Higgs bosons and beyond

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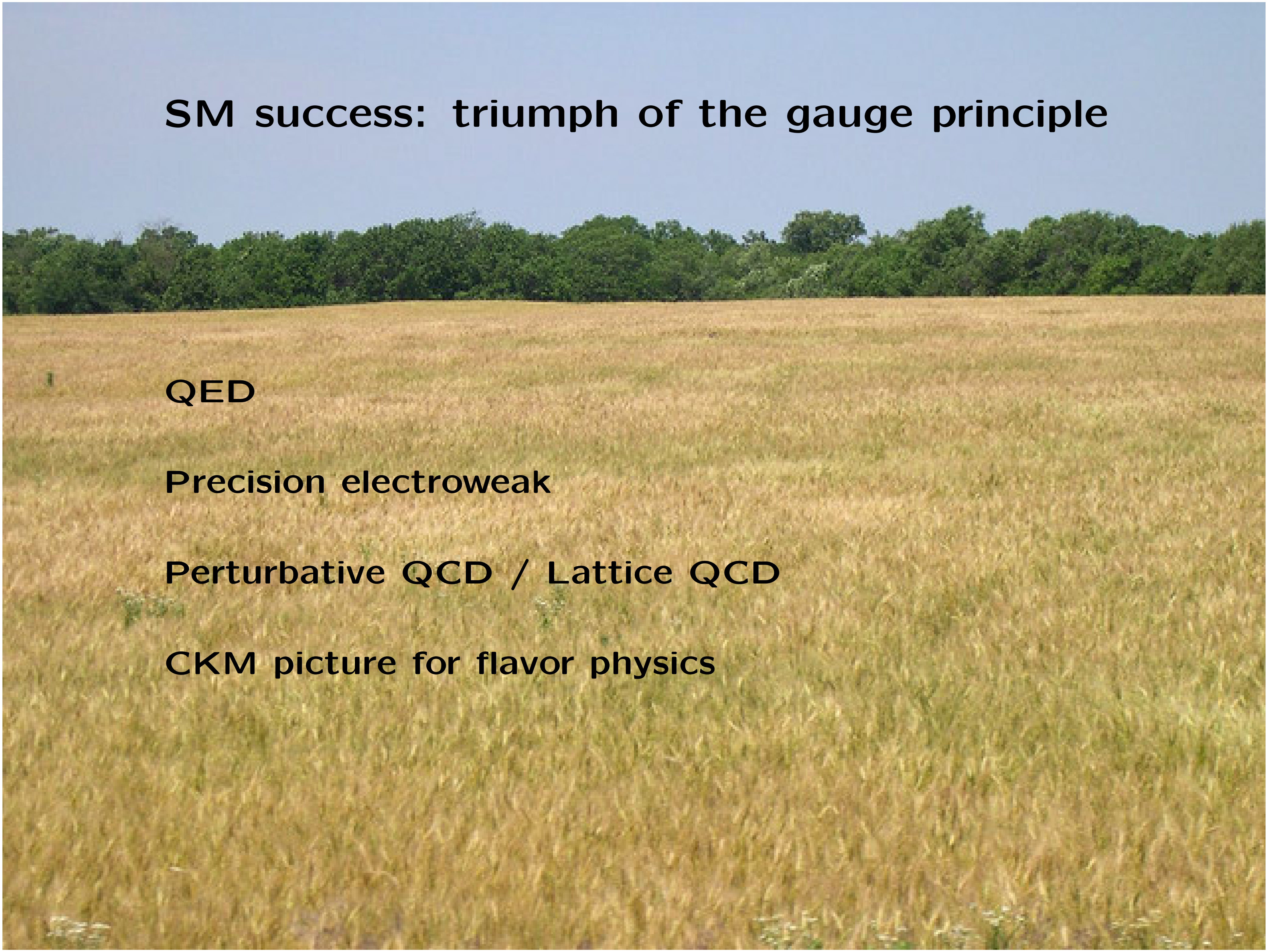


SM success: triumph of the gauge principle

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

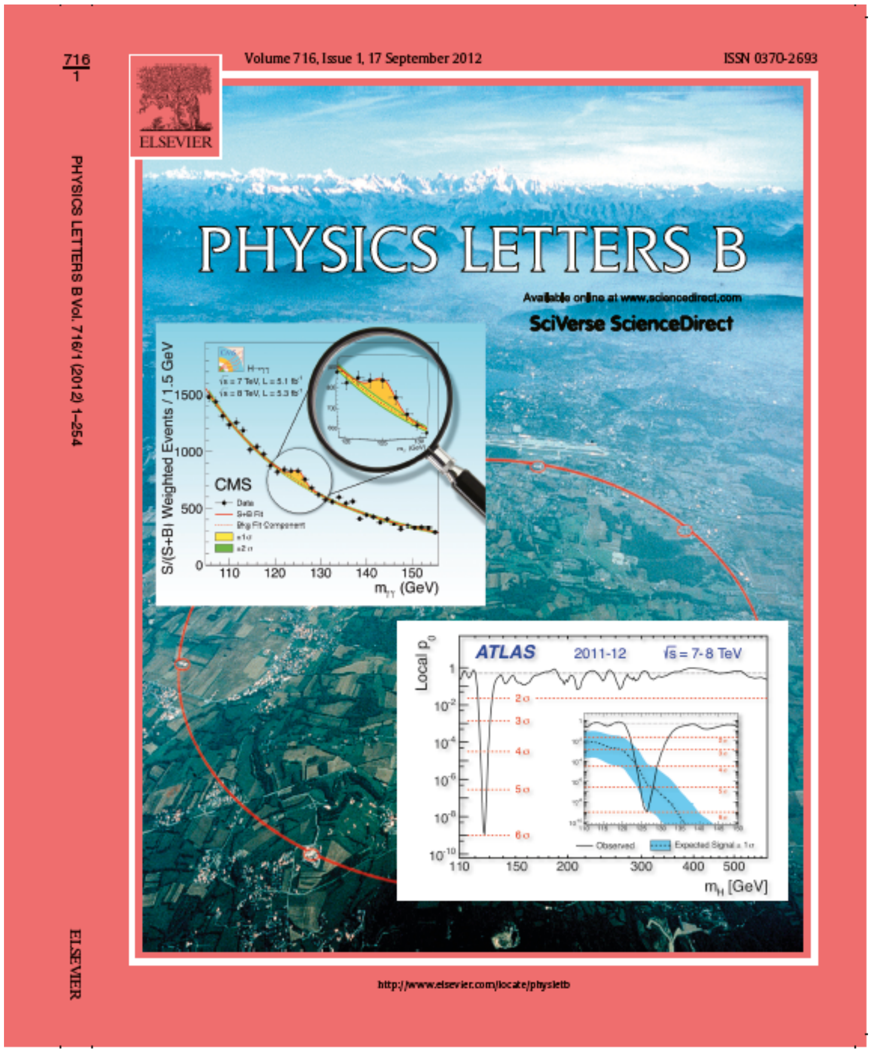
Origin of neutrino masses, mixing

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

Three questions about the vacuum:
– Is there more than one vacuum condensate?
– Why is there a vacuum condensate?
– What can we learn about relevant operators?

