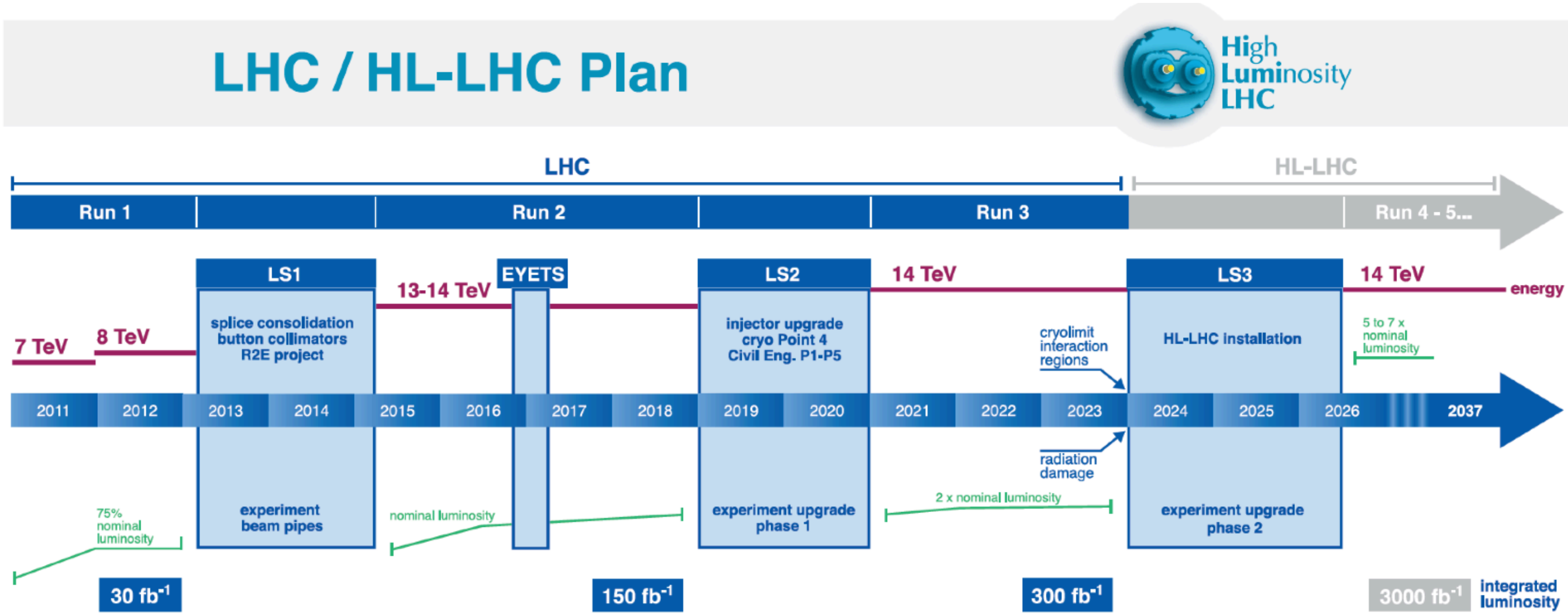
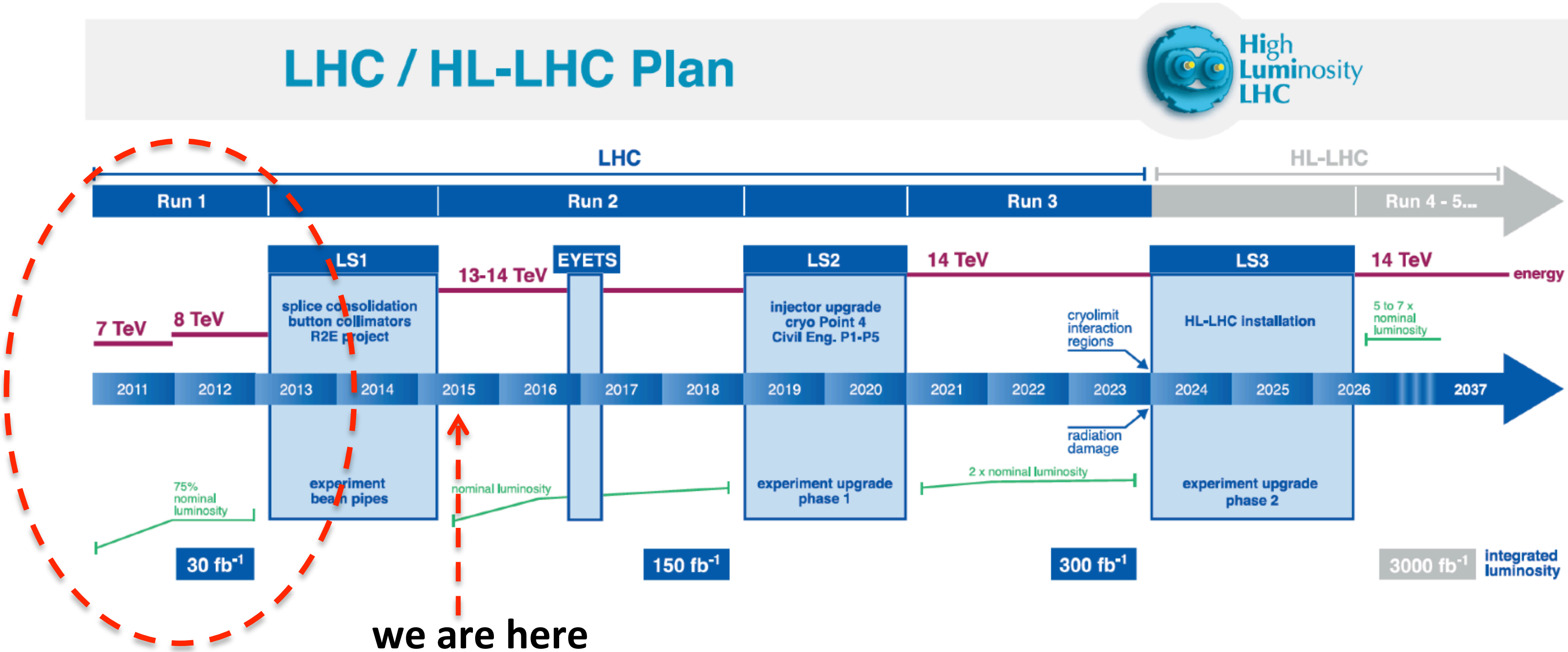


Higgs Physics Reach at HL-LHC

Mingshui Chen
(On behalf of the ATLAS & CMS Collaborations)
Institute of High Energy Physics, CAS

Workshop on Physics at CEPC
10-12/08/2015, Beijing



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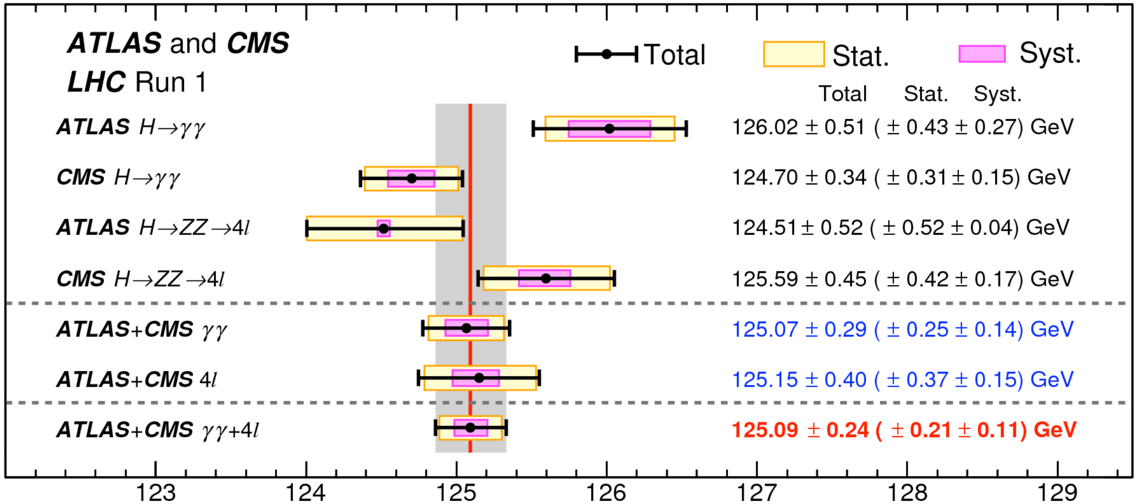
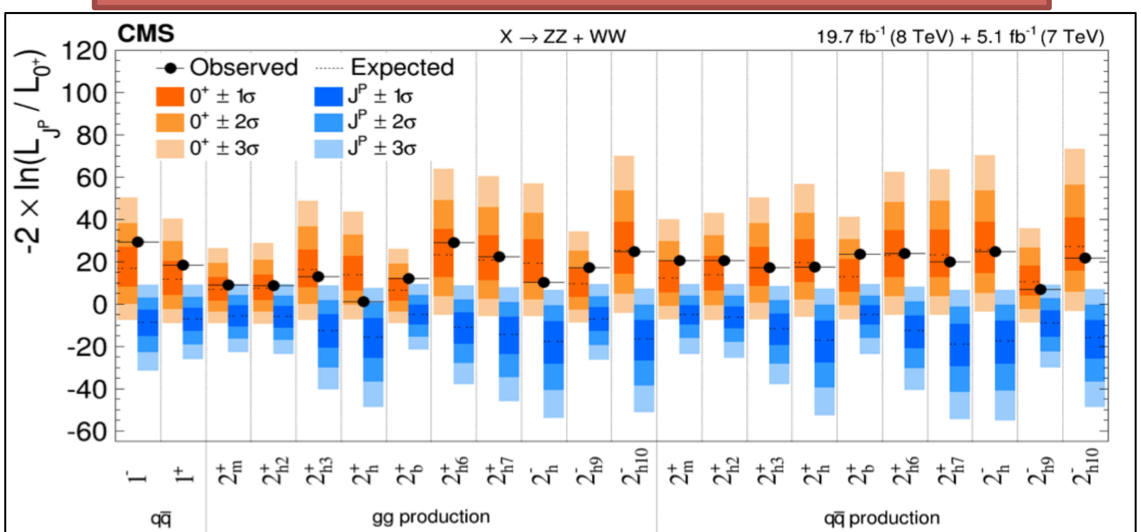
Current Status of Higgs Measurements



LHC combined m_H = 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV

Spin/CP strongly favors the SM 0^+ hypothesis



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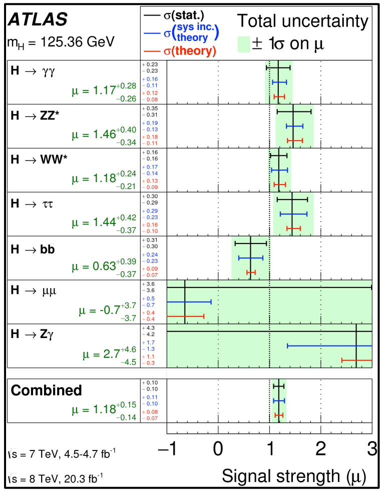
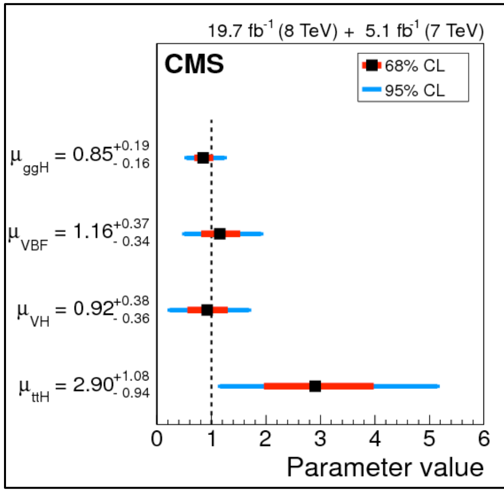
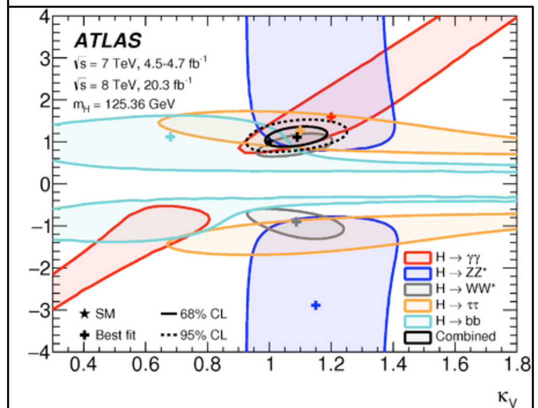
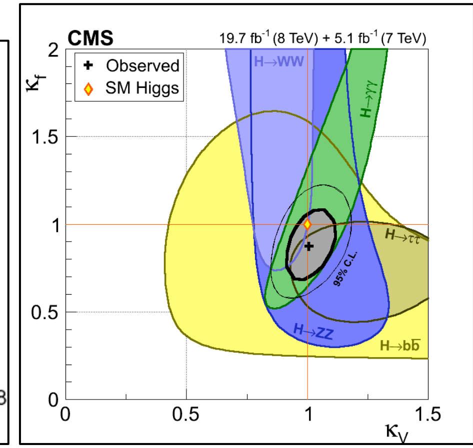
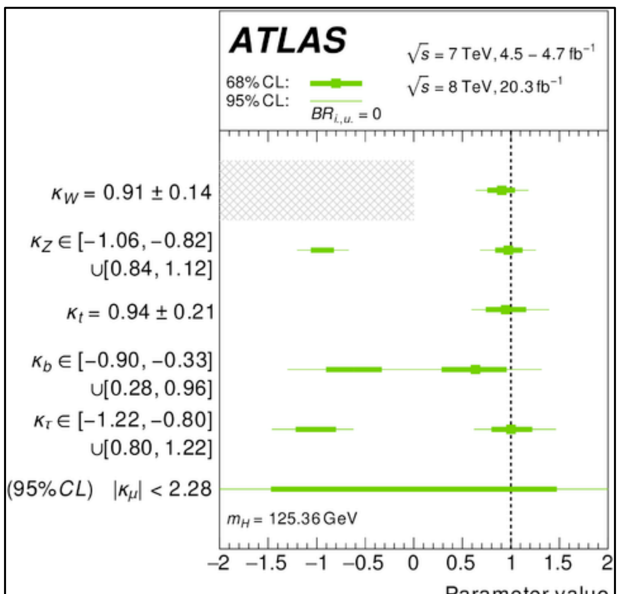
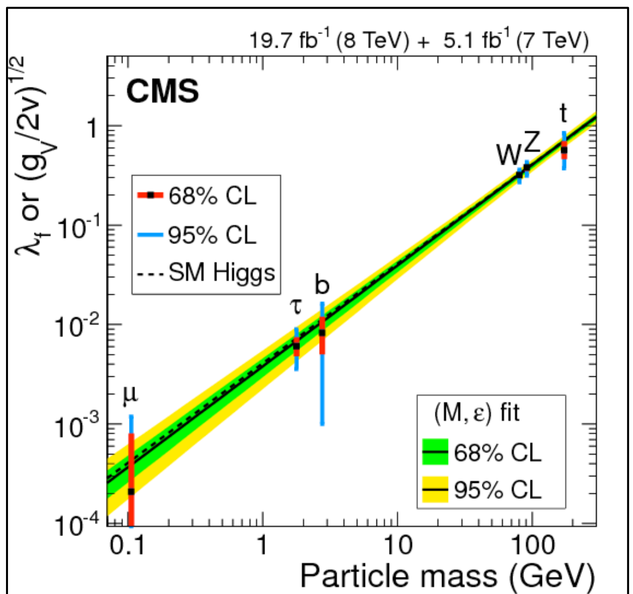


