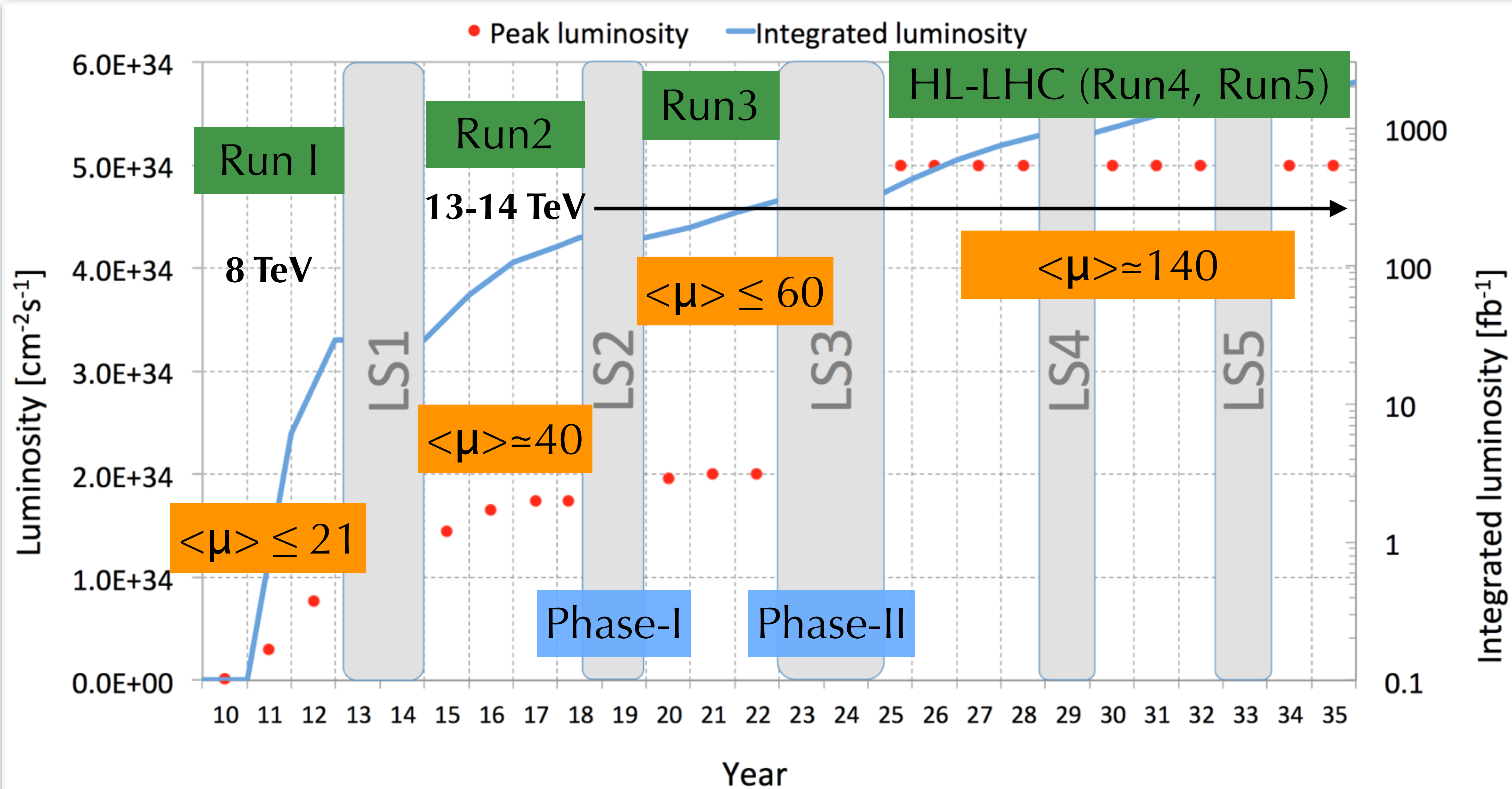
Prospects for future precision measurements of Higgs properties at HL-LHC

Monica Trovatelli
University of Victoria

On behalf ATLAS and CMS Collaborations

25th International Workshop on Weak Interactions and Neutrinos
Heidelberg, June 8-13 2015

The High Luminosity-LHC project



- HL-LHC will start in mid-2025 after ~2.5 years of shutdown
- Levelled luminosity of $5 \cdot 10^{34}$ cm^{-2} s^{-1}
- Average number of pile-up interactions per bunch crossing <μ> ≃ 140
- Expect to collect ~ 300 fb^{-1} with LHC and ~3000 fb^{-1} with the HL-LHC

Experimental Challenges

★ High pile-up ⇒ detector and trigger improvements needed

★ High radiation level ⇒ detector damage

Goal: keep detectors performance at the same level as today

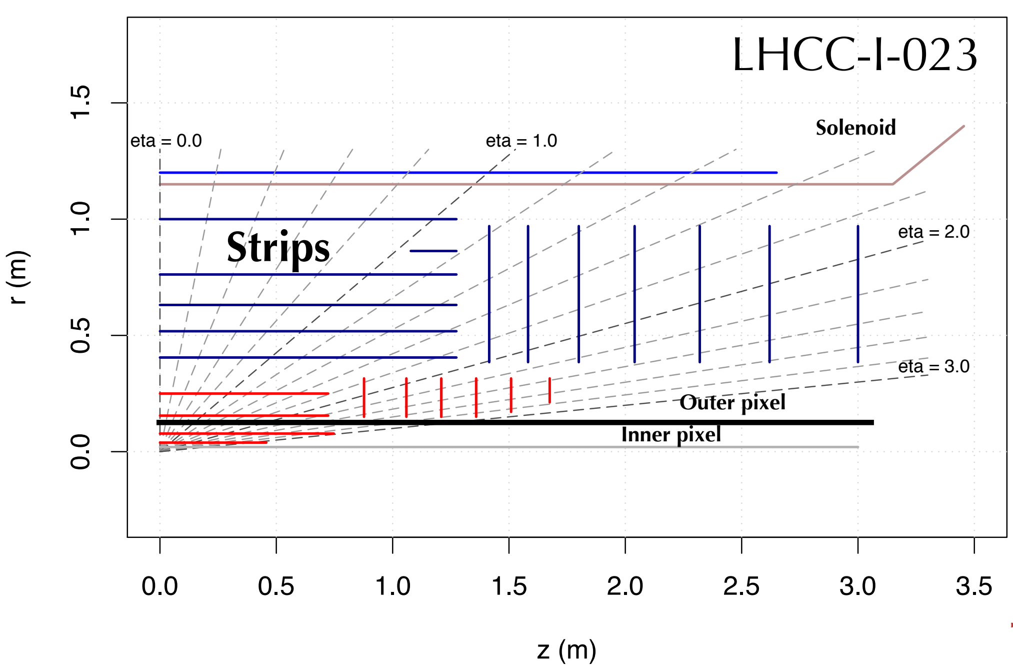
ATLAS and CMS detector upgrade

ATLAS and CMS detectors must be updated:
1) Deterioration due to aging
2) Cannot handle with <μ> ≃ 140

Different technologies will be used in the Phase-II upgrade, but common strategy:
→ Re-visit the L1 trigger logic to keep leptons p_T thresholds and L1 trigger rates low
→ Tracker replacement due to efficiency loss and fake rate increase
→ Extension of detectors coverage to increase acceptance and improve performances

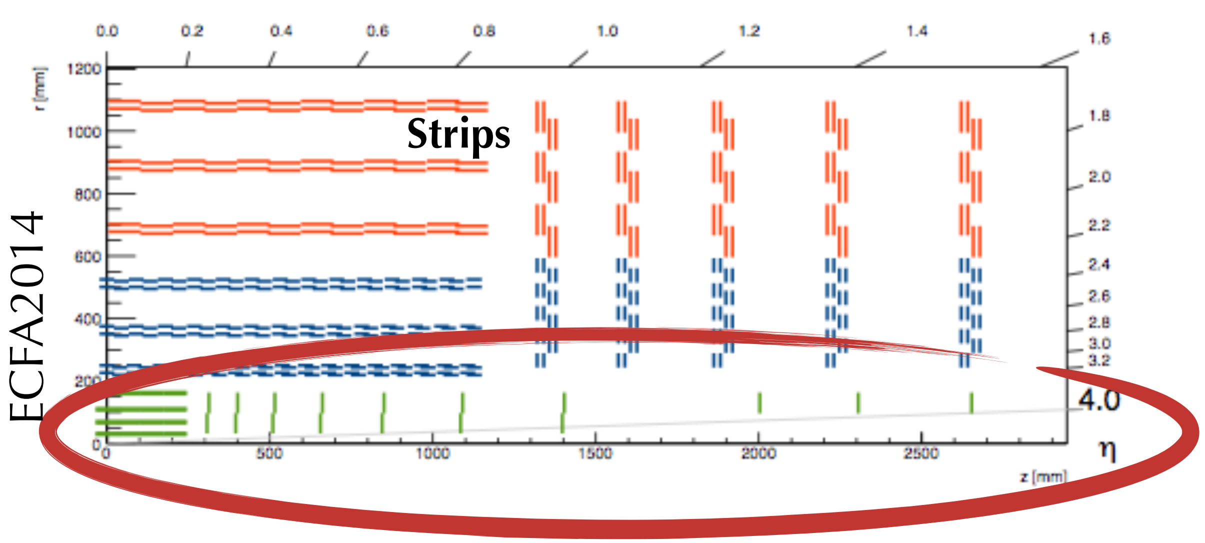
ATLAS Upgrade

- New all-Silicon Tracker (ITK)
- Replace calorimeter electronics
- Replace Phase-I L1 trigger with a two stage L0/L1 trigger. Use calorimeter information and tracks to reduce L1 output rate to ~ 200 kHz
- Extension of the coverage to larger η



CMS Upgrade

- New all-Silicon tracker (radiation tolerant, high granularity, less material)
- New end-cap calorimeters (fast scintillators)
- Muons: complete RPC coverage in forward region (new RPC/GEM technology)
- Tracker and calorimeters extension to |η| < 4



Inner pixel layer with extension

The detectors upgrade is not yet finalized!

Prospects for the Higgs physics

HL-LHC will be a **Higgs factory**: Over 100 million of SM Higgs boson produced

Precision measurements

- ✓ Signal strengths
- ✓ Couplings

New measurements?

- ✓ Assessment of the top Yukawa coupling via $t\bar{t}H$ production
- ✓ New rare decays (H→μμ, H→Zγ)
- ✓ Higgs boson pair production

Projections studies(*) for the Higgs properties measurements based on realistic/conservative assumptions on the detector performance at HL-LHC

<u>ATLAS</u> (ATL-PHYS-PUB-2013-004):

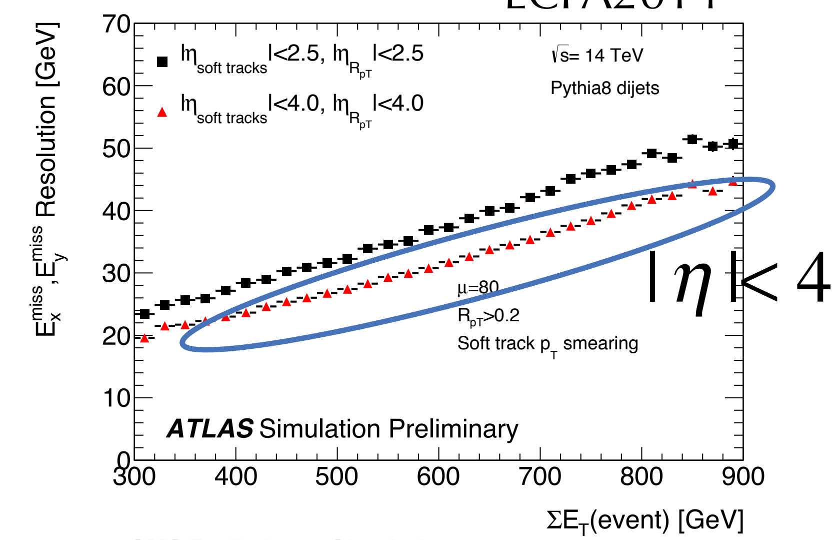
- Full GEANT4 simulation used to evaluate performance
- Detector response parametrized and applied at the generator level
- Systematic uncertainties based on Run I, improvements from statistics. w/ & w/o current theory uncertainties

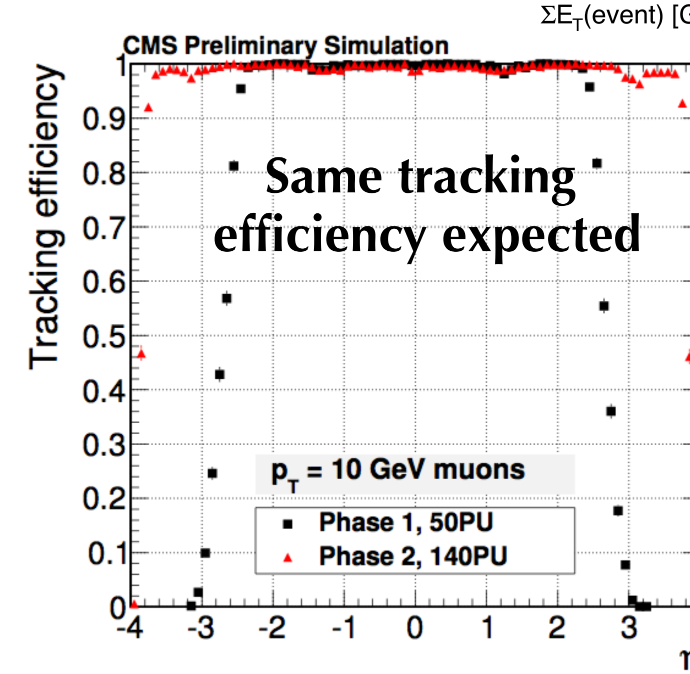
<u>CMS</u> (arXiv:1307.7135):

- Assumes that the upgraded detector will compensate the effects of higher pile-up and extrapolates Run I event rates
- Two scenario for systematic uncertainties considered:
  1) Systematic uncertainties the same as in Run I
  2) Theory uncertainties scaled by a factor of 1/2, experimental uncertainties scale as 1/√L

(*) submitted at the European Strategy for Particle Physics and presented at the EFCA HL-LHC workshops