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

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

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

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

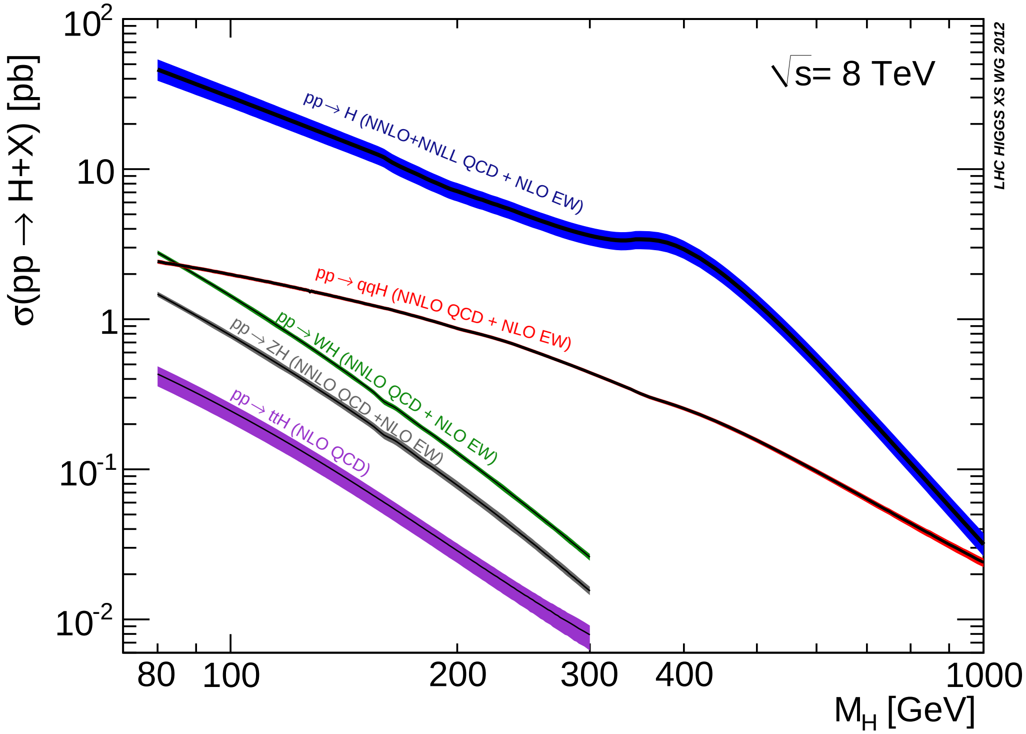
Fermions:

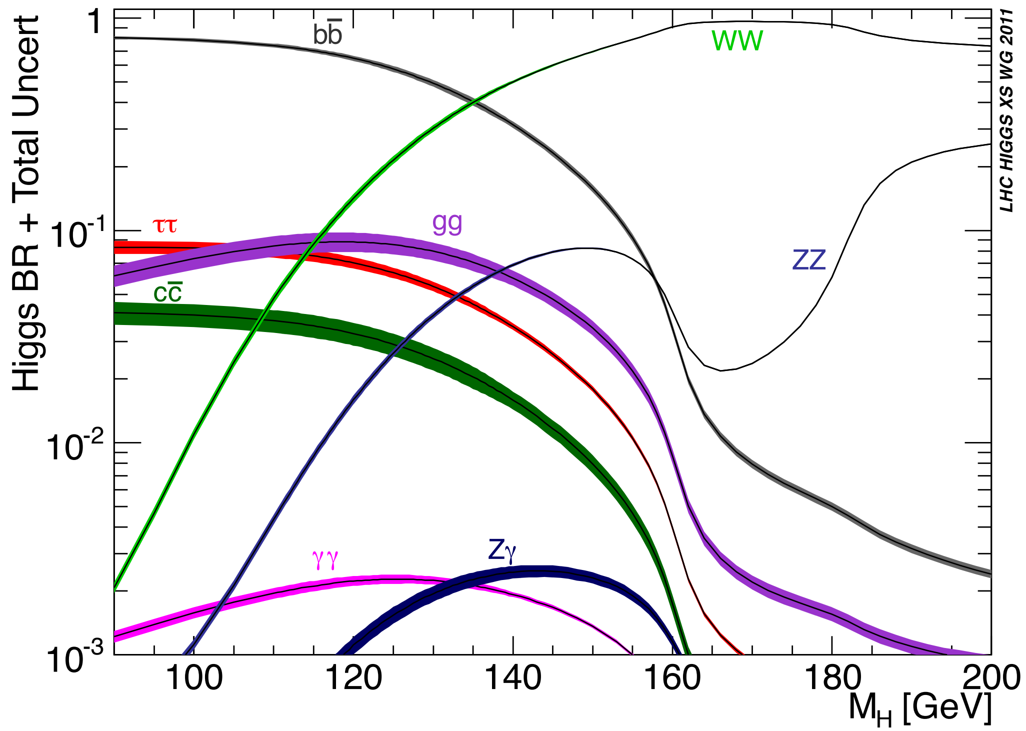
$$\mathcal{L} = -y_f \bar f_R H^\dagger Q_L + \cdots \;\rightarrow\; -(y_f/\sqrt{2})(h+v) \bar f_R f_L + \text{h.c.}$$

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

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)





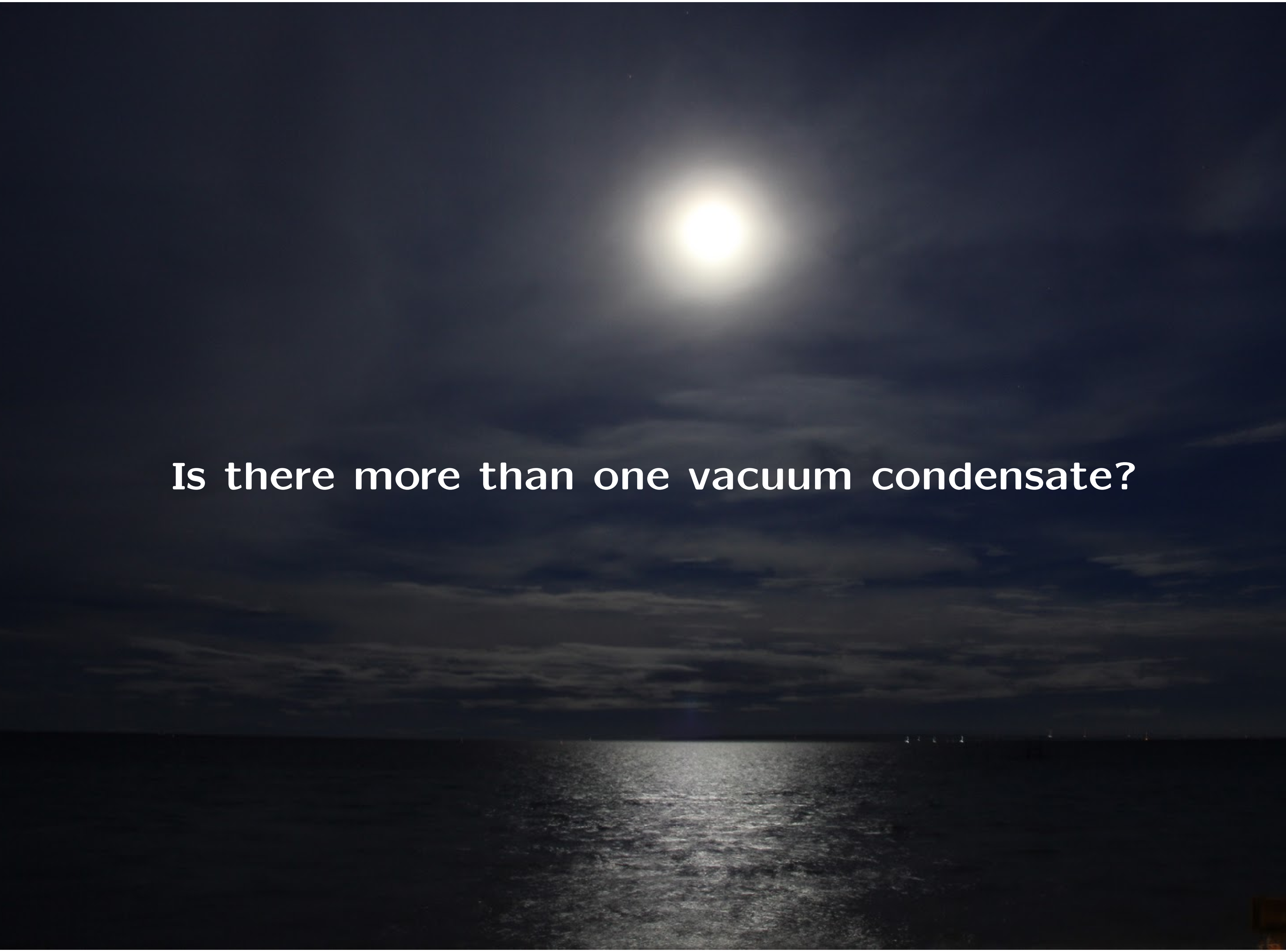
We know that the Standard Model cannot be the whole story.

