

# Are pair of Higgs bosons more interesting than just one?



Louis D'Eramo,  
*Northern Illinois University*





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# Investigating the Higgs potential



The full expression of the Higgs potential is encoded with parameters  $\mu$  and  $\lambda$  as:

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

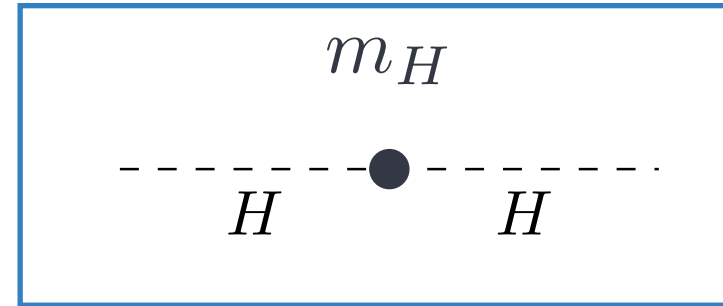
When linearising the Higgs field after the EWSB around the vacuum expected value  $\nu$  one gets:

$$V(H) \supset \underbrace{\frac{\mu^2}{2} H^2}_{\frac{1}{2} m_H^2} + \lambda \nu H^3 + \frac{\lambda}{4} H^4$$

Where the potential parameters are linked by :

$$\nu = \sqrt{\frac{\mu^2}{\lambda}} = \sqrt{\frac{1}{\sqrt{2} G_F}}$$

Relationship between the electron charge, the weak boson masses, and the **Fermi Constant**.



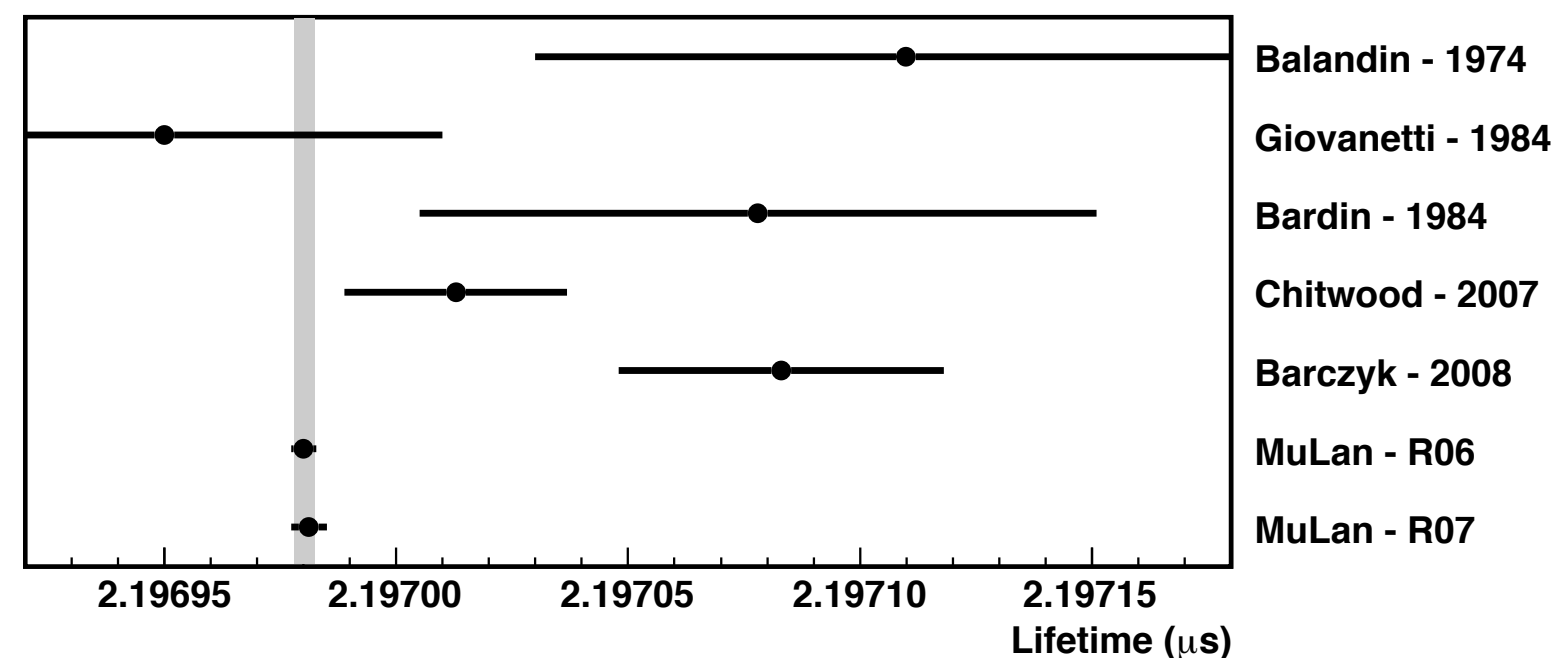
- ▶ The first piece of information came from the Higgs boson discovery:
  - ▶ Existence of a new particle with couplings according to prediction from EWSB;
  - ▶ First measurement of Higgs mass:

$$m_H = 125.09 \text{ GeV} \leftrightarrow \mu = 88.45 \text{ GeV}$$

- ▶ The **Fermi constant** can be determined thanks to the **muon lifetime measurement**:

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^2}{192\pi^3} (1 + \Delta q)$$

1010.0991



- ▶ From most precise MuLan experiment:

$$G_F = 1.1663788(7) \times 10^{-5} \text{ GeV}^{-2}$$

$$\hookrightarrow \nu \simeq 246.23 \text{ GeV}$$

$$\hookrightarrow \lambda \sim 0.13$$



# Investigating the Higgs potential

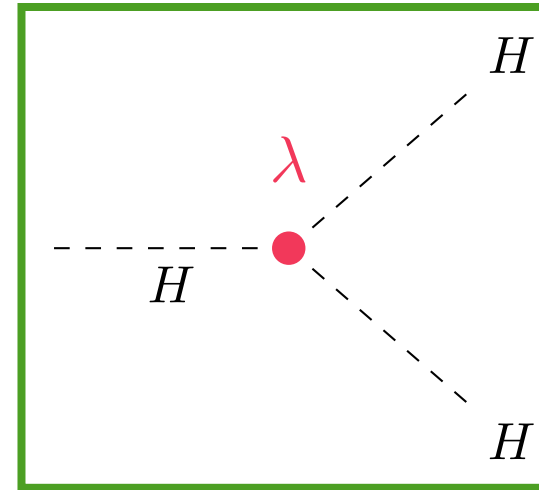


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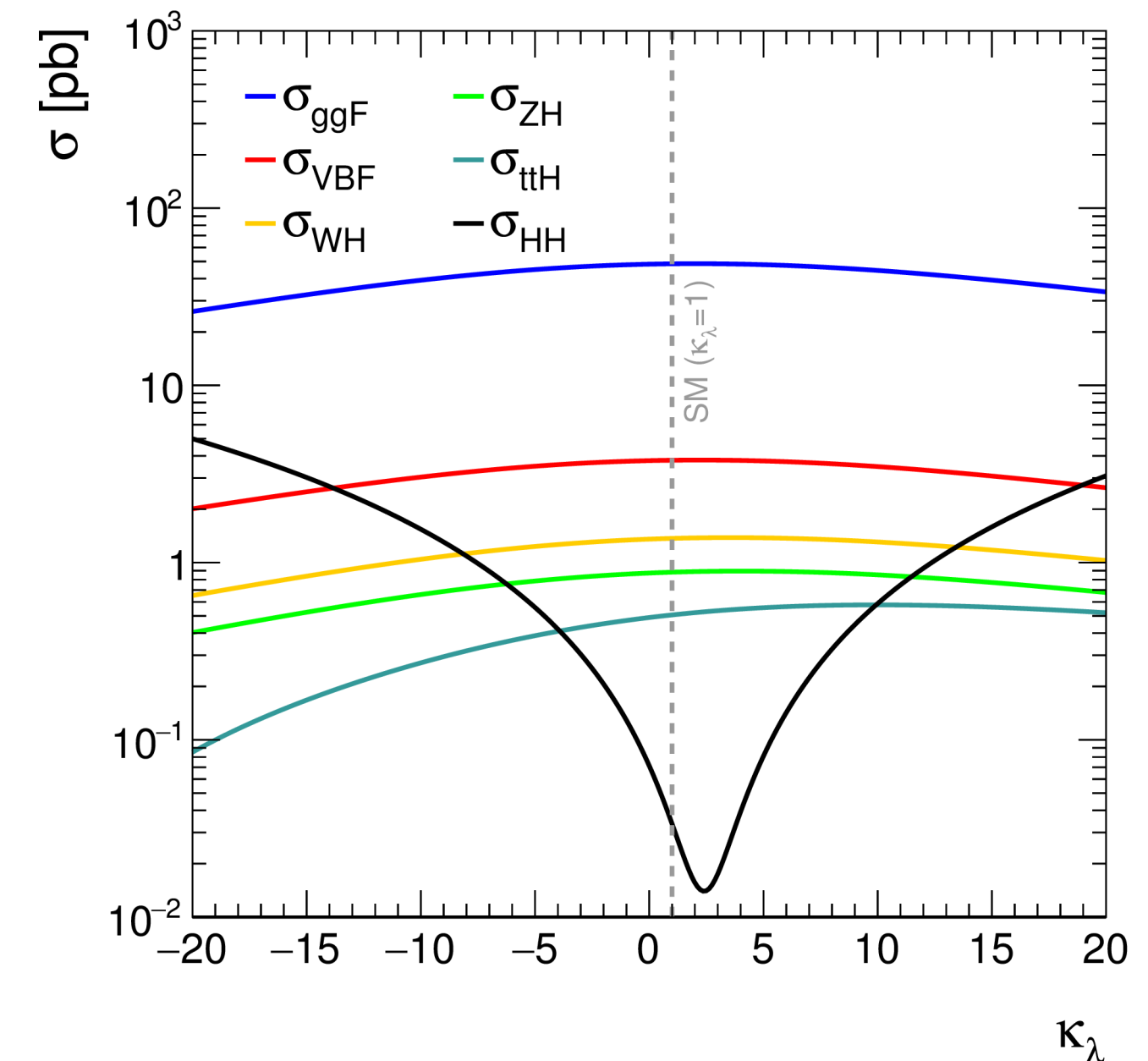
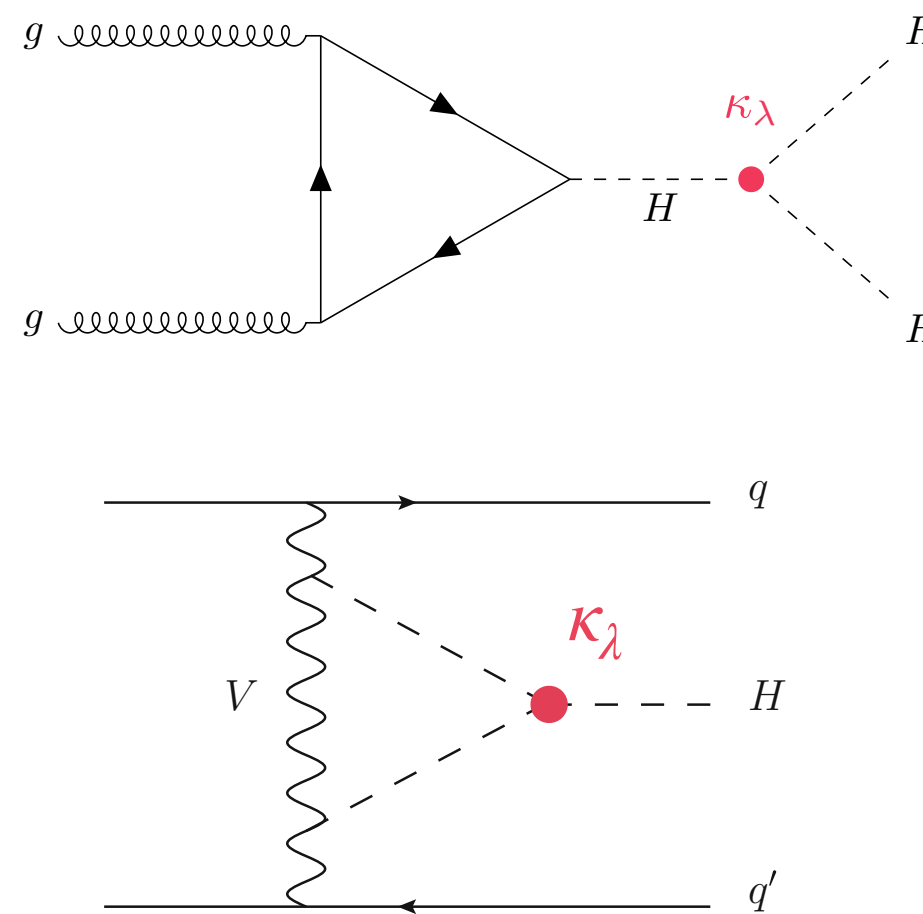
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$$V(H) \supset \underbrace{\mu^2 H^2}_{\frac{1}{2}m_H^2} + \lambda\nu H^3 + \frac{\lambda}{4}H^4$$



► Direct access to  $\lambda$  through Higgs pair creation:

- Coupling strength denoted as  $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$
- At tree level: production of pair of Higgs bosons → strong effect on XS.
- At loop level: effect on the single Higgs cross-section and deviations in kinematics.





# Investigating the Higgs potential

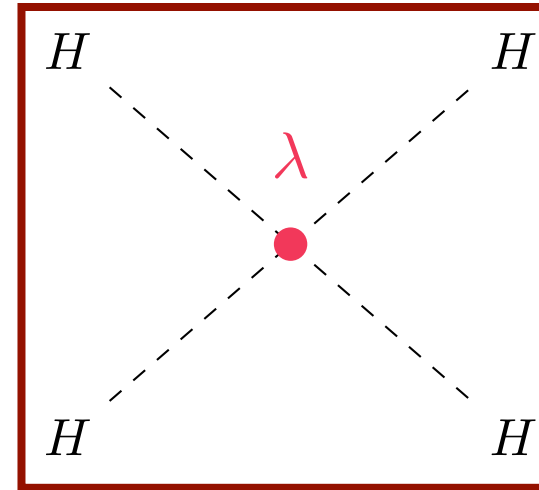


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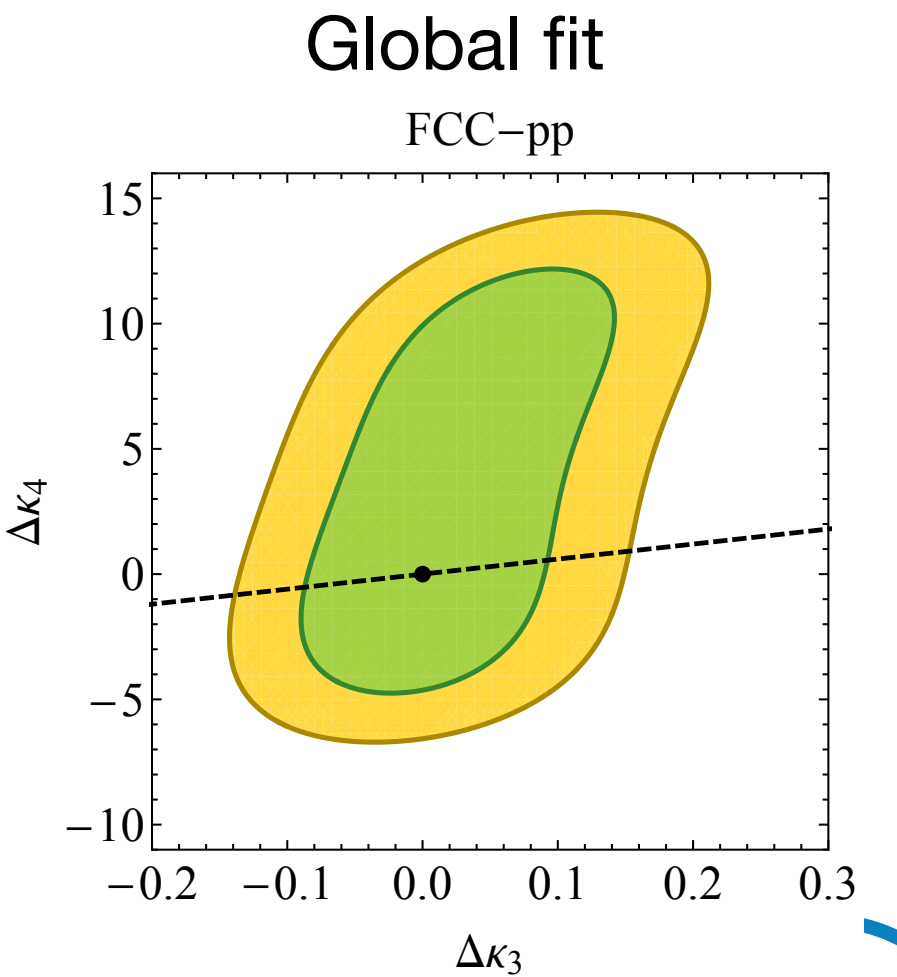
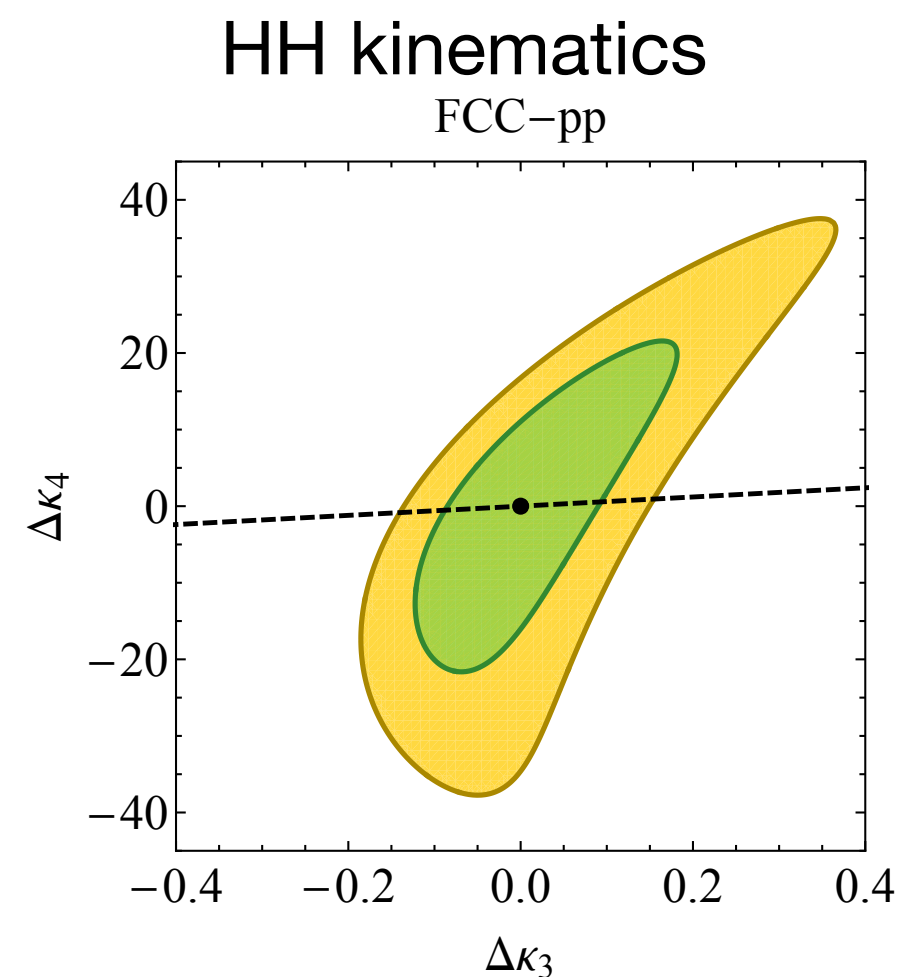
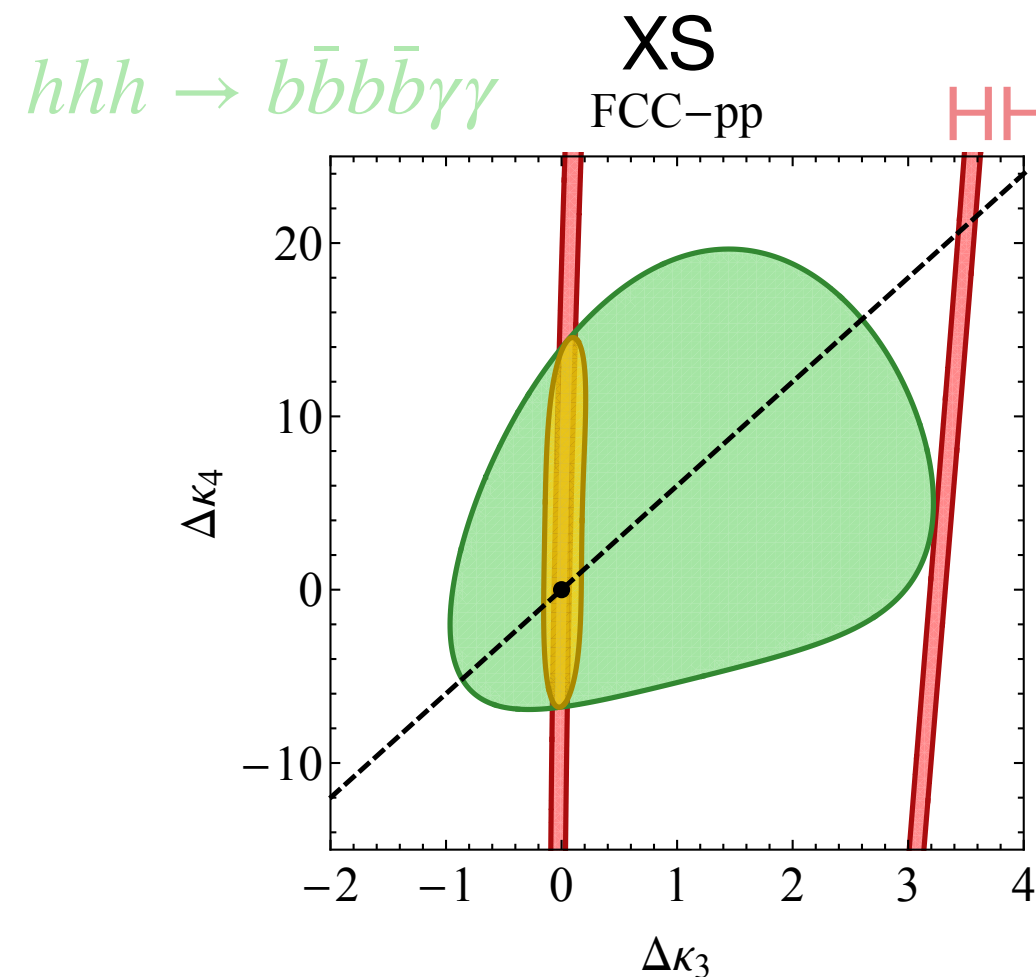
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► **Quartic interaction even rarer :**

- At tree level: very mild effect on XS and kinematic distributions.
- At loop level: similar constraints obtained on XS, but stronger effect kinematics.
- No strong constraints even with FCC 100 TeV collider ( $\kappa_4 \in [-3, 13]$ ) or the CLIC 3000 GeV ( $\kappa_4 \in [-5, 7]$ ).





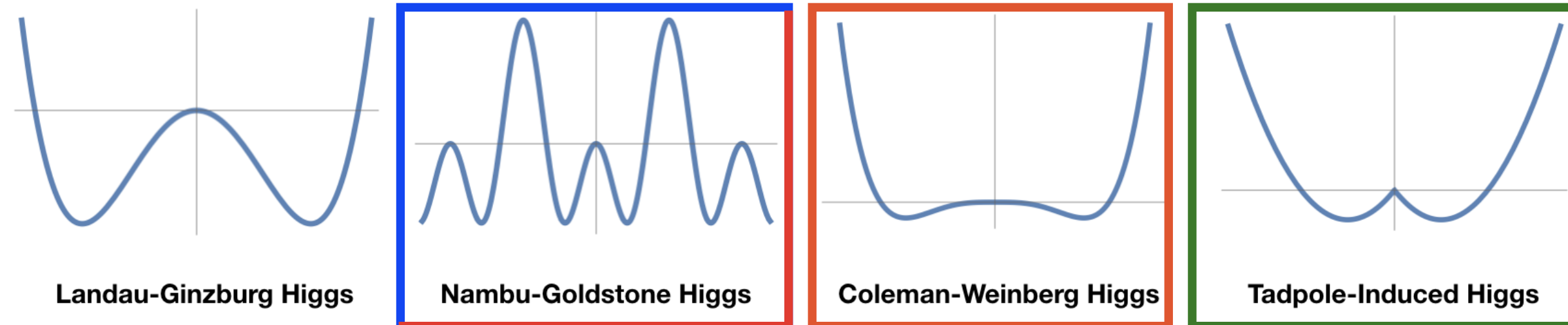
# Exploring alternative scenarios



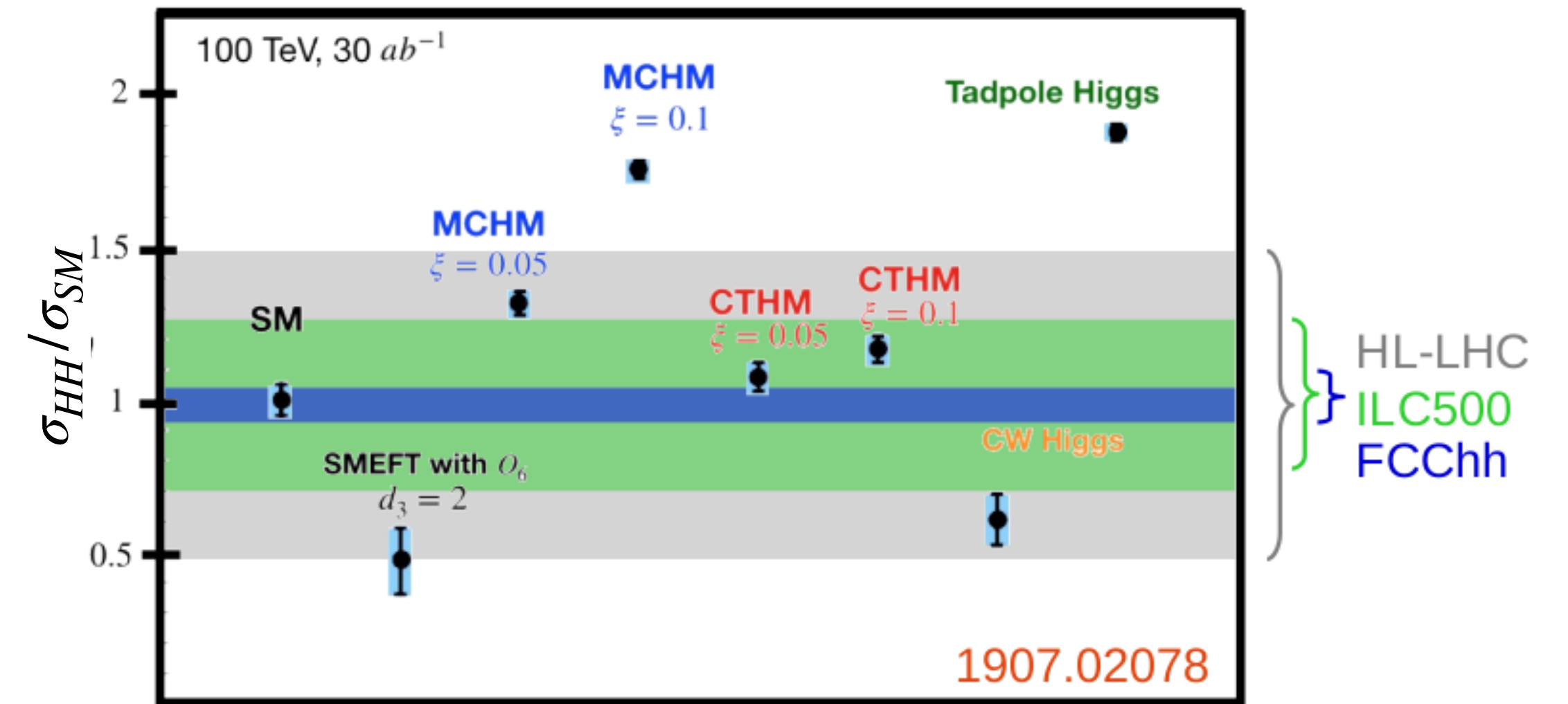
The measurement of the Higgs potential is answering the fundamental question of its nature.  
 Several other models can show a non zero vacuum expected value with a different second order contribution:

$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2} (H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

pseudo Nambu-Goldstone boson emerging from strong dynamics at a high scale  
 EWSB is triggered by renormalization group (RG) running effects  
 EWSB is triggered by the Higgs tadpole



minimal composite Higgs model/  
 composite twin Higgs model :  
 different coupling to top quark



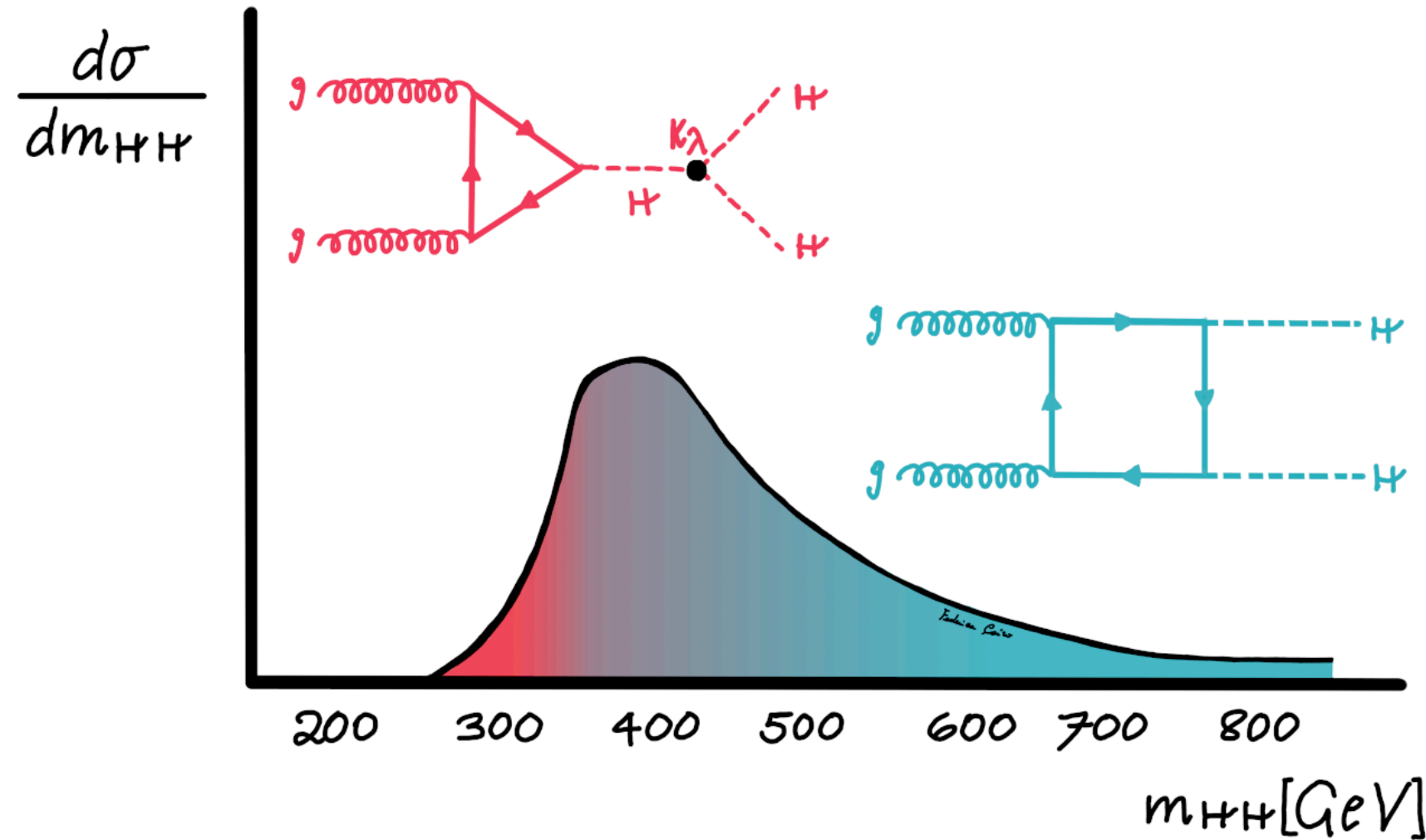
Courtesy of Elisabeth Petit

Models



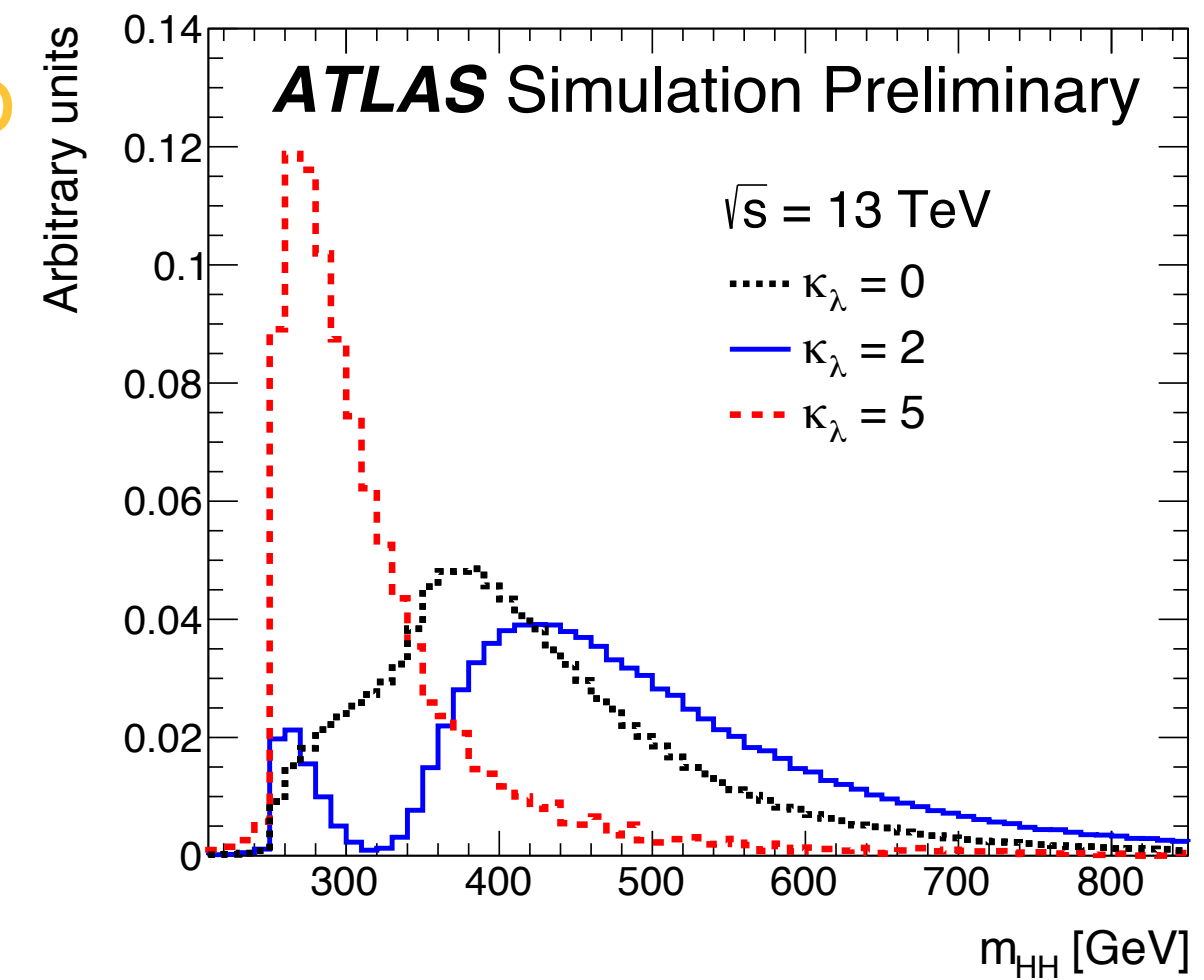


# How are Higgs pairs produced?



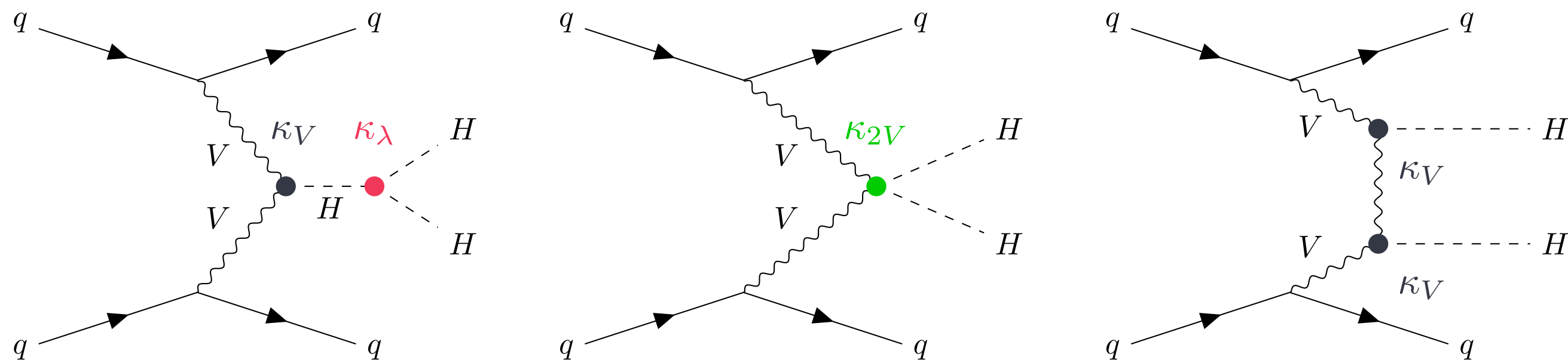
► **gluon-gluon Fusion (ggF):**  $\sigma_{HH}^{ggF} = 31.02 \text{ fb}$

- Destructive interference between **triangle** and **box** diagrams makes the cross-section tiny (1000x smaller than single Higgs).
- Low masses essential to constrain trilinear coupling  $\kappa_\lambda$
- $m_{HH}$  shape very dependent on the  $\kappa_\lambda$



► **Vector Boson Fusion (VBF):**  $\sigma_{HH}^{VBF} = 1.72 \text{ fb}$

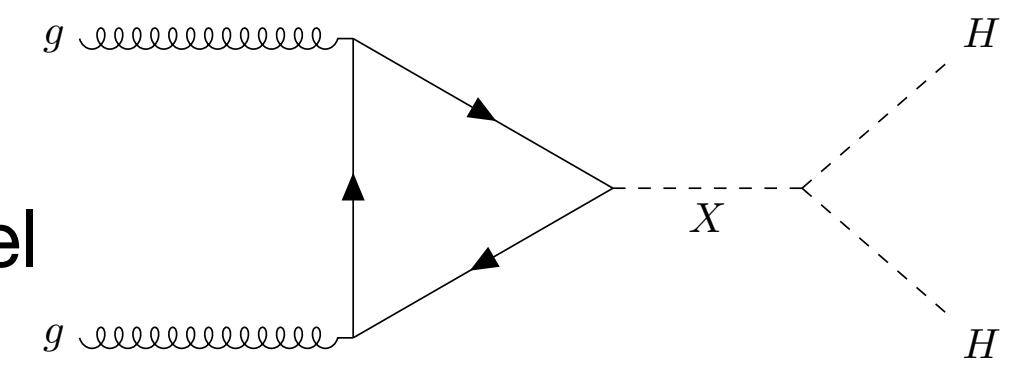
Second order contribution to total production, but direct handle to vector boson coupling modifiers  $\kappa_{2V}$  and  $\kappa_V$ :



## ► BSM resonances:

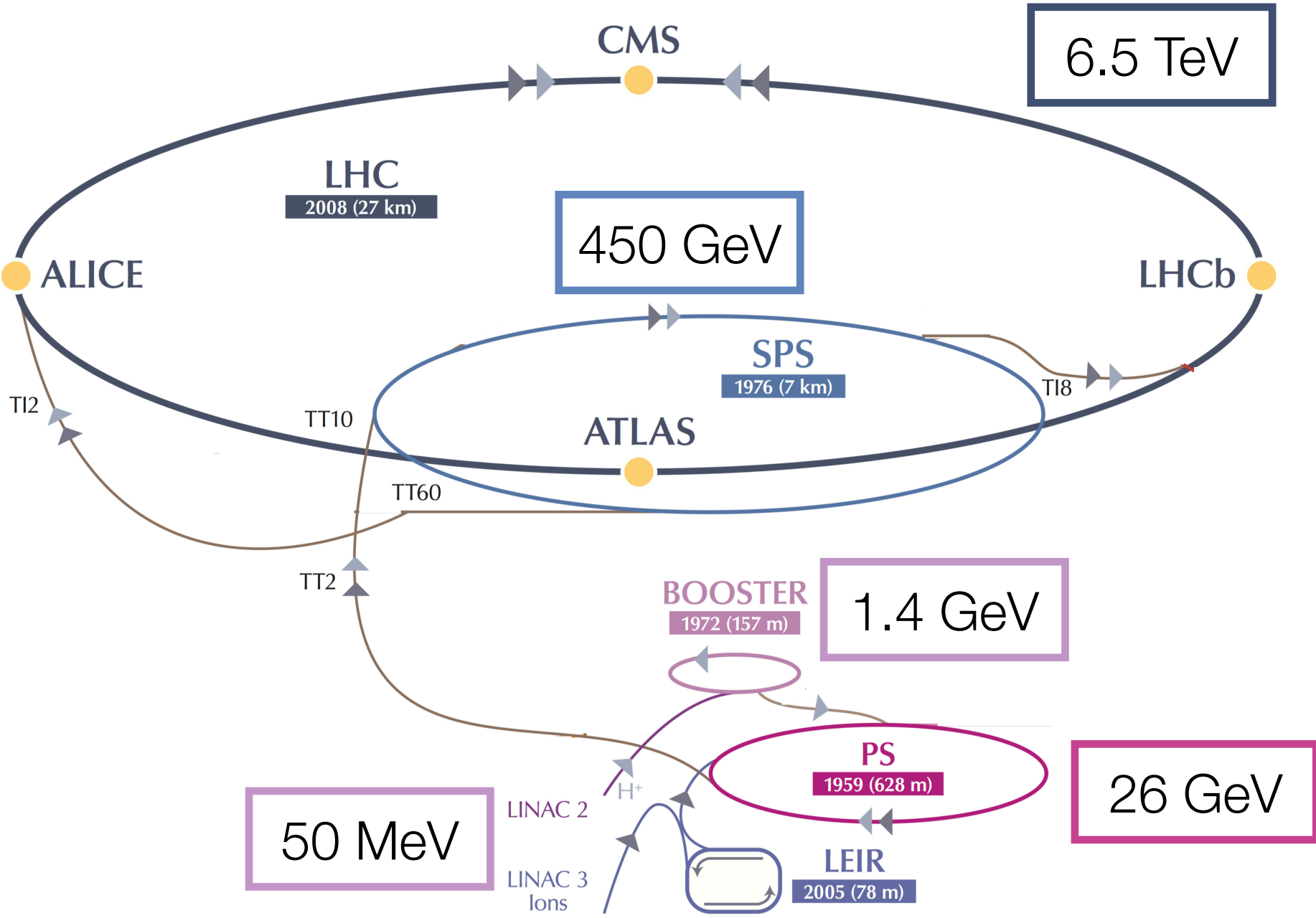
Possible increase in signal from new physics benchmarks:

- **Spin-0:** predicted by Two-Higgs-Doublet-Models and Electroweak Singlet models
- **Spin-2:** predicted by Randall-Sundrum (RS) model of warped extra dimensions





# The LHC: a (double) Higgs factory ?

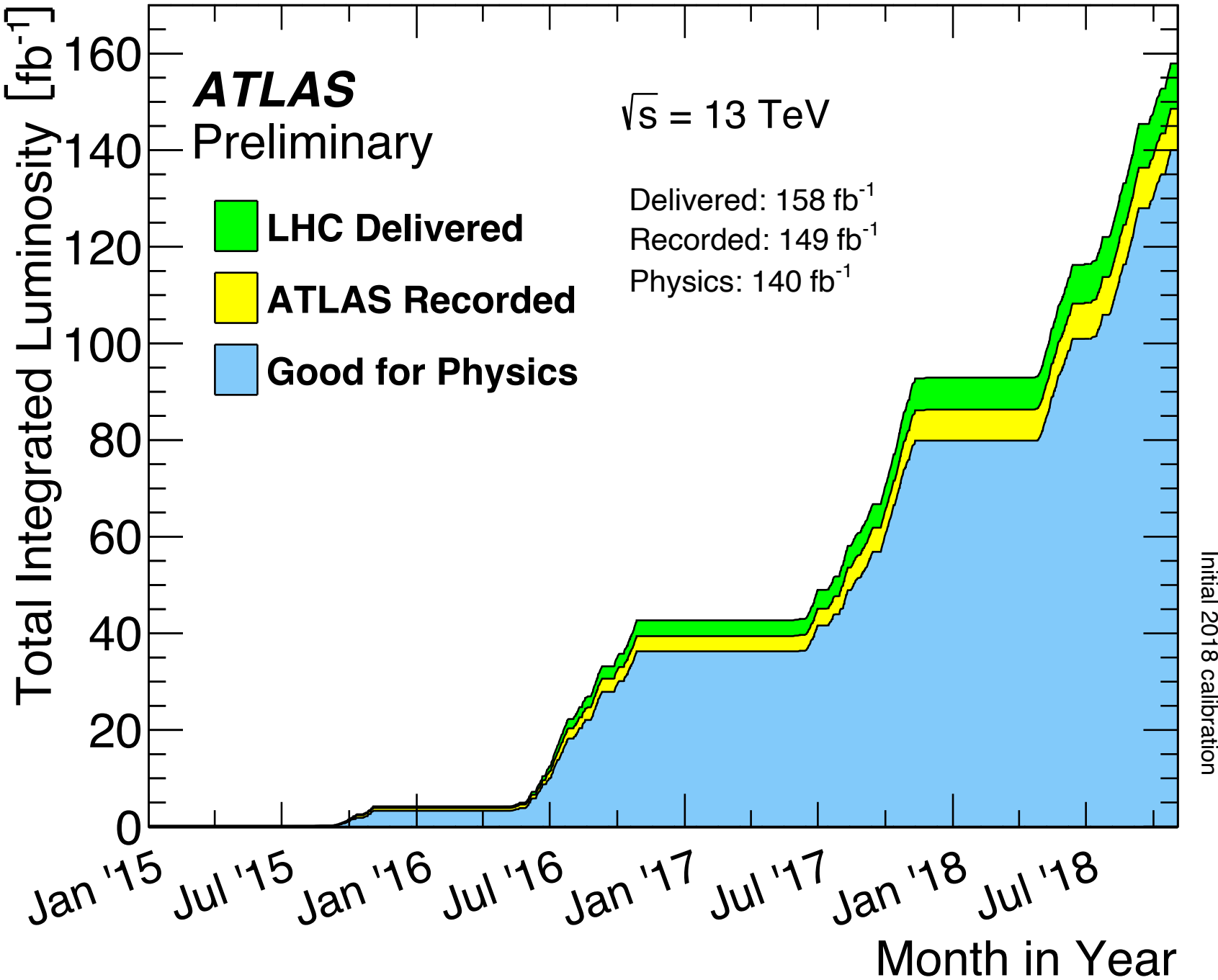


Located under the French Swiss Border, the **Large Hadron Collider** is the final piece of a staged acceleration chain allowing high luminosity **proton-proton** collisions.

