Higgs properties from experiments

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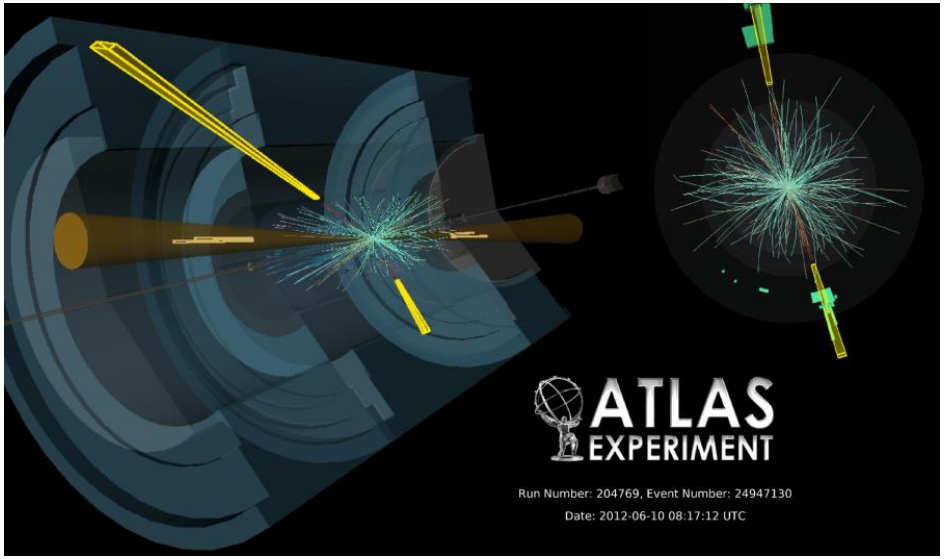
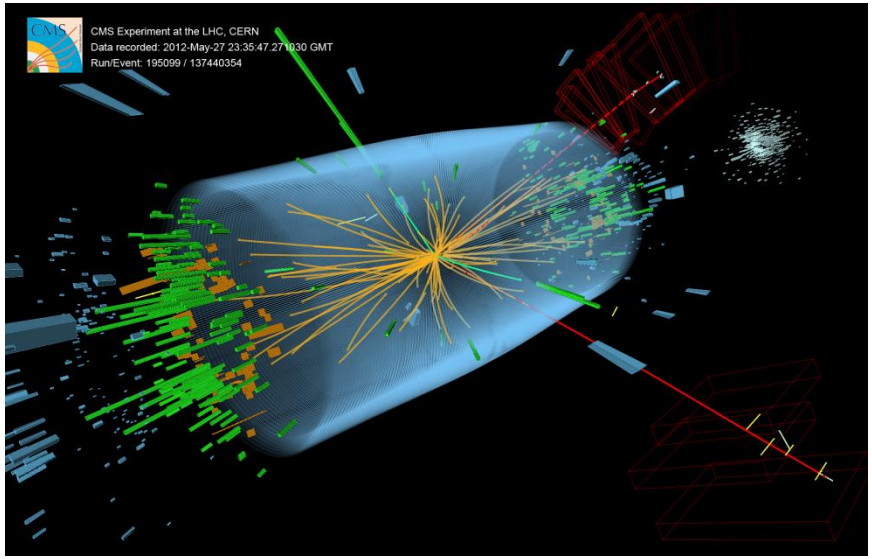




Contents

- m_H : m($\gamma\gamma$) and m(ZZ*)
- Γ_H (limits): direct ($\gamma\gamma$) , invisible, interferometry (ZZ*)
- Spin/CP: $\gamma\gamma$, WW*, ZZ*
- Higgs couplings
  - Signal strength with respect to SM : global (μ), per channel (μ_i)
  - Production modes: Vector Boson Fusion / gluon fusion
  - Couplings analyses

"Is this the SM Higgs boson?"

- **Remark: Impossible to answer this question! Even if we have 1/1000 precision on one variable, it could be 1/10000 away from the SM.**

Karl Popper => impossible to prove a theory. Only possible to falsify **competing ones…**

- **Particle ID card versus model dependence?**
  - **m_H , Γ_H ; ~ assumes 1 resonance only;**
  - **Spin/Parity : SM 0^+ ; no good alternative model with 100 % contribution**

    but nevertheless, 100% 0^- or 2^+ are benchmarks. Attempt at admixture.
  - **Couplings: try to extract general features, although each alternative model has its distinctive couplings structure…**

- ***Complementarity: global features / test of alternative model (2HDM, MSSM…)***
- **Large work of LHC-Higgs-XS-WG** ***http://arxiv.org/pdf/1307.1347v1.pdf***

Tools for Higgs Physics (from Rei Tanaka)

ggF, VBF, WH/ZH, ttH, BSM Higgs

Cross Section

ggF
HIGLU (NNLO QCD+NLO EW)
iHixs (NNLO QCD+NLO EW)
FeHiPro (NNLO QCD+NLO EW)
HNNLO, HRes (NNLO+NNLL QCD)
ggh@NNLO (NNLO QCD)

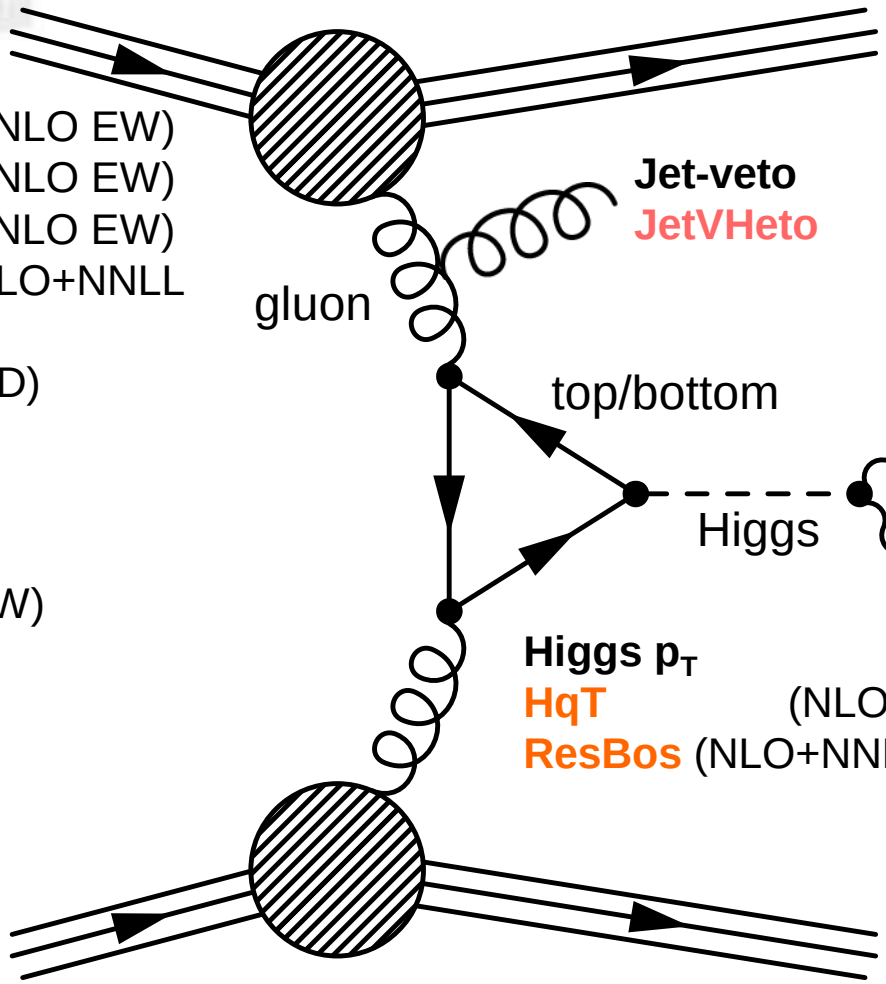
VBF
VV2H (NLO QCD)
VBFNLO (NLO QCD)
HAWK (NLO QCD+EW)
VBF@NNLO (NNLO)

WH/ZH
V2HV (NLO QCD)
VH@NNLO (NNLO)

ttH
HQQ (LO QCD)

bbH
bbH@NNLO (NNLO QCD)

+ private codes.



Jet-veto
JetVHeto

MSSM/2HDM
FeynHiggs, SusHi
2HDMC, CPSuperH

Higgs Decay
(e)HDECAY (NLO)
Prophecy4f (NLO)

Higgs p_T
HqT (NLO+NNLL)
ResBos (NLO+NNLL)

Higgs Properties
MELA/JHU, MEKD
MadGraph5

NLO MC
aMC@NLO, POWHEG,
SHERPA, HERWIG++
MCFM

PDF: MSTW2008, CT10, NNPDF2.1, etc.

Statistical methods

- **Measurements (mass, couplings) from *profiled likelihood method***

$$\Lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}}(\mu))}{L(\hat{\mu}, \hat{\theta})}$$

μ : parameter(s) of interest

θ : nuisance parameters

$L(\hat{\mu}, \hat{\theta})$ **global likelihood maximum: μ and θ adjusted for max L**

$L(\mu, \hat{\hat{\theta}}(\mu))$ **tested μ point : θ adjusted for max L *at this μ point***

***–2 Ln Λ(μ)* follows χ^2 distribution with n d.o.f. ($\mu_{1\ldots n}$) => P(χ^2 > x)…**

- **Importance of a consistent, global "error model" for an experiment.**

  Global couplings fit in Atlas: over 1500 nuisance parameters!

