Why we care about the Higgs boson

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Graduate Student Physics Conference

Washington, D.C., September 29–October 1, 2011

Outline

Introduction

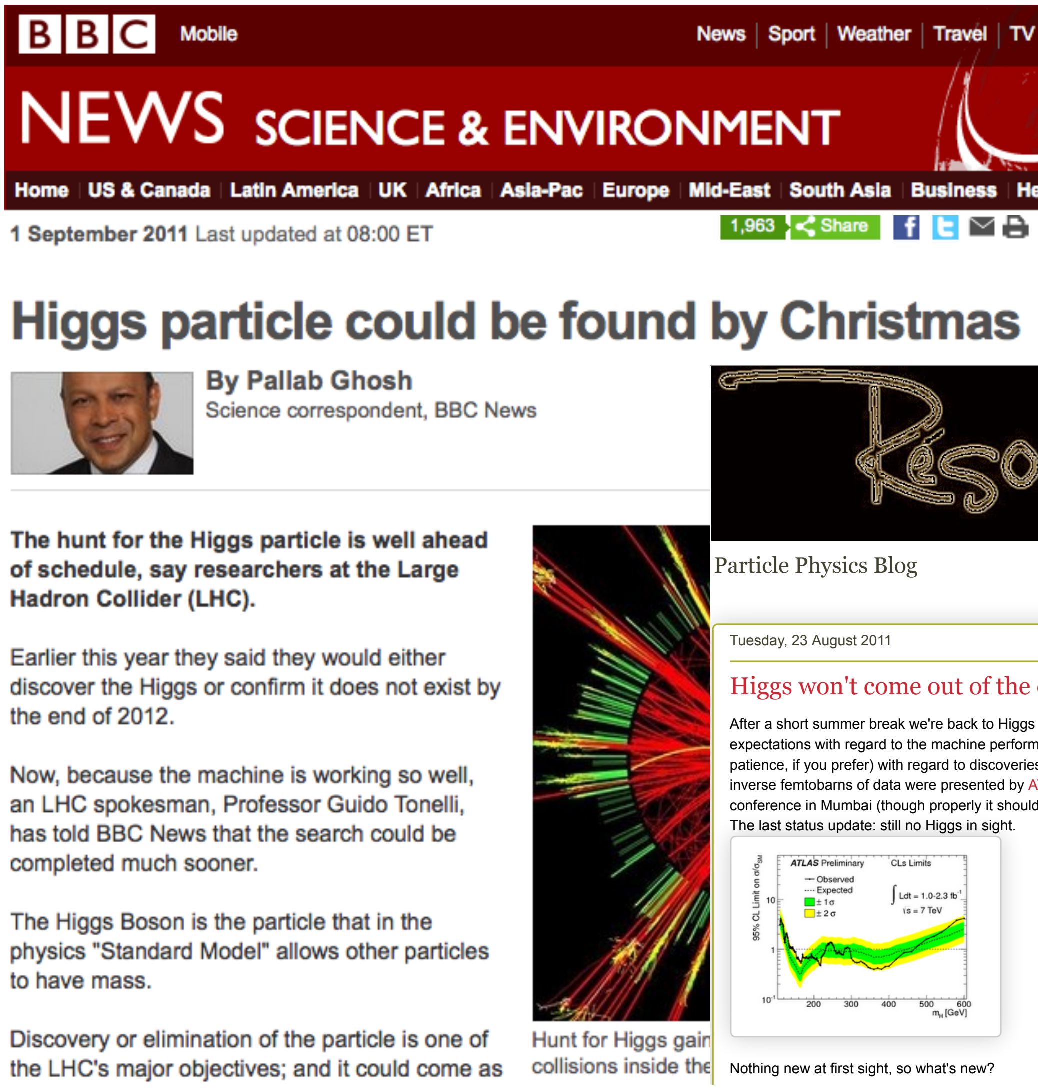
The problem with weak interactions

Higgs searches at the Large Hadron Collider

Outlook

Introduction

The hunt for the Higgs boson is all over the media.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1 September 2011 Last updated at 08:00 ET

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Higgs particle could be found by Christmas

By Pallab Ghosh
Science correspondent, BBC News

The hunt for the Higgs particle is well ahead of schedule, say researchers at the Large Hadron Collider (LHC).

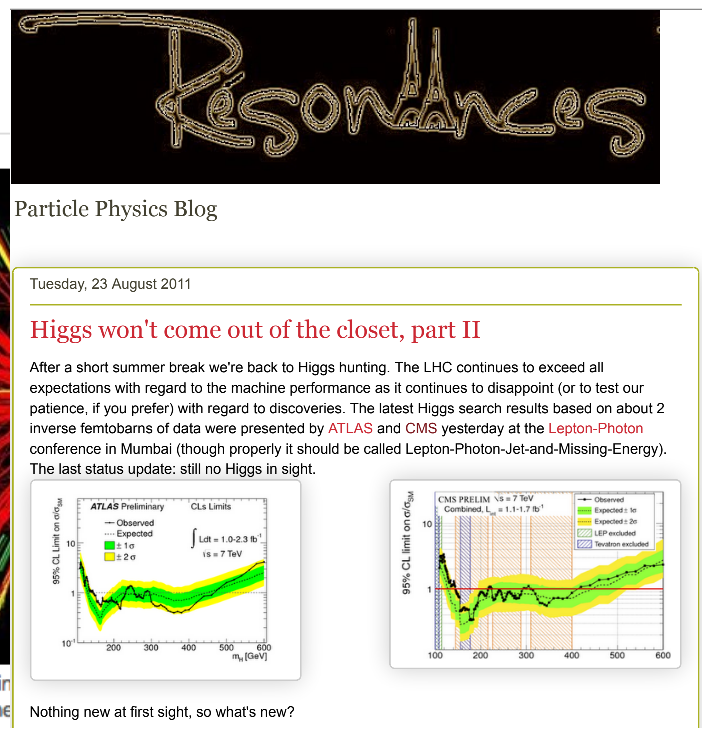
Earlier this year they said they would either discover the Higgs or confirm it does not exist by the end of 2012.

Now, because the machine is working so well, an LHC spokesman, Professor Guido Tonelli, has told BBC News that the search could be completed much sooner.

The Higgs Boson is the particle that in the physics "Standard Model" allows other particles to have mass.

Discovery or elimination of the particle is one of the LHC's major objectives; and it could come as

Hunt for Higgs gain collisions inside the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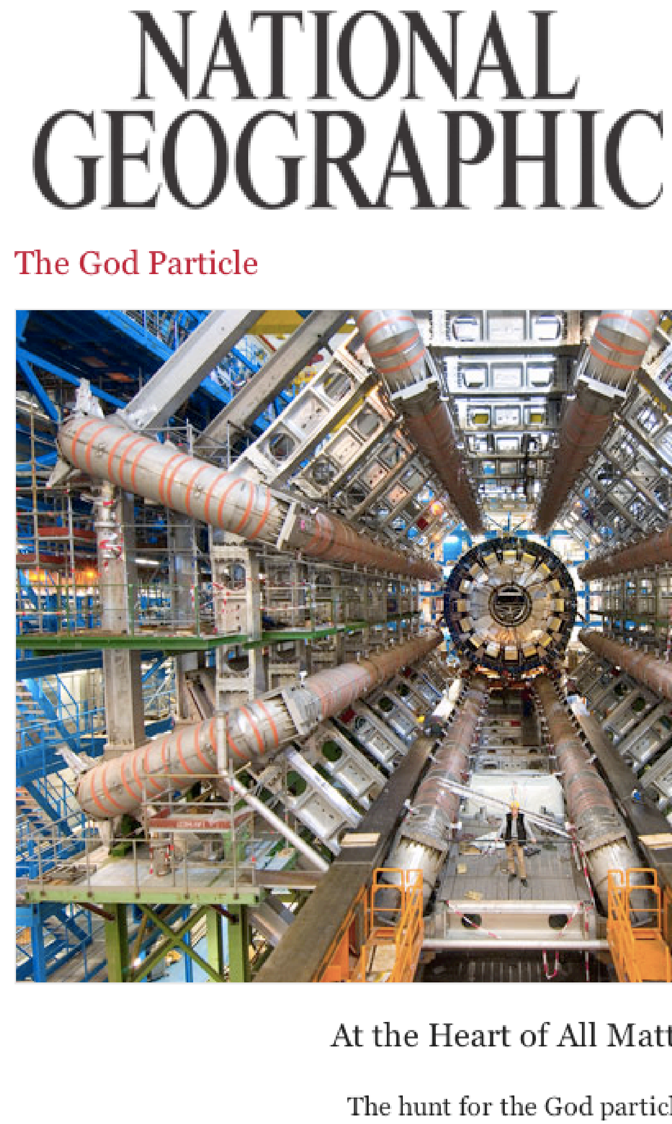
Particle Physics Blog

Tuesday, 23 August 2011

Higgs won't come out of the closet, part II

After a short summer break we're back to Higgs hunting. The LHC continues to exceed all expectations with regard to the machine performance as it continues to disappoint (or to test our patience, if you prefer) with regard to discoveries. The latest Higgs search results based on about 2 inverse femtobarns of data were presented by ATLAS and CMS yesterday at the Lepton-Photon conference in Mumbai (though properly it should be called Lepton-Photon-Jet-and-Missing-Energy). The last status update: still no Higgs in sight.

Nothing new at first sight, so what's new?


NATIONAL GEOGRAPHIC

The God Particle

At the Heart of All Matte

The hunt for the God particle

The Higgs boson is supposed to be responsible for
"giving things mass."

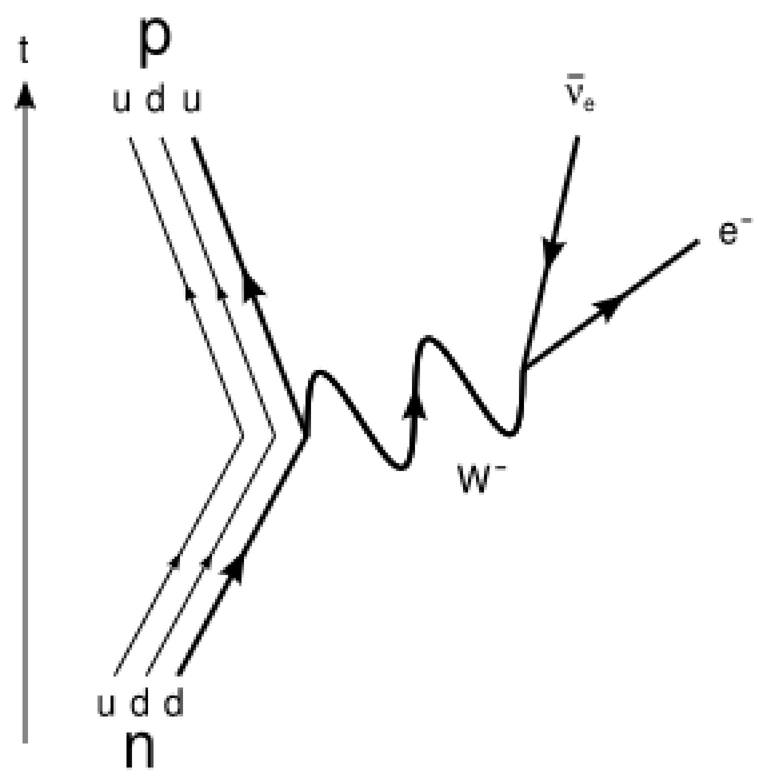
What does this mean? What does the Higgs really do?

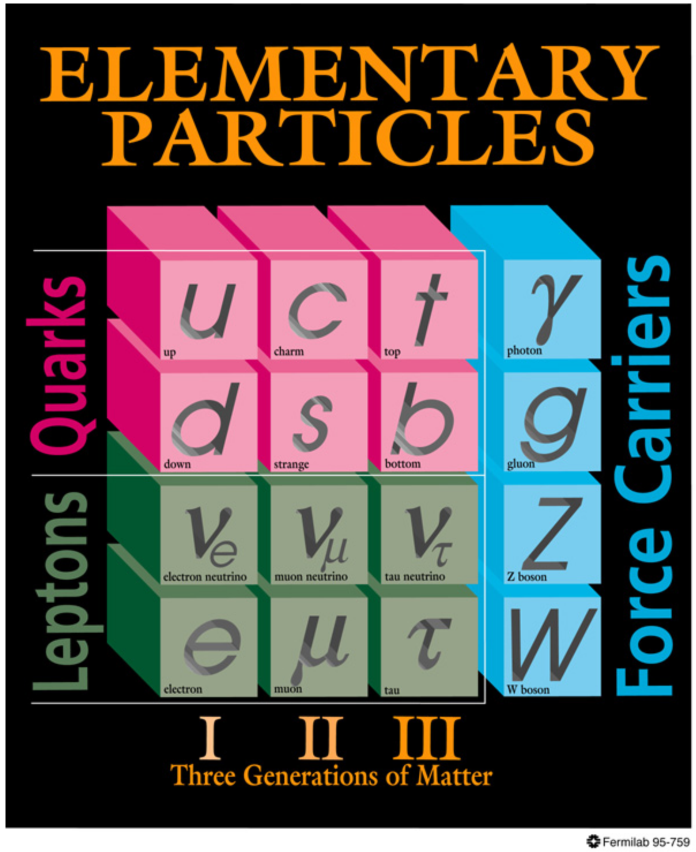
Why are we convinced that it—or something that does its job—must exist?

This story starts with the weak interactions.

The problem with weak interactions

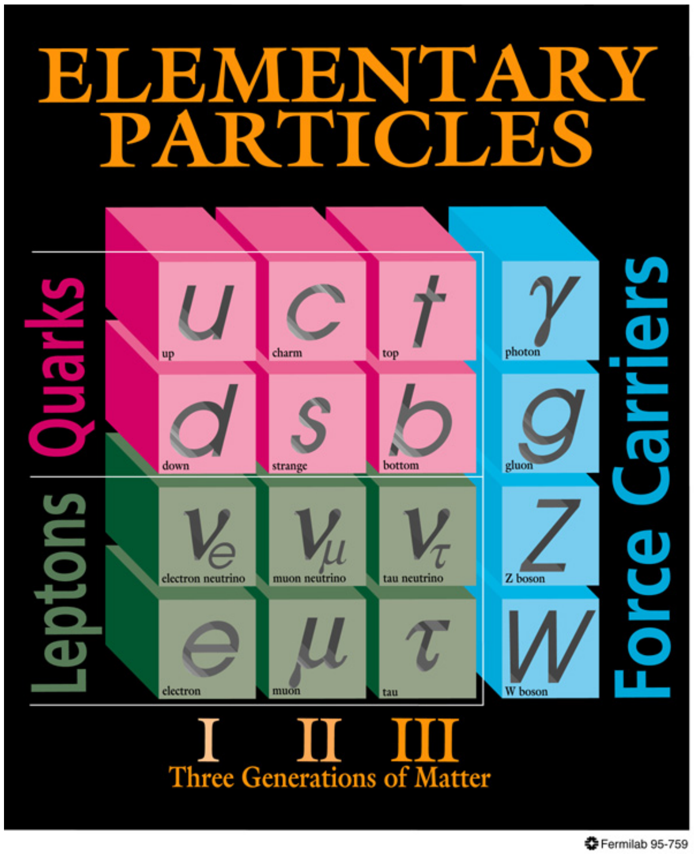
Weak interactions are responsible, e.g., for nuclear beta decay.



