HL-LHC Higgs Coupling and Rare Decay Prospects

Jonathan Long

University of Michigan

On behalf of the ATLAS and CMS collaborations

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Higgs Hunting 2014

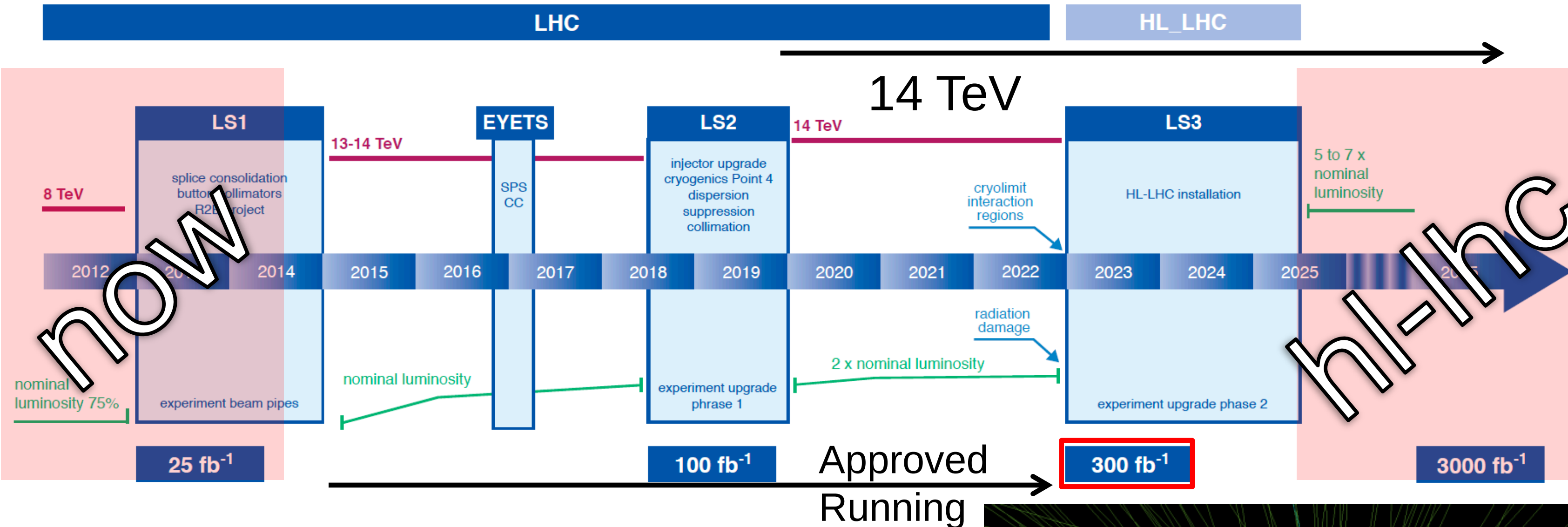
Outline

- HL-LHC Introduction
- Individual channel and rare decay prospects
- Combined coupling prospects

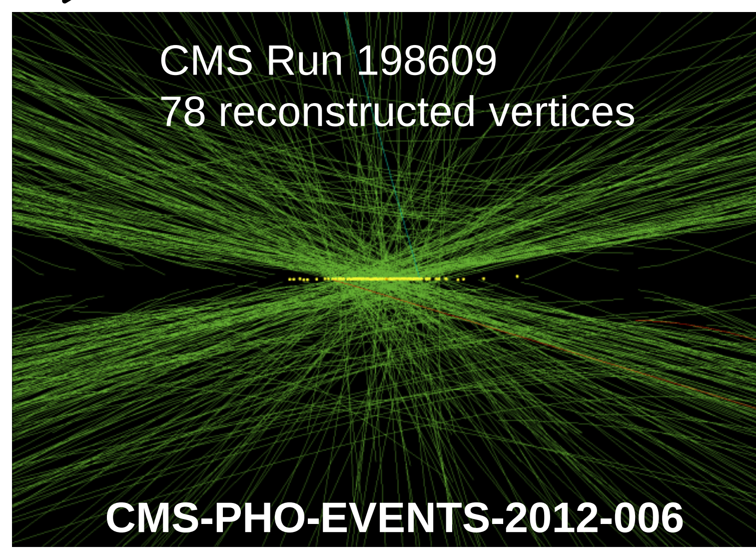
Note:

- These will focus on SM. BSM prospects will be covered by Andre in the next talk.

HL-LHC New LHC / HL-LHC Plan (2025-2035)



- $5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (lumi. leveling)
- 250-300 fb^{-1} per year → 3 ab^{-1}
- 25 ns bunch spacing
- Large event pile-up: ~ 140 inelastic collisions / bunch crossing



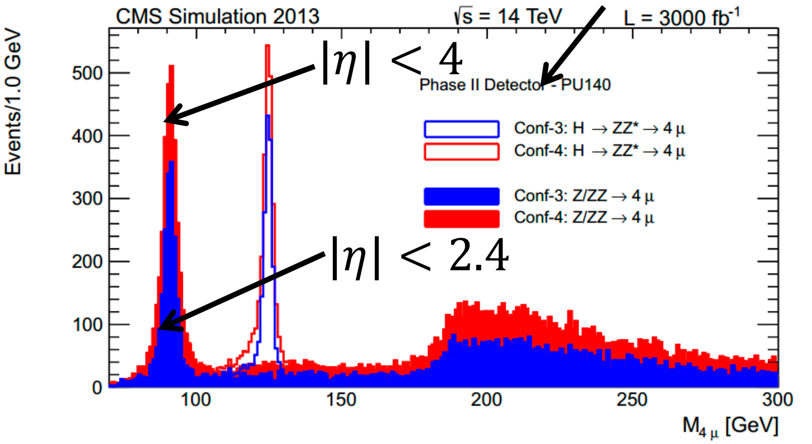
HL-LHC Project Talks: Rossi ICHEP ‘14
Bordy ECFA ‘13

Detector Upgrades (Phase II)

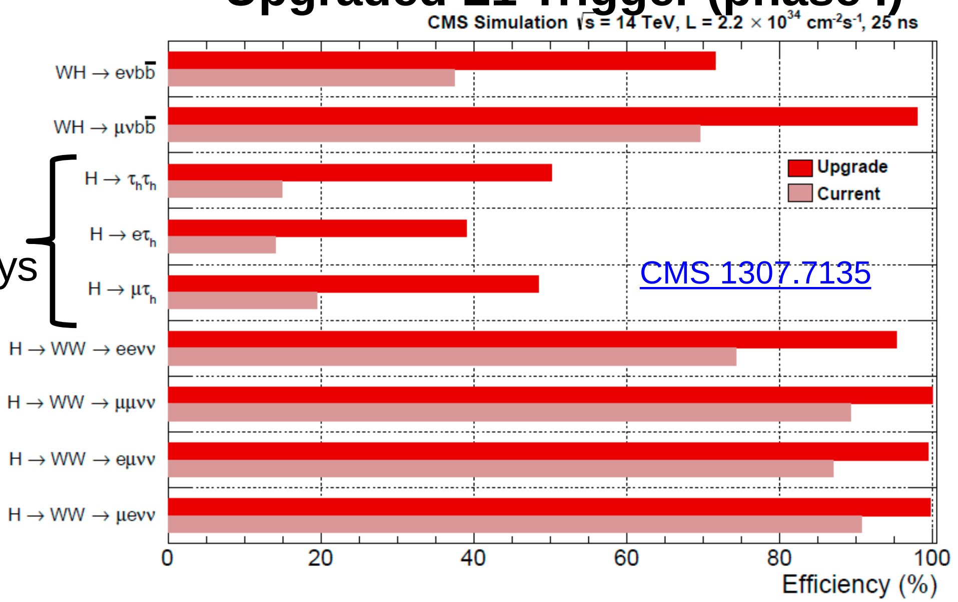
- Detector designs are not final
- Radiation considerations (esp. fwd.)
- ATLAS + CMS
  - New inner trackers ('ITK' in ATLAS)
- CMS – forward calorimeter
- Trigger thresholds are important