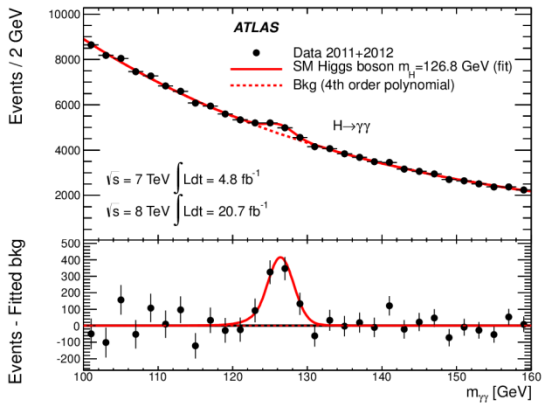
- **Test of hypothesis (Spin, CP): ratio of likelihoods for each hypothesis.**

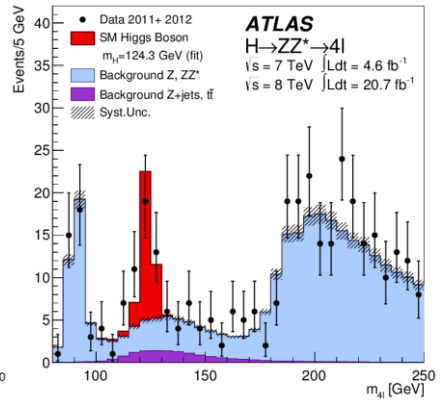
$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\rm alt}, \hat{\hat{\mu}}_{J^P_{\rm alt}}, \hat{\hat{\theta}}_{J^P_{\rm alt}})}$$

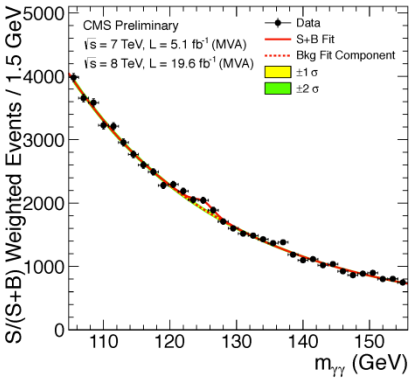
$$p_0(hyp) = \int_{q_{obs}}^{\infty} f_{hyp}(q)dq$$

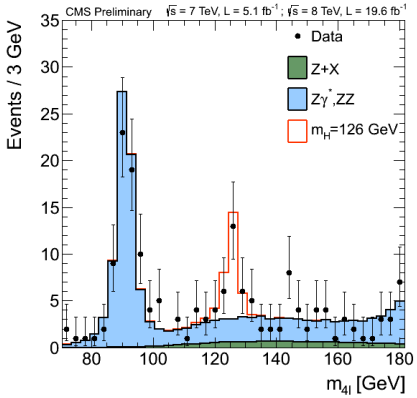
$$\mathrm{CL_s}(J^P_{\rm alt}) = \frac{p_0(J^P_{\rm alt})}{1 - p_0(0^+)}$$

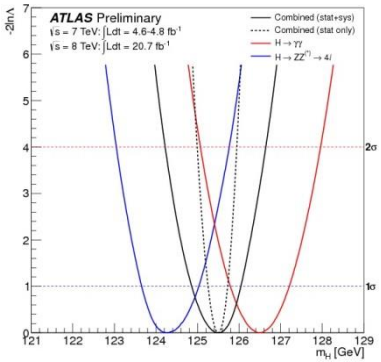
Mass measurement from γγ and ZZ*

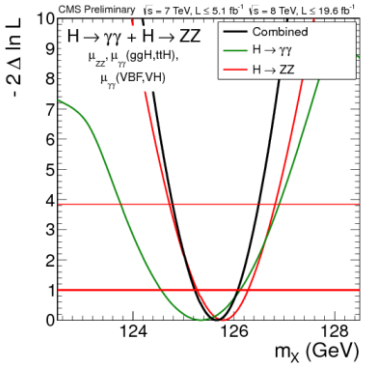












- m_H = 125.5 ± 0.2 (stat) $^{+0.5}_{-0.6}$ (sys) GeV 125.7 ± 0.3 (stat) ± 0.3 (sys) GeV
  - m_H : parameter of interest ; $\mu_{\gamma\gamma}$ and μ_{4l} treated as independent nuisance parameters
  - m_H almost independent on the signal strengths.
  - value important in couplings determination: BR(WW, ZZ) vary quickly with m_H!

Width

- **SM Higgs width for 125.5 GeV: 4 MeV.**

- **Direct measurement on mass peak**
  - **$\gamma\gamma$ in CMS: observed (expected) upper limit on width 6.9 (5.9) GeV (95% CL).**

- **Interferometry**
  - **Non-zero width enables Higgs to interfere with the continuum far from peak:**

    $\gamma\gamma$ and 4 leptons. Caola/Melnikov with (4ZZ*) CMS data: $\Gamma_H < 39\ \Gamma_H^{SM} = 160$ MeV

- ***Invisible* decay modes from Z H , H→ invisible. (typically Z + E_{T_miss} > 100 GeV)**
  - ***Assume $\sigma(ZH)$ as in SM***

  ATLAS: BR < 65% @95% CL

  CMS: BR < 75% @95% CL

  - **Beware that this does not count the *undetected* modes like H → light jets**

Spin/CP

- **Analysis of internal distributions, irrespective of signal strength.**

- **Different (and complementary) sensitivities from different decay modes.**
  - **Atlas compares 0^+ to : $\gamma\gamma$: 2^+ ; *ZZ*: 0^-, 1^+, 1^-, 2^+ ; *WW*: 1^+, 1^-, 2^+ ; combination.**
  - **CMS : $\gamma\gamma$: 2^+ ; *ZZ*: 0^-, 1^+, 1^-, 2^+ ; *WW*: 2^+ ; comb (WW+ZZ ; 100% gg)**

- **Spin 1 forbidden for $\gamma\gamma$ decay (Landau-Yang theorem).**

  Only looked at in ZZ and WW

- **Spin 2: many models possible. Graviton-like selected. (JHU: 2^+_m)**

  (others can be *very* exotic…)

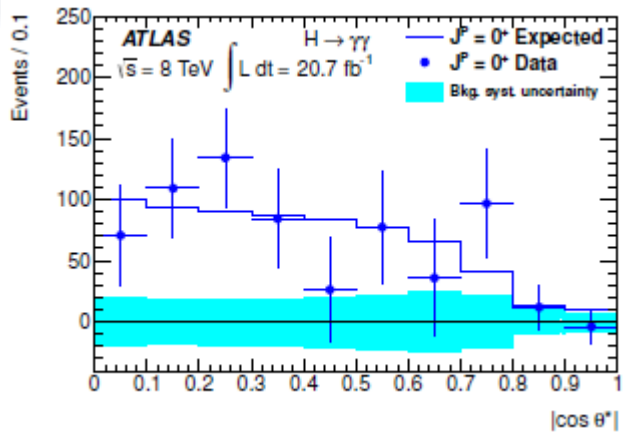
Spin/CP: examples

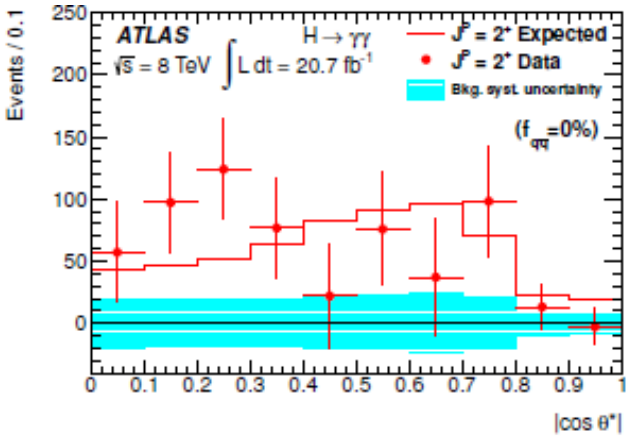
- $\gamma\gamma$:

$0^+/2^+$ separation:

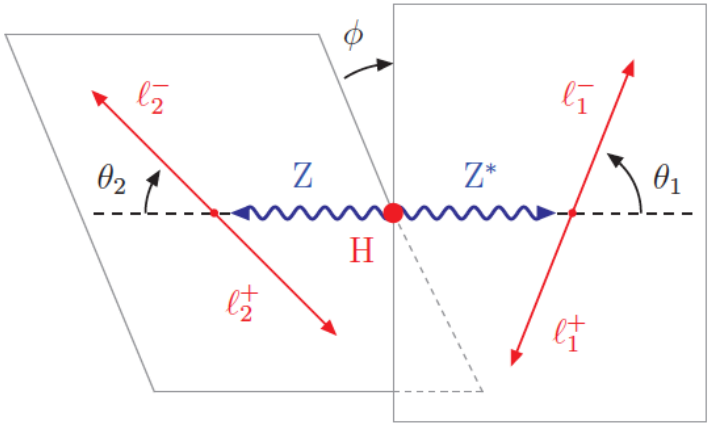
cos (θ*)

(Collins-Soper frame)