ECFA2014

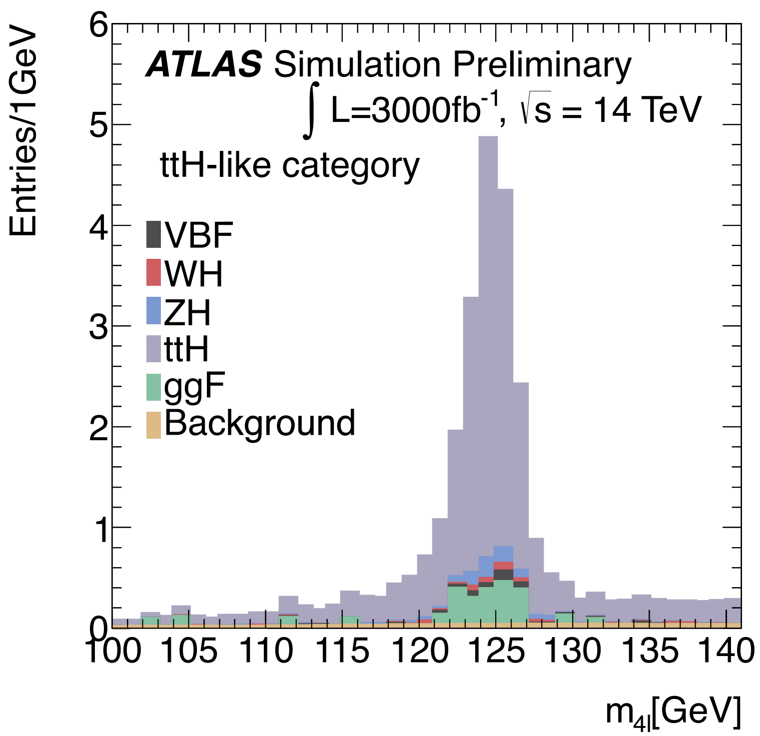




CMS-PAS-FTR-13-003

$H \to ZZ^{(*)} \to 4\ell$

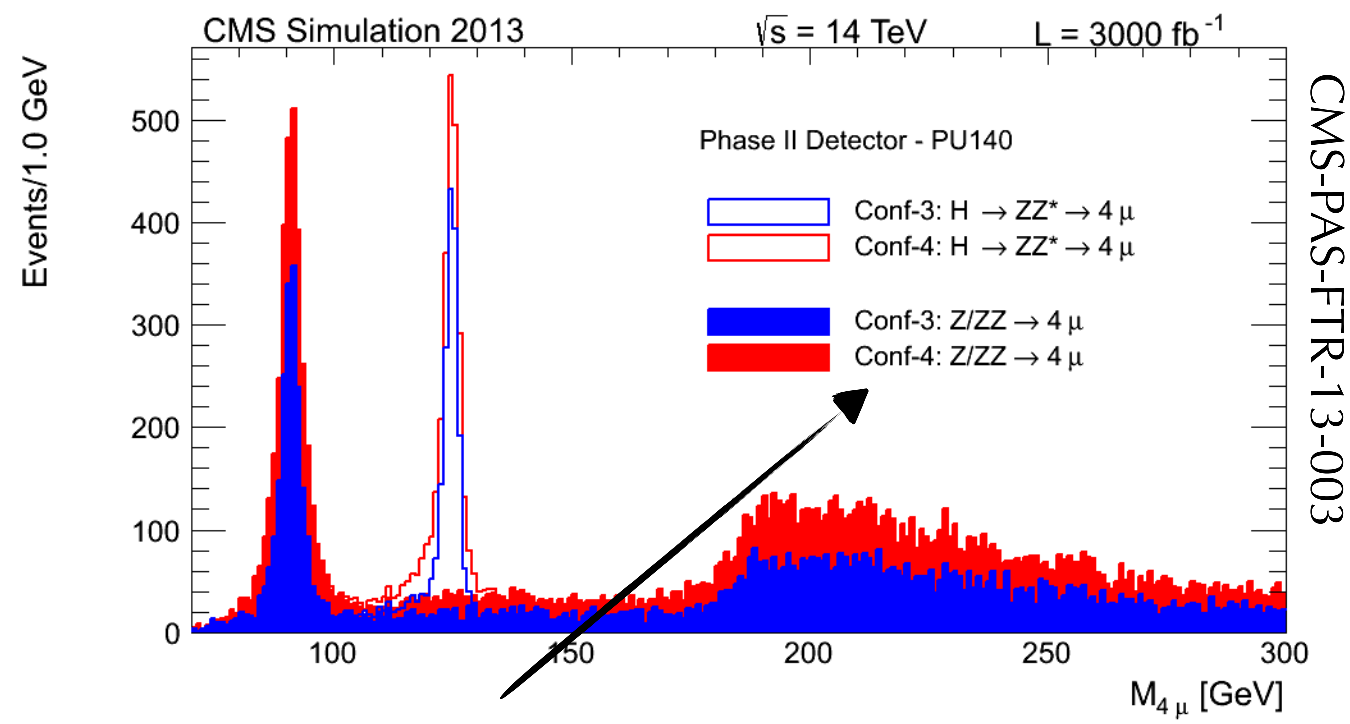
ATL-PHYS-PUB-2013-014



$\Delta\mu/\mu$	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

Error is dominated by theoretical uncertainty

- ZZ decay channel has one of the cleanest final state
- The large number of events in a 3000 fb^{-1} sample allows the study of the Higgs production modes separately (improving the precision on couplings)
- Precision of O(10%) or lower on the signal strength is expected by both ATLAS and CMS



Conf-3 = ITK + forward calorimeter

Conf-4 = Conf-3 but $|\eta| < 4$

⇒ These channels can also benefit from an extended eta coverage

Currently ~25% uncertainty on μ

(ATLAS-CONF-2015-007, PHYSICAL REVIEW D89, 092007)

$H \to \gamma\gamma$

- This channel offers a clean final state → peak on top of a smooth background
- Measurement in all the production channel is possible
- In particular, for the associated production modes $t\bar{t}H$, WH and ZH more than 100 events could be observed

H-t Yukawa coupling

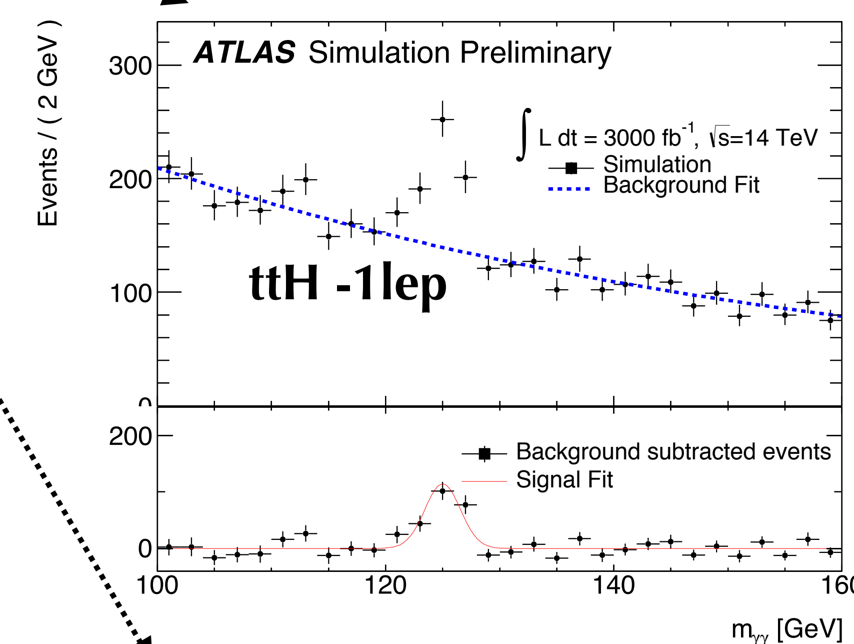
ATL-PHYS-PUB-2014-012

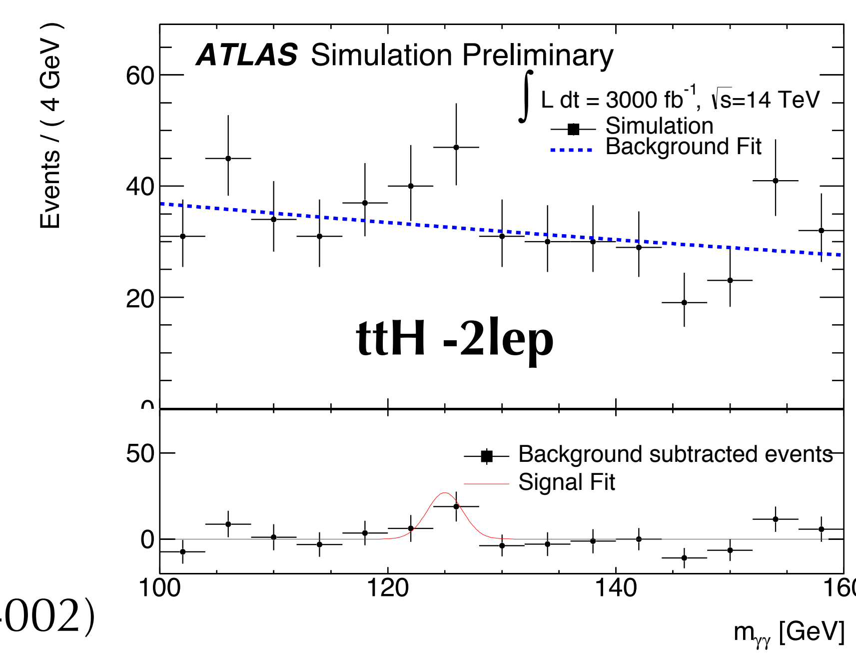
	Production mode	$\Delta\hat{\mu}/\hat{\mu}$ (%) Total	Statistical	Experimental	Theoretical
S/B~10% }	$t\bar{t}H$	$^{+21}_{-17}$	$^{+13}_{-12}$	$^{+5}_{-4}$	$^{+17}_{-11}$
S/B~2% }	WH	$^{+26}_{-25}$	$^{+21}_{-20}$	$^{+13}_{-12}$	$^{+10}_{-8}$
S/B ~20% }	ZH	$^{+35}_{-31}$	$^{+32}_{-29}$	$^{+7}_{-7}$	$^{+12}_{-8}$
	ggF	$^{+19}_{-14}$	$^{+3}_{-3}$	$^{+1}_{-1}$	$^{+19}_{-14}$
	VBF	$^{+29}_{-29}$	$^{+18}_{-18}$	$^{+1}_{-1}$	$^{+23}_{-23}$

↪

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

- Observation for all the production modes
- Statistics limits the WH/ZH sensitivity even at 3000 fb^{-1}
- CMS expects a precision of ~4/8% on the signal strength with scenario 2/1 (CMS-NOTE-13-002)





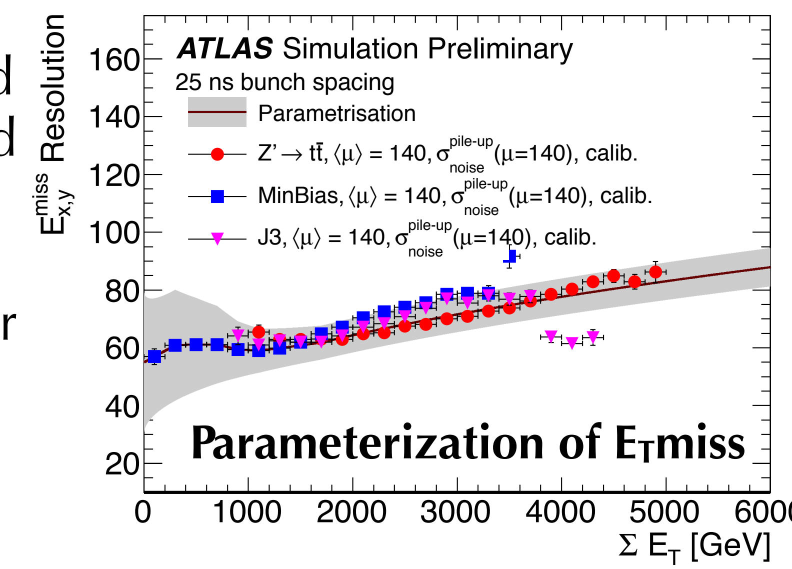
ATL-PHYS-PUB-2014-012

$H \to WW^{(*)} \to \ell\nu\ell\nu(\ell = e,\mu)$

- Harsh pile-up conditions ⇒ $E_T$miss and jet energy resolution degradation
  → current categories have a poor S/√B, specific optimization studies needed (e.g. higher jet p_T threshold, even considering that $t\bar{t}$ cross section increased by a factor of ~4 going from 8 TeV to 14 TeV)

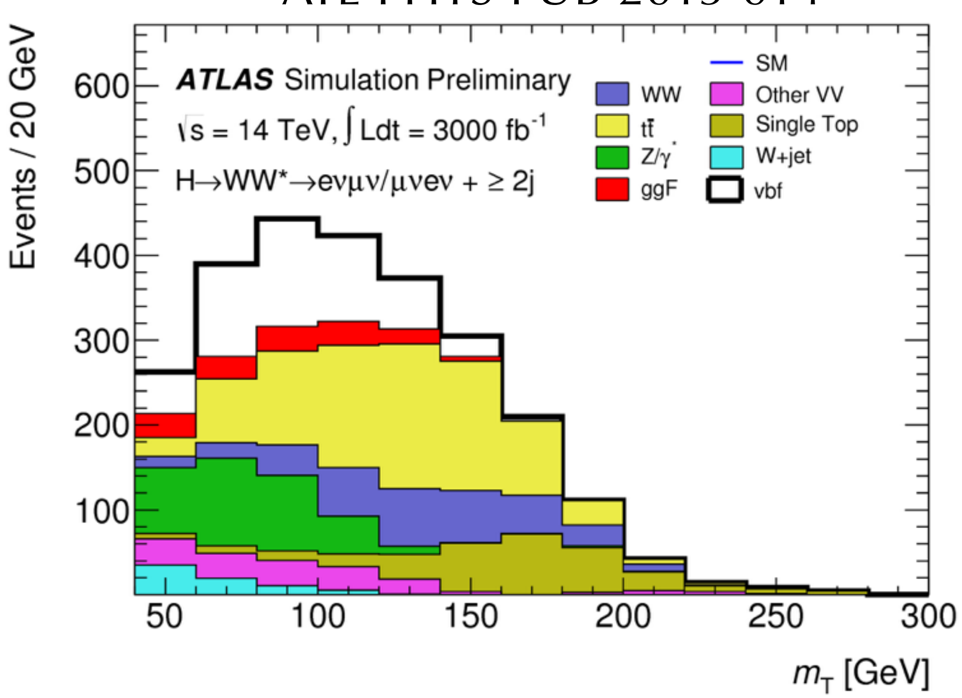
- Perspectives based on reconstructed events with 8 TeV, rather than generator level 14 TeV samples → PDF reweighting used to estrapolate to 14 TeV