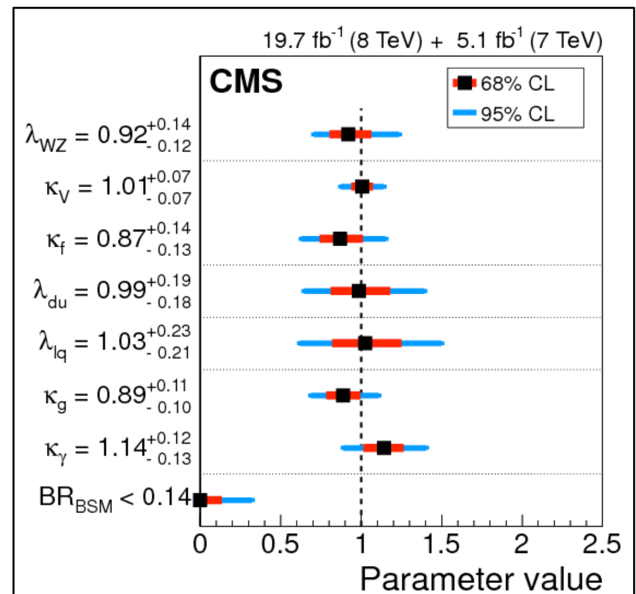






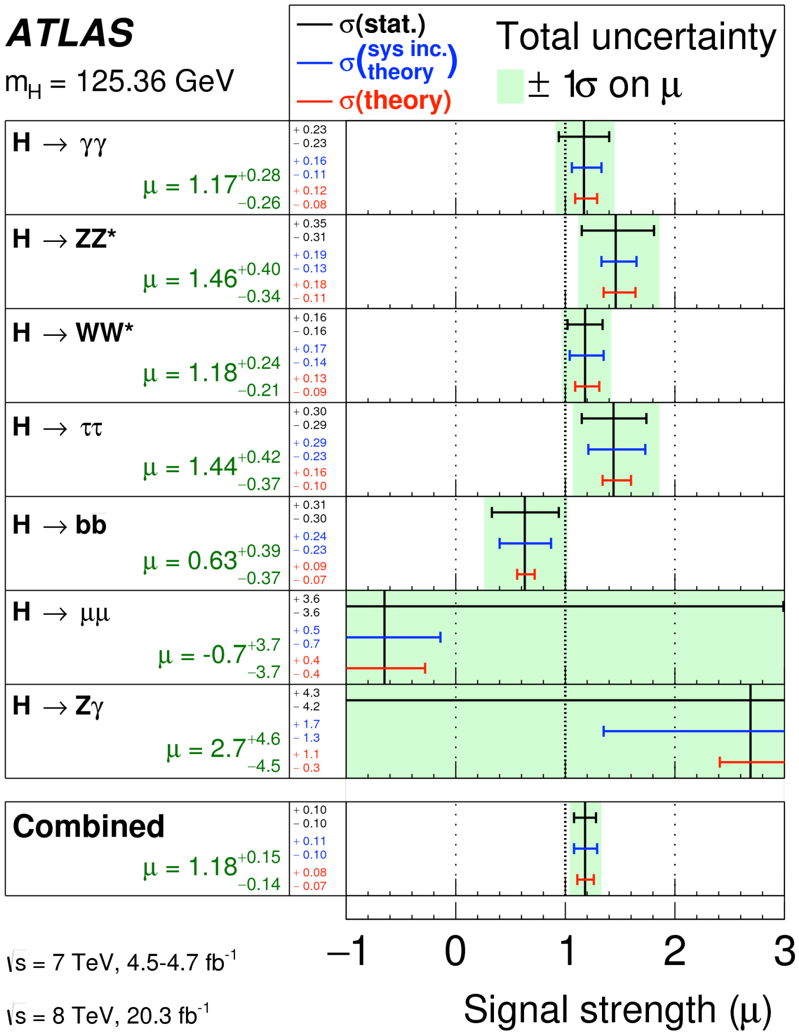






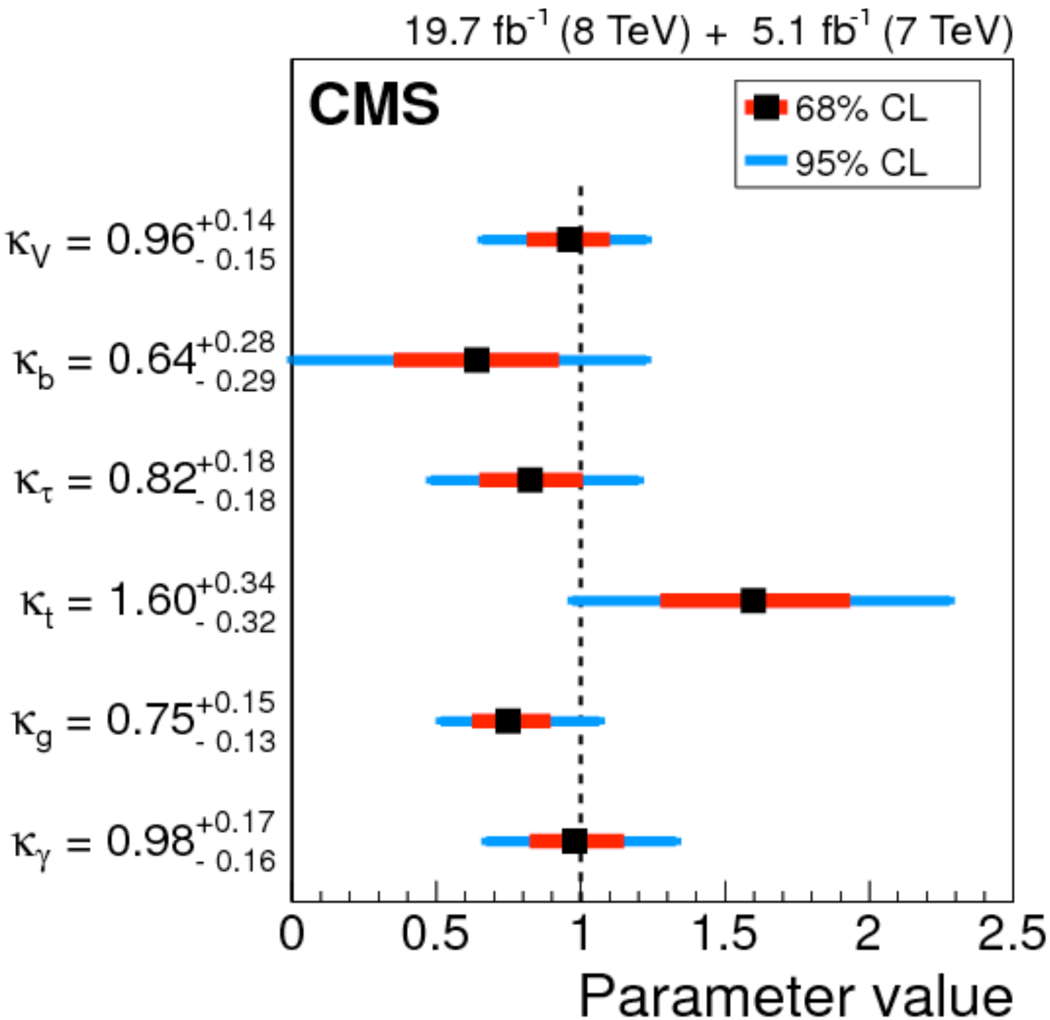
Consistent with SM prediction within current level of accuracy

Current Status of Higgs Measurements



Precision on signal strengths: 20-50%

Current Status of Higgs Measurements



Precision on coupling measurements: 15-40%

Coupling Deviations in BSM

- How well do we need to measure Higgs couplings ?
- Typical effect on coupling from heavy particle M or new physics at scale M:

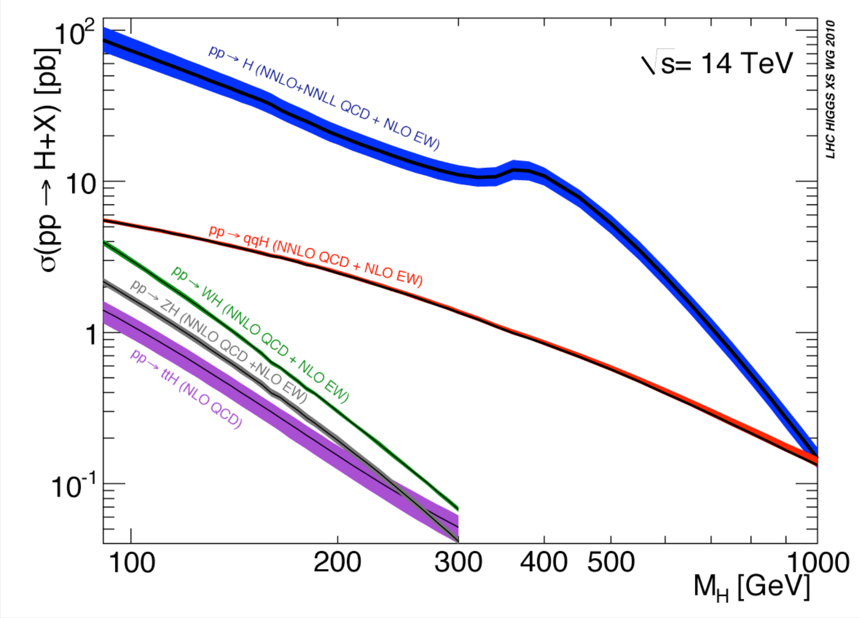
$$\Delta \sim \left(\frac{v}{M}\right)^2 \sim 5\% \text{ @ } M \sim 1\text{ TeV}$$

*Han et al., hep-ph/*0302188
*Gupta et al., arXiv:*1206.3560
……

Typical sizes of coupling modifications: arXiv:1310.8361

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

HL-LHC as a Higgs Factory

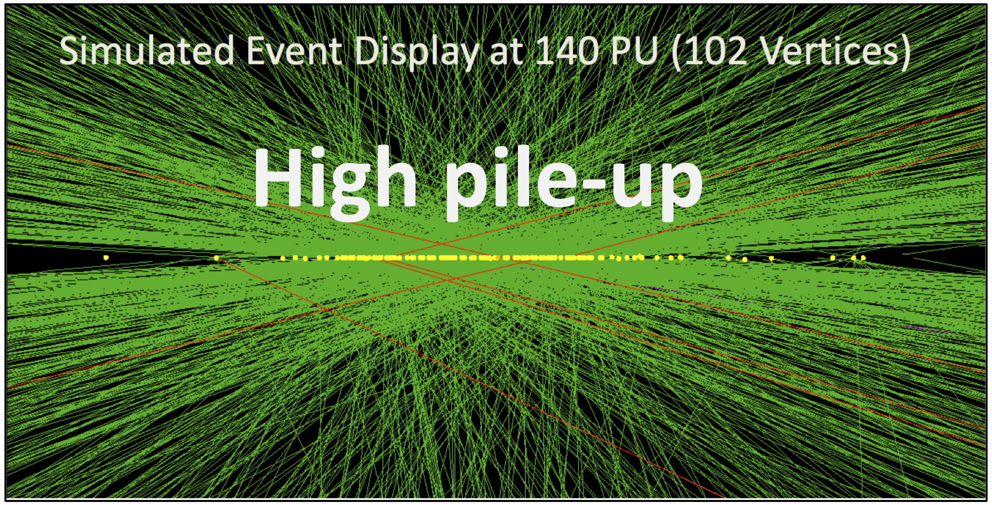


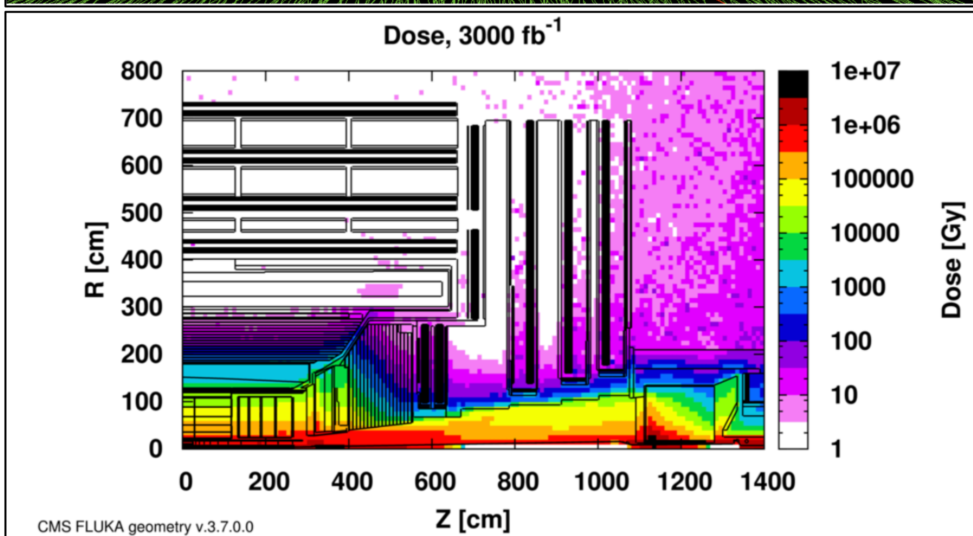
Higgs bosons at $\sqrt{s}$=14 TeV 3000 fb^{-1}	
HL-LHC total	170 M
VBF (main decays)	13M
ttH (main decays)	1.8M
H→Zγ	230k
H→μμ	37k
HH (all)	121k

