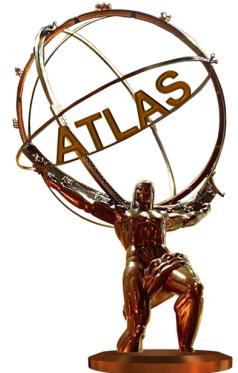




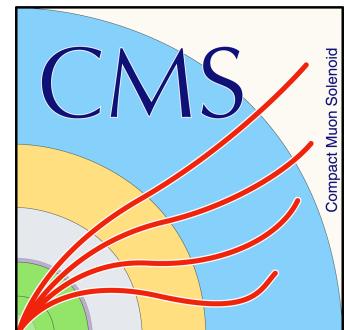
Higgs Coupling Prospects at the LHC with ATLAS & CMS

Eric Feng (Argonne)

on behalf of the ATLAS & CMS Collaborations

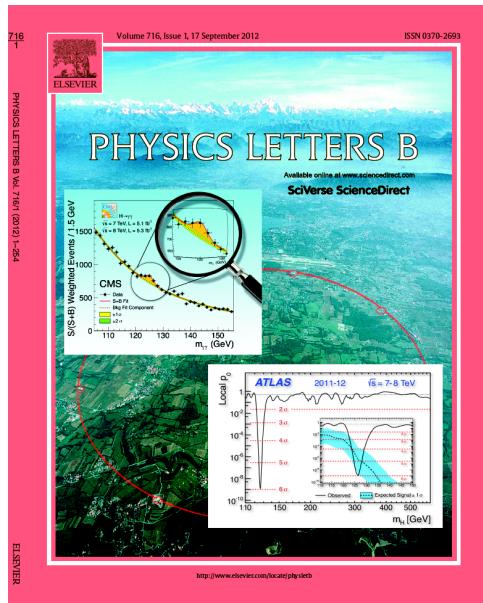


BSM Higgs Workshop
Fermilab
Nov 3, 2014



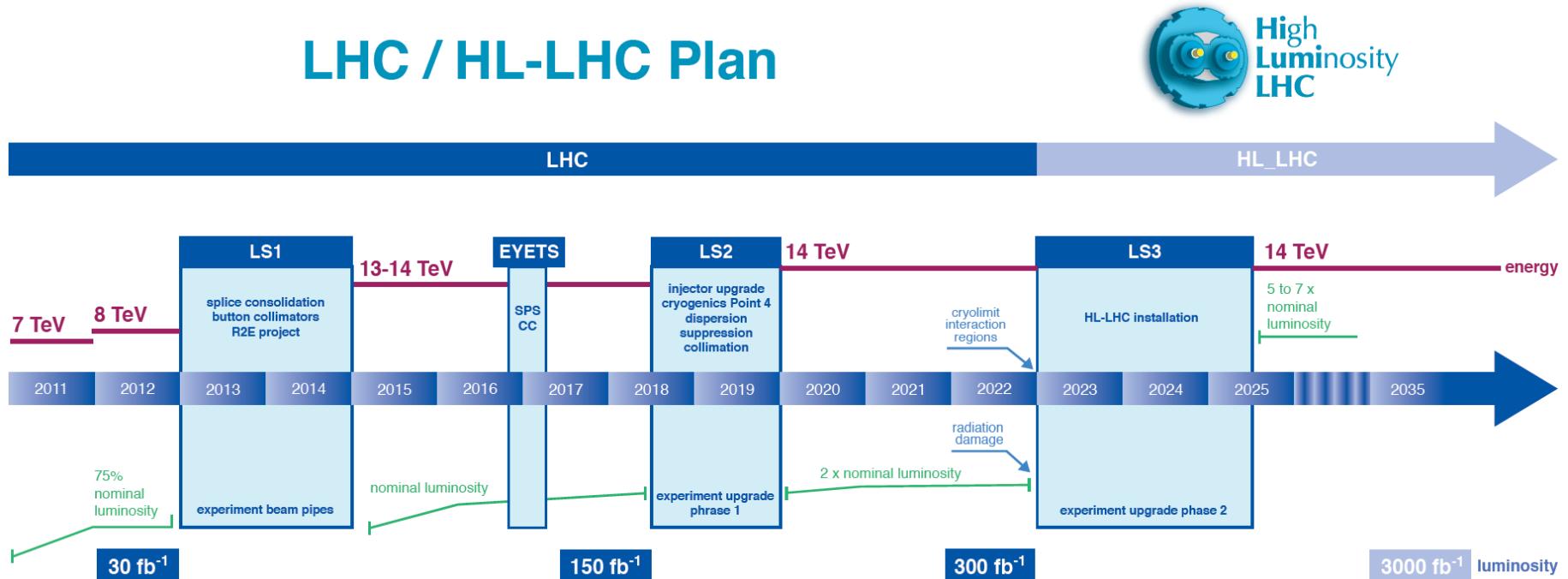
Introduction

- July 2012: Discovery of new Higgs-like boson with $m_h \sim 125$ GeV by ATLAS and CMS experiments
- Wonderful new era in particle physics
 - Precision tests of the SM Higgs boson: mass scaling of couplings, etc.
 - Indirectly probe new physics: composite Higgs, SUSY, dark matter, etc.
- Project coupling precision at 14 TeV assuming $m_h = 125.0$ GeV
 - Same κ framework as described earlier by N. Wardle & K. Schmieden



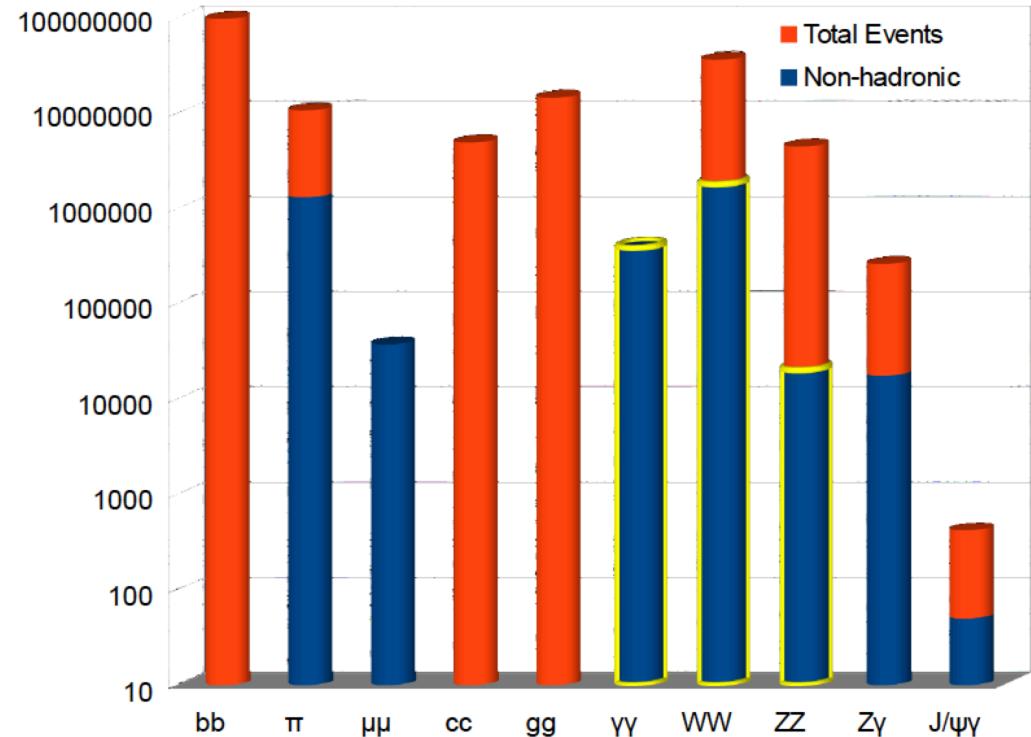
LHC schedule

- Current LHC / HL-LHC schedule
- **300 fb⁻¹ by 2022 will give 20 times current Higgs boson production**
 - However Phase 1 upgrade required to trigger on them
- After LS2 (LS3): ~50 (140 lumi-leveled) pp interactions/bunch crossing
 - Phase 1 (2) upgrades required for radiation hardness and pileup



HL-LHC as a Higgs factory

Process at 14 TeV	Higgs bosons with 3000 fb^{-1}
All prod. & decay modes	170M
VBF (all decays)	13M
tth (all decays)	1.8M
$h \rightarrow Z\gamma$	230k
$h \rightarrow \mu\mu$	37k
hh	121k



- Rate per experiment

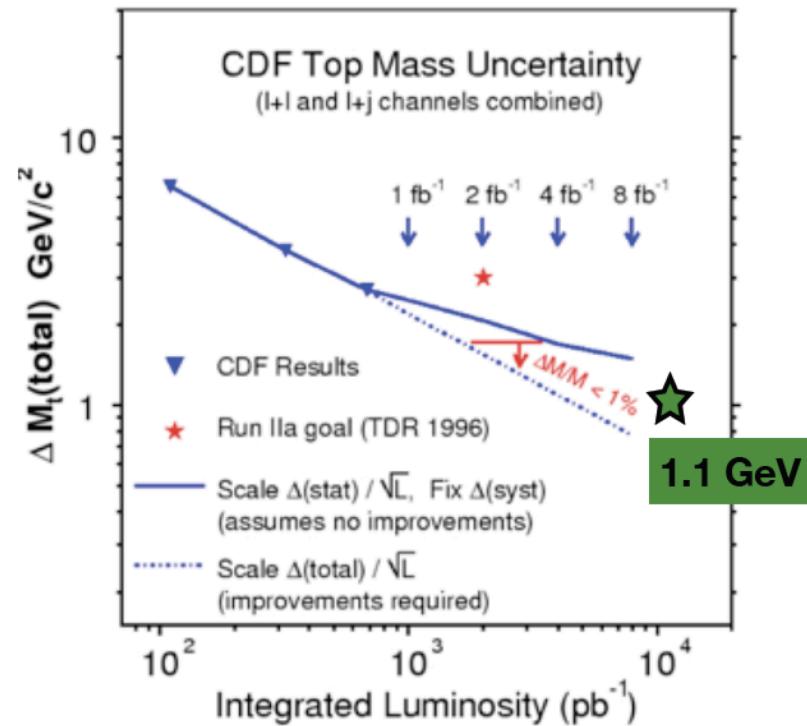
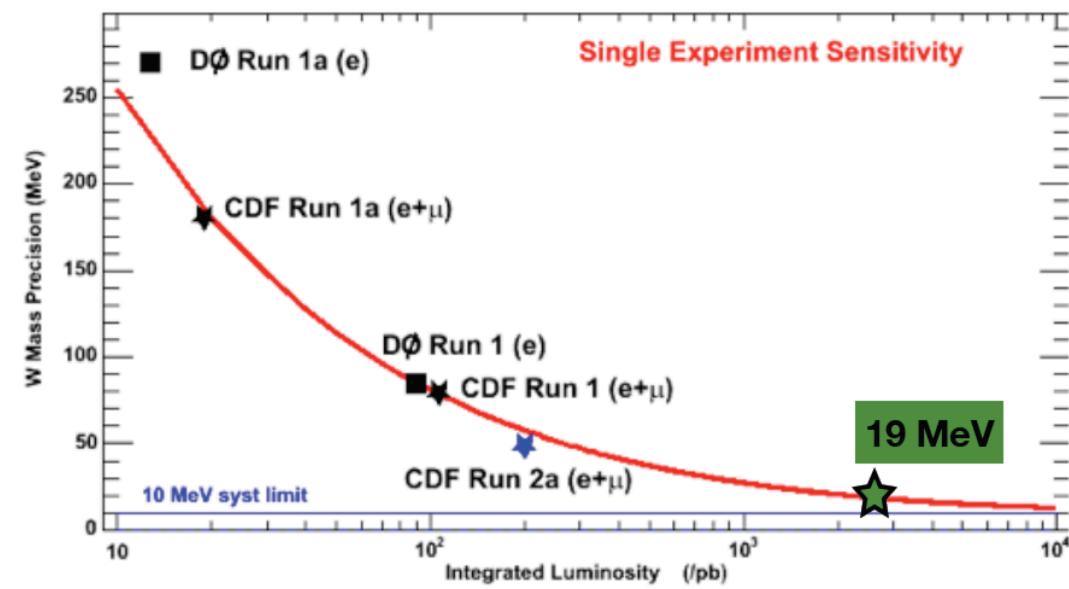
Detector performance assumptions

- Complementary approaches based on different performance assumptions
- ATLAS:
 - Efficiency and resolution functions applied to physics objects
 - Based on full simulation of IBL and LAr trigger upgrades (300 fb^{-1}); full ITK, pileup in calorimeter (3000 fb^{-1})
 - Concrete demonstration of performance with current knowledge
 - Two scenarios for theoretical uncertainties
 - Scenario 1: Same as now
 - Scenario 2: None i.e. negligible
- CMS:
 - Scale signal and background yields of current analyses
 - Assume detector upgrades maintain at least Run 1 performance
 - Augmented by full-simulation studies
 - Characterization of potential performance with future knowledge
 - Two scenarios for systematic uncertainties
 - Scenario 1: All systematic uncertainties same as now
 - Scenario 2: Scale theory unc. by $\frac{1}{2}$, experimental syst. by $1/\sqrt{L}$

Projections of performance

- W and top mass measurements at Tevatron show experimentalists (and theorists) improve systematics significantly over time
 - Experiment: More data allows more sophisticated in-situ calibrations and data-driven background estimates
 - Theory: Higher order predictions, tune to measurements, etc
- Ceiling on performance is uncertainties $\propto 1/\sqrt{L}$

M. Klute



Many new results

- Many updated/new results shown at ECFA HL-LHC workshop 2 weeks ago
- ATLAS
 - 5 main channels ($\gamma\gamma$, ZZ, WW, bb, $\tau\tau$)
 - New VH(bb): ATL-PHYS-PUB-2014-011
 - Improved ttH/VH($\gamma\gamma$): ATL-PHYS-PUB-2014-012
 - Also H- $\rightarrow\mu\mu$ and H- $\rightarrow Z\gamma$
 - Improved H- $\rightarrow Z\gamma$: ATL-PHYS-PUB-2014-006
 - Updated combination: ATL-PHYS-PUB-2014-016
- CMS:
 - Same input channels as above
 - Mature results already last year with rescaling procedure:
arXiv:1307.7135 (CMS-NOTE-13-002)
 - Also new results for di-Higgs production HH (bb $\gamma\gamma$, bbWW):
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP>

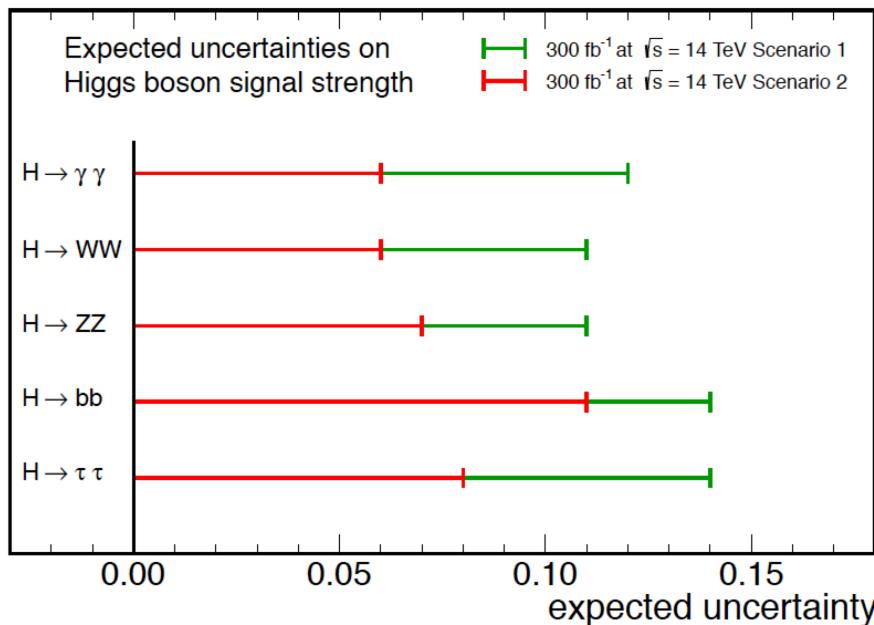
Precision on Higgs signal strengths

- Uncertainties on inclusive μ can be driven below 5%
 - Systematics play important role

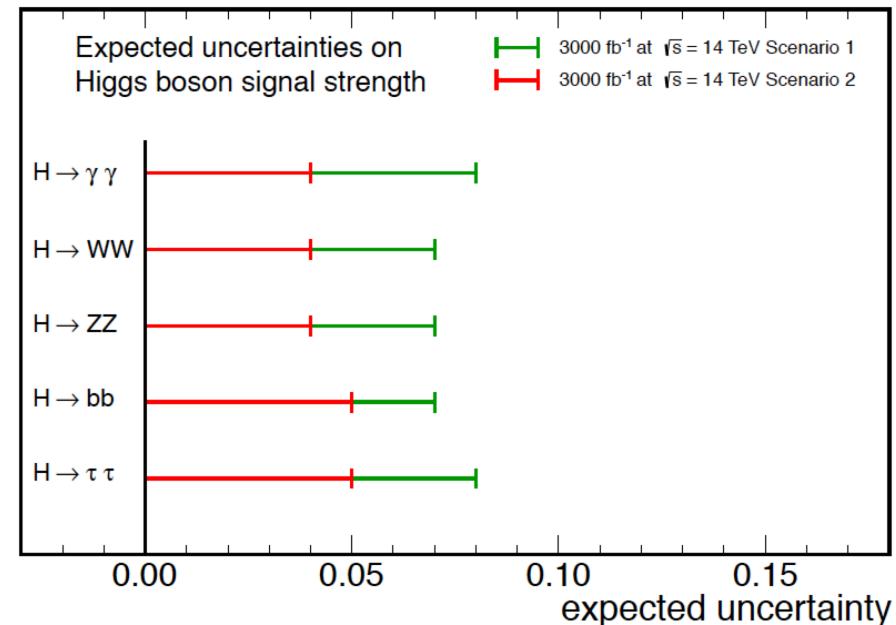
arXiv:1307.7135
(CMS-NOTE-13-002)

