Effective Lagrangian for a light Higgs-like scalar

Low mass/LHC Higgs XS working group
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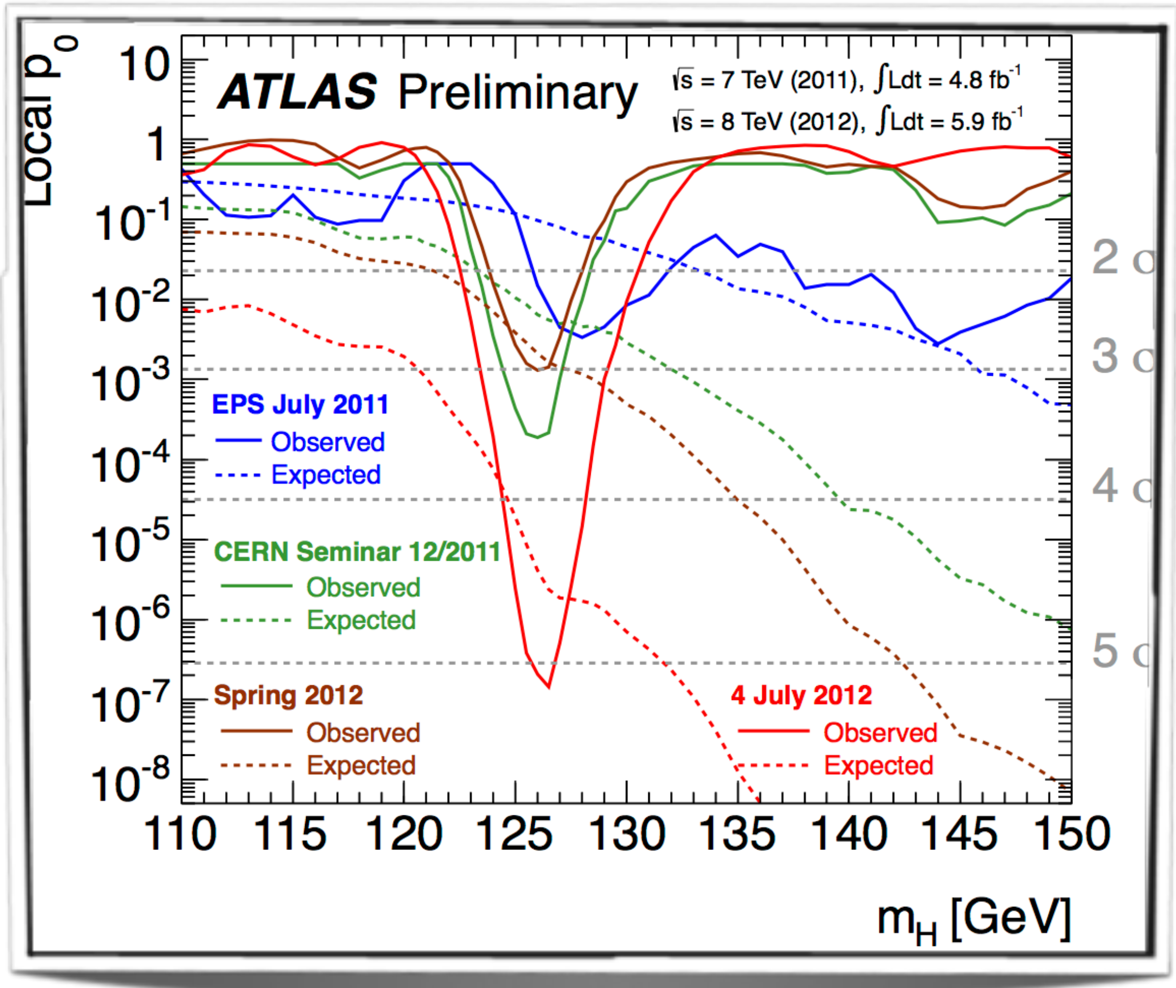
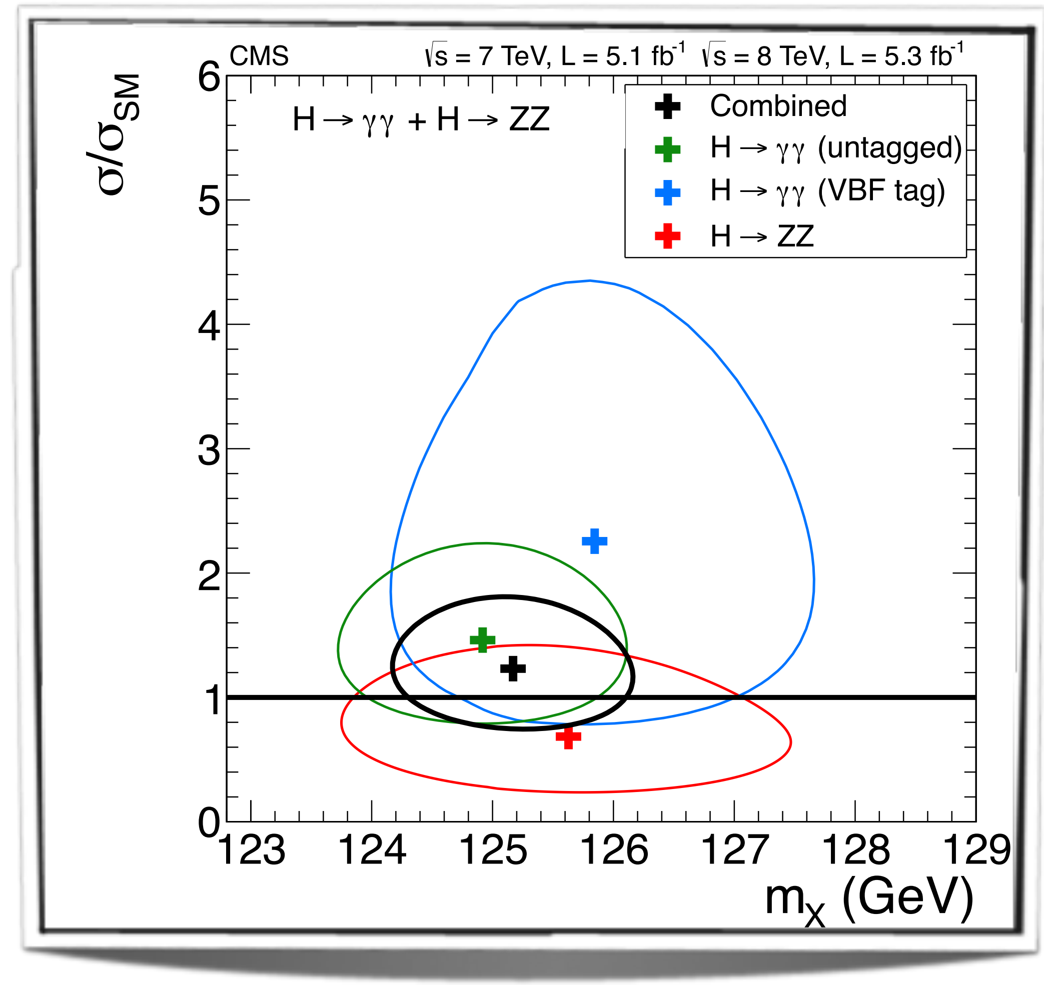
Where are we? What's next?

