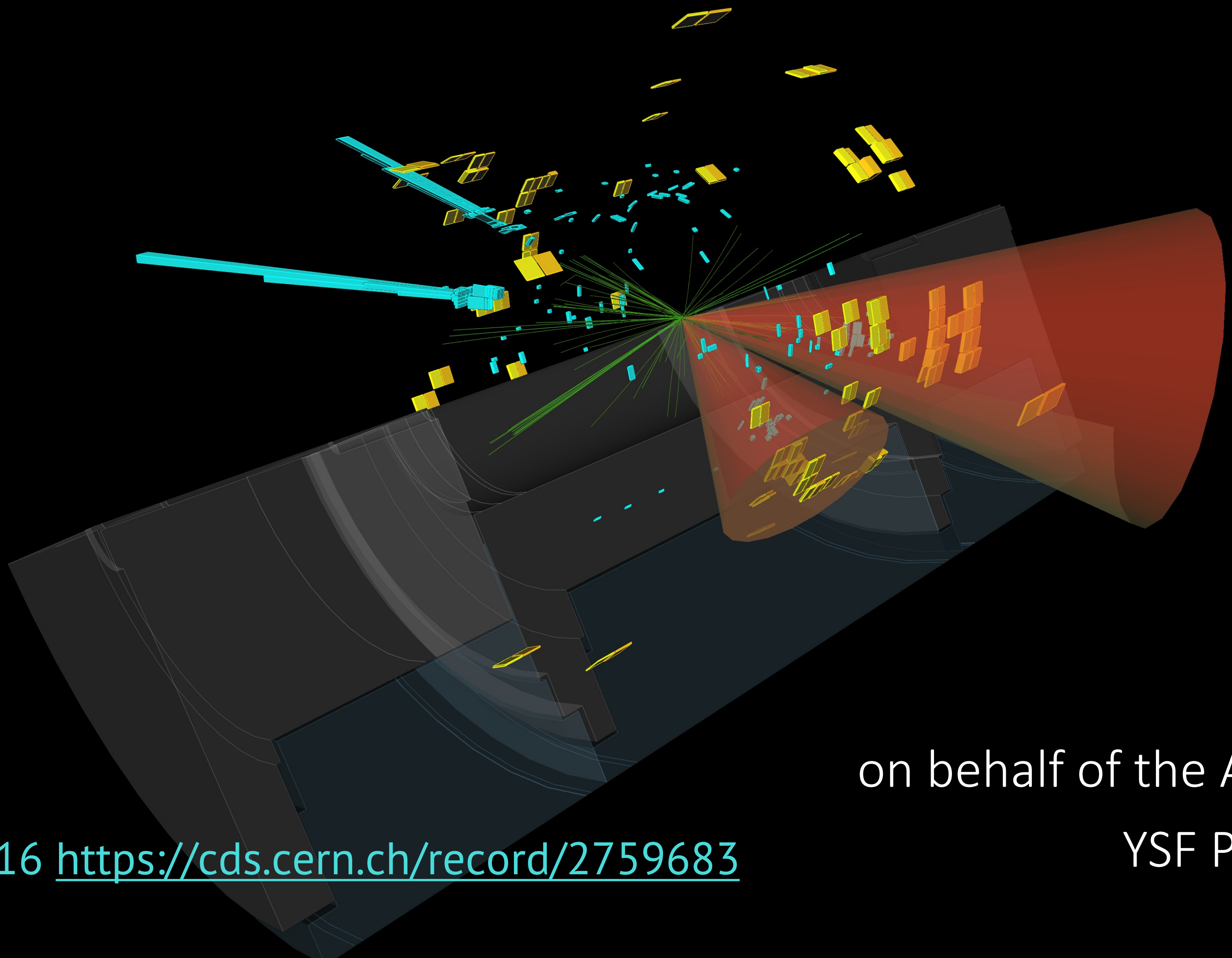
Search for Non-Resonant Di-Higgs Production in the $bb\gamma\gamma$ Final State at 13 TeV with the ATLAS Experiment



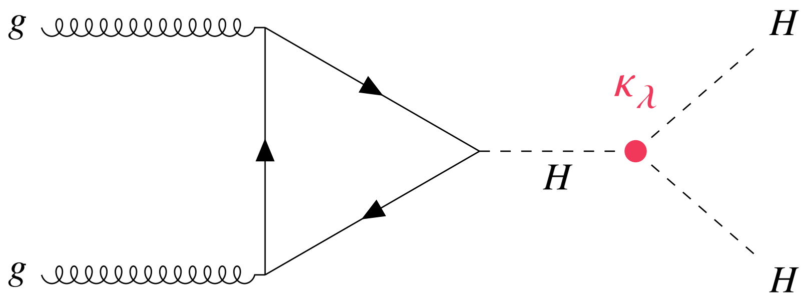
Jannicke Pearkes

on behalf of the ATLAS Collaboration

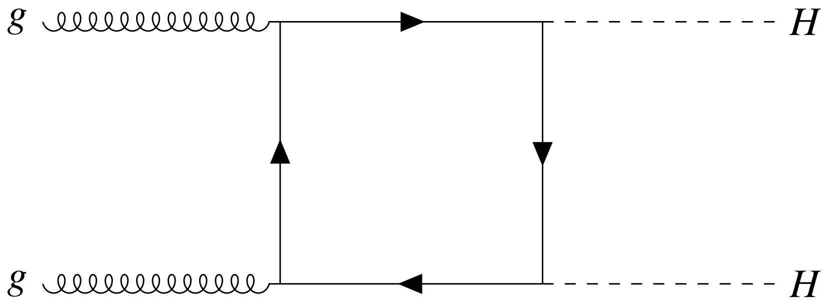
YSF Plenary - Higgs 2021

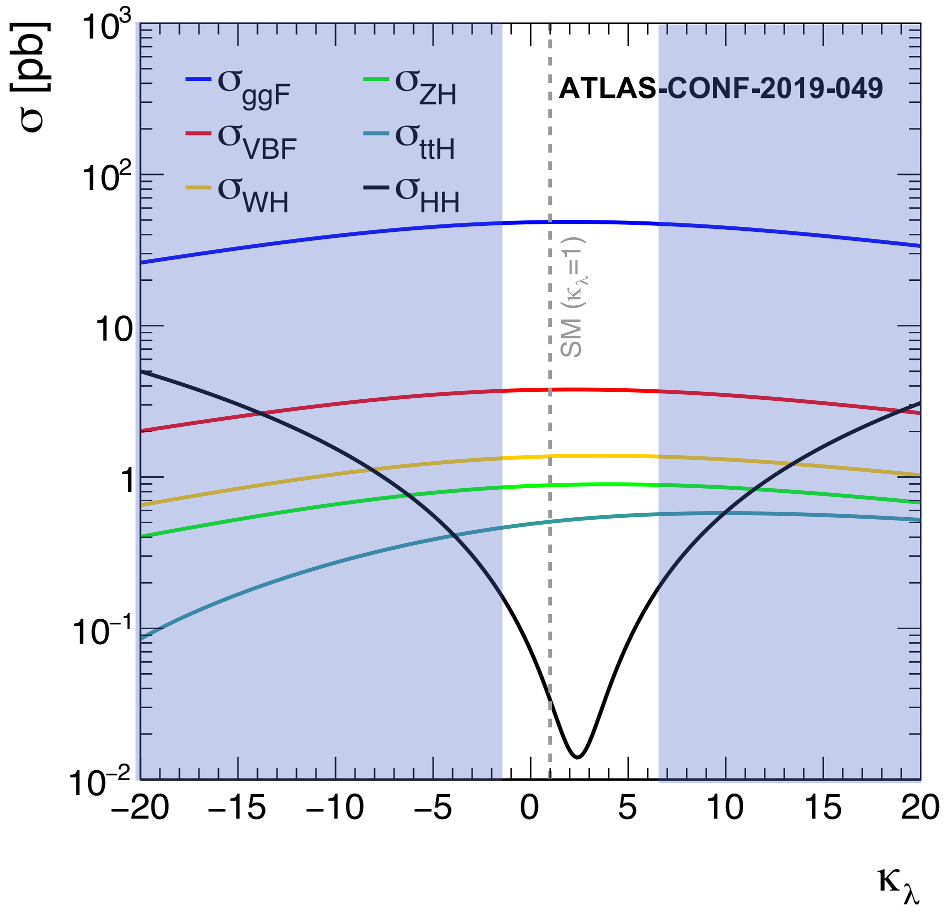
ATLAS-CONF-2021-016 https://cds.cern.ch/record/2759683

Why Di-Higgs?



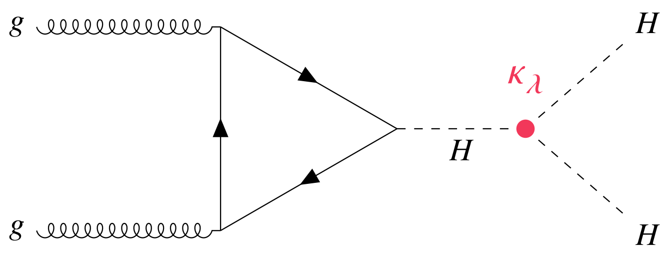
$$\kappa_\lambda = \frac{\lambda_{\mathrm{measured}}}{\lambda_{\mathrm{SM}}}$$





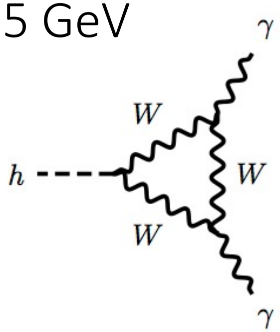
New physics could affect the Higgs self-coupling (λ), and greatly impact the HH cross-section.

HH to bb$\gamma\gamma$

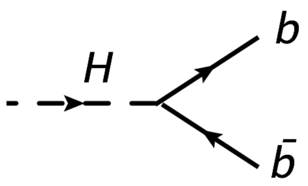


Higgs to $\gamma\gamma$ has a low branching ratio, but also a relatively low background.

Clean di-photon signature can be used for trigger with low thresholds: $p_{T,1} > 35$ GeV & $p_{T,2} > 25$ GeV



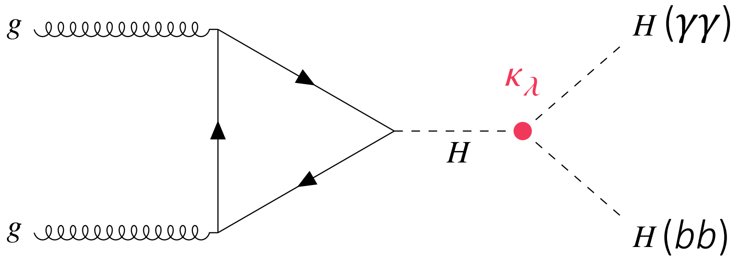
Higgs to bb has a high branching ratio, but also a high background



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%

Branching ratio for bb$\gamma\gamma$ is tiny, ~10 events in all of Run 2 😱

Why HH to bb$\gamma\gamma$?

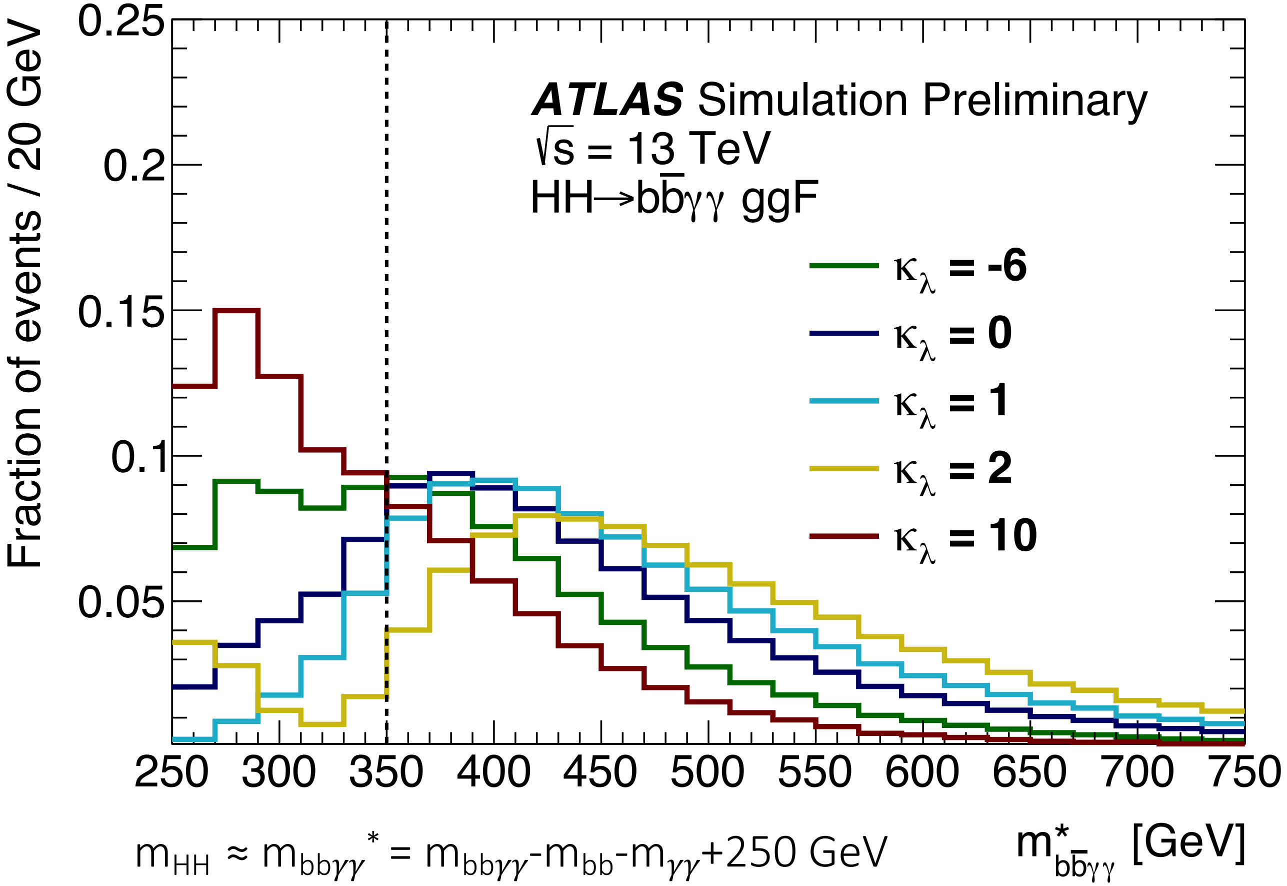


Non-SM values of κ_λ tend to enhance the HH production rate, especially at *low* HH invariant masses (m_{HH}).