Higgs physics goals

- **Rare decays and couplings**
- **CP mixing**
- **Higgs pair productions**
- **……**

Challenges at HL-LHC



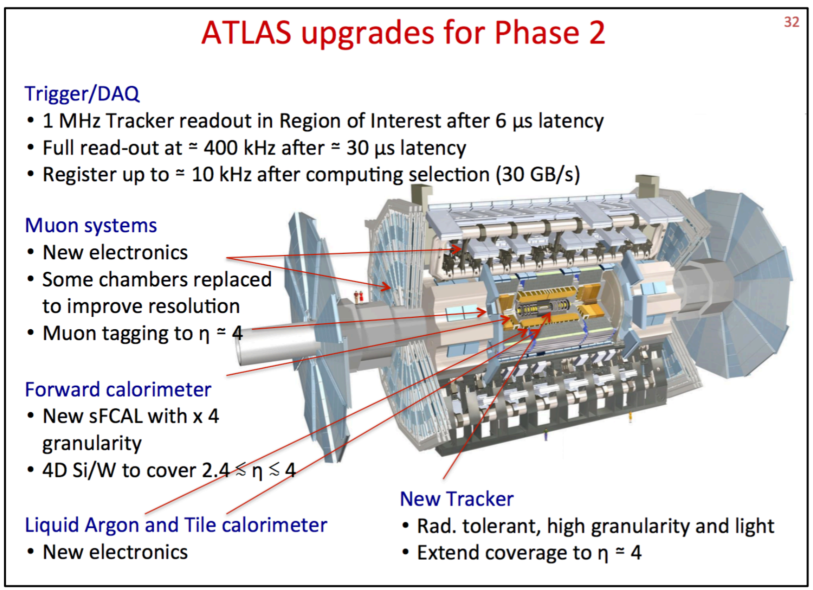


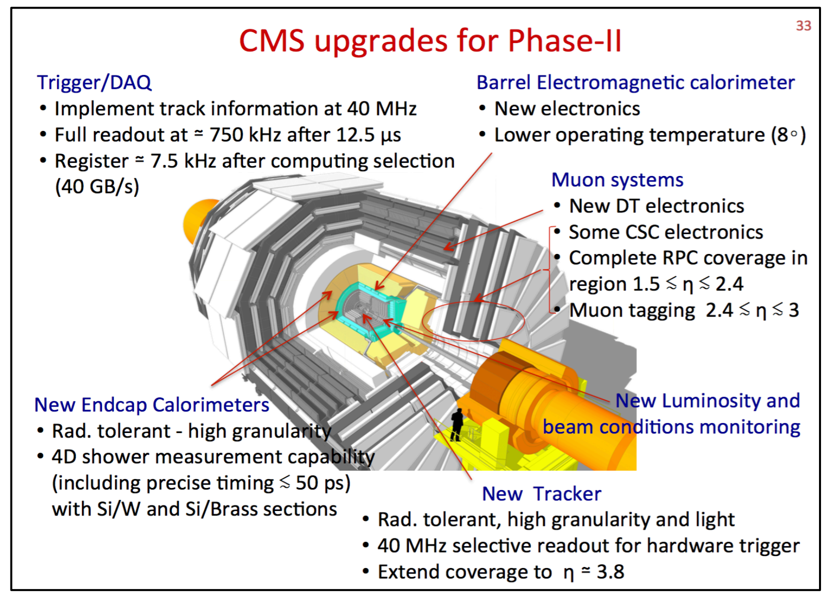
High radiation level

ATLAS & CMS Phase II Upgrade

Common strategy to cope with high pile-up and high radiation dose and to obtain similar performance as that in RUN1

- Re-design L1 trigger logic to keep leptons pT thresholds and L1 trigger rate low
- New tracker with high granularity and radiation resistance and extended η coverage
- Extension of calorimeter and muon detectors coverage to increase acceptance and improve performances





Projection Approaches

ATLAS

- Detector response functions based on full Geant4 simulation
    - pileup $\langle\mu_{PU}\rangle = 60$ for 300 fb^{-1} projection
    - pileup $\langle\mu_{PU}\rangle = 140$ for 3000 fb^{-1} projection

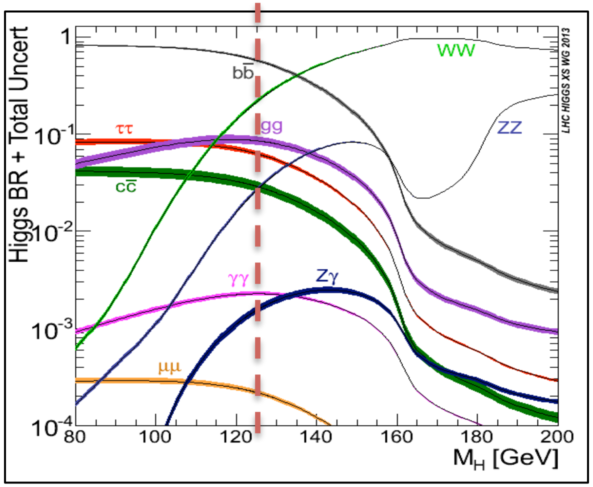
CMS

- Extrapolated from RUN1 analyses
    - RUN1 pileup <m> ~20
- Assume detector upgrades keep current performance
    - Verified with full detector simulation in recent Phase II TP
- Two scenarios for systematic uncertainties
    - Scenario 1: systematics remain the same as RUN1
    - Scenario 2: theory uncertainties scale by 50%, others scale by $1/\sqrt{L}$

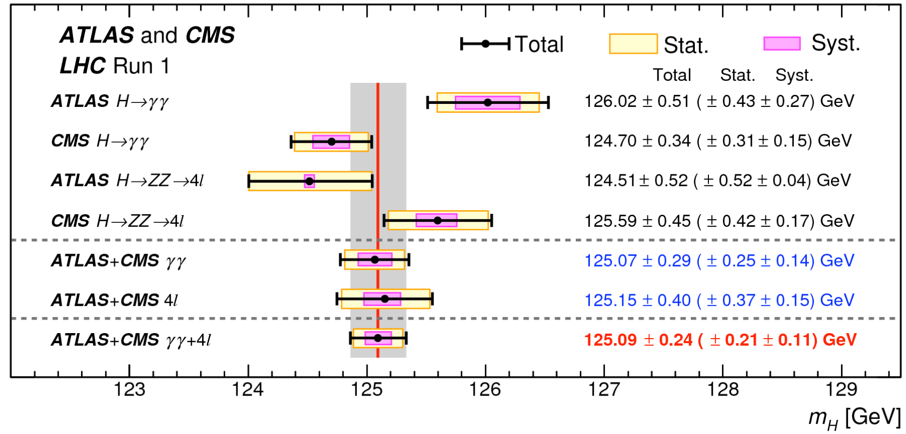
Higgs Mass

A fundamental parameter

important input to precision Higgs measurement



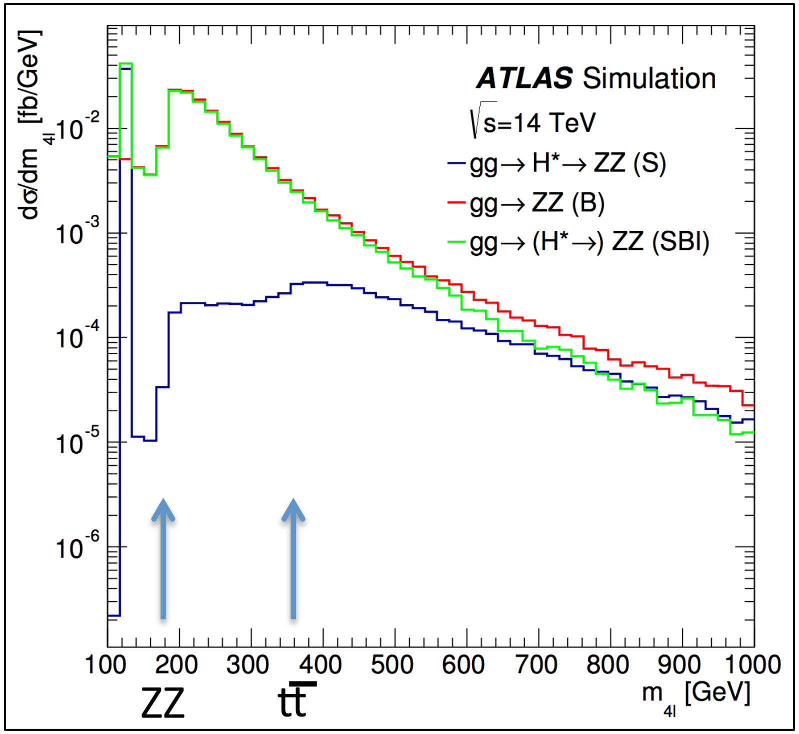
- For HWW/HZZ: $(\Delta BR/BR)/\Delta m_H \approx 8\%/\text{GeV}$
- A 50 MeV of Δm_H → ~ 0.5% uncertainty on BR measurement



Snowmass report (arXiv:1310.8361)

- Assuming both stat and syst uncertainties scale as $1/\sqrt{L}$
  - projected from previous preliminary old results [±0.25 (stat) ±0.45(syst) GeV]
- Precision@3000fb^{-1}
  ±15 (stat) ±25(syst) MeV

Total Width from Offshell Higgs



$\sqrt{s}/\sigma$	S (fb)	B (fb)	SBI (fb)	$qq \to ZZ$ (fb)
8 TeV	0.03	0.67	0.64	16.7
14 TeV	0.11	1.96	1.86	36.9

cross sections for ZZ→2e2mu, gen level cut on m4l >200 GeV for gg initiated processes and > 40 GeV for qqZZ

$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

The ratio of $\mu_{\text{off-shell}}$ to $\mu_{\text{on-shell}}$ provides a measurement of the total width of the Higgs boson, under several assumptions*:

$$\Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1}\ \text{MeV (stat+sys)}$$

L2: 3000 fb^{-1} scenario

*see backup

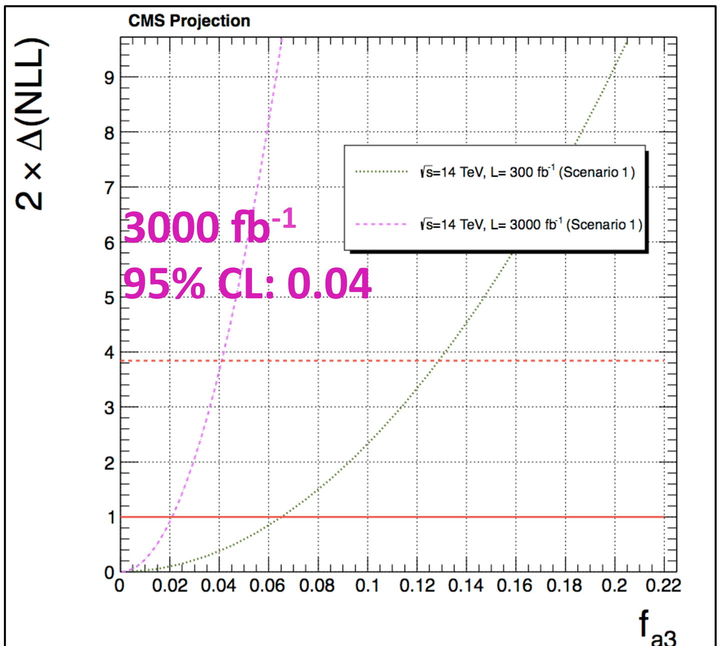
CP-mixing in H→ZZ→4l

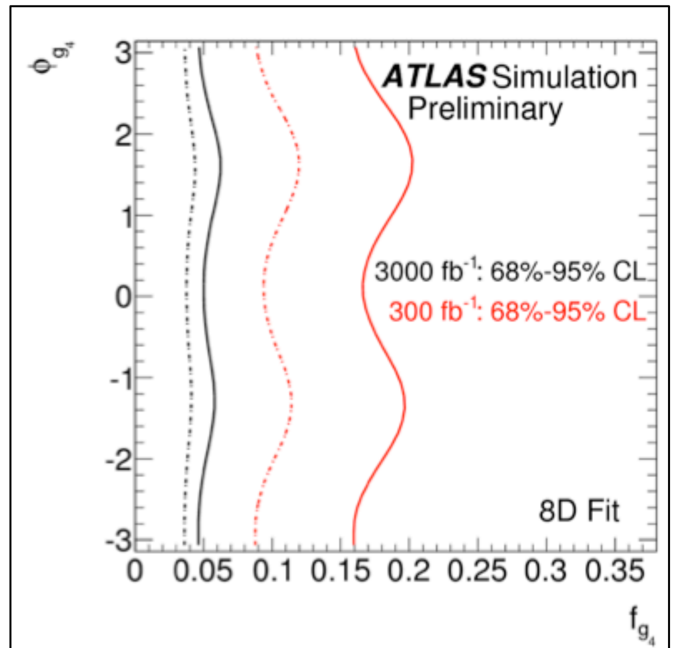
Decay amplitude for spin-0 boson decaying to spin-1 gauge bosons

$$A(H \to ZZ) = v^{-1}\left(\underbrace{a_1 m_Z^2 \epsilon_1^* \epsilon_2^*}_{\text{SM tree process}} + \underbrace{a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}}_{\text{BSM CP-even}} + \underbrace{a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}_{\text{CP-odd term}}\right)$$

