Prospects for single and di-Higgs measurements at the HL-LHC with the ATLAS experiment

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Introduction (1)

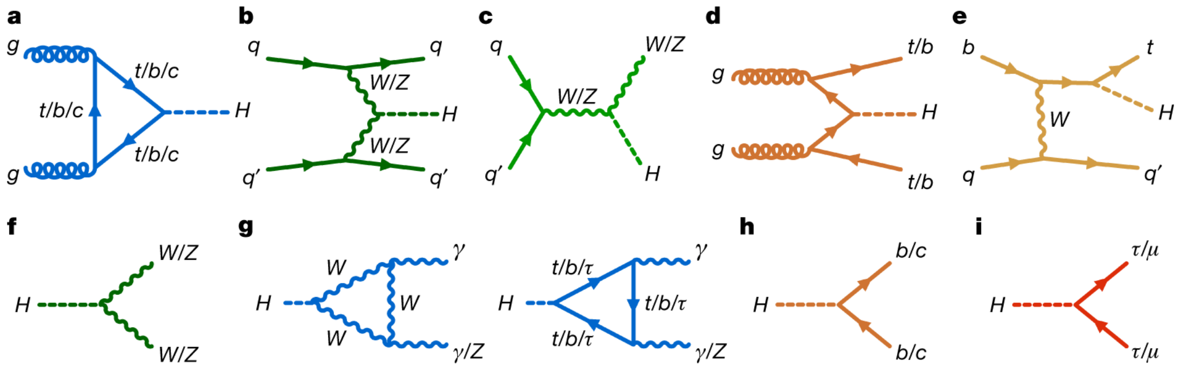
With Run 2 data, ATLAS and CMS have been able to study many of the dominant Higgs production and decay modes

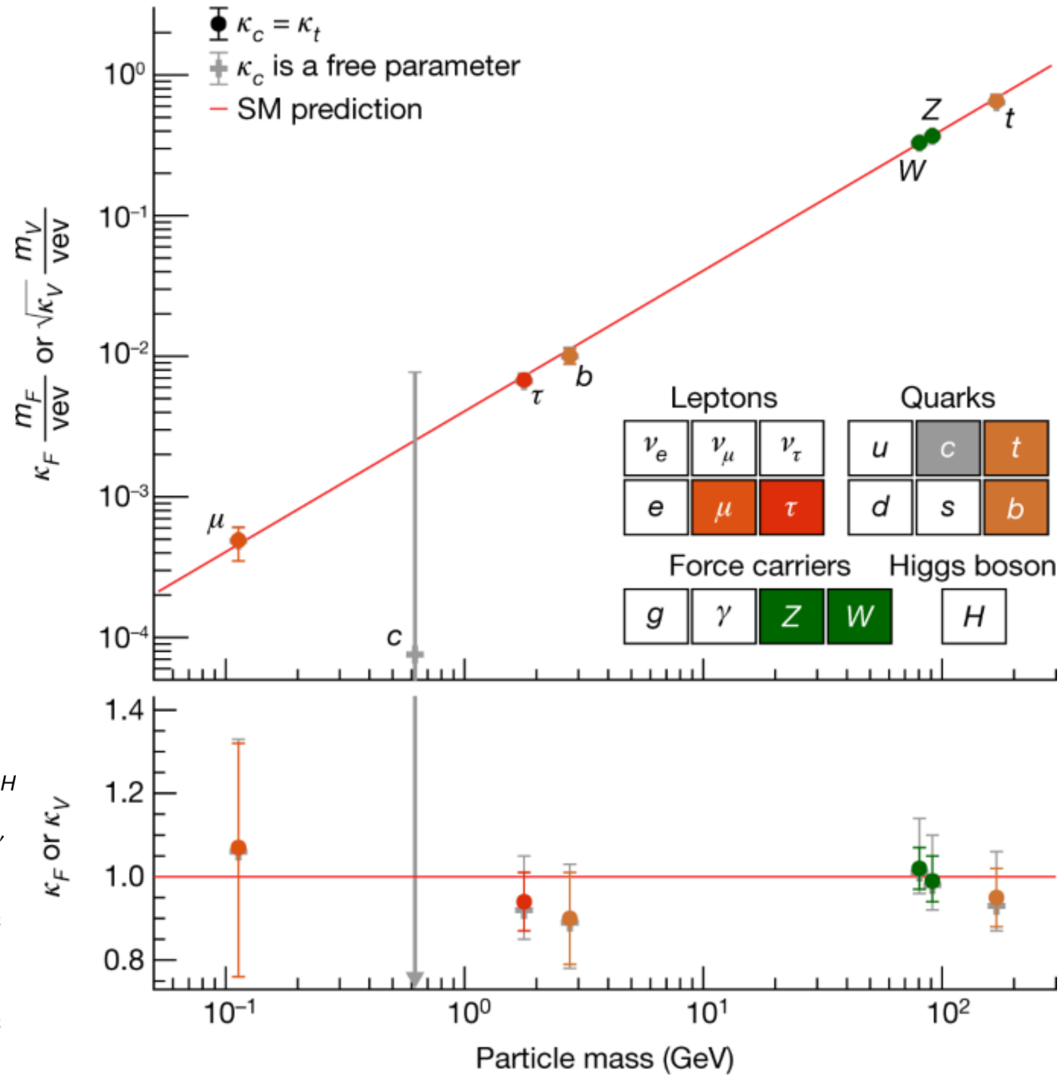
All compatible so far with the SM

Still hope for BSM physics!

- measurements of **rare Higgs boson couplings**
- **precision measurements** in specific kinematic regions

But many are limited by Run 2 statistics

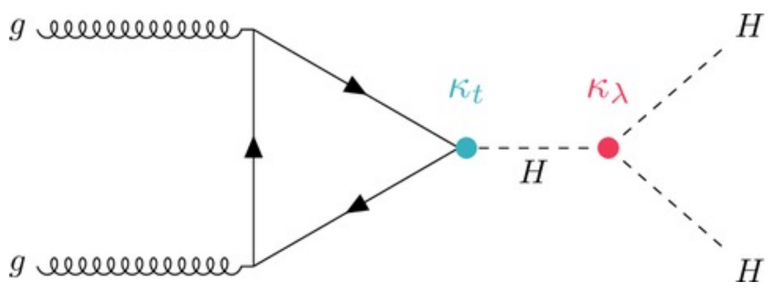


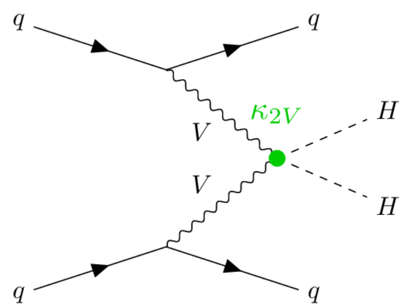


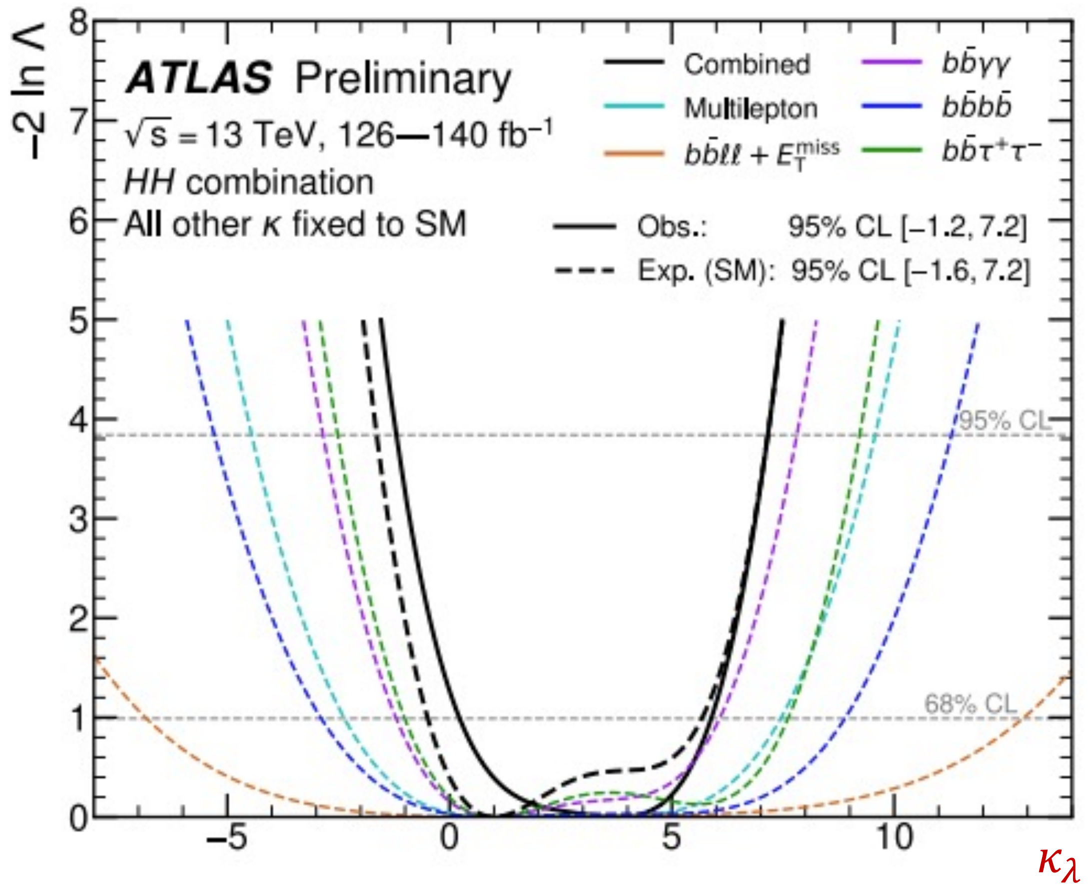
Introduction (2)

Di-Higgs (HH) production can give access to the Higgs trilinear self coupling $\lambda_{HHH}^{SM} = m_H^2/2v^2$ and the shape of the Higgs potential

But the production rate is ~30fb, 1000x smaller than single Higgs production

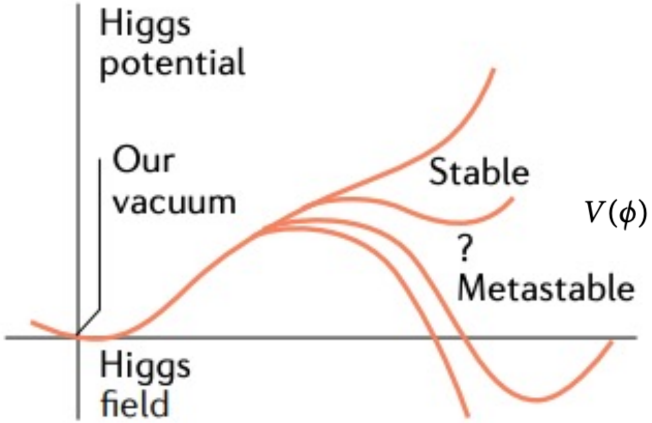






These kinds of measurements will be one of the main focuses of the **High Luminosity LHC**, which will aim for **3000ifb of 14 TeV data**

How well can we do?



