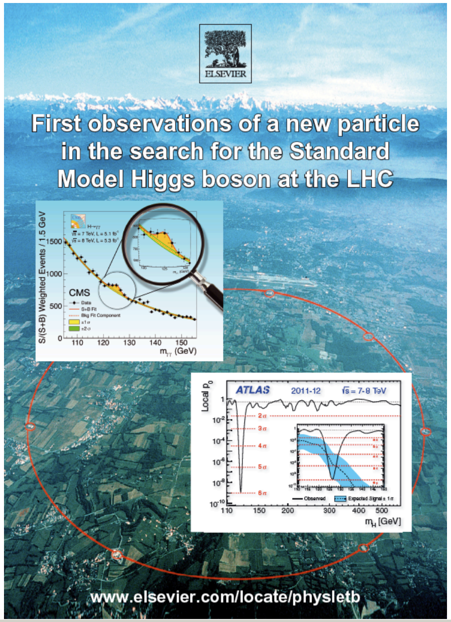
Higgs Boson status and prospects at LHC



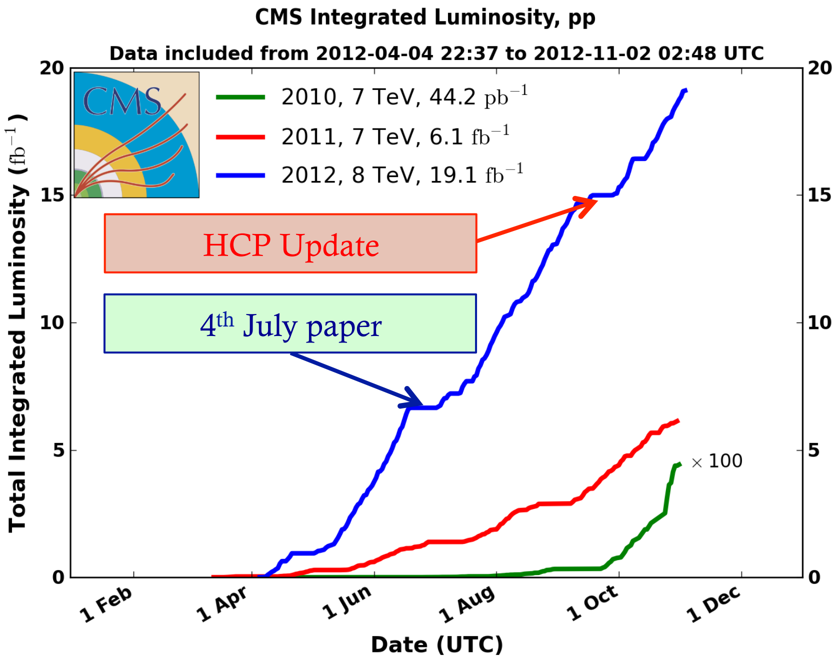
Higgs Factory WS- Fermilab

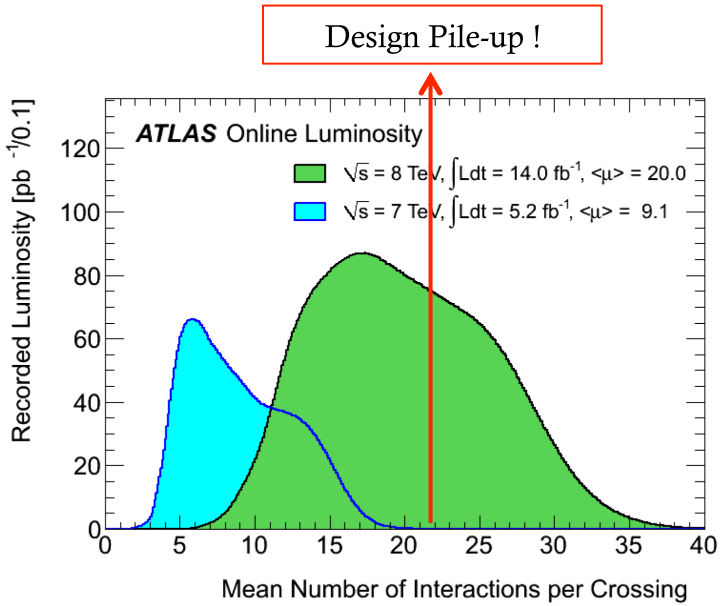
Fabio Cerutti – LBNL
On behalf of
CMS and ATLAS
collaborations

Outline

- SM Higgs results at LHC:
  - Detectors and Accelerator status
  - Higgs properties: including some *new* HCP results
    - Mass, Spin/CP and Couplings
- Prospects for High Luminosity-LHC (High Energy)
  - Couplings (Mass and Spin/CP in backup)
- Conclusions

Detectors and LHC operation





Excellent LHC performance in 2012

L_{peak} up to 7.7×10^{33} cm^{-2} s^{-1} at 8 TeV

$L_{integrated}$ ~ 21 fb^{-1} delivered

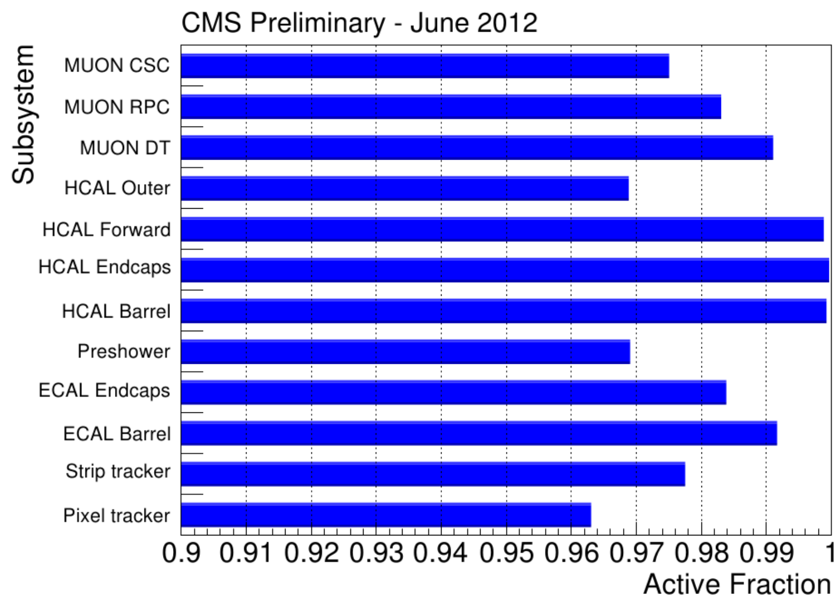
LHC operated with 50ns bunch spacing:

- 2012 pile-up conditions challenging
- Moving to 25ns will halves the pile-up

Detectors and LHC operation

ATLAS - 2012

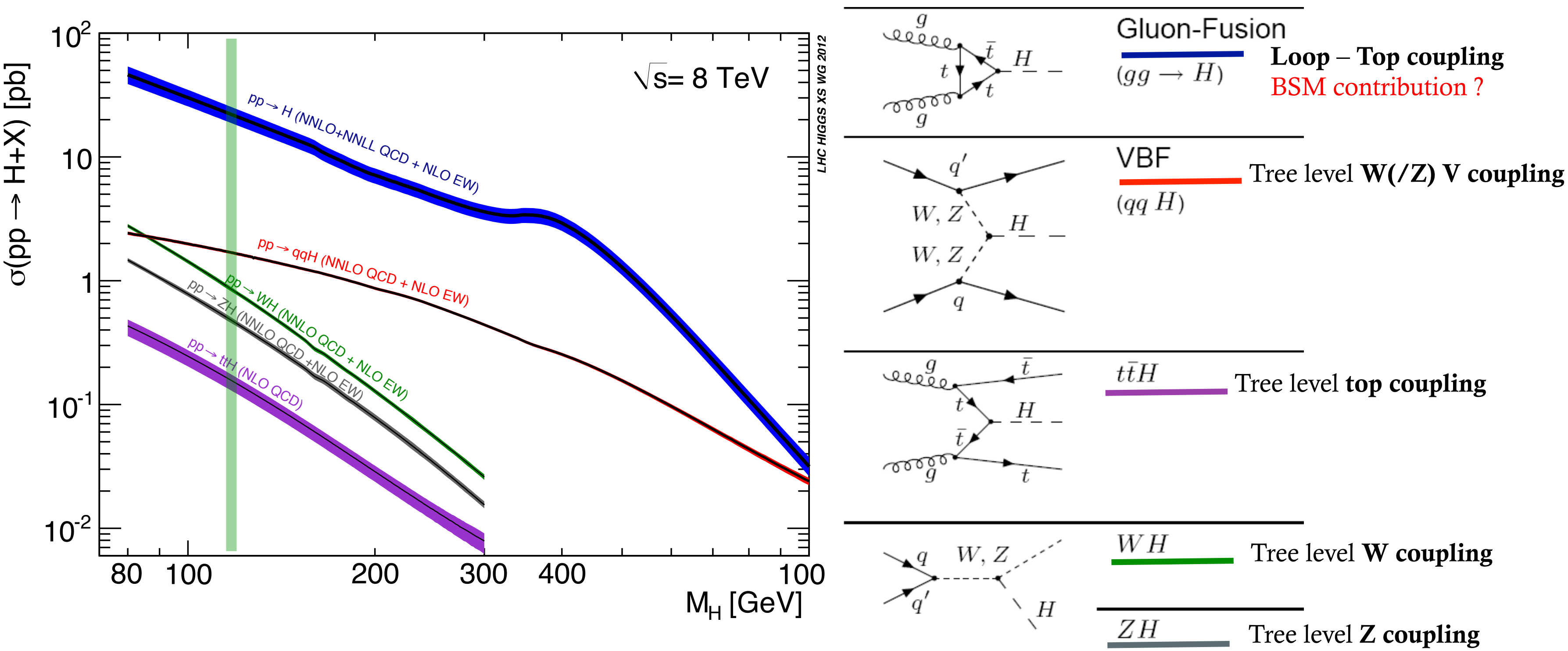
Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.0%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.9%
Tile calorimeter	9800	98.3%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	370 k	100%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	96.0%
RPC Barrel Muon Chambers	370 k	97.1%
TGC Endcap Muon Chambers	320 k	98.2%



- ATLAS and CMS in very good shape: Fraction of Active Channels >96%
- 90% of delivered luminosity used in physics analysis

SM Higgs Boson Production and Decay at LHC

Higgs boson production at LHC



- Main production mode: ggH
- Access to top (direct and Loop), W and Z couplings via production cross section

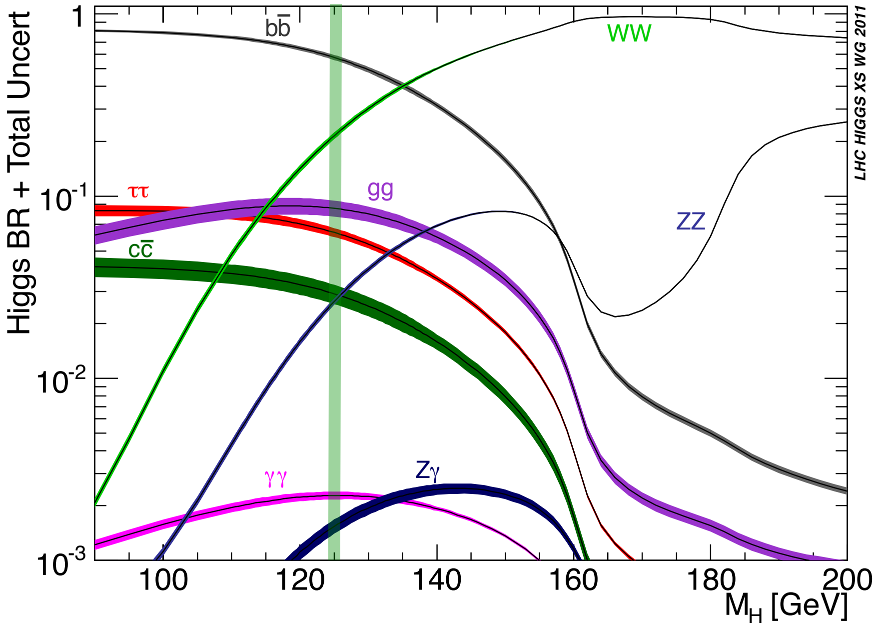
Higgs boson production at LHC

8 TeV

M_H(125 GeV)	σ(fb)	$\delta(th)_{TOT}$	$\delta(th)_{QCD\text{-}Scale}$	$\delta(th)_{PDF+\alpha s}$	$\delta\sigma/\delta M$(.5GeV)
ggH	19.5×10^3	**15%**	**8%**	**7%**	0.8%
VBF	1.58×10^3	3%	0.2%	3%	0.4%
WH	697	4%	0.5%	4%	1.3%
ZH	394	5%	1.5%	4%	1.3%
ttH	130	**14%**	**7%**	**8%**	1.9%

