ATLAS & CMS
Higgs Prospects for future (HL)LHC runs

Rencontres du Vietnam 2014
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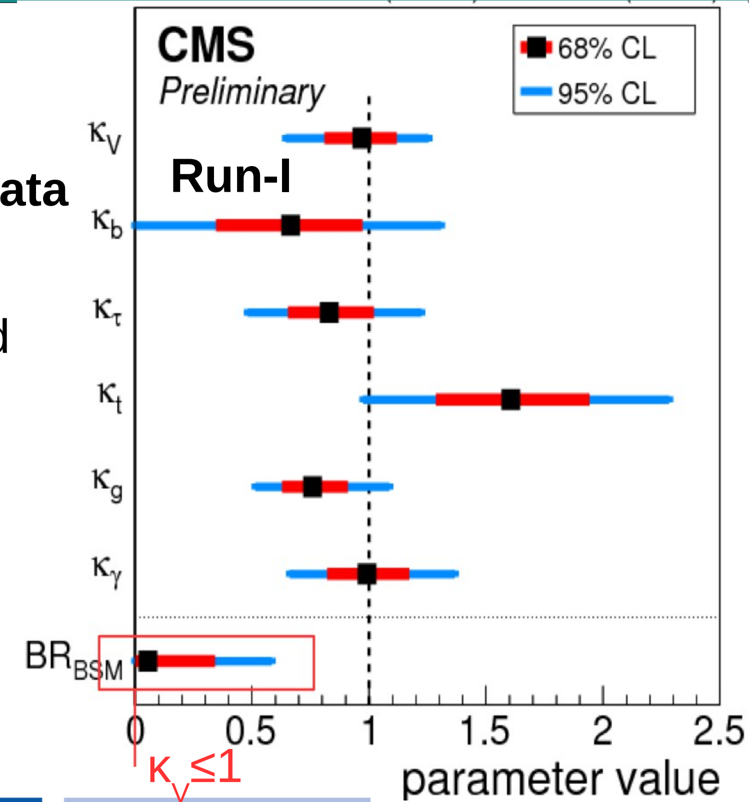
CERN

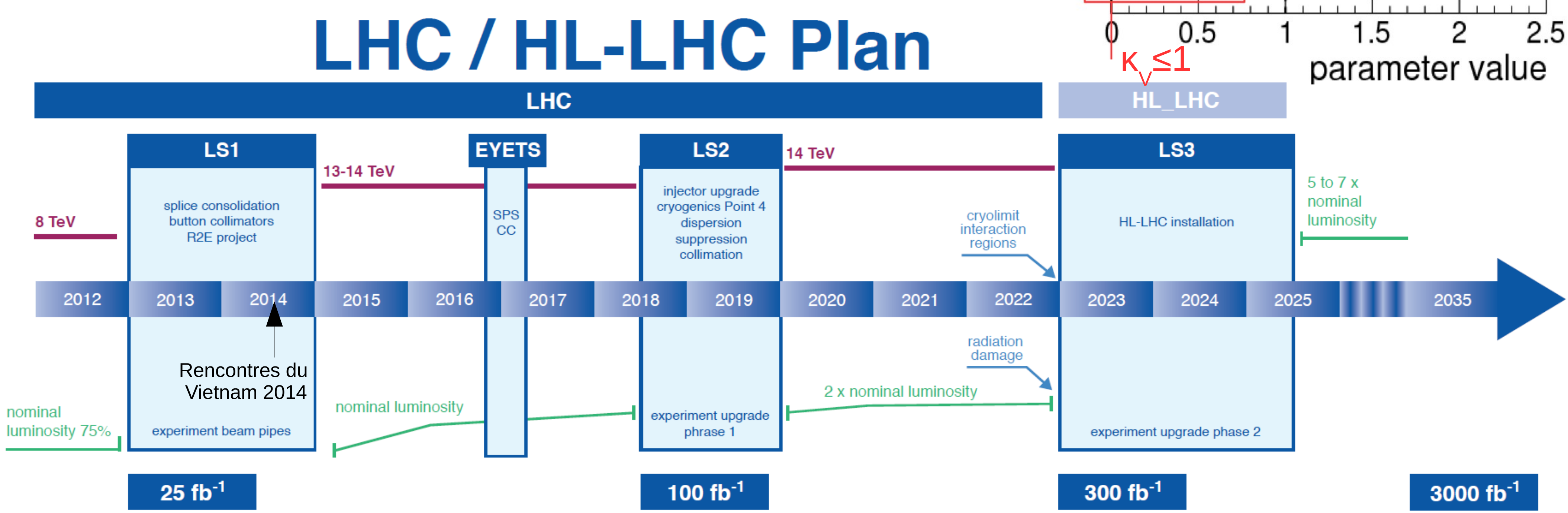
Introduction

- **Search and discovery** of the Brout-Englert-Higgs-Guralnik-Hagen-Kibble boson, a.k.a. "Higgs" boson and the initial **measurements** of its properties **with the LHC Run-I data**

- Expected to collect up to **~300 fb^{-1} of data with the LHC** and **3000 fb^{-1} with the upgraded HL-LHC**

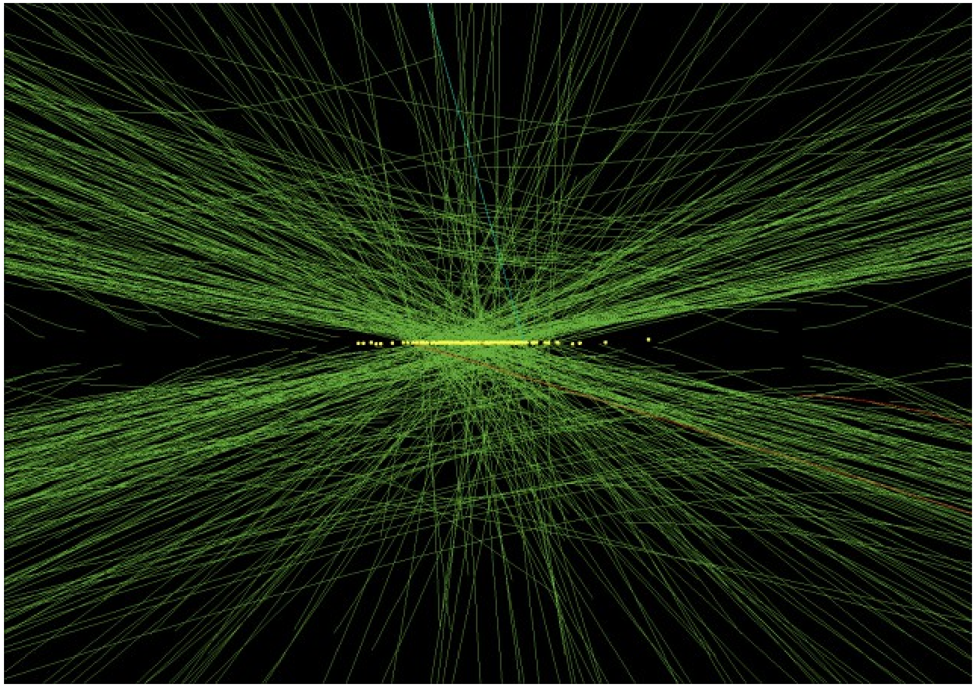
- This talk: expected precision from ATLAS and CMS on Higgs property measurements and on sensitivities to direct new physics searches in the Higgs sector at the HL-LHC

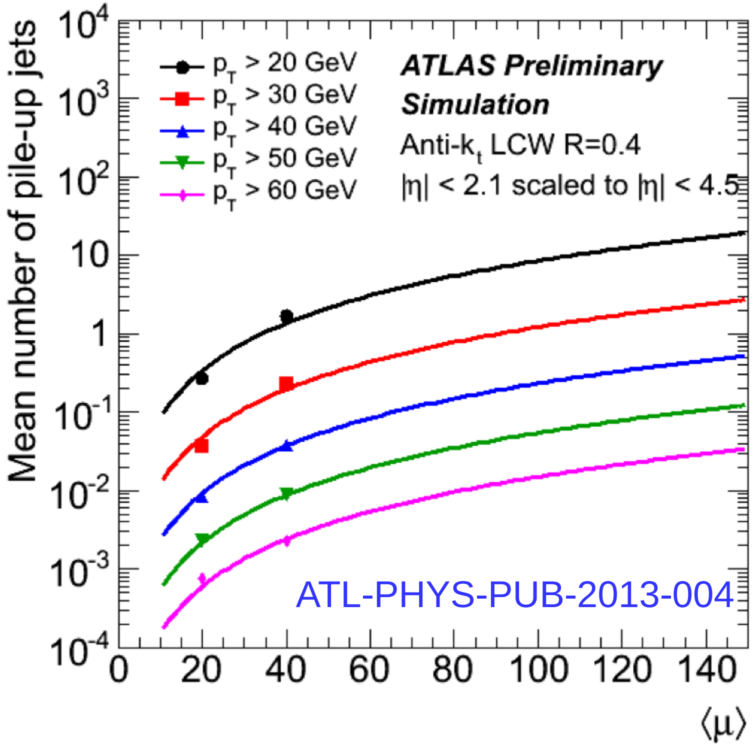




Performance and methodology

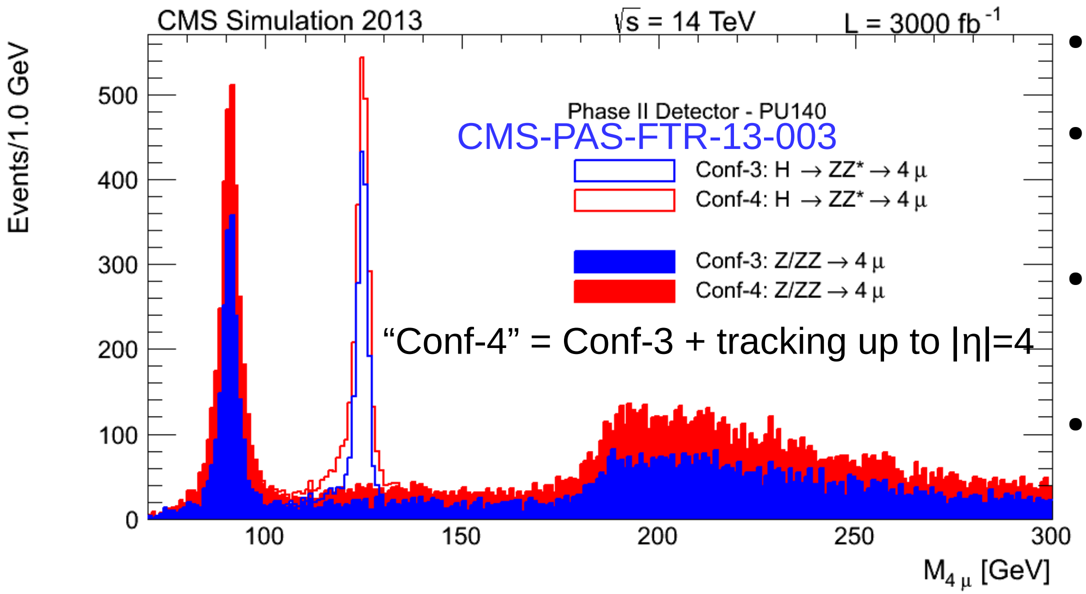
- Experimental environment are degraded at high number of interactions per bunch-crossing, μ, because of pile-up in the subdetectors



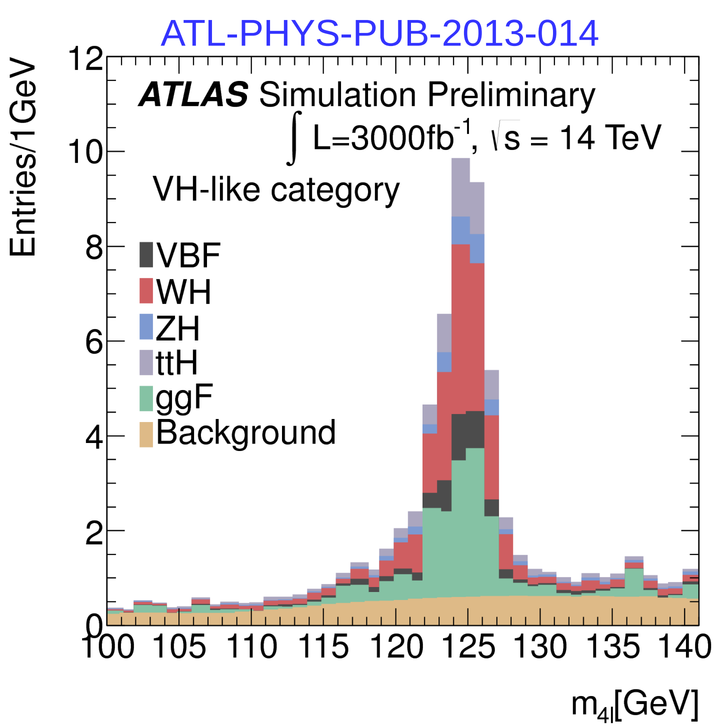


- Higgs prospects are studied by refining current analyses or designing new ones
  - CMS assumes that the upgraded detector will compensate the effects of higher pile-up and extrapolates event rates from existing Run I-like selections
  - ATLAS evaluated the performance using full-simulation studies (sometimes similar, some-times worse than today) and most often smeared truth-level info with efficiencies/resolution
  - Different scenarios usually considered for what concerns the reduction of systematic uncertainties (in particular the signal theoretical ones)

A peak! A cape! It's a peninsula!