$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4.$$

Extrapolation procedure

HL-LHC sensitivity is estimated by projecting current Run 2 analyses:

- Luminosity: $X \rightarrow 3000$ / fb
- Cross-section from increased c.m. energy of 13 → 14 TeV: generally ~ 1.10 – 1.20

Object reco and i.d. efficiencies (such as b-tagging) at the HL-LHC assumed to be identical to the full Run 2 analysis

- increased pile-up will be canceled out by improved software and hardware, such as the ITk upgrade

Source	Scale factor
Luminosity	0.6
b/c tagging efficiency	0.5
Photon ID	0.8
ETmiss	0.5
Leptons, Jets	1
Theory	0.5
+ others…	

Baseline Scenario

Optimistic ↓ Pessimistic

4 common systematic uncertainty scenarios (optimistic to pessimistic)

- Stat-only (no systematic uncertainties)
- Baseline, following YR18 recommendations (with some updates for Snowmass 2022)
  - Theory uncertainties halved
  - Run 2 experimental systematics due to stat limitations is scaled down with $\sqrt{L}$
- Theory uncertainties halved; Run 2 experimental systematic uncertainties
- All run 2 systematic uncertainties

See Bill's talk for more details on Run 2 HH analyses

Projection: ATL-PHYS-PUB-2022-001
Run2: Phys. Rev. D 106 (2022) 052001

$HH \rightarrow bb\gamma\gamma$

Small branching ratio but high S/B, excellent ATLAS photon resolution

Signature: two high p_T photons and bjets

Analysis regions defined based on $m^*_{bb\gamma\gamma}$ and MVA output, with $m_{\gamma\gamma}$ as final discriminant

High and low $m^*_{bb\gamma\gamma}$ categories to target SM (BSM)-like signals

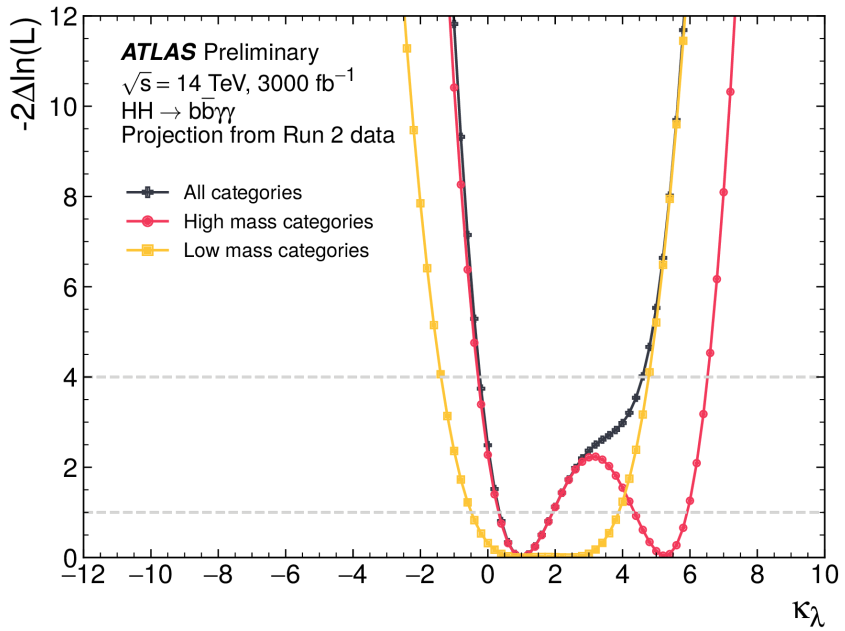
SM signal significance of 2.2σ (2.3σ) with the baseline (stat-only) scenario
$\kappa_\lambda \in [0.3, 1.9]$ ($[0.4, 1.8]$) $\rightarrow$ **Still heavily dominated by stats at the HL-LHC**

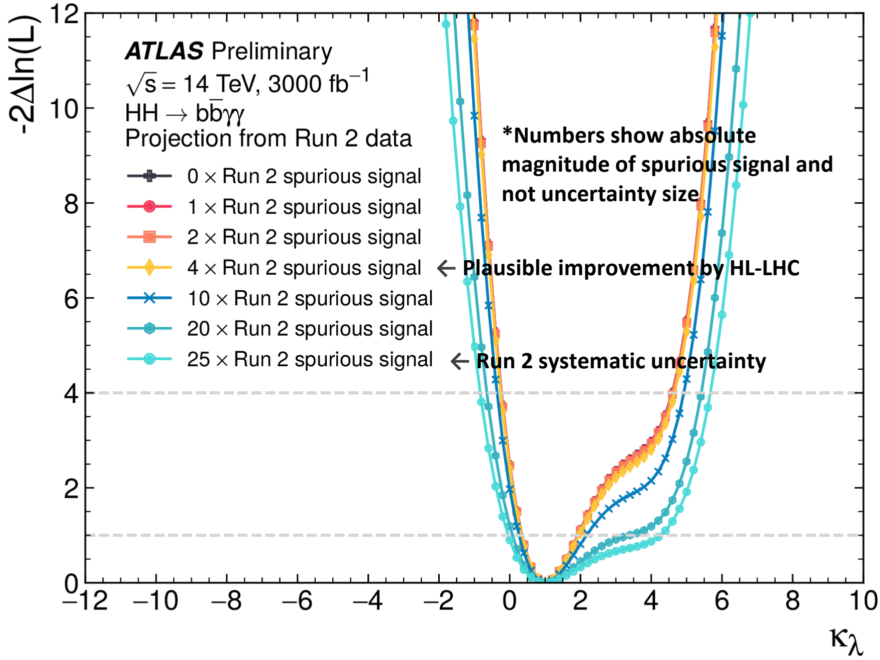
Projection systematics include theory signal uncertainties, single Higgs + heavy-flavour quark production cross-section, and photon energy resolution

No background systematic uncertainty (spurious signal) included in baseline scenario

However additional studies scan various plausible scaling values for this uncertainty

$m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - (m_{\gamma\gamma} - 125GeV) - (m_{bb} - 125GeV)$





No κ_{2V} result in this early paper

See Bill's talk for more details on Run 2 HH analyses

Projection: ATL-PHYS-PUB-2022-053
Run 2: Phys. Rev. D 108 (2023) 052003

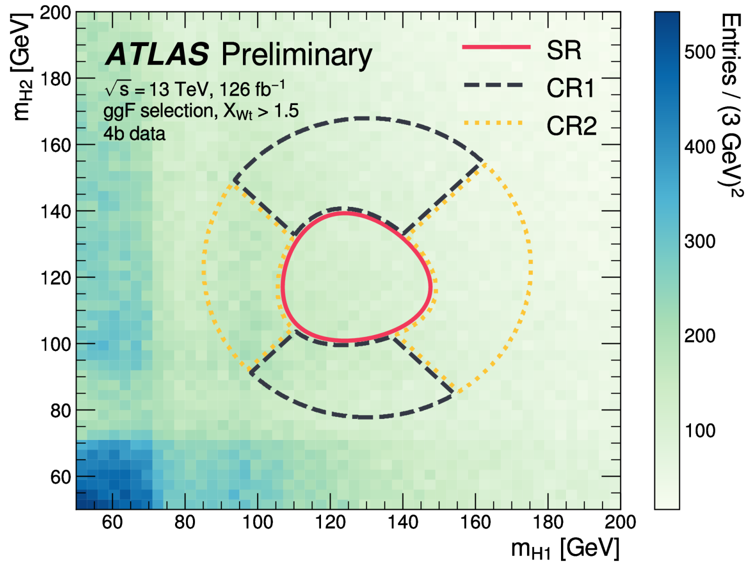
(resolved) $HH \to bbbb$

Largest branching ratio but challenging combinatorial multi-jet background

Jets paired to minimize the ΔR separation for the highest p_T bjets with additional kinematic cuts based on ggF/VBF topology and rejecting $\bar{t}t$

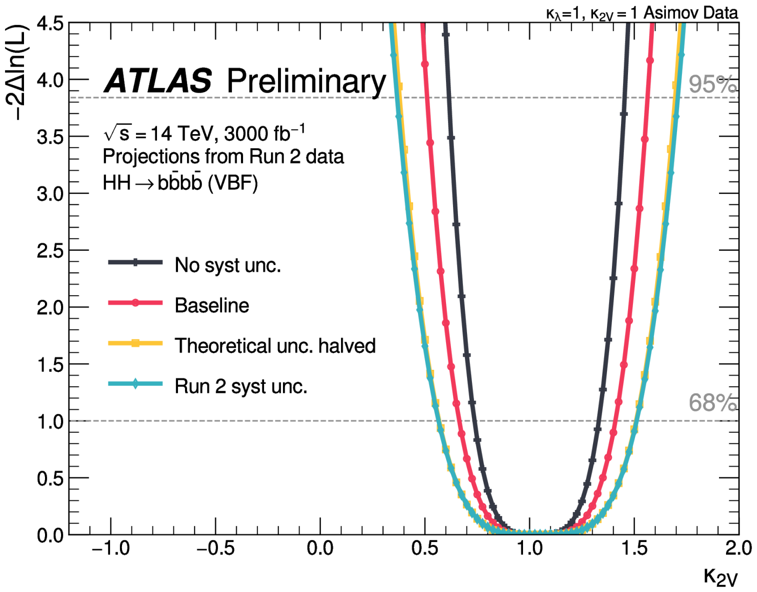
Background estimated with data-driven NN-based reweighting of a 2b control region to the 4b signal region; final fit to m_{HH} discriminant

SM signal significance of 1.0σ (1.8σ) with the baseline (stat-only) scenario



Current strategy will become systematics limited at the HL-LHC

$\kappa_\lambda \in [-0.5, 6.1], \kappa_{2V} \in [0.7, 1.4]$ baseline



Caveat: The projected κ_{2V} constraint here is already surpassed by the boosted VBF $HH \to bbbb$ (Phys. Lett. B 858 (2024) 139007) with Run 2!

See Bill's talk for more details on Run 2 HH analyses

Projection: ATL-PHYS-PUB-2022-053
Run 2: Phys. Rev. D 108 (2023) 052003

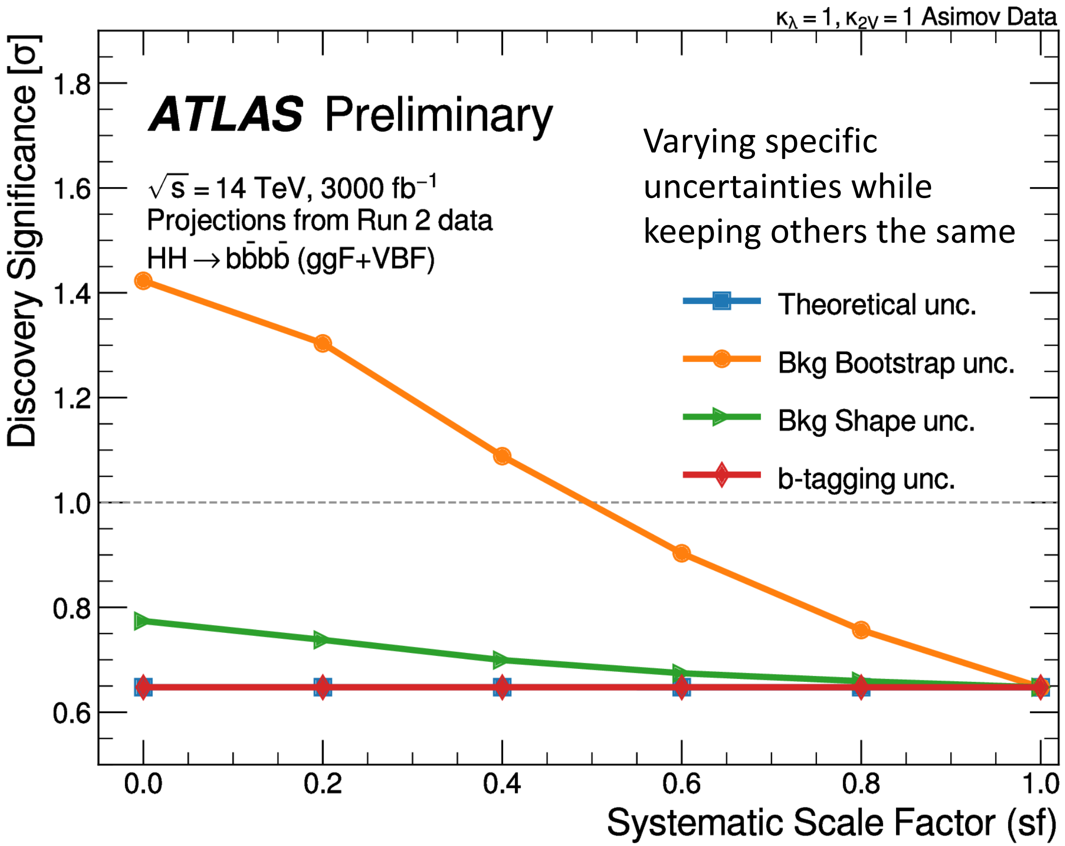
$HH \rightarrow bbbb$

Projection heavily dominated by systematic uncertainties from reweighting: **bootstrap (training of the reweighting NN)** and **shape (choice of reweighting control region)**

