A TeV Linear Collider: Why? Why now?

Chris Quigg
Fermilab

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Why atoms?

Why chemistry?

Why complex structures?

Why is the world the way it is?

These questions are coming within the reach of particle physics.

The answers will be landmarks in our understanding of nature.

A TeV linear collider will play an important role in answering them.

A Decade of Discovery Past . . .

- ▷ Electroweak theory $\longrightarrow$ law of nature $[Z,\ e^+e^-,\ \bar{p}p,\ \nu N,\ (g-2)_\mu,\ \ldots]$
- ▷ Higgs-boson influence observed in the vacuum [EW experiments]
- ▷ Neutrino flavor oscillations: $\nu_\mu \to \nu_\tau,\ \nu_e \to \nu_\mu/\nu_\tau$ $[\nu_\odot,\ \nu_{\mathrm{atm}}]$
- ▷ Understanding 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 universe dominated by dark matter & energy [SN Ia, CMB, . . .]
- ▷ Detection of ν_τ interactions [fixed-target]
- ▷ Quarks & leptons structureless at TeV scale [mainly colliders]

Electroweak theory has many successes

- Neutral currents; Charm; Weak bosons $W^{\pm}$, Z^0
- Testing the quantum field theory at one per mille

Tested at distances from few $\times 10^{-17}$ cm to $\sim 10^{22}$ cm ...

origin Coulomb's law (tabletop experiments)

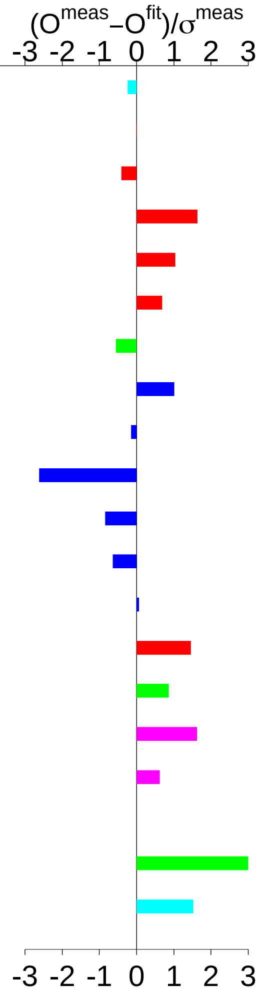
smaller $\begin{cases} \text{Atomic physics} \longrightarrow \text{QED} \\ \text{high-energy experiments} \longrightarrow \text{EW theory} \end{cases}$

larger $M_\gamma \approx 0$ in planetary ... measurements

Precision measurements test the theory . . .

Summer 2002

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.24
m_Z [GeV]	91.1875 ± 0.0021	0.00
Γ_Z [GeV]	2.4952 ± 0.0023	-0.41
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.04
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.68
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.55
R_b	0.21644 ± 0.00065	1.01
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.62
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.84
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.06
A_l(SLD)	0.1513 ± 0.0021	1.46
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.87
m_W [GeV]	80.449 ± 0.034	1.62
Γ_W [GeV]	2.136 ± 0.069	0.62
m_t [GeV]	174.3 ± 5.1	0.00
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
$Q_W(Cs)$	-72.18 ± 0.46	1.52



Our Picture of Matter

Pointlike ($r \lesssim 10^{-18}$ m) **quarks**

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

and **leptons**

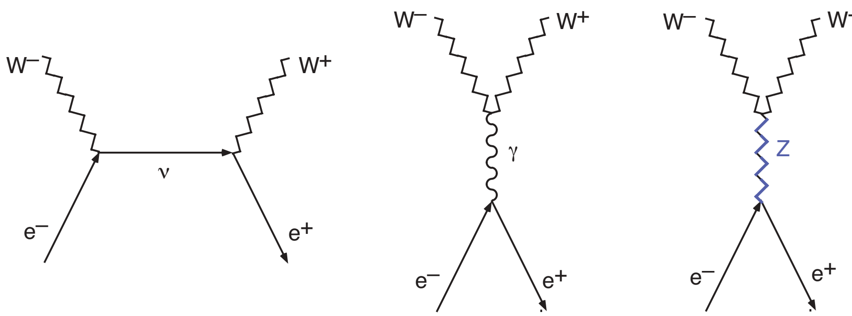
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

(+ RH singlets) with interactions specified by

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

gauge symmetries . . .

