The Big Picture

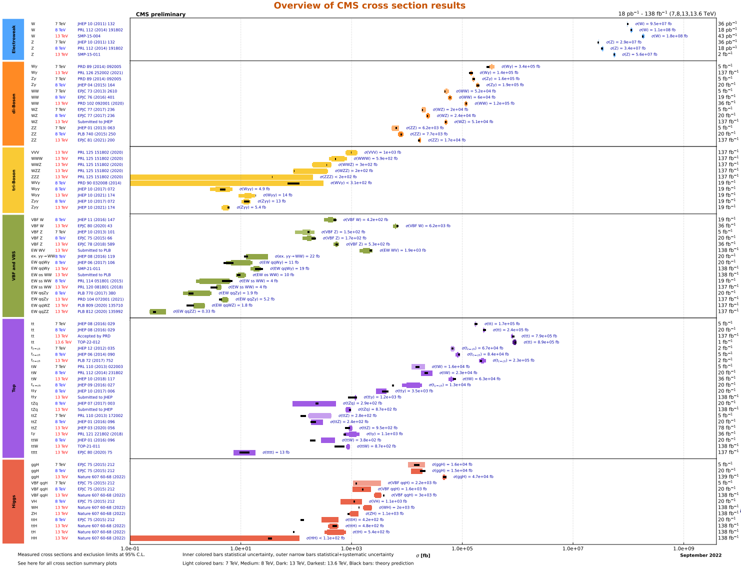
Chris Quigg

Fermilab

USCMS Undergraduate Summer Interns · July 12, 2023


NO STEP

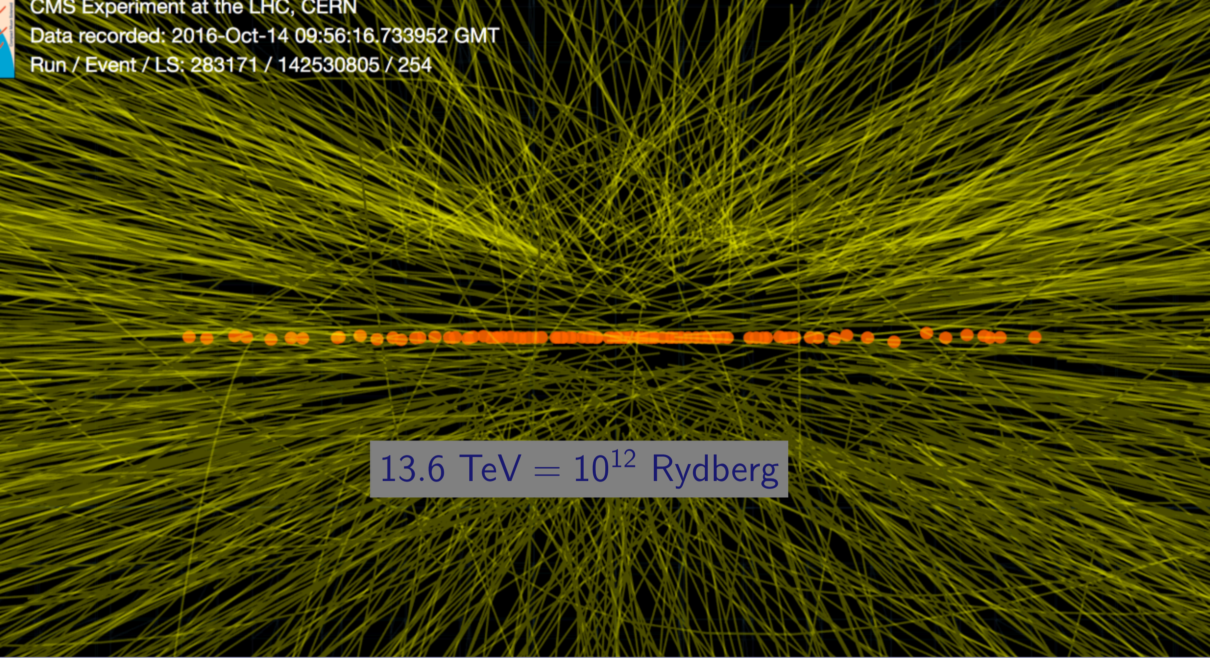
July 4, 2012



$W : 10^{-6}$

$H : 10^{-9}$

13-TeV Inelastic cross section within acceptance ≈ 70 mb $\approx 7 \times 10^{13}$ fb

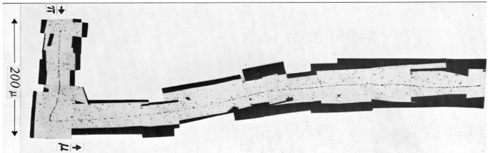


$13.6\ \text{TeV} = 10^{12}\ \text{Rydberg}$

Rutherford's conclusion to his lectures on the nucleus (ca. 1925)

"It's all right, don't worry, we haven't discovered it all; much remains to be done."

