The Standard Model:

Current Status & Open Questions

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Anticipating the LHC

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.

What is the nature of the mysterious new force that hides electroweak symmetry?

- A *fifth* fundamental force of a new character, based on interactions of an elementary scalar
- A new gauge force, perhaps acting on undiscovered constituents
- A residual force that emerges from strong dynamics among the weak gauge bosons
- An echo of extra spacetime dimensions

We have explored examples of all four, theoretically.

Which path has Nature taken?

Search for the Standard-Model Higgs Boson

$$\Gamma(H \to f\bar{f}) = \frac{G_F m_f^2 M_H}{4\pi\sqrt{2}} \cdot N_c \cdot \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2}$$

$\propto M_H$ in the limit of large Higgs mass; $\propto \beta^3$ for scalar

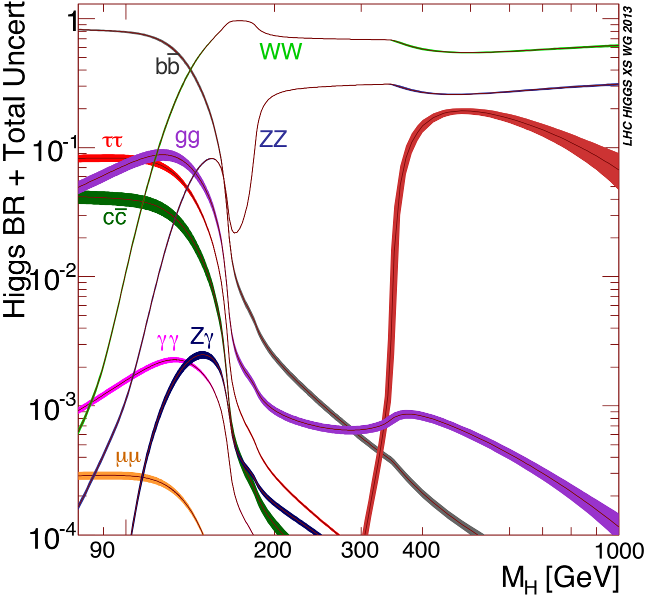
$$\Gamma(H \to W^+W^-) = \frac{G_F M_H^3}{32\pi\sqrt{2}}(1-x)^{1/2}(4-4x+3x^2) \quad x \equiv 4M_W^2/M_H^2$$

$$\Gamma(H \to Z^0Z^0) = \frac{G_F M_H^3}{64\pi\sqrt{2}}(1-x')^{1/2}(4-4x'+3x'^2) \quad x' \equiv 4M_Z^2/M_H^2$$

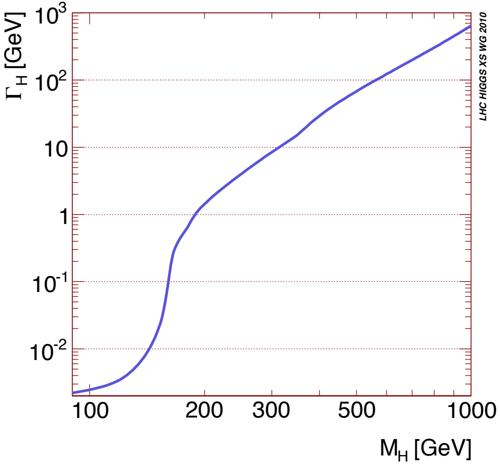
asymptotically $\propto M_H^3$ and $\frac{1}{2}M_H^3$, respectively

$2x^2$ and $2x'^2$ terms $\Leftrightarrow$ decays into transverse gauge bosons
Dominant decays for large M_H: pairs of longitudinal weak bosons

Standard-model Higgs Boson Branching Fractions



Total width of the standard-model Higgs boson



Below W^+W^- threshold, $\Gamma_H \lesssim 1$ GeV

Far above W^+W^- threshold, $\Gamma_H \propto M_H^3$

A few words on Higgs production . . .

$e^+e^- \to H$: hopelessly small
$\mu^+\mu^- \to H$: scaled by $(m_\mu/m_e)^2 \approx 40\,000$
$e^+e^- \to HZ$: prime channel

Hadron colliders:
$gg \to H \to b\bar{b}$: background ?!
$gg \to H \to \tau\tau, \gamma\gamma$: rate ?!

