Higgs 2023 Conference, 27 Nov. - 2 Dec. 2023, Beijing

Search for Higgs boson pair production in the *bbγγ* final state from 13 TeV *pp* collision data with the ATLAS detector

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ATLAS EXPERIMENT

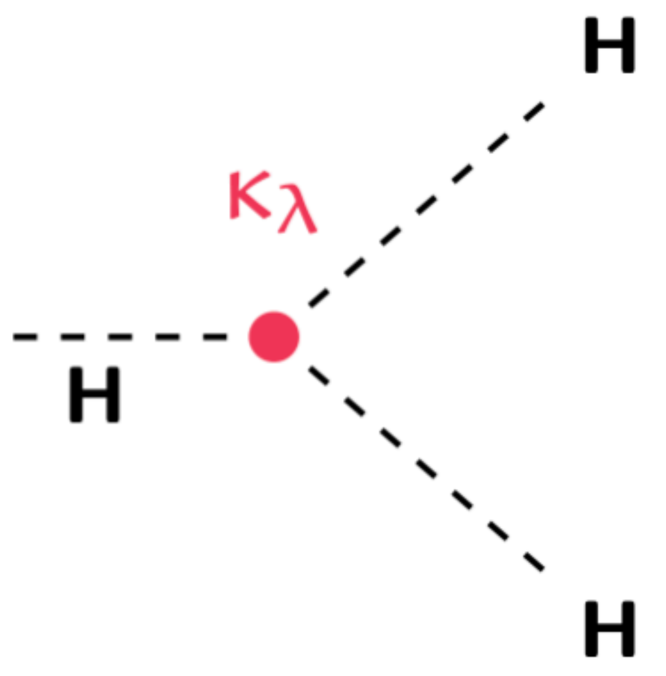
The Higgs boson self-coupling

Observation of the Higgs boson by ATLAS and CMS ($H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ channels)

Ongoing campaign of **measurements** of the Higgs boson **properties**… → **Excellent agreement** with the **Standard Model** (SM)!

2012 — **Observation** of the $H \rightarrow b\bar{b}$ decay — **2018** — **Now**

However, the **couplings** of the Higgs boson with **itself** are still largely experimentally **unconstrained**.



- The **SM** provides a well-defined **prediction** of the **trilinear Higgs boson self-coupling** $\lambda_{\mathrm{HHH}}^{\mathrm{SM}}$.

$$\lambda_{HHH}^{SM} = \approx 0.13$$

× 10^3 **rarer** (= more difficult to spot!) than **single Higgs boson** production!

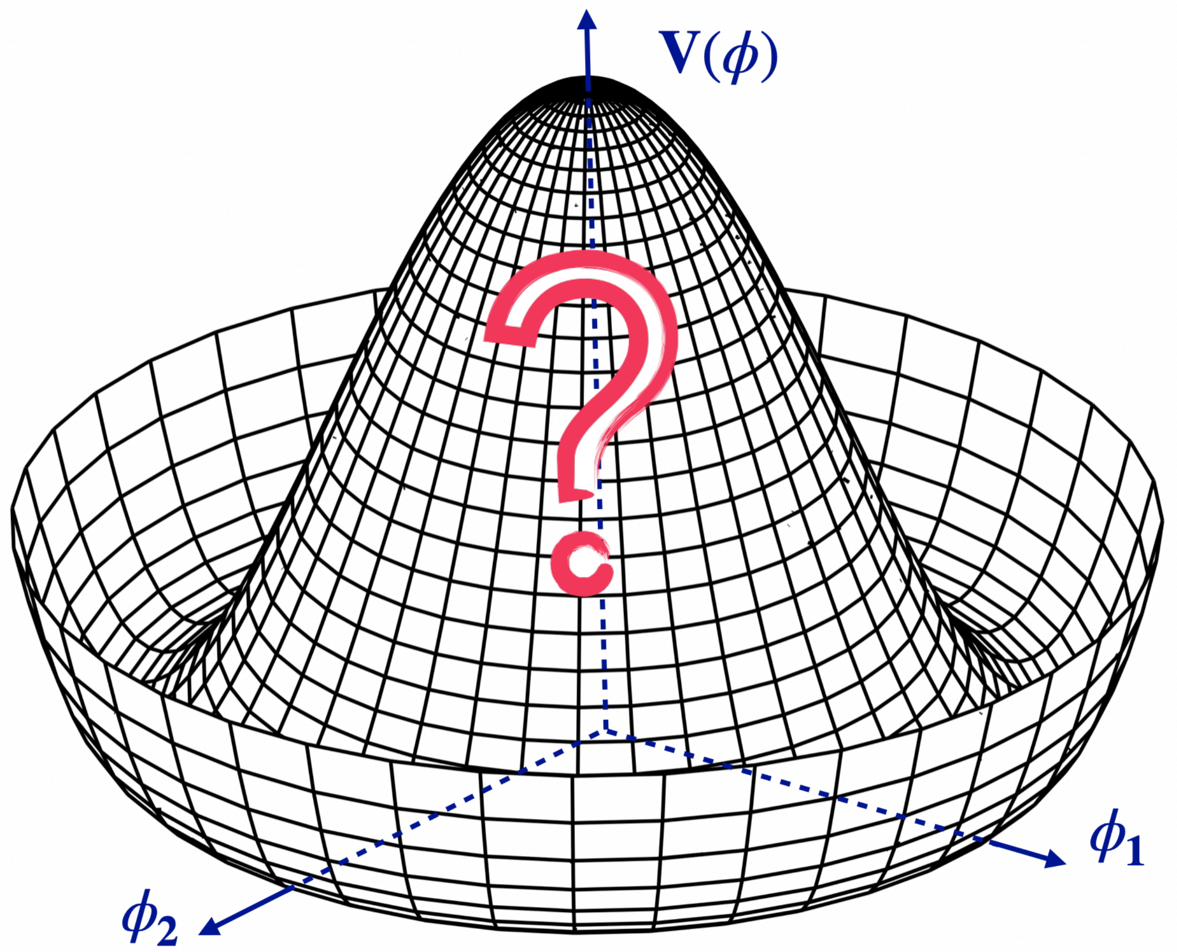
- The only **direct way** to access $\kappa_\lambda = \lambda_{\mathrm{HHH}}/\lambda_{\mathrm{HHH}}^{\mathrm{SM}}$ is via **Higgs boson pair production**!

Measuring κ_λ would help to shed light on the **shape** of the **Higgs potential close to its minima**.

Crucial for our understanding of the **Electroweak Symmetry Breaking** (EWSB).

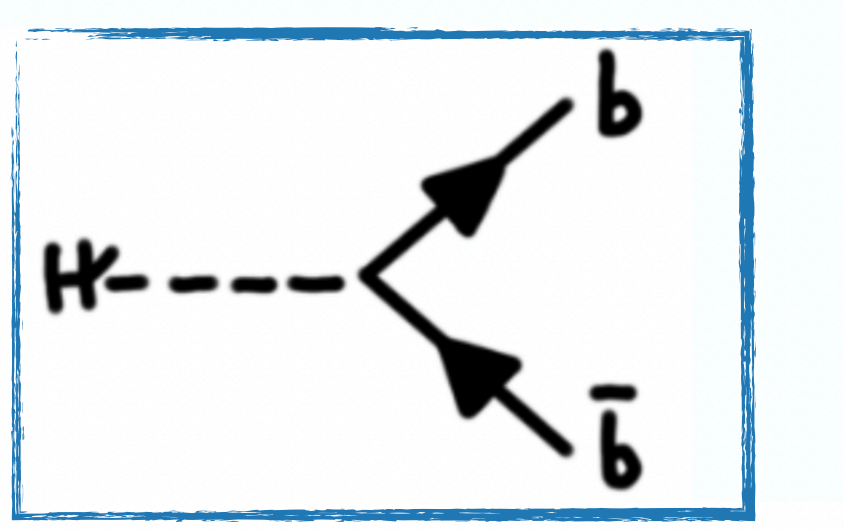
What happens if $\kappa_\lambda \neq 1$? →

- Force us to rethink the **EWSB** mechanism.
- Clear hint of **new physics**.

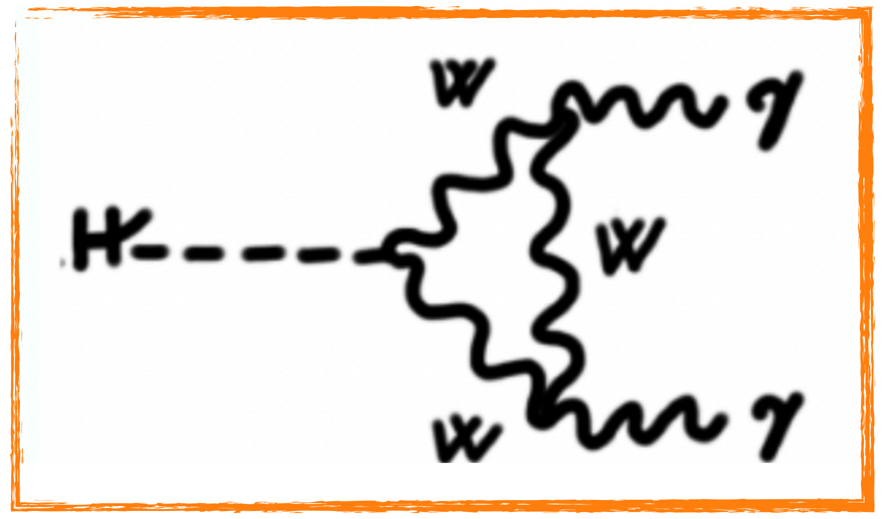


The $b\bar{b}\gamma\gamma$ final state

What's **special** about the $b\bar{b}\gamma\gamma$ **final state**?



Highest BR for a SM Higgs boson (58%), but large **QCD background**.



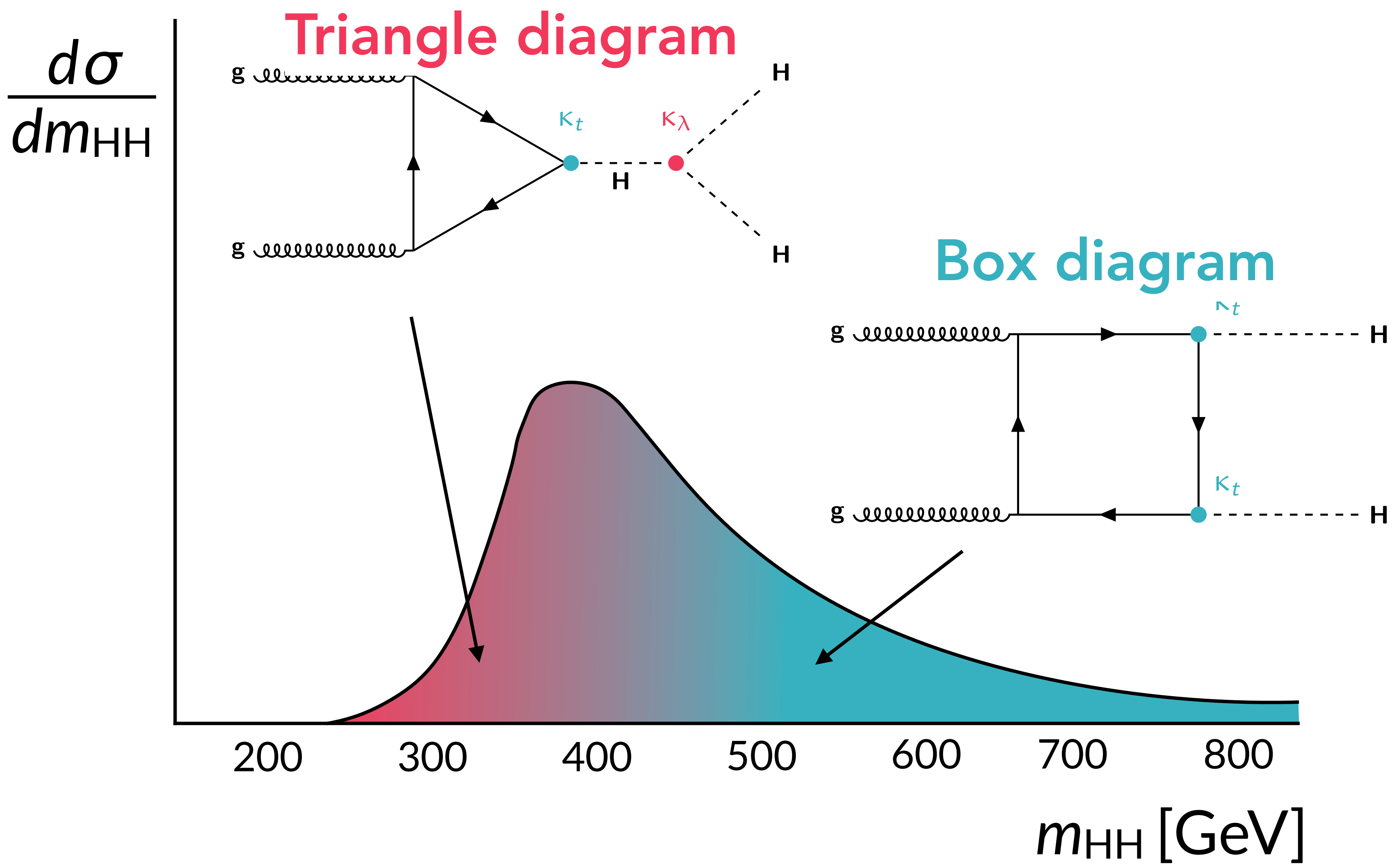
Very **low BR** for a SM Higgs boson (0.2%), but:

- **Excellent trigger and reconstruction efficiency** for photons with ATLAS.
- Excellent **di-photon invariant mass** $m_{\gamma\gamma}$ **resolution** (1-2 GeV).

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

+ Especially sensitive to **HH production @ softer m_{HH} values.**

- **More sensitive** than other HH channels to the **ggF triangle diagram**.
- Unique handle to **trilinear self-coupling modifier κ_λ**!



$b\bar{b}\gamma\gamma$ is one of the **golden channels** for **HH searches**!

The $HH \to bb\gamma\gamma$ analysis

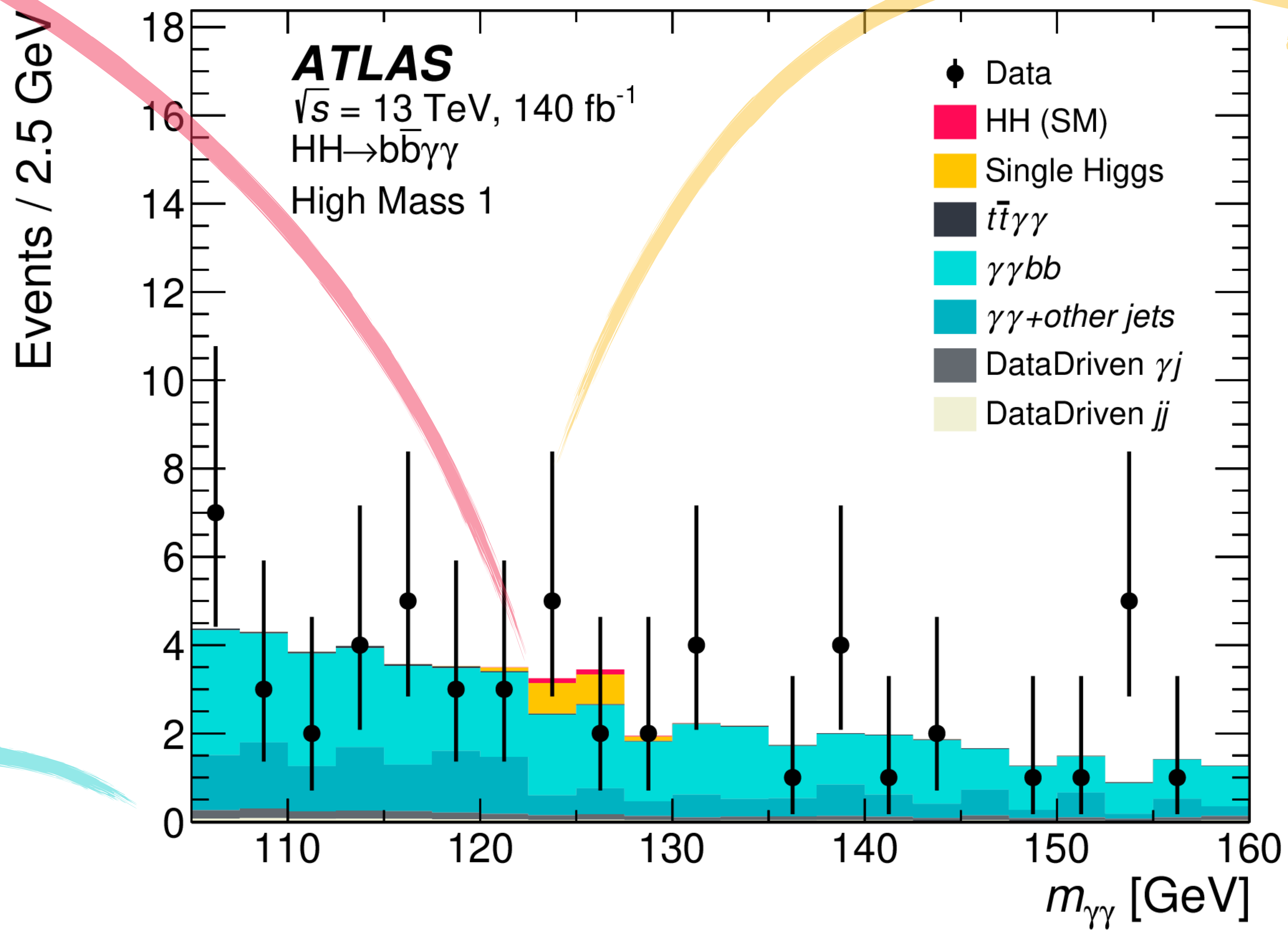
This **updated** $HH \to b\bar{b}\gamma\gamma$ **analysis** targets **Higgs boson pair production** in the **final state** involving **two photons** and **two bottom quarks**, in **13 TeV** pp **collision data** collected by the **ATLAS experiment** during the full **Run 2** of the LHC (**=140 fb^{-1}**).

New paper on **ArXiv**, submitted to JHEP.

Signal → $\sigma(\mathbf{HH}) \approx$ **32.8 fb @ 13 TeV**!

- **HH** production via **ggF** and via **VBF**. **Included in the optimization for the first time in the $b\bar{b}\gamma\gamma$ channel!**

ggF	VBF
- **Dominant** production mode. - **Drives** the sensitivity to **SM HH production** and to **self-coupling modifier κ_λ**. → Thanks to the **triangle** diagram.	- Peculiar **VBF signature with 2 hard forward jets** helps to isolate **VBF HH events** from bkg.! - **Additional sensitivity** to **self-coupling modifier κ_λ**. - **Unique** probe to the **quartic HHVV vertex = κ_{2V}**.



$\sigma(\mathbf{H}) \approx$ **55.6 pb @ 13 TeV**.

Resonant background

- Single Higgs processes, where $H \to \gamma\gamma$.

- **Same shape** as the **signal** in the $\mathbf{m}_{\gamma\gamma}$ **spectrum**!
- Rely more on **(b)-jet kinematics** to **reject** the **single Higgs background**.

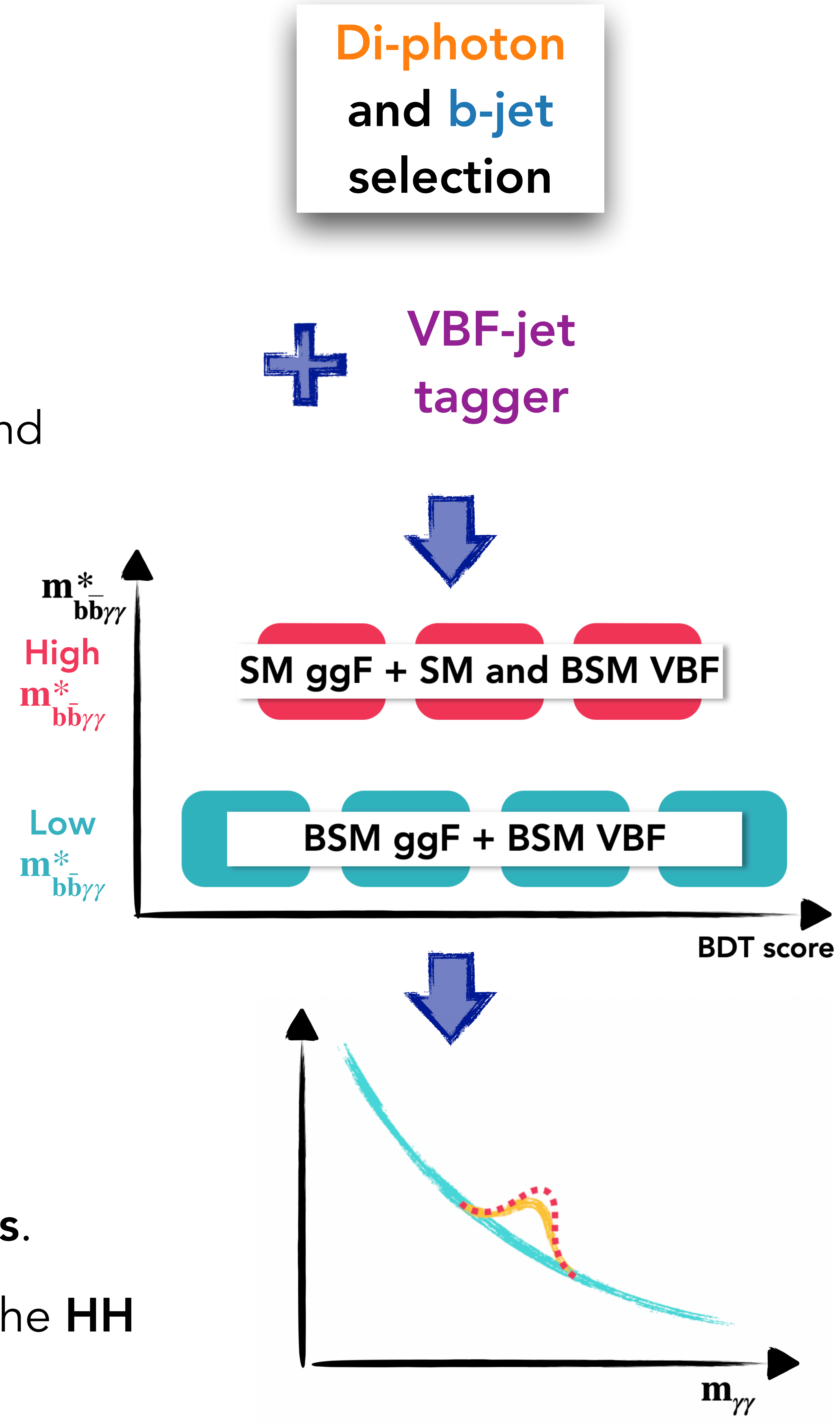
Non-resonant (continuum) bkg.

- Main contribution from $\gamma\gamma$ production + additional jets.
  - Rate ($\gamma\gamma$)= **10^3** × rate ($H \to \gamma\gamma$) = **10^6** × rate ($HH \to b\bar{b}\gamma\gamma$).

Extremely rare signal process + very large background.

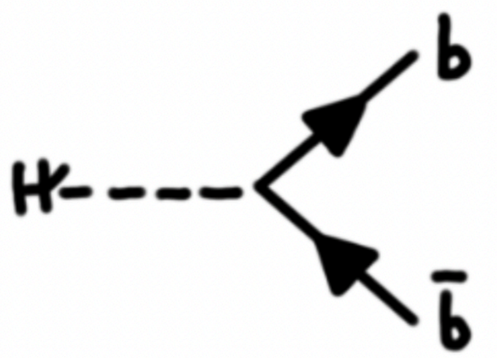
Analysis recipe

1. **Event selection.**
   - An **event selection** aimed at retaining $H \to b\bar{b}$ and $H \to \gamma\gamma$ **candidates** is applied.
   - A **Machine Learning (ML)-based VBF-jet tagger** is used to identify **candidate VBF jets**.
2. **Categorization.**
   - Selected events are divided into mutually exclusive **categories**.
     - Based on the $\mathbf{m}^{*}_{b\bar{b}\gamma\gamma}$ **invariant mass** and **ML techniques**. = **Anomalous** κ_λ and **anomalous** κ_{2V}**!**
     - Targeting ggF + **VBF HH production** and separate SM and BSM-like **scenarios**.
3. **Signal & Background Modelling & Systematic uncertainties.**
   - The signals and backgrounds are **modeled** in the $\mathbf{m}_{\gamma\gamma}$ **spectrum**.
     - The continuum bkg. **shape** and **normalization** are **data-driven**.
   - The impact of each source of **systematic uncertainty** is evaluated.
     - Affecting the HH or single Higgs **yields**, or the **position** and **width** of the $\mathbf{m}_{\gamma\gamma}$ **peak**, + **custom systematic (= spurious signal)** on continuum bkg. modelling.
4. **Statistical model & interpretations.**
   - The results are extracted via a **maximum-likelihood unbinned fit** on the $\mathbf{m}_{\gamma\gamma}$ **distributions**.
   - We search for an **excess** over the expected background, and we set **exclusion limits** on the **HH signal strength** and **set constraints** on the **coupling modifiers** κ_λ, κ_{2V}!



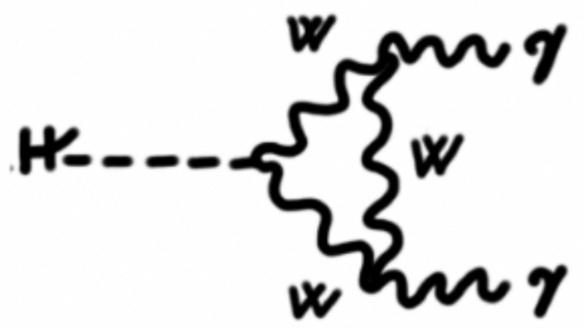
Event selection & categorization

Interesting events are selected if they fulfill the selection requirements **targeting** the $b\bar{b}\gamma\gamma$ **signature**.



- **2 b-jets** selected with the 77% efficiency WP.
- Dedicated **corrections to b-jets 4-momentum**.

+



- **Two** tight and isolated **photons**.
- $\mathbf{p_T^{\gamma_{1(2)}}/m_{\gamma\gamma} > 0.35(0.25)}$.
- $\mathbf{105 < m_{\gamma\gamma} < 160}$ **GeV**.

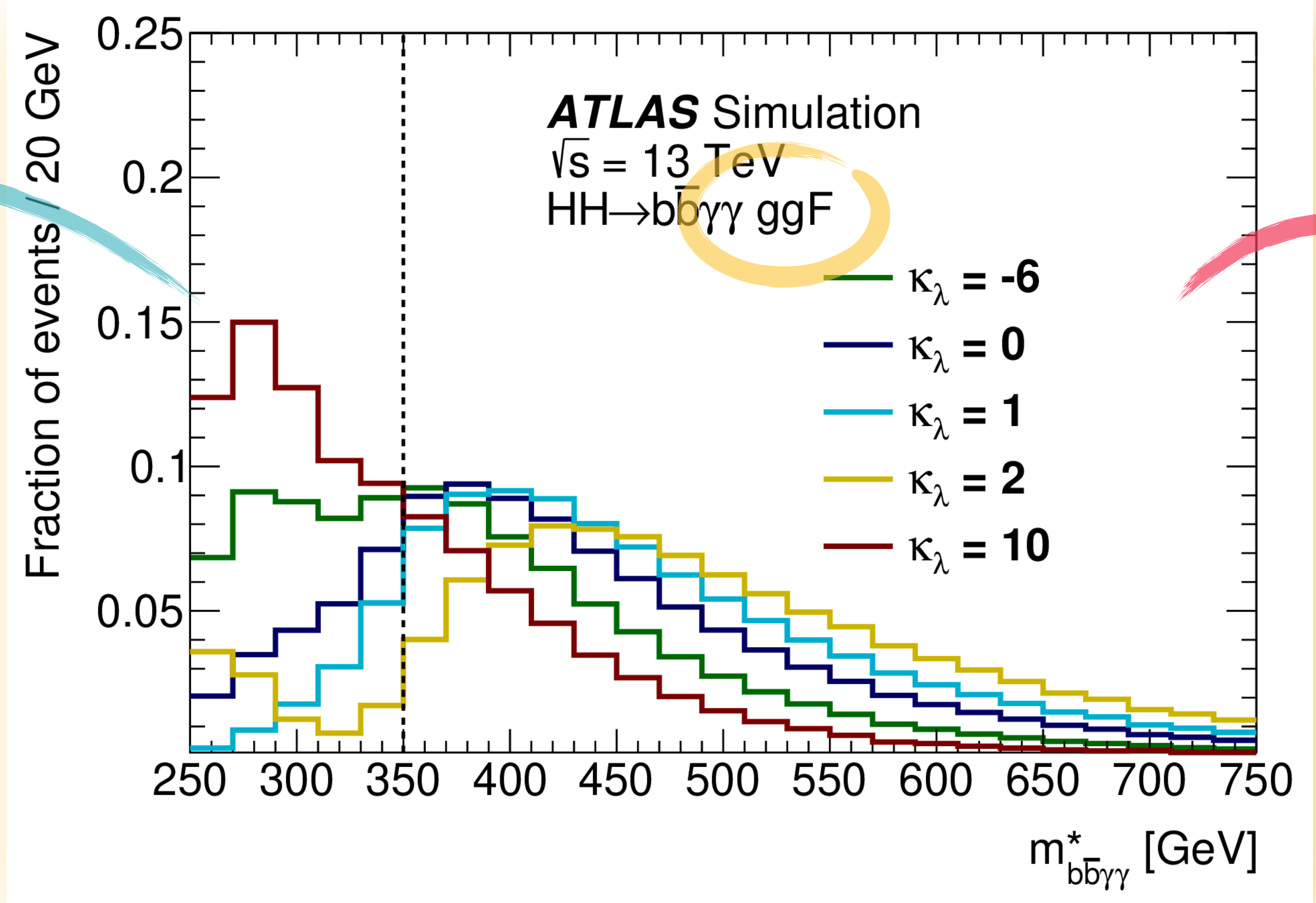
+

In events with **more than 4 jets**, the **candidate VBF-jets** are **tagged** via a dedicated **BDT-based classifier**.

Events in the signal region are then categorized, relying on the **reduced 4-object invariant mass** $\mathbf{m^*_{b\bar{b}\gamma\gamma}}$ and **BDT outputs**!

$$= m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125\text{ GeV}) - (m_{\gamma\gamma} - 125\text{ GeV})$$

Two bins in $\mathbf{m^*_{b\bar{b}\gamma\gamma}}$ are defined:



Low mass region:

$\mathbf{m^*_{b\bar{b}\gamma\gamma} \leq 350}$ **GeV**

Targets **ggF HH** events with **larger κ_λ values**, and **VBF HH** samples with **anomalous κ_λ** and **κ_{2V} couplings**.

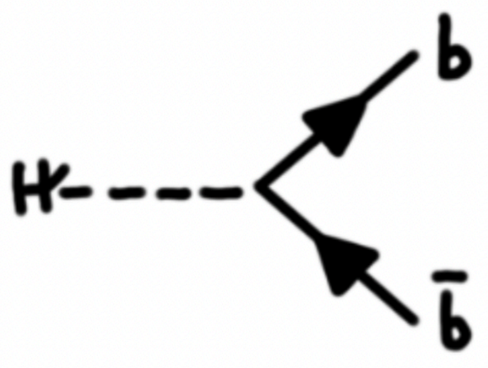
High mass region:

$\mathbf{m^*_{b\bar{b}\gamma\gamma} > 350}$ **GeV**

Targets **SM ggF HH** and **VBF HH** production with **SM + anomalous κ_λ** and **κ_{2V} couplings**.

Event selection & categorization

Interesting events are selected if they fulfill the selection requirements **targeting** the $b\bar{b}\gamma\gamma$ **signature**.



- **2 b-jets** selected with the 77% efficiency WP of **DL1r tagger**.
- Dedicated **corrections to b -jets 4-momentum**.