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

CMS Projection



CMS Projection

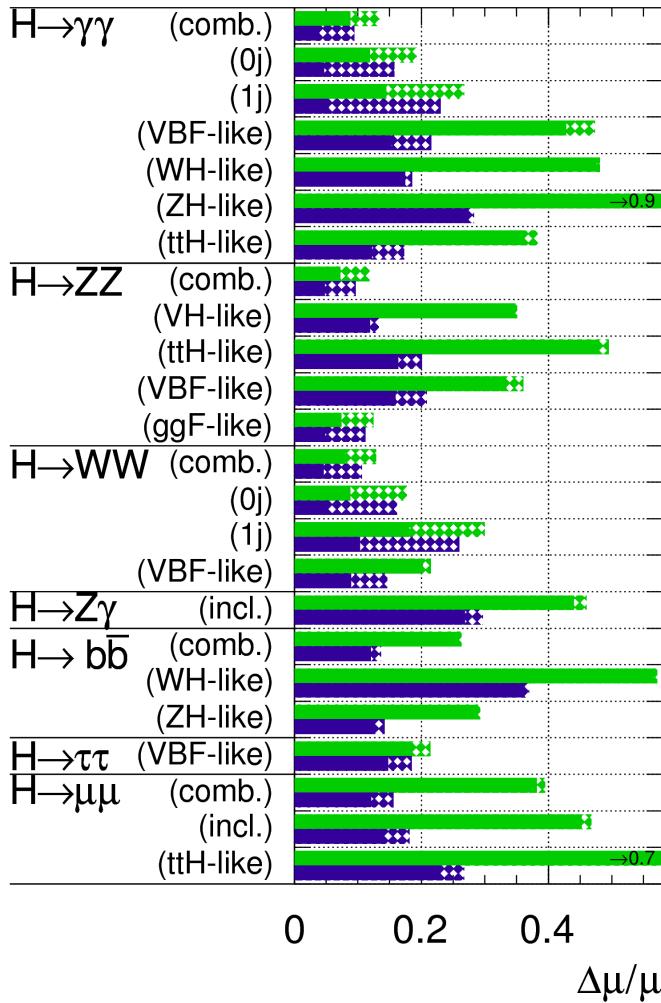




Precision on Higgs signal strengths

ATLAS Simulation Preliminary

$\sqrt{s} = 14 \text{ TeV}$: $\int L dt = 300 \text{ fb}^{-1}$; $\int L dt = 3000 \text{ fb}^{-1}$



ATL-PHYS-PUB-2014-016

- Separation by production mode vital for coupling measurements
 - Exploit correlations from e.g. jet migration
- Large impact from theory uncertainties (dashed) i.e. QCD scale, jet binning, etc in some cases

Precision on Higgs couplings



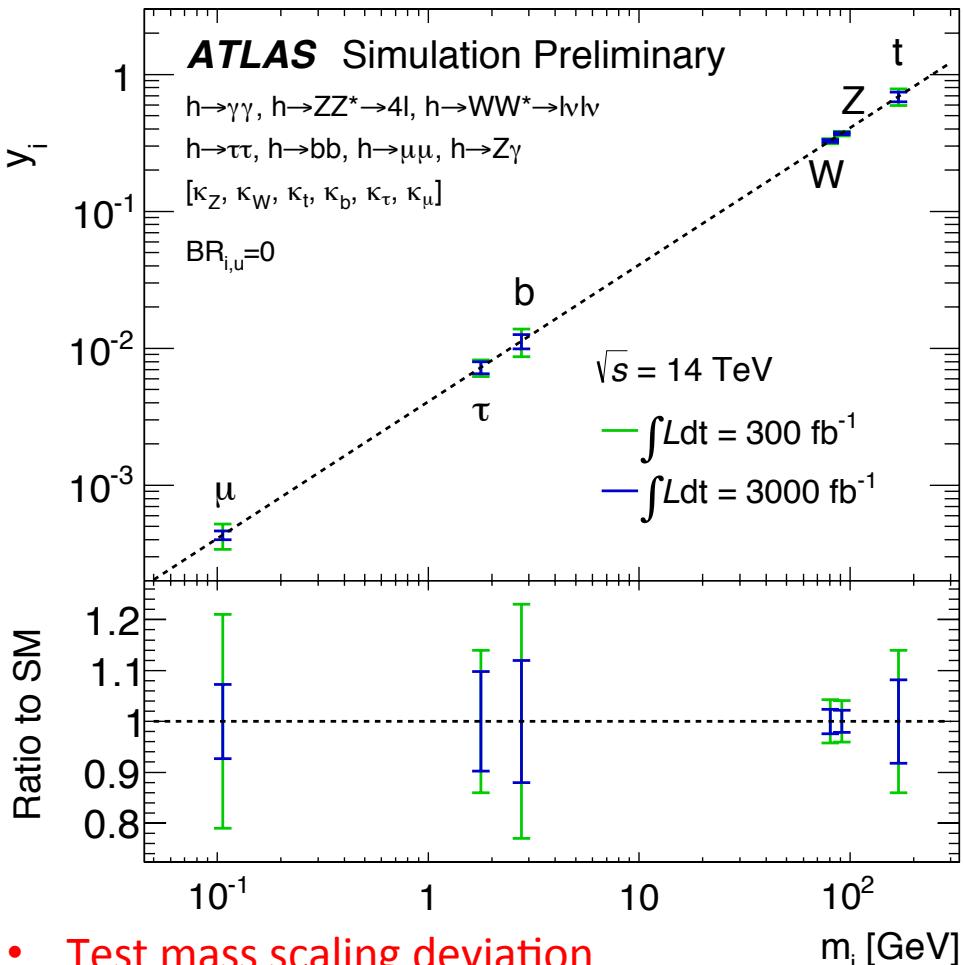
Lumi	Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	κ_{Zg}	κ_μ
300 fb ⁻¹	ATLAS	9%	9%	8%	11-14%	22-23%	20-22%	13-14%	24%	21%
	CMS	5-7%	4-6%	4-6%	6-8%	10-13%	14-15%	6-8%	41%	23%
3000 fb ⁻¹	ATLAS	4-5%	4-5%	4%	5-9%	10-12%	8-11%	9-10%	14%	7-8%
	CMS	2-5%	2-5%	2-4%	3-5%	4-7%	7-10%	2-5%	10-12%	8%

- Comparable precision for most couplings between experiments
- For CMS scenario 2, many couplings (γ , W , Z , g , τ) determined to 4-6% level with 300 fb^{-1} assuming not limited by theory systematics
 - Bottom and top quark couplings probed at 10-14%
- Then with 3000 fb^{-1} , these uncertainties go down to 2-3% and 4-7% respectively
 - Statistically-limited κ_μ and $\kappa_{Z\gamma}$ measured to 8-10%

Mass scaling of Higgs couplings



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- Test mass scaling deviation ϵ to 0.03 (0.01) with 300 (3000) fb^{-1}
- Probe “vev” to 5 GeV level at HL-LHC

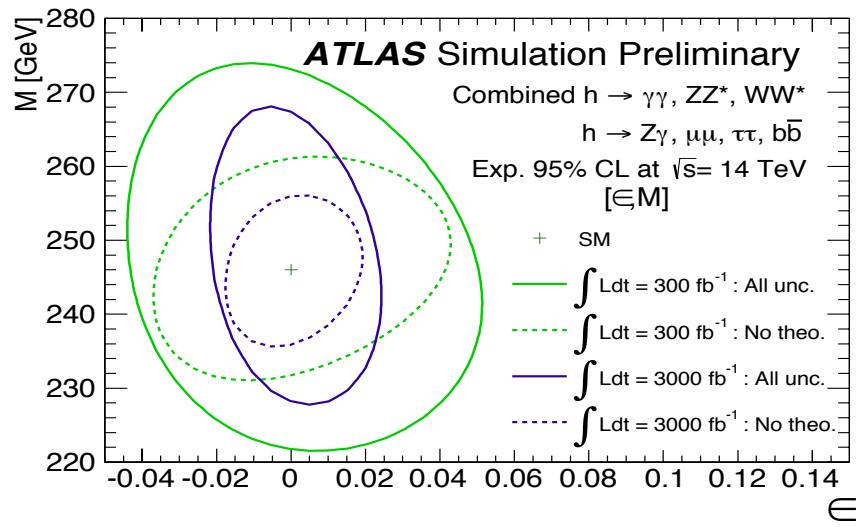
$$y_{V,i} = \sqrt{\kappa_{V,i} \frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}} \frac{m_{V,i}}{v}$$

$$y_{F,i} = \kappa_{F,i} \frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i} \frac{m_{F,i}}{v}$$

ATL-PHYS-PUB-2014-017

$$\kappa_{V,j} = v \frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}} \quad \kappa_{f,i} = v \frac{m_{f,i}^\epsilon}{M^{1+\epsilon}}$$

SM: $\epsilon = 0$, $M = v = 246 \text{ GeV}$



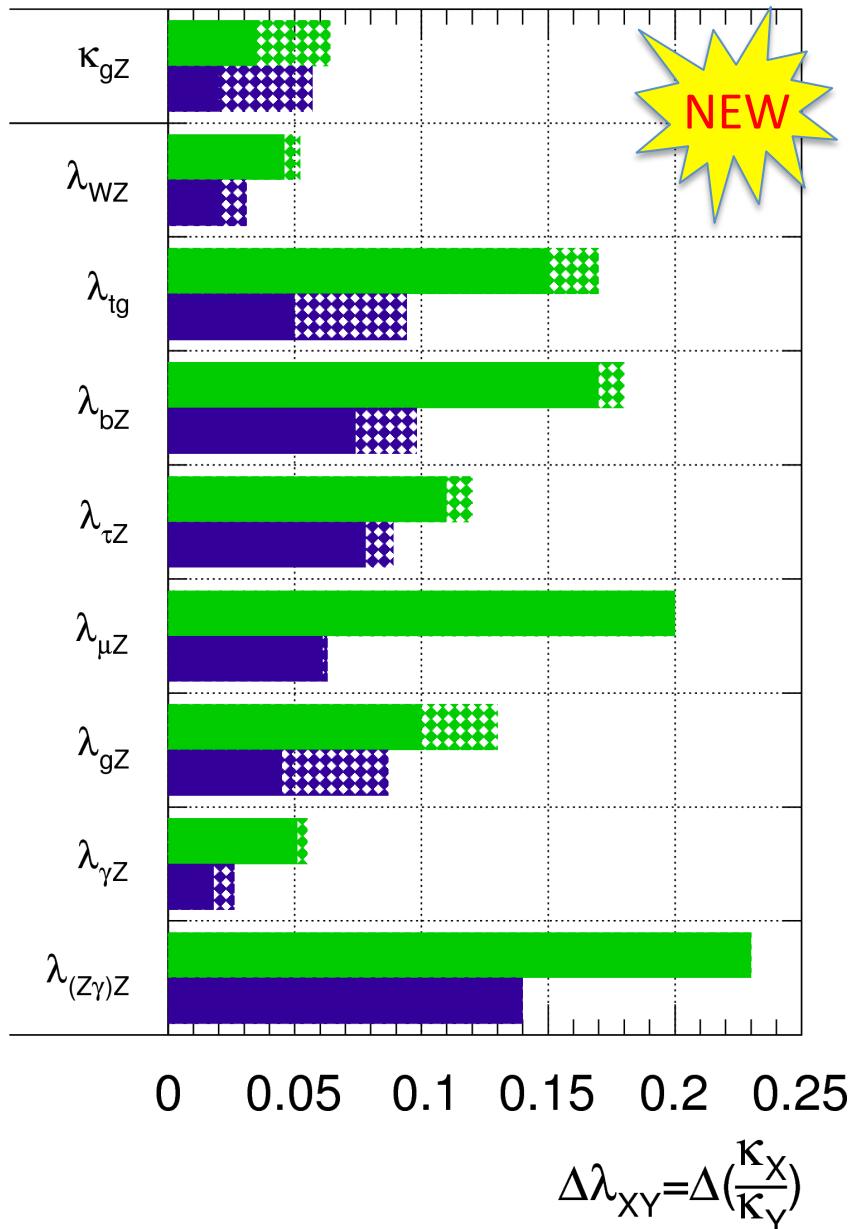
Ratios of Higgs couplings

- In ratios of couplings, Higgs total width cancels out along with many systematics
- Can be determined down to $\sim 5\%$ level with 300 fb^{-1}
- Improve by up to factor 2-3 at HL-LHC without theory unc. (no hash)
- Model-independent probe of NP
 - κ_γ / κ_z constrains new physics in $H \rightarrow \gamma\gamma$ loop at 2-3% level

ATL-PHYS-PUB-2014-016

ATLAS Simulation Preliminary

$\sqrt{s} = 14 \text{ TeV}$: $\int L dt = 300 \text{ fb}^{-1}$; $\int L dt = 3000 \text{ fb}^{-1}$

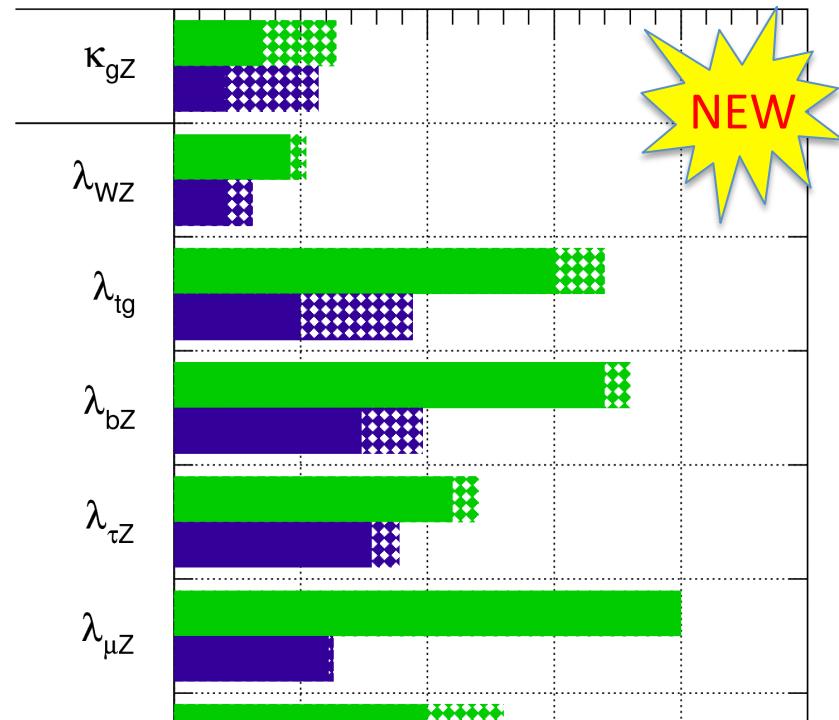


Ratios of Higgs couplings

- Without assumption on Higgs total width, only ratios of couplings can be determined at LHC
- Can be determined down to $\sim 5\%$ level with 300 fb^{-1}
- Improve by up to factor 2-3 at HL-LHC without theory unc. (no hash)
- Model-independent probe of NP
 - κ_γ / κ_z constrains new physics in $H \rightarrow \gamma\gamma$ loop at 2-3% level

ATLAS Simulation Preliminary

$\sqrt{s} = 14 \text{ TeV}$: $\int L dt = 300 \text{ fb}^{-1}$; $\int L dt = 3000 \text{ fb}^{-1}$