Gauge symmetry (group-theory structure) tested in $e^+e^- \to W^+W^-$



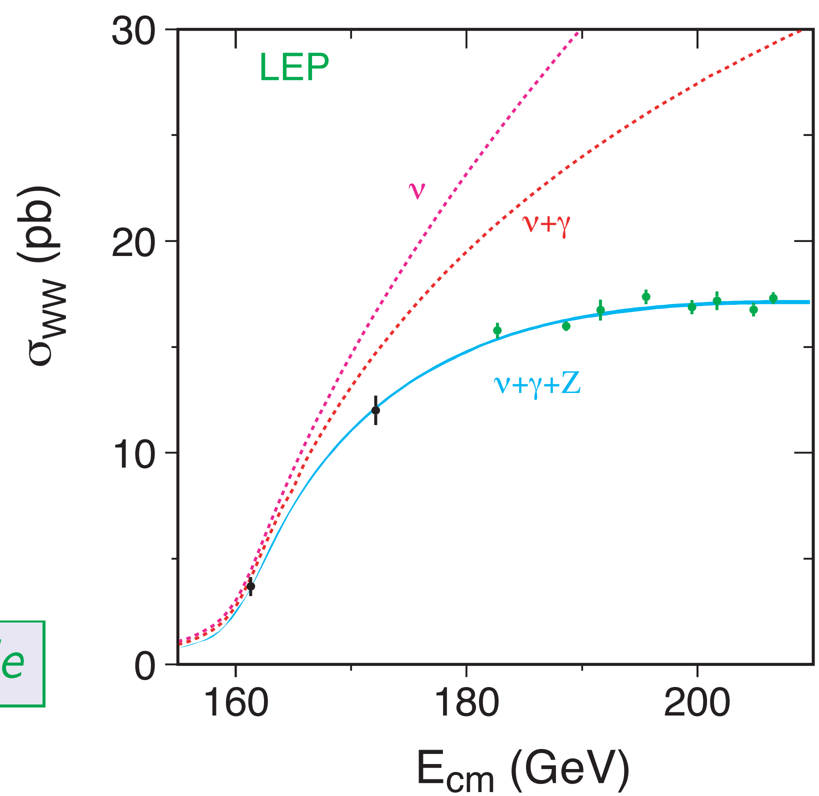
each grows unacceptably . . .

but the sum

is well-behaved

. . . and describes Nature!

New physics on TeV scale



If $SU(2)_L \otimes U(1)_Y$ gauge symmetry were unbroken, the world would be very different:

- ▷ quarks, leptons, gauge bosons move at c
- ▷ no EM, but long-range hypercharge force
- ▷ QCD confines quarks (baryon masses . . .)
- ▷ β decay not weak; $SU(2)_L$ confines q_L, ℓ_L
- ▷ ∞ Bohr radius for e, ν

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

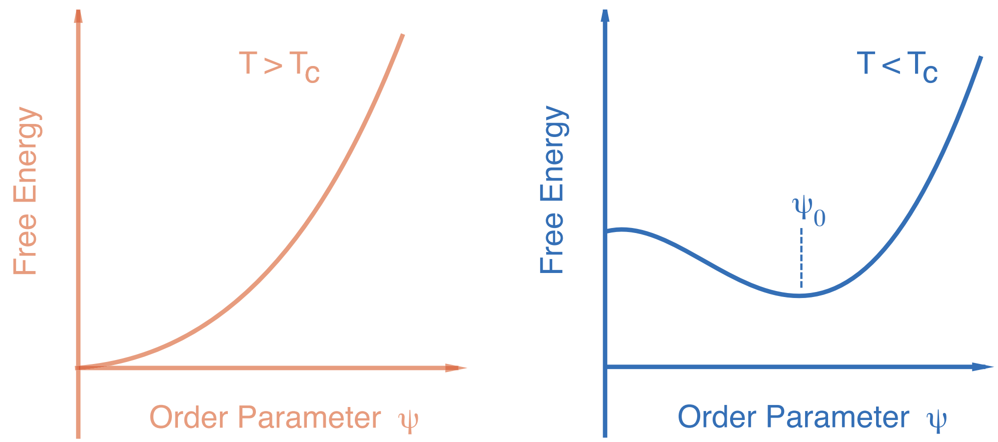
We do not know the nature of the new force.

