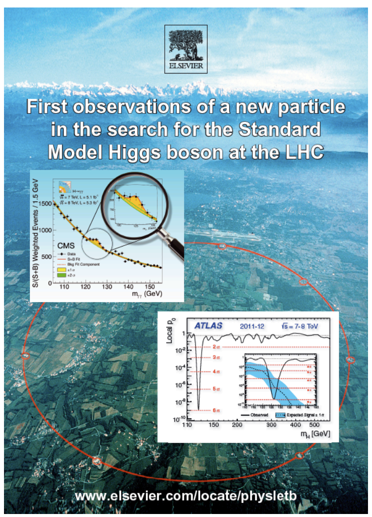
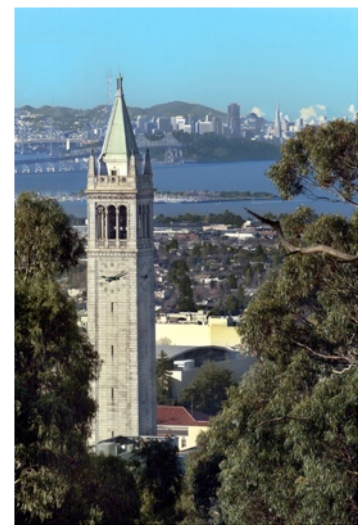
Higgs Boson properties status and prospects



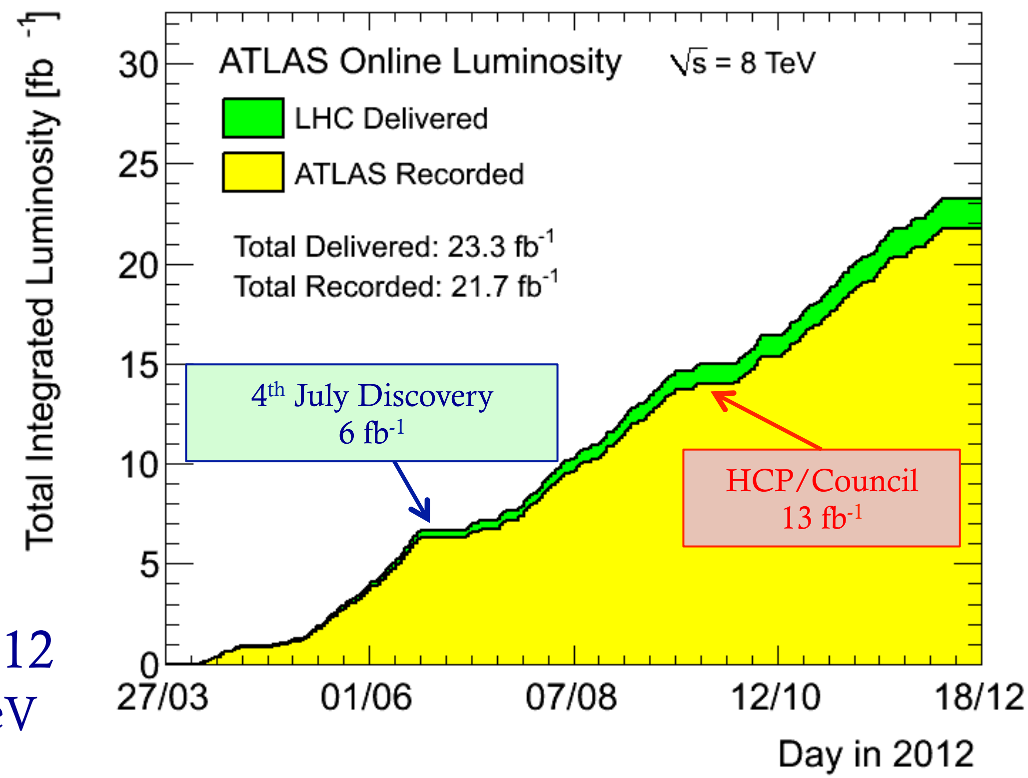
Fabio Cerutti – LBNL



Outline

- Current SM Higgs results at LHC:
  - Higgs properties: including *latest* (HCP+Council) results
    - Mass, Spin/CP and Couplings
- Prospects for measurement of properties
  - High Luminosity-LHC: Couplings (Mass and Spin/CP in backup)
  - Comparison with future e^+e^- colliders
- Conclusions

LHC 2012 operation



Excellent LHC performance in 2012

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

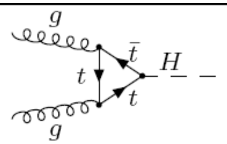
$L_{integrated}$ ~ 23 fb^{-1} delivered

Total 2011-2012 ~ 29 fb^{-1} delivered

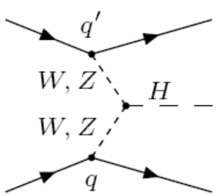
>90% will end up in physics results

SM Higgs Boson Production and Decay at LHC

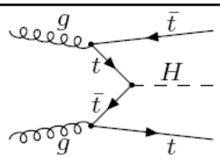
Higgs boson production at LHC



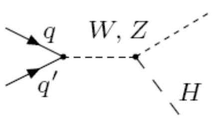
Gluon-Fusion
$(gg \to H)$
Loop – Top coupling
BSM contribution ?



VBF
$(qq\ H)$
Tree level **W(/Z) V coupling**



$t\bar{t}H$
Tree level **top coupling**



WH
Tree level **W coupling**

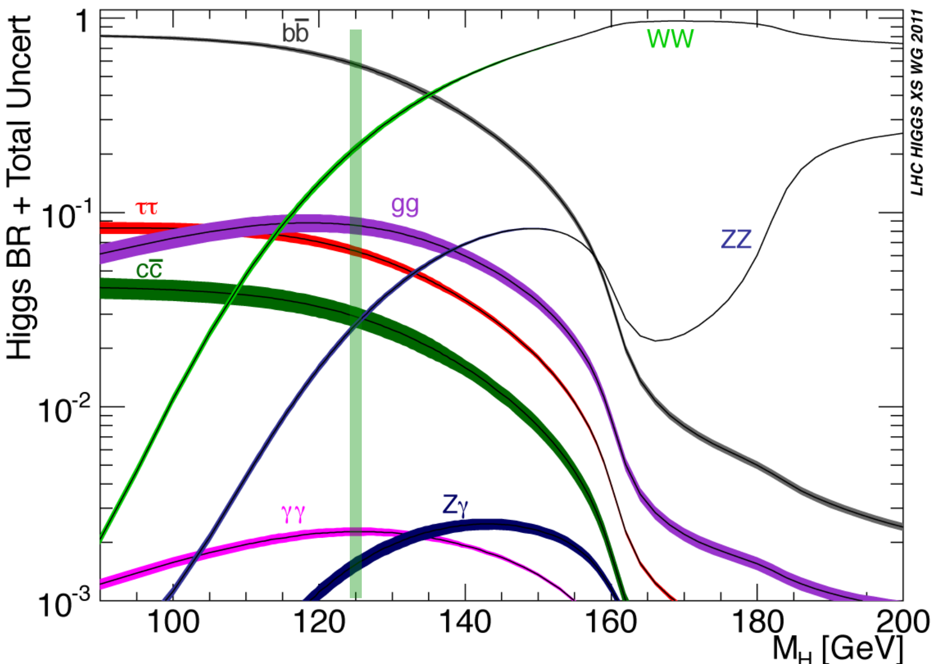
ZH
Tree level **Z coupling**

8 TeV

M_H(125 GeV)	σ(fb)	$\delta(th)_{TOT}$	δσ/δM(.5GeV)
ggH	19.5 x 10^3	**11-15%**	0.8%
VBF	1.58 x 10^3	3%	0.4%
WH	697	4%	1.3%
ZH	394	5%	1.3%
ttH	130	**11-14%**	1.9%

- Cross-sections are LARGE: LHC **is** the first Higgs Factory → Produced H~600k/Exp.
- Theory systematics more relevant for ggH and ttH - Mass dependency very weak

Higgs boson decay at LHC



M_H=125 GeV

Process	Branching ratio	Uncertainty	
$H \to bb$	5.77 x 10-1	+3.2%	-3.3%
$H \to \tau\tau$	6.32 x 10-2	+5.7%	-5.7%
$H \to \mu\mu$	2.20 x 10-4	+6.0%	-5.9%
$H \to cc$	2.91 x 10-2	+12.2%	-12.2%
$H \to gg$	8.57 x 10-2	+10.2%	-10.0%
$H \to \gamma\gamma$	2.28 x 10-3	+5.0%	-4.9%
$H \to Z\gamma$	1.54 x 10-3	+9.0%	-8.8%
$H \to WW$	2.15 x 10-1	+4.3%	-4.2%
$H \to ZZ$	2.64 x 10-2	+4.3%	-4.2%
Γ_H [GeV]	4.07 x 10-3	+4.0%	-3.9%

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

Mass dependency:

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

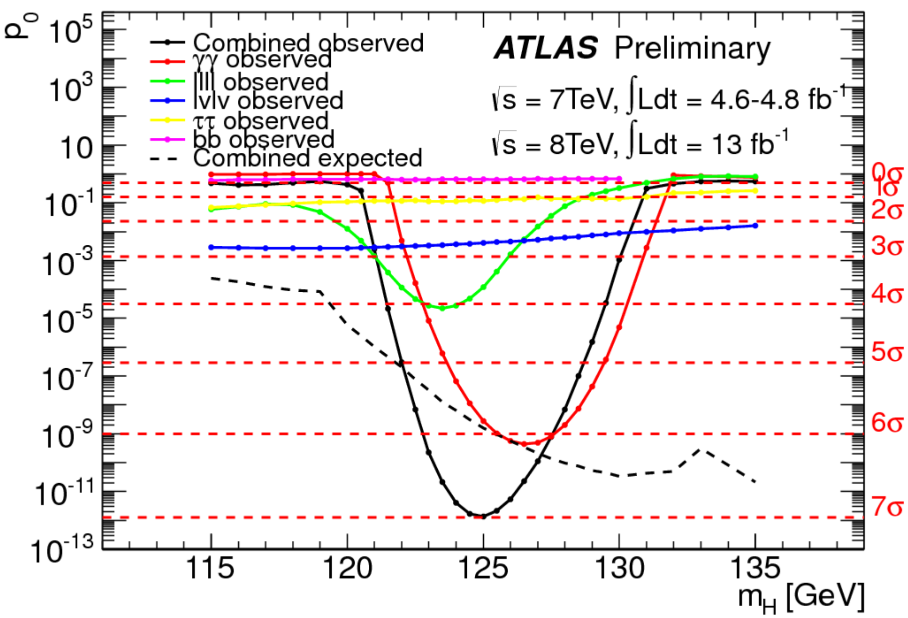
SM Higgs Boson
ATLAS and CMS
current results

