

Prospects for Higgs and di-Higgs at the ATLAS experiment

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On behalf of the ATLAS Collaboration



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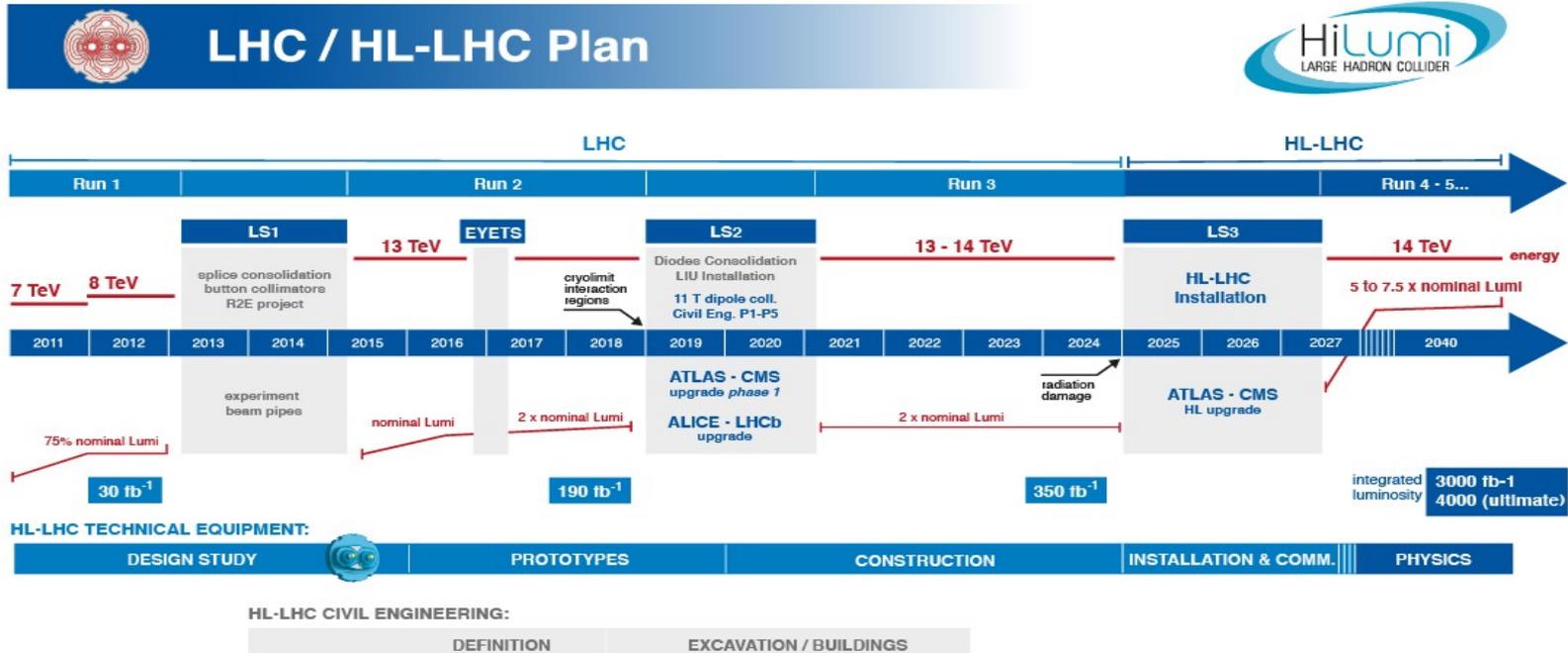
40th INTERNATIONAL CONFERENCE
ON HIGH ENERGY PHYSICS

VIRTUAL
CONFERENCE

28 JULY - 6 AUGUST 2020

PRAGUE, CZECH REPUBLIC

- ◆ High Luminosity LHC (HL-LHC) : Machine and detector upgrade
- ◆ SM Higgs physics programme (BSM Higgs not covered in this talk)
 - Single Higgs production
 - Probing $H \rightarrow c\bar{c}$
 - Differential cross-section
 - Higgs boson couplings to fermions/bosons
 - Non resonant di-Higgs production
 - First observation of HH production and
measurement of Higgs boson self-coupling
- ◆ Next steps towards optimal Higgs program @ HL-LHC



◆ Maximum integrated luminosity achievable in a decade with LHC infrastructure

- Integrated luminosity (3000 fb⁻¹) : Gain factor 9 compared to *Run 3*
- Physics program
 - ▶ Physics Beyond Standard Model
 - ▶ Understanding Electroweak Symmetry Breaking
 - Higgs properties : One of the main portals to understand fundamental basis of SM

◆ 2018-2019 : Last global update campaign published in CERN Yellow Report (YR) → Used for this presentation

■ Based on 3000 fb⁻¹ assumption : Still potential increase to 4000 fb⁻¹ (+ 33 %)

- ◆ New operation conditions for detectors
 - Sustain increased instantaneous luminosity by factor 2-4 vs Run 3
 - Number of interactions per bunch-crossing reaching mean value of 200
 - Larger integrated radiation dose
- ◆ Maximise physics outcome
 - Maintain or improve object reconstruction efficiency and resolution
 - Reduce fake rate even with more pile-up jets
- ◆ Implemented solutions (*Documented in Technical Design Reports*)
 - Upgrade electronic readout
 - Replace detectors with most recent technologies (new Inner Tracker)
 - Extend angular coverage to forward region : High Granularity Timing Detector (HGTD) and new Inner Tracker
 - Trigger and data acquisition systems : Sustain higher rate and extended capabilities

Not possible to have same strategy as for standard *Run 2* analysis

- Main limitation is lack of simulated p-p collisions

→ Expected results are computed from :

◆ Latest published LHC analysis results

- Use early *Run 2* data with 2015+2016 sample (36 fb^{-1})
or 2015+2016+2017 (80 fb^{-1}) : Optimal usage of *Run 2* expertise and tools
- Scale to 3000 fb^{-1} → Statistical unc. reduced by factor $\sqrt{\left(\int L_{\text{HL-LHC}} / \int L_{\text{Run2}} \right)}$
- Scale signal and background cross-section to $\sqrt{s}=14 \text{ TeV}$ (Increase by 10-20 %)
- Default assumption on object reconstruction performances and fake rates:
Upgraded detector performances compensate pile-up degradation

◆ Parametrised performances of upgraded detector layout

- Only when *Run 2* analysis tools not optimised for HL-LHC
- Particles produced at event-generator level and smeared according to particle/object (e, γ , μ , τ , jet, missing- E_T) expected efficiencies/resolutions/fake rates

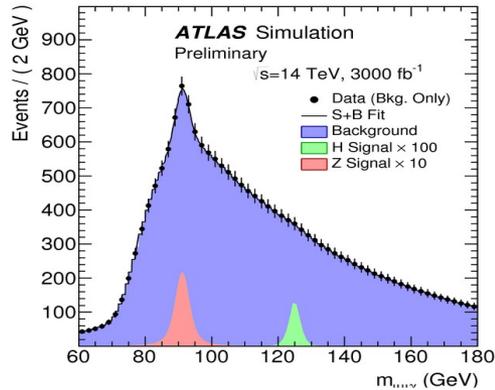
Large event statistics → systematic uncertainty critical for many analyses

- ◆ Joint ATLAS-CMS effort to define common systematics
- ◆ Theoretical systematics : ATL-PHYS-PUB-2019-005
 - Reduced by factor 2 *except PDF, energy scale values and tt+Heavy Flavour*
- ◆ Experimental systematics : Scaled to floor value
- ◆ Limited number of simulated events :
Impact documented but not included for CERN YR

Scenarii on systematics uncertainty reduction

- Keep early Run 2 values (pessimistic) : *S1*
- Reduction as defined for CERN YR : *S2 or reduced*