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?


Is there more than one vacuum condensate?

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

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

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$$\Gamma_j = \kappa_j^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$

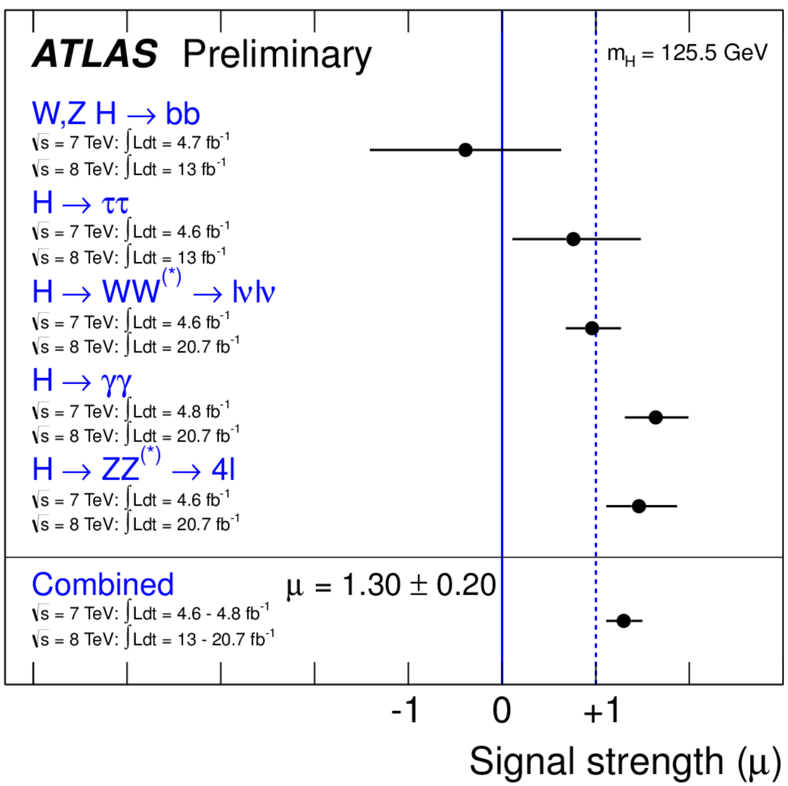
$$\Gamma_{\text{tot}} = \sum \Gamma_k = \sum_{\text{SM}} \kappa_k^2 \Gamma_k^{\text{SM}} + \sum_{\text{new}} \Gamma_k^{\text{new}}$$

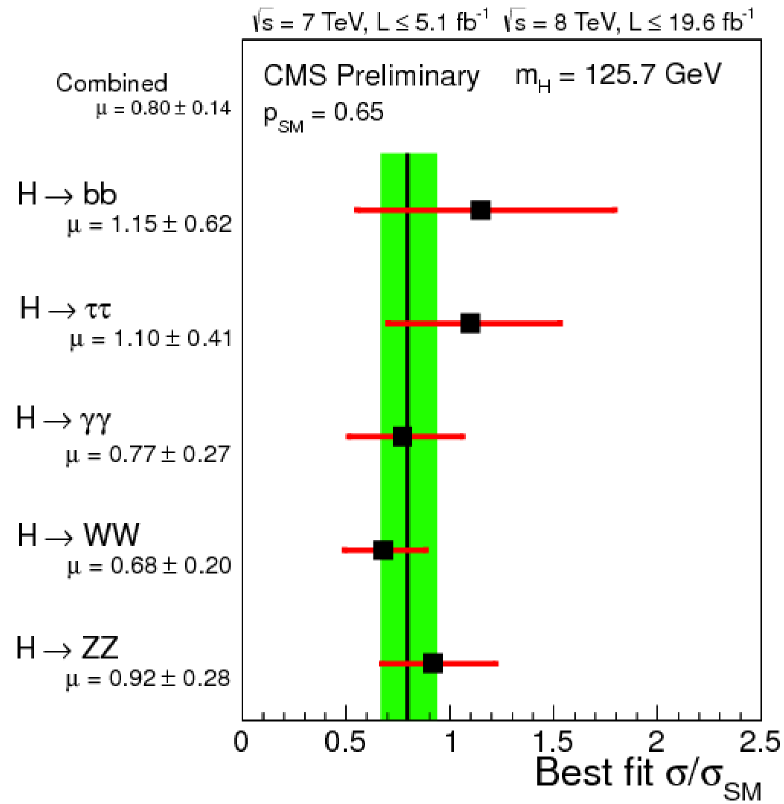
Each rate depends on multiple couplings. $\rightarrow$ correlations

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)