A new particle has been discovered!





"this discovery came at half the LHC design energy, much more severe pileup, and one-third of the integrated luminosity that was originally judged necessary" ATLAS

This discovery raises some questions:

Deviations from SM?

What are the true couplings of this particle

SM Higgs Lagrangian

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu h\right)^2 - \frac{1}{2}m_h^2 h^2 - \frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4$$

$$- \left(m_W^2\, W_\mu W^\mu + \frac{1}{2}m_Z^2\, Z_\mu Z^\mu\right)\left(1 + 2\frac{h}{v} + \frac{h^2}{v^2}\right)$$

$$- \sum_{\psi=q,l} m_\psi\, \bar{\psi}\psi\left(1 + \frac{h}{v}\right)$$

Chiral Lagrangian for a light Higgs-like scalar

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \dots$$

$$-\left(m_W^2\, W_\mu W^\mu + \frac{1}{2}m_Z^2\, Z_\mu Z^\mu\right)\left(1 + 2c_V\frac{h}{v} + b_V\frac{h^2}{v^2} + \dots\right)$$

$$-\sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar\psi^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + b_\psi\frac{h^2}{v^2} + \dots\right)$$

O(p²)

$$+\frac{\alpha_{em}}{8\pi}\left(2\,c_{WW}\, W^+_{\mu\nu}W^{-\,\mu\nu} + c_{ZZ}\, Z_{\mu\nu}Z^{\mu\nu} + 2\,c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + c_{\gamma\gamma}\,\gamma_{\mu\nu}\gamma^{\mu\nu}\right)\frac{h}{v}$$

$$+\frac{\alpha_s}{8\pi}\, c_{gg}\, G^a_{\mu\nu}G^{a\,\mu\nu}\,\frac{h}{v}$$

$$+c_W\left(W^-_\nu D_\mu W^{+\,\mu\nu} + W^+_\nu D_\mu W^{-\,\mu\nu}\right)\frac{h}{v} + c_Z\, Z_\nu\partial_\mu Z^{\mu\nu}\,\frac{h}{v}$$

$$+\left(\frac{c_W}{\sin\theta_W\cos\theta_W} - \frac{c_Z}{\tan\theta_W}\right) Z_\nu\partial_\mu\gamma^{\mu\nu}\,\frac{h}{v}$$

O(p⁴)

$$+\mathcal{O}\left(p^6\right)$$

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

SM

$$a = b = c = d_3 = d_4 = 1$$

$$c_{2\psi} = c_{WW} = c_{ZZ} = c_{Z\gamma} = c_{\gamma\gamma} = \dots = 0$$

A few (reasonable) assumptions:

- ☑ spin-0 & CP-even
  - ↖ $\gamma\gamma$ ↖ WW & ZZ
- ☑ custodial symmetry
  - ↖ EWPD
- ☑ no Higgs FCNC (generalization of Glashow-Weinberg th.)
  - ↖ Flavor

Remarks on NLO Chiral Lagrangian

could describe linearly or non-linearly realized $SU(2)_L \times U(1)_Y$

$$m_W^2 W_\mu^+ W^{\mu\,-} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu = \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)$$

$$\Sigma = e^{i\sigma^a \pi^a / v}$$

Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\left(m_W^2 W_\mu^+ W^{\mu\,-} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2\frac{h}{v} + \frac{h^2}{v^2}\right) = |D_\mu H|^2$$

\+ higher dimensional operators with a Higgs doublet

the linear realization implies some relations among the coefficients:

dimension-6: single operator for c_V and b_V: $b-1 = 2\,(a^2-1)$

dimension-6: only three operators for c_{WW}, c_{ZZ}, $c_{Z\gamma}$, $c_{\gamma\gamma}$: $2c_{Z\gamma} = \frac{c_{WW}}{\sin(2\theta_W)} - \frac{c_{ZZ}}{\tan\theta_W} - \tan\theta_W c_{\gamma\gamma}$

i.e. can predict the rate $Z\gamma$ from the other channels!

Remarks on NLO Chiral Lagrangian

$$c_W \left(W^-_\nu D_\mu W^{+\,\mu\nu} + W^+_\nu D_\mu W^{-\,\mu\nu}\right) \frac{h}{v} + c_Z\, Z_\nu \partial_\mu Z^{\mu\nu}\, \frac{h}{v} \;\; + \left(\frac{c_W}{\sin\theta_W \cos\theta_W} - \frac{c_Z}{\tan\theta_W}\right) Z_\nu \partial_\mu \gamma^{\mu\nu}\, \frac{h}{v}$$

custodial symmetry imposes the relation above between the 3 operators

(remark: accidental custodial sym. at dim-6 level for the linear realization)

control the off-shell h->VV* decay

$$D^\mu V_{\mu\nu} = m_V^2 V_\nu + J_\nu$$

local contribution to h->Vff unlike in the SM (different distributions?)

operator w/ photon: different BR to fermions in final state compared to ZZ*

corrections to cV

Chiral Lagrangian for a light Higgs-like scalar

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2} m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right) \ldots$$

$$-\left(m_W^2 W_\mu W^\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(1 \ldots\right.$$

$$-\sum_{\psi=u,d,l} m_{\psi^{(i)}} \bar\psi^{(i)}\psi^{(i)}\left(1 + c_\psi \frac{h}{v} + \ldots\right.$$

$$+\frac{\alpha_{em}}{8\pi}\left(2\, c_{WW}\, W^+_{\mu\nu} W^{-\,\mu\nu} + c_{ZZ}\, Z_{\mu\nu}Z^{\mu\nu} + 2\, c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + c_{\gamma\gamma}\, \gamma_{\mu\nu}\gamma^{\mu\nu}\right)\frac{h}{v}$$

still large LO parameter space

⇓ ⇓ ⇓

4 operators @ $O(p^2)$: c_V, c_t, c_b, c_T

2 operators @ $O(p^4)$: c_g c_γ

(contribute to the same order as $O(p^2)$ to $gg \to h$ and $h \to \gamma\gamma$)

Not enough data/sensitivity to determine all these parameters

⇓ ⇓ ⇓

But we can put some of the SM structures under probation

assumptions:

- ☑ spin-0 & CP-even
  - ↖ $\gamma\gamma$ ↖ WW & ZZ
- ☑ custodial symmetry
  - ↖ EWPD
- ☑ no Higgs FCNC (generalization of Glashow-Weinberg th.)
  - ↖ Flavor