Low trigger thresholds with $\gamma\gamma$ system
→ Can select lower energy Higgs bosons

Lower energy Higgs bosons
→ Sensitive to events with low m_{HH}

This leads to bb$\gamma\gamma$ being one of the best channels for measuring the Higgs self-coupling!



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

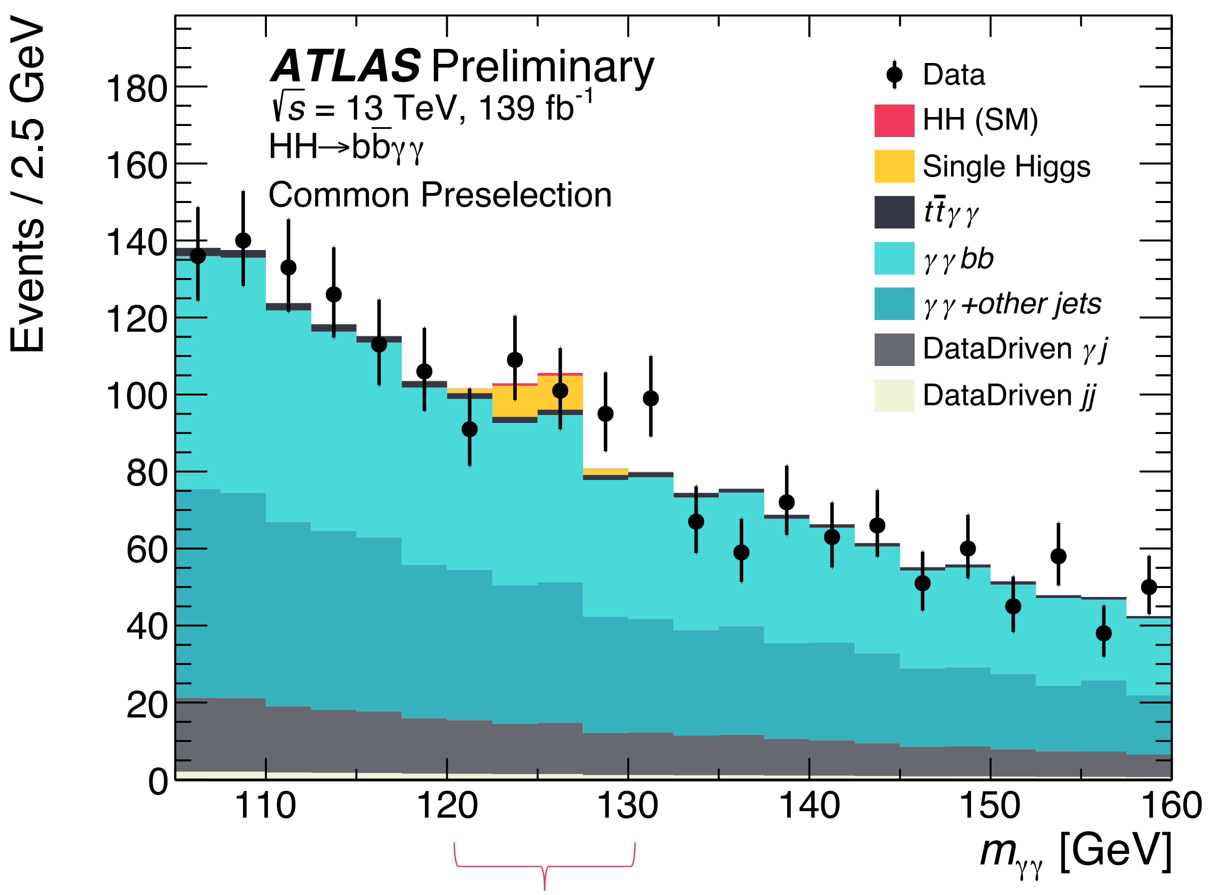
Selection Strategy

2 photons
& 2 b-jets

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

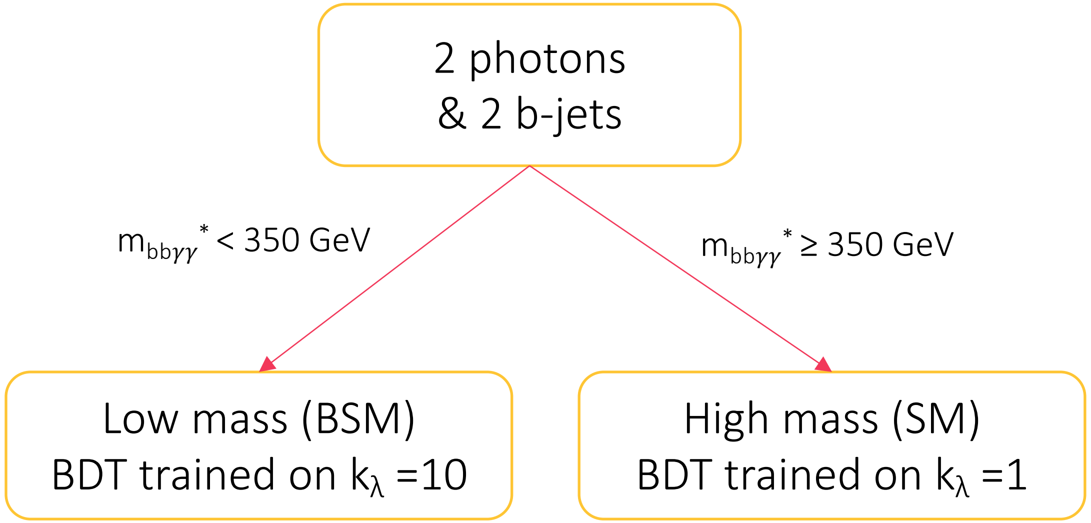
Major backgrounds:
- Diphoton $\gamma\gamma$ (largest contributor)
- Single Higgs (peaks at same $m_{\gamma\gamma}$ as signal)

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



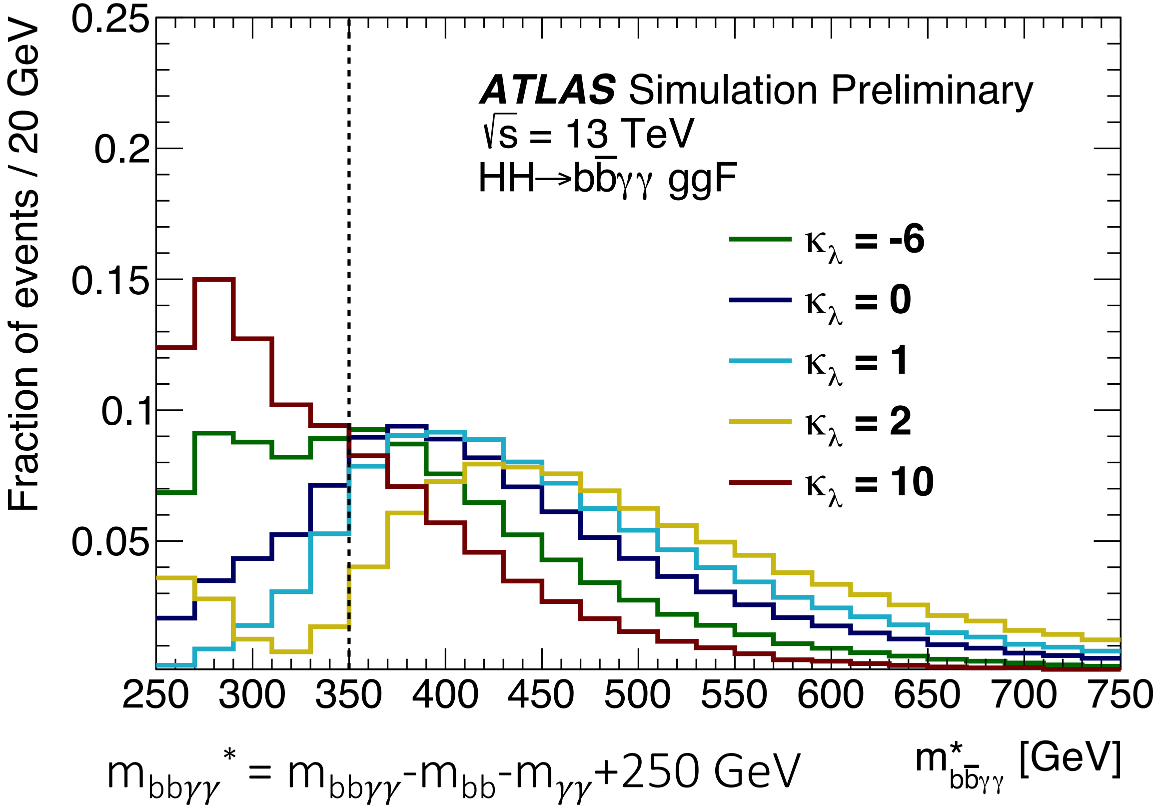
Signal region
$m_{\gamma\gamma}$ = 120-130 GeV

Selection Strategy



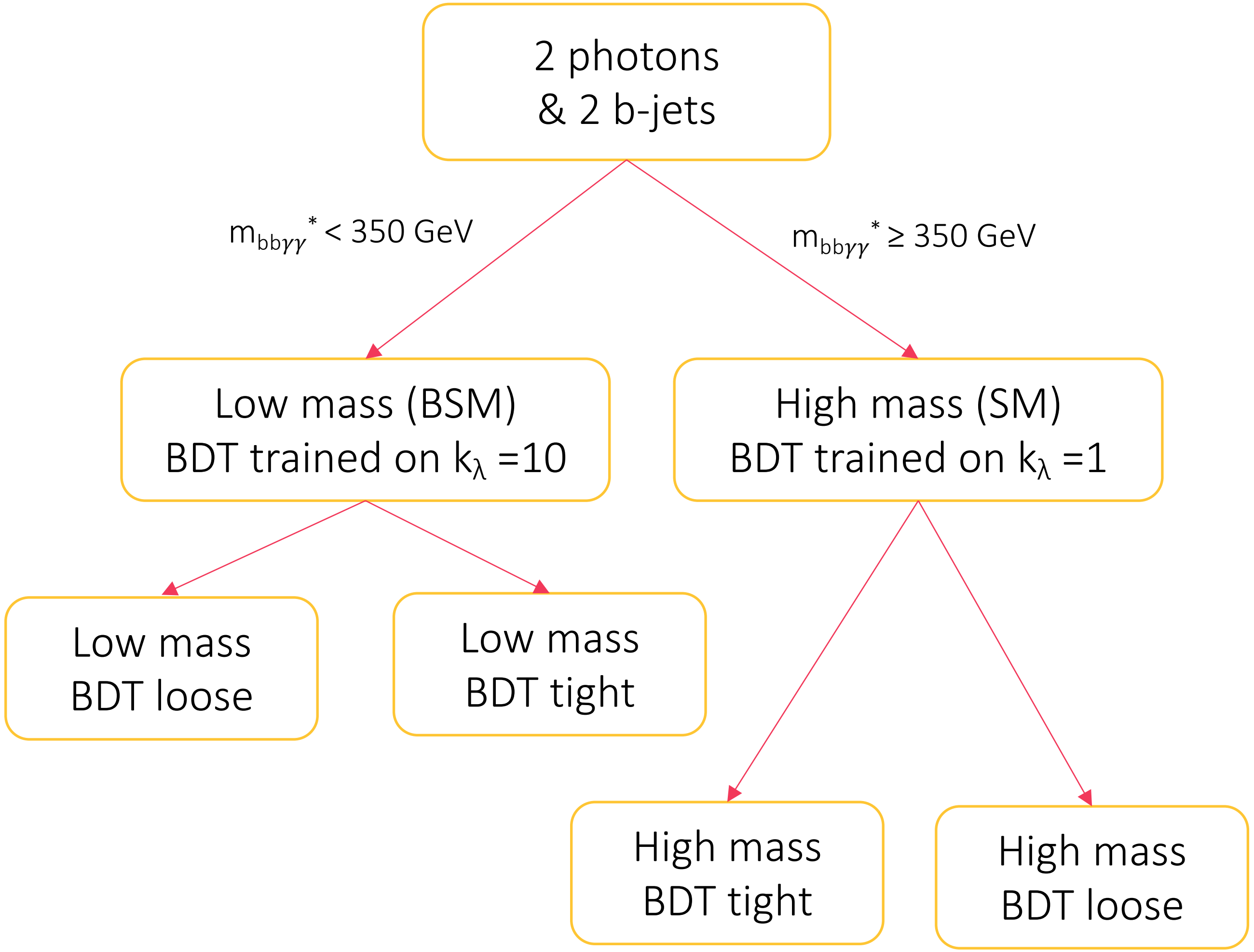
Split signal regions by mbb$\gamma\gamma$* for sensitivity to SM and BSM HH.