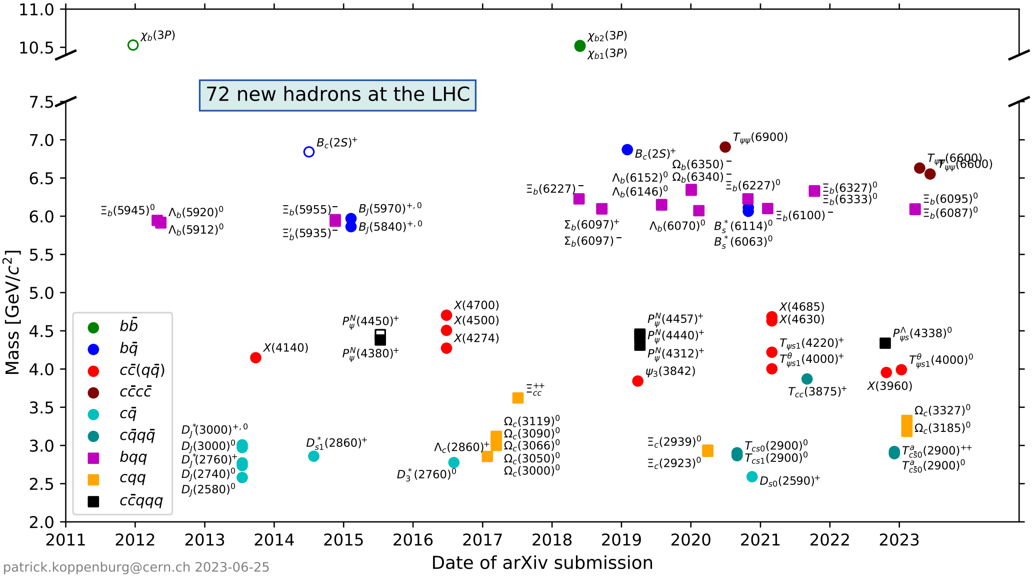
Powell (1950) on Occhialini's emulsions from Pic du Midi



"It was immediately apparent that a whole new world had been revealed . . .
. . . It was as if, suddenly, we had broken into a walled orchard, where protected trees had flourished and all kinds of exotic fruits had ripened in great profusion."

$$\pi^+ \to \mu^+ \nu_\mu$$

Exotic fruits in great profusion (at the LHC)



Another voice from the past

If you know the elementary particles and their interactions, and you call yourself a physicist, you ought to be able to calculate the consequences—or at least you should feel guilty if you can't!

CQ, Les Houches Lectures (1981)

Aspirations:

- Compute the properties of hadrons, explain the absence of unseen species, and *predict the existence of new varieties of hadrons;*
- Explain why quarks and the quanta of the color force, gluons, are not observed;
- Derive the interactions among hadrons as a collective effect of the interactions among constituents.

Don't forget the strong interactions!

Heroic progress in perturbative and lattice methods
including resummation and electroweak quantum corrections

QCD could be complete, up to M_{Planck} (modulo strong CP problem)
...but that doesn't prove it must be

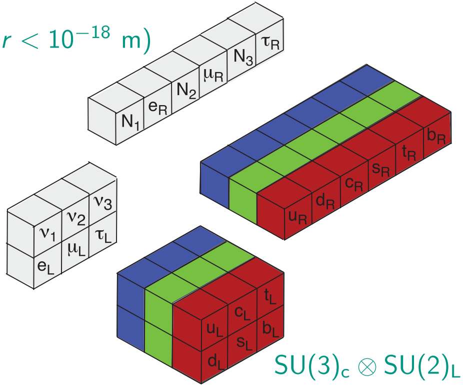
Prepare for surprises, such as
(Breakdown of factorization)
Free quarks / unconfined color
New kinds of colored matter
Quark compositeness
Larger color symmetry containing $SU(3)_c$

