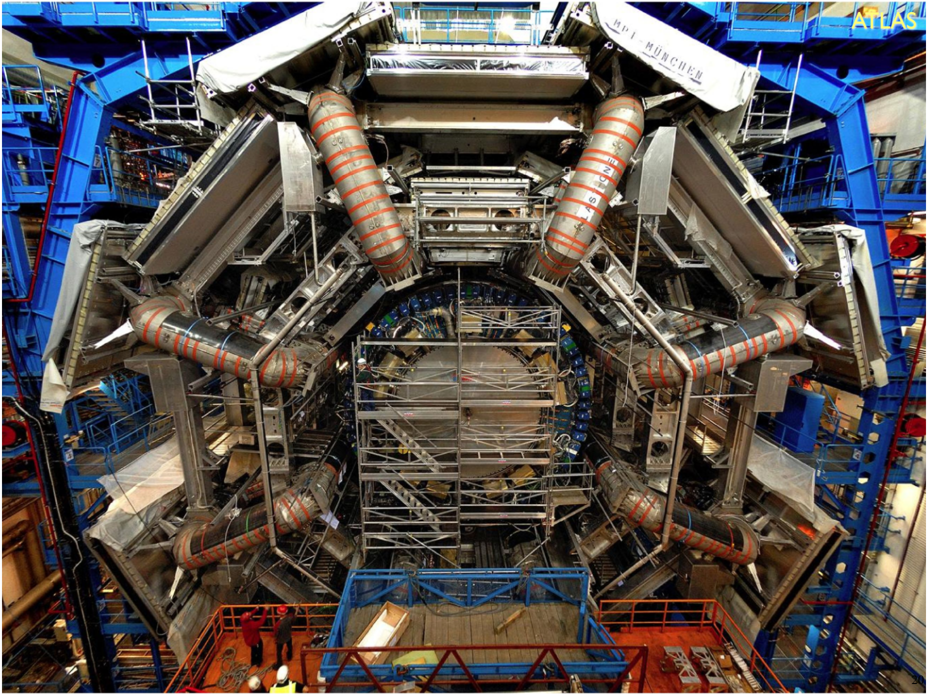
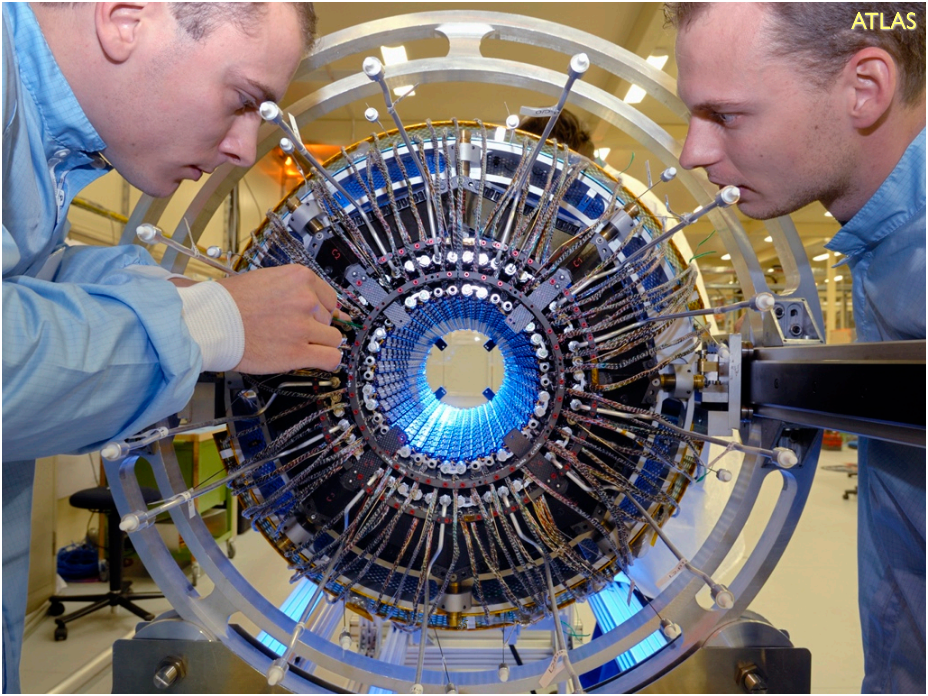
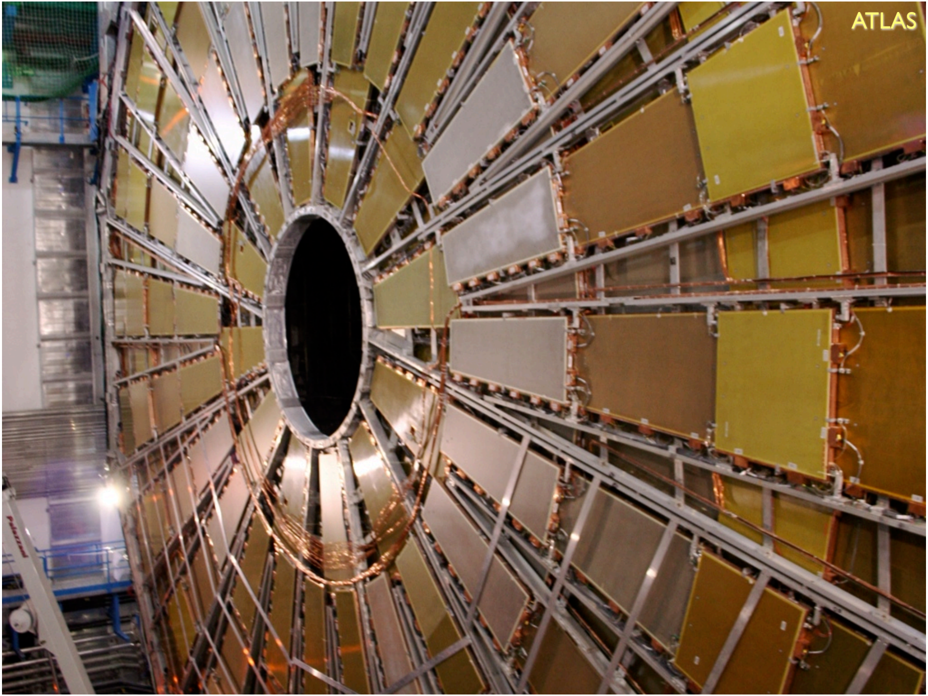
Physics of the Large Hadron Collider

