

PRECISION HIGGS MEASUREMENTS

$H \rightarrow \gamma\gamma, ZZ^*, WW^*$ and combination

Stefan Gadatsch¹ on behalf of the ATLAS and CMS collaborations

11th May, 2015

¹CERN



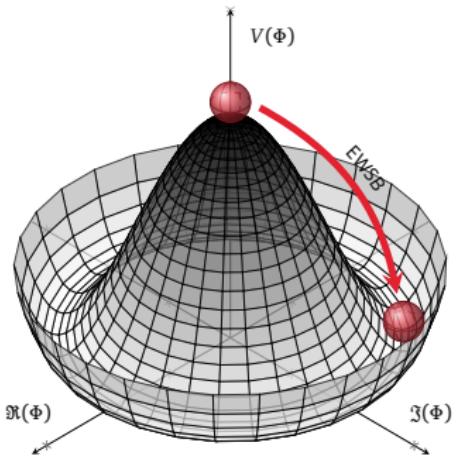
Current status

Higgs boson decays to dibosons

Combination of Higgs analyses

Coupling measurements

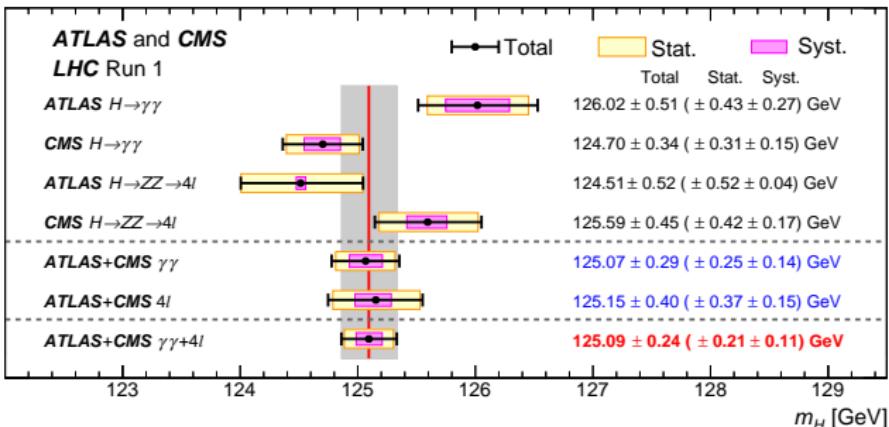
Theoretical uncertainties



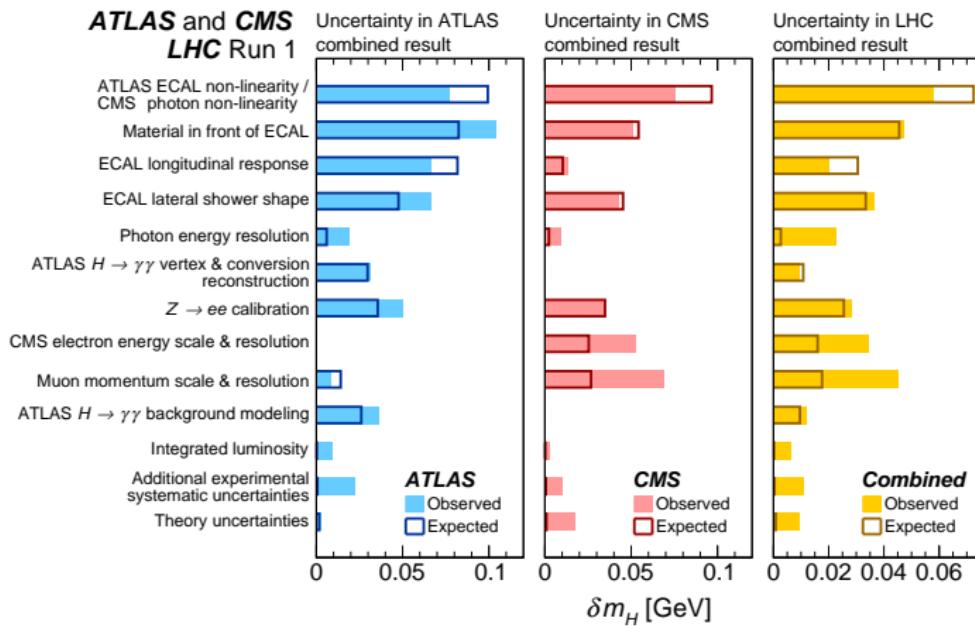
CURRENT STATUS

- Observation in three **bosonic channels**
 - Strong evidence for **fermion couplings**
 - High precision **mass** measurement
 - **Spin** determined
 - Limits on **CP mixing**
-
- No evidence for **non-SM** production or decay modes
 - No evidence for **extended/modified scalar sector**

- Free parameter in the SM: once known, all Higgs couplings can be predicted
- Use fully reconstructed final states: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$
 - Extensive categorization in $H \rightarrow \gamma\gamma$: ATLAS: photon conversions, detector region, diphoton momentum. CMS: BDT based on kinematics, photon ID/shower shape, and resolution, and (rarer) production modes
 - 2D/3D fit in $H \rightarrow ZZ^* \rightarrow 4\ell$: $m_{4\ell}$ vs. ZZ^* continuum rejection, and per-event uncertainty on $m_{4\ell}$ (CMS)
- First joint ATLAS and CMS paper: 0.2 % precision (stat. limited)

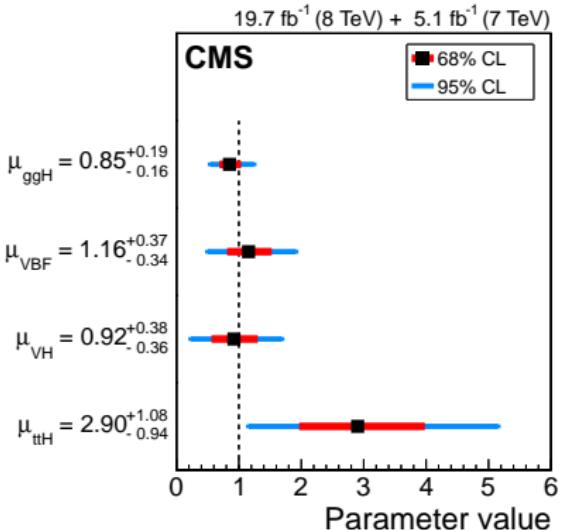
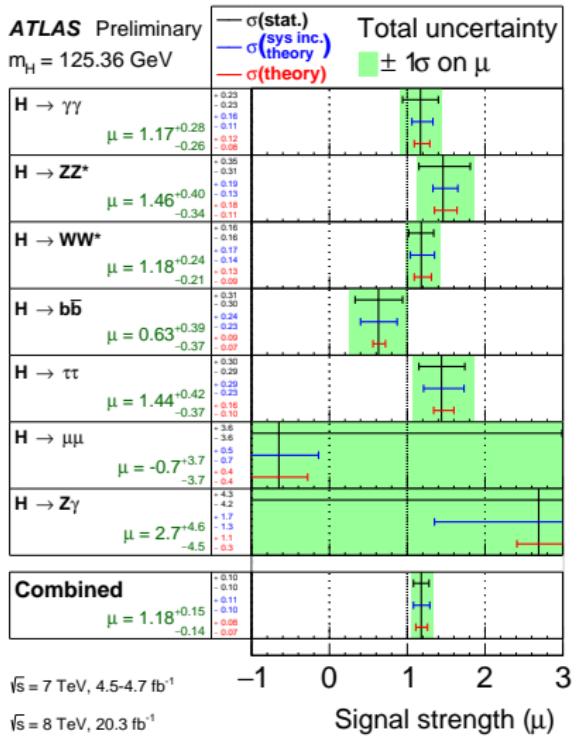


- Extensive effort to understand systematic uncertainties: ~ 200 individual theory and experimental systematic uncertainties!
- Dominated by energy/momentum scale/resolution on γ, e, μ
- Expected small interference between Higgs signal and continuum background neglected