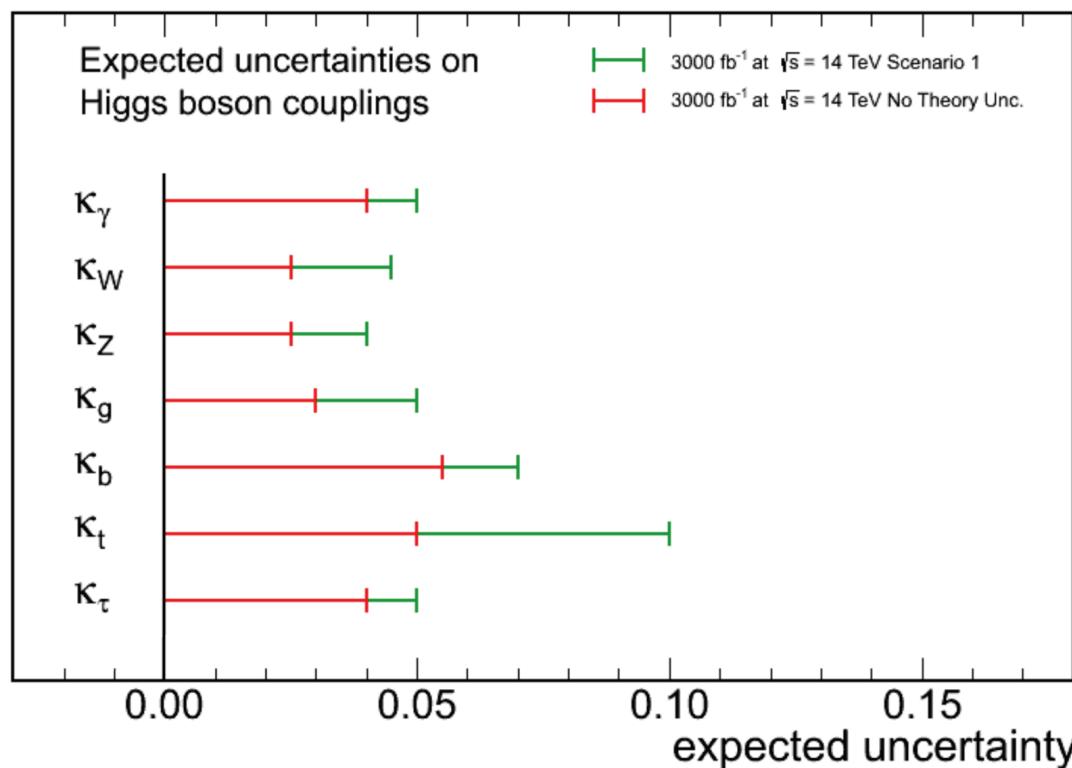


Lumi	Exp.	$\kappa_g \kappa_z / \kappa_H$	κ_γ / κ_z	κ_w / κ_z	κ_b / κ_z	κ_τ / κ_z	κ_g / κ_z	κ_t / κ_g	κ_μ / κ_z	$\kappa_{z\gamma} / \kappa_z$
300 fb^{-1}	ATLAS	4-6%	5-6%	5%	17-18%	11-12%	10-13%	15-17%	20%	23%
	CMS	4-6%	5-8%	4-7%	8-11%	6-9%	6-9%	13-14%	22-23%	40-42%
3000 fb^{-1}	ATLAS	2-6%	2-3%	2-3%	7-10%	8-9%	5-9%	5-9%	6%	14%
	CMS	2-5%	2-5%	2-3%	3-5%	2-4%	3-5%	6-8%	7-8%	12%

Theory uncertainties in couplings

- CMS:
 - Current uncertainties
 - No theory uncertainty

CMS Projection



Theory uncertainties in coupling ratios



- Deduced size of theory uncertainty to increase total uncertainty by <10% for given lumi
 - Requires each source of theory unc. to be less than $\sim 1/3$ of total uncertainty

ATL-PHYS-PUB-2014-016

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

Higgs boson compositeness



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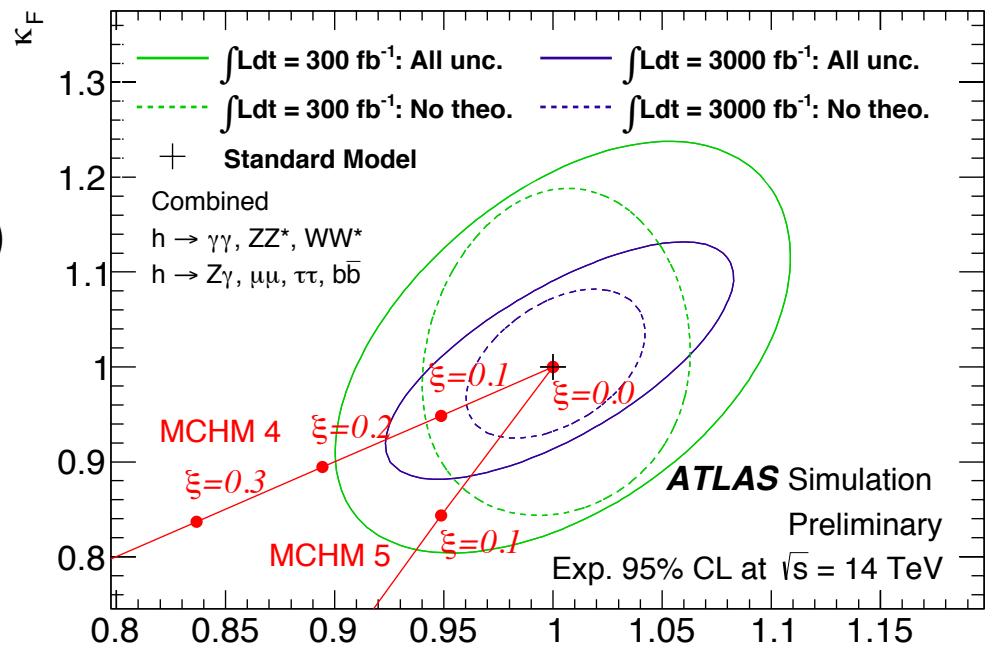
- Pseudo-Nambu-Goldstone boson instead of elementary particle
 - Modified couplings as function of scaling parameter $\xi = v^2/f^2$
- MCHM4 i.e. SO(4): (SM: $\xi \rightarrow 0$)

$$\kappa = \kappa_V = \kappa_F = \sqrt{1 - \xi}$$

- MCHM5 i.e. SO(5):

$$\kappa_V = \sqrt{1 - \xi}$$

$$\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$



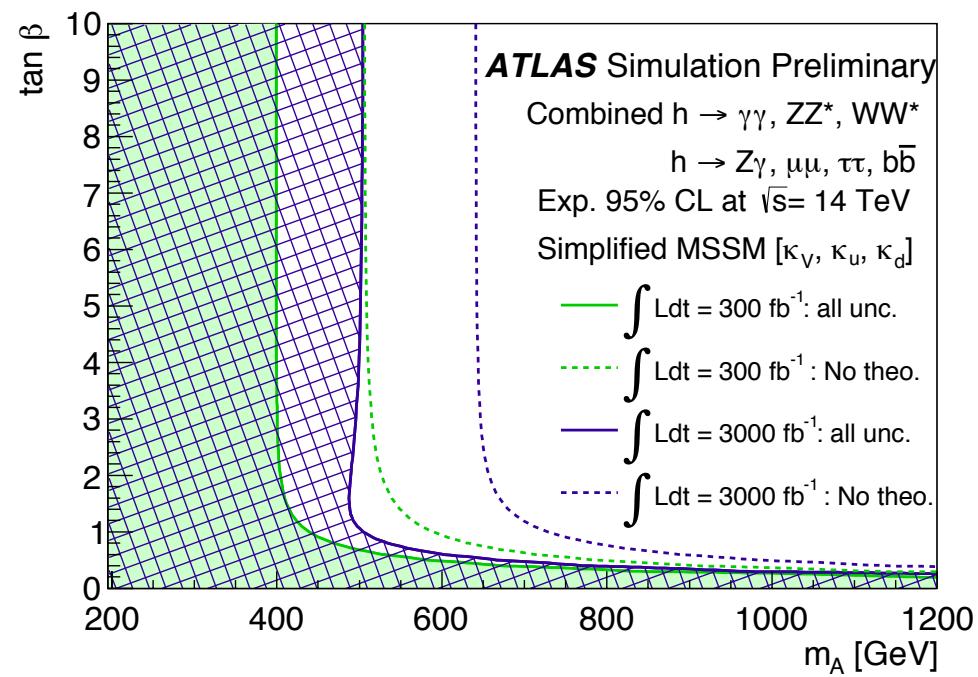
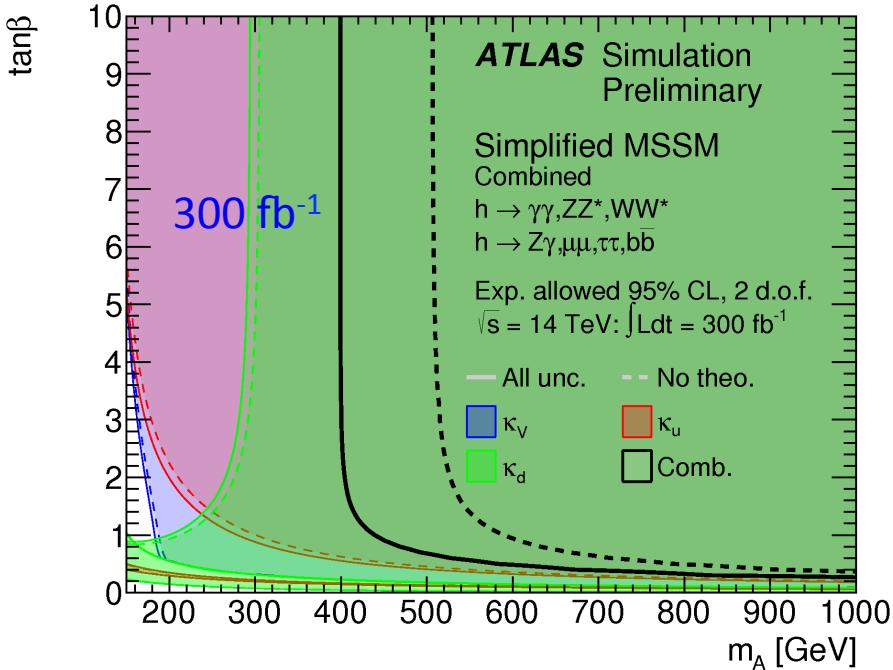
Lower limit on Higgs compositeness scale, f (460-550 GeV exp. now):

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

Simplified MSSM



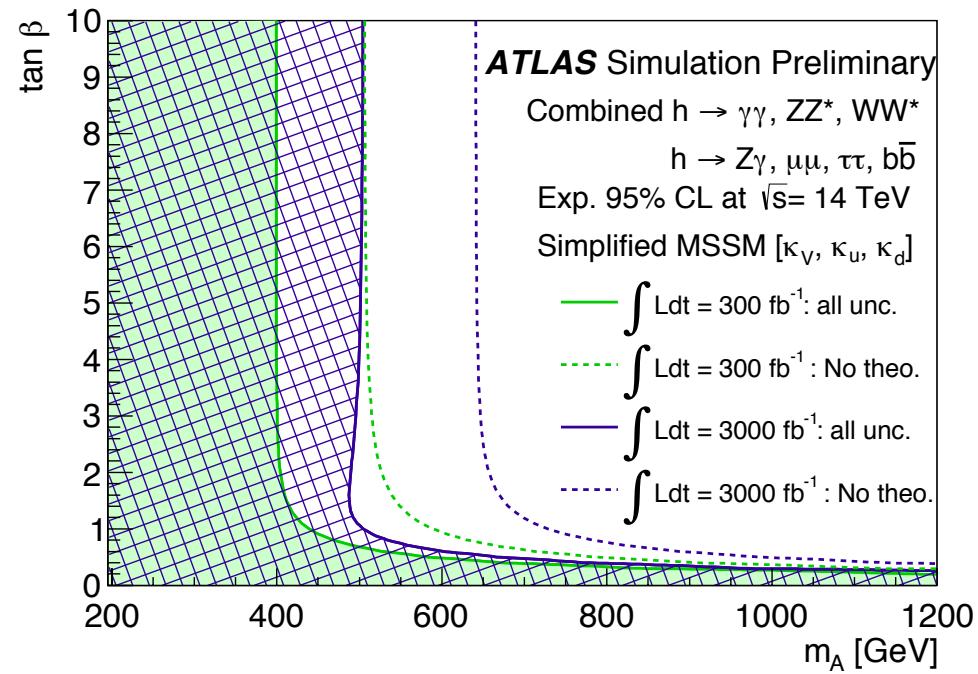
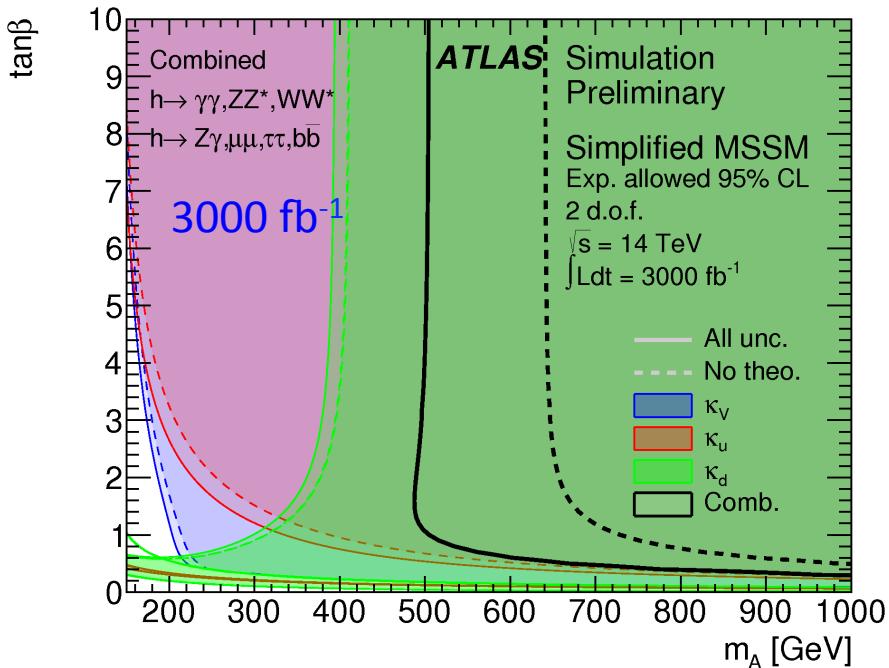
- Second Higgs doublet present in many BSM models, such as MSSM
 - More general 2HDMs, or extra EW singlet e.g. in NMSSM, in backup slides
- Light Higgs mass & couplings constrain heavy Higgses, depending on assumptions
- For $\tan \beta > 2$, expected limit of $m_A > 500$ GeV (650 GeV) with 300 (3000) fb^{-1} if not limited by theory uncertainties
 - Improve wrt expected limit of 290 GeV in current data



Simplified MSSM



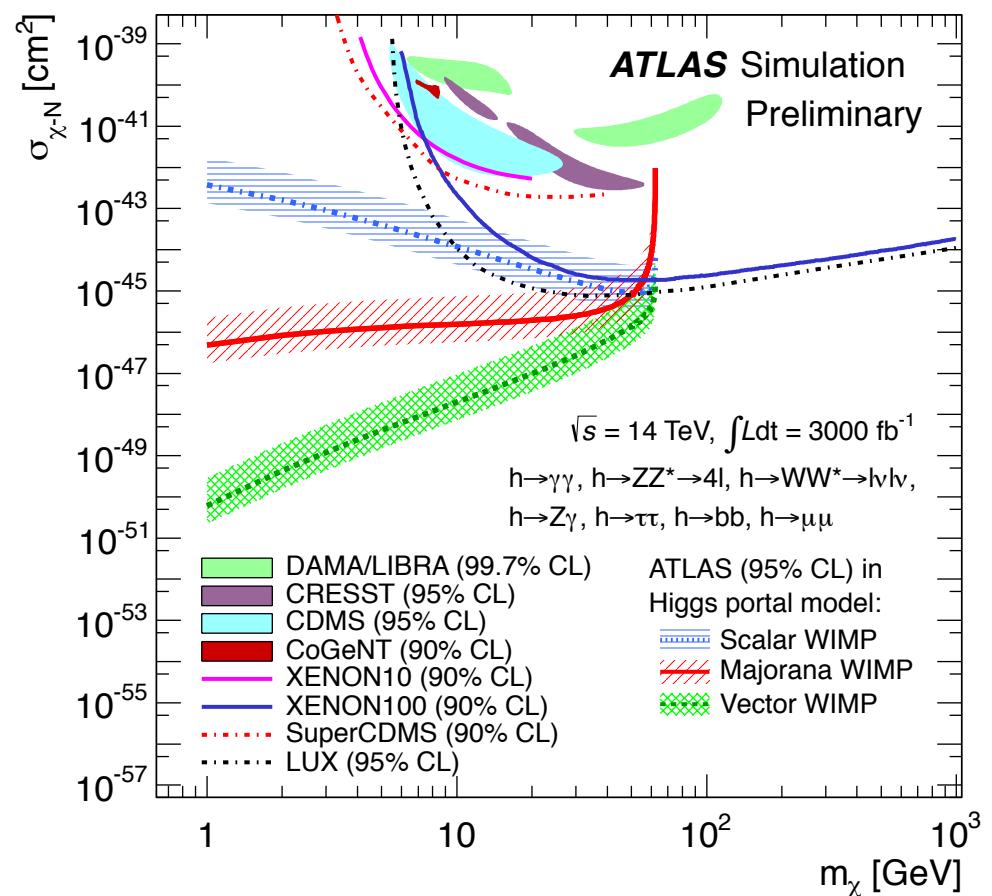
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Invisible Higgs decays & dark matter