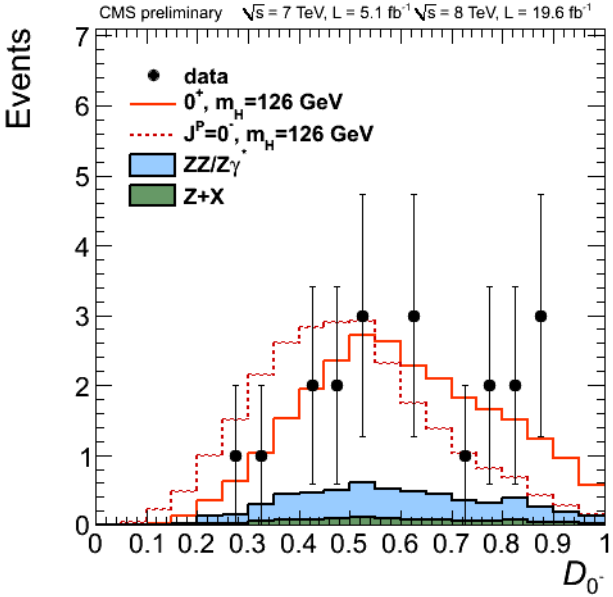


- **ZZ* : 2 masses + 5 angles (but few events)**



0^+ / 0^- separation

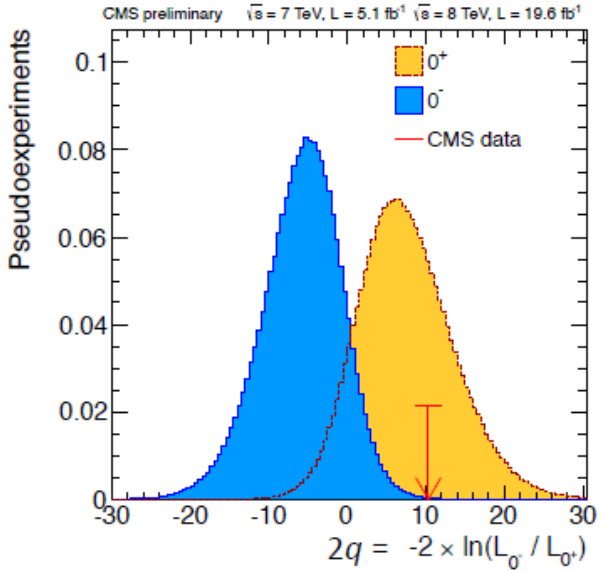
(BDT)

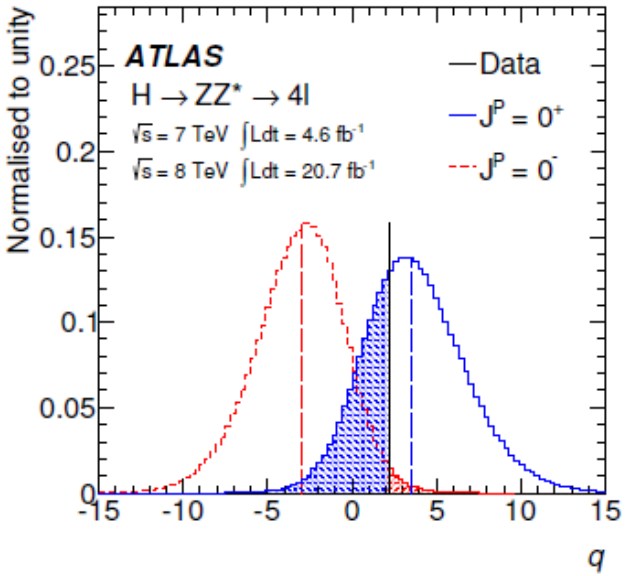


0^+ / 0^-

- 0^- : only produced by gg fusion ($q\bar{q}$ negligible)

- Only ZZ* mode
  - Ratio of likelihoods for each hypothesis: 100 % 0^+ versus 100% 0^- :





CMS excludes 0^- at 99.8% CL (exp: 99.5)

Atlas:excludes 0^- at 97.8% CL (exp: 99.6)

Data well compatible with 0^+

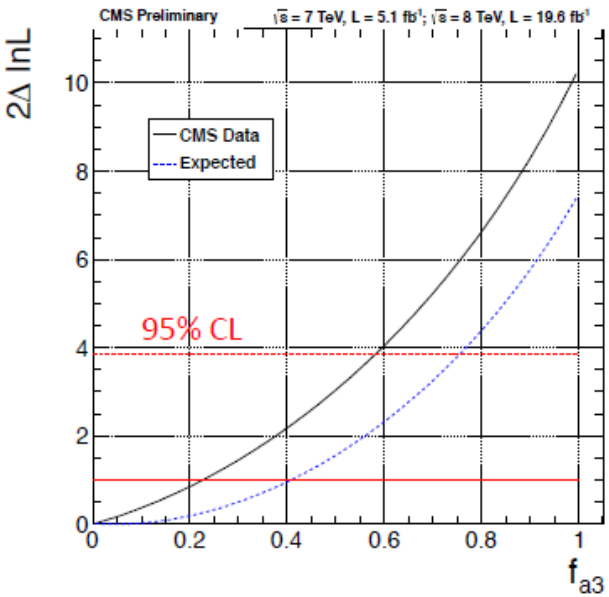
0^+ / 0^- : testing the admixture

- **100% 0^- : ~ impossible because does not couple to WW at tree level.**
  Effective Lagrangian models allow typically up to ~ 5% of 0^-

$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_H^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right) = A_1 + A_2 + A_3$$

- **CMS: probes content of CP violating a_3 term in ZZ decays.**

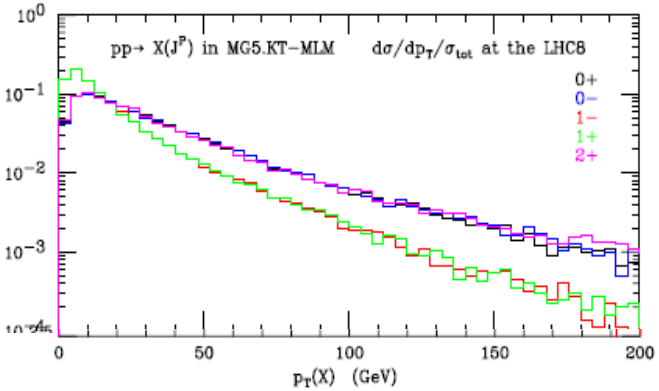
f (a3) < 0.56 @ 95%CL (exp 0.76)



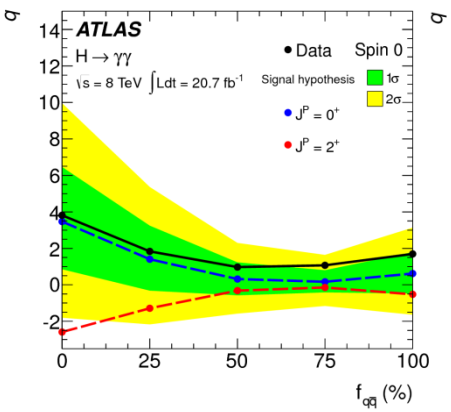
Could be improved by VBF and VH modes with more statistics

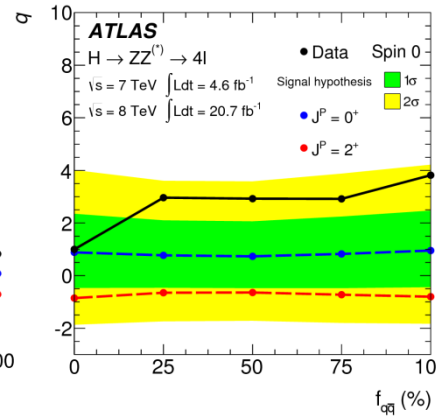
Spin 1 and 2

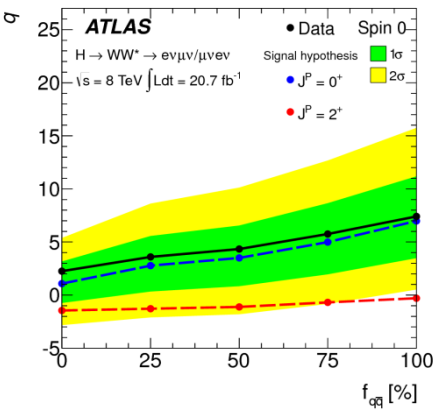
- **Spin 1**
  - **Only looked at in ZZ and WW**
  - **Landau-Yang also forbids gg (onshell gluons)→H, hence only $q\bar{q} \rightarrow H$ assumed**



- **Spin 2**
  - **JHU 2^+_m assumed**
  - **gg and $q\bar{q}$ production different**
    - polarization
    - Kinematics
  - **2^+_m at LO : 4% $q\bar{q}$ but NLO unknown => scan in $f_{q\bar{q}}$**







Spin

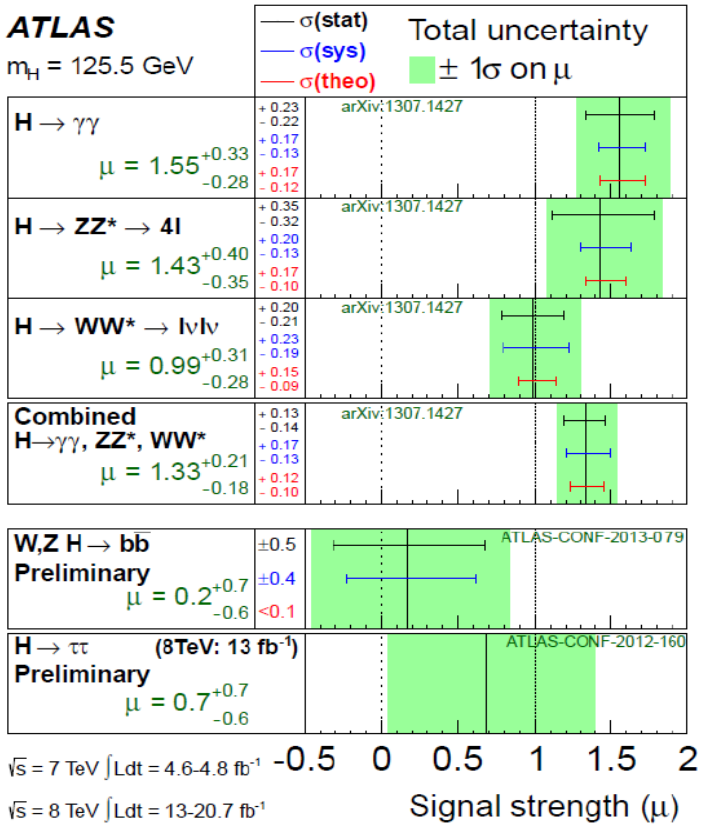
- **CL_S values of the models tested against 0^+**

