Large Hadron Collider Physics: The Next Generation

Lecture 2

Chris Quigg

Fermilab & LPTENS

Anyone unfamiliar with electroweak theory?

Electroweak Symmetry Breaking in Historical Perspective

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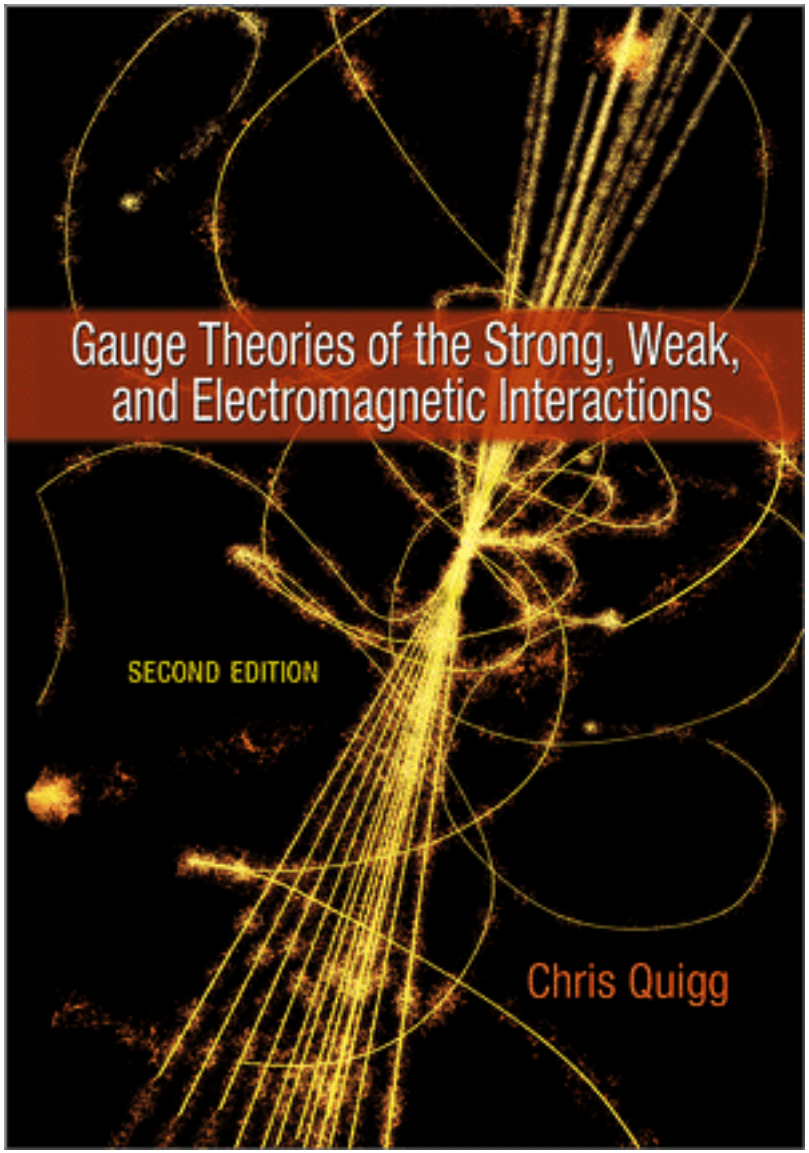
The discovery of the Higgs boson is a major milestone in our progress toward understanding the natural world. A particular aim of this article is to show how diverse ideas came together in the conception of electroweak symmetry breaking that led up to the discovery. I will also survey what we know that we did not know before, what properties of the Higgs boson remain to be established, and what new questions we may now hope to address.

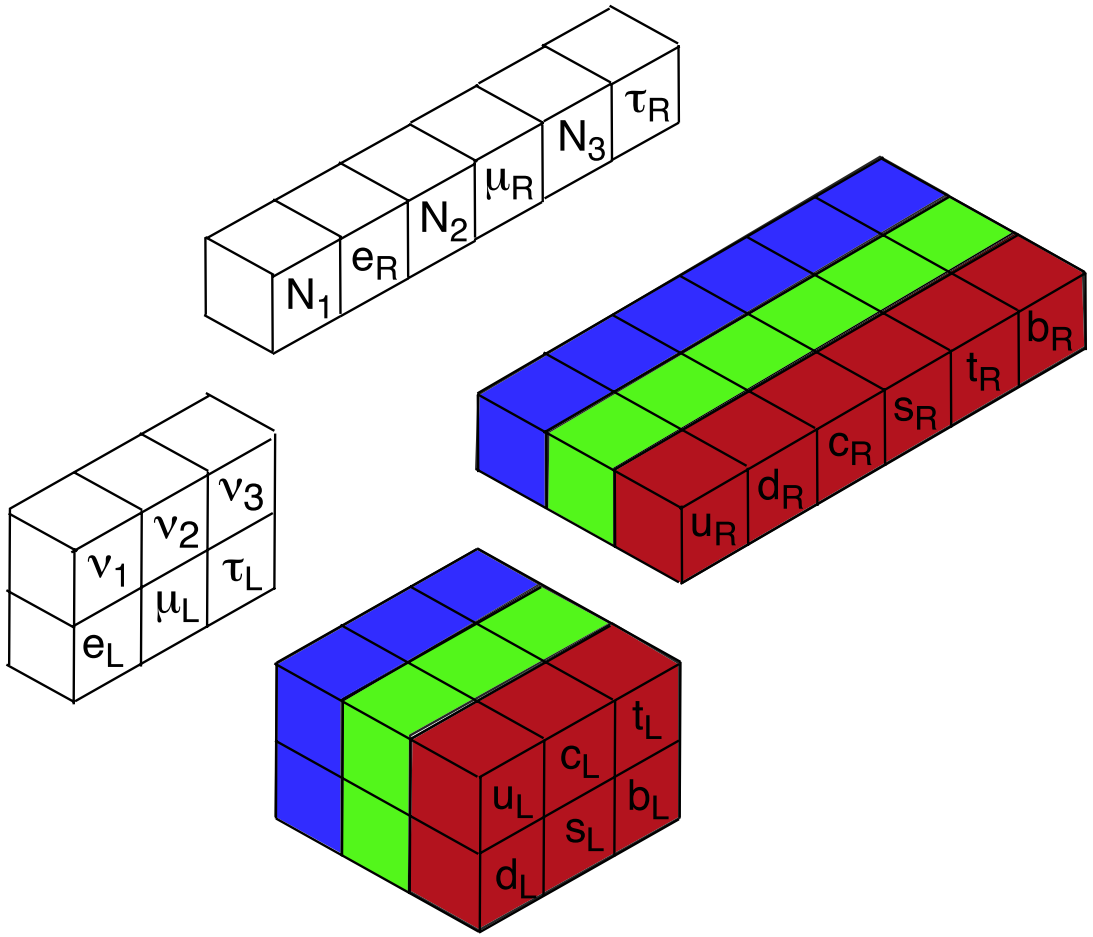
For a short course, see my five lectures, "The Standard Model—Its Magic and Its Shortcomings," at the São Paulo school, *Particle Physics in the LHC Era,* April 2013.

The whole story . . .



Our Picture of Matter

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



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

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

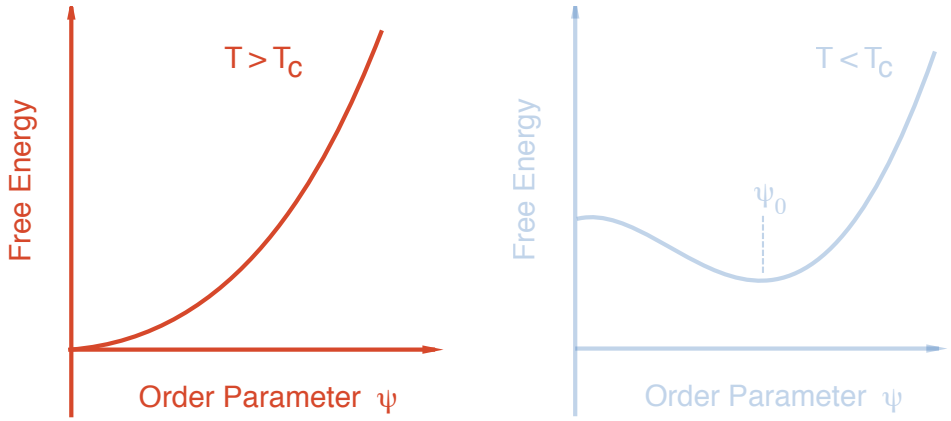
Massive Gauge Boson? *Hiding Symmetry*

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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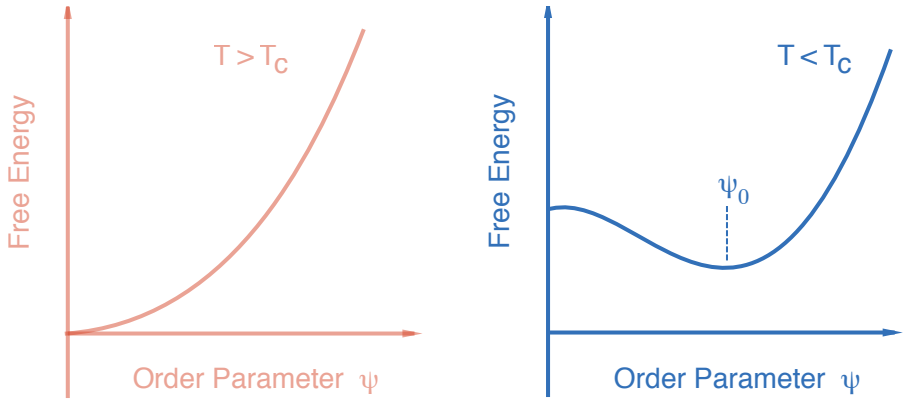


$$\mathbf{B} = 0: \qquad G_{\text{super}}(0) = G_{\text{normal}}(0) + \alpha\,|\psi|^2 + \beta\,|\psi|^4$$

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

In a nonzero magnetic field . . .

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

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

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, $Q = I_3 + \frac{1}{2} Y$

$\mathrm{SU}(2)_{\mathsf{L}} \otimes \mathrm{U}(1)_Y$ 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

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

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

Interaction Lagrangian

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

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

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

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 inv.

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

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

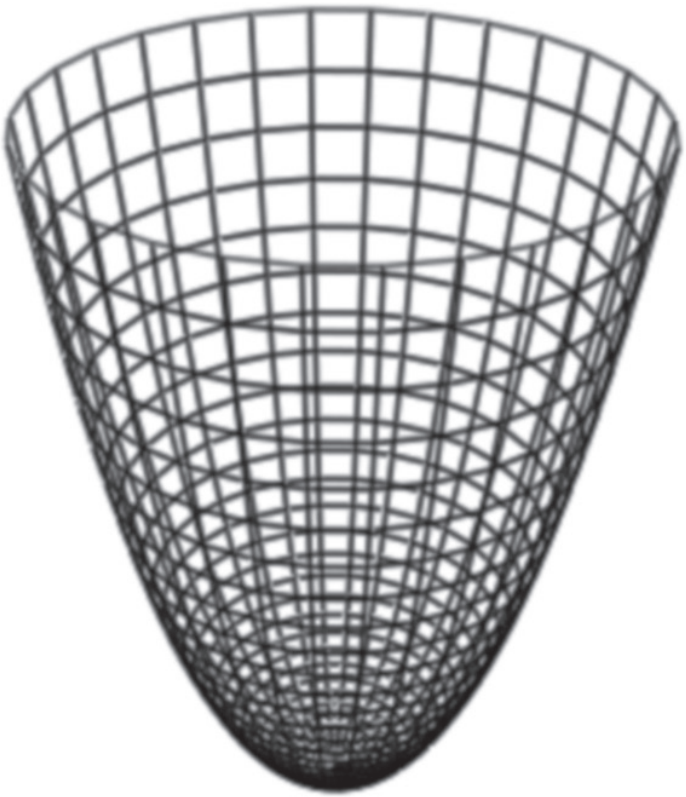
where $\mathcal{D}_\mu = \partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y + i\frac{g}{2}\vec{\tau}\cdot\vec{b}_\mu$ and

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

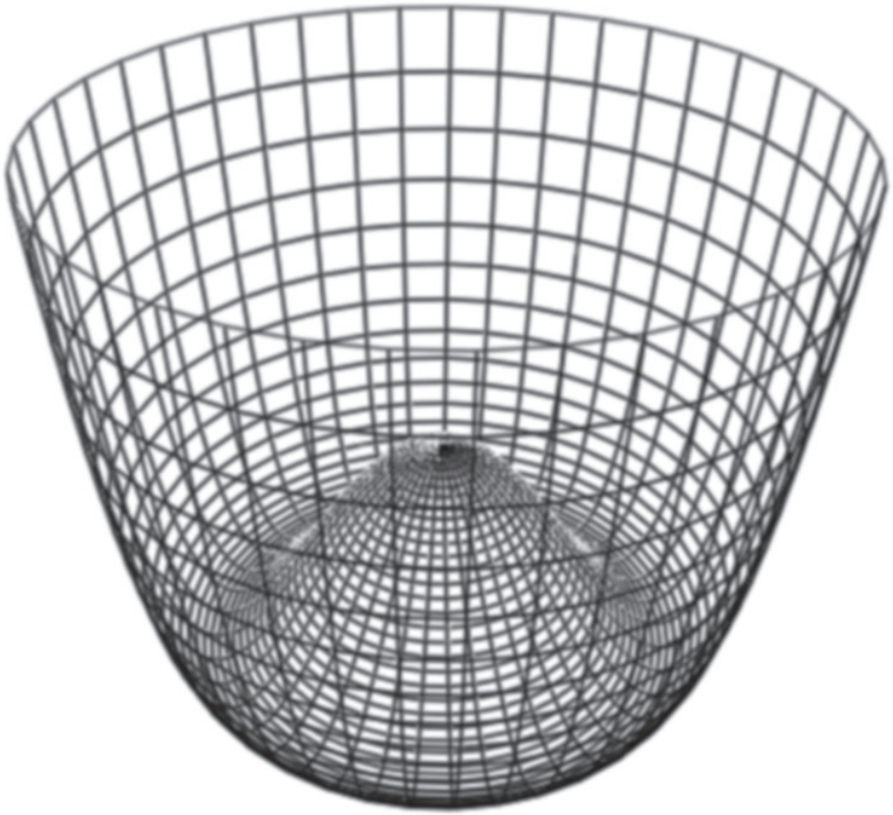
- Add a Yukawa interaction $\mathcal{L}_{\text{Yukawa}} = -\zeta_e\left[\overline{\mathrm{R}}(\phi^\dagger \mathrm{L}) + (\overline{\mathrm{L}}\phi)\mathrm{R}\right]$

