HH @ ATLAS
Run 2 & beyond

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New Methods and Ideas in Particle Physics

Aspen, Colorado - 22.03.2022

ATLAS EXPERIMENT

SLAC NATIONAL ACCELERATOR LABORATORY

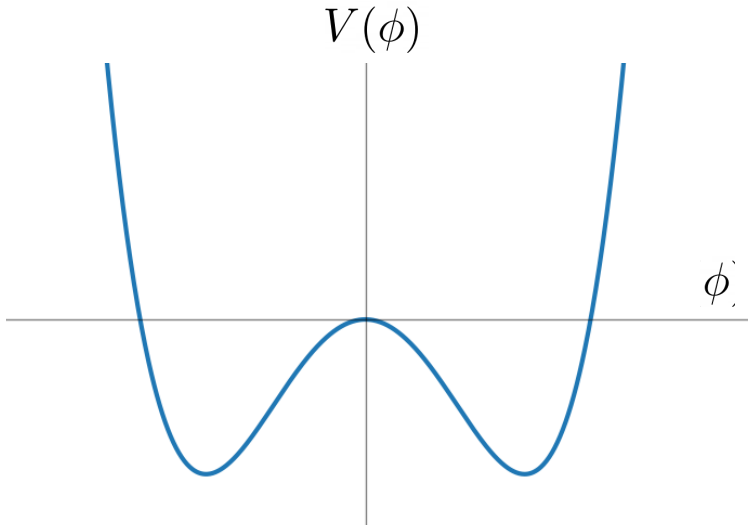
The Higgs Potential

The Standard Model Higgs Potential is:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

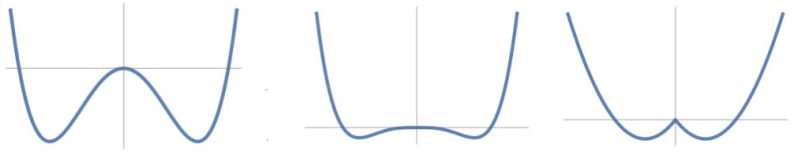
mass term

self-coupling term



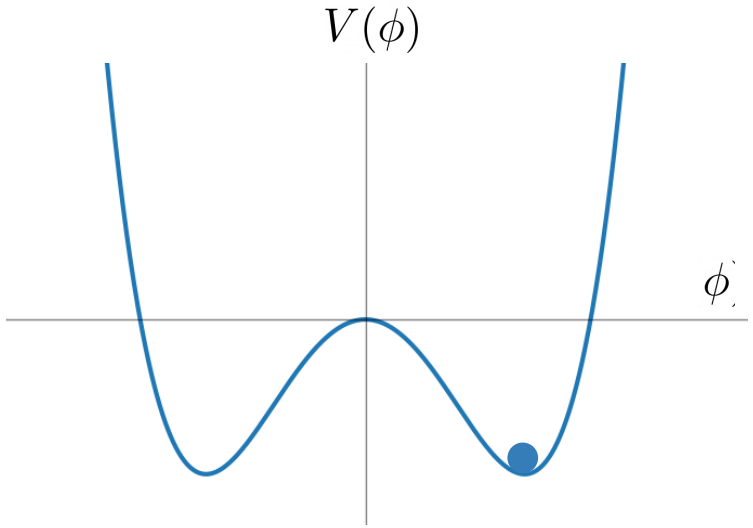
In the SM the shape of the potential is well constrained by the Higgs boson mass and vacuum expectation value. $\lambda = \frac{m_h^2}{2v^2} = 0.129$

But we have not directly measured the shape of the potential!



Phys. Rev. D 101, 075023 (2020)

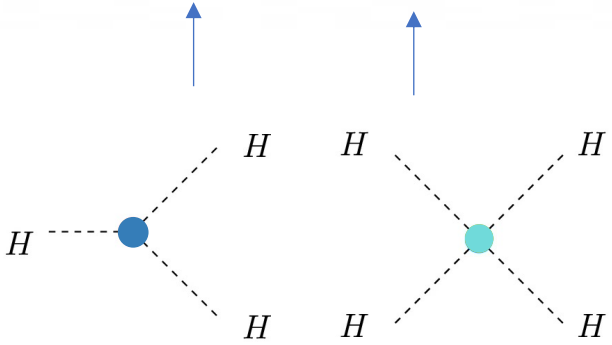
Measuring the Shape



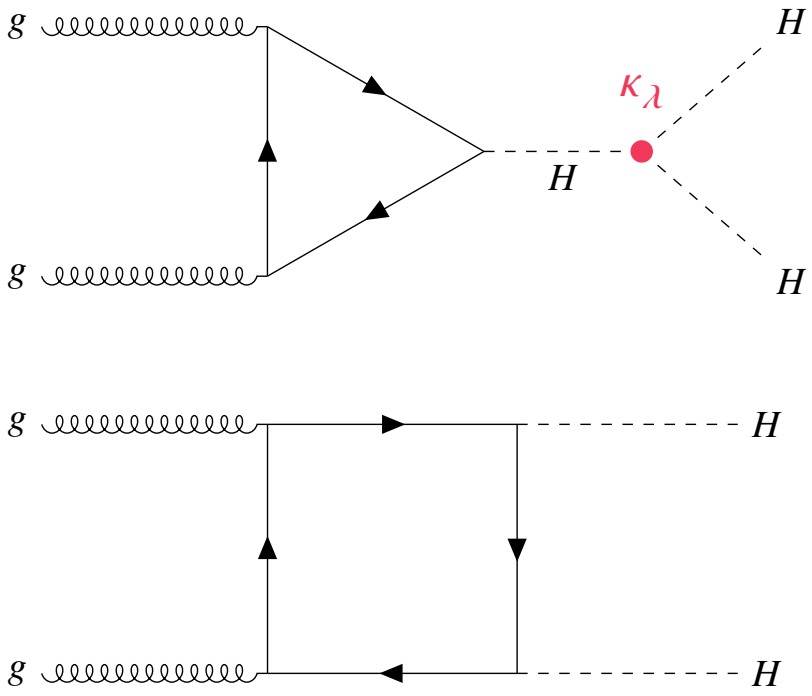
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

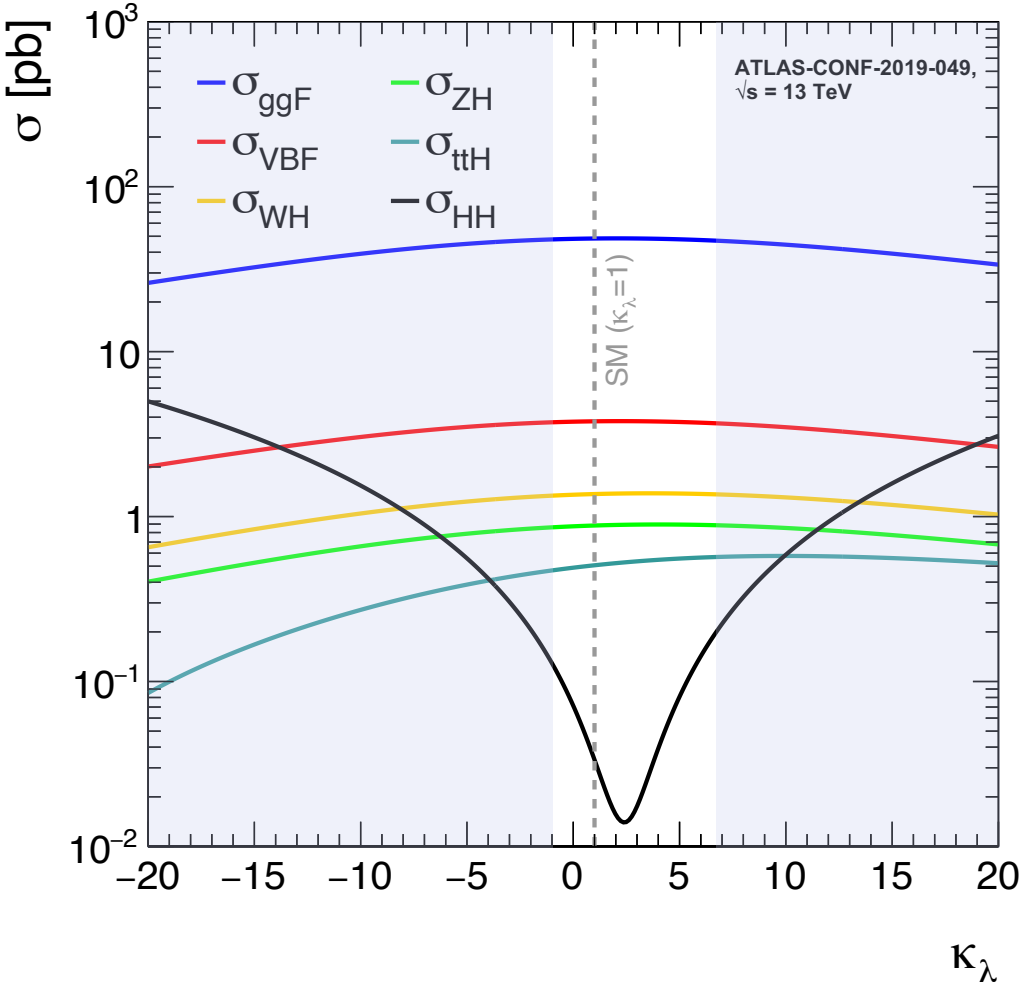
Perturb about minimum

$$V(\nu + h) = -\mu^2(\nu + h)^2 + \lambda(\nu + h)^4$$
$$= V_0 + \frac{1}{2}{m_h}^2h^2 + \lambda v h^3 + \lambda h^4 + \ldots$$



HH Production



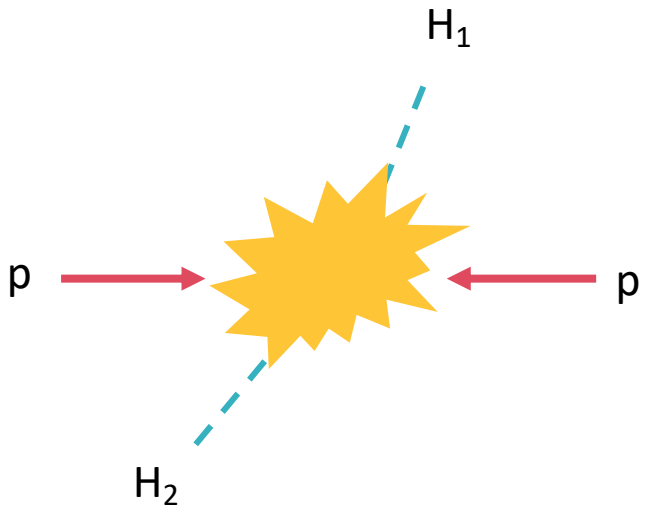


We can probe the shape of the Higgs potential by measuring the Higgs self-coupling parameter k_λ.

$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

Run 2 (search mode)	HL-LHC (measurement mode)
~4,000 events	~115,000 events

HH Decay Channels used in Latest Combination



bbττ - ATLAS-CONF-2021-030
https://cds.cern.ch/record/2777236

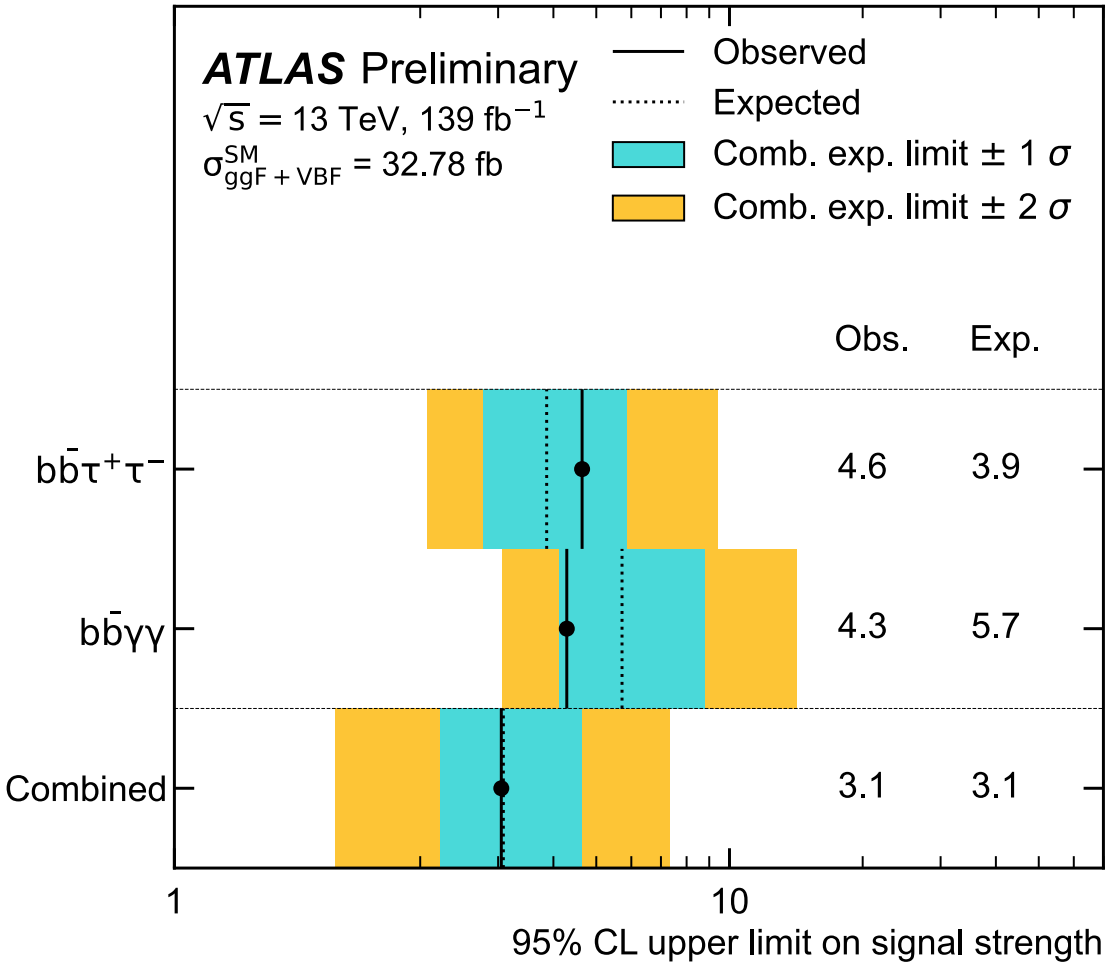
bb$\gamma\gamma$ - CERN-EP-2021-180
https://arxiv.org/abs/2112.11876

Combination - ATLAS-CONF-2021-052
https://cds.cern.ch/record/2786865

H_2 \ H_1	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%

Latest Limits on HH Signal Strength

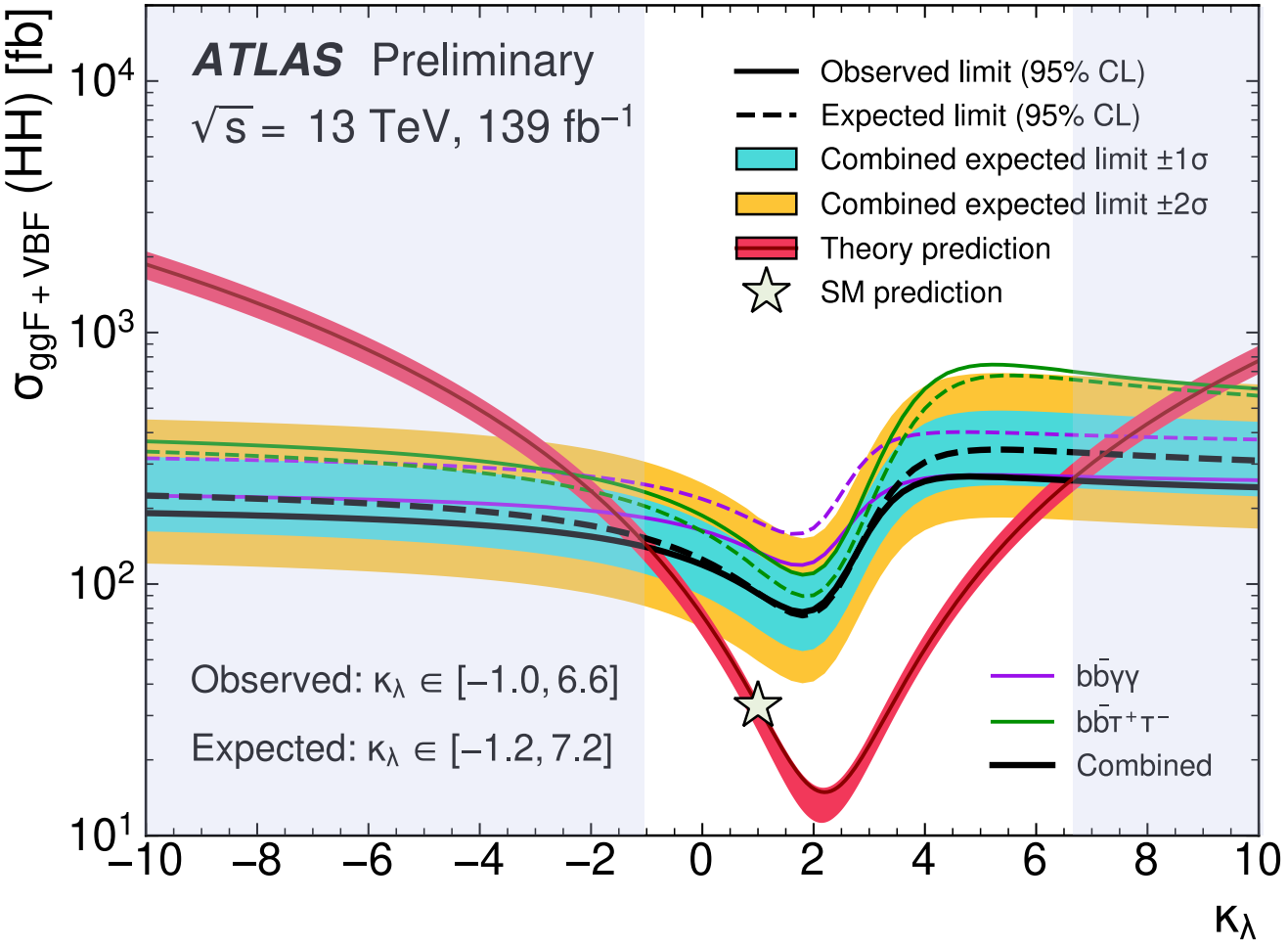
Interpretation: As no HH signal is observed, can place the following limits at 95% confidence level



ATLAS-CONF-2021-052
https://cds.cern.ch/record/2786865

Latest Constraints on the Higgs Boson Self-Coupling

Interpretation: As no HH signal is observed, can place the following constraints at 95% confidence level



ATLAS-CONF-2021-052
https://cds.cern.ch/record/2786865

HL-LHC Extrapolation Procedure

ATL-PHYS-PUB-2022-005
http://cdsweb.cern.ch/record/2802127

Extrapolating from Run 2 results obtained with 139fb^{-1} of data at 13 TeV

Luminosity scaled to 3000 fb^{-1} 21x more data than Run 2!