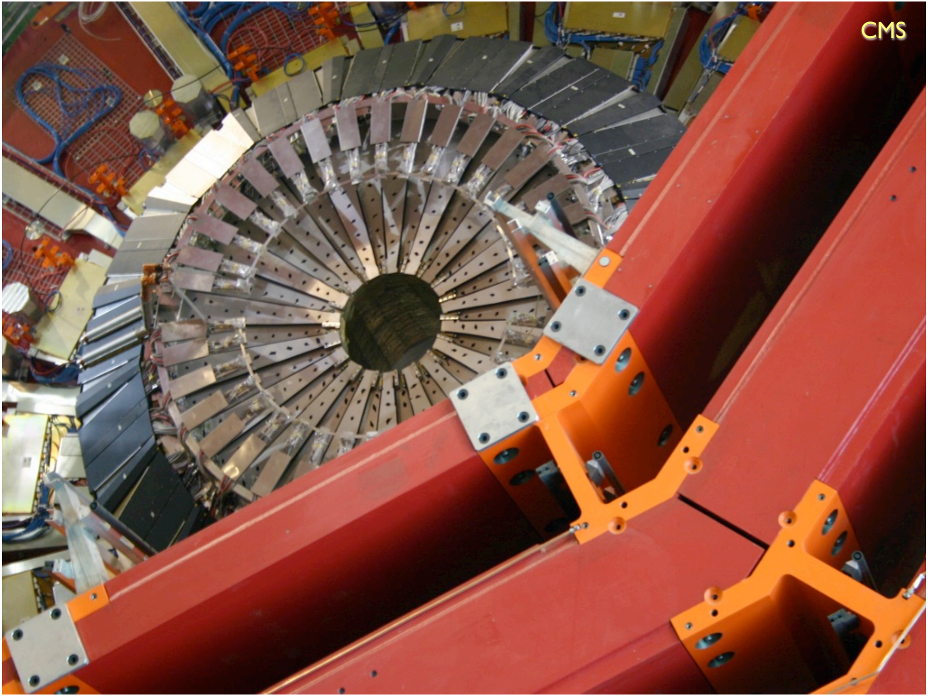
Chris Quigg

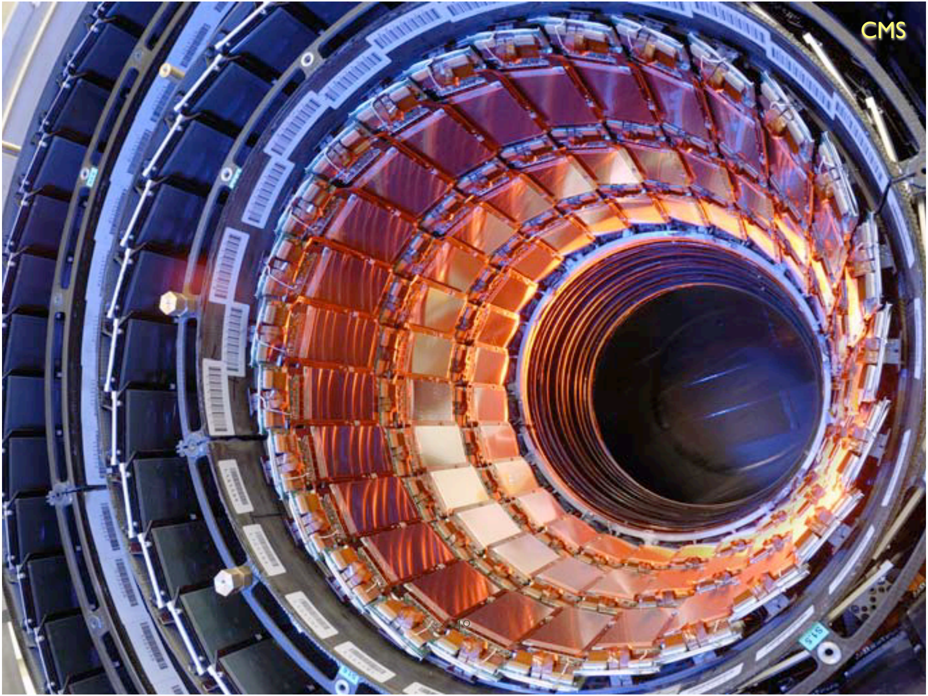
Fermilab

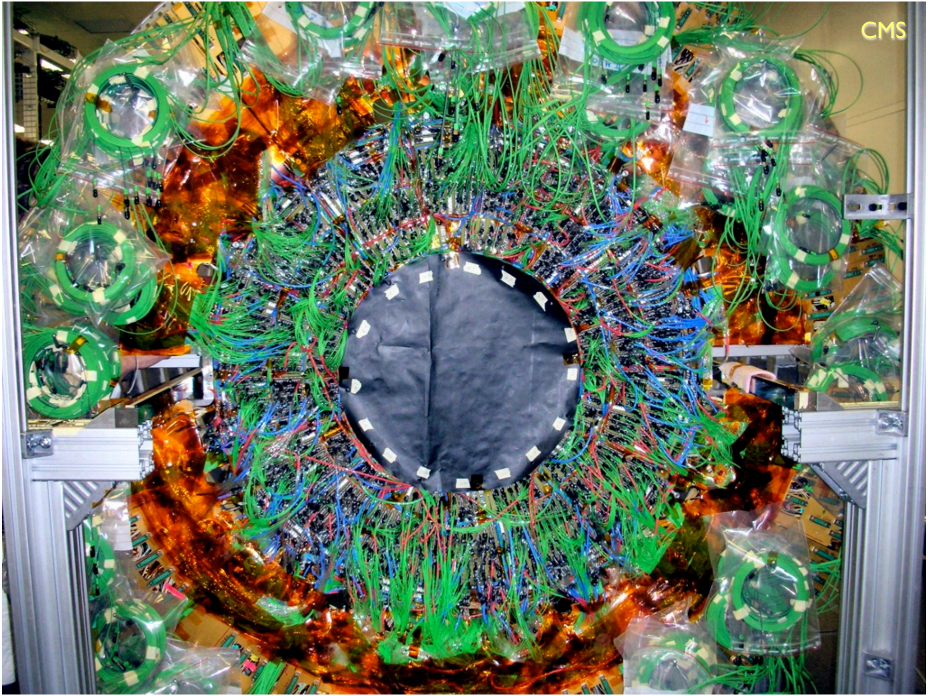

ATLAS
MPI-MÜNCHEN

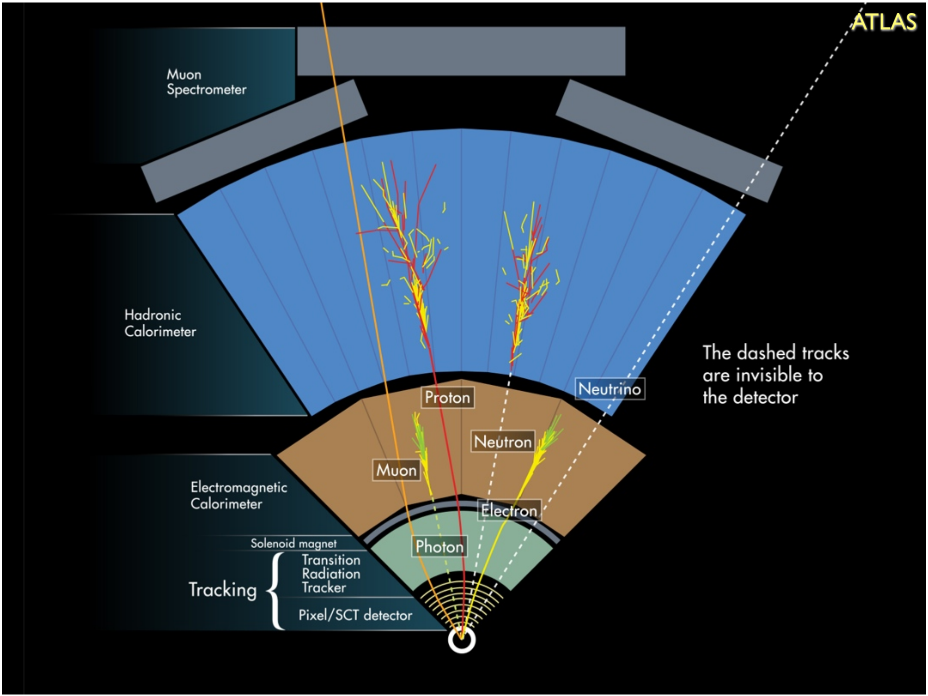

ATLAS


ATLAS


CMS


CMS


CMS

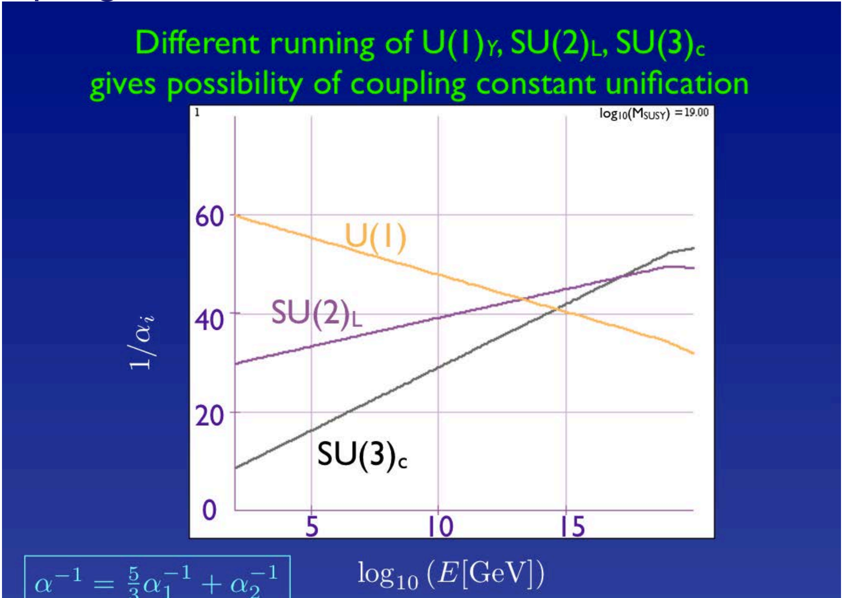

ATLAS
Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks are invisible to the detector

Exercise 5

Explain the response of the ATLAS detector to different particle species, as shown in the graphic on the preceding page.

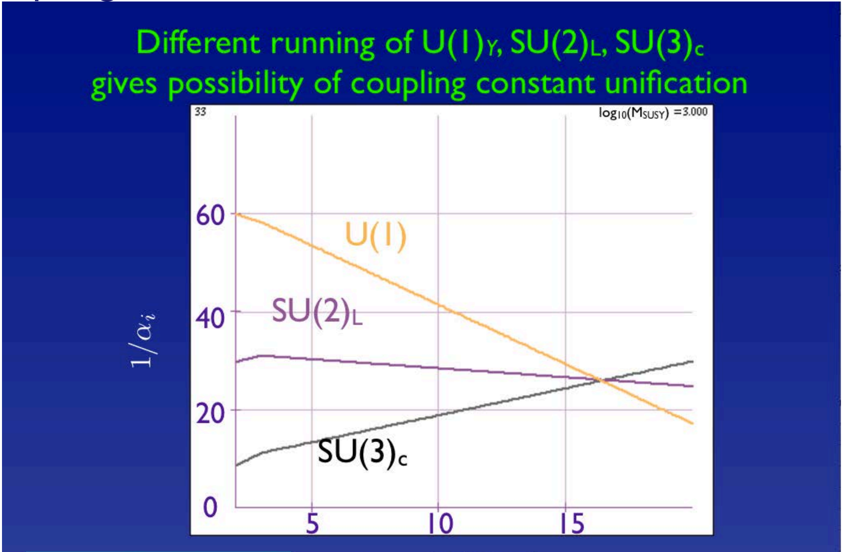
An interactive slice through the CMS detector animates the response to five particle types.