- ◆ Low BR (2.9 %) → Could be enhanced by presence of new physics
- ◆ First attempt through exclusive reconstruction $H \rightarrow J/\psi (\rightarrow \mu^+\mu^-) \gamma$
- Extrapolated from Run 1 analysis

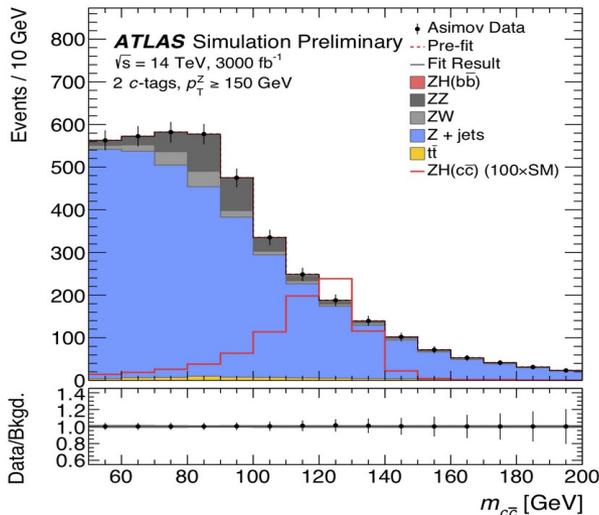


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Expected branching ratio limit (no syst.) :
 $\mathcal{B}(H \rightarrow J/\Psi \gamma) < \sim 15 \times SM @ 95\% C.L.$

- ◆ $Z(\rightarrow ll)H(\rightarrow c\bar{c})$ extrapolated from 36 fb⁻¹ sample

ATL-PHYS-PUB-2018-016



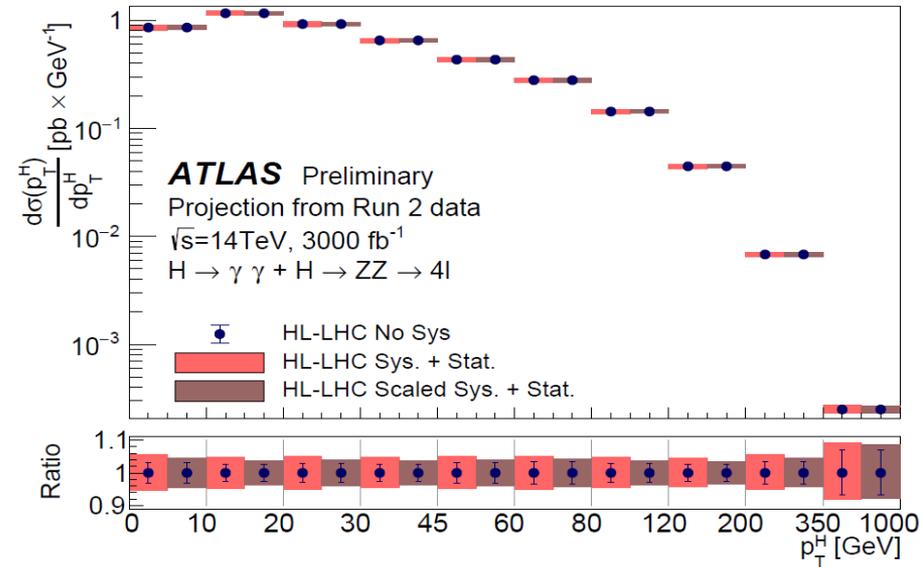
Expected branching ratio limit (no syst.) :
 $\mathcal{B}(H \rightarrow c\bar{c}) < 6.3 \times SM @ 95\% C.L.$

Source of uncertainty	Change in limit
Background shape	+36%
Jet energy scale and resolution	+17%
Lepton reconstruction and identification	+12%
c-jet tagging efficiency	+11%

Enhanced sensitivity expected : Add $W \rightarrow l\nu$ and $Z \rightarrow \nu\bar{\nu}$

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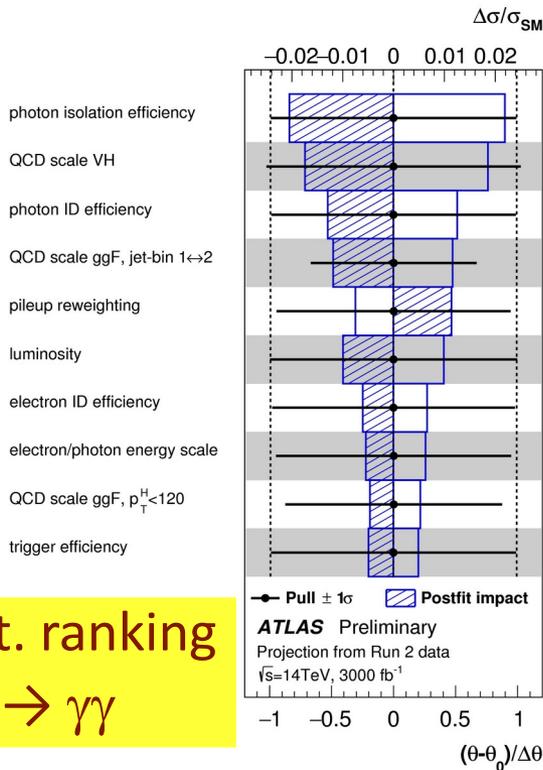
- Sensitivity to new physics
 - Low P_T^H : Couplings to c and b quarks
 - High P_T^H : New physics at large scale
- Final states : $\gamma\gamma, ZZ \rightarrow 4$ leptons
 - Best precision with $\gamma\gamma$ final state
- Extrapolated from 80 fb^{-1} sample



- Low-medium P_T^H regime
 - 3 % (stat) \rightarrow 5 % (stat+syst) \rightarrow 4 % (stat + reduced syst.)
 - Achieving reduced systematics mandatory
- Large P_T^H regime [350-1000 GeV] : 8 % precision dominated by stat. uncert.

Next step : Same exercise for $H \rightarrow b\bar{b}$ through VH channel

- ◆ All channels studied at Run 2 extrapolated to HL-LHC
- ◆ Systematic uncertainties : Extrapolation from Run 2 values required checks at unusual precision for experts
 - Scenario S1 : Keep Run 2 systematic uncertainties (pessimistic)
 - Scenario S2 : Reduction of syst. uncertainties defined for CERN YR