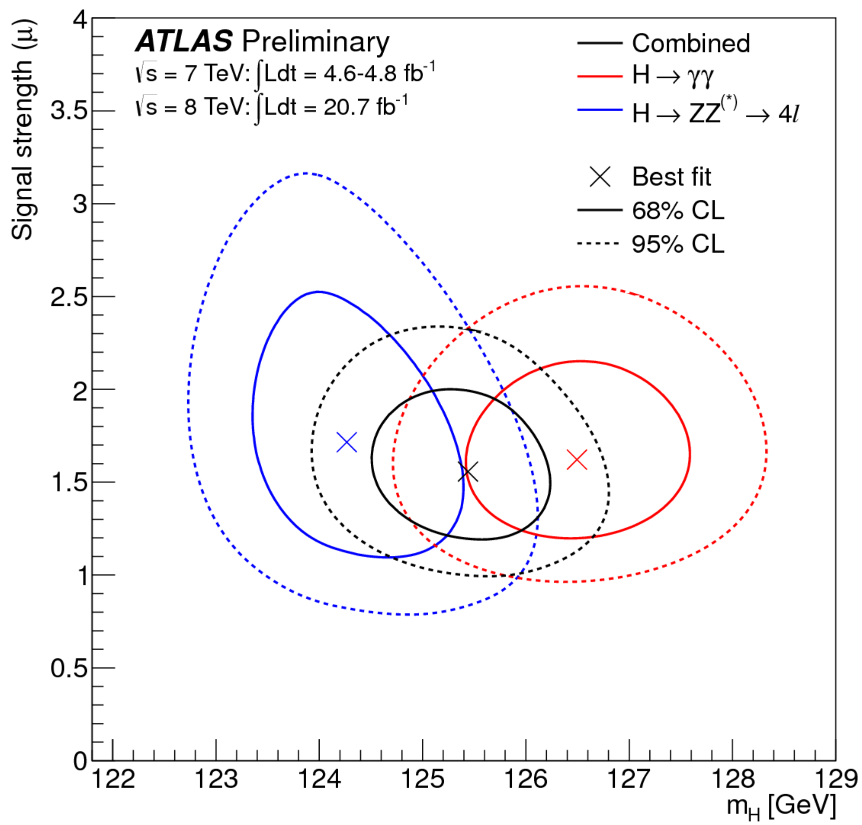
Uncertainties still large

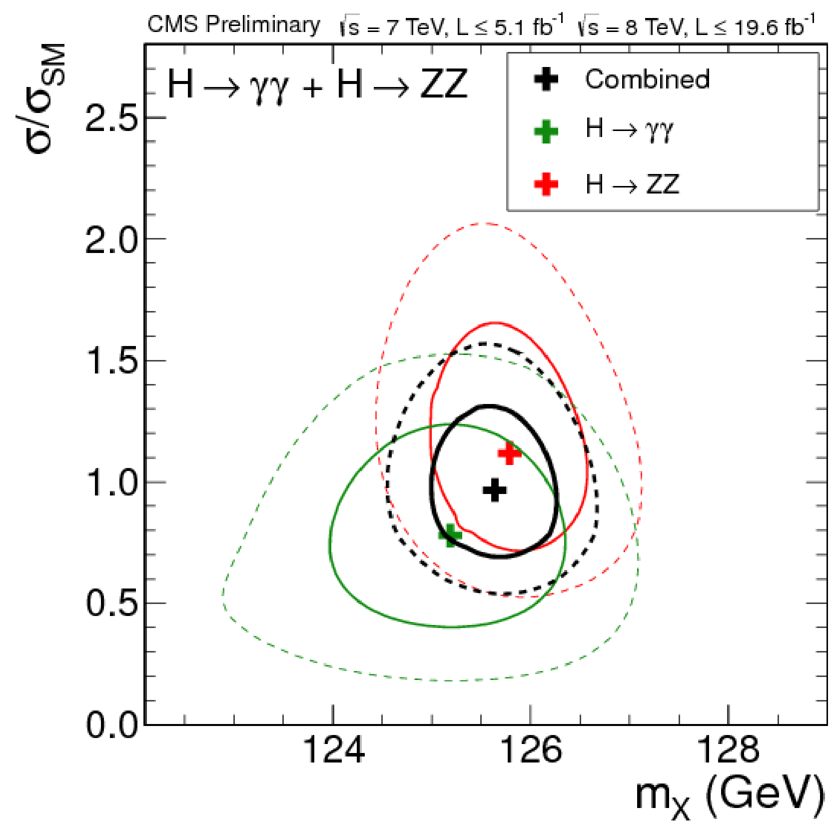
Few production $\times$ decay modes with uncertainties below 30%