Latest results 5 “main” channels

γγ, ZZ*→ 4ℓ, WW*→ℓνℓν, ττ, Vbb

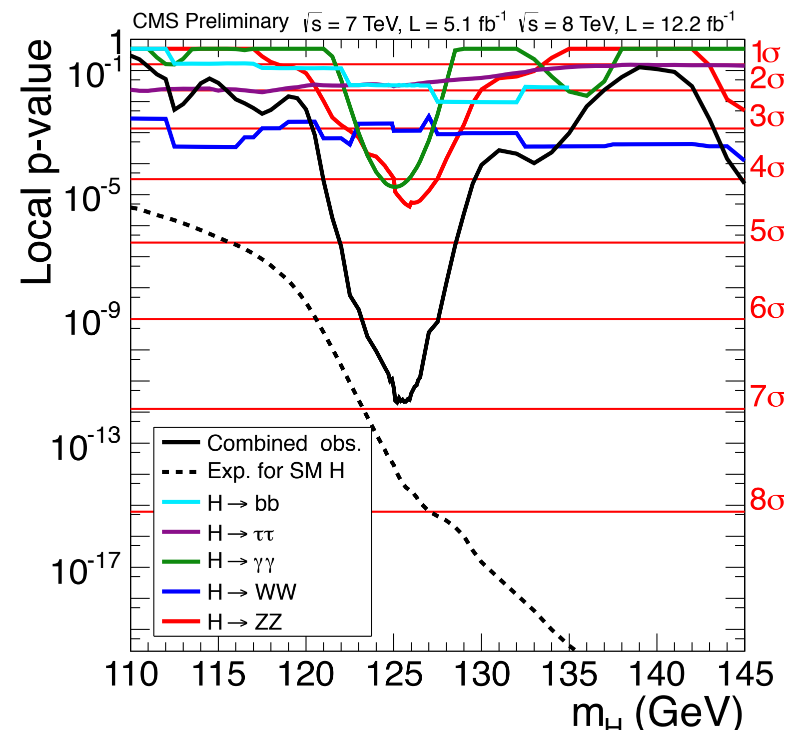
ATLAS

γγ, ZZ*, WW*, ττ, bb: $13 fb^{-1}$ – 2012



CMS

ZZ*, WW*, ττ, bb: $12 fb^{-1}$ 2012 γγ as PLB

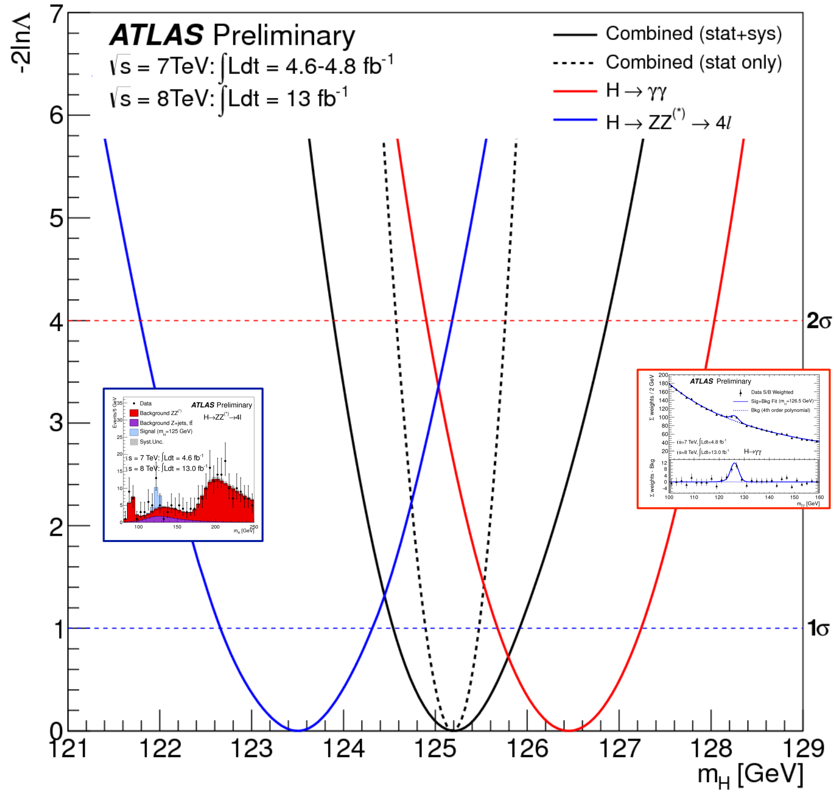


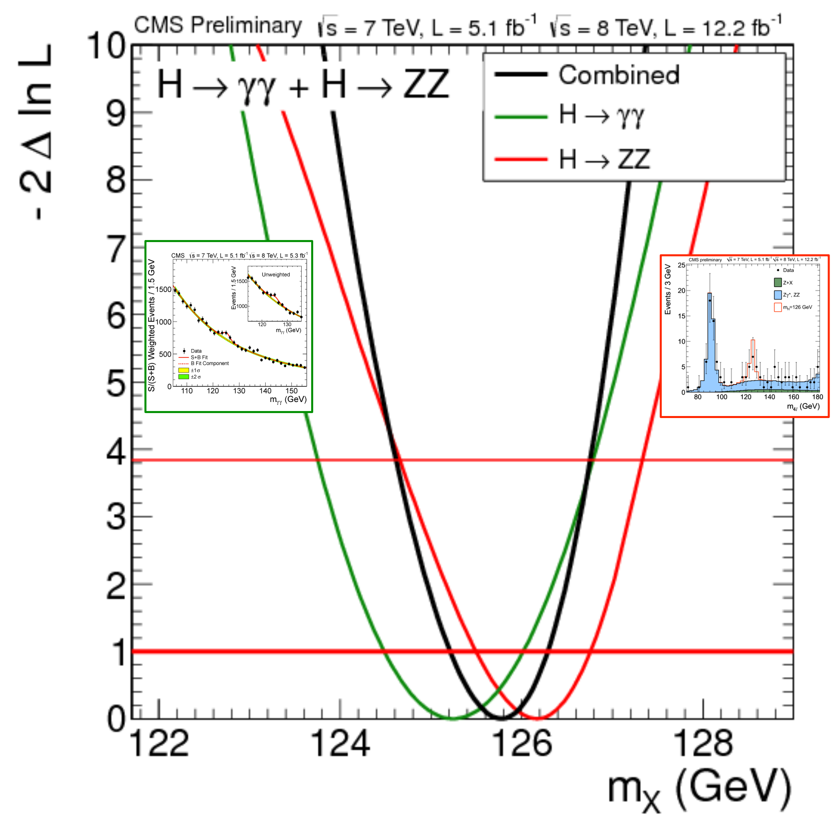
Both Experiments: ~7σ – ZZ*→ 4ℓ, WW*→ℓνℓν and γγ ~>3σ

CMS: Vbb and ττ ~2σ

Mass Measurement

Only Missing SM observable: From $\gamma\gamma$ and ZZ*(4l) mass spectrum





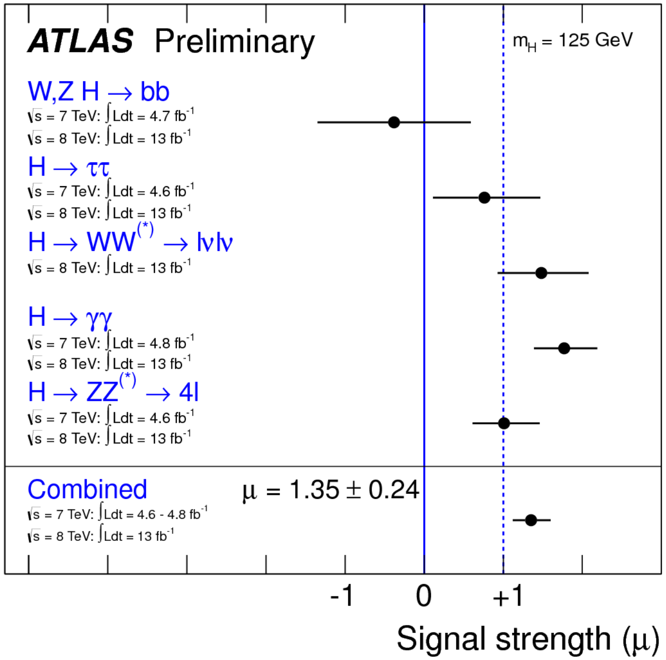
ATLAS: $M_H = 125.2 \pm 0.3_{stat} \pm \mathbf{0.6}_{sys}$ GeV

CMS: $M_H = 125.8 \pm 0.4_{stat} \pm \mathbf{0.4}_{sys}$ GeV

Signal strength $\mu = \sigma BR / \sigma BR_{SM}$

ATLAS

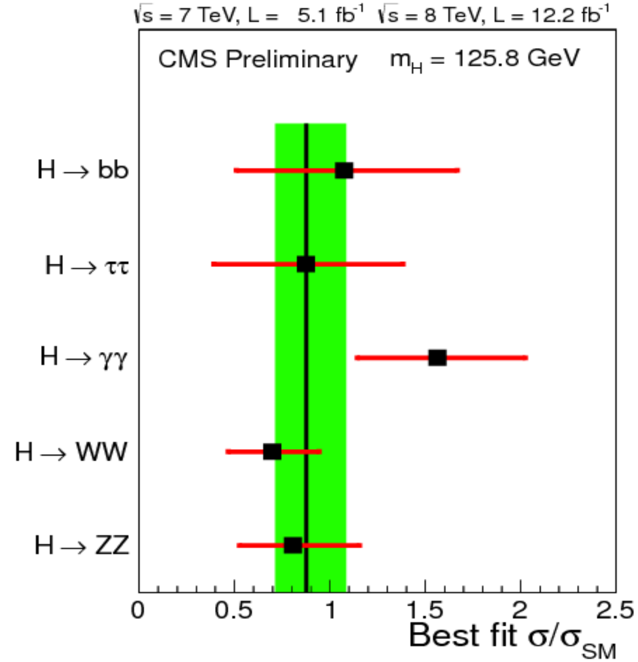
ZZ*, WW*, γγ, ττ, bb: $13 fb^{-1}$ – 2012



ATLAS $\mu = 1.35 \pm 0.24$

CMS

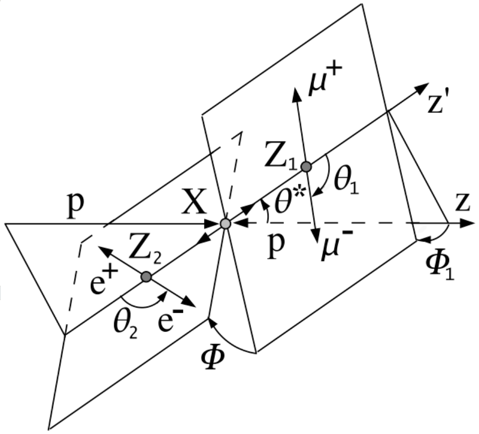
ZZ*, WW*, ττ, bb: 12 fb^{-1} 2012 γγ as PLB



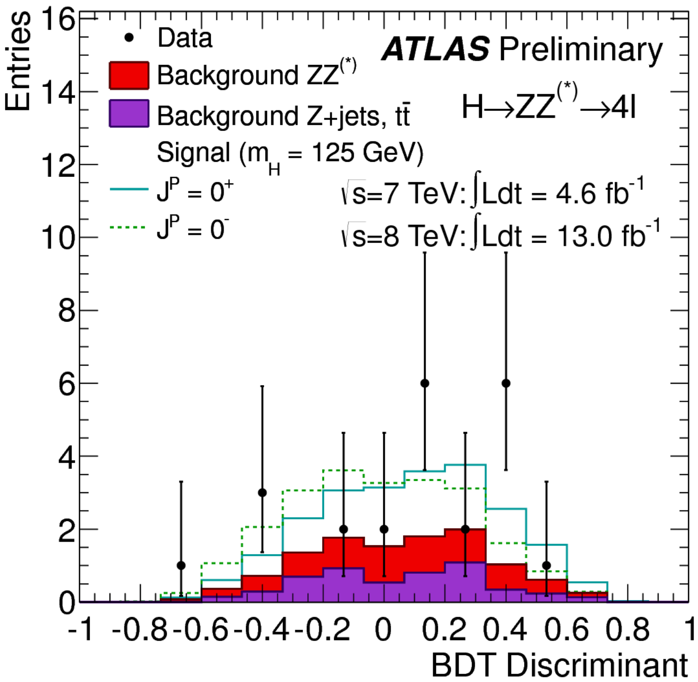
CMS $\mu = 0.88 \pm 0.21$

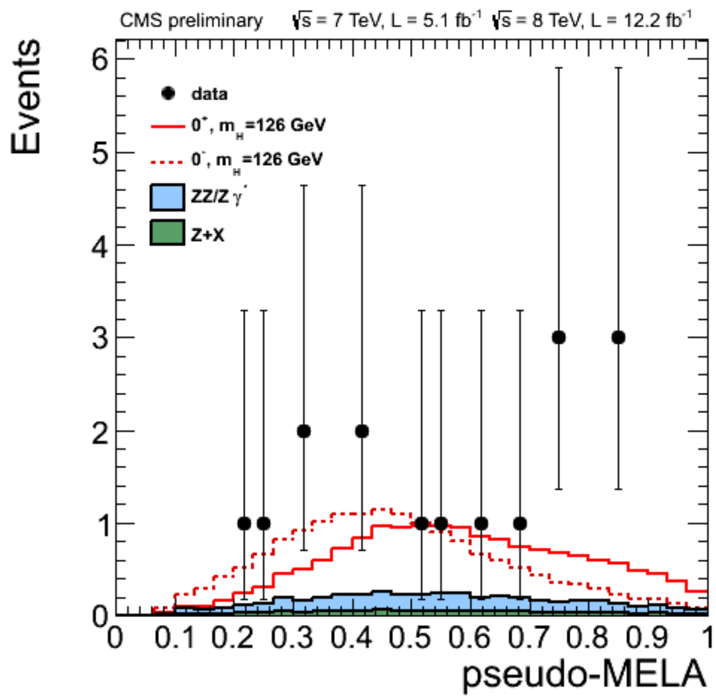
Agreement with SM prediction (and CMS/ATLAS) Precision already ~20%

Spin/CP



- $ZZ^* \to 4\ell$ sensitive to Spin and CP properties
  - Complete set of kinematic variables (8)
  - CMS: Combined in a ME-based discriminant: pseudo-MELA
  - ATLAS: Two methods used a) MVA based on BDT + b) pseudo-MELA

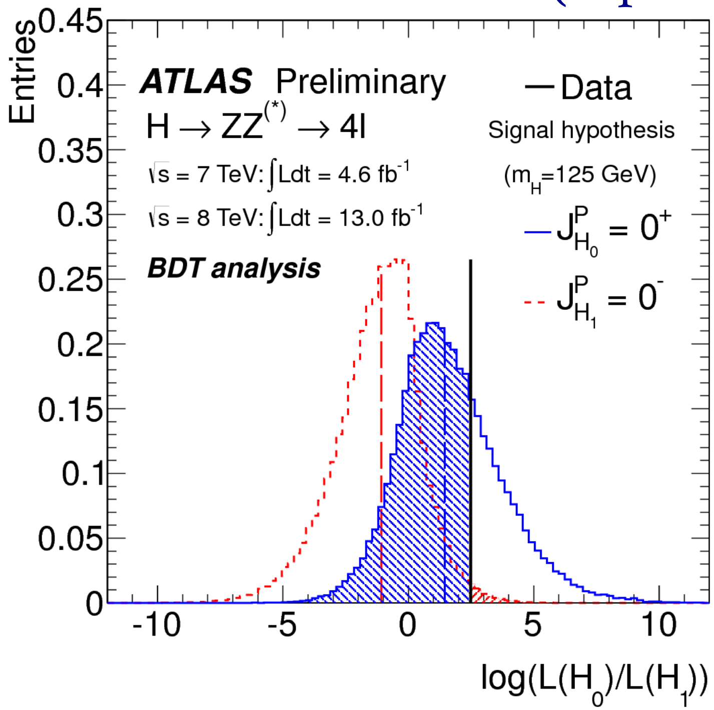




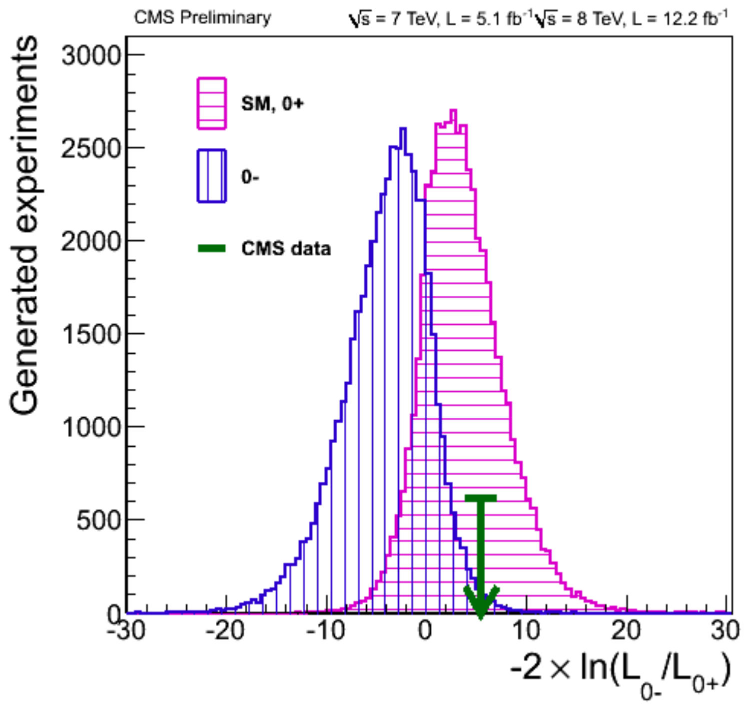
Spin/CP

ZZ* → 4ℓ Test Data Compatibility with 0^- vs 0^+

ATLAS: 0^- Excluded at 2.3σ (exp 1.7)



CMS: 0^- Excluded at 2.5σ (exp 1.9)



*Results on 0^+ vs Spin 2 models in Backup: in general 0^+ favored

The Couplings fit

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

Production modes: gg, VBF, W/ZH, ttH + Final states: $\gamma\gamma$, WW, ZZ, bb, $\tau\tau$, Zγ, $\mu\mu$

- 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 (test 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