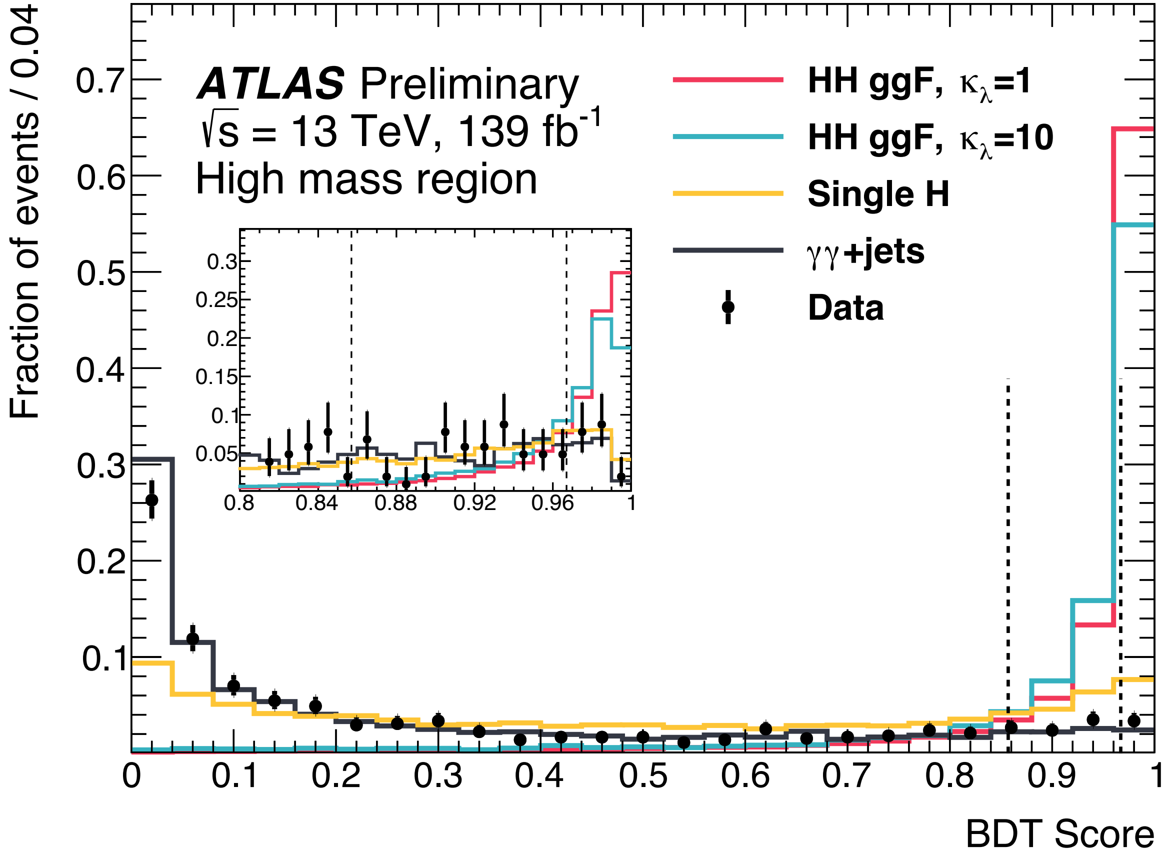
Train two BDTs to target each signal region.



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

Selection Strategy

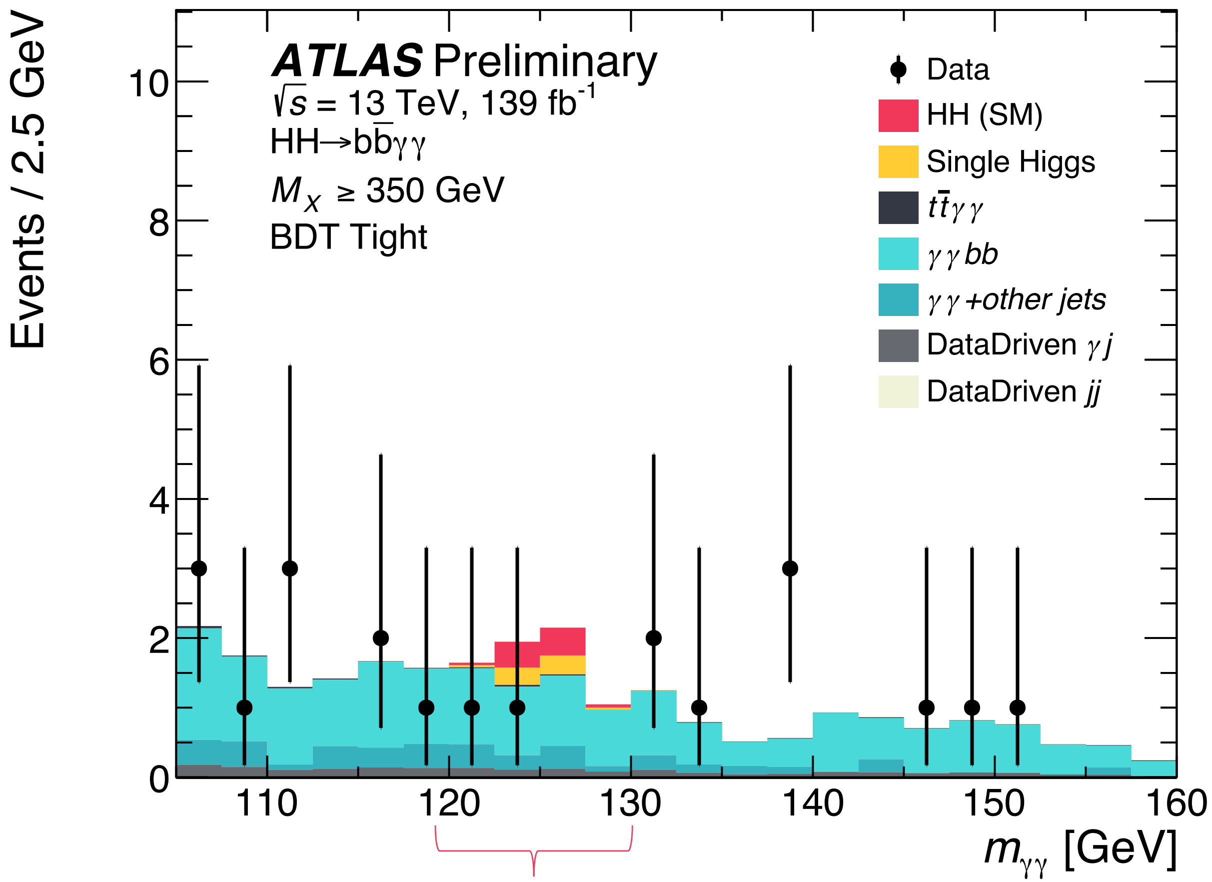




<u>4 BDT Categories</u>

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%

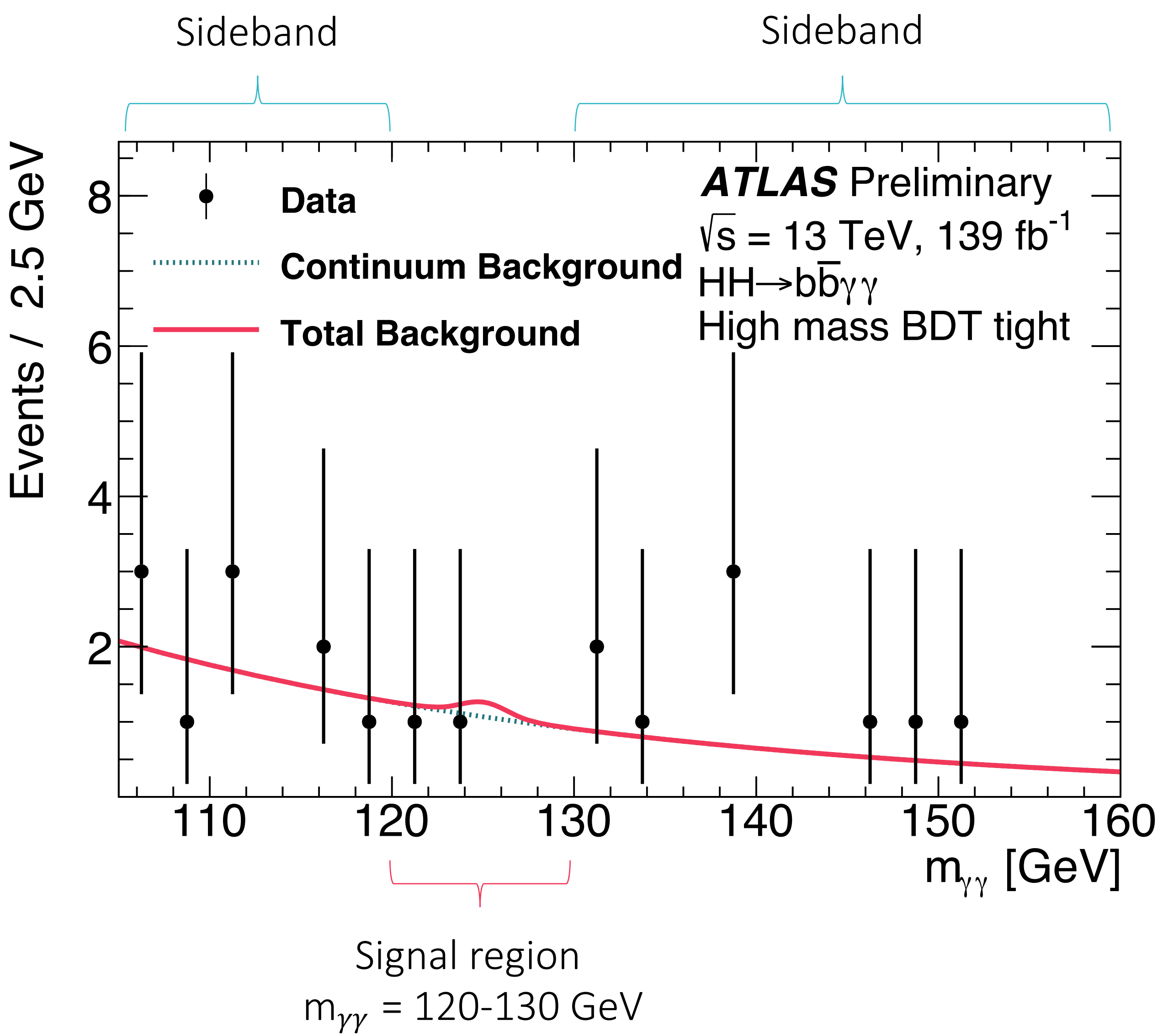
Signal Extraction

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 where $m_{\gamma\gamma}$ is between 105-120 & 130-160 GeV.