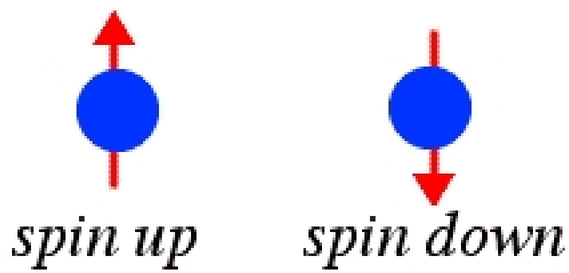


The force carriers are the charged W^+ and W^- bosons and the neutral Z boson.

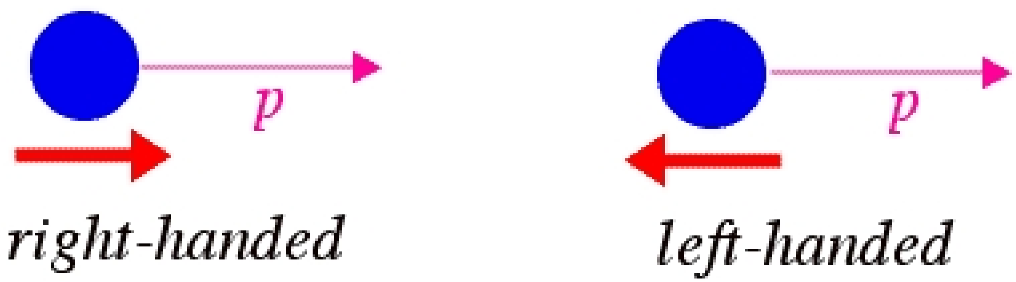
To describe the problem with weak interactions, I need to introduce the spin of quarks and leptons, and what we know from experiment about how the weak interaction "talks" to them.



Standard Model matter particles are fermions: spin-1/2.



For fast-moving particles, it's convenient to quantize spin along the direction of motion: these are called helicity states.



Can transform a right-handed particle into a left-handed particle (in your reference frame) by running faster than it:

(This is only possible for particles with nonzero mass. Massless particles move at the speed of light: you can't run faster than them, so the two helicity states are physically distinct.)

So what's the problem?

Weak interactions treat left-handed and right-handed particles differently!

- $W^{\pm}$ bosons couple only to left-handed fermions 'doublet' $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$
- Z bosons couple with different strengths to left- and right-handed fermions

This "handedness" is called parity violation (discovered in the weak interactions in 1957).

This would be like the charge of the electron being different depending on which reference frame you look at it from—impossible, since electric charge is conserved!

The only sensible solution is for all the fermions to be massless, so that the left- and right-handed fermions are distinct particles. Obviously this is wrong.

How can we account for the measured masses of the quarks and leptons?

Need to find a way for a fermion to "dump its excess weak charge" when you boost past it.

This is actually possible if the vacuum is filled with a sea of weak-charged stuff. (This will be related to the Higgs field.)

What are the properties of this sea of stuff?

Weak isospin:

Left-handed fermions are in doublets (isospin 1/2) $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$

Right-handed fermions are singlets (isospin 0)

$\Rightarrow$ Sea must carry isospin 1/2

Hypercharge:

Sea is electrically neutral

$\Rightarrow$ Sea must carry hypercharge such that $Q = T^3 + Y = 0$

Spin:

Sea shouldn't violate Lorentz invariance

$\Rightarrow$ Sea must not carry any spin

Result: a spin-zero "field" filling all space that we can write

$$\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

Here v is a constant number with units of energy and the $\sqrt{2}$ is a conventional normalization. ($v \equiv$ vacuum expectation value)

This "sea" filling all of space lets us write down masses for fermions in a way consistent with weak-charge conservation.

E.g., mass term for a down-type quark:

$$
\begin{aligned}
\mathcal{L} &\supset -y_d \left[\left(\bar{u}_L \ \bar{d}_L \right) \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} d_R + \bar{d}_R \left(0 \ v/\sqrt{2} \right) \begin{pmatrix} u_L \\ d_L \end{pmatrix} \right] \\
&= -\frac{y_d v}{\sqrt{2}} \left[\bar{d}_L d_R + \bar{d}_R d_L \right] \\
&\equiv -m_d \left[\bar{d}_L d_R + \bar{d}_R d_L \right]
\end{aligned}
$$

Can do similar thing for each fermion: mass is $m_f = y_f v/\sqrt{2}$.
Coefficient y_f is different for each different fermion.

Doing the full details gives masses for all 6 quarks and 3 charged leptons, and the CKM matrix for quark mixing.

No predictions for mass relations; measured parameters are all needed as inputs to fix the y_f couplings. (We'll determine v on the next slide.)

This "sea" also lets us write masses for the W and Z bosons:

$$\begin{aligned} \mathcal{L} &\supset \left| \mathcal{D}_\mu \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \right|^2 \\ &= \left| \frac{g}{\sqrt{2}} W_\mu^+ \frac{v}{\sqrt{2}} \right|^2 + \left| \frac{g}{2\cos\theta_W} Z_\mu \frac{v}{\sqrt{2}} \right|^2 \\ &\equiv M_W^2 \left| W_\mu^+ \right|^2 + \frac{1}{2} M_Z^2 \left| Z_\mu \right|^2 \end{aligned}$$

The masses of the W and Z are $M_W = gv/2$, $M_Z = gv/2\cos\theta_W$.

We know g (from measuring weak interaction process rates) and M_W (from direct measurement).

$\Rightarrow$ Solve for v: $v = 246$ GeV.

So far we have a vacuum-filling "sea" which is constant. $\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$

Let's see what happens when we do gauge transformations.

Recall in electromagnetism: $A^\mu \to A^\mu - \partial^\mu \lambda(x)$, $\psi \to e^{-i\lambda(x)}\psi$.

$$\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \to e^{-i\xi^a(x)\sigma^a/v} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} \left[-\xi^2(x) - i\xi^1(x)\right]/\sqrt{2} \\ \left[v + i\xi^3(x)\right]/\sqrt{2} \end{pmatrix} + \cdots$$

σ^a are the three Pauli spin matrices.

We have populated our doublet with real and imaginary parts in both components.

The new gauge-transform-induced pieces are "dynamical": the field value depends on spacetime position x.

These are not actually physical particles; the ξ^a degrees of freedom correspond to the third polarization state possessed by the massive W and Z (which is not there for the massless photon).

(They are usually called the Goldstone bosons.)

Q: Does the real part of the lower component of our doublet have a dynamical part?

$$\begin{pmatrix} \left[-\xi^2(x) - i\xi^1(x)\right]/\sqrt{2} \\ \left[v + i\xi^3(x)\right]/\sqrt{2} \end{pmatrix} \longrightarrow \begin{pmatrix} \left[-\xi^2(x) - i\xi^1(x)\right]/\sqrt{2} \\ \left[v + h(x) + i\xi^3(x)\right]/\sqrt{2} \end{pmatrix}?$$

$h(x)$ would correspond to waves in the vacuum-filling "sea" itself.

- Not required to be there by gauge transformations.
- This would be a new physical particle.
- This is the Higgs boson of the Standard Model.

Before asking "is it there", let's ask "can it *not* be there?"

The answer is yes, but the pure Standard Model without $h(x)$ is intrinsically incomplete.

Consider a thought-experiment: scattering of two longitudinally-polarized W bosons off each other.

A (massive) W boson is a spin-1 particle: at rest its three possible polarization 4-vectors are

$$(0,1,0,0) \qquad (0,0,1,0) \qquad (0,0,0,1)$$

Choose a W polarized in the z direction and boost it in the z direction: its momentum and polarization 4-vectors are

$$p^\mu = (E, 0, 0, |\vec{p}|) \qquad \epsilon^\mu = (|\vec{p}|, 0, 0, E)/M_W$$

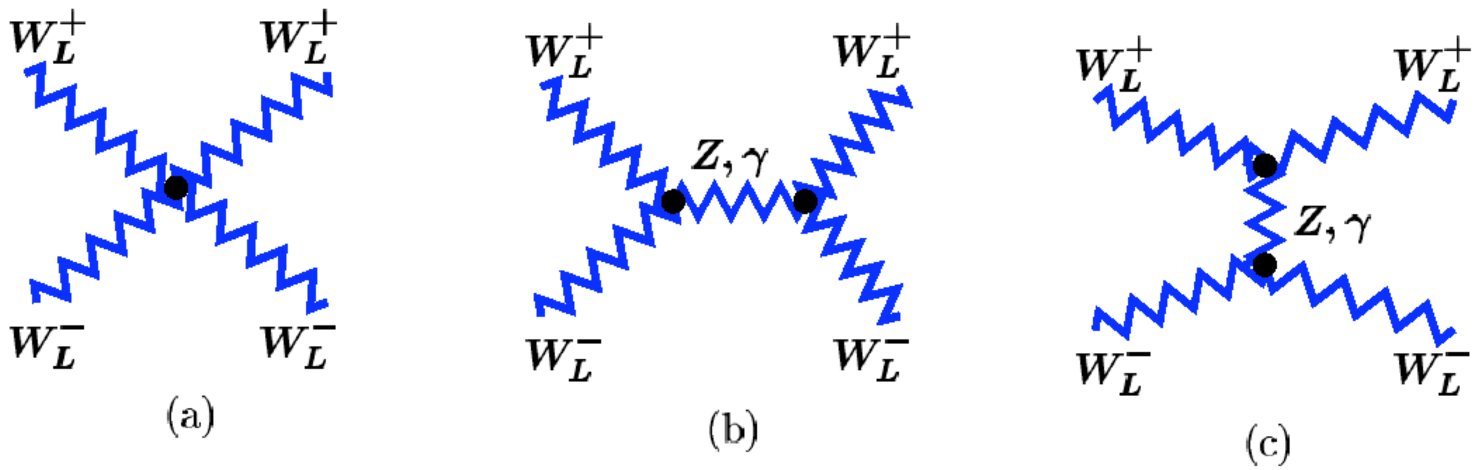
The scattering diagram for $WW \to WW$ basically takes four ϵ^μ 4-vectors and multiplies them together in various Lorentz-invariant ways.

Generically this gives a result $\propto$ (energy)$^4/M_W^4$.

This grows without bound at very large energies: unphysical! There must be some clever cancellations, or probability conservation will be violated.

Scattering of longitudinally-polarized Ws exposes need for a Higgs*

SU(2) x U(1) @ E^4



Graphs	$g^2 \frac{E^4}{m_w^4}$
(a)	$-3 + 6\cos\theta + \cos^2\theta$
(b)	$-4\cos\theta$
(c)	$+3 - 2\cos\theta - \cos^2\theta$
Sum	0

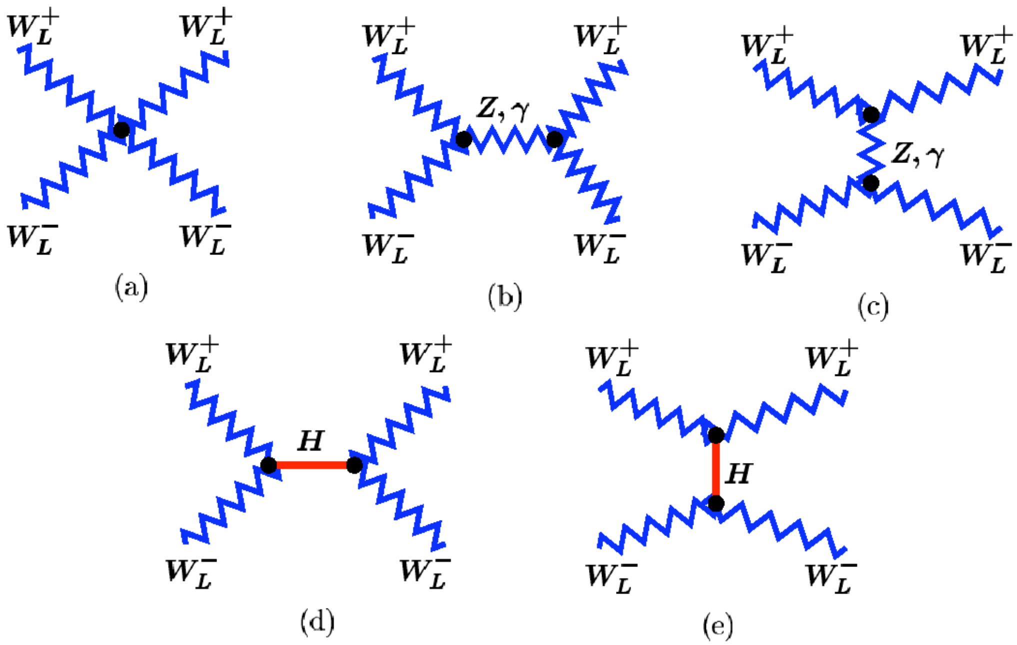
$$\epsilon_L^\mu(k) = \frac{k^\mu}{m_w} + \mathcal{O}\left(\frac{m_w}{E}\right)$$

Graphics from R.S. Chivukula, LHC4ILC 2007

*or something to play its role

Scattering of longitudinally-polarized Ws exposes need for a Higgs*

SU(2) x U(1) @ E^2



Graphs	$g^2 \frac{E^2}{m_w^2}$
(a)	$+2 - 6\cos\theta$
(b)	$-\cos\theta$
(c)	$-\frac{3}{2} + \frac{15}{2}\cos\theta$
(d + e)	$-\frac{1}{2} - \frac{1}{2}\cos\theta$
Sum including (d+e)	**0**

- $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound: $m_H < \sqrt{16\pi/3}\, v \simeq 1.0$ TeV
- If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow E < \sqrt{8\pi} v \simeq 1.2\,\mathrm{TeV}$

Graphics from R.S. Chivukula, LHC4ILC 2007

*or something to play its role

So we really do need a Higgs! (or something to play its role*)
Let's go look for it.

How to look?
- Need to know how we expect the Higgs to be produced.
- Need to know how we expect the Higgs to decay.

Fortunately both of these things are tightly predicted because of the way v generates the masses of the known particles.
The only unknown in the Standard Model is the mass of the Higgs itself.