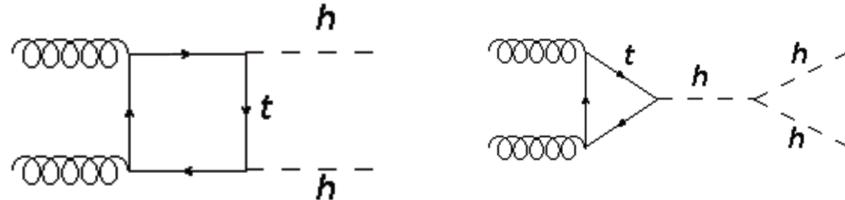


- Higgs decays to invisible final states at 300 fb^{-1}
 - ATLAS: $\text{BR}_{\text{inv}} < 0.20\text{-}0.22$
 - CMS: $\text{BR}_{\text{inv}} < 0.14\text{-}0.18$
- With 3000 fb^{-1} :
 - ATLAS: $\text{BR}_{\text{inv}} < 0.10\text{-}0.14$
 - CMS: $\text{BR}_{\text{inv}} < 0.07\text{-}0.11$
- Higgs decays to coupling of WIMP to Higgs boson taken as free parameter
- Translate limit on BR into coupling of Higgs to wimp, and into cross-section for WIMP-nucleon scattering
 - Improve by up to a factor of 4 wrt current data



Di-Higgs production at the HL-LHC

- HH production with destructive interference between processes:



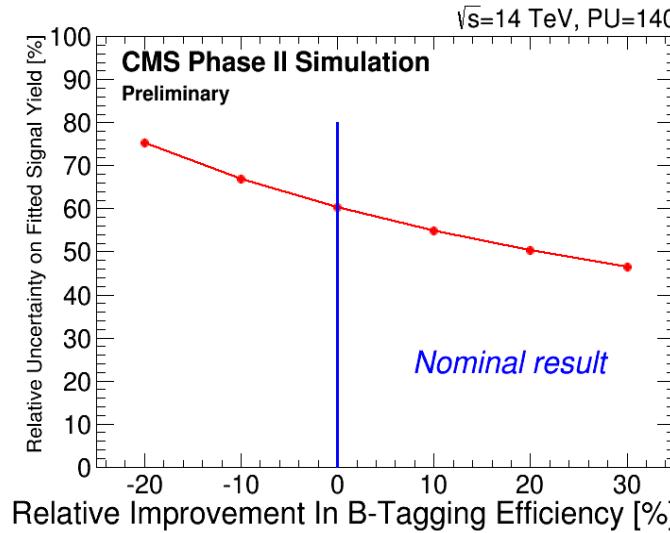
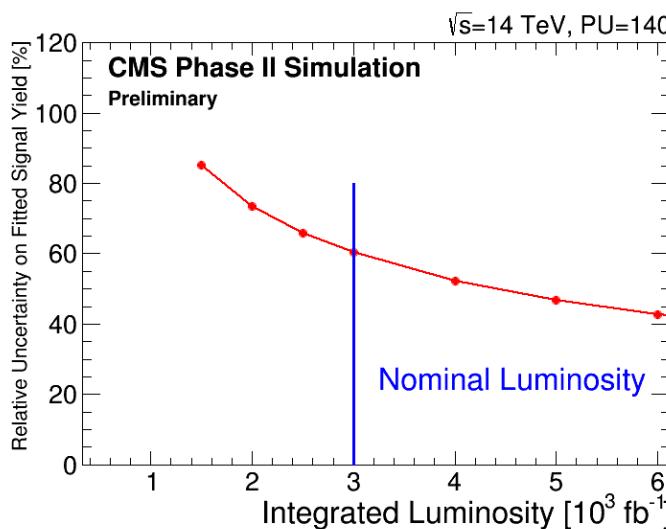
- Holy grail: Probe Higgs self-coupling λ_{HHH} , and therefore vacuum potential of universe
- Challenging measurement: SM cross-section at 14 TeV is 40.8 fb (NNLO)
 - Very large enhancements can be possible with BSM physics like Higgs compositeness
- Final states give yields per experiment, before selection:
 - bb $\gamma\gamma$ (clean): 320 expected events with 3000 fb $^{-1}$
 - bbWW (large backgrounds): 30k expected events at 3000 fb $^{-1}$
 - bbbb and bb $\tau\tau$ final states under study
- No silver bullet – will need combination of all final states for max sensitivity

HH \rightarrow bb $\gamma\gamma$ analysis

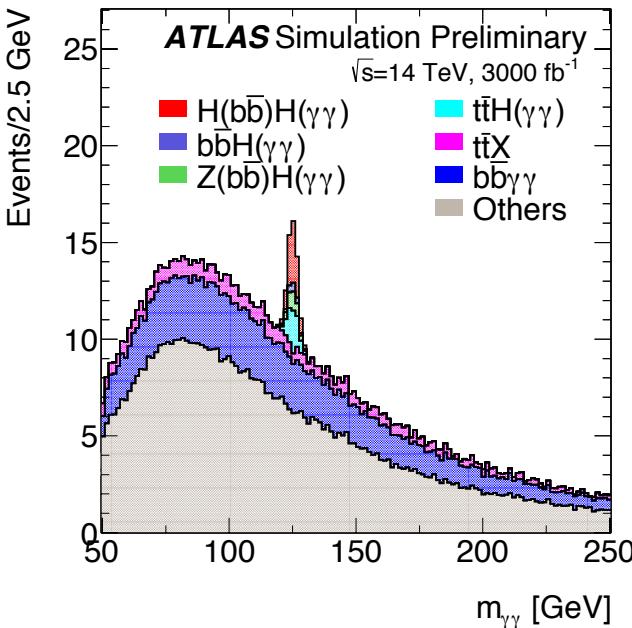
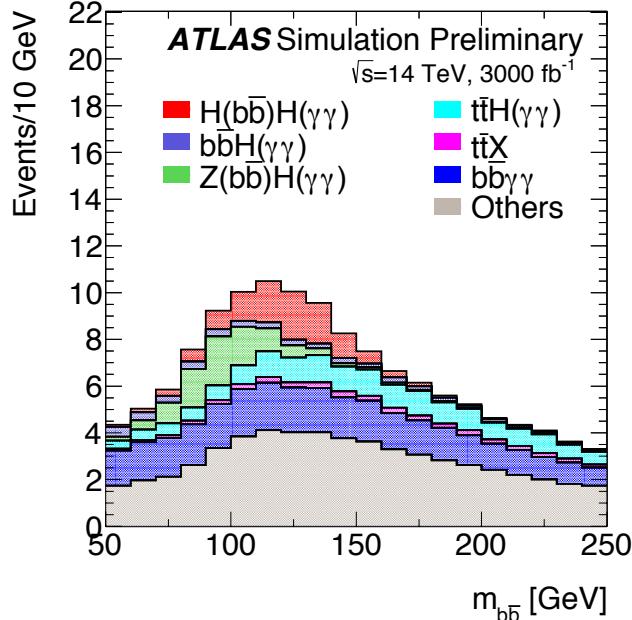


- CMS: 2D fit of m_{bb} & $m_{\gamma\gamma}$, with parametrized object performance for $\mu=140$
- ATLAS (ATL-PHYS-PUB-2014-019): Cut-based analysis
- Both are discussing analyses to better understand differences and optimization
 - CMS event yield:

Process / Selection Stage	HH	ZH	$t\bar{t}H$	bbH	$\gamma\gamma+jets$	$\gamma+jets$	$jets$	$t\bar{t}$
Object Selection & Fit Mass Window	22.8	29.6	178	6.3	2891	1616	292	113
Kinematic Selection	14.6	14.6	3.3	2.0	128	96.9	20	20
Mass Windows	9.9	3.3	1.5	0.8	8.5	6.3	1.1	1.1



- Could observe evidence of signal with $\mu \sim 2.8$
- $\mu < 2.2$ at 95% CL expected

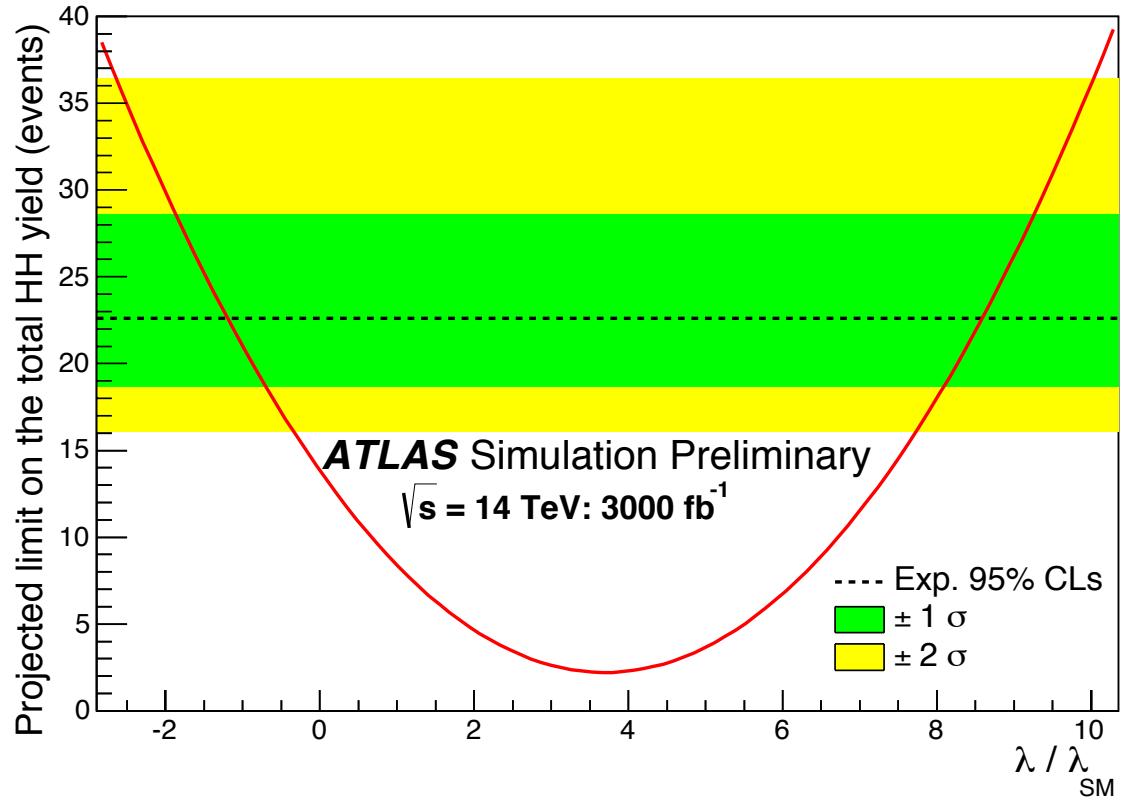


Higgs self-coupling



- ATLAS and CMS are discussing analysis to understand differences in event yields and optimize
- Values of Higgs self-coupling *outside* $-1.3 < \lambda/\lambda_{SM} < 8.7$ can be rejected with 3000 fb^{-1}

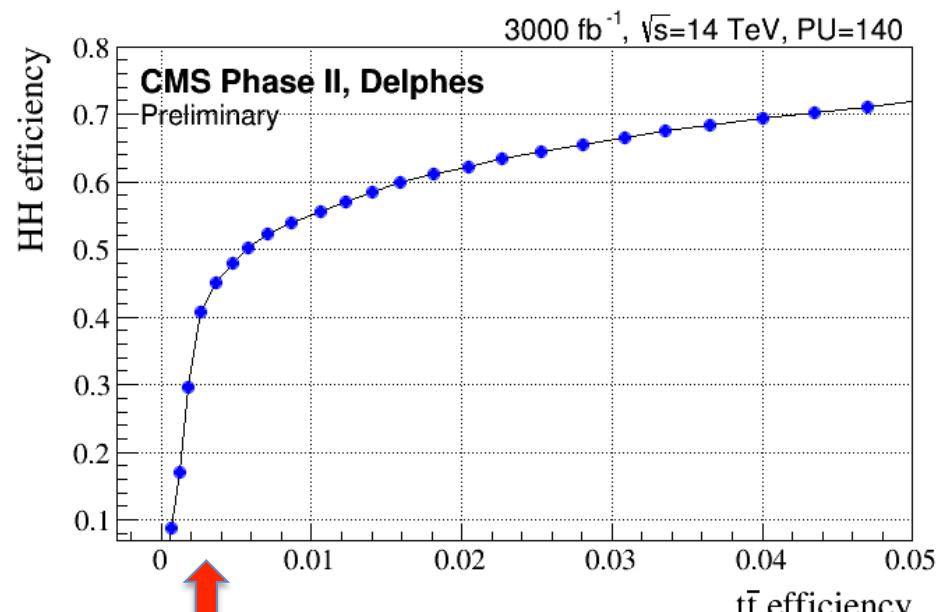
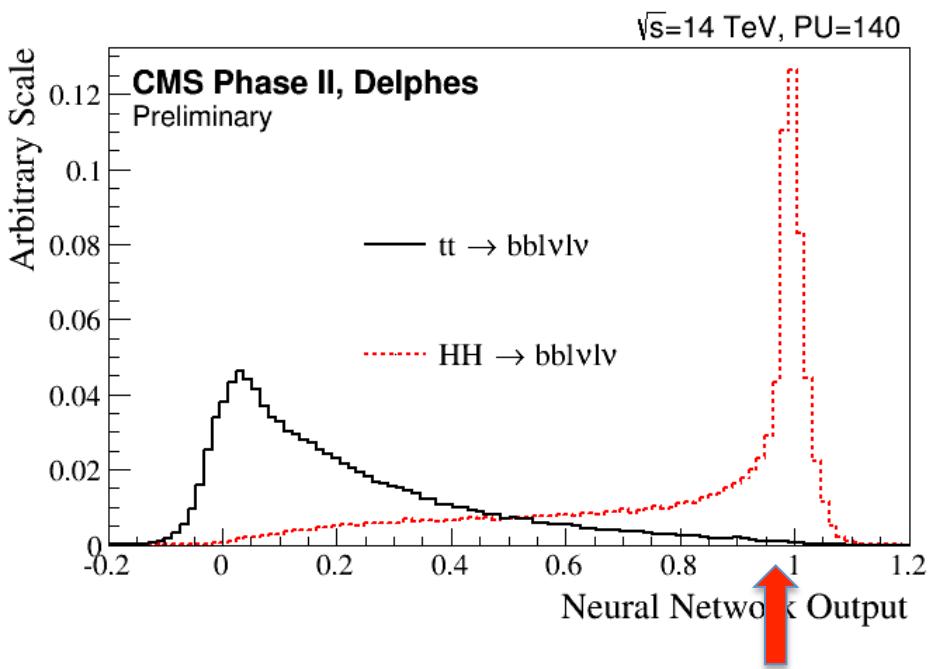
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HH->bbWW analysis



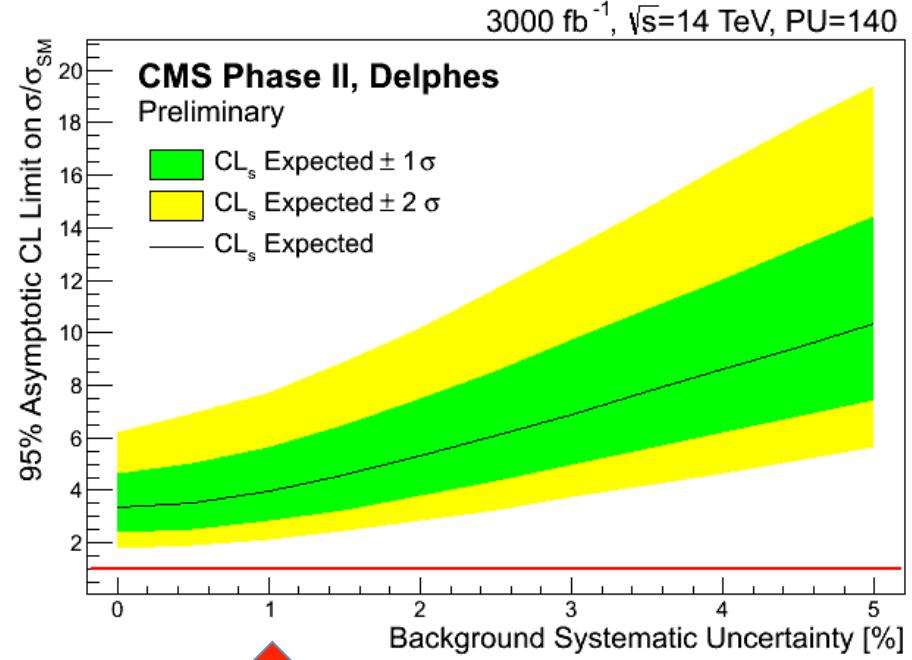
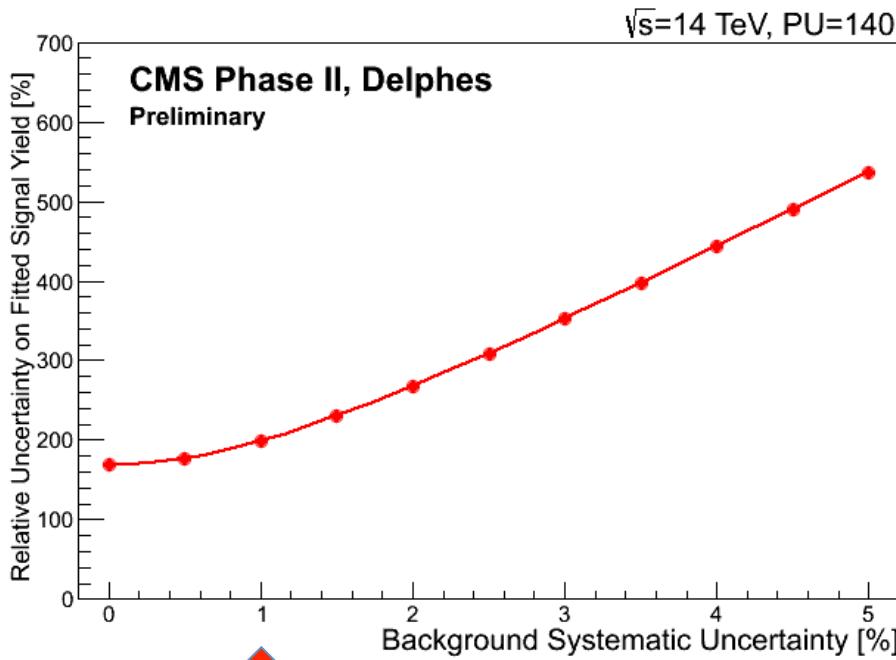
- CMS uses neural network discriminant to suppress main $t\bar{t}$ background
 - Rest of SM processes are negligible and not considered
- NN output > 0.97 gives 40% signal (HH) efficiency with 99.73% background rejection