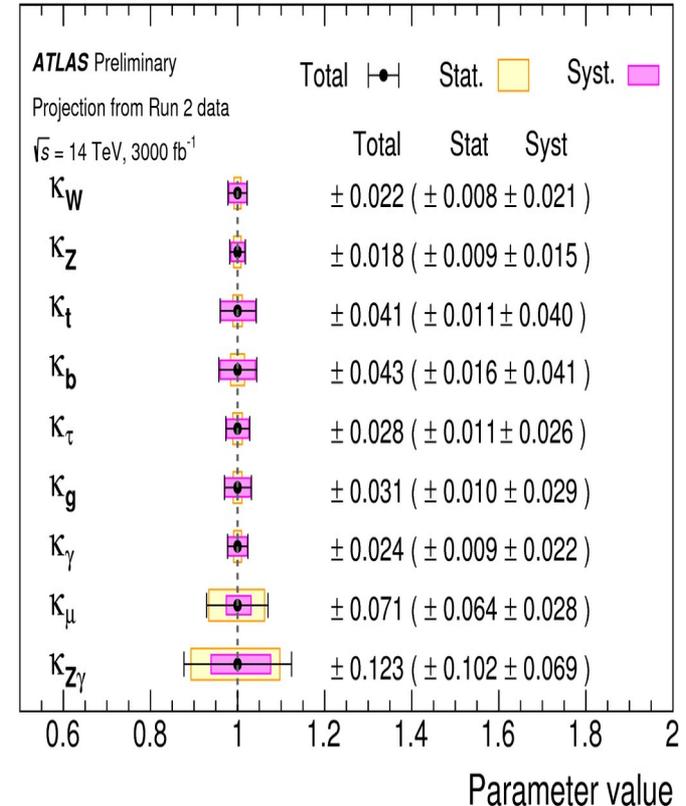
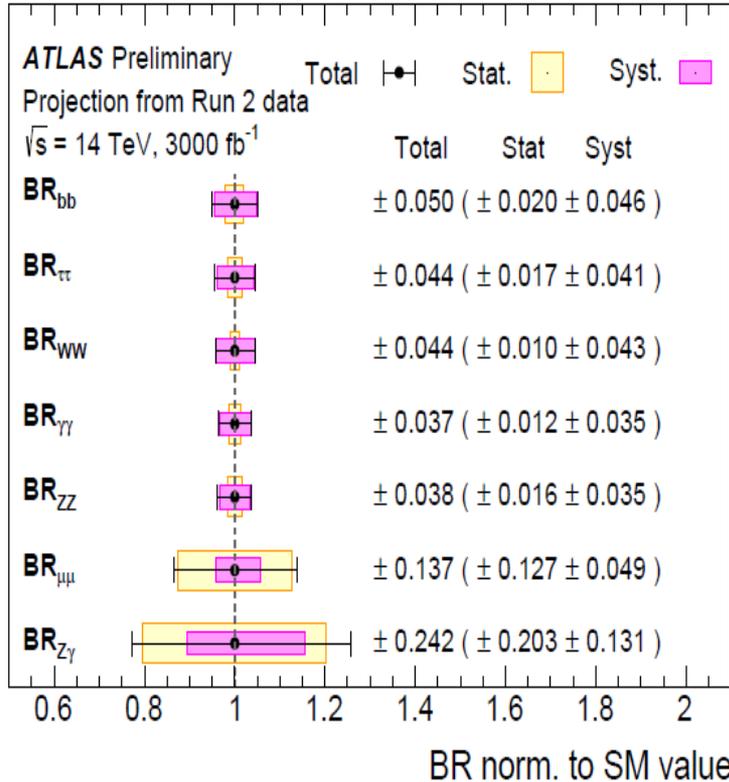


Syst. ranking
VH $\rightarrow \gamma\gamma$

Prod. mode	Scenario	Δ_{tot}/σ_{SM}	$\Delta_{stat}/\sigma_{SM}$	Δ_{exp}/σ_{SM}	Δ_{sig}/σ_{SM}	$\Delta\mu_{sig}$
ggF+ $b\bar{b}H$	Run 2, 80 fb $^{-1}$	+0.15	+0.11	+0.09	+0.03	+0.08
	HL-LHC S1	-0.14	-0.11	-0.08	-0.02	-0.06
	HL-LHC S2	+0.06	+0.02	+0.05	+0.01	+0.07
VBF	Run 2, 80 fb $^{-1}$	-0.05	-0.02	-0.05	-0.01	-0.06
	HL-LHC S1	+0.04	+0.02	+0.03	+0.01	+0.03
	HL-LHC S2	-0.03	-0.02	-0.03	-0.01	-0.03
VH	Run 2, 80 fb $^{-1}$	+0.36	+0.30	+0.16	+0.13	+0.15
	HL-LHC S1	-0.31	-0.28	-0.11	-0.09	-0.10
	HL-LHC S2	+0.14	+0.04	+0.08	+0.11	+0.11
top	Run 2, 80 fb $^{-1}$	-0.13	-0.04	-0.07	-0.10	-0.10
	HL-LHC S1	+0.10	+0.04	+0.06	+0.06	+0.06
	HL-LHC S2	-0.09	-0.04	-0.06	-0.05	-0.06
VH	Run 2, 80 fb $^{-1}$	+0.59	+0.54	+0.22	+0.12	+0.18
	HL-LHC S1	-0.54	-0.50	-0.20	-0.09	-0.11
	HL-LHC S2	+0.11	+0.08	+0.06	+0.05	+0.09
top	Run 2, 80 fb $^{-1}$	-0.10	-0.08	-0.05	-0.04	-0.08
	HL-LHC S1	+0.09	+0.08	+0.04	+0.03	+0.05
	HL-LHC S2	-0.09	-0.08	-0.03	-0.03	-0.05
top	Run 2, 80 fb $^{-1}$	+0.37	+0.34	+0.10	+0.10	+0.18
	HL-LHC S1	-0.32	-0.30	-0.07	-0.07	-0.11
	HL-LHC S2	+0.11	+0.05	+0.07	+0.07	+0.13
top	Run 2, 80 fb $^{-1}$	-0.10	-0.05	-0.06	-0.07	-0.11
	HL-LHC S1	+0.08	+0.05	+0.05	+0.04	+0.07
	HL-LHC S2	-0.08	-0.05	-0.04	-0.04	-0.06

Relative uncertainties on σ for H $\rightarrow \gamma\gamma$

κ_f : Higgs boson coupling modifier per particle f
 No modification on Γ_H from BSM



- ◆ Reaching few % precision dominated by systematics uncertainties
- ◆ Exceptions : $Z\gamma$ and $\mu\mu$ reaching 10 % precision dominated by stat. uncertainties

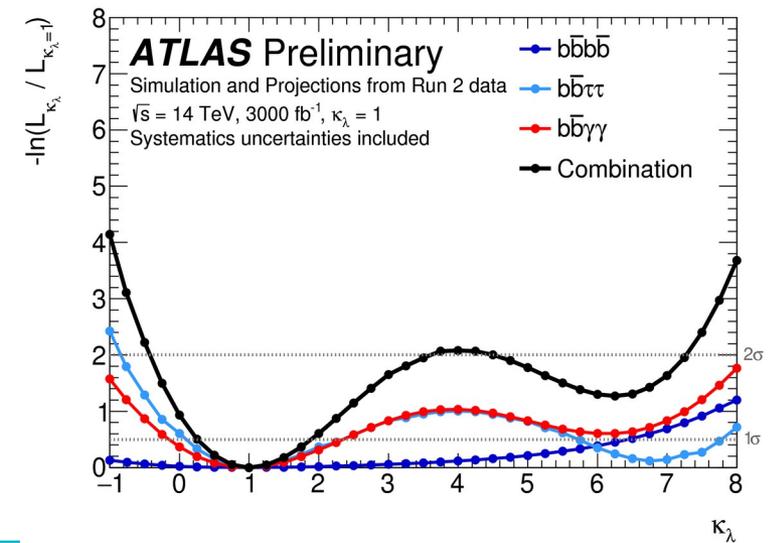
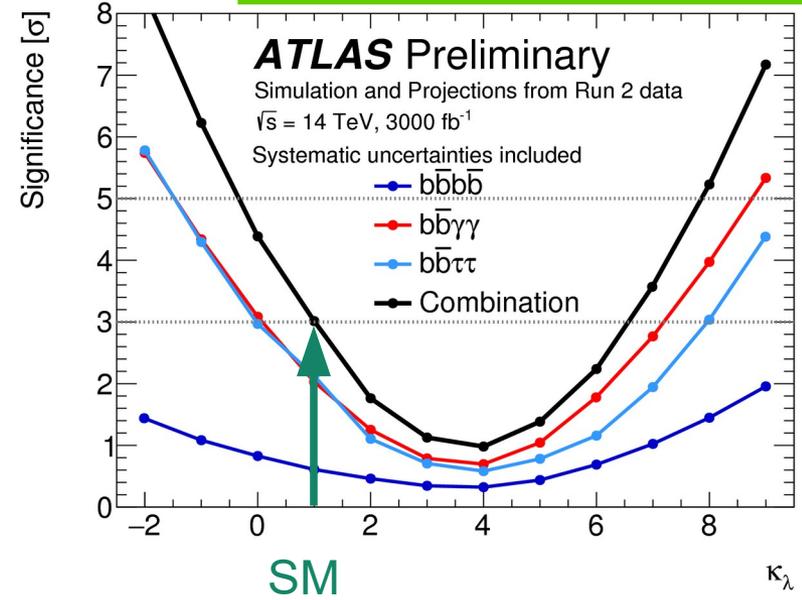
ATLAS+CMS combination : Previous presentation from Sandhya J. (CMS)



