A Journey in Distant Countries
To the Electroweak Scale and Beyond

Chris Quigg
Fermilab
quigg@fnal.gov

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In conclusion it appears to me that nothing can be more improving to a young naturalist than a journey in distant countries. It both sharpens and partly allays that want and craving, which . . . a man experiences although every corporeal sense be fully satisfied. The excitement from the novelty of objects, and the chance of success, stimulate him to increased activity. Moreover, as a number of isolated facts soon become uninteresting, the habit of comparison leads to generalisation. On the other hand, as the traveller stays but a short time in each place, his descriptions must generally consist of mere sketches, instead of detailed observations. Hence arises, as I have found to my cost, a constant tendency to fill up the wide gaps of knowledge by inaccurate and superficial hypotheses.

—Charles Darwin

A Decade of Discovery Past ...

- EW theory $\rightarrow$ law of nature [Z, e^+e^-, $\bar{p}p$, νN, $(g-2)_\mu, \ldots$]
- Higgs-boson influence in the vacuum [EW experiments]
- ν oscillations: $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\mu/\nu_\tau$ [$\nu_\odot$, ν_{atm}, reactors]
- Understanding QCD [heavy flavor, Z^0, $\bar{p}p$, νN, ep, ions, lattice]
- Discovery of top quark [$\bar{p}p$]
- Direct $\mathcal{CP}$ violation in $K \rightarrow \pi\pi$ [fixed-target]
- B-meson decays violate $\mathcal{CP}$ [$e^+e^- \rightarrow B\bar{B}$]
- Flat universe: dark matter, energy [SN Ia, CMB, LSS]
- Detection of ν_τ interactions [fixed-target]
- Quarks, leptons structureless at 1 TeV scale [mostly colliders]

Tevatron Collider is breaking new ground in sensitivity

LHC will break new ground in energy and luminosity

The importance of the 1-TeV scale

EW theory does not predict Higgs-boson mass

▷ Conditional *upper bound* from Unitarity

Compute amplitudes $\mathcal{M}$ for gauge boson scattering at high energies, make a partial-wave decomposition

$$\mathcal{M}(s,t) = 16\pi \sum_J (2J+1) a_J(s) P_J(\cos\theta)$$

Most channels decouple – pw amplitudes are small at all energies (except very near the particle poles, or at exponentially large energies) – $\forall M_H$.

Four interesting channels:

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

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

In HE limit, s-wave amplitudes $\propto G_F M_H^2$

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

Require that largest eigenvalue respect pw unitarity condition $|a_0| \leq 1$

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

condition for perturbative unitarity

- 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

  $\Rightarrow$ features of *strong* interactions at GeV energies will characterize *electroweak* gauge boson interactions at TeV energies

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

Threshold behavior of the pw amplitudes a_{IJ} follows from chiral symmetry

$$
\begin{aligned}
a_{00} &\approx \quad G_F s/8\pi\sqrt{2} && \text{attractive} \\
a_{11} &\approx \quad G_F s/48\pi\sqrt{2} && \text{attractive} \\
a_{20} &\approx -G_F s/16\pi\sqrt{2} && \text{repulsive}
\end{aligned}
$$

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

The Origins of Mass

(masses of nuclei "understood")

$p, [\pi], \rho$ understood: QCD

confinement energy is the source

"Mass without mass" Wilczek, *Phys. Today* (November 1999)

We understand the visible mass of the Universe

... without the Higgs mechanism

W, Z electroweak symmetry breaking

$$M_W^2 = \tfrac{1}{2}g^2v^2 = \pi\alpha/G_F\sqrt{2}\sin^2\theta_W$$
$$M_Z^2 = M_W^2/\cos^2\theta_W$$

$q, \ell^{\mp}$ EWSB + Yukawa couplings

ν_ℓ EWSB + Yukawa couplings; new physics?

All fermion masses ⇔ physics beyond standard model

H ?? fifth force ??

Challenge:

Understanding the Everyday

- Why are there atoms?
- Why chemistry?
- Why stable structures?
- What makes life possible?