Unique and degenerate vacuum states

(a)



(b)



Origin of Fermion Masses

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

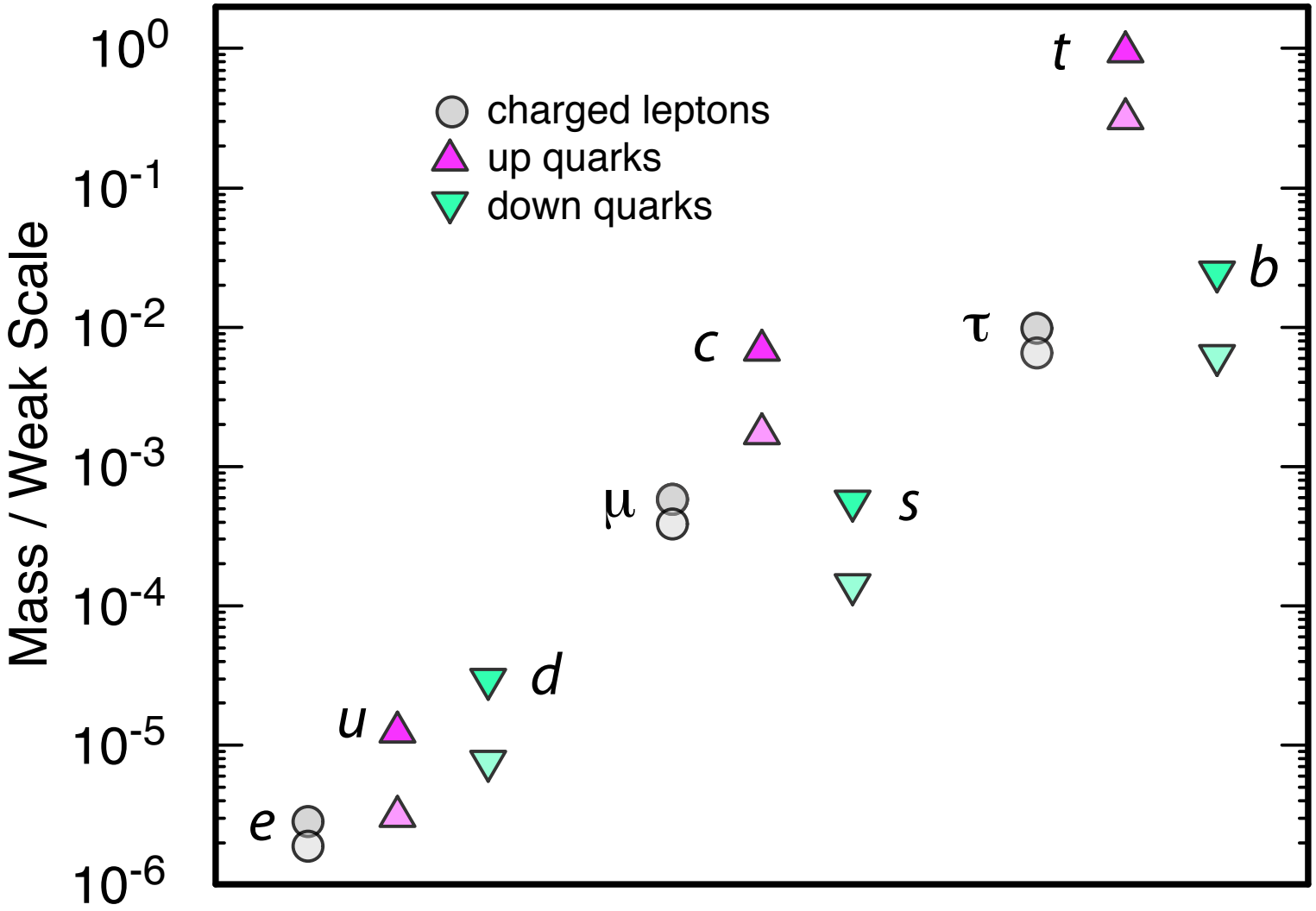
$$\zeta_e \left[(\bar{e}_L \Phi) e_R + \bar{e}_R (\Phi^\dagger e_L) \right] \rightsquigarrow m_e = \zeta_e v / \sqrt{2}$$

ζ_e is picked to give right mass, not predicted

Fermion mass implies physics beyond standard model

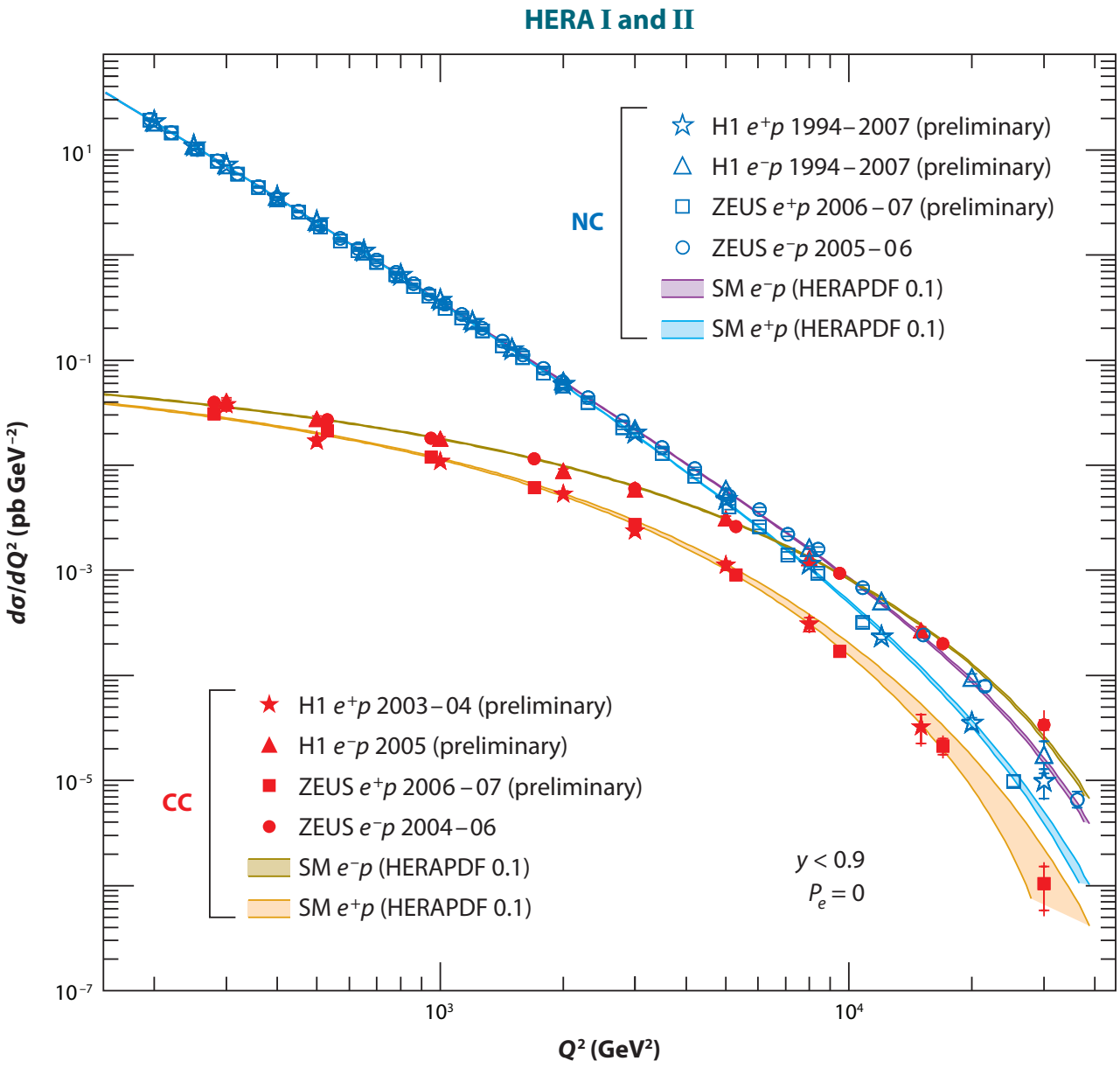
Highly economical, but is it true?