- ZZ final states remain very clear channels
- The statistics allow to probe many production modes
- Total H production cross-section uncertainty can be constrained by ZZ events at O(few %)
- CMS showed that these channels could also benefit from a tracking system extended in rapidity (increase of acceptance)



$\mu=\sigma/\sigma_{SM}$

$\Delta\mu/\mu$ ATLAS	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

Diphoton channels

- Similarly, significance in $\gamma\gamma$ decay channels grows up with clear peaks on top of smooth background shapes

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

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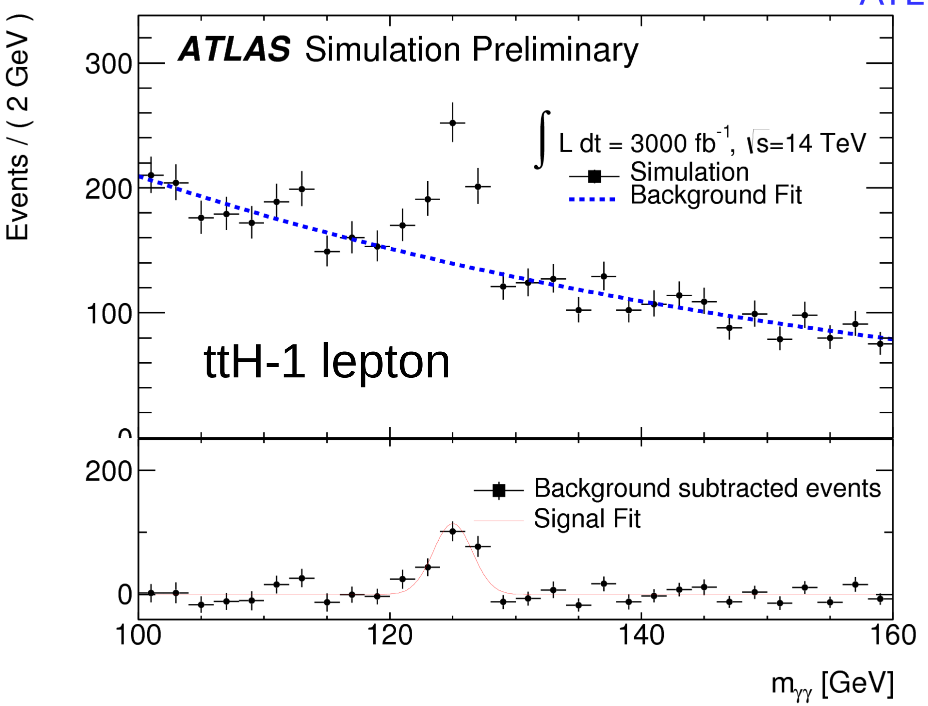
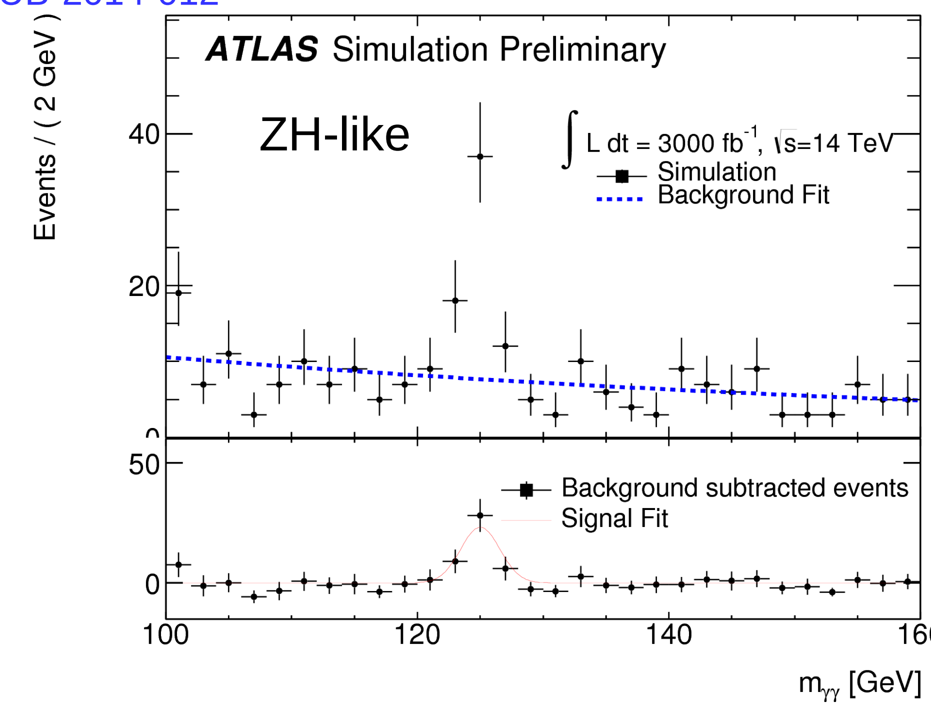


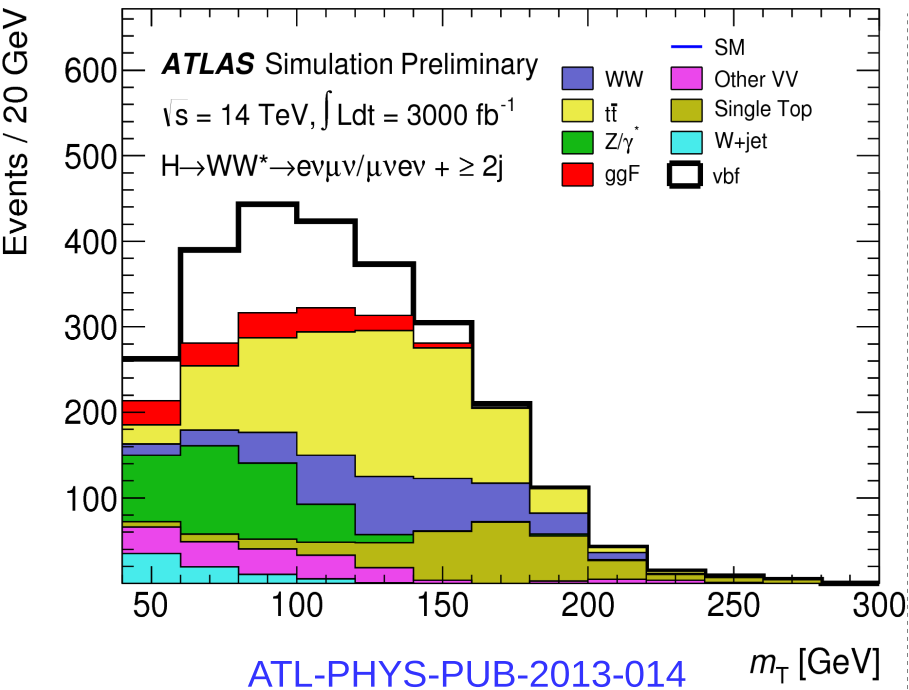


- Diphoton channels is powerful for H-t Yukawa coupling measurements
- Measurements limited by current signal uncertainties
- Reaching the ~3.5% level of precision on the combined signal strength (without th. uncertainties)

	$\Delta\hat{\mu}/\hat{\mu}$ (%)			
Production mode	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	$^{+29}_{-29}$	$^{+18}_{-18}$	$^{+1}_{-1}$	$^{+23}_{-23}$

WW, $b\bar{b}$ and ττ

- Going from 8 to 14 TeV, $t\bar{t}$ increases ~1.7x faster than the signal ; jet counting affected by pile-up conditions → in general, current categories have a largely degraded S/B → HL-LHC studies require dedicated optimizations



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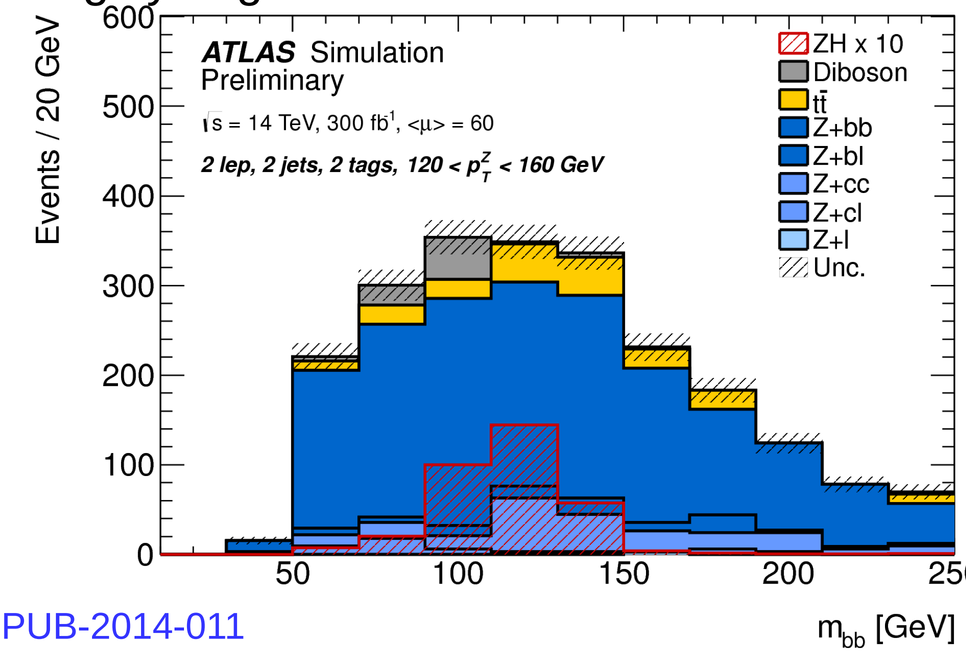
	μ_{ggF}	μ_{VBF}	$\mu_{ggF+VBF}$
300 fb^{-1}	$1^{+0.18}_{-0.15}$	$1^{+0.25}_{-0.22}$	$1^{+0.14}_{-0.13}$
3000 fb^{-1}	$1^{+0.16}_{-0.14}$	$1^{+0.15}_{-0.15}$	$1^{+0.10}_{-0.09}$



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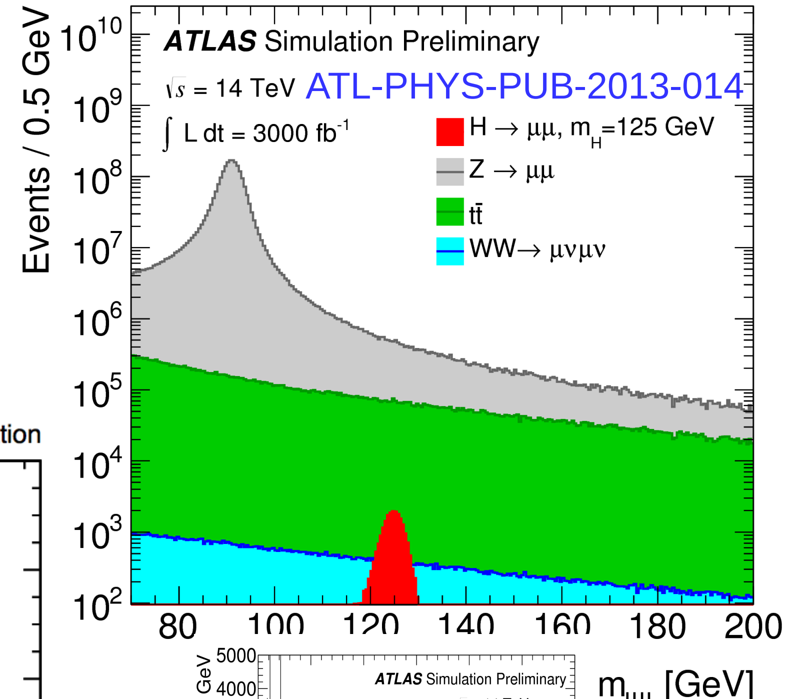
		One-lepton	Two-lepton	One+Two-lepton
Stat-only	Significance	15.4	11.3	19.1
	$\hat{\mu}_{Stats}$ error	+0.07 −0.06	+0.09 −0.09	+0.05 −0.05
Theory-only	$\hat{\mu}_{Theory}$ error	+0.09 −0.07	+0.07 −0.08	+0.07 −007
Scenario I	Significance	2.7	8.4	8.8
	$\hat{\mu}_{w/Theory}$ error	+0.37 −0.36	+0.15 −0.15	+0.14 −0.14
	$\hat{\mu}_{wo/Theory}$ error	+0.36 −0.36	+0.14 −0.12	+0.12 −0.12
Scenario II	Significance	4.7	-	9.6
	$\hat{\mu}_{w/Theory}$ error	+0.23 −0.22	-	+0.13 −0.13
	$\hat{\mu}_{wo/Theory}$ error	+0.21 −0.21	-	+0.11 −0.11

- Large stat → diff measurements ?
- ττ expectations on the signal strength precision are 8(5)% with current (/2) theory uncertainties

