Prospects for searches of rare decays of Higgs boson with ATLAS Detector

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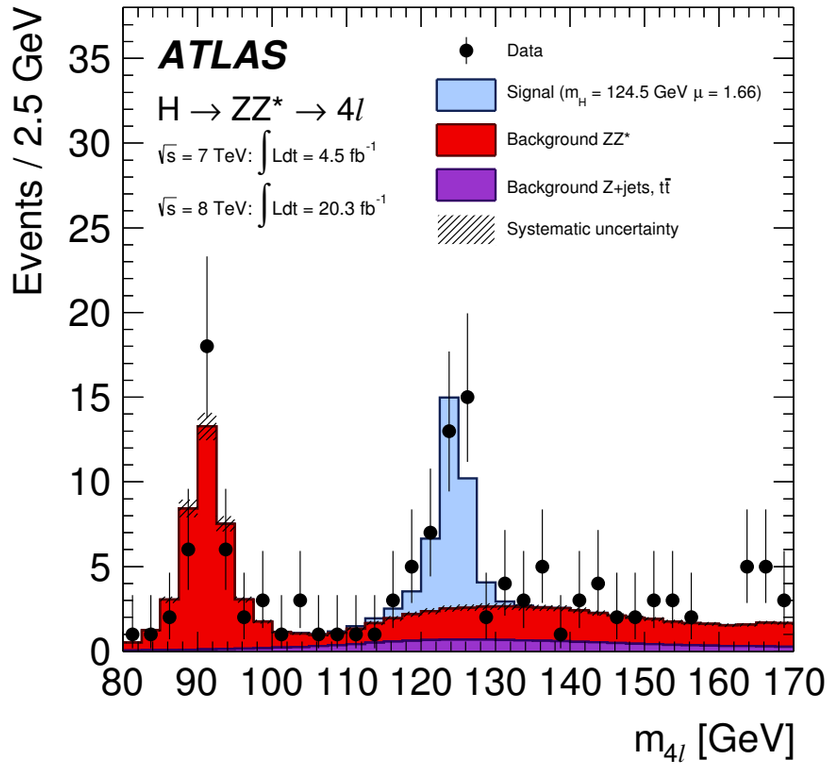
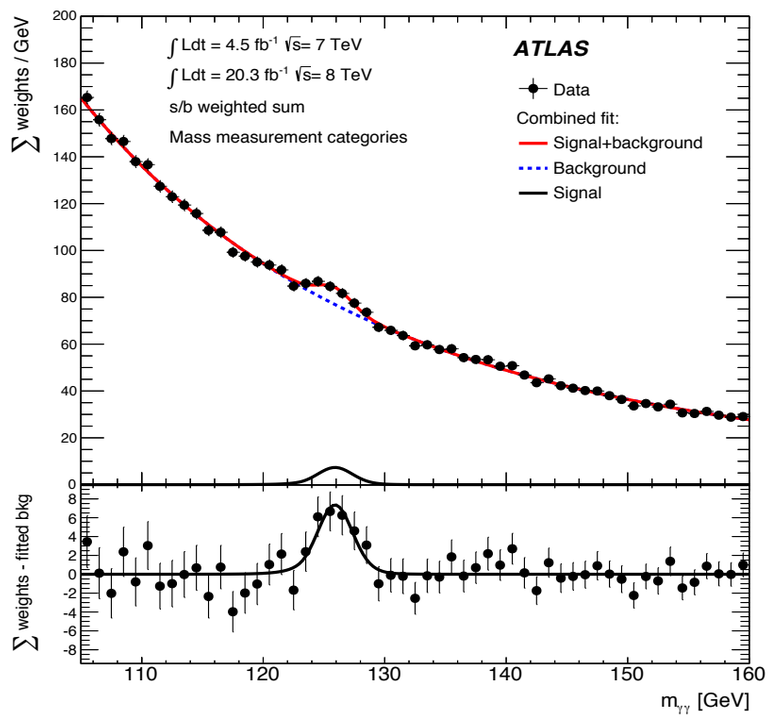
Higgs workshop, 2014

Higgs Boson Results

- All observations from the LHC consistent with a Standard Model Higgs boson with mH~125GeV

- M_H measured in ZZ and γγ final states consistent with 125GeV.





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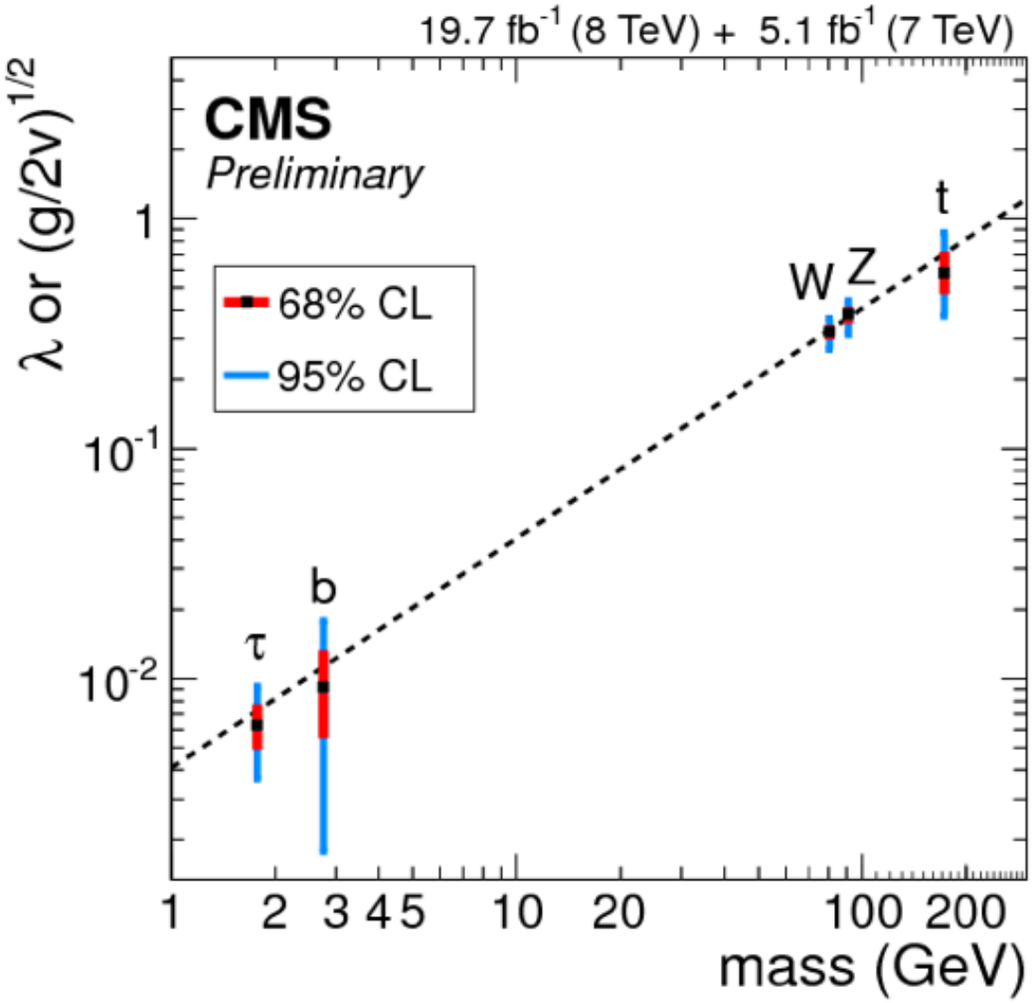

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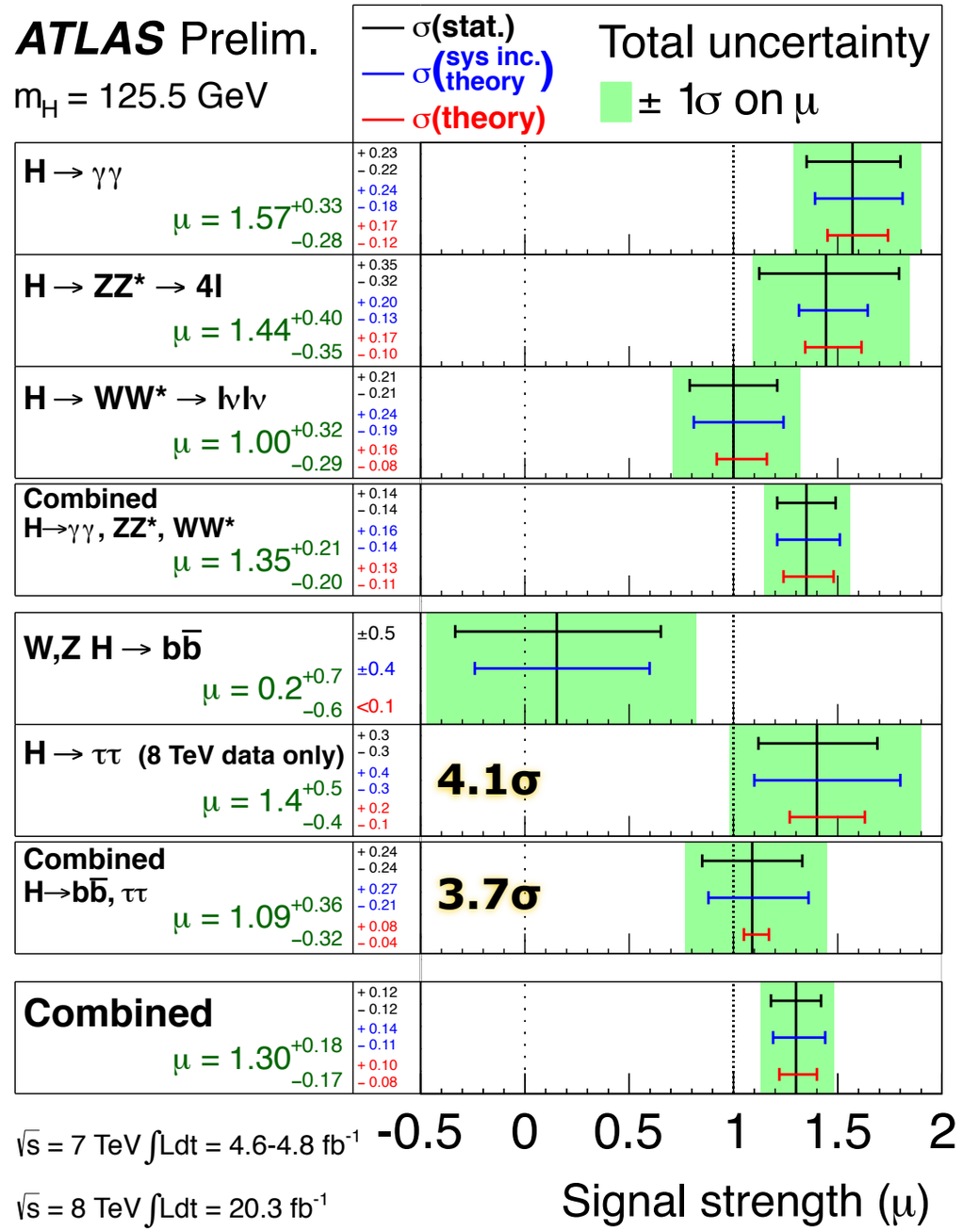
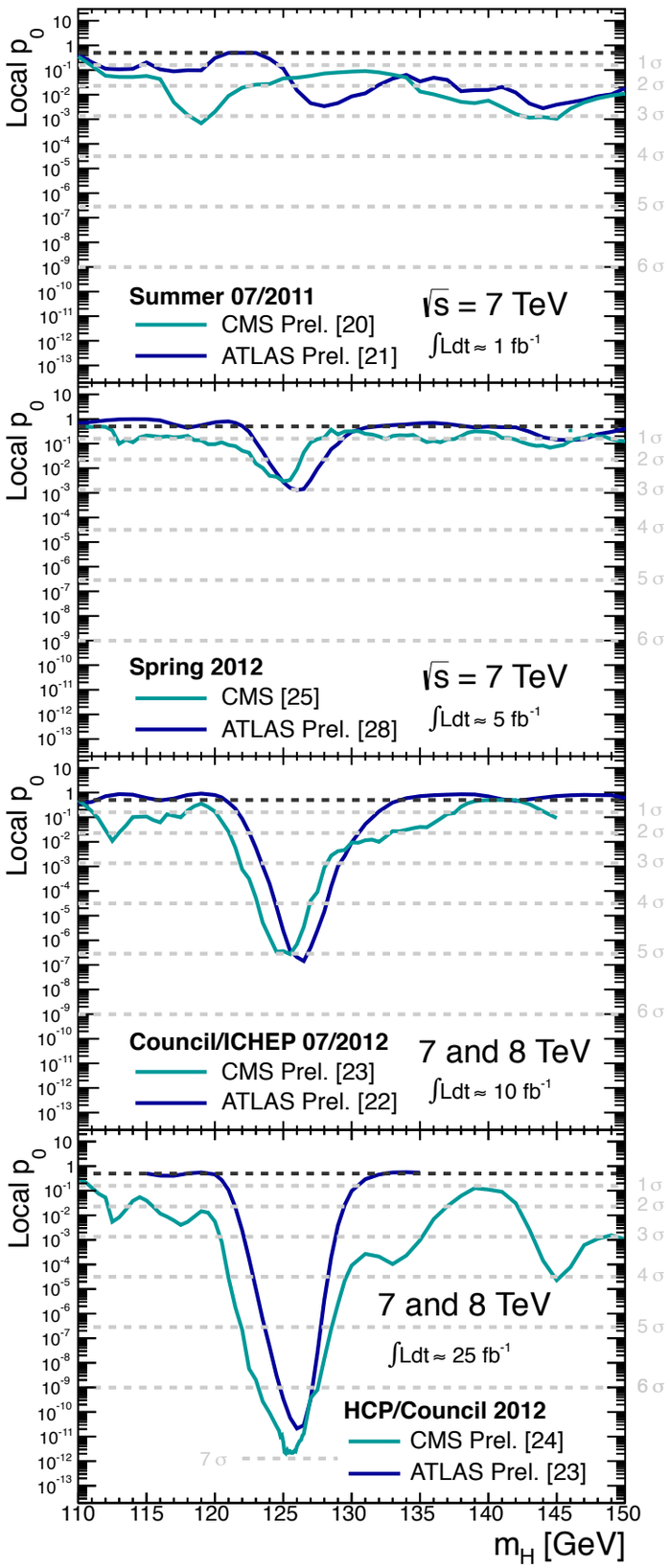
- It decays like a SM Higgs boson.



