An overview of the legacy $HH \to b\bar{b}\gamma\gamma$ analysis

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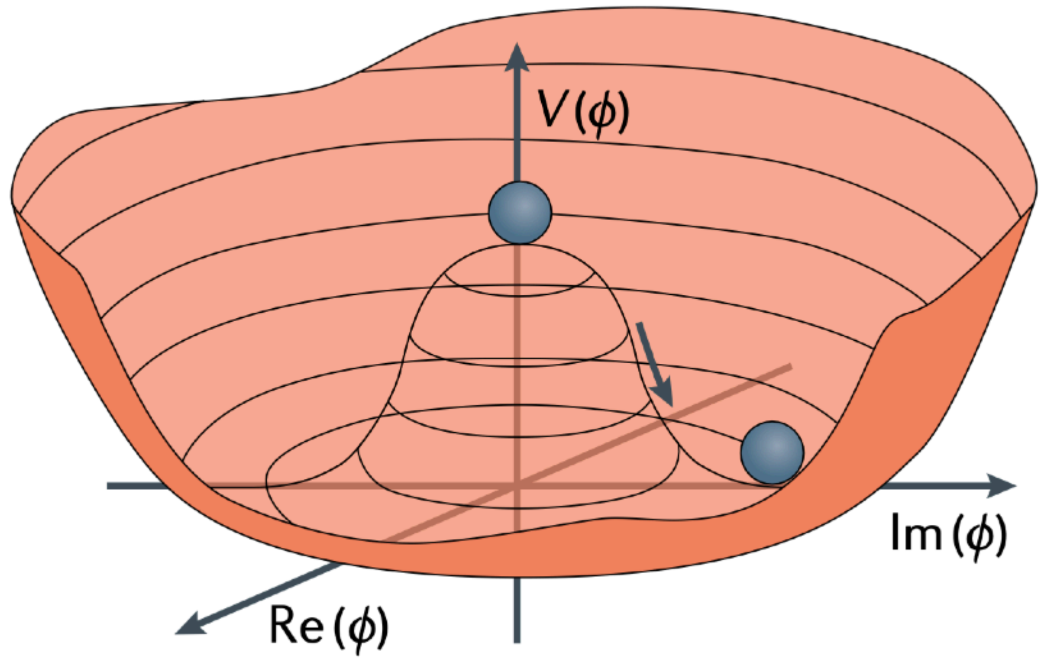
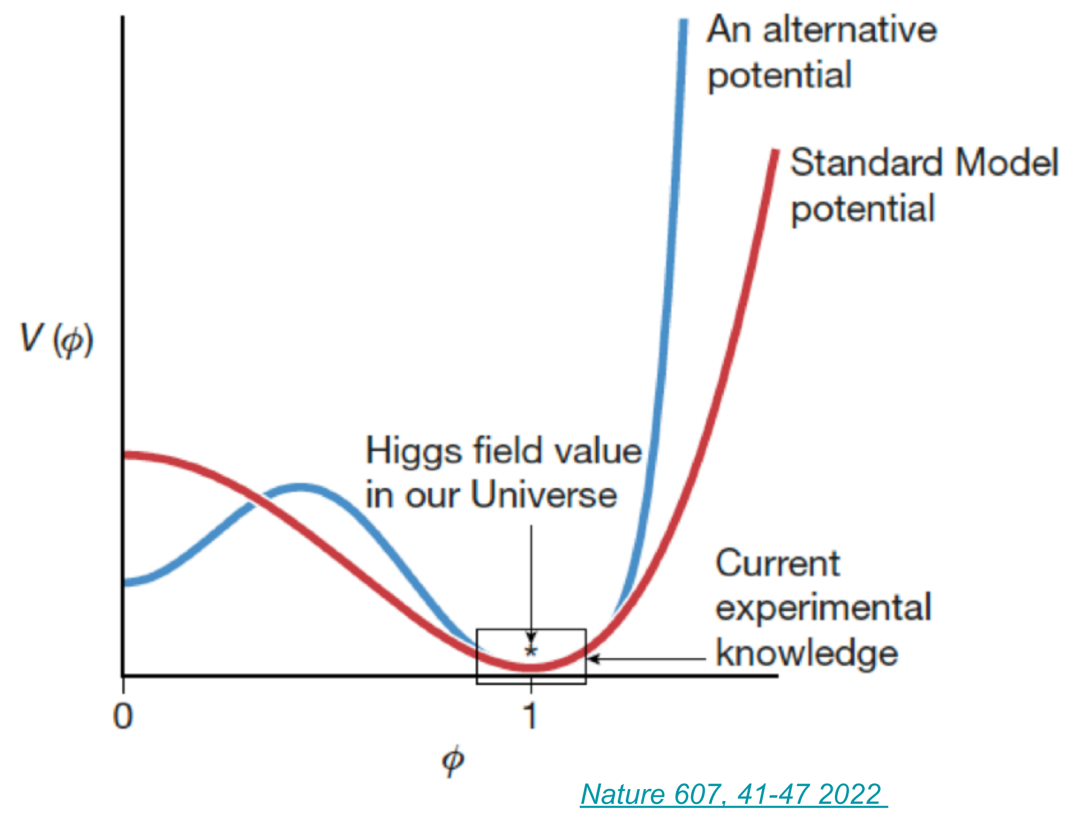
Introduction & Motivations

- Measuring HH production gives us unique access to the triple Higgs coupling (self coupling) λ_3, which gives information of the shape of the Higgs potential
- Deviations from SM could indicate BSM physics with an impact on HH production rate and kinematics
  - Dependence on κ_λ and κ_{2V} coupling modifiers
  - Probing EFT interpretations
- Linked to many open questions in particle physics
  - Characterizing it is a major goal of HL-LHC

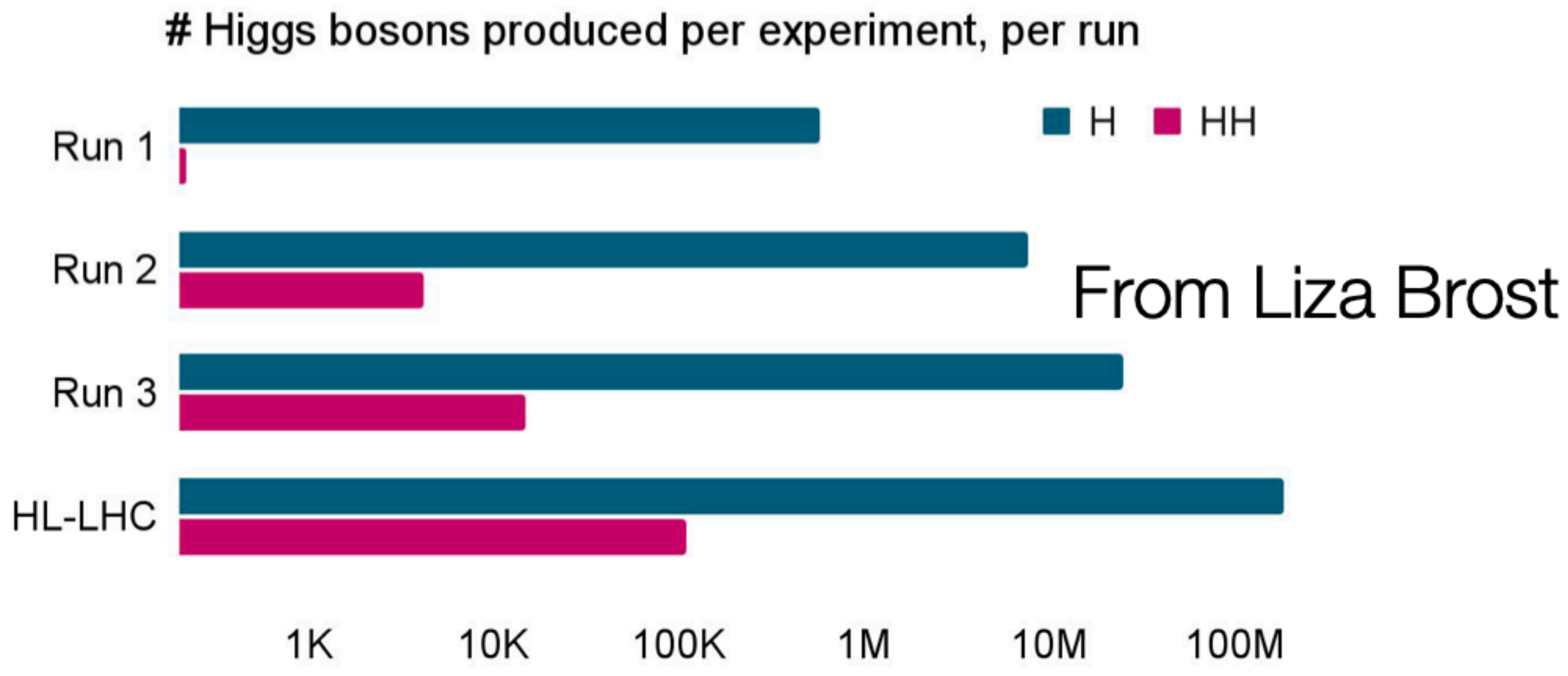




Nature 607, 41-47 2022

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 v H^4 + \mathcal{O}(H^5)$$

$$\lambda_3 = \frac{m_H^2}{2v}$$



LHC Run 3 has started and expect to ~ double the dataset and number of HH events

- Scales up to about 10^5 HH events in HL-LHC
- Observation potentialities

di-Higgs Run 2 Legacy $bb\gamma\gamma$ status report

ATLAS EXPERIMENT

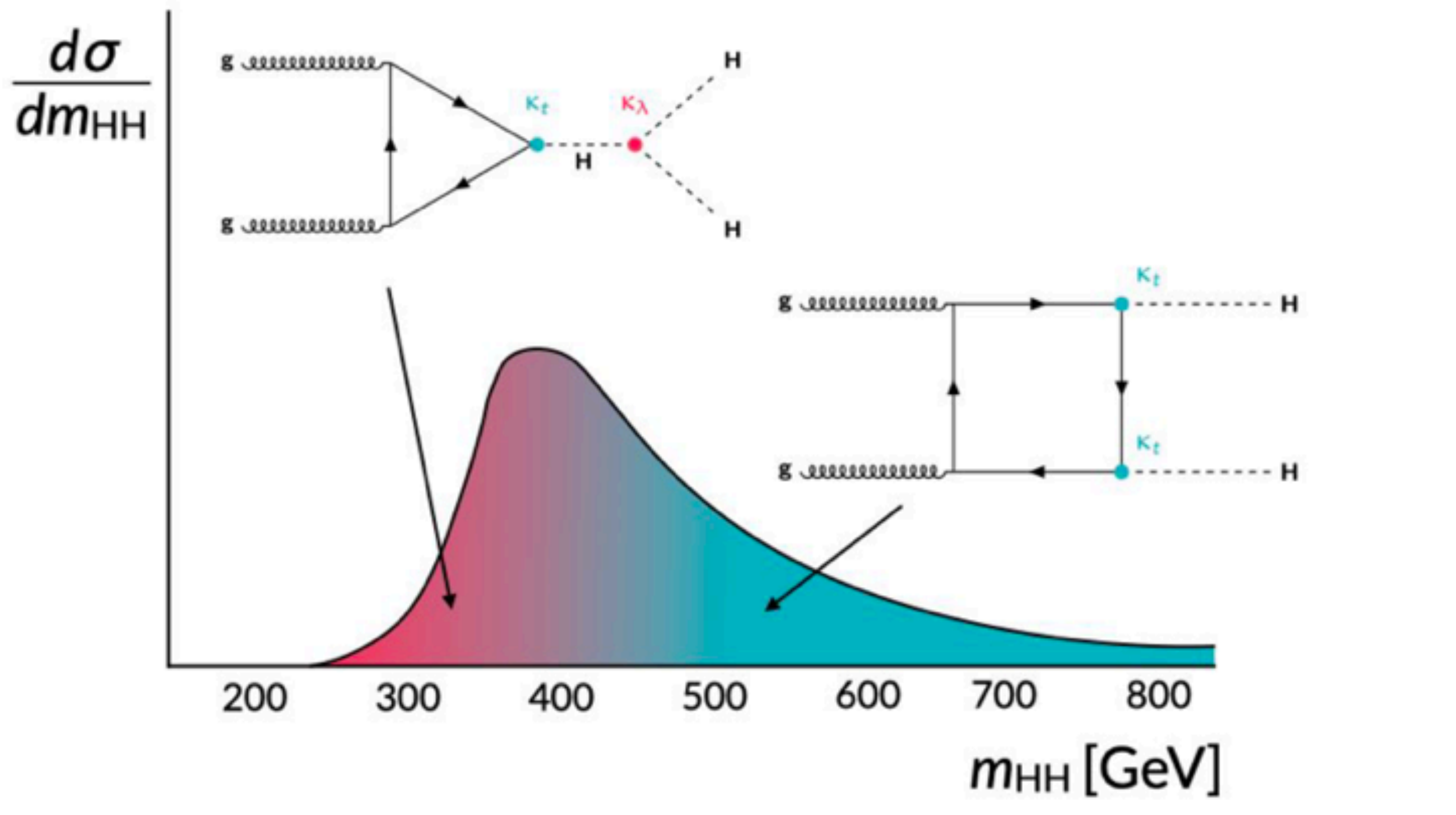
Higgs boson pair production and decay modes

- Standard Model (SM) di-Higgs production (Non Resonant)
- Gluon-gluon fusion (ggF) is the dominant production mode at LHC, accounting for ~ 90% of the total di-Higgs production
  - Destructive Interference between the triangle and the box diagrams leads to a small cross section: $\sigma_H \sim 1000\ \sigma_{HH}$
- Vector Boson Fusion (VBF) provides additional sensitivity to κ_λ and direct measurement of κ_{2V}
- Beyond SM models: Resonant di-Higgs production

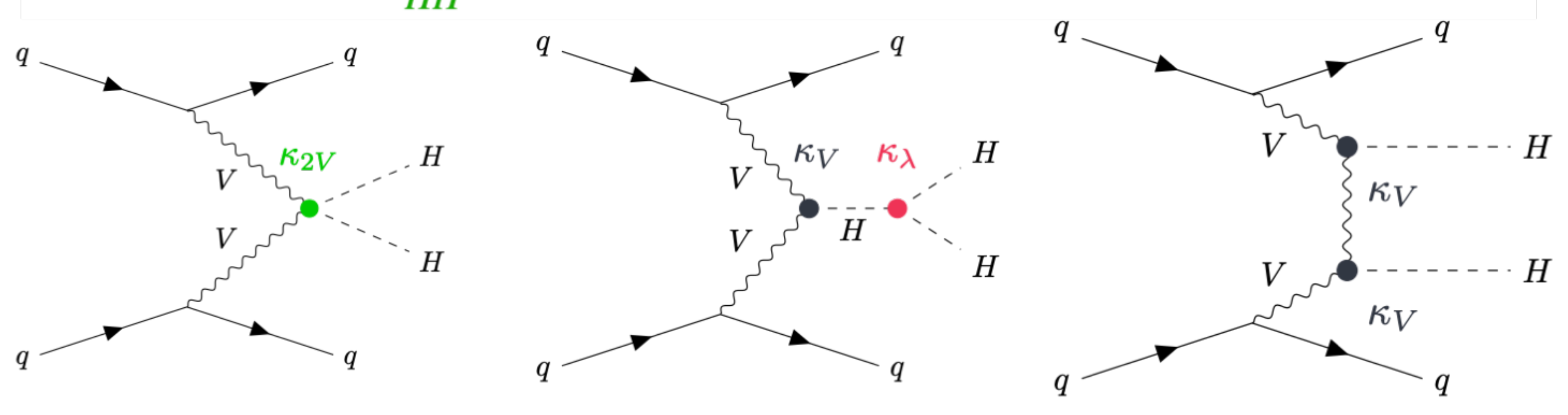
HH decay modes (Rarer →)

	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%

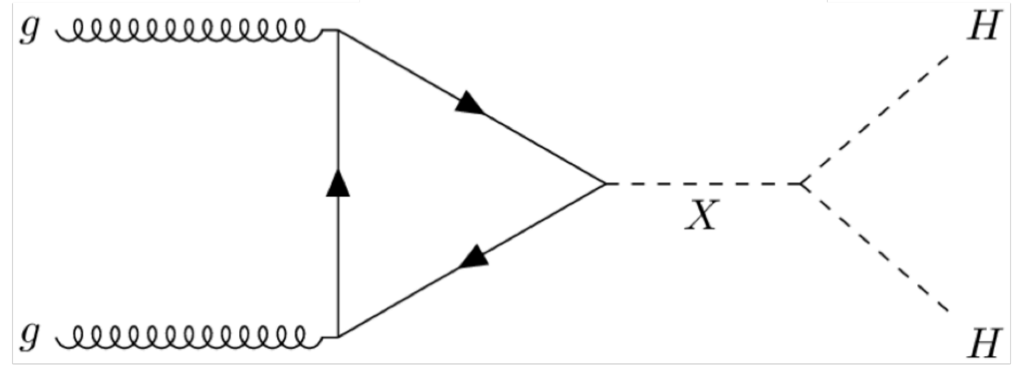
Non resonant σ_{HH}^{ggF} = 31.05 fb at 13 TeV and for m_H = 125.09 GeV



Non resonant σ_{HH}^{VBF} = 1.73 fb at 13 TeV and for m_H = 125.09 GeV



Resonant



No golden channel, combination is the key

The $HH \to b\bar{b}\gamma\gamma$ analysis

This **Legacy $HH \to b\bar{b}\gamma\gamma$ 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}**).

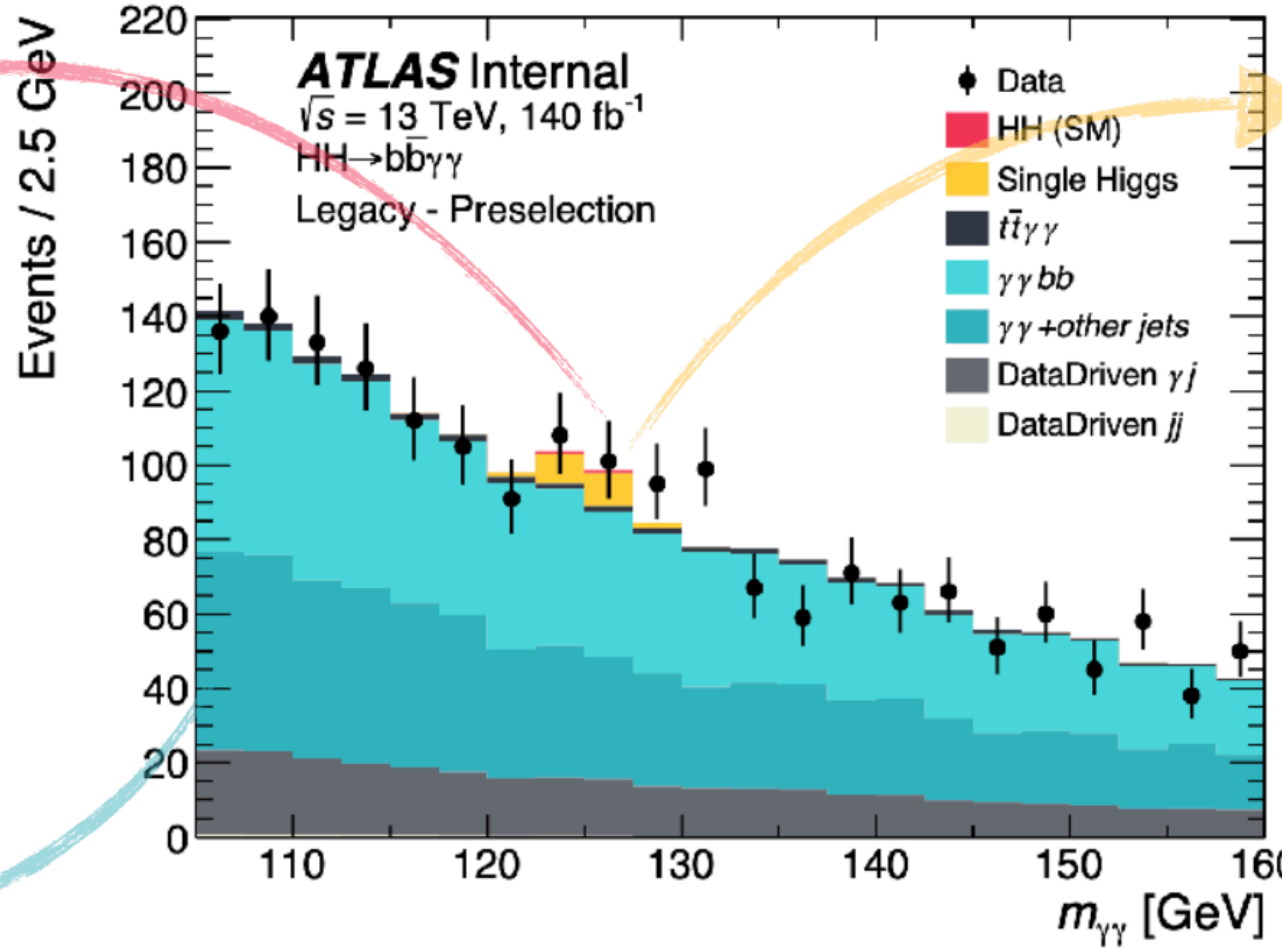
The analysis was **released** for the **EPS-HEP 2023 Conference**! → ATLAS-CONF-2023-050.

Signal

- **HH** production via **ggF** and via **VBF**.

For the first time in the $b\bar{b}\gamma\gamma$ channel!

- Peculiar **VBF signature** helps to isolate **VBF HH events** from bkg.!
- **Additional sensitivity** to **self-coupling modifier κ_λ** w.r.t. ggF only.
- **Unique** probe to the **quartic $HHVV$ vertex = κ_{2V}**.



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**.

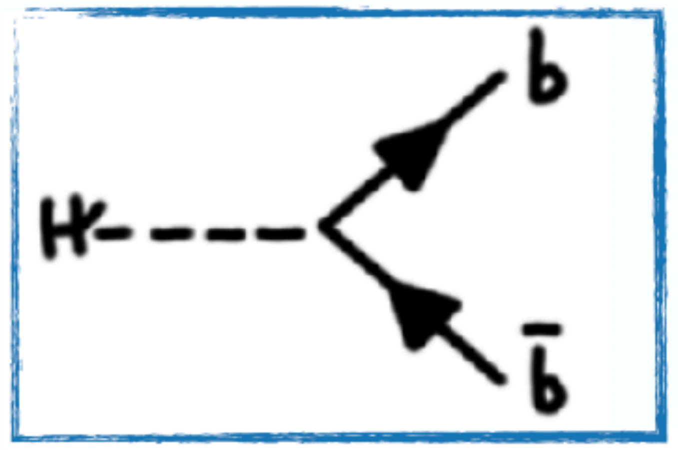
Non-resonant (continuum) bkg.

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

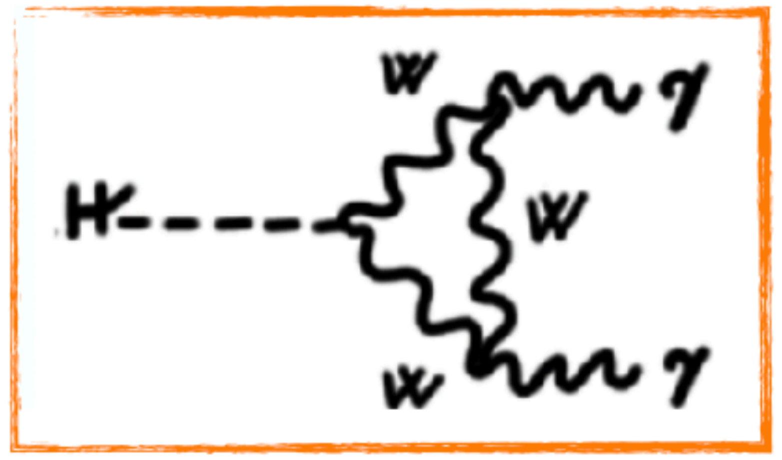
Extremely rare process + very large background.

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 (59%), but large **QCD background**.



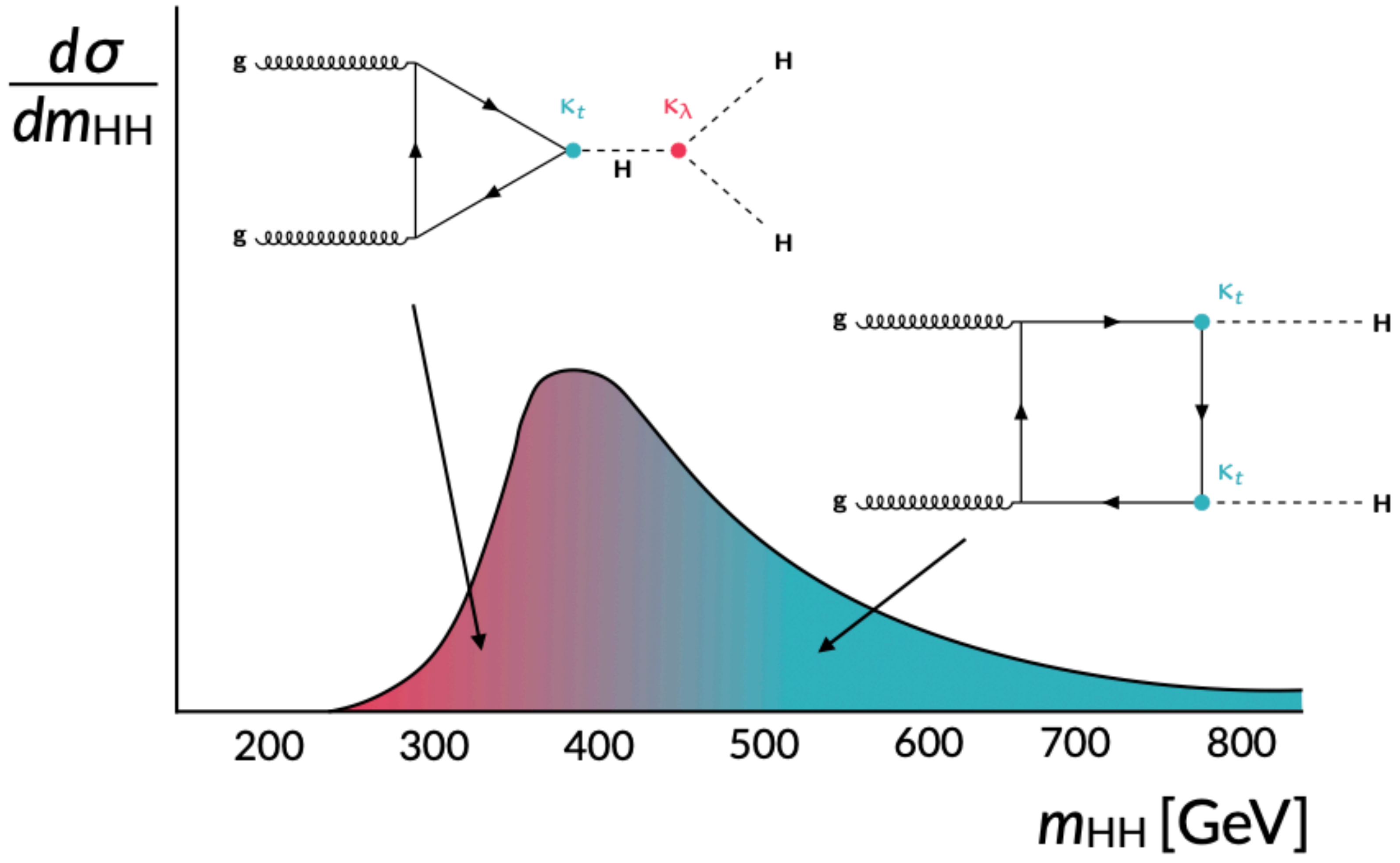
Very **low BR** for a SM Higgs boson (0.2%), but:

- **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.**

- **Stronger** contribution from 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**!

Analysis recipe

1. **Event selection.**
   - An **event selection** aimed at retaining **good** $H \to b\bar{b}$ and $H \to \gamma\gamma$ candidates is applied.
   - A special **Machine Learning (ML)-based VBF-jet tagger** is used to identify **candidate VBF jets**.

   Developed **specifically** for **this analysis**.

2. **Categorization.**

   Selected events are divided in mutually exclusive **categories**.

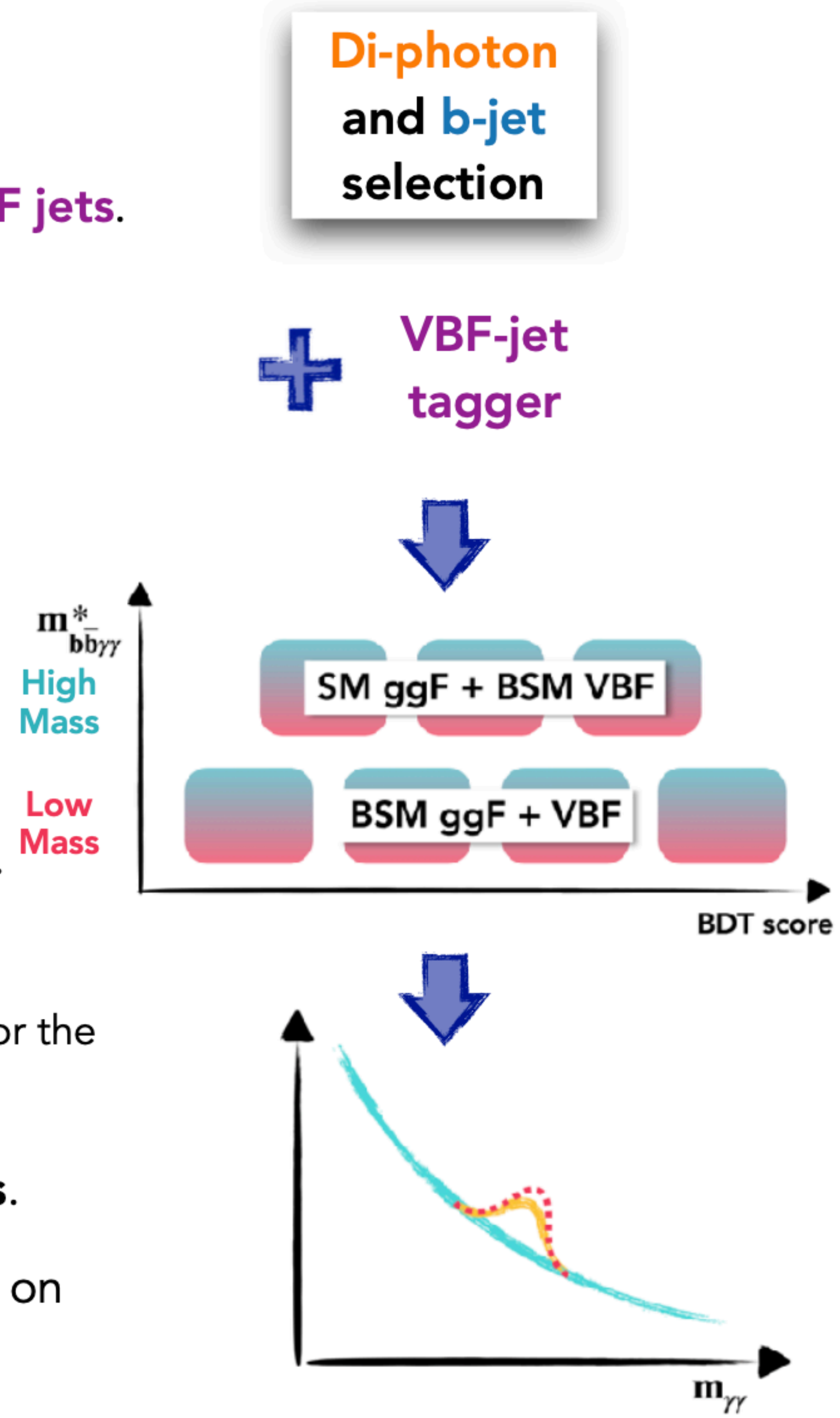
   $= m_{b\bar{b}\gamma\gamma} - (m_{\gamma\gamma} - 125\text{ GeV}) - (m_{b\bar{b}} - 125\text{ GeV})$

   - Defined based on the $\mathbf{m}^*_{\mathbf{b\bar{b}\gamma\gamma}}$ **invariant mass** and **ML techniques**.
   - Designed to target **ggF HH** + **VBF HH production** in the **SM** + **BSM-like scenarios**.

3. **Signal & Background Modeling & Systematic uncertainties.**
   - The **signal**, **single Higgs**, and **continuum background** are modeled in the $\mathbf{m}_{\gamma\gamma}$ **spectrum**.
   - The impact of each source of **systematic uncertainty** is evaluated.

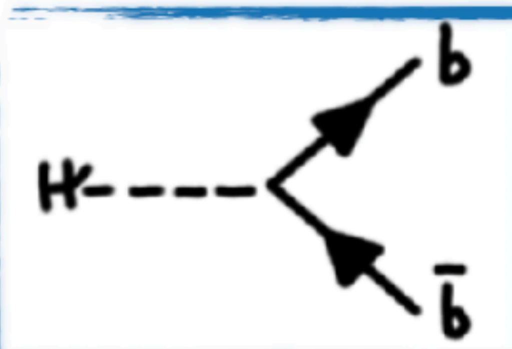
   Affecting the **HH** or **single Higgs yields**, or the **position** and **width** of the $\mathbf{m}_{\gamma\gamma}$ **peak**.

4. **Statistical model & interpretations.**
   - The results are extracted via a **maximum-likelihood unbinned fit** on the $\mathbf{m}_{\gamma\gamma}$ **distributions**.
   - If an excess of events is not observed, the statistical analysis allows to set **exclusion limits** on the **HH cross-section** and **measure** the **coupling modifiers** κ_λ, κ_{2V}!



Events selection and categorisation

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**.
- **μ-in-jet + PtReco corrections.**

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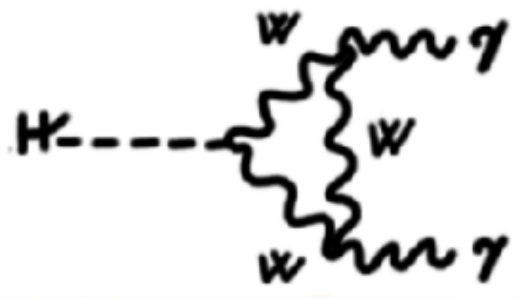


- **Two** tight and isolated **photons**.
- $p_T^{\gamma_{1(2)}}/m_{\gamma\gamma} > 0.35(0.25)$.
- $105 < m_{\gamma\gamma} < 160$ GeV.

\+

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

1

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

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

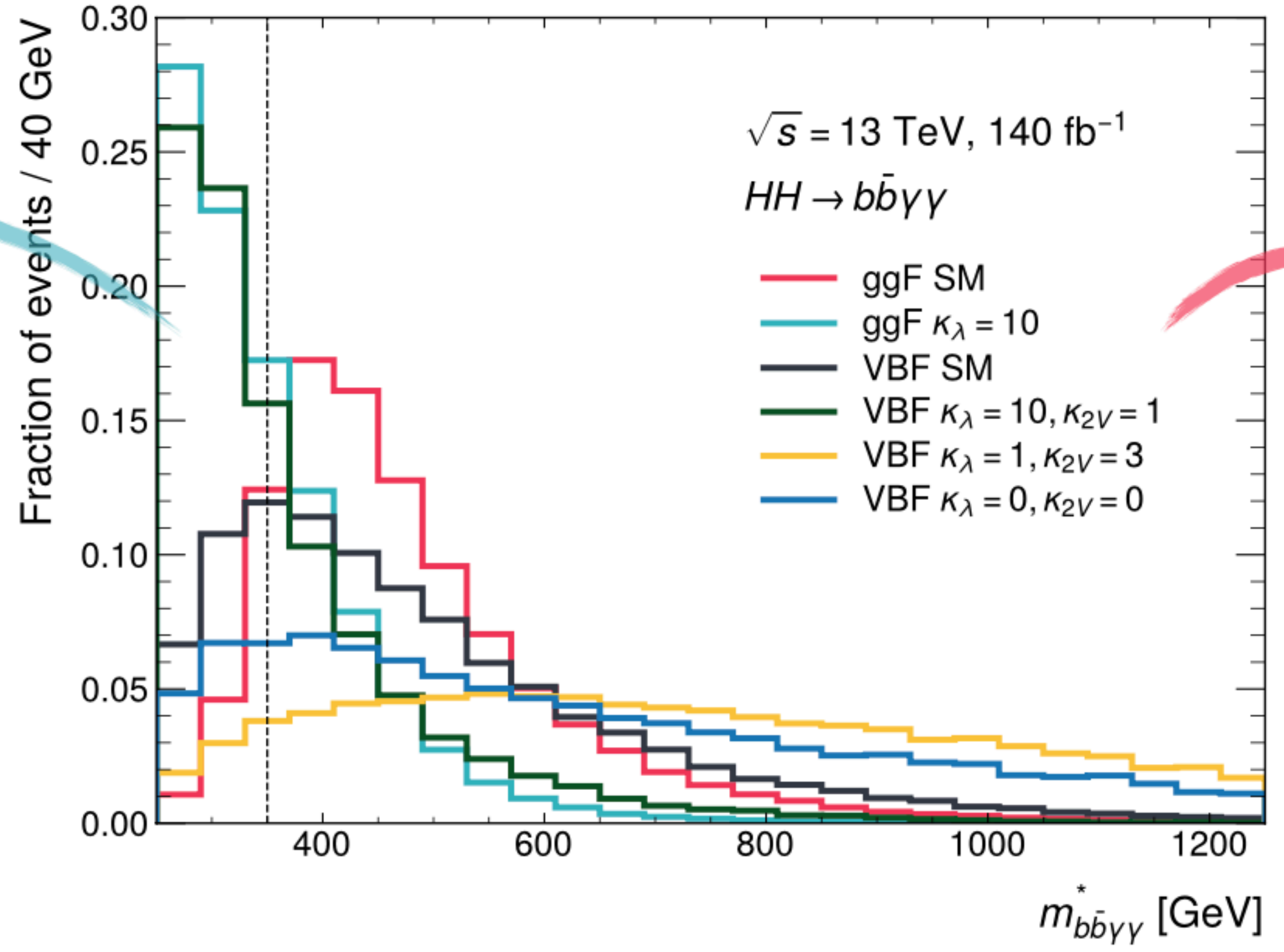
Two bins in $m^*_{b\bar{b}\gamma\gamma}$ are defined:

2

Low Mass region:

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

Targets **ggF HH** events with **larger κ_λ values**, and **VBF HH** samples with **all BSM couplings.**



High Mass region:

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

Targets **SM ggF HH** and **VBF HH** production with **SM + BSM couplings.**

Categorisation

- 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 BSM κ_λ values. • VBF HH with BSM values for κ_λ and κ_{2V}.	• SM ggF HH • SM + BSM VBF HH samples
Background	• All single Higgs processes • γγ + ttγγ samples	

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

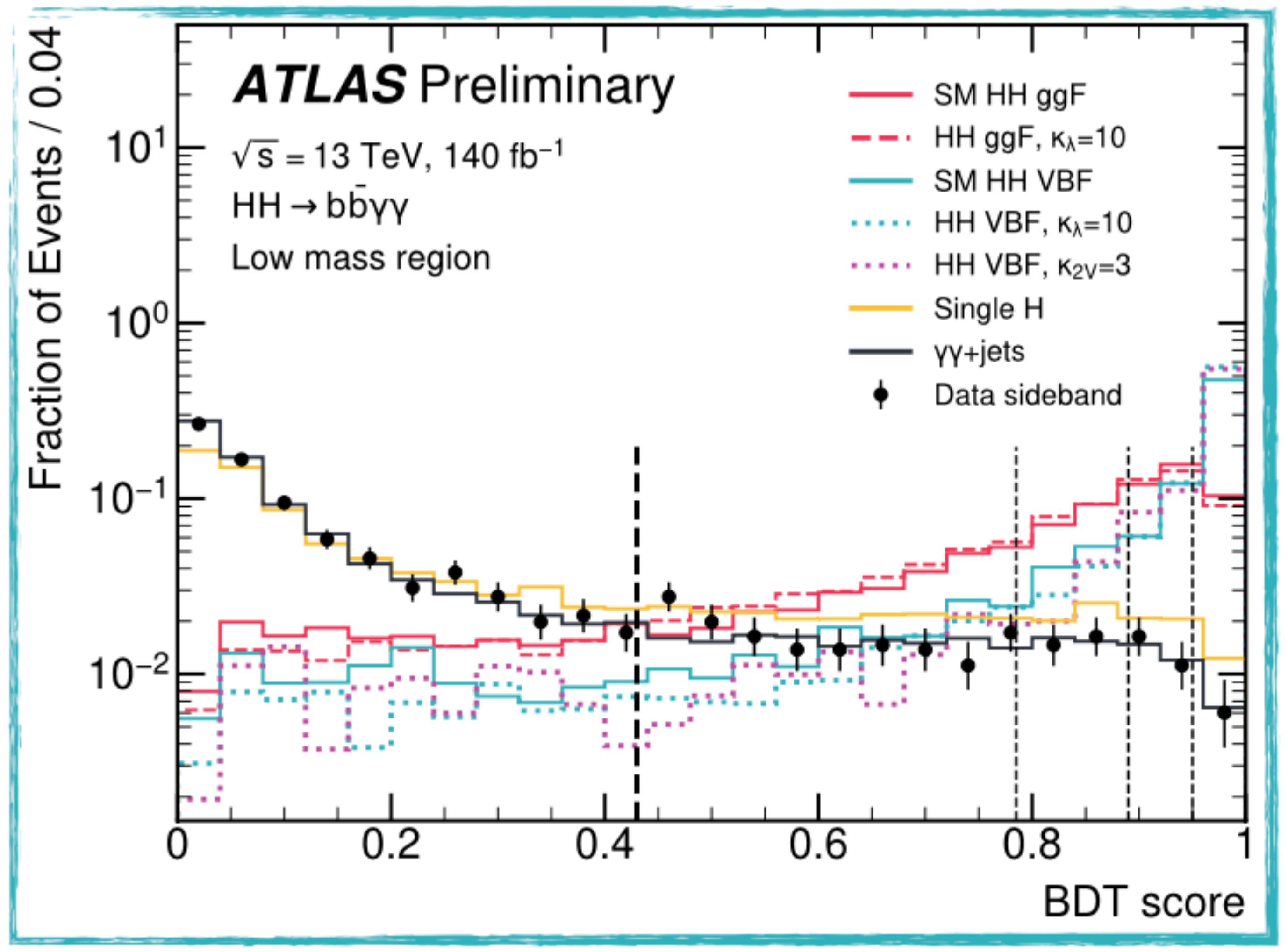
- **Photons** kinematic variables.
- **b-jet** kinematic variables.
- $H \to b\bar{b}$-targeting variables;
- Extra-jet related variables.