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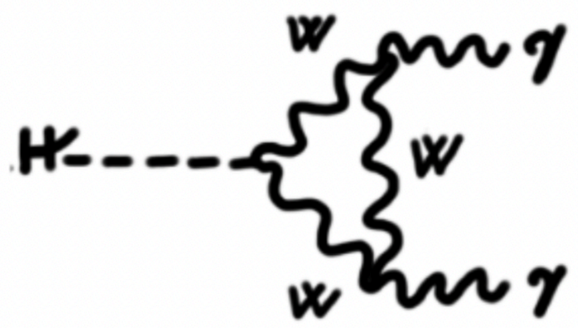

- **Two** tight and isolated **photons**.
- $\mathbf{p_T^{\gamma_{1(2)}}/m_{\gamma\gamma} > 0.35(0.25)}$.
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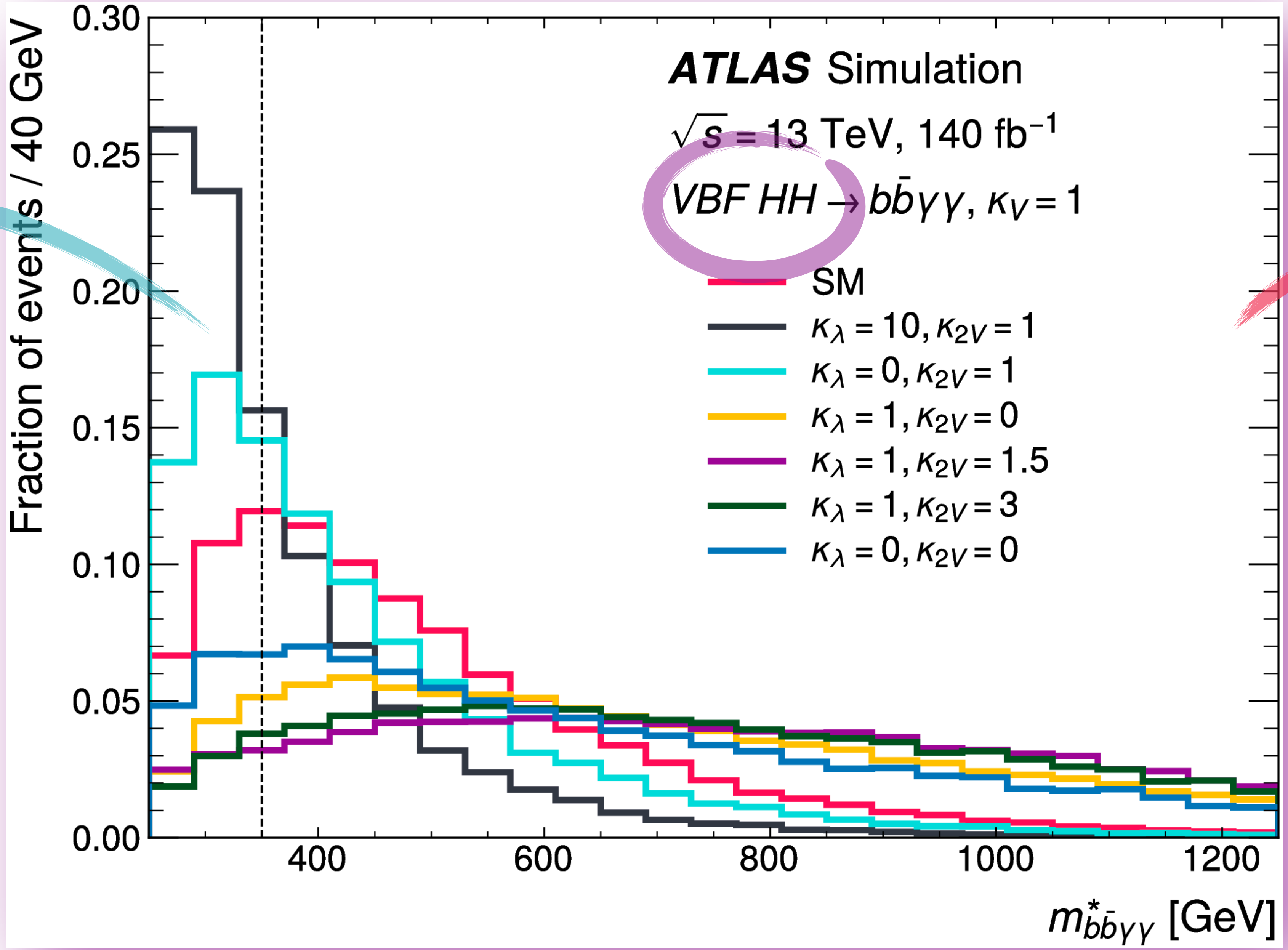
$$= m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125\ \text{GeV}) - (m_{\gamma\gamma} - 125\ \text{GeV})$$

Two bins in $\mathbf{m^*_{b\bar{b}\gamma\gamma}}$ are defined:

Low mass region:

$\mathbf{m^*_{b\bar{b}\gamma\gamma} \leq 350}$ **GeV**

Targets **ggF HH** events with **larger κ_λ values**, and **VBF HH** samples with **anomalous κ_λ** and **κ_{2V} couplings**.



High mass region:

$\mathbf{m^*_{b\bar{b}\gamma\gamma} > 350}$ **GeV**

Targets **SM ggF HH** and **VBF HH** production with **SM + anomalous κ_λ** and **κ_{2V}** **couplings**.

Categorization

- A **separate BDT** is trained in **each $m^*_{b\bar{b}\gamma\gamma}$ bin**, to separate **di-Higgs ggF + VBF signals** from **backgrounds**.

	Low Mass	High Mass
Signal	• **ggF HH** with **anomalous κ_λ values**. • **VBF HH** with **anomalous** values for κ_λ and κ_{2V}.	• **SM ggF HH** • **SM + anomalous VBF HH** samples
Background	• **All** single Higgs processes • **γγ + ttγγ** samples	

Both the BDTs use the **same set** of **input variables**.

Good discriminating power between HH signals and bkg.

- **Photon** kinematic variables.
- ***b*-jet** kinematic variables.
- $H \rightarrow b\bar{b}$-targeting variables;
- Extra-jet related variables.

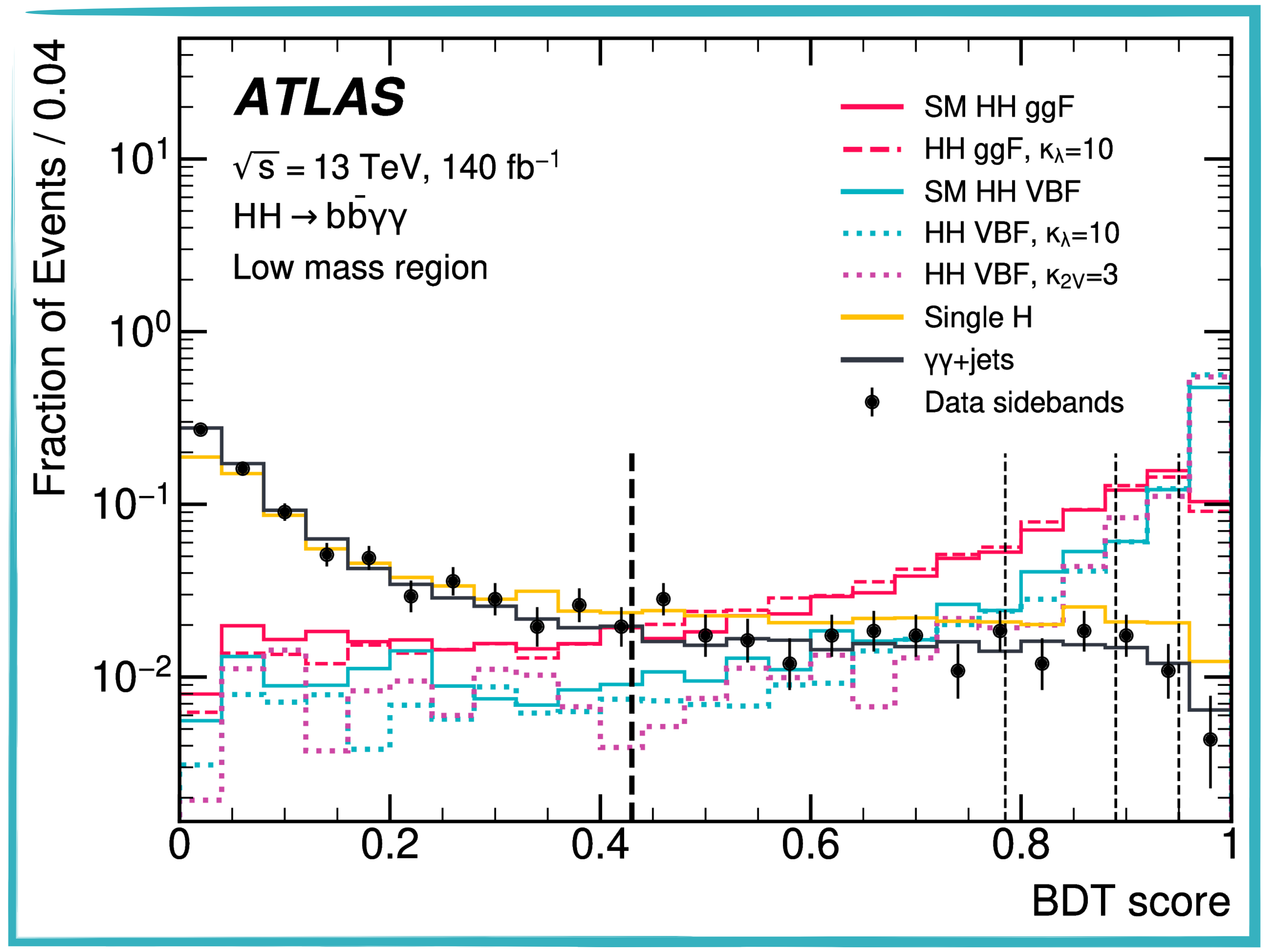
$m^*_{b\bar{b}\gamma\gamma}$

Targeting VBF signals

- Variables directly related to **VBF-like topology**, i.e. invariant mass of the two VBF jets.
- Event-shape variables.

- Based on the BDT outputs, **4** and **3** categories are defined in the **Low Mass** and **High Mass regions**!

Low Mass



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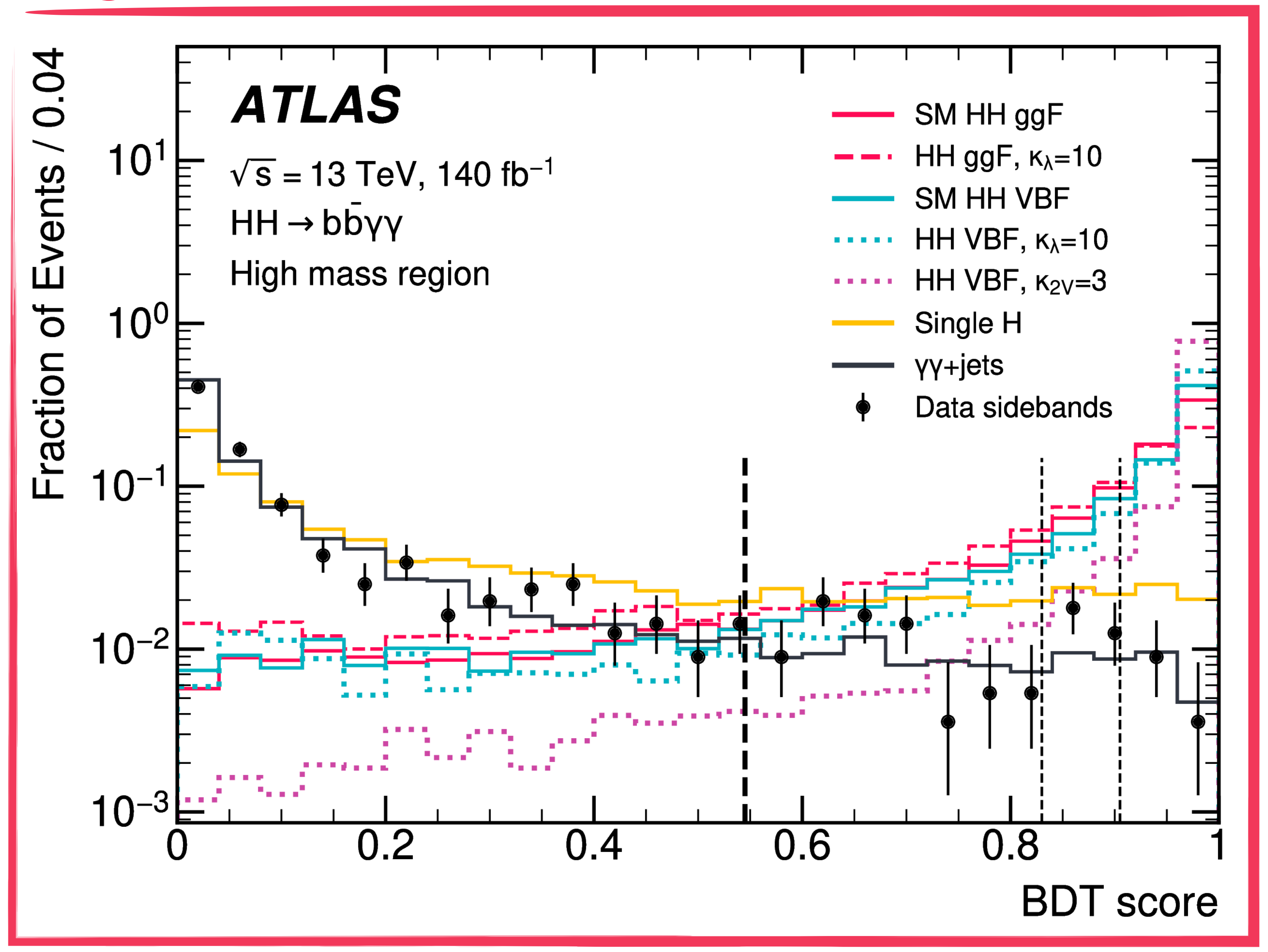
High Mass



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- **Categories** specifically **optimized** to **target simultaneously** both the **ggF HH** and **VBF HH production**.
- **Maximize** the **sensitivity** to **SM HH** + a wide range of **anomalous** κ_λ and κ_{2V} **values**!

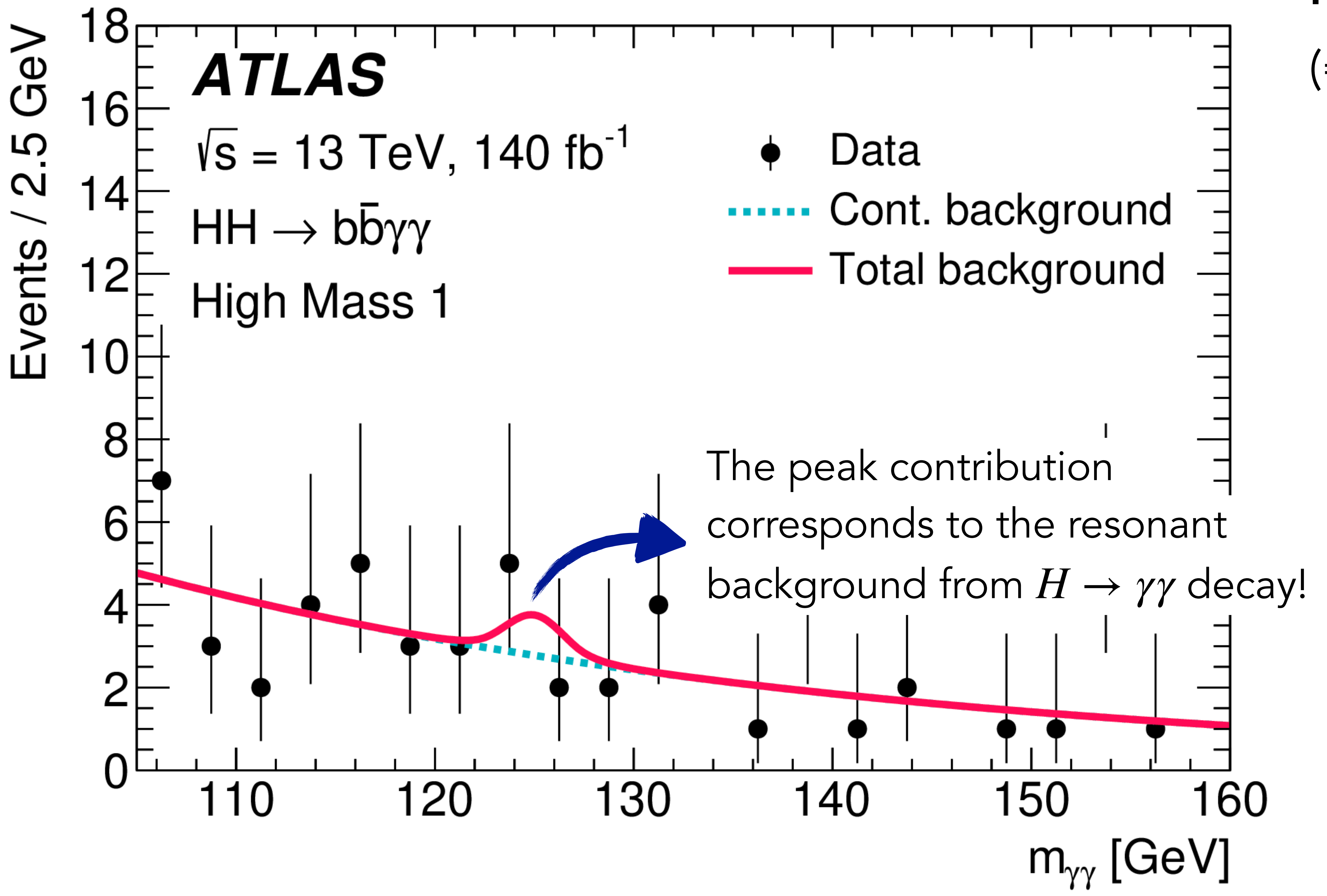
Signal extraction

The **statistical results** are derived by performing an **unbinned maximum likelihood fit** to the $\mathbf{m_{\gamma\gamma}}$ **distribution** in $m_{\gamma\gamma} \in [105,160]$ GeV.

	Resonant (HH and single H)	Non-resonant (continuum background)
Modelling in the $m_{\gamma\gamma}$ spectrum	- **Resonant peak** around $\mathbf{m_H \approx 125}$ **GeV**. - Modelled by a **double-sided crystal ball** fitted on **SM ggF HH + VBF HH Monte-Carlo** events.	- **Smoothly falling background**. - Modelled using an **exponential function**, whose **shape parameter** and **normalization** are **fitted from data**.

Mitigated impact of continuum bkg. modelling **syst. unc.** (= **spurious signal**) thanks to new dedicated $\gamma\gamma + b\bar{b}$ **MC sample**!

Fit results



- **No excess** of events w.r.t. **background expectation**.
- **We interpret** the results in terms of:
  - **95% CL upper limits** on the di-Higgs signal strength.
  - **Constraints @ 95% CL** on the **coupling modifiers** κ_λ and κ_{2V}.

Upper limits on HH production and constraints on κ_λ and κ_{2V}

- **Exclusion limits** are set on the **di-Higgs signal strength** at **95% CL**.

Upper limits on $\mu(\mathrm{HH})$ @ 95% CL.

	Observed	Expected
μ(HH)	4.0	5.0

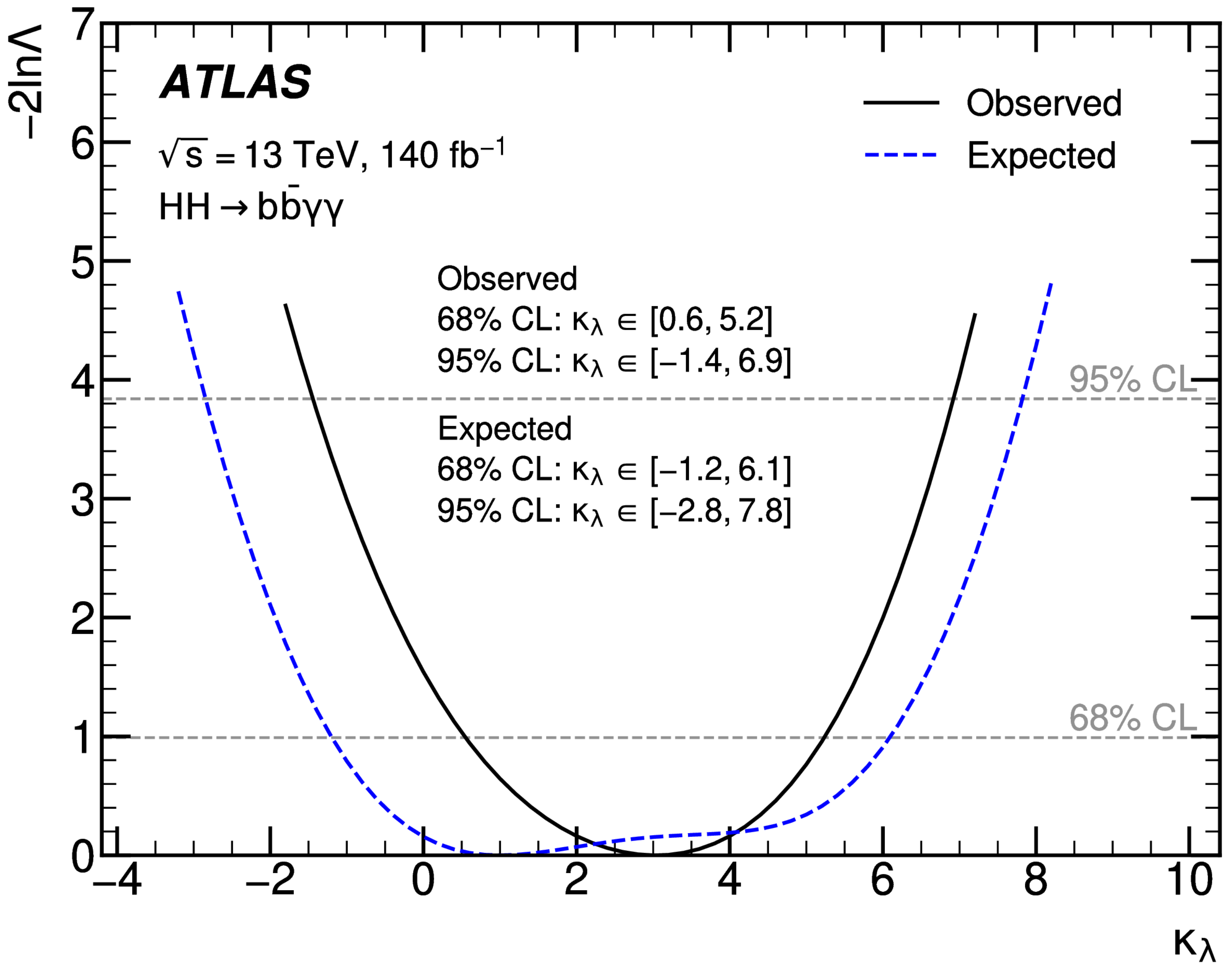
$> 10\,\%$ **improvement** w.r.t. **old full Run 2 analysis**, from **analysis strategy** only!

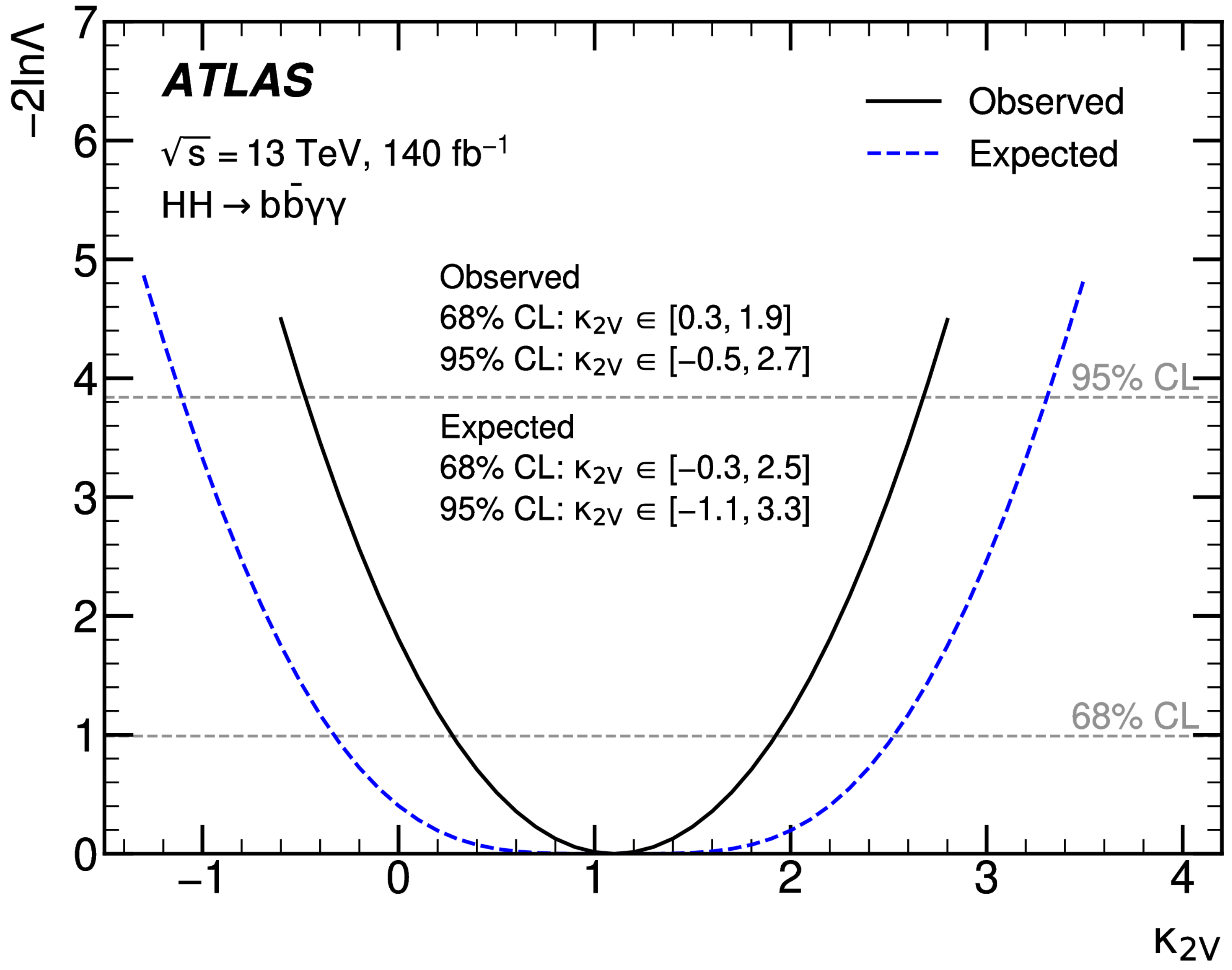
	Old analysis	This analysis
Expected limit on μ(HH)	5.7	5.0

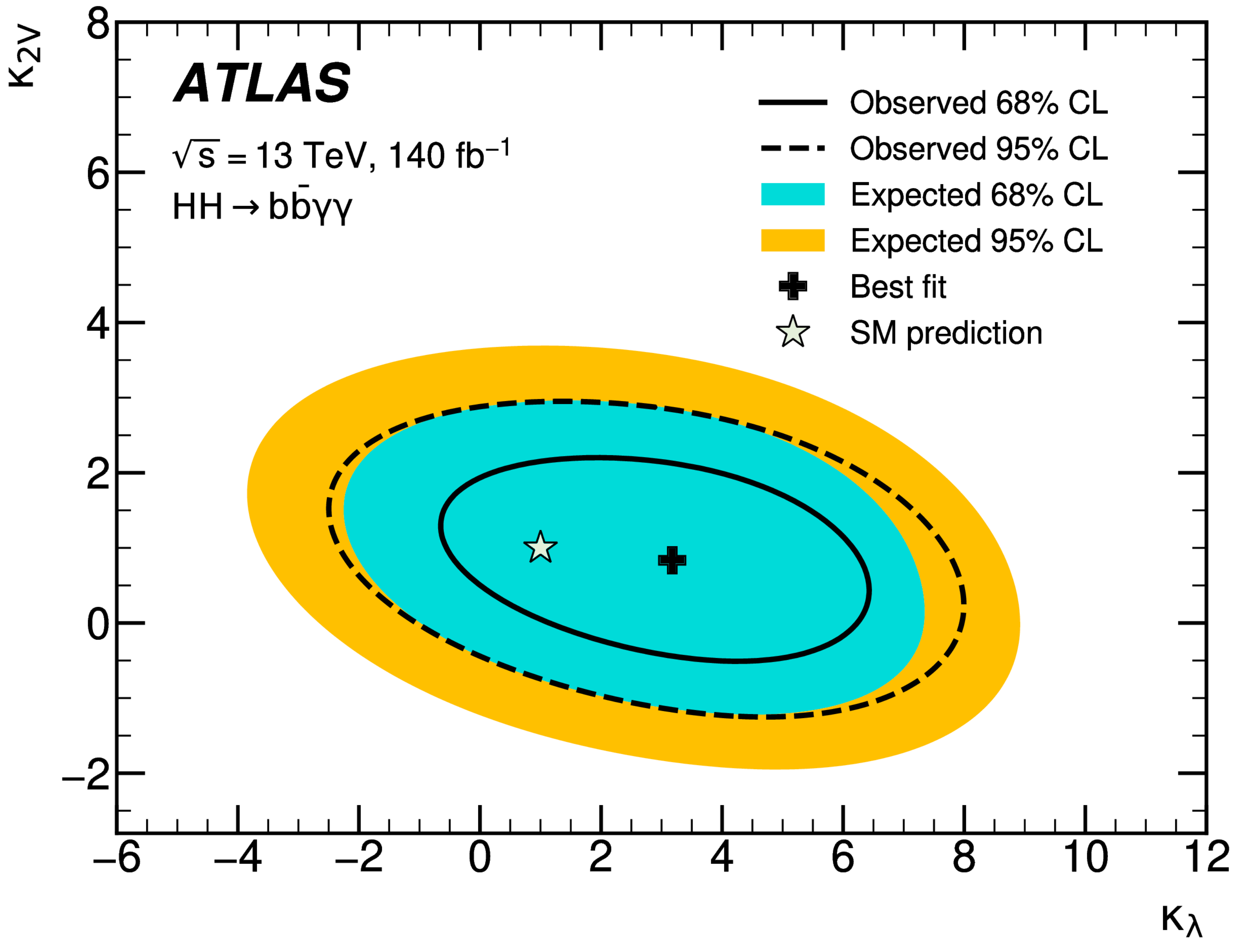
Old full Run 2 analysis: [Phys. Rev. D 106 (2022) 052001]

- **Best-fit** values for κ_λ and κ_{2V} and their **68%** and **95% confidence intervals** are evaluated via a **profile log-likelihood ($-2\Delta\,\ln(\mathrm{L})$) scan**.

A **simultaneous measurement** of κ_λ and κ_{2V} is also provided by performing a **2-dimensional profile log-likelihood scan**.







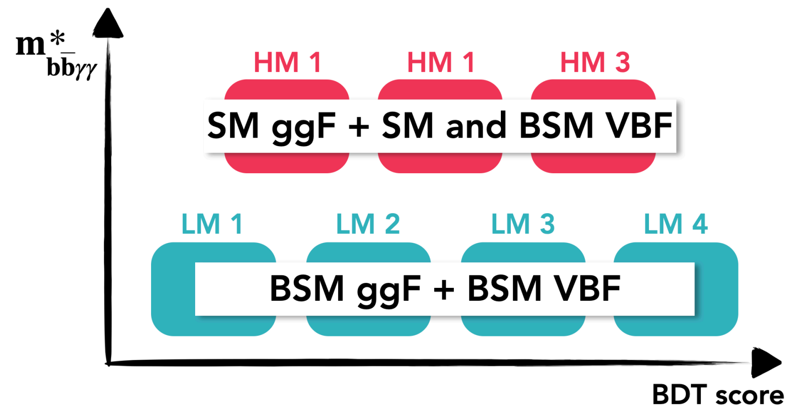
Summary

- Searching for **Higgs boson pair production** constitutes the only **direct probe** to the **trilinear Higgs self-coupling modifier κ_λ**.
- Exploiting the **two** dominant **production modes**, via **ggF HH** and **VBF HH**, allow to **probe** both κ_λ and the **quartic $HHVV$ interaction κ_{2V}**.
- The $\mathbf{b\bar{b}}\gamma\gamma$ is one of the **golden channels** for **HH searches**! → **Large** $H \to b\bar{b}$ branching fraction **+ very clean di-photon** signature.
- This **updated search for Higgs boson pairs** in the $\mathbf{b\bar{b}}\gamma\gamma$ **final state** using data collected by the **ATLAS detector** during the **full Run 2** was presented.

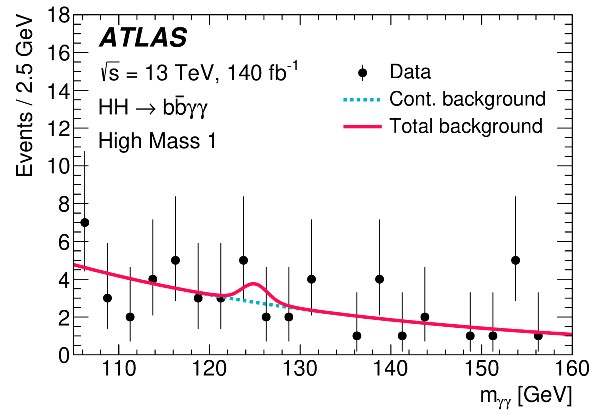
From applying a pre-selection targeting the $\mathbf{b\bar{b}}\gamma\gamma$ signature…

Di-photon and b-jet selection

…to splitting the events into mutually exclusive categories, based on $\mathbf{m}^*_{b\bar{b}\gamma\gamma}$ and BDT outputs…



…to extracting the final results via a maximum likelihood fit on the $\mathbf{m}_{\gamma\gamma}$ distribution!



New result!

- **No excess of events** was observed w.r.t. background only expectations.

This analysis places **upper limits** on the **di-Higgs signal strength**, as well as **95% CL constraints** on κ_λ and κ_{2V}.