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



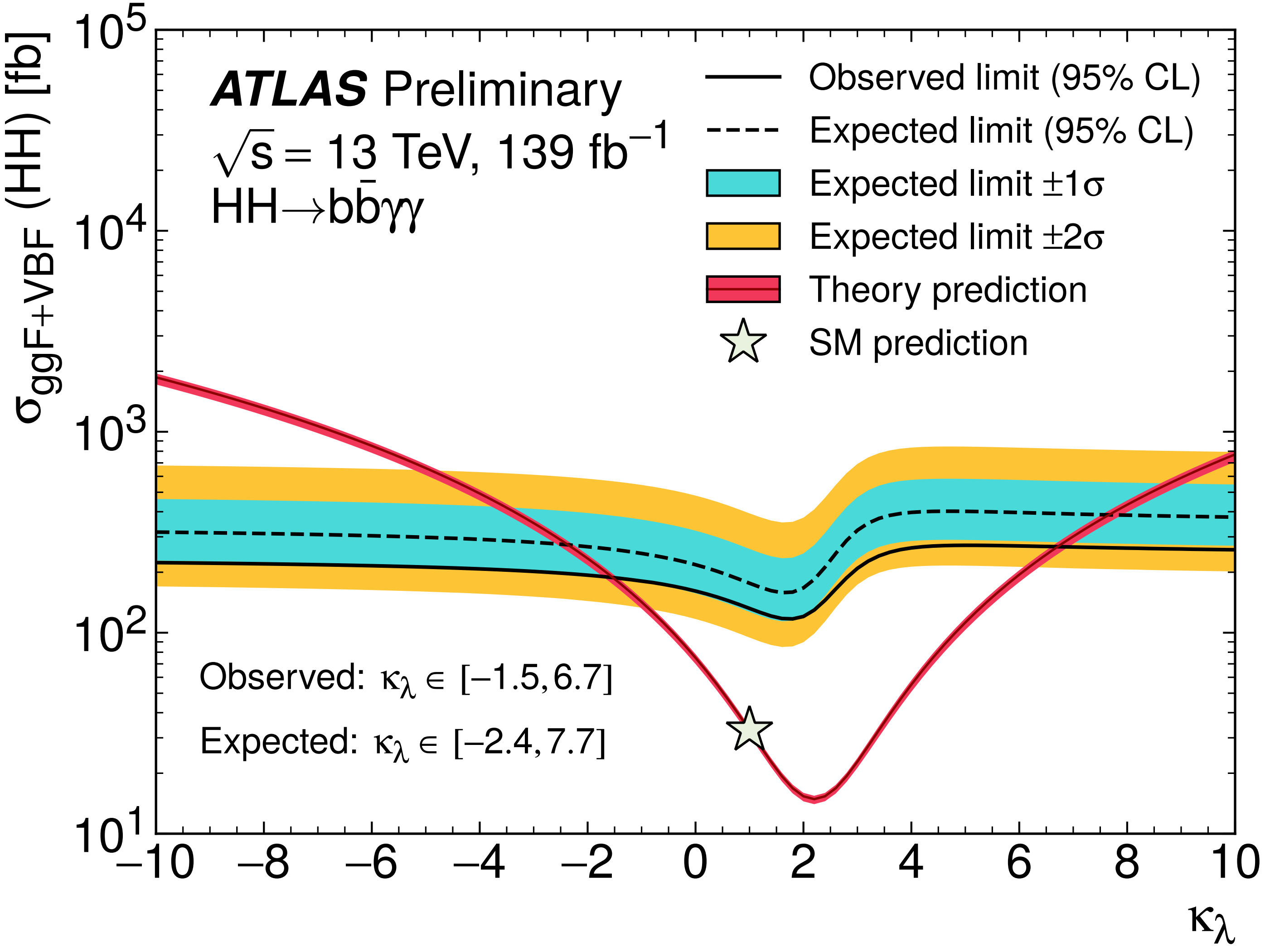
Results

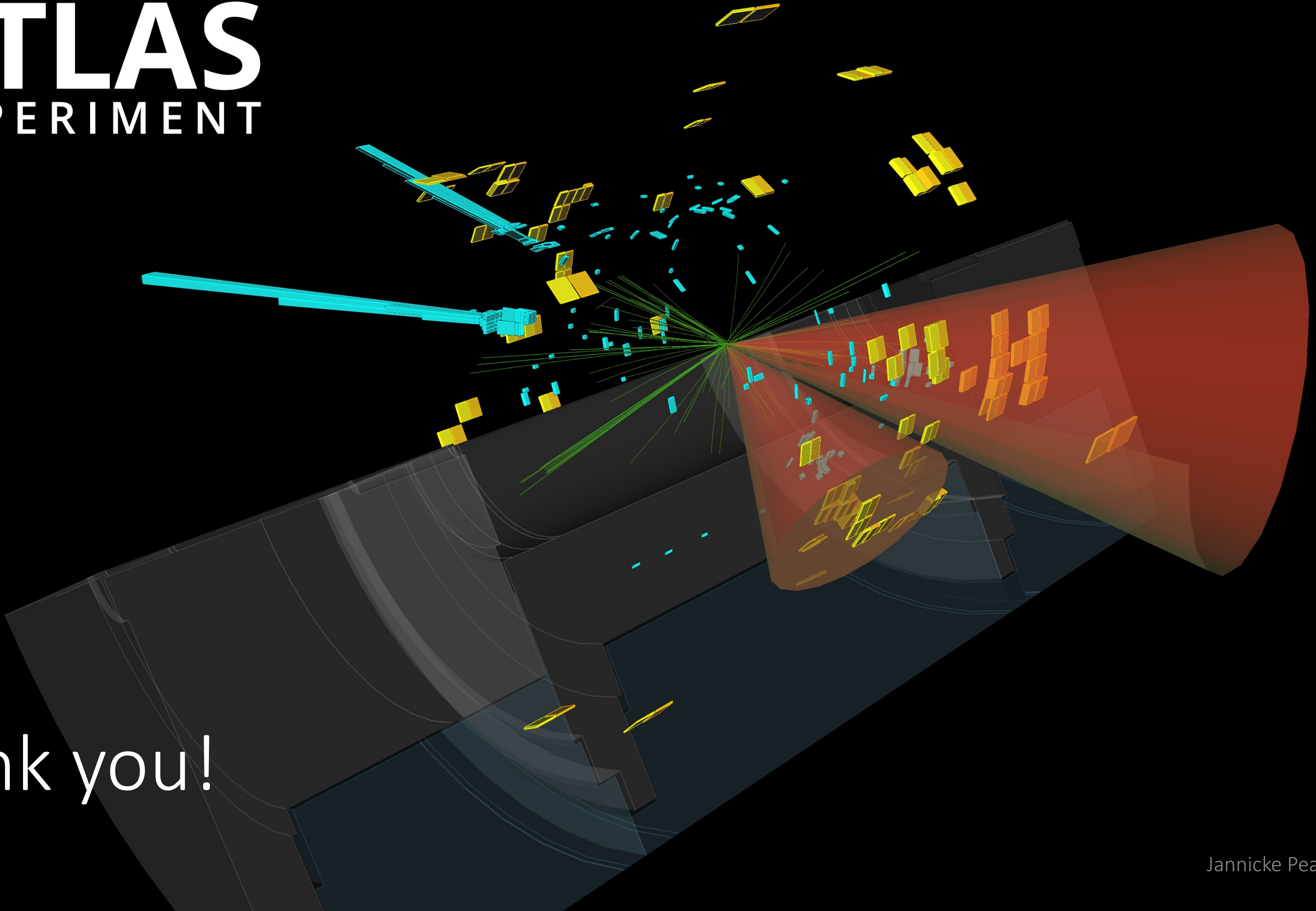
No excess was observed, upper limits on the SM cross-section are set using the CLs method.

Observed 95% CL limit on SM cross-section is <u>4.1xSM</u> (5.5xSM expected)

Observed (expected) limits on k_λ :
$-1.5 < k_\lambda < 6.7$, ($-2.4 < k_\lambda < 6.7$)

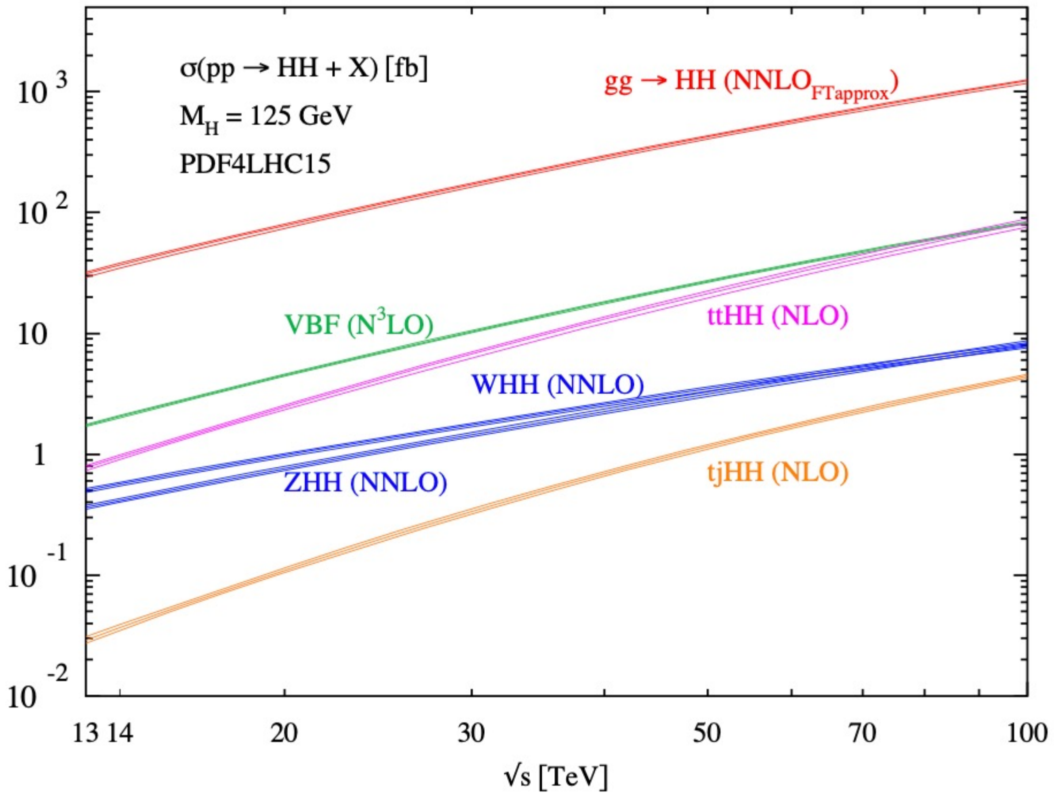
Previous Run 2 limits with 36.1 fb^{-1} : 20xSM, $-8.2 < k_\lambda < 13.2$. New limits greatly improved by updated selection strategies.