x 0.5 in baseline

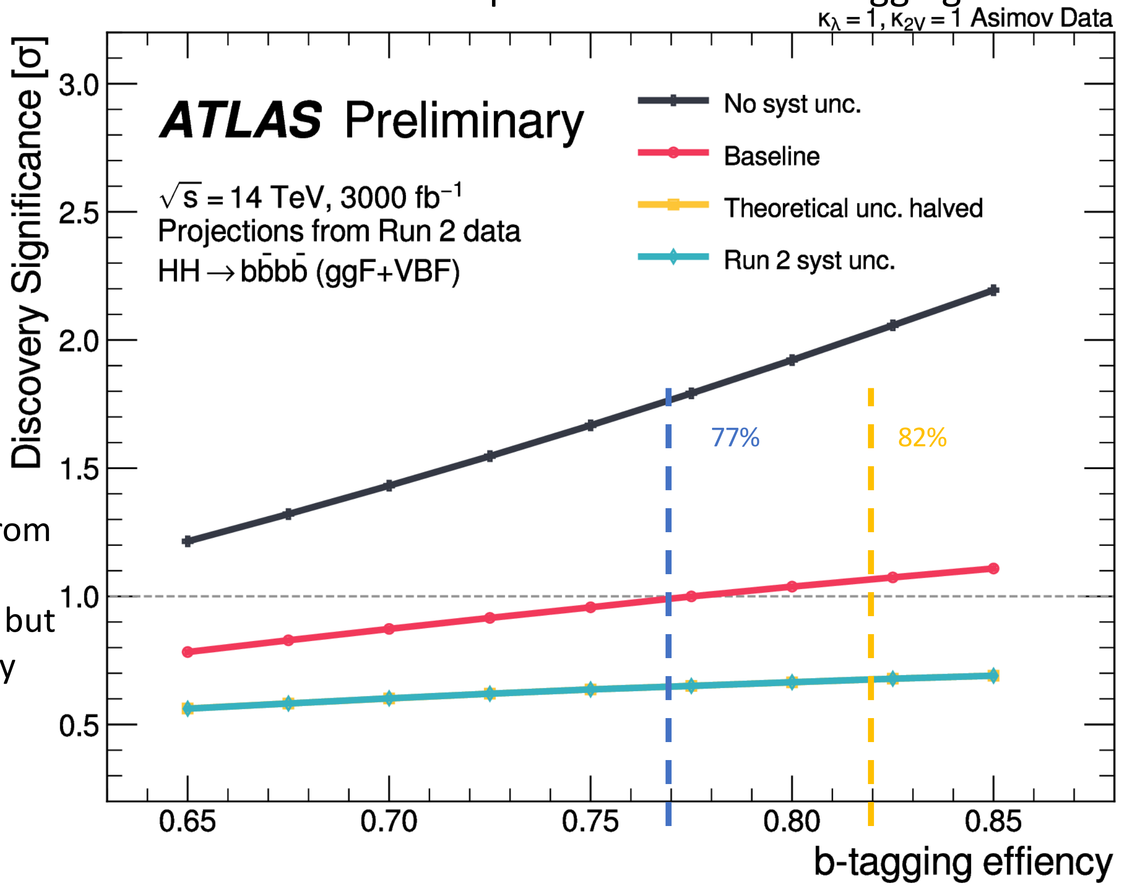
x 1 in baseline

Large impact from bootstrap unc.



Low impact from btagging uncertainty… but btag efficiency matters!

Potential improvements from b-tagging



Projection: ATL-PHYS-PUB-2024-016
Legacy Run 2: Phys. Rev. D 110 (2024) 032012

See Bill's talk for more details on Run 2 HH analyses

$HH \rightarrow bb\tau\tau$ NEW

Balanced branching ratio and S/B

Analysis signature of two b-jets and two τs

Fully hadronic ($\tau_{had}\tau_{had}$) and semi-leptonic ($\tau_{lep}\tau_{had}$) regions with final fit on MVA discriminant

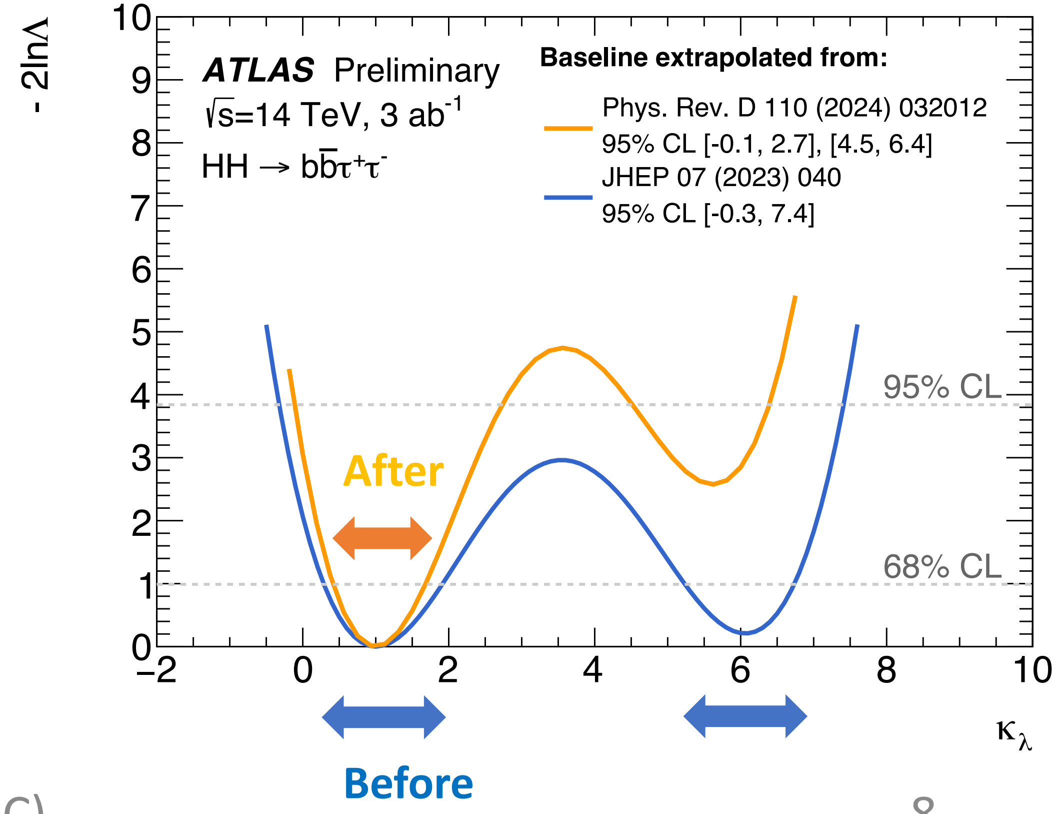
Very recent **update to be based on the Legacy Run 2 analysis** instead of the full Run 2 analysis!!

Improved MVA classifiers increase sensitivity to SM and BSM ggF HH production, as well as VBF HH

- 3.5σ (4.6σ) sensitivity to SM HH in the baseline (stat-only) scenario, compared to 2.8 (4.0) before

Projected sensitivity evenly split between statistical and systematics (dominated by theory and background modelling)

Addition of m_{HH} split in ggF and VBF SR help resolve previous double-minimum structure in κ_λ likelihood

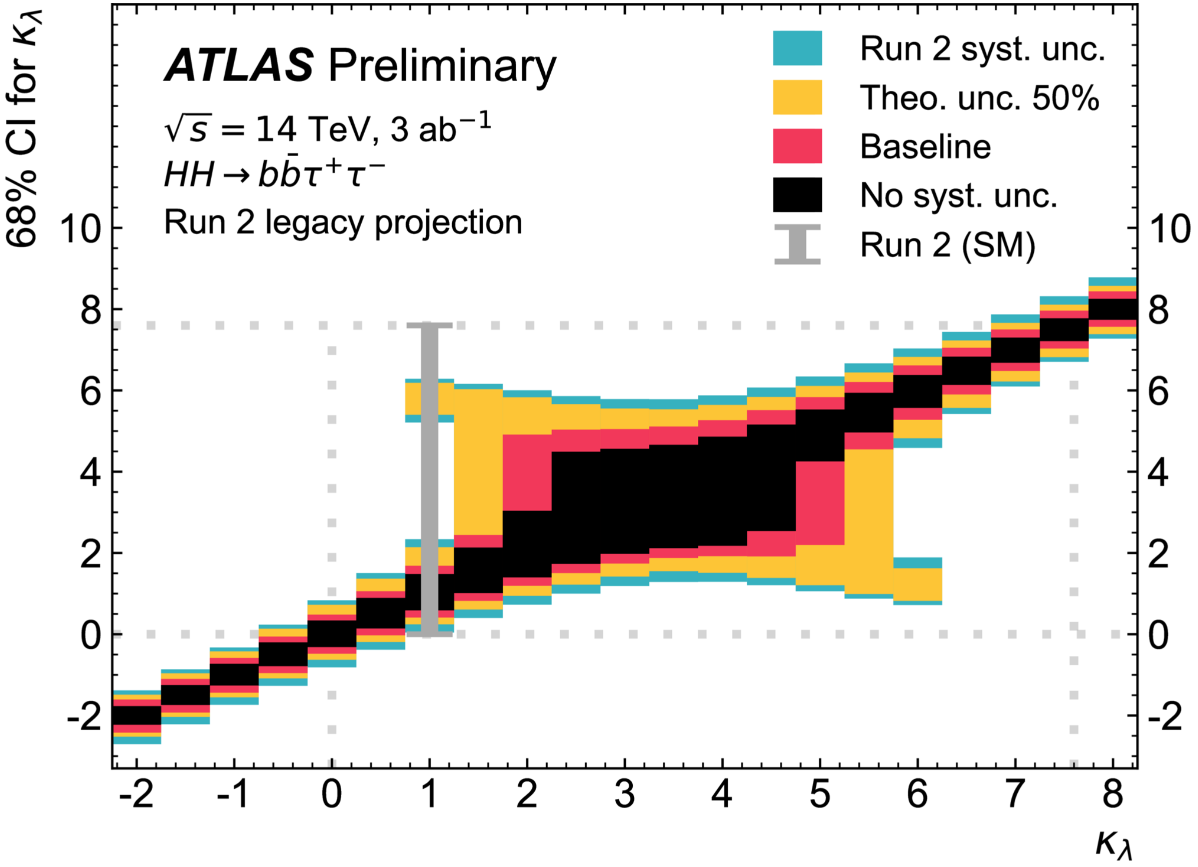


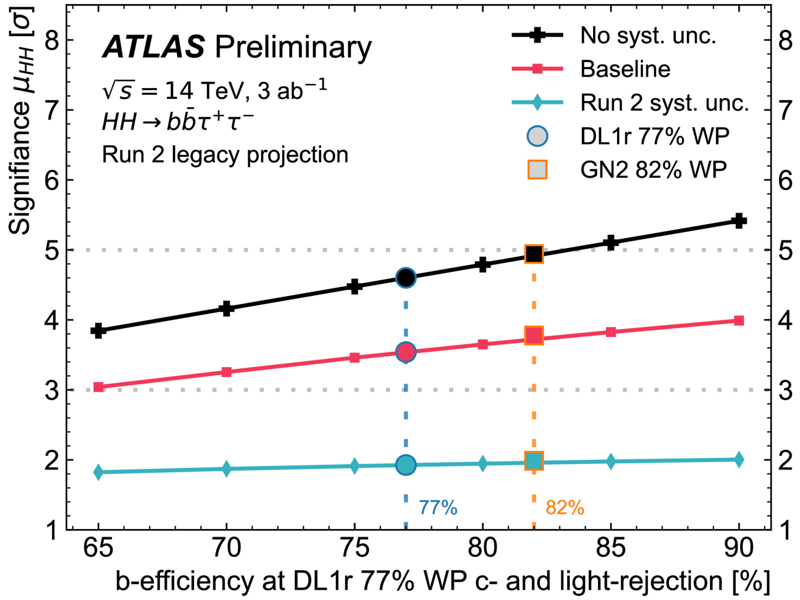
Projection: ATL-PHYS-PUB-2024-016
Legacy Run 2: Phys. Rev. D 110 (2024) 032012