CMS-PAS-FTR-13-003

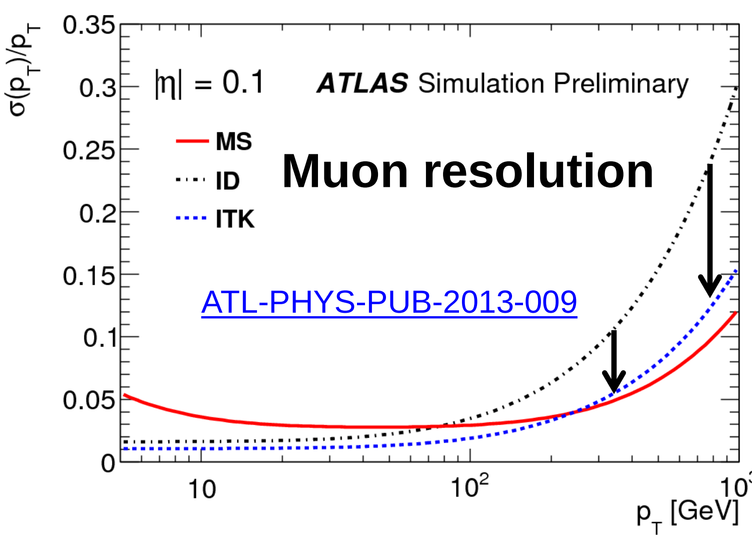
Extend Trk, Calo, Muon



Upgraded L1 Trigger (phase I)



CMS 1307.7135



ATL-PHYS-PUB-2013-009

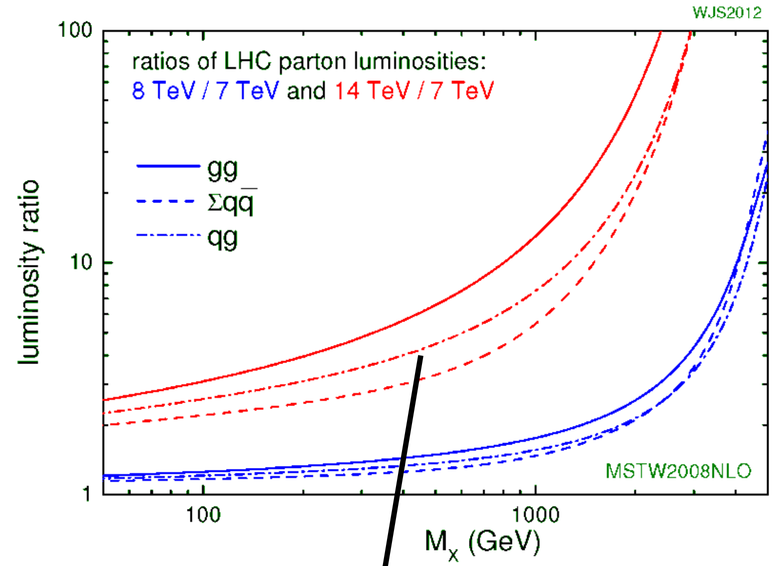
14 TeV…

Signal at 125 GeV

14 TeV and 3 ab^{-1}		
Mode	**14/8**	**Yield**
ggF	2.6	150 M
VBF	2.7	13 M
WH	2.2	4.5 M
ZH	2.3	2.9 M
ttH	4.7	1.8 M
bbH	2.9	1.7 M

LHC HXSWG

Decay	BR
bb	0.58
WW	0.22
gg	0.086
$\tau\tau$	0.063
cc	0.029
ZZ	0.026
$\gamma\gamma$	0.0023
$Z\gamma$	0.0015
$\mu\mu$	0.00022



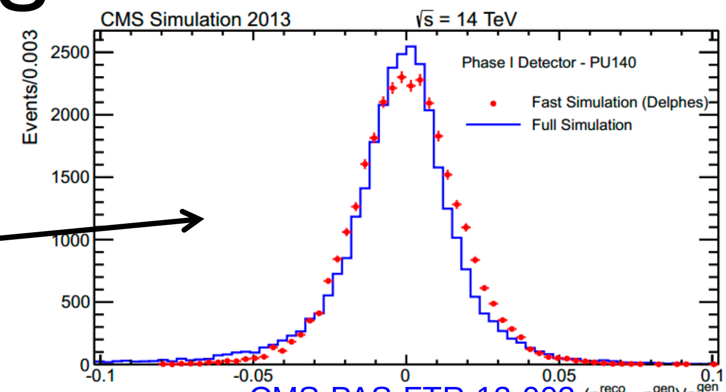
Backgrounds

Process	14/8 Ratio
WW/WZ/Wγ	2.3
ttbar	**4.1**
single top	2-3.4
Z/γ^*	2.2
EW diboson	2.7

Benchmark Assumptions

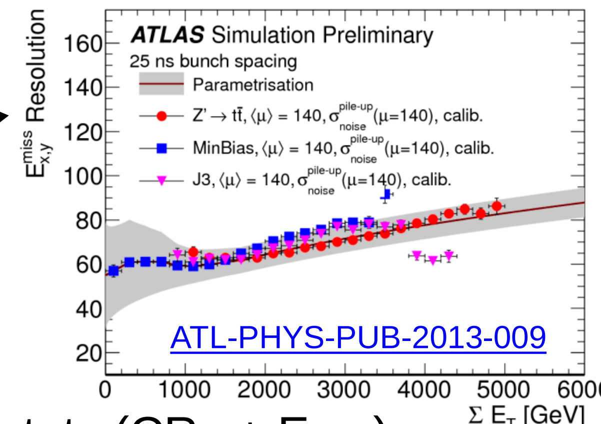
- CMS
  - Extrapolation from current data analyses
    - Checked with some full simulation
  - Systematic scenarios
    - Scenario 1 systematics remain the same as Run I
    - Scenario 2 theory / 2 and scale experimental with 1 / sqrt(L)

Scn 1/2



CMS-PAS-FTR-13-003

- ATLAS
  - Response functions based on full simulation
    - including expected pile-up
  - Systematic scenarios
    - Systematics based on Run I, improvements from stats (CRs + Exp.)
    - No theory systematics



ATL-PHYS-PUB-2013-009

- Assume detector upgrades will keep current performance

Individual Channels

- $H \to ZZ \to 4\ell$
  - ggF, VBF, WH, ZH, ttH
  - cp-mixing
- $H \to \gamma\gamma$
  - ggF, VBF, WH, ZH, ttH New since ECFA '13 ATL-PHYS-PUB-2014-012
- $H \to WW \to \ell\nu\ell\nu$
  - ggF, VBF
- $VHbb$ and $H \to \tau\tau$ New since ECFA '13 ATL-PHYS-PUB-2014-011
- $H \to \mu\mu$
- $H \to Z\gamma$ New since ECFA '13 ATL-PHYS-PUB-2014-006
- Other rare processes

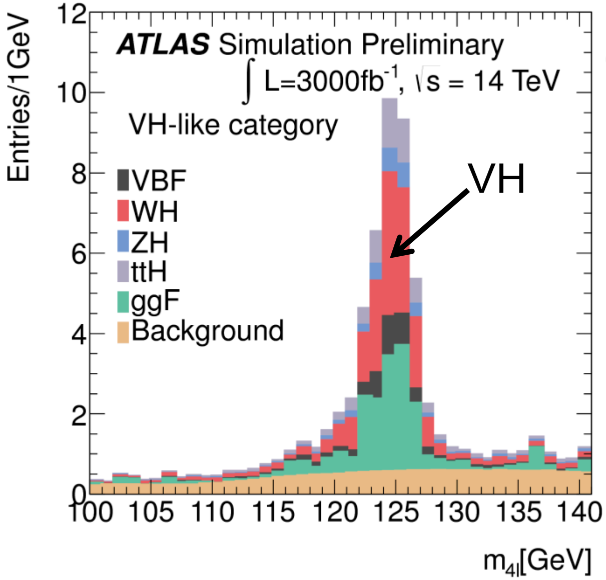
$H \to ZZ \to 4\ell$

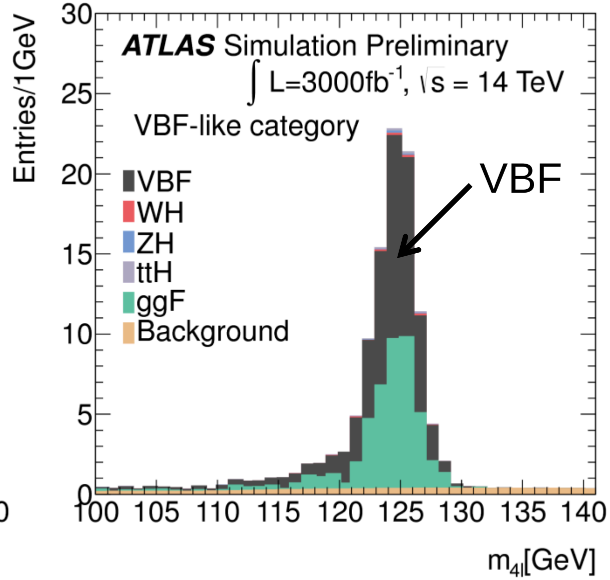
- Very clean channel
- Tag categories with (b-)jets or extra leptons
- Sensitive to all production modes
- CMS expects 7/4% (scn. 1/2) uncert. on μ