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

Superconductivity analogy sets M_W, M_Z & breaks to EM



Meissner effect: EM field disturbs condensate of supercarriers

EW theory: gauge bosons disturb Higgs condensate, acquire masses

$$M_W^2 = \frac{g^2 v^2}{2} = \frac{\pi\alpha}{G_\mathrm{F}\sqrt{2}\sin^2\theta_\mathrm{W}} \; ; \quad M_Z^2 = \frac{M_W^2}{\cos^2\theta_\mathrm{W}}$$

g: gauge coupling; EW scale is $v = \left(G_\mathrm{F}\sqrt{2}\right)^{-\frac{1}{2}} \approx 246$ GeV

A massive spin-zero particle must exist: “Higgs boson”

Disturbing EW condensate may generate fermion mass

EWSB is necessary, not sufficient

Electroweak theory: each fermion mass $\Rightarrow$ new, *unknown* Yukawa coupling

$$\mathcal{L}^{(e)}_{\text{Yukawa}} = -\zeta_e \left[\bar{e}_R(\varphi^\dagger e_L) + (\bar{e}_L\varphi)e_R\right] \quad \varphi\text{: Higgs field}$$

$$\boxed{m_e = \zeta_e v/\sqrt{2}}$$

All fermion masses $\sim$ physics beyond the standard model!

$$\zeta_t \approx 1 \qquad \zeta_e \approx 3 \times 10^{-6} \qquad \zeta_\nu \approx 10^{-10} \text{ ??}$$

What accounts for the range and values of the Yukawa couplings?

There may be *other sources* of neutrino mass

Excitations of EW condensate: Higgs boson

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

We have explored examples of all three, theoretically.

Which path has Nature taken?

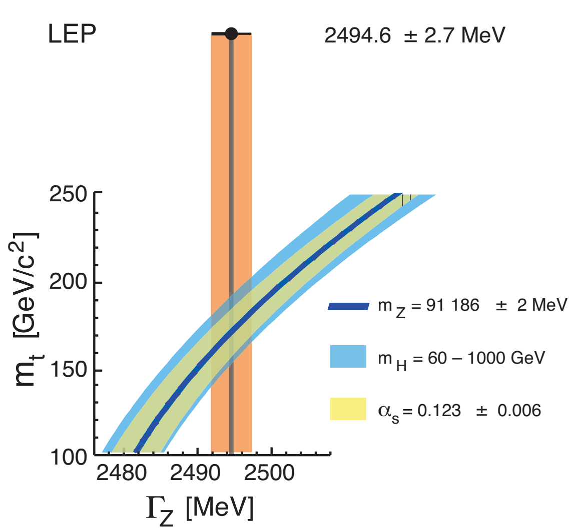
Essential step toward understanding the new force that shapes our world:

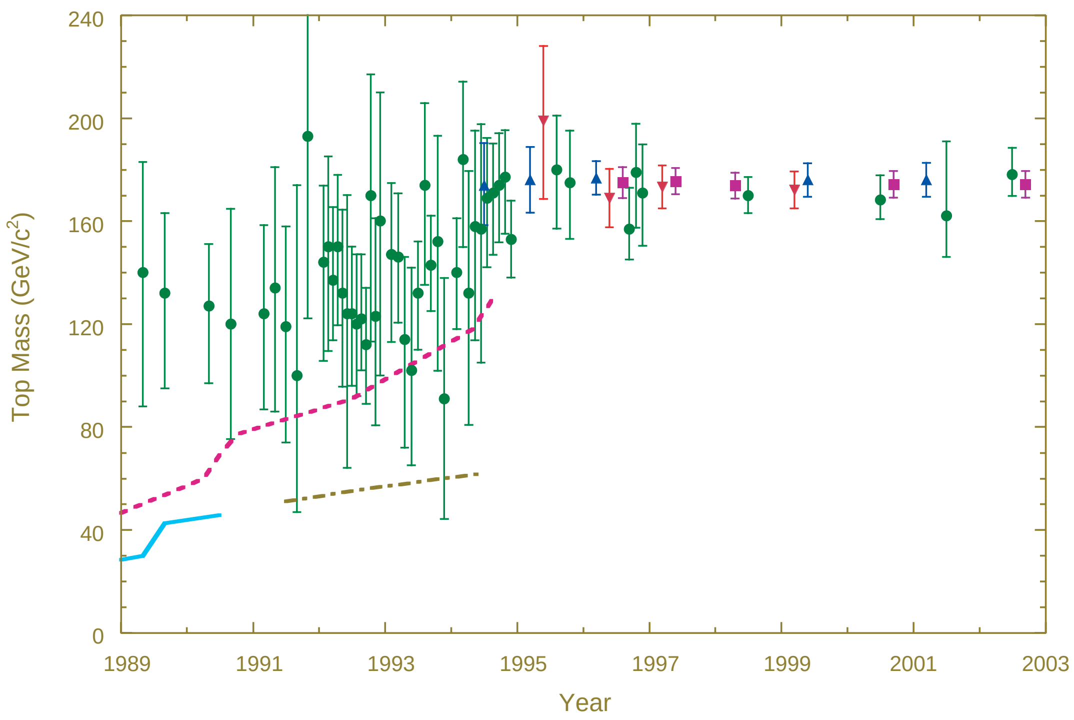
find the Higgs boson and explore its properties.