See Bill's talk for more details on Run 2 HH analyses

$HH \rightarrow bb\tau\tau$ NEW

New type of plot showing the expected constraints on κ_λ (κ_{2V}) for a given assumption on κ_λ (κ_{2V})





Impact of improved b-tagging and τ-identification algorithms also studied

10% increase in significance using new GN2 already in Run 3

HH combination

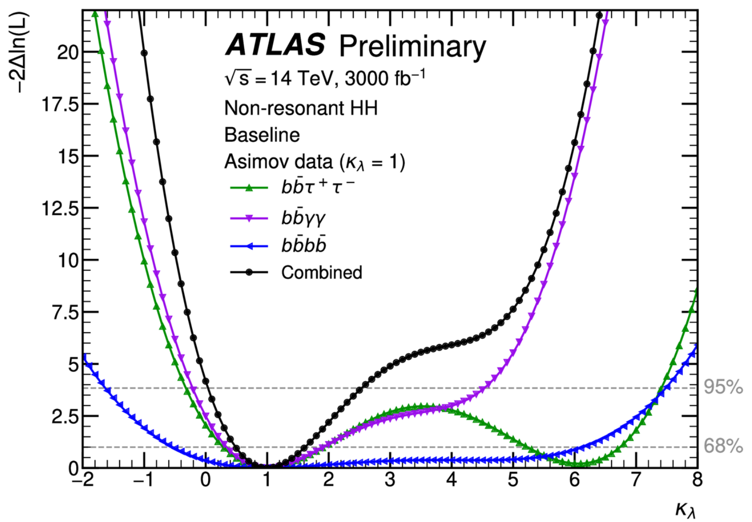
Statistical combination of $HH \rightarrow bb\gamma\gamma, bbbb, (old) bb\tau\tau$ channels

SM significance of 3.4σ (4.9σ) with the baseline (stat-only) scenario, primarily from $bb\tau\tau$ and $bb\gamma\gamma$

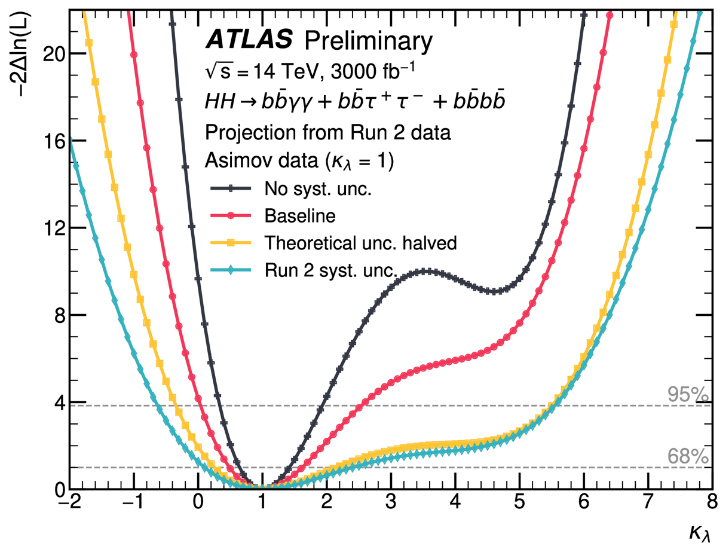
- **Potential for 5σ with baseline scenario if further combined with CMS!**

κ_λ precision of ~50% (30%) – compare to latest run 2 HH combination precision of $1.0^{+4.7}_{-1.5}$

Expect even better results with updated projections based on Legacy Run 2



Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	old $b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination
No syst. unc.	2.3	4.0	1.8	4.9
Baseline	2.2	2.8	0.99	3.4
Theoretical unc. halved	1.1	1.7	0.65	2.1
Run 2 syst. unc.	1.1	1.5	0.65	1.9



Projection: ATL-PHYS-PUB-2021-039
Run 2: Eur. Phys. J. C 81 (2021) 178, Eur. Phys. J. C 82 (2022) 717

See Marion's talk or Giulia's talk for the latest VH results

$VH \to bb/cc$

$VH \to bb$

Analysis regions separated by p_T^V, jet multiplicity, signal/control regions, with BDT as discriminant

Measurement uncertainty of 8% (7%) on WH (ZH) signal strength

Current projections limited by systematic uncertainties, especially signal modelling

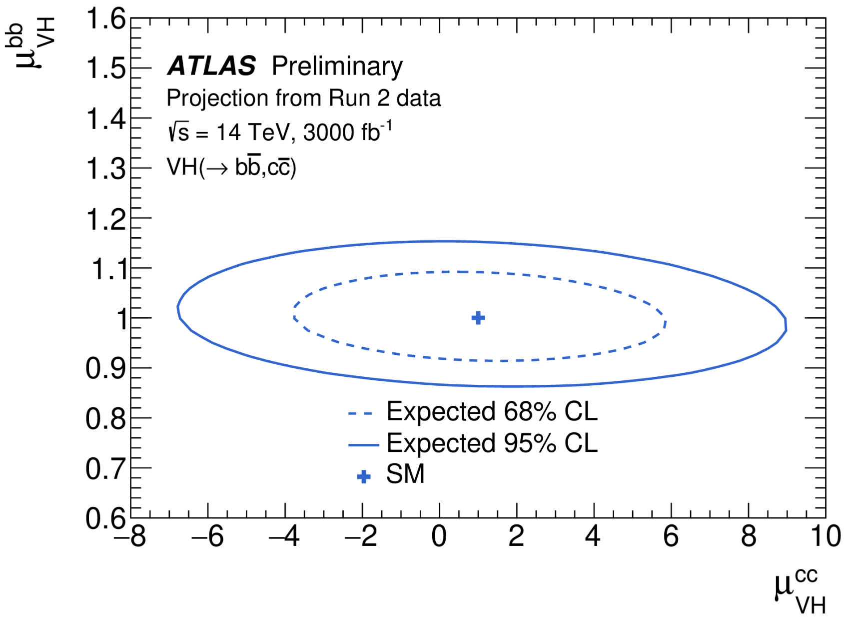
$VH \to cc$

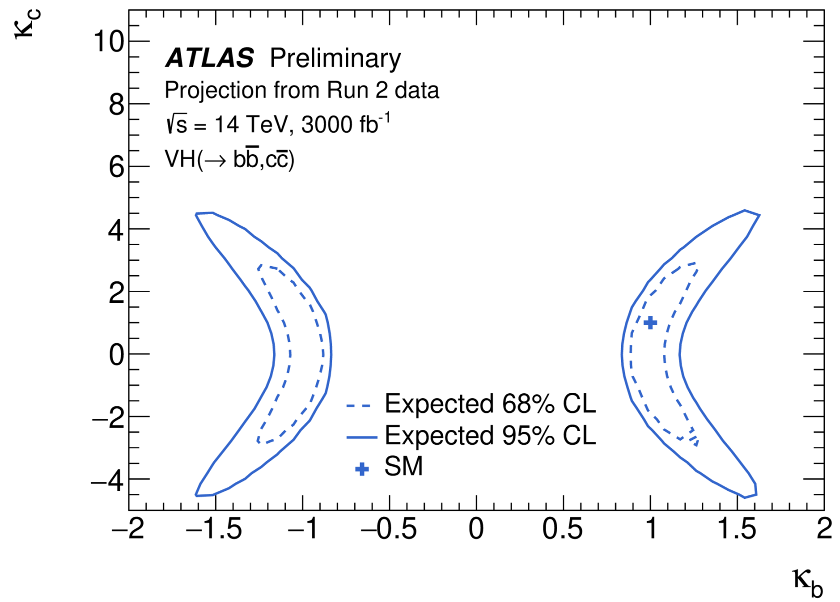
Analysis regions separated by number of c-tags, p_T^V, jet multiplicity, signal/control regions, m_{cc} as discriminant

- 95% CL Upper limit of 6.4 times SM cross-section
- $|\kappa_c| < 3.0$ at 95% CL

Combined $VH \to bb/cc$ measurement performed with uncertainty of 6% (320%) on $VH \to bb(cc)$ signal strength

$\left|\frac{\kappa_c}{\kappa_b}\right| < 2.7$ at 95% CL (compared to 5.1 from Run 2)





Projection: ATL-PHYS-PUB-2022-003
Run 2: JHEP 08 (2022) 175

See Enrique's talk for the latest run 2 results

$H \rightarrow \tau\tau$

Events separated into τ_{lep}, τ_{lep}; τ_{lep}, τ_{had}; τ_{had}, τ_{had} channels

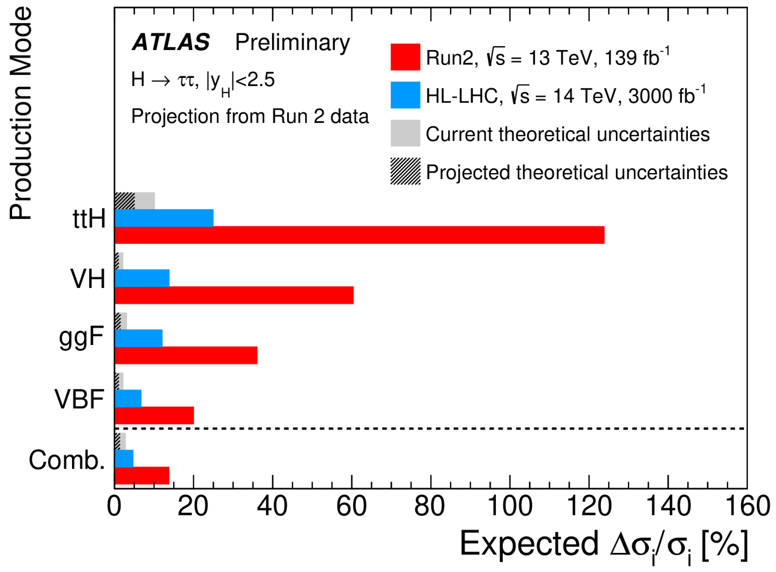
Further categorized into Boost (high p_T ggF), VBF, and $V(had)H$, and ttH sensitive regions

