HL-LHC Expected Physics Reach with ATLAS

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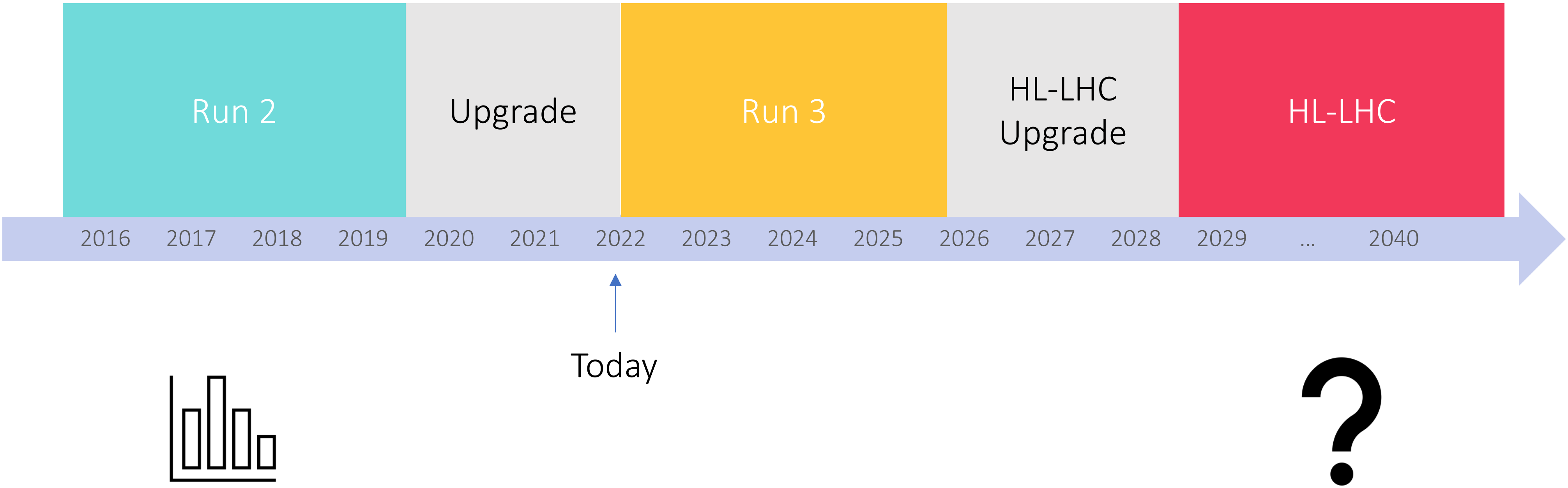
SLACMass, May 12th, 2022

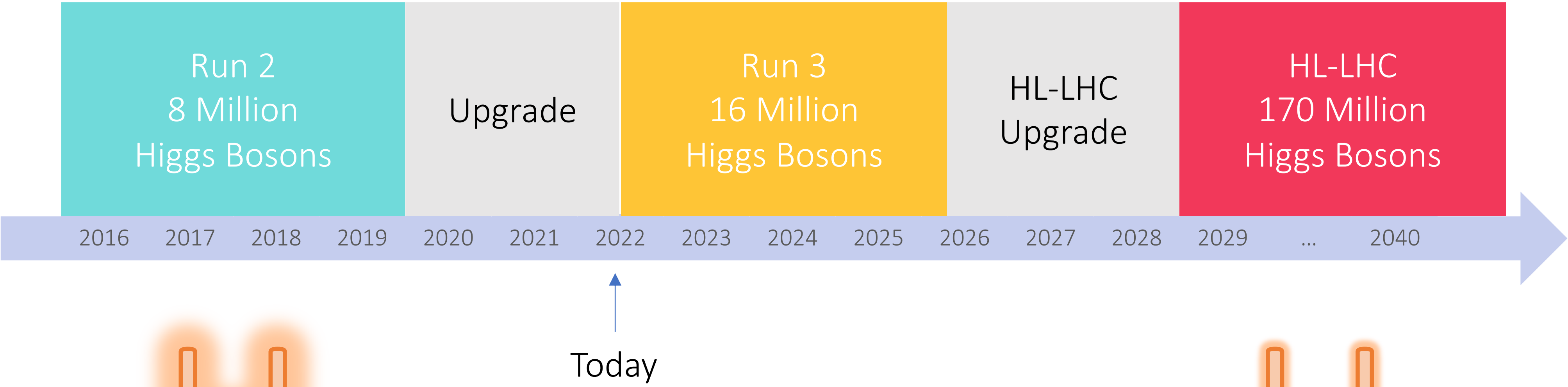
ATLAS EXPERIMENT

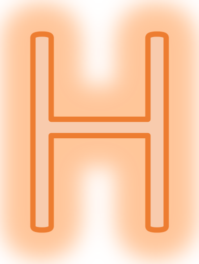
SLAC NATIONAL ACCELERATOR LABORATORY

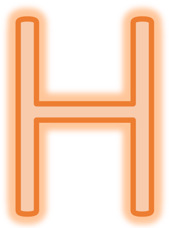
HL-LHC Timeline



HL-LHC Timeline



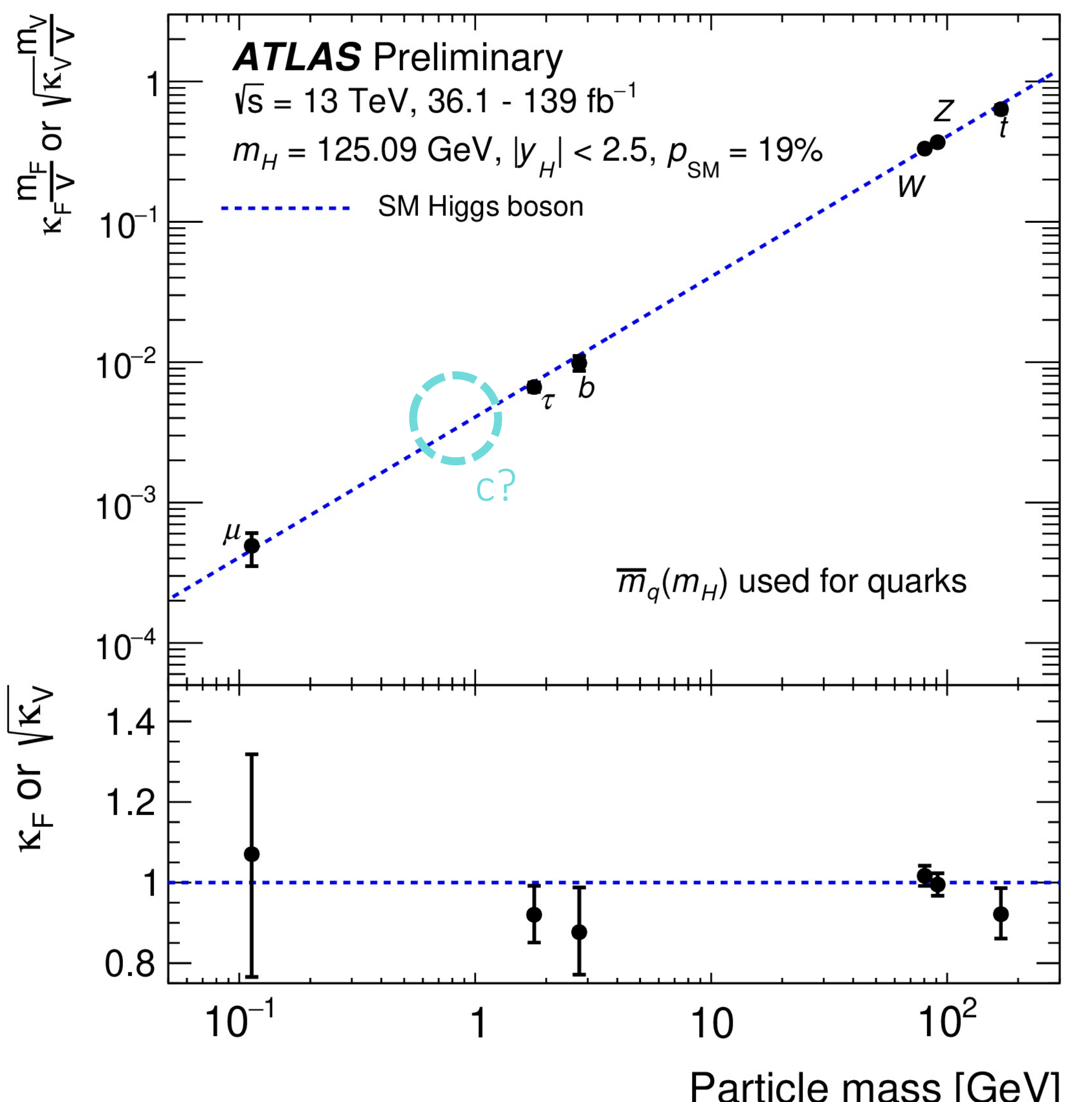




HL-LHC will bring the Higgs into focus

Why are we excited about HL-LHC?

ATLAS-CONF-2021-053



More data!

Will allow us to focus in on many measurements including getting a clearer picture of the Higgs.

Additional data will allow us to improve precision, *especially* in statistically limited arenas.

E.g.

- Higgs coupling to charm

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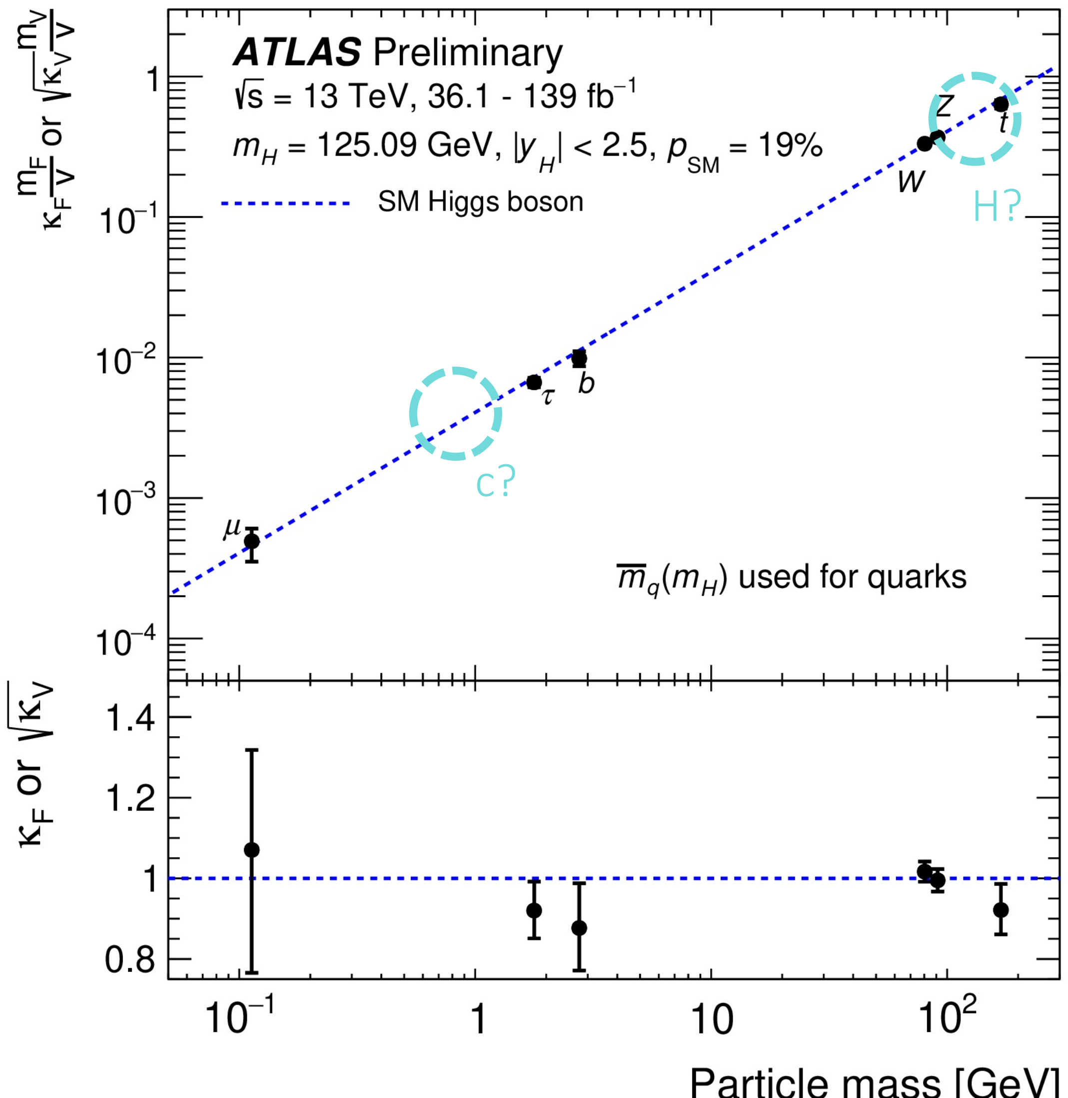
- Higgs self-coupling

ATLAS-CONF-2021-053



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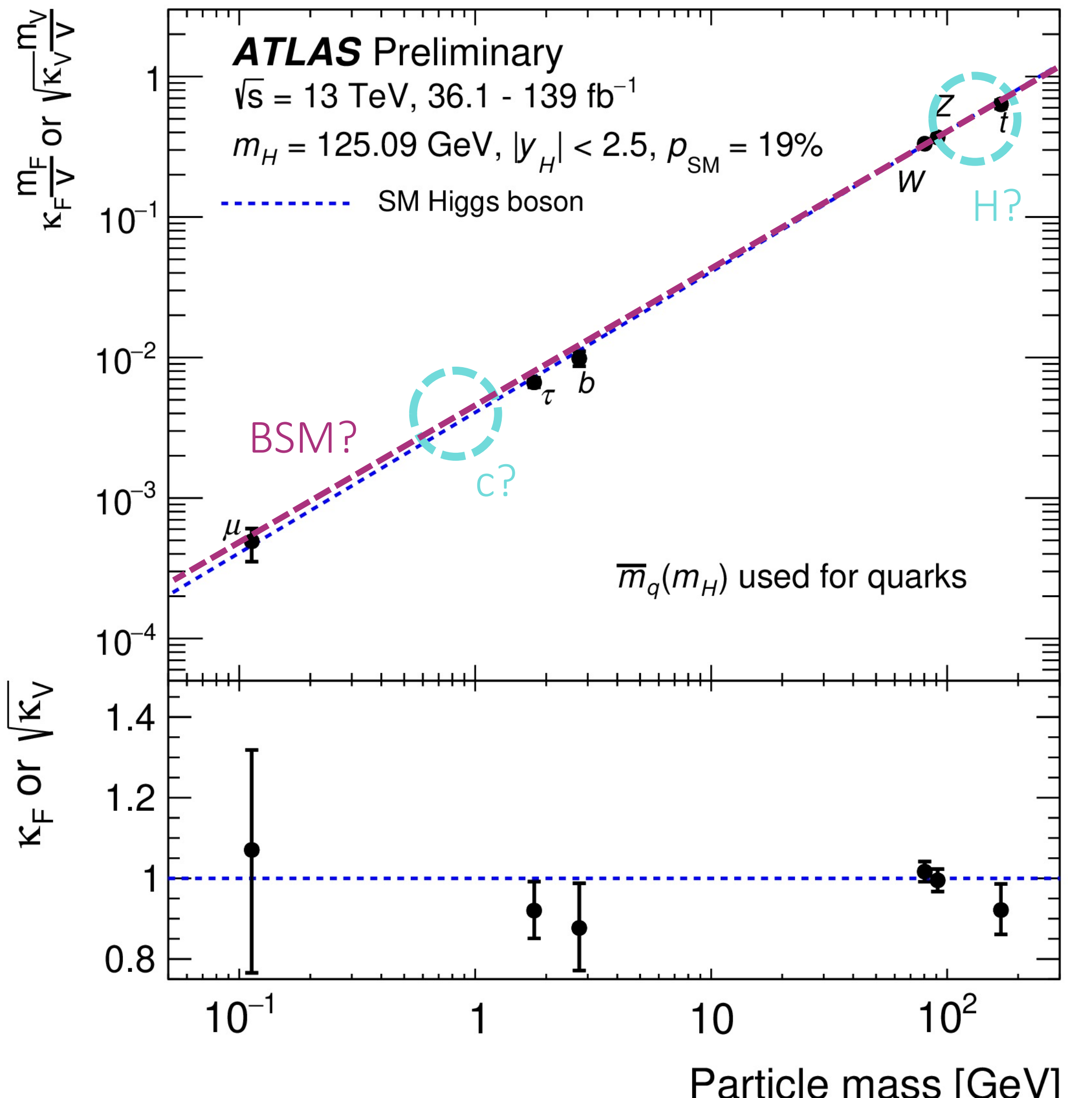
E.g.

- Higgs coupling to charm
- Higgs self-coupling
- BSM effects

ATLAS-CONF-2021-053



HL-LHC Projections

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

Typically, a few systematic uncertainty scenarios scaled as follows:

Statistical Uncertainties	$\propto 1/\sqrt{L}$
Experimental Uncertainties	$\propto 1/\sqrt{L}$ Until floor reached
Theoretical Uncertainties	x 0.5

Projections updated as new Run 2 results come out.

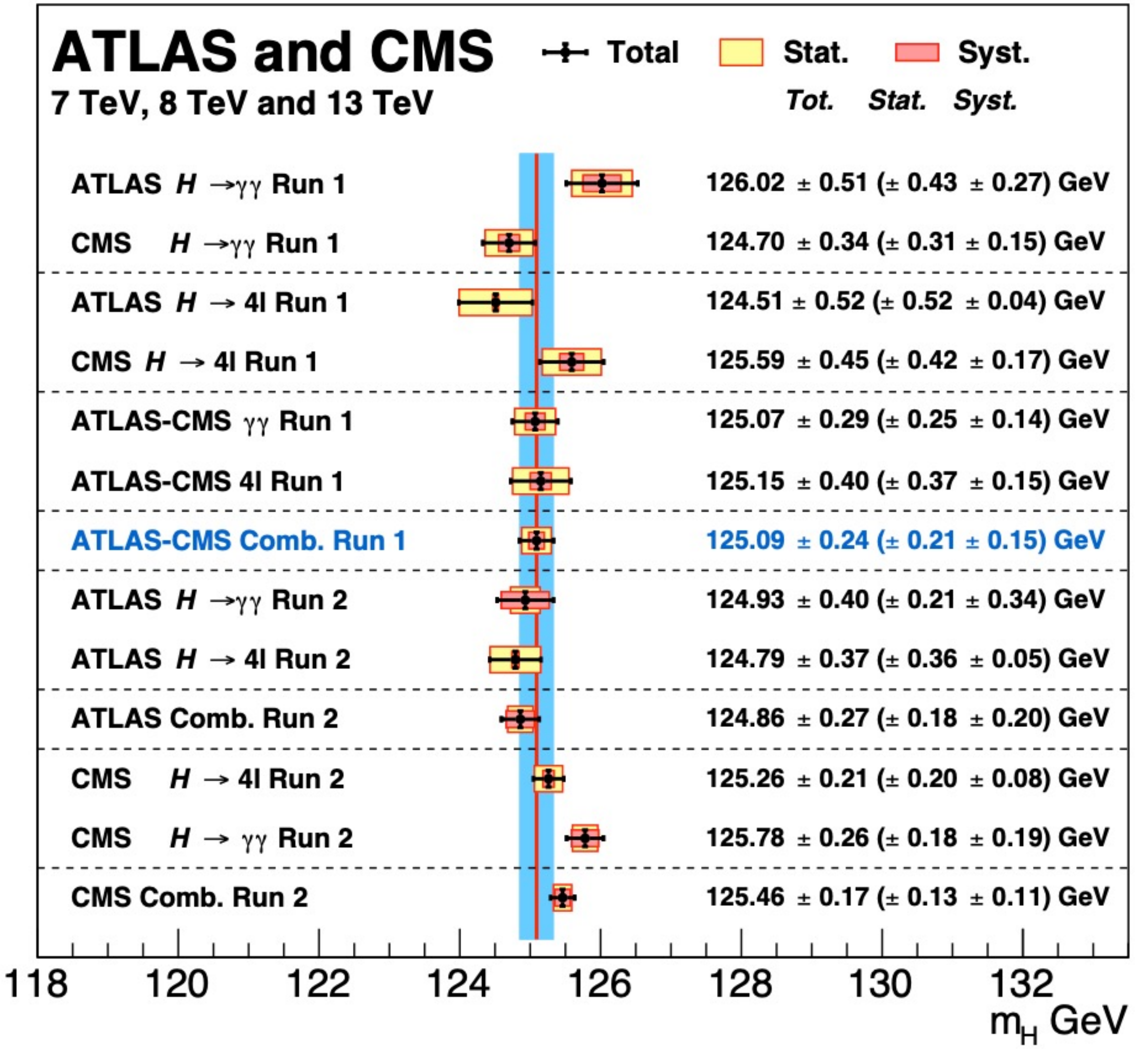
https://pdg.lbl.gov/2020/reviews/rpp2020-rev-higgs-boson.pdf

Higgs Mass & Width

Main precision channels: $H \to \gamma\gamma \quad H \to ZZ \to 4\ell$

Precision expected to improve from ~0.2 GeV to ~0.03 GeV

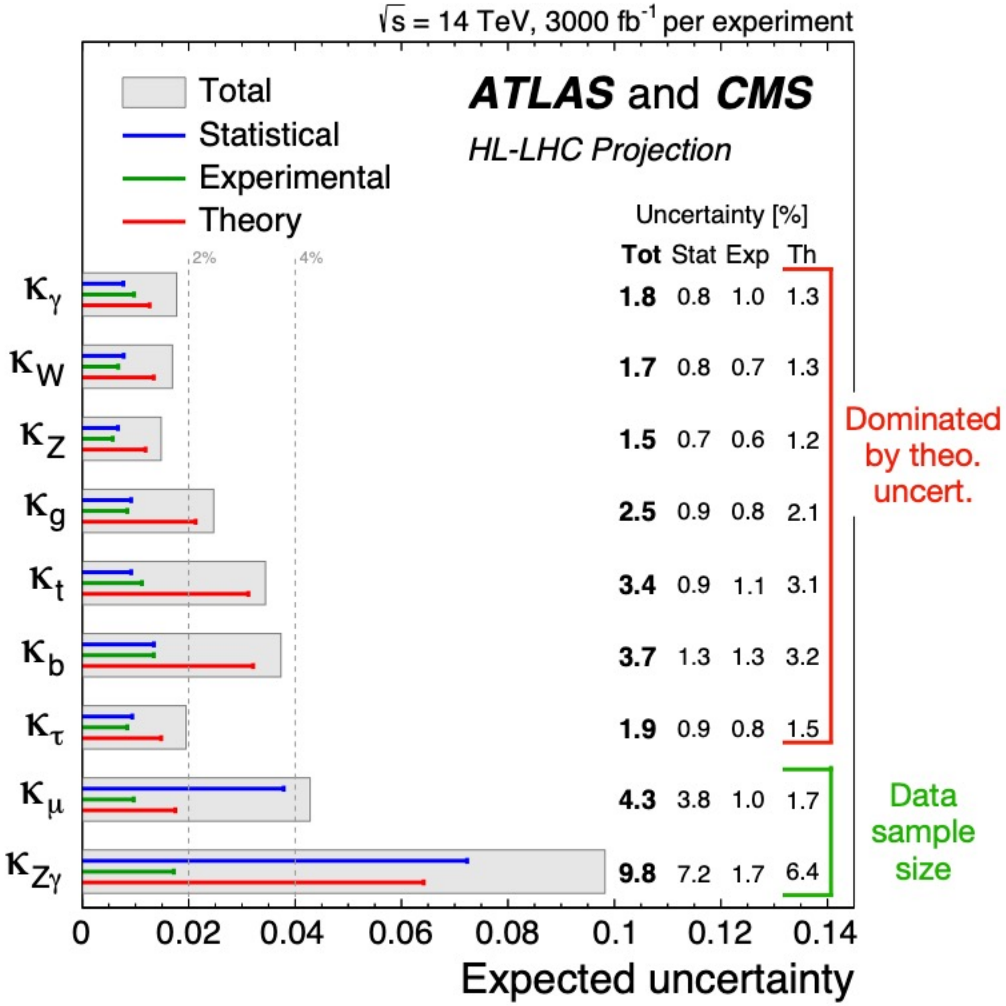
ATLAS-PHYS-PUB-2022-018/ CMS-PAS-FTR-22-001
https://cds.cern.ch/record/2805993



HL-LHC ATLAS & CMS projected uncertainties on m_H ~ 0.03 GeV!