- Analysis challenge :**
- ◆ $\sigma(HH) \sim \sigma(H)/1000$
 - ◆ ≥ 4 particles in final state
 - selection efficiencies $< 10\%$
 - ◆ Largest B.R. : $bbbb$ (33%) and $bb\tau\tau$ (7.4%)
 - large background
 - ◆ Low B.R. : $bb\gamma\gamma$ (0.26%) → few signal events but small background

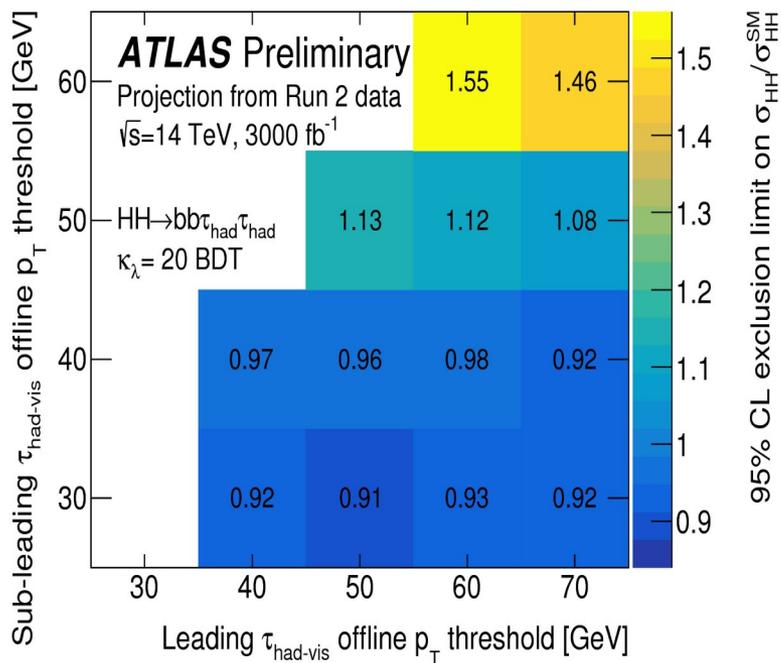
κ_λ : Higgs self-coupling normalized to its SM value

	Statistical-only	Statistical + Systematic
$HH \rightarrow b\bar{b}b\bar{b}$	$-0.4 \leq \kappa_\lambda \leq 4.3$	$-2.3 \leq \kappa_\lambda \leq 6.4$
$HH \rightarrow b\bar{b}\tau\tau$	$0.2 \leq \kappa_\lambda \leq 2.0 \cup 5.9 \leq \kappa_\lambda \leq 7.2$	$0.1 \leq \kappa_\lambda \leq 2.3 \cup 5.7 \leq \kappa_\lambda \leq 7.8$
$HH \rightarrow b\bar{b}\gamma\gamma$	$-0.1 \leq \kappa_\lambda \leq 2.4$	$-0.2 \leq \kappa_\lambda \leq 2.5$
combined	$0.4 \leq \kappa_\lambda \leq 1.7$	$0.25 \leq \kappa_\lambda \leq 1.9$



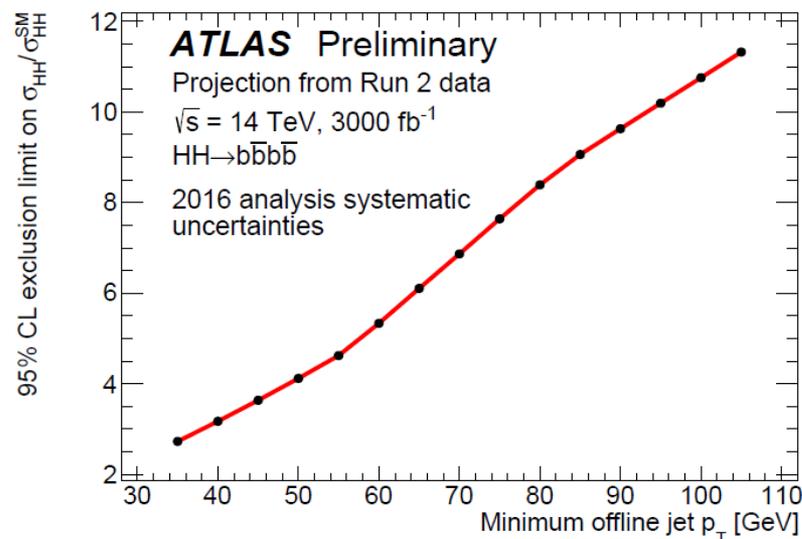
@ 95 % C.L.

Triggering on both had-vis τ
for $HH \rightarrow bb\tau\tau$



Background : fake- τ

Triggering on min b-jet P_T
for $HH \rightarrow bbbb$



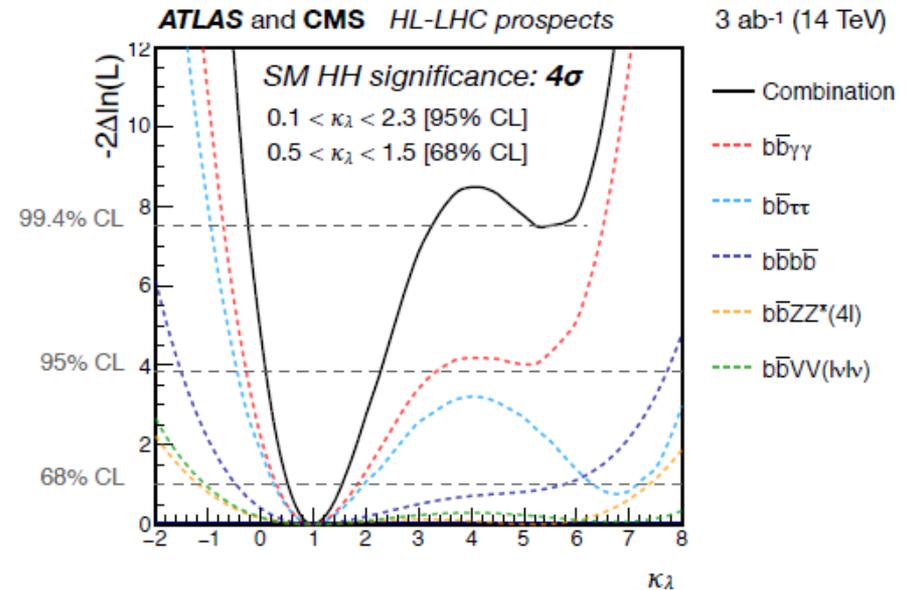
Background : Multijet events

Maintaining low p_T thresholds for τ and b-jets at the trigger level
challenging but critical

arXiv:1902.00134

Significance for HH production ($\kappa_\lambda=1$)

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \rightarrow b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \rightarrow b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \rightarrow b\bar{b}VV(l\nu\nu)$	-	0.59	-	0.56
$HH \rightarrow b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		4.0	