- Uncertainty on signal strength μ dominated by theoretical error



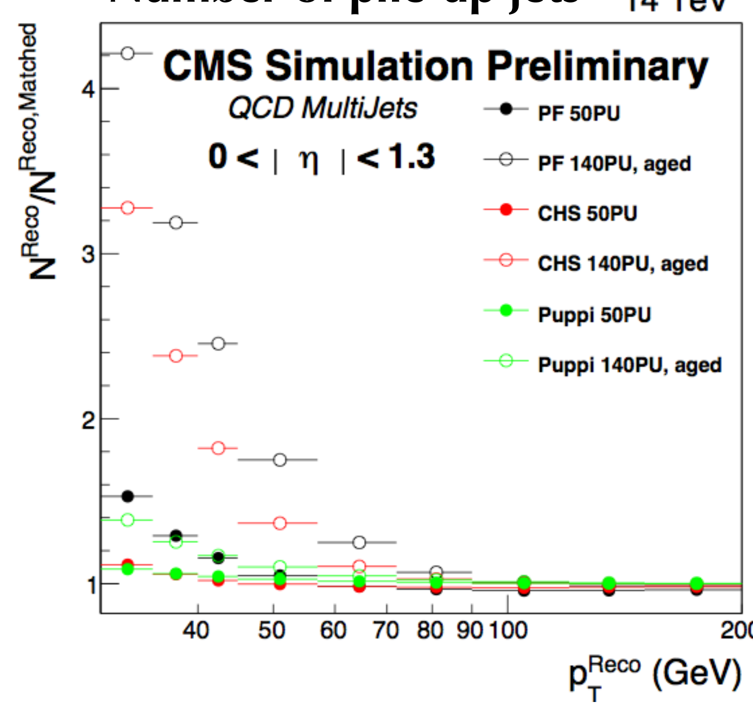
ATL-PHYS-PUB-2013-009

ATL-PHYS-PUB-2013-014



	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}	$1^{+0.16}_{-0.14}$	$1^{+0.15}_{-0.15}$	$1^{+0.10}_{-0.09}$

Number of pile-up jets 14 TeV



ECFA2014

CMS expects a precision of 4/7% on the signal strength in scenario 2/1 (CMS NOTE-13-002)

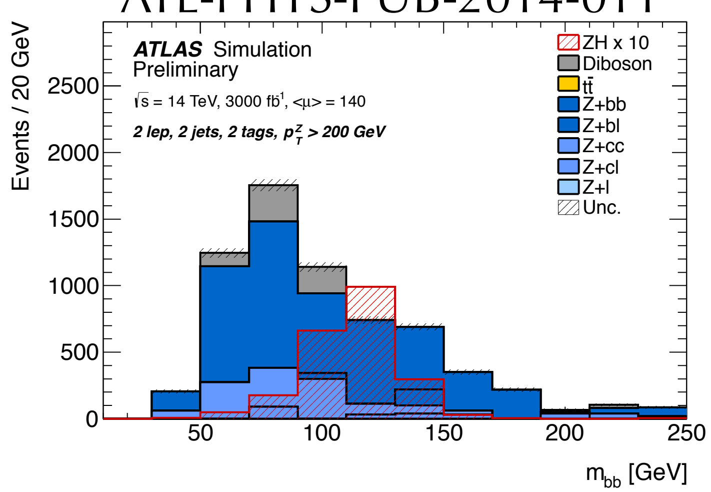
Currently ~21% uncertainty on μ
(arXiv:1412.2641, CMS-HIG-14-009)

$VH \to b\bar{b}, H \to \tau\tau$

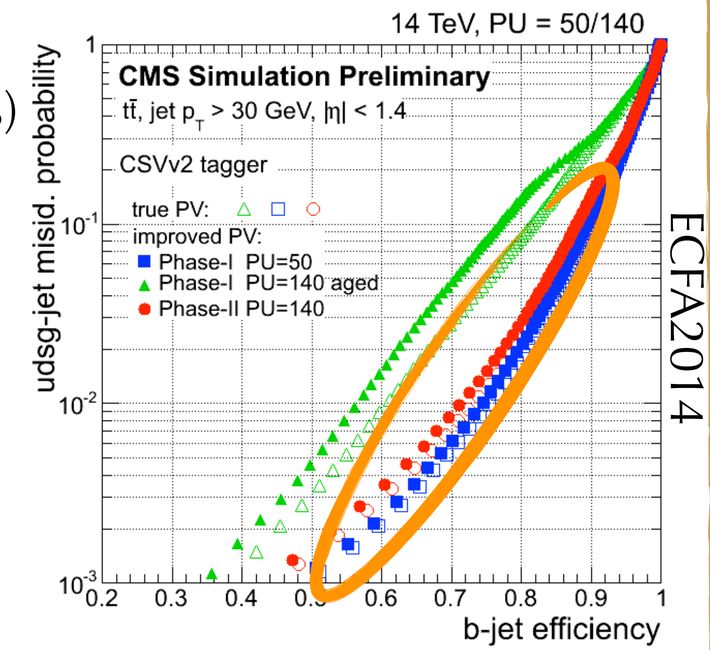
$VH \to b\bar{b}, (V = W/Z)$

b-tagging perfomance will degrade (primary vertex mis-identification, pile-up tracks)
→ new b-tagging approaches and MVA techniques can help

ATL-PHYS-PUB-2014-011



		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 −0.07
	Significance	2.7	8.4	8.8
Scenario I	$\hat{\mu}_{w/Theory}$ error	+0.37 −0.36	+0.15 −0.15	+0.14 −0.14
10%JES uncert.	$\hat{\mu}_{wo/Theory}$ error	+0.36 −0.36	+0.14 −0.12	+0.12 −0.12
	Significance	4.7	-	9.6
Scenario II	$\hat{\mu}_{w/Theory}$ error	+0.23 −0.22	-	+0.13 −0.13
5%JES uncert.	$\hat{\mu}_{wo/Theory}$ error	+0.21 −0.21	-	+0.11 −0.11



CMS expects a precision of 5/7% on the signal strength in scenario 2/1

$H \to \tau\tau$

- VBF $\tau_{lep}\tau_{had}$ category considered
- 8 TeV MC samples used
- projections with new pile-up conditions

CMS expects a precision of 5/8% on the signal strength in scenario 2/1

ATL-PHYS-PUB-2014-018

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

Extension of tracker would help in rejecting fake jets

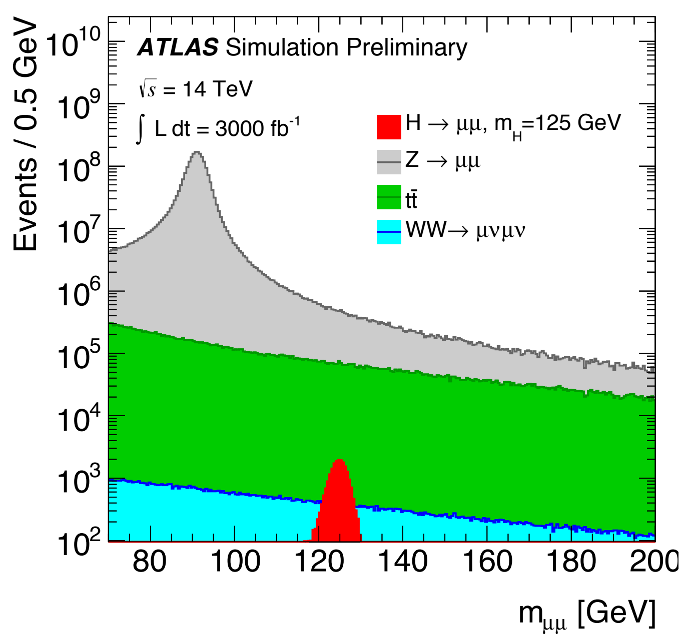
Rare decays

Higgs rare decay channels will be those mostly benefit from the large dataset available with the HL-LHC

$H \to \mu\mu$

- Probe the 2nd generation coupling
- BR O(10^{-4}) and high background from Z/γ*
- High mass resolution

CMS: uncertainty of ~20/24% with scenario 2/1
ATLAS: prospective studies based on the 2012 analysis



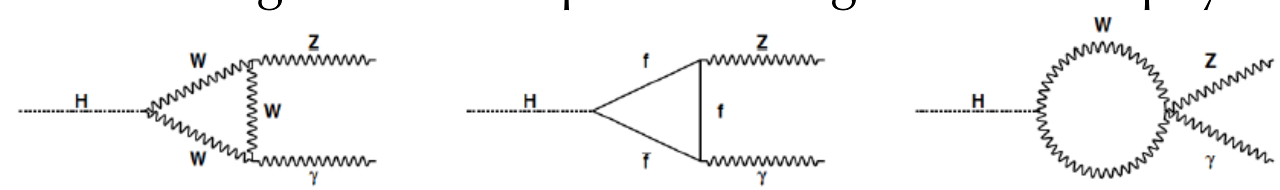
ATL-PHYS-PUB-2013-014

ATLAS expects observation with 7.0σ and 21% of uncertainty

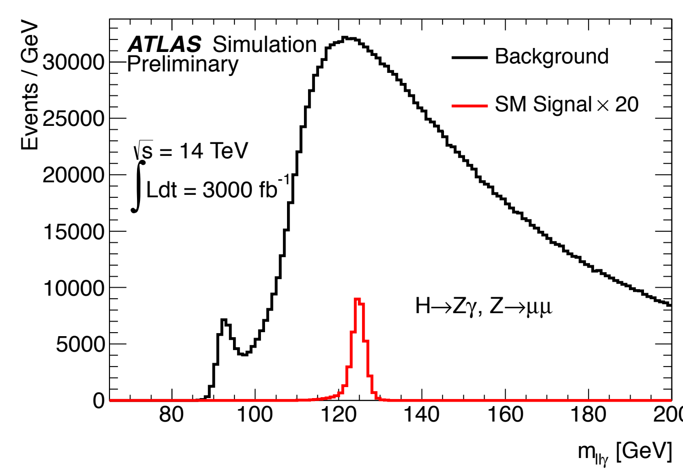
$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
Δ^{sys}_{Bkg} (model)	68	110
Δ^{sys}_{Bkg} (fit)	190	620
Δ^{stat}_{S+B}	750	2380
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%

$H \to Z\gamma$

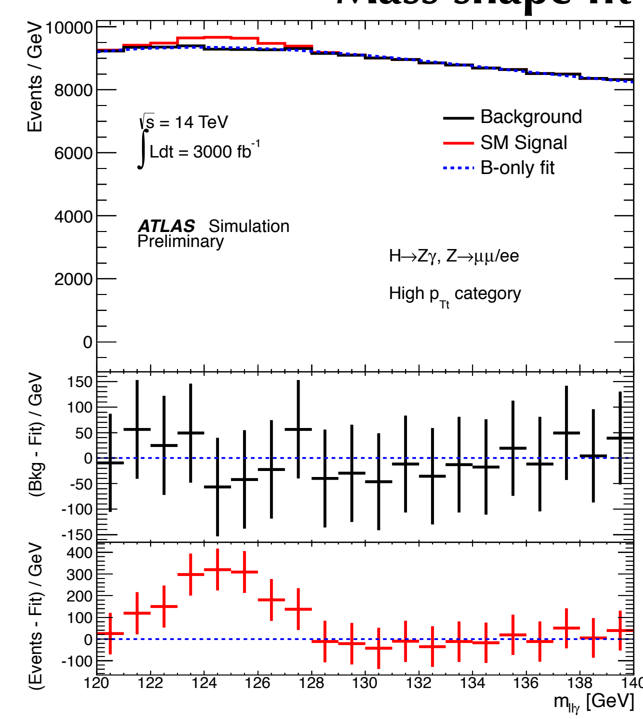
- Challenging study: high Z+γ/Z+jets background
- not-Higgs mediated background
- Measuring its rate can provide insight into BSM physics



ATL-PHYS-PUB-2014-006

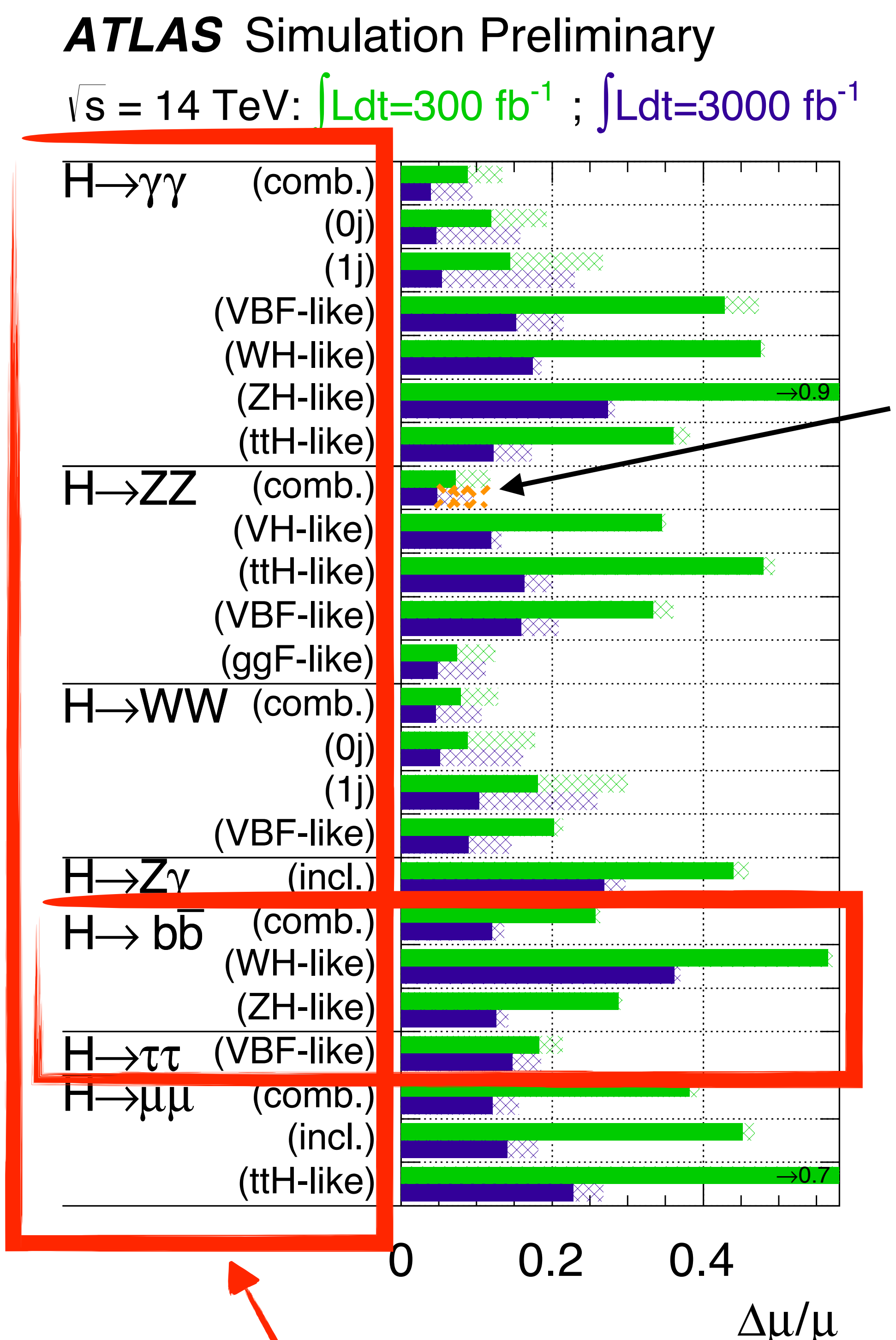


Mass shape fit



Z in ee/μμ considered, 3.9σ expected
CMS expects 20/24% uncertainty with scenario 2/1
ATLAS expects 30% uncertainty