Timely Discovery



- **Summer 2011: EPS and Lepton-Photon**

  First (and last) focus on limits (scrutiny of the p_0)

- **December 2011: CERN Council**

  First hint

- **Summer 2012: CERN Council and ICHEP**

  Discovery

- **December 2012: CERN Council**

  Beginning of a new era of property measurement

The Noble Prize in Physics 2013

LHC/HL-LHC Plan

$\sqrt{s} = 13$ TeV
bunch spacing **25 ns**

$\mathscr{L} \sim 1.6 \times 10^{34}\ cm^{-2}s^{-1}$
Pile Up ~ 40

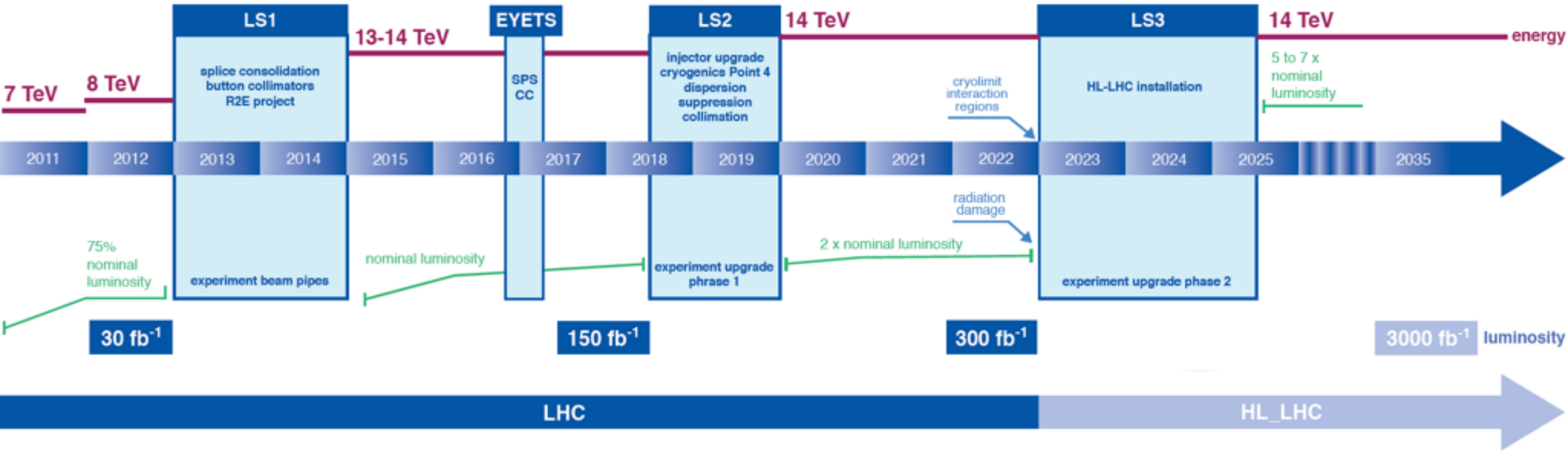
$\sqrt{s} = 14$ TeV
LHC injector upgrade

$\mathscr{L} \sim 2 \times 10^{34}\ cm^{-2}s^{-1}$
Pile Up ~ 60

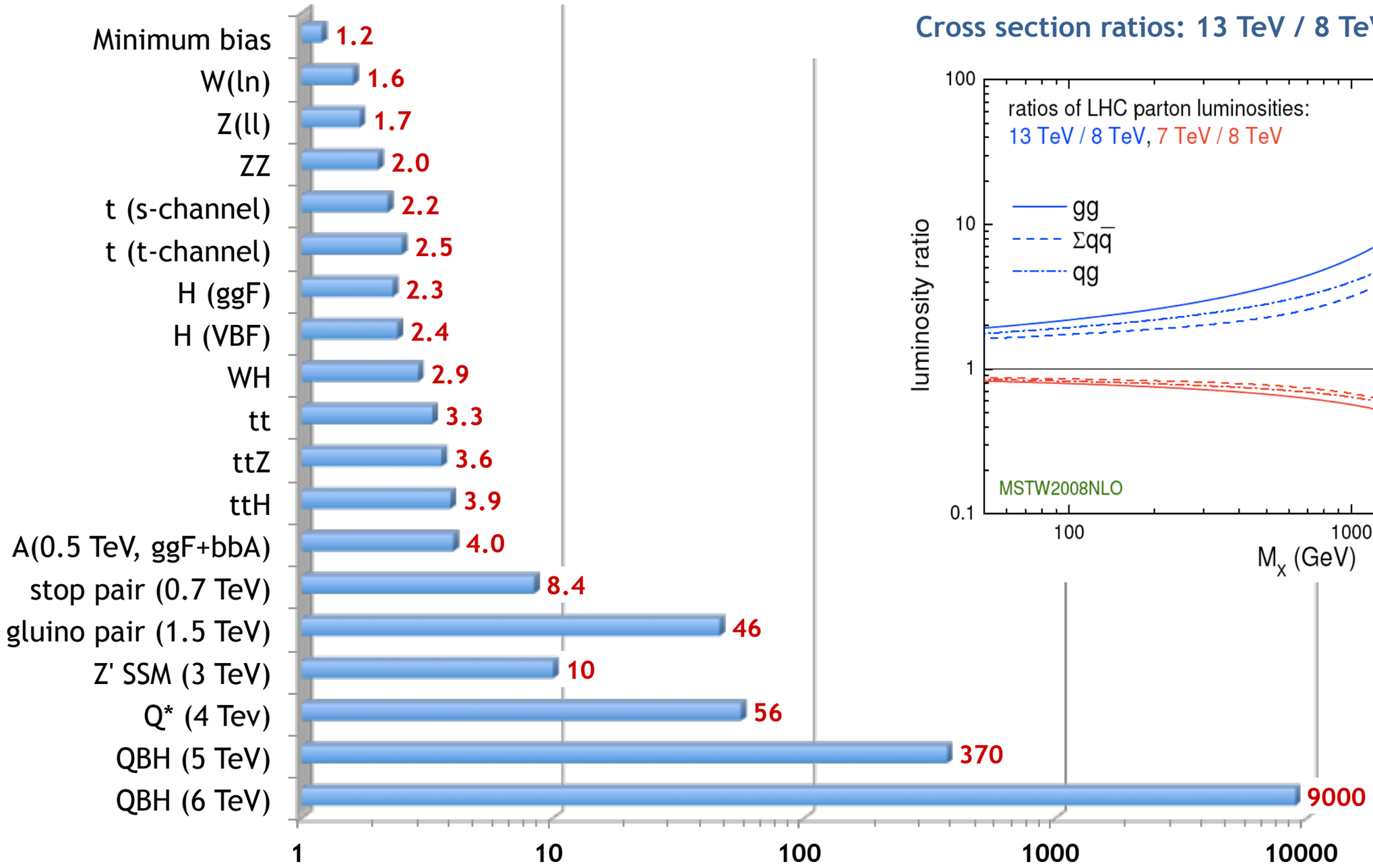
New interaction region layout

Crab cavity

luminosity levelling
$\mathscr{L} \sim 5 \times 10^{34}\ cm^{-2}s^{-1}$
Pile Up ~ 140