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

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

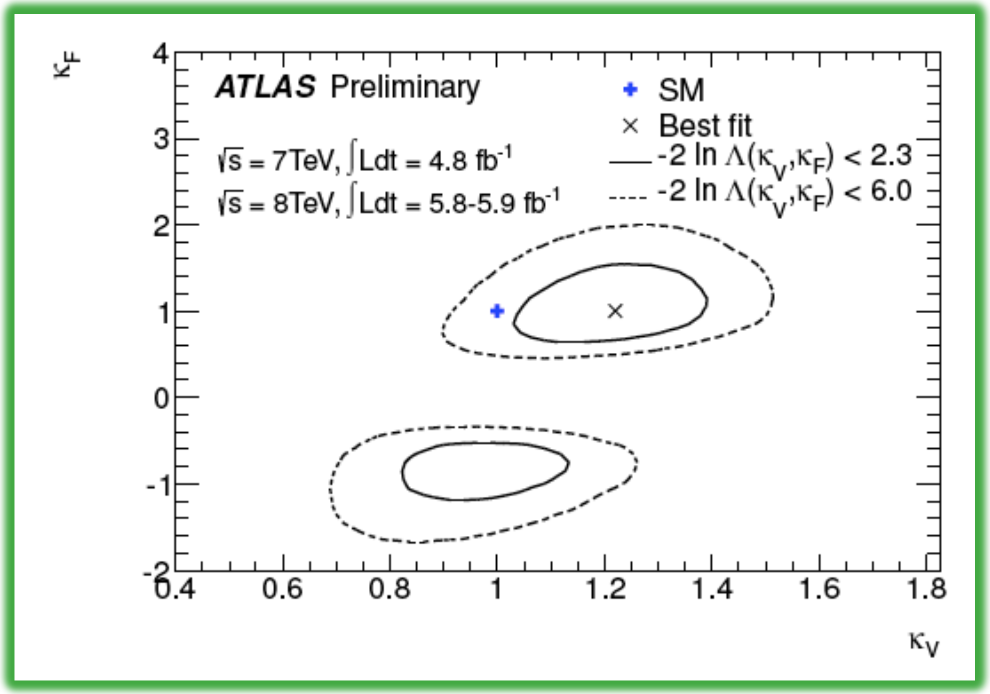
$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$

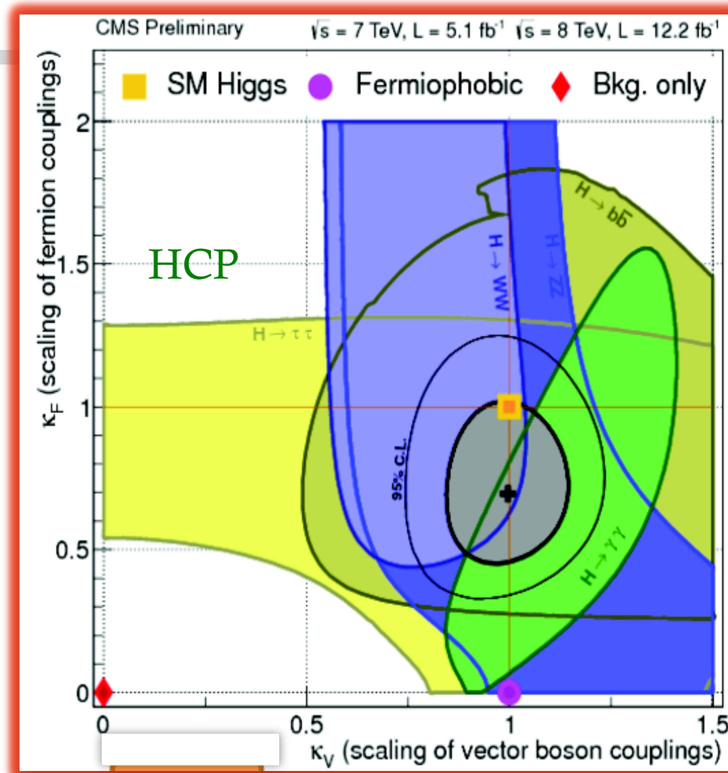
$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

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

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

κ_F vs κ_V fit





- Assumption only SM particles in $\Gamma_H \rightarrow \kappa^2_H(\kappa_F\ \kappa_V) \sim 0.7\ \kappa^2_F + 0.3\ \kappa^2_V$

  Agreement with SM tested at 20-30%
- $\kappa_F = 0$ (Fermiophobic Higgs) Excluded at (much) more than 3σ

Higgs Boson properties: High Luminosity LHC and future e^+e^- colliders

High Luminosity LHC: The timeline

2009		✧ LHC startup, $\sqrt{s}$ = 900 GeV	
2010–2012		$\sqrt{s}$=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns	✔ Done ~20-25 fb^{-1}
2013–2014	LS1	Go to design energy, nominal luminosity (Phase-0)	
2015–2017		$\sqrt{s}$=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns	~75-100 fb^{-1}
2018	LS2	Injector and LHC Phase-I upgrade to full design luminosity	
2019–2021		$\sqrt{s}$=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns	Approved 300 fb^{-1} at 14 TeV
2022	LS3	HL-LHC Phase-II upgrade, IR, crab cavities	
2023 … 2030?		$\sqrt{s}$=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity levelling	HL-LHC: 3000 fb^{-1} at 14 TeV

Couplings at HL-LHC: CMS

- Mainly based on extrapolation of current analyses plus dedicated **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 ..)
- $ZZ^*\to 4\ell$ and γγ and μμ channels: Scenario 2 ~realistic from Exp. Point of view
- ττ, bb, WW: Experimental systematics on backgrounds dominant, data driven but need extrapolation to signal region …

Couplings fit at HL-LHC

CMS

Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 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

✓ Loop couplings: γγ at 2-5% level + gg at 3-8% level

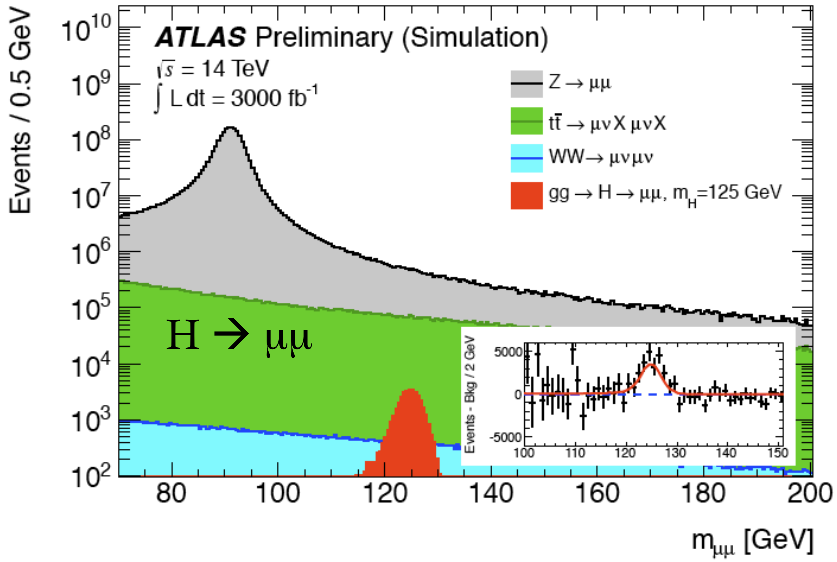
✓ down-type fermion couplings at 2-10% level

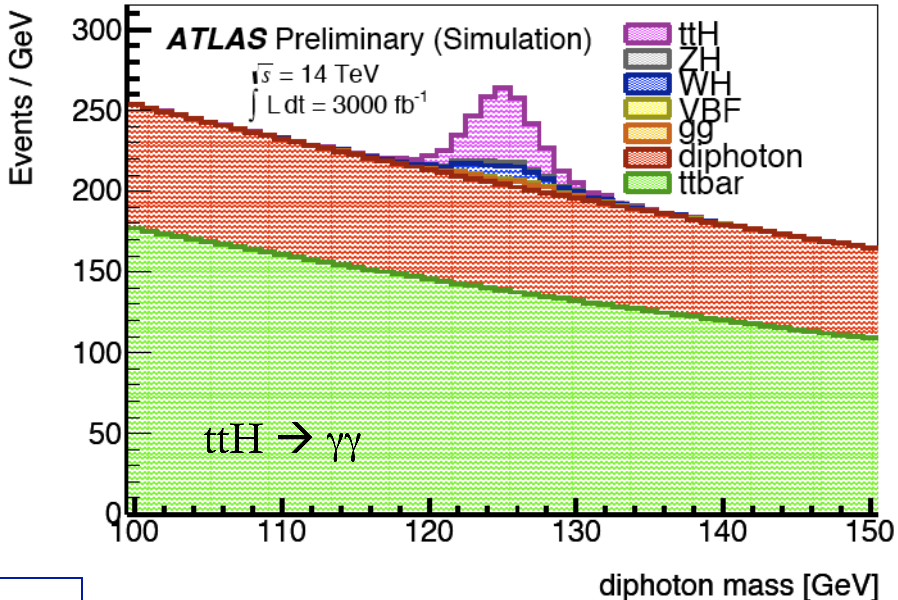
✓ direct top coupling at 4-8% level

Couplings at HL-LHC: ATLAS

- MC Samples at 14 TeV from dedicated HL Fast-Simulation: estimate of physic objects dependency on pile-up
  - Validated with full-sim. up to μ~50
- In addition to "current" analyses dedicated HL ones:
  - **ttH → γγ** Direct top Y coupling
  - **H → μμ** Second generation F coupling
  - **HH→ bbγγ** Higgs Self-Couplings

κ_μ and κ_t Coupling at HL-LHC





Narrow mass peak over Z/DY backg.

ATLAS and CMS >5σ/Exper.

μ~20%/Exper. → κ_μ at **10%/Exper**

Very Robust channel
Good S/B
With 3000 fb^{-1}
Measure κ_t at **10%/Eper.**

Higgs self-couplings λ_{HHH}

- Need to distinguish between HH production via H or V (**negative** interference)
  - CMS: HH → $bb\gamma\gamma$ or HH → $bb\mu\mu$ (HE-LHC)
  - ATLAS: HH → $bb\gamma\gamma$ (under study HH → $bb\tau\tau$)
- Example ATLAS analysis $bb\gamma\gamma$ − 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: ~1.6σ significance for λ_{HHH}=1 → 2 Experiments ~2.2σ
- Only one channel and very simple CUT-based analysis:

we can do better

HL-LHC summary

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

- Mass: <100 MeV (statistical)
- Coupling κ rel. precision*
  - 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:

- Mass: ~ <50 MeV (statistical)
- Couplings κ rel. precision*
  - Z, W, b, τ, t, μ 2-10%
  - γγ and gg 2-5%
  - H→HH >2-3 σ obs. (2 Exper.)

**Assuming sizeable (1/2) reduction of theory errors*

"QCD scale" go to Higher order QCD computation ?

gg "PDF" from LHC data ?

Mass Measurement:

Several exp./theory challenges to reach 50 MeV (e/γ/μ calibration E-scale, Interference, FSR, ..)

More details on analyses backup slides

Higgs Properties at e^+e^- L/C colliders

More details Higgs factories: linear vs circular collider FERMILAB

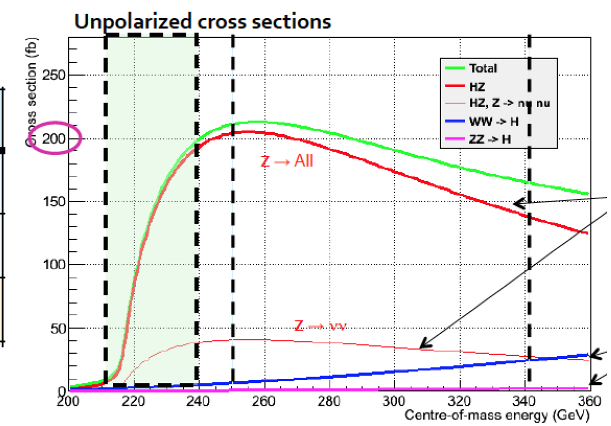
https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=5775

- Options for **Higgs factory** at E_{CM} ~250GeV Threshold M_H+M_Z

$\sigma(e^+e^- \rightarrow ZH)_{Max}$~0.2 pb t.b.c. with ~60pb at LHC-14 TeV

- Machine related issues discussed in next talks by John and Jean-Pierre

Patric Janot	ILC	LEP3	TLEP
Lumi / IP / 5 yrs	250 fb^{-1}	500 fb^{-1}	2.5 ab^{-1}
# IP	1	2 - 4	2 - 4
Lumi / 5 years	0.25 ab^{-1}	1 - 2 ab^{-1}	5 - 10 ab^{-1}



Higgs Precision measurements at e^+e^- colliders

Patric Janot	ILC	LEP3 (4)	TLEP (4)
σ_{HZ}	2.5%	1.3%	0.4%
BR(H→bb)	2.7%	1.4%	0.5%
BR(H→cc)	7.3%	4% (*)	1.4%
BR(H→gg)	8.9%	4.5% (*)	1.5%
BR(H→WW*)	8.6%	3.0%	1.0%
BR(H→ττ)	7.0%	3.0%	0.9%
BR(H→ZZ*)	21%	7.1%	3.1%
BR(H→γγ)	30%	6.8%	3.0%
BR(H→μμ)	–	28%	13%
$\sigma_{WW\to H}$	12%	5% (*)	2.2%
Γ_H, Γ_{INV}	10% , < 1.5%	4% , < 0.7%	1.8% , < 0.3%
m_H	40 MeV	26 MeV	8 MeV

ILC vs HL-LHC

ILC Will Measure Γ_H, Γ_{Inv}

Higgs to everything/ H→ZZ* → 10-2%

HL-LHC competitive or better then **ILC** for:

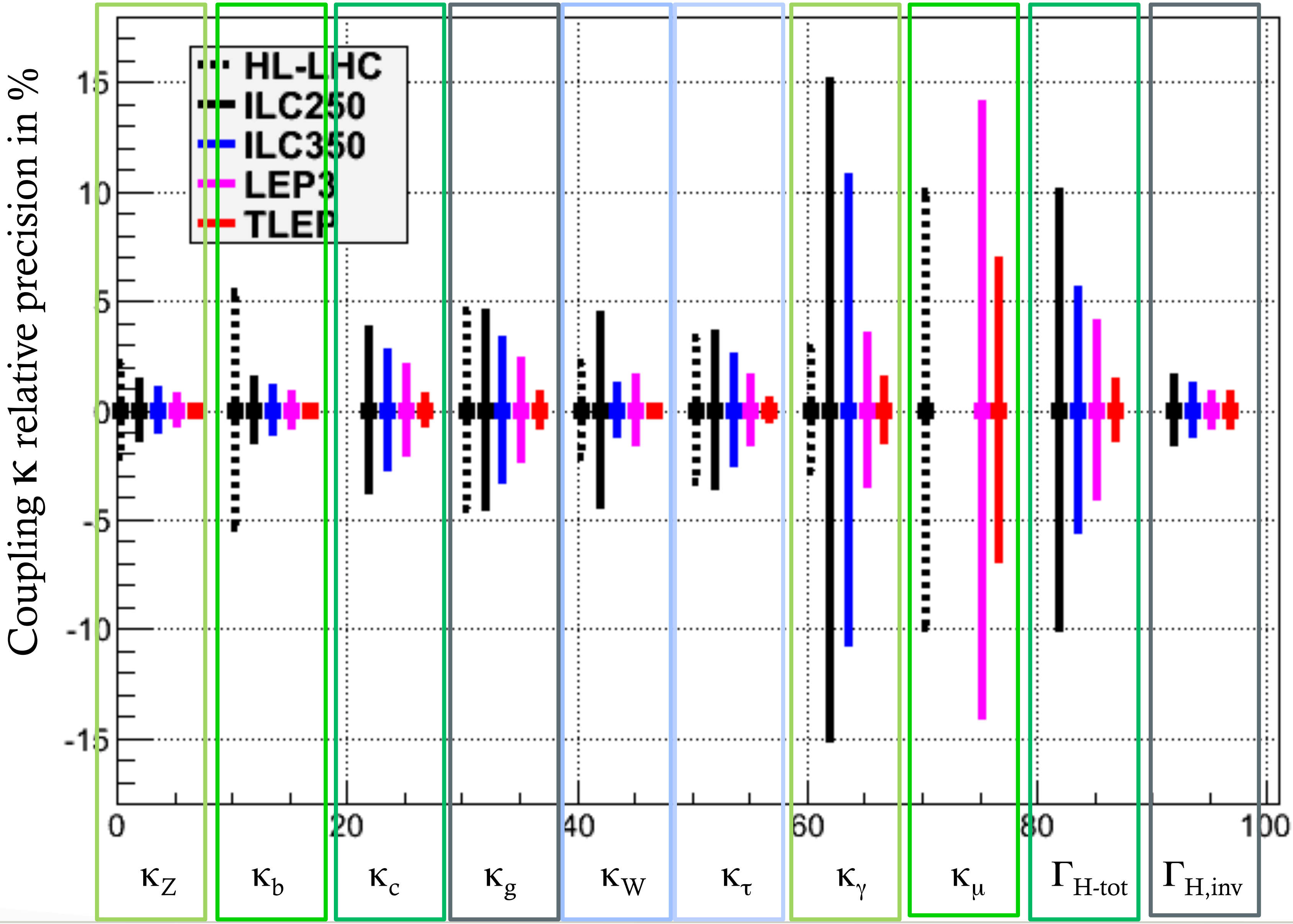
H→ γγ, H→ gg, tt-H, H→ μμ, (H→HH ?)