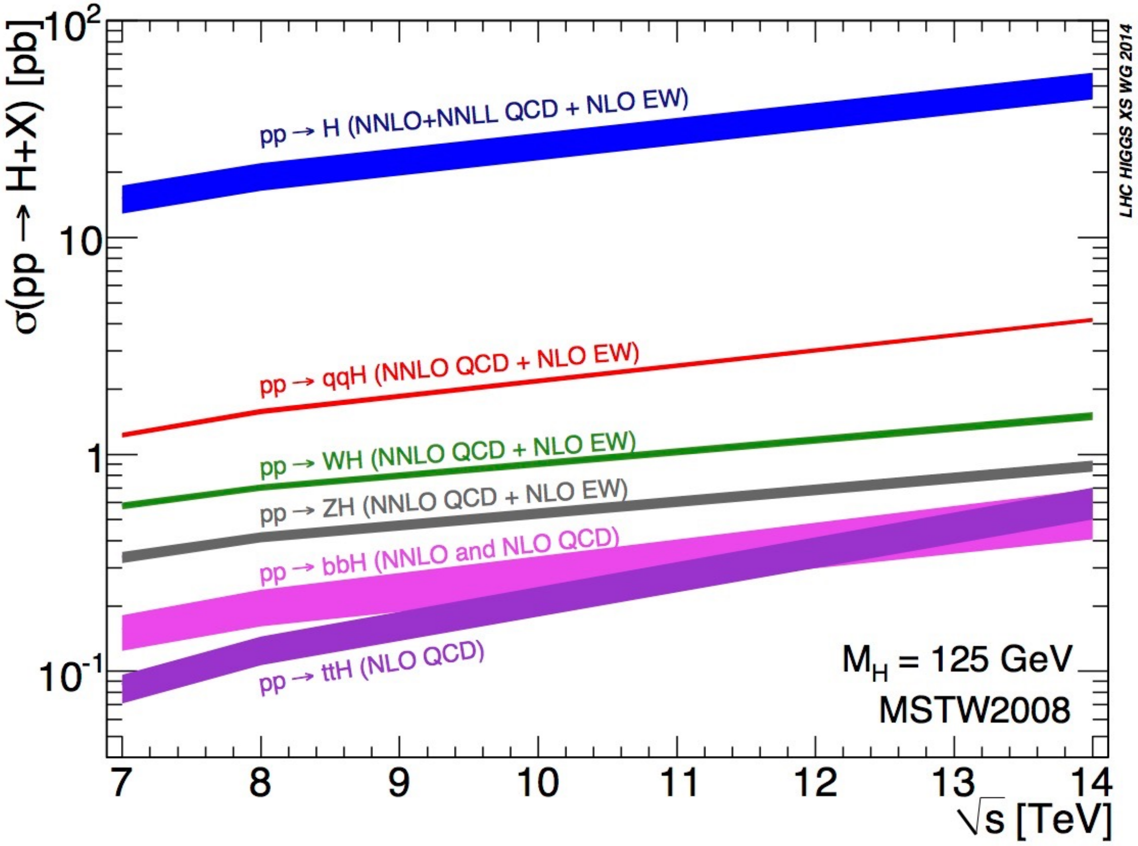




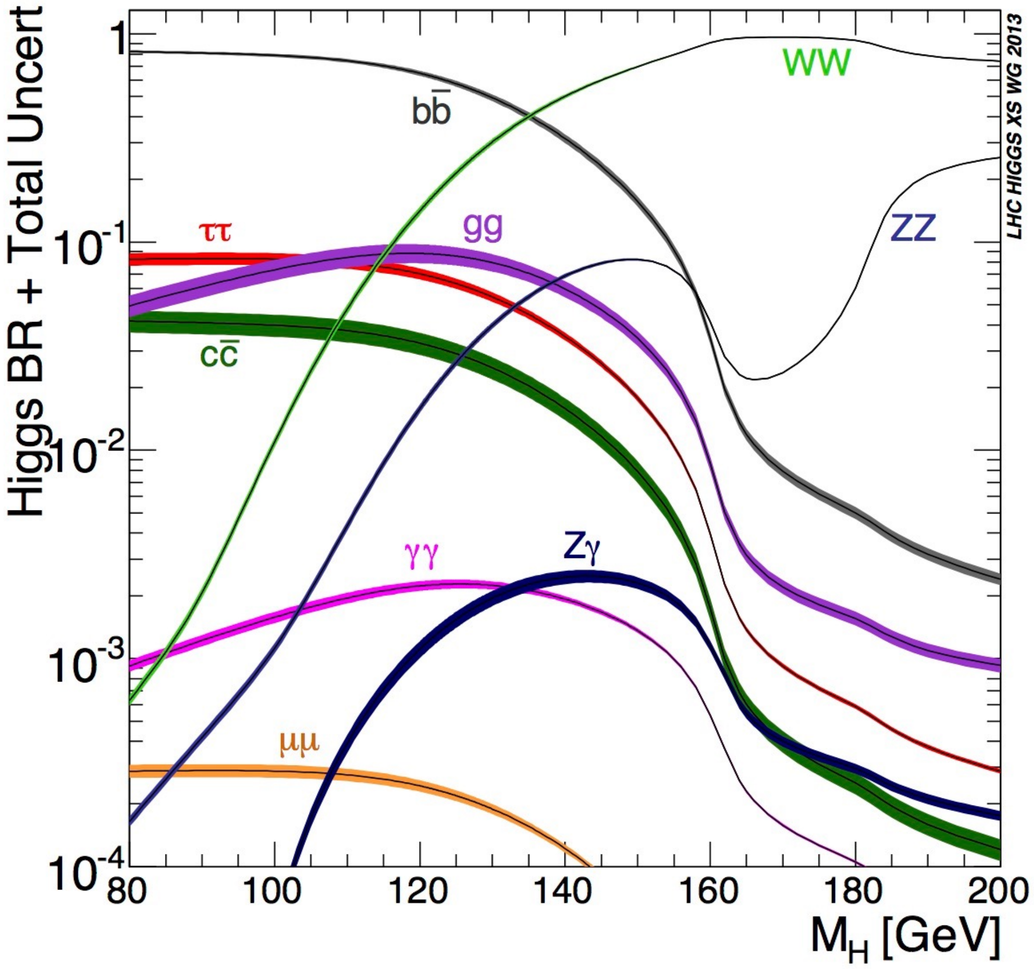
Thank you!

HH Production Cross-Sections





Higgs Branching Ratios



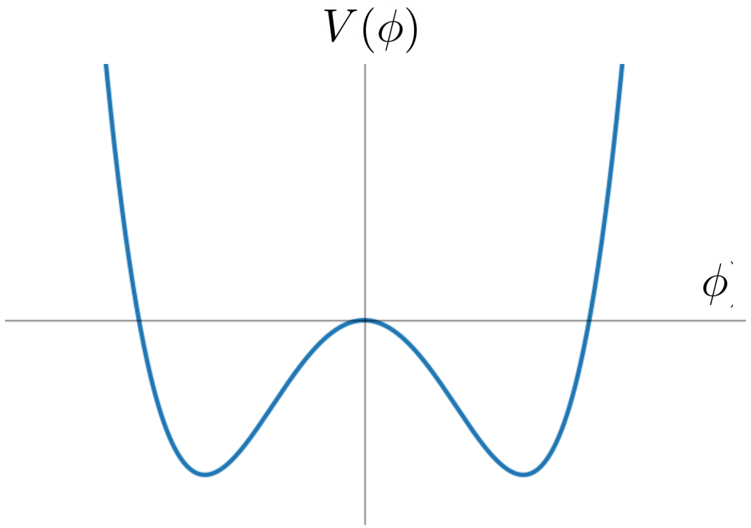
Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.28×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.64×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.15×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.32×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.77×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.54×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.19×10^{-4}	$^{+6.0\%}_{-5.9\%}$

The Higgs Potential

The Standard Model Higgs Potential is:

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

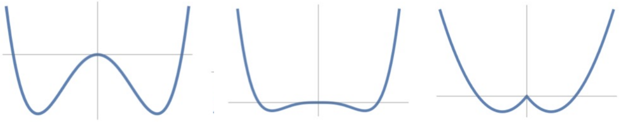
mass term   self-coupling term



In the SM the shape of the potential is is well constrained by the Higgs mass and vacuum expectation value.

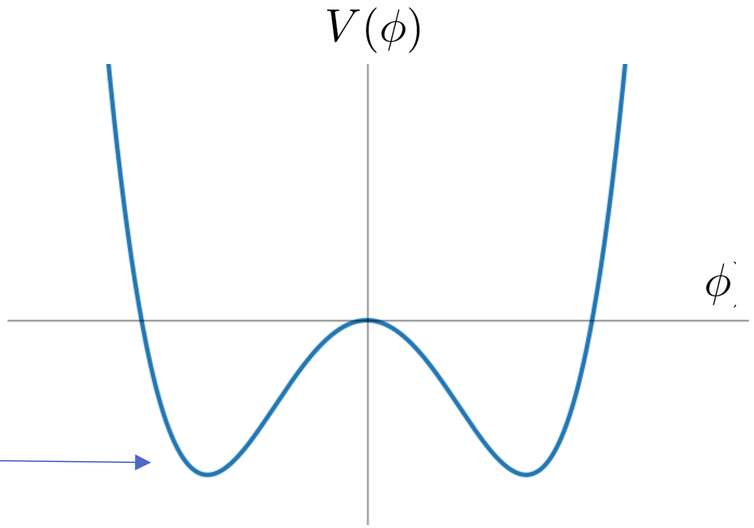
$$\mu = \frac{m_h}{\sqrt{2}} \qquad \lambda = \frac{m_h^2}{2\nu^2} = 0.129 \qquad \nu = \frac{\mu}{\sqrt{\lambda}} = 246\ \text{GeV}$$

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



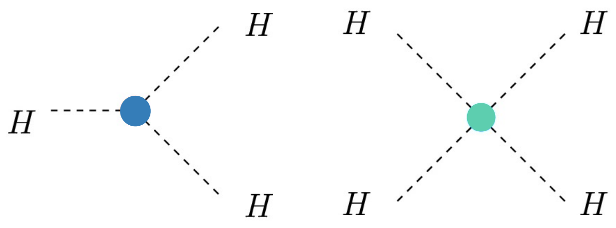
Measuring the Shape

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



Perturb about minimum

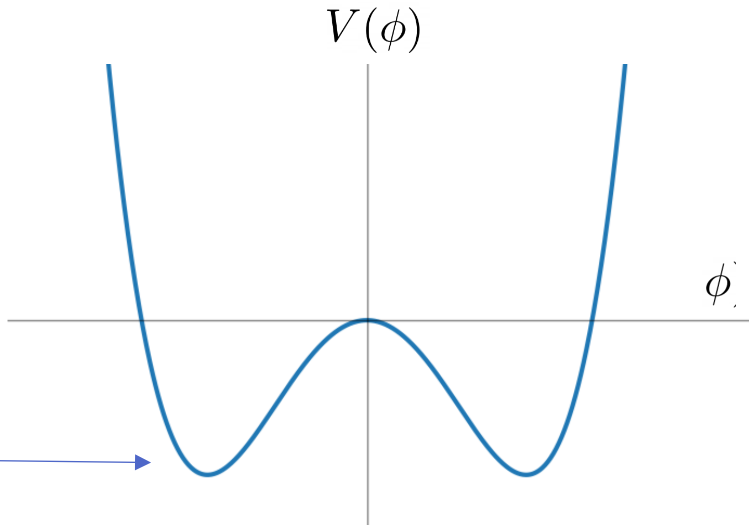
$$V(\nu + h) = -\mu^2(\nu + h)^2 + \lambda(\nu + h)^4$$
$$= V_0 + \frac{1}{2}{m_h}^2h^2 + \lambda v h^3 + \lambda h^4 + \ldots$$



Extremely rare process, inaccessible at LHC

Measuring the Shape

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



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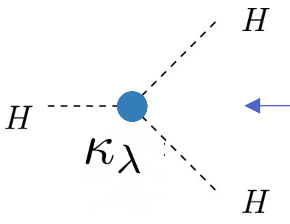
$$= V_0 + \frac{1}{2}{m_h}^2h^2 + \lambda v h^3 + \lambda h^4 + \ldots$$

$$\lambda_{\text{SM}} = \frac{m_h^2}{2\nu^2} = 0.129$$

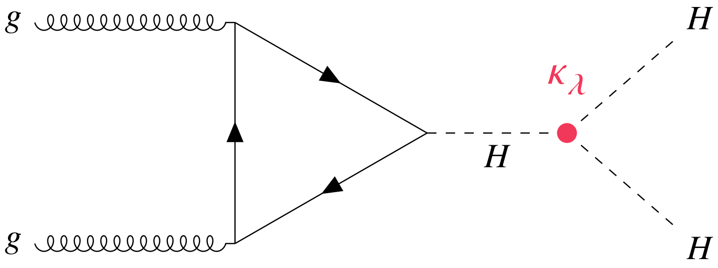
$$\kappa_\lambda = \frac{\lambda_{\text{measured}}}{\lambda_{\text{SM}}}$$



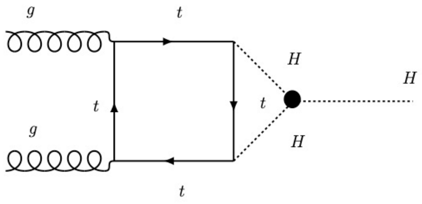
Also, extremely rare process, but easier to probe

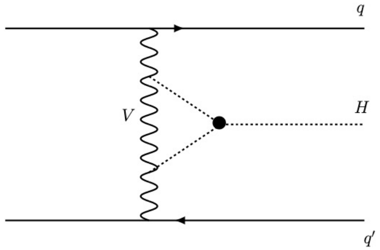
Measuring κ_λ

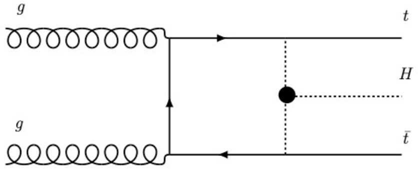
Direct measurement:

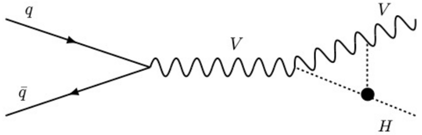


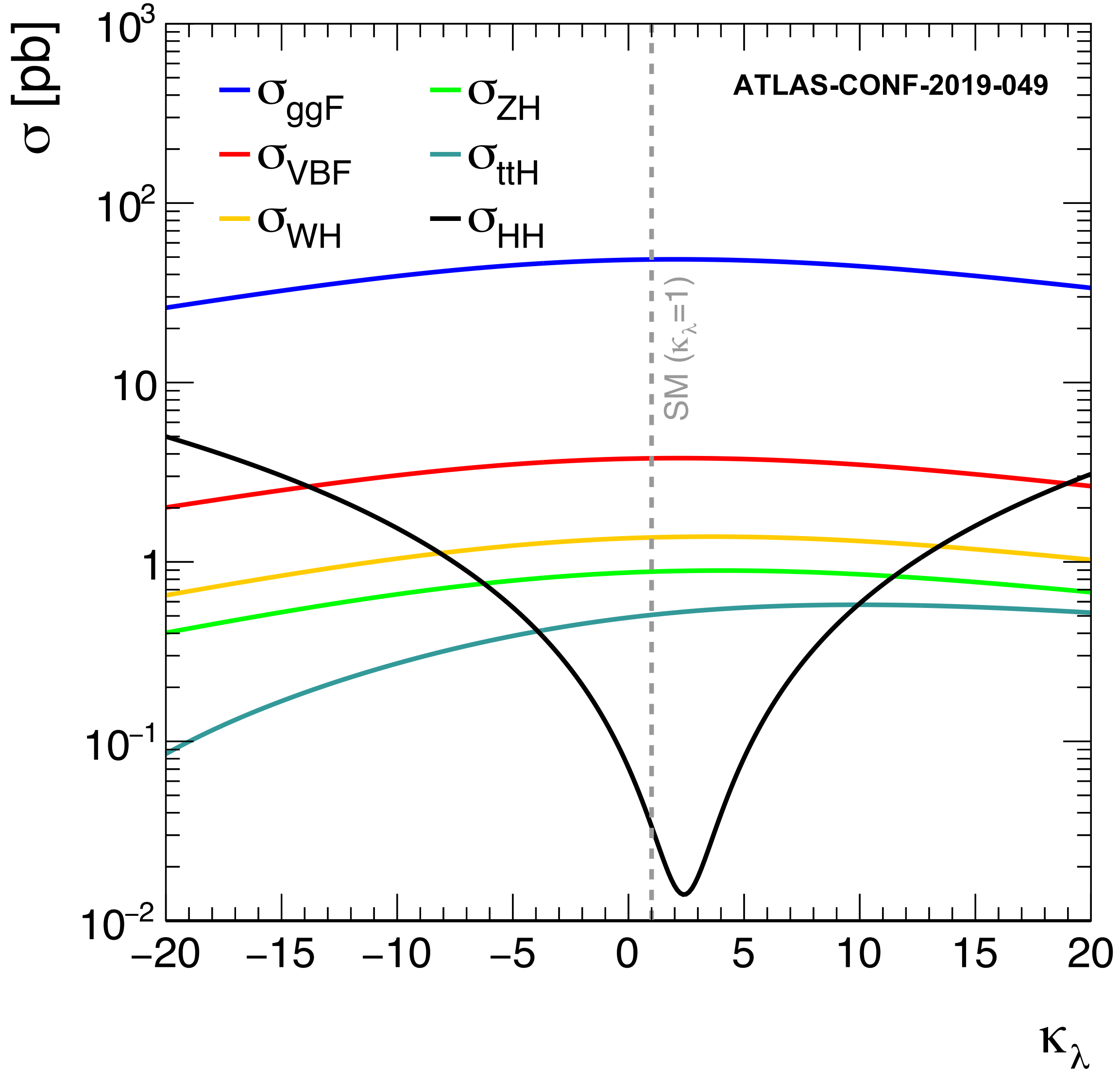
Indirect measurement:











Single Higgs + HH κ_λ

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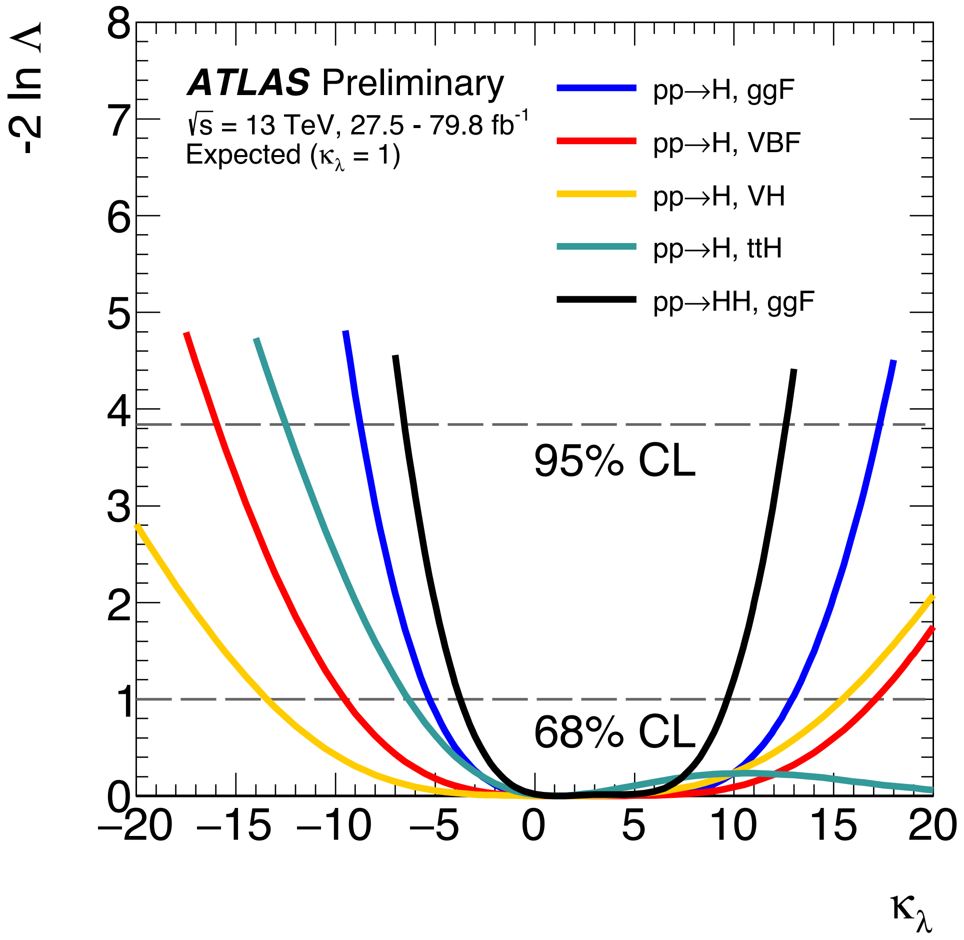
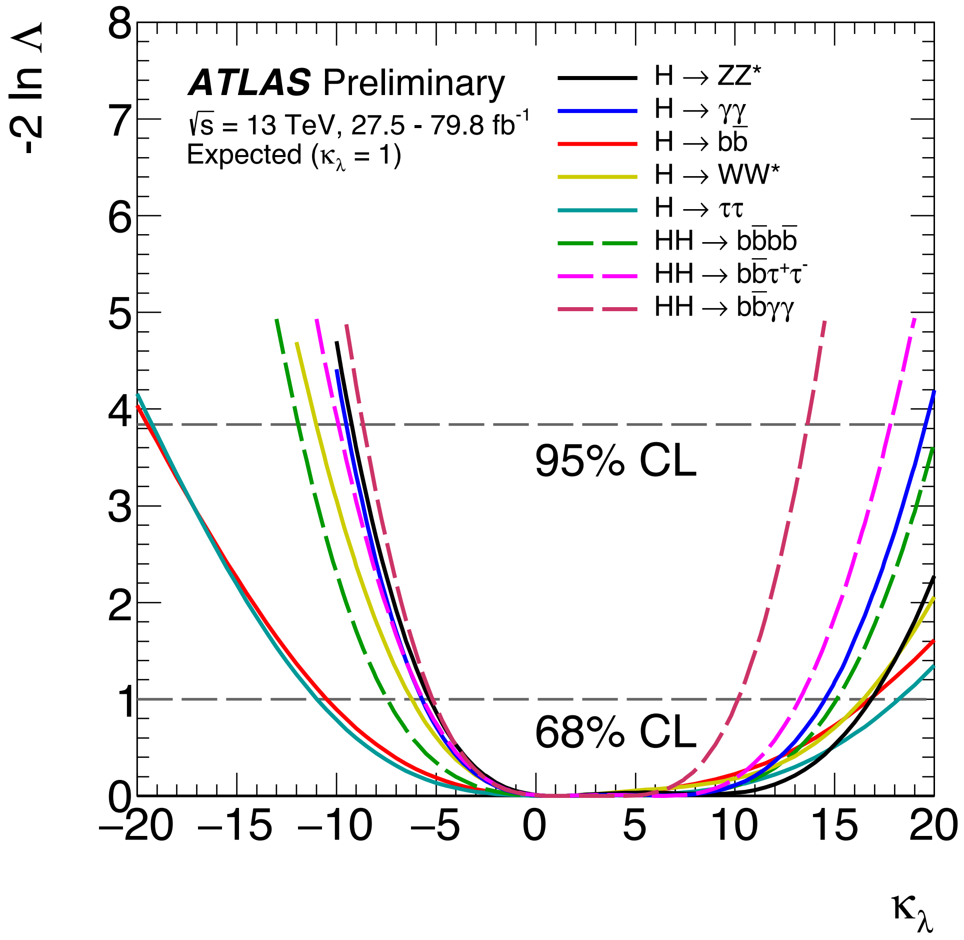
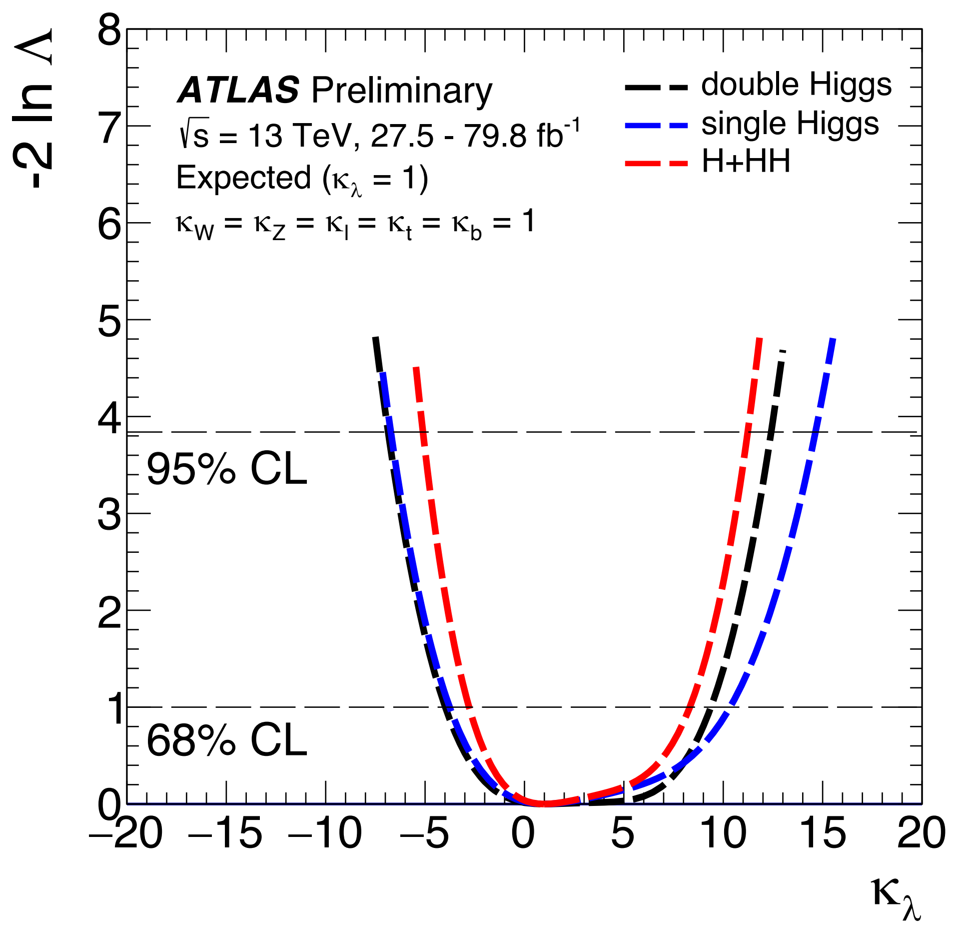


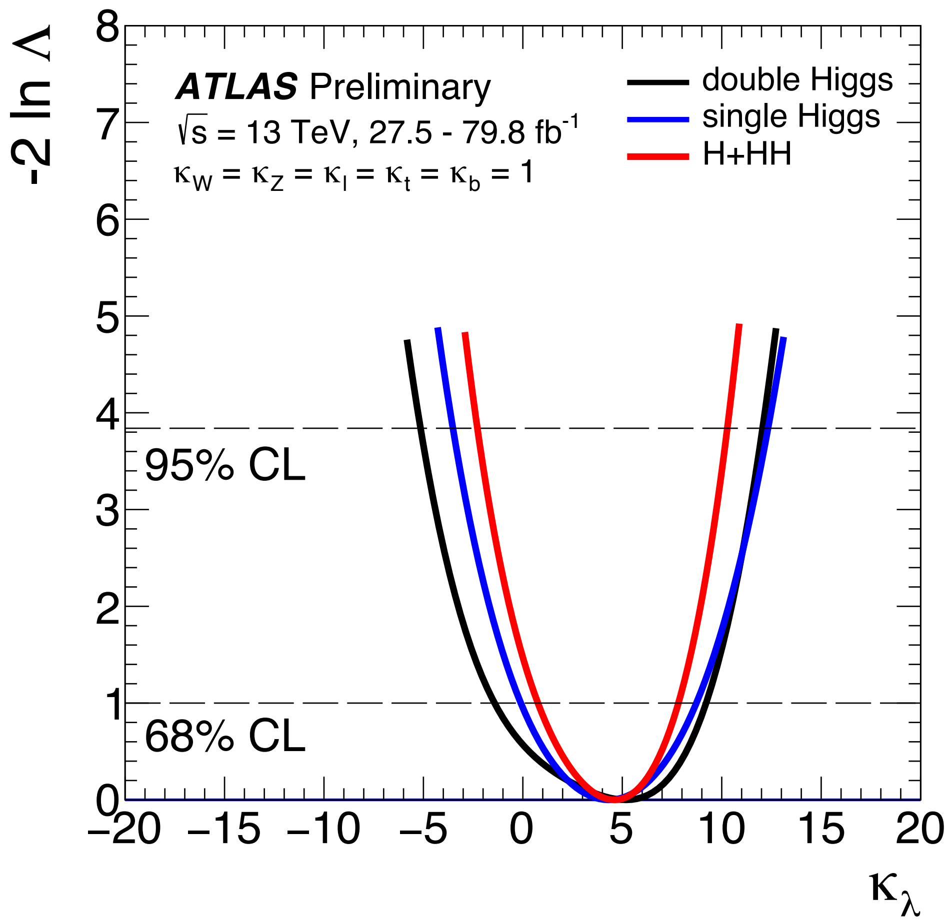


Single Higgs + HH κ_λ

ATLAS-CONF-2019-049

Model	$\kappa_W{}^{+1\sigma}_{-1\sigma}$	$\kappa_Z{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_\ell{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
κ_λ-only	1	1	1	1	1	$4.6^{+3.2}_{-3.8}$	$[-2.3, 10.3]$	obs.
						$1.0^{+7.3}_{-3.8}$	$[-5.1, 11.2]$	exp.
Generic	$1.03^{+0.08}_{-0.08}$	$1.10^{+0.09}_{-0.09}$	$1.00^{+0.12}_{-0.11}$	$1.03^{+0.20}_{-0.18}$	$1.06^{+0.16}_{-0.16}$	$5.5^{+3.5}_{-5.2}$	$[-3.7, 11.5]$	obs.
	$1.00^{+0.08}_{-0.08}$	$1.00^{+0.08}_{-0.08}$	$1.00^{+0.12}_{-0.12}$	$1.00^{+0.21}_{-0.19}$	$1.00^{+0.16}_{-0.15}$	$1.0^{+7.6}_{-4.5}$	$[-6.2, 11.6]$	exp.