Close to observe HH @ HL-LHC

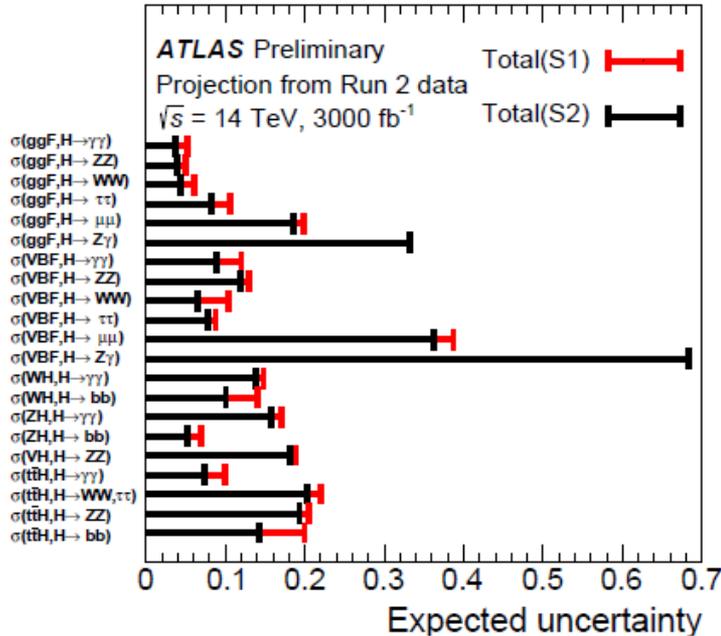
Reaching precision measurement :

- ◆ κ_λ : 50 % precision
- ◆ $\kappa_\lambda = 0$ excluded > 95 % C.L.

- ◆ Studies over last years focused on CERN Yellow Report
 - Updates in expected precisions benefiting from progress @ Run 2
 - Key sources of syst. uncertainties identified → roadmap on theory and experimental effort
- ◆ Next round of potential physics achievements for SNOWMASS
 - Targetting critical topics with recent improvements
 - Adding subjects not covered in CERN YR
- ◆ Preparation for HL-LHC program in ATLAS
 - Optimise reconstruction algorithm with new HL-LHC environment (pile-up) and detector layout (new detectors or readout)
 - Integration of new algorithms developed for *Run 2* or *Run 3*

HL-LHC era : an exciting period for Higgs physics studies

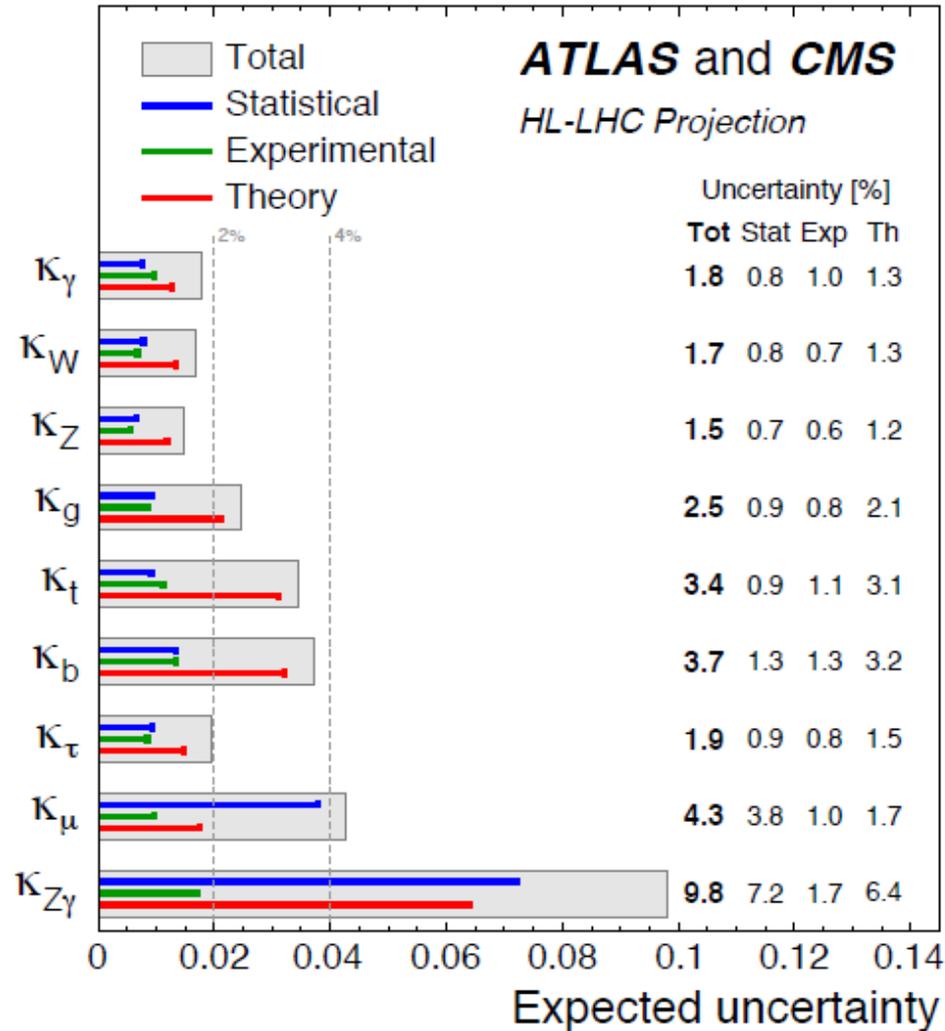
Backup slides



POI	Scenario	Δ_{tot}	Δ_{stat}	Δ_{exp}	Δ_{sig}	Δ_{bkg}
$\sigma_{\text{ggF}}/\sigma_{\text{ggF}}^{\text{SM}}$	HL-LHC S1	+0.035 -0.034	+0.008 -0.008	+0.021 -0.021	+0.022 -0.021	+0.016 -0.015
	HL-LHC S2	+0.024 -0.024	+0.008 -0.008	+0.017 -0.017	+0.012 -0.012	+0.010 -0.010
$\sigma_{\text{VBF}}/\sigma_{\text{VBF}}^{\text{SM}}$	HL-LHC S1	+0.056 -0.054	+0.020 -0.020	+0.027 -0.026	+0.038 -0.037	+0.022 -0.020
	HL-LHC S2	+0.042 -0.041	+0.020 -0.020	+0.023 -0.022	+0.023 -0.022	+0.018 -0.017
$\sigma_{\text{WH}}/\sigma_{\text{WH}}^{\text{SM}}$	HL-LHC S1	+0.095 -0.092	+0.041 -0.040	+0.041 -0.039	+0.053 -0.048	+0.055 -0.054
	HL-LHC S2	+0.078 -0.076	+0.041 -0.040	+0.035 -0.034	+0.034 -0.031	+0.045 -0.045
$\sigma_{\text{ZH}}/\sigma_{\text{ZH}}^{\text{SM}}$	HL-LHC S1	+0.063 -0.061	+0.034 -0.034	+0.025 -0.024	+0.035 -0.033	+0.031 -0.030
	HL-LHC S2	+0.049 -0.048	+0.034 -0.034	+0.018 -0.018	+0.020 -0.019	+0.022 -0.021
$\sigma_{\text{t}\bar{\text{t}}H}/\sigma_{\text{t}\bar{\text{t}}H}^{\text{SM}}$	HL-LHC S1	+0.069 -0.066	+0.019 -0.019	+0.032 -0.031	+0.038 -0.036	+0.044 -0.041
	HL-LHC S2	+0.054 -0.052	+0.019 -0.019	+0.028 -0.027	+0.025 -0.023	+0.034 -0.033