HH->bbWW sensitivity



- Data-driven techniques likely will constrain uncertainties on ttbar background to percent level in CMS
- 1% systematic on background would produce 200% uncertainty on di-Higgs rate
 - $\mu < 4$ at 95% CL



Conclusions

- Fantastic new era of Higgs coupling measurements and indirect probes of new physics will be extended in Run 2
- Uncertainties on couplings can be driven as low as 5% (2%) with 300 fb^{-1} (3000 fb^{-1}) of 14 TeV data
 - Precise tests of mass scaling of couplings to 8 particles, and their coupling ratios
 - Measure rare decays like $\mu\mu$, $Z\gamma$, HH not easily accessible at a LC
 - HL-LHC may offer sensitivity to Higgs self-coupling via di-Higgs
- Corresponding improvement in discovery potential for Higgs compositeness, MSSM, Higgs portal to dark matter, and other new physics
- LHC 13 TeV data in 2015 will already bring big improvements, especially top Yukawa coupling via $t\bar{t}H$ (P. Onyisi's talk tomorrow)
- ***Run 1 is only the beginning of an exciting, long-term program of Higgs coupling measurements!***

ADDITIONAL INFORMATION

Coupling fit framework

- Leading-order tree-level motivated framework

$$\frac{\sigma \cdot B(gg \rightarrow H \rightarrow \gamma\gamma)}{\sigma_{\text{SM}}(gg \rightarrow H) \cdot B_{\text{SM}}(H \rightarrow \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

- Signal cross-section rescaled using couplings

- Quantify possible small deviations from SM

- Assumptions

- Single resonance of mass 125.0 GeV
 - Narrow-width approximation
 - SM tensor structure of Lagrangian (0^+)

- Possible effective couplings for loop-induced processes

- $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$, $gg \rightarrow H$

Coupling framework

$$\frac{\sigma \cdot B(gg \rightarrow H \rightarrow \gamma\gamma)}{\sigma_{\text{SM}}(gg \rightarrow H) \cdot B_{\text{SM}}(H \rightarrow \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

$$\kappa_g^2(\kappa_b, \kappa_t) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt} + \kappa_b^2 \cdot \sigma_{ggH}^{bb} + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}}$$

$$\kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{Z\gamma}^{ij}}{\sum_{i,j} \Gamma_{Z\gamma}^{ij}}$$

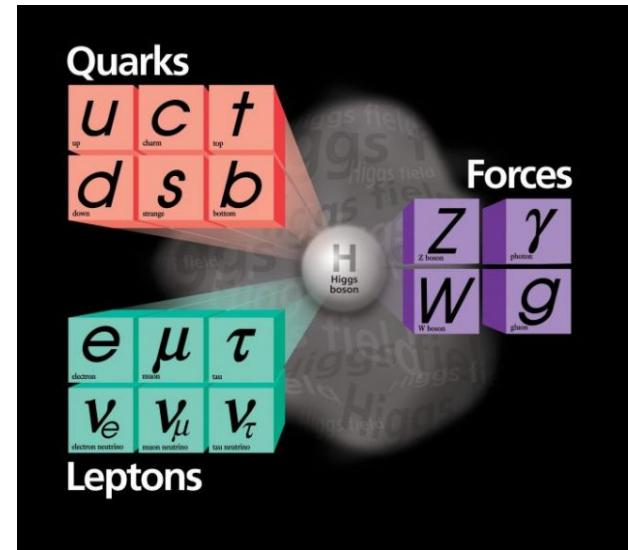
$$\kappa_H^2 = \sum_{\substack{jj=WW, ZZ, b\bar{b}, \tau^-\tau^+, \\ \gamma\gamma, Z\gamma, gg, t\bar{t}, c\bar{c}, s\bar{s}, \mu^-\mu^+}} \frac{\kappa_j^2 \Gamma_{jj}^{\text{SM}}}{\Gamma_H^{\text{SM}}}$$

Coupling observables measured

- Physical parameters of interest are (strengths of) couplings, width, etc
 - Signal cross-section (times branching ratio): $\mu = (\sigma^* BR)/(\sigma^* BR)_{SM}$
 - Tree-level couplings to SM particles: $K_W, K_Z, K_t, K_b, K_\tau, \dots$
 - Effective loop couplings: K_γ, K_g
 - Total width: $(\kappa_H)^2 = \Gamma / \Gamma_{SM}$ or equivalently BR_{inv}
 - Defined in analogy to rates (scaled with squared couplings)
- But current measurements insufficient to simultaneously fit *all* couplings with high precision
- Universality: Define variables under simplifying assumptions that certain couplings have same *strength* κ_i wrt SM values, e.g.
 - $K_V = K_W = K_Z$
 - $K_f = K_t = K_b = K_\tau = \dots$
- Note that the actual *couplings* g_i are still different for various particles

Benchmark models

- Probe symmetries, each with and without Higgs total width fixed:
 - Fewer DOF's gives greater statistical precision in combined fit
 - Primary goal is to test SM (null hypothesis)
 - Possible bias from model assumptions not important
- Benchmark models defined by LHC Higgs XS WG:
[arXiv:1209.0040](https://arxiv.org/abs/1209.0040)
 - $\kappa = \text{sqrt}(\mu)$: Universal scaling of couplings to all particles
 - κ_v vs. κ_f : Spin, vector bosons vs. fermions
 - κ_w vs. κ_z : Custodial symmetry, W vs. Z boson
 - κ_q vs. κ_l : Fermion flavor, quarks vs. leptons
 - κ_u vs. κ_d : Fermion type, up vs. down
 - κ_g vs. κ_γ : Effective loop couplings for effects of heavy BSM particles
 - κ_H & BR_{inv} : Allow decays to light invisible BSM particles



Precision on category signal strengths (ATLAS)

$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$gg \rightarrow H$	0.12	0.06	0.11	0.04
VBF	0.18	0.15	0.15	0.09
WH	0.41	0.41	0.18	0.18
$qqZH$	0.80	0.79	0.28	0.27
$ggZH$	3.71	3.62	1.47	1.38
ttH	0.32	0.30	0.16	0.10

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

Precision on couplings and ratios (ATLAS)

Nr.	Coupling	300 fb ⁻¹			3000 fb ⁻¹		
		Theory unc.: All Half None			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%

Nr.	Coupling ratio	300 fb ⁻¹			3000 fb ⁻¹		
		Theory unc.: All Half None			Theory unc.: 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%
16	$\lambda_{(Z\gamma)Z}$	23%	23%	23%	14%	14%	14%
	$\kappa_{\gamma\gamma}$	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%

Invisible Higgs decays (ATLAS)

- In BSM scenarios, Higgs can decay to (light) invisible or undetected particles
- Parameterize width Γ_H as:

$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{inv.,undet.})} \Gamma_H^{SM}$$

where:

- $\Gamma_{H,SM}$ = SM width
- $\kappa_H^2(\kappa_i)$ = expected strength of width from the coupling strengths
- BR_{inv} = branching ratio to invisible/undetected BSM particles
- CMS derives upper limit on BR_{inv} by assuming $k_V < 1$
- ATLAS assumes tree-level couplings to be 1 (SM), then can extract upper limit:

Nr.	Parameter	300 fb^{-1}			3000 fb^{-1}		
		Theory unc.:			Theory unc.:		
		All	Half	None	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%

Additional electroweak singlet

- Additional EW singlet predicted in NMSSM (1 singlet + 2 doublets)
 - Singlet mixes with h , resulting in heavy higgs H
- Couplings of h (H) are decreased by a factor of κ (κ') such that:

$$\kappa^2 + \kappa'^2 = 1$$

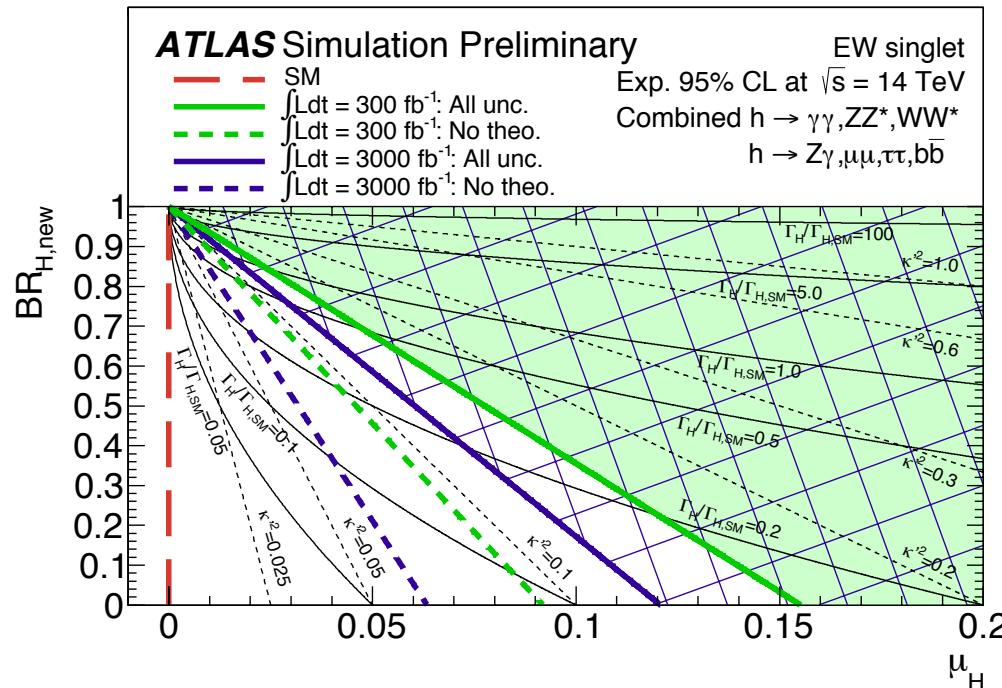
- New decay modes of H are denoted by $\text{BR}_{H,\text{new}}$
- Signal strengths are normalized wrt those of a SM Higgs at corresponding mass:

$$\mu_h = \frac{\sigma_h \times \text{BR}_h}{(\sigma_h \times \text{BR}_h)_{\text{SM}}} = \kappa^2$$

$$\mu_H = \frac{\sigma_H \times \text{BR}_H}{(\sigma_H \times \text{BR}_H)_{\text{SM}}} = \kappa'^2 (1 - \text{BR}_{H,\text{new}})$$

- Note that $\kappa'^2 = 1 - \mu_h$

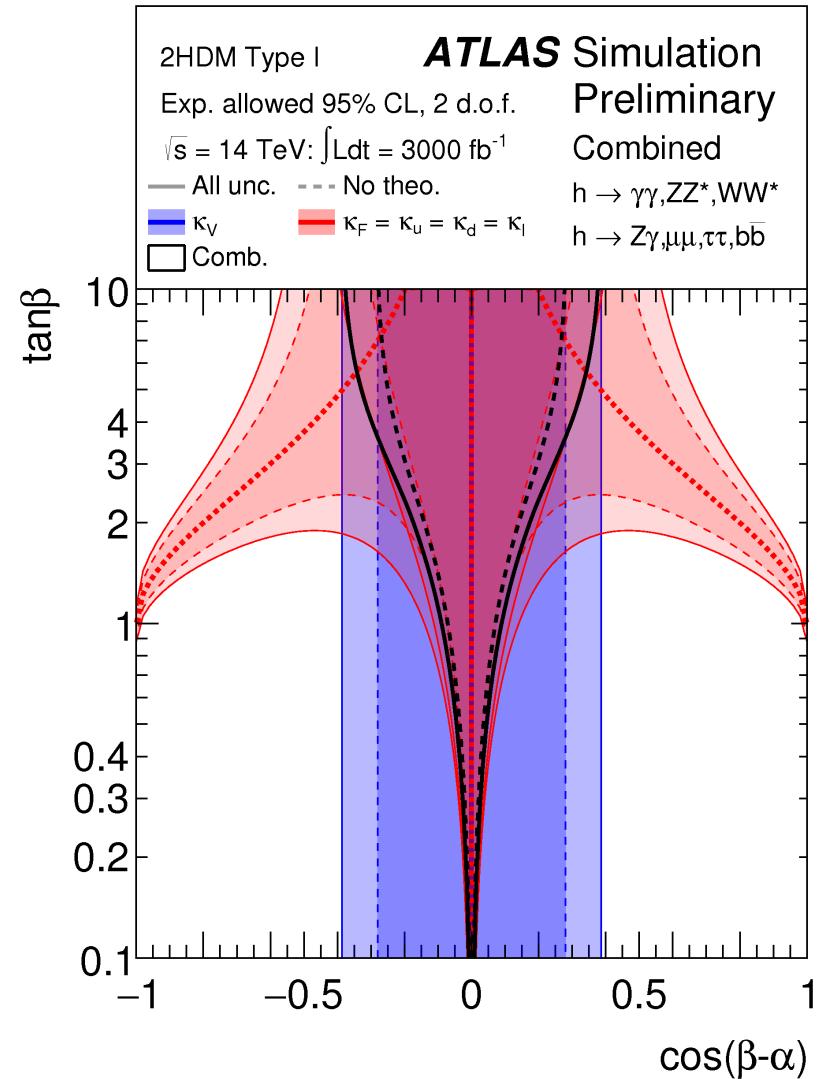
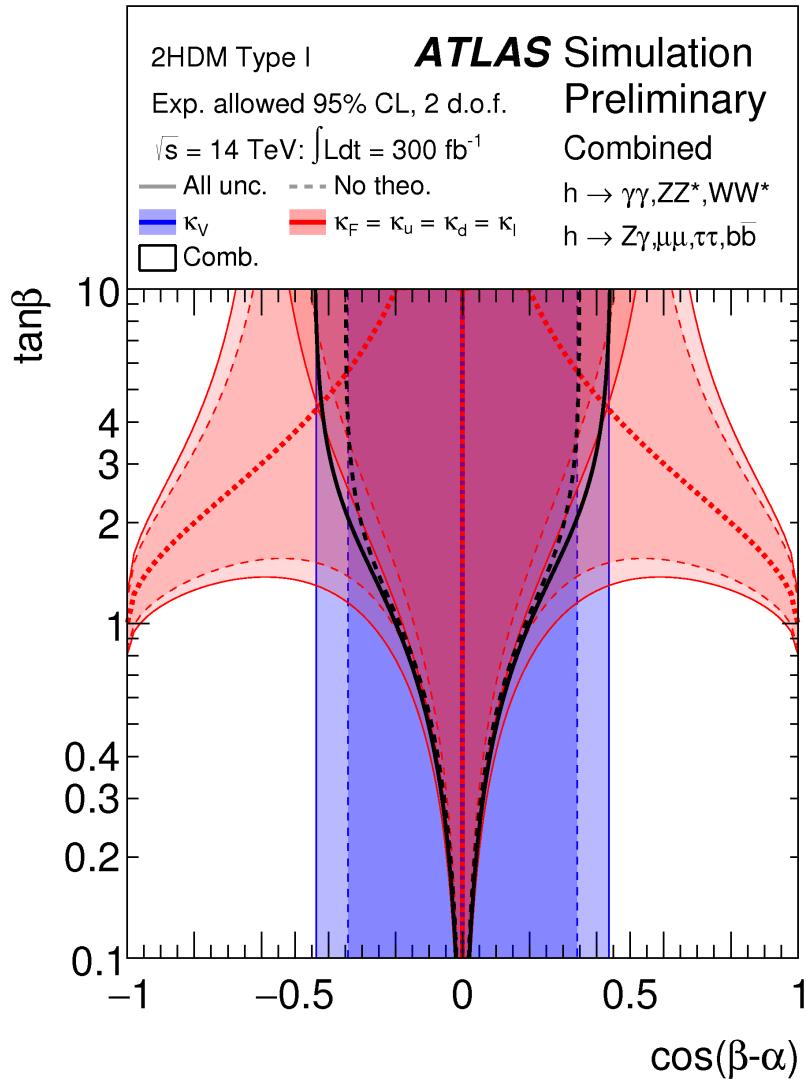
EW singlet



