Higgs prospects at HL-LHC

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On behalf of the ATLAS and CMS Collaborations

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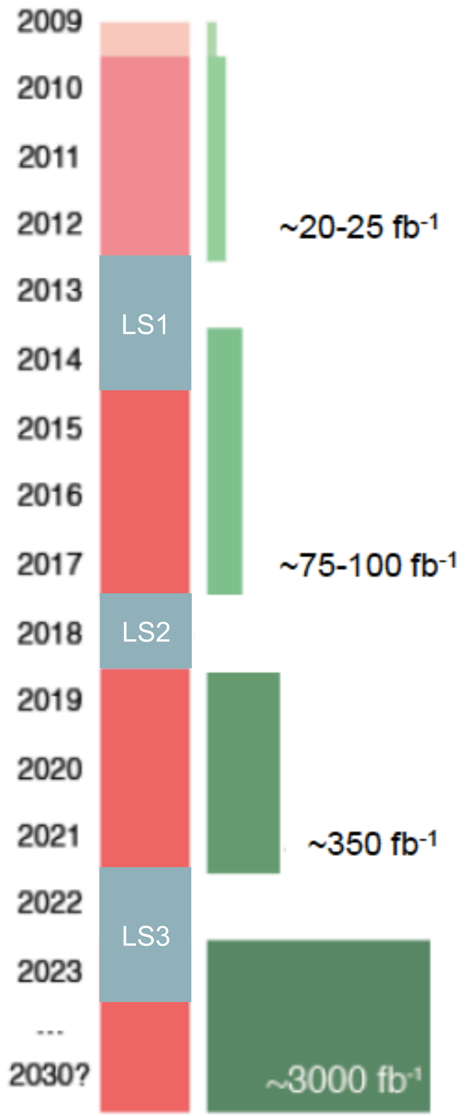
Outline

- HL-LHC: timelines, targets and assumptions
- Higgs properties
  - Rare Higgs processes
  - Couplings to fermions and bosons
  - Self-couplings
- Vector boson scattering
- Conclusions

The HL-LHC programme



More details on LHC upgrades in plenary talk by Mike Lamond and in several parallel sessions

- Start at 2024 after a ~2-year shutdown (LS3)
  - LHC: new IR magnets, crab cavities, …
- LHC peak luminosity: ~5e34
  - ~140 pp collisions per bunch crossing
- Collect ~250-300fb^{-1}/year for a total of ~3000fb^{-1} per experiment by the early 2030s
- An ambitious programme of detector upgrades proposed by ATLAS and CMS to maintain/improve current performance
  - In trigger, offline reconstruction, identification of physics objects
  - Also to address key experimental systematics that would limit in particular the Higgs studies

Assumptions and projections

- Projections use realistic/conservative assumptions about detector performance at HL-LHC and the evolution of systematic uncertainties
  – Impressive progress in minimizing the impact of pile-up during 2012
  – In 2012, <μ> up to ~35; extrapolation to <μ>~140 not huge

- ATLAS performed generator-level studies, applying resolution and efficiency parameterisation functions for the HL-LHC conditions
  – With realistic/conservative assumptions for the effects of pile-up
    - E.g. full sim. studies of b-tagging with tracker upgrade now show better performance

- CMS extrapolate current results with different assumptions
  (1) Pessimistic: experimental and theory systematics as of today
  (2) Optimistic: experimental systematics scale as $1/\sqrt{L}$, theory systematics halved

- Past experience: projections almost invariably proved conservative!