Cross-sections scaled to adjust to 14 TeV

Systematic uncertainties updated to provide envelope for interpreting the results:

1. No systematic uncertainties
2. Baseline - Experimental uncertainties scaled, and theory uncertainties halved
3. Theory uncertainties halved – but with Run 2 experimental systematic uncertainties
4. Run 2 systematic uncertainties

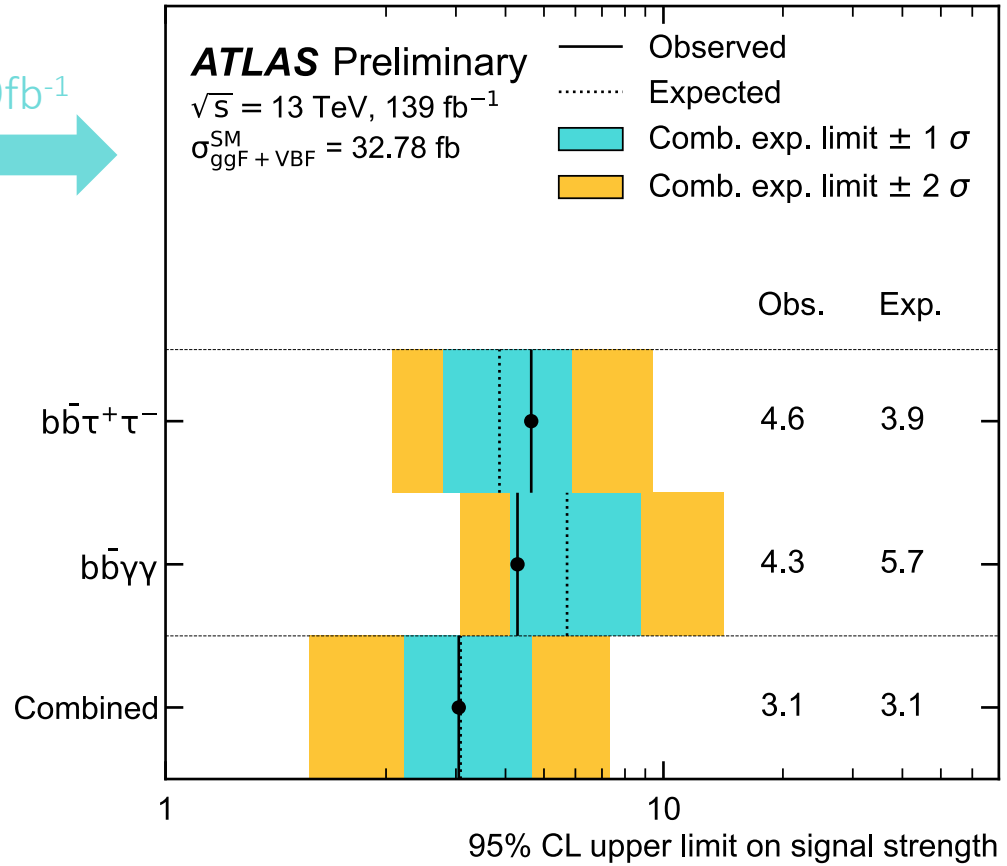
optimistic

conservative

Projected Limits on HH Signal Strength

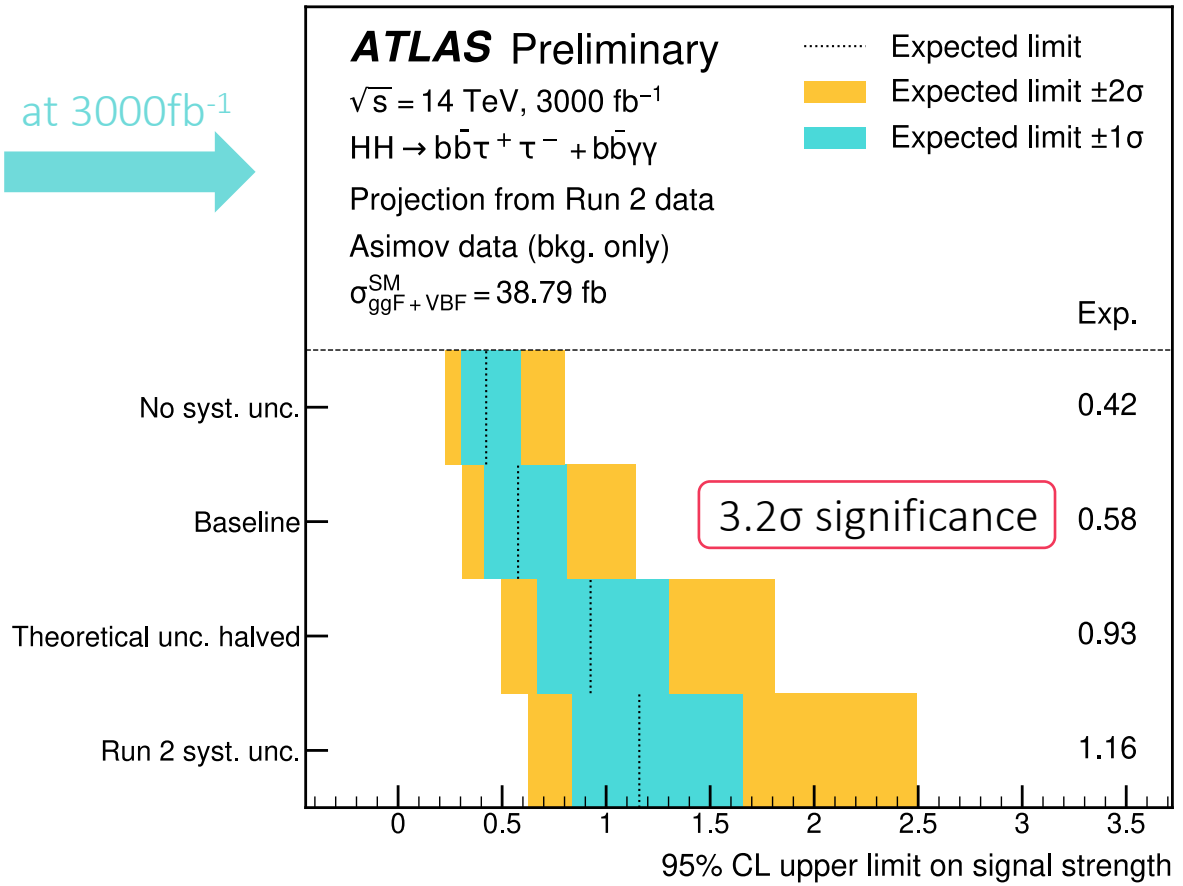
Interpretation: If no HH signal is observed, can place the following limits at 95% confidence level

at 139fb^{-1}



at 3000fb^{-1}

ATL-PHYS-PUB-2022-005 http://cdsweb.cern.ch/record/2802127

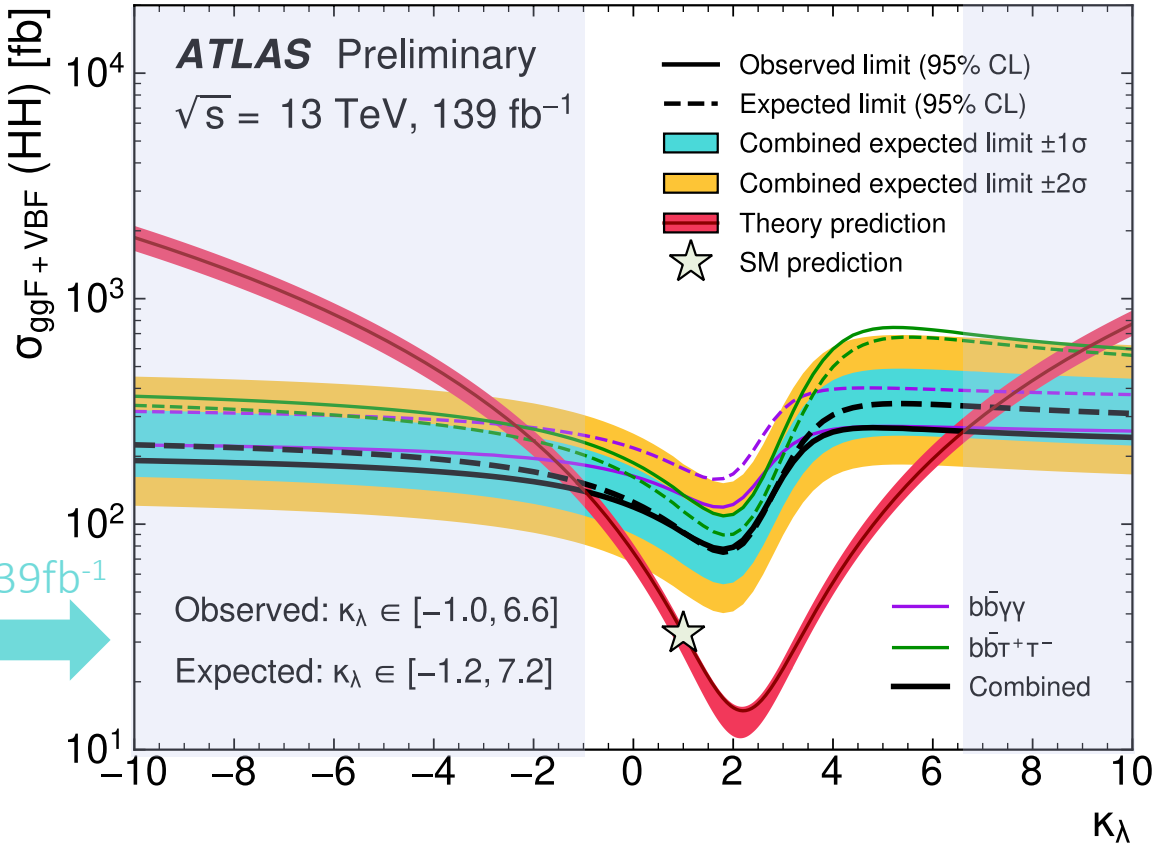


Projected Constraints on Higgs Boson Self-Coupling

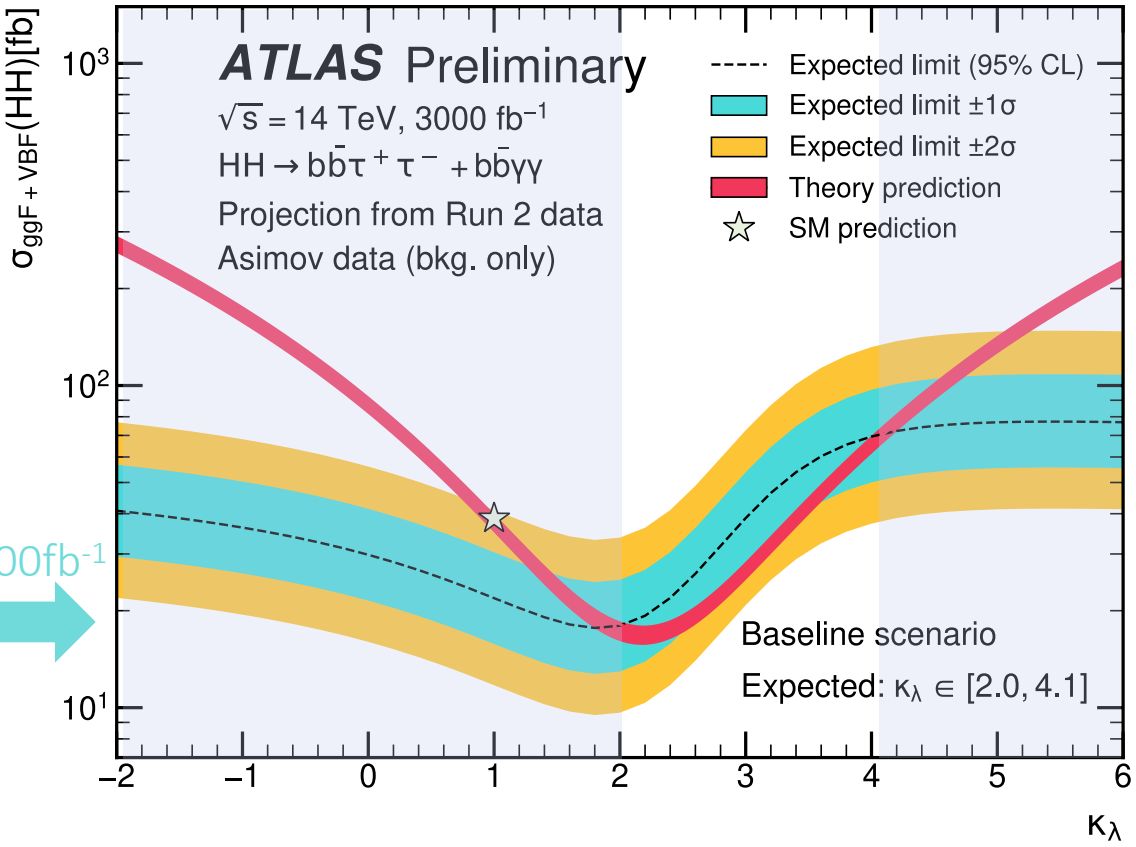
Interpretation: If no HH signal is observed, can place the following constraints at 95% confidence level

ATL-PHYS-PUB-2022-005 http://cdsweb.cern.ch/record/2802127

at 139fb^{-1}



at 3000fb^{-1}



Note: k_λ=1 expected to be excluded during HL-LHC if we see no evidence of SM HH production

Conclusions and Outlook

Current combination of Run 2 bbττ and bb$\gamma\gamma$ analyses leads to limits on HH signal strength at 3.1xSM and constraints of Higgs boson self-coupling between $-1.0 < k_\lambda < 6.6$.

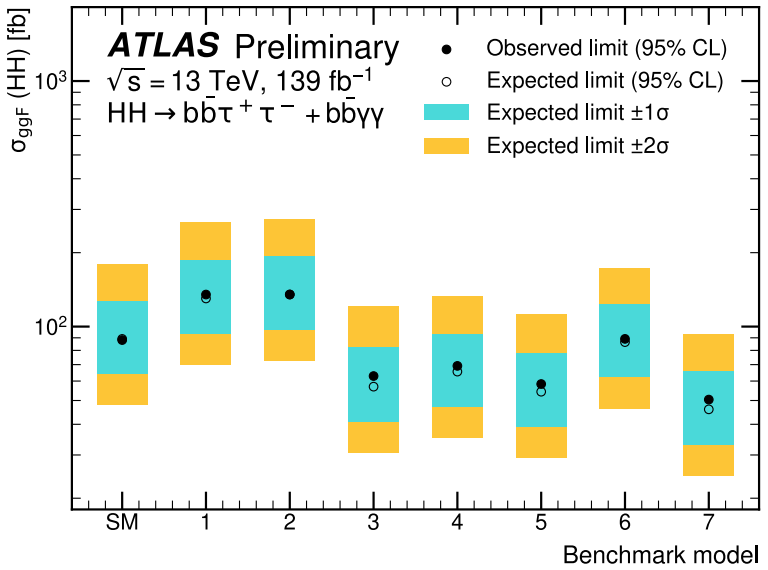
Brand-new results with HEFT interpretations available (see link on right).

Baseline combined expected SM significance @ HL-LHC of 3.2σ with just bbττ and bb$\gamma\gamma$ channels.

Further steps: more channels, combination with single Higgs analyses and more data will improve current and projected results.

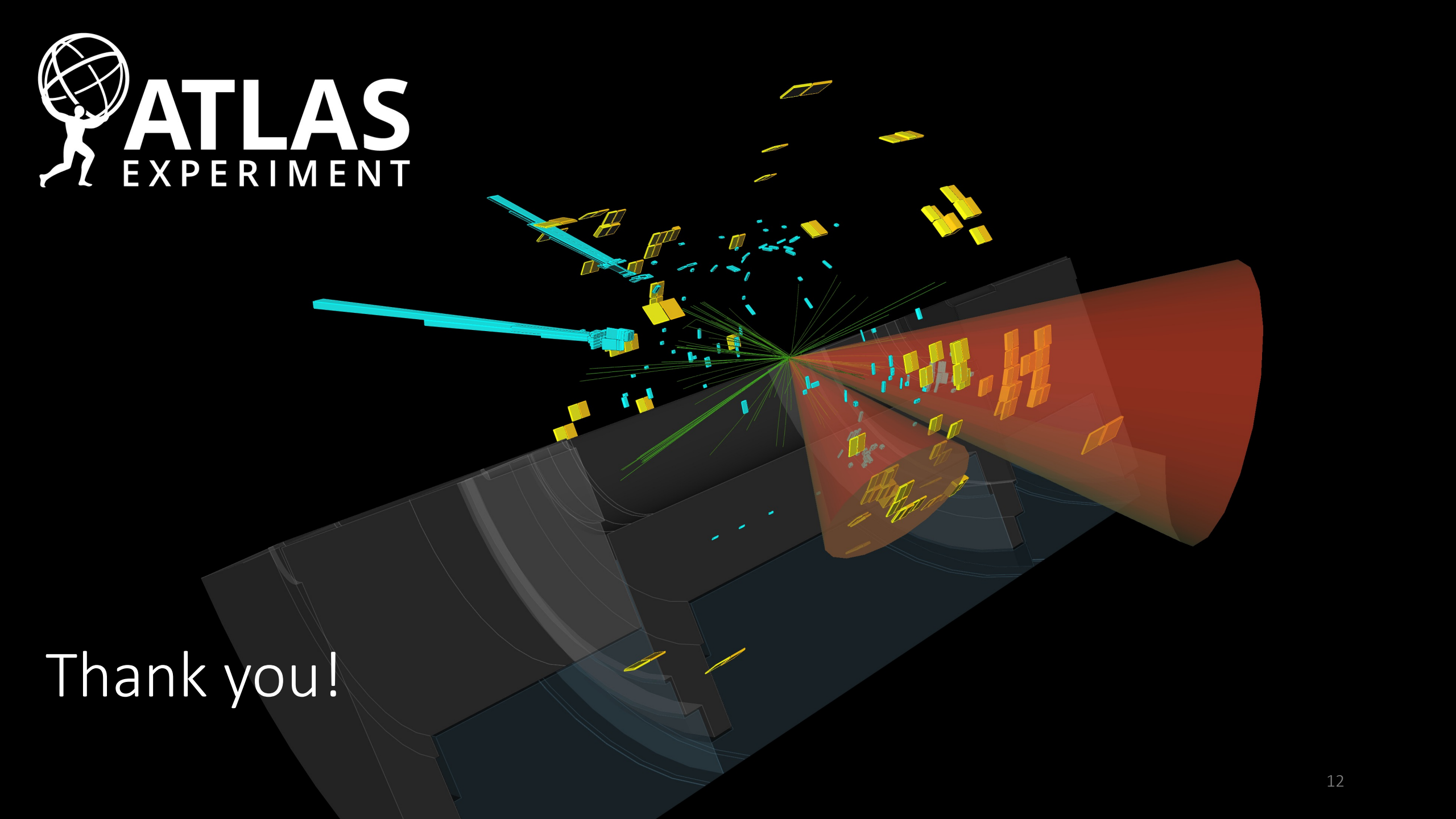
Future e+e- Higgs factory colliders will allow us to further study the Higgs boson self-coupling with precision.

HEFT interpretations: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-021/



collider	single-H	HH	combined
HL-LHC	100-200%	50%	50%
$CEPC_{240}$	49%	–	49%
C^3 ILC_{250}	49%	–	49%
C^3 ILC_{500}	38%	27%	22%
ILC_{1000}	36%	10%	10%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
FCC-hh	-	5%	5%

Expected precision on k_λ at future colliders https://arxiv.org/abs/1910.00012



Thank you!

