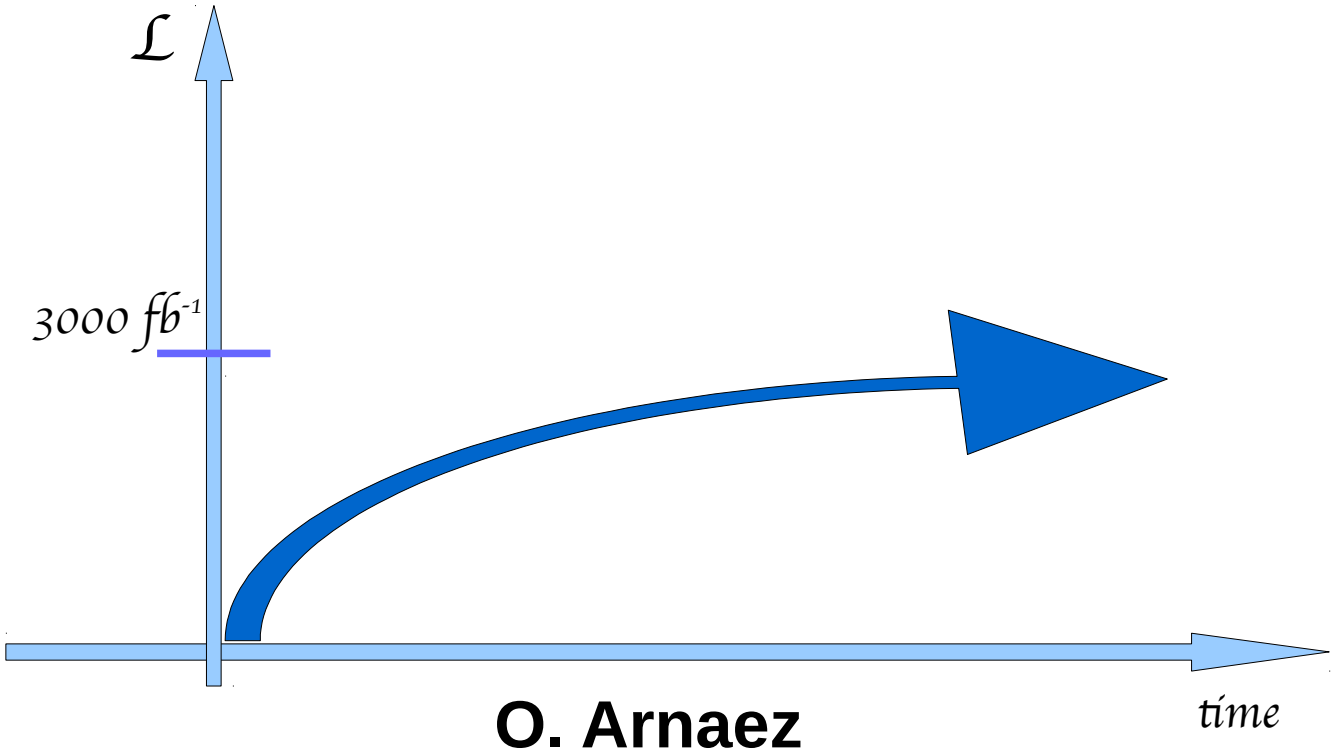
Higgs Prospects for future (HL)LHC runs

based on public ATLAS and CMS prospects studies
(but likely biased towards showing more ATLAS material)



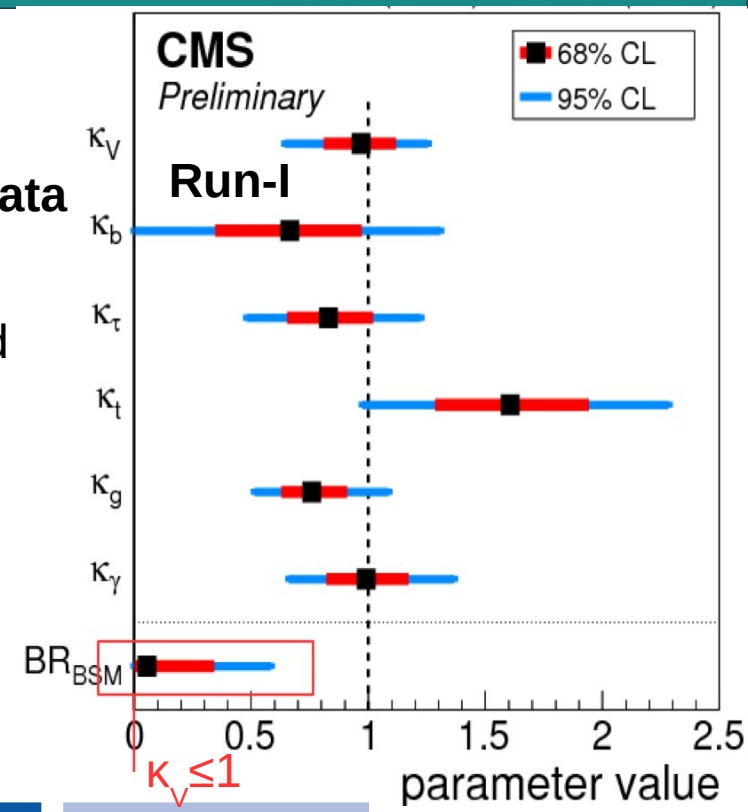
O. Arnaez
CERN

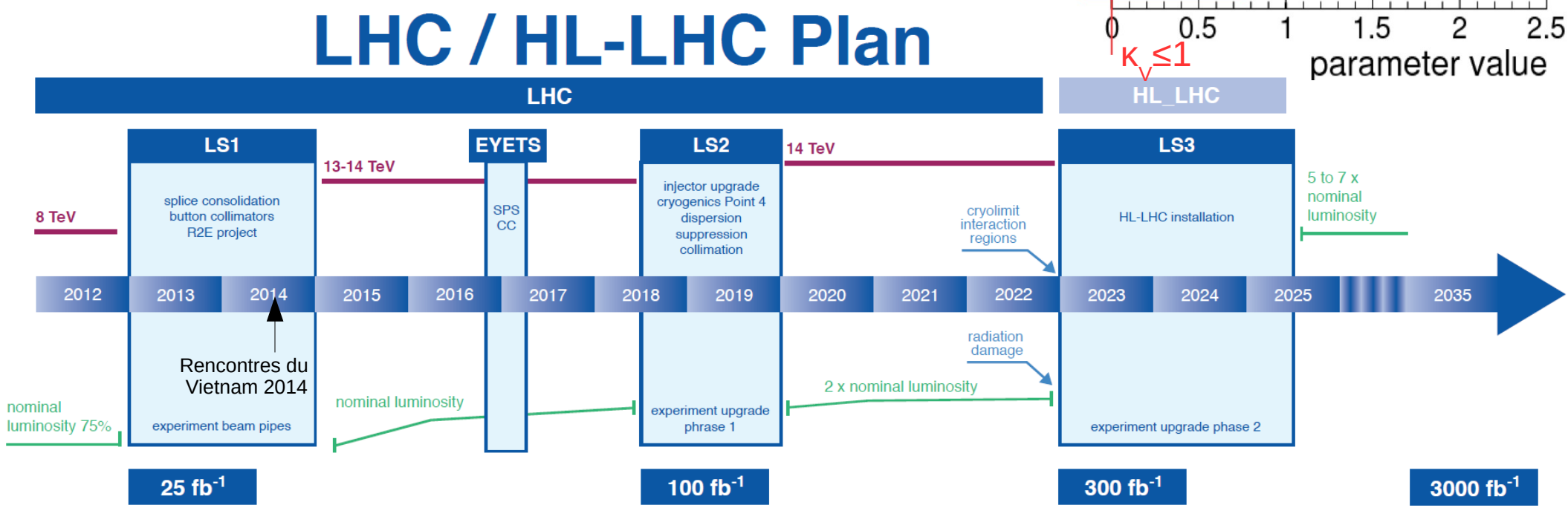
Introduction

- **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**

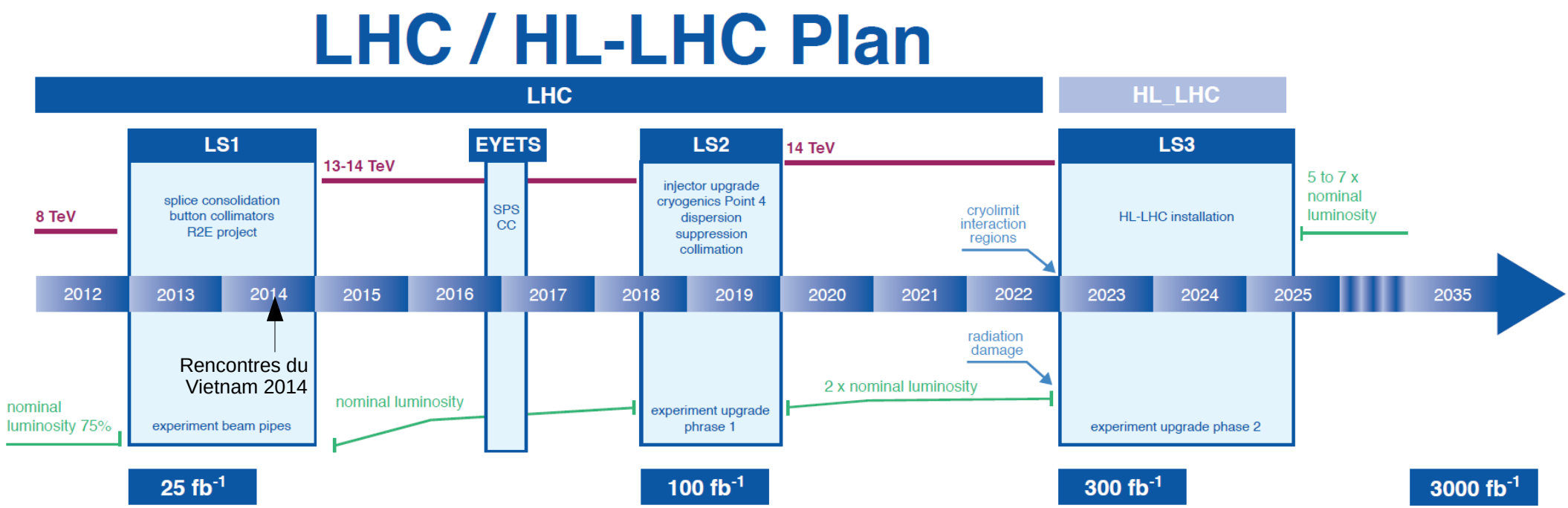
- This talk: expected precision from ATLAS and CMS on Higgs property measurements and on sensitivities to direct new physics searches in the Higgs sector at the HL-LHC





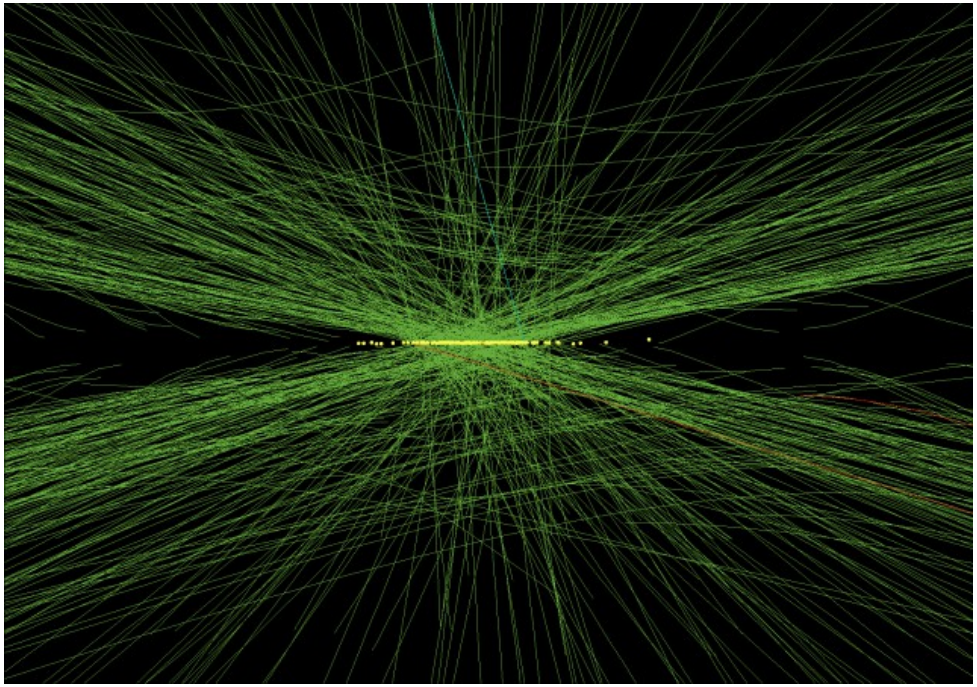
Introduction (2)

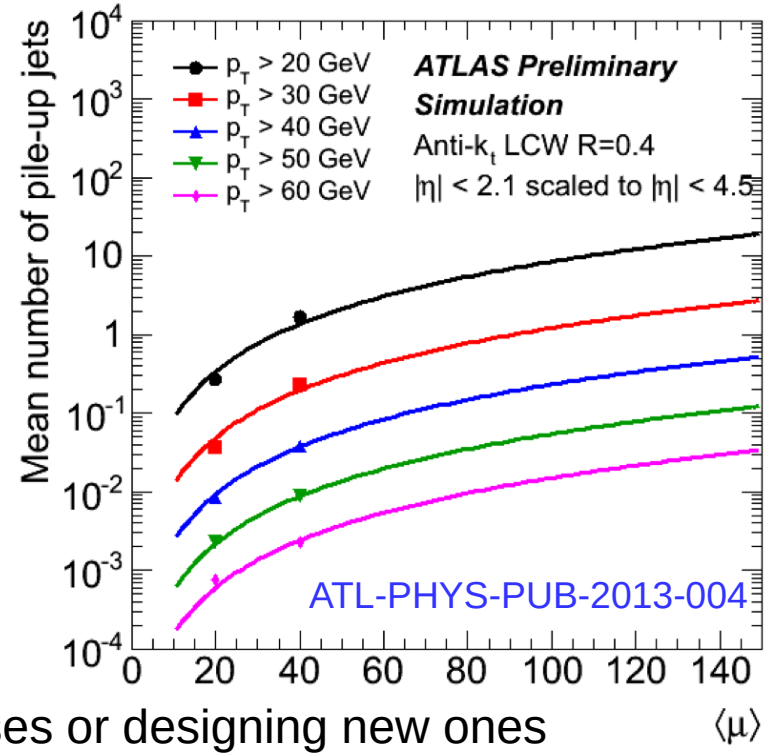
- HL-LHC Benchmark scenario:
  - LHC approved for running to deliver 300 fb^{-1} by ~2021
  - Post-LS3 operation at $5x10^{34}$ $cm^{-2}s^{-1}$ (lumi leveling)
    - 25 ns bunch spacing
    - 140 events per bunch crossing
    - 3000 fb^{-1} over 10 years
  - Detector upgrades needed to cope with radiation damage and pileup
    - aim to maintain/enhance physics performance