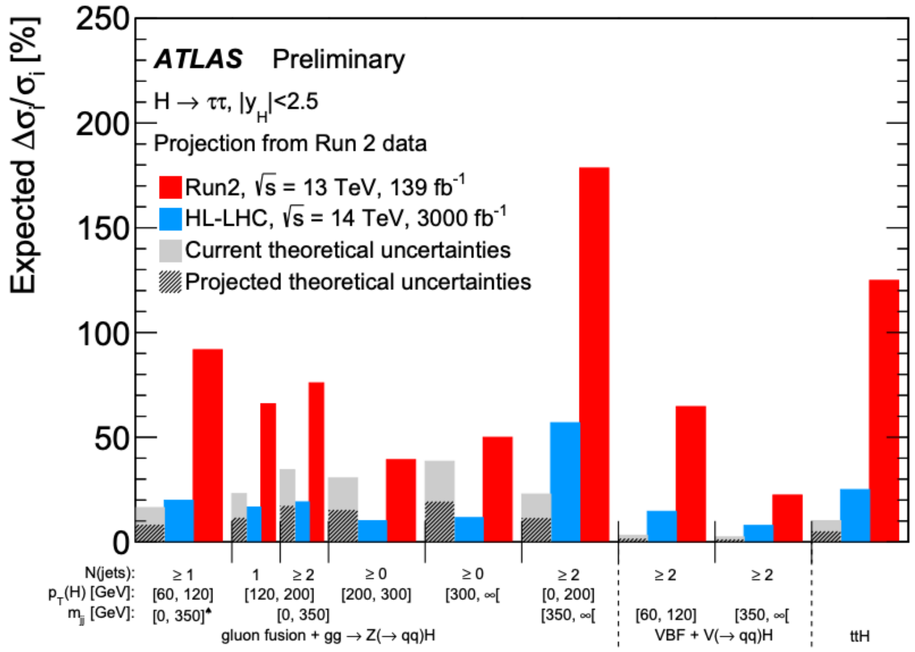
Uncertainty on inclusive $H \rightarrow \tau\tau$ cross-section of 5%

Uncertainties on the order of 10% - 15% for ggF, VBF, and VH production modes, and 25% for ttH

Kinematic dependence also studied using Simplified Template Cross-section (STXS) framework, contributing especially to the high p_T^H region

Dominant uncertainties from theory signal for all production modes, and jet + ETmiss for VH and ttH





Summary

First set of projections based on full Run 2 datasets already show great potential for single and di-Higgs measurements at the HL-LHC

New round of improved projections based on the legacy results under way for the European Strategy Update next year ($bb\tau\tau$ already out)

Projections are often simple and and **don't account for new analysis/object reconstruction improvements** that will be developed in the meantime

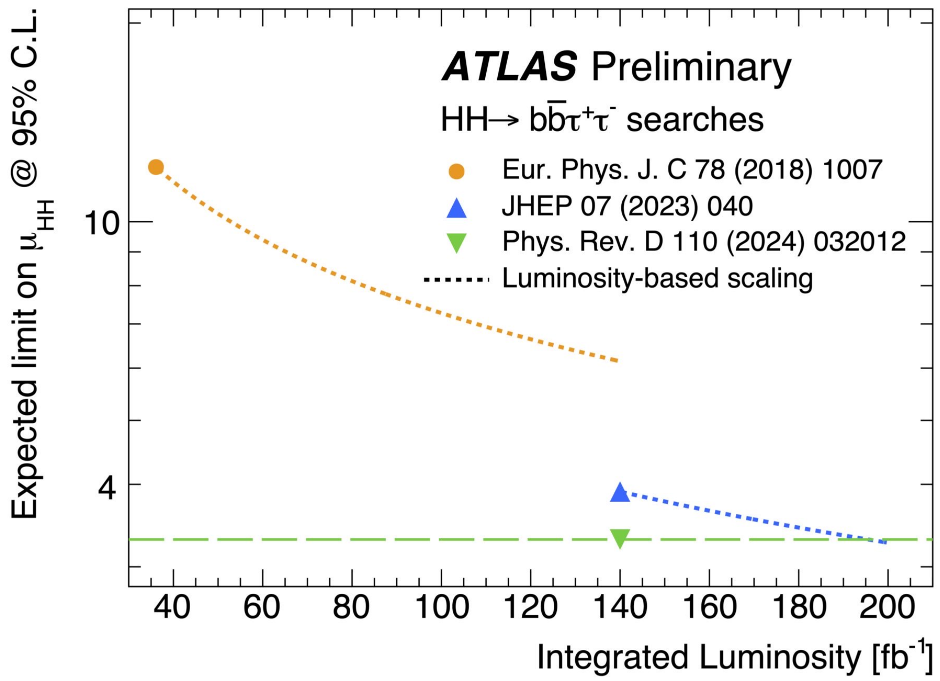
Stay tuned for updated projections soon!

[ATL-PHYS-PUB-2024-016]

Updated projection of the sensitivity of searches for Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ final state from LHC Run 2 to the High Luminosity LHC with the ATLAS detector

An updated projection of the sensitivity to non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ final state from LHC Run 2 to the High Luminosity LHC with the ATLAS detector is presented. Sensitivites are projected assuming a centre-of-mass energy of $14\,\mathrm{TeV}$ for a variety of integrated luminosities ranging from 1000 to $3000\,\mathrm{fb}^{-1}$. Assuming SM HH production, a signal significance of $3.5\,\sigma$ ($4.6\,\sigma$) is expected in the baseline (statistical only) extrapolation scenario for an integrated luminosity of $3000\,\mathrm{fb}^{-1}$. This translates into expected 95\% confidence level constraints on κ_λ which correspond to two allowed regions, $[-0.1, 2.7]$ and $[4.5, 6.4]$ in the baseline scenario and just one, $[0.2, 2.1]$ in the one without systematic uncertainties. Furthermore, the impact of b-tagging and τ-identification algorithms on the sensitivity is studied. Improvements in b-tagging developed for Run 3 are expected to further increase the signal significance to $3.8\,\sigma$ ($4.9\,\sigma$).

20 September 2024



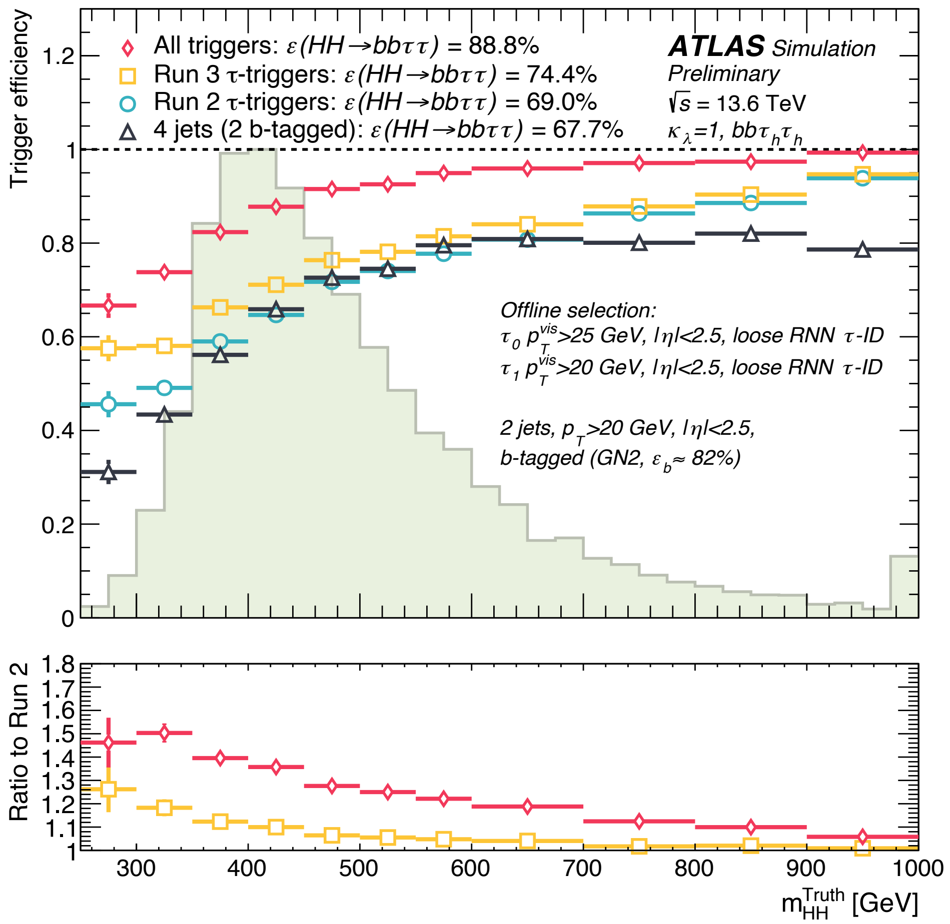
We always do better than simple lumi scaling!