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

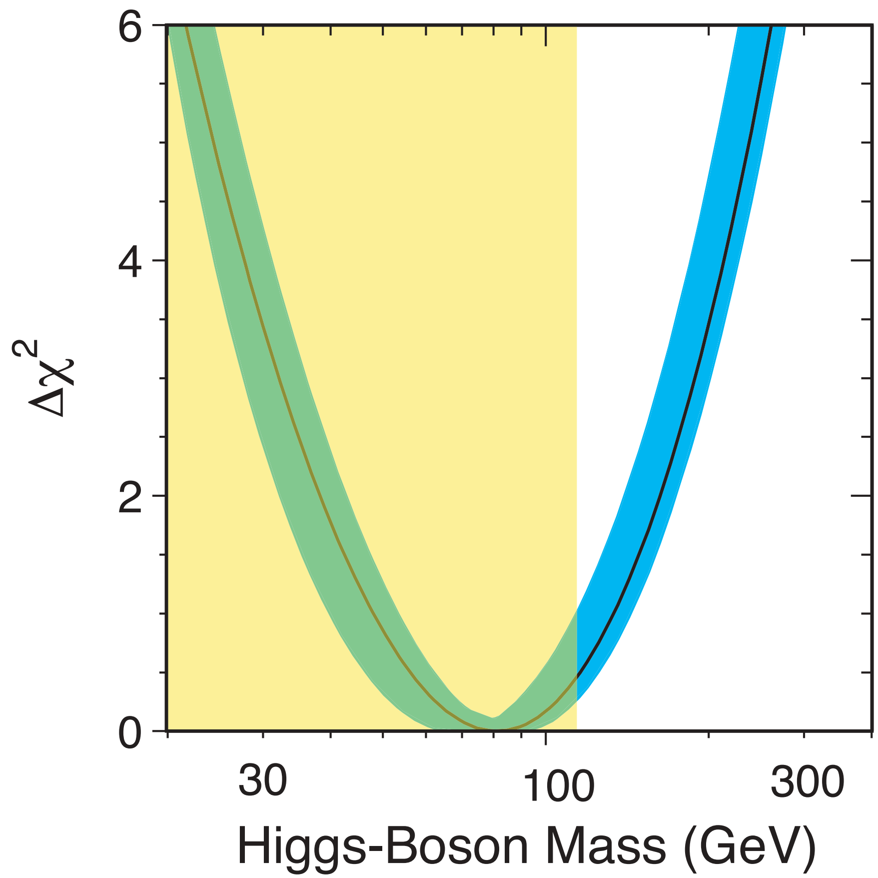
Precision measurements determine unknown parameters . . .

Infer top mass through quantum corrections:



