The Higgs boson: where we go from here

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SM success: triumph of the gauge principle

QED

Precision electroweak

Perturbative QCD / Lattice QCD

CKM picture for flavor physics

SM challenge: mystery of the vacuum

Origin of W, Z masses

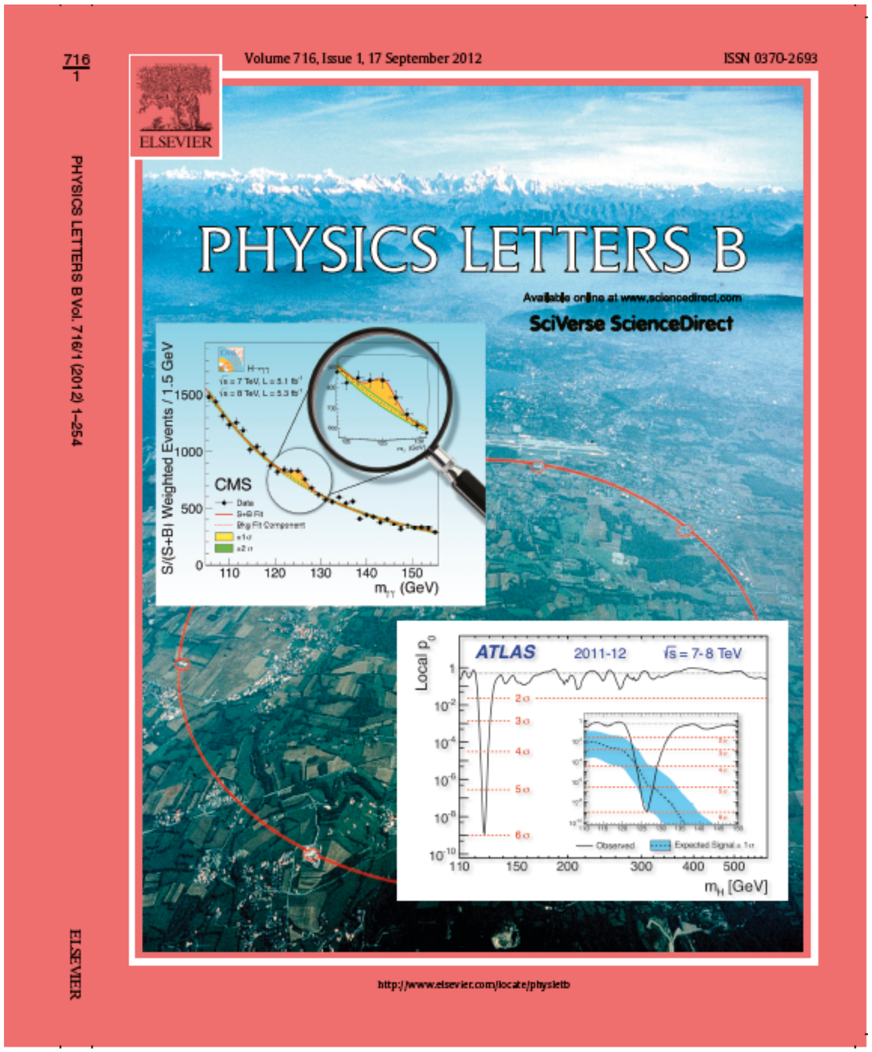
Origin of quark & lepton masses, mixing, CP violation

Origin of neutrino masses, mixing

Dark energy / Inflation

Hierarchy

Higgs discovery gives us first solid experimental handle:
The Higgs boson is a piece of the vacuum!



Cartoon: CERN

Outline

Introduction: Higgs couplings in the Standard Model

What can we learn from measuring Higgs couplings?
- Higgs couplings beyond the Standard Model
- Current status
- Future prospects

Conclusions

Higgs couplings in the Standard Model

A one-line theory:

$$\mathcal{L}_{Higgs} = |\mathcal{D}_\mu H|^2 - [-\mu^2 H^\dagger H + \lambda(H^\dagger H)^2] - [y_f \bar{f}_R H^\dagger F_L + \text{h.c.}]$$

Most general, renormalizable, gauge-invariant theory involving a single scalar field with isospin 1/2, hypercharge 1.

$-\mu^2$ term: electroweak symmetry spontaneously broken; Goldstones can be gauged away leaving one physical particle h.

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

Mass and vev of h are fixed by minimizing the Higgs potential:

$$v^2 = \mu^2/\lambda \qquad\qquad M_h^2 = 2\lambda v^2 = 2\mu^2$$

Higgs couplings in the Standard Model

SM Higgs couplings to SM particles are fixed by the mass-generation mechanism.

W and Z: $g_Z \equiv \sqrt{g^2 + g'^2}$, $v = 246$ GeV

$$\mathcal{L} = |\mathcal{D}_\mu H|^2 \;\rightarrow\; (g^2/4)(h+v)^2 W^+ W^- + (g_Z^2/8)(h+v)^2 ZZ$$

$$M_W^2 = g^2 v^2/4 \qquad hWW: \; i(g^2 v/2) g^{\mu\nu}$$

$$M_Z^2 = g_Z^2 v^2/4 \qquad hZZ: \; i(g_Z^2 v/2) g^{\mu\nu}$$

Fermions:

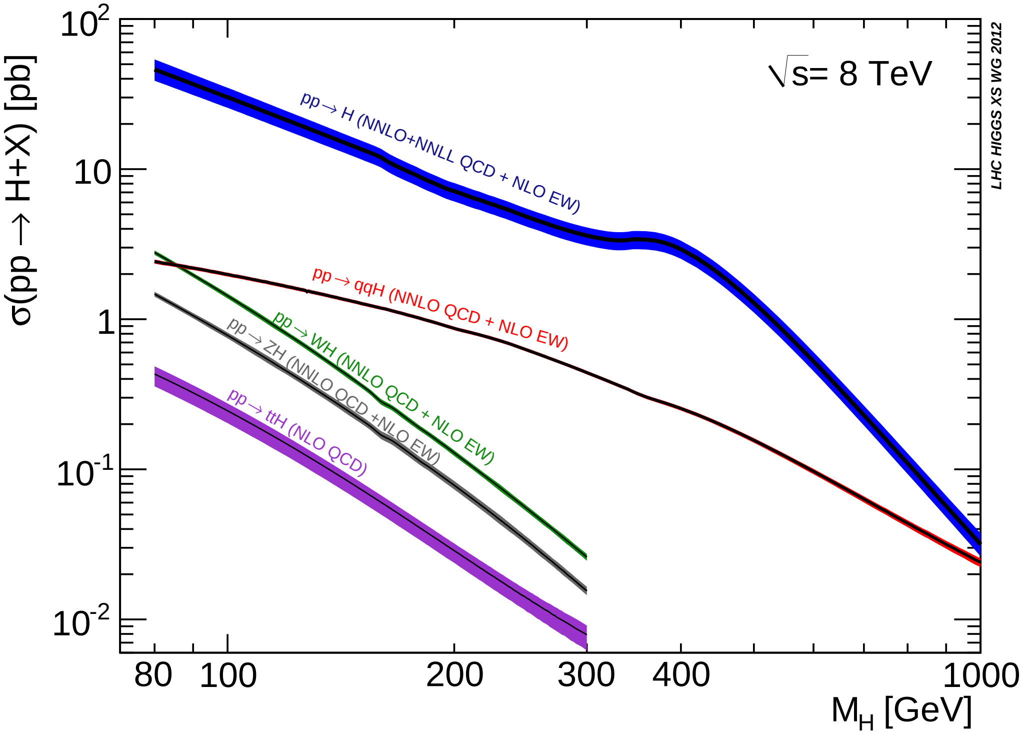
$$\mathcal{L} = -y_f \bar{f}_R H^\dagger Q_L + \cdots \;\rightarrow\; -(y_f/\sqrt{2})(h+v)\bar{f}_R f_L + \text{h.c.}$$

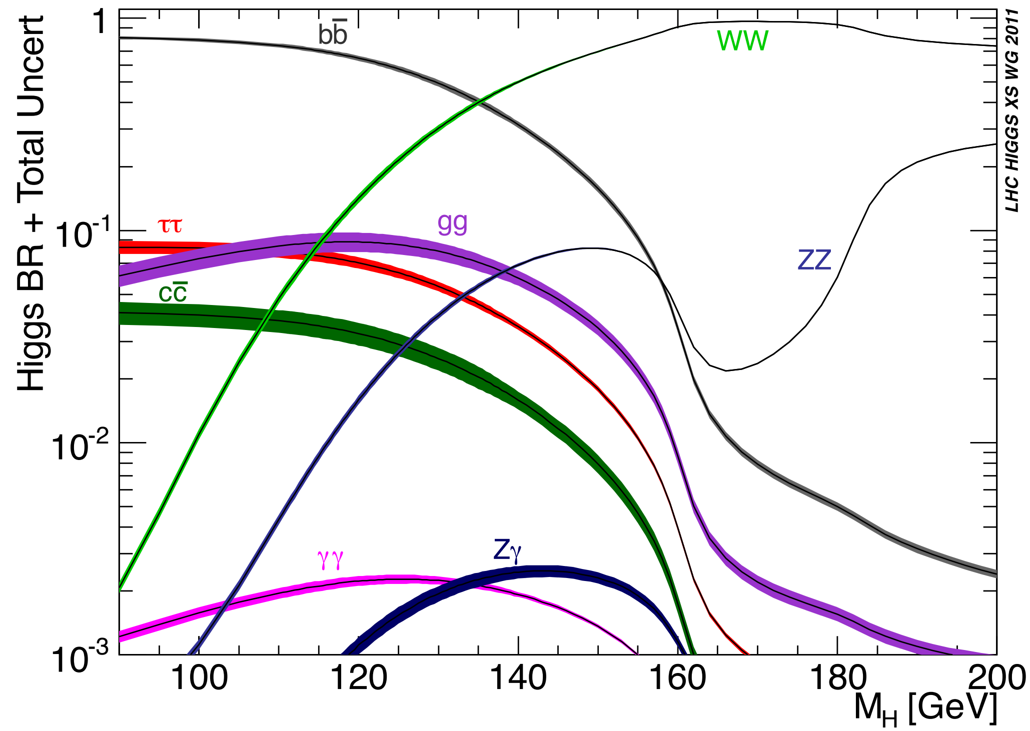
$$m_f = y_f v/\sqrt{2} \qquad h\bar{f}f: \; i m_f/v$$

Gluon pairs and photon pairs:

induced at 1-loop by fermions, W-boson.