$gg \to H \to W^+W^-$: best Tevatron sensitivity
$\bar{p}p \to H(W, Z)$: prime Tevatron channel for light Higgs

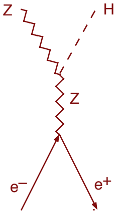
At the LHC:
Many channels accessible, search sensitive up to 1 TeV

Higgs search in e^+e^- collisions

$\sigma(e^+e^- \to H \to \text{all})$ is *minute*, $\propto m_e^2$

Even narrowness of low-mass H is not enough to make it visible . . . Sets aside a traditional strength of e^+e^- machines—*pole physics*

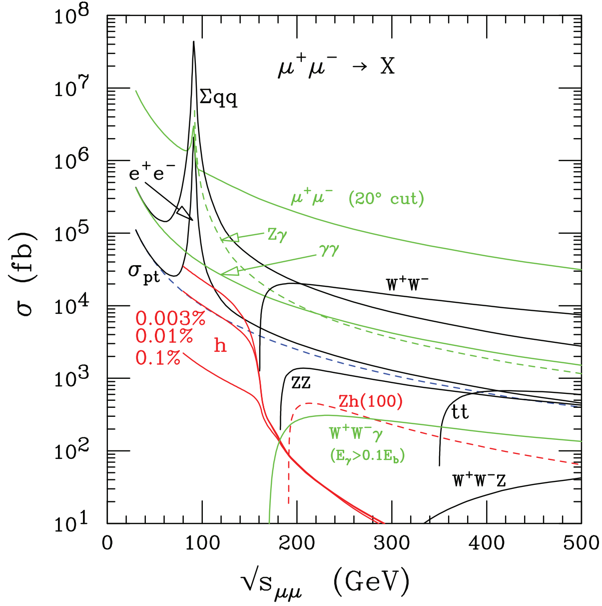
Most promising:
associated production $e^+e^- \to HZ$
(has no small couplings)



$$\boxed{\sigma = \frac{\pi\alpha^2}{24\sqrt{s}} \frac{K(K^2 + 3M_Z^2)[1 + (1 - 4x_W)^2]}{(s - M_Z^2)^2 \quad x_W^2(1 - x_W)^2}}$$

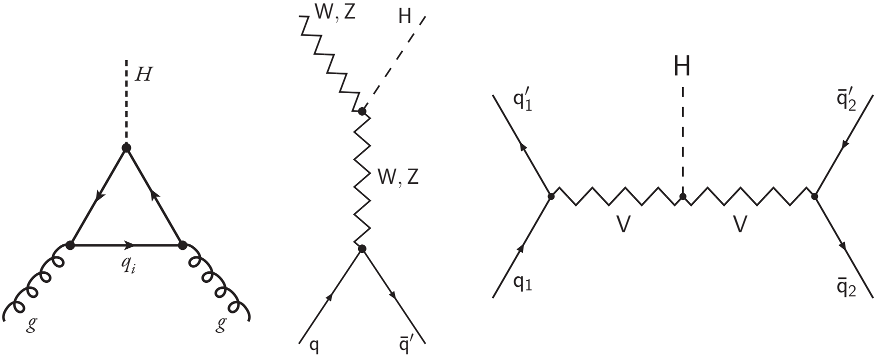
K: c.m. momentum of H $x_W \equiv \sin^2\theta_W$