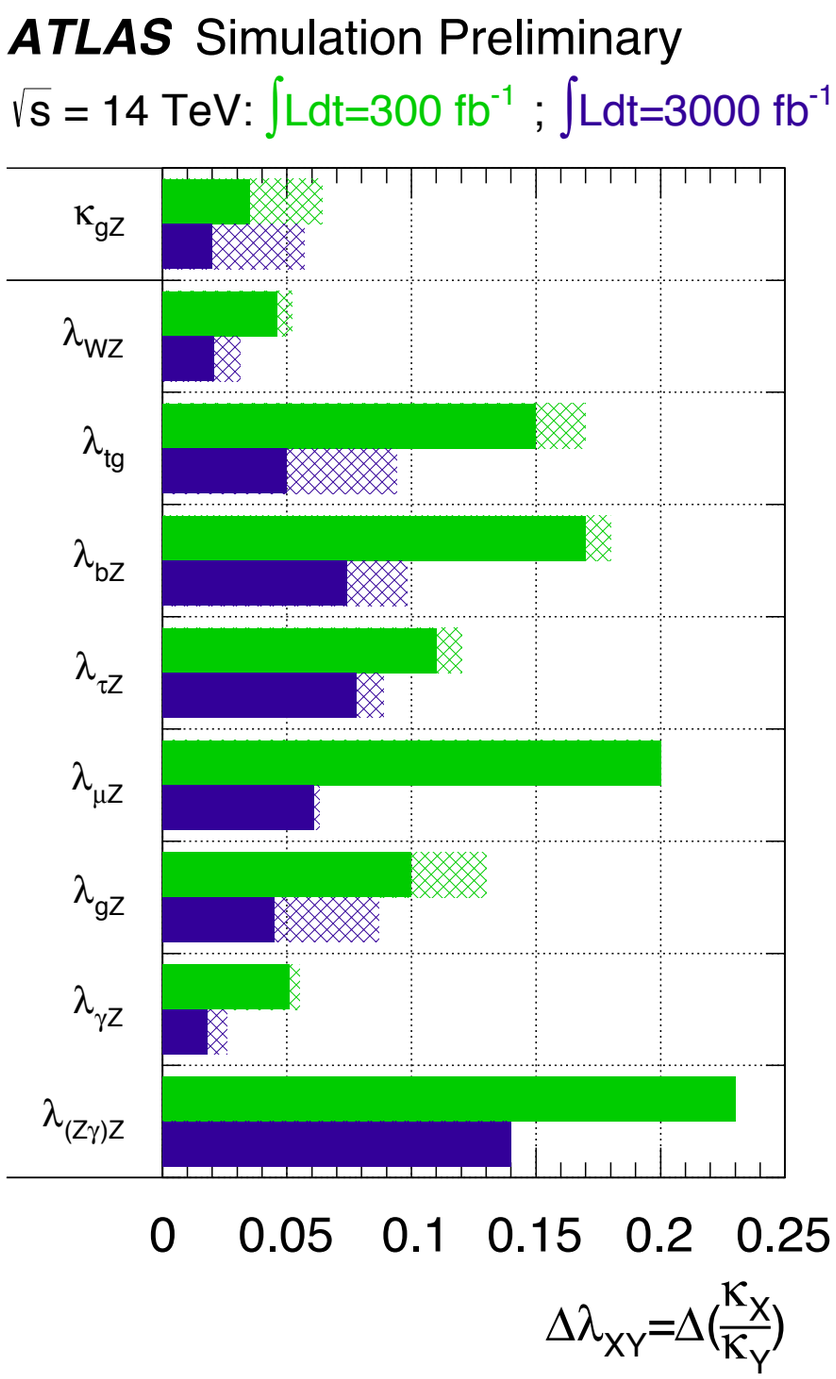


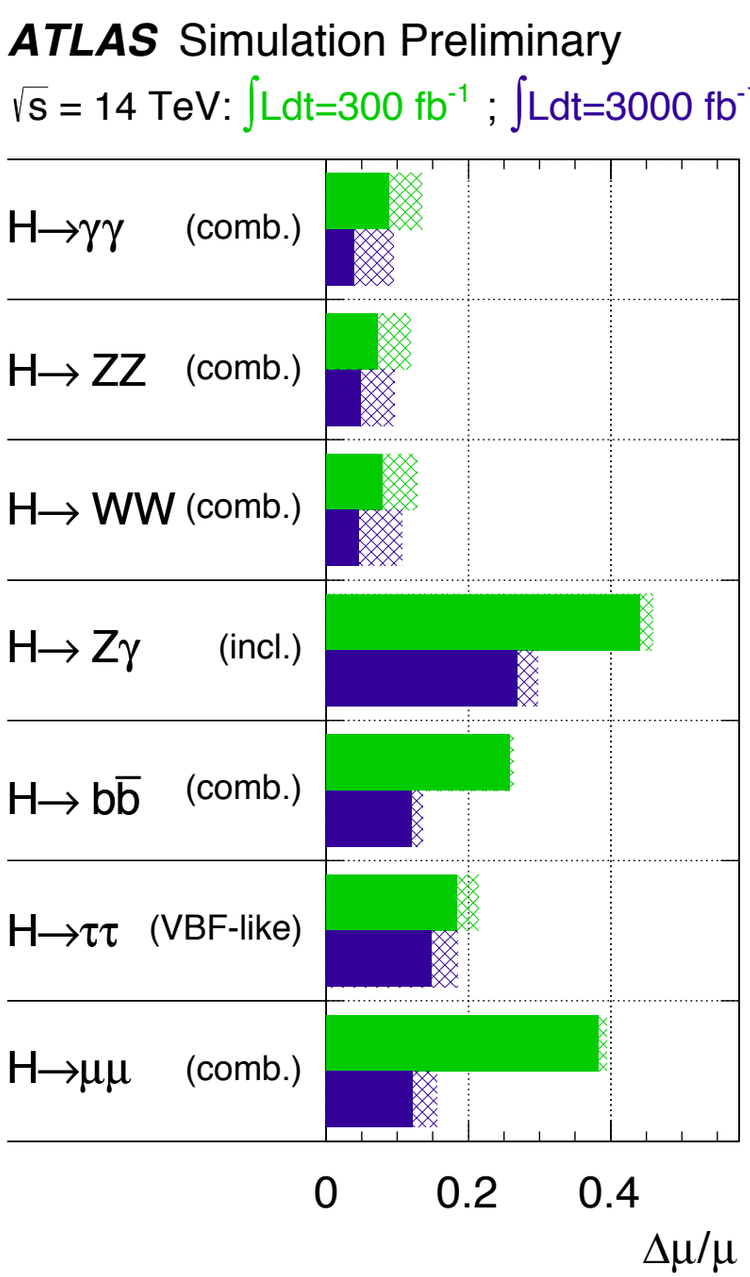
Cross section ratios

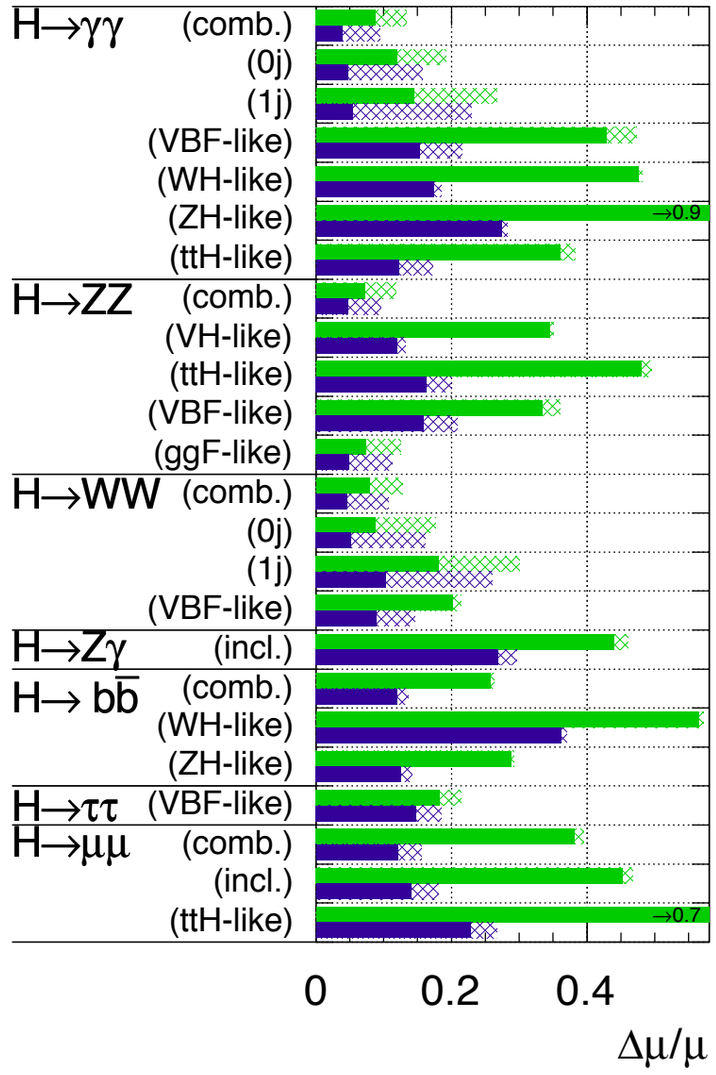


- Huge increase in cross section for many interesting processes.
- but life may also become harder for states lighter than tt

Higgs Boson Decays and Couplings





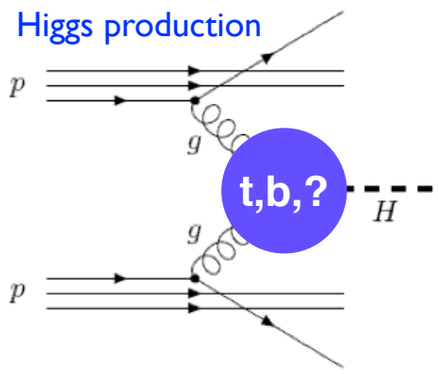


More detail in Elisabeth's talk

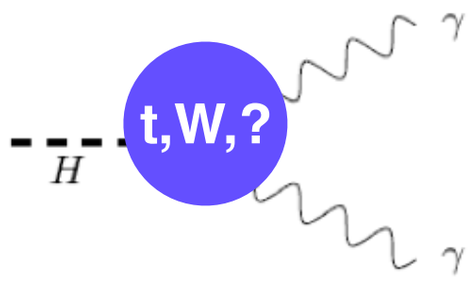
Higgs Yukawa coupling Y_t

- Indirect constraints on the Yt from measuring top-quark dominant loop-induced process like gg→H or H→γγ decays.(No beyond-standard model particles)

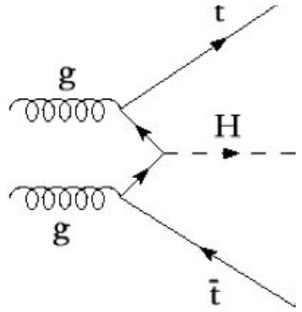
Higgs production



Higgs decay to photons

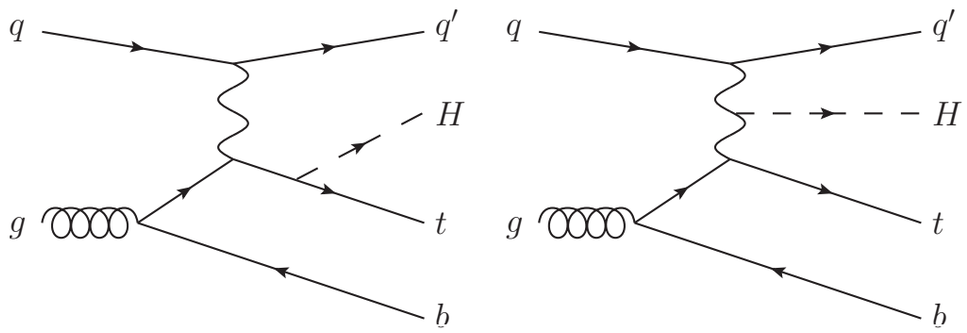


- Direct measurement of Yt in ttH production

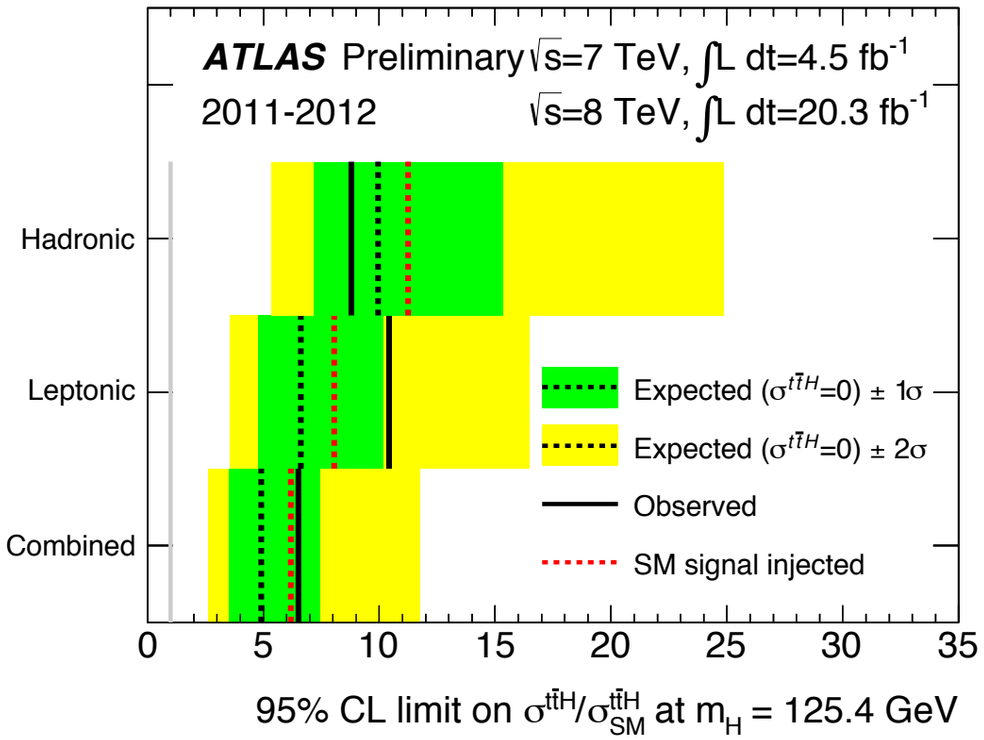


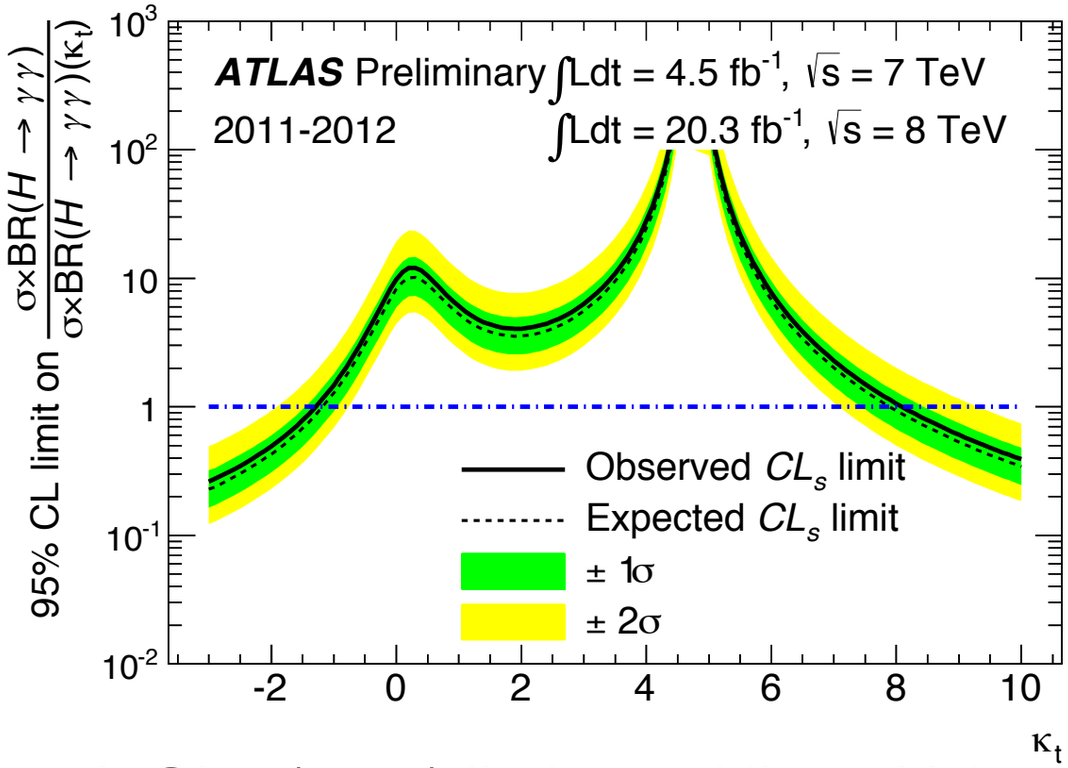
$$\sigma(t\bar{t}H) \propto g^2_{t\bar{t}H}$$

- tH produce, a small contribution due to a destructive interference, while sensitive to the sign of Yt

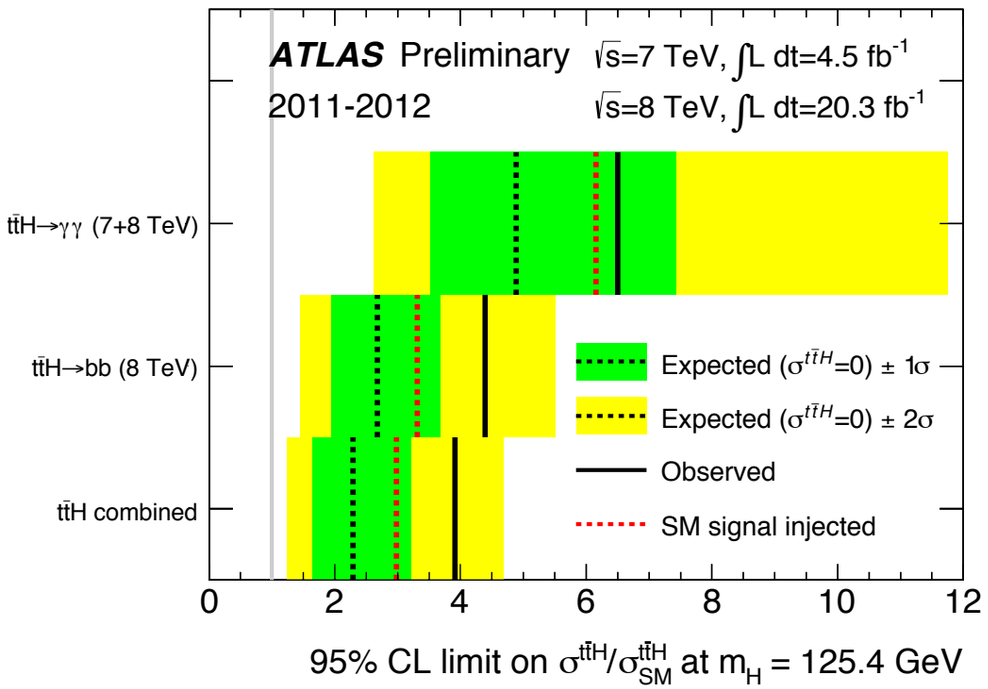


ttH: H→γγ and H→bb





Run I: Obs.(exp.) limits on Higgs Yukawa coupling strength parameter κ_t @ 95%CL: [-1.3, 8.1] ([-1.2, 7.9])