$\Rightarrow$ 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



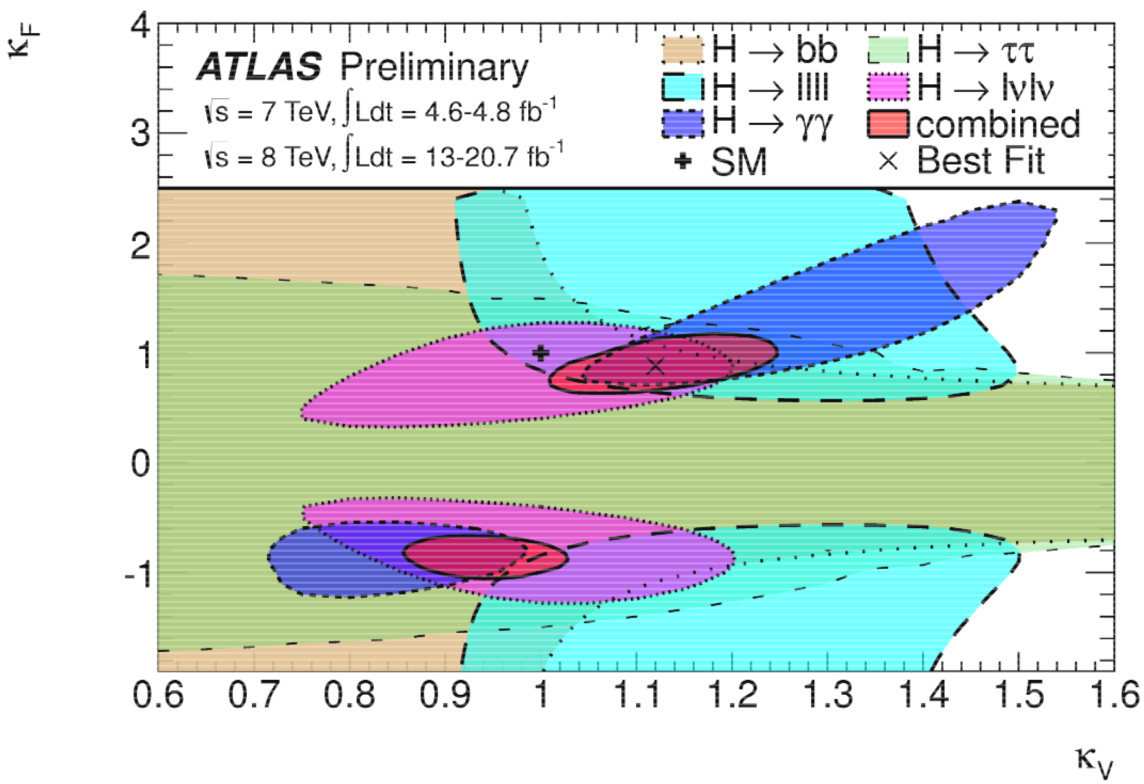


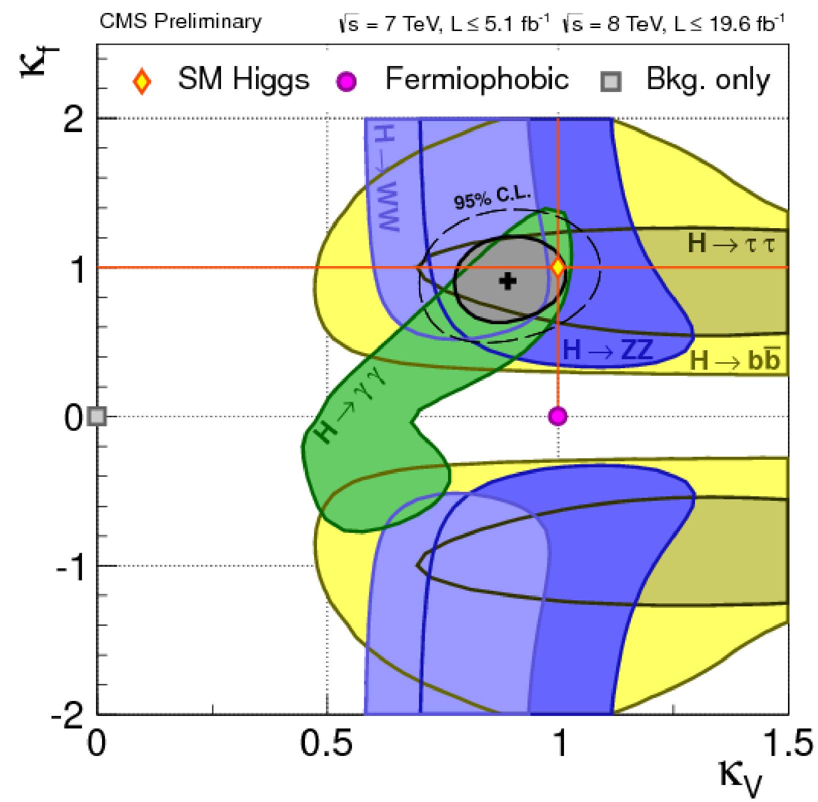
Highly constrained: 1-parameter coupling measurement

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
- 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)

High precision buys you New Physics reach.

Typical Higgs mass matrix for two mixed states:

$$\begin{pmatrix} m^2 & \lambda v^2 \text{ or } \mu v \\ \lambda v^2 \text{ or } \mu v & M^2 \end{pmatrix}$$

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

$h \rightarrow$ 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.

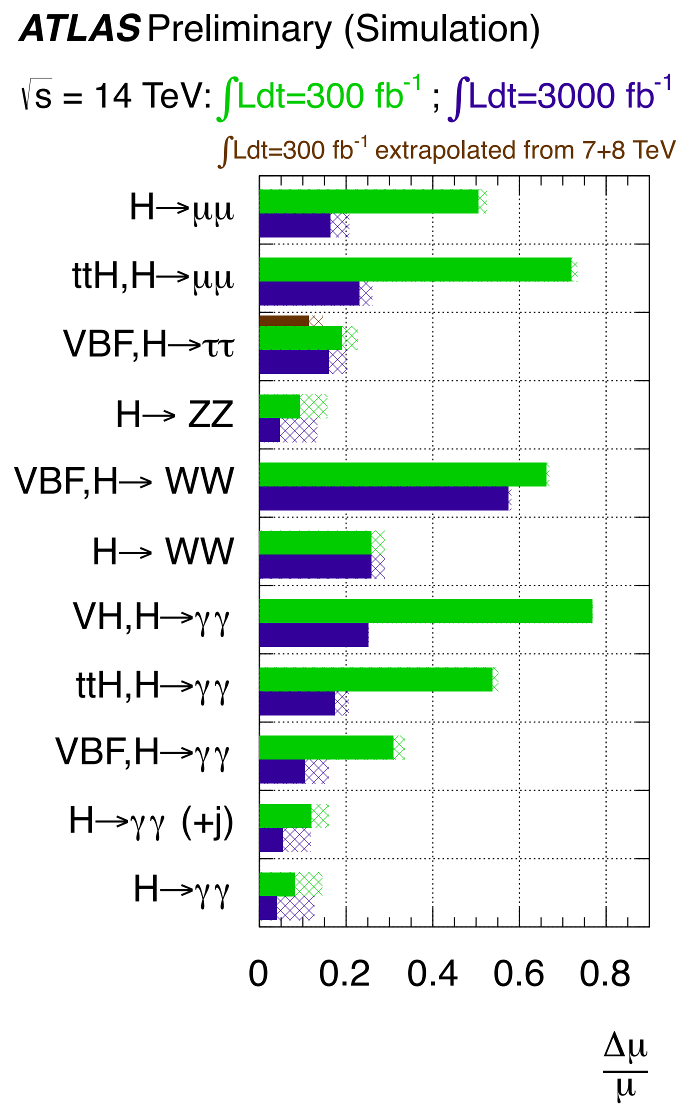
LHC: About 27 fb^{-1} collected per expt. at 7 + 8 TeV.

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: e^+e^- Higgs factory

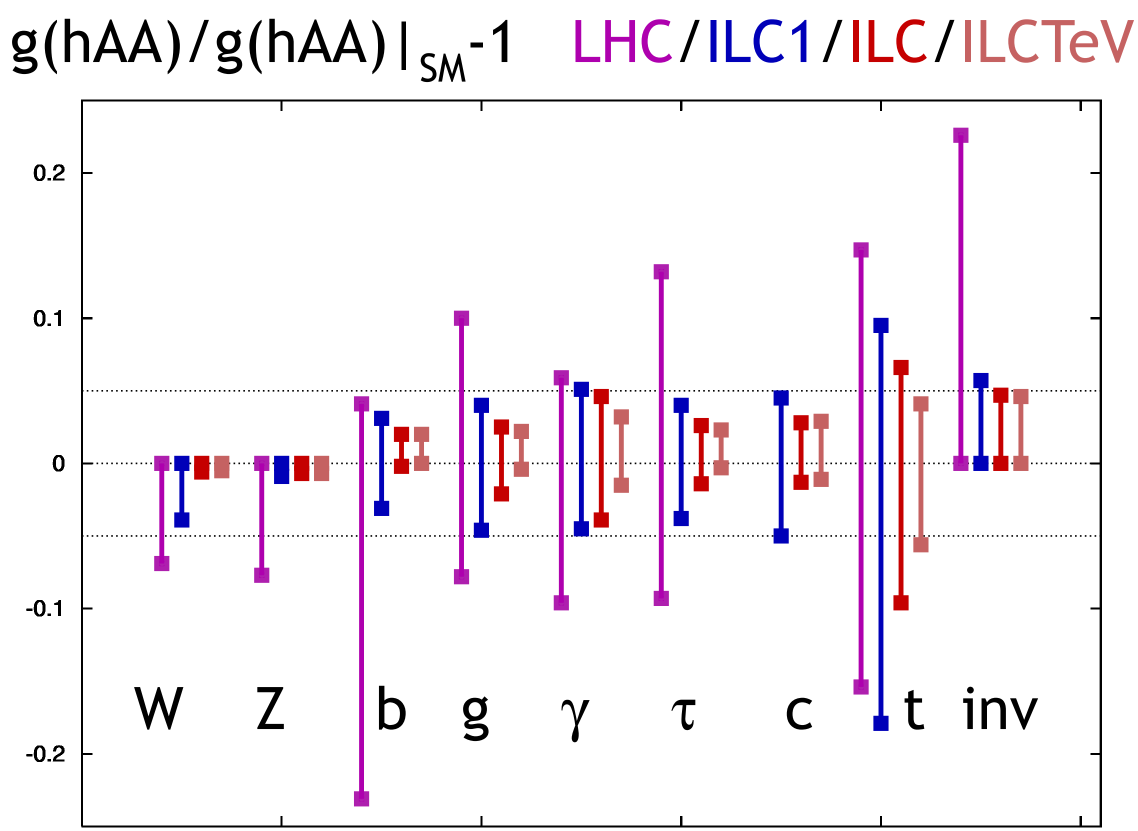
ILC: 250 fb^{-1} at 250 GeV: peak of $e^+e^- \to Zh$ cross section
- "Tagged" Higgs: measure $\sigma(Zh)$ independent of BRs to 2.5%
- BRs to bb ($<$ 3%), $\tau\tau$, cc ($\sim$ 7%), WW, gg ($\sim$ 9%)
- BRs to ZZ, $\gamma\gamma$ statistics limited (20-30%)