$\ell^+\ell^- \to X \ldots$



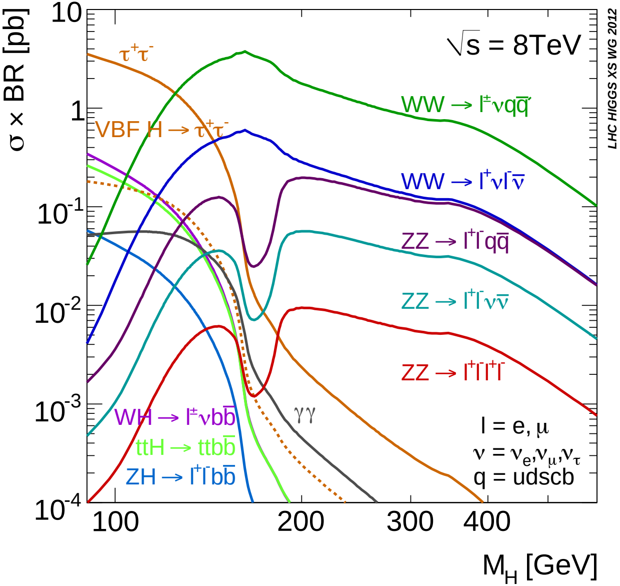
LHC: Multiple looks at the new boson

3 production mechanisms, $\geq$ 5 decay modes

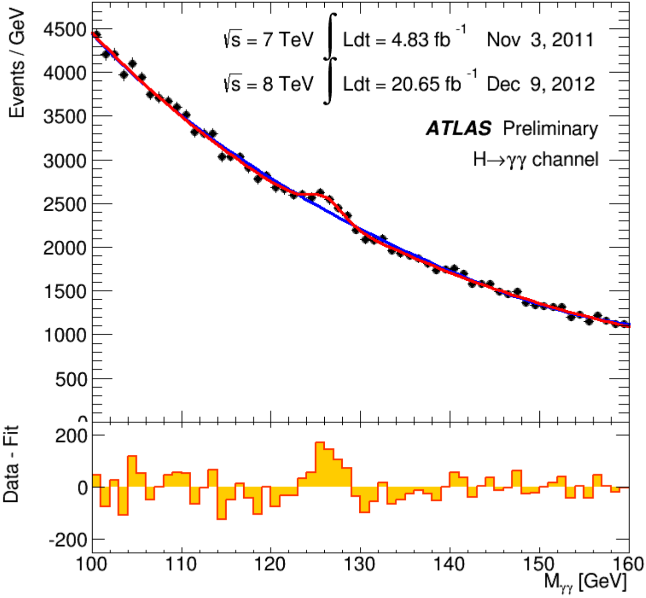


$$\gamma\gamma, WW^*, ZZ^*, b\bar{b}, \tau^+\tau^-, Z\gamma(?)$$

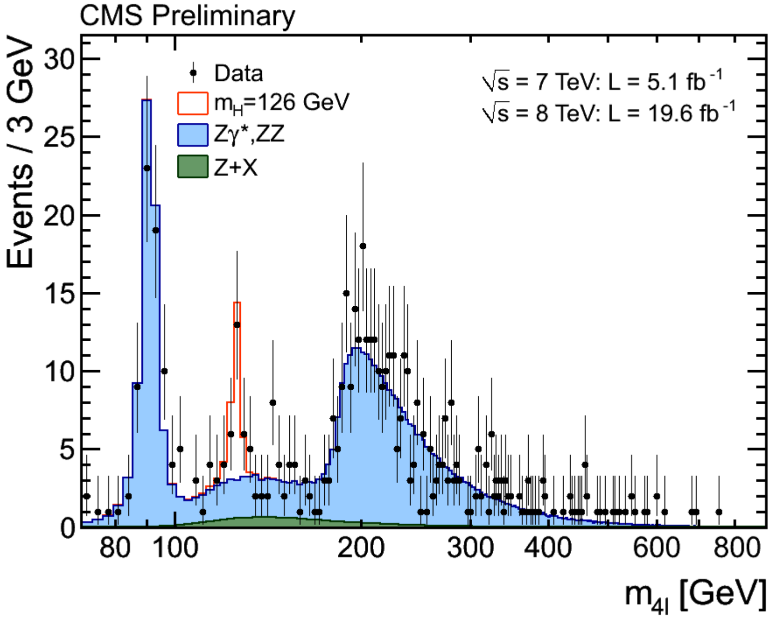
Higgs-boson production and decay: 8 TeV



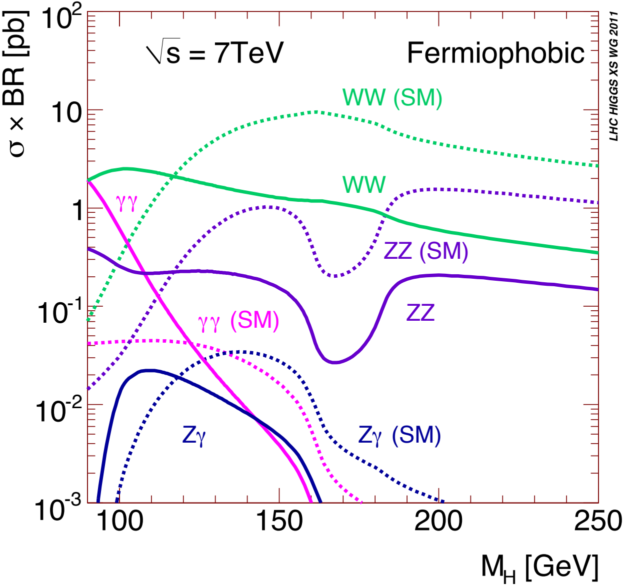
ATLAS $\gamma\gamma$ signal 2013



CMS 4μ signal 2013



Distinguishing SM, bosogamous Higgs bosons



Problem 11

Suppose that a signal for a putative Higgs boson is found in the $\gamma\gamma$, W^+W^-, and ZZ channels with a mass $M_H = 125$ GeV. Refer to the products of production cross section times branching fraction shown in the figure on the preceding page.

(a) What values of $\sigma \times \mathrm{BR}$ are expected for the three rates in the standard electroweak theory?

