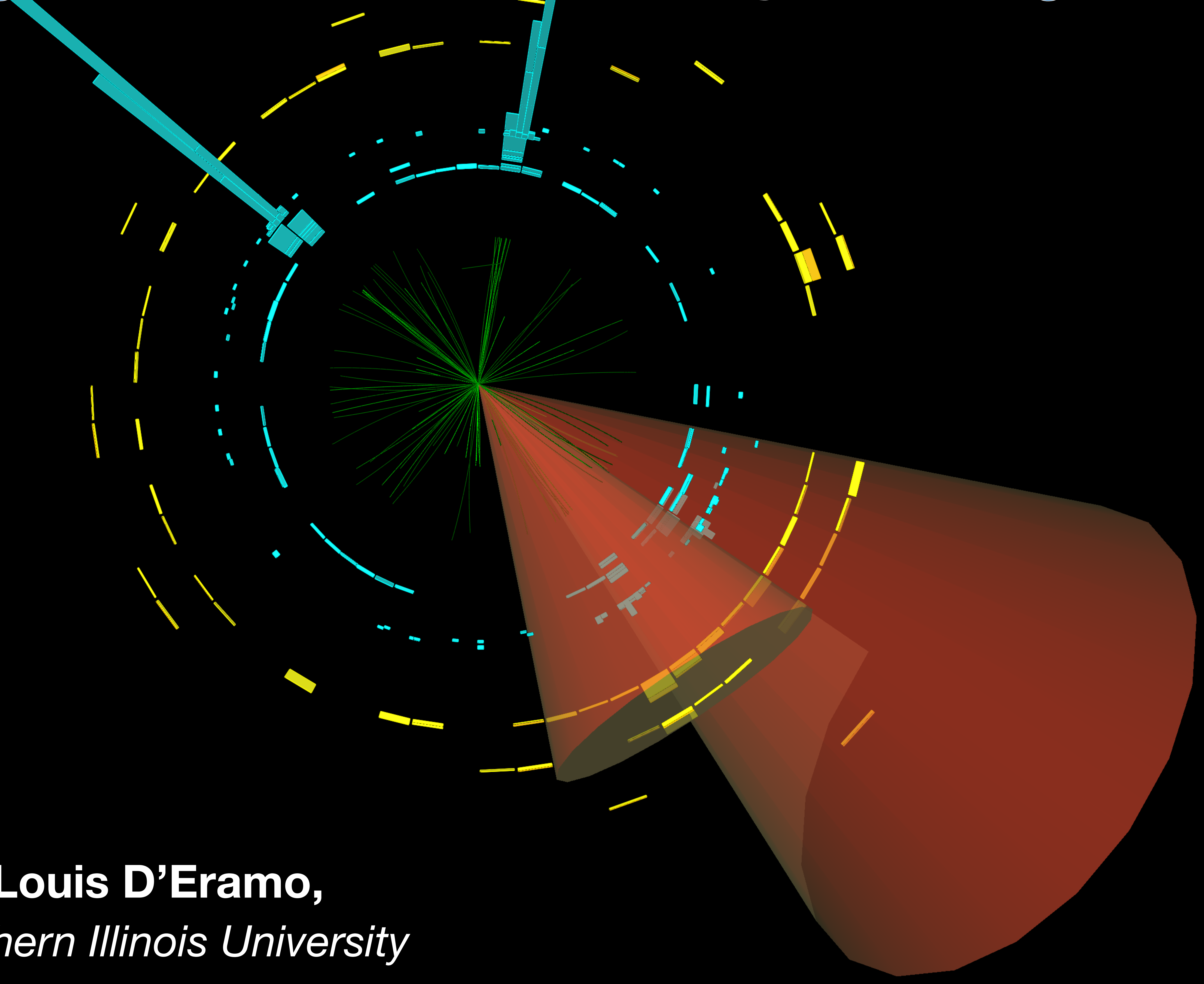
Higgs pair production at the LHC: a unique investigation of the EW symmetry breaking.

ATLAS EXPERIMENT



Louis D’Eramo,
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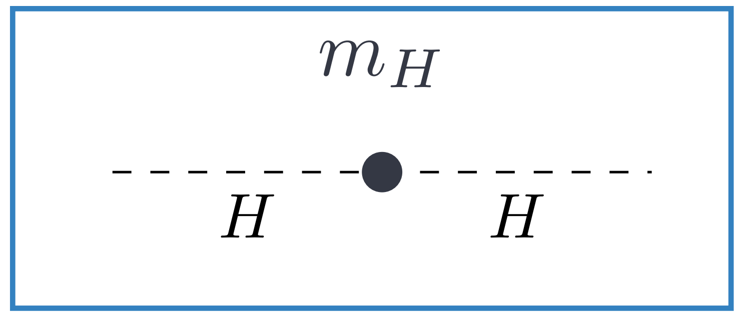
Investigating the Higgs potential



The full expression of the Higgs potential is encoded with parameters μ and λ 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 ν one gets:

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

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:

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

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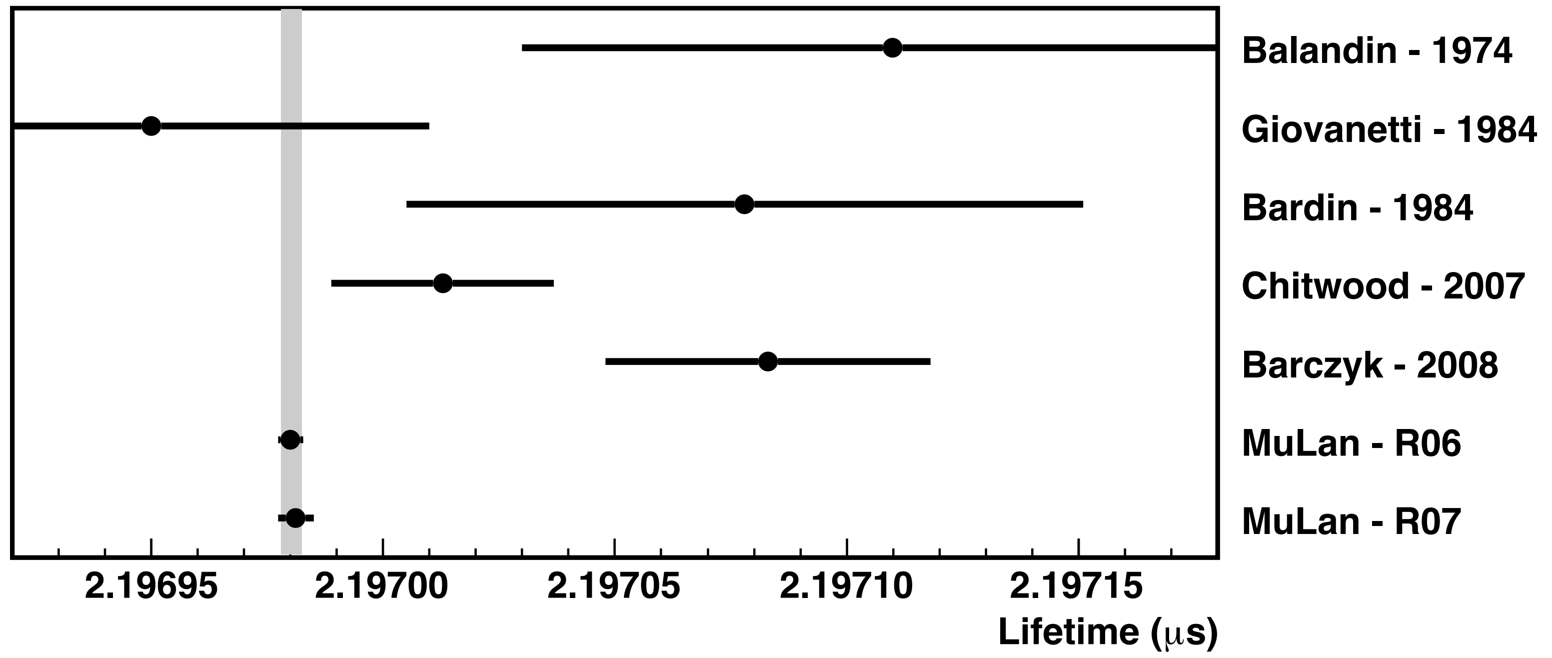

- From most precise MuLan experiment:

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

$\hookrightarrow \nu \simeq 246.23$ GeV

$\hookrightarrow \lambda \sim 0.13$

Investigating the Higgs potential

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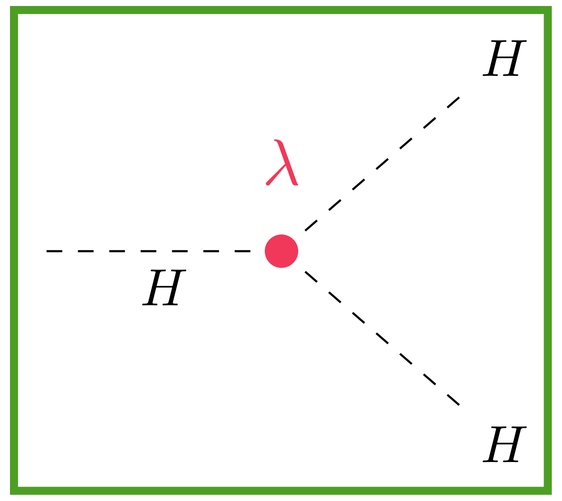
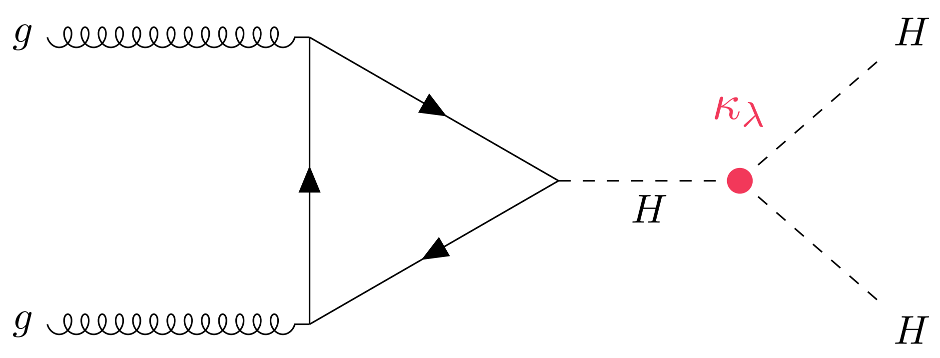
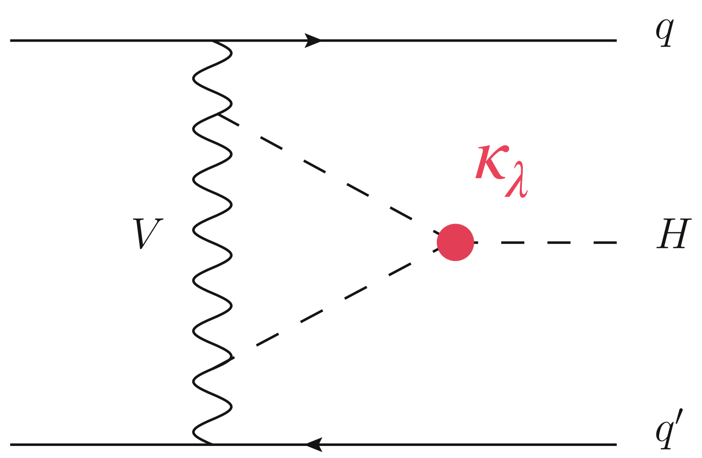
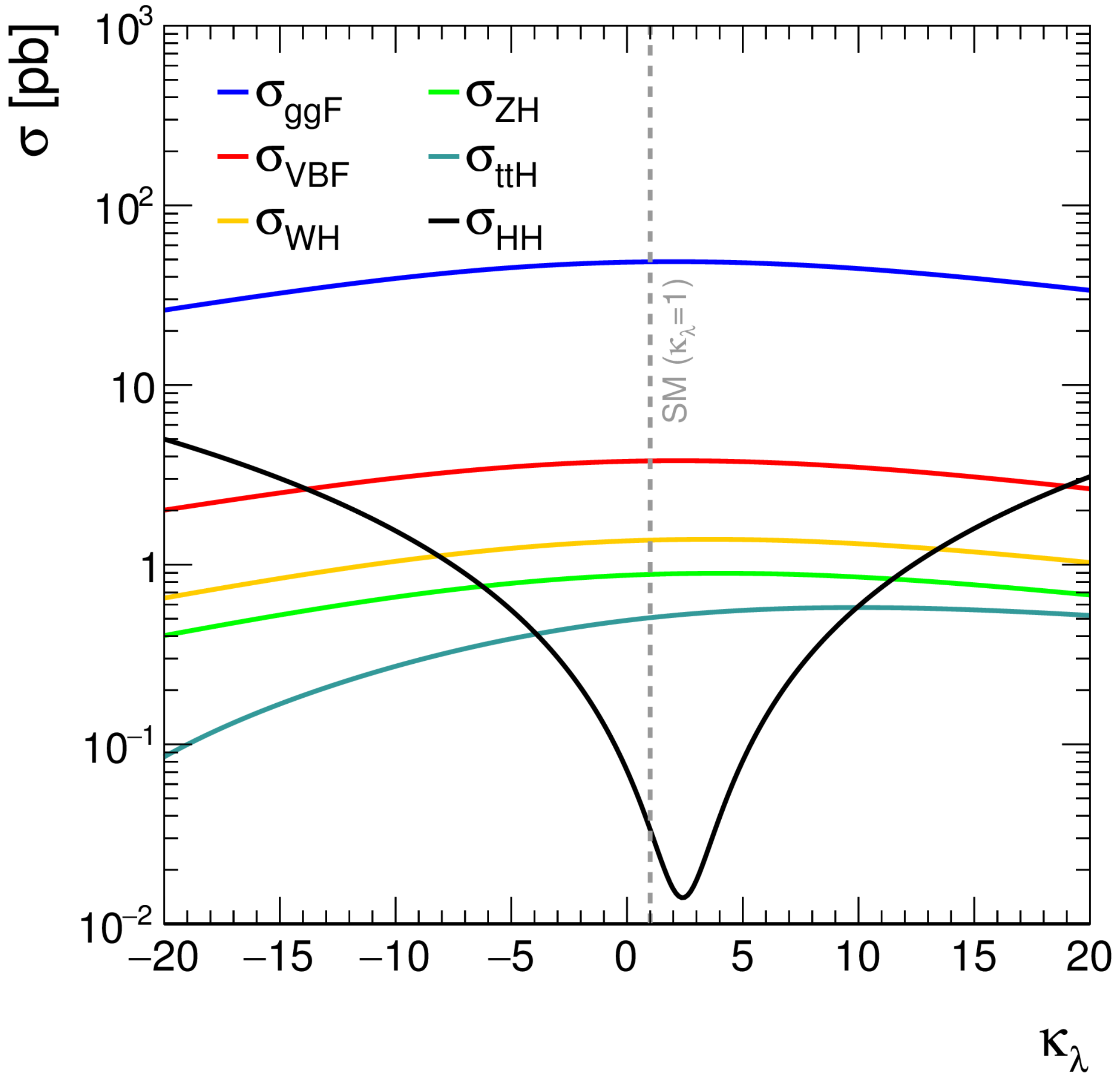


- Direct access to λ through Higgs pair creation:
  - Coupling strength denoted as $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$
  - At tree level: production of pair of Higgs bosons →strong effect on XS.
  - At loop level: effect on the single Higgs cross-section and deviations in kinematics.







Investigating the Higgs potential

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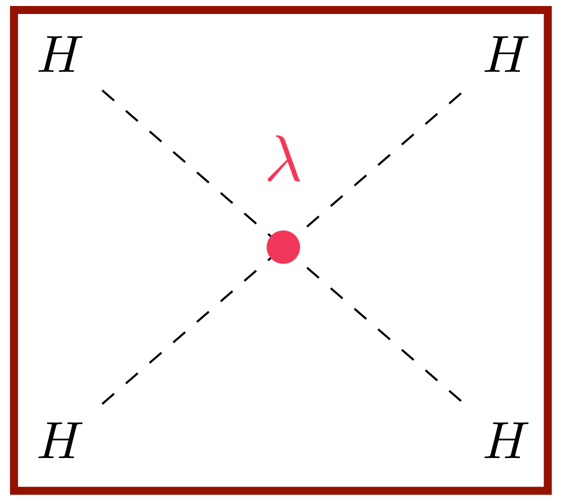

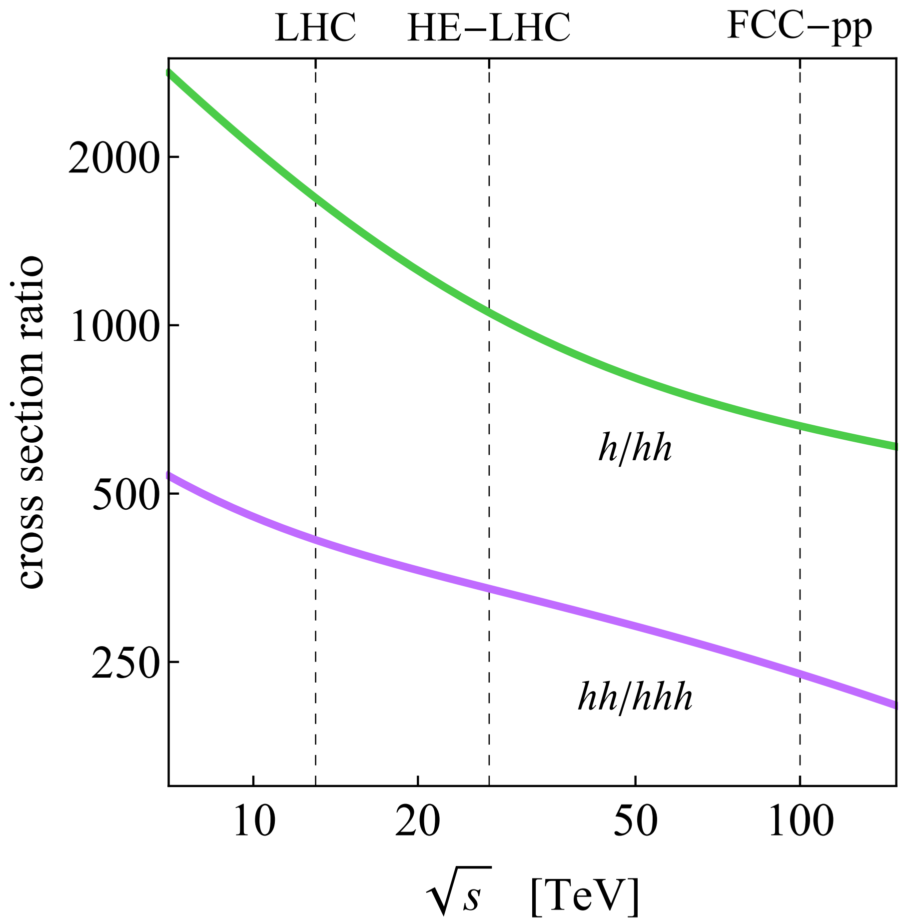

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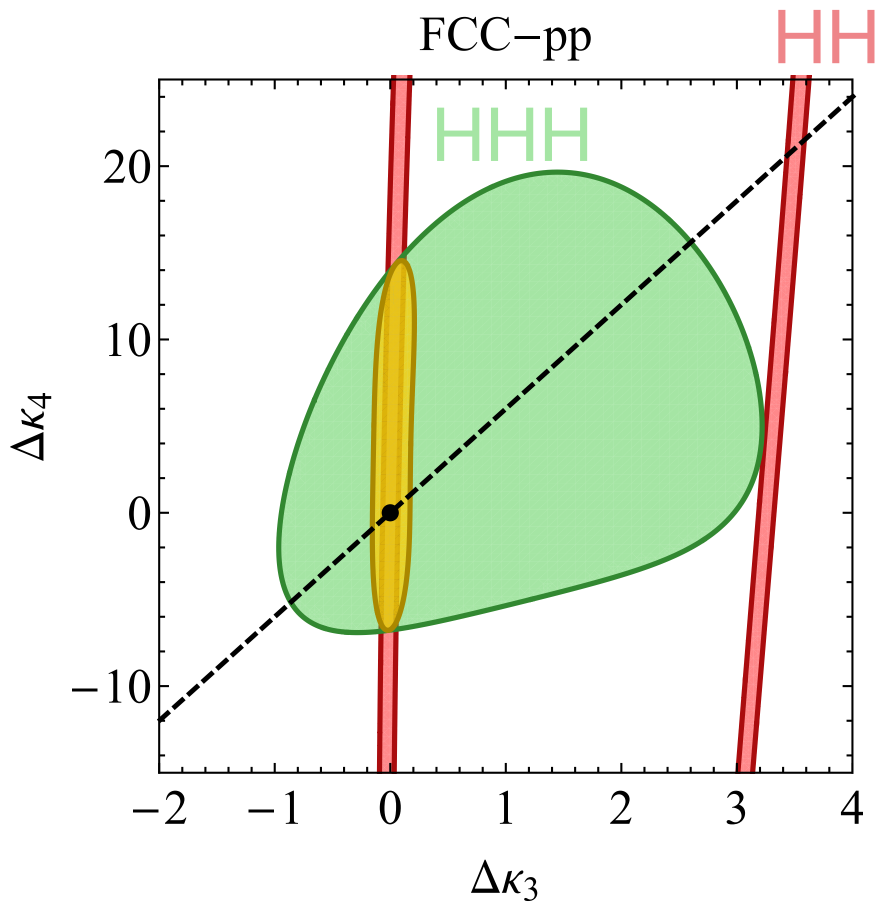
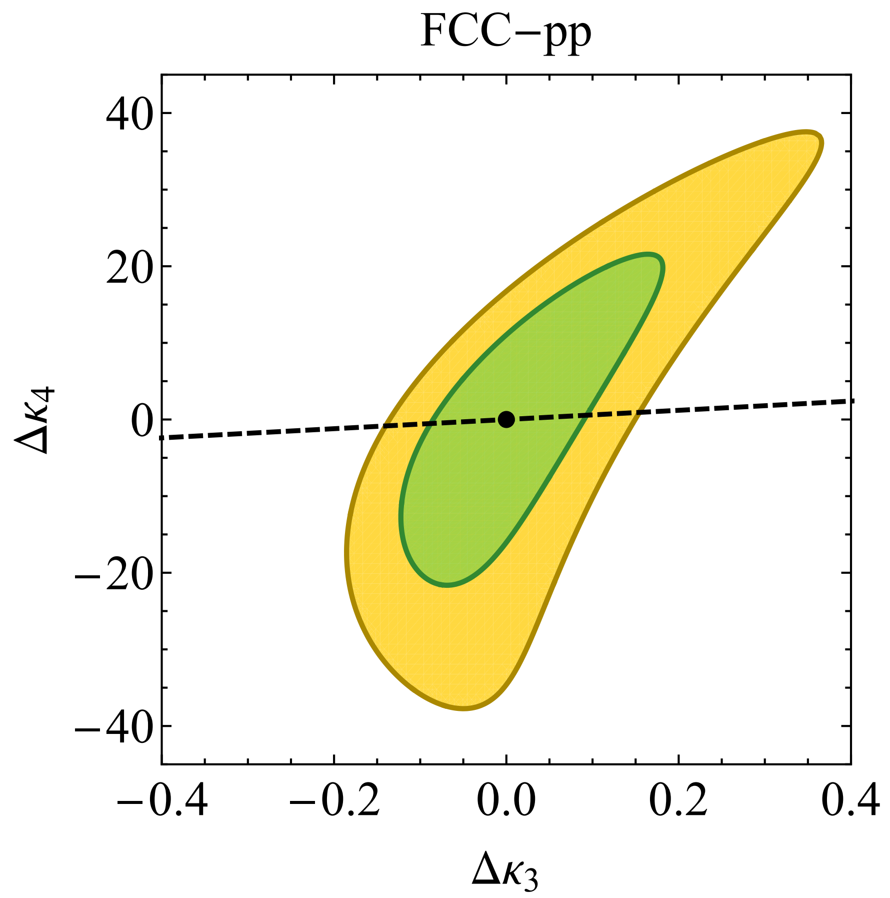
- Quartic interaction even rarer :
  - At tree level: very mild effect on XS and kinematic distributions.
  - At loop level: similar constraints obtained on XS, but stronger effect kinematics.
  - No strong constraints even with FCC 100 TeV collider.

XS



HH kinematics

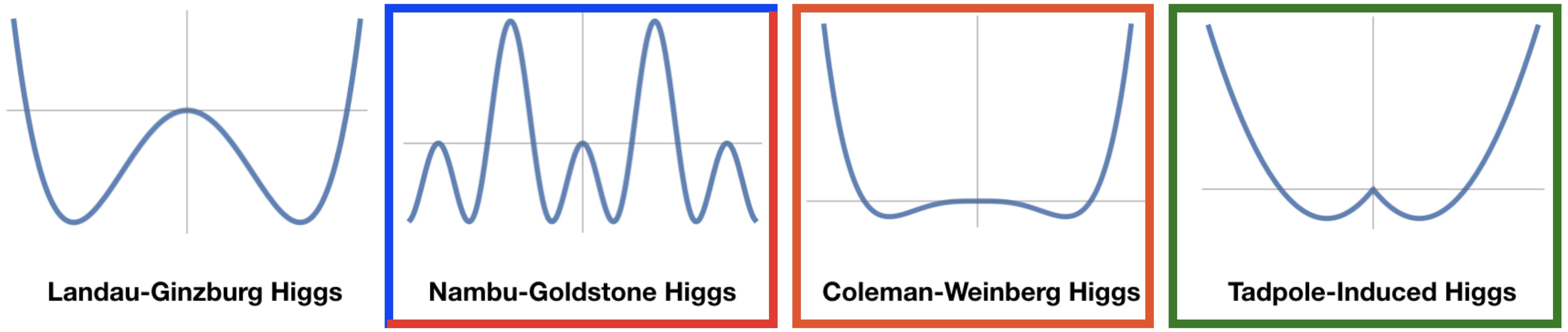


Exploring alternative scenarios

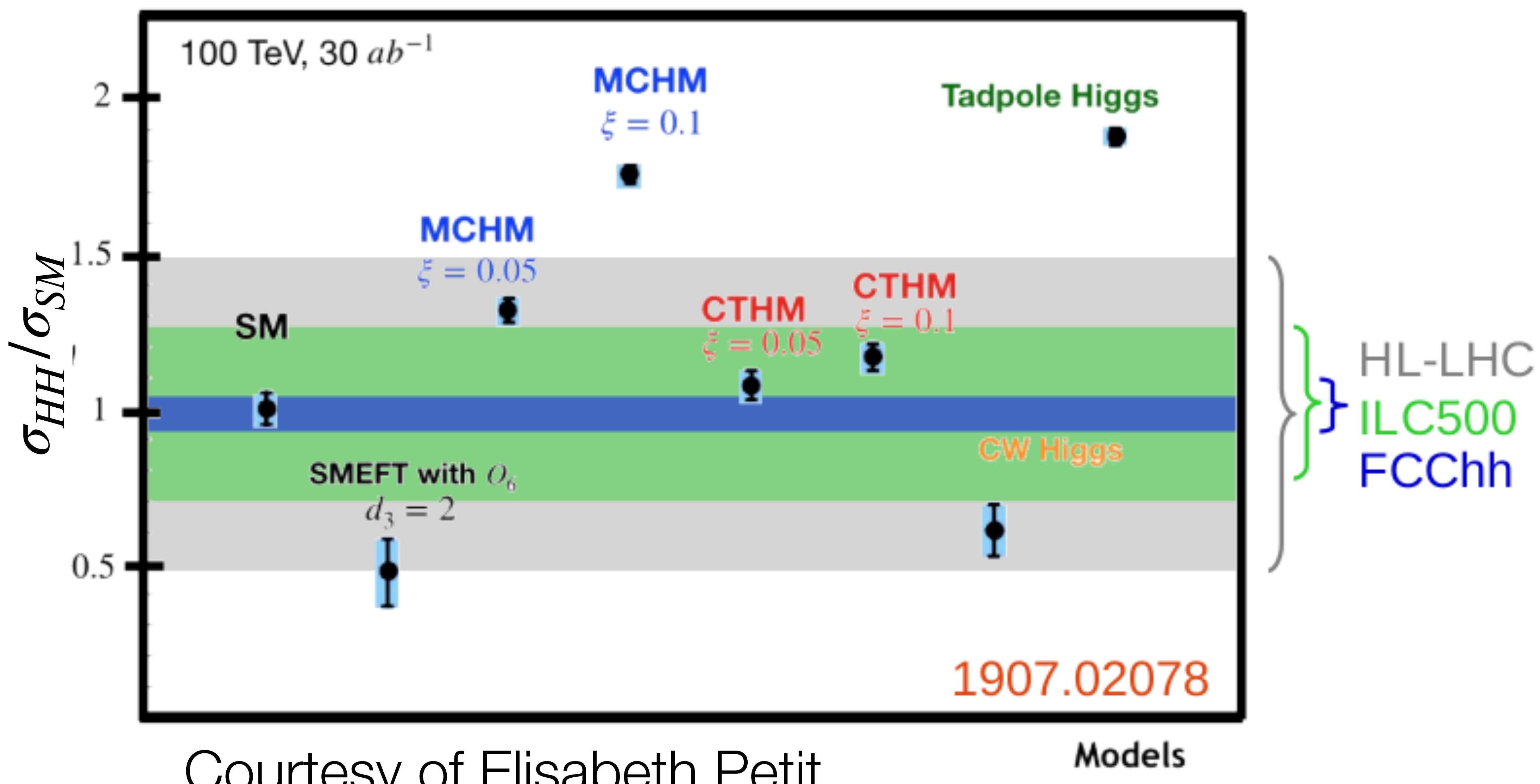
The measurement of the Higgs potential is answering the fundamental question of its nature.
Several other models can show a non zero vacuum expected value with a different second order contribution:

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

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

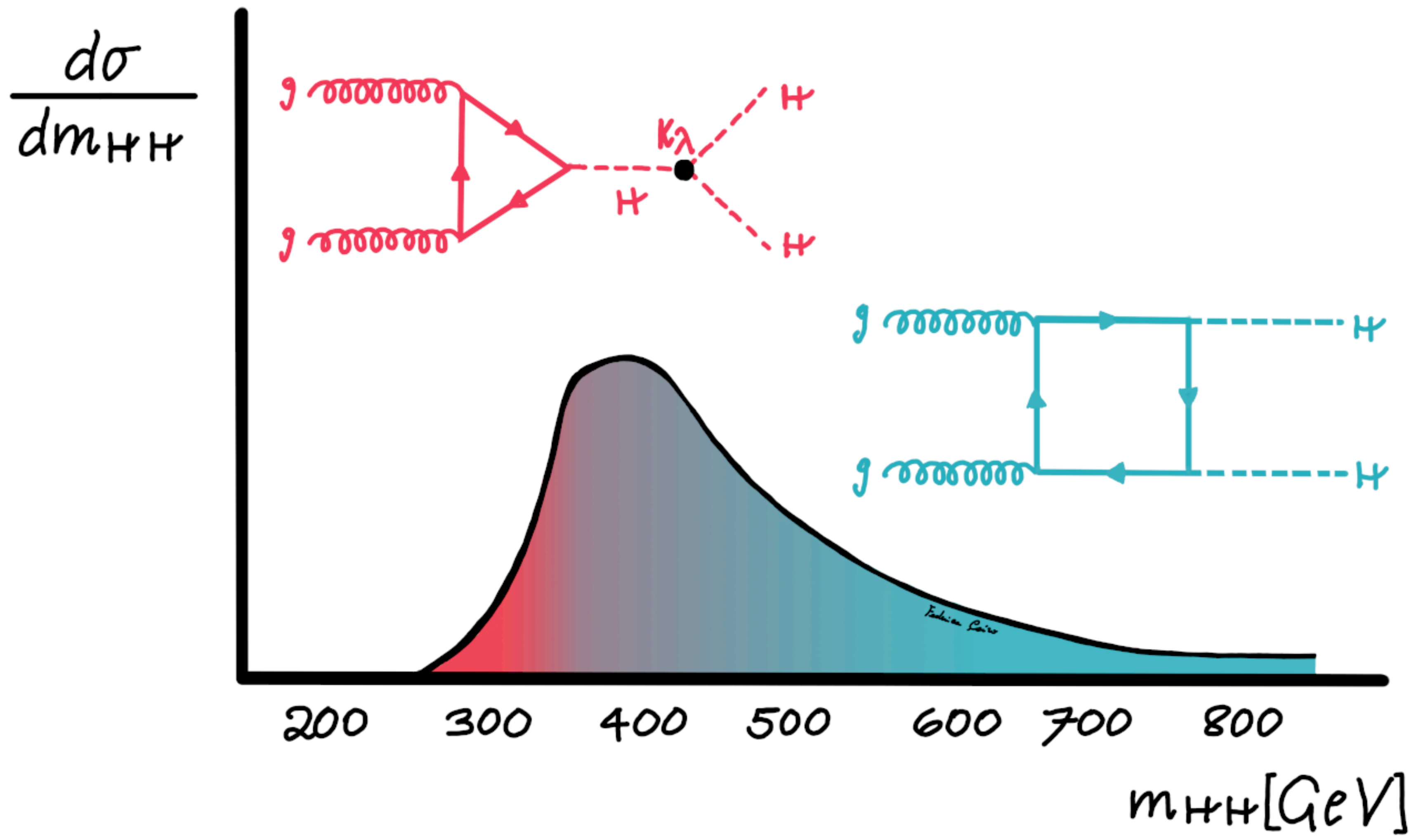


minimal composite Higgs model/
composite twin Higgs model :
different coupling to top quark

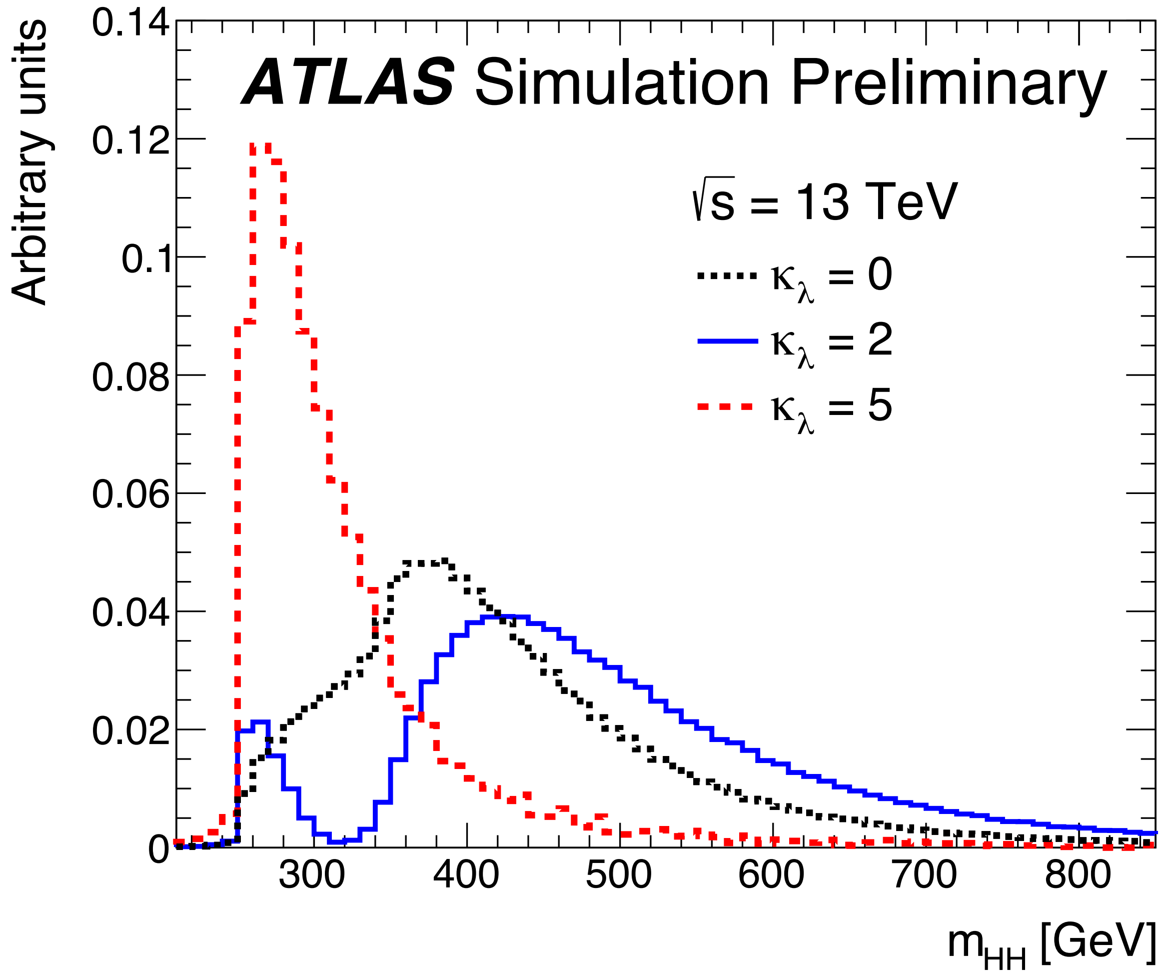


Courtesy of Elisabeth Petit

How are Higgs pairs produced?