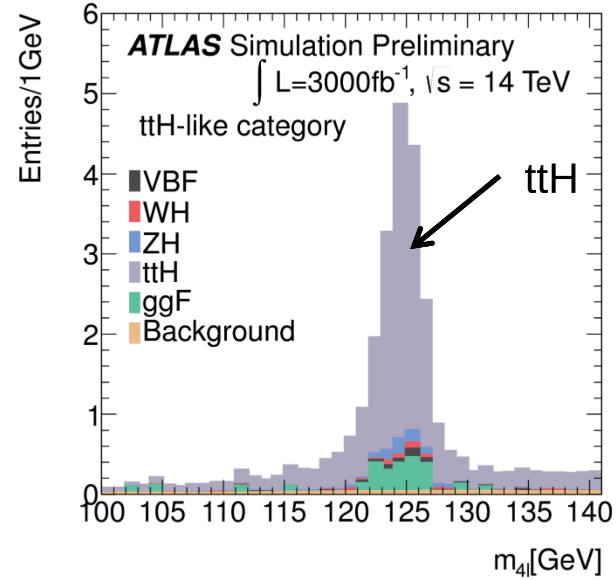
$\Delta\mu/\mu$ atlas	Total	Stat.	Expt. syst.	Theory
production	3000 fb^{-1}			
ggF	0.131	0.025	0.040	0.124
VBF	0.371	0.187	0.225	0.226
WH	0.390	0.375	0.061	0.085
ZH	0.532	0.526	0.038	0.073
$t\bar{t}$H	0.224	0.184	0.034	0.120
Combined	0.100	0.016	0.036	0.093

ATLAS 1307.1427 HIG-14-009-pas

Currently ~25% uncert. on μ







$H \to ZZ$ cp-mixing

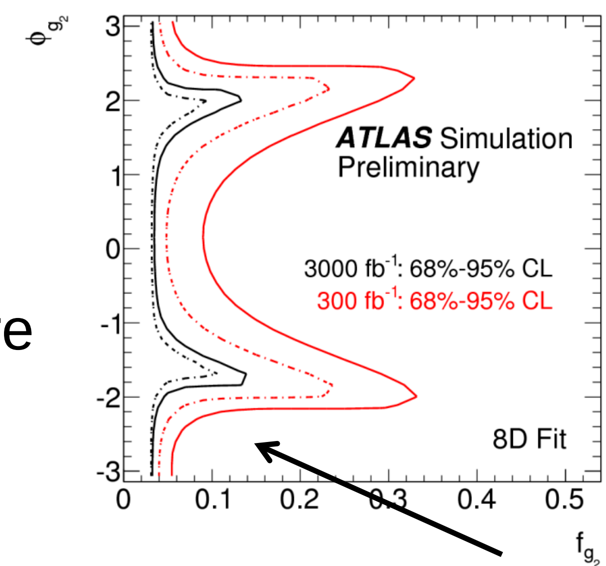
$$A(H \to ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

0^+ 0^-

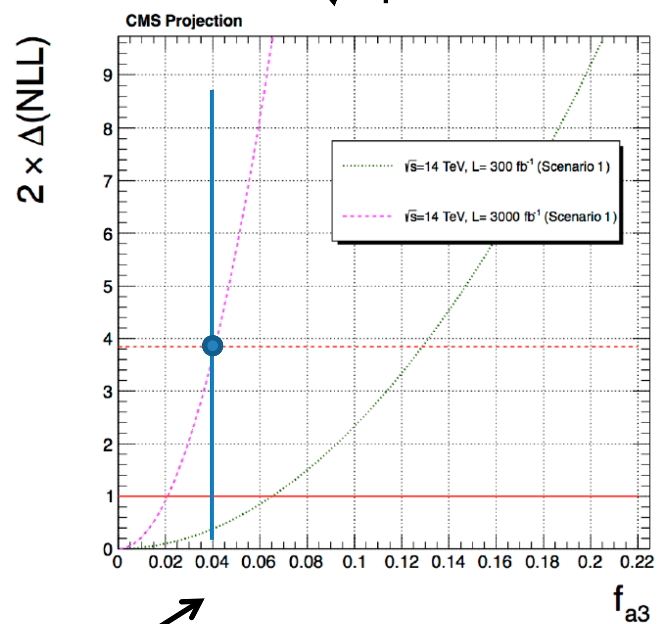
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_3|^2\sigma_3}$$

- Limits on fraction of non-SM 0^+
- Very sensitive to non-SM contributions to HZZ coupling structure

loop-induced cp even



cp odd



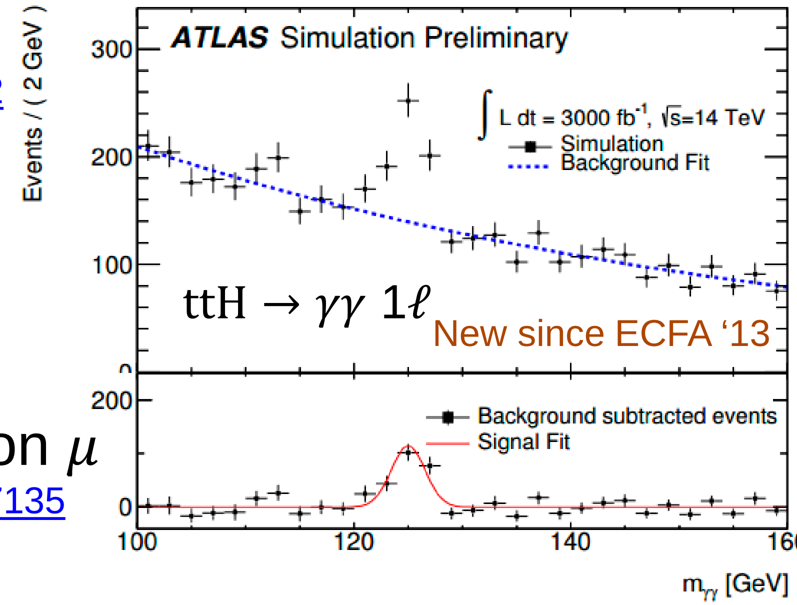
- loop-induced cp-even contribution $f_{g2} < 0.12$
- cp-odd fraction expected limit (f_{a3} or f_{g4}) < 0.04

$H \to \gamma\gamma$

New since ECFA '13
ATL-PHYS-PUB-2014-012

- HL-LHC: likely best ttH sensitivity
- Theory uncertainties are significant
- CMS expects 8/4% (scn. 1/2) uncert. on μ

CMS 1307.7135

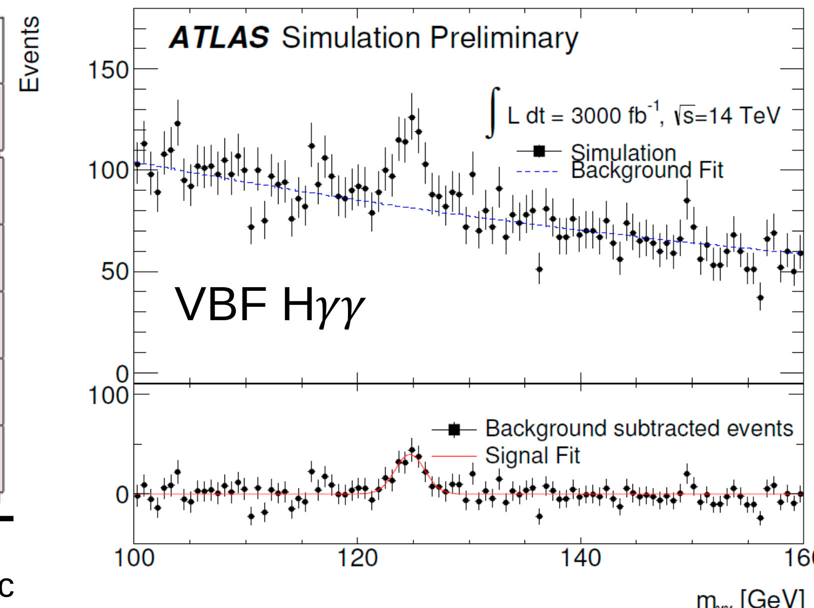


ATLAS 1307.1427 HIG-14-009-pas

Currently ~25% uncert. on μ

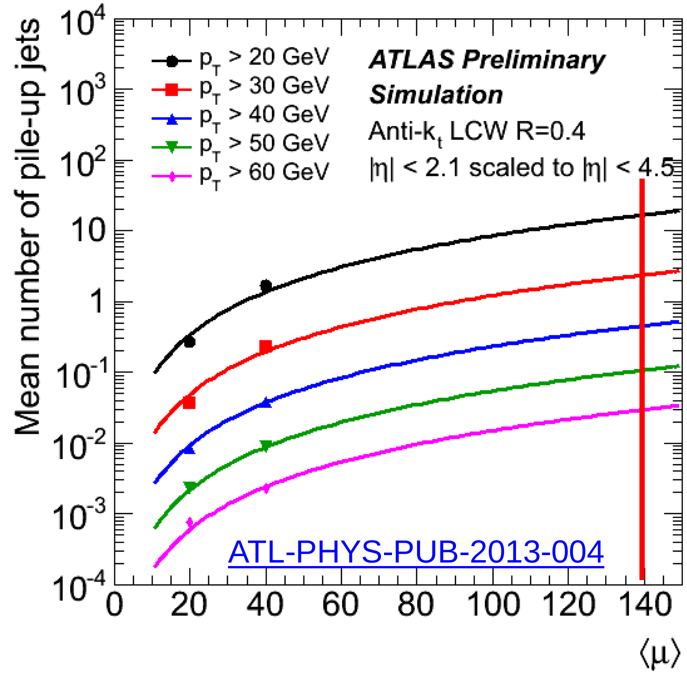
ATLAS	$t\bar{t}H$	WH	ZH	VBF
Significance	8.2	4.2	3.7	3.8