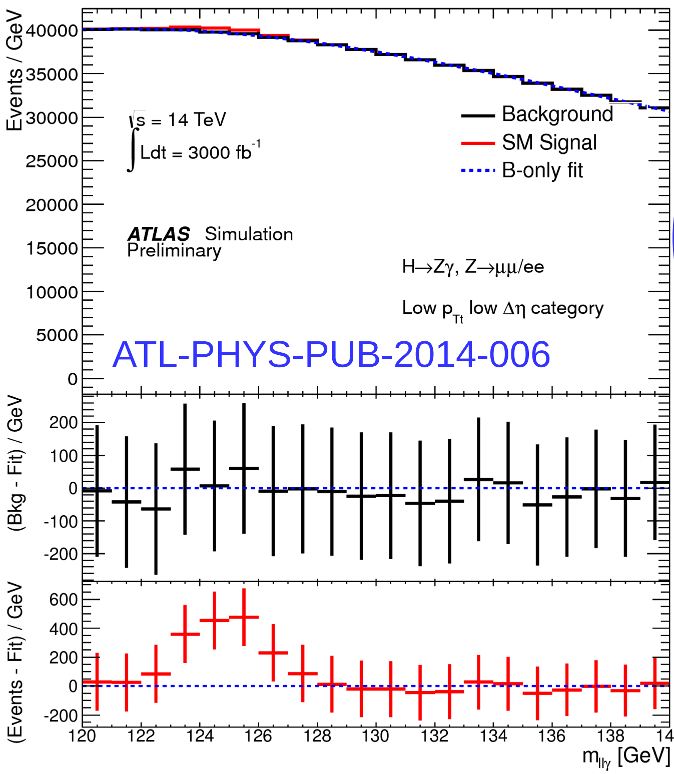
Rare channels

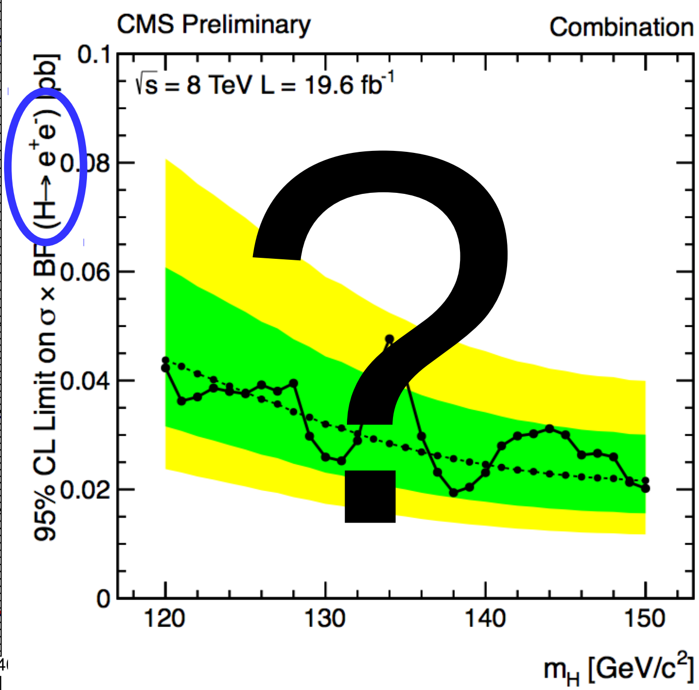
- Rare decays are the ones benefitting the most from the large HL-LHC dataset
- $Z\gamma$ sensitive to potential new particles in loop
  - ~20-30% precision on signal strength (~4σ) expected by CMS/ATLAS (Currently limits are at ~10x the SM prediction)
- μμ sensitive to the 2nd generation couplings
  - 7-8σ and Δμ/μ~20% expected, ttH(μμ) observable
- H→e+e-, H→cc decays and bbH productions observable ?