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})

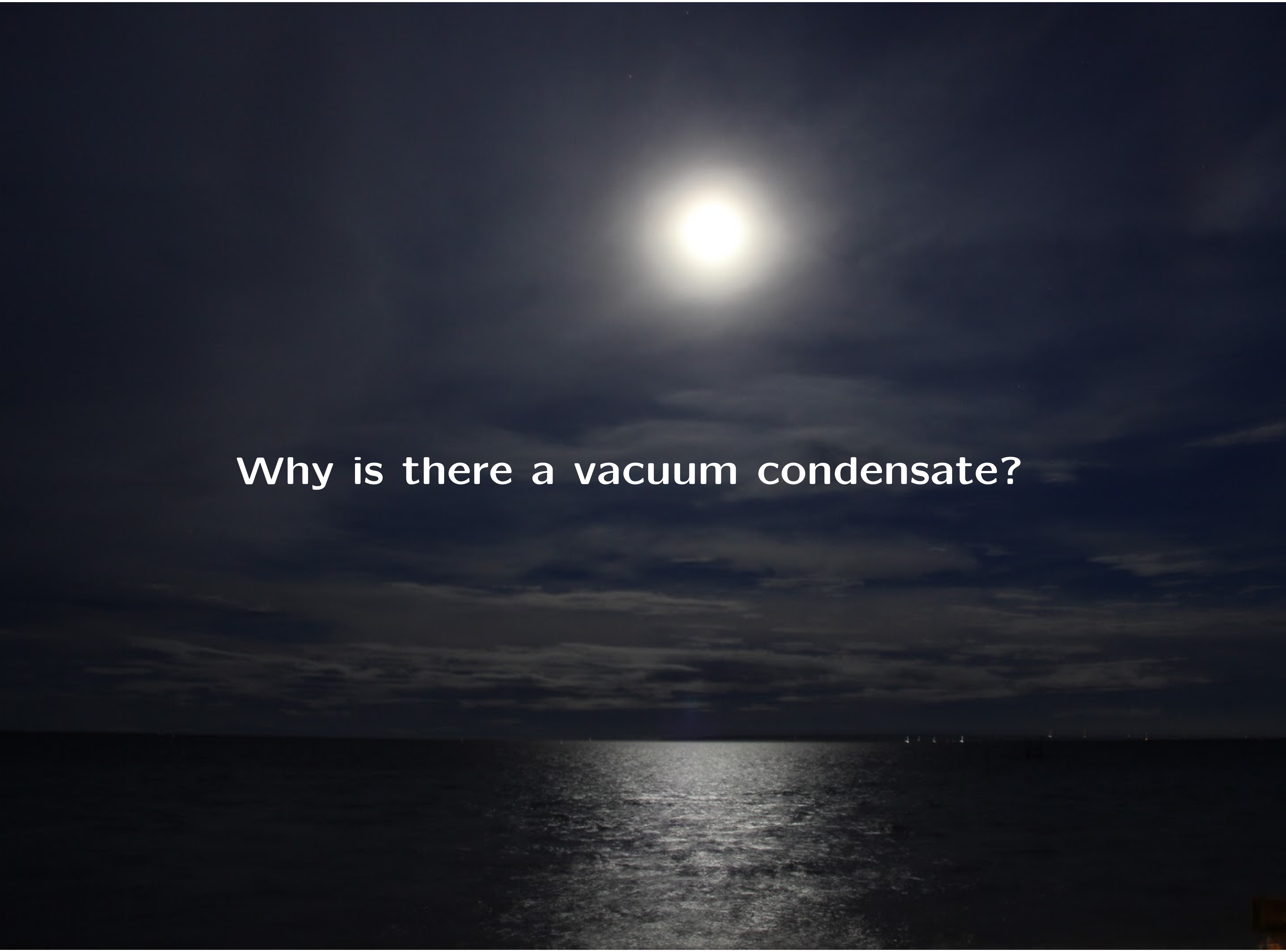
ILC upgrade: 1000 fb^{-1} at 1000 GeV:
- ultimate precision on $\sigma\times$BRs
- $e^+e^- \to \nu\bar{\nu}hh$ for Higgs self-coupling ($\sim$ 20% with 2000 fb^{-1})

Extracting individual Higgs couplings:

- need to do a fit of multiple channels
- LHC: must make theory assumption to constrain total width



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

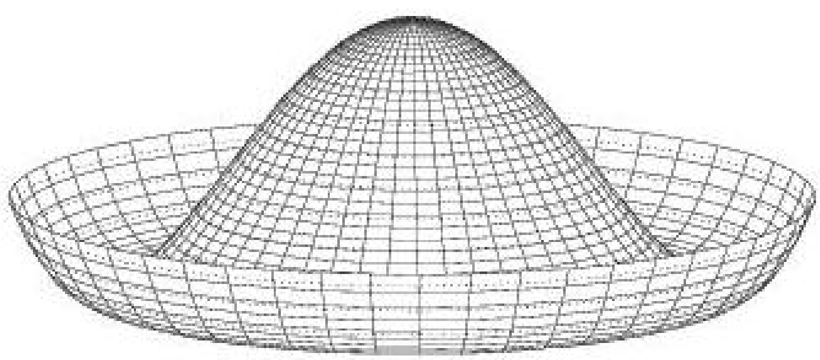

Why is there a vacuum condensate?

Spontaneous symmetry breaking:

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

Negative mass-squared term and positive self-interaction push minimum energy configuration to nonzero Higgs field strength.

Higgs potential ↓



"Mexican" hat of Harry S. Truman ↓

Image: U.S. National Park Service

Testing it: Reconstruct the shape of the Higgs potential around the minimum.

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

$$V = -\frac{\lambda}{4}v^4 + \frac{1}{2}M_h^2 h^2 + \lambda v h^3 + \frac{\lambda}{4}h^4$$

Feynman rules:

$$hhh: \quad -6i\lambda v = -3i\frac{M_h^2}{v} \qquad\qquad hhhh: \quad -6i\lambda = -3i\frac{M_h^2}{v^2}$$

using $\lambda = M_h^2/2v^2 \simeq 0.13$ $\leftarrow$ we know this now :-)

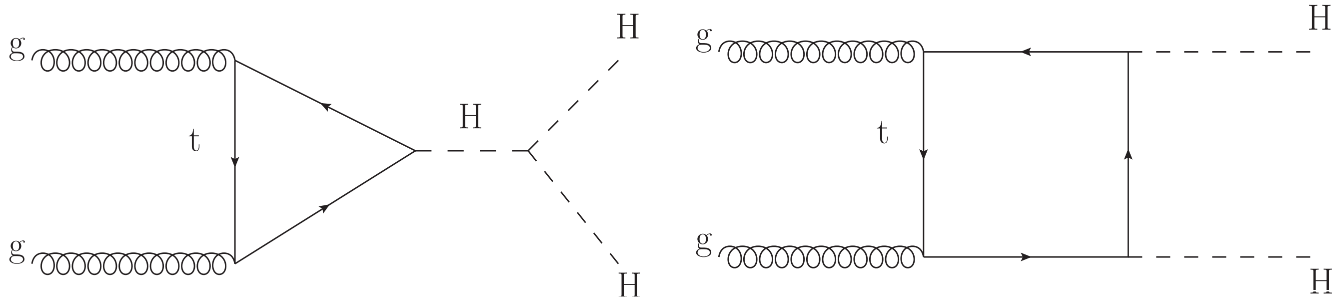
Trilinear coupling: measure double Higgs production xsec.