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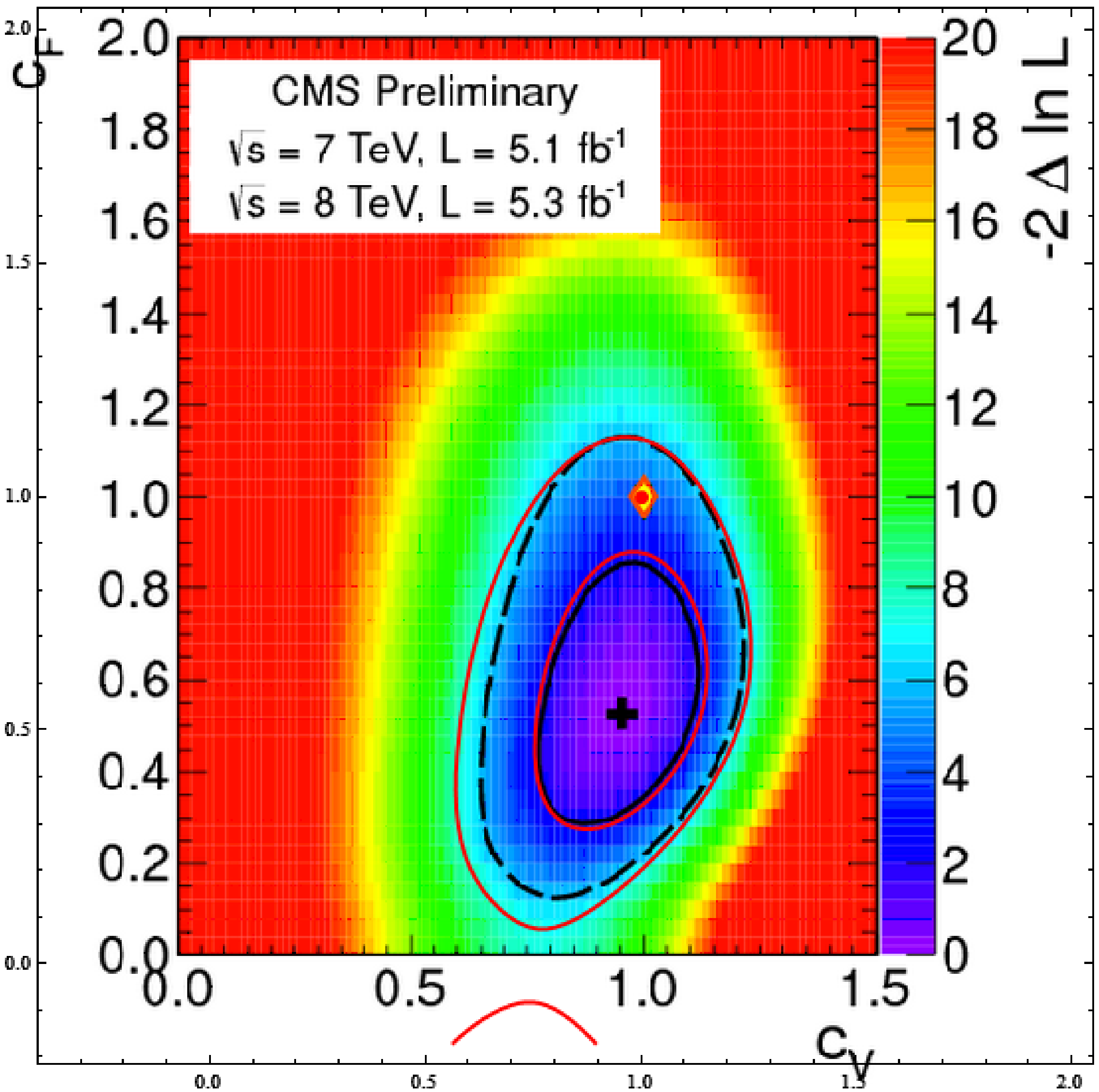