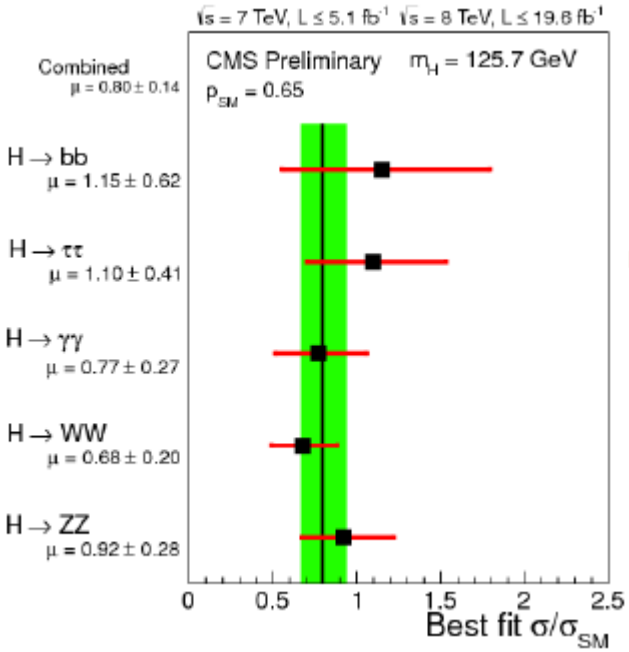
1 (qq)	ATLAS			CMS
	WW	ZZ	Combined	ZZ
1^+	0.08	$2\ 10^{-3}$	$3\ 10^{-4}$	$< 10^{-3}$
1^-	0.06	0.017	$2.7\ 10^{-3}$	$< 10^{-3}$

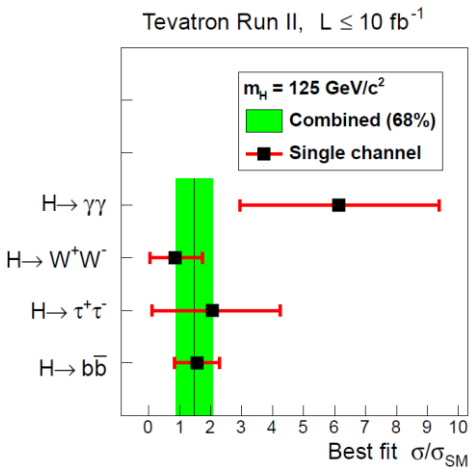
2^+	ATLAS				CMS			
	WW	ZZ	$\gamma\gamma$	Comb	WW	ZZ	Comb WW + ZZ	$\gamma\gamma$
100% gg	.086	.17	.007	$4\ 10^{-4}$	0.14	0.015	.006	0.61
100% qq	.0013	.026	.12	$8\ 10^{-6}$		10^{-3}		0.16

- **Data fully compatible with 0^+**
- **All other models tested excluded with a large confidence level.**

Signal strength







ATLAS (γγ, ZZ, WW) **μ = 1.33 ± 0.20** ***[1.23 ± 0.18 including bb, ττ)]***

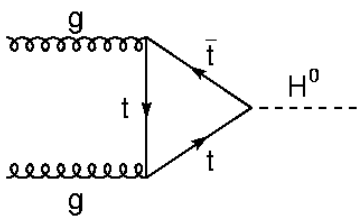
CMS (γγ, ZZ, WW, bb, ττ) **μ = 0.80 ± 0.14**

Tevatron (γγ, WW, bb, ττ) **μ = 1.44 ± 0.60**

Good overall compatibility with the SM Higgs.