ILC better than **HL-LHC**:

$\Gamma_{H,inv}$, H→bb, cc, ττ

TLEP Better or similar to **HL-LHC** for all couplings but ttH

Alain Blondel – Physics overview summary talk



Conclusions

- LHC started precision measurement campaign of the *newly discovered* "SM Higgs-*like*" boson
  - Mass measured at 3 per mill level
  - Spin/CP: first studies favors 0^+ in VB final states
  - Couplings: in agreement with SM predictions
    - slight tension from ATLAS in $\gamma\gamma$ final state: updates coming soon
- HL-LHC CRUCIAL step towards *deeper understanding* of Higgs properties:
  - top coupling, second generation fermions, gg and $\gamma\gamma$ Loop-couplings sensitive to BSM physics (H self-coupling very challenging)
- Next generation e^+e^- collider (L/C) complementary to LHC:
  - $\Gamma_{\text{H-Tot}}$ $\Gamma_{\text{invisible}}$ and $\Gamma_{b,c}$
  - High Luminosity 5-10 ab^{-1} important for LARGE improvements

Backup

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

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
~ 30 fb^{-1}

LHC
Upgrade

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

results in backup slides

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

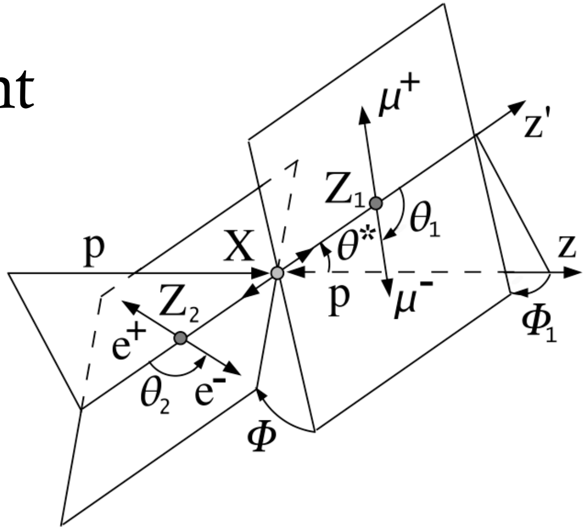
- Factor ~2 reduction on main theory errors very challenging but possible

HL-LHC mass measurement

- Mass measurement in $ZZ^* \to 4\ell$ 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 $Z \to ll$ (Huge statistics) Today 200-300 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
  - γγ decay angle cosθ*
  - WW* set of kinematic variables
  - **ZZ* complete set of kinematic variables (8)**
  - VBF production → ΔΦjj
  - VH→bb – M_{VH}



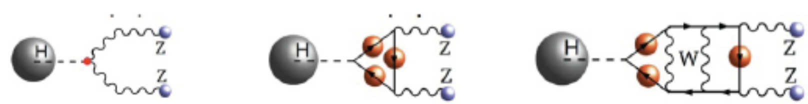
- Spin 0^+ SM all observable can be predicted:
  - Strategy: Use SM-0^+ as benchmark to test agreement with Spin/CP sensitive observables

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:

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

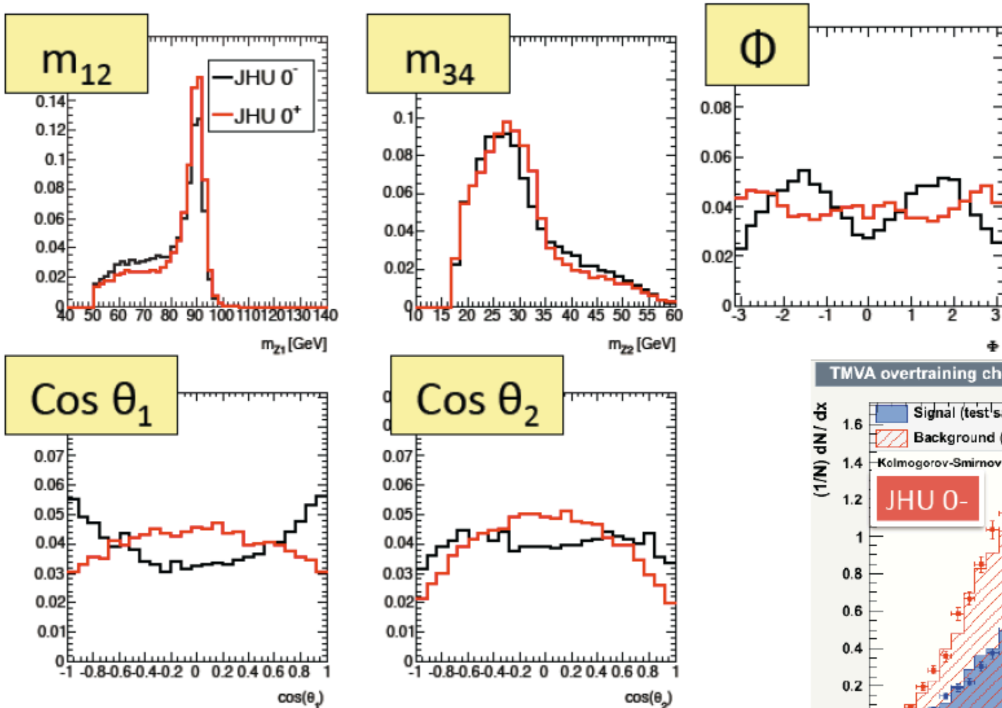
- Complex form factors a_i:

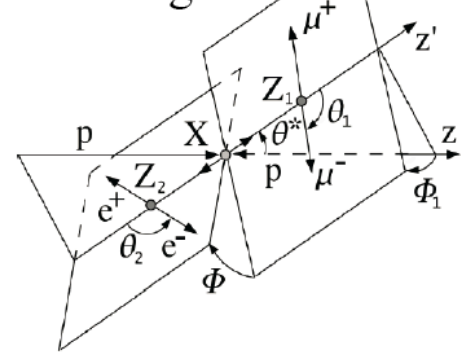


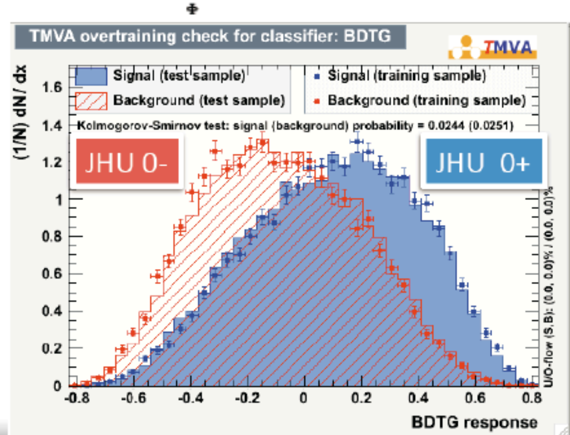
  - SM tree level a_1=1, a_2=a_3=0 –
    - Generated at loop level a_2(~few %) and a_3(~10^{-10})
- CP violation requires (a_1 OR a_2 ≠ 0) AND (a_3 ≠ 0)

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 30fb^{-1} using BDT





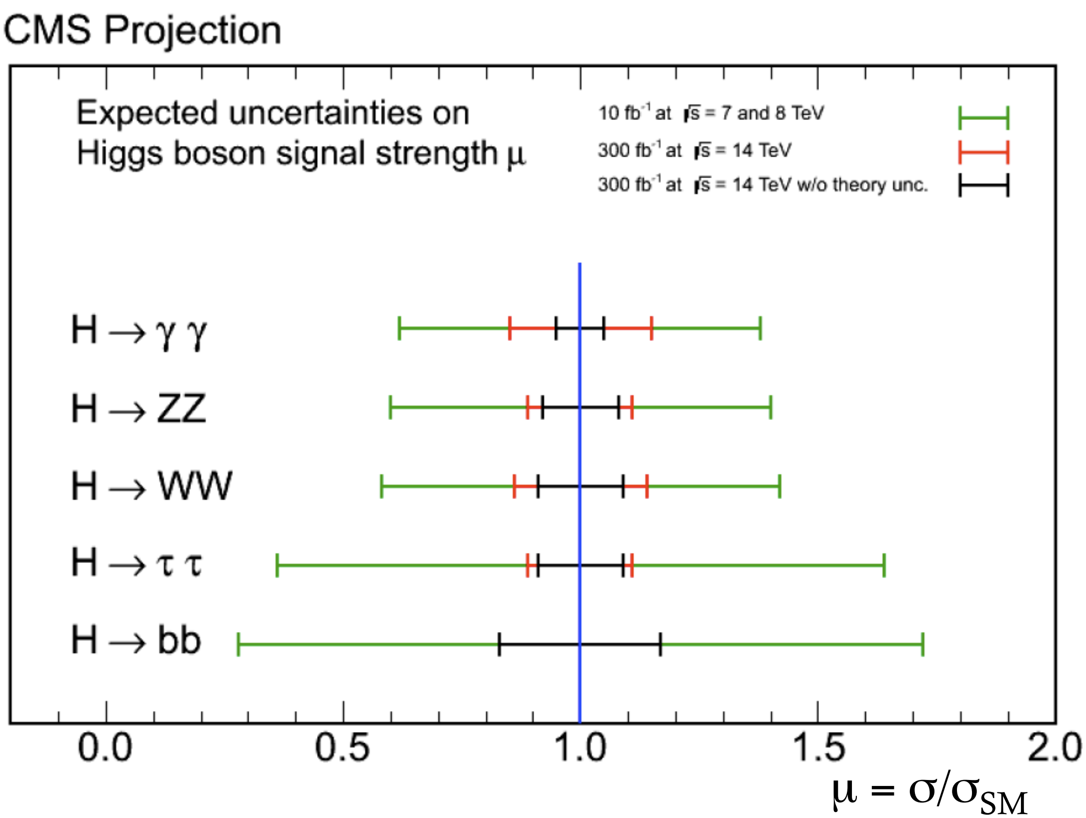


Spin/CP: ATLAS

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)

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

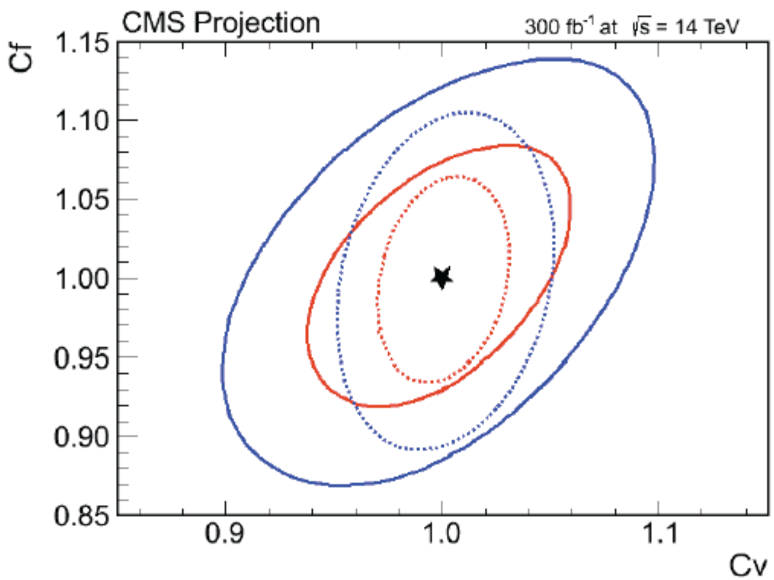
Measurements at:

μ~10-20%

κ ~5-10%

Similar results obtained by ATLAS (*backup slides*)

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

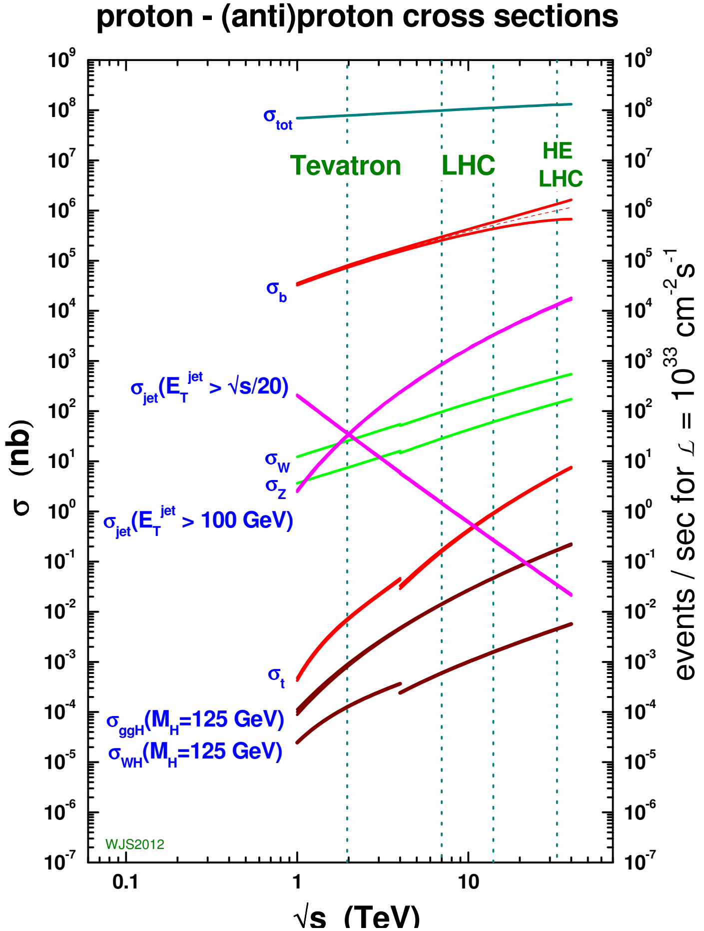
	$300\ fb^{-1}$	$3000\ fb^{-1}$
κ_V	3.0% (5.6%)	1.9% (4.5%)
κ_F	8.9% (10%)	3.6% (5.9%)