	@ 95% CL	
	observed	**expected**
ttH(bb)	4.1×SM	2.6×SM
ttH(γγ)	5.6×SM	4.9×SM
Combination	3.9×SM	2.3×SM

ttH: H→γγ

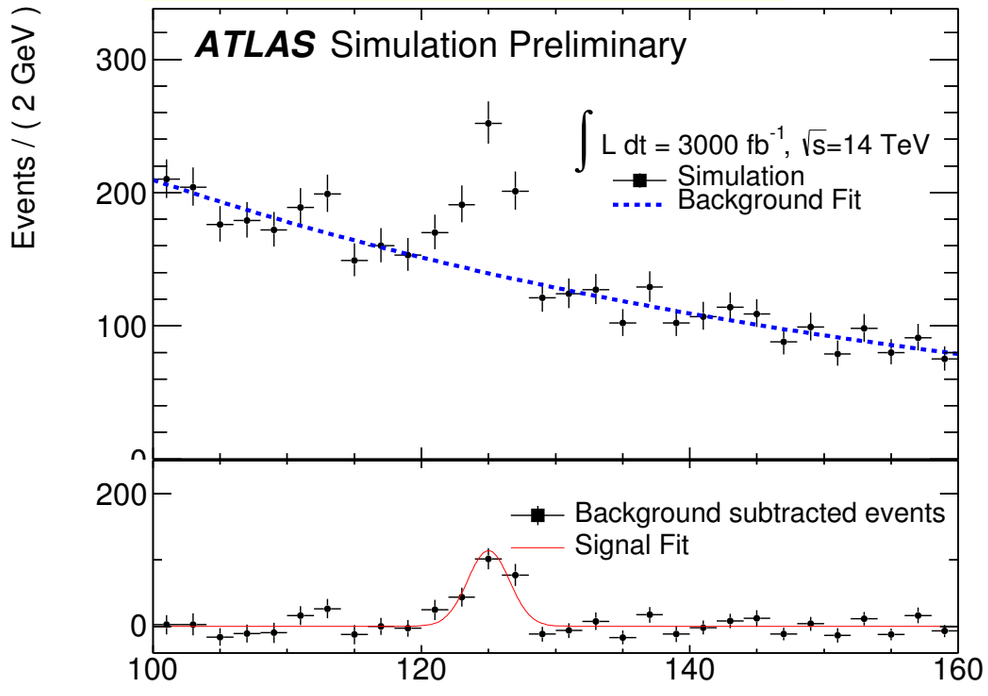
- Clean signal allows to probe ttH production.

	$t\bar{t}H$	WH	ZH	VBF
Significance	8.2	4.2	3.7	3.8

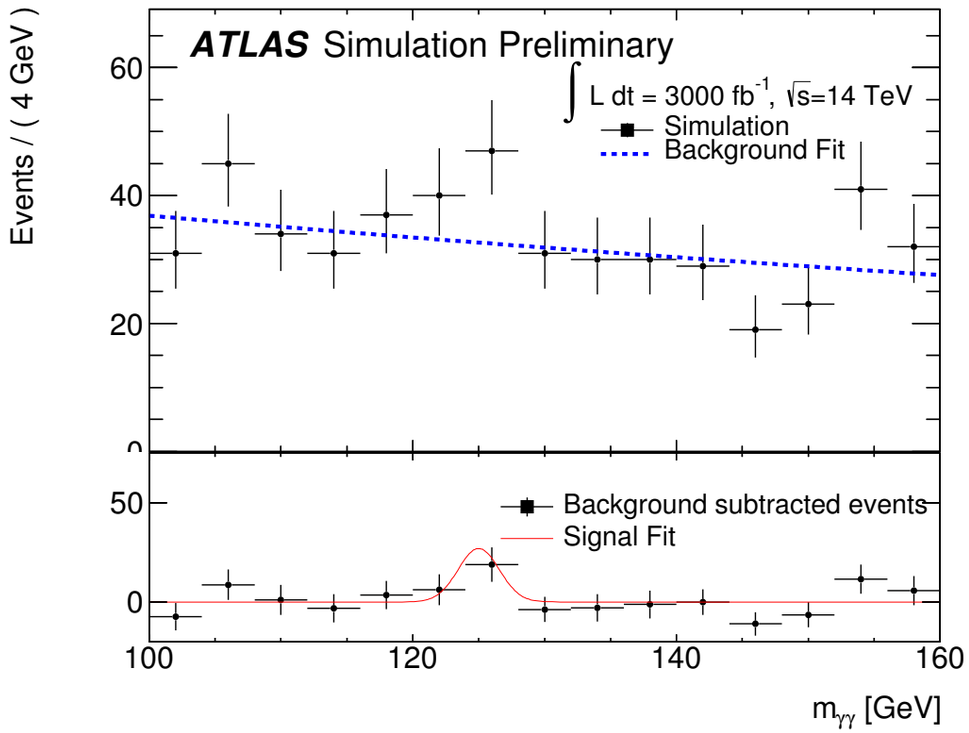
- The measurement limited by current theoretical uncertainties on Higgs boson production

Production mode	$\Delta\hat{\mu}/\hat{\mu}$ (%) Total	Statistical	Experimental	Theoretical
$t\bar{t}H$	+21 −17	+13 −12	+5 −4	+17 −11
WH	+26 −25	+21 −20	+13 −12	+10 −8
ZH	+35 −31	+32 −29	+7 −7	+12 −8
ggF	+19 −14	+3 −3	+1 −1	+19 −14
VBF	+29 −29	+18 −18	+1 −1	+23 −23

ttH, H→γγ; 1 lepton



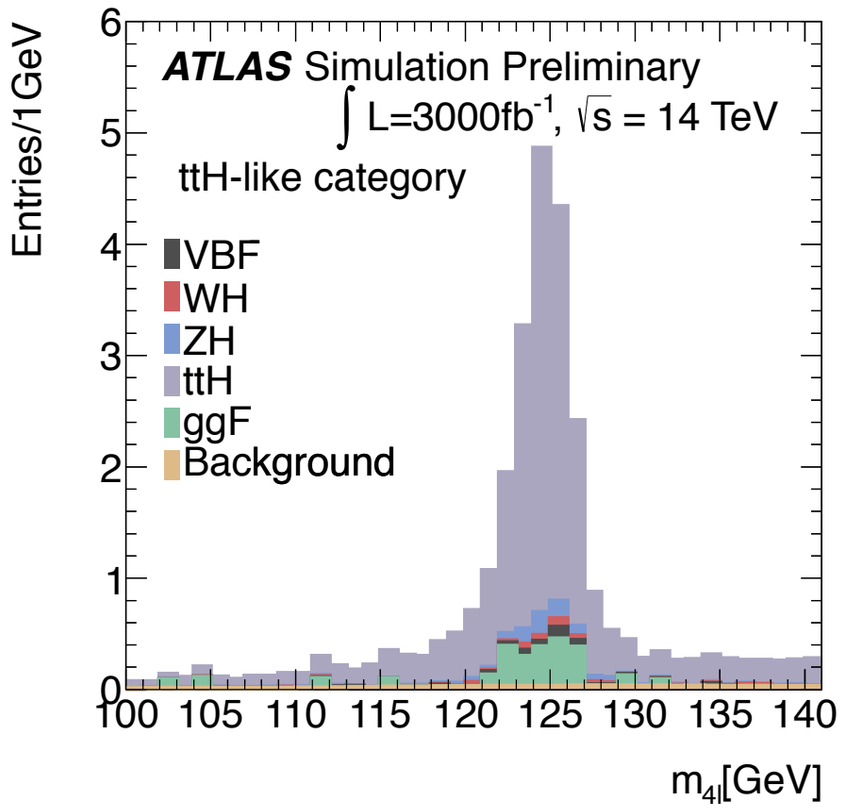
ttH, H→γγ; 2 lepton



ttH: H→ZZ

Category	True Origin					
	ggF	VBF	*WH*	*ZH*	*ttH*	Background
ttH-like	3.1 ±1.0	0.6 ±0.1	0.6 ±0.1	1.1 ±0.2	30 ±6	1.6 ±1.0
ZH-like	0.0	0.0	0.01 ±0.01	4.4 ±0.3	1.3 ±0.3	0.06 ±0.06
WH-like	22 ±7	6.6 ±0.4	25 ±2	4.4 ±0.3	8.8 ±1.8	13 ±0.8
VBF-like	41 ±14	54 ±6	0.7 ±0.1	0.4 ±0.1	1.0 ±0.2	4.2 ±1.5
ggF-like	3380 ±650	274 ±17	77 ±5	53 ±3	25 ±4	2110 ±50

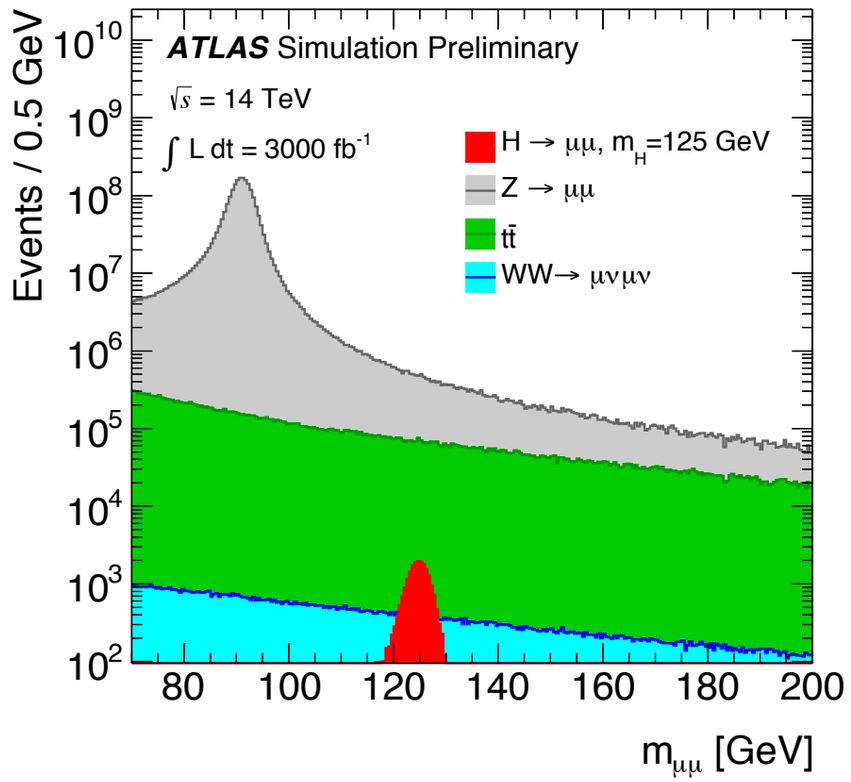
$\Delta\mu/\mu$	Total	Stat.	Expt. syst.	Theory
Production mode	300 fb^{-1}			
ggF	0.152	0.066	0.053	0.124
VBF	0.625	0.545	0.233	0.226
WH	1.074	1.064	0.061	0.085
$t\bar{t}$H	0.535	0.516	0.038	0.120
Combined	0.125	0.042	0.044	0.108
	3000 fb^{-1}			
ggF	0.131	0.025	0.040	0.124
VBF	0.371	0.187	0.225	0.226
WH	0.390	0.375	0.061	0.085
ZH	0.532	0.526	0.038	0.073
$t\bar{t}$H	0.224	0.184	0.034	0.120
Combined	0.100	0.016	0.036	0.093



- Possible to measure the signal strength with a reasonable precision.

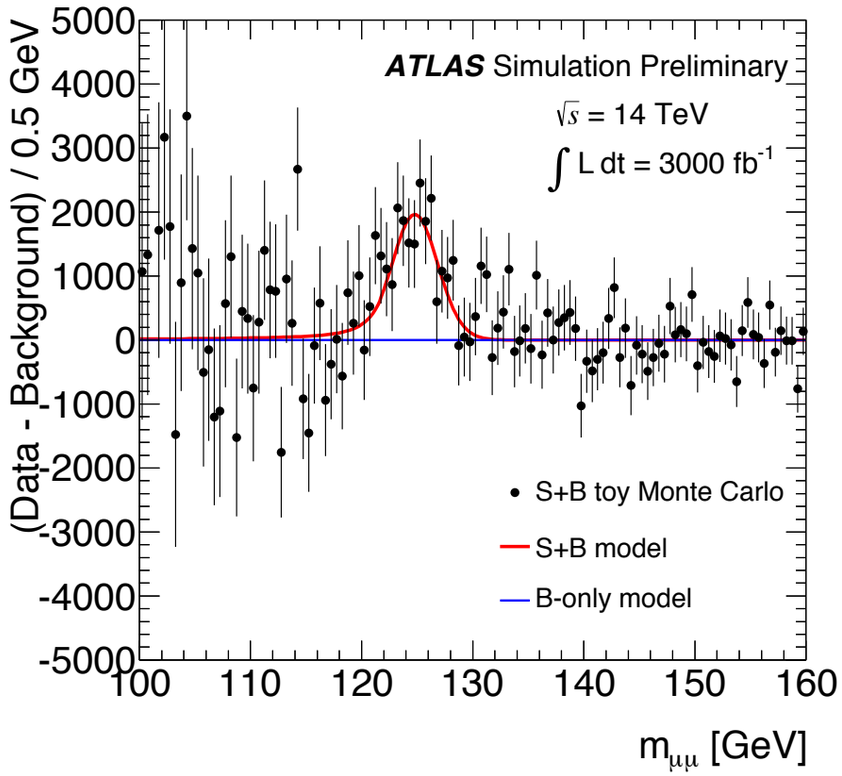
$H \rightarrow \mu^+\mu^-$

- SM Prediction is BR($H \rightarrow \mu^+\mu^-$)=2.19×10^{-4}
- Observation of $H \rightarrow \mu^+\mu^-$ gives access to Higgs coupling to 2nd generation of fermions.
- Run1 limit: 7*SM
- With 3000 fb^{-1}: Observation at 7σ; uncertainty of ~20% expected.