With an unprecedented 13 TeV center of mass energy, it has allowed the ATLAS and CMS collaboration to record  $\mathcal{L} = 140 \text{ fb}^{-1}$  of data during the Run-2.

	$N_H$	$N_{HH}$
Run-1	512 000	200
Run-2	6 800 000	4 300
Run-3*	7 700 000	5 000
HL-LHC*	165 000 000	110 000

\*estimated

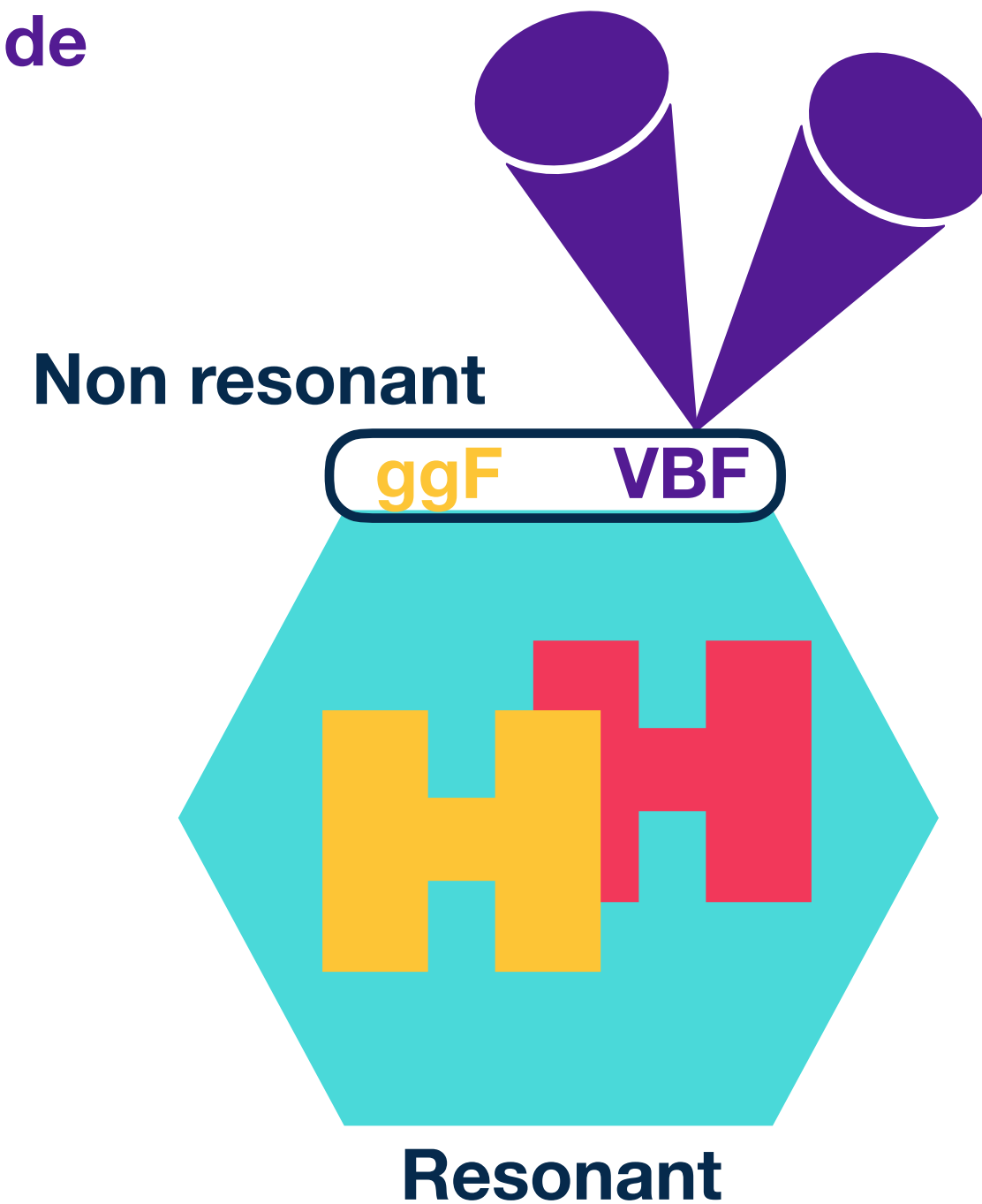




# How to look for Higgs pairs?



At the origin of the event, the **production mode** defines the **kinematics** of the two Higgs bosons as well as eventual **side products**.





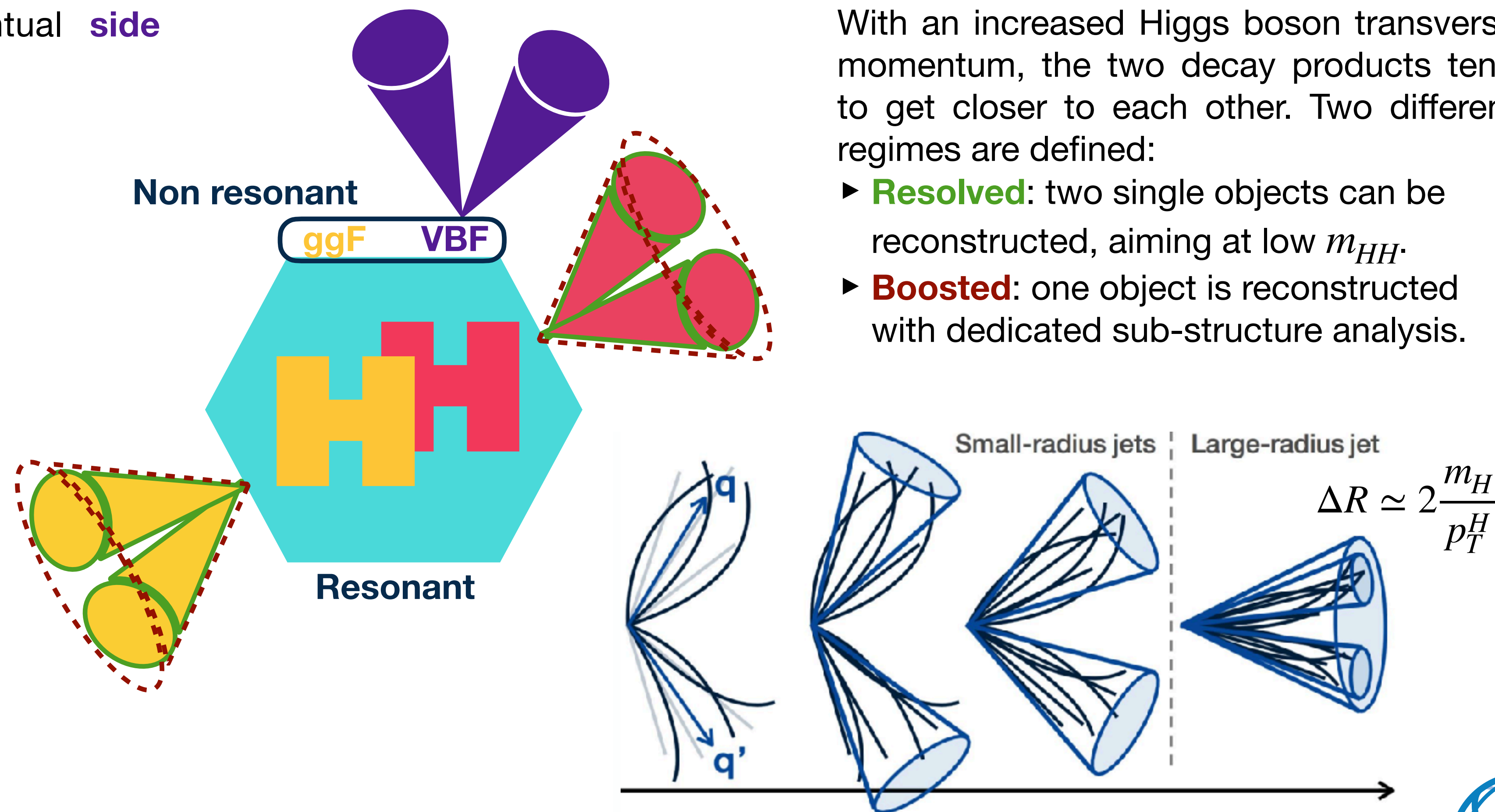
# How to look for Higgs pairs?



At the origin of the event, the **production mode** defines the **kinematics** of the two Higgs bosons as well as eventual **side products**.

Experimentally only the **decay products** of the Higgs bosons can be **measured**. They define the **strategy** of the analysis:

- ▶ Trigger ;
- ▶ Object reconstruction ;
- ▶ Statistical procedure.



With an increased Higgs boson transverse momentum, the two decay products tend to get closer to each other. Two different regimes are defined:

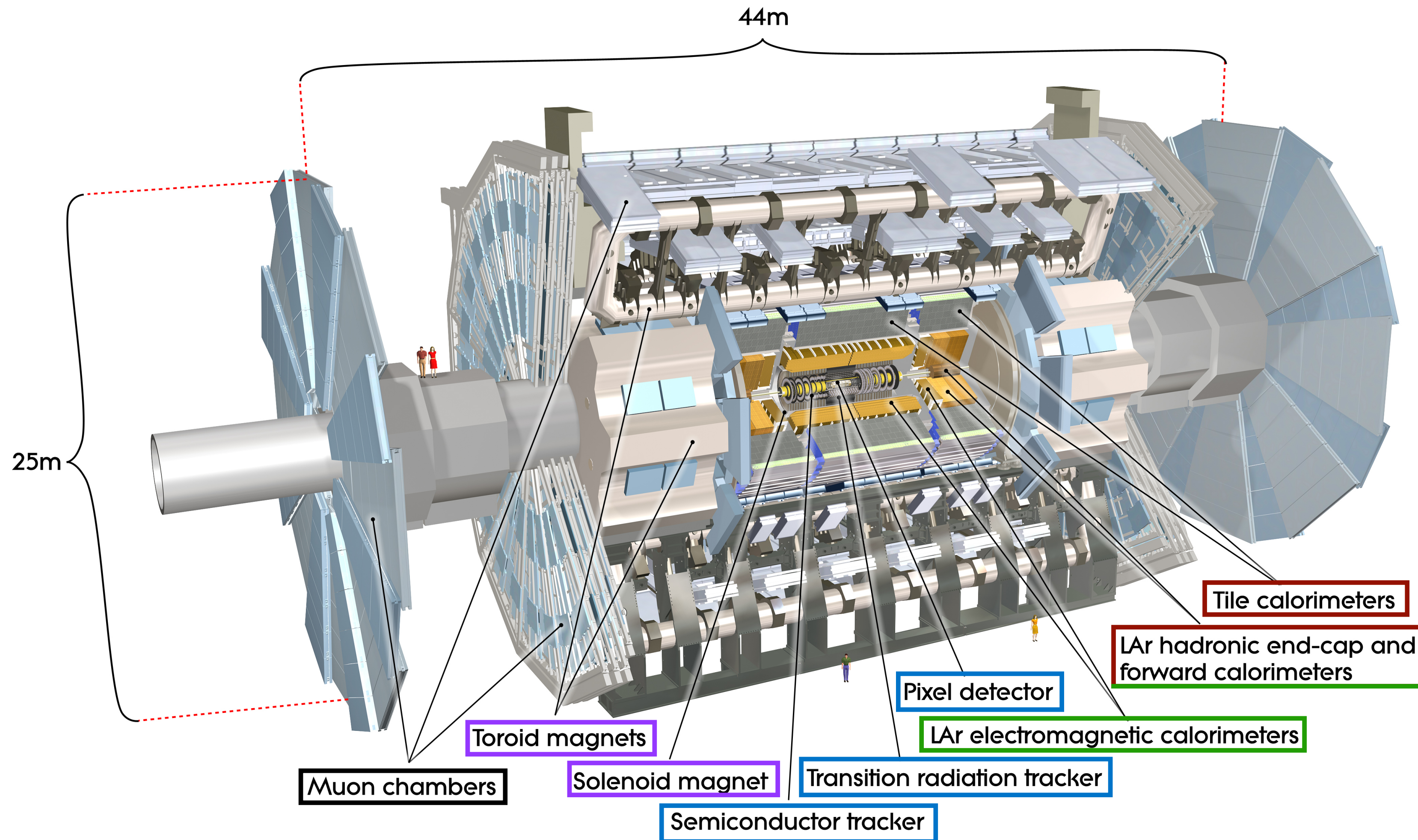
- ▶ **Resolved:** two single objects can be reconstructed, aiming at low  $m_{HH}$ .
- ▶ **Boosted:** one object is reconstructed with dedicated sub-structure analysis.



# How to look for Higgs pairs?



The produced particles are recorded by the ATLAS detector designed as an onion like structure with specific sub-detectors:



## Inner detector:

Charged particles tracks and vertices.

## Electromagnetic calorimeter:

Electron and photon reconstruction (E, direction)

## Hadronic calorimeter:

Charged and neutral hadron reconstruction (E, direction)

## Muon spectrometer:

Muon trajectories

## Magnet system:

Bends the charged particles for momentum measurements



# How to look for Higgs pairs?



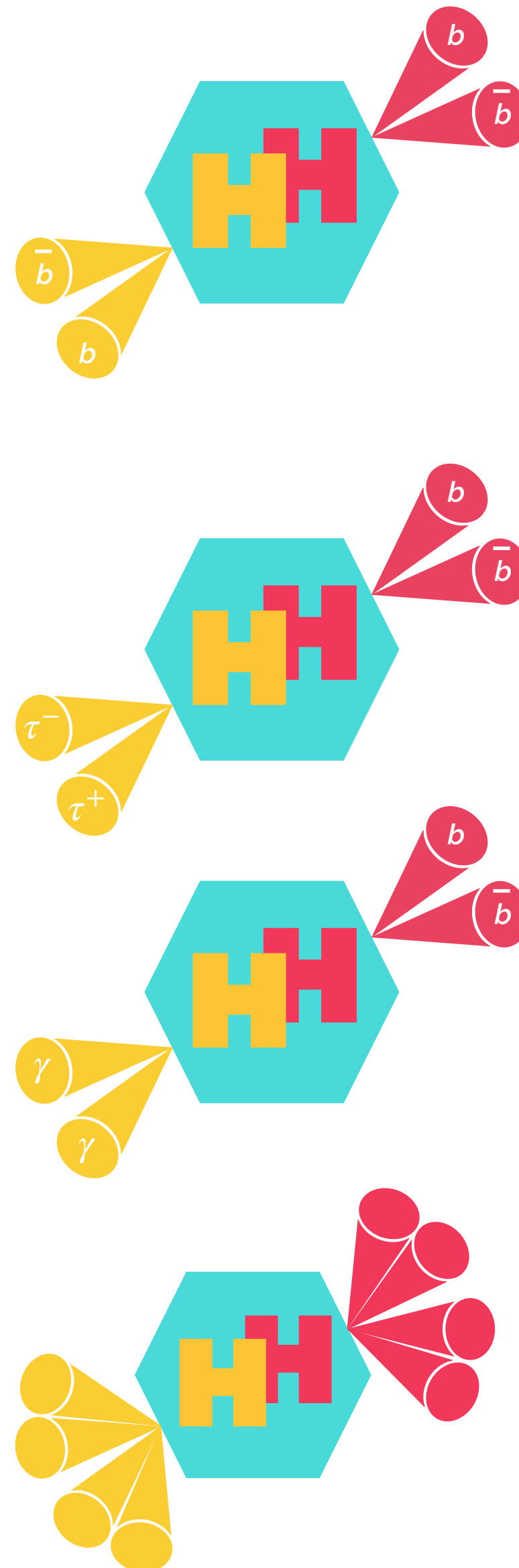
No clear *Golden channel*, but several promising signatures:

$BR(HH \rightarrow XXYY)$

	bb	WW	gg	$\tau\tau$	cc	ZZ	$\gamma\gamma$	Z $\gamma$	$\mu\mu$
bb	33%								
WW	25%	4.6%							
gg									
$\tau\tau$	7.4%								
cc									
ZZ	3.1%								
$\gamma\gamma$	0.26%	0.1%							
Z $\gamma$									
$\mu\mu$									

= results from ATLAS

Combining the results is necessary for observation.



$HH \rightarrow b\bar{b}b\bar{b}$

- ▶  $H \rightarrow b\bar{b}$ : High BR
- ▶ Large hadronic background

ggF:  $\mathcal{L} = 36\text{fb}^{-1}$

[JHEP 01 \(2019\) 030](#)

Resonant ggF:  $\mathcal{L} = 139\text{fb}^{-1}$

[ATLAS-CONF-2021-035](#)

VBF:  $\mathcal{L} = 126\text{fb}^{-1}$

[JHEP 07 \(2020\) 108](#)

$HH \rightarrow b\bar{b}\tau^+\tau^-$

- ▶  $H \rightarrow b\bar{b}$ : High BR
- ▶  $H \rightarrow \tau^+\tau^-$ : Low background

Resolved:  $\mathcal{L} = 139\text{fb}^{-1}$

[ATLAS-CONF-2021-030](#)

Boosted:  $\mathcal{L} = 139\text{fb}^{-1}$

[JHEP 11 \(2020\) 163](#)

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

- ▶  $H \rightarrow b\bar{b}$ : High BR
- ▶  $H \rightarrow \gamma\gamma$ : Good mass resolution

ggF. resolved:  $\mathcal{L} = 139\text{fb}^{-1}$

[ATLAS-CONF-2021-016](#)

$HH \rightarrow W^+W^- + XX / HH \rightarrow b\bar{b}ZZ$

- ▶ Decent BR from  $H \rightarrow VV$
- ▶ Complex final signatures due to the decay of Vs

$b\bar{b}l\nu l\nu$ :  $\mathcal{L} = 139\text{fb}^{-1}$

[Phys. Lett. B 801 \(2020\) 135145](#)

$\gamma\gamma WW^*$ :  $\mathcal{L} = 36\text{fb}^{-1}$

[Eur. Phys. J. C 78 \(2018\) 1007](#)

$b\bar{b}l\nu q\bar{q}$ :  $\mathcal{L} = 36\text{fb}^{-1}$

[JHEP 04 \(2019\) 092](#)

$WW^*WW^*$ :  $\mathcal{L} = 36\text{fb}^{-1}$

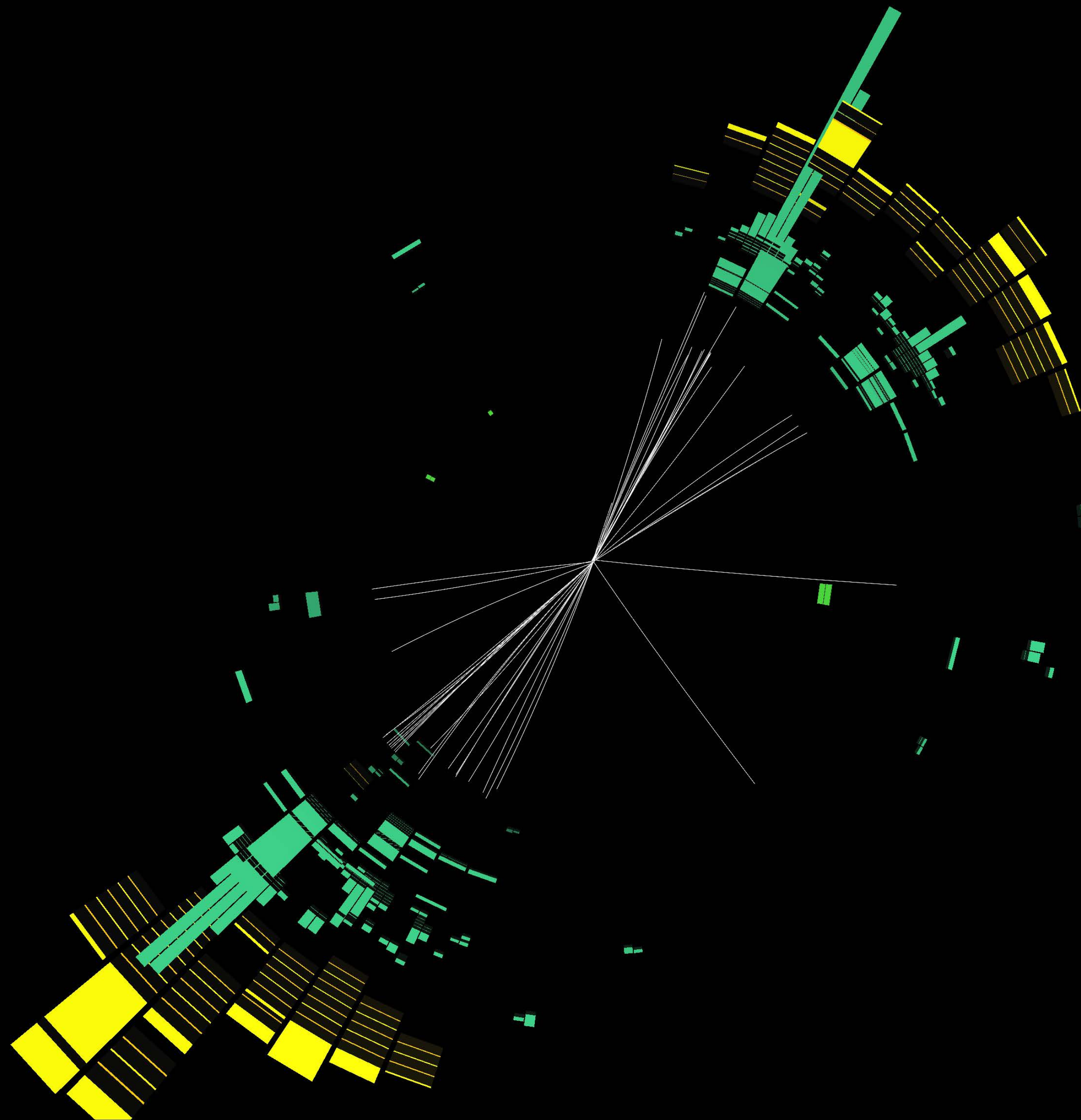
[JHEP 05 \(2019\) 124](#)





Run: 356259  
Event: 311347503  
2018-07-22 20:00:32 CEST

$HH \rightarrow b\bar{b}b\bar{b}$



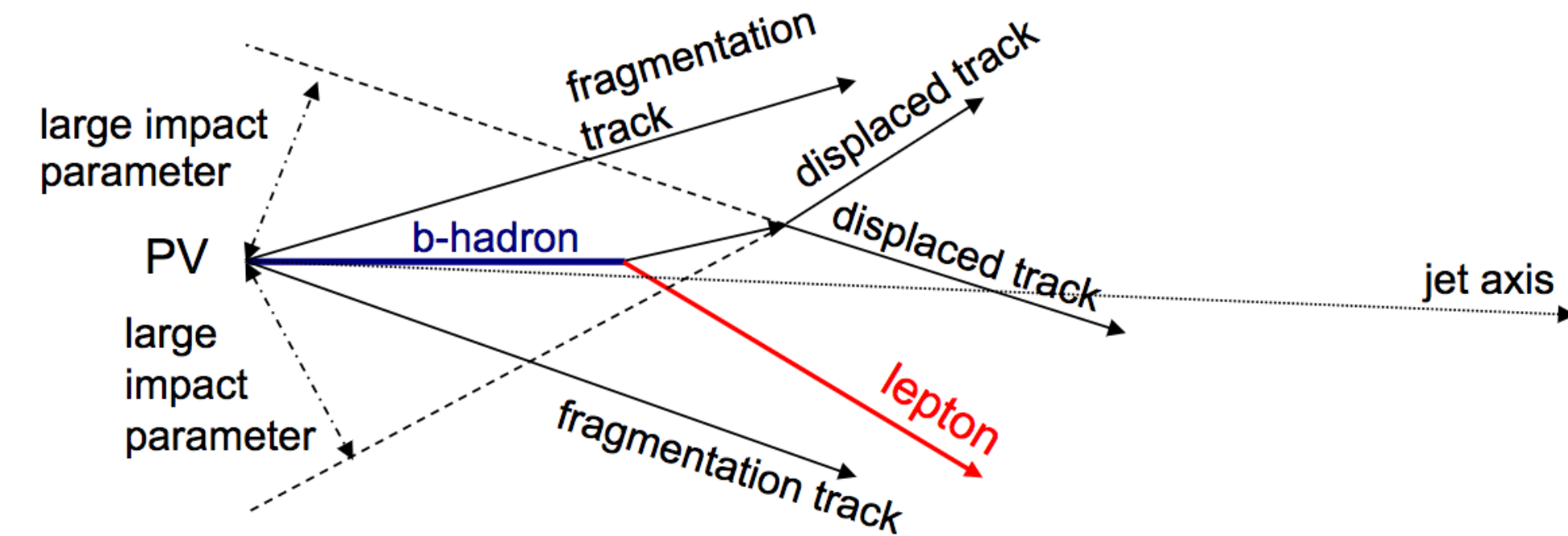


# How to identify b-jets

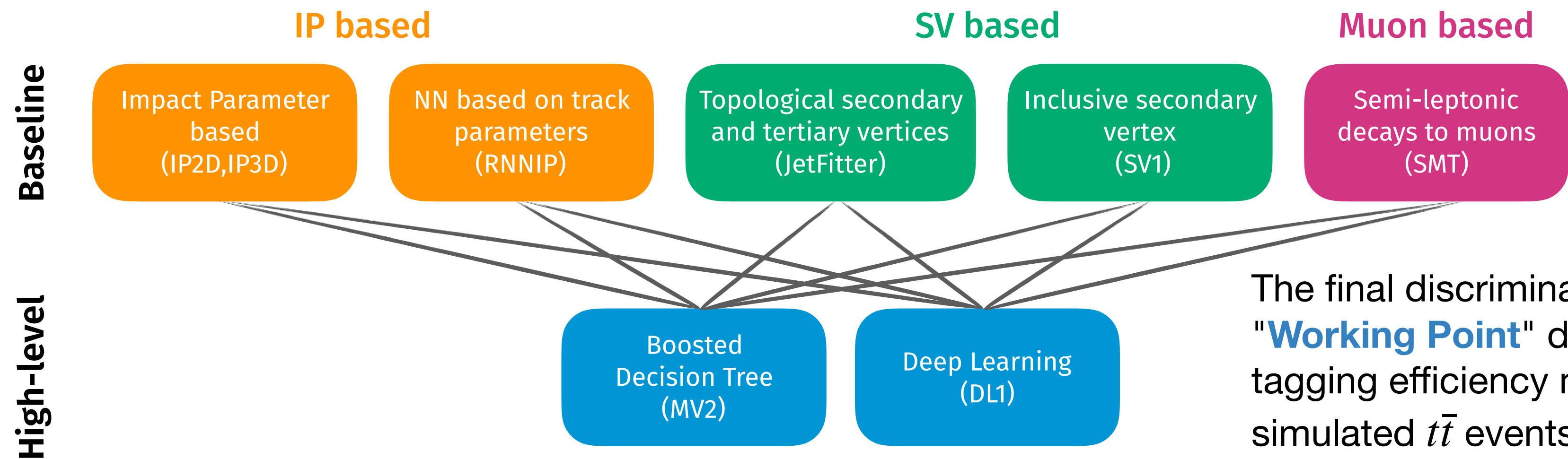


B-hadrons have a unique experimental signature that allow to identify them:

- ▶ **Large lifetime** ( $\sim 1.5$  ps)  $\rightarrow$  **Secondary Vertex** and tracks with large **Impact Parameter**.
- ▶ High **decay multiplicity** (average: 5 charged particles).
- ▶ In  $\sim 42\%$  of the cases the b-hadron decays **semi-leptonically**  $\rightarrow$  search for **“soft” muons** in the Secondary Vertex.



These features are used by **Baseline** taggers (targeting one behaviour) that are then combined in **Higher-Level** algorithms:



The final discriminant is based on a **“Working Point”** defined by the b-tagging efficiency measured in MC simulated  $t\bar{t}$  events.

Dedicated **energy corrections** are also applied to account for the soft muon as well as energy mis measurements.





# Strategy

ggF:  $\mathcal{L} = 36\text{fb}^{-1}$

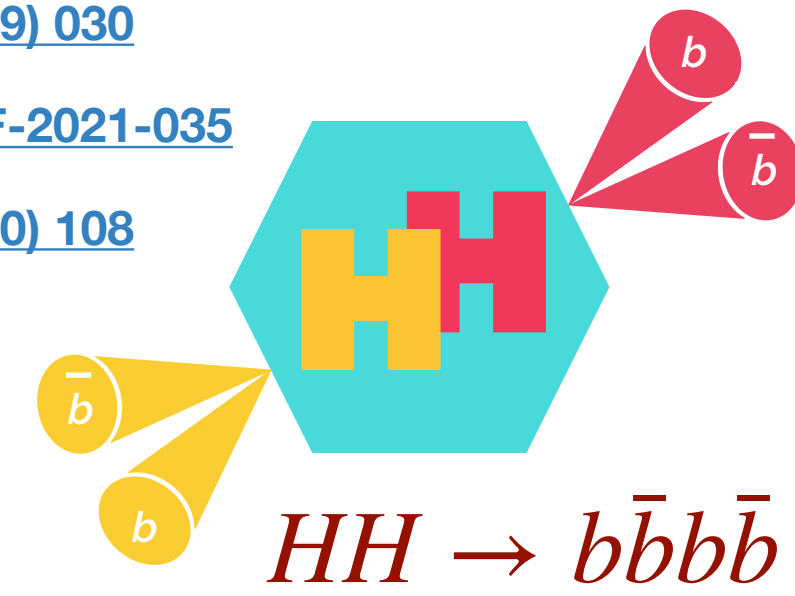
Resonant ggF:  $\mathcal{L} = 139\text{fb}^{-1}$

VBF:  $\mathcal{L} = 126\text{fb}^{-1}$

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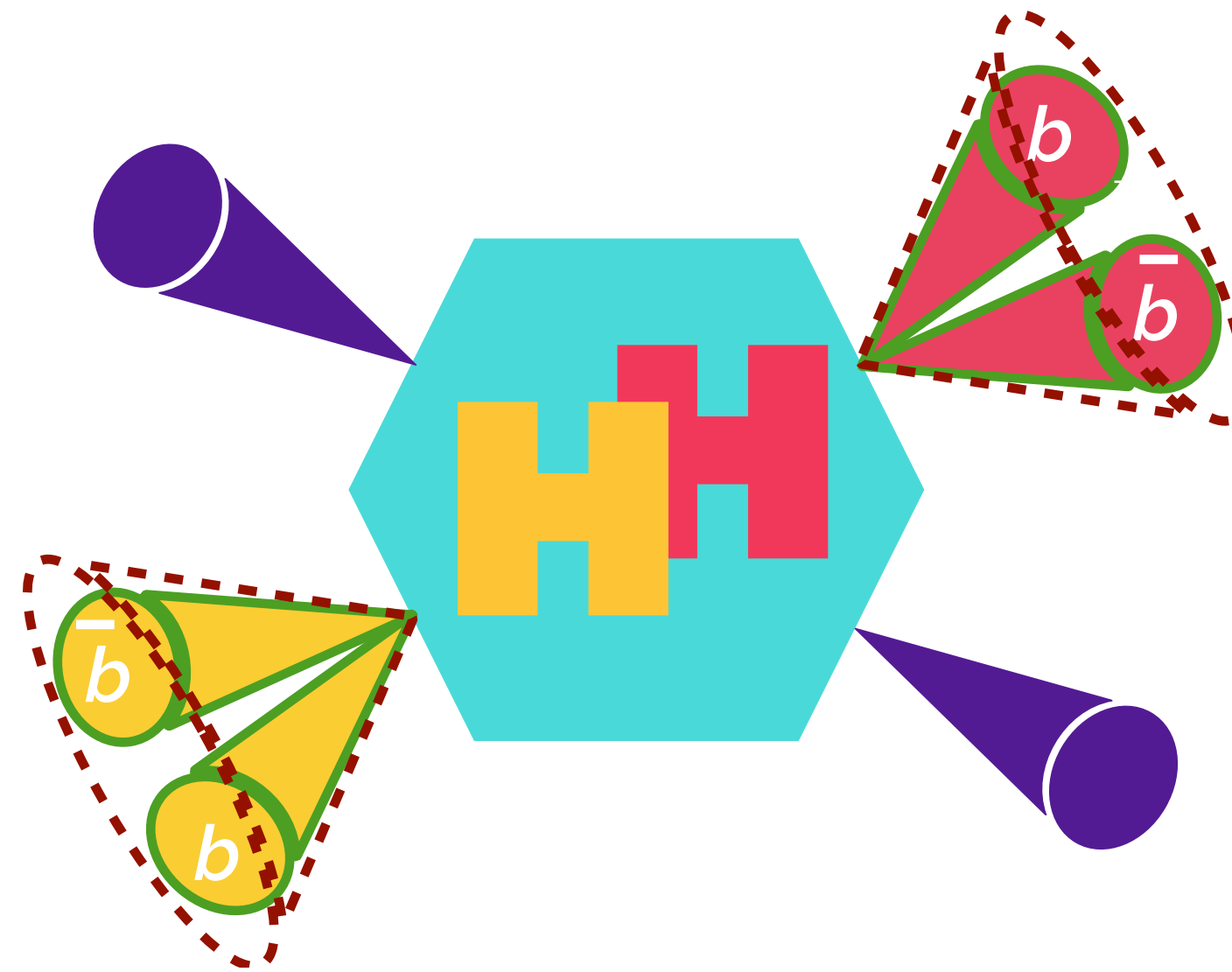
## ggF Non resonant / Resonant

### Resolved:

- ▶ At least 4 central b-tagged jets.

### Boosted:

- ▶ At least 2 large R jets;
- ▶ At least 1 variable radius b-tagged jet in each large R jet.



## VBF Non resonant / Resonant

### Central jets:

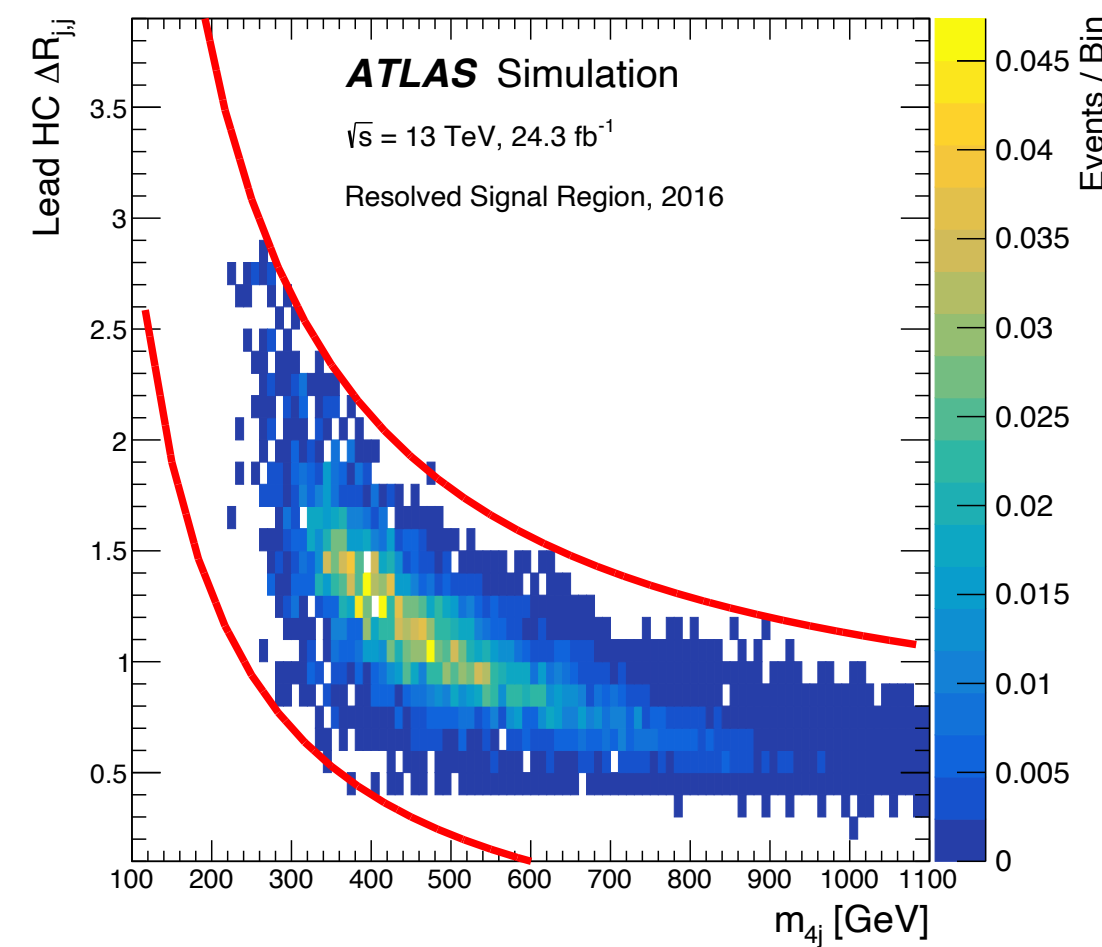
- ▶ At least 4 central b-tagged jets.

### VBF jets:

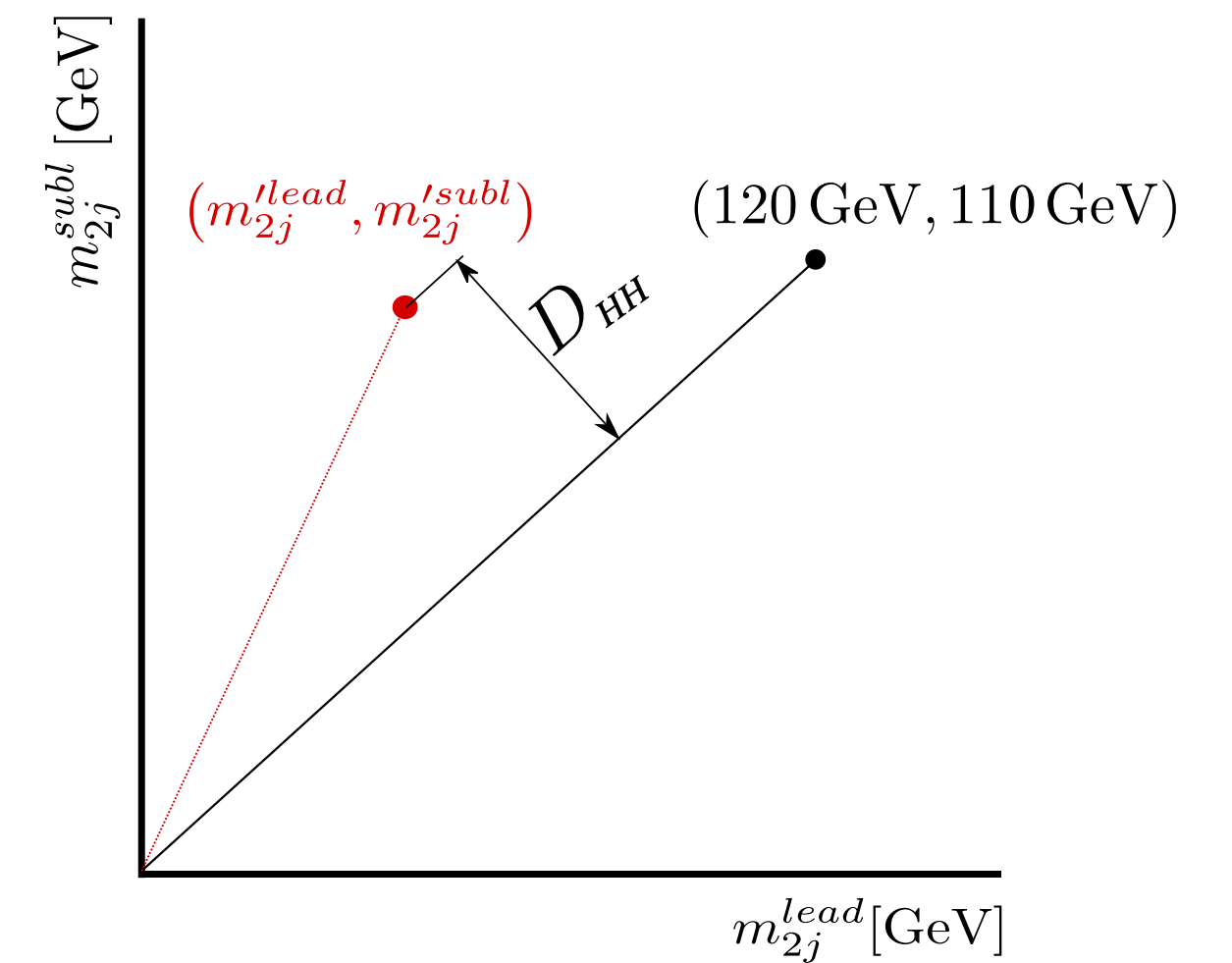
- ▶ At least 2 forward jets with opposite  $\eta$  sign.

## Pairing Jets

- Angular distance between jets in each Higgs candidate  $|\Delta R_{jj}|$  is compared to the 4 body invariant mass  $m_{4j}$



- Given that the reconstructed masses should be similar, the distance to median of the signal expectation is minimised.



This method has been replaced with a **BDT method** in the latest **resonant** result using angular quantities ( $\Delta\eta$ ,  $\Delta\phi$  and  $\Delta R$ ).