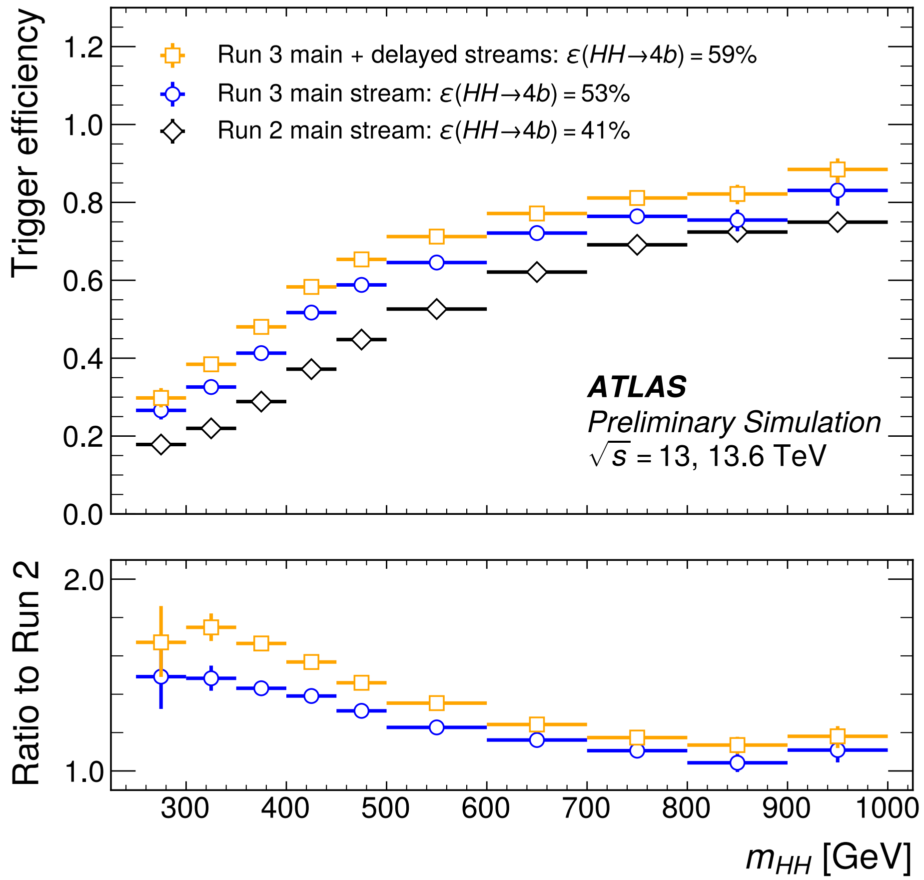
Backup

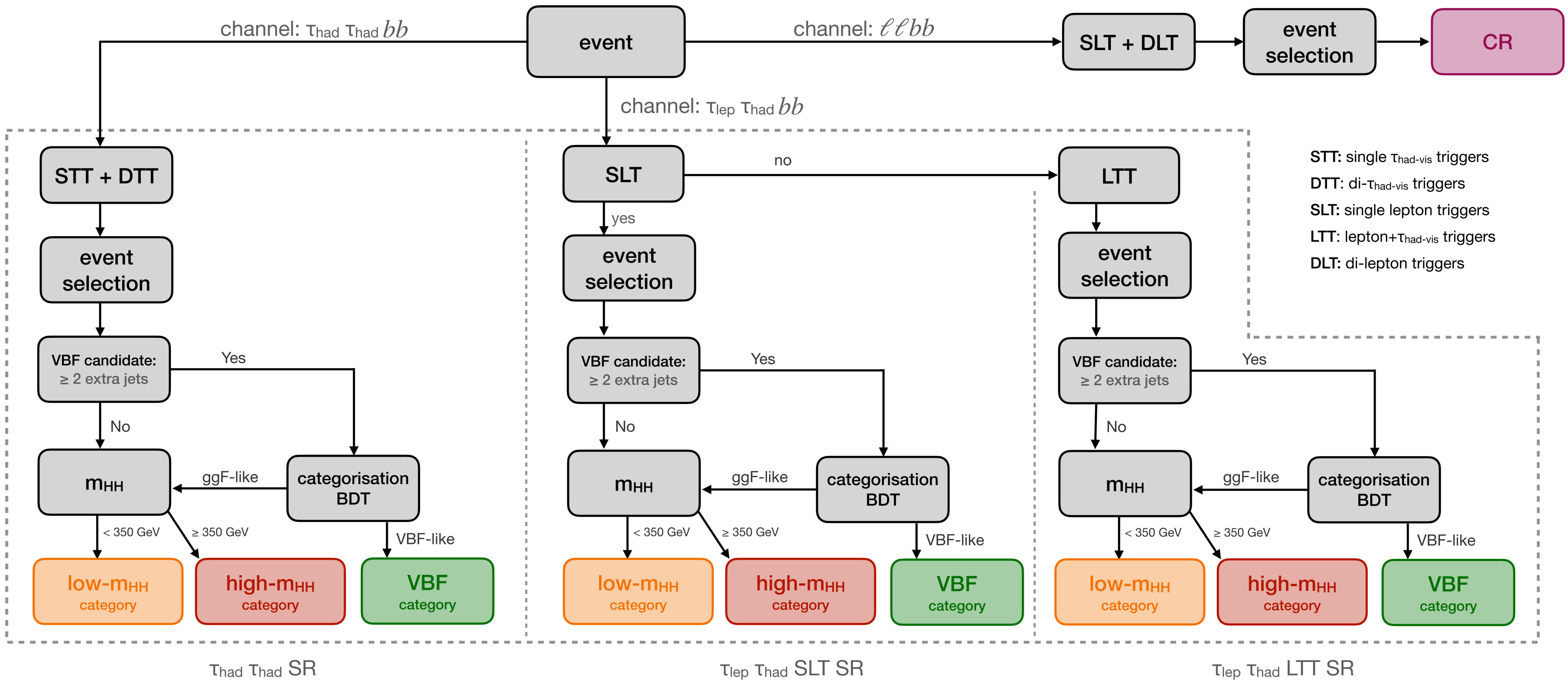
XS scaling

Process	**Scale factor**
Signals	
ggF HH	1.18
VBF HH	1.19
Backgrounds	
ggF H	1.13
VBF H	1.13
WH	1.10
ZH	1.12
ttH	1.21
Others	1.18

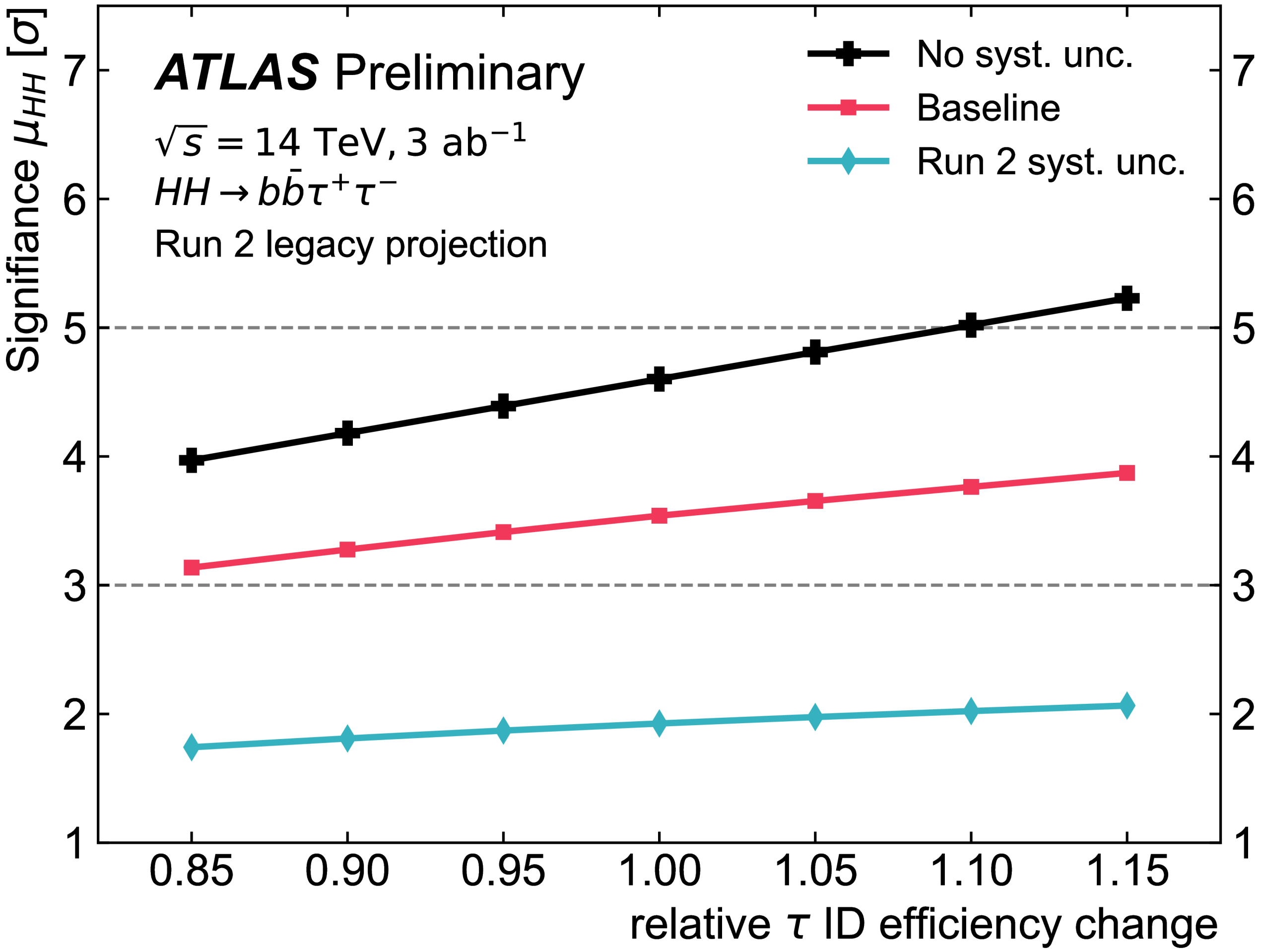
Hadronic triggers






channel: τhad τhad bb
event
channel: ℓℓbb
SLT + DLT
event selection
CR
channel: τlep τhad bb
STT + DTT
event selection
VBF candidate: ≥ 2 extra jets
Yes
No
mHH
ggF-like
categorisation BDT
< 350 GeV
≥ 350 GeV
VBF-like
low-mHH category
high-mHH category
VBF category
SLT
no
yes
LTT
STT: single τhad-vis triggers
DTT: di-τhad-vis triggers
SLT: single lepton triggers
LTT: lepton+τhad-vis triggers
DLT: di-lepton triggers
τhad τhad SR
τlep τhad SLT SR
τlep τhad LTT SR

τ ID



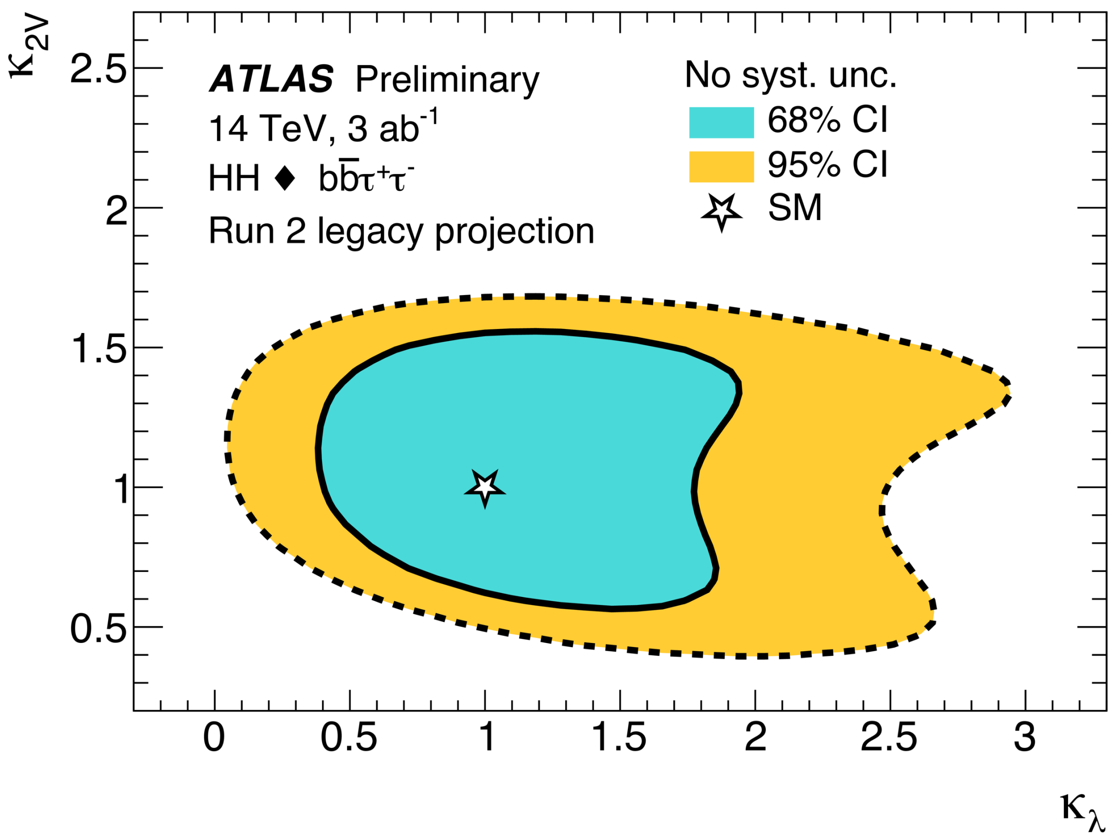
ATLAS Preliminary
$\sqrt{s} = 14$ TeV, 3 ab^{-1}
$HH \to b\bar{b}\tau^+\tau^-$
Run 2 legacy projection
No syst. unc.
Baseline
Run 2 syst. unc.
Significance μ_{HH} [σ]
relative τ ID efficiency change
0.85
0.90
0.95
1.00
1.05
1.10
1.15
1
2
3
4
5
6
7