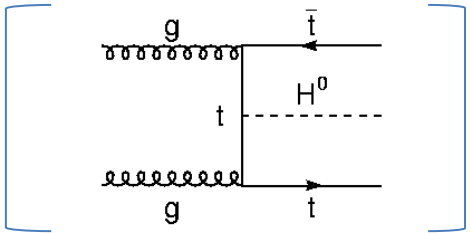
Higgs production modes

- **Through t coupling**
  - **fermion masses…**



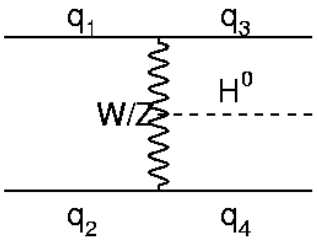
g g F

+



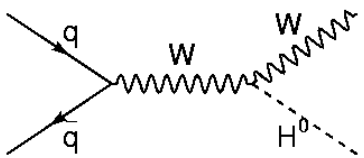
t t̄ H

- **Through W/Z coupling**
  - **W/Z masses…**
  - **unitarity of SM**



Vector Boson Fusion

+



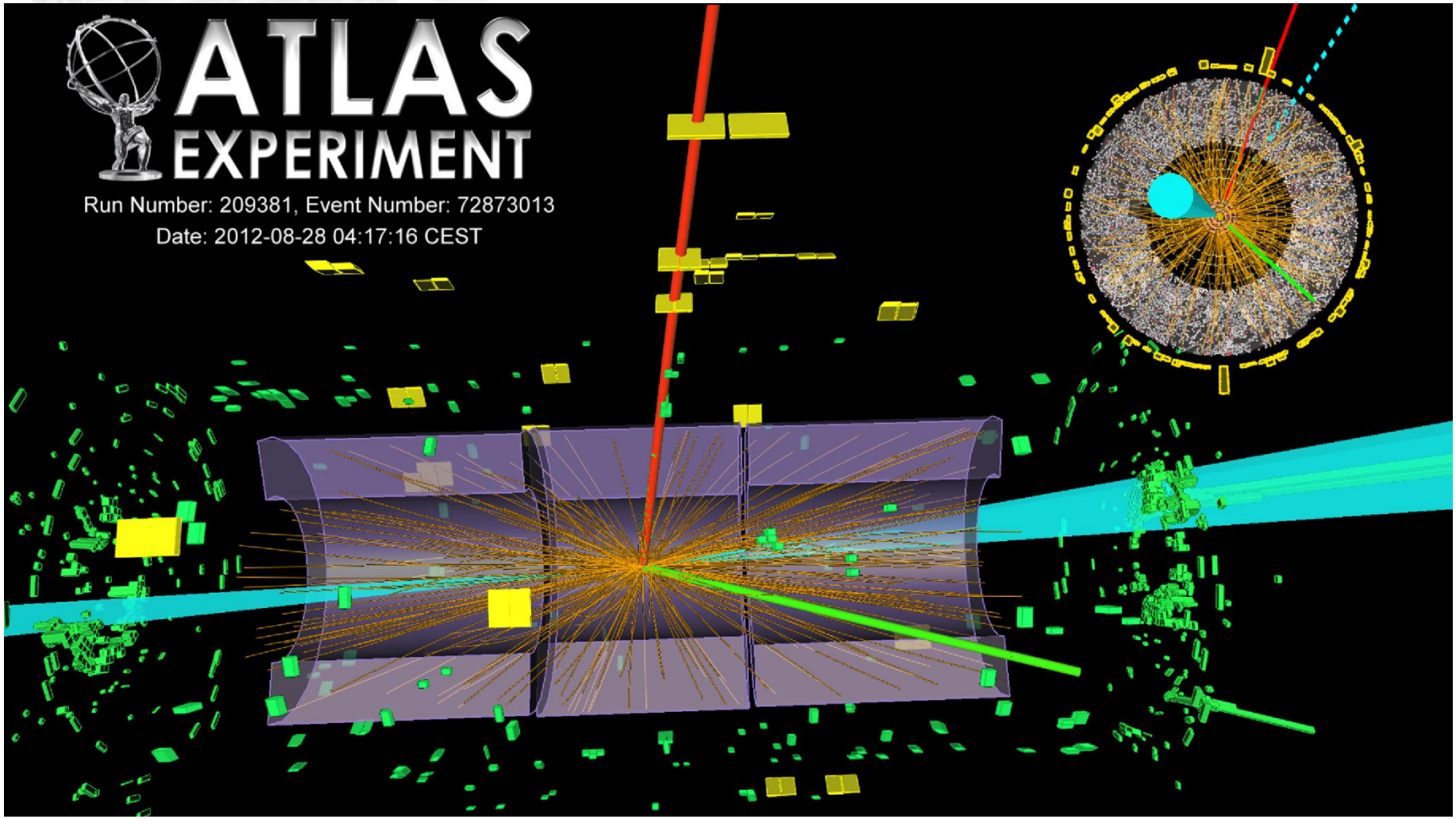
VH

Can be tested for all modes with VBF sensitivity

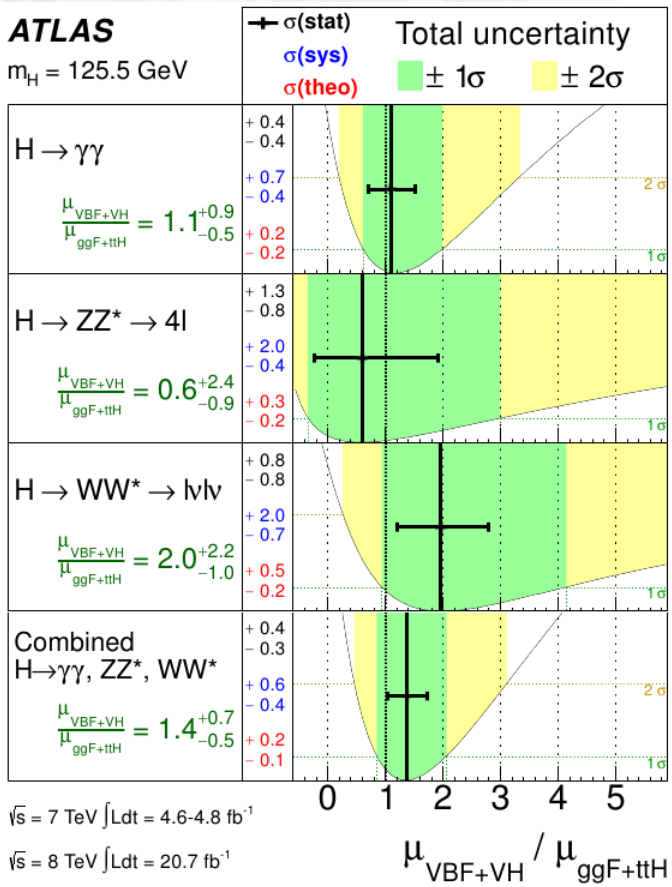
request 2 hard, forward jets. Beware of significant gg contamination in VBF

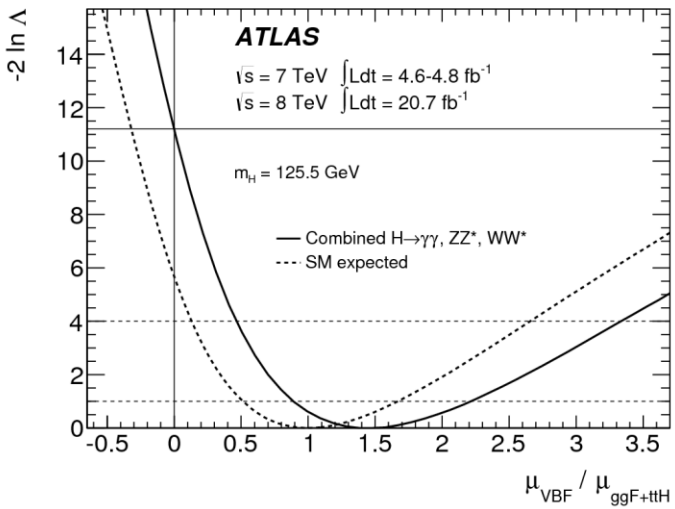
- **CMS: γγ, ZZ, WW, ττ**
- **ATLAS: γγ, ZZ, WW**

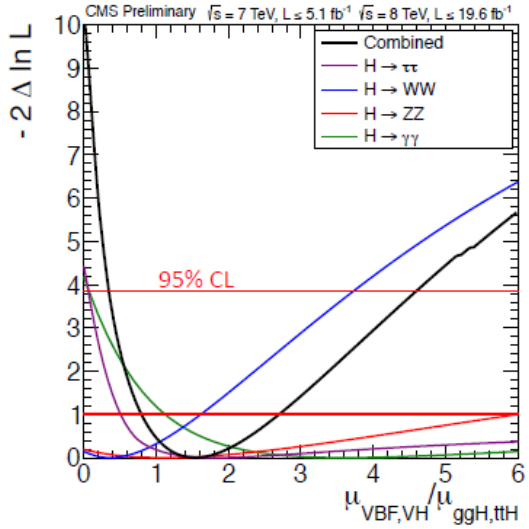
Candidate VBF H -> τ (e) τ (μ)



Production modes: [VBF (+VH)] / [ggF +$t\bar{t}$H]







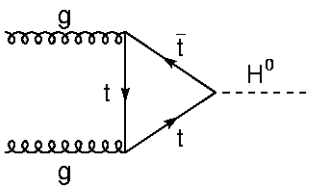
- **Atlas: evidence for VBF production 3.3 σ**
- **CMS : evidence for VBF + VH : 3.2 σ**

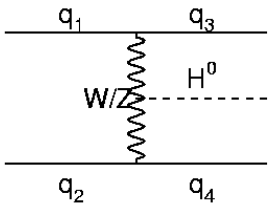
Compatible with SM : W (Z) production of Higgs

Higgs couplings

- **For each observed final state, production and decay involve several couplings**

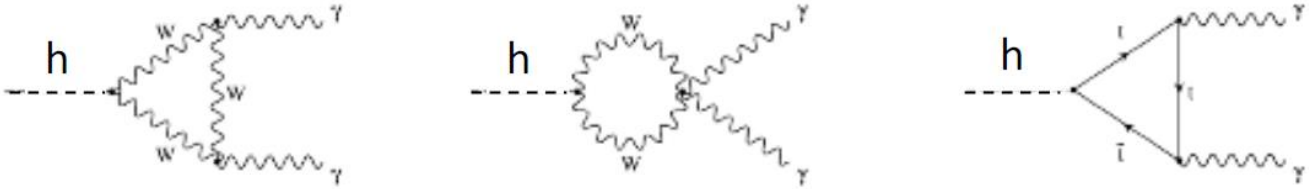
- **Example: $\gamma\gamma$**
  - **Production**





$\sim \kappa_g^2\ (\kappa_t, \kappa_b, m_H)$ + $\sim \kappa_W^2$ $\kappa_i = g_i/g_i^{SM}$

  - **Decay**



Decay width : $\sim (\kappa_W - 0.2\ \kappa_t)^2$ ***[note: interference]***

- **Need consistent parametrization => LHC Higgs -XS-WG**
- **Ideally: use all production and decay modes to measure all κ's**
- **Reality: some modes are statistically limited, or even invisible (κ_c , κ_μ...?)**

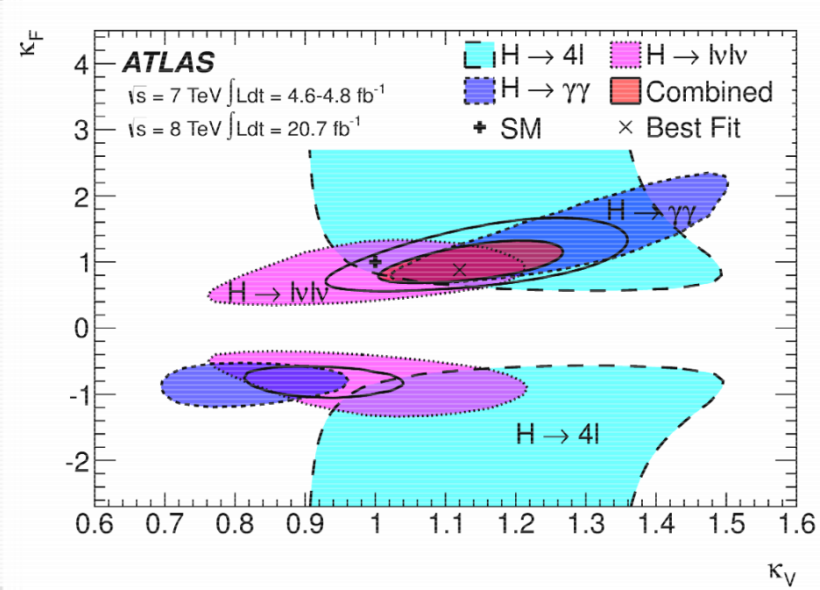
  => Group some κ's in order to test salient/important features
- **Loops : κ_γ, κ_g : as functions of elementary κ's, or left free to test BSM contributions**

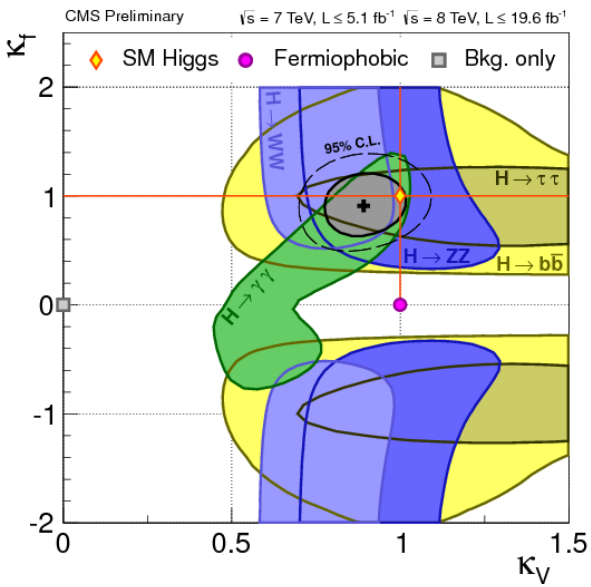
Fermion versus Vector couplings

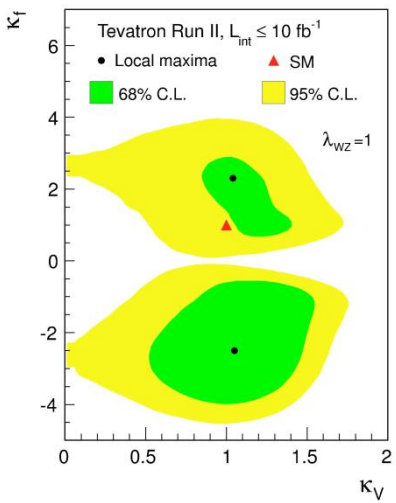
- **Group couplings : $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$; $\kappa_V = \kappa_W = \kappa_Z$**