SIGNAL STRENGTH

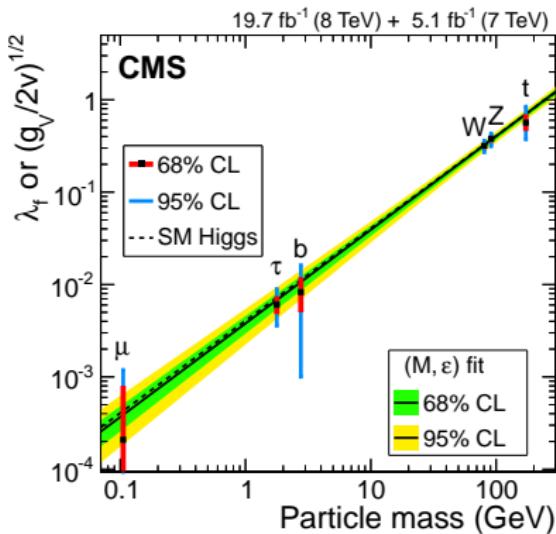
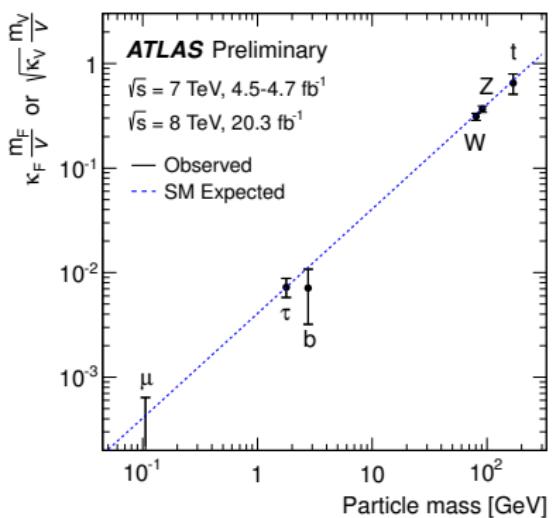
ATLAS Preliminary
 $m_H = 125.36 \text{ GeV}$

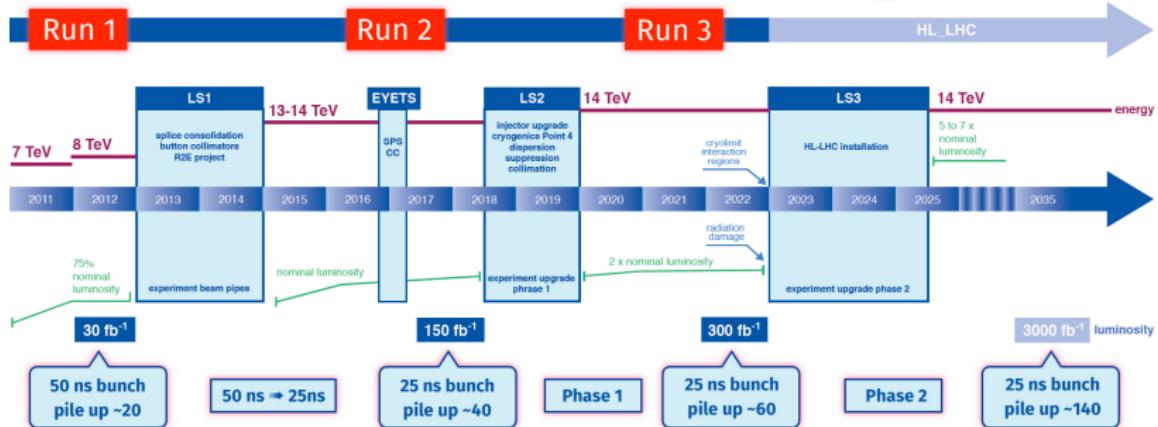


- Precise measurements of diboson decay modes (theoretical uncertainties become relevant!)
- Some channels (e.g. $H \rightarrow b\bar{b}$) dominated by exp. uncertainties
- Rare decay modes statistics limited

COUPLING MEASUREMENTS

- Interpret production and decay rates in leading-order tree level coupling framework
 - Treat correlations between production and decay
- Typically precision of 10 % to 20 % in generic benchmark models
- Measurements very compatible with the SM prediction, e.g. scaling of couplings with particle mass





Detector performance as good or better as today – key: trigger

Phase 1

- ATLAS: Fast tracker (FTK), New Small Whell (NSW), Calorimeter readout
- CMS: Level 1 trigger, silicon pixel detector, HCal photodetector and electronics

Phase 2

- Re-design of trigger system
- Tracking
- Calo electronics and forward region
- Muon system

Higgs boson candidates for 3000 fb^{-1} at 13 TeV (approximate numbers, given LHCHXSWG cross sections)

ggF	VBF	WH	ZH	ttH	bbH	tH	HH	total
130M	11M	4.1M	2.6M	1.5M	1.5M	260k	120k	150M

Higgs boson physics goals

SM Higgs

- High precision coupling measurements
- Rare decays
- Spin and parity
- Higgs boson pair production

BSM Higgs

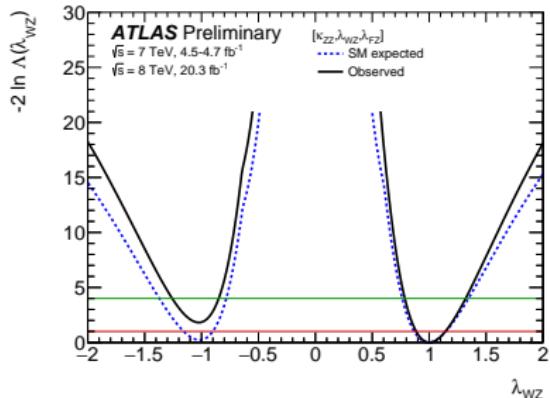
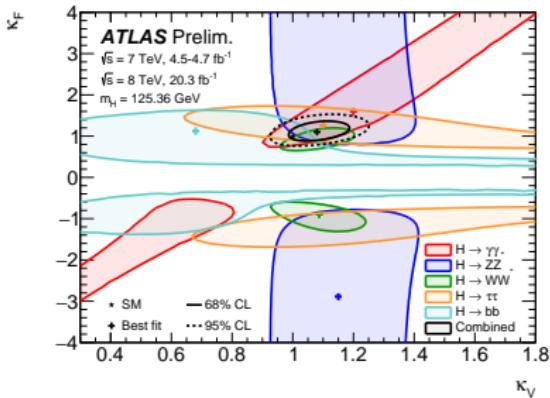
- Extended scalar sector: heavy Higgs, charged Higgs, composite Higgs, MSSM, ...
- Couplings to Dark Matter

We need to understand **all** production and decay modes!

see talk by Giovanni Marchiori

Example from ATLAS in run 1:

- $gg \rightarrow ZH$ cross section less than 10 % of $qq \rightarrow ZH$ cross section, but: Z - t interference
- tH cross section small in SM, but can become when constructive interference at tree level: W - t interference
- Sensitivity to relative sign between W and Z !



ATLAS

- Detector response based on full Geant4 simulations
- Apply acceptance, efficiency, and resolution functions to physics objects (“smearing simulation”)
 - $\mu_{\text{PU}} \sim 50 - 60$ for 300 fb^{-1} – Includes IBL and LAr trigger updates
 - $\mu_{\text{PU}} \sim 140$ for 3000 fb^{-1} – Includes full upgrade of ID (ITK)
- Study scenarios with current/half/no theoretical uncertainties

CMS

- Studies scale run 1 analyses
- Detector performance uses Delphes parametrization
- Two scenarios for systematic uncertainties
 1. Systematics remain the same as in run 1
 2. Theoretical uncertainties reduced by 50 %, others scale by $1/\sqrt{L}$



see talks by Markus Klute, Richard Polifka, Tim Scanlon

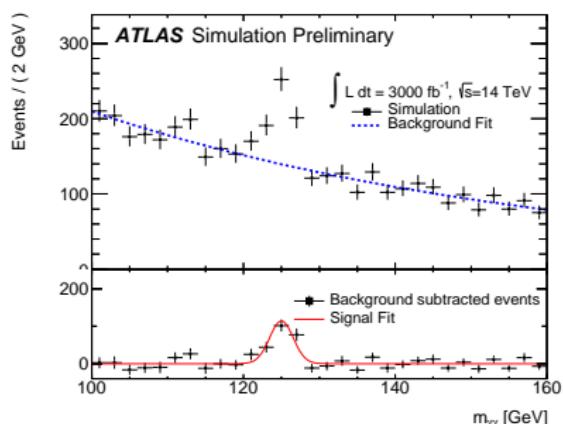
HIGGS BOSON DECAYS TO DIBOSONS

Possibility to measure all production modes with 3000 fb^{-1}

- Interesting in particular $t\bar{t}H/tH(H \rightarrow \gamma\gamma)$ owing to top-quark Higgs Yukawa coupling in production and decay
- Rates scales well with $\sigma \times L$ in general. Exception: selected VBF candidates
- Theoretical uncertainties become more and more relevant