Higgs width measurement expected to reach ~5% uncertainty through indirect measurements

Higgs Coupling Measurements



Expect 2-5% precision on most Higgs couplings.

Theory uncertainties dominate in many measurements. Some of the common ones are:

- QCD scale uncertainties
- PDF + $alpha_s$
- Parton shower
- Higgs + heavy flavour

Measurements that will benefit the most from HL-LHC are those that are statistically limited.

Cross-Section Measurements – ATLAS latest

$\Delta\sigma/\sigma[\%]$

<table>
<tr><th></th><th>ggF</th><th>VBF</th><th>WH</th><th>ZH</th><th>ttH (+tH)</th></tr>
<tr><td>$\gamma\gamma$</td><td>11.0</td><td>27.0</td><td colspan="2">33.0</td><td>27.0</td></tr>
<tr><td>ZZ</td><td>11.0</td><td>51.0</td><td colspan="2">117.0</td><td>169.0</td></tr>
<tr><td>WW</td><td>13.0</td><td>19.0</td><td></td><td></td><td>65.0</td></tr>
<tr><td>$\tau\tau$</td><td>28.0</td><td>20.0</td><td colspan="2">59.0</td><td>86.0</td></tr>
<tr><td>bb</td><td colspan="2">38.0</td><td>28.0</td><td>24.0</td><td>34.0</td></tr>
<tr><td>$\mu\mu$</td><td>91.0</td><td>134.0</td><td></td><td></td><td></td></tr>
<tr><td>cc</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$Z\gamma$</td><td></td><td></td><td></td><td></td><td></td></tr>
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Data from ATLAS-CONF-2021-053

Cross-Section Measurements – HL-LHC ATLAS+CMS

$\Delta\sigma/\sigma[\%]$

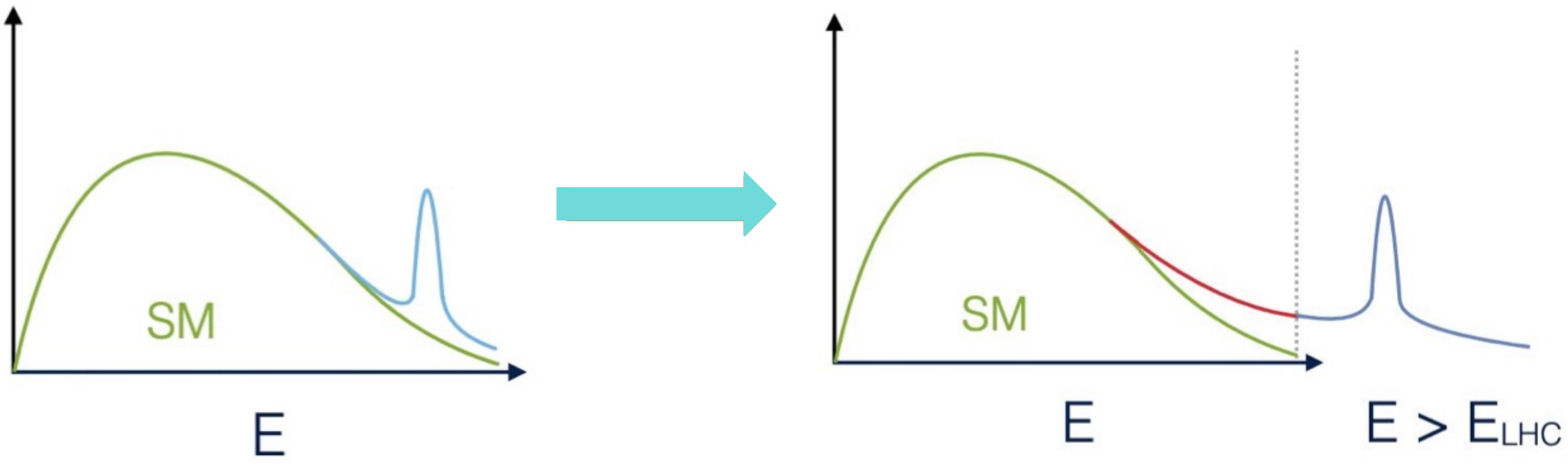
	ggF	VBF	WH	ZH	ttH
$\gamma\gamma$	2.5	7.9	9.9	13.2	5.9
ZZ	2.5	9.5	13.0		15.2
WW	2.5	5.5	9.9	12.8	6.6
$\tau\tau$	4.5	3.9	10.0 (ATLAS)		10.7
bb	19.0		8.3	4.6	10.2
$\mu\mu$	7.0 (CMS)				
cc			80.0 (CMS)		
$Z\gamma$	24.0	51.2			

rare processes ($\mu\mu$, cc, $Z\gamma$)

New for Snowmass!

Data from Snowmass EF04

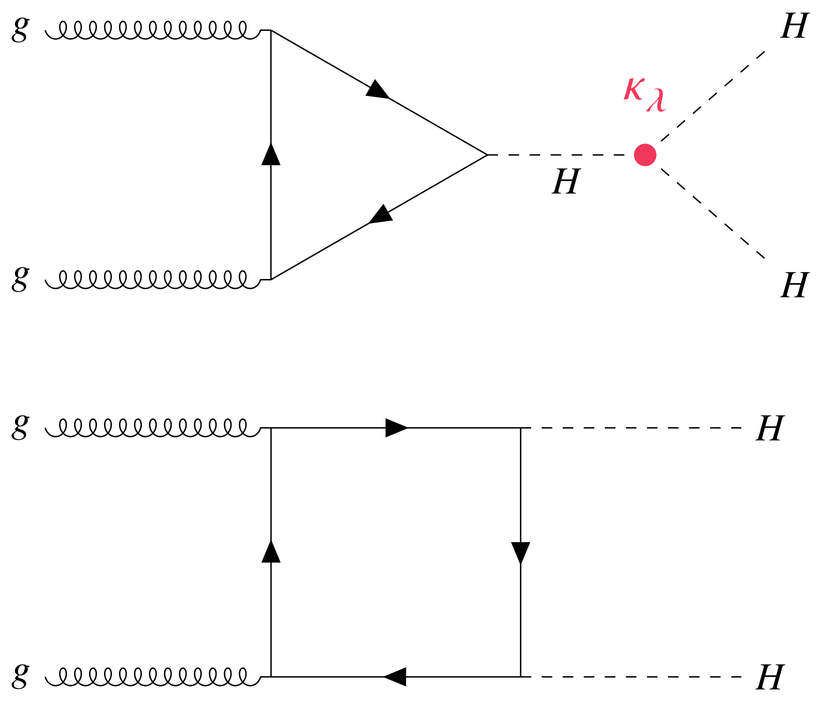
Differential Cross-Sections and Effective Field Theory Interpretations



Measurements in low-stats, high p_T tails will also be most accessible at HL-LHC.

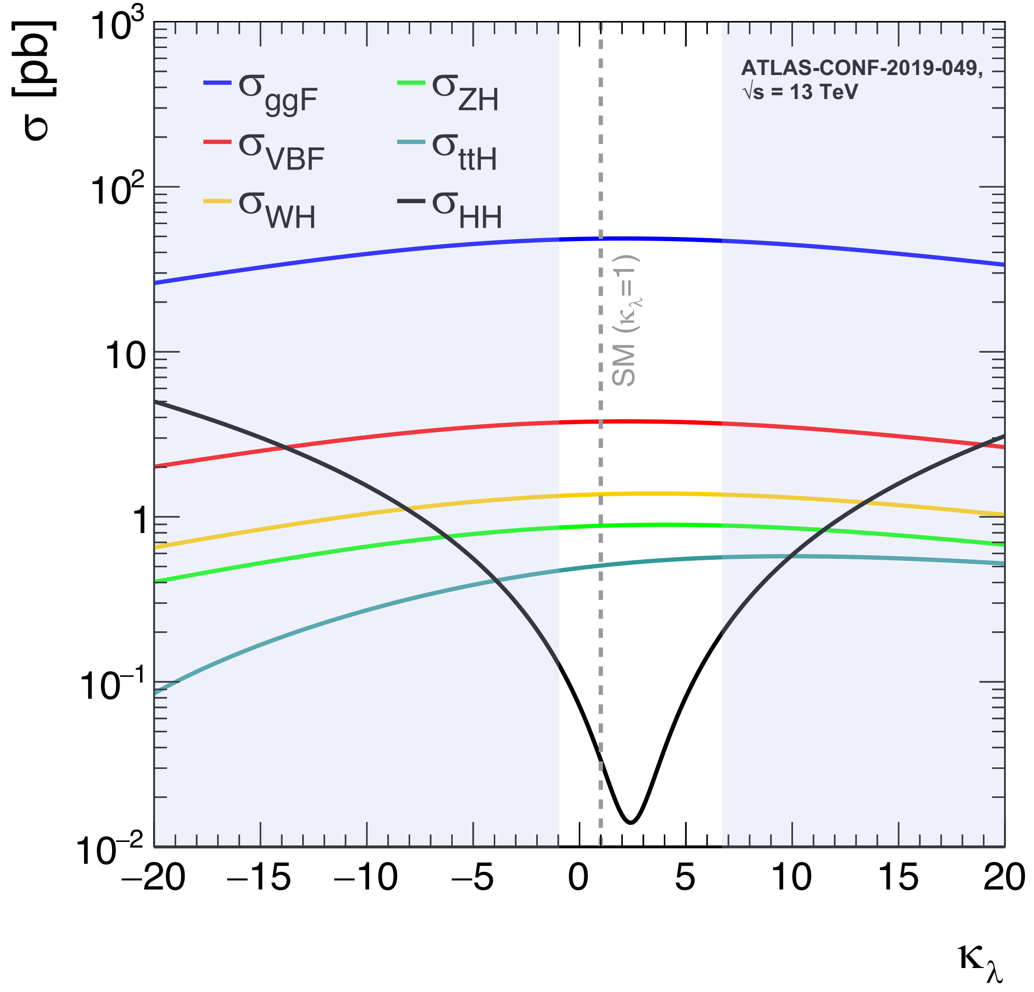
Differential measurements and their interpretations will maximize sensitivity to new physics.

HH Production



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

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



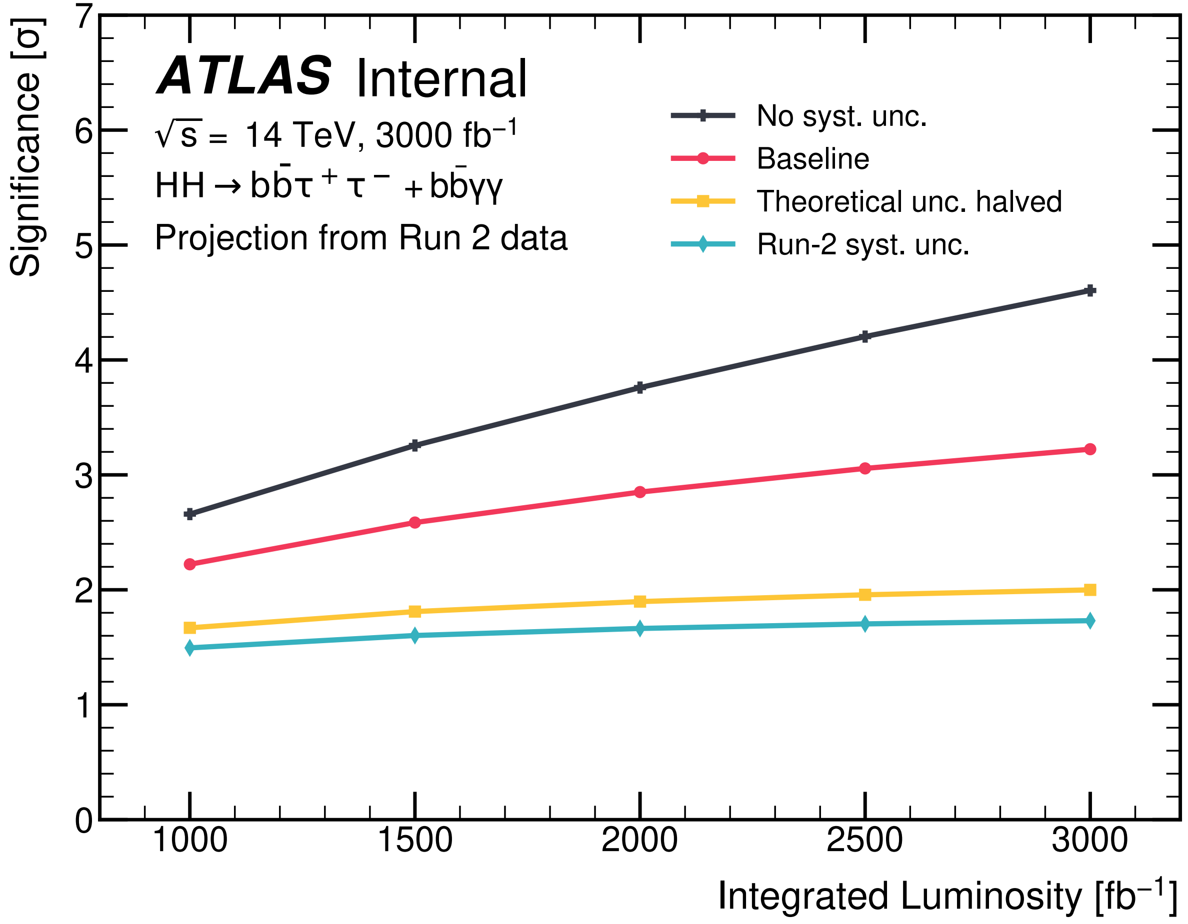
Run 2 (search mode)	HL-LHC (measurement mode)
~4,000 events	~115,000 events

HH Significance

ATLAS-CONF-2021-052

This Combination – 2 channels

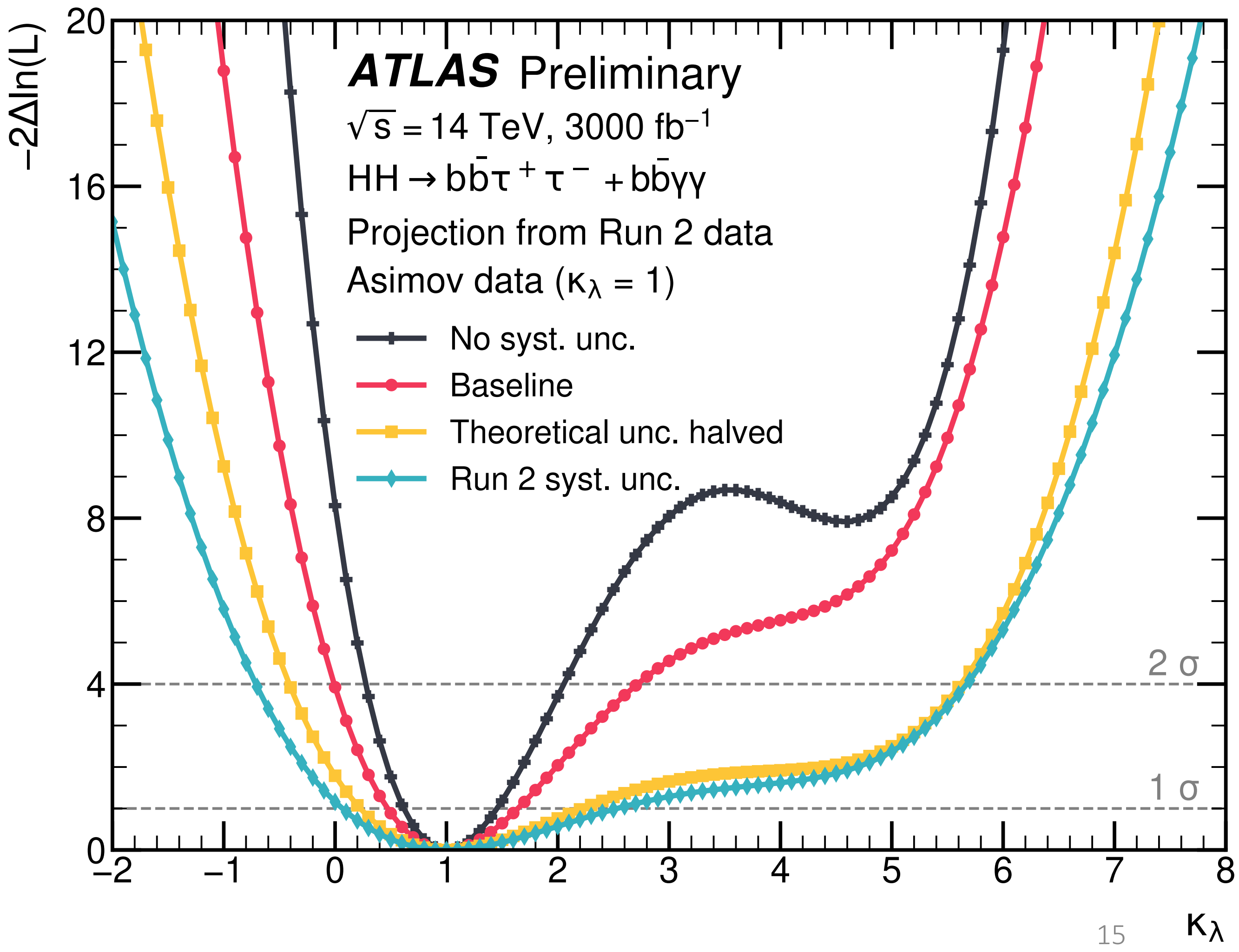
Uncertainty scenario	Significance $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination
No systematic uncertainties	2.3	4.0	4.6
Baseline	2.2	2.8	3.2
Theory uncertainties halved	1.1	1.7	2.0
Run-2 systematic uncertainties	1.1	1.5	1.7



HH Likelihood Scan ATLAS-CONF-2021-052

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	$[0.1, 2.5]$	$[-0.7, 5.7]$



Summary

High statistics from HL-LHC will bring the Higgs further into focus.