95% CL upper limits on HH signal strength

	Observed	Expected
μ(HH)	4.0	5.0

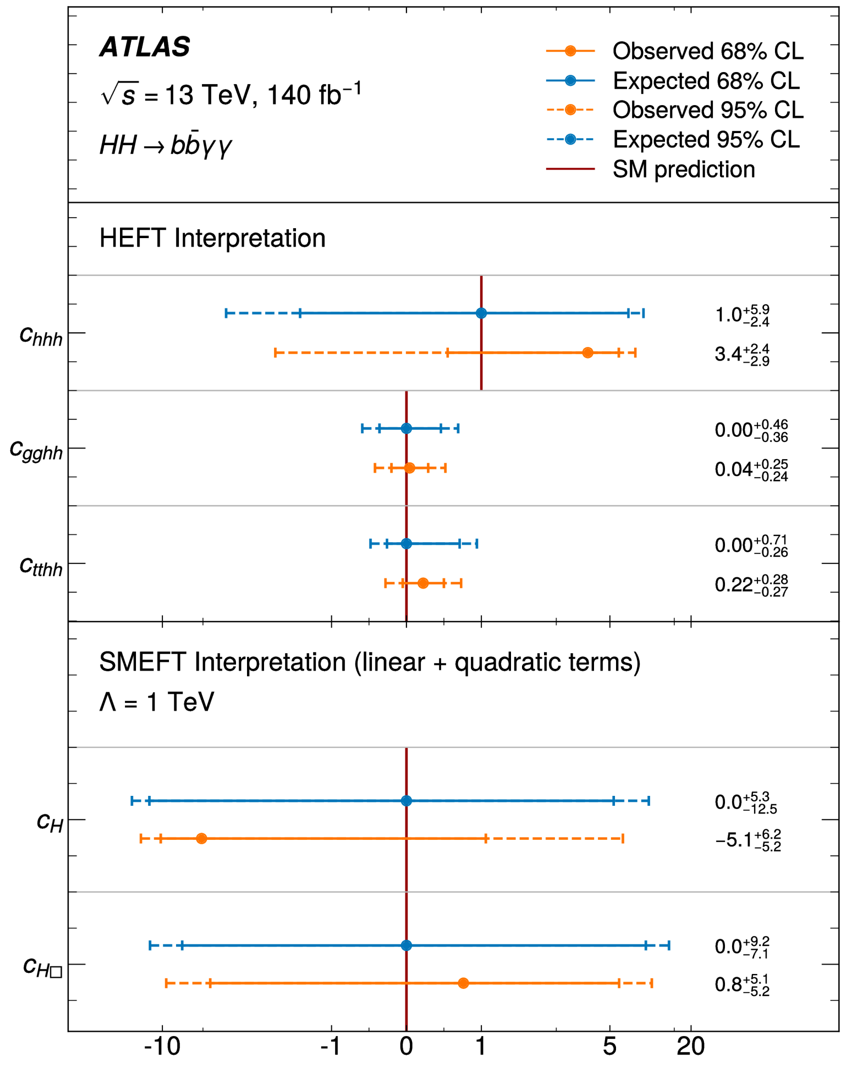
+

95% CL constraints on couplings

	Observed	Expected
κ_λ	[-1.4, 6.9]	[-2.8, 7.8]
κ_{2V}	[-0.5, 2.7]	[-1.1, 3.3]

For the first time in the $\mathbf{b\bar{b}}\gamma\gamma$ channel, the analysis was also **interpreted** in the context of the **EFT** frameworks **HEFT** and **SMEFT**.

More details in **backup**!



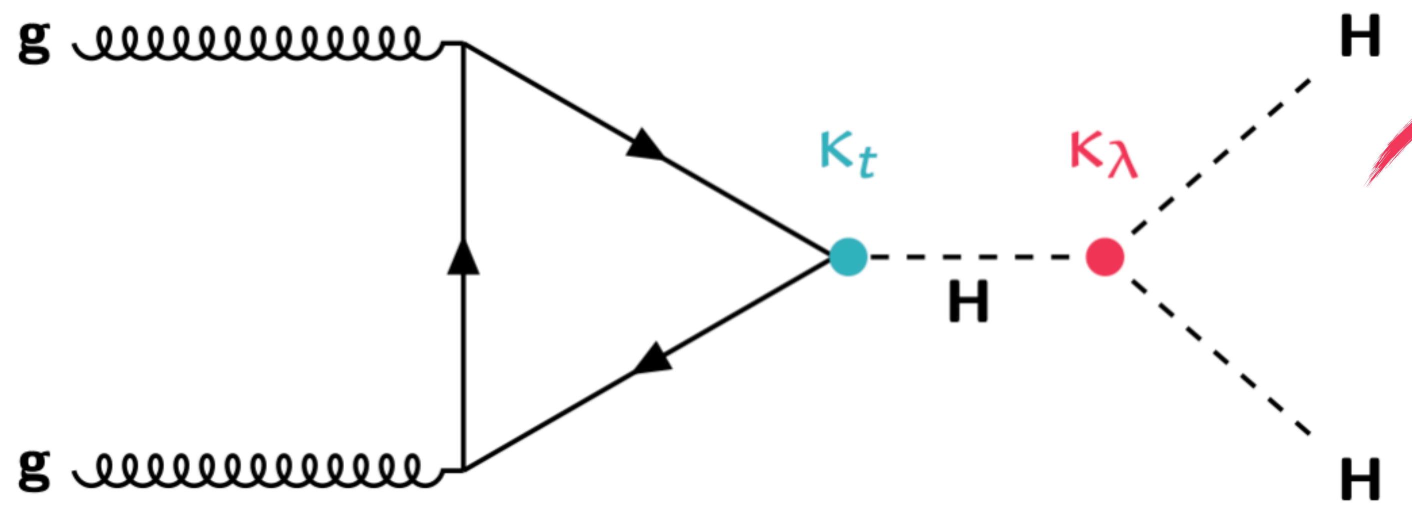
Thank you for your attention!

Backup

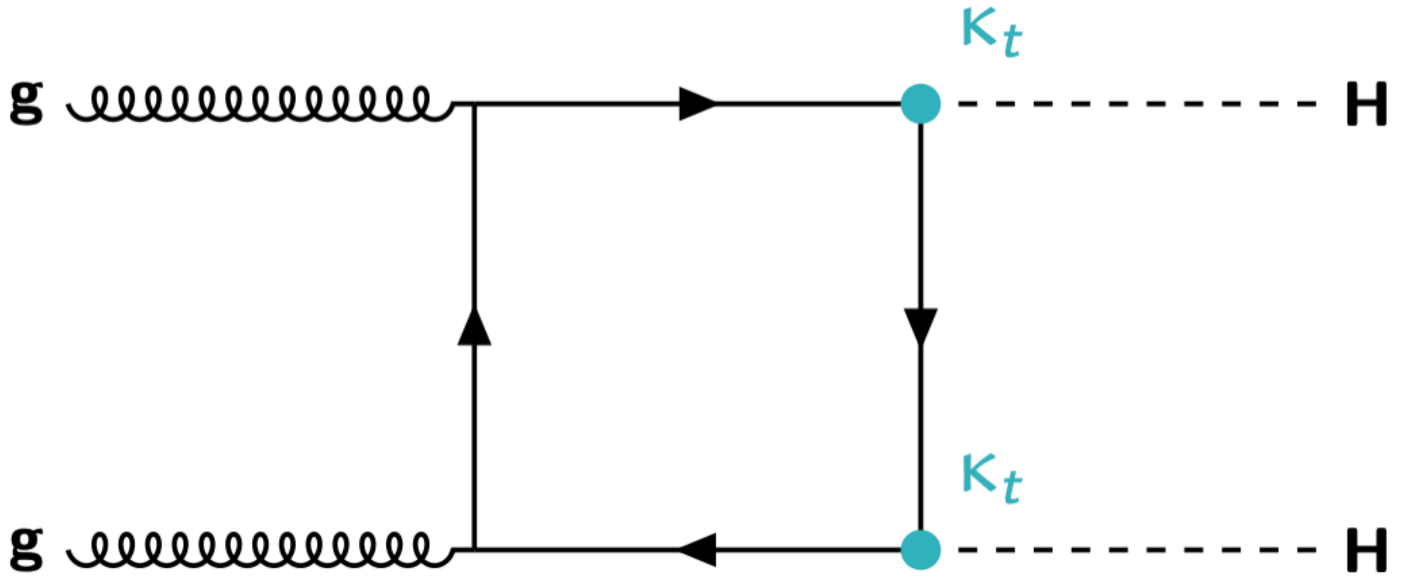
Higgs pair production at the LHC

In the SM, **di-Higgs production** at the **LHC** is **dominated** by the gluon-gluon Fusion (ggF HH) **mechanism**.

Triangle diagram



Box diagram



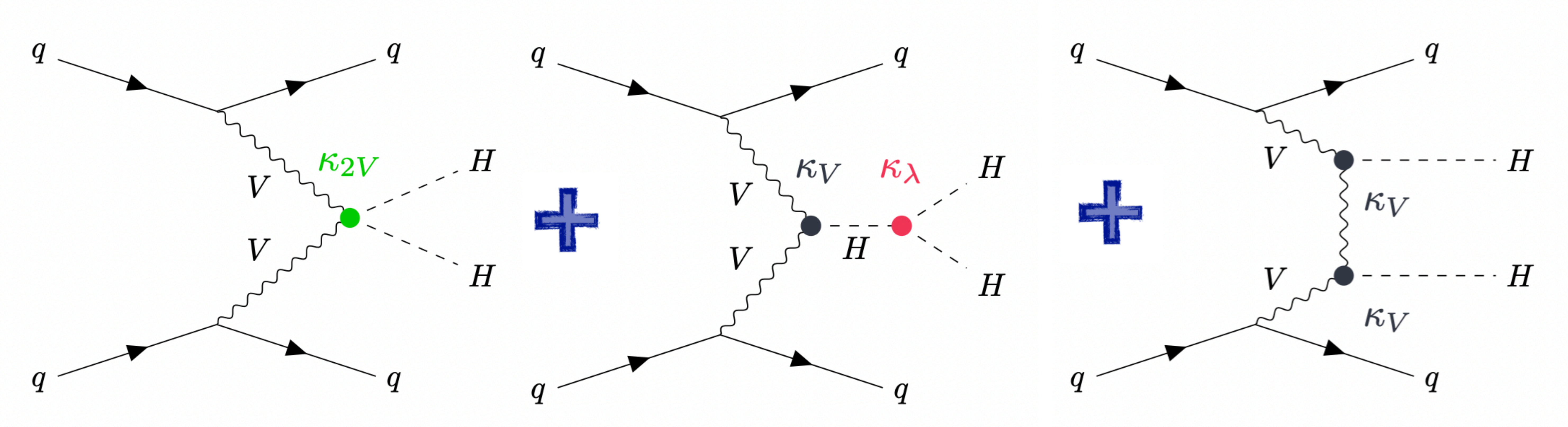
Drives the **sensitivity** to κ_λ.

- $\sigma^{\rm SM}_{\rm ggF}(\rm HH) = 31.05$ **fb** @ 13 TeV.
  - $\sim$ **1/1000** times the production rate for **single Higgs**!
- This is an **extremely rare** process!
  - Can be strongly **enhanced** by **BSM values** of the Higgs couplings, e.g. $\kappa_\lambda \neq 1$.

Expected SM HH and single Higgs production in the 140 fb^{-1} dataset registered by ATLAS during the full Run 2.

	140 fb^{-1}
HH	4000
HH→bbγγ	12
Single H	8 million

The **subdominant** production mode for Higgs pairs is via Vector-Boson-Fusion (VBF HH).



$\sim 1/20 \times \sigma^{\rm SM}_{\rm ggF}(\rm HH)$!

- $\sigma^{\rm SM}_{\rm VBF}(\rm HH) = 1.726$ **fb** @ 13 TeV.
- The peculiar VBF signature involves **two** highly **energetic forward jets**.
  - Helps to **isolate** this **production mode.**
- Provides **additional sensitivity** to κ_λ.
- **Unique** probe to the quartic $HHVV$ **vertex**.

EFT interpretations for the $HH \rightarrow b\bar{b}\gamma\gamma$ analysis

In addition to interpreting the statistical results in terms of constraints on the coupling modifiers κ_λ and κ_{2V}, the $HH \rightarrow b\bar{b}\gamma\gamma$ analysis provides **1-dimensional** and **2-dimensional constraints** on **anomalous Higgs** boson **couplings** in the **EFT framework**!

➡ **Two EFT frameworks** are available in HH: ⟶ **HEFT and SMEFT!**

HEFT

- Only minimal assumption are set in the scalar sector.

  ➡ The observed Higgs boson is a singlet.

- In the HEFT framework, ggF HH production is affected by 5 Wilson coefficients and their operators.

  ➡ c_{hhh}, c_{tth}, c_{tthh}, c_{ggh}, and c_{gghh}.

  SM-like HH couplings (c_{hhh}, c_{tth}); BSM-like HH couplings (c_{tthh}, c_{ggh}, c_{gghh})

- We would like to set limits on the HH cross-section for 7 HEFT benchmarks.

Benchmark	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1.00	1.00	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	−1/3	0	1/6
3	2.21	1.05	1/2	1/2	−1/3
4	2.79	0.90	−1/3	−1/2	−1/6
5	3.95	1.17	1/6	−1/2	−1/3
6	−0.68	0.90	1/2	1/4	−1/6
7	−0.10	0.94	1/6	−1/6	1

\+ 1-dimensional constraints on c_{tthh} and c_{gghh} and 2-dimensional likelihood scans in the (c_{hhh},c_{gghh}) and (c_{hhh},c_{tthh}) planes.

➡ The **parametrization** allows to vary **all HEFT couplings**.

SMEFT

- The observed Higgs boson is a complex doublet of the $SU(2)_L$ group. ⟶ More **SM-like** description!

- We would like to set 1-dimensional constraints on 2 Wilson coefficients.

Wilson Coef.	Operator
c_H	$(\Phi^\dagger\Phi)^3$
$c_{H\Box}$	$\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$

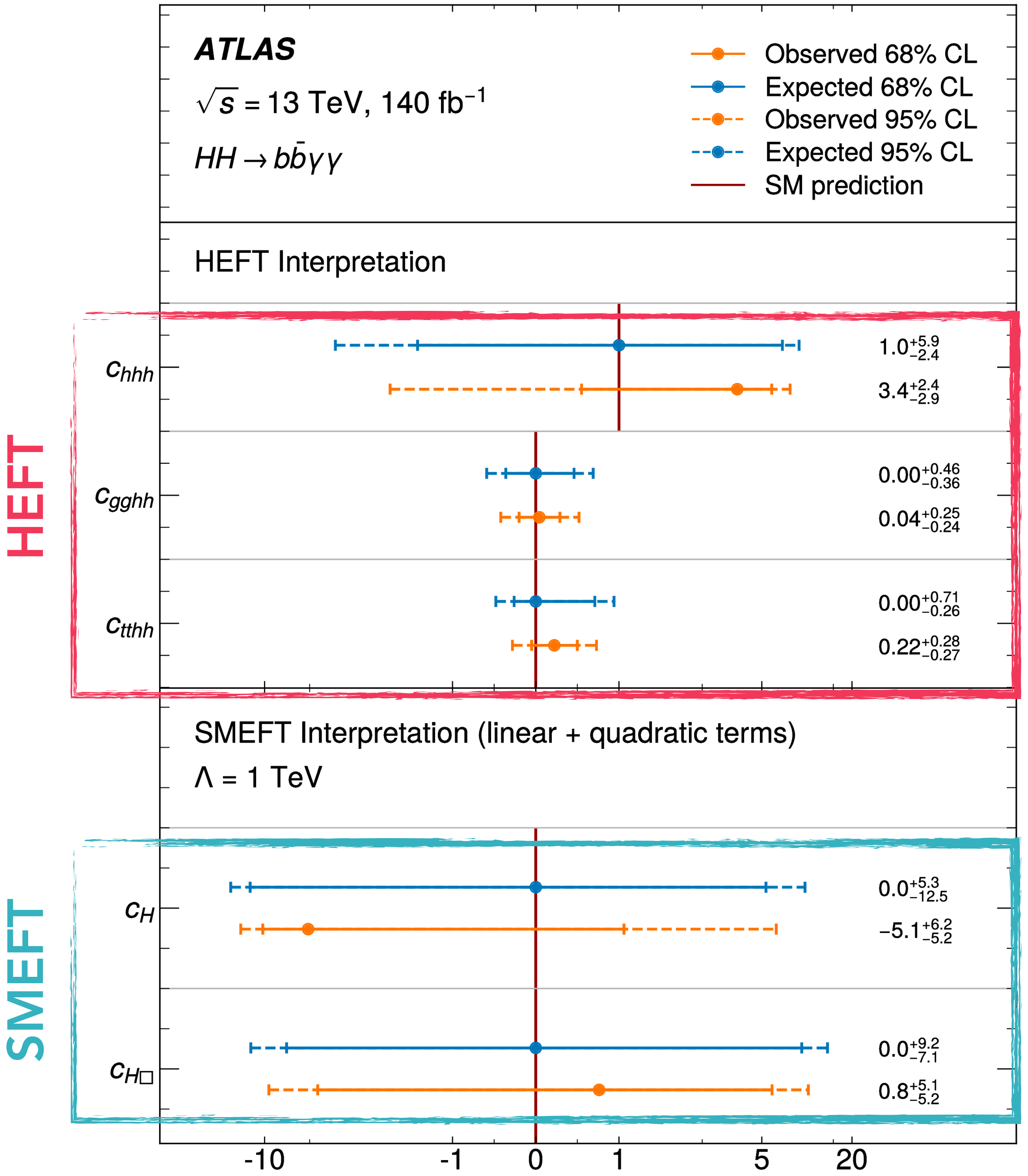
\+ 2-dimensional constraints on $(C_H, C_{H\Box})$!

- Both the HH and the single Higgs processes are parametrized as a function of C_H and $C_{H\Box}$, considering the **linear + quadratic parametrization** only.

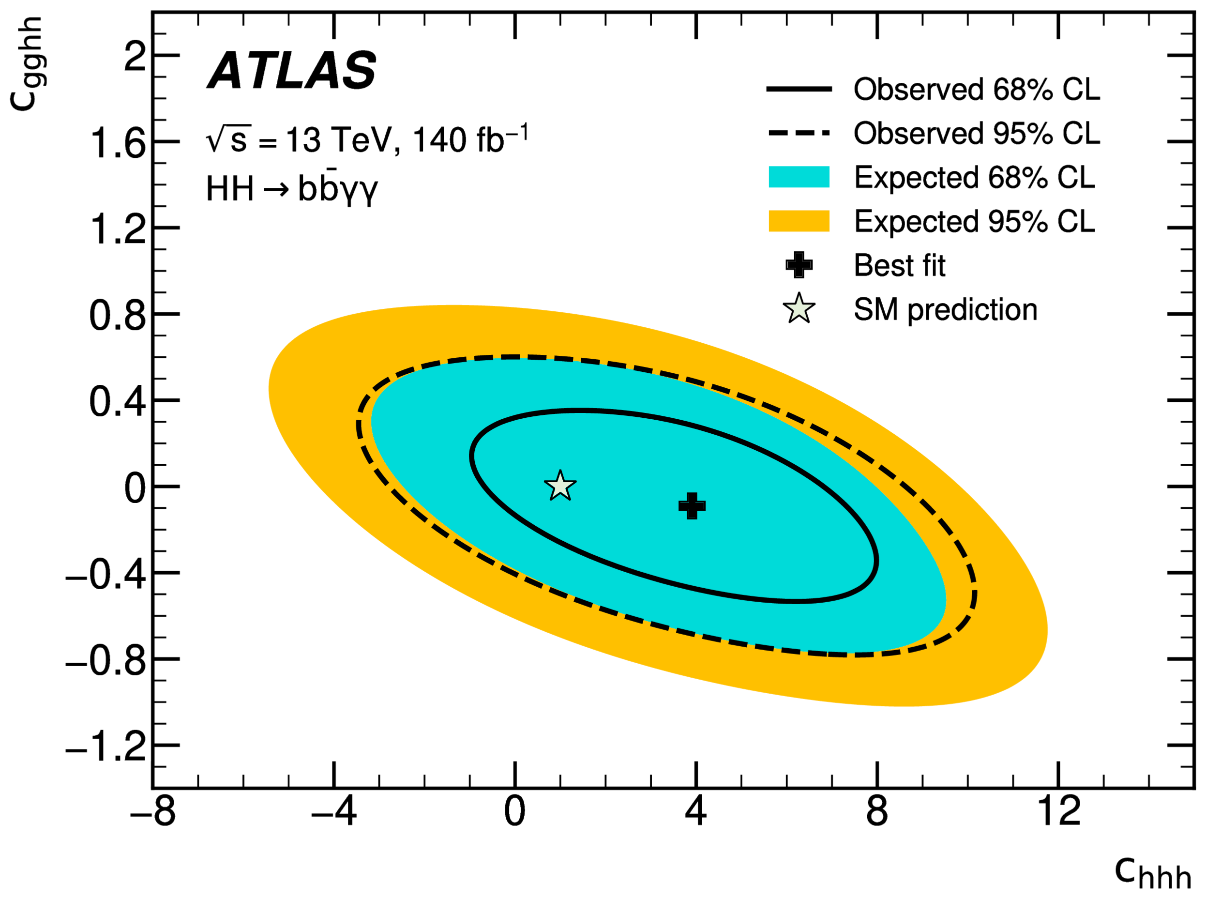
EFT interpretations for the $HH \to b\bar{b}\gamma\gamma$ analysis

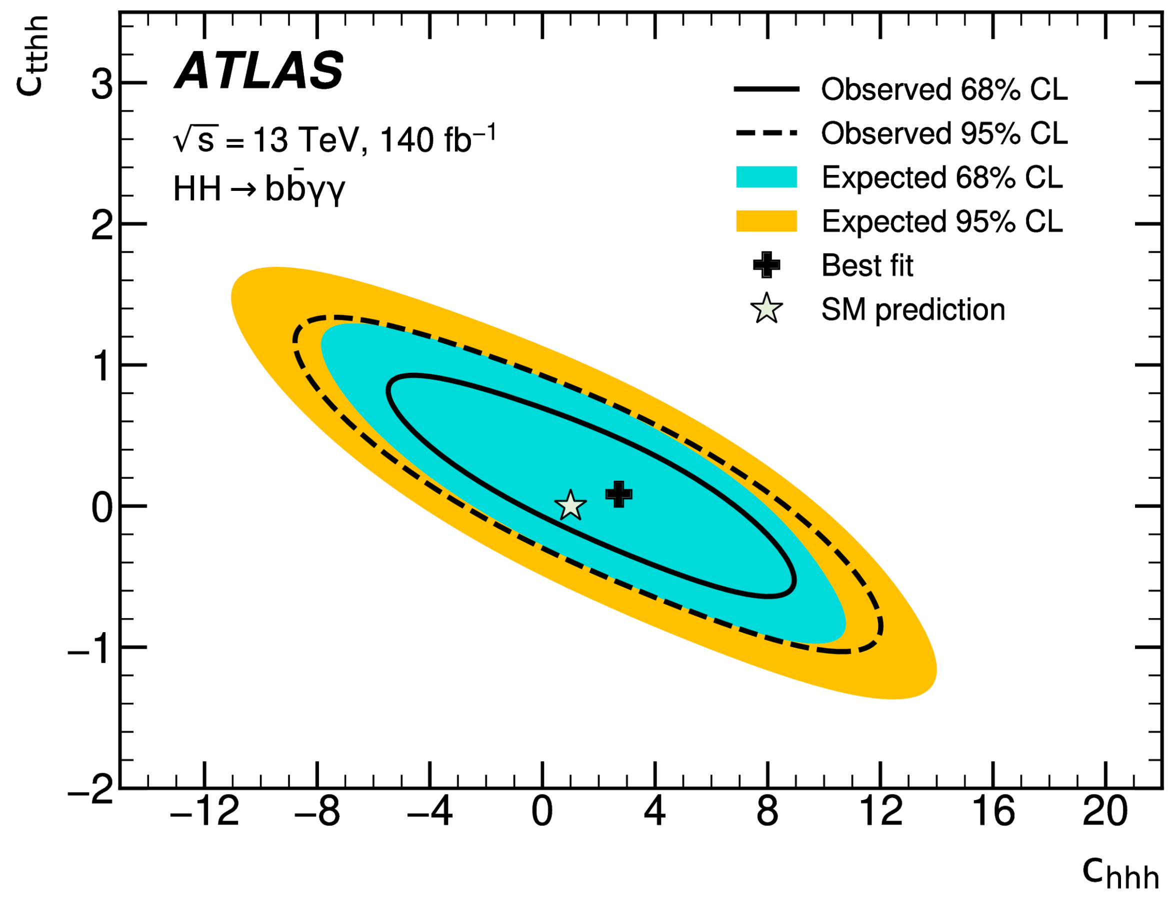
A summary of the constraints on the EFT couplings set by the $HH \to b\bar{b}\gamma\gamma$ analysis is presented here.

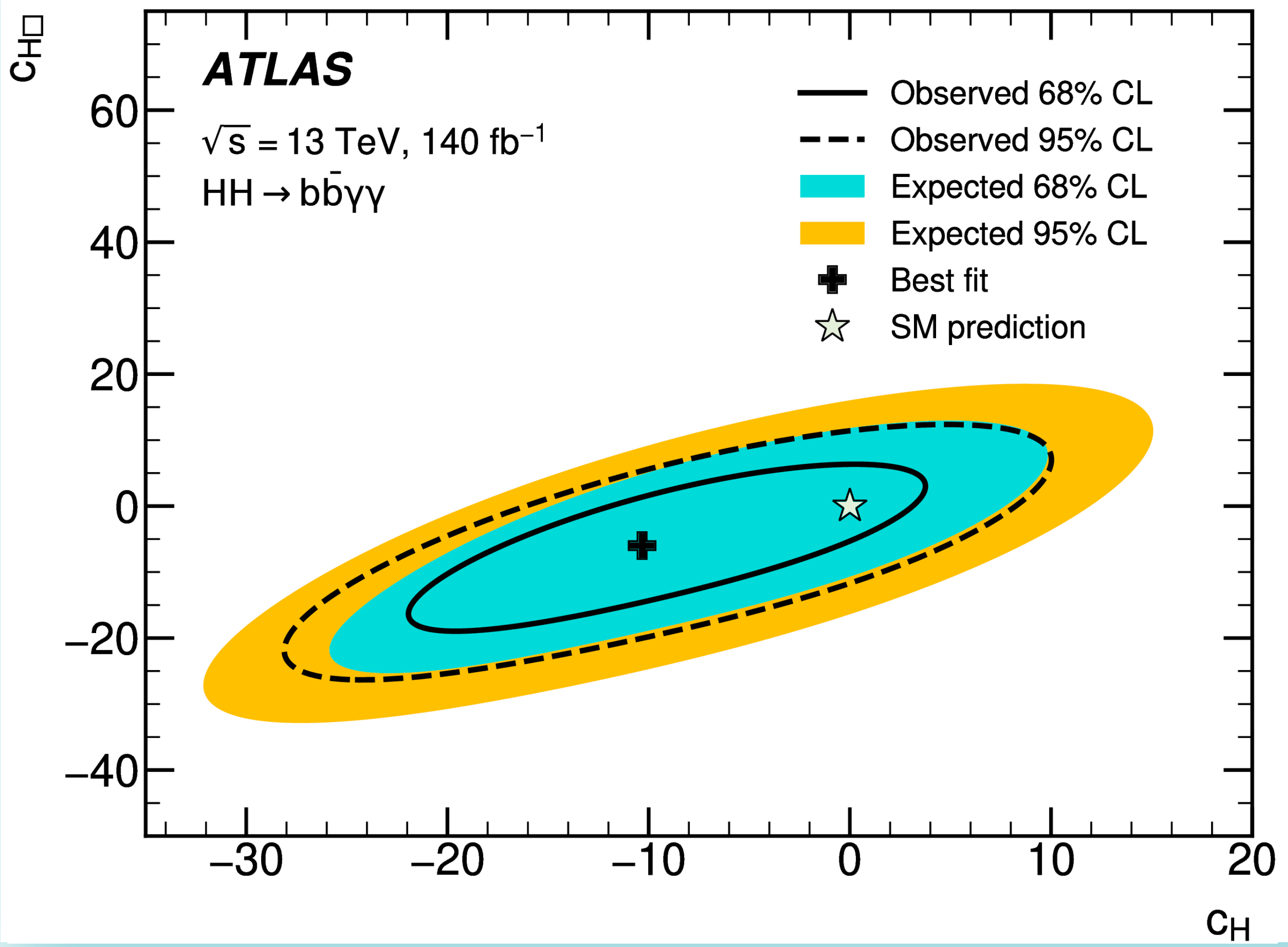
1-dimensional measurements of the HEFT and SMEFT couplings.



2-dimensional measurement in the (c_{hhh}, c_{gghh}) and (c_{hhh}, c_{tthh}) planes.

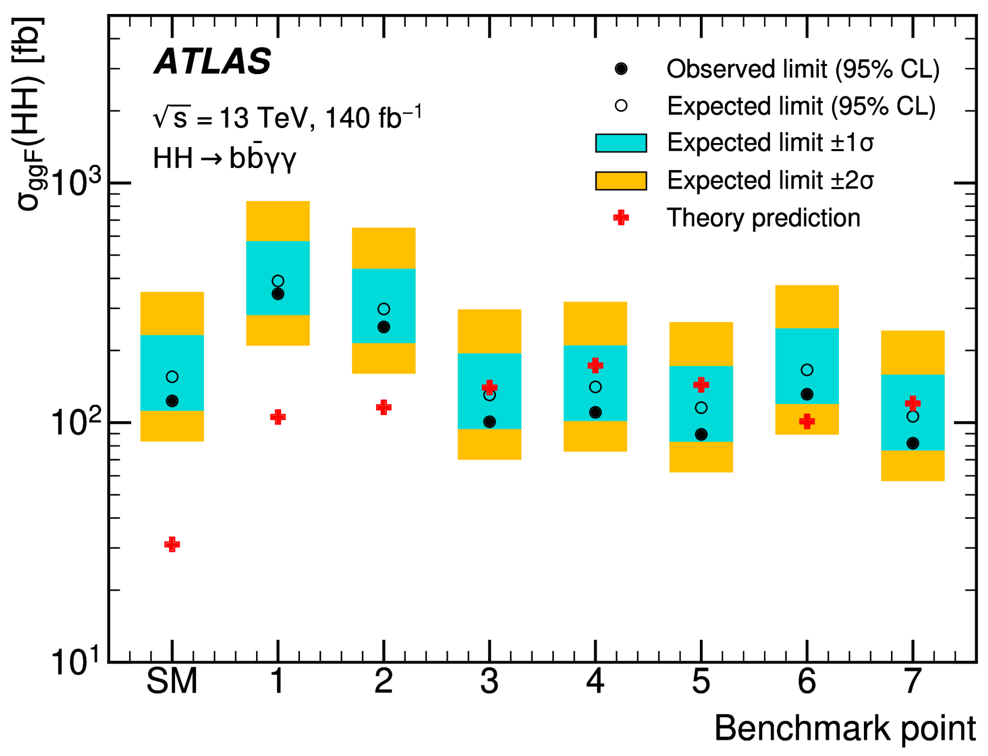






2-dimensional measurement in the $(C_H, C_{H\Box})$ plane.

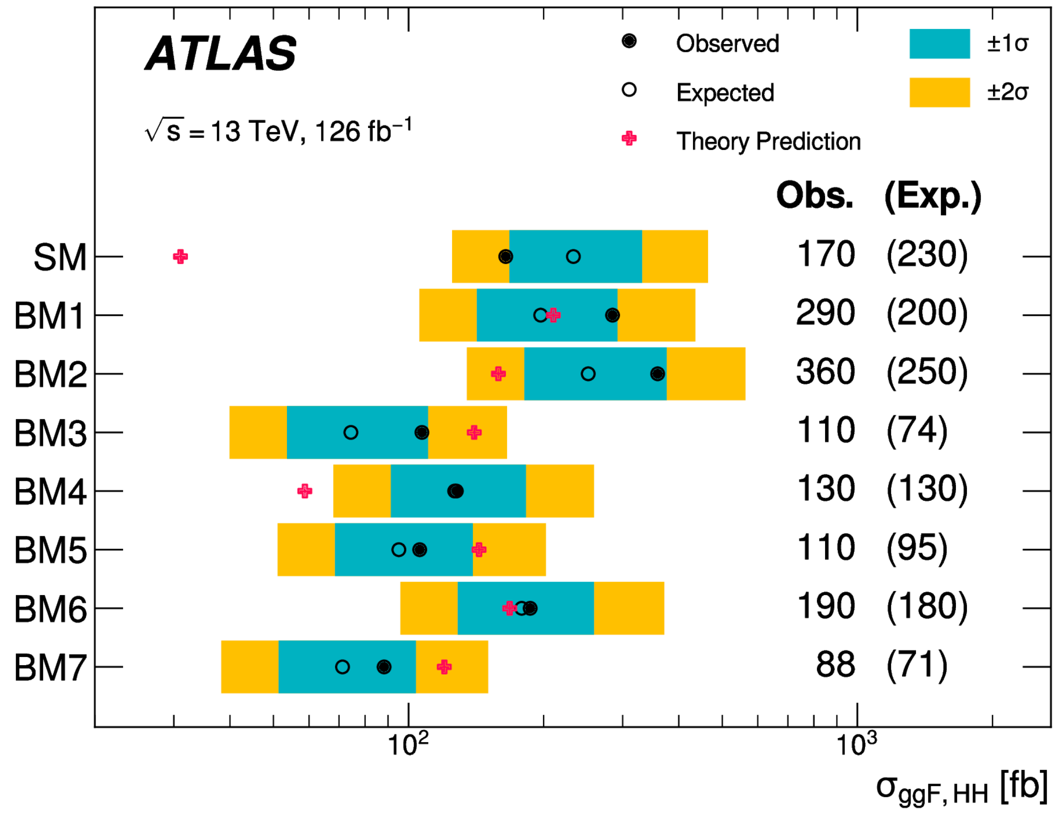
Upper limits on σ for 7 benchmark points.