References

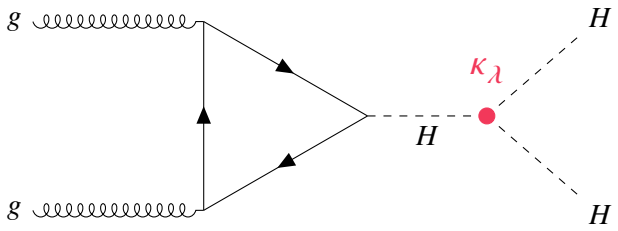
2018 HL-LHC Prospects Combination http://cdsweb.cern.ch/record/2652727

2021 HL-LHC Prospects bbττ https://cds.cern.ch/record/2798448
2022 HL-LHC Prospects bb$\gamma\gamma$ http://cdsweb.cern.ch/record/2799146
2022 HL-LHC Prospects Combination http://cdsweb.cern.ch/record/2802127

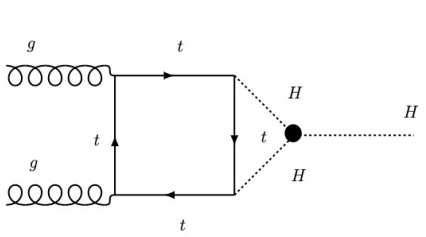
2021 Full Run 2 bbττ https://cds.cern.ch/record/2777236
2021 Full Run 2 bb$\gamma\gamma$ https://arxiv.org/abs/2112.11876
2021 Full Run 2 HH Combination https://cds.cern.ch/record/2786865
2022 Full Run 2 HH HEFT Interpretations
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-021/

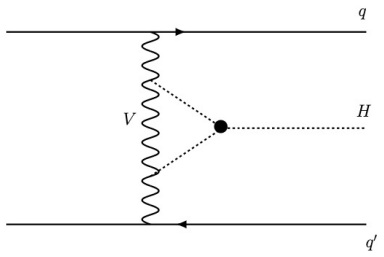
Measuring κ_λ

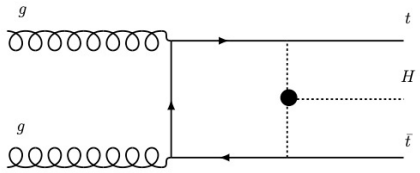
Direct measurement:

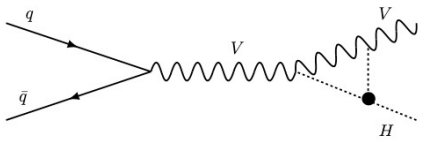


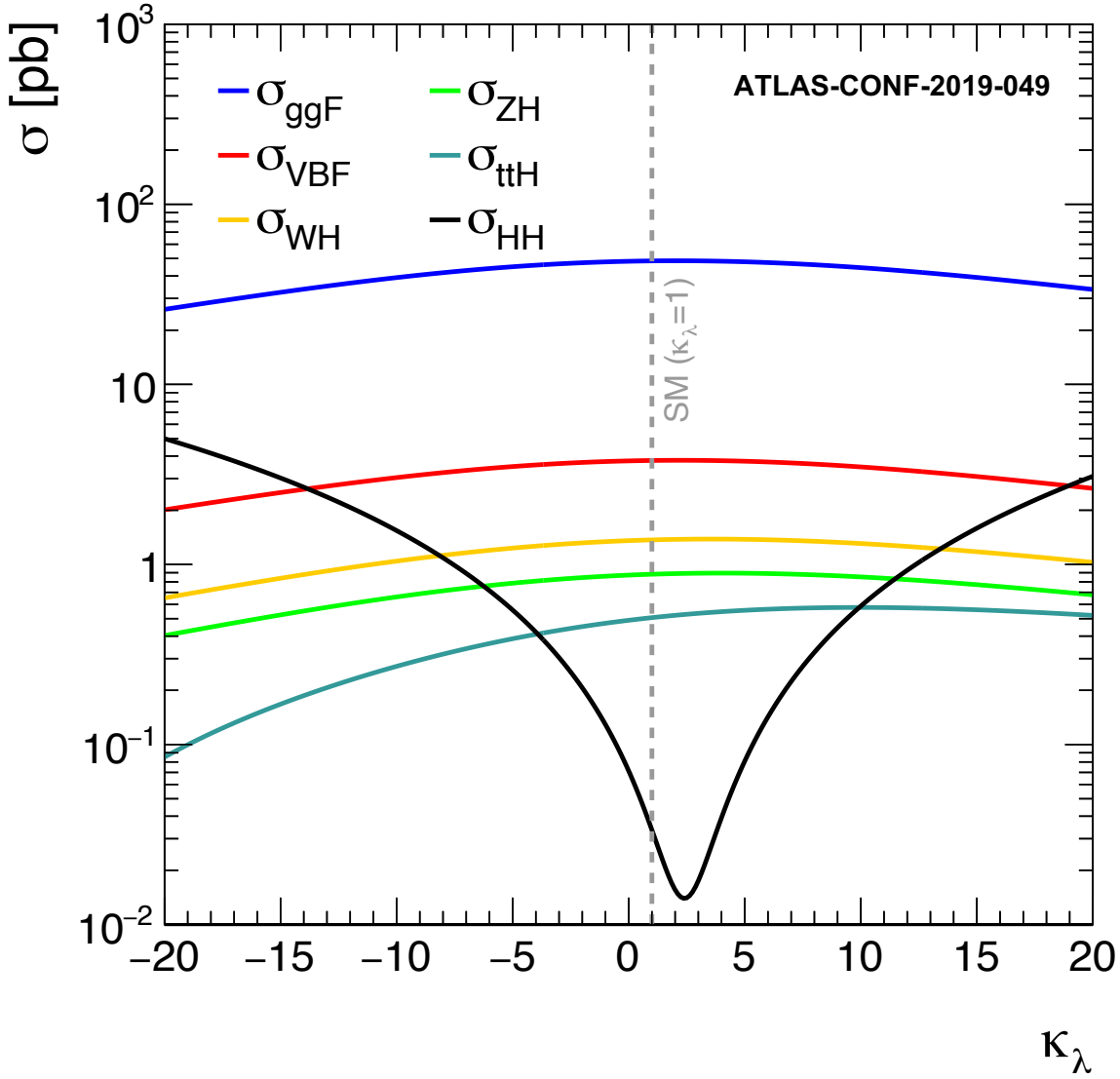
Indirect measurement:







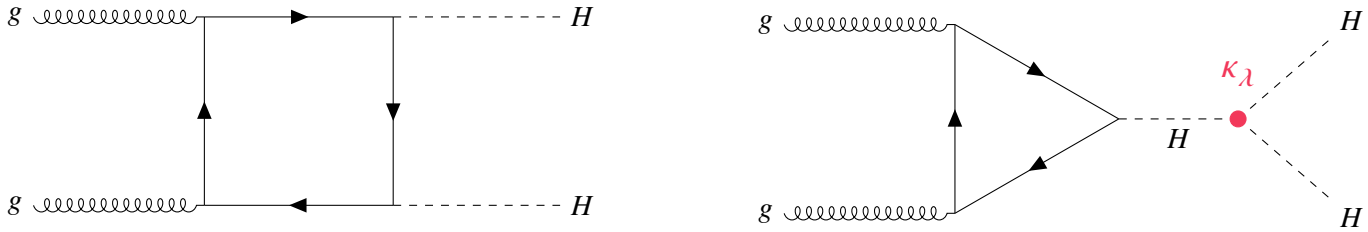




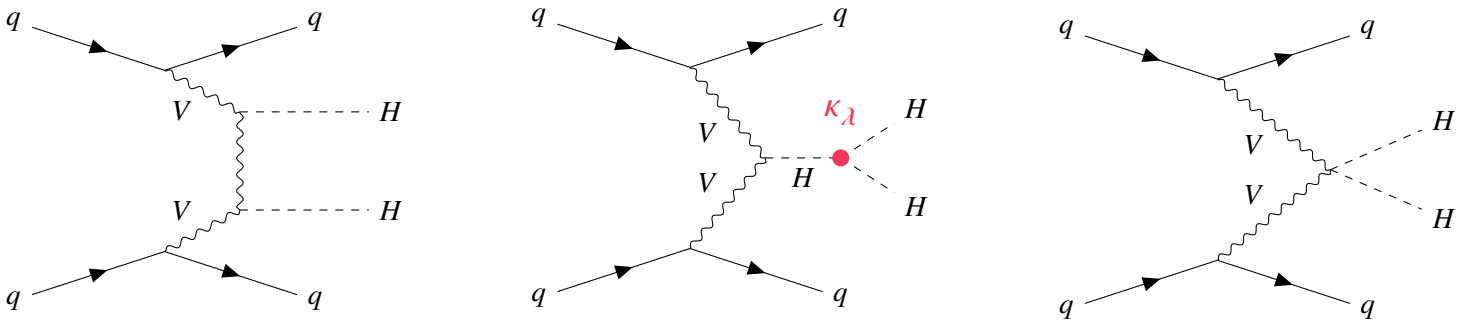
HH Production Channels

Non-Resonant

ggF: σ_{SM} = 31.05 fb



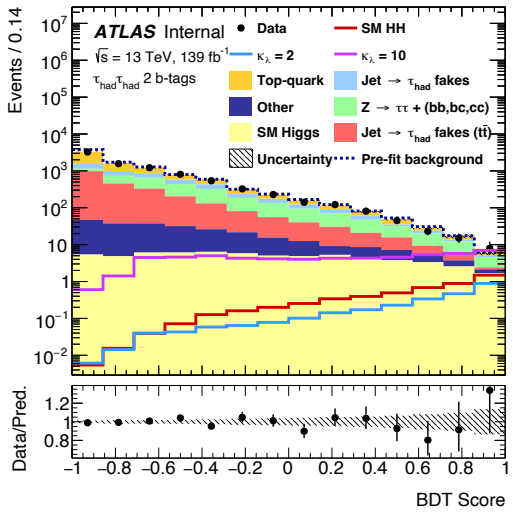
VBF: σ_{SM} = 1.73 fb



Analysis Overviews

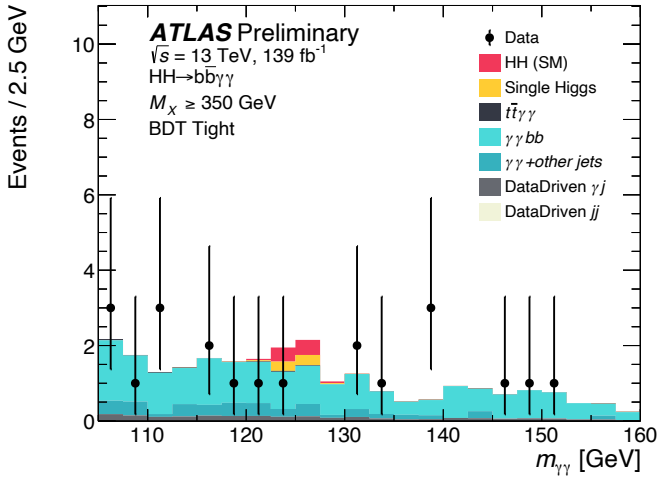
bbττ: https://cds.cern.ch/record/2777236

- Lep-had and had-had channels
- Lep-had includes single-lepton (SLT) and lepton+tau (LTT) triggers
- NN used in lep-had channels
- BDT used for had-had channel
- Final fit on MVA output distributions in 3 signal regions and m_{ll} in Z+HF control region

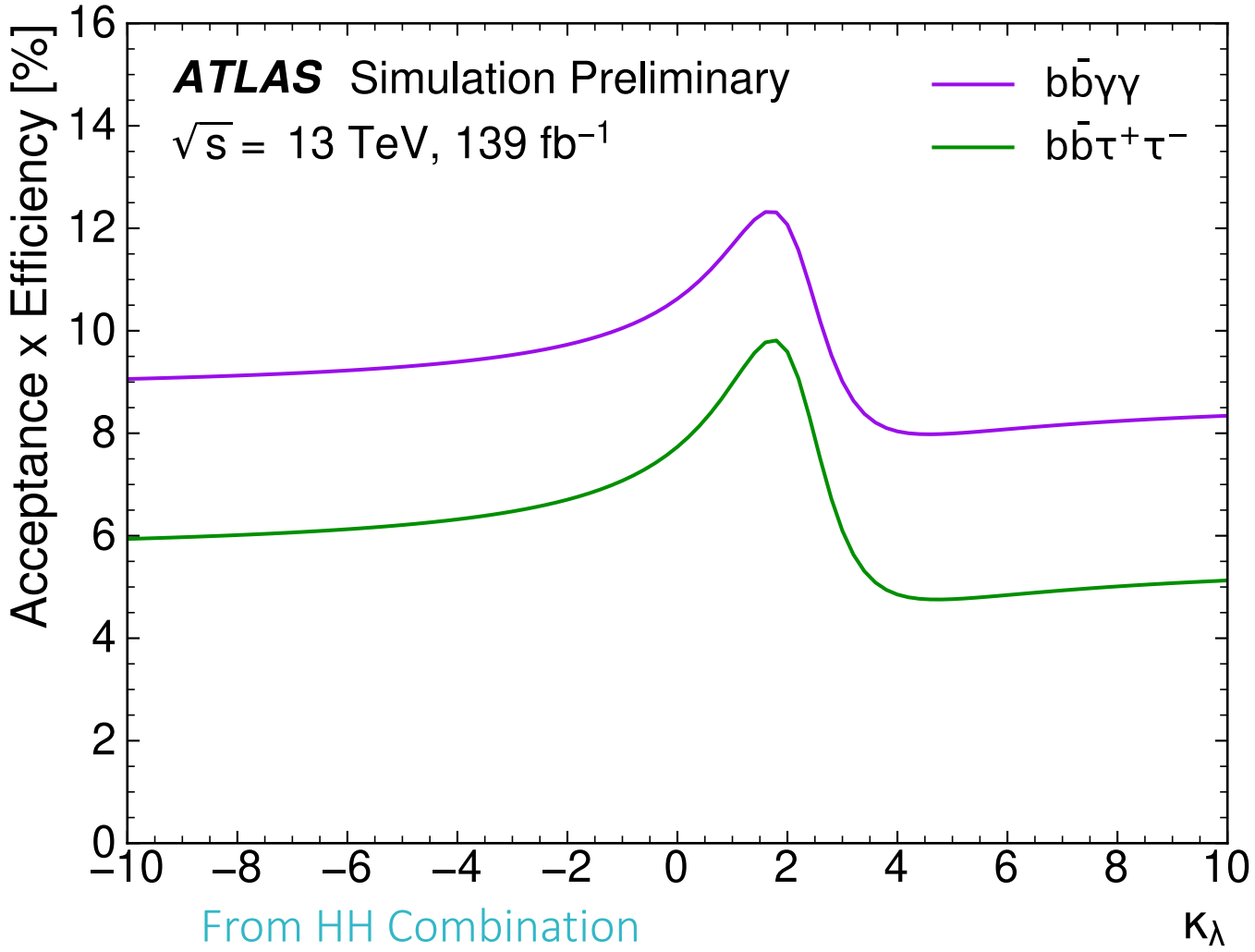


bbγγ: https://arxiv.org/abs/2112.11876

- Small branching ratio, but clean diphoton signature for triggering
- Excellent $m_{\gamma\gamma}$ resolution (~1.5 GeV)
- BDTs with for high mass and low mass categories
- $m_{\gamma\gamma}$ peak fit with double-sided crystal ball
- Continuum $\gamma\gamma$+jets background fit with exponential
- Un-binned maximum likelihood fit in $m_{\gamma\gamma}$



Acceptance x Efficiency as a function of k_λ

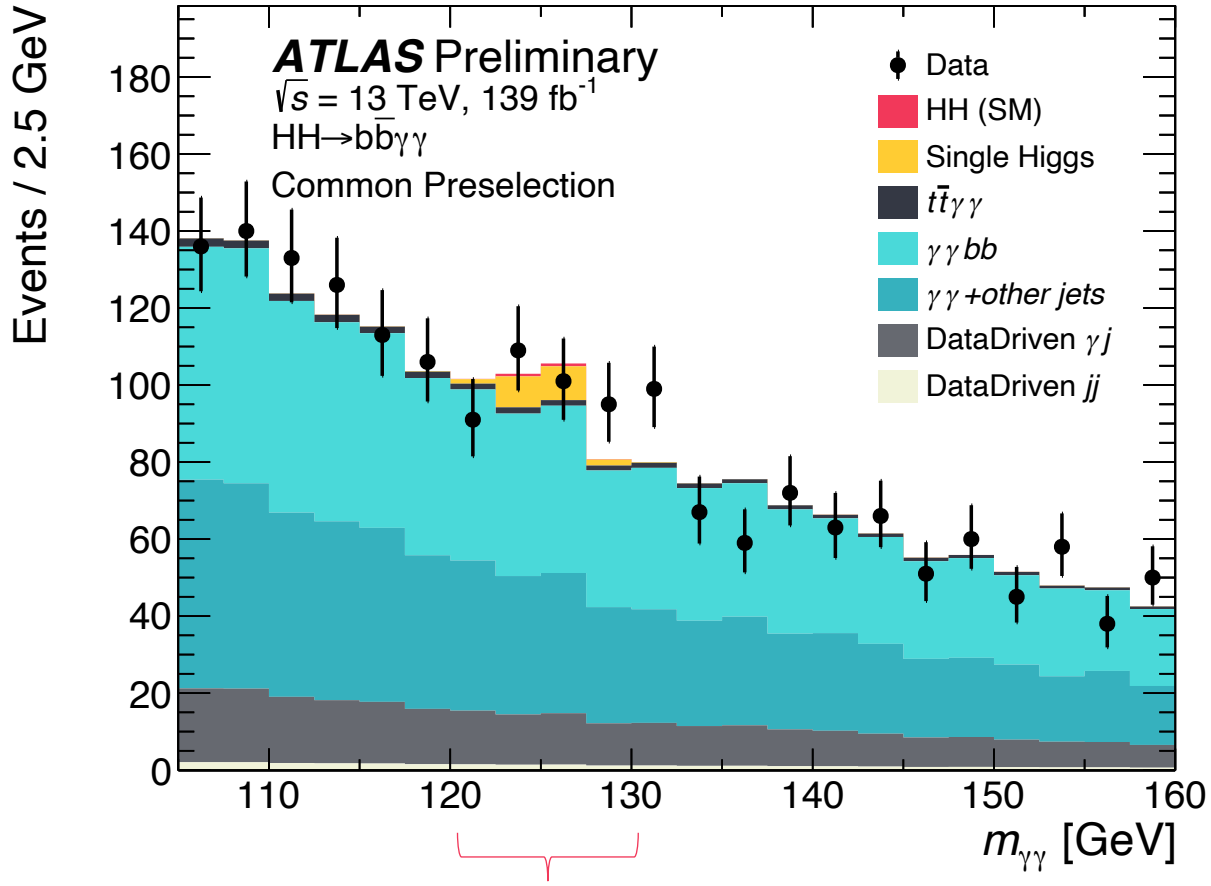


From HH Combination

$$\text{Acceptance x Efficiency} = \frac{\text{Yield}}{\sigma * \text{BR} * 139\,\text{fb}^{-1}}$$

Selection Strategy

2 photons
& 2 b-jets



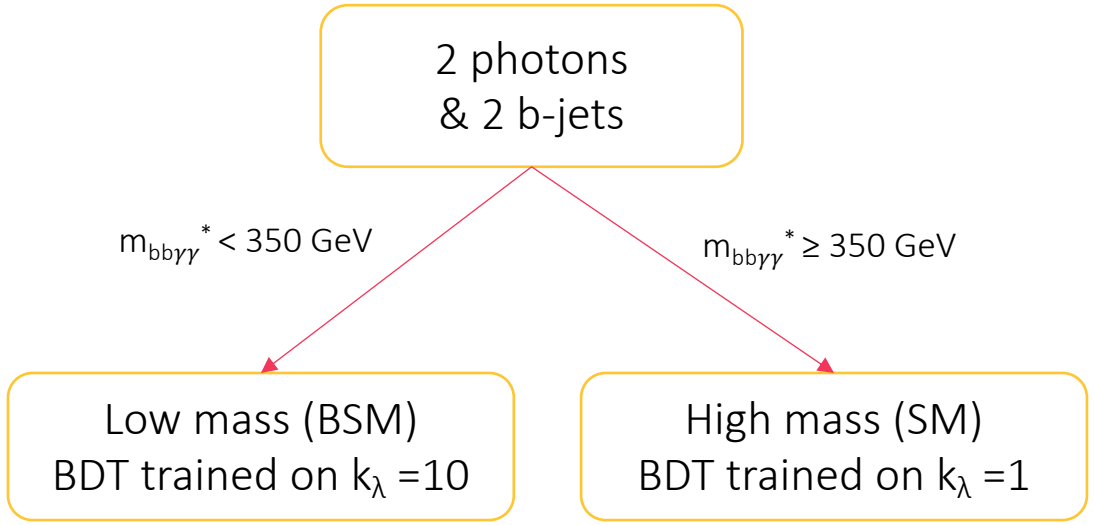
Excellent di-photon mass resolution allows for signal extraction in $m_{\gamma\gamma}$