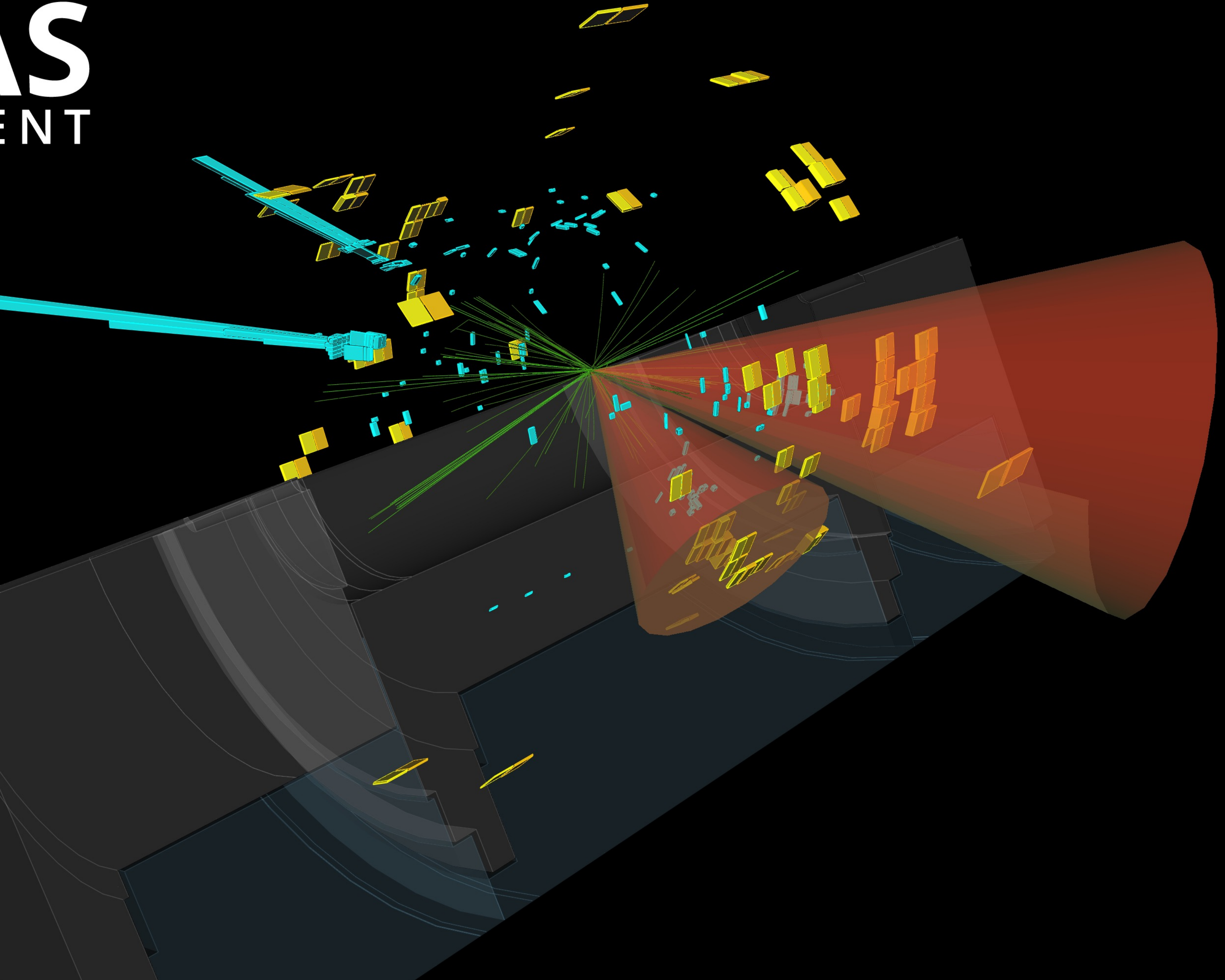
Rare processes such as H(cc), H(Zγ) and HH production may be measured for the first time.

Wealth of precision measurements and their interpretations will allow us to continue to constrain BSM physics.

Many other (non-Higgs) projections detailed in Snowmass Whitepaper: https://cds.cern.ch/record/2805993/

Success of HL-LHC relies on accelerator & detector upgrades going smoothly and continued progress in experimental and theory frontiers.

ATLAS EXPERIMENT



Thank you!

Higgs Width

$$\Gamma_H < 1.10\,\text{GeV, at 95\% confidence level.}$$

- Direct measurement possible in precision channels
  - $\Gamma_H < 177$ MeV (95% CL)
  - Limited by the mass lineshape resolution
- Indirect measurement
  - $\Gamma_H = 4.1^{+0.7}_{-0.8}$ MeV
  - Rely on the assumption that offshell/onshell Higgs production is as predicted by the SM

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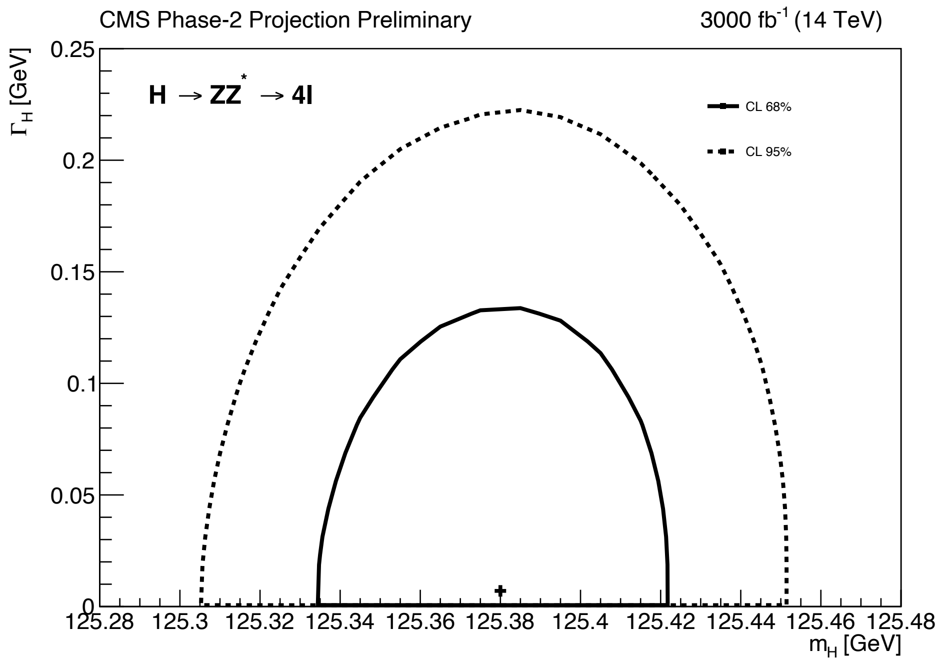


CMS-PAS-FTR-21-007

Latest CMS results on indirect measurement Width$_H$ = 3.2 +2.8,-2.2 MeV (CMS-HIG-18-002)

Higgs to Charm - VH(cc)

Updated projections from ATLAS and CMS at 3000 fb^{-1}

ATL-PHYS-PUB-2021-039 & CMS-PAS-HIG-21-008

Current limits on signal strength at 95% confidence:

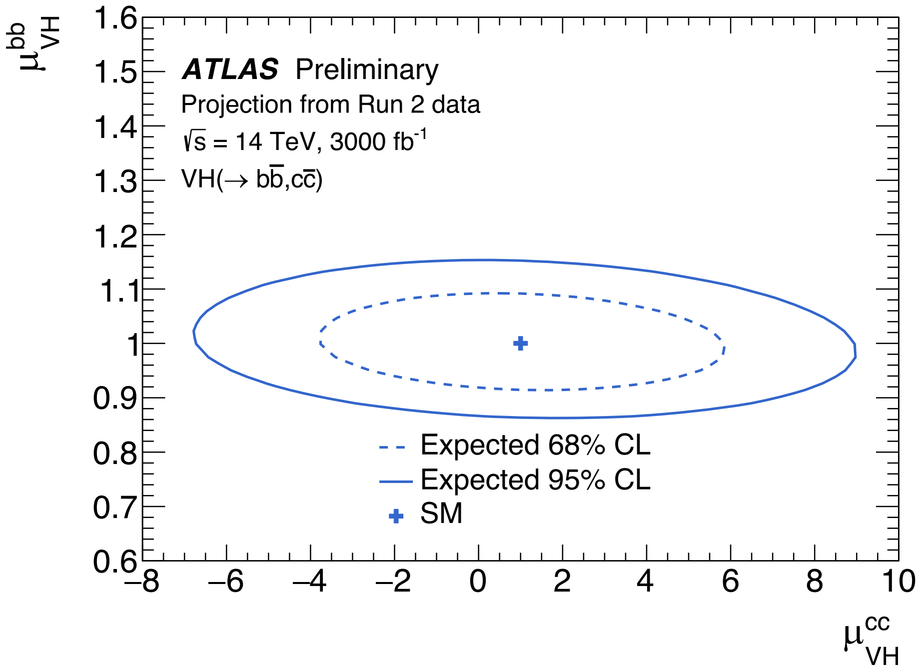
ATLAS $\mu < 26$ (31 expected)

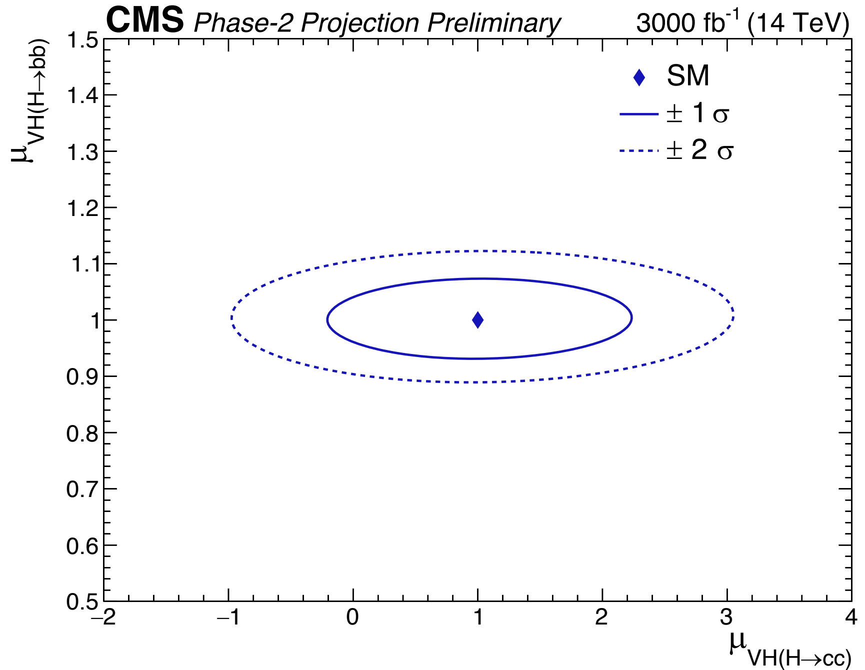
CMS $\mu < 14$ (7.6 expected)

Expected projected limits on signal strength at 95% confidence:

ATLAS $\mu < 6.4$

CMS $\mu < 1.6$ (uses boosted analysis strategy)





Projected likelihood scans under SM hypothesis

Theory Uncertainties

- Missing higher-order effects of QCD corrections beyond N^3LO (δ(scale)).
- Missing higher-order effects of electroweak and mixed QCD-electroweak corrections at and beyond $\mathcal{O}(\alpha_S\alpha)$ (δ(EW)).
- Effects due to finite quark masses neglected in QCD corrections beyond NLO (δ(t,b,c) and $\delta(1/m_t)$)
- Mismatch in the perturbative order of the parton distribution functions (PDF) evaluated at NNLO and the perturbative QCD cross sections evaluated at N^3LO (δ(PDF-TH)).

https://cds.cern.ch/record/2703572/files/94-87-PB.pdf

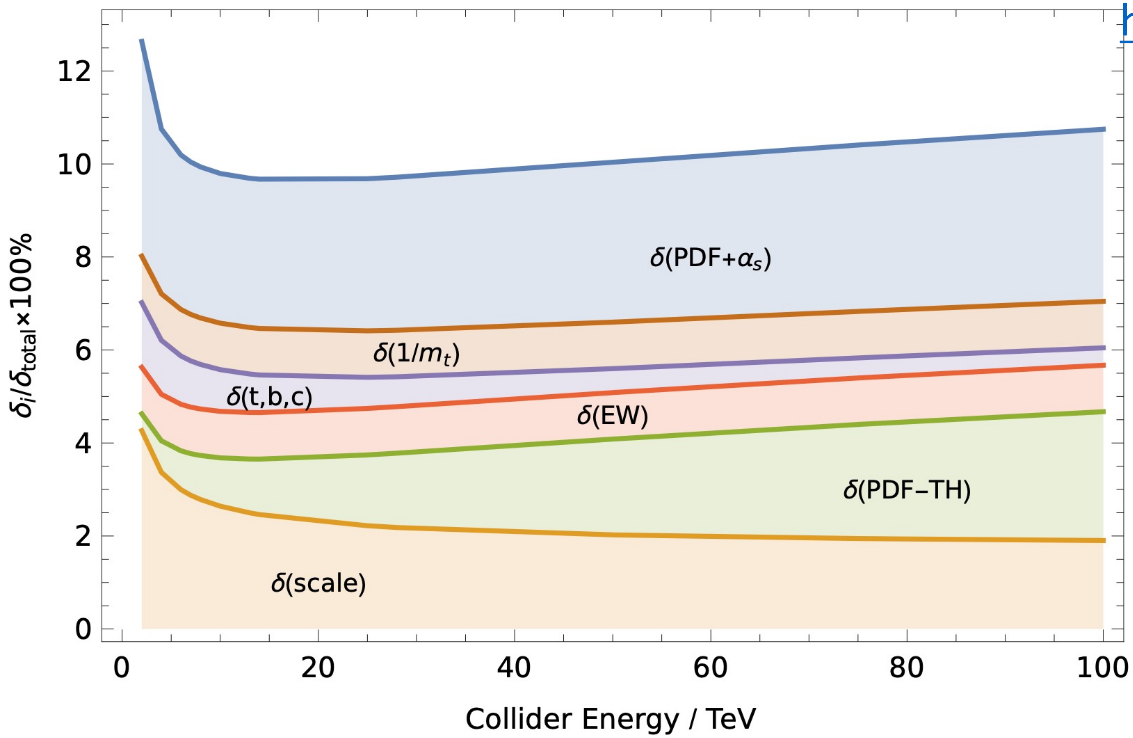
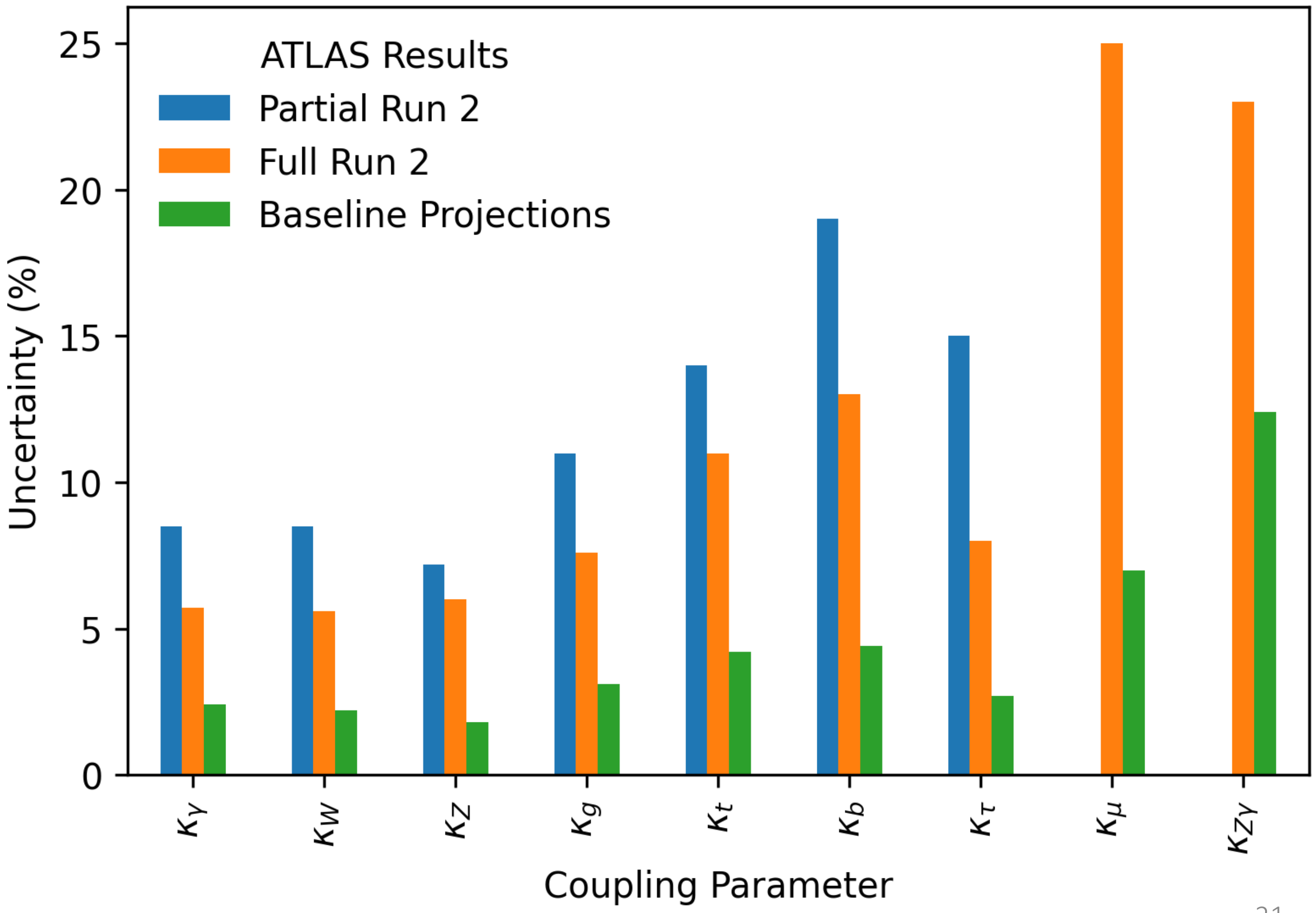


Fig. 1: The figure shows the linear sum of the different sources of relative uncertainties as a function of the collider energy. Each coloured band represents the size of one particular source of uncertainty as described in the text. The component $\delta(\text{PDF}+\alpha_S)$ corresponds to the uncertainties due to our imprecise knowledge of the strong coupling constant and of parton distribution functions combined in quadrature.

Coupling Measurements

Projections are often a little pessimistic. These projections were done on Partial Run 2 dataset, but in many cases systematically limited Full Run 2 measurements have improved at ~sqrt(L) scaling.



Data from Quentin Buat

H(μμ)

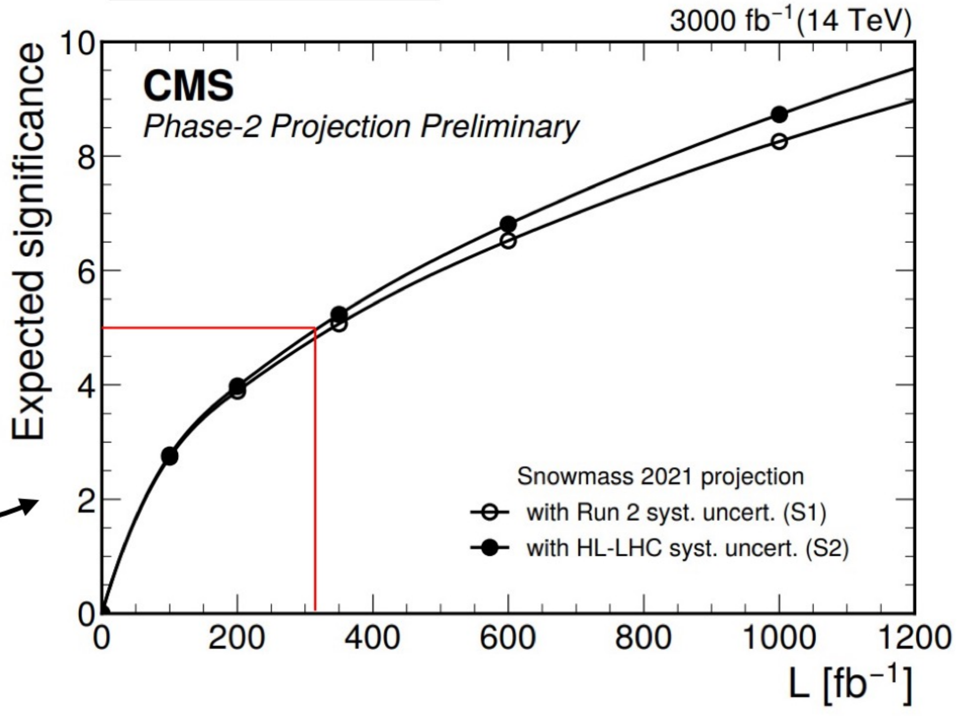
CMS-PAS-FTR-21-006

Evidence for H→μμ decay in Run-2

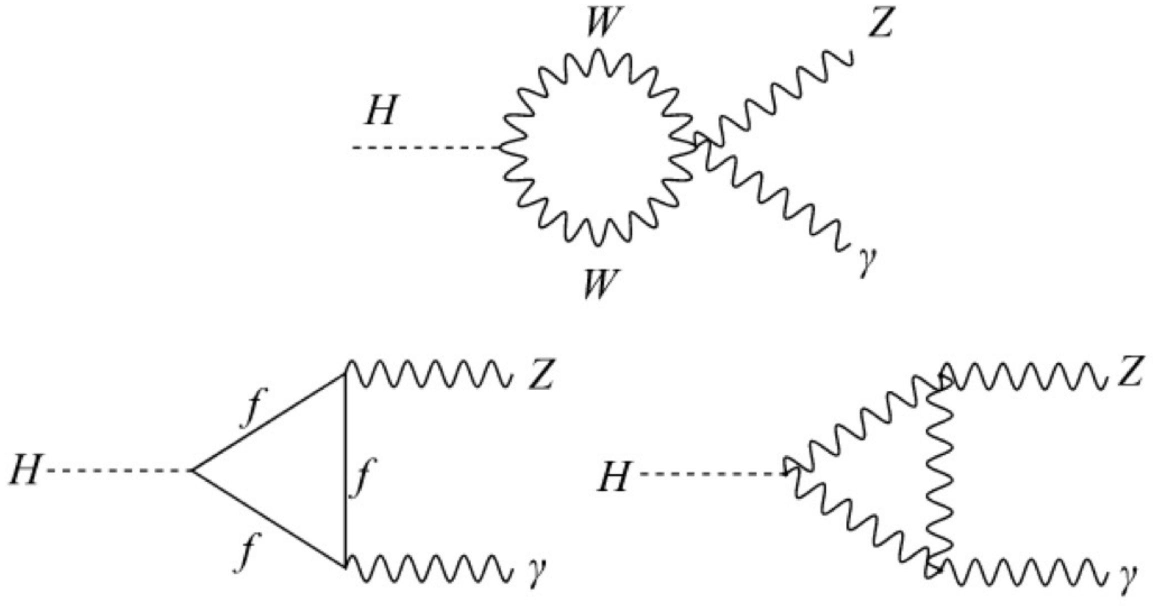
- ATLAS: 2.0σ (1.7σ) obs (exp) Phys. Lett. B 812 (2021)
- CMS: 3.0σ (2.5σ) obs (exp) JHEP 01 (2021) 148

New projection from CMS based on Run-2 analysis

- Expect to reach 5σ @~300/fb – by the end of LHC Run-3
- Combination with ATLAS to reach 5σ sooner!