SM tree process | BSM CP-even | **CP-odd term**

Measure fraction of CP-odd contribution $f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_3|^2\sigma_3}$





Note: $f_{a_3} \equiv f(g_4) = \frac{|g_4|^2\sigma_4}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}$

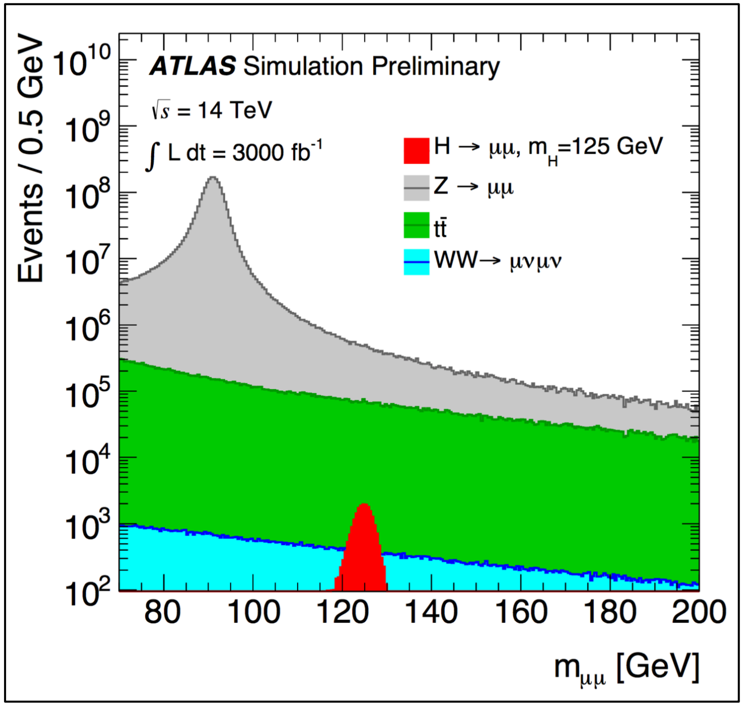
(CMS neglects small |g₂| term)

Rare Decay: H→μμ

ATL-PHYS-PUB-2014-016
CMS-NOTE-13-002
CERN-LHCC-2015-010

Probe the second generation couplings

- BR (2.2 x 10^{-4}), benefit largely from dataset increase @ HL
- Main backgrounds from Z+jets, ttbar and WW
  - high $p_T^{\mu\mu}$ to suppress Drell-Yan
  - need excellent dimuon mass resolution



Expected significance > 7 σ with 3000 fb^{-1}

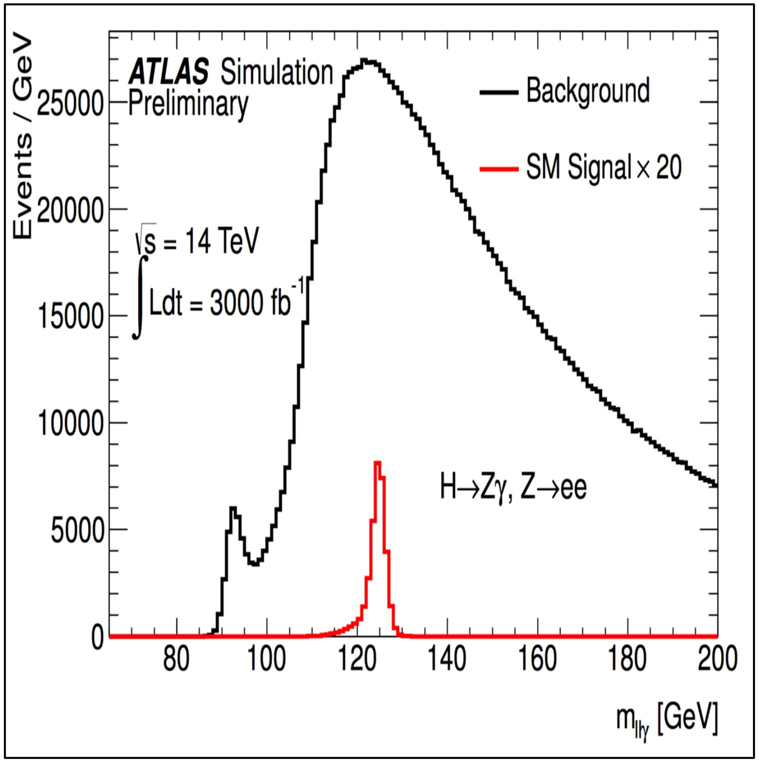
		μ-hat error	
	$\mathscr{L}$ (fb^{-1})	Scenario 1	Scenario 2
ATLAS	300	± 0.39	± 0.38
CMS	300	± 0.42	± 0.40
ATLAS	3000	± 0.16	± 0.12
CMS	3000	± 0.20	± 0.14

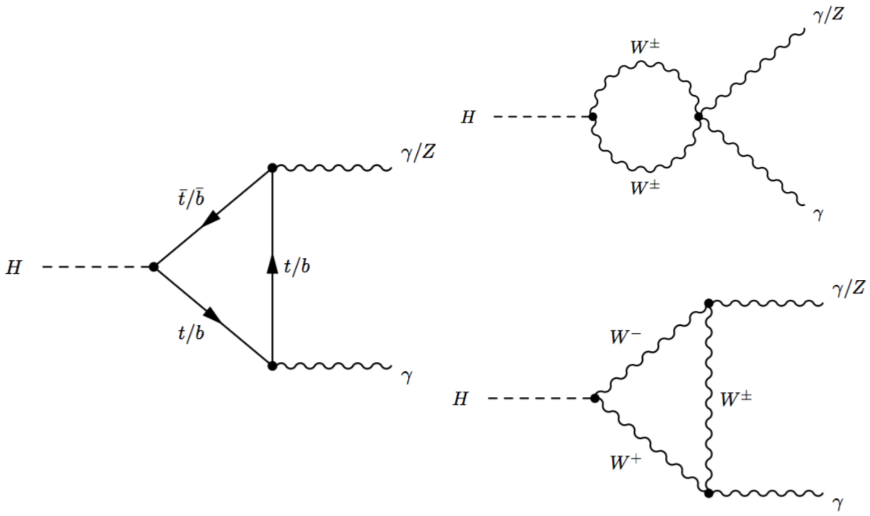
ATLAS scenarios: 1- full sys 2- no theory sys
CMS scenarios: 1- run-1 sys 2- reduced sys

Rare Decay: H→Zγ

Sensitive to new physics via decay loops

- SM BR is only 10^{-4} (including Z→ee/μμ)
- Large backgrounds from Z+γ and Z+jets





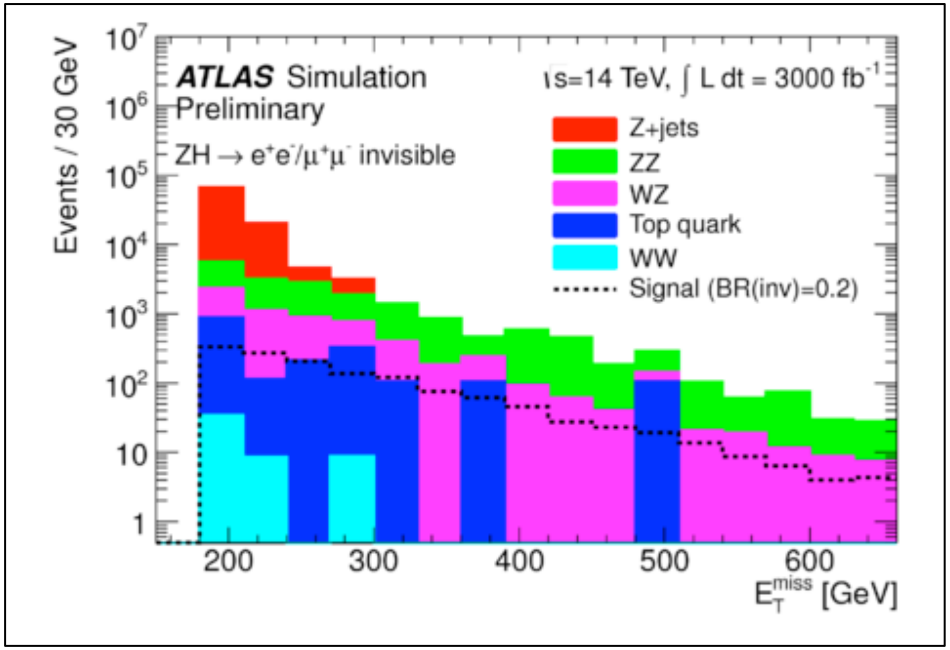
CMS	300 fb^{-1}	3000 fb^{-1}
$\Delta\mu/\mu$	62%	20-24%

ATLAS	300 fb^{-1}	3000 fb^{-1}
Significance		3.9 σ

Higgs to Invisible

Search for the invisible branching ratio of the Higgs boson

- Projection studies use ZH → ll + invisible
- Look for excess in high missing E_T tail



Expected 95% CL upper limits on the inv. branching fraction

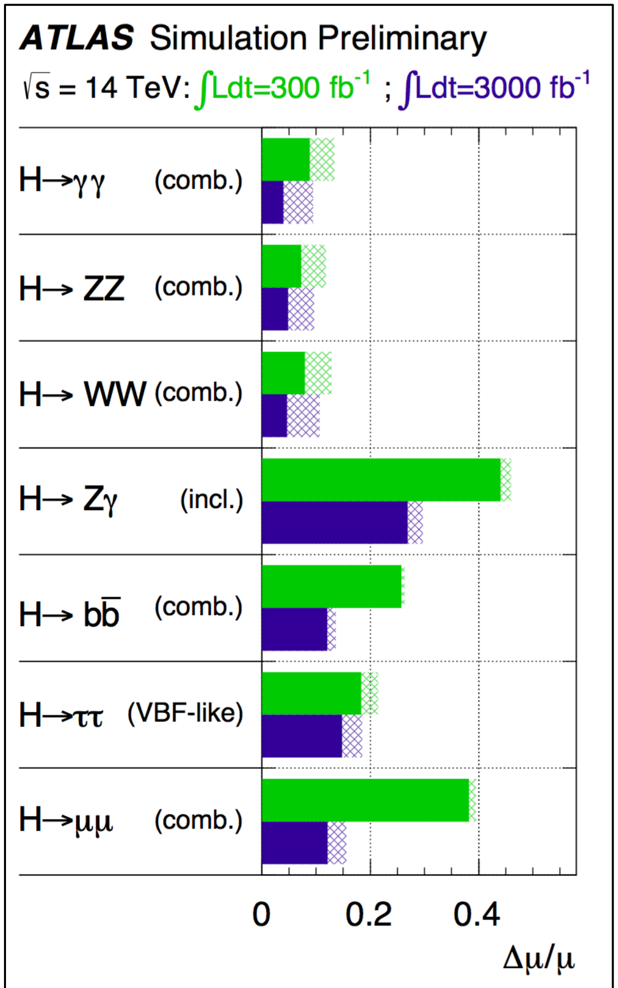
L (fb^{-1})	ATLAS	CMS
300	[23, 32]%	[17,28]%
3000	[8,16]%	[6,17]%

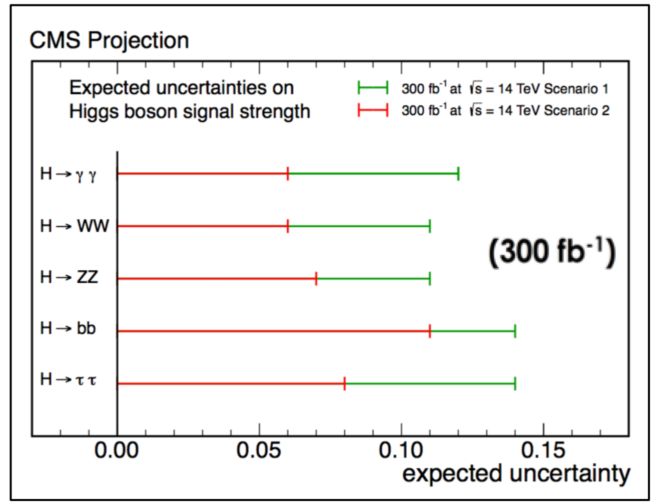
Numbers in brackets are estimated under [Scenario2, Scenario1] for CMS, and [realistic scenario (~2-3% unc.), conservative scenario (~5% exp and 5% theo unc)] for ATLAS

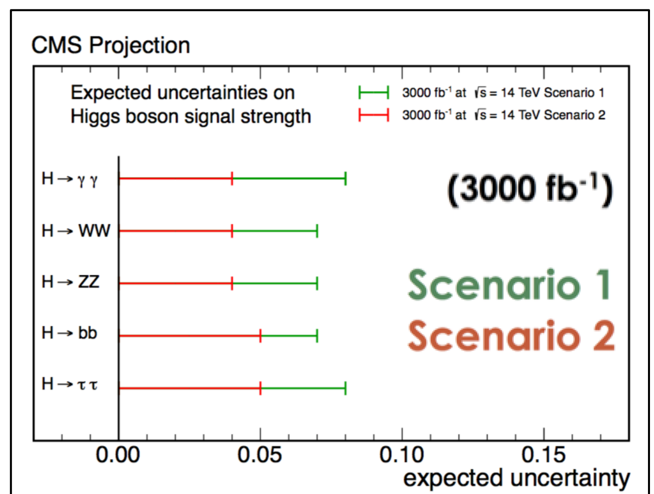
Signal Strengths

LHC only allows to measure σxBR

- Express a ratio μ to SM value







Coupling Fits

- Model-dependent fits
  - single resonance
  - Narrow width approximation
  - CP even tensor structure

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

$$k_i^2 = \frac{\Gamma_i}{\Gamma_I^{SM}} \qquad k_H^2 = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$$

- Without further assumptions, LHC can measure ratios: $\lambda_{ij} = \kappa_i/\kappa_j$, $\kappa_{ij} = \kappa_i\kappa_j/\kappa_H$