Charged Lepton and Quark Masses

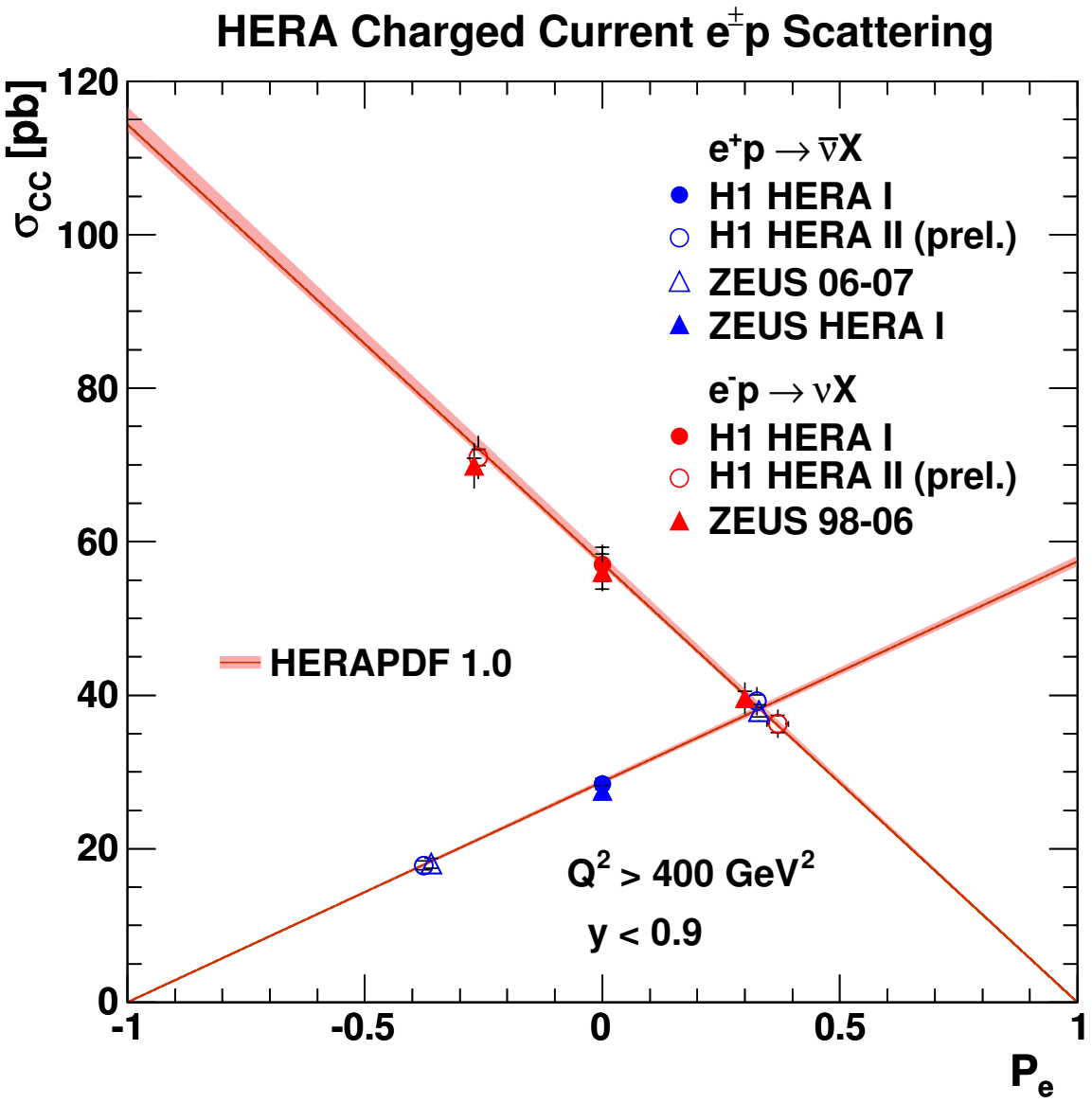


Running mass $m(m) \ldots m(U)$

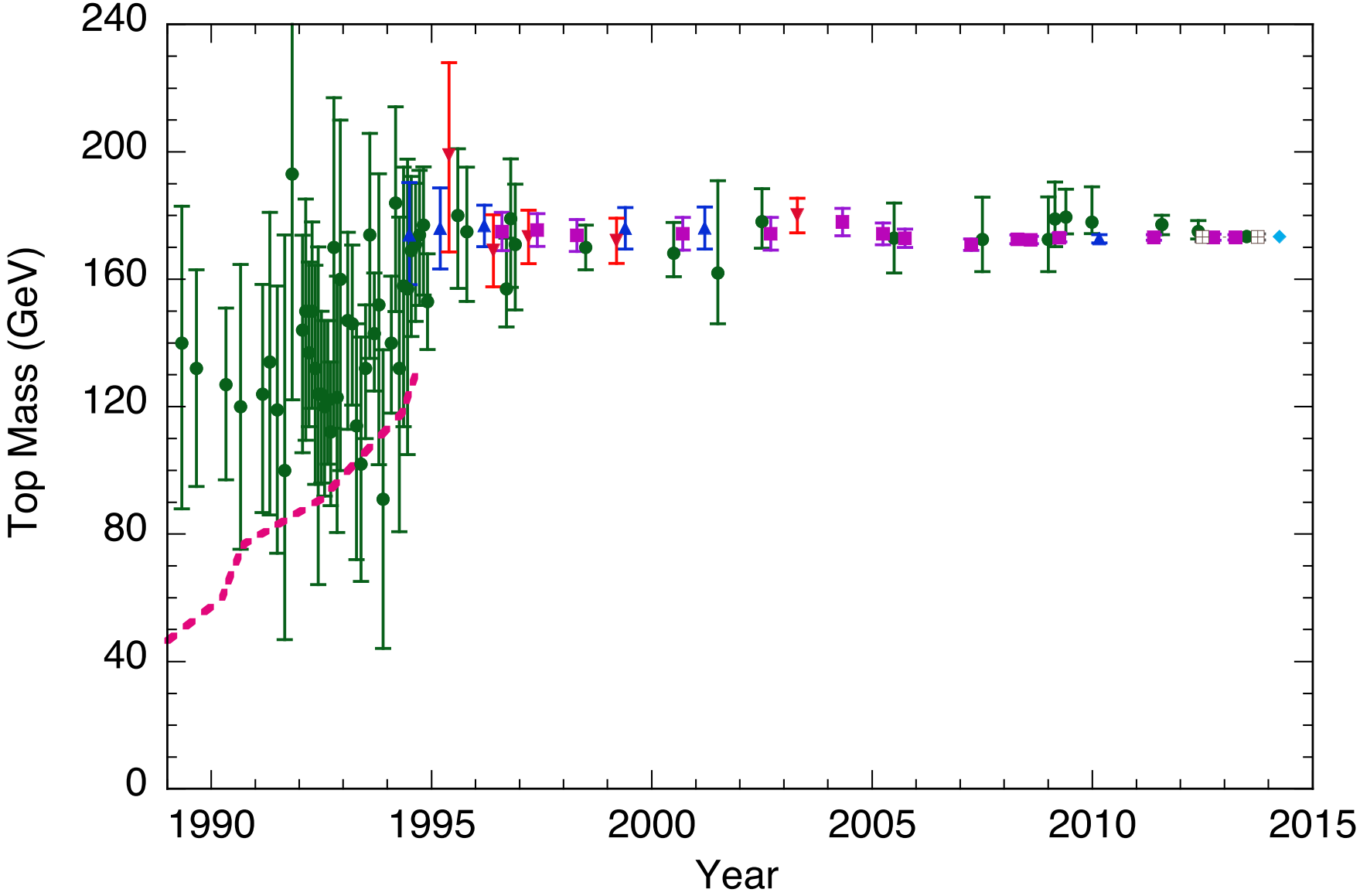
Electroweak theory tests: tree level



Electroweak theory tests: tree level (no RHCC)



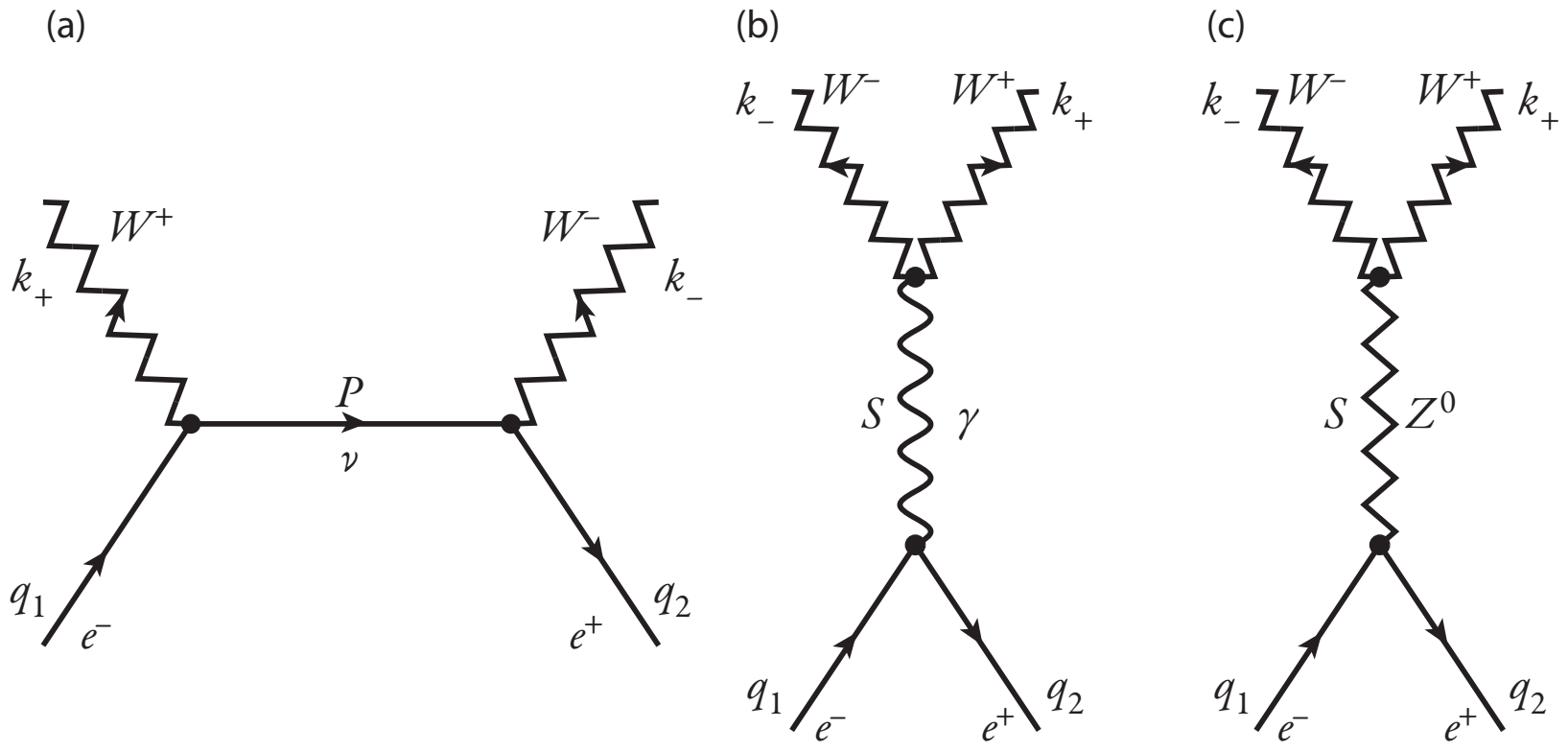
Electroweak theory tests: loop level



▸ H

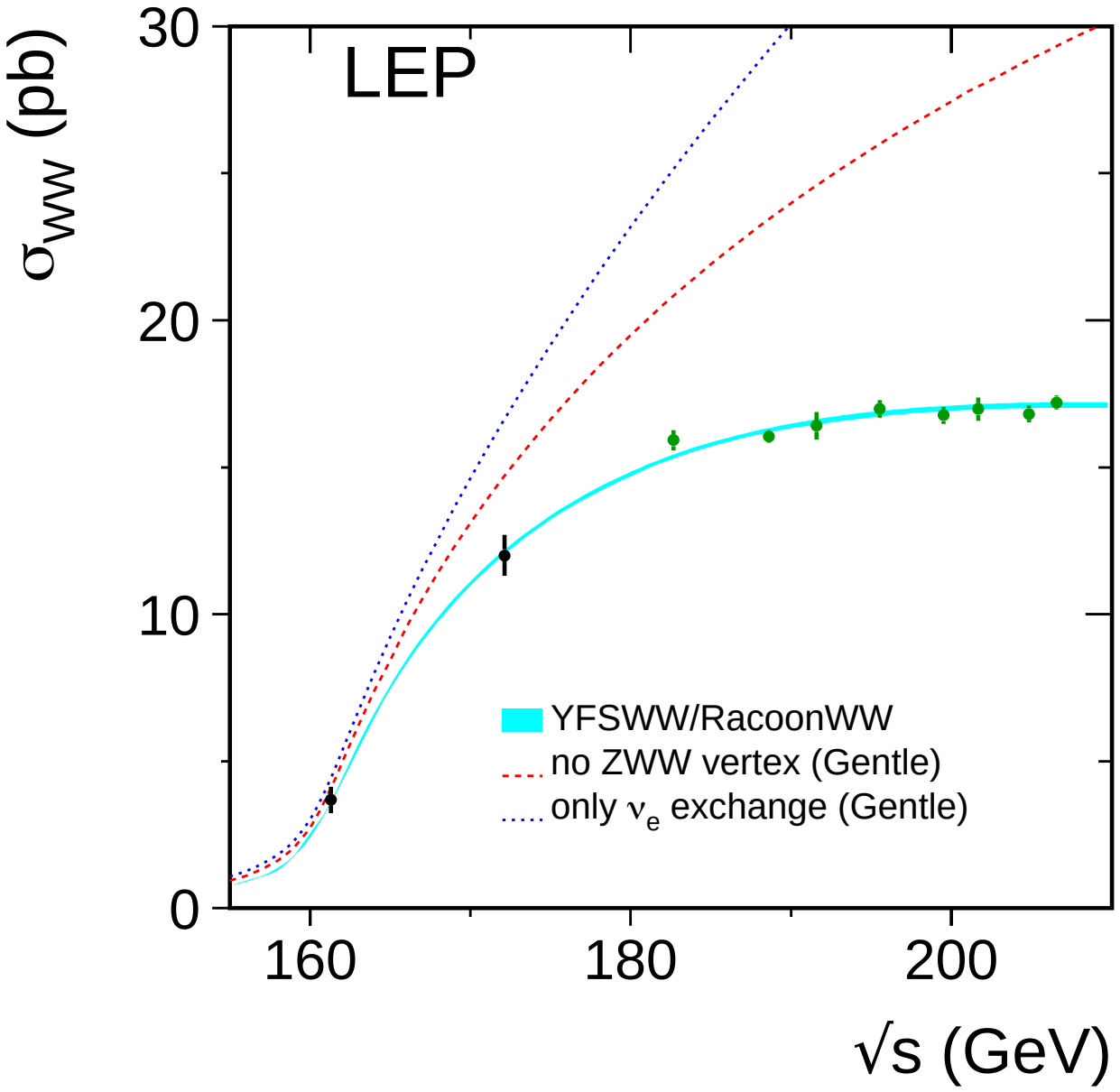
Why a Higgs boson "must" exist (first look)

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 (LEPEWWG)

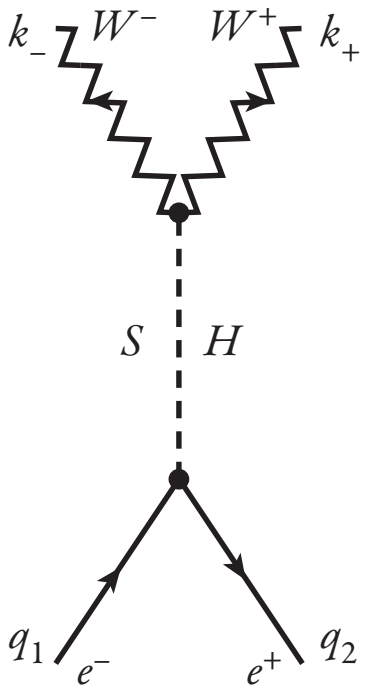


"Gauge cancellation" is not the final word

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

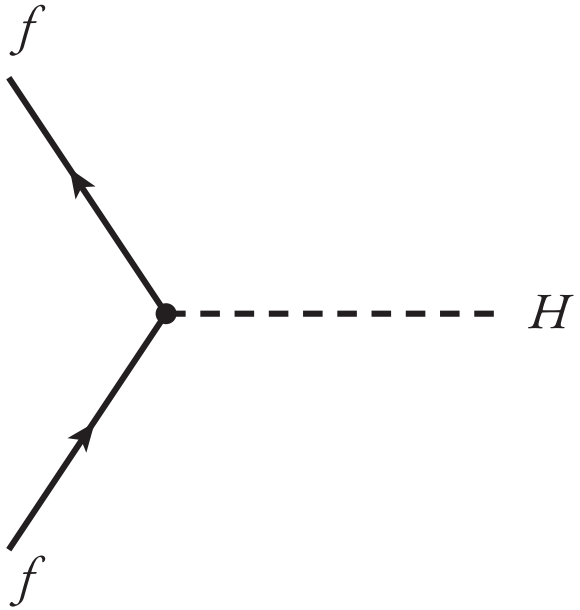
$$\mathcal{M}_{\nu}^{(0)} \propto s^{\frac{1}{2}} \quad \text{: unacceptable HE behavior}$$

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

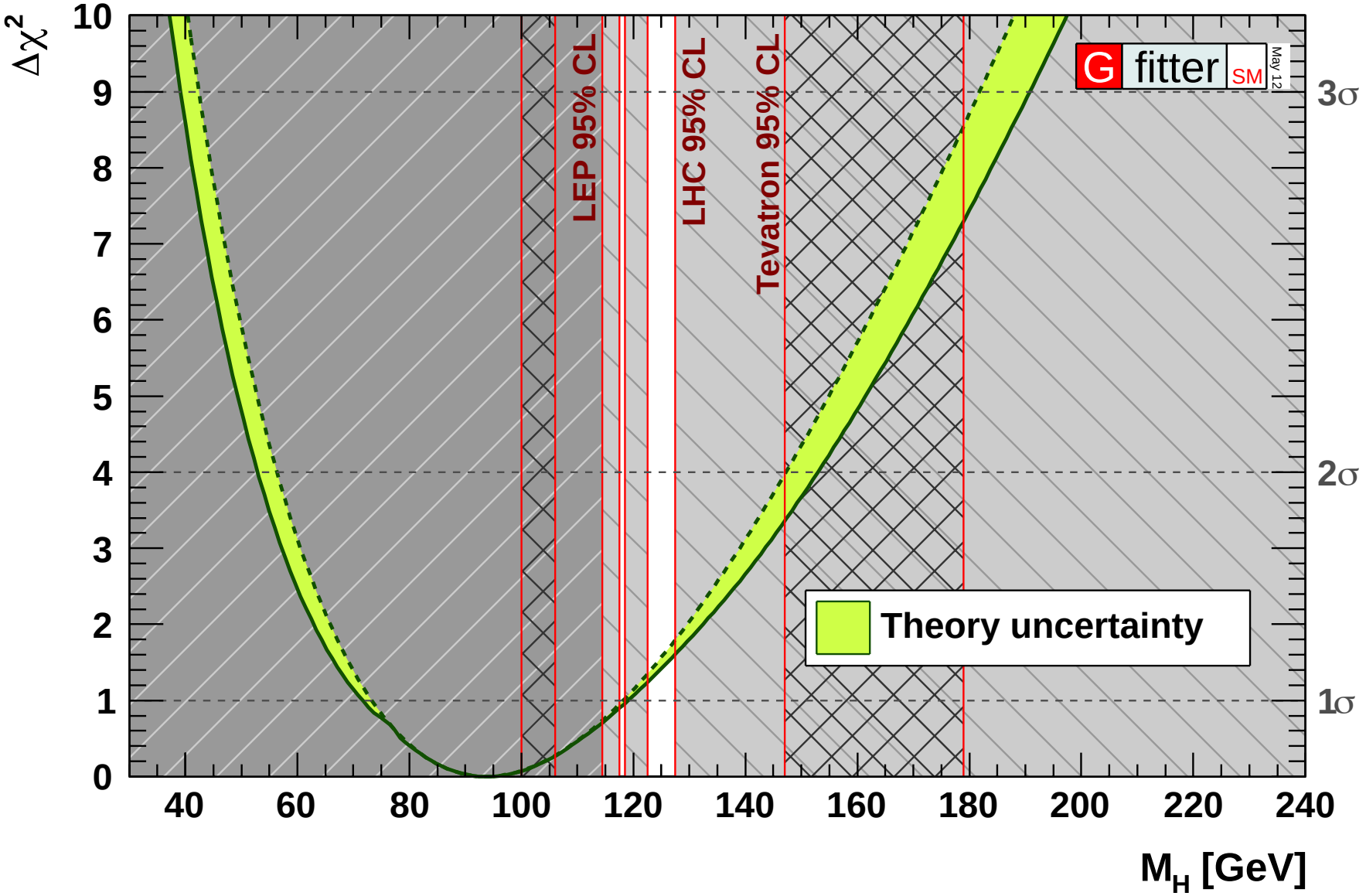
. . . and no viable low-energy phenomenology