Coupling-constant Unification



$$\alpha^{-1} = \frac{5}{3}\alpha_1^{-1} + \alpha_2^{-1}$$

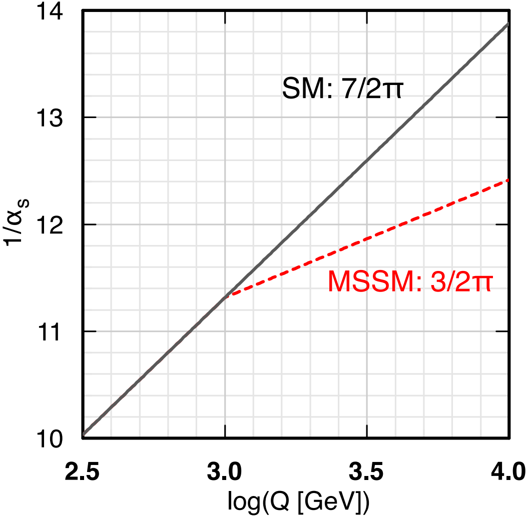
Coupling-constant Unification



$$\alpha^{-1} = \frac{5}{3}\alpha_1^{-1} + \alpha_2^{-1}$$

Can LHC See Change in Evolution?

Sensitive to new colored particles



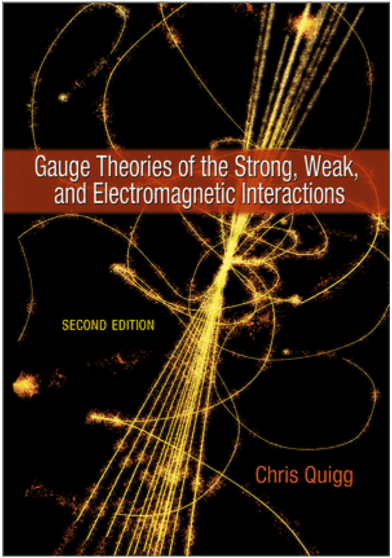
(sharp threshold illustrated)

. . . also for $\sin^2\theta_W$

Anyone unfamiliar with electroweak theory?

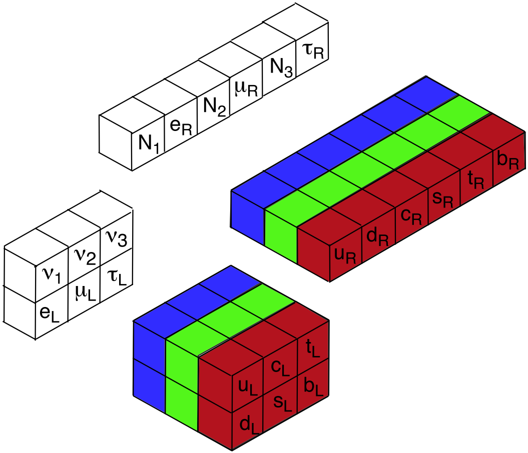
See my five lectures, "The Standard Model—Its Magic and Its Shortcomings," at the São Paulo school, *Particle Physics in the LHC Era*, April 2013.

Coming soon . . .