*Viable "Higgsless" models do exist: they usually contain spin-1 particles that show up in the WW scattering diagrams to cancel the bad high-energy behavior. The search strategy for these is to look for the new spin-1 particles.

Fermions:

$$\begin{aligned}\mathcal{L} &\supset -y_d\left[\left(\bar u_L\ \bar d_L\right)\begin{pmatrix}0\\ v/\sqrt{2}\end{pmatrix}d_R + \bar d_R\left(0\ v/\sqrt{2}\right)\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right]\\ &= -\frac{y_d v}{\sqrt{2}}\left[\bar d_L d_R + \bar d_R d_L\right] \to -\frac{y_d(v+h)}{\sqrt{2}}\left[\bar d_L d_R + \bar d_R d_L\right]\\ &\equiv -m_d\left[\bar d_L d_R + \bar d_R d_L\right] \to m_d = y_d v/\sqrt{2}\end{aligned}$$

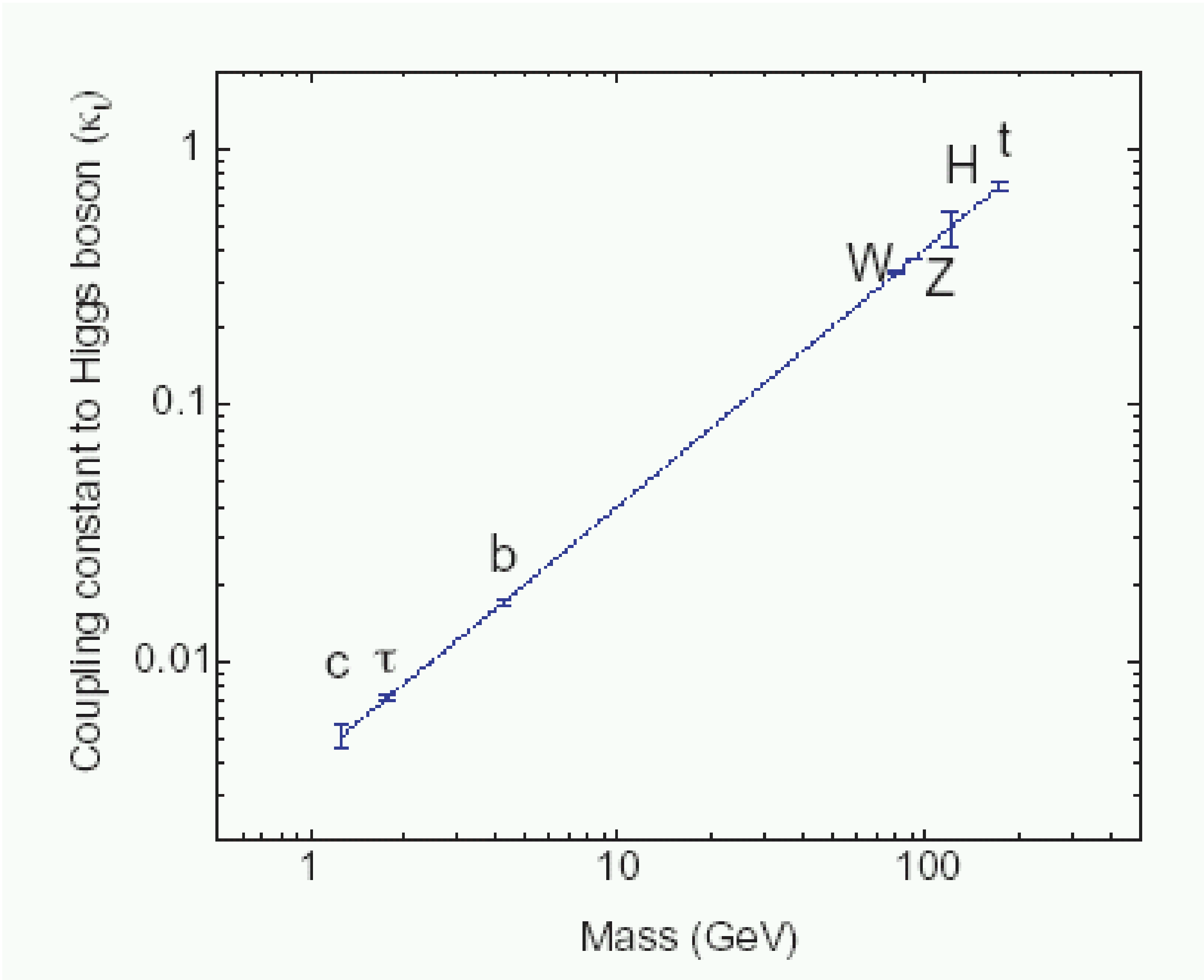
Get a Higgs coupling to fermion pair of strength $y_f/\sqrt{2} = m_f/v$.
We know v and we know m_f for each fermion already.

Gauge bosons:

$$\begin{aligned}\mathcal{L} &\supset \left|\mathcal{D}_\mu\begin{pmatrix}0\\ v/\sqrt{2}\end{pmatrix}\right|^2\\ &= \left|\frac{g}{\sqrt{2}}W_\mu^+\frac{v}{\sqrt{2}}\right|^2 + \left|\frac{g}{2\cos\theta_W}Z_\mu\frac{v}{\sqrt{2}}\right|^2 \to \left|\frac{g}{\sqrt{2}}W_\mu^+\frac{(v+h)}{\sqrt{2}}\right|^2 + \left|\frac{g}{2\cos\theta_W}Z_\mu\frac{(v+h)}{\sqrt{2}}\right|^2\\ &\equiv M_W^2\left|W_\mu^+\right|^2 + \frac{1}{2}M_Z^2\left|Z_\mu\right|^2\end{aligned}$$

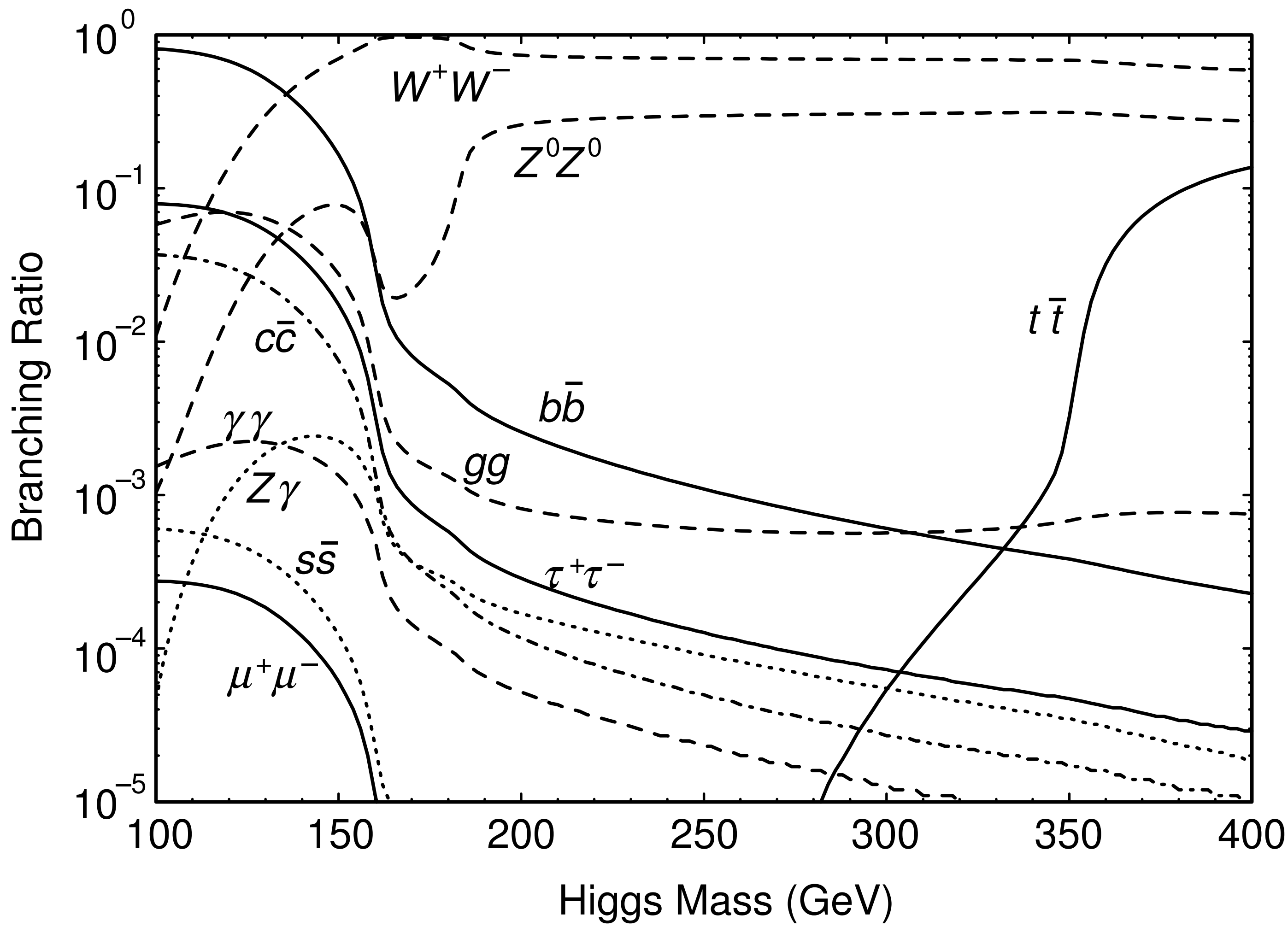
Get Higgs couplings to W and Z bosons of known strength.

Nice simple proportionality relation between mass of the particle and coupling to Higgs.



Can use this to predict the Higgs decay "branching ratios" into various final states.

Depends on Higgs mass: which final states are light enough to be produced.



Most important modes:

$M_H \lesssim 135$ GeV: $b\bar{b}$, $\tau^+\tau^-$, $\gamma\gamma$

$M_H \gtrsim 135$ GeV: W^+W^-, ZZ

HDECAY, M. Spira et al.

When I was a grad student, Higgs searches were going on at CERN at the Large Electron-Positron Collider (LEP).

LEP was an e^+e^- collider in the same tunnel at CERN where the LHC is now.

LEP ran from 1989 to 2000, with collision energies around 91 GeV (LEP-I, for high-precision studies of the Z boson) and $\sim$100–209 GeV (LEP-II, for measurements of W pair production and searches for the Higgs).

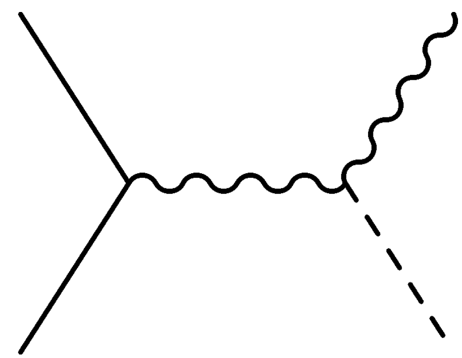
Photo: CERN

Making a Higgs in e^+e^- collisions

$e^+e^- \to H$?

The Higgs does couple to electrons, with strength m_e/v.
This is very tiny! Production rate way too small to see at LEP.

$e^+e^- \to Z^* \to ZH$?

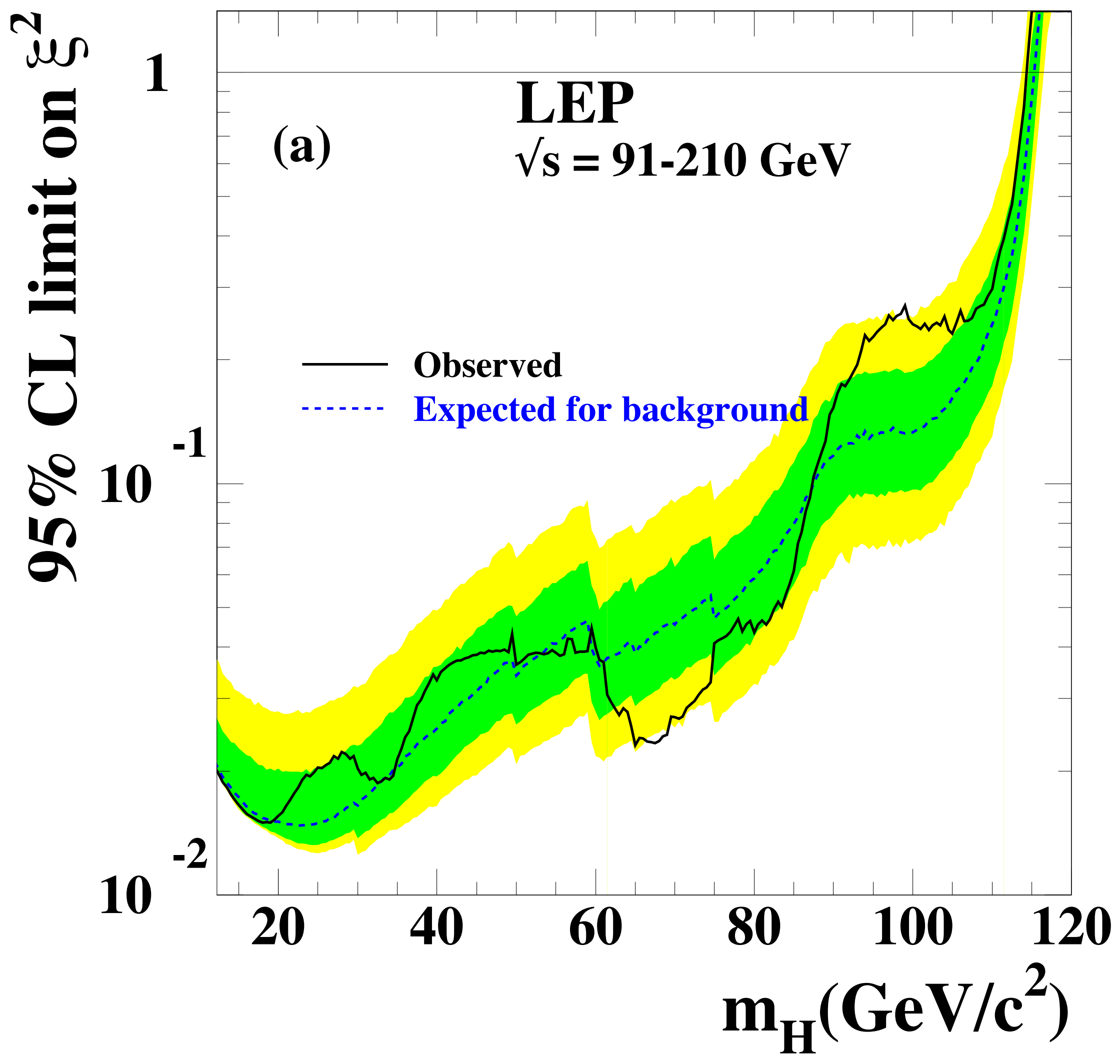


Nice large Higgs coupling, M_Z^2/v.