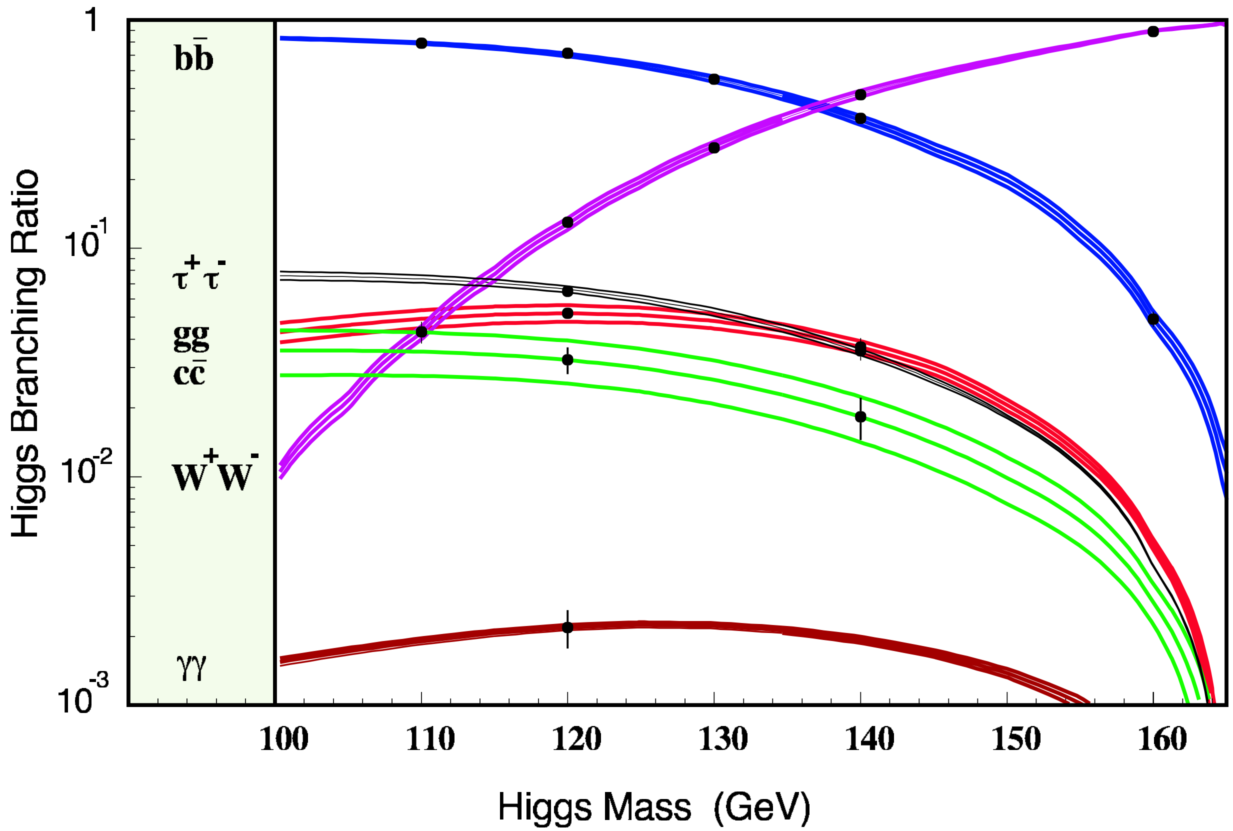


Quantum corrections suggest the Higgs-boson mass . . .



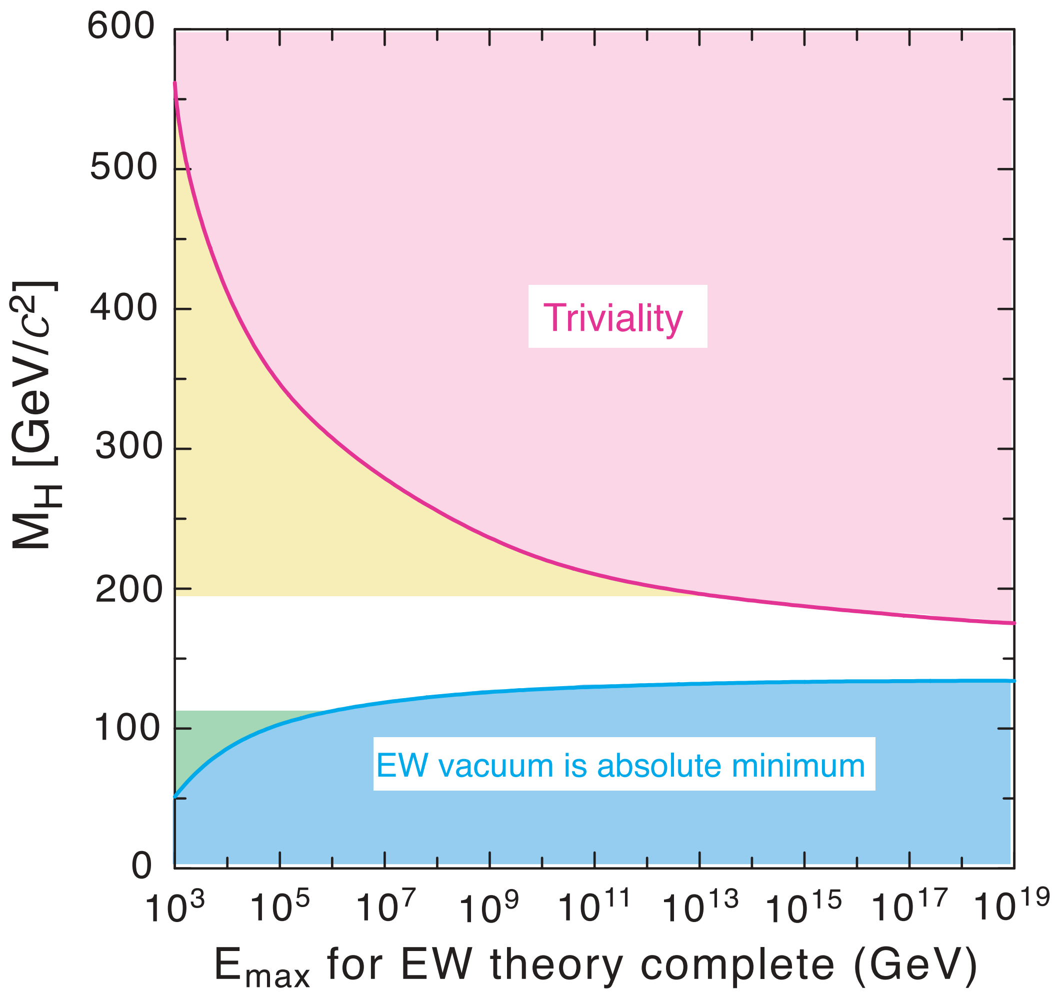
. . . within the standard electroweak theory