Rare Higgs processes

- H→μμ
  - ATLAS finds ~2σ with 300fb^{-1} and ~6σ with 3000fb^{-1}
  - CMS should achieve similar (or better) sensitivity
- ttH, H→μμ (ATLAS)
  - Involves only fermion couplings
  - Only ~30 events in 3000fb-1, but very pure: s/b~1
- ttH, H→γγ (ATLAS)
  - Another rare, but relatively pure process (s/b~20%)
  - Important probe of top Yukawa coupling

H→μμ

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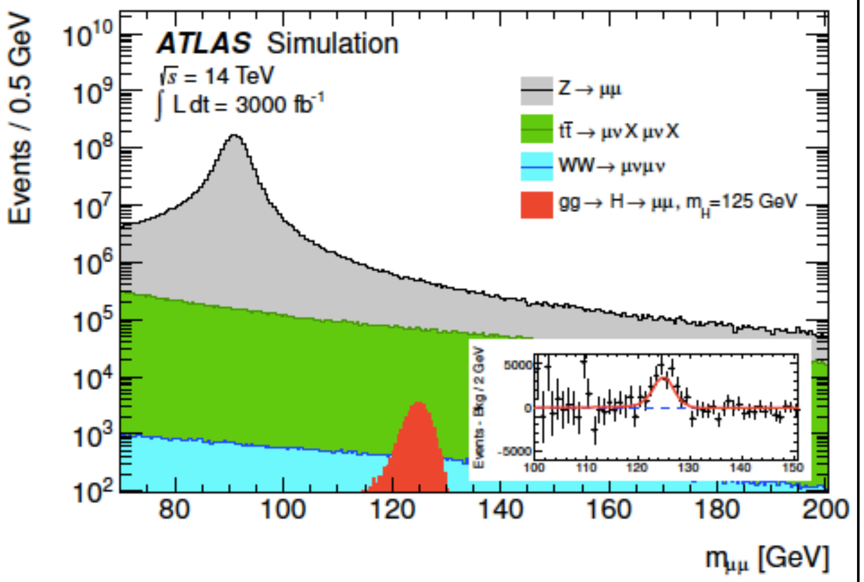
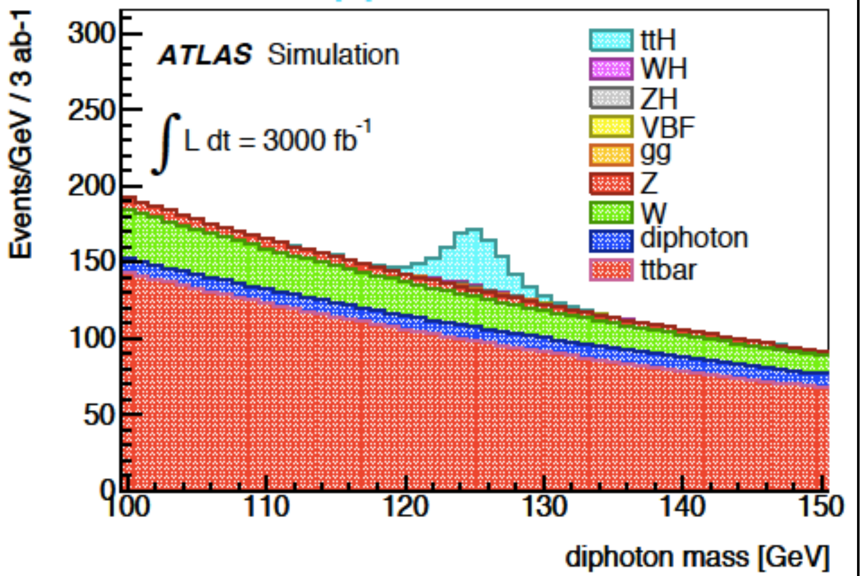
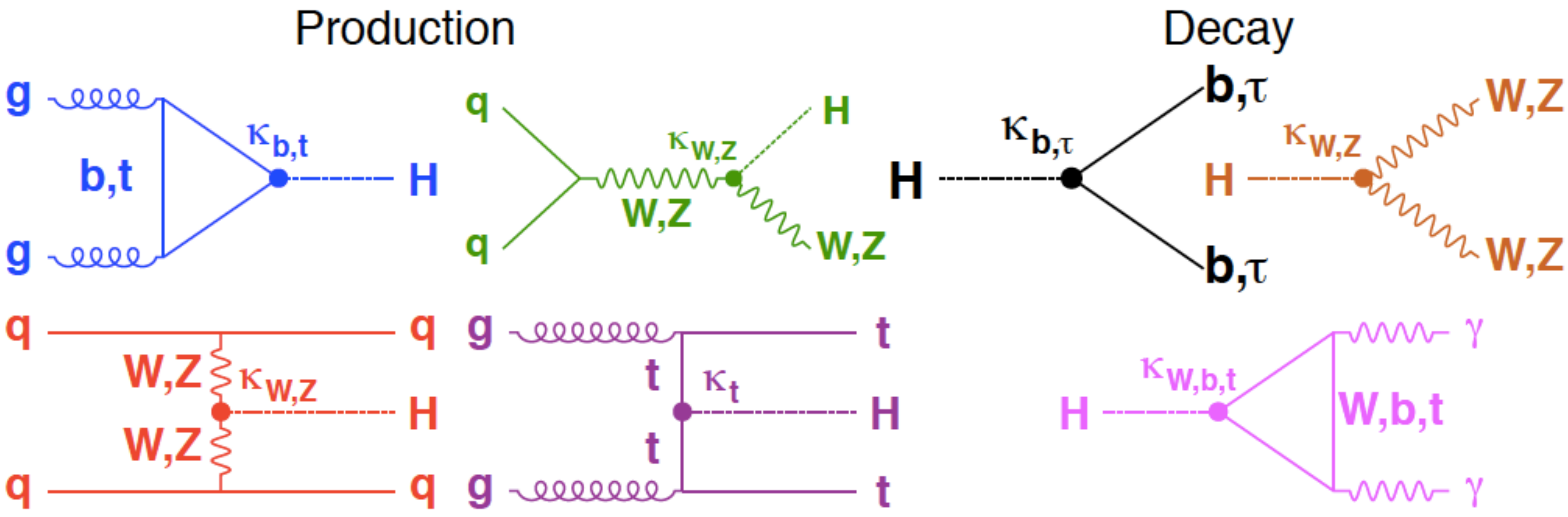