Questions pertaining to QCD

1. Why is isospin a good symmetry? What does it mean?
2. Are there new phenomena within QCD? Role for machine learning?
   Multiple production beyond diffraction + short-range order?
   Long-range correlations in y (or η)? Unusual event structures?
3. How will high density of wee partons affect pp collisions?
4. How will the 1-d ∞-momentum frame parton-model break down?
5. How will correlations among partons in a proton manifest themselves?
6. Can we distinguish spatial configurations of partons within protons?
7. What is the importance of intrinsic heavy flavors?
8. Hadron body plans beyond qqq and $q\bar{q}$? $XYZ, qqqQ\bar{Q}, QQ\bar{q}\bar{q}, \ldots$
9. Can we *prove* that QCD confines color?
10. What resolves the strong CP problem? PQ symmetry $\rightsquigarrow$ axions?

Have we found the “periodic table” of elementary particles?

Pointlike spin-1/2 constituents ($r < 10^{-18}$ m)



$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \rightarrow SU(3)_c \otimes U(1)_{em}$

11. What do generations mean? Is there a family symmetry?
12. Why are there three families of quarks and leptons? (Is it so?)
13. Are there new species of quarks and leptons? exotic charges?

Through 1950s and 1960s . . .

Continued interest in a Yang–Mills Theory of nuclear forces.

After $V - A$ description of weak interactions, interest in a gauge theory of weak interactions. Glashow explored $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$

Three challenges: massive weak bosons, massive fermions, observed symmetry is $\mathrm{U(1)_{em}}$.

Mass term $\mathcal{L}_e = -m_e(\bar{e}_\mathrm{R} e_\mathrm{L} + \bar{e}_\mathrm{L} e_\mathrm{R}) = -m_e \bar{e} e$ violates local gauge invariance.

Key insights: hidden symmetries, Meissner effect

Brout, Englert, Higgs, Guralnik, Hagen, Kibble (1964)

Weinberg (1967) combined with $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$

Introduce an $\mathrm{SU(2)_L}$ doublet scalar field to hide the symmetry

- $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y \to \mathrm{U(1)_{em}}$: $\rightsquigarrow$ massless photon, coupled to charge;
- Mediator of charged-current weak interaction acquires a mass $M_W^2 = \pi\alpha/G_F\sqrt{2}\sin^2\theta_W = g^2v^2/4$,
- Mediator of (new!) neutral-current weak interaction acquires mass $M_Z^2 = M_W^2/\cos^2\theta_W$;
- Massive neutral scalar particle, the Higgs boson, appears, but its mass is not predicted;
- Fermions can acquire mass—values not predicted.
  $\rightsquigarrow$ $Hf\bar{f}$ coupling $\propto m_f$

The importance of the electroweak (1-TeV) scale

EW theory does not predict Higgs-boson mass

Thought experiment: conditional upper bound

W^+W^-, ZZ, HH, HZ satisfy s-wave unitarity,

provided $\boxed{M_H \lesssim (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1 \text{ TeV}}$

If bound is respected, perturbation theory is "everywhere" reliable

If not, weak interactions among $W^\pm, Z, H$ become strong on 1-TeV scale

New phenomena (*H or something else*) are to be found around 1 TeV

Before ATLAS and CMS,

what is in the textbooks notwithstanding,

we did not know

what the answer would be!

LHC has changed our view of the world

and opened many new questions

What LHC has taught us about the Higgs Boson*

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

Unstable neutral particle with $M_H = 125.25 \pm 0.17$ GeV [PDG22]

Decays to W^+W^-, ZZ implicate H as agent of EWSB

Decay to $\gamma\gamma$ as expected (loop-level)   Indirect constraint on Γ_H

Dominant spin-parity $J^P = 0^+$

$Ht\bar{t}$ coupling from gg fusion, $t\bar{t}H$ production link to fermion mass origin