Gauge Theories of the Strong, Weak, and Electromagnetic Interactions
SECOND EDITION
Chris Quigg

Our Picture of Matter

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



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

Unbroken $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ Theory:

As in QED, massless gauge bosons

but weak interaction is short-range

In contrast to QED, massless fermions

Mass term $\mathcal{L}_e = -m_e \bar{e} e = -m_e(\bar{e}_R e_L + \bar{e}_L e_R)$

violates local gauge invariance

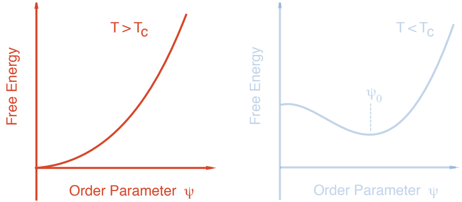
Massive Gauge Boson? *Hiding Symmetry*

Recall 2 miracles of superconductivity:

- No resistance . . . . . . Meissner effect (exclusion of **B**)

Ginzburg–Landau Phenomenology (not a theory from first principles)

normal, resistive charge carriers . . . . . . + superconducting charge carriers



$$\mathbf{B} = 0: \qquad G_{\text{super}}(0) = G_{\text{normal}}(0) + \alpha\,|\psi|^2 + \beta\,|\psi|^4$$

$$T > T_c: \quad \alpha > 0 \quad \langle|\psi|^2\rangle_0 = 0$$

Massive Gauge Boson? *Hiding Symmetry*

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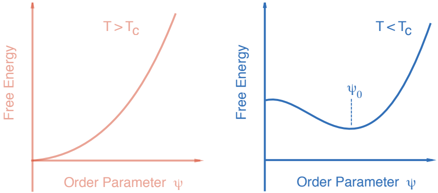


$$\mathbf{B} = 0: \qquad G_{\text{super}}(0) = G_{\text{normal}}(0) + \alpha\,|\psi|^2 + \beta\,|\psi|^4$$

$$T < T_c: \quad \alpha < 0 \quad \langle|\psi|^2\rangle_0 \neq 0$$

In a nonzero magnetic field . . .

$$G_{\text{super}}(\mathbf{B}) = G_{\text{super}}(0) + \frac{\mathbf{B}^2}{8\pi} + \frac{1}{2m^*}\left|-i\hbar\nabla\psi - \frac{e^*}{c}\mathbf{A}\psi\right|^2$$

$$\left.\begin{matrix} e^* = -2 \\ m^* \end{matrix}\right\}\text{ of superconducting carriers}$$

Weak, slowly varying field: $\psi \approx \psi_0 \neq 0$, $\nabla\psi \approx 0$

Variational analysis $\rightsquigarrow$

$$\boxed{\nabla^2\mathbf{A} - \frac{4\pi e^{*2}}{m^* c^2}\left|\psi_0\right|^2\mathbf{A} = 0}$$

wave equation of a *massive photon*

Photon – *gauge boson* – acquires mass within superconductor

origin of Meissner effect

In gauge theory: Brout, Englert, Higgs, Guralnik, Hagen, Kibble

Hide EW Symmetry in Analogy to Ginzburg–Landau

- Electromagnetism is mediated by a massless photon, coupled to the electric charge;
- Mediator of charged-current weak interaction acquires a mass $M_W^2 = \pi\alpha / G_F\sqrt{2}\sin^2\theta_W$,
- 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.

Determine $\sin^2\theta_W$ to predict M_W, M_Z

▸ Vacua

A theory of leptons

$$\mathsf{L} = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_{\mathsf{L}} \qquad \mathsf{R} \equiv e_{\mathsf{R}}$$

weak hypercharges $Y_{\mathsf{L}} = -1$, $Y_{\mathsf{R}} = -2$

Gell-Mann–Nishijima connection, $Q = I_3 + \frac{1}{2}Y$

$SU(2)_{\mathsf{L}} \otimes U(1)_Y$ gauge group $\Rightarrow$ gauge fields:

- weak isovector $\vec{b}_\mu$, coupling g $\quad$ $\boxed{b^\ell_\mu = b^\ell_\mu - \varepsilon_{jk\ell}\alpha^j b^k_\mu - (1/g)\partial_\mu\alpha^\ell}$
- weak isoscalar $\mathcal{A}_\mu$, coupling $g'/2$ $\quad$ $\boxed{\mathcal{A}_\mu \to \mathcal{A}_\mu - \partial_\mu\alpha}$

Field-strength tensors

$$F^\ell_{\mu\nu} = \partial_\nu b^\ell_\mu - \partial_\mu b^\ell_\nu + g\varepsilon_{jk\ell} b^j_\mu b^k_\nu \;, SU(2)_{\mathsf{L}}$$

$$f_{\mu\nu} = \partial_\nu \mathcal{A}_\mu - \partial_\mu \mathcal{A}_\nu \;, U(1)_Y$$

Interaction Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{leptons}}$$

$$\mathcal{L}_{\text{gauge}} = -\tfrac{1}{4} F^{\ell}_{\mu\nu} F^{\ell\mu\nu} - \tfrac{1}{4} f_{\mu\nu} f^{\mu\nu},$$

$$\begin{aligned} \mathcal{L}_{\text{leptons}} &= \overline{\mathsf{R}}\, i\gamma^{\mu}\left(\partial_{\mu} + i\frac{g'}{2}\mathcal{A}_{\mu} Y\right)\mathsf{R} \\ &+ \overline{\mathsf{L}}\, i\gamma^{\mu}\left(\partial_{\mu} + i\frac{g'}{2}\mathcal{A}_{\mu} Y + i\frac{g}{2}\vec{\tau}\cdot\vec{b}_{\mu}\right)\mathsf{L}. \end{aligned}$$

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

Theory: 4 massless gauge bosons ($\mathcal{A}_{\mu}$ b^1_{μ} b^2_{μ} b^3_{μ}); Nature: 1 (γ)

Hiding EW Symmetry

Higgs mechanism: relativistic generalization of Ginzburg-Landau superconducting phase transition

- Introduce a complex doublet of scalar fields

$$\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad Y_\phi = +1$$

- Add to $\mathcal{L}$ (gauge-invariant) terms for interaction and propagation of the scalars,

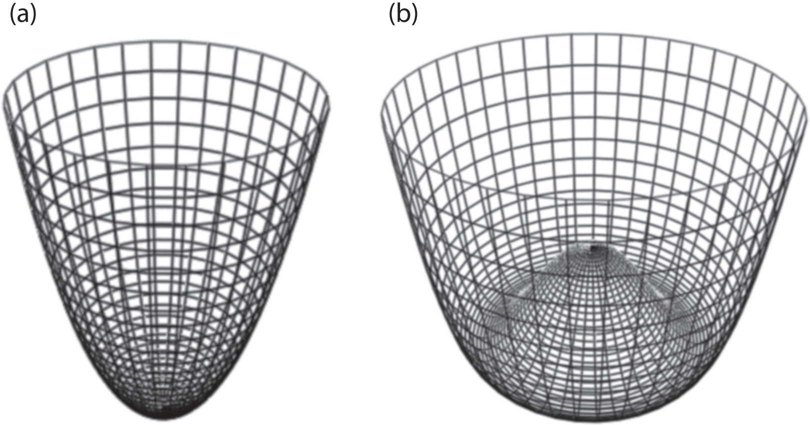
$$\mathcal{L}_{\text{scalar}} = (\mathcal{D}^\mu \phi)^\dagger (\mathcal{D}_\mu \phi) - V(\phi^\dagger \phi),$$

where $\mathcal{D}_\mu = \partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y + i\frac{g}{2}\vec{\tau} \cdot \vec{b}_\mu$ and

$$\boxed{V(\phi^\dagger \phi) = \mu^2(\phi^\dagger \phi) + |\lambda| (\phi^\dagger \phi)^2}$$

- Add a Yukawa interaction $\mathcal{L}_{\text{Yukawa}} = -\zeta_e \left[\overline{\text{R}}(\phi^\dagger \text{L}) + (\overline{\text{L}}\phi)\text{R}\right]$

Unique and degenerate vacuum states



Origin of Fermion Masses

By decree, Weinberg & Salam add interactions between fermions and scalars that give rise to quark and lepton masses.