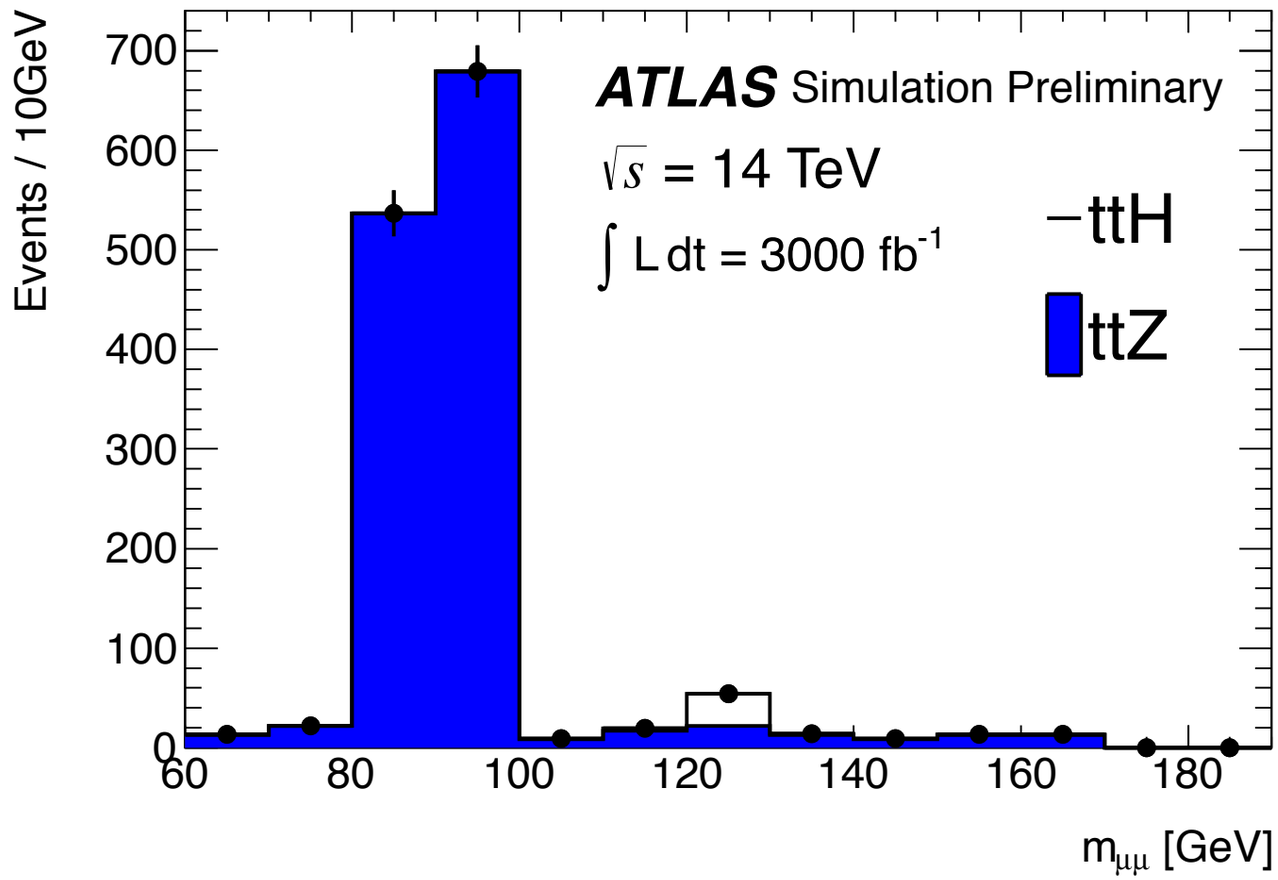


***ATLAS* Preliminary**

$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
Δ^{sys}_{Bkg} (model)	68	110
Δ^{sys}_{Bkg} (fit)	190	620
Δ^{stat}_{S+B}	750	2380
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%



ttH: $H \rightarrow \mu^+\mu^-$

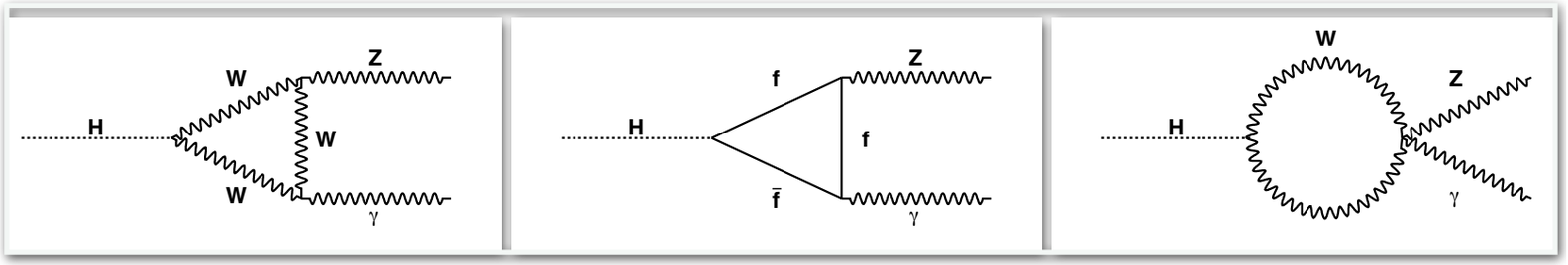


- A direct measurement of top and μ- Yukawa coupling
- Valuable for CP nature determination
- expected signal: 33, expected background: 22
- Allow to be observed with the HL-LHC

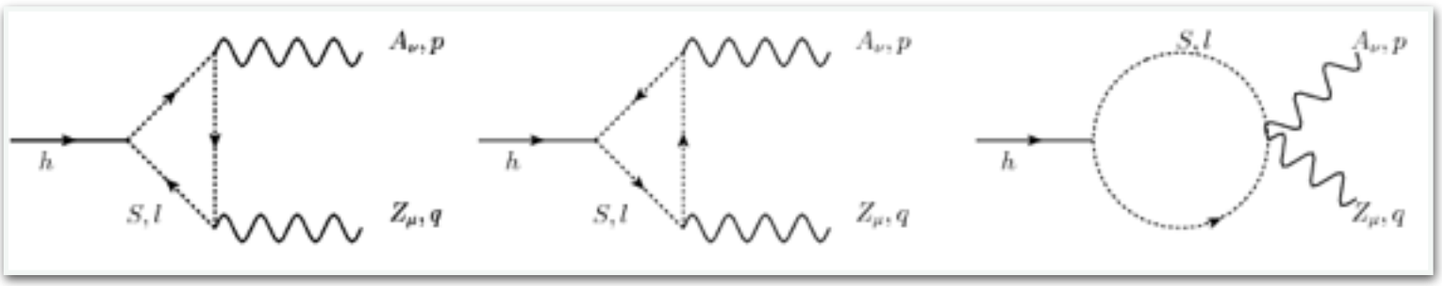
H→Zγ

- H→Zγ sensitive to potential new particles in loop

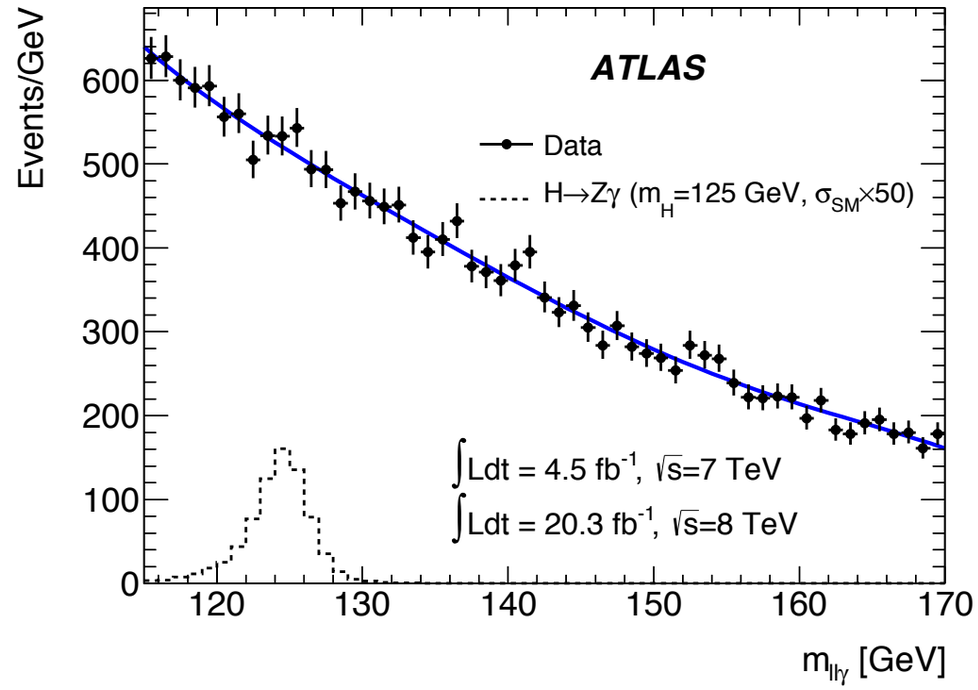
SM

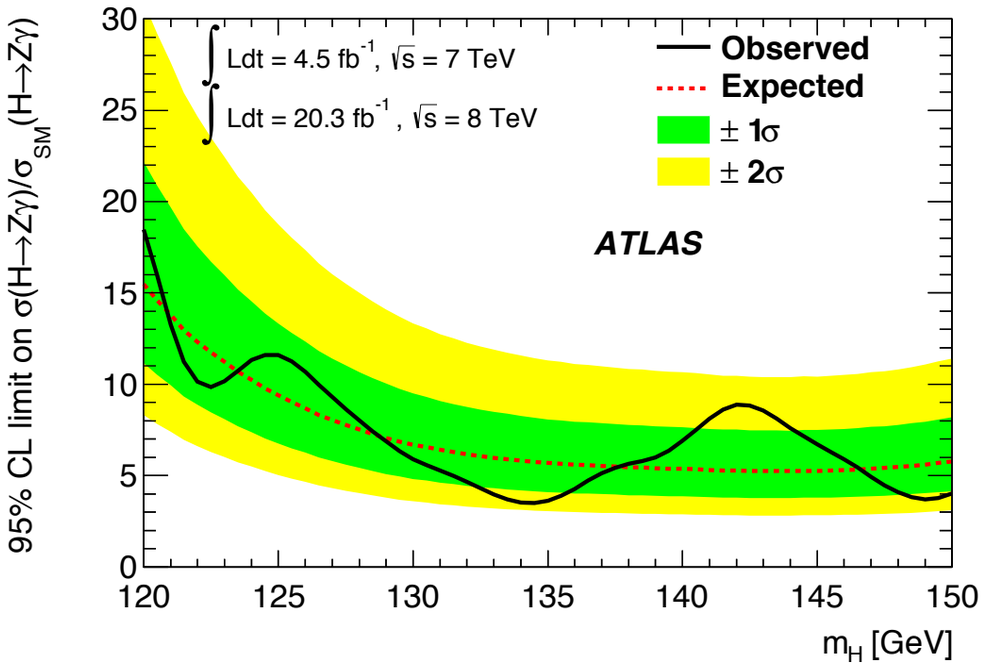


e.g. new scalar contribution



Run I: Obs. (Exp.) limit @95% C. L is 11(9)*SM



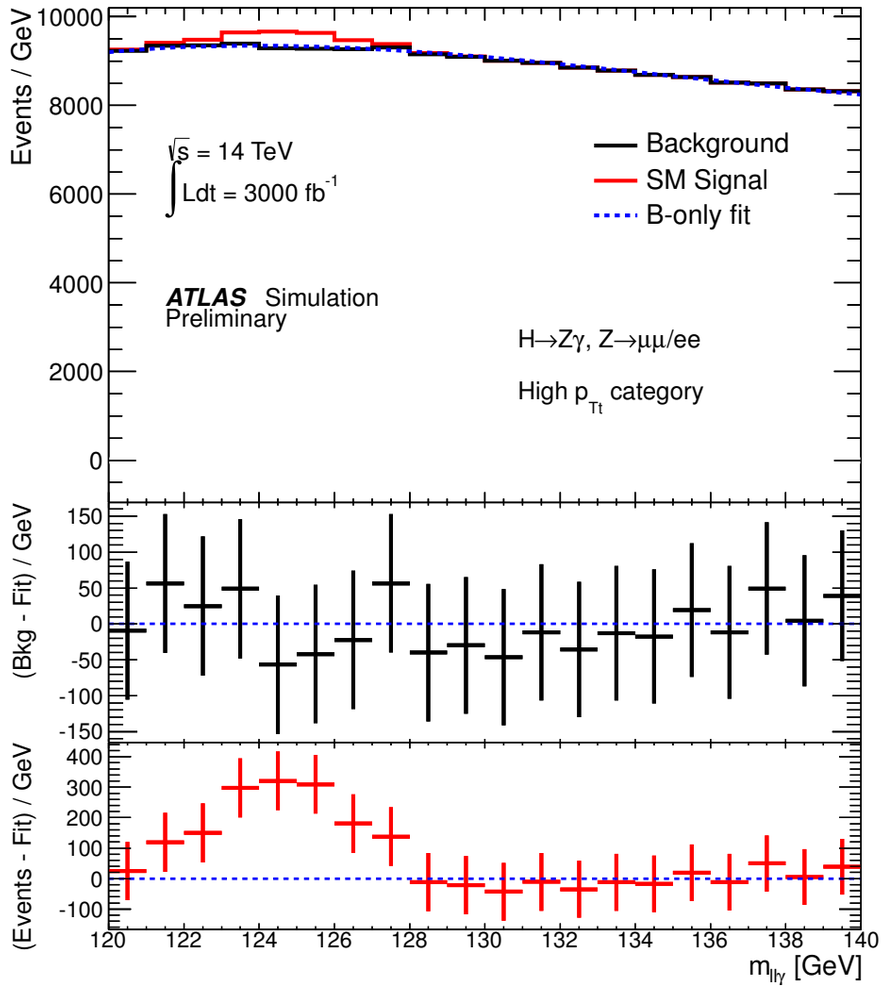


$H \rightarrow Z\gamma$

14 TeV for 3000 fb^{-1}

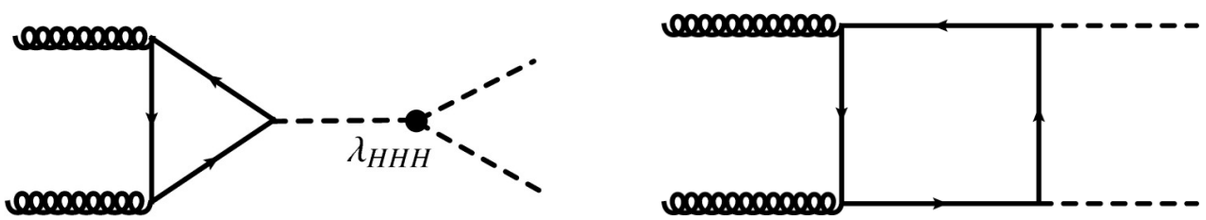
Category	high p_{Tt}		low p_{Tt} low $\lvert\Delta\eta_{Z\gamma}\rvert$		low p_{Tt} high $\lvert\Delta\eta_{Z\gamma}\rvert$	
Final states	$ee\gamma$	$\mu\mu\gamma$	$ee\gamma$	$\mu\mu\gamma$	$ee\gamma$	$\mu\mu\gamma$
S	602	721	703	839	138	165
B	$2.56 \cdot 10^4$	$3.05 \cdot 10^4$	$1.09 \cdot 10^5$	$1.30 \cdot 10^5$	$2.56 \cdot 10^4$	$3.06 \cdot 10^4$
S/B (%)	2.4	2.4	0.64	0.64	0.54	0.54
S/ $\sqrt{B}$	3.8	4.1	2.1	2.3	0.86	0.94