H->Zy

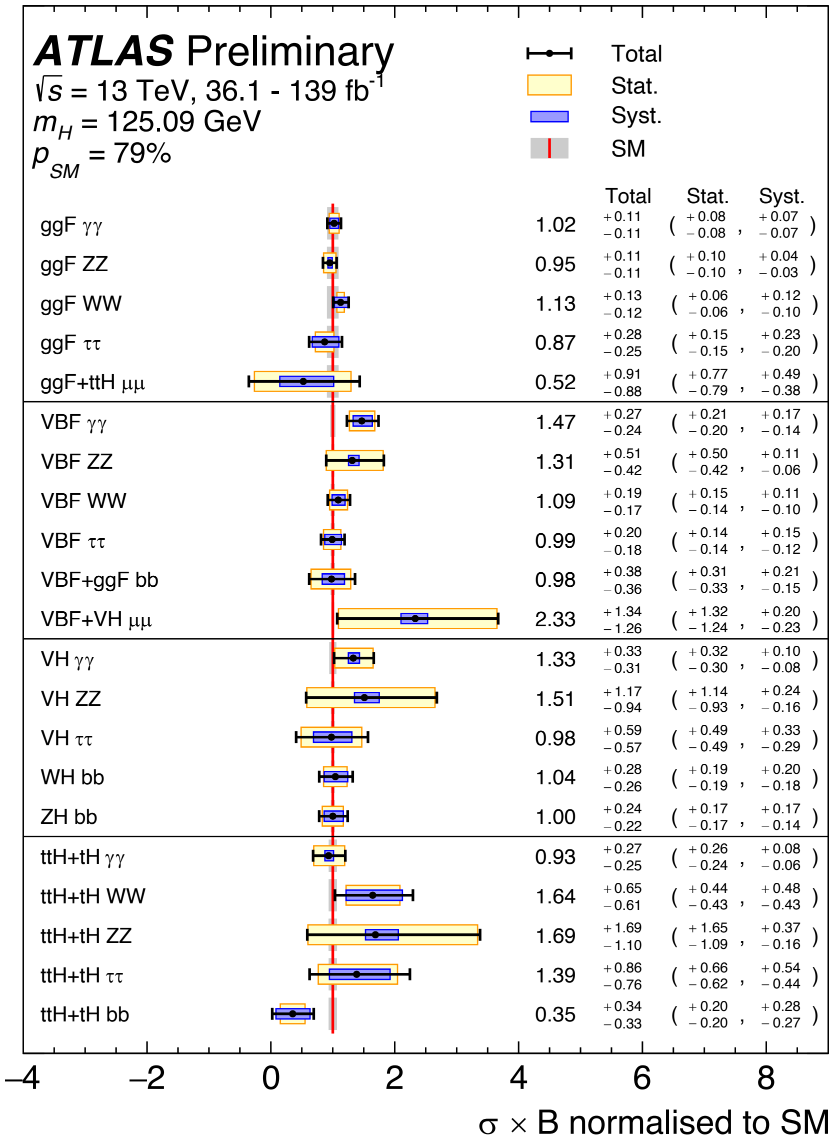


https://arxiv.org/abs/2005.05382

Current ATLAS limits are at 3.6xSM

ATLAS Combined Higgs Results

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-053/



Higgs Mass

CMS projected uncertainties

	Mass uncertainty (MeV)					Width upper limit at 95 % CL (MeV)
	Combined	4μ	4e	$2e2\mu$	$2\mu 2e$	Combined
Stat. uncertainty	22	28	83	51	59	94
Syst. uncertainty	20	15	189	94	95	150
Total	30	32	206	107	112	177

HH References

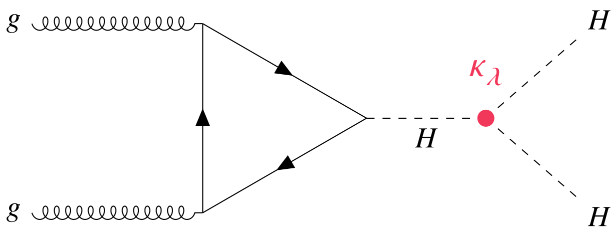
2018 HL-LHC Prospects Combination http://cdsweb.cern.ch/record/2652727

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

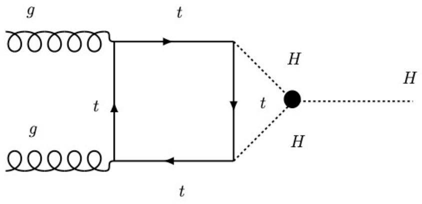
2021 Full Run 2 bbττ https://cds.cern.ch/record/2777236
2021 Full Run 2 bb$\gamma\gamma$ https://arxiv.org/abs/2112.11876
2021 Full Run 2 HH Combination https://cds.cern.ch/record/2786865
2022 Full Run 2 HH HEFT Interpretations
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-021/

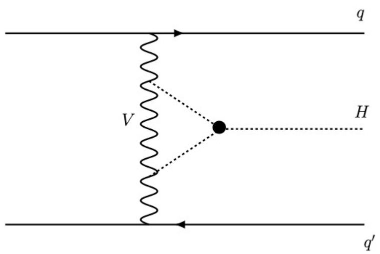
Measuring κ_λ

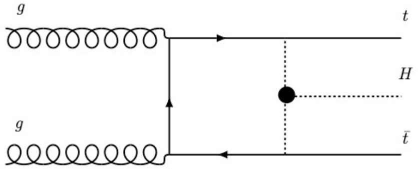
Direct measurement:

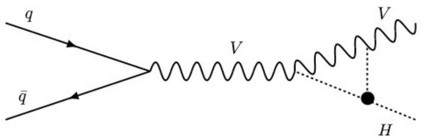


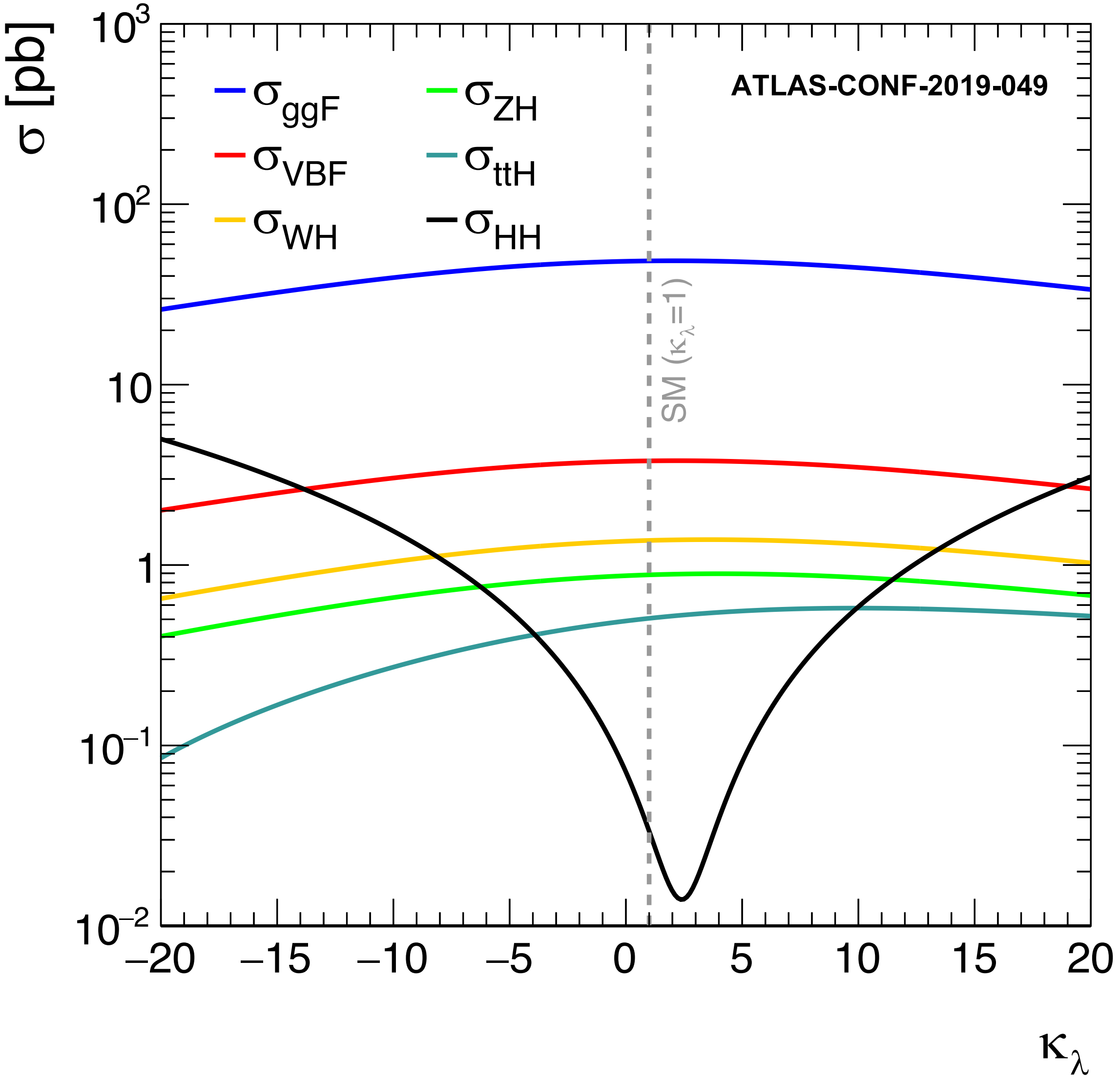
Indirect measurement:







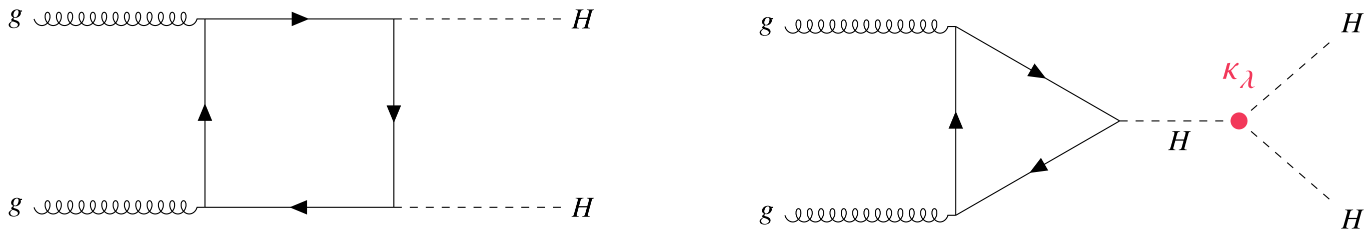




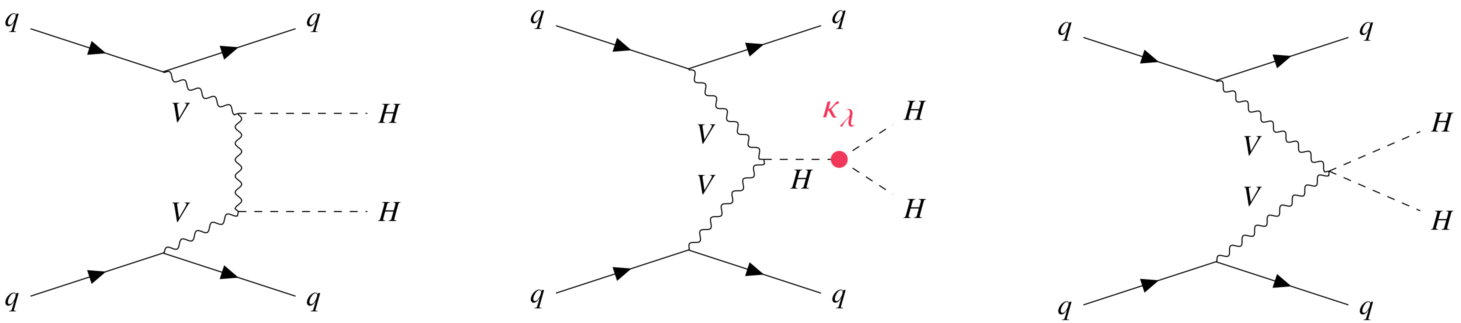
HH Production Channels

Non-Resonant

ggF: σ_{SM} *= 31.05 fb*



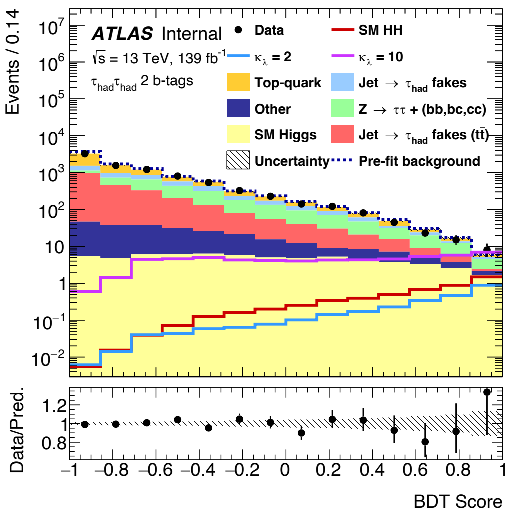
VBF: σ_{SM} *= 1.73 fb*



Analysis Overviews

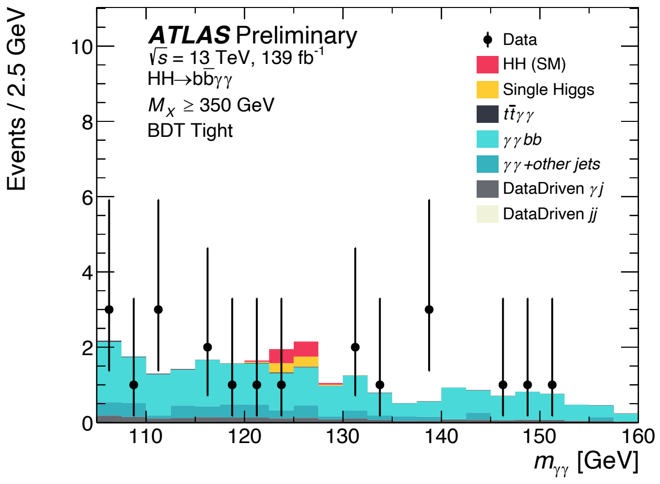
bbττ: https://cds.cern.ch/record/2777236

- 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

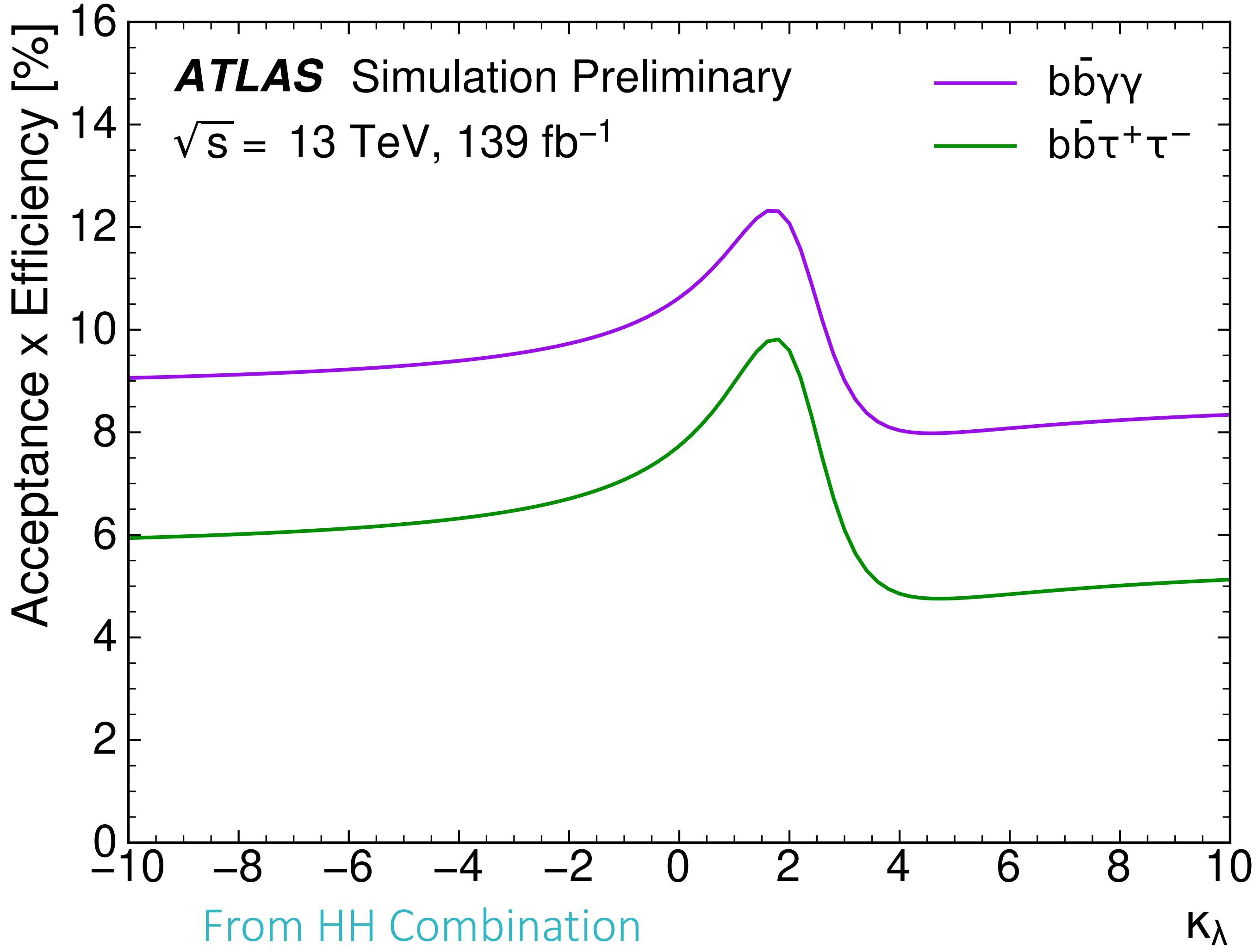


bb$\gamma\gamma$: https://arxiv.org/abs/2112.11876

- 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

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

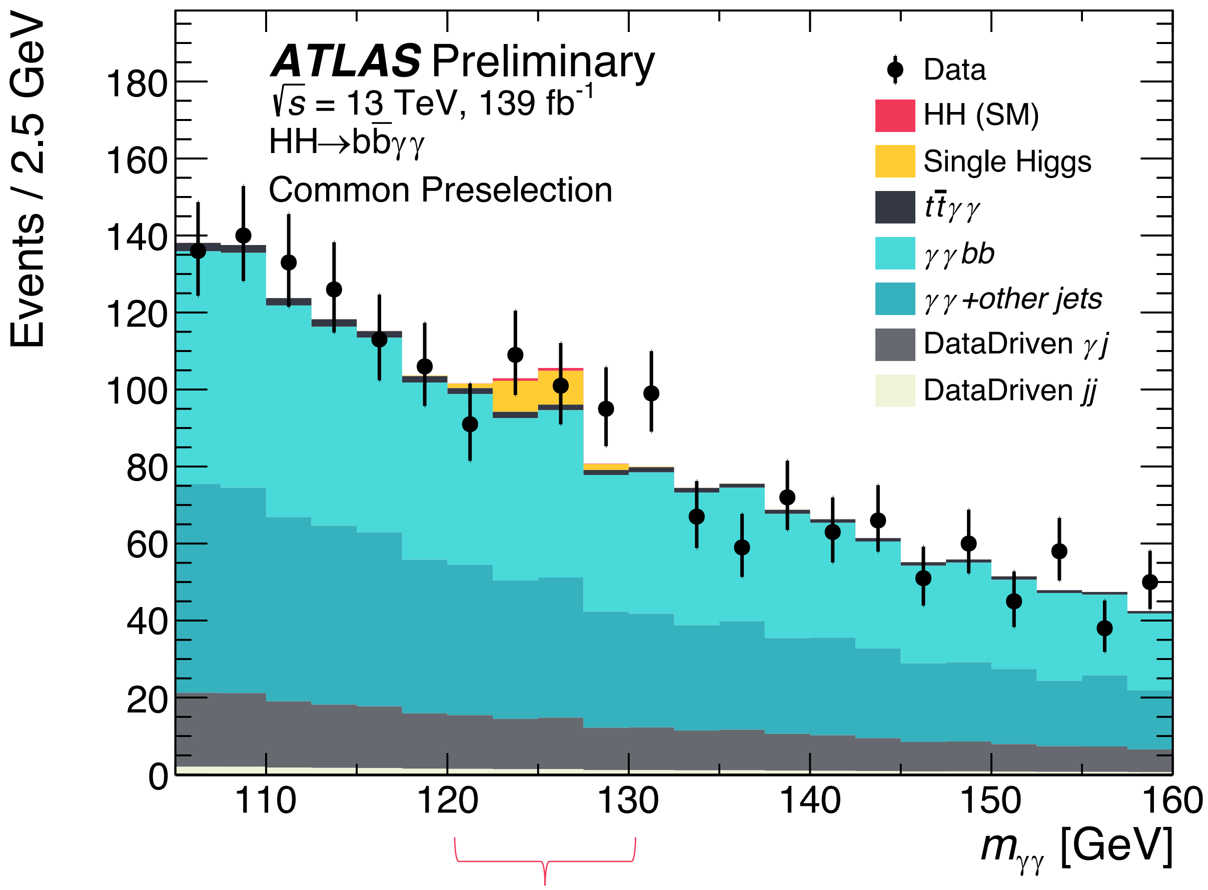
Selection Strategy

2 photons
& 2 b-jets

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

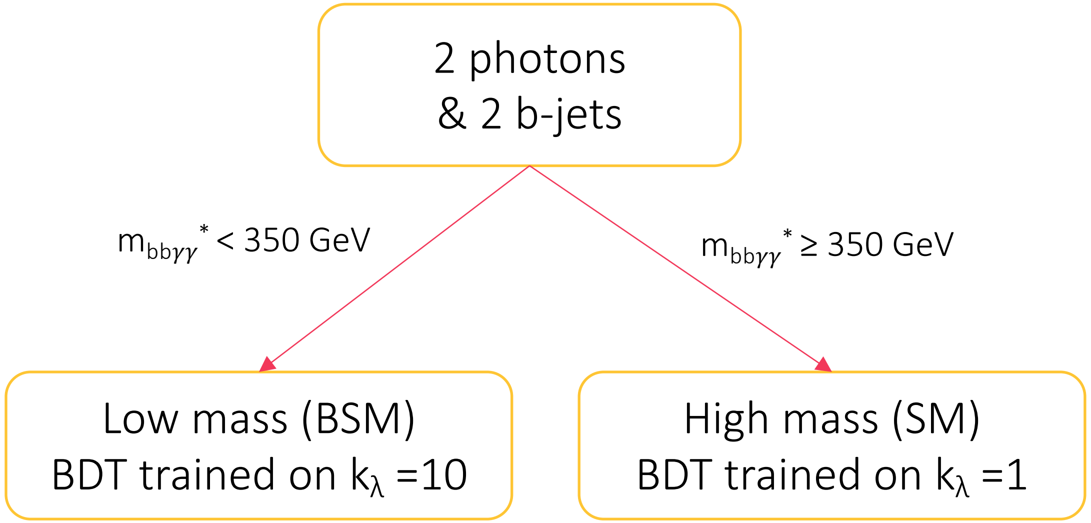
Major backgrounds:
- Diphoton $\gamma\gamma$ (largest contributor)
- Single Higgs (peaks at same $m_{\gamma\gamma}$ as signal)