Predict SM Higgs production cross sections and decay branching ratios (as function of M_h)





We know that the Standard Model cannot be the whole story.

Problems from data:

- Dark matter (and dark energy?!?)
  Higgs portal; $h \to$ invisible
- Matter-antimatter asymmetry
  Electroweak baryogenesis, need modified Higgs potential

Problems from theory:

- Hierarchy problem
  SUSY; composite Higgs/Randall-Sundrum; little Higgs; fine tuning??
- Neutrino masses (why so very tiny?)
  Type-2 seesaw scalar triplet; neutrino-coupled doublet
- Flavour (origin of quark and lepton masses, mixing, CP violation?)
  Clues from fermion couplings to Higgs?

To probe for this new physics:

Measure couplings of the discovered Higgs particle h

- Mixing within extended Higgs sector shows up in h couplings

- New charged/coloured particles contribute to $h\gamma\gamma$, hgg loops

- Compositeness affects couplings at order v^2/f^2

Search directly for the new states

- Adapt SM Higgs searches; h coupling measurements constrain production/decay of additional states

- $h \to$ new particles

- Direct searches for SUSY / composite sector / KK modes / ...

Is there more than one vacuum condensate?

Imagine two SU(2) doublets with nonzero vevs.

- Both condensates contribute to W and Z masses

- Say one gives masses to up-type quarks, one gives masses to down-type quarks and charged leptons (like in MSSM)
  $\rightarrow$ need stronger couplings to give measured fermion masses

- Discovered Higgs particle h is a coupled excitation of the two vacuum-condensate fields
  $\rightarrow$ mixing angle affects h couplings to W, Z, fermions

- Orthogonal excitation H is out there somewhere
(along with uneaten would-be Goldstones A^0, $H^{\pm}$)

Concrete models

SM Higgs + singlet

all couplings of h scaled by mixing angle $\cos\theta$

SM Higgs + additional doublet(s)

different choices for fermion mass generation $\rightarrow$ coupling patterns

SM Higgs + larger SU(2) multiplet

possible custodial symmetry violation

These extensions often appear in BSM models:

- MSSM: need second Higgs doublet for anomaly cancellation, holomorphic fermion couplings

- NMSSM: additional singlet to generate μ parameter

- Little Higgs models: global symmetry often yields additional SU(2) reps of PNGBs: doublets, triplet, singlet(s)

Higgs couplings beyond the Standard Model

W and Z:

- EWSB can come from more than one Higgs doublet, which then mix to give h mass eigenstate. $v \equiv \sqrt{v_1^2 + v_2^2}$, $\phi_v = \frac{v_1}{v} h_1 + \frac{v_2}{v} h_2$

$$\mathcal{L} = |\mathcal{D}_\mu H_1|^2 + |\mathcal{D}_\mu H_2|^2$$
$$M_W^2 = g^2 v^2/4 \qquad hWW: \ i\langle h|\phi_v\rangle (g^2 v/2) g^{\mu\nu} \equiv i\kappa_W (g^2 v/2) g^{\mu\nu}$$
$$M_Z^2 = g_Z^2 v^2/4 \qquad hZZ: \ i\langle h|\phi_v\rangle (g_Z^2 v/2) g^{\mu\nu} \equiv i\kappa_Z (g^2 v/2) g^{\mu\nu}$$

Note $\kappa_W = \kappa_Z$. Also, $\kappa_{W,Z} = 1$ when $h = \phi_v$: "decoupling limit".

- Part of EWSB from larger representation of SU(2): $Q = T^3 + Y/2$

$$\mathcal{L} \supset |\mathcal{D}_\mu \Phi|^2 \ \rightarrow \ (g^2/4)[2T(T+1) - Y^2/2](\phi + v)^2 W^+ W^- + (g_Z^2/8) Y^2 (\phi + v)^2 ZZ$$

Can get $\kappa_W \neq \kappa_Z$ and/or $\kappa_{W,Z} > 1$ after mixing to form h.

Tightly constrained by rho parameter, $\rho \equiv M_W^2 / M_Z^2 \cos^2\theta_W = 1$ in SM.

Higgs couplings beyond the Standard Model

Fermions:

Masses of different fermions can come from different Higgs doublets, which then mix to give h mass eigenstate:

$$\mathcal{L} = -y_f \bar{f}_R \Phi_f^\dagger F_L + \text{(other fermions)} + \text{h.c.}$$

$$m_f = y_f v_f/\sqrt{2} \qquad h\bar{f}f: \ i\langle h|\phi_f\rangle(v/v_f)m_f/v \equiv i\kappa_f m_f/v$$

In general $\kappa_t \neq \kappa_b \neq \kappa_\tau$; e.g. MSSM with large $\tan\beta$ (Δ_b).

Note $\langle h|\phi_f\rangle(v/v_f) = \langle h|\phi_f\rangle/\langle\phi_v|\phi_f\rangle$

$\Rightarrow$ $\kappa_f = 1$ when $h = \phi_v$: "decoupling limit".

Higgs couplings beyond the Standard Model

Gluon pairs and photon pairs:

- κ_t and κ_W change the normalization of top quark and W loops.

New coloured or charged particles give new loop contributions.

e.g. top squark, charginos, charged Higgs in MSSM

New particles in the loop can affect $h \leftrightarrow gg$ and $h \to \gamma\gamma$ even if h is otherwise SM-like.

$\Rightarrow$ Most general treatment: take κ_g and κ_γ as additional independent coupling parameters.

Coupling extraction strategy at LHC

Measure event rates at LHC: sensitive to production and decay couplings. Narrow width approximation:

$$\text{Rate}_{ij} = \sigma_i \, \text{BR}_j = \sigma_i \frac{\Gamma_j}{\Gamma_{\text{tot}}}$$

Coupling dependence (at leading order):

$$\sigma_i = \kappa_i^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$
$$\Gamma_j = \kappa_j^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$
$$\Gamma_{\text{tot}} = \sum \Gamma_k = \sum \kappa_k^2 \Gamma_k^{\text{SM}}$$

Each rate depends on multiple couplings. $\rightarrow$ correlations

Coupling extraction strategy at LHC

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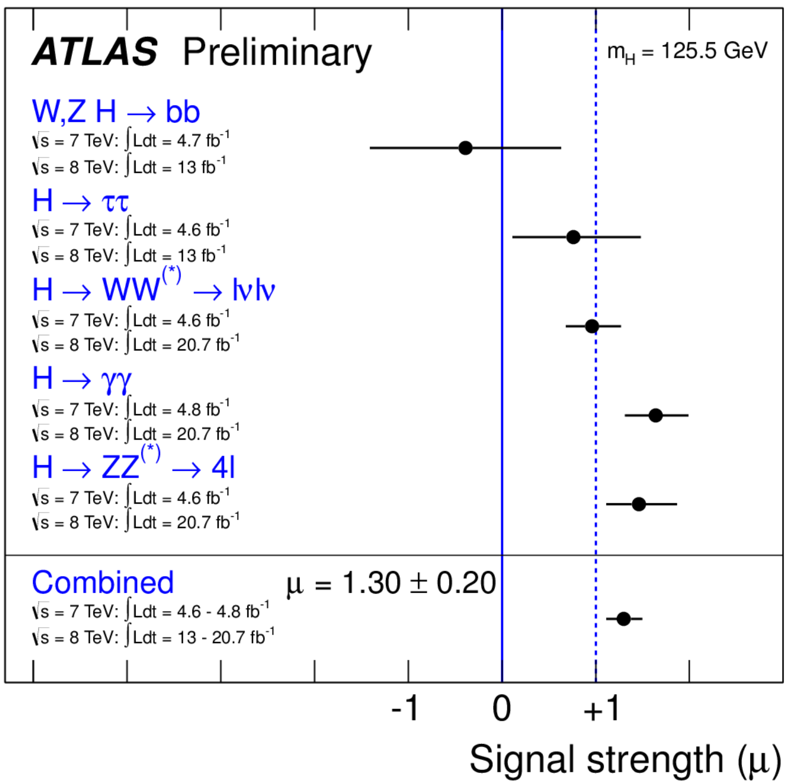
$$\Gamma_{\text{tot}} = \sum \Gamma_k = \sum_{\text{SM}} \kappa_k^2 \Gamma_k^{\text{SM}} + \sum_{\text{new}} \Gamma_k^{\text{new}}$$

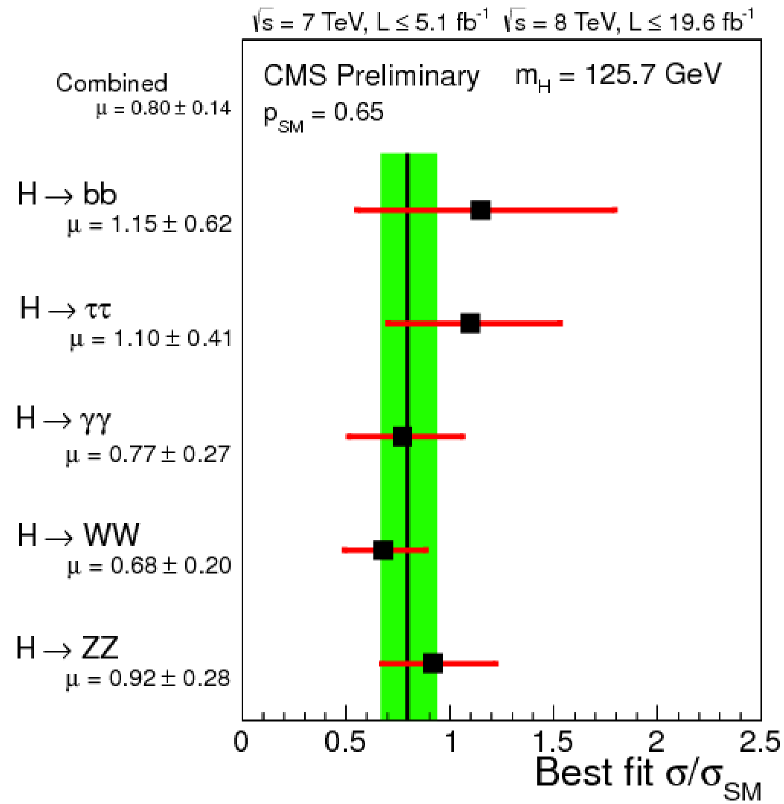
Each rate depends on multiple couplings. $\rightarrow$ correlations