Performance and methodology

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

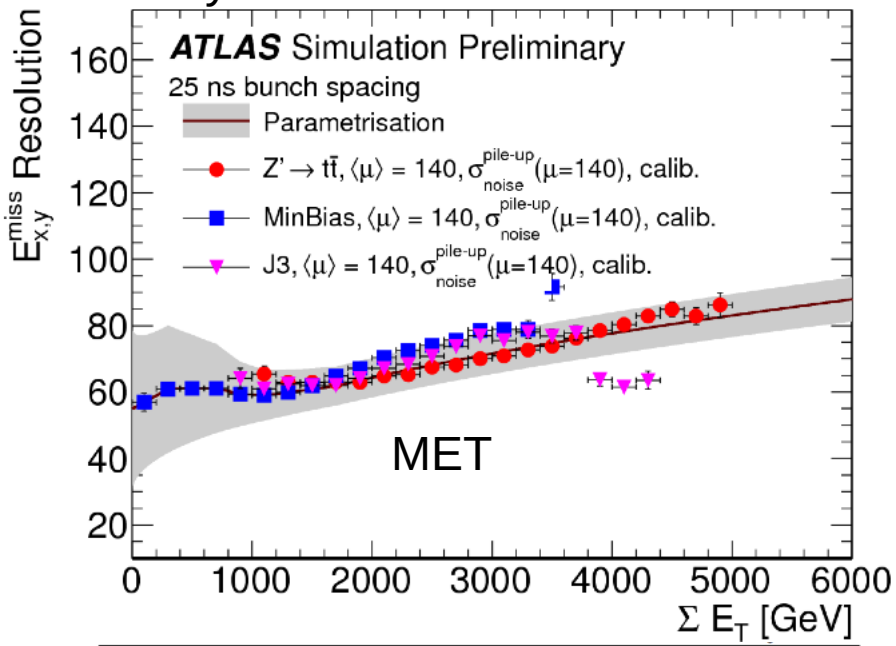


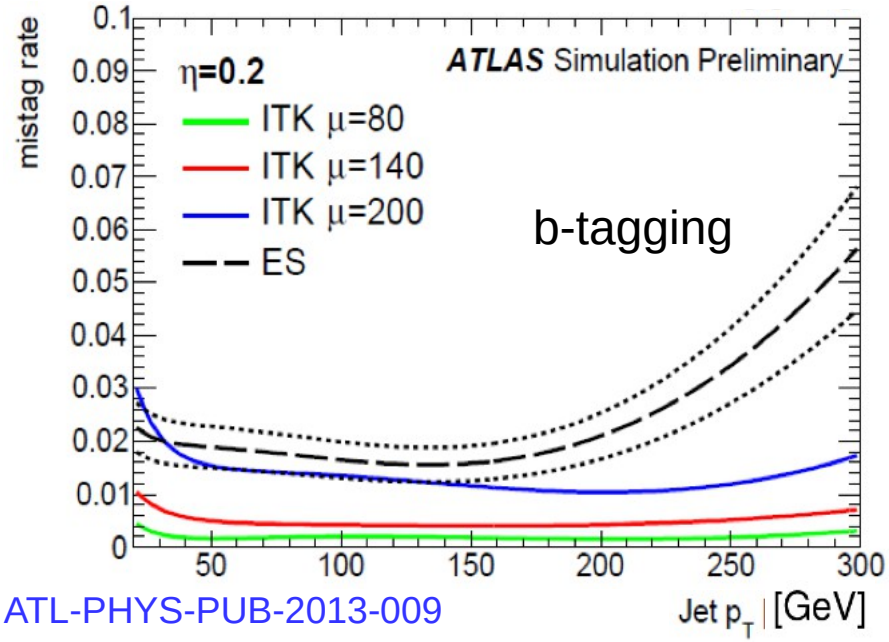


- Higgs prospects are studied by refining current analyses or designing new ones
  - CMS assumes that the upgraded detector will compensate the effects of higher pile-up and extrapolates event rates from existing Run I-like selections or using DELPHES (fast simulation with uniform magnetic field and particle smearing)
  - ATLAS evaluated the performance using full-simulation studies (sometimes similar, sometimes 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: 'current', 'best guess', 'halved', 'none')

Performance and methodology (2)

- Full simulation studies help to get an idea of the future detector's performance under high-luminosity conditions





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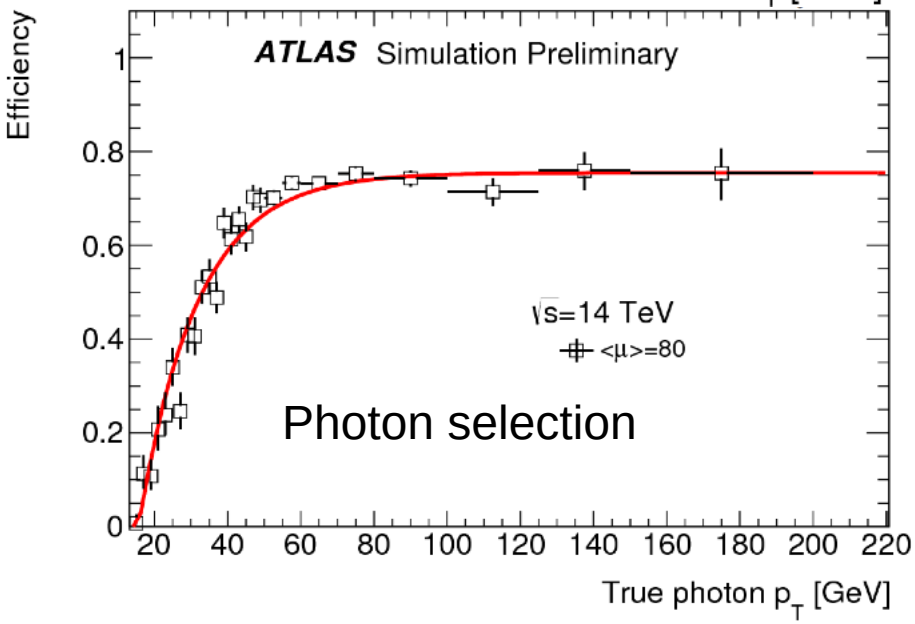
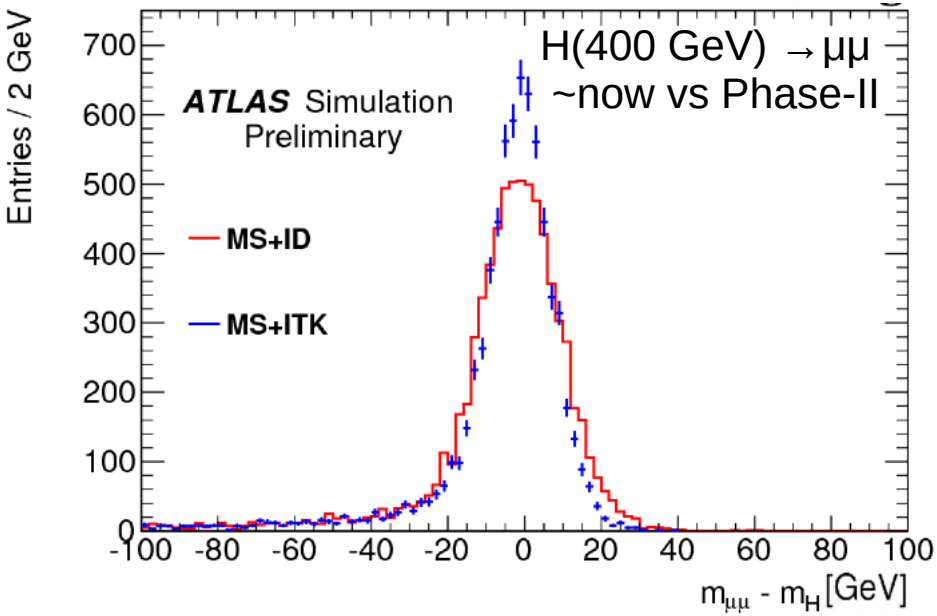
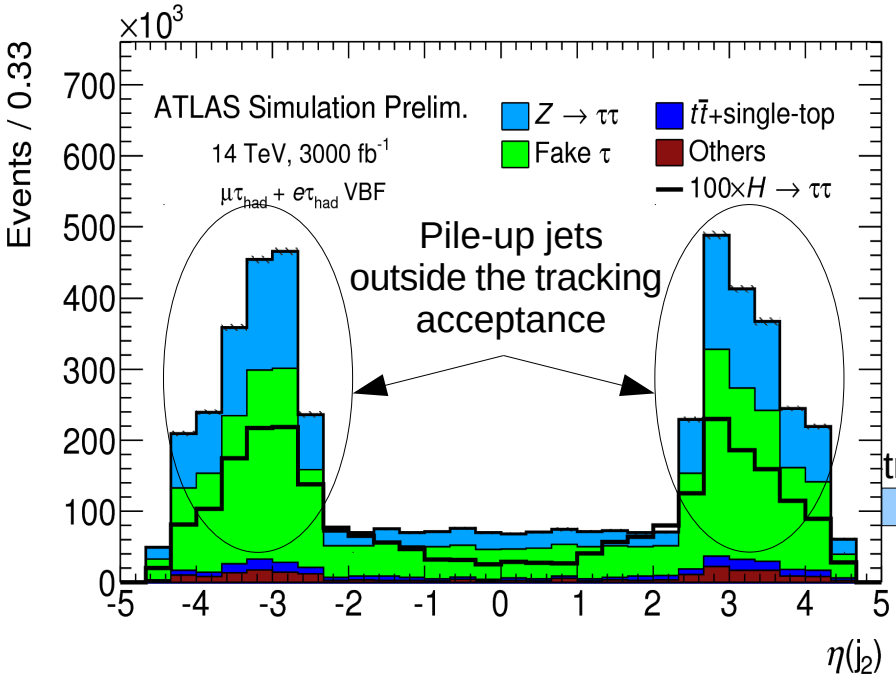


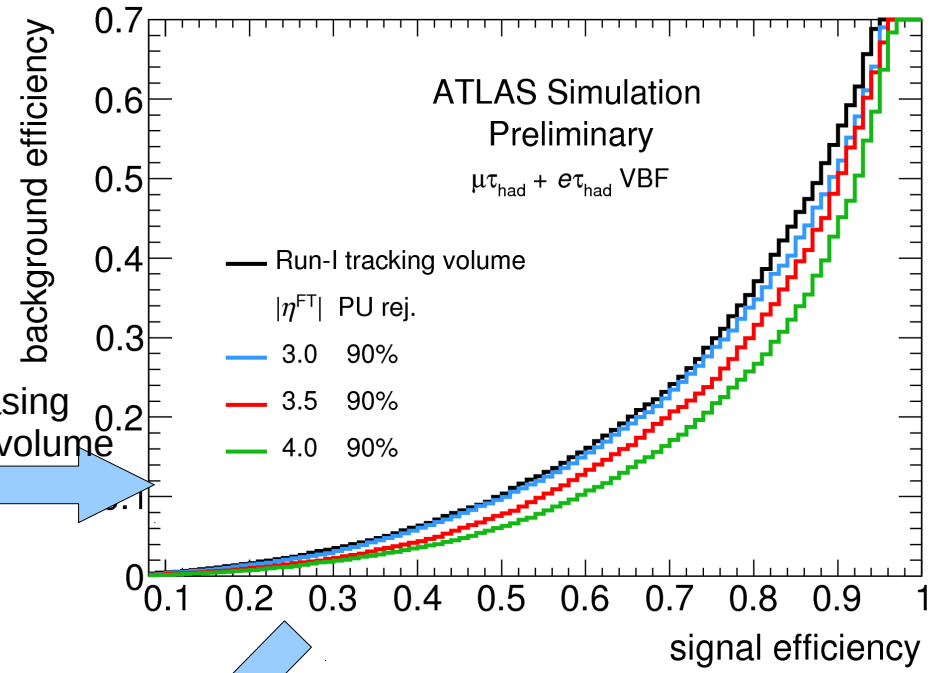


Extending the detectors

- Also looked at increase of the acceptance for some signals if using an extended tracker volume, here ATLAS H → tautau prospects:
-



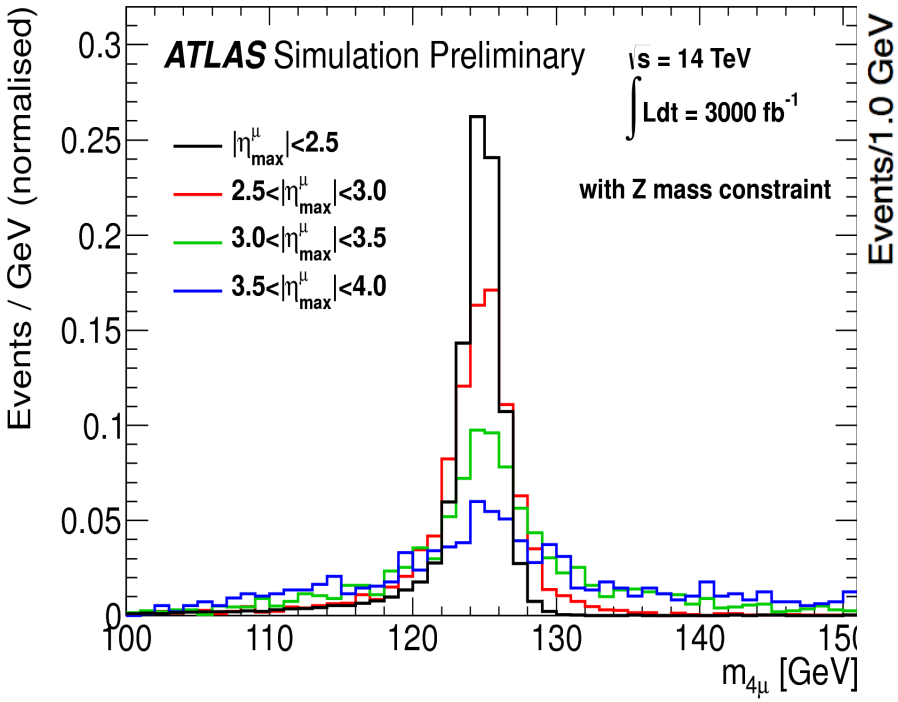
Increasing tracking volume

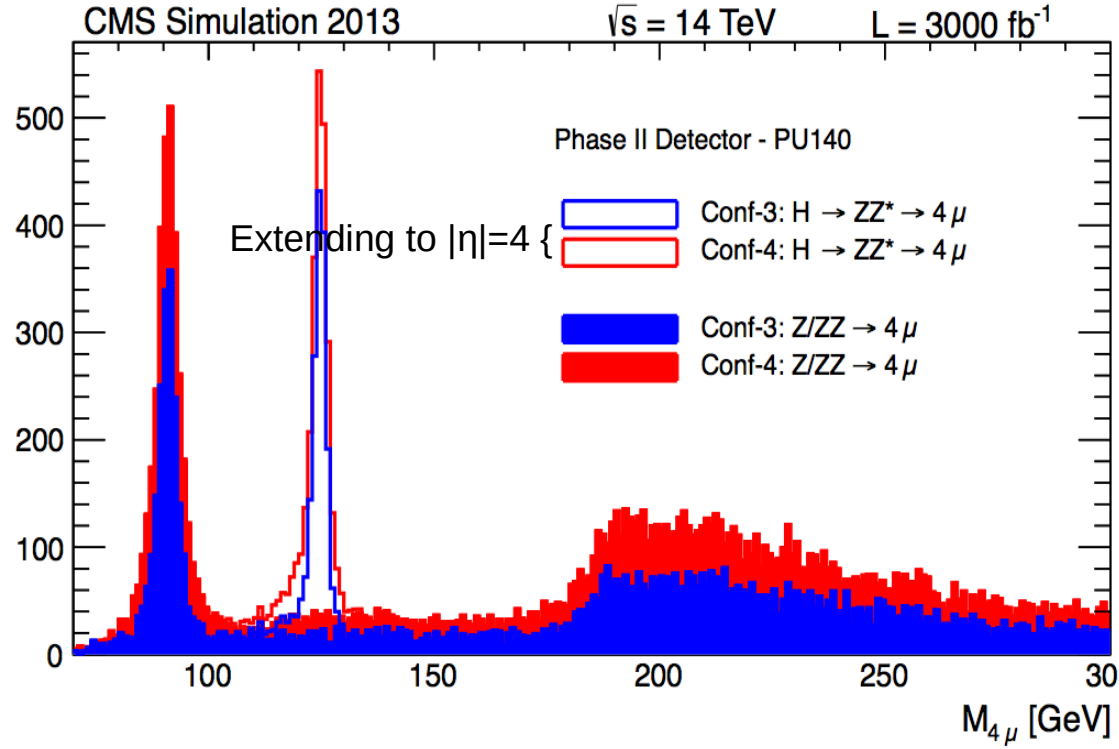


forward pile-up jet rejection	50%	75%	90%
forward tracker coverage	$\Delta\mu$		
Run-I tracking volume	0.24		
$\lvert\eta\rvert < 3.0$	0.18	0.15	0.14
$\lvert\eta\rvert < 3.5$	0.18	0.13	0.11
$\lvert\eta\rvert < 4.0$	0.16	0.12	0.08

Extending the detectors (2)