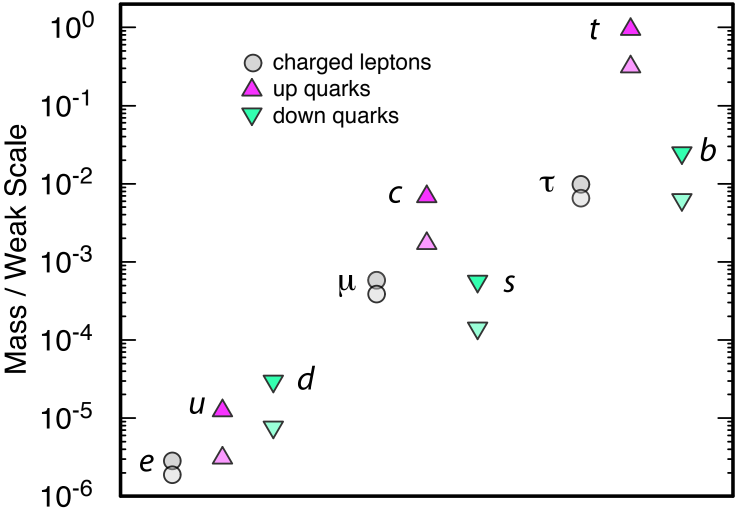
$$\zeta_e \left[(\bar{e}_{\mathrm{L}}\Phi)e_{\mathrm{R}} + \bar{e}_{\mathrm{R}}(\Phi^\dagger e_{\mathrm{L}})\right] \rightsquigarrow m_e = \zeta_e v/\sqrt{2}$$

ζ_e is picked to give right mass, not predicted

Fermion mass implies physics beyond standard model

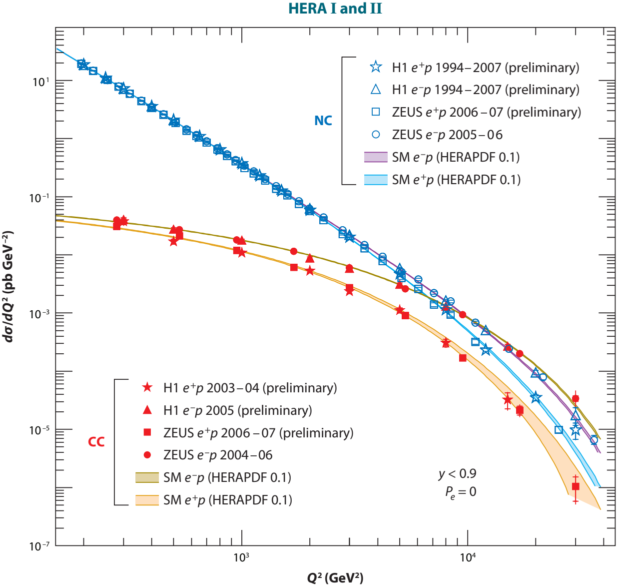
Highly economical, but is it true?

Charged Lepton and Quark Masses

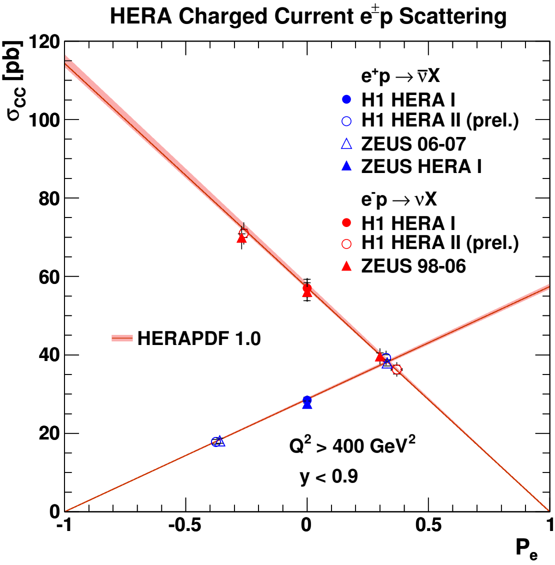


Running mass $m(m) \ldots m(U)$

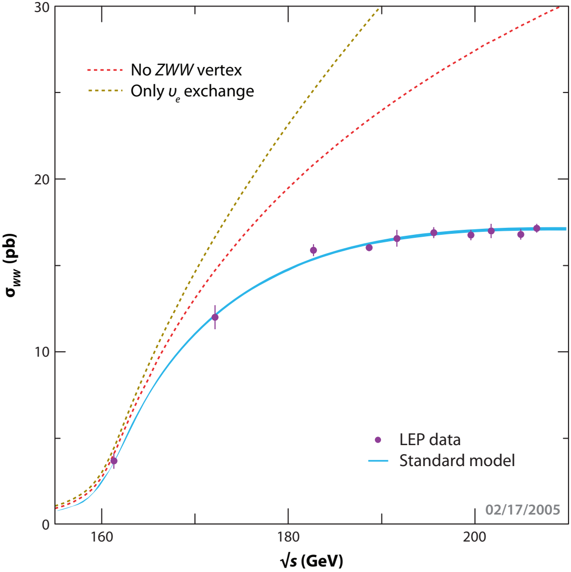
Electroweak theory tests: tree level



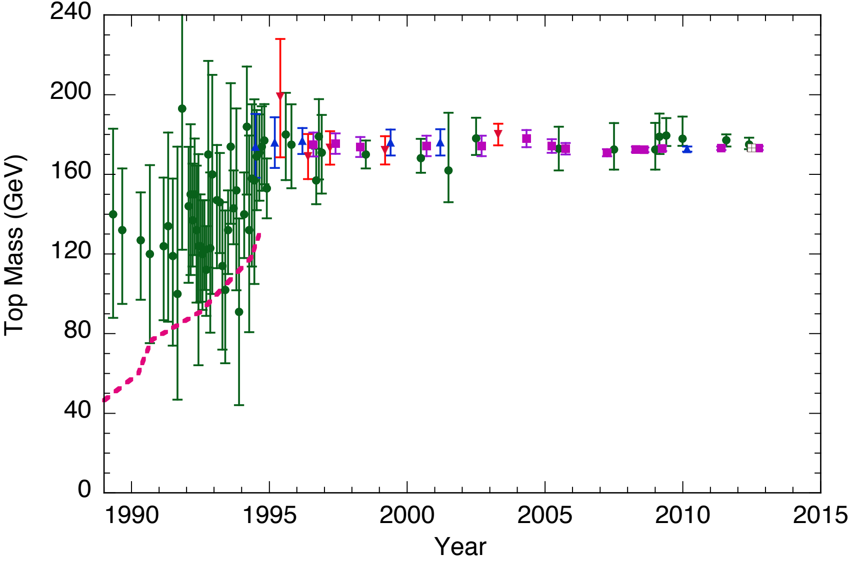
Electroweak theory tests: tree level (no RHCC)