Non-SM decays could also be present:

- invisible final state (look for this with dedicated searches: $h \rightarrow$ ETmiss)
- "unobserved" final state (e.g., $h \rightarrow$ jets)

LHC measurements (March 2013)





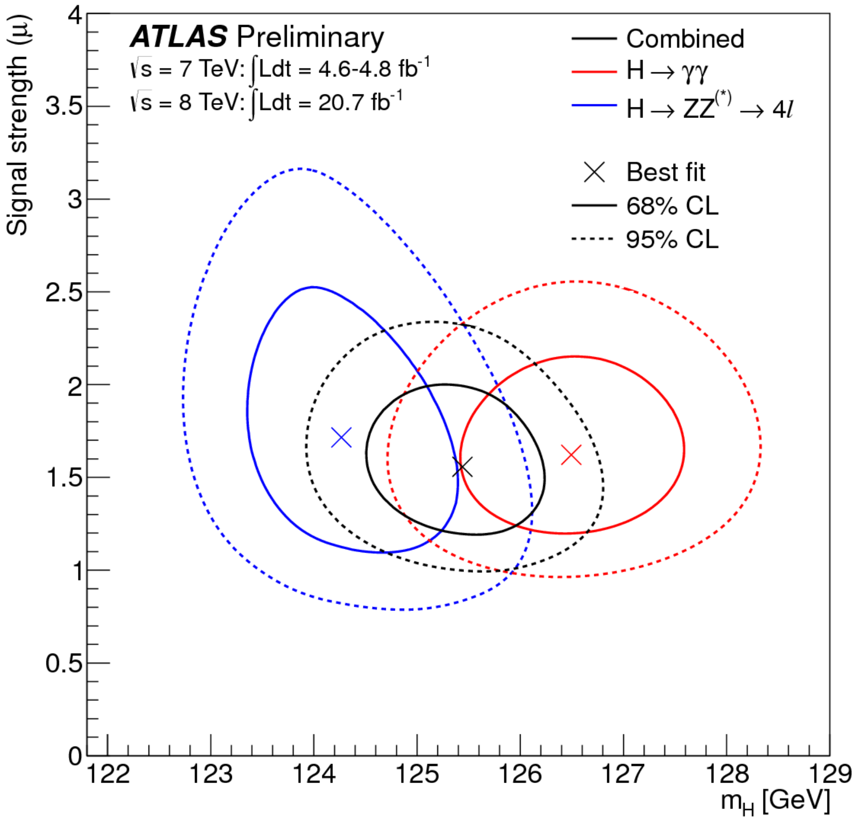
Uncertainties still large

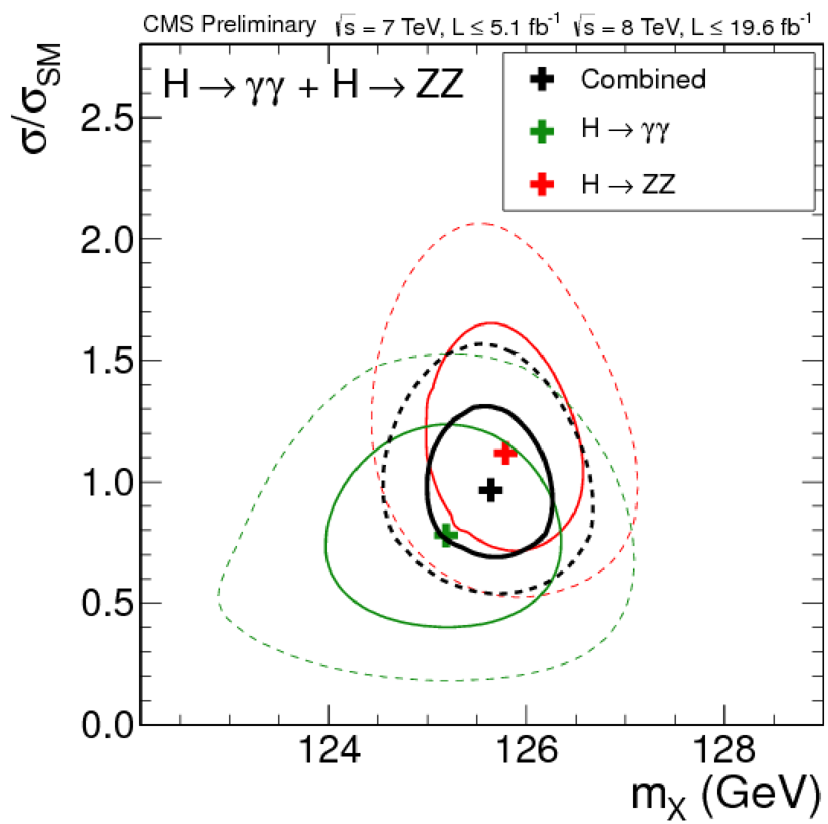
Few production × decay modes with uncertainties below 30%

⇒ Rely on constrained fits within particular models for now

LHC measurements (March 2013)

Overall signal strength $\mu \equiv \sigma/\sigma_{SM}$
- Assume that all decays are in their SM proportions



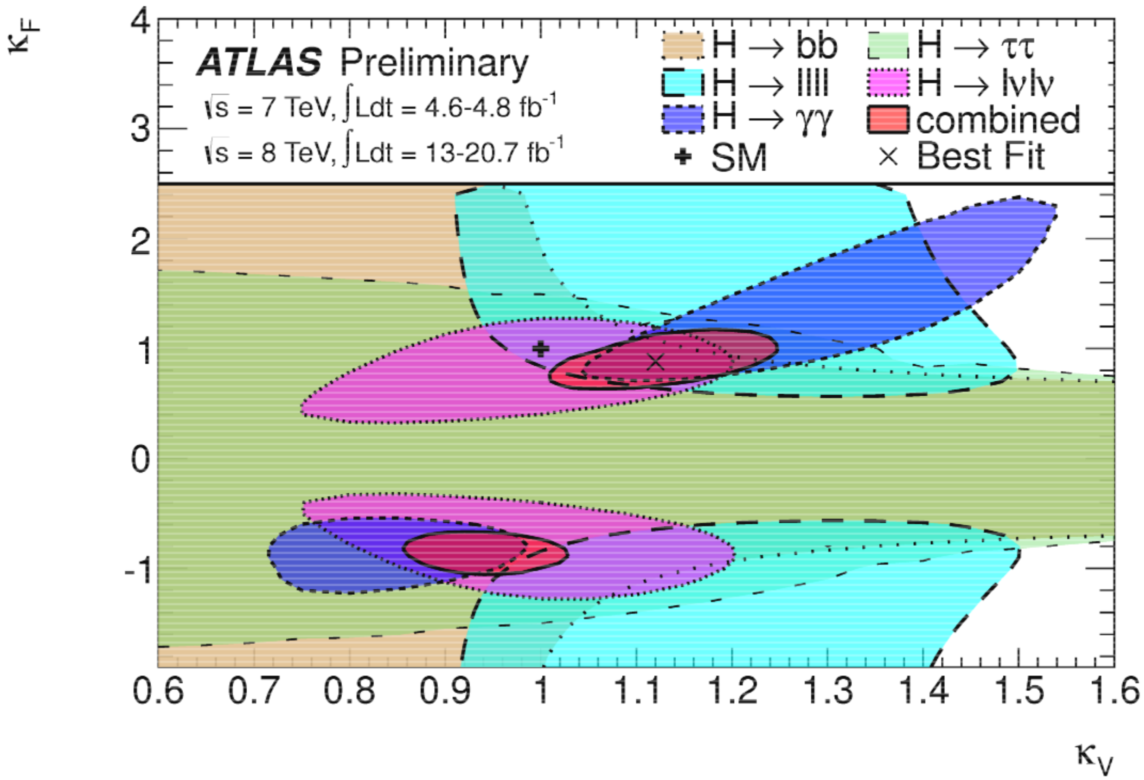


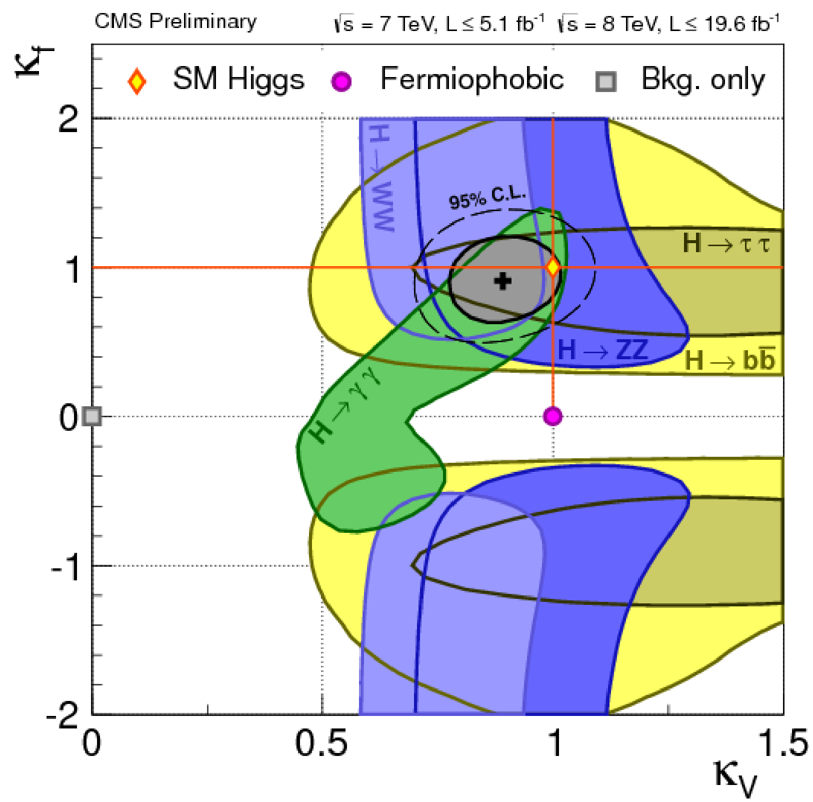
Highly constrained: 1-parameter coupling measurement

SM Higgs mixed with a singlet: $\mu \equiv \cos^2\theta$

LHC measurements (March 2013)

Going beyond one parameter: $\mathcal{L} \supset \frac{v^2}{4} g^2 V_\mu V^\mu \left(\kappa_V \frac{2h}{v}\right) - m_i \bar{\psi}_i \psi_i \left(\kappa_F \frac{h}{v}\right)$





Highly constrained: 2-parameter coupling fit assumes no exotic decays

Two-Higgs-doublet-model (Type I): $\kappa_V = \sin(\beta - \alpha)$, $\kappa_F = \cos\alpha / \sin\beta$

$hf\bar{f}$ couplings: first non-gauge interaction we've ever seen!