Prod. mode	Scenario	$\Delta_{\text{tot}}/\sigma_{\text{SM}}$	$\Delta_{\text{stat}}/\sigma_{\text{SM}}$	$\Delta_{\text{exp}}/\sigma_{\text{SM}}$	$\Delta_{\text{sig}}/\sigma_{\text{SM}}$	$\Delta\mu_{\text{sig}}$
ggF+bbH	Run 2, 80 fb ⁻¹	+0.15 -0.14	+0.11 -0.11	+0.09 -0.08	+0.03 -0.02	+0.08 -0.06
	HL-LHC S1	+0.06 -0.05	+0.02 -0.02	+0.05 -0.05	+0.01 -0.01	+0.07 -0.06
	HL-LHC S2	+0.04 -0.03	+0.02 -0.02	+0.03 -0.03	+0.01 -0.01	+0.03 -0.03
VBF	Run 2, 80 fb ⁻¹	+0.36 -0.31	+0.30 -0.28	+0.16 -0.11	+0.13 -0.09	+0.15 -0.10
	HL-LHC S1	+0.14 -0.13	+0.04 -0.04	+0.08 -0.07	+0.11 -0.10	+0.11 -0.10
	HL-LHC S2	+0.10 -0.09	+0.04 -0.04	+0.06 -0.06	+0.06 -0.05	+0.06 -0.06
VH	Run 2, 80 fb ⁻¹	+0.59 -0.54	+0.54 -0.50	+0.22 -0.20	+0.12 -0.09	+0.18 -0.11
	HL-LHC S1	+0.11 -0.10	+0.08 -0.08	+0.06 -0.05	+0.05 -0.04	+0.09 -0.08
	HL-LHC S2	+0.09 -0.09	+0.08 -0.08	+0.04 -0.03	+0.03 -0.03	+0.05 -0.05
top	Run 2, 80 fb ⁻¹	+0.37 -0.32	+0.34 -0.30	+0.10 -0.07	+0.10 -0.07	+0.18 -0.11
	HL-LHC S1	+0.11 -0.10	+0.05 -0.05	+0.07 -0.06	+0.07 -0.07	+0.13 -0.11
	HL-LHC S2	+0.08 -0.08	+0.05 -0.05	+0.05 -0.04	+0.04 -0.04	+0.07 -0.06

$\sqrt{s} = 14 \text{ TeV}, 3000 \text{ fb}^{-1}$ per experiment



Bin [GeV]	Relative uncertainty [%]		
	Without Sys.	With Unscaled Syst.	With Scaled Syst.
0, 10	3.2	5.5	4.5
10, 20	3.0	4.8	3.8
20, 30	2.8	5.0	3.9
30, 45	2.7	4.7	3.6
45, 60	3.2	5.0	4.1
60, 80	3.3	5.1	4.2
80, 120	2.9	4.6	3.7
120, 200	2.7	4.4	3.5
200, 350	3.4	5.4	4.5
350, 1000	6.8	8.7	8.2

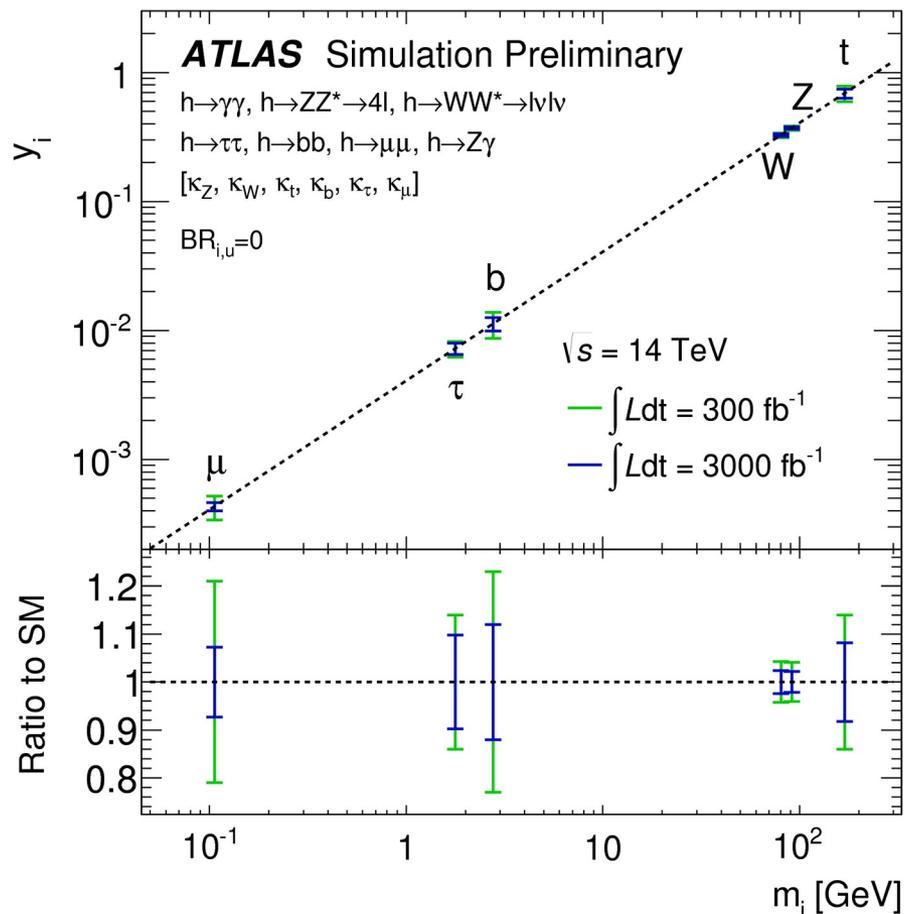
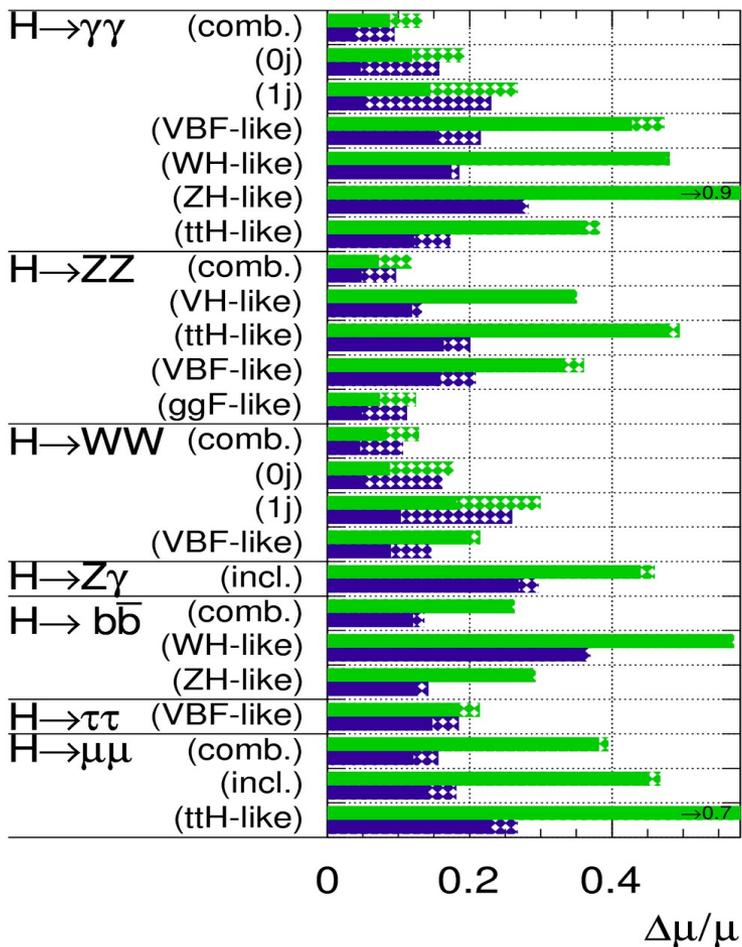
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Systematic Uncertainties	Scale Factor
Jet energy scale, forward region	Set to 0
Jet energy scale, Jet punch-through	Set to 0
High- p_T jet energy scale	Set to 0
$H \rightarrow \gamma\gamma$ background modeling	Set to 0
$4\ell m_H$	Scaled by 0.25
PDF	Scaled by 0.41
Jet flavor	Scaled by 0.5
Jet energy scale	Scaled by 0.5
Pileup modelling	Scaled by 0.5
QCD scale	Scaled by 0.5
Underlying event and parton shower modeling	Scaled by 0.5
Higgs branching ratios	Scaled by 0.5
Photon energy scale and resolution	Scaled by 0.8
Photon reconstruction, ID, and isolation	Scaled by 0.8
$qq \rightarrow ZZ$ irreducible background	Set to 2%
Luminosity	Set to 1% of expected integrated luminosity