Electroweak theory tests: tree level



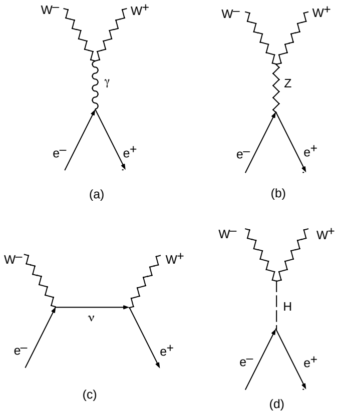
Electroweak theory tests: loop level



▸ *H*

Why a Higgs boson must exist

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



Individual $J = 1$ partial-wave amplitudes $\mathcal{M}_\gamma^{(1)}$, $\mathcal{M}_Z^{(1)}$, $\mathcal{M}_\nu^{(1)}$ have 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

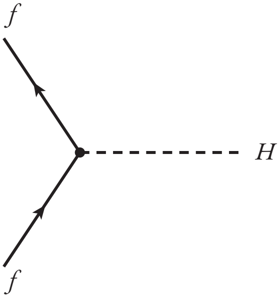
$$\mathcal{M}_{\nu}^{(0)} \propto s^{\frac{1}{2}} \text{ : unacceptable HE behavior}$$

(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 $\propto m_e$



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

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

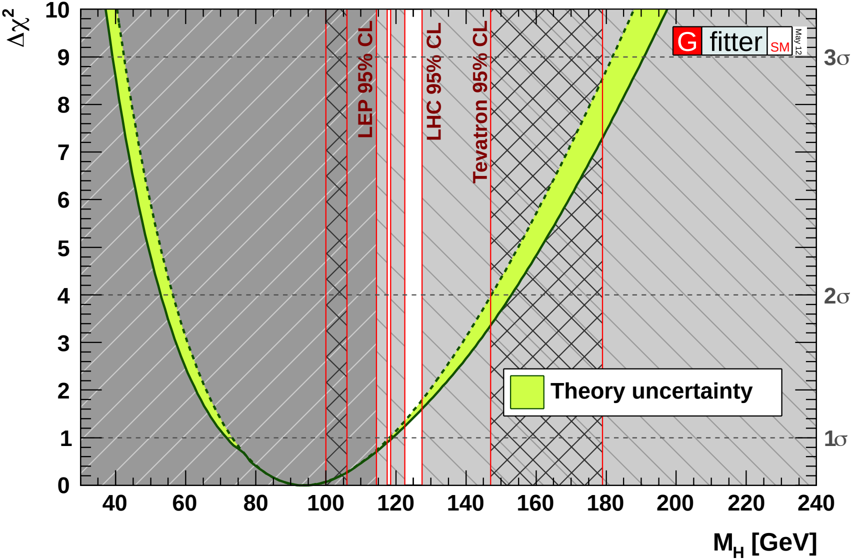
. . . and no viable low-energy phenomenology

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 SSB
- SSB provides its own cure—the Higgs boson

Similar interplay and compensation *must exist* in any acceptable theory

Electroweak theory tests: Higgs influence



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

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

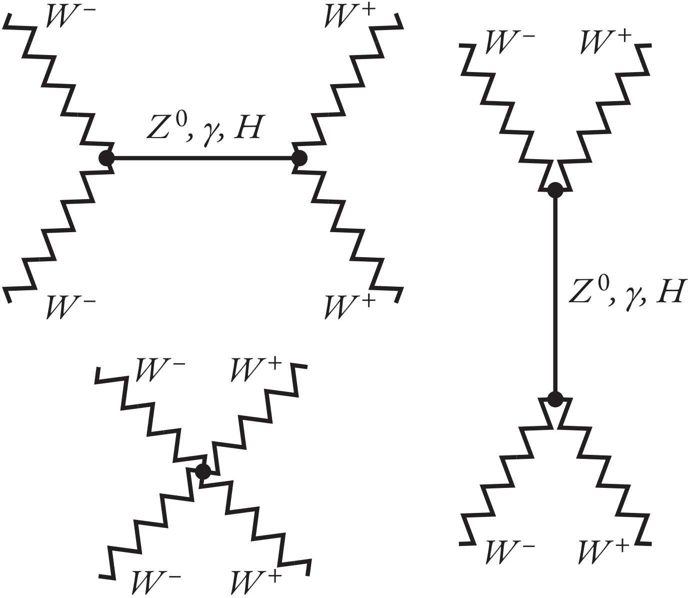
Most channels decouple – pw amplitudes are small at "all" energies – $\forall M_H$.

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

The importance of the 1-TeV scale . . .



The importance of the 1-TeV scale . . .

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 partial-wave unitarity condition $|a_0| \leq 1$

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

condition for perturbative unitarity

The importance of the 1-TeV scale . . .

If the bound is respected

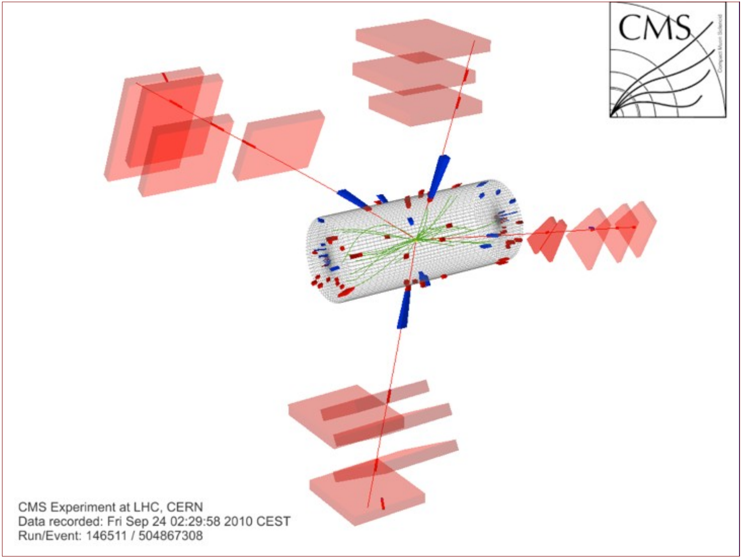
- weak interactions remain weak at all energies
- perturbation theory is everywhere reliable

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

Heavy Higgs Signature: $ZZ \to \mu^+\mu^-\mu^+\mu^-$



What the Higgs Field Accomplishes

Hides the electroweak symmetry

Gives masses to W and Z
(provides longitudinal components)

Generates fermion masses and mixings
through mysterious Yukawa terms

Makes electroweak theory behave at high energies

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

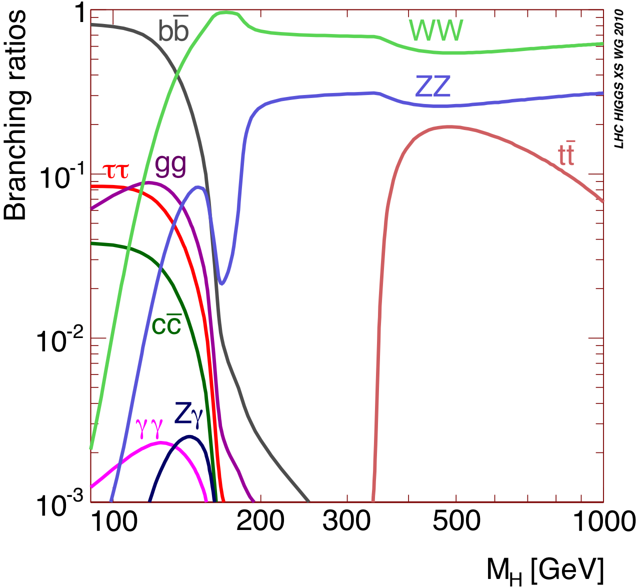
Exercise 6

Compute the decay rate for the Higgs boson into fermion pairs given on the previous page,