$\tau^+\tau^-$ and $b\bar{b}$ at expected rates; $\mu^+\mu^-$ constrained

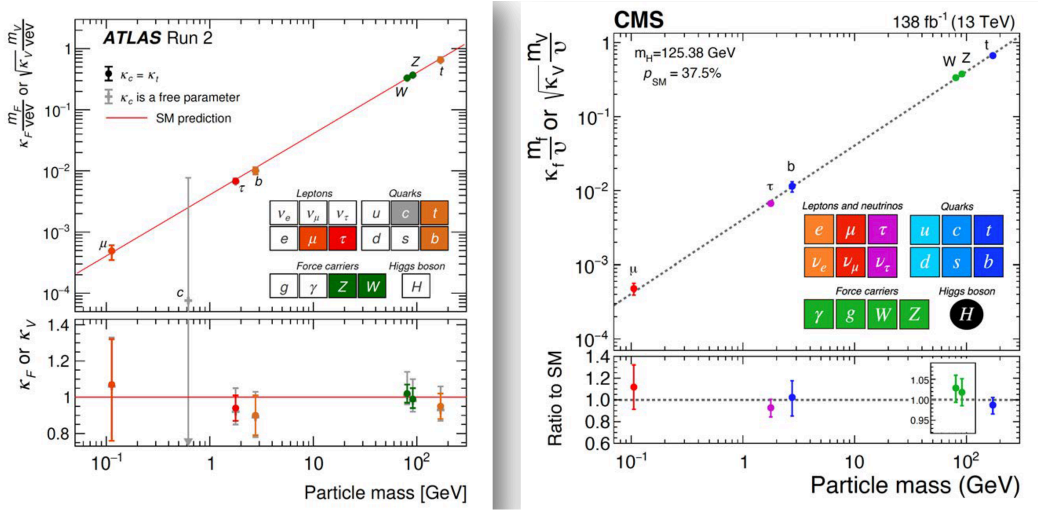
*ATLAS and CMS summaries in July 4, 2022, *Nature*

CQ (2009), "Unanswered Questions in the Electroweak Theory"

CQ (2015), "Electroweak Symmetry Breaking in Historical Perspective,"

CQ (2022), "Unanswered Questions ... (Before & After the Higgs-Boson Discovery)"

Higgs Coupling Strengths



Snowmass 2021–22 Higgs Report, arXiv:2209.07510

Consequences for the everyday world

$1/M_W^4$ controls β-decay rates, energy production in Sun, etc.

No Higgs: QCD breaks EW symmetry to EM, $M_W \approx 28$ MeV

Role of Higgs boson established

Bohr radius $\propto 1/m_e$ controls size of atoms; m_e sets scale of energy levels.

Role of Higgs boson not yet established

up/down quark mass difference determines proton/neutron stability

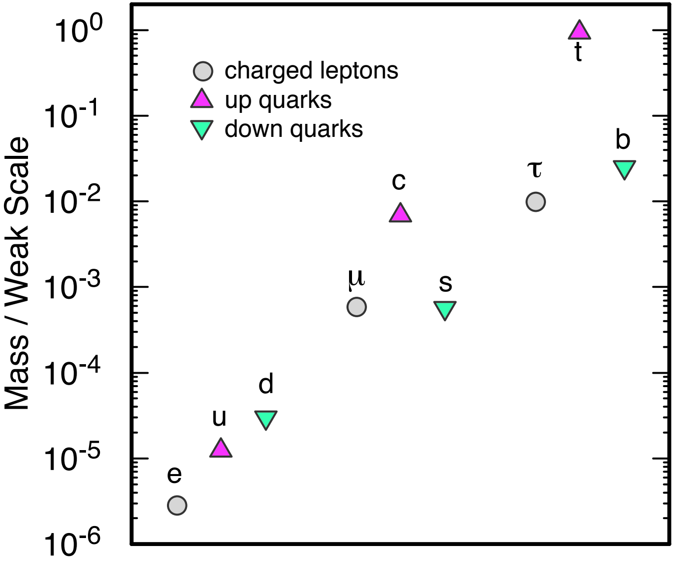
Role of Higgs boson not yet established

Quigg & Shrock, "Gedanken Worlds without Higgs . . . ," Phys. Rev. D **79**, 096002 (2009)
Salam, Wang, & Zanderighi, "The Higgs boson turns ten," Nature 607, 41–47 (2022).