Quadrilinear coupling: need triple Higgs production; no prospects in foreseeable future.

Higgs potential would be distorted by:

- mixing and interactions in an extended Higgs sector
- composite Higgs or other strong dynamics (higher-dim. operators)
- large loop contributions from new physics coupled to Higgs

LHC: Small cross sections; significant backgrounds; very challenging.

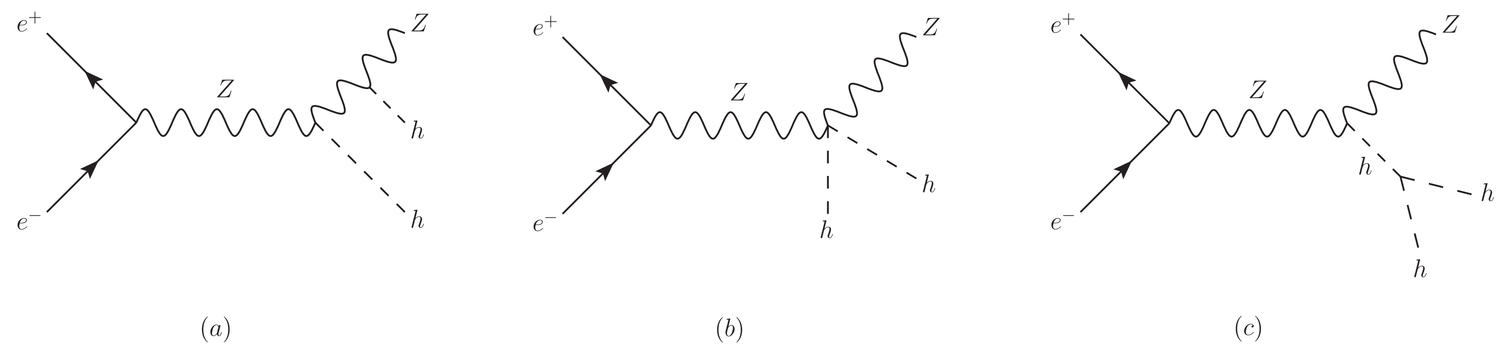


14 TeV pp: 35 fb (no BRs folded in)
600 fb^{-1}: $\Delta\lambda/\lambda$ to $\sim 45\%$
3000 fb^{-1}: $\Delta\lambda/\lambda$ to $\sim 35\%$
phenomenological analysis by Goertz et al., 1301.3492

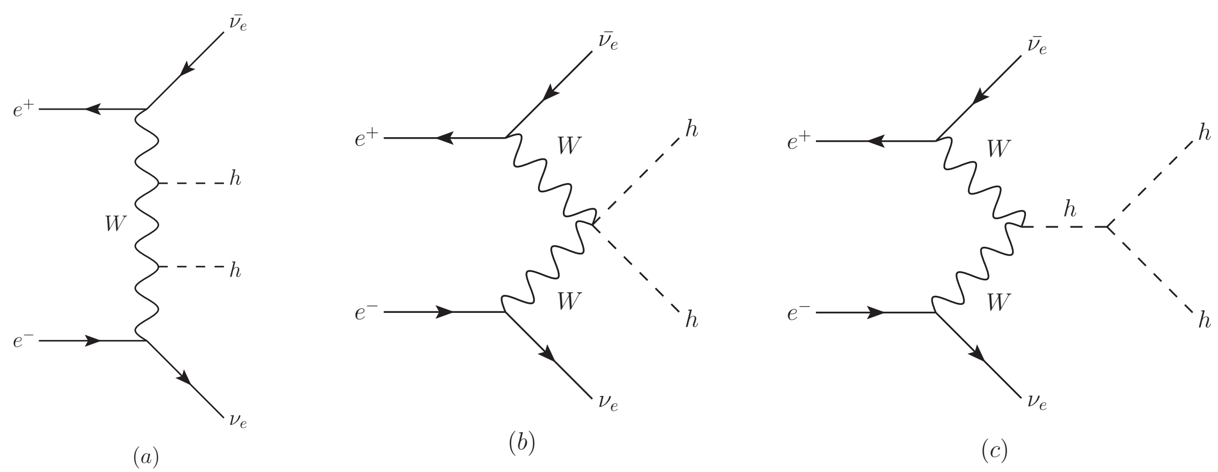
Depends on tth coupling.

New physics in loop can affect cross section significantly.

ILC: Tiny cross sections; appreciable backgrounds; still very challenging.