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

- 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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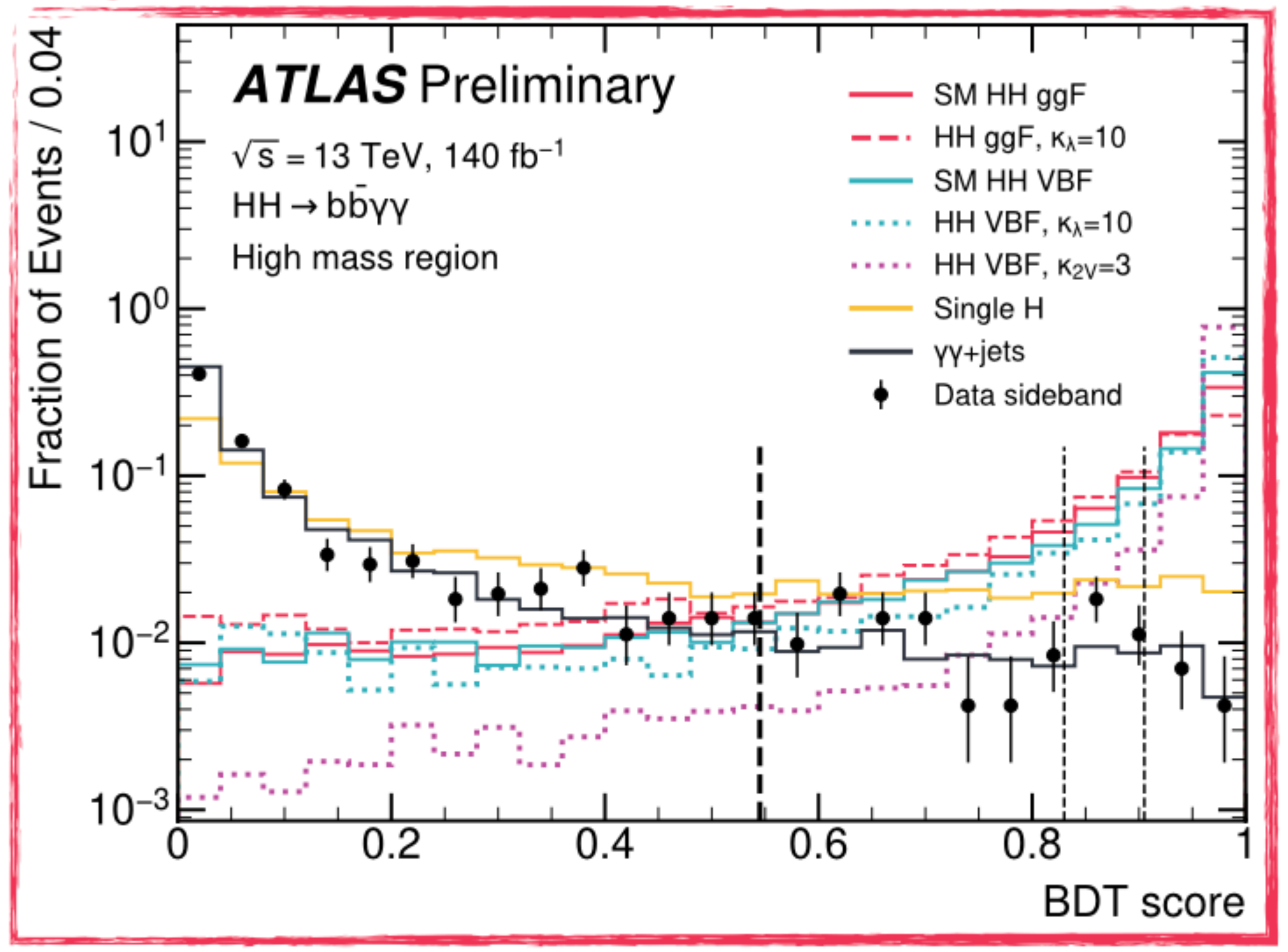
High Mass



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2

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

di-Higgs Run 2 Legacy $bb\gamma\gamma$ status report

Signal extraction

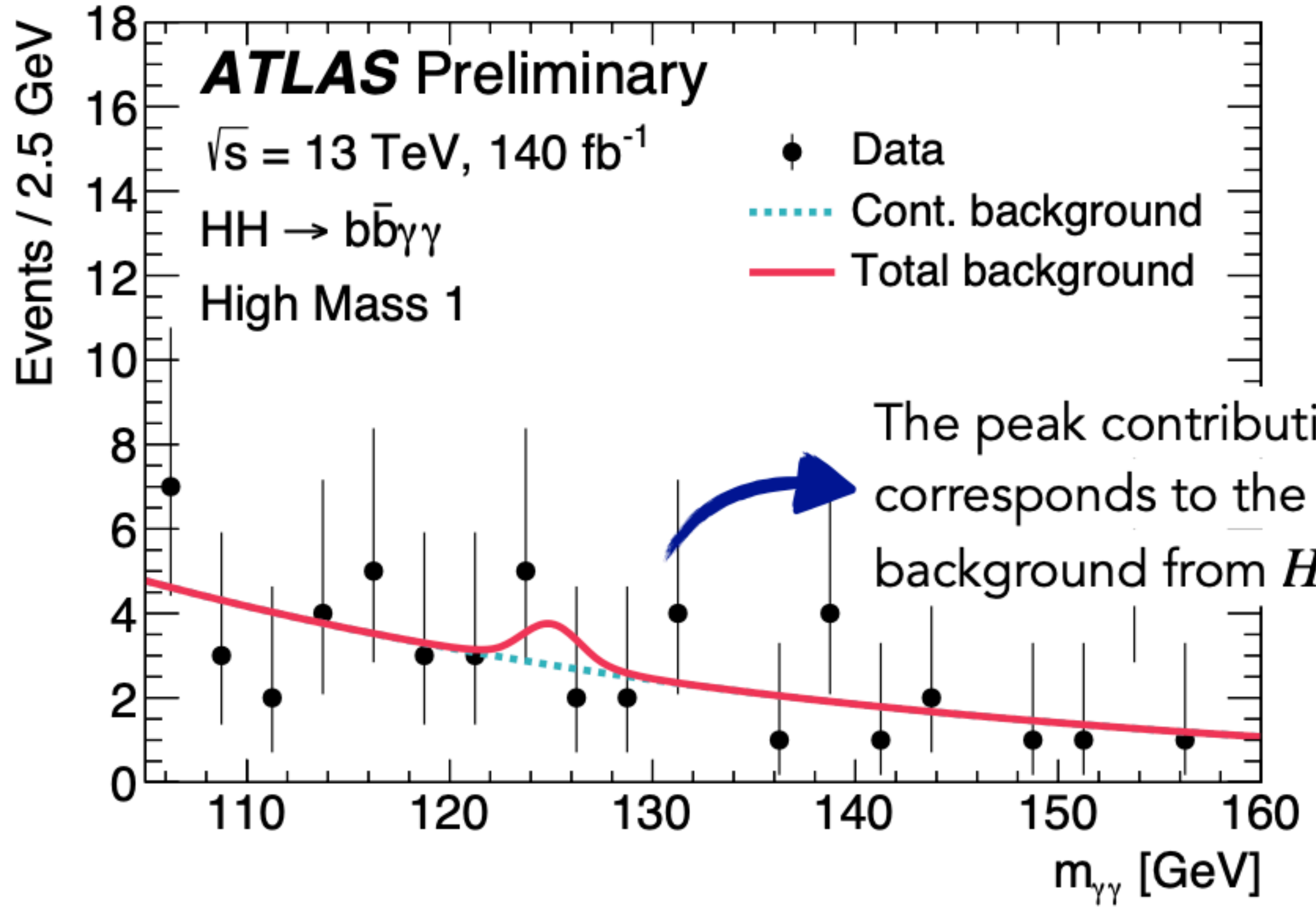
The **statistical results** are derived by performing an **unbinned maximum likelihood fit** to the $\mathbf{m}_{\gamma\gamma}$ **distribution** in $m_{\gamma\gamma} \in [105,160]$ GeV.

	Resonant (HH and single H)	Non-resonant (continuum γγ 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 using an **exponential function**, whose **shape parameters** and **normalization** are **fitted from data**.

3

- The contributions of the **systematic uncertainties** are included as **constrained nuisance parameters** (**NPs**), which are **profiled on data**.
- The category yields for the single Higgs processes are fixed to their **SM values**.
- The **signal HH yields** depend from the **HH cross-section** and the coupling modifiers κ_λ and κ_{2V}.

Fit results



The peak contribution corresponds to the resonant background from $H \to \gamma\gamma$ decay!

- **No excess** of events w.r.t. **background expectation** emerges from the maximum likelihood fit!
- The **statistical analysis** allows to **interpret** our 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}.

4

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 modeling.

- 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 × **40 w.r.t. the older** $\gamma\gamma$+ **jets Sherpa 2.2.4 sample!**

Systematic uncertainties

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- 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.

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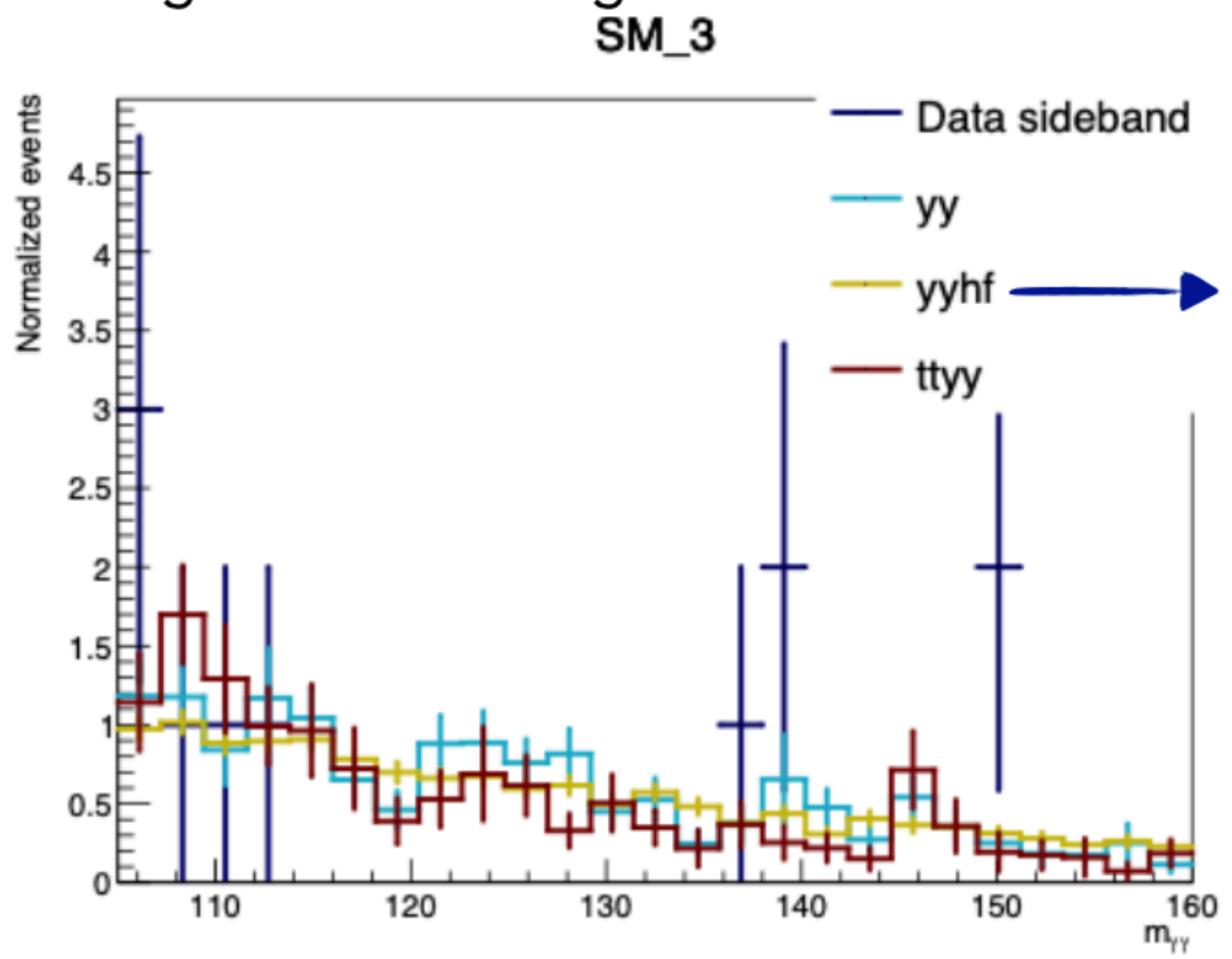


New high efficiency $\gamma\gamma$+$b\bar{b}$ sample, targeting specifically the $b\bar{b}\gamma\gamma$ **phase space**!

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

- **Exclusion limits** are set on the **di-Higgs production cross-section** at **95% CL.**

Upper limits on σ(HH) @ 95% CL.

	Observed	Expected
Stat. only	$3.7 \times \sigma^{SM}$	$4.7 \times \sigma^{SM}$
Syst.	$4.0 \times \sigma^{SM}$	$5.0 \times \sigma^{SM}$

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

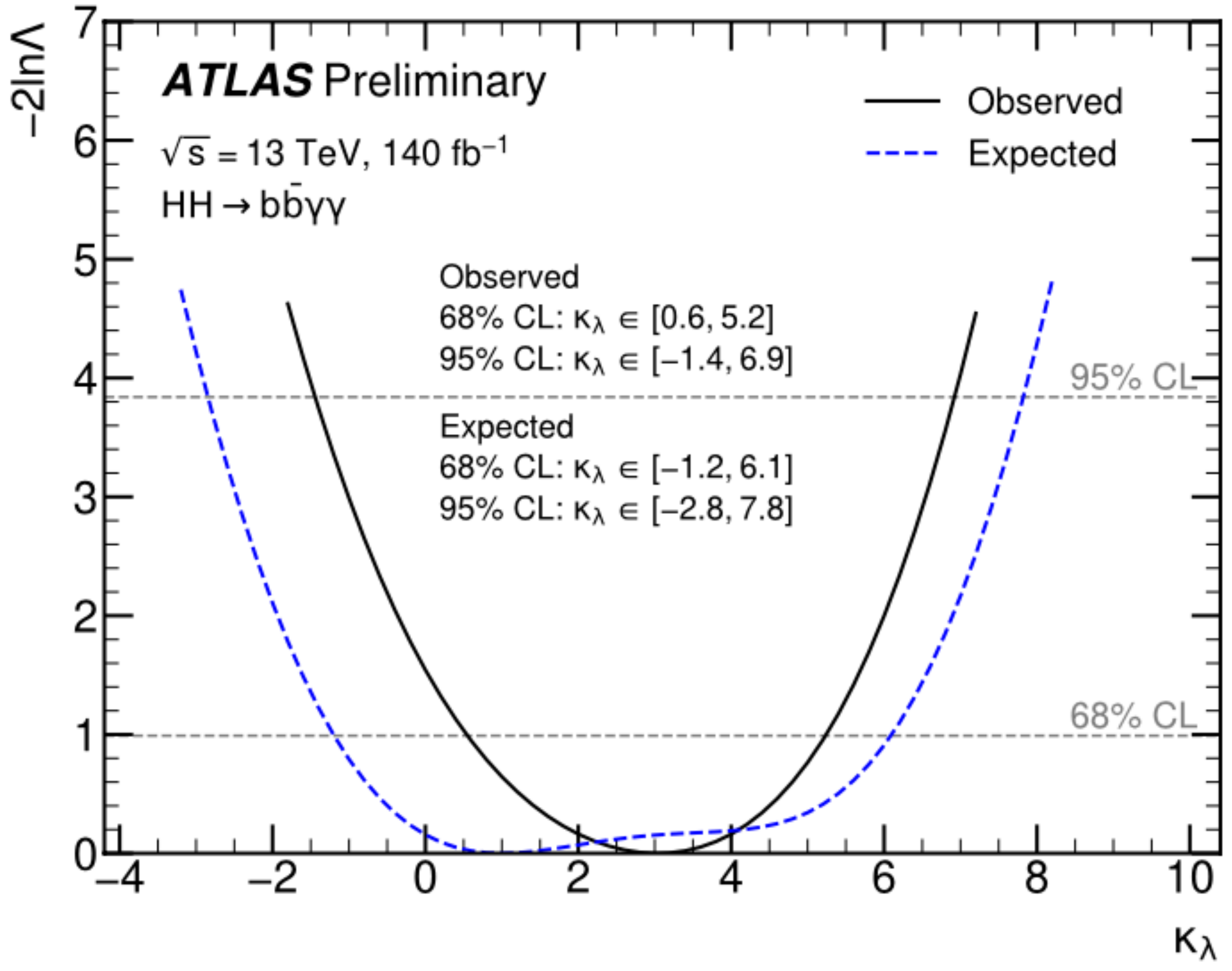
	ggF Run 2	Legacy Run 2
Expected limit on σ(HH)	$5.7 \times \sigma^{SM}$	$5.0 \times \sigma^{SM}$

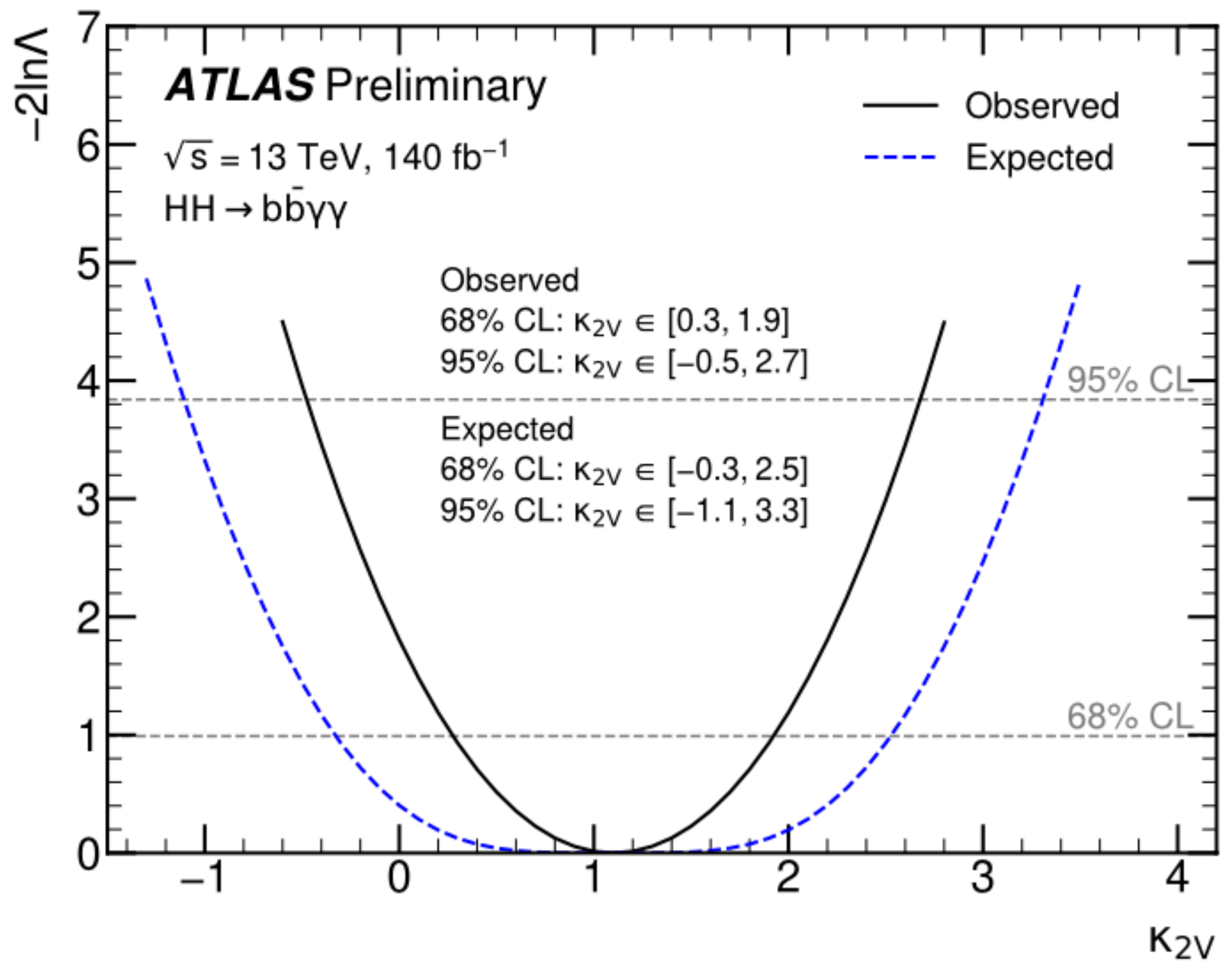
ggF Run 2 analysis: Phys. Rev. D 106 (2022) 052001

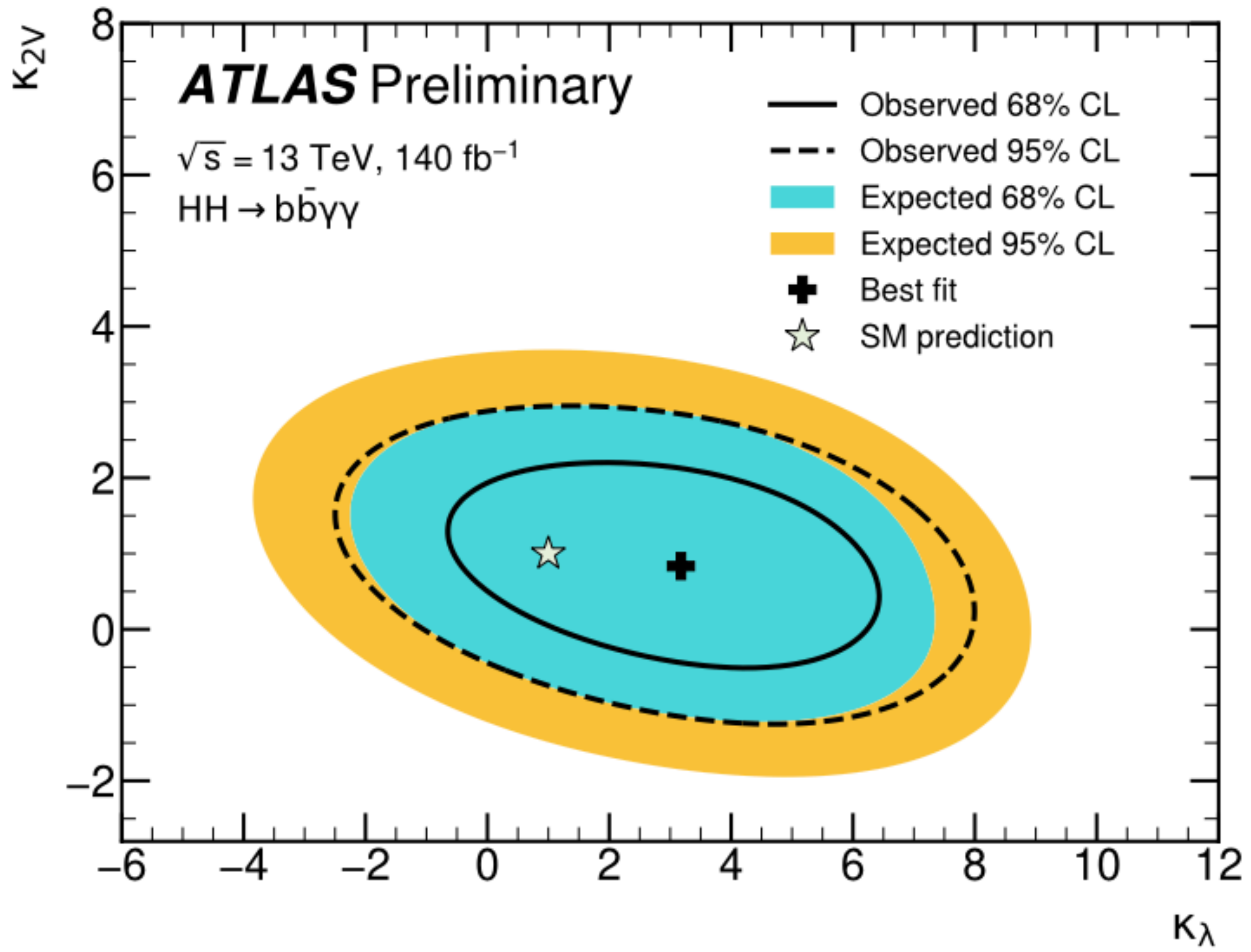
4

- **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

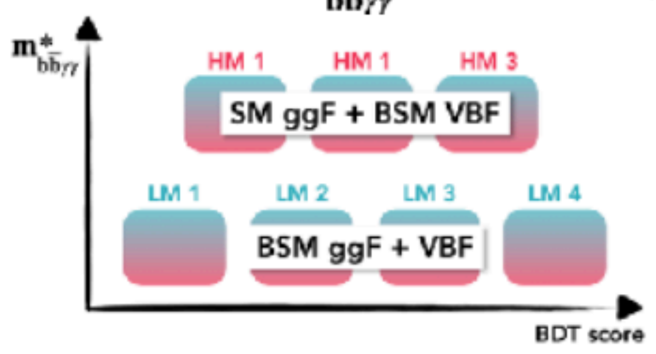
- Searching for **Higgs boson pair production** constitutes the only **direct probe** to the **exact shape** of the **Higgs boson potential**, in particular the **trilinear Higgs self-coupling modifier κ_λ**.
- Exploiting the **two** dominant **production modes**, via **ggF HH** and **VBF HH**, allow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

→ One of the **most awaited** ATLAS measurements.

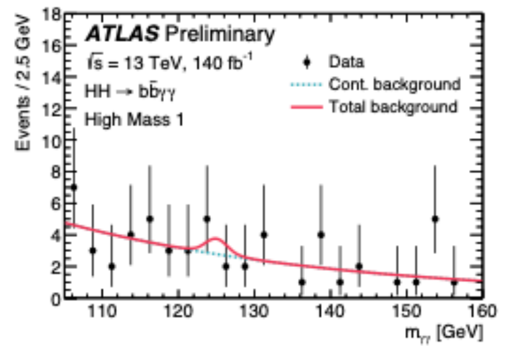
From applying a pre-selection targeting the $b\bar{b}\gamma\gamma$ signature…

Di-photon and b-jet selection

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



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



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

→ The analysis placed **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 cross-section

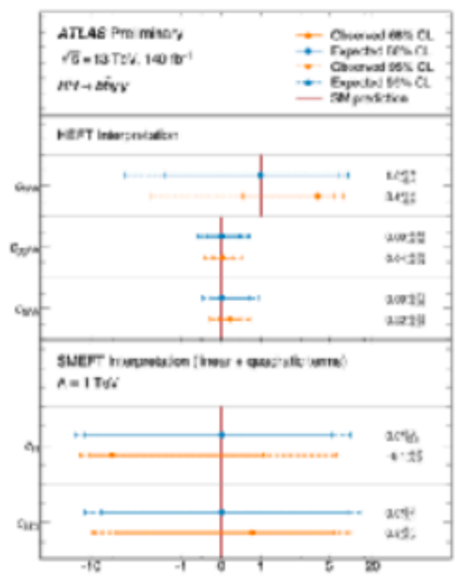
	Observed	Expected
σ(HH)	4.0 × σ^{SM}	5.0 × σ^{SM}

+

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]

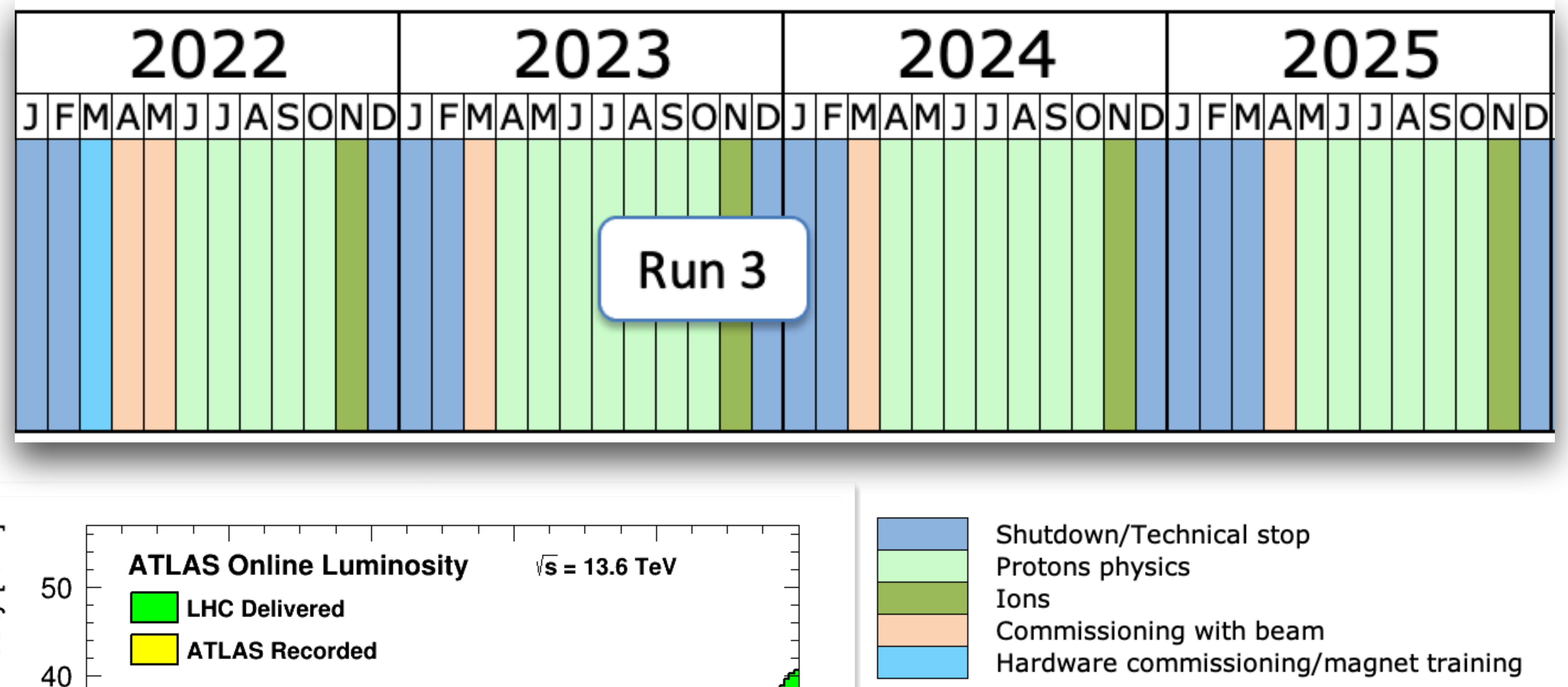
For the first time in the $b\bar{b}\gamma\gamma$ channel, the analysis was also **interpreted** in the context of the **EFT** frameworks **HEFT** and **SMEFT**.

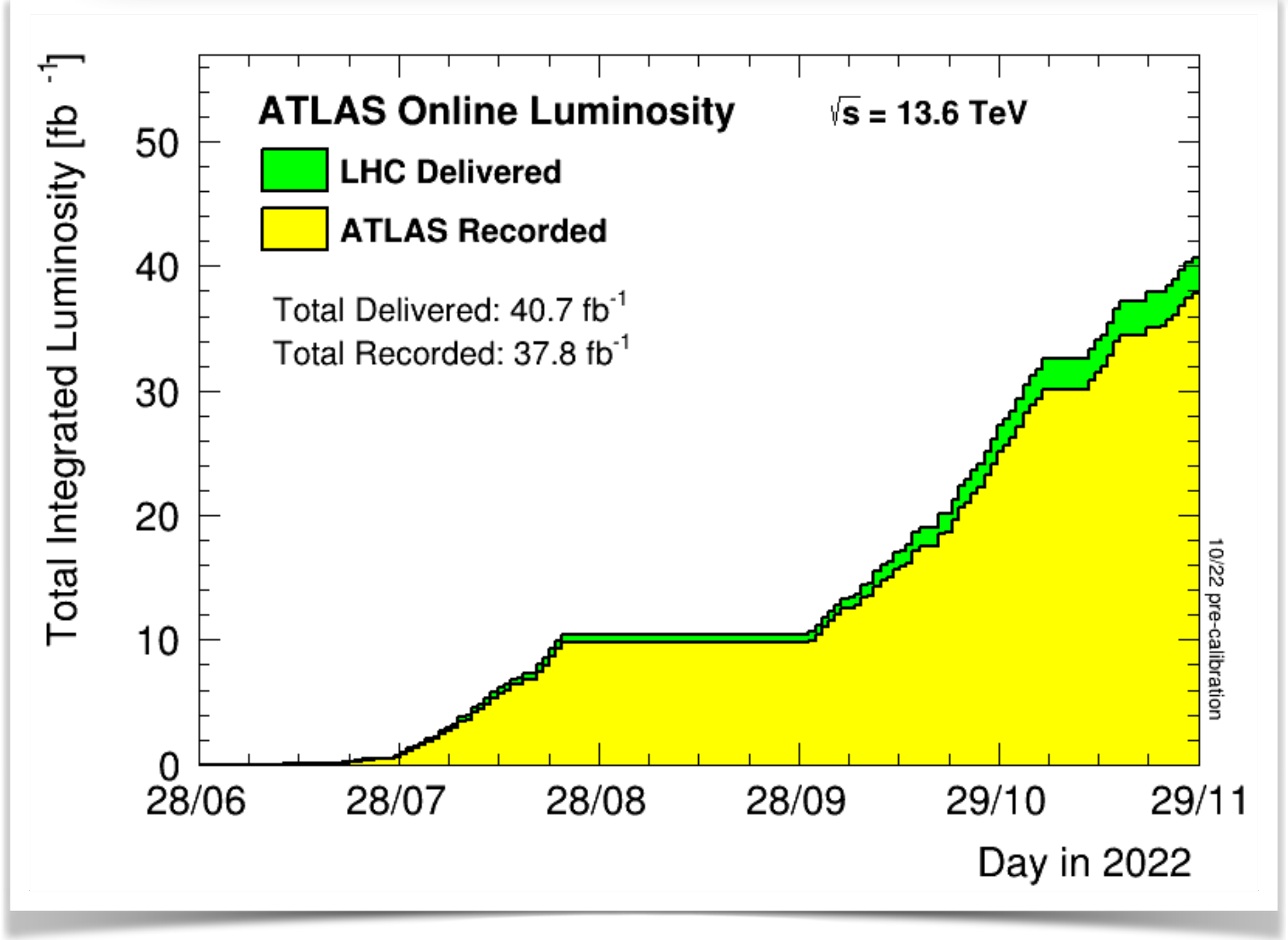


→ More details in **backup**!