ttH, H→γγ



Higgs couplings at the LHC

- At the LHC, only possible to measure σxBR's
  - Expressed as ratio to the SM values: $\mu=(\sigma x BR)/(\sigma x BR)_{SM}$
- Ratios of partial widths or couplings can be derived without model assumptions
- Interpretation in terms of couplings is model dependent
  - Expressed in terms of scale factors, κ, wrt SM values: $\Gamma_X/\Gamma_Y=(\kappa_X/\kappa_Y)^2$



Couplings – ATLAS

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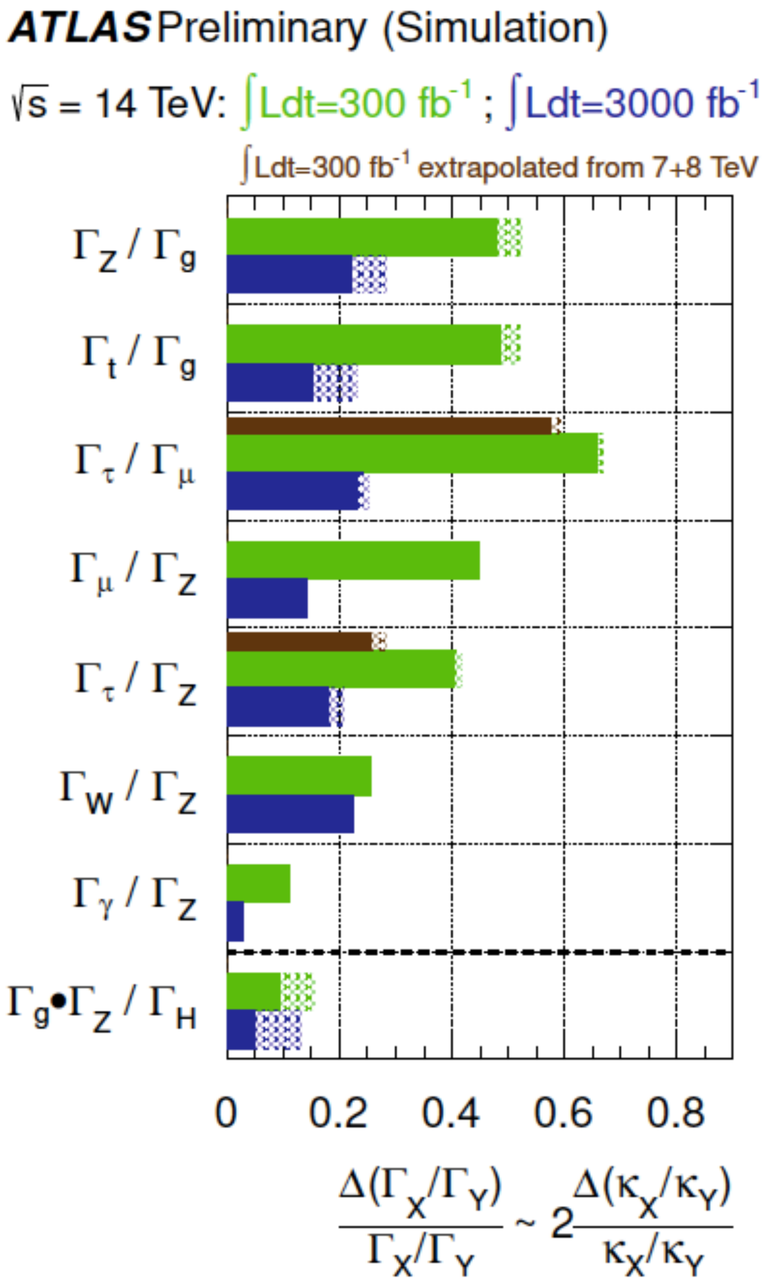


- Minimal fit: only two coupling scale factors, kF for fermions and kV for vector bosons
  - No BSM contributions in either loops or in the total Higgs width

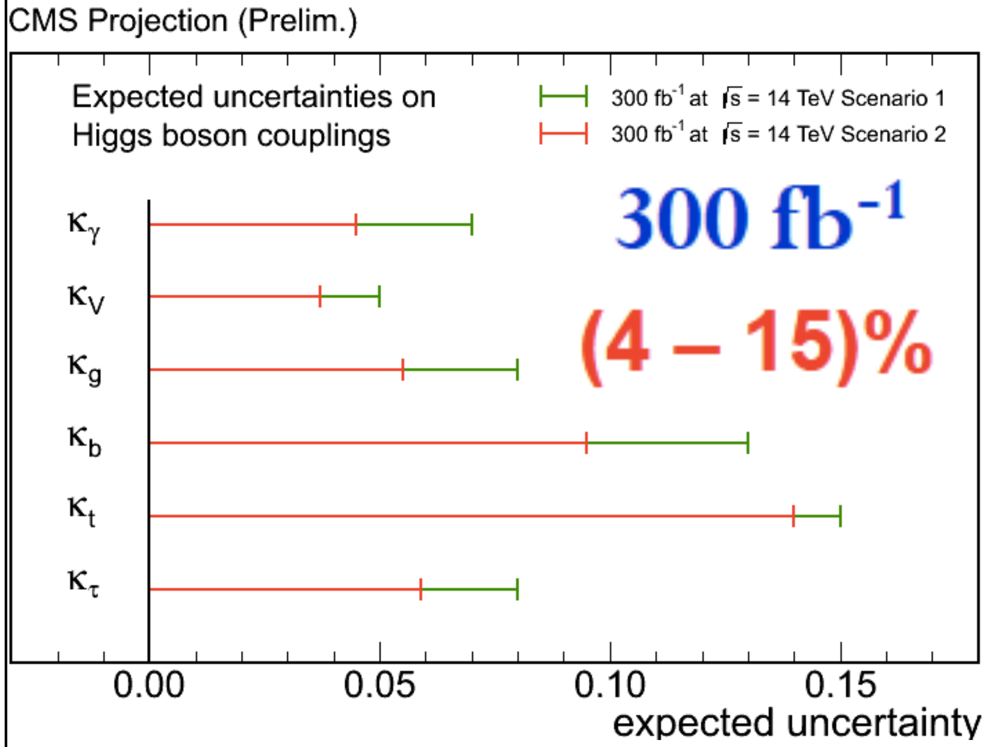
Sensitivity without (with) theory uncertainties:

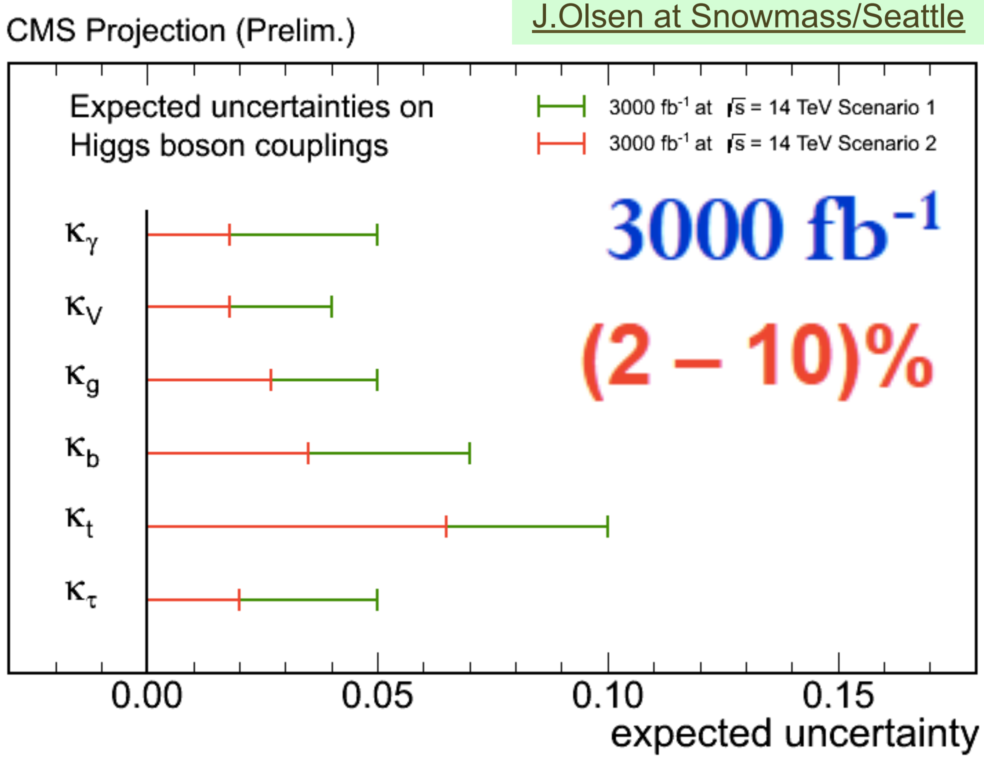
ATLAS	300 fb^{-1}	3000 fb^{-1}
κ_V	3.0 % (5.6 %)	1.9 % (4.5 %)
κ_F	8.9 % (10 %)	3.6 % (5.9 %)

A factor 2.5 improvement on κ_F, with 3000fb^{-1} provided the theory uncertainties are halved!