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

Searching for the mechanism of electroweak symmetry breaking, we seek to understand

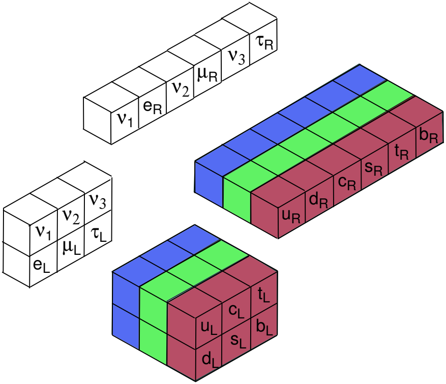
why the world is the way it is.

This is one of the deepest questions humans have ever pursued, and

it is coming within the reach of particle physics.

Our picture of matter (the revolution just past)

Pointlike constituents ($r < 10^{-18}$ m)



Forces derived from $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries

Electroweak symmetry breaking: Higgs mechanism?

Symmetry of laws $\not\Rightarrow$ symmetry of outcomes

The agent of electroweak symmetry breaking represents a novel fundamental interaction at an energy of a few hundred GeV.

We do not know the nature of the new force.

Inspired by the Meissner effect, we describe the EWSB interaction as an analogue of the Ginzburg–Landau picture of superconductivity.

light Higgs boson $\Leftrightarrow$ perturbative dynamics
heavy Higgs boson $\Leftrightarrow$ strong dynamics

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

- A 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

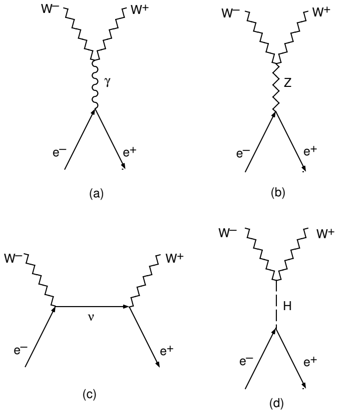
We have explored examples of all four, theoretically.

Which path has Nature taken?

Why a Higgs boson must exist

▷ Role in canceling high-energy divergences

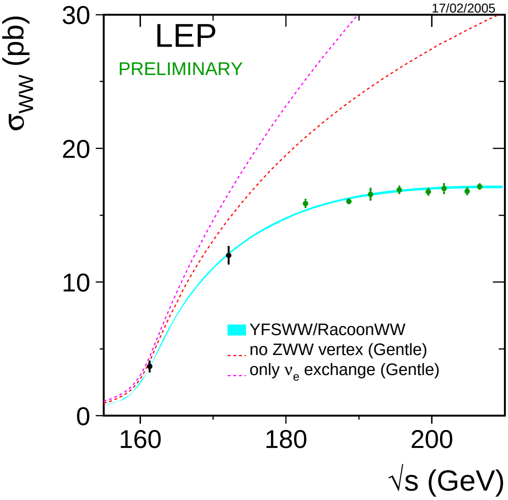
S-matrix analysis of $e^+e^- \to W^+W^-$



$J = 1$ partial-wave amplitudes $\mathcal{M}_{\gamma}^{(1)}$, $\mathcal{M}_{Z}^{(1)}$, $\mathcal{M}_{\nu}^{(1)}$ have –individually– unacceptable high-energy behavior $(\propto s)$

. . . But sum is well-behaved

"Gauge cancellation" observed at LEP2, Tevatron



$J = 0$ amplitude exists because electrons have mass, and can be found in "wrong" helicity state

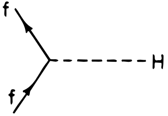
$$\mathcal{M}_\nu^{(0)} \propto s^{\frac{1}{2}} \quad \text{: unacceptable HE behavior}$$

(no contributions from γ and Z)

This divergence is canceled by the Higgs-boson contribution

$\Rightarrow He\bar{e}$ coupling must be $\propto m_e$,

because "wrong-helicity" amplitudes $\propto m_e$



$$\frac{-im_f}{v} = -im_f(G_F\sqrt{2})^{1/2}$$

If the Higgs boson did not exist, something else would have to cure divergent behavior

If gauge symmetry were unbroken . . .