LHC measurements (March 2013)

Additional constrained fits:

- κ_V, κ_u, κ_d: test up vs. down quarks
- κ_V, κ_q, κ_ℓ: test quarks vs. leptons

  Can reduce to 2-parameter fits in particular 2HDM models
- κ_W, κ_Z: test custodial symmetry (probe for Higgs triplet contributions)

Synergy between couplings of h and searches for additional states

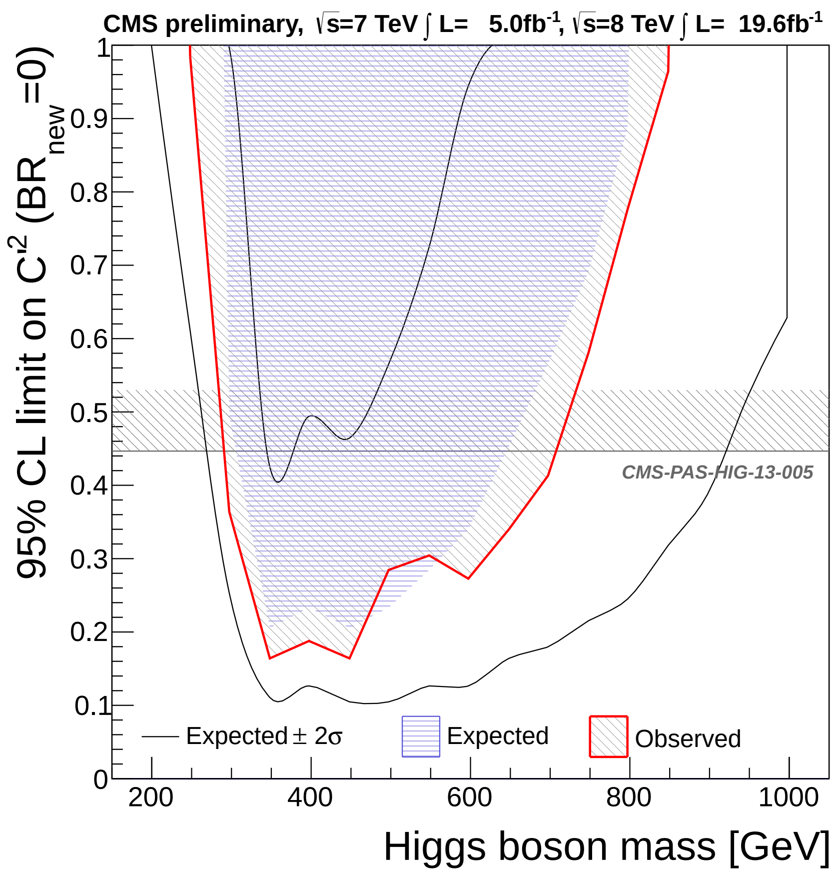
The vacuum condensate(s) generate mass through couplings to SM particles.

If more than one mass eigenstate contains excitation(s) of the condensate(s), then they must share these couplings.

Sum rules: $\kappa(h)^2 + \kappa(H)^2 = 1$

Important implications for searches for additional Higgs-like states.

Example: brand new CMS search for EW singlet mixed with SM Higgs. Adapt heavy-Higgs search to narrower, rarer 2nd Higgs.



CMS-PAS-HIG-13-014 ($H \to ZZ \to 2\ell 2\nu$)

High precision buys you New Physics reach.

Typical Higgs mass matrix for two mixed states:

$$\left(\begin{array}{cc} m^2 & \lambda v^2 \text{ or } \mu v \\ \lambda v^2 \text{ or } \mu v & M^2 \end{array} \right)$$

Larger $M^2 \to$ smaller mixing angle $\to h$ couplings more SM-like.
Similarly, loop corrections from NP $\sim$ (loop factor)(v^2/M^2)

$h \to$ SM-like called the "decoupling limit".

A few examples:

Compositeness: $\Delta\kappa_V \sim -3\%(\frac{TeV}{f})^2$, $\Delta\kappa_F \sim -(3\% \sim 10\%)(\frac{TeV}{f})^2$

2HDM-II: $\Delta\kappa_b = \Delta\kappa_\tau \sim 40\%(\frac{200GeV}{M_A})^2 \simeq 2\%(\frac{TeV}{M_A})^2$ for $\tan\beta = 5$

Little Higgs: $\Delta\kappa_g, \Delta\kappa_\gamma \sim -5\%$ for 1 TeV top-partner

MSSM: $\Delta\kappa_b, \Delta\kappa_\tau \sim (2\% \sim 4\%)$ for $m_A = 1$ TeV, $\tan\beta = 5$
Significant parameter dependence including large SUSY loop corrections.

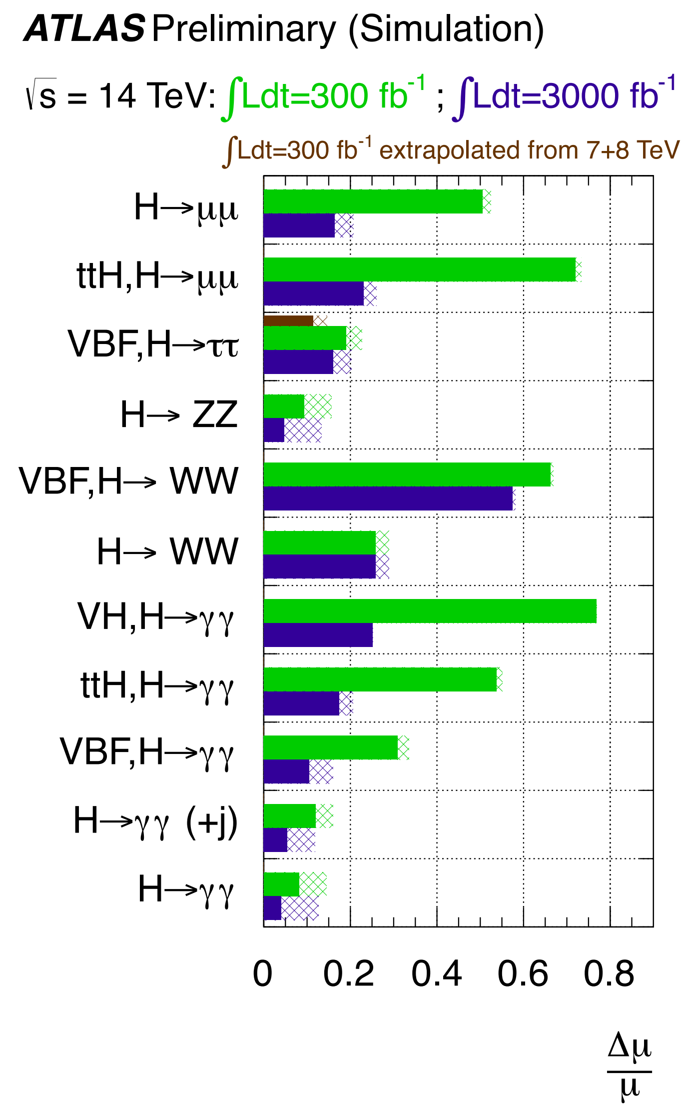
LHC: About 27 fb^{-1} collected per expt. at 7 + 8 TeV.

Expect 300 fb^{-1}/expt. at 13-14 TeV
- Also, larger cross sections

Expected precisions:
$\sim$ 30% for $h \to WW$, VBF $h \to \gamma\gamma$
$\sim$ 20% for VBF $h \to \tau\tau$
$\sim$ 10% for $h \to ZZ$, $h \to \gamma\gamma$

High-luminosity LHC upgrade
$>$ 2022, $\to$ 3000 fb^{-1}/expt.

Add tth channels $\sim$ 20%, $h \to \mu\mu$
Improve VBF, Vh $h \to \gamma\gamma$ 15-30%



More careful studies needed for $h \to bb$.

ATL-PHYS-PUB-2012-004 (European Strategy study)

For higher precision: high-energy e^+e^- Higgs "factory"

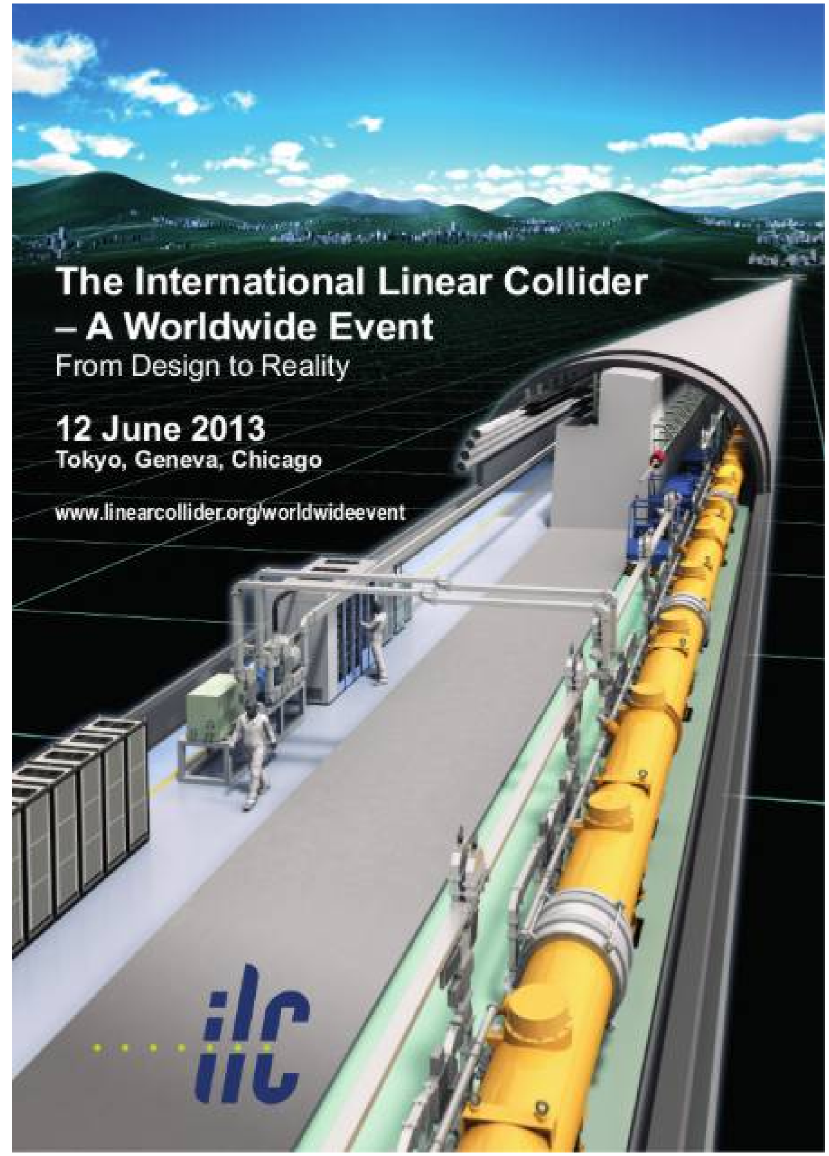
International Linear Collider:
- e^+e^- collisions: very clean.
- Linear: no synchrotron radiation.