Have to have enough energy to produce a Z and a Higgs:

$M_Z \simeq 91$ GeV, so this limited the "reach" of LEP to Higgs masses below $(209 - 91 -$ a few) GeV $\simeq 114$ GeV.

Direct SM Higgs searches – LEP experiments final combination



$e^+e^- \to Z^* \to ZH$

Standard Model Higgs decays assumed: mostly $b\bar{b}$, $\tau^+\tau^-$.

ξ = scaling factor on ZZH relative to SM (often ≤ 1 in beyond-the-SM)

Limit (for SM): $M_H \geq 114.4$ GeV

Final LEP combination, Phys. Lett. B565, 61 (2003)

Tevatron and LHC: “hadron colliders”

- Tevatron collides protons and antiprotons
- LHC collides protons and protons

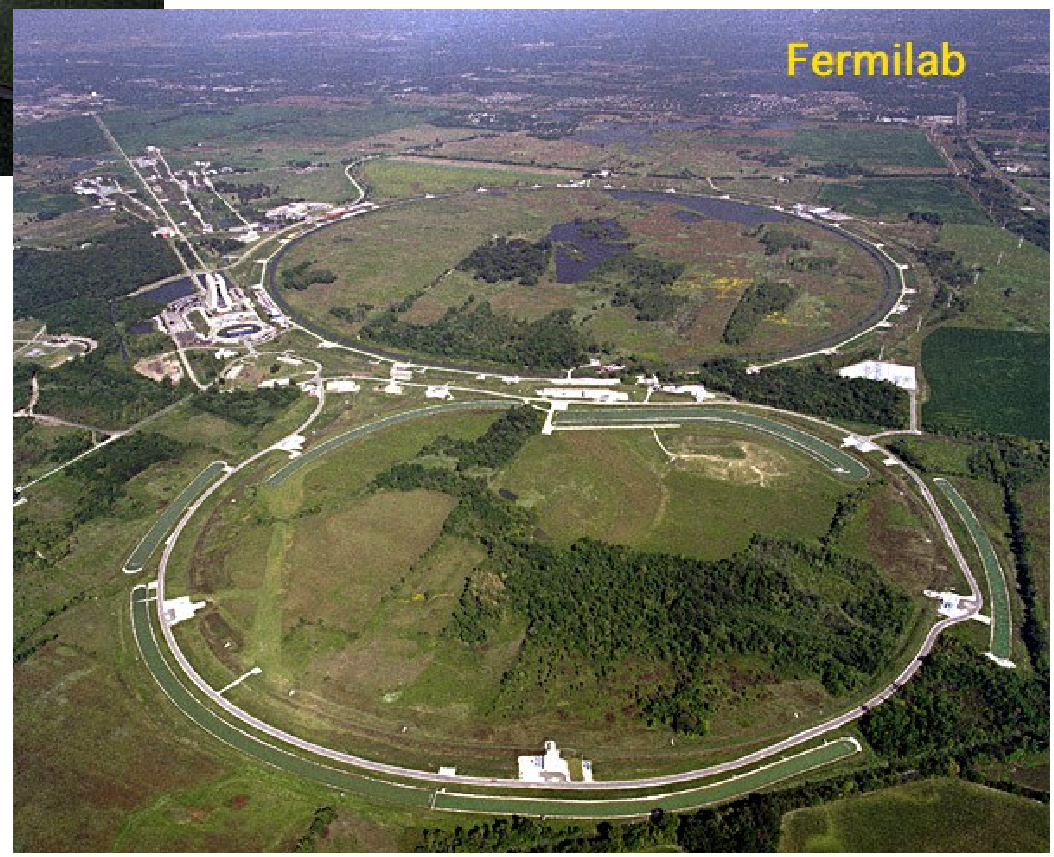
Easier to get high energy beams than with super-light electrons.

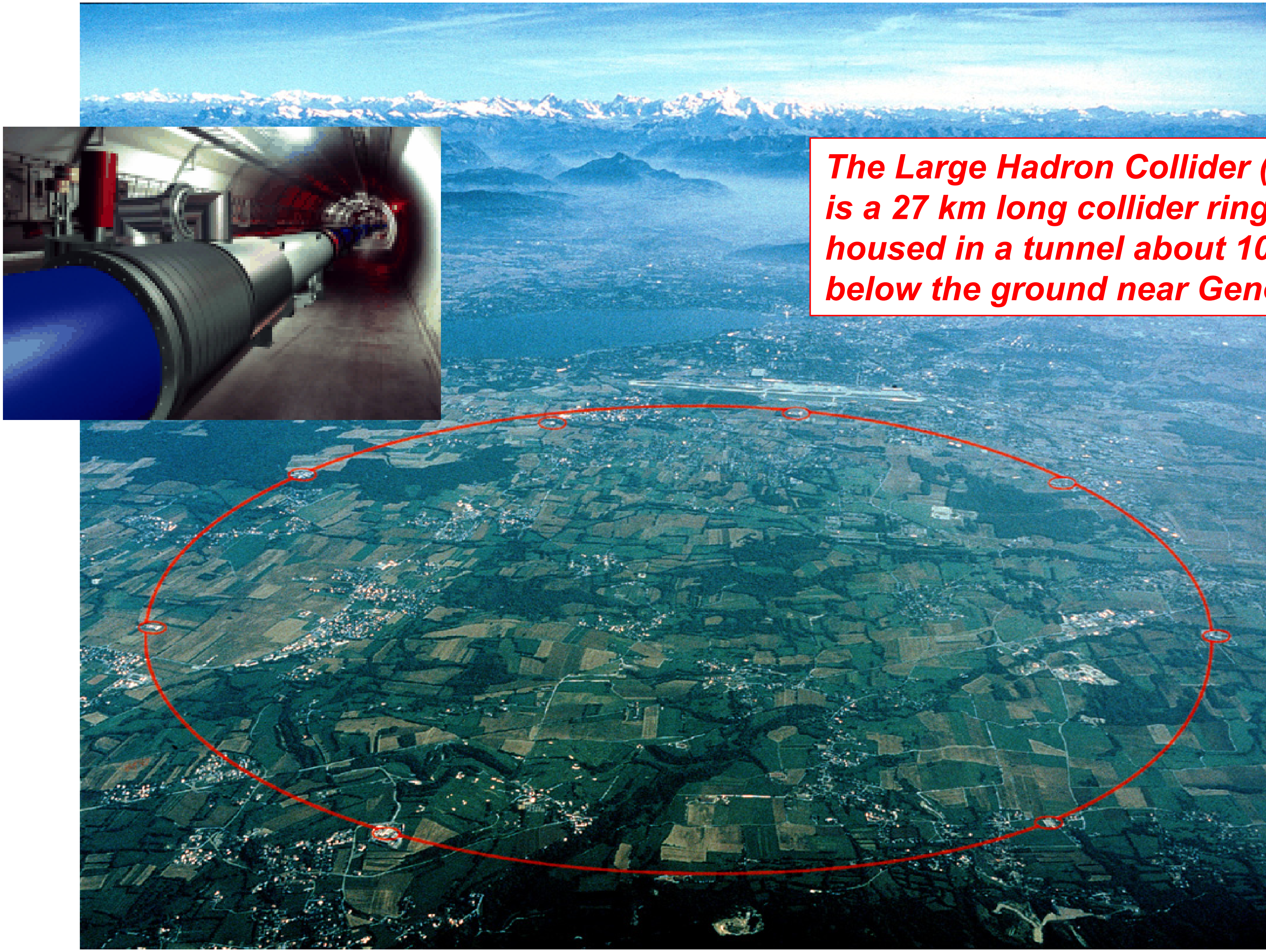
Tevatron has been hunting for the Higgs since 2001; will shut down for good tomorrow at 2 p.m. Chicago time (can’t compete with LHC any more).

LHC started taking data in 2010 and is running fantastically well this year. Massive progress on SM Higgs searches (and a bunch of other new-physics searches too).

Tevatron

(name is from TeV beam energy)

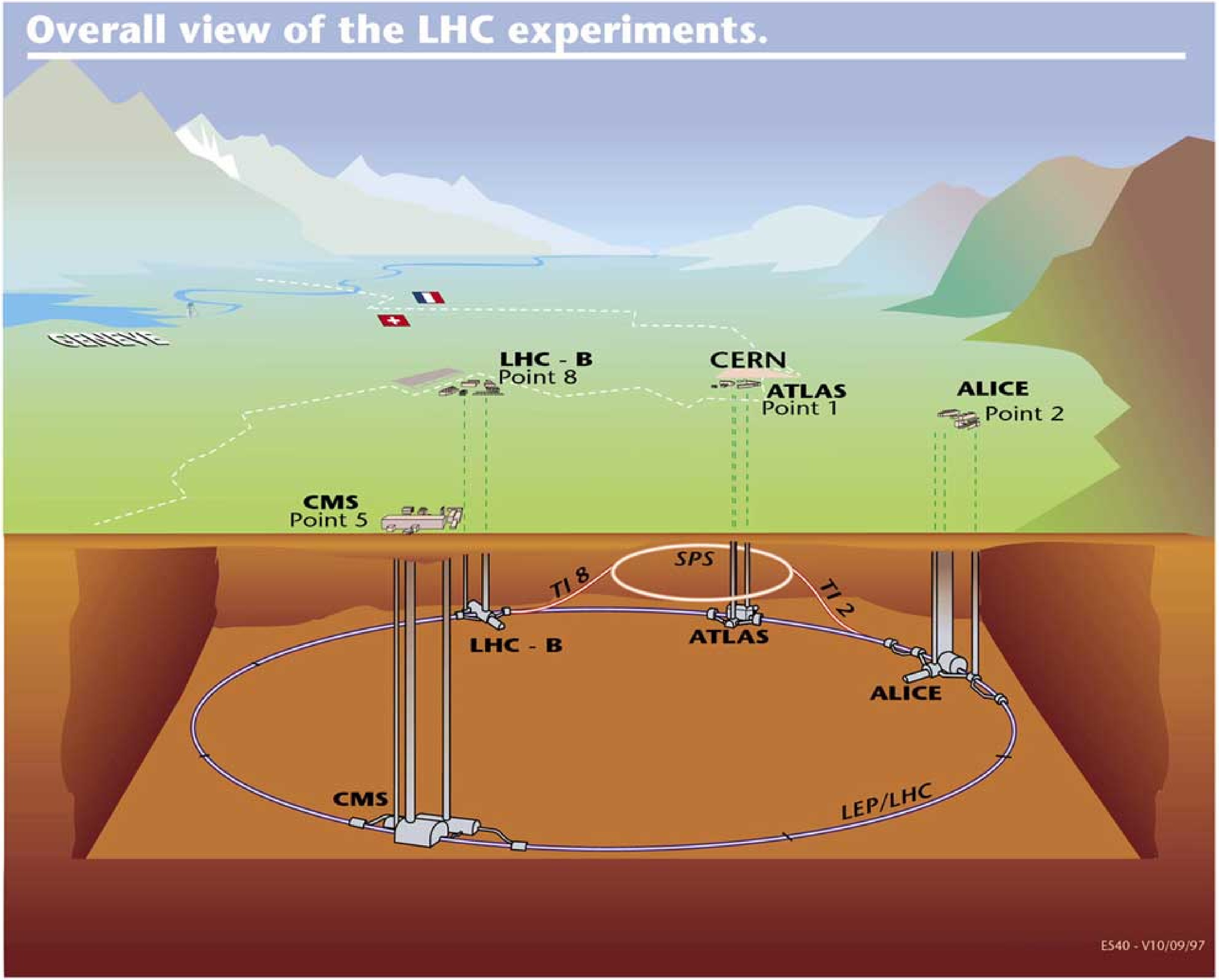




The Large Hadron Collider (LHC) is a 27 km long collider ring housed in a tunnel about 100 m below the ground near Geneva

CERN

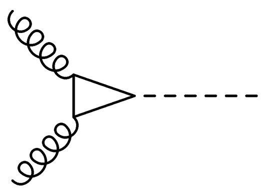
CERN


Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

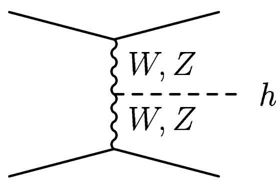
CERN

Higgs production rates at hadron colliders:
Signal rate = production rate $\times$ decay branching ratio.