  Assume:

  - **gg → H and H → γγ only through SM particles: $\kappa_g(\kappa_F, \kappa_V)$, $\kappa_\gamma(\kappa_F, \kappa_V)$**
  - **only SM particles contribute to decay: $\kappa_H(\kappa_F, \kappa_V) \sim 0.7\,\kappa_F^2 + 0.3\,\kappa_V^2$**







- **sensitivity to relative sign: only from interference term in H → γγ**
- **sensitivity to κ_F is mostly through top in loops.**

W and Z couplings (test of 'custodial symmetry')

- group $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$, un-group κ_W, κ_Z, test $\lambda_{WZ} = \kappa_W / \kappa_Z$

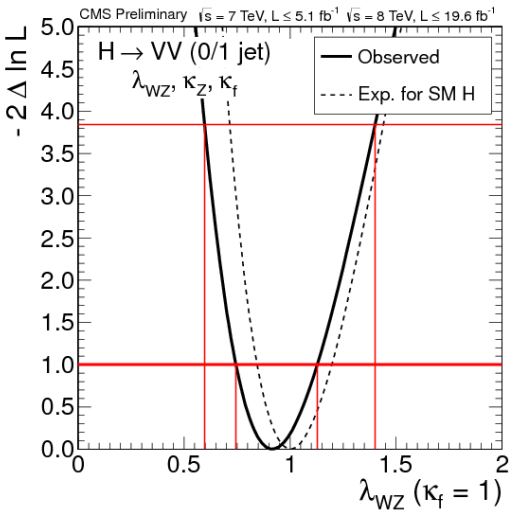
Direct contribution: WW and ZZ ; indirect: $\gamma\gamma$ (through W loop)

– 1) Use only inclusive WW and ZZ decay modes

more model-independent

ATLAS: $\lambda_{WZ} = 0.81 \pm 0.16$

CMS: $\lambda_{WZ} \in [0.60, 1.40]$ (95% CL)

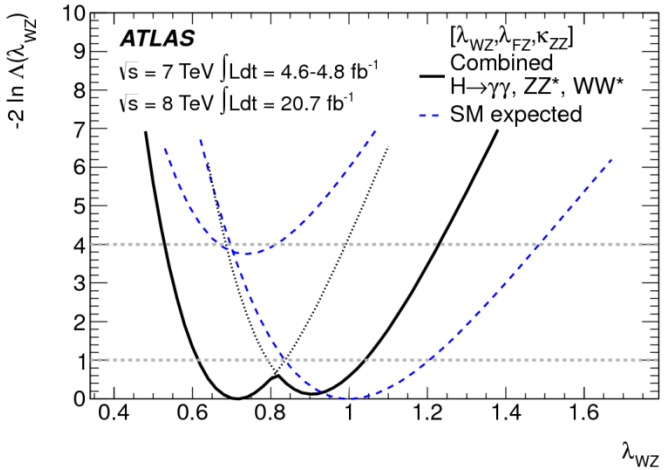


– 2) Also use $\gamma\gamma$ and VBF (+VH) modes

assuming SM content in $\gamma\gamma$ loop

ATLAS: $\lambda_{WZ} = [0.61, 1.04]$ (68% CL)

CMS: $\lambda_{WZ} \in [0.62, 1.19]$ (95% CL)

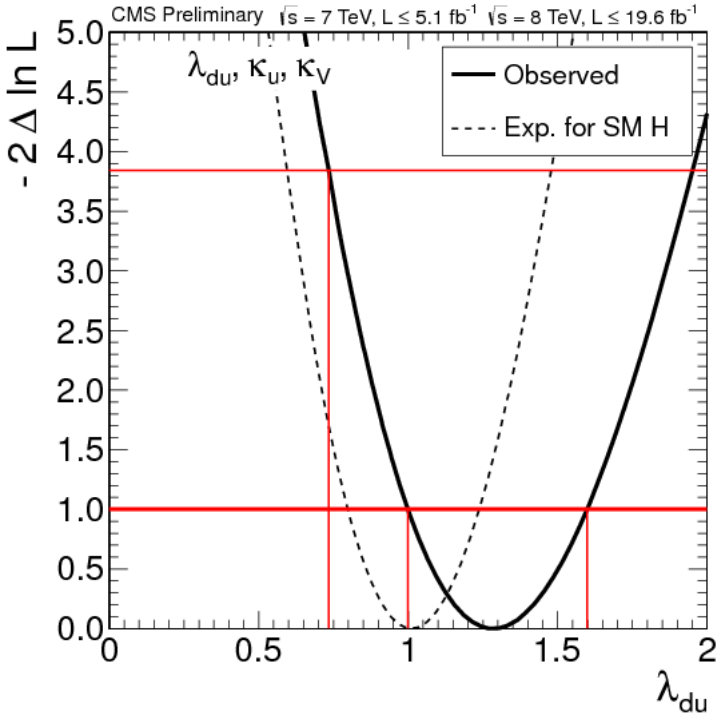


Coupling to up / down fermions

- set $\kappa_u = \kappa_t$, $\kappa_d = \kappa_b = \kappa_\tau$, test $\lambda_{du} = \kappa_d / \kappa_u$; (profile κ_u and κ_V , assume $\Gamma_{BSM}=0$)
- different κ_u, κ_d : typical of 2 Higgs Doublet Models, ex MSSM.

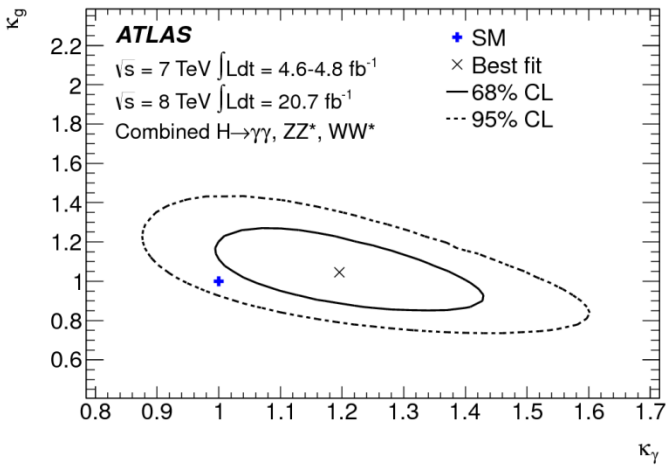
- sensitivity :
  - $\kappa_u = \kappa_t$ from loops
  - $\kappa_d = \kappa_b = \kappa_\tau$ from $b\bar{b}$ and $\tau\tau$ decay modes
- CMS: $\lambda_{du} \in [0.74, 1.95]$ (95% CL)

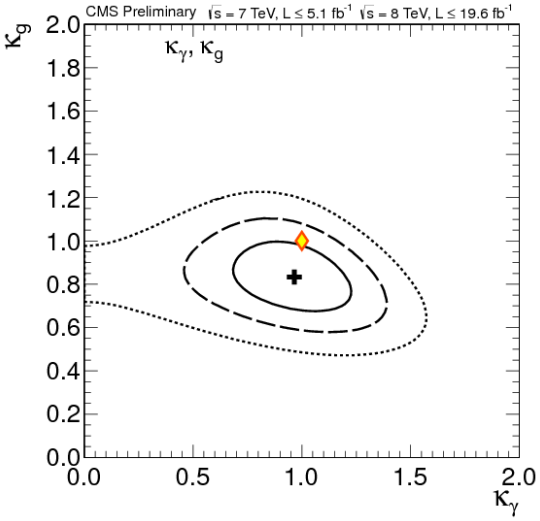
(i.e. seen at ~ 3 sigmas merging b and τ)



Loop couplings: contributions from non-SM particles?

- **Introduce effective, *independent*, κ_g , κ_γ (allow additional contributions to loops)**
- **Assume all couplings to SM particles $\kappa_i = 1$**
- **Assume no contributions to the total width in undetected modes**





ATLAS

- $\kappa_g = 1.04 \pm 0.14$
- $\kappa_\gamma = 1.20 \pm 0.15$

CMS

- $\kappa_g = [0.63, 1.05]$ (95% CL)
- $\kappa_\gamma = [0.59, 1.30]$ (95% CL)

BSM decay modes?