- Other example where H → ZZ events have served as benchmark to look at the different peak resolutions (ATLAS, left) obtained with forward tracking devices or acceptance gain (CMS, right)

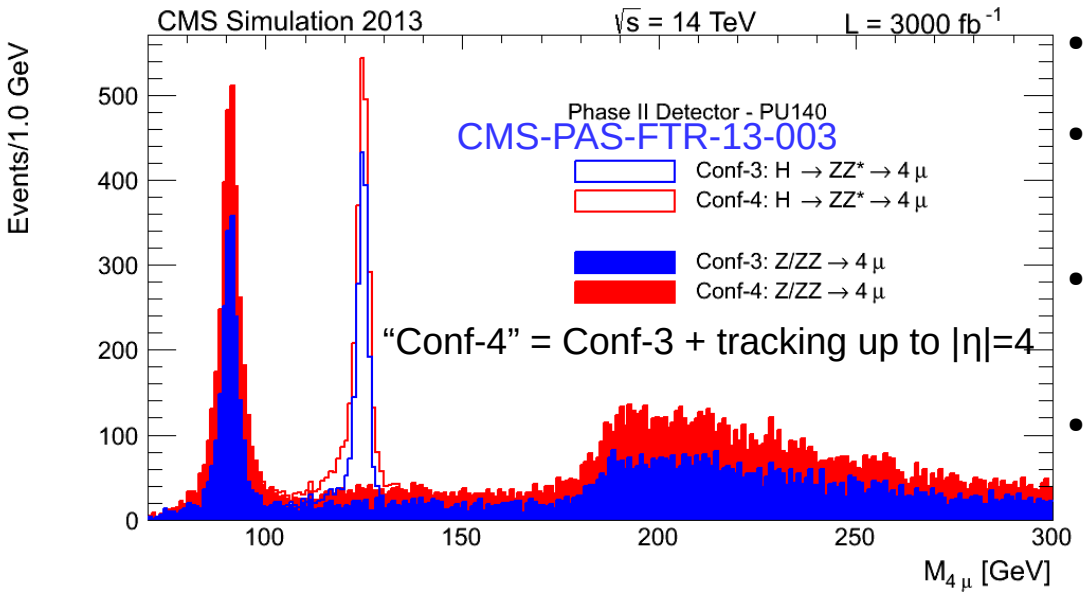




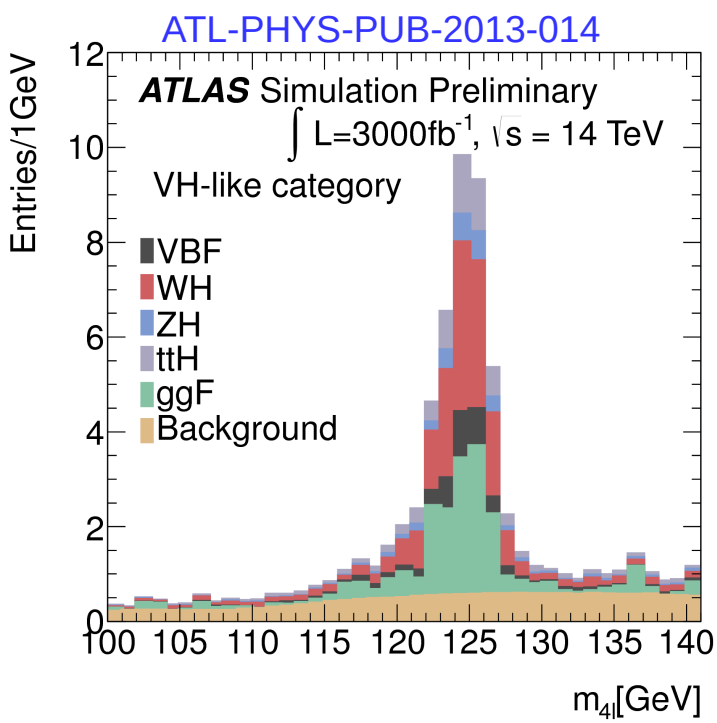
	Phase I detector	
Pileup	Full Simulation	Delphes
50	35.87±0.48	35.68±0.48
70	35.65±0.48	34.69±0.48
140	34.74±0.48	36.05±0.48

	Phase II detector	
Pileup	Full Simulation	Delphes
140 Configuration 3		37.88±0.49
140 Configuration 4		52.00±0.50

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 γγ 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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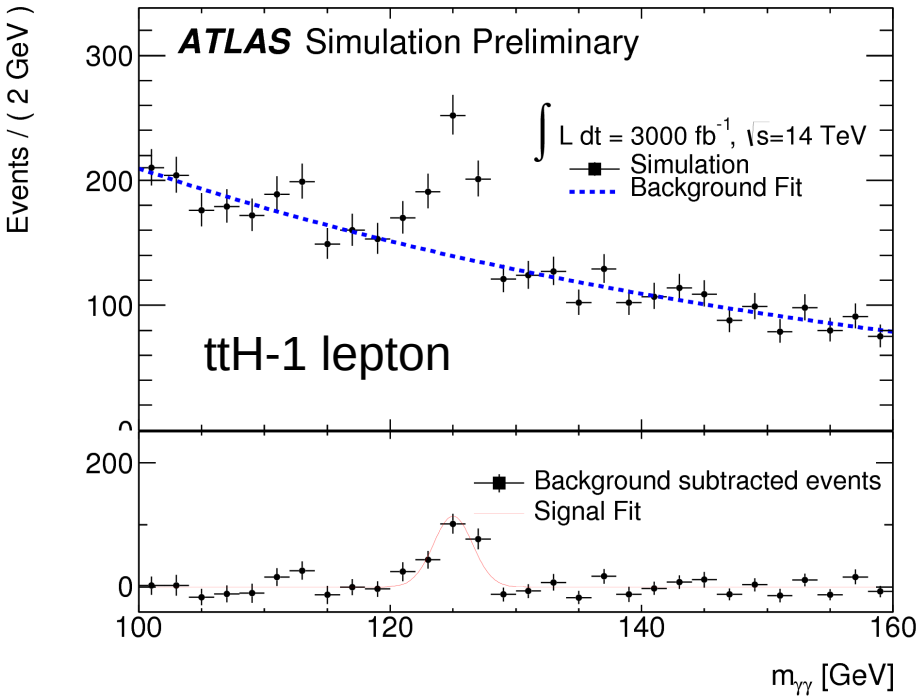
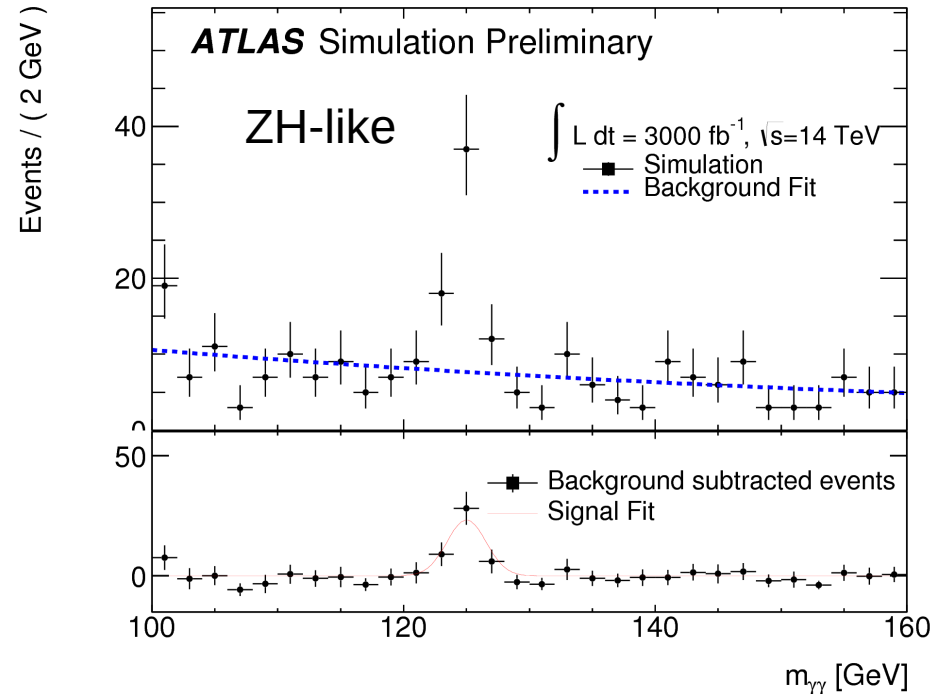


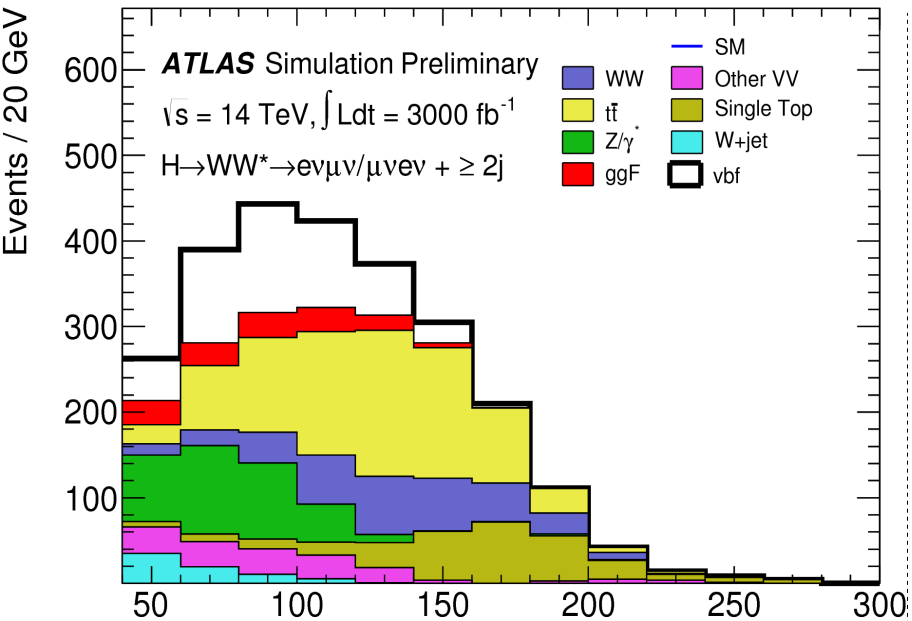


- Diphoton channels is powerful for H-t Yukawa coupling measurements
- Measurements limited by current signal uncertainties
- Reaching the ~3.5% level of precision on the combined signal strength (without th. uncertainties)

	$\Delta\hat{\mu}/\hat{\mu}$ (%)			
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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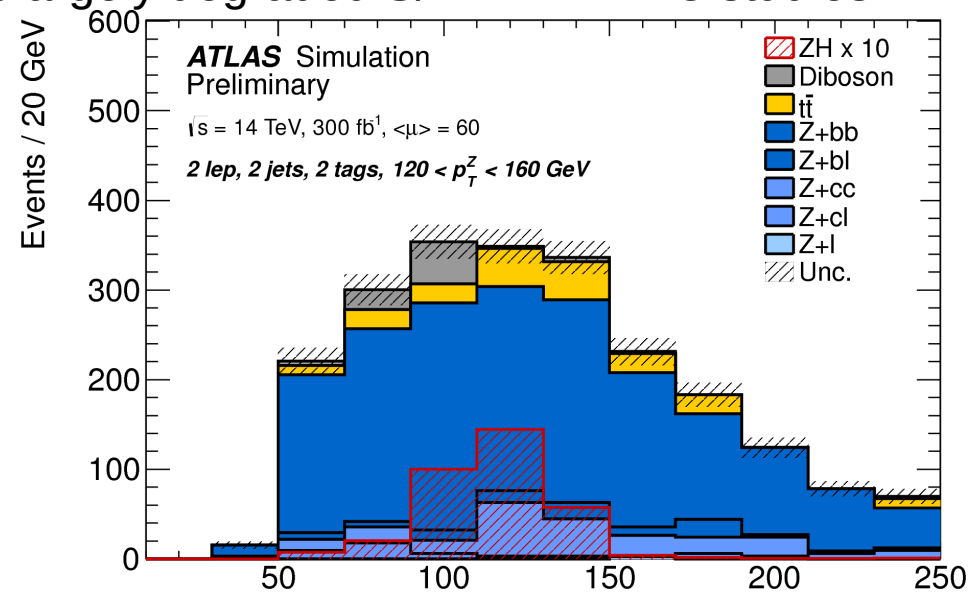
	μ_{ggF}	μ_{VBF}	$\mu_{ggF+VBF}$
300 fb^{-1}	$1^{+0.18}_{-0.15}$	$1^{+0.25}_{-0.22}$	$1^{+0.14}_{-0.13}$
3000 fb^{-1}	$1^{+0.16}_{-0.14}$	$1^{+0.15}_{-0.15}$	$1^{+0.10}_{-0.09}$



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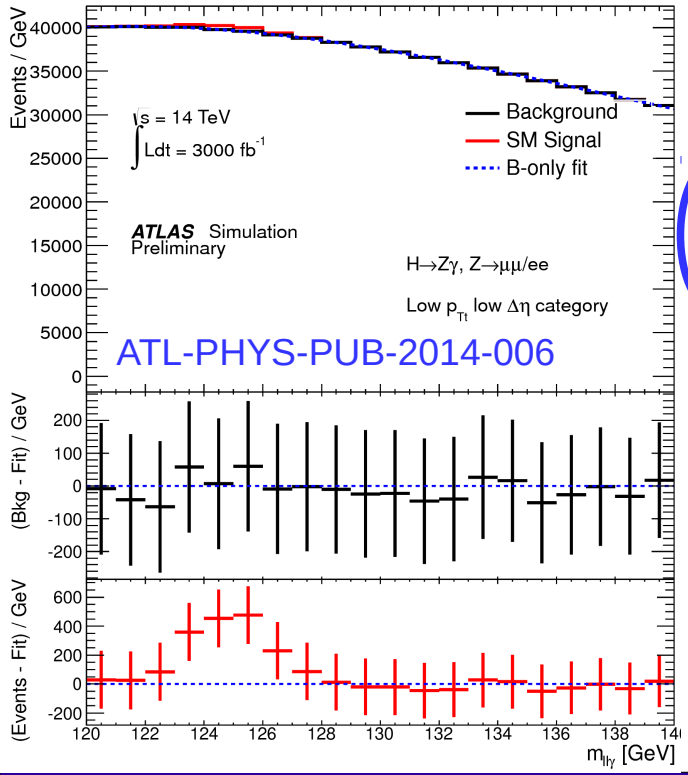
		One-lepton	Two-lepton	One+Two-lepton
Stat-only	Significance	15.4	11.3	19.1
	$\hat{\mu}_{Stats}$ error	+0.07 −0.06	+0.09 −0.09	+0.05 −0.05
Theory-only	$\hat{\mu}_{Theory}$ error	+0.09 −0.07	+0.07 −0.08	+0.07 −007
Scenario I	Significance	2.7	8.4	8.8
	$\hat{\mu}_{w/Theory}$ error	+0.37 −0.36	+0.15 −0.15	+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

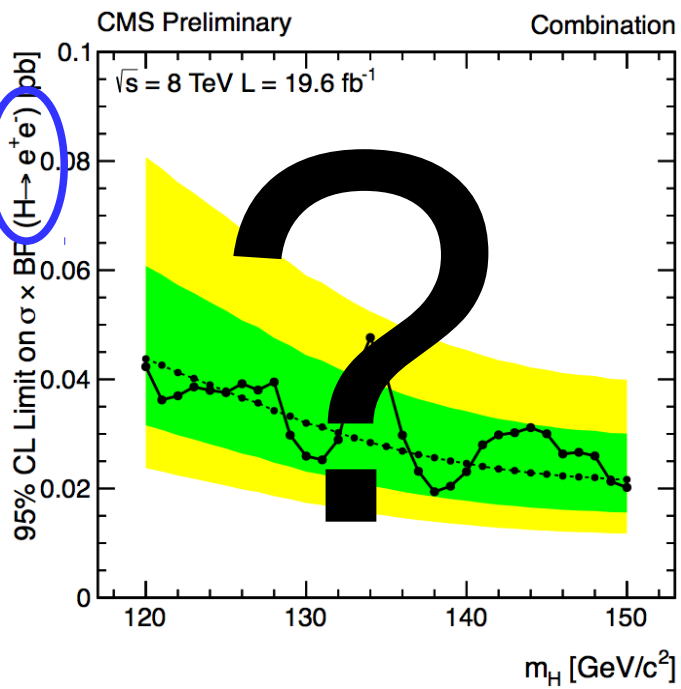
- Large stat → diff measurements ?
- ττ expectations on the signal strength precision are 8(5)% with current (/2) theory uncertainties