Towards Run 3 data analysis

LHC Schedule



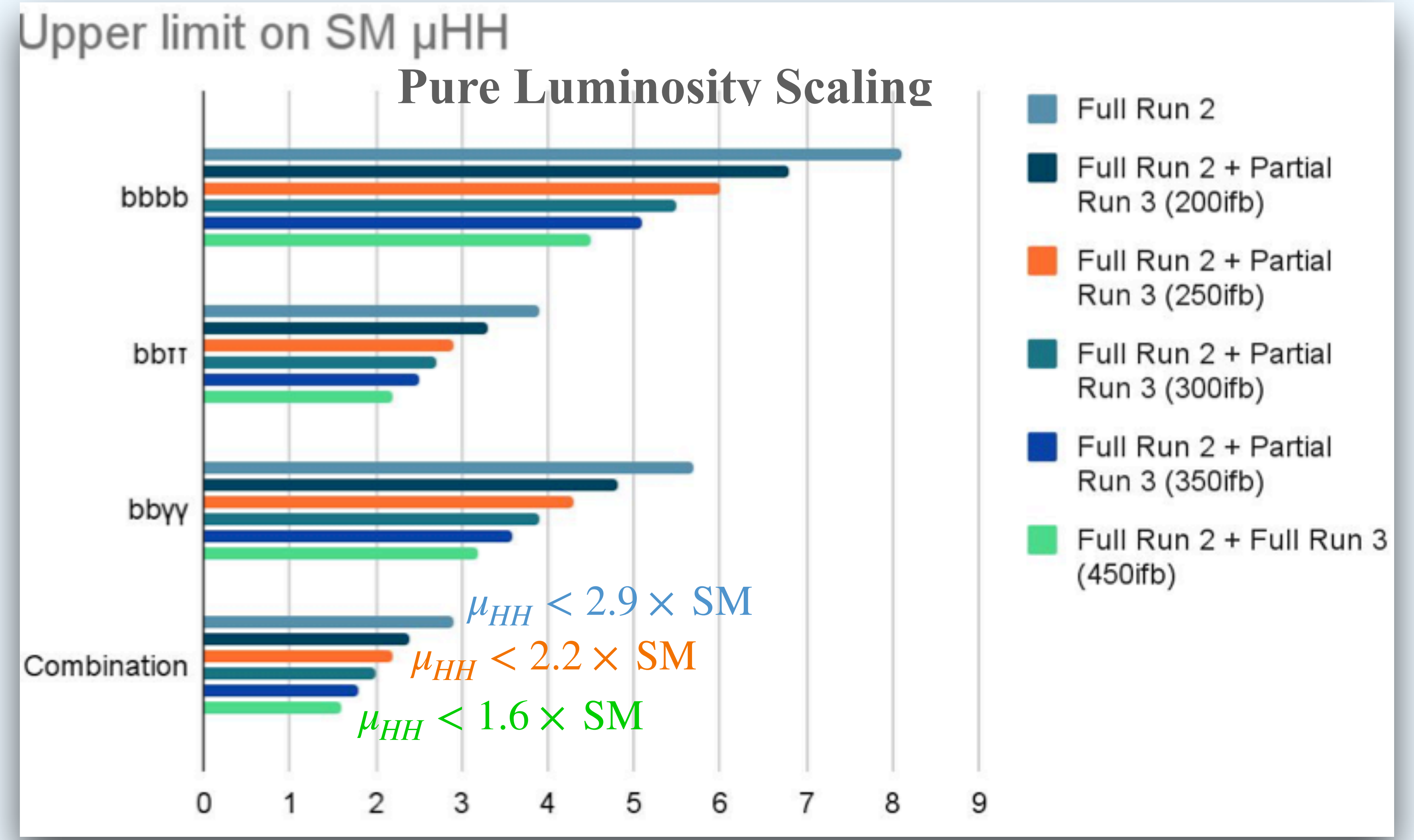


- Run 3 of the LHC:
  - 2022: ~40 fb^{-1}
  - 2023: ~70-80 fb^{-1}
  - Full Run-3: ~300 fb^{-1}

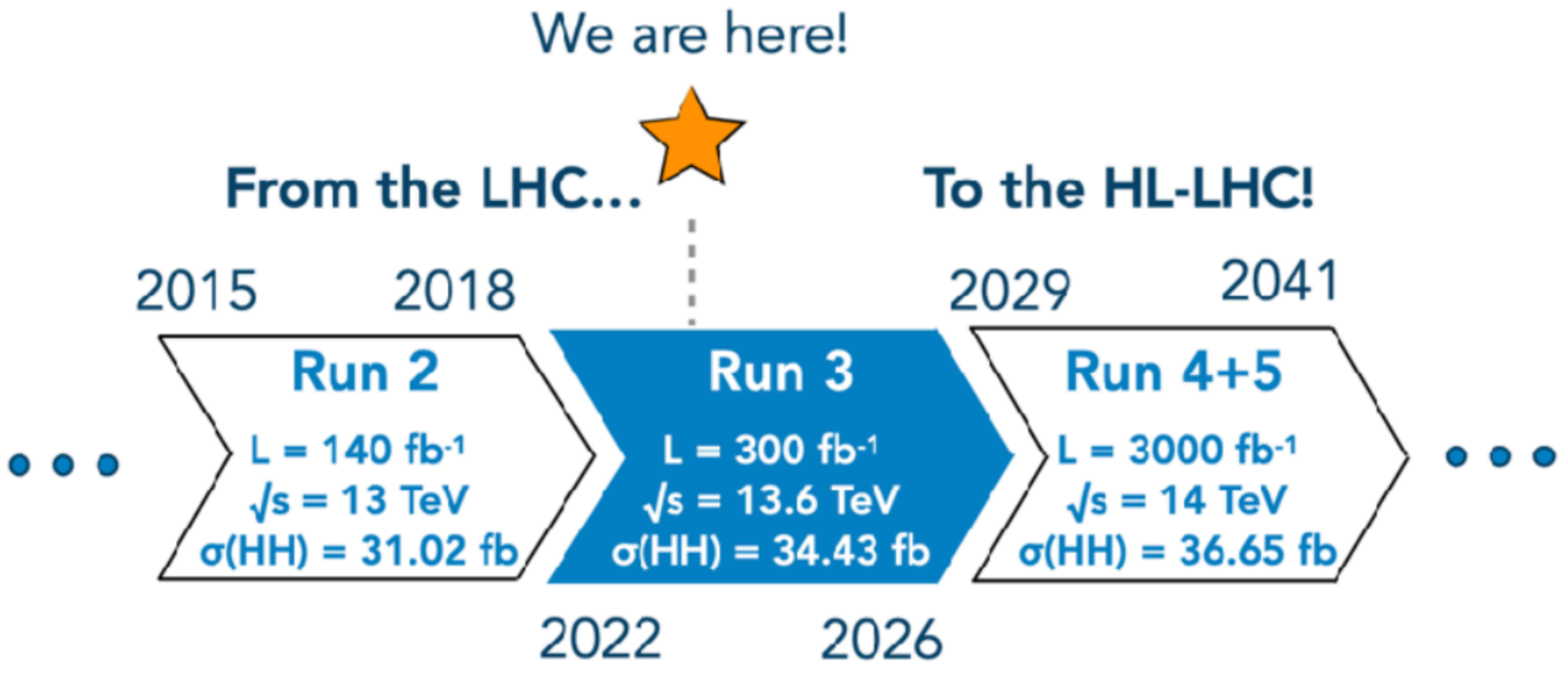
Increase in √s (13 TeV -> 13.6 TeV) —> cross section increase will benefit certain physics processes

Non-resonant Searches

- Run 2 + early Run 3 paper on non-resonant production with most sensitive channels (bbγγ, bbττ, 4b) —> Useful to push the developments of new analyses
- Upper limit of 1 (and a significance of 2σ in ATLAS - > 3σ ATLAS+CMS!) at the end of Run 3!
- *Ambitious* ~40% improvement to reach this so we have to try hard and work towards this!



Towards Run 3 $HH \rightarrow b\bar{b}\gamma\gamma$ analysis



Expected SM HH: 4000 | $\sim 10^4$ | $\sim 10^5$!

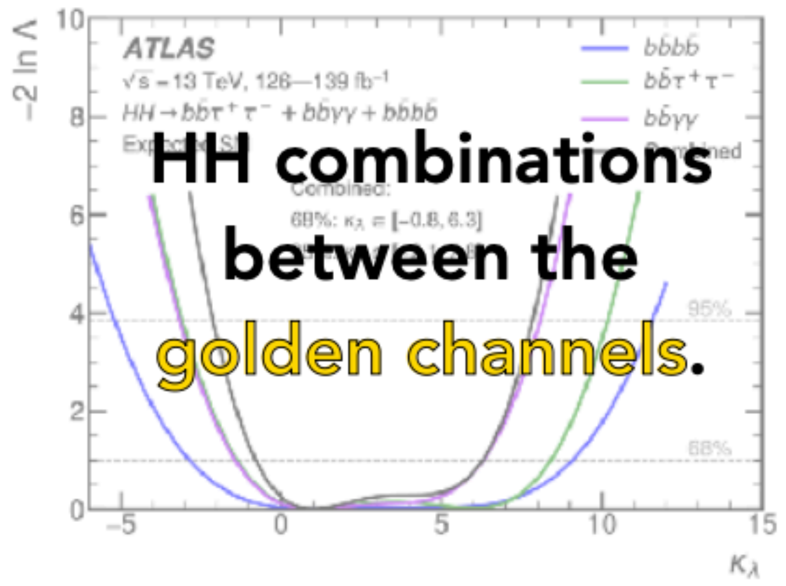
- With the **full Run 2 analyses**, the sensitivity to the HH production has improved of a **factor 3.5** w.r.t. **partial Run 2**!

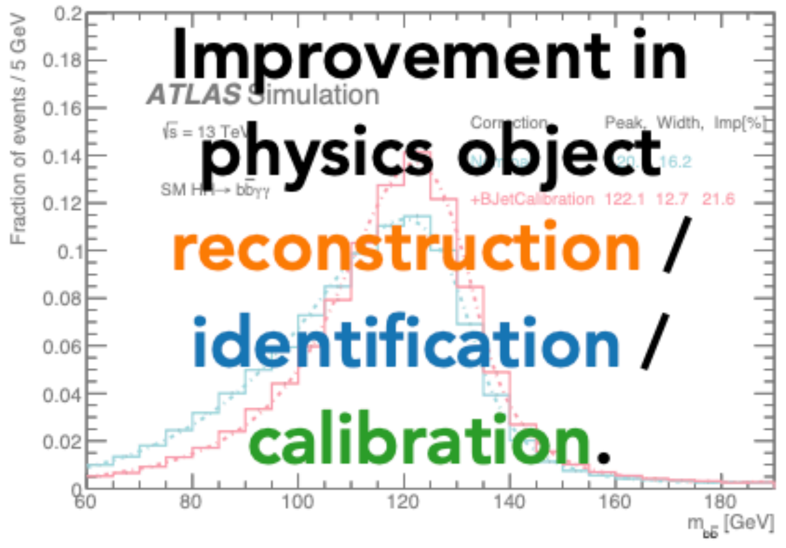
HH combination

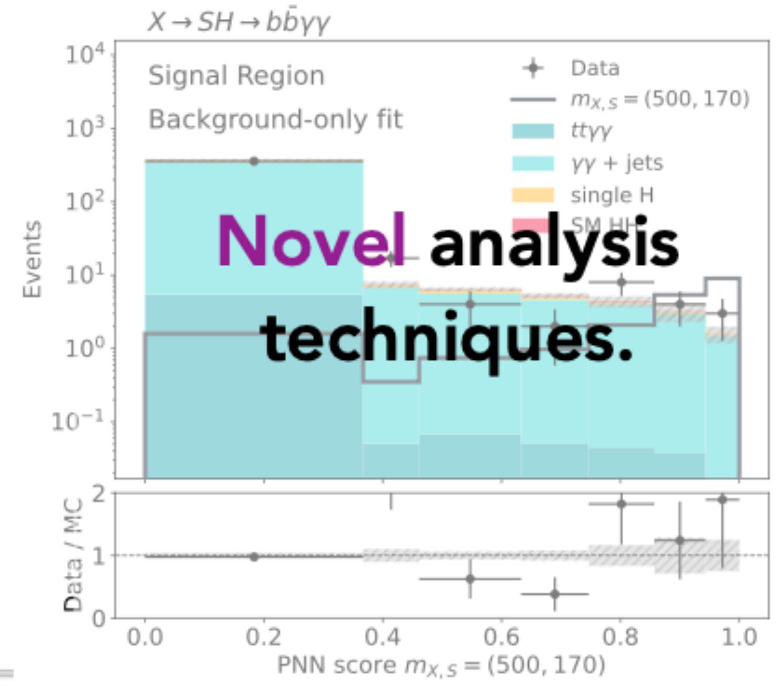
	36.1 fb^{-1}	139 fb^{-1}
Expected limit on μ_{HH}	10	2.9

→ **Additional improvement** expected from the **Legacy Run 2 analyses**!

- According to the **current** projections, we are expecting to have a **4.9σ observation** of **HH production** at the **end** of the **HL-LHC data-taking**!



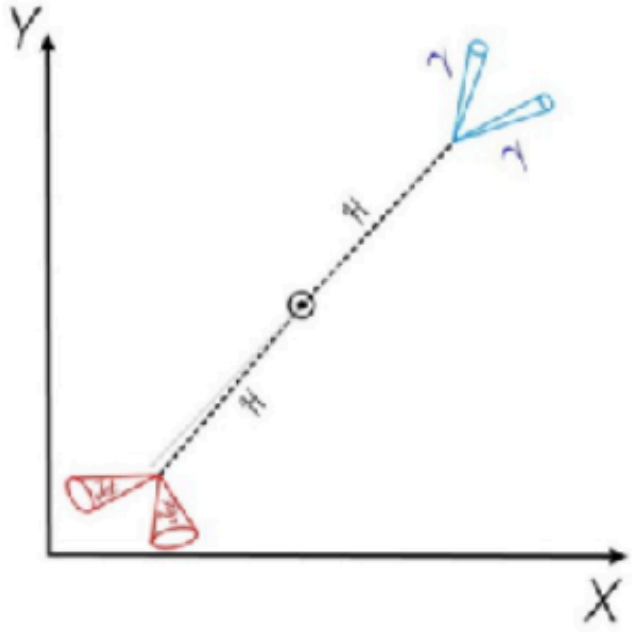




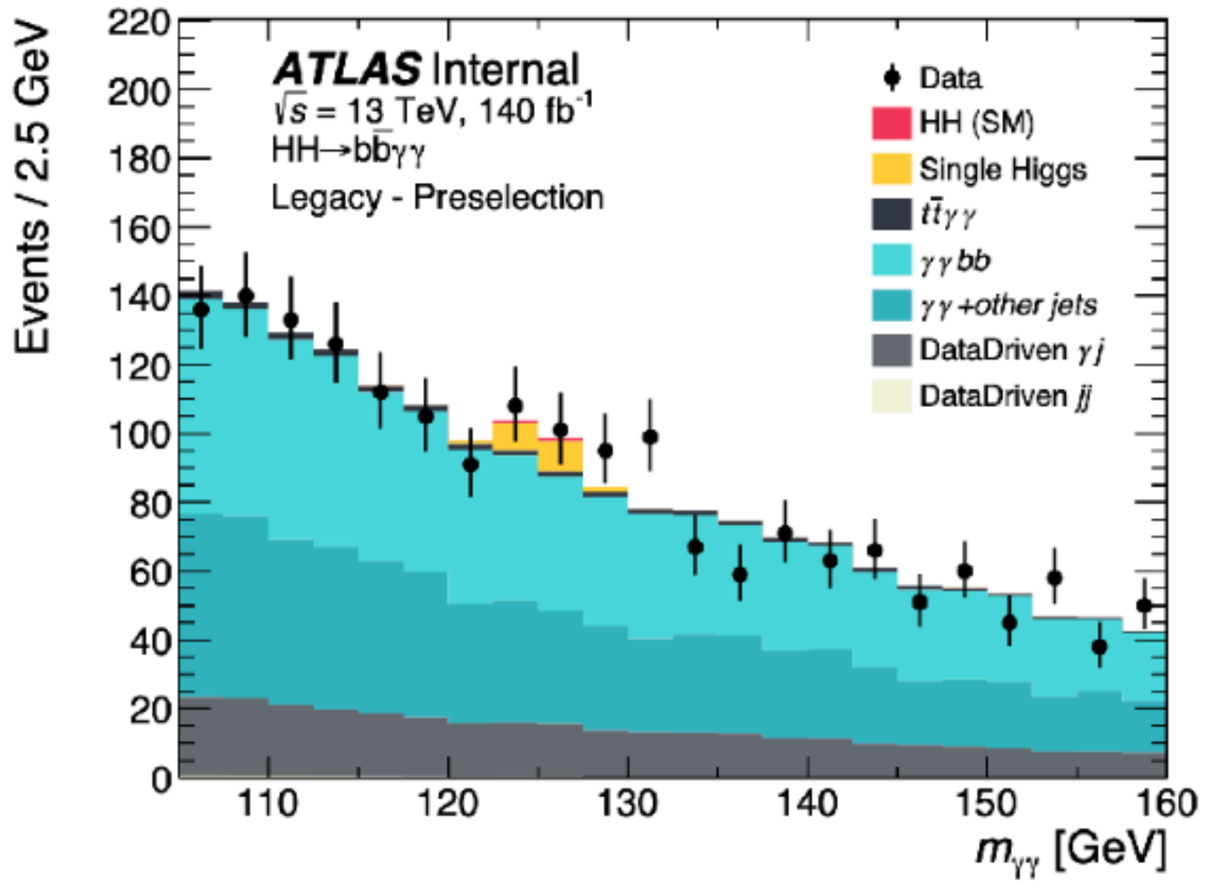
- **Run 3** represents a **unique opportunity** for **HH searches**!
  - → **High momentum** and **increasing interest** from many teams / institutions!
- There are **many aspects** that we can (and should) **explore** to try and **reach** a **first hint of observation of HH production** already with the **full Run 3 dataset**.

Personal contributions

- A. D'Onofrio, B. Di Micco, F. Montereali, R. Orlandini.
- **Contributions**: focused on the **Legacy Run 2** analysis and the **outlook for Run 3**.
  - Development & optimization of the kinematic fit.



- A. D'Onofrio.
- **Contributions**: focused on the **Legacy Run 2** analysis.
  - Background modelling & background decomposition.



  - Theoretical systematic uncertainties.
  - Editing of the Supporting documentation.
  - Analysis coordination.

Thanks for listening!

Back-up

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

In addition to interpreting the statistical results in terms of constraints on the coupling modifiers κ_λ and κ_{2V}, the **Legacy** $HH \to b\bar{b}\gamma\gamma$ 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 (* = modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1*	5.11	1.10	0	0	0
2*	6.84	1.03	$\frac{1}{6}$	$-\frac{1}{3}$	0
3	2.21	1.05	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$
4*	2.79	0.90	$-\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$
5	3.95	1.17	$-\frac{1}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$
6*	−0.68	0.90	$-\frac{1}{6}$	$\frac{1}{2}$	0.25
7	−0.10	0.94	1	$\frac{1}{6}$	$-\frac{1}{6}$

\+ 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	$(\Phi^\dagger\Phi)^3$
$c_{H\Box}$	$\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$

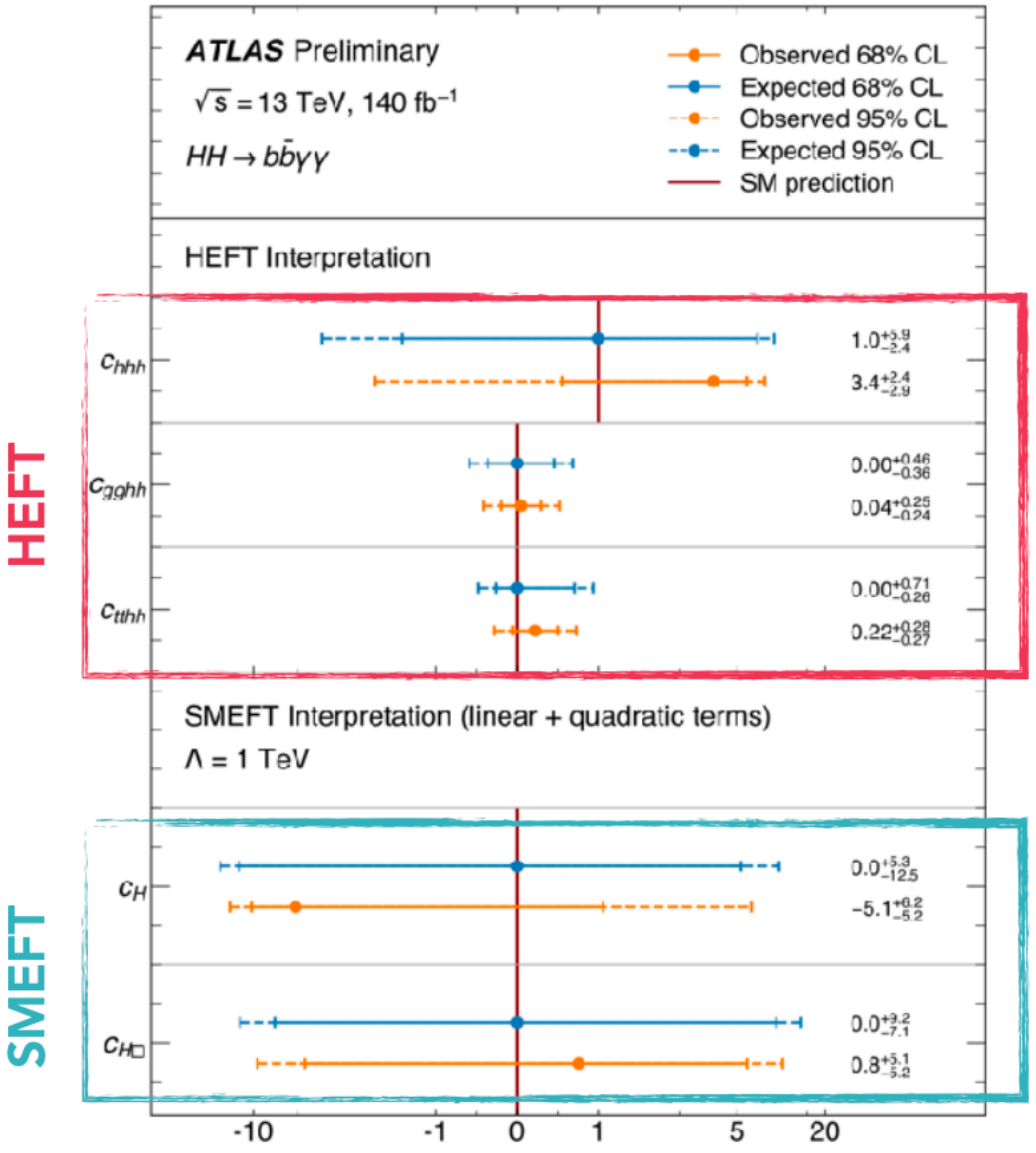
\+ 2-dimensional constraints on $(C_H, C_{H\Box})$!

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

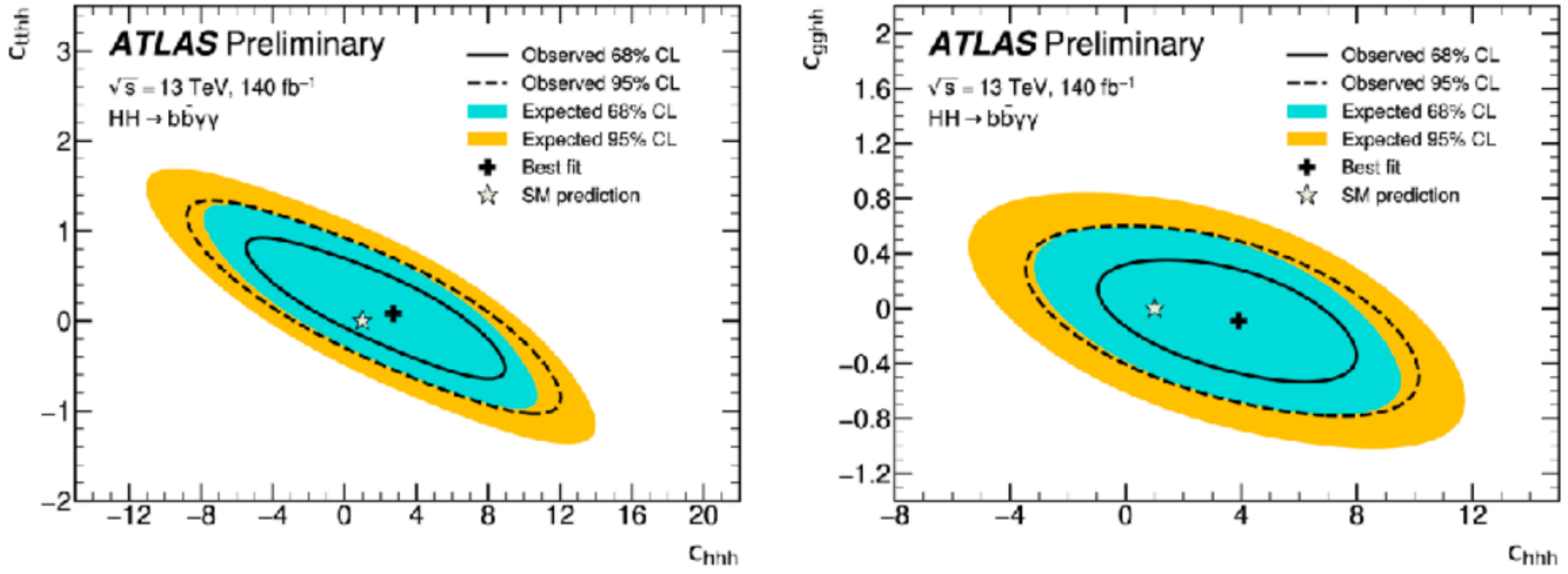
EFT interpretations for the Legacy $HH \rightarrow b\bar{b}\gamma\gamma$

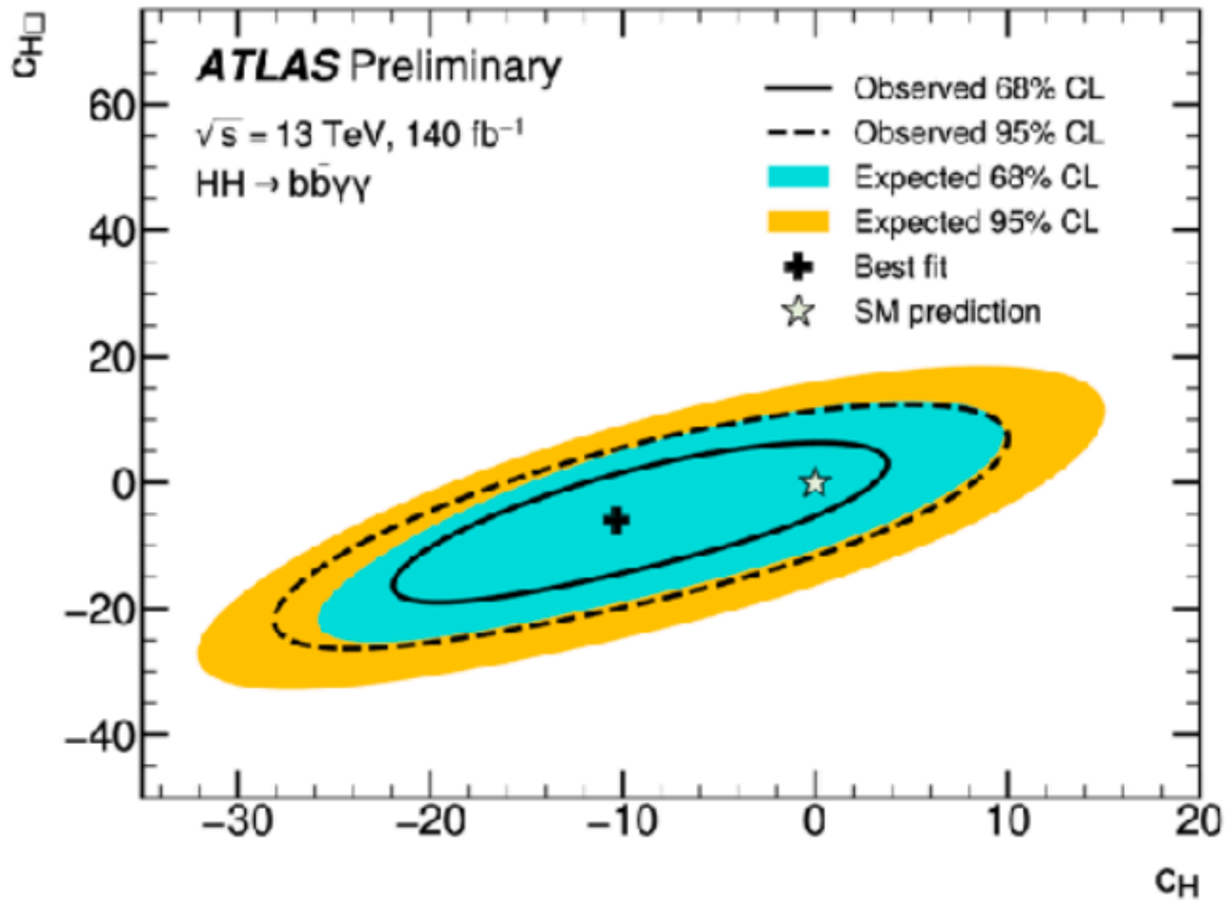
A summary of the constraints on the EFT couplings set by the Legacy $HH \rightarrow b\bar{b}\gamma\gamma$ analysis is presented here.

1-dimensional measurements of the HEFT and SMEFT couplings.



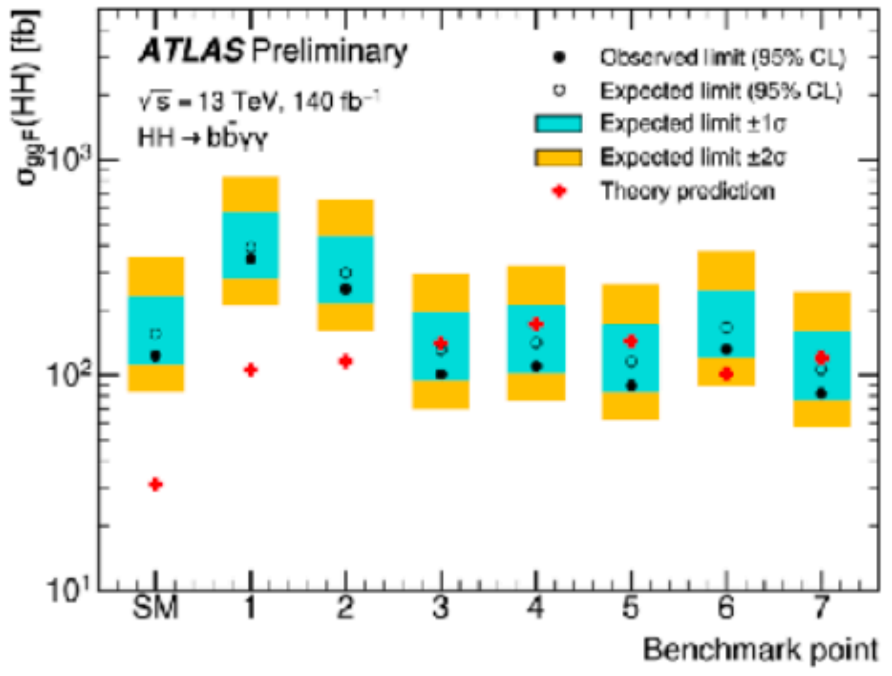
2-dimensional measurement in the (c_{hhh}, c_{gghh}) and (c_{hhh}, c_{tthh}) planes.





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

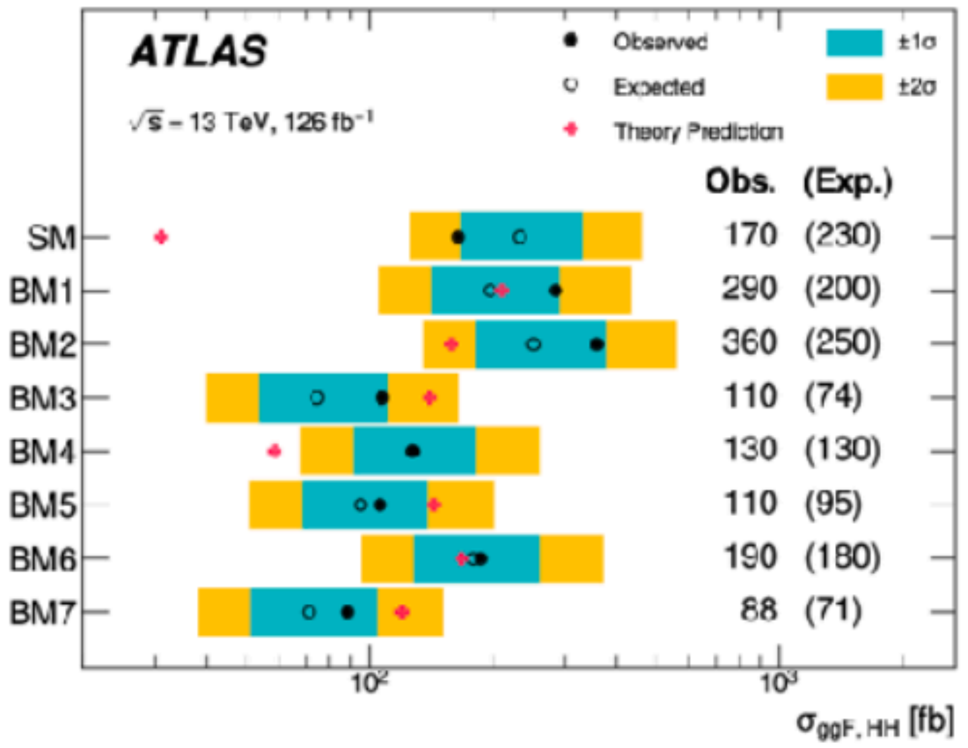
Upper limits on σ for 7 benchmark points.



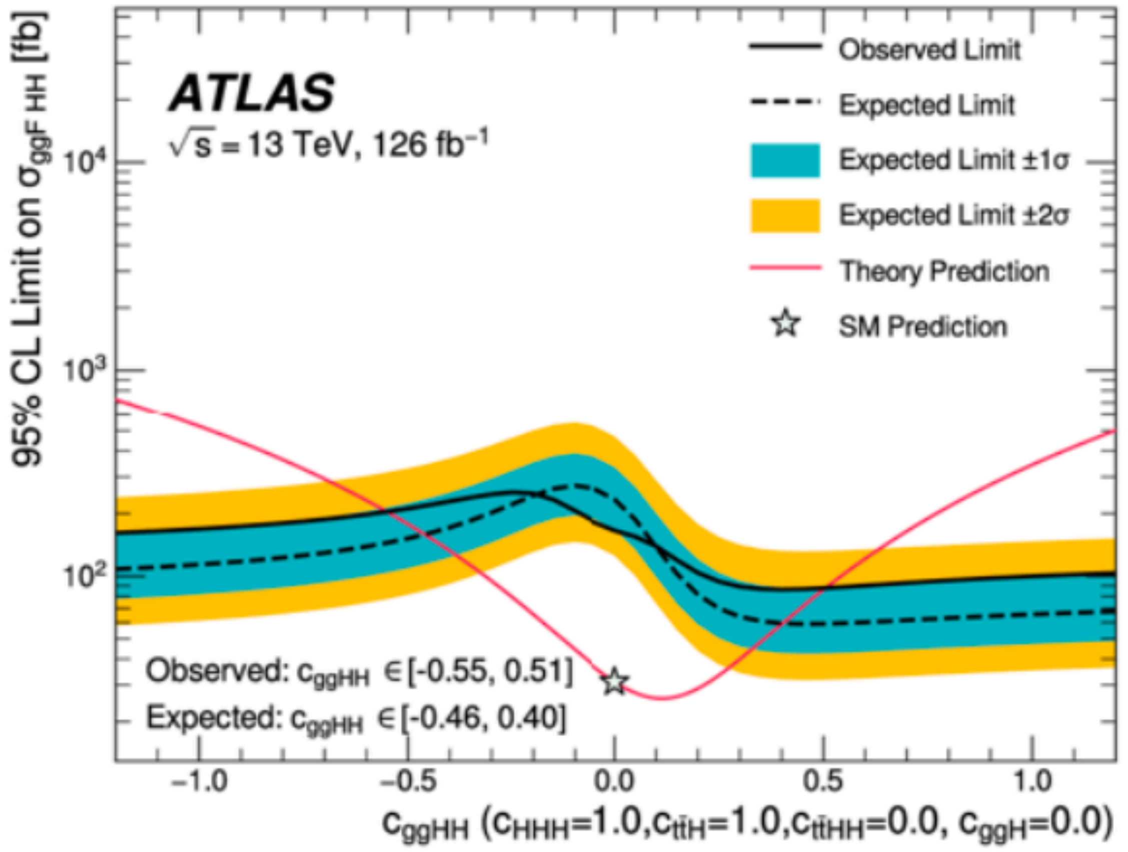
EFT interpretations for the Legacy $HH \to b\bar{b}\gamma\gamma$

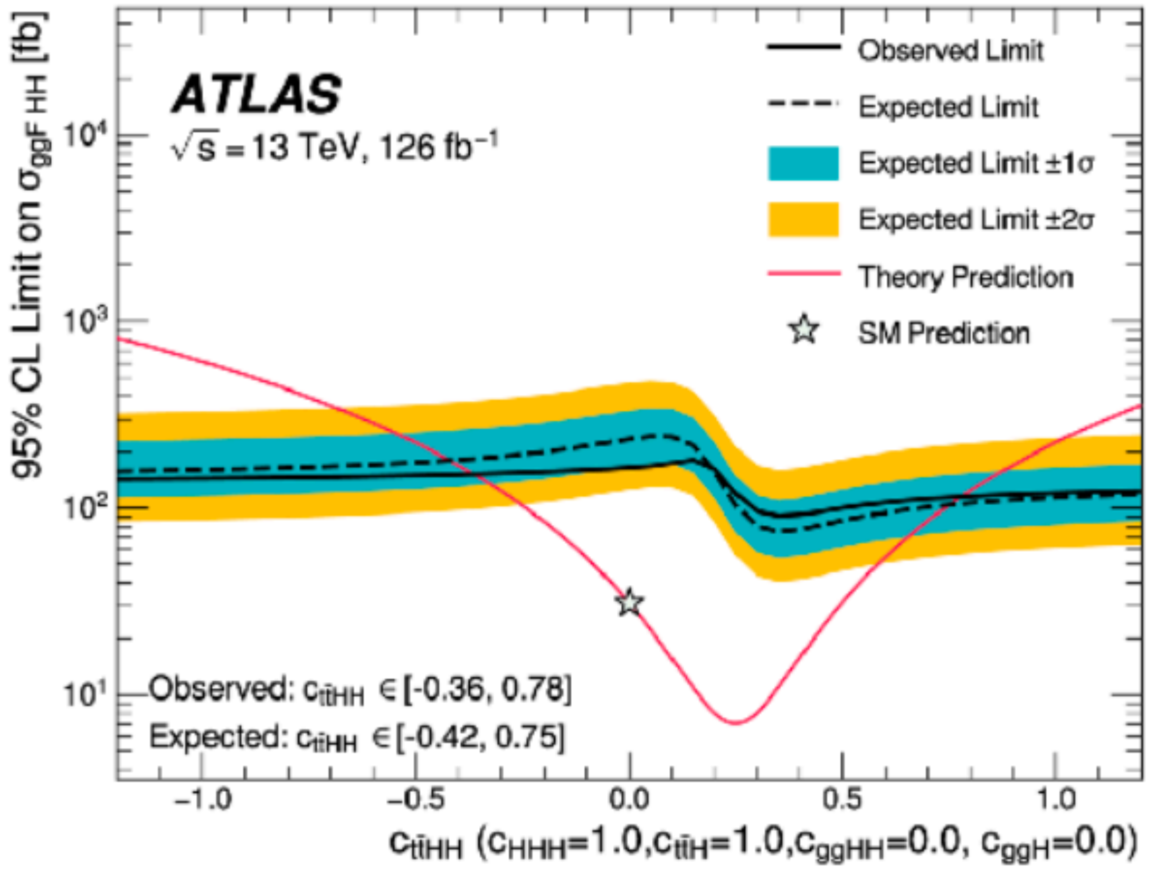
The new $HH \to b\bar{b}b\bar{b}$ **analysis** with **full Run 2** data has also provided an interpretation of their statistical results in both the **HEFT** and **SMEFT** frameworks!

Upper limits on σ for 7 benchmark points.