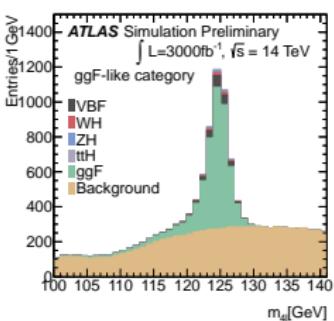
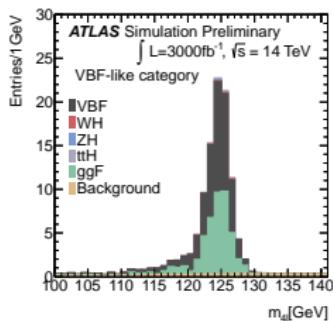
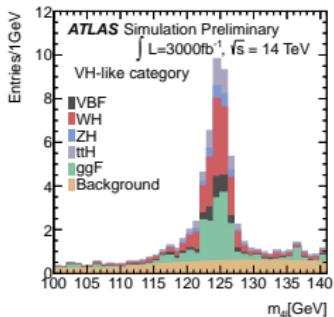
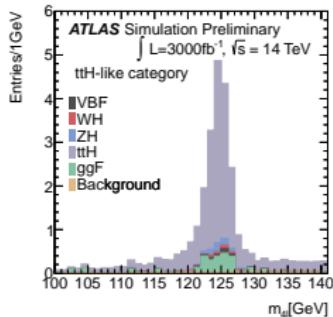
ATLAS	$\Delta\hat{\mu}/\hat{\mu} (\%)$				
	Prod. mode	Total	Stat.	Exp.	Theo.
ttH	+21	+13	+5	+17	
	-17	-12	-4	-11	
WH	+26	+21	+13	+10	
	-25	-20	-12	-8	
ZH	+35	+32	+7	+12	
	-31	-29	-7	-8	
ggF	+19	+3	+1	+19	
	-14	-3	-1	-14	
VBF	+29	+18	+1	+23	
	-29	-18	-1	-23	

ATLAS	ttH	WH	ZH	VBF
Significance	8.2	4.2	3.7	3.8



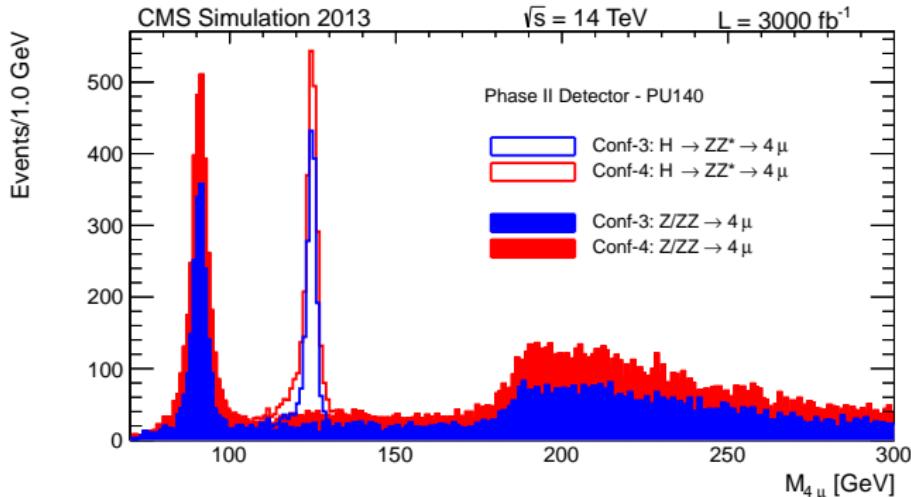
$ttH(H \rightarrow \gamma\gamma)$ -1 lepton

High purity and fully reconstructable final state – Possibility to measure all production modes with 3000 fb^{-1}

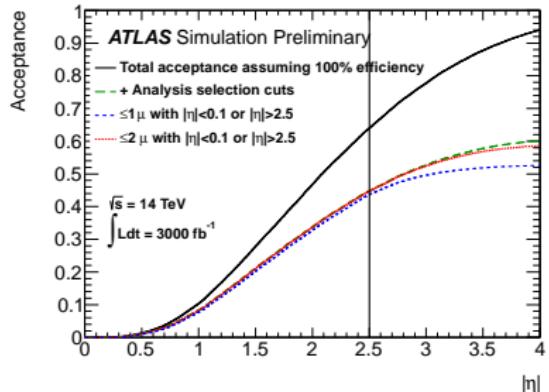


$\Delta\mu/\mu$	Total	Stat.	Expt. syst.	Theory
300 fb^{-1}				
ggF	0.152	0.066	0.053	0.124
VBF	0.625	0.545	0.233	0.226
WH	1.074	1.064	0.061	0.085
tH	0.535	0.516	0.038	0.120
Combined	0.125	0.042	0.044	0.108
3000 fb^{-1}				
ggF	0.131	0.025	0.040	0.124
VBF	0.371	0.187	0.225	0.226
WH	0.390	0.375	0.061	0.085
ZH	0.532	0.526	0.038	0.073
tH	0.224	0.184	0.034	0.120
Combined	0.100	0.016	0.036	0.093

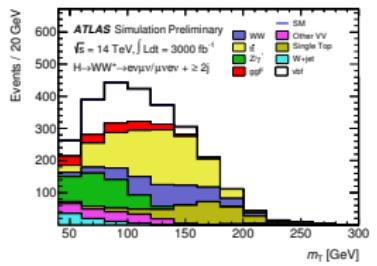
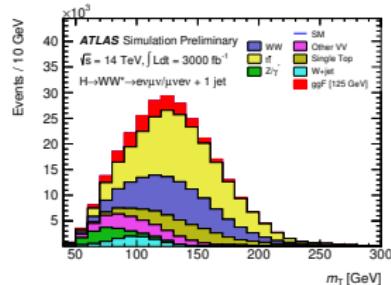
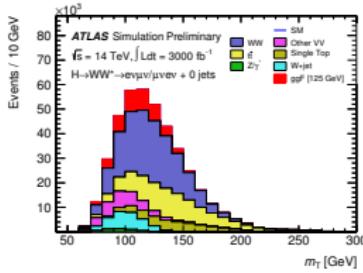
- ggF and VBF production modes not anymore stat. limited
- VBF: exp. and theo. systematics equally large
- VH and ttH still stat. limited



Acceptance increases by 40 % for a detector with $|\eta| < 4.0$ coverage compared to $|\eta| < 2.5$ coverage



- Dominant backgrounds from $t\bar{t}$ and WW production increase with event pileup
- Rise jet p_T requirements (30/35 GeV at $\mu_{PU} = 50/140$) to cope with pileup and fakes
 - Threshold in VBF-enriched category increased further
- Key: understanding systematic uncertainties
- Dominant experimental systematics decrease
 - b -tagging, JES/JER
 - Background modeling improved through improved analysis design



- Large event yields
- Need to understand systematic uncertainties, especially theory

Projections

Process	Rel. unc.	
	0-jet	2-jet
WW	1.5	10
VV	2	10
$t\bar{t}$	7	10
$tW/tb/tqb$	7	10
Z+jets	10	10
$W+$ jets	20	20

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

Run 1

Sample	Total error	Stat. error	Expt. syst. err.	Theo. syst. err.
N_{sig}	16	-	6.7	15
N_{bkg}	2.5	1.5	1.2	1.7
N_{WW}	4.2	2.4	2.3	2.6
N_{top}	7.4	2.3	4.2	5.6
N_{misid}	17	-	9.9	14
N_{VV}	9.9	4.8	4.6	7.4
$N_{\tau\tau}$	34	1.7	33	7.2
$N_{ee/\mu\mu}$	30	14	26	5.5