- no Higgs boson
- no longitudinal gauge bosons
- no extreme divergences
- no wrong-helicity amplitudes

. . . and no viable low-energy phenomenology

In spontaneously broken theory . . .

- gauge structure of couplings eliminates the most severe divergences
- lesser—but potentially fatal—divergence arises because the electron has mass . . . due to the Higgs mechanism
- SSB provides its own cure—the Higgs boson

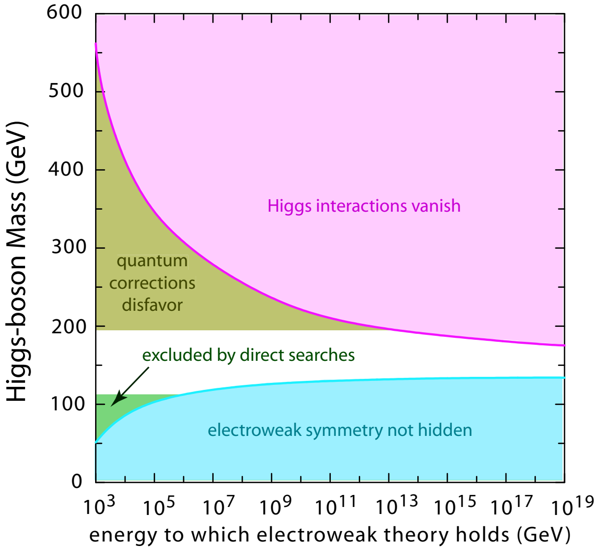
A similar interplay and compensation *must exist* in any acceptable theory

Essential step toward understanding the new force that shapes our world:

Find the Higgs boson and explore its properties.

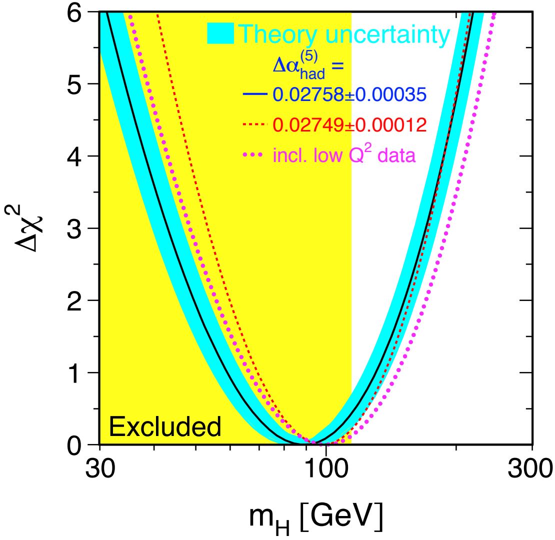
- Is it there? How many?
- Verify $J^{PC} = 0^{++}$
- Does H generate mass for gauge bosons, fermions?
- How does H interact with itself?

Finding the Higgs boson starts a new adventure!



If EW theory is to make sense all the way up to a unification scale $\Lambda^\star = 10^{16}$ GeV, then $134\ \text{GeV}/c^2 \lesssim M_H \lesssim 177\ \text{GeV}$

Fit to a universe of data (within the standard model)



Standard-Model $M_H \lesssim 207$ GeV at 95% CL

- Tevatron, LHC measurements will determine m_t within 1 or 2 GeV
  ... and improve δM_W to about 15 MeV
- As the Tevatron's integrated luminosity approaches 10 fb^{-1}, CDF and DØ will explore the region of M_H not excluded by LEP
- ATLAS and CMS will carry on the exploration of the Higgs sector at the LHC;
  could require a few years, at low mass;
  full range accessible, $\gamma\gamma, \ell\ell\nu\nu, b\bar{b}, \ell^+\ell^-\ell^+\ell^-, \ell\nu jj, \tau\tau$ channels.

EWSB: another path?