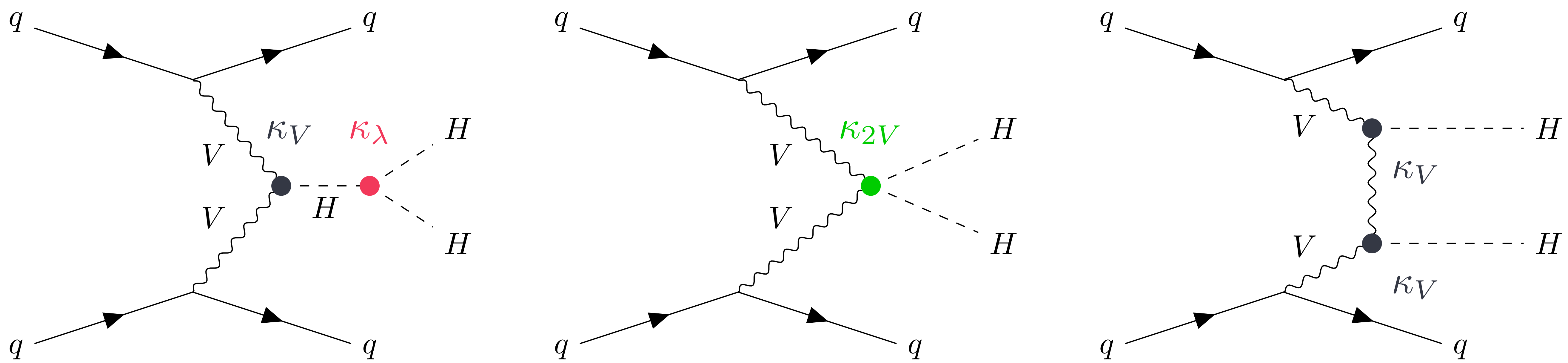


- **gluon-gluon Fusion (ggF):** $\sigma_{HH}^{ggF} = 31.02$ fb
  - Destructive interference between triangle and box diagrams makes the cross-section tiny (1000x smaller than single Higgs).
  - Low masses essential to constrain trilinear coupling κ_λ
  - m_{HH} shape very dependent on the κ_λ



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

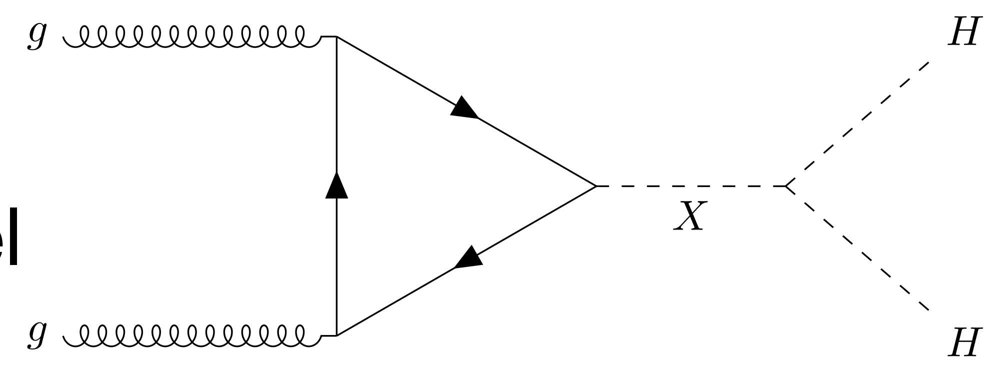
Second order contribution to total production, but direct handle to vector boson coupling modifiers κ_{2V} and κ_V:



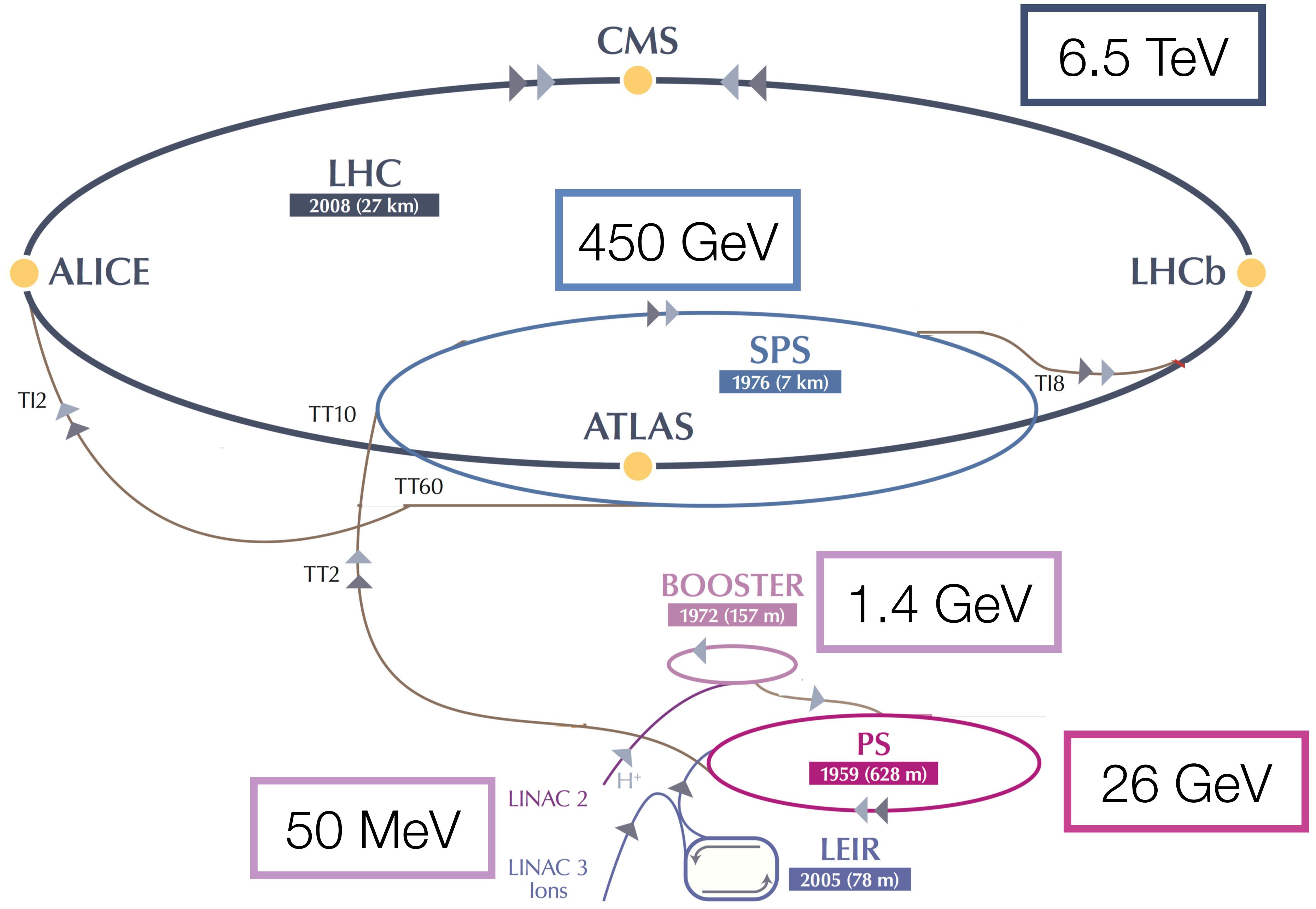
- **BSM resonances:**

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 ?

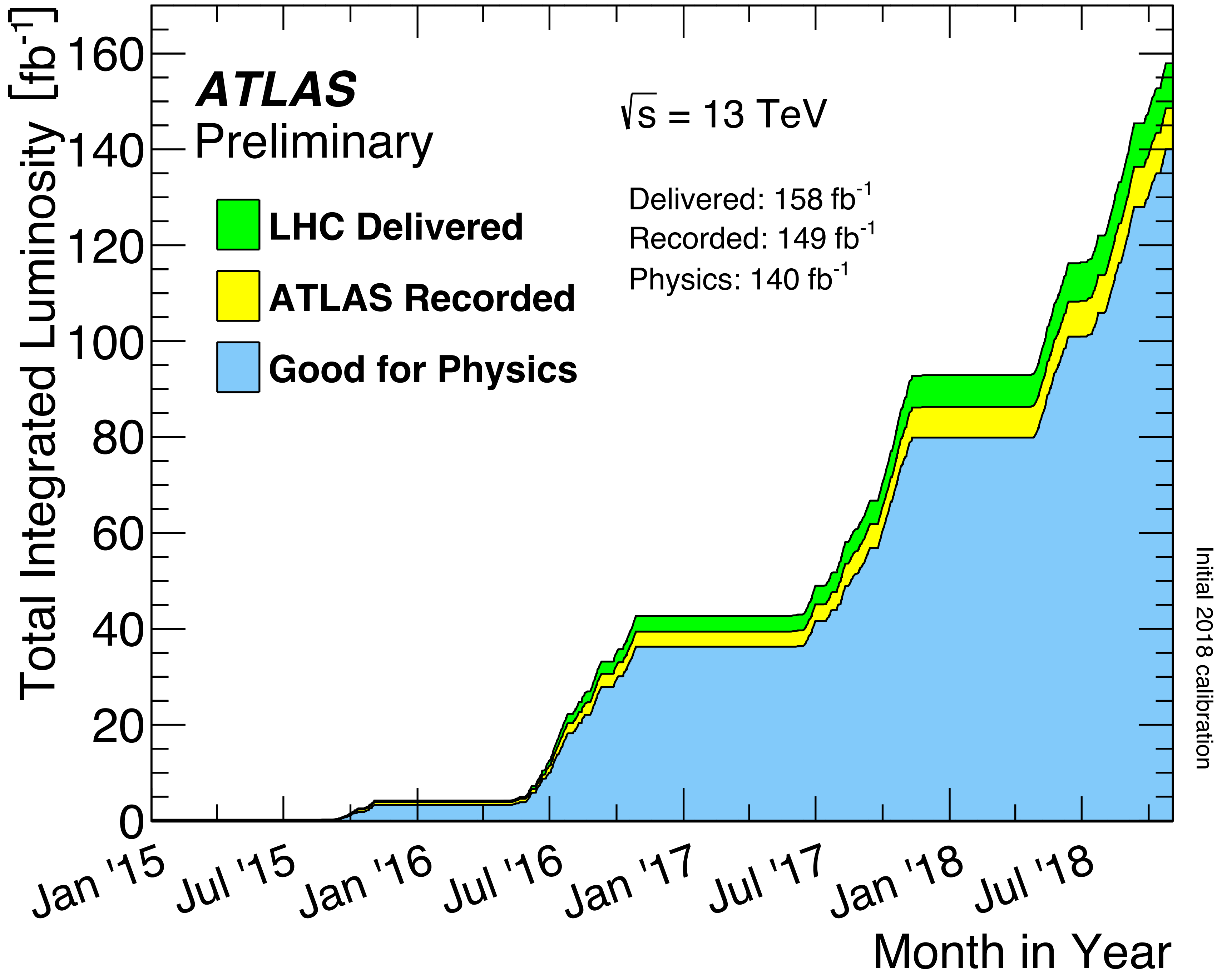


Located under the French Swiss Border, the **Large Hadron Collider** is the final piece of a staged acceleration chain allowing high luminosity **proton-proton** collisions.

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

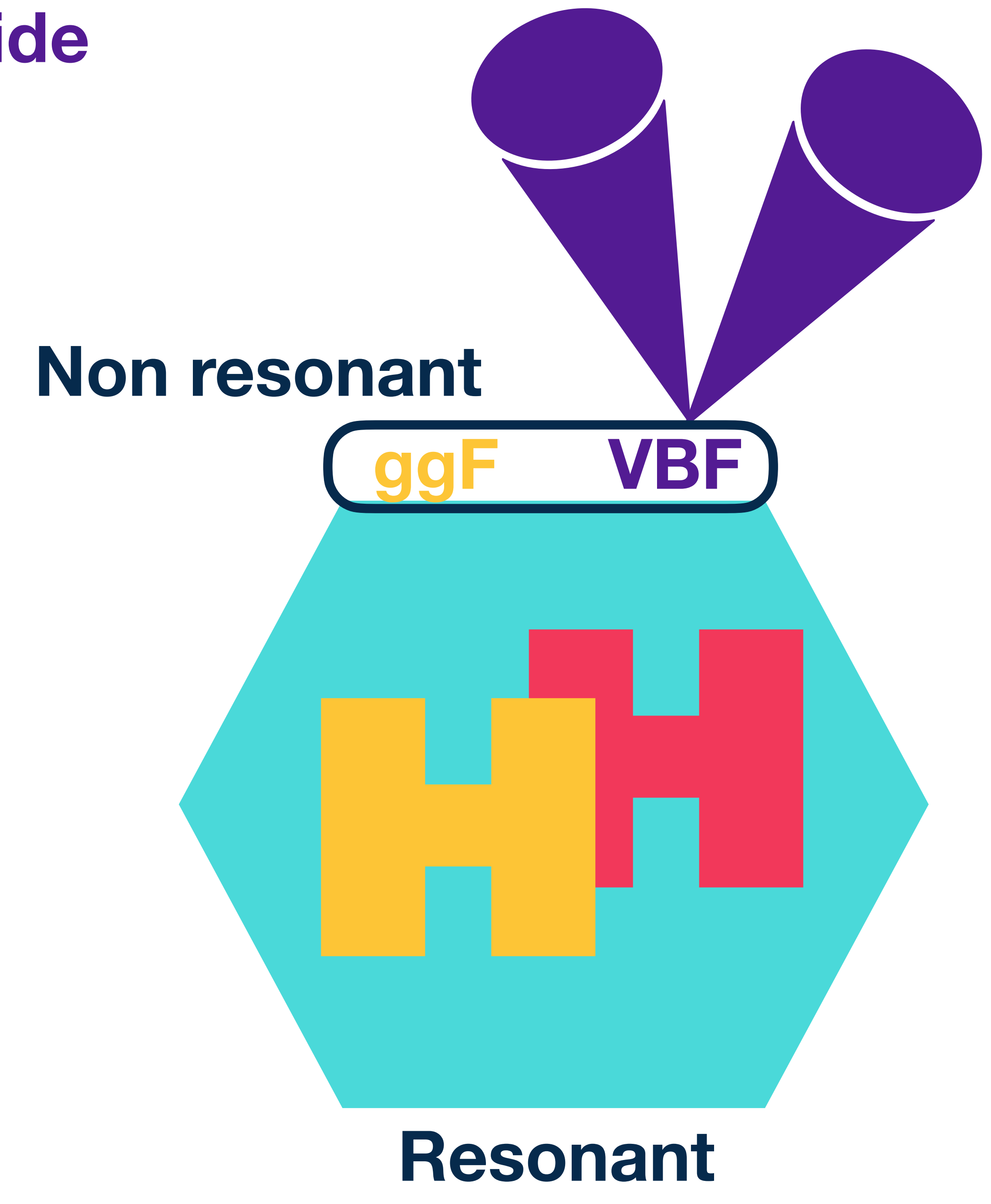
	N_H	N_{HH}
Run-1	512 000	200
Run-2	6 800 000	4 300
Run-3*	7 700 000	5 000
HL-LHC*	165 000 000	110 000

*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**.

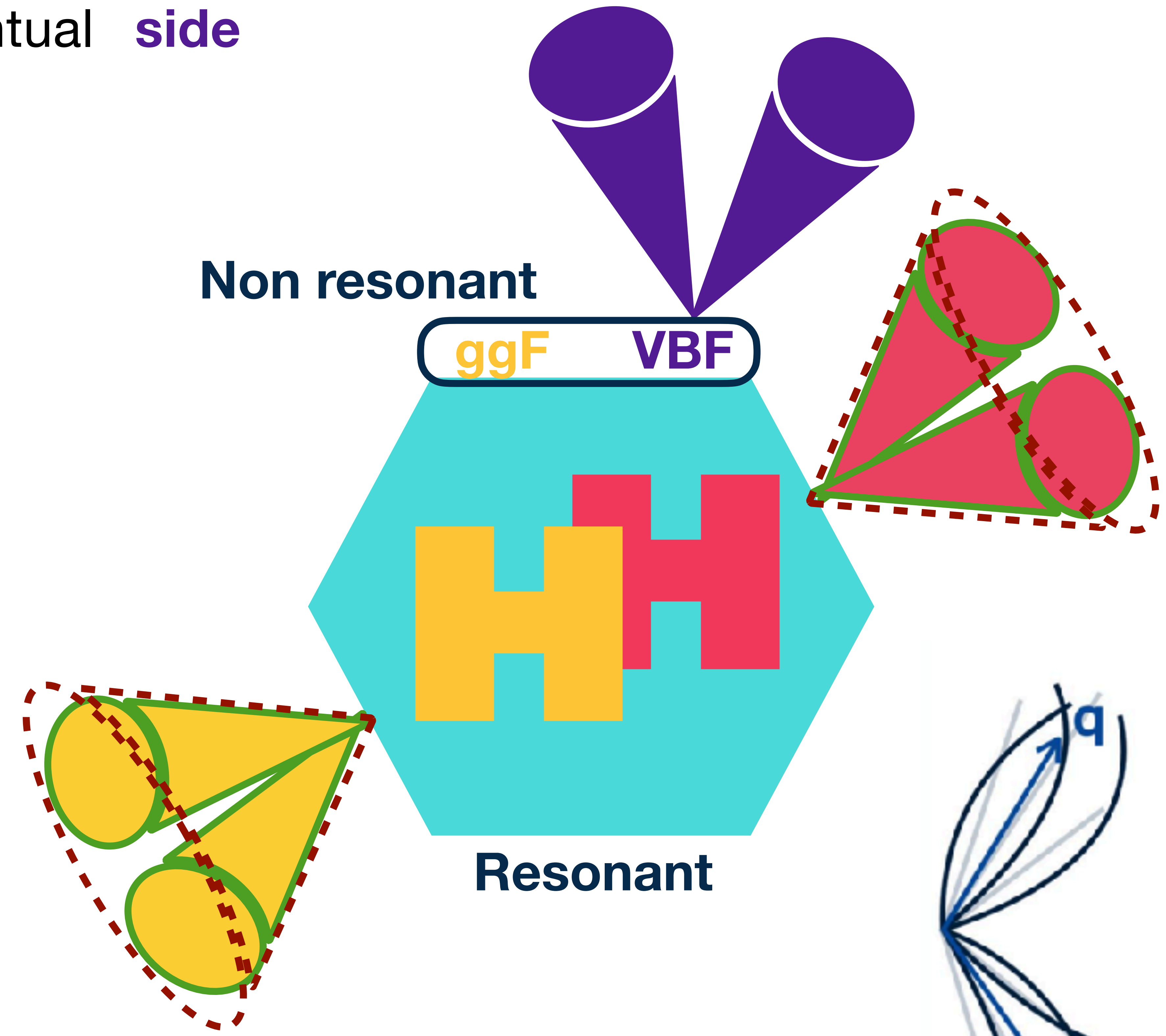


How to look for Higgs pairs?

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

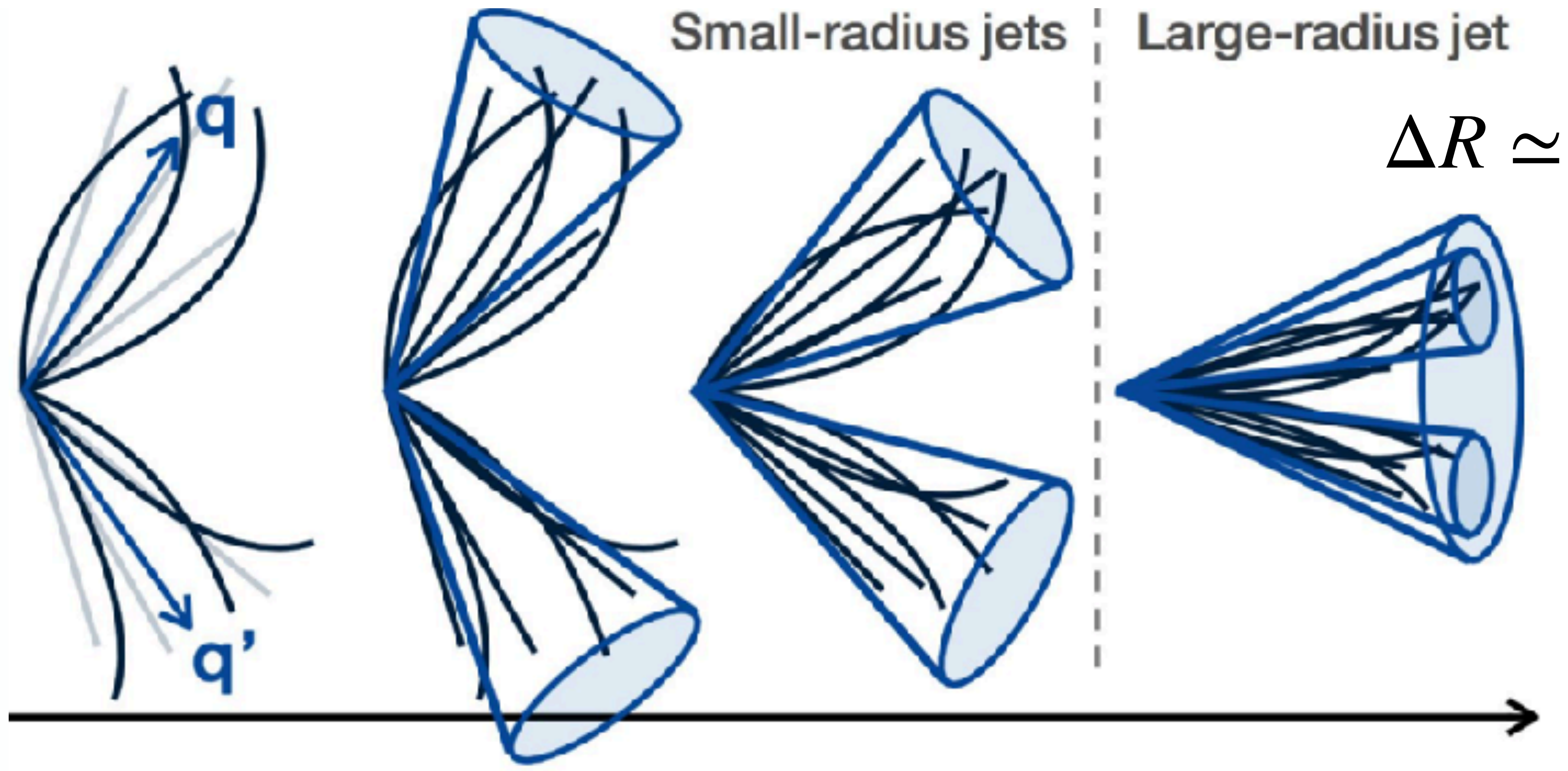
Experimentally only the **decay products** of the Higgs bosons can be **measured**. They define the **strategy** of the analysis:

- 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:

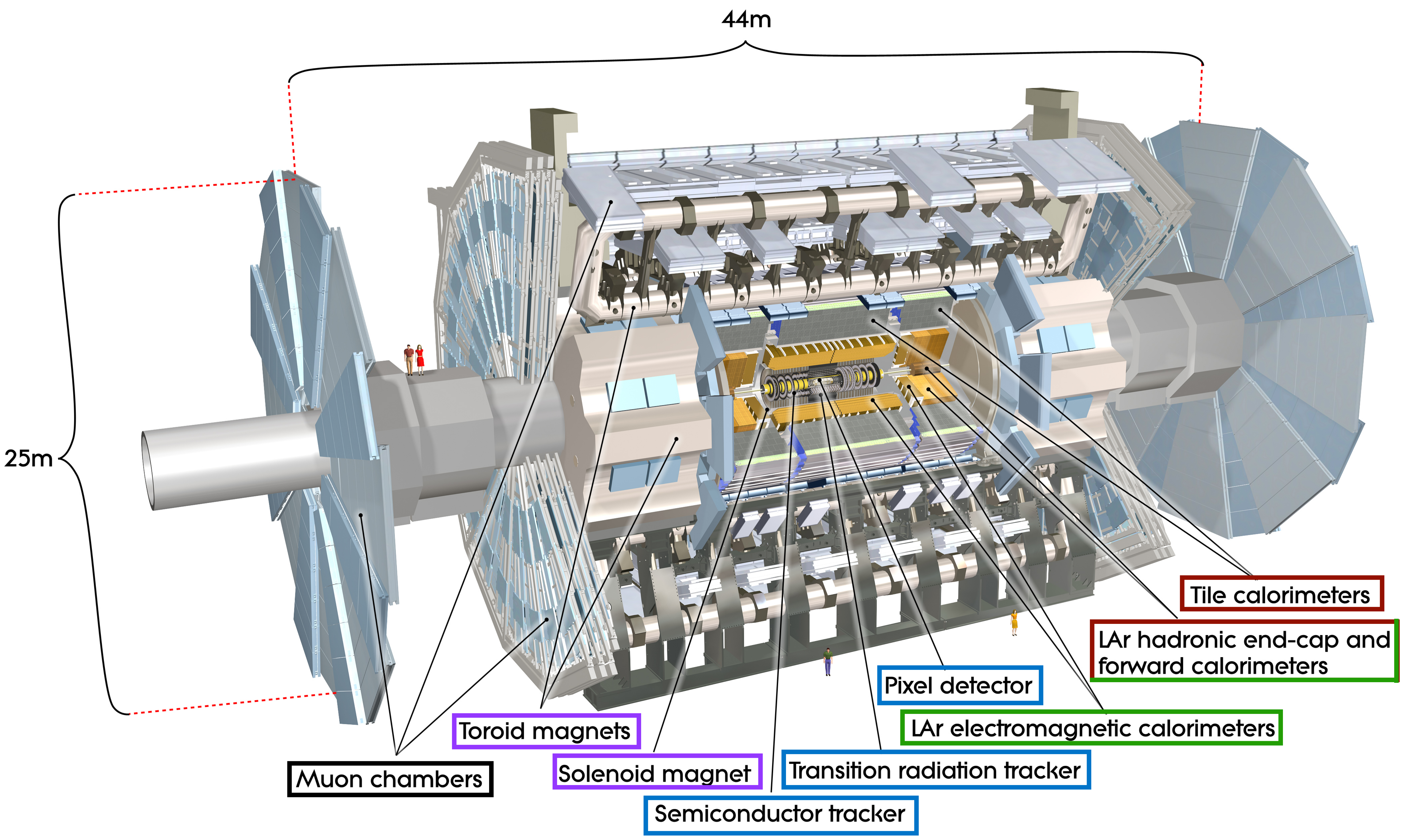
- **Resolved**: two single objects can be reconstructed, aiming at low m_{HH}.
- **Boosted**: one object is reconstructed with dedicated sub-structure analysis.



$$\Delta R \simeq 2\frac{m_H}{p_T^H}$$

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?

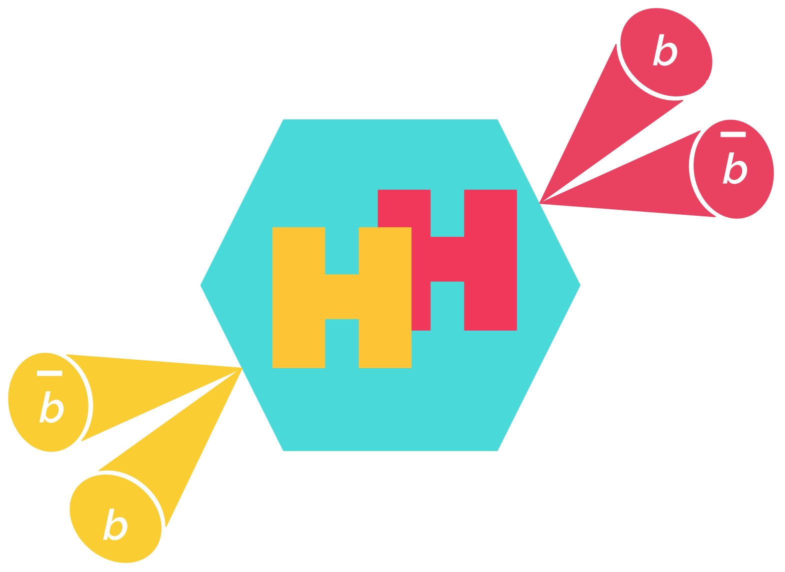
No clear *Golden channel*, but several promising signatures:

$BR(HH \to XXYY)$

	bb	WW	gg	ττ	cc	ZZ	γγ	Zγ	μμ
bb	33%								
WW	25%	4.6%							
gg									
ττ	7.4%								
cc									
ZZ	3.1%								
γγ	0.26%	0.1%							
Zγ									
μμ									

□ = results from ATLAS

Combining the results is necessary **for observation**.