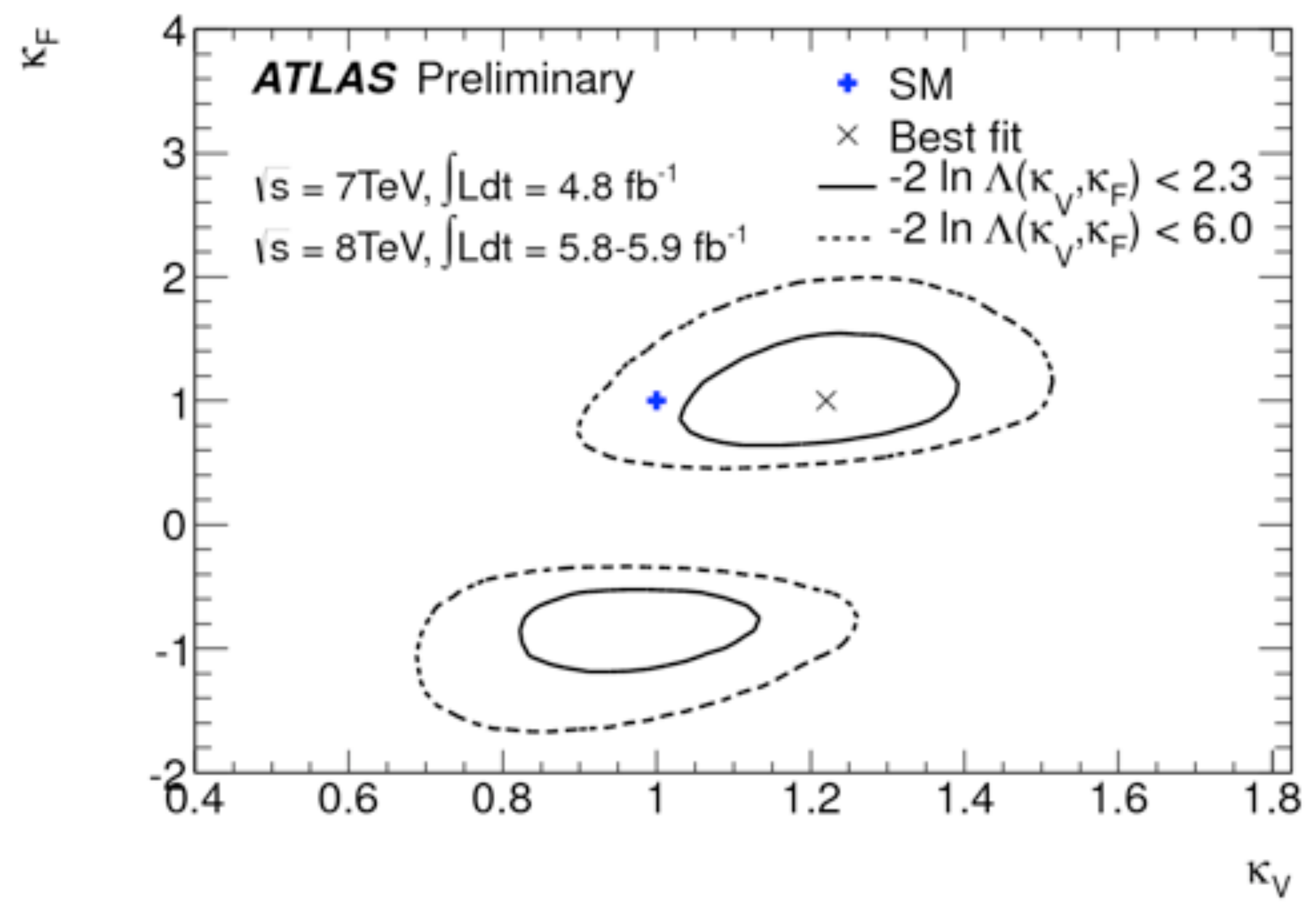
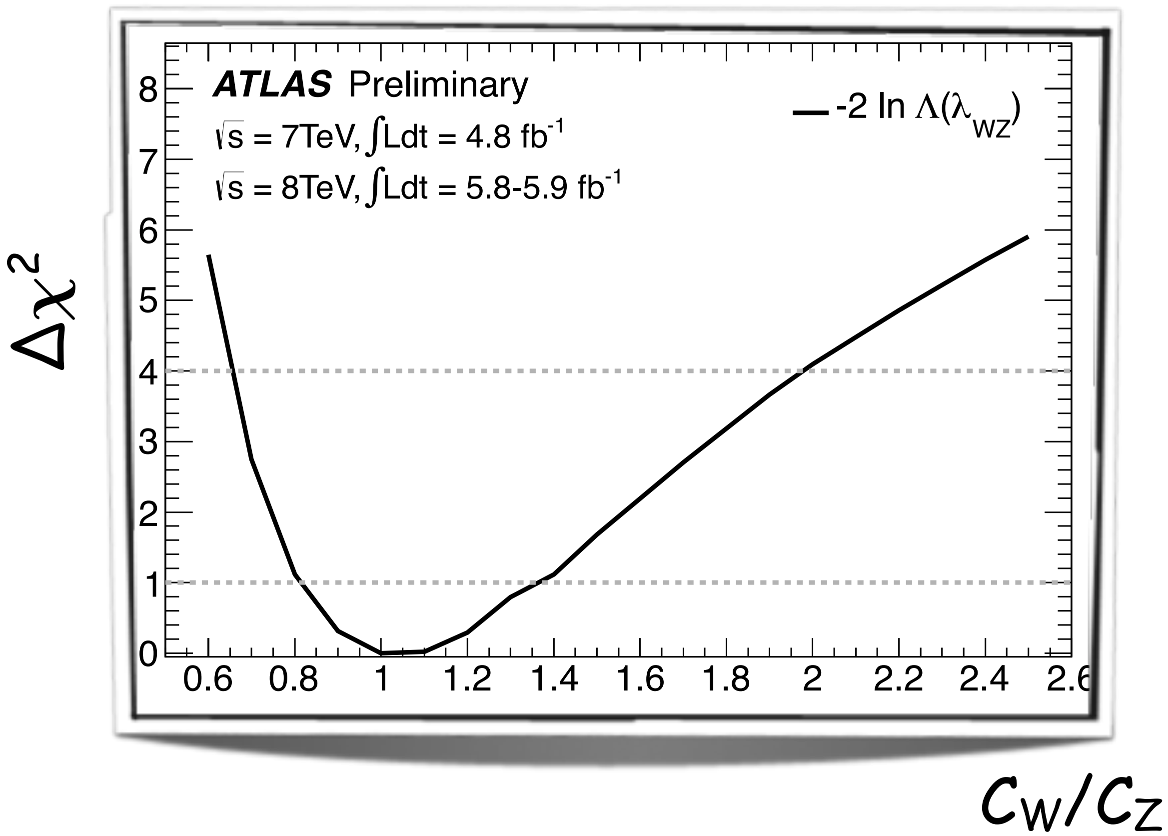
LO fits: test of unitarity