$bb\tau\tau$

Uncertainty scenario	Significance [σ] $b\bar{b}\tau_{lep}\tau_{had}$	$b\bar{b}\tau_{had}\tau_{had}$	Combination	Combined signal strength precision [%]
L_{int} = 2000 fb^{-1}				
No syst. unc.	1.9	3.2	3.8	-28 / 29
Baseline	1.5	2.6	3.0	-36 / 40
Baseline with MC luminosity scaled	1.4	2.5	2.9	-37 / 41
MC luminosity scaled	1.3	2.1	2.4	-42 / 59
Theoretical unc. halved	0.9	1.8	2.0	-49 / 51
Run 2 syst. unc.	0.9	1.7	1.8	-52 / 65
L_{int} = 3000 fb^{-1}				
No syst. unc.	2.3	4.0	4.6	-23 / 24
Baseline	1.8	3.1	3.5	-31 / 34
Baseline with MC luminosity scaled	1.7	3.0	3.4	-32 / 35
MC luminosity scaled	1.6	2.4	2.7	-37 / 53
Theoretical unc. halved	1.0	1.9	2.2	-46 / 47
Run 2 syst. unc.	0.9	1.8	1.9	-51 / 65

Source of uncertainty	Baseline $\Delta\mu_{HH}$		Run 2 Syst. $\Delta\mu_{HH}$	
Total	+0.35	-0.31	+0.65	-0.51
Statistical	+0.24	-0.23	+0.24	-0.23
↪ Data stat only	+0.24	-0.23	+0.24	-0.23
↪ Floating normalisations	+0.02	-0.02	+0.04	-0.02
Systematic	+0.25	-0.20	+0.61	-0.46
Experimental uncertainties				
Electrons and muons	< 0.01		< 0.01	
τ-leptons	+0.03	-0.03	+0.06	-0.05
Jets	+0.06	-0.06	+0.06	-0.07
b-tagging	+0.02	-0.02	+0.04	-0.03
E_T^{miss}	+0.03	-0.02	+0.04	-0.02
Pile-up	+0.01	-0.01	+0.01	-0.01
Luminosity	+0.02	-0.01	+0.02	-0.01
Theoretical and modelling uncertainties				
Signal	+0.12	-0.05	+0.39	-0.07
Backgrounds	+0.19	-0.17	+0.37	-0.30
↪ Single Higgs boson	+0.17	-0.15	+0.34	-0.27
↪ Z + jets	+0.06	-0.05	+0.10	-0.09
↪ W + jets	< 0.01		< 0.01	
↪ $t\bar{t}$	+0.02	-0.02	+0.03	-0.02
↪ Single top quark	+0.01	-0.01	+0.03	-0.04
↪ Diboson	< 0.01		< 0.01	
↪ Jet → τ_{had} fakes	+0.05	-0.05	+0.09	-0.08
MC statistical	< 0.01		+0.38	-0.36

$bb\tau\tau$



ATLAS Preliminary
14 TeV, 3 ab-1
HH → bb̄τ+τ-
Run 2 legacy projection
No syst. unc.
68% CI
95% CI
SM
κ2V
κλ
2.5
2
1.5
1
0.5
0
0.5
1
1.5
2
2.5
3

Combination uncertainty scenarios

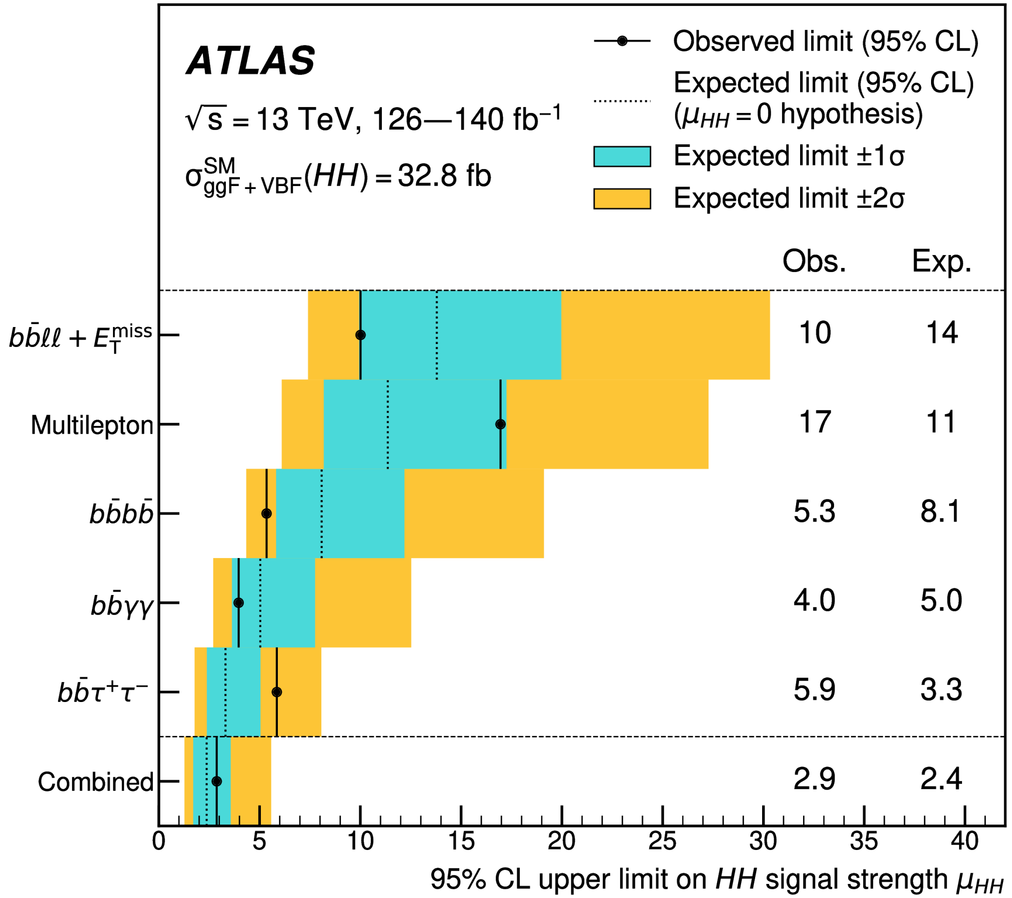
Systematic uncertainties	Scale factors for HL-LHC baseline scenario
Theoretical uncertainty	0.5
b-jet tagging efficiency	0.5
c-jet tagging efficiency	0.5
Light-jet tagging efficiency	1.0
Jet energy scale and resolution	1.0
Luminosity	0.6
Background bootstrap uncertainty	0.5
Background shape uncertainty	1.0

	Scaling factors (sf)	
Uncertainty scenario	Bootstrap unc.	Shape unc.
Pessimistic bkg. unc.	1.0	1.0
Conservative bkg. unc. 1 (fix bootstrap unc.)	1.0	0.2
Conservative bkg. unc. 2 (fix shape unc.)	0.2	1.0
Optimistic bkg. unc.	0.2	0.2

Source	Scale factor
Experimental Uncertainties	
Luminosity	0.6
b-jet tagging efficiency	0.5
c-jet tagging efficiency	0.5
Light-jet tagging efficiency	1.0
Jet energy scale and resolution, $E_{\mathrm{T}}^{\mathrm{miss}}$	1.0
κ_λ reweighting	0.0
Photon efficiency (ID, trigger, isolation efficiency)	0.8
Photon energy scale and resolution	1.0
Spurious signal	0.0
Value of m_H	0.08
τ_{had} efficiency (statistical)	0.0
τ_{had} efficiency (systematic)	1.0
τ_{had} energy scale	1.0
Fake-τ_{had} estimation	1.0
MC statistical uncertainties	0.0
Theoretical Uncertainties	0.5

HH production

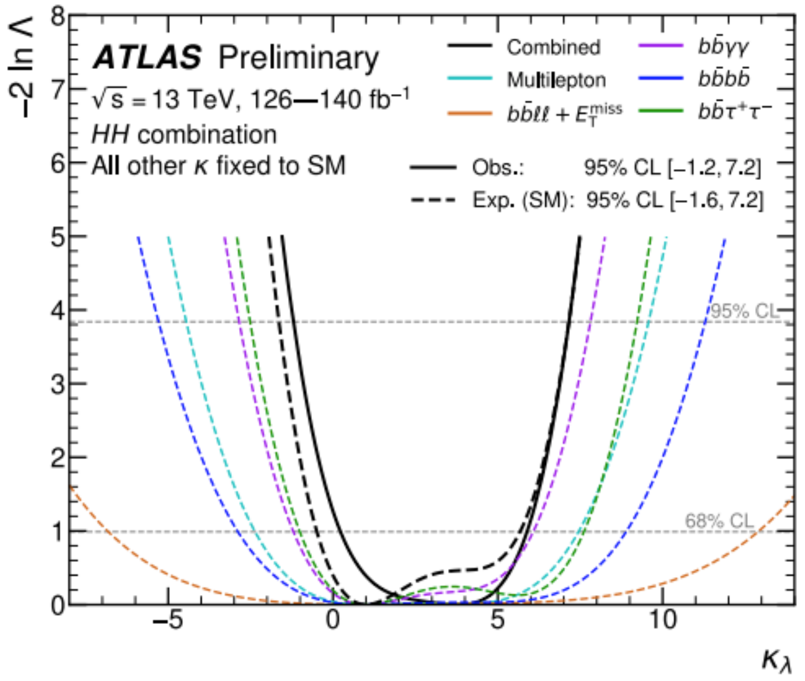
Sensitivity to HH at ATLAS is dominated by three channels:
$bb\tau\tau$, $bbbb$, and $bb\gamma\gamma$