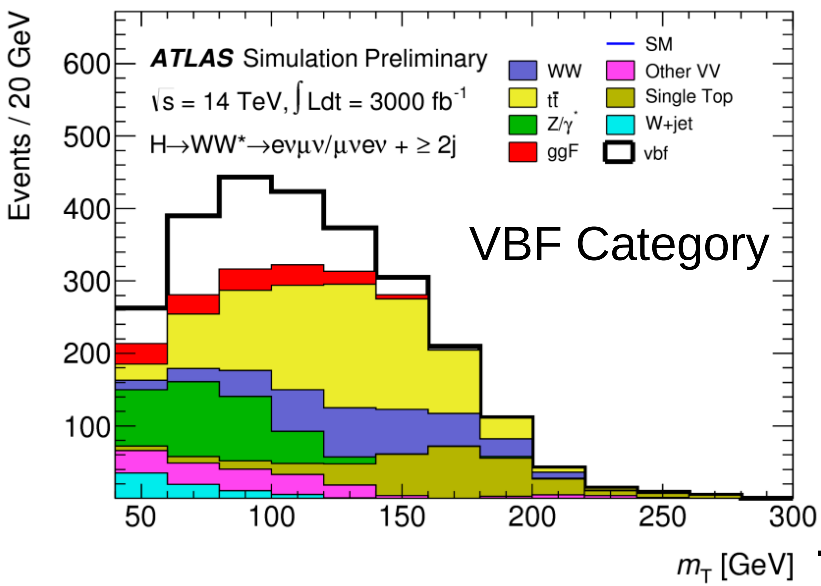
	ATLAS $\Delta\hat{\mu}/\hat{\mu}$ (%)			
Production mode	Total	Statistical	Experimental	Theoretical
$t\bar{t}H$	$^{+21}_{-17}$	$^{+13}_{-12}$	$^{+5}_{-4}$	$^{+17}_{-11}$
WH	$^{+26}_{-25}$	$^{+21}_{-20}$	$^{+13}_{-12}$	$^{+10}_{-8}$
ZH	$^{+35}_{-31}$	$^{+32}_{-29}$	$^{+7}_{-7}$	$^{+12}_{-8}$
ggF	$^{+19}_{-14}$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



$H \to WW \to \ell\nu\ell\nu$

- Pile-up conditions and ttbar rate increase are difficult (jet thresholds)
- Will be dominated by systematics (esp. theory)
- Control regions and dominant exp. systematics benefit from statistics
- CMS expects 7/4% (scn. 1/2) μ uncert.





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

ATLAS 1307.1427 HIG-14-009-pas

Currently ~25% uncert. on μ

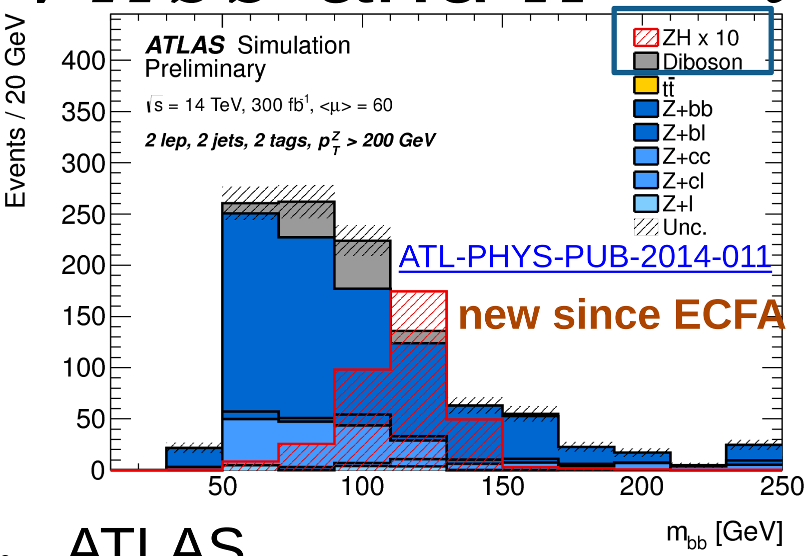
ATL-PHYS-PUB-2013-014

CMS 1307.7135

$VHbb$ and $H \to \tau\tau$

ATLAS-CONF-2013-108 HIG-14-009-pas

Currently ~30% uncert. on μ



$H \to \tau\tau$

- CMS expects 8/5% (scn. 1/2) uncert. on μ
- ATLAS uses older European Strat. numbers for projection

- ATLAS
  - First HL-LHC projection based on current data analysis
  - Conservatively expect 5.9σ with uncertainty on μ of 0.19
  - With improvements in b-tagging and an MVA signal selection expect 8.8σ and an uncertainty on μ of 0.14
- CMS expects 7/5% (scn. 1/2) μ uncert.
- Important input for total width in coupling fits

HIG-14-009-pas

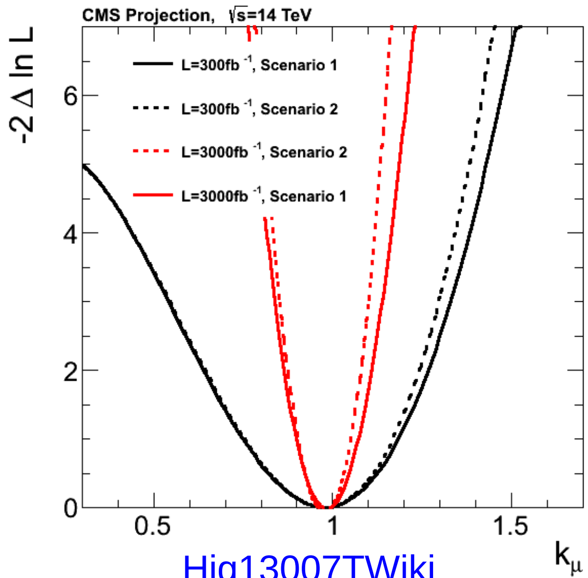
Currently ~50% uncert. on μ

ATLAS 1406.7663 HIG-13-007-pas

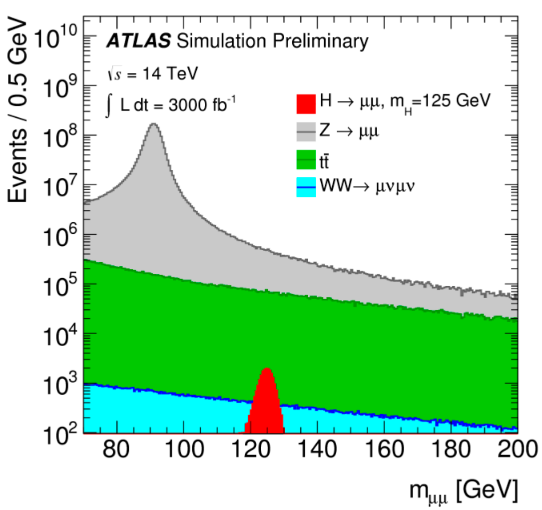
Current limit 7 times SM

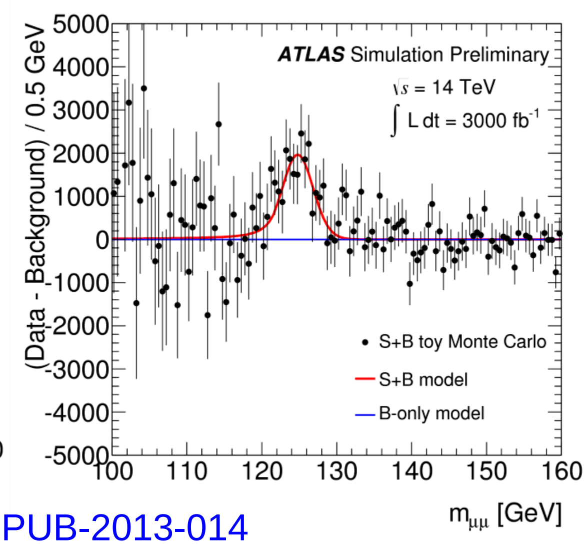
$H \rightarrow \mu\mu$

- Sensitivity to second generation couplings
- CMS
  - Expected 7.9σ at 3 ab^{-1} (5 with 1.2 ab^{-1})
  - Uncert. on μ 20/14% (scn. 1/2)
- ATLAS expects 7σ and 21%
- ttH production should be visible