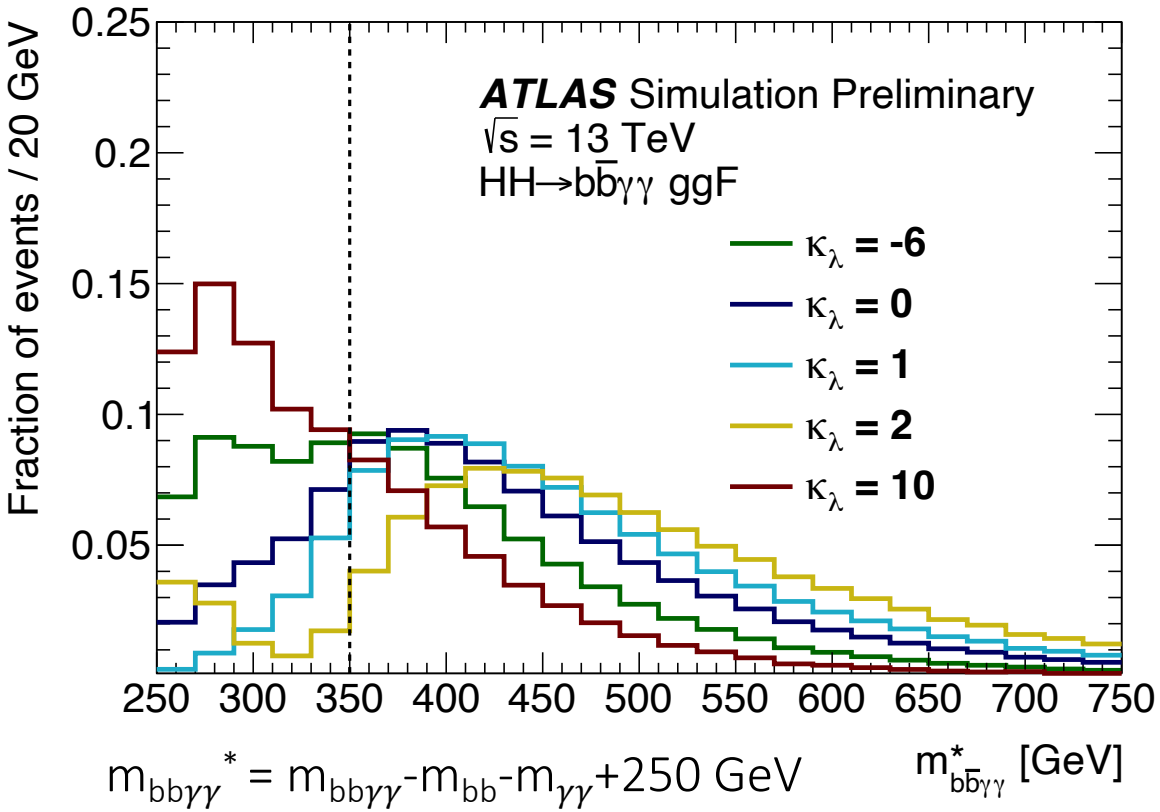
Major backgrounds:
- Diphoton $\gamma\gamma$ (largest contributor)
- Single Higgs (peaks at same $m_{\gamma\gamma}$ as signal)

s/b in signal region after pre-selection is ~0.1%

Signal region
$m_{\gamma\gamma}$ = 120-130 GeV

bb$\gamma\gamma$ Selection Strategy

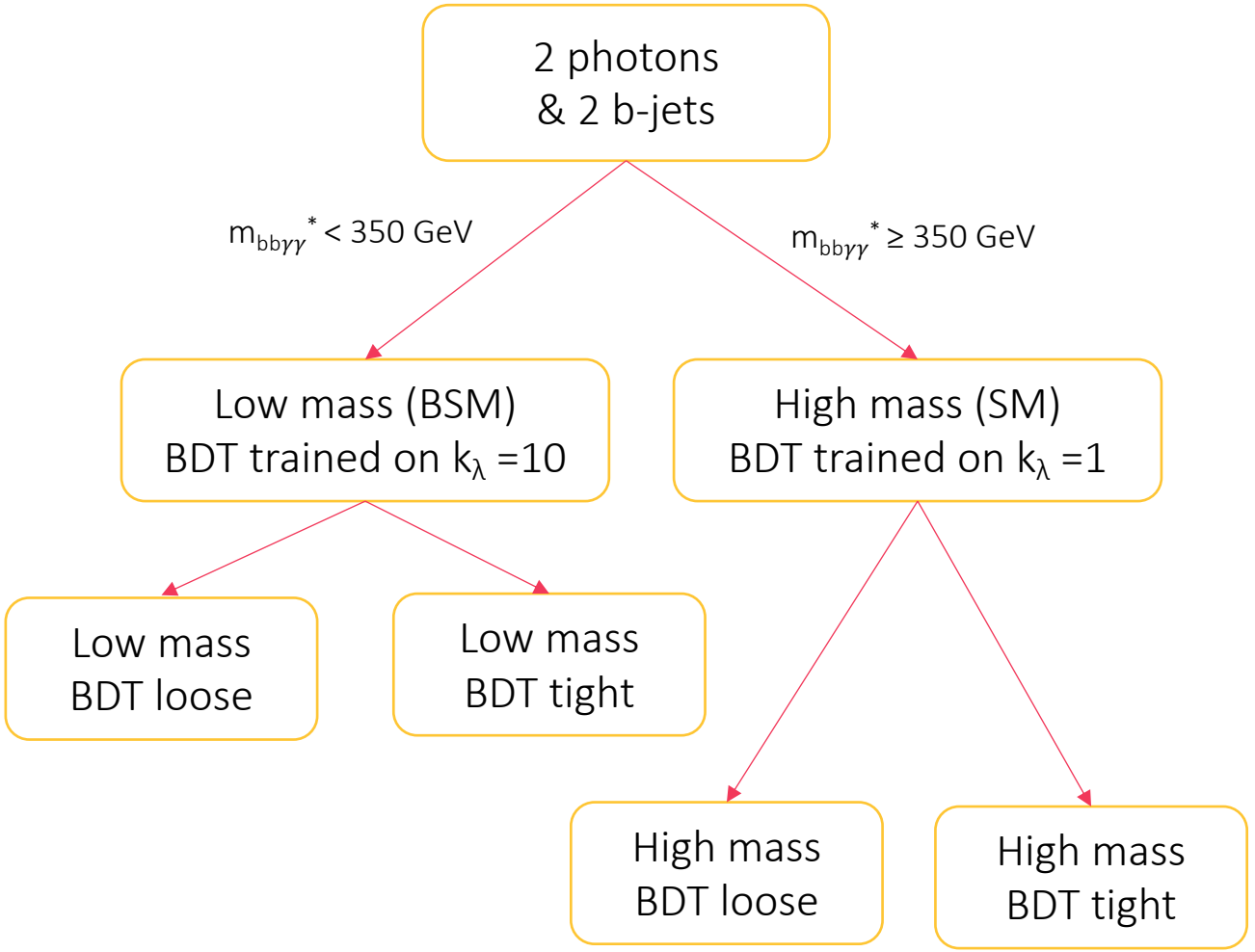


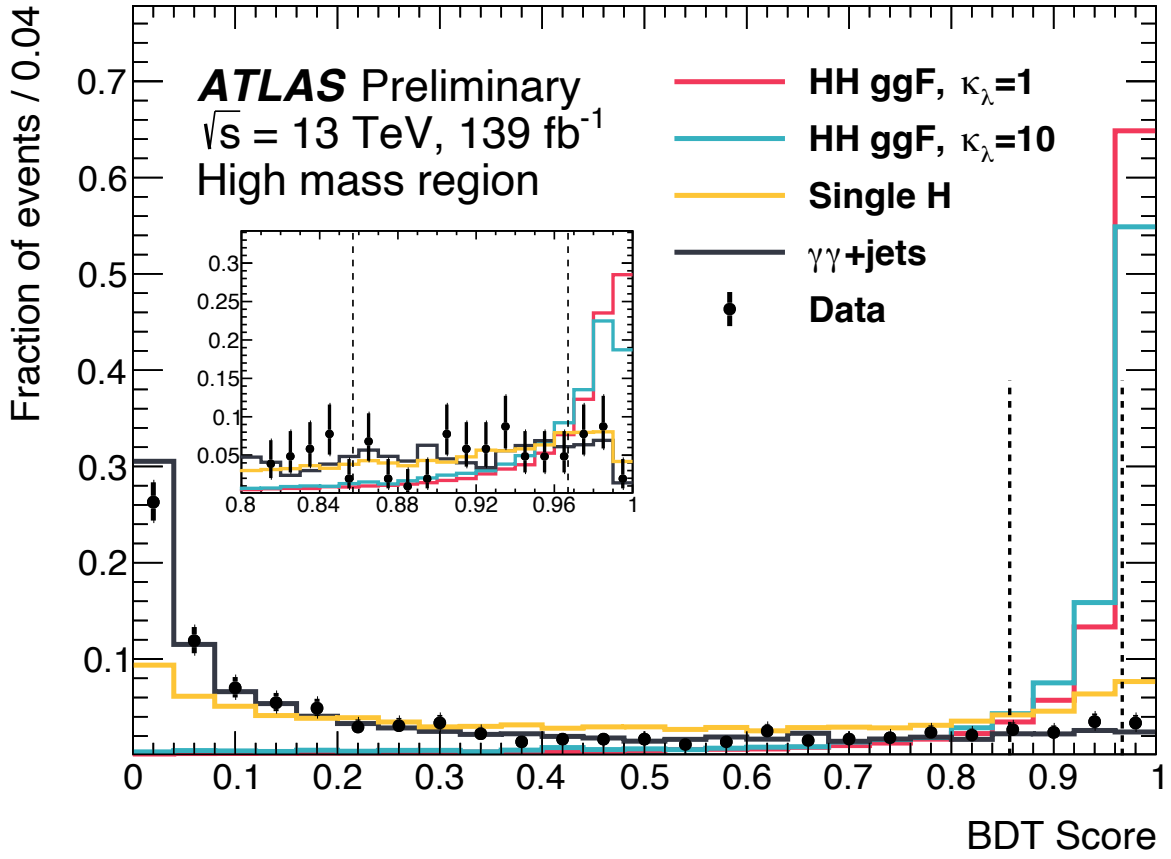


Split signal regions by $m_{bb\gamma\gamma}^{*}$ for sensitivity to SM and BSM HH.

Train two BDTs to target each signal region.

bb$\gamma\gamma$ Selection Strategy

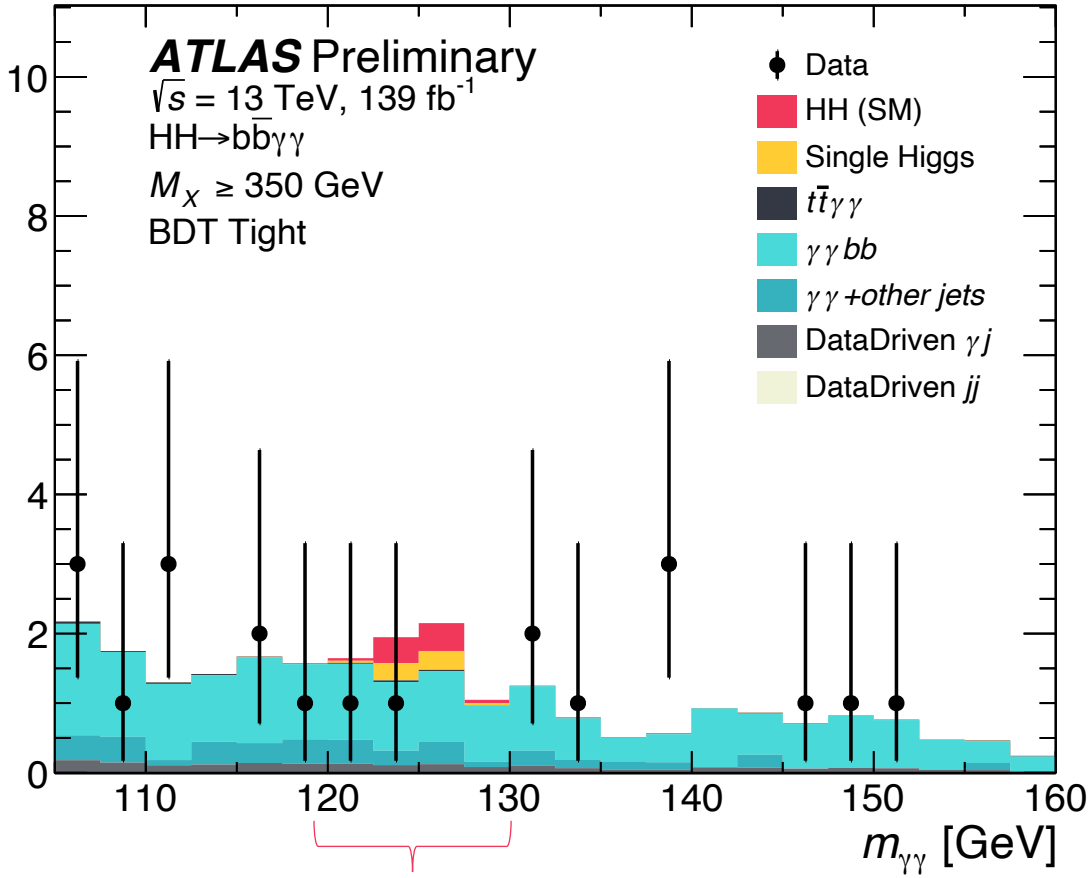




4 BDT Categories

Cuts on BDT scores optimized to maximize Asimov significance.

Post Selection Data/Predictions



Signal region
$m_{\gamma\gamma}$ = 120-130 GeV

s/b in signal region after high mass BDT tight selection is 14%

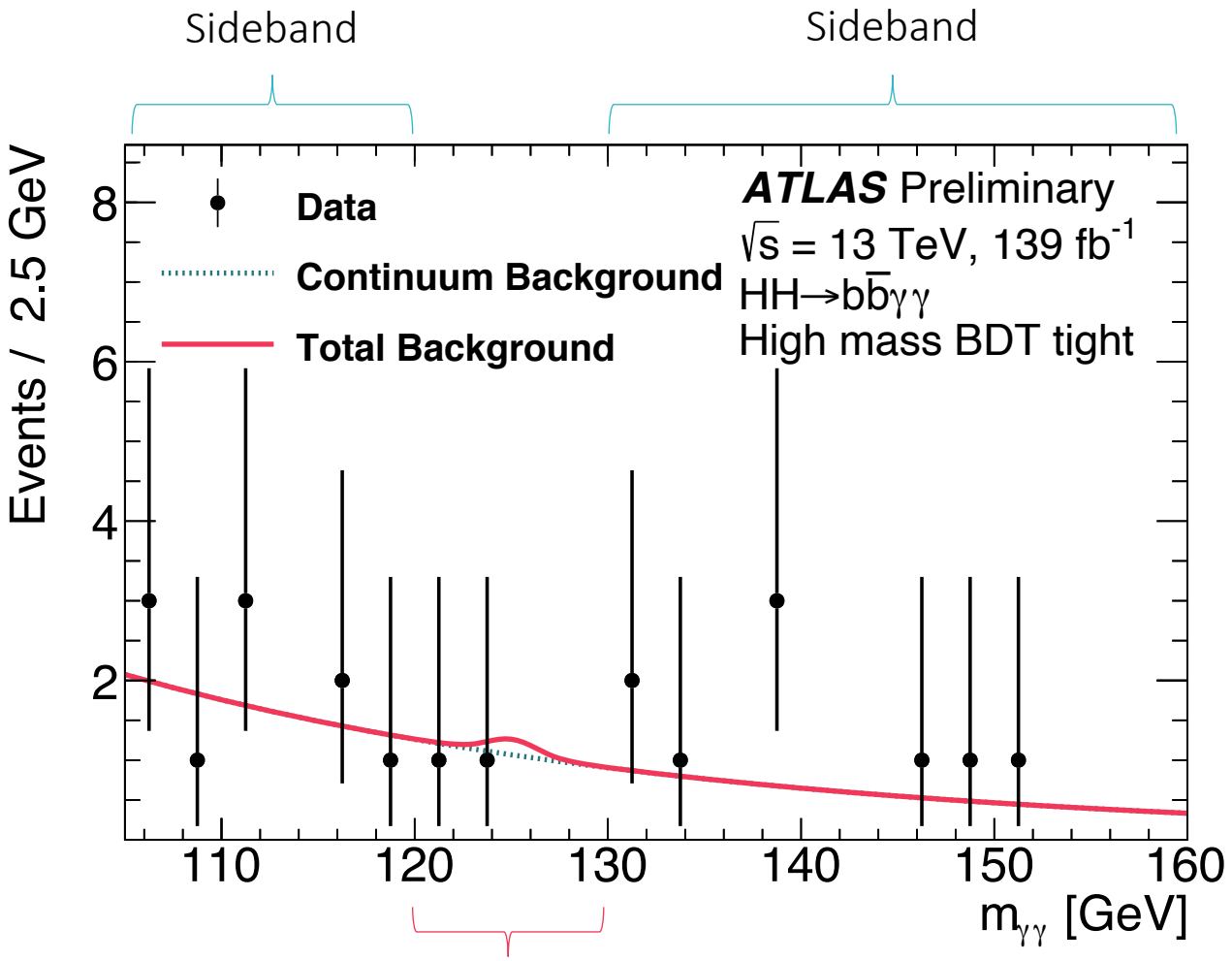
Signal Extraction

Signal model: Double-Sided Crystal Ball
Normalization and shape for HH signal and single Higgs background models determined from fits to Monte Carlo simulation.

Background model: Exponential function
Shape chosen by fitting Monte Carlo simulation. Normalized to the data sidebands.

Spurious signal tests performed to estimate bias introduced by choice of functional form.