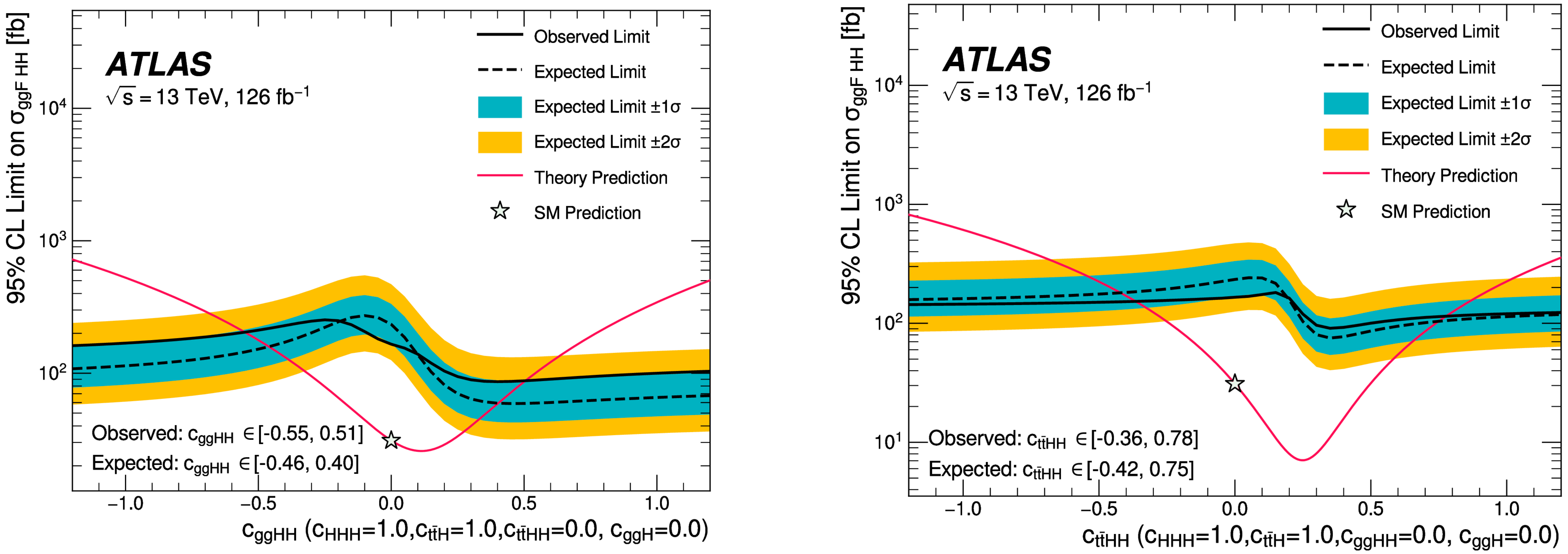
EFT interpretations for the $HH \to b\bar{b}b\bar{b}$ analysis

The new $HH \to b\bar{b}b\bar{b}$ **analysis** with **full Run 2** data has also provided an interpretation of their statistical results in both the **HEFT** and **SMEFT** frameworks!

Upper limits on σ for 7 benchmark points.



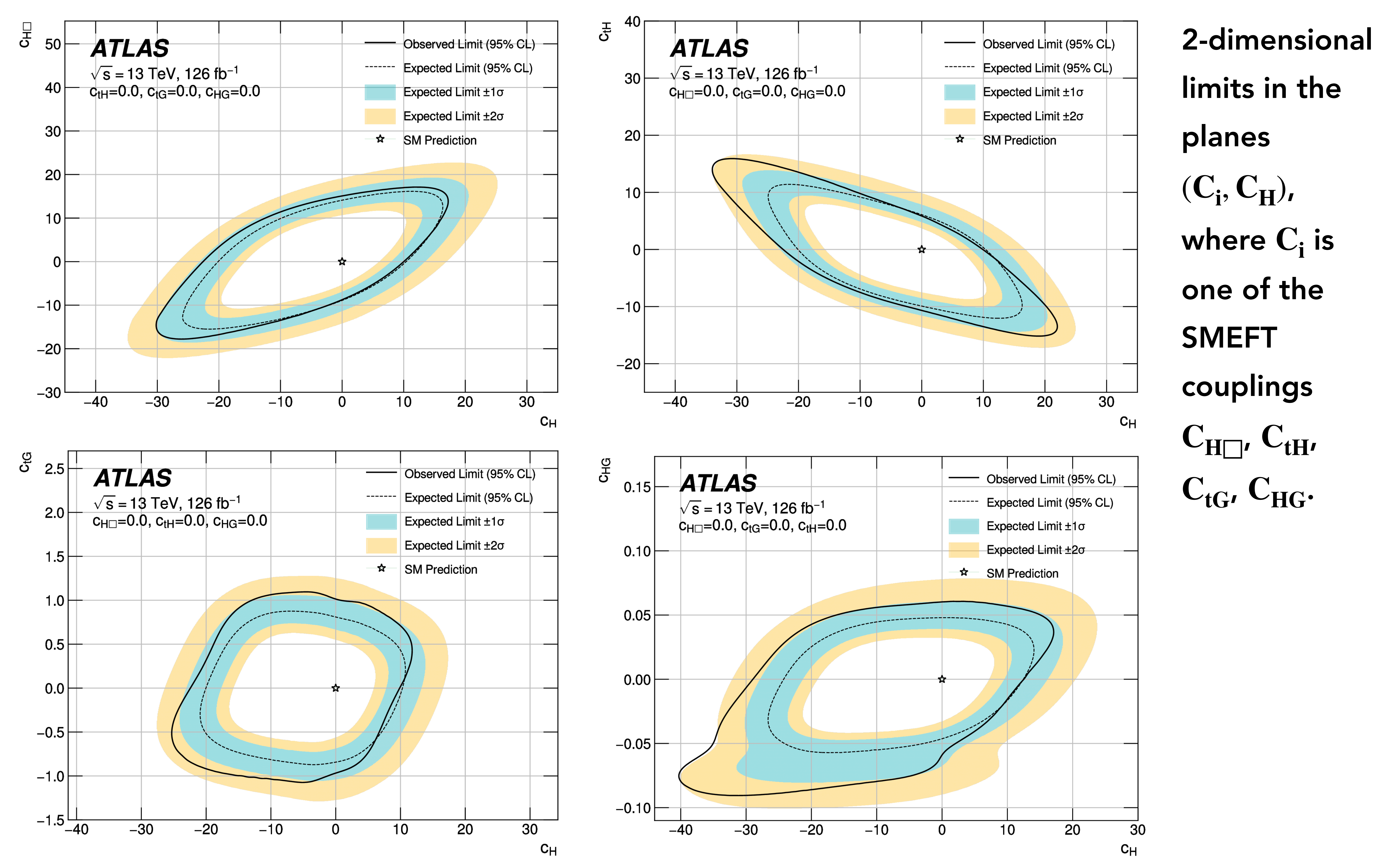
1-dimensional limits on the HEFT couplings c_{ggHH} and c_{ttHH}.



Parameter	Expected Constraint		Observed Constraint	
	Lower	Upper	Lower	Upper
c_H	−20	11	−22	11
c_{HG}	−0.056	0.049	−0.067	0.060
$c_{H\Box}$	−9.3	13.9	−8.9	14.5
c_{tH}	−10.0	6.4	−10.7	6.2
c_{tG}	−0.97	0.94	−1.12	1.15

1-dimensional limits on the SMEFT couplings.

EFT interpretations for the $HH \rightarrow b\bar{b}b\bar{b}$ analysis



2-dimensional limits in the planes (C_i, C_H), where C_i is one of the SMEFT couplings $C_{H\Box}$, C_{tH}, C_{tG}, C_{HG}.

Outlook for HL-LHC: projections of the old Run 2 $HH \to b\bar{b}\gamma\gamma$ analysis

- With the **Run 2 old and new HH analyses** we made a nice **step** in **improving** our constraints on **SM HH production** as well as **anomalous** κ_λ **and** κ_{2V} **values**.
- However, the **final statement** about **HH production** and the **trilinear self-coupling** is expected only after the **HL-LHC data-taking**.

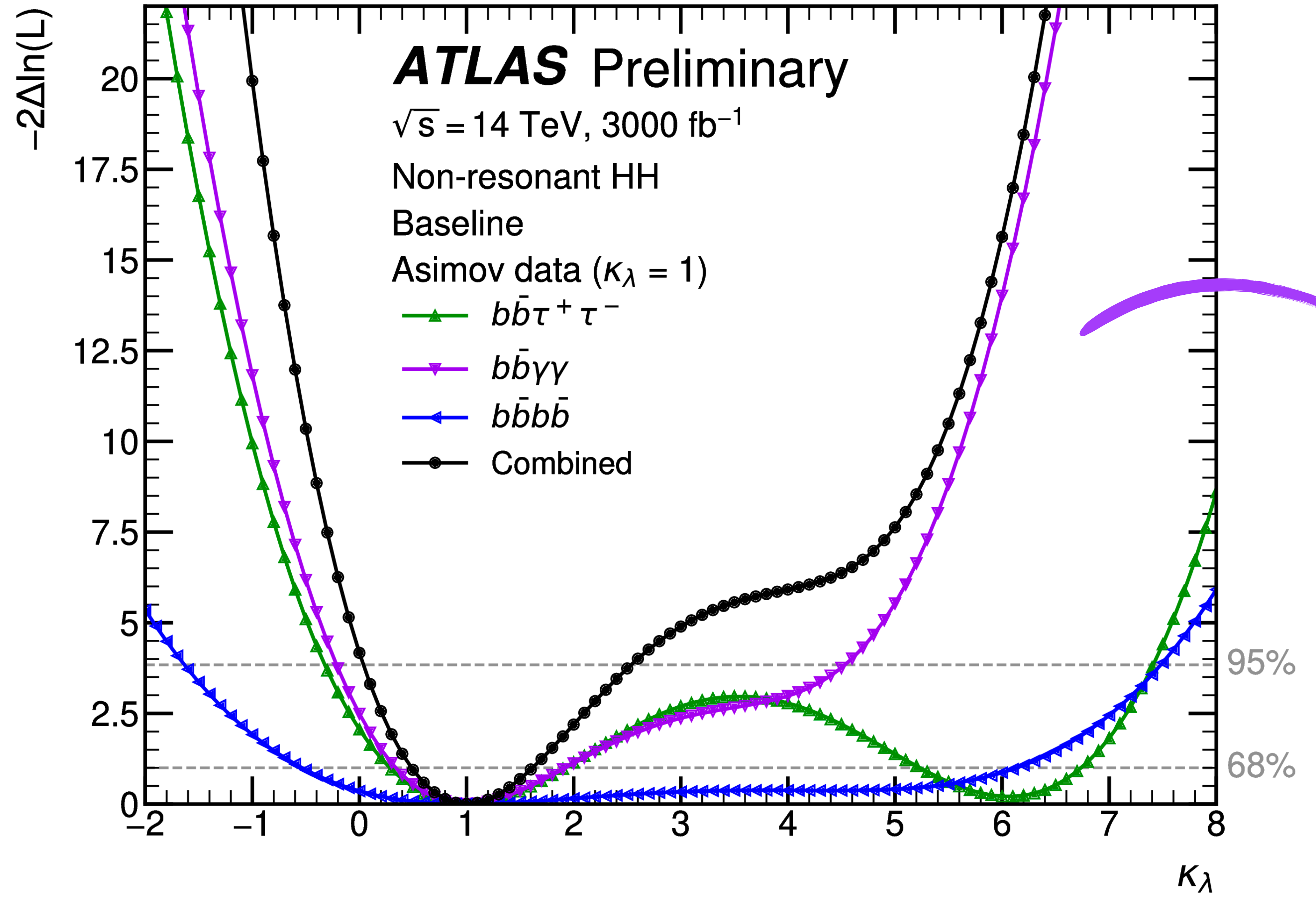
The **HH Run 2 old analyses** in the three golden channels were projected to the **HL-LHC data-taking scenario**!

$\sqrt{s}$ = 14 TeV, 3000 fb^{-1}!

$b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, and $b\bar{b}b\bar{b}$!

Four systematic uncertainty schemes:

No syst. unc.	Optimistic scenario: no syst. unc.
Baseline	- Experimental and theoretical unc. halved. - Modelling uncertainties same as Run 2. - Luminosity unc. scaled by 0.6
Theoretical unc. halved	- Theoretical unc. halved. - Experimental, luminosity and modelling uncertainties same as Run 2.
Run 2 syst. unc.	Pessimistic scenario: same unc. as Run 2.



The $b\bar{b}\gamma\gamma$ **channel** is expected to provide the **leading sensitivity** to κ_λ at the **HL-LHC**!

HL-LHC prospects for $HH \to b\bar{b}b\bar{b}$ and HH combination: ATL-PHYS-PUB-2022-053.

Outlook for HL-LHC: projections of the old Run 2 $HH \to b\bar{b}\gamma\gamma$ analysis

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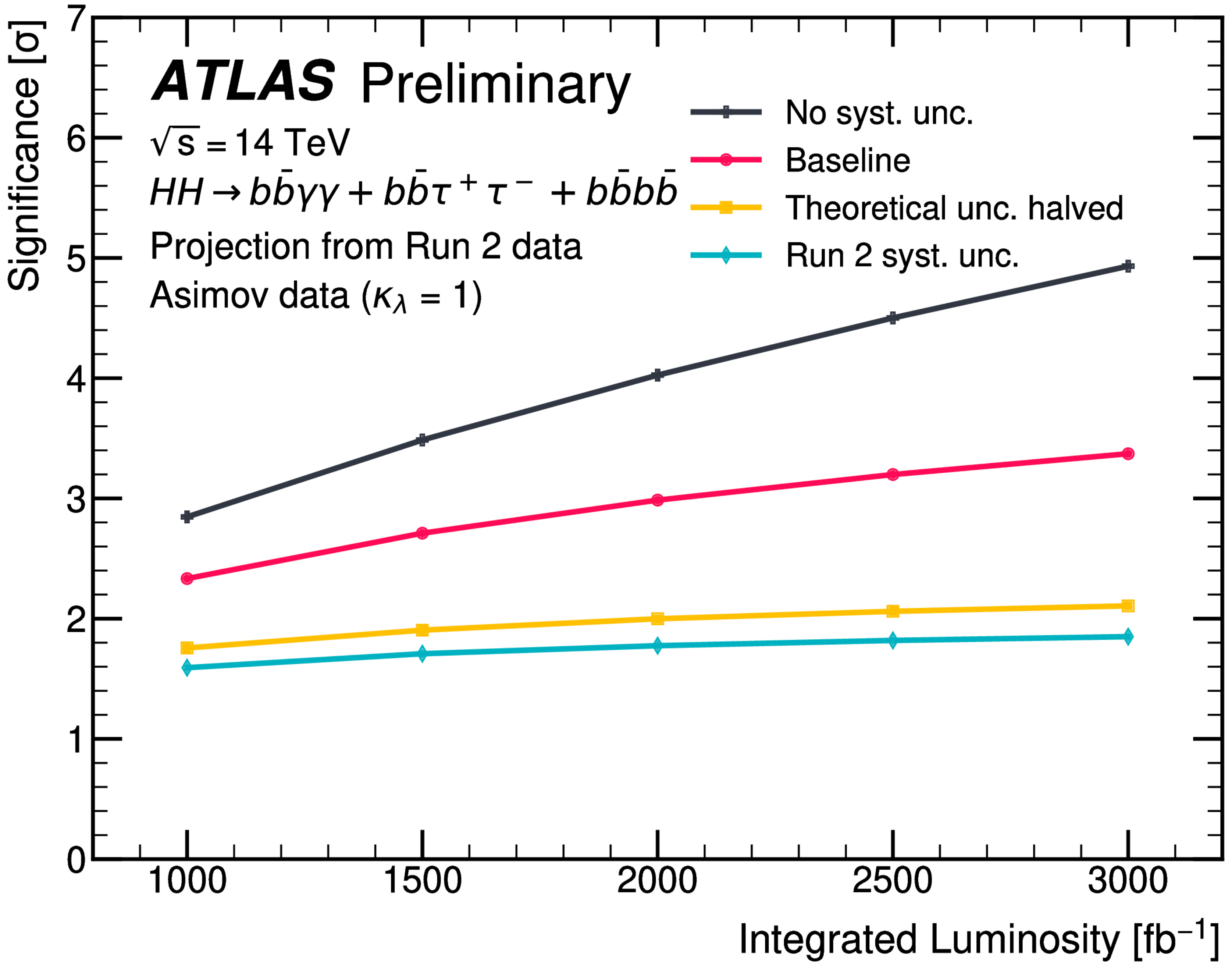

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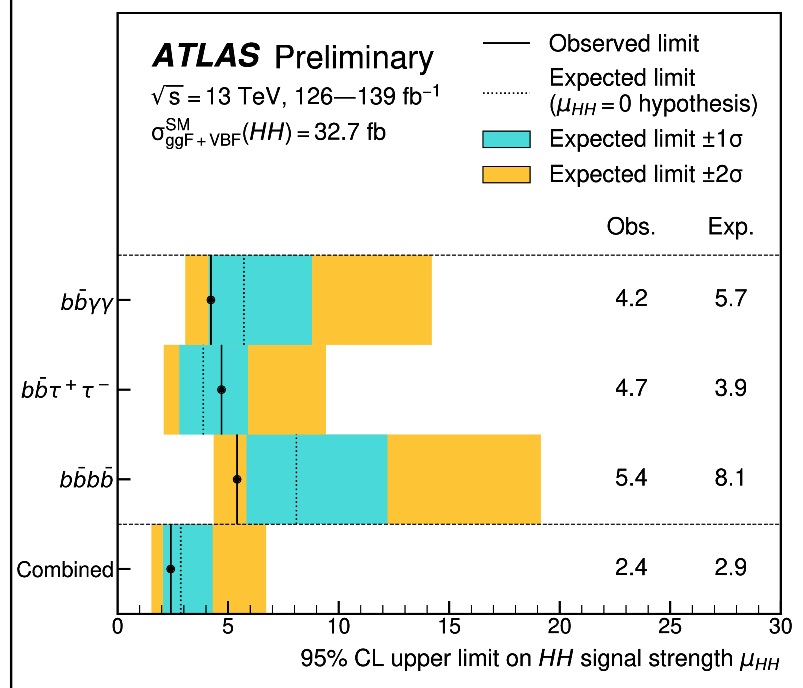
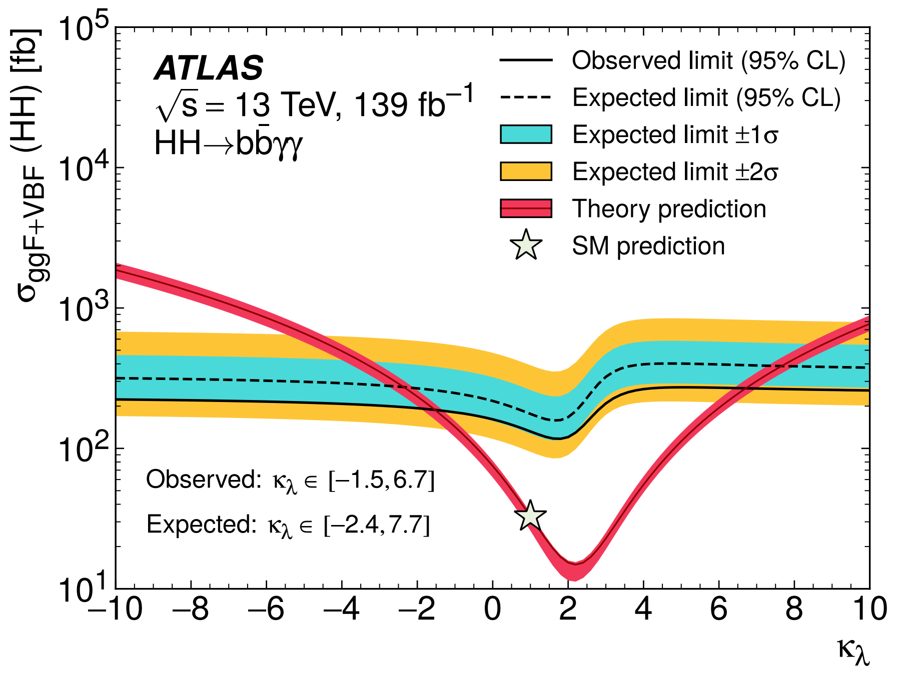
Theoretical unc. halved	- Theoretical unc. halved. - Experimental, luminosity and modelling uncertainties same as Run 2.
Run 2 syst. unc.	Pessimistic scenario: same unc. as Run 2.

- While **Run 2** analyses are **mostly statistically limited**, the **systematic uncertainties** start to be a **limiting factor** in the **analysis sensitivity** at **HL-LHC**!
- **Crucial** to start **now** to **understand and tackle** our **dominant systematics**!

HL-LHC prospects for $HH \to b\bar{b}b\bar{b}$ and HH combination: ATL-PHYS-PUB-2022-053.

Other di-Higgs searches: ATLAS

<table>
<tr><th></th><th>HH → bbγγ</th><th>HH → bbττ</th><th>HH → bbbb</th><th>HH combination</th></tr>
<tr><td>Constraints on $\sigma_{ggF+VBF}(HH)$</td>
<td>Expected: $5.7 \times \sigma^{SM}$
Observed: $4.2 \times \sigma^{SM}$</td>
<td>Expected: $3.9 \times \sigma^{SM}$
Observed: $4.7 \times \sigma^{SM}$</td>
<td>Expected: $8.1 \times \sigma^{SM}$
Observed: $5.4 \times \sigma^{SM}$</td>
<td>

Expected: $2.9 \times \sigma^{SM}$
Observed: $2.4 \times \sigma^{SM}$</td></tr>
<tr><td>Constraints on κ_λ</td>
<td>
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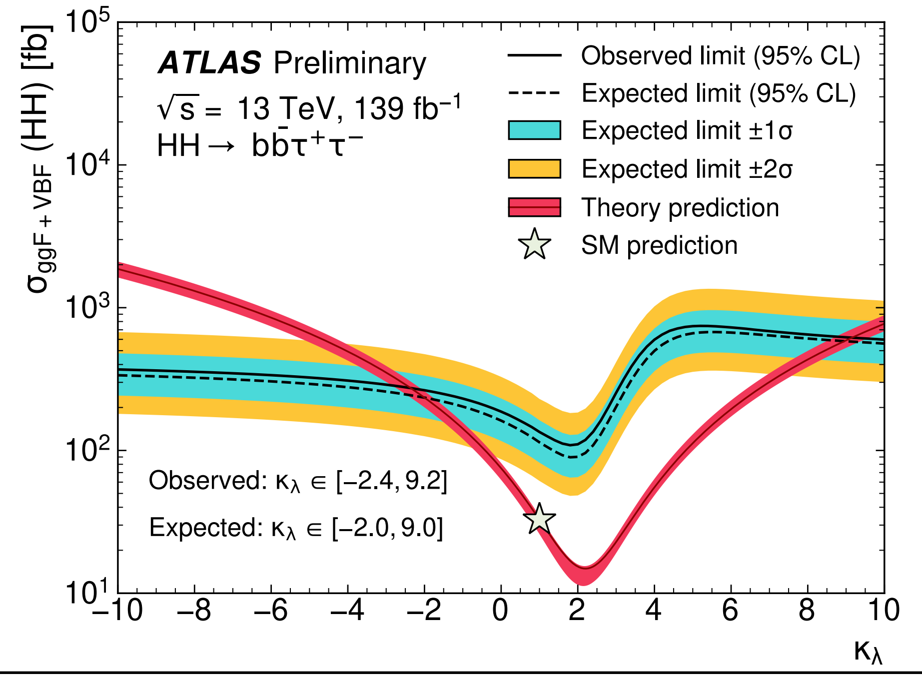
<td>
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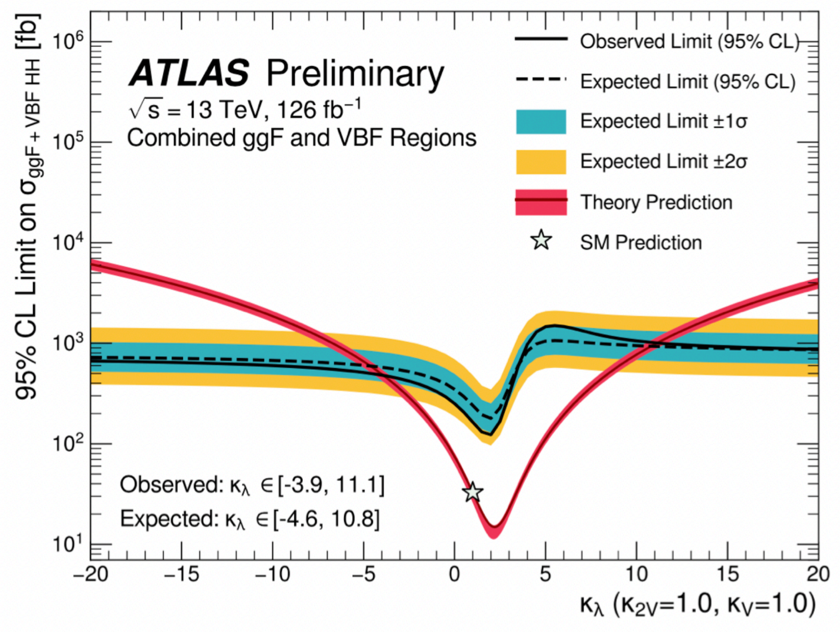
<td>
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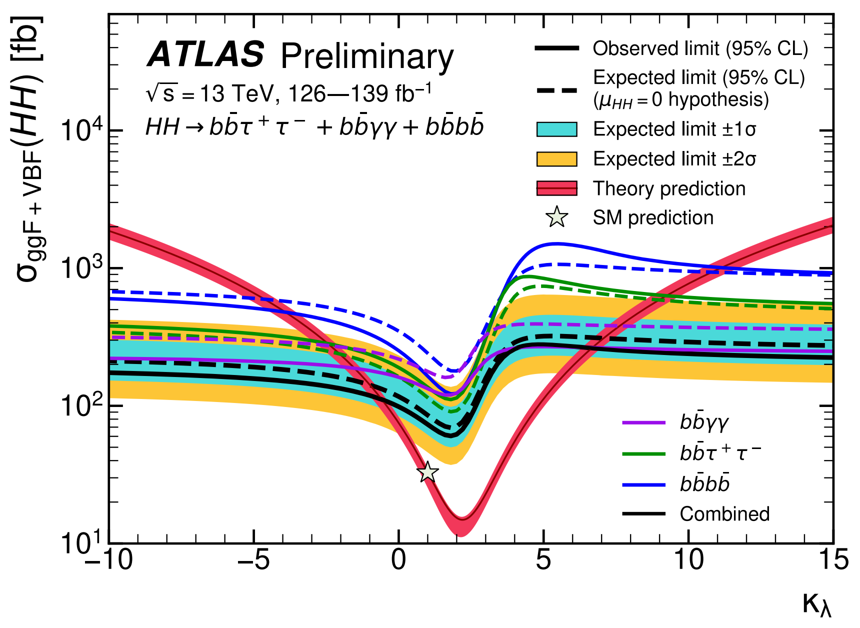
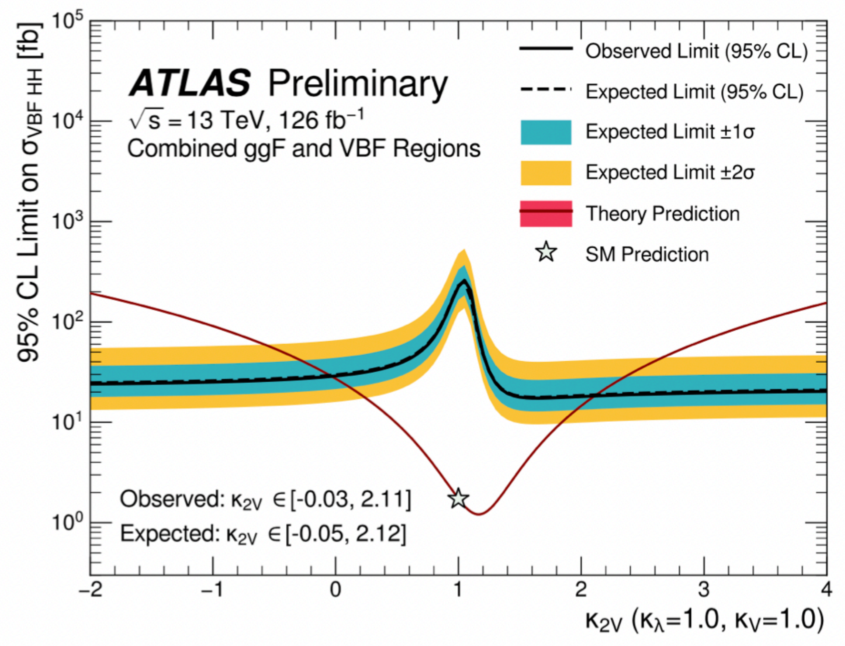
<td>