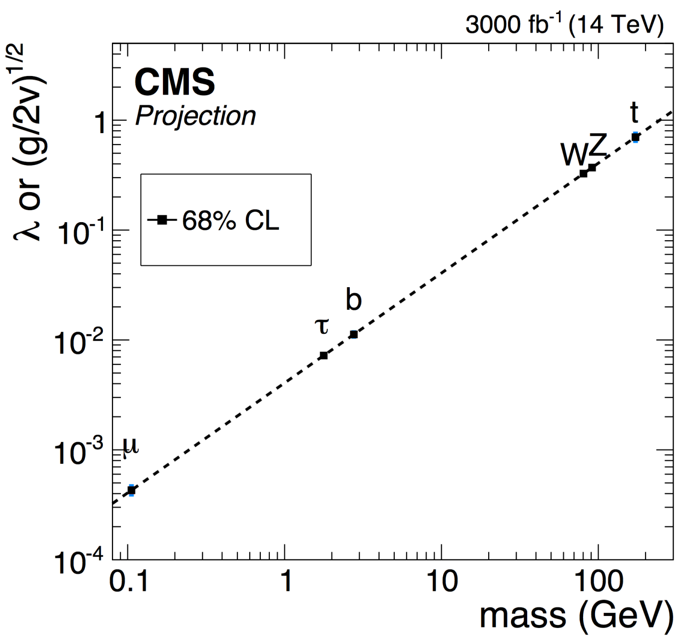
Couplings vs. Particle Mass

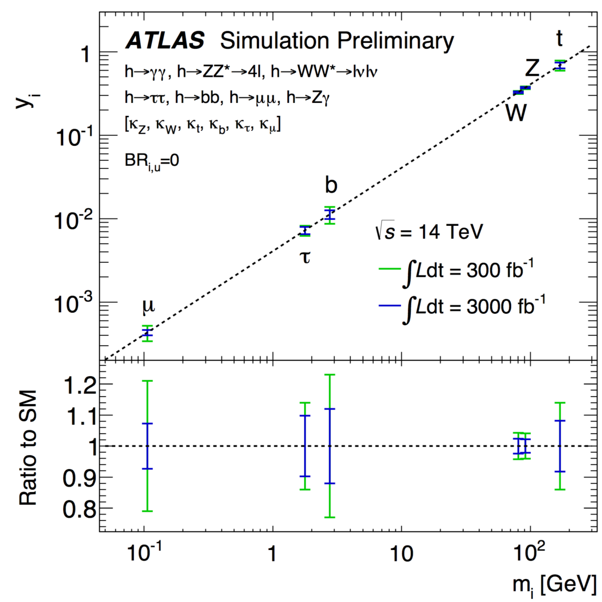
Couplings are mass dependent in SM

- assume no new Higgs decay modes
- loops resolved

$$g_{Hff} = \frac{m_f}{\upsilon},\ g_{HVV} = \frac{2m_V^2}{\upsilon} \quad \Rightarrow$$

$$g_{Hff} = \kappa_f \cdot \frac{m_f}{\upsilon},\ g_{HVV} = \kappa_V \cdot \frac{2m_V^2}{\upsilon}$$

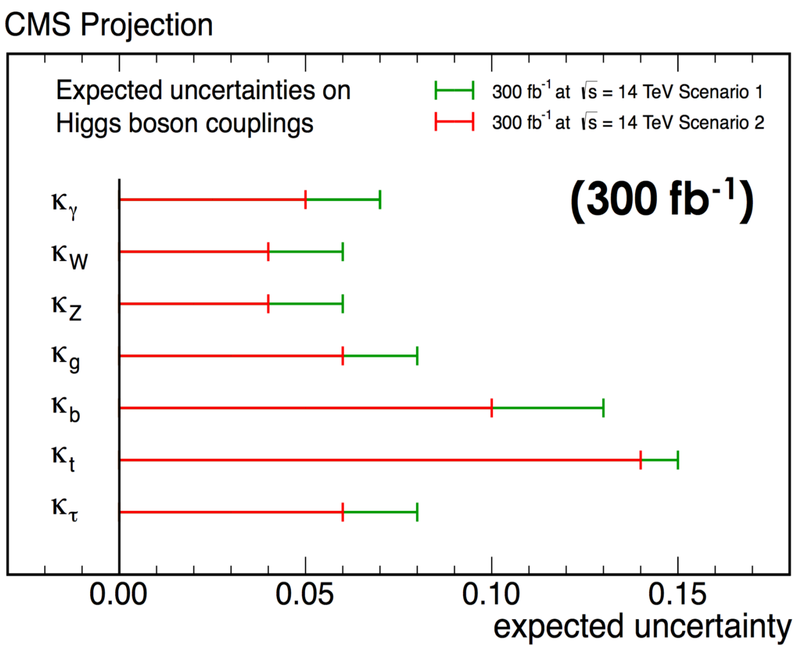


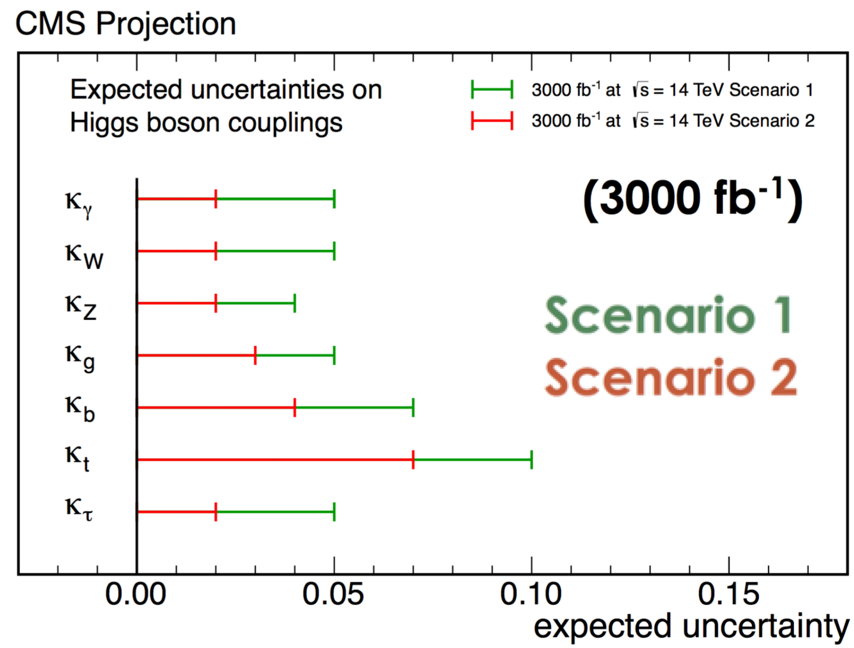


Percent level precision for most of the couplings

Effective Couplings for Loops

Allow new physics entering in loops



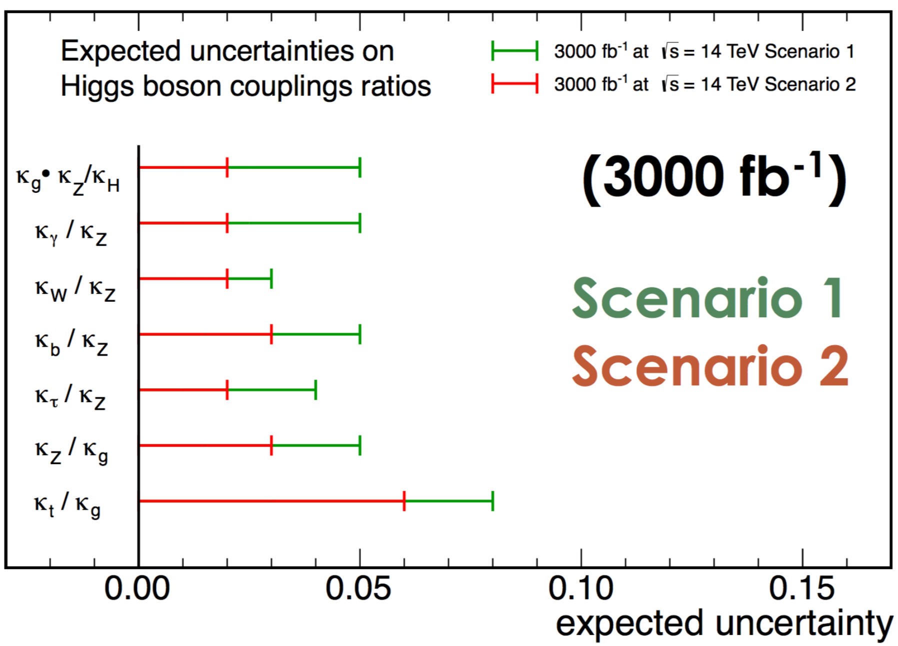


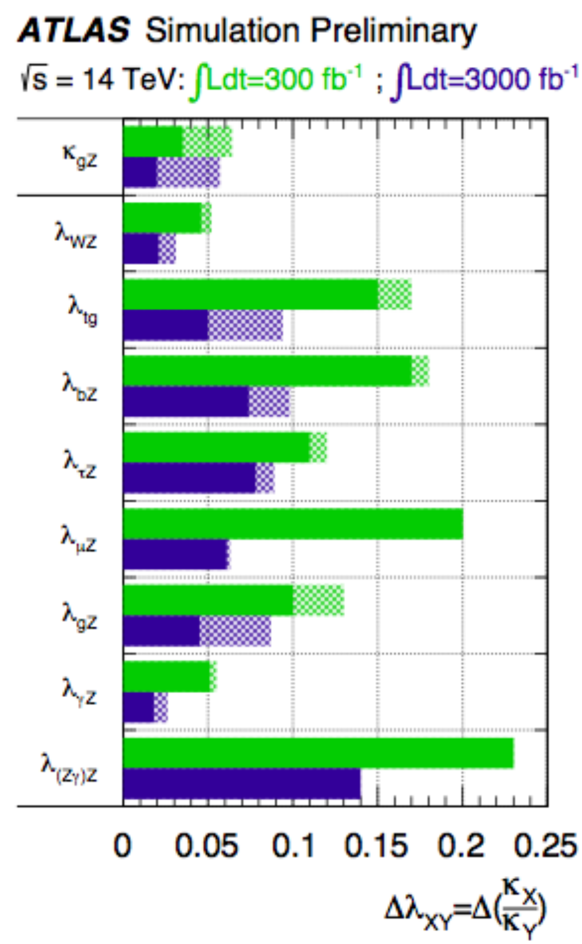
Ultimate precision 2-10%, varies by coupling
Similar sensitivity for ATLAS

Coupling Ratios

Most generic fit, removing assumption on the total width

- only ratios of coupling scale factors can be determined at LHC
- also probe for new physics contributions in loop processes





Theory Uncertainties

What is needed to keep it below 10% of total
(30% of the expected total experimental uncertainty)

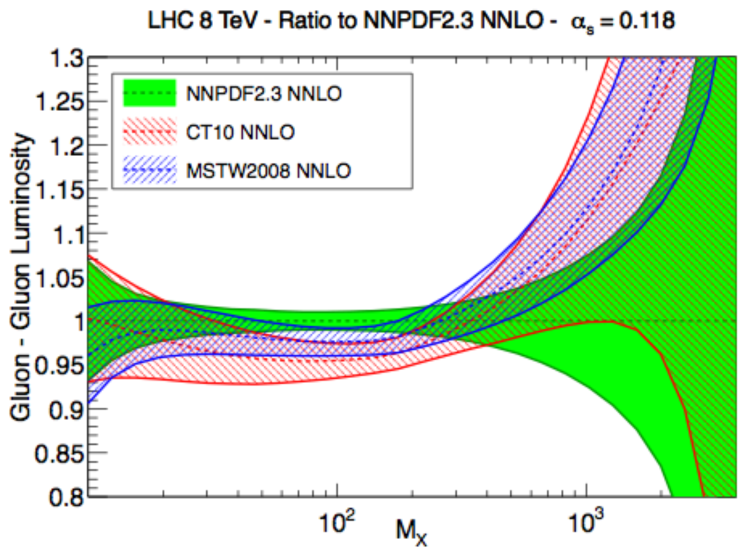
Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty by $\lesssim$10% for 300 fb^{-1}			by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j → 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j → 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j → VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j → VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9	-	-	-	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	-	-	-	2

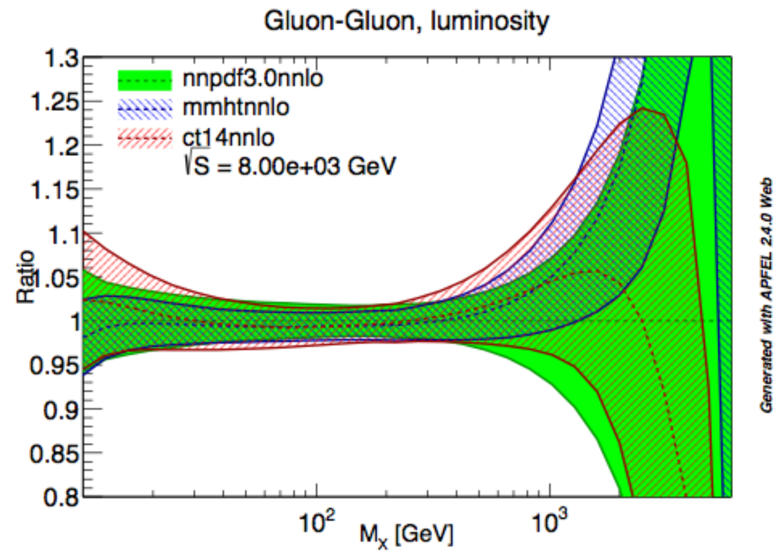
Recent Improvements in Theory Prediction