- **Reminder: ZH , H invisible (Z + E_T_missing)**

- **Here: test invisible *and* undetectable decay modes**
  - ***Need assumption to normalize some width (eitherwise compensation possible)***

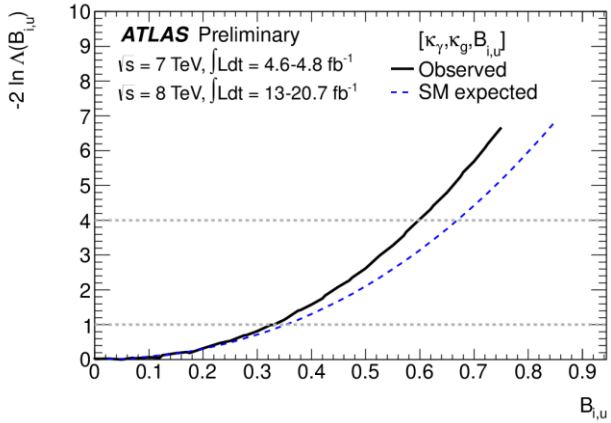
- **ATLAS:**

assume tree-level couplings

of SM particles κ_t , …, $\kappa_{W,\ldots} = 1$

3 parameter fit: κ_γ, κ_g , $BR_{invis,\ undet}$

$BR_{invis,\ undet} < 0.60$ (95%CL)

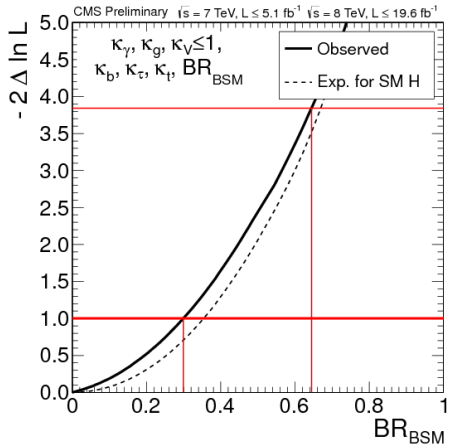


- **CMS:**

assume $\kappa_{W,Z} < 1$

7 parameter fit: κ_γ, κ_g , κ_b, κ_τ, κ_t, $BR_{invis,\ undet}$

$BR_{invis,\ undet} < 0.64$ (95%CL)



Conclusion

- **Entering era of Higgs precision measurements**
- **No deviation from SM Higgs seen up to now**

- **Complete the work on run I (2011 + 2012) data**
  - **finalize present modes**
  - **$t\bar{t}H$**

  - **Add the new modes to the combination: $t\bar{t}H$, ZH (inv), …**
  - **Explore admixtures (like 0^-)**
  - **Explore (further) particular models: 2HDM, MSSM…**

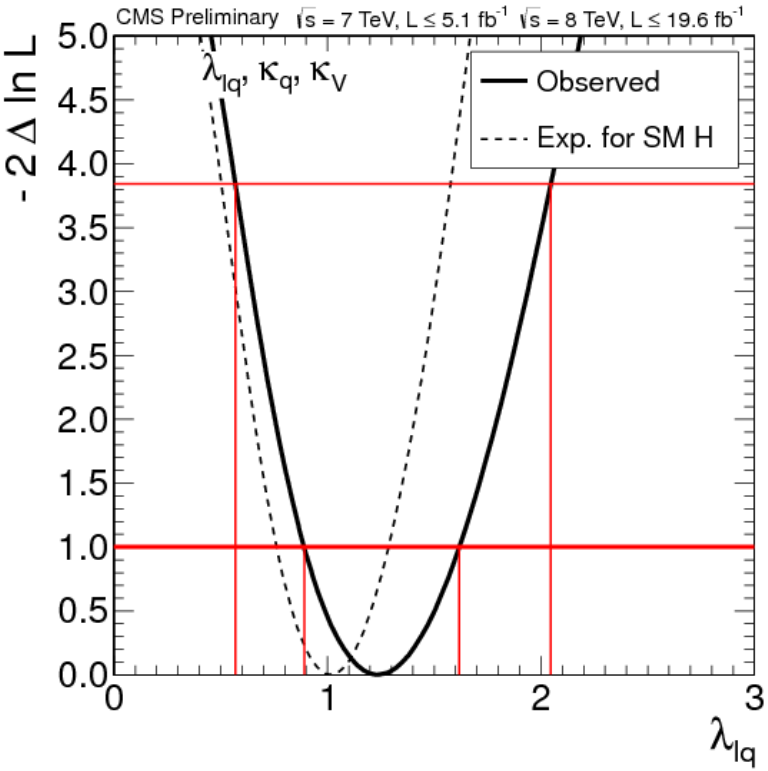
- **Extrapolate**
  - **Run II phase 0, 1**
  - **phase 2**
  - **role in big policy decisions**

Additional slides

Fermions: quark / leptons?

- **sensitivity :**
  - $\kappa_l = \kappa_\tau$ **from** $\tau\tau$ **decay mode**
  - $\kappa_q = \kappa_b = \kappa_t$ **from** $b\bar{b}$ **decay mode and loops**

- **CMS:** λ_{lq} **[0.57, 2.05] (95% CL)**

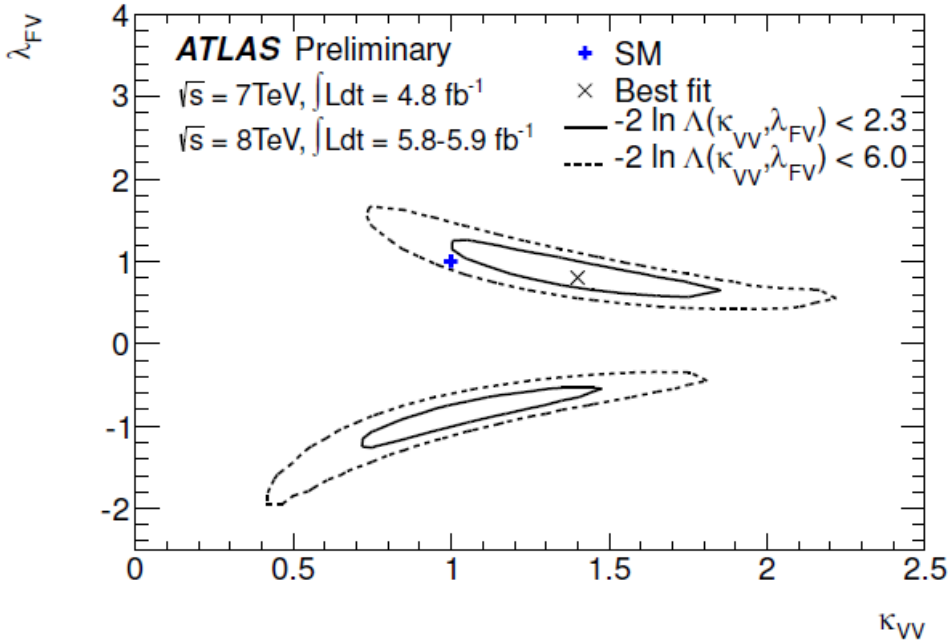


Fermion versus Vector couplings (2)

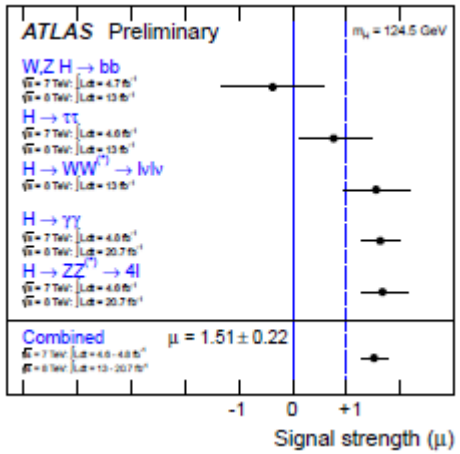
- **Group couplings : $\kappa_V = \kappa_W = \kappa_Z$; $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$**
  - **Assume: gg → H and H → γγ only through SM particles**

- **No assumption on total width:**

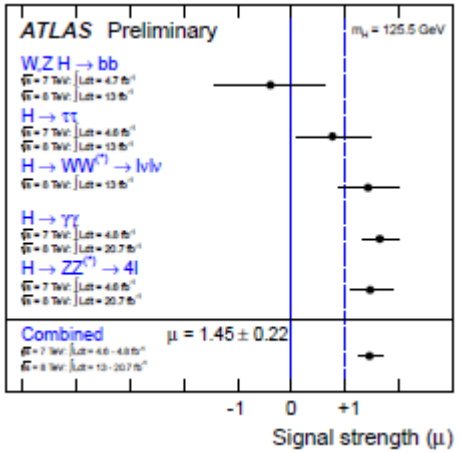
$$\lambda_{FV} = \kappa_F / \kappa_V \; ; \quad \kappa_{VV} = \kappa_V \kappa_V / \kappa_H$$