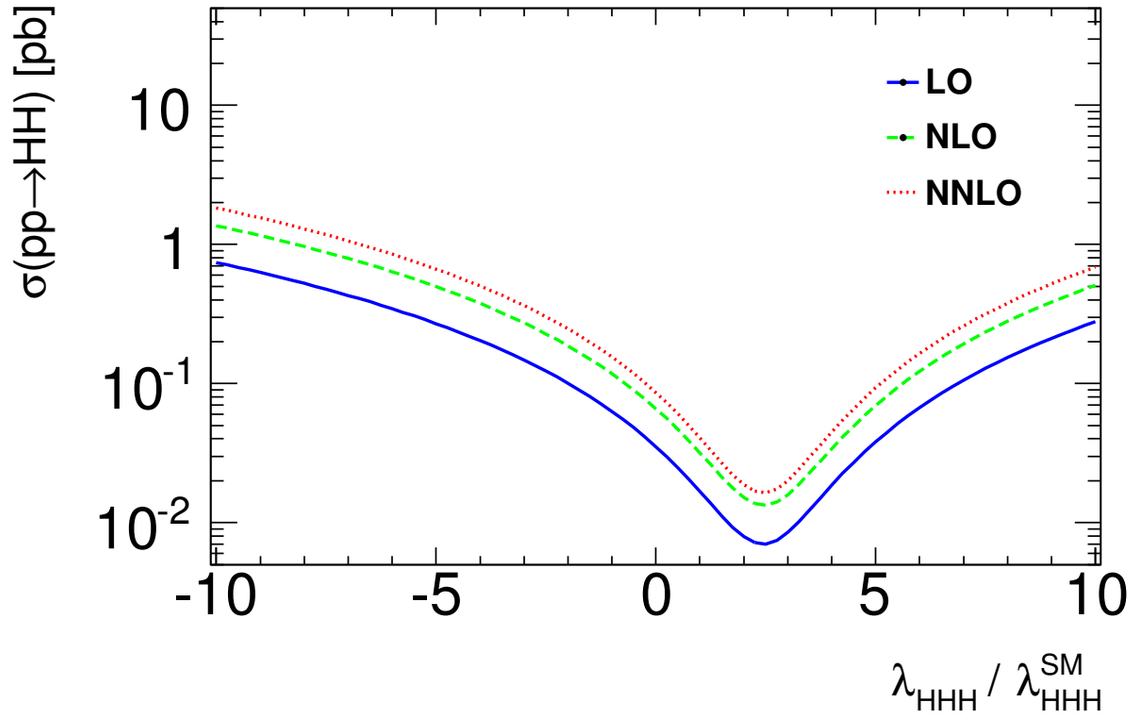
- With 3000 fb^{-1} at M_H=125GeV:
  - Exp. CL limit: 0.52×σ_{SM}
  - Exp. significance: 3.9σ
  - Exp. signal strength: $1.00^{+0.25}_{-0.26}(\text{stat.})^{+0.17}_{-0.15}(\text{sys.})$
- With 300 fb^{-1}: exp. significance=2.3σ



Di-Higgs Boson Production

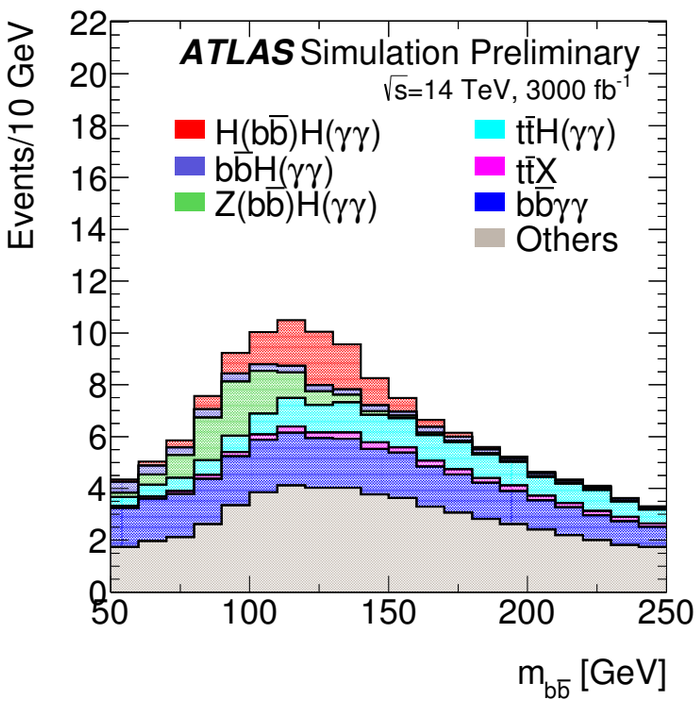
- One of the exciting prospects of HL-LHC.
- Destructive interference

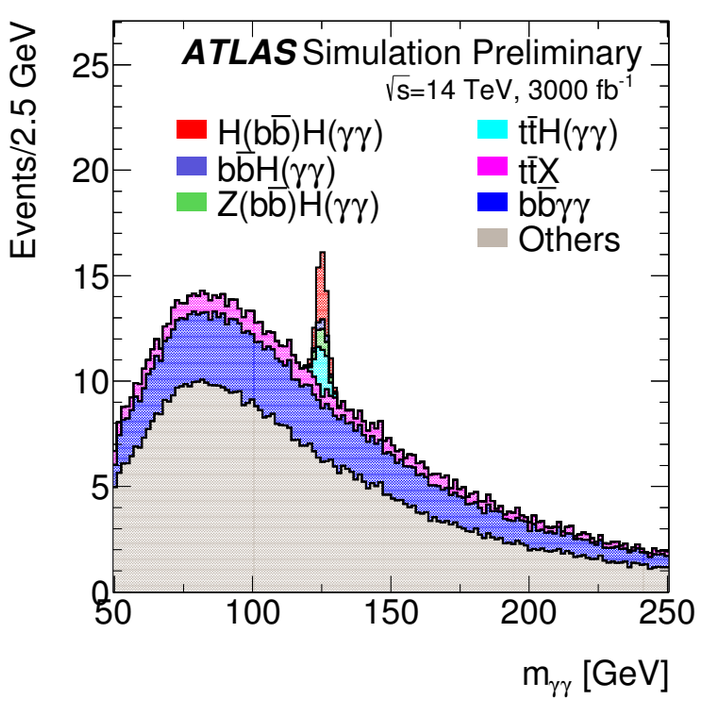


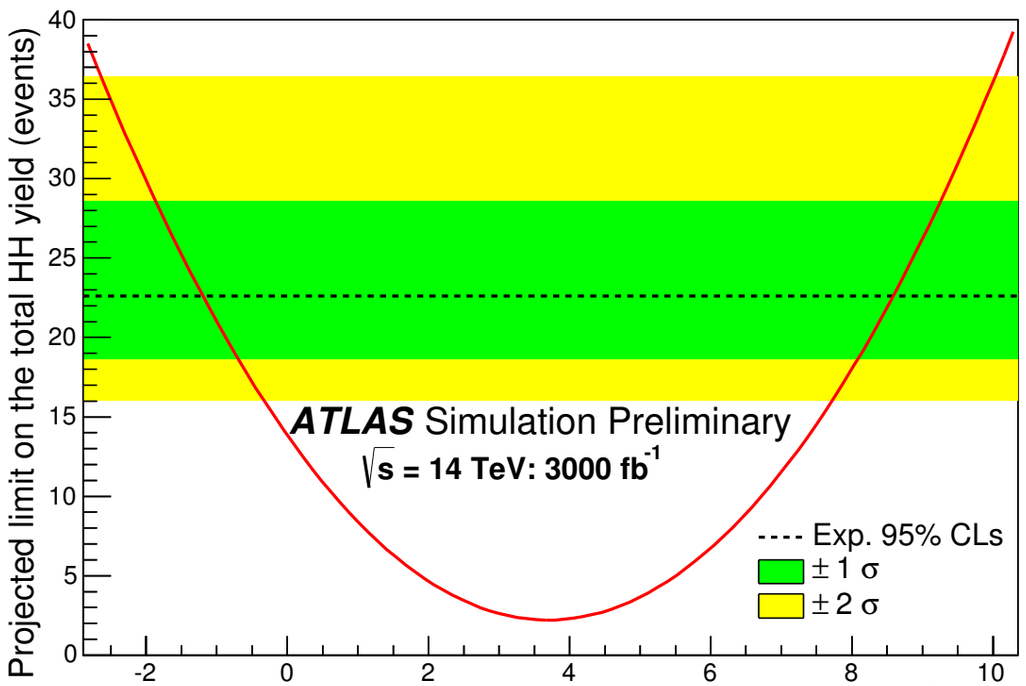


- Cross section of H(bb)H(γγ) @14TeV: 0.11fb [NNLO]
- Run I Non-resonant 95% CL limit:
  - $\sigma_{HH}BR_{bb\gamma\gamma}$<2.2(1.0)pb (2.4σ excess)