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



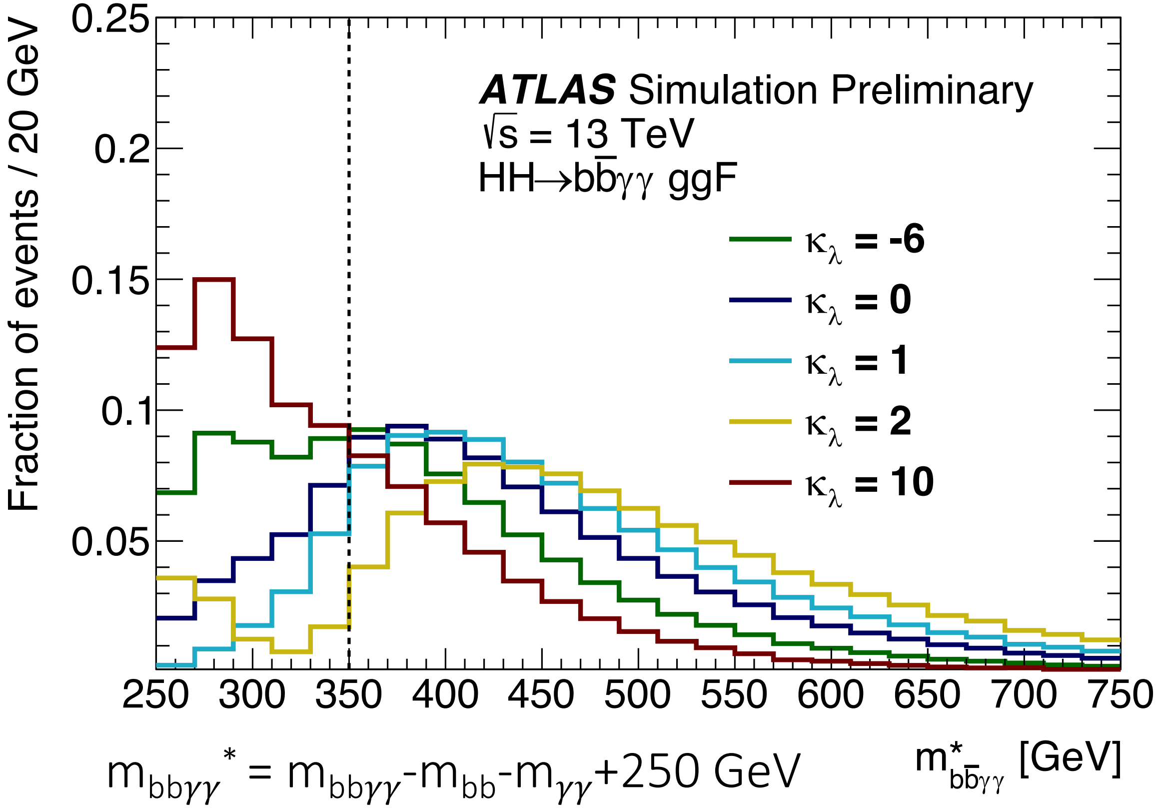
Signal region
$m_{\gamma\gamma}$ = 120-130 GeV

$bb\gamma\gamma$ Selection Strategy



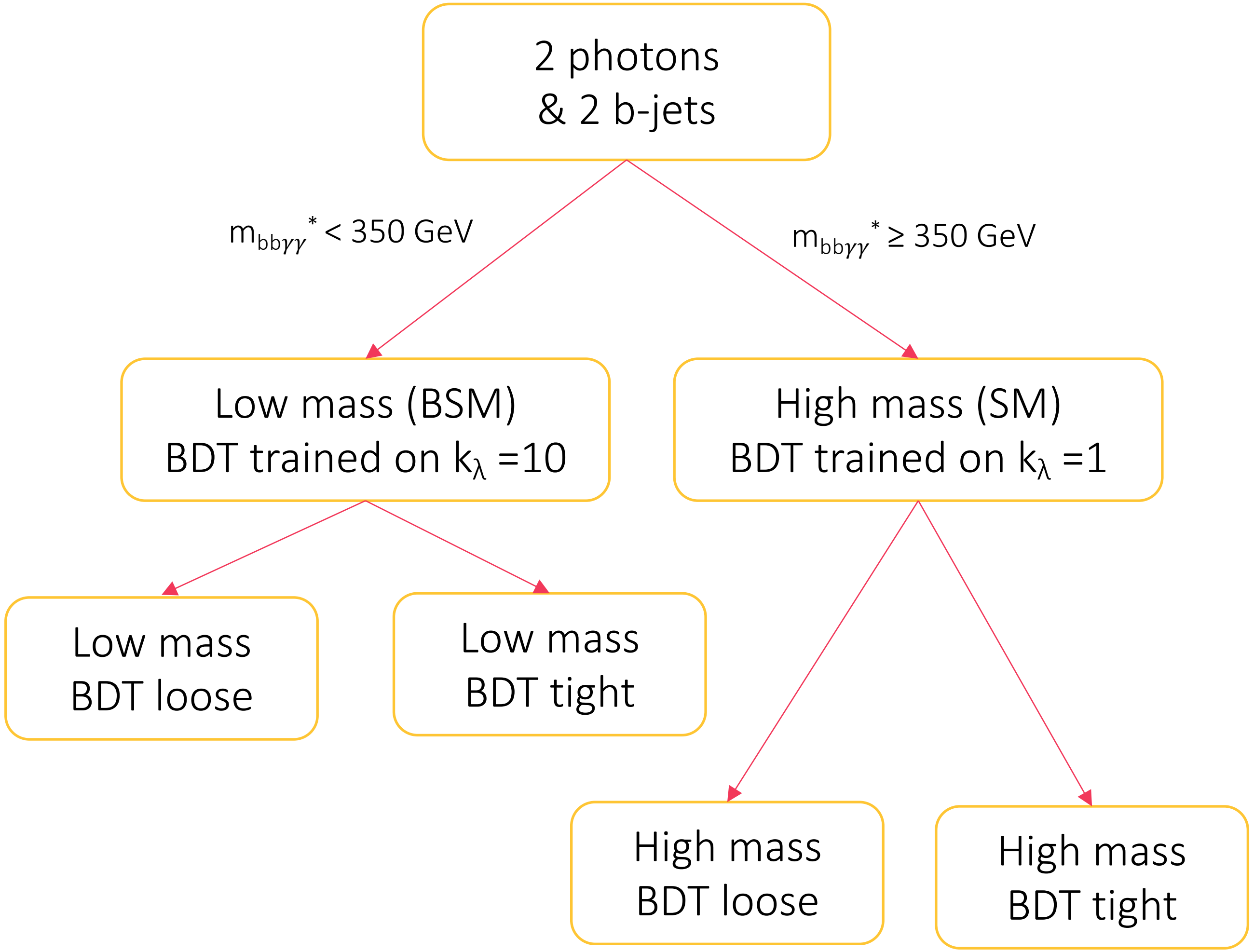
Split signal regions by $m_{bb\gamma\gamma}{}^{*}$ for sensitivity to SM and BSM HH.

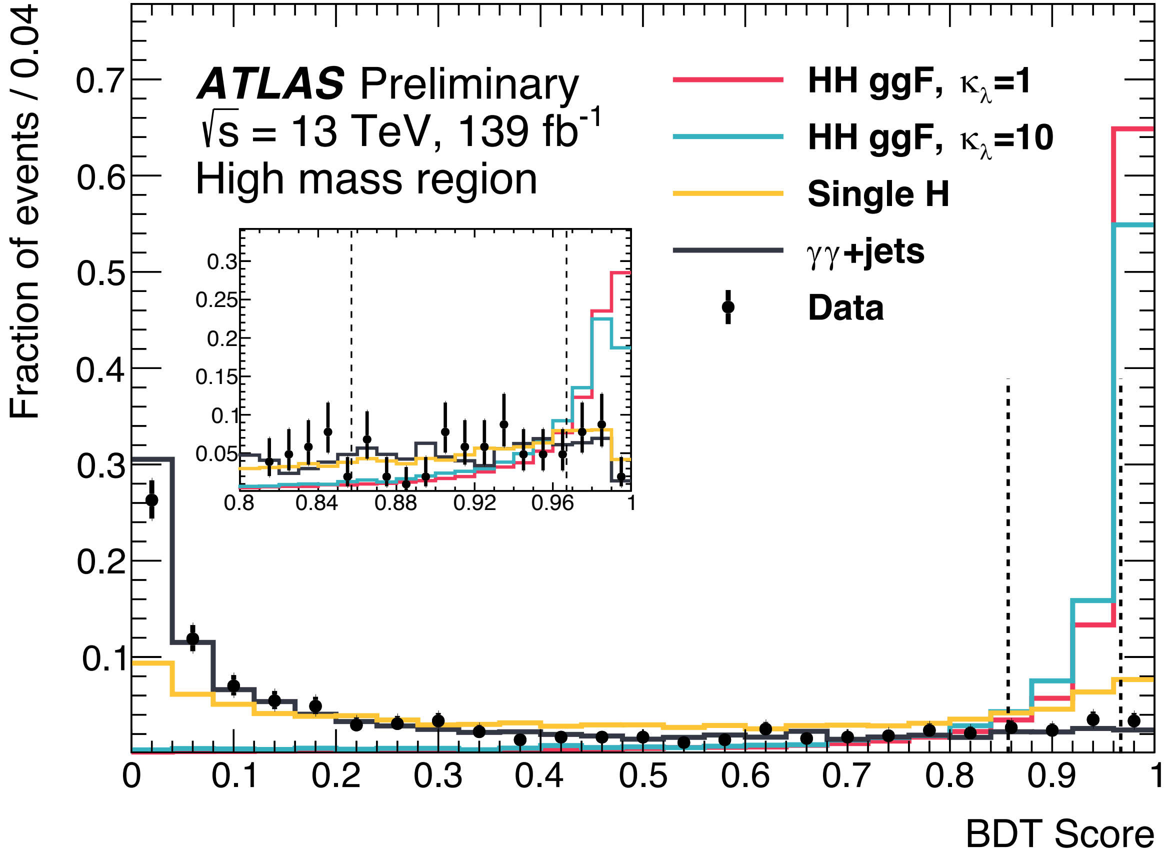
Train two BDTs to target each signal region.



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

bb$\gamma\gamma$ Selection Strategy

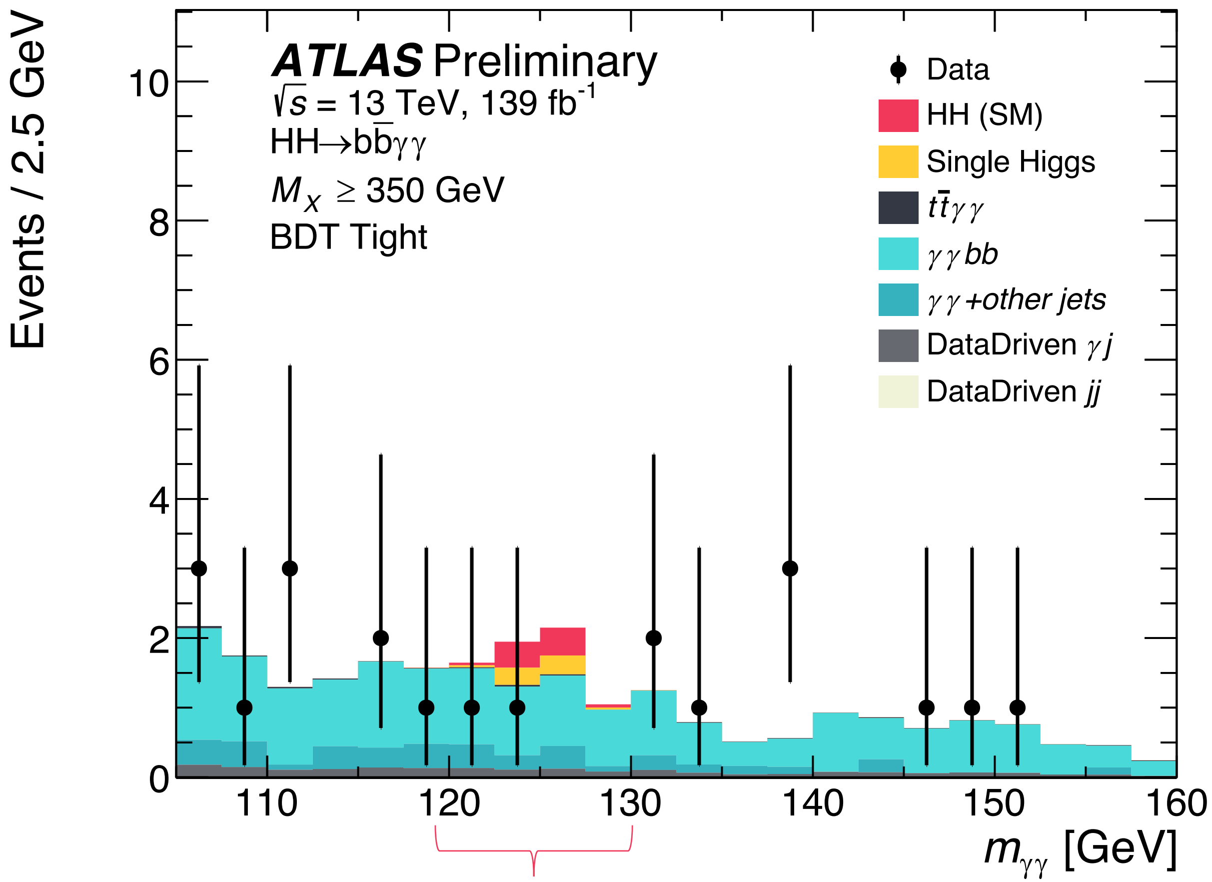




<u>4 BDT Categories</u>

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%

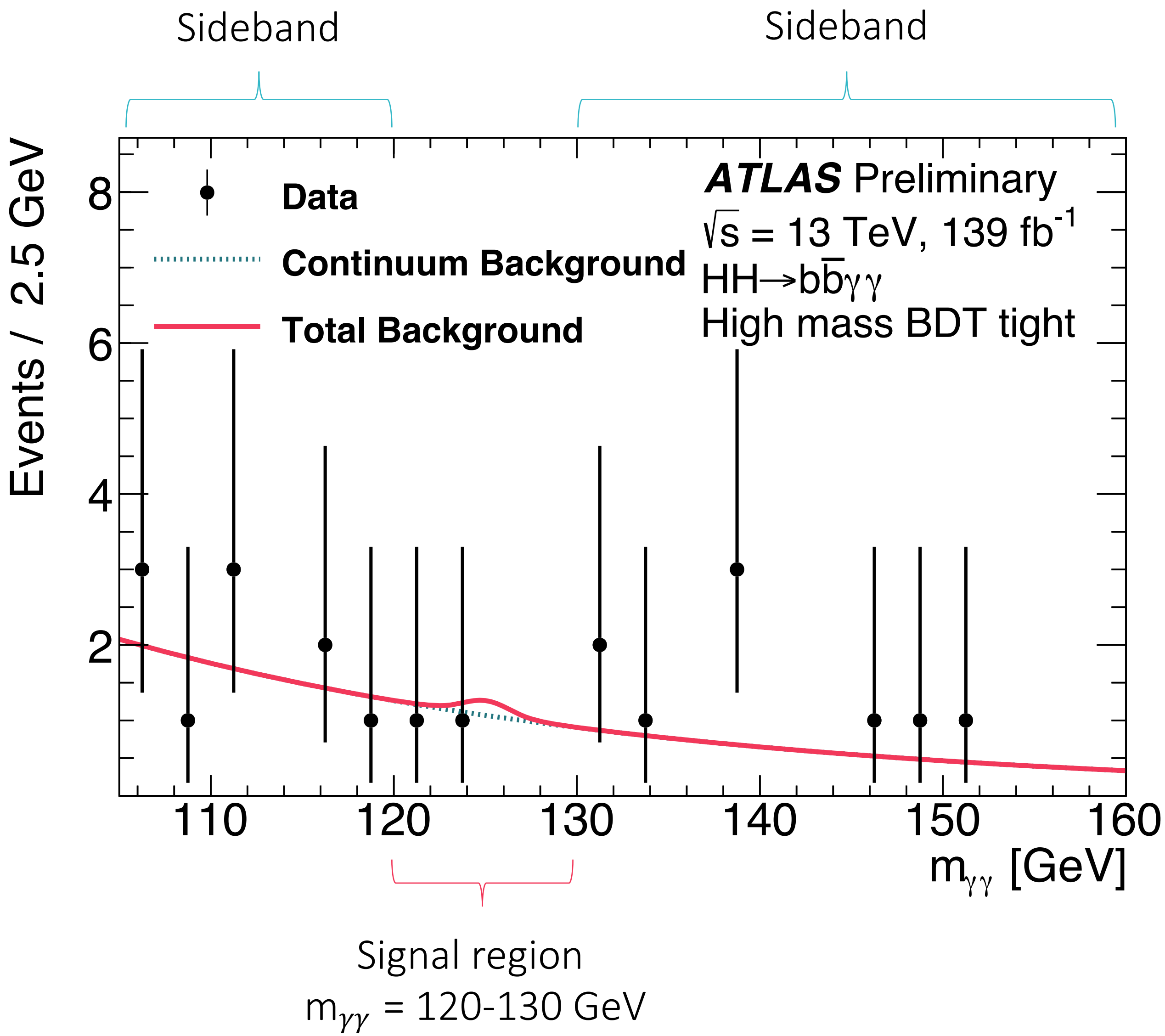
Signal Extraction

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



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 (ggF HH through $t\bar{t}H$)

Increased gluon-luminosity (Others)