15+ years globally coordinated R&D

In Canada:
- TPC (tracker) R&D
- calorimeter R&D
- accelerator R&D (TRIUMF)
- theory work

Technical Design Report release June

Serious interest from Japanese government to host machine



For higher precision: high-energy e^+e^- Higgs "factory"

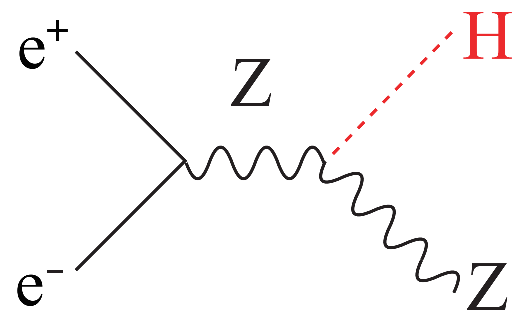
Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings
	$e^+e^- \to WW$	precision W couplings
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top
	$e^+e^- \to Zhh$	Higgs self-coupling
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry

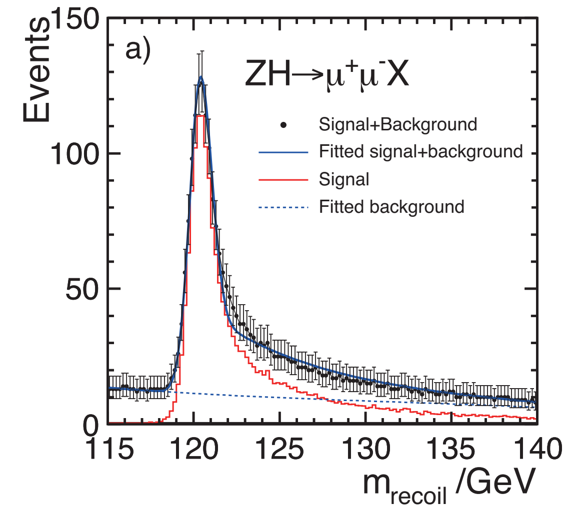
draft ILC TDR (2013)

Multi-purpose program; focus on Higgs physics.

$e^+e^- \to Zh$ at peak xsec, $\sqrt{s} \simeq 250$ GeV: recoil mass method

"Z-tagged" Higgs:
- measure $\sigma(Zh)$ independent of BRs to 2.5%
- measure BRs in inclusive Higgs sample: no model assumptions needed





ILC 250 fb^{-1} at $\sqrt{s} = 250$ GeV draft ILC TDR (2013) $m_h = 120$ GeV

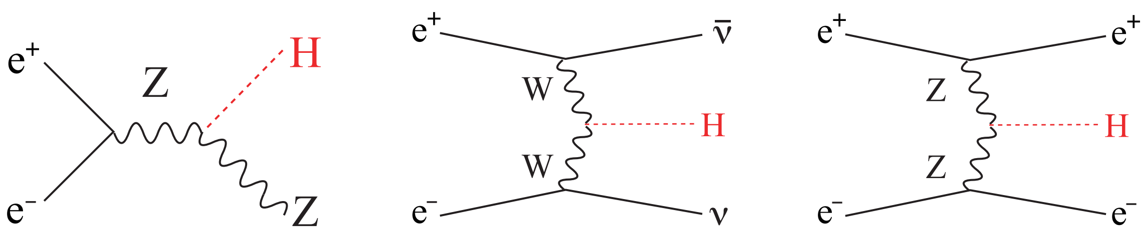
mode	BR	$\sigma \cdot BR$ (fb)	$N_{evt}/250\,\text{fb}^{-1}$	$\Delta(\sigma BR)/(\sigma BR)$	$\Delta BR/BR$
$h \to b\bar{b}$	65.7%	232.8	58199	1.0%	2.7%
$h \to c\bar{c}$	3.6%	12.7	3187	6.9%	7.3%
$h \to gg$	5.5%	19.5	4864	8.5%	8.9%
$h \to WW^*$	15.0%	53.1	13281	8.1%	8.5%
$h \to \tau^+\tau^-$	8.0%	28.2	7050	3.6%	4.4%
$h \to ZZ^*$	1.7%	6.1	1523	26%	26%
$h \to \gamma\gamma$	0.29%	1.02	255	23-30%	23-30%

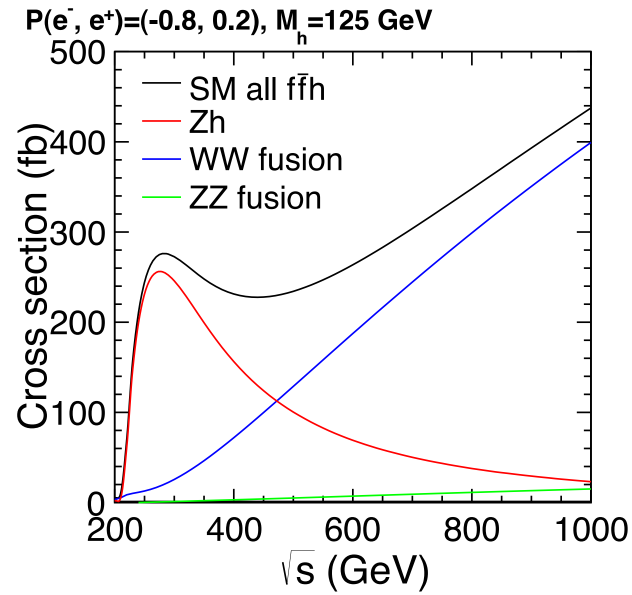
- BRs to bb ($< 3\%$), $\tau\tau$, cc ($\sim 7\%$), WW, gg ($\sim 9\%$)
- BRs to ZZ, $\gamma\gamma$ statistics limited (20-30%)

Higher energy e^+e^- collisions:

More statistics

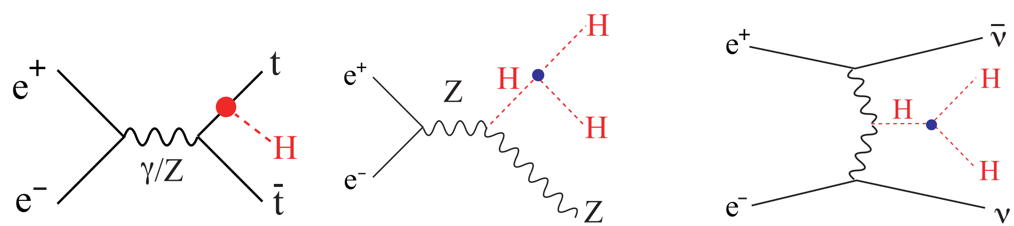
- WBF Higgs production cross section grows with collision energy.
- ILC luminosity grows with beam energy.





Access to new processes

- $t\bar{t}h$ coupling
- triple-Higgs self coupling



ILC baseline design up to $\sqrt{s} \simeq 500$ GeV.
ILC upgrade to $\sqrt{s} \simeq 1000$ GeV.

Full ILC program, $m_h = 125$ GeV draft ILC TDR (2013)

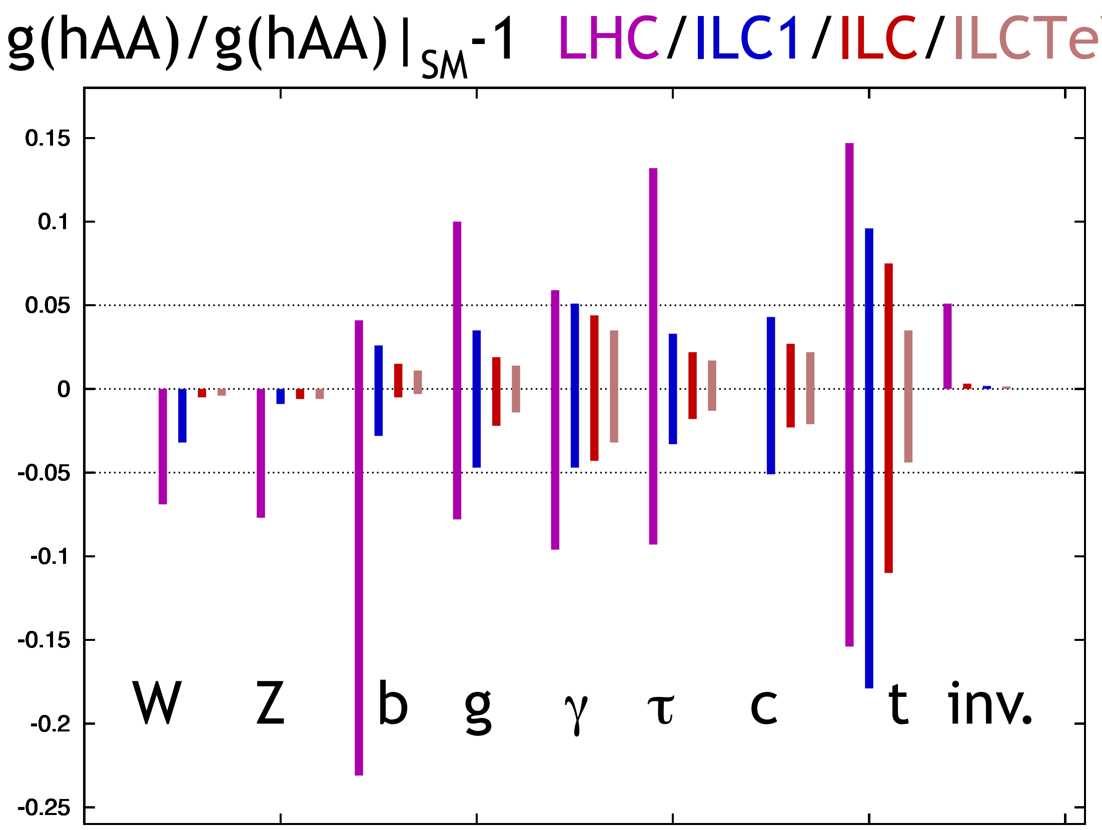
	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$				
$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	$250\,\mathrm{fb}^{-1}$ at $250\,\mathrm{GeV}$ (-0.8,+0.3)		$500\,\mathrm{fb}^{-1}$ at $500\,\mathrm{GeV}$ (-0.8,+0.3)		$1\,\mathrm{ab}^{-1}$ at $1\,\mathrm{TeV}$ (-0.8,+0.2)
mode	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$
$h \to b\bar{b}$	1.1%	10.5%	1.8%	0.66%	0.47%
$h \to c\bar{c}$	7.4%	-	12%	6.2%	7.6%
$h \to gg$	9.1%	-	14%	4.1%	3.1%
$h \to WW^*$	6.4%	-	9.2%	2.6%	3.3%
$h \to \tau^+\tau^-$	4.2%	-	5.4%	14%	3.5%
$h \to ZZ^*$	19%	-	25%	8.2%	4.4%
$h \to \gamma\gamma$	29-38%	-	29-38%	20-26%	7-10%
$h \to \mu^+\mu^-$	100%	-	-	-	32%