Sample	Total error	Stat. error	Expt. syst. err.	Theo. syst. err.
1-jet				
N_{sig}	13	-	6.8	12
N_{bkg}	9.2	4.7	6.4	4.5
N_{WW}	32	-	14	28
N_{top}	15	9.6	7.6	8.5
N_{misid}	22	-	12	19
N_{VV}	20	-	12	15
$N_{\tau\tau}$	40	25	31	2.9
$N_{ee/\mu\mu}$	19	11	15	-

COMBINATION OF HIGGS ANALYSES

ATLAS

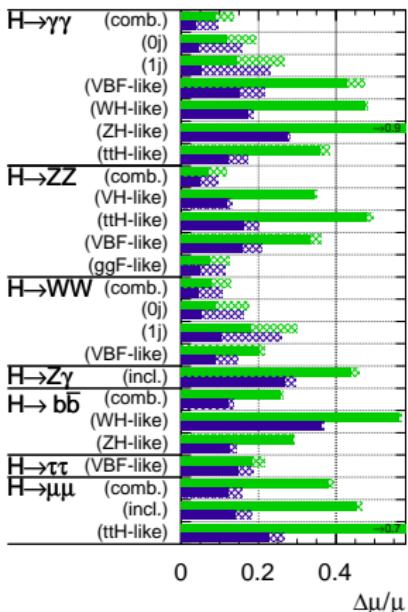
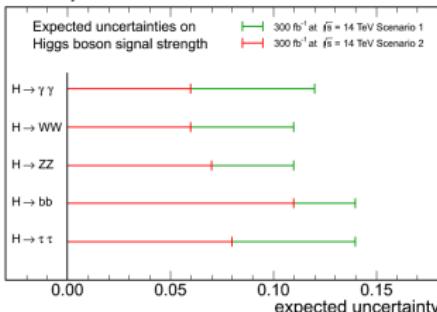
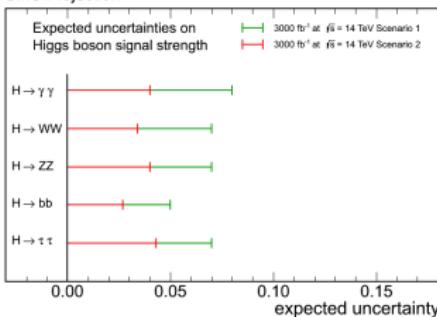
- $\gamma\gamma$: 0/1-jet, VBF, WH, ZH, ttH tag
- $ZZ^* \rightarrow 4\ell$: ggF, VBF, VH, ttH tag split by final state leptons
- $WW^* \rightarrow \ell\nu\ell\nu$: 0/1-jet, VBF tag
- $\tau\tau$: VBF tag
- bb : WH, ZH tag
- $Z\gamma$: inclusive
- $\mu\mu$: inclusive

CMS

- $\gamma\gamma$: untagged, VBF, VH, ttH tag
- $ZZ^* \rightarrow 4\ell$: $N_{\text{jet}} < 2$, $N_{\text{jet}} \geq 2$, split by final state leptons
- $WW^* \rightarrow \ell\nu\ell\nu$: 0/1-jet, VBF, WH tag
- $\tau\tau$: 0/1 jet (categorized by final state and p_T^τ) 1-jet τ_h , VBF, ZH, WH tag
- bb : VH, ttH tag
- $Z\gamma$: inclusive
- $\mu\mu$: 0/1-jet, VBF tag



see previous talk by Lorenzo Bianchini

ATLAS Simulation Preliminary
 $\sqrt{s} = 14 \text{ TeV}$: $\int L dt = 300 \text{ fb}^{-1}$; $\int L dt = 3000 \text{ fb}^{-1}$
**CMS Projection****CMS Projection**

- Categorization vital for measurement and understanding of limitations
- Diboson channels measured at 10 % (5 %) precision with(out) theory uncertainties
 - Improvement of factor 2-3 with increased luminosity
- Rare decay modes benefit most from increased statistics

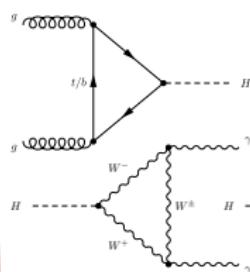
- Practically no improvement for ggF and VBF production modes
 - Theory uncertainties very important for ggF production
 - Remnant experimental uncertainties
- Precision on other production modes scales with luminosity
 - Effect of theory uncertainties becomes relevant for ttH at HL-LHC

$\Delta\mu/\mu$	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

COUPLING MEASUREMENTS

- Coupling strengths g of the Higgs to other SM particles scale with the particle mass
 - Fermions: $g_F = \sqrt{2}m_F/v$, Gauge bosons: $g_V = 2m_V^2/v$
- Measure strength in units of SM expectation, $\kappa_i = g_i/g_{i,\text{SM}}$, in a leading-order tree-level motivated framework

Example: $gg \rightarrow H \rightarrow \gamma\gamma$



$$\sigma(gg \rightarrow H) \propto \kappa_g^2 \simeq 1.058\kappa_t^2 + 0.007\kappa_b^2 - 0.065\kappa_t\kappa_b$$

Assumptions: only one CP-even scalar Higgs ($m_H = 125$ GeV), narrow-width approx.: $\sigma \cdot BR(ii \rightarrow H \rightarrow ff) = \sigma_{ii} \cdot \Gamma_{ff}/\Gamma_H$

$$\begin{aligned} \Gamma(H \rightarrow \gamma\gamma) &\propto \kappa_\gamma^2 \\ &\simeq |1.26\kappa_W - 0.27\kappa_t|^2 \end{aligned}$$

Total decay width scales with $\kappa_H^2 = \sum_{jj} \frac{\kappa_j^2 \Gamma_{jj}^{\text{SM}}}{\Gamma_H^{\text{SM}}}$

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

PARAMETRIZATIONS AND INTERFERENCE



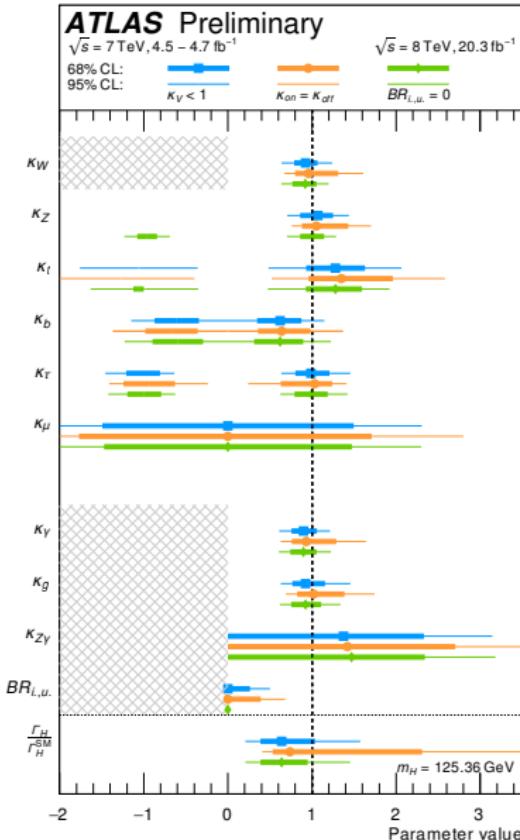
Many relevant interference effects (numeric values from 7/8 TeV)

Production	Loops	Interference	Expression in terms of fundamental coupling strengths	
$\sigma(ggF)$	✓	$b - t$	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	-	-	\sim	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	\sim	κ_W^2
$\sigma(q\bar{q} \rightarrow ZH)$	-	-	\sim	κ_Z^2
$\sigma(gg \rightarrow ZH)$	✓	$Z - t$	$\kappa_{ggZH}^2 \sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	\sim	κ_b^2
$\sigma(ttH)$	-	-	\sim	κ_t^2
$\sigma(gb \rightarrow WtH)$	-	$W - t$	\sim	$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qg \rightarrow tHq'b)$	-	$W - t$	\sim	$3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
Partial decay width				
Γ_{bb}	-	-	\sim	κ_b^2
Γ_{WW}	-	-	\sim	κ_W^2
Γ_{ZZ}	-	-	\sim	κ_Z^2
$\Gamma_{\tau\tau}$	-	-	\sim	κ_τ^2
$\Gamma_{\mu\mu}$	-	-	\sim	κ_μ^2
$\Gamma_{\gamma\gamma}$	✓	$W - t$	$\kappa_\gamma^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma_{Z\gamma}$	✓	$W - t$	$\kappa_{Z\gamma}^2 \sim$	$1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$
Total decay width				
Γ_H	✓	$W - t$ $b - t$	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_t^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$

Parametrization for $gg \rightarrow ZH$ process, but also ggF process, have p_T dependence!