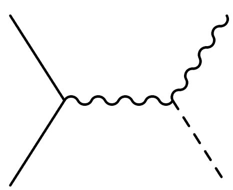
- Gluon fusion, $gg \to H$



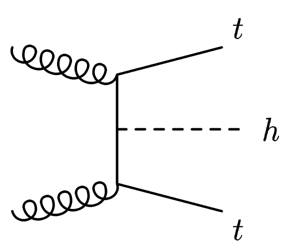
- Weak boson fusion, $qq \to Hqq$

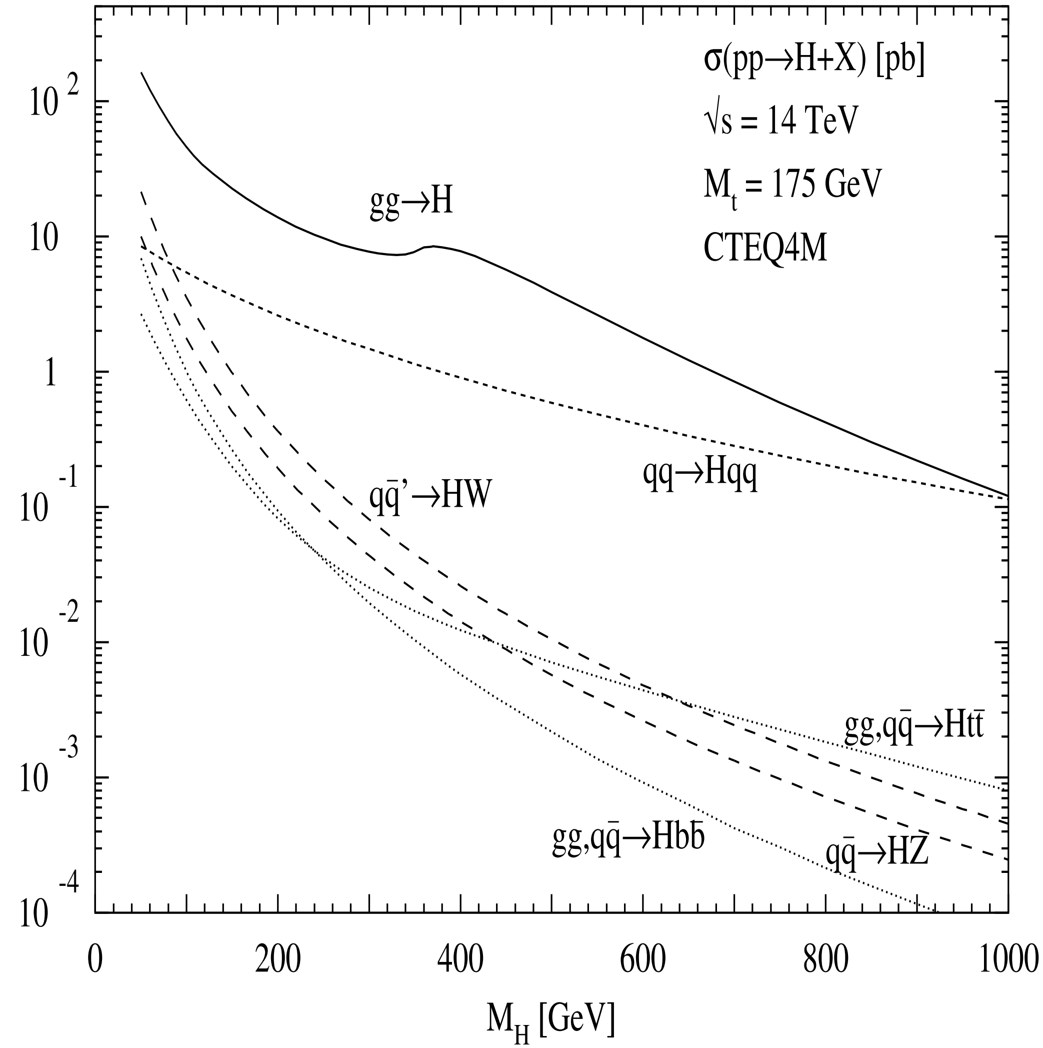


- WH, ZH associated production



- ttH associated production

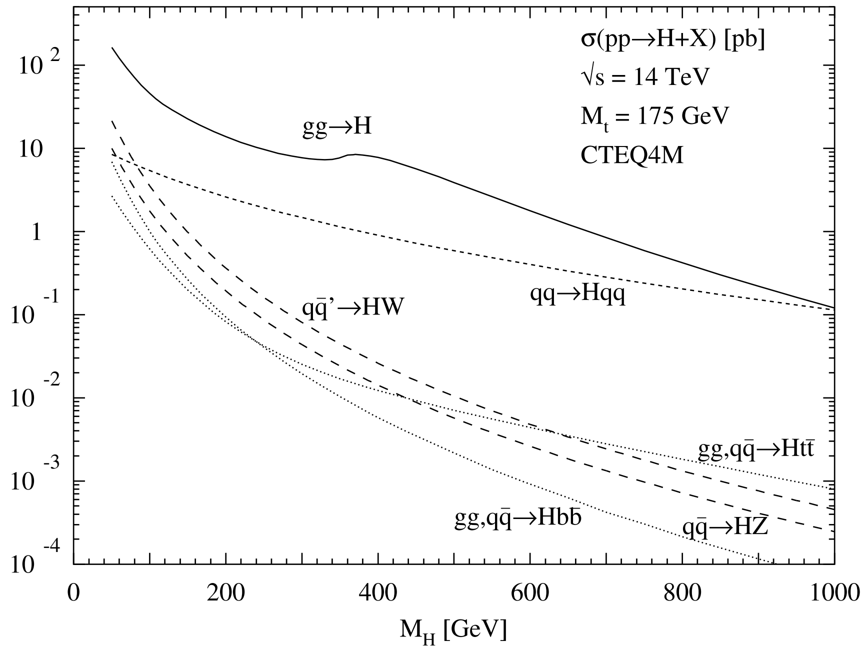


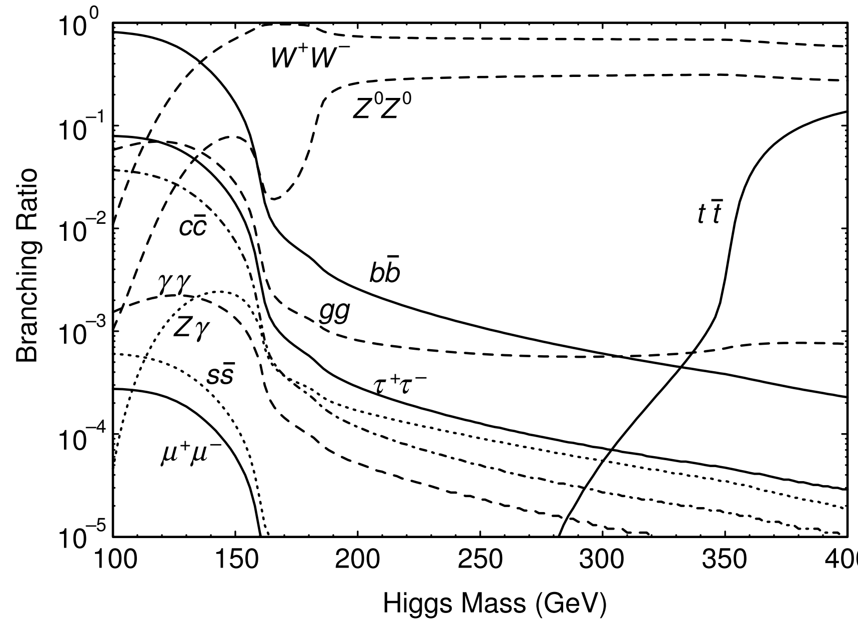


M. Spira, Fortsch. Phys. 46, 203 (1998), for LHC

LHC Higgs searches combine multiple "channels"

As an example, let's look at $gg \to H$ ("gluon fusion"), $H \to WW$.





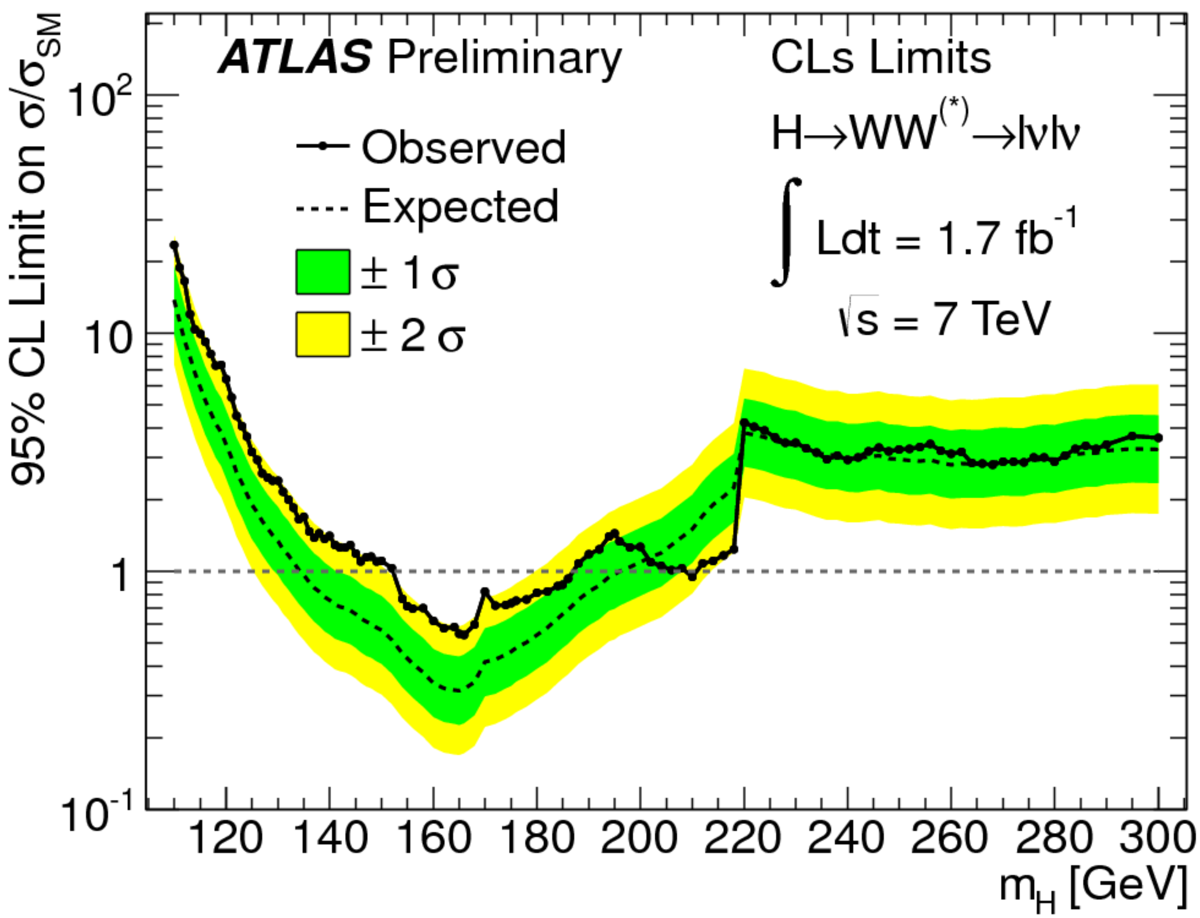
M. Spira, Fortsch. Phys. 46, 203 (1998), for LHC HDECAY

The W bosons decay: the detector sees just their decay products. Again choose a channel: $W \to e\nu$ and $W \to \mu\nu$ are particularly nice (relatively little background).

- Detect ee, $\mu\mu$, or $e\mu$. ($\ell \equiv e$ or μ)
- The neutrinos are "detected" by the momentum imbalance.

For each Higgs mass value, ask the question: what events would we expect if the Higgs is there (including backgrounds), and what events do we see?

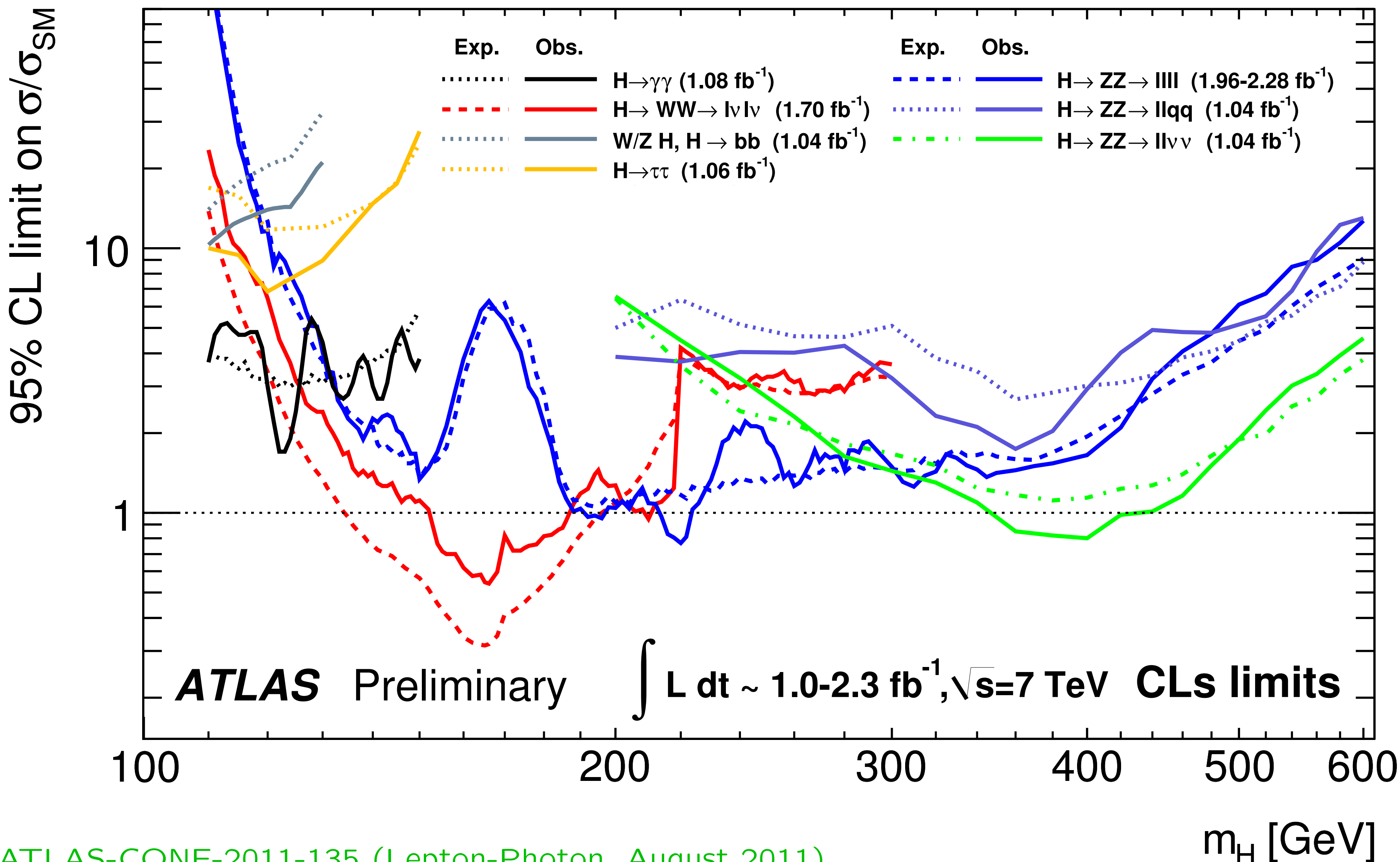
$\Rightarrow$ set an upper limit (so far) on the cross section for $pp \to H \to WW \to \ell\nu\ell\nu$ (handy convention is to normalize to SM Higgs cross section).



ATLAS-CONF-2011-134

Do the same for many different Higgs signal channels.