Modeled EWSB on Ginzburg–Landau description of SC phase transition; had to introduce new, elementary scalars

GL is not the last word on superconductivity: *dynamical* Bardeen–Cooper–Schrieffer theory

The elementary fermions – electrons – and gauge interactions – QED – needed to generate the scalar bound states are already present in the case of superconductivity. Could a scheme of similar economy account for EWSB?

$$\boxed{SU(3)_c \otimes SU(2)_L \otimes U(1)_Y + \text{massless } u \text{ and } d}$$

Treat $SU(2)_L \otimes U(1)_Y$ as perturbation

$m_u = m_d = 0$: QCD has exact $SU(2)_L \otimes SU(2)_R$ chiral symmetry. At an energy scale $\sim \Lambda_{\text{QCD}}$, strong interactions become strong, fermion condensates appear, and $SU(2)_L \otimes SU(2)_R \to SU(2)_V$

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

Broken generators: 3 axial currents; couplings to π measured by pion decay constant f_π.

Turn on $SU(2)_L \otimes U(1)_Y$: EW gauge bosons couple to axial currents, acquire masses of order $\sim g f_\pi$.

$$\mathcal{M}^2 = \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g'^2 \end{pmatrix} \frac{f_\pi^2}{4} \quad (W^+, W^-, W_3, \mathcal{A})$$

same structure as standard EW theory.

Diagonalize: $M_W^2 = g^2 f_\pi^2/4$, $M_Z^2 = (g^2 + g'^2) f_\pi^2/4$, $M_A^2 = 0$, so

$$\frac{M_Z^2}{M_W^2} = \frac{(g^2 + g'^2)}{g^2} = \frac{1}{\cos^2\theta_W}$$

Massless pions disappear from physical spectrum, to become longitudinal components of weak bosons. $M_W \approx 30\ \mathrm{MeV}/c^2$ No fermion masses . . .

Challenge:

Understanding the Everyday (bis)

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

Consider the effects of all the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ *interactions!*

With no Higgs mechanism . . .

- Quarks and leptons would remain massless
- QCD confines quarks in color-singlet hadrons
- *N mass little changed,* but p outweighs n
- QCD breaks EW symmetry, gives ($1/2500\times$observed) masses to W, Z, so weak-isospin force doesn't confine
- Rapid! β-decay $\Rightarrow$ lightest nucleus is n; no H atom
- Some light elements in BBN (?), but ∞ Bohr radius
- No atoms (as we know them) means no chemistry, no stable composite structures like the solids and liquids

. . . the character of the physical world would be profoundly changed

Parameters of the Standard Model

3	coupling parameters $\alpha_s, \alpha_{\mathrm{EM}}, \sin^2\theta_W$
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 . . .)
26^+	arbitrary parameters

parameter count not improved by unification

The EW scale and beyond

EWSB scale, $v = (G_F\sqrt{2})^{-\frac{1}{2}} \approx 246$ GeV, sets

$$M_W^2 = g^2 v^2/2 \qquad M_Z^2 = M_W^2/\cos^2\theta_W$$

But it is not the only scale of physical interest

anticipated: $M_{\text{Planck}} = 1.22 \times 10^{19}$ GeV

probable: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ unification scale $\sim 10^{15-16}$ GeV

somewhere: flavor scale

How to keep the distant scales from mixing in the face of quantum corrections?

OR

How to stabilize the mass of the Higgs boson on the electroweak scale?

OR

Why is the electroweak scale small?

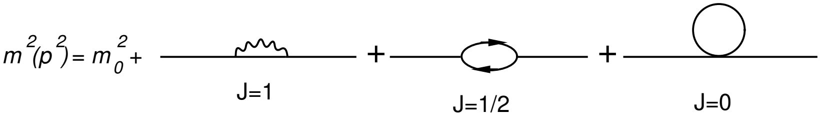
"The hierarchy problem"

Higgs potential $V(\phi^\dagger\phi) = \mu^2(\phi^\dagger\phi) + |\lambda|\,(\phi^\dagger\phi)^2$