Need assumption on the Higgs boson width to measure absolute coupling strengths

- No invisible or undetected Higgs boson decay
- $\kappa_W < 1$ and $\kappa_Z < 1$ holds for a wide class of BSM models (e.g. arbitrary number of Higgs doublets); unitarity problem in VBS
- Coupling strengths in on/off-shell Higgs boson production are identical
 - Requires further assumptions
- Assumptions yield very similar results



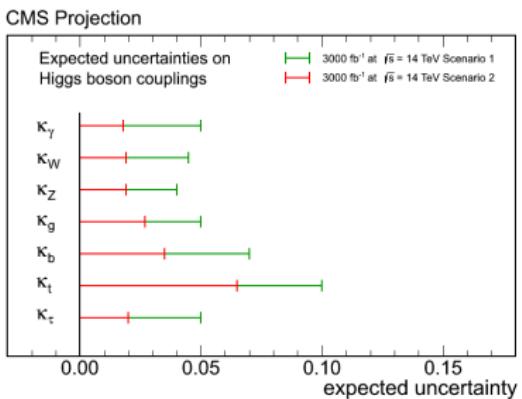
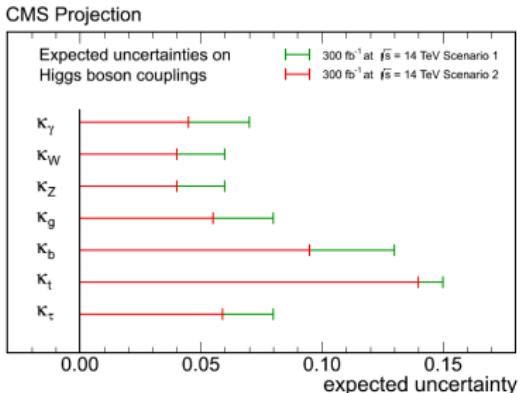
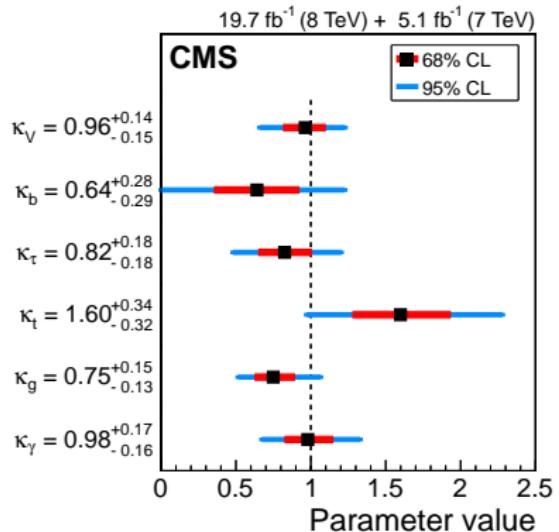
PRECISION ON ABSOLUTE COUPLING STRENGTHS (ATLAS)



Model	Coupling Parameter	25 fb ⁻¹		300 fb ⁻¹			3000 fb ⁻¹		
		All theory unc.		Theory unc.:			Theory unc.:		
		Obs.	Exp.	All	Half	None	All	Half	None
1	κ	5.7	6.2	4.2	3.0	2.4	3.2	2.2	1.7
2	κ_V	6.4	6.5	4.3	3.0	2.5	3.3	2.2	1.7
	κ_F	14	15	8.8	7.5	7.1	5.1	3.8	3.2
3	κ_Z	14	15	8.1	7.9	7.8	4.3	3.9	3.8
	κ_W	16	14	8.5	8.2	8.1	4.8	4.1	3.9
	κ_t	22	21	14	12	11	8.2	6.1	5.3
	κ_b	53	33	23	22	22	12	11	10
	κ_τ	21	23	14	13	13	9.8	9.0	8.7
	κ_μ	-	-	21	21	21	7.3	7.1	7.0
	κ_Z	14	16	8.1	7.9	7.9	4.4	4.0	3.8
4	κ_W	16	15	9.0	8.7	8.6	5.1	4.5	4.2
	κ_t	26	40	22	21	20	11	8.5	7.6
	κ_b	47	37	23	22	22	12	11	10
	κ_τ	20	24	14	14	13	9.7	9.0	8.8
	κ_μ	-	-	21	21	21	7.5	7.2	7.1
	κ_g	19	21	14	12	11	9.1	6.5	5.3
	κ_γ	17	19	9.3	9.0	8.9	4.9	4.3	4.1
	$\kappa_{Z\gamma}$	-	-	24	24	24	14	14	14

- Significant improvement in (κ_V, κ_F) with 3000 fb⁻¹
- In more generic benchmark models improvements of factor 2
- Large improvements on κ_b
- κ_μ stat. limited: factor 3 improvement
- $\kappa_{Z\gamma}$ partially limited by exp. uncertainties: factor 1.5 improvement

PRECISION ON ABSOLUTE COUPLING STRENGTHS (CMS)



- Typically improvements by a factor 2 to 3 at HL-LHC
- Can reach uncertainties as low as 2 % for couplings to bosons, assuming half theo. unc. and exp. scaling as $1/\sqrt{L}$

- Similar precision for ATLAS and CMS
 - CMS $H \rightarrow bb$ projections more optimistic
 - ATLAS $H \rightarrow \tau\tau$ less optimized
- Important to improve on experimental and theoretical side

Int. lumi. [fb ⁻¹]	Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	ATLAS	[9,9]	[9,9]	[8,8]	[11,14]	[22,23]	[20,22]	[13,14]	[24,24]	[21,21]
300	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	ATLAS	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]
3000	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

- ATLAS: [no theo. unc. , full theo. unc.]
- CMS: [reduced unc., run 1 unc.]

Two approaches:

1. Indirect using Higgs boson couplings

Model	Coupling Parameter	25 fb ⁻¹		300 fb ⁻¹			3000 fb ⁻¹		
		All theory unc.		Theory unc.:			Theory unc.:		
		Obs.	Exp.	All	Half	None	All	Half	None
5	κ_g	11	14	8.9	7.1	6.3	6.7	4.1	2.8
	κ_γ	12	13	4.9	4.8	4.7	2.1	1.8	1.7
	$\kappa_{Z\gamma}$	-	-	23	23	23	14	14	14
	$BR_{i,u.}$	<27	<37	<22	<20	<20	<14	<11	<10

2. Direct search using ZH or VBF production

- Similar or better performance compared to SM combination

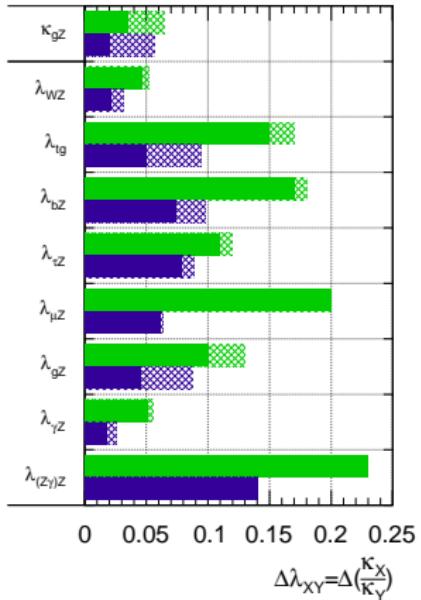
We will benefit from combining direct and indirect measurements.