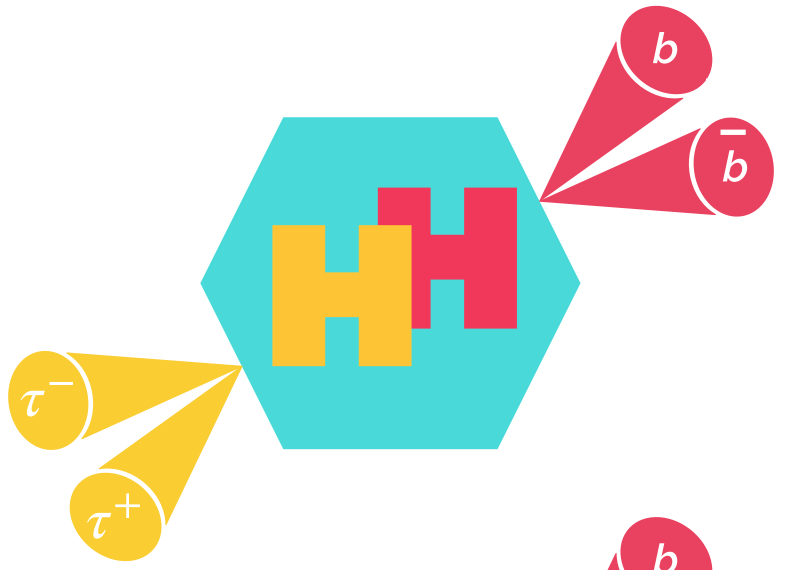
$HH \to b\bar{b}b\bar{b}$

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

ggF: $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 01 (2019) 030

Resonant ggF: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-035

VBF: $\mathscr{L} = 126\text{fb}^{-1}$ JHEP 07 (2020) 108

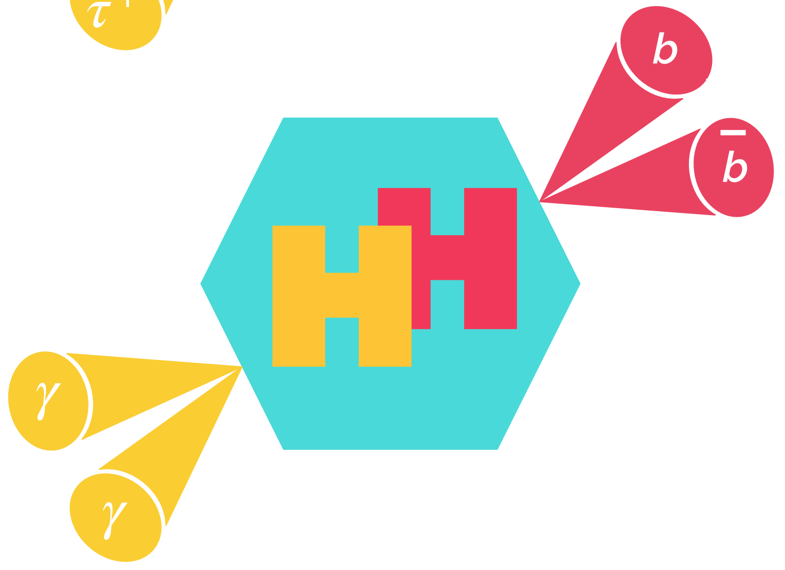


$HH \to b\bar{b}\tau^+\tau^-$

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

Resolved: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-030

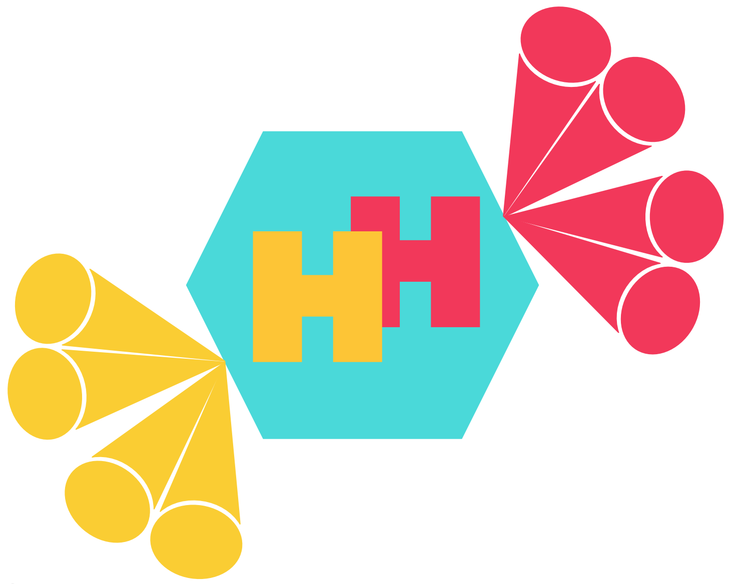
Boosted: $\mathscr{L} = 139\text{fb}^{-1}$ JHEP 11 (2020) 163



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

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

ggF. resolved: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-016



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

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

$b\bar{b}l\nu l\nu$: $\mathscr{L} = 139\text{fb}^{-1}$ Phys. Lett. B 801 (2020) 135145

$\gamma\gamma WW^*$: $\mathscr{L} = 36\text{fb}^{-1}$ Eur. Phys. J. C 78 (2018) 1007

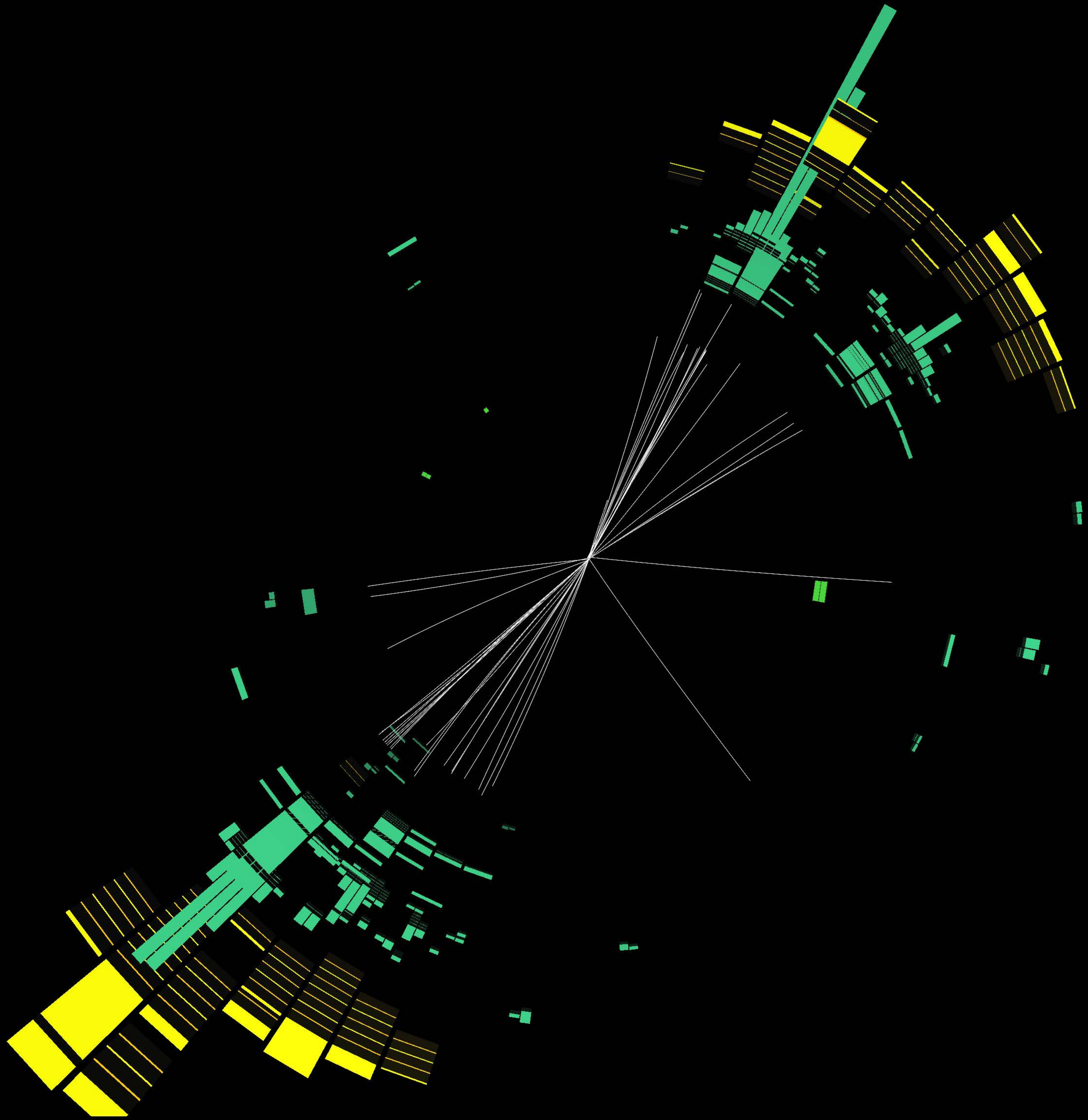
$b\bar{b}l\nu q\bar{q}$: $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 04 (2019) 092

WW^*WW^*: $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 05 (2019) 124

ATLAS EXPERIMENT

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

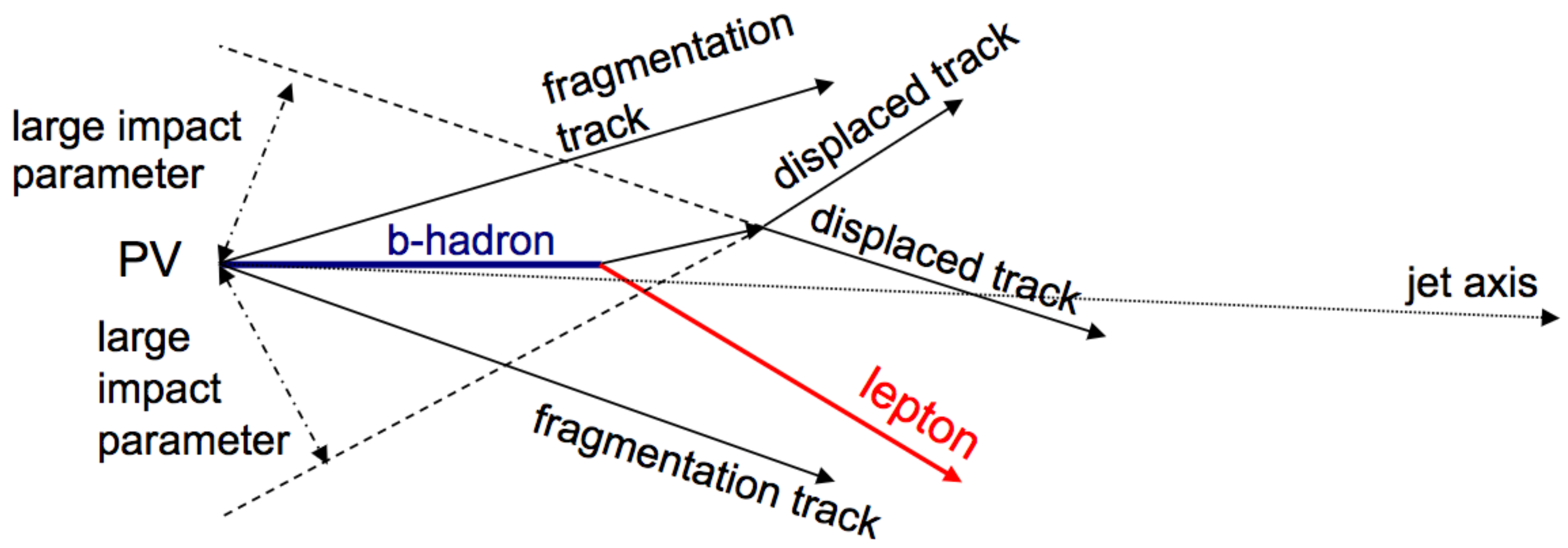
$HH \to b\bar{b}b\bar{b}$



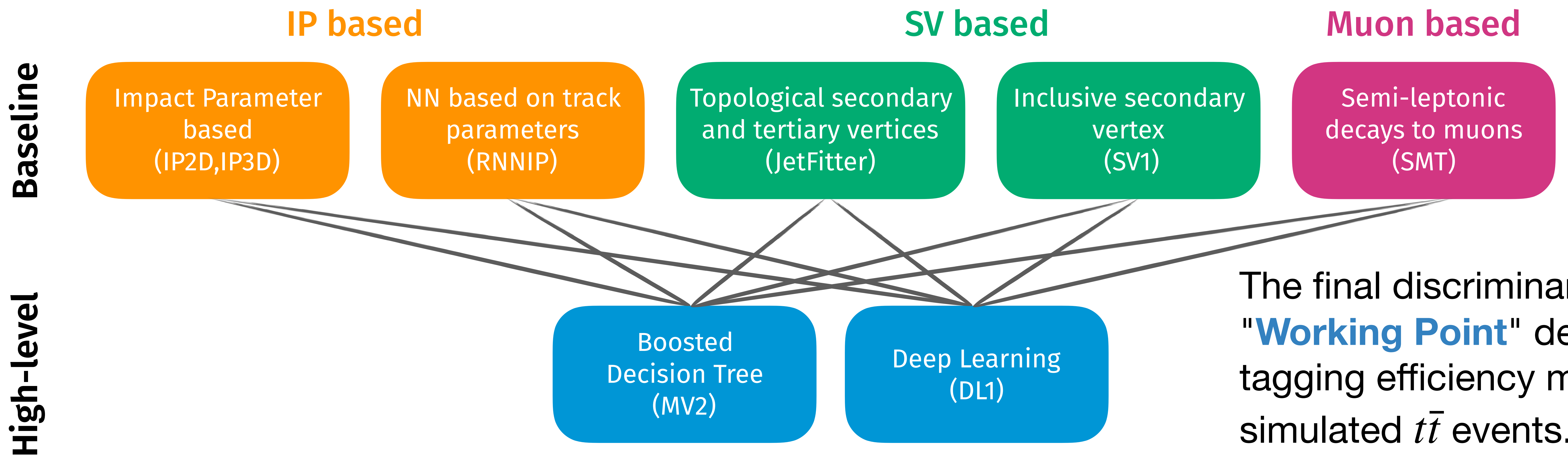
How to identify b-jets

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

- Large lifetime (~1.5 ps) → Secondary Vertex and tracks with large Impact Parameter.
- High decay multiplicity (average: 5 charged particles).
- In ~42% of the cases the b-hadron decays semi-leptonicaly → 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:

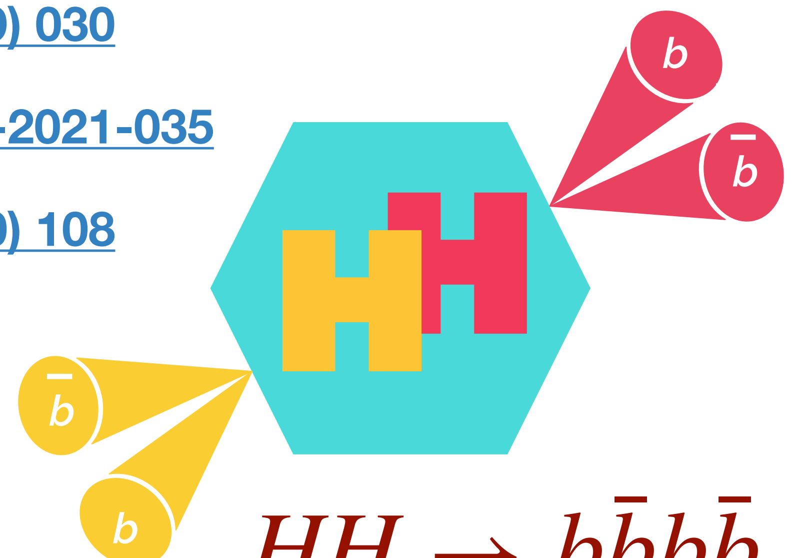


The final discriminant is based on a "**Working Point**" defined by the b-tagging efficiency measured in MC simulated $t\bar{t}$ events.

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

Strategy

ggF: $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 01 (2019) 030
Resonant ggF: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-035
VBF: $\mathscr{L} = 126\text{fb}^{-1}$ JHEP 07 (2020) 108

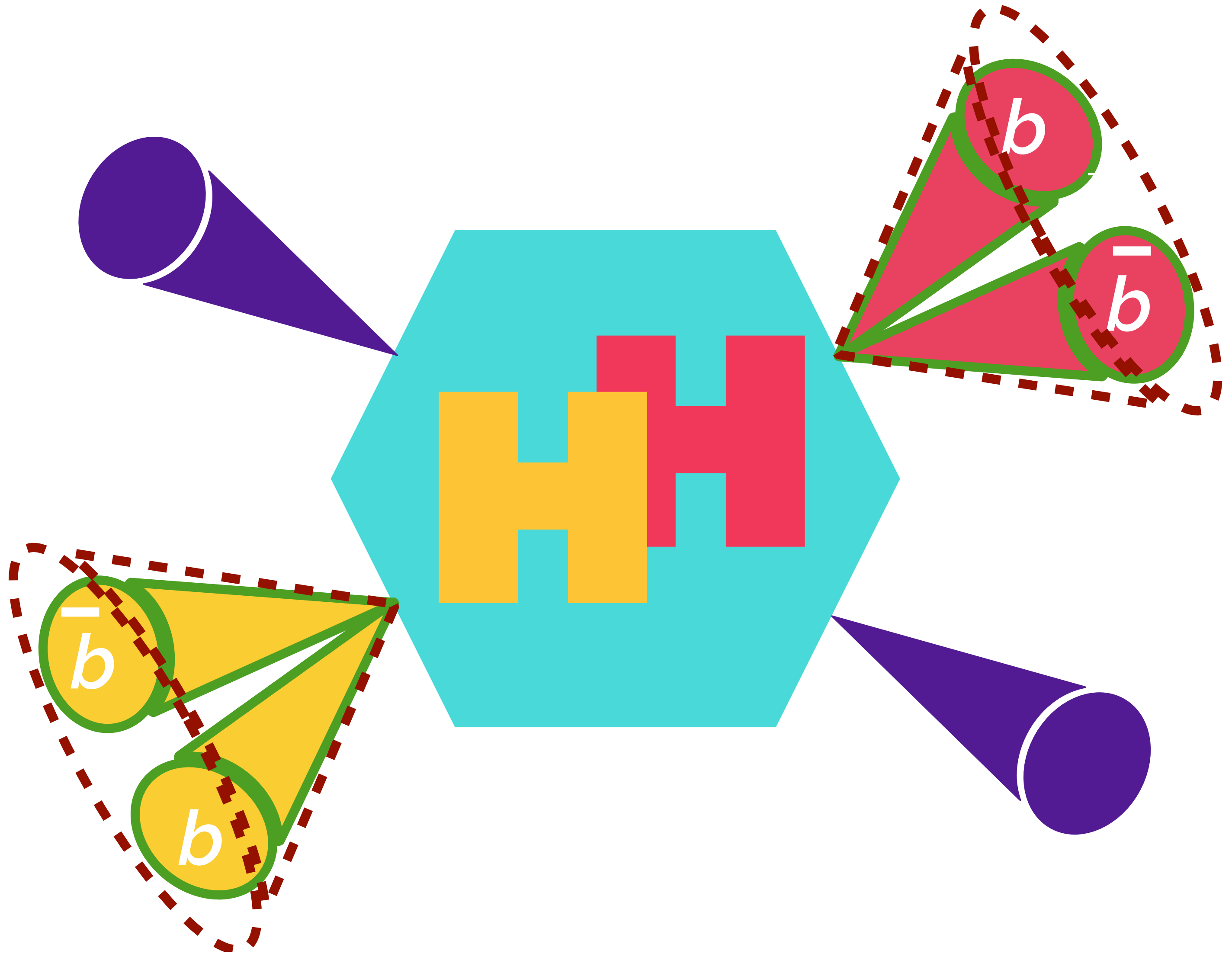


$HH \to b\bar{b}b\bar{b}$

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.



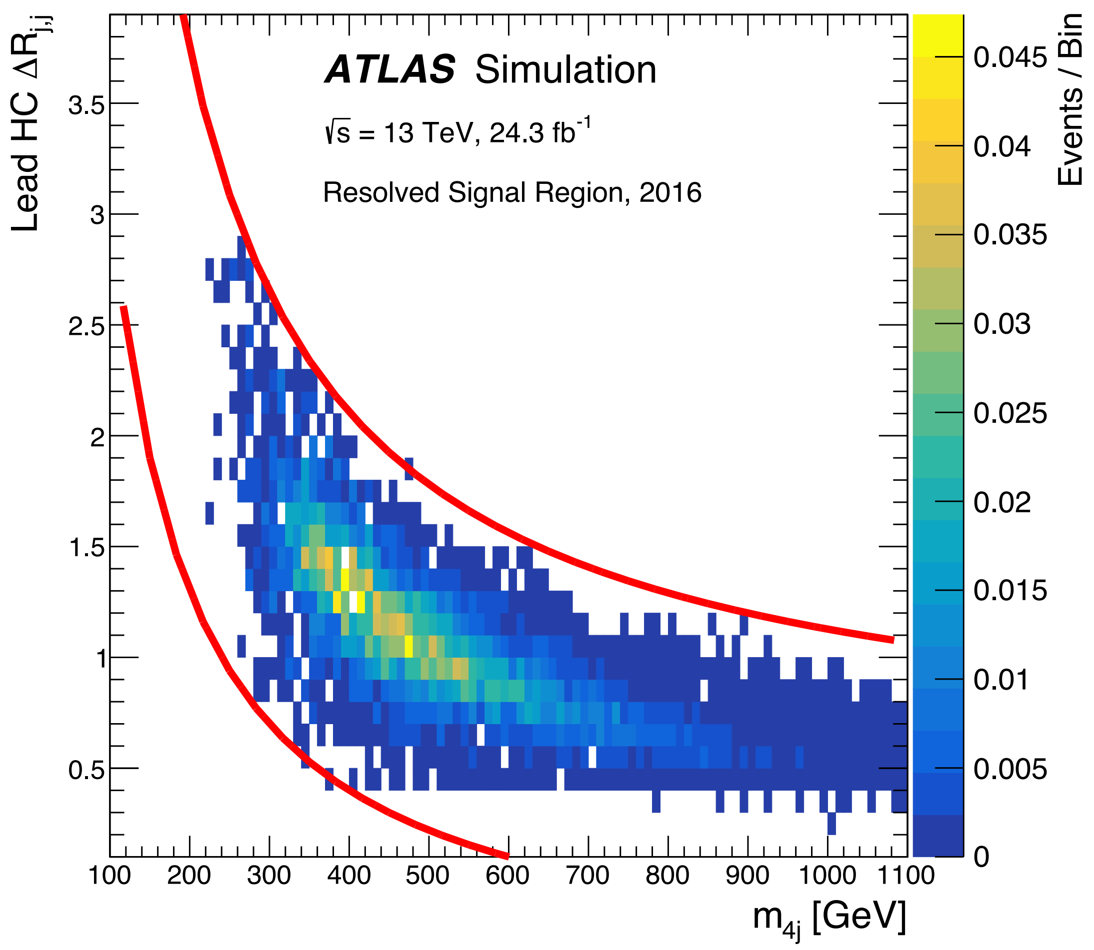
VBF Non resonant / Resonant

Central jets:
- At least 4 central b-tagged jets.

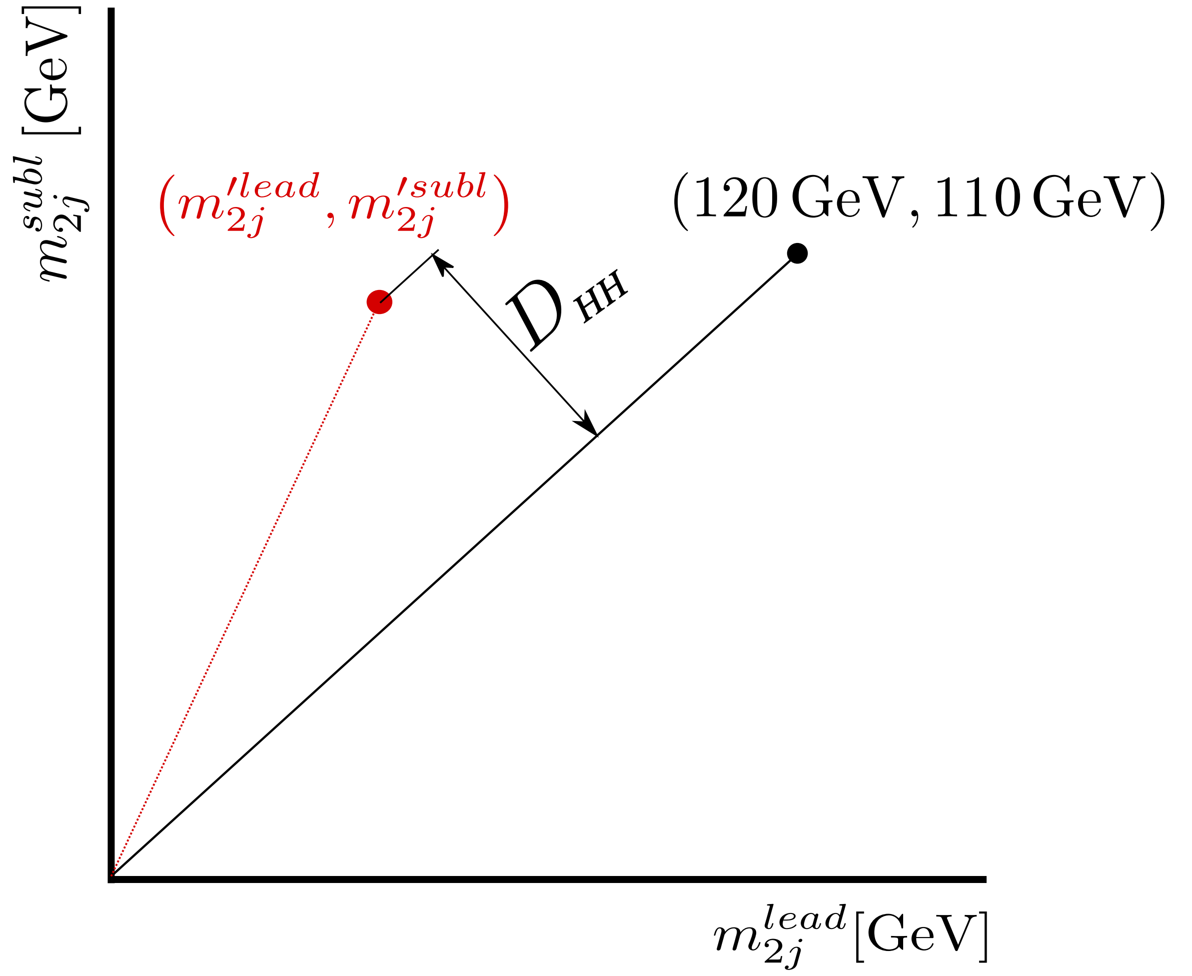
VBF jets:
- At least 2 forward jets with opposite η sign.

Pairing Jets

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



2. 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 ΔR).

How to look for signal?

ggF: $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 01 (2019) 030
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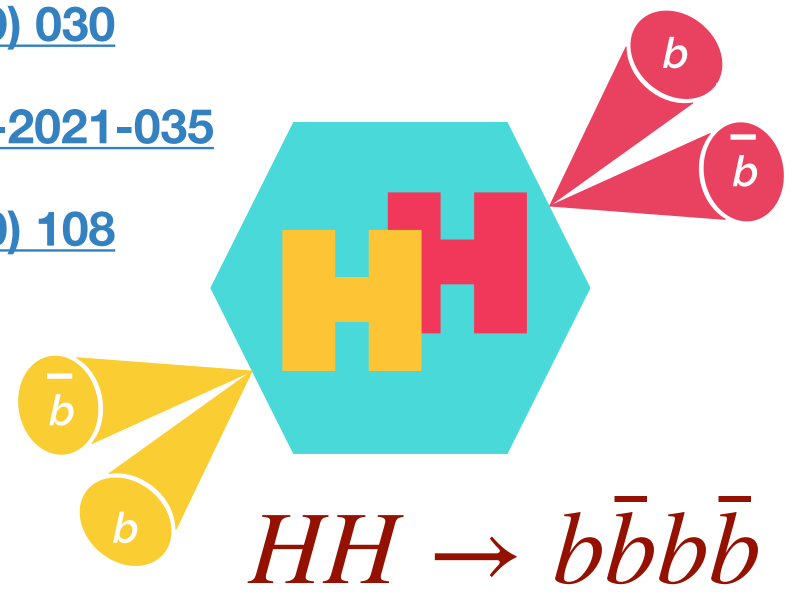


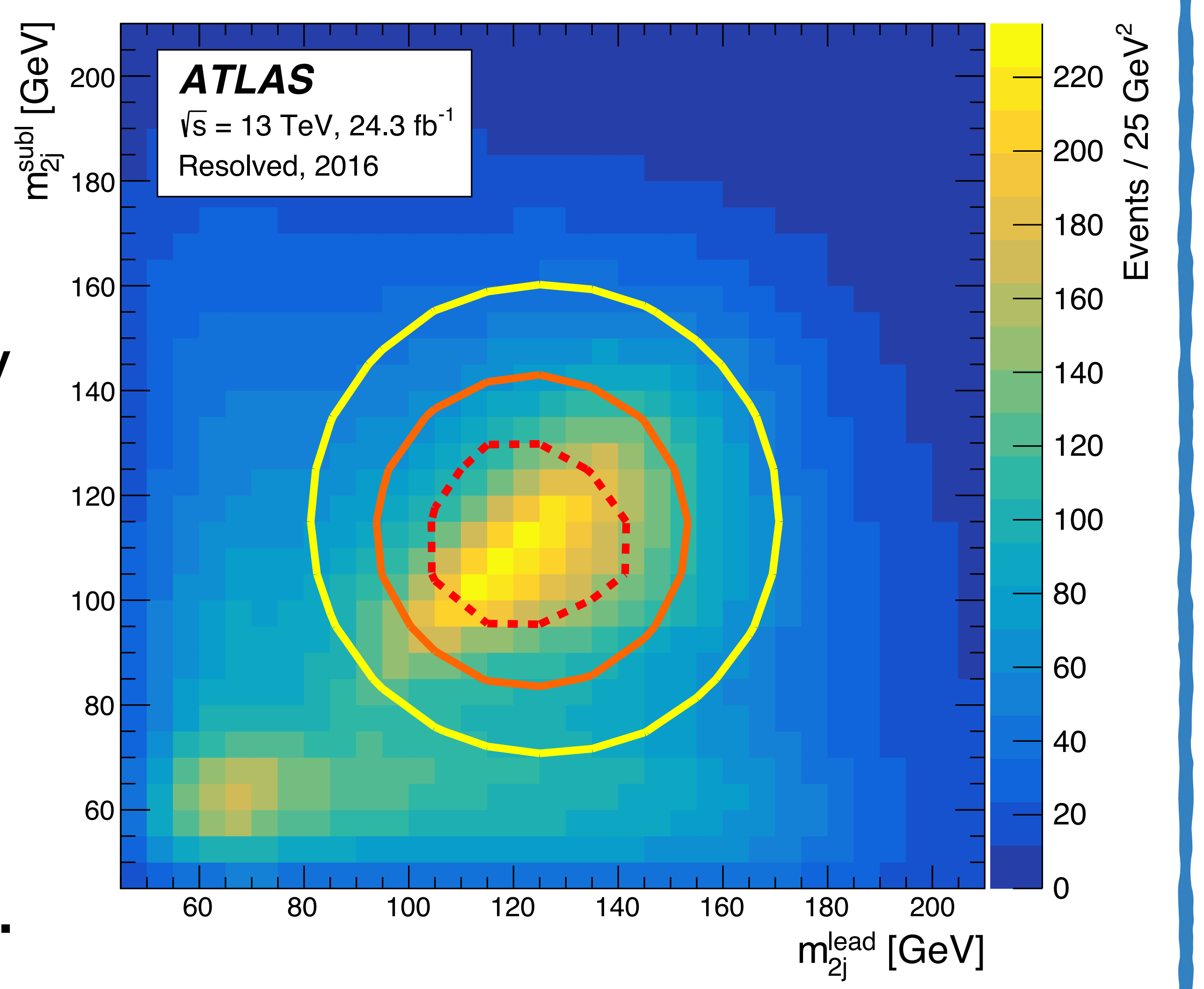
ggF

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.