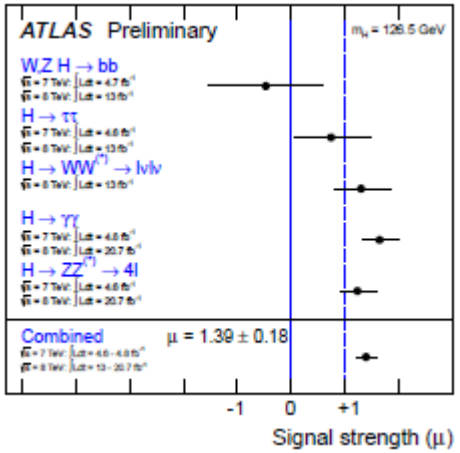
μ_i dependence on assumed m_H



$m_H = 124.5$



$m_H = 125.5$



$m_H = 126.5$

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}

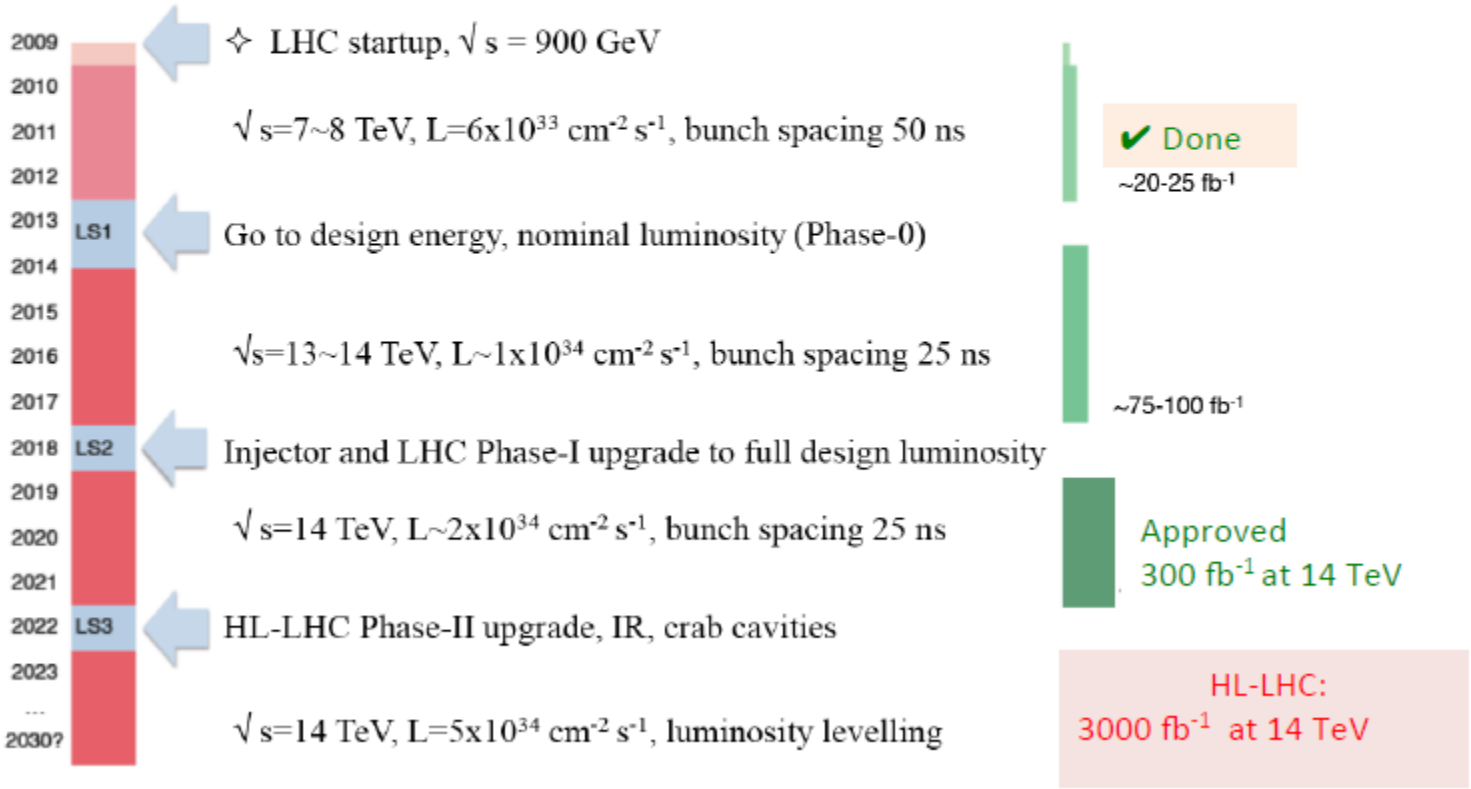
LHC Upgrade

14 TeV

~ 3000 fb^{-1}

*results in backup slides

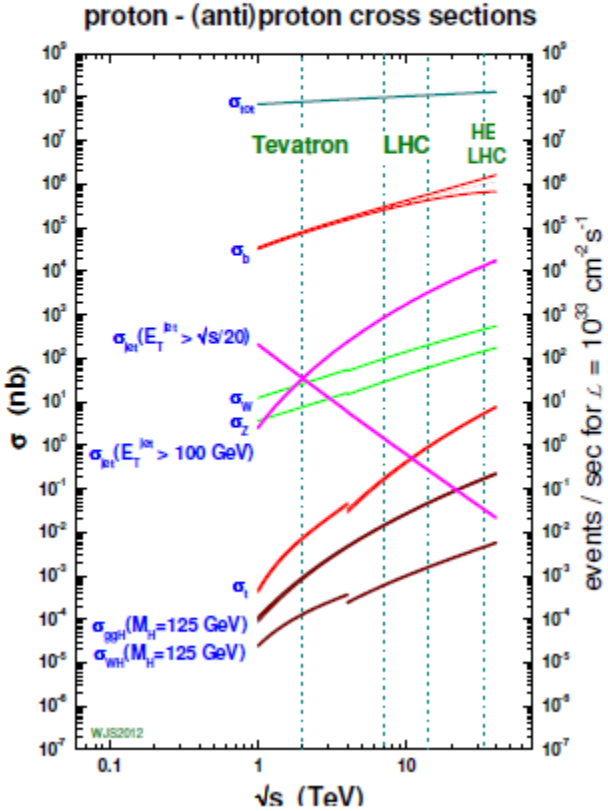
High Luminosity LHC: The timeline



High Luminosity LHC: the detectors 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
  - ....
- CRUCIAL to profit of L increase

Signal σ and Yields: HL/HE

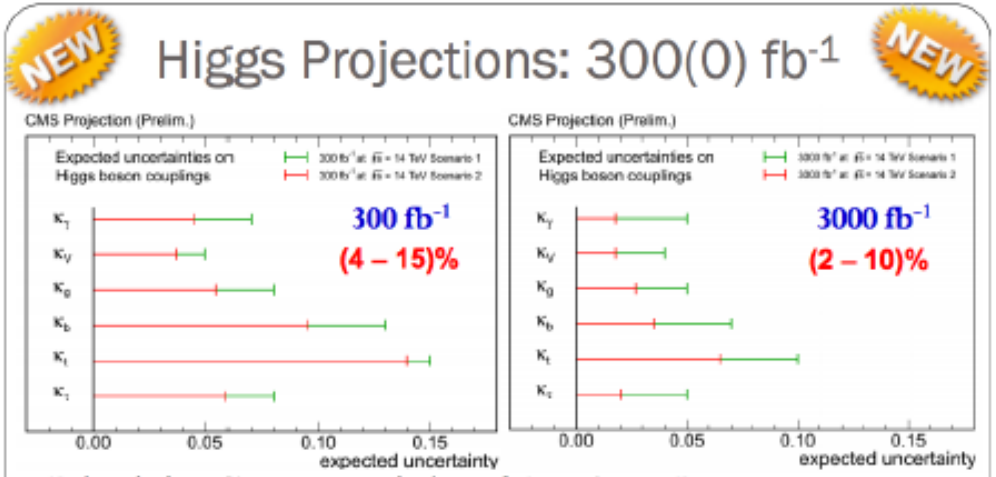


8 → 33 TeV: ggH x9.2 14 → 33 TeV: ggH→ HH x6

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

CMS: Couplings f at HL-LHC



Numbers in brackets are % uncertainties on coupling deviations for [scenario 2, scenario 1]

L (fb^{-1})	κ_γ	κ_V	κ_g	κ_b	κ_t	κ_τ
300	[5, 7]	[4, 5]	[6, 8]	[10, 13]	[14, 15]	[6, 8]
3000	[2, 5]	[2, 3]	[3, 5]	[4, 7]	[7, 10]	[2, 5]

Goal: ultimate precision of ~5% or better

CMS Projection

Assumption NO invisible/undetectable contribution to Γ_H:

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

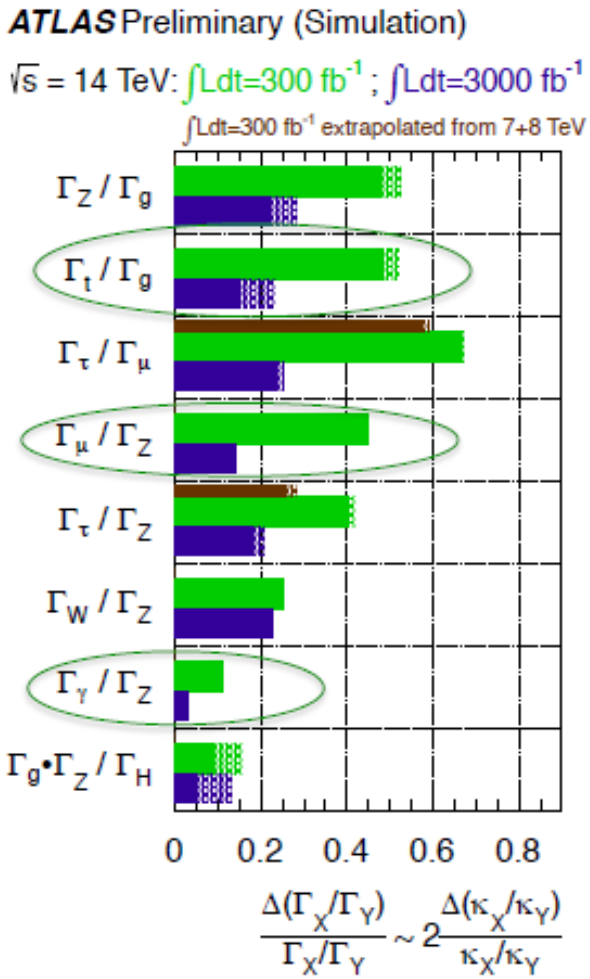
✓ γγ loop at 2-5% level

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

✓ direct top coupling at 7-10% level

✓ gg loop at 3-5% level

ATLAS: Coupling Ratios 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%

HL-LHC outlook

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
  - $\gamma\gamma$ 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%
  - $\gamma\gamma$ and gg 2-5%

**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, ..)