- Cross-sections are LARGE: LHC **is** the first Higgs Factory
- Theory systematics more relevant for ggH and ttH - Mass dependency very weak

Higgs boson decay at LHC



- Experimentally accessible:
  - **bb, ττ, WW, ZZ, γγ, Zγ, μμ**
- Γ_H ~4MeV NO direct measure at LHC

M_H=125 GeV

Process	Branching ratio	Uncertainty	
H → bb	5.77 x 10^{-1}	+3.2%	-3.3%
H → ττ	6.32 x 10^{-2}	+5.7%	-5.7%
H → μμ	2.20 x 10^{-4}	+6.0%	-5.9%
H → cc	2.91 x 10^{-2}	+12.2%	-12.2%
H → gg	8.57 x 10^{-2}	+10.2%	-10.0%
H → γγ	2.28 x 10^{-3}	+5.0%	-4.9%
H → Zγ	1.54 x 10^{-3}	+9.0%	-8.8%
H → WW	2.15 x 10^{-1}	+4.3%	-4.2%
H → ZZ	2.64 x 10^{-2}	+4.3%	-4.2%
Γ_H [GeV]	4.07 x 10^{-3}	+4.0%	-3.9%

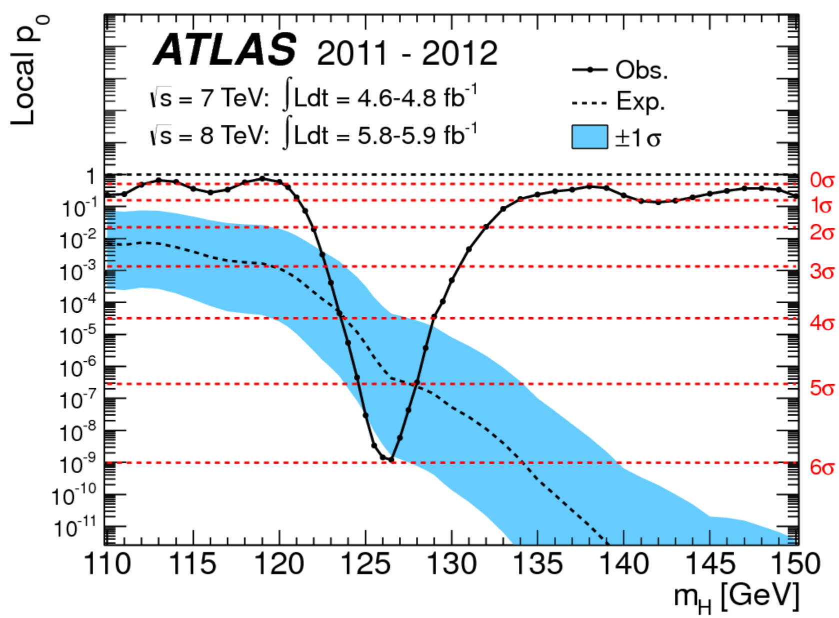
Mass dependency:

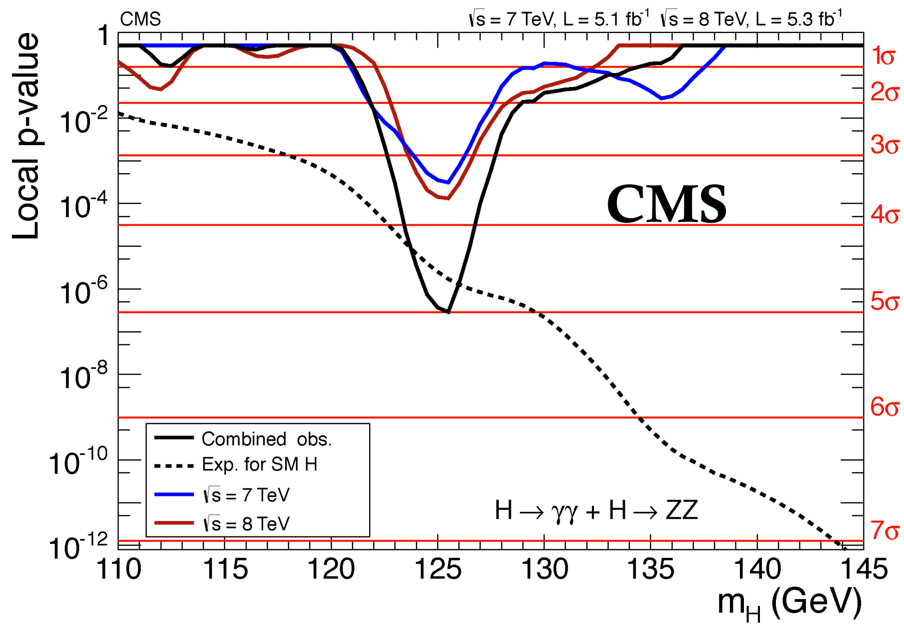
- δBR(bb)/0.5 GeV → 1%
- δBR(WW)/0.5 GeV → 4%
- δBR(ZZ)/0.5 GeV → 4%

SM Higgs Boson CMS and ATLAS results

The Higgs Boson Discovery

4th July 2012



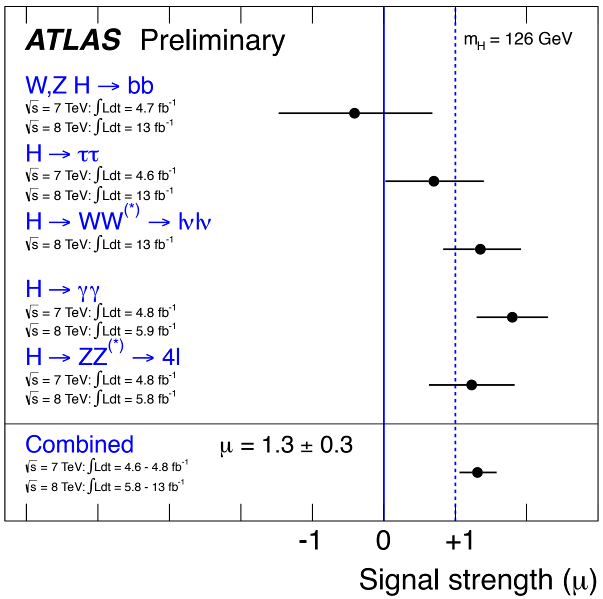


Discovered Higgs-like Boson: Clear mass peak in γγ and ZZ*→4ℓ

Is this the SM one ? From searches to measurements

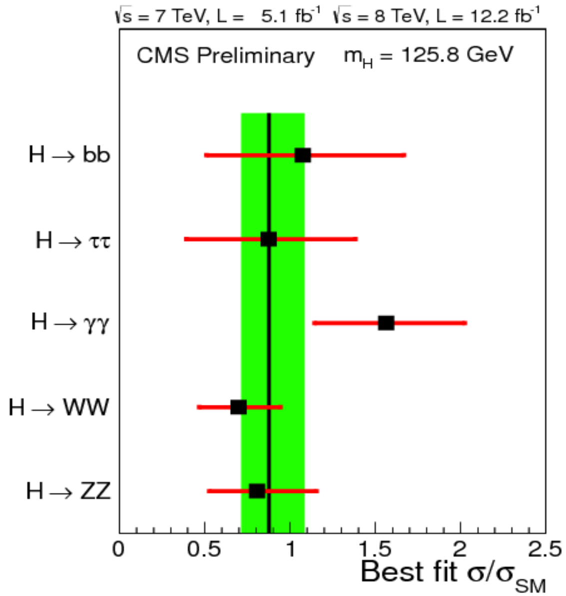
Signal strength $\mu = \sigma BR / \sigma BR_{SM}$ *new* HCP results

ATLAS
WW*, ττ, bb: 13fb^{-1} – 2012
γγ and ZZ* as PLB 4th July



New HCP

CMS
ZZ*, WW*, ττ, bb: 12 fb^{-1} 2012
γγ as PLB 4th July



ATLAS $\mu = 1.3 \pm 0.3$

CMS $\mu = 0.88 \pm 0.21$

Agreement with SM prediction (and CMS/ATLAS) Precision already ~20%

Mass Measurement

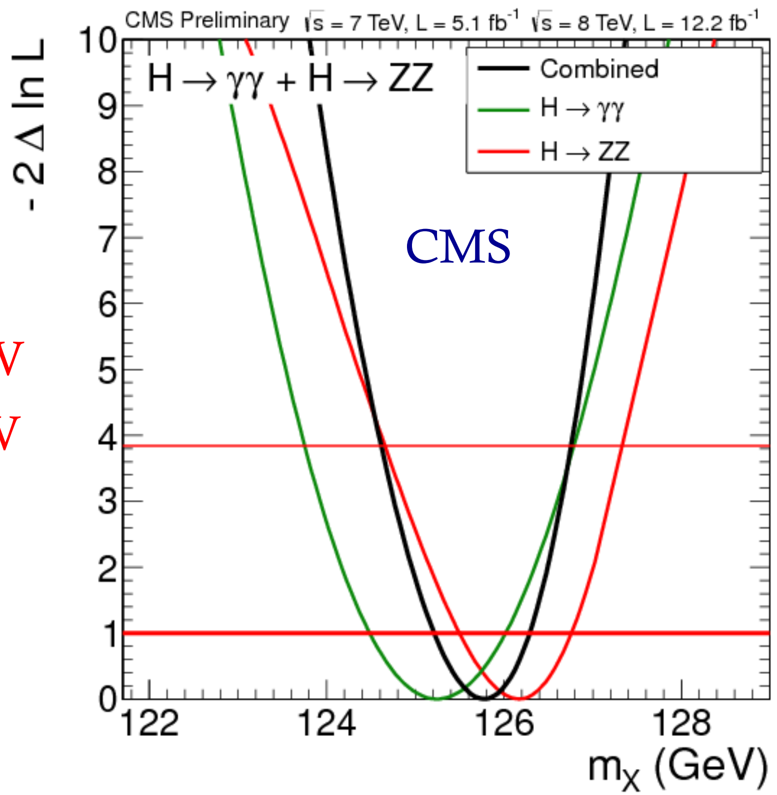
Only missing SM parameter

- From $\gamma\gamma$ and ZZ*(4l) mass spectrum
  - ATLAS: $M_H = 126.0 \pm 0.4_{stat} \pm 0.4_{sys}$ GeV
  - CMS: $M_H = 125.8 \pm 0.4_{stat} \pm 0.4_{sys}$ GeV

Error on the average (*guess the value*) will be …:

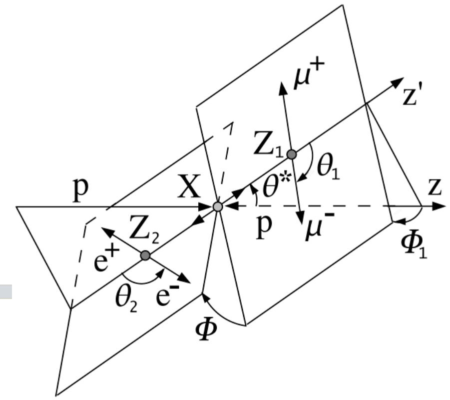
~ 0.4 GeV (3 per mill)

- Impact of mass error on LHC **yields**
  - **less than 4%** (WW/ZZ most sensitive)

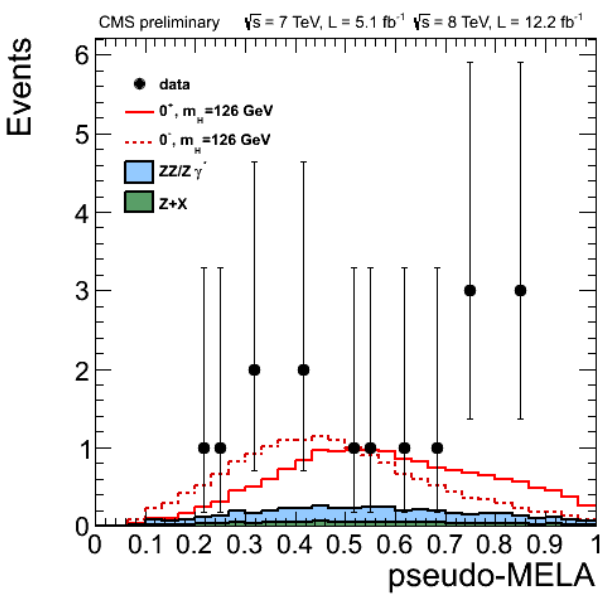


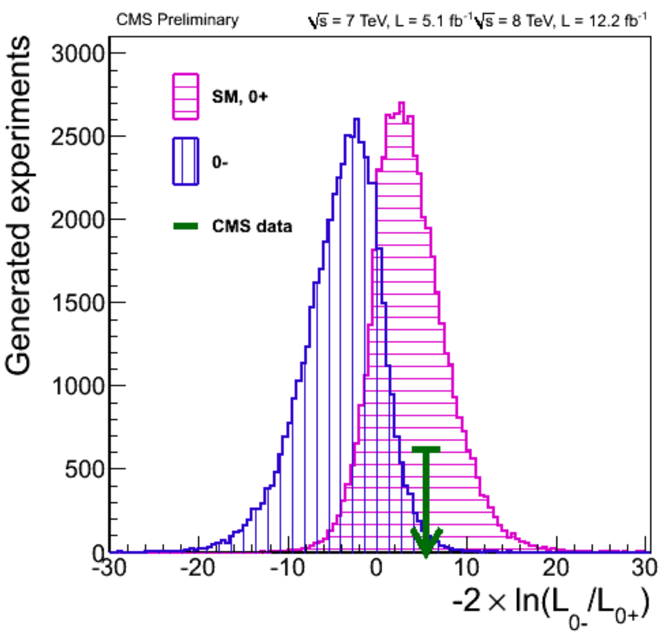
New HCP Update $ZZ^* \rightarrow 4\ell$

Spin/CP



- ZZ* sensitive to Spin and CP properties
  - ZZ* complete set of kinematic variables (8)
  - Combined in a ME-based discriminant: pseudo-MELA





New HCP

Data tested vs 0^+ or 0^-

Data prefers 0^+

0^- consistency ONLY at 2.45σ (1.93 exp)

The Couplings fit

- Basic ingredient Yields per category/channel (e.g., VBF 2J tag of H→ γγ)

Production modes: gg, VBF, W/ZH, ttH + Final states: γγ, WW, ZZ, bb, ττ, Zγ, μμ

- Follow prescription form LHC-XS working group assuming:
  - Only one resonance + Narrow Width Approx. + SM Lagrangian tensor structure (also implies $CP=0^+$)
- Observed yields parameterized SM prediction x coupling scaling factors κ^2
  - SM equivalent to all $\kappa=1$
- *This simplified approach is sufficient for Today's available statistics*

$$\sigma \times BR(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

$$(\sigma \cdot \mathrm{BR})(gg \to \mathrm{H} \to \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \boxed{\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}}$$

The Couplings fit

- Loop contributions can:
  - Expressed as a function of SM couplings
  - Treated as free parameter (assume possible BSM contributions)

- Total width Γ_H two kind of assumptions
  - Only SM particles contribute to $\Gamma_H(\Gamma_i)$
  - Measure ratio of couplings

Production modes

$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases} \quad (3)$$

$$\frac{\sigma_{VBF}}{\sigma^{SM}_{VBF}} = \kappa^2_{VBF}(\kappa_W, \kappa_Z, m_H) \quad (4)$$

$$\frac{\sigma_{WH}}{\sigma^{SM}_{WH}} = \kappa_W^2 \quad (5)$$

$$\frac{\sigma_{ZH}}{\sigma^{SM}_{ZH}} = \kappa_Z^2 \quad (6)$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa_t^2 \quad (7)$$

LHC-XS wg

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\kappa^2_{\gamma\gamma} = (1.6\,\kappa^2_W + 0.07\,\kappa^2_t - 0.67\,\kappa_W\kappa_t)$$

κ_F vs κ_V fit

Couplings to Fermion and Vector boson sectors: κ_F vs κ_V

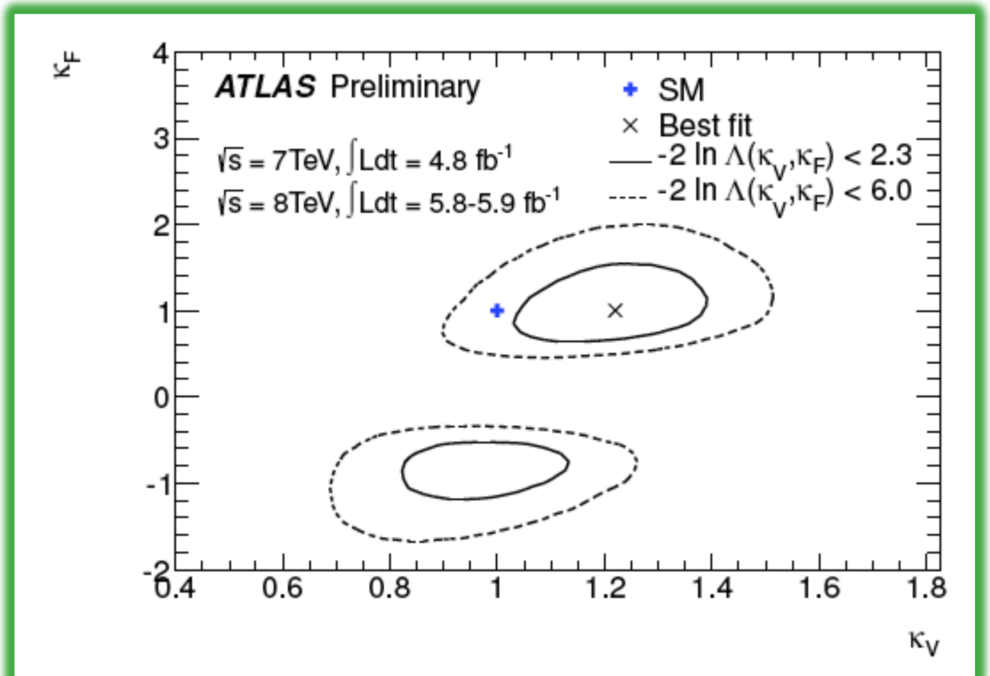
- All Fermion couplings scale with the same factor κ_F $(=\kappa_t=\kappa_b=\kappa_\tau=\ldots)$
- All Boson couplings scale with the same factor κ_V $(=\kappa_W=\kappa_Z)$
- Assumption only SM particles in $\Gamma_H \rightarrow \kappa^2_H(\kappa_F\ \kappa_V) \sim 0.7\ \kappa^2_F + 0.3\ \kappa^2_V$

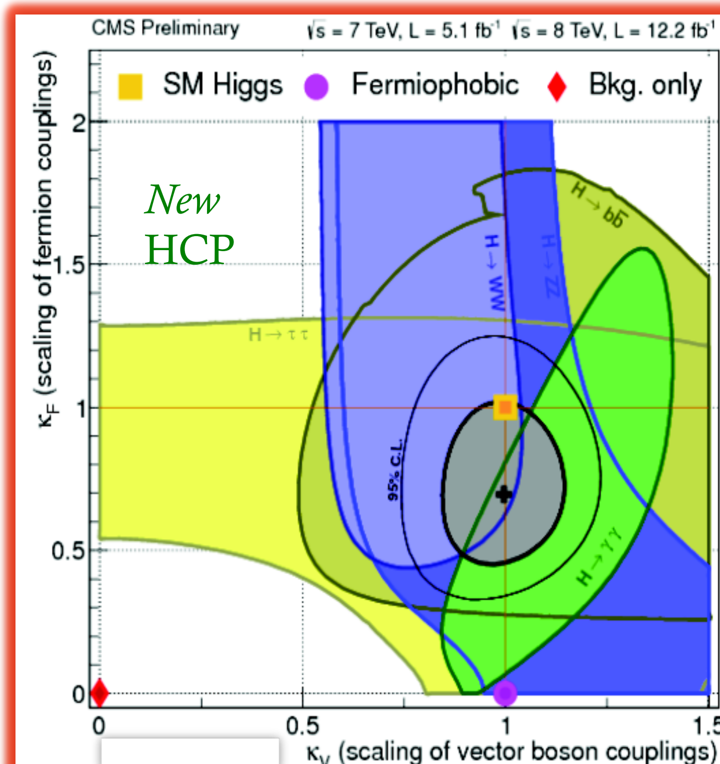
Boson and fermion scaling assuming no invisible or undetectable widths

Free parameters: $\kappa_V(=\kappa_W=\kappa_Z)$, $\kappa_f(=\kappa_t=\kappa_b=\kappa_\tau)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_f^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	

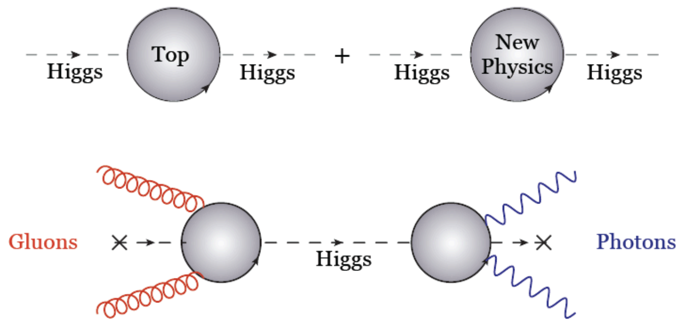
κ_F vs κ_V fit





- Agreement with SM tested at 20-30%
- $\kappa_F = 0$ (Fermiophobic Higgs) Excluded at (much) more than 2σ