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

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

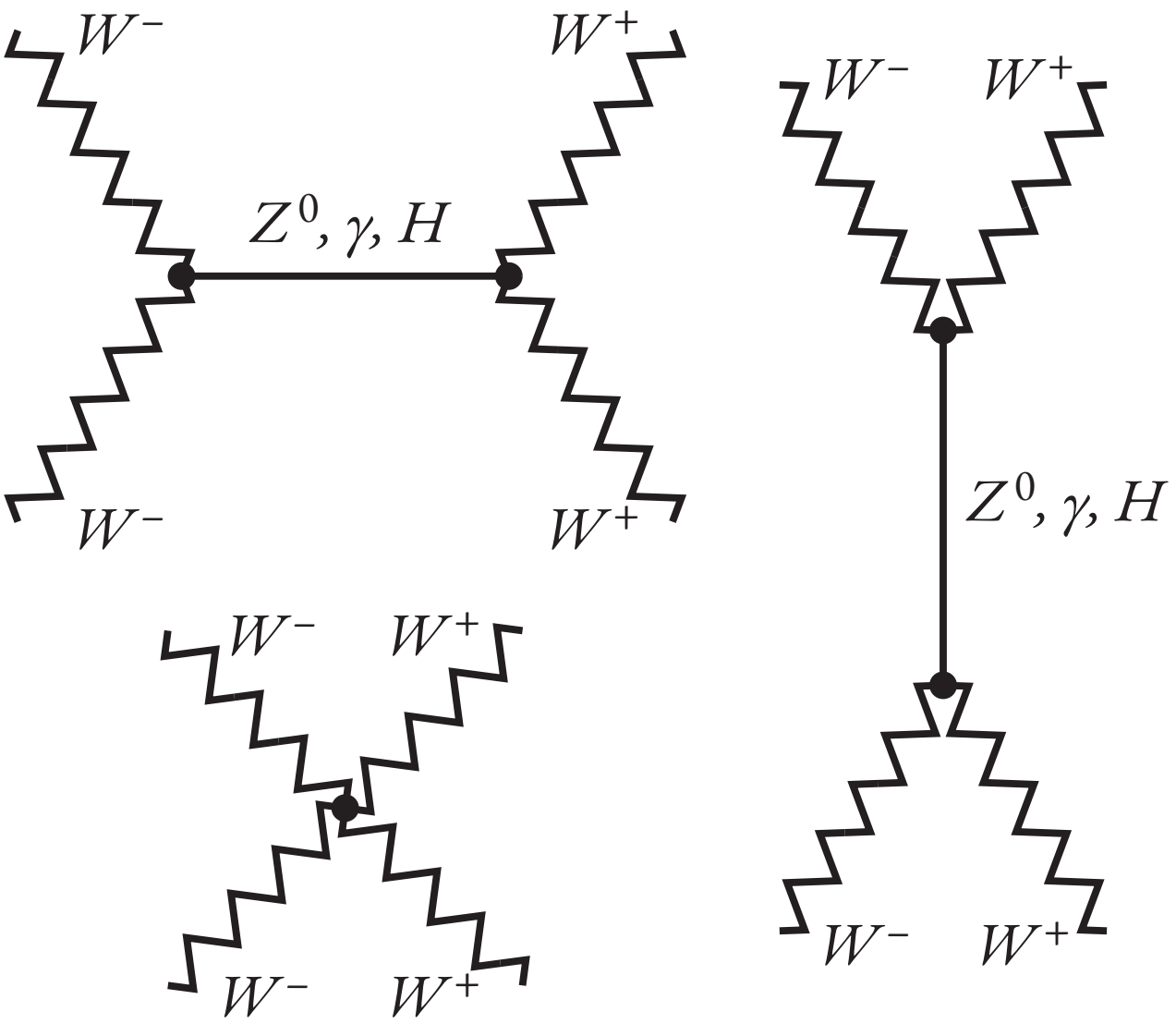
Most channels decouple – pw amplitudes are small at "all" energies – $\forall M_H$.

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

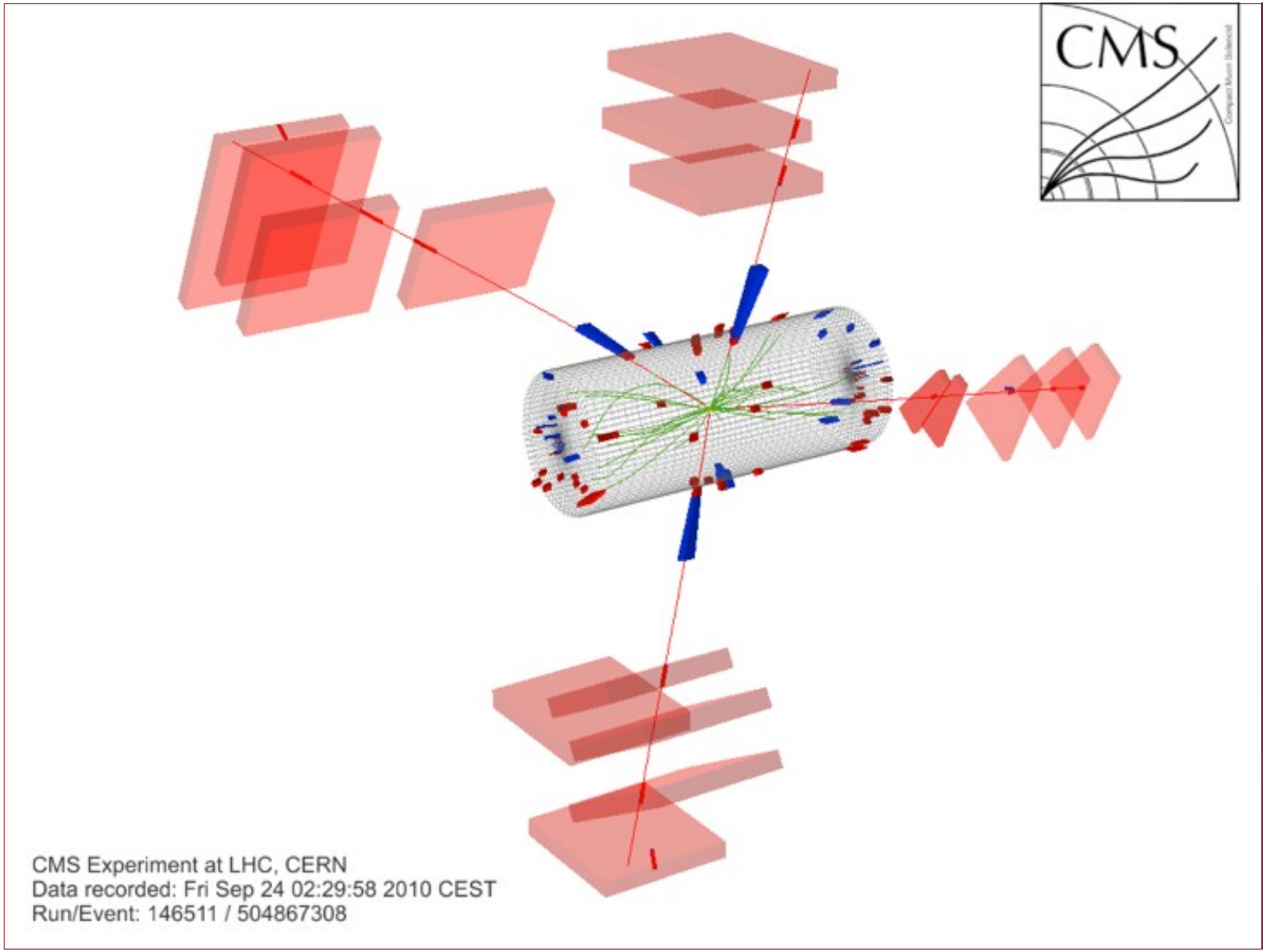
- weak interactions remain weak at all energies
- perturbation theory is everywhere reliable