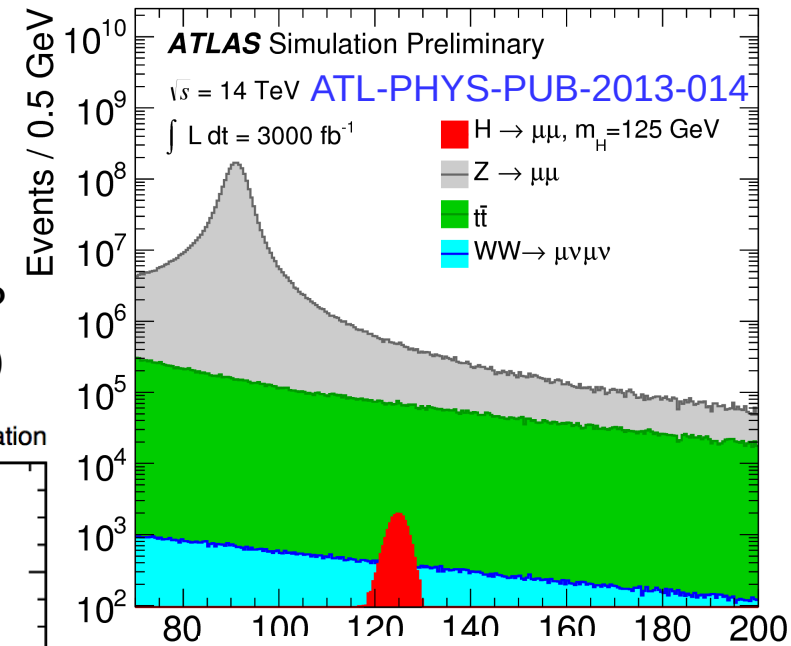
Rare channels

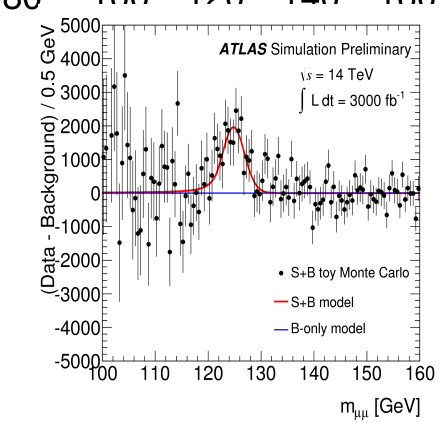
- Rare decays are the ones benefitting the most from the large HL-LHC dataset
- $Z\gamma$ sensitive to potential new particles in loop
  - ~20-30% precision on signal strength (~4σ) expected by CMS/ATLAS (Currently limits are at ~10x the SM prediction)
- μμ sensitive to the 2nd generation couplings
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

(H → J/ψγ at O(500)xSM in Run-I)

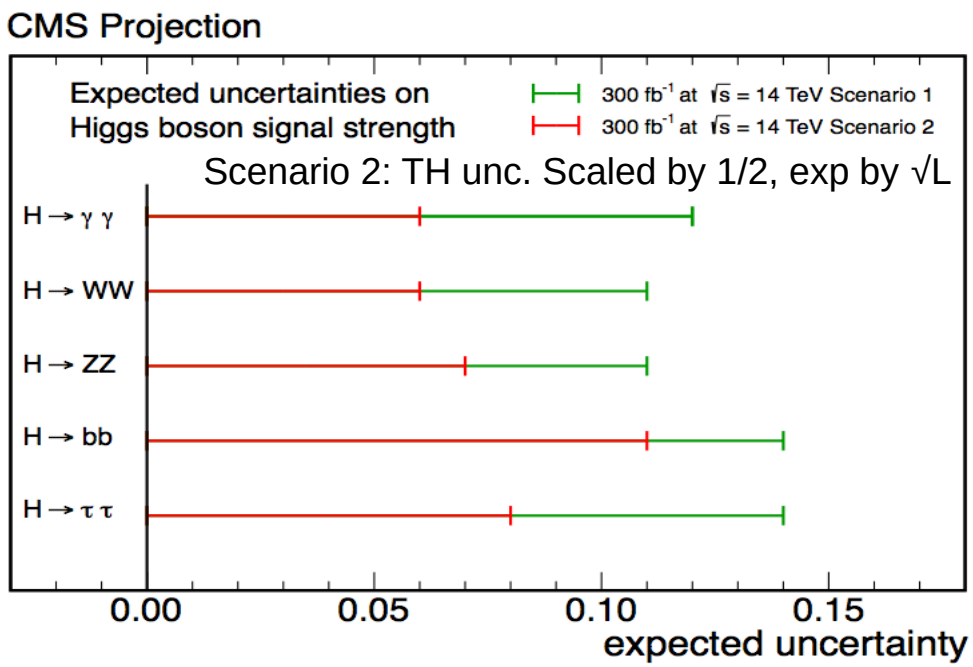


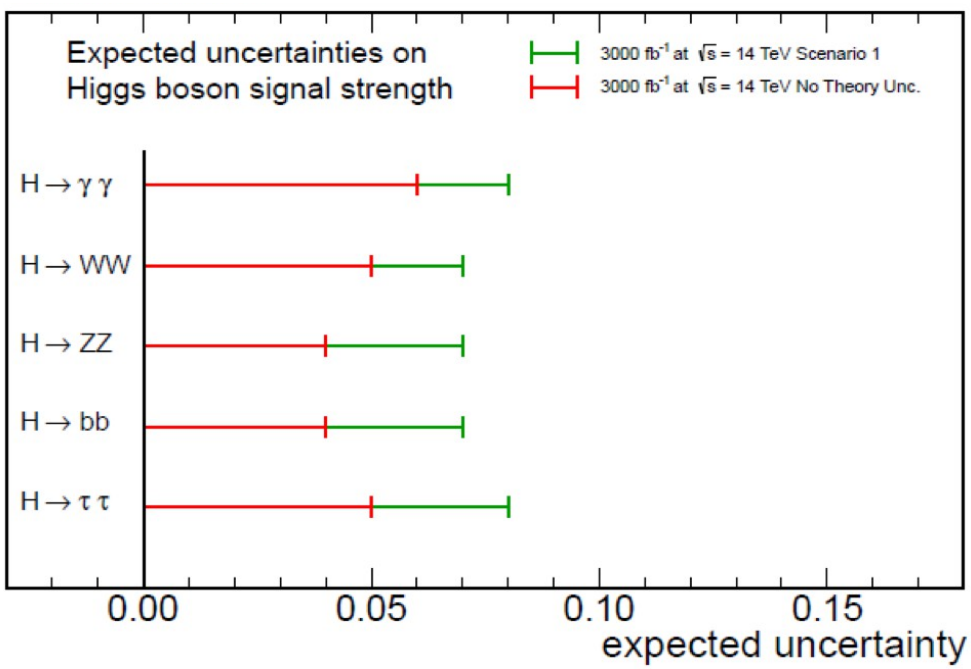


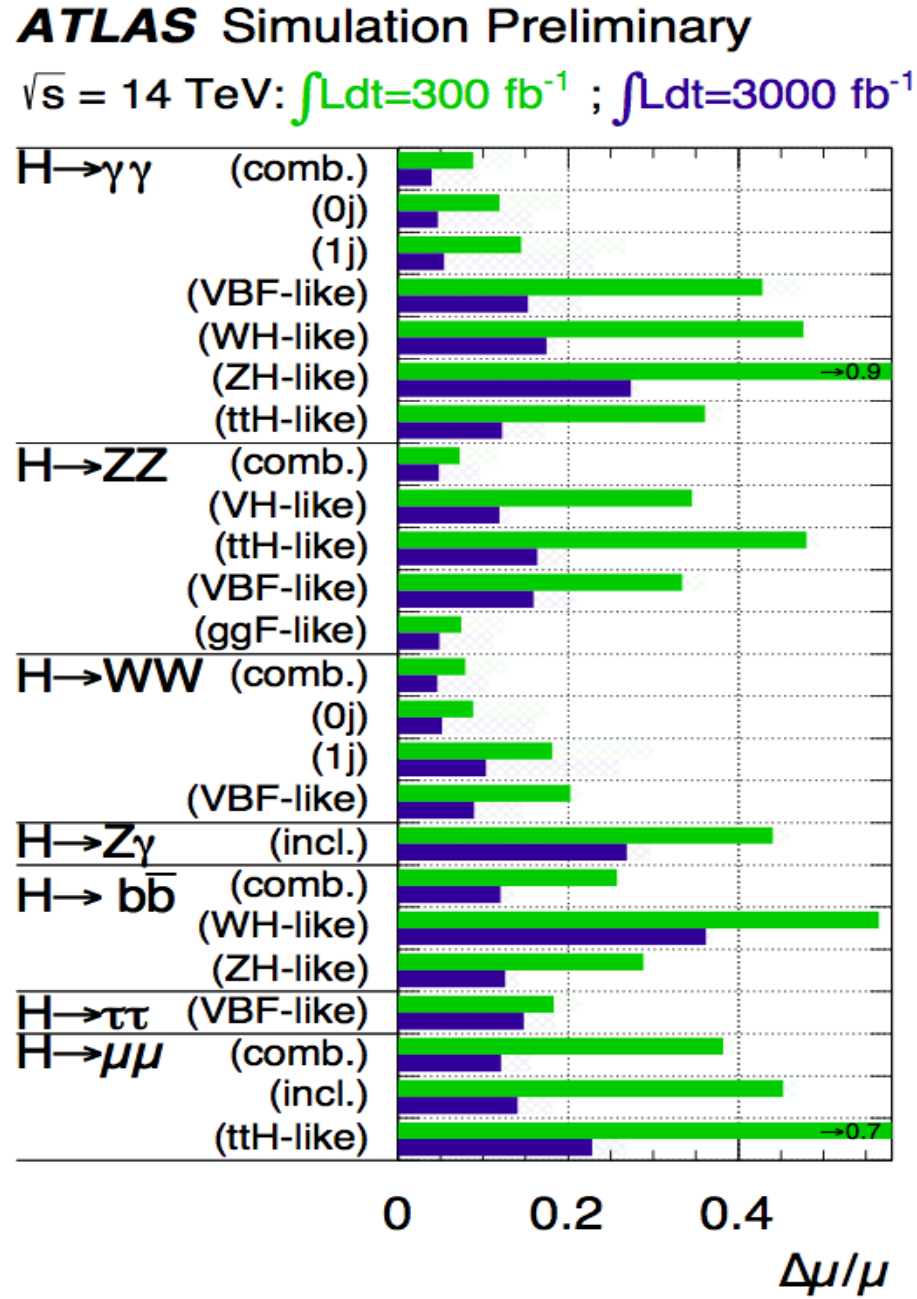




Channels summary





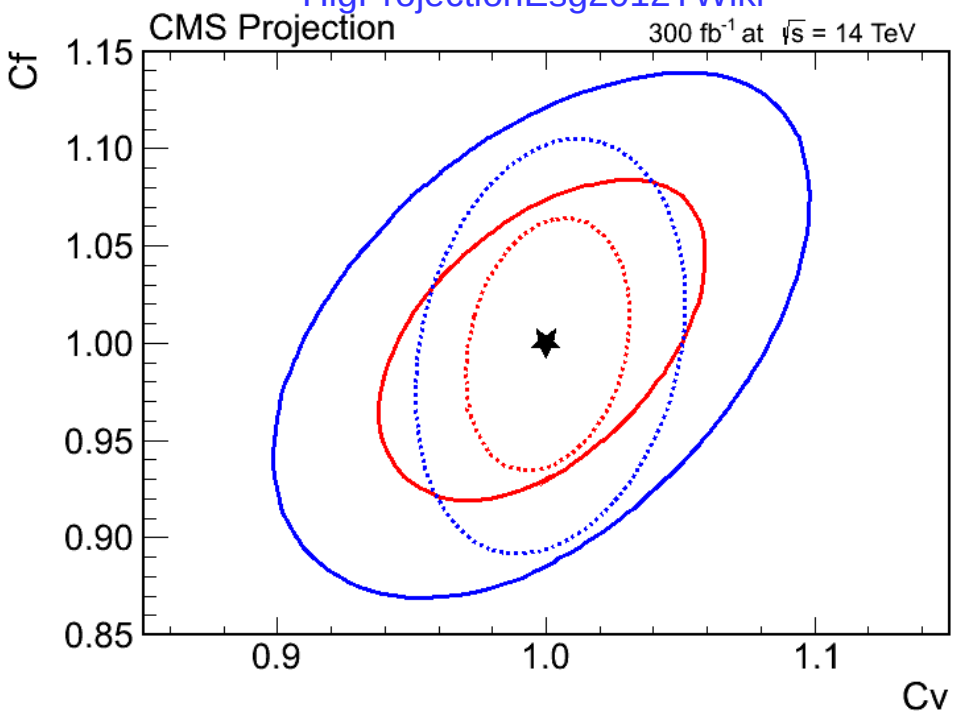


Dashed band = adding current theo. unc.

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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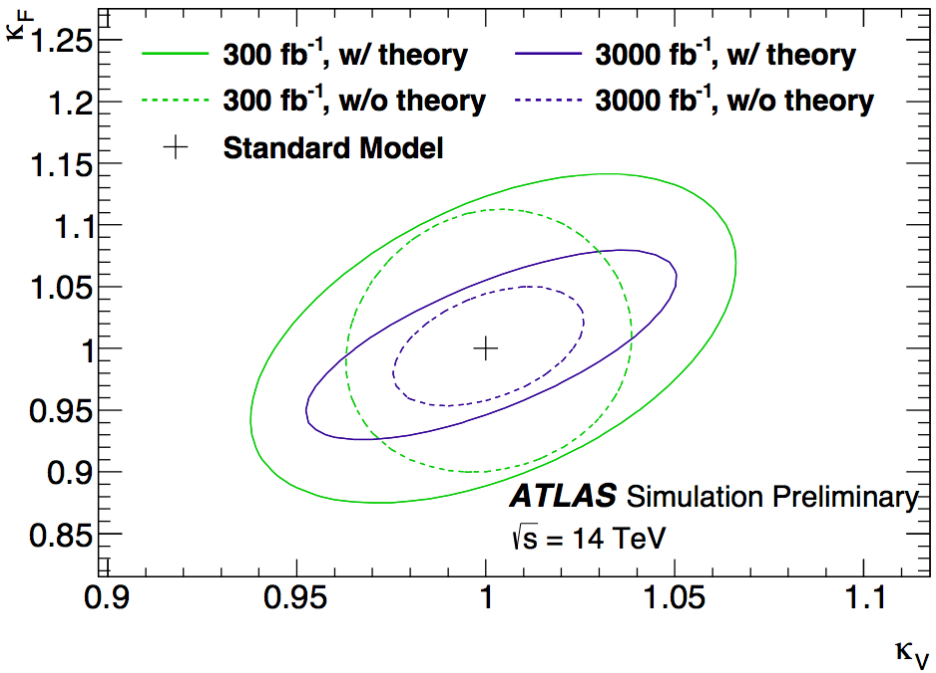
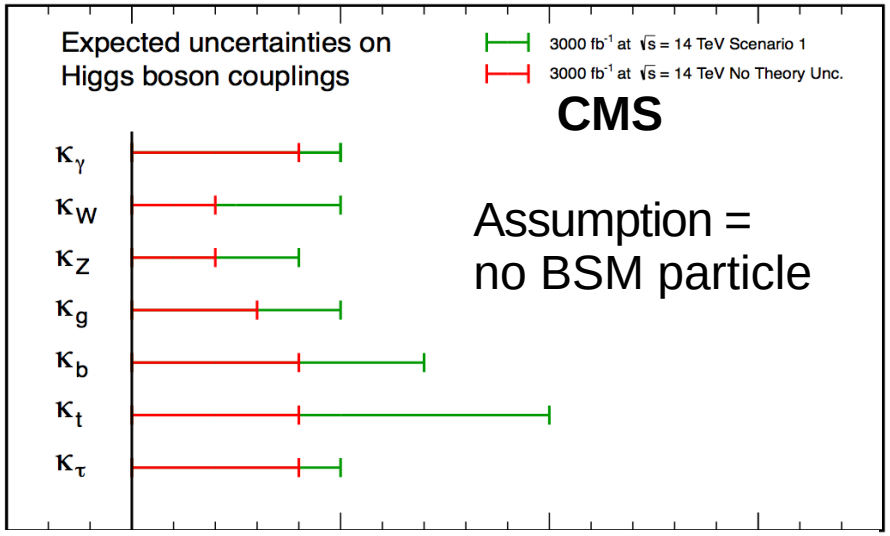
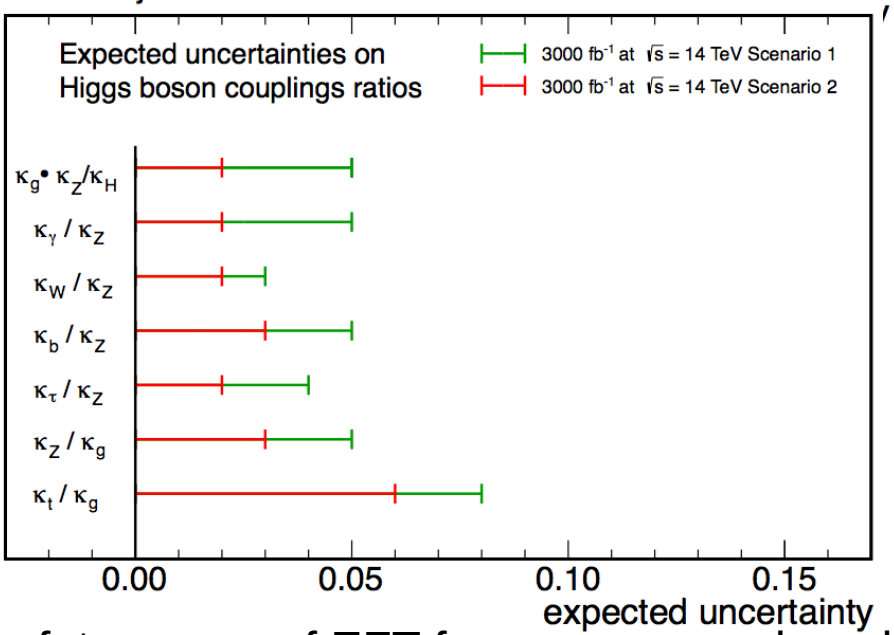