# How to look for signal?

ggF:  $\mathcal{L} = 36\text{fb}^{-1}$

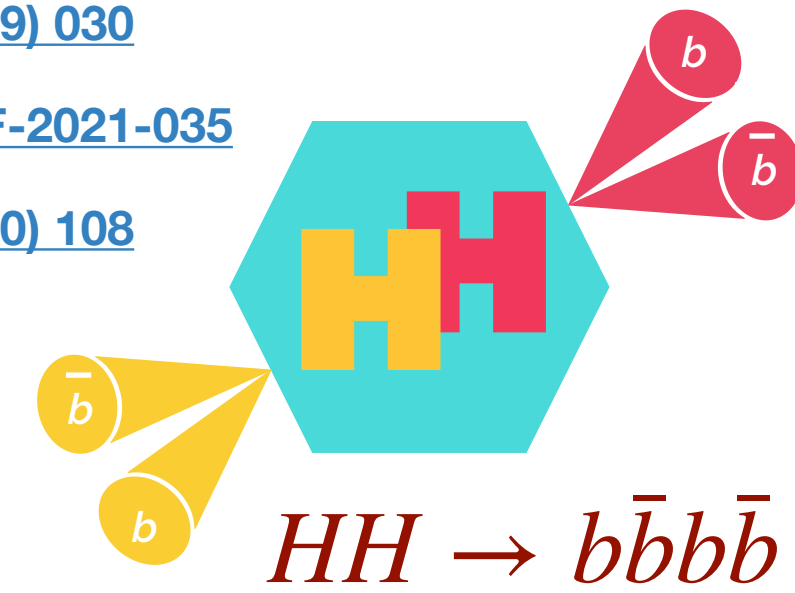
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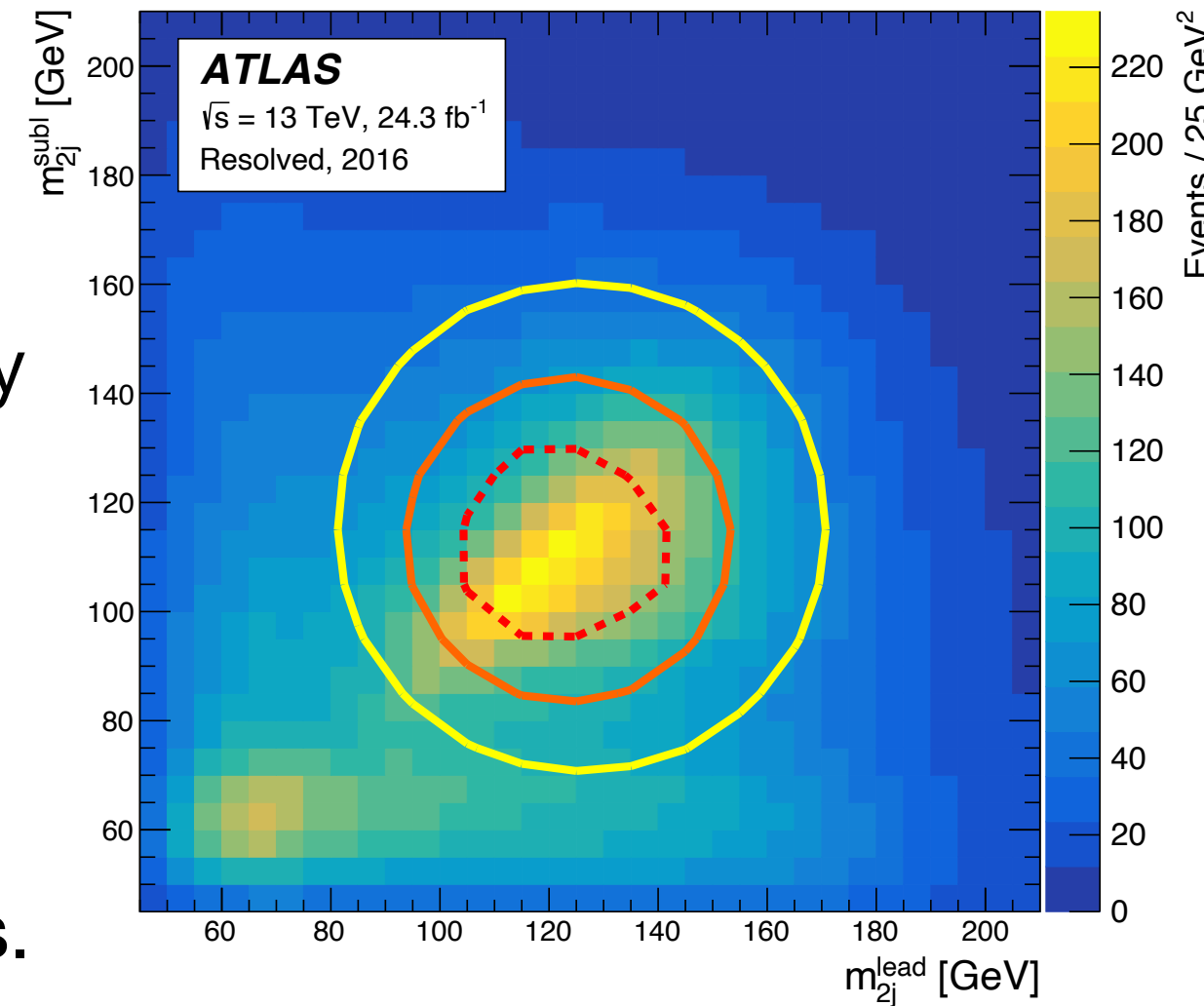
ggF

**Fit:** using the  $HH$  invariant mass

**Resolved:** Non resonant / Resonant

**Main backgrounds:**

- ▶  $t\bar{t}$ : Rejected by specific variable measuring consistency of jet originating from top quark.
- ▶ multi-jets:
  - ▶ Dedicated Signal, Validation and Control Regions based Higgs bosons masses;
  - ▶ Shape is obtained by reweighting data in the 2 b-tagged SR: from sets of weights to MVA techniques.



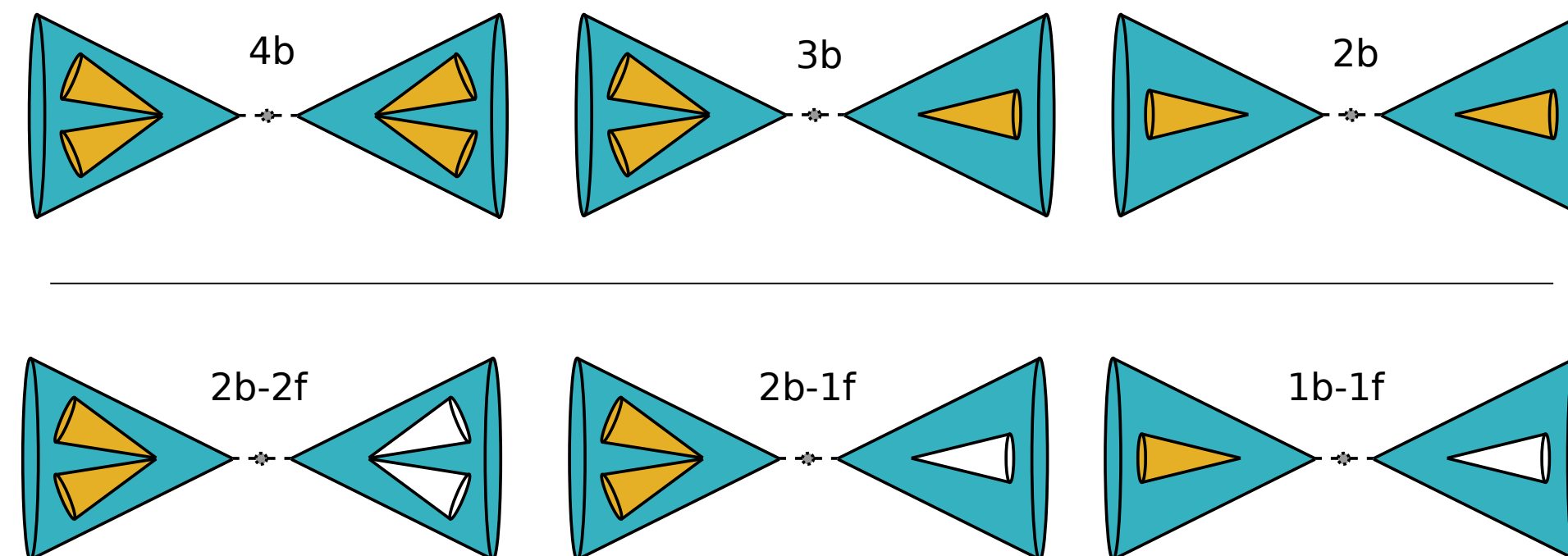
**Boosted:** Resonant

Due to low VR jet finding efficiency in large jets, 3 signal regions are defined.

**Main backgrounds:**

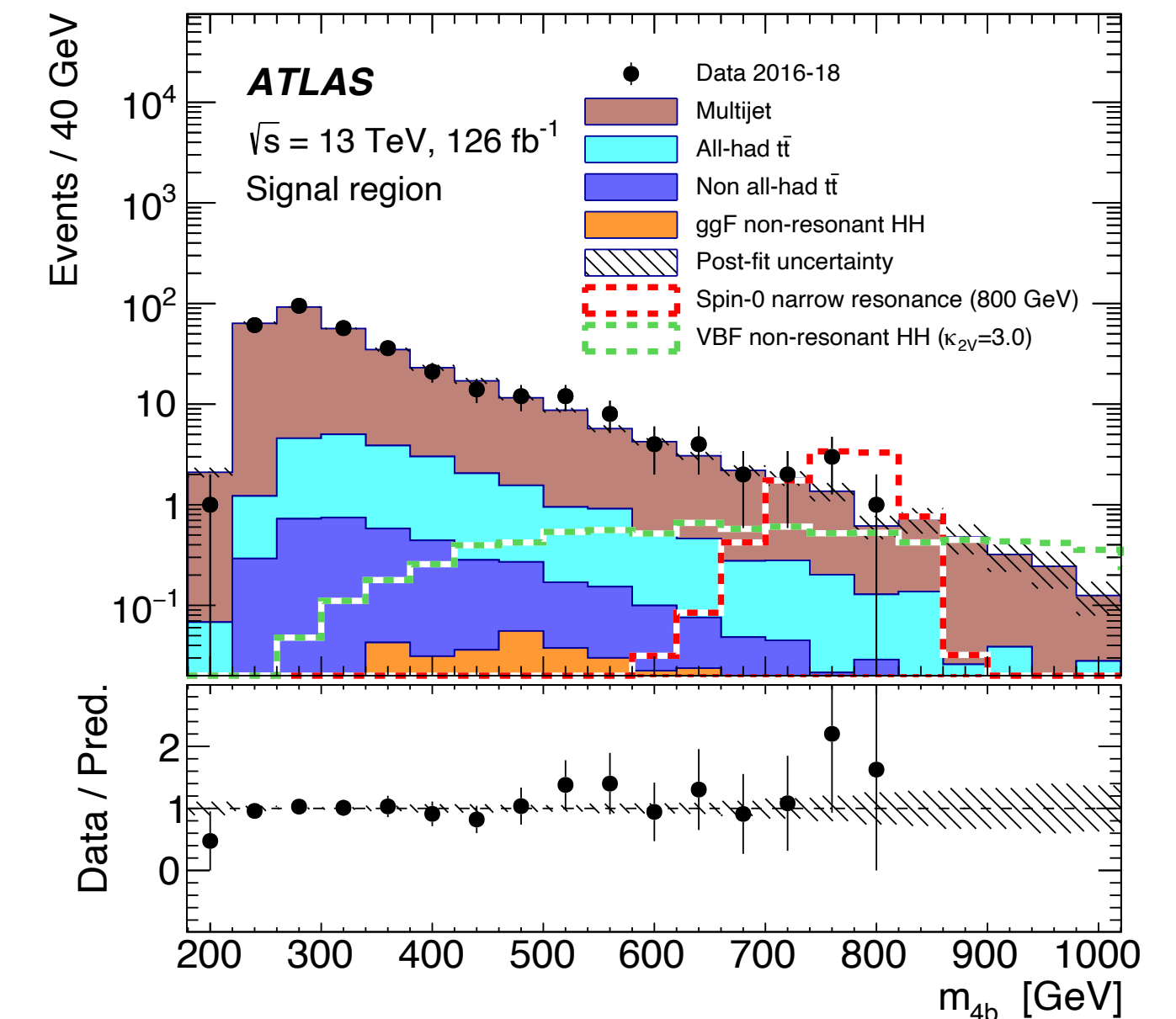
$t\bar{t}$  and multi-jets contribute:

- ▶ Normalisation is taken from fit to the CR data.
- ▶ For multi-jets an iterative reweighting technique is used to match kinematics between untagged and tagged jets.



VBF

Similar cuts as for the ggF resolved analysis.





# Results

ggF:  $\mathcal{L} = 36\text{fb}^{-1}$

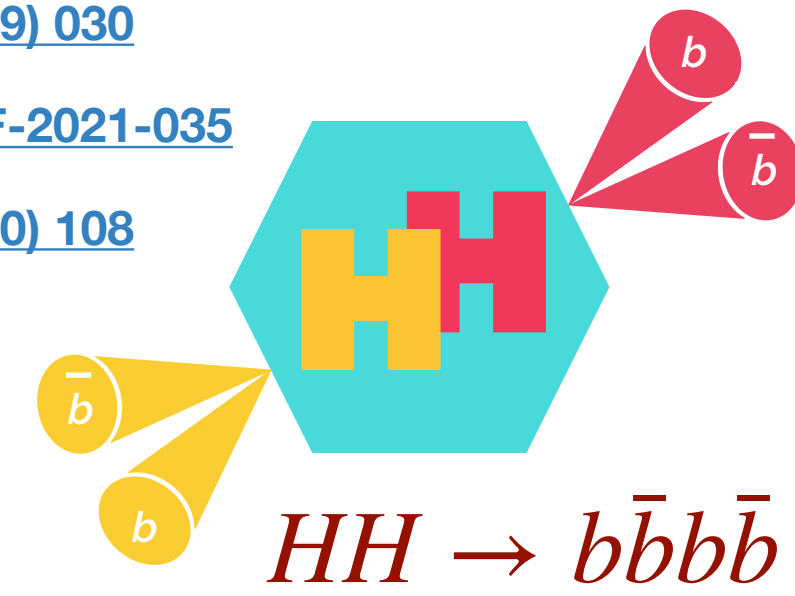
Resonant ggF:  $\mathcal{L} = 139\text{fb}^{-1}$

VBF:  $\mathcal{L} = 126\text{fb}^{-1}$

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## ggF

No significant excess found

**Non-resonant Resolved**

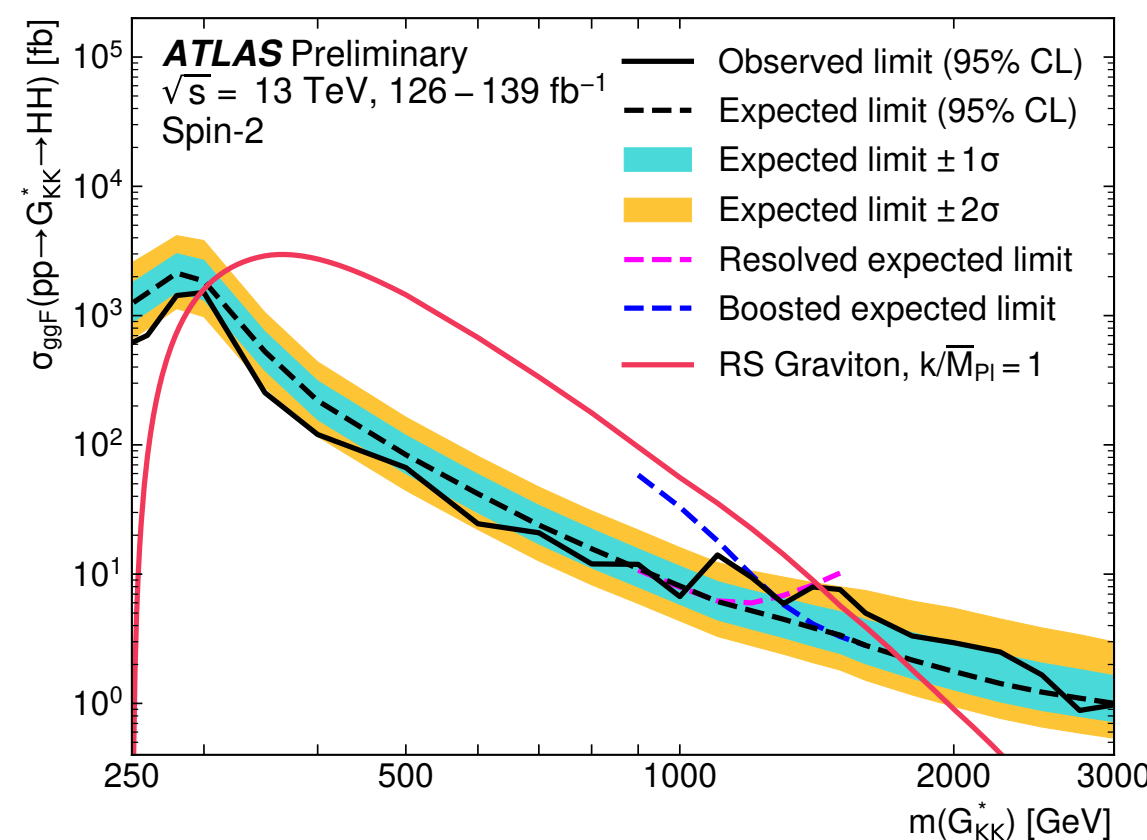
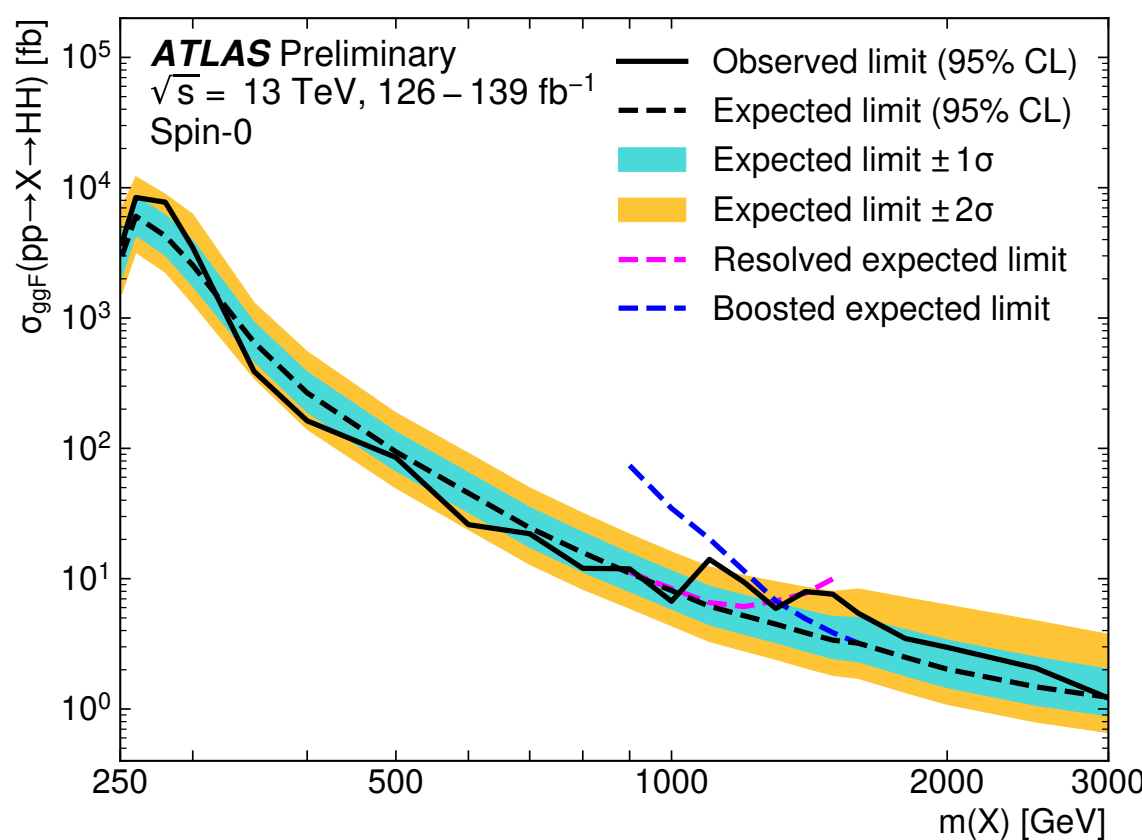
$$\sigma_{HH}^{ggF} \times BR(HH \rightarrow b\bar{b}b\bar{b})$$

observed (expected) limit is  
12.9 (14.8) times the SM prediction.

**Resonant Resolved** (251–1500 GeV) **Boosted** (900–3000 GeV)

Limits set on  $\sigma(X/G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b})$ :

Most significant excess is found at 1.1 TeV with a local (global) significance of  $2.6 \sigma$  ( $1.0 \sigma$ ).



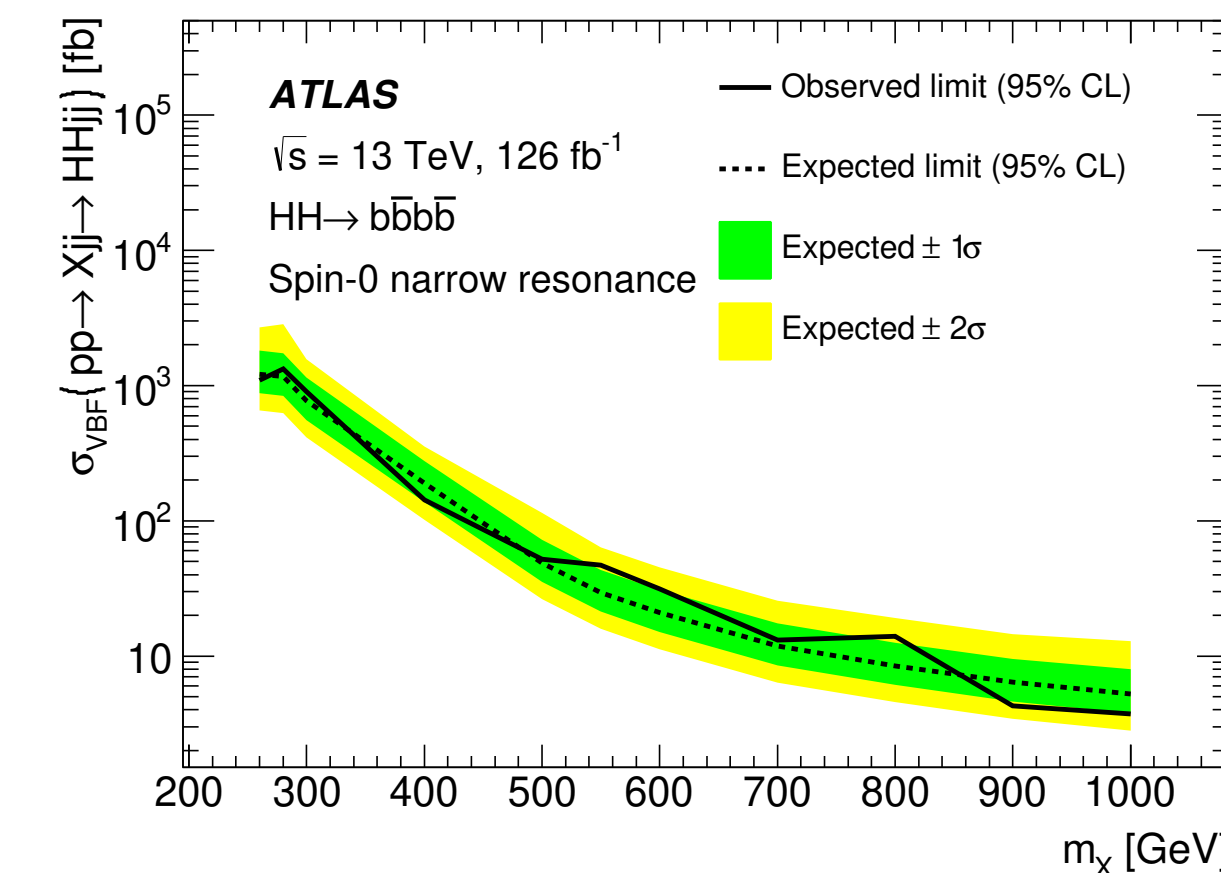
**Non-resonant**

observed (expected) limit is 840 (550) times the SM prediction.

Limits are set on  $\kappa_{2V}$ :

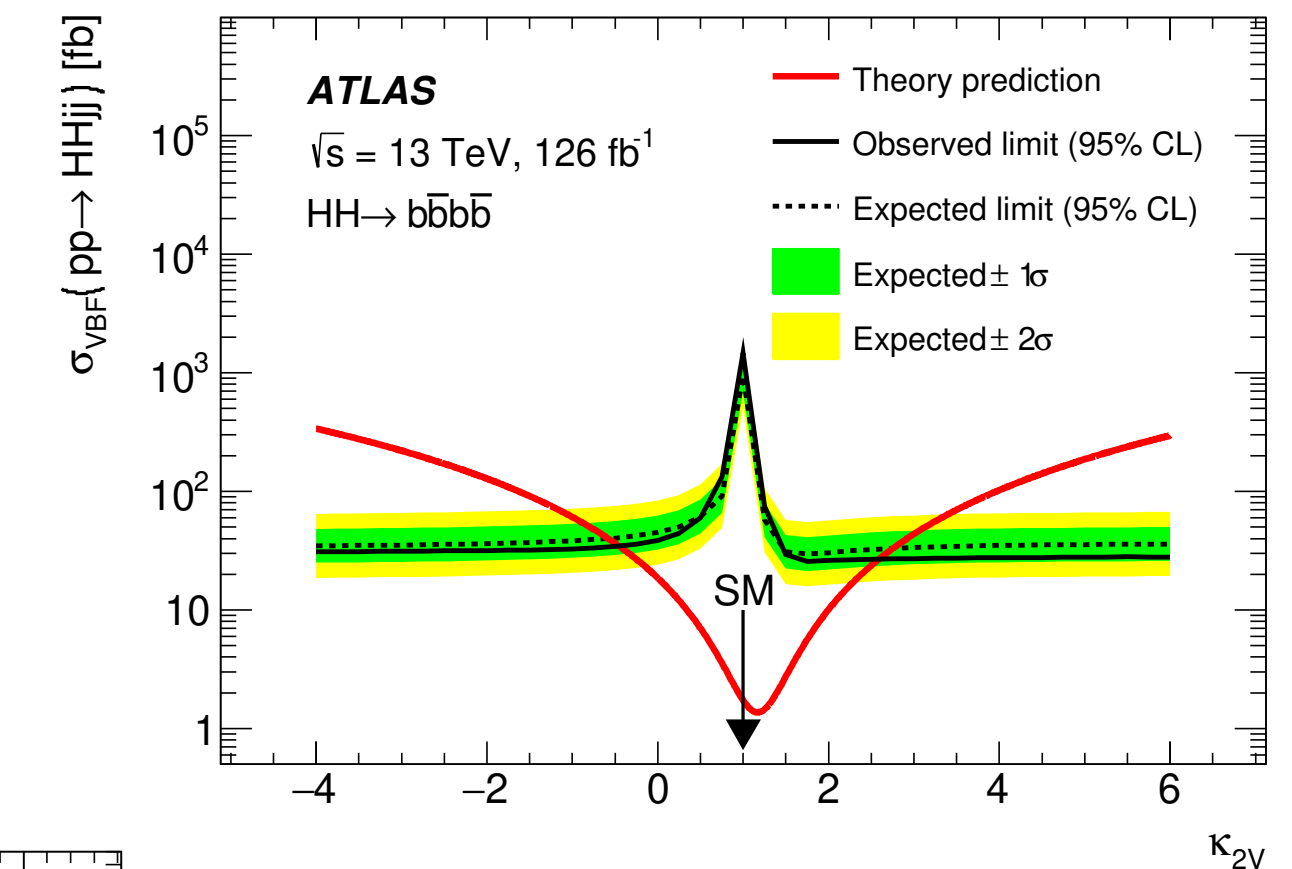
$-0.4 < \kappa_{2V} < 2.6$  (observed),

$-0.6 < \kappa_{2V} < 2.7$  (expected).



## VBF

No significant excess found



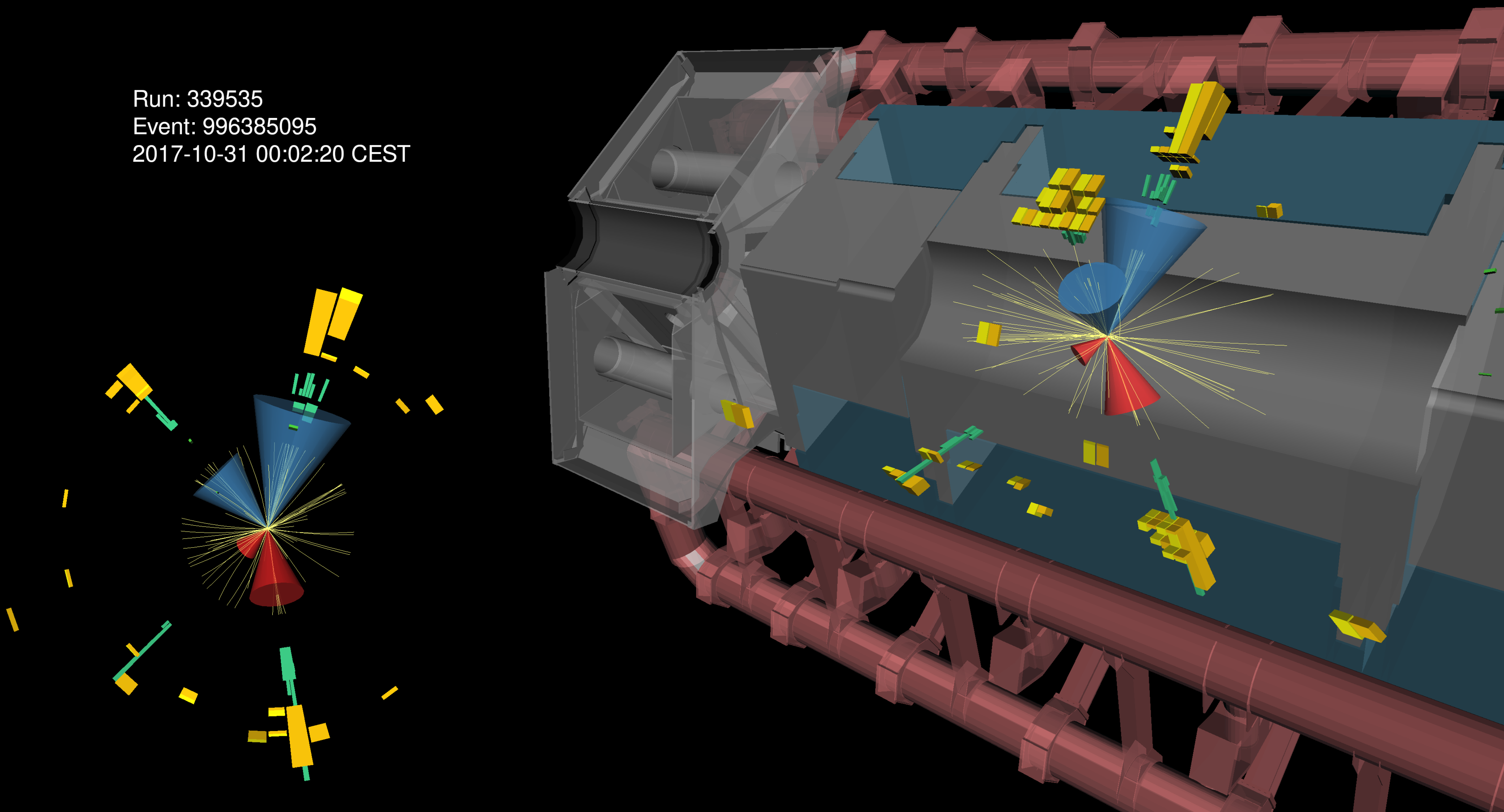
**Resonant**

Limits set on  $\sigma_{VBF}(X \rightarrow HH)$  where X is either a narrow- or broad-width scalar resonance



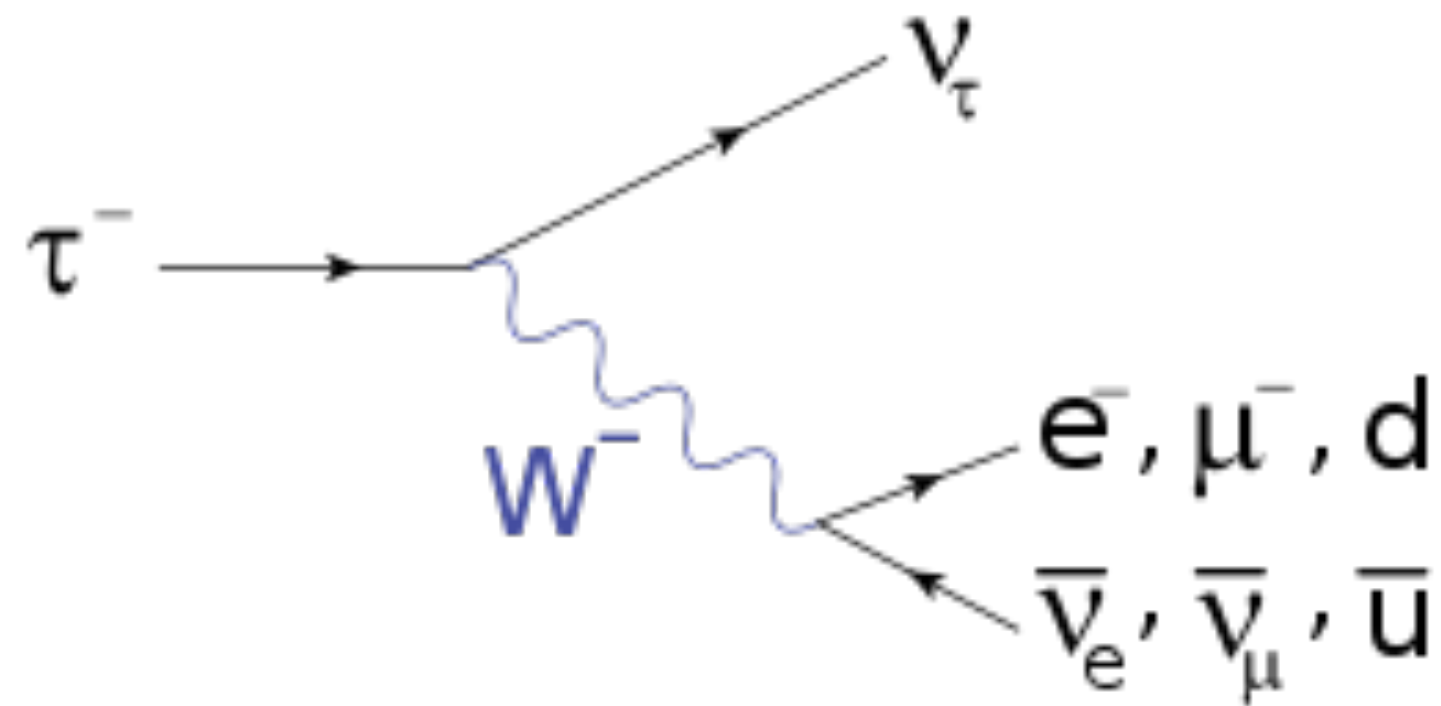
$$HH \rightarrow b\bar{b}\tau^+\tau^-$$

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Event: 996385095  
2017-10-31 00:02:20 CEST



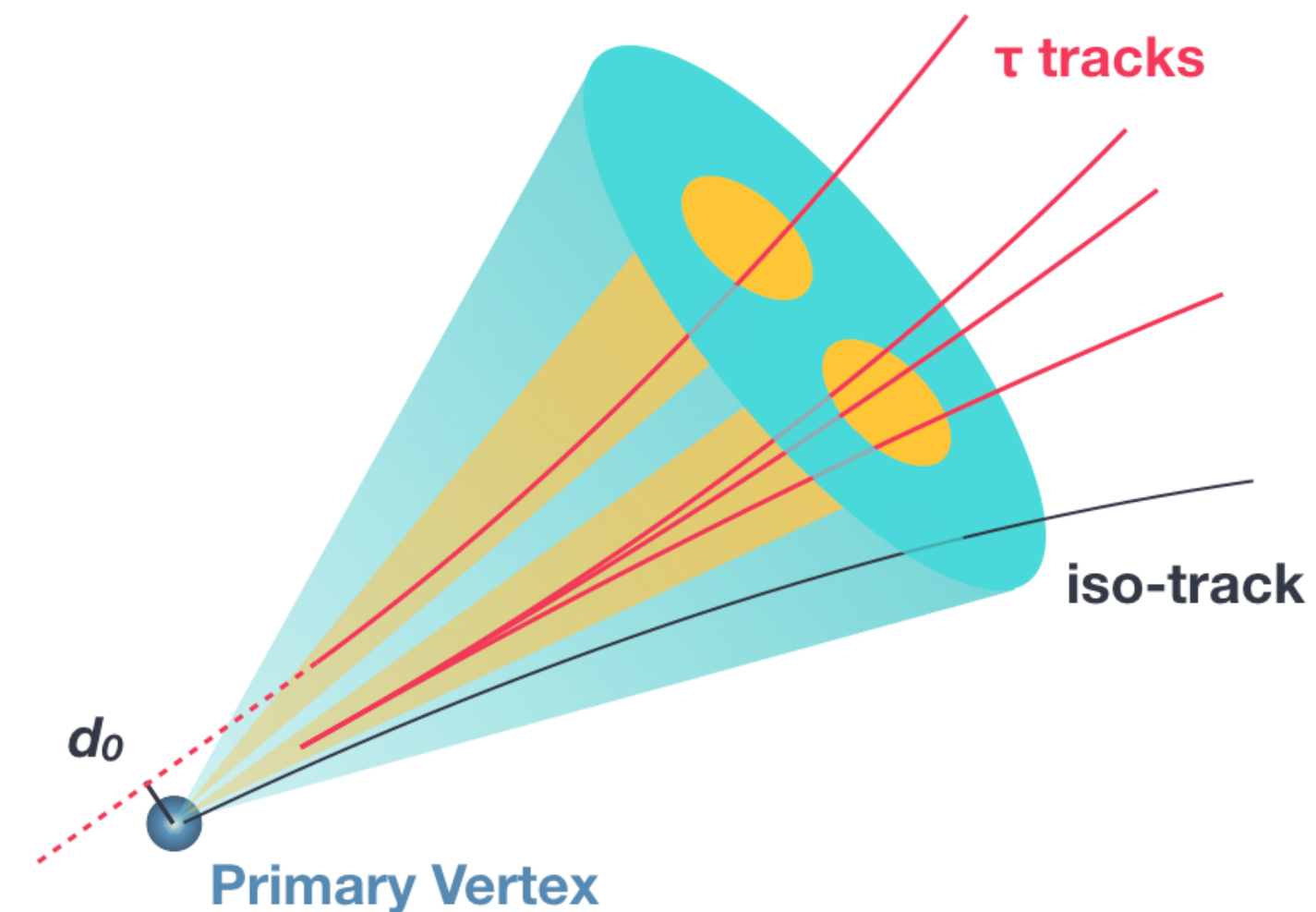
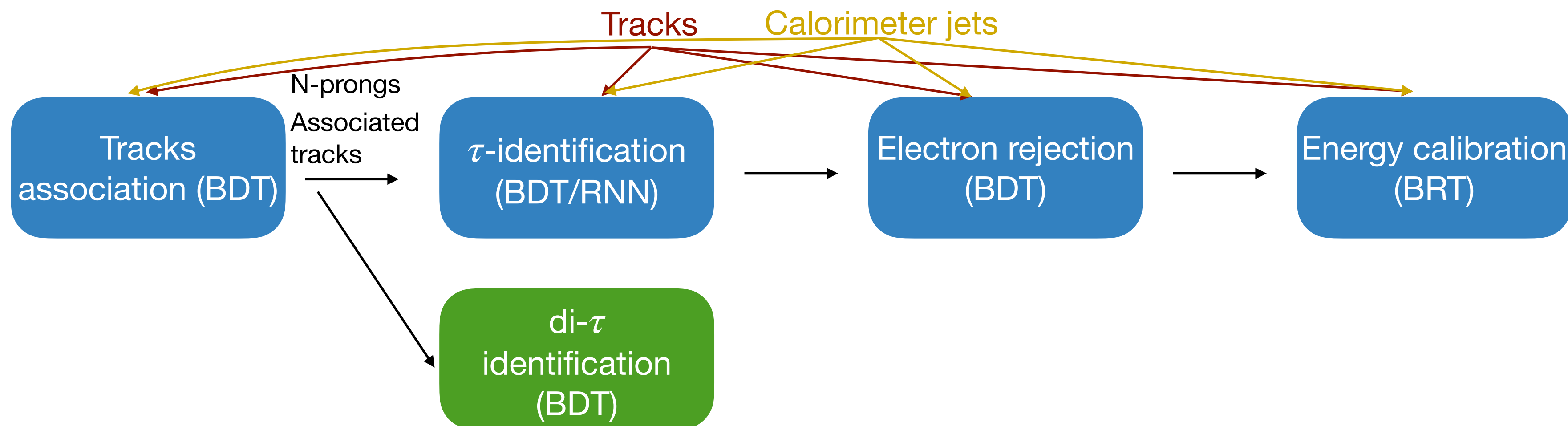


# How to reconstruct tau leptons ?



Similarly to B-hadron, **tau leptons** have a unique complex experimental signature:

- ▶ Small lifetime ( $\sim 0.3$  ps) with large mass (1.78 GeV).
- ▶ Decays in **35 %** of the time to **electrons** or **muons** + neutrinos (undetected).
- ▶ In the other case it decays **hadronically**, mostly into 1 or 3 charged pions, with one possible additional neutral pion.
  - ▶ Challenging final state to identify and reconstruct.
  - ▶ Wider energetic deposit and more tracks compared to quark-like jet.
  - ▶ Dedicated MVA algorithms are used to **identify** and **reconstruct** the tau candidates.



In **boosted topologies**, the reconstructed jets are closer to each other. A dedicated BDT is therefore trained to account for **smaller radius jets** and the **specific topologies**. No additional energy correction was found to be needed in these cases.



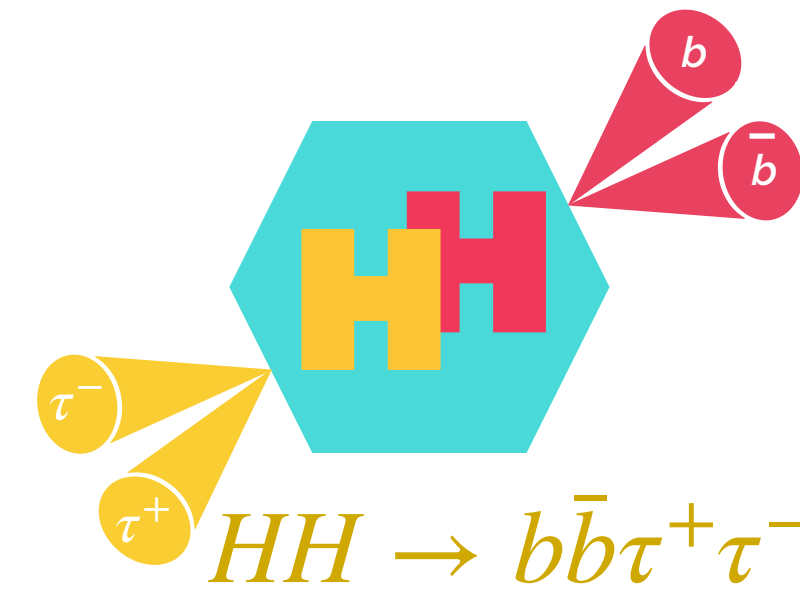
# Strategy

Resolved:  $\mathcal{L} = 139\text{fb}^{-1}$

[ATLAS-CONF-2021-030](#)

Boosted:  $\mathcal{L} = 139\text{fb}^{-1}$

[JHEP 11 \(2020\) 163](#)



The analyses are build on the final state of the tau decay:

## Resolved:

At least one hadronic tau is requested:

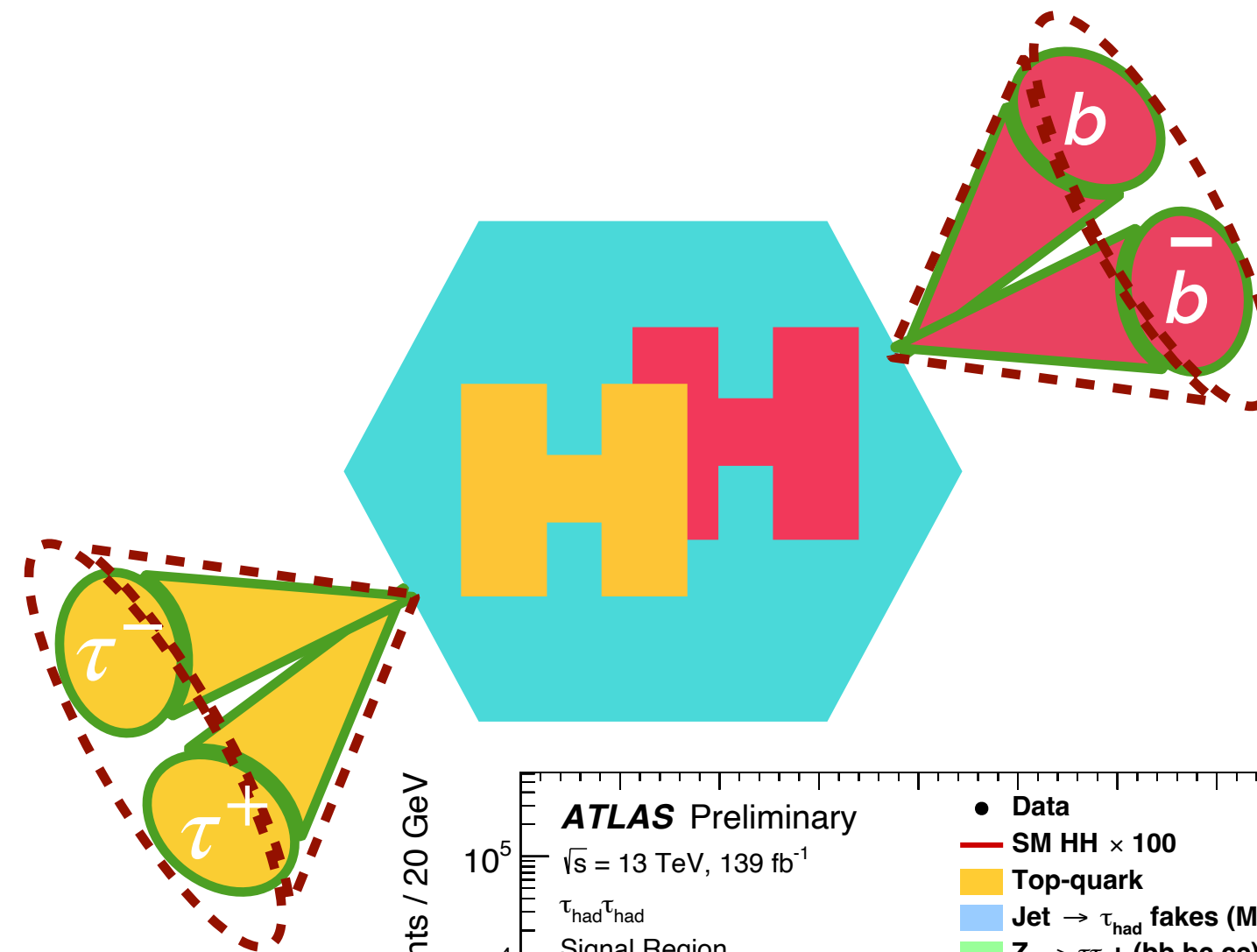
- ▶  $\tau_{\text{lep}}\tau_{\text{had}}$ : exactly 1 lepton + 1 hadronic  $\tau$ ;
- ▶  $\tau_{\text{had}}\tau_{\text{had}}$ : exactly two hadronic  $\tau$ s.

As the mass of the system is not well defined, the **Missing Mass Calculator** is used to get a better estimate.

## Boosted:

Only hadronic taus are considered inside one large angular jet :

- ▶  $\leq 3$  sub-jets, sum of track charge  $\pm 1$  in each sub- $\tau$ .