Loop Couplings κ_g vs κ_γ

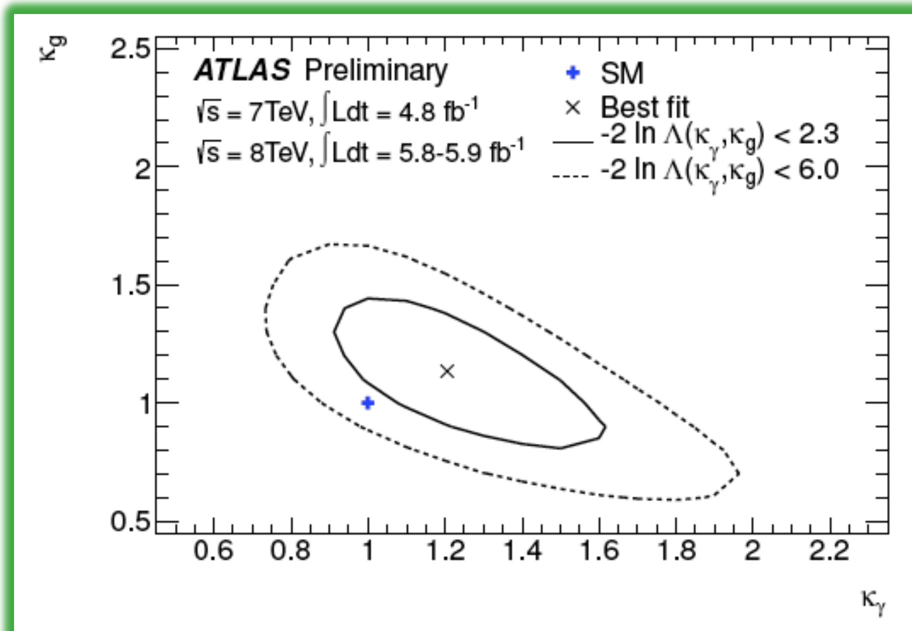


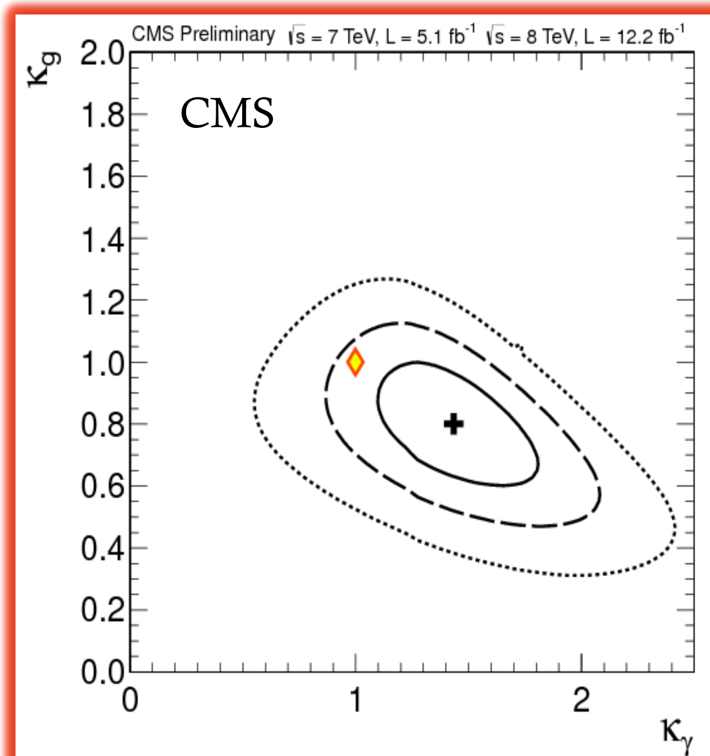
S. Dimopoulos

A Natural Higgs is not the SM Higgs

- Hierarchy problem related to top loop same that contributes to gg coupling
- Assumptions in κ_g vs κ_γ fit:
  - Direct Coupling to known SM particles assumed to be as in SM:
    - $\kappa_b = \kappa_W = \kappa_Z = \kappa_\tau = \ldots. = 1$
    - $\kappa_H \sim 0.9 + 0.1\ \kappa_g$
  - No extra contributions to Γ_H (only known SM and gg)

Loop Contributions κ_g vs κ_γ





___ 69% CL

- - - 95% CL

Agreement with SM prediction at better than 2σ

The Couplings roadmap

Test Higgs boson couplings depending on available L:

- Total signal yield μ: tested at 20% (κ tested at 10%)
- Couplings to Fermions and Vector Bosons 20-30%
- Loop couplings tested at 40%
- *Custodial symmetry W/Z Couplings tested at 30%
- Test Down vs Up fermion couplings
- Test Lepton vs Quark fermion couplings
- Top Yukawa direct measurement ttH: κ_t
- Test second generation fermion couplings: κ_μ
- Higgs self-couplings couplings HHH: κ_H

Today

7/8 TeV
~ 10-15 fb^{-1}

LHC
Upgrade

14/33 TeV
~ 3000 fb^{-1}

*results in backup slides

SM Higgs Boson Prospects at High Luminosity LHC

High Luminosity LHC: The timeline

2009		✧ LHC startup, $\sqrt{s} = 900$ GeV
2010		
2011		$\sqrt{s}$=7~8 TeV, L=6×10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns
2012		
2013	LS1	Go to design energy, nominal luminosity (Phase-0)
2014		
2015		
2016		$\sqrt{s}$=13~14 TeV, L~1×10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns
2017		
2018	LS2	Injector and LHC Phase-I upgrade to full design luminosity
2019		
2020		$\sqrt{s}$=14 TeV, L~2×10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns
2021		
2022	LS3	HL-LHC Phase-II upgrade, IR, crab cavities
2023		
...		
2030?		$\sqrt{s}$=14 TeV, L=5×10^{34} cm^{-2} s^{-1}, luminosity levelling

✔ Done

~20-25 fb^{-1}

~75-100 fb^{-1}

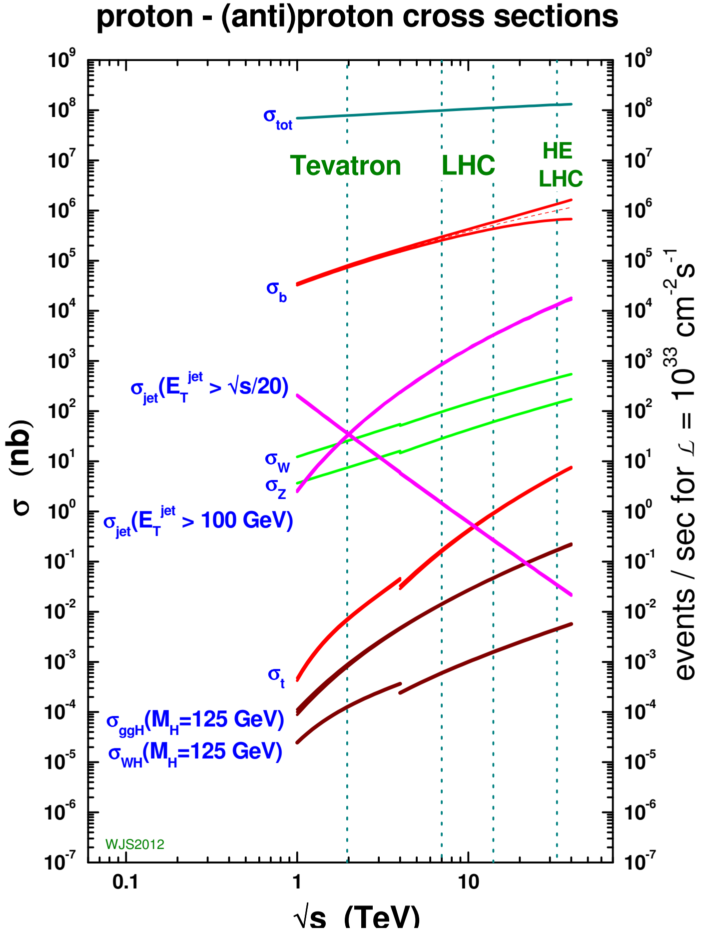
Approved
300 fb^{-1} at 14 TeV

HL-LHC:
3000 fb^{-1} at 14 TeV

High Luminosity LHC: the detector upgrades

- Both detectors are planning **important upgrades** to stand the harsher running conditions at HL-LHC: pile-up, rates, radiation damage
  - Pile-up ~ 4-5 times more pile-up then today
- Plan: keep detector performance for main physics objects at the same level as we have today
  - Improved trigger system
  - New tracking systems
  - Improved forward detectors
  - ….
- Not discussed in this talk but CRUCIAL to profit of L increase

Signal σ and Yields: HL/HE



8 → 33 TeV: ggH x9.2   14 → 33 TeV: ggH→ HH x6

Process	3000 fb^{-1} 14 TeV	300 fb^{-1} 33 TeV
ggH→γγ	350k	123k
ggH→4ℓ	19k	6.7k
ttH→γγ	**42k**	**30k**
ttH→4ℓ/μμ	**0.2k/0.4k**	**0.16k/0.3k**
ggH→HH→bbγγ	**270**	**160**

LHC upgrades give access to <u>rare decays</u>
Better signal Yields at HL-LHC
BUT Pile-up and S/B better at HE-LHC

Couplings at HL-LHC: CMS

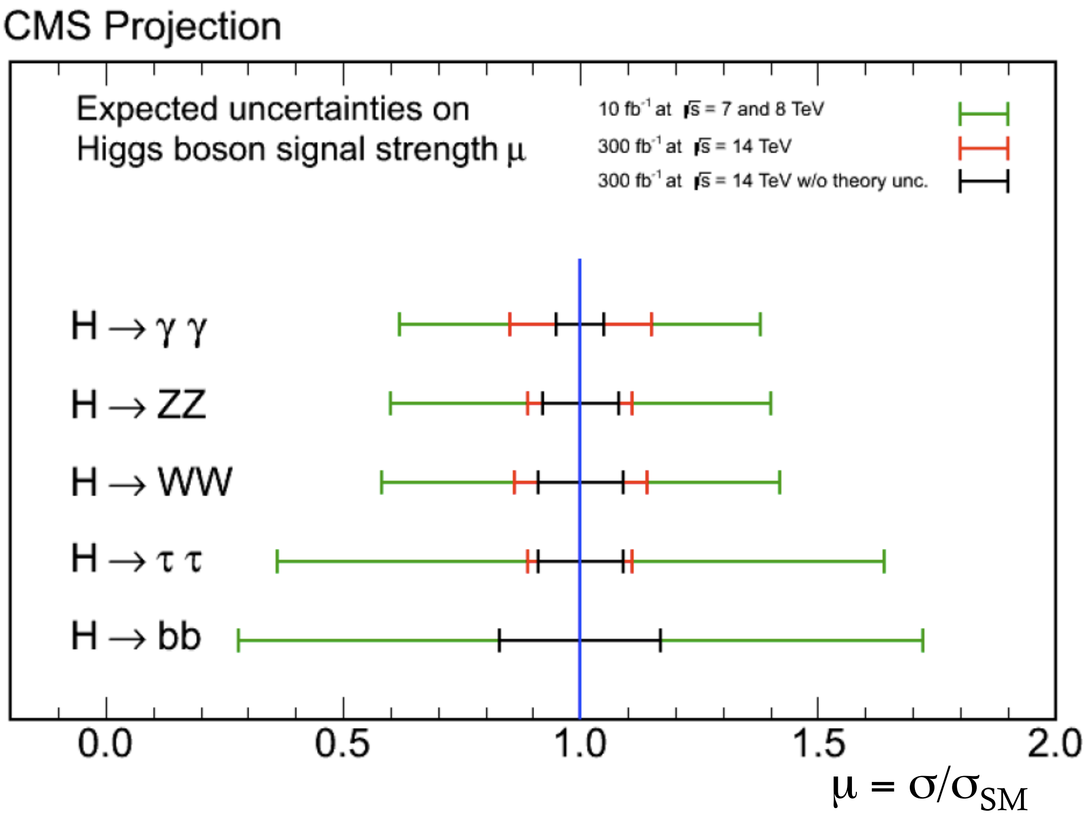
- Analyses included in CMS projection:
  - H→ γγ inclusive and VBF
  - H → ττ all final state, Inclusive, Boosted, VBF,…
  - H → ZZ → 4ℓ Inclusive
  - H→ WW → ℓνℓν 0-jet, 1-jet, WH and VBF
  - VH→bb
  - ttH→ bb Direct top Y coupling
  - **H→ μμ**

- Projection assumptions:
  - Scenario 1: all systematic + theory uncertainty kept unchanged
  - Scenario 2: exp. systematics scaled 1/sqrt(L) and theory by ½ (see backup slides ..)
  - Scenario 3: as 2 but theory uncertainties=0 (shows statistical limit !)