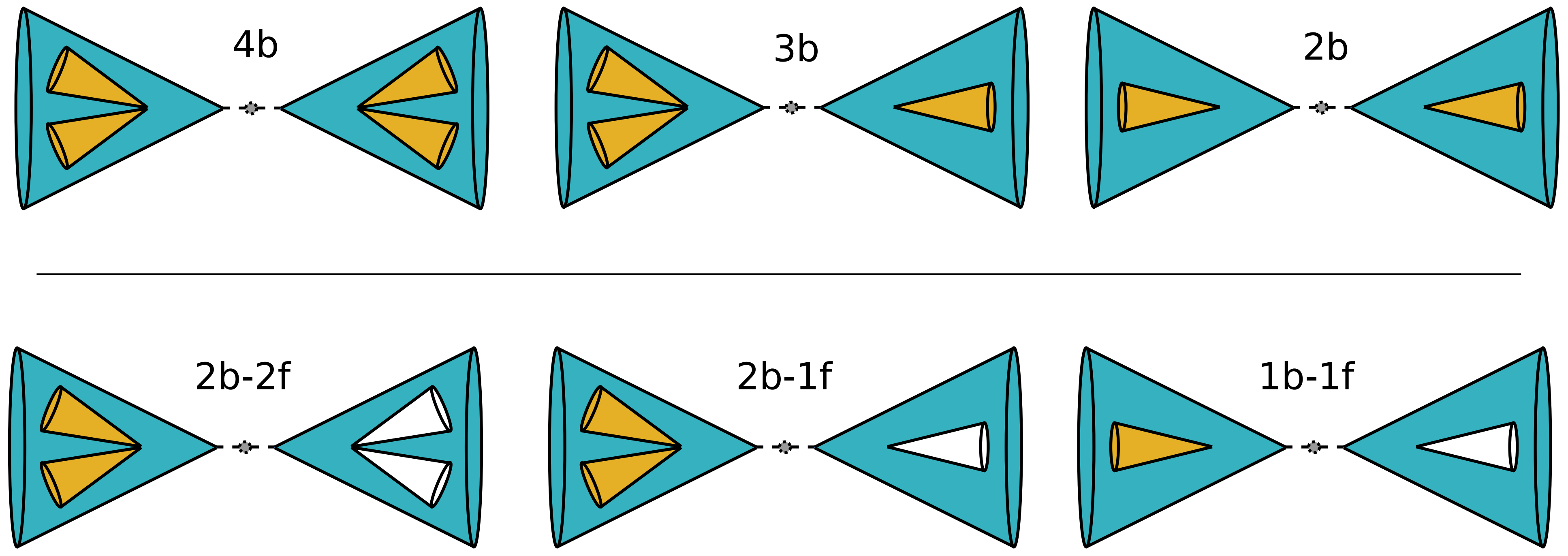
Boosted: **Resonant**

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

Main backgrounds:

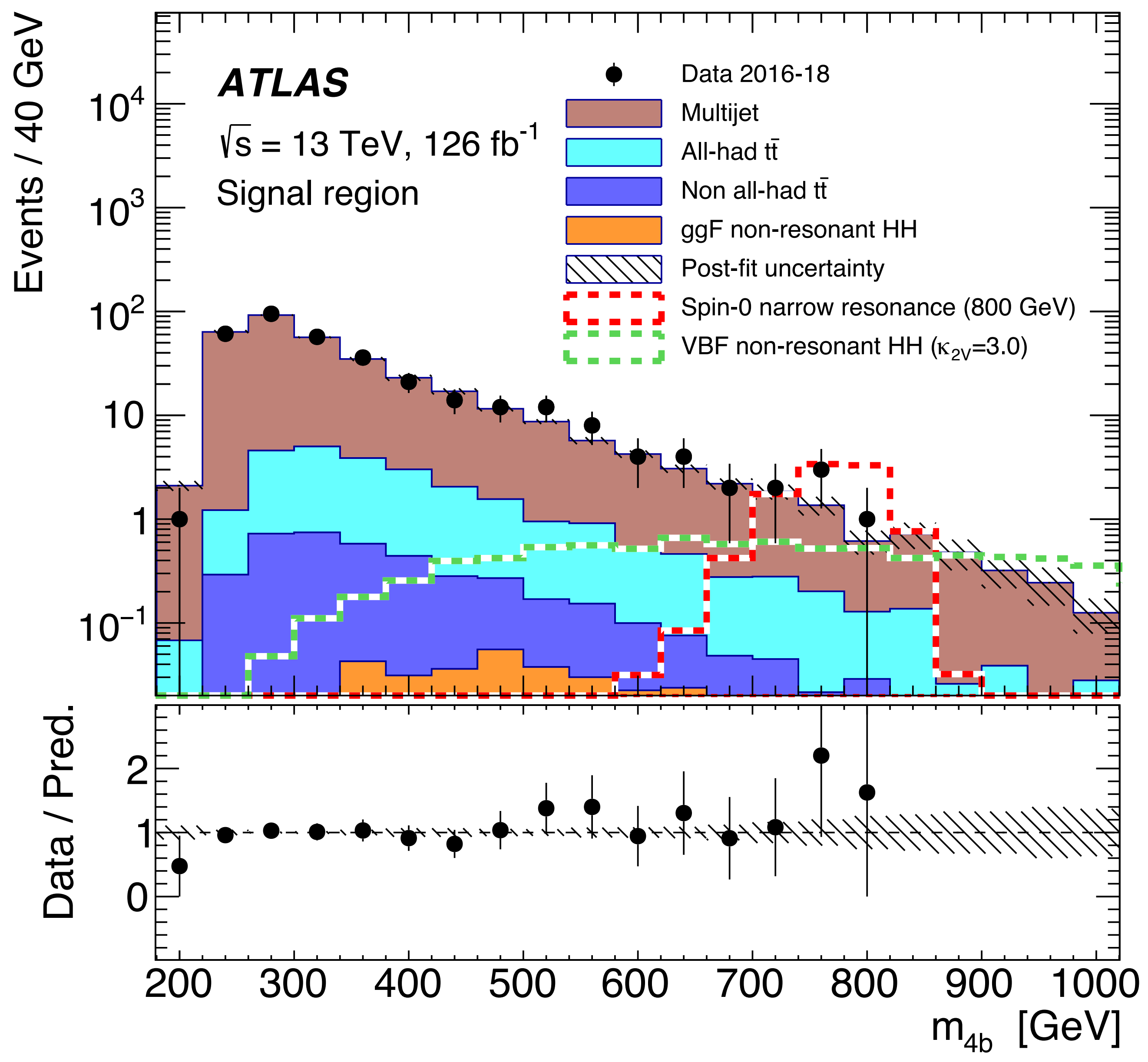
$t\bar{t}$ and multi-jets contribute:

- 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: $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 01 (2019) 030
Resonant ggF: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-035
VBF: $\mathscr{L} = 126\text{fb}^{-1}$ JHEP 07 (2020) 108

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

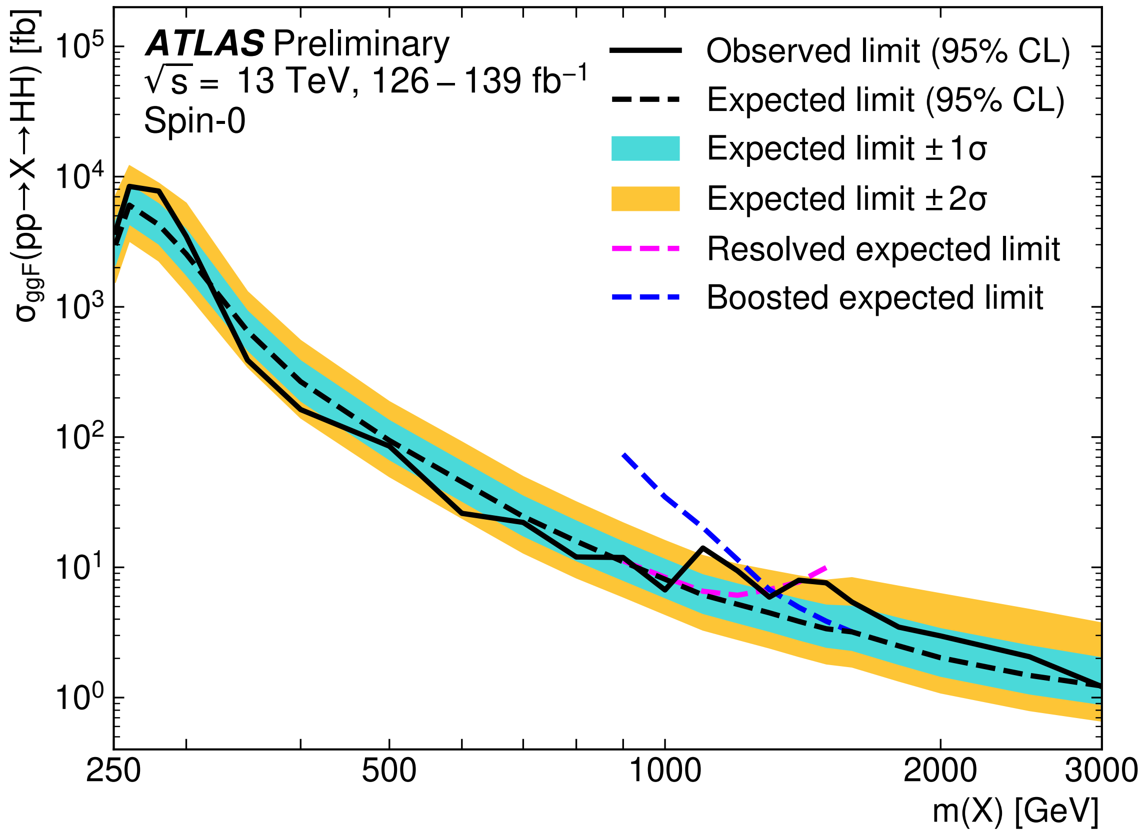
ggF — No significant excess found

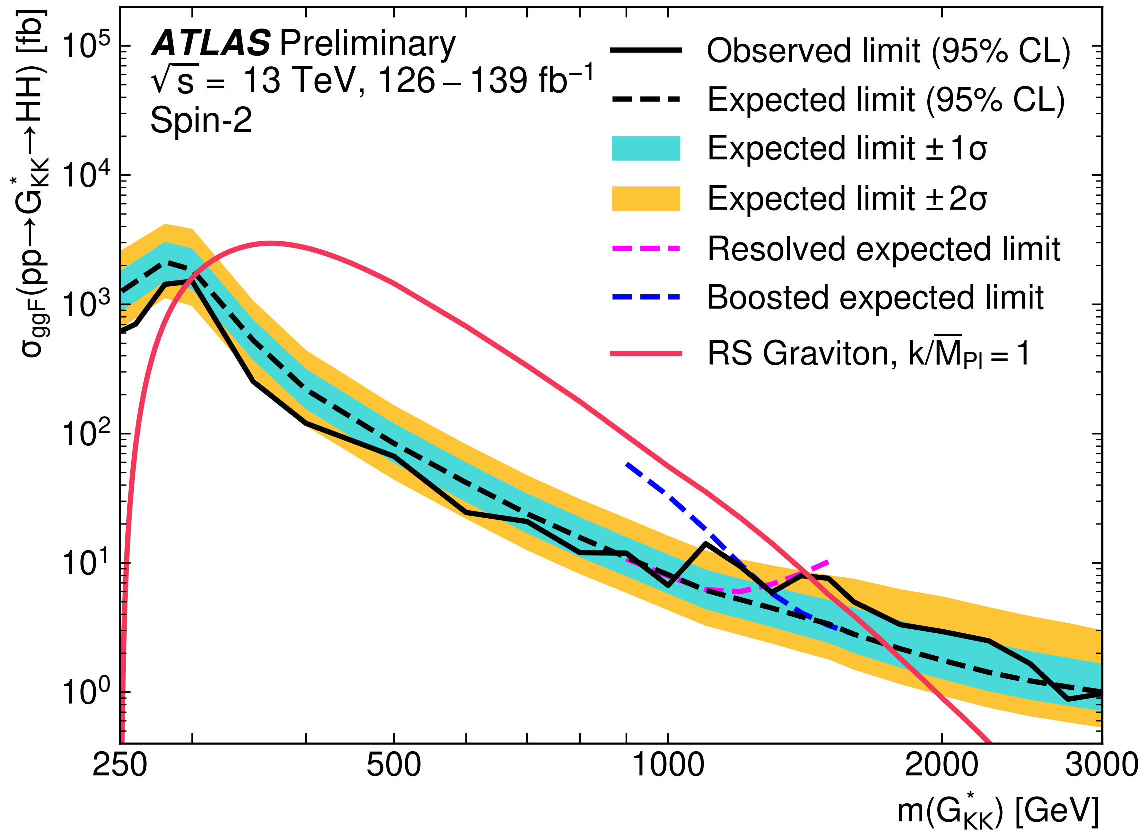
Non-resonant **Resolved**

$\sigma_{HH}^{ggF} \times BR(HH \rightarrow b\bar{b}b\bar{b})$ **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 σ (1.0 σ).



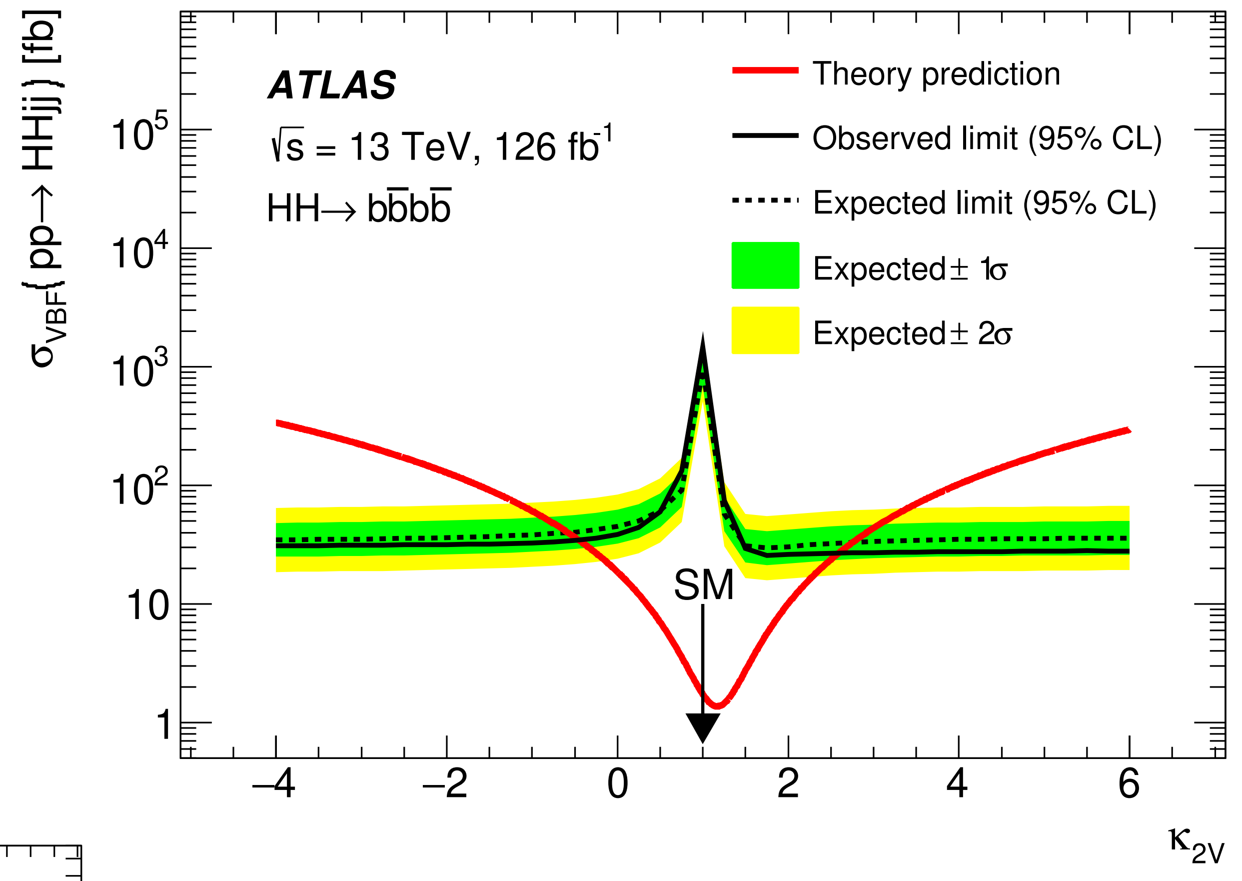


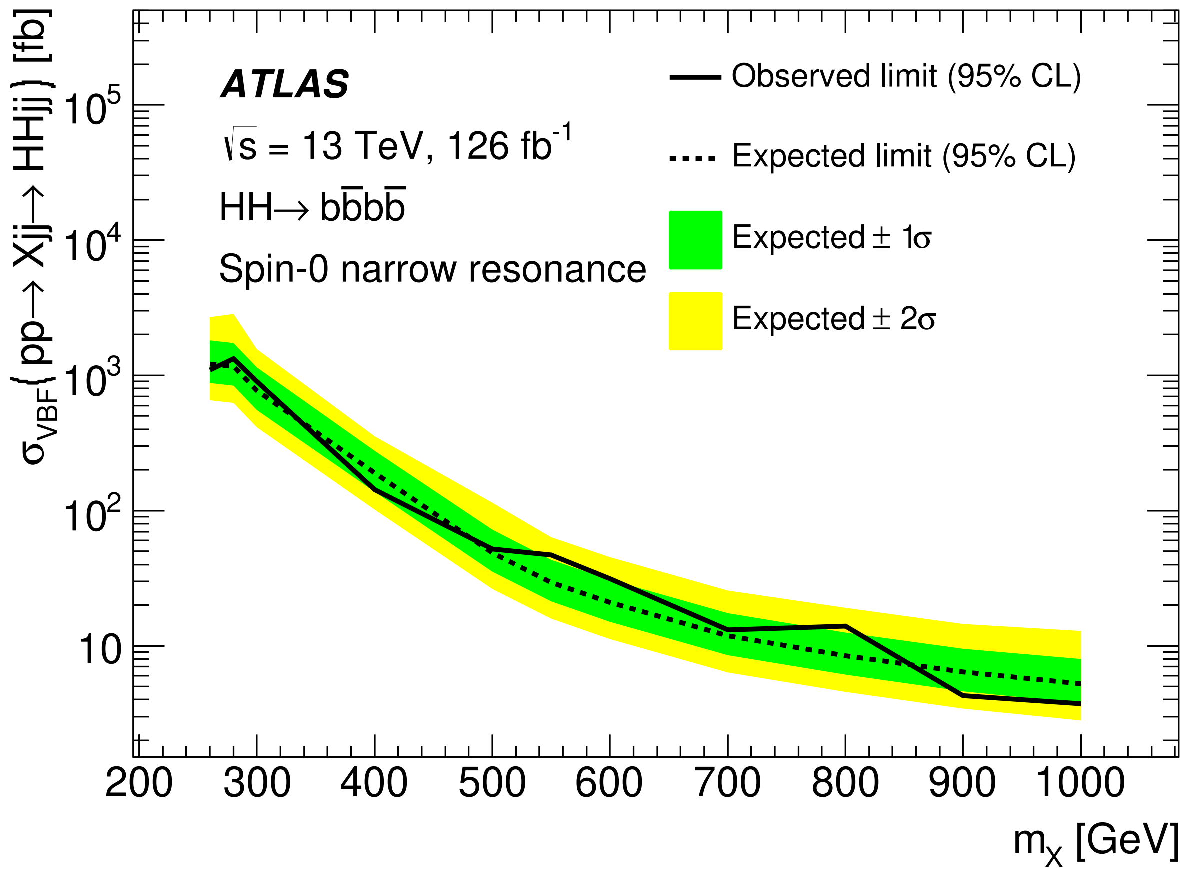
VBF — No significant excess found

Non-resonant

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

Limits are set on κ_{2V}:
$-0.4 < \kappa_{2V} < 2.6$ (observed),
$-0.6 < \kappa_{2V} < 2.7$ (expected).





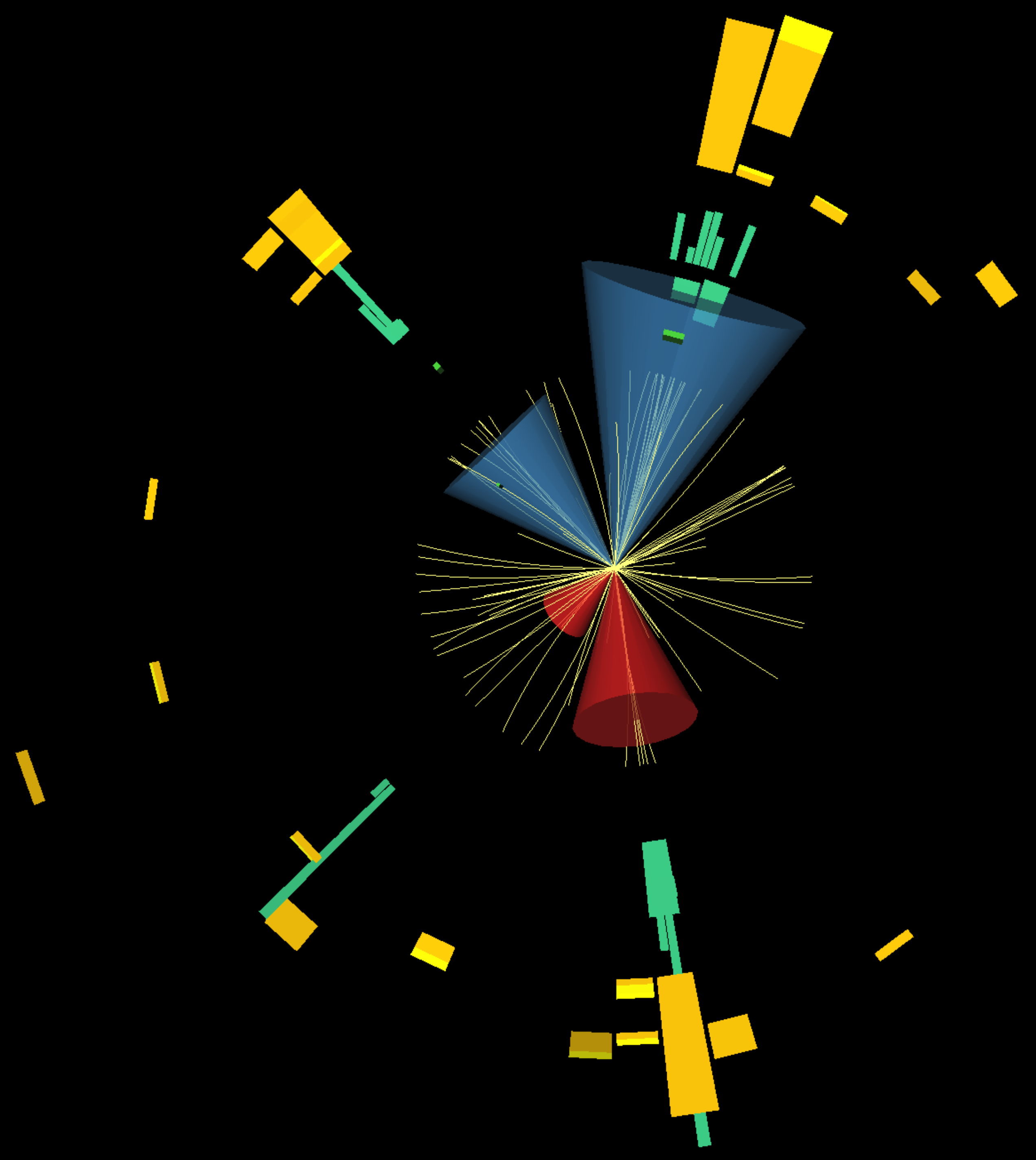
Resonant

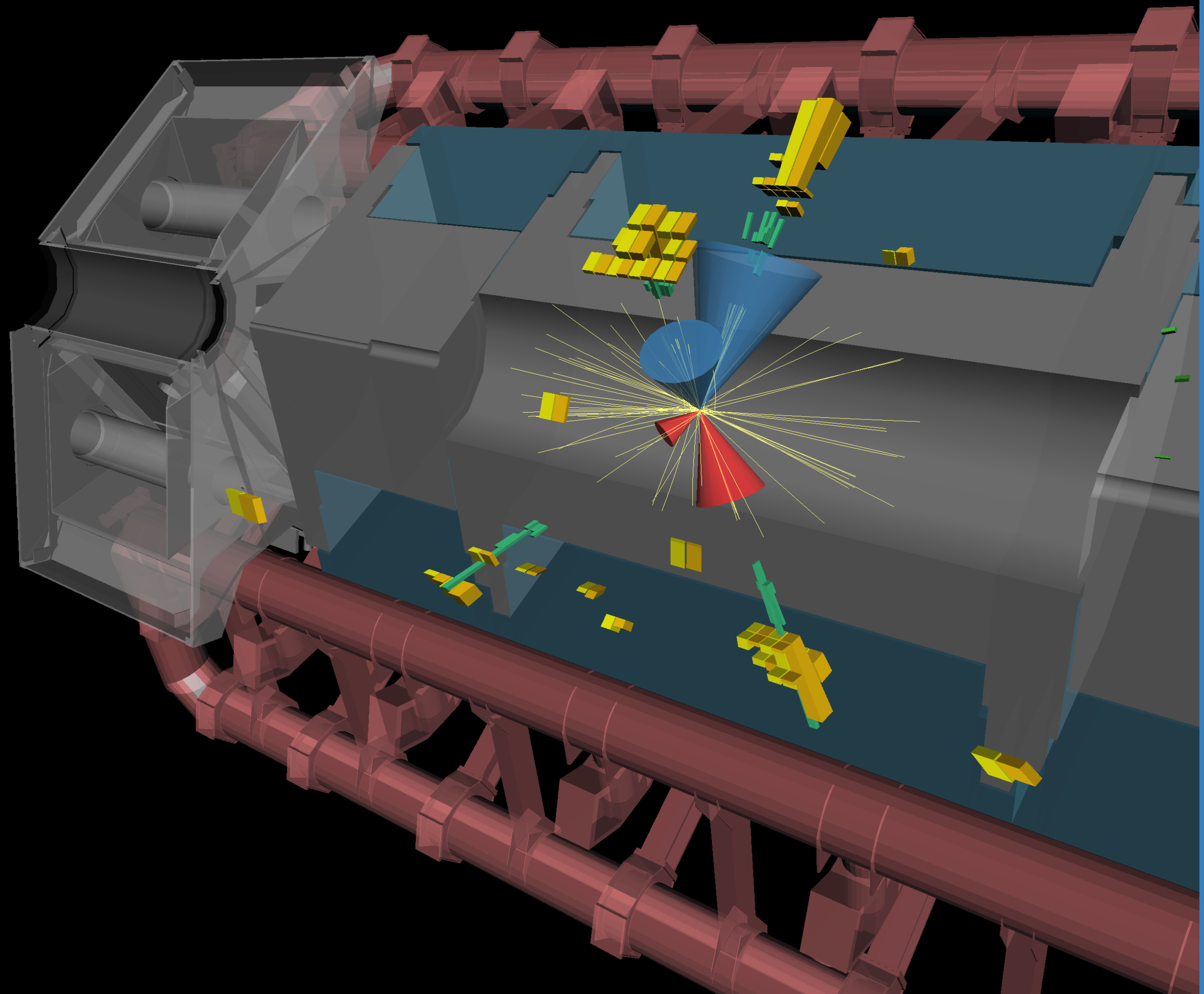
Limits set on $\sigma_{VBF}(X \rightarrow HH)$ where X is either a narrow- or broad-width scalar resonance

ATLAS
EXPERIMENT

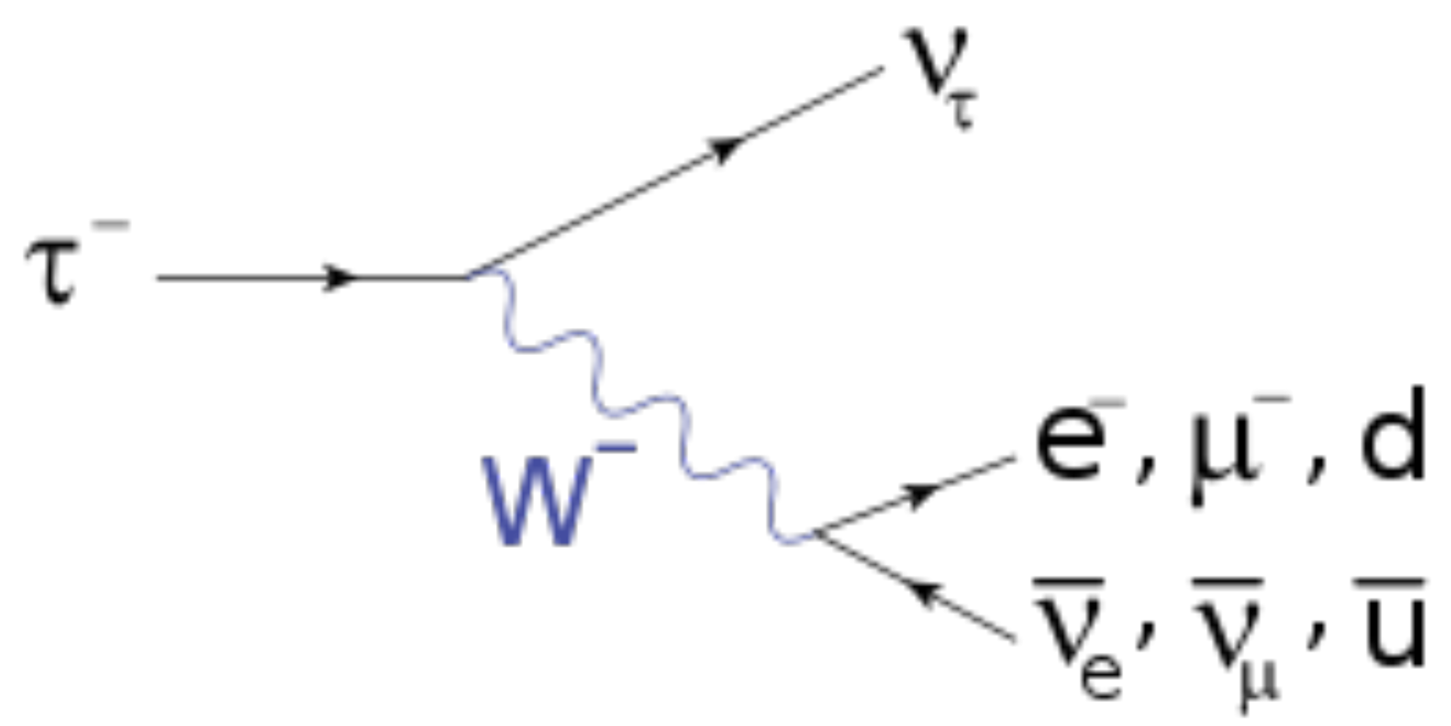
$HH \to b\bar{b}\tau^+\tau^-$

Run: 339535
Event: 996385095
2017-10-31 00:02:20 CEST



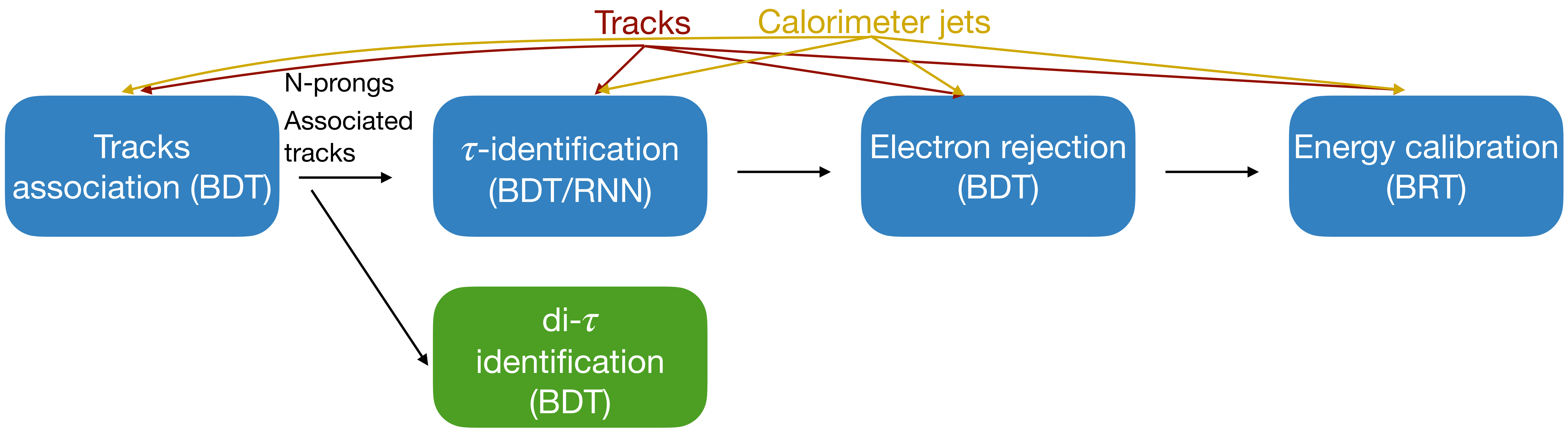


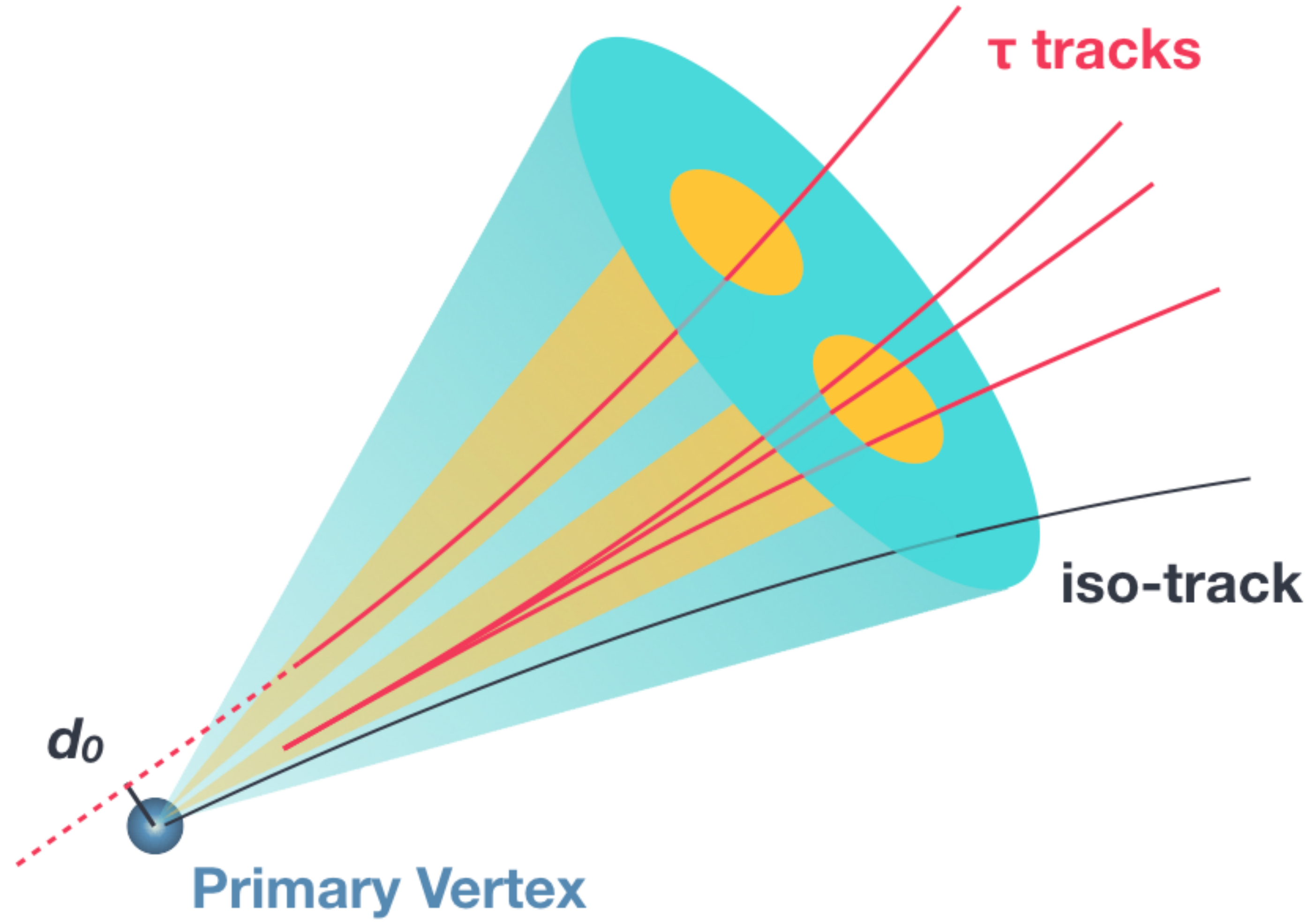
How to reconstruct tau leptons ?