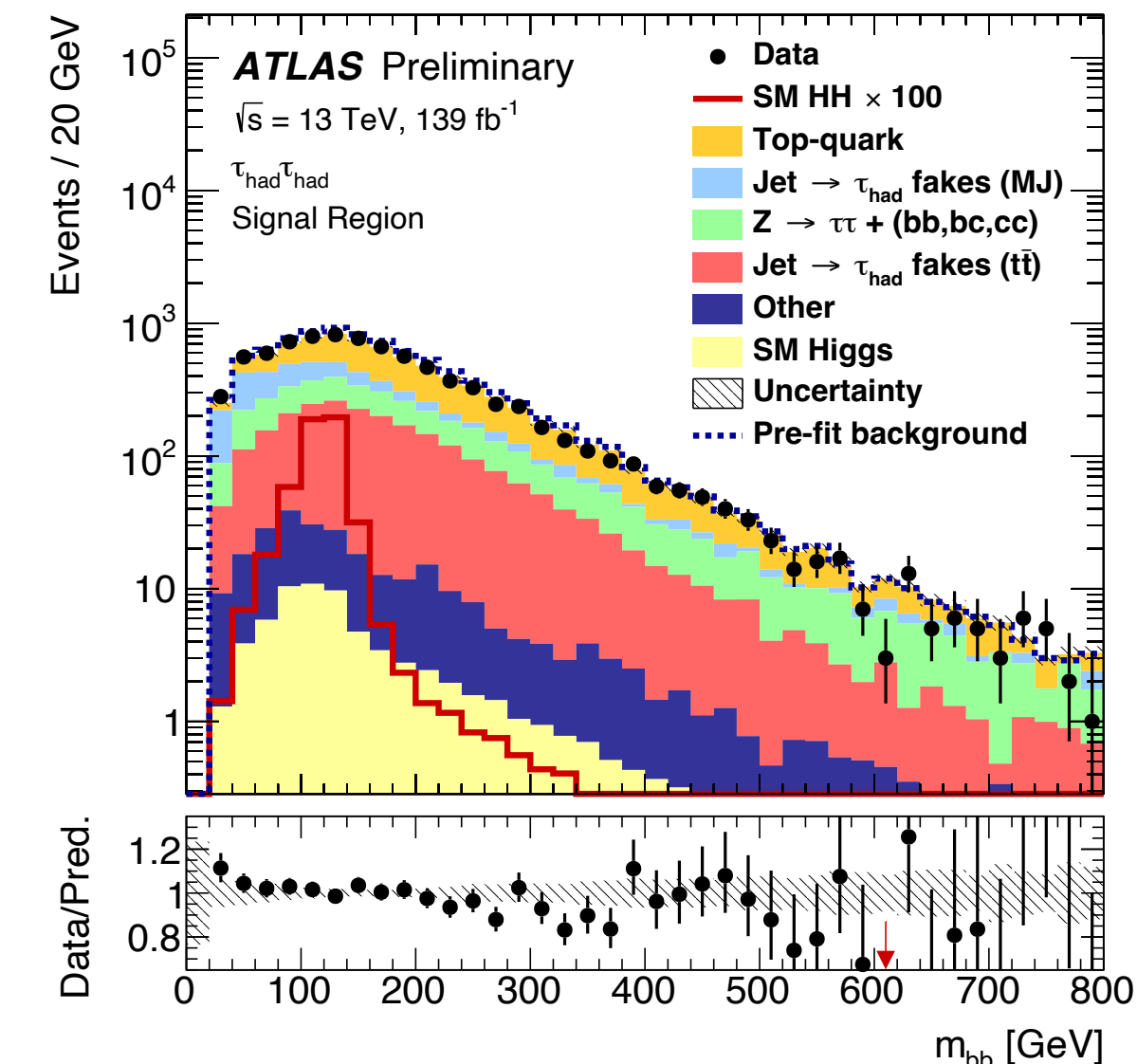
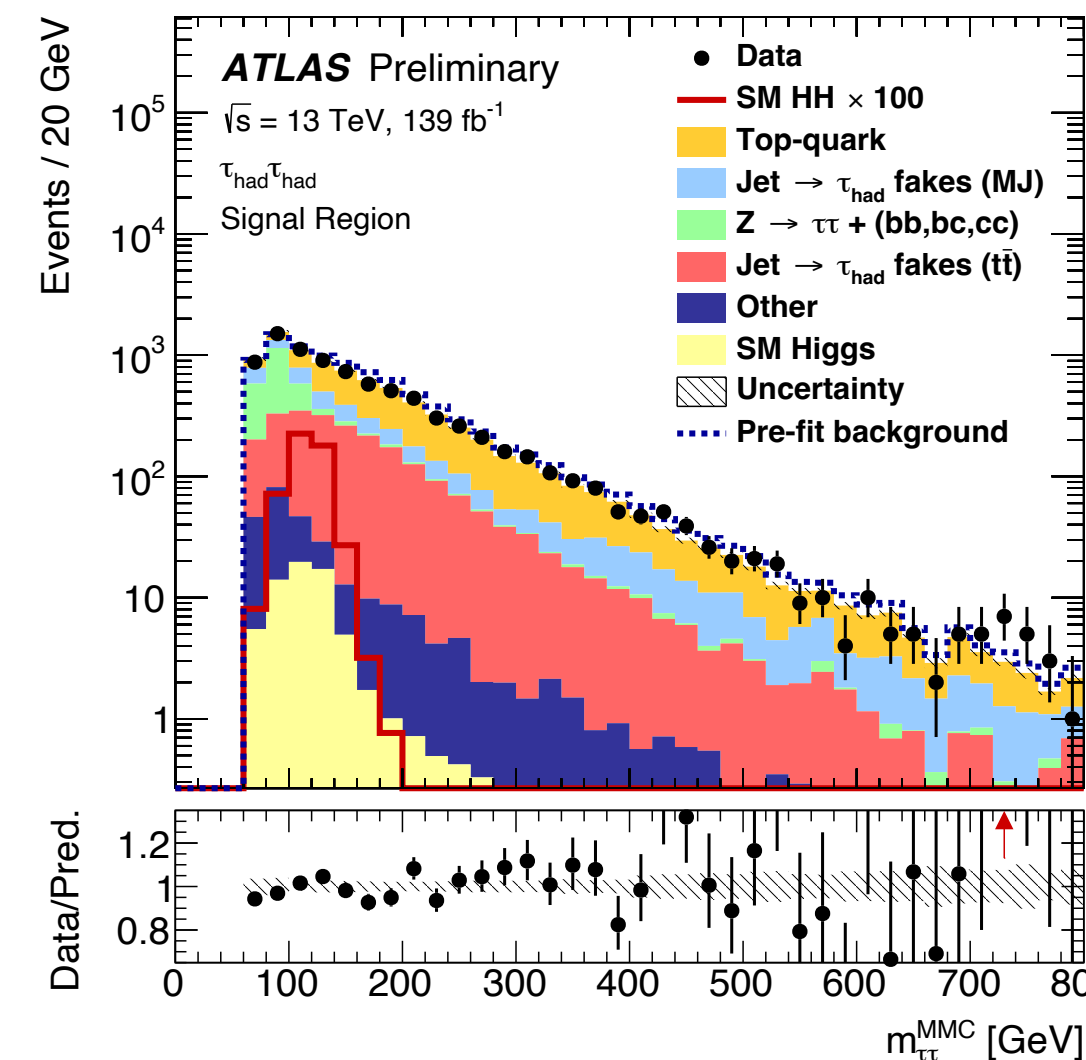


## Resolved:

Exactly 2 b-jets

## Boosted:

- ▶  $\geq 1$  extra large R jet;
- ▶ 2 variable radius b-tagged jets inside.





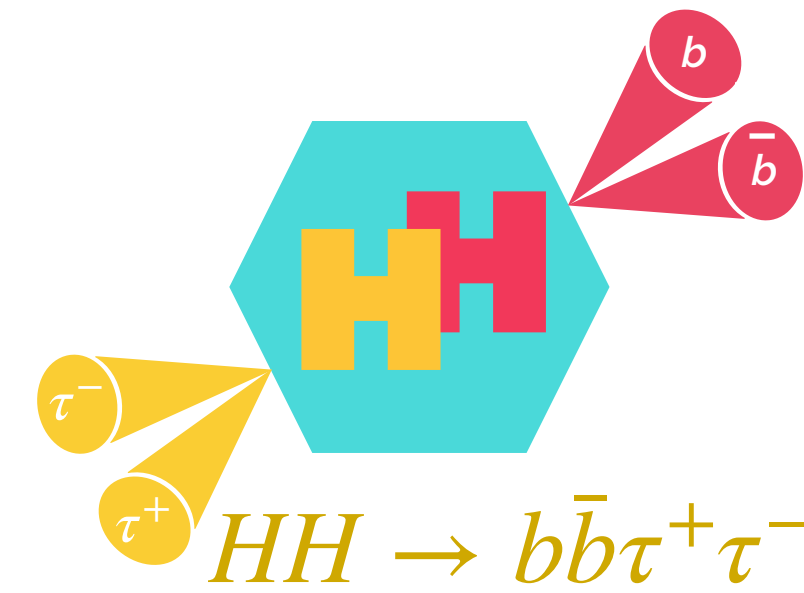
# How to look for signal?

Resolved:  $\mathcal{L} = 139\text{fb}^{-1}$

ATLAS-CONF-2021-030

Boosted:  $\mathcal{L} = 139\text{fb}^{-1}$

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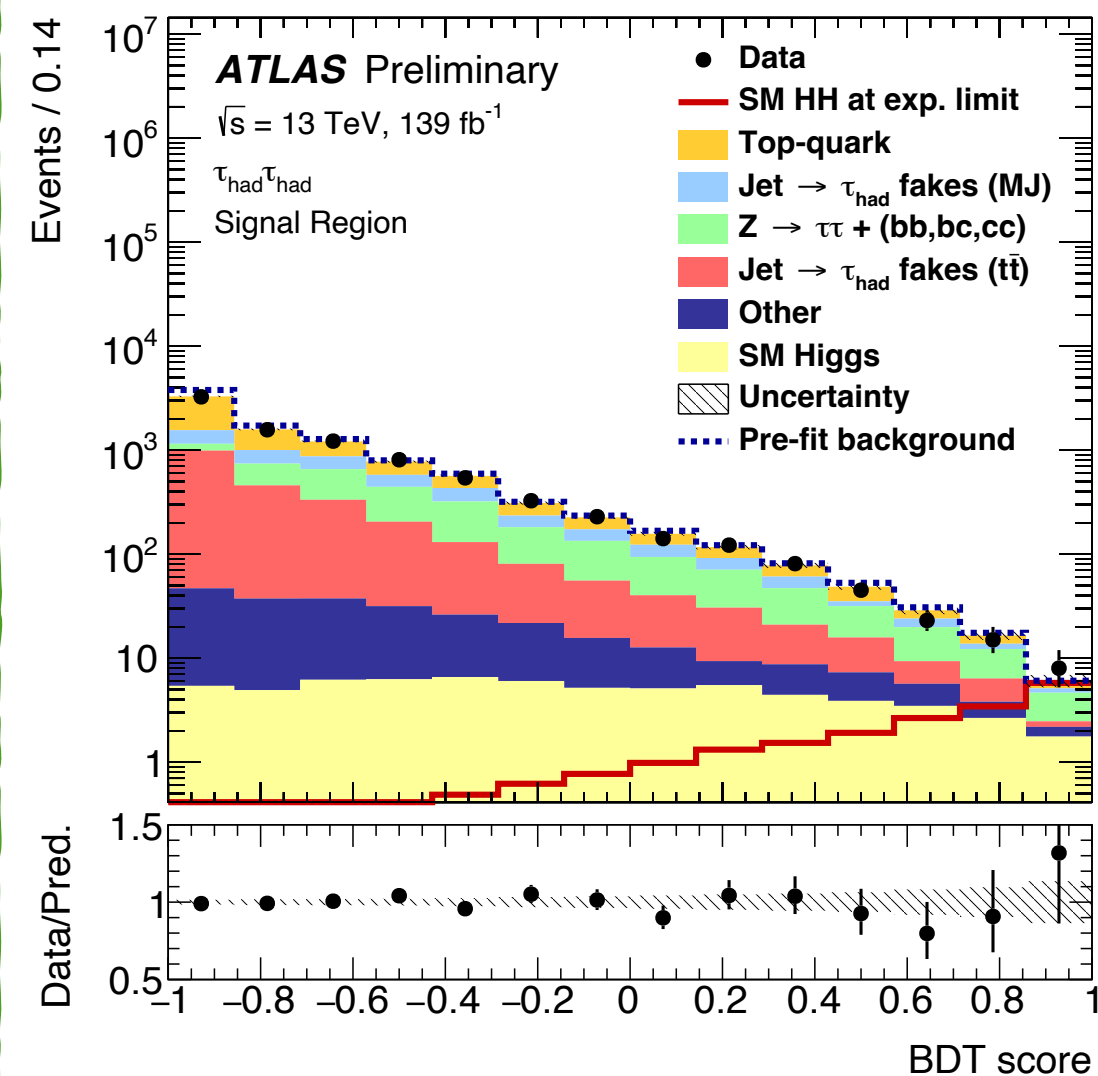
## Resolved:

**Fit:** based on a **MVA distribution** trained in 3 SRs:

- ▶  $\tau_{\text{lep}}\tau_{\text{had}}$ : Single Lepton Trigger (STT), Lepton + Tau Trigger (LTT);
- ▶  $\tau_{\text{had}}\tau_{\text{had}}$ : Single/Di Tau Triggers.

## Non-resonant

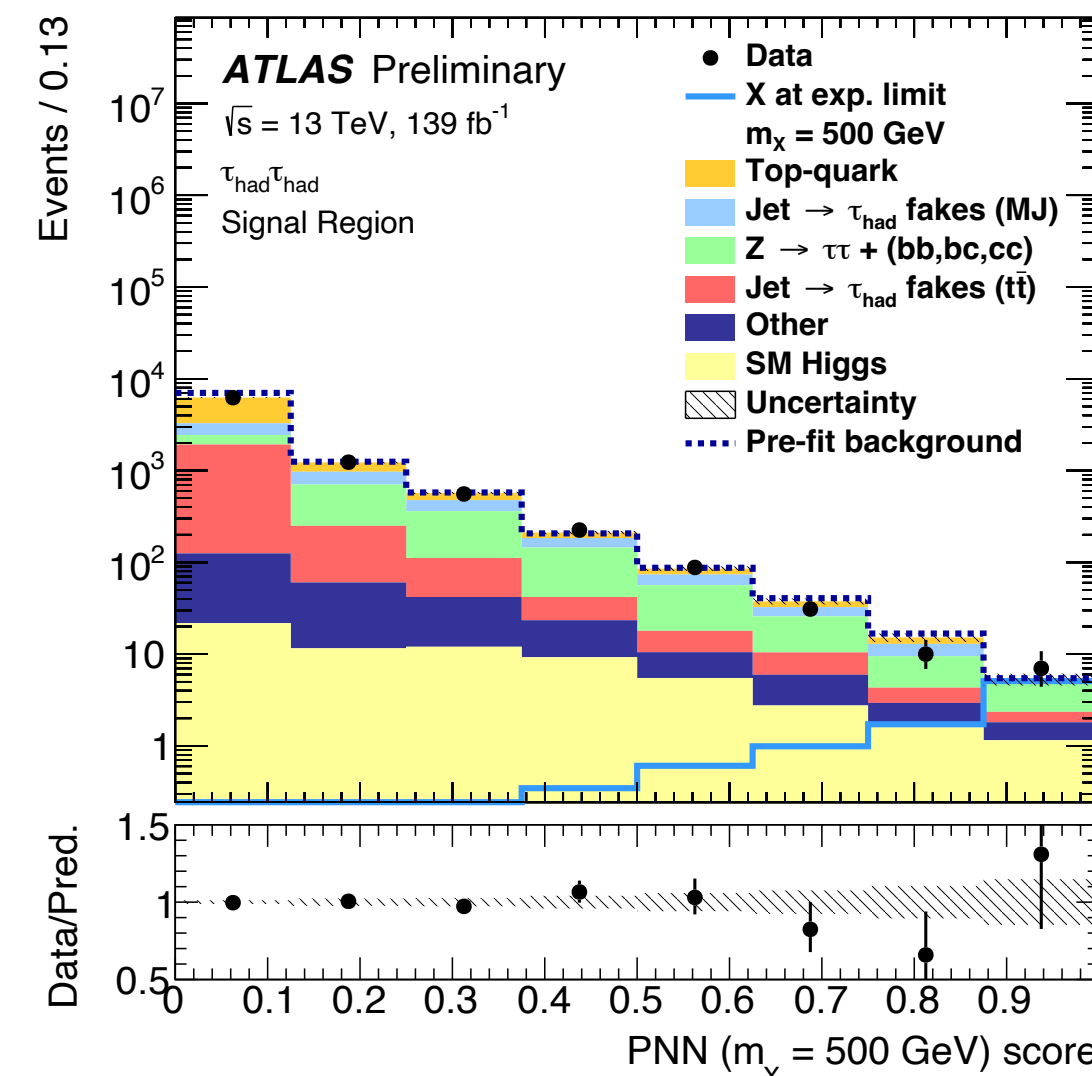
- ▶ BDT in  $\tau_{\text{had}}\tau_{\text{had}}$  category;
- ▶ NN in  $\tau_{\text{lep}}\tau_{\text{had}}$  category.



dedicated Control Regions for:  
 $t\bar{t}$ ,  $Z \rightarrow \tau\tau$ , multi-jets (evaluated from data-driven ABCD method)

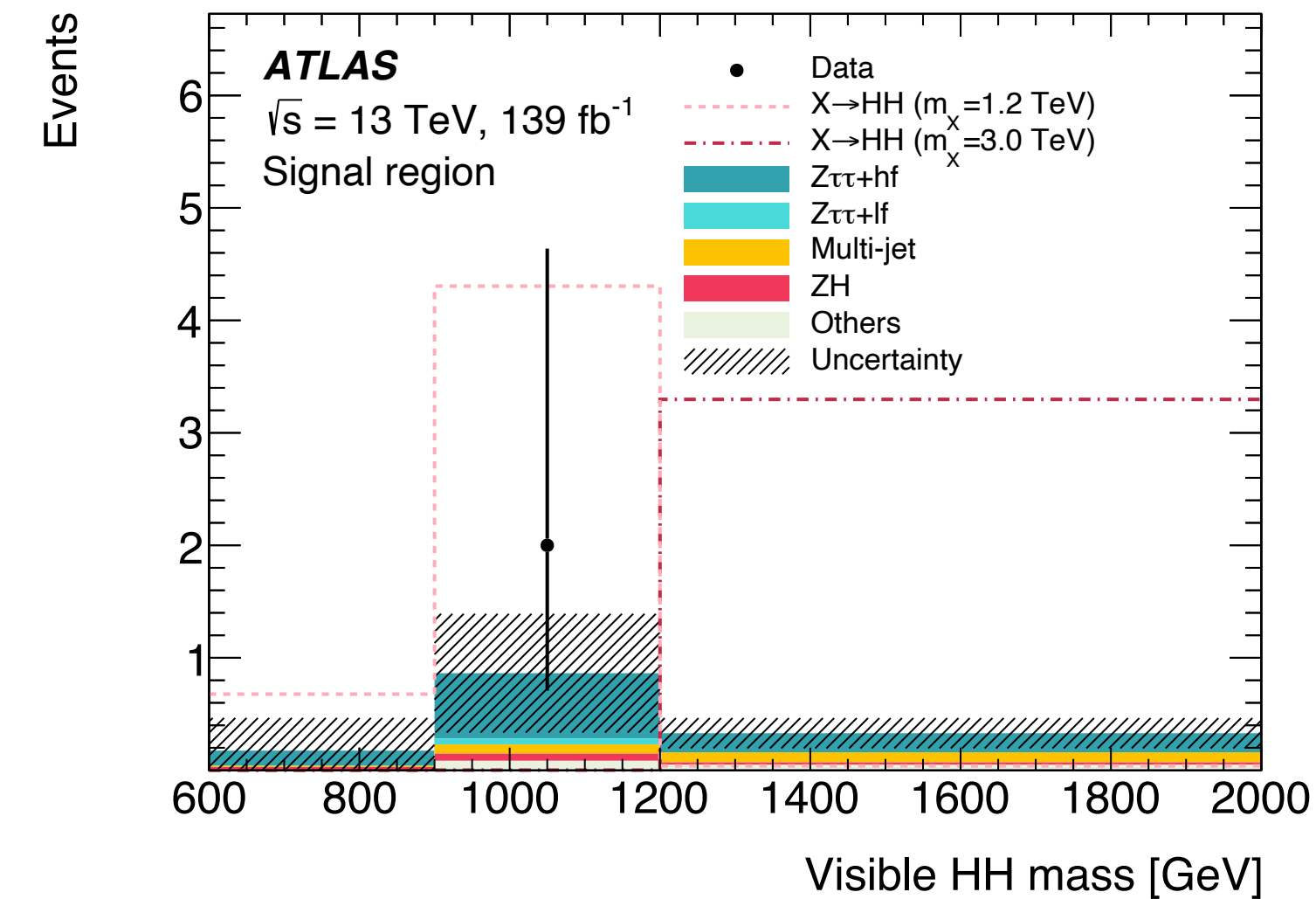
## Resonant

Parametrised NN to ease the interpolation between mass points



## Boosted:

**Fit:** Single bin fit for different *resonant* masses.



Selections based on:

- ▶ Mass of Large R jet;
- ▶ visible di-Higgs mass  $m_{HH}^{vis}$ .

dedicated Control Regions for:

$Z \rightarrow \tau\tau$  + jets, multi-jets (evaluated from data-driven ABCD method)



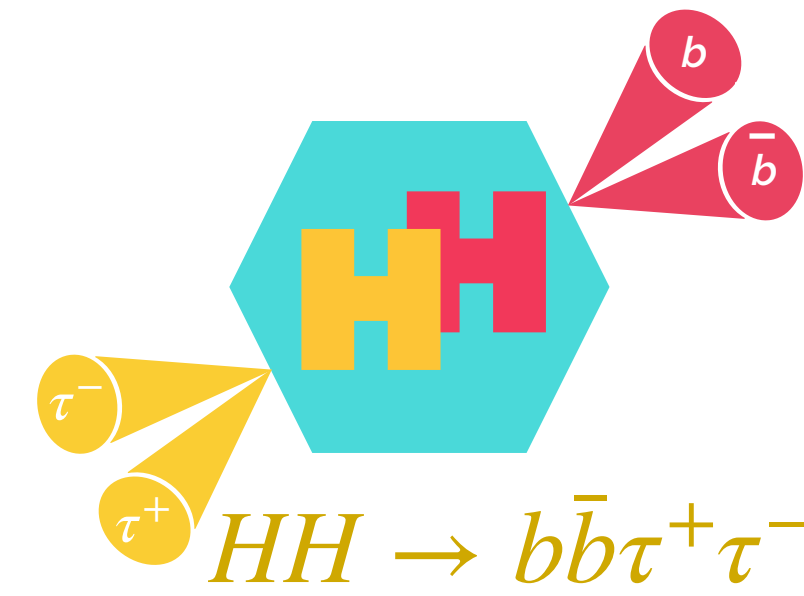
# Results

Resolved:  $\mathcal{L} = 139\text{fb}^{-1}$

ATLAS-CONF-2021-030

Boosted:  $\mathcal{L} = 139\text{fb}^{-1}$

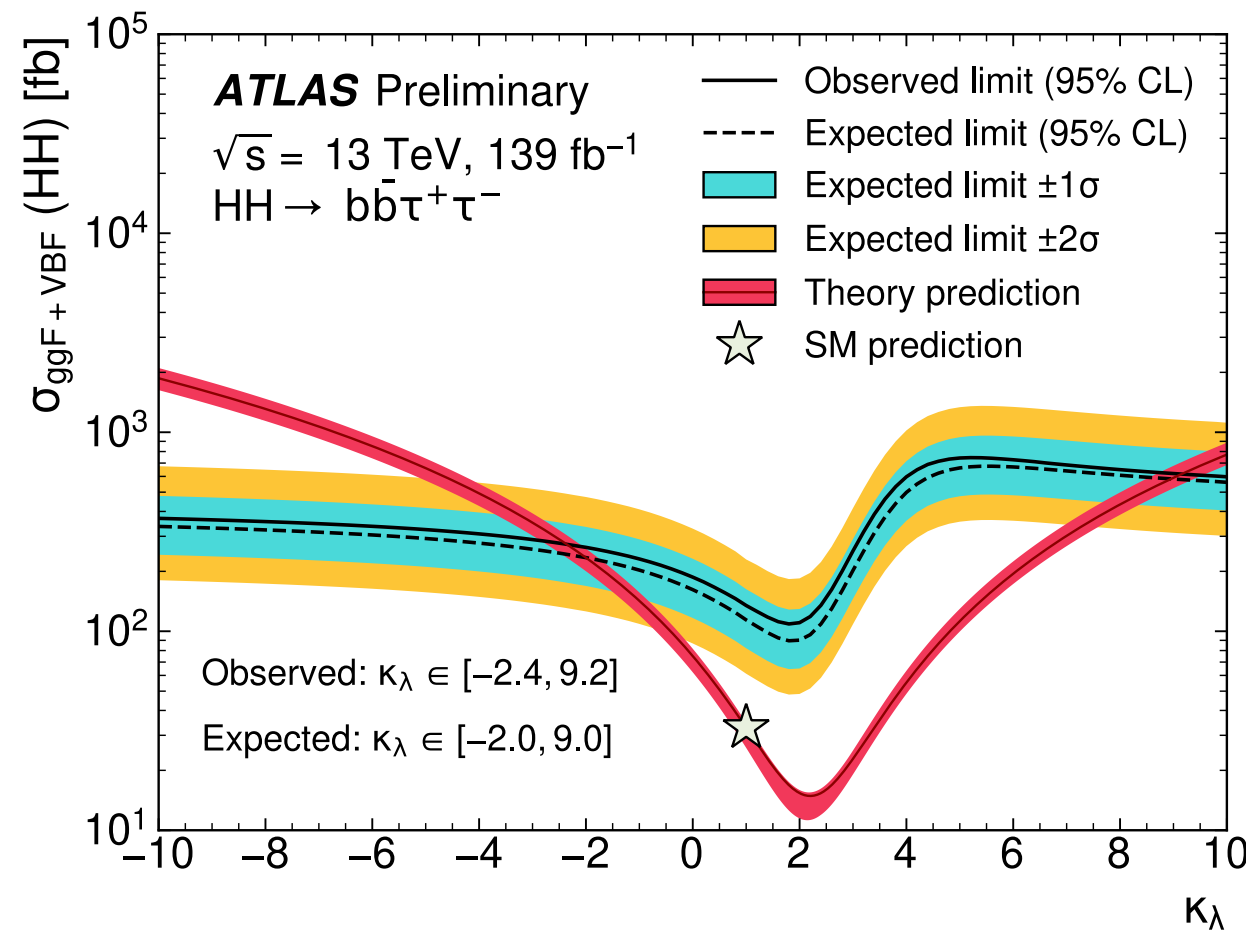
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**Resolved:**

*Non-resonant*

No significant excess found



$$\sigma_{HH}^{ggF+VBF}$$

**observed (expected) limit is 4.7 (3.9) times the SM prediction.**

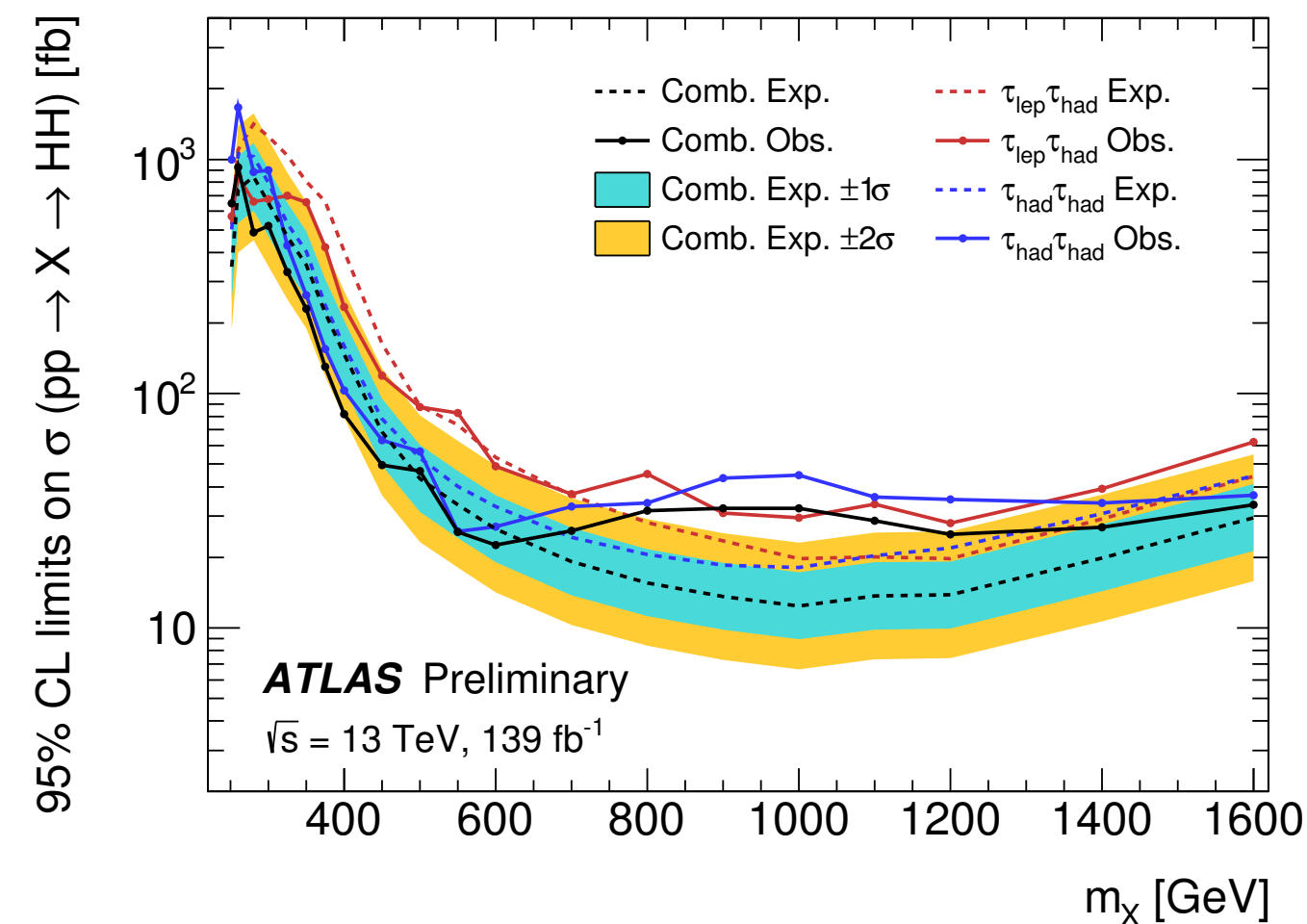
► Limits are set on  $\kappa_\lambda$ :

$$-2.4 < \kappa_\lambda < 9.2 \text{ observed}$$

$$-2.0 < \kappa_\lambda < 9.0 \text{ expected.}$$

*Resonant*

Highest deviation from the SM prediction seen at 1 TeV with a local (global) significance of  $3.0\sigma$  ( $2.0\sigma$ ).

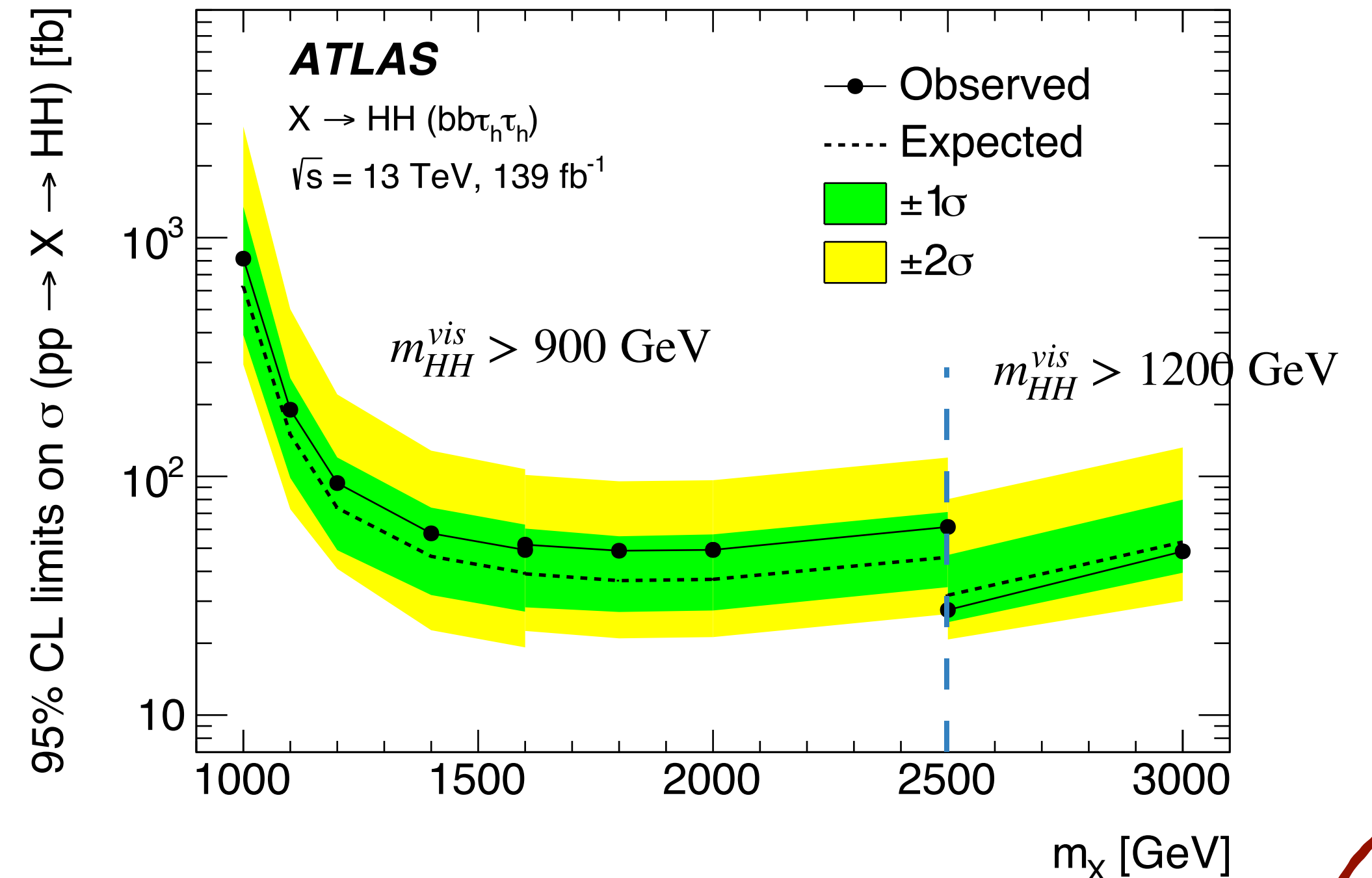


**Boosted:**

No significant excess found

Limits set on  $\sigma(X \rightarrow HH \rightarrow b\bar{b}\tau\tau)$  where X is a narrow-width scalar resonance:

► Two regimes based on the cut on  $m_{HH}^{vis}$





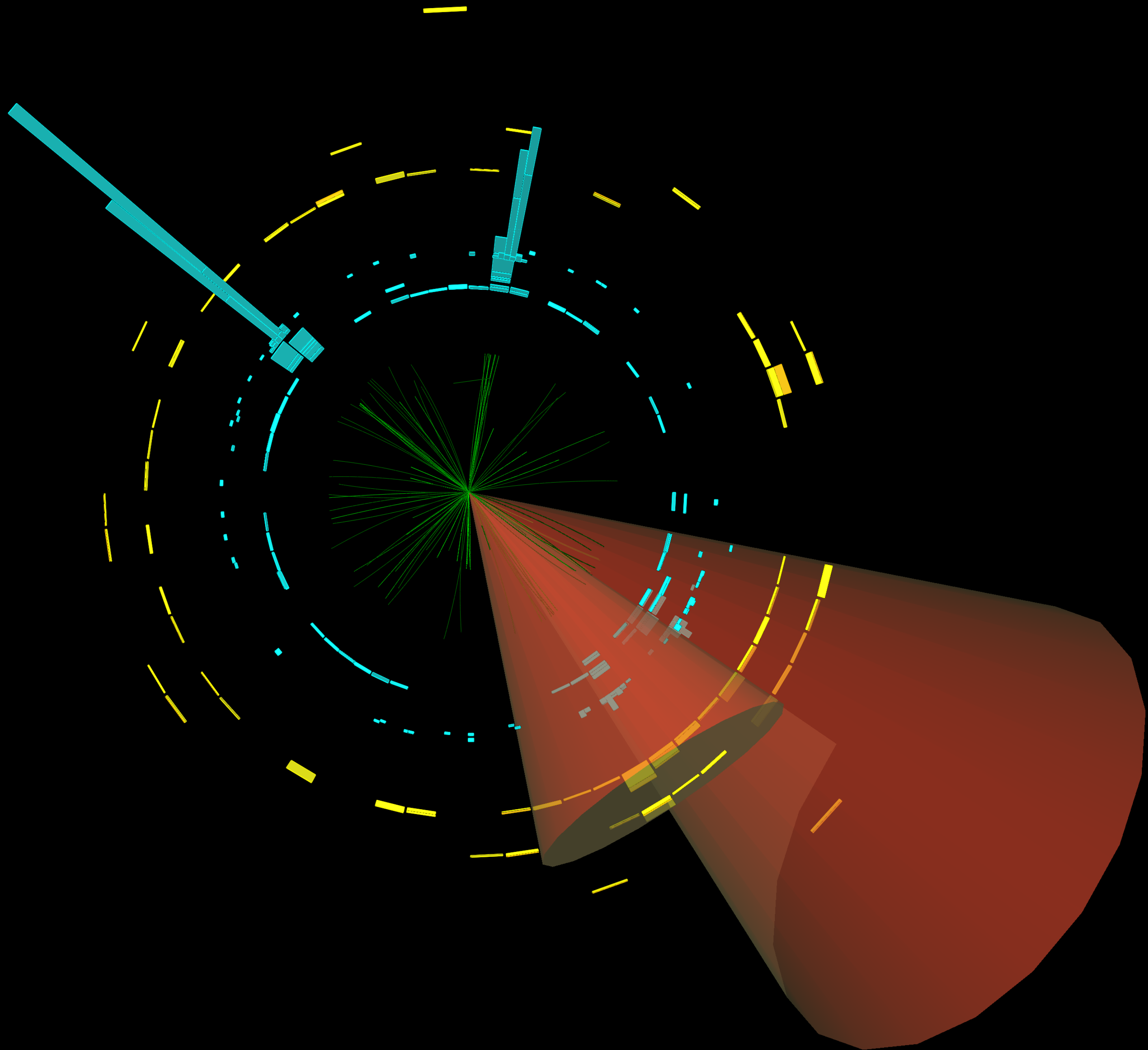


Run: 329964

Event: 796155578

2017-07-17 23:58:15 CEST

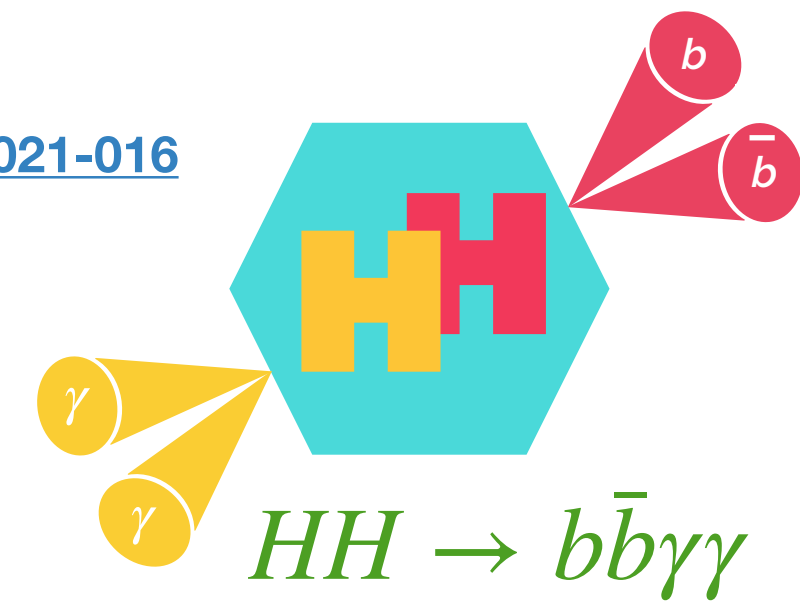
$HH \rightarrow b\bar{b}\gamma\gamma$





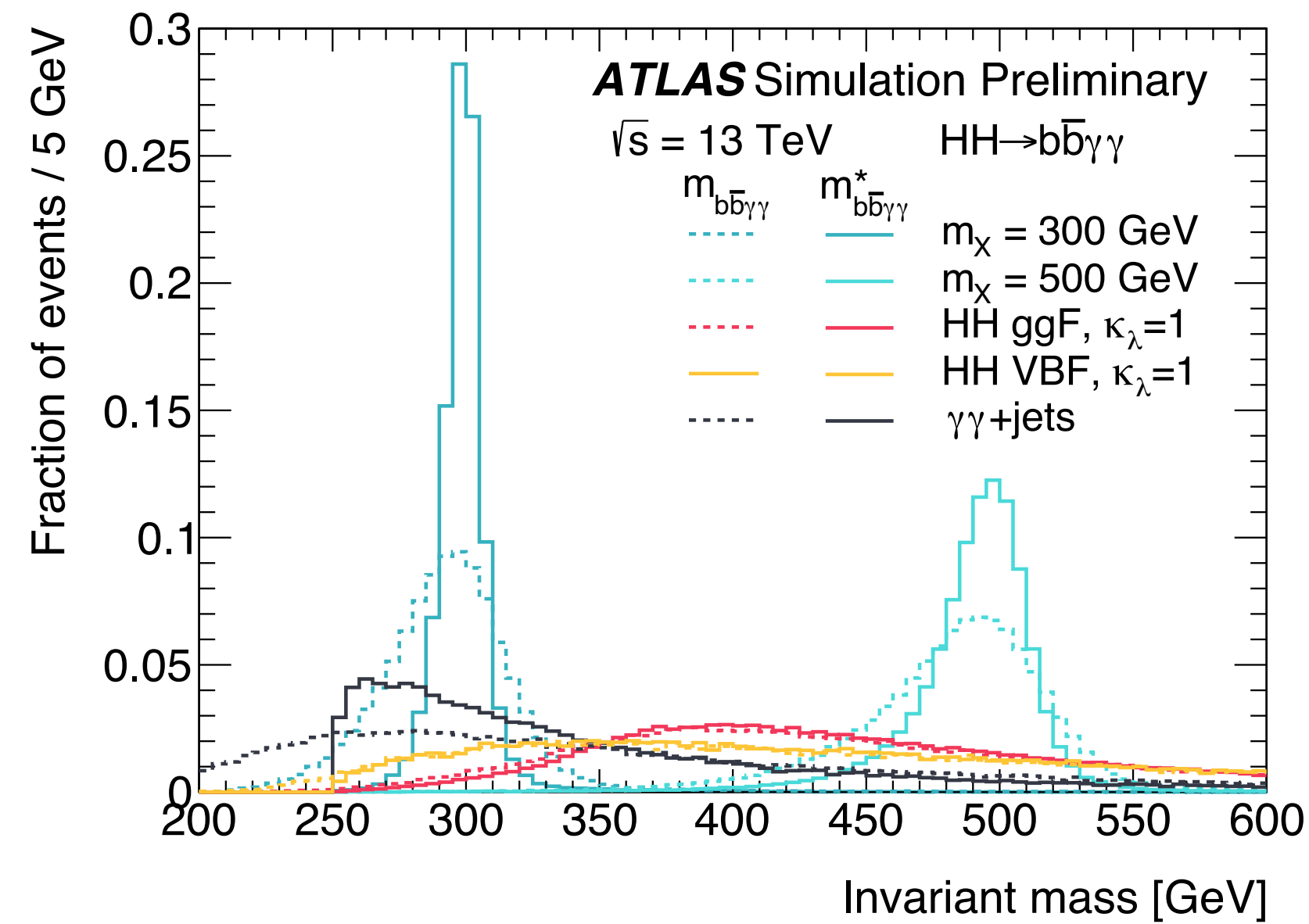
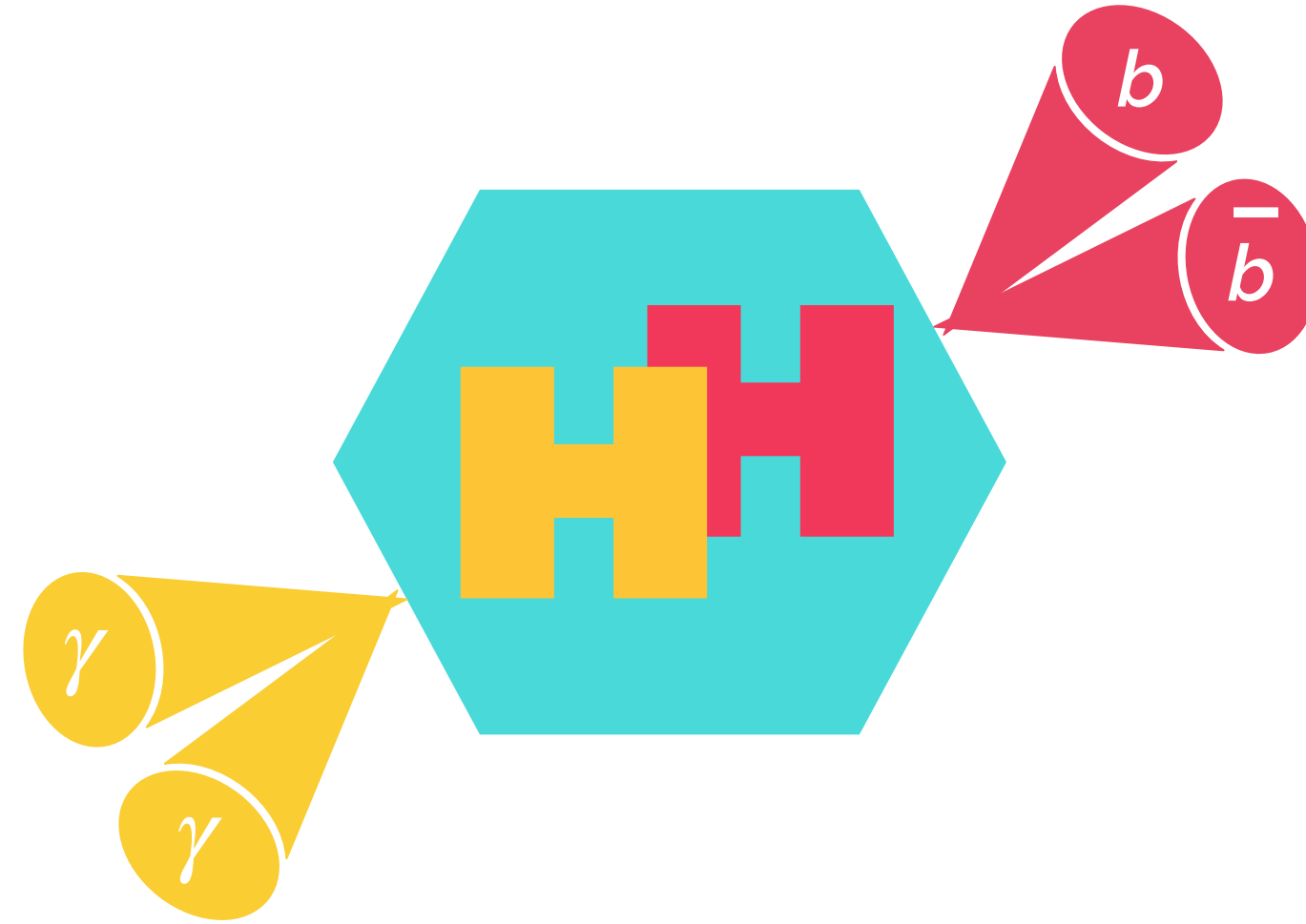
# Strategy

ggF:  $\mathcal{L} = 139\text{fb}^{-1}$  [ATLAS-CONF-2021-016](#)



- ▶ Exactly 2 b-jets;
- ▶ < 6 central jets.