Channels summary



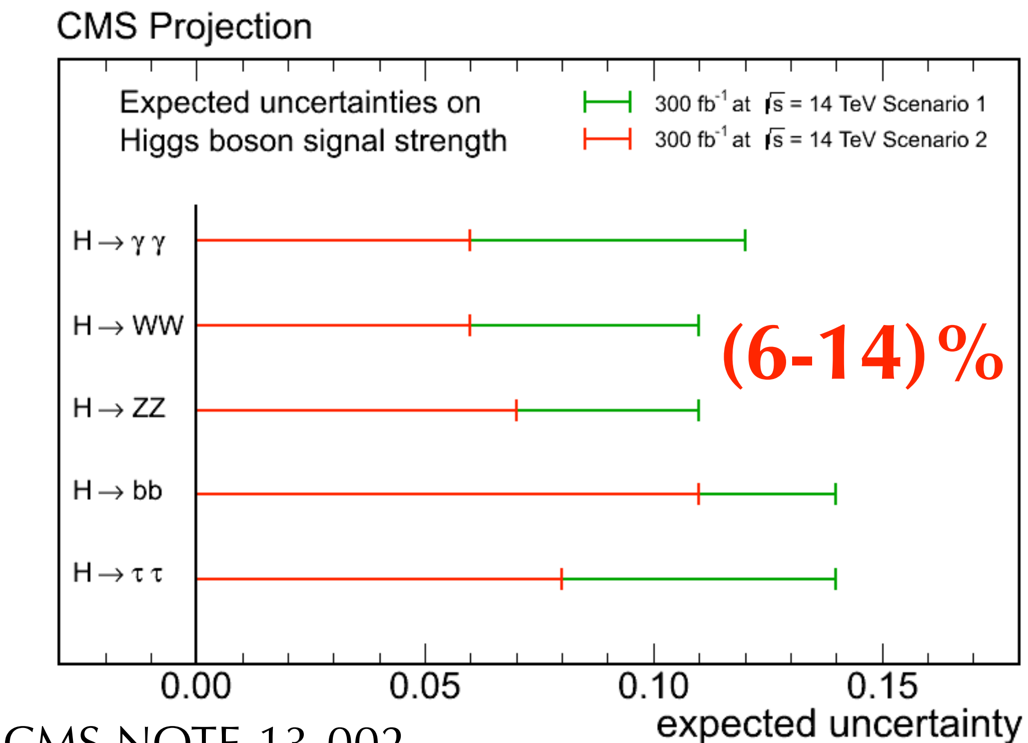
The hashed areas indicate the increase of the estimated error due to current theory systematic uncertainties (CERN-2011-002, CERN-2012-002)

New Results (ATL-PHYS-PUB-2014-016)

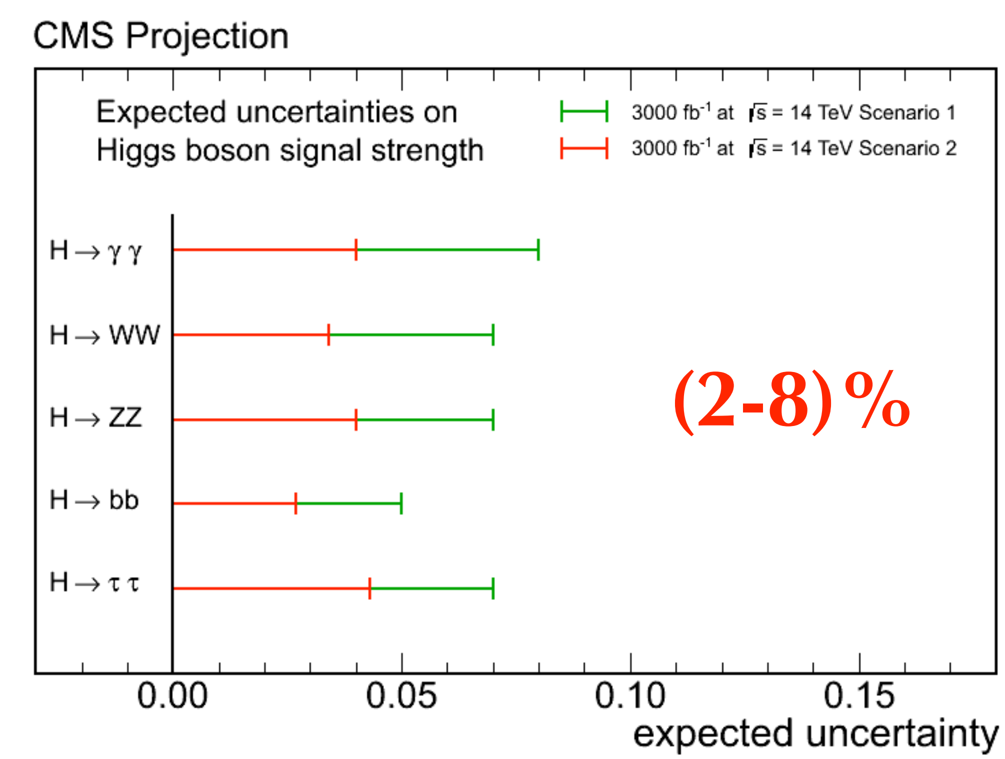
Different experimental categories considered

comb. = all combined

inclu. = only inclusive result shown



CMS NOTE-13-002



Couplings

- ✦ Use results found above to extract perspectives for the Higgs **couplings**
- ✦ Coupling fit framework:

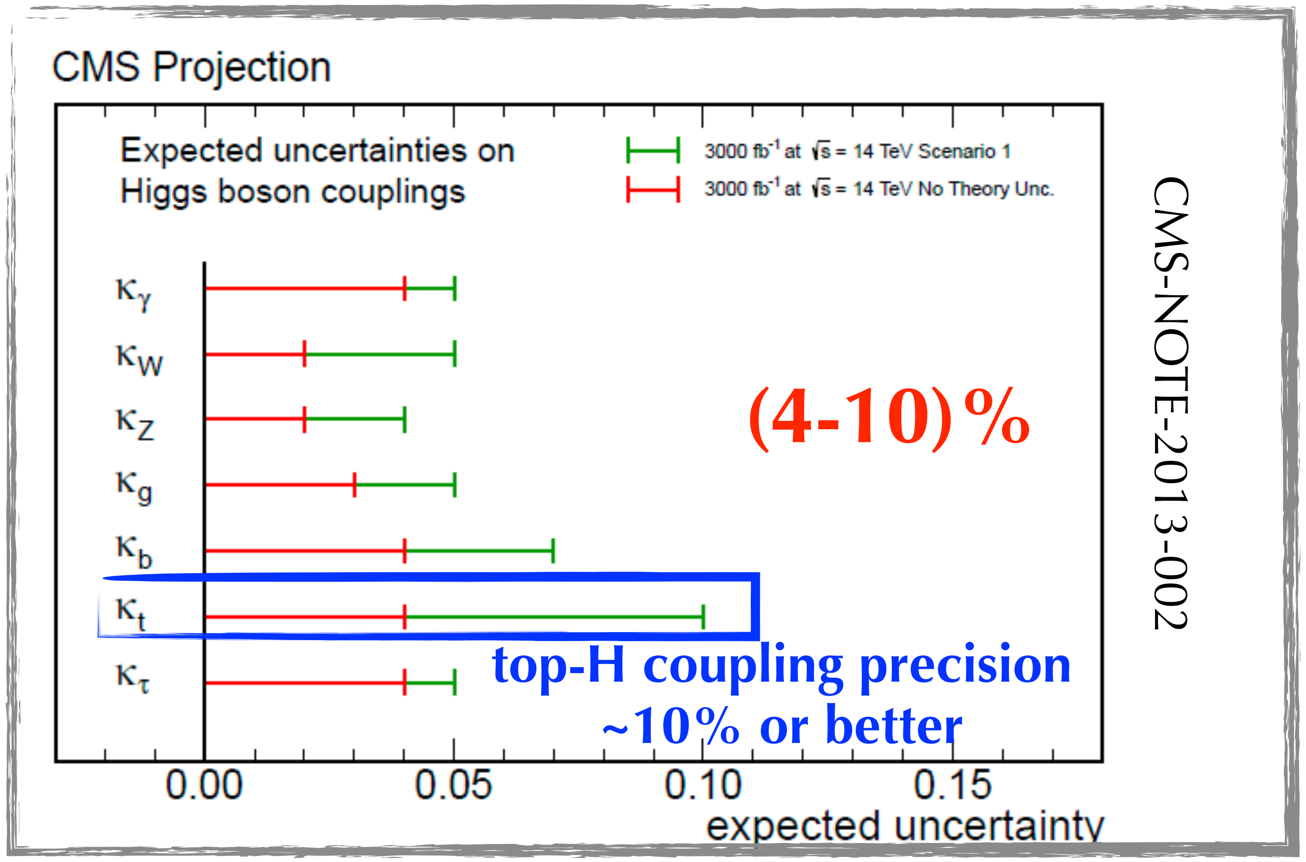
→ Zero width approximation

$$\frac{\sigma \cdot B(gg \to H \to \gamma\gamma)}{\sigma_{SM}(gg \to H) \cdot B_{SM}(H \to \gamma\gamma)} = \frac{k_g^2 \cdot k_\gamma^2}{k_H^2}$$

Coupling deviation from SM parameterized with multiplicative modifiers k

$\Rightarrow$ Γ_i, σ_i scale as k_i^2

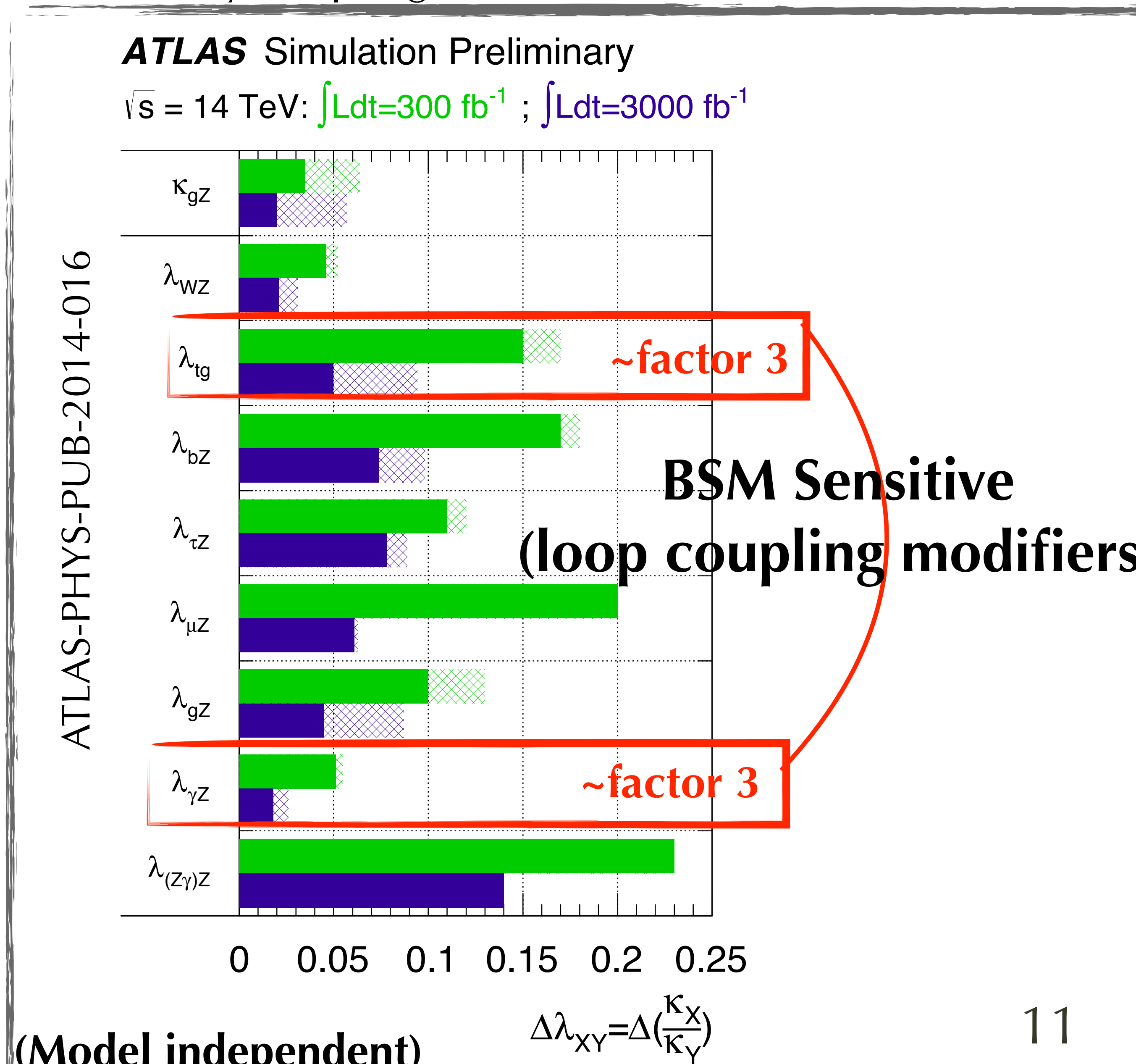
→ If no assumptions on the total width only coupling ratios $\lambda_{XY} = k_X/k_Y$



↳ • no BSM particles inside loops

$$\Gamma_H = \sum_i \Gamma_i$$

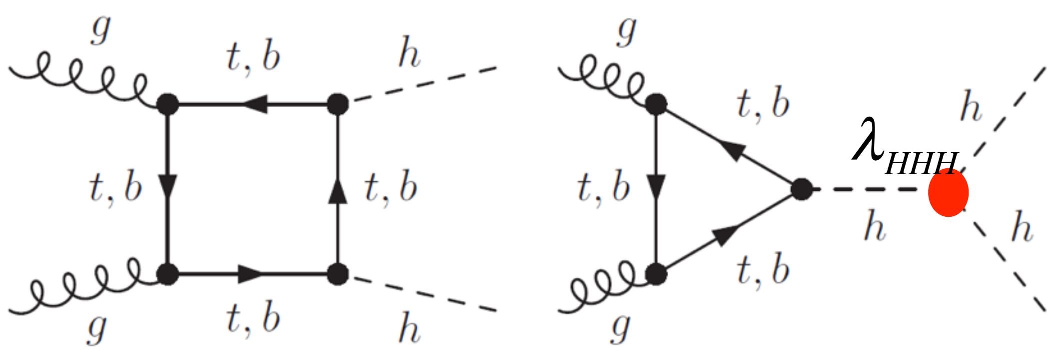
(Model dependent)