HH→bbγγ



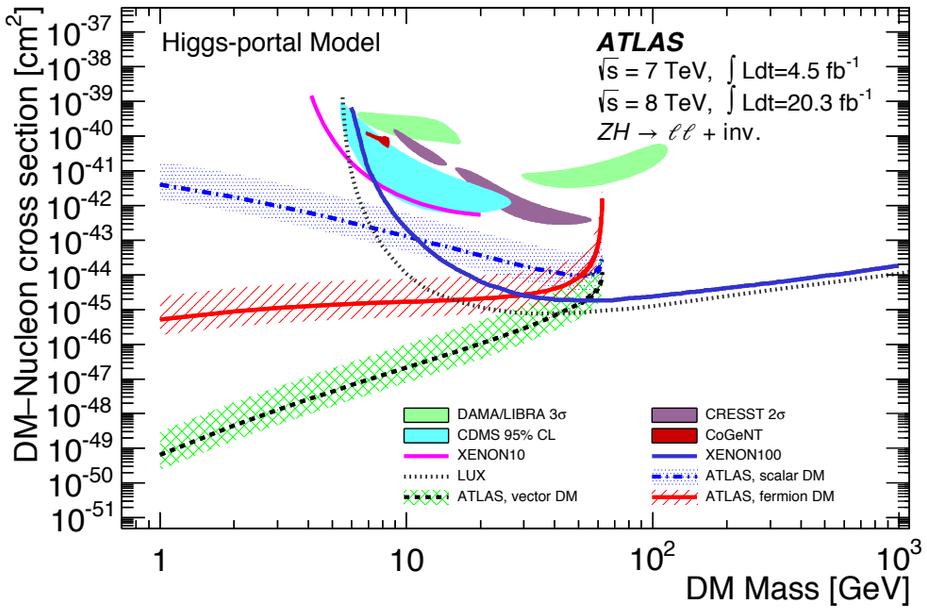


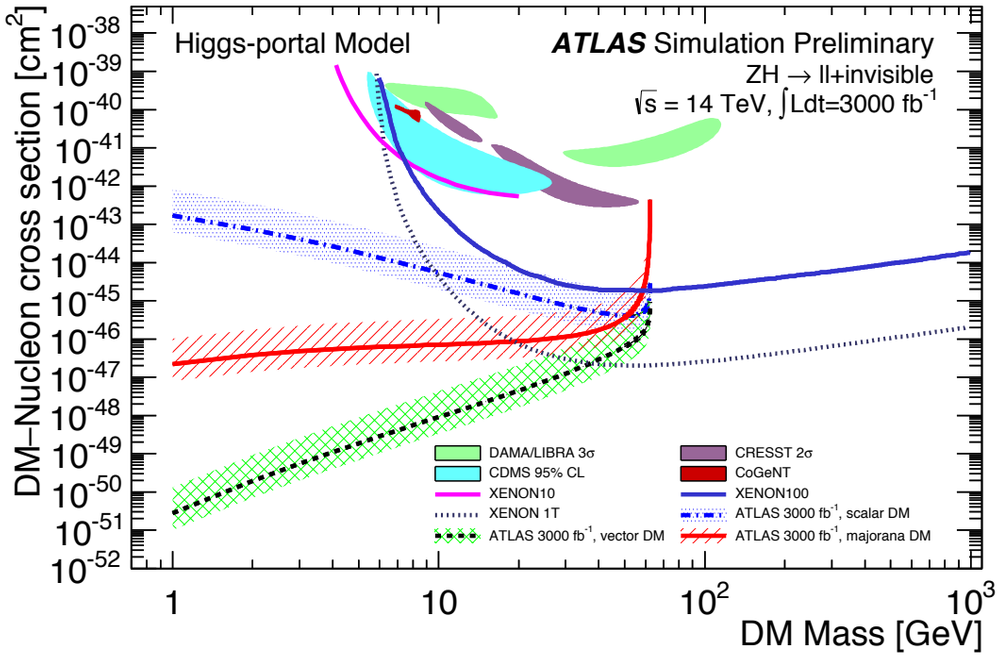


Expected yields (3000 fb^{-1}) Samples	Total	Barrel	End-cap
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=1)$	8.4±0.1	6.7±0.1	1.8±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=0)$	13.7±0.2	10.7±0.2	3.1±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=2)$	4.6±0.1	3.7±0.1	0.9±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=10)$	36.2±0.8	27.9±0.7	8.2±0.4
$b\bar{b}\gamma\gamma$	9.7±1.5	5.2±1.1	4.5±1.0
$c\bar{c}\gamma\gamma$	7.0±1.2	4.1±0.9	2.9±0.8
$b\bar{b}\gamma j$	8.4±0.4	4.3±0.2	4.1±0.2
$b\bar{b}jj$	1.3±0.2	0.9±0.1	0.4±0.1
$jj\gamma\gamma$	7.4±1.8	5.2±1.5	2.2±1.0
$t\bar{t}$(≥ 1 lepton)	0.2±0.1	0.1±0.1	0.1±0.1
$t\bar{t}\gamma$	3.2±2.2	1.6±1.6	1.6±1.6
$t\bar{t}H(\gamma\gamma)$	6.1±0.5	4.9±0.4	1.2±0.2
$Z(b\bar{b})H(\gamma\gamma)$	2.7±0.1	1.9±0.1	0.8±0.1
$b\bar{b}H(\gamma\gamma)$	1.2±0.1	1.0±0.1	0.3±0.1
Total Background	47.1±3.5	29.1±2.7	18.0±2.3
$S/\sqrt{B}(\lambda/\lambda_{SM}=1)$	1.2	1.2	0.4

- Signal significance: 1.2σ
- Possible Self coupling measurement:
  - additional dependence of kinematic variables
  - a combination across several channels, as well as CMS.

H→invisible

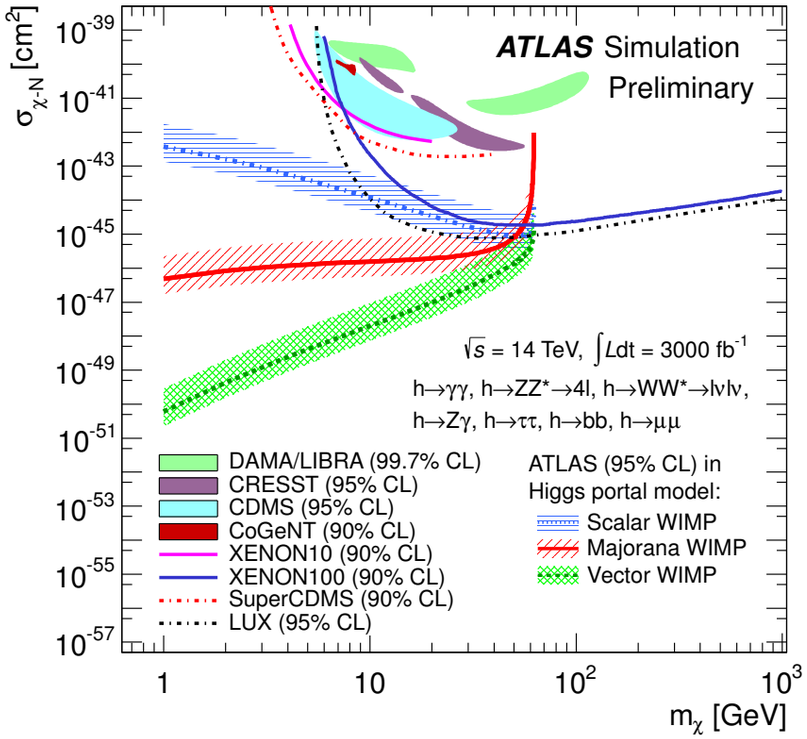




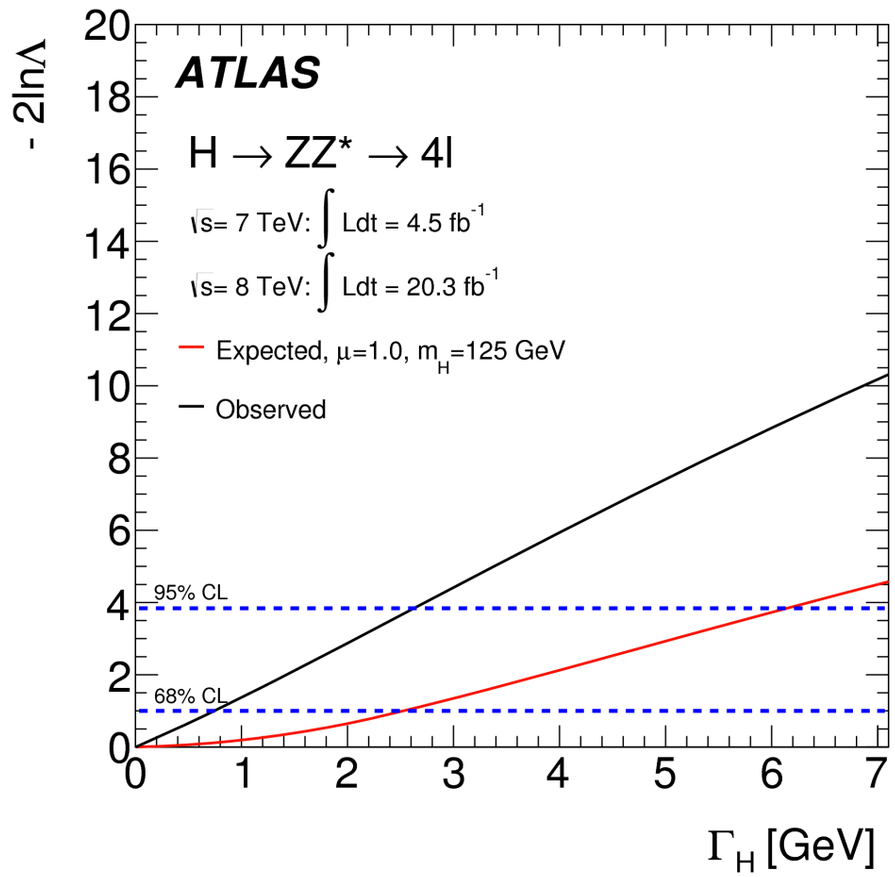
- Run 1: Br(H→inv)<0.37(0.39)@95% CL

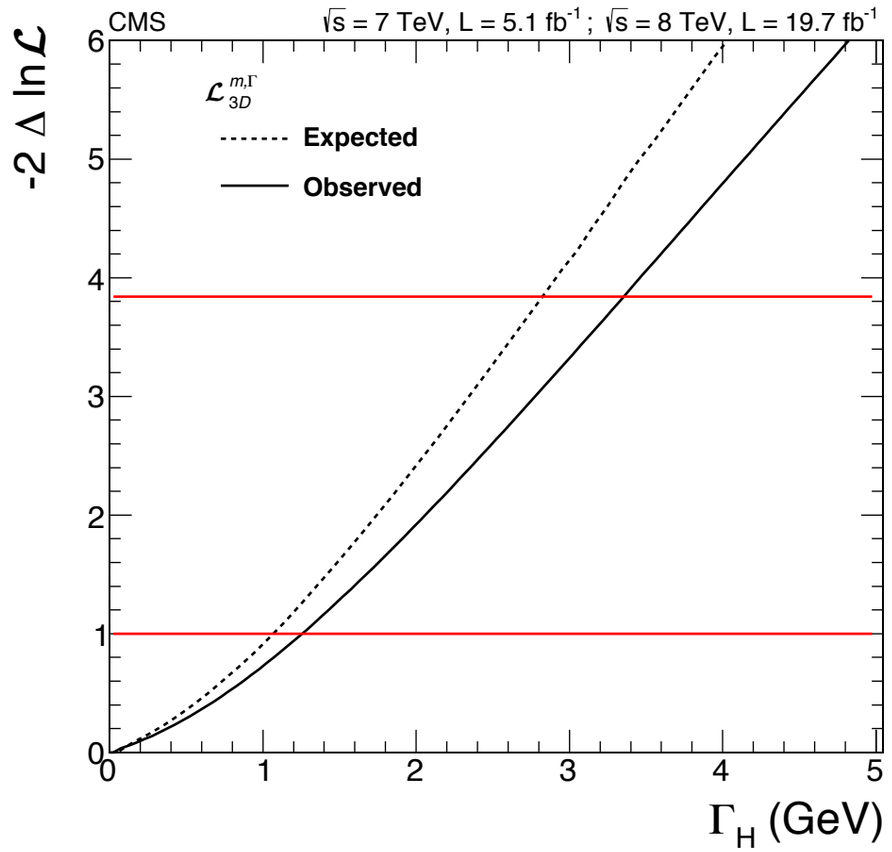
BR(H →inv.) limits at 95% (90%) CL	300 fb^{-1}	3000 fb^{-1}
Realistic scenario	23% (19%)	8.0% (6.7%)
Conservative scenario	32% (27%)	16% (13%)

- Indirect constrant from Higgs coupling measurement:
  - 300fb^{-1}Br(H→inv)<0.22(0.19)@95%(90%) CL
  - 3000fb^{-1}Br(H→inv)<0.13(0.09)@95% (90%)CL
- Higgs Portal to Dark Matter:
  - Invisible branching ratio
  - Coupling constant λ_{HXX}
  - Dark matter-nucleon cross section



Direct Width measurement



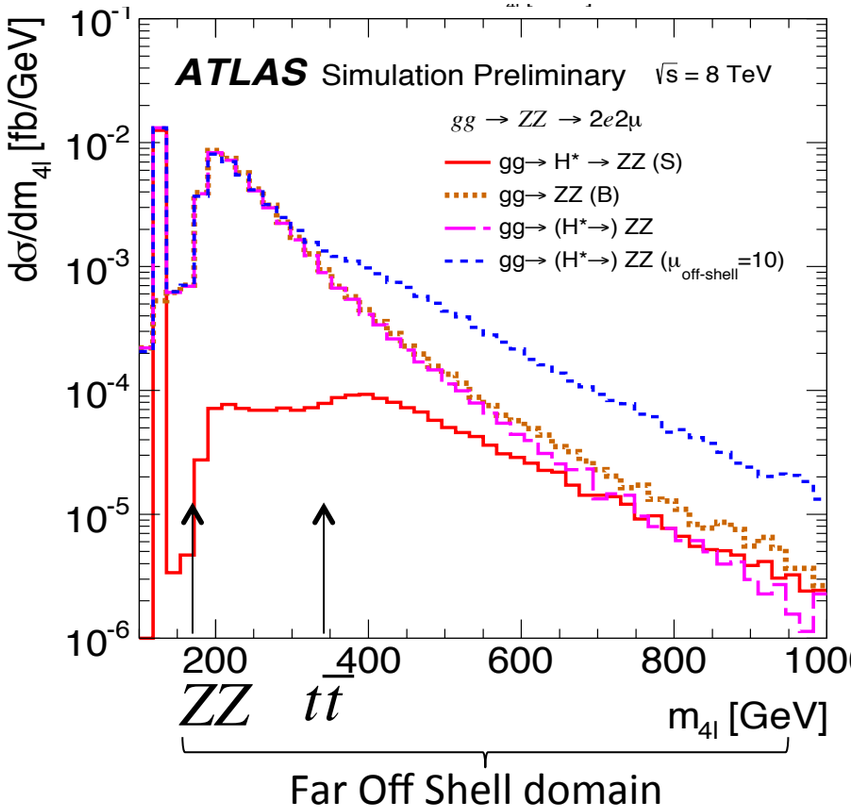


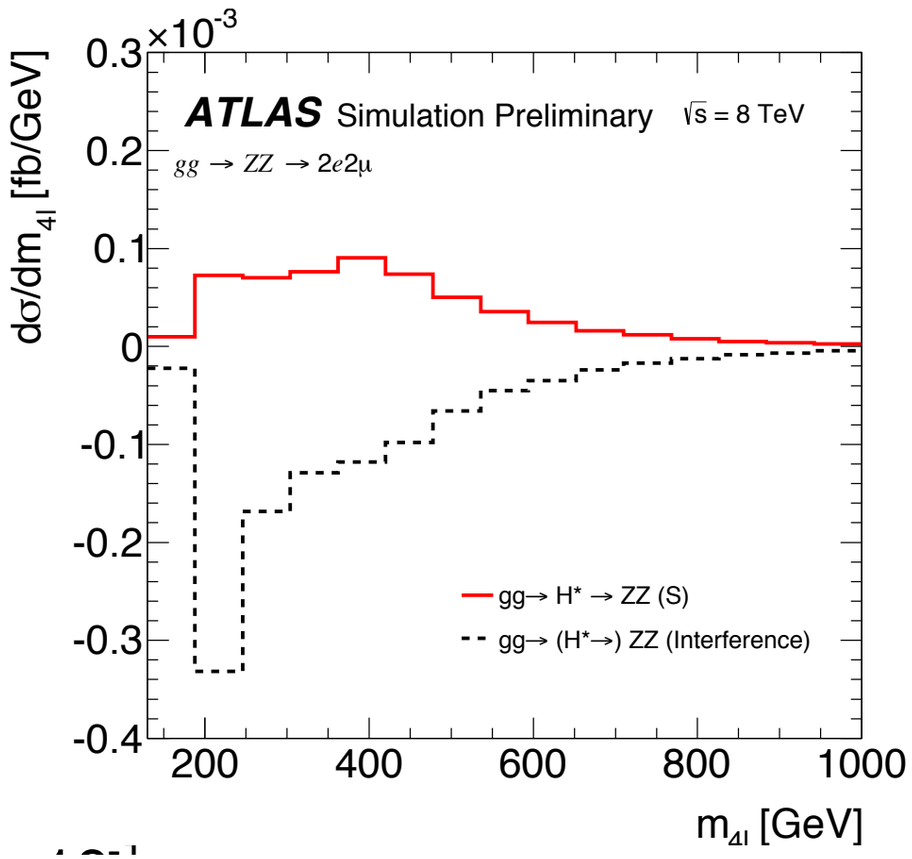
obs.(exp.)@ 95% CL	H→γγ	H→ZZ
ATLAS	5.0 (6.2) GeV	2.6 (6.2) GeV
CMS	2.4 (3.1) GeV	3.4 (2.8) GeV