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

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

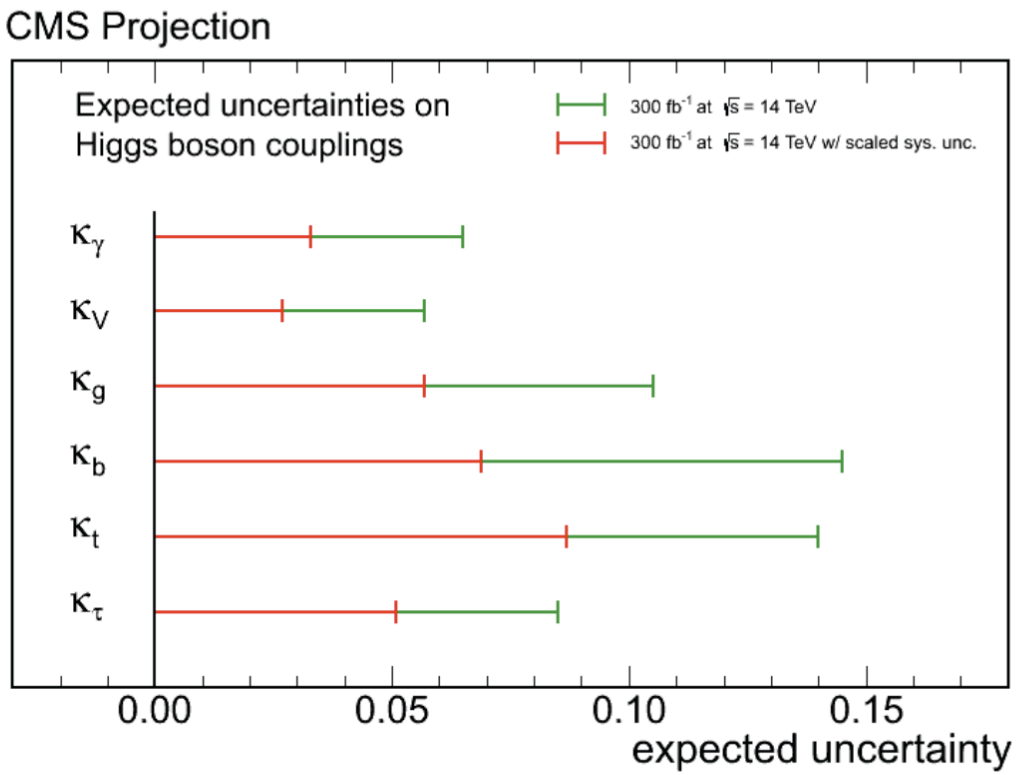


8 → 14 TeV: ggH x2.6   14 → 33 TeV: ggH→ HH x6

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 rare decays
Better signal Yields at HL-LHC
BUT Pile-up and S/B better at HE-LHC

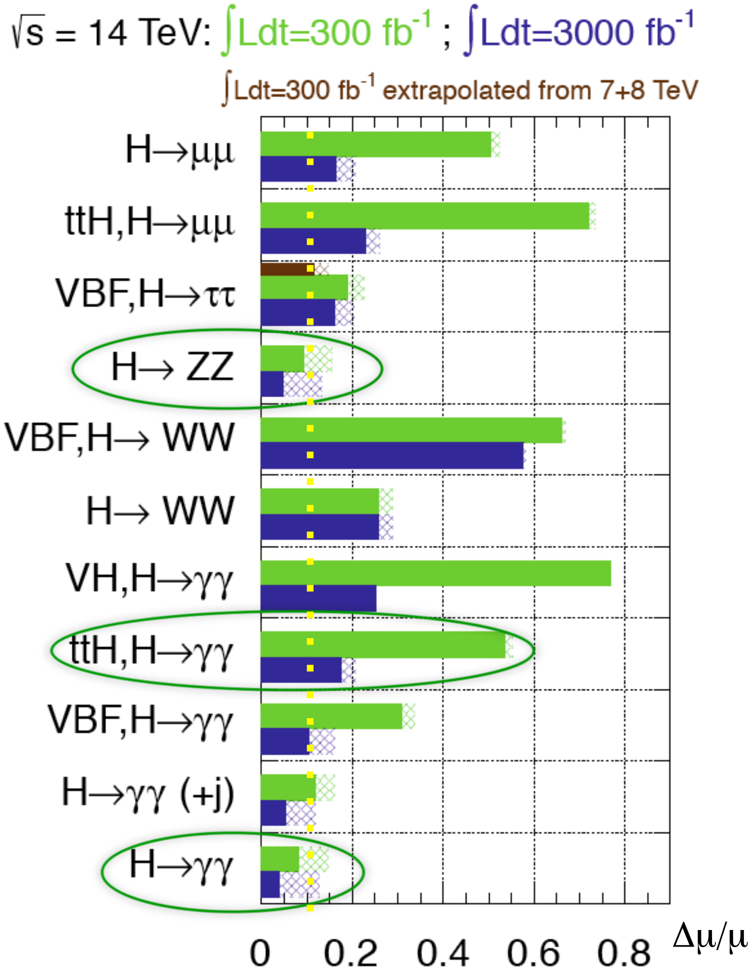
CMS studies 300 fb^{-1}



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%

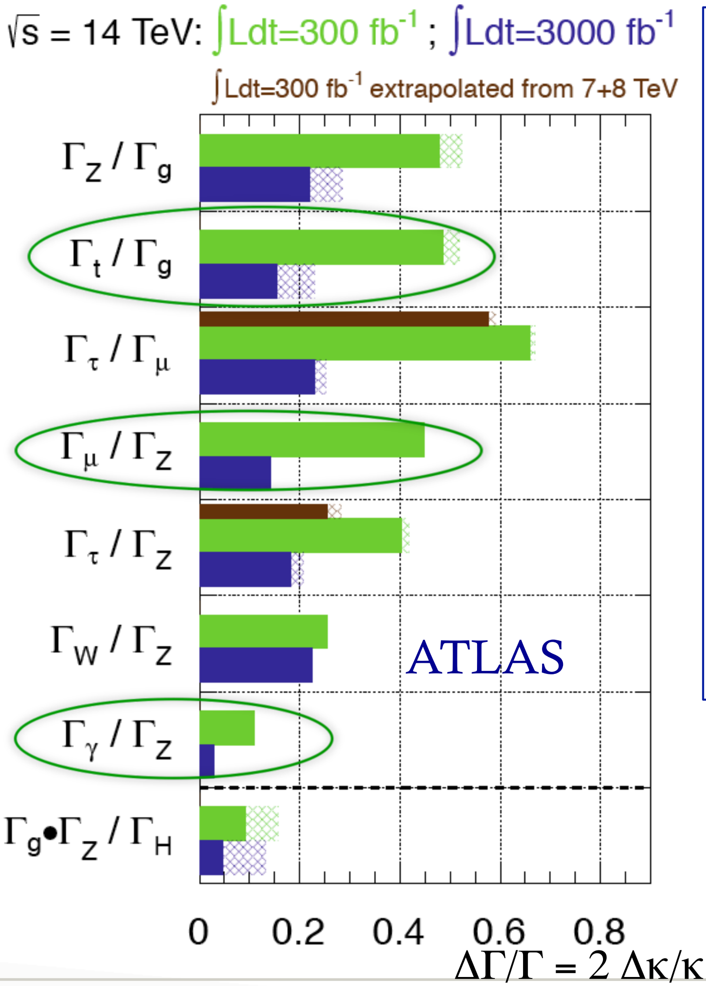
ATLAS studies: μ at HL-LHC



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)

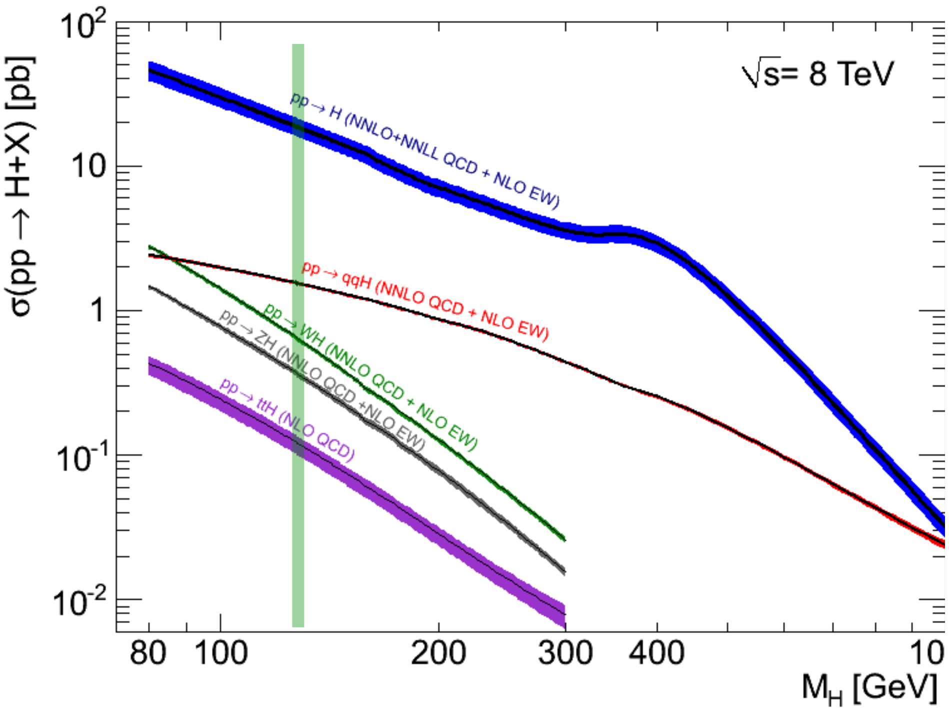
Coupling Ratios Fit at HL-LHC

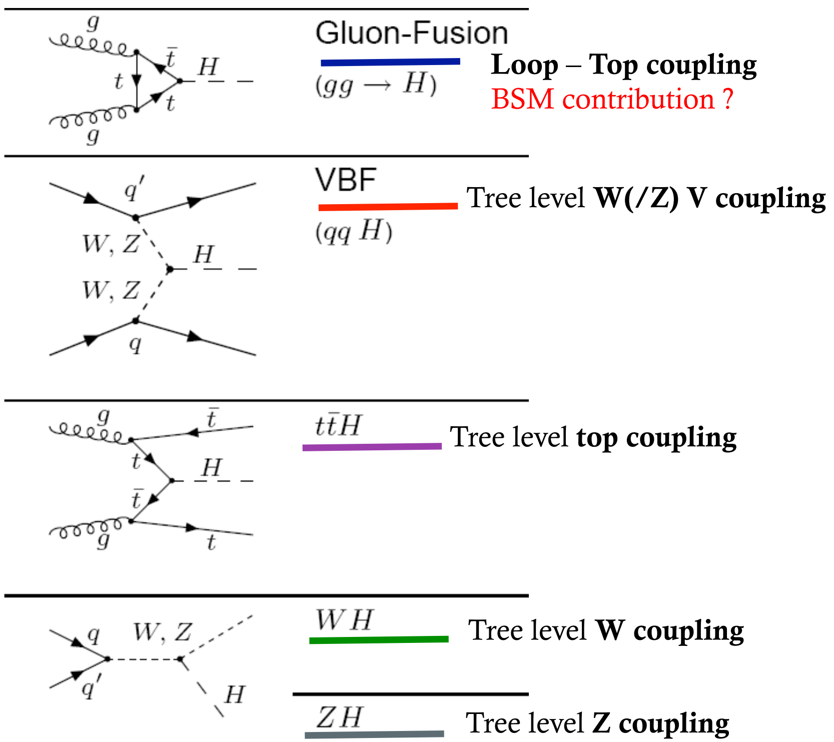


- Fit to coupling ratios:
  - No assumption BSM contributions to Γ_H
  - Some theory systematics cancels in the ratios
- Loop-induced Couplings γγ and gg treated as independent parameter (BSM)
  - κ_γ/κ_Z (γγ Loop BSM) tested at 2%
  - gg loop (BSM) κ_t/κ_g at 7-12%
  - 2nd generation ferm. κ_μ/κ_Z at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

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

Higgs boson production at LHC





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

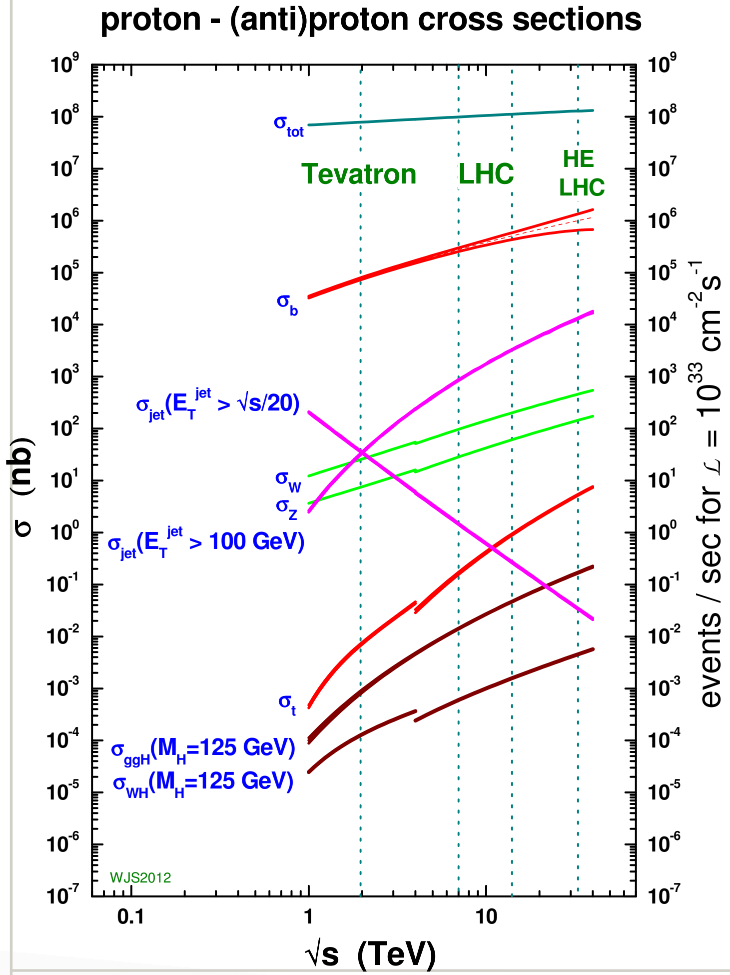
Higgs boson production at LHC

8 TeV

M_H(125 GeV)	σ(fb)	$\delta(th)_{TOT}$	$\delta(th)_{QCD\text{-}Scale}$	$\delta(th)_{PDF+\alpha s}$	δσ/δM(.5GeV)
ggH	19.5×10^3	**11-15%**	**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	**11-14%**	**7%**	**8%**	1.9%