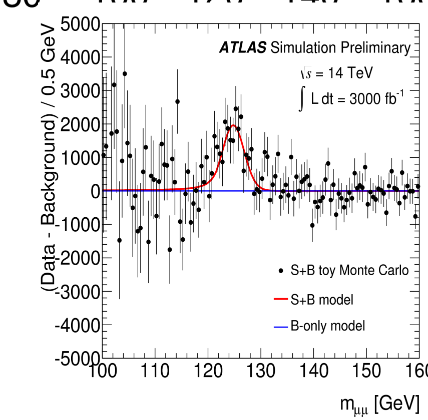
See Hulin's talk



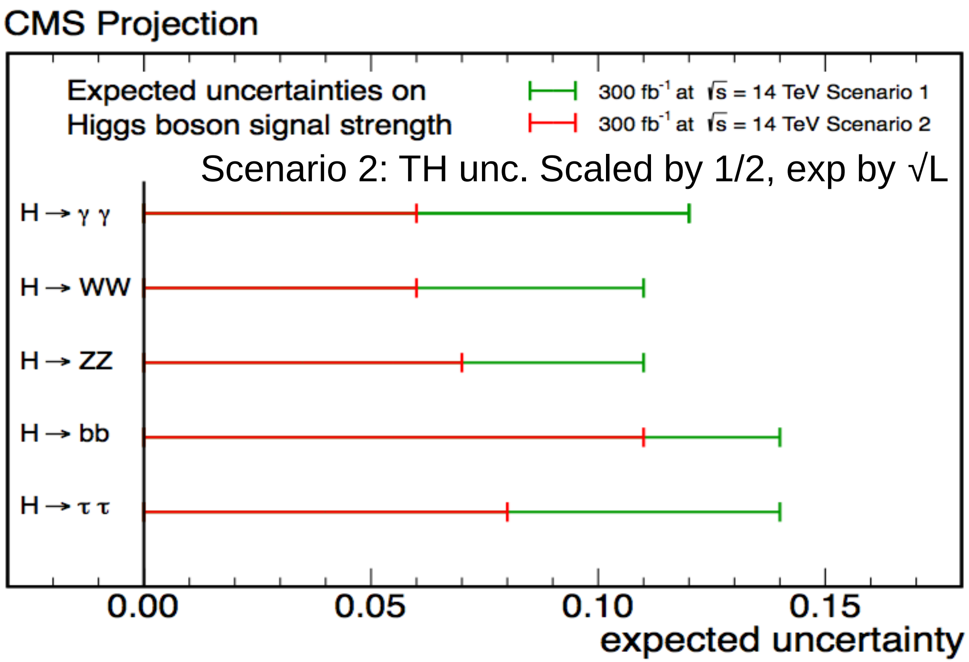
See Stoyan's talk

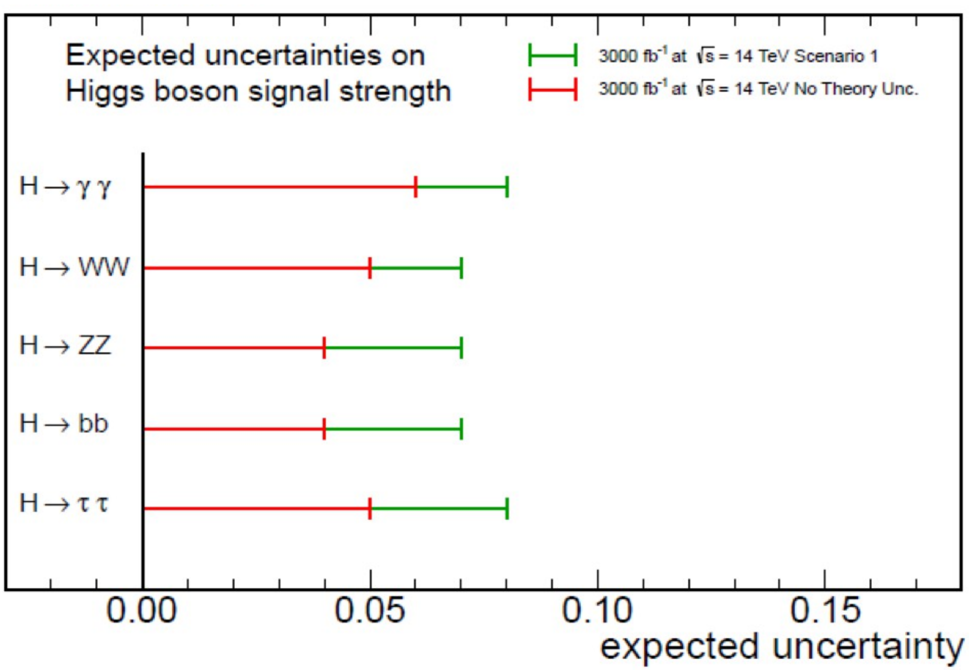


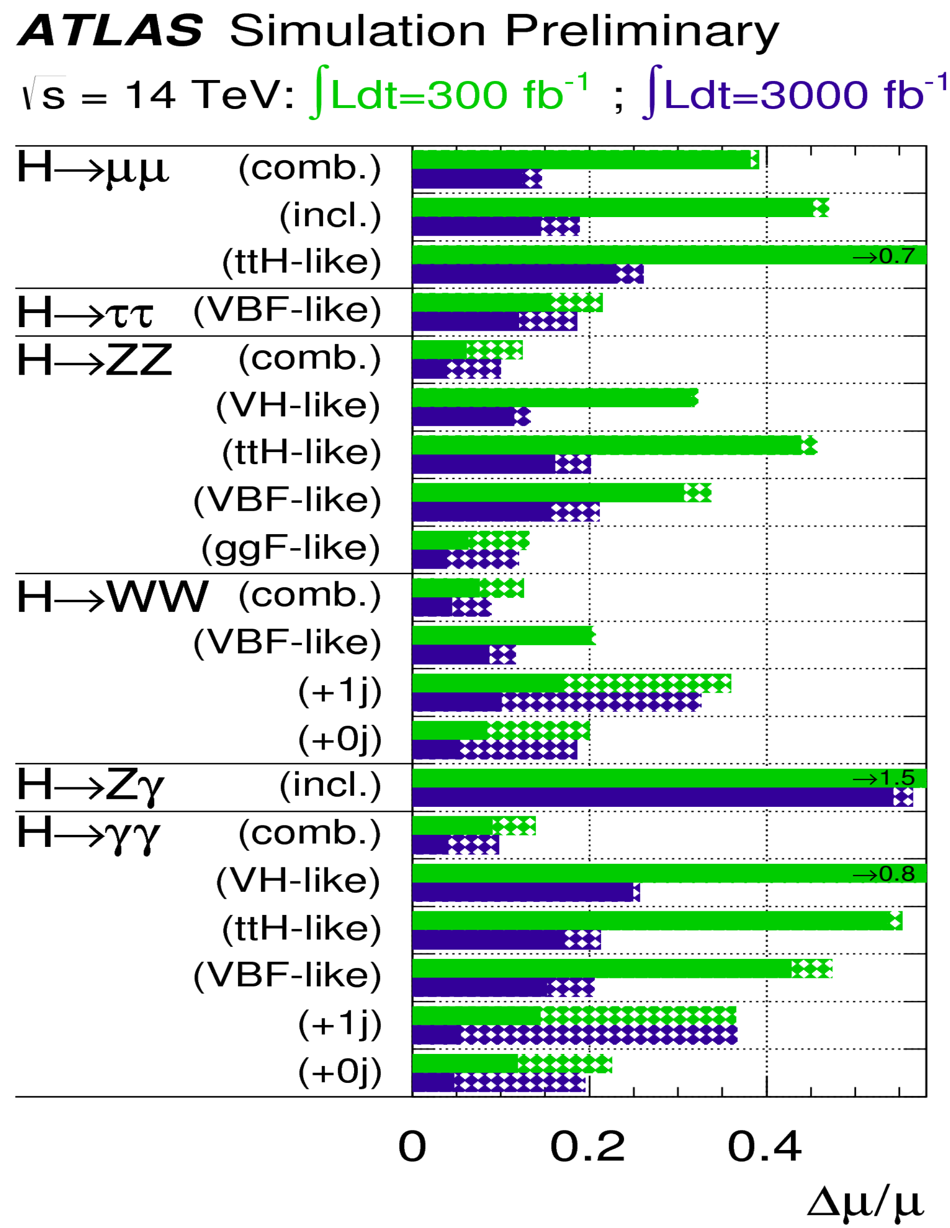




Channels summary



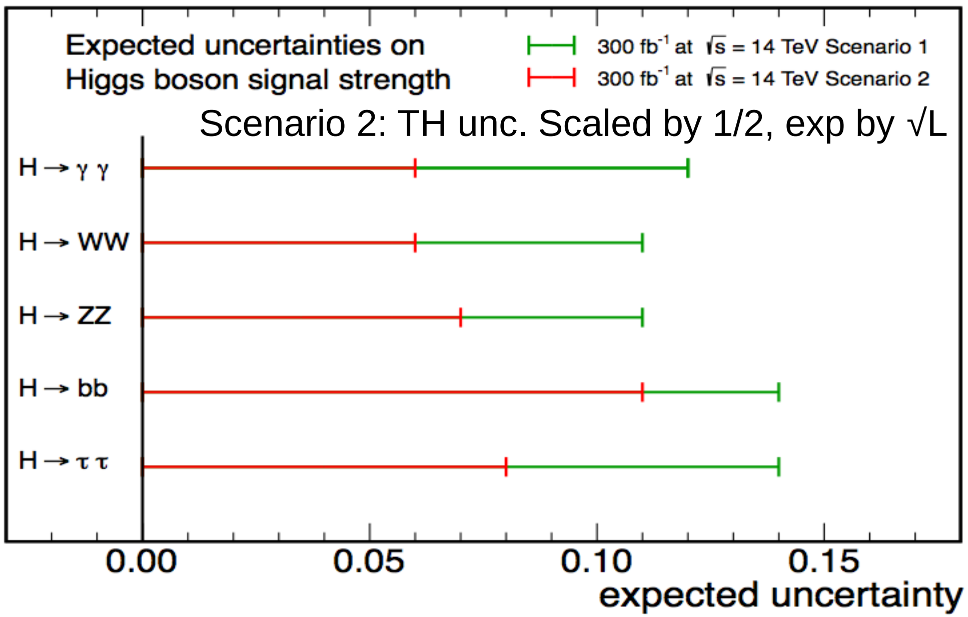


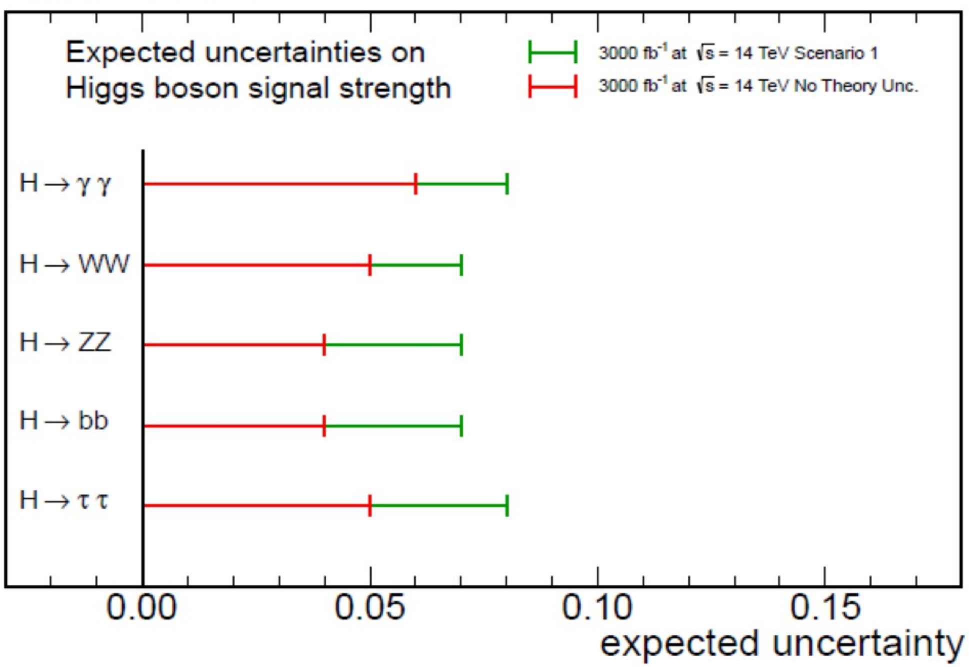


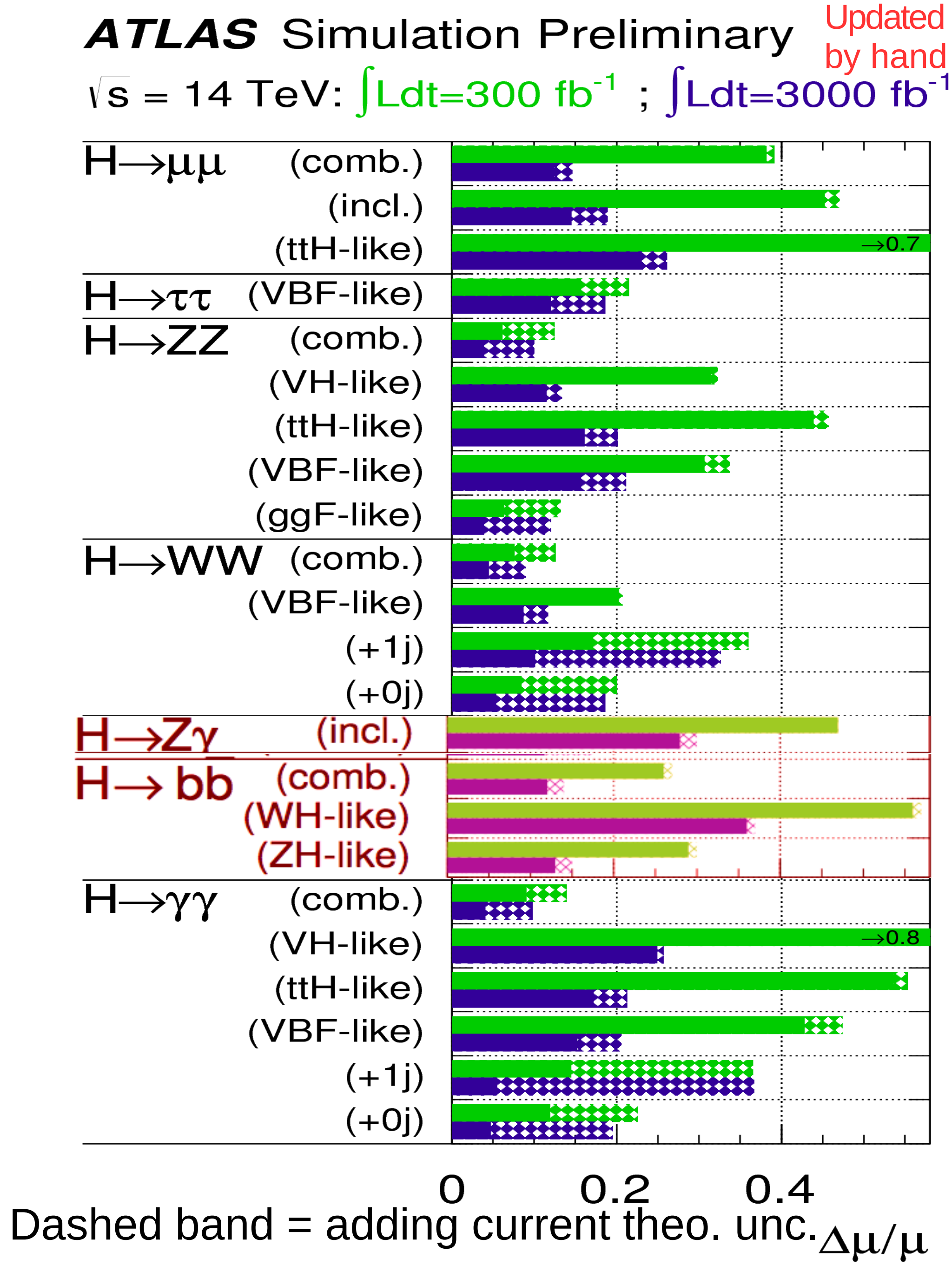
Dashed band = adding current theo. unc.

Channels summary

CMS Projection



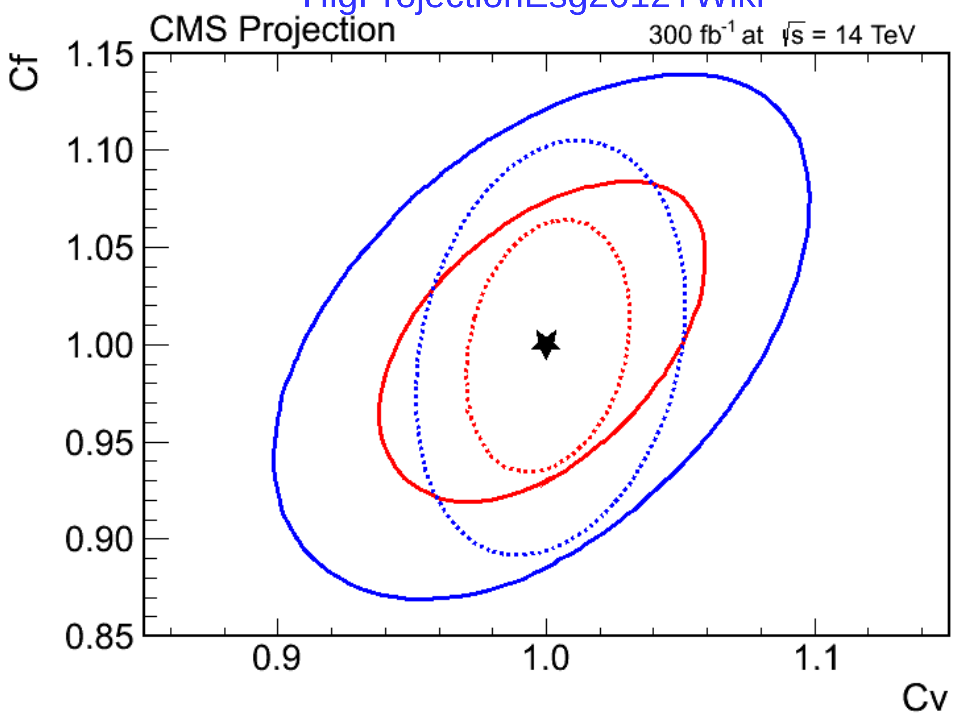




Combination

- Inputs from ATLAS and CMS concerning the individual channels are very similar although techniques to obtain those prospects are quite different
- As for run-I data, those channels prospects can be combined to obtain precision on couplings measurements
- One very simple model consists in fitting scale factors for fermions on one hand and bosons on the other hand:

HigProjectionEsg2012TWiki



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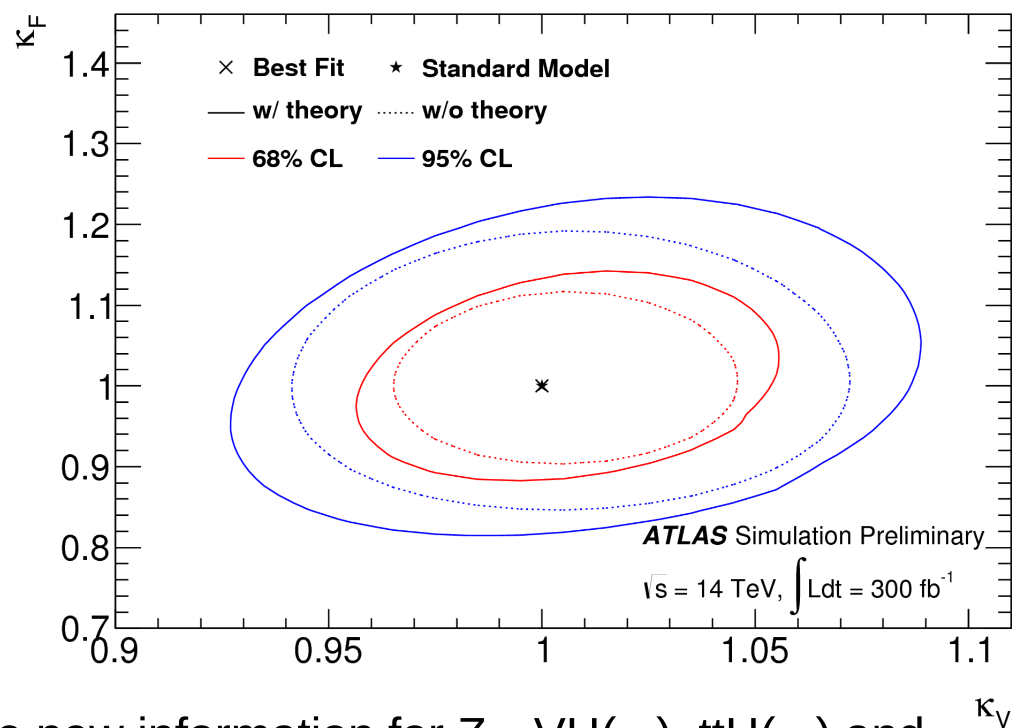

- ATLAS combined results do not include yet the new information for Zγ, VH($\gamma\gamma$), ttH($\gamma\gamma$) and VH(bb)

Combination (2)

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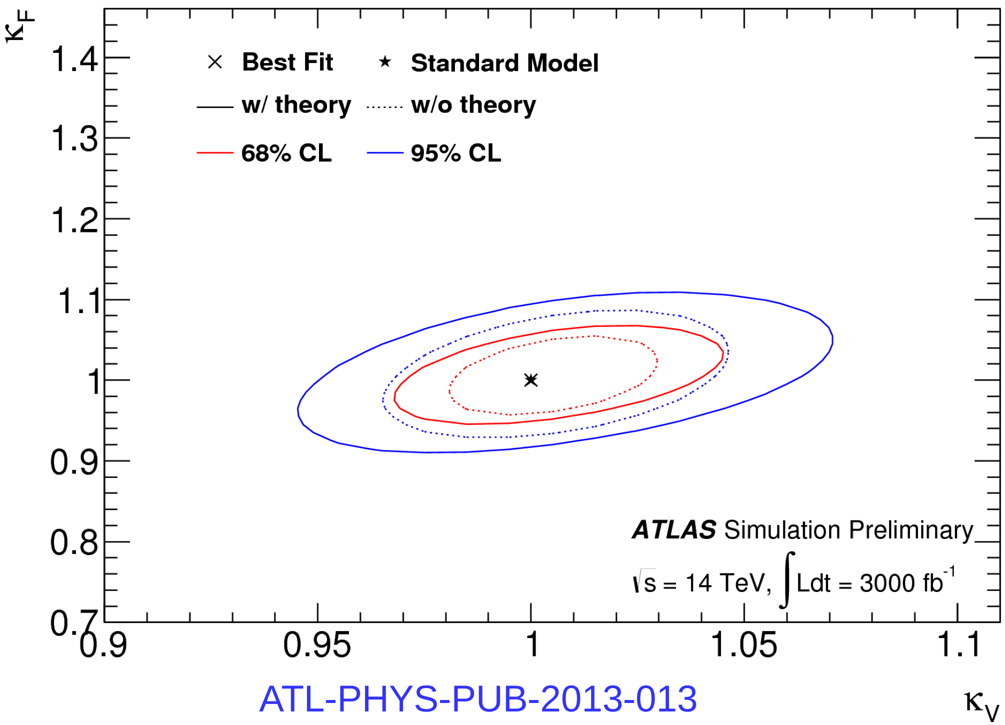