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

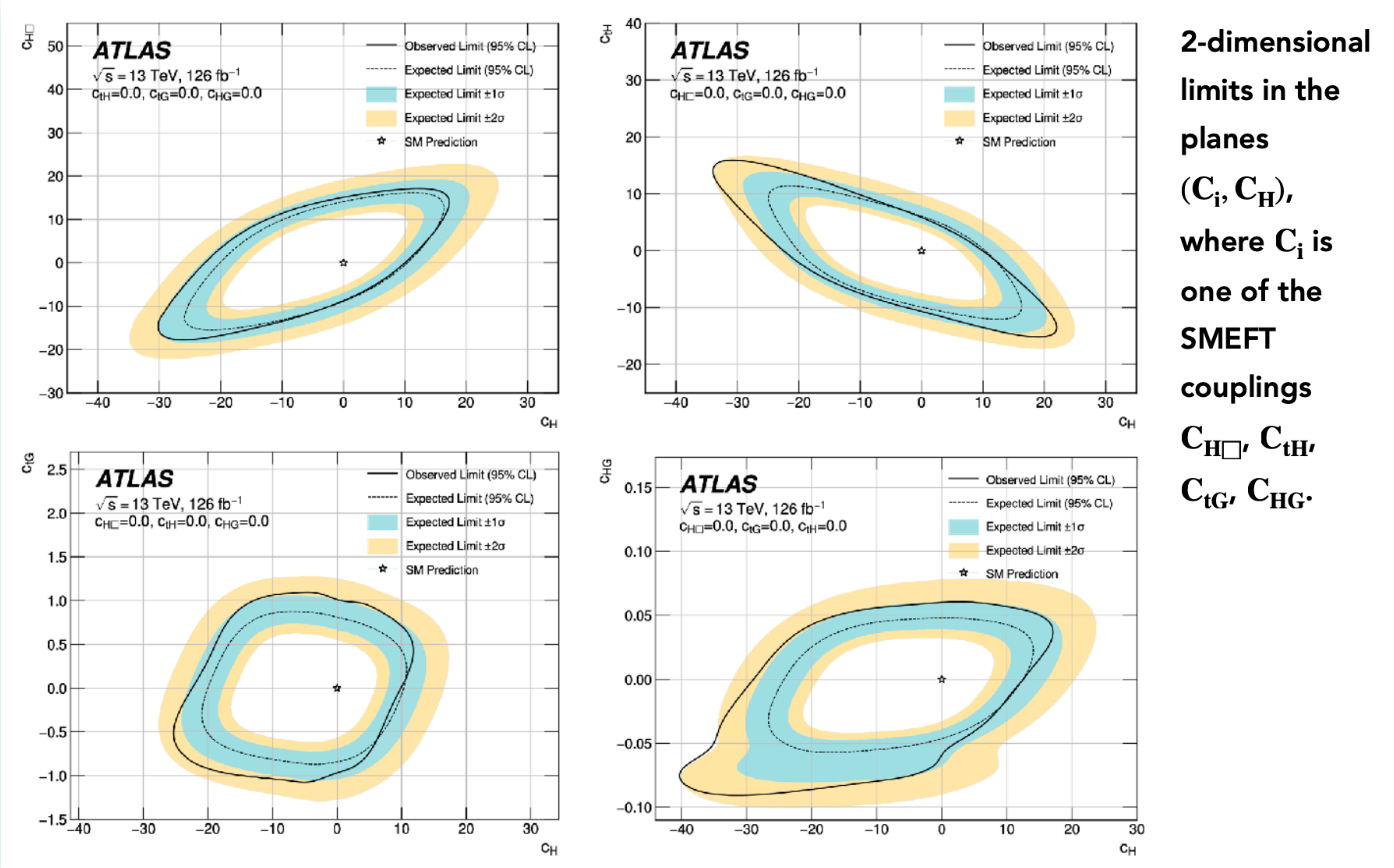




Parameter	Expected Constraint		Observed Constraint	
	Lower	Upper	Lower	Upper
c_H	−20	11	−22	11
c_{HG}	−0.056	0.049	−0.067	0.060
$c_{H\Box}$	−9.3	13.9	−8.9	14.5
c_{tH}	−10.0	6.4	−10.7	6.2
c_{tG}	−0.97	0.94	−1.12	1.15

1-dimensional limits on the SMEFT couplings.

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



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

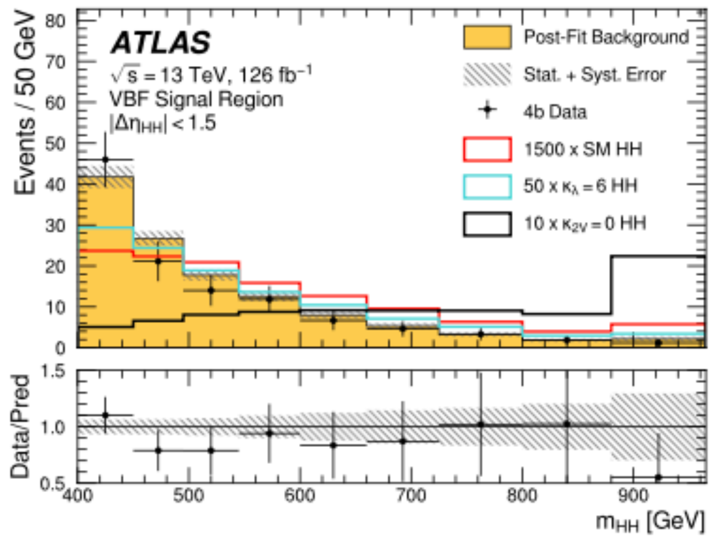
Combination of double Higgs searches

- Many decay modes are possible for a single Higgs boson.

➡ A **very rich variety of signatures** is available to probe the **production of HH pairs**!

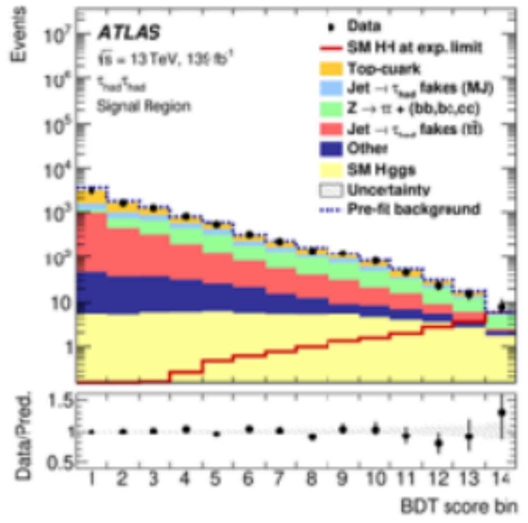
- Three **golden channels**:

$HH \to b\bar{b}b\bar{b}$



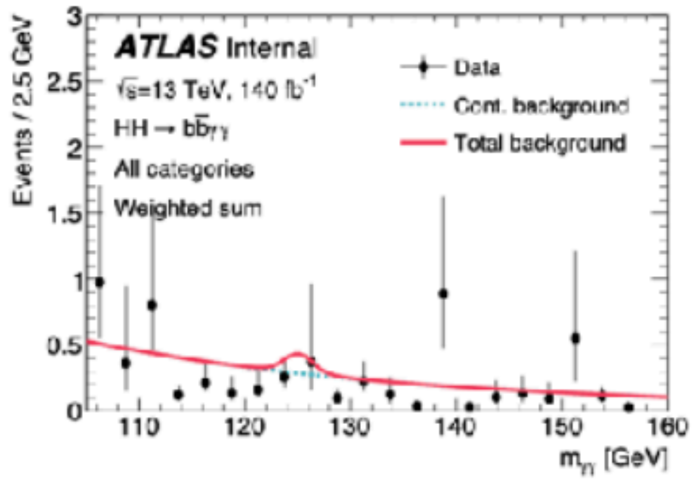
- **Highest cross-section**, but **very challenging bkg. estimation.**
- Sensitive for **boosted m_{HH}**.
- Excellent probe for **VBF HH** production and κ_{2V}!

$HH \to b\bar{b}\tau\tau$



- **Good compromise** between bkg. and branching fraction.
- Best sensitivity to medium m_{HH} values.
- Best channel to **observe HH** in **SM-like scenario**!

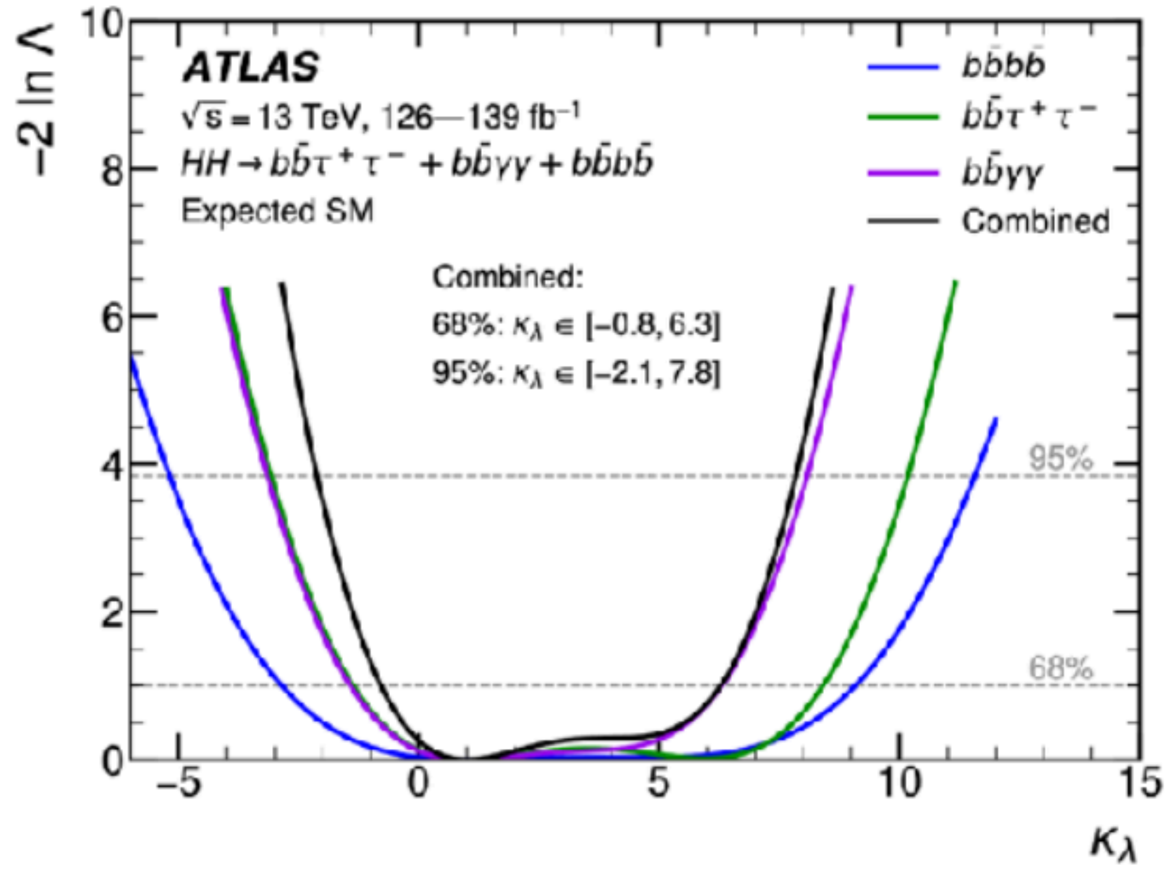
$HH \to b\bar{b}\gamma\gamma$

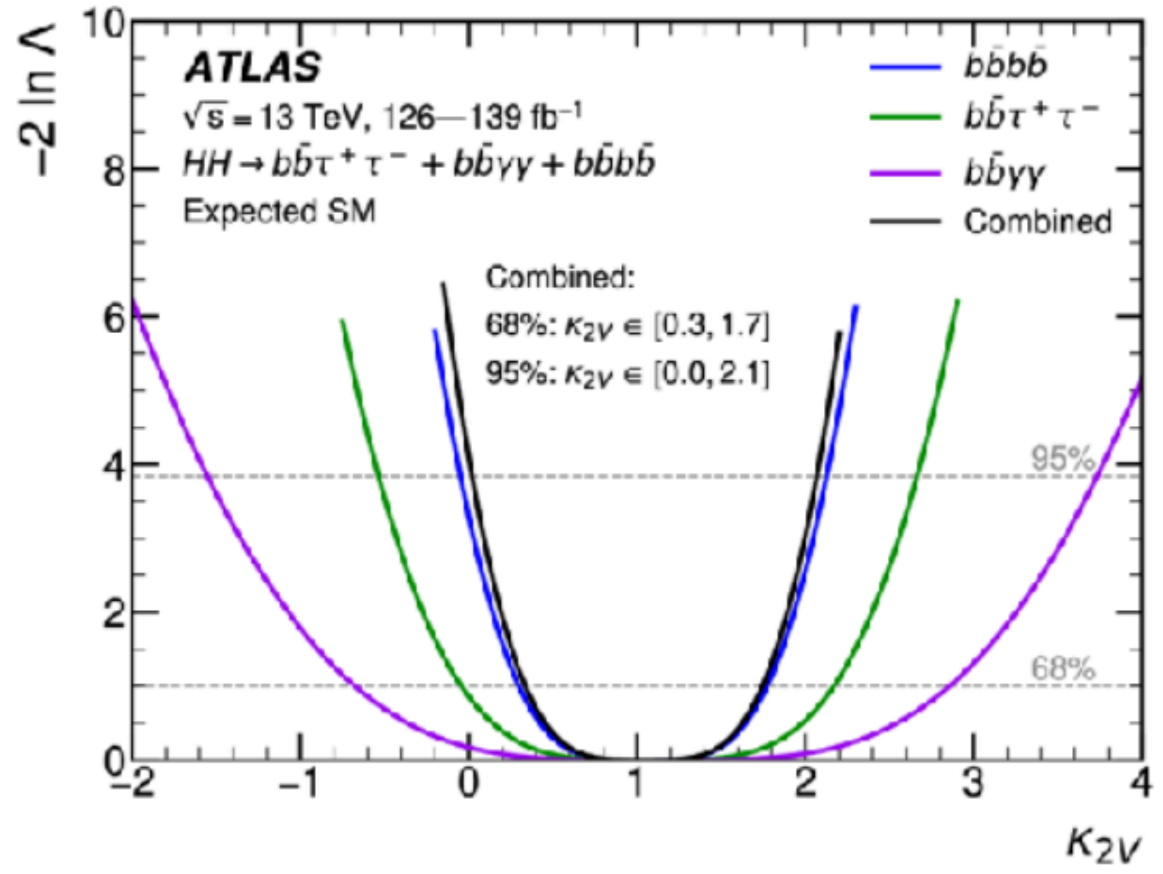


- Very clean $H \to \gamma\gamma$ signature.
- Especially sensitive to **low m_{HH} values.**
- **Unique handle** to κ_λ!

The **combination** of the **HH final states** offers a **great opportunity**!

- **Takes advantage** of their **complementarity**.
- Extracts the **best possible sensitivity** to **SM-like** and **anomalous HH production**!

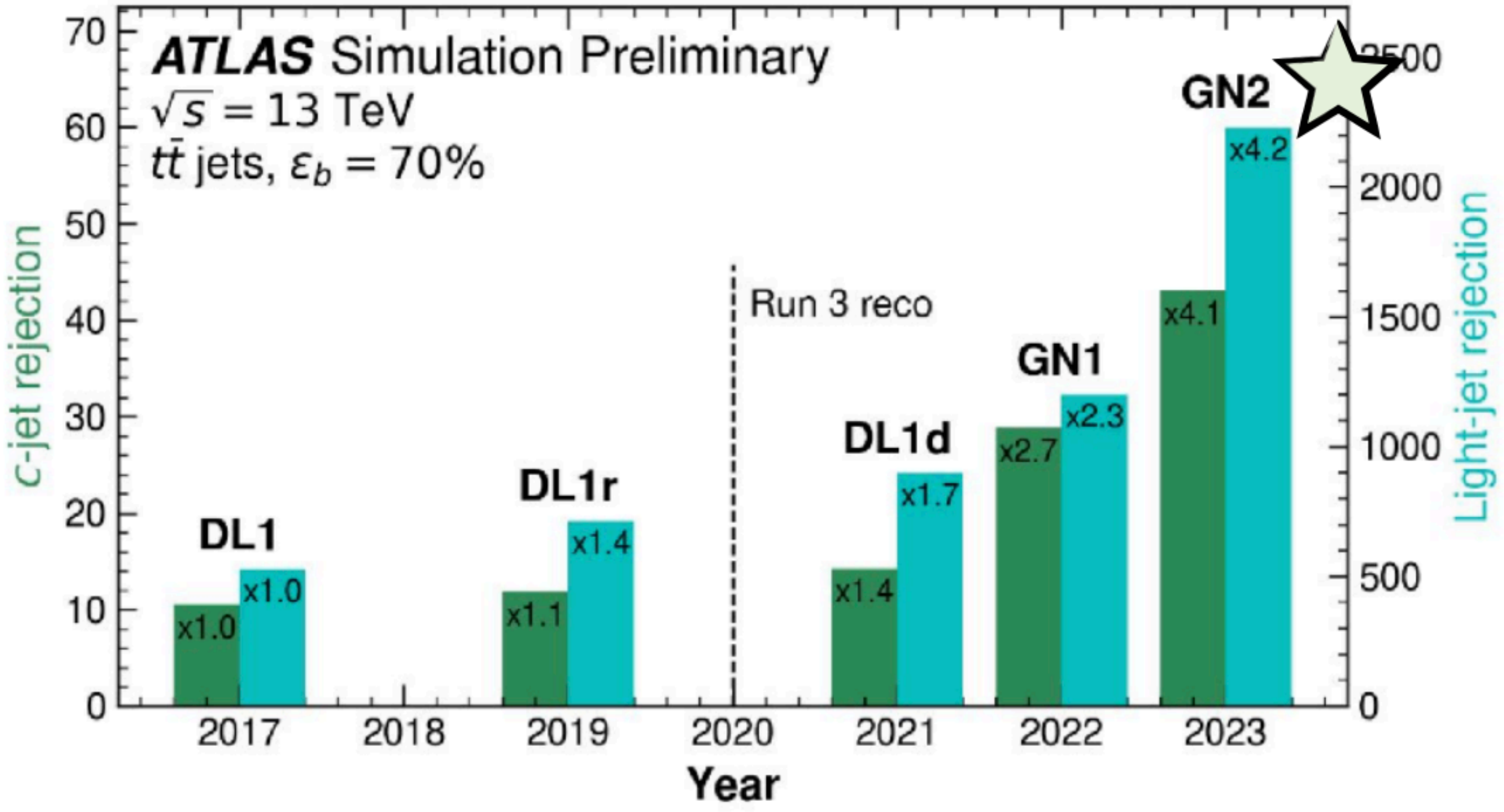




Run 3 improvements from the CP side

Many improvements are foreseen for the **reconstruction** / **identification** / **calibration** of **physics objects relevant for HH searches**!

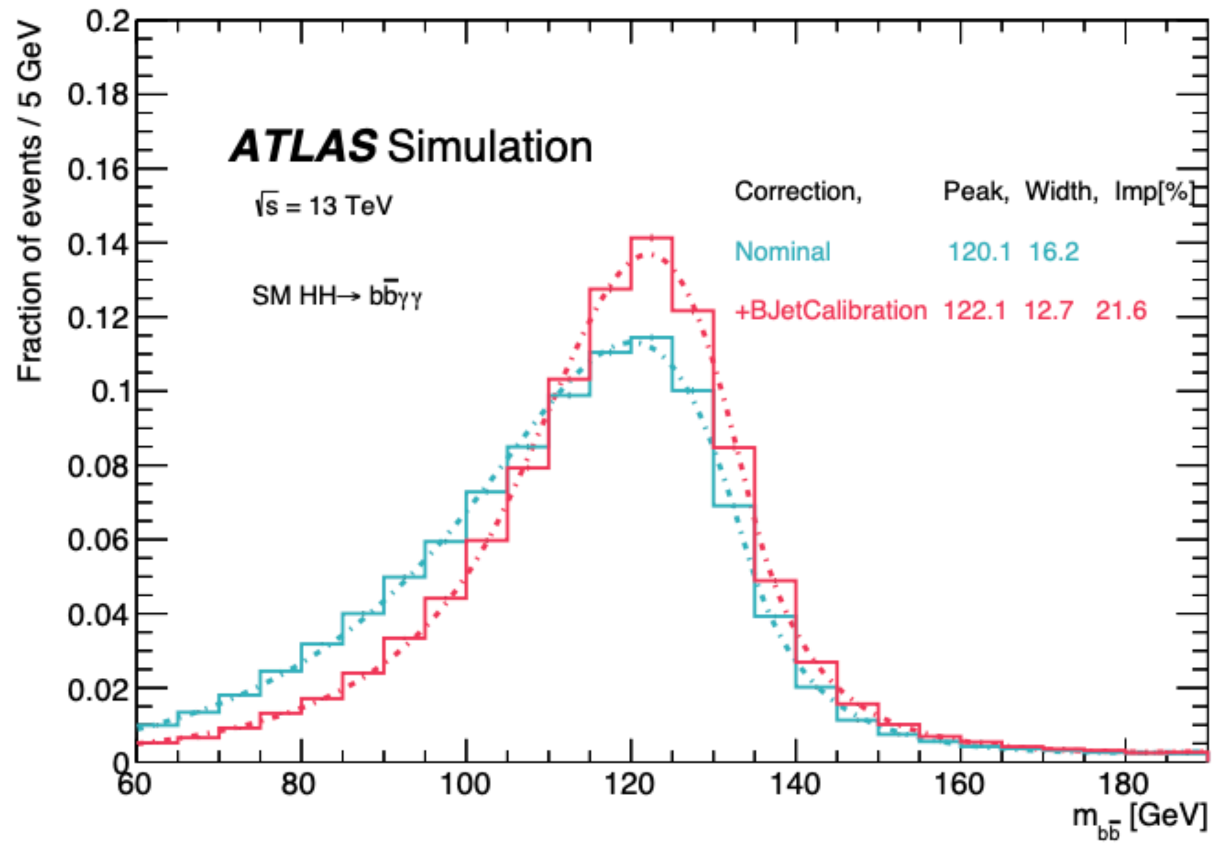
- A boost in the performances of jet taggers is seen in the new generation of GNN-based algorithms developed by ATLAS.



- Might help to **sharpen** our **sensitivity** to HH production for **Run 3** analyses!
- Example: large improvement on the boosted $HH \to 4b$ analysis by CMS after the **adoption** of their new **ParticleNet-based tagger**.

	35.9 fb^{-1}	138 fb^{-1}
Expected limit on μ_{HH}	114	5.1

- The **b-jet kinematic variables** play a special role in discriminating the HH signals from the backgrounds.



The μ-in-jet + PtReco b-jet calibration improves the $\mathbf{m_{bb}}$ **resolution** of **~22%**, and the expected HH **significance** of **7%**. for the $b\bar{b}\gamma\gamma$ channel!

- Can we do better?
  - **Dedicated MC calibration** for b-jets?
  - Constraining the $H \to b\bar{b}$ **4-momentum** with a **kinematic fit**?
    - Interesting for the $b\bar{b}\gamma\gamma$ channel, since it allows to exploit the **excellent 4-momentum resolution** for the **di-photon decay**.
    - Explored for the **previous ggF Run 2 analysis**, and **optimization ongoing** in light of the future Run 3 analysis!

Outlook for Run 3: the kinematic fit

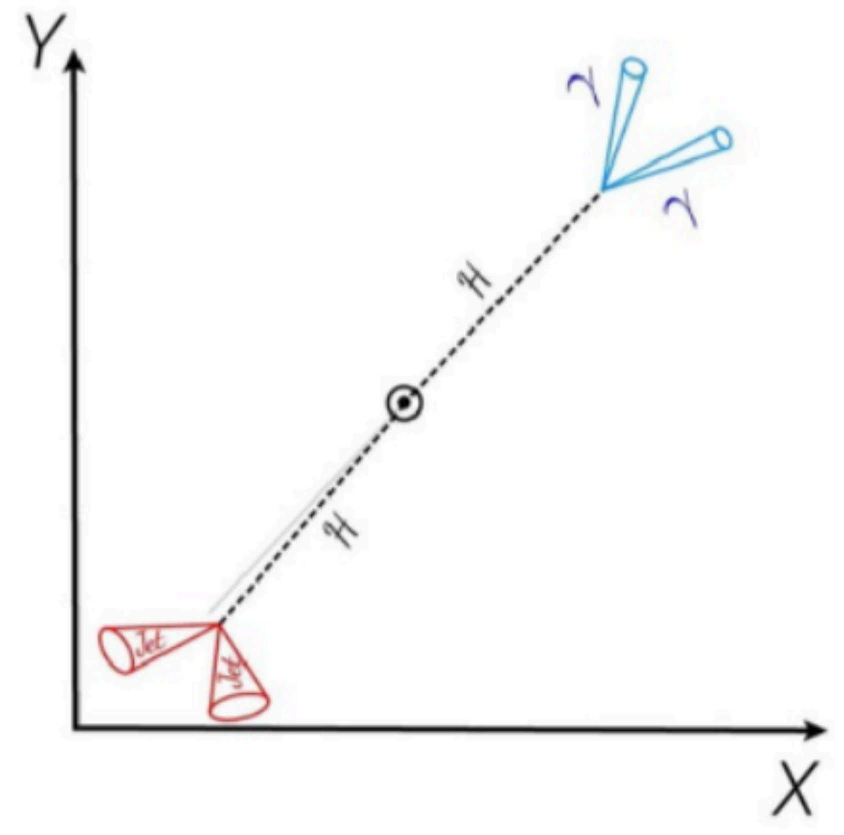
- A **promising tool** for improving the resolution of the **4-momentum** of the **$H \to b\bar{b}$ decay** is the **kinematic fit**.

  ➡ By assuming that the the $\mathbf{p_T}$ of the $b\bar{b}\gamma\gamma$ system is zero, constrains the **$H \to b\bar{b}$ kinematics** by exploiting the **excellent resolution** for the 4-momentum of the **$H \to \gamma\gamma$ decay**!

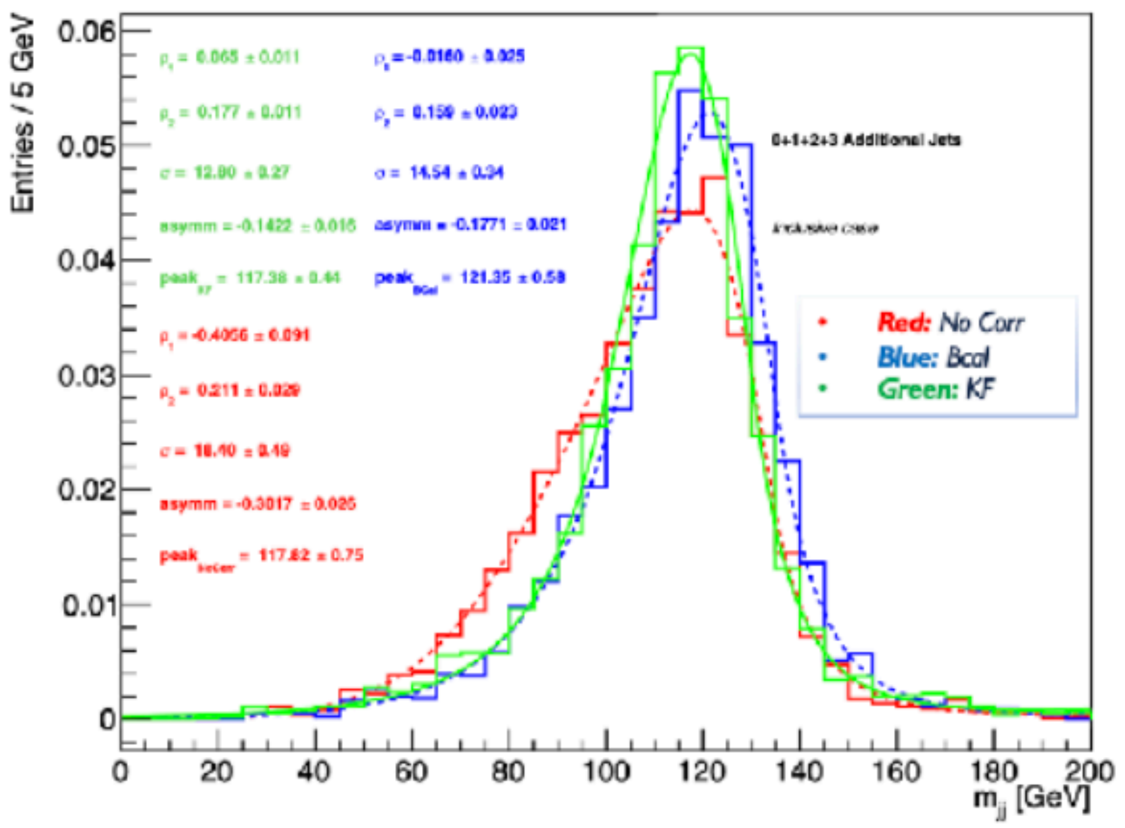
- **Minimization of a per event-likelihood**:

$$-2\log(\mathcal{L}) = \sum_{j=jets}\left[-2\,log\left[f\left(\frac{E_{fit}-E_{Event}}{E_{Event}}\right)\right] - 2\,log\left[f\left(\frac{pT_{fit}-pT_{Event}}{pT_{fit}}\right)\right]\right]$$

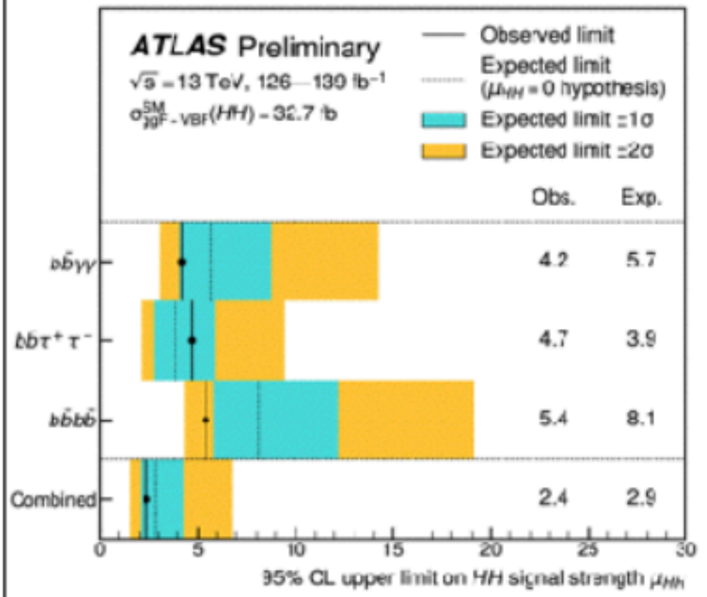
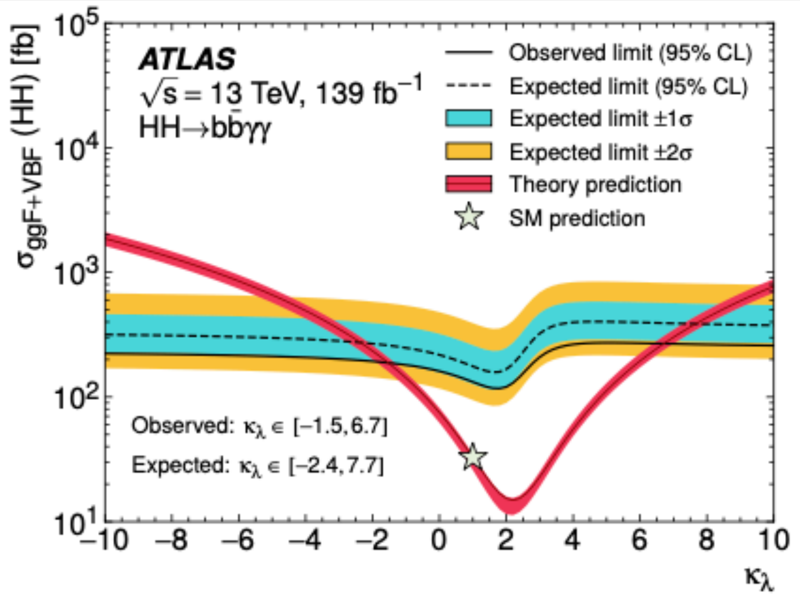
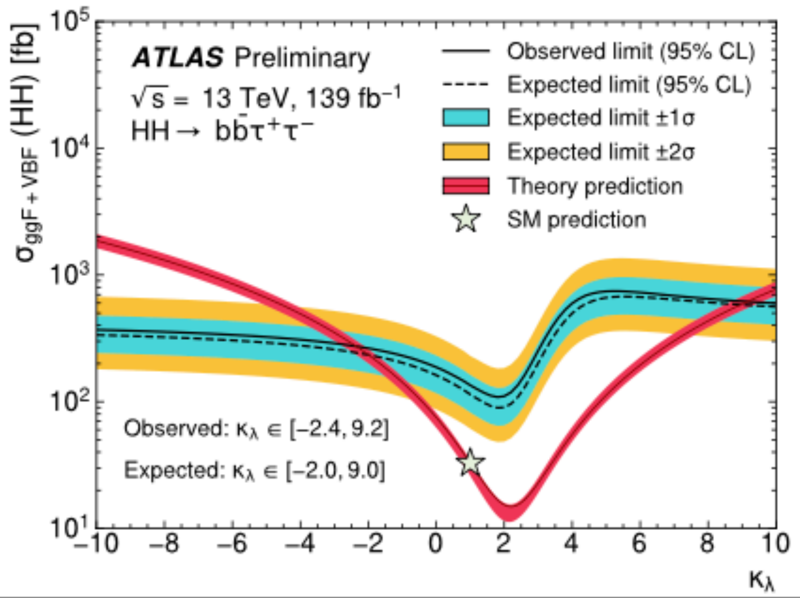
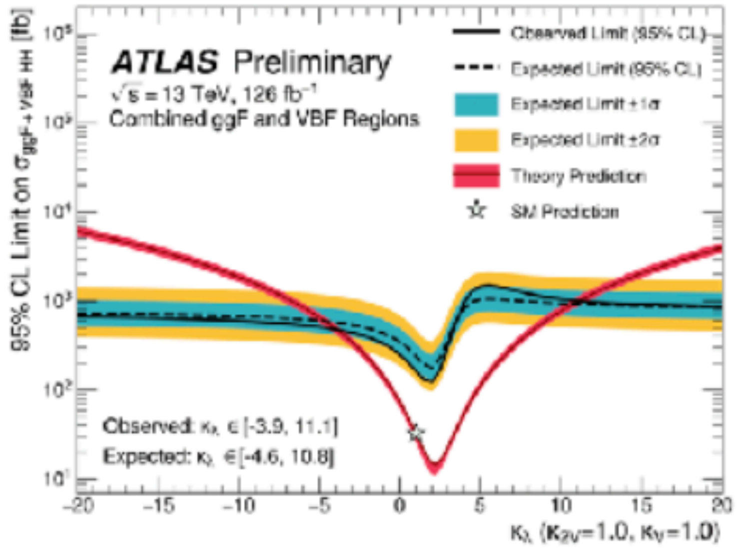
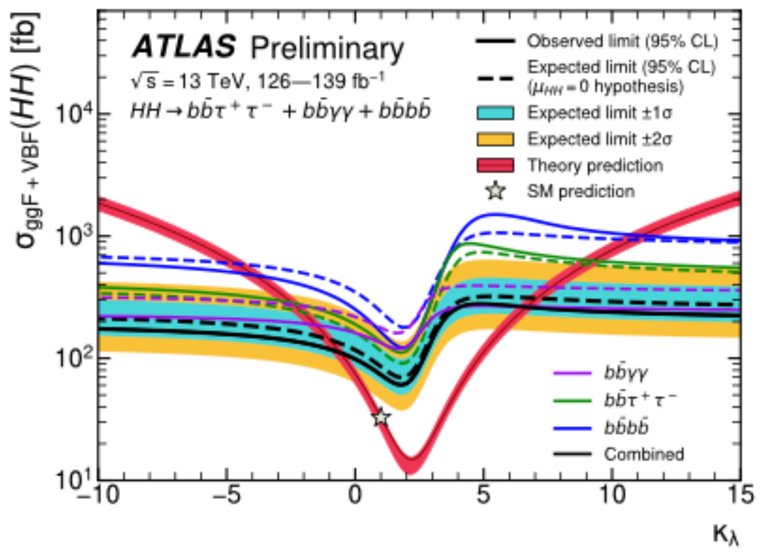
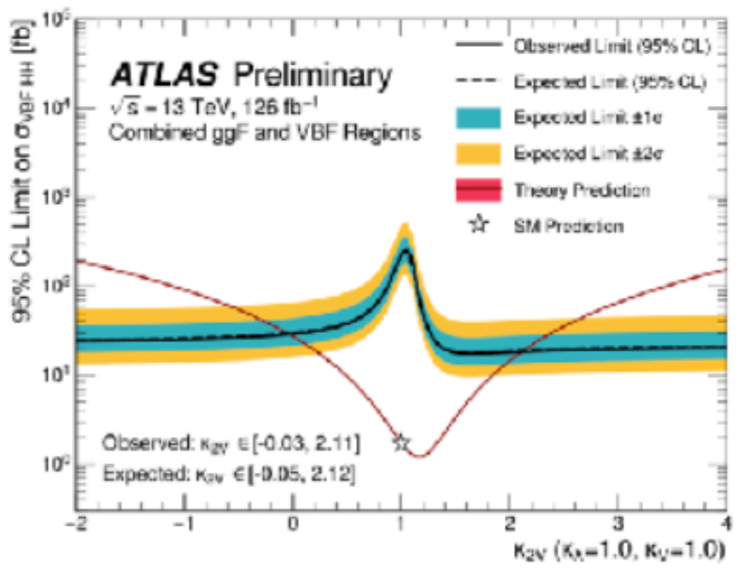
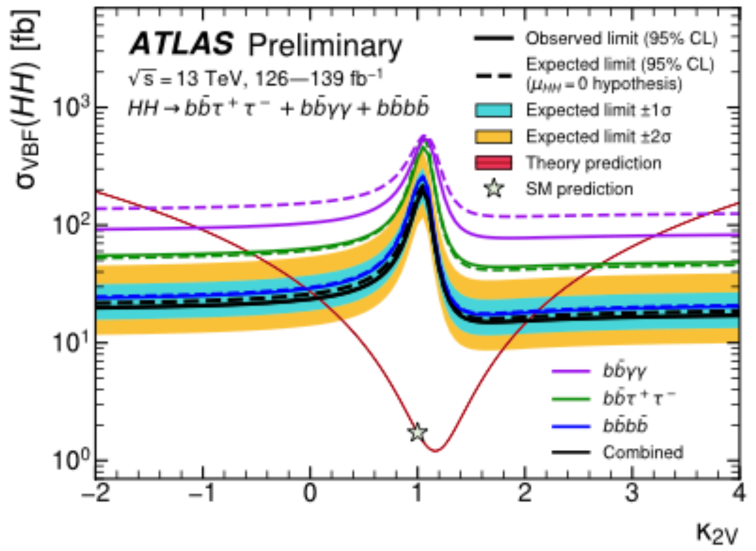
$$+\sum_{j=\gamma}\left[\sum\left(\frac{\Omega^{*}_{j,i}-\Omega_{j,i}}{\sigma_{\Omega_i}}\right)^2\right] - 2\,\lambda\,\log[f_3(p_X^{HH})] - 2\,\lambda\,log[f_3(p_Y^{HH})]$$



- The kinematic fit, applied on top of the μ-in-jet + `PtReco` corrections, improves the **$m_{b\bar{b}}$ resolution** of an **additional 12%**, and of **more than 30%** w.r.t. the **nominal jet calibration**!