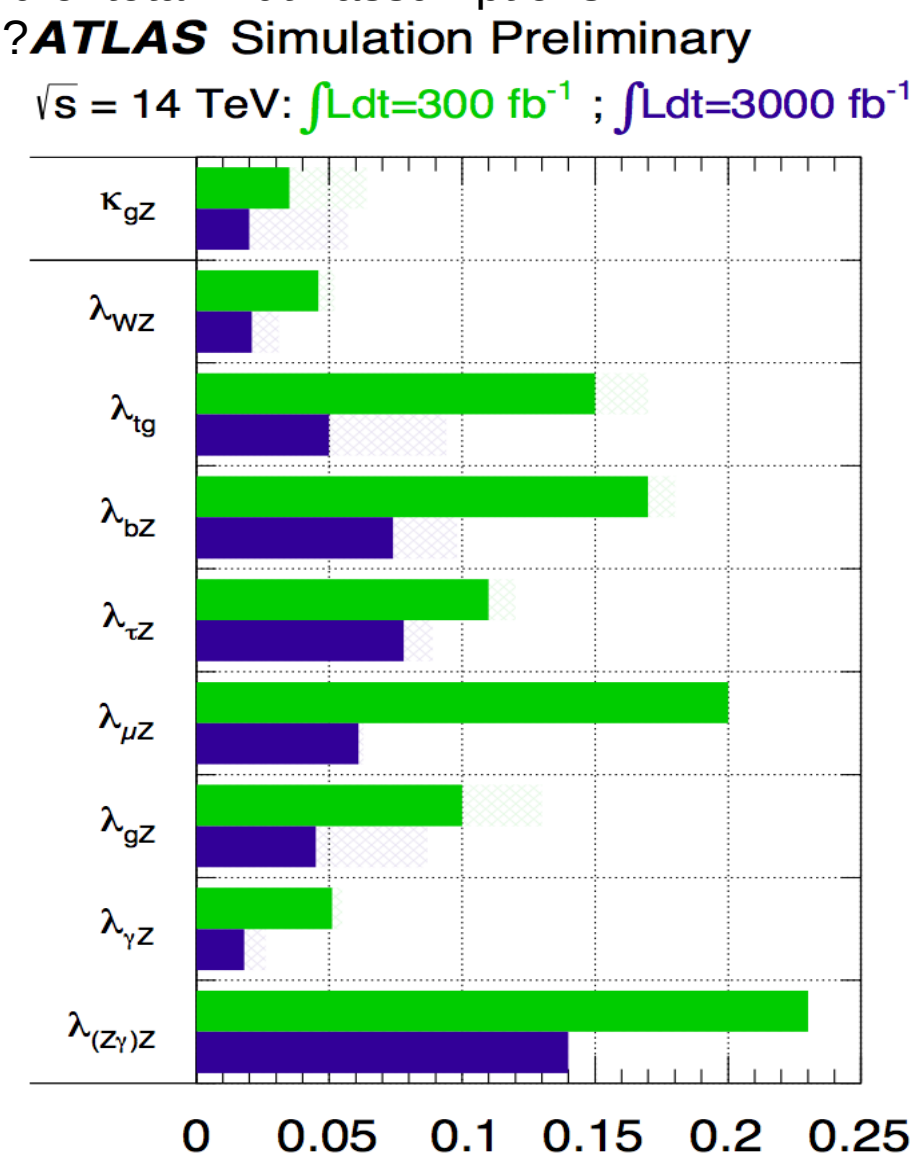
Couplings fit

- κ-framework to scale couplings or their ratios to get rid of total width assumptions
  Which precision do we need to go? < $5\% \times (\frac{1\ \mathrm{TeV}}{\Lambda})^2$?



CMS Projection





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

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

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

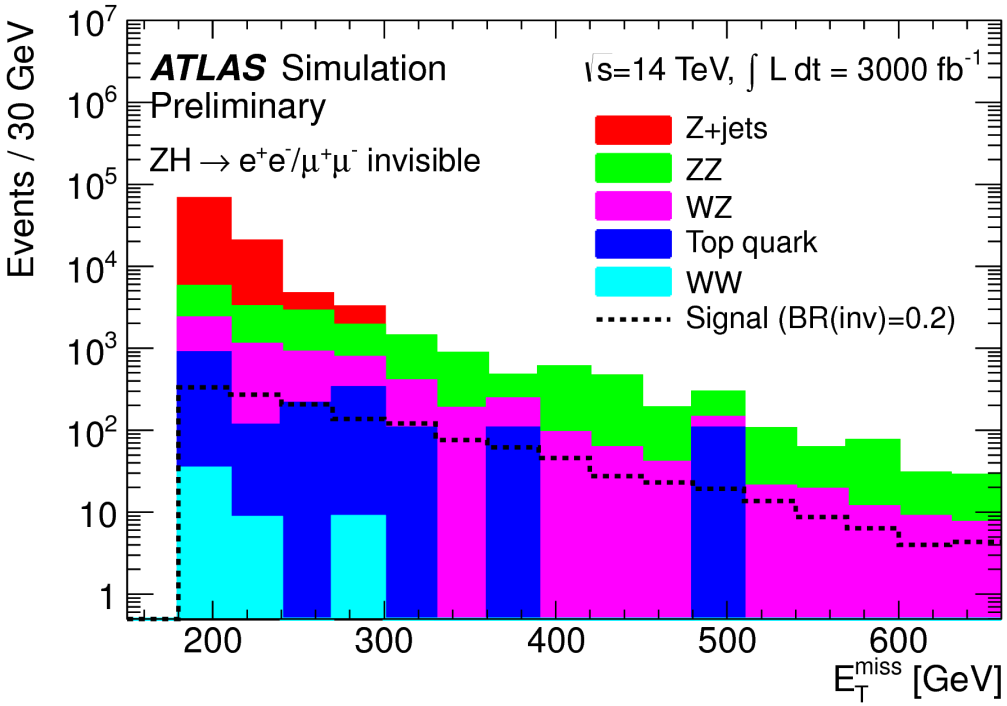
Missing partial decay width ?

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

BR(H →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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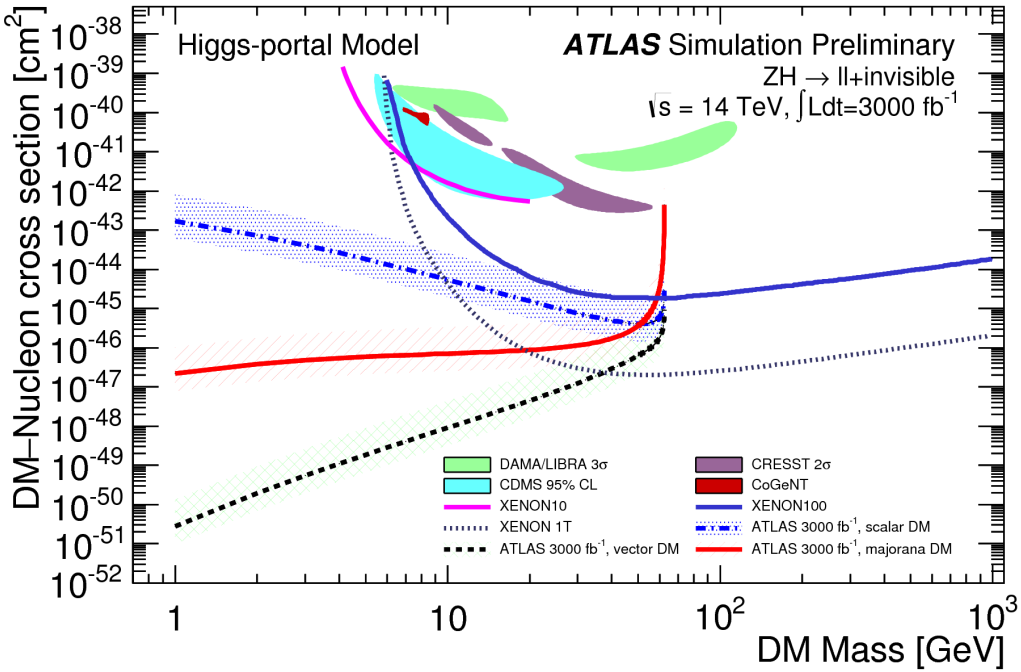
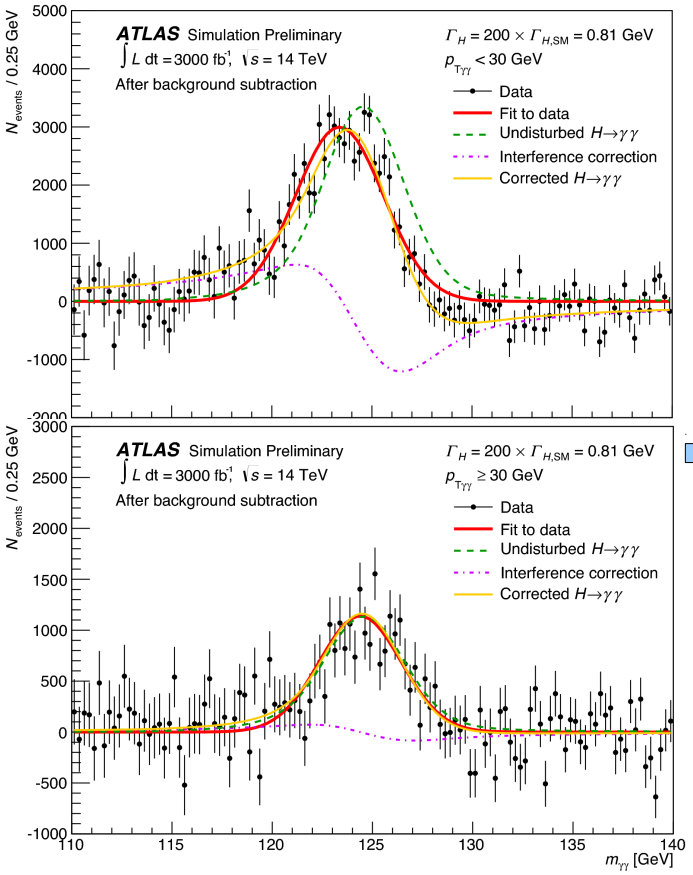


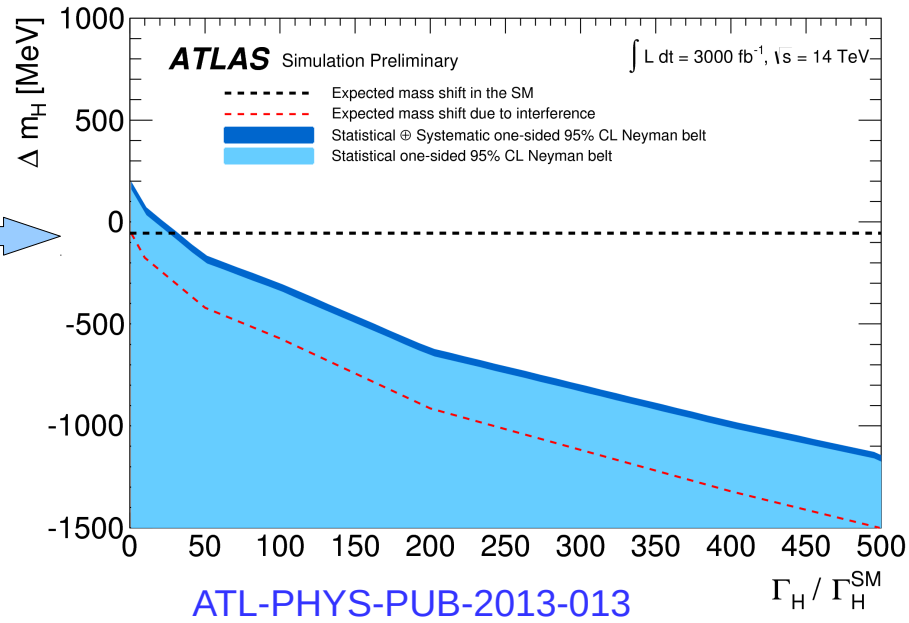
arXiv:hep-ph0605188 arXiv:1109.4398
arXiv:1112.3299 arXiv:1203.2064

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}
  - Almost already theoretical uncertainties-limited
  - mu_off vs mu_on → refined differential measurements could help ?