2014

2015 now

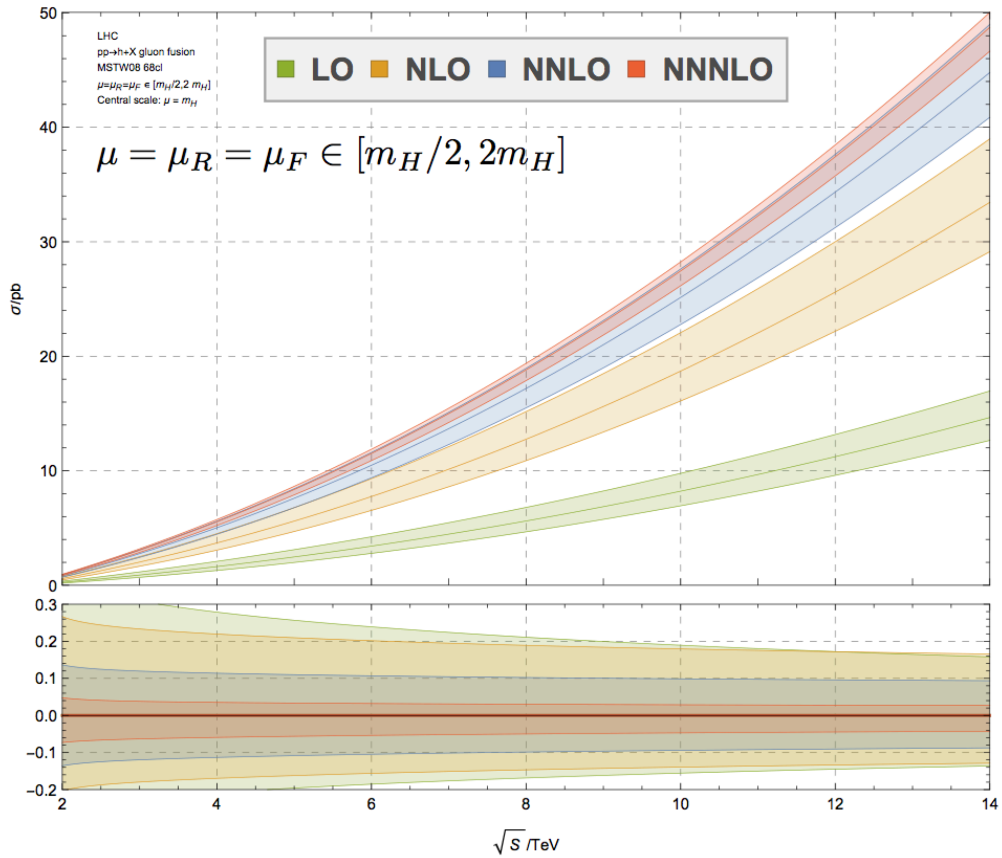
GLUON-GLUON





For 125 GeV ggH, PDF uncertainty decreases from 7% → 3%

Recent Improvements in Theory Prediction



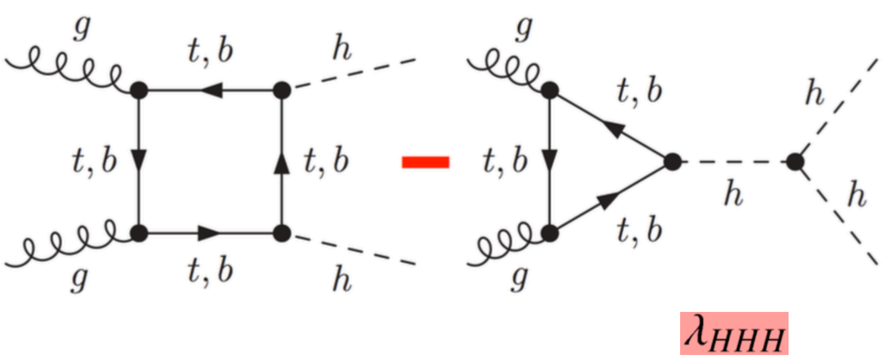
Inclusive gluon fusion cross section now available at N^3LO, scale variation is only 3%, a big reduction for the uncertainty due to missing higher order QCD corrections

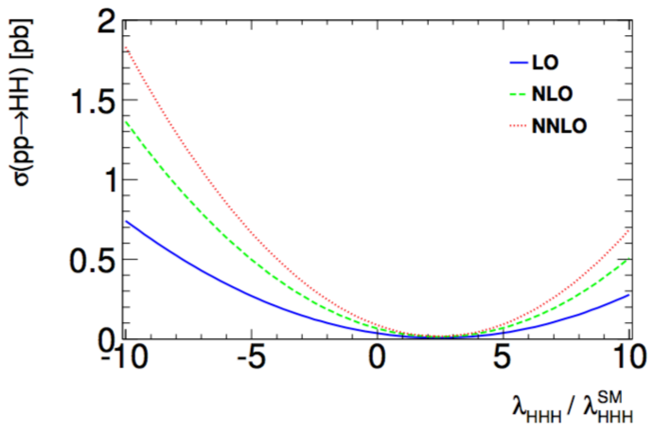
Higgs Pair Production

Probe Higgs self-interaction

- directly probe the Higgs field potential
- crucial to test the Higgs sector to its full extent

Two interfering diagrams (destructive)



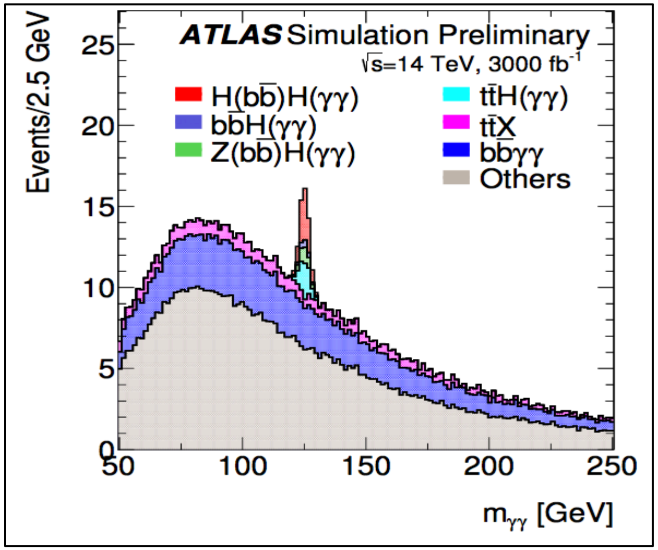


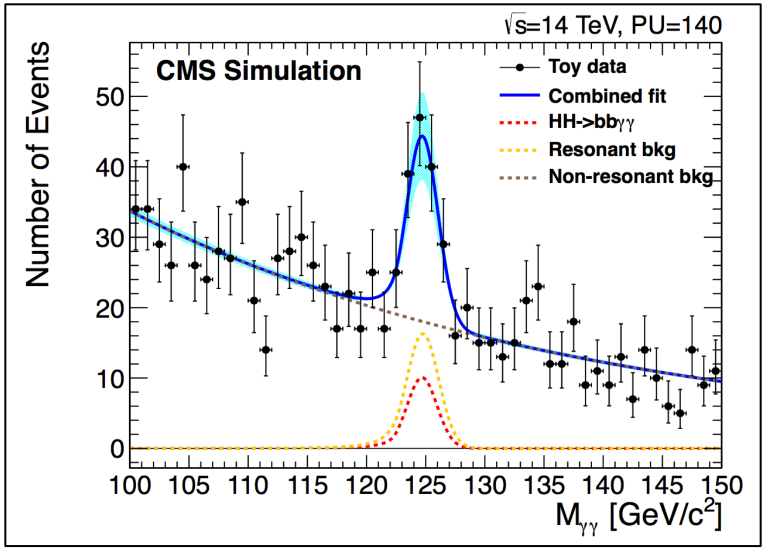
SM cross section @ 14 TeV: **40.8 fb** (NNLO)

ATL-PHYS-PUB-2014-019
CERN-LHCC-2015-010

HH→bbγγ

- Branching ratio 0.26%, total yield 320 events for 3000 fb^{-1}
- Much larger resonant and non-resonant backgrounds



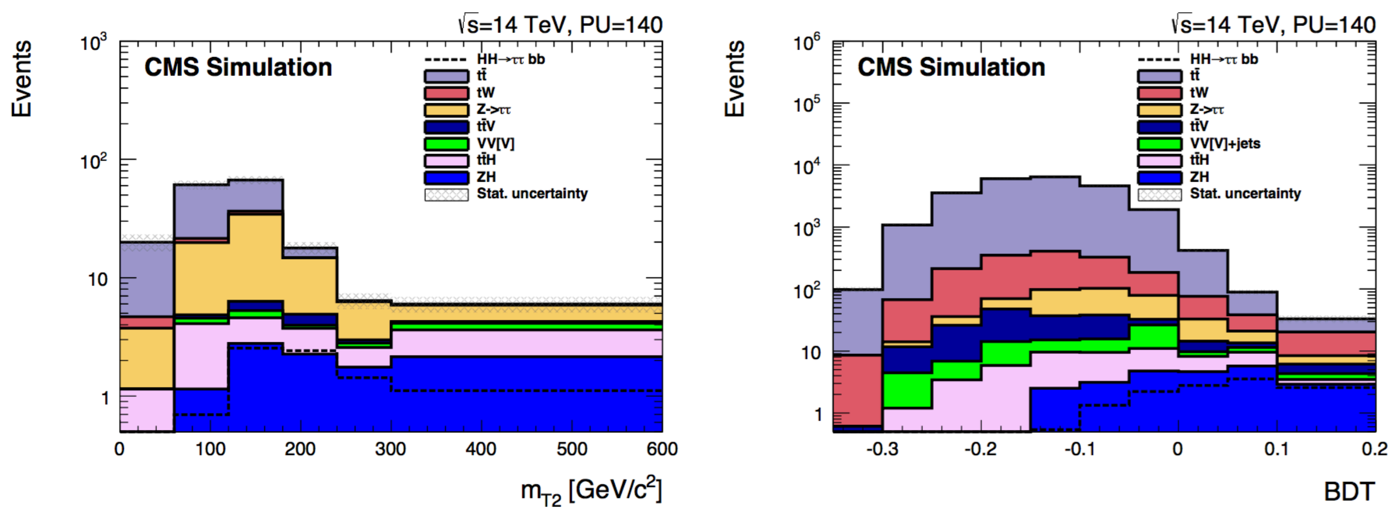


- Both experiments expect 8-9 events after event selections corresponding to ~1.3 σ for ATLAS and 67% uncertainty on signal strength for CMS

CERN-LHCC-2015-010

HH→bbττ

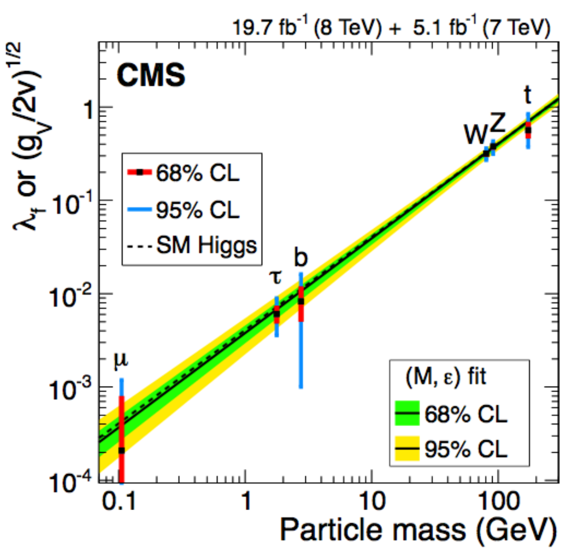
- Branching ratio 7.3%, total yield 8900 events for 3000 fb^{-1}
- CMS studied it in $\tau_\mu\tau_h$ and $\tau_h\tau_h$ final states, expects a combined bbττ significance 0.9 σ



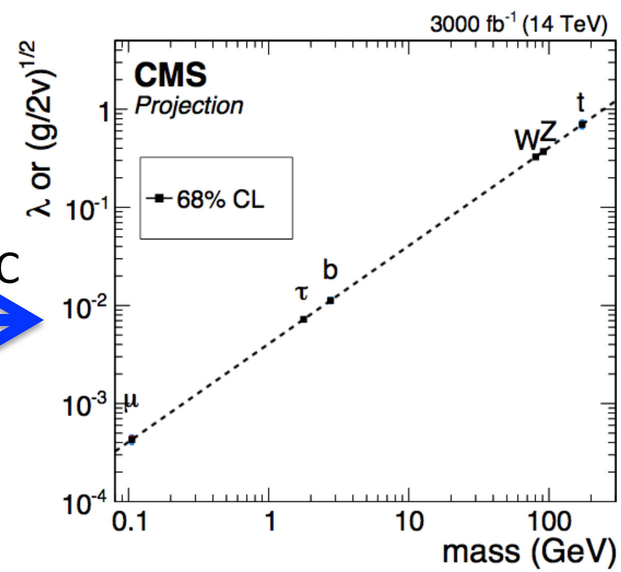
- 1.9 σ expected by combing bbγγ and bbττ, with an uncertainty 54% on signal strength
- Significant improvements are expected by adding more channels and using MVA techniques