$\mu^2 < 0$: $SU(2)_L \otimes U(1)_Y \to U(1)_{\text{em}}$, as

$$\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ \sqrt{-\mu^2/2|\lambda|} \end{pmatrix} \equiv \begin{pmatrix} 0 \\ \underbrace{(G_F\sqrt{8})^{-1/2}}_{175\ \text{GeV}} \end{pmatrix}$$

Beyond classical approximation, quantum corrections to scalar mass parameters:



Loop integrals are potentially divergent

$$m^2(p^2) = m^2(\Lambda^2) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2 + \cdots$$

Λ: reference scale at which m^2 is known
g: coupling constant of the theory
C: coefficient calculable in specific theory

For mass shifts induced by radiative corrections to remain under control (not greatly exceed the value measured on the laboratory scale), *either*

- Λ must be small, *or*
- New Physics must intervene to cut off integral

But natural reference scale for Λ is

$$\Lambda \sim M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}}\right)^{1/2} \approx 1.22 \times 10^{19}\ \text{GeV}$$

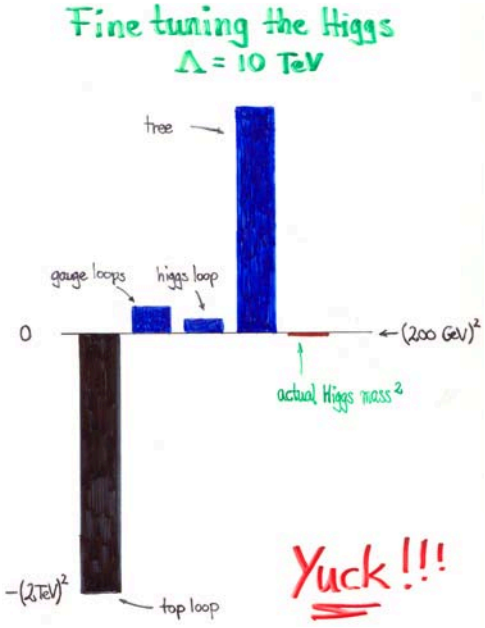
for $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

or

$$\Lambda \sim M_U \approx 10^{15}\text{-}10^{16}\ \text{GeV} \quad \text{for unified theory}$$

Both $\gg v/\sqrt{2} \approx 175$ GeV $\Longrightarrow$

New Physics at $E \lesssim 1$ TeV



Martin Schmaltz, ICHEP02

Only a few distinct scenarios . . .

- Supersymmetry: balance contributions of fermion loops (-1) and boson loops $(+1)$
  Exact supersymmetry,

$$\sum_{i=\substack{\text{fermions}\\+\text{bosons}}} C_i \int dk^2 = 0$$

  Broken supersymmetry, shifts acceptably small if superpartner mass splittings are not too large

$$g^2 \Delta M^2 \text{ “small enough”} \Rightarrow \widetilde{M} \lesssim 1 \text{ TeV}/c^2$$

Only a few distinct scenarios . . .

- Composite scalars (technicolor): New physics arises on scale of composite Higgs-boson binding,

$$\Lambda_{\mathrm{TC}} \simeq O(1\ \mathrm{TeV})$$

"Form factor" cuts effective range of integration

- Strongly interacting gauge sector: WW resonances, multiple W production, probably scalar bound state "quasiHiggs" with $M < 1$ TeV
- Extra spacetime dimensions: pseudo-Nambu – Goldstone bosons, extra particles cancel integrand . . .
- Planck mass is a mirage, based on a false extrapolation of Newton's $1/r^2$ force law

Challenge:

The Problem of Identity

- What sets masses & mixings of quarks & leptons?
  What makes an e an e, a top a top . . . ?
- What is CP violation trying to tell us?
- Neutrino oscillations offer another take, might hold a key to matter excess in the Universe.

All fermion masses and mixings mean new physics

- Will new kinds of matter help us see the pattern?
  sterile neutrinos, dark matter, superpartners, . . .