HH signal strength determined through maximum likelihood fit on $m_{\gamma\gamma}$ across all four BDT categories



Signal region
$m_{\gamma\gamma}$ = 120-130 GeV

Extrapolation Procedure

1. Luminosity scaling to 3000 fb^{-1}
2. Cross-sections scaled to adjust to 14 TeV

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
$t\bar{t}H$	1.21
Others	1.18

Recommendations from Higgs HL-LHC WG

Increased gluon-luminosity

3. Systematic uncertainties updated (next page)

Systematic Uncertainty Extrapolation

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

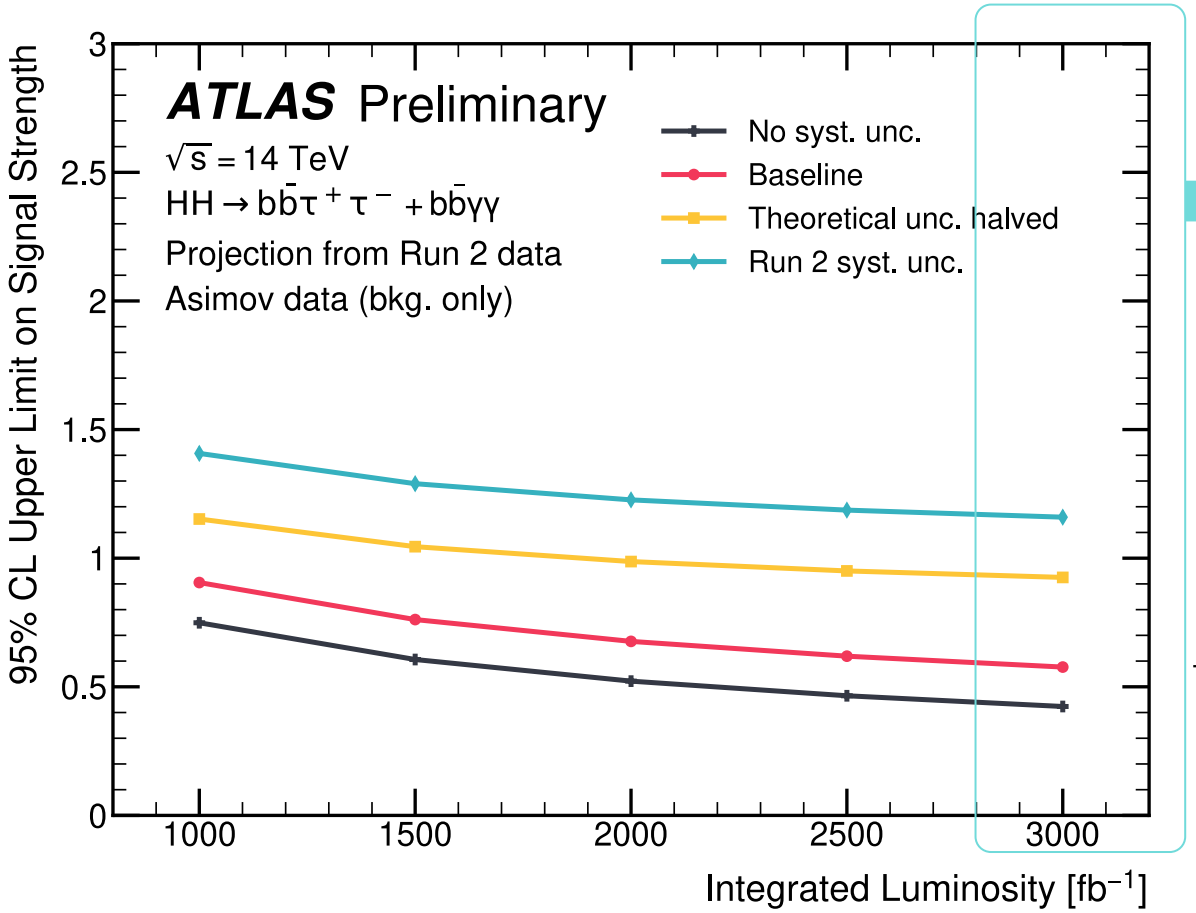
Detector performance expected to remain similar, but uncertainties on heavy jet tagging expected to decrease

MC related uncertainties

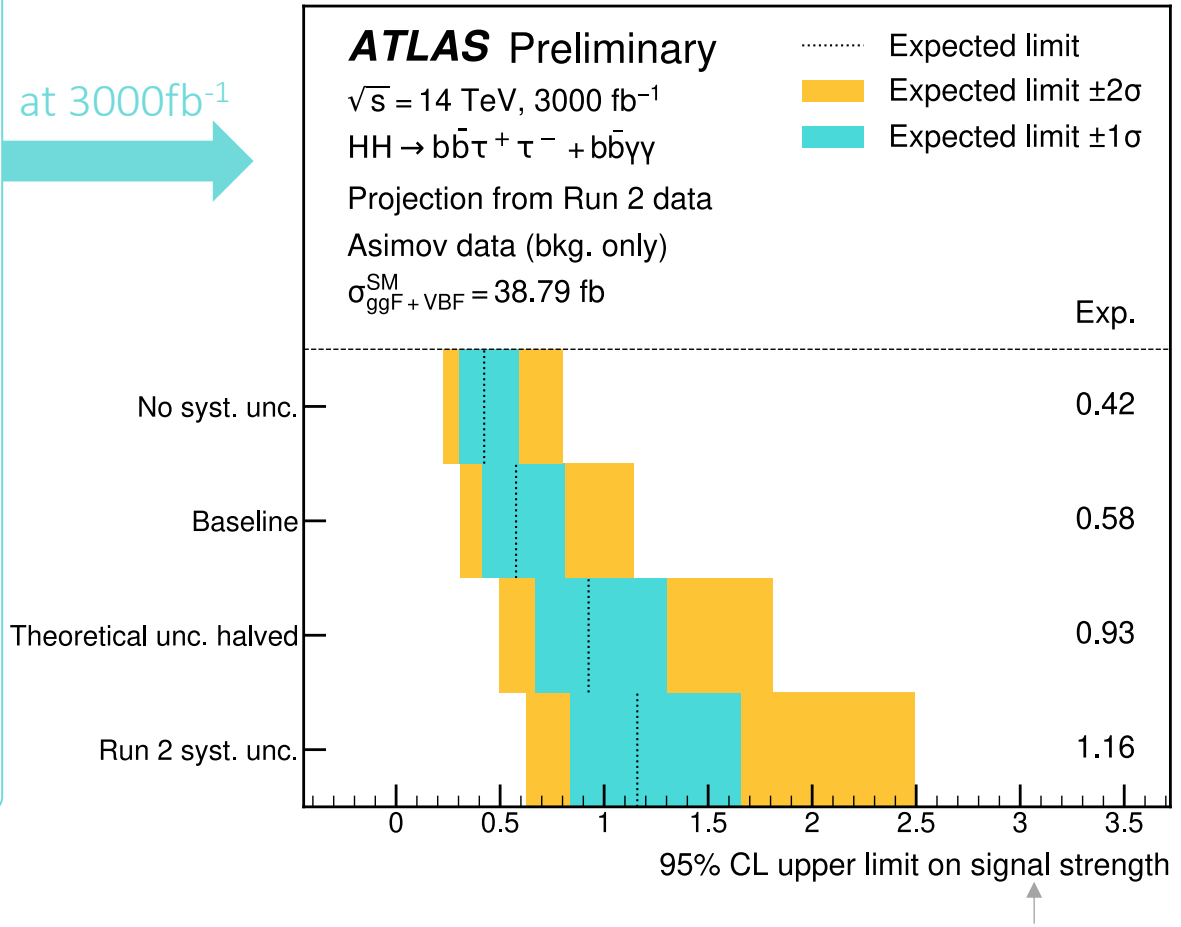
Theory uncertainties halved

Upper Limits on SM Signal Strength

Interpretation: If no HH signal is observed, can place the following limits at 95% confidence level



at 3000fb^{-1}

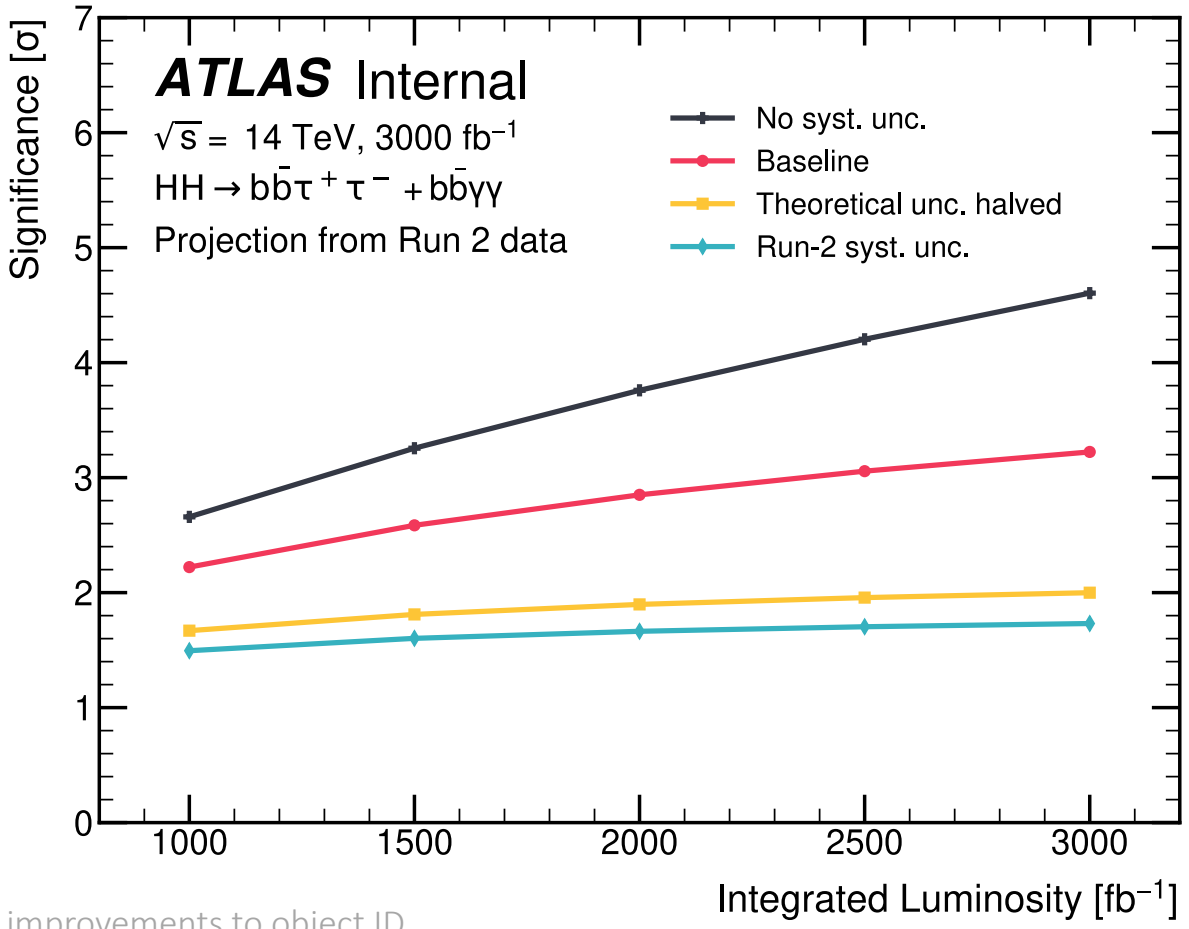


For comparison, Full Run 2 bbττ, and bb$\gamma\gamma$ combination is at 3.1x SM

Significance - Combination

This Combination – 2 channels

Uncertainty scenario	Significance $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination
No systematic uncertainties	2.3	4.0	4.6
Baseline	2.2	2.8	3.2
Theory uncertainties halved	1.1	1.7	2.0
Run-2 systematic uncertainties	1.1	1.5	1.7

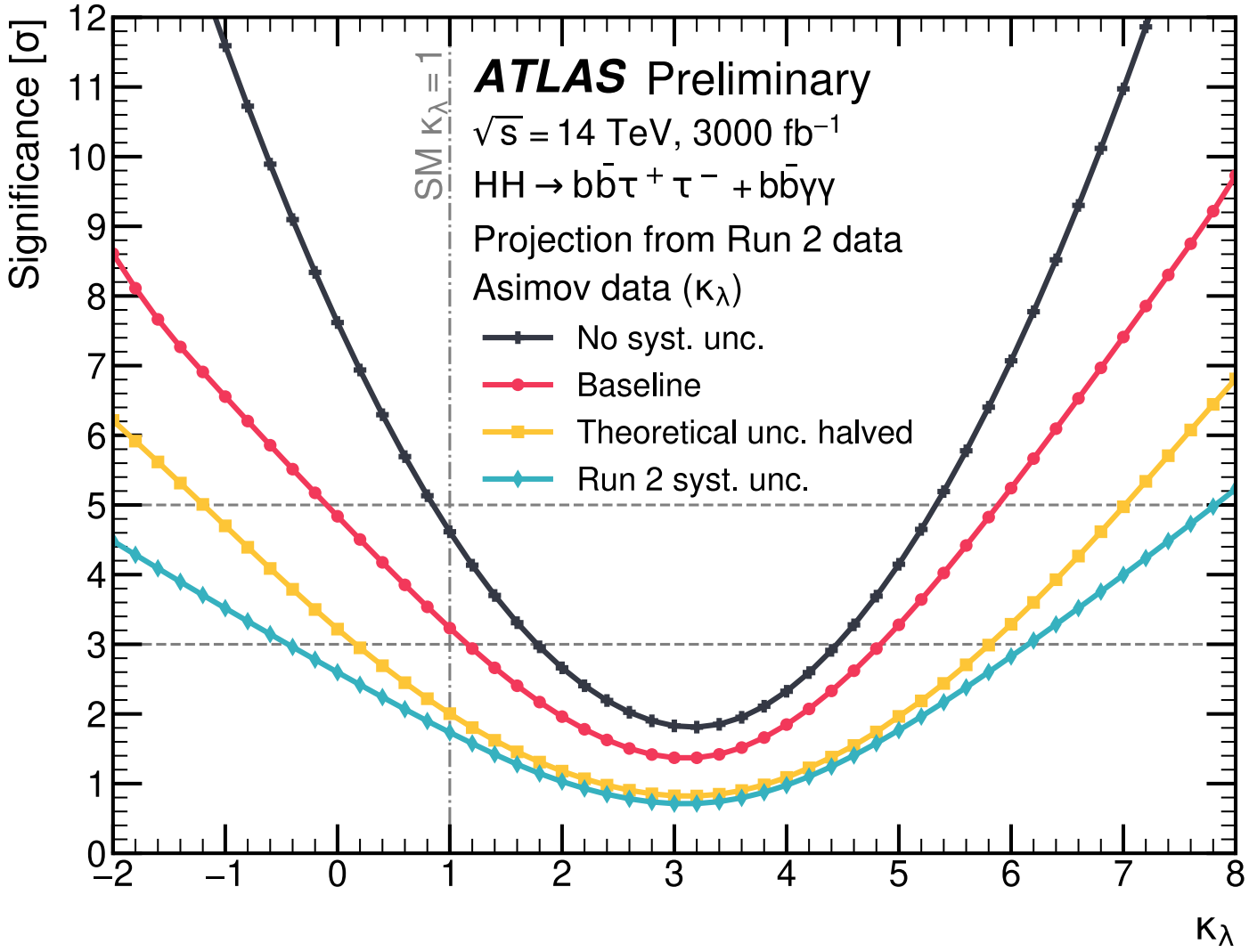


2018 Projections Combination – 3 channels
(ATL-PHYS-PUB-2020-005)

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.2	0.5
$HH \to b\bar{b}\tau^+\tau^-$	2.3	2.0
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.3	2.9

bbττ: gains mainly from improvements to object ID
bb$\gamma\gamma$: previous results from truth MC

Significance as a function of k_λ - Combined

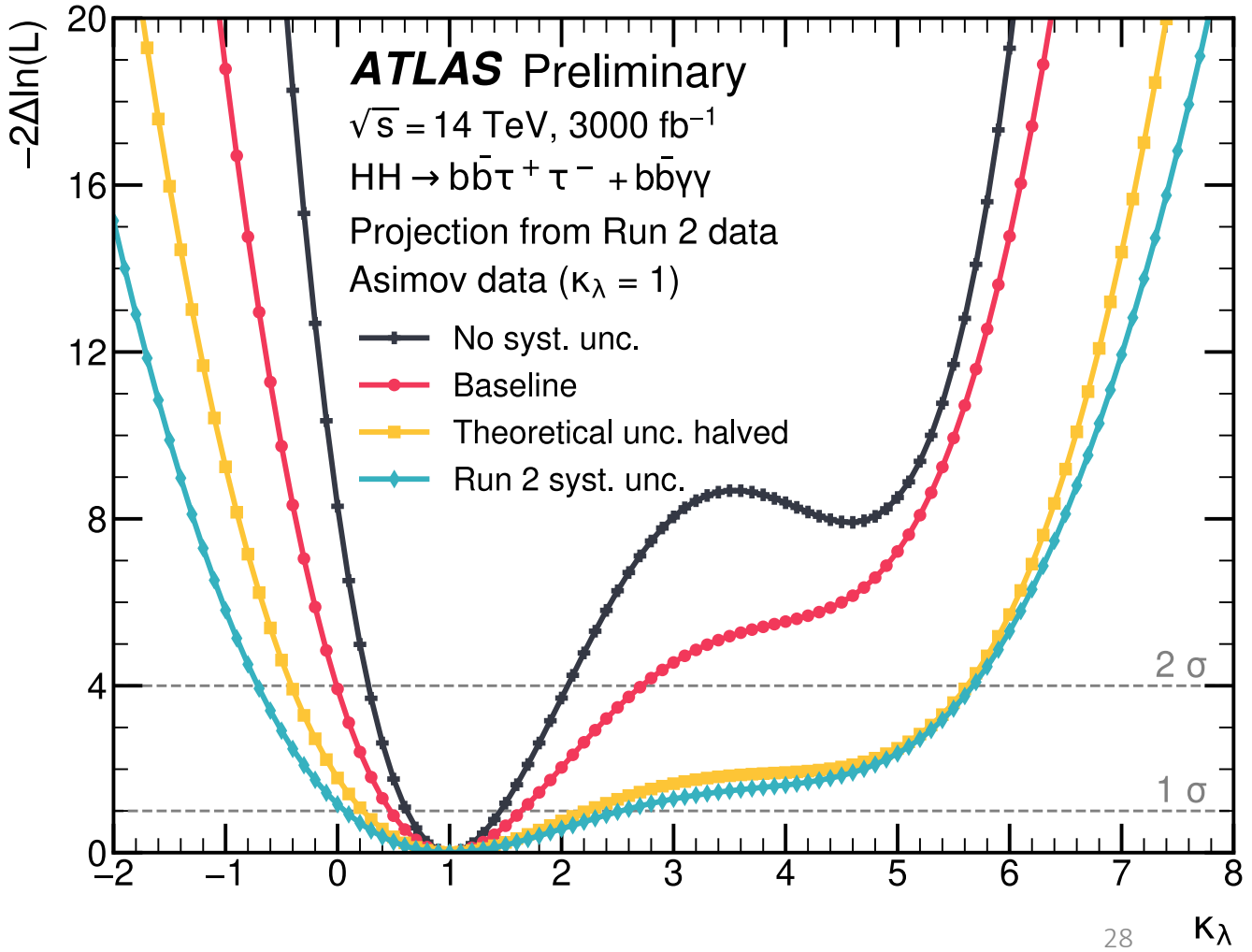


Interpretation:
If HH signal present at these k_λ values, expect to measure the signal with the shown significance.