(Model independent)

Higgs pair production

- Measuring the Higgs pair production will constraint the Higgs self-coupling, allowing a partial reconstruction of the Higgs potential → any deviation from SM hint of new physics



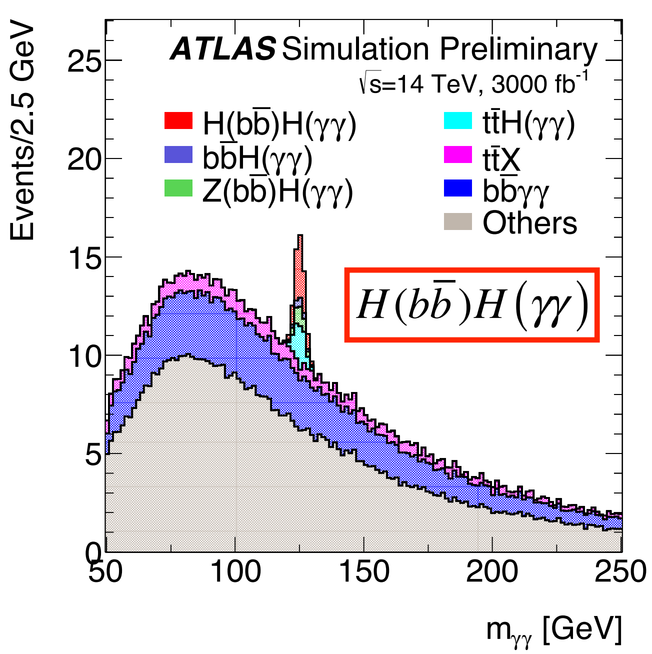
Destructive interference ⇒ SM cross section decrease

$\sigma \simeq 40.8\,fb$ (Phys. Rev. Lett. 111 (2013) 201801)

Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$bb + W^+W^-$	25%	31,000
$bb + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

ECFA2014

- Small cross section + huge background (top and fakes processes)

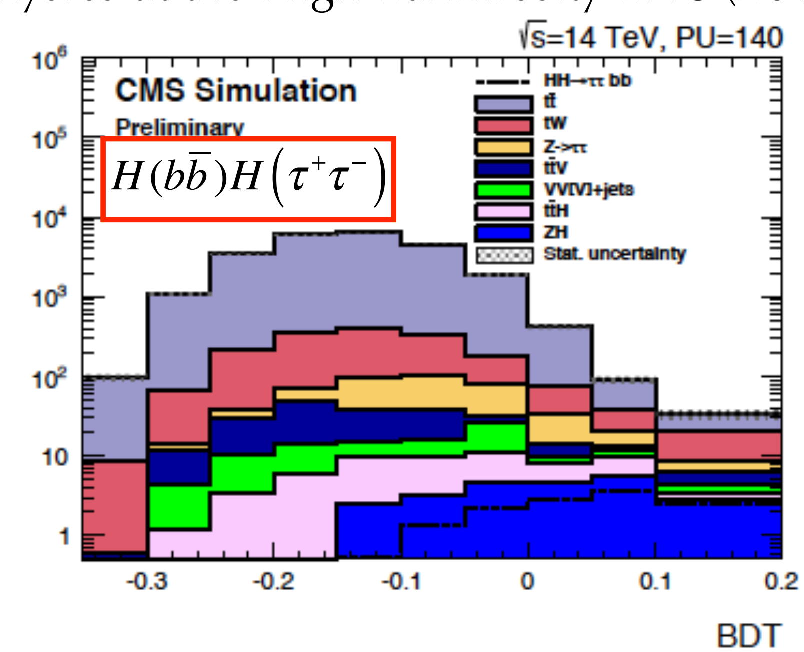


ATL-PHYS-PUB-2014-019

ATLAS expects ~ 8 events after selections corresponding to a signal significance of 1.3σ for the SM scenario

ATLAS and CMS are discussing the analyses for sensitivity improvement (e.g. use MVA techniques)

Physics at the High-Luminosity LHC (2015)



CMS expects a signal significance of 0.9σ

Remarks and Conclusions

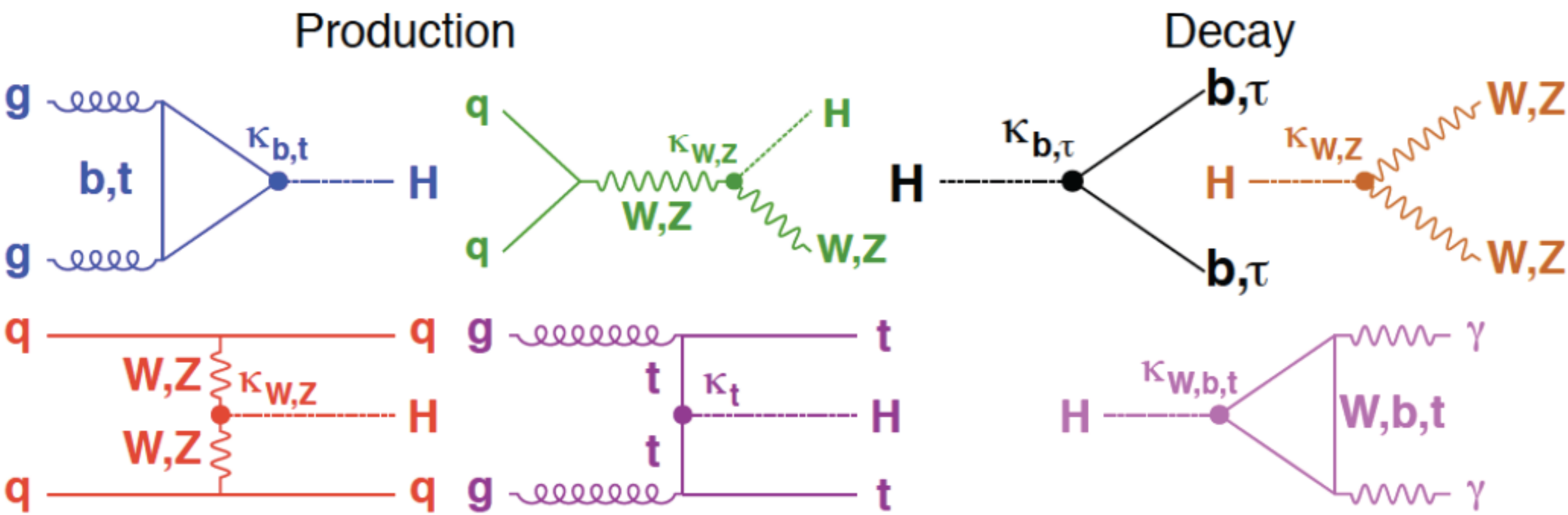
- ✦ The HL-LHC will provide a great opportunity for Higgs precision measurements:
  - ✦ ~10% of precision expected for the signal strengths
  - ✦ few % of precision expected for the Higgs couplings
- ✦ The rare $t\bar{t}H$ production cross-section should be measured with an ultimate precision of less than 10% and accordingly enable precise measurements of the top Yukawa-coupling
- ✦ New rare processes will become accessible thanks to the 3000 fb^{-1} collected, with the observation of $H \rightarrow \mu\mu$ and $H \rightarrow Z\gamma$
- ✦ The rare HH production will also be accessible at the HL-LHC

…….and a lot of work-in-progress to add more exciting perspectives to this list

The best is yet to come!

Backup

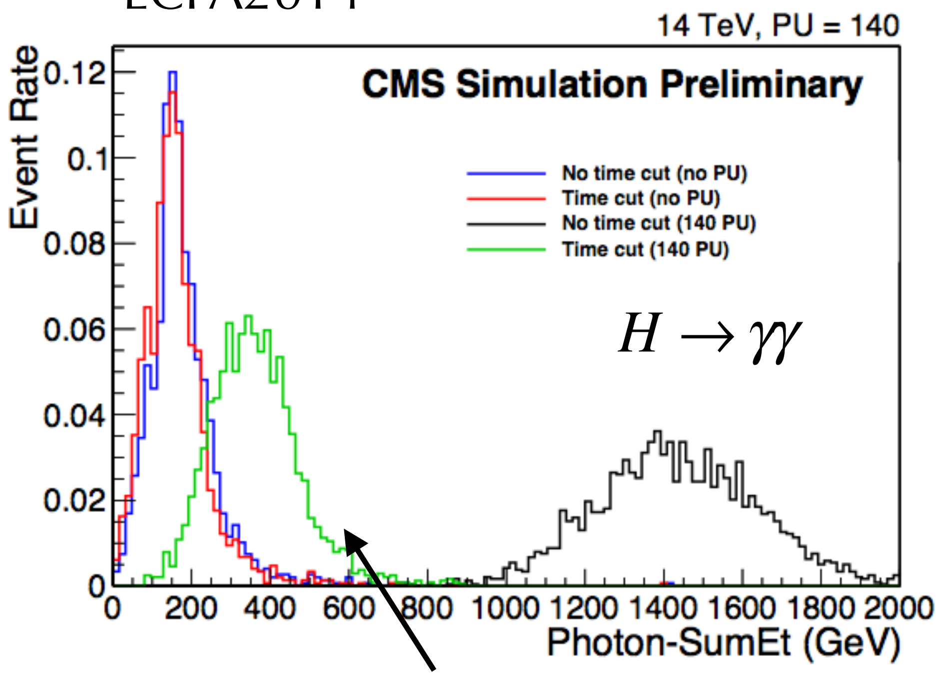
Higgs physics at HL-LHC



Performance studies

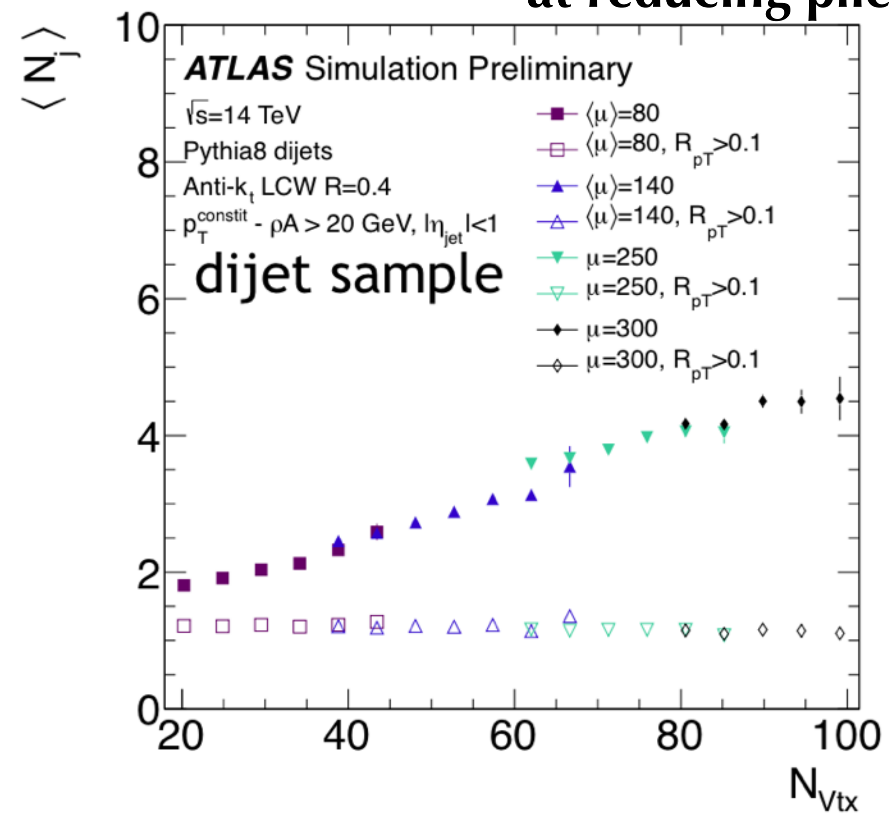
- Luminosity levelling after the start of each fill → keep luminosity constant for an extended time, by adjusting the transverse size of the beam β* along the beam trajectory
- Mitigation of pile-up effects $\mu = \frac{\sigma_{inel} L}{n_b f_r}$

ECFA2014



precision timing helps

Charged fraction effective at reducing pile-up jets



- b-tagging performances crucial for Higgs physics and BSM physics (higher mis-identification probability for fixed b-tagging probability)

- Re-visit the trigger logic: (ATLAS) L1→L0/L1 hardware design. Only the RoIs identified by L0 are transferred to the L1 for further processing ⇒ allows L0 trigger rate much higher than the actual L1 rate

Performance studies

- The true $E_T$miss is smeared in x and y using a parametrized function:

$$E_{x,y}^{miss} = E_{x,y}^{miss,true} + Gaussian(0,\sigma(\mu))$$

Resolution depending on the pile-up

- Parametrization derived from Z′->ttbar, minimum-bias and di-jet events.
- $E_T$miss resolution depending on the total ΣE_T

$$\Sigma E_T^{PU} = \Sigma E_T - \Sigma E_T^{true}$$

- $E_T$miss resolution is than calculated as a function of the ΣE_T:

1. In the low ΣE_T region the resolution is obtained from that minimum bias sample
2. In the high ΣE_T region the fit obtained from the Z′->ttbar events is used
3. In the small region between the two regimes, a linear interpolation is used