- Cross-sections are LARGE: LHC **is** the first Higgs Factory → Produced H~600k/Exp.
- Theory systematics more relevant for ggH and ttH - Mass dependency very weak

Signal XS evolution

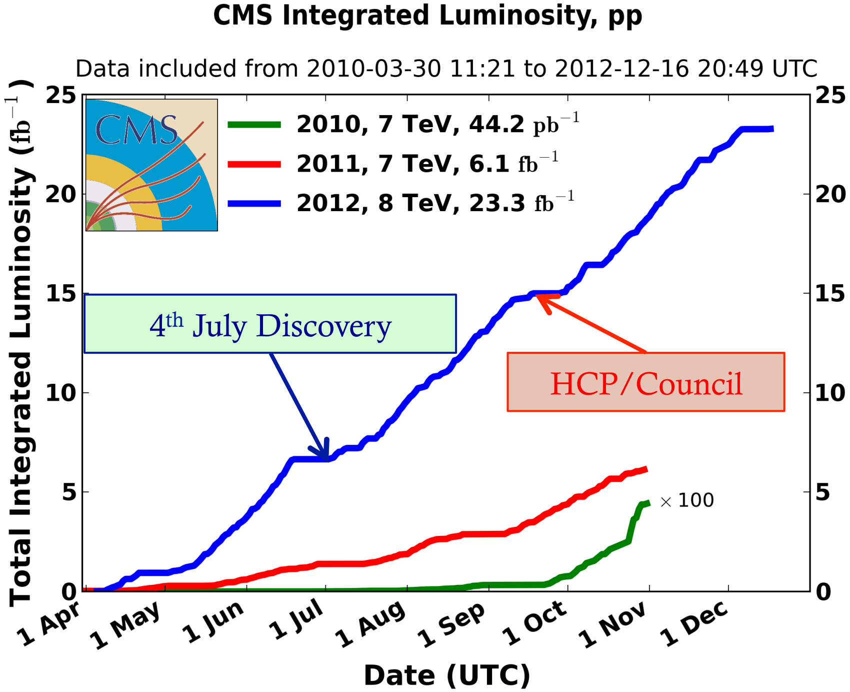


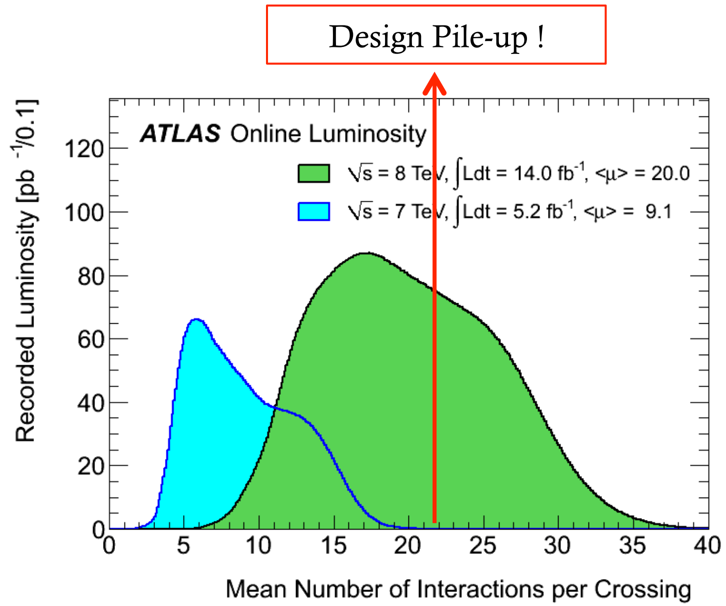
	M_H=125 GeV 14 TeV				
Process	Cross section	Scale uncertainty		PDF+α_s uncertainty	
ggF [a]	50.35 pb	+7.5%	-8.0%	+7.2%	-6.0%
VBF [b]	4.172 pb	+0.4%	-0.3%	+1.9%	-1.5%
WH [c]	1.504 pb	+0.3%	-0.6%	+3.8%	-3.8%
ZH [c]	0.8830 pb	+2.7%	-1.8%	+3.7%	-3.7%
ttH [c]	0.6113 pb	+5.9%	-9.3%	+8.9%	-8.9%

- 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

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

LHC 2012 operation !





Excellent LHC performance in 2012

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

$L_{integrated}$ ~ 23 fb^{-1} delivered

Total 2010-2012 ~ 29 fb^{-1} delivered

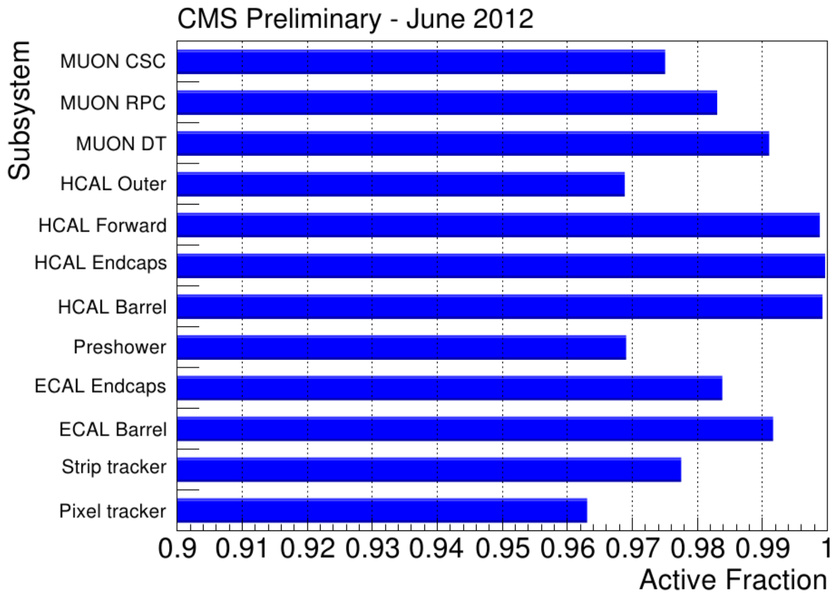
LHC operated with 50ns bunch spacing:

- 2012 pile-up conditions challenging

Detectors and LHC operation

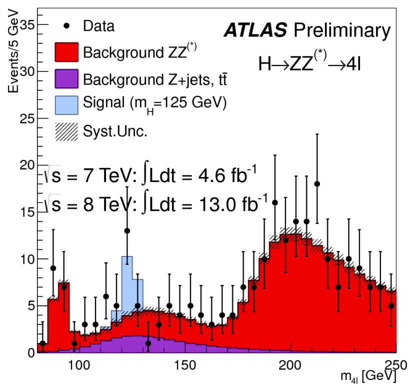
ATLAS - 2012

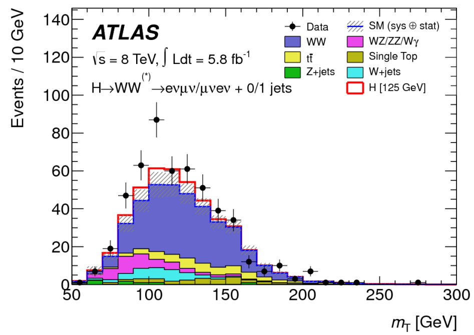
Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.0%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.9%
Tile calorimeter	9800	98.3%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo 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%

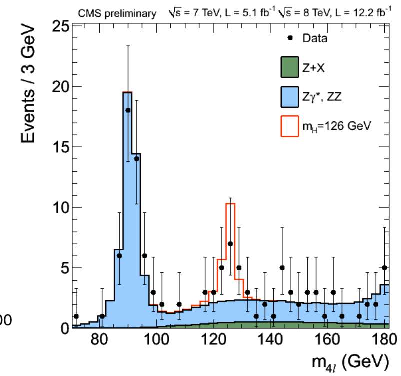


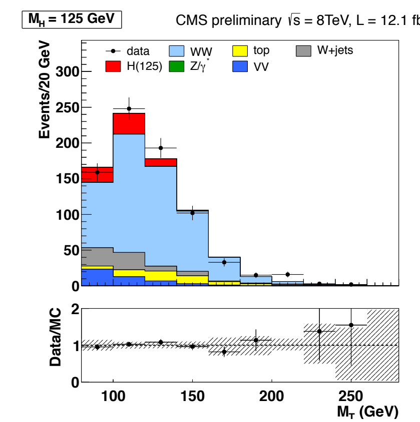
- ATLAS and CMS in very good shape: Fraction of Active Channels >96%
- 90% of delivered luminosity used in physics analysis

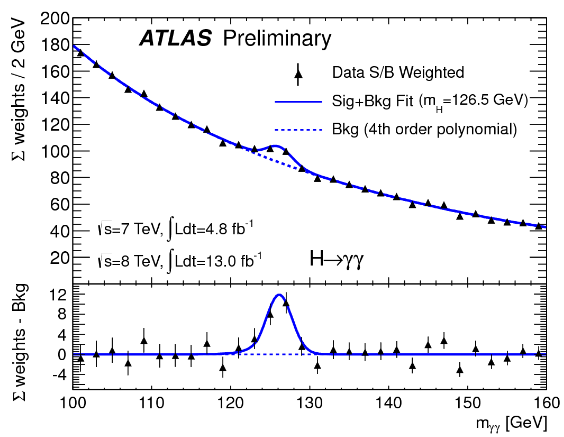
Latest HCP + Council results

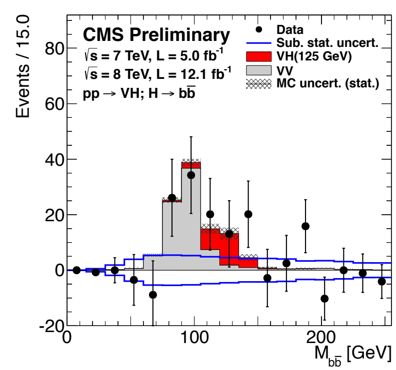


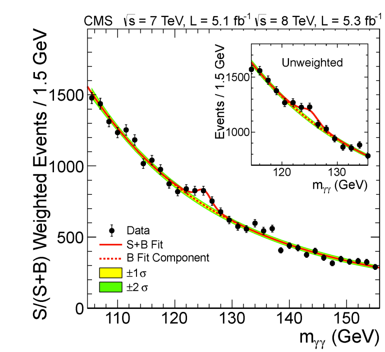












ATLAS

γγ, ZZ*, WW*, ττ, bb: 13fb^{-1} 2012

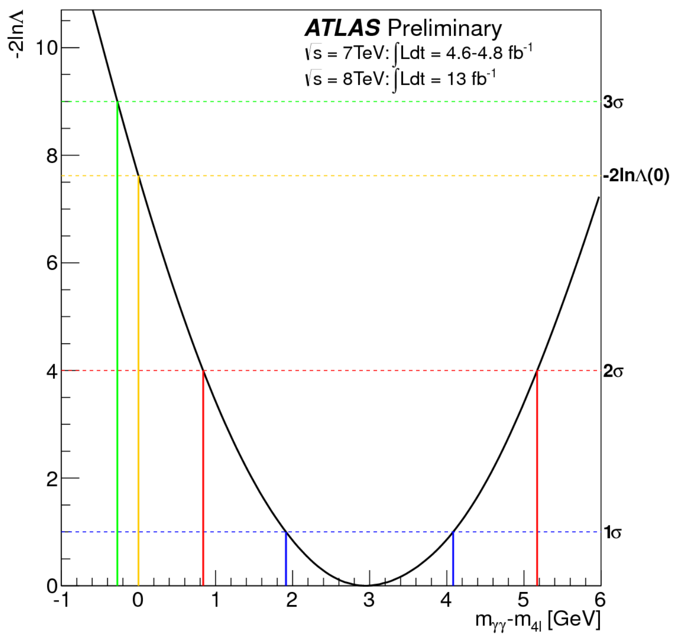
CMS

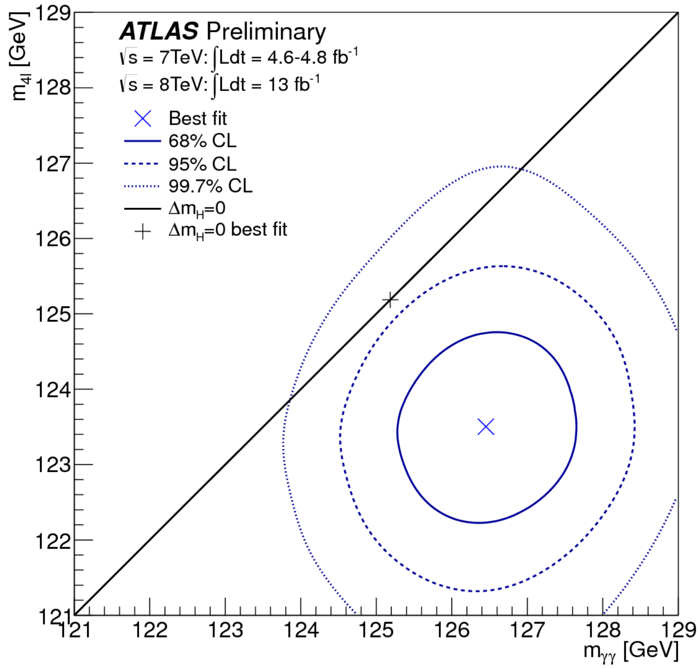
ZZ*, WW*, ττ, bb: 12 fb^{-1} 2012

γγ as PLB 4th July

Mass Measurement

ATLAS tension between γγ and ZZ*(4l) mass measurements



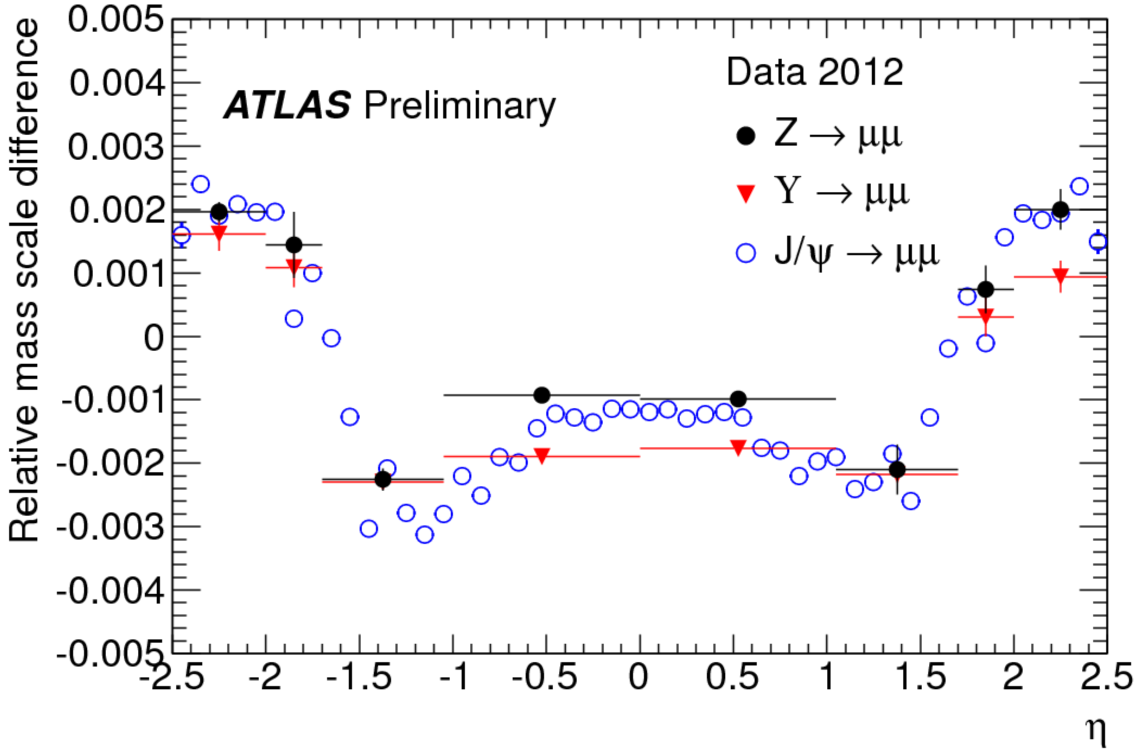


Studies in DEEP details: Agreement evaluated at 2.3- 2.7σ

Depending on assumption on systematics PDF's for Energy Scale (Box vs Gauss)