Summary

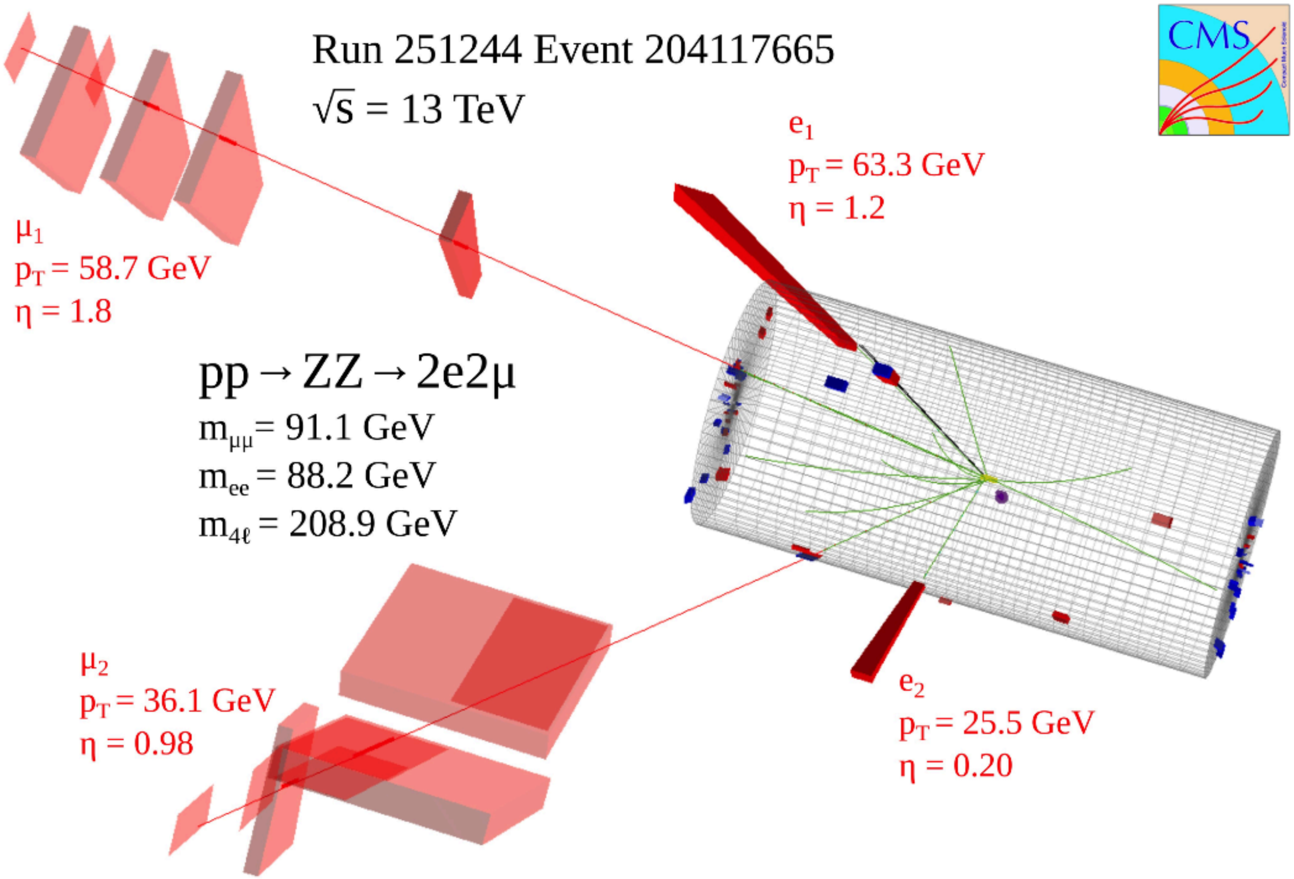
- The discovery of the Higgs boson has opened the door towards a deeper understanding of particle physics
- The HL-LHC with a ten times more luminosity will offer unique opportunities to explore the Higgs sector
  - Coupling measurements within 2-10% precision
  - Study of the Higgs boson self-couplings
- Detector upgrade foreseen by ATLAS and CMS will ensure optimal performances despite the very harsh conditions
- + Improvement on theory prediction progresses faster than expected



From RUN 1 to HL-LHC



Stay tuned: Run 2 has started



Event display of a SM ZZ →2e2μ candidate @ 13TeV

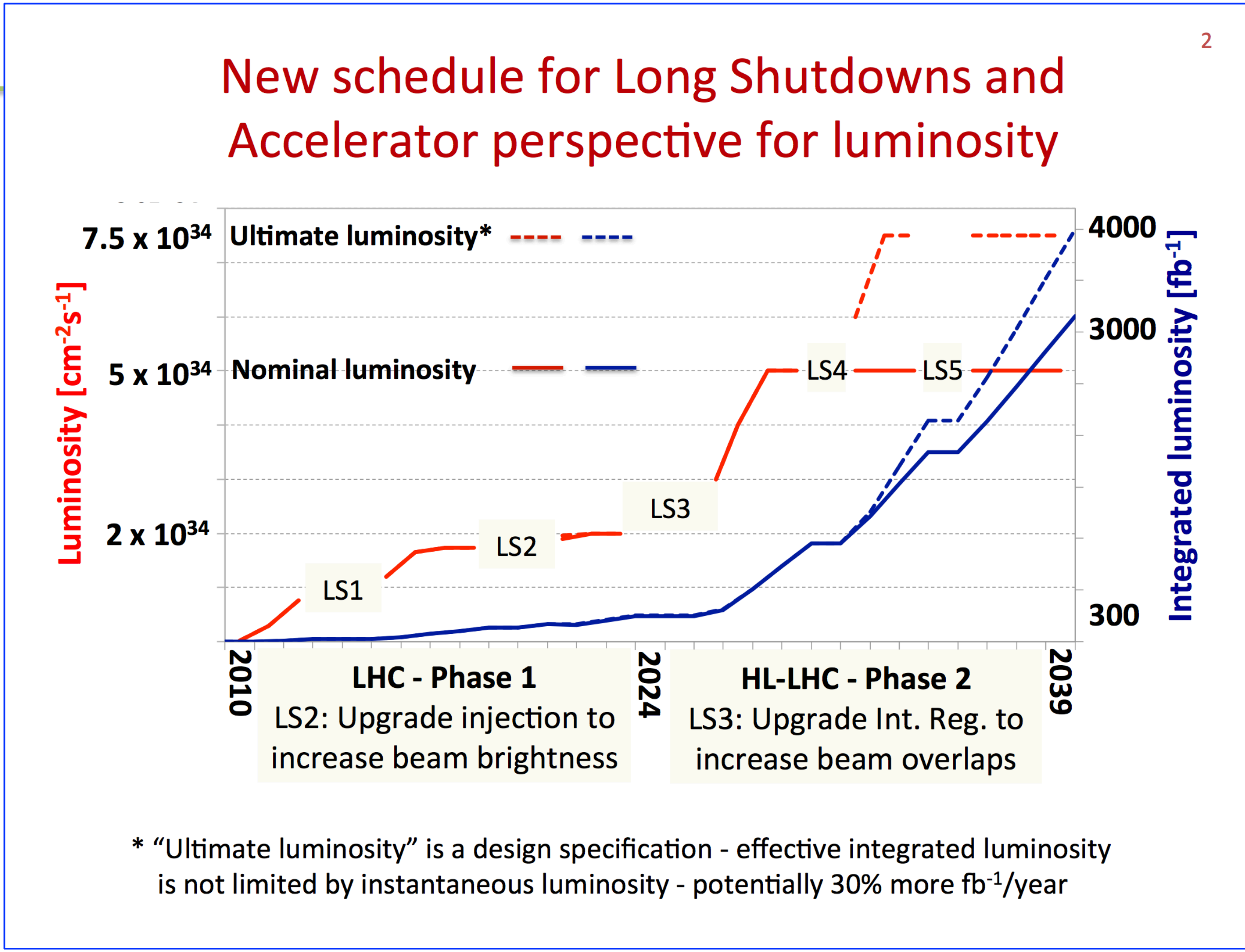
Thanks !

References

- CMS Public Projected Physics Results
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP
- ATLAS Public Projected Physics Results
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

Backup

From D. Contardo at EPS

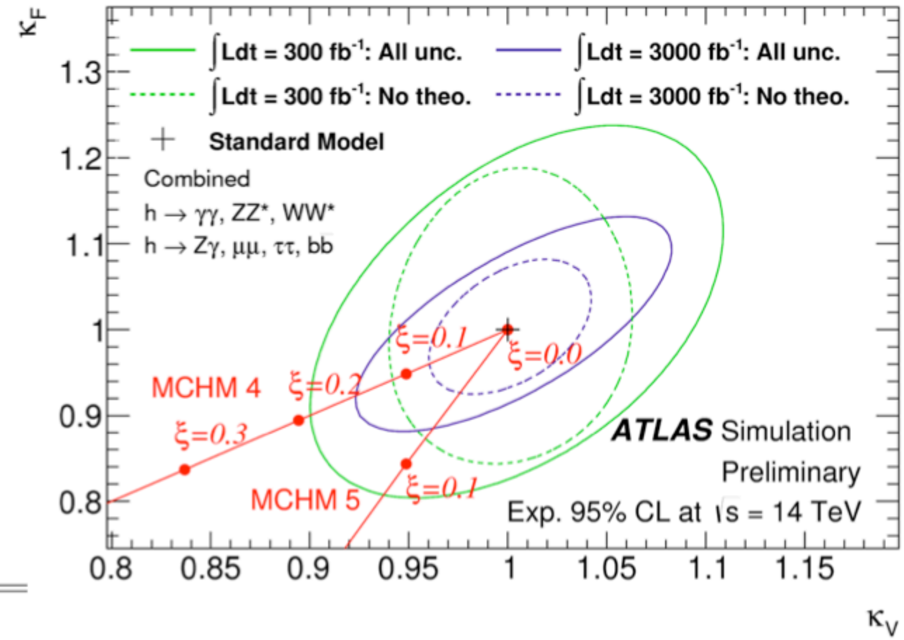


Ultimate goal is still under discussion

ATLAS/CMS Phase II upgrades are preparing for even higher radiation level and more PileUp (200)

Minimal Composite Higgs Model (MCHM)

- Higgs boson composite, pseudo-Nambu-Goldstone boson
  - ➡ Couplings modified as a function of compositeness scale f: $\xi = v^2/f^2$
  - ➡ MCHM4: $\kappa = \kappa_V = \kappa_F = \sqrt{(1-\xi)}$
  - ➡ MCHM5: $\kappa_V = \sqrt{(1-\xi)}$; $\kappa_F = 1-2\xi / \sqrt{(1-\xi)}$



ATL-PHYS-PUB-2014-017

Model	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
MCHM4	620 GeV	810 GeV	710 GeV	980 GeV
MCHM5	780 GeV	950 GeV	1.0 TeV	1.2 TeV

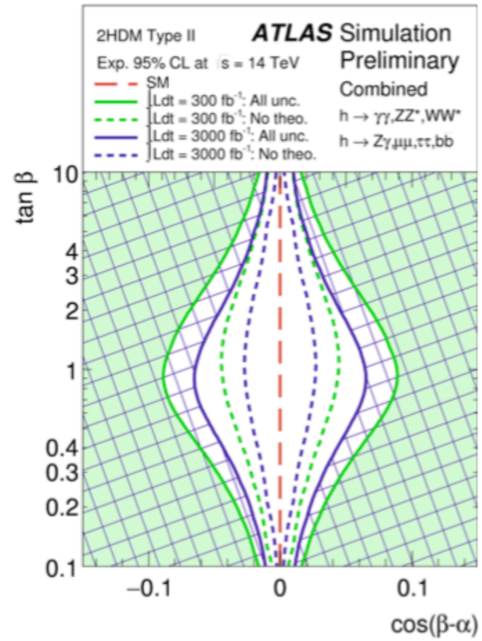
Expected 95% CL lower limit on Higgs boson compositeness scale

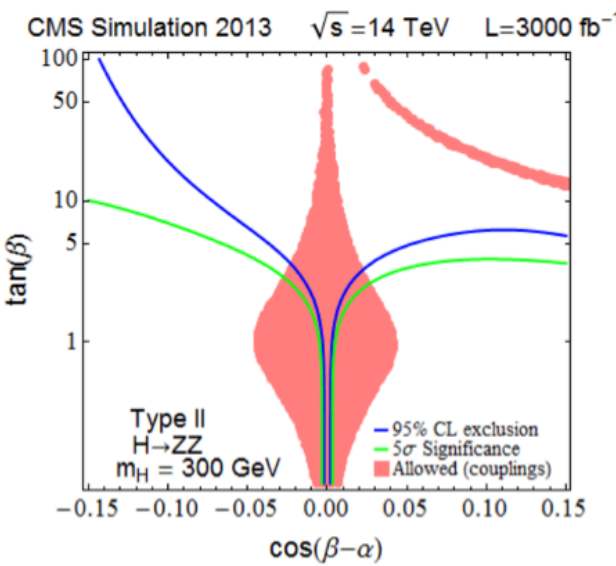
Two Higgs Doublets Models (2HDM)

- Higgs sector extended by additional doublet
  - ➡ Concrete example: MSSM
- Five Higgs bosons
  - ➡ Two neutral CP-even h and H, one neutral CP-odd A, and two charged $H^{\pm}$

ATL-PHYS-PUB-2014-017
CMS-PAS-FTR-13-024

- Gauge invariance:
  - ➡ $g^{2HDM}{}_{hVV} / g^{SM}{}_{hVV} = \sin(\beta-\alpha)$
  - ➡ $g^{2HDM}{}_{HVV} / g^{SM}{}_{HVV} = \cos(\beta-\alpha)$
- Type-II example:
  - ➡ $\kappa V = \sin(\beta-\alpha)$; $\kappa u = \cos\alpha / \sin\beta$; $\kappa d = \kappa \ell = -\sin\alpha / \cos\beta$