$\langle \mu_{pU} \rangle = 140$

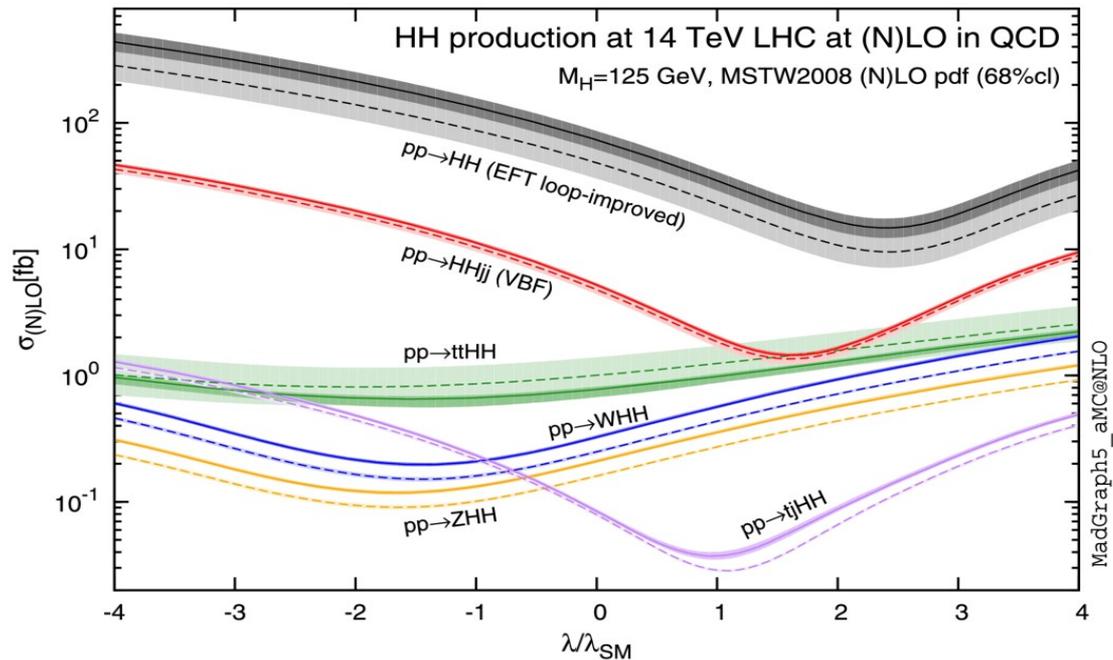
ATLAS Simulation Preliminary

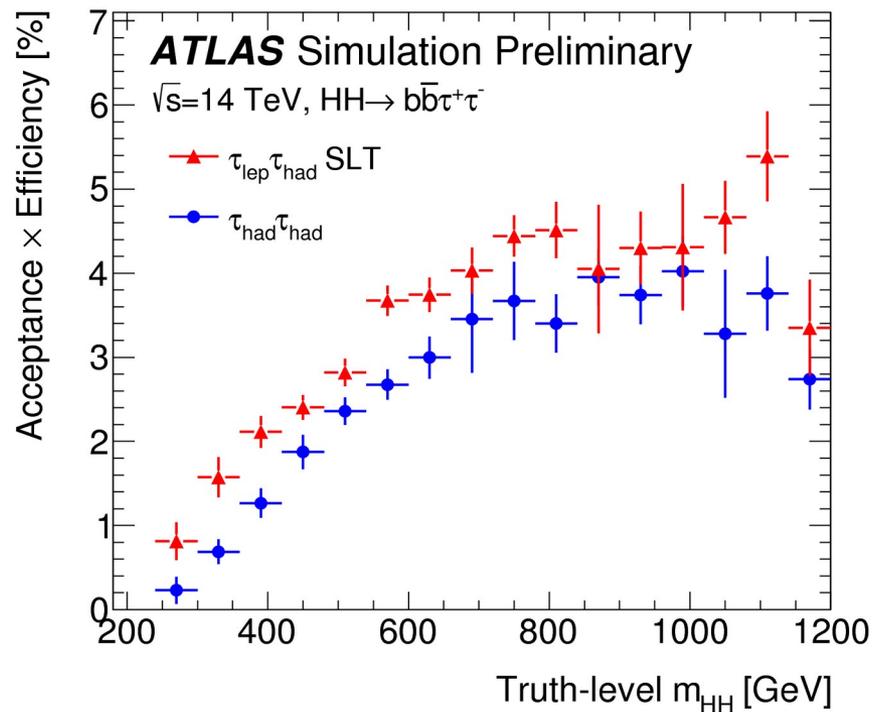
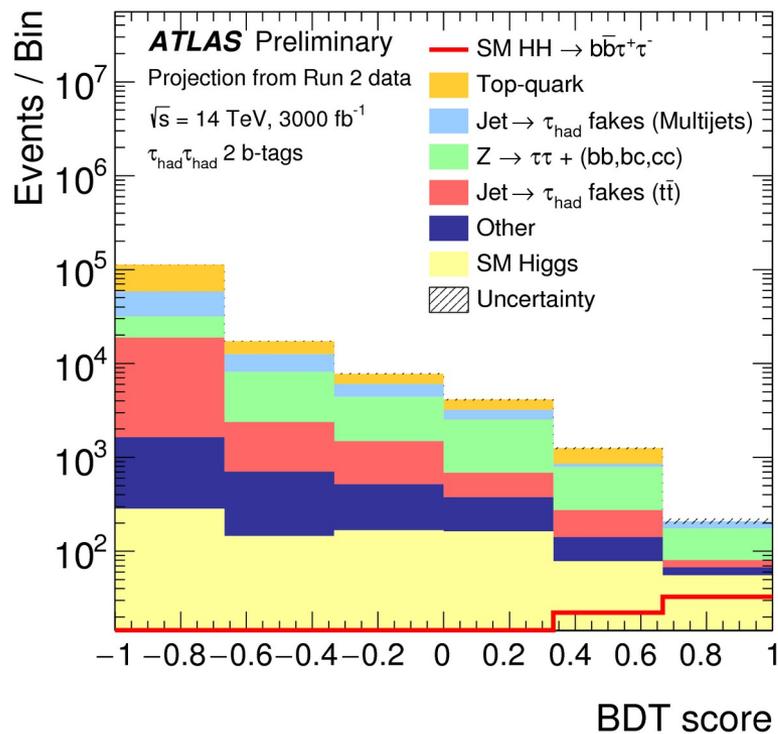
$\sqrt{s} = 14 \text{ TeV}$: $\int L dt = 300 \text{ fb}^{-1}$; $\int L dt = 3000 \text{ fb}^{-1}$