Hig13007TWiki





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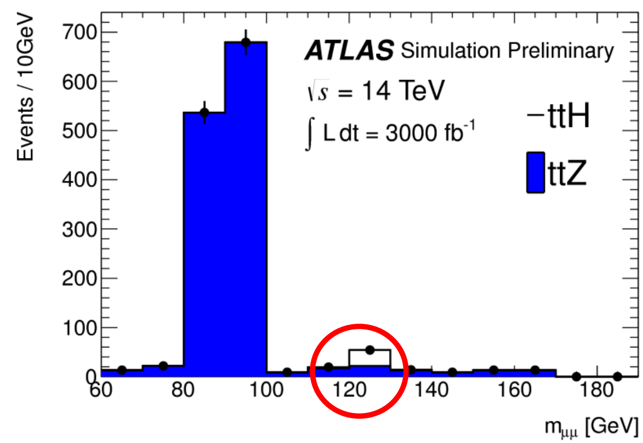


$H \rightarrow Z\gamma$

[ATLAS-CONF-2013-009](#) [CMS 1307.5515](#)

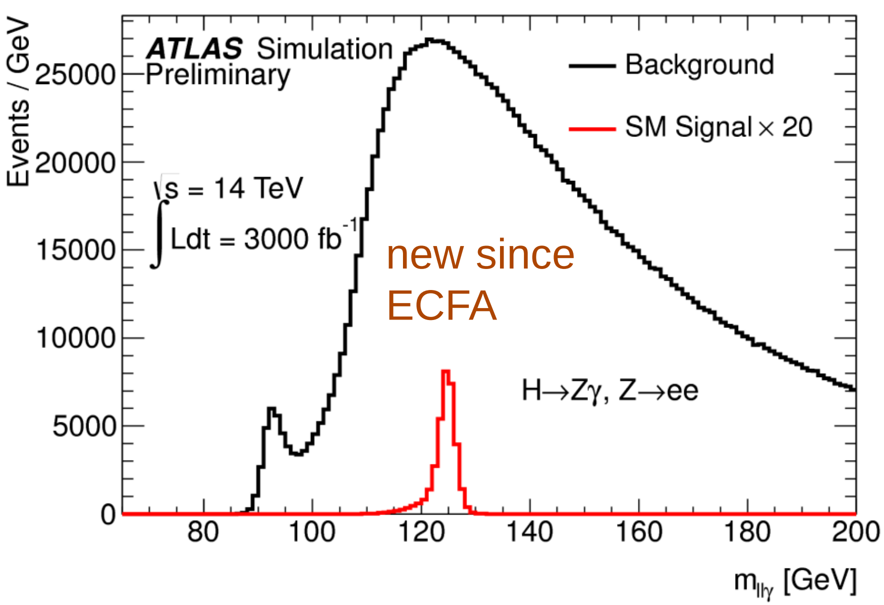
Current limit ~20 times SM

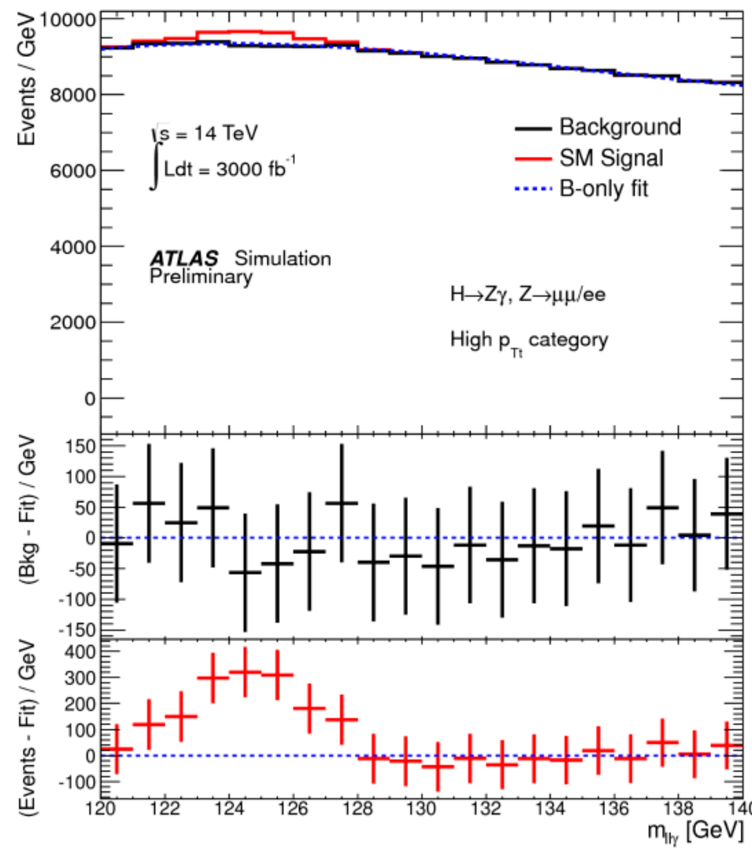
- Sensitive to new particles in loop
- CMS expects 24/20% (scn. 1/2) μ uncert.

  CMS 1307.7135
- ATLAS
  - Expect 3.9σ with 3 ab^{-1}
  - 0.25(stat)0.16(sys)→30%

ATL-PHYS-PUB-2014-006

New since ECFA





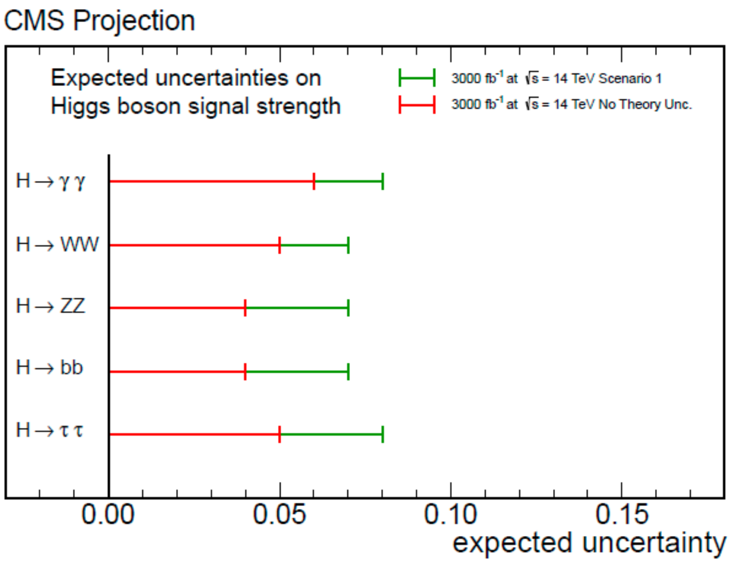
Other rare processes?

- bbH production is a similar order to ttH
  - Large uncertainty on XS
  - More difficult without lepton tag?
- Hcc is ~3% of width
  - Access through $\mathrm{H} \rightarrow J/\psi\ \gamma$?
    - Low rate ~50 events of $\mu\mu + ee$ ATLAS+CMS 3 ab^{-1} 1306.5770
- Hee
  - CMS 8 TeV expected upper limit is 1.4 times H$\mu\mu$ HIG-13-007

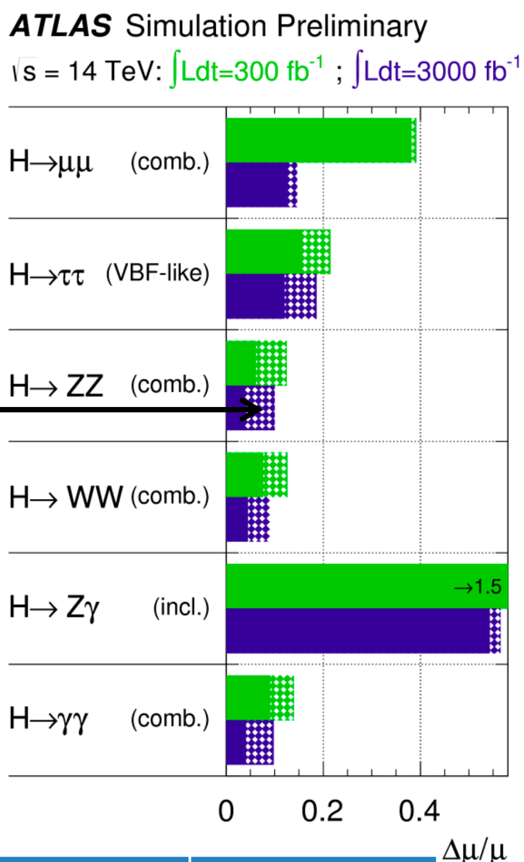
Signal Strength Precision

Current Results ATLAS-CONF-2014-009 HIG-14-009-pas

- ~ 2x improvement over 300 fb^{-1}
- ATLAS drops theory syst.
- CMS theory/2 and scales sys with 1 / sqrt(L)



Hashed area est. contribution from current theory sys.