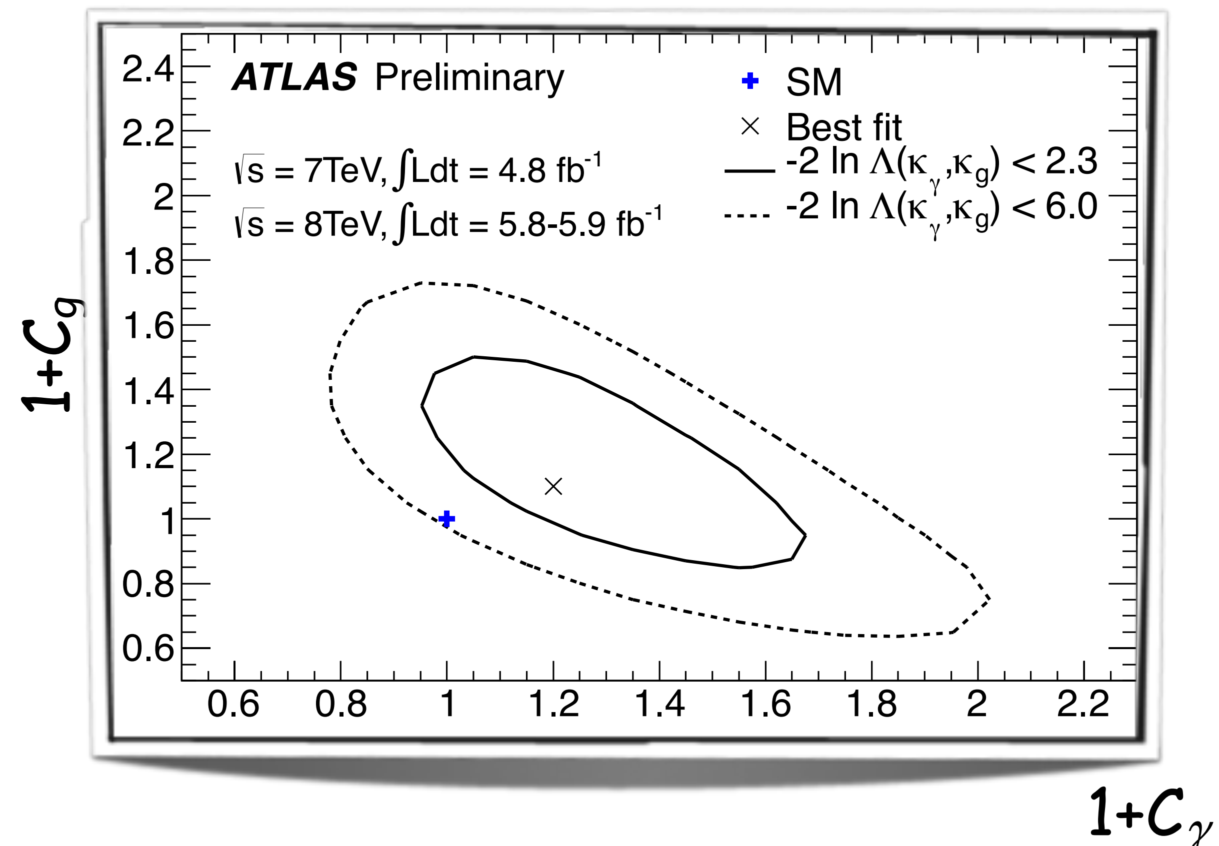




LO fits: other tests of the SM structures

- custodial symmetry: $c_W = c_Z$?
- probing the weak isospin symmetry: $c_u = c_d$?
- quark and lepton symmetry: $c_q = c_l$?
- new non-SM particle contribution: BR_{inv}? $c_g = c_\gamma = 0$?