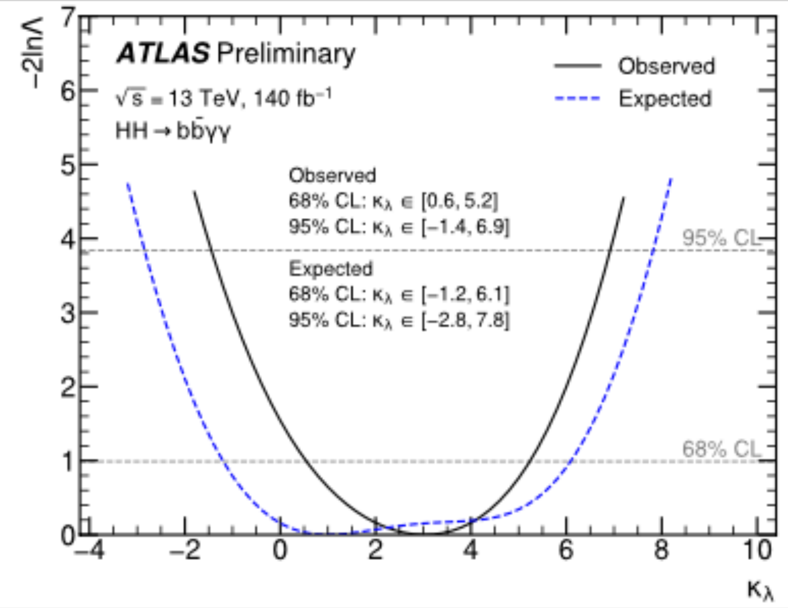
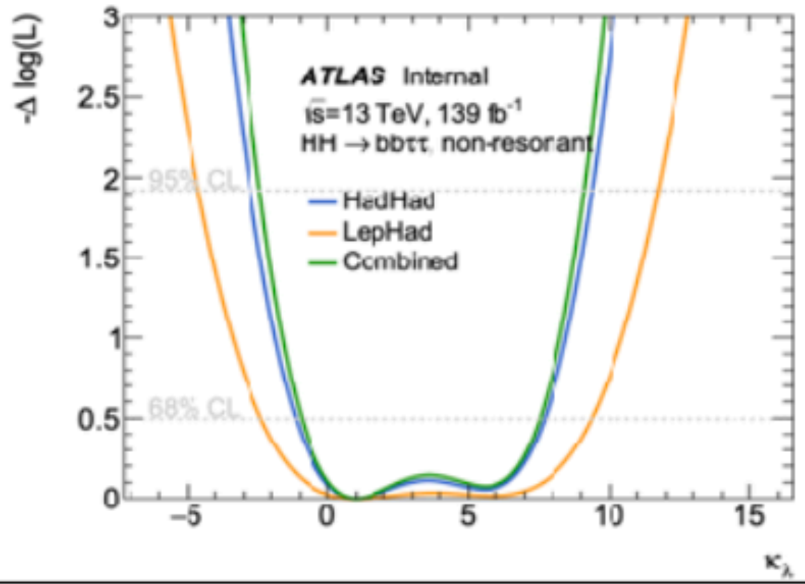
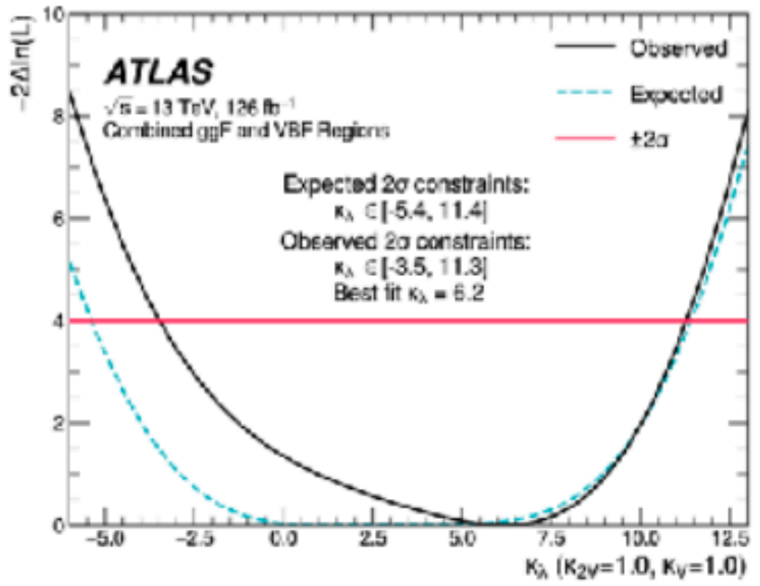
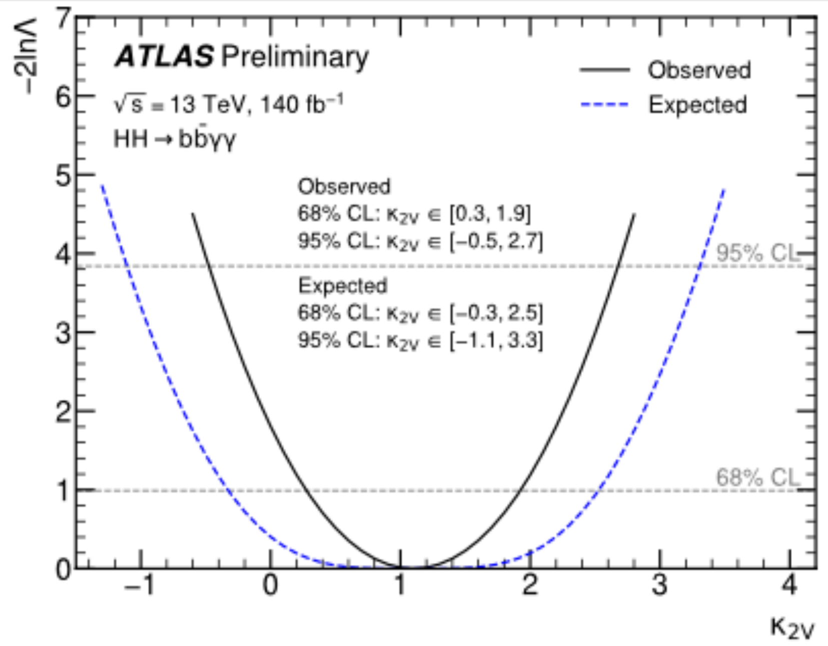
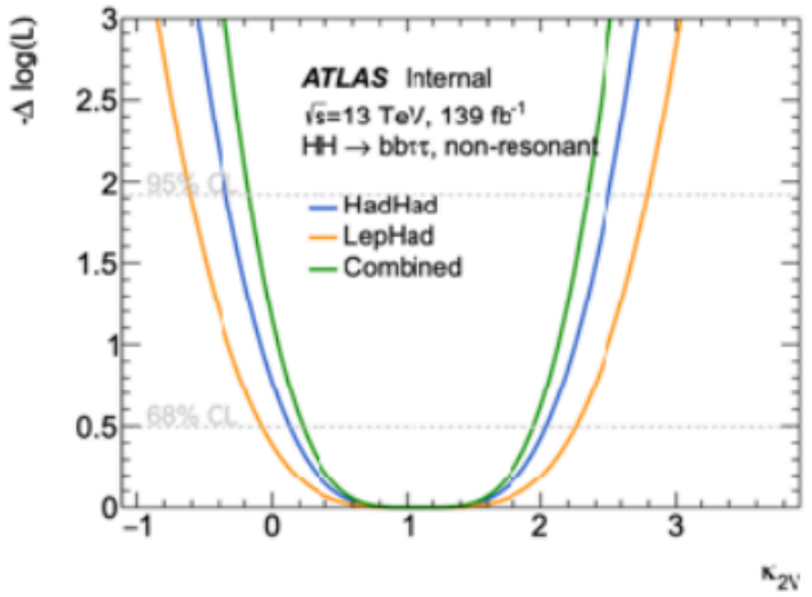
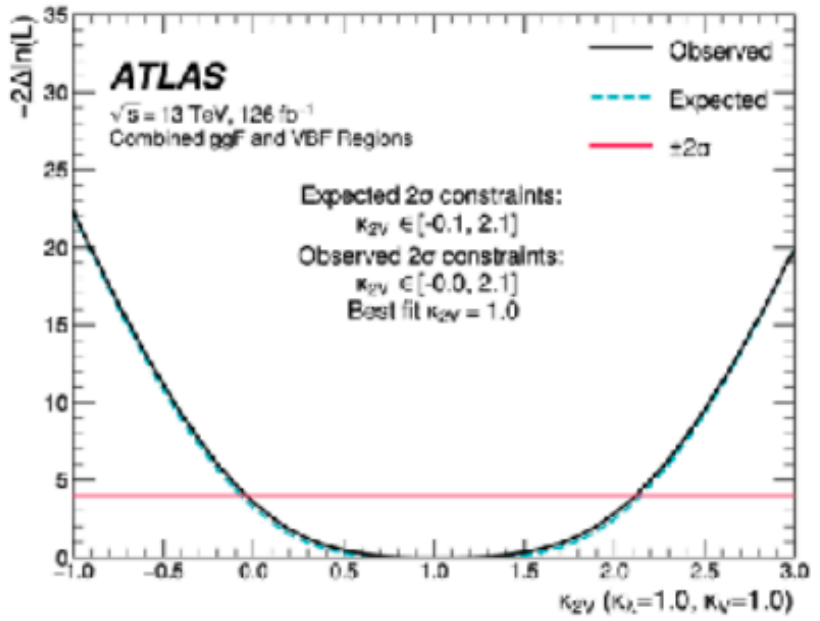


Other di-Higgs searches: ATLAS full Run 2

	HH → bbγγ	HH → bbττ	HH → bbbb	HH combination
Constraints on $\sigma_{ggF+VBF}(HH)$	**Expected** 5.7 × σ^{SM} **Observed** 4.2 × σ^{SM} [Phys. Rev. D 106 (2022) 052001]	**Expected** 3.9 × σ^{SM} **Observed** 4.7 × σ^{SM} [JHEP 07 (2023) 040]	**Expected** 8.1 × σ^{SM} **Observed** 5.4 × σ^{SM} [Phys. Rev. D 108 (2023) 052003]	 **Expected** 2.9 × σ^{SM} **Observed** 2.4 × σ^{SM} [Phys. Lett. B 843 (2023) 137745]
Constraints on κ_λ				 • Expected: $\kappa_\lambda \in [-2.1, 7.8]$ • Observed: $\kappa_\lambda \in [-0.6, 6.6]$
Constraints on κ_{2V}	-	-		 • Expected: $\kappa_{2V} \in [0.0, 2.1]$ • Observed: $\kappa_\lambda \in [0.1, 2.0]$

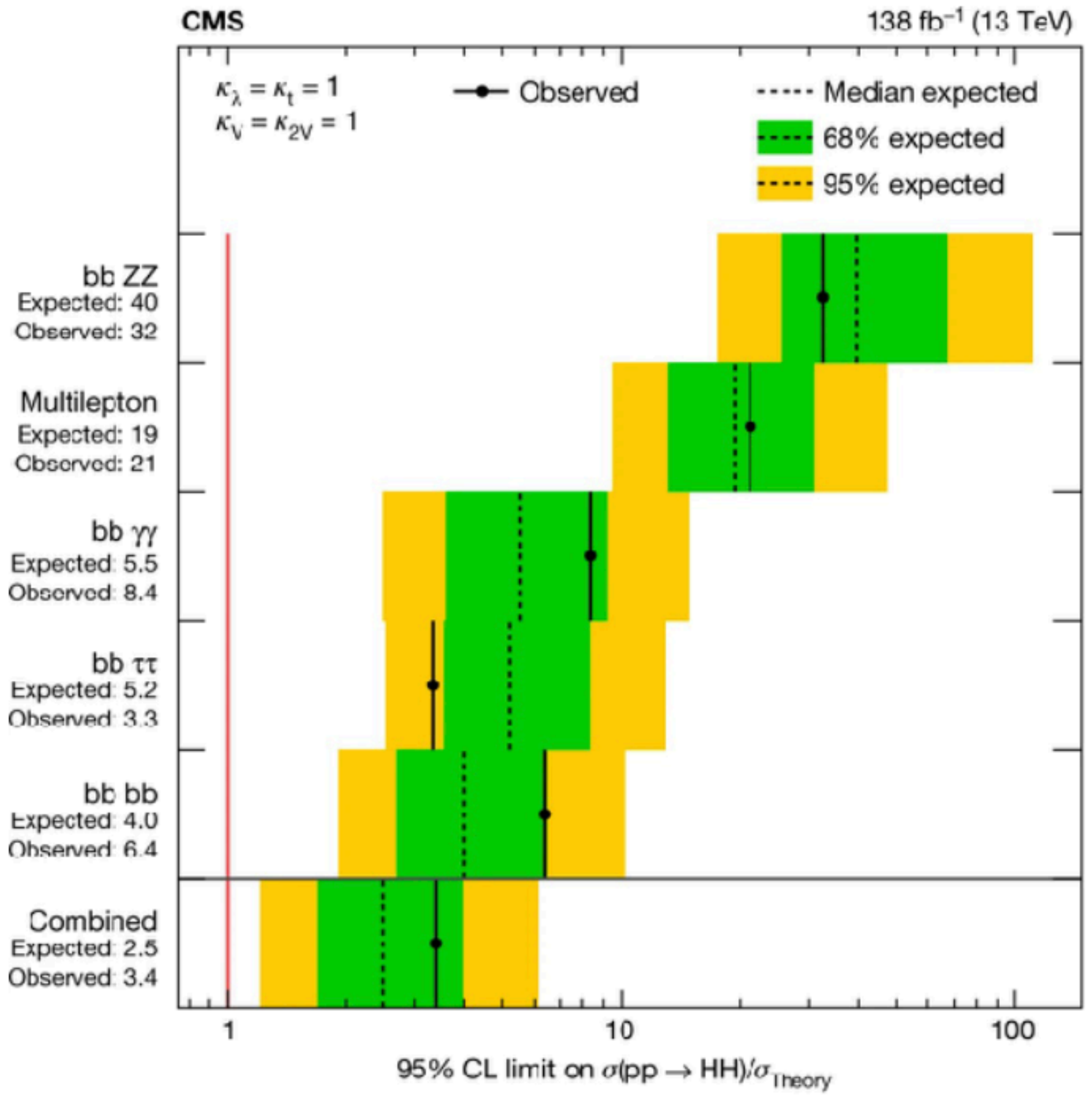
di-Higgs Run 2 Legacy *bbγγ* status report

Other di-Higgs searches:ATLAS legacy Run 2

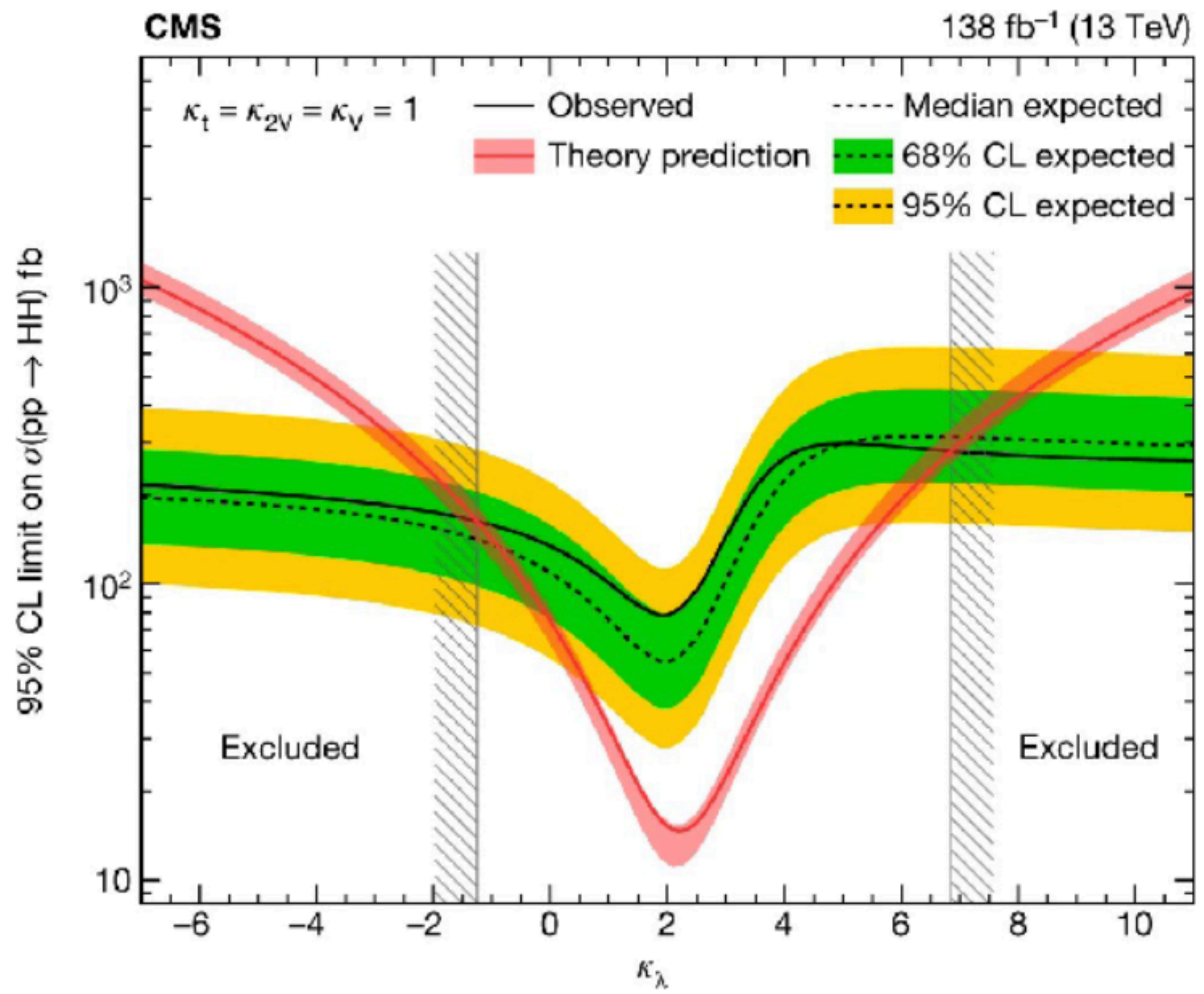
	HH → bbγγ	HH → bbττ	HH → bbbb
Status	• Analysis public for the EPS-HEP2023 Conference! • The Phase 2 approval process of the paper is ongoing.	• Aiming to be public for the Higgs2023 Conference. • Unblinding approval meeting on [15 Sept. @ the HH meeting]().	• Paper published in Phys. Rev. D ([Phys. Rev. D 108 (2023) 052003]())!
Constraints on $\sigma_{ggF+VBF}(HH)$	Expected: $5.0 \times \sigma^{SM}$ Observed: $4.0 \times \sigma^{SM}$	Expected: $3.0 \times \sigma^{SM}$ Observed: -	Expected: $8.1 \times \sigma^{SM}$ Observed: $5.4 \times \sigma^{SM}$
Constraints on κ_λ		 Expected @ 95% CL: $\kappa_\lambda \in [-2.4, 9.1]$	
Constraints on κ_{2V}		 Expected @ 95% CL: $\kappa_{2V} \in [-0.2, 2.3]$	

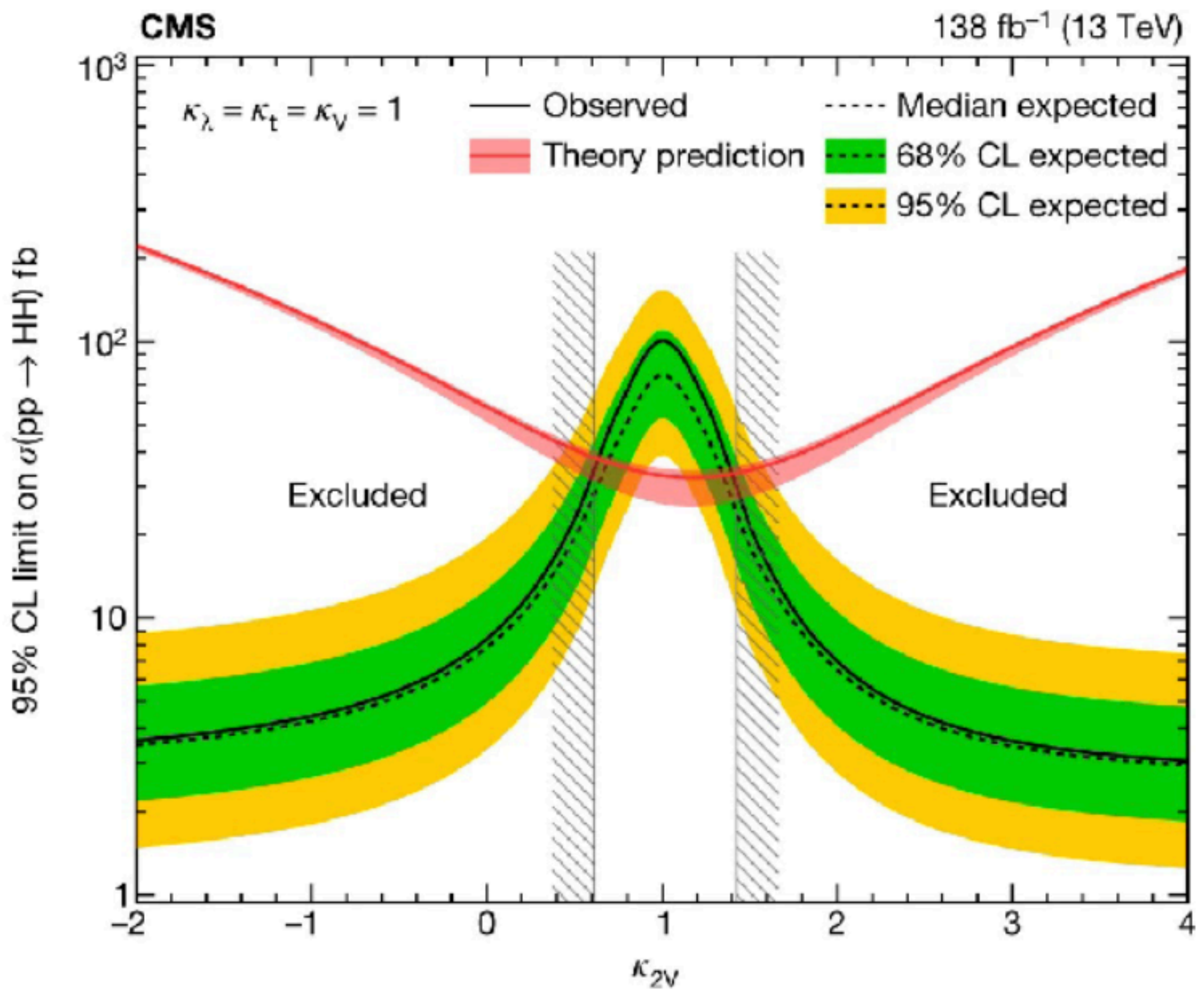
Other di-Higgs searches: CMS Run 2

- The current constraints on the di-Higgs production cross-section, 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.



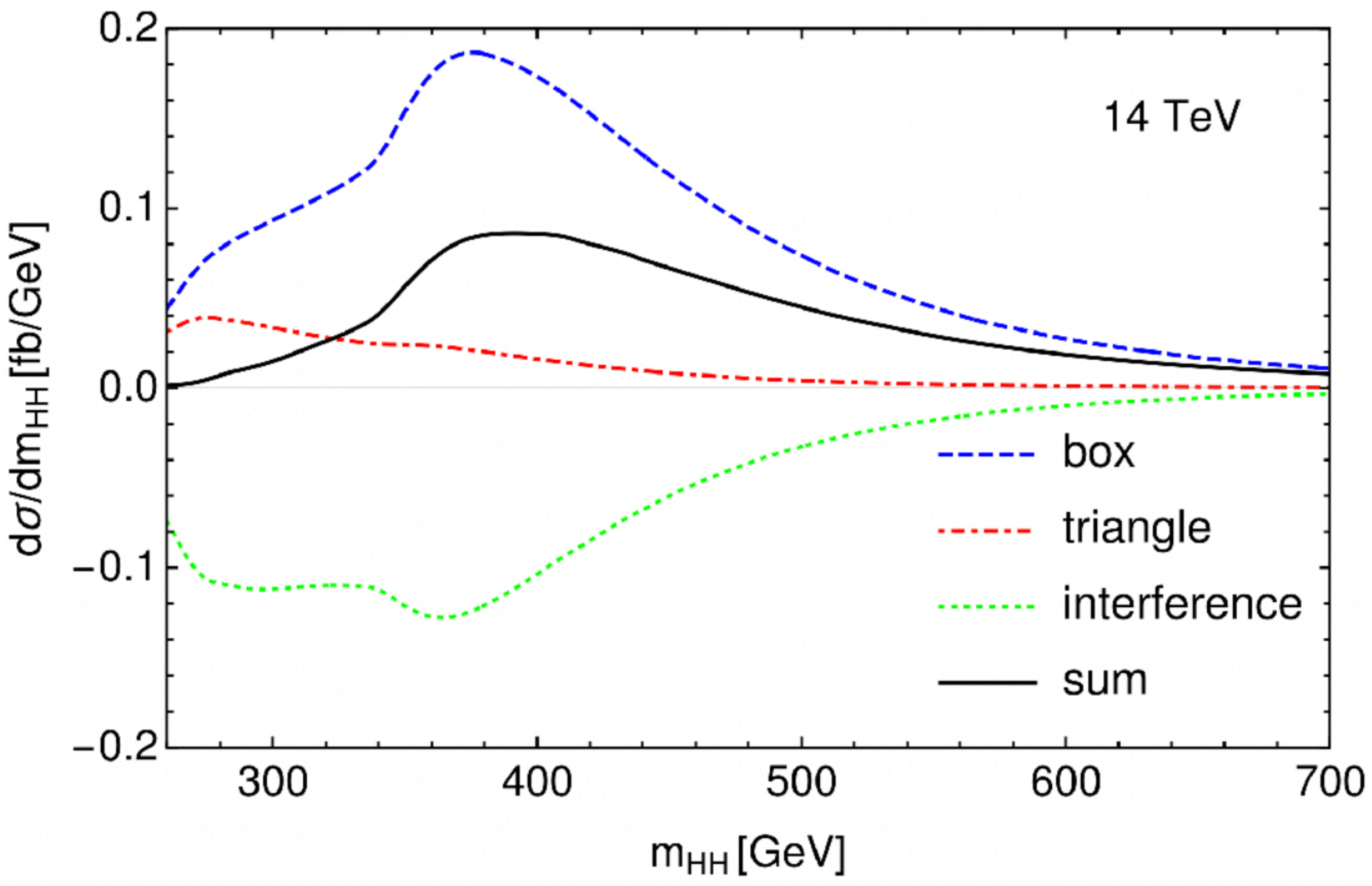
	Allowed κ_λ values	Allowed κ_{2V} values
Expected	[-0.89, 7.12]	-
Observed	[-1.25, 6.85]	[0.67, 1.38]





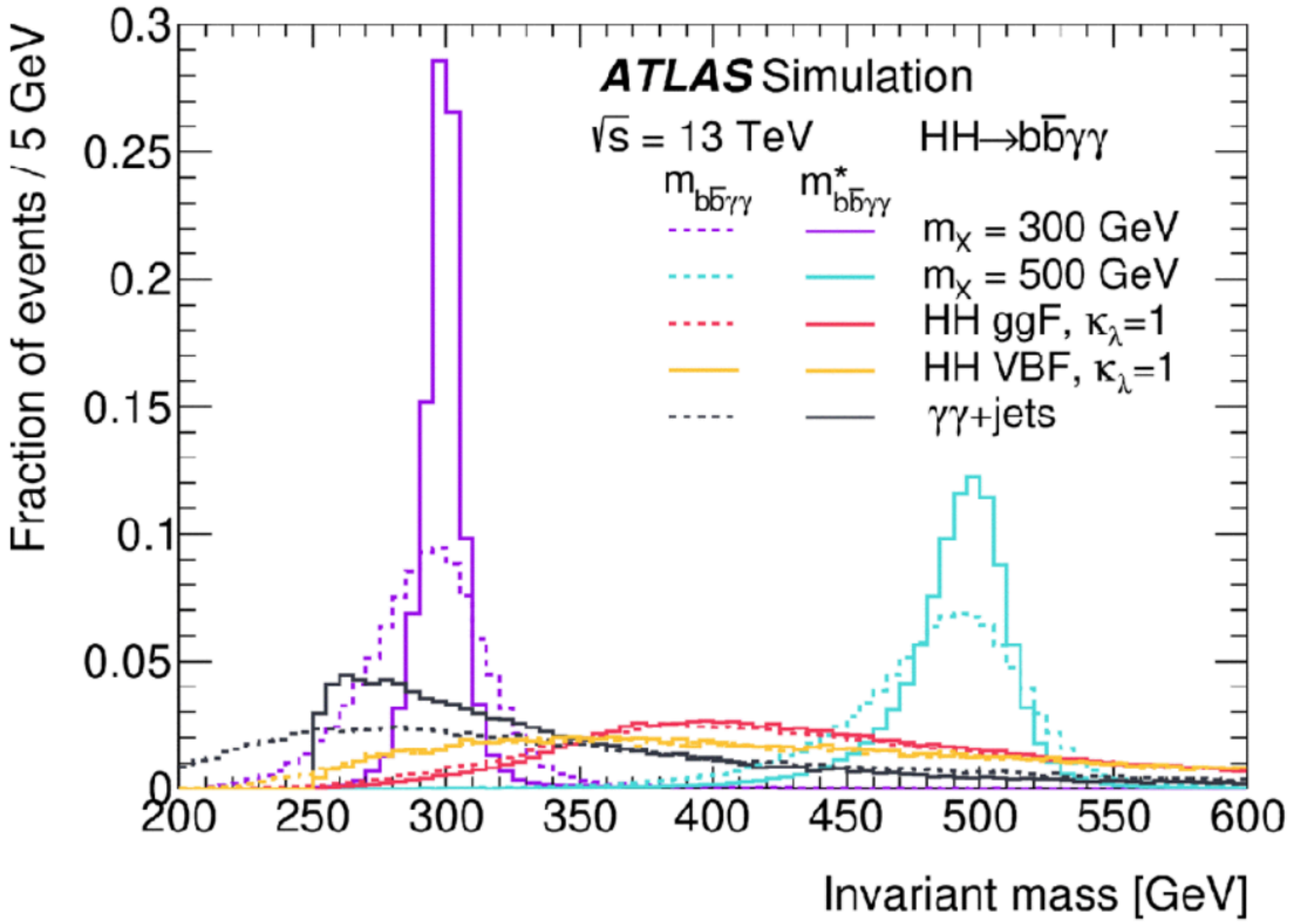
ggF HH cross section

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

- The reduced 4-object invariant mass $\mathbf{m}^*_{\mathbf{b\bar{b}}\gamma\gamma}$, defined as $\mathbf{m}^*_{\mathbf{b\bar{b}}\gamma\gamma} = \mathbf{m}_{\mathbf{b\bar{b}}\gamma\gamma} - (\mathbf{m}_{\gamma\gamma} - \mathbf{125}$ GeV$) - (\mathbf{m}_{\mathbf{b\bar{b}}} - \mathbf{125}$ 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 $\mathbf{m}_{\mathbf{b\bar{b}}\gamma\gamma}$ variable.
- Therefore, for historical reasons, $\mathbf{m}^*_{\mathbf{b\bar{b}}\gamma\gamma}$ 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 modeling is **data-driven**!
- These **samples** are used only for the **BDT training**, for the evaluation of the **background modelling uncertainty**, and for cross-checks.

Signal MC samples

- The **nominal** **di-Higgs signal samples** used in this analysis are summarized in this table.

DSID	Generator	PDF (ME)	PDF+Tune (PS)	Prod. Mode	Events in AOD
600021	POWHEG + PYTHIA8	PDFLHC	A14NNPDF23LO	SM ggF HH	1.518M
600022	POWHEG + PYTHIA8	PDFLHC	A14NNPDF23LO	ggF HH $\kappa_\lambda = 10$	0.719M
503004	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF	A14NNPDF23LO	SM VBF HH	0.4M
503005	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF	A14NNPDF23LO	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 0$, $\kappa_V = 1$	0.399M
503006	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF	A14NNPDF23LO	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 0.5$, $\kappa_V = 1$	0.2M
503007	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF	A14NNPDF23LO	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 1.5$, $\kappa_V = 1$	0.2M
503008	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF	A14NNPDF23LO	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 2$, $\kappa_V = 1$	0.199M
503009	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF	A14NNPDF23LO	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 3$, $\kappa_V = 1$	0.199M
503010	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF	A14NNPDF23LO	VBF HH $\kappa_\lambda = 0$, $\kappa_{2V} = 1$, $\kappa_V = 1$	0.2M
503011	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF	A14NNPDF23LO	VBF HH $\kappa_\lambda = 2$, $\kappa_{2V} = 1$, $\kappa_V = 1$	0.198M
503012	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF	A14NNPDF23LO	VBF HH $\kappa_\lambda = 10$, $\kappa_{2V} = 1$, $\kappa_V = 1$	0.198M
503013	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF	A14NNPDF23LO	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 1$, $\kappa_V = 0.5$	0.2M
503014	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF	A14NNPDF23LO	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 1$, $\kappa_V = 1.5$	0.2M
503015	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF	A14NNPDF23LO	VBF HH $\kappa_\lambda = 0$, $\kappa_{2V} = 0$, $\kappa_V = 1$	0.2M
508689	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF	A14NNPDF23LO	VBF HH $\kappa_\lambda = -5$, $\kappa_{2V} = 1$, $\kappa_V = 0.5$	0.2M

Background MC samples

- The **nominal** single Higgs and $\gamma\gamma$ background samples used in this analysis are summarized in this table.

DSID	Generator	PDF (ME)	PDF+Tune (PS)	Prod. Mode	Events in AOD
343981	NNLOPS + PYTHIA8	PDFLHC	AZNLOCTEQ6	ggH	18.3M
346214	POWHEG + PYTHIA8	PDFLHC	AZNLOCTEQ6	VBF	7M
345318	POWHEG + PYTHIA8	PDFLHC	AZNLOCTEQ6	W^+H	0.6M
345317	POWHEG + PYTHIA8	PDFLHC	AZNLOCTEQ6	W^-H	0.6M
345319	POWHEG + PYTHIA8	PDFLHC	AZNLOCTEQ6	$qq \to ZH$	1.5M
345061	POWHEG + PYTHIA8	PDFLHC	AZNLOCTEQ6	$gg \to ZH$	0.15M
346525	POWHEG + PYTHIA8	PDFLHC	A14NNPDF23	ttH	7.8M
345315	POWHEG + PYTHIA8	PDFLHC	A14NNPDF23	bbH	0.299M
346188	MGMCatNLO + PYTHIA8	NNPDF	A14NNPDF23	tHbj	0.4M
346486	MGMCatNLO + PYTHIA8	NNPDF	A14NNPDF23	tHW	0.208M
364352	SHERPA 2.2.4 (ME@NLO+PS)			$\gamma\gamma$+0,1(NLO),2,3(LO), $m_{\gamma\gamma} \in$ 90-175 GeV	1.2B (AF2)
700673	SHERPA 2.2.12 (ME@NLO+PS)			$\gamma\gamma + b\bar{b}$(NLO),3+(PS), $m_{\gamma\gamma} \in$ 90-175 GeV	20M
345868	MGMCatNLO + PYTHIA8			$t\bar{t}\gamma\gamma$ (noallhad)	1.94M
345869	MGMCatNLO + PYTHIA8			$t\bar{t}\gamma\gamma$ (allhad)	1.6M

Triggers and 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.

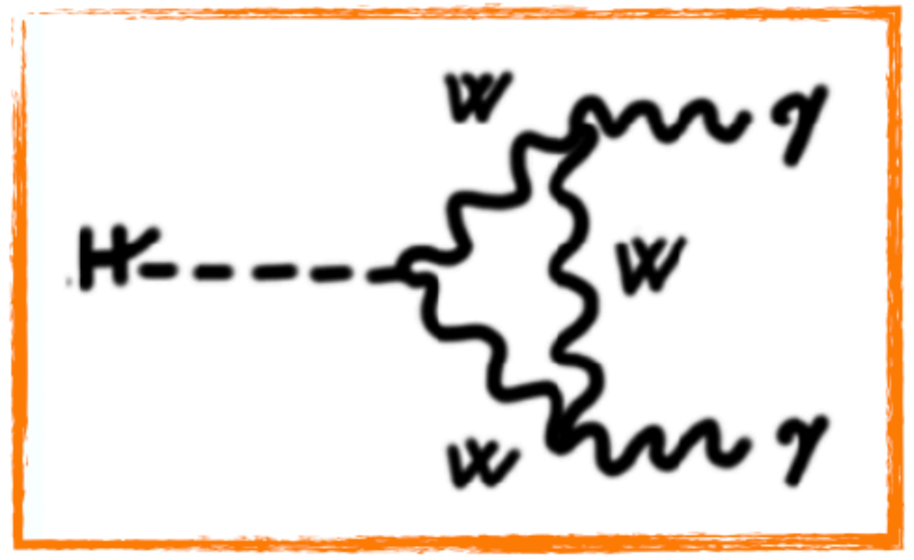
Single-photon triggers:

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

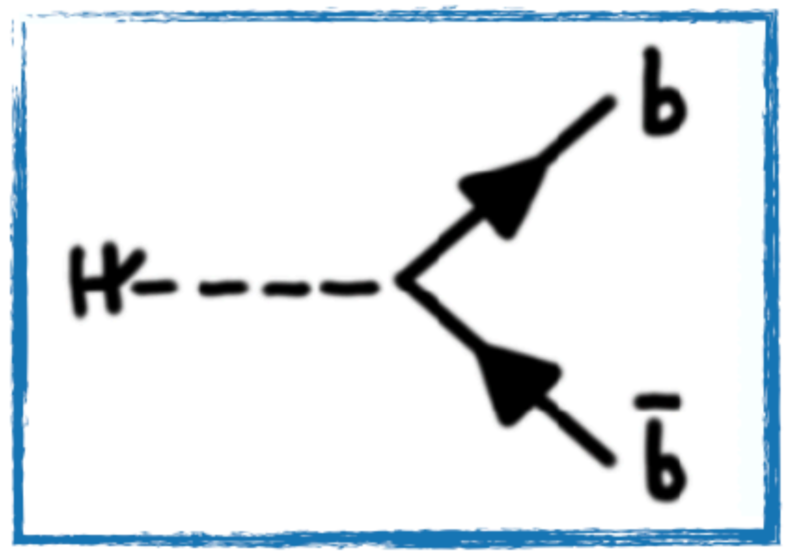
Require one loose photon with $p_T > 120$ or 140 GeV.