Probing the coupling structure

- ZZ events provide the full angular information
- 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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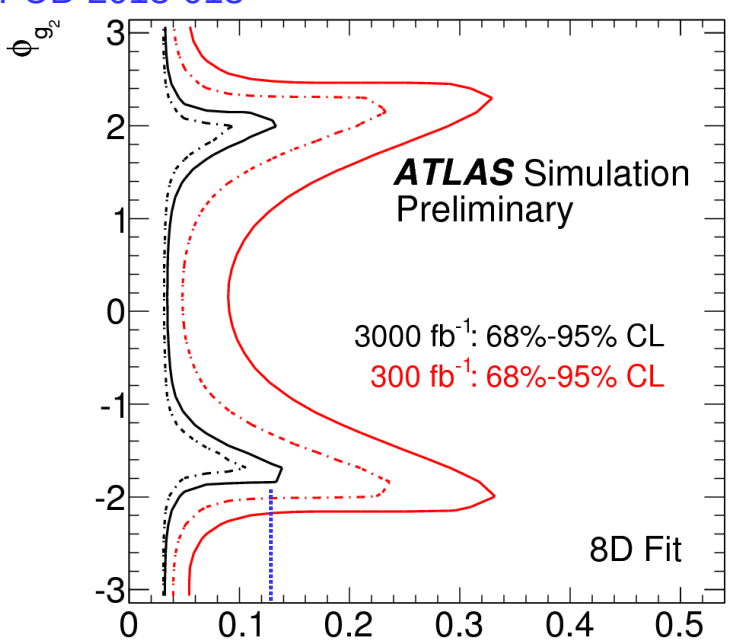
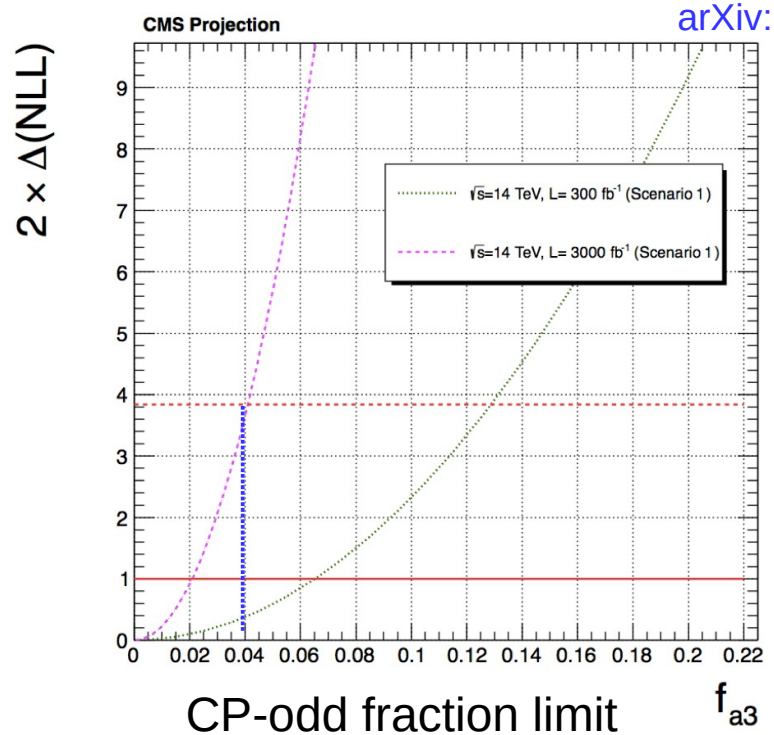


Loop-induced CP-even contribution

CMS-FTR-13-013, arXiv:1307.7135



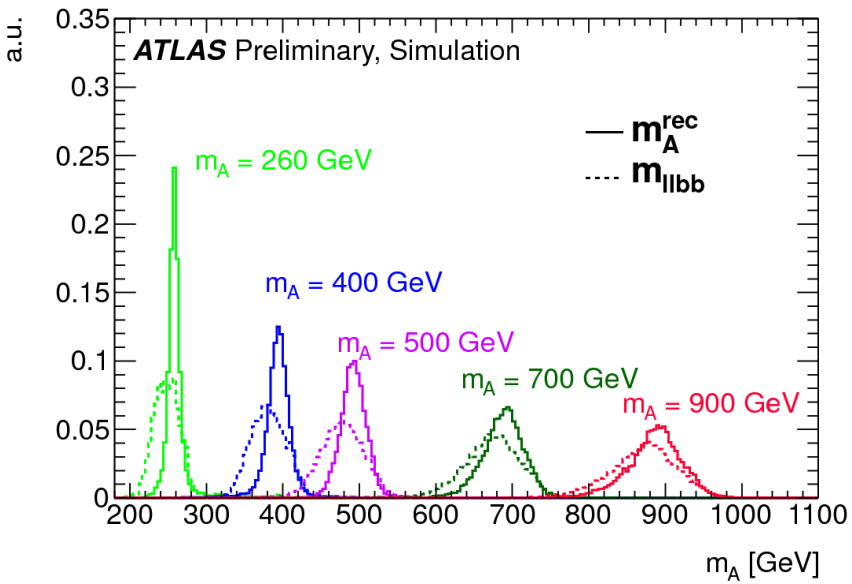
CP-odd fraction limit

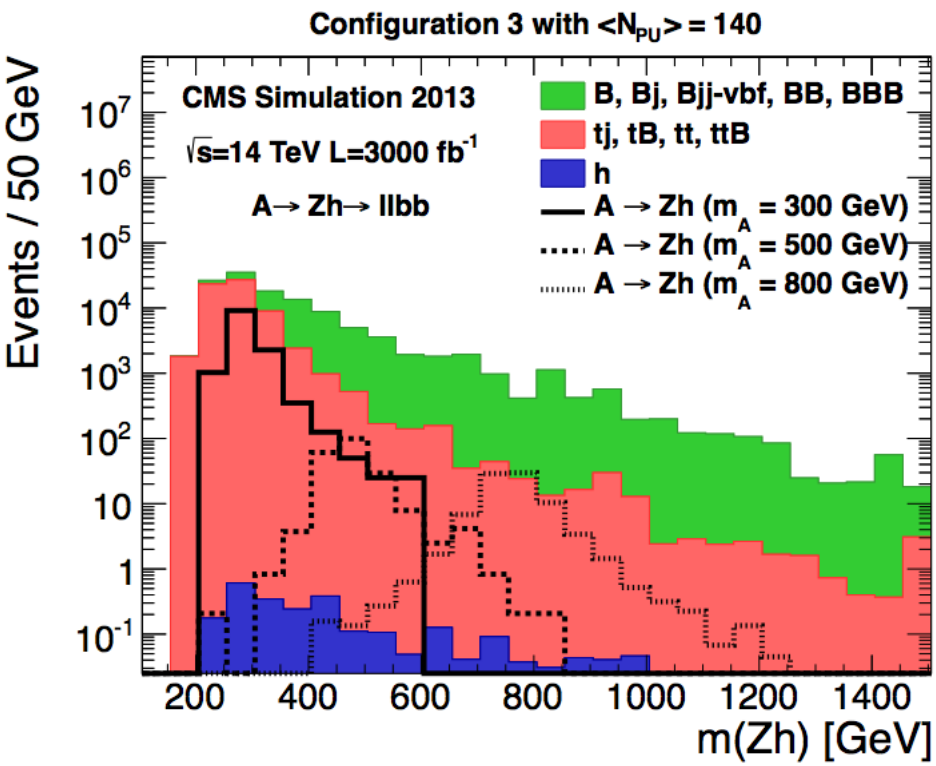
A → hZ

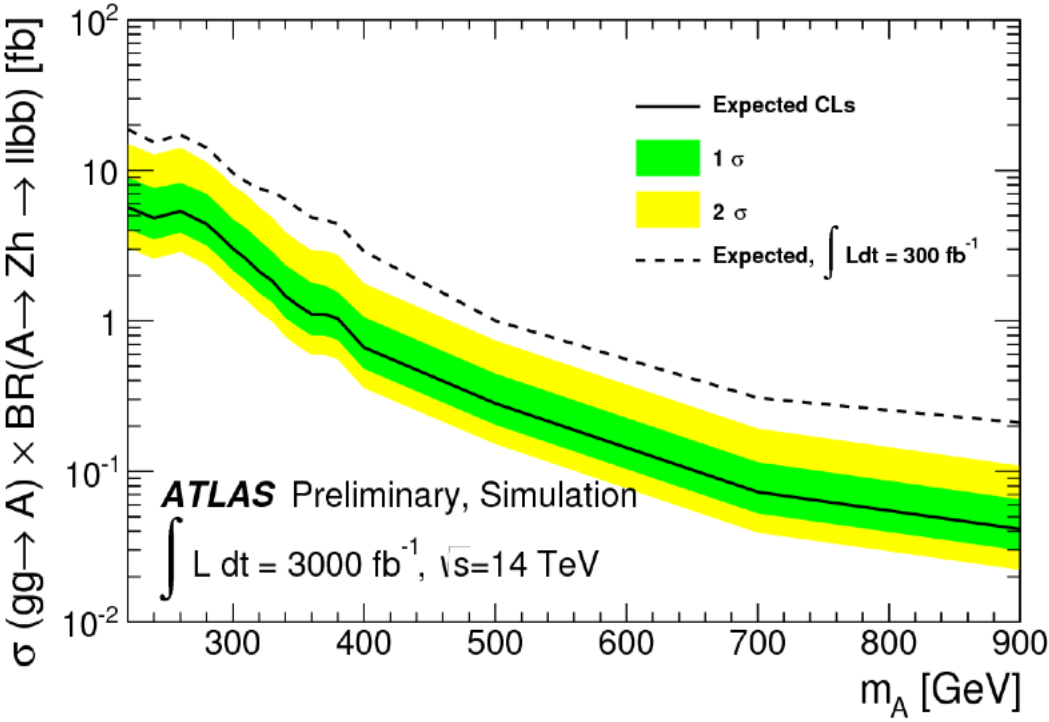
- 2HDM models can be probed in A→Zh→2l2b selections

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
$\mathcal{A} \to$ Zh ($m_{\mathcal{A}}$ = 300 GeV)	1.3×10^4
$\mathcal{A} \to$ Zh ($m_{\mathcal{A}}$ = 500 GeV)	210
$\mathcal{A} \to$ Zh ($m_{\mathcal{A}}$ = 800 GeV)	85