- ▶ Exactly 2 High quality photons;
- ▶ No lepton.

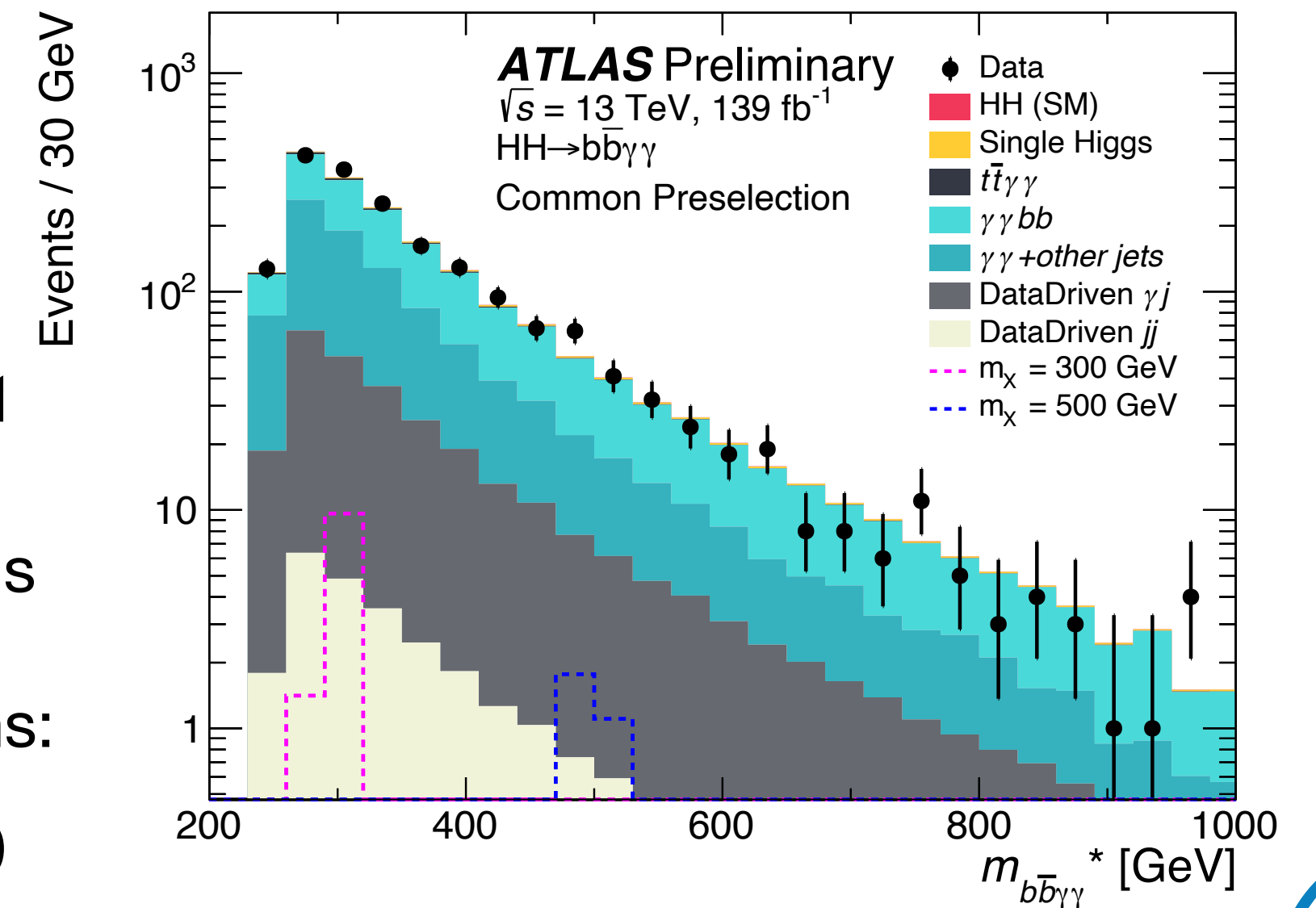


While the  $m_{\gamma\gamma}$  variable is now used for the fit, the HH invariant mass  $m_{b\bar{b}\gamma\gamma}$  is still useful for both the:

- ▶ **Non-resonant** search (sensitive to  $\kappa_\lambda$ );
- ▶ **Resonant** searches (sensitive to mass of resonance).

Due to experimental resolution effects, this can be corrected, assuming the two sub-systems are originating from Higgs bosons:

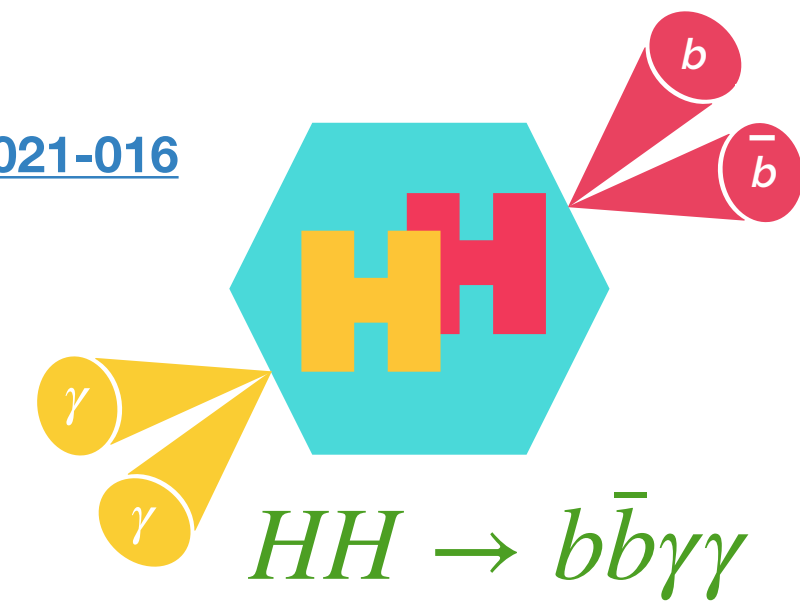
$$m_{b\bar{b}\gamma\gamma}^* [\text{GeV}] = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250$$





# How to look for signal?

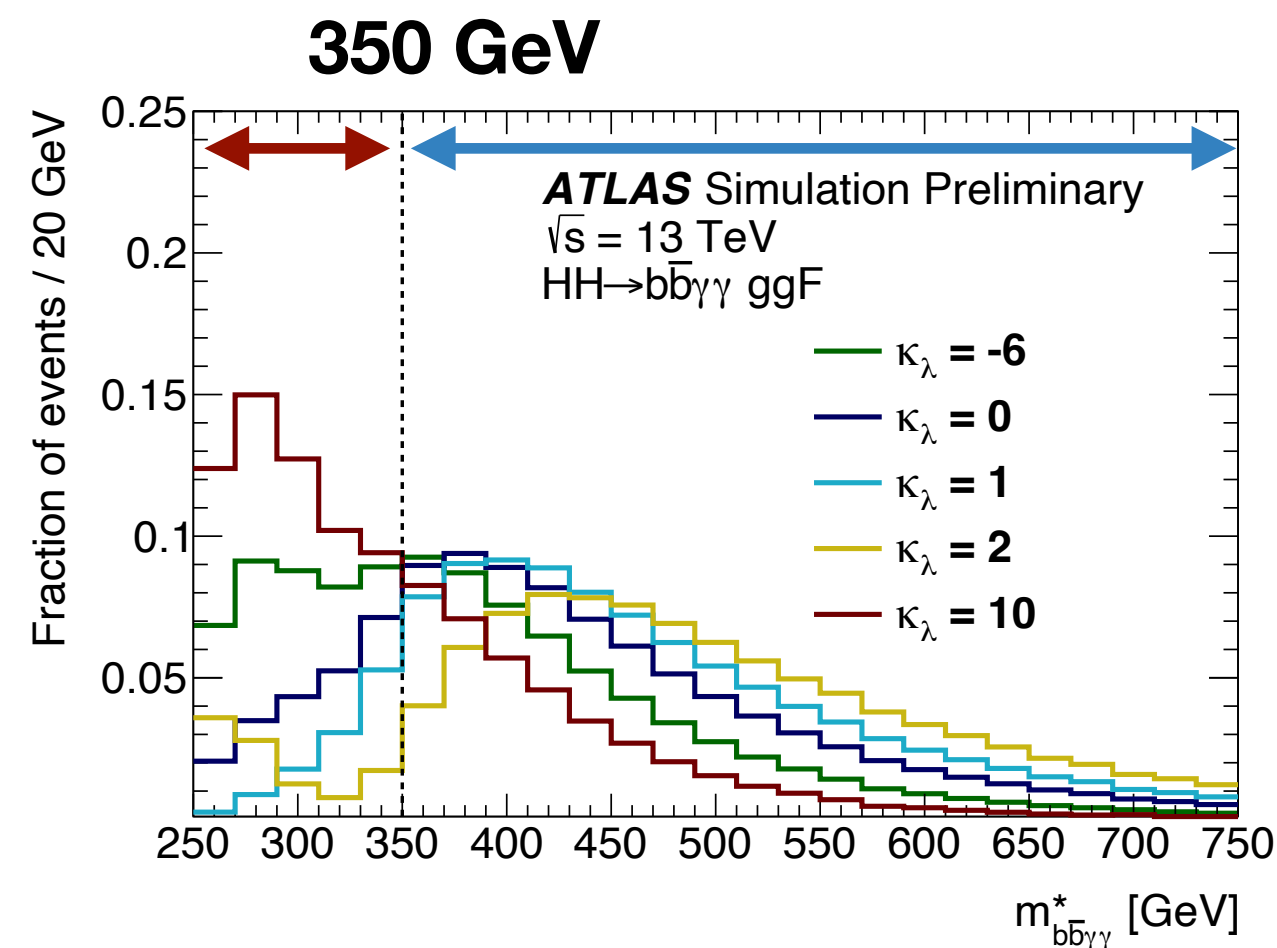
ggF:  $\mathcal{L} = 139\text{fb}^{-1}$  [ATLAS-CONF-2021-016](#)



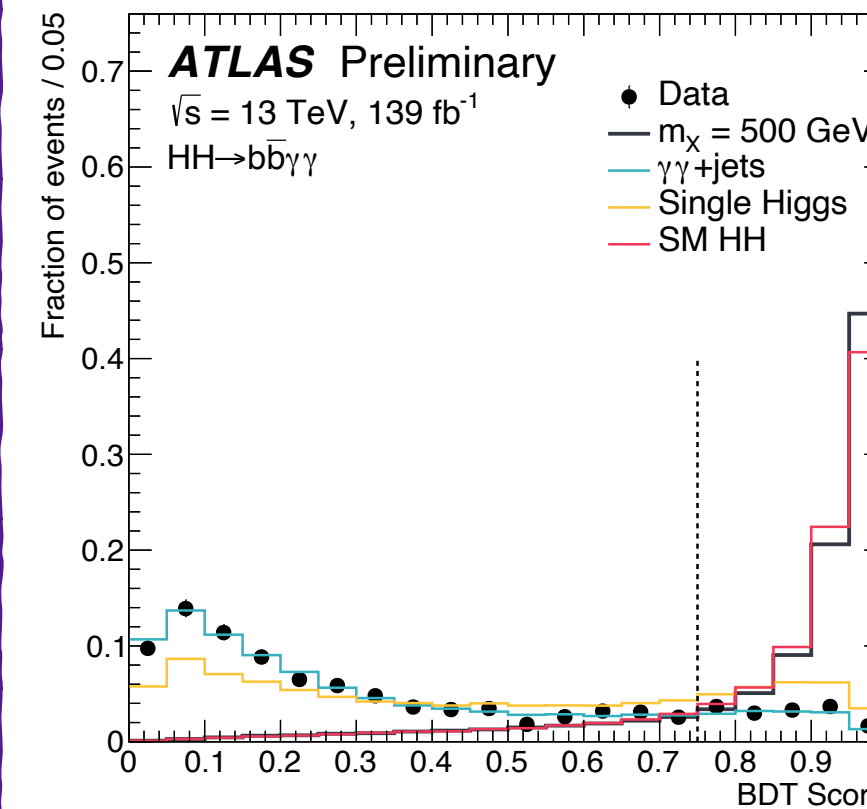
## Non Resonant :

A *BDT* is used to select signal like events w.r.t di-photon + single Higgs. *Categories* are created from  $m_{b\bar{b}\gamma\gamma}^*$  :

- ▶ **Low mass**, focussed on **BSM**
  - ▶  $\kappa_\lambda = 10$  ggF HH used as signal;
- ▶ **High mass**, focussed on **SM**
  - ▶  $\kappa_\lambda = 1$  ggF HH used as signal.



## Resonant:

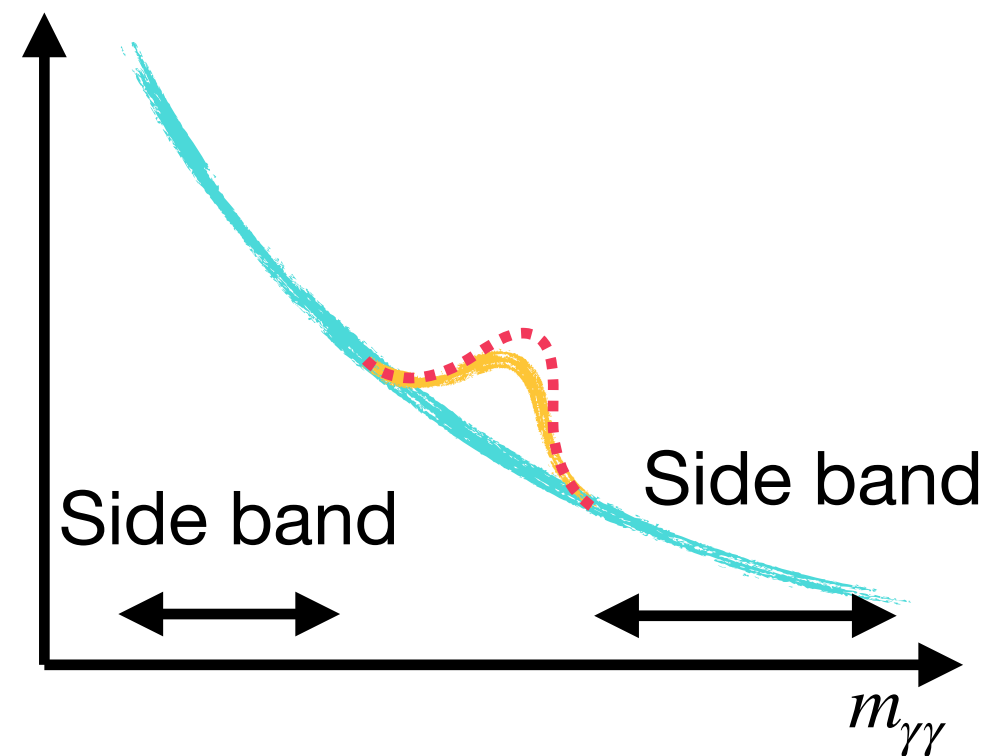


- 1 2 *BDTs* are trained and combined to separate resonant signals from di-photon and single Higgs:
  - ▶ **Mass dependent cut on BDT score**
  - ▶ 22 mass categories created.
- 2 A  $m_{b\bar{b}\gamma\gamma}^*$  window cut is made around the  $m_X$  hypothesis.

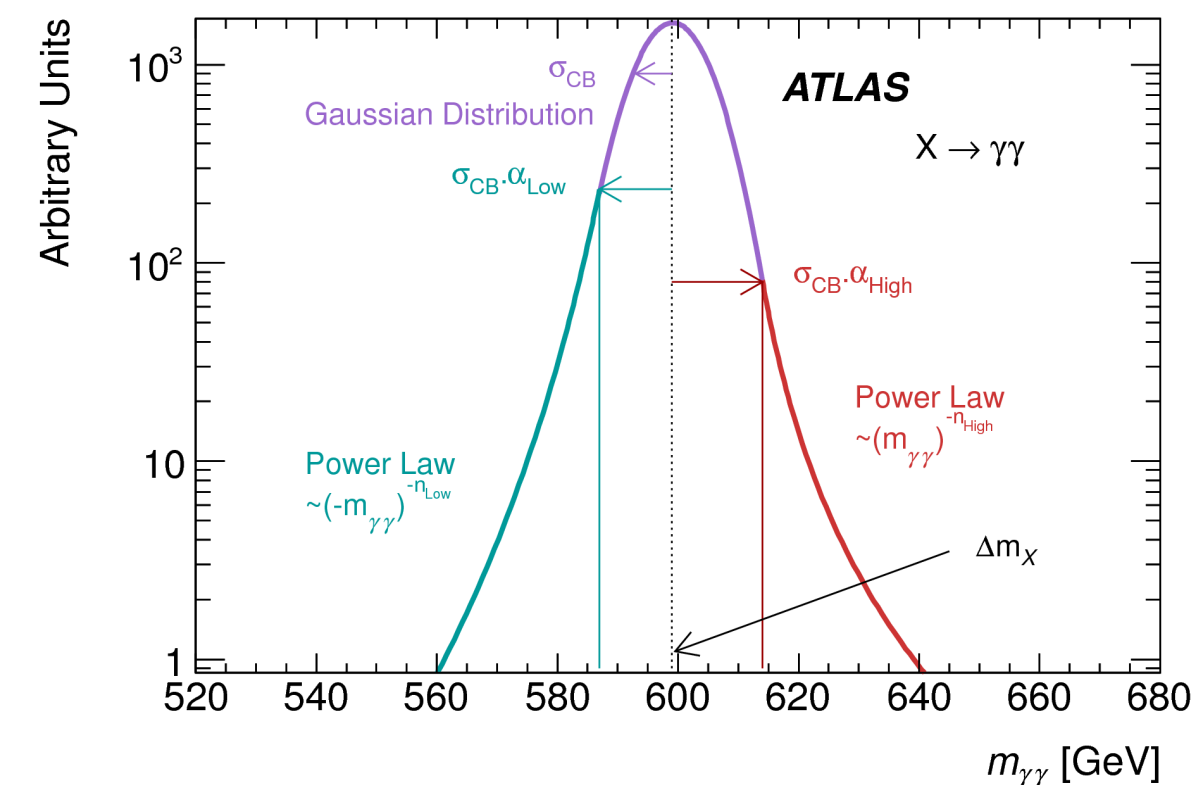
The background and signal processes are modelled thanks to **functional forms** used in the final fit:

## Diphoton Background

- ▶ Several **monotonic functions** fitted to background template normalised to data sideband are tested;
- ▶ **Minimisation** of the **signal biases**.
- ▶ Final choice: **exponential**.

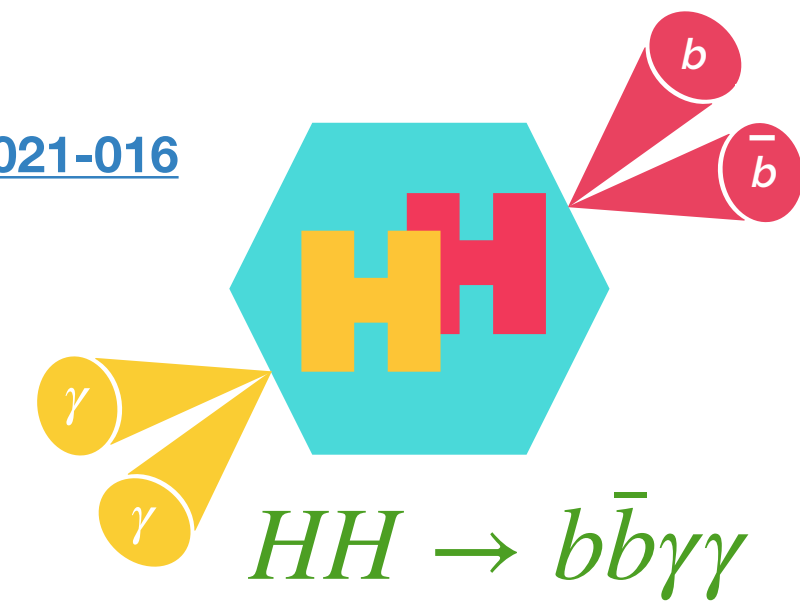


## Single Higgs HH signal



- ▶ Single Higgs and HH processes can be modelled with **double-sided Crystal Ball** function.





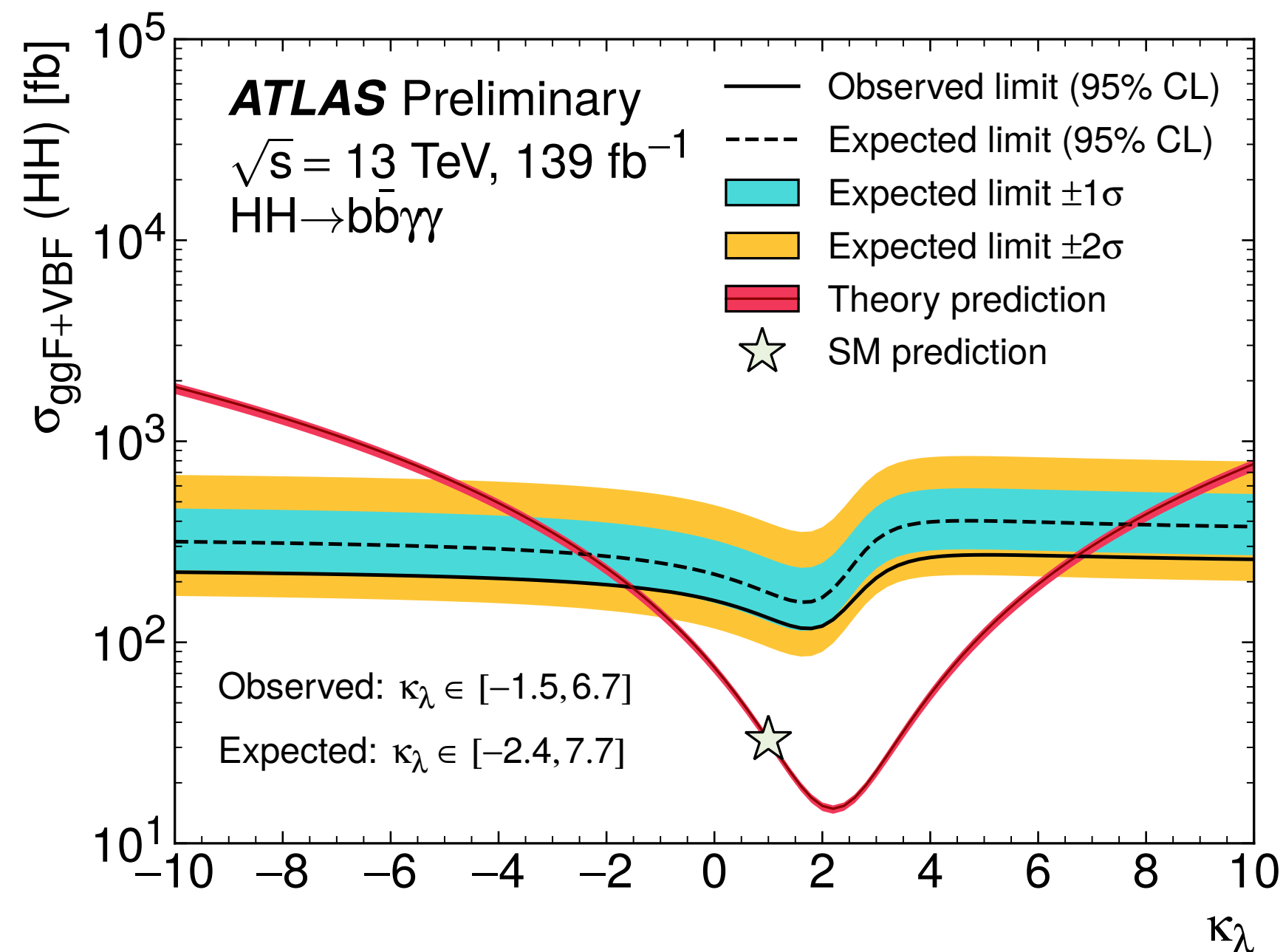
## Non Resonant

No significant excess found

$$\sigma_{HH}^{ggF+VBF}$$

**observed (expected)** limit is  
**4.1 (5.5)** times the SM prediction.

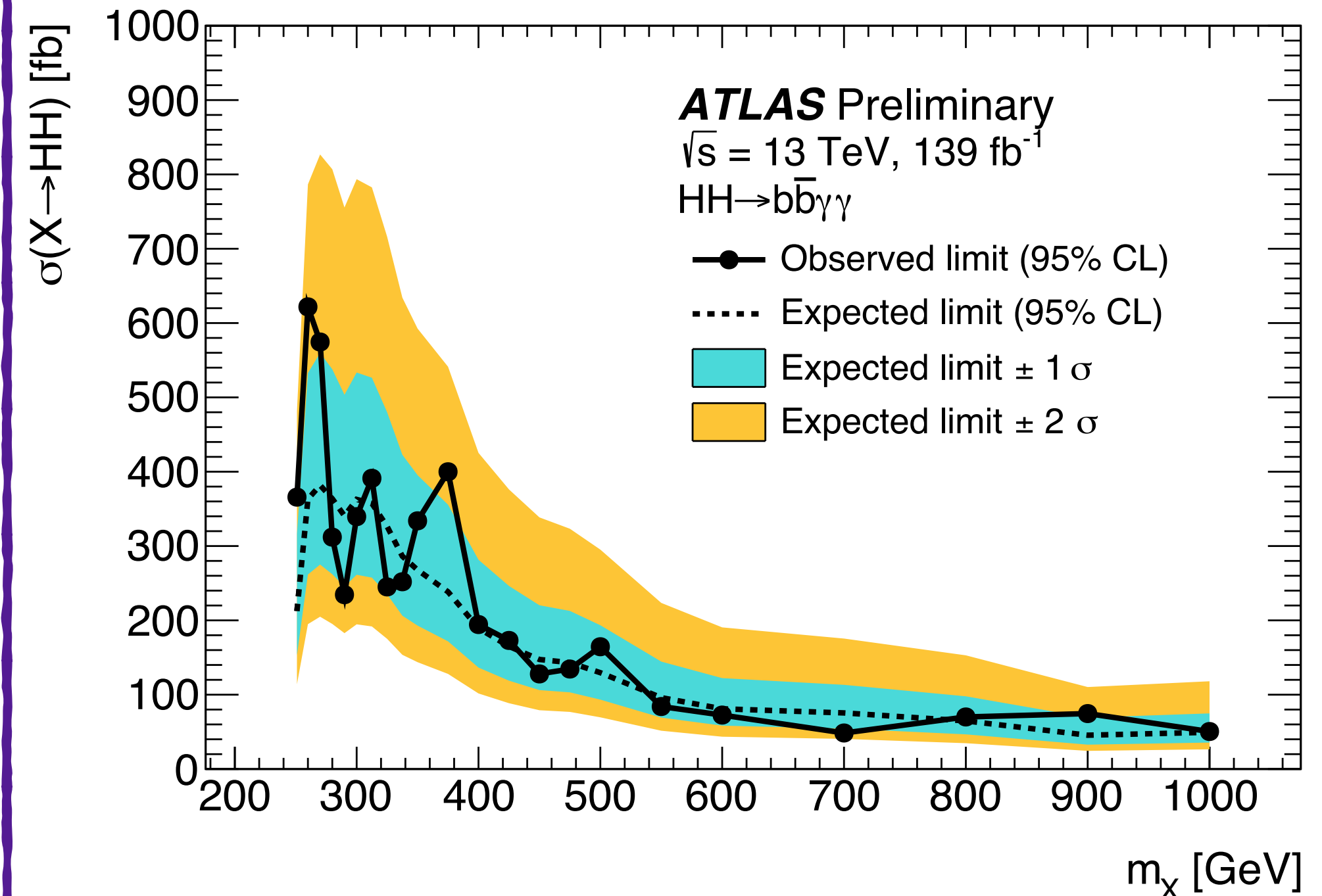
- ▶ *Best result* from single channel *observed to date*;
- ▶ Statistically dominated.
- ▶ Limits are set on  $\kappa_\lambda$ :  $-1.5 < \kappa_\lambda < 6.7$  observed  
 $-2.4 < \kappa_\lambda < 7.7$  expected.



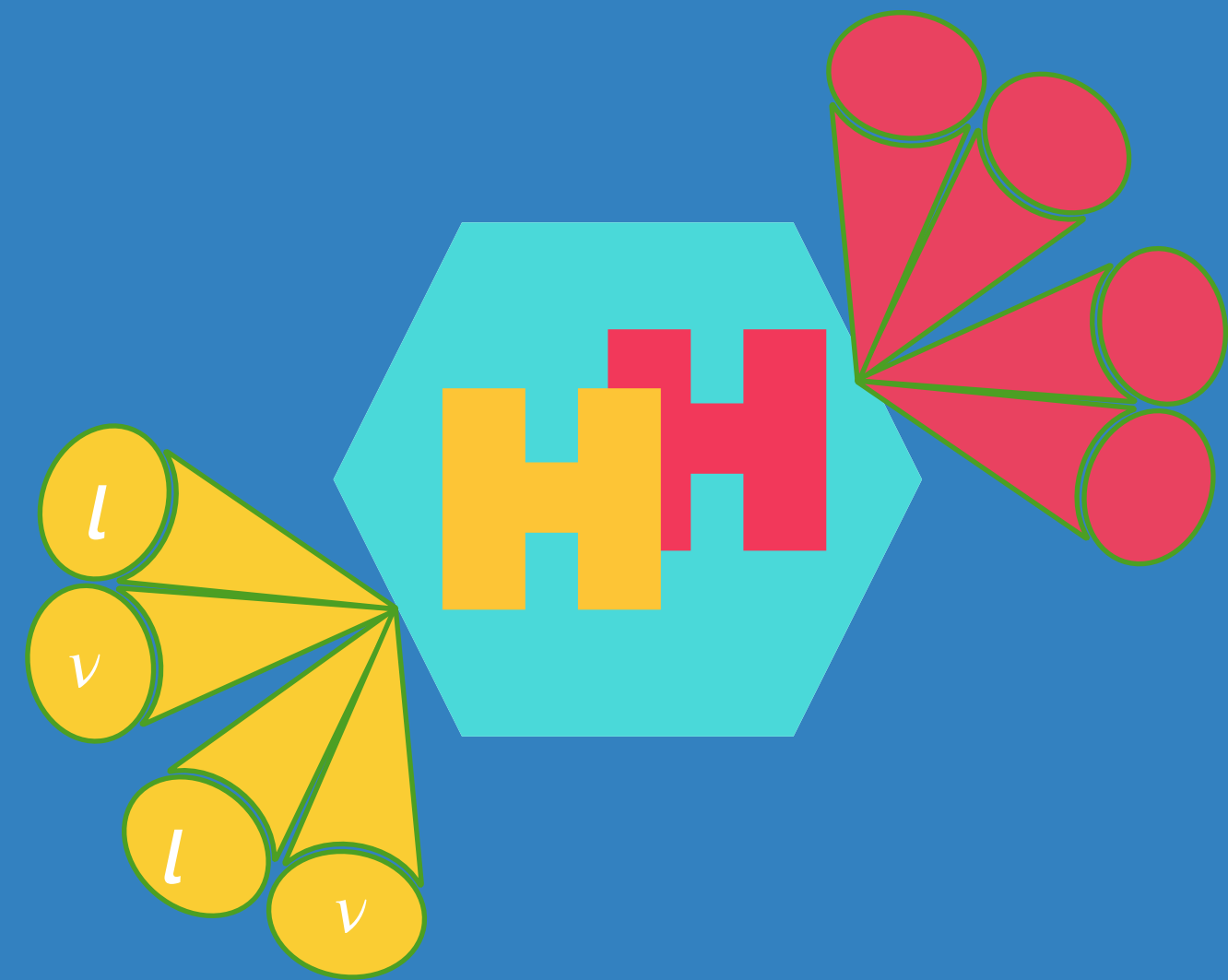
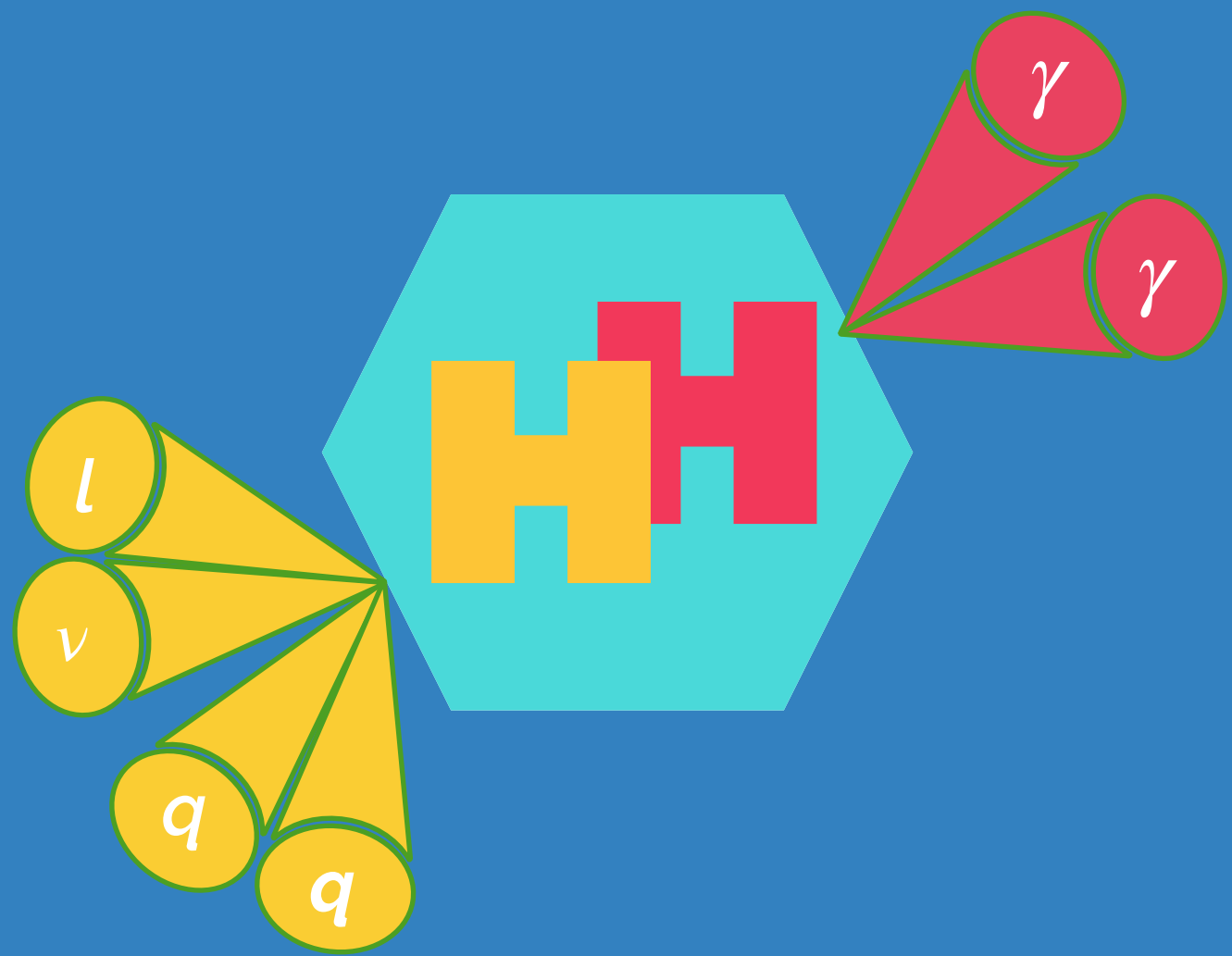
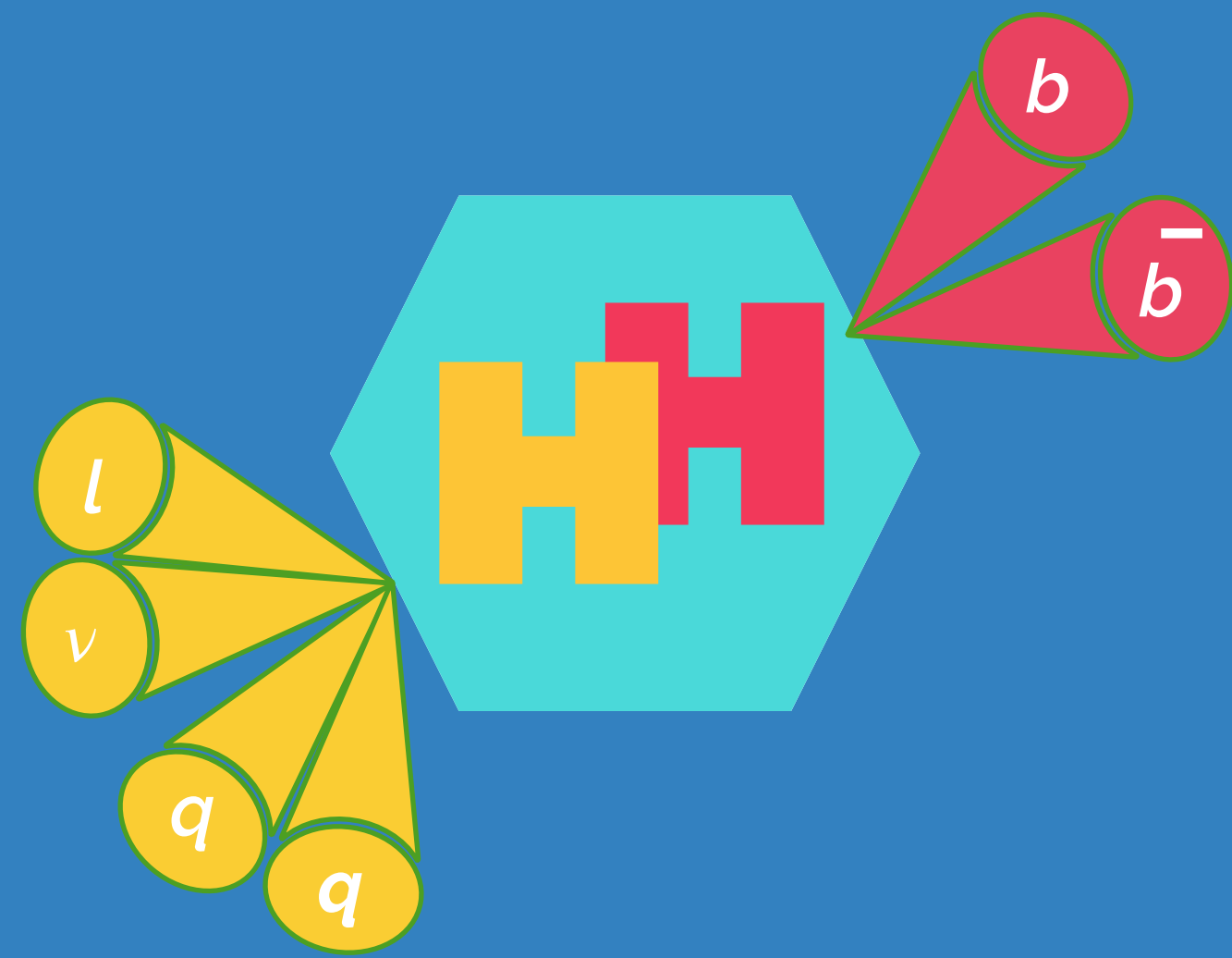
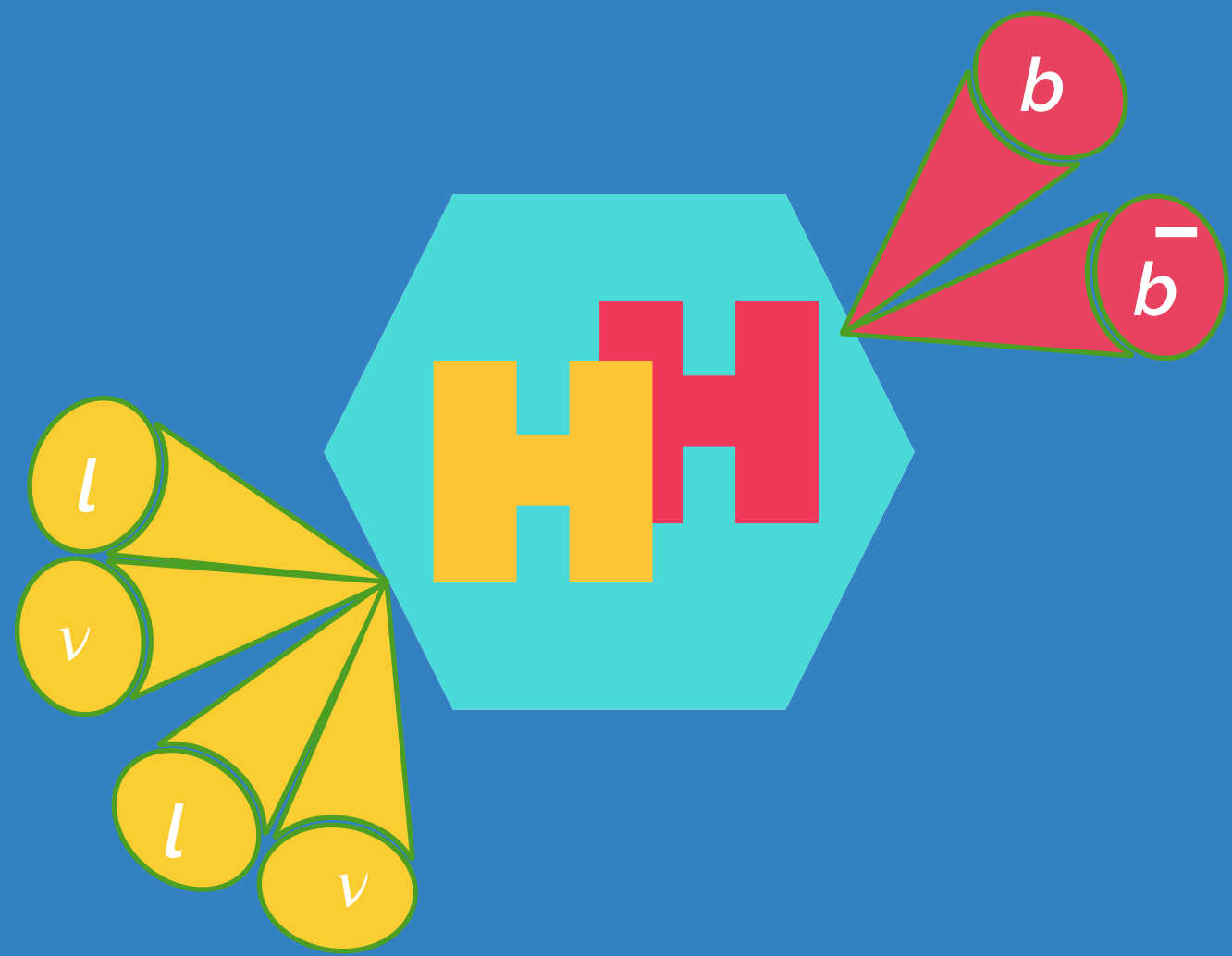
## Resonant:

No significant excess found

Limits set on  $\sigma(X \rightarrow HH)$  where  $X$  is a narrow-width scalar resonance:



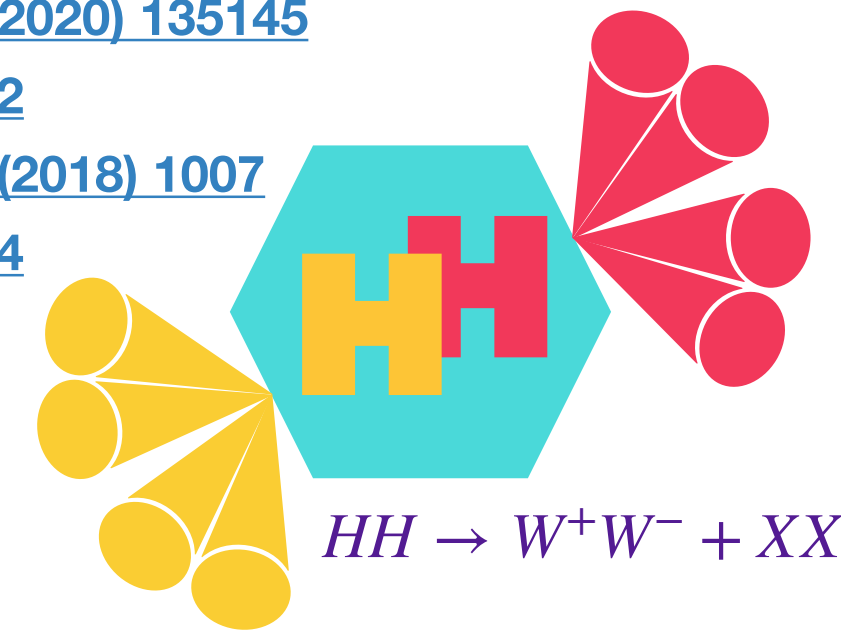




# Selection

$b\bar{b}l\nu l\nu$  final state :  $\mathcal{L} = 139\text{fb}^{-1}$   
 $b\bar{b}l\nu q\bar{q}$  final state :  $\mathcal{L} = 36\text{fb}^{-1}$   
 $\gamma\gamma WW^*$  final state :  $\mathcal{L} = 36\text{fb}^{-1}$   
 $WW^* WW^*$  final state :  $\mathcal{L} = 36\text{fb}^{-1}$

[Phys. Lett. B 801 \(2020\) 135145](#)  
[JHEP 04 \(2019\) 092](#)  
[Eur. Phys. J. C 78 \(2018\) 1007](#)  
[JHEP 05 \(2019\) 124](#)



$b\bar{b}l\nu q\bar{q}$  final state

This channel is aiming at reducing the contamination of  $t\bar{t}$  events by requesting one W boson to decay leptonically:

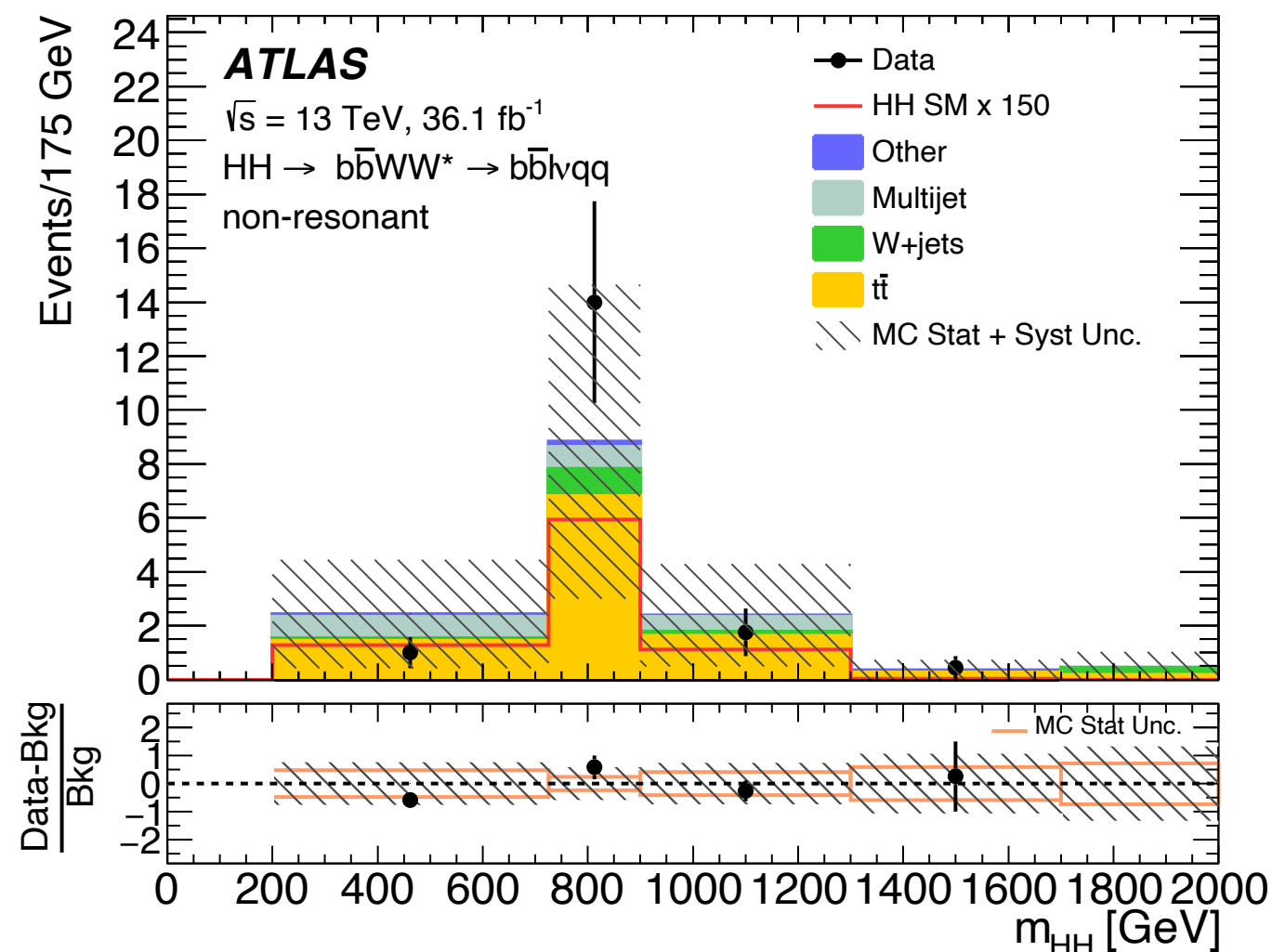
$H \rightarrow b\bar{b}$ :

- ▶ **Resolved**: exactly 2 b-tagged
- ▶ **Boosted**: One large R jet with 2 VR b-tagged jets

$H \rightarrow WW^* \rightarrow l\nu q\bar{q}$ :

- ▶ **Resolved/Boosted**:
  - ▶  $\geq 1$  high quality lepton.
  - ▶  $\geq 2$  additional jets, pair chosen with minimising  $\Delta R(\text{jet}, \text{jet})$
  - ▶ Kinematic fit to find the neutrino momentum assuming  $m_H = 125$  GeV

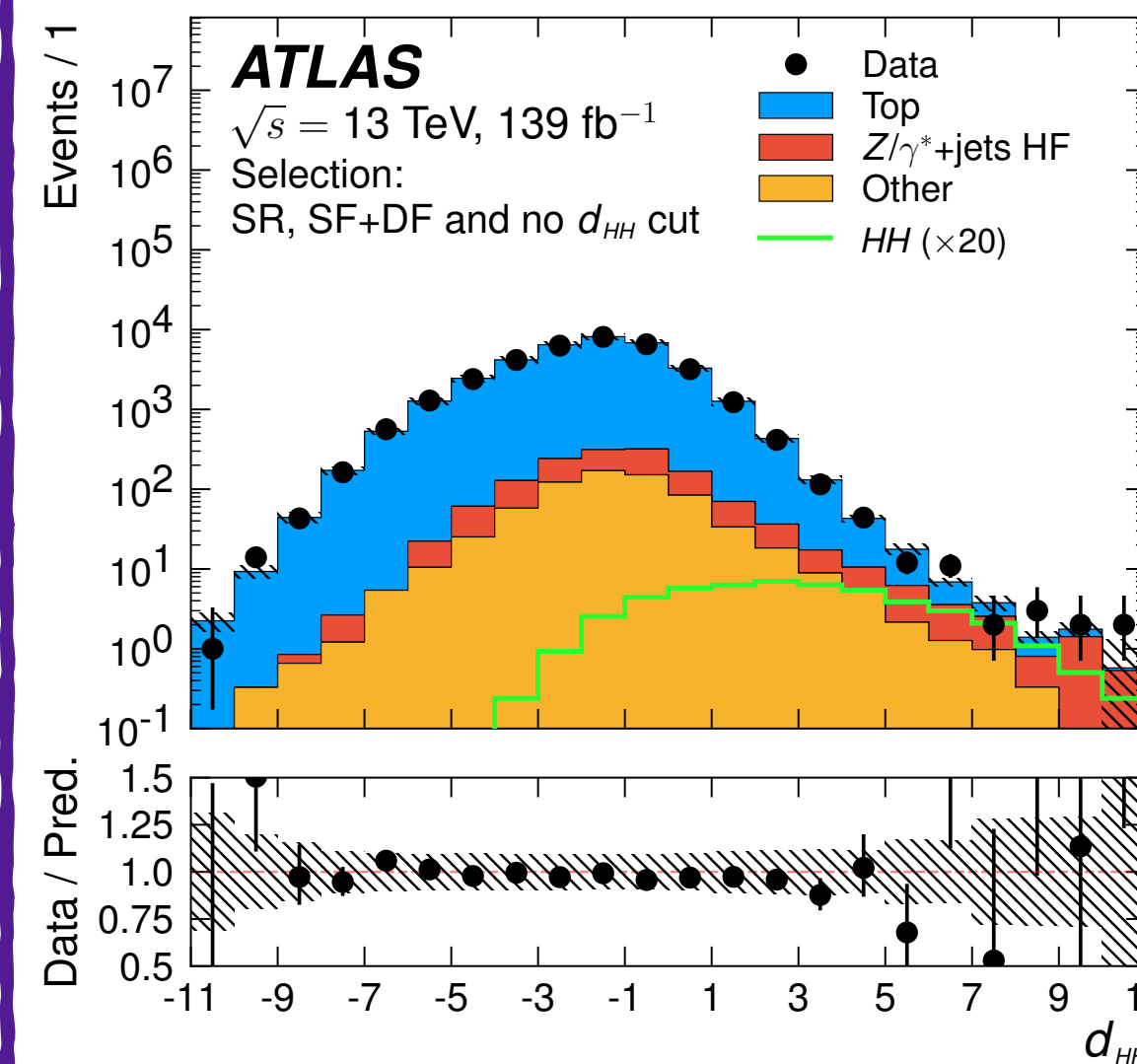
**Fit:**  $m_{HH}$  in different categories



$b\bar{b}l\nu l\nu$  final state

Resolved

This channel is aiming at  $HH \rightarrow b\bar{b}WW^*$  signal, but is also sensitive to  $HH \rightarrow b\bar{b}ZZ^*$  and  $HH \rightarrow b\bar{b}\tau\tau$



$H \rightarrow b\bar{b}$ :

- ▶ Exactly 2 b-tagged jets

$H \rightarrow WW^* \rightarrow l\nu l\nu$ :

- ▶ Exactly 2 opposite charge high quality leptons.
- ▶ Categories: based on flavour.

▶ **Deep neural Network**:

- ▶ To remove dominant backgrounds

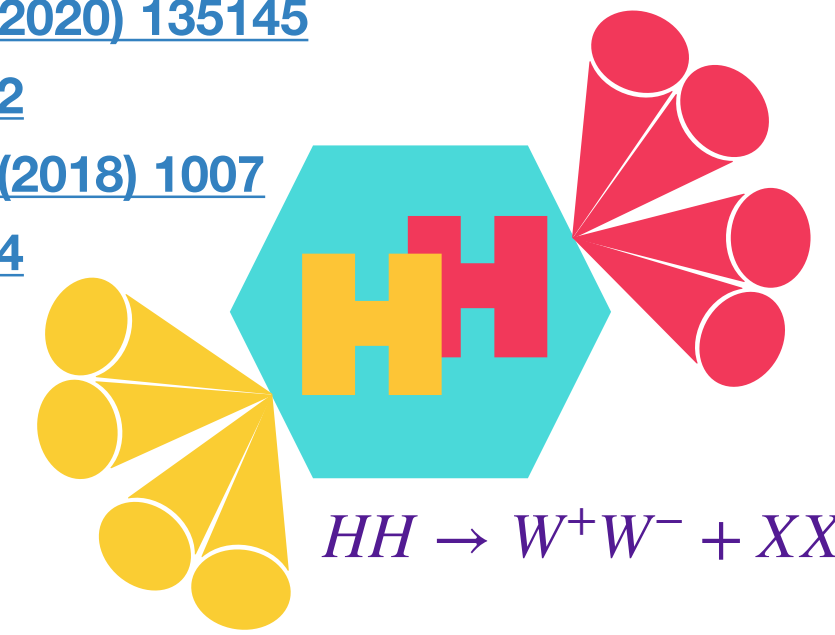
**Fit:** single bin in different categories



# Results

$b\bar{b}l\nu l\nu$  final state :  $\mathcal{L} = 139\text{fb}^{-1}$   
 $b\bar{b}l\nu q\bar{q}$  final state :  $\mathcal{L} = 36\text{fb}^{-1}$   
 $\gamma\gamma WW^*$  final state :  $\mathcal{L} = 36\text{fb}^{-1}$   
 $WW^*WW^*$  final state :  $\mathcal{L} = 36\text{fb}^{-1}$

[Phys. Lett. B 801 \(2020\) 135145](#)  
[JHEP 04 \(2019\) 092](#)  
[Eur. Phys. J. C 78 \(2018\) 1007](#)  
[JHEP 05 \(2019\) 124](#)

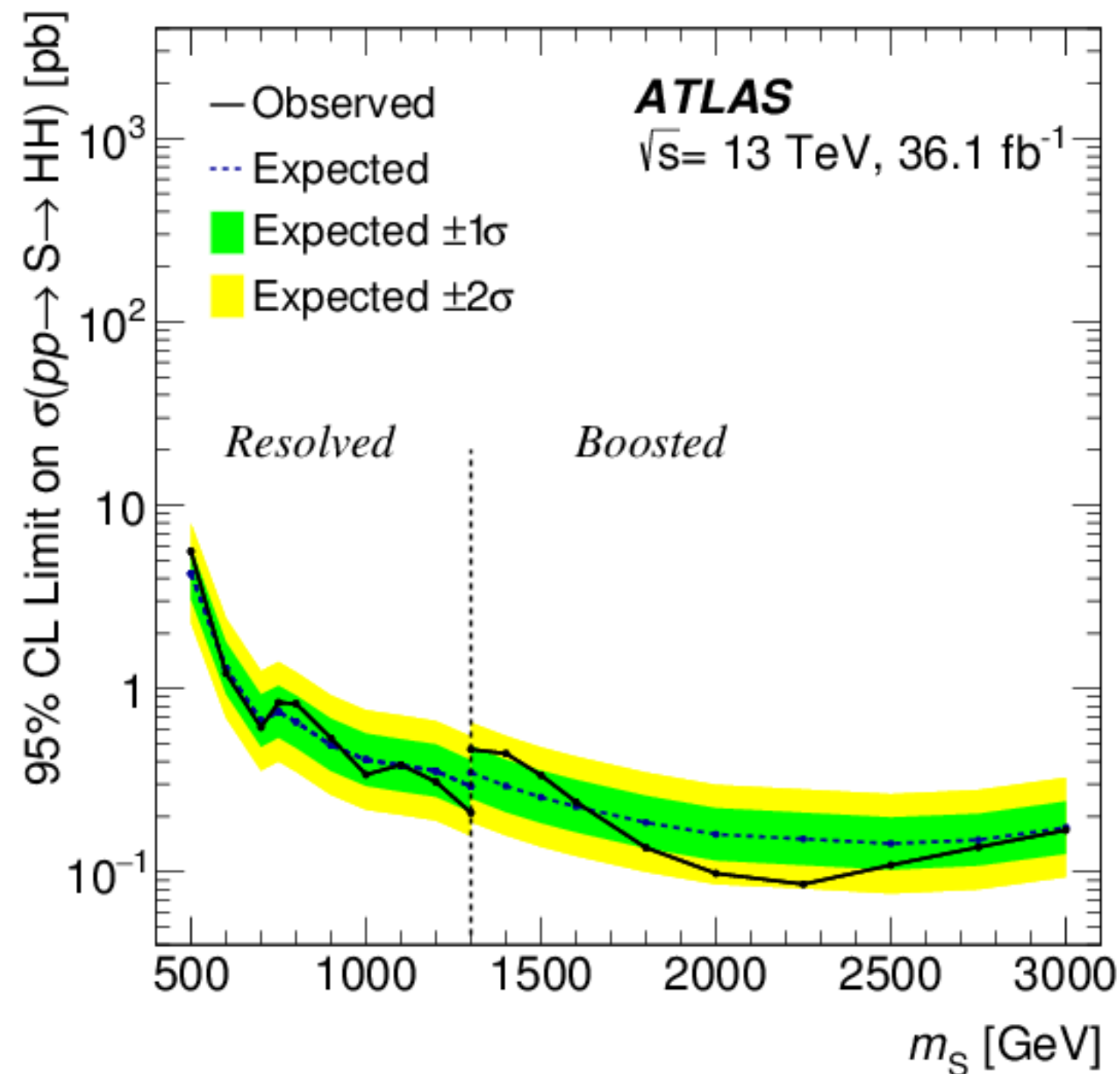


$b\bar{b}l\nu q\bar{q}$  final state

Non-resonant **Resolved**

$\sigma_{HH}^{ggF}$  **observed (expected) limit is 300 (190) times the SM prediction.**

Resonant: **Resolved Boosted**

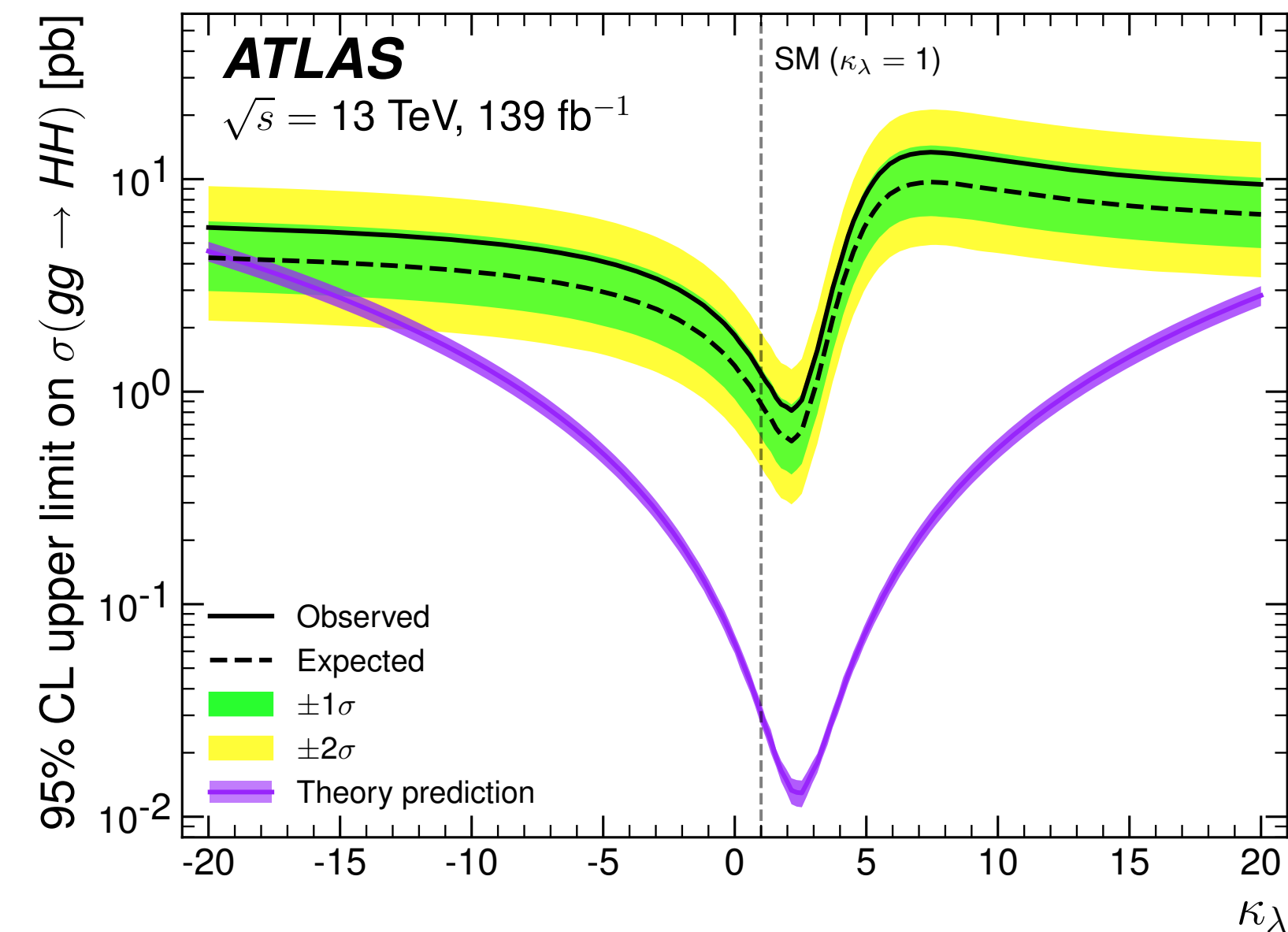


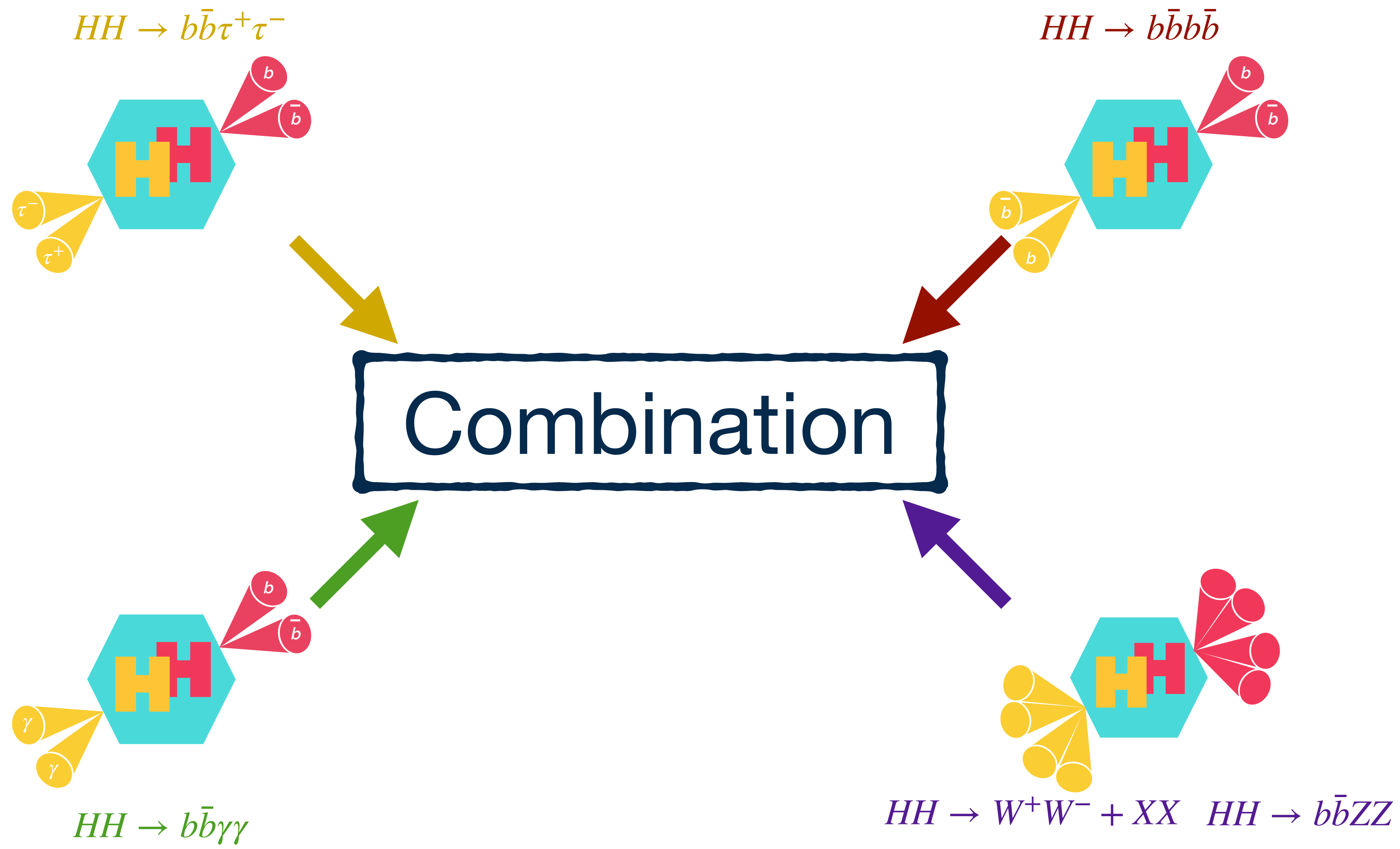
Limits set on  $\sigma(X \rightarrow HH)$  where X is a narrow-width scalar resonance

$b\bar{b}l\nu l\nu$  final state **Resolved**

Non-resonant

$\sigma_{HH}^{ggF}$  **observed (expected) limit is 14 (29) times the SM prediction.**







# Conclusion



Combination done with most of the analyses with  $\mathcal{L} = 36\text{fb}^{-1}$

**Additional results** with  $\mathcal{L} = 139\text{fb}^{-1}$ :

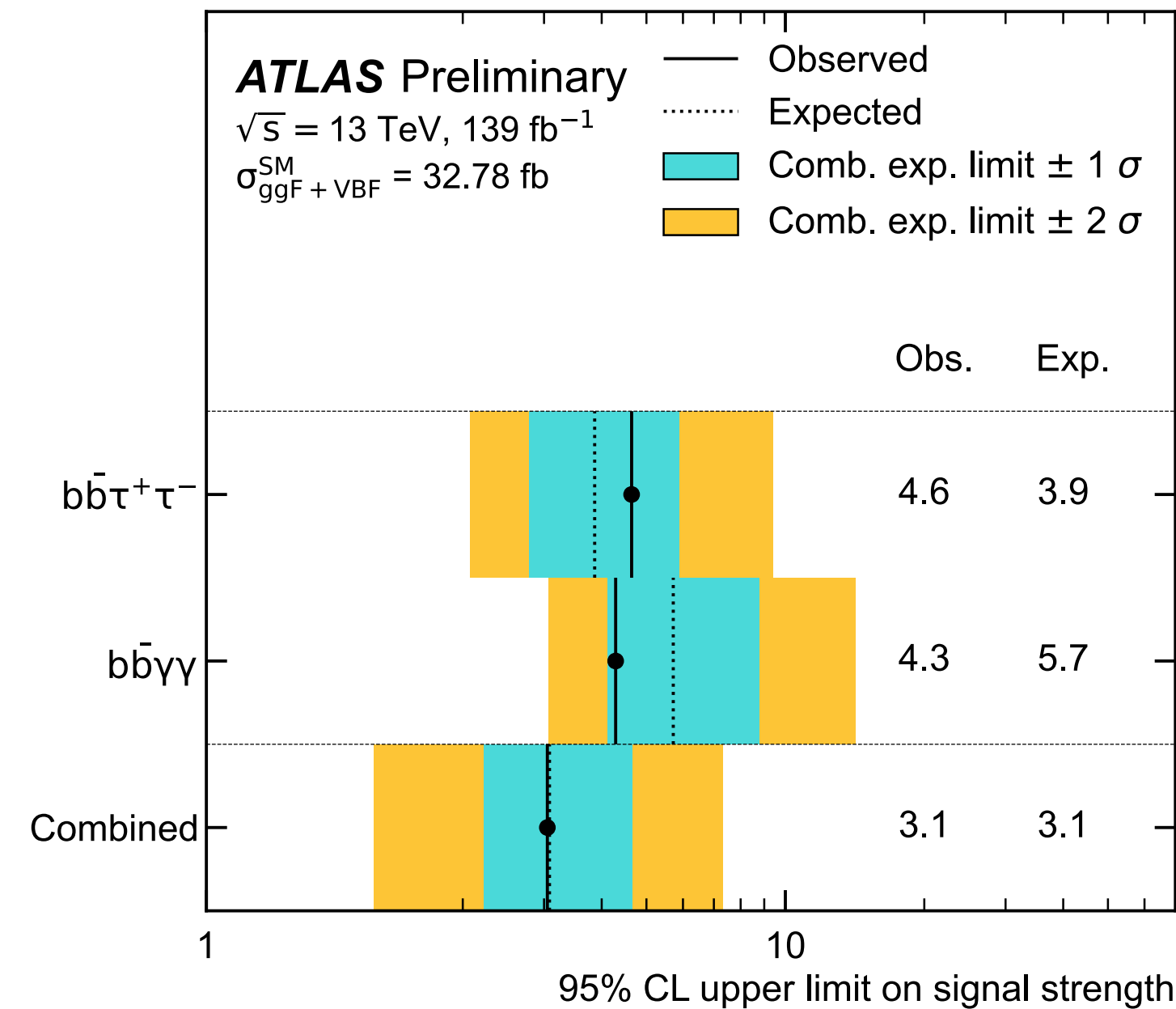
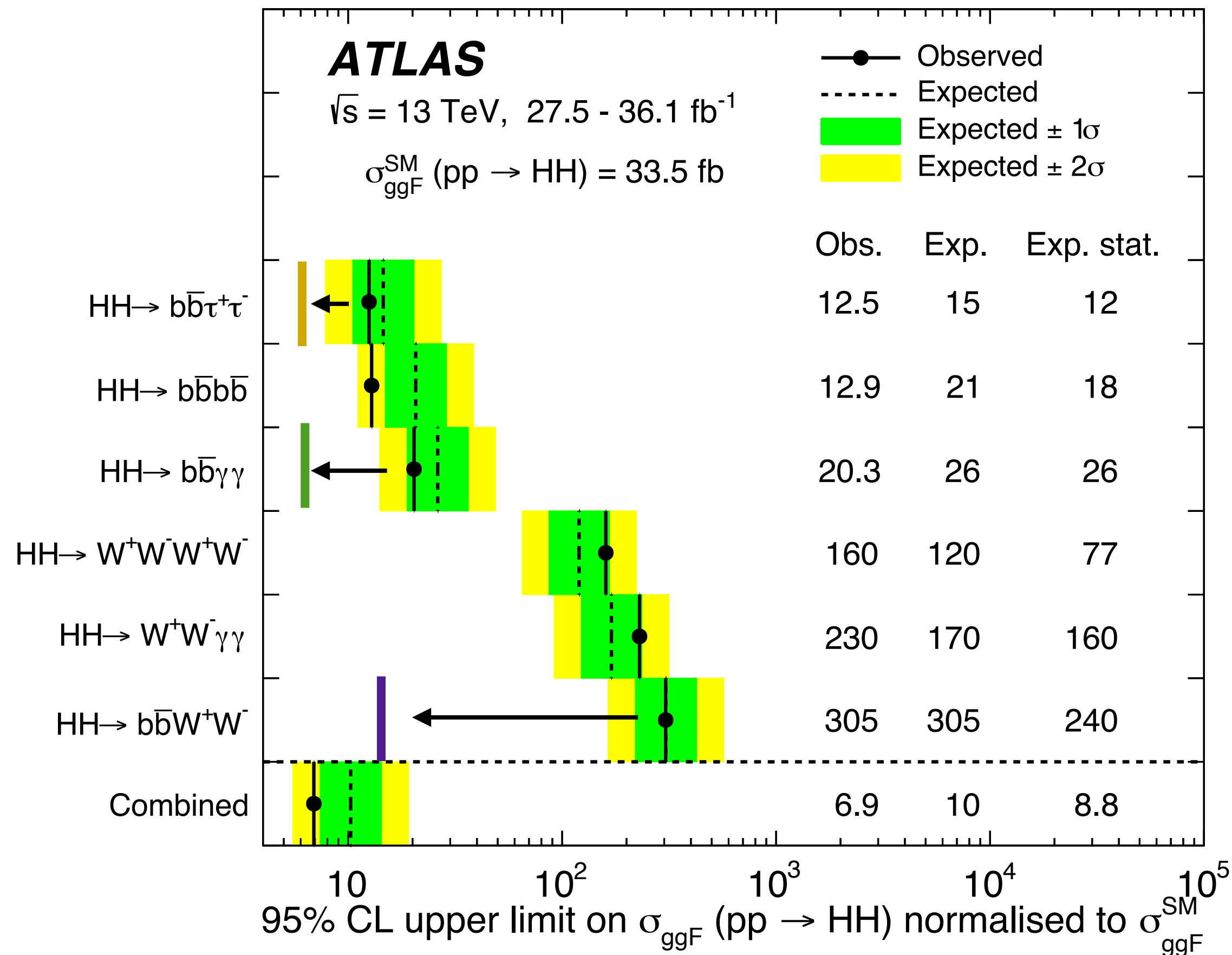
$b\bar{b}l\nu l\nu$  final state:

**observed (expected) limit is 14 (29) times the SM prediction.**

$b\bar{b}\gamma\gamma$  and  $b\bar{b}\tau\tau$  final states:

Brand new combination result:

- Only the main latest two Full Run-2 results included for non resonant ;
- **observed (expected) limit is 2.8 (2.8) times the SM prediction.**



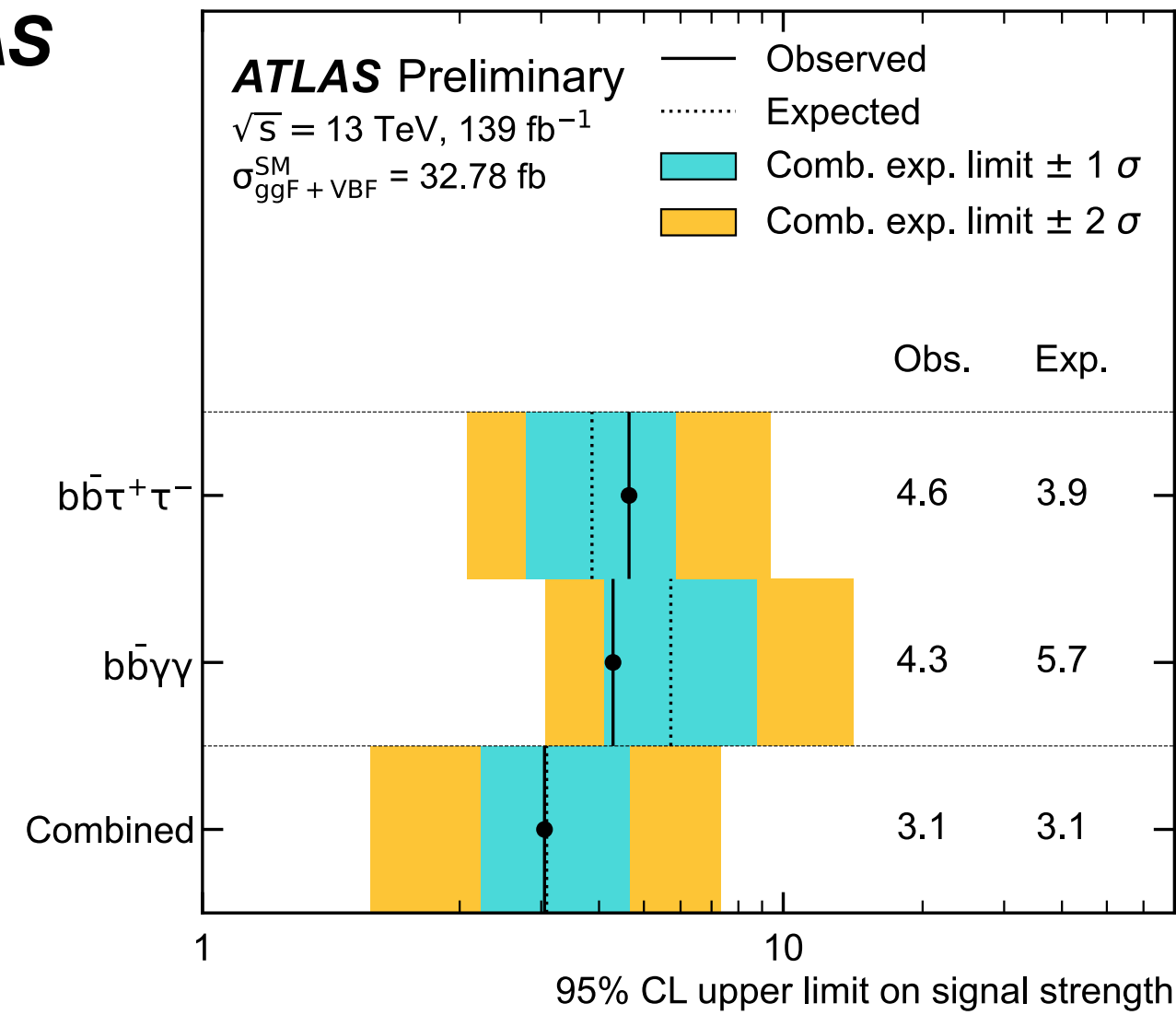
First look at **VBF**:  $HH \rightarrow b\bar{b}b\bar{b}$

$\sigma_{HH}^{VBF}$  **observed (expected) limit is 840 (550) times the SM prediction.**

# Conclusion



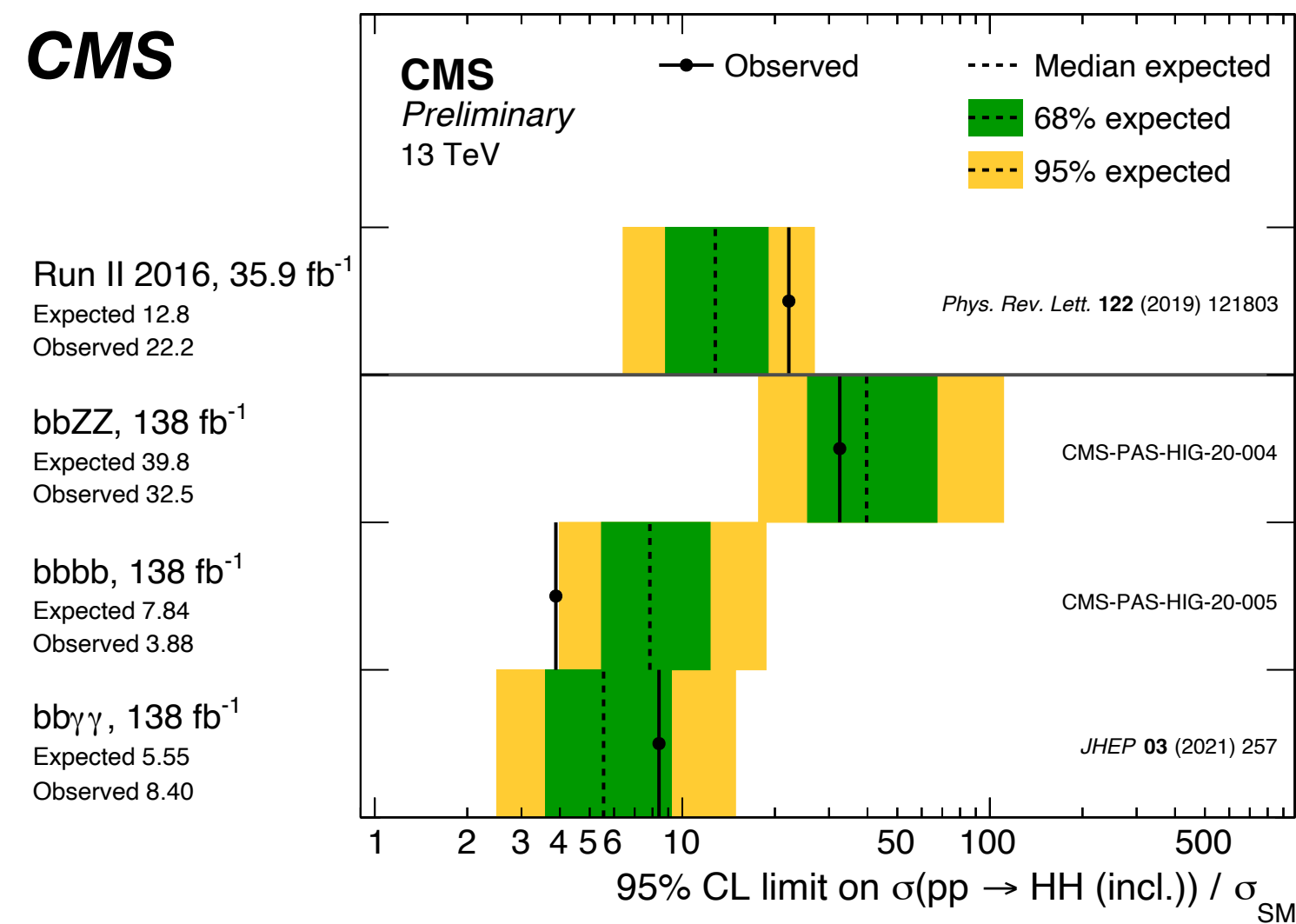
## ATLAS



New combination made with the two leading channels:  
**observed (expected) limit** on the HH cross-section is **2.8 (2.8)** times the SM prediction.

First measurement of  $\sigma_{HH}^{\text{VBF}}$   
**observed (expected) limit** is:  
**ATLAS Resolved**  
**840 (550)** times the SM prediction.  
**CMS Boosted**  
**226 (412)** times the SM prediction.  
**HH → b $\bar{b}$ γγ Resolved**  
**225 (208)** times the SM prediction.