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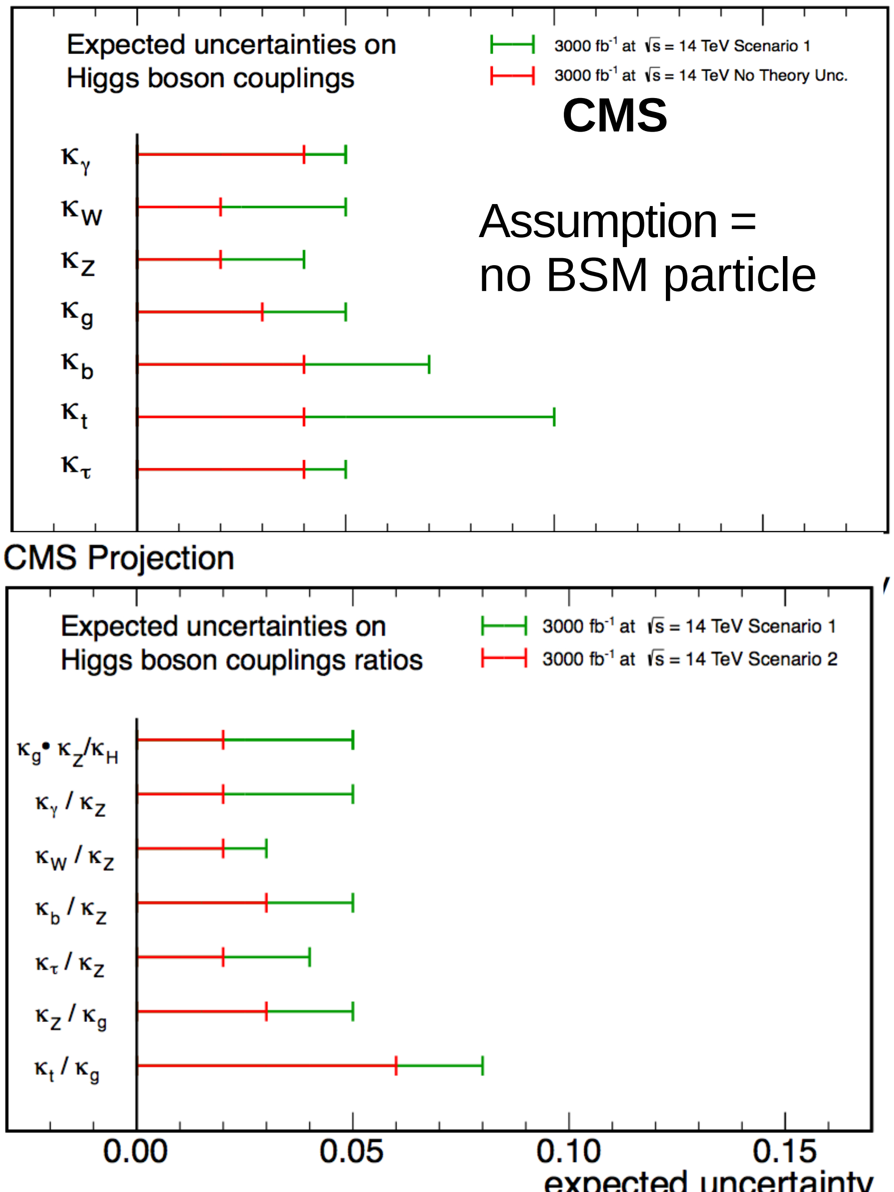
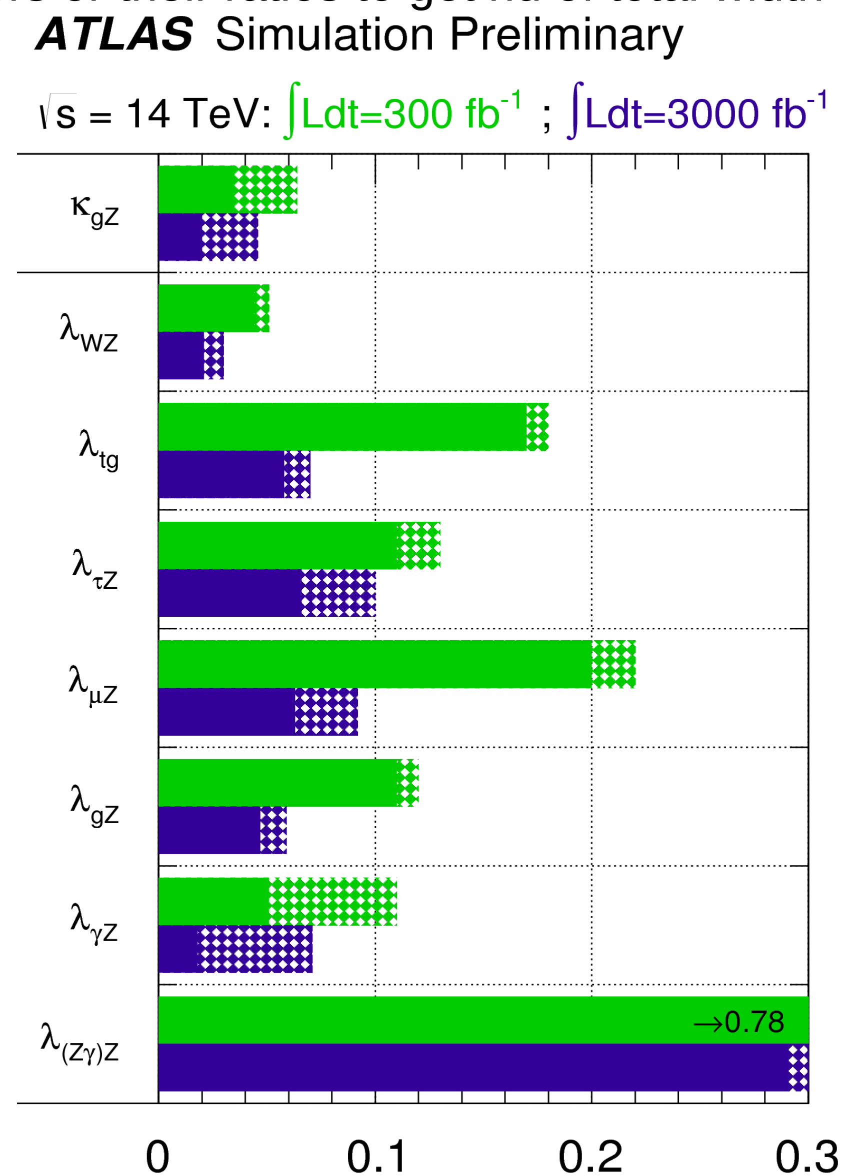
Couplings fit

- Using the κ-framework one can fit couplings scale factors or their ratios to get rid of total width assumptions   See Giovanni's talk





ATLAS combined results do not include yet the new information for Zγ, VH(γγ), ttH(γγ) and VH(bb)

$$\Delta\lambda_{XY}=\Delta\left(\frac{\kappa_X}{\kappa_Y}\right)$$

- In the future, use of EFT for more general model fits

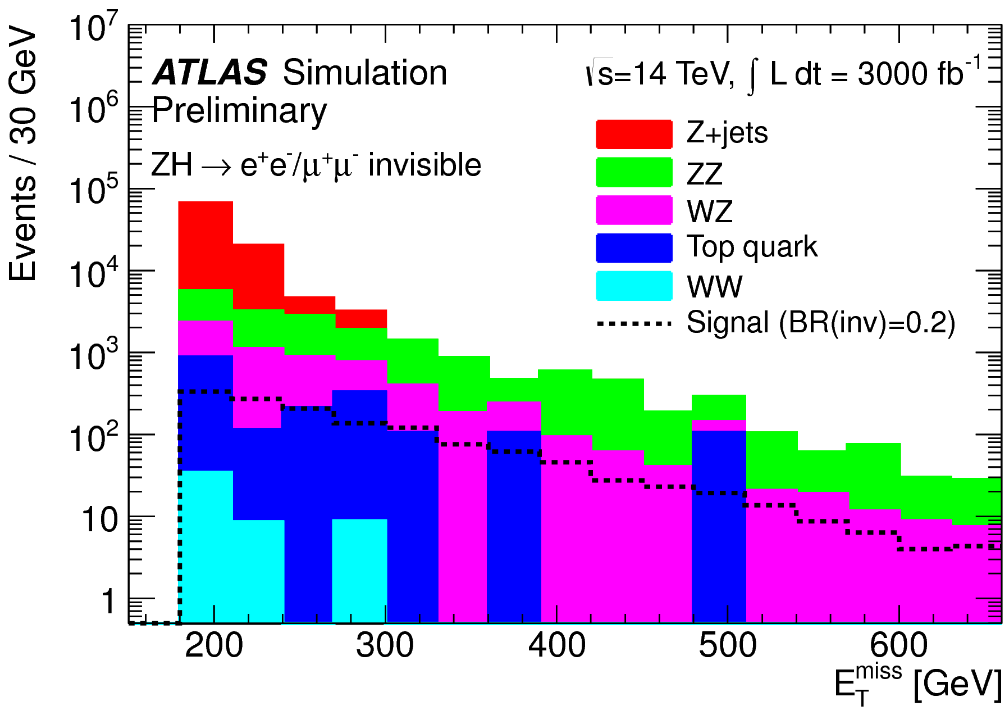
Missing partial decay width ?

- Using Z-tagging, direct search for invisible branching fraction in ZH events can be carried out

BR($H \to$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%)

ATLAS

- Through the coupling fit, CMS expects to constrain the BR(inv) to better than 11%
- Limits on the invisible branching fraction can be interpreted as bounds on the strength of the interaction between the dark matter and the Higgs boson



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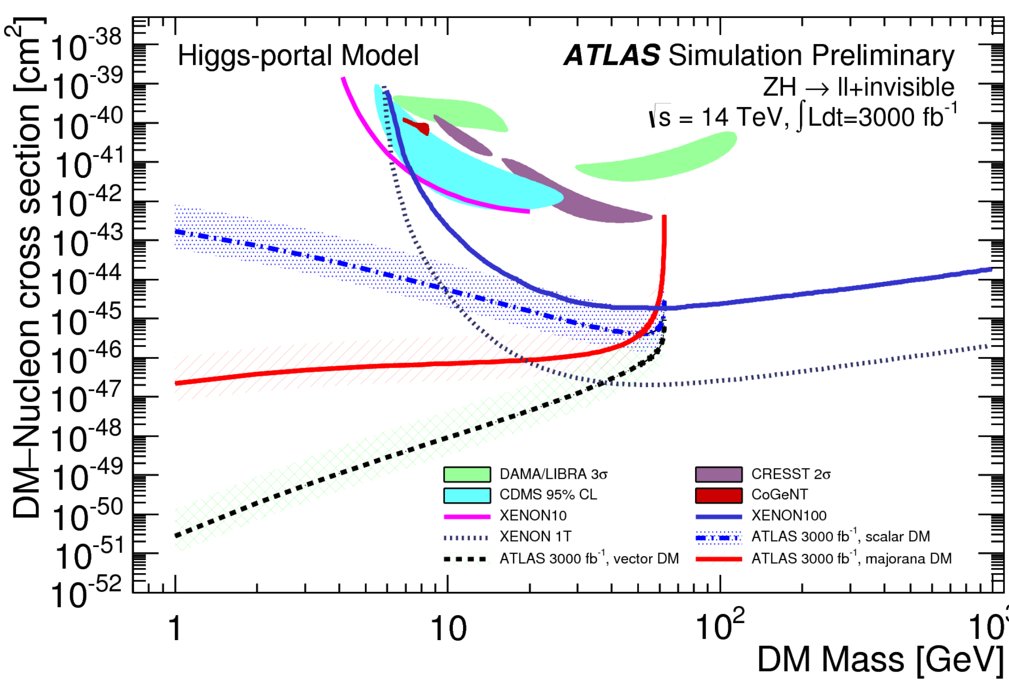
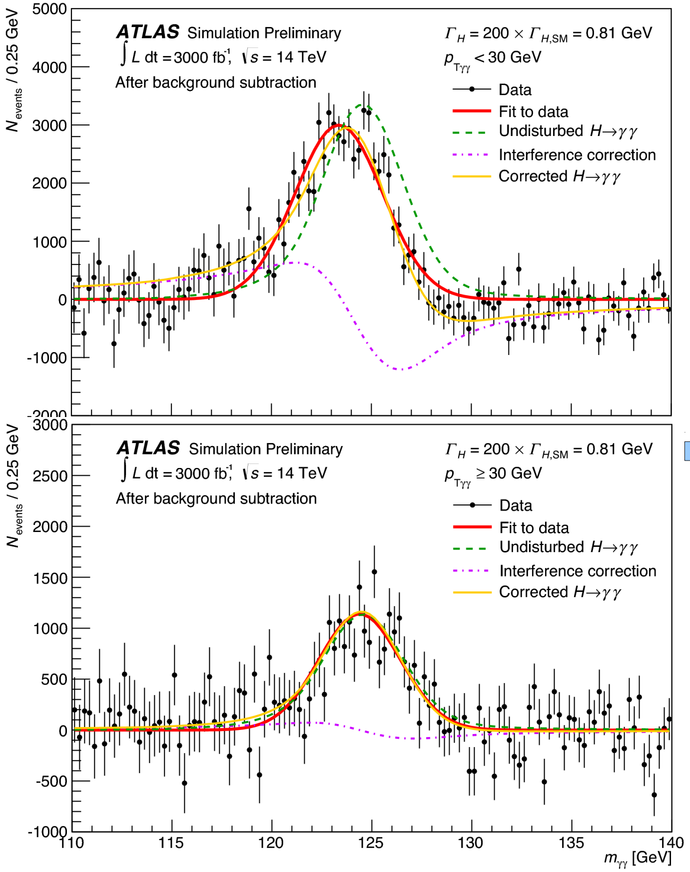