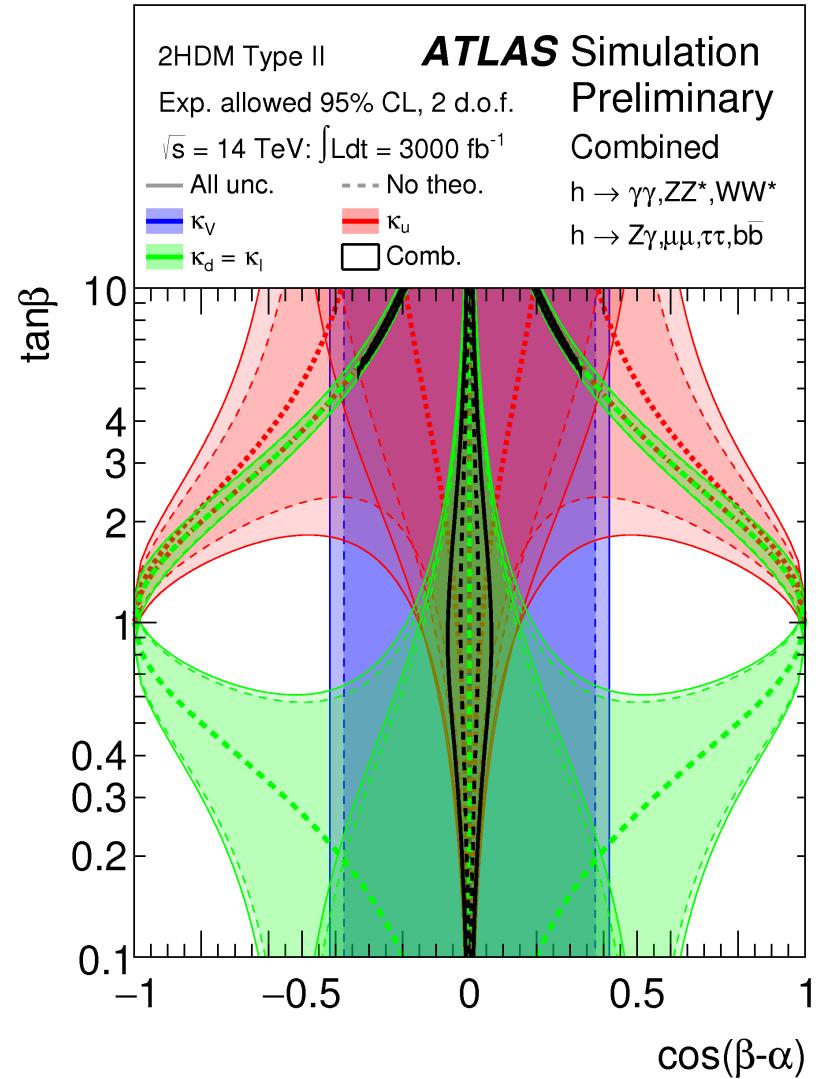
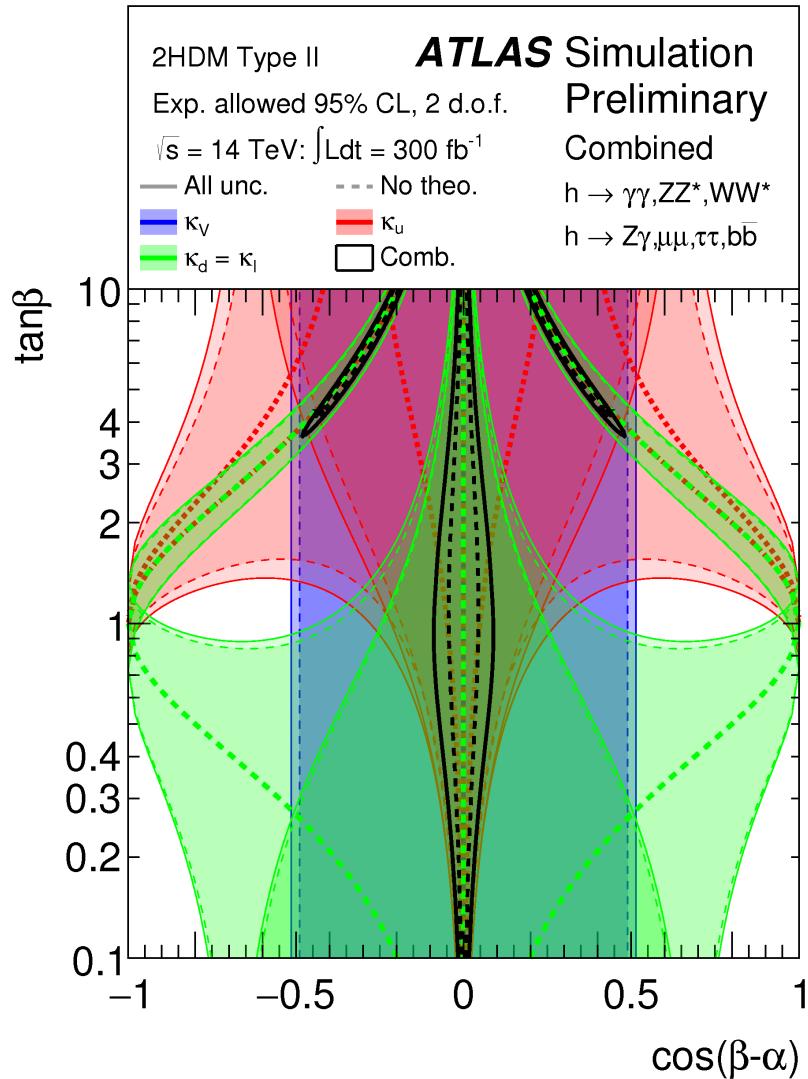
Upper limit on square of heavy Higgs coupling:

Coupling	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
κ'^2	0.17	0.10	0.13	0.06

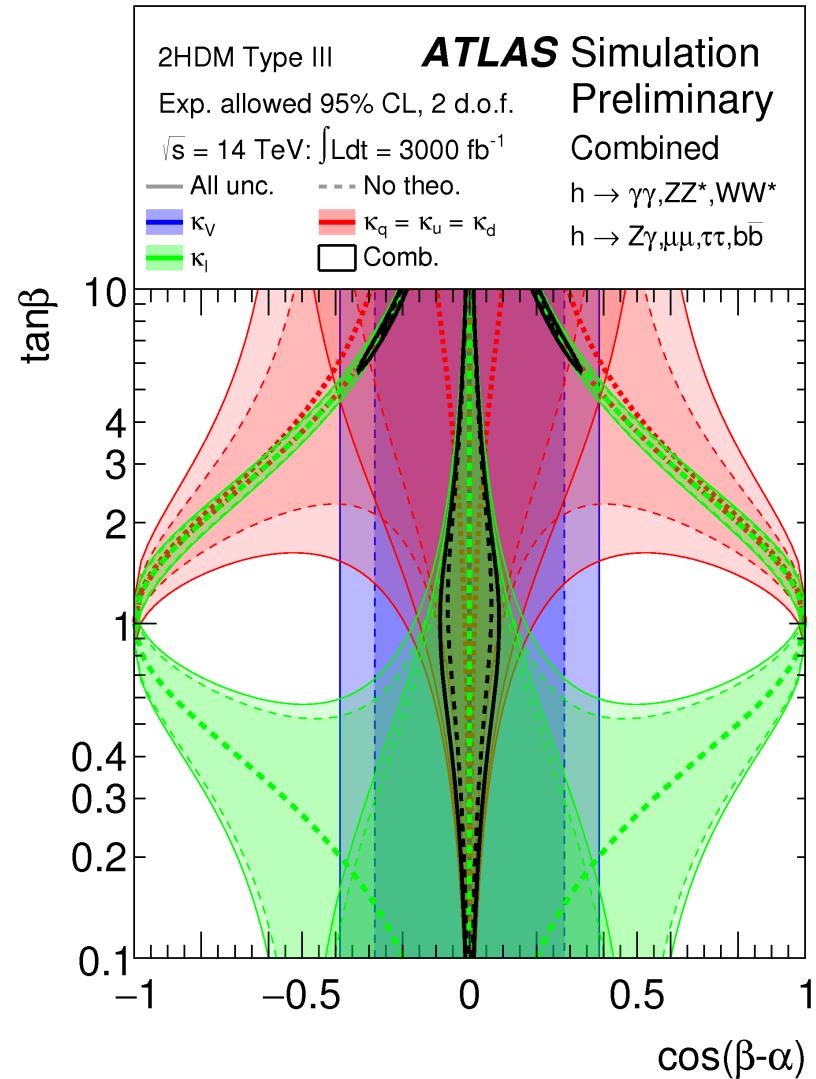
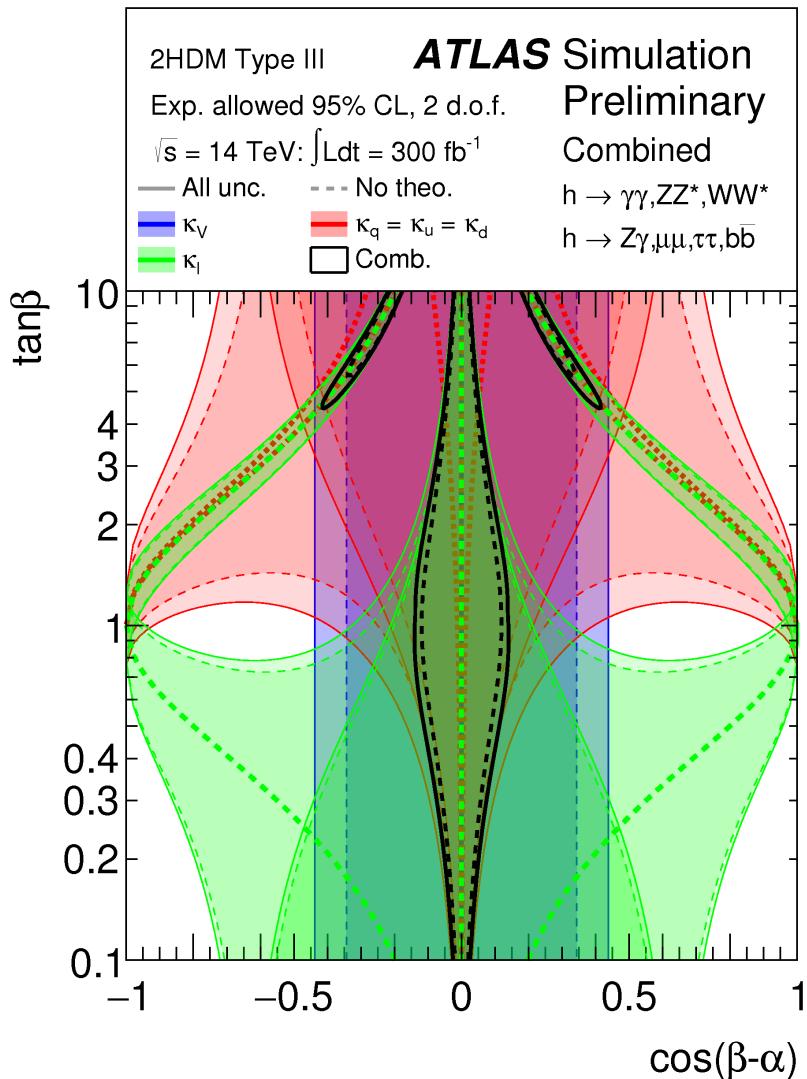
Couplings in 2HDM Type I



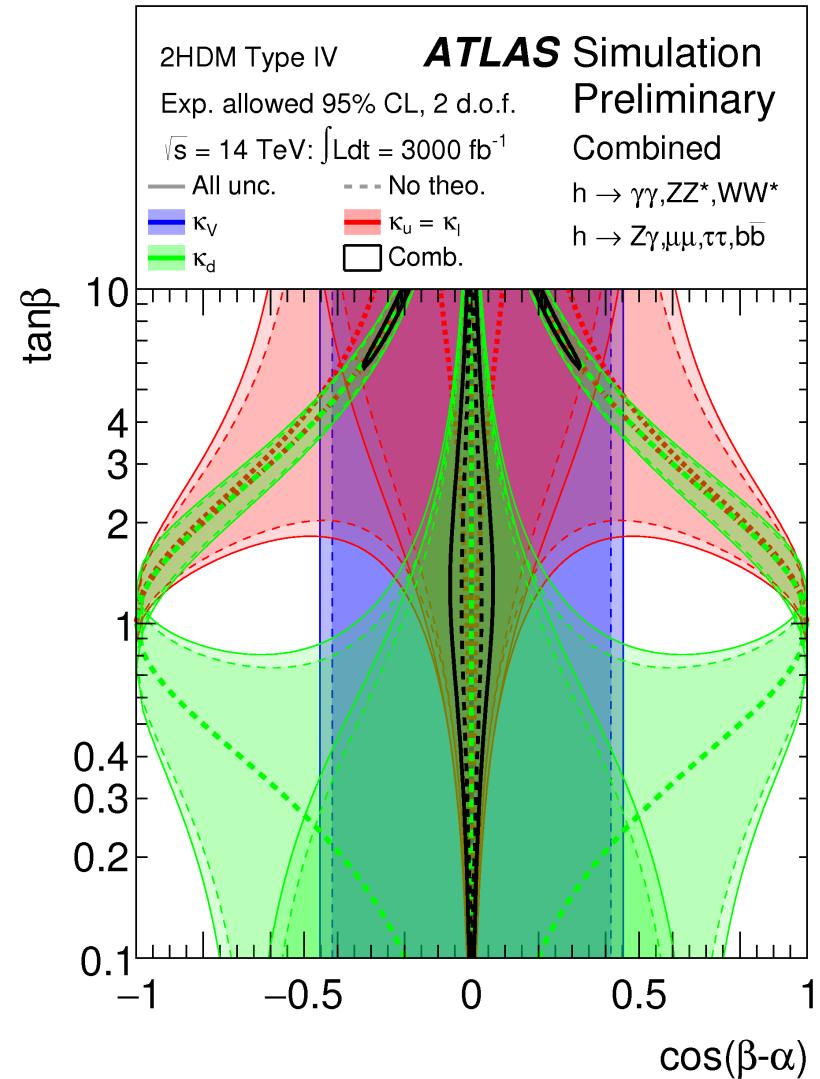
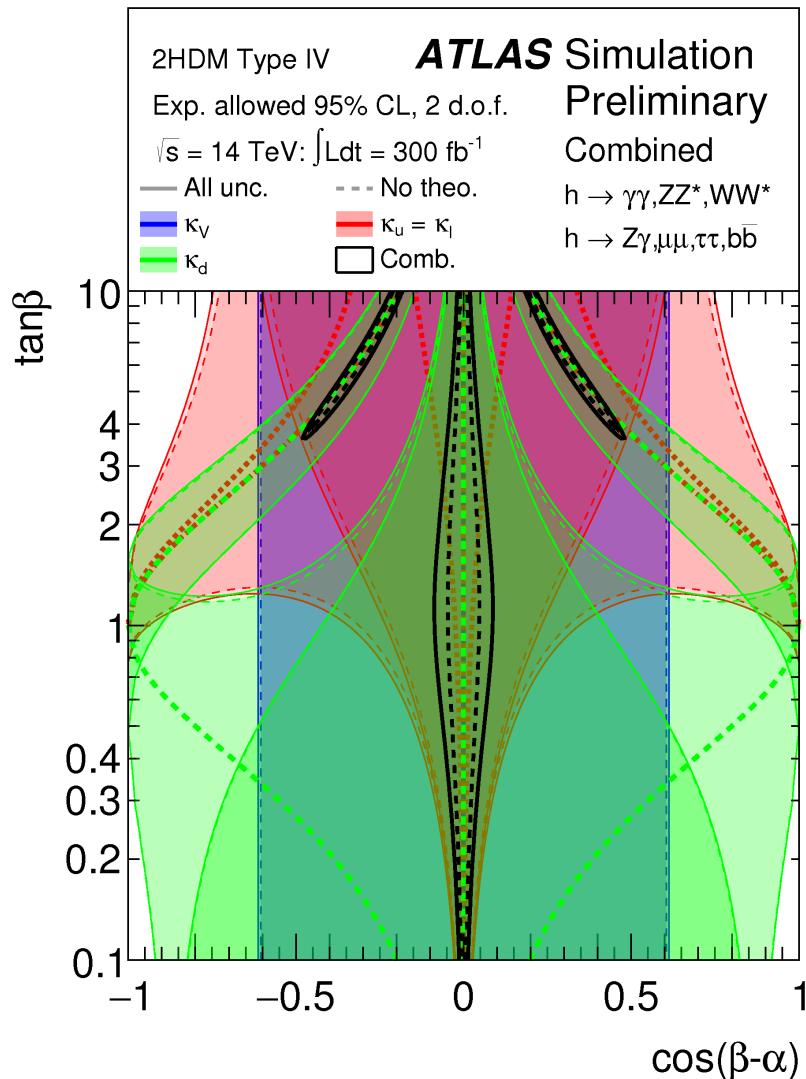
Couplings in 2HDM Type II