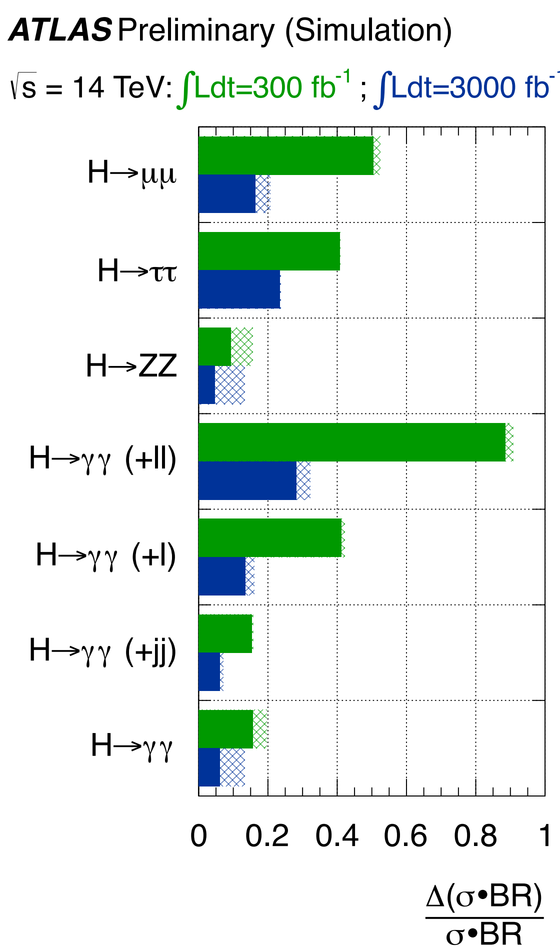
ATLAS-CONF-2012-127

Some tensions
but no statistically significant deviations from the SM structure

NLO fits: Higgs couplings measurements?

$LHC_{300/fb}$, HL-LHC, ILC, CLIC

will measure Higgs couplings with good/excellent precision



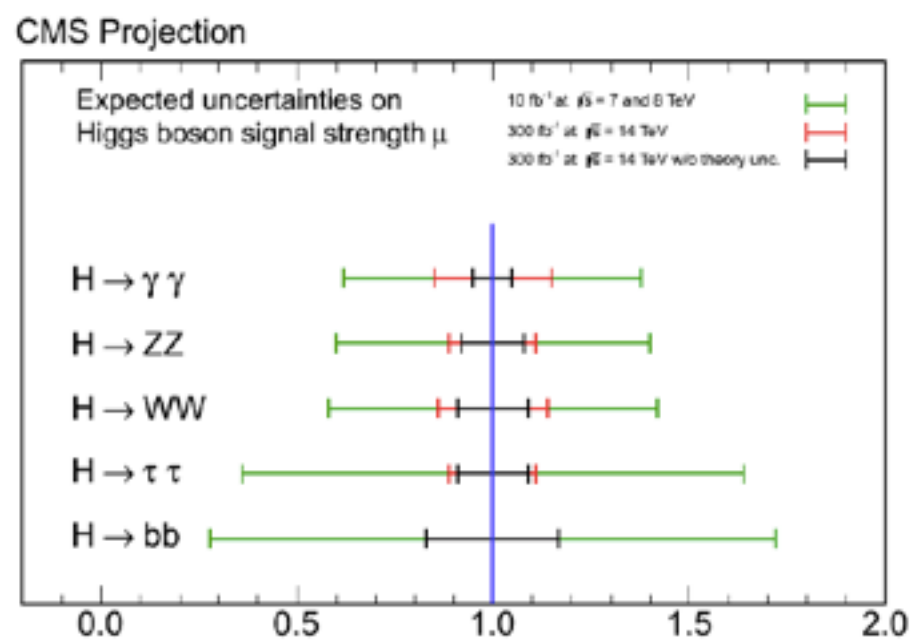


Table 5: Summary of results obtained in the Higgs studies for m_H =120 GeV. All analyses at centre-of-mass energies of 350 GeV and 500 GeV assume an integrated luminosity of 500 fb^{-1}, while the analyses at 1.4 TeV (3 TeV) assume 1.5 ab^{-1}(2 ab^{-1}).

Higgs studies for m_H =120 GeV							
$\sqrt{s}$ (GeV)	Process	Decay mode	Measured quantity	Unit	Generator value	Stat. error	Comment
350	SM Higgs production	$ZH \to \mu^+\mu^- X$	σ	fb	4.9	4.9%	Model
			Mass	GeV	120	0.131	independent, using Z-recoil
500		$ZH \to q\bar{q}q\bar{q}$	$\sigma\times$ BR	fb	34.4	1.6%	$ZH \to q\bar{q}q\bar{q}$
			Mass	GeV	120	0.100	mass reconstruction
500		$ZH, H\nu\bar{\nu}$	$\sigma\times$ BR	fb	80.7	1.0%	Inclusive
		$\to \nu\bar{\nu}q\bar{q}$	Mass	GeV	120	0.100	sample
1400	WW fusion	$H \to \tau^+\tau^-$	$\sigma\times$ BR	fb	19.8	<3.7%	
3000		$H \to b\bar{b}$ $H \to c\bar{c}$ $H \to \mu^+\mu^-$			285 13 0.12	0.22% 3.2% 15.7%	
1400 3000	WW fusion		Higgs tri-linear coupling g_{HHH}			∼20% ∼20%	

5-10% @ $LHC^{14TeV}_{300/fb}$

1-5% @ ILC/CLIC

direct acces to Γ_{inv}

NLO fits: Higgs couplings measurements?