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

- Small lifetime (~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.



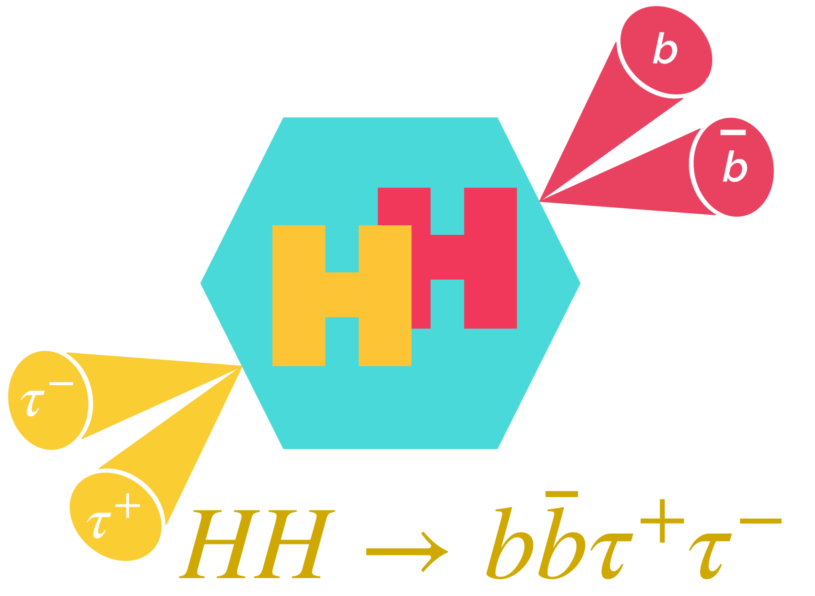


In **boosted topologies**, the reconstructed jets are closer to each other. A dedicated BDT is therefore trained to account for **smaller radius jets** and the **specific topologies**. No additional energy correction was found to be needed in these cases.

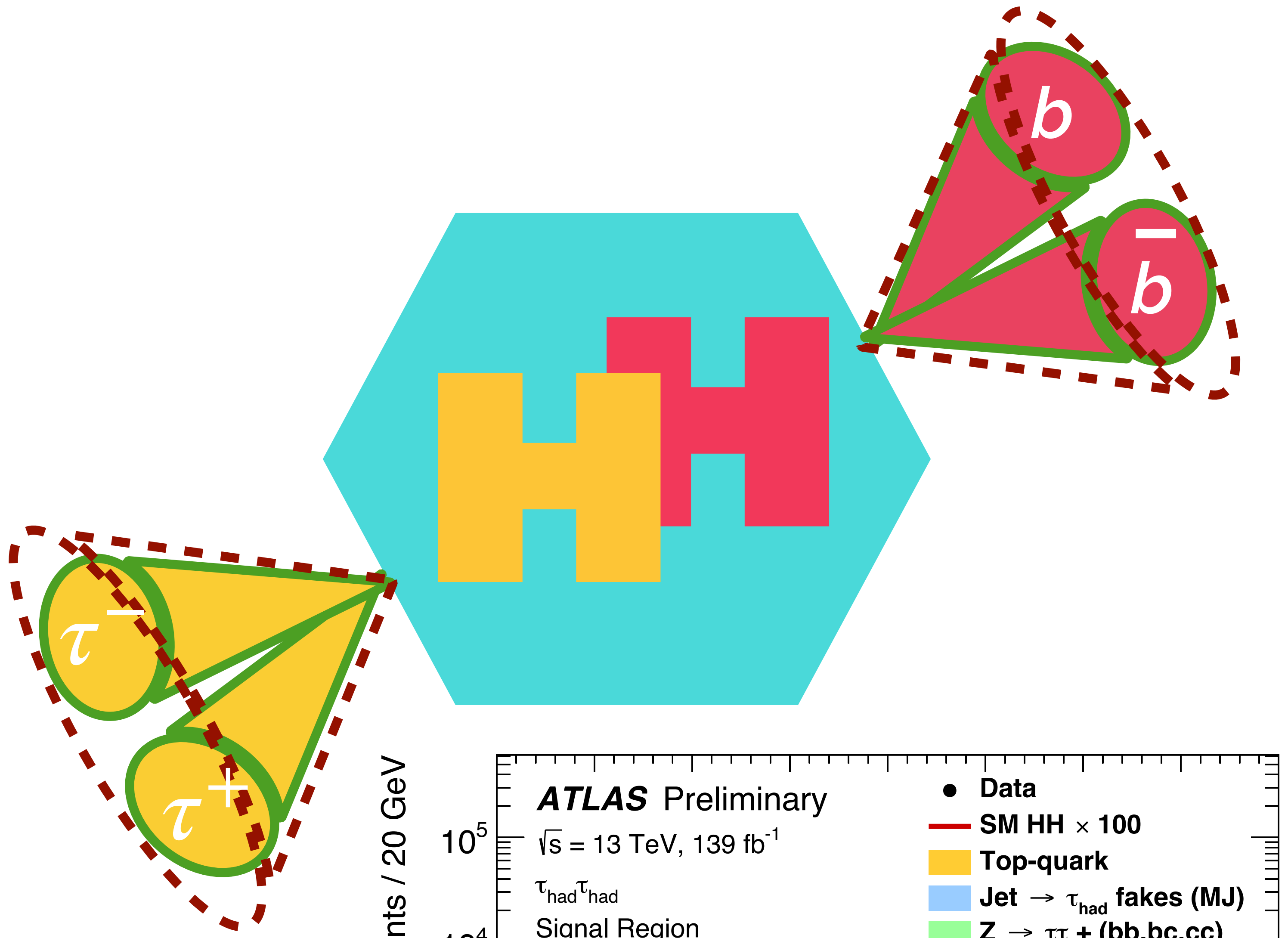
Strategy

Resolved: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-030

Boosted: $\mathscr{L} = 139\text{fb}^{-1}$ JHEP 11 (2020) 163



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



Resolved:

Exactly 2 b-jets

Boosted:

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

Resolved:

At least one hadronic tau is requested:

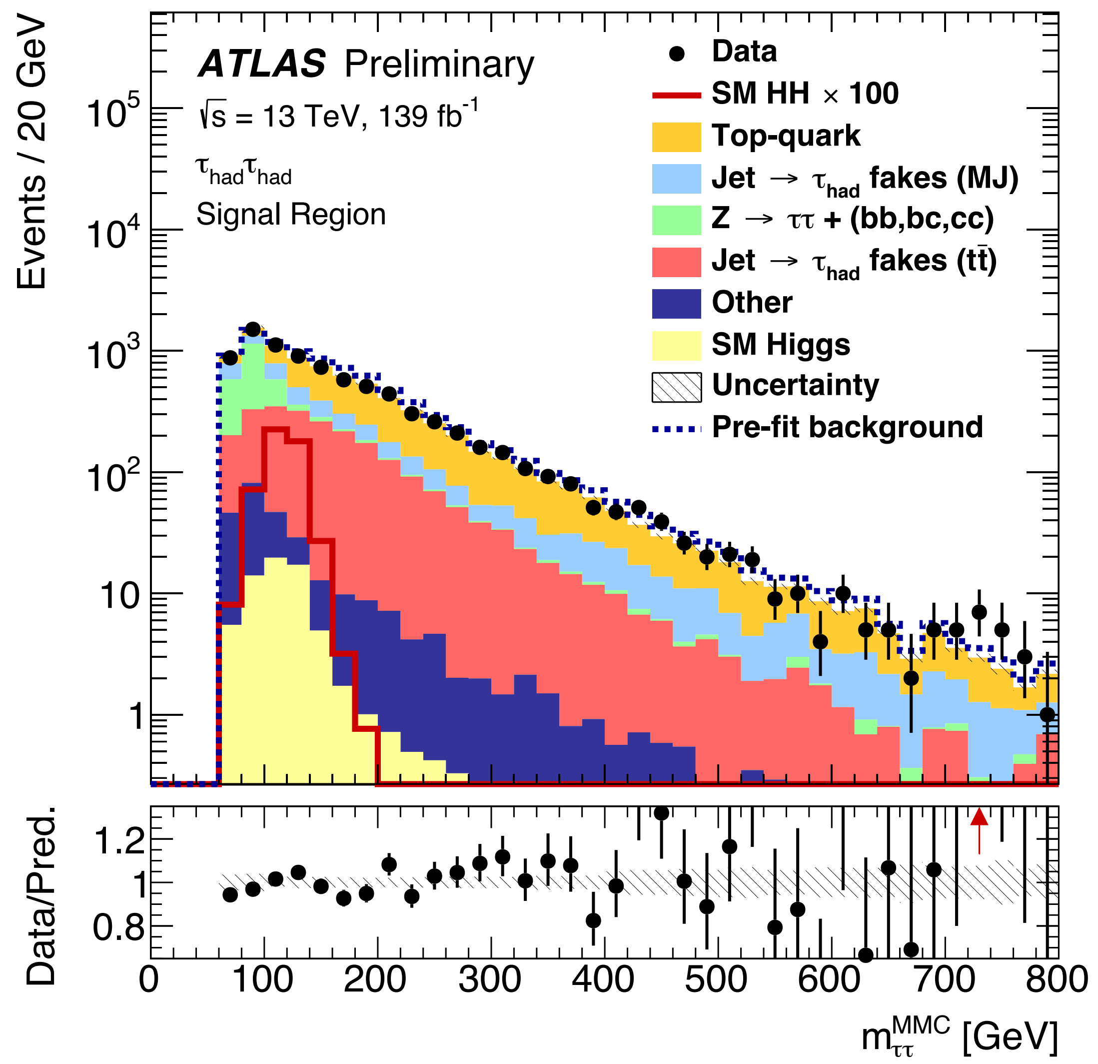
- $\tau_{\text{lep}}\tau_{\text{had}}$: exactly 1 lepton + 1 hadronic τ;
- $\tau_{\text{had}}\tau_{\text{had}}$: exactly two hadronic τs.

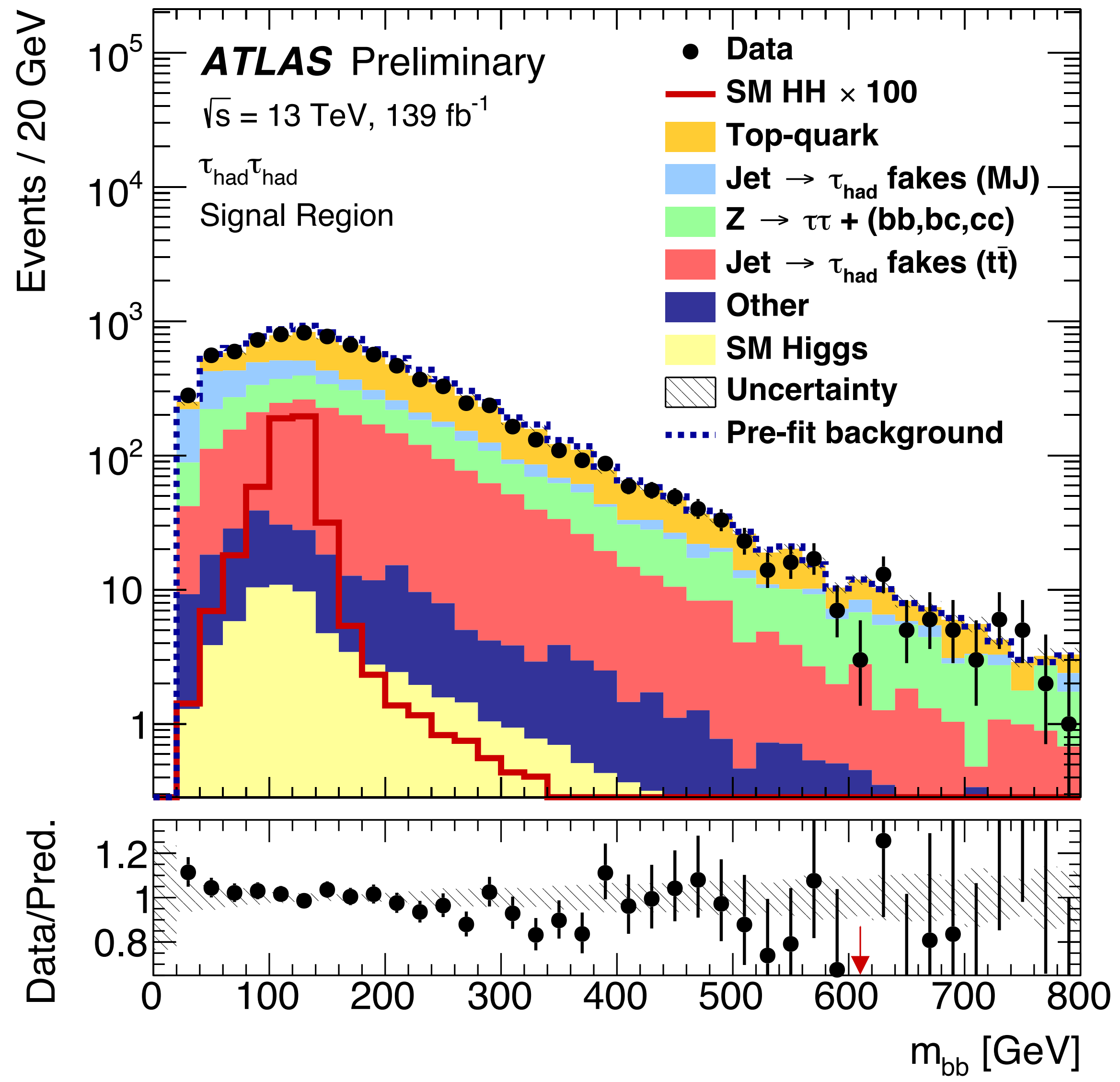
As the mass of the system is not well defined, the Missing Mass Calculator is used to get a better estimate.

Boosted:

Only hadronic taus are considered inside one large angular jet :

- $\leq$ 3 sub-jets, sum of track charge ± 1 in each sub-τ.





How to look for signal?

Resolved: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-030
Boosted: $\mathscr{L} = 139\text{fb}^{-1}$ JHEP 11 (2020) 163

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

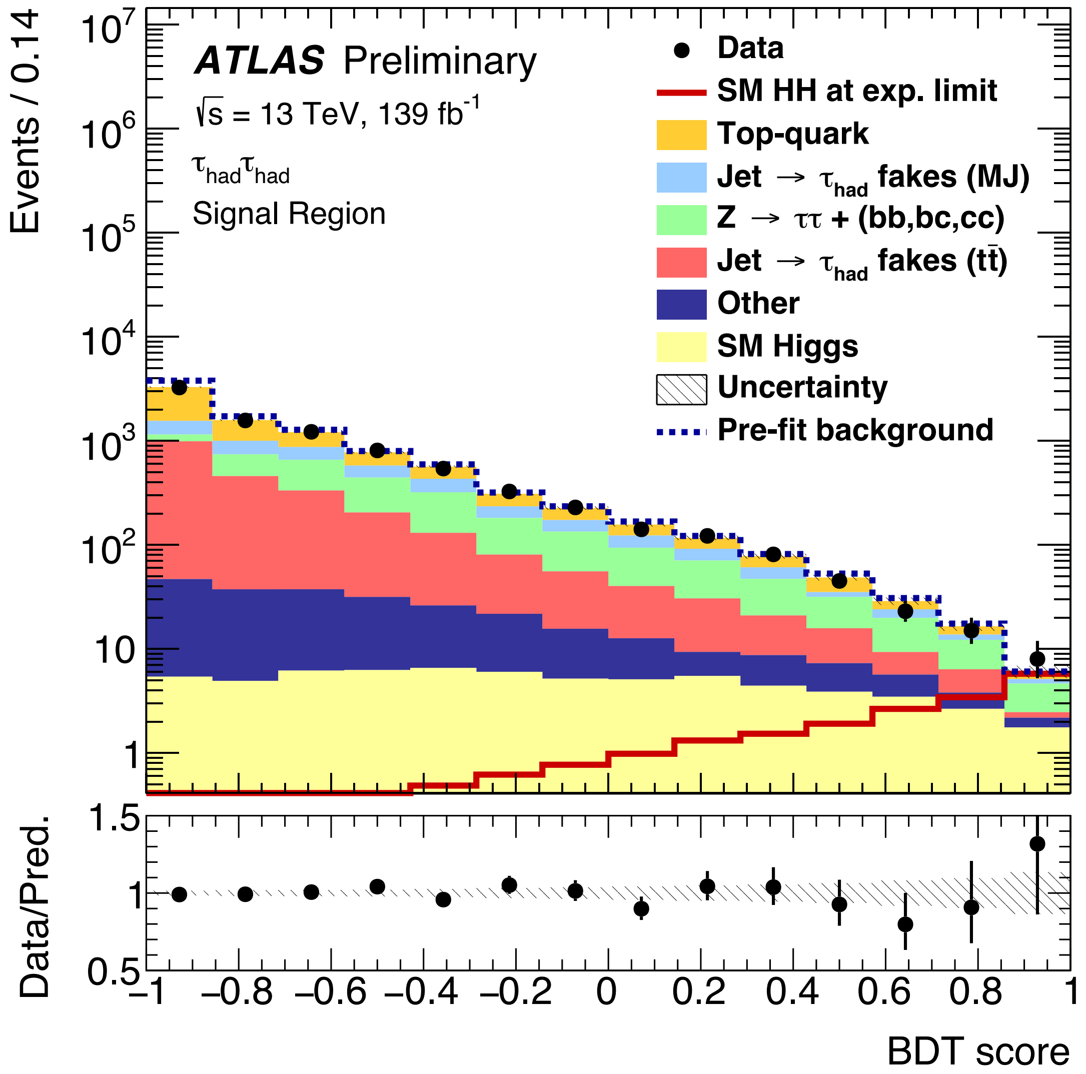
Resolved:

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.

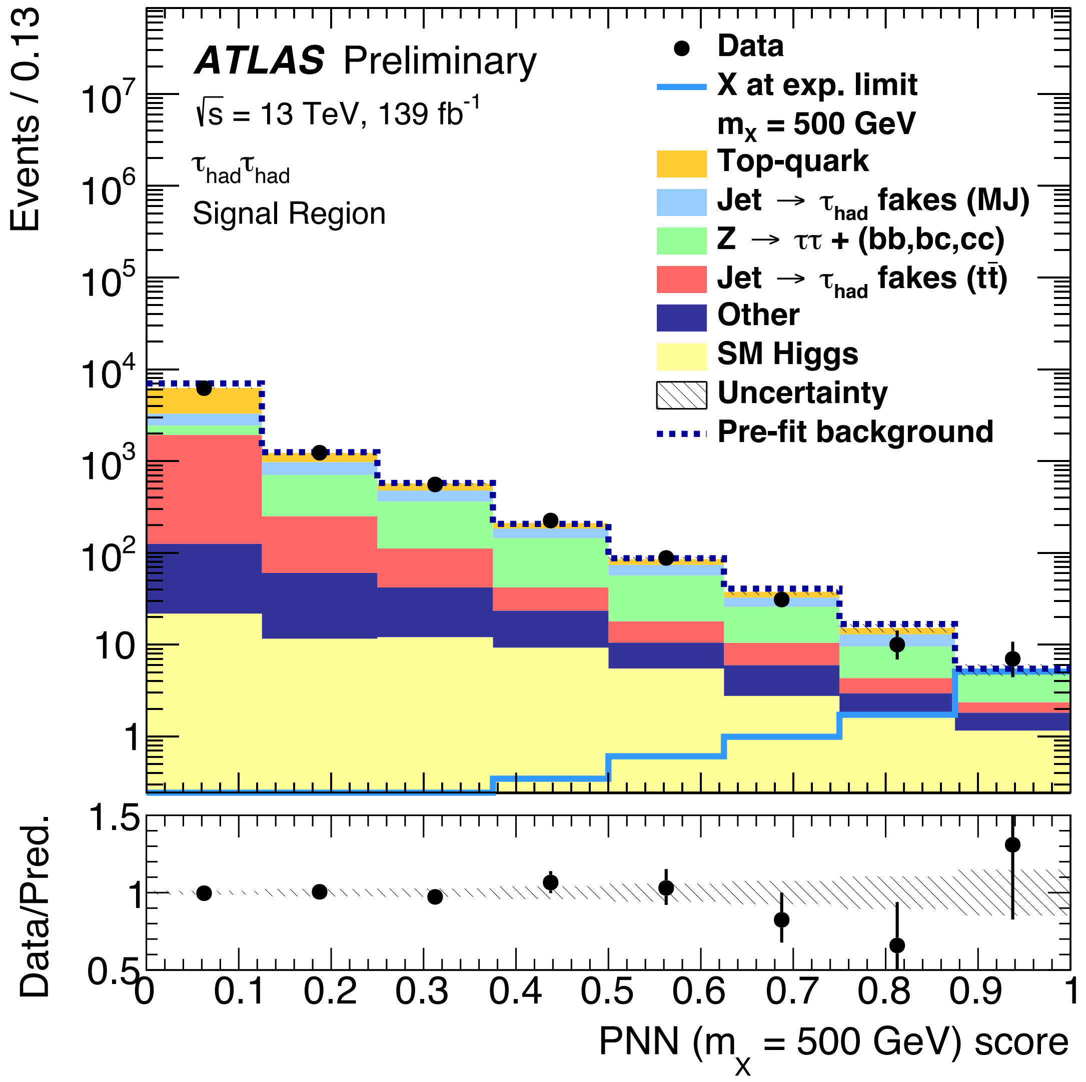
Non-resonant

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



Resonant

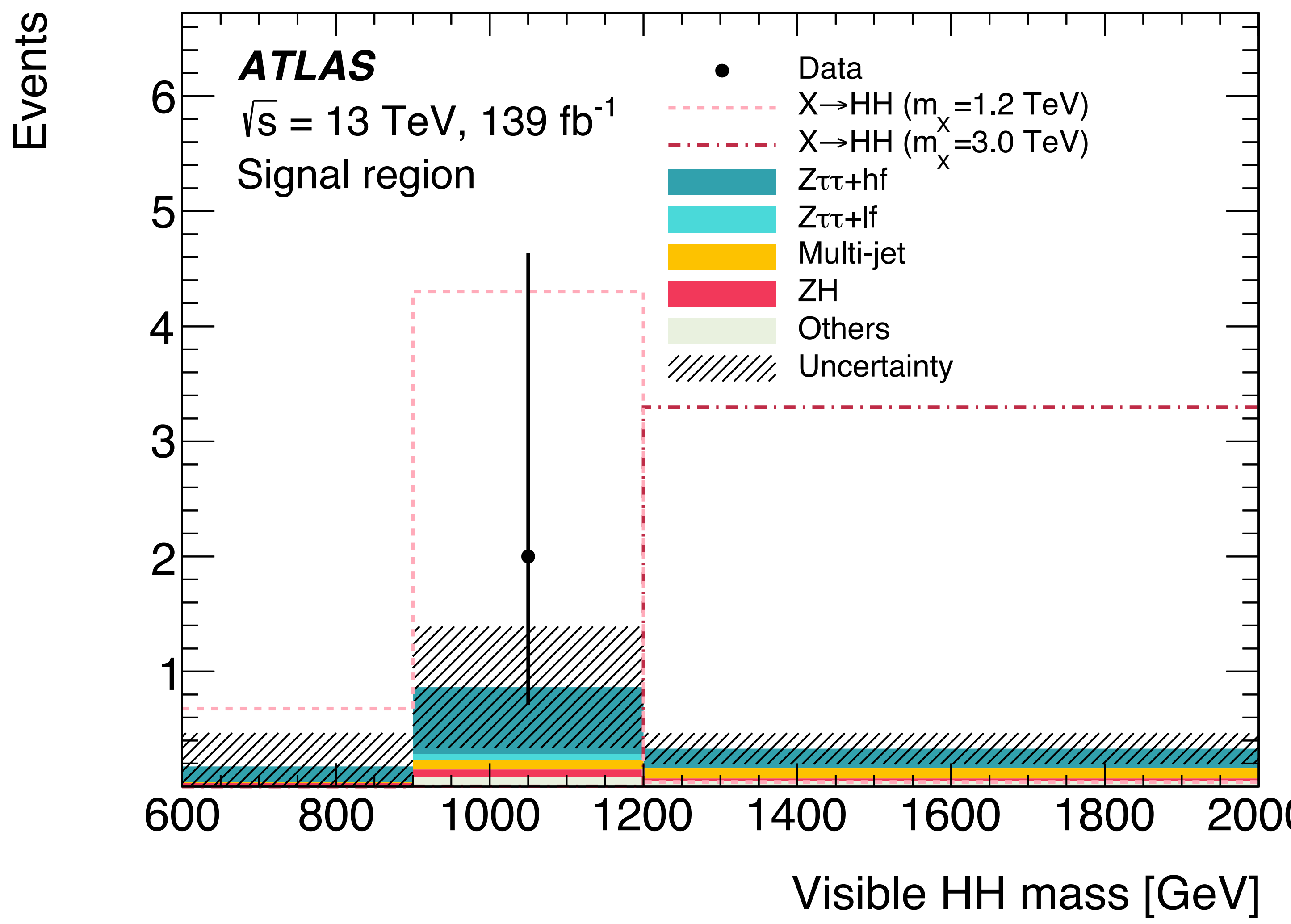
Parametrised NN to ease the interpolation between mass points



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

Boosted:

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



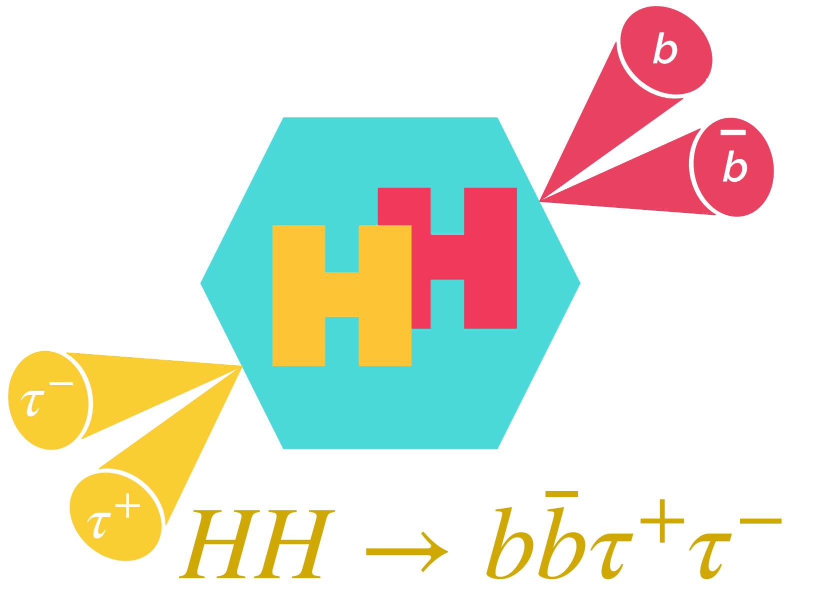
Selections based on:

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

dedicated Control Regions for:
$Z \to \tau\tau$ + jets, multi-jets (evaluated from data-driven ABCD method)