- ZZ*→4ℓ and γγ and μμ channels: Scenario 2 ~realistic

- ττ, bb, WW: Experimental systematics on backgrounds dominant, data driven but need extrapolation to signal region …

Signal Strength: μ at 300 fb^{-1}



300 fb^{-1} at 14 TeV

Red: Scenario 1

Black: Scenario 3

Theory errors dominant for γγ

Most difficult channel bb

Measurements at:

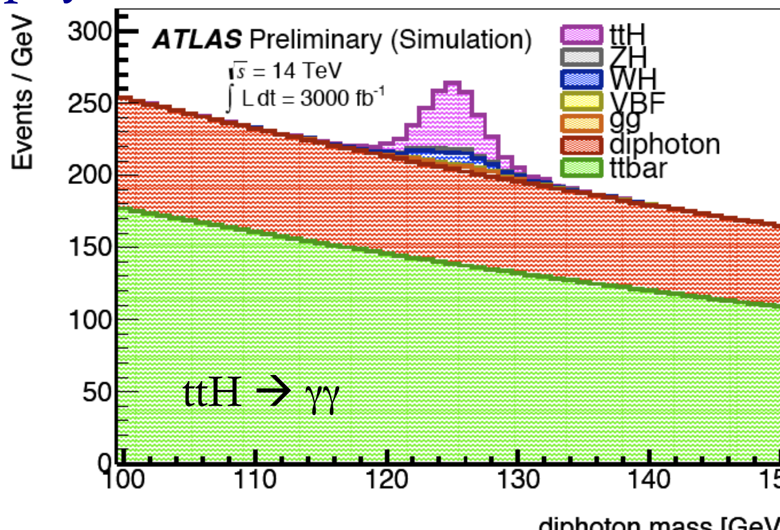
μ~10-20%

κ ~5-10%

Similar results obtained by ATLAS (backup slides)

Couplings at HL-LHC: ATLAS

- MC Samples at 14 TeV from Fast-Sim.
  - Truth with smearing: best estimate of physics objects dependency on pile-up
  - Validated with full-sim. up to μ~70
- Analyses included in ATLAS study:
  - H→ γγ 0-jet and VBF
  - H → ττ VBF lep-lep and lep-had
  - H → ZZ → 4ℓ
  - H→ WW → ℓνℓν 0-jet and VBF
  - WH/ZH → γγ
  - **ttH → γγ** (ttH → μμ) **Direct top Y coupling**
  - **H → μμ Second generation fermion coupling**
  - **HH→ bb γγ Higgs Self-Couplings**



Very Robust channel
Good S/B
Statistically limited

Couplings fit at HL-LHC

CMS

Coupling	Uncertainty (%)			
	$300\ \mathrm{fb}^{-1}$		$3000\ \mathrm{fb}^{-1}$	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

CMS Projection

Assumption NO invisible/undetectable contribution to Γ_H:

- Scenario 1: system./Theory err. unchanged w.r.t. current analysis
- Scenario 2: systematics scaled by 1/sqrt(L), theory errors scaled by ½

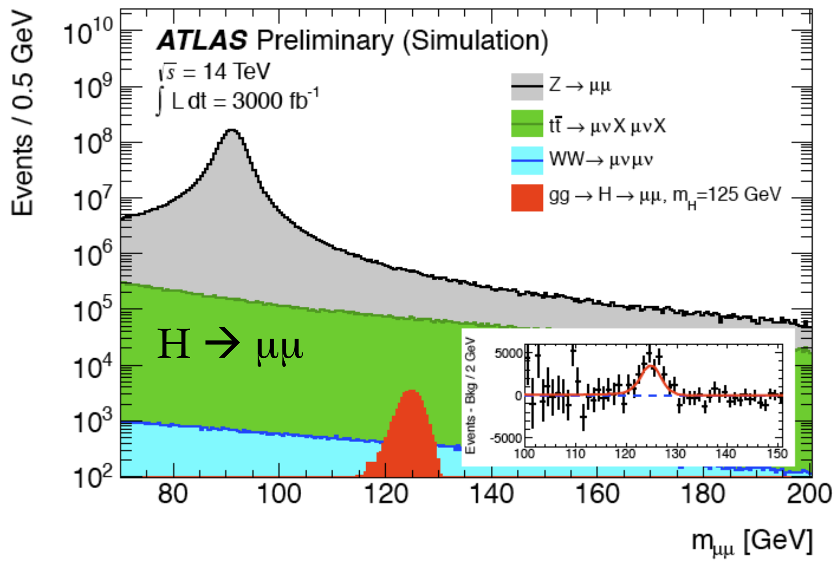
✓ γγ loop at 2-5% level

✓ down-type fermion couplings at 2-10% level

✓ direct top coupling at 4-8% level

✓ gg loop at 3-8% level

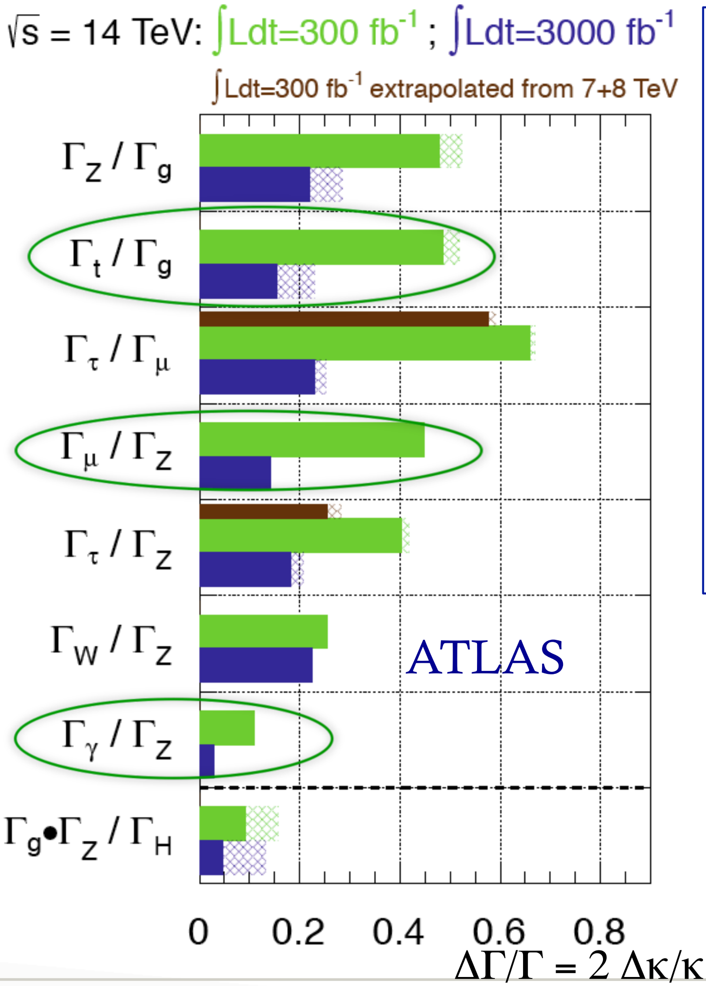
κ_μ Coupling at HL-LHC



H → μμ Second generation fermion coupling:

- Analysis strategy very similar to γγ (advantage that DY spectrum is predictable):
  - Look for a narrow mass peak over continuous Z/DY background
- ATLAS and CMS can go (well) above 5σ/Experiment at HL-LHC
  - **κ_μ at 10% level/Experiment** (statistically limited)

Coupling Ratios Fit at HL-LHC



- Fit to coupling ratios:
  - No assumption BSM contributions to Γ_H
  - Some theory systematics cancels in the ratios
- Loop-induced Couplings $\gamma\gamma$ and gg treated as independent parameter
  - κ_γ/κ_Z tested at 2%
  - gg loop (BSM) κ_t/κ_g at 7-12%
  - 2nd generation ferm. κ_μ/κ_Z at 8%

Higgs self-couplings λ_{HHH}

- Need to distinguish between HH production via H or V (**negative** interference)
  - CMS: HH → bbγγ or HH → bbμμ (HE-LHC)
  - ATLAS: HH → bbγγ (under study HH → bbττ)
- Example ATLAS analysis bbγγ – Simple analysis M_H=125 GeV:
  - Cuts on Pt 2 γ (40/25) and 2 b-jets (25) and relative angles
  - 50 <M_{bb}<130 GeV - 120 <$M_{\gamma\gamma}$<130 GeV
- Signal[λ_{HHH}=1]=15, Signal[λ_{HHH}=0]=26, Background = 24 (mainly ttH)
  - 1 experiment: ~2σ observation for λ_{HHH}=1
- Only one channel and very simple CUT-based analysis: we can do better

Conclusions

Approved LHC 300 fb^{-1} at 14 TeV:

- Higgs mass at 100 MeV
- Disentangle Spin 0 vs Spin 2 and main CP component in ZZ*
- Coupling rel. precision/Exper.
  - Z, W, b, τ   10-15%
  - t, μ   3-2 σ observation
  - γγ and gg   5-11%

HL-LHC 3000 fb^{-1} at 14 TeV:

- Higgs mass at 50 MeV
- More precise studies of Higgs CP sector
- Couplings rel. precision/Exper.
  - Z, W, b, τ, t, μ   2-10%
  - γγ and gg   2-5%
  - H→HH >3 σ observation (2 Exper.)

Assuming sizeable reduction of theory errors

LHC experiments entered the Higgs properties measurement era: this is just the beginning !
LHC Upgrade crucial step towards precision tests of the nature of the newly-discovered boson

Backup

SM Higgs Boson Prospects at High Luminosity LHC Mass, spin/CP, …

Theory Errors

- Quite large in gg and ttH production ~ 15% - Contributions:
  - QCD scale~8%
  - PDF+α_s~7%

- Prospects:
  - gg QCD scale uncertainty: ~8%@NNLO → ~5%@NNNLO
    - E.g., see Anastasious http://www.ggi.fi.infn.it/talks/talk2773.pdf
  - PDF+α_s~7% → <5% with fit to LHC data
    - Jet, top, prompt-γ, Z → $d\sigma/dP_t$ contribute to gluon PDF

- Factor ~2 reduction on main theory errors very challenging but possible

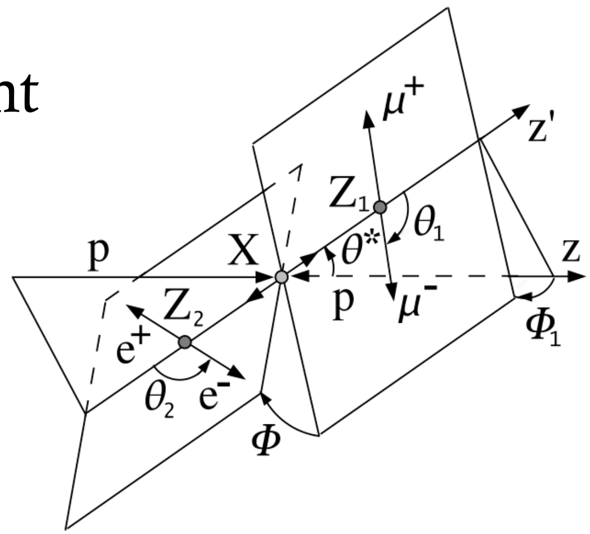
HL-LHC mass measurement

- Mass measurement in $ZZ^* \rightarrow 4\ell$ and $\gamma\gamma$:
  - Statistical error down to ~50 (~15) MeV in 4l ($\gamma\gamma$) /Experiment
  - Systematics more difficult to predict:
    - $\gamma\gamma$: Photon Energy scale at the moment 600 MeV
    - 4l: calibrated with $Z \rightarrow ll$ (Huge statistics) Today 200 MeV
- *"Educated guess"*: 50 MeV achievable at HL-LHC