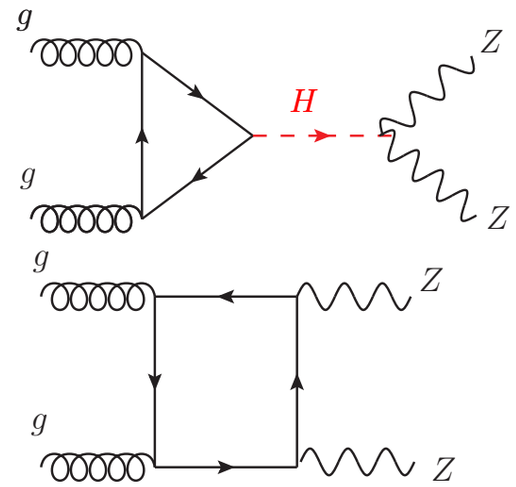
Standard Model predicts a width of Γ=4.2MeV (3 order of magnitude smaller)

Off-shell Higgs coupling properties measurement

Further constraint the Higgs width via indirect measurements based on off-shell higgs production





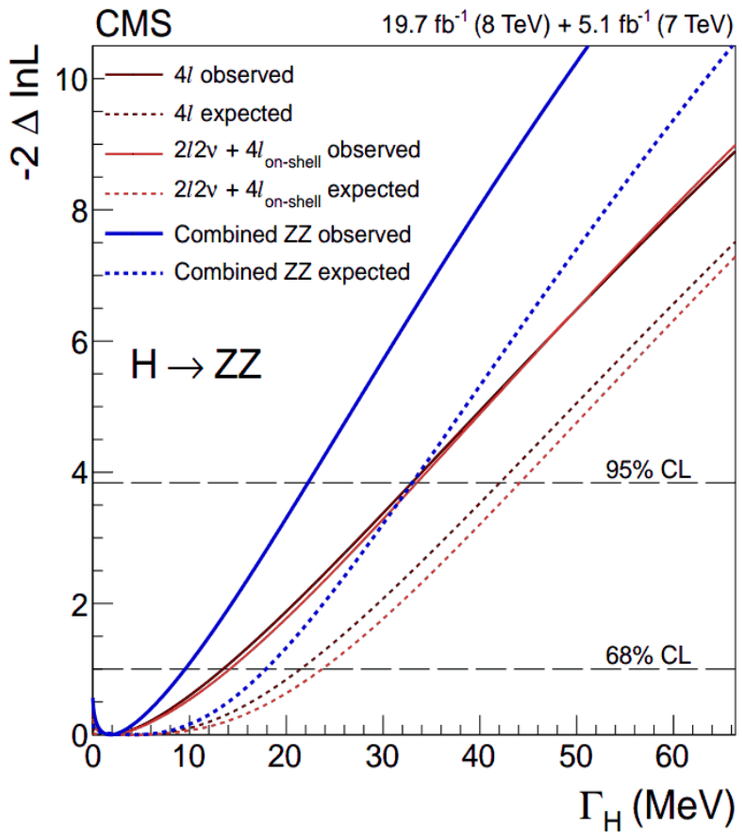


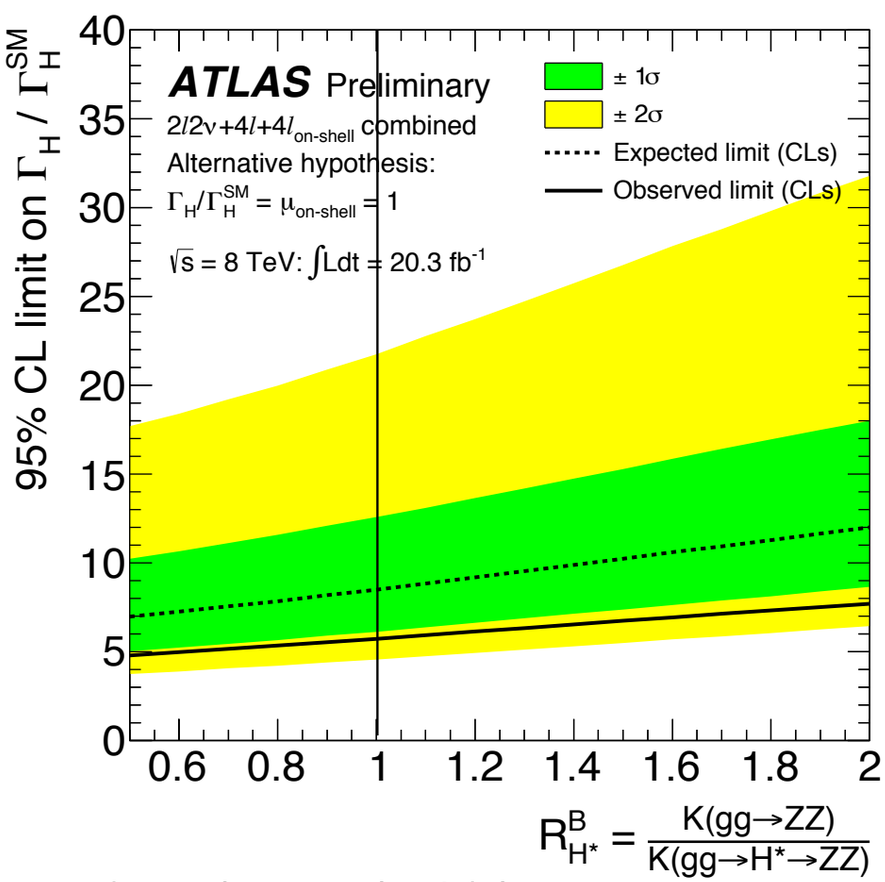
$$\mu_{OffShell} \equiv \frac{\sigma_{OffShell} Br_{VV}}{(\sigma_{OffShell} Br_{VV})_{SM}} = \kappa_t^2 \kappa_V^2$$

$$\mu_{OnShell} \equiv \frac{\kappa_t^2 \kappa_V^2}{\Gamma_H / \Gamma_H^{SM}}$$

- Sizeable off-shell contribution, large negative interference.
- No assumption on gg->ZZ continuum background: $R^b_{H^*} = \frac{k_{gg\to ZZ}}{k_{gg\to H^*\to ZZ}}$

Indirect width measurement in H->ZZ

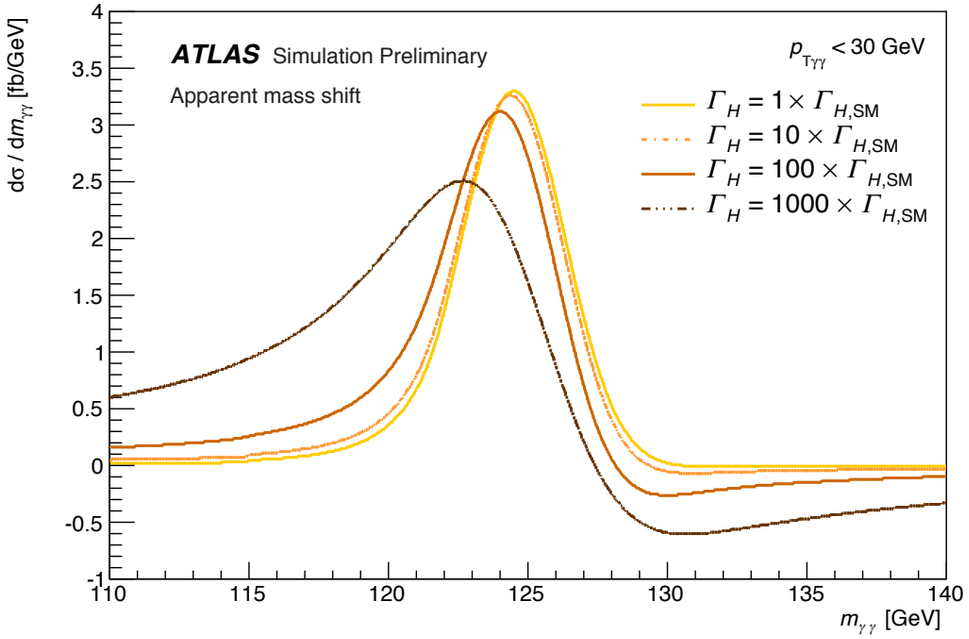


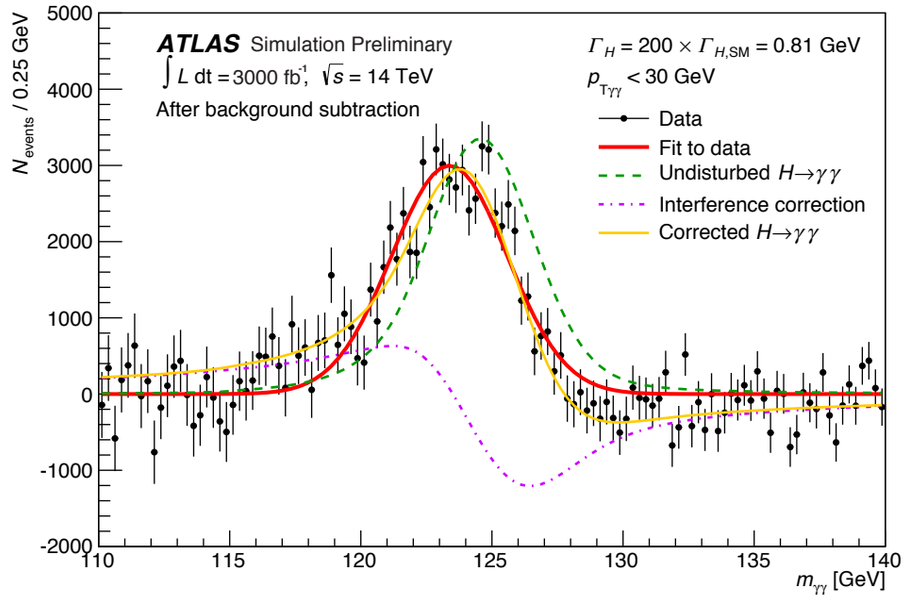


- Dominated by the Stat. Un. and QCD scale uncertainty
- It would be more promising in HL_LHC and with more precision theory prediction.

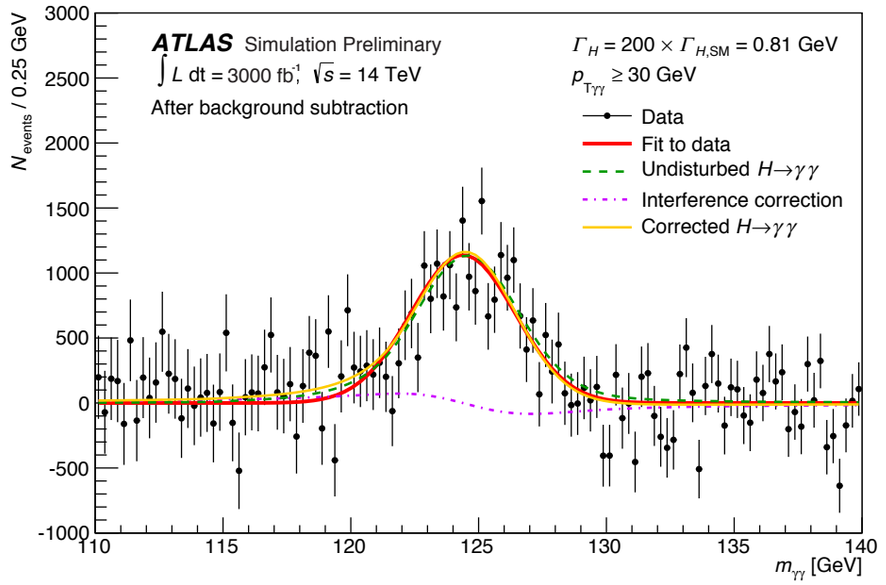
Γ/ΓSM =obs.(exp.)	CMS	ATLAS
4l	8.0(10.1)	7.2(10.2)
2l2v	8.1(10.6)	11.3(9.9)
combined	5.4(8.0)	6.7(7.9)

Indirect width measurement in H→γγ





- Interference in diphoton:
  - SM shift of approximately 30MeV.
- Use pT dependence of shift(~200MeV limit 3ab-1)



Conclusion

- We've come a long way, but there's still far to go …
- With 3000fb^{-1}, the LHC will be able to offer a comprehensive physics programme: precision Higgs production rates to a few %
- 3000fb^{-1} offers significantly better physics reach than 300fb^{-1}
- Theory uncertainties become dominant for many key processes
- Challenge for the HL-LHC:
  - di-Higgs and triple-higgs observation
  - Model independent measurement.