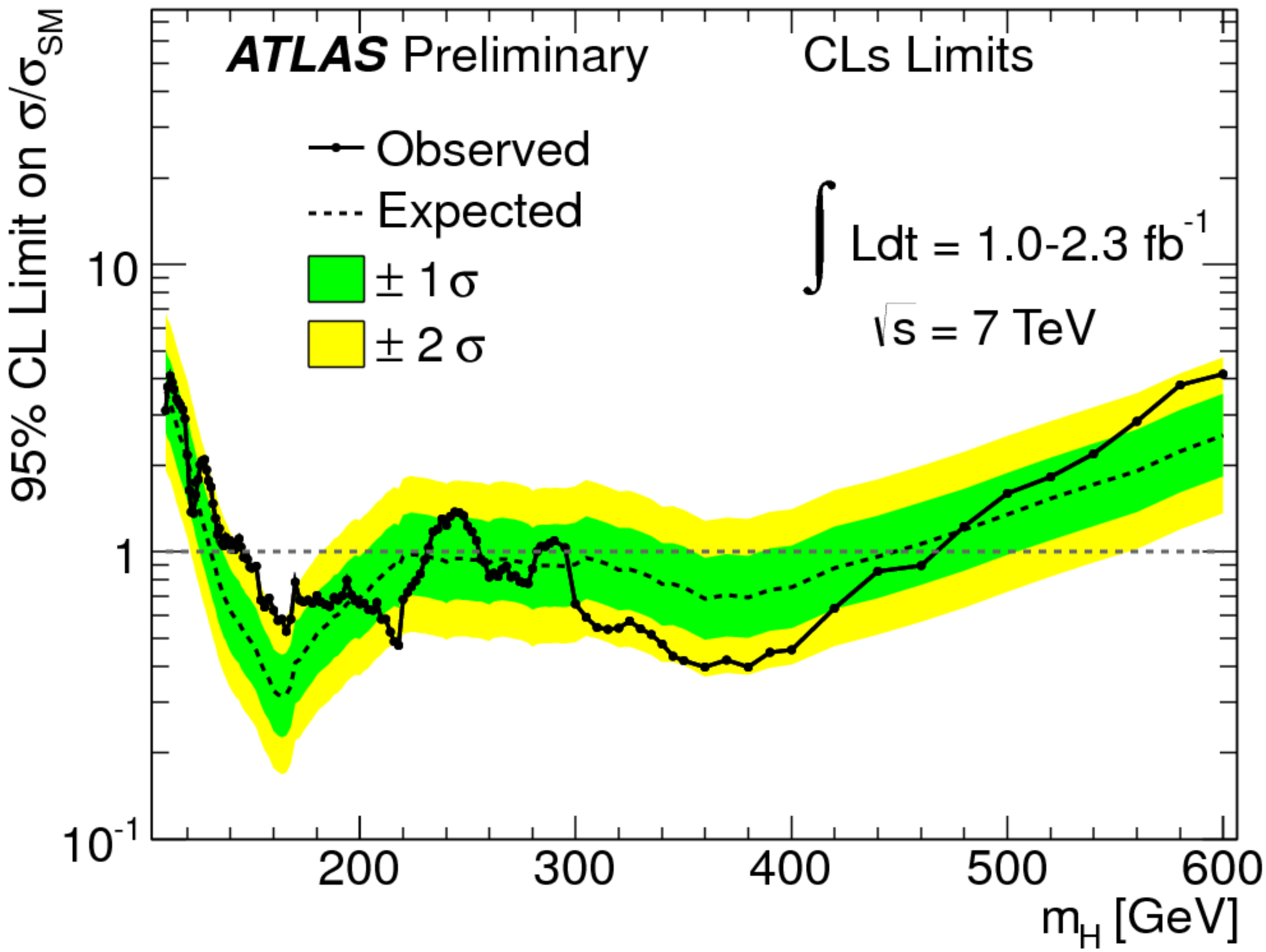
Branching ratios and backgrounds vary with the Higgs mass.



ATLAS-CONF-2011-135 (Lepton-Photon, August 2011)

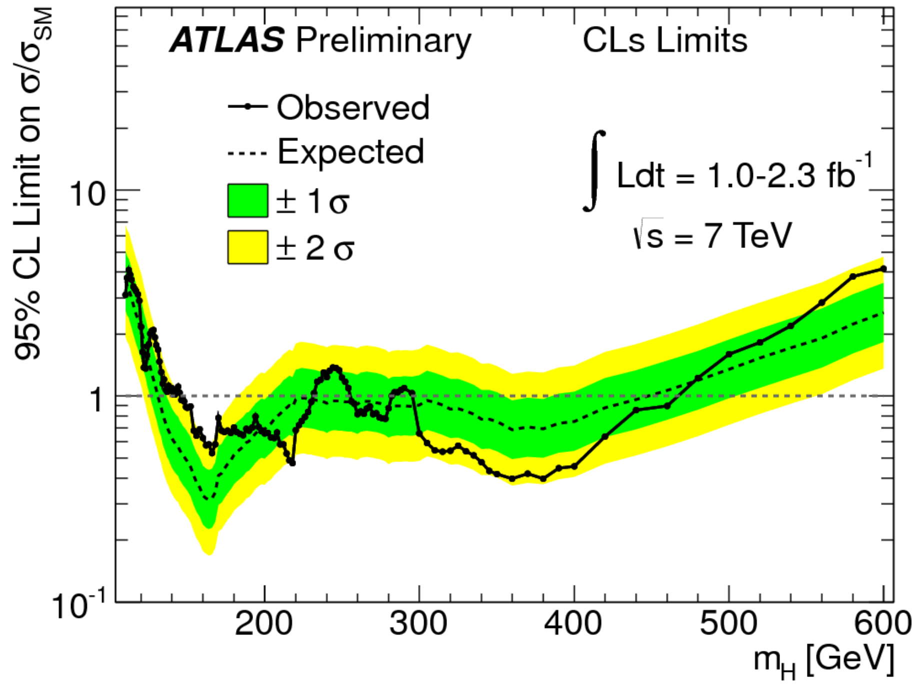
Statistically combine all the search channels.

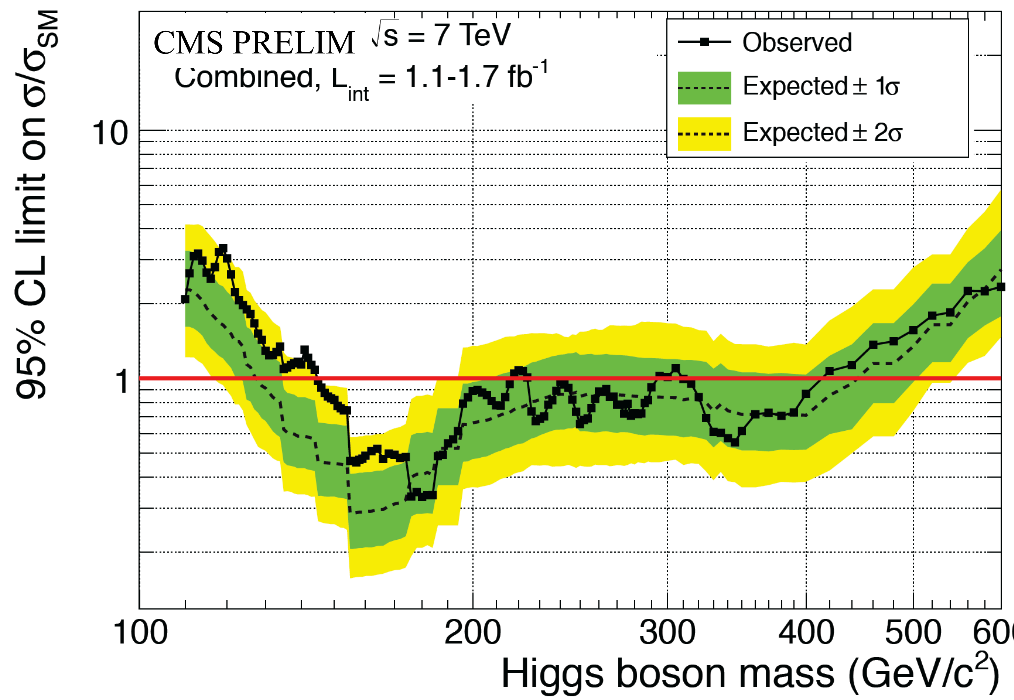
Physical meaning of y-axis gets a bit obscured for values other than 1.



ATLAS-CONF-2011-135

CMS has done the same kind of analyses (competition is good!)





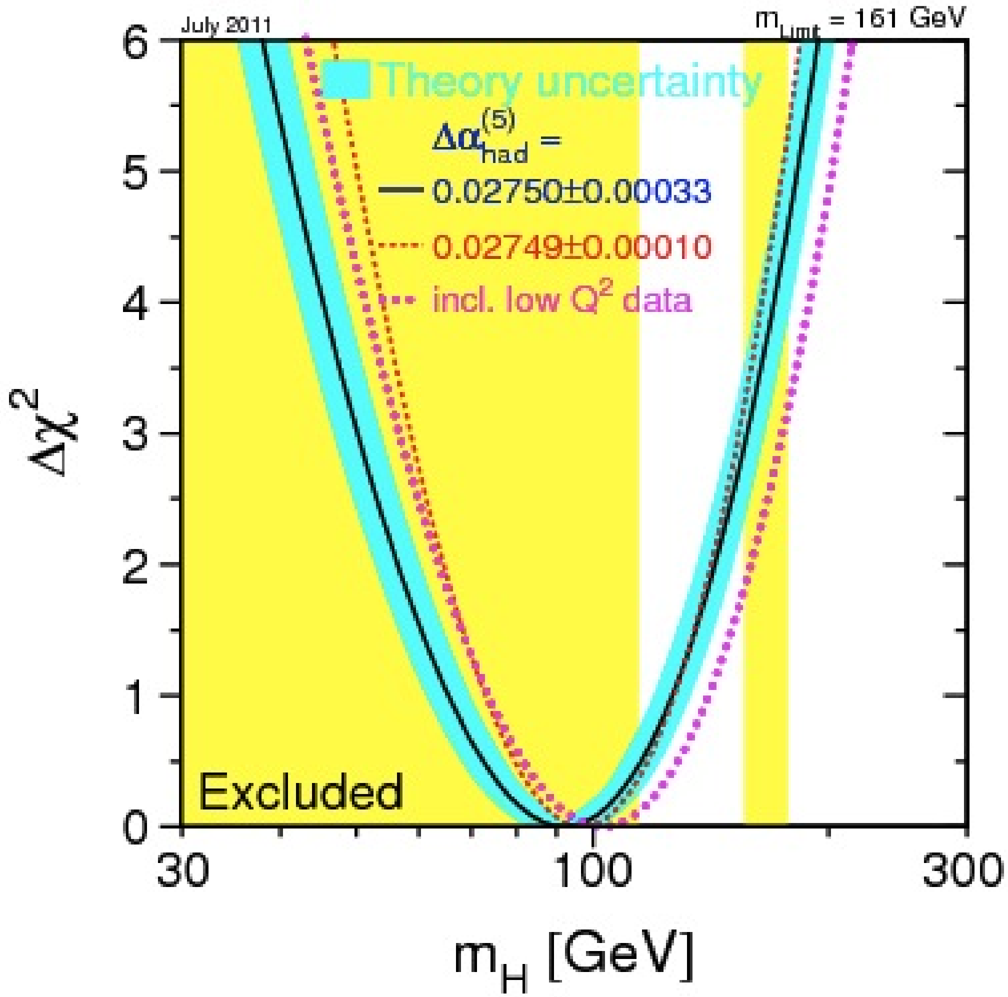
ATLAS-CONF-2011-135

CMS PAS HIG-11-022 (LP2011)

ATLAS + CMS exclude (at 95% CL) all mass regions except: below 145 GeV, 288–296 GeV, and above 464 GeV.

Higgs with suppressed gluon-fusion production coupling and/or suppressed WW, ZZ decay BRs still allowed in the SM-excluded mass regions.

Precision electroweak SM Higgs mass fit (summer 2011)

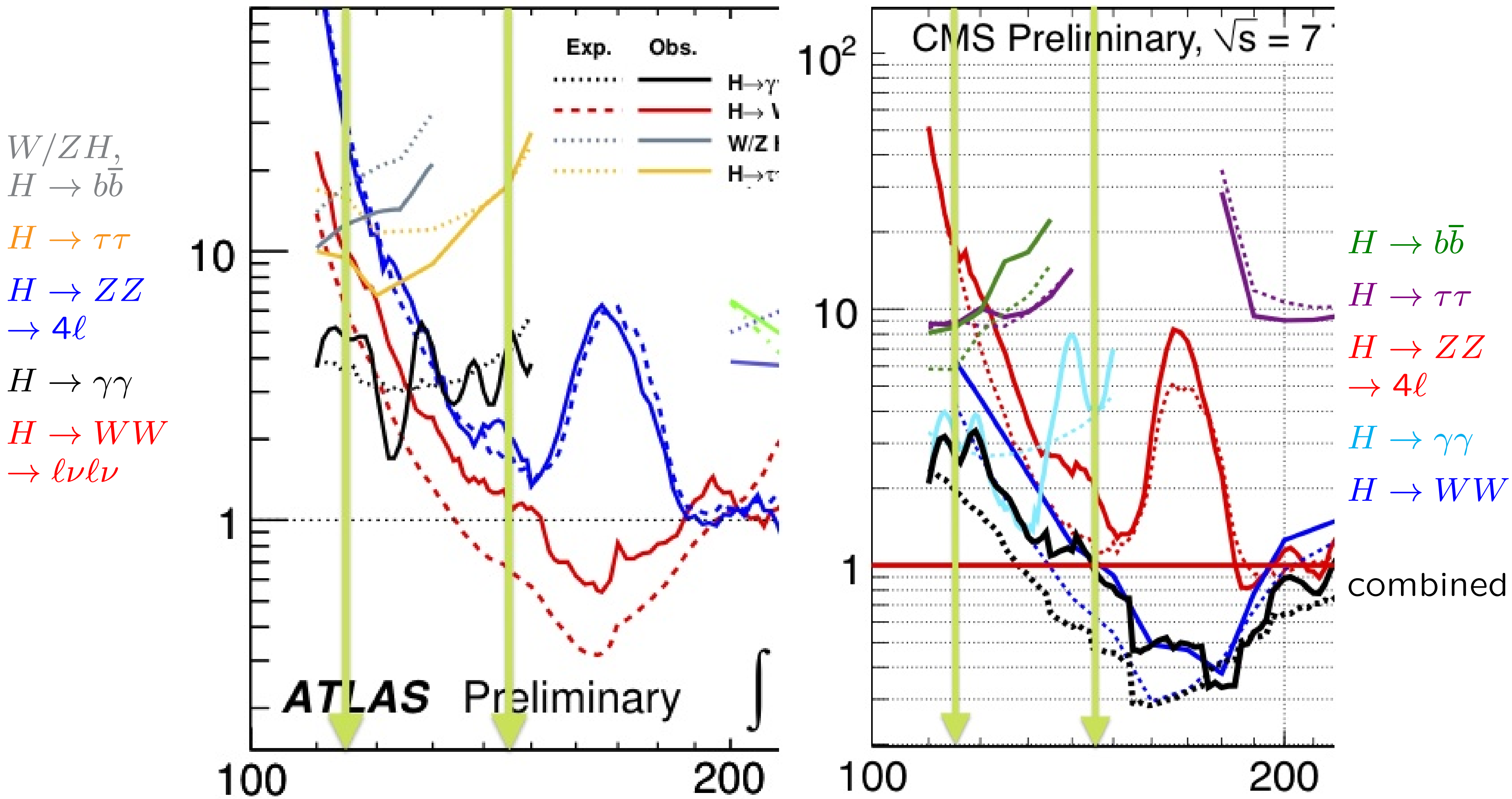


LEP Electroweak Working Group (2011)

Precision EW favors low-mass allowed window, 114.4–145 GeV.