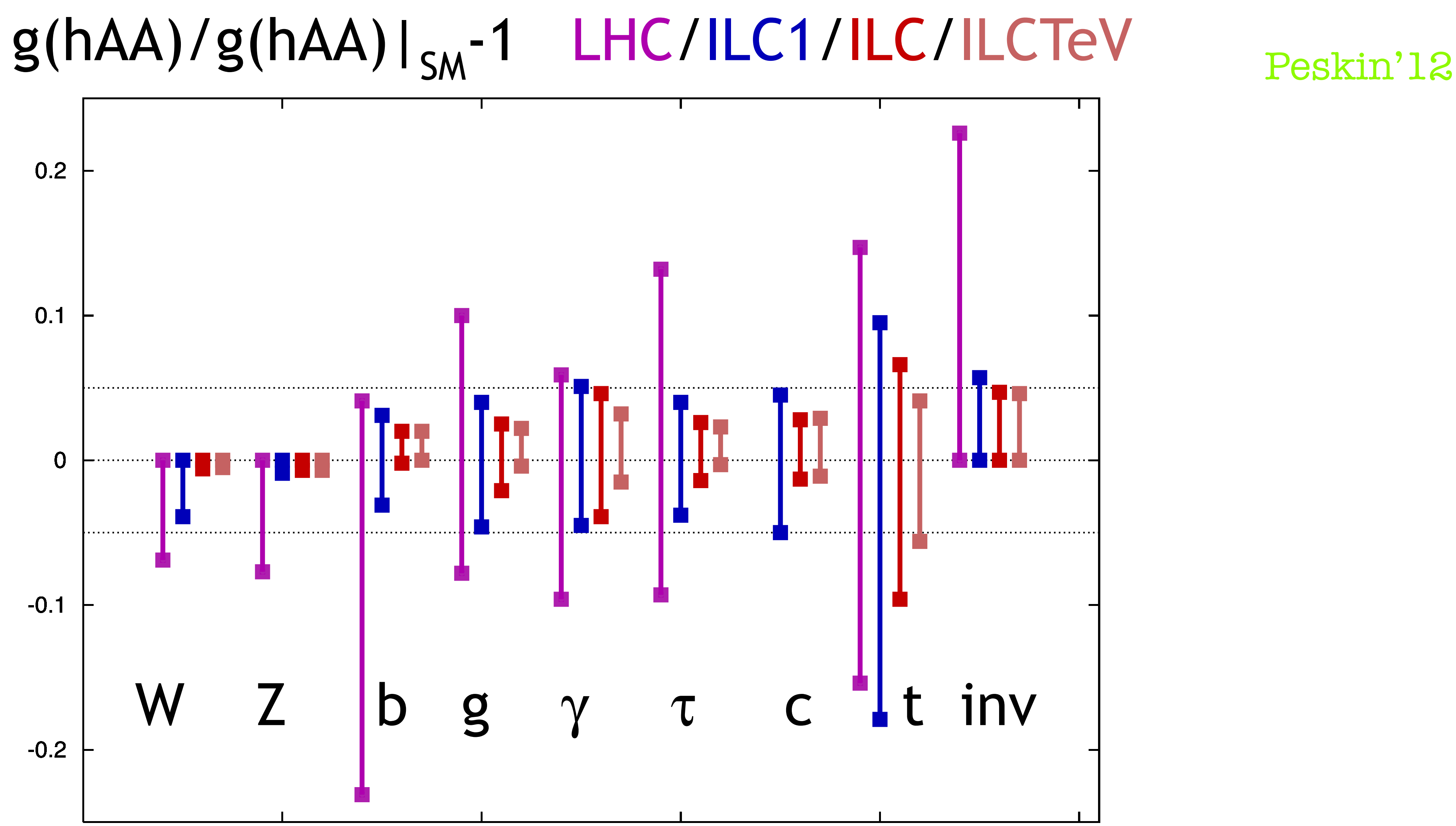


Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

5-10% @ $\mathrm{LHC}^{14\mathrm{TeV}}_{300/\mathrm{fb}}$ 1-5% @ ILC/CLIC

NLO fits: effective Lagrangian fit!

the previous analyses are not entirely theoretically sound:
Inclusive quantities that receive contribution from different operators!
The goal is to have access to the individual operators

$$g_{hWW} \leftrightarrow c_V, \boxed{c_{WW}, c_W}$$

not included in Peskin's fit!

$$g_{h\gamma\gamma} \leftrightarrow c_V, c_t, c_b, c_{\gamma\gamma}$$

NLO effective Lagrangian scaling

g_*: Higgs-NP couplings, g: SM couplings

generically

$$c_{WW}, c_{ZZ}, c_{Z\gamma}, c_{\gamma\gamma}, c_{gg} \propto \mathcal{O}(g_* v/M)$$

$$c_W, c_Z \propto \mathcal{O}(gv/M)$$

linear realization

$$c_{WW}, c_{ZZ}, c_{Z\gamma}, c_{\gamma\gamma}, c_{gg} \propto \mathcal{O}(g_* v/M)^2$$

Higgs = pseudo-Goldstone

$$c_{\gamma\gamma}, c_{gg} \propto \mathcal{O}\left((g/g_*)^2 \times (g_* v/M)^2\right)$$