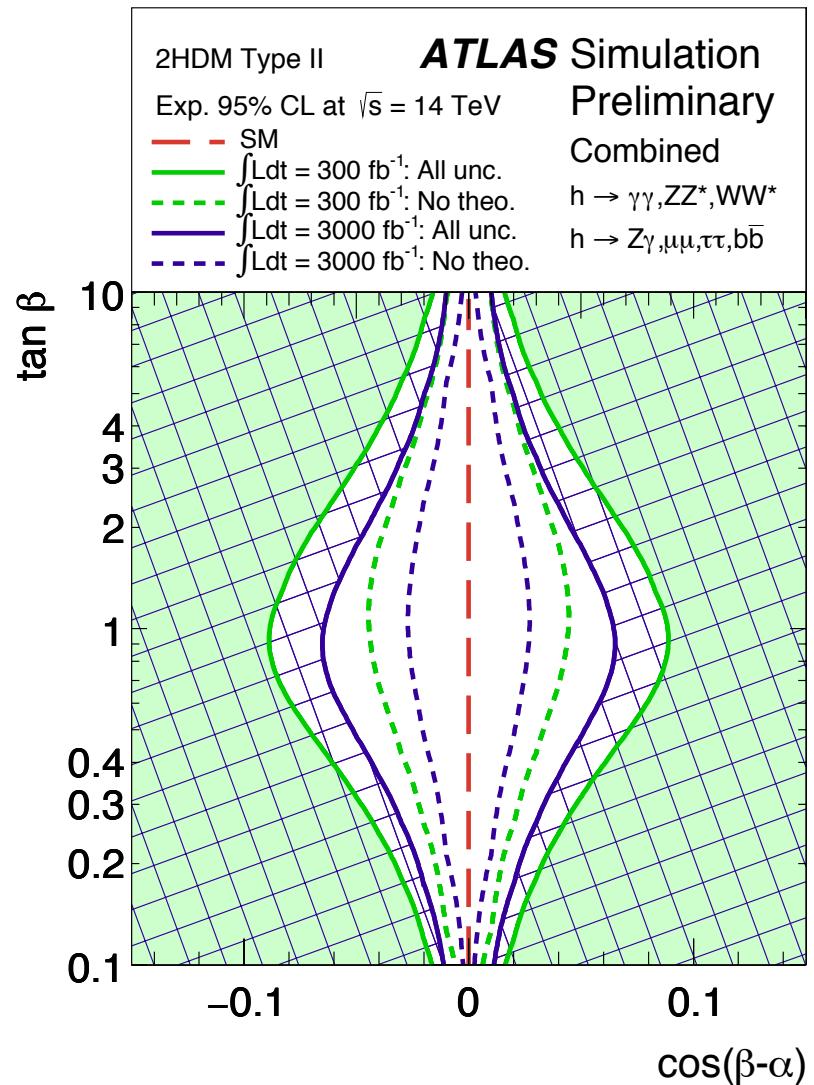
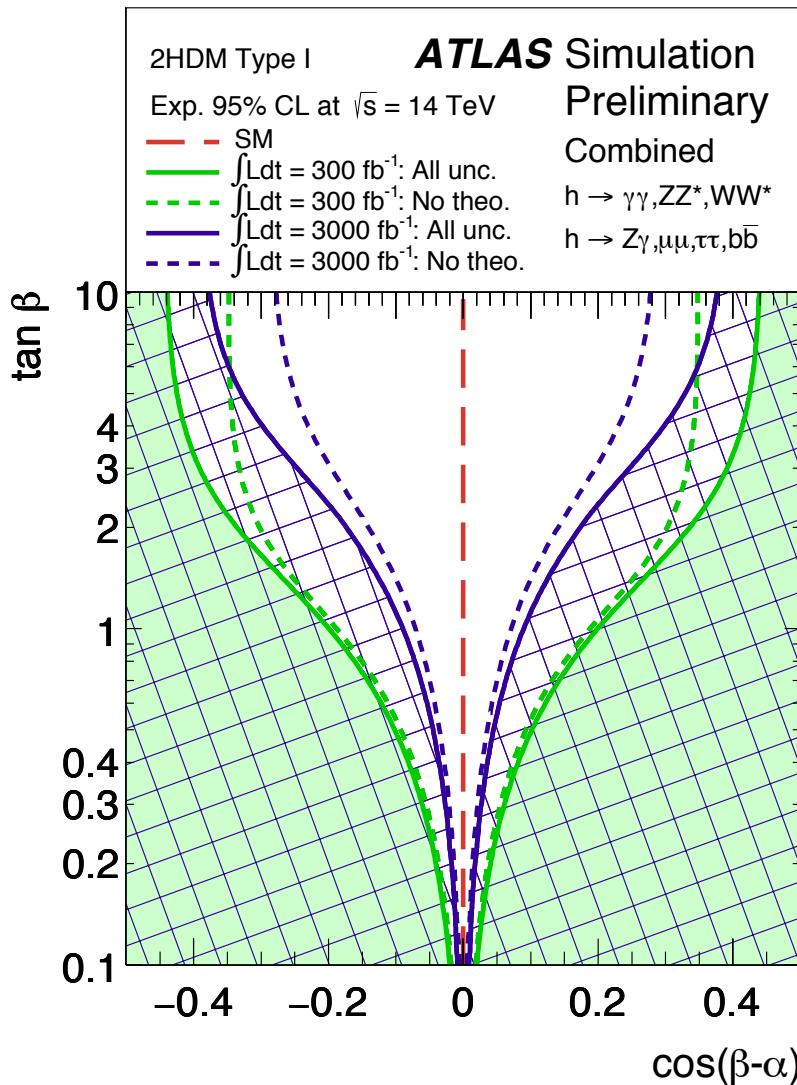
Couplings in 2HDM Type III



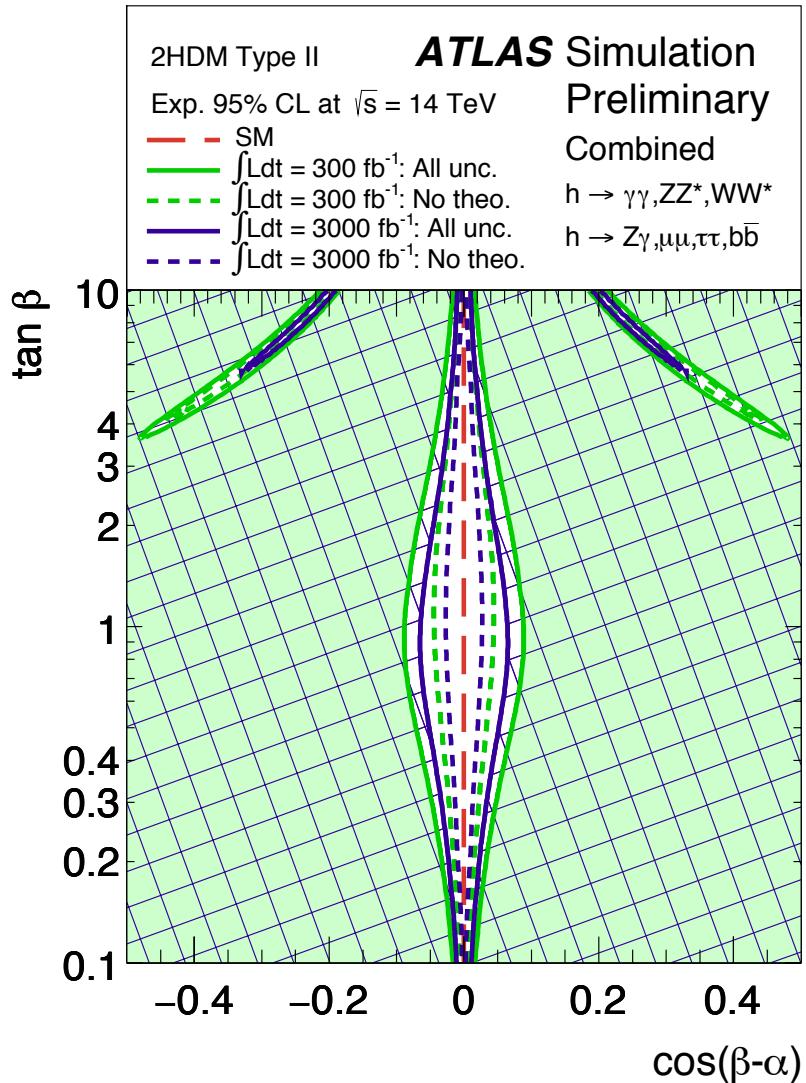
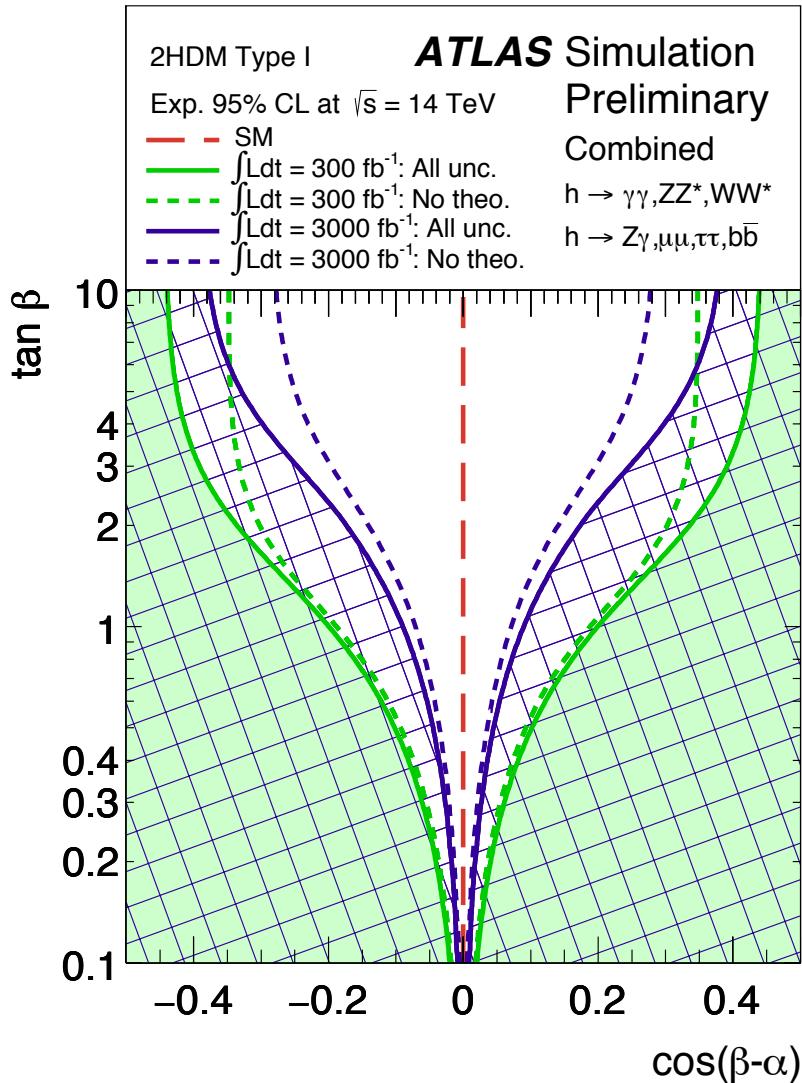
Couplings in 2HDM Type IV



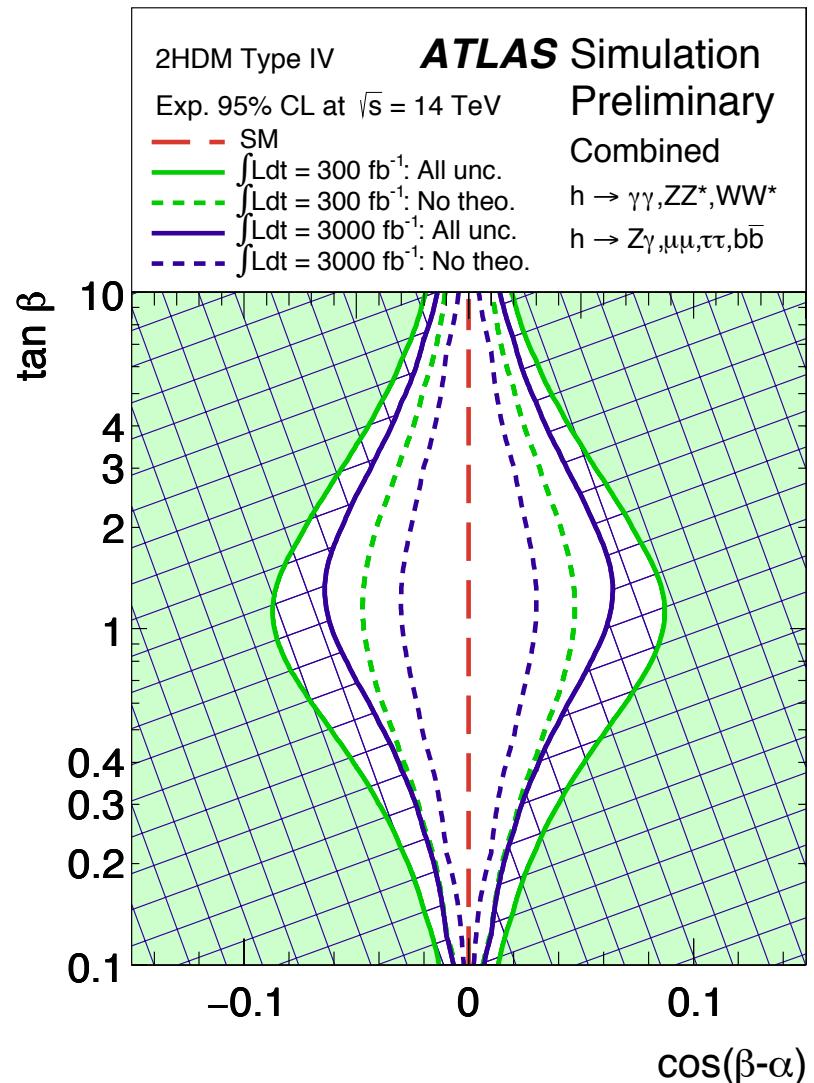
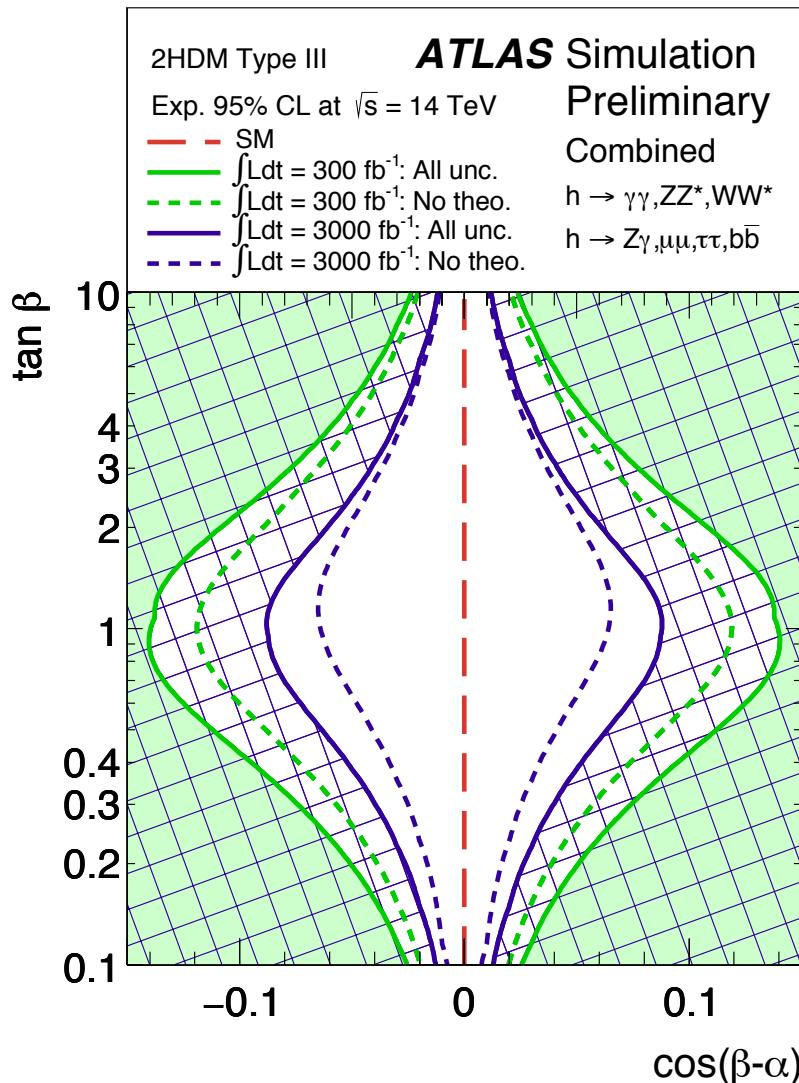
Limits on 2HDM Types I and II