Spin-parity

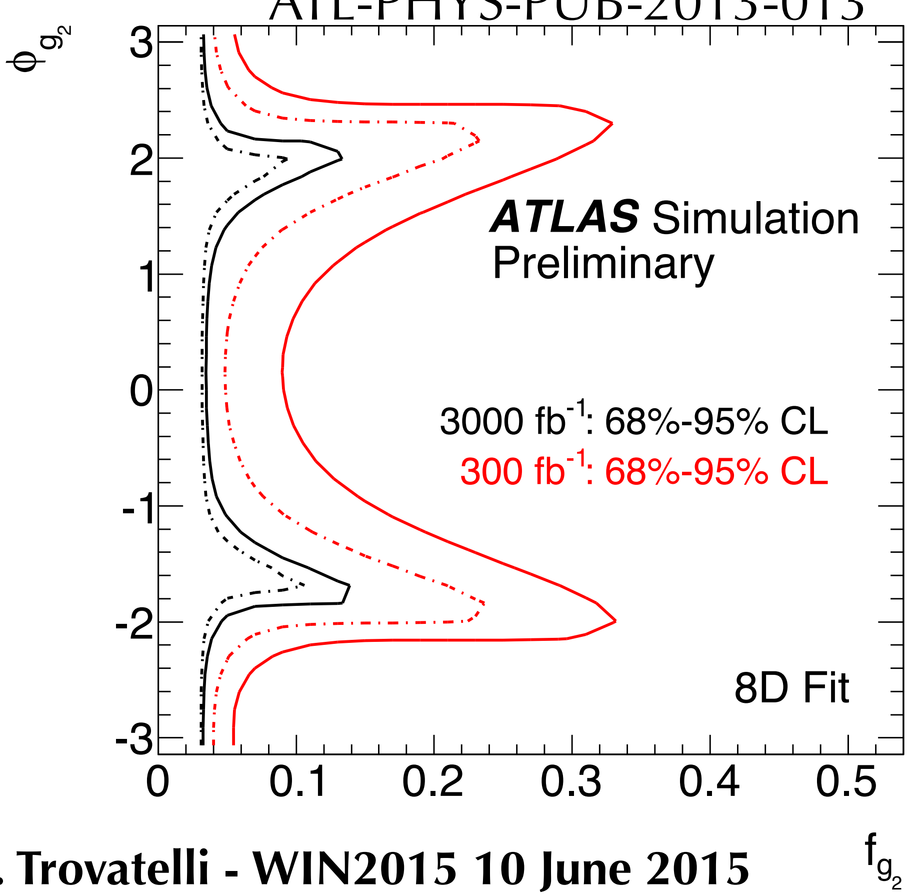
The H→ZZ process is sensitive to non SM contributions (0^+)

$$A(H \to ZZ) = v^{-1}\left(\underbrace{a_1 m_Z^2 \varepsilon_1^* \varepsilon_2^*}_{\text{SM tree process}} + \underbrace{a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}}_{\text{loop CP-even contributions}} + \underbrace{a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}_{\text{CP-odd contributions (BSM)}}\right)$$

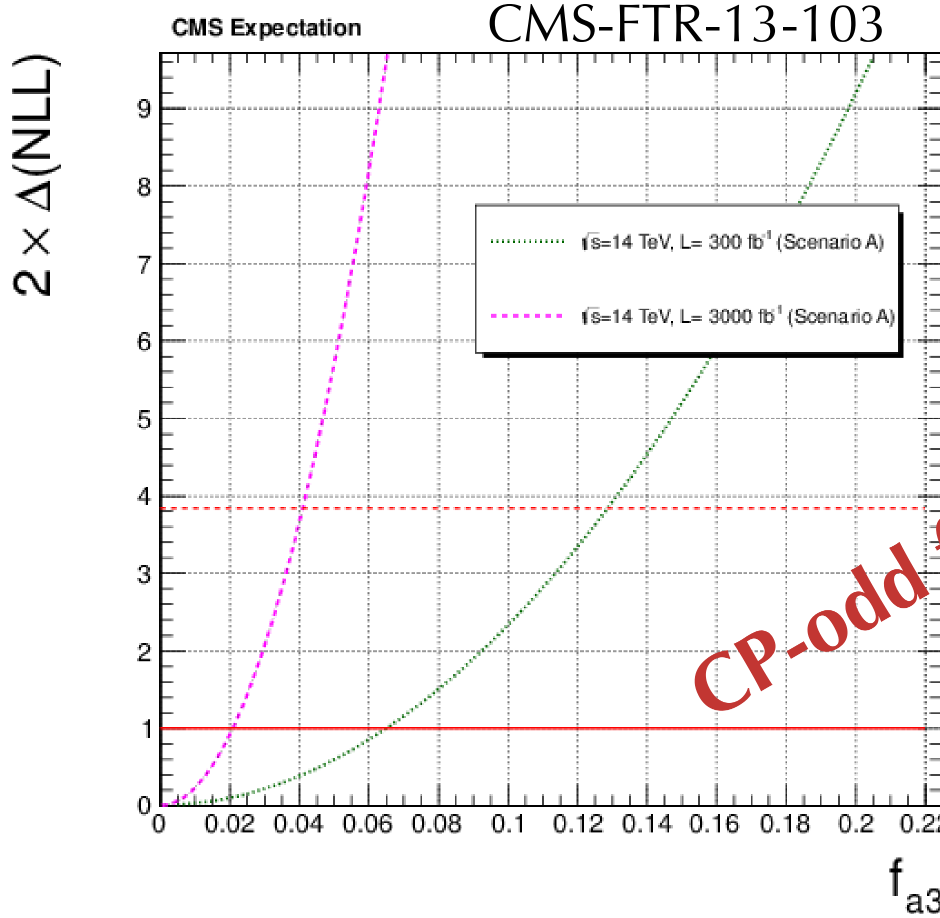
CP violation in the Higgs sector if a_3 and a_1 or $a_2 \neq 0$

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

ATL-PHYS-PUB-2013-013



CMS-FTR-13-103



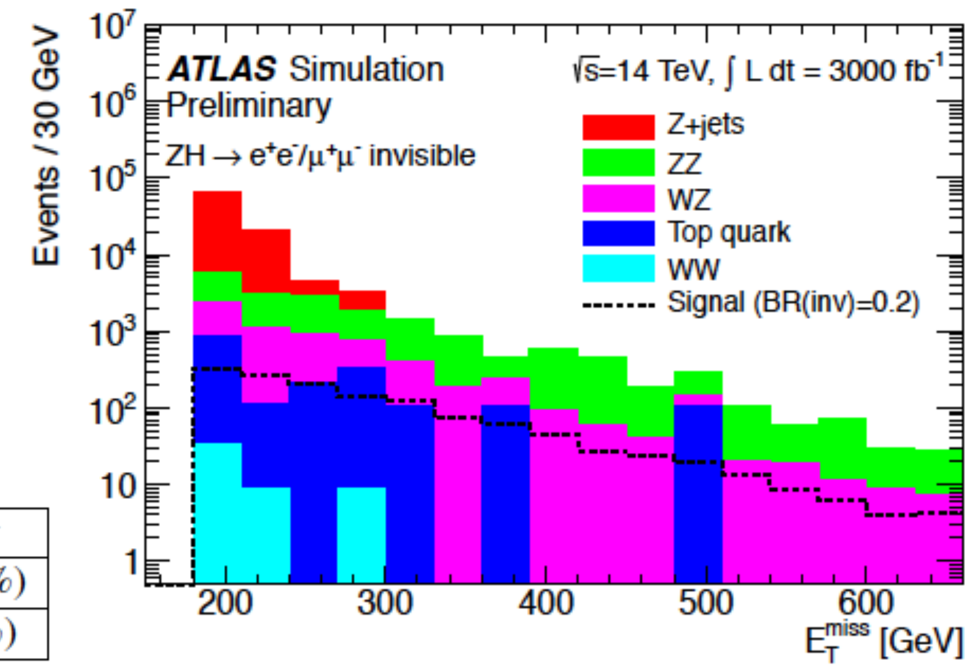
CP-odd fraction

ZH→invisible

- ZH→ℓℓ +invisible offers the possibility to search for the invisible branching ratio of the Higgs boson
- signature: 2 p_T > 20 GeV leptons + MET > 180 GeV (MET cut is relaxed w.r.t. Run I analysis due to the degradation of MET performance in the high pile-up conditions

ATL-PHYS-PUB-2013-014

Expected yields	300 fb^{-1}	3000 fb^{-1}
ZZ	1321 ± 53	12000 ± 500
WZ	440 ± 2	4501 ± 22
WW	0.9 ± 0.9	52 ± 21
Top	127 ± 37	1810 ± 440
Z+jets	172 ± 87	82000 ± 6100
Signal (125 GeV, BR($H \to$ inv.)=20%)	154 ± 2	1379 ± 21



ATL-PHYS-PUB-2013-014

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%)

~5% exp. uncertainty
~5% theo. uncertainty

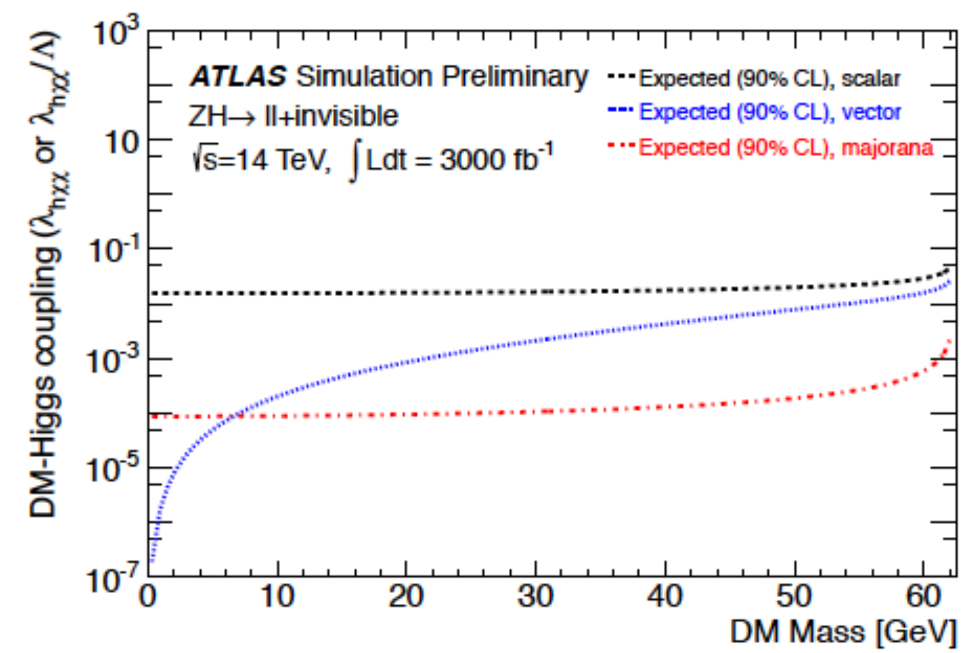
~2-3% uncertainty

CMS expects to constrain the BR(inv) to better than 11%
current upper limit is 58% (CMS-HIG-13-030)

- Limits on BR can be interpreted in the context of Dark Matter particles coupling to Higgs, with a coupling constant λ_{hXX}

Study dependent on the spin of the Dark Matter particle

Limit on the Higgs-Dark matter coupling



ATL-PHYS-PUB-2013-014

Couplings

Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
1	κ	4.2%	3.0%	2.4%	3.2%	2.2%	1.7%
2	$\kappa_V = \kappa_Z = \kappa_W$	4.3%	3.0%	2.5%	3.3%	2.2%	1.7%
	$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$	8.8%	7.5%	7.1%	5.1%	3.8%	3.2%
3	κ_Z	4.7%	3.7%	3.3%	3.3%	2.3%	1.9%
	κ_W	4.9%	3.6%	3.1%	3.6%	2.4%	1.8%
	κ_F	9.3%	7.9%	7.3%	5.4%	4.0%	3.4%
4	κ_V	5.9%	5.4%	5.3%	3.7%	3.2%	3.0%
	κ_u	8.9%	7.7%	7.2%	5.4%	4.0%	3.4%
	κ_d	12%	12%	12%	6.7%	6.2%	6.1%
5	κ_V	4.3%	3.1%	2.5%	3.3%	2.2%	1.7%
	κ_q	11%	8.7%	7.8%	6.6%	4.5%	3.6%
	κ_l	10%	9.6%	9.3%	6.0%	5.3%	5.1%
6	κ_V	4.3%	3.1%	2.5%	3.3%	2.2%	1.7%
	κ_q	11%	9.0%	8.1%	6.7%	4.7%	3.8%
	κ_τ	12%	11%	11%	9.2%	8.4%	8.1%
	κ_μ	20%	20%	19%	6.9%	6.3%	6.1%
7	κ_Z	8.1%	7.9%	7.8%	4.3%	3.9%	3.8%
	κ_W	8.5%	8.2%	8.1%	4.8%	4.1%	3.9%
	κ_t	14%	12%	11%	8.2%	6.1%	5.3%
	κ_b	23%	22%	22%	12%	11%	10%
	κ_τ	14%	13%	13%	9.8%	9.0%	8.7%
	κ_μ	21%	21%	21%	7.3%	7.1%	7.0%
8	κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
	κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
	κ_t	22%	21%	20%	11%	8.5%	7.6%
	κ_b	23%	22%	22%	12%	11%	10%
	κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
	κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
	κ_g	14%	12%	11%	9.1%	6.5%	5.3%
	κ_γ	9.3%	9.0%	8.9%	4.9%	4.3%	4.1%
	$\kappa_{Z\gamma}$	24%	24%	24%	14%	14%	14%

ATL-PHYS-PUB-2014-016

Nr.	Parameter	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
9	κ_g	8.9%	7.1%	6.3%	6.7%	4.1%	2.8%
	κ_γ	4.9%	4.8%	4.7%	2.1%	1.8%	1.7%
	$\kappa_{Z\gamma}$	23%	23%	23%	14%	14%	14%
	$BR_{i,u}$	<22%	<20%	<20%	<14%	<11%	<10%

Minimal model

Theo. systematics give a sizeable contribution to the total uncert. ATLAS estimates how much each source of theory uncertainty would have to be reduced to be small compared to the experimental uncertainties.