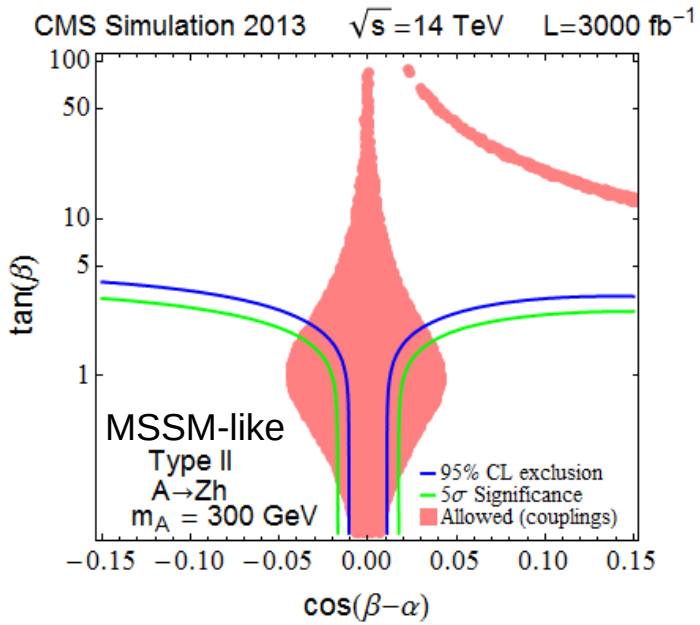
Expected events for 3000 fb^{-1}

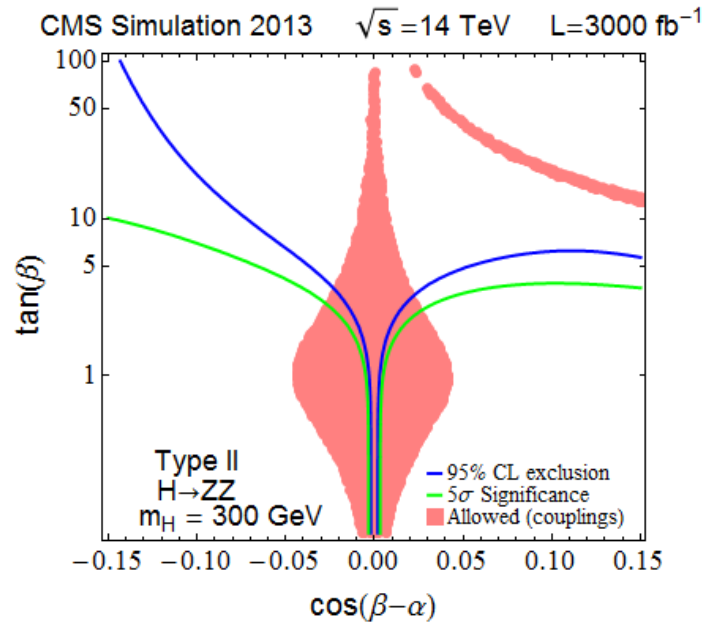




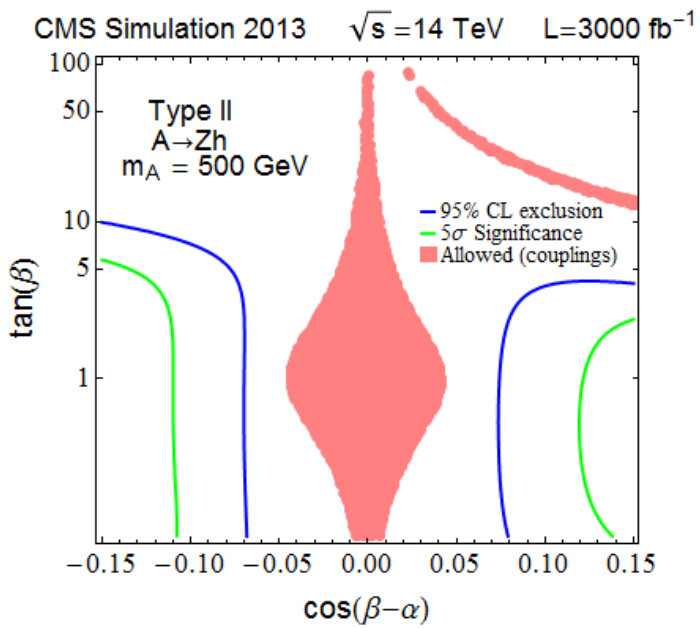


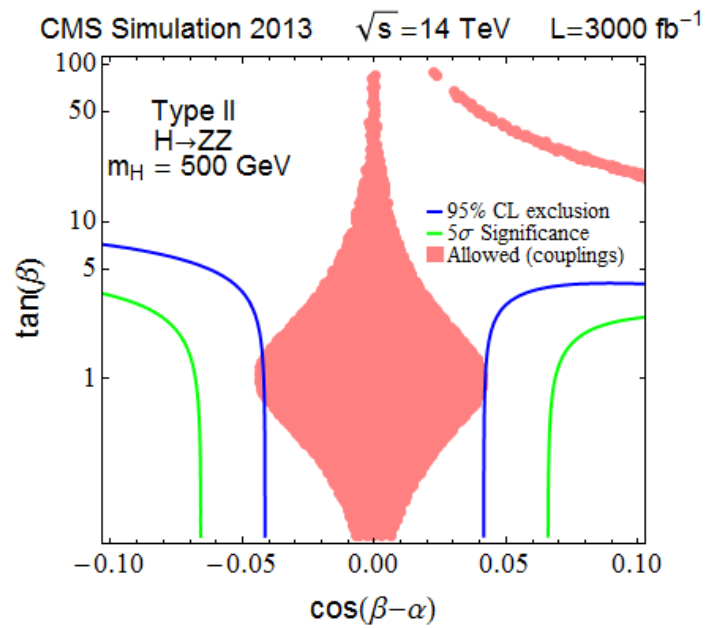
2HDM expected sensitivity





$m_{A/H}$ = 300 GeV



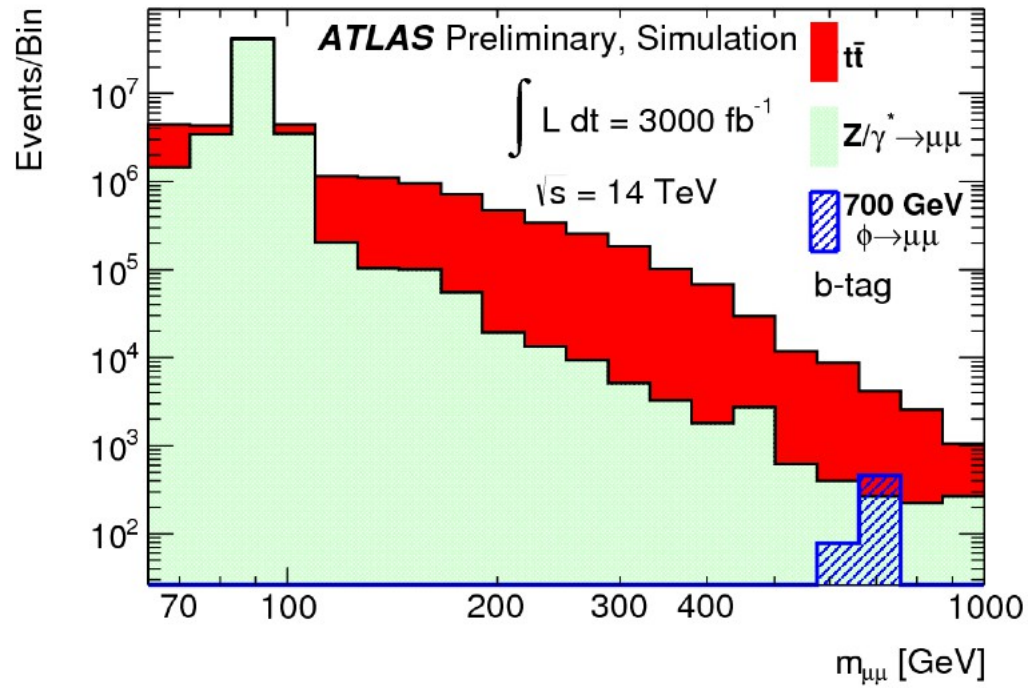


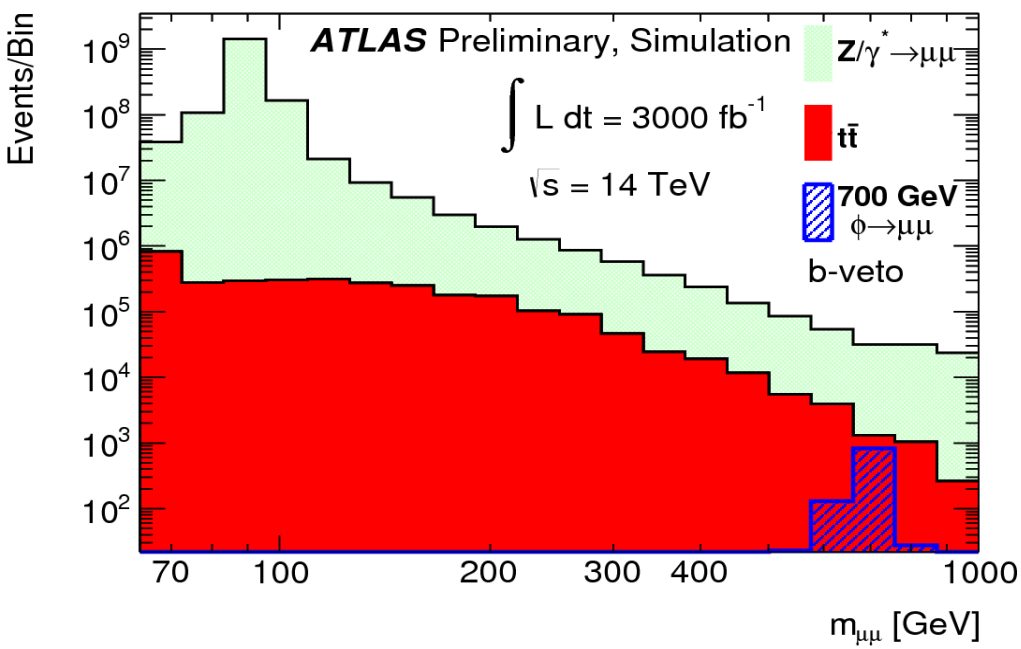
$m_{A/H}$ = 500 GeV

A → Zh → 2l2b

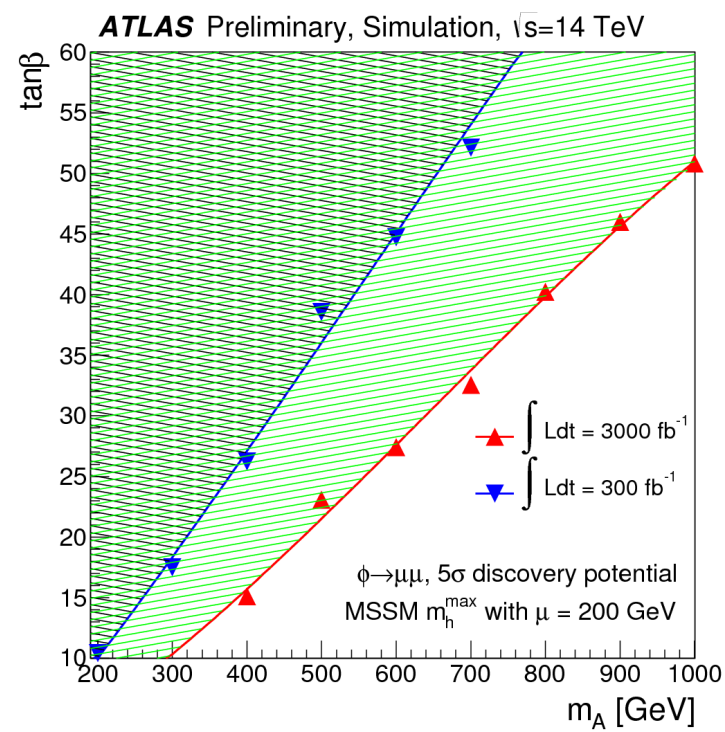
H → ZZ → 4l

MSSM μμ limits



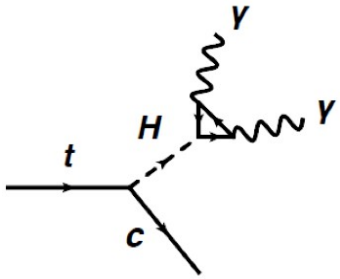


- high tan β region complementary to A → Zh for MSSM constraints
- High mass resolution at high dimuon mass
- Search for two production modes
  - gluon fusion
  - b associated production



FCNC top to Higgs

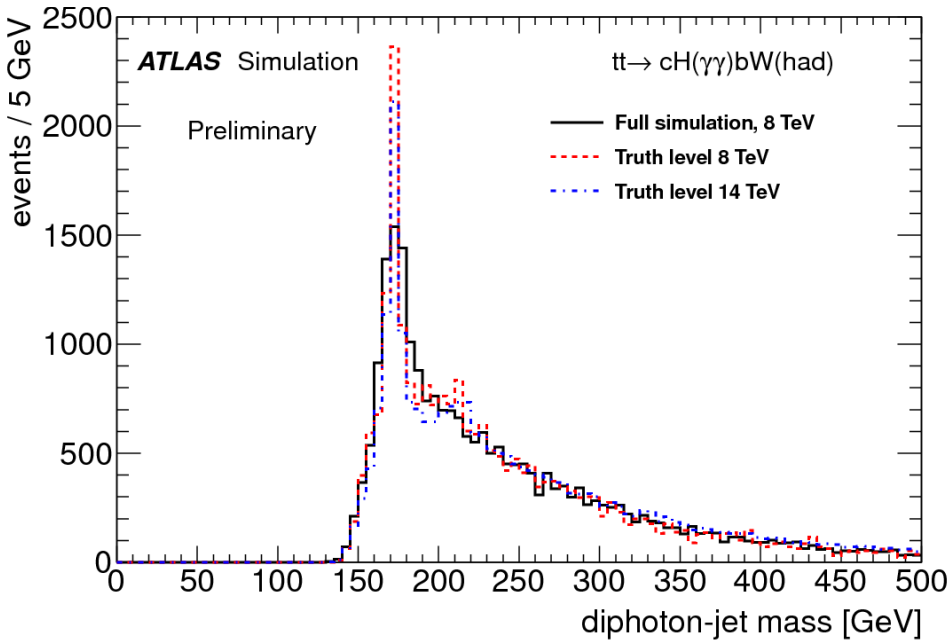
- FCNC processes are forbidden at tree level in the SM
- t→cH observation in ttbar events would certainly be a sign of new physics

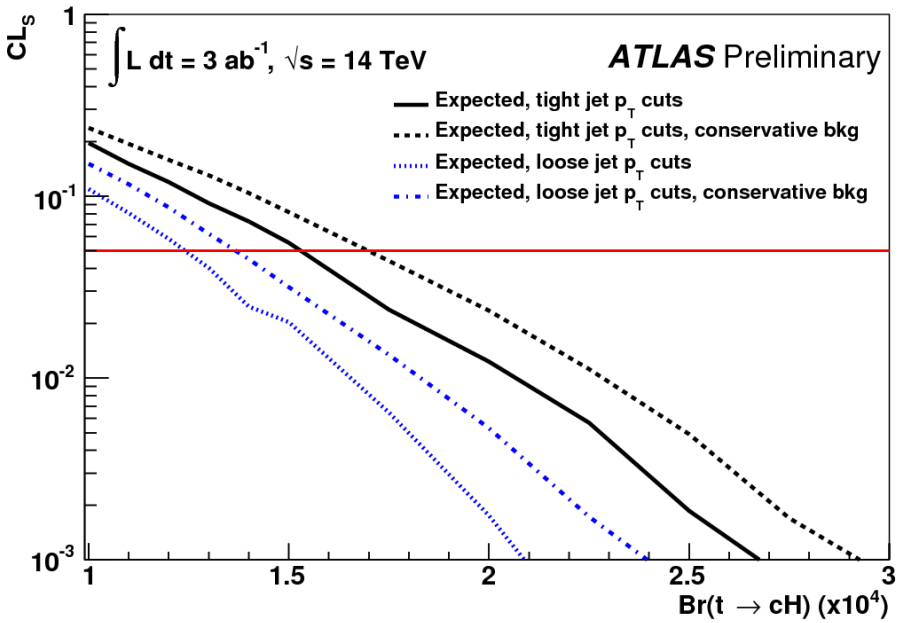


Typical BRs of EW FCNC-top decays:

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}

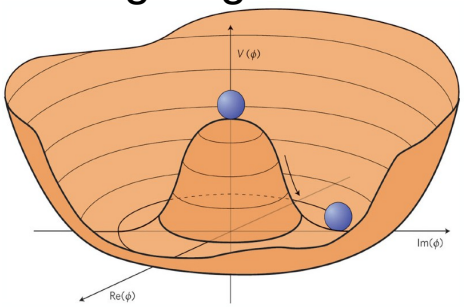
- Event selection relies on diphoton Higgs decay for its clear signature





Self-coupling & di-Higgs production

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



$$V(|\phi|^2) = \mu^2|\phi|^2 + \lambda|\phi|^4 \longrightarrow$$

$$V(H^0) = 2\lambda v^2 \frac{(H^0)^2}{2} + 6\lambda v \frac{(H^0)^3}{3!} + 6\lambda \frac{(H^0)^4}{4!} - \frac{v^4\lambda}{4}$$
$$\equiv m_H^2 \frac{(H^0)^2}{2} + \lambda_{3H} \frac{(H^0)^3}{3!} + \lambda_{4H} \frac{(H^0)^4}{4!} - \frac{v^4\lambda}{4}$$

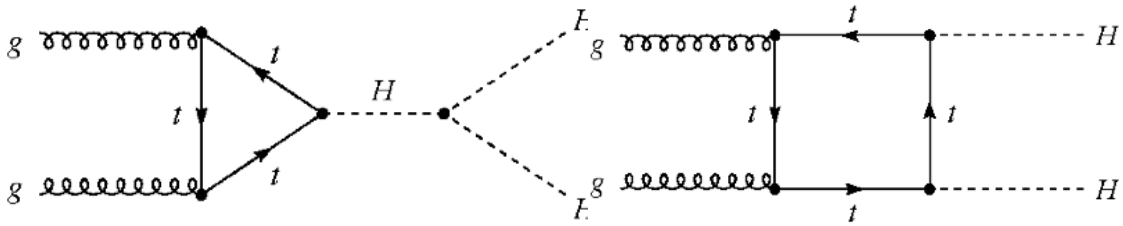
- Origin of matter relies in baryon/anti-baryon asymmetry
- Electroweak baryogenesis: generate baryon asymmetry with particle mass generation at EW scale, under some conditions on the way the EWSB happens
- Inflation of the Universe usually modeled using a scalar field (inflaton) : could this be related to the Higgs boson ?
- All this may happen in some extended Higgs sector in which the trilinear coupling

$\lambda_{3H} = \frac{3m_H^2}{v}$ is modified

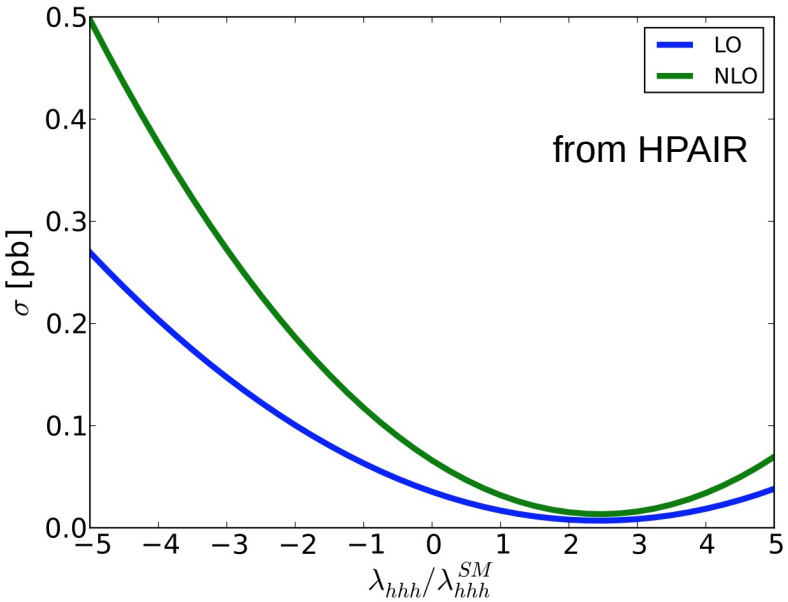
Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$

Di-Higgs boson production

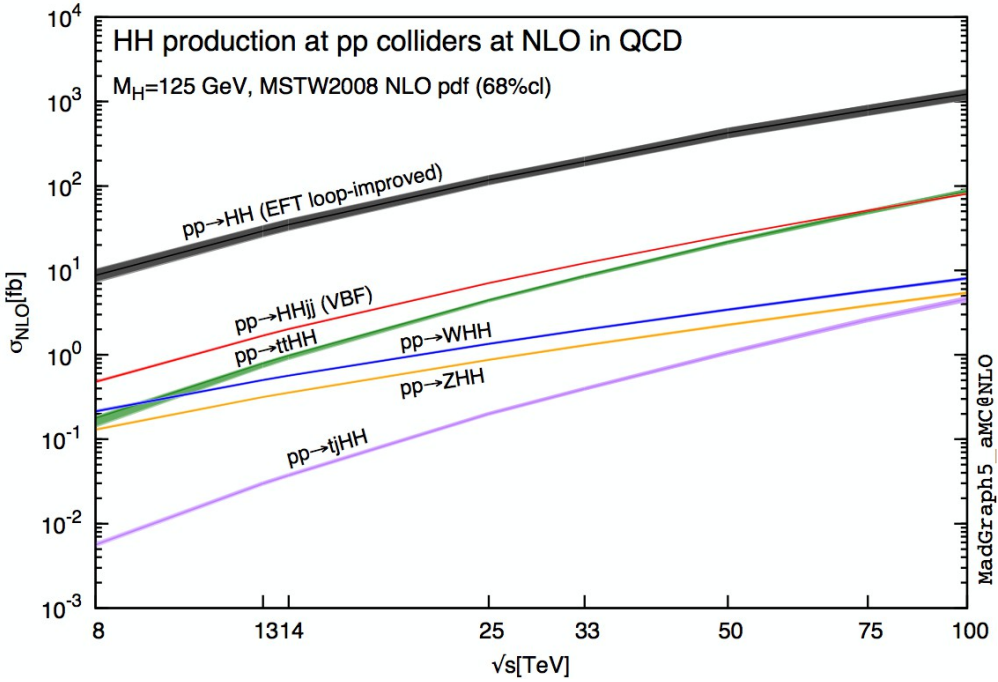
- Di-Higgs boson production dominated by box diagram
- Negative interference with self-coupling diagrams