Challenge:

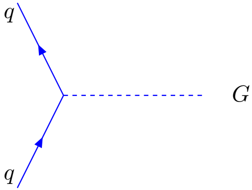
The Unity of Quarks & Leptons

- What do quarks and leptons have in common?
- Why are atoms so remarkably neutral?
- Which quarks pair with which leptons?
- Quark–lepton extended families $\rightsquigarrow$ proton decay:
  SUSY estimates of proton lifetime $\sim 5 \times 10^{34}$ y
- Unified theories $\rightsquigarrow$ coupling constant unification
- Rational fermion mass pattern at high scales?

Gravity rejoins Particle Physics rejoins

Natural to neglect gravity in particle physics

$$G_{\text{Newton}} \textit{ small} \iff M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}}\right)^{\frac{1}{2}} \approx 1.22 \times 10^{19}\ \text{GeV}\ \textit{large}$$



$$\sim \frac{E}{M_{\text{Planck}}}$$

$$\text{Estimate } B(K \to \pi G) \sim \left(\frac{M_K}{M_{\text{Planck}}}\right)^2 \sim 10^{-38}$$

300 years after Newton: Why is gravity weak?

But gravity is not always negligible . . .

The vacuum energy problem

$$\text{Higgs potential } V(\varphi^\dagger\varphi) = \mu^2(\varphi^\dagger\varphi) + |\lambda|\,(\varphi^\dagger\varphi)^2$$

At the minimum,

$$V(\langle\varphi^\dagger\varphi\rangle_0) = \frac{\mu^2 v^2}{4} = -\frac{|\lambda|\,v^4}{4} < 0.$$

$$\text{Identify } M_H^2 = -2\mu^2$$

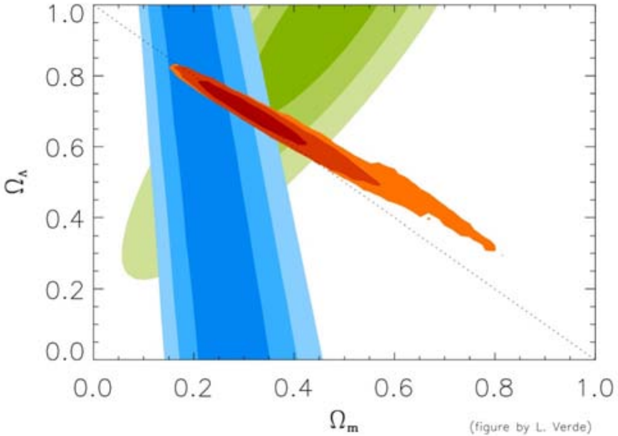
$V \neq 0$ contributes field-independent vacuum energy density

$$\boxed{\varrho_H \equiv \frac{M_H^2 v^2}{8}}$$

Adding vacuum energy density $\varrho_{\text{vac}} \Leftrightarrow$ adding cosmological constant Λ to Einstein's equation

$$R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} = \frac{8\pi G_N}{c^4}T_{\mu\nu} + \Lambda g_{\mu\nu} \qquad \Lambda = \frac{8\pi G_N}{c^4}\varrho_{\text{vac}}$$