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

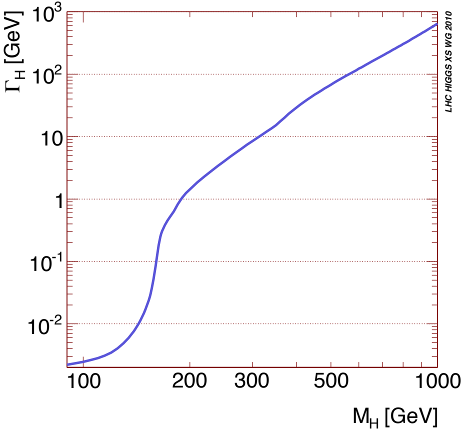
using the Feynman rule given above.

SM Higgs Boson Branching Fractions



Total width of the standard-model Higgs boson

$$\Gamma_H(M_H = 126\text{ GeV}) = 4.2\text{ MeV}$$



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

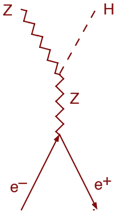
At the LHC:
Many channels accessible, search sensitive up to 1 TeV

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*

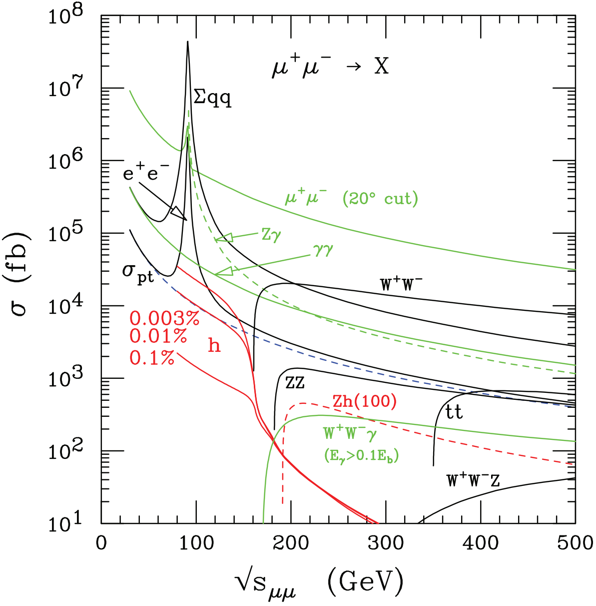
Most promising:
associated production $e^+e^- \to HZ$
(has no small couplings)



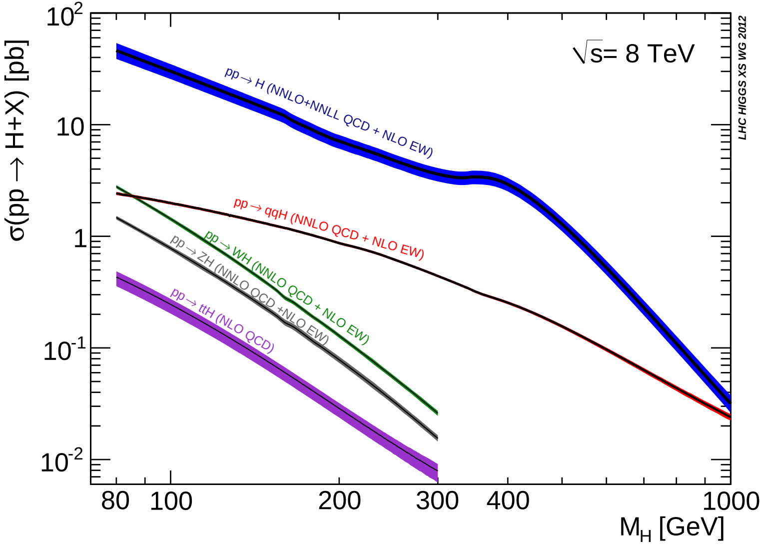
$$\sigma = \frac{\pi\alpha^2}{24\sqrt{s}} \frac{K(K^2 + 3M_Z^2)[1 + (1 - 4x_W)^2]}{(s - M_Z^2)^2 \quad x_W^2(1 - x_W)^2}$$

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

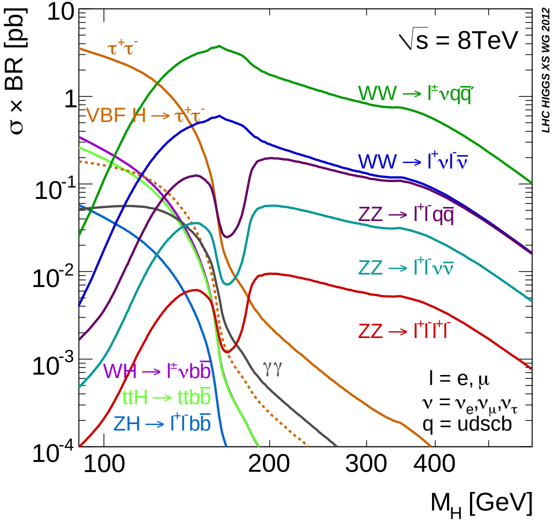
$\ell^+\ell^- \to X \ldots$



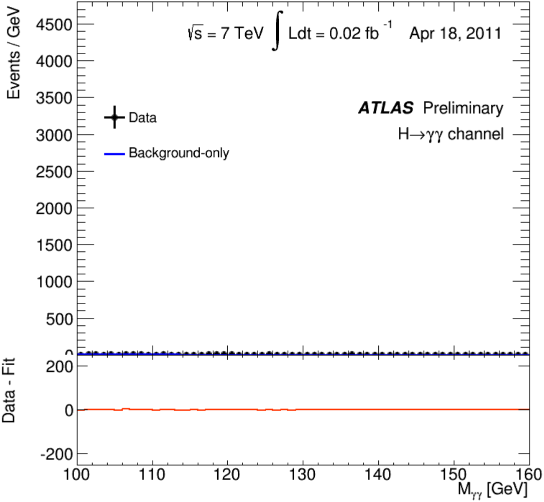
Higgs-boson production at the LHC: 8 TeV



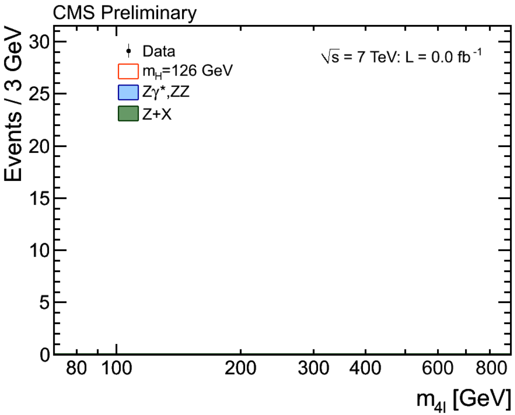
Higgs-boson production and decay: 8 TeV



ATLAS $\gamma\gamma$ signal evolution



CMS 4μ signal evolution



Evolution of evidence at the LHC

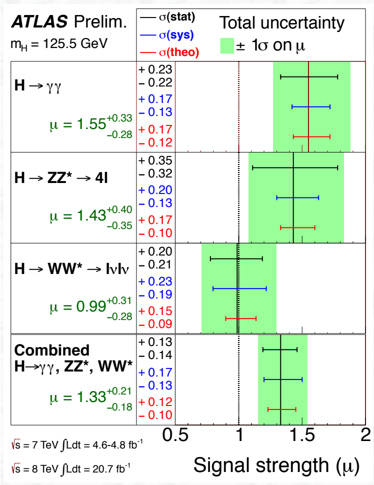
Evidence is developing as it would for
a "standard-model" Higgs boson