CMS projections similar to ATLAS numbers

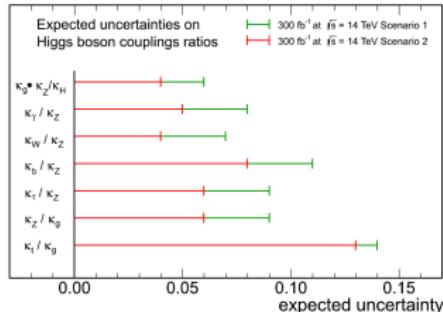
NO ASSUMPTION ON THE TOTAL WIDTH

ATLAS Simulation Preliminary

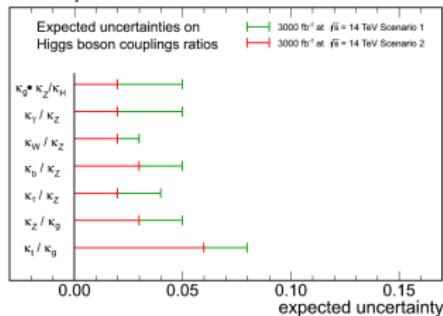
$\sqrt{s} = 14 \text{ TeV}$: $\int L dt = 300 \text{ fb}^{-1}$; $\int L dt = 3000 \text{ fb}^{-1}$



CMS Projection



CMS Projection



- Can only measure ratios of coupling scale factors:
 $\sigma \times BR(ii \rightarrow H \rightarrow ff) \sim \lambda_{iY}^2 \cdot \kappa_{YY'}^2 \cdot \lambda_{fY'}^2$, with $\lambda_{xy} = \kappa_x / \kappa_y$ and $\kappa_{xy} = \kappa_x \kappa_y / \kappa_H$
- Exp. and theo. uncertainties cancel in ratio, e.g. uncertainty on integrated luminosity

- Good agreement between ATLAS and CMS estimate
- High precision coupling strength measurements possible at the HL-LHC – improvements of factor 2
 - 2% for electroweak bosons
 - 5% to 8% for gluons, second/third generation fermions
- Further improvements include differential measurements of Higgs boson production
 - E.g. transverse momentum and rapidity

Int. lumi. [fb^{-1}]	Exp.	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{WZ}	λ_{bZ}	$\lambda_{\tau Z}$	$\lambda_{gZ} / \lambda_{Zg}$	λ_{tg}	$\lambda_{\mu Z}$	$\kappa_{(Z\gamma)Z}$
300	ATLAS	[4,6]	[5,6]	[4,4]	[17,18]	[11,12]	[10,13]	[15,17]	[20,20]	[23,23]
300	CMS	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	ATLAS	[2,6]	[2,3]	[2,2]	[7,10]	[8,9]	[5,9]	[5,9]	[6,6]	[14,14]
3000	CMS	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

- ATLAS: [no theo. unc. , full theo. unc.]
- CMS: [reduced unc., run 1 unc.]

COMPARISON TO RUN 1 (ATLAS)



Model	Coupling Parameter	25 fb ⁻¹		300 fb ⁻¹			3000 fb ⁻¹		
		All theory unc.		Theory unc.:			Theory unc.:		
		Obs.	Exp.	All	Half	None	All	Half	None
5	κ_{ZZ}	25	28	9.8	9.1	8.9	5.1	4.3	3.9
	λ_{WZ}	13	14	4.3	4.0	3.9	2.3	1.8	1.6
	λ_{FZ}	19	20	9.2	8.5	8.3	4.4	3.7	3.5
6	κ_{uu}	26	29	14	11	9.7	8.7	5.7	4.2
	λ_{Vu}	18	21	9.4	8.3	7.9	5.1	3.8	3.2
	λ_{du}	16	18	9.7	8.2	7.7	6.0	4.6	4.0
7	κ_{qq}	22	22	14	11	9.9	8.1	5.6	4.5
	λ_{Vq}	16	17	9.6	8.5	8.1	5.2	3.9	3.4
	λ_{lq}	18	21	12	10	9.4	7.3	6.0	5.4
8	κ_{gZ}	13	14	6.4	4.4	3.5	5.7	3.3	2.0
	λ_{WZ}	14	15	5.2	4.8	4.6	3.1	2.4	2.1
	λ_{tg}	25	47	17	16	15	9.4	6.4	5.0
	λ_{bZ}	45	32	18	17	17	9.8	8.1	7.4
	$\lambda_{\tau Z}$	21	24	12	12	11	8.9	8.1	7.8
	$\lambda_{\mu Z}$	-	-	20	20	20	6.3	6.2	6.1
	λ_{gZ}	22	24	13	11	10	8.7	5.8	4.5
	$\lambda_{\gamma Z}$	17	18	5.5	5.2	5.1	2.6	2.0	1.8
	$\lambda_{(Z\gamma)Z}$	-	-	23	23	23	14	14	14

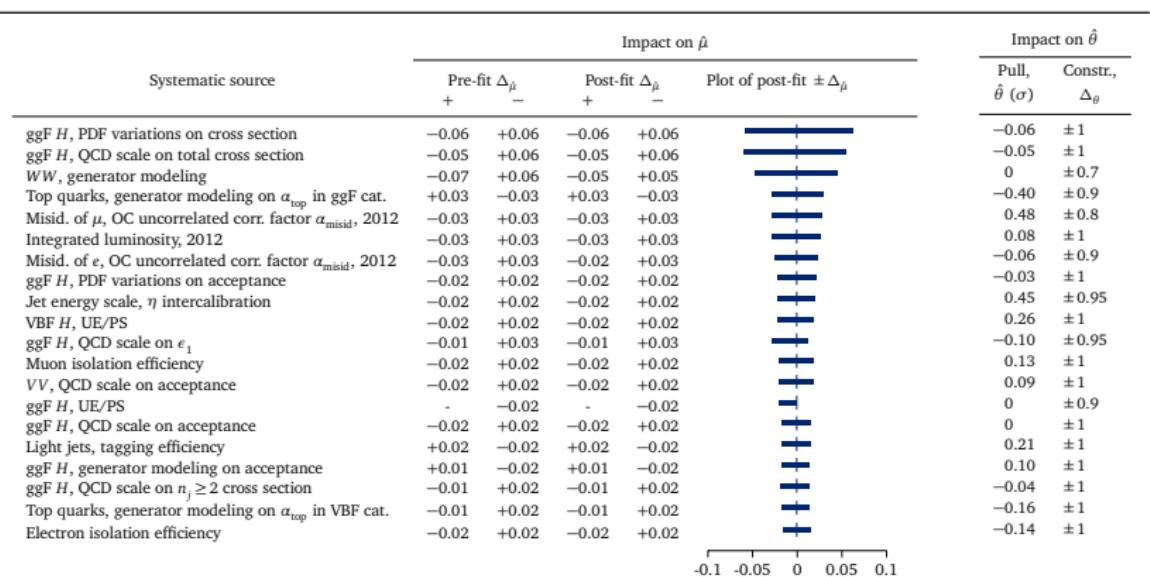
- Improvements reduced when including theory systematic uncertainties
- Some exp. uncertainties do not scale down with luminosity
- $\lambda_{\gamma Z}$ as a probe of new charged particles contributing to $H \rightarrow \gamma\gamma$ decay loop as compared to $H \rightarrow ZZ^*$
- λ_{tg} as a probe of new colored particles contributing to ggF production loop as compared to ttH/tH production

THEORETICAL UNCERTAINTIES

SYSTEMATIC UNCERTAINTIES (EXAMPLE 1 – RUN 1)

Many efforts to quantify importance of systematic uncertainties, here ATLAS
 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$