Observed vacuum energy density $\varrho_{\text{vac}} \lesssim 10^{-46}$ GeV^4



But $M_H \gtrsim 114$ GeV$/c^2 \Rightarrow \varrho_H \gtrsim 10^8$ GeV^4

Mismatch by 54 orders of magnitude

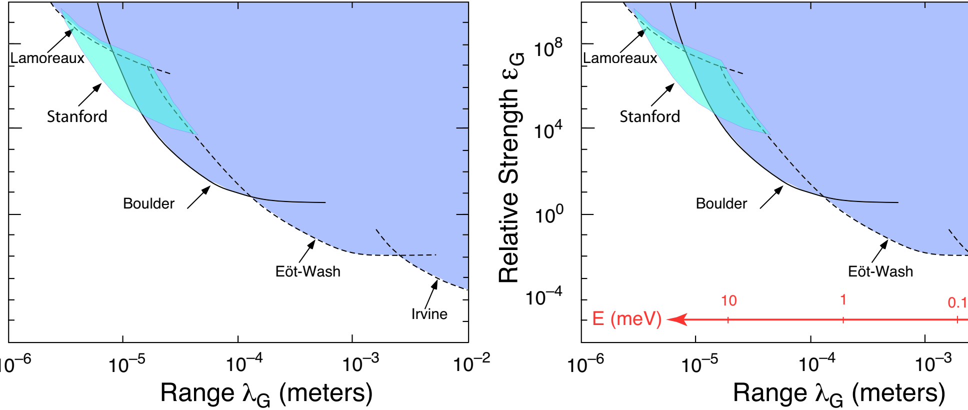
The cosmic connection

- Observational cosmology is like paleontology: reading the fossil record.

  Only a few layers are preserved, can we find more?
- Our reading of the fossil record is influenced by our world-view / theoretical framework.
- Cosmology shows us the world we must explain, provides questions and constraints; many answers will come from particle physics.

Gravity follows $1/r^2$ law down to $\lesssim 1$ mm (few meV)

$$V(r) = -\int dr_1 \int dr_2 \frac{G_N \rho(r_1)\rho(r_2)}{r_{12}} [1 + \varepsilon_G \exp(-r_{12}/\lambda_G)]$$



Experiment leaves us free to consider modifications to Gravity even at (nearly) macroscopic distances

Challenge:

A New Conception of Spacetime

- Could there be more space dimensions than we have perceived?
- What is their size?
- What is their shape?
- How can we map them?
- How do they influence the world?

strength of gravity . . .

hierarchy problem . . .

fermion masses . . .

Need to Prepare Many Revolutions!

- Experiments at the energy frontier
- Experiments at high sensitivity
- Fundamental physics with “found beams”
- Astrophysical observations
- The importance of scale diversity for a healthy and productive future

The most ambitious accelerators are major drivers of our science

Refine e, p technologies · Exotic technologies · Exotic particles

A Decade of Discovery Ahead . . .

- Higgs search and study; EWSB / TeV scale [$p^{\pm}p$ colliders; $e^{+}e^{-}$ LC]
- CP violation (B); Rare decays (K, D, . . .) [$e^{+}e^{-}$, $p^{\pm}p$, fixed-target]
- Neutrino oscillations [$\nu_{\odot}$, ν_{atm}, reactors, ν beams]
- Top as a tool [$p^{\pm}p$ colliders; $e^{+}e^{-}$ LC]
- New phases of matter; hadronic physics [heavy ions, ep, fixed-target]
- Exploration! [colliders, precision measurements, tabletop, . . .]
  Extra dim$^{\mathrm{ns}}$ / new dynamics / SUSY / new forces & constituents
- Proton decay [underground]
- Composition of Universe [SN Ia, CMB, LSS, underground, colliders]

In a decade or two, we can hope to . . .

Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
Thoroughly explore CPV in B decays
Exploit rare decays (K, D, . . .)
Observe n EDM, pursue e EDM
Use top as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover QCD's full implications
Observe proton decay
Understand the baryon excess
Catalogue matter, energy of universe
Measure dark energy equation of state
Search for new macroscopic forces
Determine GUT symmetry

Detect neutrinos from the universe
Learn how to quantize gravity
Learn why empty space is nearly weightless
Test the inflation hypothesis
Understand discrete symmetry violation
Resolve the hierarchy problem
Discover new gauge forces
Directly detect dark-matter particles
Explore extra spatial dimensions
Understand origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek [TeV] dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate problem of identity

. . . learn the right questions to ask

. . .

. . . and rewrite the textbooks!

Here I first saw the glory of tropical vegetation. Tamarinds, Bananas & Palms were flourishing at my feet . . . I expected a good deal . . . & I was afraid of disappointments: how utterly vain such fear is . . . I returned to the shore, treading on Volcanic rocks, hearing the notes of unknown birds, & a glorious day, like giving a blind man eyes. — he is overwhelmed with what he sees & cannot justly comprehend it. — Such are my feelings, & may they remain

Charles Darwin