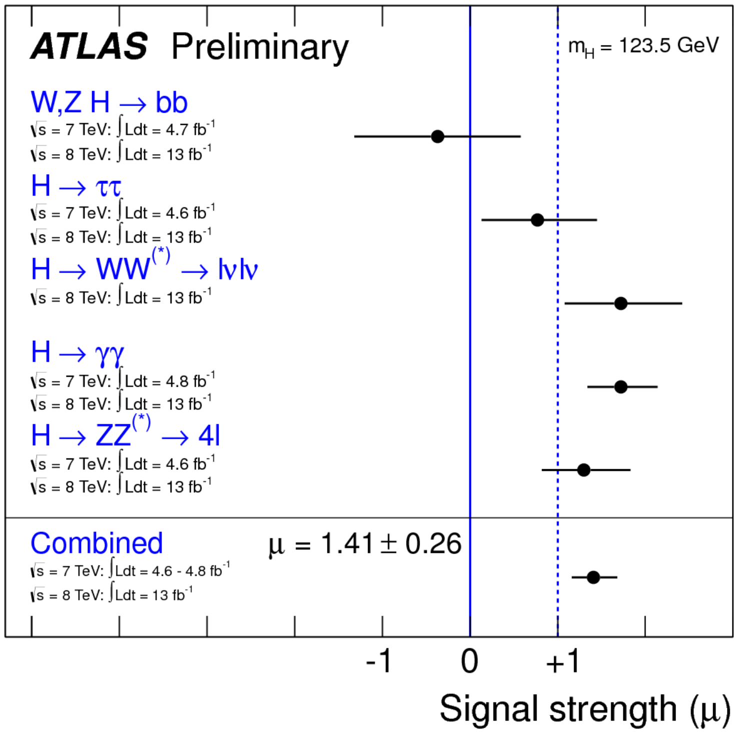
Mass Measurement

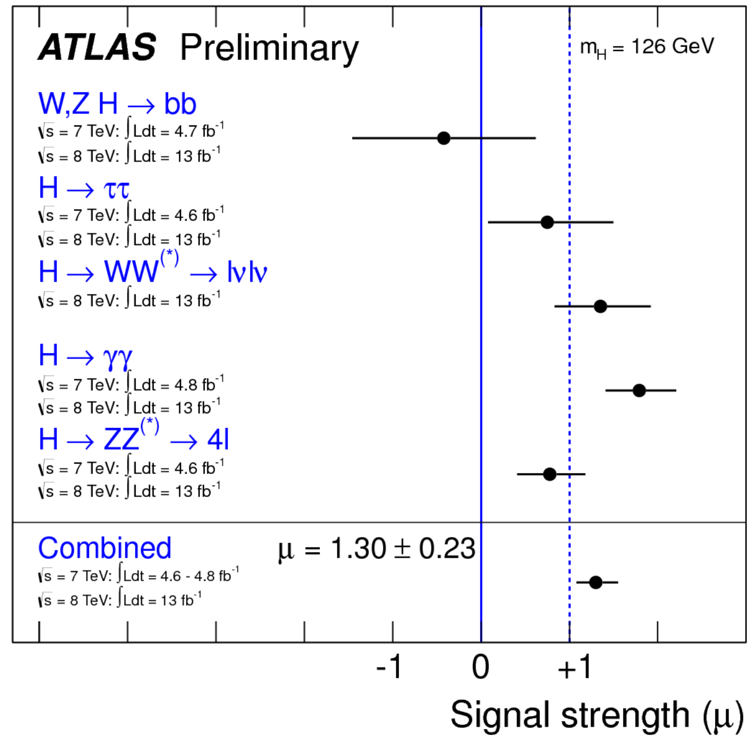
ATLAS slight tension between γγ and ZZ*(4l) mass measurements



Muon Mass Scale

Signal Strength vs Mass

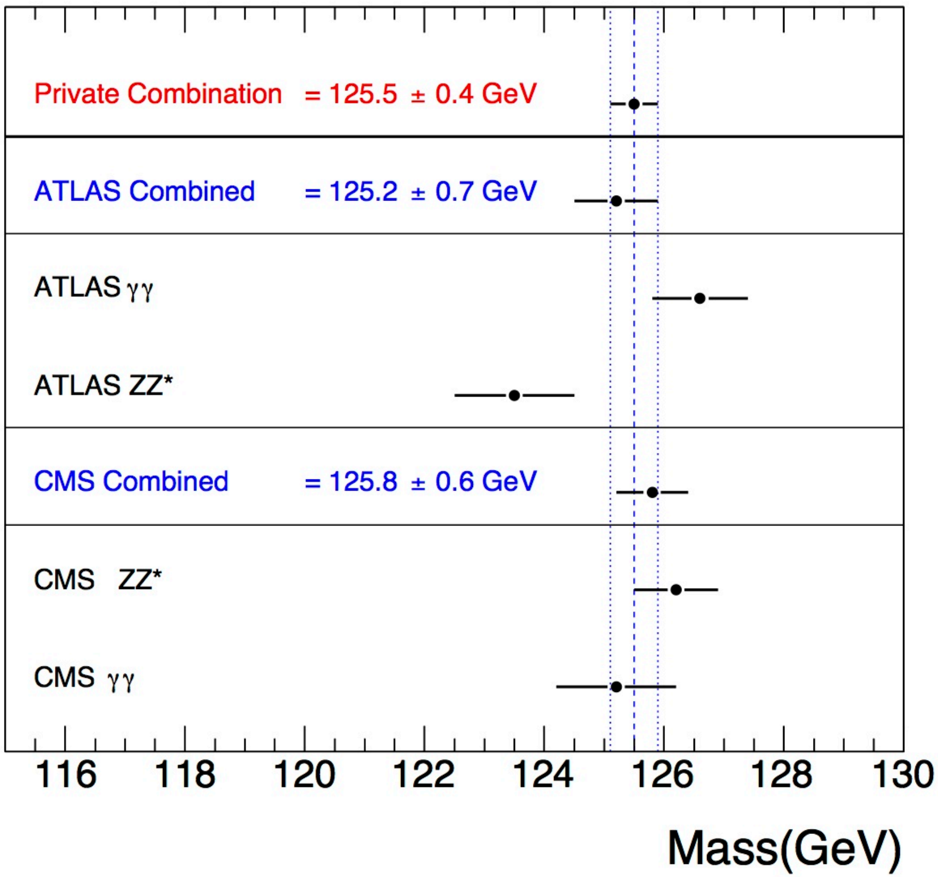




ATLAS slight tension between γγ and ZZ*(4l) mass measurements

Signal strength dependency is mild (Mainly ZZ*)

Mass Measurement: full picture



Private COMBINATION
Weighted average of averages

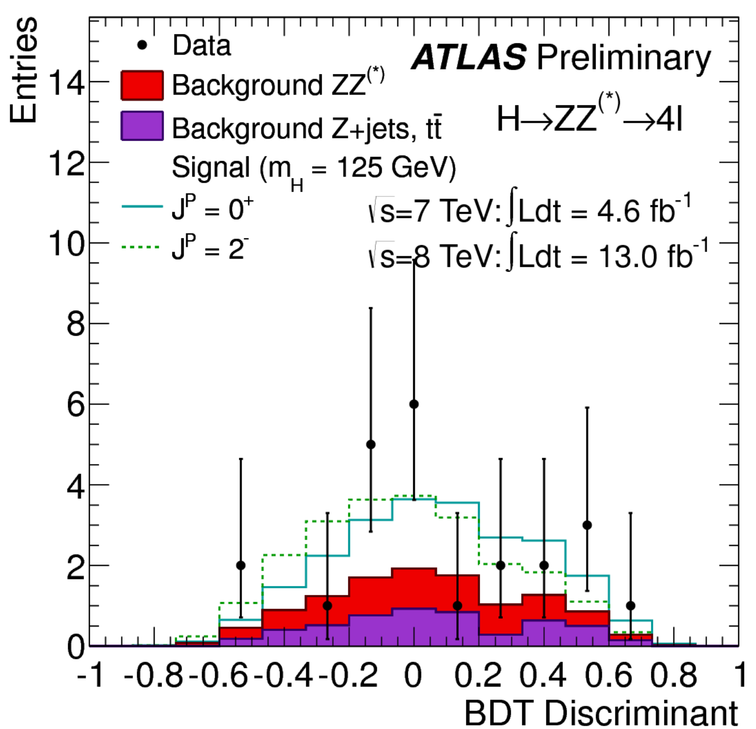
Possible correlations between 2 experiments SYSTEMATICS NOT taken into account

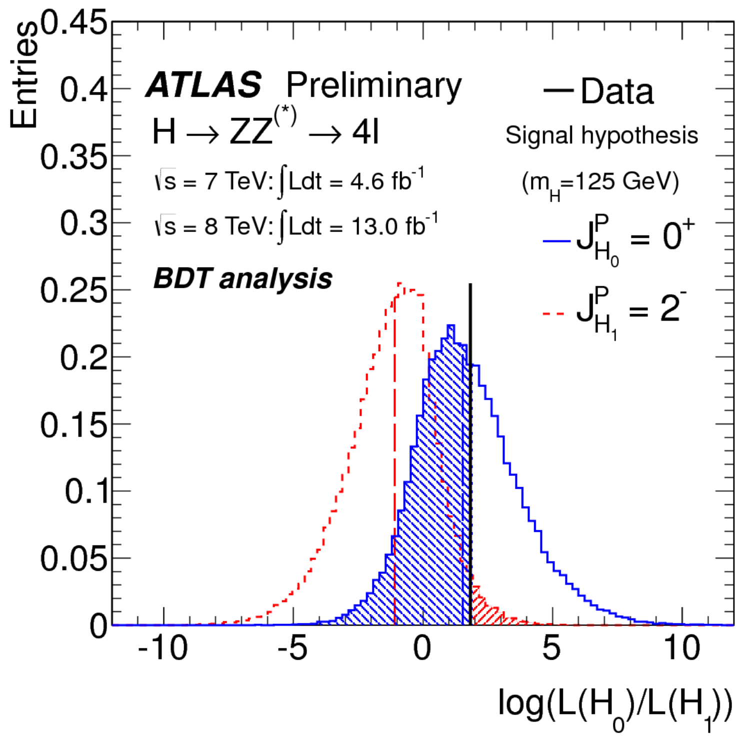
Impact of mass error on LHC **yields pred.: less than 4%** (WW/ZZ most sensitive)

Spin/CP

$ZZ^* \rightarrow 4\ell$ Test Compatibility with 2^- *(Specific Model)* vs 0^+

ATLAS: 2^- Disfavored at 1.9σ (Expected 1.7)

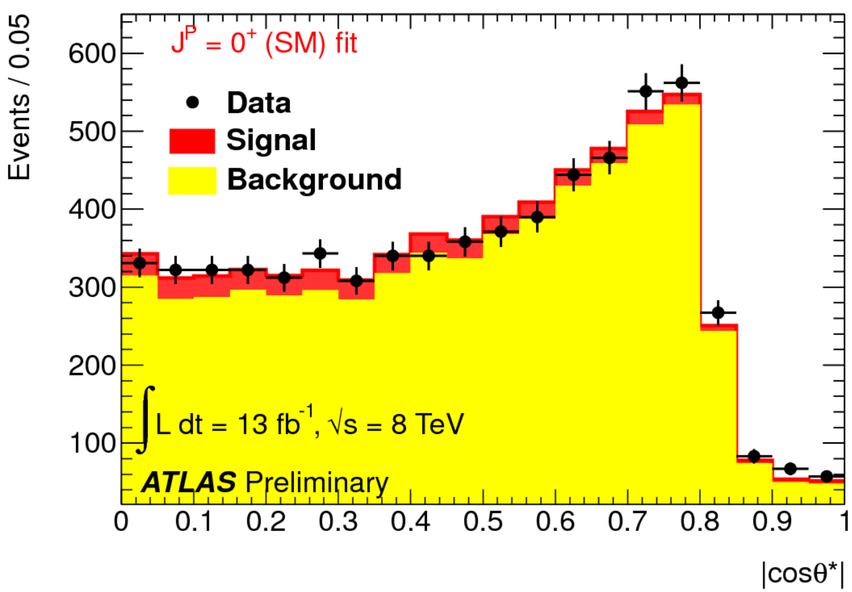


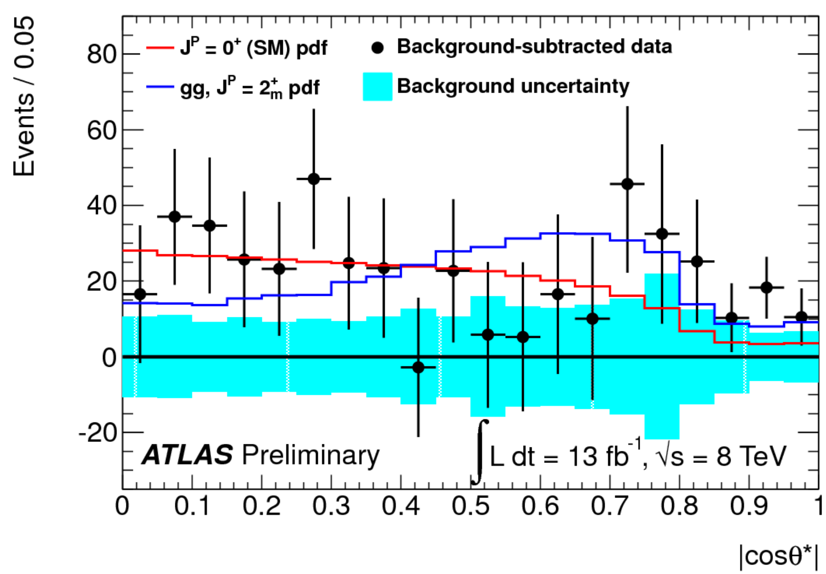


Spin/CP

H→ γγ final state decay angle cosθ* can be used to measure Spin

ATLAS: graviton-like 2^+_m Disfavored at 1.4σ (exp 1.8) assuming 100% gg production