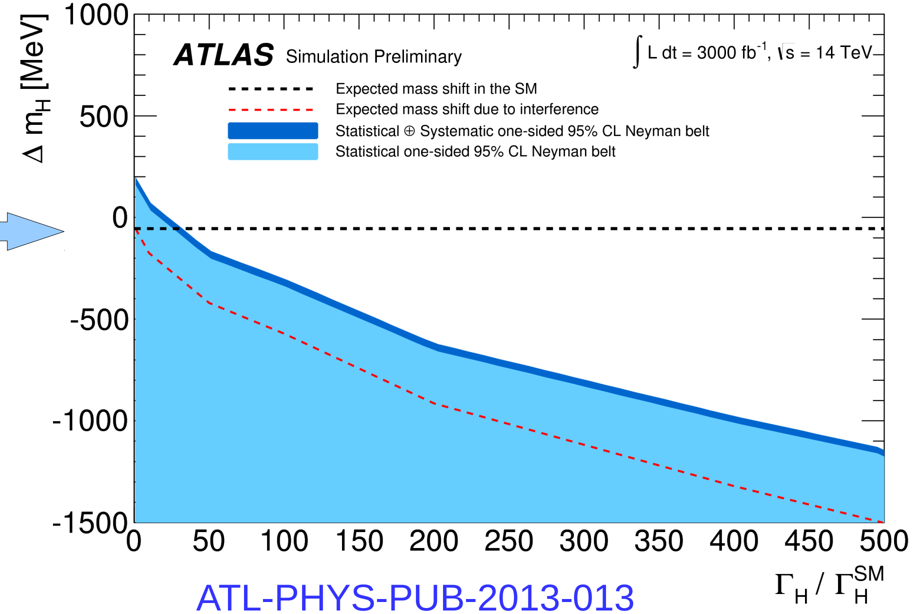
arXiv:hep-ph0605188 arXiv:1109.4398
arXiv:1112.3299 arXiv:1203.2064

Total width

- Interference of the H→γγ signal with respect to the continuum diphoton background (gg→γγ box diagrams)



- Causes pT(H)-dependent apparent shift in mass
- Looking at the mass difference between pT(H) categories



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- New techniques based on off-shell measurements have not been extrapolated yet to high-luminosity datasets:
  - Currrent limits at 5-10x Γ_{SM} — See Giacomo's talk
  - Almost already theoretical uncertainties-limited

Probing the coupling structure

- ZZ events provide the full angular information See Jana's talk
- Very sensitive to non-SM (0^+) contributions

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

- Fit fraction of events $f_{a_i} = \dfrac{|a_i|^2\sigma_i}{|a_1|^2\sigma_1 + |a_i|^2\sigma_i}$ and phases $\phi_{a_i} = \arg\left(\dfrac{a_i}{a_1}\right)$ to angular discriminant distributions

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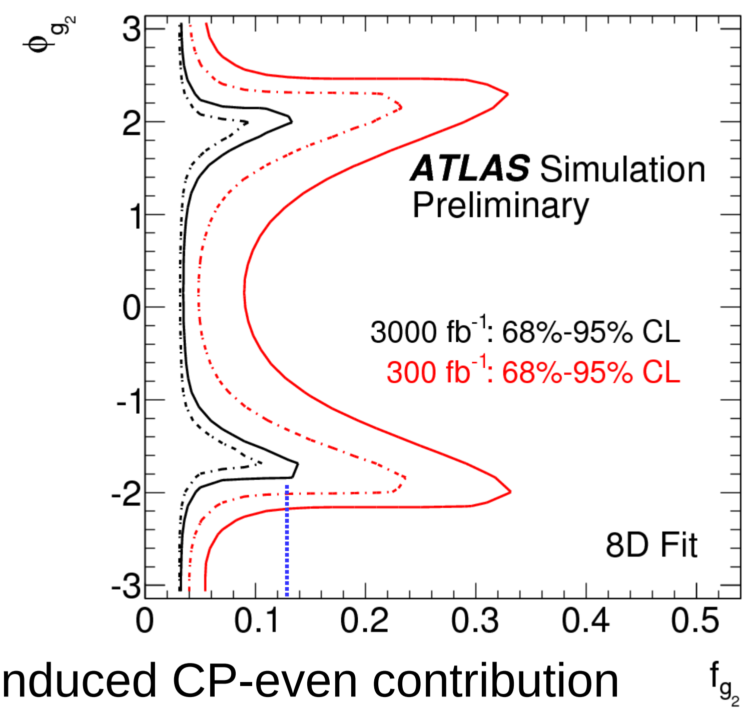
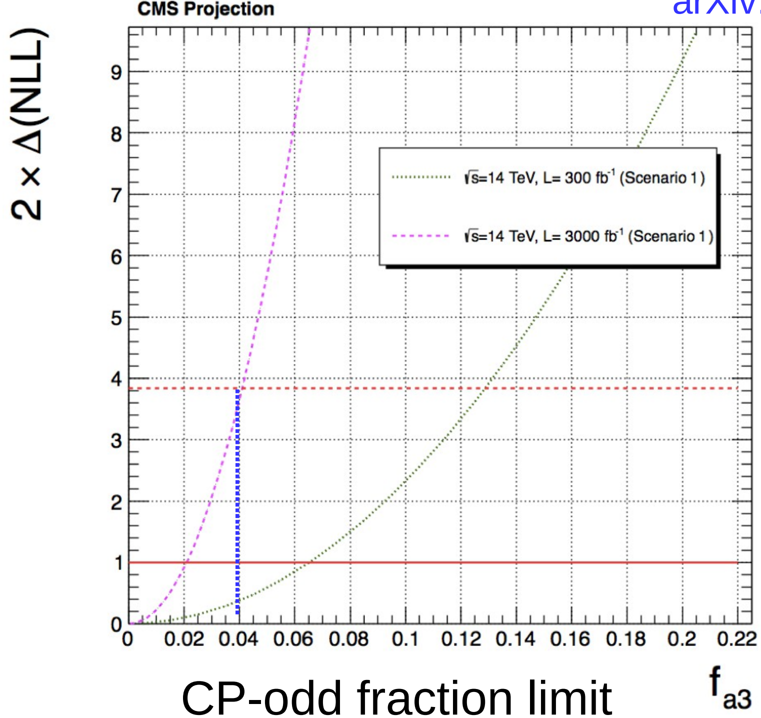


Loop-induced CP-even contribution

CMS-FTR-13-013, arXiv:1307.7135



CP-odd fraction limit

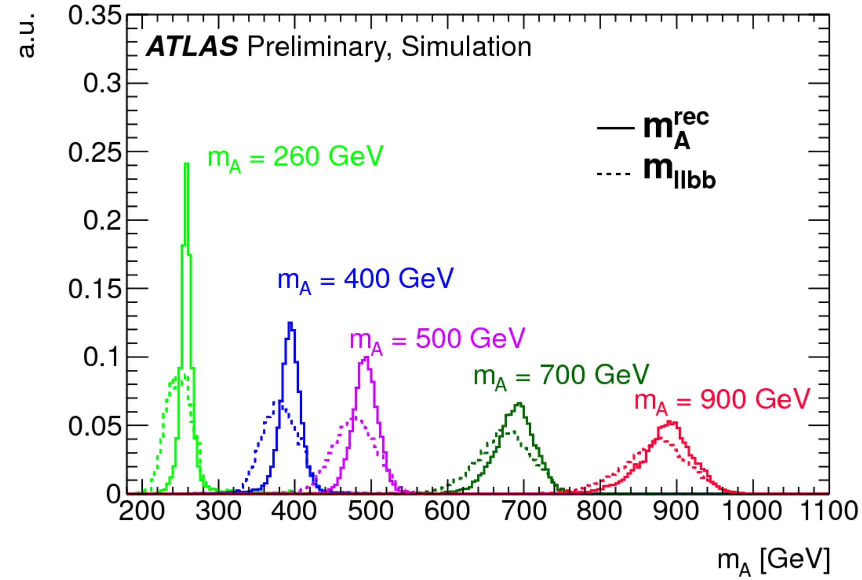
A → hZ

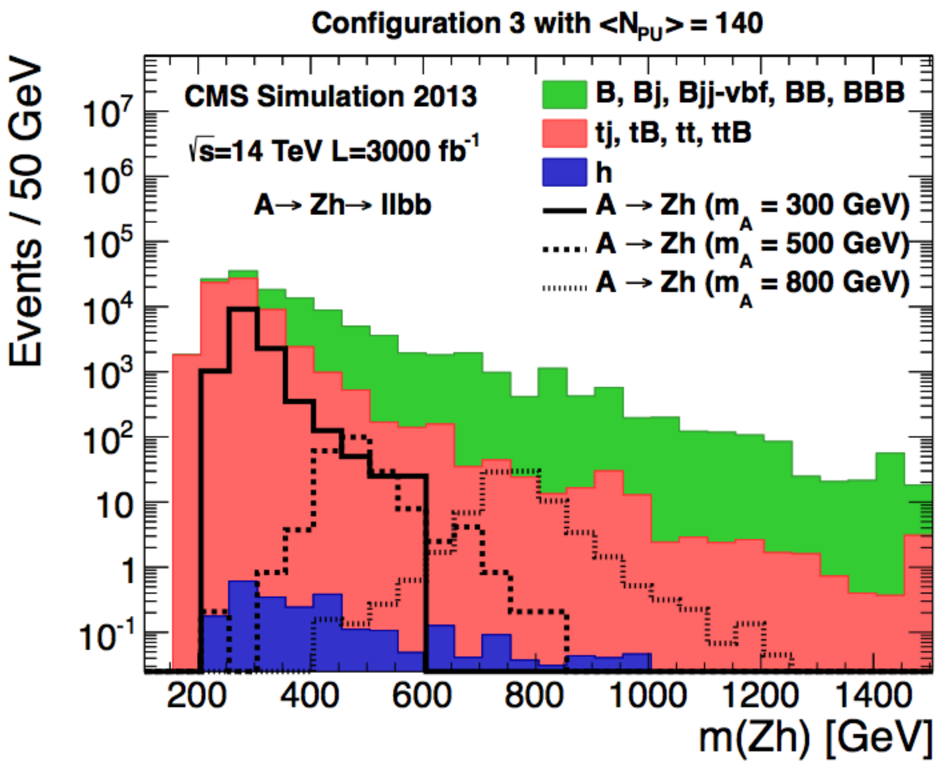
- 2HDM models can be probed in A → Zh → 2l2b selections

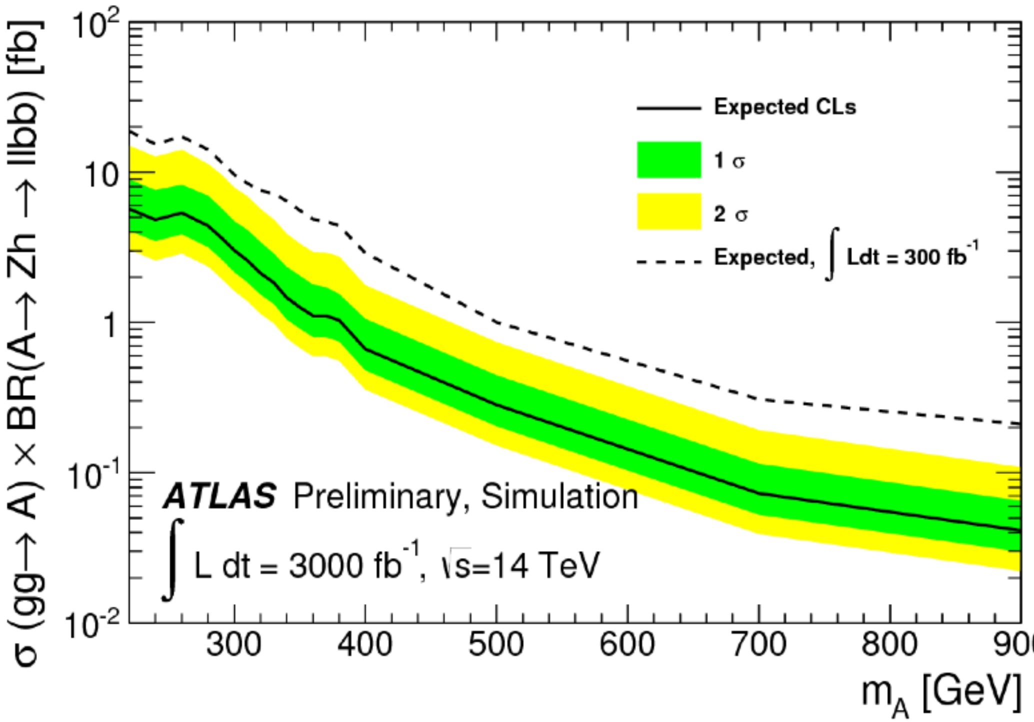
See Maxim's talk

Source	Selected Events
B, Bj, Bjj-vbf, BB, BBB	5.8×10^4
tj, tt, tB, ttB	6.6×10^4
h (m_h=125 GeV)	$< 1\%$
Total Background	1.2×10^5
$A \to Zh$ ($m_A = 300$ GeV)	1.3×10^4
$A \to Zh$ ($m_A = 500$ GeV)	210
$A \to Zh$ ($m_A = 800$ GeV)	85