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

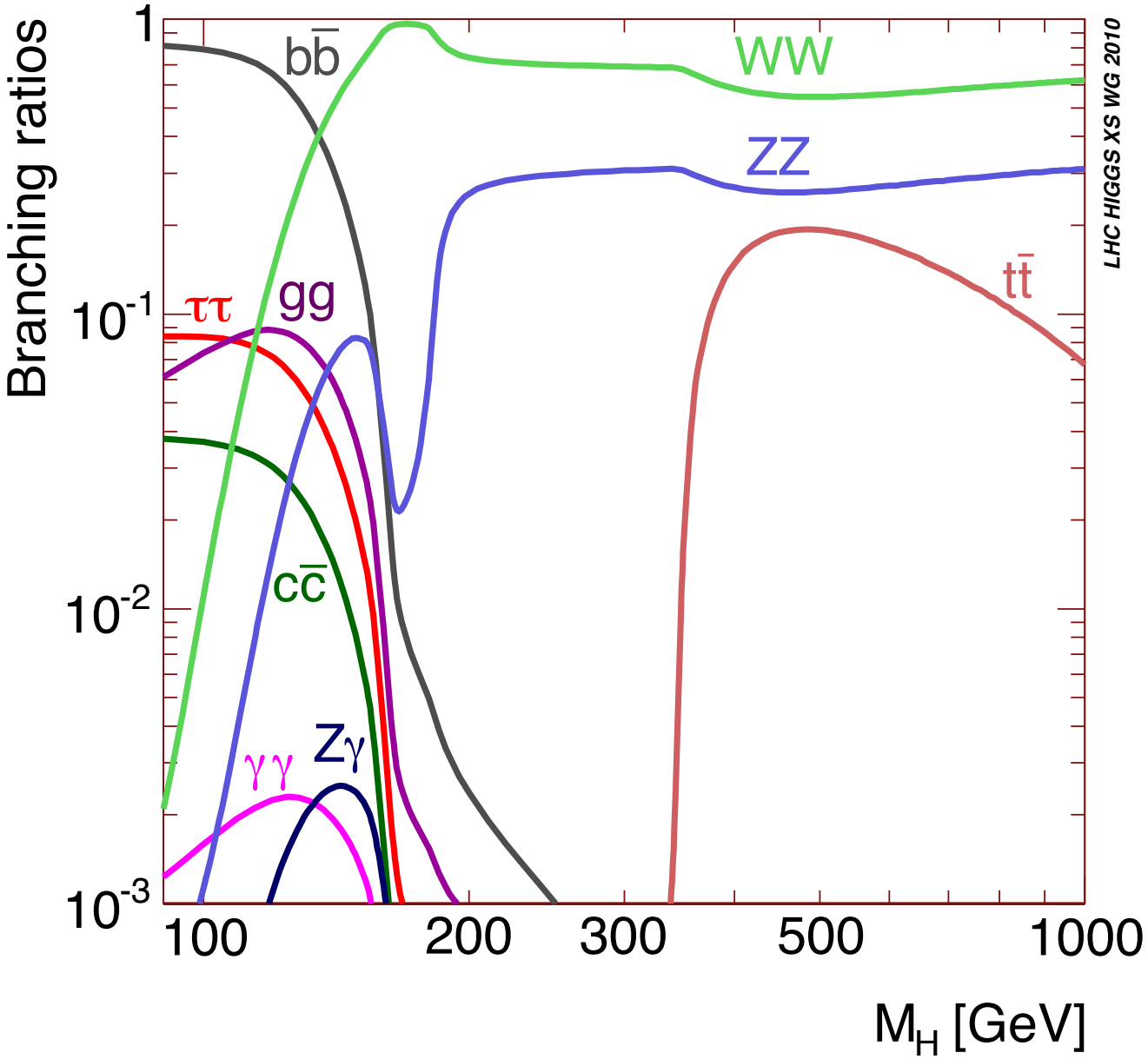
Exercise 6

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

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

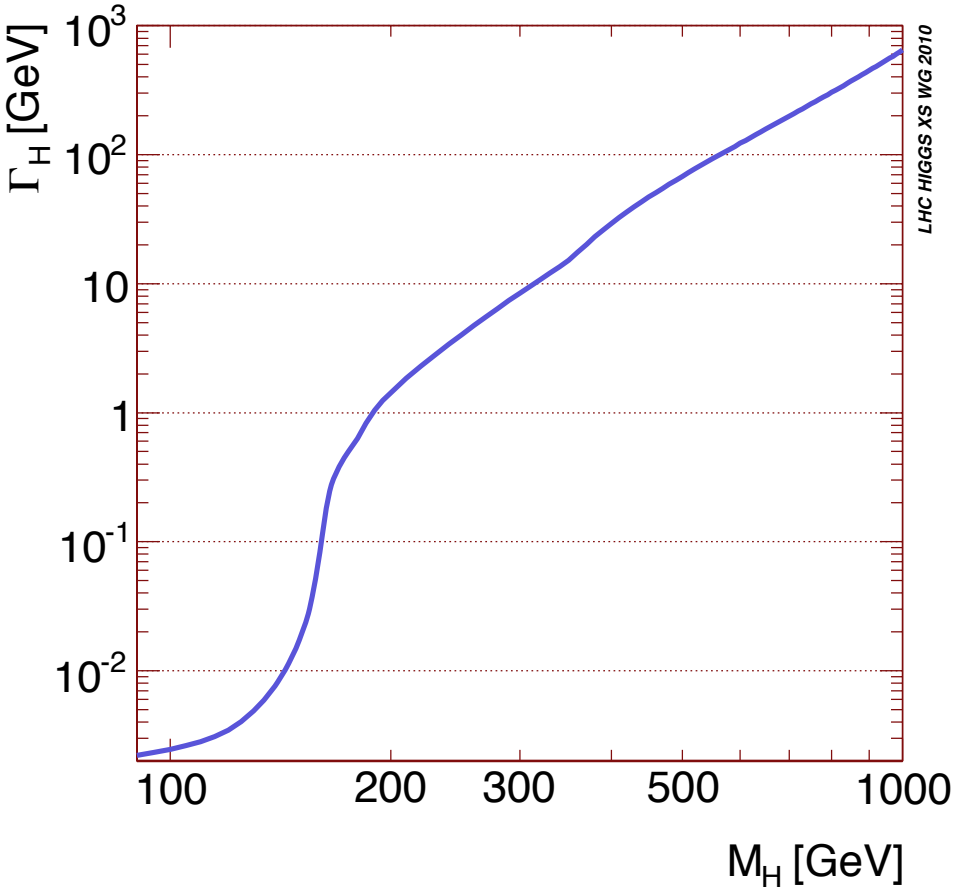
using the Feynman rule given above.

SM Higgs Boson Branching Fractions



Total width of the standard-model Higgs boson

$$\Gamma_H(M_H = 125.09 \text{ GeV}) = 4.08 \text{ MeV}$$



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 LEP $\rightsquigarrow M_H \gtrsim 114.4$ GeV

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

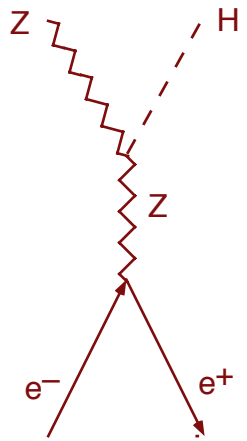
At the LHC:
Many channels accessible, search sensitive up to 1 TeV

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*

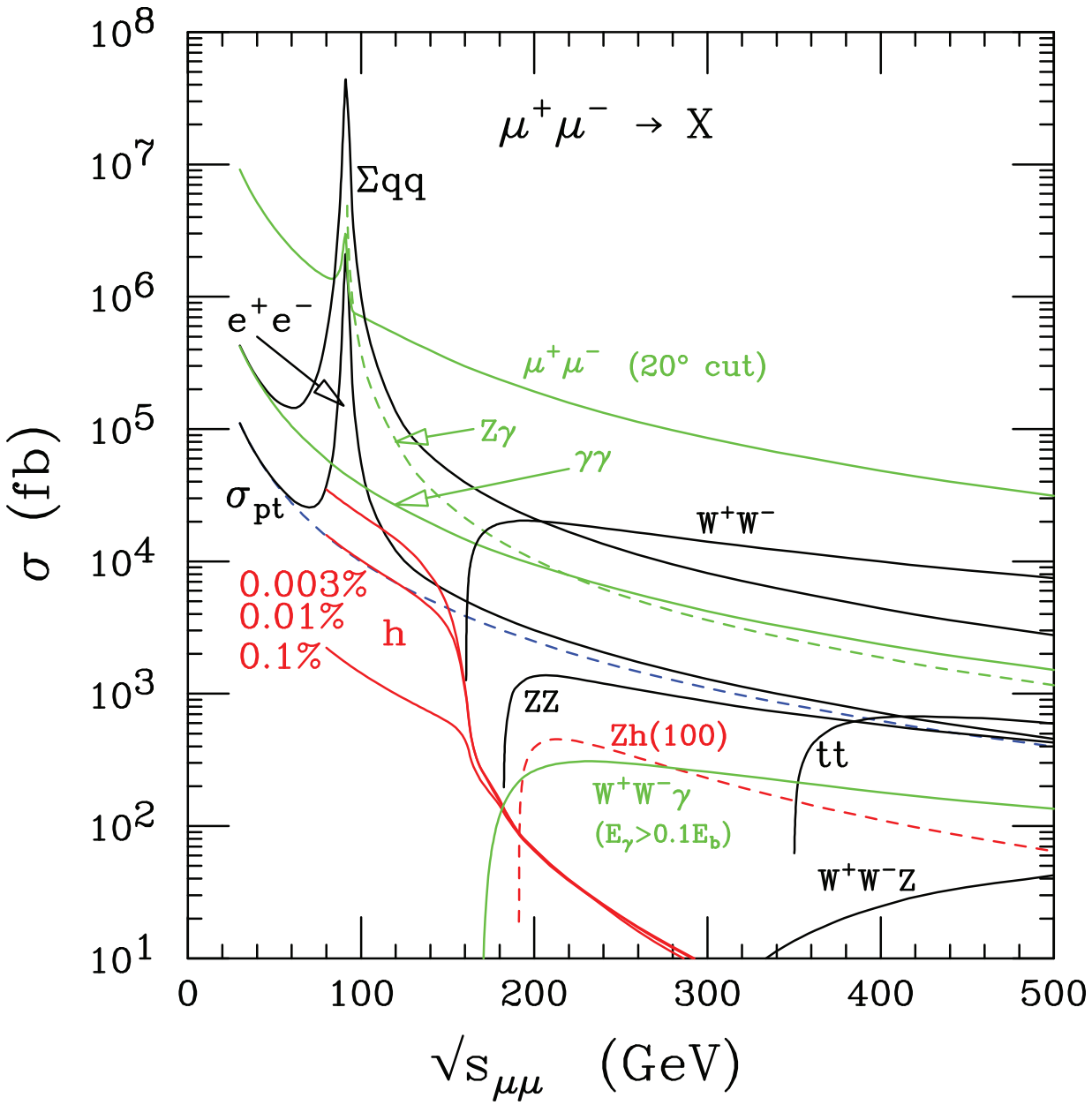
Most promising:
associated production $e^+e^- \to HZ$
(has no small couplings)



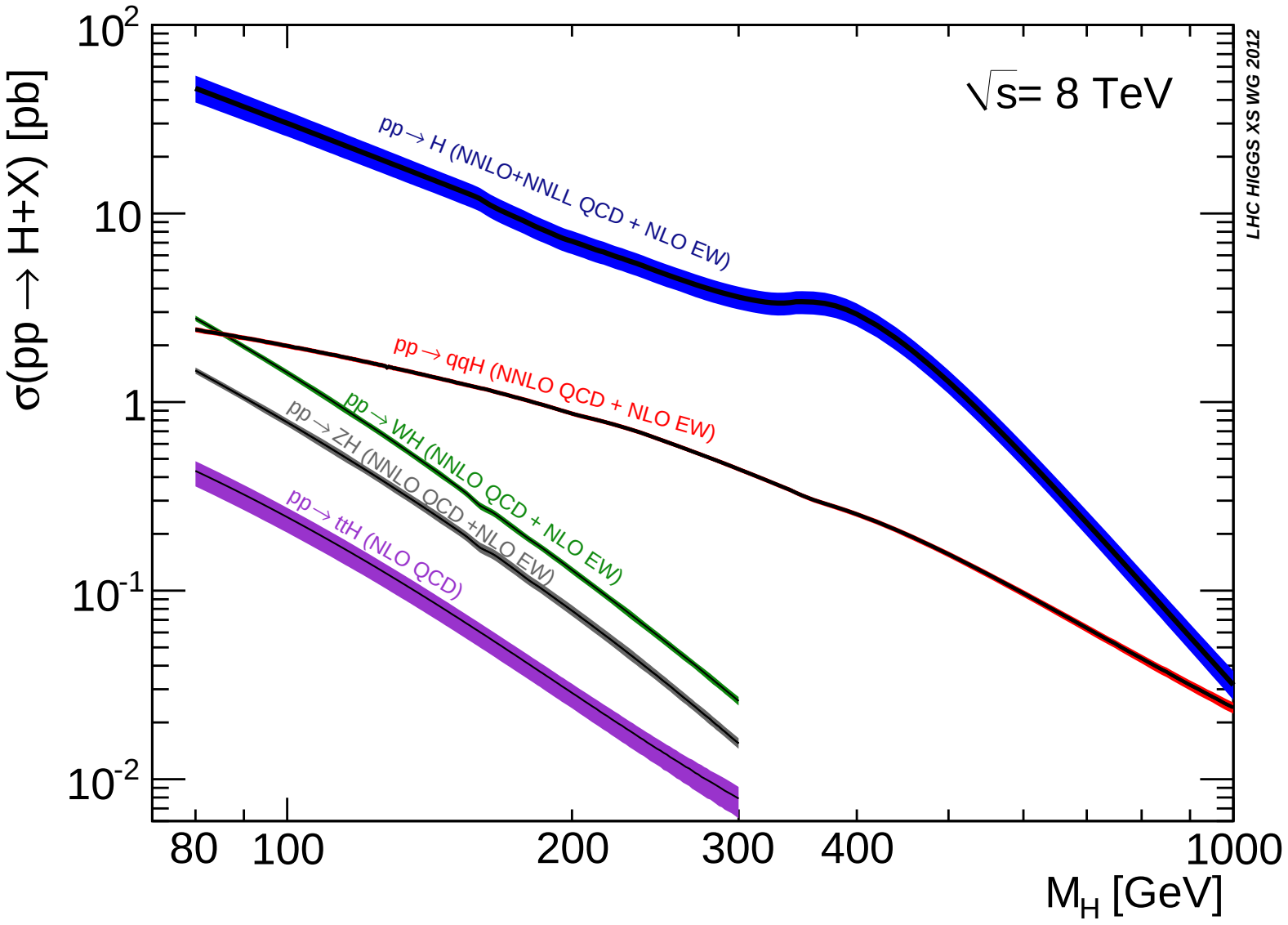
$$\sigma = \frac{\pi\alpha^2}{24\sqrt{s}} \frac{K(K^2 + 3M_Z^2)[1 + (1 - 4x_W)^2]}{(s - M_Z^2)^2 \quad x_W^2(1 - x_W)^2}$$