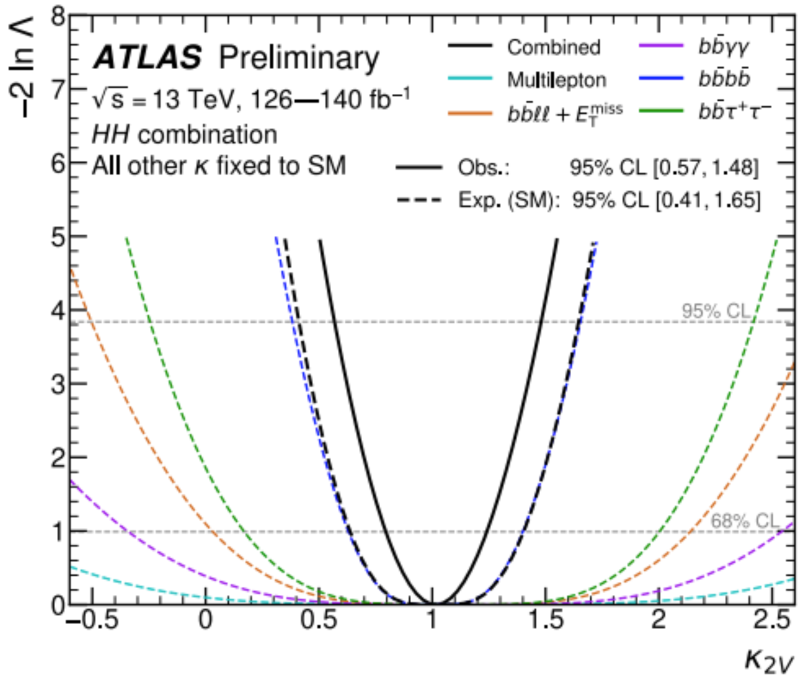


Branching Ratio	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

https://arxiv.org/abs/2406.09971

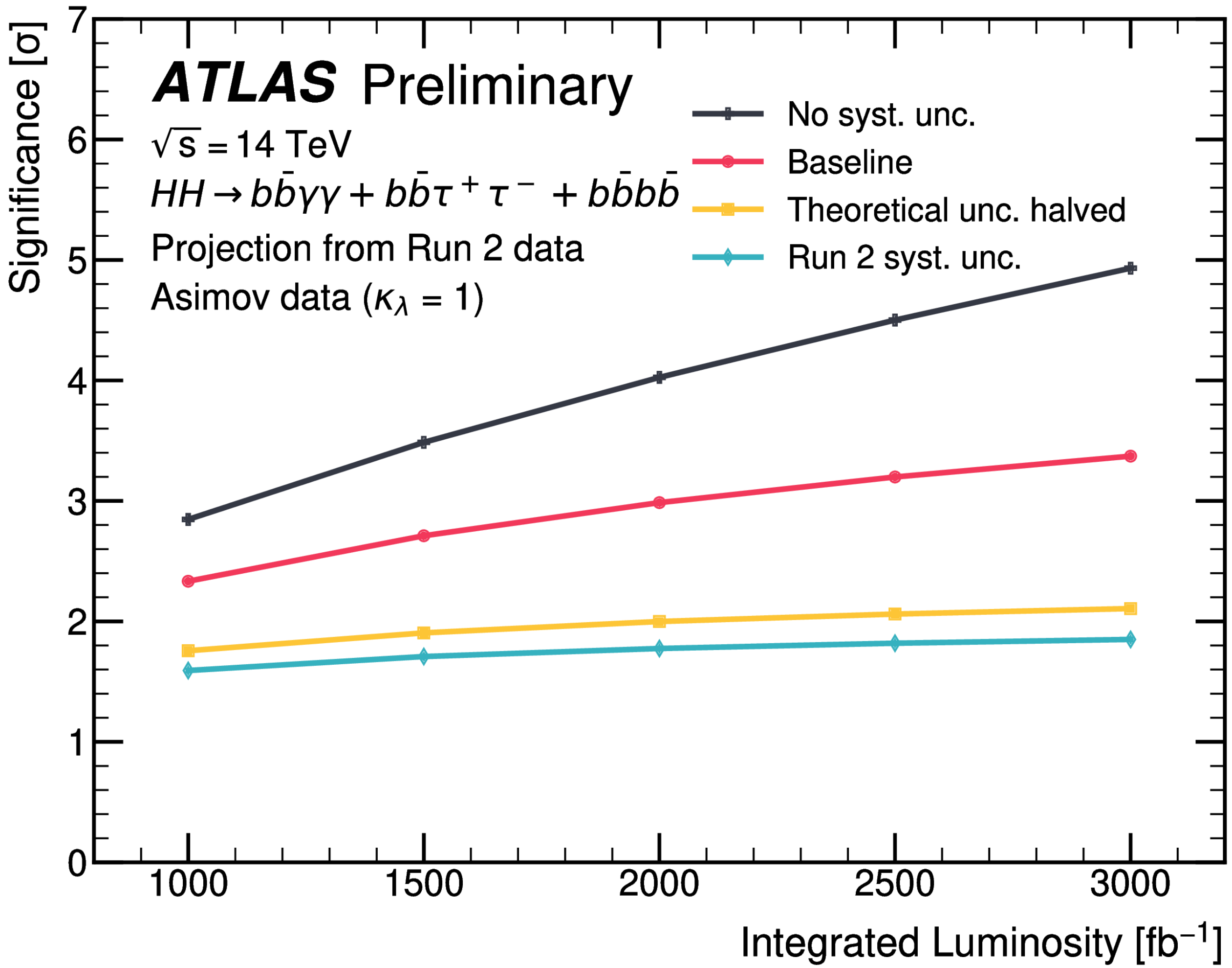
Combination





	Best fit	Obs 95% CL	Exp 95% CL	Leading channel
κ_λ	3.8	[–1.2, 7.2]	[–1.6, 7.2]	bbγγ, bbττ
κ_{2V}	1.0	[0.6, 1.5]	[0.4, 1.6]	bbbb (boosted)

As function of Lumi



$VH \rightarrow cc$

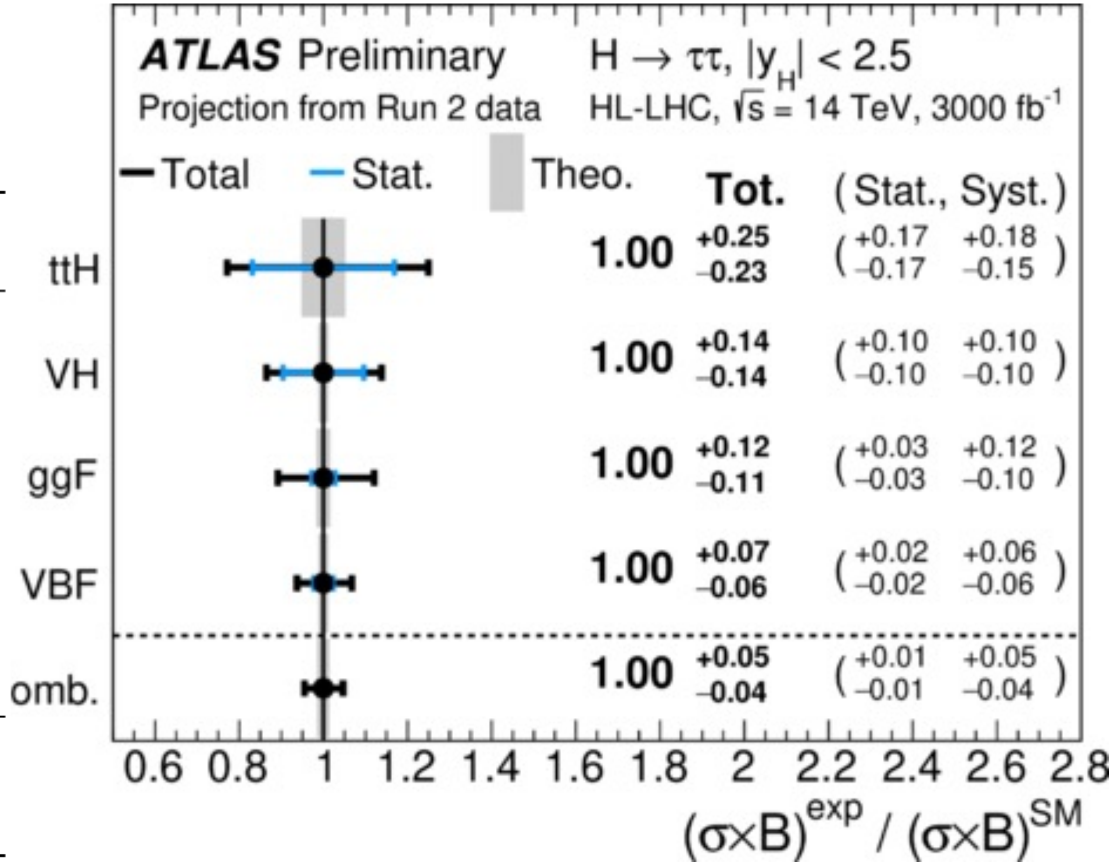
Source of uncertainty		$\Delta\mu_{ZH}^{b\bar{b}}$	$\Delta\mu_{WH}^{b\bar{b}}$
Total		0.070	0.081
Statistical		0.034	0.039
Systematics		0.063	0.070
Statistical uncertainties			
Data statistics only		0.031	0.037
$t\bar{t}$ $e\mu$ control region		0.006	0.003
Floating normalisations		0.017	0.028
Theoretical and modelling uncertainties			
Signal		0.047	0.031
Z+jets		0.017	0.010
W+jets		0.004	0.022
single top		0.005	0.012
$t\bar{t}$		0.007	0.017
Diboson		0.020	0.027
Multi-Jet		< 0.001	0.001
Experimental uncertainties			
Jets		0.022	0.032
Leptons		0.006	0.011
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.006	0.005
Pile-up and luminosity		0.009	0.009
Flavour tagging	b-jets	0.018	0.009
	c-jets	0.004	0.035
	light-jets	0.006	0.009

Source of uncertainty		$\Delta\mu_{VH}^{c\bar{c}}$
Total		3.21
Statistical		1.97
Systematics		2.53
Statistical uncertainties		
Data statistics only		1.59
Floating normalisations		0.95
Theoretical and modelling uncertainties		
$VH, H \rightarrow c\bar{c}$		0.27
Z+jets		1.77
Top-quark		0.96
W+jets		0.84
Diboson		0.34
$VH, H \rightarrow b\bar{b}$		0.29
Multi-Jet		0.09
Experimental uncertainties		
Jets		0.59
Leptons		0.20
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.18
Pile-up and luminosity		0.19
Flavour tagging	c-jets	0.61
	b-jets	0.16
	light-jets	0.51
	τ-jets	0.19

Uncertainties	Scale Factor
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.5
Lepton	1
Jet	1
Flavour tagging c-, b- and τ-jets	0.5
Flavour tagging light-jets (MV2c10 in $VH(bb)$)	0.5
Flavour tagging light-jets (DL1 in $VH(cc)$)	1.0
Luminosity	0.58
Signal modelling	0.5
Background modelling	0.5
MC statistics	0
Truth-tagging uncertainties ($VH, H \rightarrow c\bar{c}$ only)	0

$H \rightarrow \tau\tau$

Source of uncertainty	Impact on $\Delta\sigma / \sigma(pp \rightarrow H \rightarrow \tau\tau)$ [%] ggF	VBF	VH	$t\bar{t}H$
Theoretical uncertainty on the signal	10.0	5.6	5.6	9.5
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	4.1	1.9	4.8	7.6
Background sample size	1.9	1.0	3.7	4.9
Hadronic τ decays	1.9	1.1	2.6	2.4
Misidentified τ	1.9	1.0	1.8	3.0
Luminosity	1.2	0.6	0.2	0.2
Theoretical uncertainty in $Z+$jets processes	1.4	0.8	0.5	1.0
Theoretical uncertainty in Top processes	0.8	0.3	0.9	4.7
Flavor tagging	0.7	0.2	0.3	2.2
Electrons and muons	0.9	0.4	1.4	1.3
Total systematic uncertainty	10.8	5.9	9.2	17.2
Data sample size	2.8	2.3	9.6	16.9
Total	11.2	6.4	13.1	23.1



Looking Ahead: HH at HL-LHC

Table 9: Expected significance for several channel combinations, for a luminosity of 3 ab^{-1}, including the expected uncertainties quoted in the text, using the asymptotic approximation. This table only takes into account the $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels.

Channel	Significance	Combined in channel	Total combined
e + jets	0.31	0.43	0.60
μ+jets	0.30		
$\tau_{had}\tau_{had}$	0.41	0.41	

HL-LHC bbττ significance expected in 2015
(ATL-PHYS-PUB-2015-046)

assuming SM kinematics for the signal, the 95% CL upper limit on the HH signal strength is projected to be at 0.71 times the SM prediction with respect to the background-only hypothesis assuming an integrated luminosity of 3000 fb^{-1} and $\sqrt{s}$ = 14 TeV. The signal significance is extrapolated to 2.8σ, and assuming a true value of $\kappa_\lambda = 1$, the self-coupling modifier is constrained to the 1σ CI [0.3, 1.9] ∪ [5.2, 6.7]. If no HH

HL-LHC bbττ significance expected in 2021
(ATL-PHYS-PUB-2021-044)

a variety of integrated luminosities ranging from 1000 to 3000 fb^{-1}. Assuming SM HH production, a signal significance of 3.5 σ (4.6 σ) is expected in the baseline (statistical only) extrapolation scenario for an integrated luminosity of 3000 fb^{-1}. This translates into expected

HL-LHC bbττ significance expected in 2024
(ATL-PHYS-PUB-2024-016)