Expected: $\kappa_\lambda \in [-2.1, 7.8]$
Observed: $\kappa_\lambda \in [-0.6, 6.6]$</td></tr>
<tr><td>Constraints on κ_{2V}</td>
<td>-</td>
<td>-</td>
<td>
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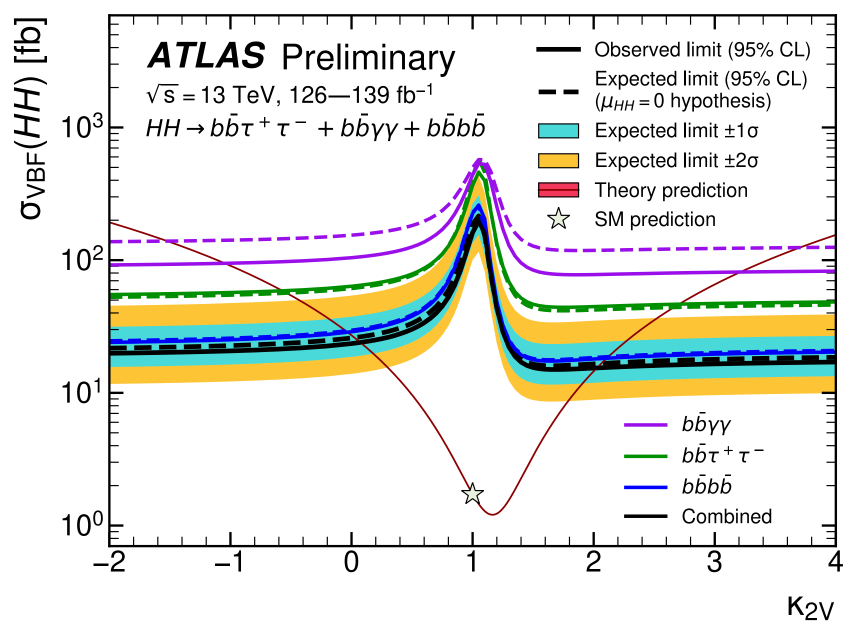
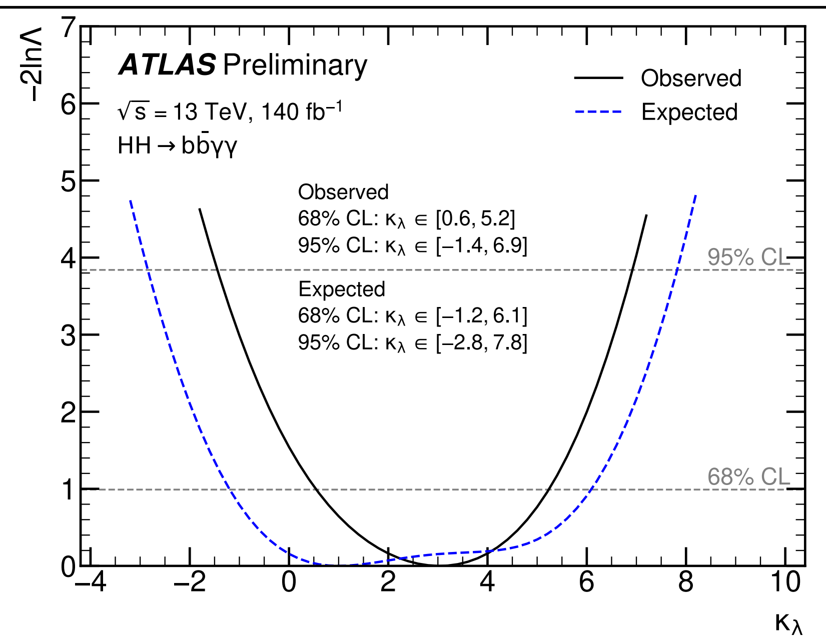
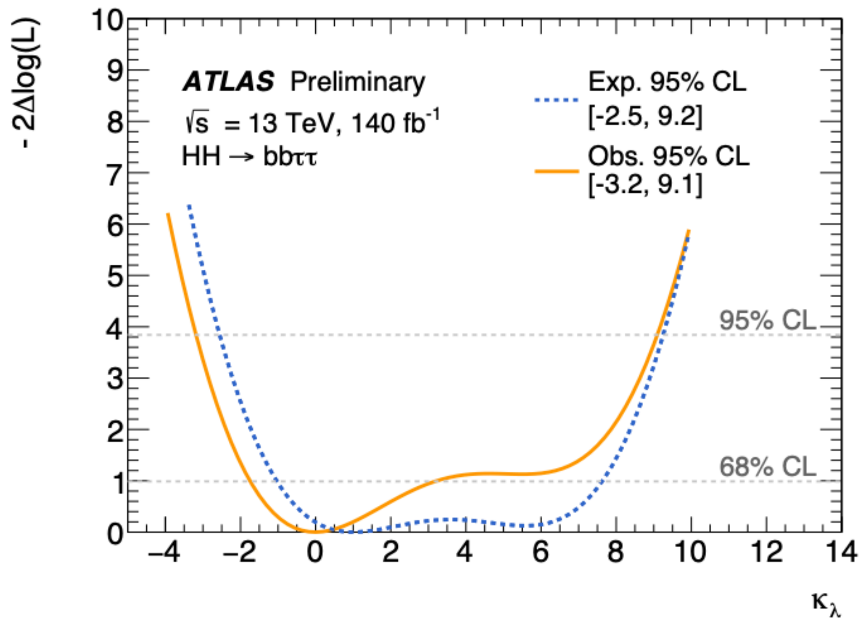
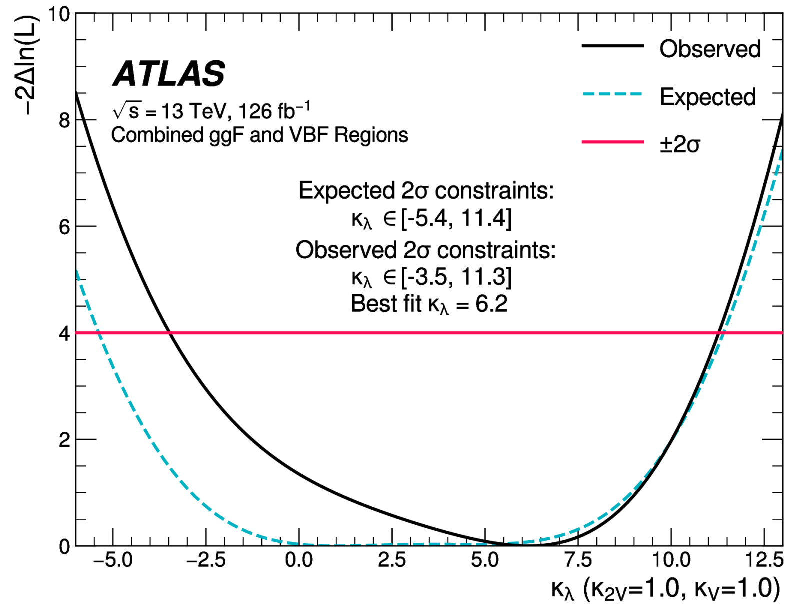
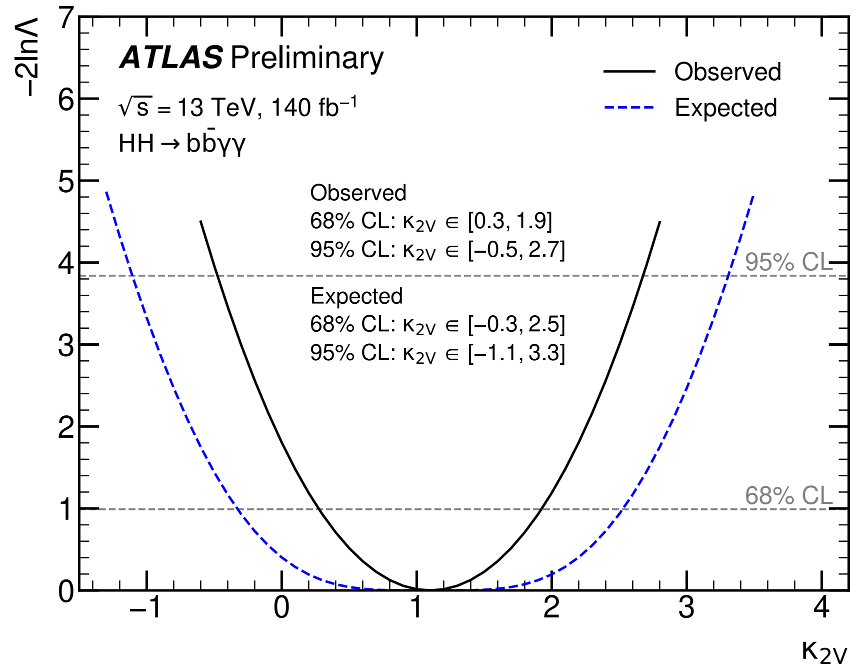
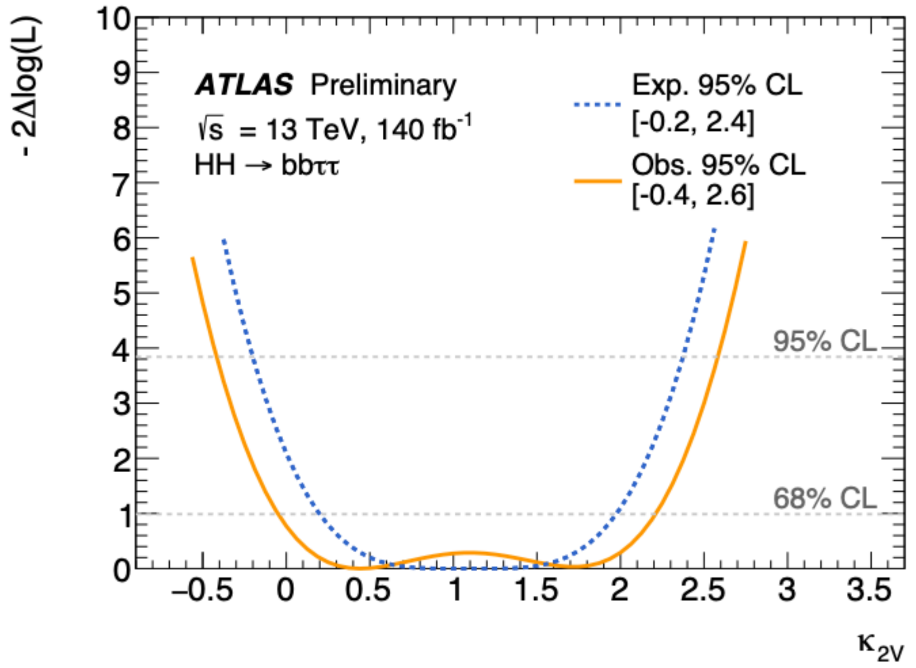
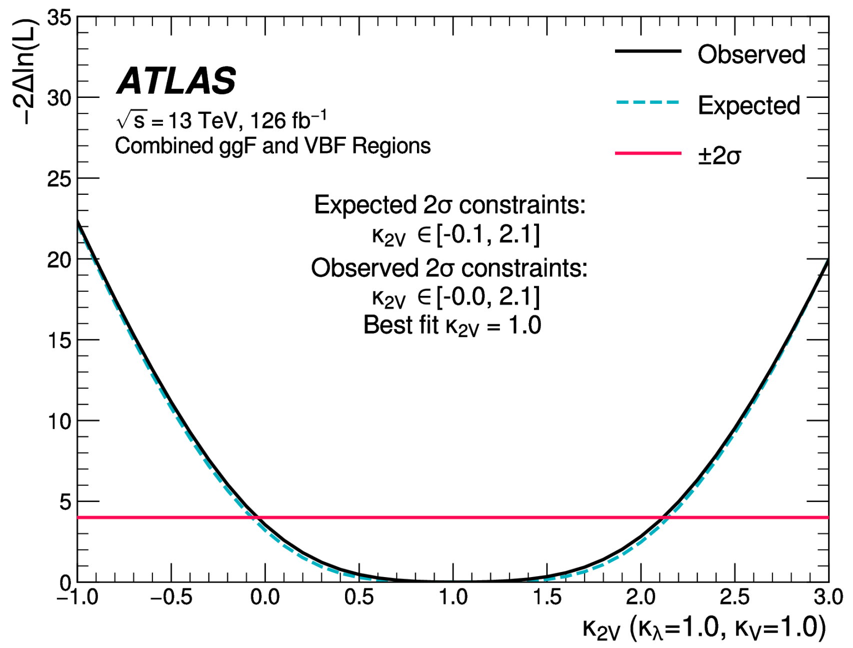
<td>

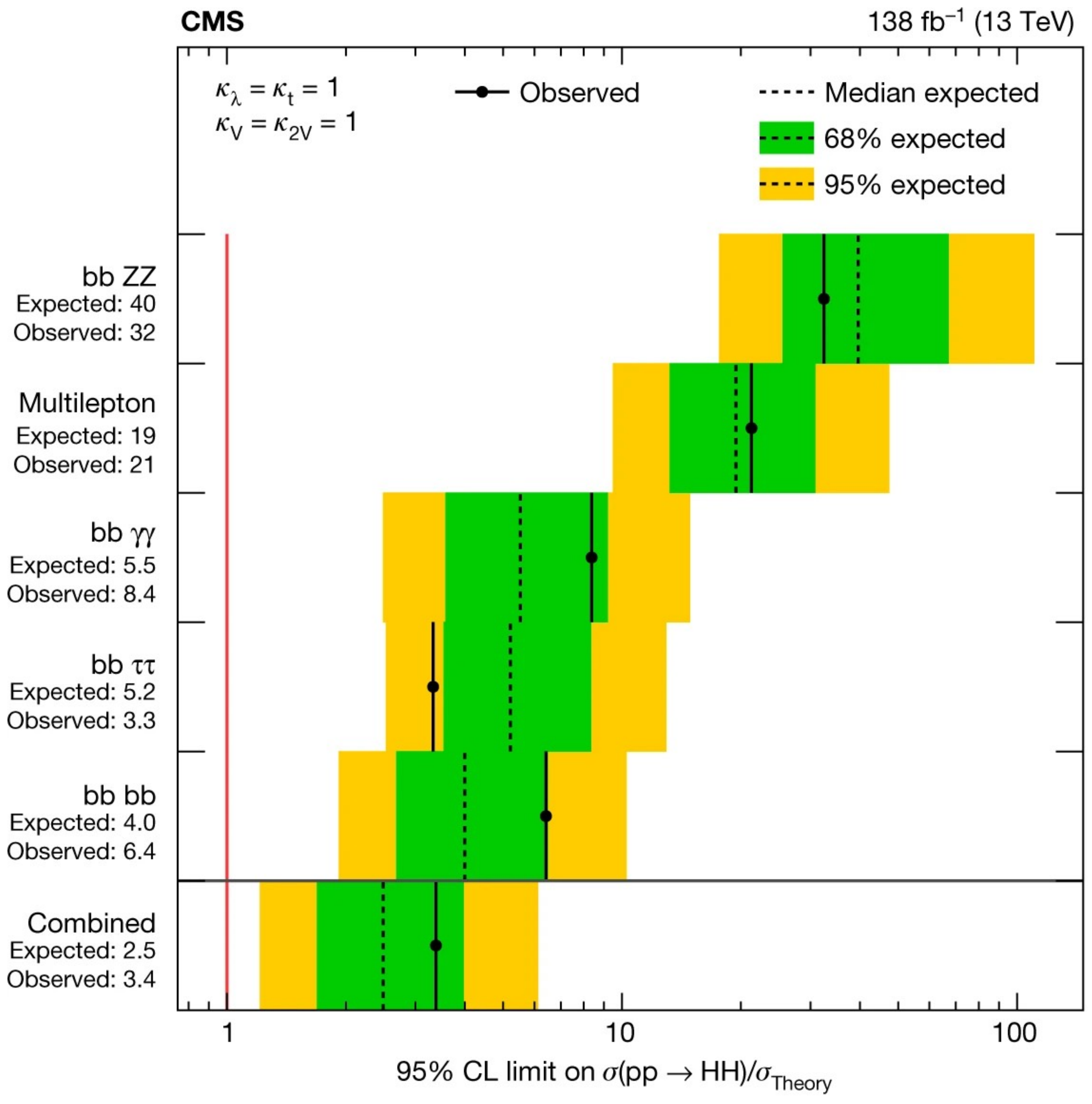
Expected: $\kappa_{2V} \in [0.0, 2.1]$
Observed: $\kappa_\lambda \in [0.1, 2.0]$</td></tr>
</table>

Other di-Higgs searches: ATLAS new Run 2 analyses

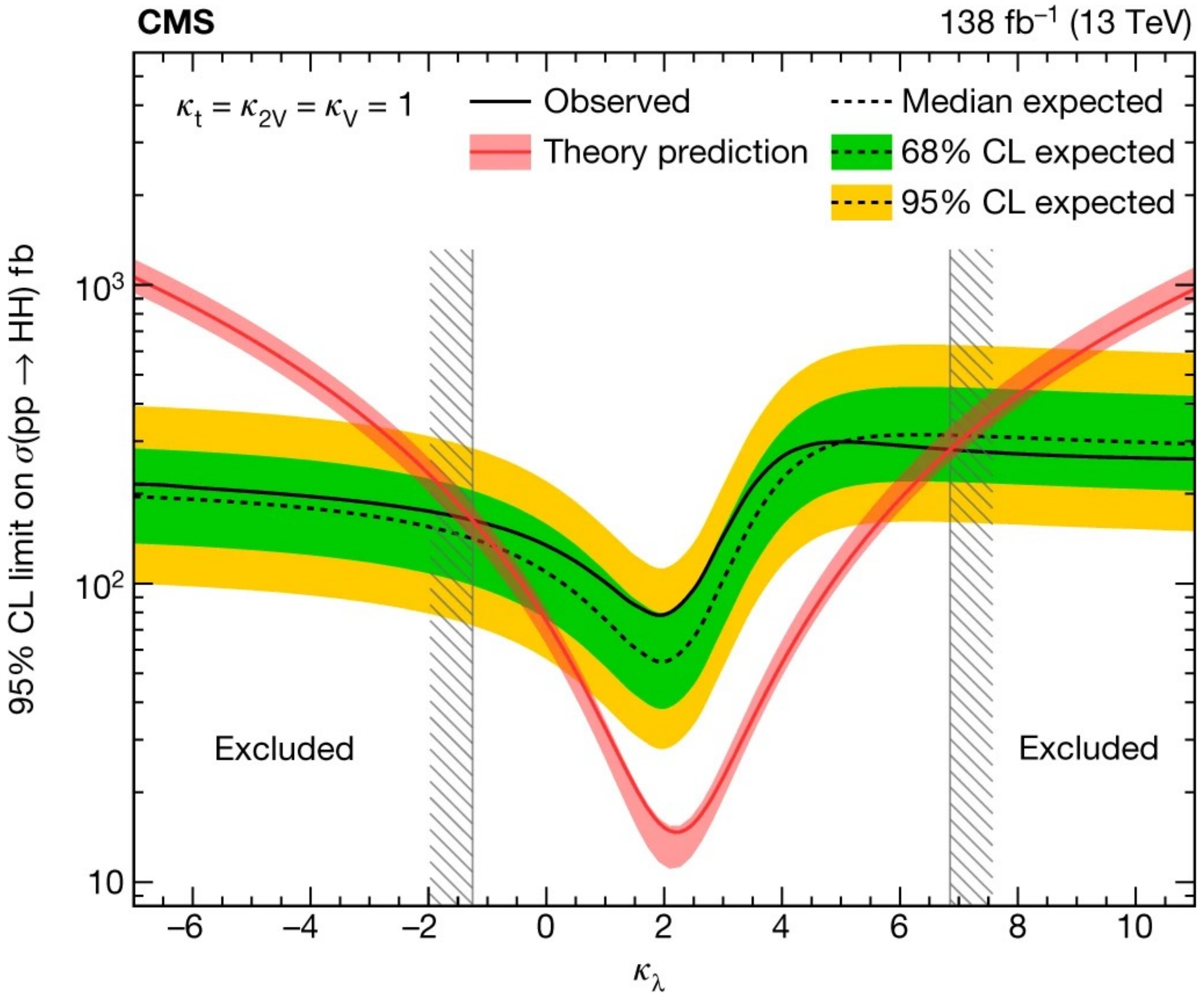
	HH → bbγγ	HH → bbττ	HH → bbbb
Status	• New result! • The paper is on ArXiv, and was submitted to JHEP.	• New result for Higgs 2023! • Check out Brian's [presentation]().	• Paper published in Phys. Rev. D ([Phys. Rev. D 108 (2023) 052003]())!
Constraints on $\sigma_{ggF+VBF}(HH)$	**Expected** $5.0 \times \sigma^{SM}$ **Observed** $4.0 \times \sigma^{SM}$	**Expected** $3.1 \times \sigma^{SM}$ **Observed** $5.9 \times \sigma^{SM}$	**Expected** $8.1 \times \sigma^{SM}$ **Observed** $5.4 \times \sigma^{SM}$
Constraints on κ_λ			
Constraints on κ_{2V}			

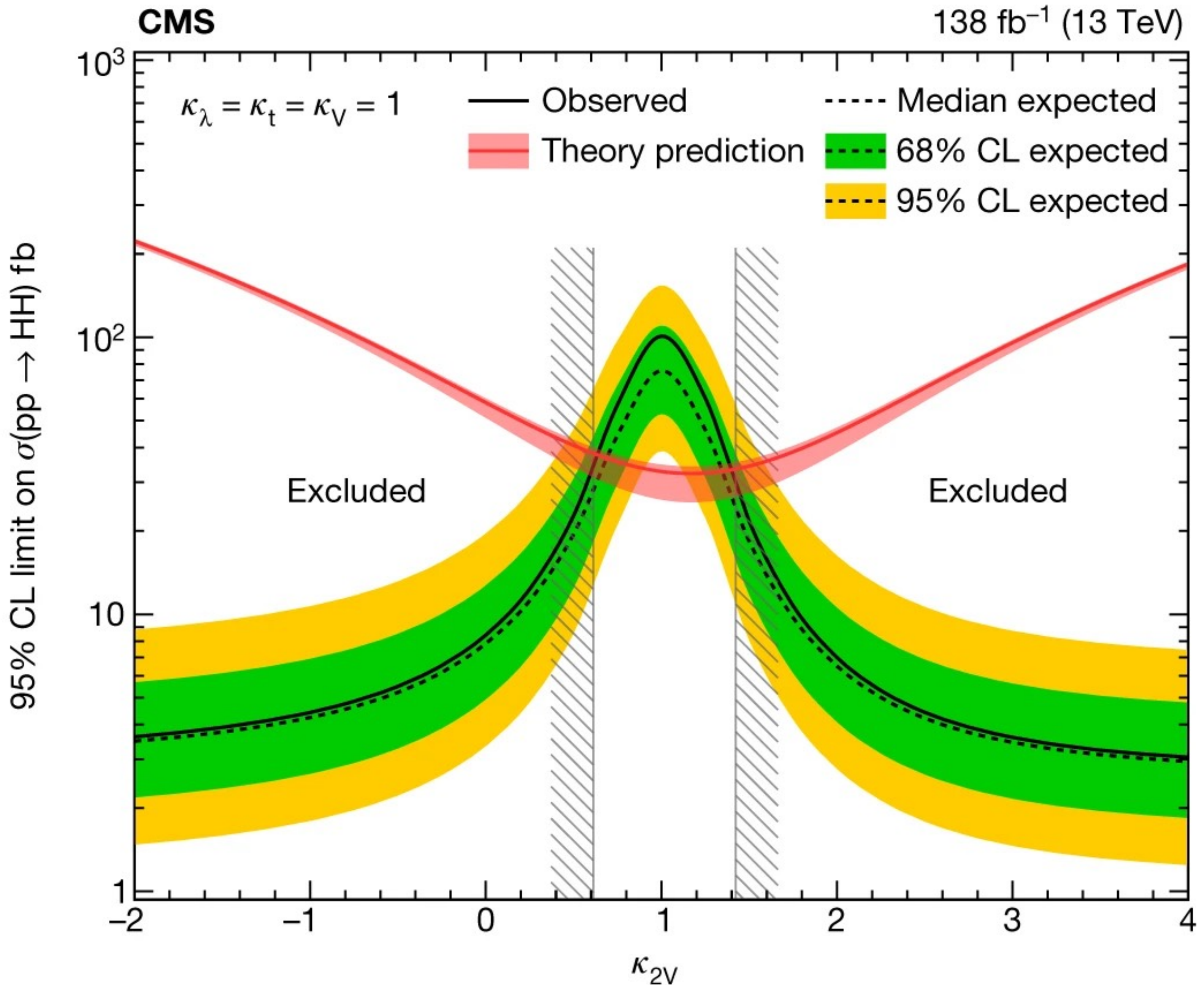
Other di-Higgs searches: CMS

- The current constraints on the di-Higgs production signal strength, VBF HH production cross section, κ_λ, and and κ_{2V} obtained from the HH searches based on data collected by CMS are shown below.



	Allowed κ_λ values	Allowed κ_{2V} values
Expected	[-0.89, 7.12]	-
Observed	[-1.25, 6.85]	[0.67, 1.38]





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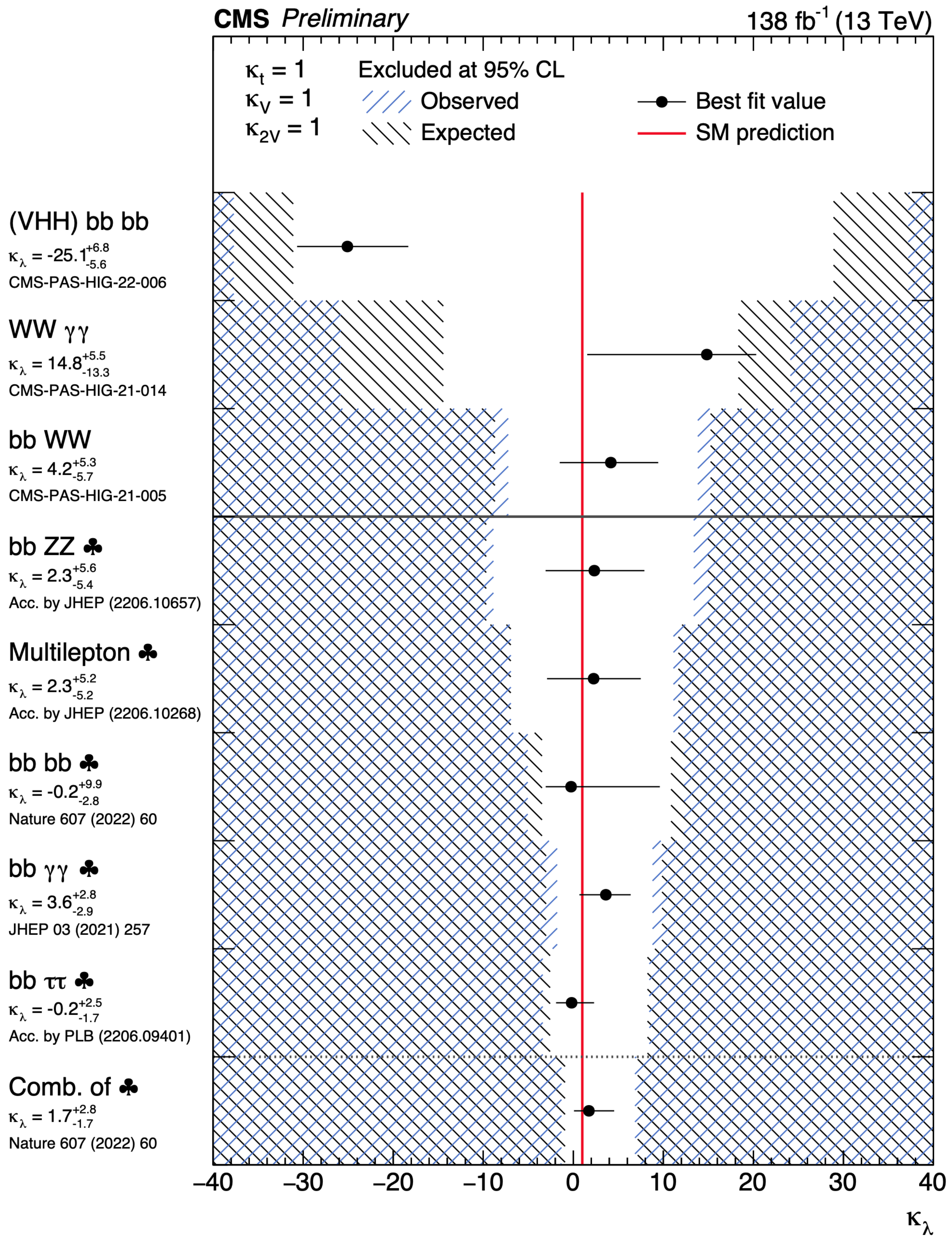
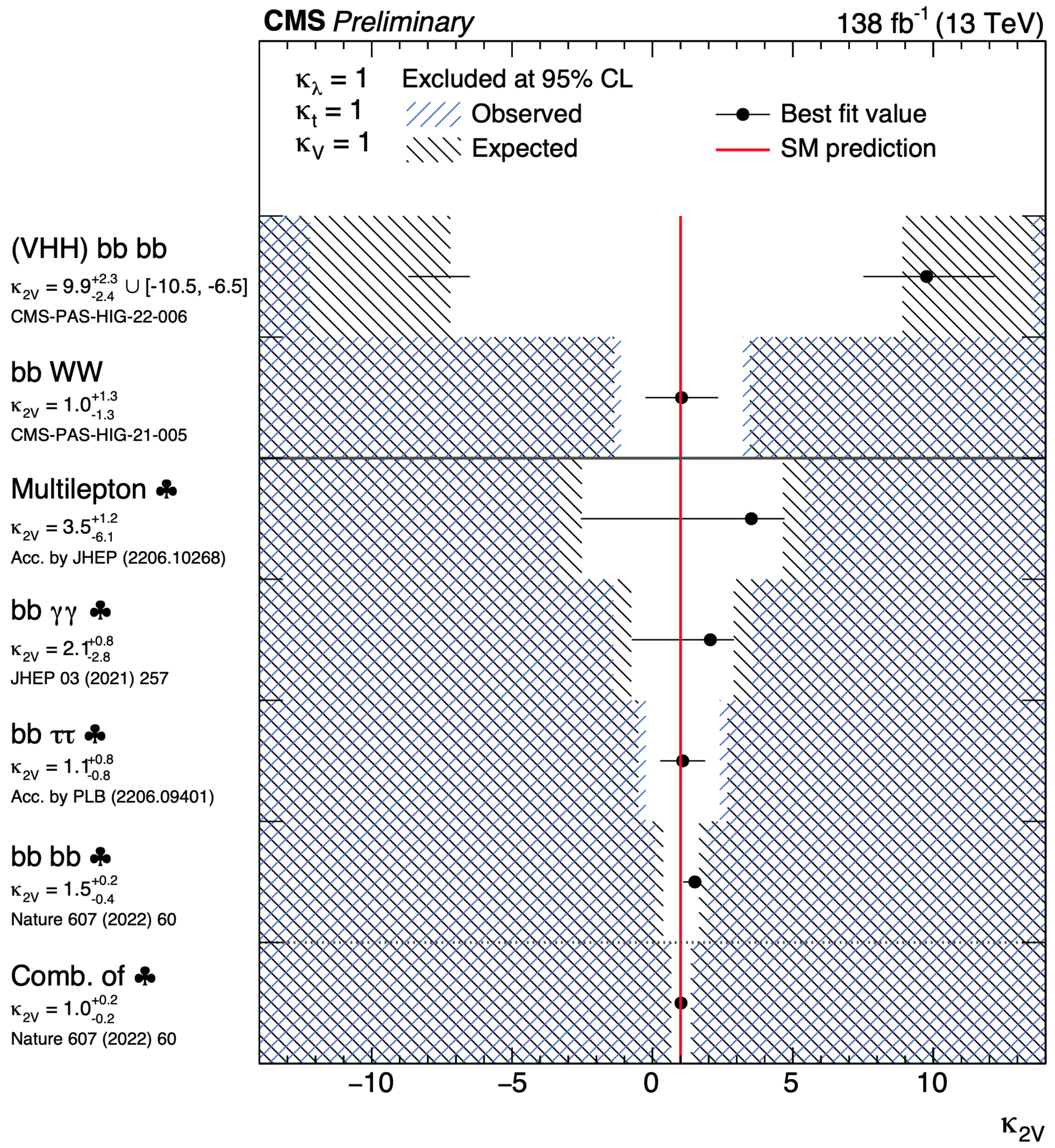
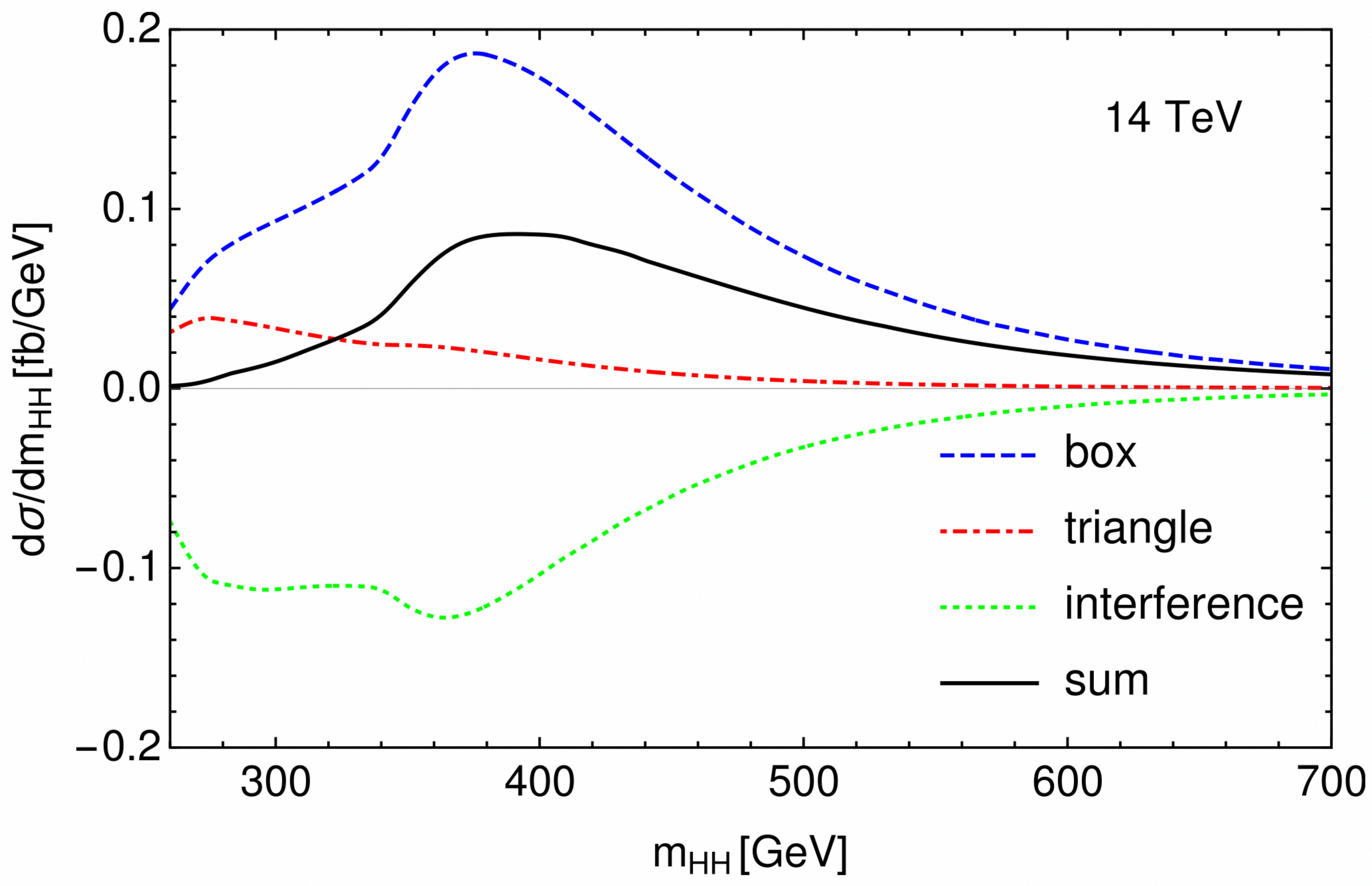
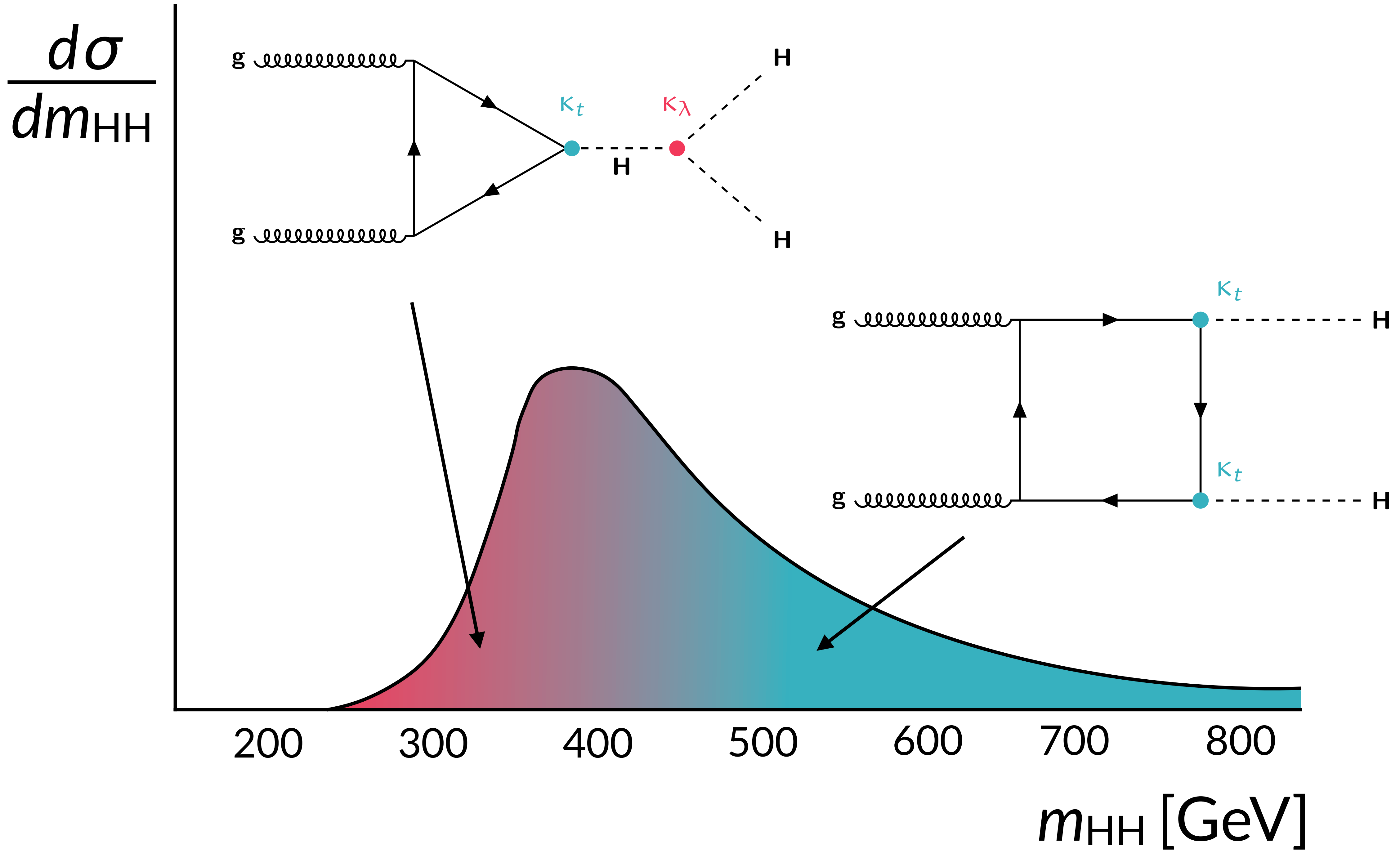




ggF HH cross section

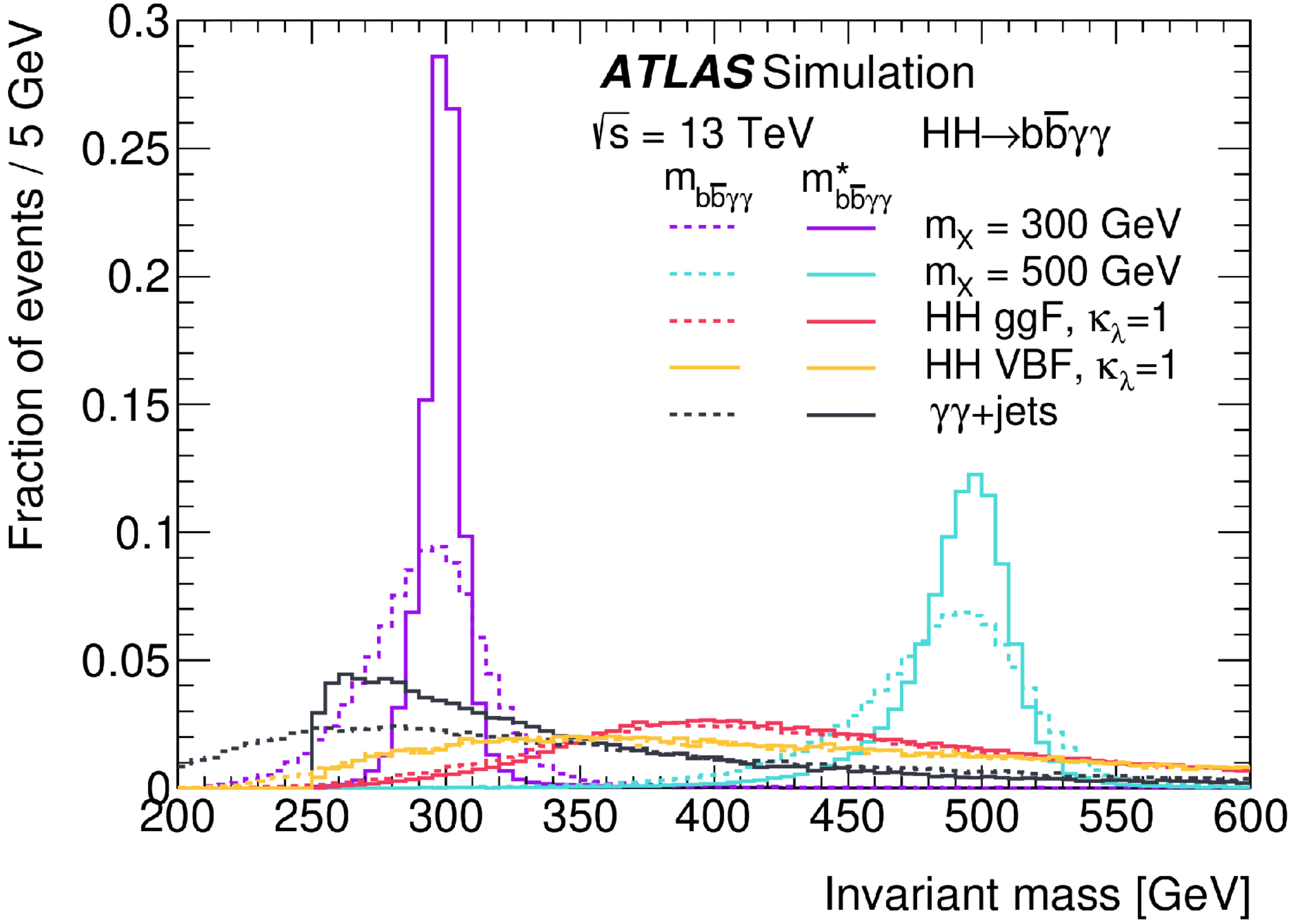
- The contribution of the box diagram, triangle diagram, and their interference to the **ggF HH cross section** in the $\mathbf{m_{HH}}$ **spectrum** is presented in the two plots below.