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

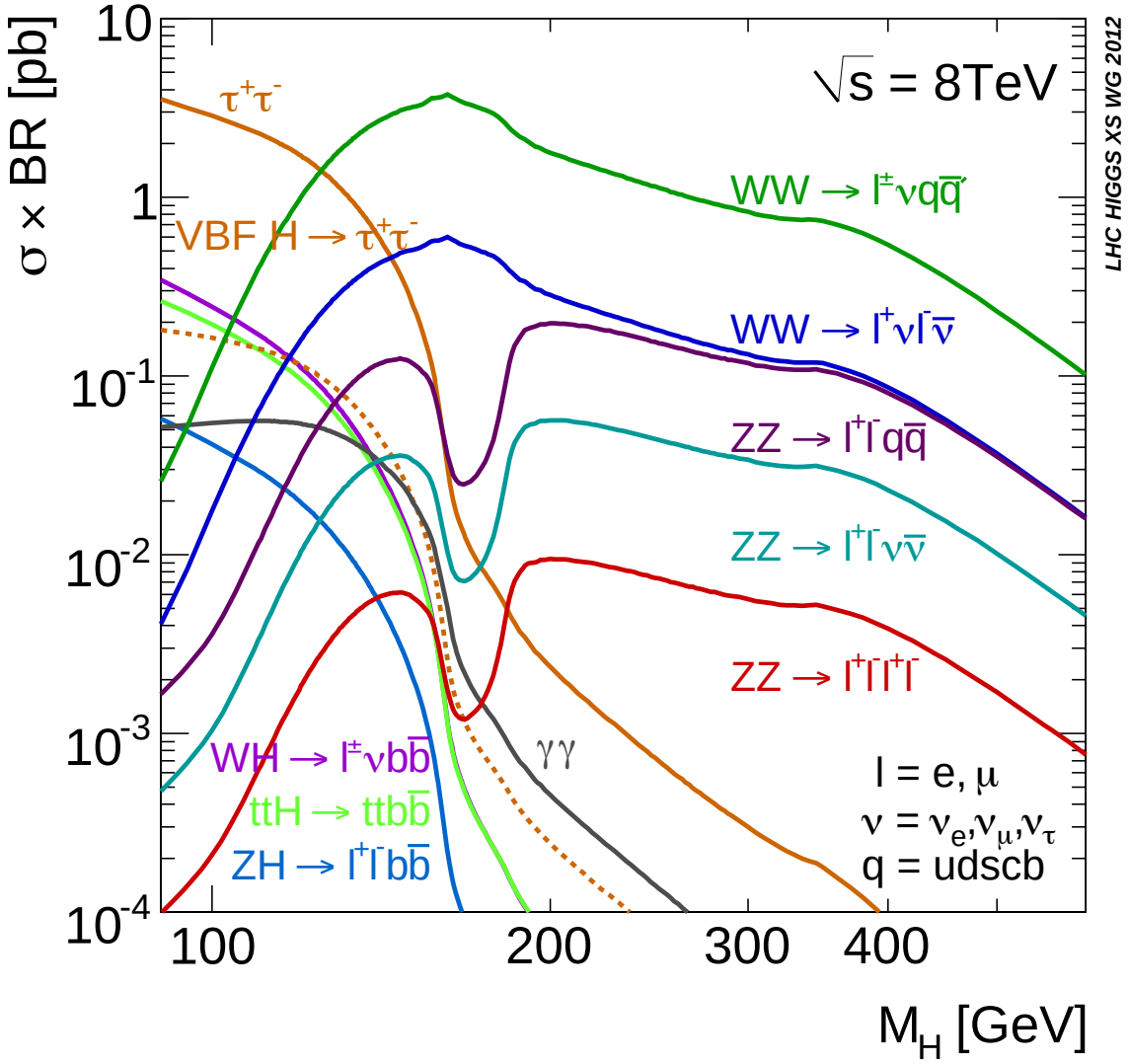
$\ell^+\ell^- \to X \ldots$



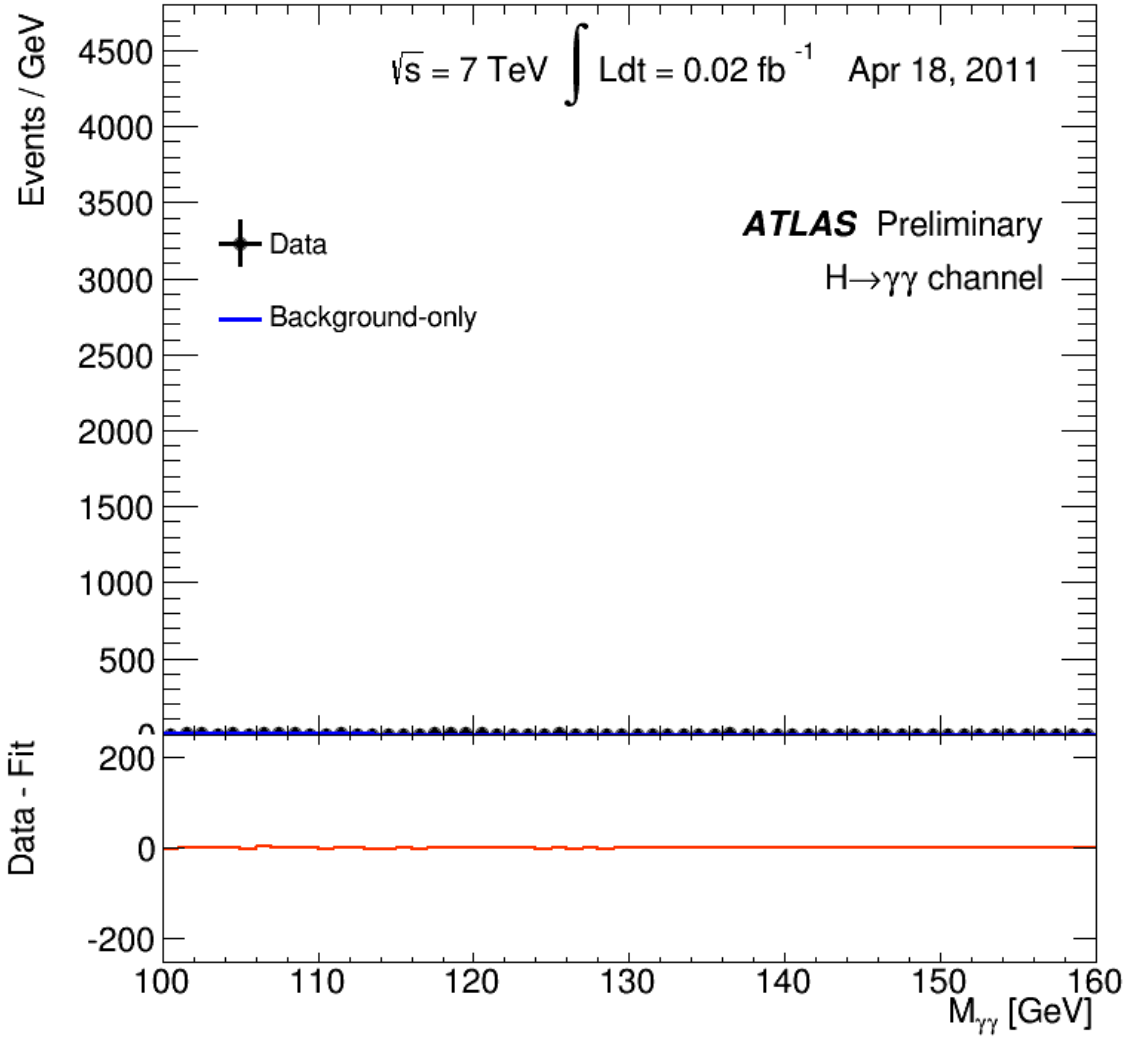
Higgs-boson production at the LHC: 8 TeV



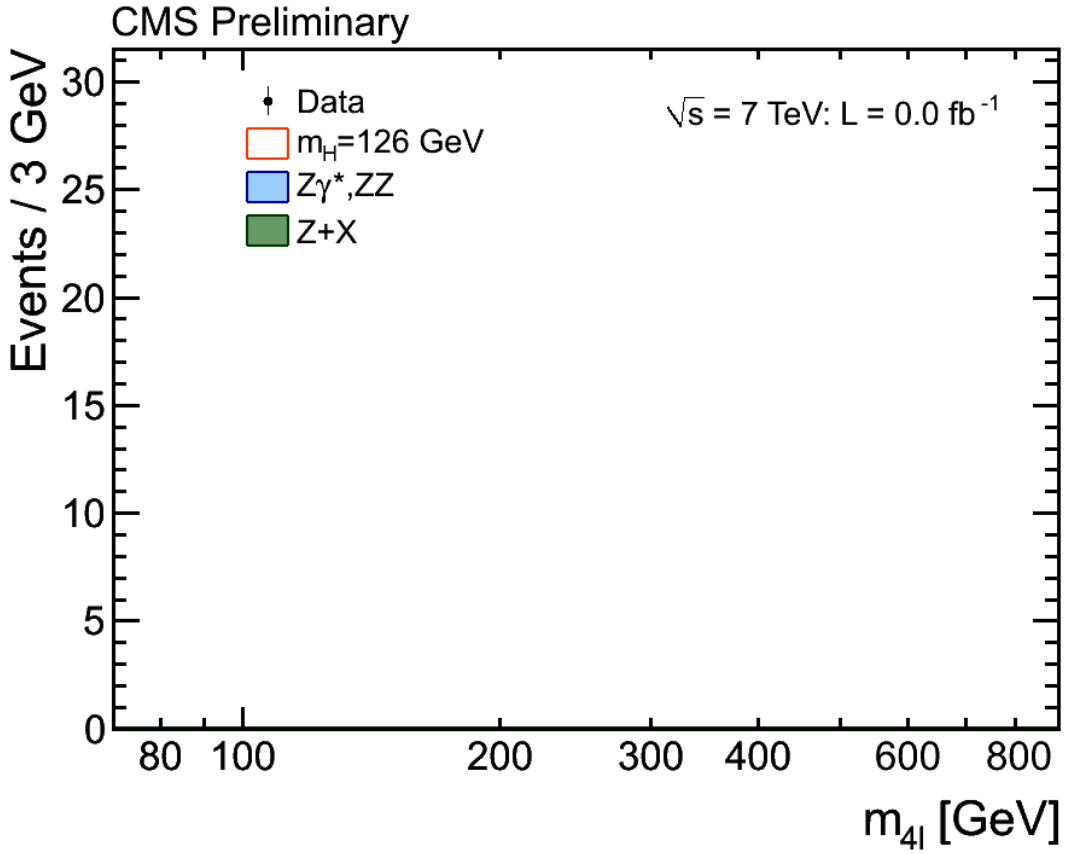
Higgs-boson production and decay: 8 TeV



ATLAS $\gamma\gamma$ signal evolution



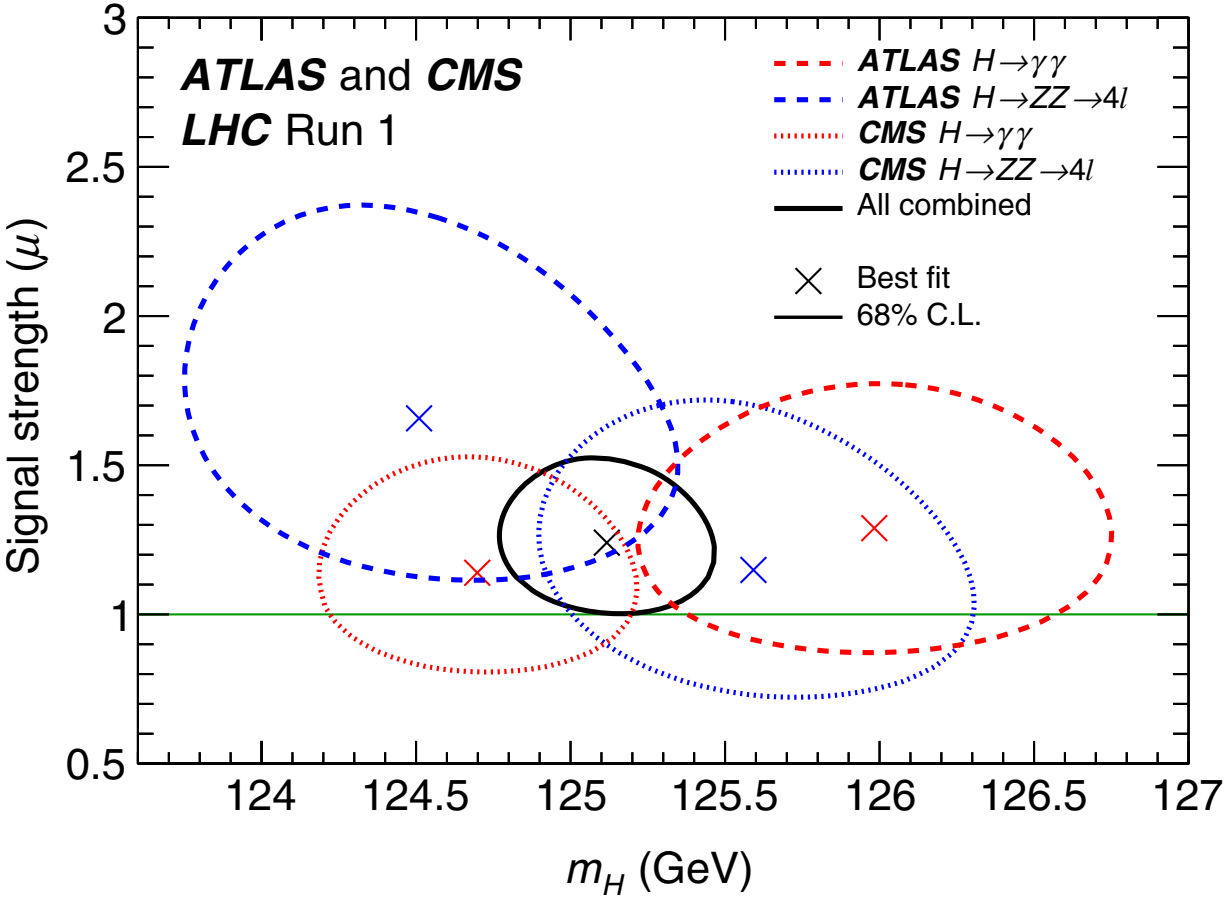
CMS 4μ signal evolution



Evolution of evidence at the LHC (+ Tevatron)

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

Unstable neutral particle, $M_H = 125.09 \pm 0.24$ GeV



CQ *Viewpoint*

Calculated Branching Fractions, $M_H = 125.1$ GeV

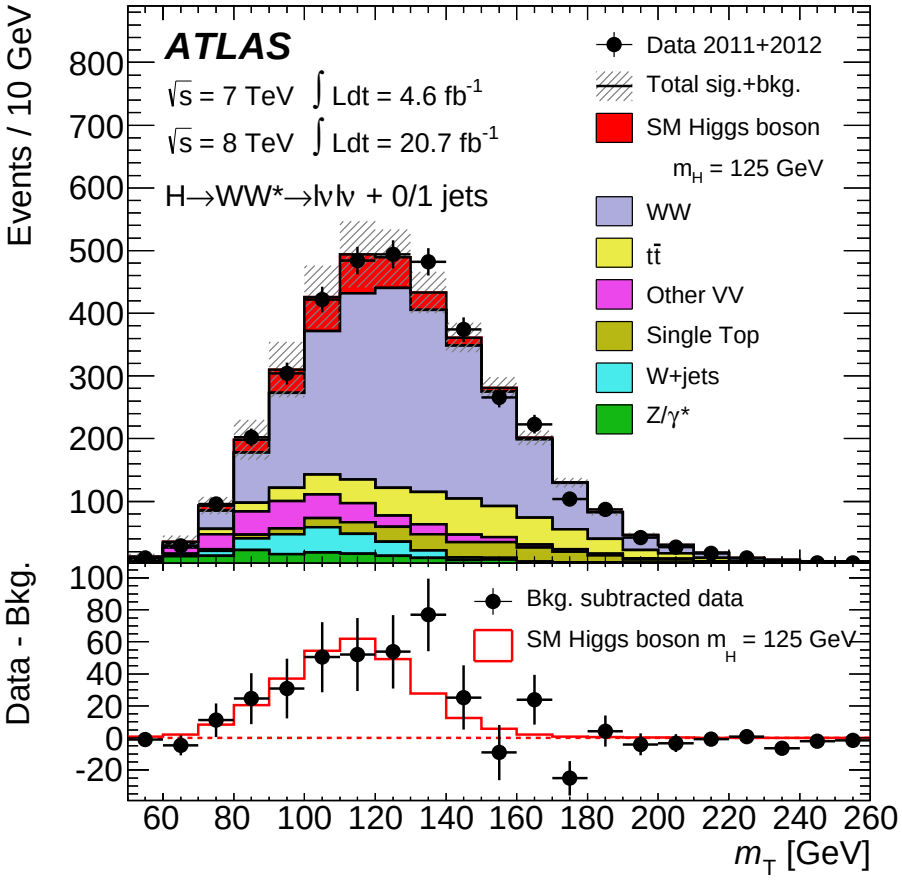
$b\bar{b}$	0.575
W^+W^-	0.216
gg	0.0856
$\tau^+\tau^-$	0.0630
$c\bar{c}$	0.0290
Z^0Z^0	0.0267
$\gamma\gamma$	2.28×10^{-3}
γZ^0	1.55×10^{-3}
$s\bar{s}$	2.46×10^{-4}
$\mu^+\mu^-$	2.19×10^{-4}
...	