## CMS



No update on the **partial Run-2 combination**, but new results:  
 - boosted 4b ;  
 - bb4l ;

$\frac{\sigma(pp \rightarrow HH)}{\sigma_{\text{SM}}}$ at 13 TeV	Partial Run 2 (2015-16)		Ful Run 2 (2015-18)		
	Obs	Exp	Obs	Exp	
$HH \rightarrow b\bar{b}\gamma\gamma$	ATLAS	20.3	26	4.1	5.5
	CMS	23.6	18.8	7.7	5.2
$HH \rightarrow b\bar{b}\tau\tau$	ATLAS	12.5	15	4.7	3.9
	CMS	31.4	25.1		
$HH \rightarrow b\bar{b}b\bar{b}$	ATLAS	12.9	21		
	CMS	74.6	36.9	3.6	7.3
Combination	ATLAS	6.9	10	2.8	2.8
	CMS	22.2	12.8		

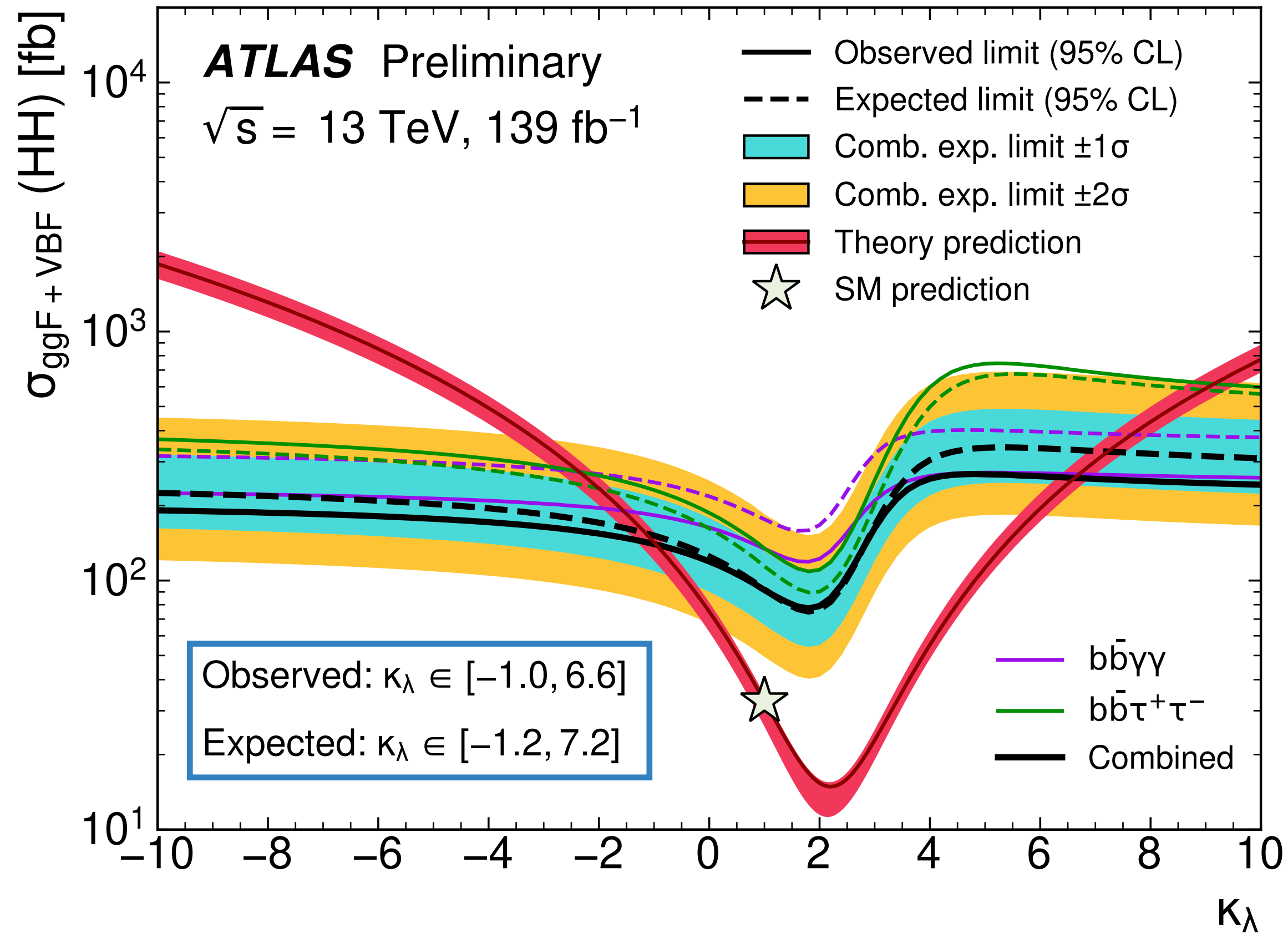




# Conclusion



Combination done with Full Run-2 analyses with  $\mathcal{L} = 139\text{fb}^{-1}$



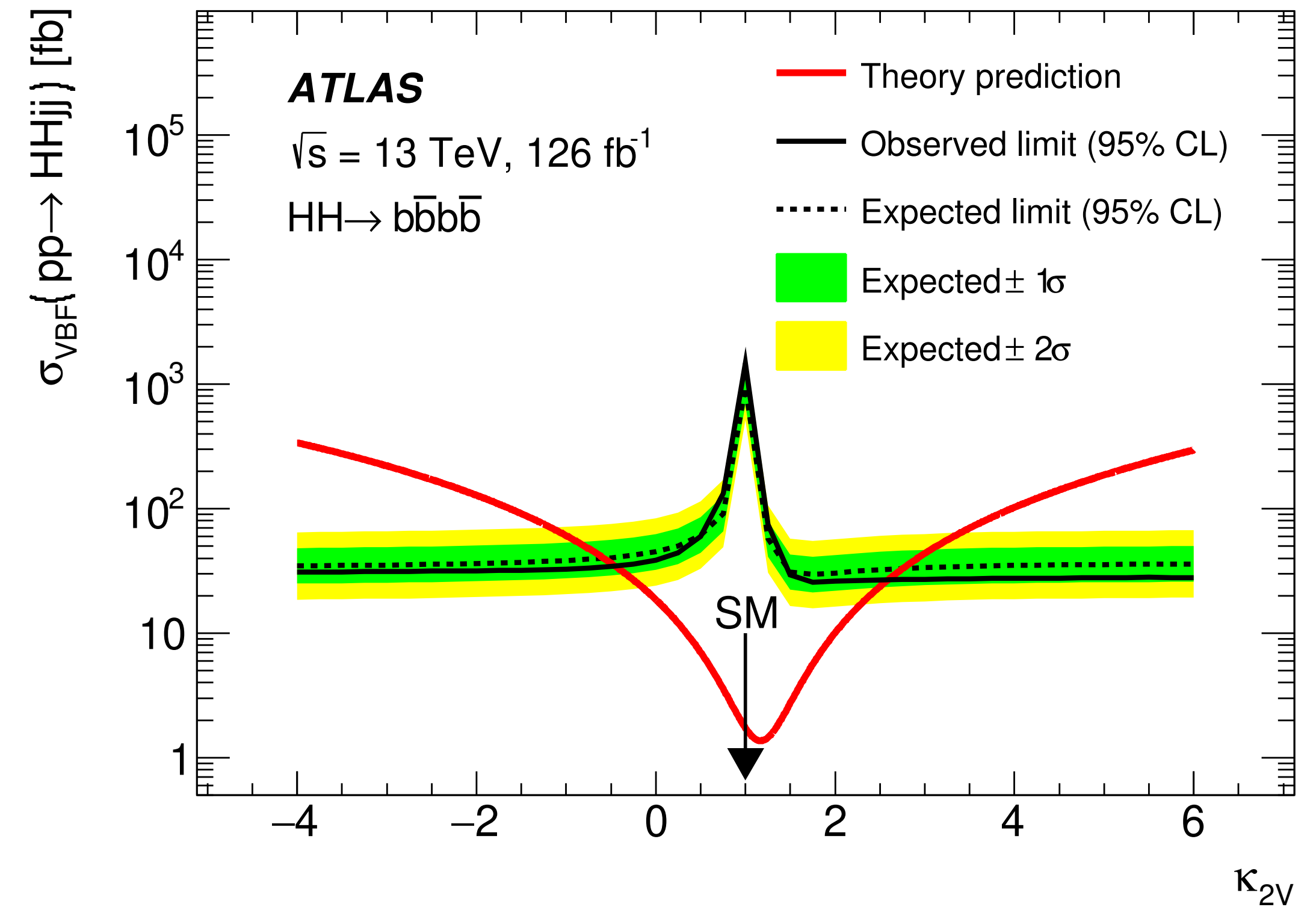
Best limit set so far on  $\kappa_\lambda$  so far.

First look at **VBF**:  $b\bar{b}b\bar{b}$  final state

Limits are set on the  $\kappa_{2V}$  coupling modifier to:

$-0.4 < \kappa_{2V} < 2.6$  observed,

$-0.6 < \kappa_{2V} < 2.7$  expected.



# Conclusion

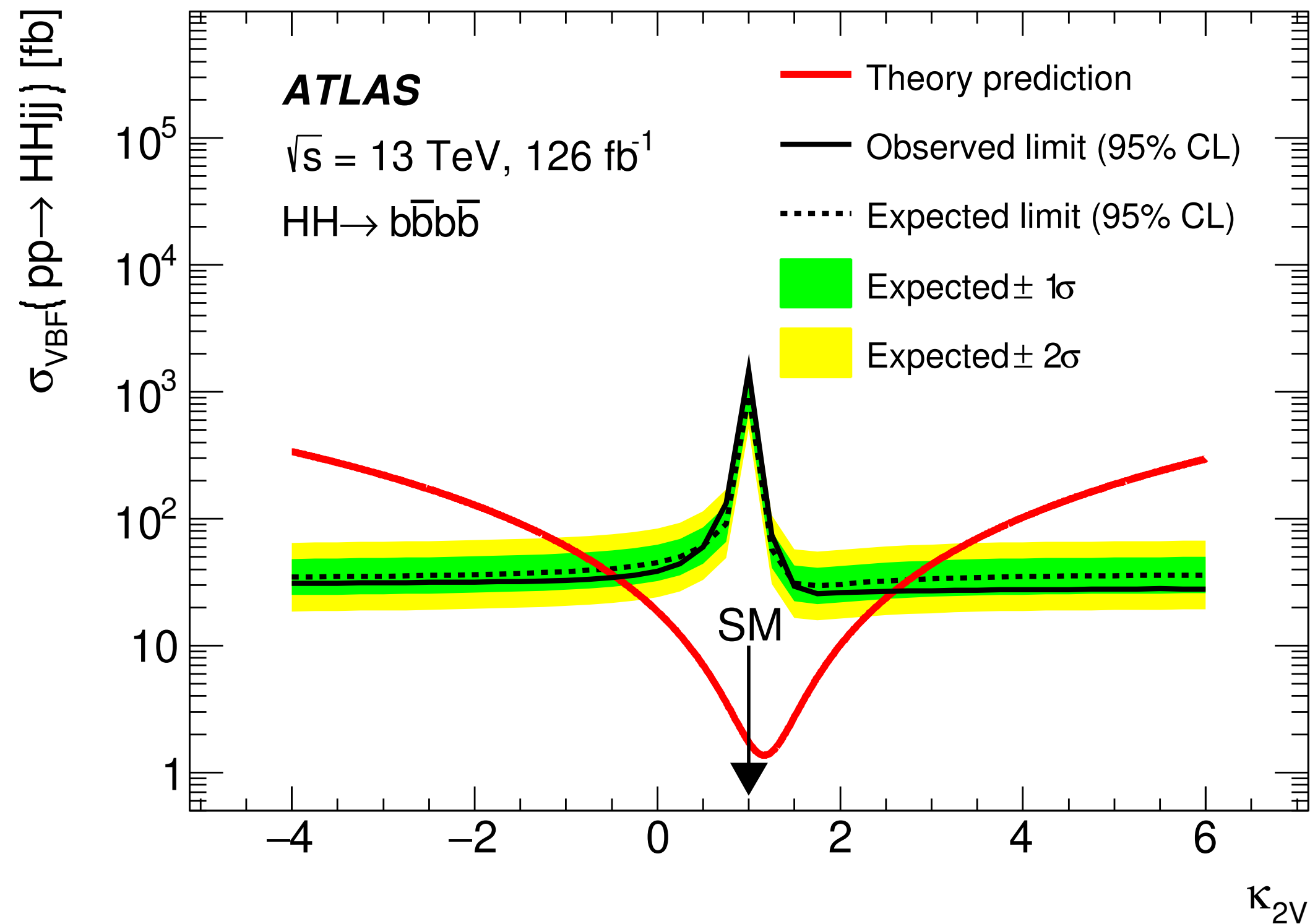


## ATLAS $b\bar{b}b\bar{b}$ final state

Limits are set on the  $\kappa_{2V}$  coupling modifier to:

$$-0.4 < \kappa_{2V} < 2.6 \text{ observed,}$$

$$-0.6 < \kappa_{2V} < 2.7 \text{ expected.}$$

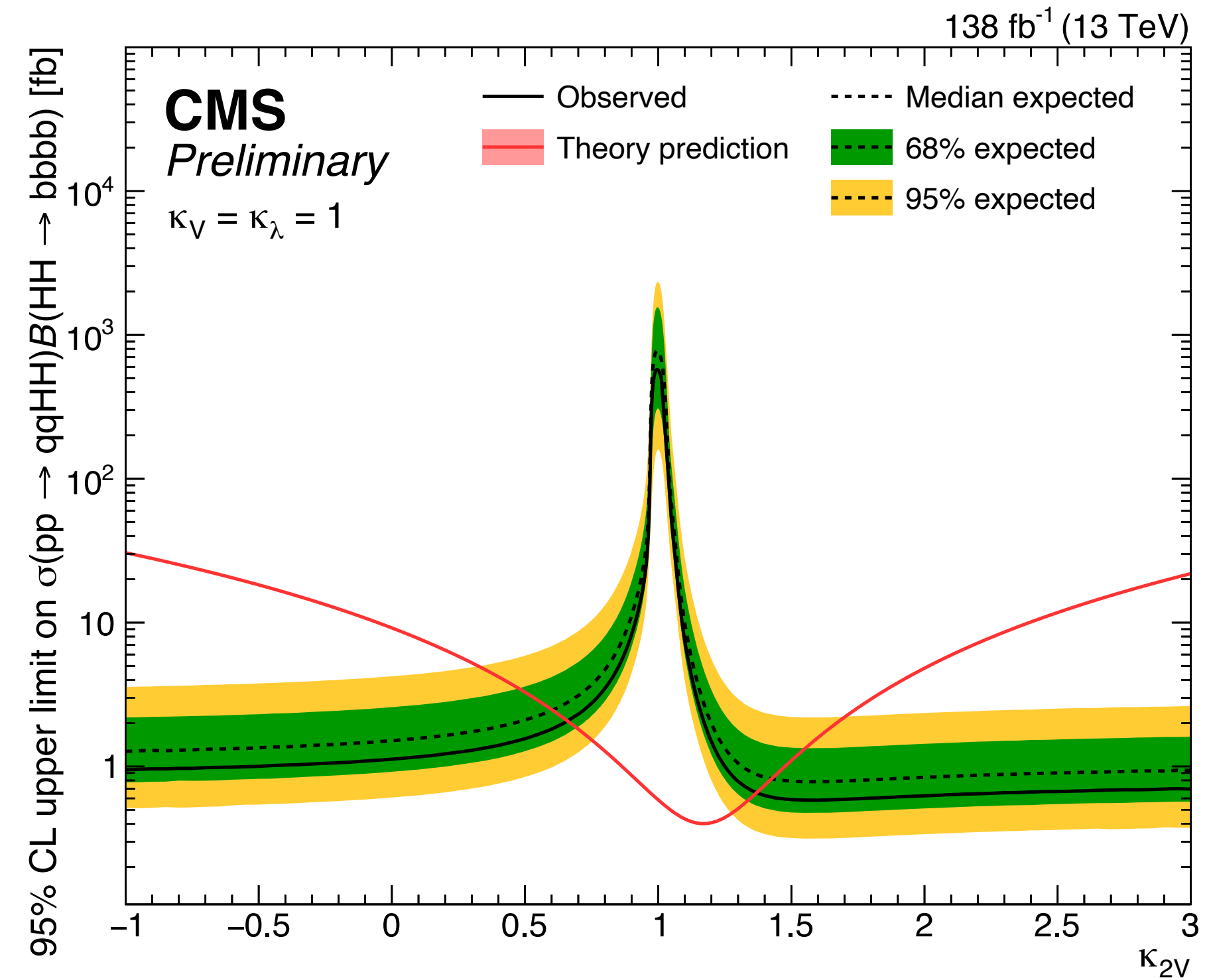


## CMS $b\bar{b}b\bar{b}$ Boosted CMS-PAS-B2G-21-001

Several results are now including the  $\kappa_{2V}$  measurement, the best measurement is:

$$0.6 < \kappa_{2V} < 1.4 \text{ observed,}$$

$$0.8 < \kappa_{2V} < 1.2 \text{ expected.}$$



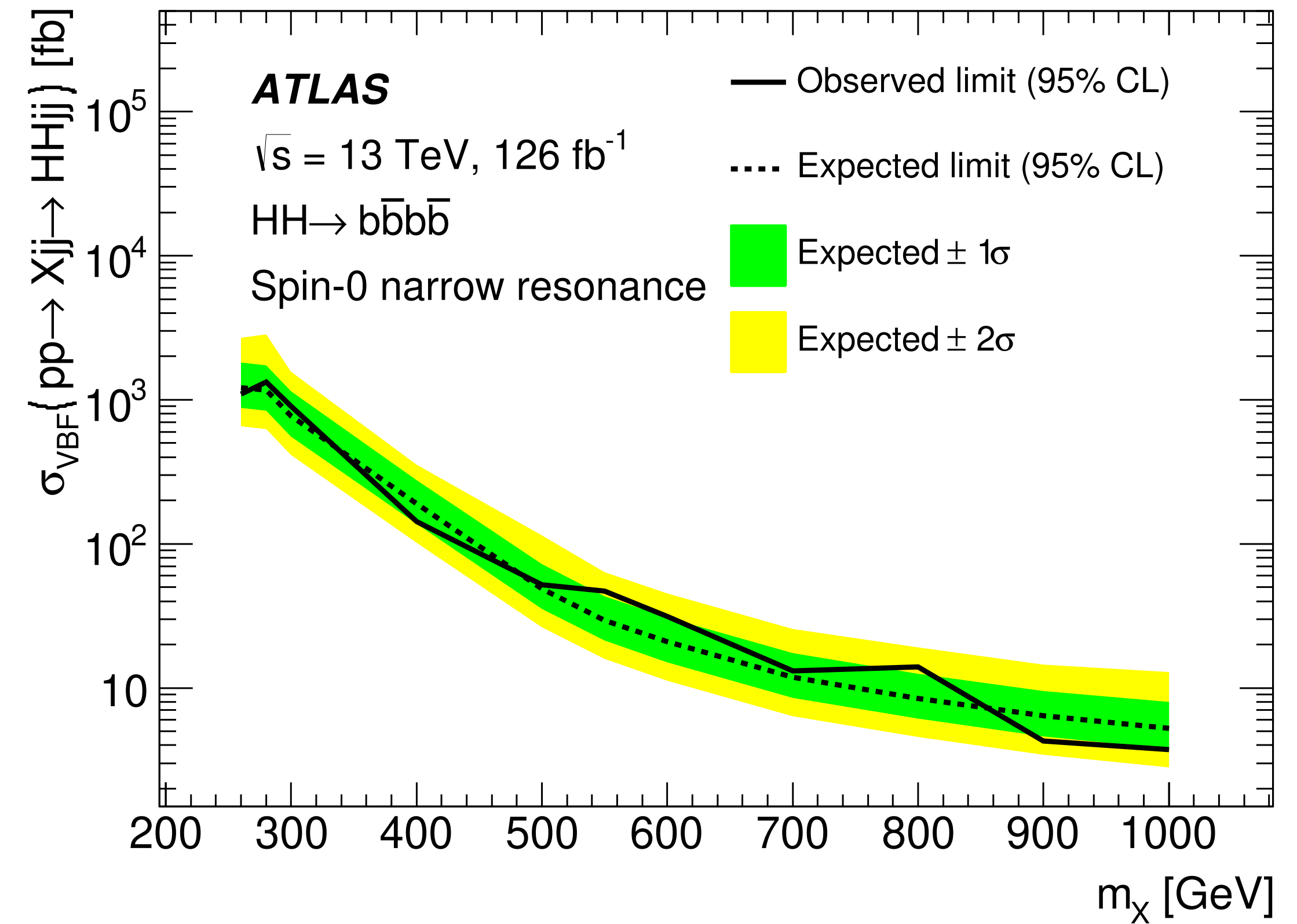
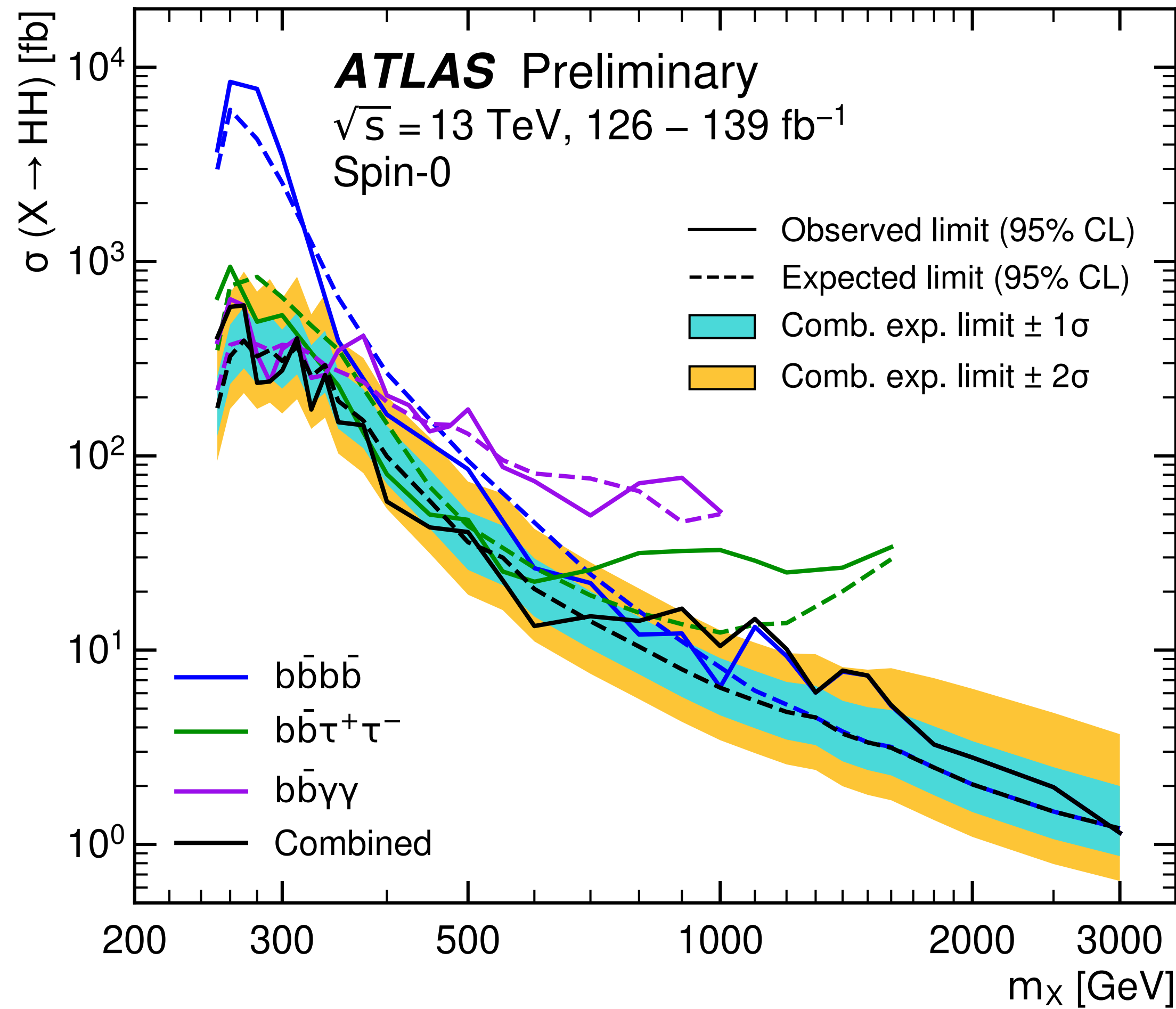


# Conclusion



Combination done with Full Run-2 analyses with  $\mathcal{L} = 139\text{fb}^{-1}$

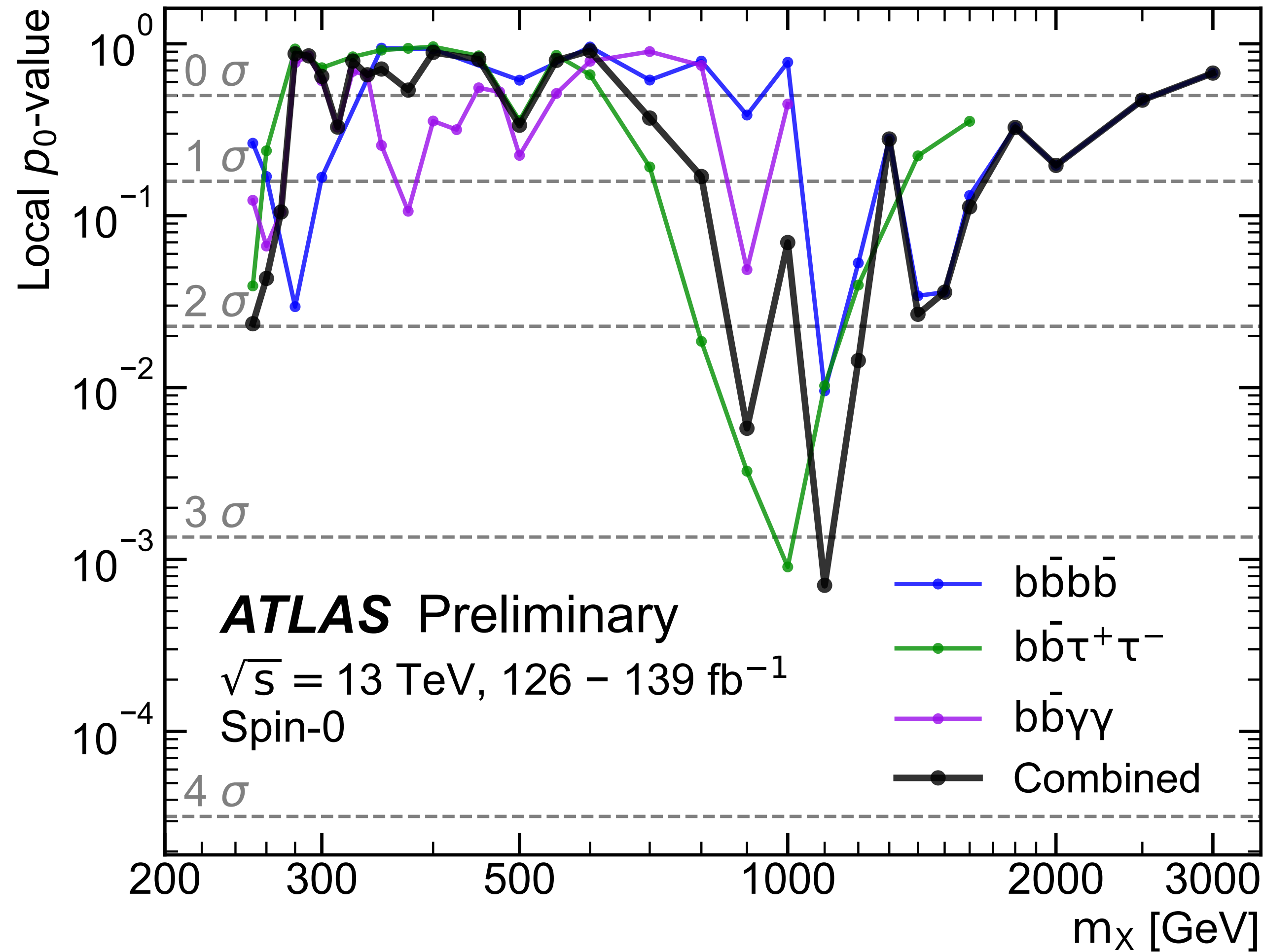
First look at **VBF**:  $b\bar{b}b\bar{b}$  final state



# Conclusion



Combination done with Full Run-2 analyses with  $\mathcal{L} = 139\text{fb}^{-1}$



The **largest deviation** from the SM expectation is seen at **1.1 TeV** with combined local (global\*) significance of **3.2  $\sigma$  (2.1  $\sigma$ )**.

In comparison the local significance at 1.1 TeV was found to be 2.8  $\sigma$  (1.5  $\sigma$ ) in the  $\tau_{had}\tau_{had}$  ( $\tau_{lep}\tau_{had}$ ) channel.

\* The global significance accounts for a look-elsewhere effect with a trial factor (see [Eur. Phys. J. C 70, 525–530 \(2010\)](#) )



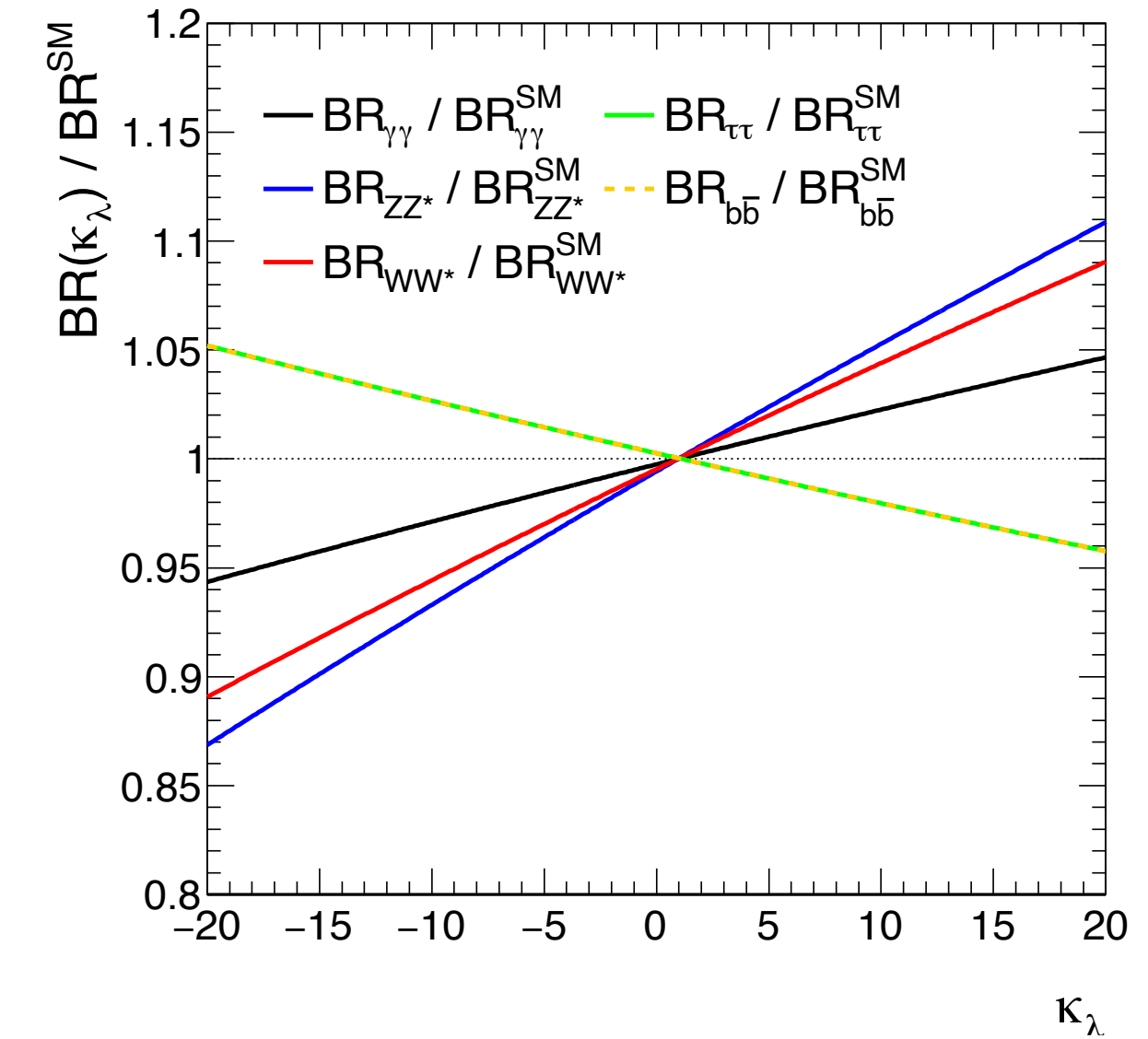
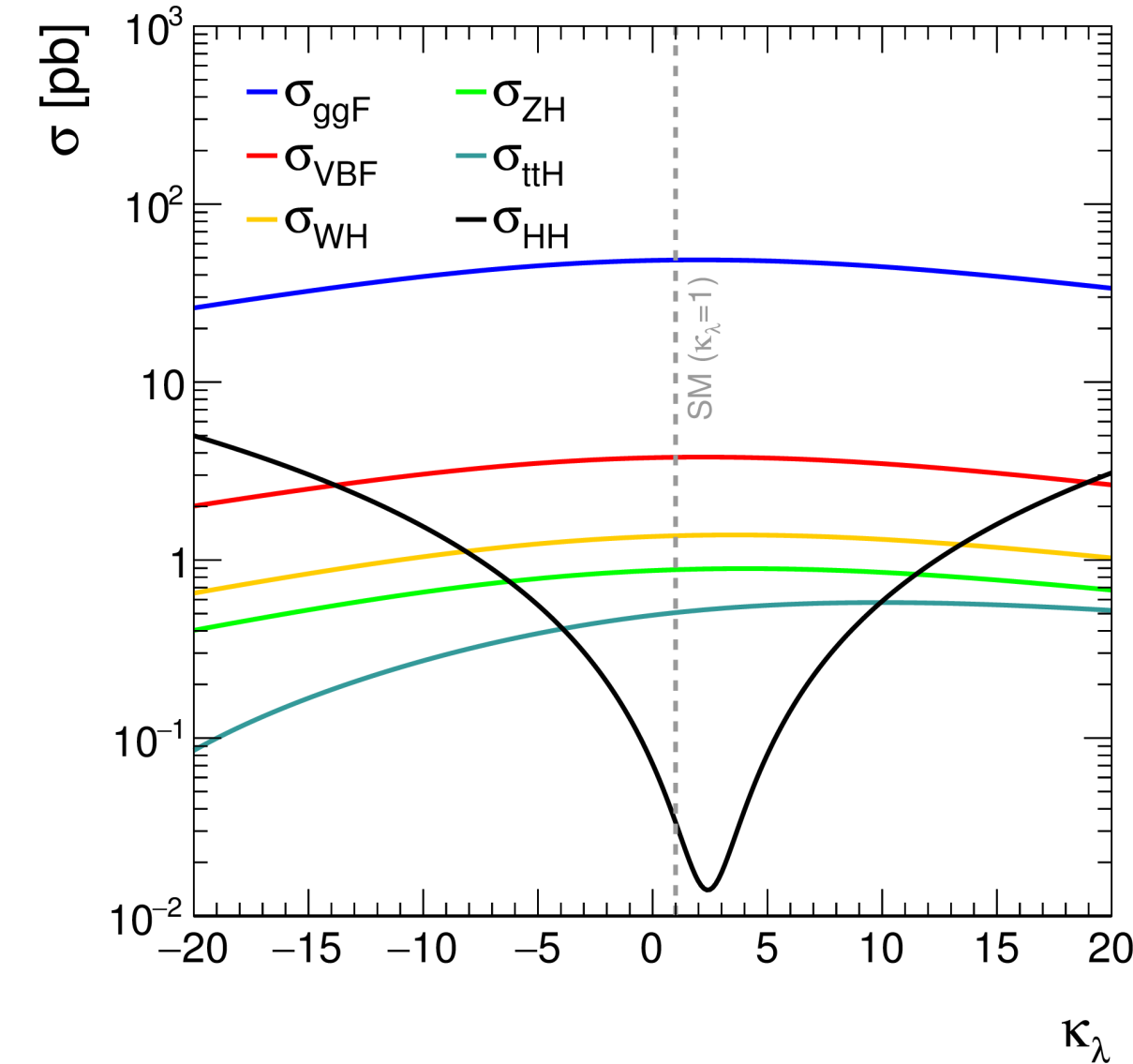
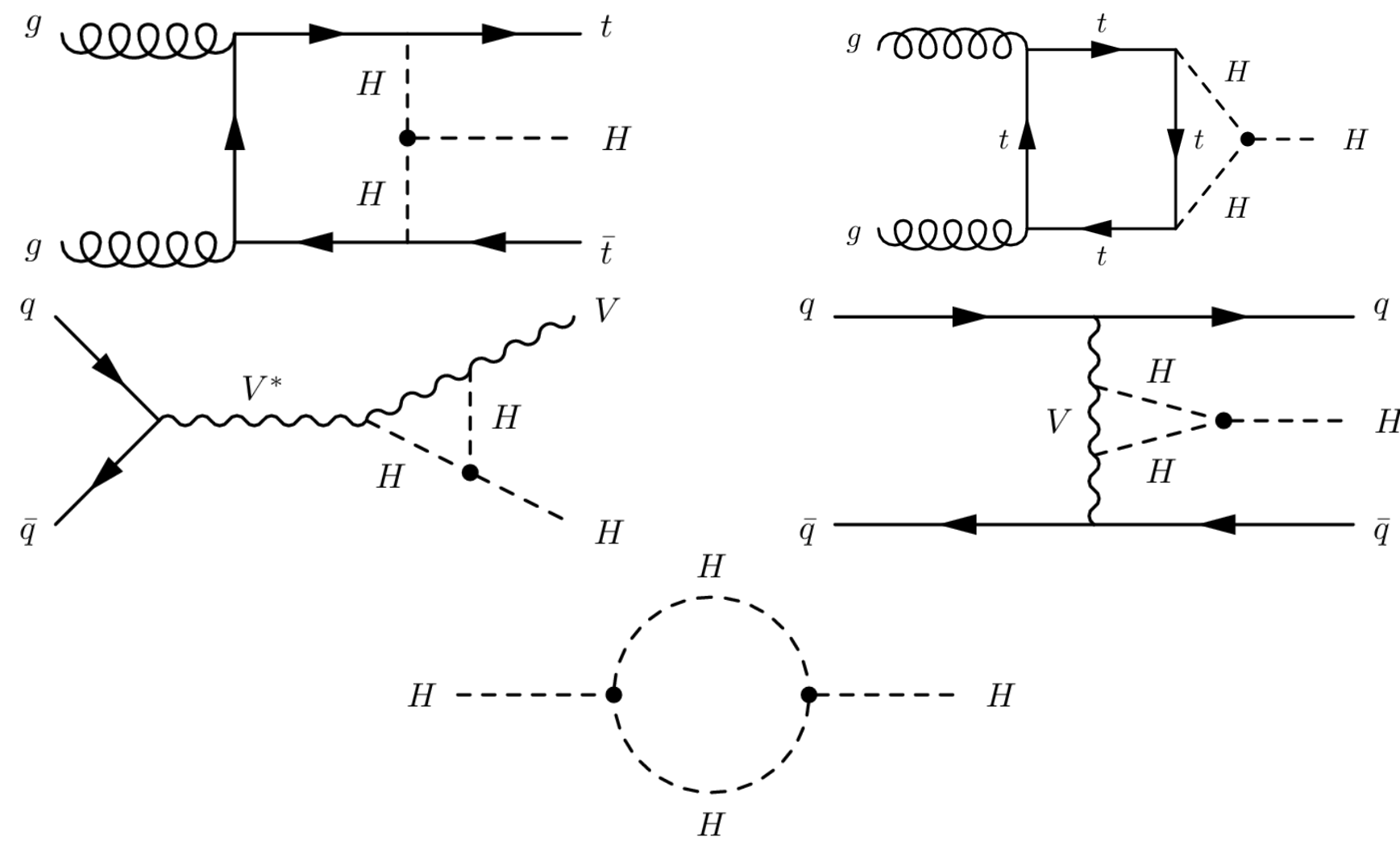


**Thanks for your attention.**

**BACK-UP**

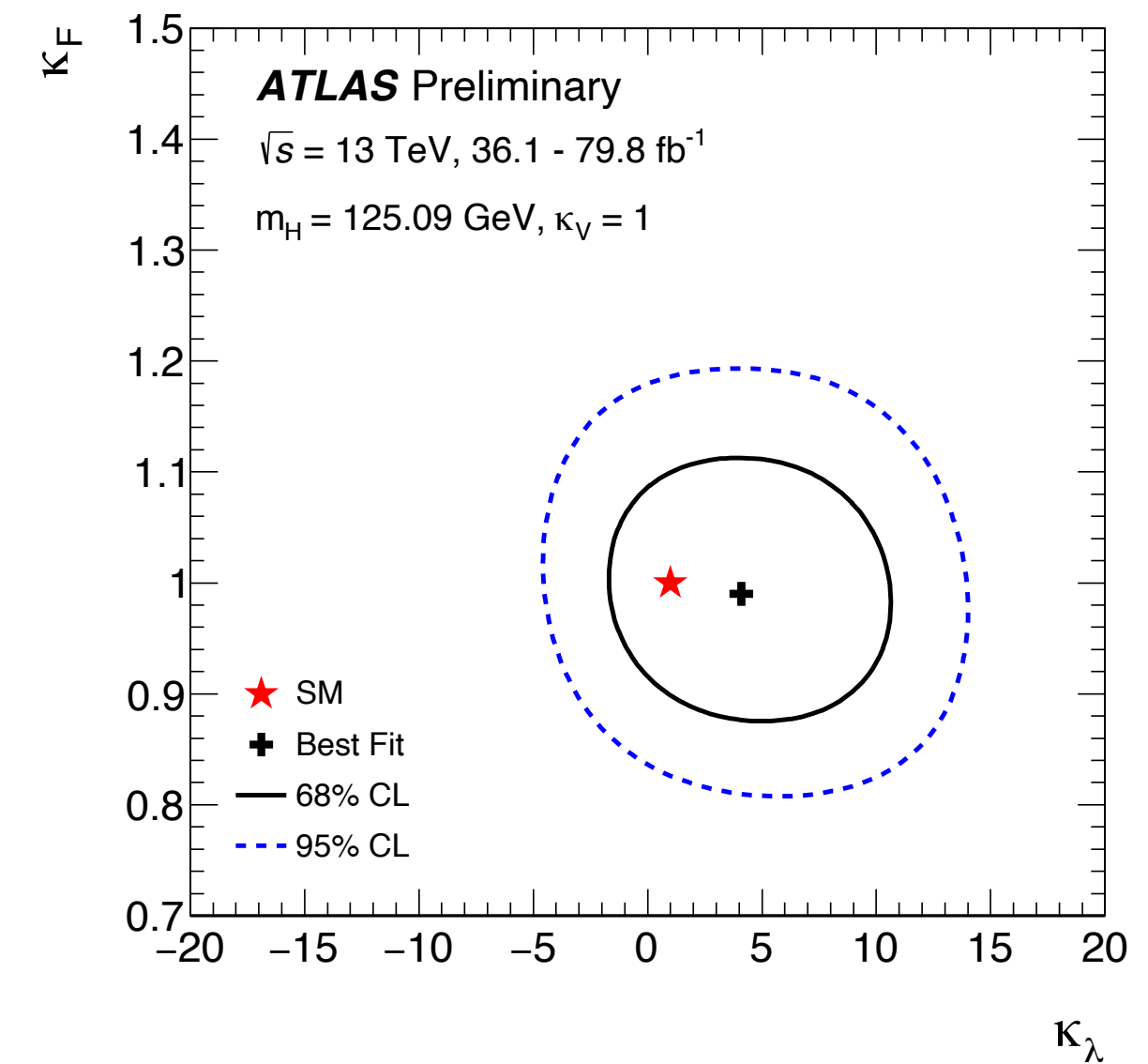
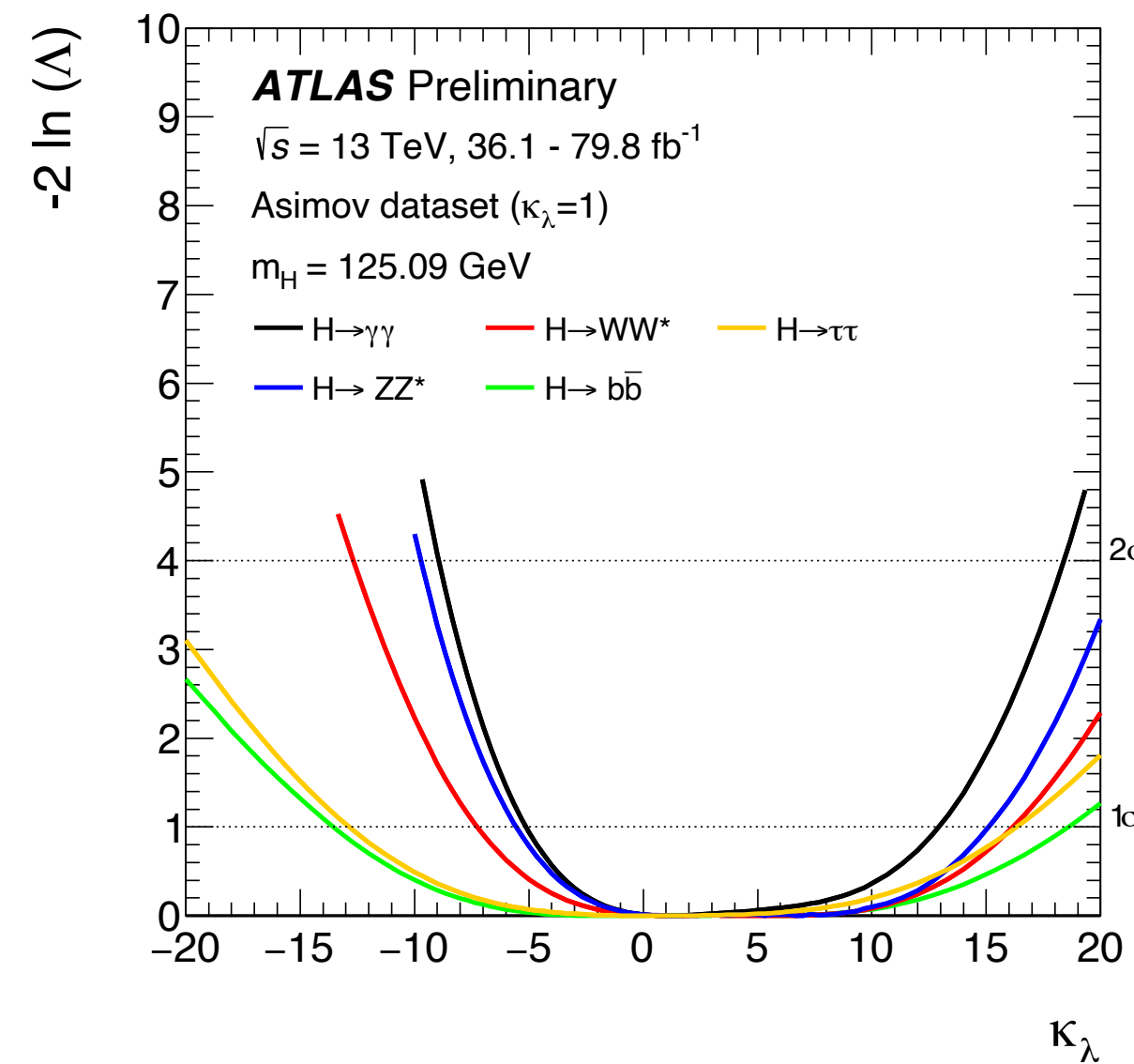
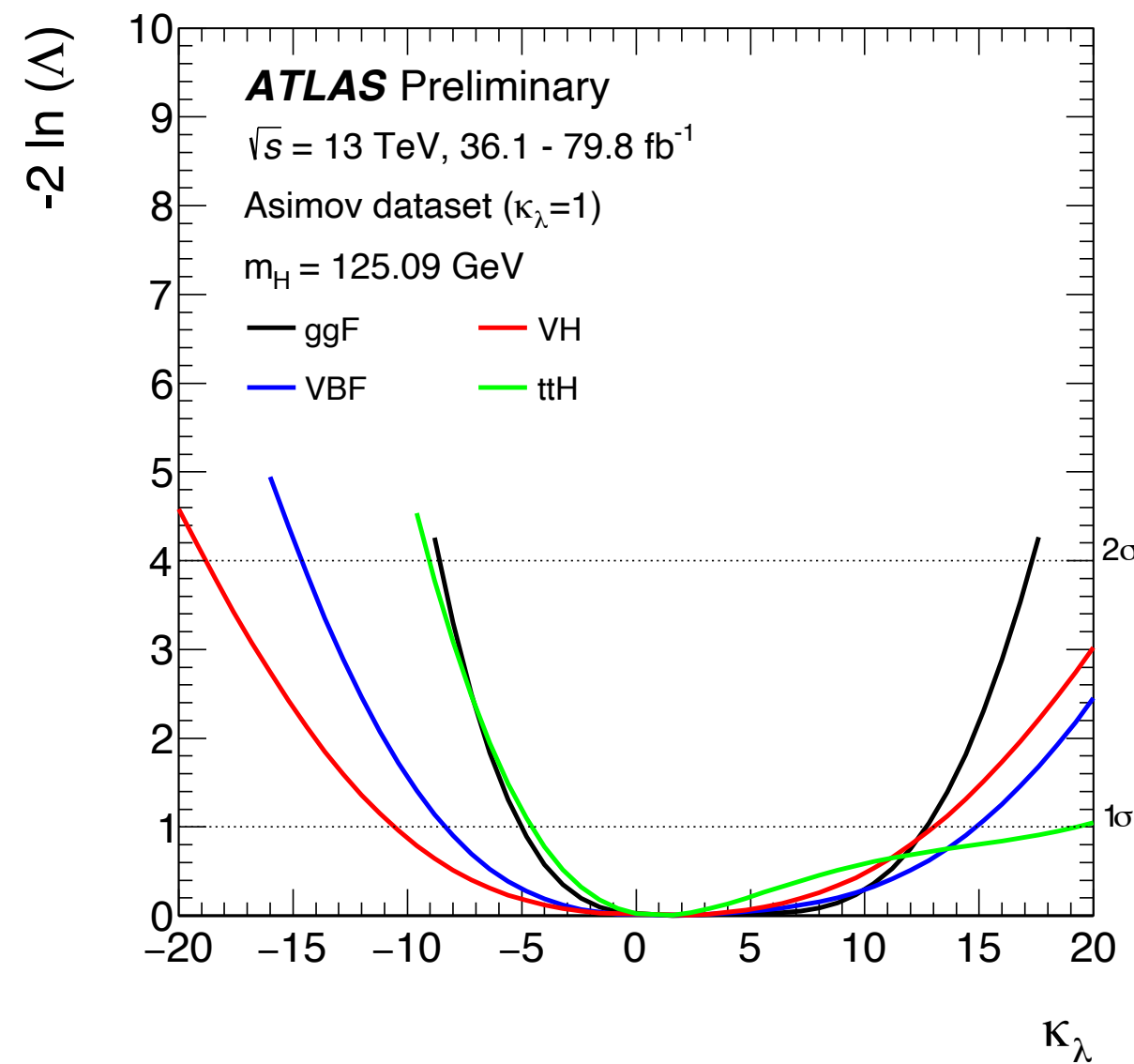