Definition of $\mathbf{m}^*_{b\bar{b}\gamma\gamma}$

- The reduced 4-object invariant mass $\mathbf{m}^*_{b\bar{b}\gamma\gamma}$, defined as $\mathbf{m}^*_{b\bar{b}\gamma\gamma} = \mathbf{m}_{b\bar{b}\gamma\gamma} - (\mathbf{m}_{\gamma\gamma} - \mathbf{125}\text{ GeV}) - (\mathbf{m}_{b\bar{b}} - \mathbf{125}\text{ GeV})$, significantly improves the resolution of the $b\bar{b}\gamma\gamma$ invariant mass for the resonant $X \to HH \to b\bar{b}\gamma\gamma$ decay with respect to the usual $\mathbf{m}_{b\bar{b}\gamma\gamma}$ variable.
- Therefore, for historical reasons, $\mathbf{m}^*_{b\bar{b}\gamma\gamma}$ is also adopted as a discriminant variable also for the **non-resonant $HH \to b\bar{b}\gamma\gamma$ search**.



Data and MC samples

- **Data:**

This analysis relies on the **full Run2 dataset**. → Amounting to an integrated luminosity of **140 fb^{-1}**.

- **MC samples:**

Signals

- **ggF HH** samples at **NLO**
  - Nominal samples use Powheg + Pythia8.
  - Alternative samples are based on Powheg + Herwig7.
  - With $\kappa_\lambda = 1$ (**SM** case) and $\kappa_\lambda = 10$.
- **VBF HH** samples at **LO**
  - Nominal samples use MadGraph + Pythia8.
  - Alternative samples are based on MadGraph + Herwig7.
  - **SM sample + 12 samples** with **BSM** values for the coupling modifiers κ_λ, κ_{2V}, and κ_V.

Backgrounds

→ Samples in common with the $H \to \gamma\gamma$ analyses.

- **Single Higgs** samples including all the production modes.
  - ggH, $VBF\ H$, WH, $qq \to ZH$, $gg \to ZH$, $t\bar{t}H$, $tHjb$, tWH, $b\bar{b}H$.
- **Sherpa2.2.4 $\gamma\gamma$+jets MC** sample.
  - For the BDT training.
- **Sherpa2.2.12 $\gamma\gamma$+bb MC** sample.
  - For the spurious signal test.
- $t\bar{t}\gamma\gamma$ MC samples, based aMC@NLO + Pythia8.

- The continuum background modelling is **data-driven**!
- These **samples** are used only for the **BDT training**, for the evaluation of the **background modelling uncertainty**, and for cross-checks.

Triggers & Pre-selection

- A combination of **di-photon** and **single-photon triggers** are used to maximize the efficiency.

Di-photon triggers:

- 2015+2016: `HTL_g35_loose_g25_loose`
- 2017+2018: `HLT_g35_medium_g25_medium_L12EM20VH`

➡ Require two loose or medium photons with (sub-)leading $p_T > 35(25)$ GeV.

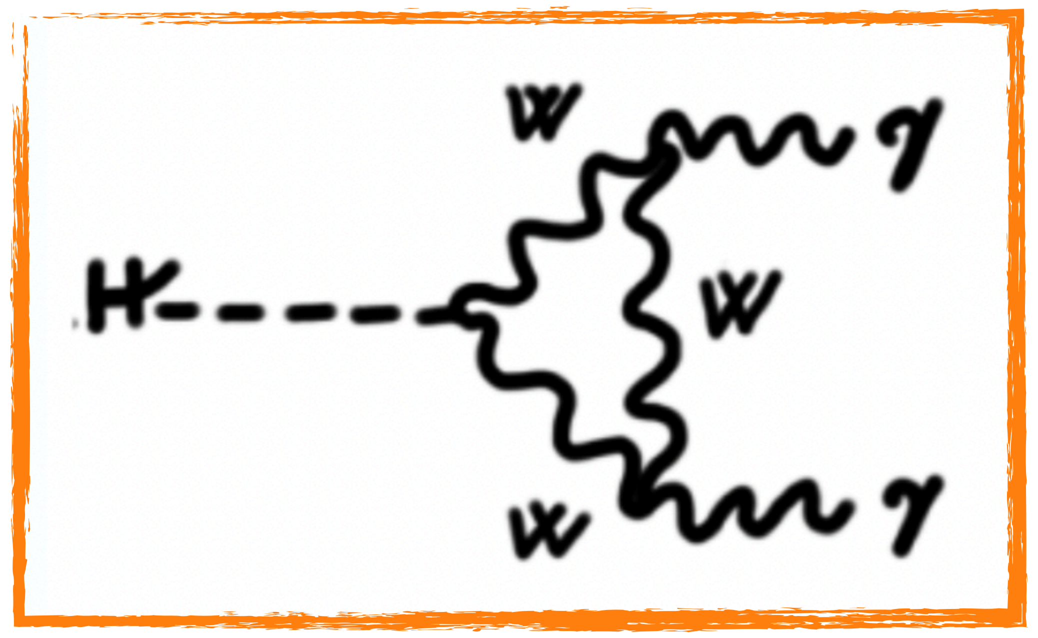
Single-photon triggers:

- 2015: `HLT_g120_loose`
- 2016+2017+2018: `HLT_g140_loose`

} Require one loose photon with $p_T > 120$ or 140 GeV.

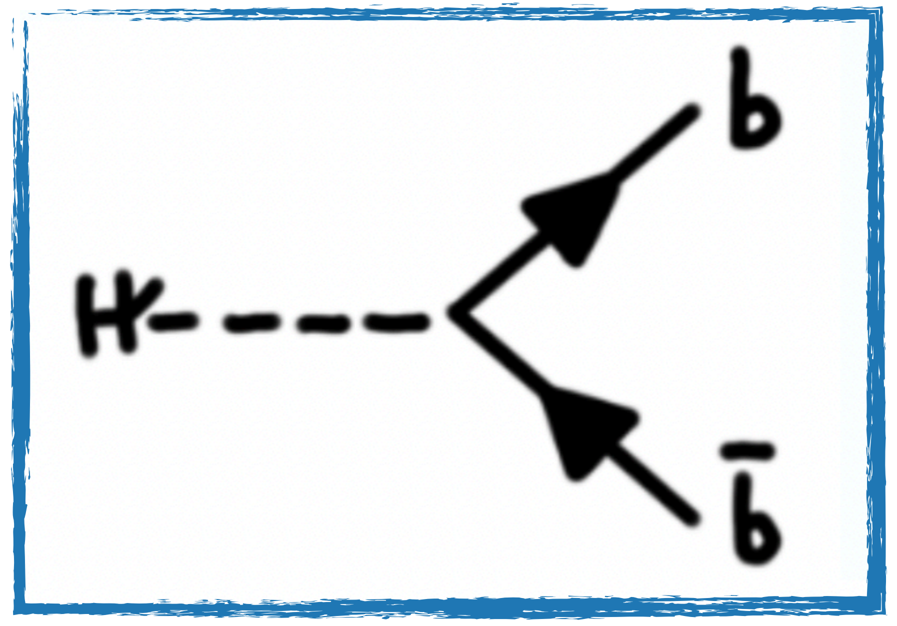
➡ Especially relevant for $H \to \gamma\gamma$ decays with highly boosted Higgs bosons, where the two photons cannot be resolved!

- **Pre-selection** requirements targeting the $b\bar{b}\gamma\gamma$ **signature** define the **signal region** of our analysis!



➡

- Two tight and isolated photons.
- (Sub-)Leading $p_T/m_{\gamma\gamma} > 0.35(0.25)$.
- Di-photon invariant mass window $105 < m_{\gamma\gamma} < 160$ GeV.



➡

- Exactly two b-jets passing the 77% efficiency WP for the DL1r b-tagging algorithm.
- The b-jets for reconstructing the candidate $H \to b\bar{b}$ are selected by **ranking** them **by their b-tag score**. ➡ I.e. the efficiency WP requirement that they fulfill!

\+

- No leptons. ➡ **Suppress** ttH **background** where the **top decay chain** generates **electrons** and **muons**.
- At least 2 jets.
- Less than 6 central jets. ➡ **Suppress** ttH **background** where the **top decays hadronically**.

VBF-jet tagger

- The **categorization BDTs** rely on kinematic variables for the training, including the **VBF-targeting variables** m_{jj} and $\Delta\eta(j_1, j_2)$.

The VBF-jets are identified with the help of a **VBF-jet tagger**. → **BDT applied** to all the **possible jet pairs** of an event, and used to select the **jet pair** that is most **likely** to arise **from VBF production**!

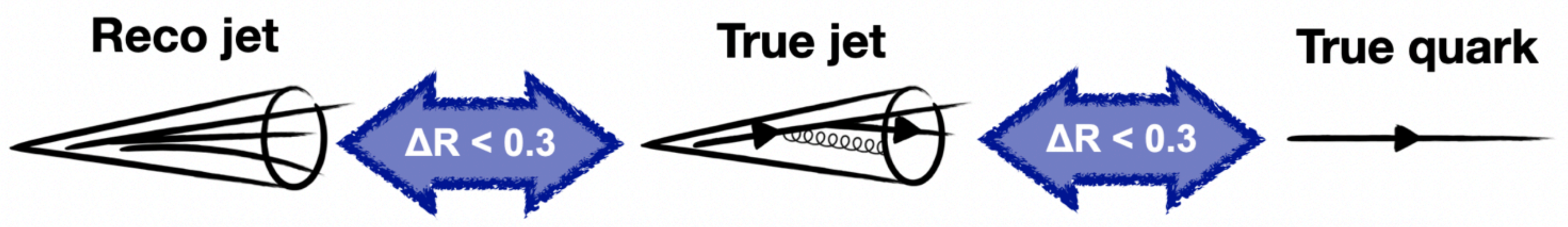
Needed to calculate the VBF-related input variables for the BDTs!

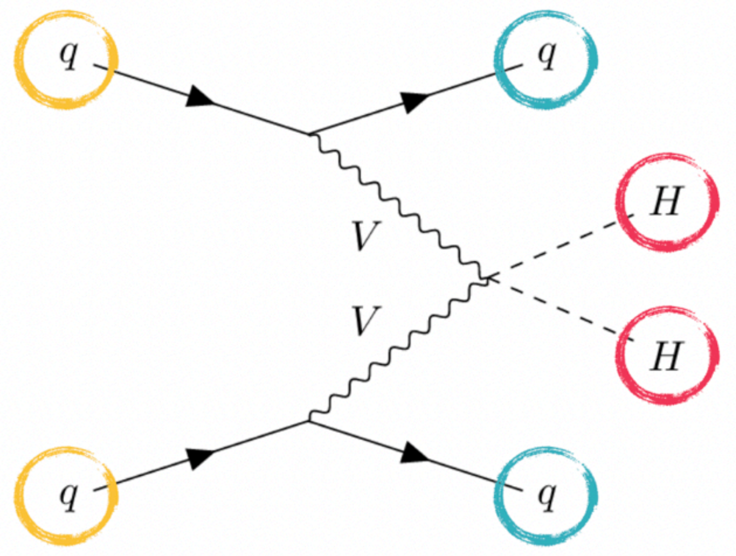
- The **BDT** is **trained** on the **SM VBF HH** sample, considering **events** with **at least 4 jets, using di-Higgs** and **VBF jet-related** variables are used as **input features**.

Signal	Jet pairs where **both jets** are **truth-matched** to a true VBF quark.
Background	All the other jet pairs, where at least one jet is not truth-matched.

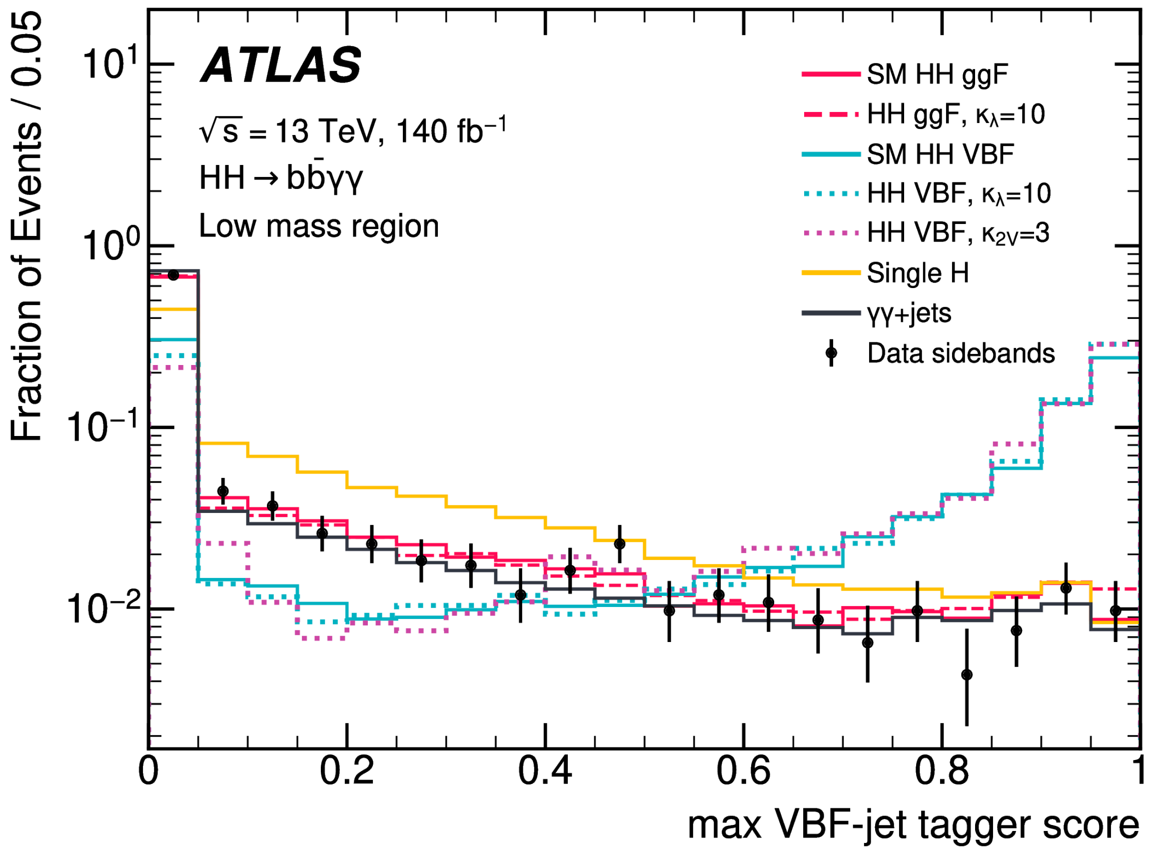
Jets already selected as **candidate *b*-jets** are **excluded**.

The **signal VBF-jets** are identified via a **truth-matching** procedure, requiring that the distance between the jet at reconstruction level, the true jet, and a true VBF quark is $\Delta R < 0.3$.





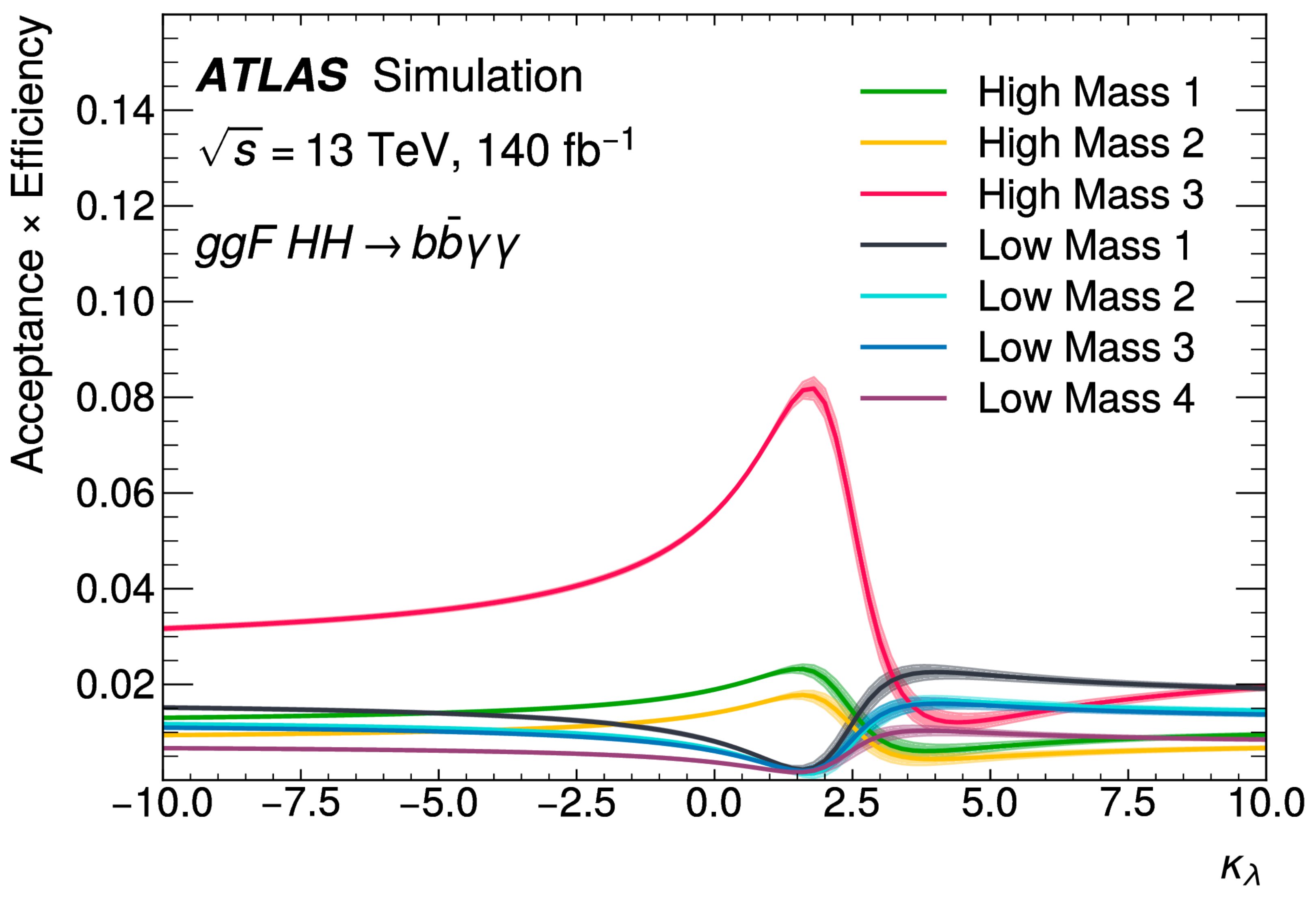
where the **true VBF-quark** are defined as the **two children** of the **incoming quarks** involved in the **hard scattering** that are **not Higgs bosons**.

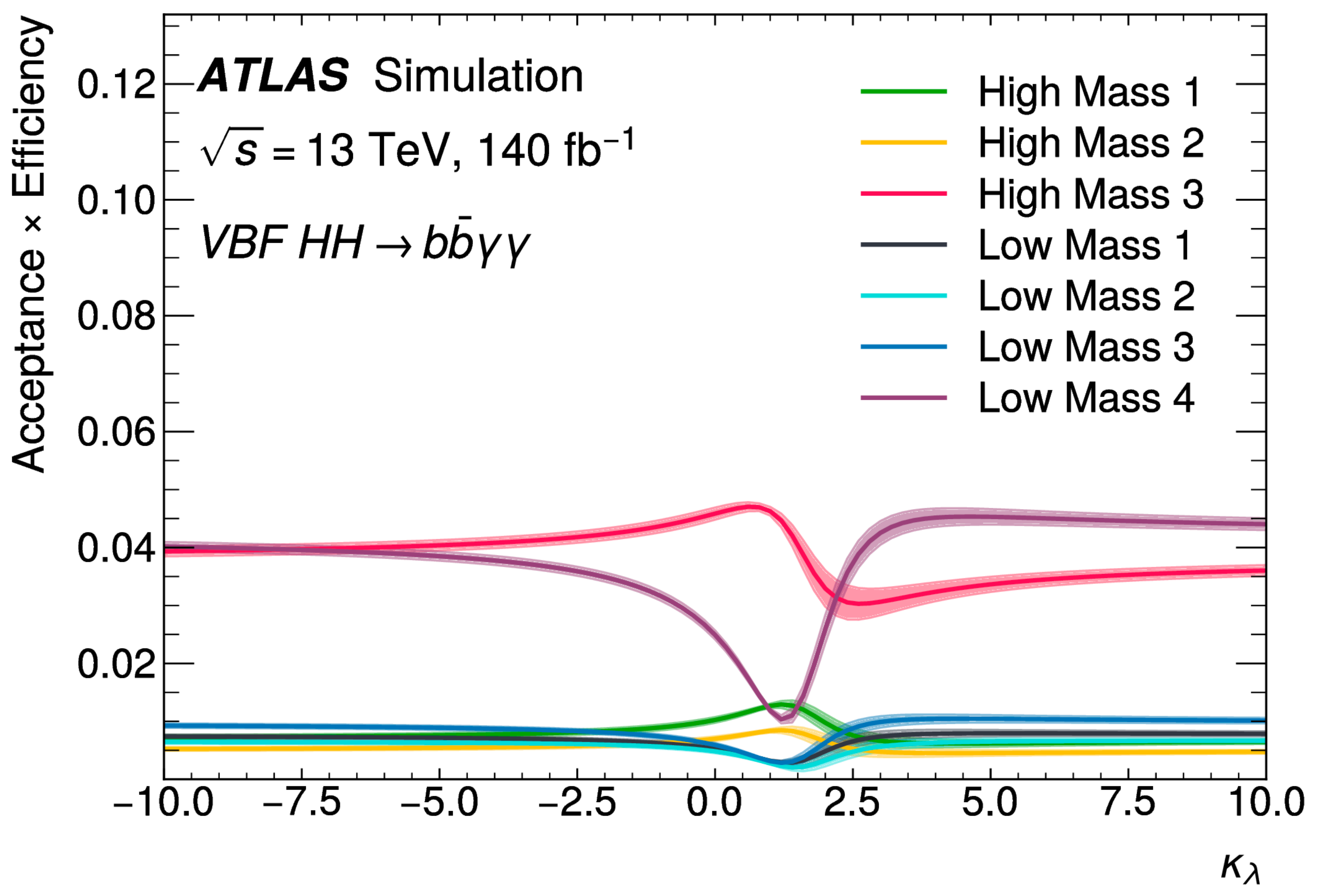


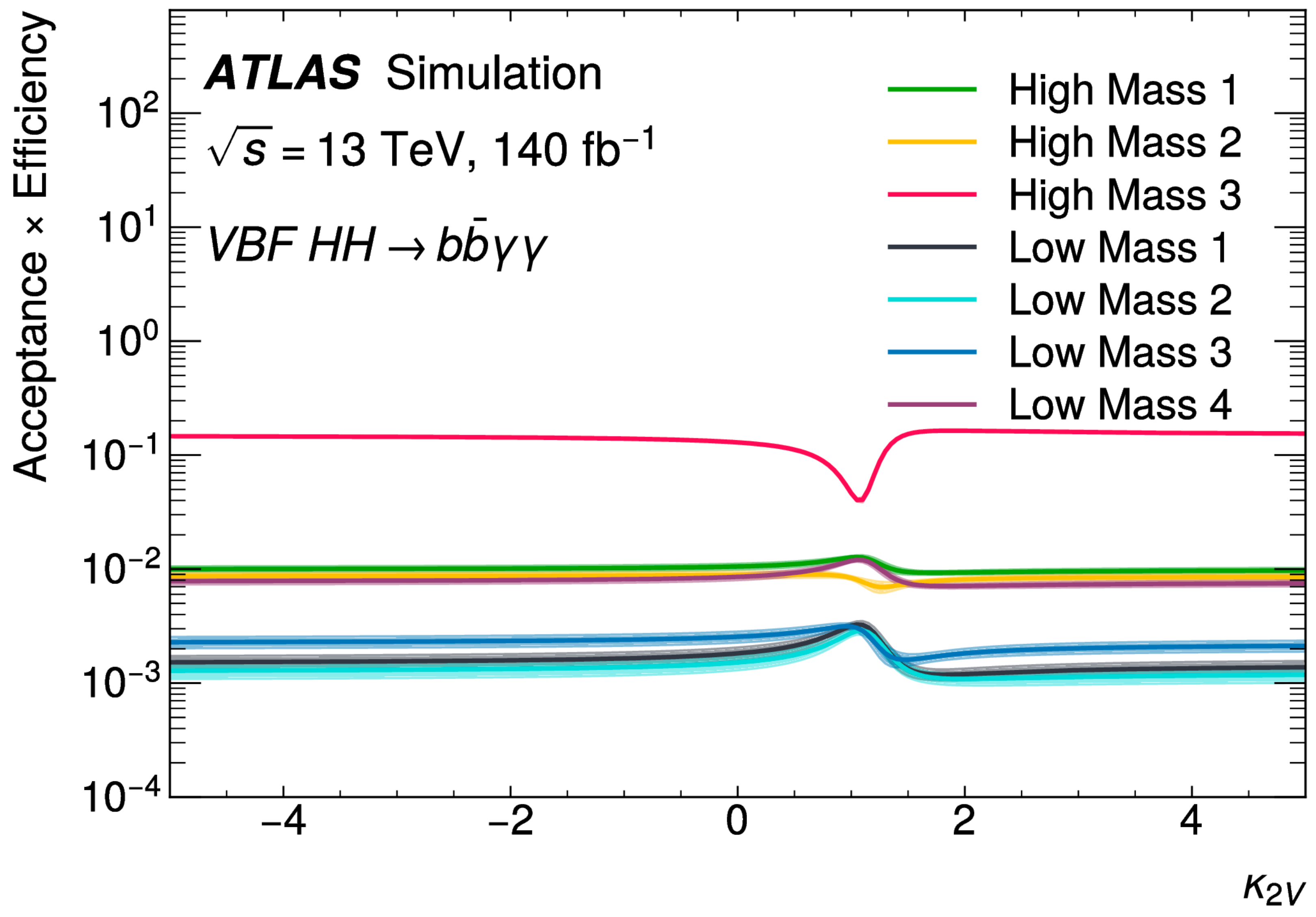
- A **BDT score** is assigned to each **jet pair** in an event.
- The **selected VBF-jets** correspond to the **di-jet system** with the **highest BDT score**!

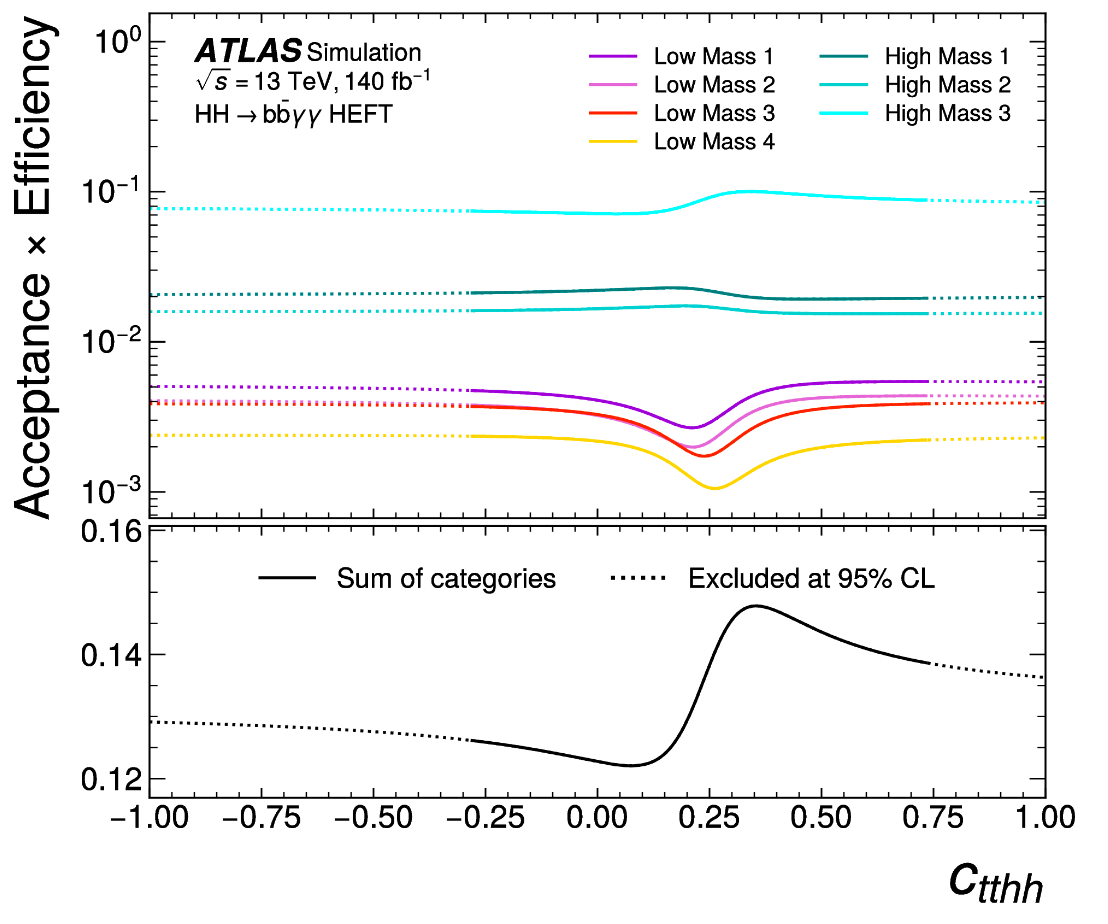
The **BDT-based** VBF jet tagger is able to **recover** a fraction of **+7%** of **correctly classified VBF jet pairs** with respect to the simpler recipe, based on the **di-jet invariant mass** m_{jj}!