Questions about EWSB and the Higgs Sector

14. Is $H(125)$ the only member of its clan? Might there be others—charged or neutral—at higher or lower masses?
15. Does $H(125)$ fully account for electroweak symmetry breaking? Does it match standard-model branching fractions to gauge bosons? Are absolute couplings to W and Z as expected in the standard model?
16. Are all production rates as expected? Any surprise sources of $H(125)$?
17. What accounts for the immense range of fermion masses?
18. Is the Higgs field the only source of fermion masses?
    Are fermion couplings proportional to fermion masses? $\mu^+\mu^-$ soon?
    How can we detect $H \to c\bar{c}$? e^+e^-?? (basis of chemistry)
19. What role does the Higgs field play in generating neutrino masses?

Fermion masses

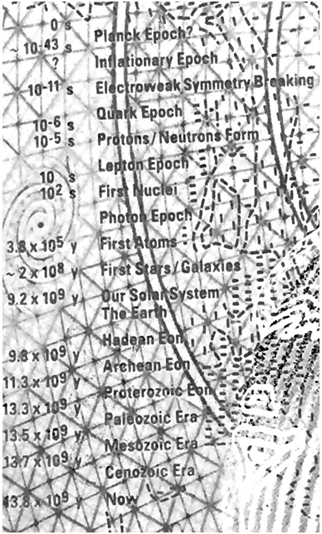


More questions about EWSB and the Higgs Sector

20. Can we establish or exclude decays to new particles?
    Does $H(125)$ act as a portal to hidden (dark/subliminal) sectors?
    How convincingly can we measure Γ_H and compare with theory?
21. Do loop-induced decays ($gg, \gamma\gamma, \gamma Z$) occur at standard-model rates?
22. What can we learn from rare decays ($J/\psi\,\gamma, \Upsilon\,\gamma, \ldots$)?
23. Does the EW vacuum seem stable, or suggest a new physics scale?
24. Can we find signs of new strong dynamics or (partial) compositeness?
25. Can we establish the HHH trilinear self-coupling?
26. How well can we test the notion that H regulates Higgs–Goldstone scattering, i.e., tames the high-energy behavior of WW scattering?
27. Is the electroweak phase transition first-order?

See Dawson, Englert, Plehn, arXiv:1808.01324 $\rightsquigarrow$ *Phys. Rep.*

CHF200 Note (2018) many scales (G. Dissertori, CMS/ETH)



$$t_{\mathrm{Pl}} \equiv \sqrt{\hbar G / c^5}$$

Lifetimes

$^{136}\mathrm{Xe}_{\beta\beta\nu\nu}: 3.2 \times 10^{21}$ yr

$^{124}\mathrm{Xe}_{\mathrm{ECEC}\nu\nu}: 2.6 \times 10^{22}$ yr

$p: > 10^{(29-33)}$ yr

Where is the next important scale?

(Higher energies needed to measure HHH, verify that H regulates $W_L W_L$)

Planck scale $\sim 1.2 \times 10^{19}$ GeV [$(3+1)$-d spacetime]; $\sim 1.6 \times 10^{-35}$ m

Unification scale $\sim 10^{15-16}$ GeV

28. At what scale are charged-fermion masses set (Yukawa couplings)?
29. At what scale are neutrino masses set?
30. Will new physics appear at $1\times, 10\times, 100\times, \ldots$ EW scale?
31. Might new phenomena appear at macroscopic scales?

More new physics on the TeV scale and beyond?

Before LHC, much informed speculation—but no guarantees—about what might be found, beyond keys to EWSB.

Many eyes were on supersymmetry or Technicolor to enforce

$M_W \lll$ unification scale or Planck scale.

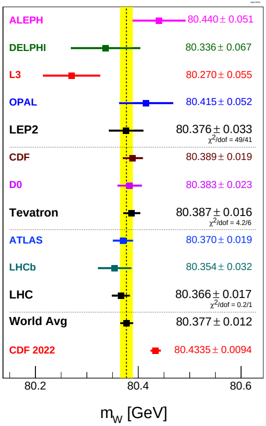
"WIMP miracle" pointed to the TeV scale for a dark matter candidate.

Some imagined that neutrino mass might be set on the TeV scale.

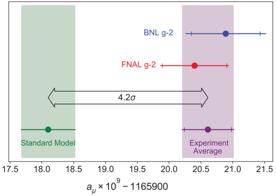
No direct sign of physics beyond the standard model has come to light.

Might first hints may come from precision measurements?

Precision measurements . . .