LC measures Higgs-boson couplings precisely,



exploring origin of elementary-particle masses and nature of the Higgs sector.

EW theory is an effective theory, will break down



What are the new *high-energy* degrees of freedom?

How to separate EW scale from higher scales?

Conventional approach: change electroweak theory to understand

why M_H, electroweak scale $\ll M_{\text{Planck}}$

To resolve the hierarchy problem: *extend the standard model*

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \begin{cases} \text{composite Higgs boson} \\ \text{technicolor / topcolor} \\ \text{supersymmetry} \\ \ldots \end{cases}$$

Novel speculation: change gravity (change spacetime) to understand

why $M_{\text{Planck}} \gg$ electroweak scale

The study of the Universe at large brings us other questions of great import.

- ▷ What is the Dark Matter that makes up $1/5$ of the mass-energy of the Universe?
- ▷ What drives the inflationary phase transition?
- ▷ What is the origin of the Dark Energy that makes up $2/3$ of the mass-energy of the Universe?

LC experiments can inform all of these

Many extensions to EW theory entail dark matter candidates.

Supersymmetry is highly developed, and has several important consequences:

- ▷ Predicts that the Higgs field condenses (breaking EW symmetry), if the top quark is heavy
- ▷ Predicts a light Higgs mass
- ▷ Predicts cosmological cold dark matter
- ▷ In a unified theory, explains the values of the standard-model coupling constants

Supersymmetry has many consequences for LC

- ▷ Predicts 5 Higgs bosons: h, H, H^+, H^-, A
- ▷ Changes branching fractions for lightest Higgs h
- ▷ Predicts a rich spectrum of superpartners
- ▷ Predicts superpartner couplings

LC is a wonderful instrument for discovering, pinning down masses of gauginos, sleptons, . . .

SUSY $\Rightarrow$ new *quantum* dimension

Did you say dark energy?

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

At the minimum,

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

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

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 $\Rightarrow$

$$\varrho_H \gtrsim 10^8 \text{ GeV}^4$$

MISMATCH BY 54 ORDERS OR MAGNITUDE

Particle physicists from Asia, Europe, North America agree that a TeV linear collider should be—in the context of a rich and balanced experimental program—the next large international initiative.

The scientific opportunities are rich and urgent.

The technological means are in sight.

The benefits of a linear collider in conversation with CERN's LHC would be very great.
(There are many different astronomies.)

The scientific case for a TeV linear collider is general and strong.

A discovery at the Tevatron or at the Large Hadron Collider would make the case for the linear collider specific and compelling.

We need *now* from our government encouragement and support to develop the technology and design for a specific proposal, to be realized internationally.

We must prepare for the moment when governments find the will to launch the vessel, and our scientific colleagues are persuaded that we have chosen well.

We do not know what the Linear Collider will find.

The LC will take us on a voyage of discovery:

hidden dimensions?

new dynamics?

supersymmetry?

new forces and constituents?

It will be one of the most fascinating—and most challenging—voyages humans have ever undertaken.

It has been—and must increasingly be—a vehicle for international cooperation and understanding.