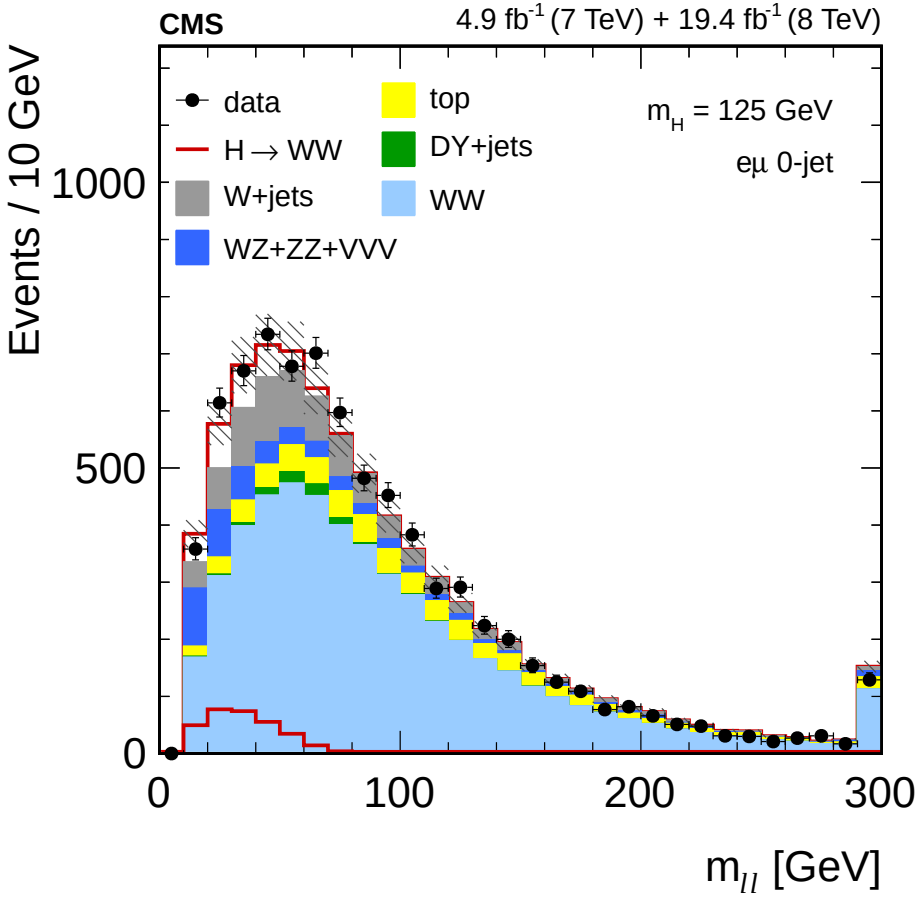
LHC Higgs Cross Section Working Group

Evolution of evidence at the LHC

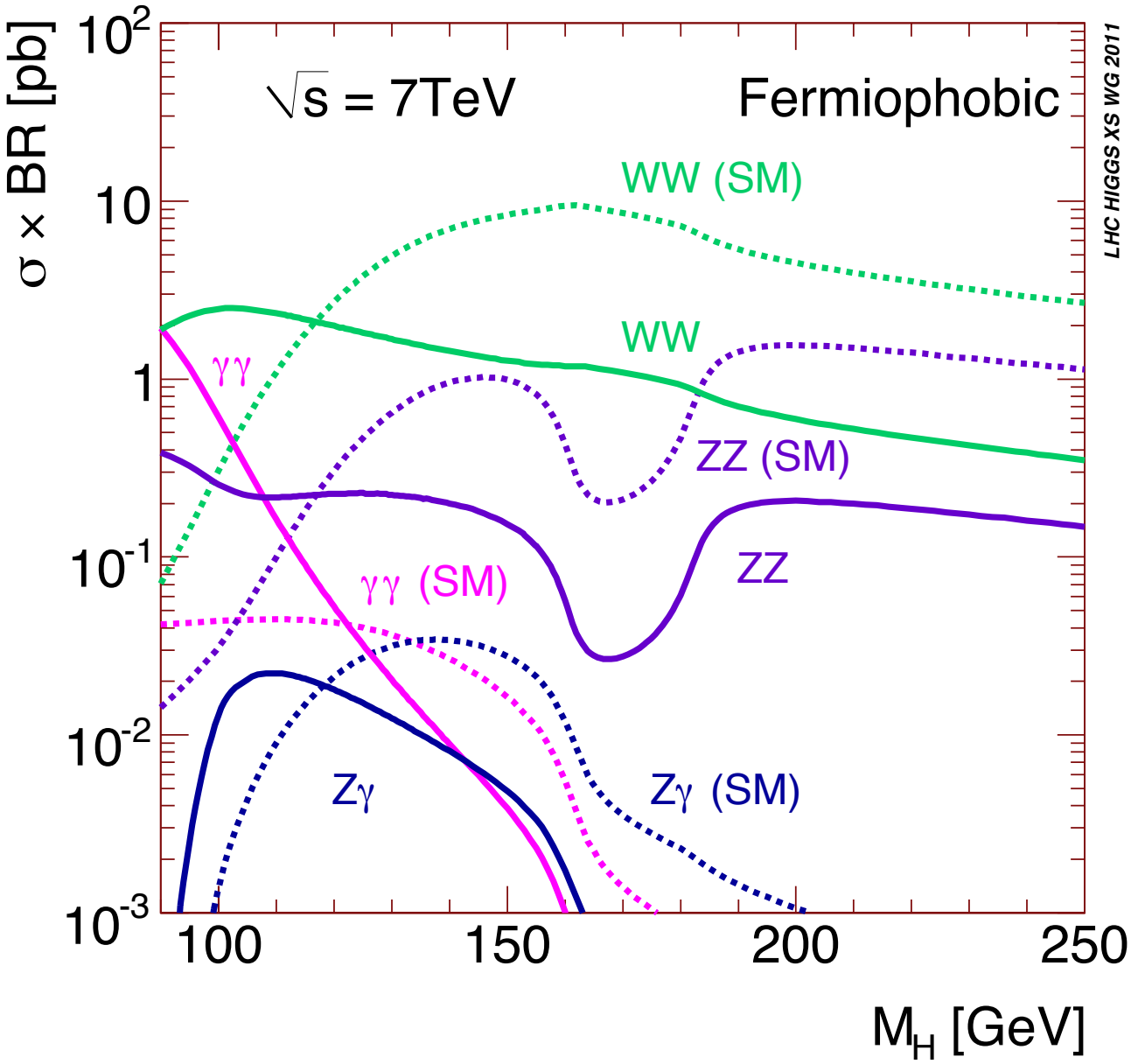
Signal established in $\gamma\gamma$, W^+W^-, Z^0Z^0

W^+W^-, Z^0Z^0 rates establish role in EWSB

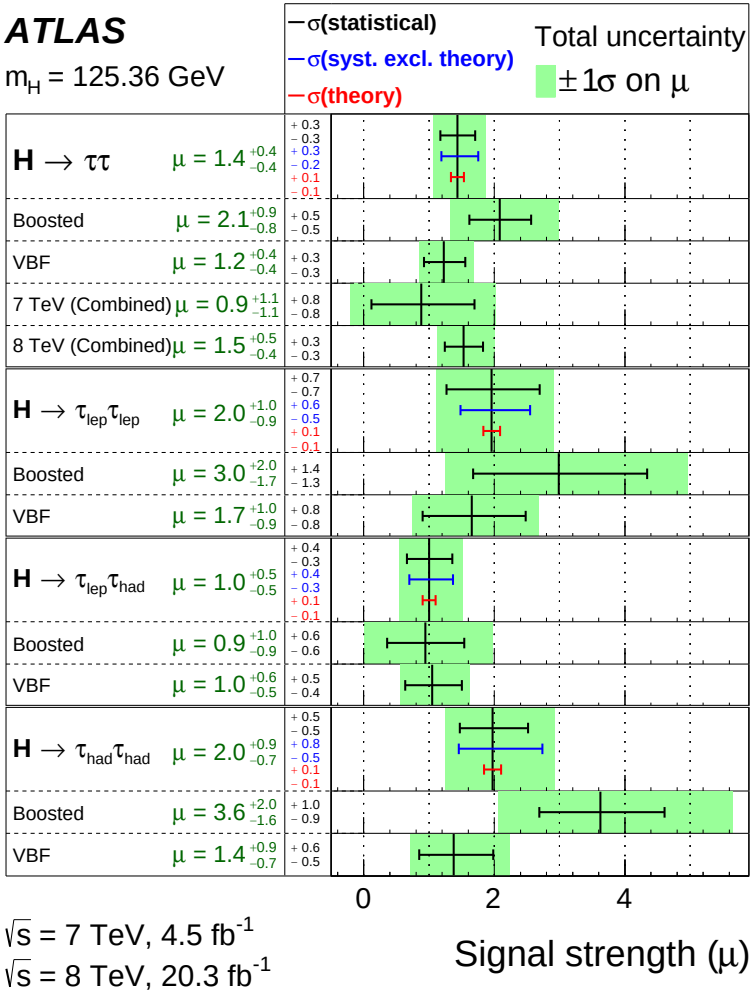


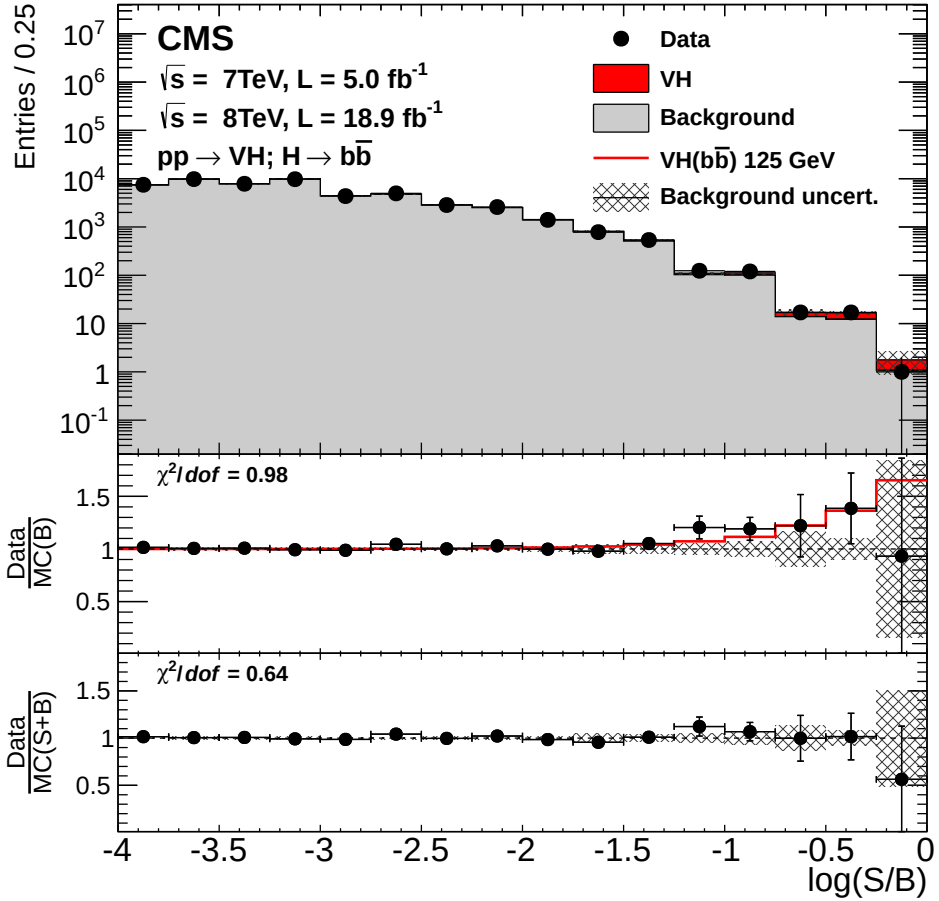


Distinguishing SM, bosogamous Higgs bosons



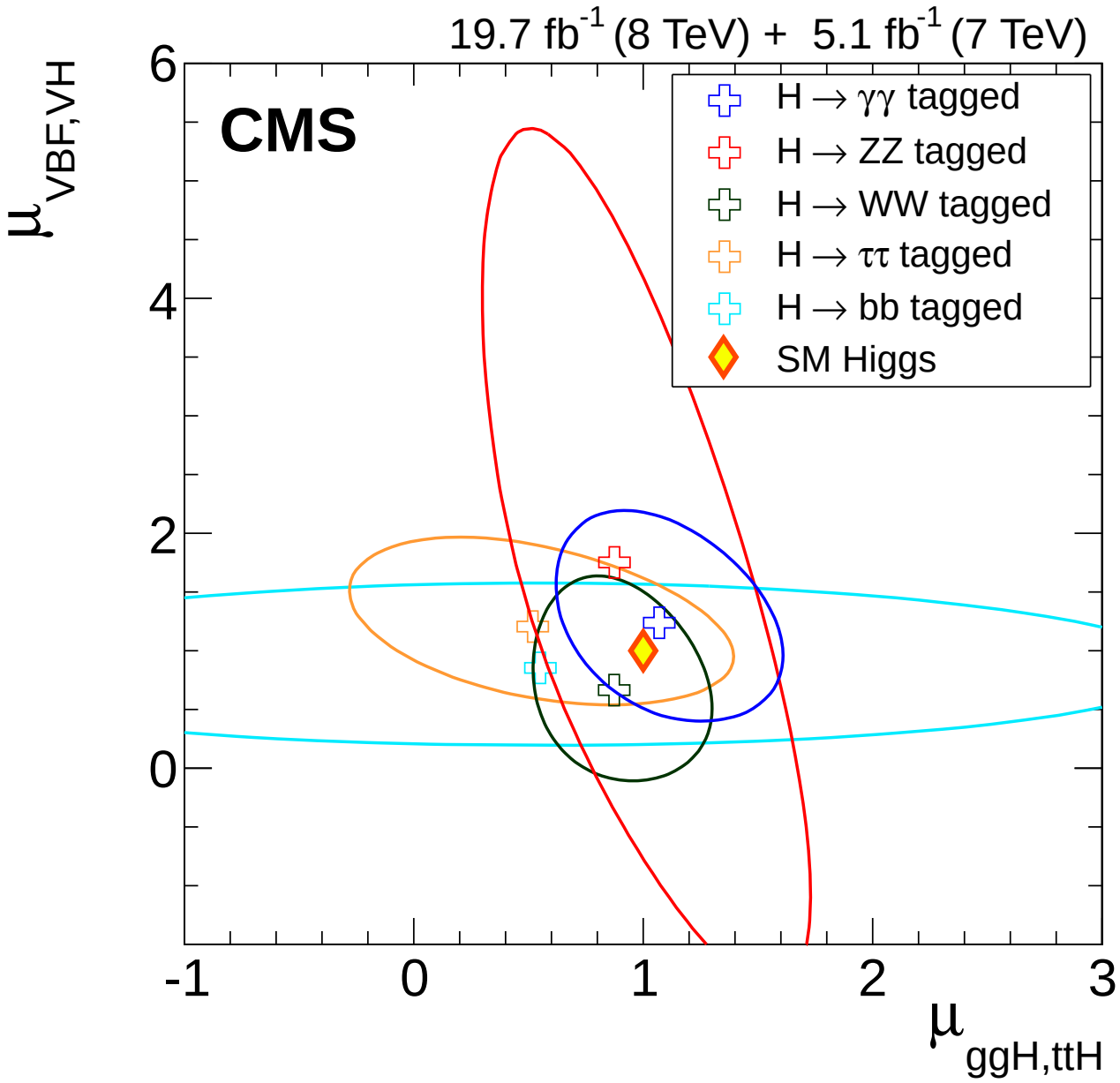
Evidence for $\tau^+\tau^-$, $b\bar{b}$, $t\bar{t}$





Tevatron summary link

Gluon fusion & vector-boson fusion . . .