(Fit valid only in SM context; new physics can change preferred mass range.)

LHC Higgs channels: focus on SM, low-mass range

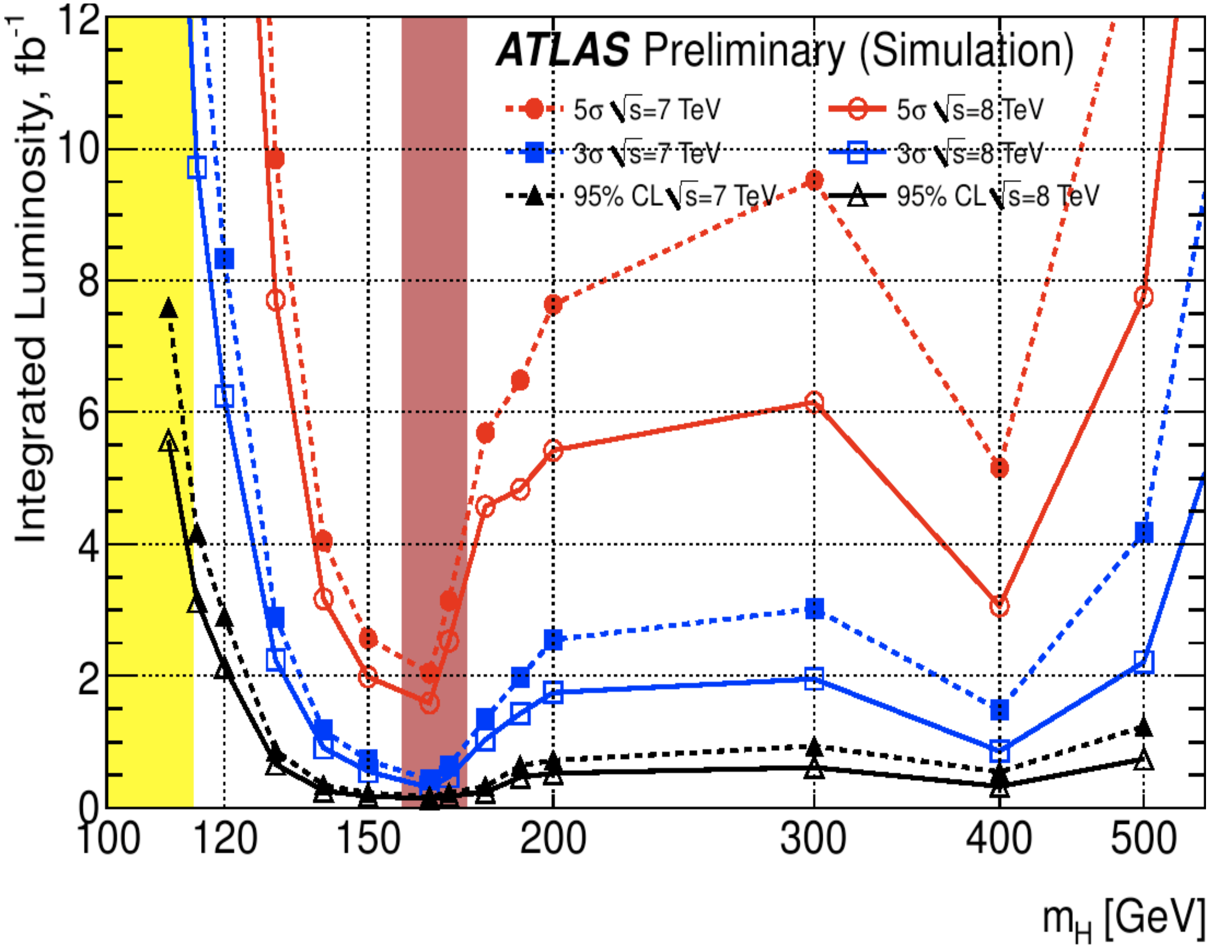


ATLAS-CONF-2011-135

CMS PAS HIG-11-022 (LP2011)

Not yet done: VBF $\to H \to \tau\tau, WW, ZZ, \gamma\gamma$; $ttH, H \to bb, \gamma\gamma, WW$; $WH, H \to \gamma\gamma$

Analyses so far: up to 1.7 fb^{-1} (channels "frozen" at different times)



ATLAS collaboration, Jan 2011

Right now (as of Monday Sept. 26): 3.6 fb^{-1} already recorded.
2011 run: expect 5 fb^{-1} by end of December.
2012 run: 10 fb^{-1} or more? LHC running better than expected.

Outlook

Weak interactions are telling us that the vacuum must be filled with a weak-charged “sea.”

If we kick the “sea” hard enough we may be able to produce a vibration: the Higgs boson.

- This depends on the structure of the “sea.”
- Best way to probe underlying structure of weak interactions!

If the Higgs is there and “Standard-Model-like,” LHC could have it in the bag by this winter.

$\Rightarrow$ Watch this space! $\Leftarrow$

Backup slides

Top-Higgs

Dedicated (composite) scalar doublet to generate most of top quark mass: common add-on for models of dynamical EWSB.
- topcolor-assisted technicolor
- deconstructed "top triangle" 3-site Moose

Top-Higgs doublet has vev $f = v_{\rm SM} \sin\omega$
(Strong dynamics responsible for most of EWSB: $v_{\rm SM} \cos\omega$)

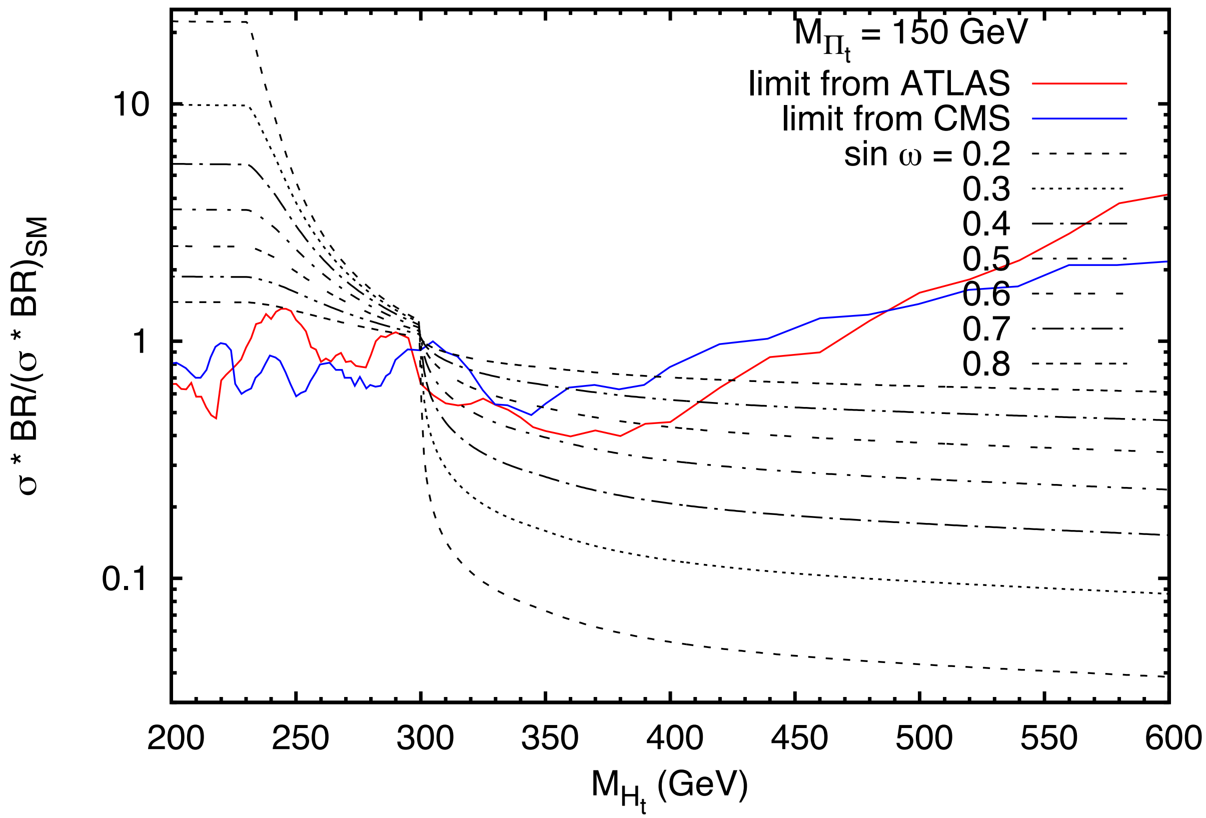
Top-Higgs particle H_t couples only to $t\bar{t}$, WW, ZZ at tree level
- WW, ZZ couplings suppressed $\sim \sin\omega$
- $t\bar{t}$ coupling enhanced $\sim 1/\sin\omega$
- $gg \to H_t$ enhanced $\sim 1/\sin^2\omega$: LHC production enhanced!

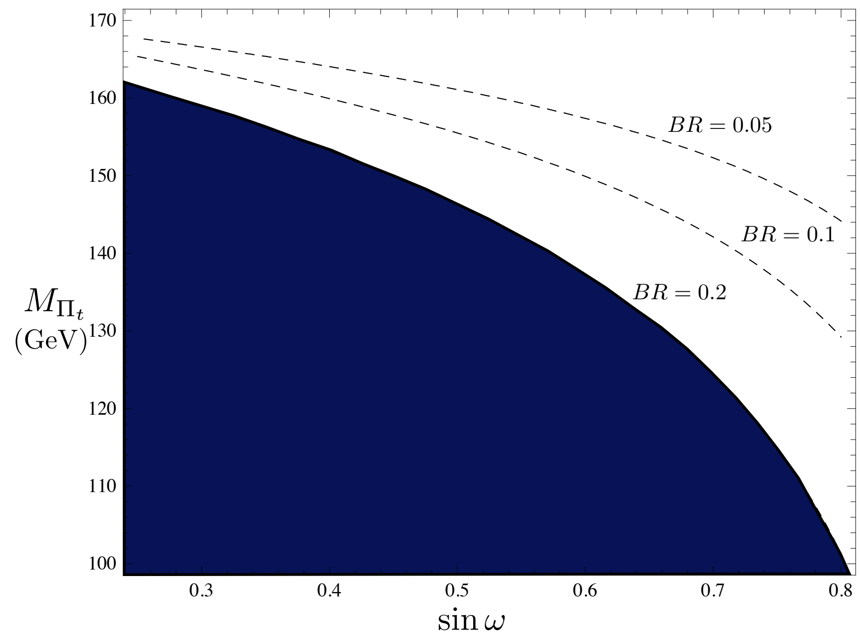
Typical mass is $M_{H_t} \lesssim 2m_t$ for dynamical top mass generation in topcolor-assisted technicolor (TC2)

LHC Higgs search: relevant channels are $gg \to H_t \to WW, ZZ$

BR($H_t \to WW, ZZ$) is suppressed when decays to top-pions ($W^\pm \Pi_t^\mp$, $Z\Pi_t^0$, $\Pi_t\Pi_t$) are kinematically accessible.

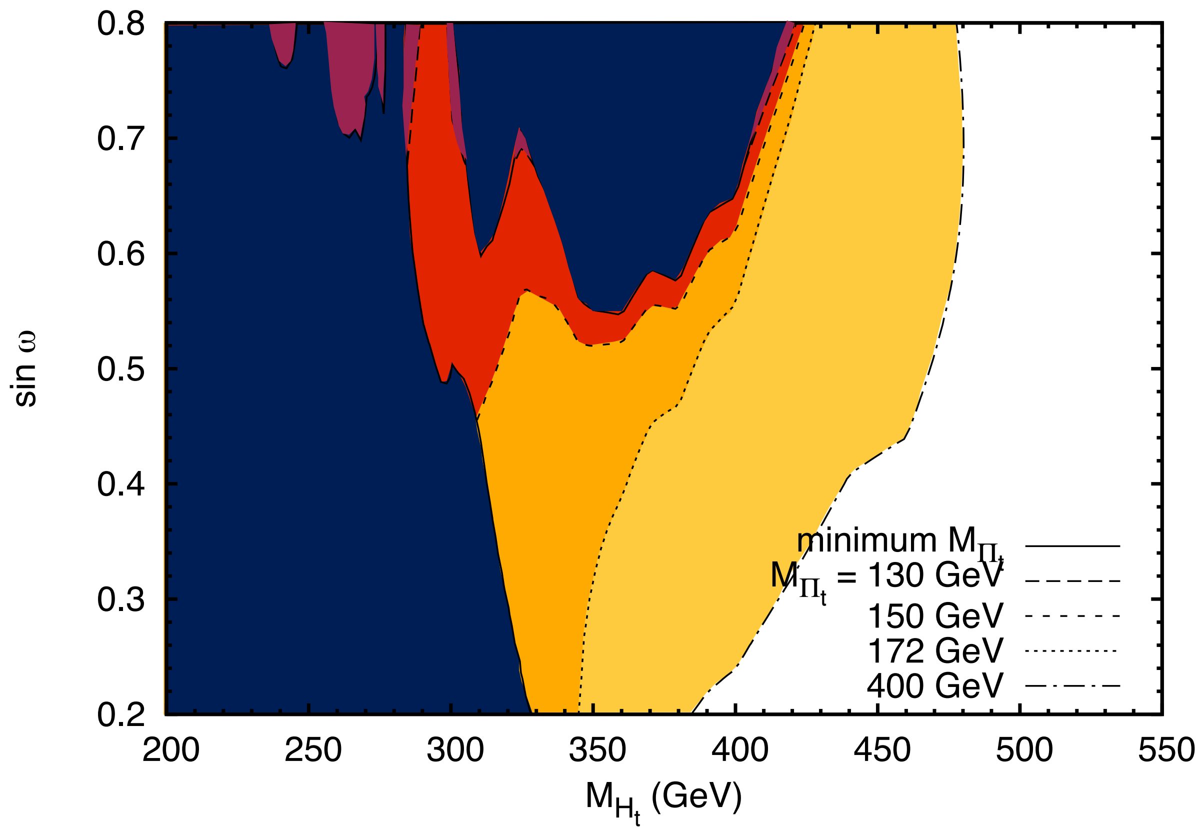
Top-pion mass constrained by exotic top decay limits: $t \to \Pi_t^+ b$.





Chivukula, Simmons, Coleppa, HEL, & Martin, arXiv:1108.4000 (updated with LP11 limits)

Most of the interesting TC2 top-Higgs parameter space has been excluded this summer!