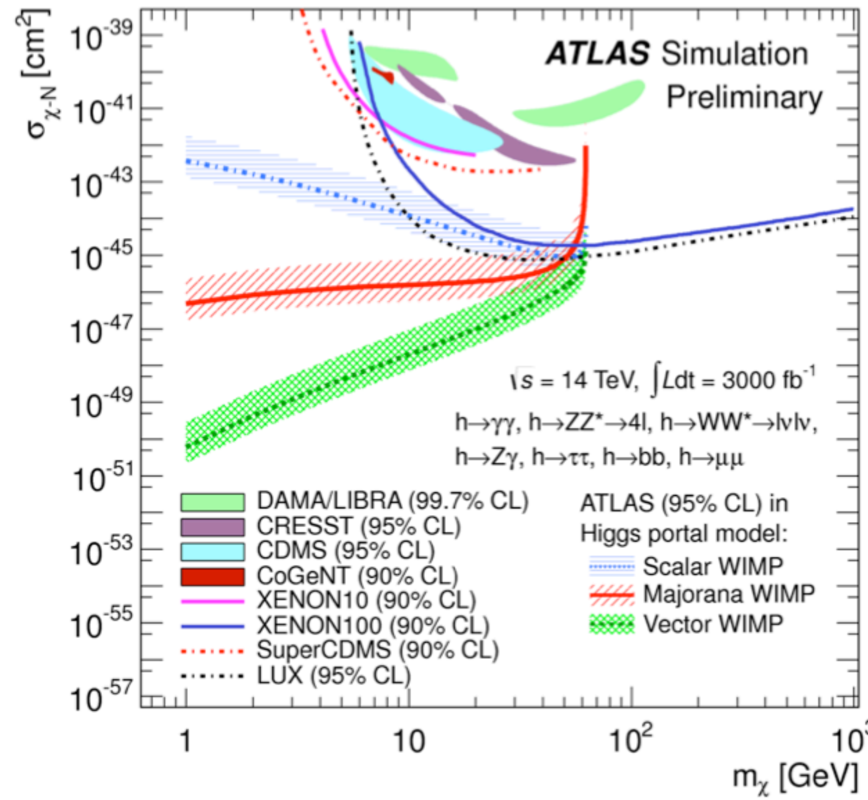
F.A. Dias - CIPANP 2015

Higgs Portal to Dark Matter

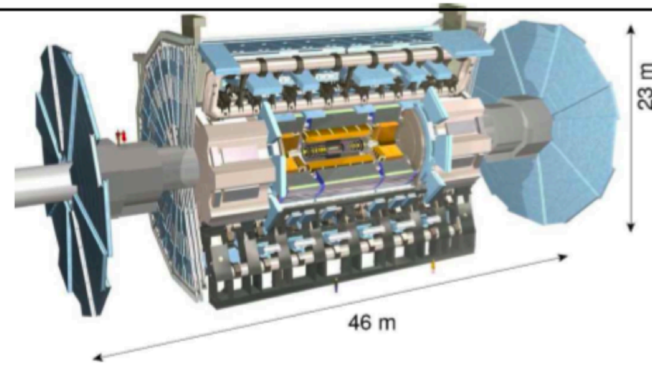
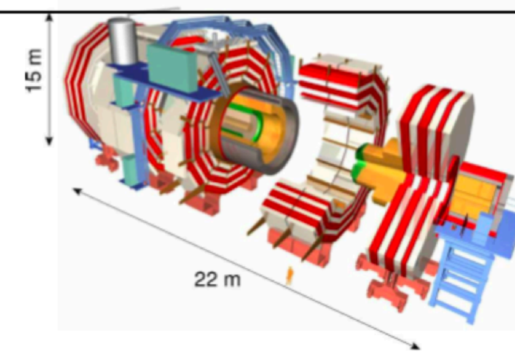
- Additional WIMP as DM candidate
- Interact very weakly with SM, except Higgs boson
- Expected 95% CL upper limit BR (H→inv) at 3000 fb^{-1}
  - ➡ ATLAS: $BR_{inv} < 0.13$ (0.09)
    Run-1: VBF: $BR_{inv} < 0.29$
  - ➡ CMS: $BR_{inv} < 0.11$ (0.07)

nominal (improved sys) scenarios
(no theory for ATLAS, Scenario 2 for CMS)

ATL-PHYS-PUB-2014-017



F.A. Dias - CIPANP 2015

Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ & Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\%$ (at 50 GeV) $\sim 11\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

Analyses used in coupling projections

ATLAS

$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \gamma\gamma$ (comb.)	0.13	0.09	0.09	0.04
(0j)	0.19	0.12	0.16	0.05
(1j)	0.27	0.14	0.23	0.05
(VBF-like)	0.47	0.43	0.22	0.15
(WH-like)	0.48	0.48	0.19	0.17
(ZH-like)	0.85	0.85	0.28	0.27
(ttH-like)	0.38	0.36	0.17	0.12
$H \to ZZ$ (comb.)	0.11	0.07	0.09	0.04
(VH-like)	0.35	0.34	0.13	0.12
(ttH-like)	0.49	0.48	0.20	0.16
(VBF-like)	0.36	0.33	0.21	0.16
(ggF-like)	0.12	0.07	0.11	0.04
$H \to WW$ (comb.)	0.13	0.08	0.11	0.05
(0j)	0.18	0.09	0.16	0.05
(1j)	0.30	0.18	0.26	0.10
(VBF-like)	0.21	0.20	0.15	0.09
$H \to Z\gamma$ (incl.)	0.46	0.44	0.30	0.27
$H \to b\bar{b}$ (comb.)	0.26	0.26	0.14	0.12
(WH-like)	0.57	0.56	0.37	0.36
(ZH-like)	0.29	0.29	0.14	0.13
$H \to \tau\tau$ (VBF-like)	0.21	0.18	0.19	0.15
$H \to \mu\mu$ (comb.)	0.39	0.38	0.16	0.12
(incl.)	0.47	0.45	0.18	0.14
(ttH-like)	0.74	0.72	0.27	0.23

Analyses used in coupling projections

CMS

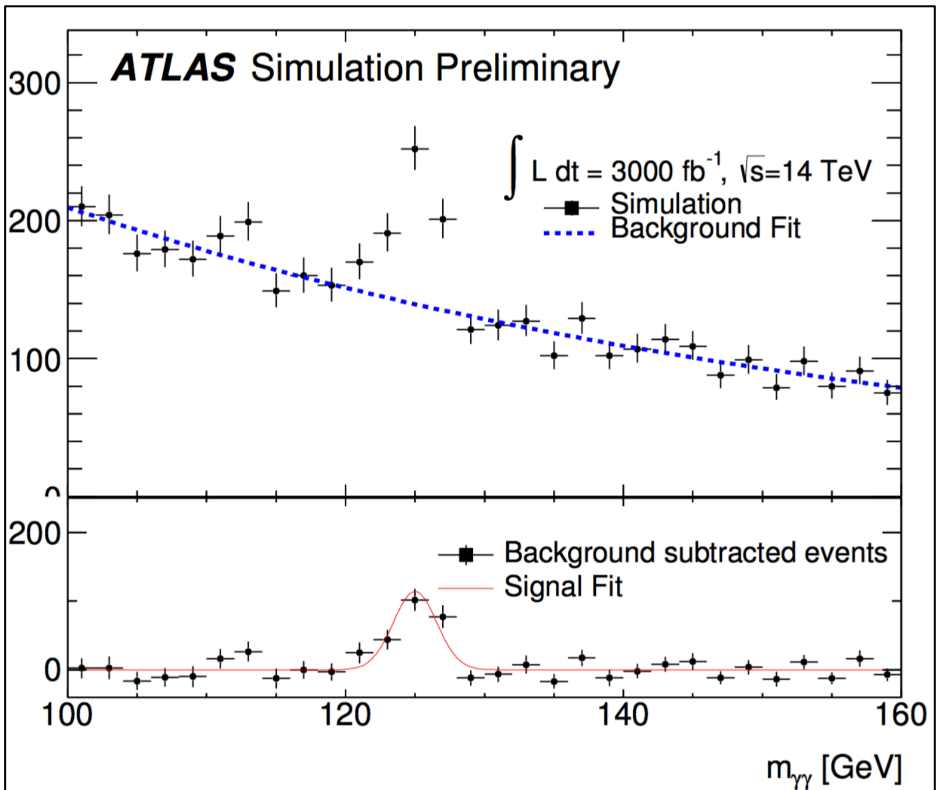
H decay	prod. tag	exclusive final states	cat.	res.
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	1-2%
	VBF-tag	$\gamma\gamma + (jj)_{\text{VBF}}$	2	<1.5%
	VH-tag	$\gamma\gamma + (\text{e}, \mu, \text{MET})$	3	<1.5%
	ttH-tag	$\gamma\gamma$ (lep. and had. top decay)	2	<1.5%
$\text{ZZ} \to 4\ell$	$N_{\text{jet}} < 2$	4e, 4μ, $2e2\mu$	3	1-2%
	$N_{\text{jet}} \geq 2$		3	
$\text{WW} \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\times$ (0 or 1 jets)	4	20%
	VBF-tag	$\ell\nu\ell\nu + (jj)_{\text{VBF}}$ (DF or SF dileptons)	2	20%
	WH-tag	$3\ell 3\nu$ (same-sign SF and otherwise)	2	
$\tau\tau$	0/1-jet	$(\text{e}\tau_h, \mu\tau_h, \text{e}\mu, \mu\mu) \times$ (low or high p_T^τ)	16	15%
	1-jet	$\tau_h\tau_h$	1	
	VBF-tag	$(\text{e}\tau_h, \mu\tau_h, \text{e}\mu, \mu\mu, \tau_h\tau_h) + (jj)_{\text{VBF}}$	5	
	ZH-tag	$(\text{ee}, \mu\mu) \times (\tau_h\tau_h, \text{e}\tau_h, \mu\tau_h, \text{e}\mu)$	8	
	WH-tag	$\tau_h\mu\mu, \tau_h \text{e}\mu, \text{e}\tau_h\tau_h, \mu\tau_h\tau_h$	4	
bb	VH-tag	$(\nu\nu$, ee, $\mu\mu$, eν, $\mu\nu$ with 2 b-jets$)\times$x	13	10%
	ttH-tag	(ℓ with 4, 5 or $\geq$6 jets) $\times$ (3 or $\geq$4 b-tags);	6	
		(ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-jets)	3	
$\text{Z}\gamma$	inclusive	$(\text{ee}, \mu\mu) \times (\gamma)$	2	
$\mu\mu$	0/1-jets	$\mu\mu$	12	1-2%
	VBF-tag	$\mu\mu + (jj)_{\text{VBF}}$	3	
invisible	ZH-tag	$(\text{ee}, \mu\mu) \times (\text{MET})$	2	

L (fb^{-1})	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$\text{Z}\gamma$	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[20,24]	[6, 17]

ATL-PHYS-PUB-2013-014
ATL-PHYS-PUB-2014-012
CMS-NOTE-13-002

ttH Production

- Directly sensitive to Top Yukawa coupling
  - the largest Yukawa coupling
  - indirectly from ggH and Hγγ loops



ATLAS projection for ttH(γγ): **> 8 σ** with 3000 fb^{-1}

Both CMS and ATLAS projected sensitivity on κ_{top} ~ 10% with 3000 fb^{-1}

Higgs total width via offshell measurement

$$\frac{\mathrm{d}\sigma_{pp\to H\to ZZ}}{\mathrm{d}M_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

- Assuming identical on-shell and off-shell Higgs couplings, the ratio of $\mu_{\text{off–shell}}$ to $\mu_{\text{on–shell}}$ provides a measurement of the total width of the Higgs boson.
    - This assump tion is particularly relevant to the running of the effective coupling κ_g ($\hat{s}$) for the loop-induced gg → *H* production process, as it is sensitive to new physics that enters at higher mass scales and could be probed in the high-mass m_{ZZ} signal region of this analysis.
- It is also assumed that any new physics which modifies the off-shell signal strength $\mu_{\text{off-shell}}$ and the off-shell coup- lings $\kappa_{i,\text{off-shell}}$ does not modify the predictions for the backgrounds.
- Further, neither are there sizeable kinematic modifications to the off-shell signal nor new, sizeable signals in the search region of this analysis unrelated to an enhanced off-shell signal strength.
- The projection on the off-shell Higgs boson coupling can be translated into a projected determination of the Higgs boson total width at 3000 fb−1 (10% systematic uncertainty on R_B), assuming that the on-shell couplings will be measured at high luminosity with much higher precision:

$$\Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1}\ \text{MeV (stat+sys)}$$

http://arxiv.org/pdf/1206.4803v2.pdf

Complex pole scheme

In this section, we consider the signal (S) in the complex-pole scheme (CPS) of Refs. [54, 74, 75]

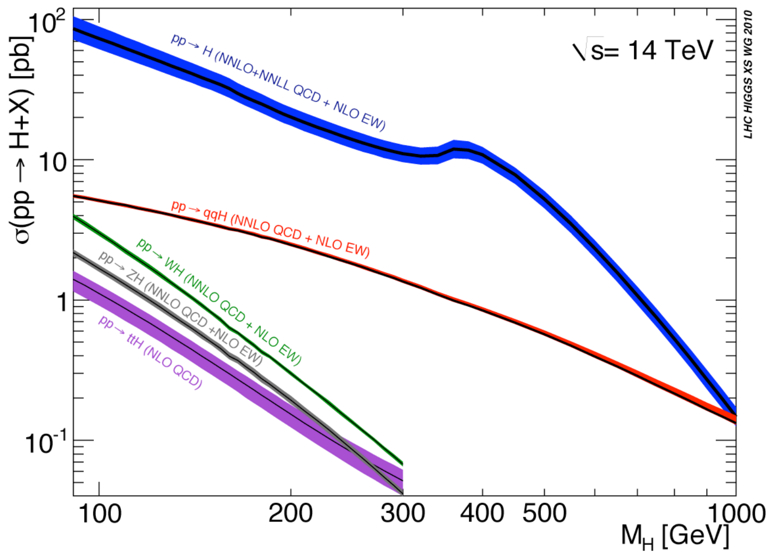
$$\sigma_{gg\to ZZ}(S) = \sigma_{gg\to H\to ZZ}(M_{\rm ZZ}) = \frac{1}{\pi}\,\sigma_{gg\to H}\,(M_{\rm ZZ})\,\frac{M_{\rm ZZ}^4}{\left|M_{\rm ZZ}^2 - s_H\right|^2}\,\frac{\Gamma_{H\to ZZ}\,(M_{\rm ZZ})}{M_{\rm ZZ}}, \qquad (2.8)$$

where s_H is the Higgs complex pole, parametrized by $s_H = \mu_H^2 - i\,\mu_H\,\gamma_H$. Note that γ_H is not the on-shell width, although the numerical difference is tiny for low values of μ_H, as shown in Ref. [54].

Away (but not too far away) from the narrow peak the propagator and the off-shell H width behave like

$$D_H\,(M_{\rm ZZ}^2) \approx \frac{1}{\left(M_{\rm ZZ}^2 - \mu_H^2\right)^2}, \qquad \frac{\Gamma_{H\to ZZ}\,(M_{\rm Z})}{M_{\rm ZZ}} \sim G_{\rm F}\,M_{\rm ZZ}^2 \qquad (2.9)$$

Higgs production @ 14 TeV



	M_H=125 GeV				
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%
bbH [d]	0.5805 pb	+13.0%	-24.0%	+6.1%	-6.1%

Branching Fractions

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

Process	Branching ratio	Uncertainty
H → 4l (l=e,μ,τ)	2.76×10^{-4}	±4.3%
H → 4l (l=e,μ)	1.25×10^{-4}	±4.3%
H → eeee	3.27×10^{-5}	±4.3%
H → eeμμ	5.93×10^{-5}	±4.3%
H → 2l2v (l=e,μ,τ, v=any)	2.34×10^{-2}	±4.3%
H → 2l2v (l=e,μ, v=any)	1.06×10^{-2}	±4.3%
H → e^+ve^-v	2.52×10^{-3}	±4.3%
H → $e^+v\mu^-v$	2.52×10^{-3}	±4.3%