Quantum Numbers

$$\gamma\gamma \rightsquigarrow C = + \text{ (assuming CPT)}$$

If a single state, $\gamma\gamma$ rules out $J = 1$

$J^P = 0^+$ overwhelmingly favored

The Standard Model $J^P = 0^+$ hypothesis for the Higgs boson has been compared to alternative spin–parity hypotheses using $\sqrt{s} = 8$ TeV (20.7 fb^{-1}) and 7 TeV (4.6 fb^{-1}) proton–proton collision data collected by the ATLAS experiment at the LHC. The Higgs boson decays $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to \ell\nu\ell\nu$ have been used to test several specific alternative models, including $J^P = 0^-, 1^+, 1^-$ and a graviton-inspired $J^P = 2^+$ model with minimal couplings to SM particles. The data favour the Standard Model quantum numbers of $J^P = 0^+$. The 0^- hypothesis is rejected at 97.8% CL by using the $H \to ZZ^* \to 4\ell$ decay alone. The 1^+ and 1^- hypotheses are rejected with a CL of at least 99.7% by combining the $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to \ell\nu\ell\nu$ channels. Finally, the $J^P = 2^+$ model is rejected at more than 99.9% CL by combining all three bosonic channels, $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to \ell\nu\ell\nu$, independent of the assumed admixture of gluon-fusion and quark–antiquark production. All alternative models studied in this Letter are excluded without assumptions on the strength of the couplings of the Higgs boson to SM parti-

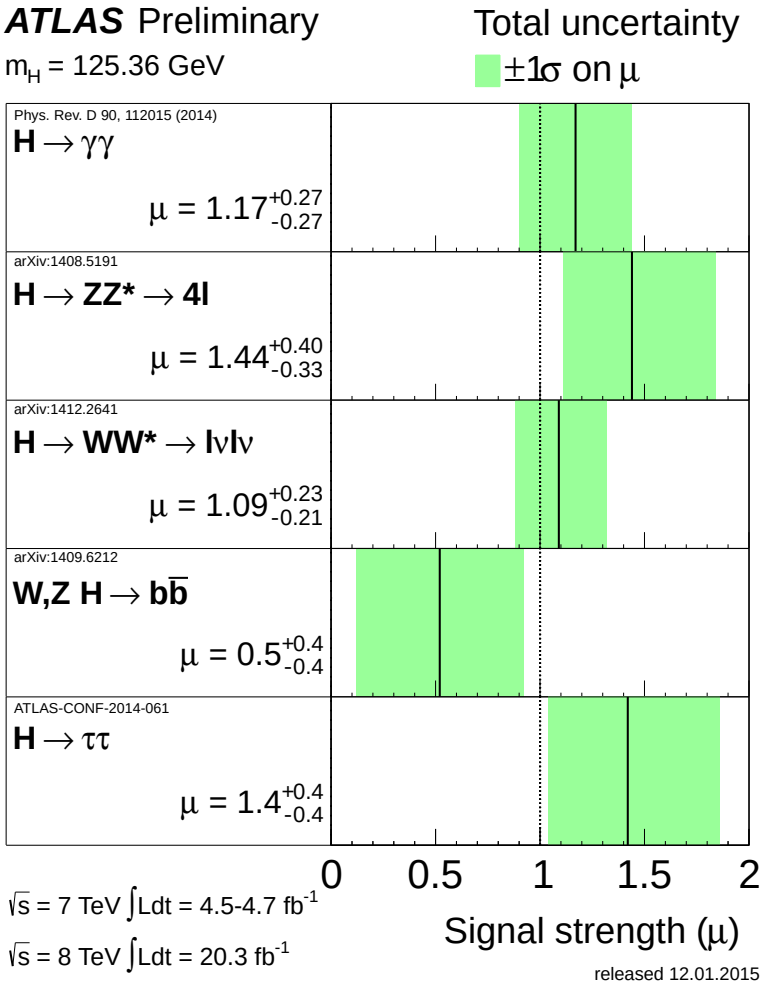
The study of the spin-parity and tensor structure of the interactions of the recently discovered Higgs boson is performed using the $H \to ZZ, Z\gamma^*, \gamma^*\gamma^* \to 4\ell$, $H \to WW \to \ell\nu\ell\nu$, and $H \to \gamma\gamma$ decay modes. The full dataset recorded by the CMS experiment during the LHC Run 1 is used, corresponding to an integrated luminosity of up to 5.1 fb^{-1} at a center-of-mass energy of 7 TeV and up to 19.7 fb^{-1} at 8 TeV. A wide range of spin-two models is excluded at a 99% confidence level or higher, or at a 99.87% confidence level for the minimal gravity-like couplings, regardless of whether assumptions are made on the production mechanism. Any mixed-parity spin-one state is excluded in the ZZ and WW modes at a greater than 99.999% confidence level. Under the hypothesis that the resonance is a spin-zero boson, the tensor structure of the interactions of the Higgs boson with two vector bosons ZZ, $Z\gamma$, $\gamma\gamma$, and WW is investigated and limits on eleven anomalous contributions are set. Tighter constraints on anomalous HVV interactions are obtained by combining the HZZ and HWW measurements. All observations are consistent with the expectations for the standard model Higgs boson with the quantum numbers $J^{PC} = 0^{++}$.

CDF+D0 rule against $J^P = 0^-, 2^+$

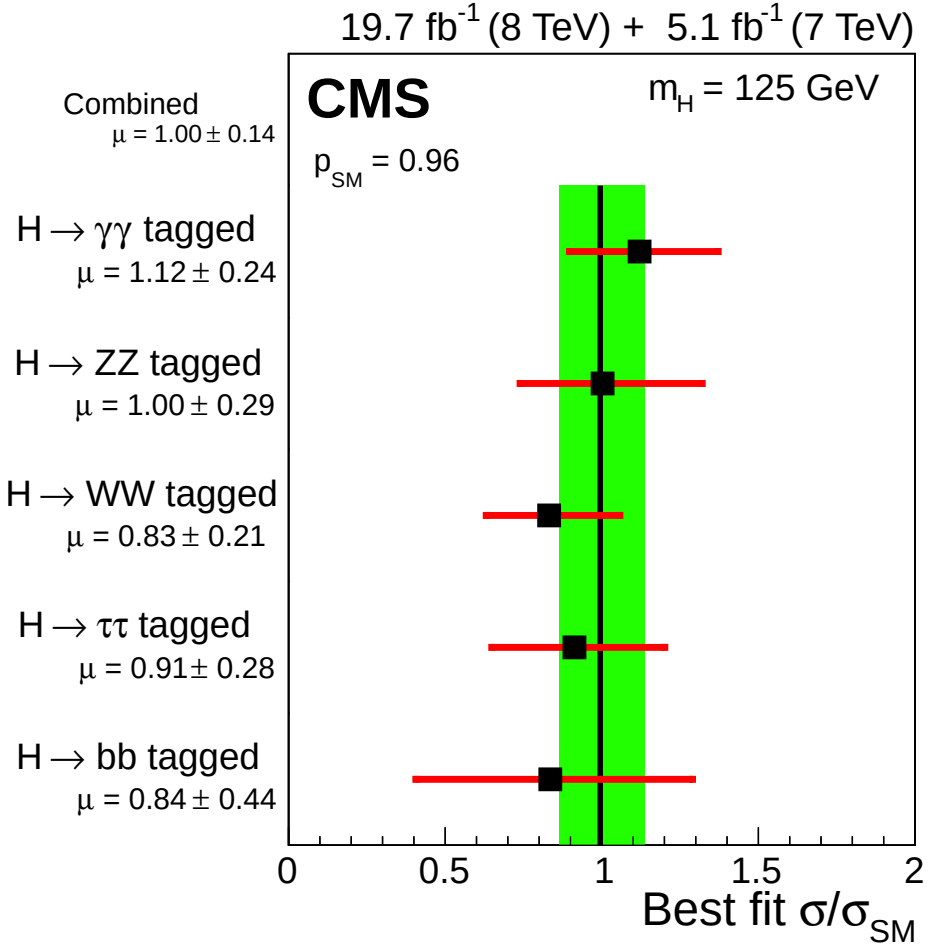
Compare KTeV determination of π^0 parity in $e^+e^-e^+e^-$

Consistency with Standard-Model Higgs

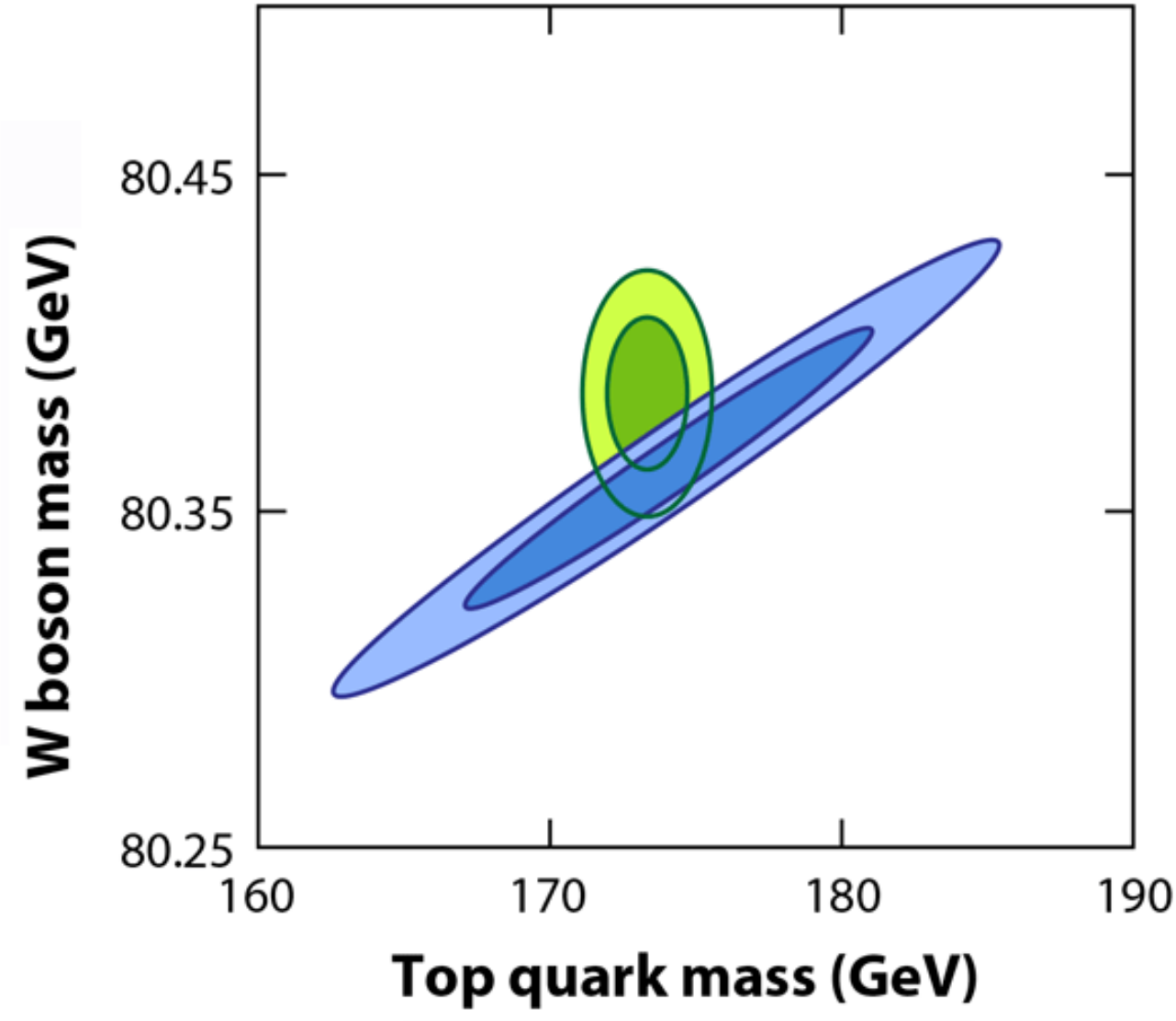
ATLAS twiki



CMS twiki



Testing Consistency: Direct vs. Indirect Measures



$M_W = 80.385 \pm 0.015$ GeV $\quad m_t = 173.21 \pm 0.87$ GeV Gfitter