Couplings – CMS

J.Olsen at Snowmass/Seattle



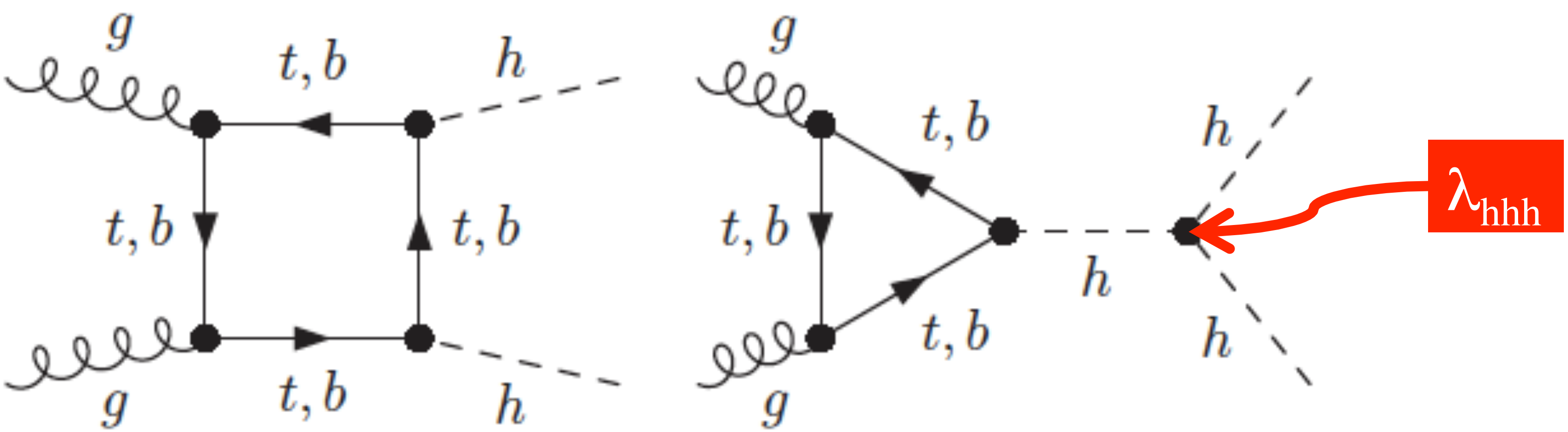


Numbers in brackets are % uncertainties on coupling deviations for [scenario 2, scenario 1]

L (fb^{-1})	κ_γ	κ_V	κ_g	κ_b	κ_t	κ_τ
300	[5, 7]	[4, 5]	[6, 8]	[10, 13]	[14, 15]	[6, 8]
3000	[2, 5]	[2, 3]	[3, 5]	[4, 7]	[7, 10]	[2, 5]

Ultimately, combined ATLAS+CMS precision down to a few %.

Higgs self-coupling



- Arguably, the most challenging measurement at the LHC!
  - Look for Higgs-pair production; destructive interference with diagrams not containing the self-coupling vertex λ_{hhh}
  - For $\lambda_{HHH}/\lambda_{HHH}^{SM} = 0/1/2$, the cross section is 71/34/16fb