➡ 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-jets tagger

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

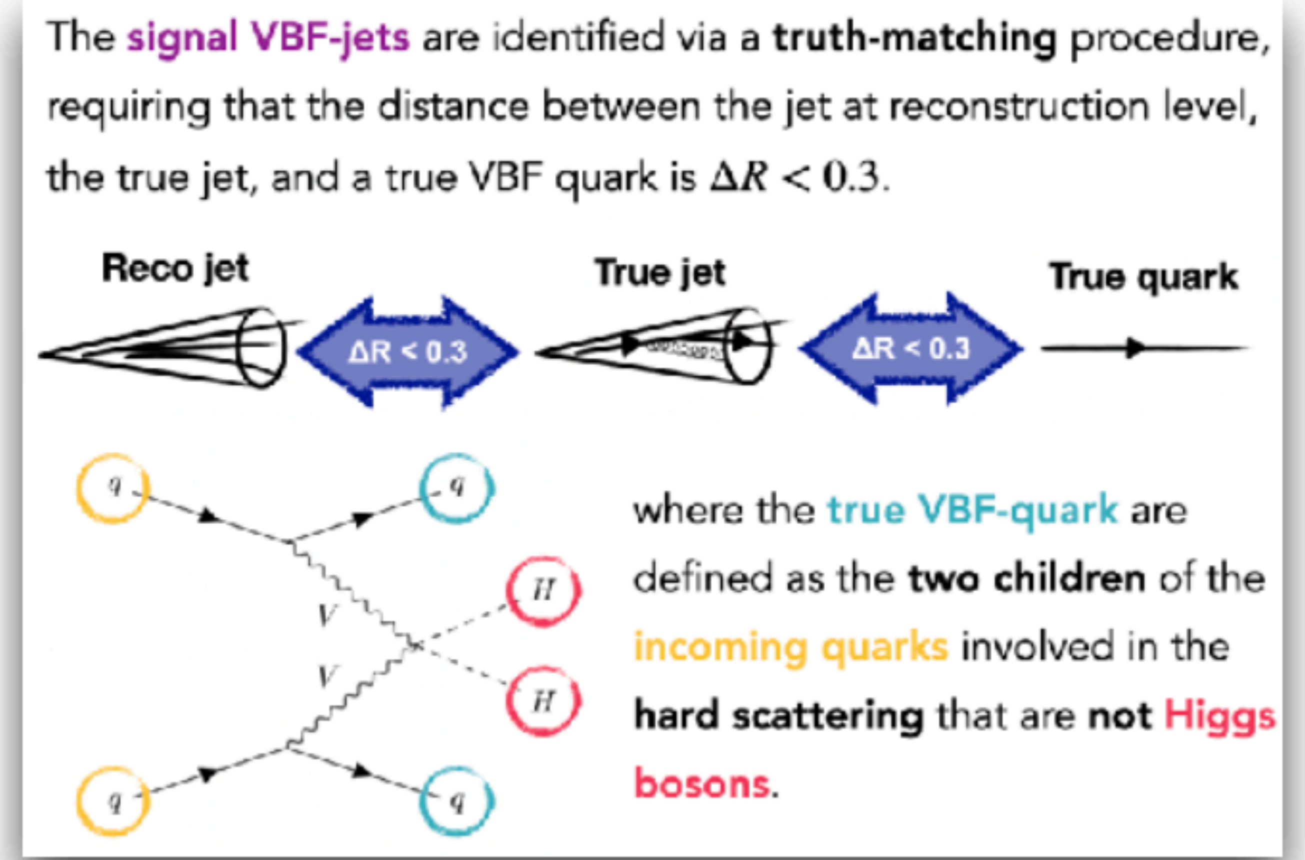
➡ The VBF-jets are identified with the help of a **VBF-jet tagger**. → **BDT applied** to all the **possible jet pairs** of an event, and used to select the **jet pair** that is most **likely** to arise **from VBF production**!

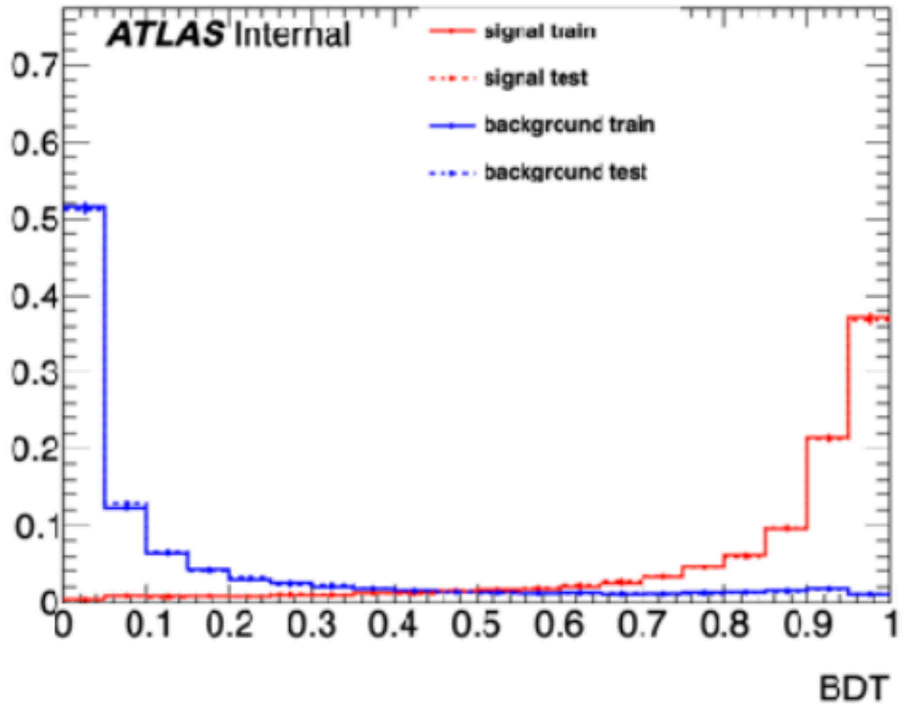
↳ Needed to calculate the VBF-related input variables for the Legacy BDTs!

- 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**.





➡
- 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}!

Events selection

- After applying the **pre-selection** requirements, events are **categorized** based on the reduced 4-object invariant mass $\mathbf{m}^*_{b\bar{b}\gamma\gamma}$ and on **BDT outputs**.

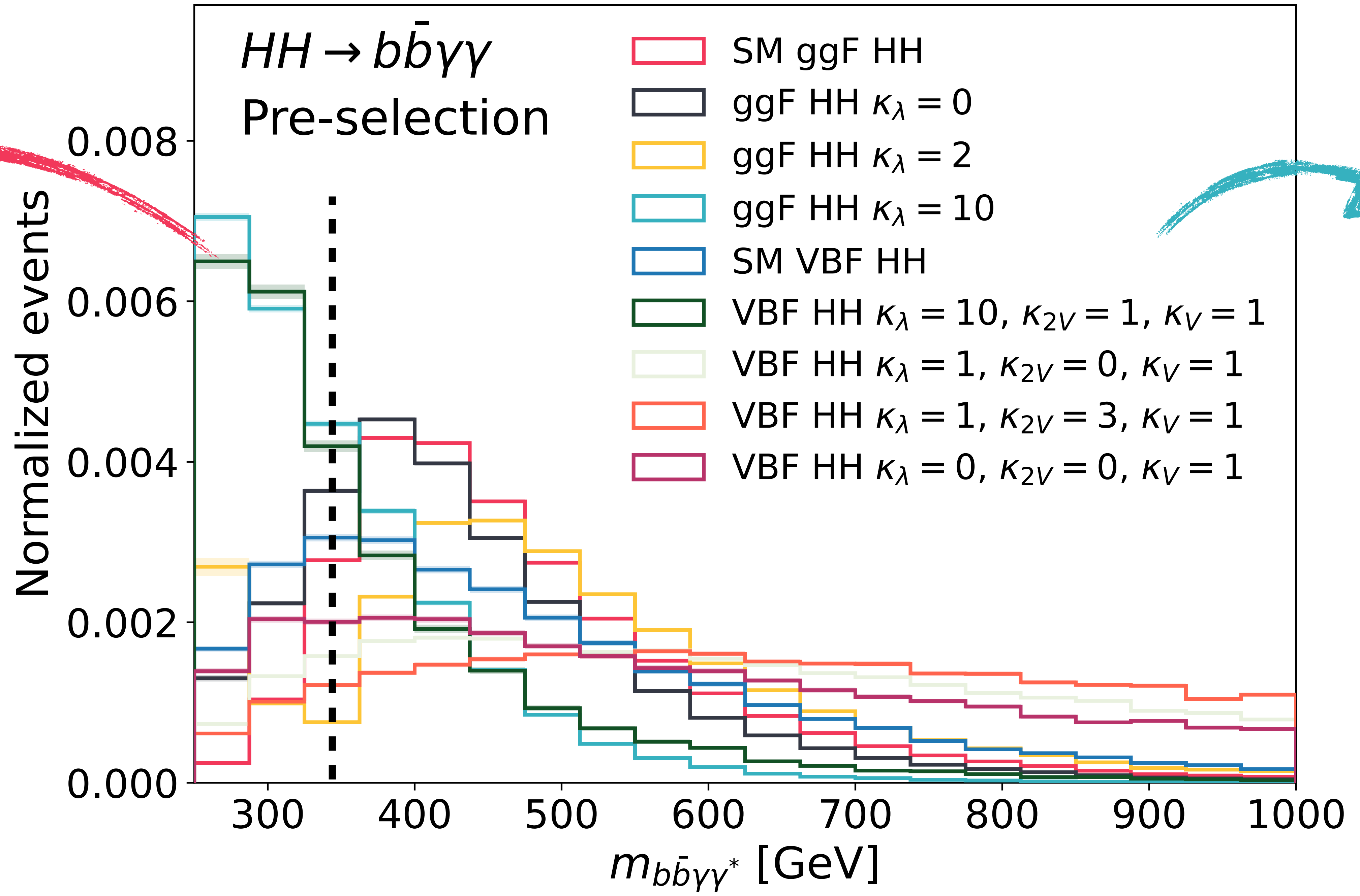
di-photon, b-jet, and VBF-jet tagger

- 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 $\kappa_\lambda = 5.6$ and $\kappa_\lambda = 10$, and **VBF HH** samples with **all BSM couplings**.



High Mass region: $\mathbf{m}^*_{b\bar{b}\gamma\gamma} >$ **350 GeV**

Targets **SM ggF HH** events and **VBF HH** samples with all the **SM + BSM couplings**.

Events selection: BDTs

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

Both the BDTs use the **same set** of **input variables**! They include **ggF-related** and **VBF-related** variables!

	Low Mass	High Mass
Signal	• ggF HH with κλ = 5.6 and κλ = 10 • VBF HH samples with (κλ, κ2V, κV) = (0,1,1), (10,1,1), (1,1.5,1), (1,3,1), (-5,1,0.5)	• SM ggF HH • SM + BSM VBF HH samples, with (κλ, κ2V, κV) = (0,1,1), (10,1,1), (1,1.5,1), (1,3,1), (-5,1,0.5)
Background	• All single Higgs processes • γγ + ttγγ samples	• All single Higgs processes • γγ + ttγγ samples

- $p_T/m_{\gamma\gamma}$, η, ϕ of the 2 candidate photons.
- $p_T/m_{\gamma\gamma}$, η, ϕ, b-tag score of the 2 candidate b-jets.
- $p_T/m_{\gamma\gamma}$, η, ϕ, b-tag score of the 3[rd] and 4[th] leading jets.
- p_T^{bb}, η^{bb}, ϕ^{bb} and m_{bb}.
- H_T and single-topness χ_{Wt}.
- E_T^{miss} and ϕ^{MET}.

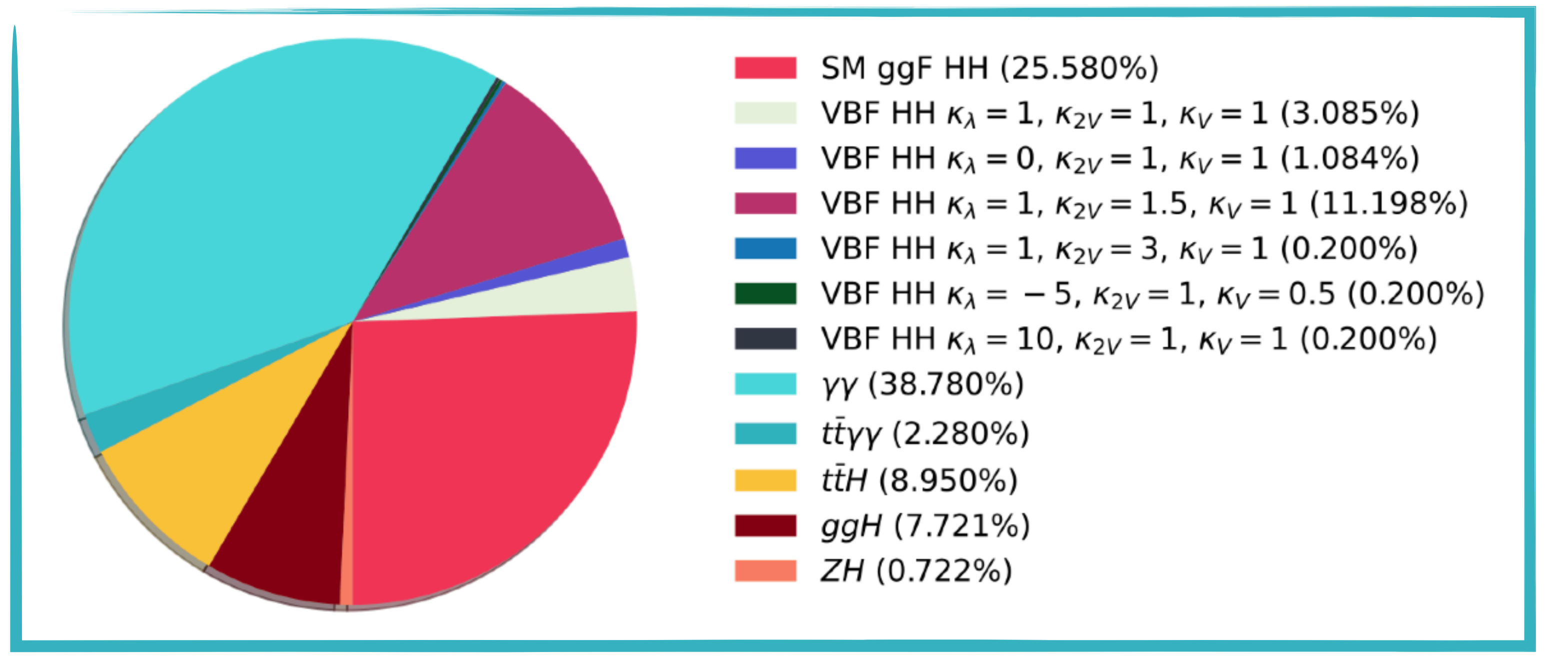
+

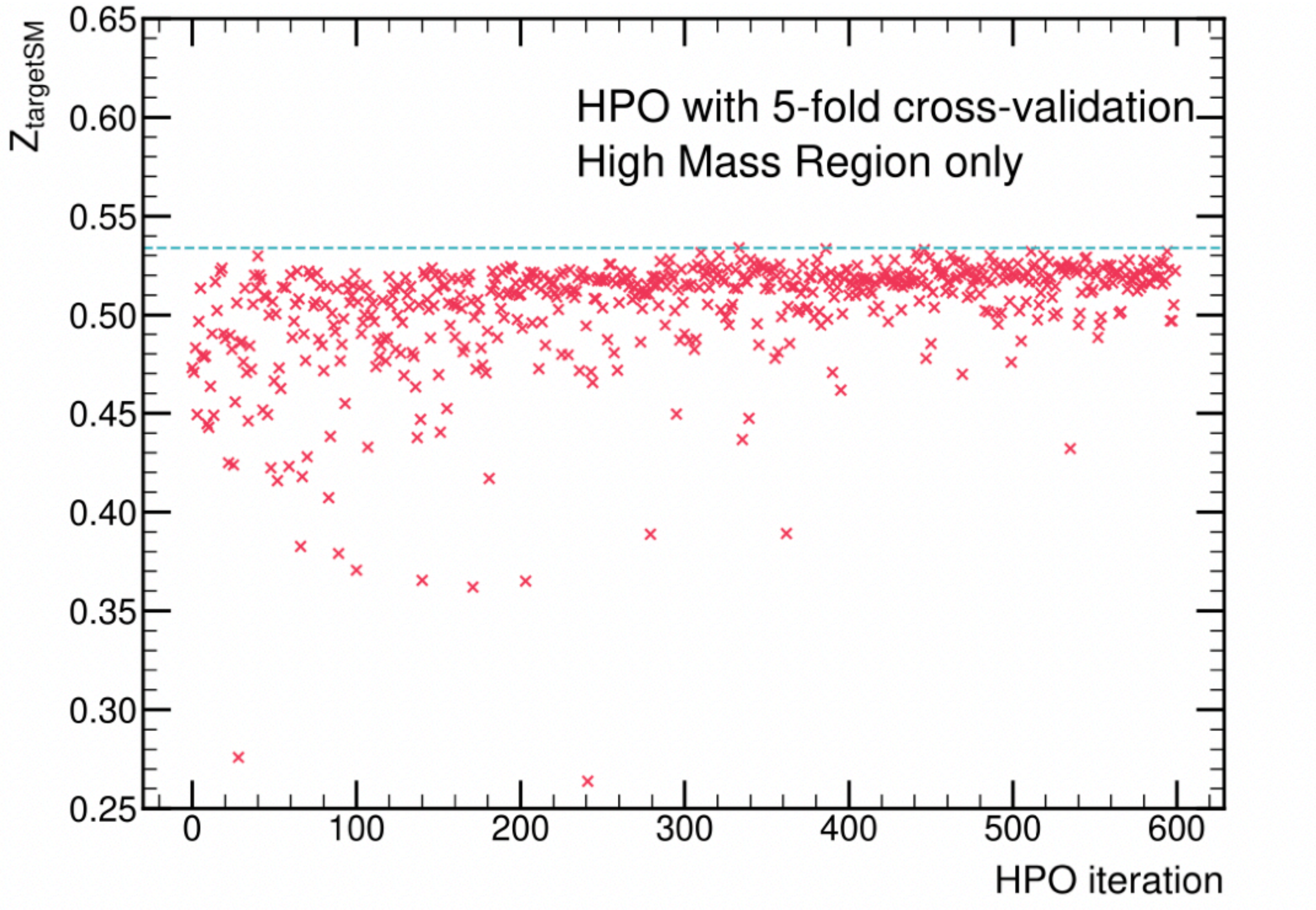
- Invariant mass of the 2 VBF jets m_{jj} and $\Delta\eta(j_1, j_2)$.
- BDT score of the VBF jet pair.
- 4-object invariant mass $m_{b\bar{b}\gamma\gamma}$.
- Distance between the 2 photons and between the 2 b-jets: $\Delta R(\gamma_1, \gamma_2)$ and $\Delta R(b_1, b_2)$.
- Event shape variables: transverse sphericity, planar flow, and p_T balance.

Each sample is assigned a **per-process weight**, chosen via a **hyperparameter optimization**!

The HPO uses directly the **overall significance** as a figure of merit!

High Mass region





Events selection: analysis categories

3 categories in the High Mass region and **4 categories** in the Low Mass region are defined, by selecting the **thresholds** in the **BDT outputs** that maximize the following **number counting significances**:

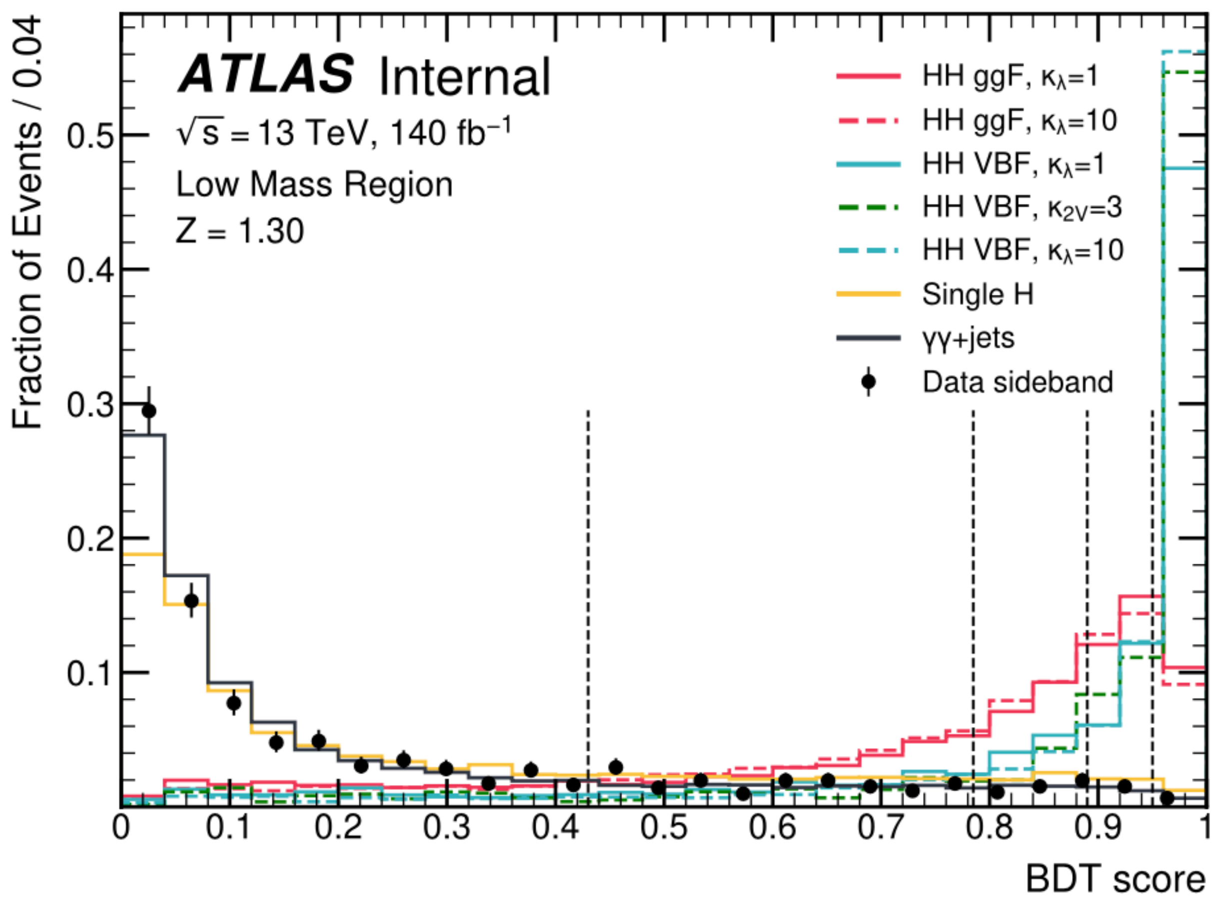
- High Mass region:

$$\mathbf{Z_{target\ SM} = \sqrt{2 \cdot [(S+B) \cdot \ln(1+S/B) - S]}}$$, where:
- S: **SM** ggF HH + VBF HH.
- B: single Higgs processes + $\gamma\gamma$.

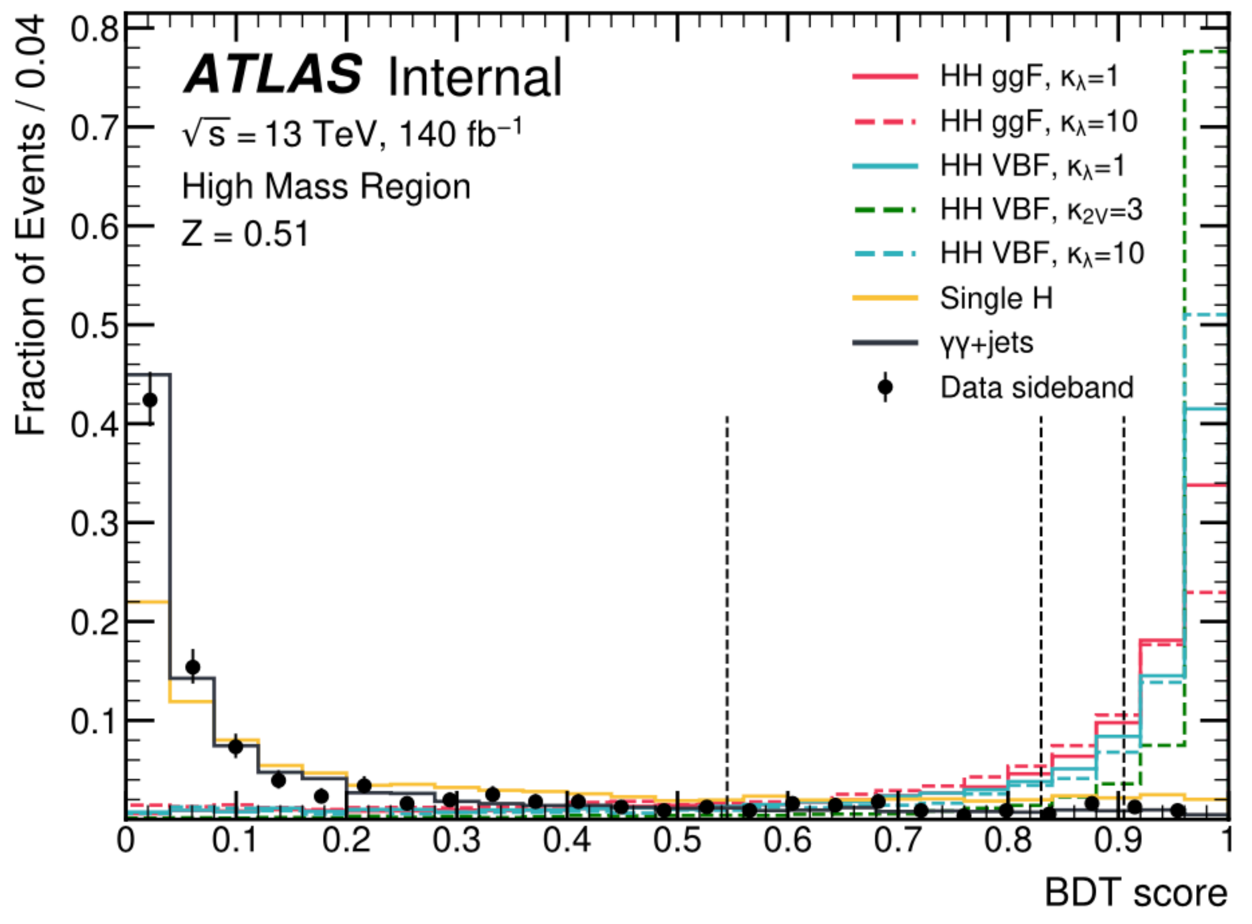
- Low Mass region:

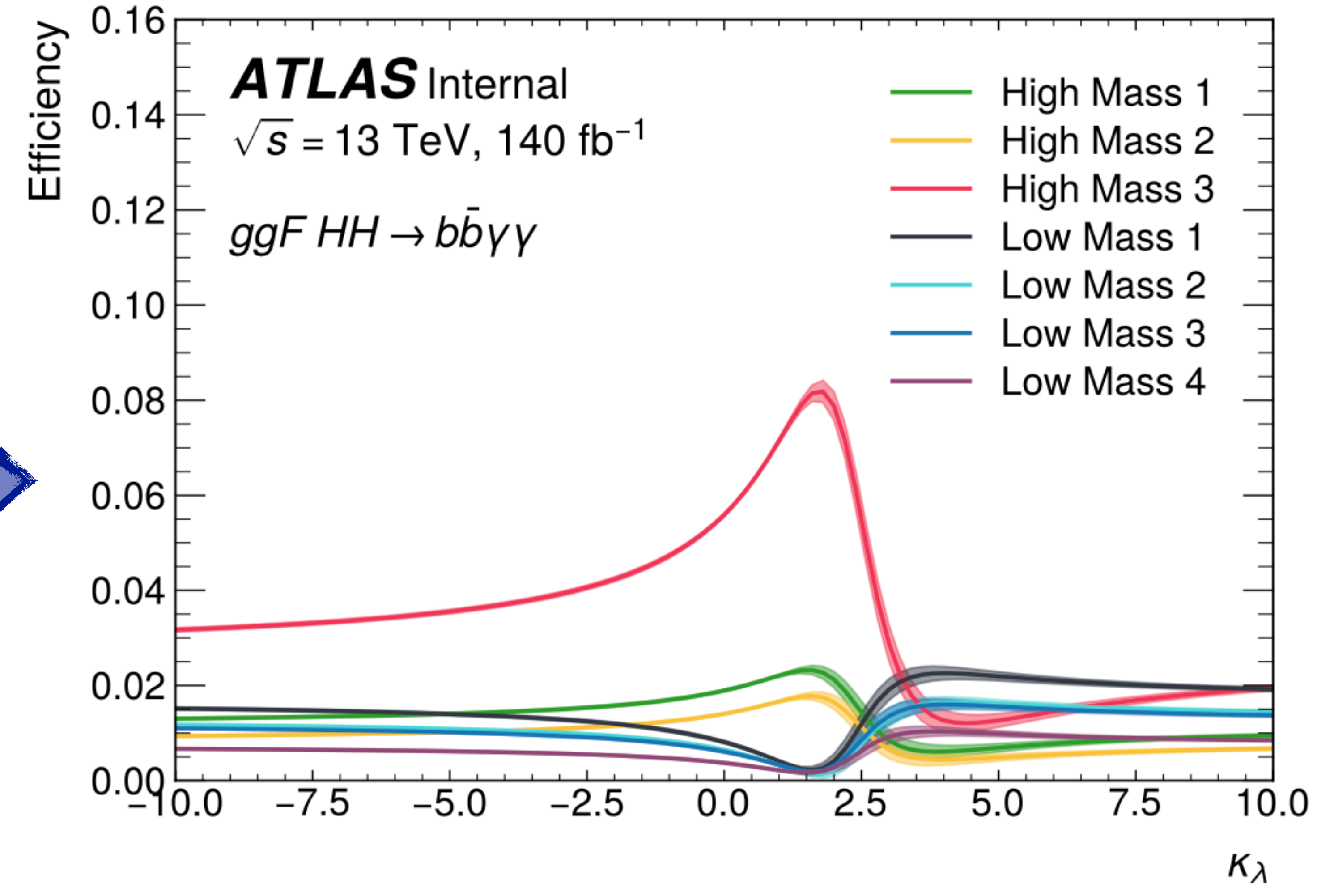
$$\mathbf{Z_{target\ \kappa_\lambda} = \sqrt{2 \cdot [(S+B) \cdot \ln(1+S/B) - S]}}$$, where:
- S: ggF HH with κ_λ = **5.6**+ VBF HH with (κ_λ, κ_{2V}, κ_V) = (10,1,1).