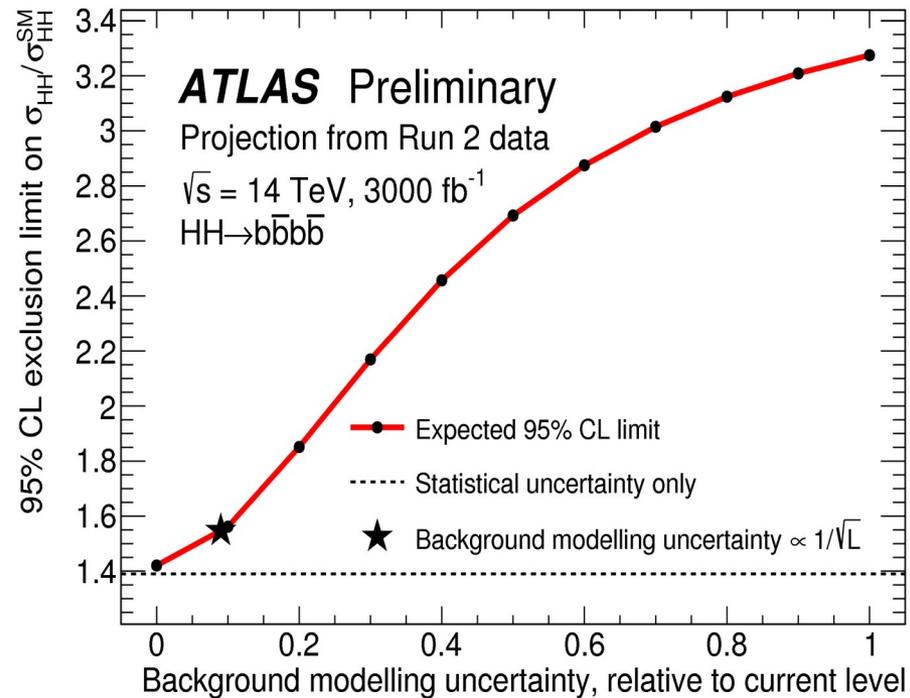
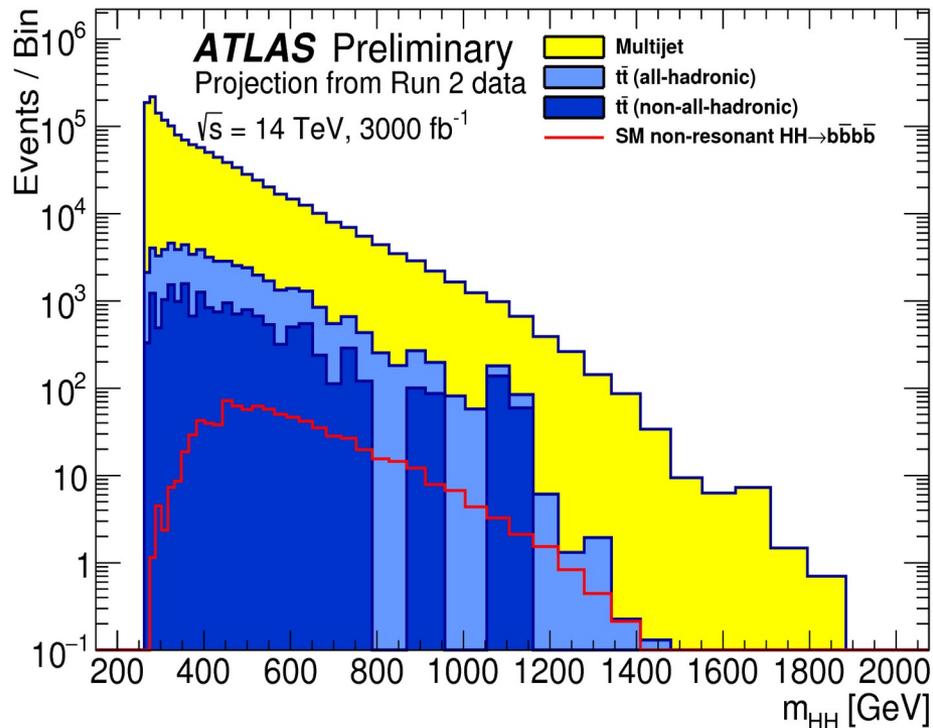


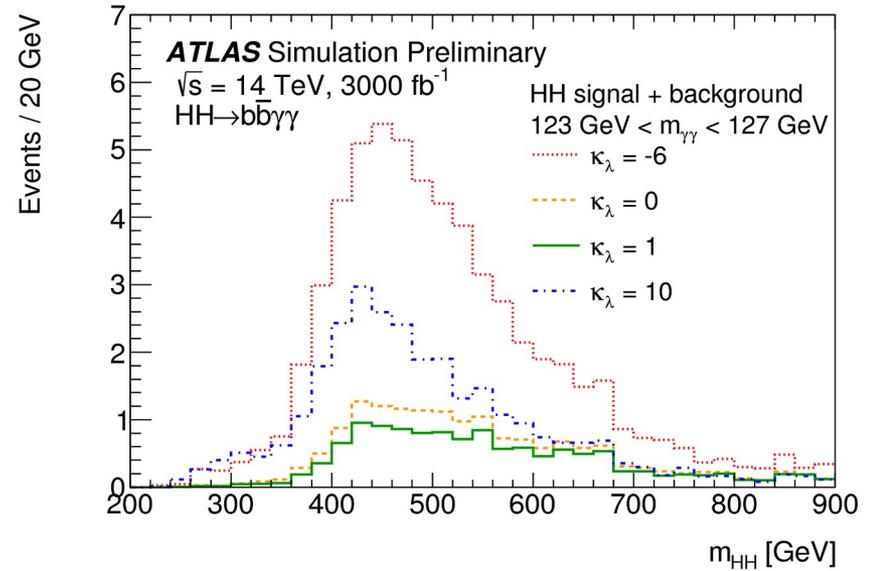
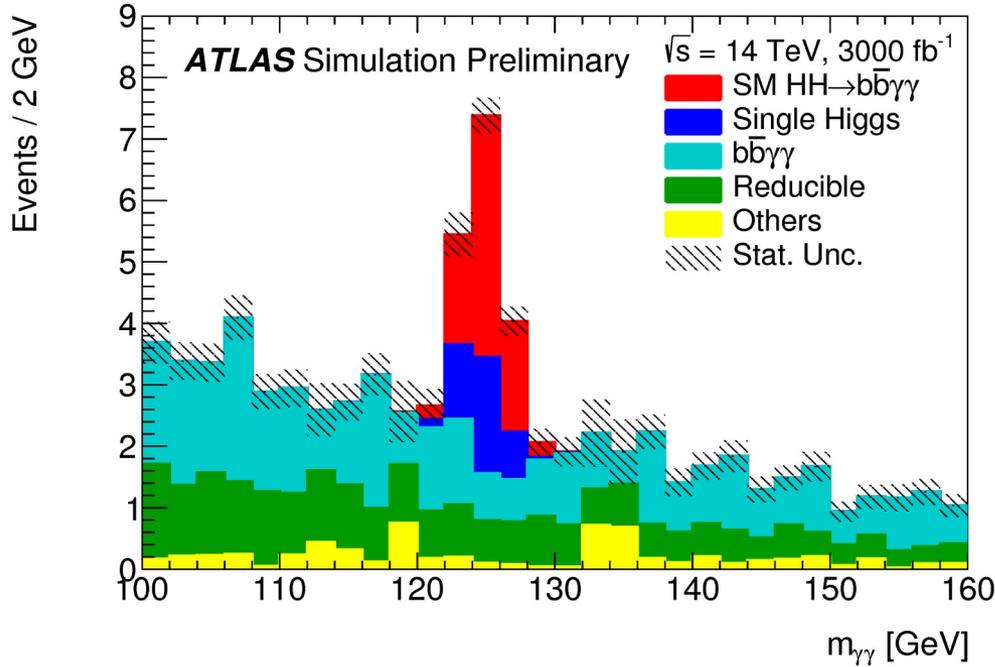
ATL-PHYS-PUB-2014-016

Phys. Lett. B732 (2014) 142-149









Channel	Statistical-only	Statistical + Systematic
$HH \rightarrow b\bar{b}b\bar{b}$	1.4	0.61
$HH \rightarrow b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5	3.0