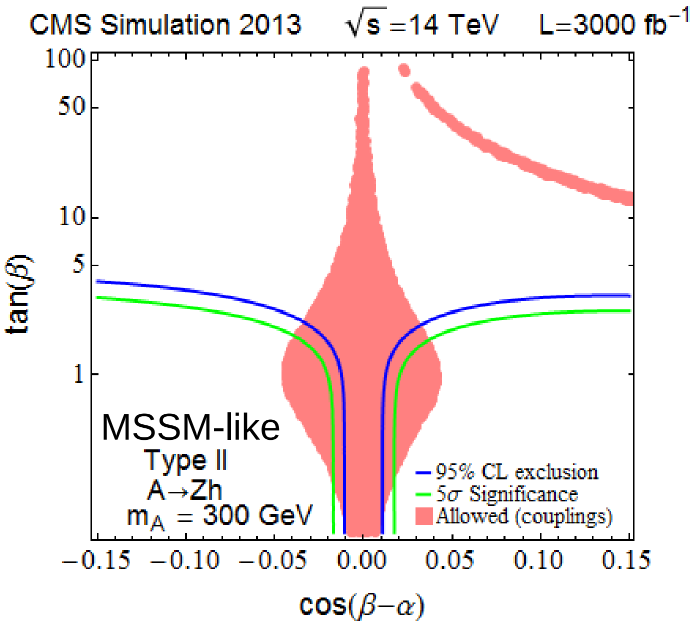
Expected events for 3000 fb^{-1}

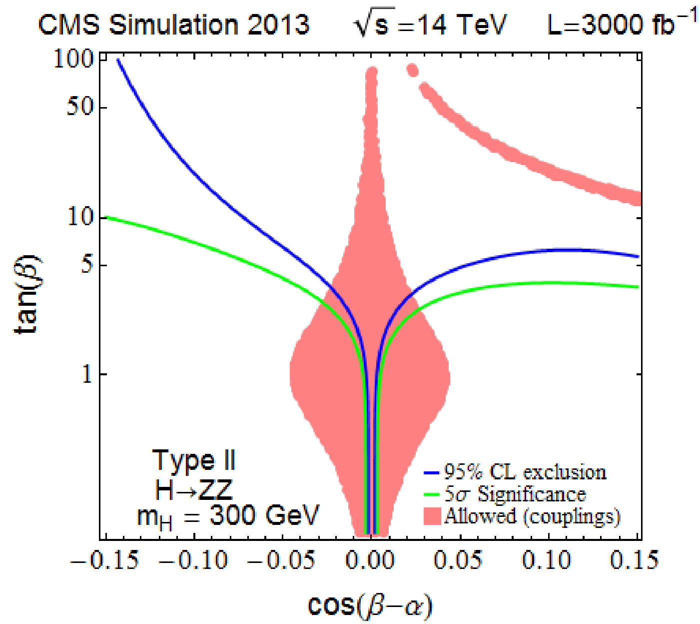




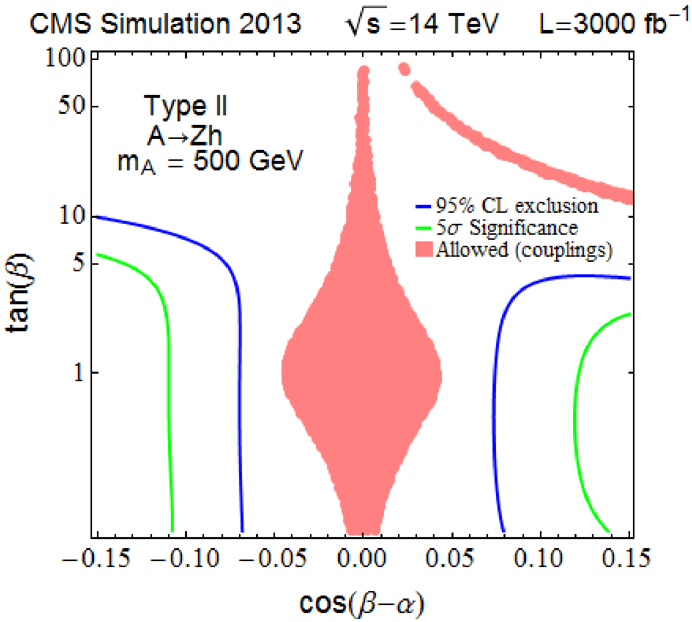


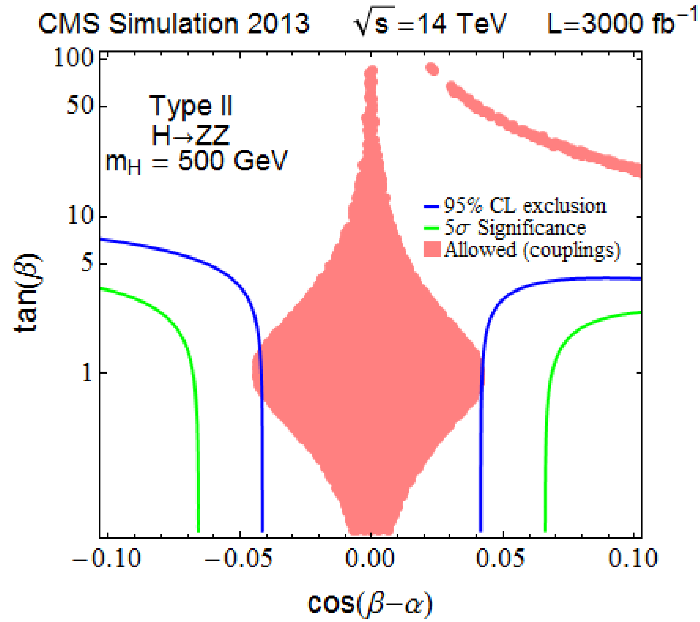
2HDM expected sensitivity





$m_{A/H}$ = 300 GeV

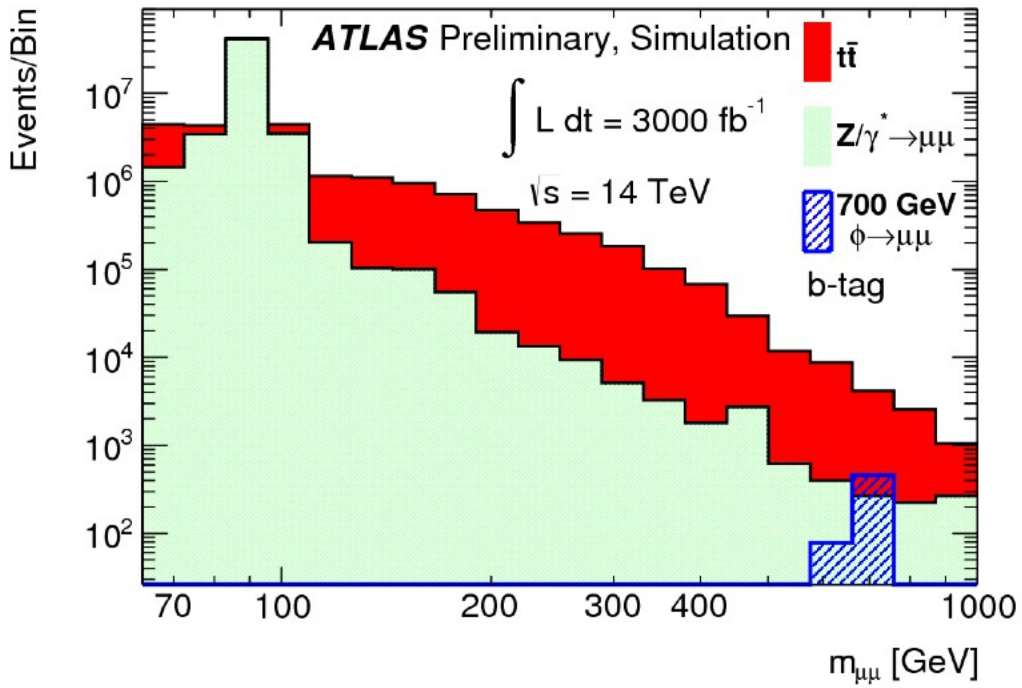


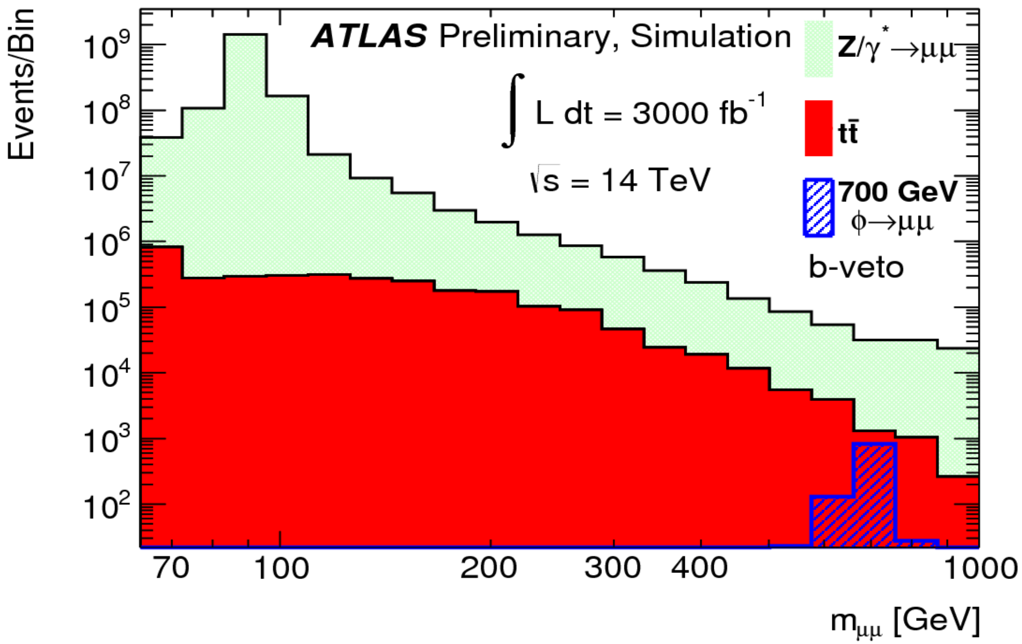


$m_{A/H}$ = 500 GeV

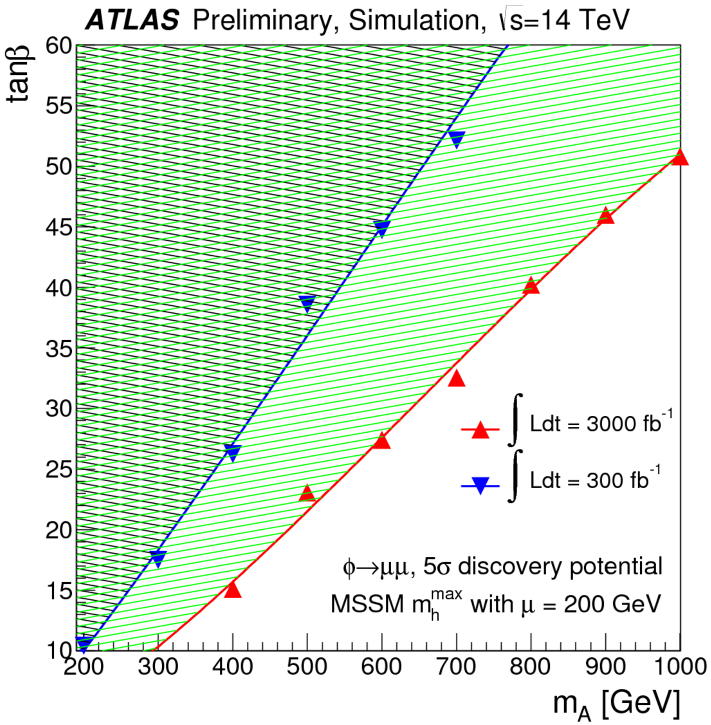
$A \rightarrow Zh \rightarrow 2l2b$ $\qquad$ $H \rightarrow ZZ \rightarrow 4l$