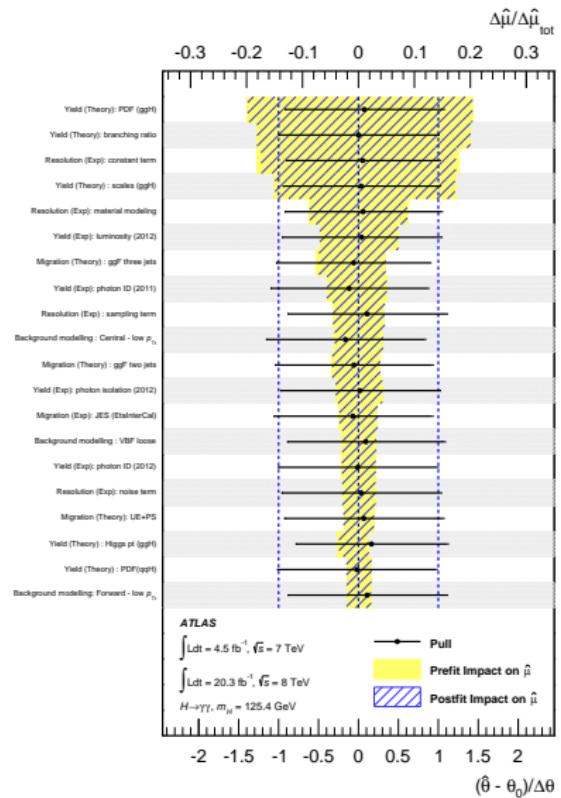
- Dominating systematic uncertainties mostly related to theory, e.g. missing higher order corrections, pdf+ α_s , modeling of WW background
- Experimental systematic uncertainties, e.g. jet energy scale, flavour tagging, lepton isolation



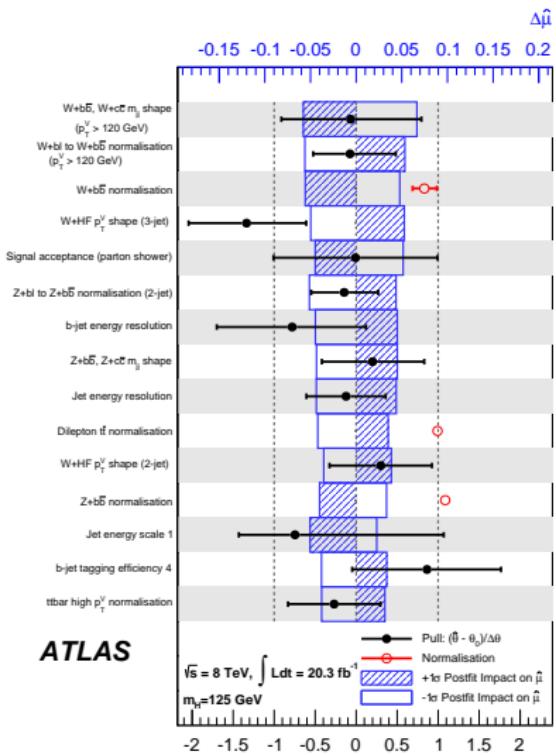
SYSTEMATIC UNCERTAINTIES (EXAMPLE 2 – RUN 1)



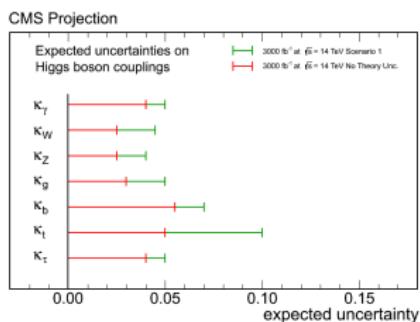
$H \rightarrow \gamma\gamma$: theo. and exp. contributions



$H \rightarrow b\bar{b}$: experimentally limited

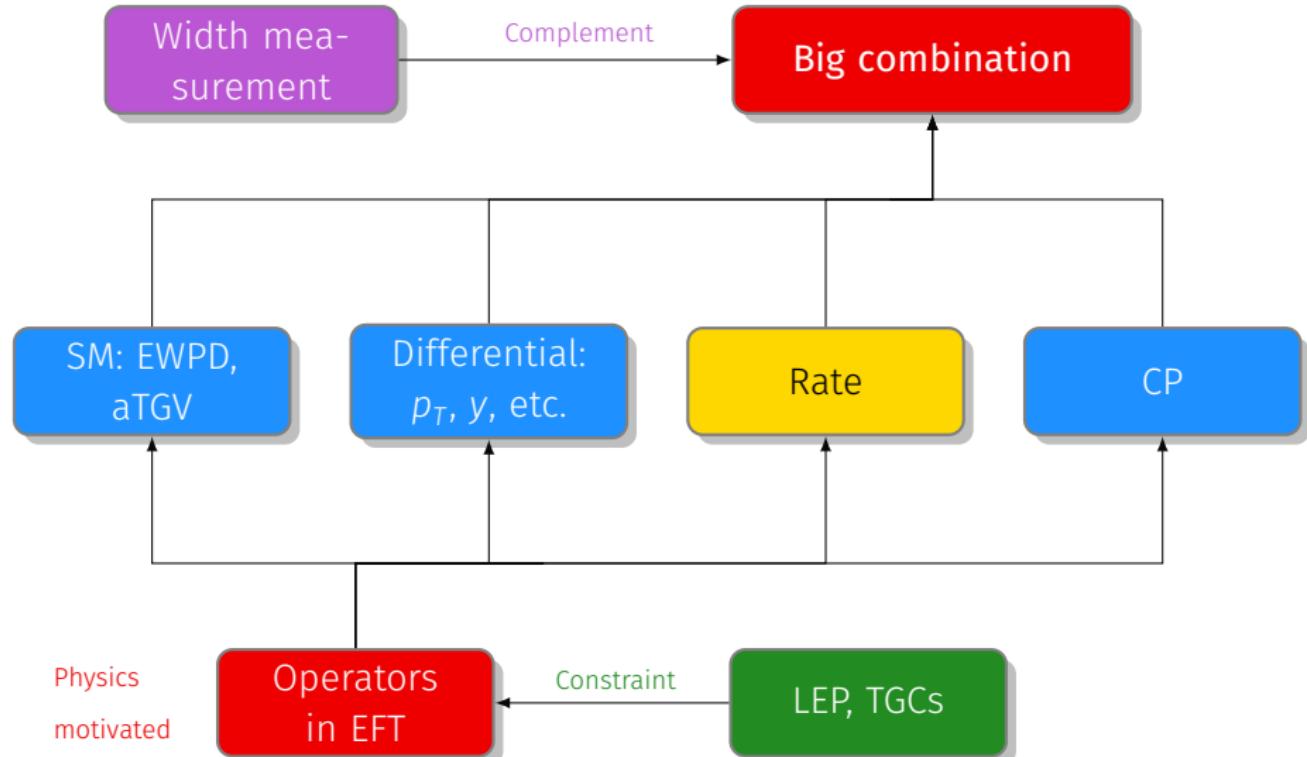


- Approximate required reduction of theory systematic uncertainty such that its effect is small
 - Less than ~30 % of the total experimental systematic uncertainty
- Insufficiently detailed model of the underlying theory uncertainties and their correlations in different phase space regions



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}			
Theory uncertainty (%)		κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \rightarrow H$									
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 VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j \rightarrow 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

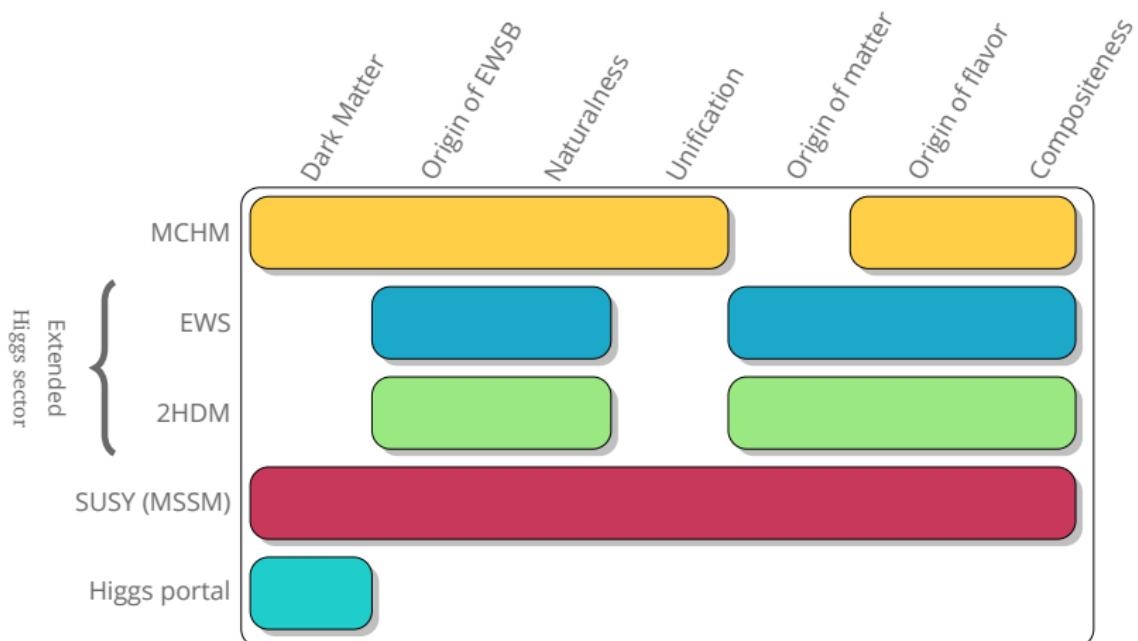
- Recent developments: ggF production in N3LO QCD (Anastasiou et al.) – scale uncertainties reduced by factor 3!