process	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [ab^{-1}]	(P_{e^-}, P_{e^+})	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$	$\Delta g/g$
$t\bar{t}h$	500	1	(-0.8,+0.3)	25%	13%
Zhh	500	2	(-0.8,+0.3)	32%	53%
$t\bar{t}h$	1000	1	(-0.8,+0.2)	8.7%	4.5%
$\nu\bar{\nu}hh$	1000	2	(-0.8,+0.2)	26%	21%

tth and double-Higgs: only $h \to bb$ final state analyzed so far.

Summary: measuring the Higgs couplings

- Do a fit of all available channels.
- LHC: must make theory assumption to constrain total width.
- LHC precisions ∼10%; ILC precisions ∼1–few%



Peskin, 1207.2516. LHC is 300 fb^{-1}, includes Sep 2012 European Strategy submissions.

Conclusions

Precision Higgs coupling measurements will let us learn about the vacuum condensate(s) and how they couple to SM particles.

- Is our Higgs fully responsible for generating the masses of W, Z, fermions?
- Is our Higgs the only excitation of the vacuum condensate?
- Is there other stuff out there that couples to our Higgs?

Higher precision buys us better reach for New Physics.

- Opportunity to shed light on TeV scale.
- Solution of hierarchy problem?
- Electroweak baryogenesis?
- Any hints about flavour, neutrino masses, or dark matter?

With the Higgs discovery we finally have a piece of the vacuum! An experimental opportunity worth taking full advantage of.

Physics Graduate Studies

Carleton UNIVERSITY
Canada's Capital University

Medical Physics…

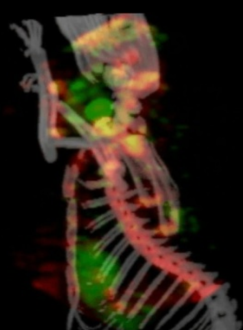
… the application of physics to problems involving human health.

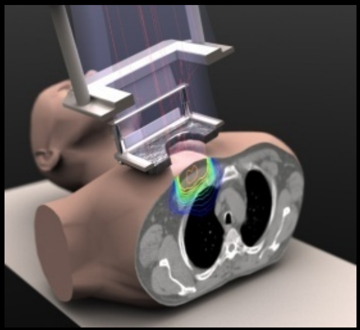
- Imaging: MRI, PET and Nuclear Medicine, X Ray
- Cancer therapy: Radiation Dosimetry and Radiotherapy
- Medical biophysics: Radiation Biology

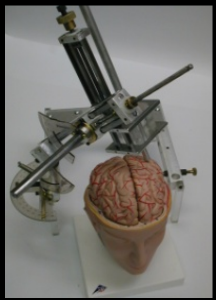
The program is offered in collaboration with medical physicists from *The Ottawa Hospital Cancer Centre*, the *National Research Council*, *Health Canada*, the *University of Ottawa Heart Institute*, and *The Ottawa Hospital*.

The PhD program is accredited by CAMPEP.

Ottawa Medical Physics Institute



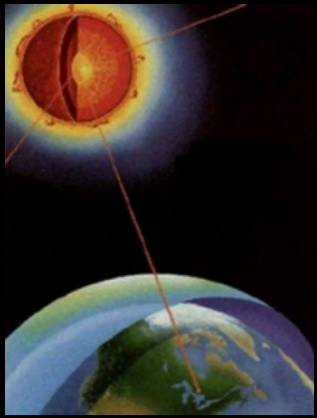


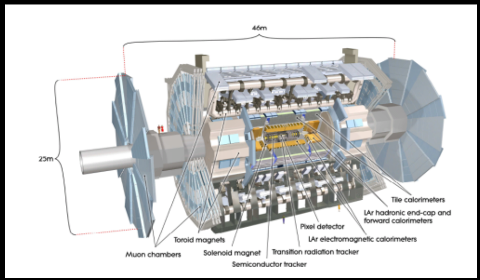


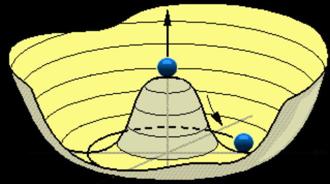
Particle Physics…

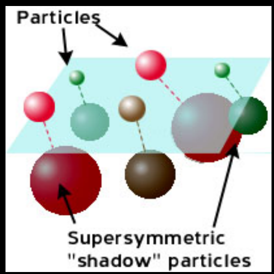
… the study of the fundamental nature of matter and the basic forces that shape our universe.

- Theory: phenomenology of elementary particles, hadron physics, string theory
- Experiment: detector instrumentation and design, physics simulation, experimental operations and data analysis on the following projects:
  - ATLAS at CERN in Geneva, Switzerland
  - DEAP at SNOLAB in Sudbury, ON
  - EXO at SNOLAB in Sudbury, ON
  - International Linear Collider (ILC)
  - Muon tomography for security imaging









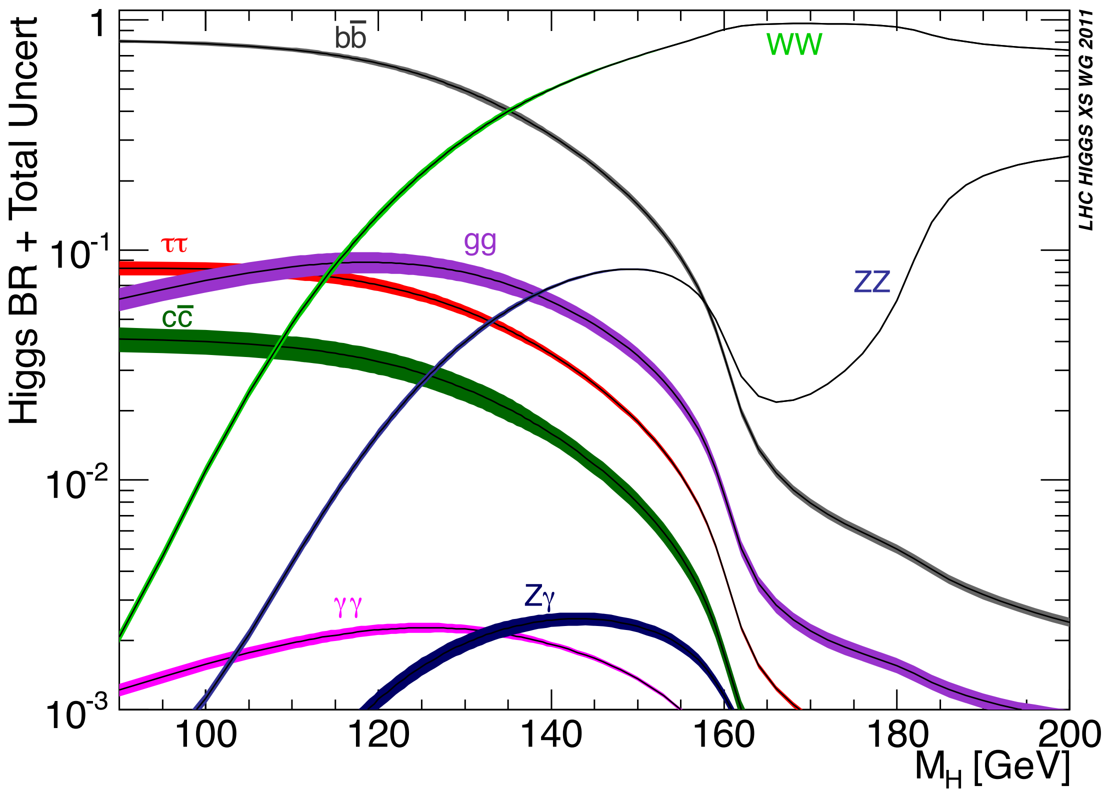
Graduate degree information…
www.physics.carleton.ca

Email: grad_supervisor@physics.carleton.ca

BACKUP SLIDES

Higgs mass dependence

Variation of SM Higgs BRs with M_h due to kinematics:
Precision Higgs mass measurement is important!



1 GeV uncertainty in M_h $\Rightarrow$ 5% uncertainty in κ_b/κ_W.
100 MeV uncertainty in M_h $\Rightarrow$ 0.5% uncertainty in κ_b/κ_W.