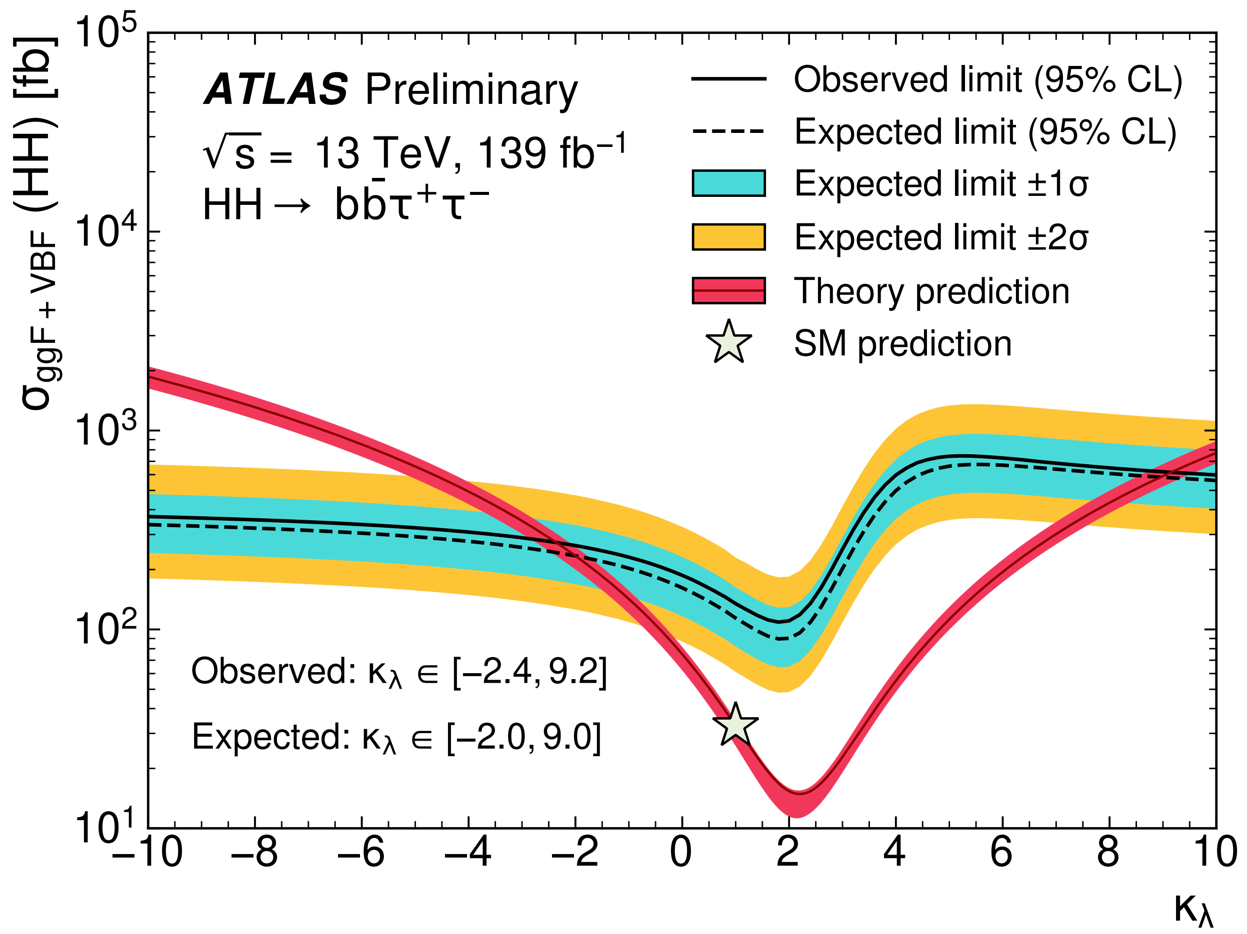
Results

Resolved: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-030
Boosted: $\mathscr{L} = 139\text{fb}^{-1}$ JHEP 11 (2020) 163



Resolved:

Non-resonant No significant excess found

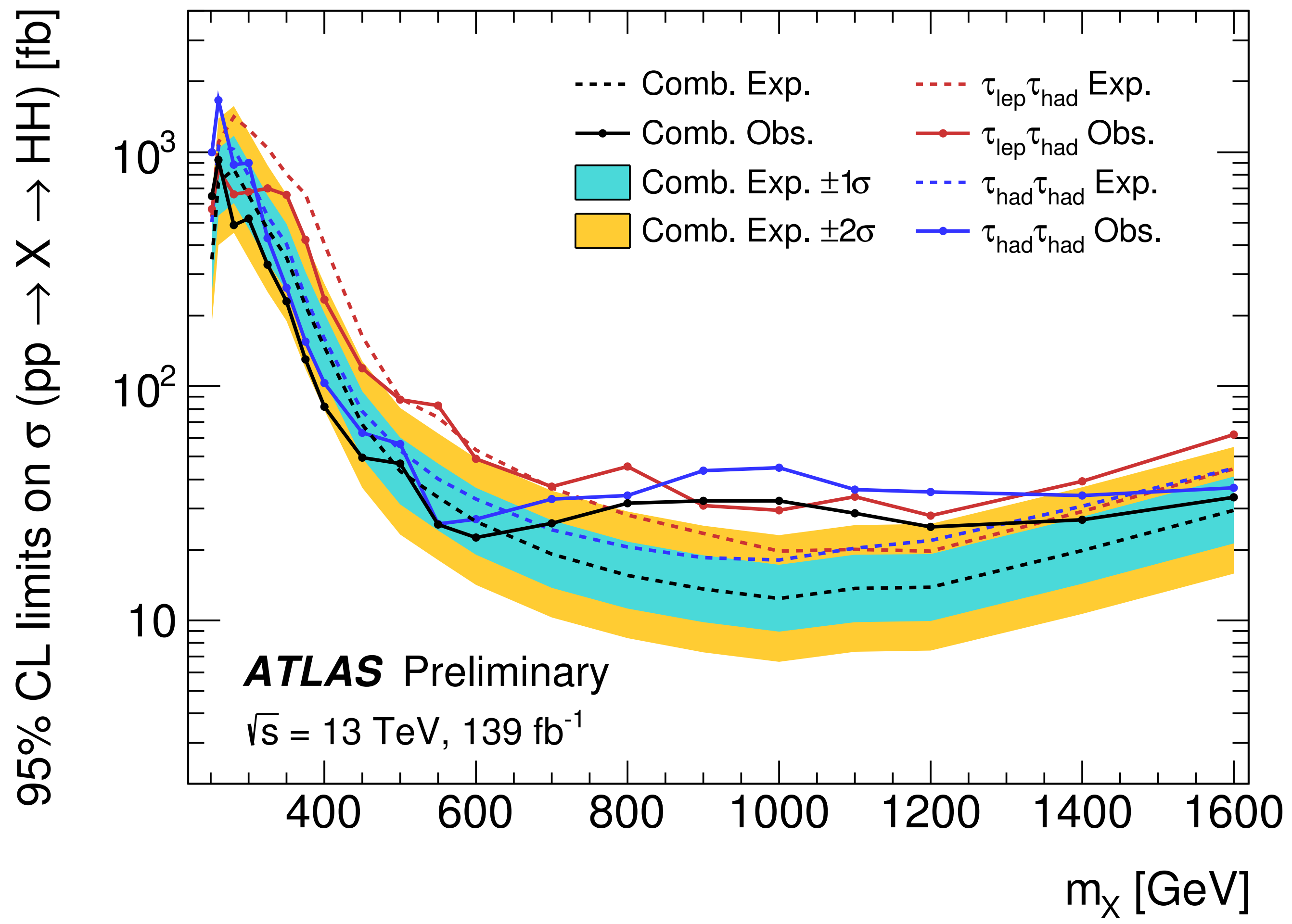


$\sigma_{HH}^{ggF+VBF}$ **observed (expected)** limit is **4.7 (3.9)** times the SM prediction.

- Limits are set on κ_λ:
  - $-2.4 < \kappa_\lambda < 9.2$ observed
  - $-2.0 < \kappa_\lambda < 9.0$ expected.

Resonant

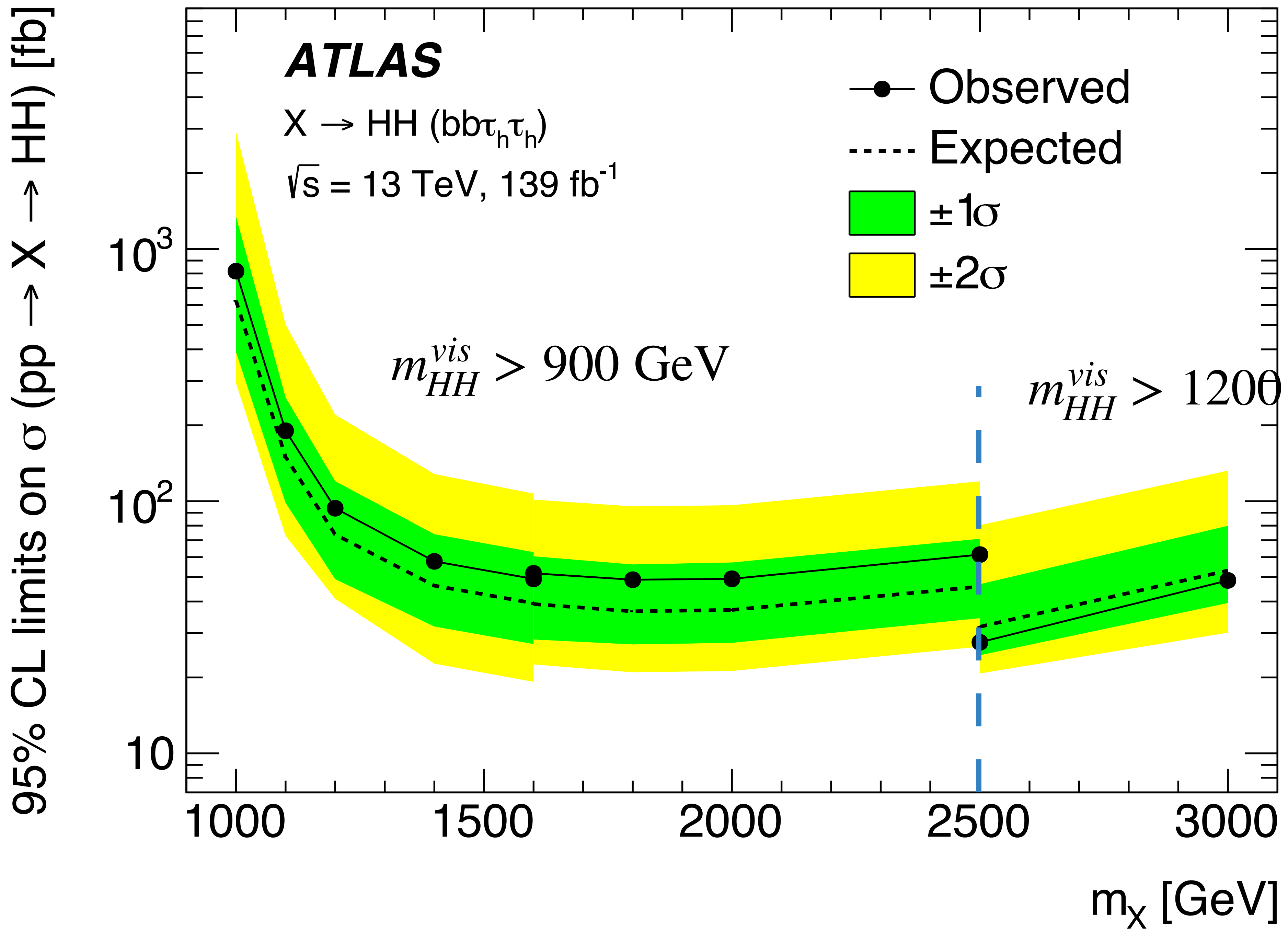
Highest deviation form the SM prediction seen at 1 TeV with a local (global) significance of 3.0σ (2.0)σ.



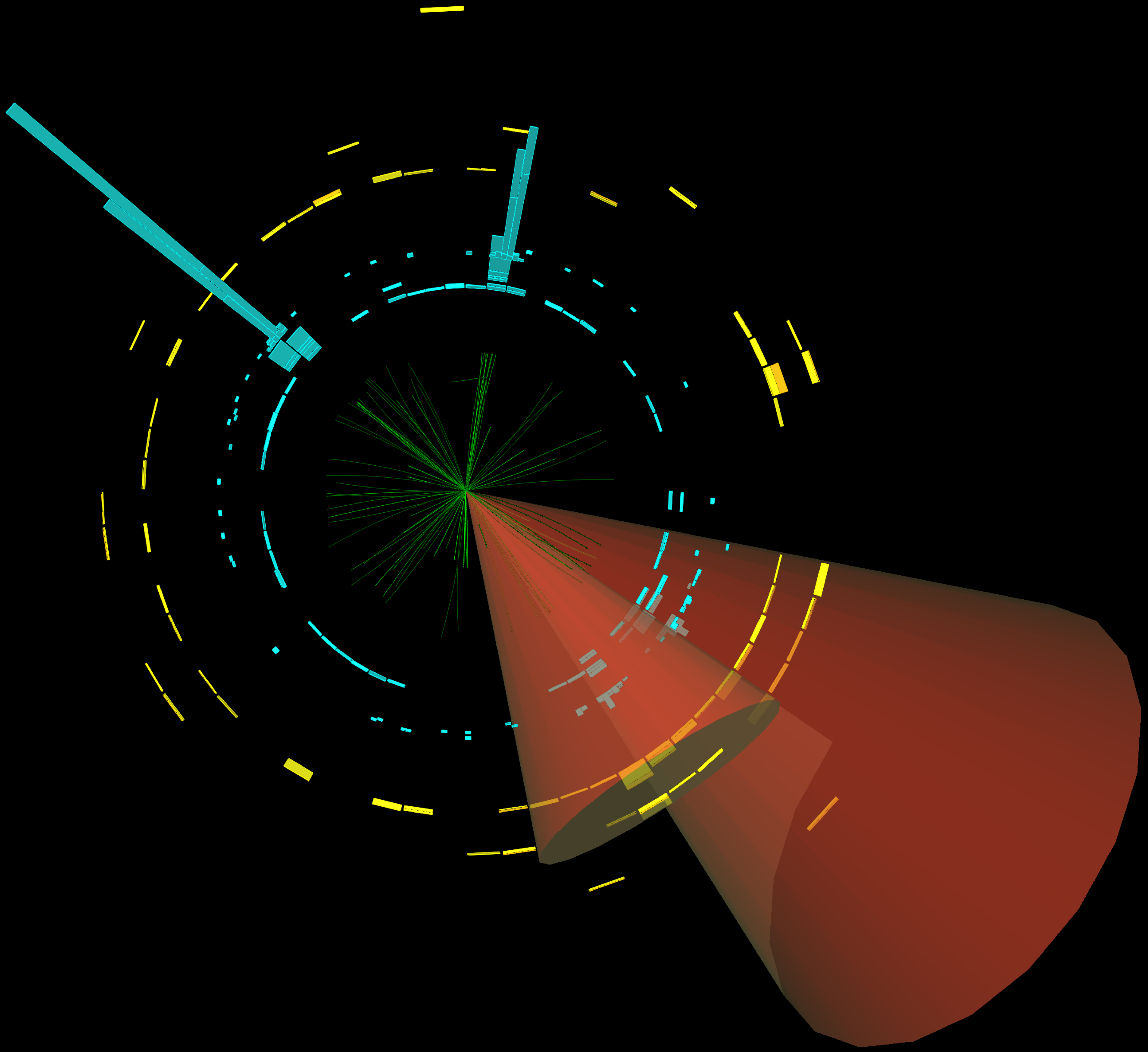
Boosted: No significant excess found

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

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



ATLAS EXPERIMENT

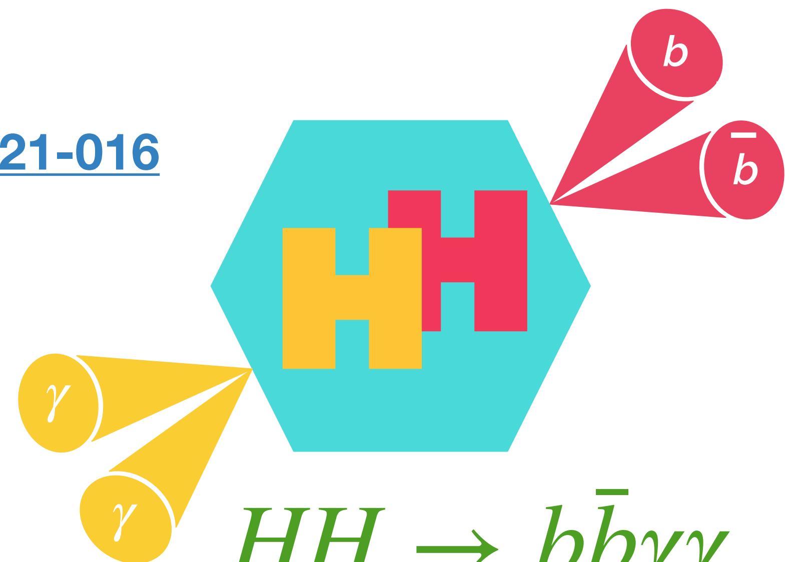


Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST

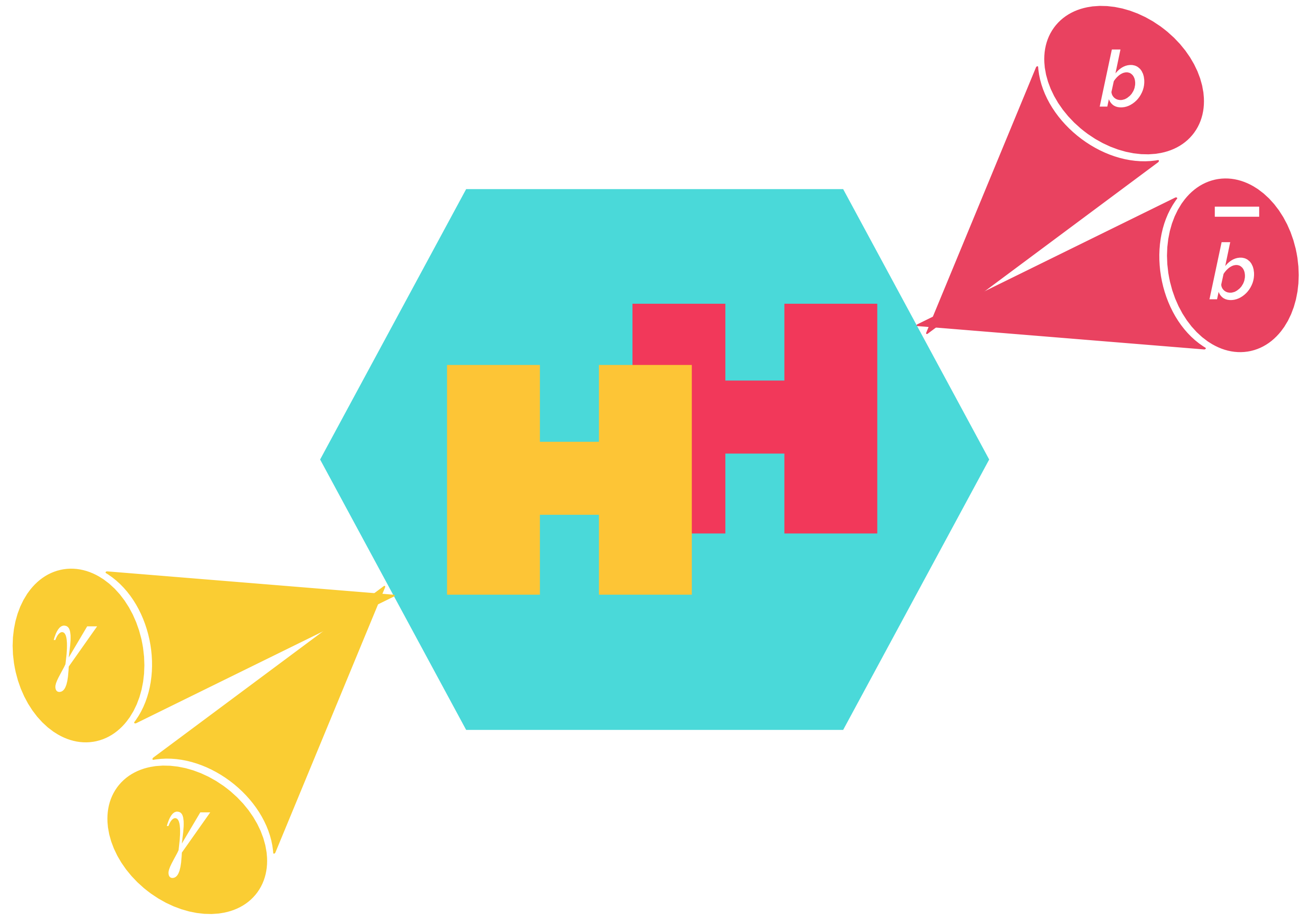
$HH \to b\bar{b}\gamma\gamma$

Strategy

ggF: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-016

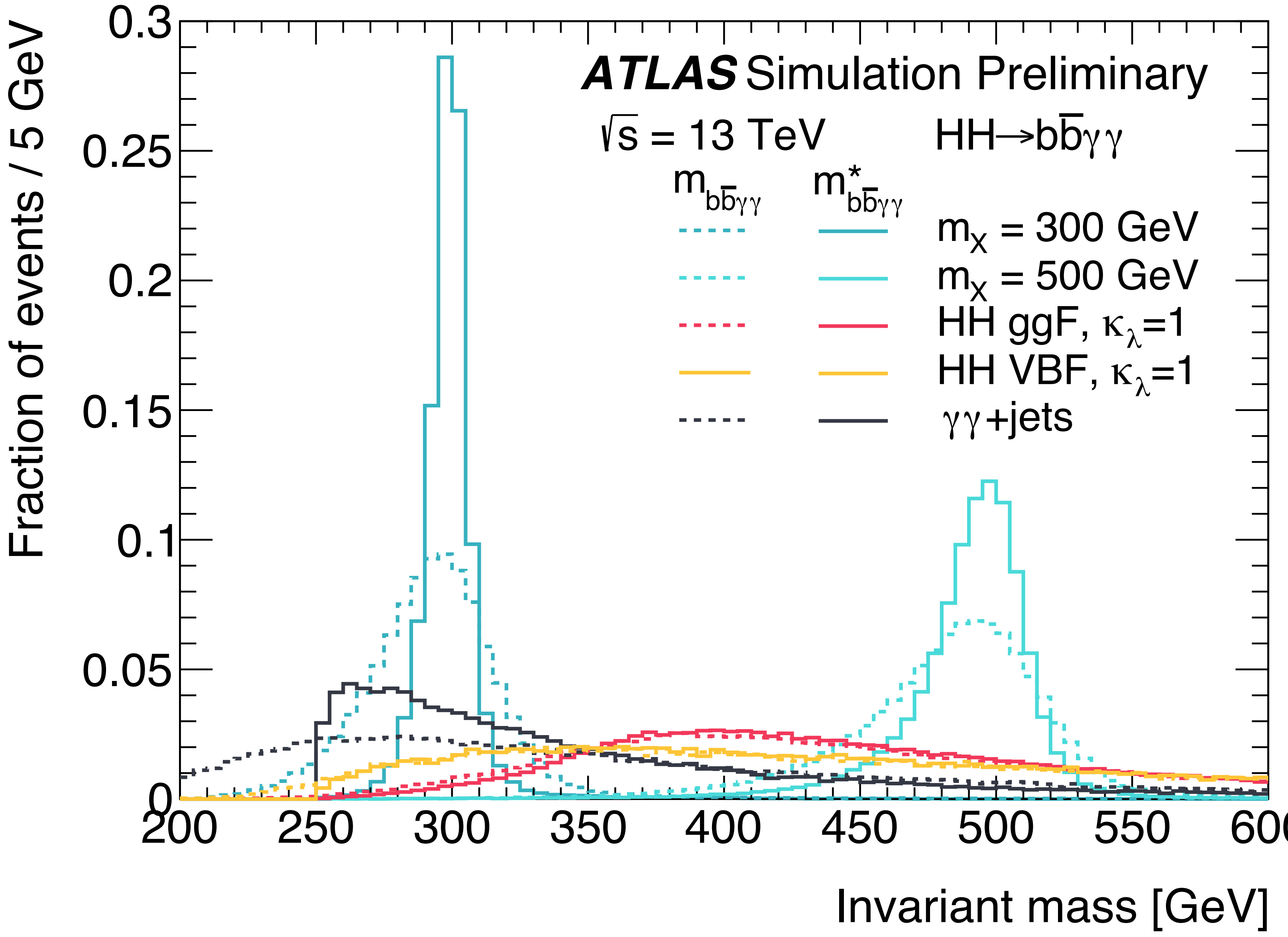


$HH \to b\bar{b}\gamma\gamma$



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

- Exactly 2 High quality photons;
- No lepton.

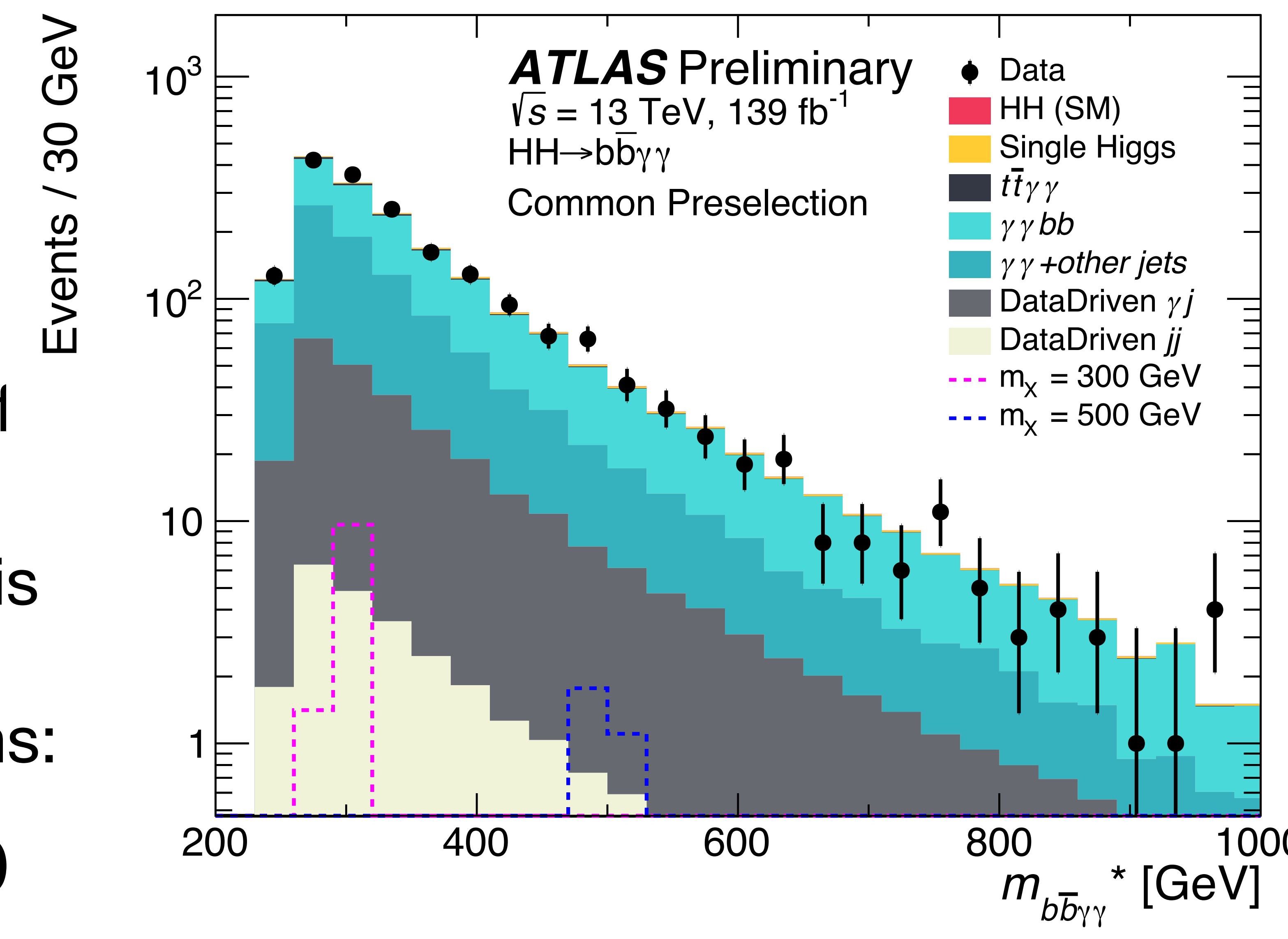


While the $m_{\gamma\gamma}$ variable is now used for the fit, the HH invariant mass $m_{b\bar{b}\gamma\gamma}$ is still useful for both the:

- Non-resonant search (sensitive to κ_λ);
- 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: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-016

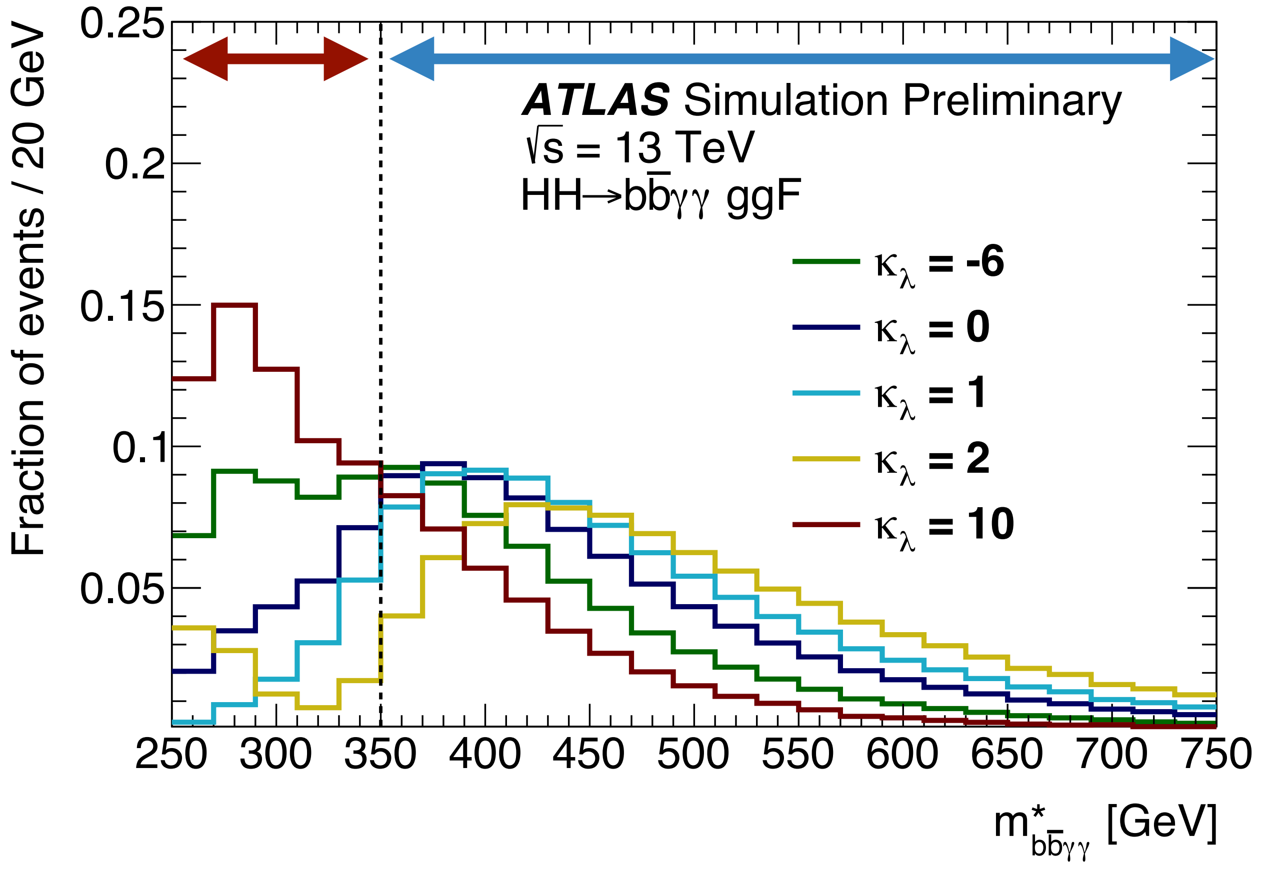
$HH \rightarrow b\bar{b}\gamma\gamma$

Non Resonant :

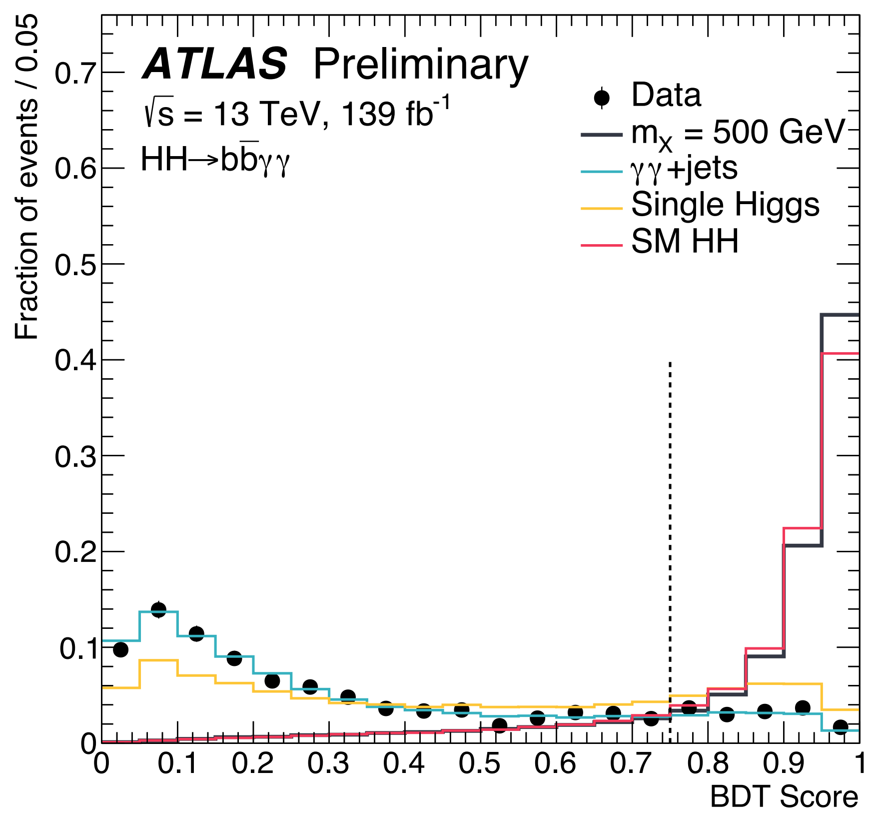
A *BDT* is used to select signal like events w.r.t di-photon + single Higgs. Categories are created from $m^*_{b\bar{b}\gamma\gamma}$:

- 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.