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

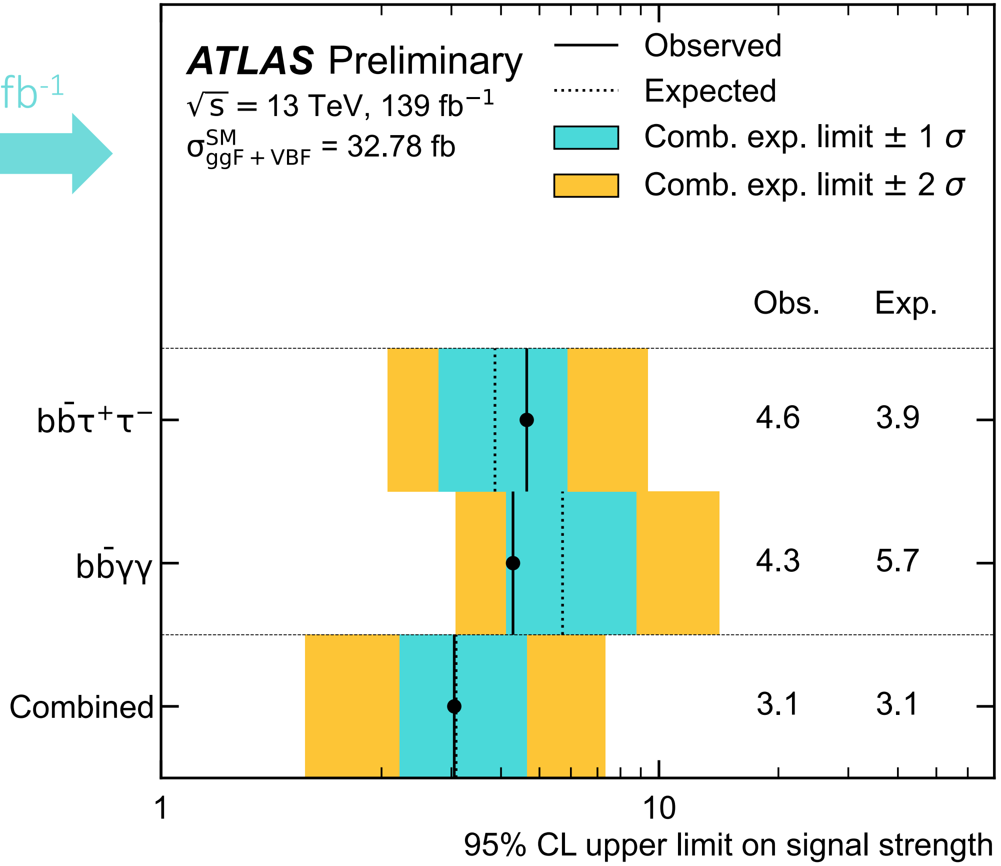
Theory uncertainties halved

Projected Limits on HH Signal Strength

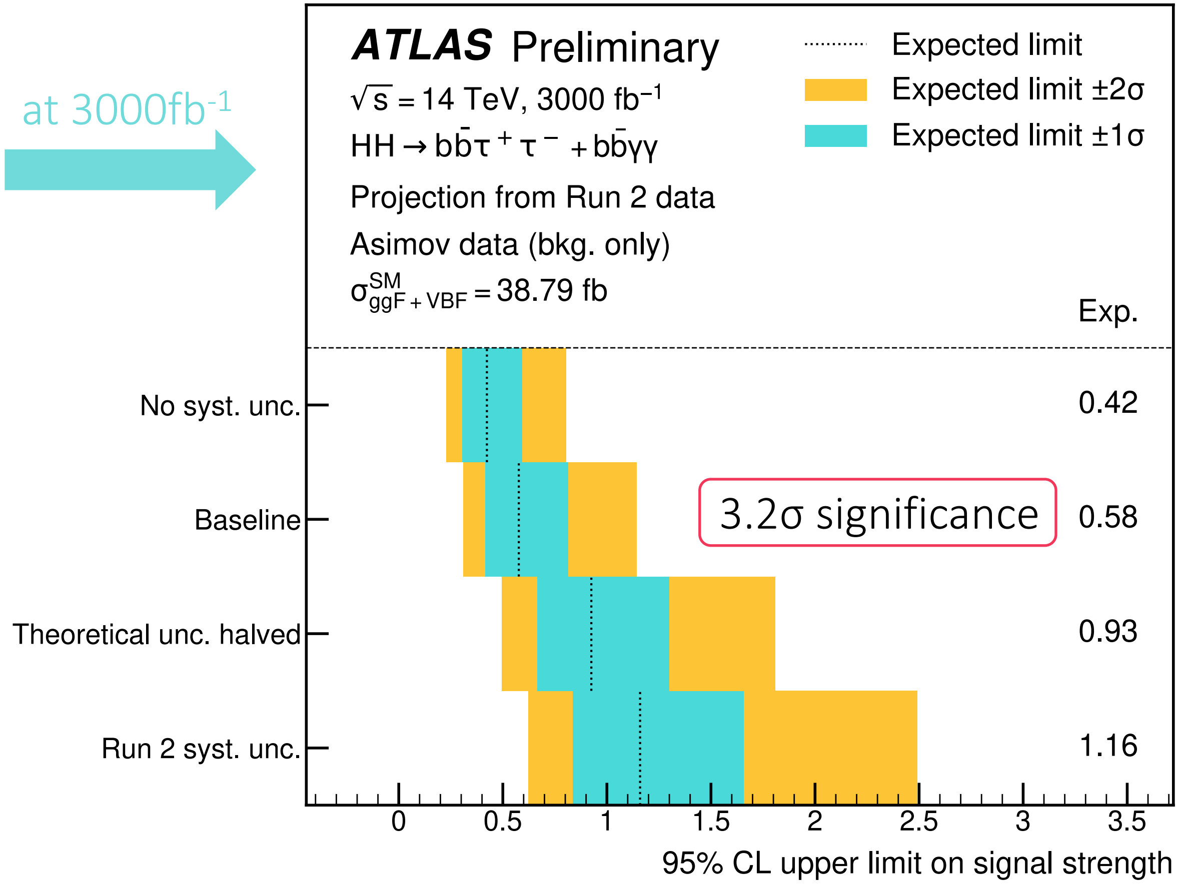
Interpretation: If no HH signal is observed, can place the following limits at 95% confidence level

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

at 139fb^{-1}



at 3000fb^{-1}

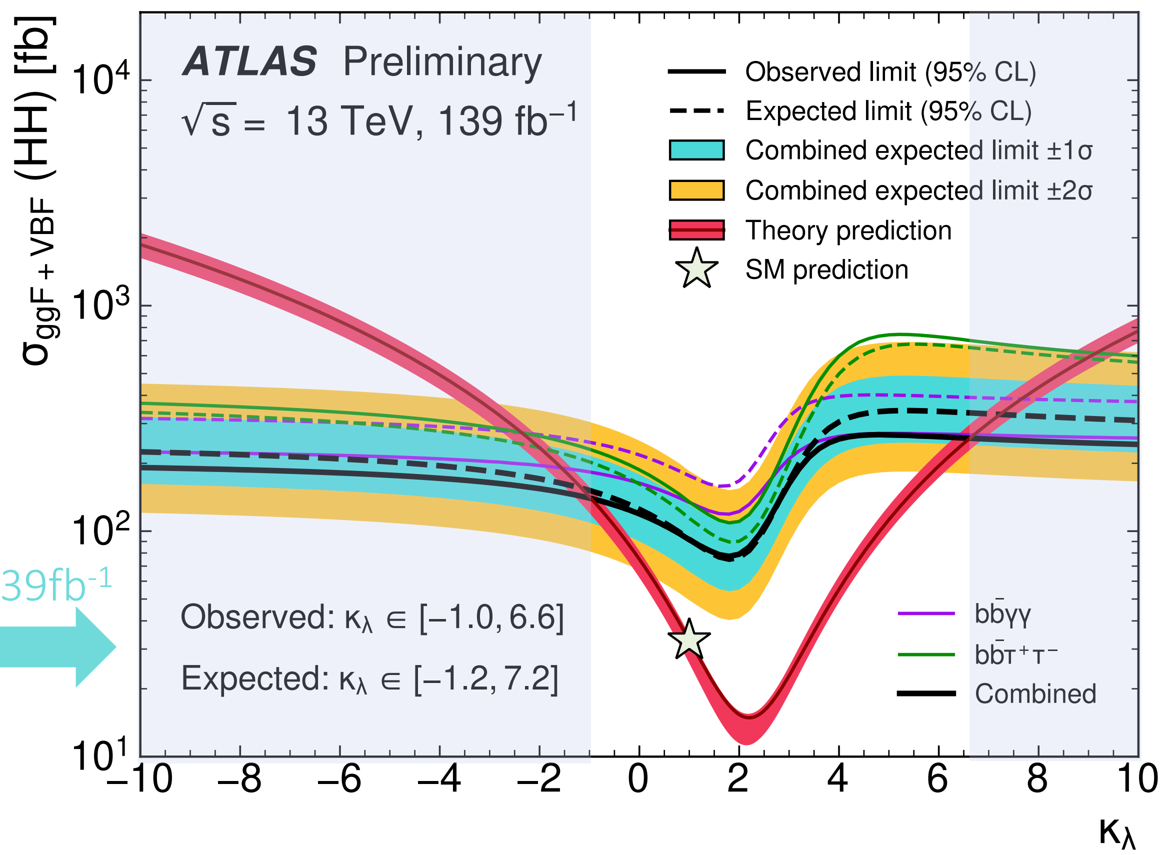


Projected Constraints on Higgs Boson Self-Coupling

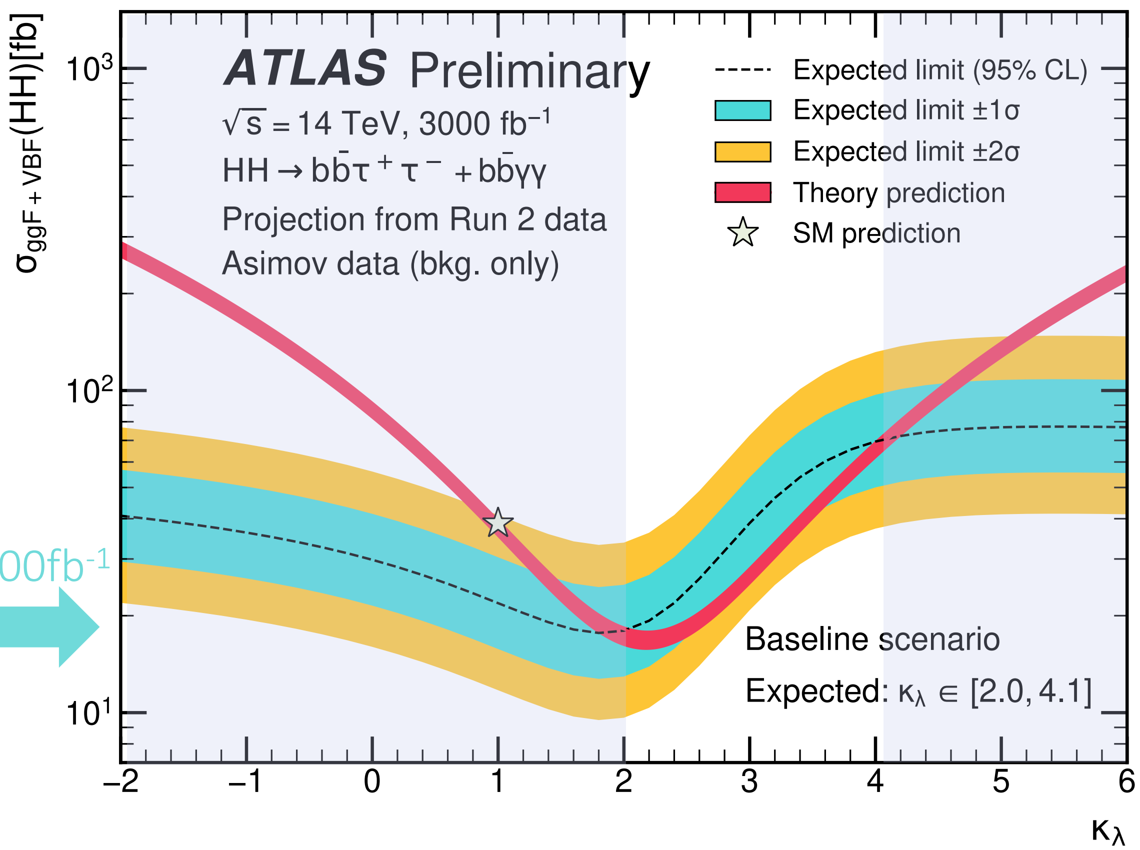
Interpretation: If no HH signal is observed, can place the following constraints at 95% confidence level

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

at 139fb^{-1}



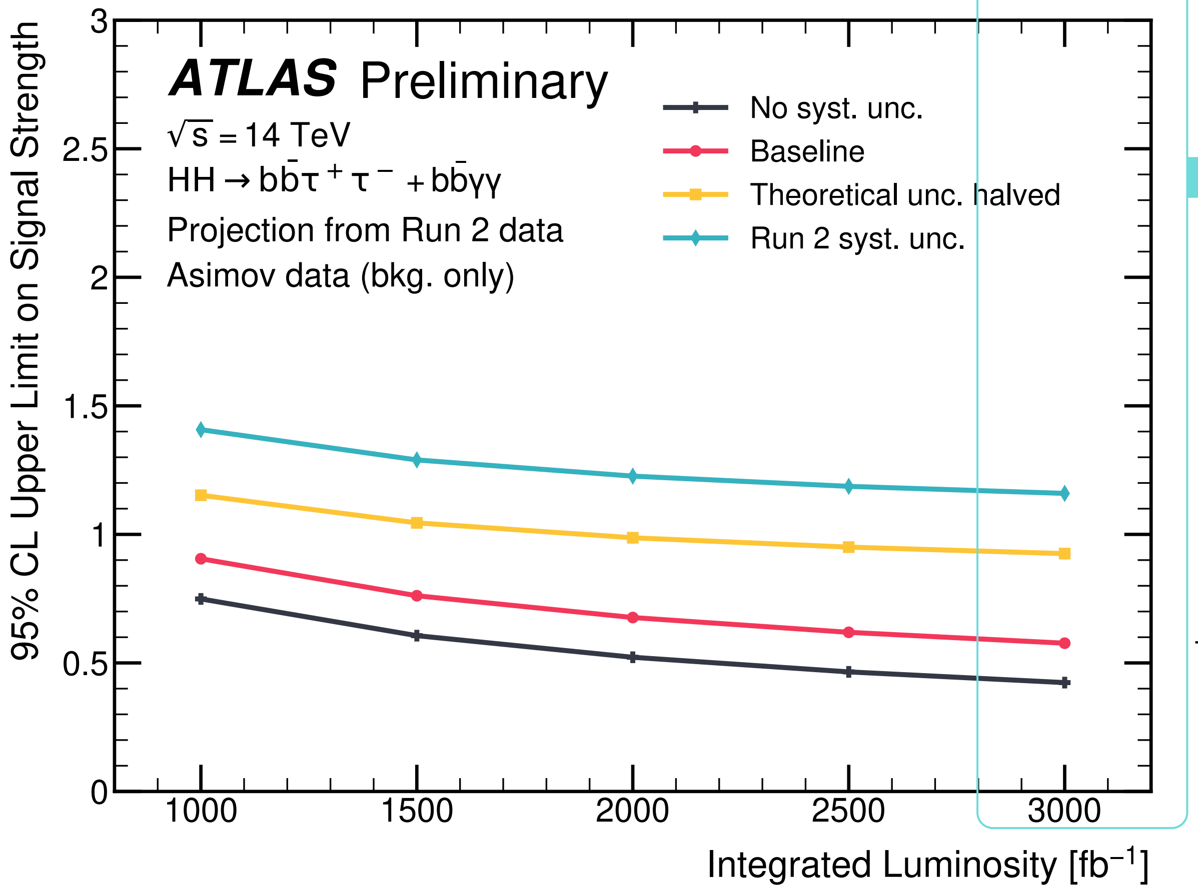
at 3000fb^{-1}



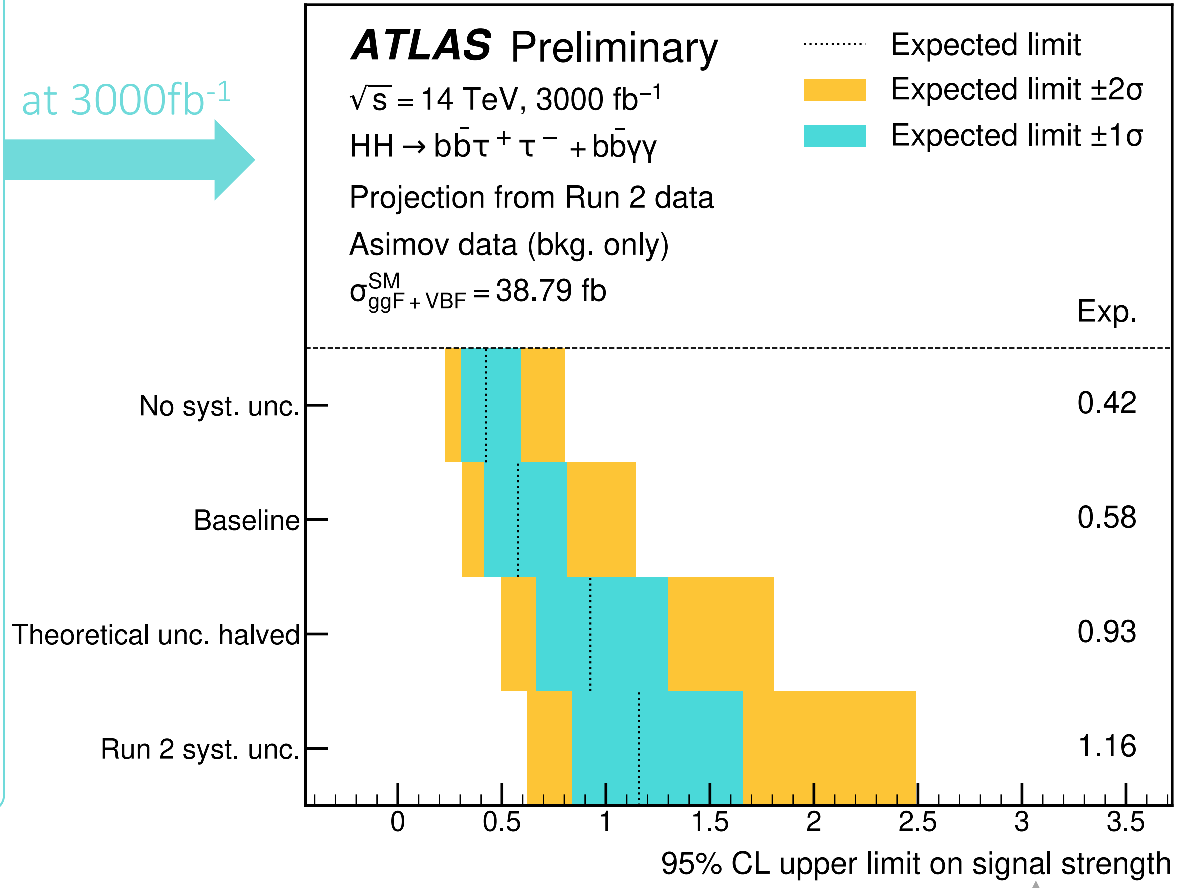
Note: k_λ=1 expected to be excluded during HL-LHC if we see no evidence of SM HH production