Spin/CP

- Several channels observables sensitive to Spin and CP properties

- Production and Decay angles of different final states
  - $\gamma\gamma$ decay angle $\cos\theta^*$
  - WW* set of kinematic variables
  - **ZZ* complete set of kinematic variables (8)**
  - VBF production → $\Delta\Phi jj$
  - VH→bb – M_{VH}



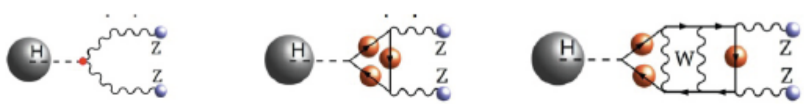
- Spin 0^+ SM all observable can be predicted:
  - Strategy: Use SM-0^+ as benchmark to test agreement with Spin/CP sensitive observables

Spin/CP

- Several spin=2 models can already be rejected with modest luminosity combining several final state
- CP in V sector can be studied with H→ ZZ → 4l
- General parameterization of CP amplitude:

$$A(X \to VV) \sim \left(a_1 M_X^2 g_{\mu\nu} + a_2(q_1+q_2)_\mu(q_1+q_2)_\nu + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\right) \varepsilon_1^{*\mu} \varepsilon_2^{*\nu}$$

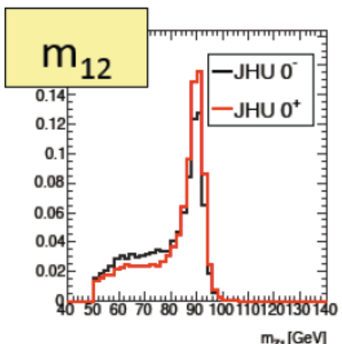
- Complex form factors a_i:

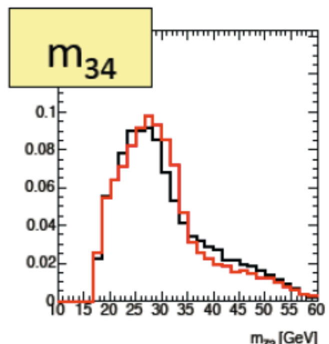


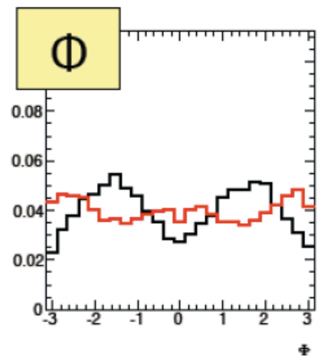
  - SM tree level $a_1=1$, $a_2=a_3=0$ –
    - Generated at loop level a_2(~few %) and $a_3(\sim 10^{-10})$
- CP violation requires (a_1 OR $a_2 \neq 0$) AND ($a_3 \neq 0$)

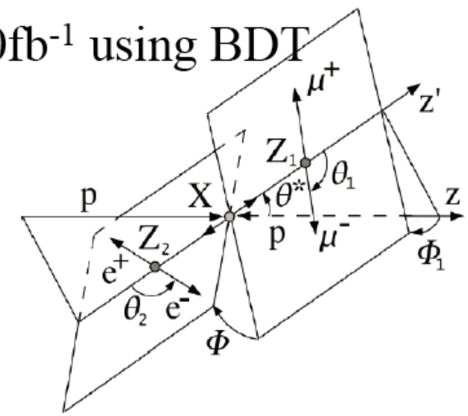
Spin/Cp ZZ→ 4l

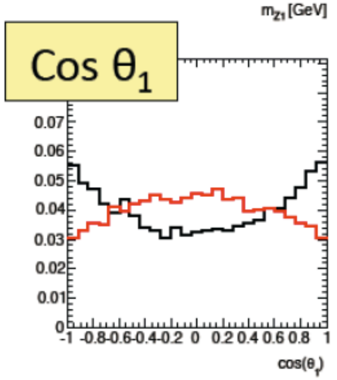
- H→ZZ*→4l is sensitive to Spin and CP
- Observables: 5 Cabibbo-Masksymowicz angles, recon. $\ell\ell$ masses
- Expect to have ~3σ separation (0^+ vs 0^-) for $30 fb^{-1}$ using BDT

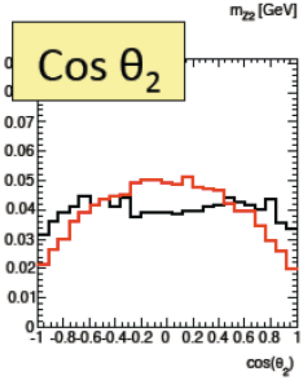


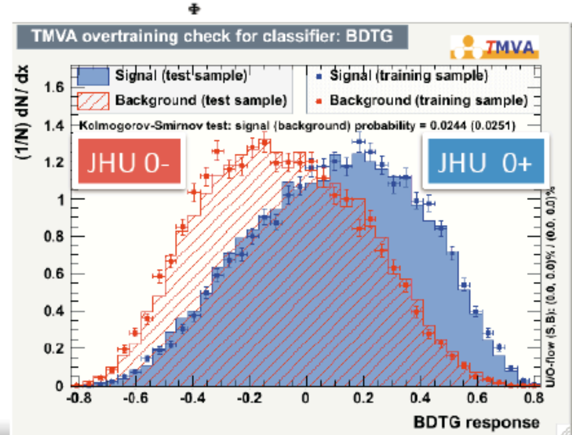










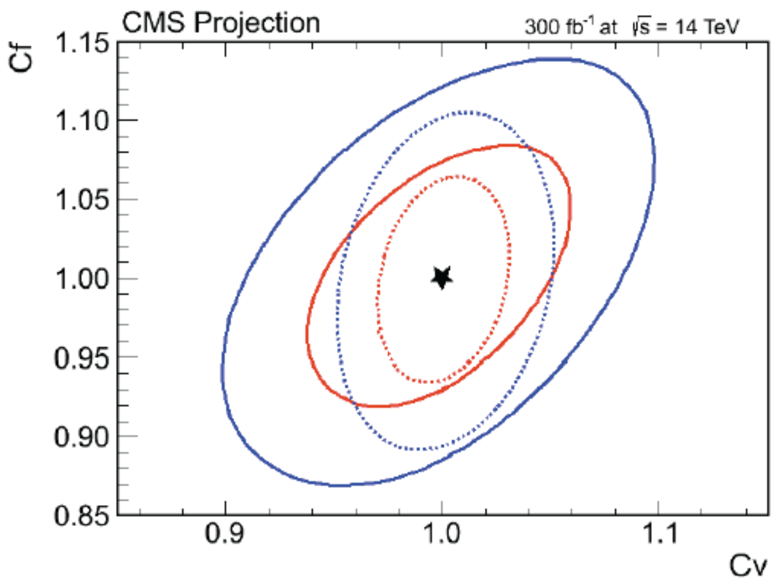


Spin/CP: ATLAS

Integrated Luminosity	Signal (S) and Background (B)	$6+6i$	$6i$	$4+4i$
100 fb^{-1}	$S = 158; B = 110$	3.0	2.4	2.2
200 fb^{-1}	$S = 316; B = 220$	4.2	3.3	3.1
300 fb^{-1}	$S = 474; B = 330$	5.2	4.1	3.8

- Sensitivity to CP odd a_3 coupling vs L
- High luminosity can allow CP studies in Higgs sector via ZZ to 4l final state (very robust against pile-up)

κ_V vs κ_F prospects



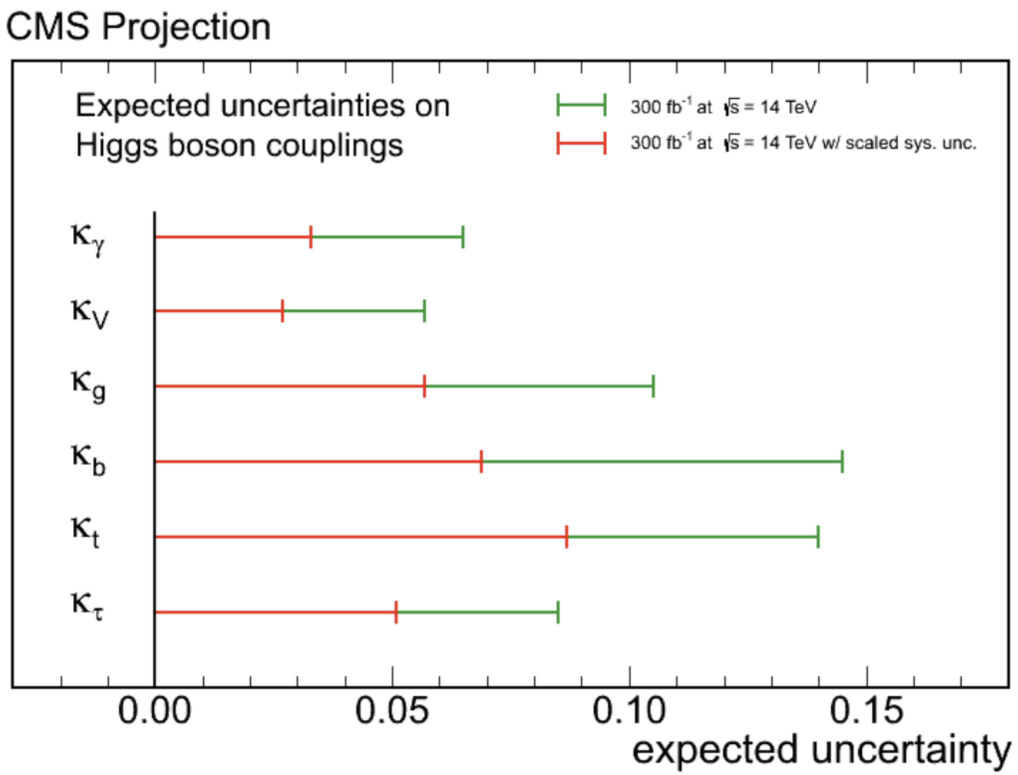
Solid: Scenario 1
Dashed: Scenario 3
Assumes no BSM physics in total width
Without theory errors better than 5%
Can reduce impact of theory uncertainty and assumptions looking at ratio

ATLAS

	300 fb^{-1}	3000 fb^{-1}
κ_V	3.0% (5.6%)	1.9% (4.5%)
κ_F	8.9% (10%)	3.6% (5.9%)

Test Fermion and Vector Boson couplings at 4-6% level !