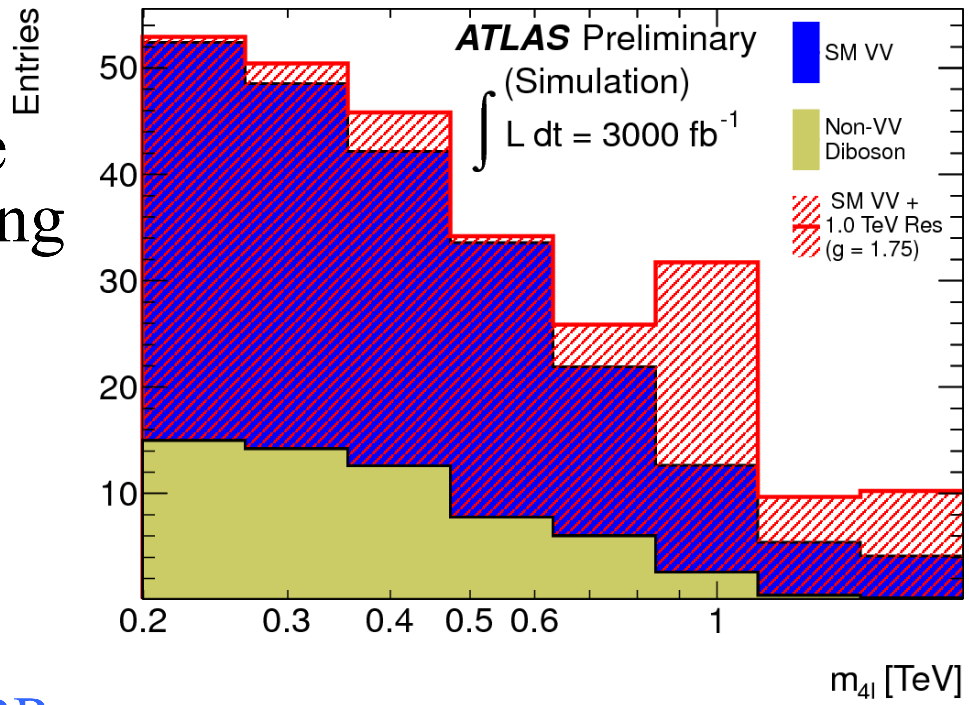
- Preliminary ATLAS studies indicate that hh→bbγγ is promising
  - σxBR~0.1fb, backgrounds are largely Xh(h→γγ) and continuum bbγγ
  - Additional signal channels under study, e.g. bbττ

- A measurement by ATLAS+CMS with 3000fb^{-1} may be possible

Vector Boson Scattering

ATL-PHYS-PUB-2012-005

- Crucial test of EWSB dynamics and the nature of the Higgs
- Model involving new, TeV-scale resonances with role in unitarising the longitudinal VBS amplitude
- Big gains in sensitivity with $3000 fb^{-1}$
  - $ZZ \rightarrow 4$leptons: low backgrounds, clear peak in m_{4l}, high sensitivity
  - Factor ~3 improvement in SM σxBR



model	$300\ fb^{-1}$	$3000\ fb^{-1}$
$m_{resonance} = 500$ GeV, $g = 1.0$	2.4σ	7.5σ
$m_{resonance} = 1$ TeV, $g = 1.75$	1.7σ	5.5σ
$m_{resonance} = 1$ TeV, $g = 2.5$	3.0σ	9.4σ

Conclusions

- Great prospects for pinning down the properties of the 125GeV Higgs boson at the HL-LHC with 3000fb^{-1} per experiment
  - Studies and projections indicate ~few % precision in all fermion and vector boson couplings
  - Based on past experience, projections are always conservative!
- Input from the theory community vital
  - Theory uncertainties will quickly become an important limiting factor
- Vector Boson Scattering, direct searches for BSM partners of the Higgs and BSM interpretation of results also very crucial for elucidating the path beyond the Standard Model

μ uncertainties at 300fb^{-1}

Channel	Uncertainty on mu value with 300 fb^{-1} [%]			
	Experimental only		Experimental + theory	
	ATLAS	CMS	ATLAS	CMS
γγ	8	5	15	15
ZZ	9	8	16	11
WW (1)	26	9	29	14
ττ (2)	11	9	15	11
ττ	19	9	23	11

(1) ATLAS uncertainty based on old result

(2) ATLAS uncertainty extrapolated with CMS approach

CP violation in Higgs sector (ATLAS)

$$A(X \to VV) \sim \left(a_1 M_X^2 g_{\mu\nu} + a_2 (q_1 + q_2)_\mu (q_1 + q_2)_\nu + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\right) \varepsilon_1^{*\mu} \varepsilon_2^{*\nu}$$