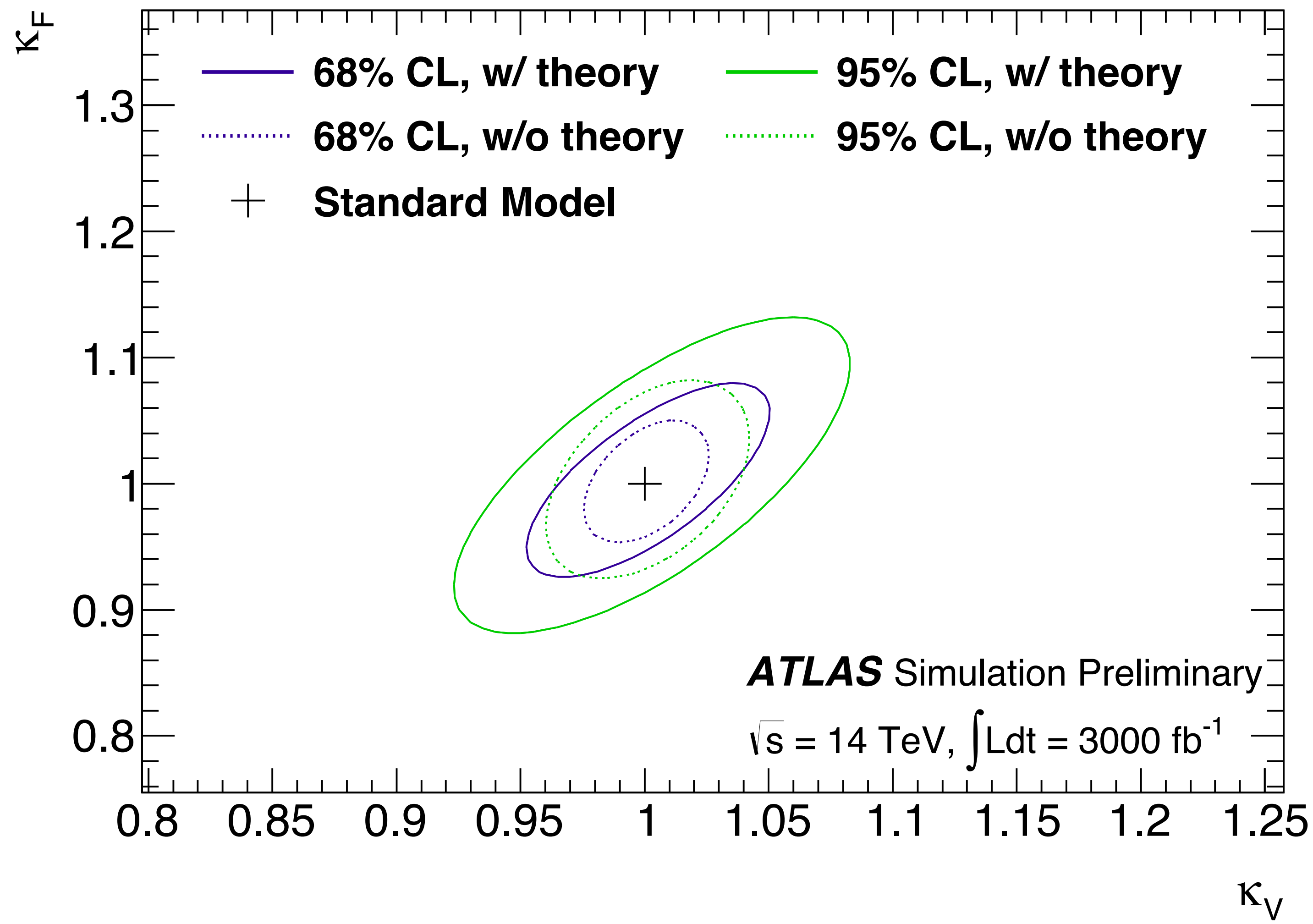
Scenario / Theory uncertainty (%)	Status 2014 [10–12]	Deduced size of uncertainty to increase total uncertainty by $\lesssim$10% for 300 fb^{-1}: κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	by $\lesssim$10% for 3000 fb^{-1}: κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	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

uncertainties on gg→H signal are the most limiting for couplings measurements

Couplings

Minimal model

- It is sensitive to deviations from the SM between the Higgs boson Gauge- and Yukawa-coupling sector
- $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$ loops only depends on k_F and K_V, no contributions from BSM



Couplings ratios

In ratio of coupling many experimental systematics cancel

The benchmark model doesn't make any assumption on the Higgs Total width

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

Nr.	Coupling ratio	300 fb^{-1} Theory unc.:			3000 fb^{-1} Theory unc.:		
		All	Half	None	All	Half	None
10	κ_{VV}	7.3%	6.7%	6.5%	4.0%	3.2%	2.9%
	λ_{FV}	7.8%	7.4%	7.2%	3.6%	3.1%	2.9%
11	κ_{ZZ}	9.8%	9.1%	8.9%	5.1%	4.3%	3.9%
	λ_{WZ}	4.3%	4.0%	3.9%	2.3%	1.8%	1.6%
	λ_{FZ}	9.2%	8.5%	8.3%	4.4%	3.7%	3.5%
12	κ_{uu}	14%	11%	9.7%	8.7%	5.7%	4.2%
	λ_{Vu}	9.4%	8.3%	7.9%	5.1%	3.8%	3.2%
	λ_{du}	9.7%	8.2%	7.7%	6.0%	4.6%	4.0%
13	κ_{qq}	14%	11%	9.9%	8.1%	5.6%	4.5%
	λ_{Vq}	9.6%	8.5%	8.1%	5.2%	3.9%	3.4%
	λ_{lq}	12%	10%	9.4%	7.3%	6.0%	5.4%
14	$\kappa_{\tau\tau}$	21%	19%	19%	17%	15%	15%
	$\lambda_{V\tau}$	11%	11%	11%	8.5%	7.8%	7.6%
	$\lambda_{q\tau}$	12%	10%	9.8%	9.3%	7.9%	7.4%
	$\lambda_{\mu\tau}$	22%	22%	22%	11%	9.8%	9.6%
15	κ_{gZ}	6.4%	4.4%	3.5%	5.7%	3.3%	2.0%
	λ_{WZ}	5.2%	4.8%	4.6%	3.1%	2.4%	2.1%
	λ_{tg}	17%	16%	15%	9.4%	6.4%	5.0%
	λ_{bZ}	18%	17%	17%	9.8%	8.1%	7.4%
	$\lambda_{\tau Z}$	12%	12%	11%	8.9%	8.1%	7.8%
	$\lambda_{\mu Z}$	20%	20%	20%	6.3%	6.2%	6.1%
	λ_{gZ}	13%	11%	10%	8.7%	5.8%	4.5%
	$\lambda_{\gamma Z}$	5.5%	5.2%	5.1%	2.6%	2.0%	1.8%
	$\lambda_{(Z\gamma)Z}$	23%	23%	23%	14%	14%	14%
16	$\kappa_{\gamma\gamma}$	14%	13%	12%	6.8%	5.5%	5.0%
	$\lambda_{Z\gamma}$	5.5%	5.2%	5.1%	2.5%	2.0%	1.8%
	$\lambda_{W\gamma}$	5.9%	5.7%	5.6%	2.7%	2.4%	2.2%
	$\lambda_{t\gamma}$	21%	20%	20%	10%	8.0%	7.0%
	$\lambda_{b\gamma}$	18%	17%	17%	9.5%	8.0%	7.4%
	$\lambda_{\tau\gamma}$	13%	12%	12%	8.7%	8.1%	7.9%
	$\lambda_{\mu\gamma}$	20%	20%	20%	6.5%	6.2%	6.1%
	$\lambda_{g\gamma}$	13%	12%	11%	8.5%	5.9%	4.6%
	$\lambda_{(Z\gamma)\gamma}$	23%	23%	23%	14%	14%	14%

ATL-PHYS-PUB-2014-016

Mass dependence

Mass-scaled couplings defined to determine the mass dependence of the Higgs boson couplings

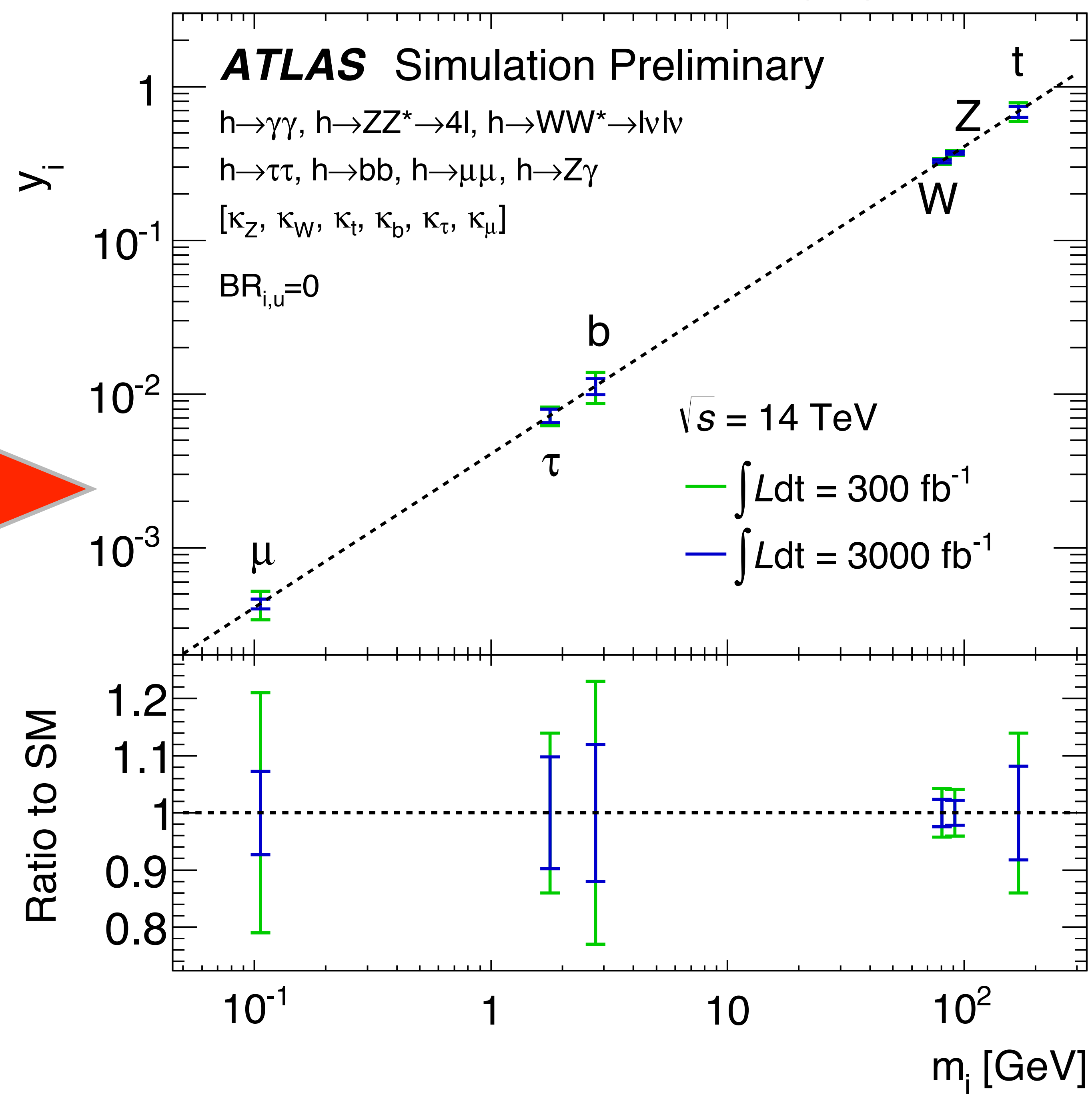
$$Y_f = \kappa_f \frac{m_f}{v}$$

$$Y_V = \kappa_V \frac{m_V}{v}$$

with
f = μ,τ,t
V = W,Z

couplings are proportional to the mass of the particle

ATL-PHYS-PUB-2014-016



Uncertainties on couplings

Two scenarios for theoretical uncertainties
1) No uncertainties at all
2) Estimate the maximum theory uncertainty compatible with <10% increase of total uncertainty

ATL-PHYS-PUB-2013-014

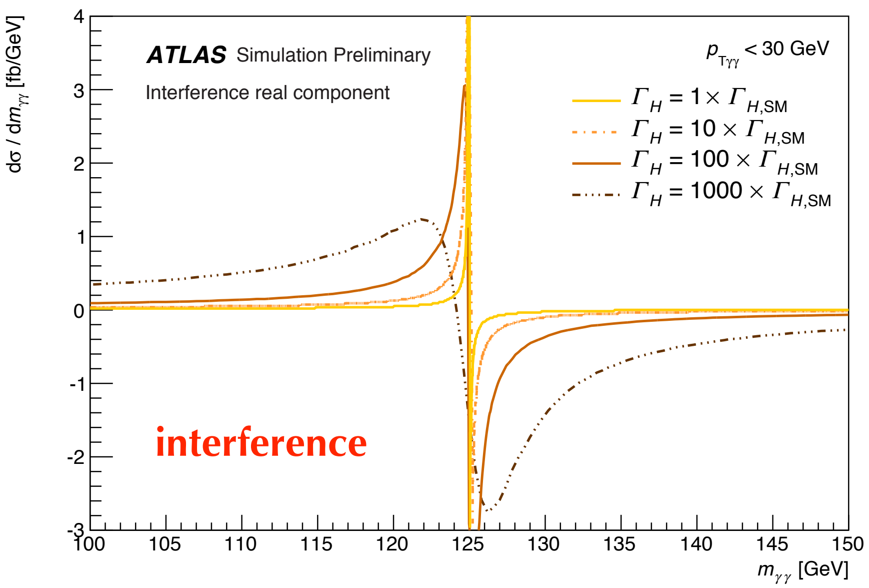
Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty by $\lesssim$10% for 300 fb^{-1}			by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF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

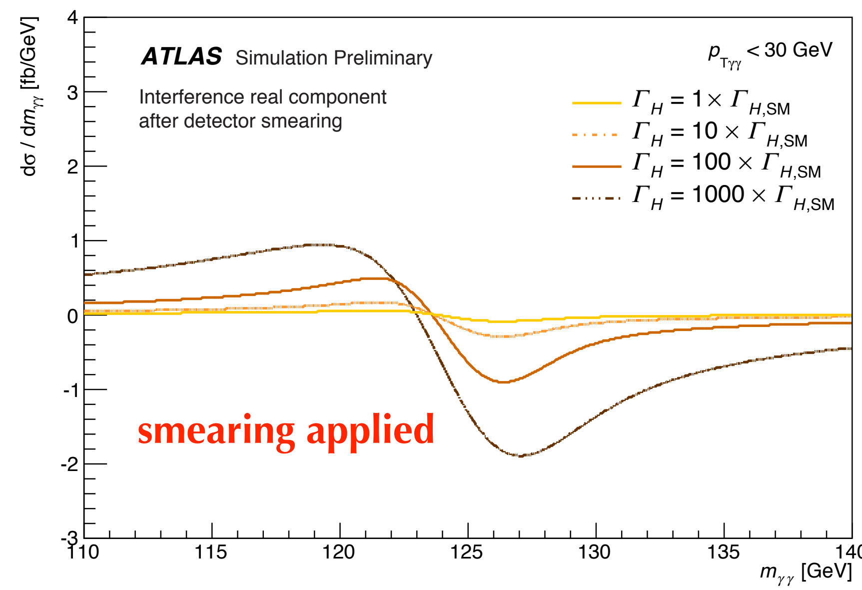
Table 6: Estimation of the deduced size of theory uncertainties, in percent (%), for different Higgs coupling measurements in the generic Model 15 from Table 5, requiring that each source of theory systematic uncertainty affects the measurement by less than 30% of the total experimental uncertainty and hence increase the total uncertainty by less than 10%. A dash "-" indicates that the theory uncertainty from existing calculations [10–12] is already sufficiently small to fulfill the condition above for some measurements. The same applies to theory uncertainties not mentioned in the table for any measurement. The impact of the jet-bin and p_T related uncertainties in $gg \to H$ depends on analysis selections and hence no single number can be quoted. Therefore the range of uncertainty values used in the different analysis is shown.