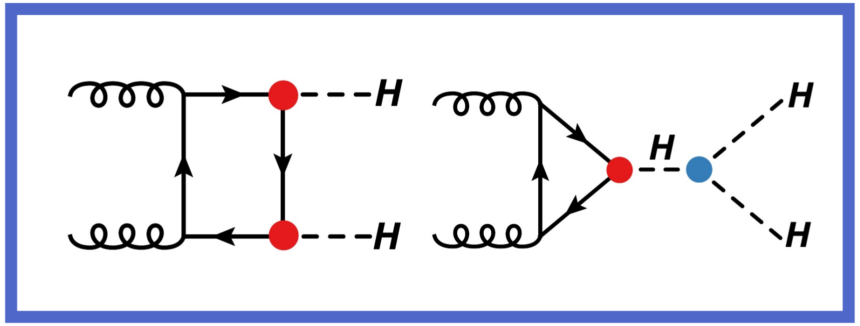


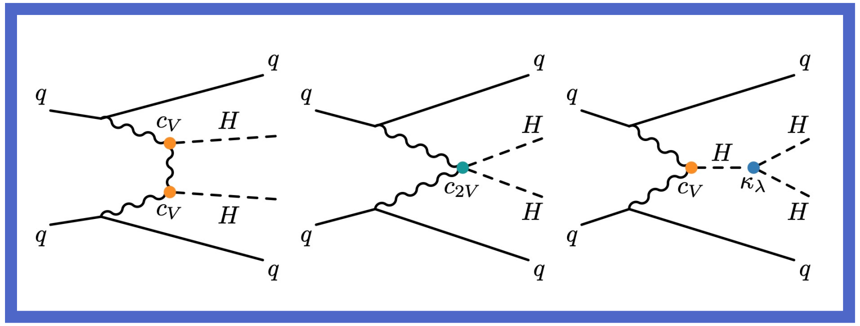
HH Production Channels

ggF

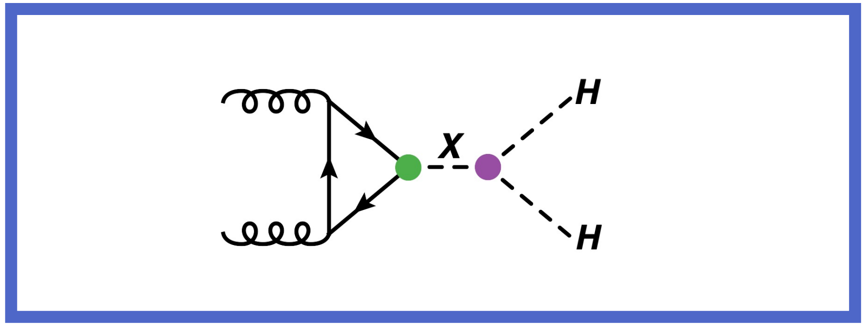
VBF

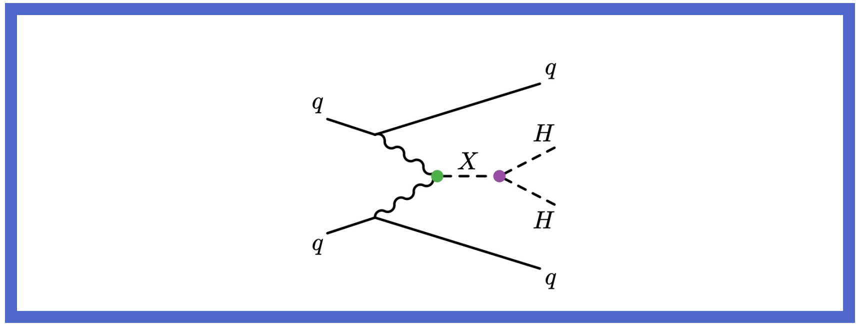
non-resonant



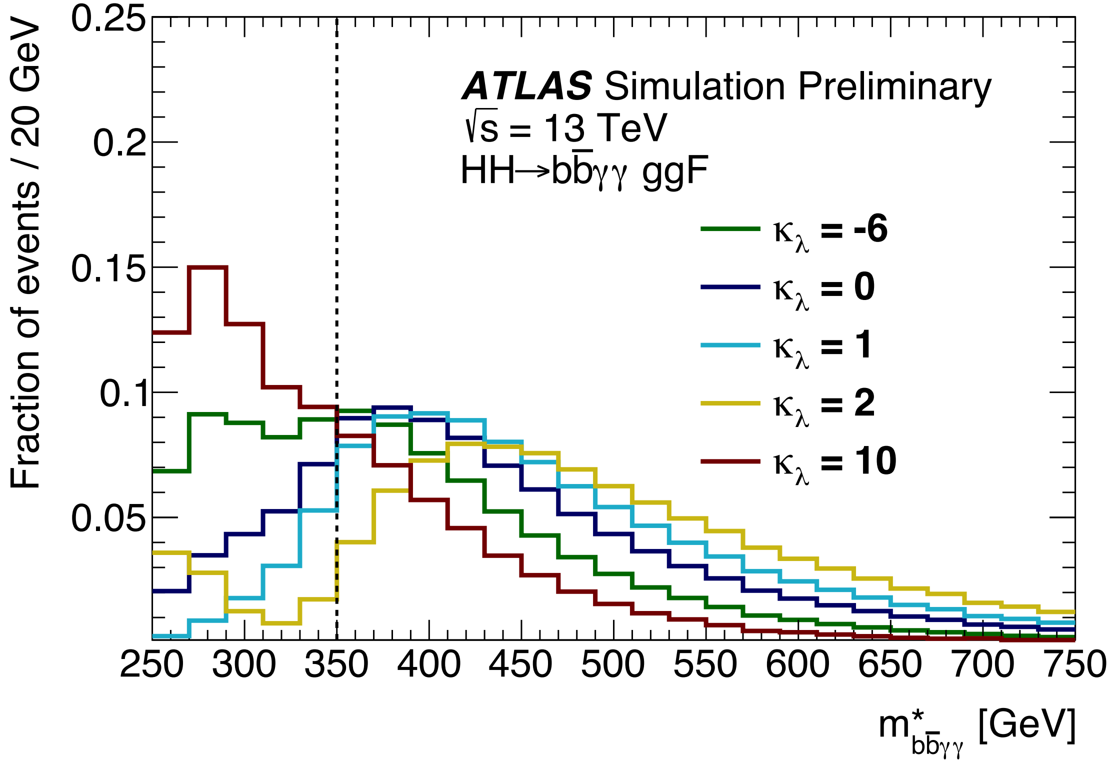


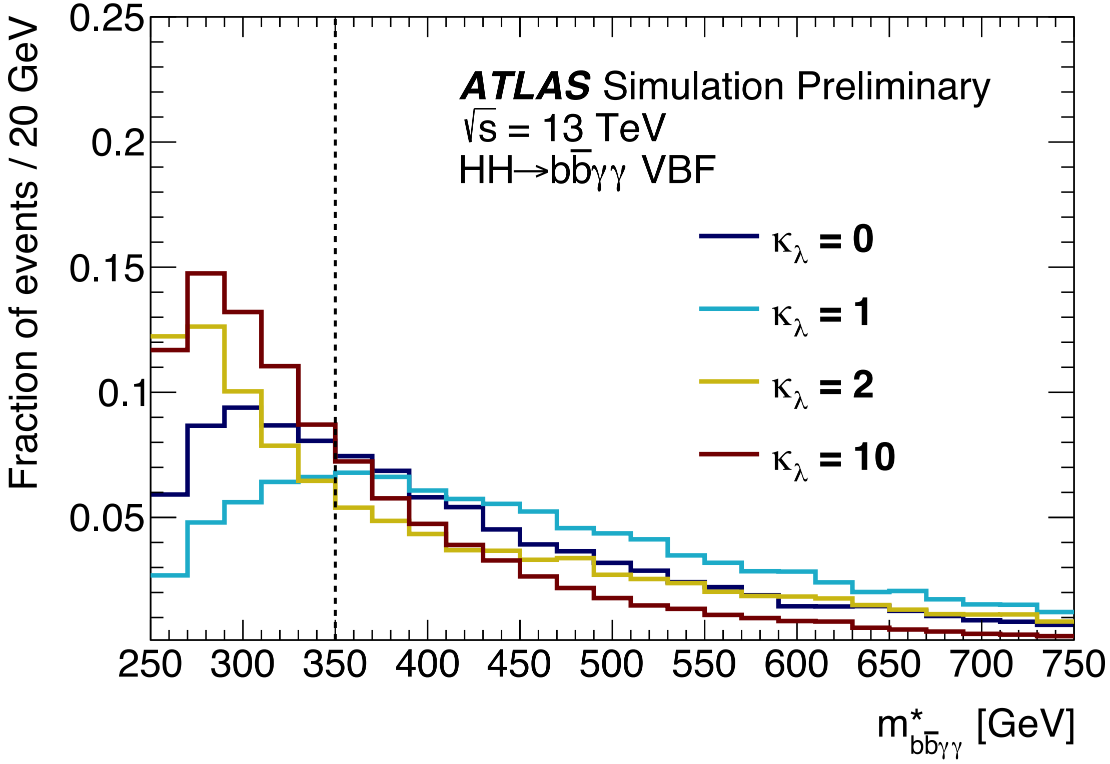
resonant





ggF and VBF HH Production



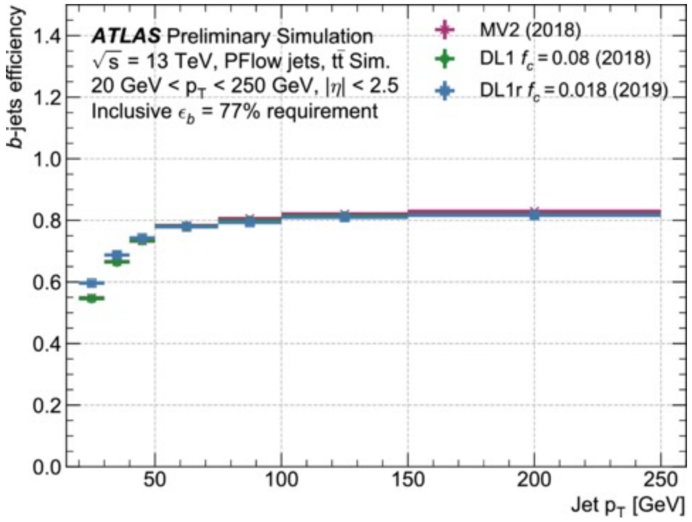


$bb\gamma\gamma$ Selection

Enlightening the beauty of the Higgs

Two b-jets

- DL1r b-tagging
- one or two jets with 77% b-tag WP



Two photons

Trigger: Loose di-photon

HLT_g35_loose_g25_loose (15-16)

HLT_g35_medium_g25_medium_L12EM20VH (17-18)

Pre-selection:

Tight and isolated

$p_{T,1} / m_{\gamma\gamma} > 0.35$, $p_{T,2} / m_{\gamma\gamma} > 0.25$,

$\eta < 1.37$ or $1.52 < \eta < 2.37$

$m_{\gamma\gamma}$ [105,160] GeV

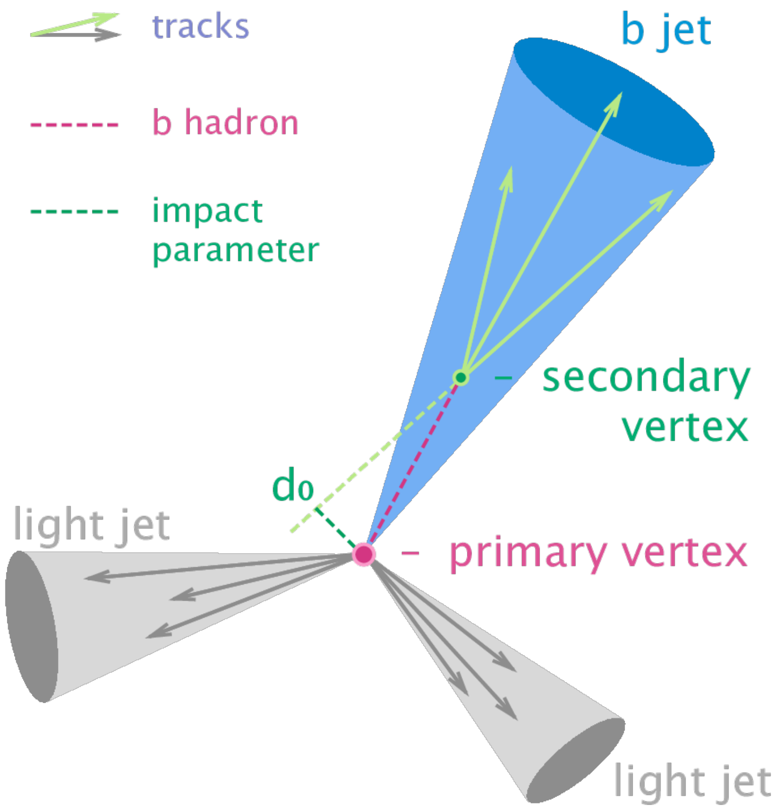
ttH suppression:

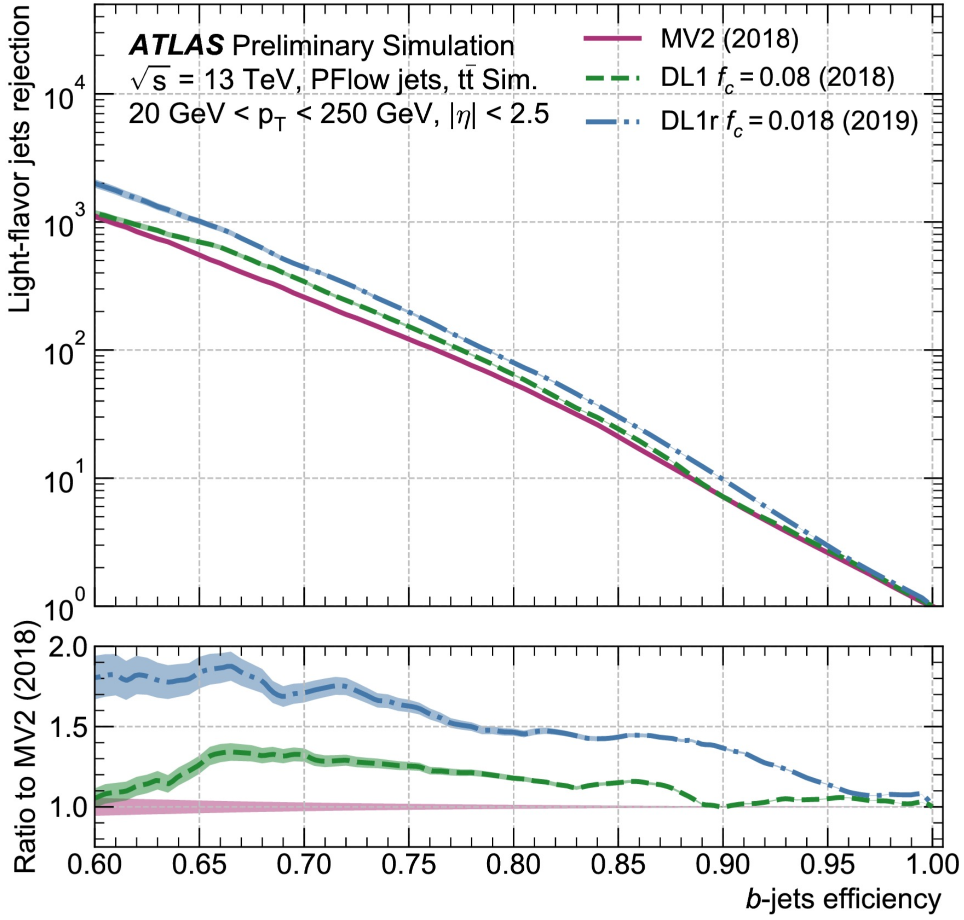
$N_{central,jets} < 6$, to help reject hadronic top decays

$N_{leptons} = 0$, to help reject leptonic top decays

b-jet Signature

Hadrons with a b-quark have a long lifetime that allows them to travel on average ~2.5mm before decaying





<u>b-tagging:</u> *multivariate method for identifying jets coming from bottom quarks*, combines information from track impact parameters, and secondary vertexing

Require exactly two jets passing the 77% b-tag working point

MC Samples

Process	Generator	PDF set	Showering	Tune
ggF	NNLOPS	PDFLHC	PYTHIA 8.2	AZNLO
VBF	POWHEG BOX v2	PDFLHC	PYTHIA 8.2	AZNLO
WH	POWHEG BOX v2	PDFLHC	PYTHIA 8.2	AZNLO
$qq \to ZH$	POWHEG BOX v2	PDFLHC	PYTHIA 8.2	AZNLO
$gg \to ZH$	POWHEG BOX v2	PDFLHC	PYTHIA 8.2	AZNLO
$t\bar{t}H$	POWHEG BOX v2	NNPDF3.0nlo	PYTHIA 8.2	A14
bbH	POWHEG BOX v2	NNPDF3.0nlo	PYTHIA 8.2	A14
$tHqj$	MADGRAPH5_AMC@NLO	NNPDF3.0nlo	PYTHIA 8.2	A14
tHW	MADGRAPH5_AMC@NLO	NNPDF3.0nlo	PYTHIA 8.2	A14
$\gamma\gamma$+jets	SHERPA v2.2.4	NNPDF3.0nnlo	SHERPA v2.2.4	–
$t\bar{t}\gamma\gamma$	MADGRAPH5_AMC@NLO	NNPDF2.3lo	PYTHIA 8.2	–

BDT Input Variables

Variable	Definition
Photon-related kinematic variables	
$p_{\mathrm{T}}/m_{\gamma\gamma}$	Transverse momentum of the two photons scaled by their invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudo-rapidity and azimuthal angle of the leading and sub-leading photon
Jet-related kinematic variables	
b-tag status	Highest fixed b-tag working point that the jet passes
p_{T}, η and ϕ	Transverse momentum, pseudo-rapidity and azimuthal angle of the two jets with the highest b-tagging score
$p_{\mathrm{T}}^{b\bar{b}}$, $\eta_{b\bar{b}}$ and $\phi_{b\bar{b}}$	Transverse momentum, pseudo-rapidity and azimuthal angle of b-tagged jets system
$m_{b\bar{b}}$	Invariant mass built with the two jets with the highest b-tagging score
H_{T}	Scalar sum of the p_{T} of the jets in the event
Single topness	For the definition, see Eq. (1)
Missing transverse momentum-related variables	
$E_{\mathrm{T}}^{\mathrm{miss}}$ and ϕ^{miss}	Missing transverse momentum and its azimuthal angle

Main Systematics

Statistically limited analysis

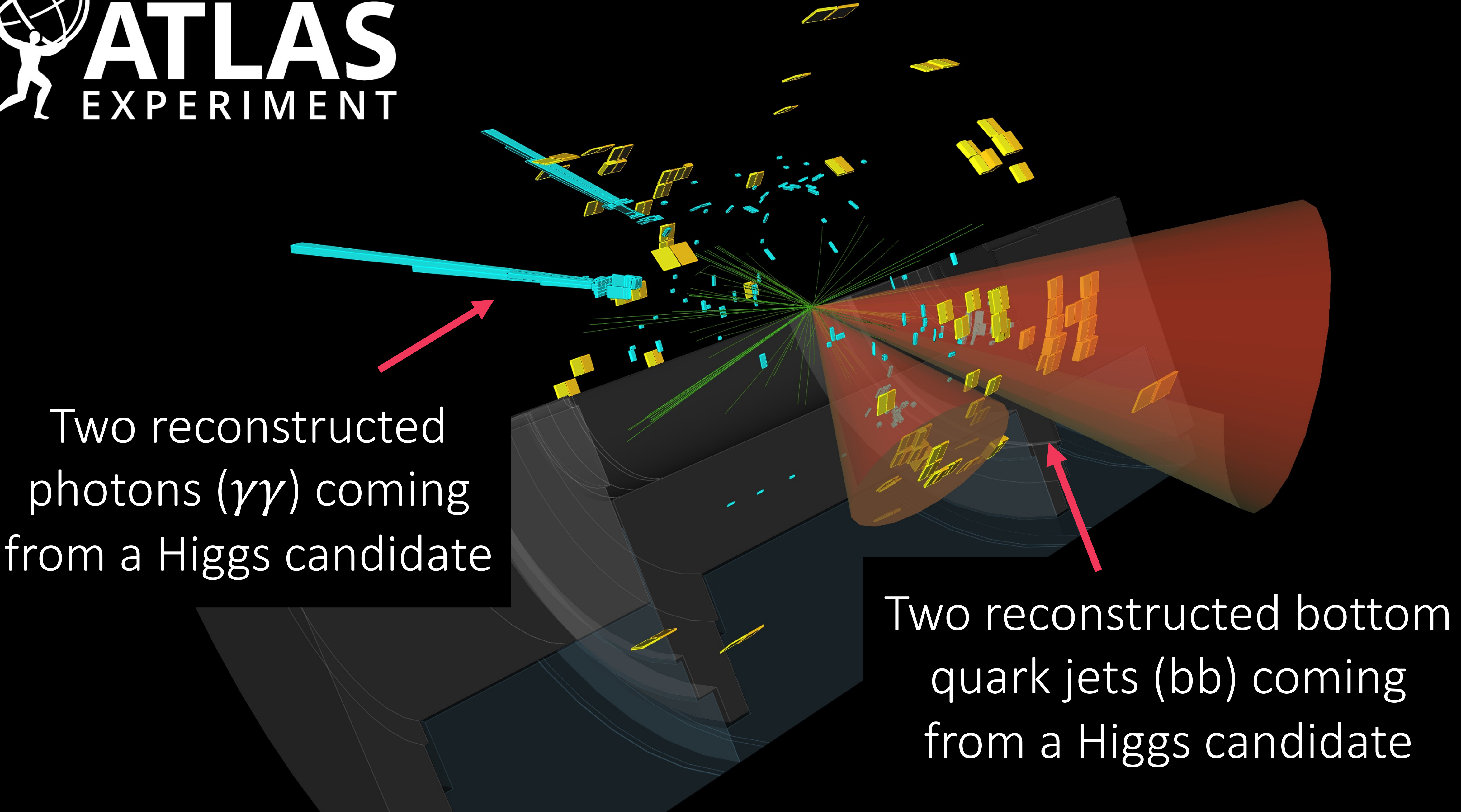
		Relative impact of the systematic uncertainties in %	
Source	Type	Non-resonant analysis HH	Resonant analysis m_X = 300 GeV
Experimental			
Photon energy scale	Norm. + Shape	5.2	2.7
Photon energy resolution	Norm. + Shape	1.8	1.6
Flavor tagging	Normalization	0.5	< 0.5
Theoretical			
Heavy flavor content	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

Many of these systematics will continue to decrease as more data is collected

Yields

In signal region (120 GeV < $m_{\gamma\gamma}$ < 130 GeV)

	High mass BDT tight	High mass BDT loose	Low mass BDT tight	Low mass BDT loose
Continuum background	4.9 ± 1.1	9.5 ± 1.5	3.7 ± 1.0	24.9 ± 2.5
Single Higgs boson background	0.670 ± 0.032	1.57 ± 0.04	0.220 ± 0.016	1.39 ± 0.04
ggF	0.261 ± 0.028	0.44 ± 0.04	0.063 ± 0.014	0.274 ± 0.030
$t\bar{t}H$	0.1929 ± 0.0045	0.491 ± 0.007	0.1074 ± 0.0033	0.742 ± 0.009
ZH	0.142 ± 0.005	0.486 ± 0.010	0.04019 ± 0.0027	0.269 ± 0.007
Rest	0.074 ± 0.012	0.155 ± 0.020	0.008 ± 0.006	0.109 ± 0.016
SM HH signal	0.8753 ± 0.0032	0.3680 ± 0.0020	$(49.4 \pm 0.7) \cdot 10^{-3}$	$(78.7 \pm 0.9) \cdot 10^{-3}$
ggF	0.8626 ± 0.0032	0.3518 ± 0.0020	$(46.1 \pm 0.7) \cdot 10^{-3}$	$(71.8 \pm 0.9) \cdot 10^{-3}$
VBF	0.01266 ± 0.00016	0.01618 ± 0.00018	$(3.22 \pm 0.08) \cdot 10^{-3}$	$(6.923 \pm 0.011) \cdot 10^{-3}$
Alternative $HH(\kappa_\lambda = 10)$ signal	6.36 ± 0.05	3.691 ± 0.038	4.65 ± 0.04	8.64 ± 0.06
Data	2	17	5	14


ATLAS EXPERIMENT
Two reconstructed photons ($\gamma\gamma$) coming from a Higgs candidate
Two reconstructed bottom quark jets (bb) coming from a Higgs candidate