***Coupling comb. does not contain new ATLAS bb, $Z\gamma$, or $\gamma\gamma$ (VH, ttH) projections**
**** new input**

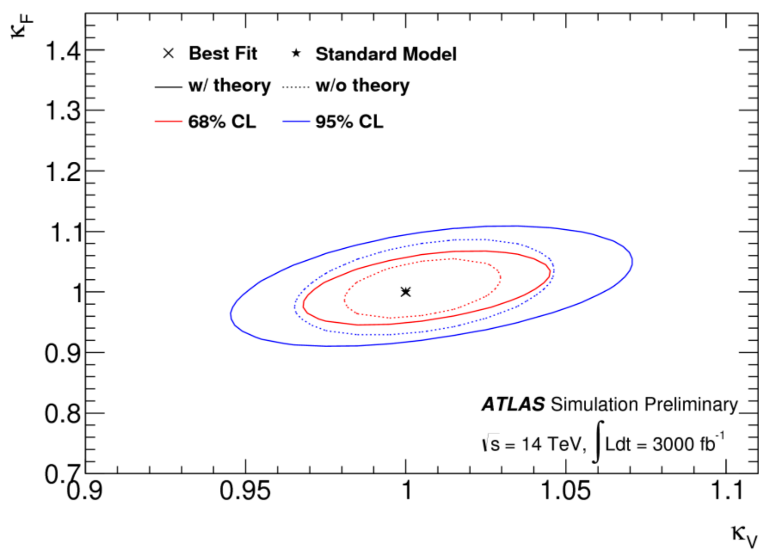
	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$
CMS	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[14, 20]
ATLAS	*[4, 10]	[5, 9]	[4, 10]	**14	[12, 19]	**30	[12, 15]

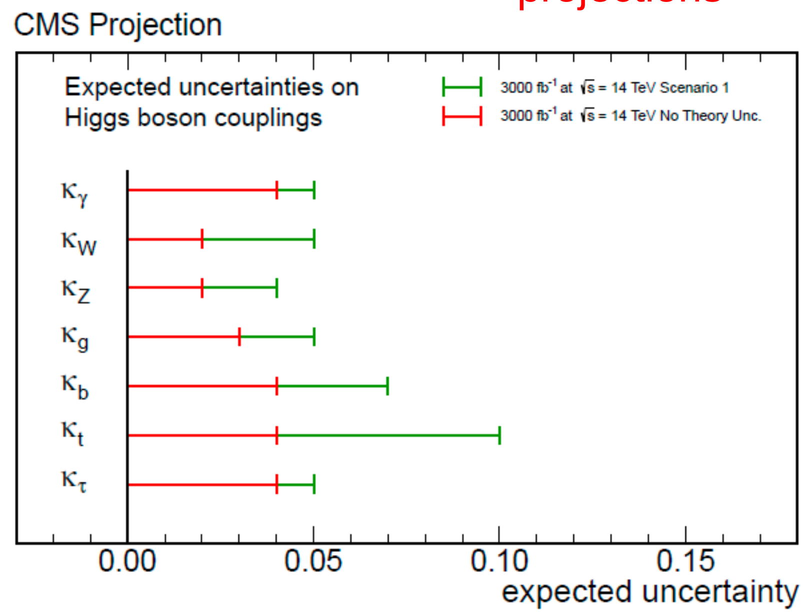
Couplings

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

- ATLAS $\mathbf{k}_b$ fixed from $\mathbf{k}_\tau$
- Total width assumed to be sum of components
- ~2 more precise than with 300 fb^{-1}
- Likely best direct (ttH) k_t sensitivity for a while

*Coupling comb. does not contain new ATLAS bb, $Z\gamma$, or $\gamma\gamma$ (VH, ttH) projections



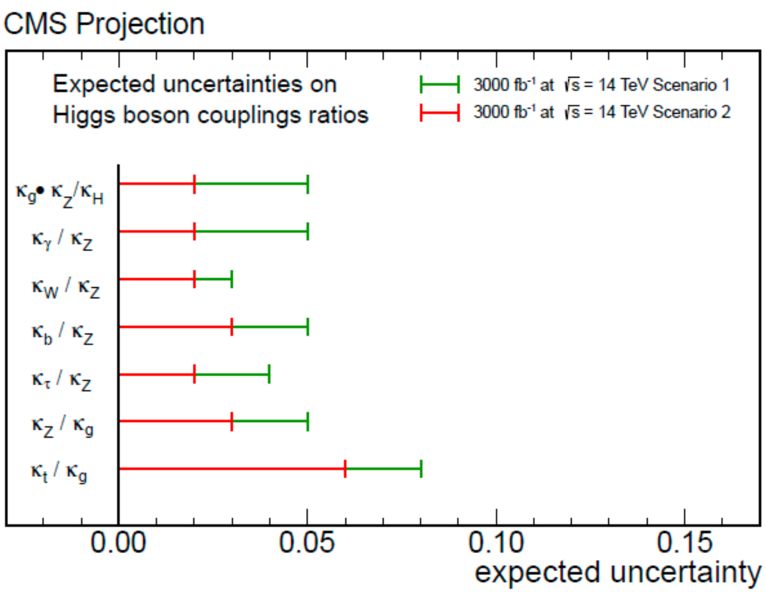


	$\mathbf{k}_\gamma$	$\mathbf{k}_W$	$\mathbf{k}_Z$	$\mathbf{k}_g$	$\mathbf{k}_b$	$\mathbf{k}_t$	$\mathbf{k}_\tau$	$\mathbf{k}_{Z\gamma}$	$\mathbf{k}_\mu$
CMS	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]
ATLAS	*[5, 9]	[4, 6]	[4, 6]	[5, 7]	*	[8, 10]	[10, 15]	*[29, 30]	[8, 11]

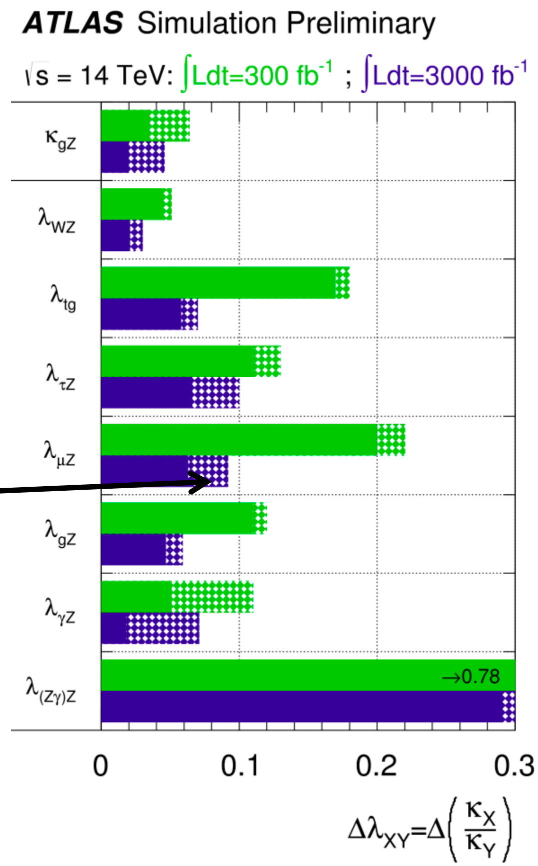
Coupling Ratios

*Coupling comb. does not contain new ATLAS bb, $Z\gamma$, or $\gamma\gamma$ (VH, ttH) projections

- Ratios don't rely on assumptions of total width
- Large improvements over current results, esp. with lower theory uncertainties