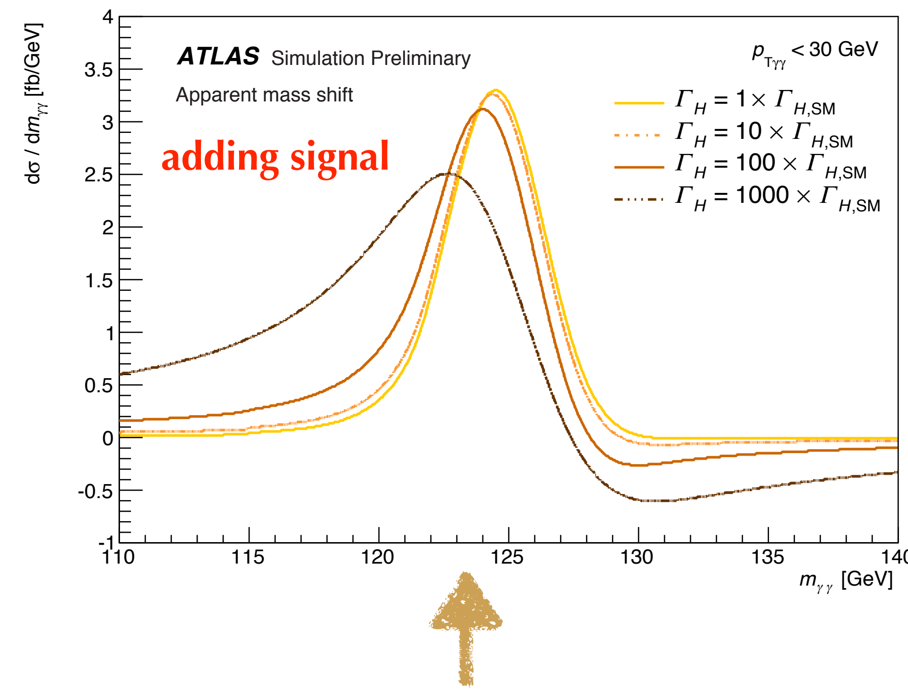
Total width

- Higgs natural width ~ 4.2 MeV << than detector resolution
- Upper limits on Γ_H through interference between $H \rightarrow \gamma\gamma$ and the continuum $gg \rightarrow \gamma\gamma$ background (Phys. Rev. Lett. 111, 111802)

ATL-PHYS-PUB-2013-014



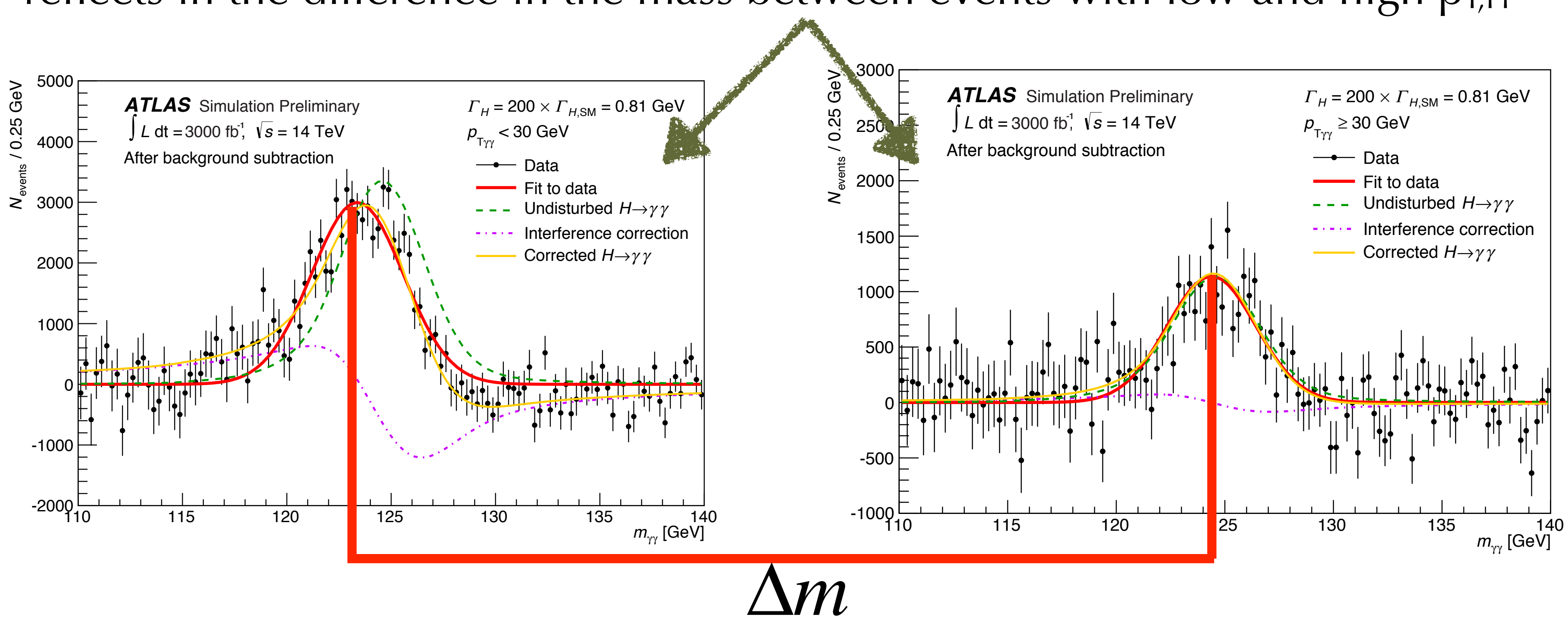




mass shift ~50MeV for the SM

The size of the shift decreases at high $p_{T,H}$

⇒ reflects in the difference in the mass between events with low and high $p_{T,H}$

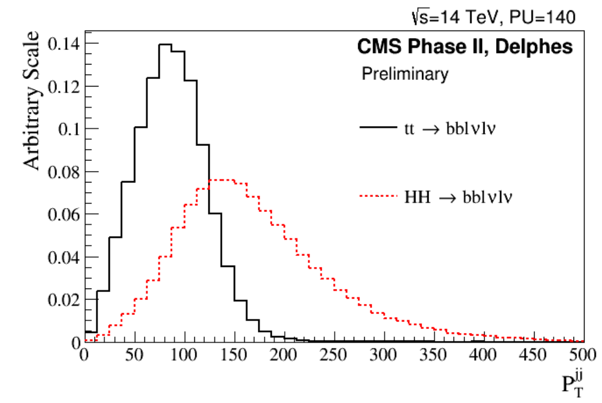


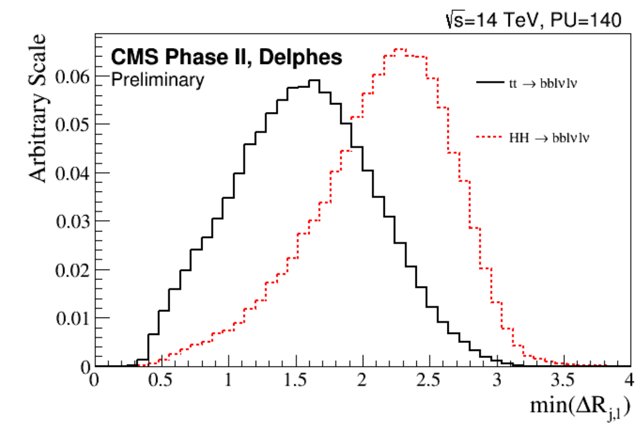
ATLAS expects $40 \cdot \Gamma_{SM}$ limit on Γ_H

Higgs pair production

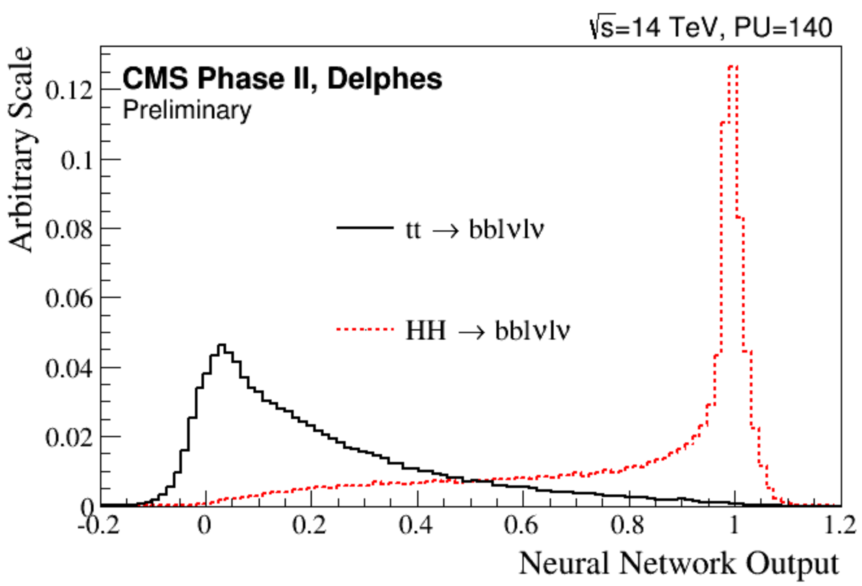
$$HH \rightarrow b\bar{b}WW \rightarrow b\bar{b}\ell\nu\ell\nu$$

ECFA2014

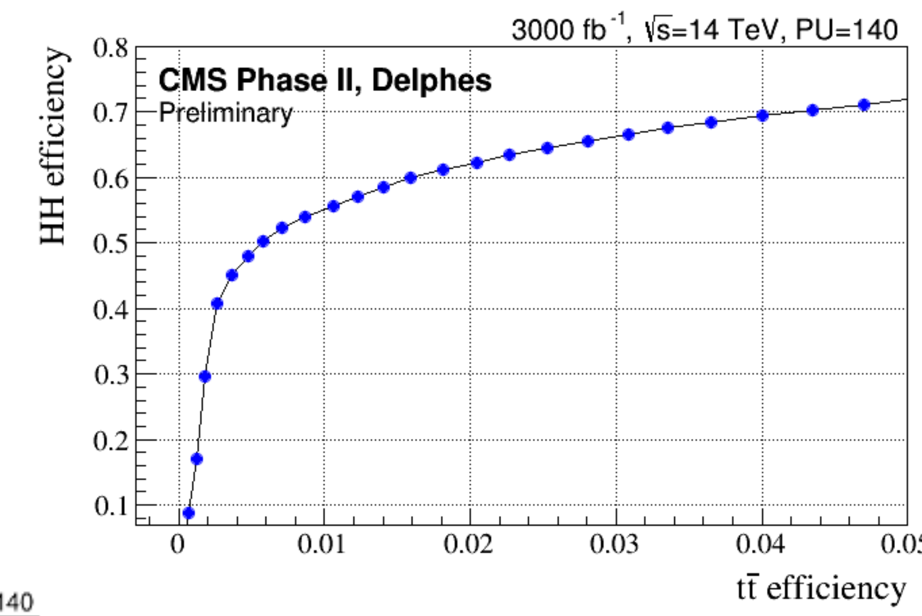




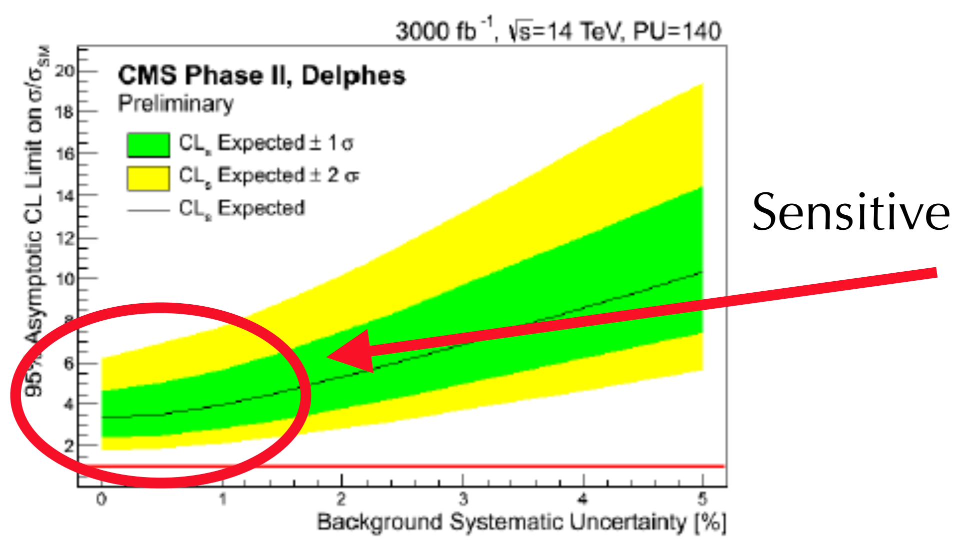
- ~30000 events expected
- Based on Delphes fast simulation tuned to CMS Phase II detector
- Only main ttbar background considered
- Neural Network discriminant from kinematic variables



NN > 0.97 leads to a 40% signal efficiency while rejecting 99.73% of the background



Cross section upper limit as a function of the background systematic uncertainties

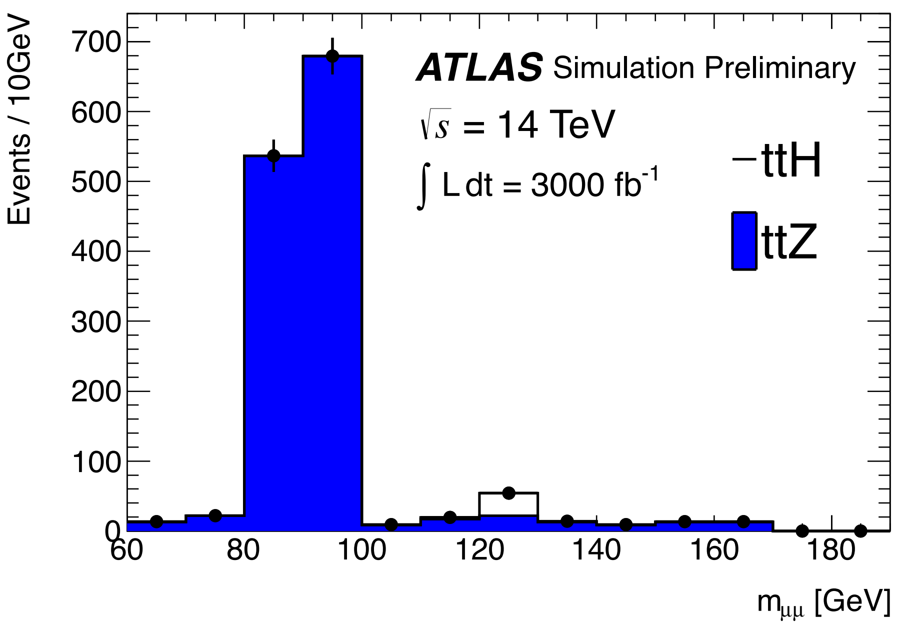


Sensitive to large deviations w.r.t. SM

$t\bar{t}H, H \to \mu\mu$

- Direct access to the product of the top- and the μ-Yukawa coupling
- Determination of the CP nature of the resonance at 125 GeV. The CP odd could be suppressed with a vector boson coupling in the initial or final state, but in this channel only fermion Yukawa couplings involved.
- Signal sample with CP even and CP odd are generated.

ATL-PHYS-PUB-2013-014



~33 signal events
~22 background events

Observation possible at HL-LHC