Unstable neutral particle near 126 GeV

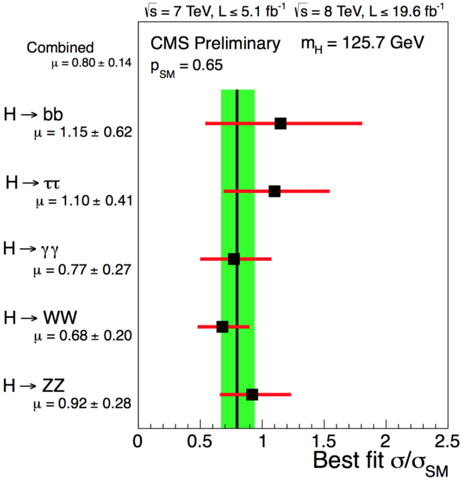
decays to $\gamma\gamma, W^+W^-, ZZ$
likely (dominantly) spin-parity 0^+
evidence for $\tau^+\tau^-, b\bar{b}$

Consistency with Standard-Model Higgs

ATLAS twiki



CMS twiki



Why Electroweak Symmetry Breaking Matters

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!

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

Without a Higgs Mechanism . . .

Electron and quarks would have no mass

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

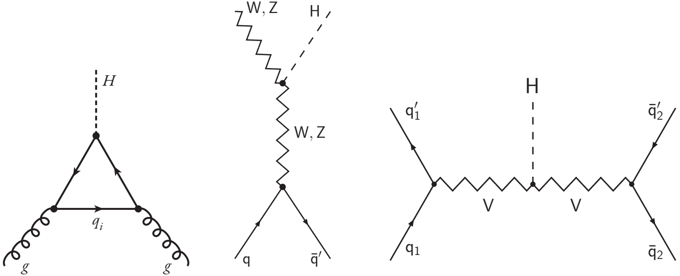
Surprise: QCD would hide EW symmetry,
give tiny masses to W, Z

Massless electron: atoms lose integrity

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

LHC: Multiple looks at the new boson

3 production mechanisms, ≥ 5 decay modes



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

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 $M_H \approx 126$ 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

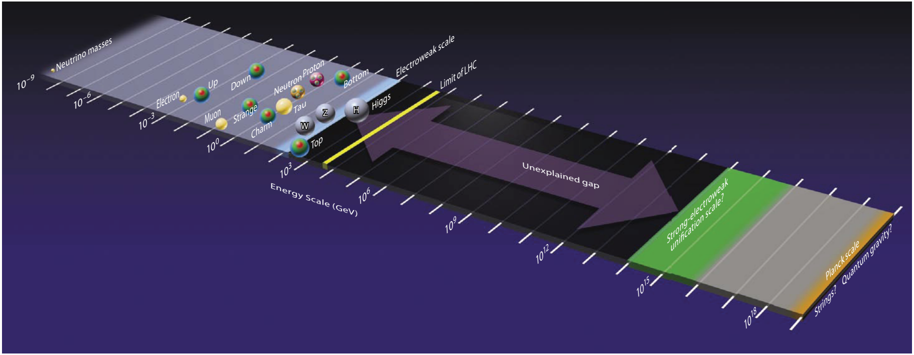
Beyond the Standard Model
More physics on the TeV scale?

Partial-wave unitarity analysis of WW scattering argues for new physics on the TeV scale.
In SM: a Higgs boson or strongly interacting gauge sector
In general, something new on the TeV scale

At the level of suggestion, rather than theorem . . .

- The hierarchy problem: if light H, new physics implicated on the TeV scale
- WIMPs as dark matter: reproduce relic density for masses 0.1−1 TeV

The Hierarchy Problem



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
Possible paths

- Fine tuning
- A new symmetry (supersymmetry)
  fermion, boson loops contribute with opposite sign
- Composite "Higgs boson" (technicolor . . .)
  form factor damps integrand
- Little Higgs models, etc.
- Low-scale gravity (shortens range of integration)

All but first require new physics near the TeV scale

But Where is the New Physics?

The unreasonable effectiveness of the Standard Model

More Electroweak Questions for the LHC

- What is the agent that hides electroweak symmetry?
- Is the "Higgs boson" elementary or composite? How does the Higgs boson interact with itself? What triggers electroweak symmetry breaking?
- New physics in pattern of Higgs-boson decays?
- Will (unexpected or rare) decays of H reveal new kinds of matter?
- What would discovery of > 1 Higgs boson imply?
- What stabilizes M_H below 1 TeV?
- How can a light H coexist with absence of new phenomena?
- Is EWSB related to gravity via extra dimensions?

More Electroweak Questions for the LHC$^{\text{bis}}$

- Is EWSB emergent, connected with strong dynamics?
- If new strong dynamics, how can we diagnose? What takes place of H?
- 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?
- Does the different behavior of left-handed and right-handed fermions with respect to charged-current weak interactions reflect a fundamental asymmetry in the laws of nature?

More Electroweak Questions for the LHC$^{\text{ter}}$

- What will be the next symmetry recognized in Nature? Is Nature supersymmetric? Is the electroweak theory part of some larger edifice?
- Are there additional generations of quarks and leptons?
- What resolves the vacuum energy problem?
- What lessons does electroweak symmetry breaking hold for unified theories of the strong, weak, and electromagnetic interactions?

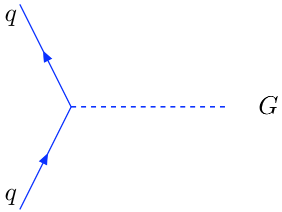
Thanks and good luck!

Why is empty space so nearly massless?

Natural to neglect gravity in particle physics . . .

Gravitational *ep* interaction $\approx 10^{-41} \times$ EM

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



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

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,

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

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

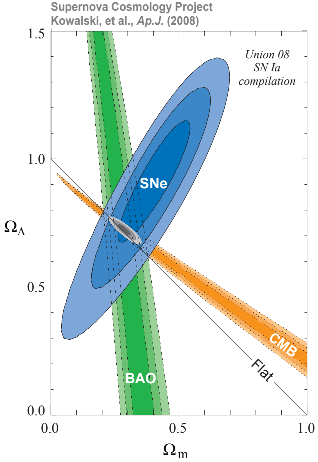
$V \neq 0$ contributes position-independent vacuum energy density

$$\boxed{\varrho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8\ \text{GeV}^4} \quad \approx 10^{24}\ \text{g cm}^{-3}$$

Adding vacuum energy density ϱ_{vac} ⇔ adding cosmological constant Λ to Einstein's equation

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

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



$\varrho_H \gtrsim 10^8\ \text{GeV}^4$: mismatch by 10^{54}

A chronic dull headache for thirty years . . .