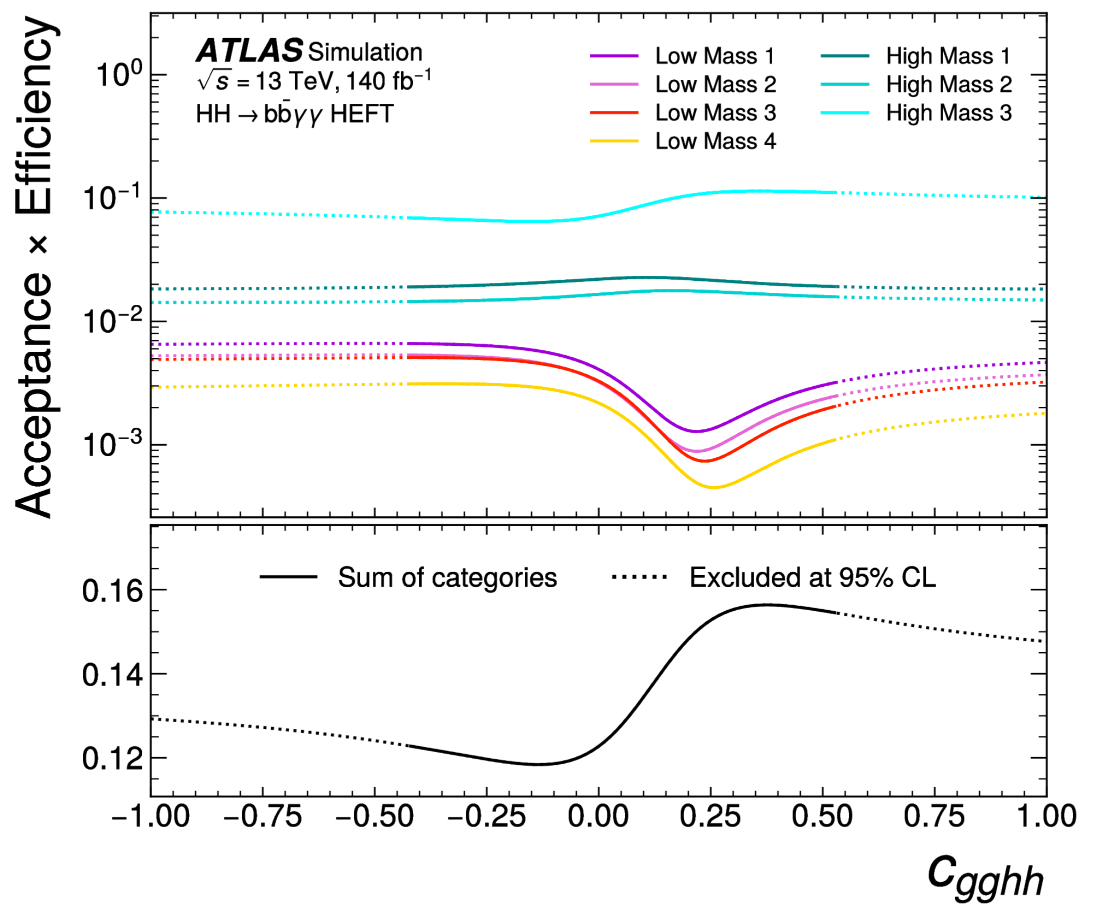
Efficiency for ggF HH and VBF HH signals

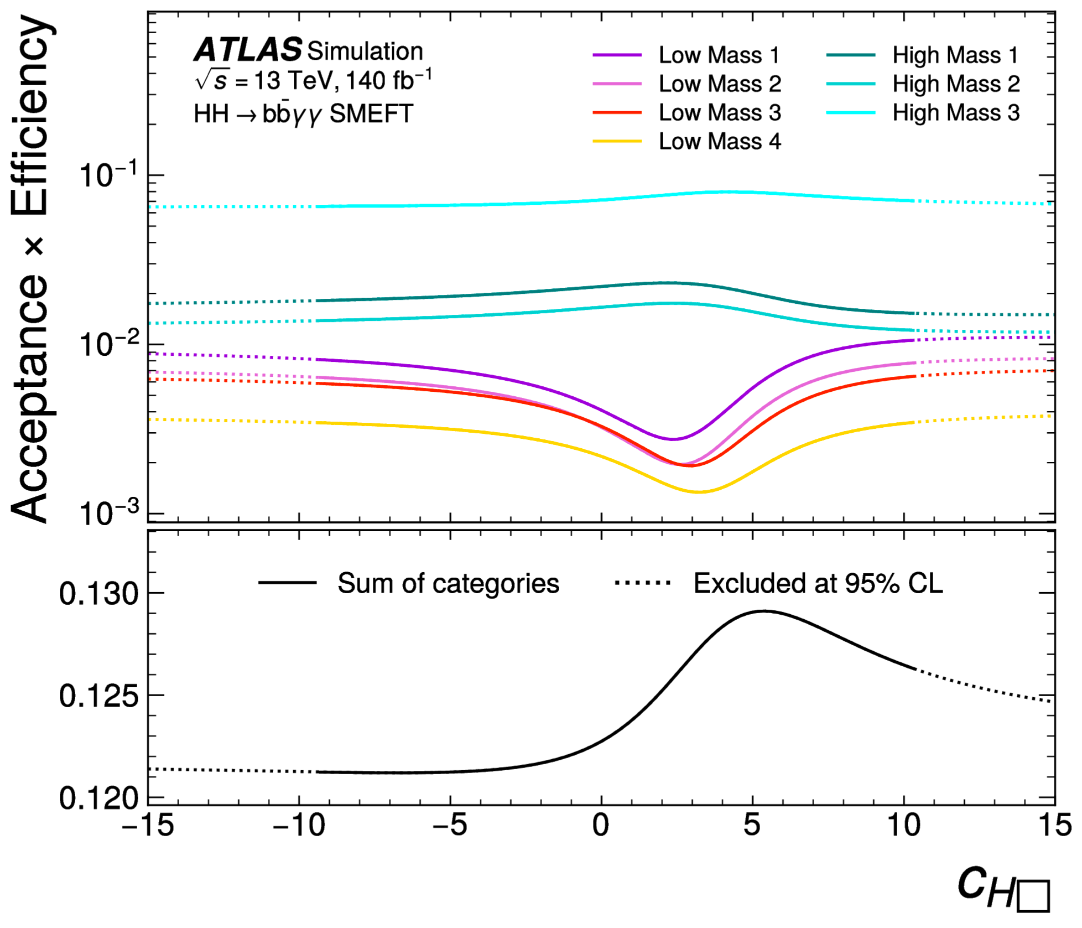


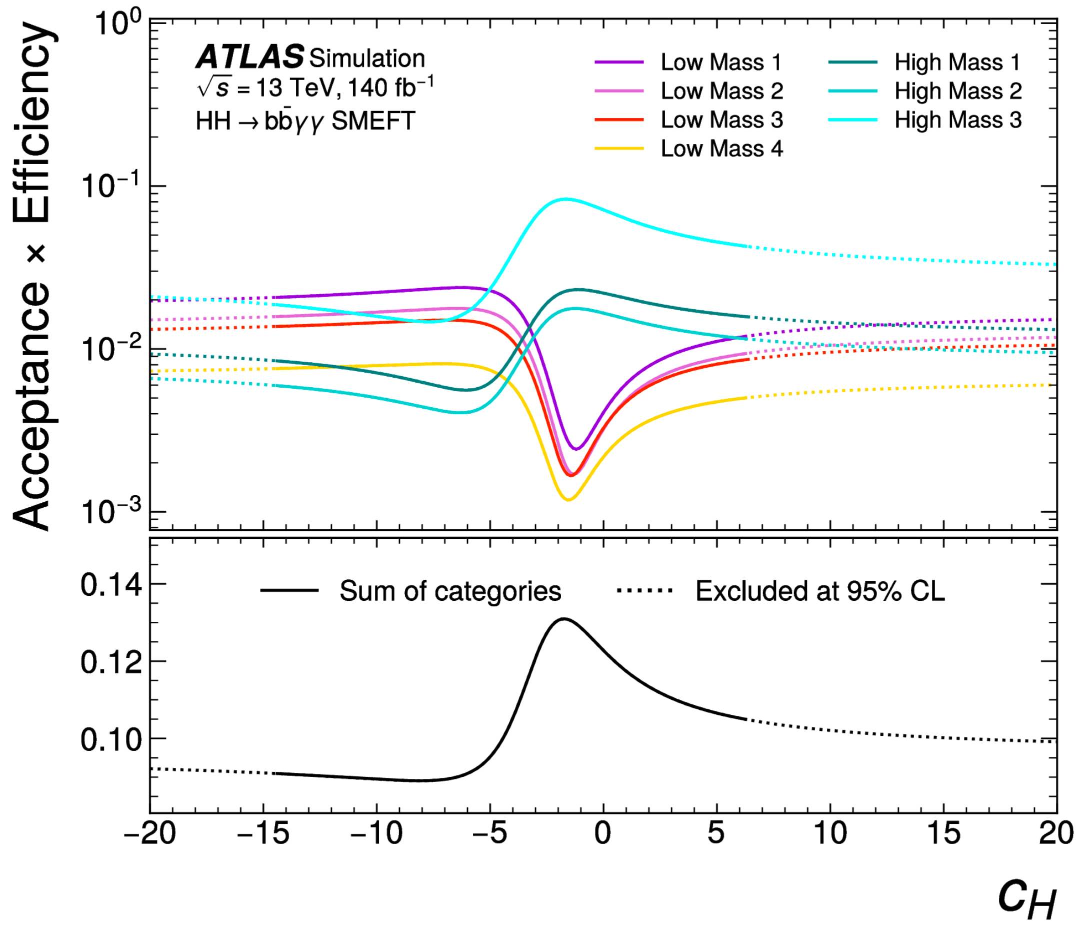






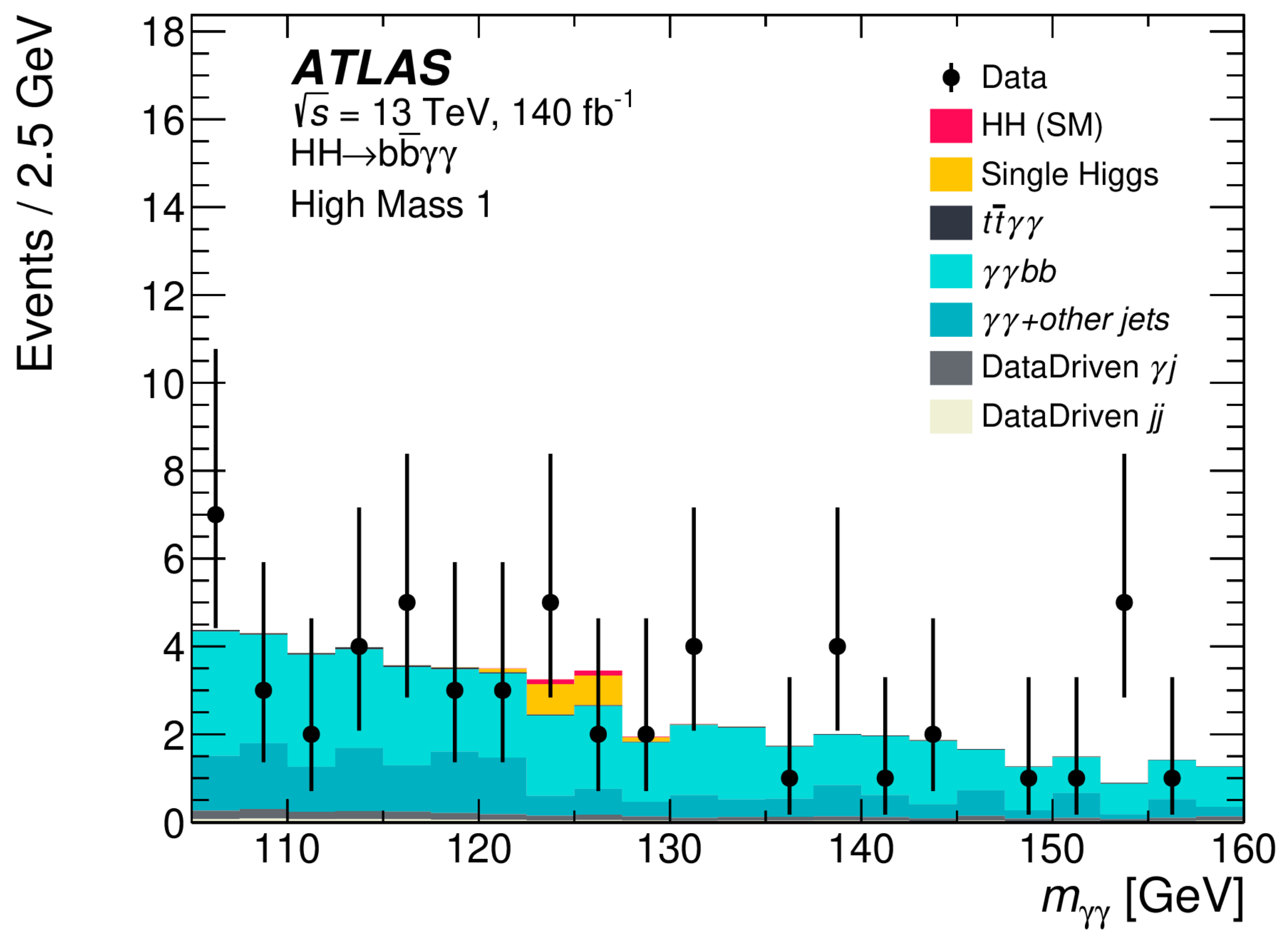


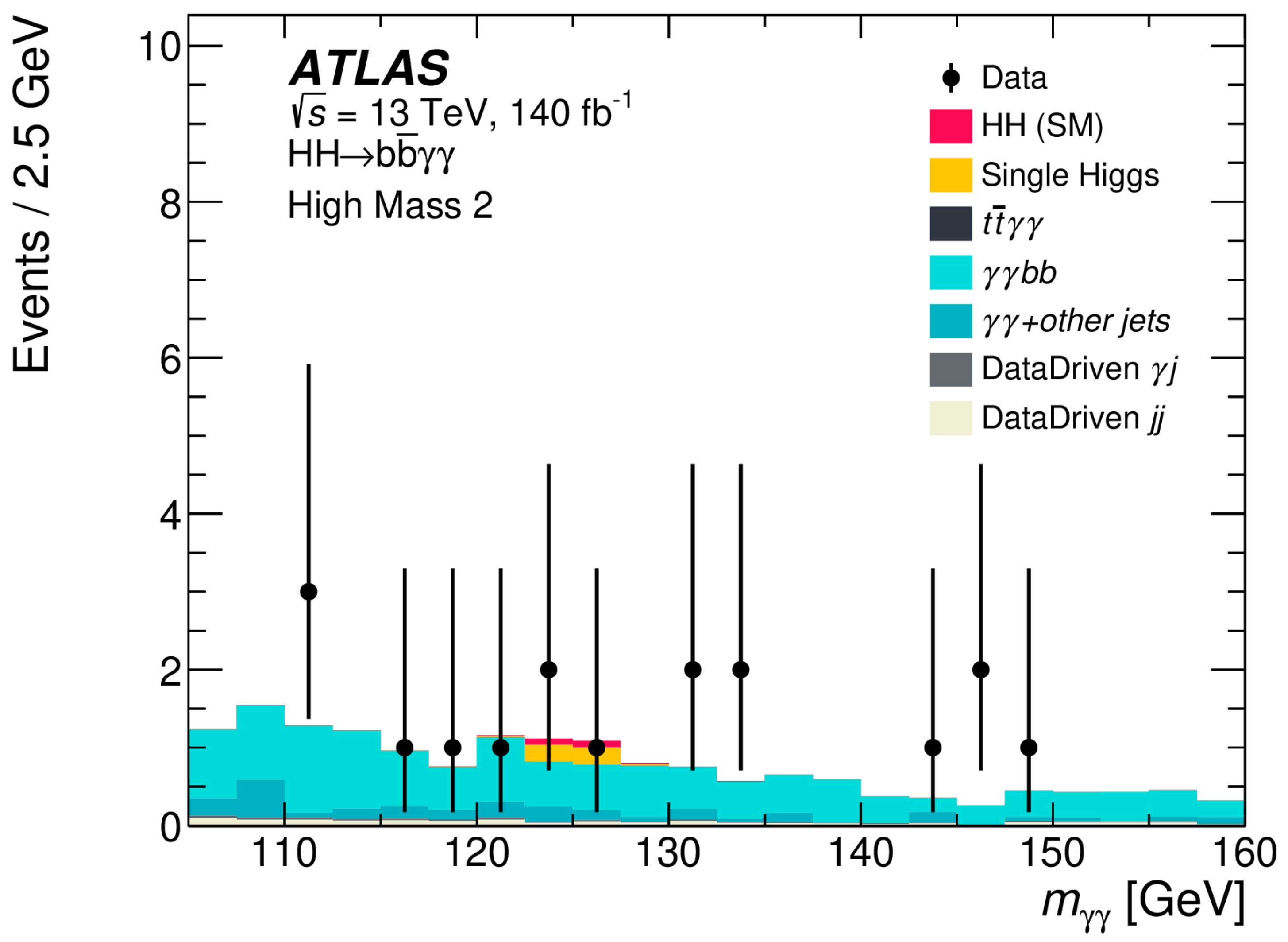


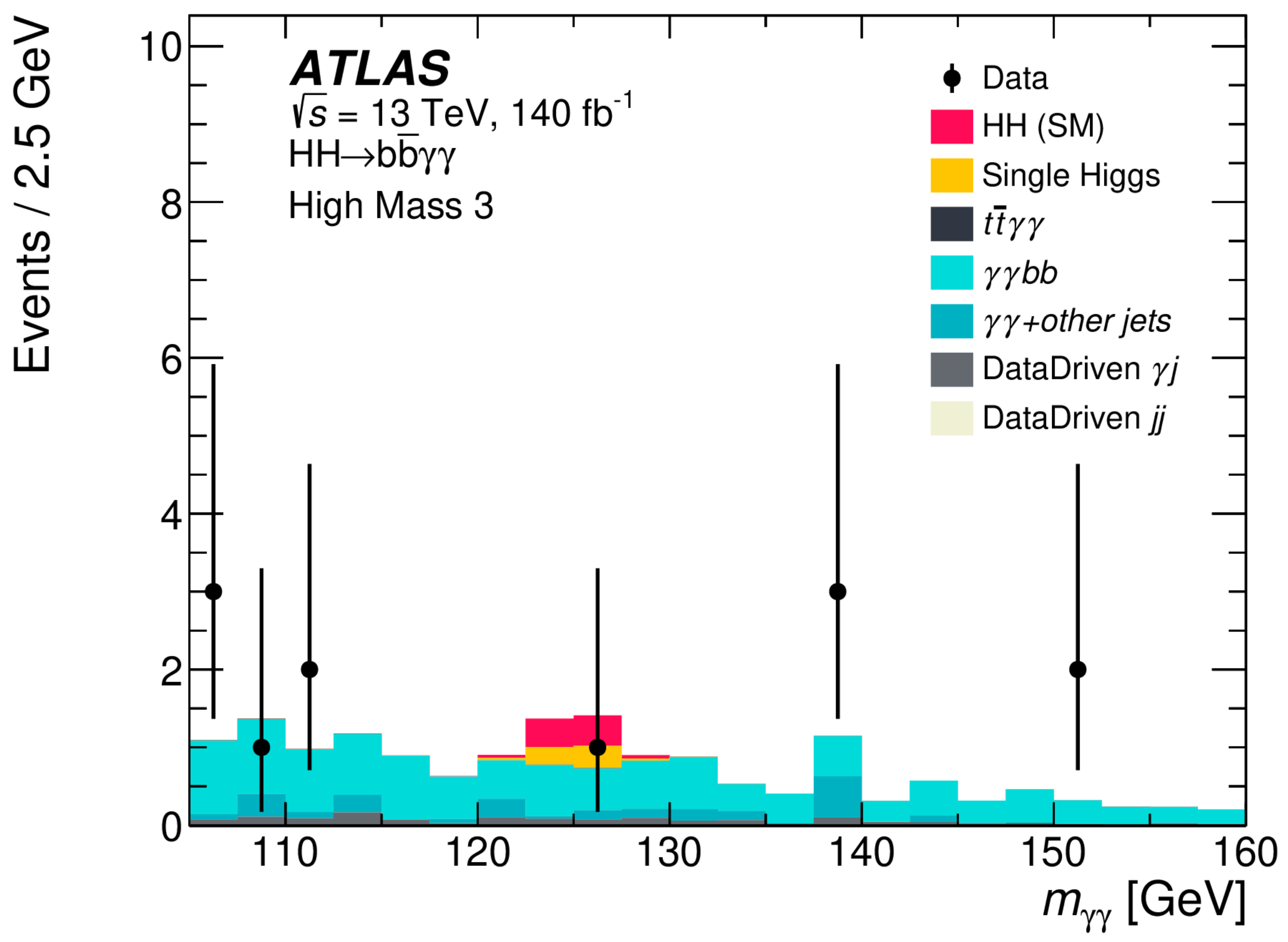


Data/MC comparison: High Mass categories

- Plots showing the **agreement** between **data and MC** in the $\mathbf{m}_{\gamma\gamma}$ **spectrum** for the **High Mass categories** are presented below.

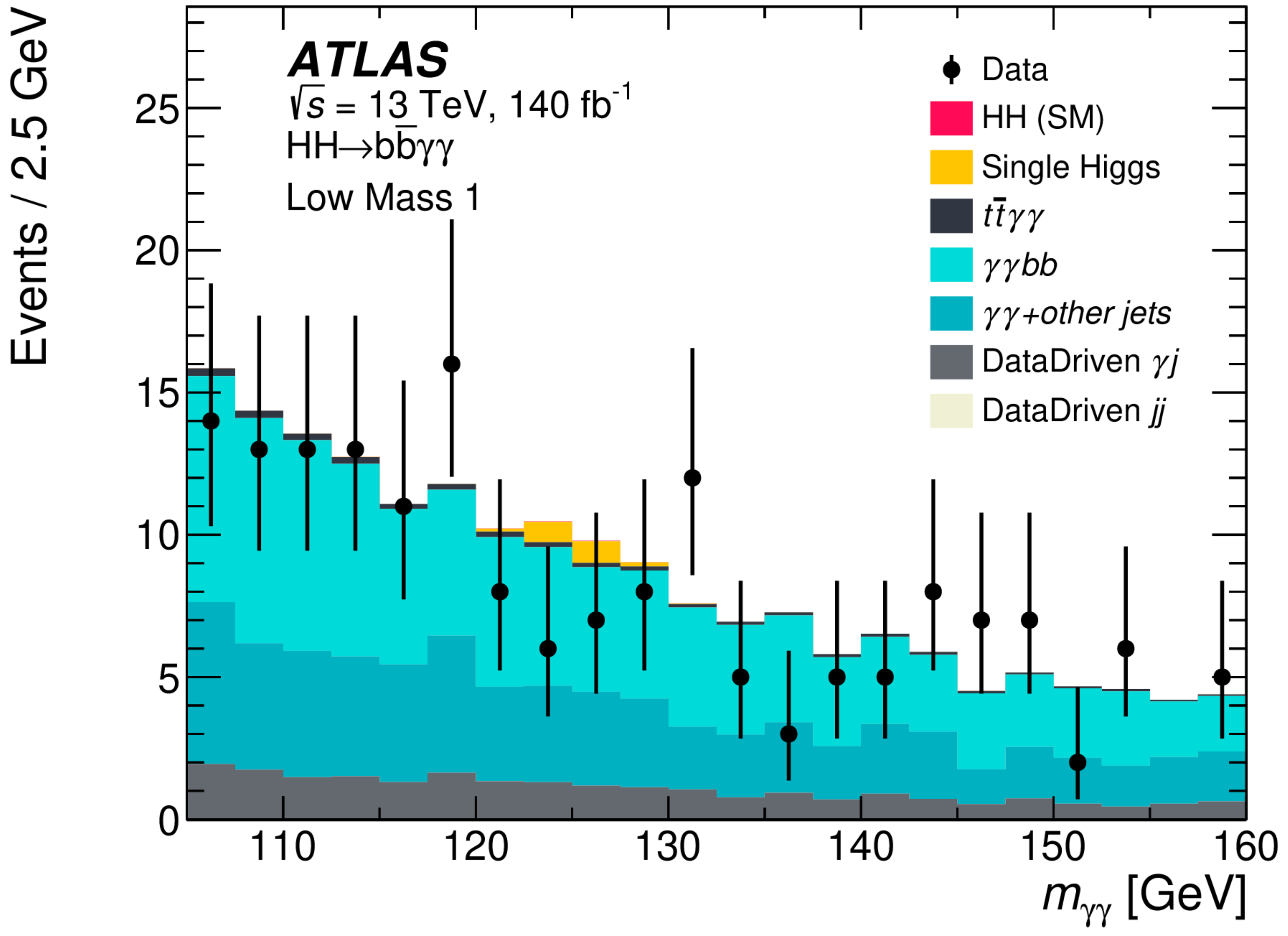


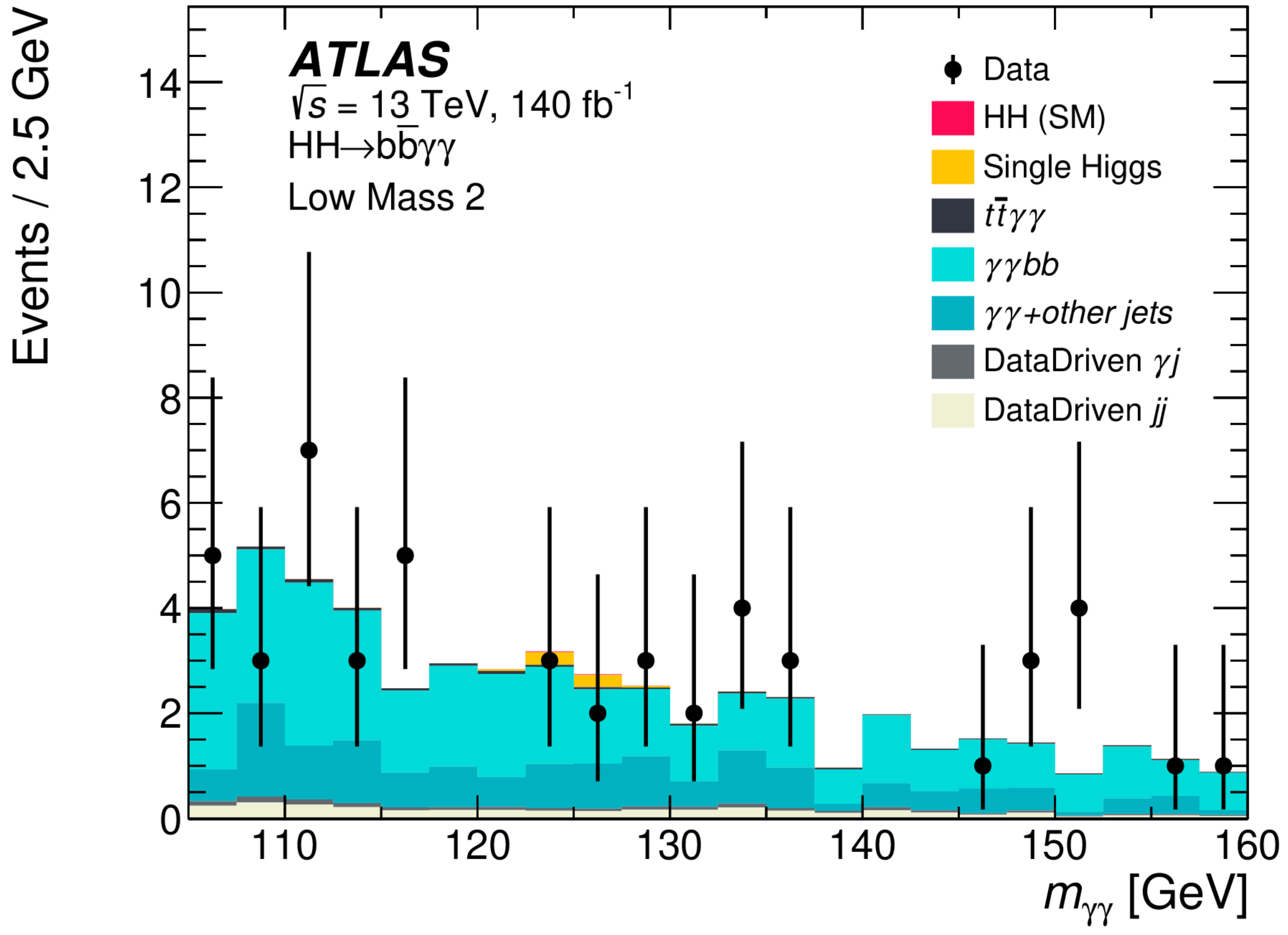


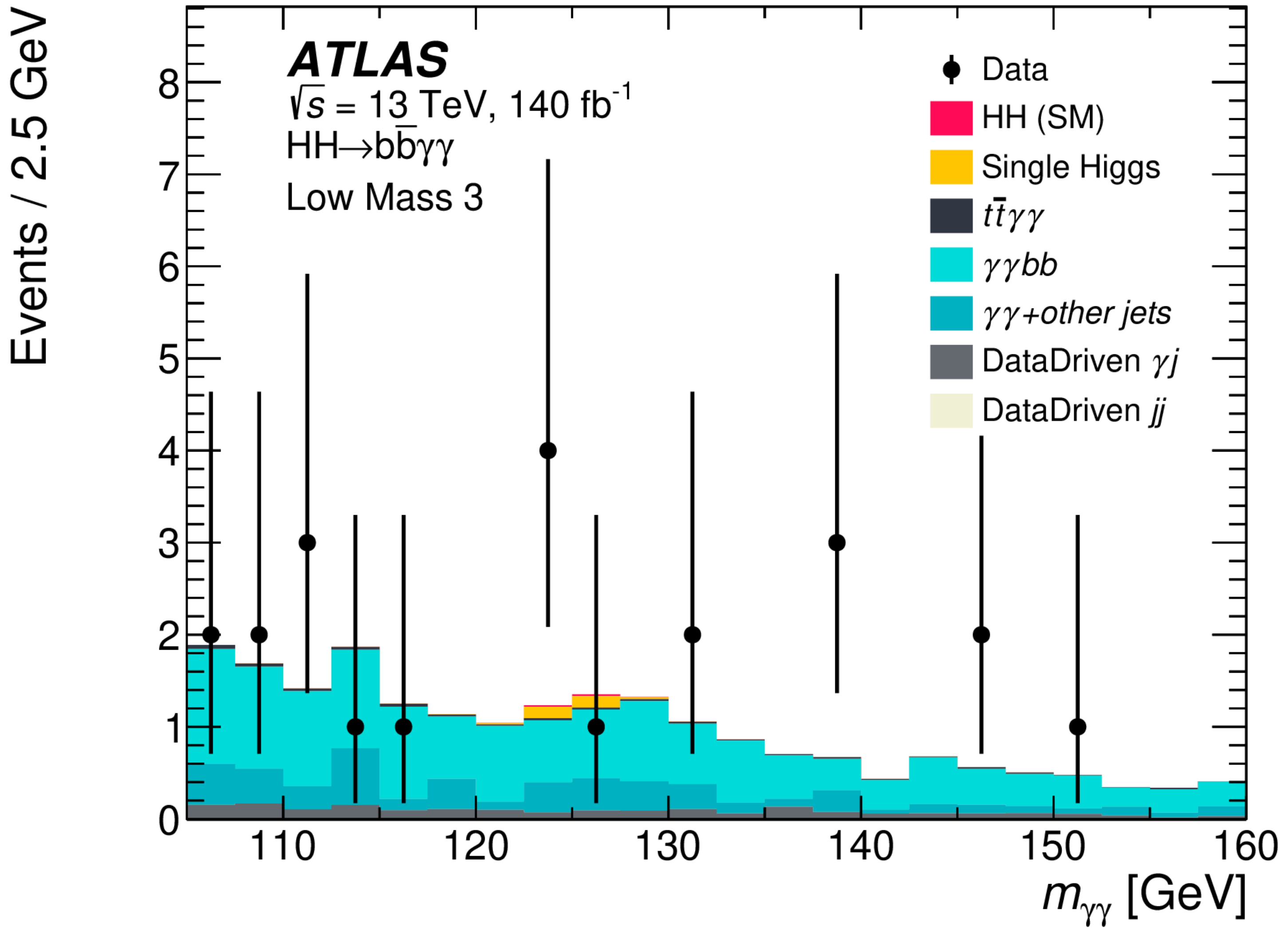


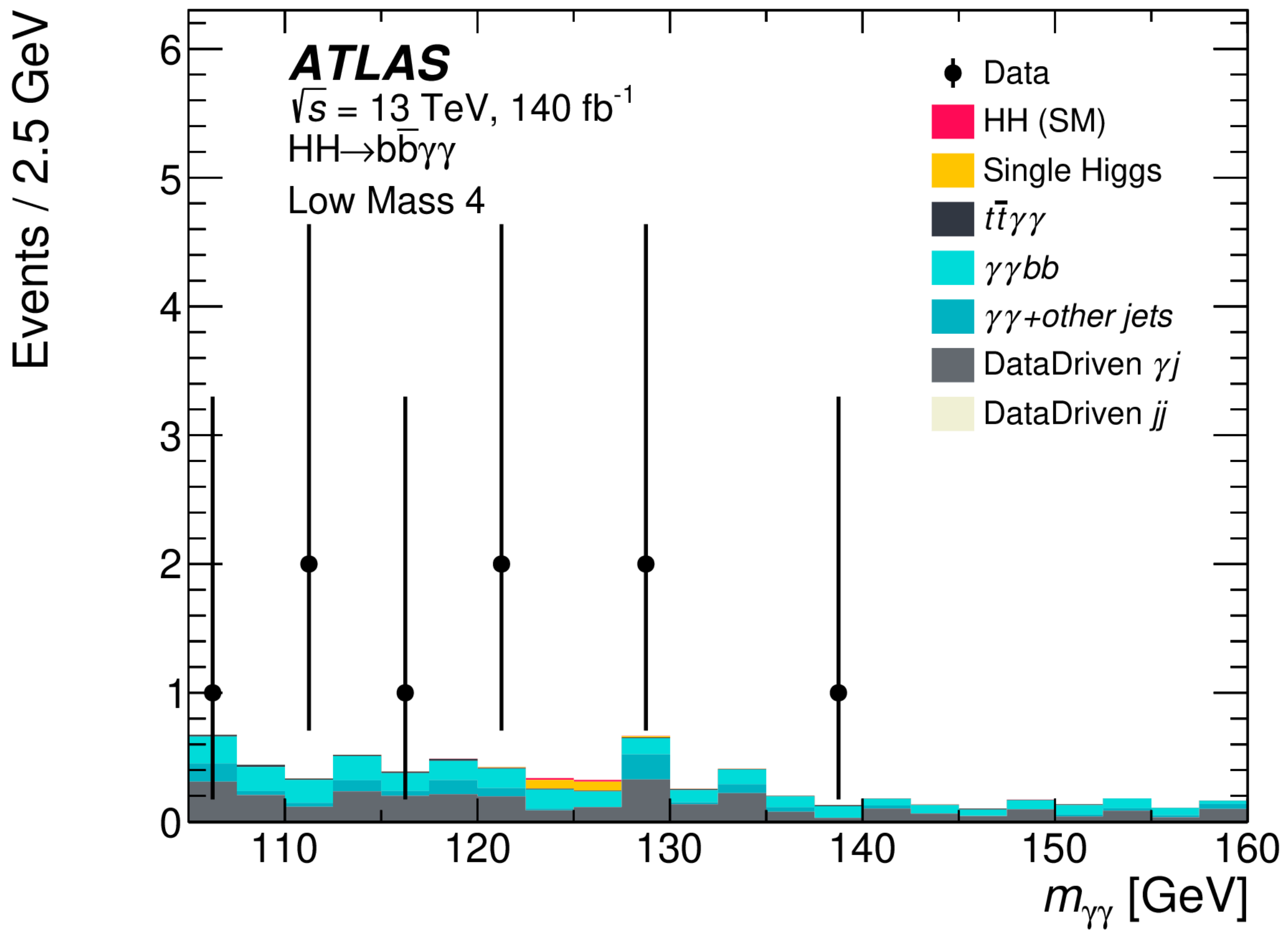
Data/MC comparison: Low Mass categories

- Plots showing the **agreement** between **data and MC** in the $\mathbf{m}_{\gamma\gamma}$ **spectrum** for the **Low Mass categories** are presented below.