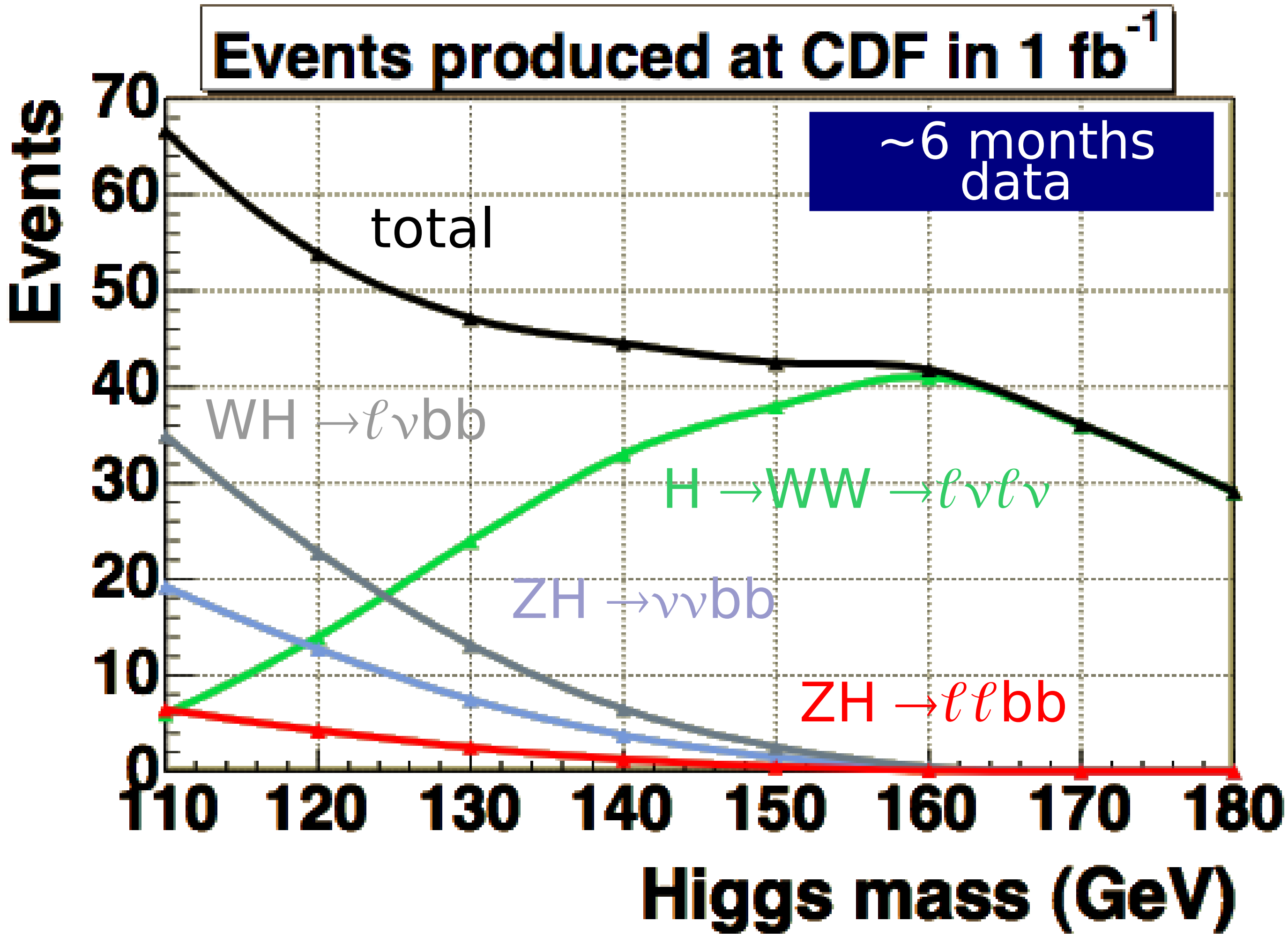


Chivukula, Simmons, Coleppa, HEL, & Martin, arXiv:1108.4000 (updated with LP11 limits)

Other options:

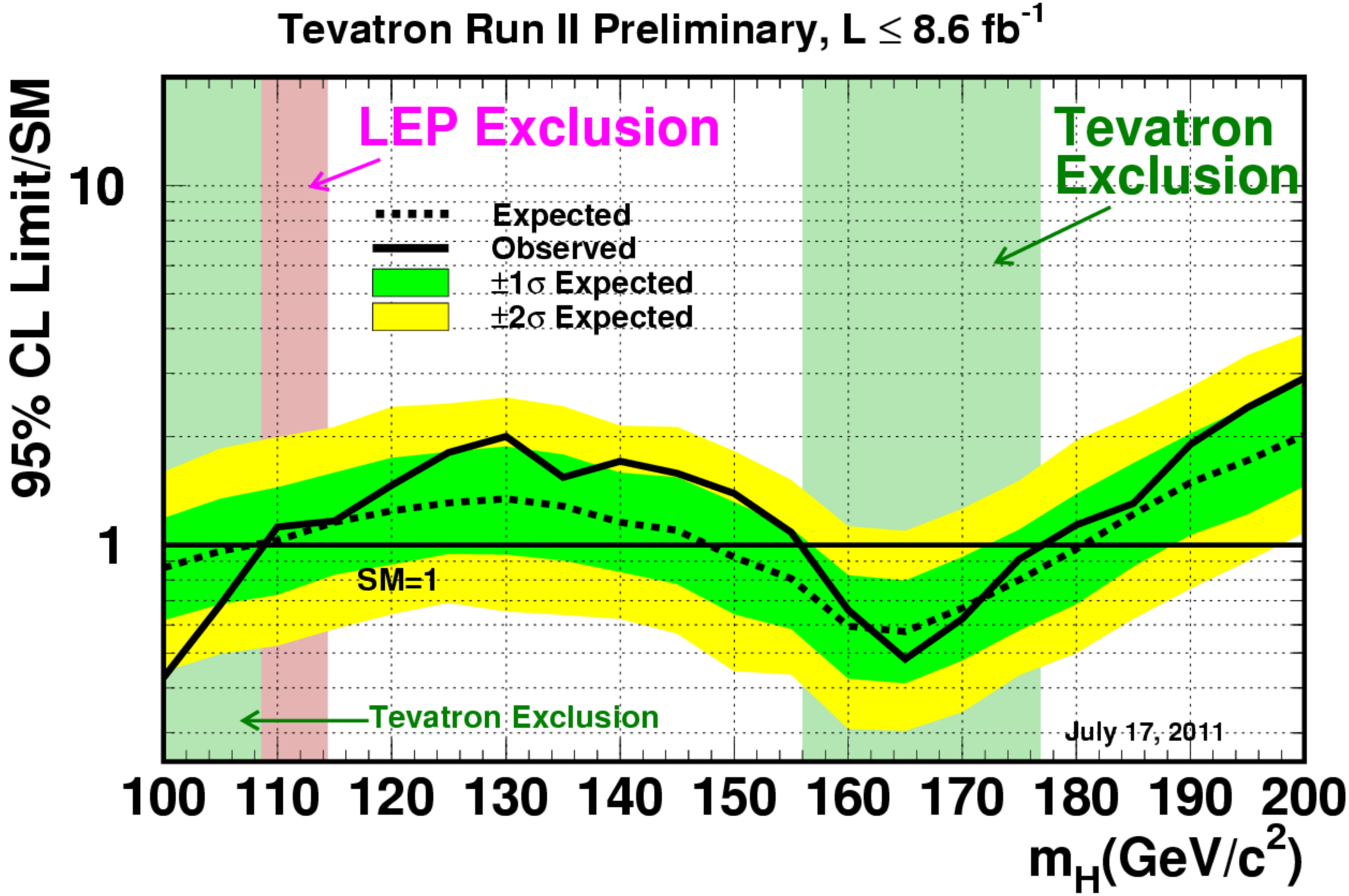
Top seesaw ⇒ much heavier top-Higgs: still viable

Signal rate = production rate × decay branching ratio.
Tevatron:



M. Casarsa, talk at Physics at the LHC, June 2011

Latest SM Higgs results from Tevatron (EPS-HEP 2011)



Tevatron combined, arXiv:1107.5518 [hep-ex], shown at EPS-HEP 2011

Standard Model Higgs mechanism:

Electroweak symmetry broken by an SU(2)-doublet scalar field:

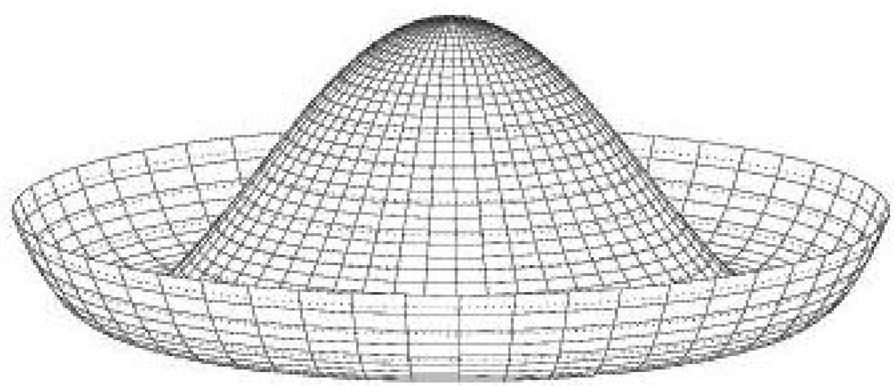
$$H = \begin{pmatrix} G^+ \\ (h+v)/\sqrt{2} + iG^0/\sqrt{2} \end{pmatrix}$$

- G^+ and G^0 are the Goldstone bosons (eaten by W^+ and Z).
- v is the SM Higgs vacuum expectation value (vev), $v = 2m_W/g \simeq 246$ GeV.
- h is the SM Higgs field, a physical particle.

Electroweak symmetry breaking comes from the Higgs potential:

$$V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

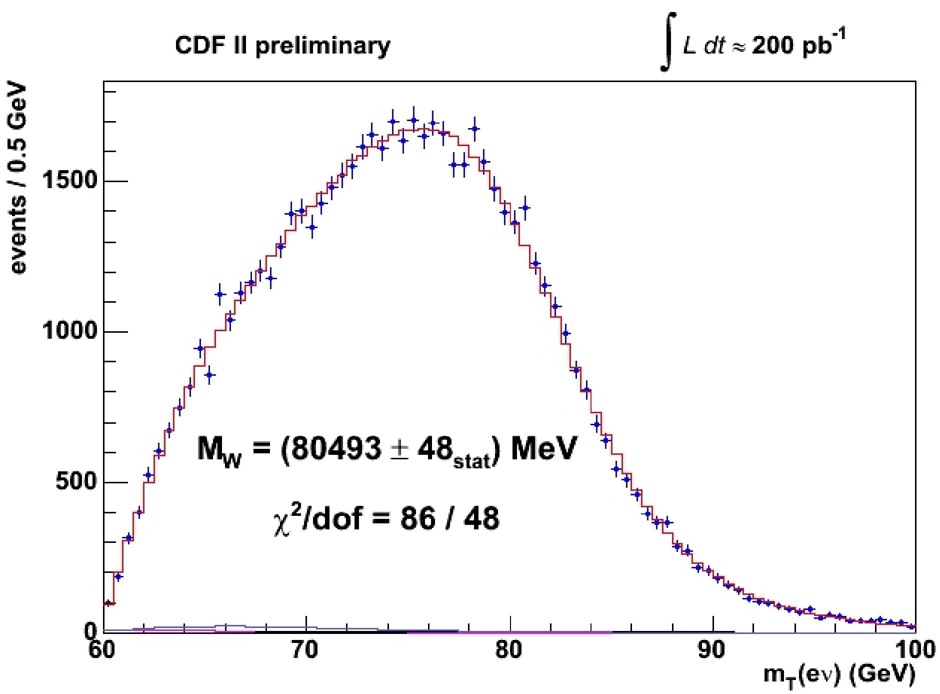
where $\lambda \sim \mathcal{O}(1)$
and $\mu^2 \sim -\mathcal{O}(M_{\rm EW}^2)$.
$\Rightarrow v^2 = -\mu^2/\lambda = (246\ \text{GeV})^2$,
$M_h^2 = 2\lambda v^2 = -2\mu^2$.

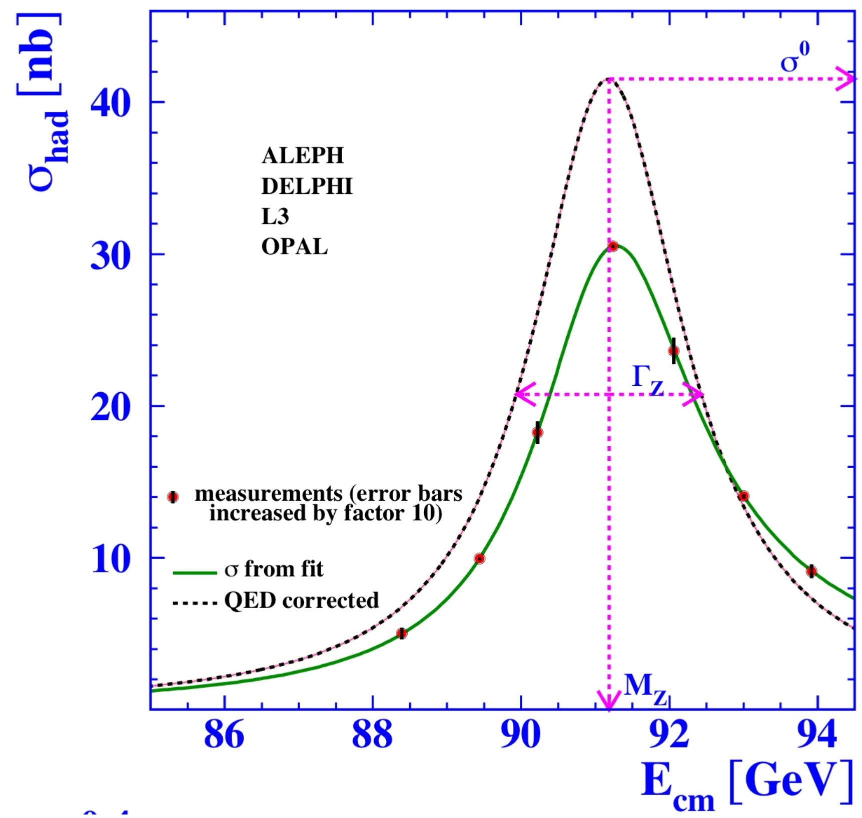


Just like electromagnetism, the theory of weak interactions is a gauge theory.

But there's a snag: the W and Z bosons are not massless!

$m_W = 80.398 \pm 0.025\,\text{GeV}/c^2$ $\qquad$ $m_Z = 91.1876 \pm 0.0021\,\text{GeV}/c^2$





Maybe weak interactions are not a gauge theory?

Requiring gauge invariance constrains the theory very tightly: stringent set of predictions, can be tested experimentally.

Results:

All the measurements are in excellent agreement with standard gauge theory predictions!

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3