# Single Higgs constrains

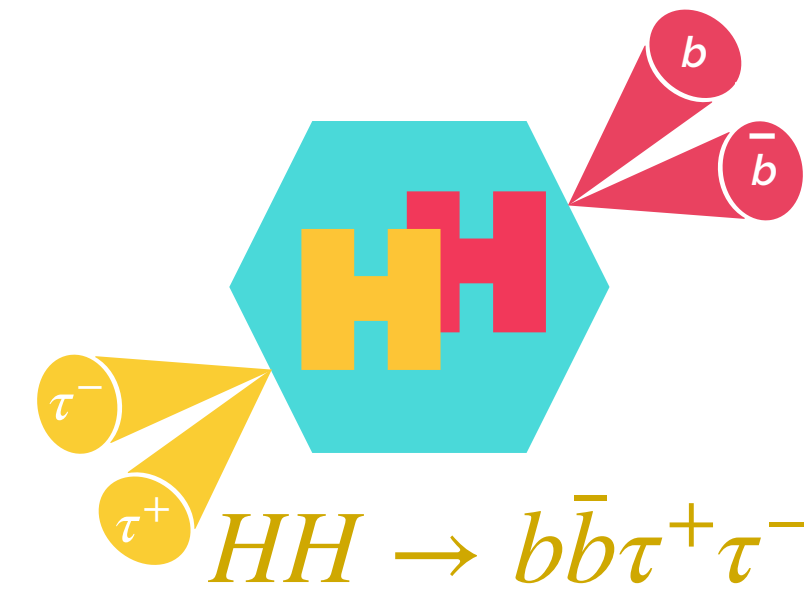


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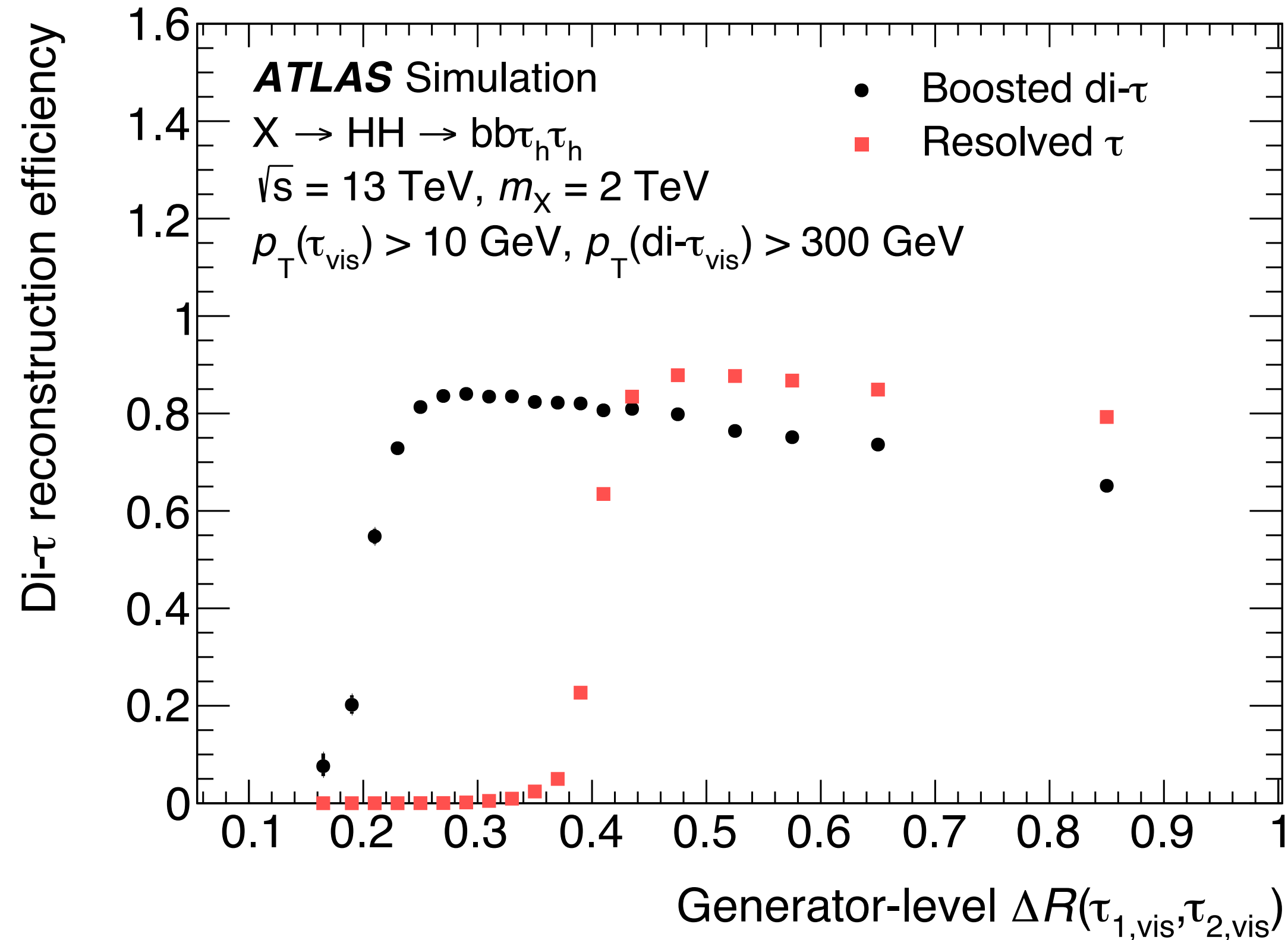
Combinaison of single Higgs channels with  $\mathcal{L} = 80\text{fb}^{-1}$  yielding:  
 $-3.2 < \kappa_\lambda < 11.9$



# Bbtautau Boosted



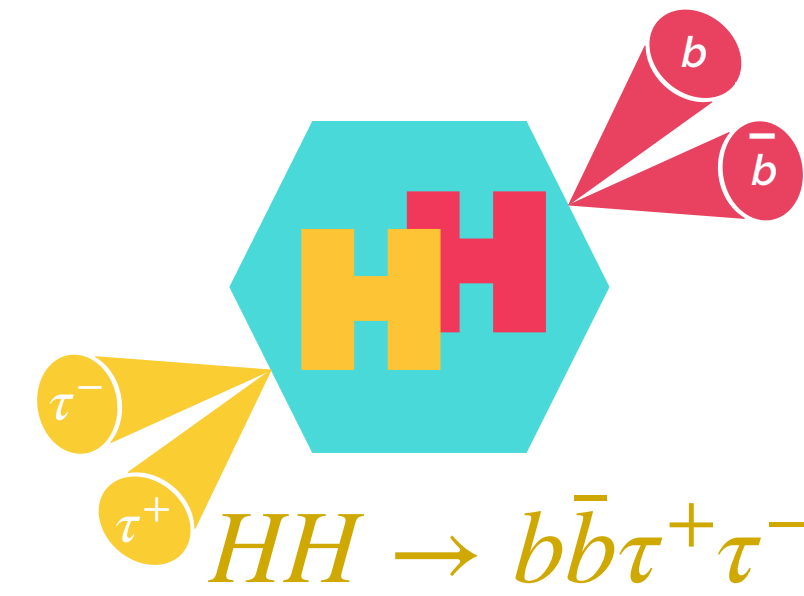
Boosted di-tau BDT identification:



Variable	Definition
$E_{\Delta R < 0.1}^{\text{sj}_1} / E_{\Delta R < 0.2}^{\text{sj}_1}$ and $E_{\Delta R < 0.1}^{\text{sj}_2} / E_{\Delta R < 0.2}^{\text{sj}_2}$	Ratios of the energy deposited in the core to that in the full cone, for the sub-jets $\text{sj}_1$ and $\text{sj}_2$ , respectively
$p_T^{\text{sj}_2} / p_T^{\text{LRJ}}$ and $(p_T^{\text{sj}_1} + p_T^{\text{sj}_2}) / p_T^{\text{LRJ}}$	Ratio of the $p_T$ of $\text{sj}_2$ to the di- $\tau$ seeding large-radius jet $p_T$ and ratio of the scalar $p_T$ sum of the two leading sub-jets to the di- $\tau$ seeding large-radius jet $p_T$ , respectively
$\log(\sum p_T^{\text{iso-tracks}} / p_T^{\text{LRJ}})$	Logarithm of the ratio of the scalar $p_T$ sum of the iso-tracks to the di- $\tau$ seeding large-radius jet $p_T$
$\Delta R_{\text{max}}(\text{track}, \text{sj}_1)$ and $\Delta R_{\text{max}}(\text{track}, \text{sj}_2)$	Largest separation of a track from its associated sub-jet axis, for the sub-jets $\text{sj}_1$ and $\text{sj}_2$ , respectively
$\sum [p_T^{\text{track}} \Delta R(\text{track}, \text{sj}_2)] / \sum p_T^{\text{track}}$	$p_T$ -weighted $\Delta R$ of the tracks matched to $\text{sj}_2$ with respect to its axis
$\sum [p_T^{\text{iso-track}} \Delta R(\text{iso-track}, \text{sj})] / \sum p_T^{\text{iso-track}}$	$p_T$ -weighted sum of $\Delta R$ between iso-tracks and the nearest sub-jet axis
$\log(m_{\Delta R < 0.1}^{\text{tracks}, \text{sj}_1})$ and $\log(m_{\Delta R < 0.1}^{\text{tracks}, \text{sj}_2})$	Logarithms of the invariant mass of the tracks in the core of $\text{sj}_1$ and $\text{sj}_2$ , respectively
$\log(m_{\Delta R < 0.2}^{\text{tracks}, \text{sj}_1})$ and $\log(m_{\Delta R < 0.2}^{\text{tracks}, \text{sj}_2})$	Logarithms of the invariant mass of the tracks with $\Delta R < 0.2$ from the axis of $\text{sj}_1$ and $\text{sj}_2$ , respectively
$\log( d_{0,\text{lead-track}}^{\text{sj}_1} )$ and $\log( d_{0,\text{lead-track}}^{\text{sj}_2} )$	Logarithms of the closest distance in the transverse plane between the primary vertex and the leading track of $\text{sj}_1$ and $\text{sj}_2$ , respectively
$n_{\text{tracks}}^{\text{sj}_1}$ and $n_{\text{tracks}}^{\text{sub-jets}}$	Number of tracks matched to $\text{sj}_1$ and to all sub-jets, respectively



# Bbtautau Resolved



BDT input variables:

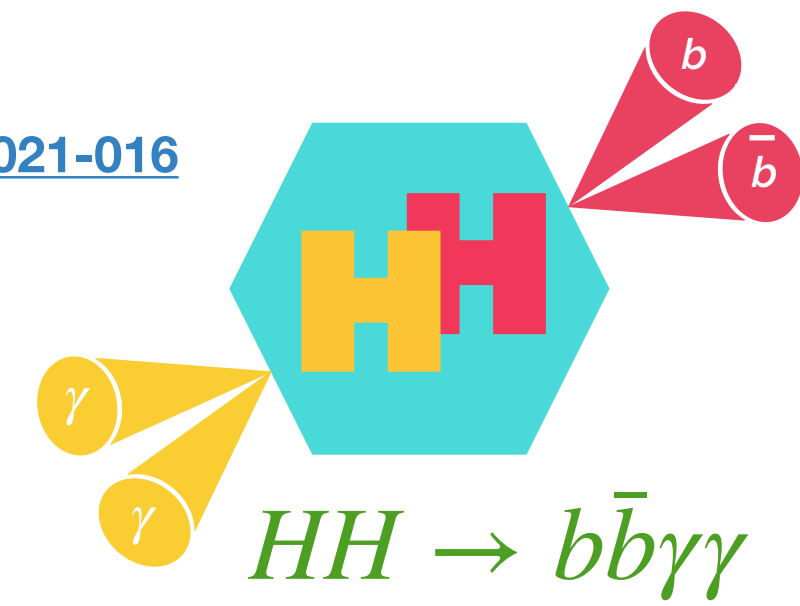
Variable	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT resonant)	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT nonresonant & LTT)	$\tau_{\text{had}}\tau_{\text{had}}$ channel
$m_{HH}$	✓	✓	✓
$m_{\tau\tau}^{\text{MMC}}$	✓	✓	✓
$m_{bb}$	✓	✓	✓
$\Delta R(\tau, \tau)$	✓	✓	✓
$\Delta R(b, b)$	✓	✓	✓
$E_T^{\text{miss}}$	✓		
$E_T^{\text{miss}}$ $\phi$ centrality	✓		✓
$m_T^W$	✓	✓	
$\Delta\phi(H, H)$	✓		
$\Delta p_T(\text{lep}, \tau_{\text{had-vis}})$	✓		
Subleading $b$ -jet $p_T$	✓		

Non resonant limits per channel:

		Observed	$-1\sigma$	Expected	$+1\sigma$
$\tau_{\text{lep}}\tau_{\text{had}}$	$\sigma(HH \rightarrow bb\tau\tau)$ [fb]	57	49.9	69	96
	$\sigma/\sigma_{\text{SM}}$	23.5	20.5	28.4	39.5
$\tau_{\text{had}}\tau_{\text{had}}$	$\sigma(HH \rightarrow bb\tau\tau)$ [fb]	40.0	30.6	42.4	59
	$\sigma/\sigma_{\text{SM}}$	16.4	12.5	17.4	24.2
Combination	$\sigma(HH \rightarrow bb\tau\tau)$ [fb]	30.9	26.0	36.1	50
	$\sigma/\sigma_{\text{SM}}$	12.7	10.7	14.8	20.6

Impact of systematics on SM limit:

Source	Uncertainty (%)
Total	$\pm 54$
Data statistics	$\pm 44$
Simulation statistics	$\pm 16$
Experimental uncertainties	
Luminosity	$\pm 2.4$
Pileup reweighting	$\pm 1.7$
$\tau_{\text{had}}$	$\pm 16$
Fake- $\tau$ estimation	$\pm 8.4$
$b$ tagging	$\pm 8.3$
Jets and $E_T^{\text{miss}}$	$\pm 3.3$
Electron and muon	$\pm 0.5$
Theoretical and modeling uncertainties	
Top	$\pm 17$
Signal	$\pm 9.3$
$Z \rightarrow \tau\tau$	$\pm 6.8$
SM Higgs	$\pm 2.9$
Other backgrounds	$\pm 0.3$



## Non Resonant

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

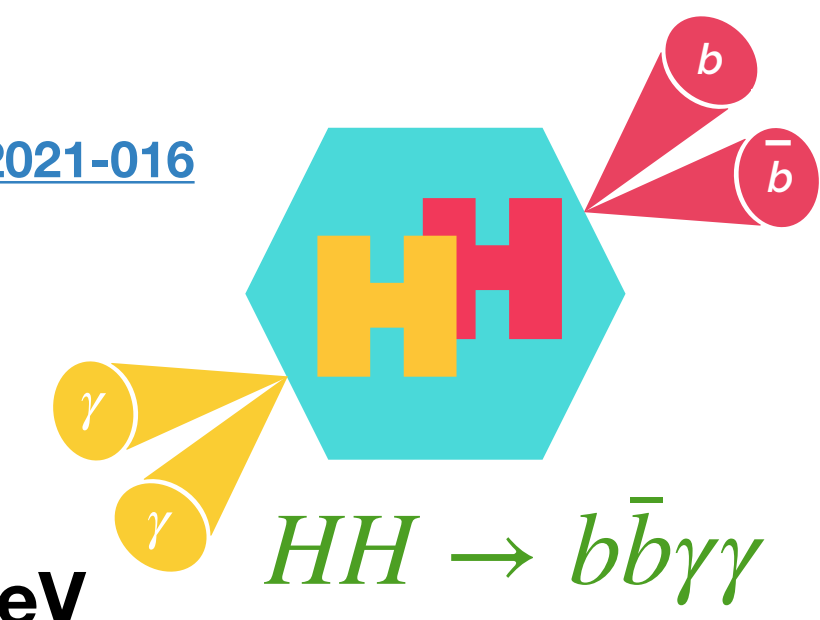
## Resonant

Variable	Definition
Photon-related kinematic variables	
$p_T^{\gamma\gamma}, y^{\gamma\gamma}$	Transverse momentum and rapidity of the di-photon system
$\Delta\phi_{\gamma\gamma}$ and $\Delta R_{\gamma\gamma}$	Azimuthal angular distance and $\Delta R$ between the two photons
Jet-related kinematic variables	
$m_{b\bar{b}}, p_T^{b\bar{b}}$ and $y_{b\bar{b}}$	Invariant mass, transverse momentum and rapidity of the $b$ -tagged jets system
$\Delta\phi_{b\bar{b}}$ and $\Delta R_{b\bar{b}}$	Azimuthal angular distance and $\Delta R$ between the two $b$ -tagged jets
$N_{\text{jets}}$ and $N_{b\text{-jets}}$	Number of jets and number of $b$ -tagged jets
$H_T$	Scalar sum of the $p_T$ of the jets in the event
Photons and jets-related kinematic variables	
$m_{b\bar{b}\gamma\gamma}$	Invariant mass built with the di-photon and $b$ -tagged jets system
$\Delta y_{\gamma\gamma, b\bar{b}}, \Delta\phi_{\gamma\gamma, b\bar{b}}$ and $\Delta R_{\gamma\gamma, b\bar{b}}$	Distance in rapidity, azimuthal angle and $\Delta R$ between the di-photon and the $b$ -tagged jets system



# Post-fit plots

ggF:  $\mathcal{L} = 139\text{fb}^{-1}$  [ATLAS-CONF-2021-016](#)

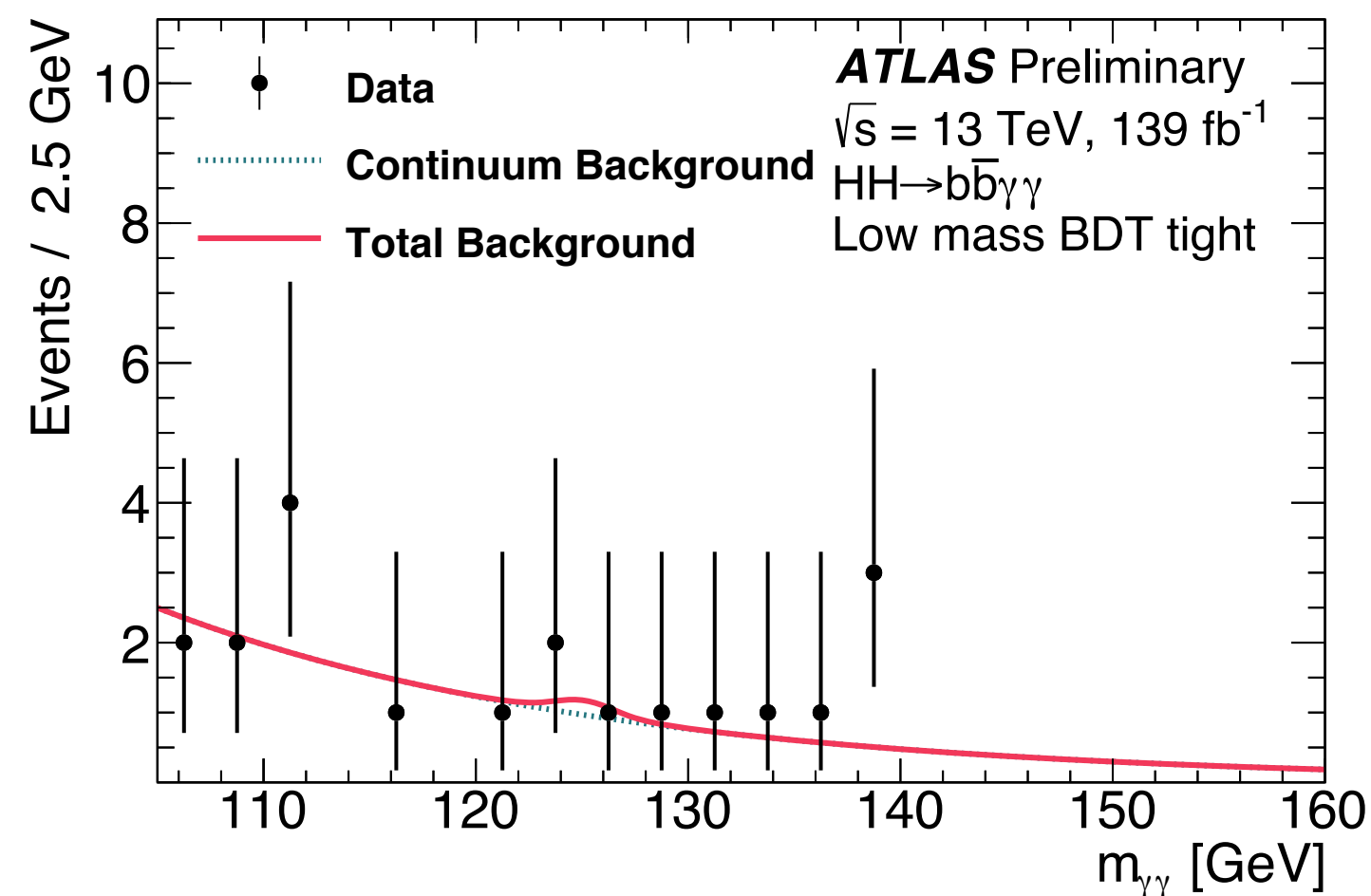
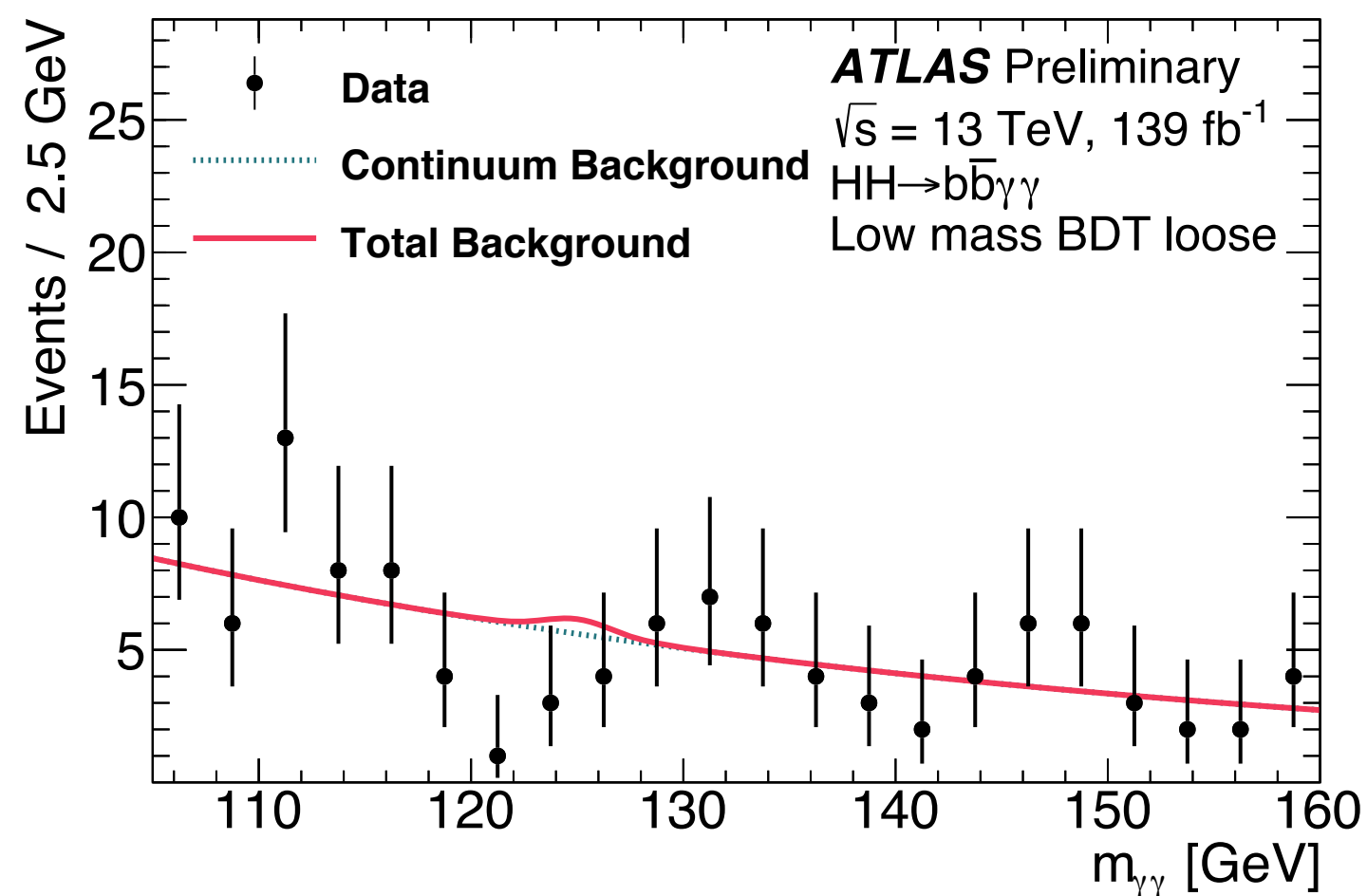


## Non Resonant

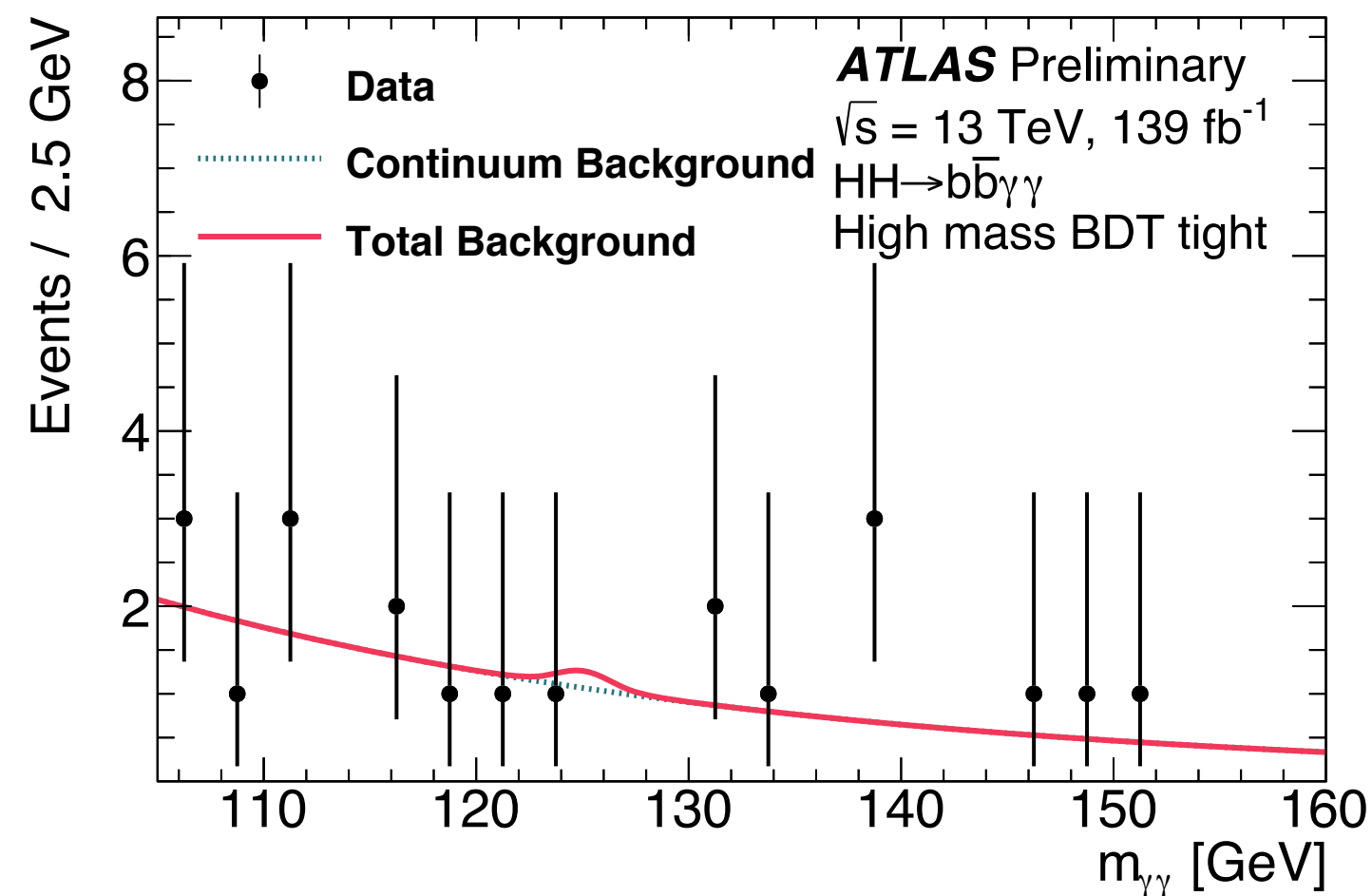
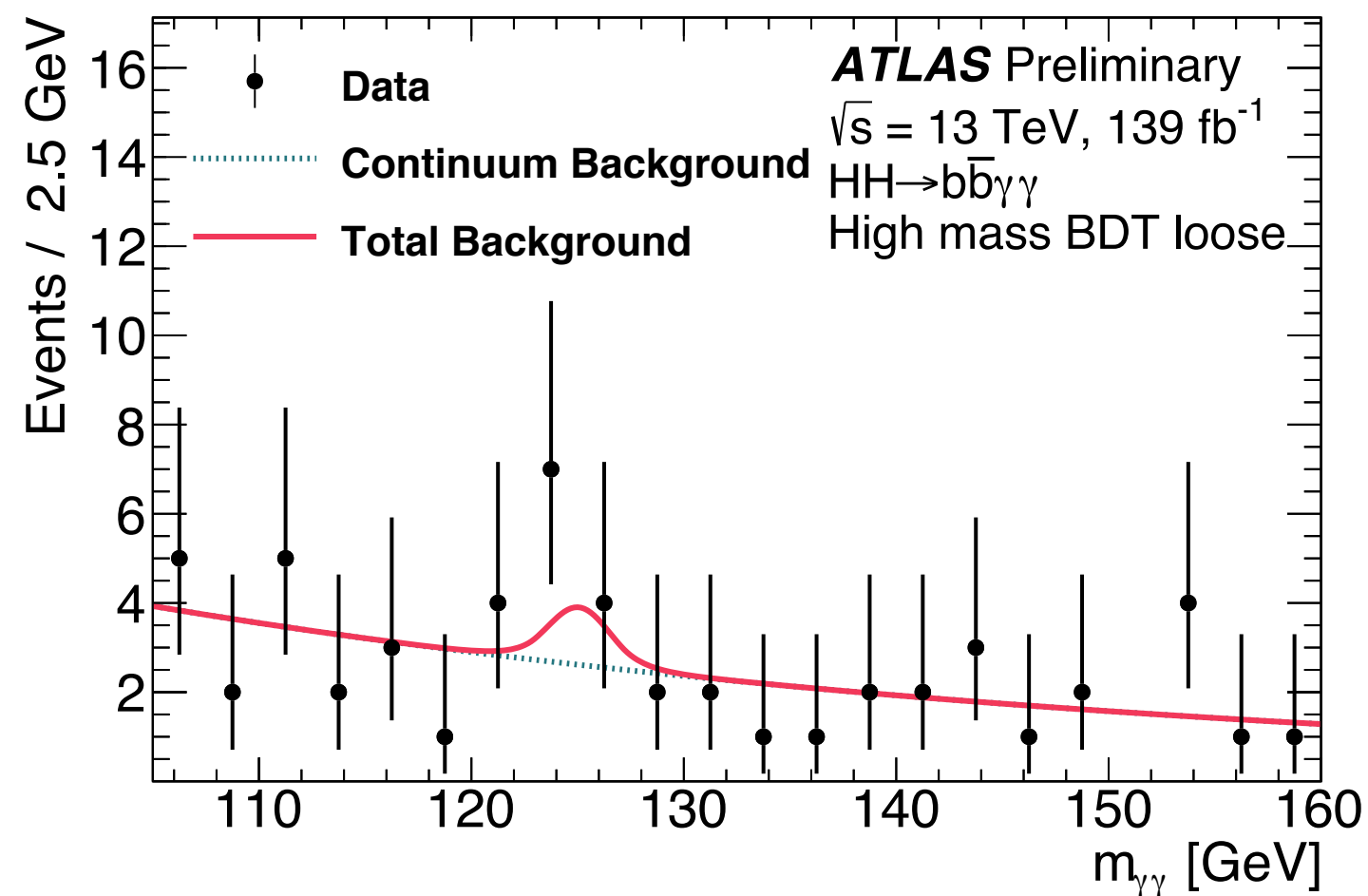
### BDT loose

### BDT tight

### Low mass

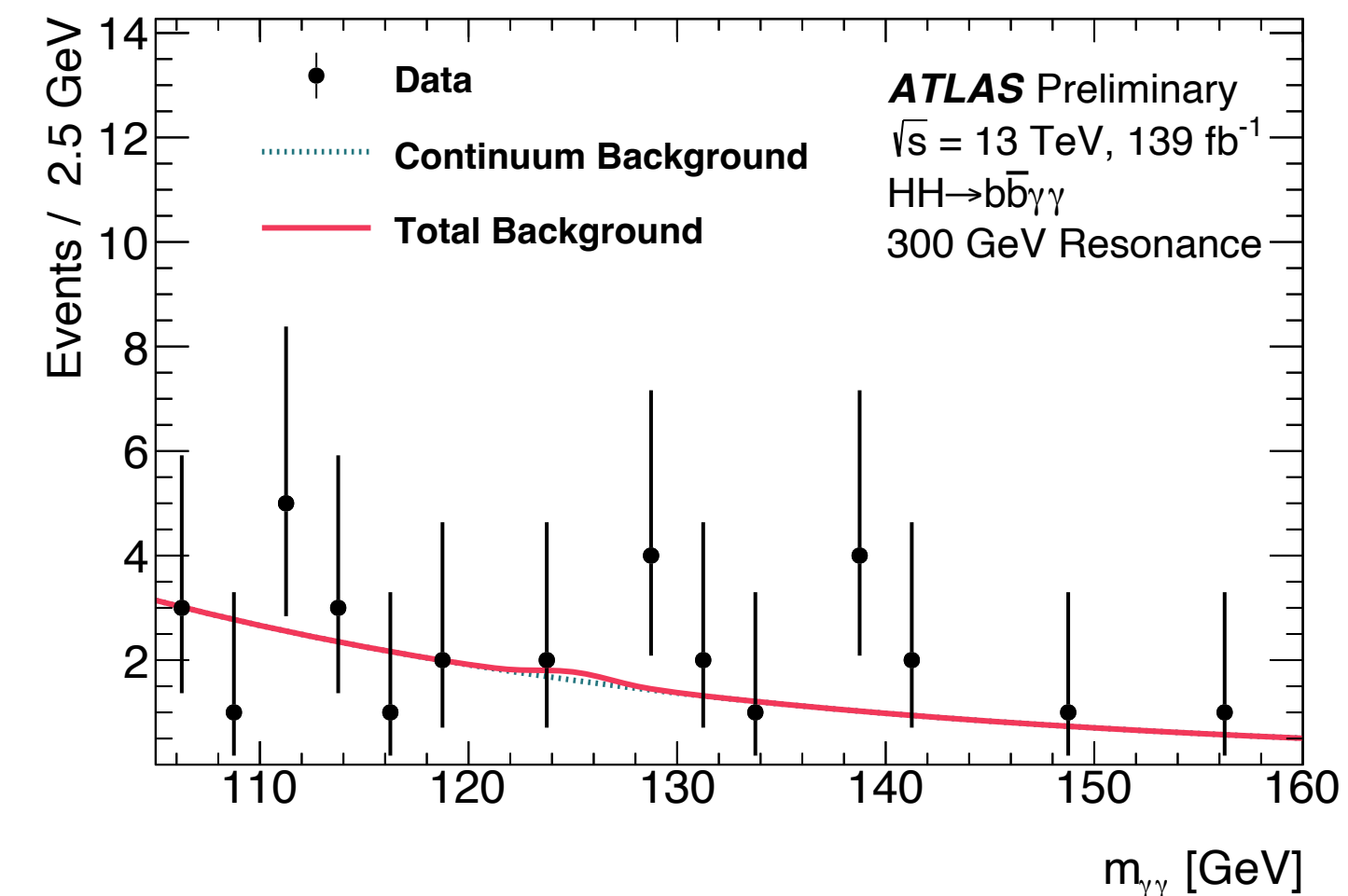


### High mass

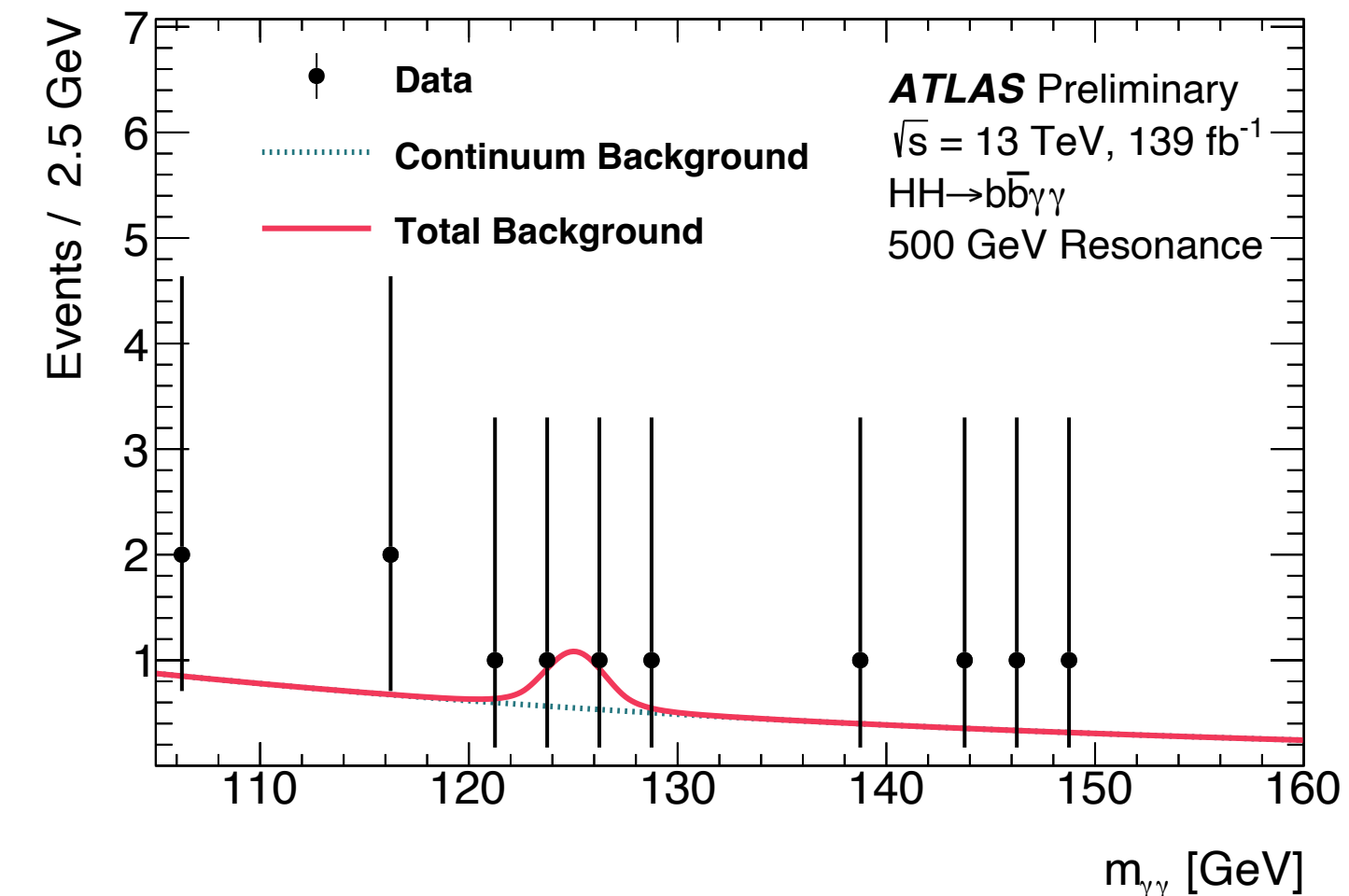


## Resonant

### Mx = 300 GeV

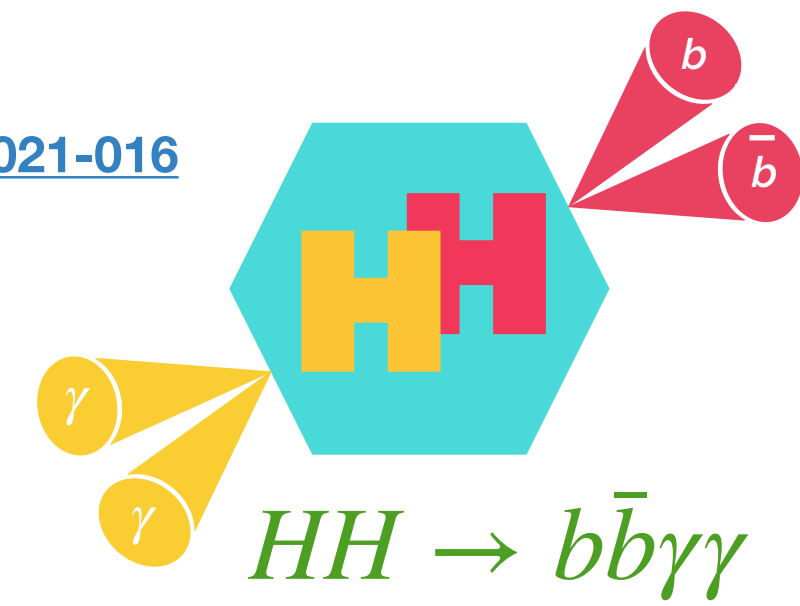


### Mx = 500 GeV



# Yields and systematics

ggF:  $\mathcal{L} = 139\text{fb}^{-1}$  [ATLAS-CONF-2021-016](#)



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

	$m_X = 300 \text{ GeV}$	$m_X = 500 \text{ GeV}$
Continuum background	$5.6 \pm 2.4$	$3.5 \pm 2.0$
Single Higgs boson background	$0.339 \pm 0.009$	$0.398 \pm 0.010$
SM $HH$ background	$(20.6 \pm 0.5) \cdot 10^{-3}$	$0.1932 \pm 0.0015$
$X \rightarrow HH$ signal	$5.771 \pm 0.031$	$5.950 \pm 0.026$
Data	6	4

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



# Comparison to CMS



$\frac{\sigma(pp \rightarrow HH)}{\sigma_{SM}}$ at 13 TeV		Partial Run 2 (2015-16)		Full Run 2 (2015-18)	
		Obs	Exp	Obs	Exp
$HH \rightarrow bbyy$	ATLAS	20.3	26	4.1	5.5
	CMS	23.6	18.8	7.7	5.2
$HH \rightarrow bb\tau\tau$	ATLAS	12.5	15	4.7	3.9
	CMS	31.4	25.1		
$HH \rightarrow bbbb$	ATLAS	12.9	21		
	CMS	74.6	36.9	3.6	7.3
Combination	ATLAS	6.9	10	2.8	2.8
	CMS	22.2	12.8		

Limit on $\kappa_\lambda$ at 95% C.L.		Obs	Exp
$HH \rightarrow bbyy$	ATLAS	-1.5 – 6.7	-2.4 – 7.7
	CMS	-3.3 – 8.5	-2.5 – 8.2
$HH \rightarrow bbbb$	ATLAS		
	CMS	-2.3 – 9.4	-5.0 – 12.0
Combination <i>partial Run 2</i>	ATLAS	-5.0 – 12.0	-5.8 – 12.0
	CMS	-11.8 – 18.8	-7.1 – 13.6
<i>Full Run 2</i>	ATLAS	-1.0 – 6.6	-1.2 – 7.2