MSSM μμ limits



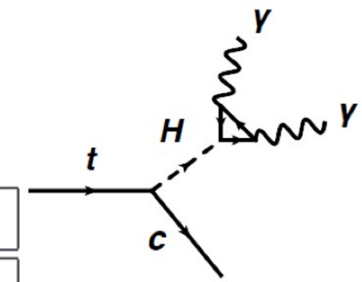


- high tan β region complementary to A→Zh for MSSM constraints
- High mass resolution at high dimuon mass
- Search for two production modes
  - gluon fusion
  - b associated production



FCNC top to Higgs

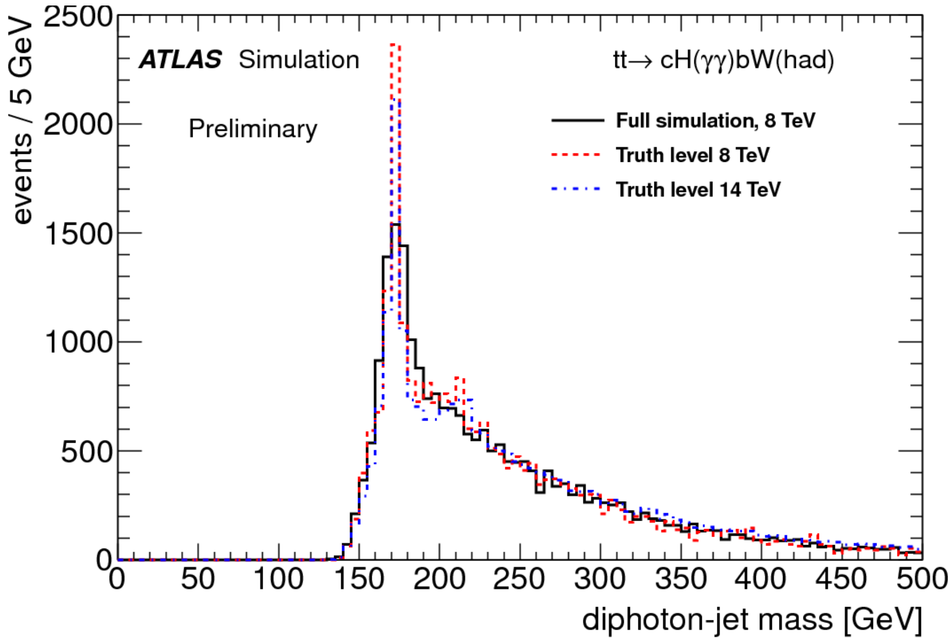
- FCNC processes are forbidden at tree level in the SM
- $t \rightarrow cH$ observation in ttbar events would certainly be a sign of new physics

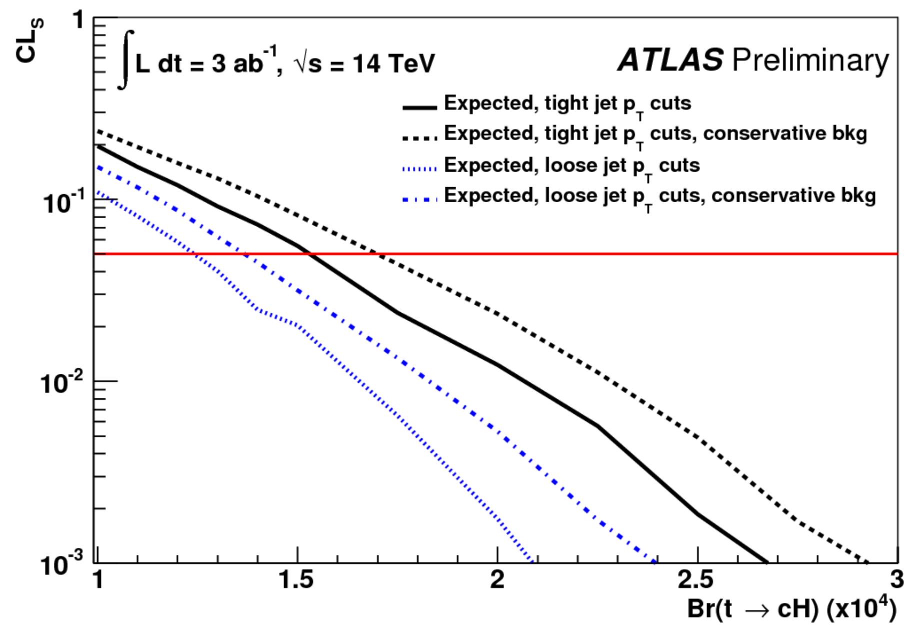


Typical BRs of EW FCNC-top decays:

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

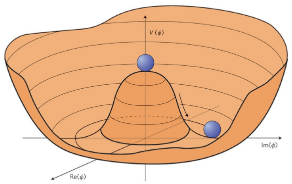
- Event selection relies on diphoton Higgs decay for its clear signature

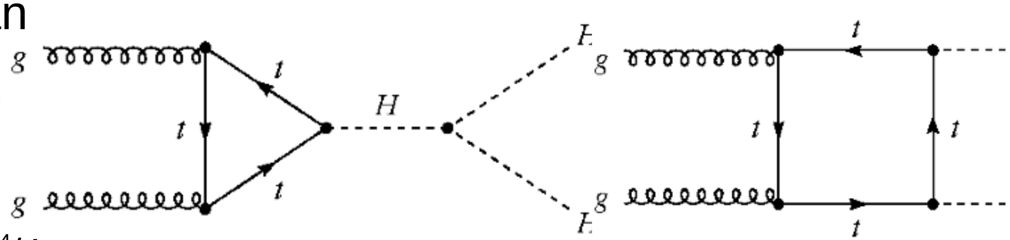




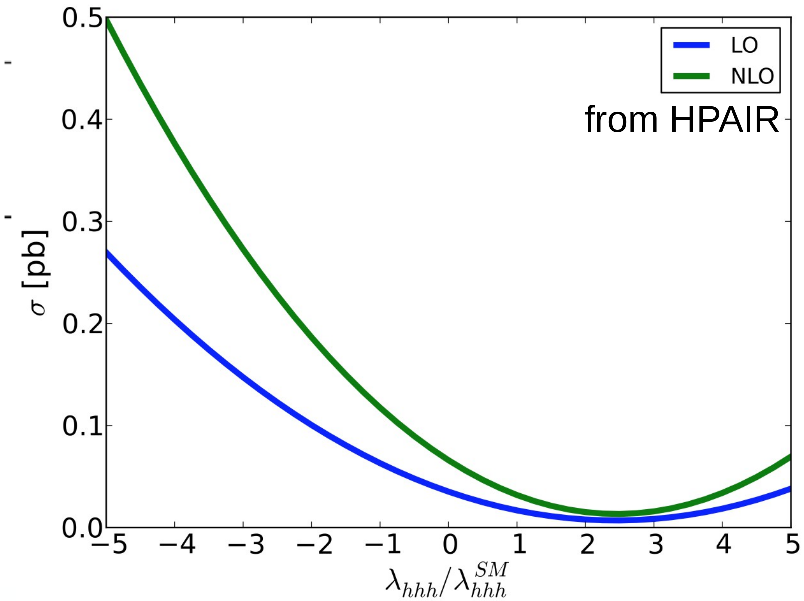
Di-Higgs boson production

- The Higgs mechanism and the shape of its potential rely on the self-coupling term of the Lagrangian

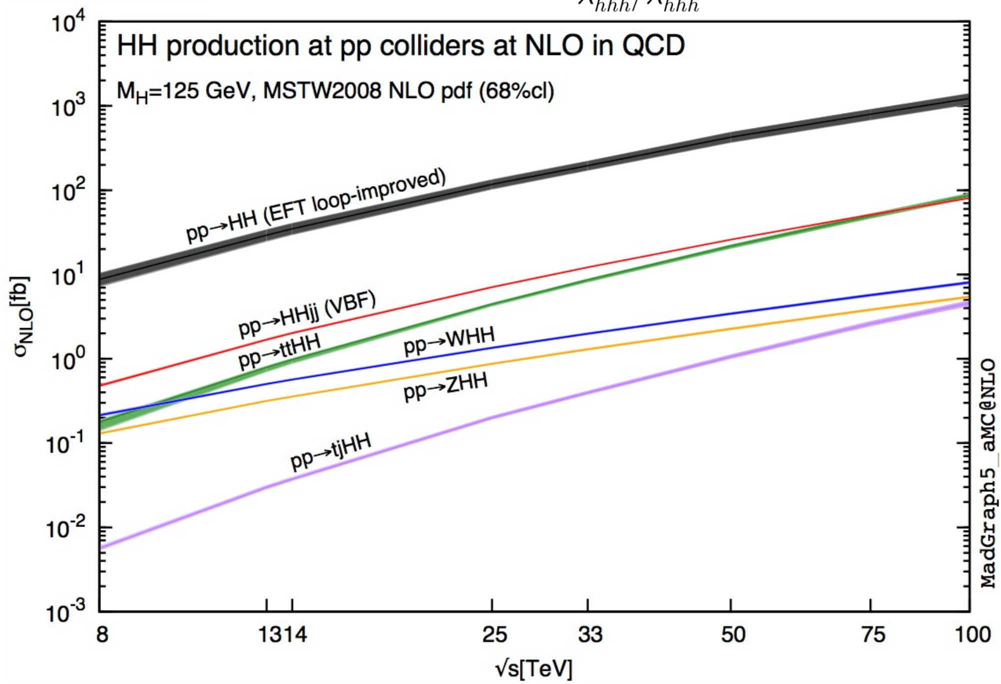




$V(\varphi) = \mu^2\varphi^2/2 + \lambda\varphi^4/4$



- Di-Higgs boson production dominated by box diagram
- Negative interference with self-coupling diagrams
- Low cross-section
- Often large background
    - Large contributions from top and/or fakes processes
- Difficult (new!) analyses to develop

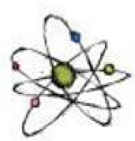


- Many channels are now being explored in order to assess the potential for the di-Higgs boson observation and the sensitivity to the self-coupling at the HL-LHC

See José's talk

Conclusions

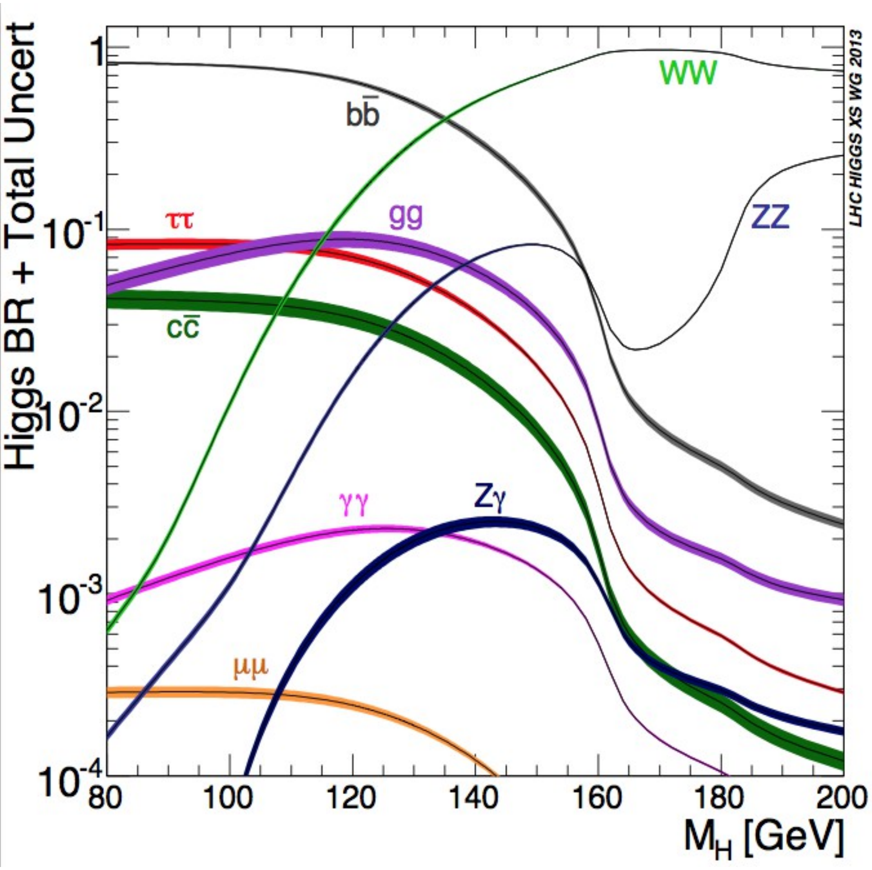
- Prospects for the precision Higgs couplings measurements are very promising !
  - Often better than 10% for couplings
  - allowing for constraining new physics which would have not shown up elsewhere in the EWSB sector (J.Wells)
- Also, great potential for direct evidence of new physics in
  - (Not so?) rare decays
  - 2DHM models-like signatures
  - FCNC
- Now working on



"Two Higgs bosons get into an elevator…'
(maintenance today)

- Adding more rare channels to this picture
- Establishing the potential for di-Higgs bosons measurements and sensitivity to the self-coupling
- Consolidating the detector designs and running conditions in order to achieve those goals
- Writing the developments of this story

BACKUP


Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
bb̄
WW
ZZ
ττ
gg
cc̄
γγ
Zγ
μμ
M_H [GeV]