(b) What values of $\sigma \times \mathrm{BR}$ are expected if the "Higgs boson" does not couple at all to fermions?

(c) How precisely must the rates be determined by experiment to distinguish between the standard and bosogamous alternatives?

Evolution of evidence at the LHC

Evidence is developing as it would for
a "standard-model" Higgs boson

Unstable neutral particle near 125 GeV

ATLAS: $M_H = 125.36 \pm 0.37$ (stat) $\pm\, 0.18$ (syst) GeV

CMS: $M_H = 125.03^{+0.26}_{-0.27}$ (stat) $^{+0.13}_{-0.15}$ (syst) GeV

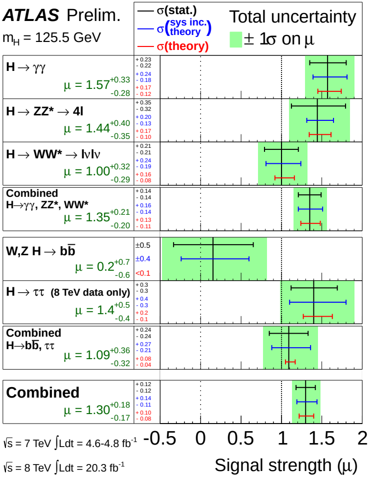
decays to $\gamma\gamma, W^+W^-, ZZ$

likely spin-parity 0^+

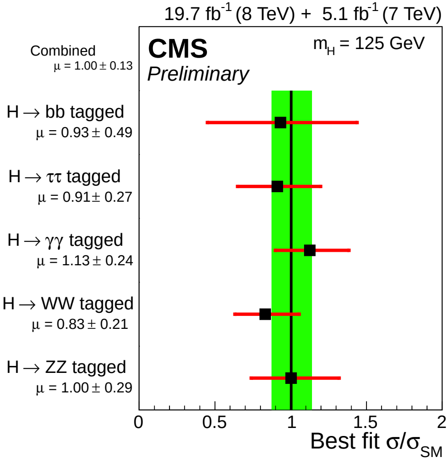
evidence for $\tau^+\tau^-, b\bar{b}$; $t\bar{t}$ from production
only third-generation fermions tested

Links to ATLAS & CMS Results

ATLAS



CMS



Problem 12

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?

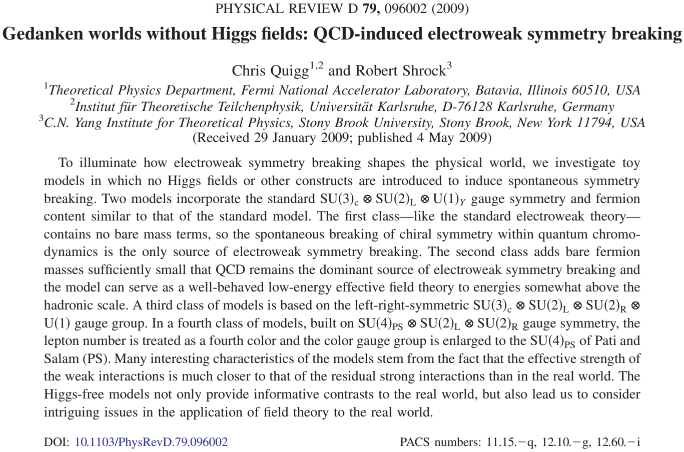
(No EWSB agent at $v \approx 246$ GeV)

Consider effects of all standard-model interactions!

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

What would I tell my mother?

Why Electroweak Symmetry Breaking Matters



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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.

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Without a Higgs mechanism . . .

Electron and quarks would have no mass

QCD would confine quarks into protons, etc.
Nucleon mass little changed

Surprise: QCD would hide EW symmetry,
give tiny masses to W, Z

Massless electron: *atoms lose integrity*

No atoms means no chemistry, no stable composite structures like liquids, solids, . . . no template for life.

Character of the world would be utterly different

Questions for ATLAS and CMS

Fully accounts for EWSB (W, Z couplings)?

Couples to fermions?

  Top from production, need direct observation for b, τ

Accounts for fermion masses?

  Fermion couplings $\propto$ masses?

Are there others?

Quantum numbers?

SM branching fractions to gauge bosons?

Decays to new particles? via new forces?

All production modes as expected?

Implications of $M_H \approx 125$ GeV?

Any sign of new strong dynamics?