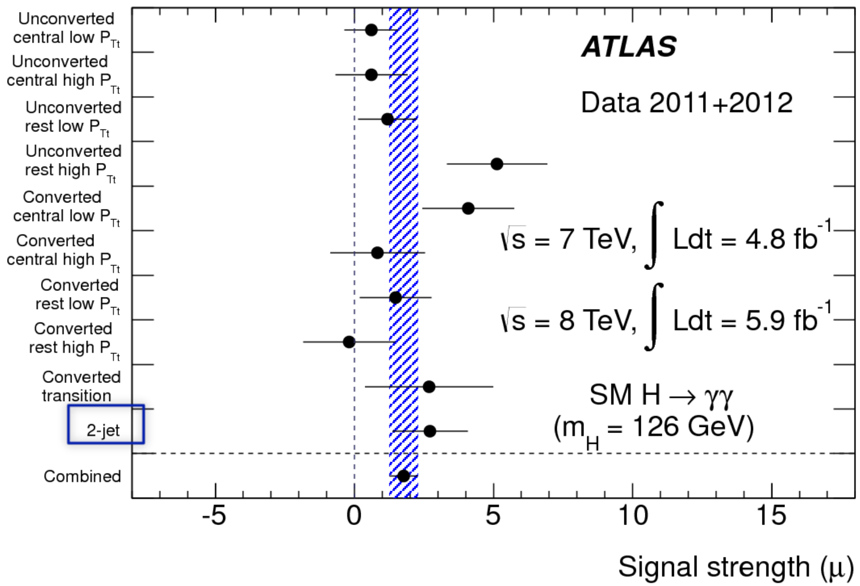


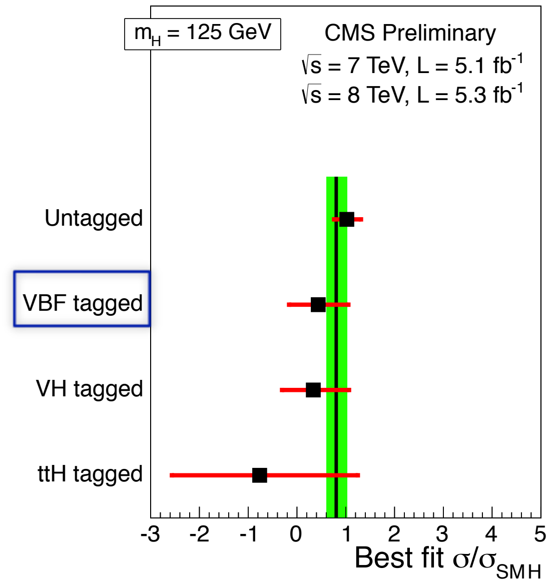
SM Higgs Boson Coupling fits results

Partial Widths in SM

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

The Couplings fit





- Basic ingredient Yields per category:
  - Production modes: gg, VBF, W/ZH, ttH
  - Final states: γγ, WW, ZZ, bb, ττ, Zγ, μμ

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 Γ_H → $\kappa^2_H(\kappa_F\ \kappa_V) \sim 0.7\ \kappa^2_F + 0.3\ \kappa^2_V$

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	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	

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}

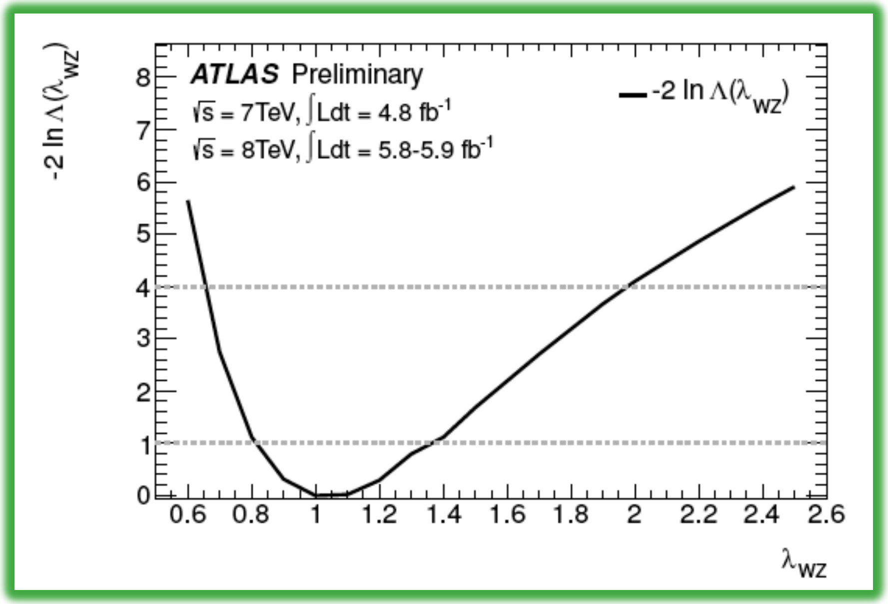
Probing custodial symmetry without assumptions on the total width

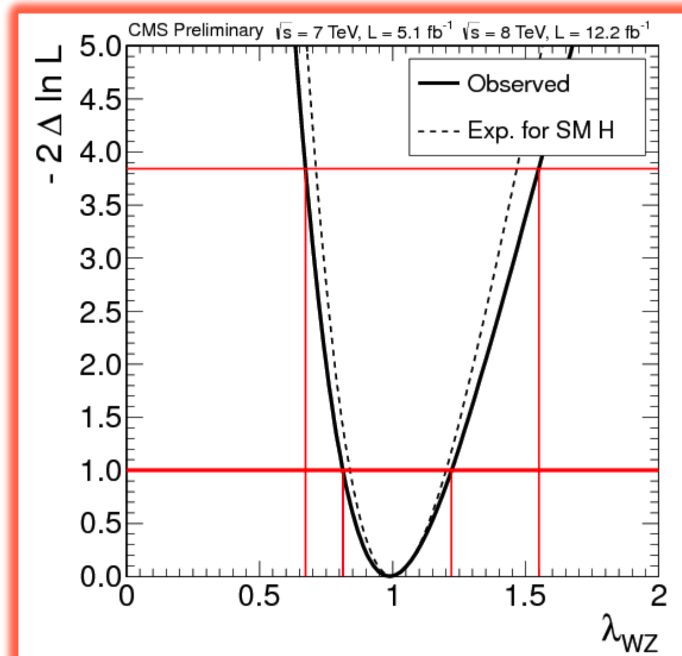
Free parameters: $\kappa_{ZZ}(=\kappa_Z\cdot\kappa_Z/\kappa_H)$, $\lambda_{WZ}(=\kappa_W/\kappa_Z)$, $\lambda_{FZ}(=\kappa_f/\kappa_Z)$.

	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$ / $H\to\tau^-\tau^+$
ggH, $t\bar{t}H$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\lambda_{FZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\lambda_{FZ}^2$
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	$\kappa_{ZZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\cdot\lambda_{FZ}^2$

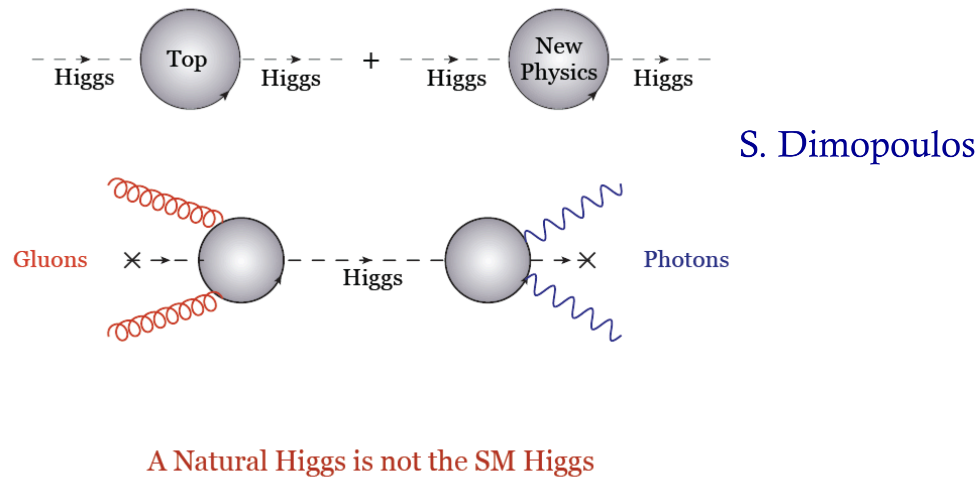
Custodial Symmetry $\lambda_{WZ} = k_W/k_Z$

- 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



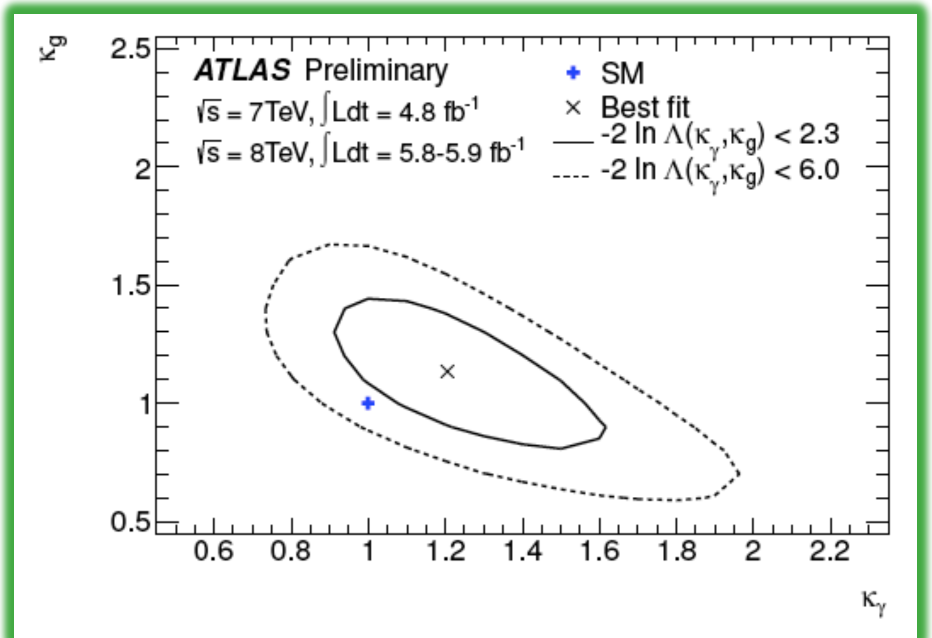


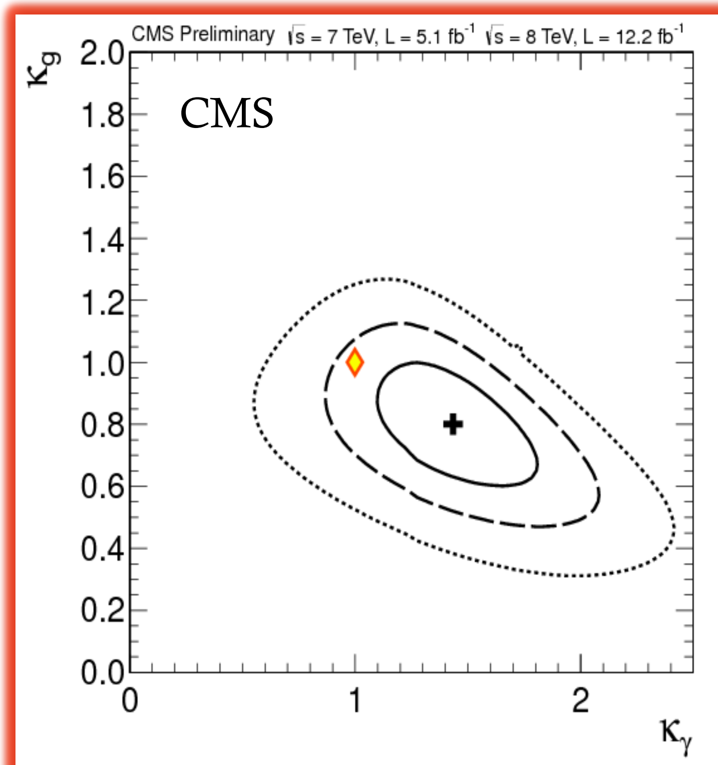
Loop Couplings κ_g vs κ_γ



- 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





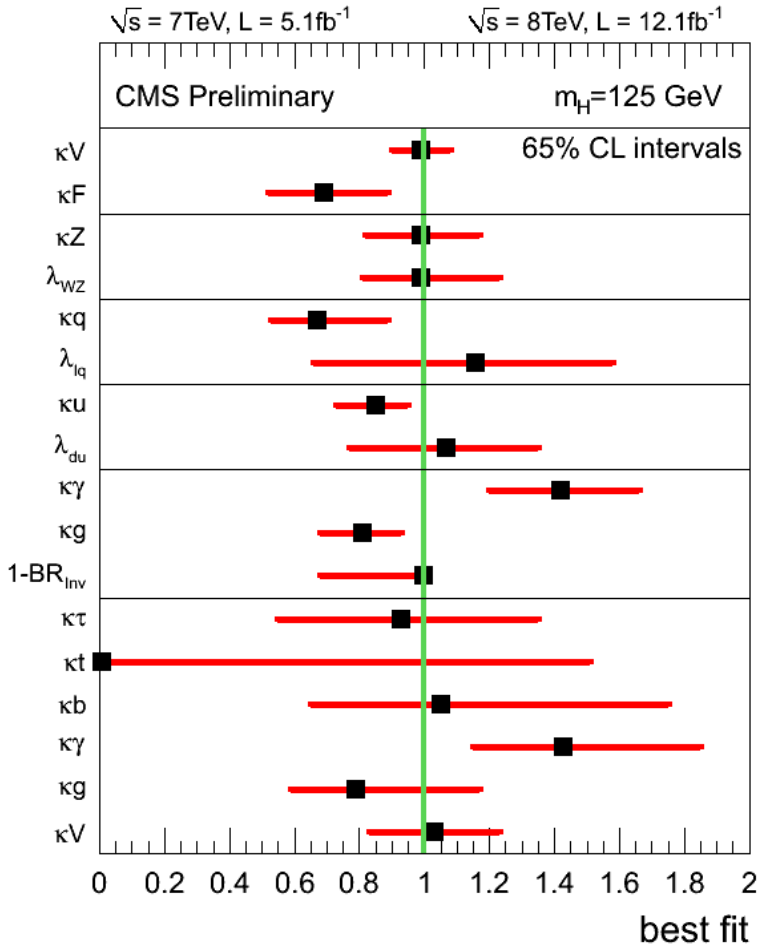
___ 69% CL

- - - 95% CL

Agreement with SM prediction at better than 2σ

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]