Upper Limits on SM Signal Strength

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

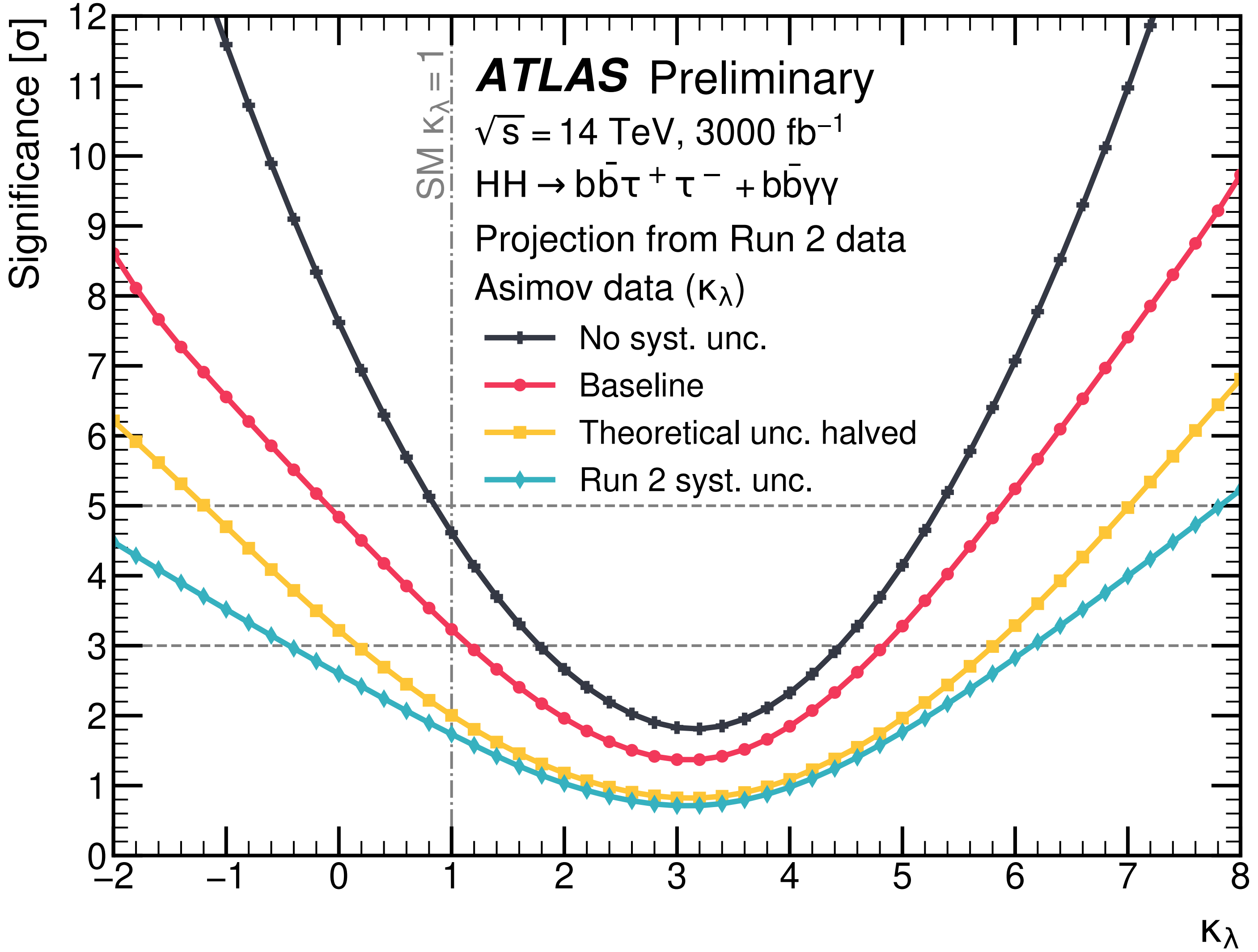


at 3000fb^{-1}



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

Significance as a function of k_λ - Combined

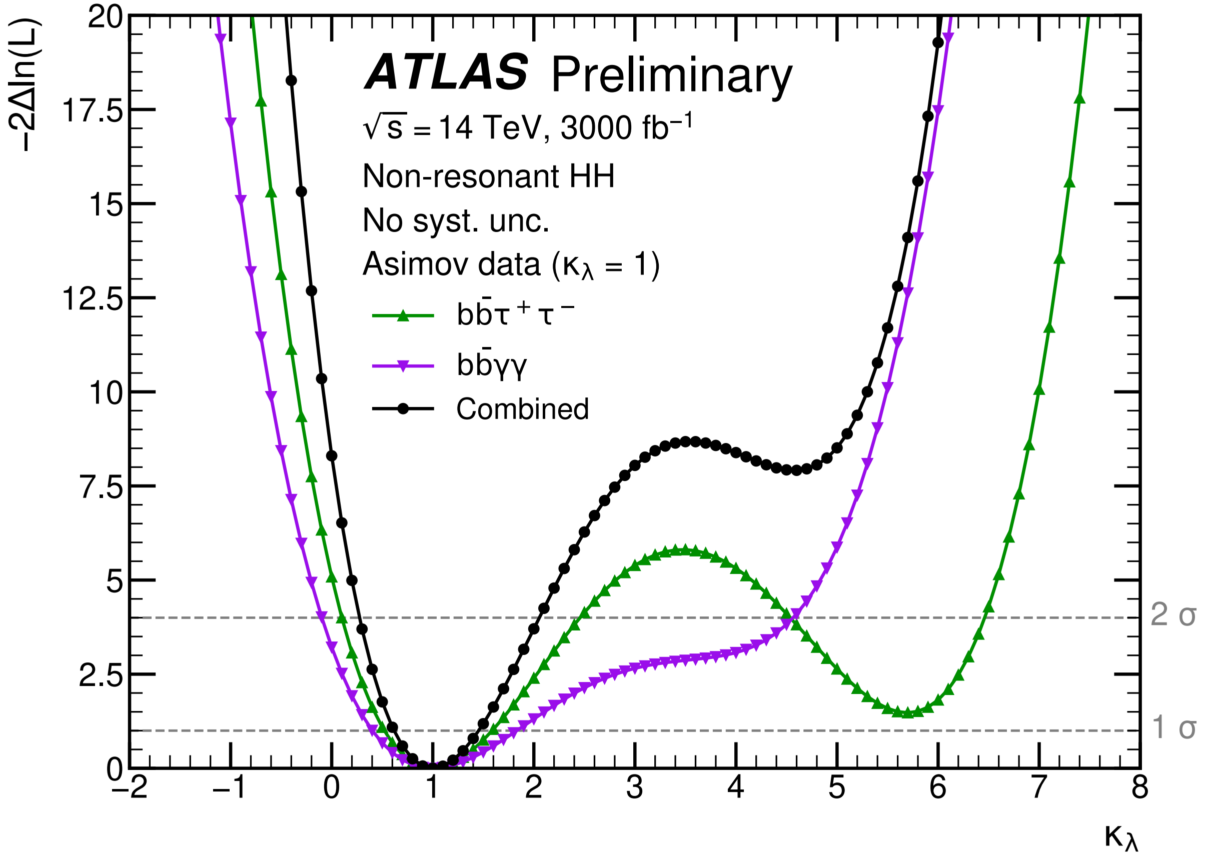


Interpretation:

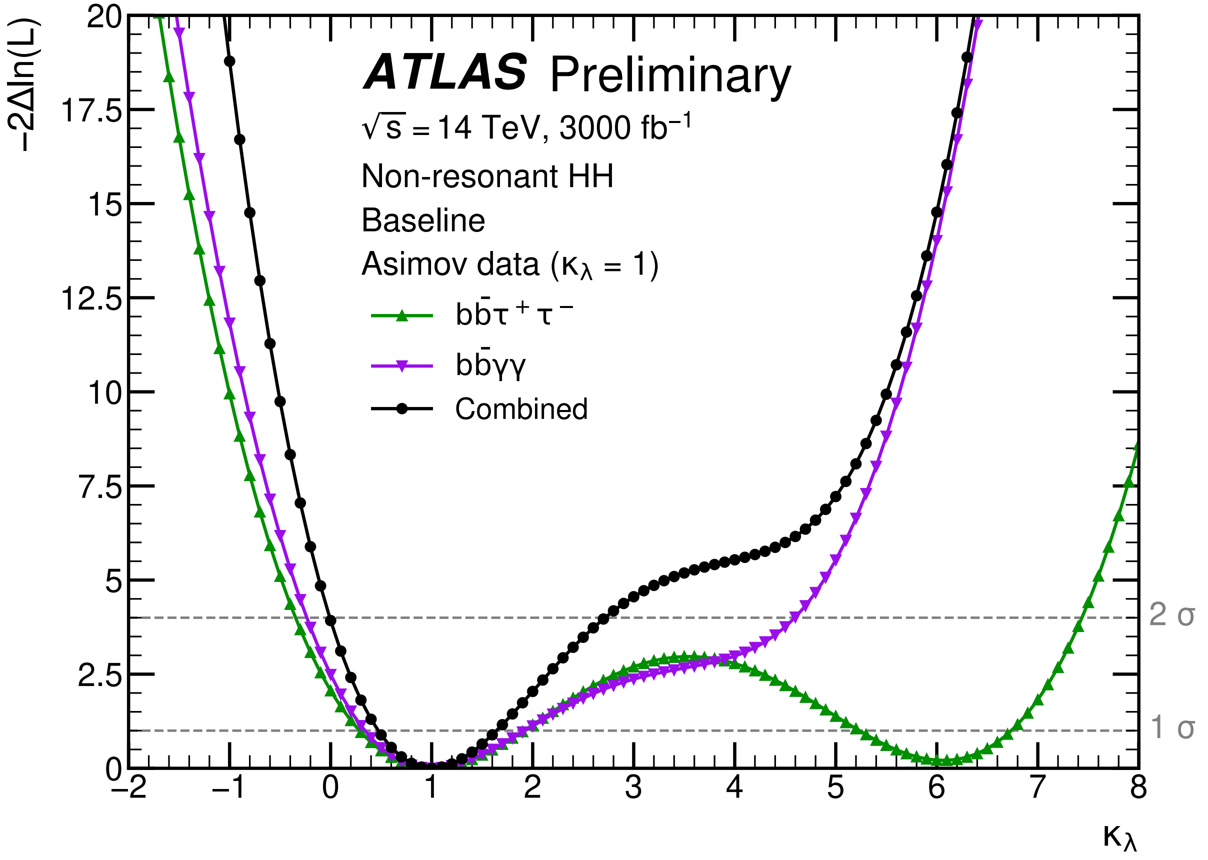
If HH signal present at these k_λ values, expect to measure the signal with the shown significance.

Likelihood Scan – Different Scenarios

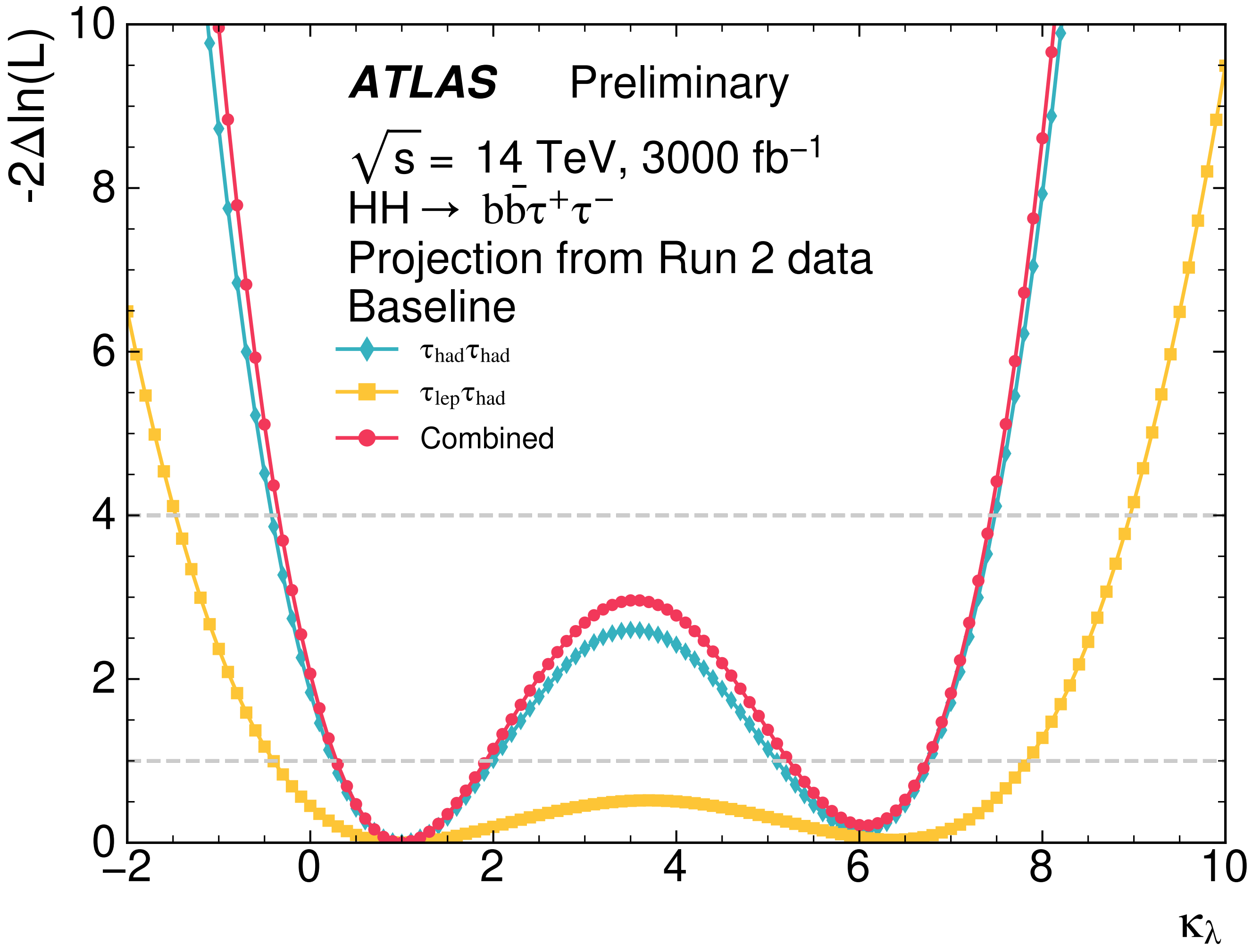
No Systematics



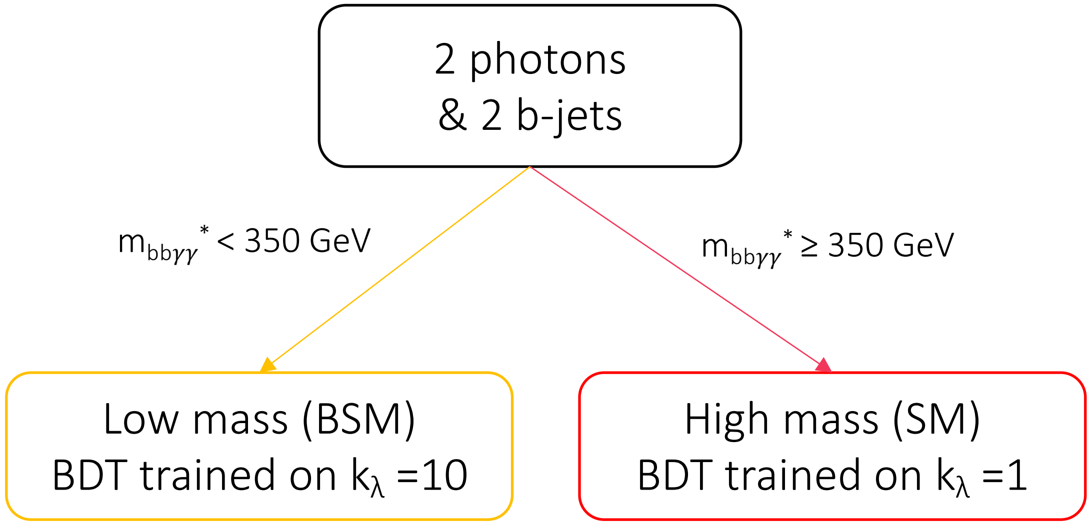
Baseline

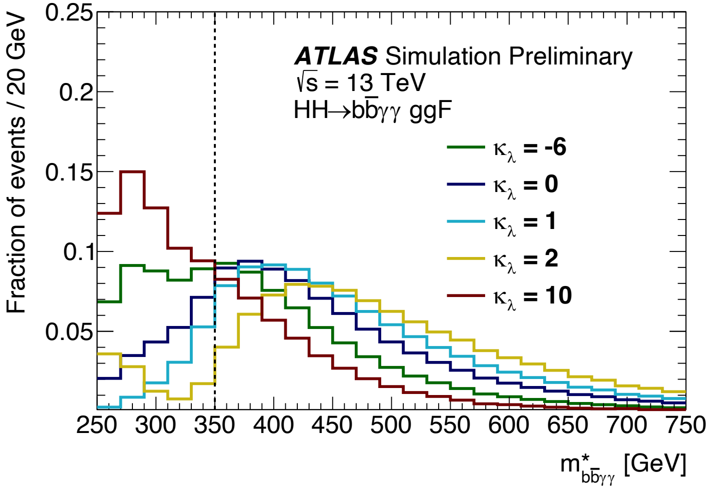


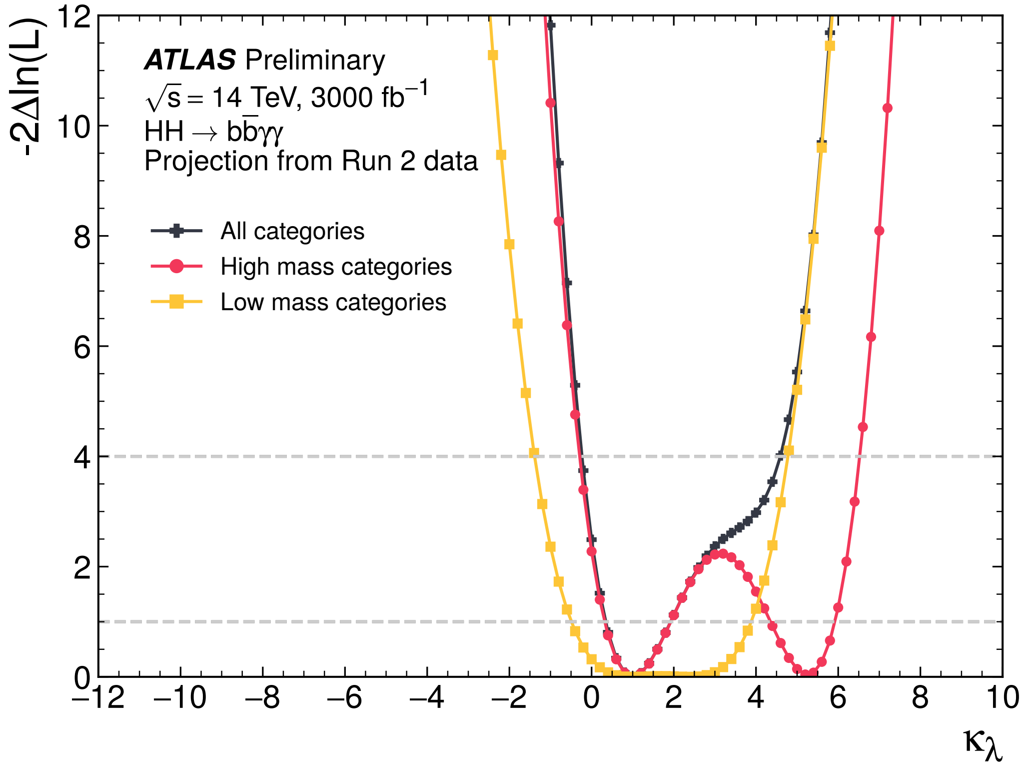
Effect of Different Channels - bbττ



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

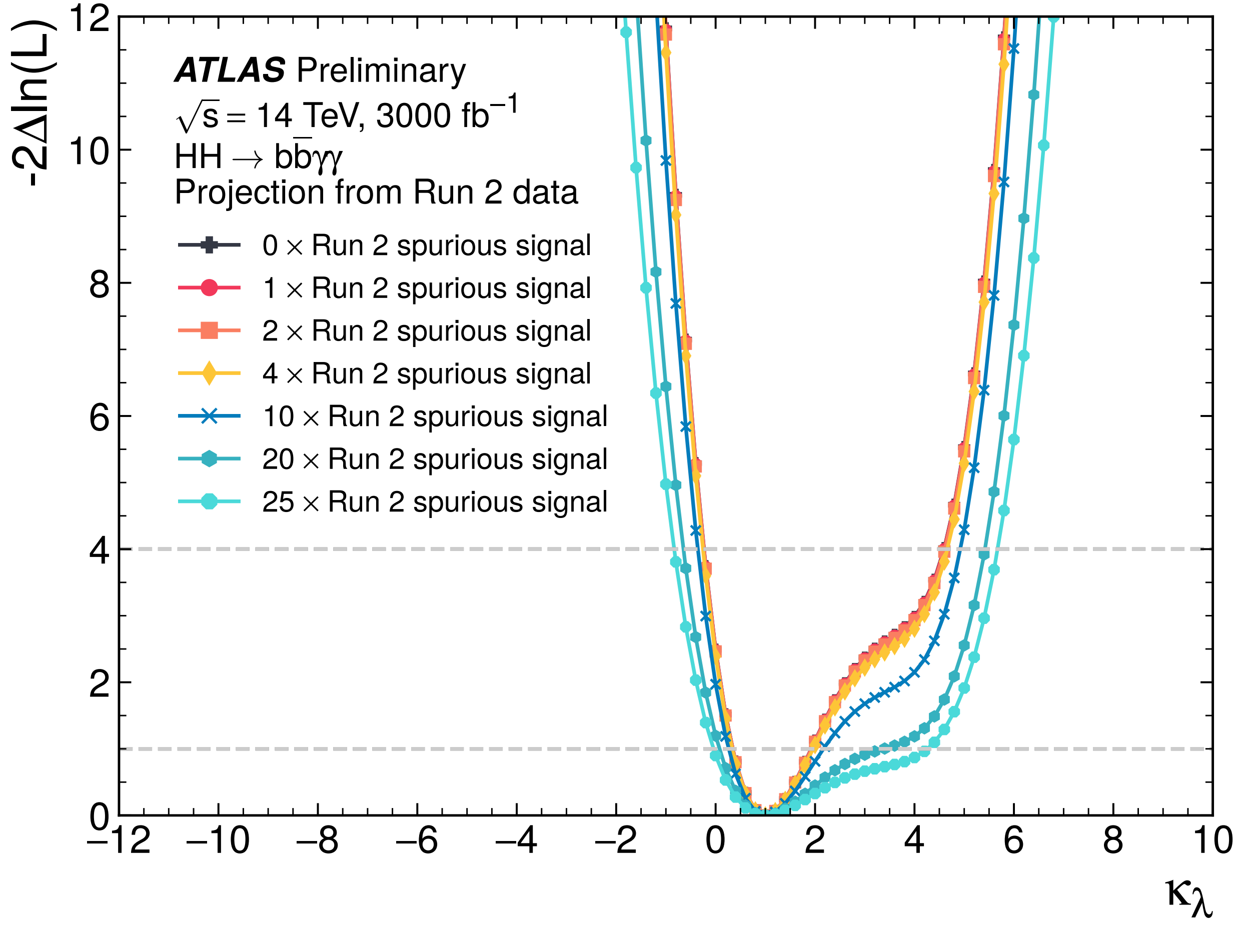






$m_{bb\gamma\gamma}^* = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV

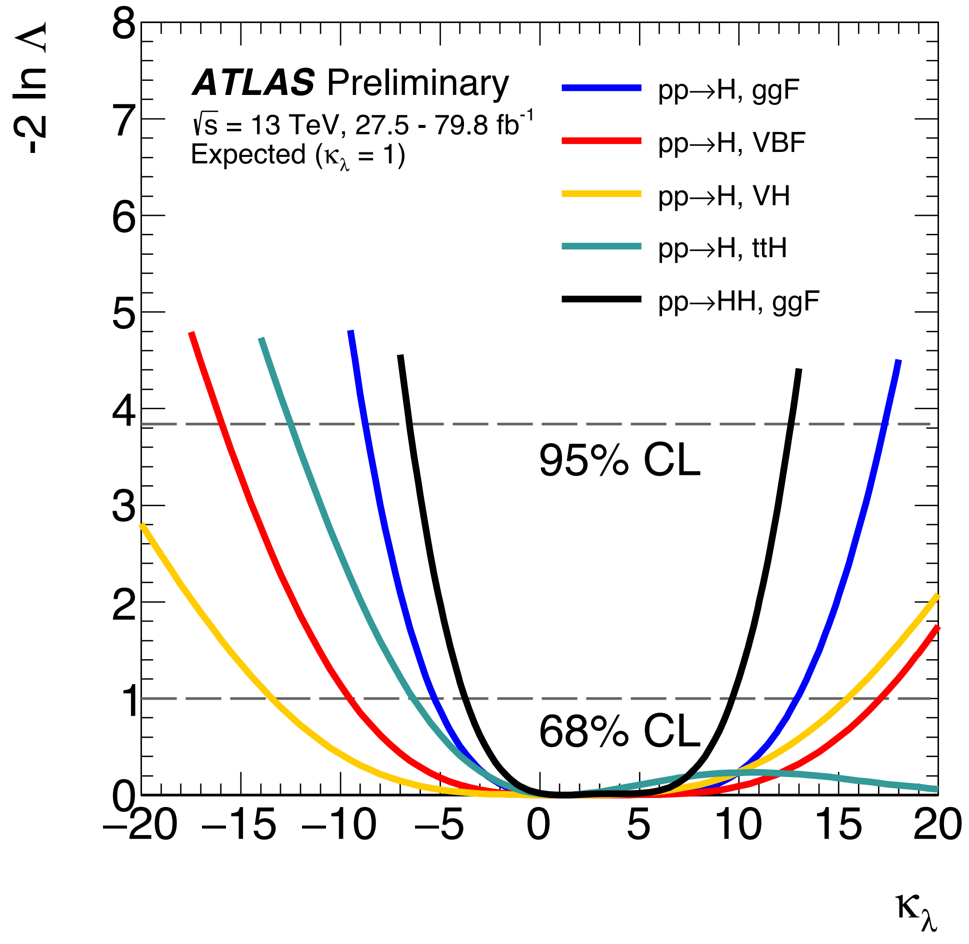
Spurious Signal Studies - $bb\gamma\gamma$