Likelihood Scan - Combined

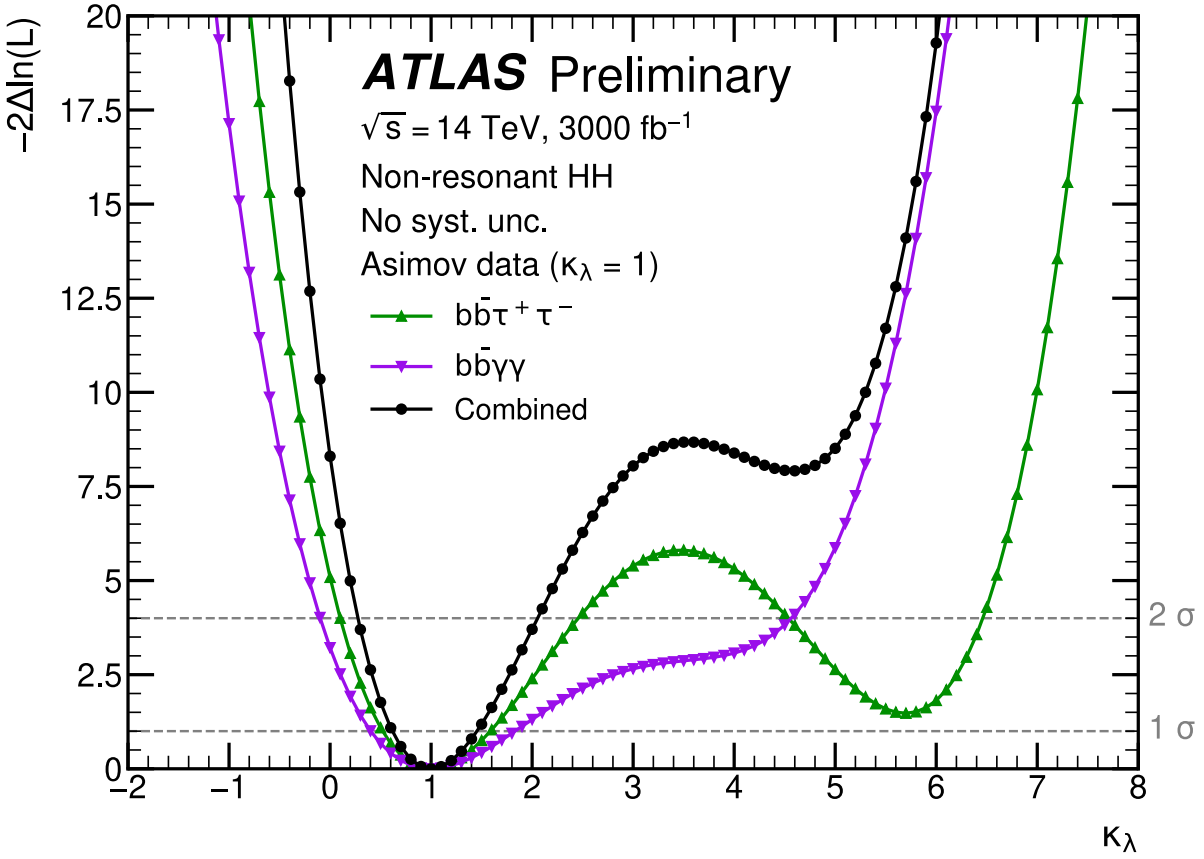
Negative log of the likelihood ratio comparing different k_λ hypotheses to an Asimov dataset constructed with $k_\lambda = 1$

Uncertainty scenario	Likelihood scan 1σ CI	Likelihood scan 2σ CI
No systematic uncertainties	[0.6, 1.5]	[0.3, 2.1]
Baseline	[0.5, 1.6]	[0.0, 2.7]
Theory uncertainties halved	[0.2, 2.2]	[−0.4, 5.6]
Run-2 systematic uncertainties	[0.1, 2.5]	[−0.7, 5.7]

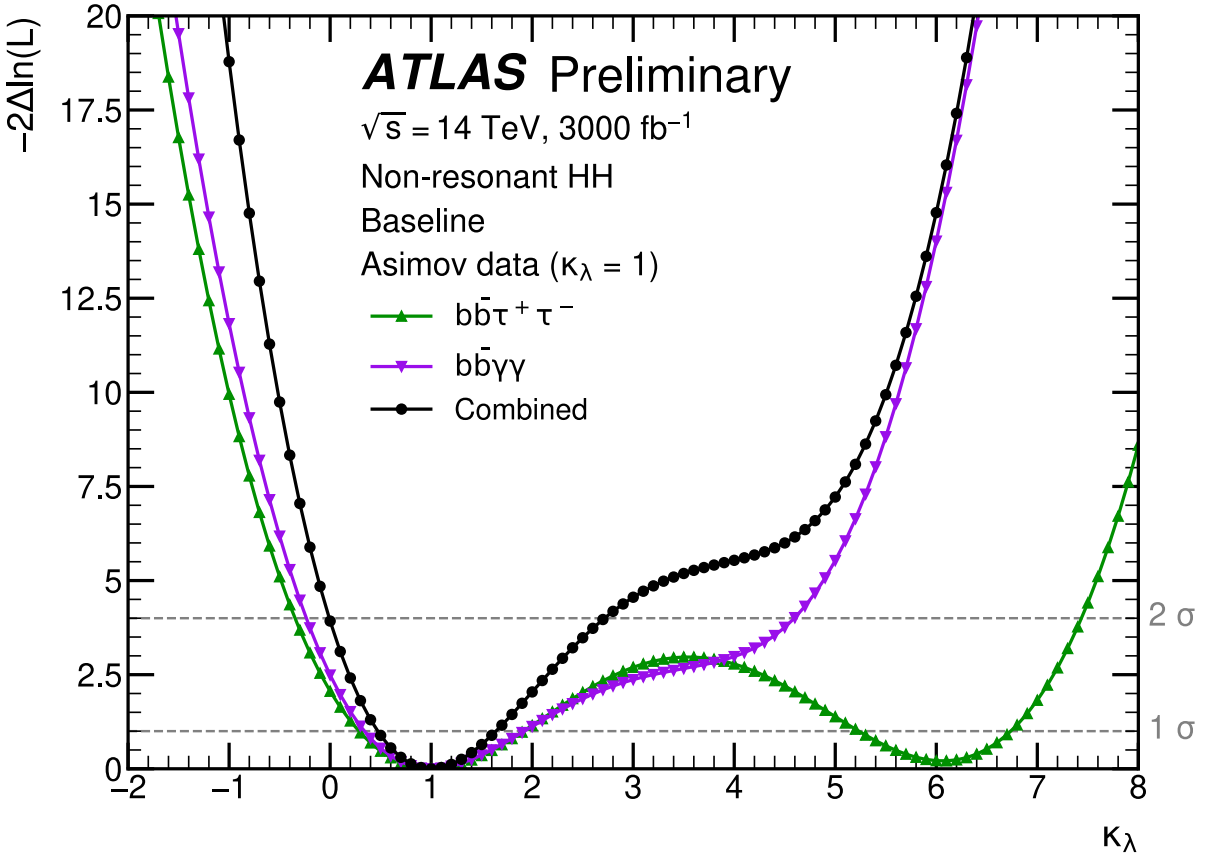


Likelihood Scan – Different Scenarios

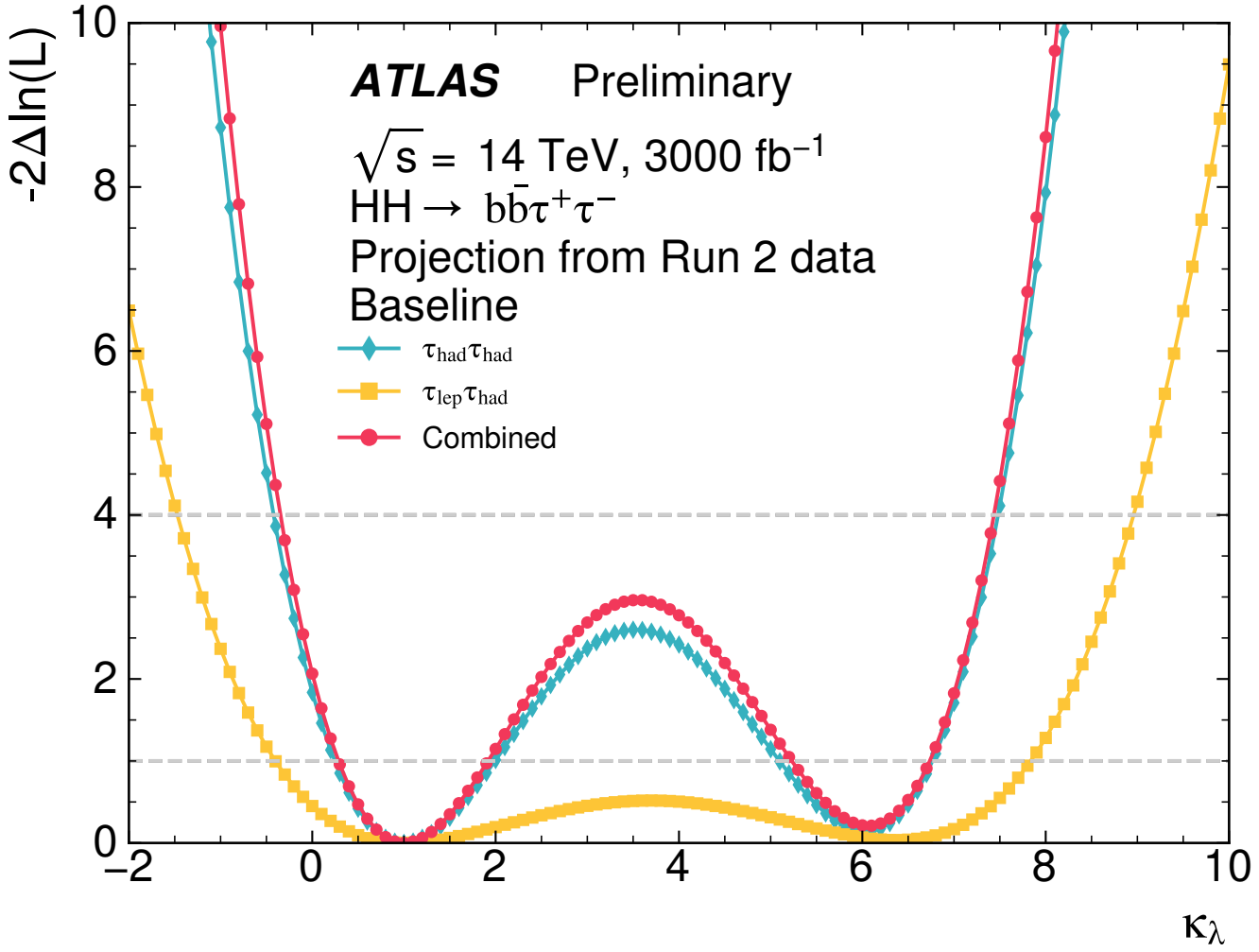
No Systematics



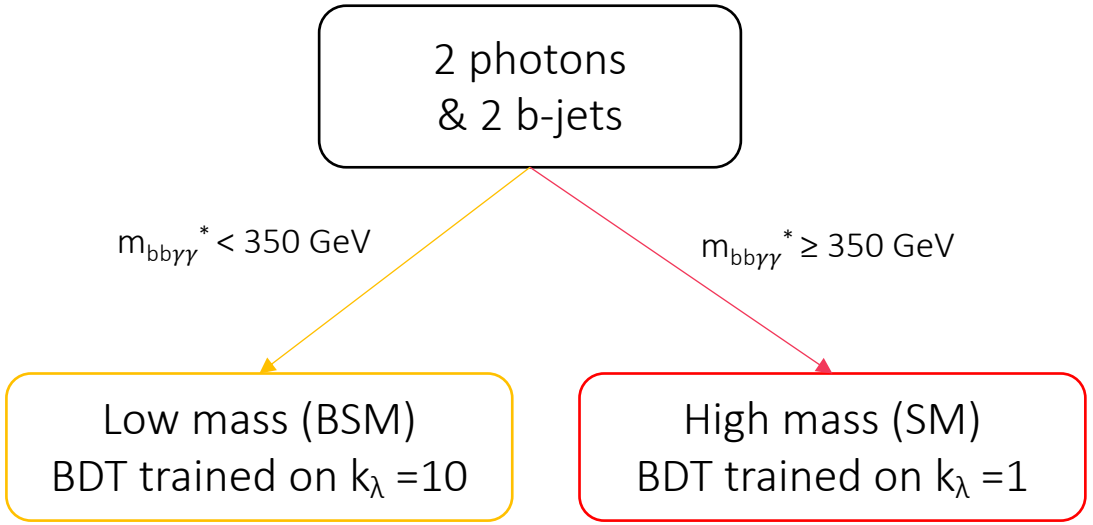
Baseline

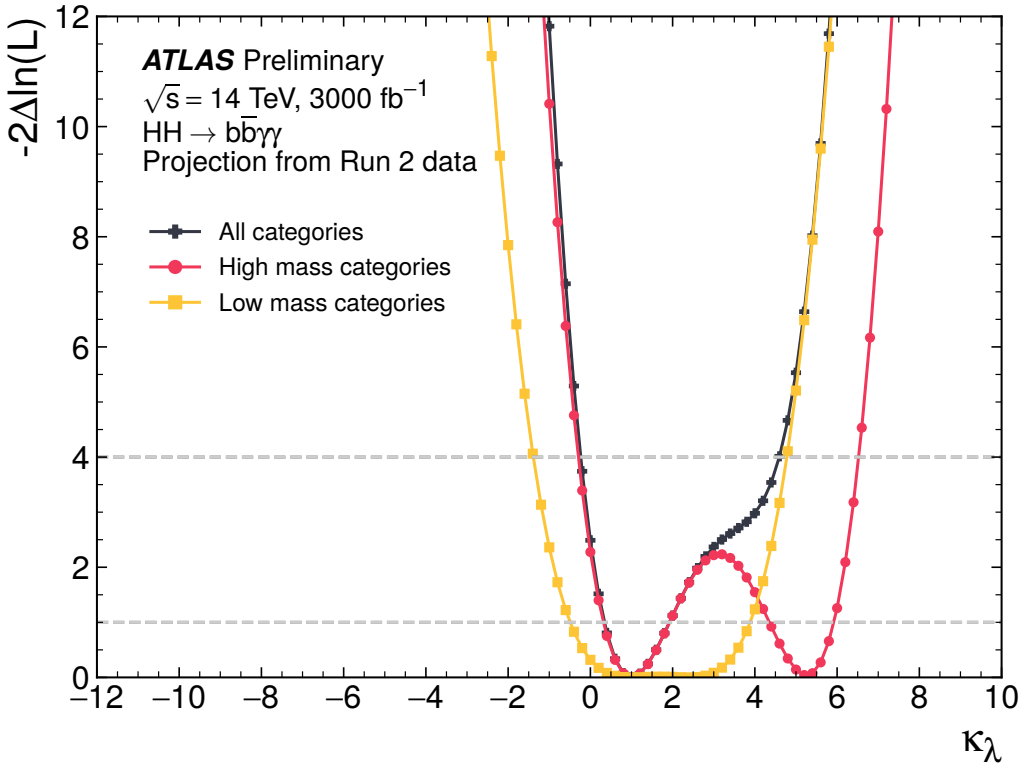


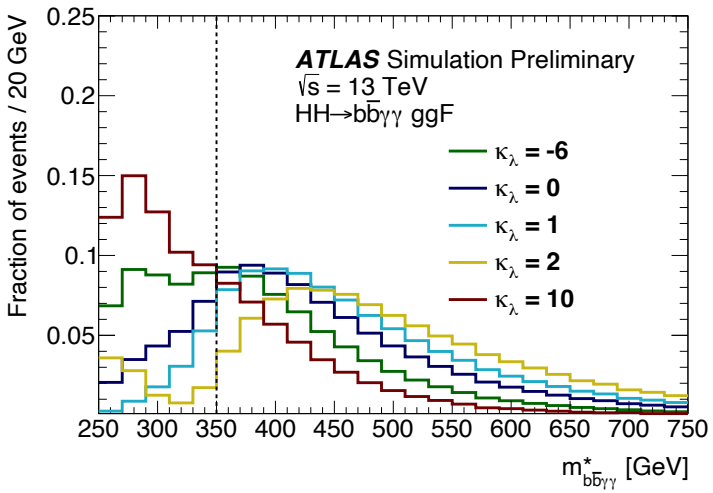
Effect of Different Channels - bbττ



Effect of Different Analysis Categories - bb$\gamma\gamma$

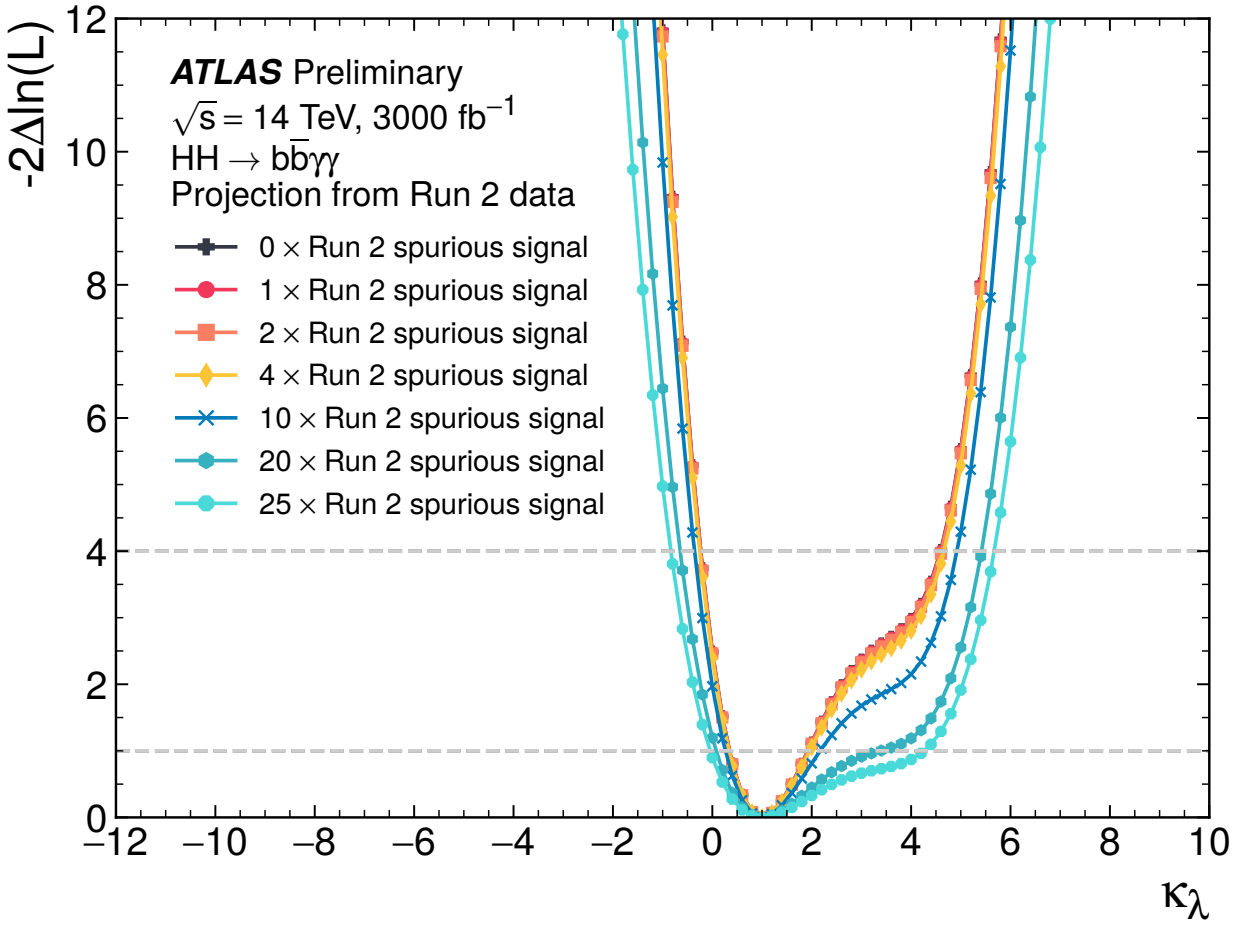






$m_{bb\gamma\gamma}^{*} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV

Spurious Signal Studies - bb$\gamma\gamma$



Spurious signal scaling	Effect on Baseline combined significance
0x	0
4x	<1%
25x	<10%