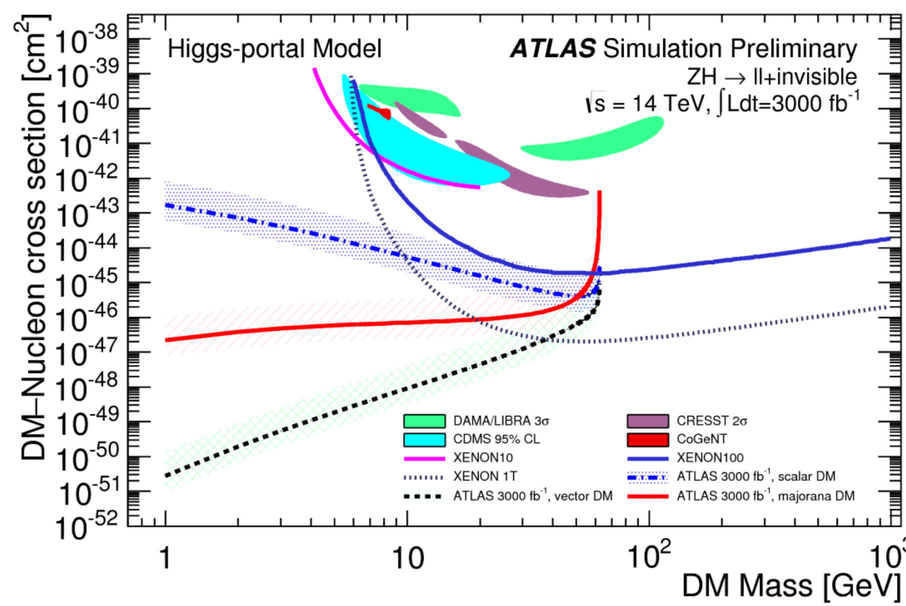
Hashed area est. contribution from current theory sys.



	$k_\gamma k_Z/k_H$	k_γ/k_Z	k_W/k_Z	k_b/k_Z	k_τ/k_Z	k_Z/k_g	k_t/k_g	k_μ/k_Z	$k_{Z\gamma}/k_Z$
CMS	[2, 5]	[2, 5]	[2, 3]	[3, 5]	[2, 4]	[3, 5]	[6, 8]	[7, 8]	[12, 12]
ATLAS	*[2, 5]	*[2, 7]	[2, 3]	*	[7,10]	[5, 6]	[6, 7]	[6, 9]	*[29, 30]

Higgs Invs (ZH->invs)

- Direct search for invisible branching fraction
- Complements indirect limit from Higgs couplings
- Exp BR Limit:
  - Atlas 16%/8% (conservative / realistic)
  - CMS 11/7% (scn. 1/2)
- Higgs-portal interpretation



CMS 1404.1344

Current direct upper limit ~58% on Invs BR

ATLAS-CONF-2013-108

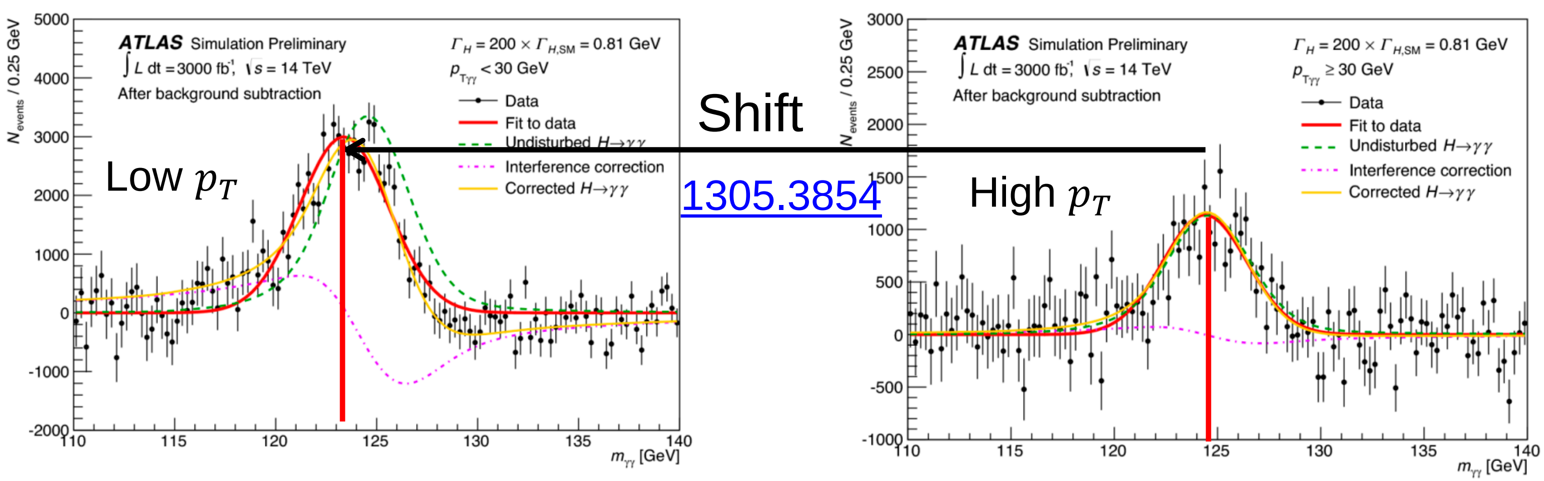
Current indirect upper limit from couplings ~37% on Invs BR

Total Width

Run I Data

- CMS current direct limit with $H\gamma\gamma < 2.4$ GeV $(\sim 600 \cdot \Gamma_{SM})$ 1407.0558
- ATLAS current direct limit with $\mathrm{HZZ} < 2.6$ GeV 1406.3827
- Constraints on width from off-shell production with HZZ
  - CMS currently measures $< 5.4 \cdot \Gamma_{SM}$ 1405.3455
  - ATLAS currently measures $< 5.6 - 9 \cdot \Gamma_{SM}$ ATLAS-CONF-2014-042
- ATLAS projections for limit through interference $\sim 50 \cdot \Gamma_{SM}$

ATL-PHYS-PUB-2013-014



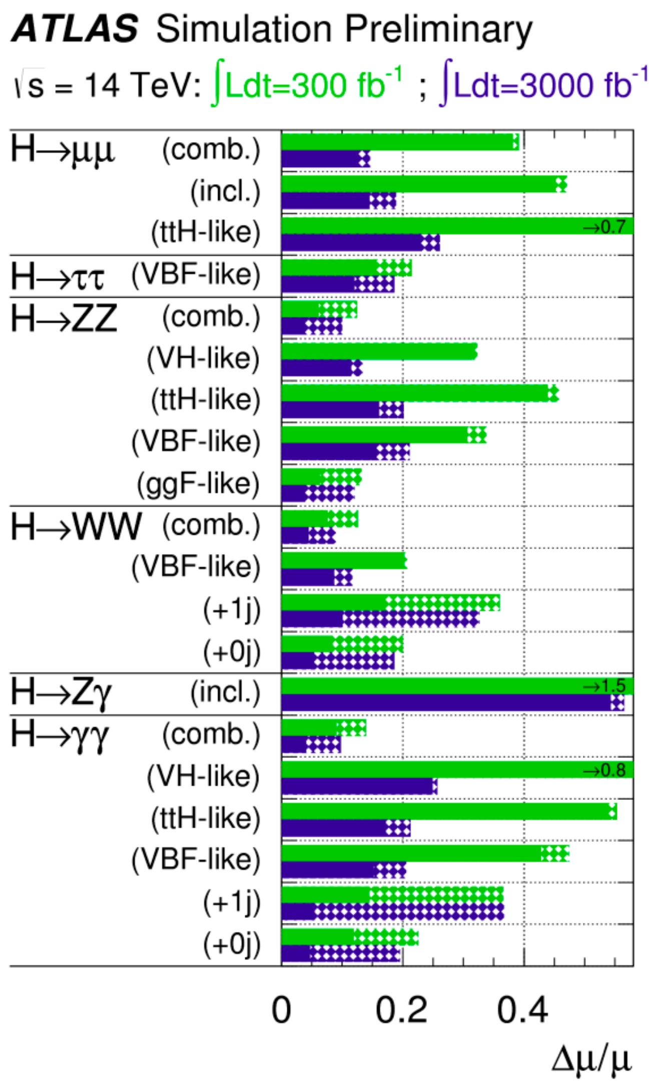
Conclusion

- Coupling measurements in general ~2 times more precise than with 300 fb^{-1}
- The HL-LHC should allow for evidence of several rare processes, e.g. ttH, $H \to \mu\mu$, and $H \to Z\gamma$
- Theory uncertainties will play a dominant role in some channels, e.g. $H \to ZZ$ and $H \to \gamma\gamma$
- With more data, ATLAS and CMS should learn how to work in the expected large pile-up environment and how to extract the full physics potential of the HL-LHC, hopefully surpassing these projections, as happened with Run I

Thanks!