- HZZ amplitude can have CP-even & CP-odd terms: CP violation

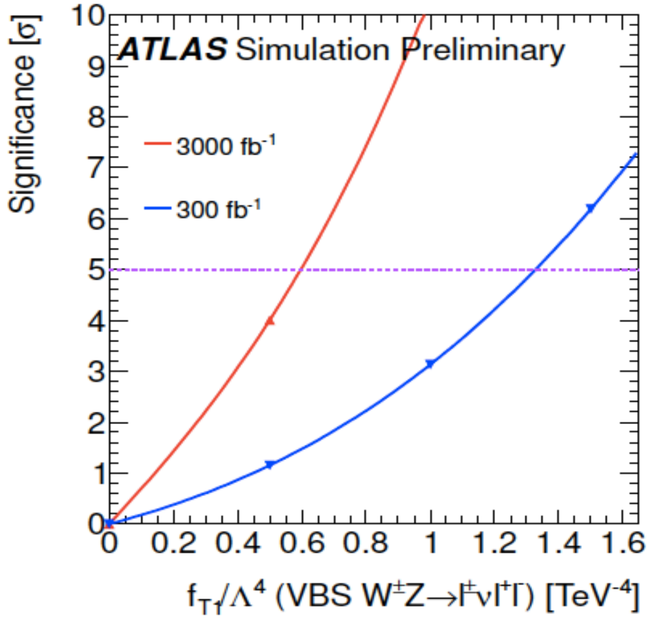
Significance for various a_3

Integrated Luminosity	Signal (S) and Background (B)	$6+6i$	$6i$	$4+4i$
100 fb^{-1}	$S = 158; B = 110$	3.0	2.4	2.2
200 fb^{-1}	$S = 316; B = 220$	4.2	3.3	3.1
300 fb^{-1}	$S = 474; B = 330$	5.2	4.1	3.8

3000fb^{-1} would give sensitivity to much smaller levels of CP violation.

More on VBS

ATL-PHYS-PUB-2013-006

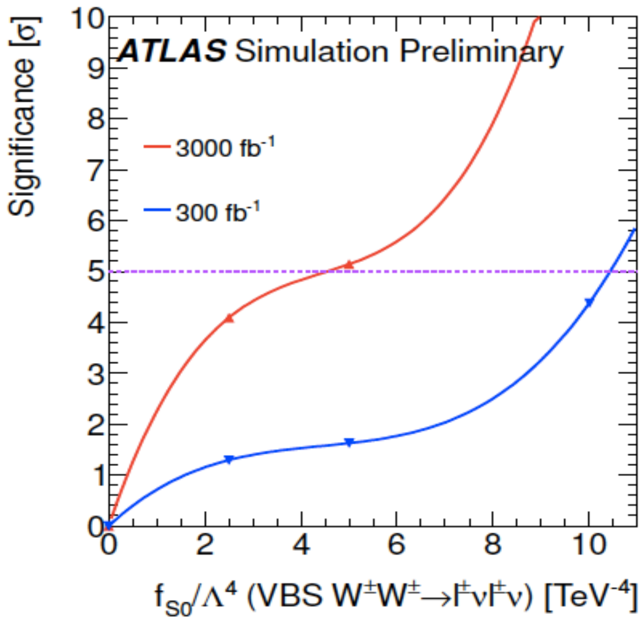


New physics parametrised in terms of higher-dimension, gauge-invariant terrms:

$$\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \mathrm{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$$

5σ sensitivity

	300 fb^{-1}	3000 fb^{-1}
f_{T1}/Λ^4	1.3 TeV^{-4}	0.6 TeV^{-4}



$$\mathcal{L}_{S,0} = \frac{f_{S0}}{\Lambda^4} [(D_\mu\phi)^\dagger D_\nu\phi)] \times [(D^\mu\phi)^\dagger D^\nu\phi)]$$

5σ sensitivity

model	300 fb^{-1}	3 ab^{-1}
f_{S0}/Λ^4	10 TeV^{-4}	4.5 TeV^{-4}