- Low cross-section
- Currently large theoretical uncertainties for the signal

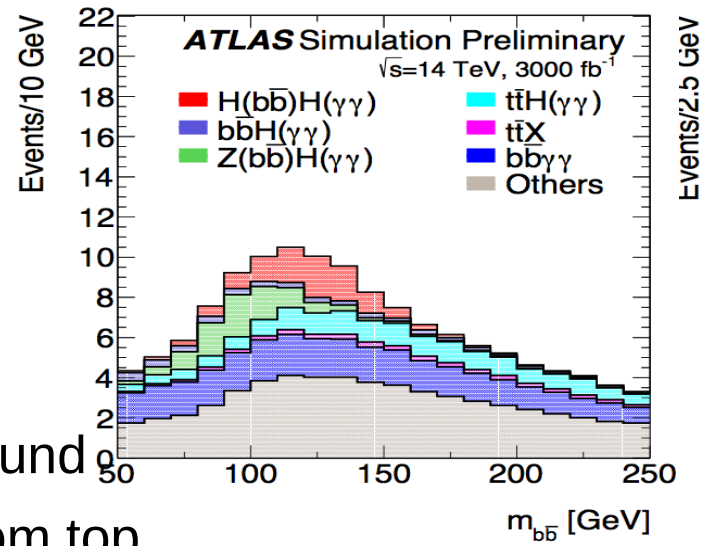


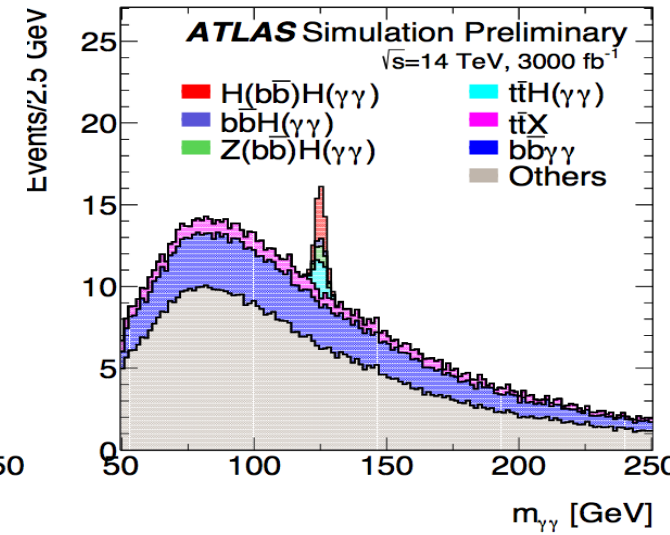
- Many channels are now being explored in order to assess the potential for the di-Higgs boson observation and the sensitivity to the self-coupling at the HL-LHC
  - The simplest (ggF with decays into b pairs) might not be the most powerful
- Difficult (new!) analyses to develop

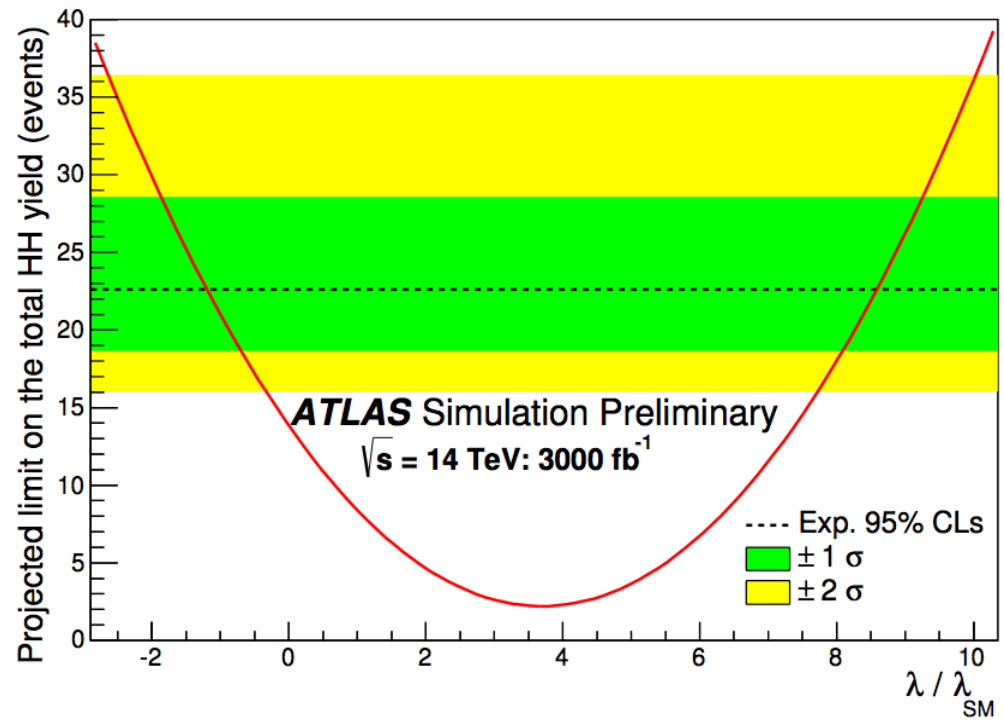


Self-coupling measurements ?

- ATLAS and CMS have documented some prospects for the di-Higgs production measurements
- Here the example of the -so far- “golden” channel : bbγγ
- Very complicated analyses
  - Often large background
    - Higgs its own background
    - Large contributions from top and/or fakes processes
    - Currently no good prediction for the continua (bbγγ, bbjj,...)
  - Working in busy environment (high pile-up for hadrons colliders) where triggering will be an issue too
- So far, barely able to see with 3000 fb^{-1} the total HH production
- Measuring precisely the trilinear coupling will be very challenging !

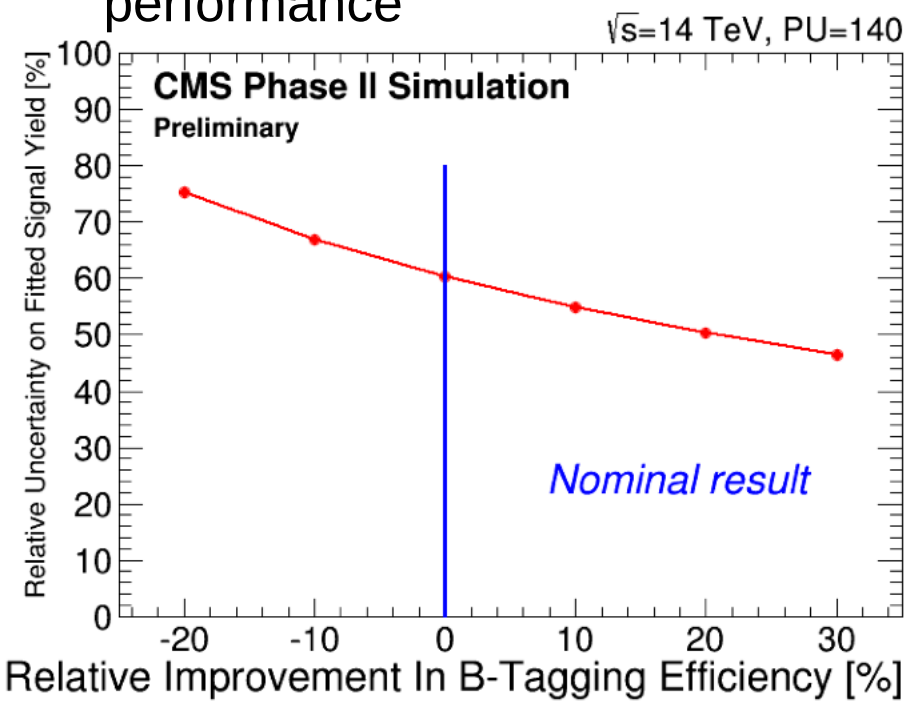


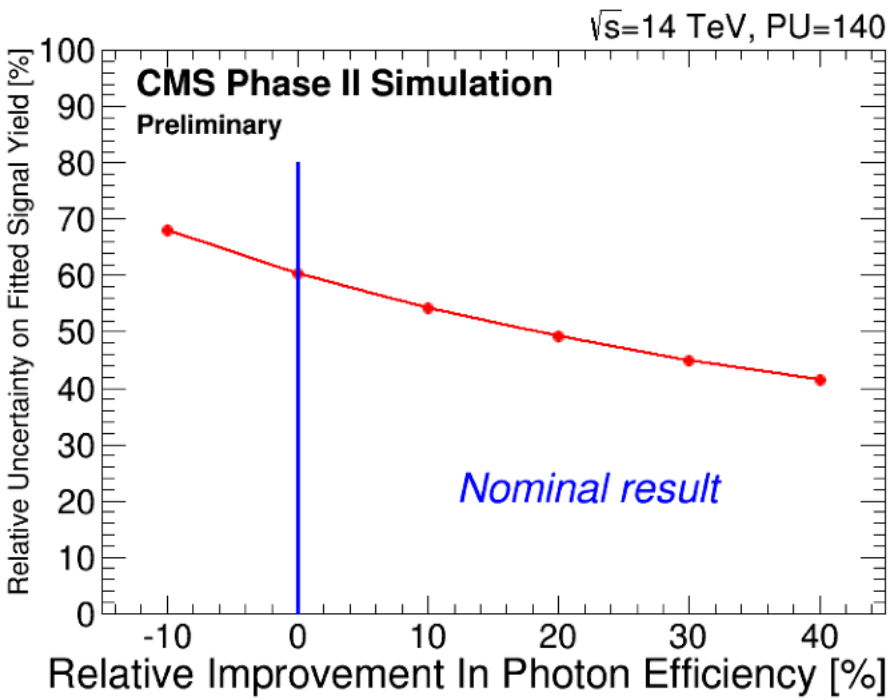




Self-coupling measurements ? (2)

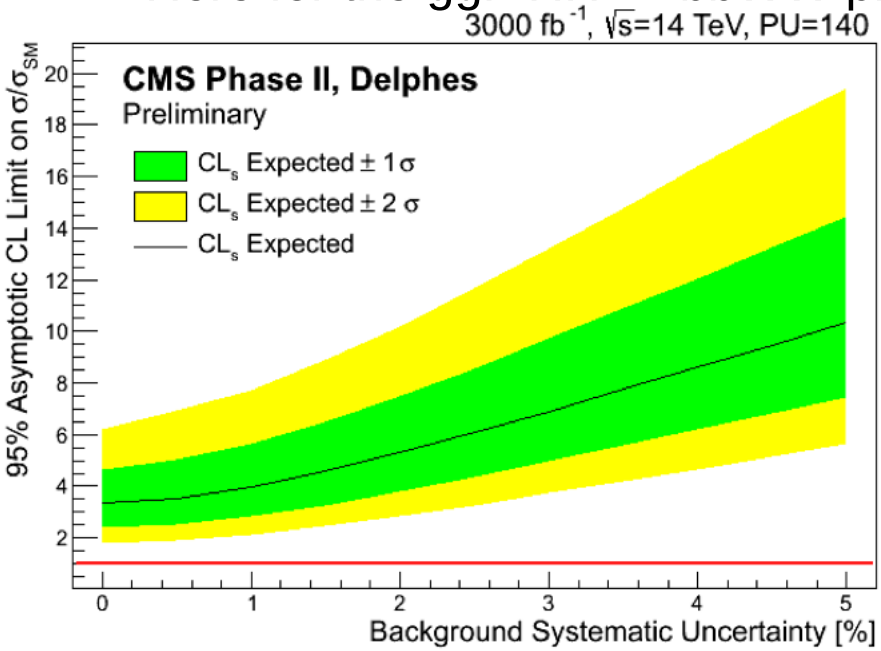
- Every bit of acceptance will matter in this respect
- Performance not precisely known
  - CMS presented projections of the performance in function of the assumed performance

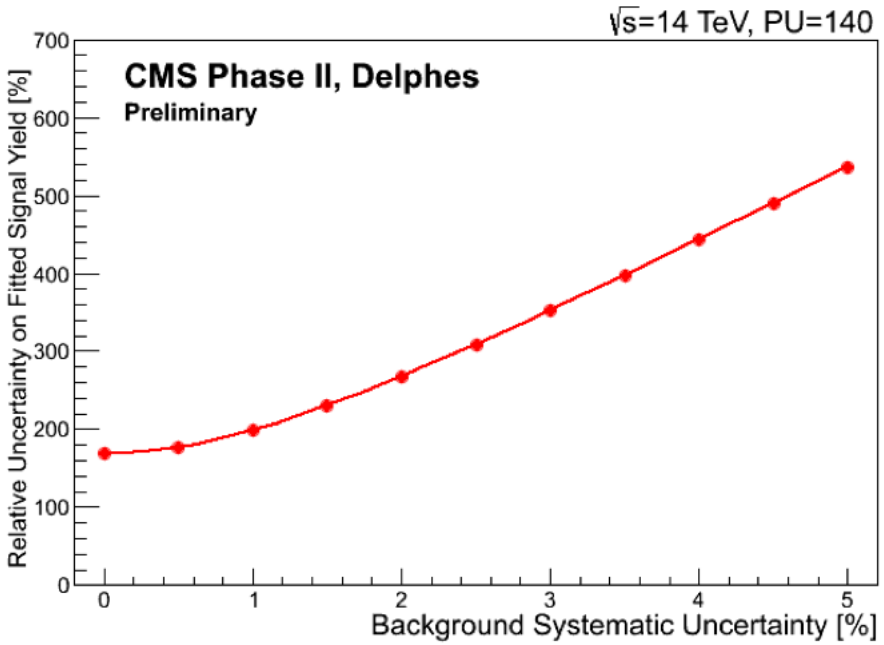




Self-coupling measurements ? (3)

- Uncertainties on the main background to the signal measurement are also unknown
  - When there are natural high-stats control regions uncertainties can sometimes be assumed to be negligible or to scale with luminosity
  - CMS also produced projections in function of the assumed background systematic uncertainty
    - Here for the ggF HH → bbWW prospects

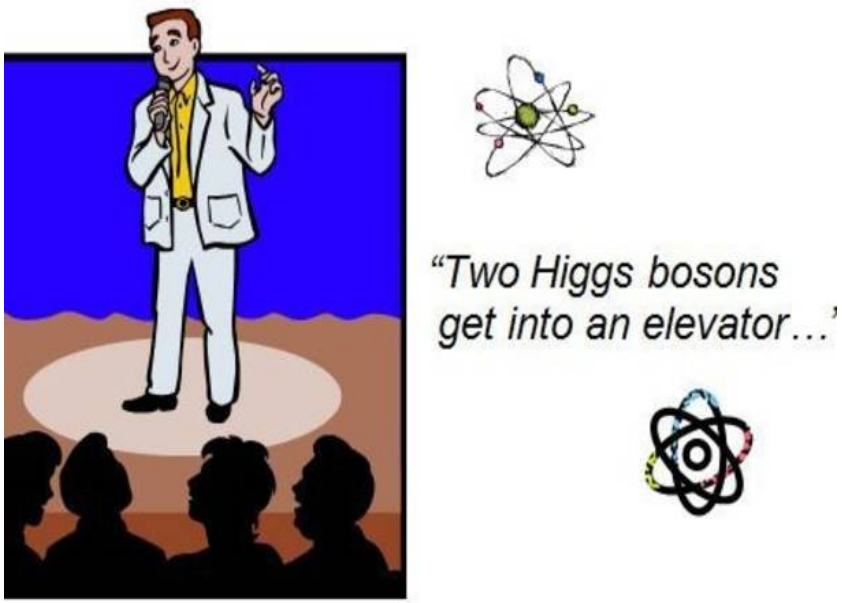




- Some other channels have also been looked at by both collaborations but no public results yet.
  - What about the associated productions ? VBF HH → 4b for instance ?
  - Combining many channels is anyway interesting even if they're not 5σ channels...

Conclusions

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



- 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
- More information about the performance assumptions at https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsFP Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2013-004/

BACKUP

Higgs total width (2)

- Higgs off-shell analysis searches for large Higgs couplings for the off-shell Higgs at large virtualities (mass) m_{VV}
- Use high mass channels $H^* \rightarrow ZZ \rightarrow 4l$, $H^* \rightarrow ZZ \rightarrow 2l2n$ and $H^* \rightarrow WW \rightarrow l\nu l\nu$
- Unknown QCD effects
  - → all analysis done inclusive in jets
  - → depending on the unknown K-factor for the $gg \rightarrow VV$ bkg
- Combination with on-shell analysis allows interpretation as measurement of Γ_H
- Assumes same on- & off-shell couplings
- $\Gamma_H < 22$ MeV

(95%CL limit on $\mu_{off\text{-}shell}$ between 5.1-8.6)