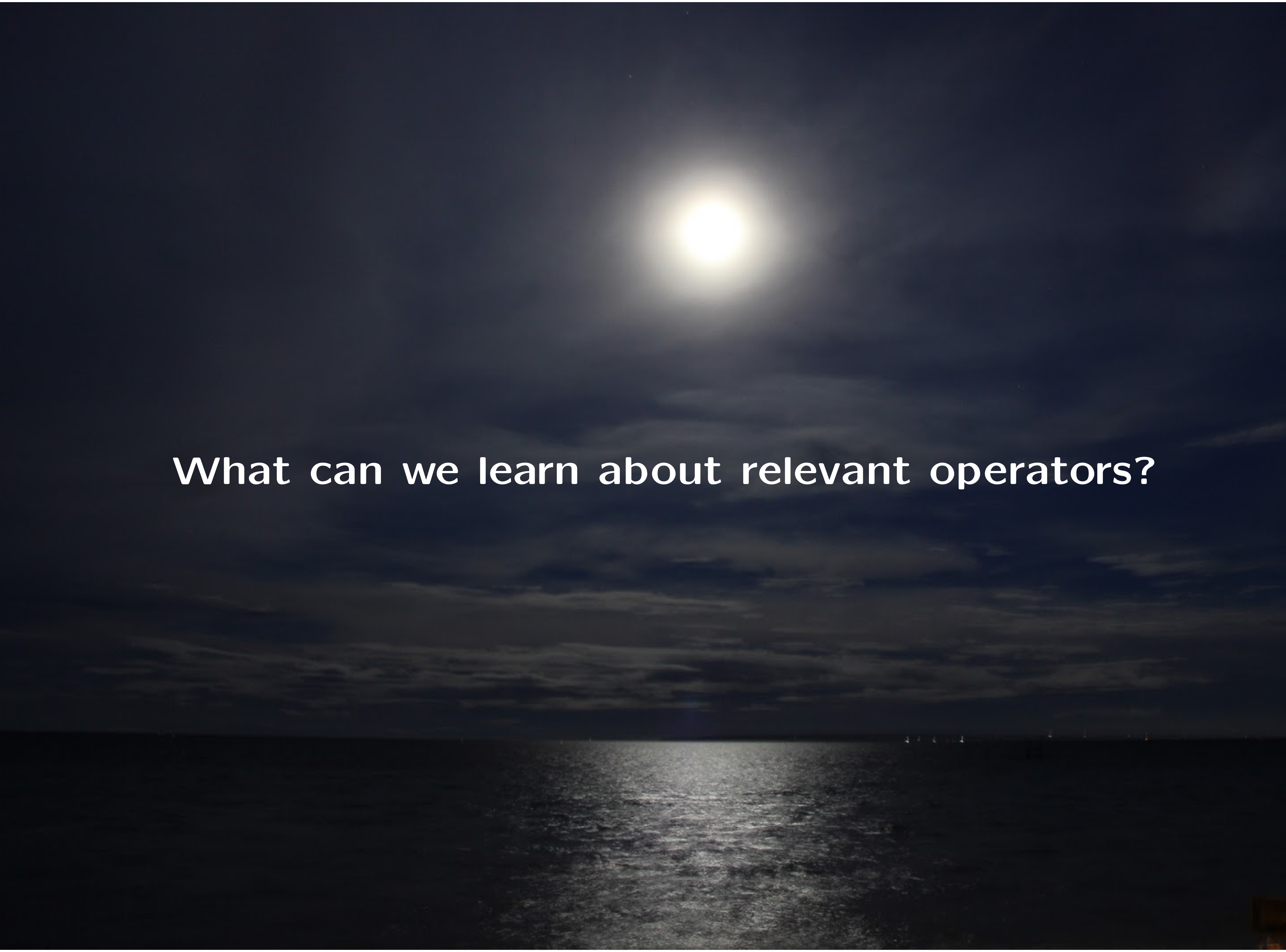


2 ab^{-1}, 500 GeV e^+e^-: 0.16 fb (no BRs folded in)
measure $\Delta\sigma/\sigma$ to 27% $\rightarrow$ $\Delta\lambda/\lambda$ to 44%



2 ab^{-1}, 1000 GeV e^+e^-: 0.071 fb (no BRs folded in)
measure $\Delta\sigma/\sigma$ to 23% $\rightarrow$ $\Delta\lambda/\lambda$ to 18%

ILD study for ILC DBD 2013


What can we learn about relevant operators?

Terminology comes from renormalization group running (from high scale Λ to low scale $p \equiv \sqrt{p^2}$)

Operator of dimension d scales like $(p/\Lambda)^{d-4}$

Marginal operators: $d = 4$, stay the same as $p \to 0$

Radiative corrections $\sim \log(\mu^2/\Lambda^2)$

Order(1) corrections running from weak scale to GUT scale

All operators in the SM are marginal except the Higgs mass

Irrelevant operators: $d > 4$, become less important as $p \to 0$

Higher-dimensional operators, due to integrating out heavier physics

This is why effective field theory works

Relevant operators: $d < 4$, become more important as $p \to 0$

Radiative corrections $\sim \Lambda^{d-4}$

Higgs mass: dimension 2, RCs $\sim$ (cutoff)^2

Vacuum energy: dimension 0, RCs $\sim$ (cutoff)^4

Vacuum energy is probably the biggest mystery in particle physics.

- Why is the "dark energy" density so close to zero, and yet not exactly zero?

- Why doesn't EW condensate or QCD condensate gravitate? I.e., what sets the zero for vacuum energy?

- What cancels the quartically-divergent radiative corrections? Why is dark energy $\sim$ (meV)^4 instead of $\sim (M_{Pl})^4$?

- Why was there apparently a much larger nonzero vacuum energy during inflation?

The hierarchy problem involving the Higgs mass gives us an opportunity to experimentally probe some of these questions on a more manageable energy scale.

- Is there a solution to the hierarchy problem that cancels the quadratically-divergent RCs?

  SUSY, compositeness, little Higgs, ...

  Physics mechanism to explain the size of this relevant operator.

- Or could it be something truly paradigm-shifting?

  Anthropic selection? Causal entropy maximization selection?

  QM interference effect among paths in the universe's wavefunction?

  ???

Search for a physics solution to hierarchy problem at (few-)TeV scale gives us a critical window on how nature deals with relevant operators.

Conclusions

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

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

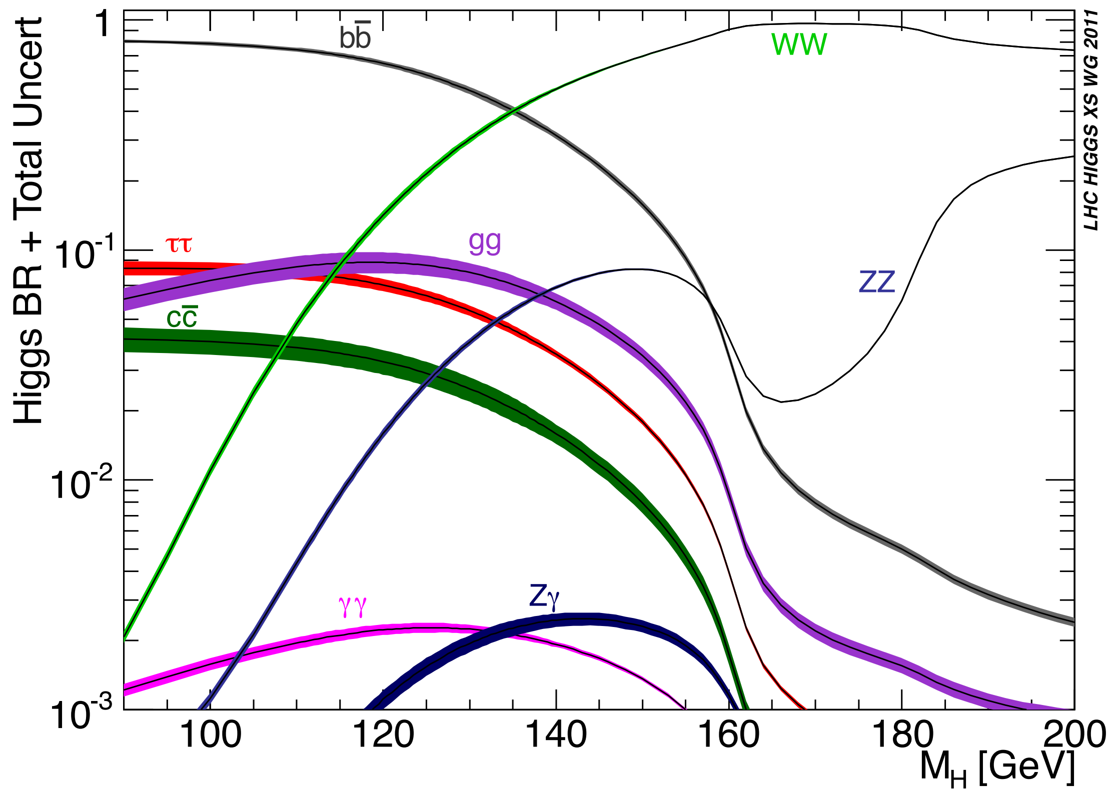
Higgs self-coupling measurements will shed light on why the Higgs field is nonzero in the first place.

Understanding the Higgs mass and its hierarchy problem may shed light on bigger mysteries surrounding relevant operators.

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.