Low Mass region



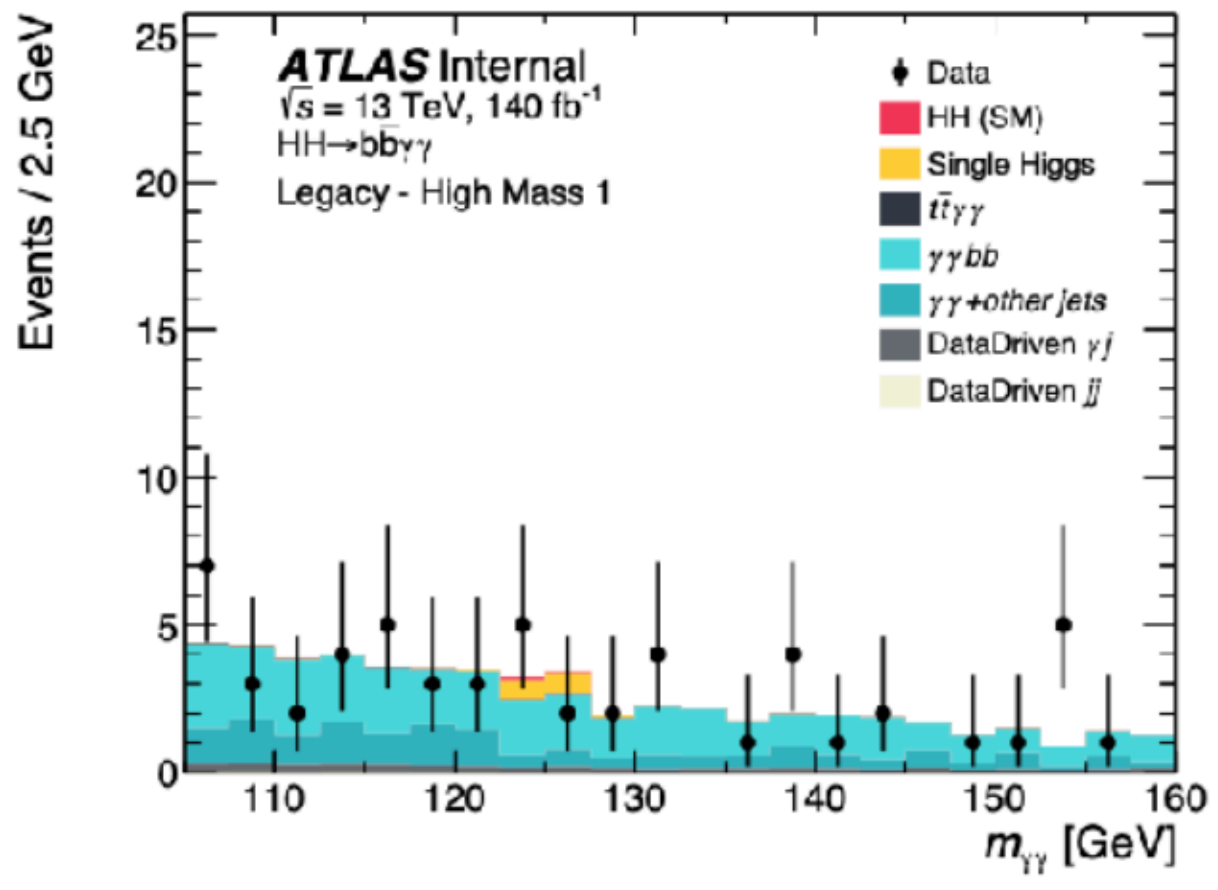
High Mass region

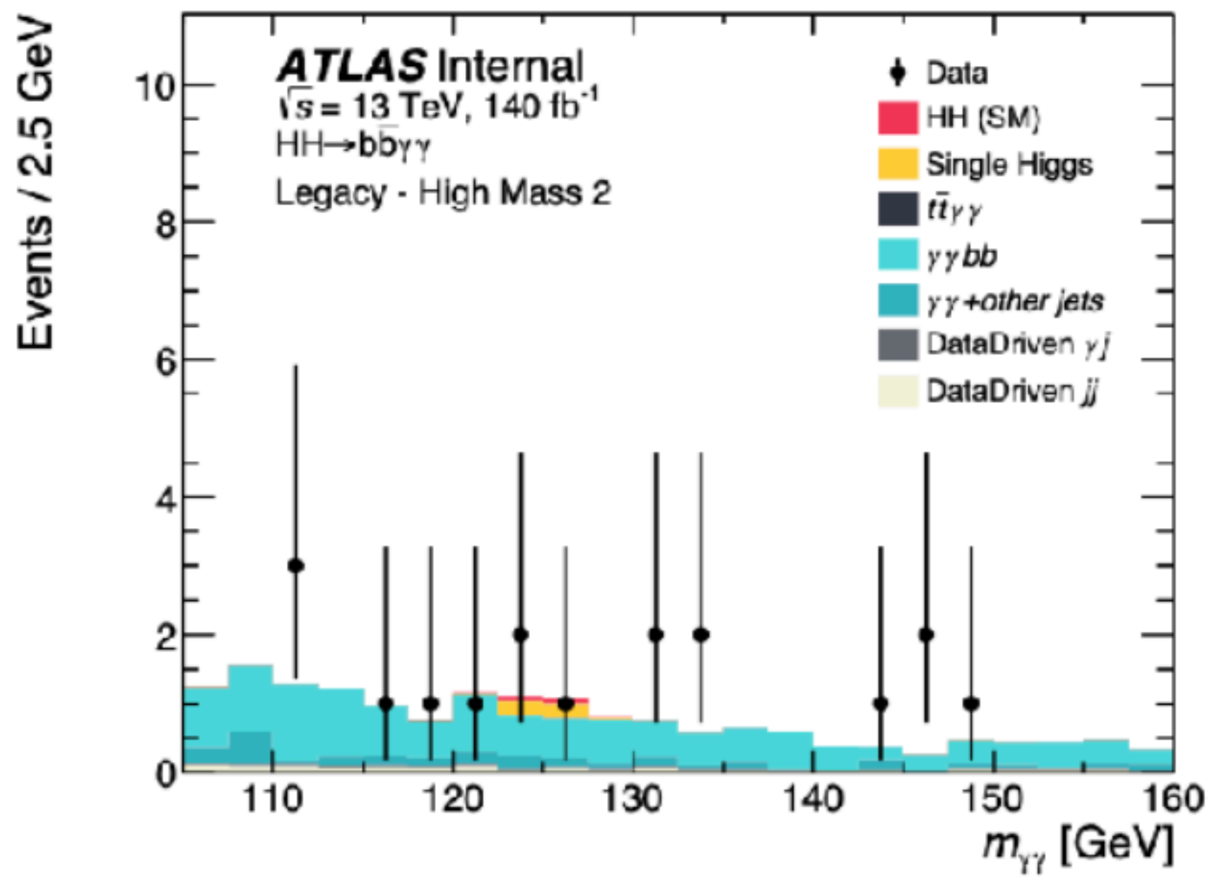


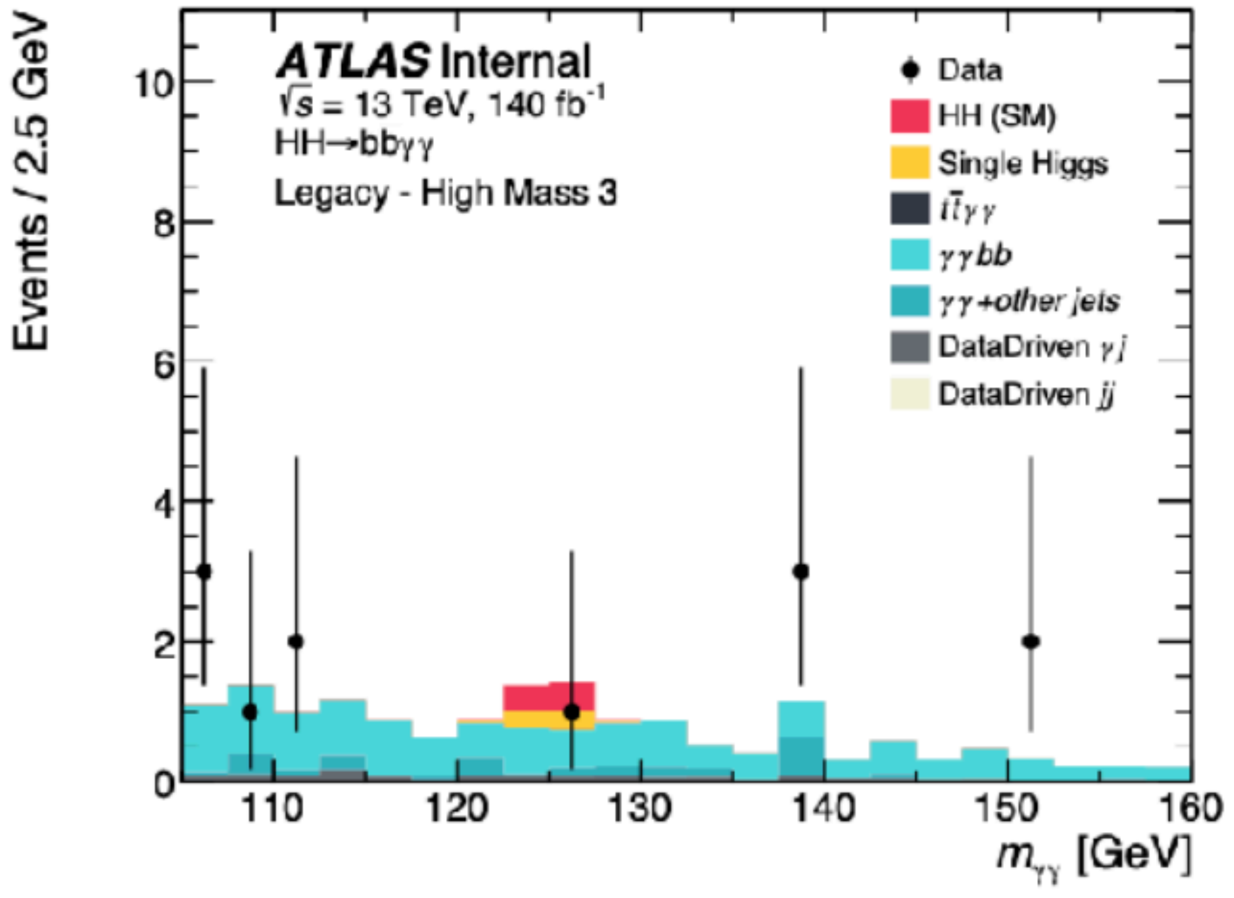


Data/MC comparison: High Mass categories

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







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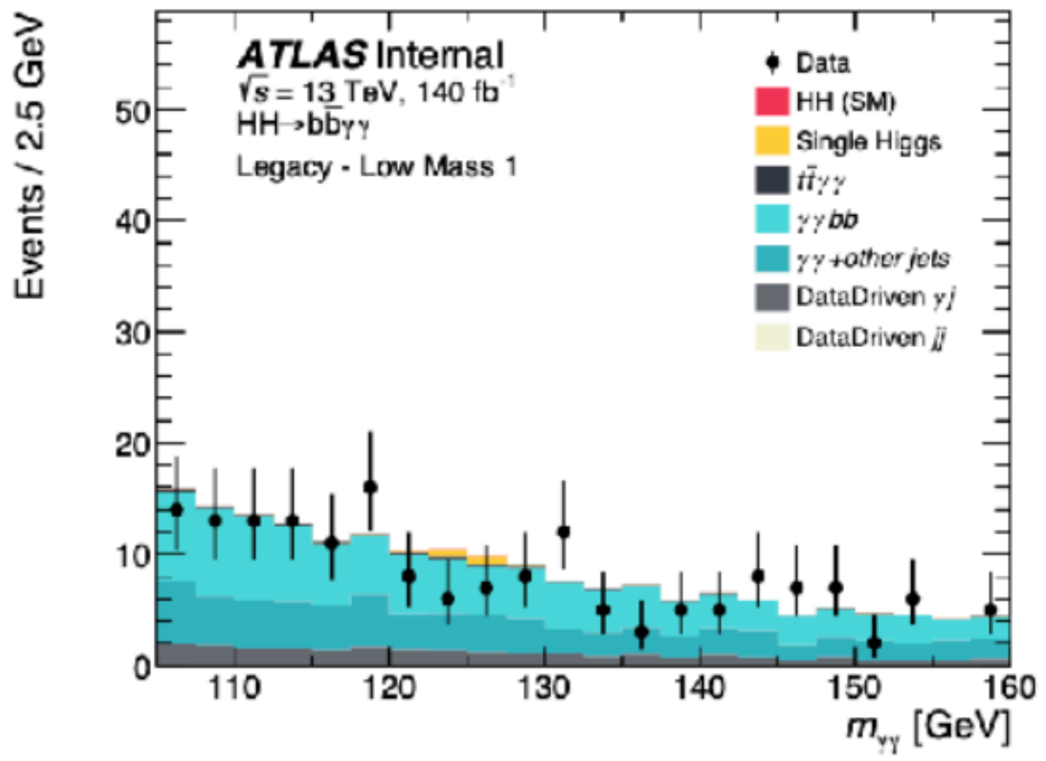
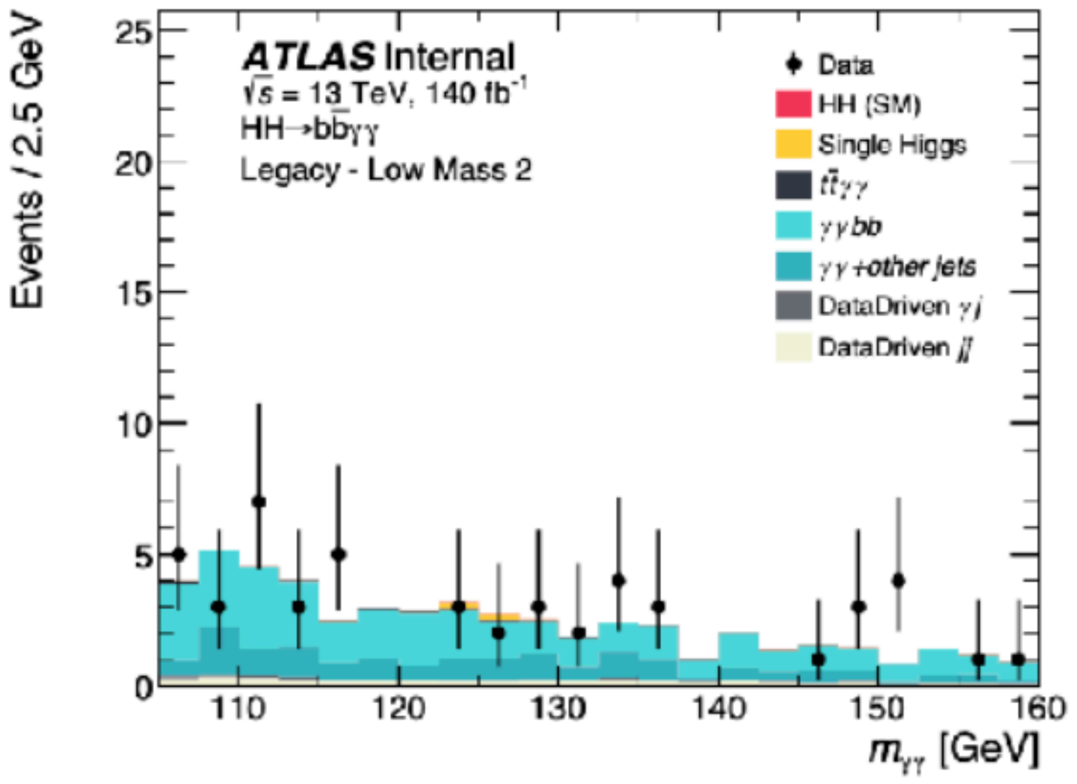
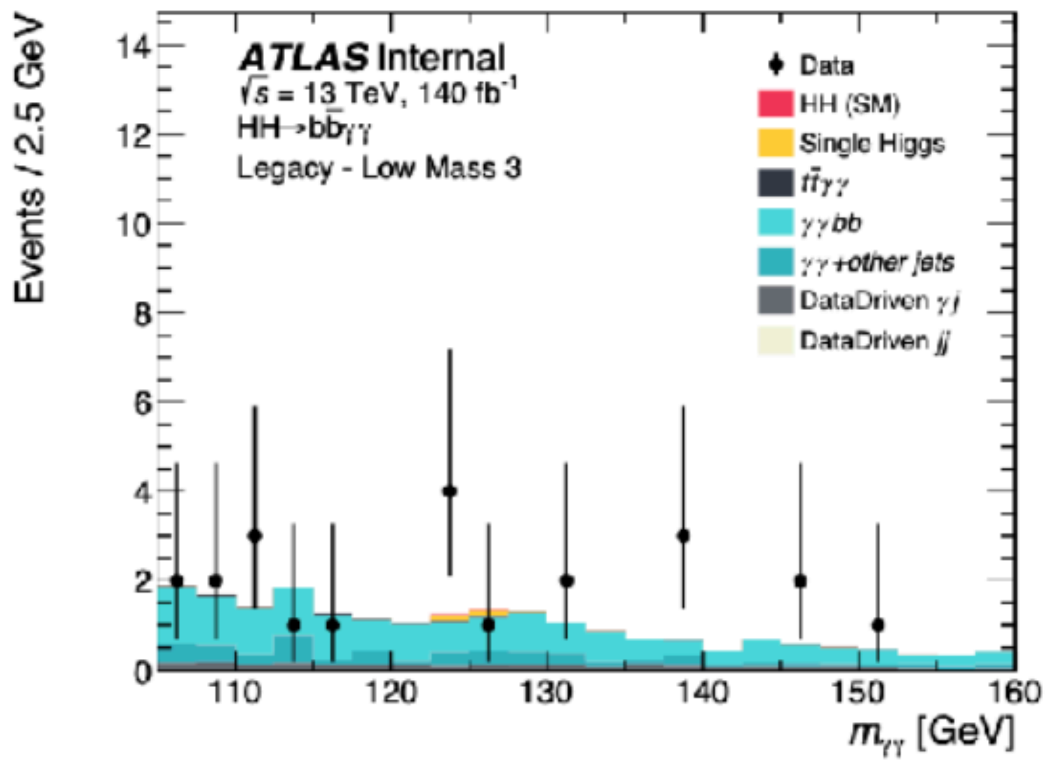
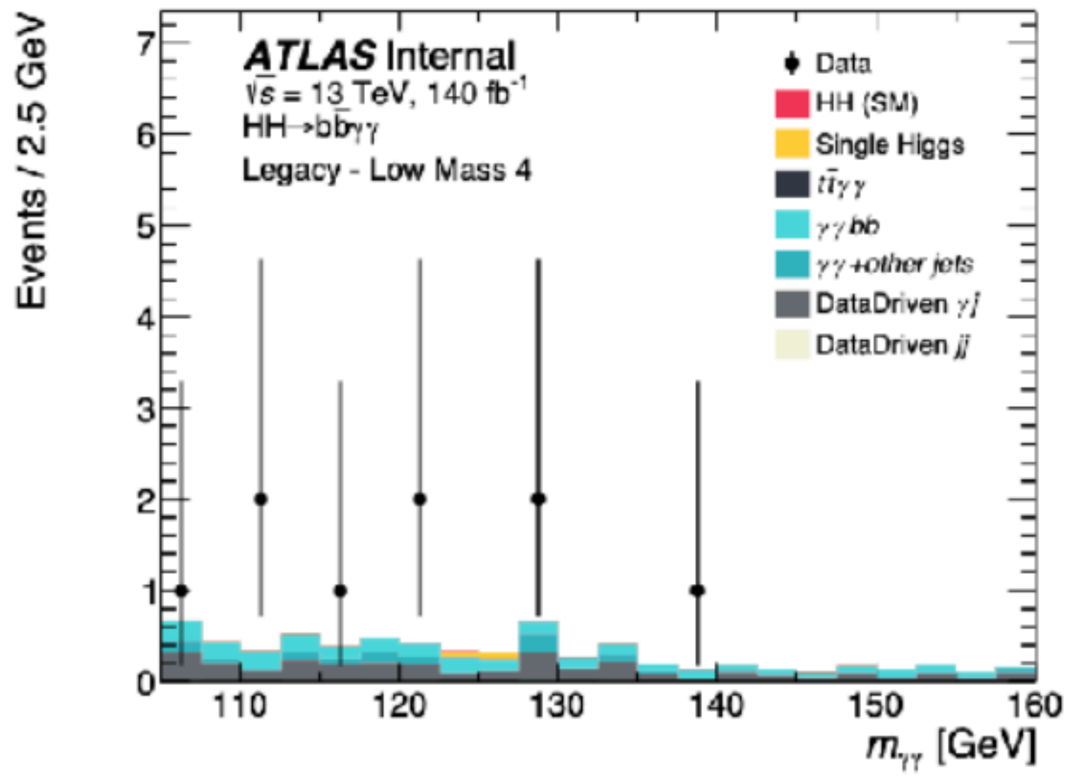


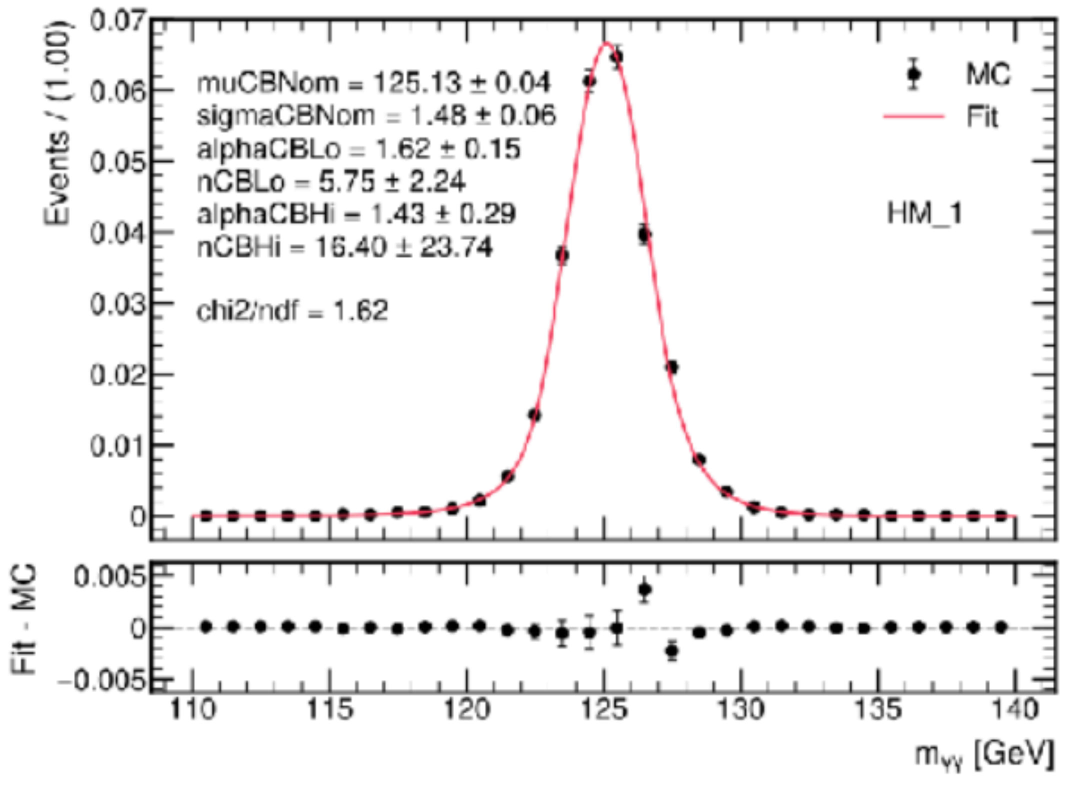




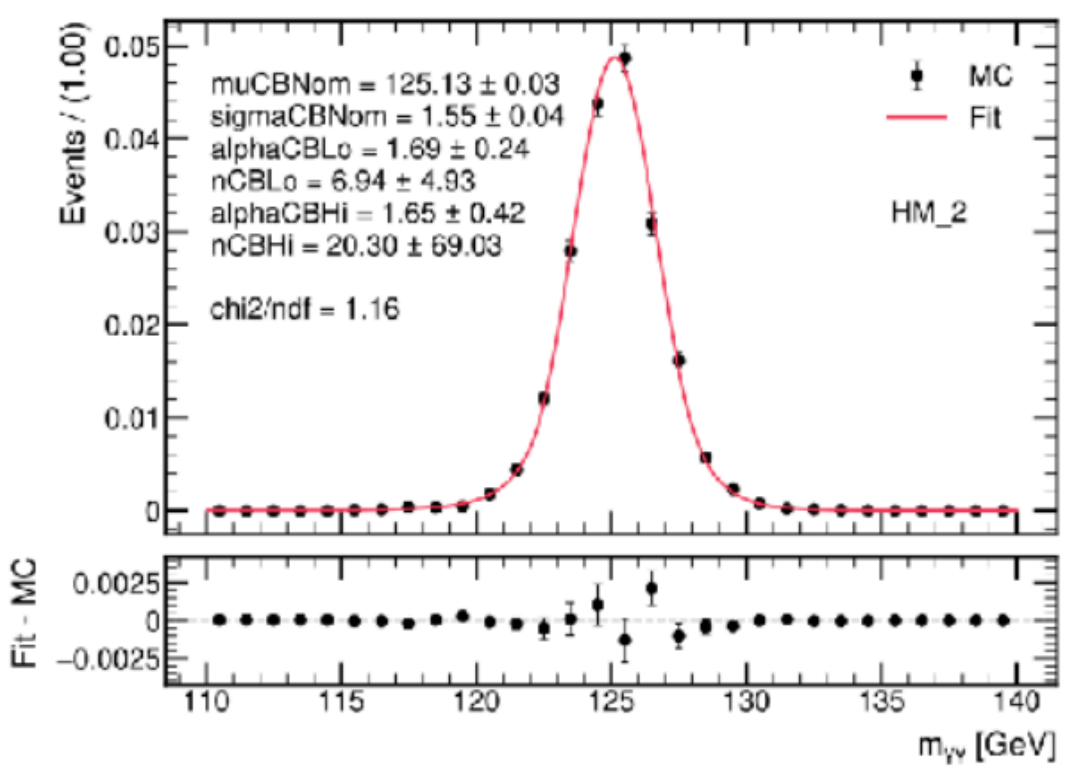


Signal modelling : High Mass categories

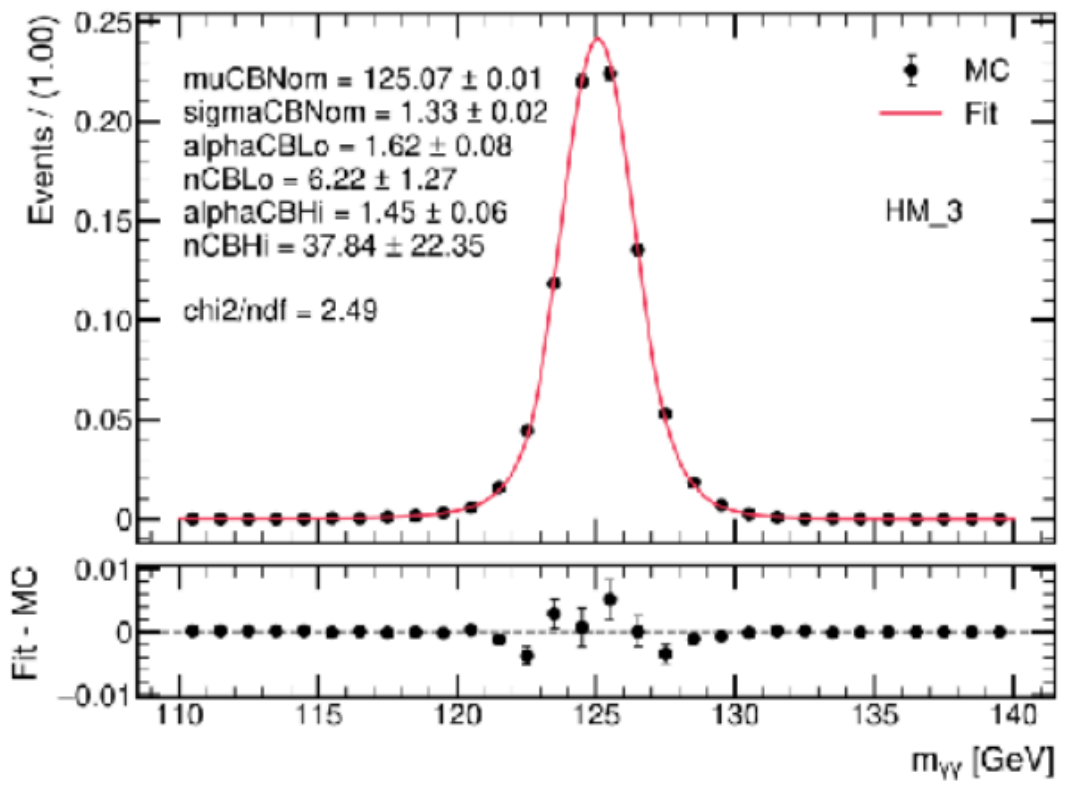
- The signal + single Higgs models for the **High Mass categories** are shown below.



(a) High Mass 1



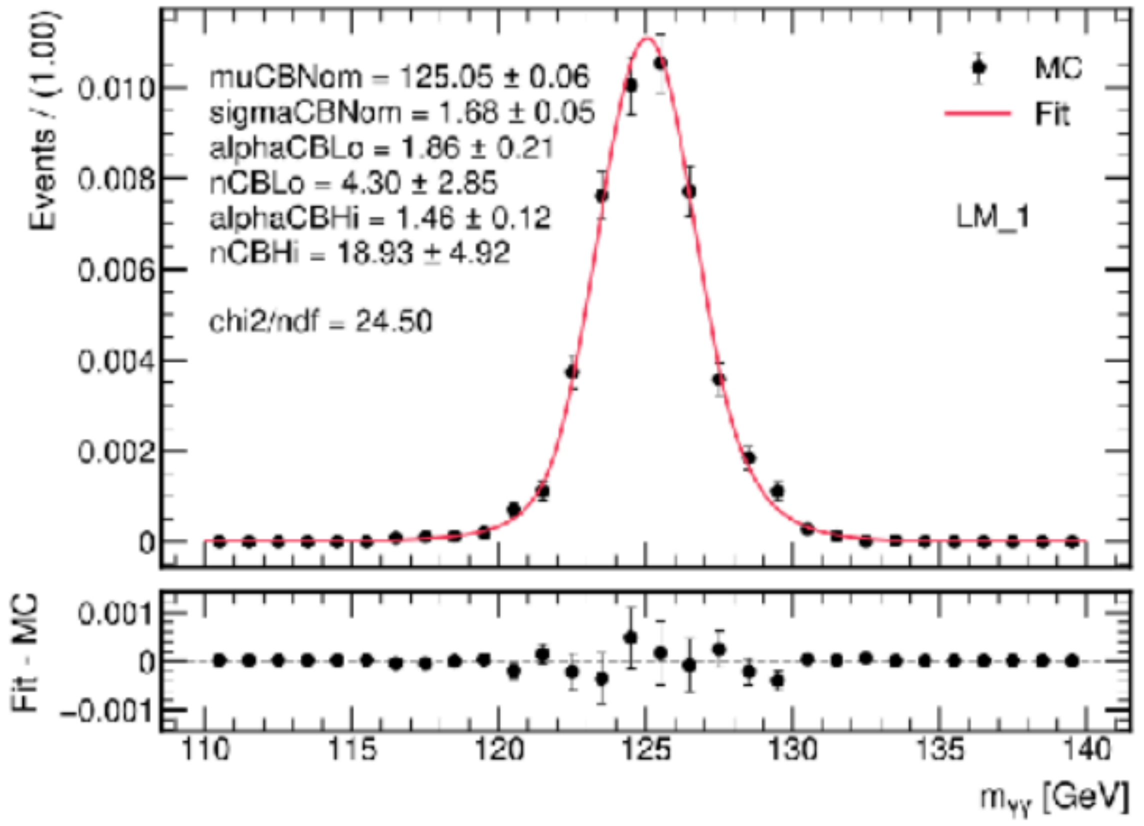
(b) High Mass 2



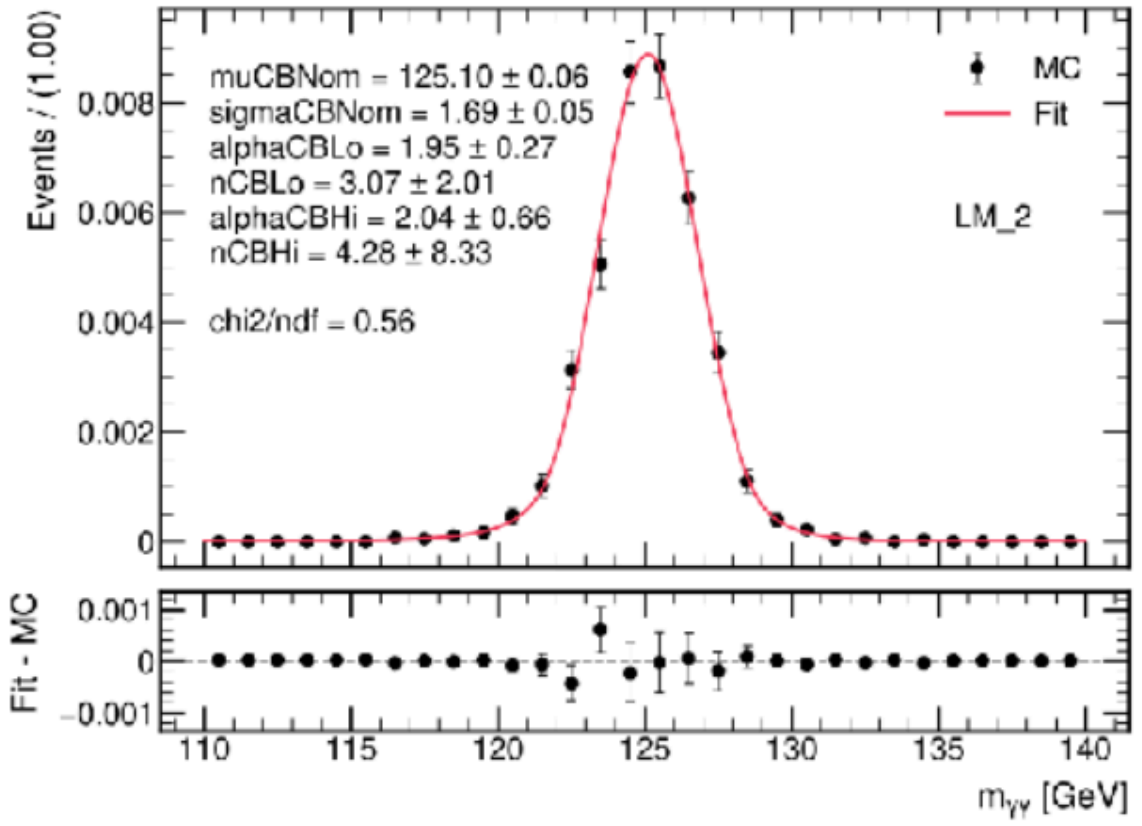
(c) High Mass 3

Signal modelling : Low Mass categories

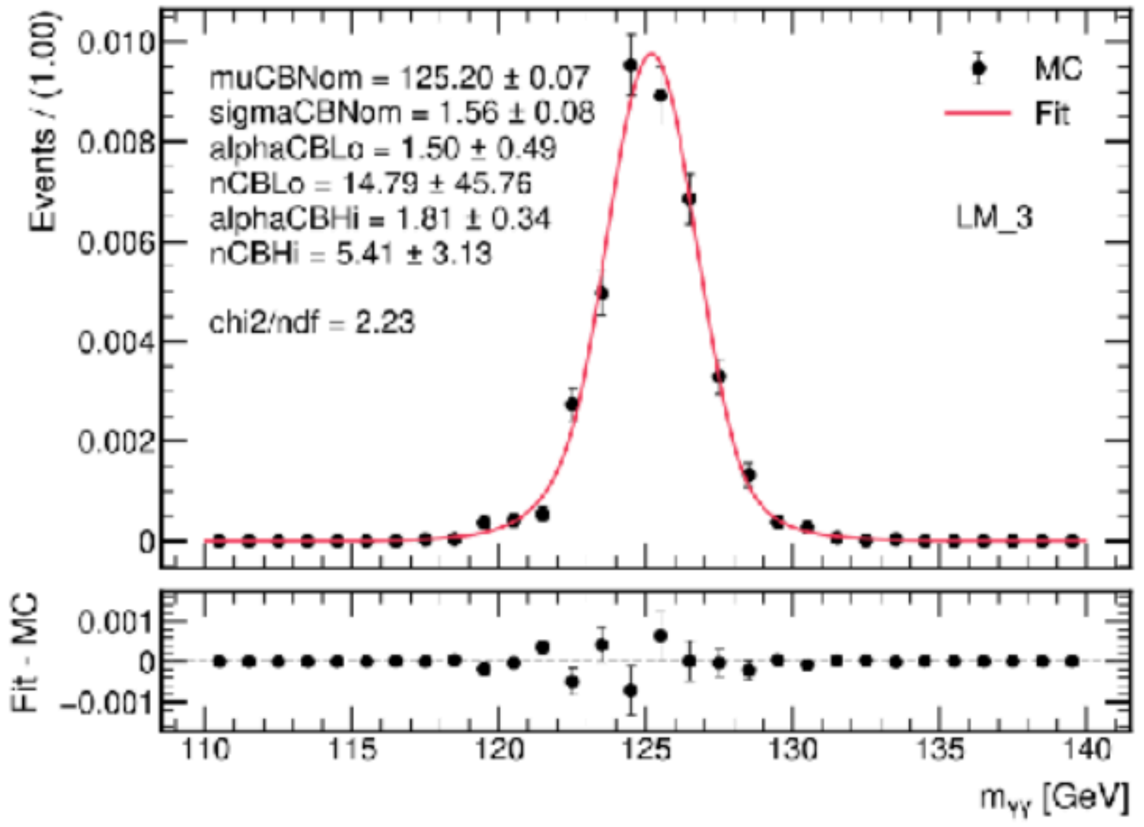
- The signal + single Higgs models for the **Low Mass categories** are shown below.



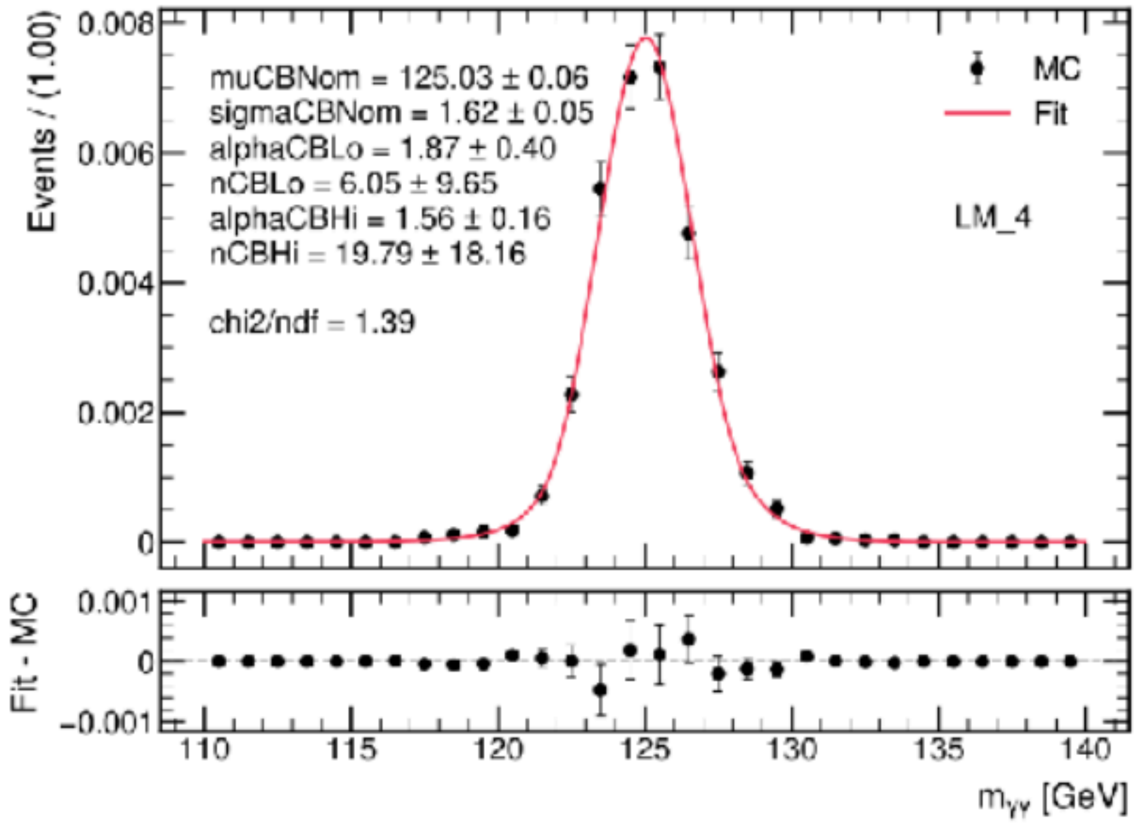
(a) Low Mass 1



(b) Low Mass 2



(c) Low Mass 3



(d) Low Mass 4

Impact of systematic uncertainties on the upper limits on $\mu_{\mathbf{HH}}$

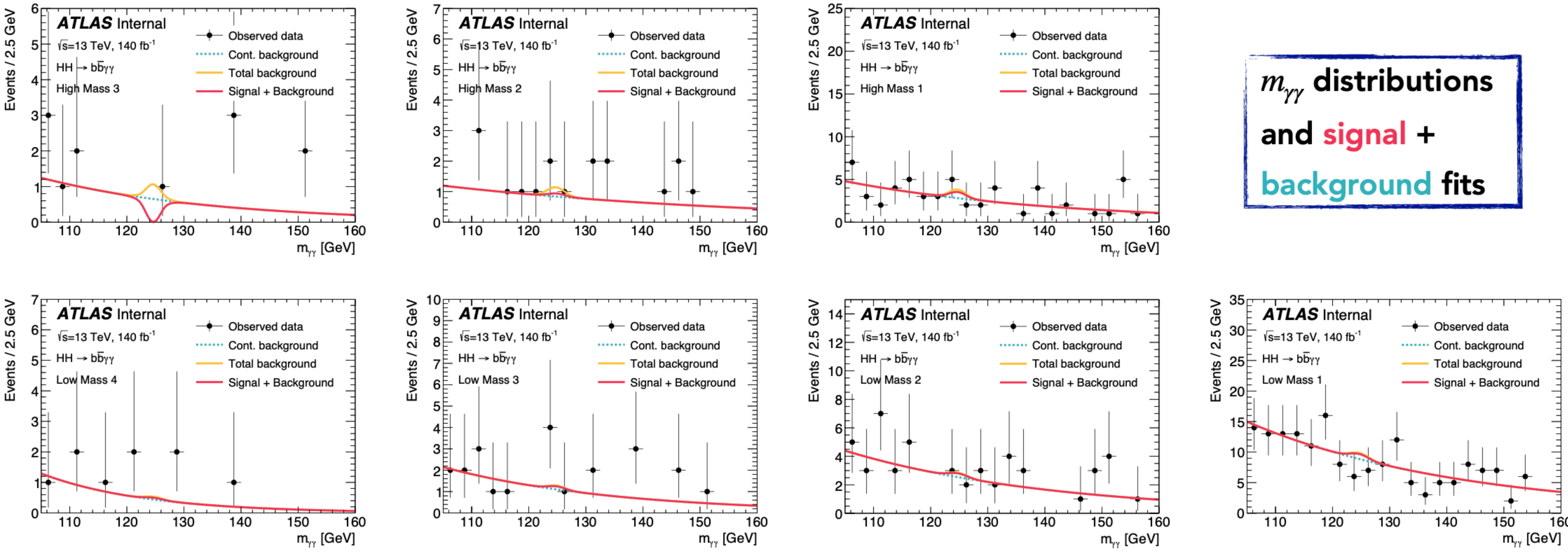
- The **sensitivity** of the **Legacy** $HH \rightarrow b\bar{b}\gamma\gamma$ **analysis** is completely **dominated** by the limited **Run 2 statistics**!
- It is however interesting to study the **impact** of **systematic uncertainties** on the upper limits on $\mu_{\mathbf{HH}}$.
  - ➡ Evaluated by **fixing** the corresponding **NPs** to the **best-fit** values and **repeating** the **limit calculation**.

Source	Type	Observed Upper limit	Observed Difference w.r.t. full syst.	Expected Upper limit	Expected Difference w.r.t. full syst.
Experimental					
Photon energy scale	Norm. + Shape	3.97	+0.34%	5.03	-0.13%
Photon energy resolution	Norm. + Shape	3.97	+0.22%	5.02	-0.37%
Jet energy scale and resolution	Normalization	3.97	+0.35%	5.03	-0.05%
Flavor tagging	Normalization	3.97	+0.31%	5.03	-0.10%
Theoretical					
Factorization and renormalization scale	Normalization	3.81	-3.71%	4.80	-4.76%
PDF set and α_S value	Normalization	3.97	+0.33%	5.03	-0.08%
Parton showering model	Normalization	3.97	+0.25%	5.03	-0.13%
Heavy flavor content	Normalization	3.96	+0.04%	5.03	-0.14%
$BR(H \rightarrow \gamma\gamma, b\bar{b})$	Normalization	3.97	+0.21%	5.02	-0.20%
Spurious signal	Normalization	3.98	+0.45%	5.03	-0.002%

- The impact of the **spurious signal** uncertainty is **suppressed** w.r.t. the previous ggF 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!

$m_{\gamma\gamma}$ distributions and signal + background fits

- After unblinding the signal region, we are able to **fit** the $m_{\gamma\gamma}$ **distributions** for **observed data** in the full window $\mathbf{105 \leq m_{\gamma\gamma} \leq 160}$ **GeV**!
- In particular, we tried to perform:
  - A **signal** + **background** fit → The signal strength $\mu_{\mathbf{HH}}$ is left floating in the fit.
  - A **background only** fit → The signal strength $\mu_{\mathbf{HH}}$ is fixed to 0.