Standard-model 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

Parameters of the Standard Model

3 coupling parameters: α_s, α_{EM}, $\sin^2\theta_{\mathsf{W}}$

2 parameters of the Higgs potential

1 vacuum phase of QCD

6 quark masses

3 quark mixing angles

1 CP-violating phase

3 charged-lepton masses

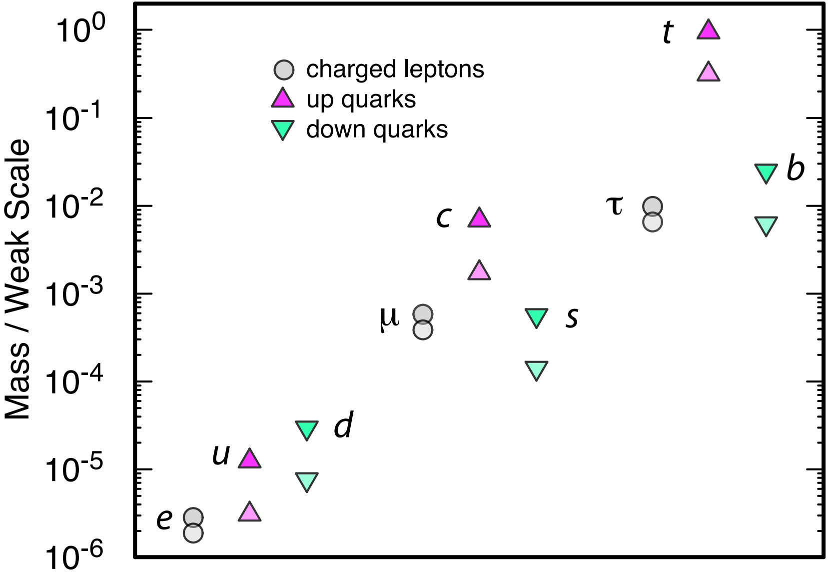
3 neutrino masses

3 leptonic mixing angles

1 leptonic CP-violating phase $(+$ Majorana$)$

≥ 26 arbitrary parameters

Fermion mass is accommodated, not explained



Flavor physics … $\rightsquigarrow$ S. Stone Lectures

may be where we see, or diagnose, the break in the SM

Some opportunities (see Buras, Flavour Theory: 2009)

- CKM matrix from tree-level decays (LHC*b*)
- $\mathcal{B}(B_{s,d} \to \mu^+\mu^-)$
- $D^0 - \bar{D}^0$ mixing; CP violation
- FCNC in top decay: $t \to (c, u)\ell^+\ell^-$, etc.
- Correlate virtual effects with direct detection of new particles to test identification
- Tevatron experiments demonstrate capacity for very precise measurements: e.g., B_s mixing.

All fermion mass is physics beyond the standard model!

The unreasonable effectiveness of the Standard Model

Issues for the Future (Now!)

1. What is the agent that hides electroweak symmetry? Might there be several Higgs bosons?
2. Is the "Higgs boson" elementary or composite? How does the Higgs boson interact with itself? What triggers electroweak symmetry breaking?
3. Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons? *(How) is fermion mass related to the electroweak scale?*
4. Are there new flavor symmetries that give insights into fermion masses and mixings?
5. What stabilizes M_H below 1 TeV?

Issues for the Future (Now!)

6. Does the different behavior of LH and RH fermions with respect to CC weak interactions reflect a fundamental asymmetry in the laws of nature?
7. What will be the next symmetry recognized in Nature? Are there additional heavy gauge bosons? Is Nature supersymmetric? Is the electroweak theory part of some larger edifice?
8. Are all flavor-changing interactions governed by the standard-model Yukawa couplings? If so, why?
9. Are there additional sequential quark & lepton generations? Or new exotic (vector-like) fermions?
10. What resolves the strong CP problem?

Issues for the Future (Now!)

11. What are the dark matters? Any flavor structure?
12. Is EWSB an emergent phenomenon connected with strong dynamics? How would that alter our conception of unified theories of the strong, weak, and electromagnetic interactions?
13. Is EWSB related to gravity through extra spacetime dimensions?
14. What resolves the vacuum energy problem?
15. (When we understand the origin of EWSB), what lessons does EWSB hold for unified theories? . . . for inflation? . . . for dark energy?

Issues for the Future (Now!)

16. What explains the baryon asymmetry of the universe? Are there new (CC) CP-violating phases?
17. Are there new flavor-preserving phases? What would observation, or more stringent limits, on electric-dipole moments imply for BSM theories?
18. (How) are quark-flavor dynamics and lepton-flavor dynamics related (beyond the gauge interactions)?
19. At what scale are the ν masses set? Do they speak to the TeV scale, unification scale, Planck scale, . . . ?

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20. How are we prisoners of conventional thinking?

Thank you & Good luck!