CMS studies 300 fb^{-1}



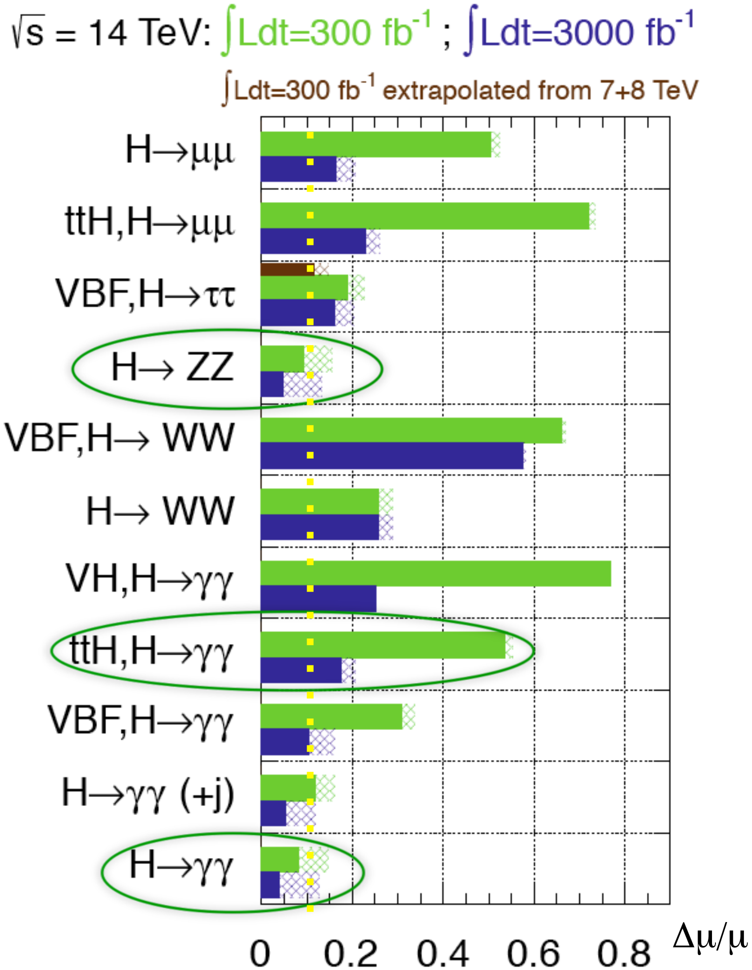
Global fit to main Higgs couplings

Assumed NO invisible/ undetectable contribution to Γ_H

- Scenario 1: sys. unchanged
- Scenario 2: sys. 1/sqrt(L), theory errors divided by 2

κ measured at 5-15%

ATLAS studies: μ at HL-LHC

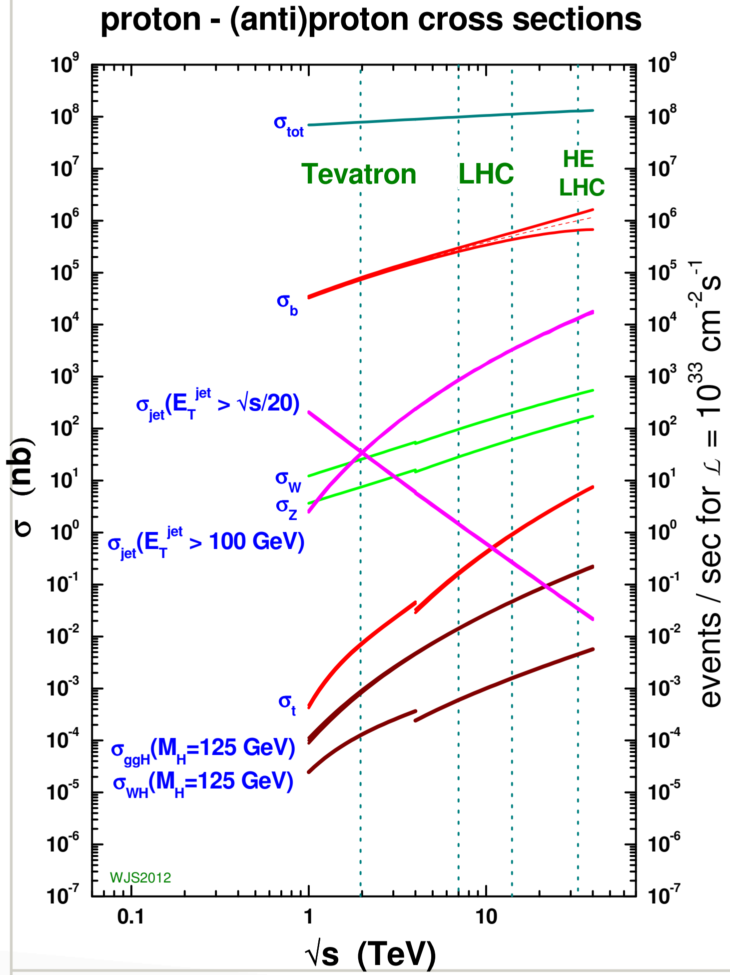


Signal strength μ

- Dashed chart indicates theory unc. Contribution:
  - Dominant for ZZ and γγ final states: hope to improve on that or consider ratios
- Extrapolation of WW and ττ is more difficult since dominated by bkg. Systematics:
- ZZ, γγ, ττ ~10% (below with reduced theory errors or ratios)
- ttH ~20% (10% on coupling)

SM Higgs Boson Prospects at High Luminosity LHC cross-sections, Partial widths…

Signal XS evolution



	M_H=125 GeV	14 TeV			
Process	**Cross section**	**Scale uncertainty**		**PDF+α_s uncertainty**	
ggF [a]	50.35 pb	+7.5%	-8.0%	+7.2%	-6.0%
VBF [b]	4.172 pb	+0.4%	-0.3%	+1.9%	-1.5%
WH [c]	1.504 pb	+0.3%	-0.6%	+3.8%	-3.8%
ZH [c]	0.8830 pb	+2.7%	-1.8%	+3.7%	-3.7%
ttH [c]	0.6113 pb	+5.9%	-9.3%	+8.9%	-8.9%

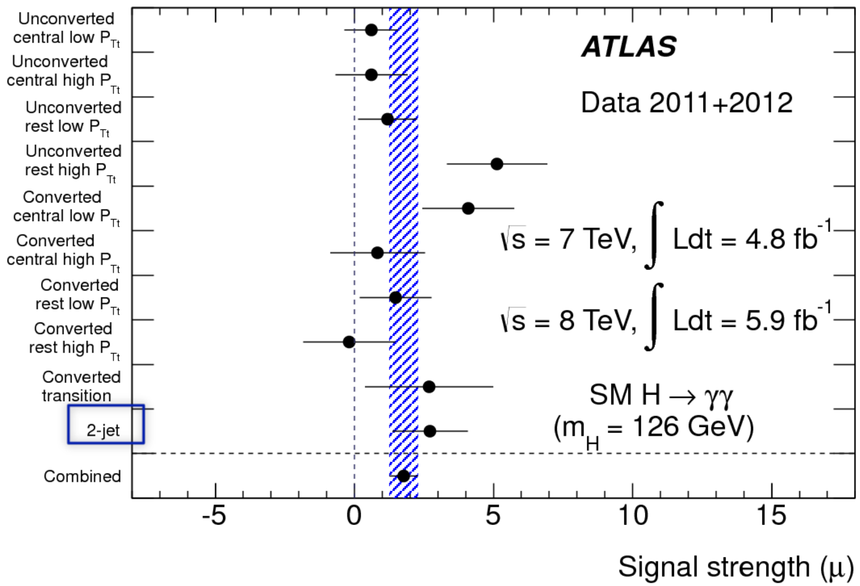
- 8 → 14 TeV
  - Higgs σ 2.6 higher
  - tt σ 3.9 higher
- 8 → 33 TeV
  - Higgs σ 9.2 higher
  - tt σ 22 higher

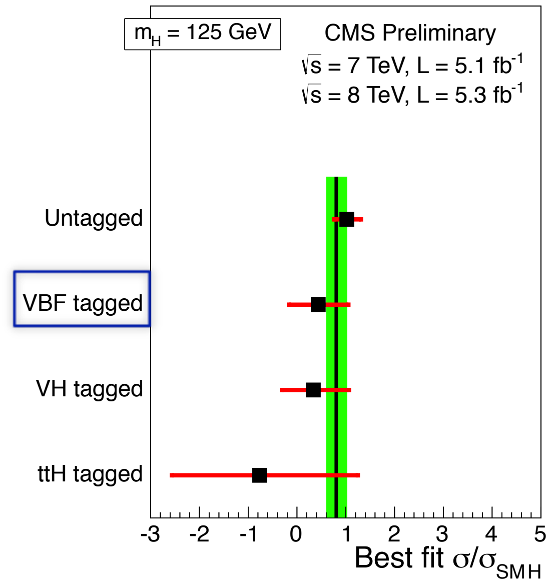
Partial Widths in SM

- SM Higgs (v= 246 GeV from G_F):
  - $\Gamma_{ff} \quad \alpha \quad (m_f / v)^2$
  - $\Gamma_{WW} \quad \alpha \quad (2\, M_W^2 / v)^2$
  - $\Gamma_{ZZ} \quad \alpha \quad (M_Z^2 / v)^2$
  - $\Gamma_{HH} \quad \alpha \quad (M_H^2 / v)^2$
  - $\Gamma_{\gamma\gamma} \quad \alpha\ (1.6\ \Gamma_{WW} + 0.07\ \Gamma_{tt} - 0.7\ \Gamma_{Wt})$ → Wt interference
  - $\Gamma_{gg} \quad \alpha\ (1.1\ \Gamma_{tt} + 0.01\ \Gamma_{bb} - 0.12\ \Gamma_{bt})$ → bt interference
  - $\Gamma_{Z\gamma} \quad \alpha\ (1.12\ \Gamma_{WW} + 0.003\ \Gamma_{tt} - 0.12\ \Gamma_{Wt})$ → Wt interference
- Γ_H (125 GeV) = 4 MeV (dominated by bb ~57%)

SM Higgs Boson Coupling fits results

The Couplings fit





- Basic ingredient Yields per category:
  - Production modes: gg, VBF, W/ZH, ttH
  - Final states: $\gamma\gamma$, WW, ZZ, bb, $\tau\tau$, $Z\gamma$, $\mu\mu$

Custodial Symmetry $\lambda_{WZ} = k_W/k_Z$

- Testing Custodial Symmetry W vs Z couplings
- Move to fit of RATIOs (can relax assumption on total width)
  - $\lambda_{WZ} = \kappa_W/\kappa_Z$
  - Two additional parameters λ_{FZ} κ_{ZZ} in the fit but with small correlation with λ_{WZ}

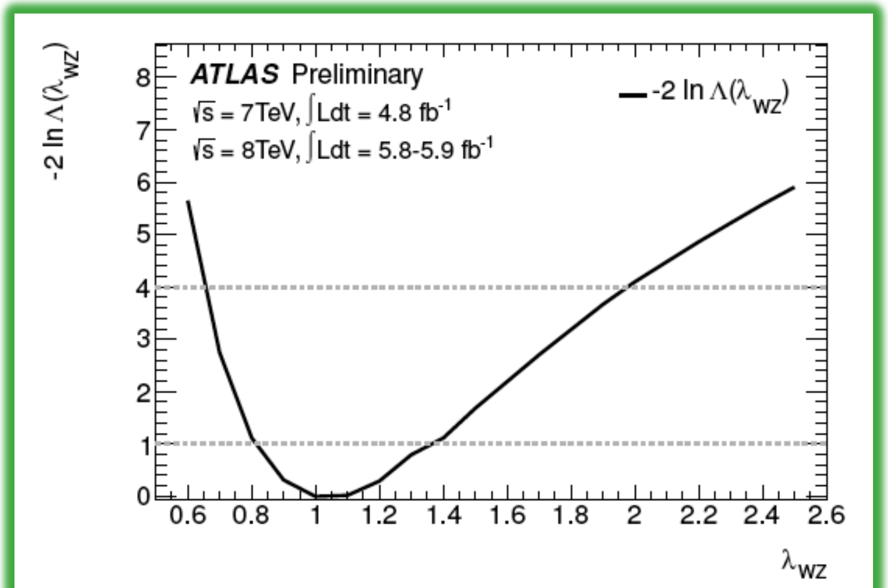
Probing custodial symmetry without assumptions on the total width