Backup

ATLAS Signal Strength Breakdown



ATLAS $HZZ, WW, \gamma\gamma$ Expected Yields

ZZ

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

atlas

$\gamma\gamma$

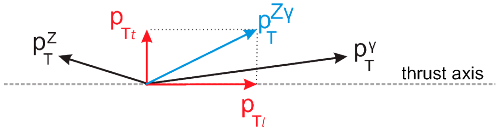
Category	Inclusive	0-jet	1-jet	2-jet
ATL-PHYS-PUB-2013-014	$3000\ fb^{-1}$			
S	$8.08 \cdot 10^4$	$4.92 \cdot 10^4$	$1.25 \cdot 10^4$	$2.13 \cdot 10^2$
B	$4.06 \cdot 10^6$	$3.16 \cdot 10^6$	$3.00 \cdot 10^5$	$8.02 \cdot 10^2$
S/B (%)	1.99	1.55	4.16	26.56
VBF/(VBF+ggF)	0.07	0.03	0.14	0.70

WW

N_{jet}	N_{bkg}	N_{signal}	N_{ggF}	N_{VBF}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z+jets}	N_{W+jets}
= 0	366450	41840	40850	990	172950	32000	96600	32150	4150	28600
= 1	259610	22375	20050	2325	68810	21570	119560	28110	11200	10360
≥ 2	1825	590	90	500	300	120	745	245	335	80

ATLAS Zgamma and Hmm Expected Yields

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



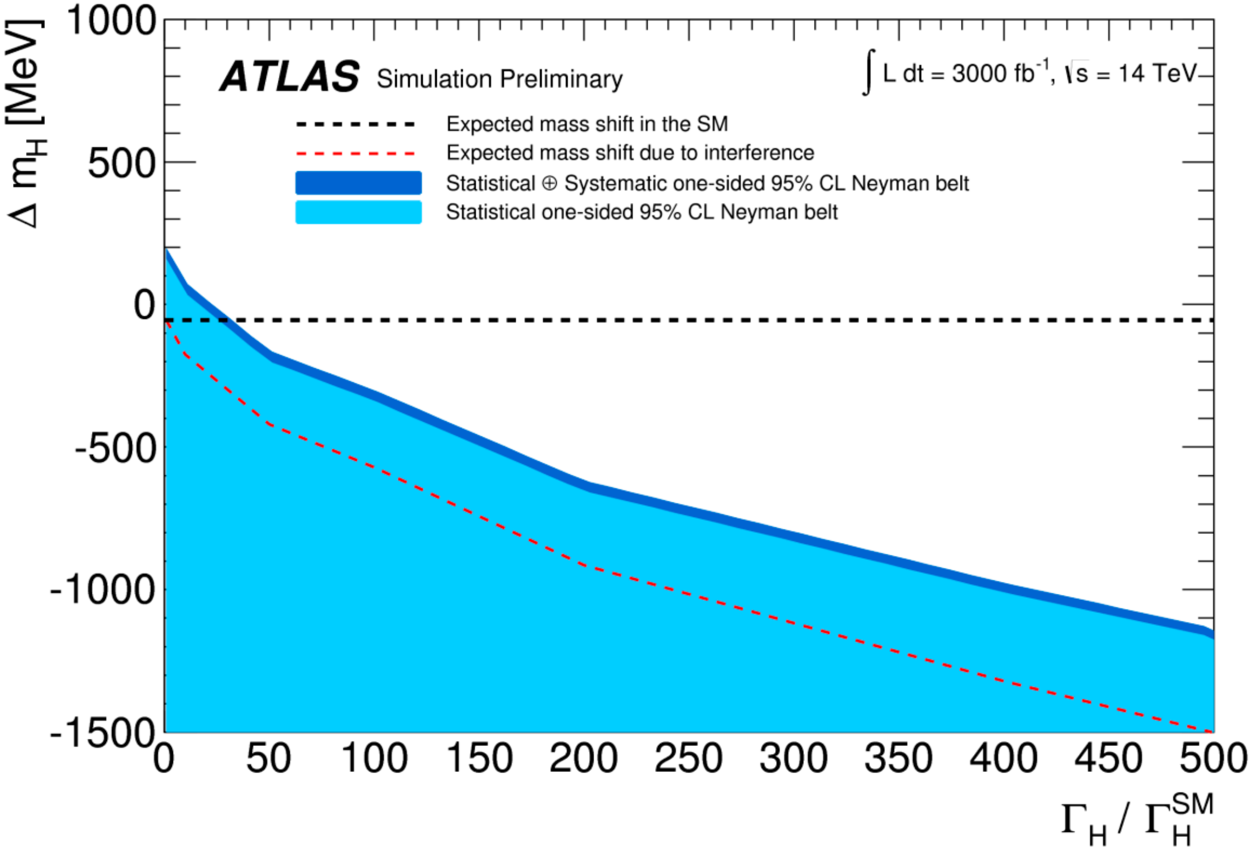
$\mathcal{L}$ [fb^{-1}] Hmm	3000
N_{ggH}	15100
N_{VBF}	1250
N_{WH}	450
N_{ZH}	270
N_{ttH}	180
N_{Bkg}	5640000
Δ^{sys}_{Bkg} (model)	110
Δ^{sys}_{Bkg} (fit)	620
Δ^{stat}_{S+B}	2380
Signal significance	7.0σ
$\Delta\mu/\mu$	21%

CMS Coupling Comb Inputs

H decay	prod. tag	exclusive final states	cat.	res.	ref.
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	1-2%	[6]
	VBF-tag	$\gamma\gamma + (jj)_{\text{VBF}}$	2	<1.5%	
	VH-tag	$\gamma\gamma + (e, \mu, \text{MET})$	3	<1.5%	
	ttH-tag	$\gamma\gamma$ (lep. and had. top decay)	2	<1.5%	[23]
$ZZ \to 4\ell$	$N_{\text{jet}} < 2$	4e, 4μ, $2e2\mu$	3	1-2%	[7]
	$N_{\text{jet}} \geq 2$		3		
$WW \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\times$ (0 or 1 jets)	4	20%	[8]
	VBF-tag	$\ell\nu\ell\nu + (jj)_{\text{VBF}}$ (DF or SF dileptons)	2	20%	[24]
	WH-tag	$3\ell3\nu$ (same-sign SF and otherwise)	2		[25]
$\tau\tau$	0/1-jet	$(e\tau_h, \mu\tau_h, e\mu, \mu\mu) \times$ (low or high p_T^{τ})	16	15%	[10]
	1-jet	$\tau_h\tau_h$	1		
	VBF-tag	$(e\tau_h, \mu\tau_h, e\mu, \mu\mu, \tau_h\tau_h) + (jj)_{\text{VBF}}$	5		
	ZH-tag	$(ee, \mu\mu) \times (\tau_h\tau_h, e\tau_h, \mu\tau_h, e\mu)$	8		[26]
	WH-tag	$\tau_h\mu\mu, \tau_h e\mu, e\tau_h\tau_h, \mu\tau_h\tau_h$	4		
bb	VH-tag	$(\nu\nu$, ee, $\mu\mu$, $e\nu$, $\mu\nu$ with 2 b-jets$)\times$x	13	10%	[27]
	ttH-tag	(ℓ with 4, 5 or $\geq$6 jets) $\times$ (3 or $\geq$4 b-tags);	6		[28]
		(ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-jets)	3		
$Z\gamma$	inclusive	$(ee, \mu\mu) \times (\gamma)$	2		[29]
$\mu\mu$	0/1-jets	$\mu\mu$	12	1-2%	[30–32]
	VBF-tag	$\mu\mu + (jj)_{\text{VBF}}$	3		
invisible	ZH-tag	$(ee, \mu\mu) \times$ (MET)	2		[21]

ATLAS Width Expected Limit

Through $\gamma\gamma$ interference



ATLAS HWW ES vs ECFA Syst.

	$N_{\text{jet}} = 0$			$N_{\text{jet}} = 1$			$N_{\text{jet}} \geq 2$		
	14 TeV	ES	8 TeV	14 TeV	ES	8 TeV	14 TeV	ES	8 TeV
WW	1.5	5	5	5	-	6.5	10	10	30
VV	2	15	15	5	-	20	10	20	20
$t\bar{t}$	7	7	12	8	-	23	10	15	33
$tW/tb/tqb$	7	7	12	8	-	23	10	15	33
Z+jets	10	10	15	10	-	18	10	10	20
W+jets	20	30	30	20	-	30	20	100	30

Table 9: The total systematic uncertainty (in %) for the background processes. The uncertainties used in the last upgrade study are shown in the columns labelled "ES". The uncertainties used in the latest public 8 TeV results are also quoted. The $N_{\text{jet}} = 1$ channel was not considered in the previous analysis.