For higher precision: e^+e^- Higgs "factory"

ILC: 250 fb^{-1} at 250 GeV: peak of $e^+e^- \to Zh$ cross section
- "Tagged" Higgs: measure $\sigma(Zh)$ independent of BRs to 2.5%
- BRs to bb ($<$ 3%), $\tau\tau$, cc ($\sim$ 7%), WW, gg ($\sim$ 9%)
- BRs to ZZ, $\gamma\gamma$ statistics limited (20-30%)

ILC: 500 fb^{-1} at 500 GeV:
- WBF $e^+e^- \to \nu\bar{\nu}h$: $\Gamma_{\rm tot}$ from combining with BR(WW)
- $e^+e^- \to tth$ for top quark Yukawa coupling
- $e^+e^- \to Zhh$ for Higgs self-coupling ($\sim$ 27% with 2000 fb^{-1})

ILC upgrade: 1000 fb^{-1} at 1000 GeV:
- ultimate precision on $\sigma\times$BRs
- $e^+e^- \to \nu\bar{\nu}hh$ for Higgs self-coupling ($\sim$ 20% with 2000 fb^{-1})

Σ is formally dimensionless (in terms of fields).

Can add powers of an extra scalar field h up to dimension 4:

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \bar{\psi}_i \mathcal{D}_\mu \gamma^\mu \psi_i$$
$$+ (\mathcal{D}_\mu \Sigma)^\dagger (\mathcal{D}^\mu \Sigma) \left(1 + a\frac{2h}{v} + b\frac{h^2}{v^2}\right) - y_{ij}\bar{\psi}_i \Sigma \psi_j \left(1 + c\frac{h}{v}\right)$$

Unitarity of tree-level scattering amplitudes:
$V_L V_L \to V_L V_L$ is unitarized by h if $a = 1$
$V_L V_L \to f\bar{f}$ is unitarized by h if $c = 1$
$V_L V_L \to hh$ is unitarized if $b = a^2$

With $a = b = c = 1$, can absorb h into the Σ field to make a "linear sigma model", i.e., the Standard Model Higgs field:

$$\overline{\Sigma} = e^{-i\xi^a(x)\sigma^a/v} \begin{pmatrix} 0 \\ (v+h)/\sqrt{2} \end{pmatrix}$$

What is the Higgs mass?

Upper bound on Higgs mass from $VV \to VV$: Lee, Quigg, Thacker 1977

$$M_h^2 \leq \frac{8\pi v^2}{3} \simeq (710 \text{ GeV})^2$$

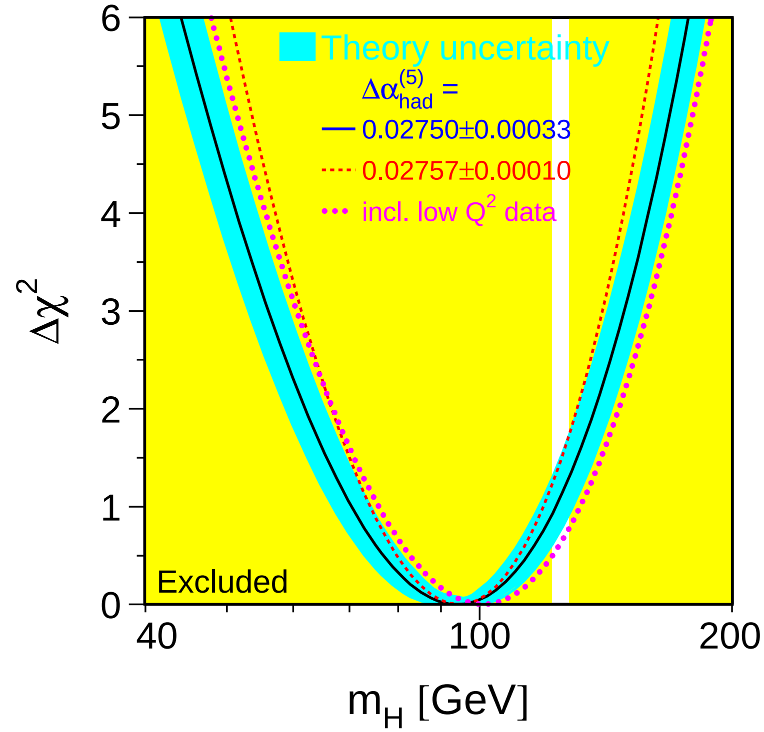
Coupled channel analysis, $|\text{Re}\, a_0| \leq 1/2$, $v \simeq 246$ GeV.

Electroweak fit in the SM:

Sensitive to M_h through 1-loop corrections to W and Z propagators.

Logarithmic dependence on M_h:
$M_h \lesssim 160$–200 GeV
(known since late '90s)

Constraint valid only in SM: fit to one remaining free parameter.



LEP Electroweak Working Group, Winter 2012

What do we learn by measuring Higgs couplings?

- Is our Higgs fully responsible for generating the masses of W, Z, and fermions?

- Is our Higgs fully responsible for unitarizing longitudinal gauge boson scattering?

- Is our Higgs the only excitation of the vacuum condensate?

Is there other physics needed to complete any of these?
(and if so, what is its energy scale?)

- Is there other stuff out there that couples to our Higgs?

Why fit to specific models?

Specific models correspond to a lower-dimensional "slice" through the most general (e.g., 5+2 dimensional) Higgs coupling parameter space.

- Test overall (in-)consistency with a model's coupling pattern

- Get much tighter constraints on a few model parameters than on many independent Higgs couplings

Ideal world: do general fit plus all of the above!

Ultimate test of LHC Higgs coupling sensitivity is the "decoupling limit" of small deviations from SM couplings.

This can be interpreted in concrete non-SM Higgs models

Type-II, lepton-specific, "flipped" 2HDMs:

Only 2 underlying free parameters (mixing angles α and β), plus small contribution of H^+ to $h \to \gamma\gamma$ loop

hWW, $hZZ \propto a = \sin(\beta - \alpha)$

Type-II: $h\bar{t}t \propto c_1 = \cos\alpha / \sin\beta$; $h\bar{b}b$, $h\tau\tau \propto c_2 = -\sin\alpha / \cos\beta$

has a top-phobic limit

Leptonic: $h\bar{t}t$, $h\bar{b}b \propto c_1$; $h\tau\tau \propto c_2$ has a tau-phobic limit

Flipped: $h\bar{t}t$, $h\tau\tau \propto c_1$; $h\bar{b}b \propto c_2$ has a bottom-phobic limit

Can do 2-parameter fits within the model
(or 3-parameter, including new loop contribution to $h\gamma\gamma$);
test relative consistency of different model coupling patterns.

Unobserved final states cause a “flat direction” in the fit.

Allow an unobserved decay mode while simultaneously increasing all couplings to SM particles by a factor a:

$$\text{Rate}_{ij} = a^2 \sigma_i^{\text{SM}} \frac{a^2 \Gamma_j^{\text{SM}}}{a^2 \Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{new}}}$$

Ways to deal with this:

- assume no unobserved decays
  (ok for checking consistency with SM, but highly model-dependent)
- assume hWW and hZZ couplings are no larger than in SM
  (valid if only SU(2)-doublets/singlets are present)
- include direct measurement of Higgs width
  (only works for heavier Higgs so that $\Gamma_{\text{tot}} >$ expt. resolution; $\Gamma_{\text{tot}}^{\text{SM}} \simeq 4$ MeV for 125 GeV Higgs)

No known model-independent way around this at LHC.
[Can we measure $h \to$ jets? Boosted object techniques?]

(ILC gets around this using decay-mode-independent measurement of $e^+e^- \to Zh$ cross section from recoil-mass method.)

This can be interpreted in concrete non-SM Higgs models

SM Higgs mixed with a gauge-singlet scalar:

- Overall 1-parameter scaling of all couplings by $0 \leq \cos\theta \leq 1$.
- BRs stay unchanged; rates scaled by $\cos^2\theta \equiv \mu = \sigma/\sigma_{\rm SM}$

$\rightarrow$ Expect to find the orthogonal state somewhere!

SM Higgs with unobserved/invisible decays (e.g. to dark matter):

- Production rates unchanged
- BRs scaled by $\Gamma_{\rm SM}/(\Gamma_{\rm SM} + \Gamma_{\rm new}) \equiv \mu = \sigma/\sigma_{\rm SM}$

unless new decay mode is picked up by SM signal/background selections and modifies kinematic shapes.

$\rightarrow$ Expect to observe invisible decay channel in a missing-energy search!

This can be interpreted in concrete non-SM Higgs models

Composite Higgs models:

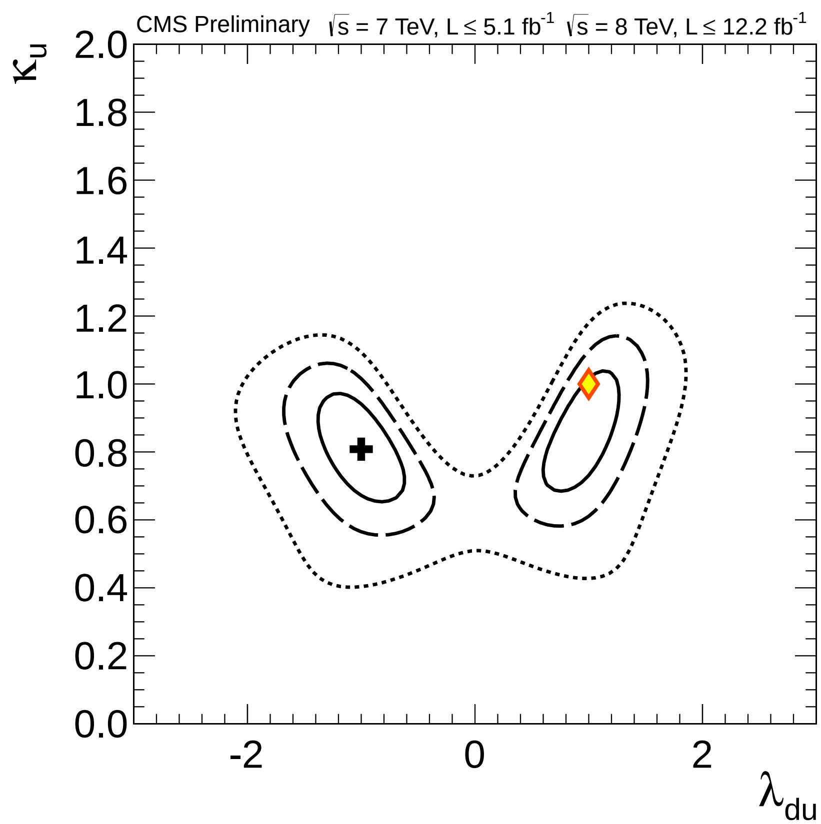
MCHM4: $a = \sqrt{1-\xi}$, $c = (1-2\xi)/\sqrt{1-\xi}$
MCHM5: $a = \sqrt{1-\xi}$, $c = \sqrt{1-\xi}$
Only one underlying parameter: can do a 1-dimensional fit for ξ