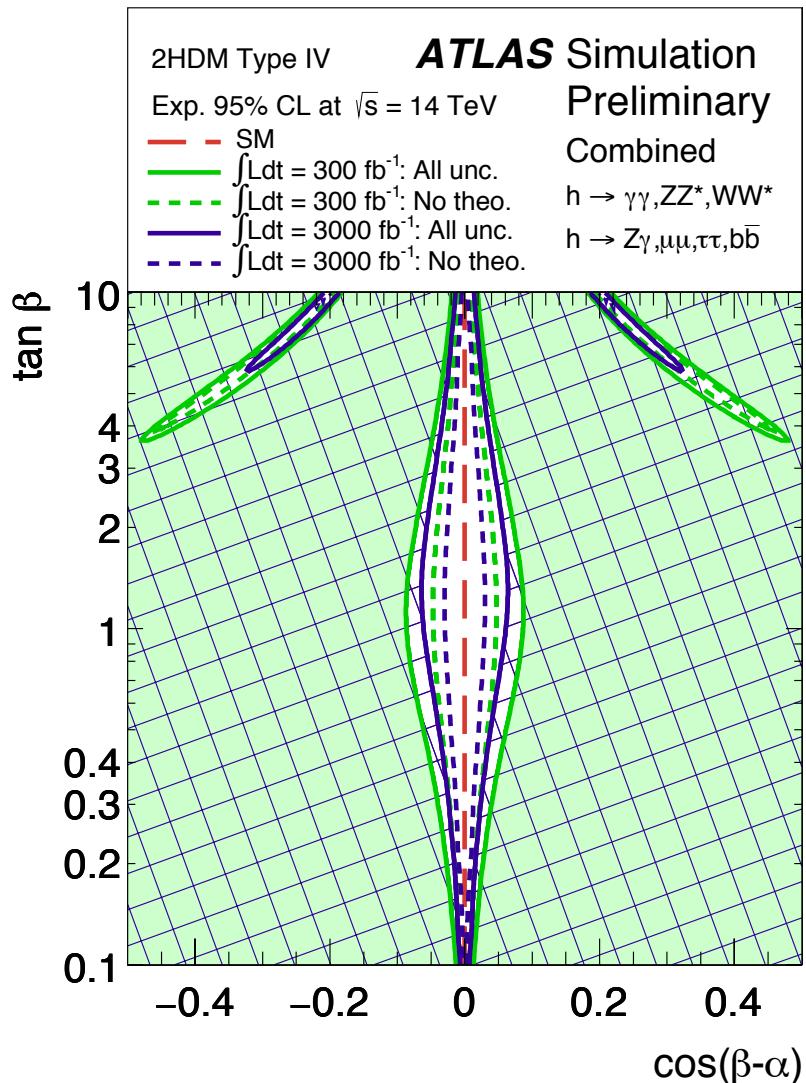
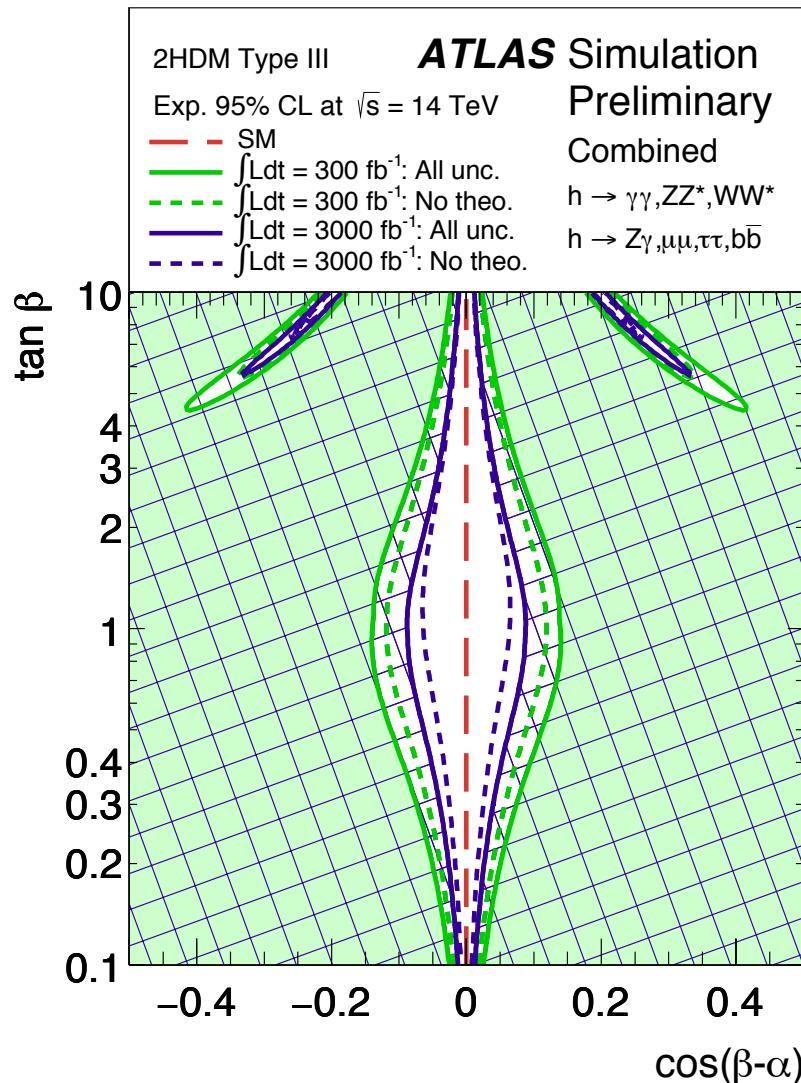
Limits on 2HDM Types I and II (zoomed out)



Limits on 2HDM Types III and IV



Limits on 2HDM Types III and IV (zoomed out)



hh->bb $\gamma\gamma$

- CMS search for non-resonant HH->bb $\gamma\gamma$
 - Cross section at $\sqrt{s}=14$ TeV is 40.2 fb [NNLO]
- Event selection
 - 2 photons: $p_T>40\text{GeV}$ and $p_T>20\text{GeV}$, $|\eta|<2.5$
 - 2 b-tagged jets, CSV medium WP, $p_T>30\text{GeV}$, $|\eta|<2.4$
- Kinematic selection
 - Additional lepton veto
 - Less than 4 jets with $|\eta|<2.4$ and $p_T>30\text{GeV}$
 - ΔR_{bb} and $\Delta R_{\gamma\gamma}$ less than 2.0, min of $\Delta R_{\gamma b}>1.5$
- Two categories considered
 - Both photons in barrel
 - At least one photon in endcap
- Likelihood fit signal extraction
 - 2D fit of M_{bb} and $M_{\gamma\gamma}$
 - Mass fit window of $100\text{GeV} < M_{\gamma\gamma} < 150\text{GeV}$ and $70\text{GeV} < M_{bb} < 200\text{GeV}$ is used
- Parameterized object performance tuned to Phase II detector
 - Preliminary tune as the final tuning need to be obtained from final Phase II samples

$b\bar{b}\gamma\gamma$ event yields

- ATLAS and CMS are discussing analyses to better understand remaining differences and further optimization
- CMS:

Process / Selection Stage	HH	ZH	$t\bar{t}H$	$b\bar{b}H$	$\gamma\gamma + \text{jets}$	$\gamma + \text{jets}$	jets	$t\bar{t}$
Object Selection & Fit Mass Window	22.8	29.6	178	6.3	2891	1616	292	113
Kinematic Selection	14.6	14.6	3.3	2.0	128	96.9	20	20
Mass Windows	9.9	3.3	1.5	0.8	8.5	6.3	1.1	1.1

Table 3: The expected event yields of the signal and background processes for 3000 fb^{-1} of integrated luminosity are shown at various stages of the cut-based selection for the both photons in the barrel region. Mass window cuts are 120 GeV to 130 GeV for $M_{\gamma\gamma}$ and 105 GeV to 145 GeV for M_{bb} . A large fit mass window, 100 GeV to 150 GeV for $M_{\gamma\gamma}$ and 70 GeV to 200 GeV for M_{bb} , is used for the likelihood fit analysis. The statistical uncertainties on the yields are of the order of percent or smaller.

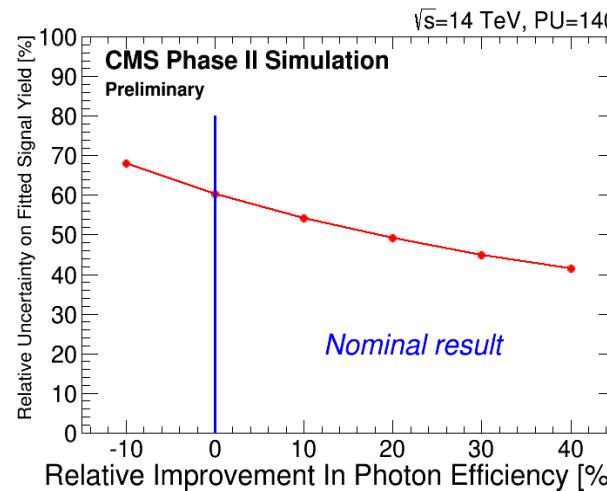
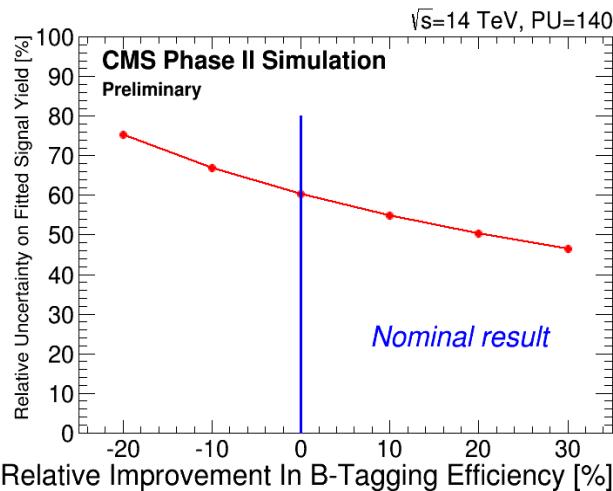
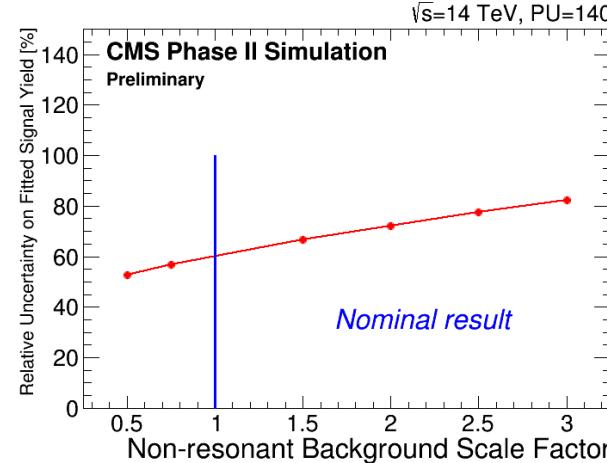
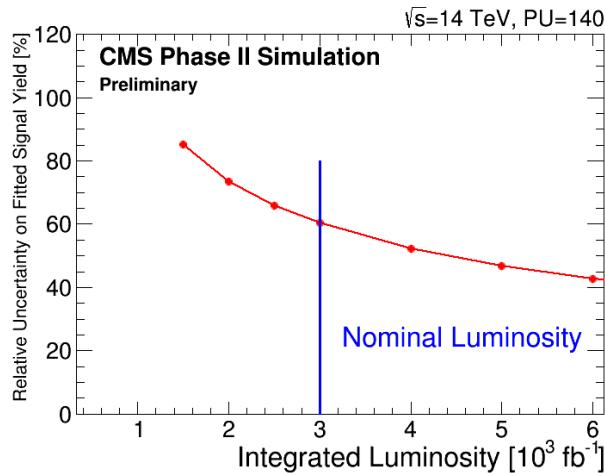
$b\bar{b}\gamma\gamma$ event yields

- ATLAS:

Process at 14 TeV	Expected events with 3000 fb^{-1}
SM $hh \rightarrow b\bar{b}\gamma\gamma$	8.4 ± 0.1
$b\bar{b}\gamma\gamma$	9.7 ± 1.5
$cc\gamma\gamma, b\bar{b}\gamma j, b\bar{b}jj, jj\gamma\gamma$	24.1 ± 2.2
Top background	3.4 ± 2.2
$t\bar{t}h(\gamma\gamma)$	6.1 ± 0.5
$Z(b\bar{b})h(\gamma\gamma)$	2.7 ± 0.1
$b\bar{b}h(\gamma\gamma)$	1.2 ± 0.1
Total background	47.1 ± 3.5
S/\sqrt{B} (barrel+endcap)	1.2
S/\sqrt{B} (split barrel and endcap)	1.3

HH->b_b $\gamma\gamma$ performance

- Average expected uncertainty on CMS di-Higgs cross section measurement



bb and $\gamma\gamma$ mass distributions

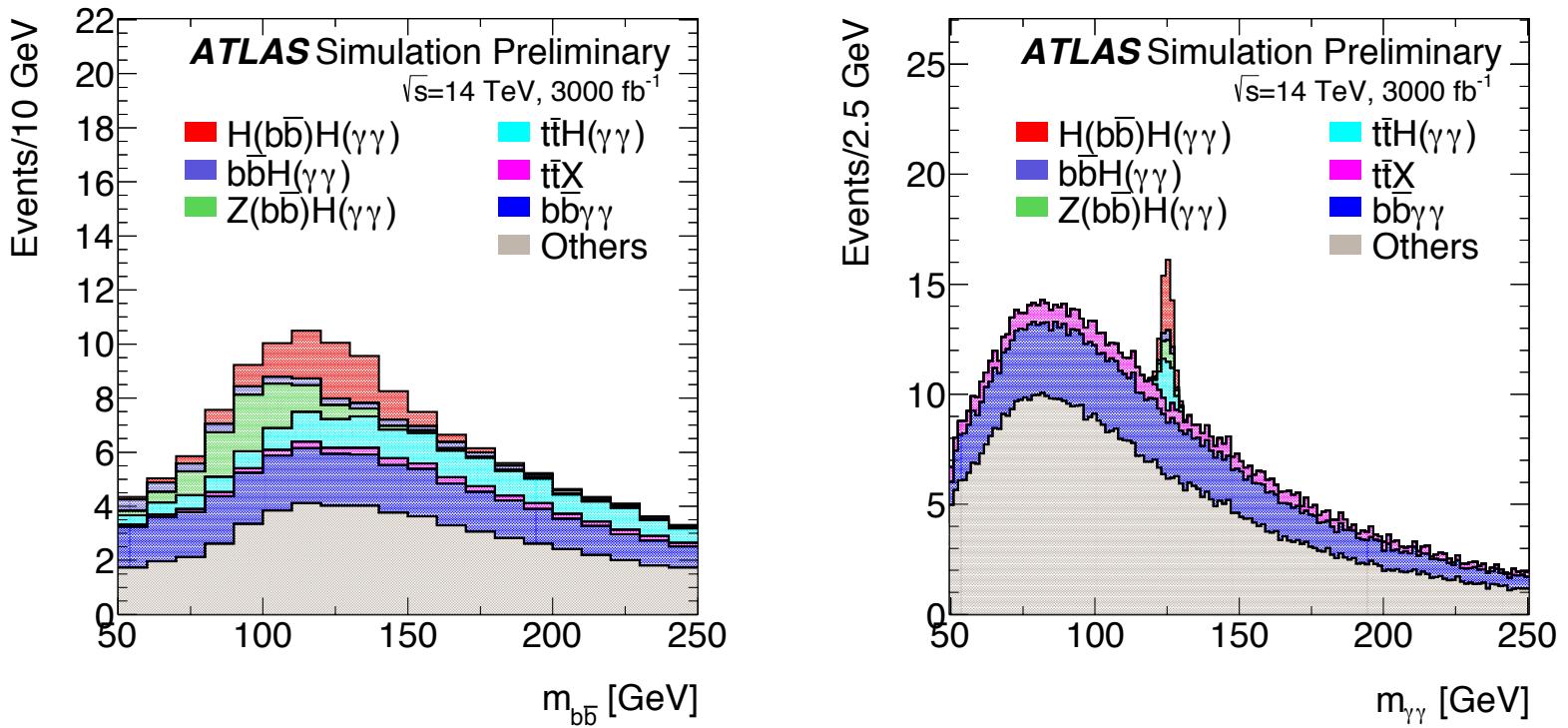


Figure 7: The distributions of $m_{b\bar{b}}$ (a) and $m_{\gamma\gamma}$ (b) for 3000 fb^{-1} after applying all the selection criteria except the $m_{b\bar{b}}$ (a) and $m_{\gamma\gamma}$ (b) mass cuts. The individual shapes of the contributions are obtained using the events surviving the event selection before the mass criteria and angular cuts are applied, but normalized to the number of expected events after the full event selection. The $t\bar{t}X$ contribution includes $t\bar{t}(\geq 1 \text{ lepton})$ and $t\bar{t}\gamma$, while ‘Others’ includes $c\bar{c}\gamma\gamma$, $b\bar{b}\gamma j$, $b\bar{b}jj$ and $jj\gamma\gamma$.

hh->bbWW

- CMS search for $HH \rightarrow b\bar{b} WW \rightarrow b\bar{b} l\bar{l} l\bar{l}$
- Event preselection:
 - 2 b-jets Medium WP, $pT > 30$ GeV
2 leptons, muons: $pT > 20$ GeV, electrons: $pT > 25$ GeV
 - MET > 20 GeV
Clean up cuts (m_{jj} , m_{ll} , ΔR_{jj} , ΔR_{ll} , $\Delta\phi_{jj,ll}$)
- Analysis Optimization:
 - Neural network discriminant from kinematic variables
 - Variables: M_{ll} , M_{jj} , ΔR_{ll} , ΔR_{jj} , ΔR_{jl} , MET, $\Delta\phi_{ll,jj}$, p_{jj} , and MT
- Analysis Setup:
 - Phase II scenario assuming 3000/fb
 - Based on Delphes reconstruction
 - Considering only the main background: $t\bar{t}$
 - The rest of the SM processes are negligible

hh->bbWW Optimization

- CMS
- (Left) p_T^{jj} distribution comparing the HH and $t\bar{t}$ shape differences. Variable used as input for the Neural Network discriminator.
- (Right) $\min(\Delta R_{j,l})$ distribution comparing the HH and $t\bar{t}$ shape differences. Variable used as input for the Neural Network discriminator.