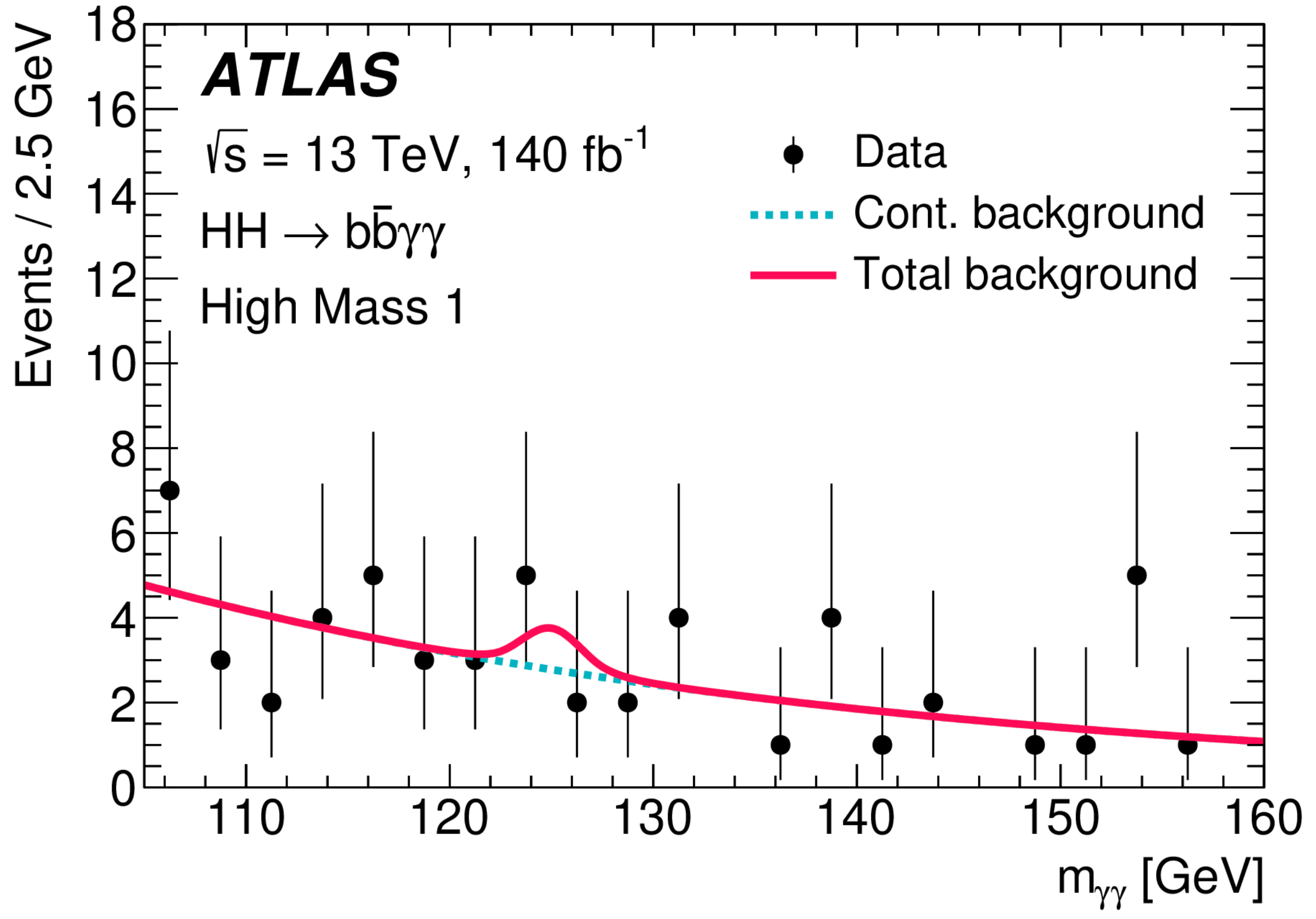


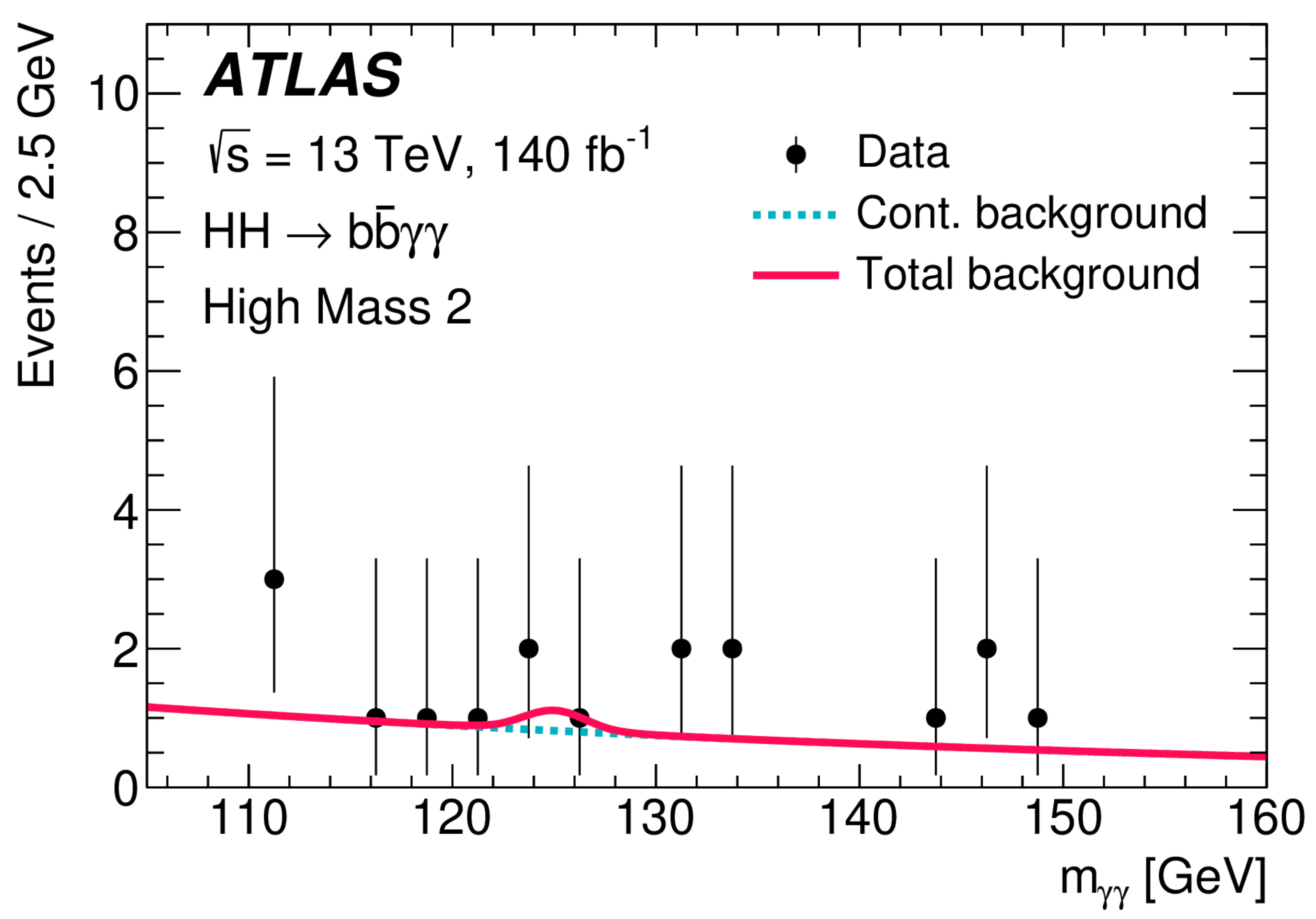


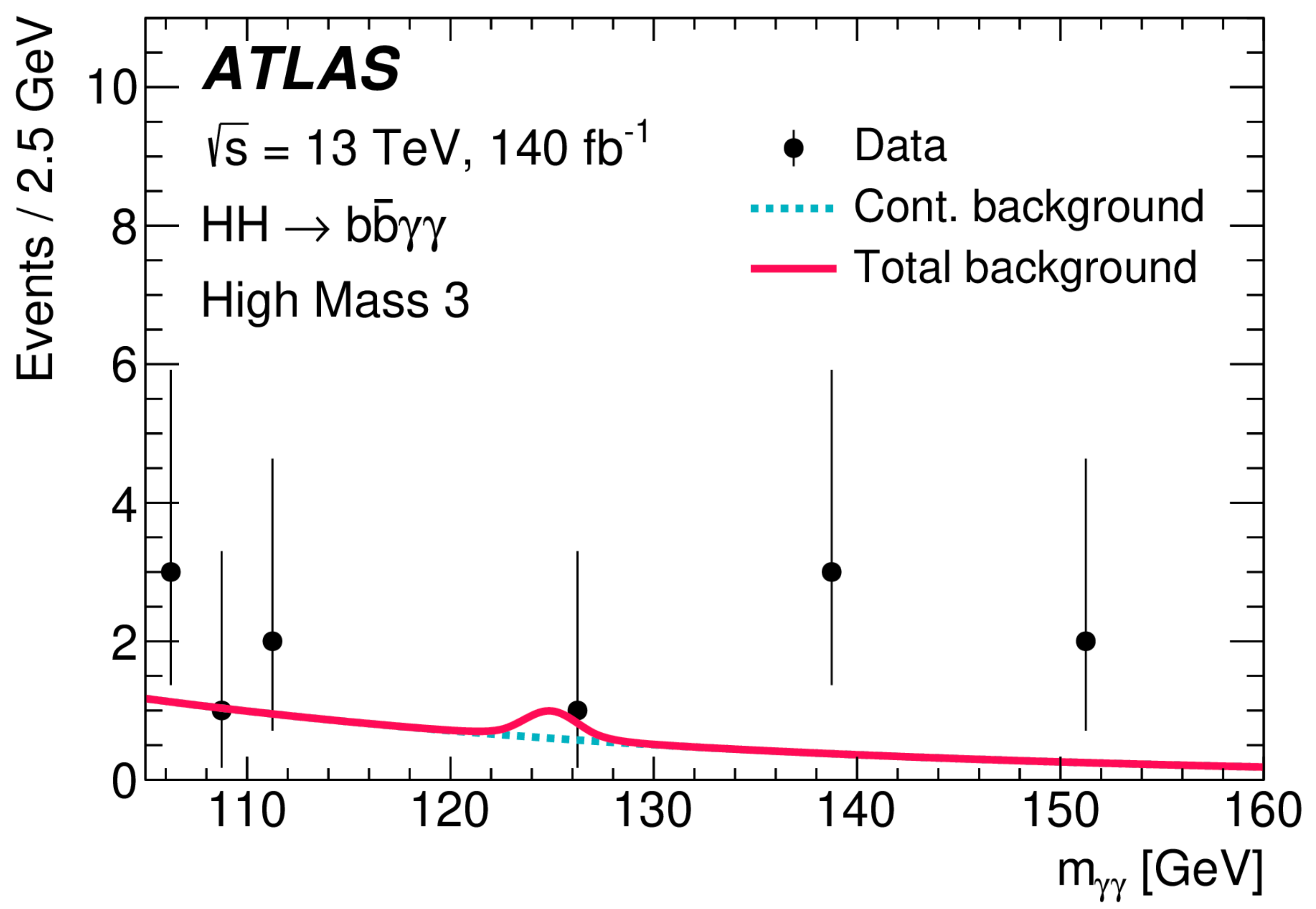


Fit results: High Mass categories

- Plots showing the **fit results to data** in the $\mathbf{m}_{\gamma\gamma}$ **spectrum** for the **High Mass categories** are presented below.

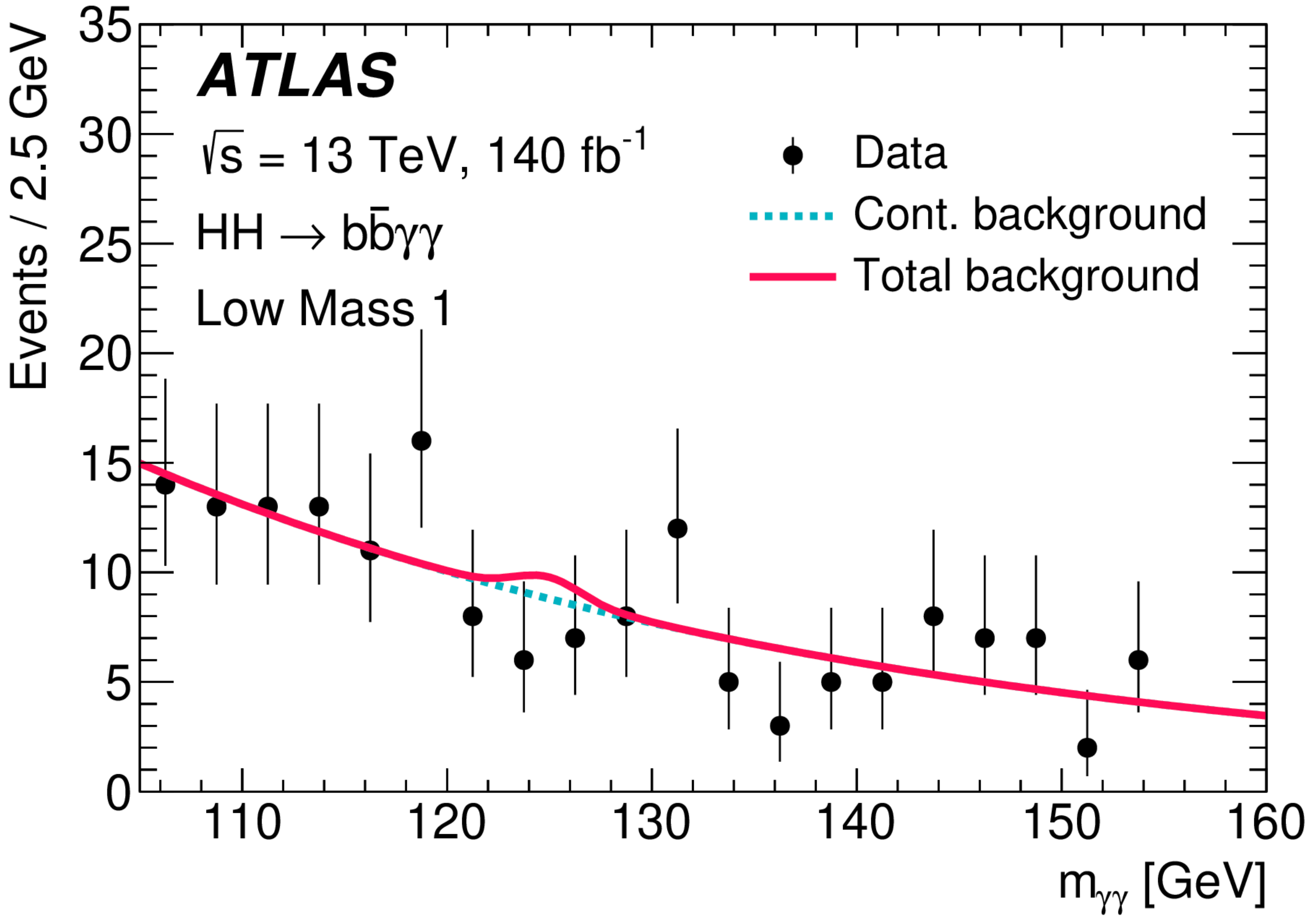


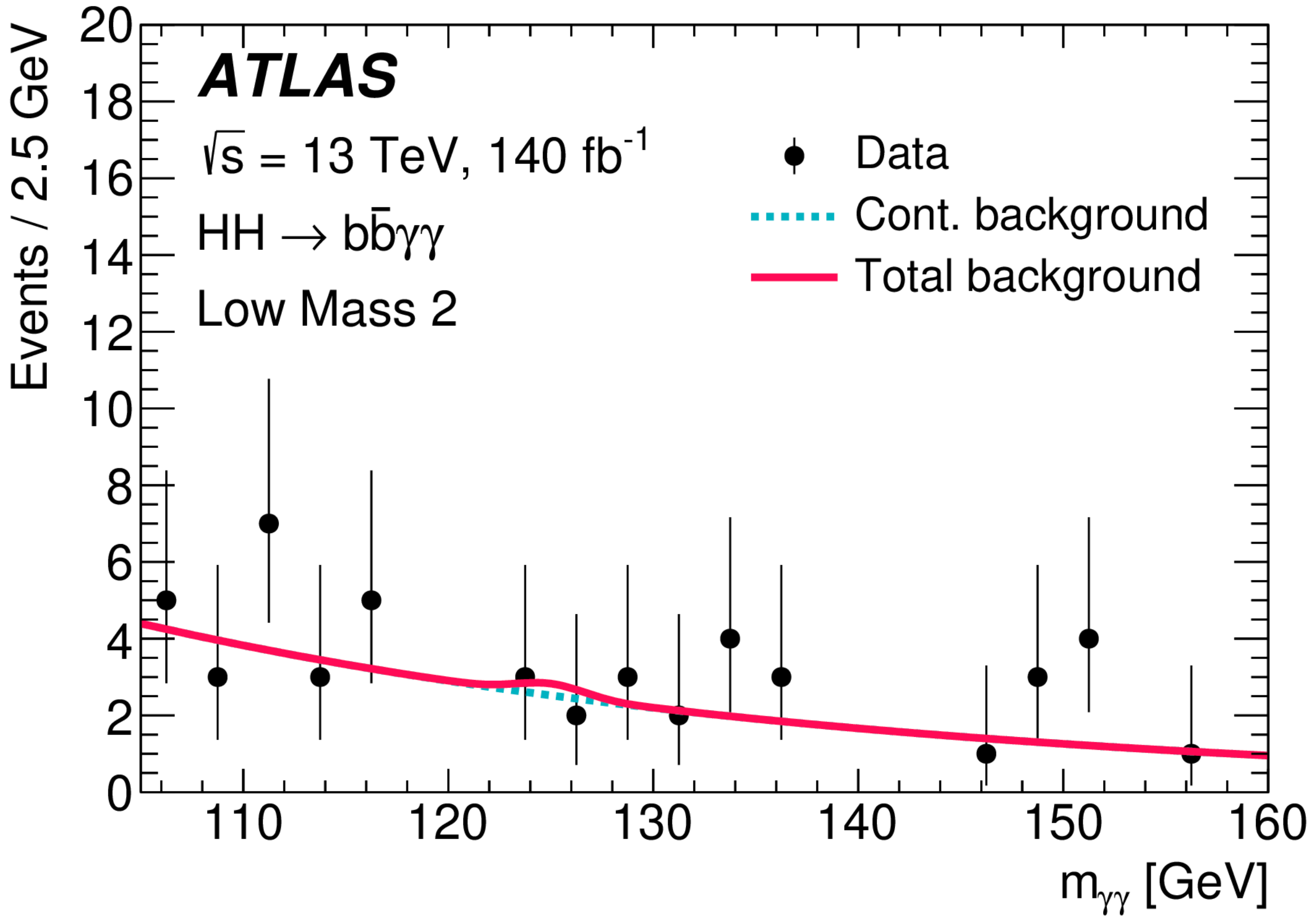


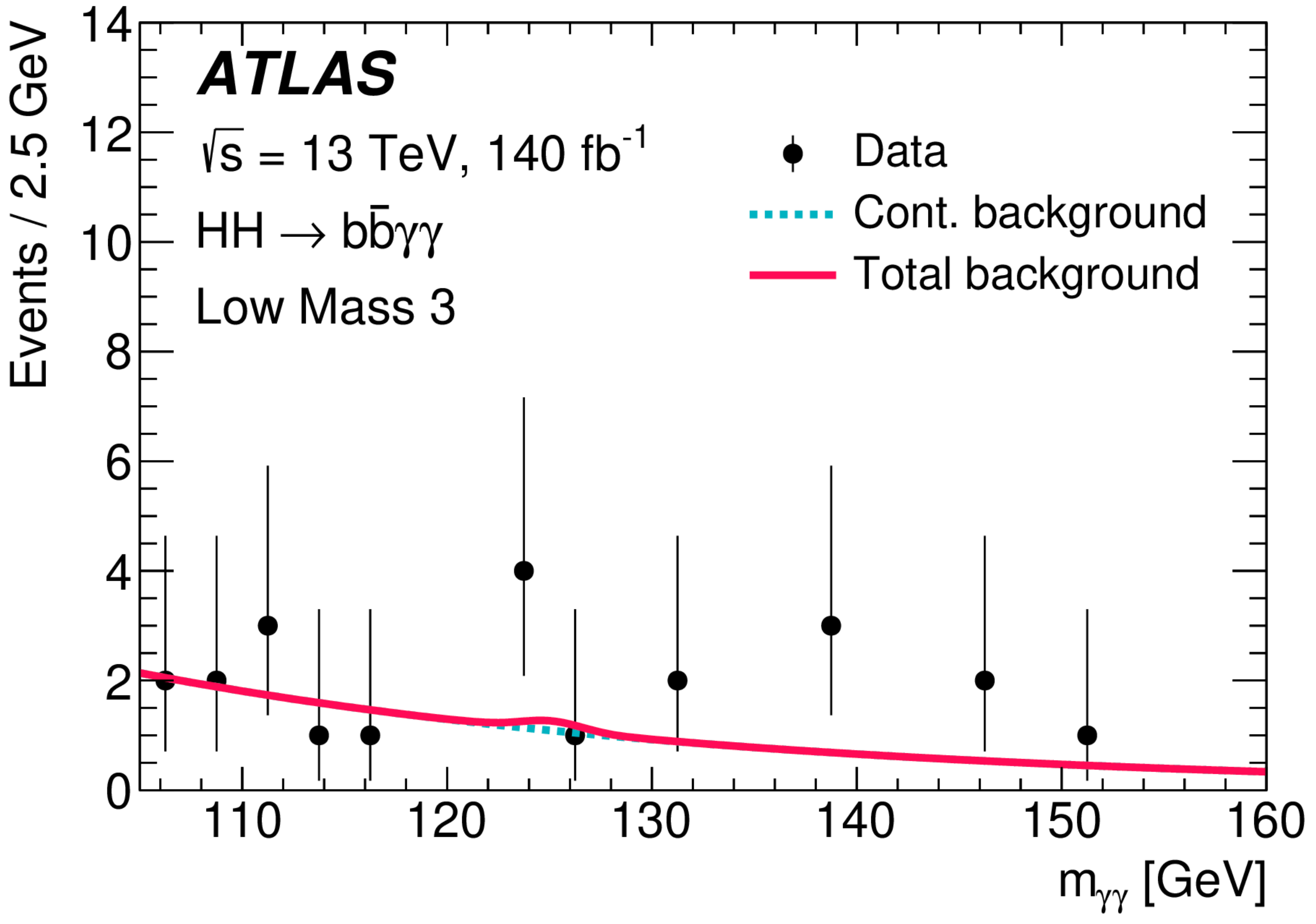


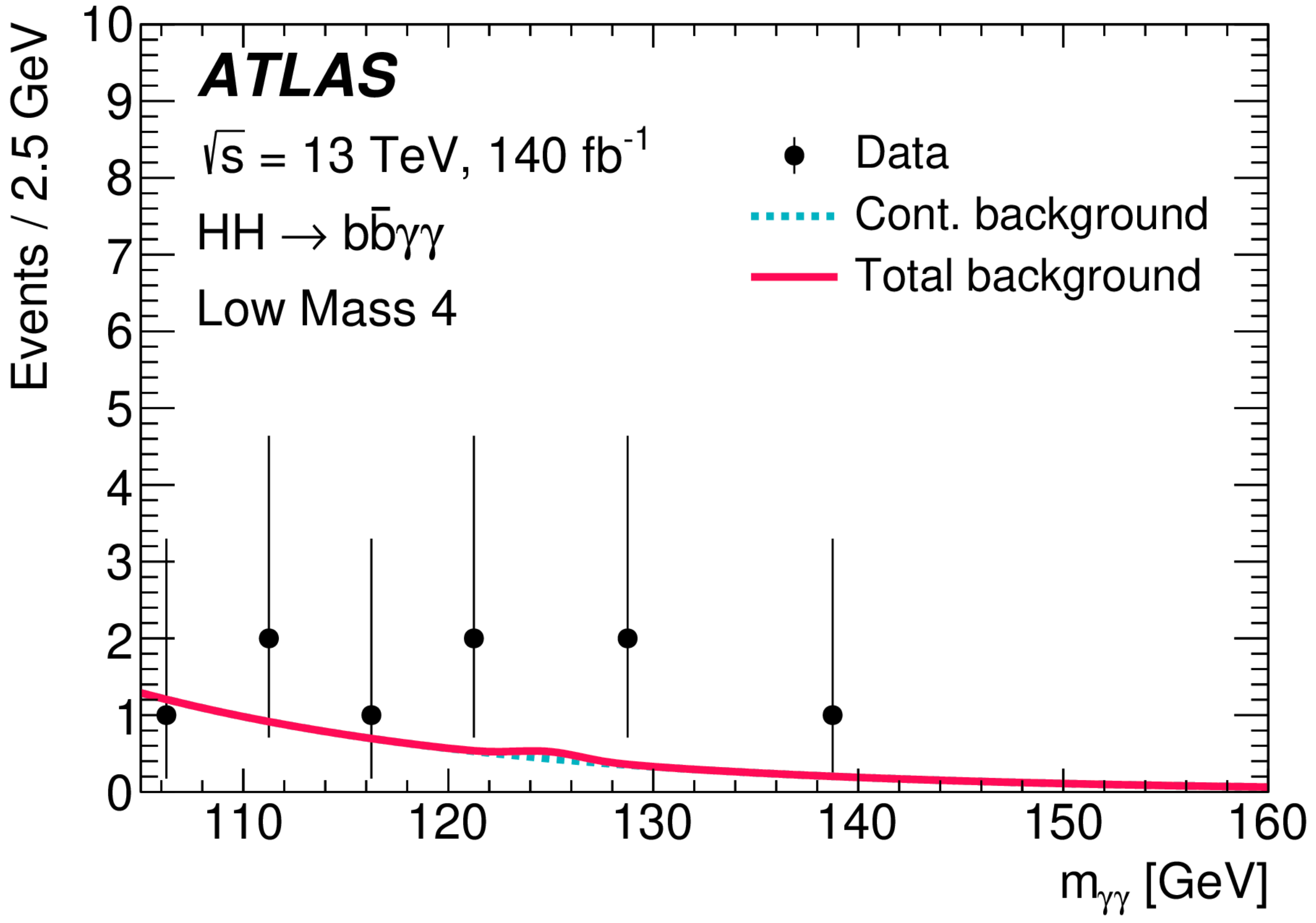
Fit results: Low Mass categories

- Plots showing the **fit results to data** in the $\mathbf{m}_{\gamma\gamma}$ **spectrum** for the Low Mass **categories** are presented below.









Systematic uncertainties

The impact of each source of **systematic uncertainty** has to be quantified and included when performing the **statistical analysis**.

➡ The systematic uncertainties are **propagated** through the **full analysis workflow**!

➡ They may result in $\pm 1\sigma$ **variations** for the **expected yields** or the **shape parameters** for the signal HH and single Higgs processes!

➡ **Peak position** and **peak width** for the resonant shape in the $m_{\gamma\gamma}$ spectrum.

		ggF HH	VBF HH	Single Higgs
Theory	Cross section and branching fraction	• BR(γγ) (2.9%) and BR(bb) (1.7%) • PDF + α_S (3%) • Scale + m_{top} ($^{+6\%}_{-23\%}$)	• BR(γγ) (2.9%) and BR(bb) (1.7%) • PDF + α_S (2.1%) • Scale (0.04%)	• BR(γγ) (2.9%) • Heavy Flavor uncertainty (100%, only for ggF, VBF, and WH)
	Acceptance	ggF HH parametrization	VBF HH parametrization	-
		Scale, PDF + α_S, Parton Shower		
Exp.	Yields	• Pile-up modelling; • Di-photon trigger efficiency; • Photon identification and isolation efficiency; • Photon energy scale and resolution; • Jet energy scale and resolution; • Jet vertex tagger efficiency; • Flavour tagging efficiencies.		
	Shape	Photon energy scale, photon energy resolution.		

+

The **spurious signal**!

➡ Only source of uncertainty affecting the continuum background modelling.

➡ • Related to the **particular choice** of the analytical **function** used for modelling the continuum background in each **analysis category**.

• Evaluated by performing a **signal + background fit** on a **MC-based background only template**, and extracting the **number of fitted signal events**.

• The main component of the spurious signal are **stat. fluctuations** in the background template.

➡ **Suppressed** in this analysis, thanks to the **new high-efficiency** $\gamma\gamma + bb$ **Sherpa 2.2.12** sample!

➡ Selection efficiency $\times$ **40 w.r.t. the older** $\gamma\gamma$**+ jets Sherpa 2.2.4 sample!**

Impact of the systematic uncertainties on the upper limits on μ_{HH}

- The **sensitivity** of this $HH \rightarrow b\bar{b}\gamma\gamma$ **analysis** is completely **dominated** by the limited **Run 2 statistics**!
- It is however interesting to study the **impact** of **systematic uncertainties** on the upper limits on μ_{HH}.

➡ Evaluated by **fixing** the corresponding **NPs** to the **best-fit** values and **repeating** the **limit calculation**.

This $HH \rightarrow b\bar{b}\gamma\gamma$ Run 2 analysis

Systematic uncertainty source	Relative impact [%]
Experimental	
Photon energy resolution	0.4
Photon energy scale	0.1
Flavour tagging	0.1
Theoretical	
Factorisation and renormalisation scale	4.8
$\mathcal{B}(H \rightarrow \gamma\gamma, b\bar{b})$	0.2
Parton showering model	0.2
Heavy-flavour content	0.1
Background model (spurious signal)	0.1

Old $HH \rightarrow b\bar{b}\gamma\gamma$ Run 2 analysis

		Relative impact of the systematic uncertainties [%]	
Source	Type	Nonresonant analysis HH	Resonant analysis m_X = 300 GeV
Experimental			
Photon energy resolution	Norm. + Shape	0.4	0.6
Jet energy scale and resolution	Normalization	< 0.2	0.3
Flavor tagging	Normalization	< 0.2	0.2
Theoretical			
Factorization and renormalization scale	Normalization	0.3	< 0.2
Parton showering model	Norm. + Shape	0.6	2.6
Heavy-flavor content	Normalization	0.3	< 0.2
$\mathcal{B}(H \rightarrow \gamma\gamma, b\bar{b})$	Normalization	0.2	< 0.2
Spurious signal	Normalization	3.0	3.3

- The impact of the **spurious signal** uncertainty is **suppressed** w.r.t. the previous analysis (where the effect on the upper limit was found to be $\sim \mathbf{3}\,\%$).

➡ Thanks to the new **high-efficiency background template** adopted for measuring this uncertainty!

According to the latest HL-LHC projections, the **spurious signal** is expected to be one of the **major limiting** factors for the **sensitivity** of the $HH \rightarrow b\bar{b}\gamma\gamma$ analysis at the **HL-LHC stage**!

➡ Crucial to address this systematic uncertainty now!