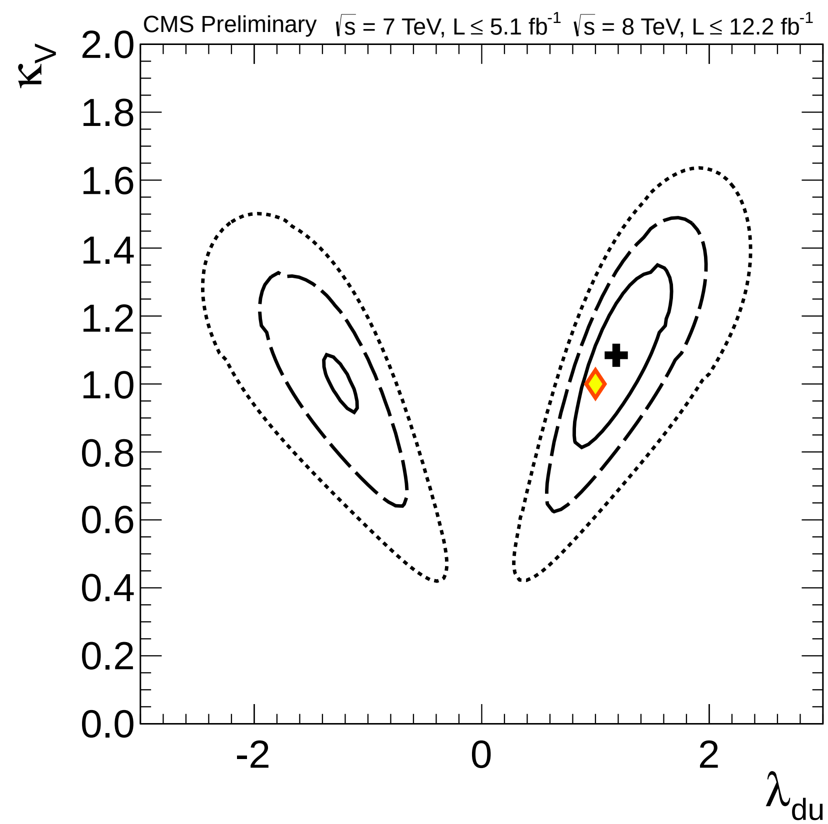
Type-I 2HDM:

$a = \sin(\beta - \alpha)$
$c = \sin(\beta - \alpha) + \cot\beta \cos(\beta - \alpha)$

Additional effect in 2HDM-I:
H^+ gives small contribution to $h \to \gamma\gamma$ loop (neglected here).

Going beyond fermion universality: let $\bar{g}_t \neq \bar{g}_b$





CMS December 2012

3 parameters: $\kappa_V = \bar{g}_V$, $\kappa_u = \bar{g}_t$, $\lambda_{du} = \bar{g}_b / \bar{g}_t$.

(Marginalized over the unshown parameter.)

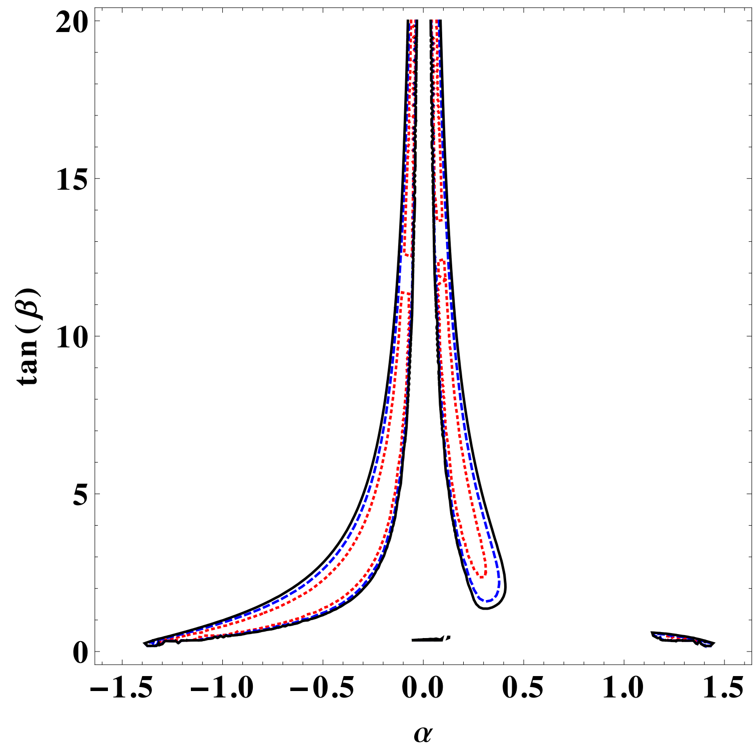
This can be interpreted in concrete non-SM Higgs models

Type-II 2HDM or MSSM:

$$\bar{g}_V = \sin(\beta - \alpha)$$
$$\bar{g}_t = \sin(\beta - \alpha) + \cot\beta \cos(\beta - \alpha)$$
$$\bar{g}_b = \bar{g}_\tau = \sin(\beta - \alpha) - \tan\beta \cos(\beta - \alpha)$$

Only 2 underlying free parameters (mixing angles α and β): can do a 2-dim fit for α and β!

Warning: theorist-made fit →



Chen and Dawson, 1301.0309

Additional effect in 2HDM-II: H^+ gives small contribution to $h \to \gamma\gamma$ loop (neglected here).

SM Higgs mixed with a gauge-singlet scalar:

$h = \phi \cos\theta - s \sin\theta \qquad H = \phi \sin\theta + s \cos\theta$

Couplings of h: $\bar{g}_V = \bar{g}_f = \cos\theta$
Couplings of H: $\bar{g}_V = \bar{g}_f = \sin\theta$

- Constrain $\cos^2\theta \equiv \sigma/\sigma_{\rm SM}$ of discovered state h.
- Predict production cross section $\sigma(H) = \sin^2\theta\, \sigma_{\rm SM}$.
- BRs of H are same as SM Higgs (unless $H \to hh$).
- Total width of H is $\Gamma_H = \sin^2\theta\, \Gamma_{\rm SM}$ (unless $H \to hh$).

Dedicated searches for H: probe $\sigma/\sigma_{\rm SM}$ as function of M_H, Γ_H.

Two Higgs doublet models:

$h = -\sin\alpha\,\phi_1 + \cos\alpha\,\phi_2 \qquad H = \cos\alpha\,\phi_1 + \sin\alpha\,\phi_2$

Vector couplings of h: $\bar{g}_V = \sin(\beta - \alpha)$
Vector couplings of H: $\bar{g}_V = \cos(\beta - \alpha)$

Type I:

Fermion couplings of h: $\bar{g}_f = \sin(\beta - \alpha) + \cot\beta\cos(\beta - \alpha)$
Fermion couplings of H: $\bar{g}_f = \cos(\beta - \alpha) - \cot\beta\sin(\beta - \alpha)$

Type II or MSSM:

Fermion couplings of h: $\bar{g}_t = \sin(\beta - \alpha) + \cot\beta\cos(\beta - \alpha)$
$\bar{g}_b = \sin(\beta - \alpha) - \tan\beta\cos(\beta - \alpha)$
Fermion couplings of H: $\bar{g}_t = \cos(\beta - \alpha) - \cot\beta\sin(\beta - \alpha)$
$\bar{g}_b = \cos(\beta - \alpha) + \tan\beta\sin(\beta - \alpha)$

Constrain couplings of $h \longrightarrow$ predict production and decays of H

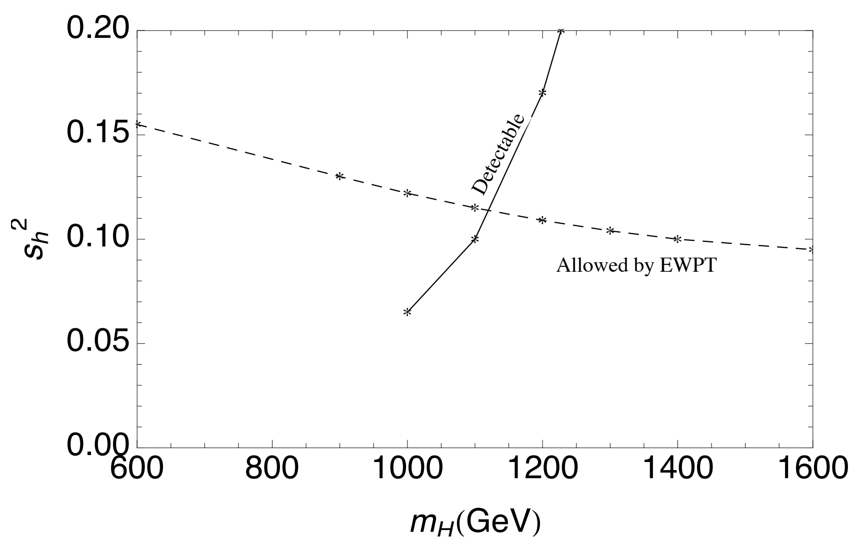
Mass of H is constrained by same physics as SM Higgs mass.

$WW \to WW$ scattering:

If $a \neq 1$, h only partly unitarizes $WW \to WW$. Job finished by H.

$$M_H^2 \lesssim \frac{4\pi v^2}{|1 - a^2|} \simeq \frac{(870 \text{ GeV})^2}{|1 - a^2|}$$

Electroweak fit:



SM + singlet:
$S = a^2 S_{SM}(M_h) + (1 - a^2) S_{SM}(M_H)$
Similar for T parameter.
Depends on $\log(M_H)$.

2HDM: Similar effects;
additional contrib'ns from $H^\pm$, A^0

Can evade limit with new physics.

Gupta, Rzehak, Wells, 1206.3560

Higgs couplings beyond the Standard Model

Composite Higgs:

- Strongly-interacting sector contributes to gauge boson & fermion masses along with h

- Deviations in couplings $\bar{g}_V, \bar{g}_f \neq 1$ can be parameterized in terms of higher-dimensional operators: $\sim 1 + \mathcal{O}(v^2/f^2)$

  $f =$ scale of strong interactions; typically $f \gg v$.

Examples:

- Little Higgs models
(also often contain additional Higgs doublets, triplets)

- 5-dimensional Composite Higgs models