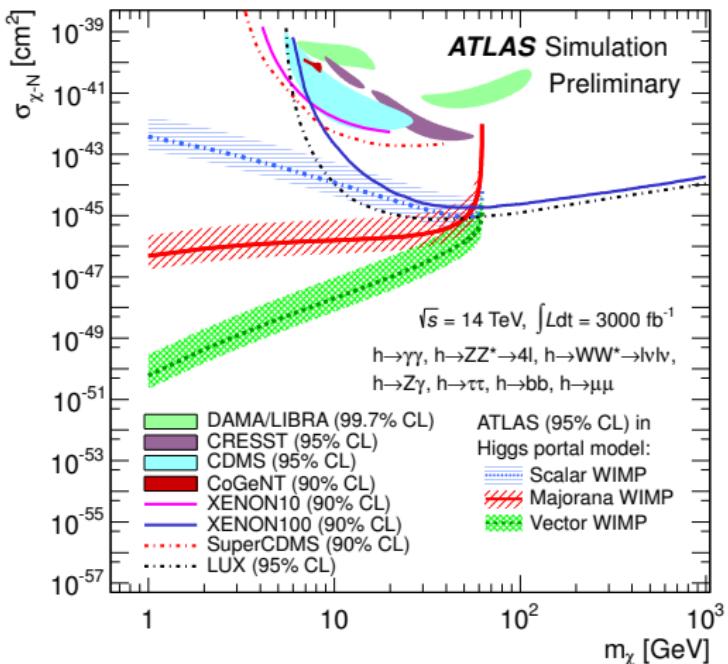
Challenges: Basis, samples, experimental design, ...

- HL-LHC provides excellent environment for Higgs precision measurements – in particular rare processes
- Upgrade of ATLAS and CMS detector essential to cope with conditions
- Coupling precision 2 % to 10 %
- Potential strong benefit from reduced theoretical uncertainties, but also remnant experimental systematics
- HH processes (Higgs self couplings) are very important for a more complete understanding of the EWSB mechanism ( see talk by Aram Apyan)
- EFT approach not discussed in detail but important for the HL-LHC data analysis

BACKUP



- Conservative assumption: *Higgs boson decays to WIMP pairs account entirely for $BR_{i,u}$.*
- Partial width for decays to dark matter particles depends on the spin of the dark matter particle

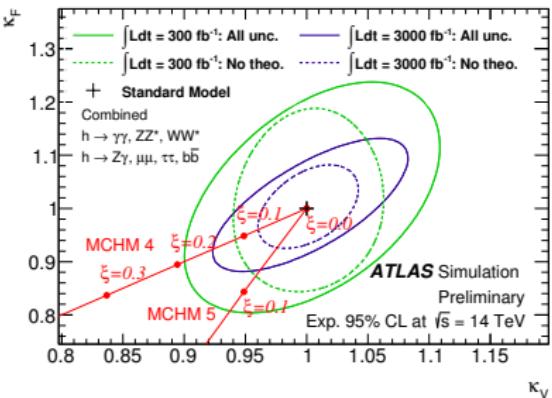


MINIMAL COMPOSITE HIGGS MODEL



Higgs boson may be a composite pseudo Nambu-Goldstone boson

- Couplings to vector bosons and fermions reduced wrt. SM
- Scaling of Higgs-fermion couplings depends on representation in which SM fermions are embedded



$$g_{hVV}^{\text{MCHM}_{4,5}} = g_{hW}^{\text{SM}} \sqrt{1 - \xi} \quad \text{with} \quad \xi = v^2/f^2$$

$$g_{hff}^{\text{MCHM}_4} = g_{hff}^{\text{SM}} \sqrt{1 - \xi} \quad \text{and} \quad g_{hff}^{\text{MCHM}_5} = g_{hff}^{\text{SM}} \frac{1 - 2\xi}{\sqrt{1 - \xi}}$$

Model	25 fb ⁻¹		300 fb ⁻¹		3000 fb ⁻¹	
	Obs.	Exp.	All unc.	No theory unc.	All unc.	No theory unc.
MCHM ₄	710 GeV	460 GeV	620 GeV	810 GeV	710 GeV	980 GeV
MCHM ₅	640 GeV	550 GeV	780 GeV	950 GeV	1000 GeV	1200 GeV

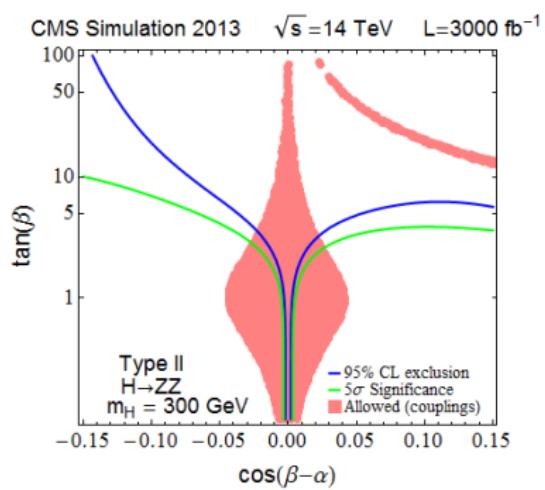
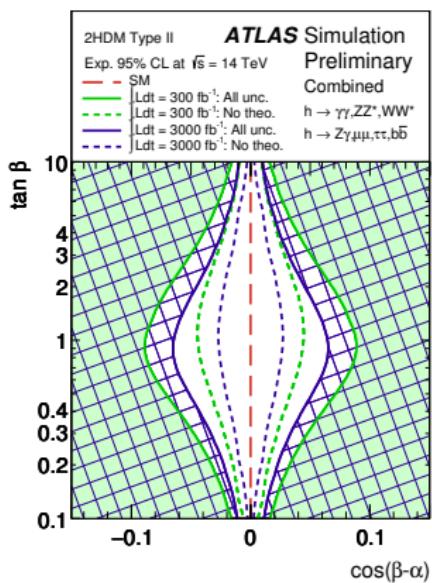
2HDM (EXAMPLE: TYPE II)



Two neutral CP -even bosons h and H , one neutral CP -odd boson A , and a pair of charged scalars H^\pm

- Identify discovered particle with light CP -even state:

$$\kappa_V = \sin(\beta - \alpha), \kappa_u = \cos \alpha / \sin \beta, \kappa_d = \kappa_\ell = -\sin \alpha / \cos \beta$$



Measured Higgs boson mass fixes radiative corrections to the mass squared mixing matrix of the neutral, CP -even Higgs bosons

$$\kappa_V = s_d(m_A, \tan \beta) \frac{1}{\sqrt{1 + \tan^2 \beta}} + s_u(m_A, \tan \beta) \frac{\tan \beta}{\sqrt{1 + \tan^2 \beta}}$$

$$\kappa_u = s_u(m_A, \tan \beta) \frac{\sqrt{1 + \tan^2 \beta}}{\tan \beta} \quad \text{and} \quad \kappa_d = s_d(m_A, \tan \beta) \sqrt{1 + \tan^2 \beta}$$

with $s_u = \sin \alpha$ and $s_d = \cos \alpha$ diagonalizing the CP -even neutral states