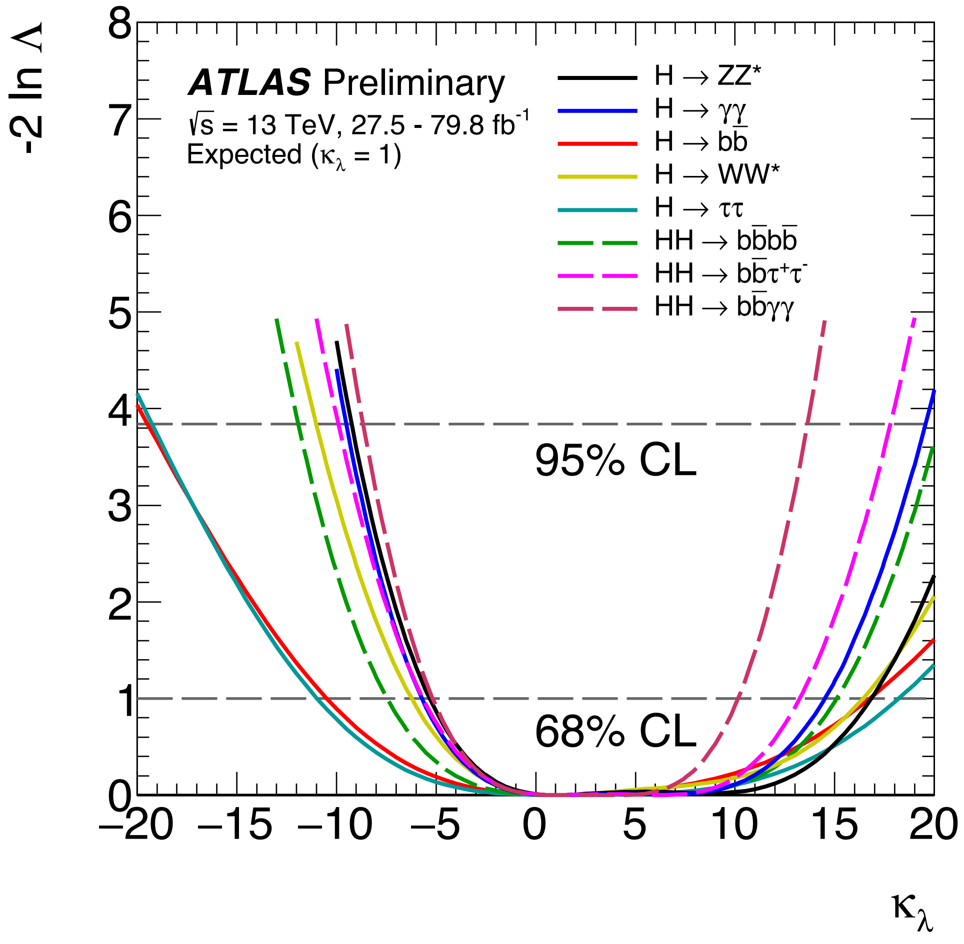


Spurious signal scaling	Effect on Baseline combined significance
0x	0
4x	<1%
25x	<10%

Single Higgs + HH κ_λ

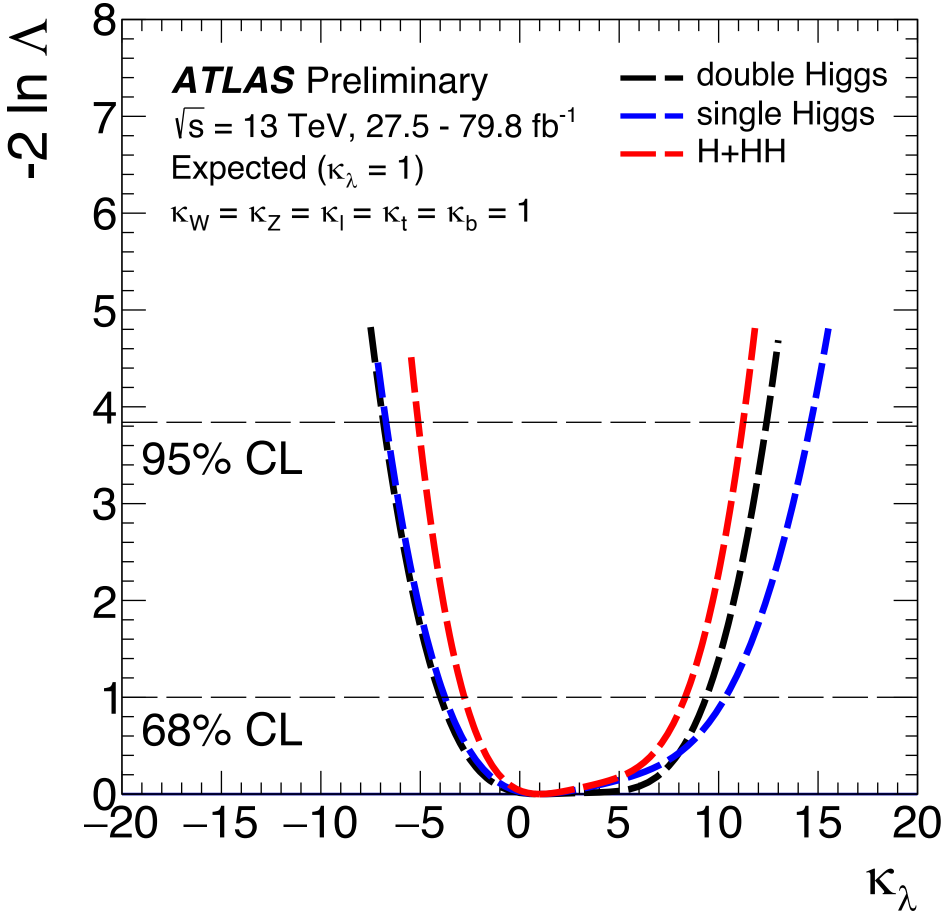
ATLAS-CONF-2019-049

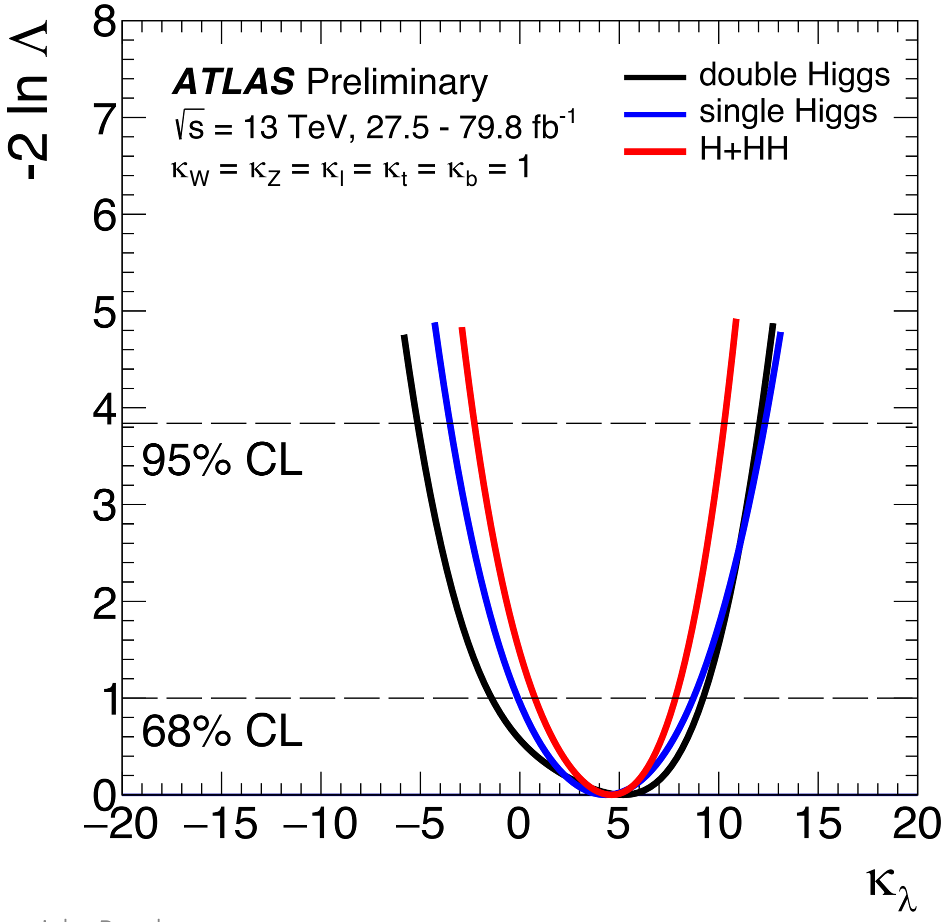




Single Higgs + HH κ_λ

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 $Z+\mathrm{HF}$ normalisations	4%
MC statistical	28%
Experimental	
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	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%
$Z(\rightarrow \tau\tau)+\mathrm{HF}$	9%
Single Higgs boson	29%
Other backgrounds	3%
Signal	5%

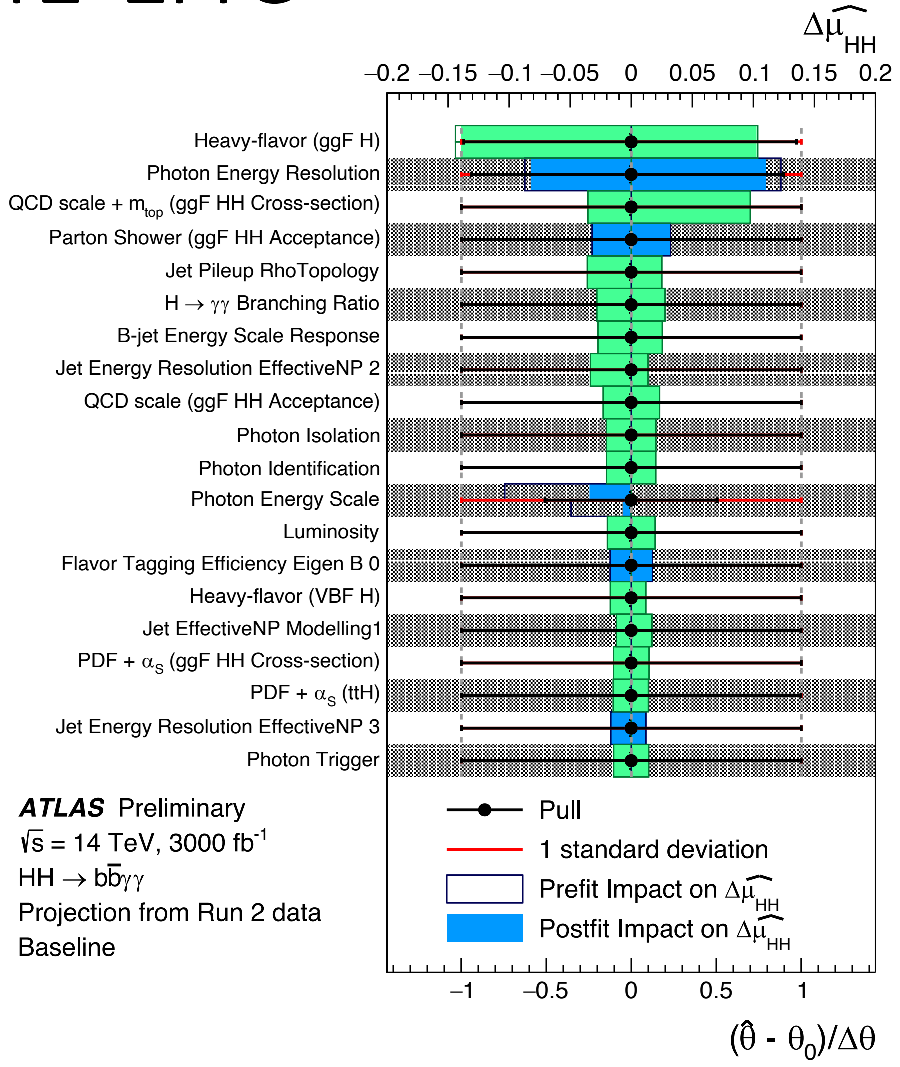
Dominant Systematics @ HL-LHC

Theory uncertainties:

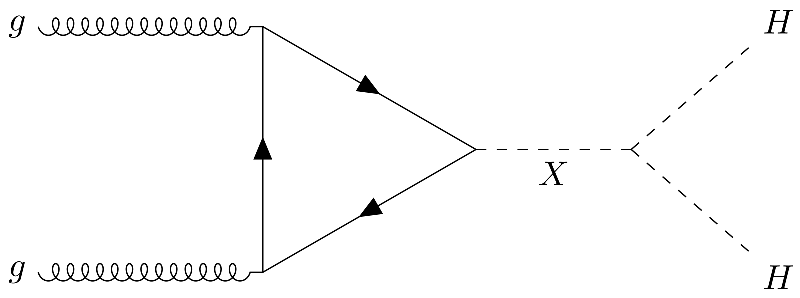
- ggF H (in association with b, or c)
- Wt tt interference (bbττ)
- ggF HH cross-section

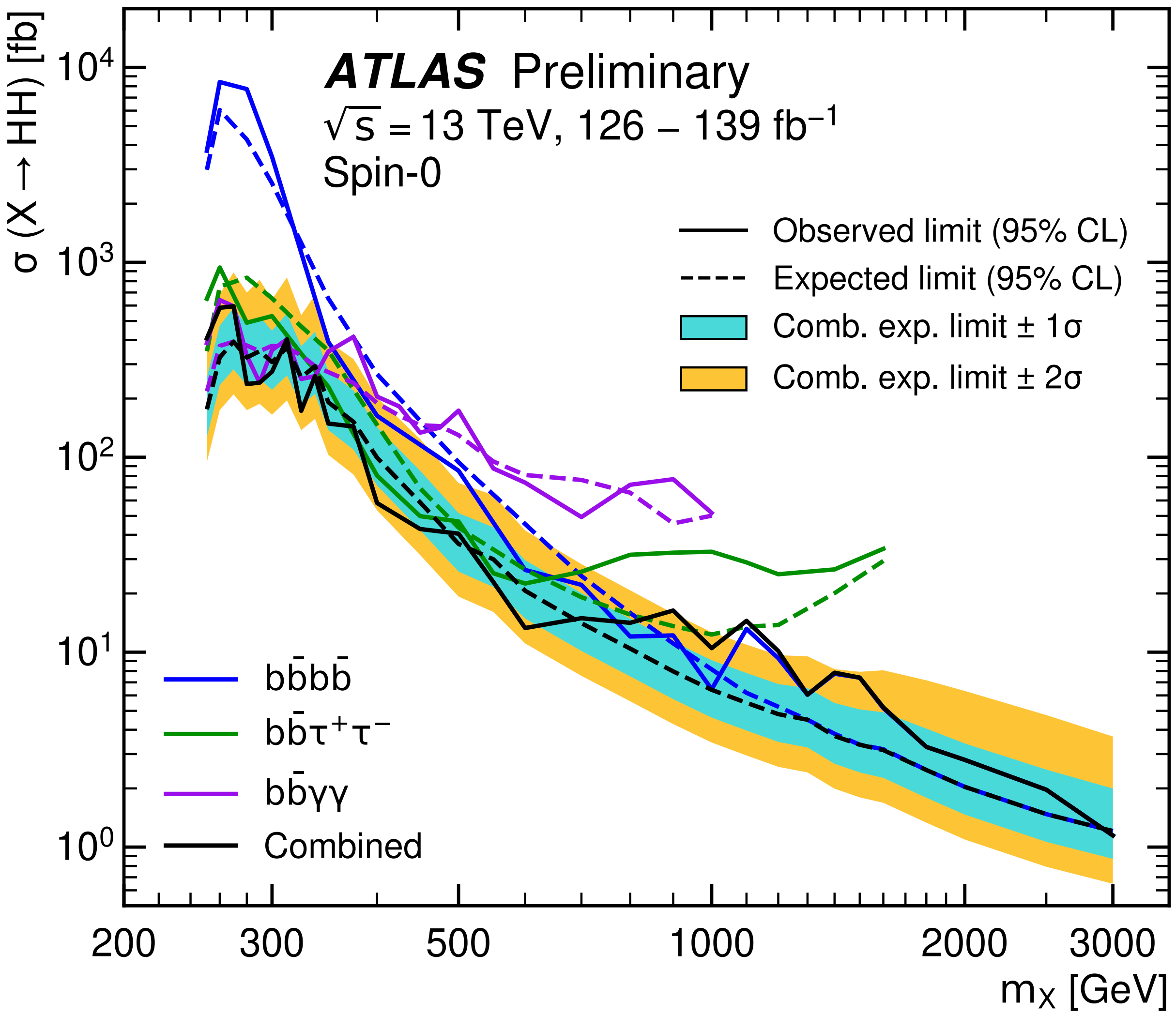
Experimental uncertainties

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



Resonant Run 2 Combined Results

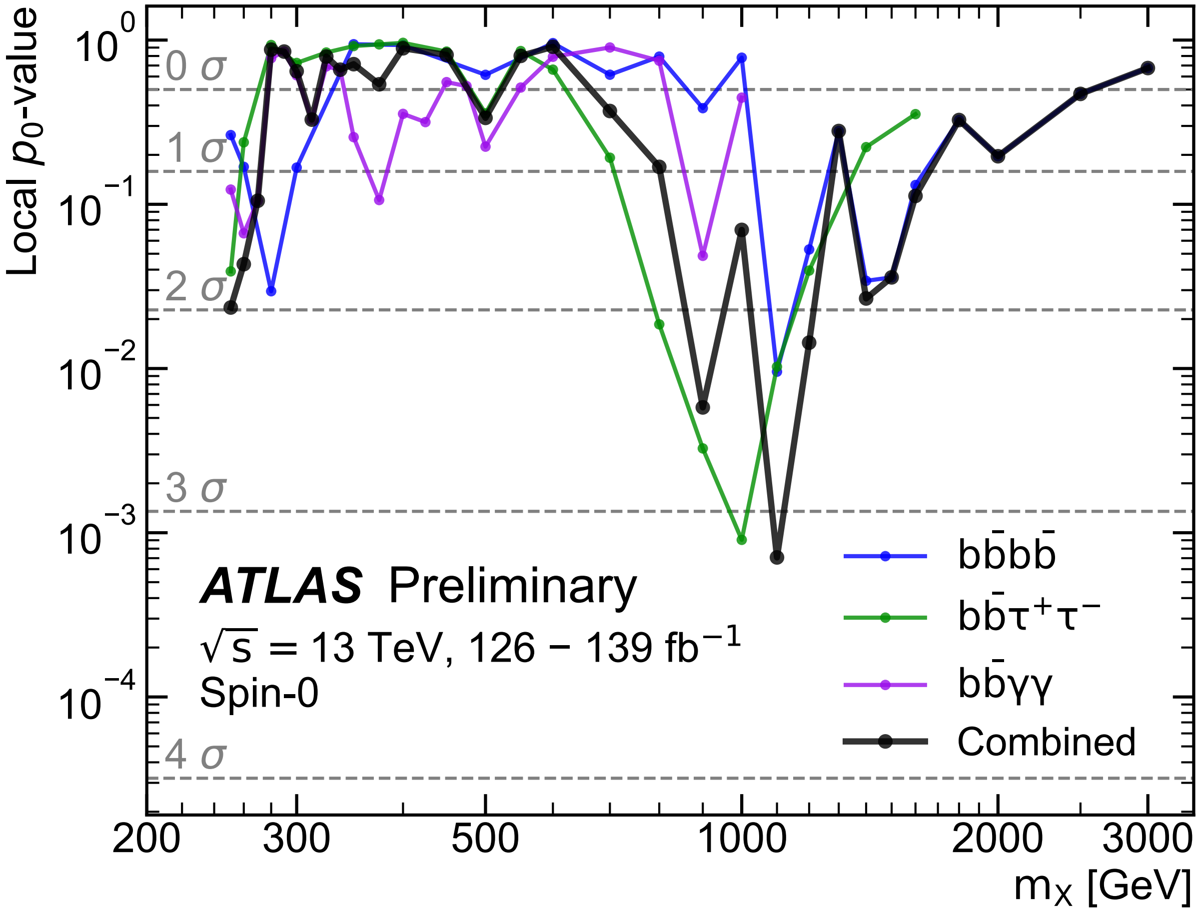




Discontinuity in region $m_X < 400$ GeV is due to partial availability of limits across all analyses. bb$\gamma\gamma$ is the only analysis to provide limits at certain low resonance mass points.

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 4.5		Combined 4.0	

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