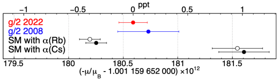


$(g-2)_\mu$



e magnetic dipole moment measured to 0.13 ppt

$-\mu_e/\mu_B =$ 1.00115965218059(13)



Gabrielse: Harvard–NU

fine structure constant

Berkeley: $\alpha^{-1}(\mathrm{Cs}) =$ 137.035 999 046(27)

Paris: $\alpha^{-1}(\mathrm{Rb}) =$ 137.035 999 206(11)

(differ by 5.4 s.d.)

Tabletop precision experiments

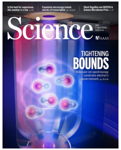
Electric dipole moment d_e: CP/T violation

$$|d_e| < 1.1 \times 10^{-29}\ e\ \text{cm, 90\% CL}$$

ACME Collaboration, ThO (2018)

$$|d_e| < 4.1 \times 10^{-30}\ e\ \text{cm, 90\% CL}$$

JILA–NIST–Colorado, trapped HfF^+ (2022)



(SM phases: $d_e < 10^{-38}\ e$ cm)

$|d_n| < 0.18 \times 10^{-25}\ e$ cm, 90% CL PSI Ultracold n Source (2020)

“Tabletop” precision experiments

(Anti)proton magnetic moments: CPT test

$$\mu_{\bar{p}} = -2.792\,847\,344\,1(42)\ \mu_N$$

vs.

$$\mu_p = +2.792\,847\,344\,62(82)\ \mu_N$$

BASE Collaboration @CERN Antiproton Decelerator

Questions about new physics on the TeV scale and beyond

32. Are there new forces of a novel kind?
33. Can we find evidence of a dark matter candidate?
34. Why is empty space so nearly massless? What resolves the vacuum energy problem? 1 USCMS intern contains 10^{-3} solar mass
35. Will "missing energy" events signal the existence of spacetime dimensions beyond the familiar $3 + 1$?
36. Can we probe dark energy in laboratory experiments?
37. Can we find clues to the origin of electroweak symmetry breaking? Is there a dynamical origin to the "Higgs potential?"
38. What separates the electroweak scale from higher scales?
39. Are new phenomena to be found on extended time scales?

Flavor: the problem of identity

40 What makes an electron an electron, a top quark a top quark, . . . ?

We do not have a clear view of how to approach the diverse character of the constituents of matter

Many parameters: no clue what determines them, nor at what energy scale they are set

Even if Higgs mechanism explains *how* masses and mixing angles arise, we do not know *why* they have the values we observe

Physics beyond the standard model!

Flavor: the problem of identity (continued)

Parameters of the Standard Model

3	Coupling parameters, α_s, α_{em}, $\sin^2\theta_W$
2	Parameters of the Higgs potential
1	Vacuum phase (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 phases?)
26^+	Arbitrary parameters

Will we see or diagnose a break in the SM?

Questions concerning the problem of identity

41. Can we find evidence of right-handed charged-current interactions?
    Is nature built on a fundamentally asymmetrical plan, or are the right-handed weak interactions simply too feeble for us to have observed until now, reflecting an underlying hidden symmetry?
42. What is the relationship of left-handed and right-handed fermions?
43. Are there additional electroweak gauge bosons, beyond $W^{\pm}$ and Z?
44. Are there additional kinds of matter?
45. Is charged-current universality exact?
46. What about lepton-flavor universality?
47. Can we find evidence for charged-lepton flavor violation?

More questions concerning the problem of identity

48. Is there any link to a dark sector?
49. What will resolve the disparate values of $|V_{ub}|$ and $|V_{cb}|$ measured in inclusive and exclusive decays?
50. Is the 3×3 (CKM) quark-mixing matrix unitary?
51. Will we establish and diagnose a break in the SM?
52. Do flavor parameters *mean* anything at all?
    Contrast the landscape perspective.
53. If flavor parameters have meaning (beyond engineering information), what is the meta-question?

Three final questions (for now)!

What deep questions have been with us for so long that they are less prominent in “top-ten” lists than they deserve to be?

What do we know that is not true?

How are we prisoners of conventional thinking?

How can we break out?

Rutherford's conclusion to his lectures on the nucleus (ca. 1925)

"It's all right, don't worry, we haven't discovered it all; much remains to be done."

We haven't even thought of it all!