Single Higgs + HH κ_λ

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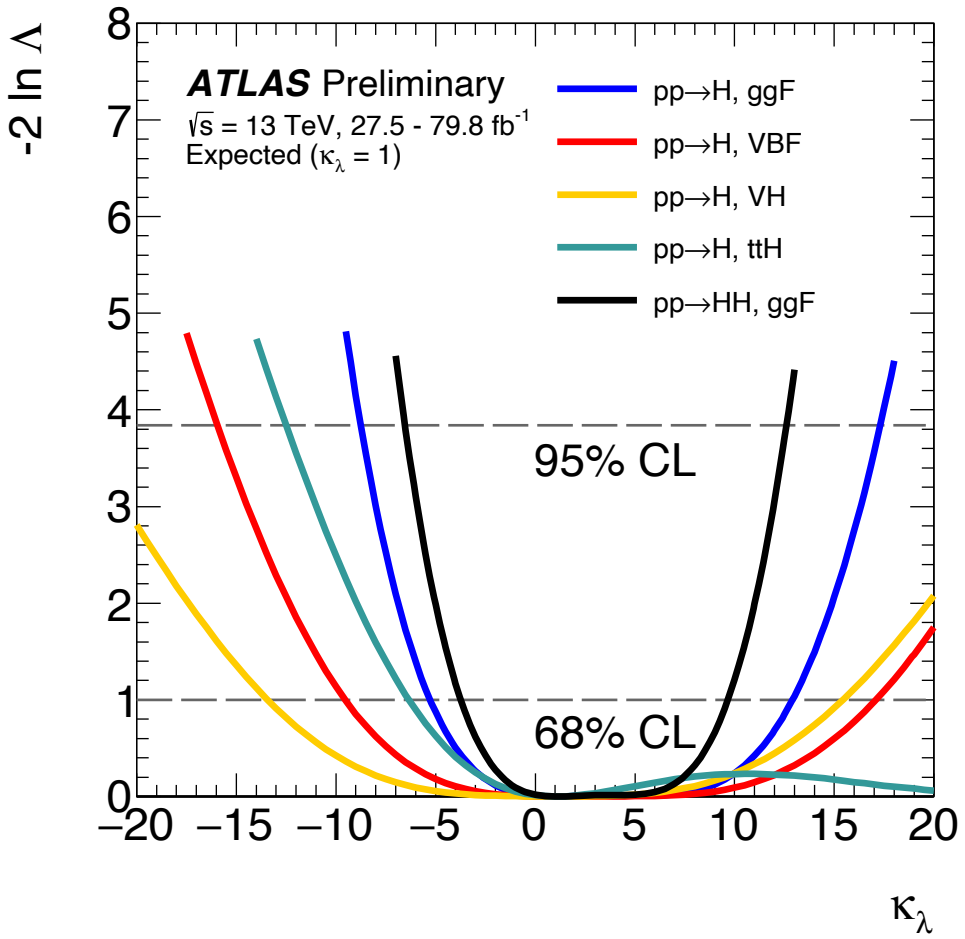
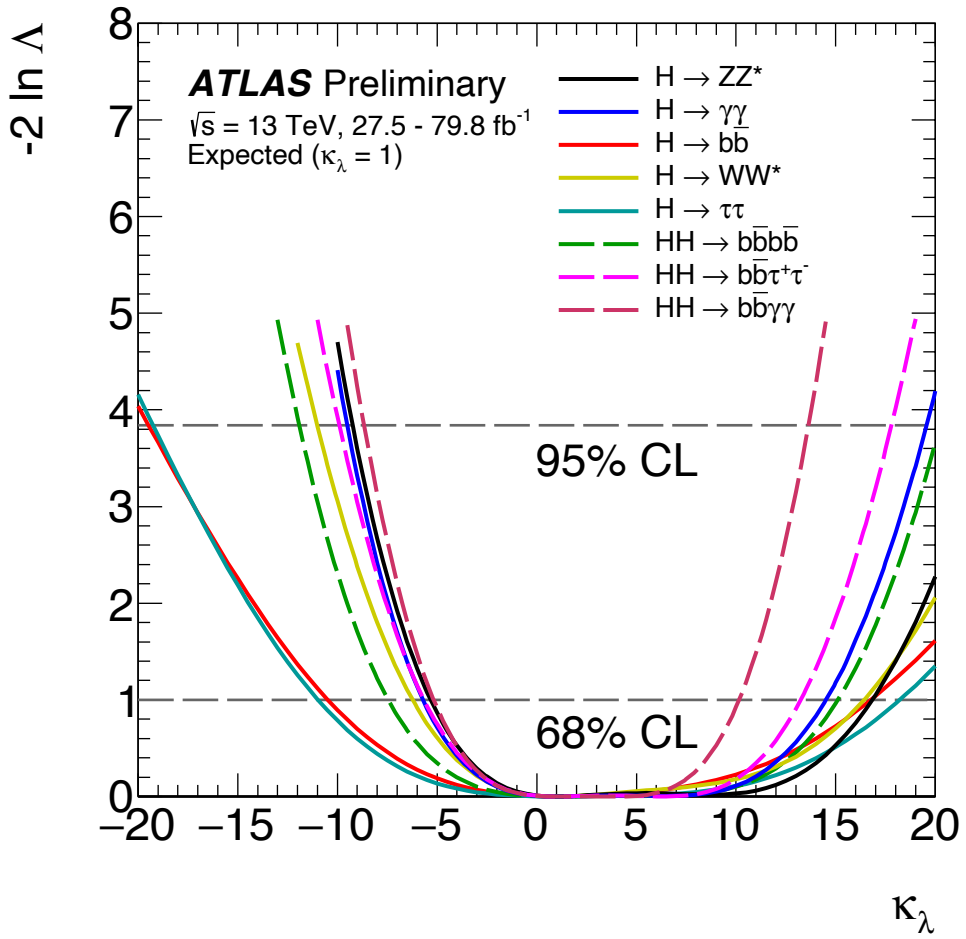
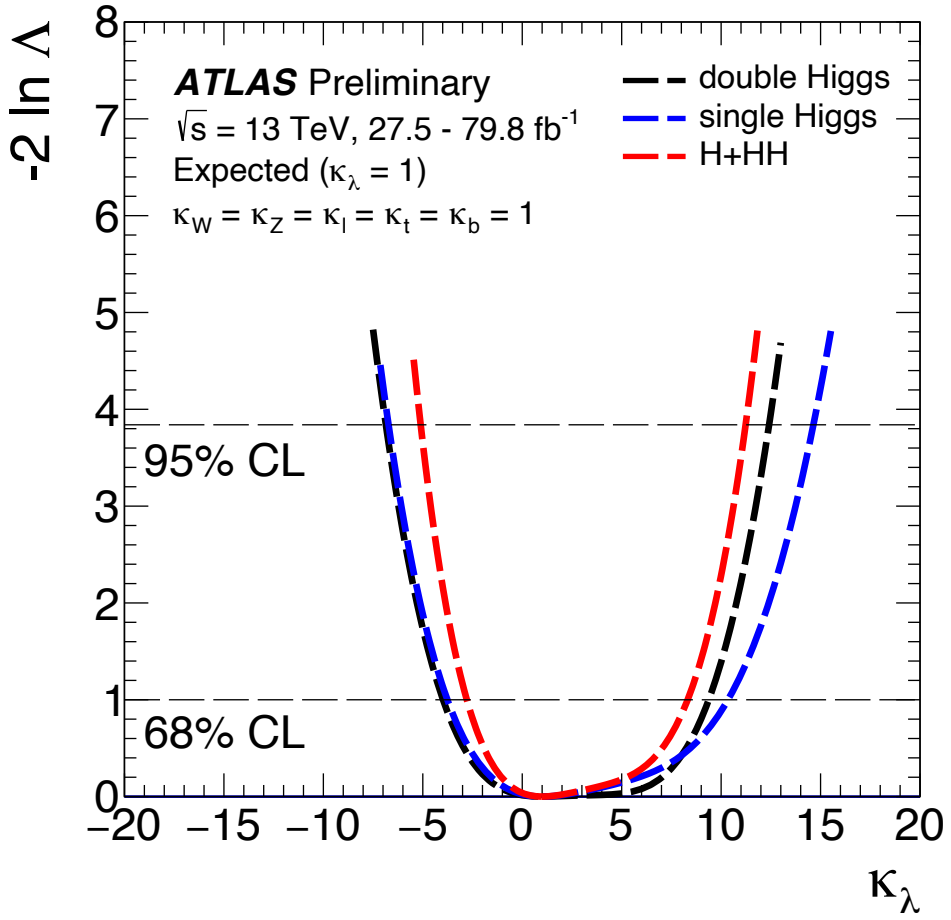
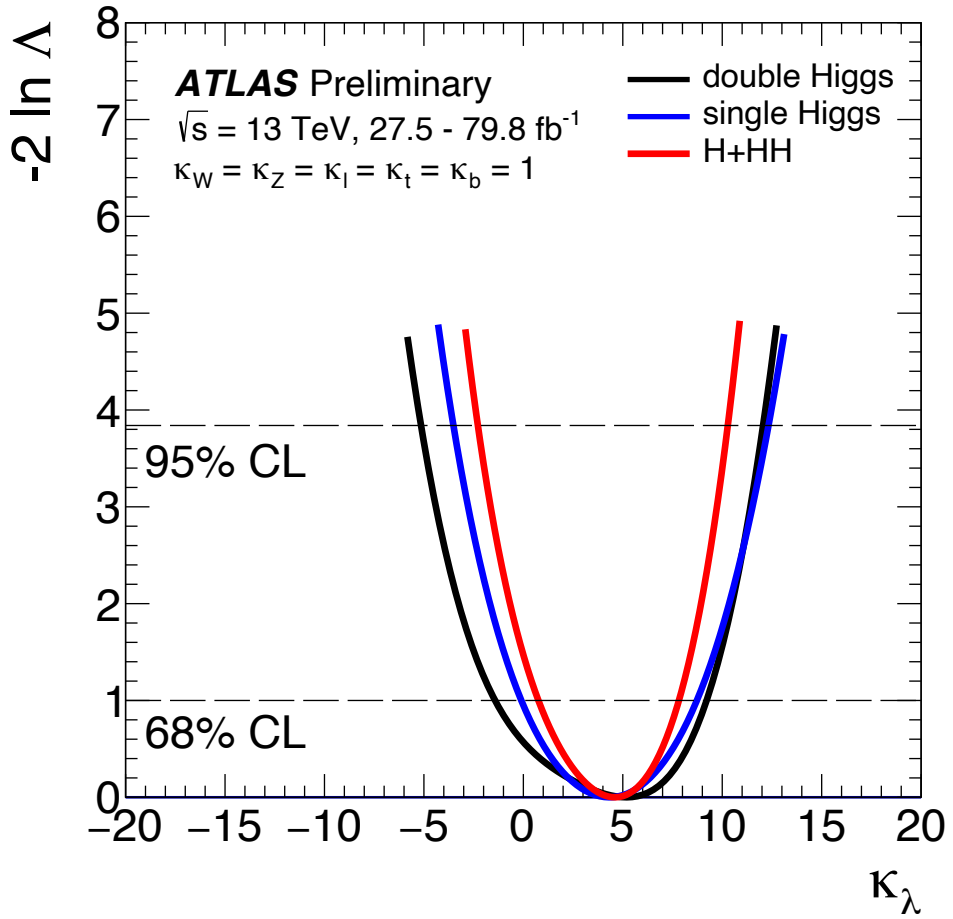




Single Higgs + HH κ_λ

ATLAS-CONF-2019-049





Dominant Systematic Uncertainties bb$\gamma\gamma$ - Full Run 2

Variation on the upper limit on the signal strength when re-evaluating the profile likelihood ratio after fixing the nuisance parameter in question to its best-fit value increased or decreased by one standard deviation, while all remaining nuisance parameters remain free to float.

		Relative impact of the systematic uncertainties in %	
Source	Type	Non-resonant analysis HH	Resonant analysis $m_X = 300$ GeV
Experimental			
Photon energy scale	Norm. + Shape	5.2	2.7
Photon energy resolution	Norm. + Shape	1.8	1.6
Flavor tagging	Normalization	0.5	< 0.5
Theoretical			
Heavy flavor content	Normalization	1.5	< 0.5
Higgs boson mass	Norm. + Shape	1.8	< 0.5
PDF+α_s	Normalization	0.7	< 0.5
Spurious signal	Normalization	5.5	5.4

Dominant Uncertainties bbττ - Full Run 2

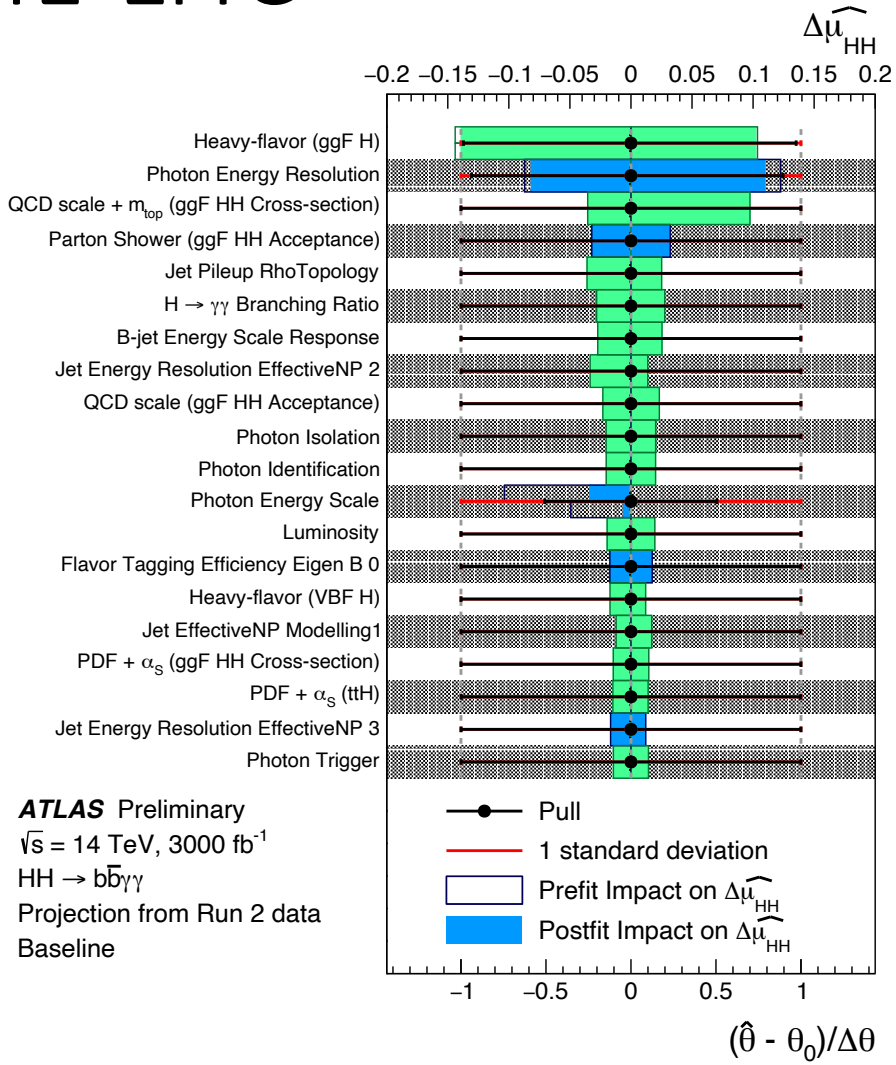
Relative contributions to the uncertainty in the extracted signal cross-sections, as determined in the likelihood fit to data.

Uncertainty source	Non-resonant HH
Data statistical	81%
Systematic	59%
$t\bar{t}$ and $Z+\text{HF}$ normalisations	4%
MC statistical	28%
Experimental	
Jet and $E_{\text{T}}^{\text{miss}}$	7%
b-jet tagging	3%
$\tau_{\text{had-vis}}$	5%
Electrons and muons	2%
Luminosity and pileup	3%
Theoretical and modelling	
Fake-$\tau_{\text{had-vis}}$	9%
Top-quark	24%
$Z(\rightarrow \tau\tau)+\text{HF}$	9%
Single Higgs boson	29%
Other backgrounds	3%
Signal	5%

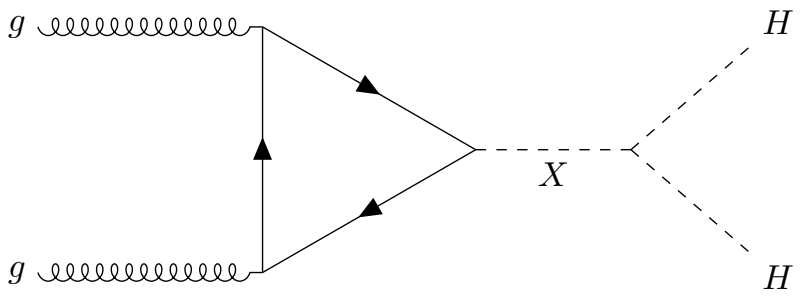
Dominant Systematics @ HL-LHC

Theory uncertainties:
- ggF H (in association with b, or c)
- Wt tt interference (bbττ)
- ggF HH cross-section

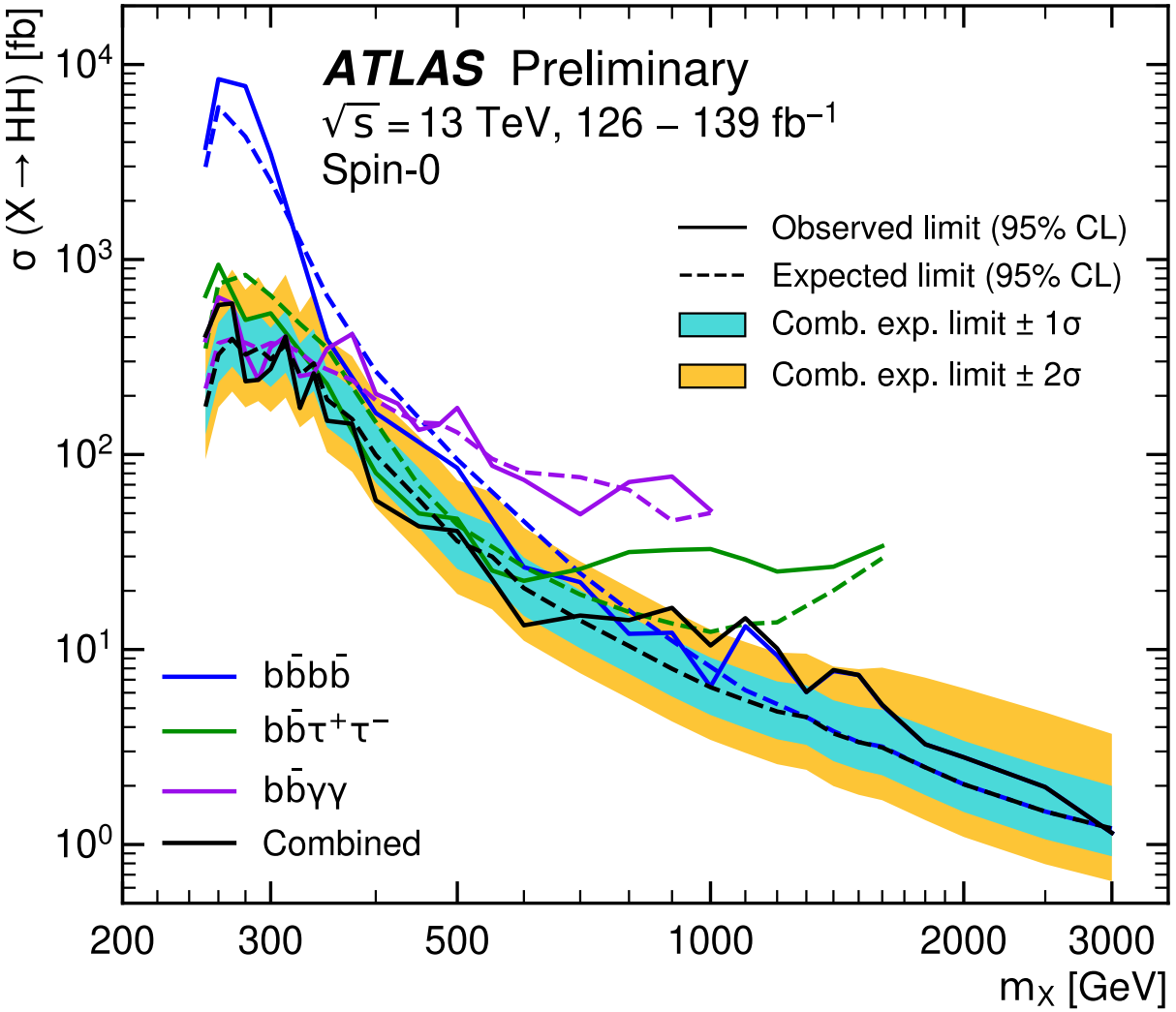
Experimental uncertainties
- MC statistical uncertainties (bbττ)
- Spurious signal, background modelling (bb$\gamma\gamma$)
- Photon energy resolution



