Obvious" that proton should outweigh neutron

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

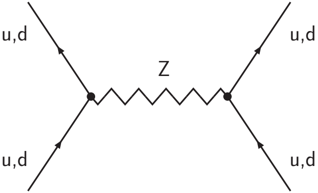
Real-world contributions,

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

. . . but weak contributions enter.

Weak contributions are not negligible

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



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

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

perhaps a few MeV?

Consequences for β decay

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

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

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

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

$$\boxed{\text{No Hydrogen Atom?}}$$

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

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

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

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

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

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

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

violated because no Higgs boson $\rightsquigarrow$ strong scattering

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

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

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

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

$\overline{\text{SM}}$ 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

Massless fermion pathologies . . .

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

. . . persists with GUT-induced tiny masses

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

NGBs ⟶ pNGBs

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

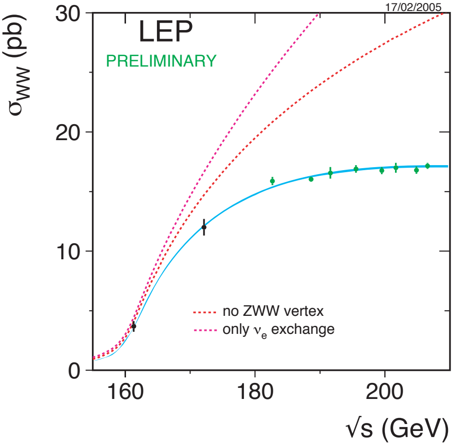
saturate p.w. unitarity at

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

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

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

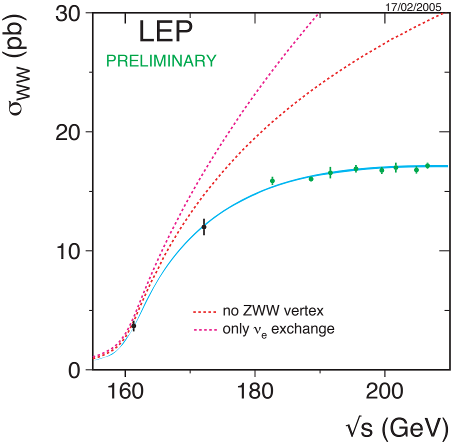
Gauge cancellation need not imply renormalizable theory



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

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

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

(condition from WW scattering)

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

would accommodate real-world e, u, d masses

In summary . . .

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