$m_{\gamma\gamma}$ distributions and signal + background fits

$m_{\gamma\gamma}$ distributions and background only fits

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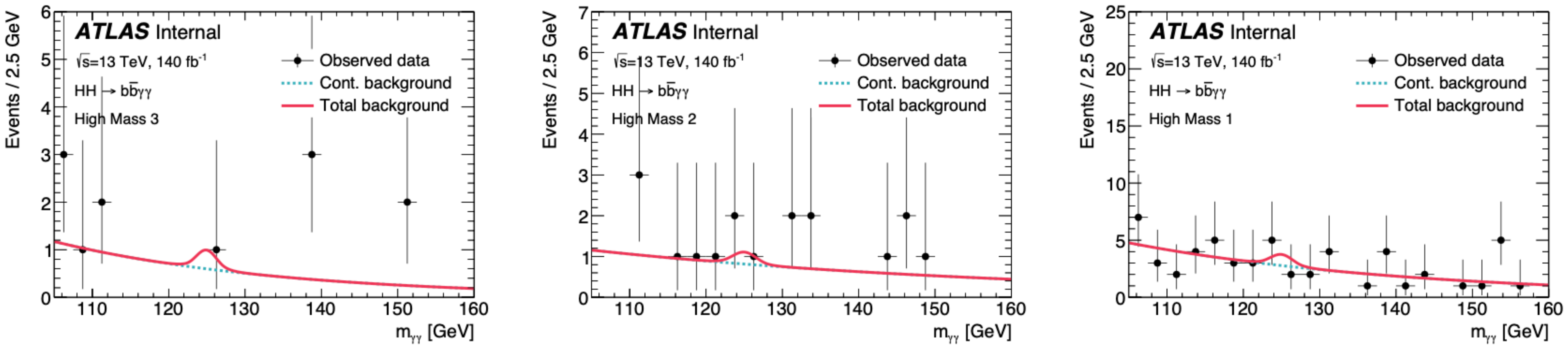
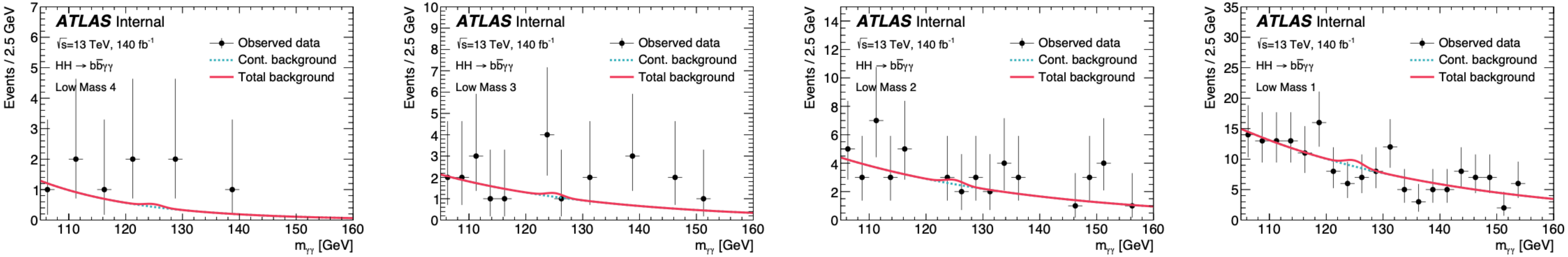


$m_{\gamma\gamma}$ distributions and background only fits



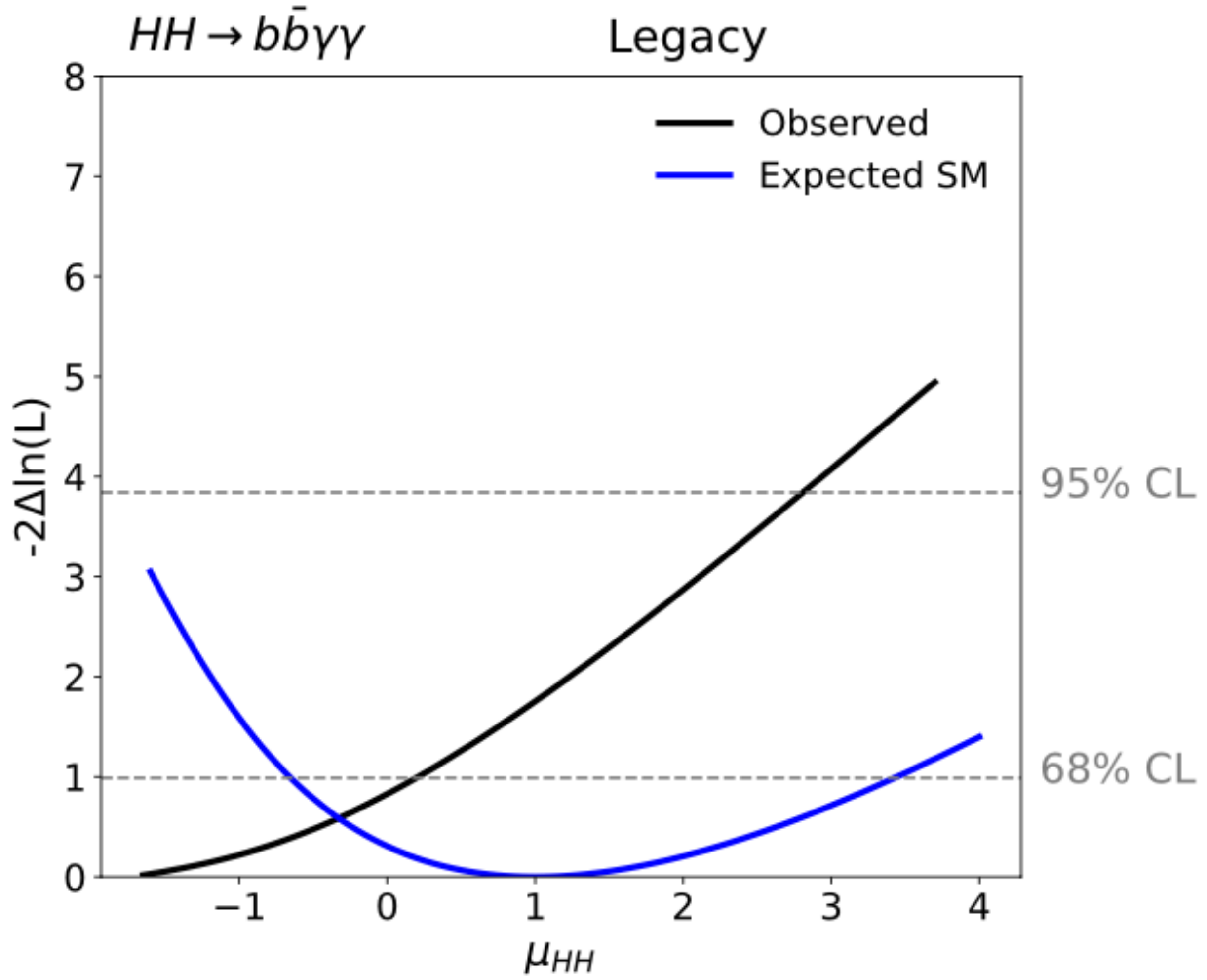
Cross checks on μ_{HH}

- As a first step, after unblinding, we tried to extract the **best-fit** value for the **HH signal strength** on observed data.

➡ $\hat{\mu_{HH}}$ = -1.72333 ± 0.00293424 ➡ **Caveat**: the fit status shows a failed fit, hinting that this result is unreliable.

- This negative $\hat{\mu_{HH}}$ is caused by the large **deficit** in our **most sensitive** categories.
  - ➡ We have a **smaller** number of **observed events w.r.t. background only** expectation in the **peak region**.
  - If we allow μ_{HH} to assume negative values, the fit prefers to assign a negative value to $\hat{\mu_{HH}}$, rather than pulling our NPs to cover the deficit!

    ➡ μ_{HH} is unconstrained, while the NPs have a gaussian / log-normal / asymmetric constraint around their central value!



- The **HH peak** is not simply negative, but the signal p.d.f. **touches zero**!
- The $\hat{\mu_{\mathrm{HH}}} \sim -1.7$ **value** is **not a real minimum of the likelihood**, but simply the threshold after which the likelihood starts to become negative.

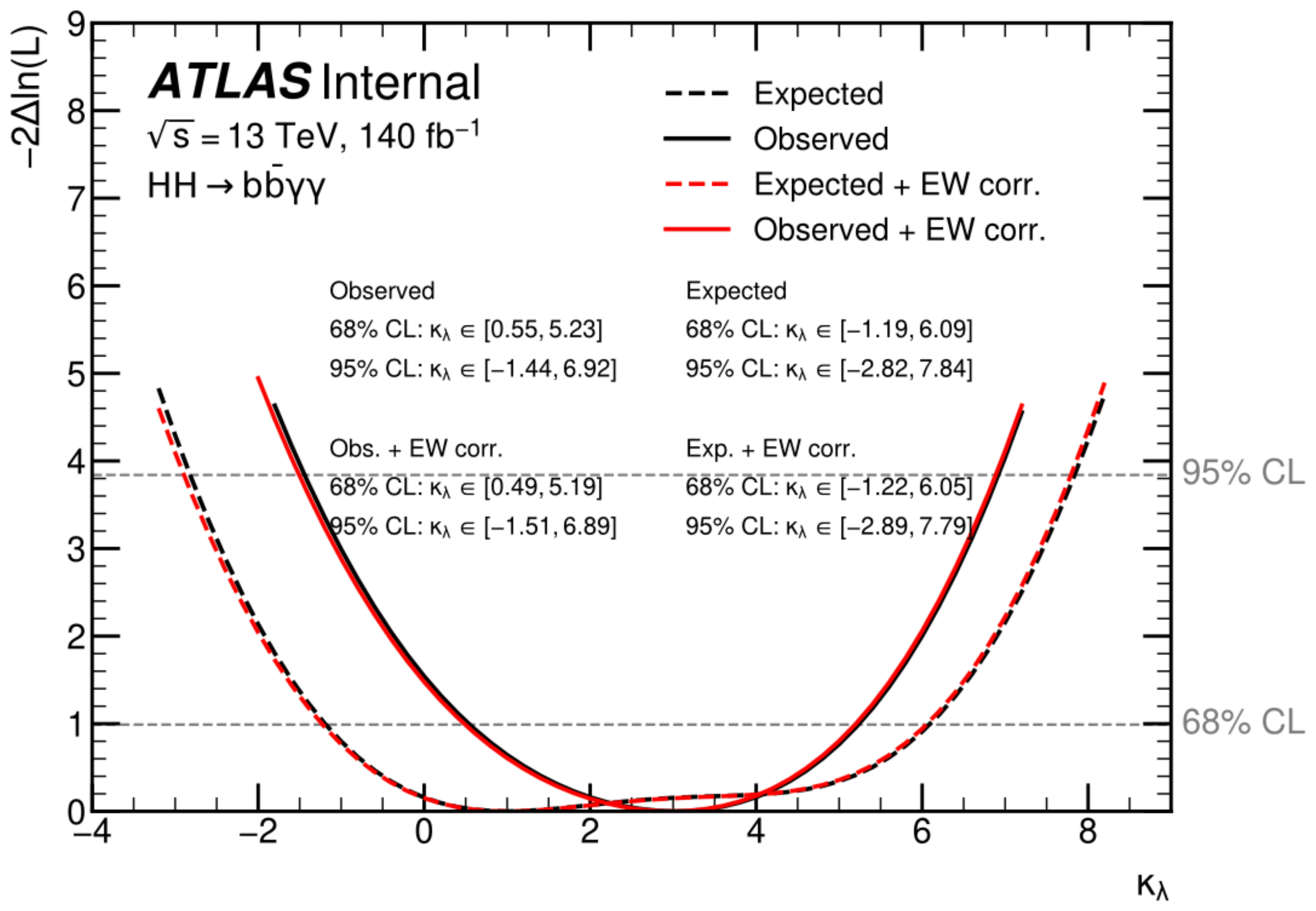
  ➡ This fit result is **not physical**.

Parametrization of the single Higgs processes as a function of κ_λ

- In addition to the sensitivity to κ_λ from **di-Higgs** production, the **likelihood-based interpretation** allows to exploit the **additional constraints** to κ_λ via the **single Higgs** processes.

  → **Single Higgs** processes are **affected** by κ_λ via **electro-weak corrections** to the tree-level diagrams!

→ We tried to include in our statistical model the **parametrization of the single Higgs processes** as a function of κ_λ and repeat the **likelihood scan**, either **considering** or **neglecting** the **EW corrections**.



- The impact of the **single Higgs** processes on the κ_λ **constraints** seems to be **very small** for our analysis!

  → A **minimal change** ($\sim 1\,\%$) of the **68% and 95% confidence intervals** is observed when **including the EW corrections**.

di-Higgs Run 2 Legacy $bb\gamma\gamma$ status report

Comparison with the previous ggF full Run 2 $HH \to b\bar{b}\gamma\gamma$ analysis

- A **previous** $HH \to b\bar{b}\gamma\gamma$ analysis was performed using the full Run 2 ATLAS data.
- It is interesting to evaluate the **improvement** and the **compatibility** of the **new Legacy** analysis, w.r.t. the **previous ggF-based analysis**.

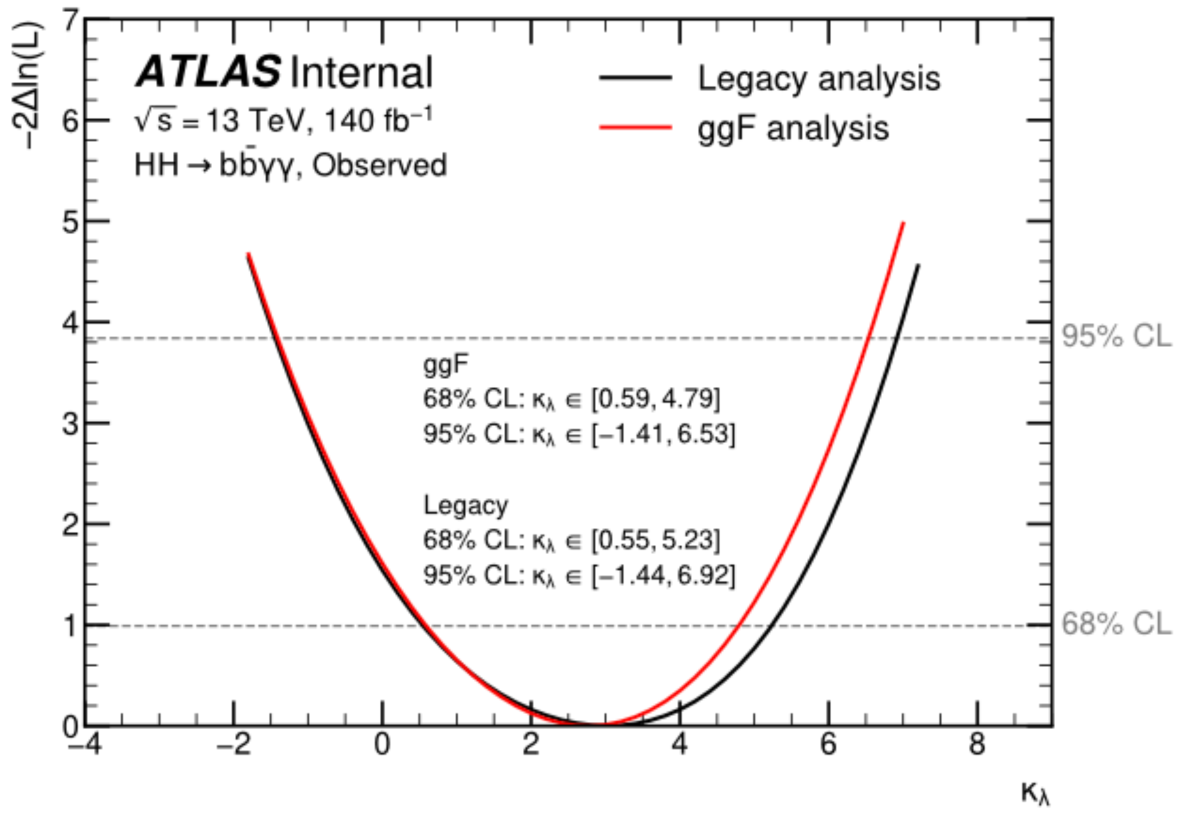
  - **Previous full Run 2 ggF analysis** → **Optimized** based on the **dominant ggF HH** production mode.
    → Placed upper limits on μ_{HH} and an set constraints on κ_λ.
  - **This full Run 2 Legacy analysis** → **Optimized** based on the **two ggF HH** and **VBF HH production modes**!
    → This ideally allows to extract the **best sensitivity** to **anomalous κ_λ values**, and provides a unique handle to κ_{2V}!

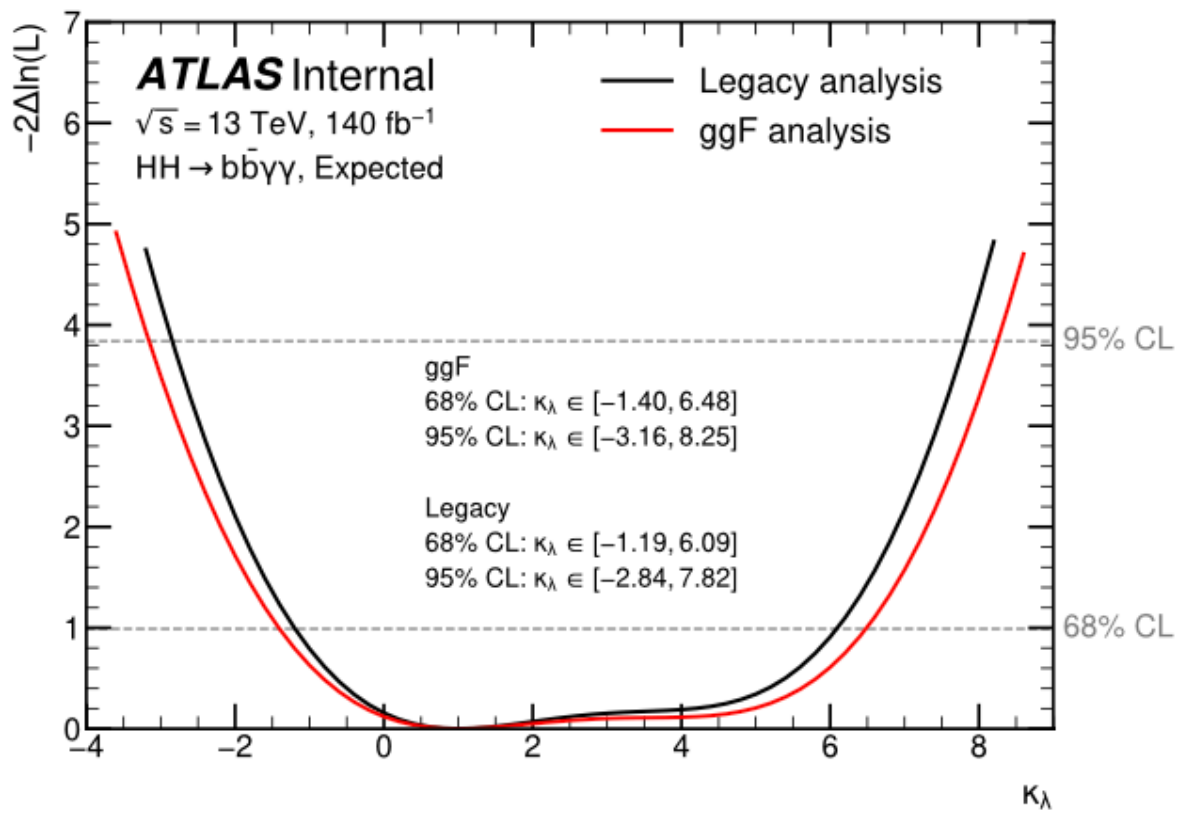
Upper limits on μ_{HH}

	Observed	Expected
ggF analysis	4.2	5.7
Legacy analysis	3.96	5.03
Difference [%]	-5.7%	-11.9%!

→ **6% (12%)** tighter **observed** (**expected**) constraints on the **HH signal strength** are placed by the Legacy analysis, w.r.t. the ggF analysis!

95% CL κ_λ constraints from $-2\Delta\ln(\mathrm{L})$





→ The **observed** 95% CL constraints on κ_λ are **slightly degraded** (by $\sim 5\,\%$), while the **expected** constraints **improve** by a factor of $\sim 9\,\%$!

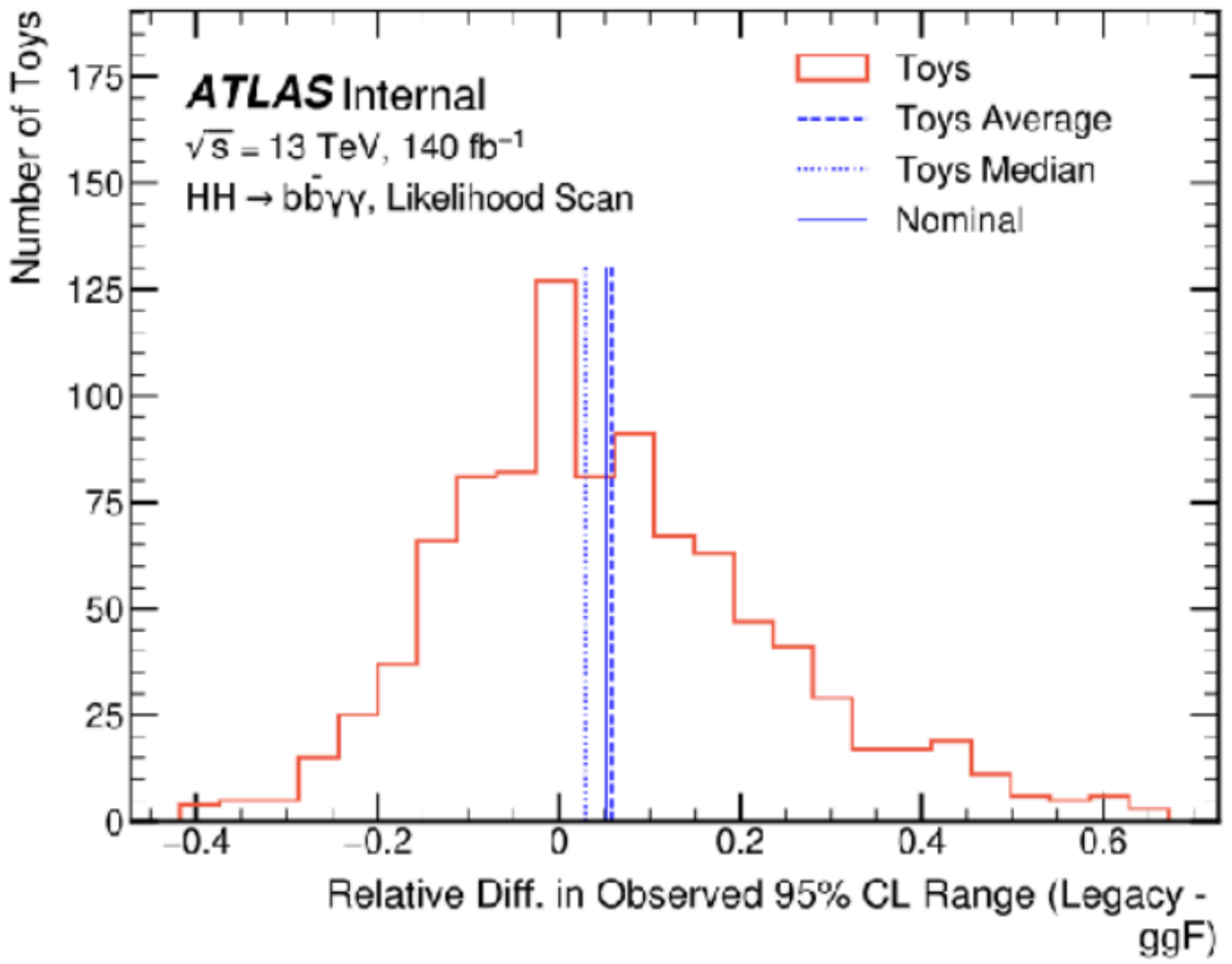
Compatibility with previous ggF full Run 2 $HH \to b\bar{b}\gamma\gamma$ analysis

1. The **observed constraints** on the **coupling modifier** κ_λ placed by the **Legacy** analysis are **slightly worse** that those provided by the **ggF analysis**.
2. The Legacy and ggF analyses rely on the **same full Run 2 dataset**!

Interesting to study the **compatibility** of the observed κ_λ **constraints** set by the two analyses!

In practice:

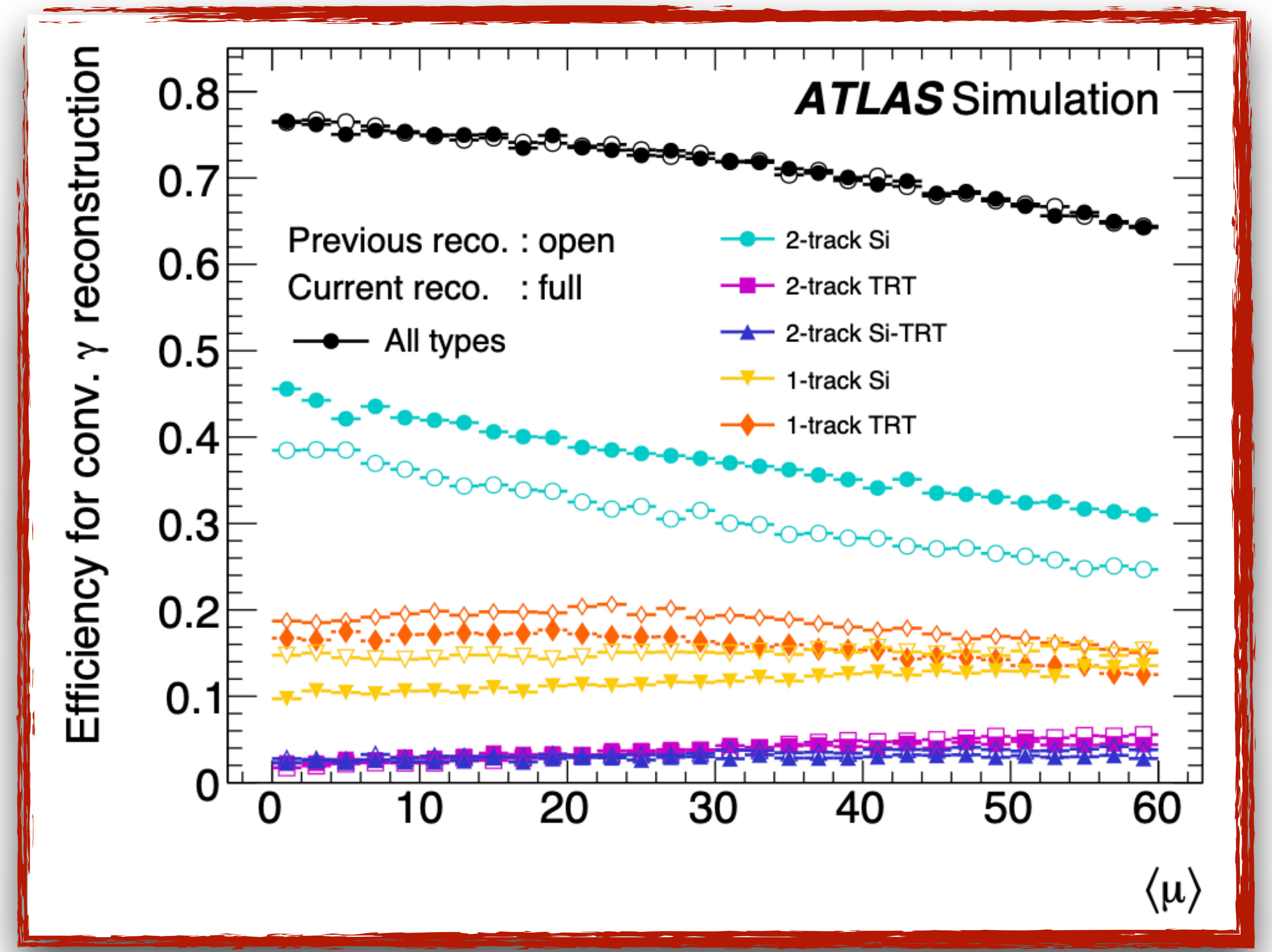
- Perform a **bootstrap study**. → **Fluctuate** the **data events** using a **poisson weight** λ with average = 1, $\times$ **1000** times, creating **1000 replicae** of the dataset.
- For each **replicated** dataset, evaluate the **95% CL constraints** on κ_λ from both the **Legacy** and the **ggF** analysis and fill an histogram with the **relative difference** between these two quantities.

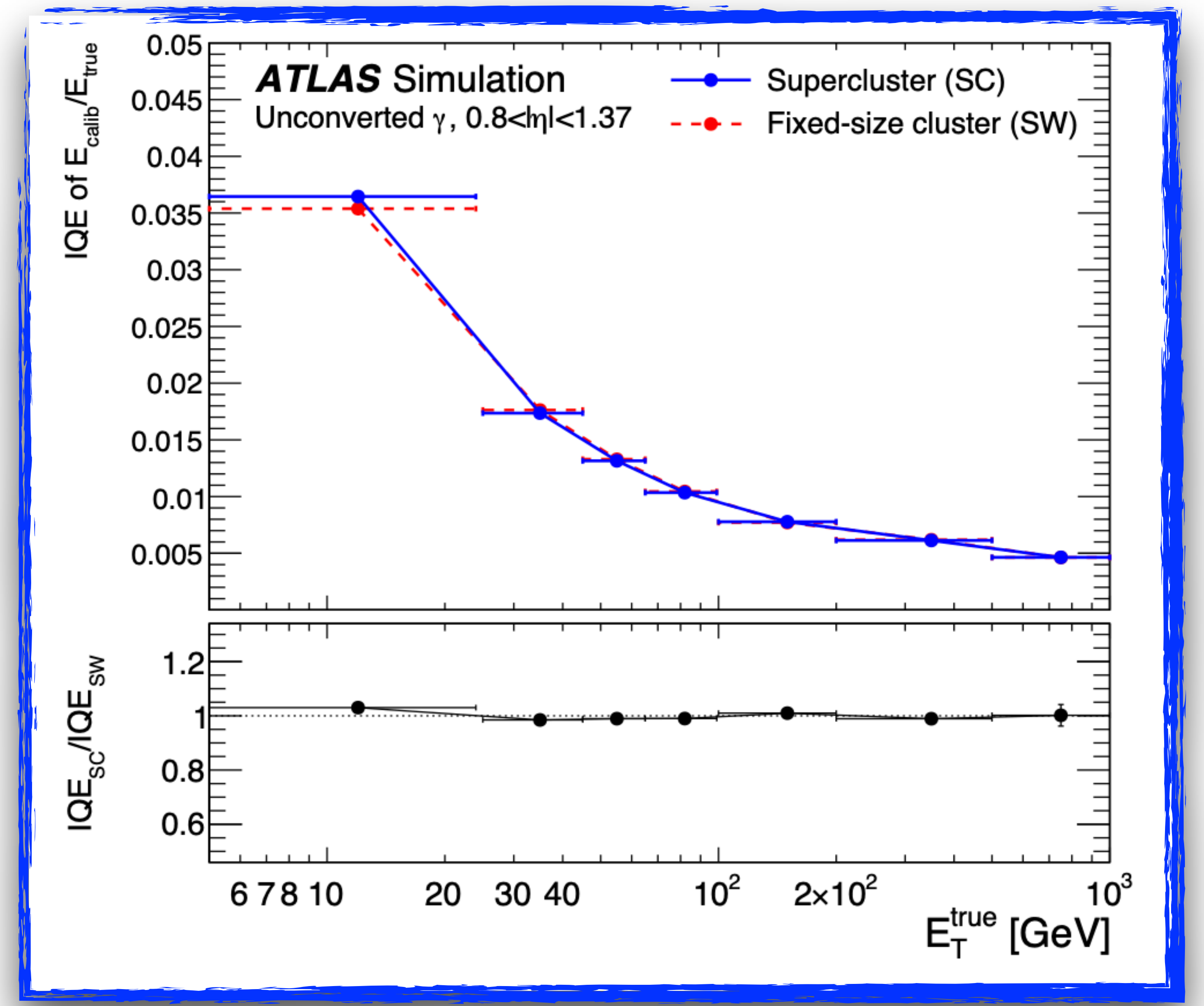


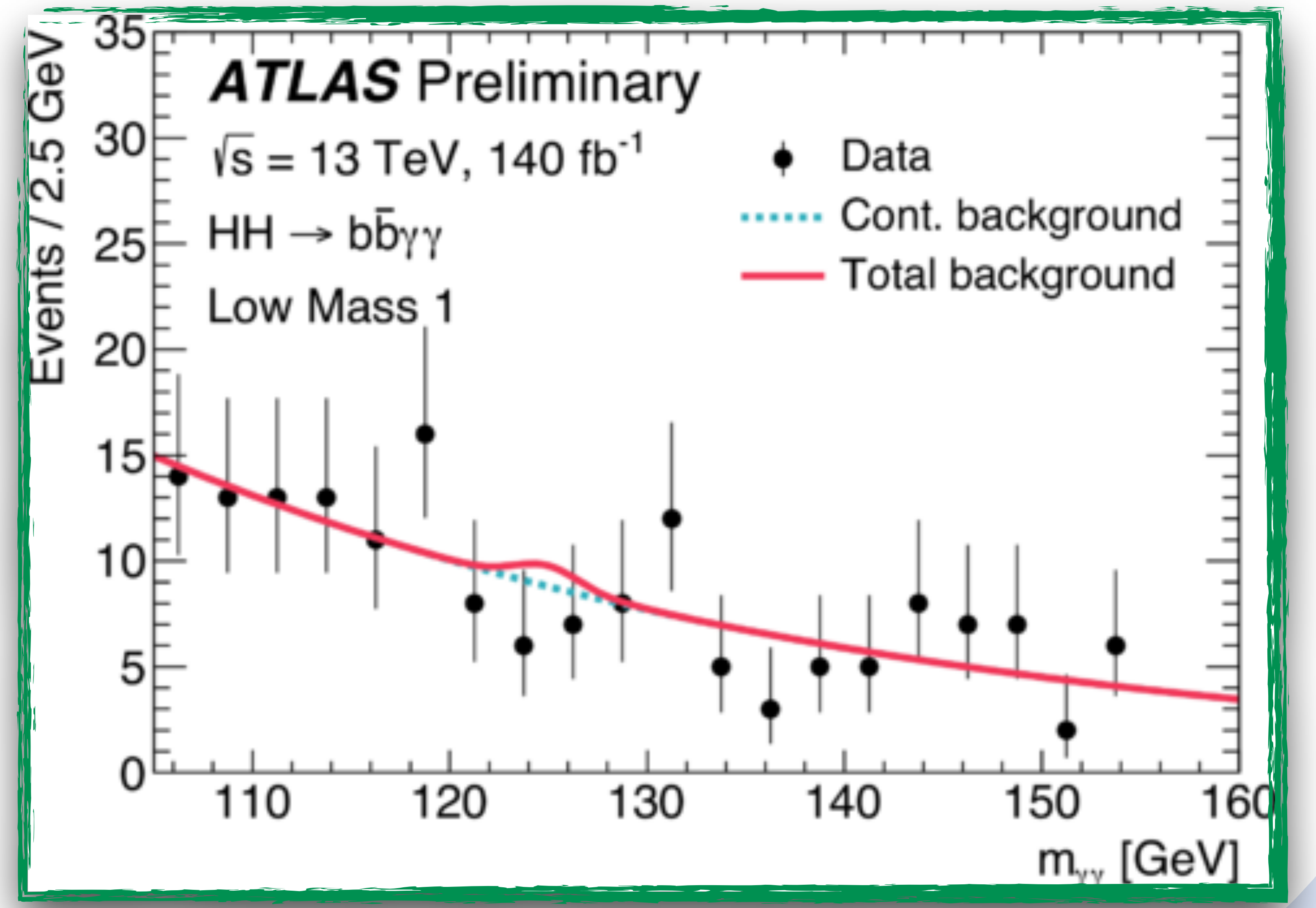
- **Mean**: Rel. difference between 95% CL constraints on κ_λ. → Legacy - ggF.
- **Width**: Statistical error on 95% CL constraints on κ_λ (Legacy) - 95% CL constraints on κ_λ (ggF) .
  - The **difference** between the **95% CL constraints** on κ_λ set by the Legacy analysis and those obtained with the ggF analysis is **compatible with zero** within the error from the stat. fluctuations in data!
  - The two **observed** κ_λ **constraints** set by the two analyses are **compatible**.

Background modelling with analytic functions

- Analytical functions are used to model backgrounds directly from data
- Typically, analytical functions in the background modelling are used when the invariant mass $m_{\gamma\gamma}$ is the discriminating variable and the main background comes from the non resonant $\gamma\gamma$ continuum spectrum
- The **high reconstruction efficiency** and low **energy resolution** of objects allows the search/measurements directly on the **mass of the reconstructed $\gamma\gamma$ system**
  - Analytical functions are used to describe the falling background on $m_{\gamma\gamma}$
- "*spurious signal*" study is crucial to choose the function form and estimate modelling uncertainties



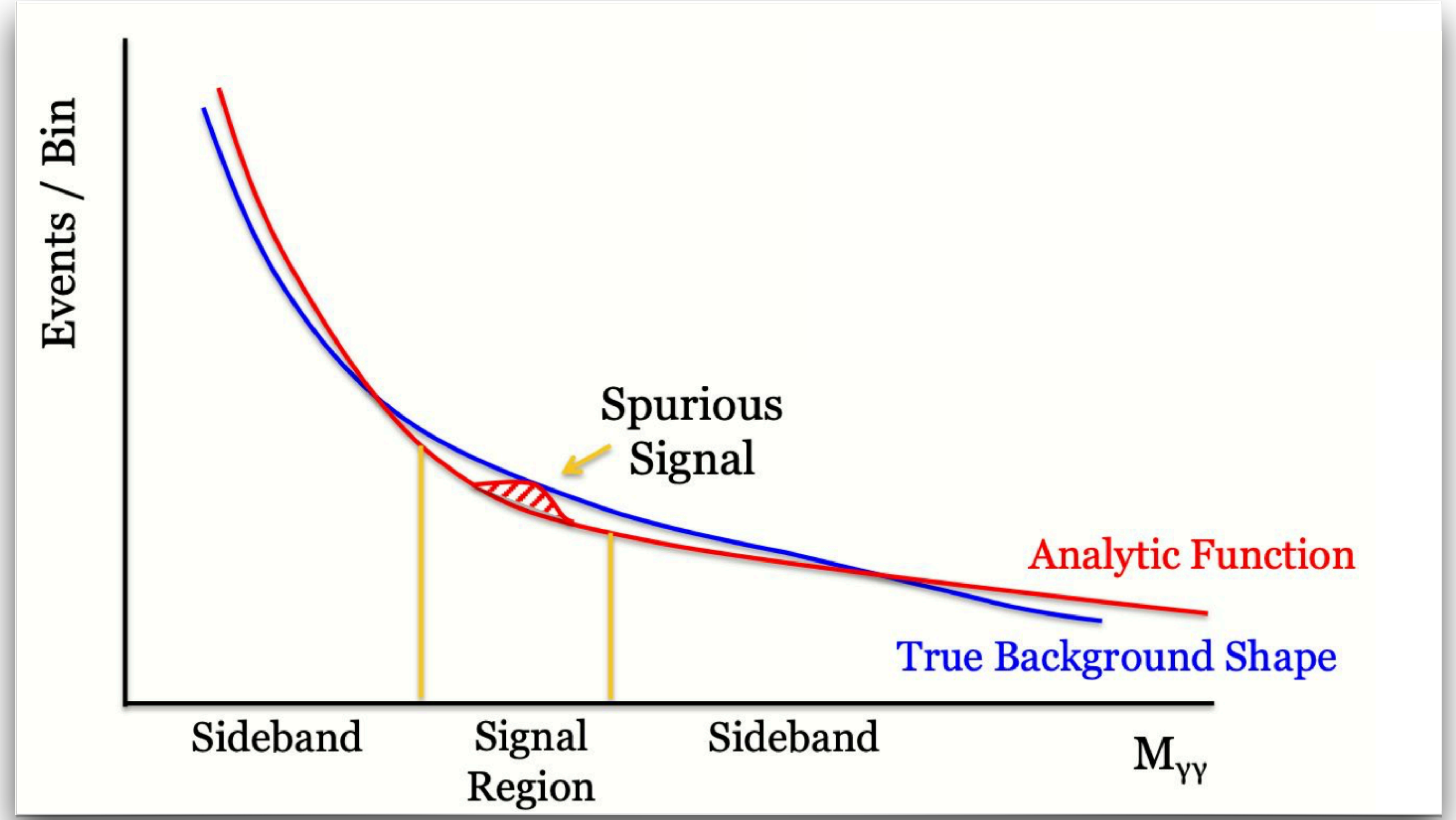




inspired by Shuo's slides, Higgs Workshop 2023

Spurious signal as a measure of potential bias

- When using S + B pdf to fit the bkg-only distribution, if the shape of the bkg-only distribution and pdf has **intrinsic difference**, the fitted signal yield would not be zero. That **non-zero fitted signal yield** is referred to as the **spurious signal**
- Here, the spurious signal can be considered as a measure of the bias introduced to the fitted signal yield by the **intrinsic difference in shape** between the analytic function and background
- In practice, our MC sample provides an approximation of the true background shape, and the spurious signal is an estimate of the bias arising from the shape difference between the analytical function and the background MC



Interpolate from the sidebands into the signal region using an analytic function

Spurious signal method

The **best functional form** for modeling the continuum background is chosen as a **compromise** between having a **minimal number of degrees of freedom** and a **small bias**!

The chosen functional form has to pass the (**relaxed**) **spurious signal test**:

- $|N_{sp}| < 10\% \cdot N_{S,exp}$ — Expected signal yield according to the SM.
- $|N_{sp}| < 20\% \cdot \sigma_{bkg}$ — Stat. uncertainty on the fitted number of signal events on the bkg template.

If no function satisfies these conditions, the test is further **relaxed** by replacing N_{sp} with ζ_{sp}, where:

$$\zeta_{sp} = \begin{cases} N_{sp} + 2\Delta_{MC} & \text{if } N_{sp} + 2\Delta_{MC} < 0 \\ N_{sp} - 2\Delta_{MC} & \text{if } N_{sp} - 2\Delta_{MC} > 0 \\ 0 & \text{otherwise} \end{cases}$$

Δ_{MC}: Local stat. fluctuations of the background template.

Measured by performing **S+B fits** on a **background-only template**!

- The number of signal events is extracted for different values of $m_H \in [123,127]$ GeV with steps of 0.5 GeV.
- **Bias** (i.e. **spurious signal**) of the tested functional form → **largest signal yield** in the m_H window!