Resonant Run 2 Combined Results

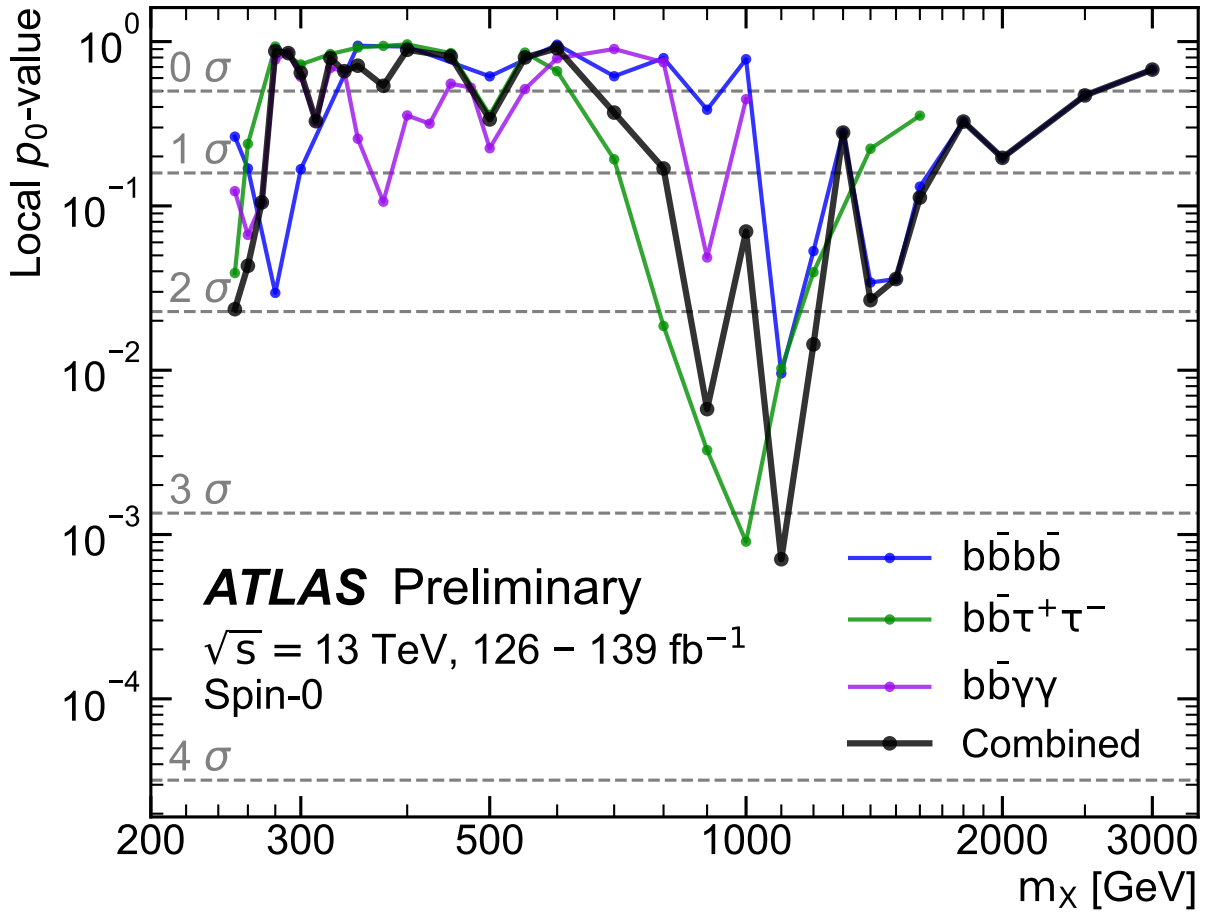


Discontinuity in region $m_X < 400$ GeV is due to partial availability of limits across all analyses. bb$\gamma\gamma$ is the only analysis to provide limits at certain low resonance mass points.



Combination - ATLAS-CONF-2021-052
https://cds.cern.ch/record/2786865

Resonant Run 2 Combination - Largest Excess



Largest excess in m_X in ~1100 GeV region

At m_X = 1100 GeV:
Local significance = 3.2 σ
Global significance = 2.1 σ

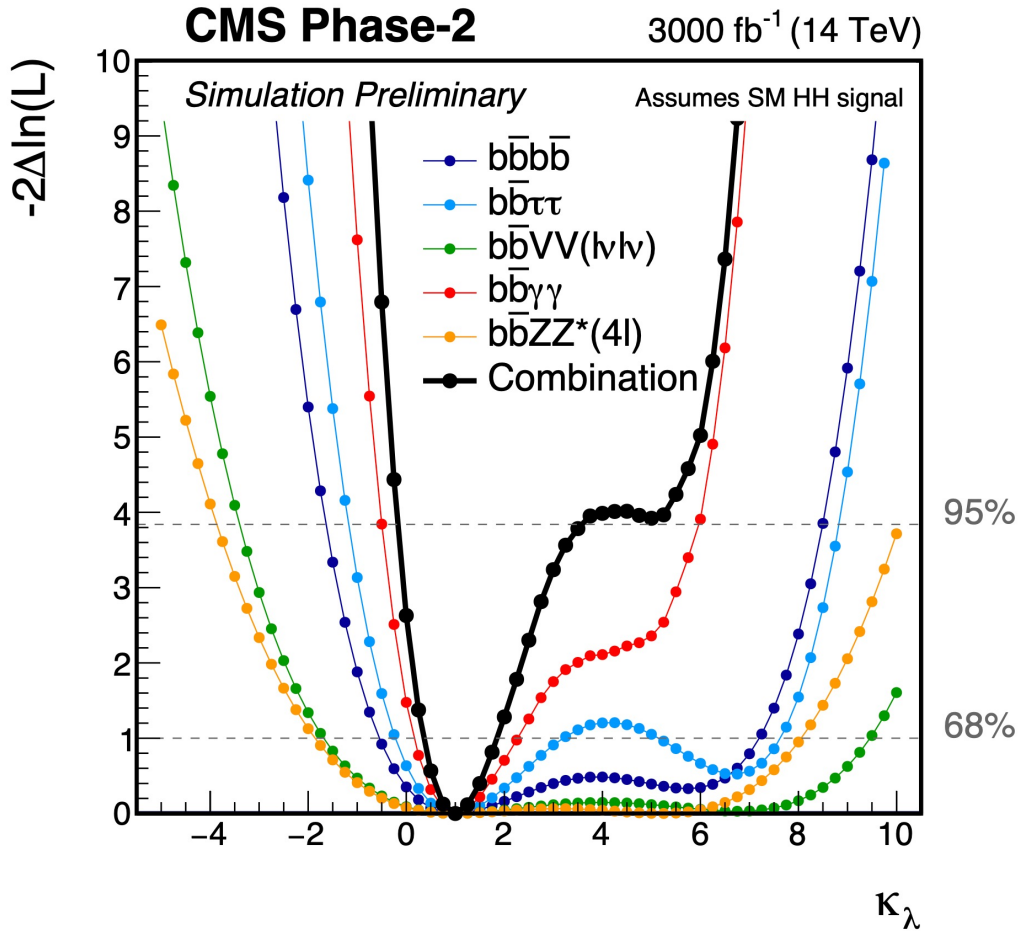
Combination - ATLAS-CONF-2021-052
https://cds.cern.ch/record/2786865

Conclusions and outlook for the future:

From Yellow Report: https://arxiv.org/abs/1902.00134

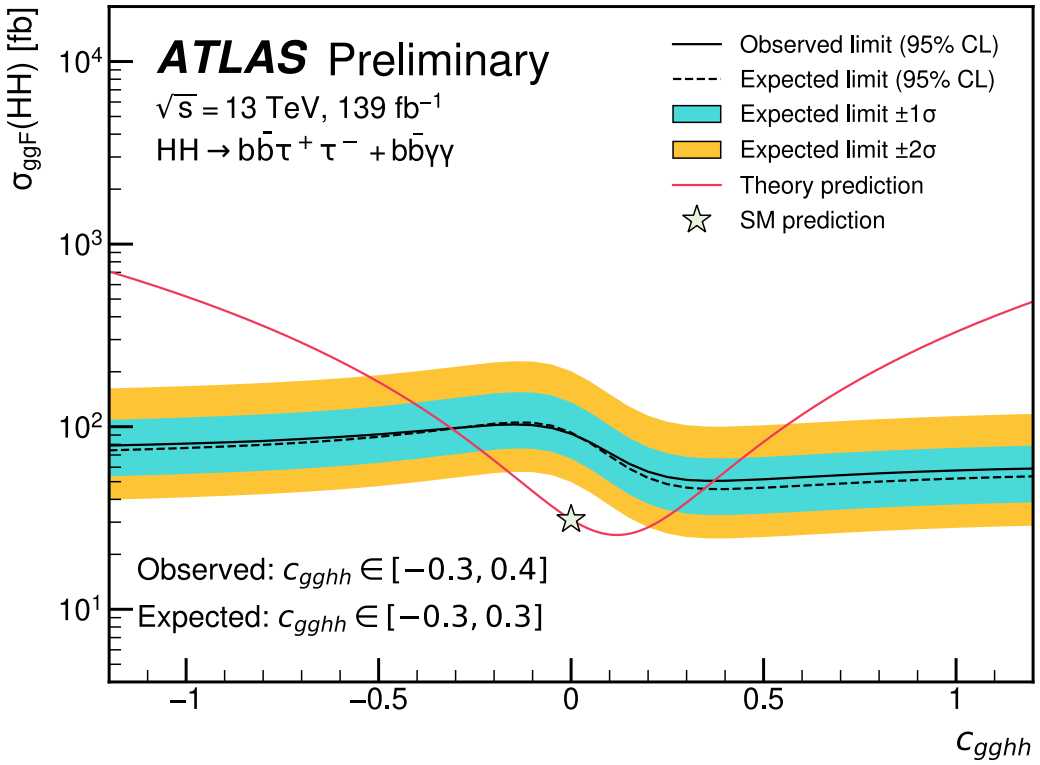
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6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

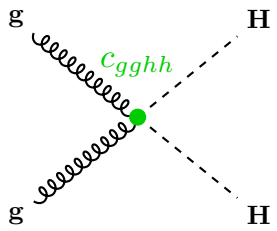
Our latest result improves on this significance with just two channels!

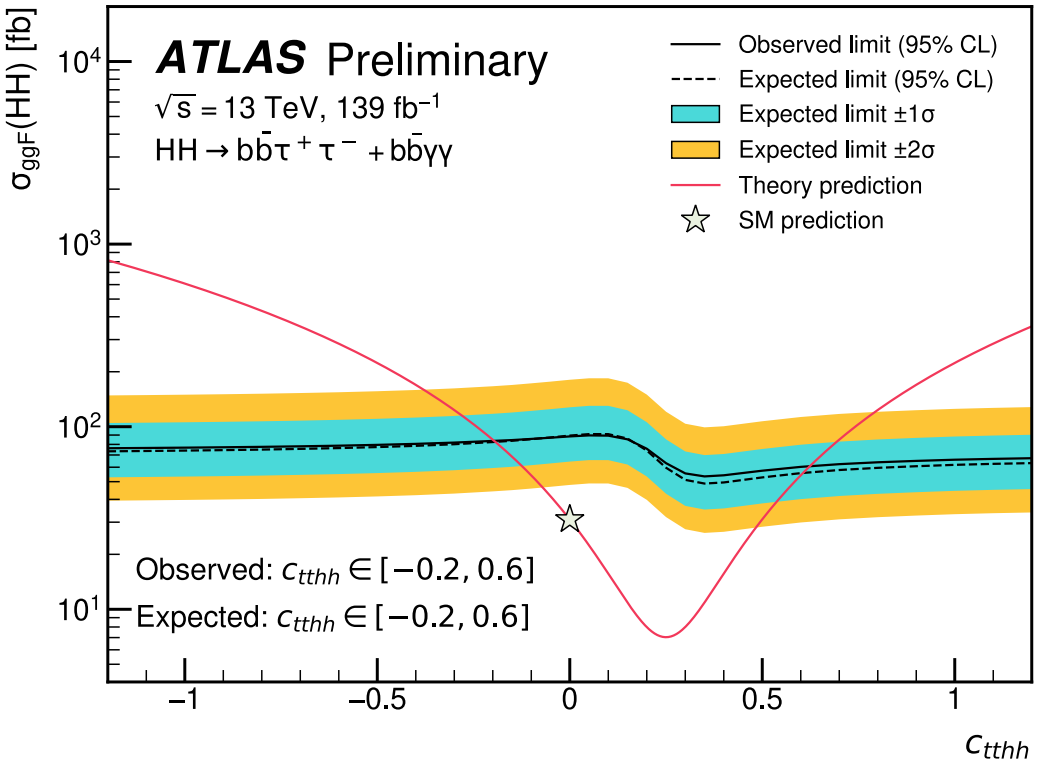


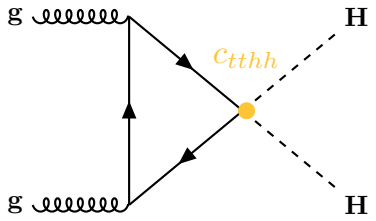
HEFT Interpretations

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-021/









HEFT Interpretations

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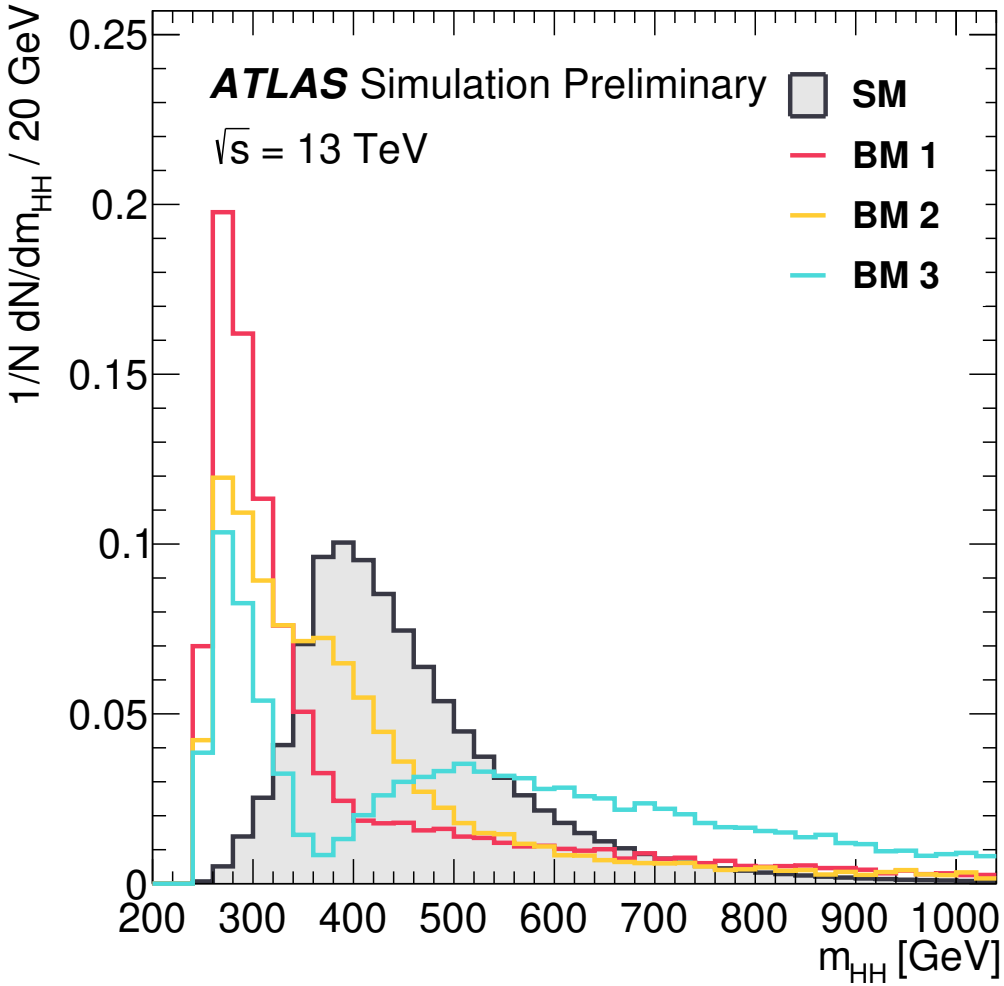

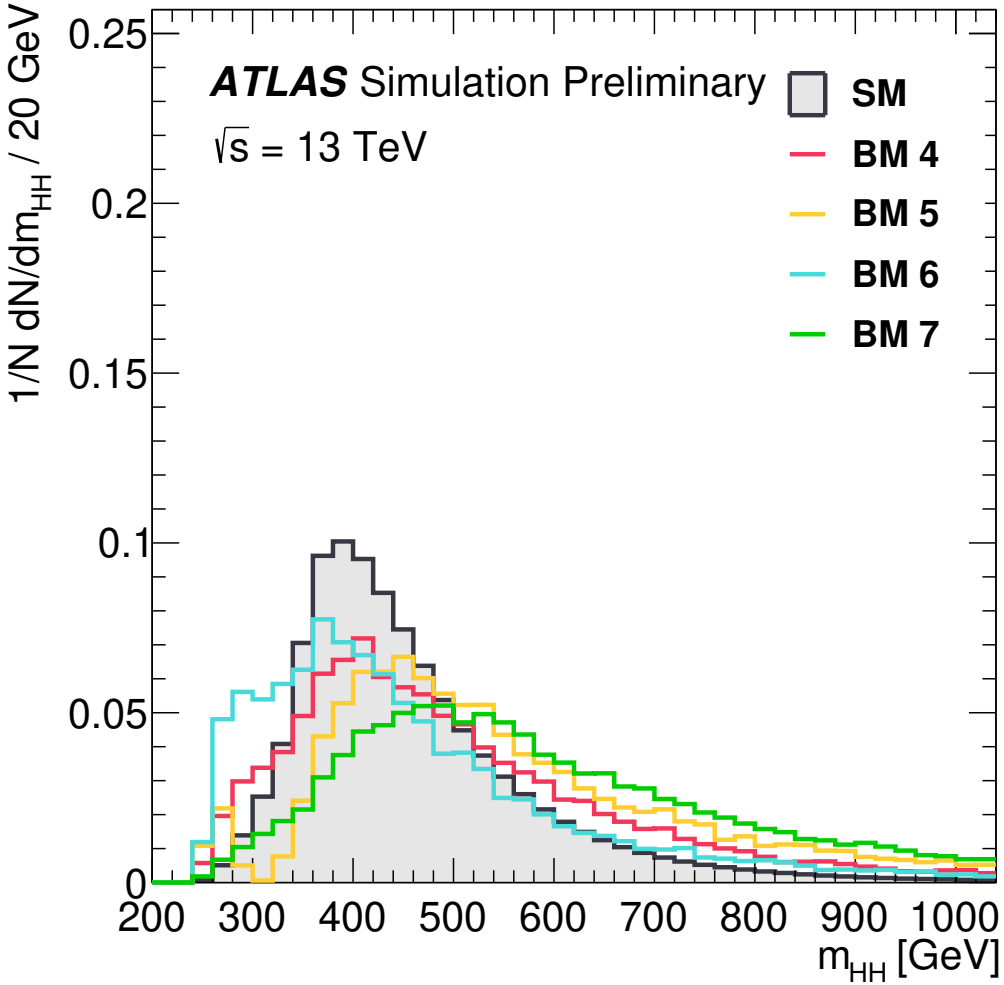

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