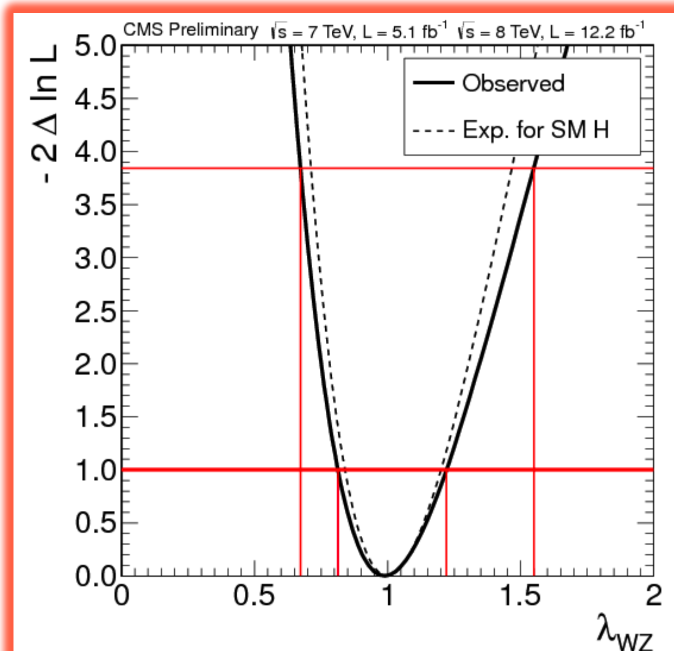
Free parameters: $\kappa_{ZZ} (= \kappa_Z \cdot \kappa_Z / \kappa_H)$, $\lambda_{WZ} (= \kappa_W / \kappa_Z)$, $\lambda_{FZ} (= \kappa_f / \kappa_Z)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\kappa_{ZZ}^2 \lambda_{FZ}^2 \cdot \boxed{\kappa_\gamma^2(\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{WZ})}$	$\boxed{\kappa_{ZZ}^2 \lambda_{FZ}^2}$	$\boxed{\kappa_{ZZ}^2 \lambda_{FZ}^2 \cdot \lambda_{WZ}^2}$	$\kappa_{ZZ}^2 \lambda_{FZ}^2 \cdot \lambda_{FZ}^2$	
VBF	$\kappa_{ZZ}^2 \kappa_{VBF}^2(1, \lambda_{WZ}^2) \cdot \kappa_\gamma^2(\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{WZ})$	$\kappa_{ZZ}^2 \kappa_{VBF}^2(1, \lambda_{WZ}^2)$	$\kappa_{ZZ}^2 \kappa_{VBF}^2(1, \lambda_{WZ}^2) \cdot \lambda_{WZ}^2$	$\kappa_{ZZ}^2 \kappa_{VBF}^2(1, \lambda_{WZ}^2) \cdot \lambda_{FZ}^2$	
WH	$\kappa_{ZZ}^2 \lambda_{WZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{WZ})$	$\kappa_{ZZ}^2 \cdot \lambda_{WZ}^2$	$\kappa_{ZZ}^2 \lambda_{WZ}^2 \cdot \lambda_{WZ}^2$	$\kappa_{ZZ}^2 \lambda_{WZ}^2 \cdot \lambda_{FZ}^2$	
ZH	$\kappa_{ZZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{WZ})$	κ_{ZZ}^2	$\kappa_{ZZ}^2 \cdot \lambda_{WZ}^2$	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2$	

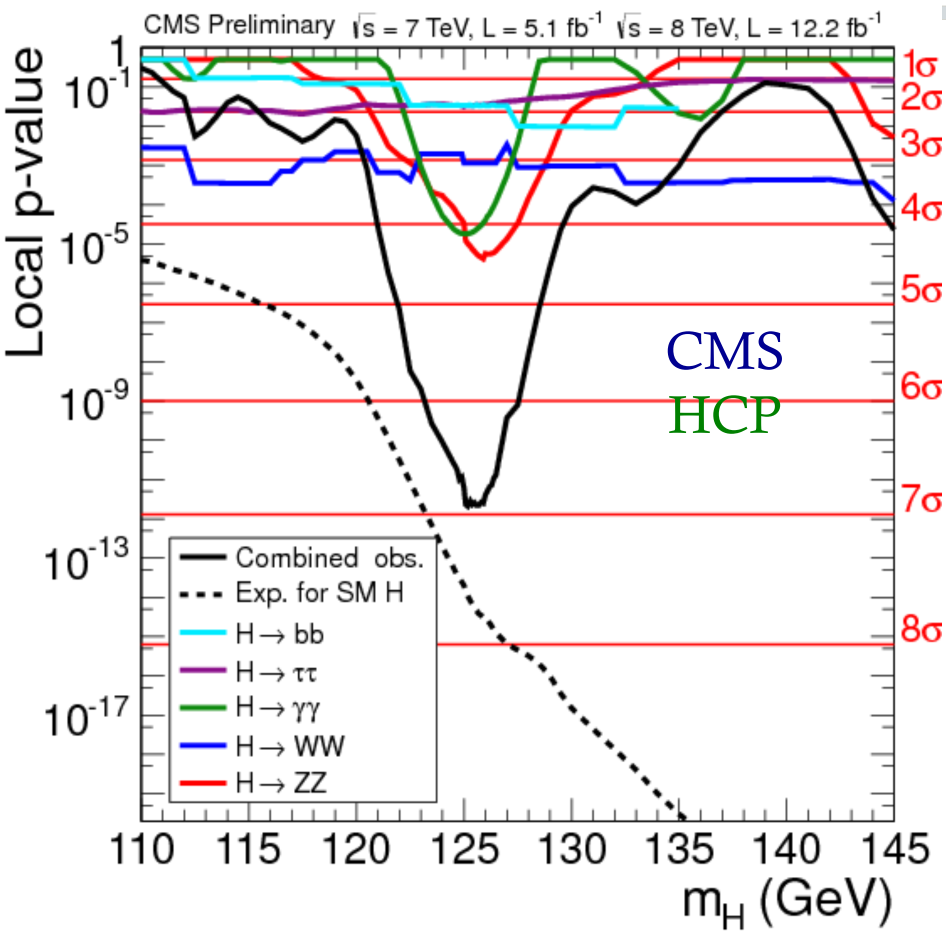
Custodial Symmetry $\lambda_{WZ} = k_W/k_Z$

- Move to fit of RATIOs (can relax assumption on total width)
  - $\lambda_{WZ} = \kappa_W/\kappa_Z$
  - Two additional parameters λ_{FZ} κ_{ZZ} in the fit but with small correlation with λ_{WZ}
  - dominated by relative WW and ZZ yields and by BRγγ that scales mainly as κ_W^2





Combination of Higgs Results



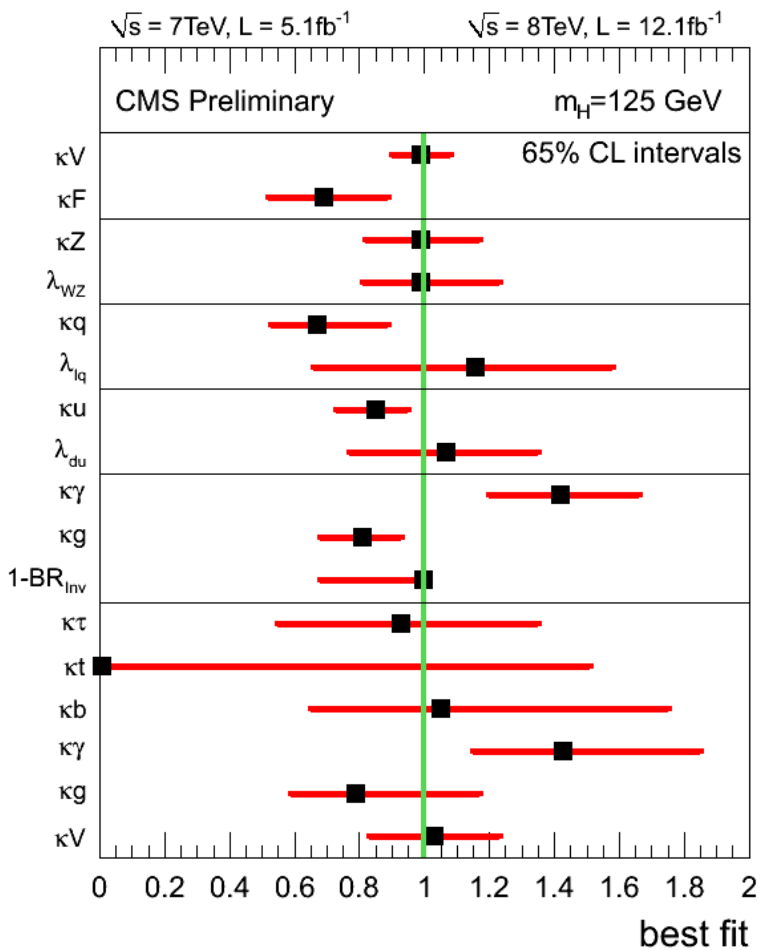
Signal Strength μ
ATLAS HCP

Higgs Boson Decay	μ (m_H=126 GeV)
$H \to ZZ^{(*)}$	1.2 ± 0.6
$H \to \gamma\gamma$	1.8 ± 0.5
$H \to WW^{(*)}$	1.4 ± 0.6
$H \to \tau\tau$	0.7 ± 0.7
$VH \to Vbb$	-0.4 ± 1.1

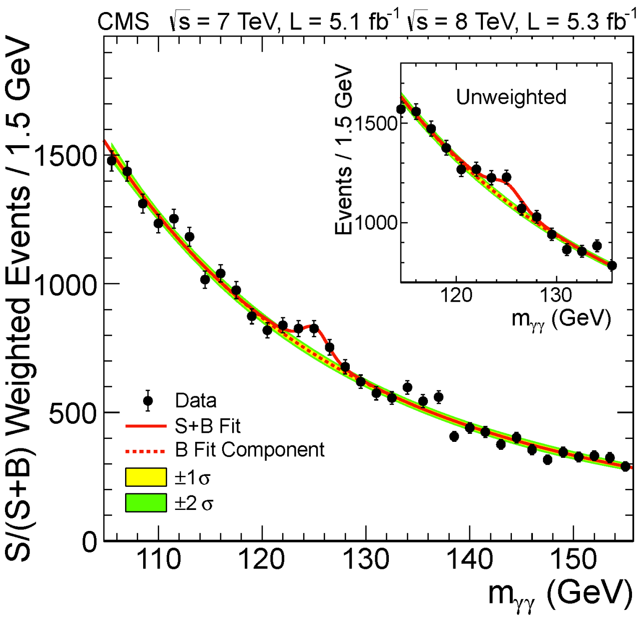
observed: 6.9; expected: 7.8

Couplings summary CMS

- Overall good compatibility with SM predictions



Model parameters	Assessed scaling factors (95% CL intervals)	
λ_{wz}, κ_z	λ_{wz}	[0.57–1.65]
$\lambda_{wz}, \kappa_z, \kappa_f$	λ_{wz}	[0.67–1.55]
κ_V	κ_V	[0.78–1.19]
κ_f	κ_f	[0.40–1.12]
κ_γ, κ_g	κ_γ	[0.98–1.92]
	κ_g	[0.55–1.07]
$\mathcal{B}(H \to BSM), \kappa_\gamma, \kappa_g$	$\mathcal{B}(H \to BSM)$	[0.00–0.62]
$\lambda_{du}, \kappa_V, \kappa_u$	λ_{du}	[0.45–1.66]
$\lambda_{\ell q}, \kappa_V, \kappa_q$	$\lambda_{\ell q}$	[0.00–2.11]
$\kappa_V, \kappa_b, \kappa_\tau, \kappa_t, \kappa_g, \kappa_\gamma$	κ_V	[0.58–1.41]
	κ_b	[not constrained]
	κ_τ	[0.00–1.80]
	κ_t	[not constrained]
	κ_g	[0.43–1.92]
	κ_γ	[0.81–2.27]



Clear evidence in mass spectra of ZZ*→ 4ℓ and γγ channels !