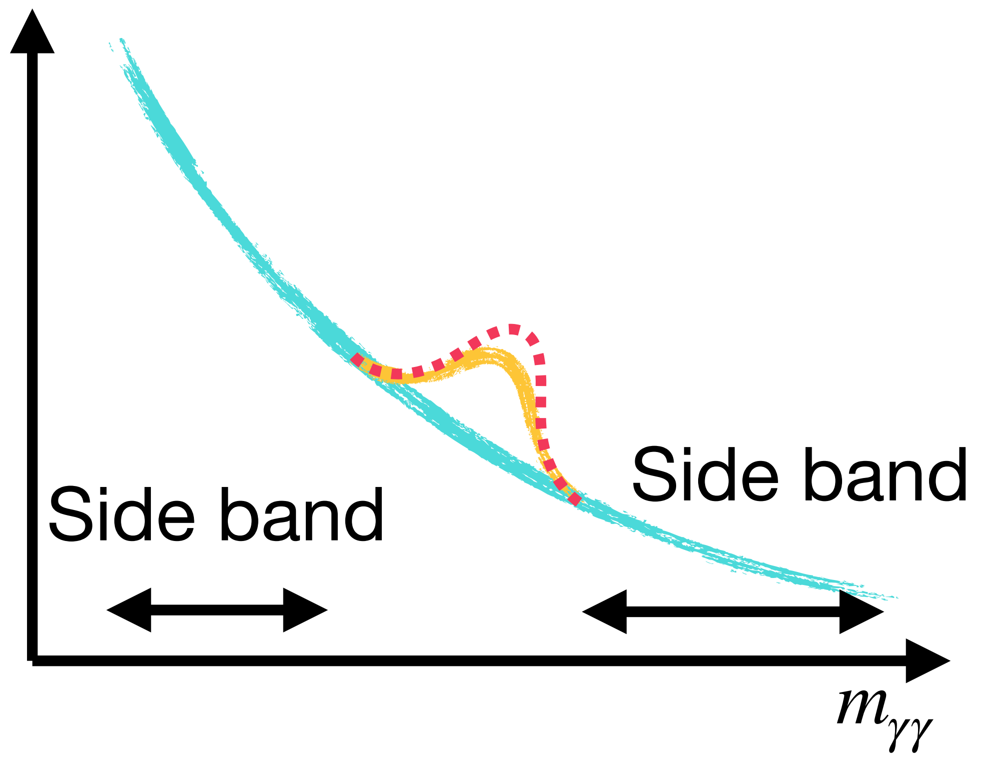
350 GeV



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.

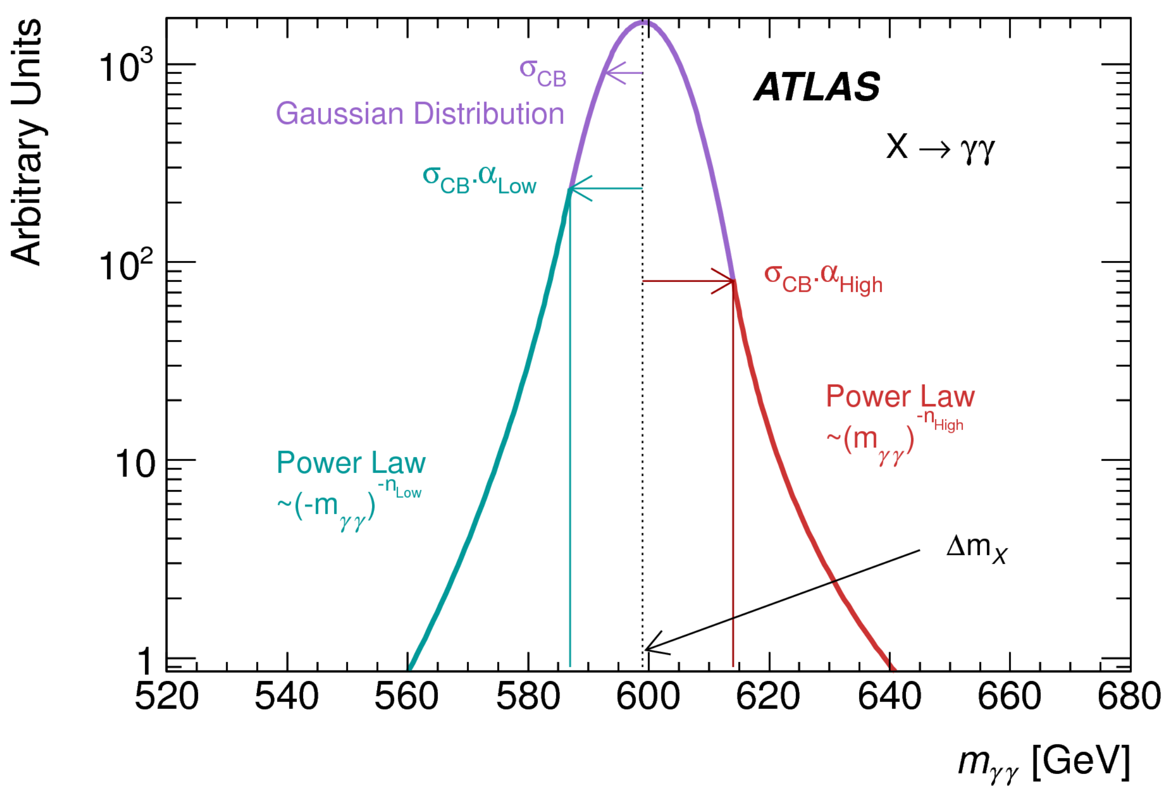


The background and signal processes are modelled thanks to **functional forms** used in the final fit:

Diphoton Background

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

Single Higgs **HH signal**



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

Results

ggF: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-016

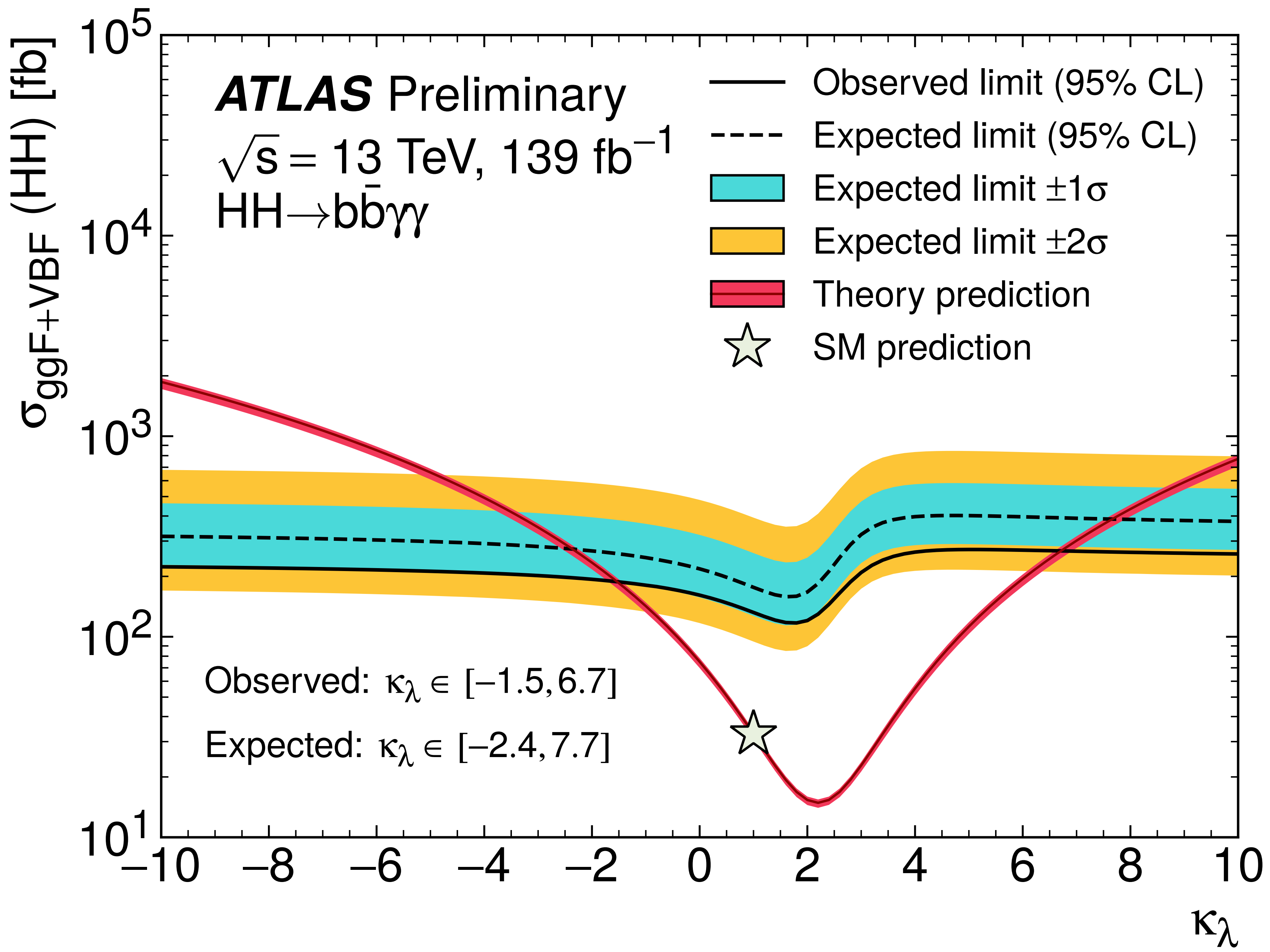
$HH \to b\bar{b}\gamma\gamma$

Non Resonant

No significant excess found

$\sigma_{HH}^{ggF+VBF}$ **observed (expected)** limit is **4.1 (5.5)** times the SM prediction.

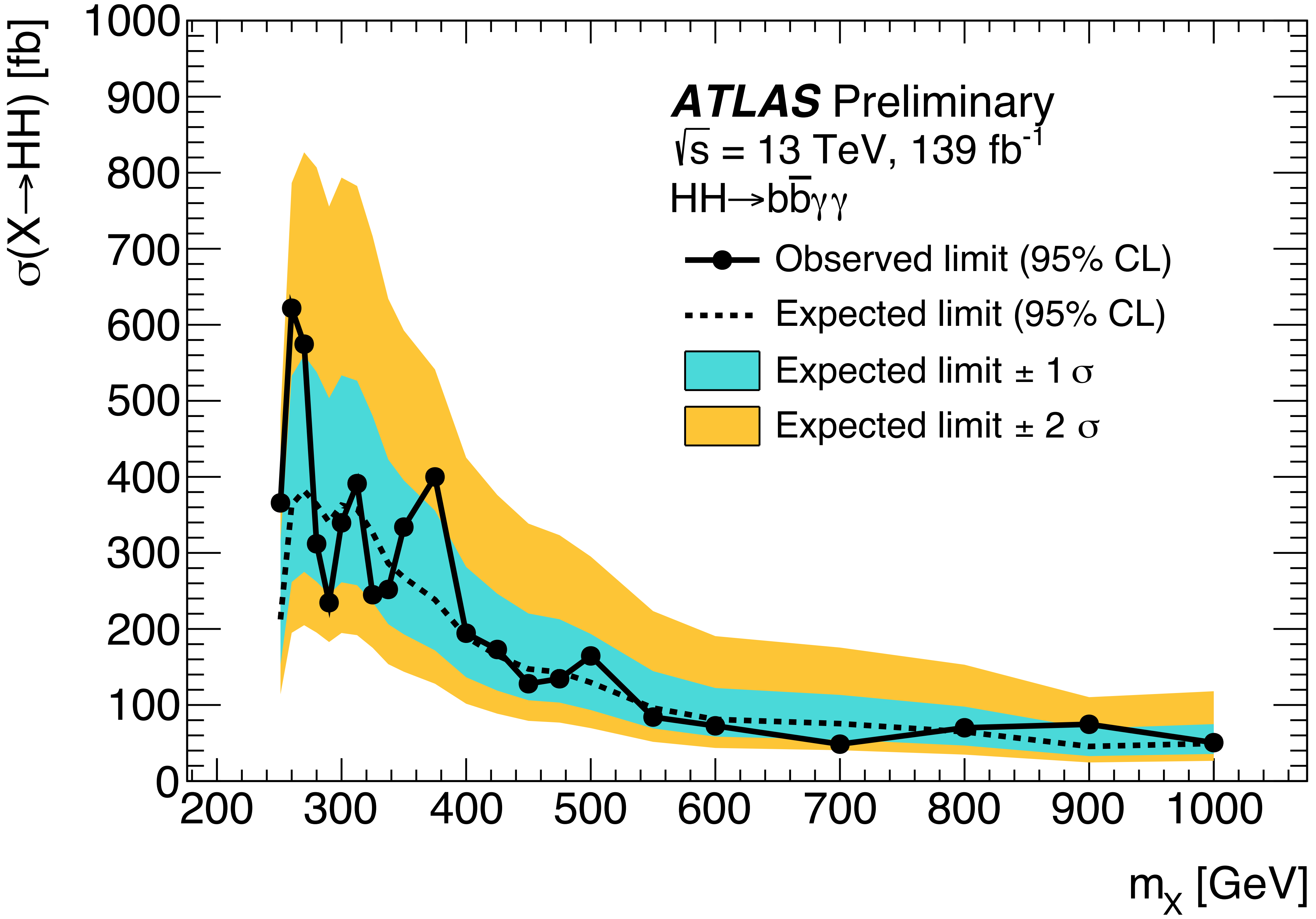
- *Best result* from single channel *observed to date;*
- Statistically dominated.
- Limits are set on κ_λ: $-1.5 < \kappa_\lambda < 6.7$ observed
  $-2.4 < \kappa_\lambda < 7.7$ expected.

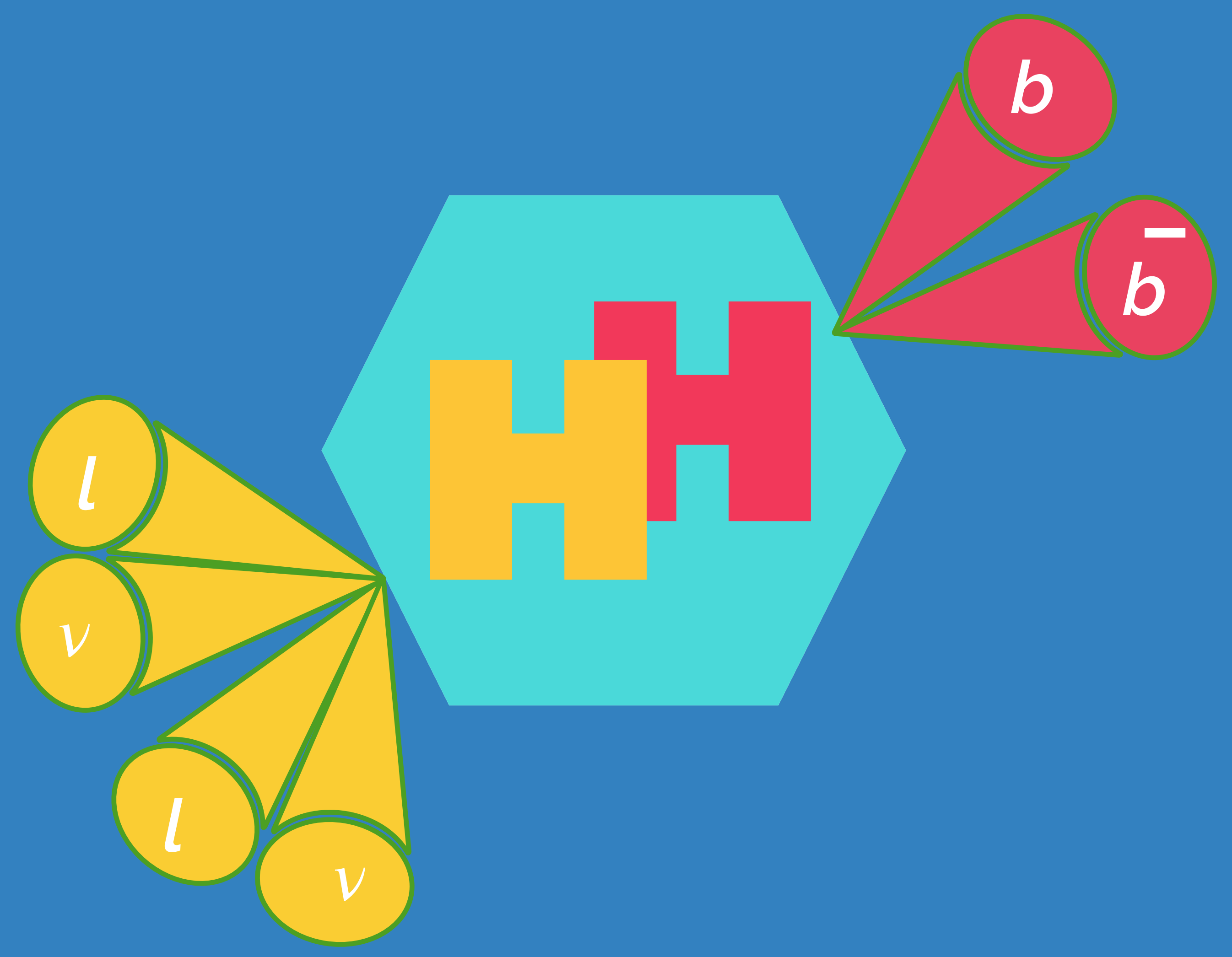


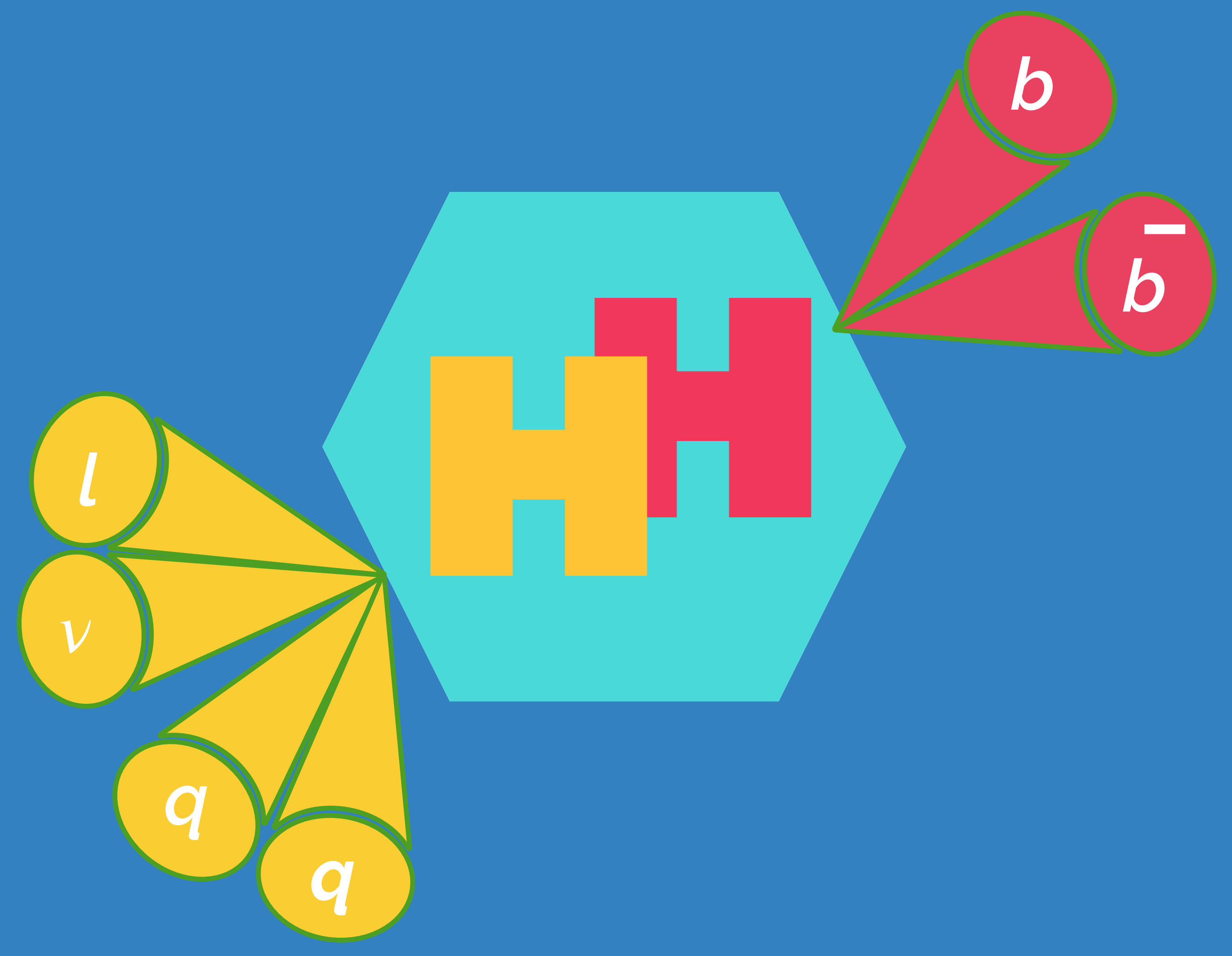
Resonant:

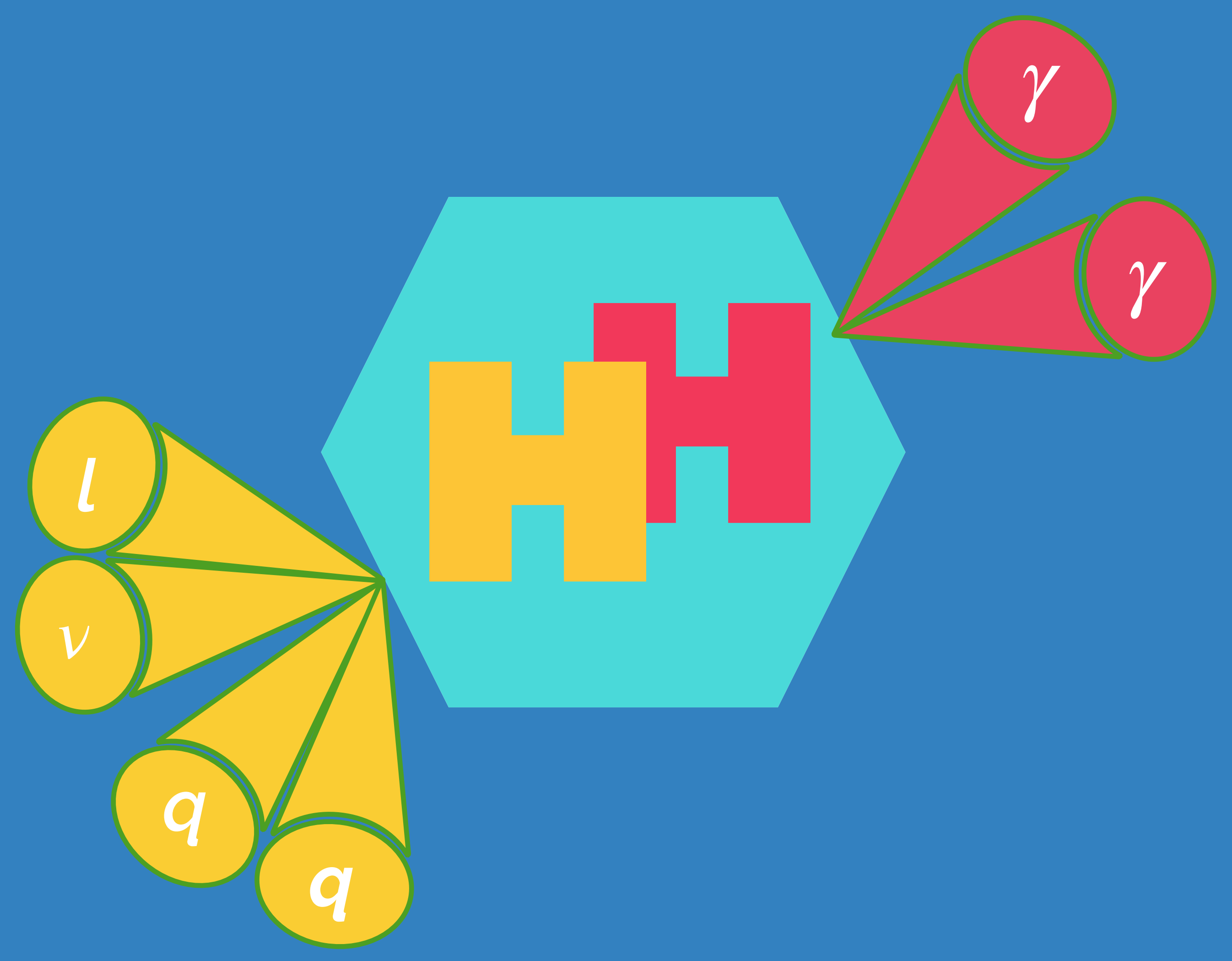
No significant excess found

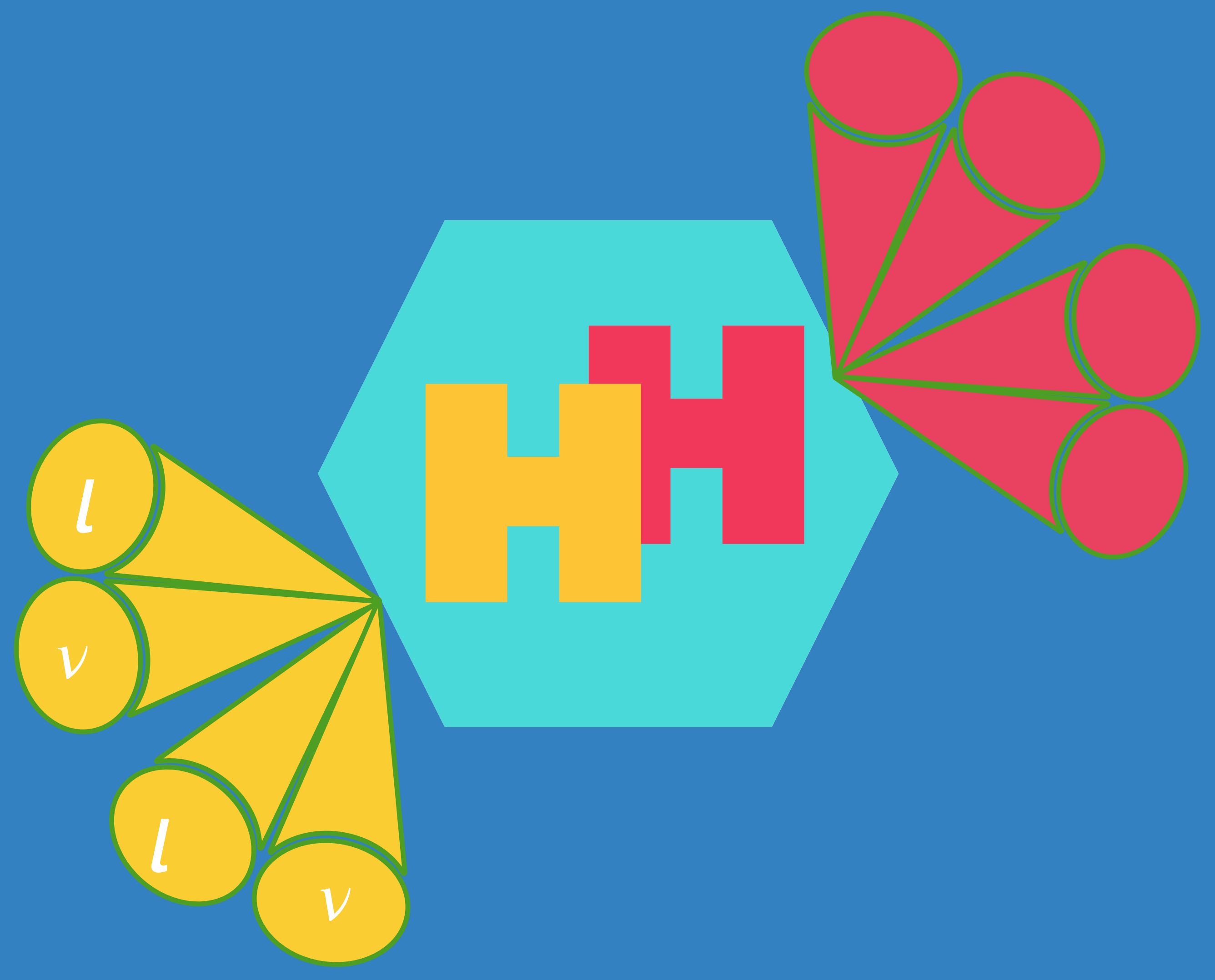
Limits set on $\sigma(X \to HH)$ where X is a narrow-width scalar resonance:




b
b̄
l
ν
l
ν


b
b̄
l
ν
q
q

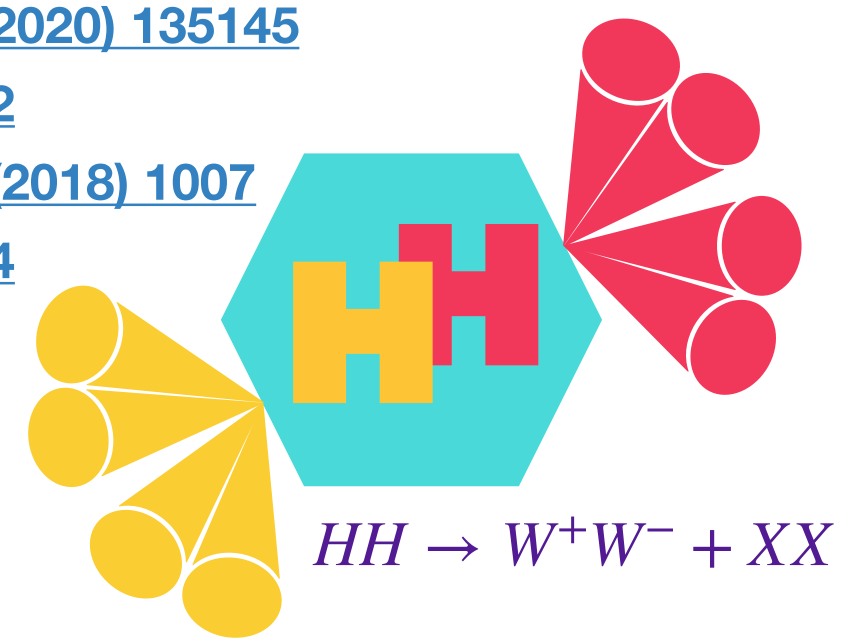

γ
γ
l
ν
q
q


l
ν
l
ν

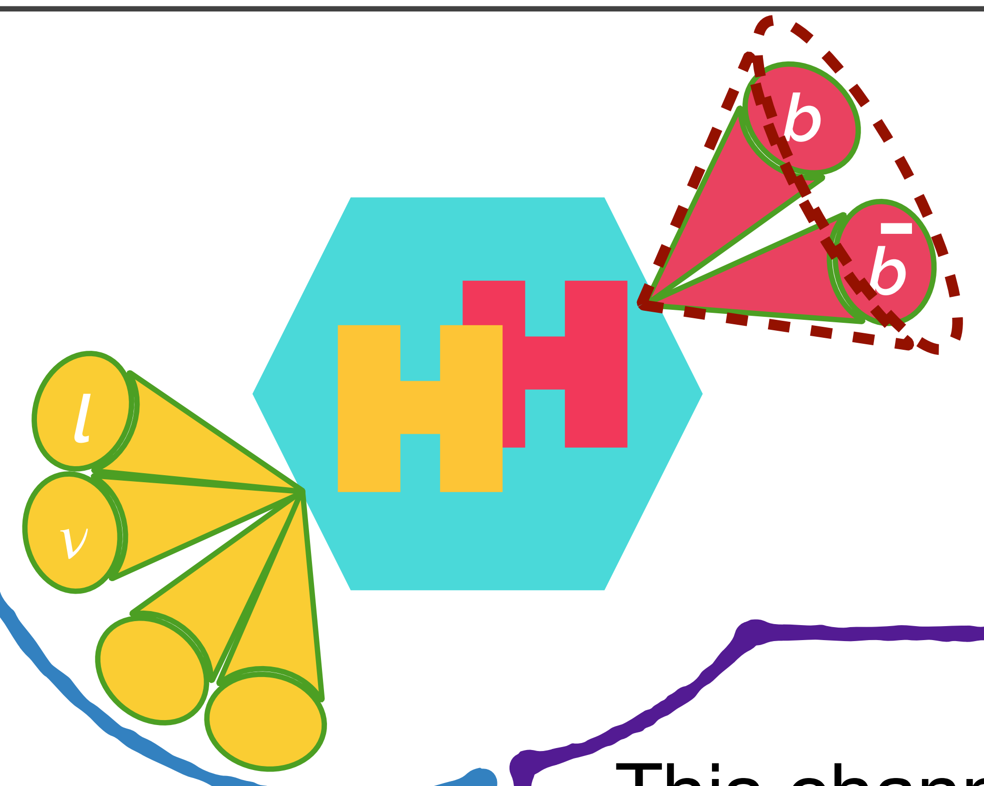
Selection

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

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



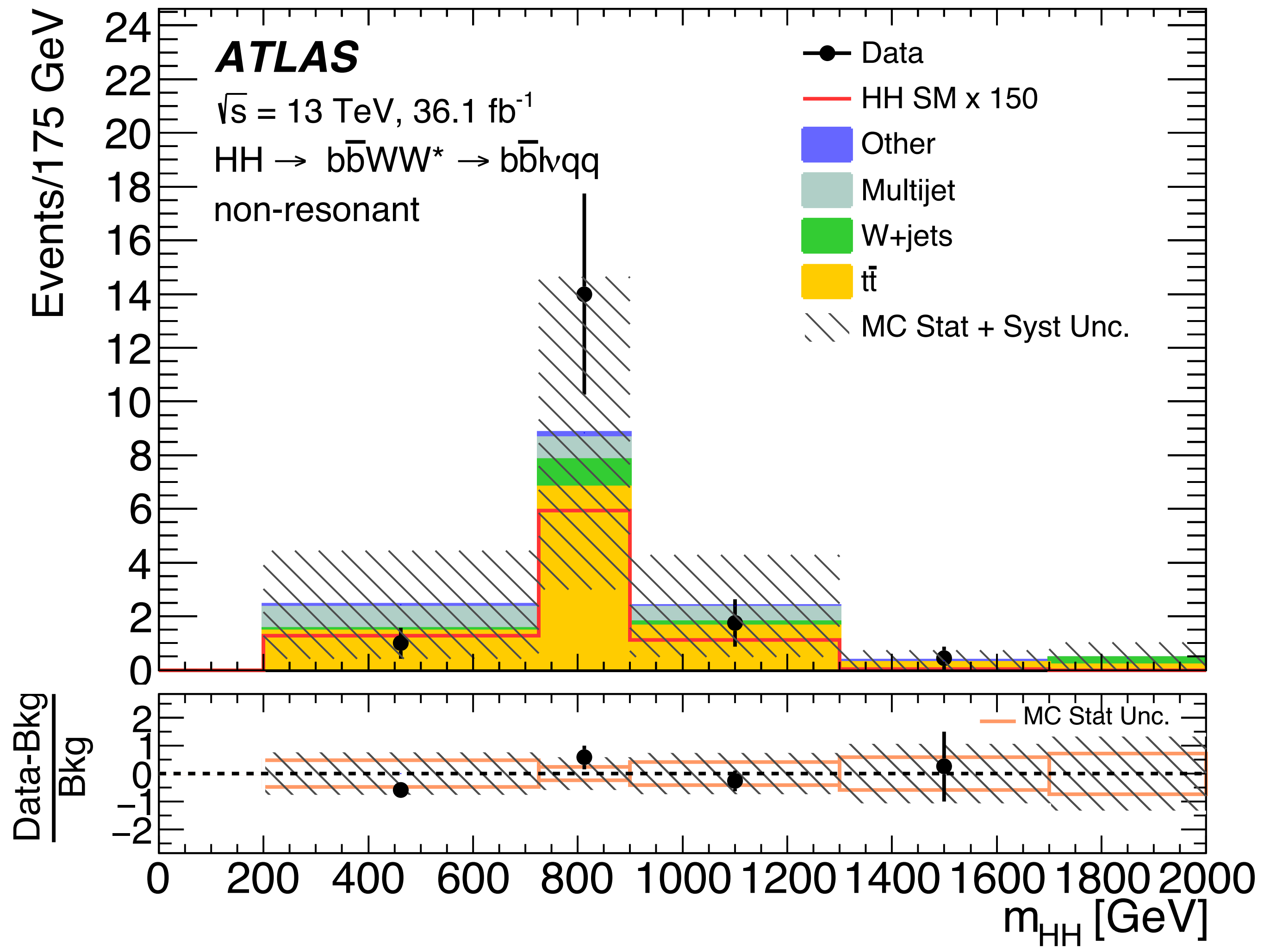
This channel is aiming at reducing the contamination of $t\bar{t}$ events by requesting one W boson to decay leptonically:

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

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

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

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

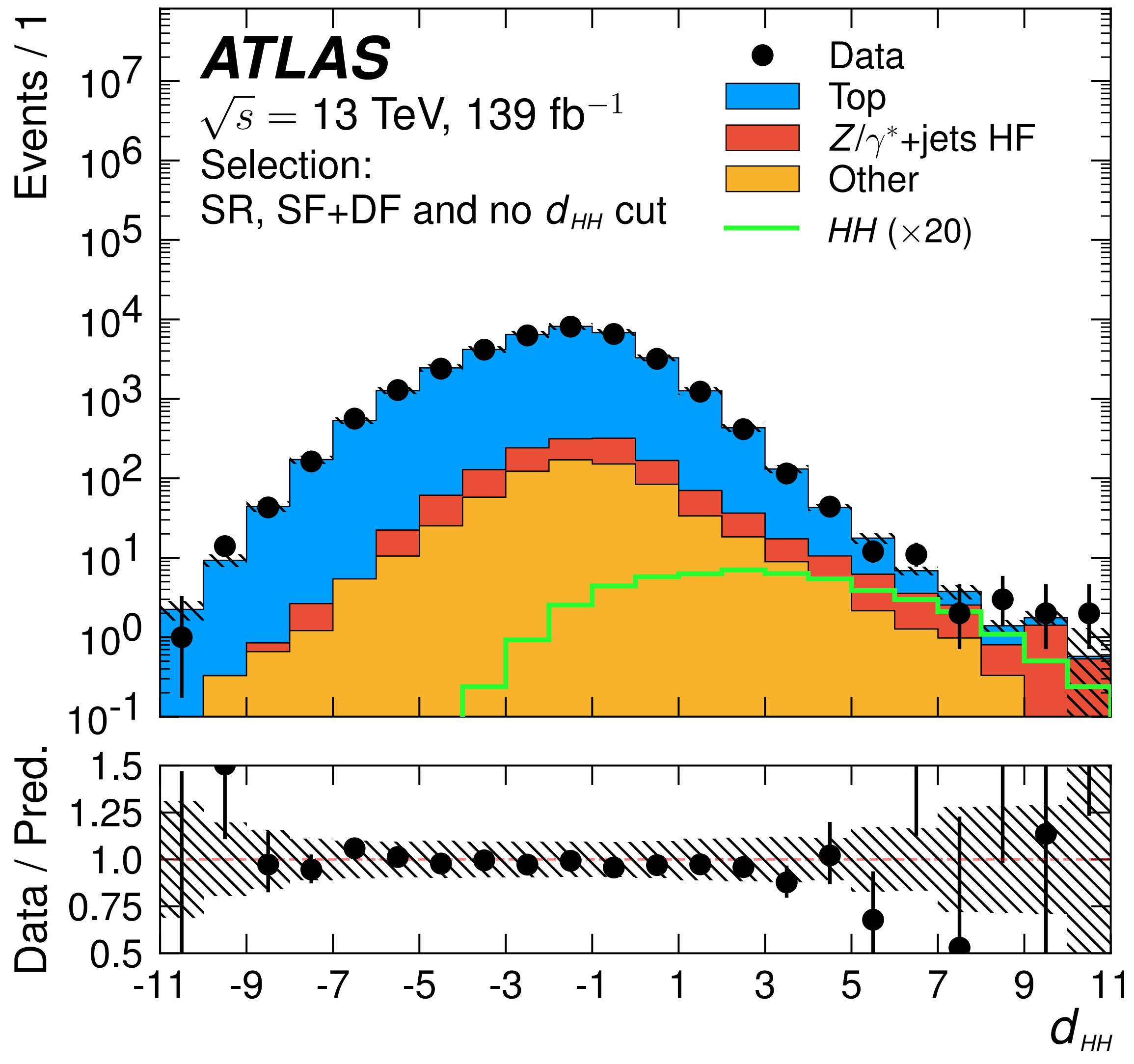


Fit: m_{HH} in different categories

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

Resolved

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



- $H \to b\bar{b}$:
  - Exactly 2 b-tagged jets
- $H \to WW^* \to l\nu l\nu$:
  - 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 : $\mathscr{L} = 139\text{fb}^{-1}$

| $b\bar{b}l\nu q\bar{q}$ final state : $\mathscr{L} = 36\text{fb}^{-1}$

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

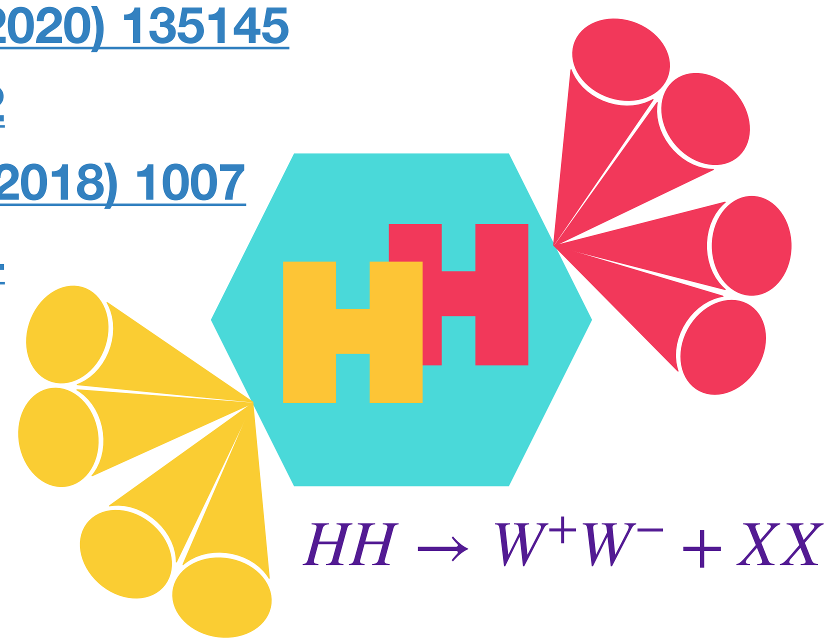
WW^*WW^* final state : $\mathscr{L} = 36\text{fb}^{-1}$

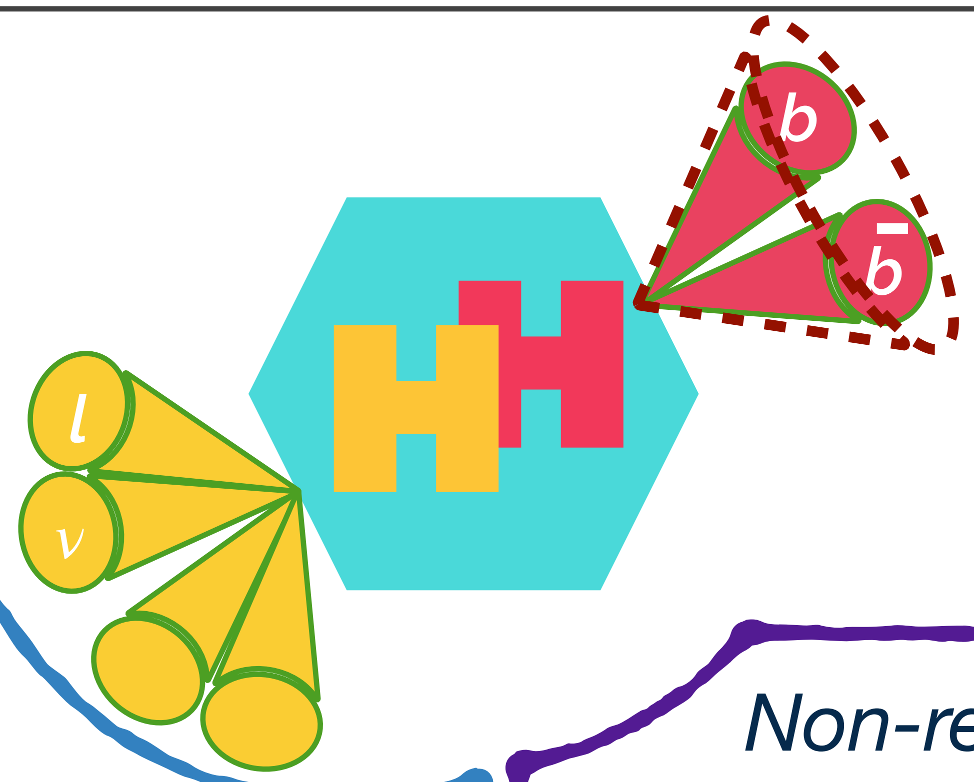
Phys. Lett. B 801 (2020) 135145

JHEP 04 (2019) 092

Eur. Phys. J. C 78 (2018) 1007

JHEP 05 (2019) 124



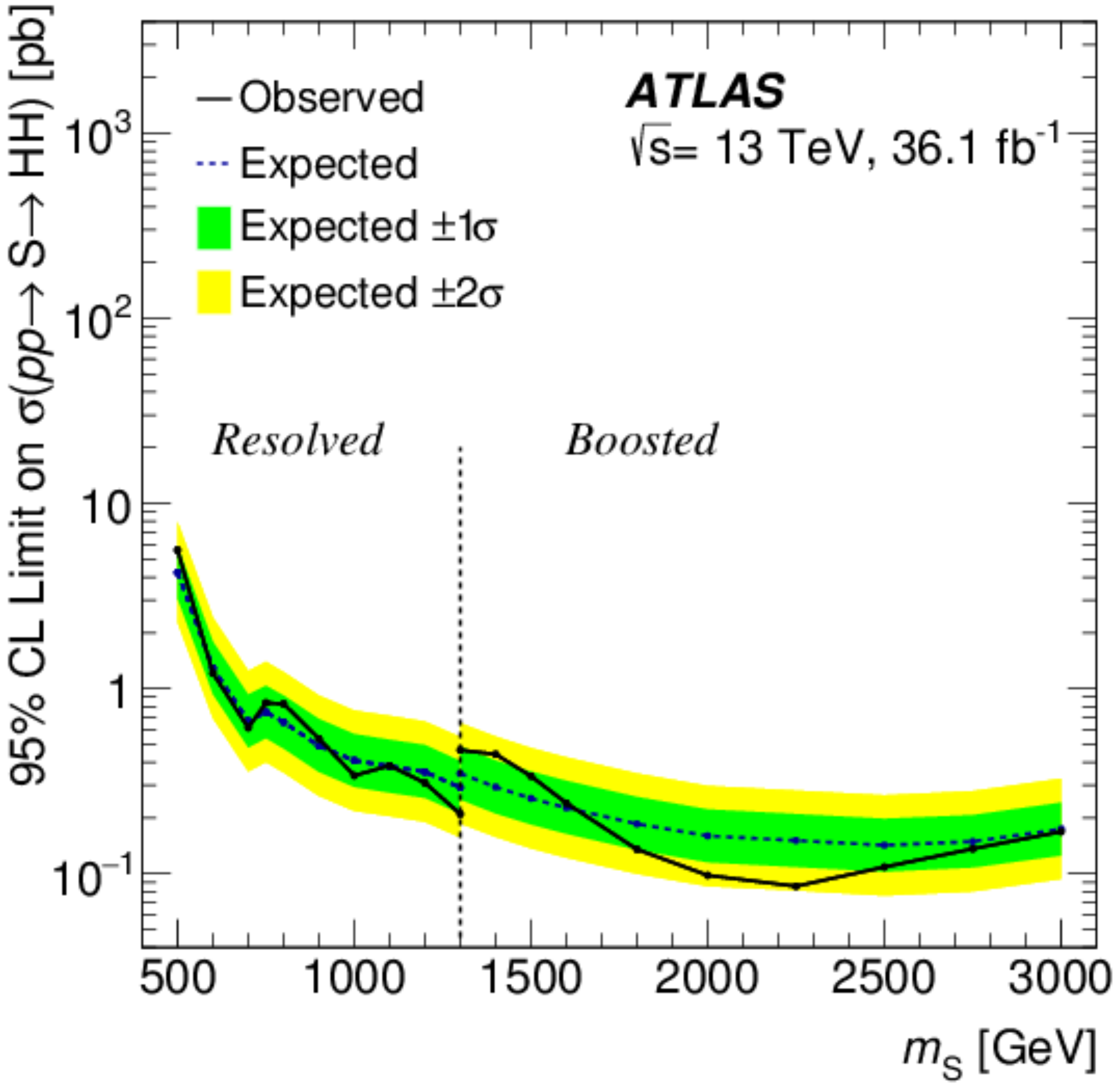


$b\bar{b}l\nu q\bar{q}$ final state

Non-resonant Resolved

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

Resonant: Resolved Boosted

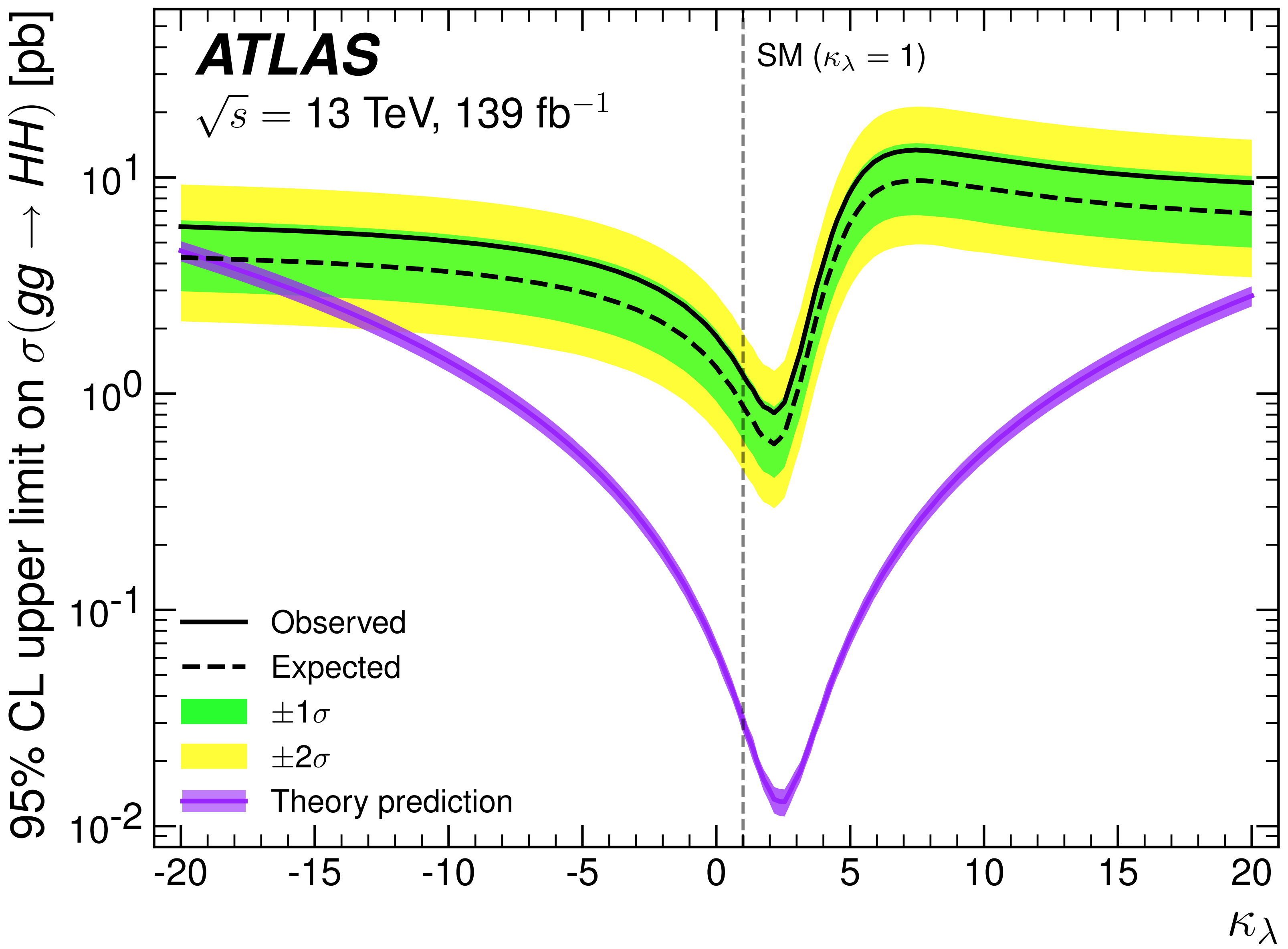


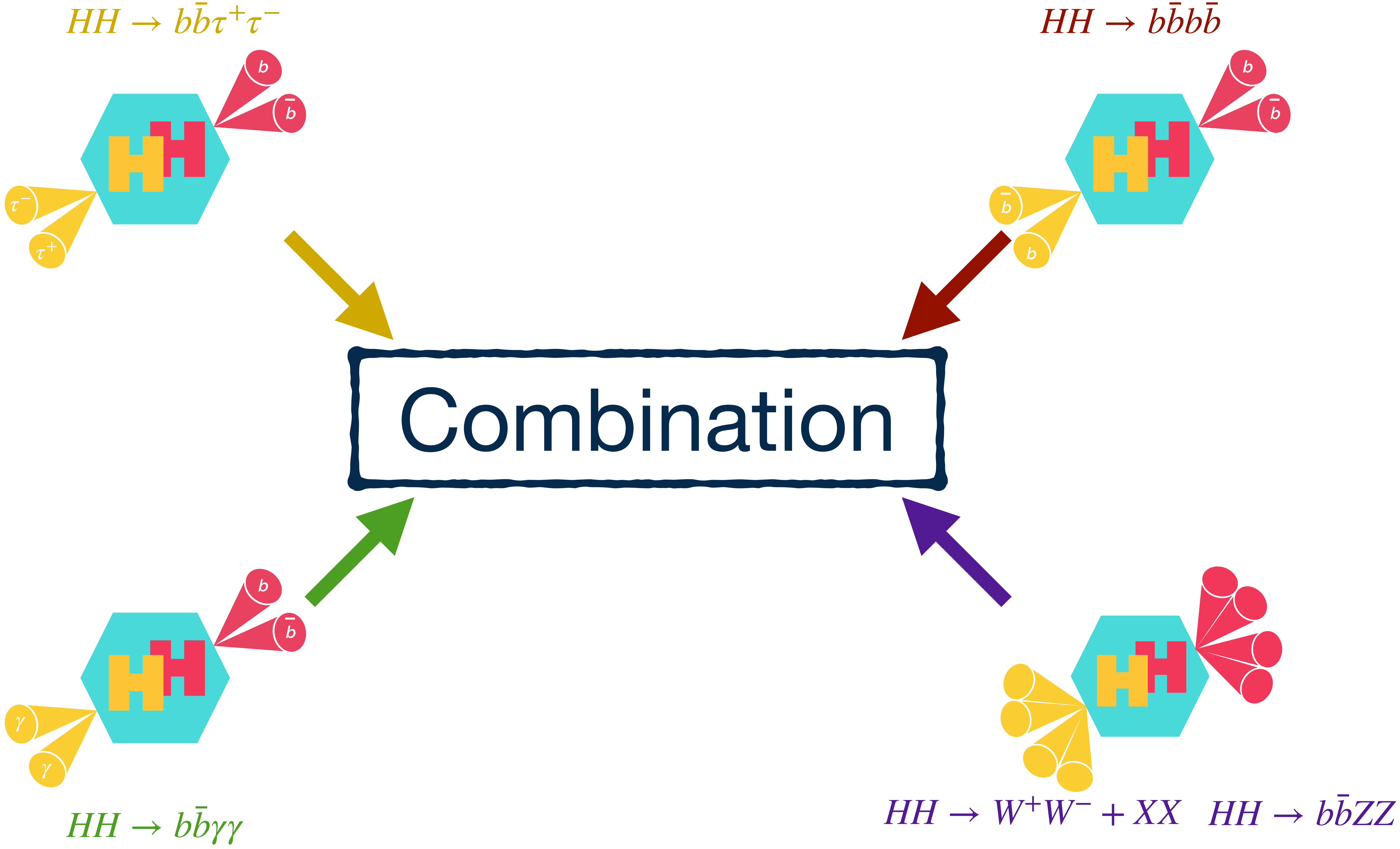
Limits set on $\sigma(X \to HH)$ where X is a narrow-width scalar resonance

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

Non-resonant

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



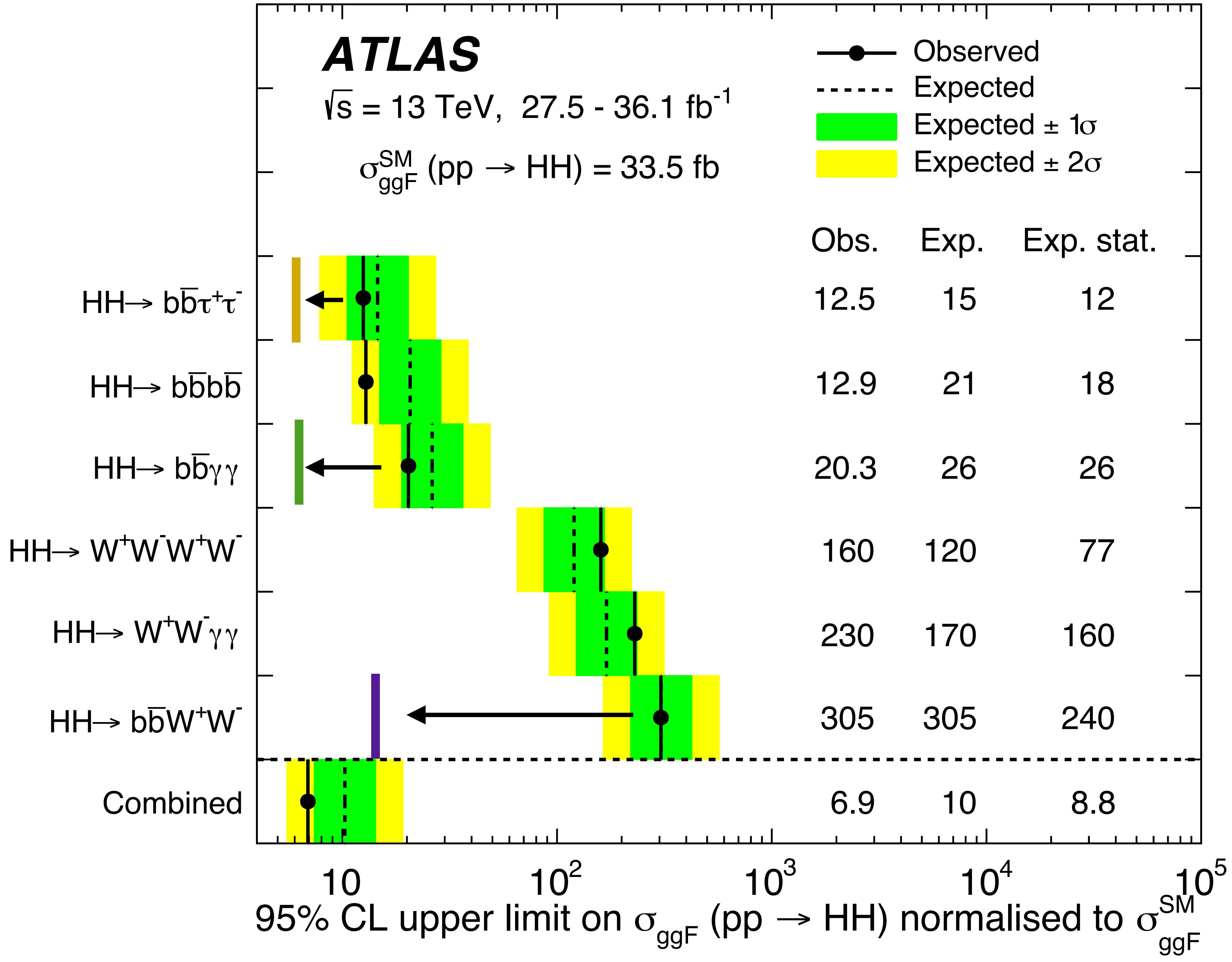


$HH \to b\bar{b}\tau^+\tau^-$
$HH \to b\bar{b}b\bar{b}$
Combination
$HH \to b\bar{b}\gamma\gamma$
$HH \to W^+W^- + XX$
$HH \to b\bar{b}ZZ$

Conclusion

Combinaison: $\mathscr{L} = 139\text{fb}^{-1}$ TBU ATL-CONF-

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

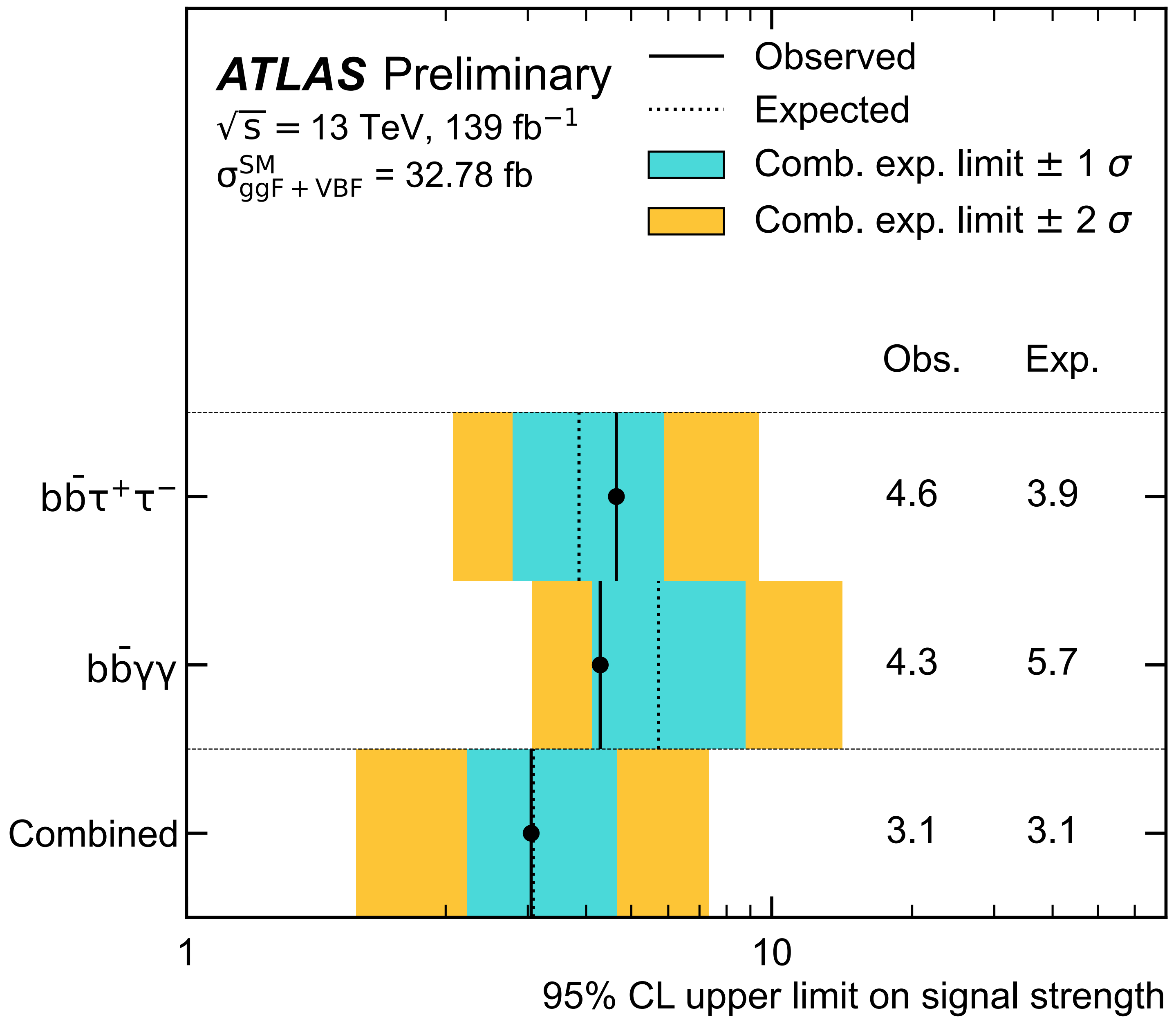


Additional results with $\mathscr{L} = 139\text{fb}^{-1}$:

$b\bar{b}l\nu l\nu$ 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.

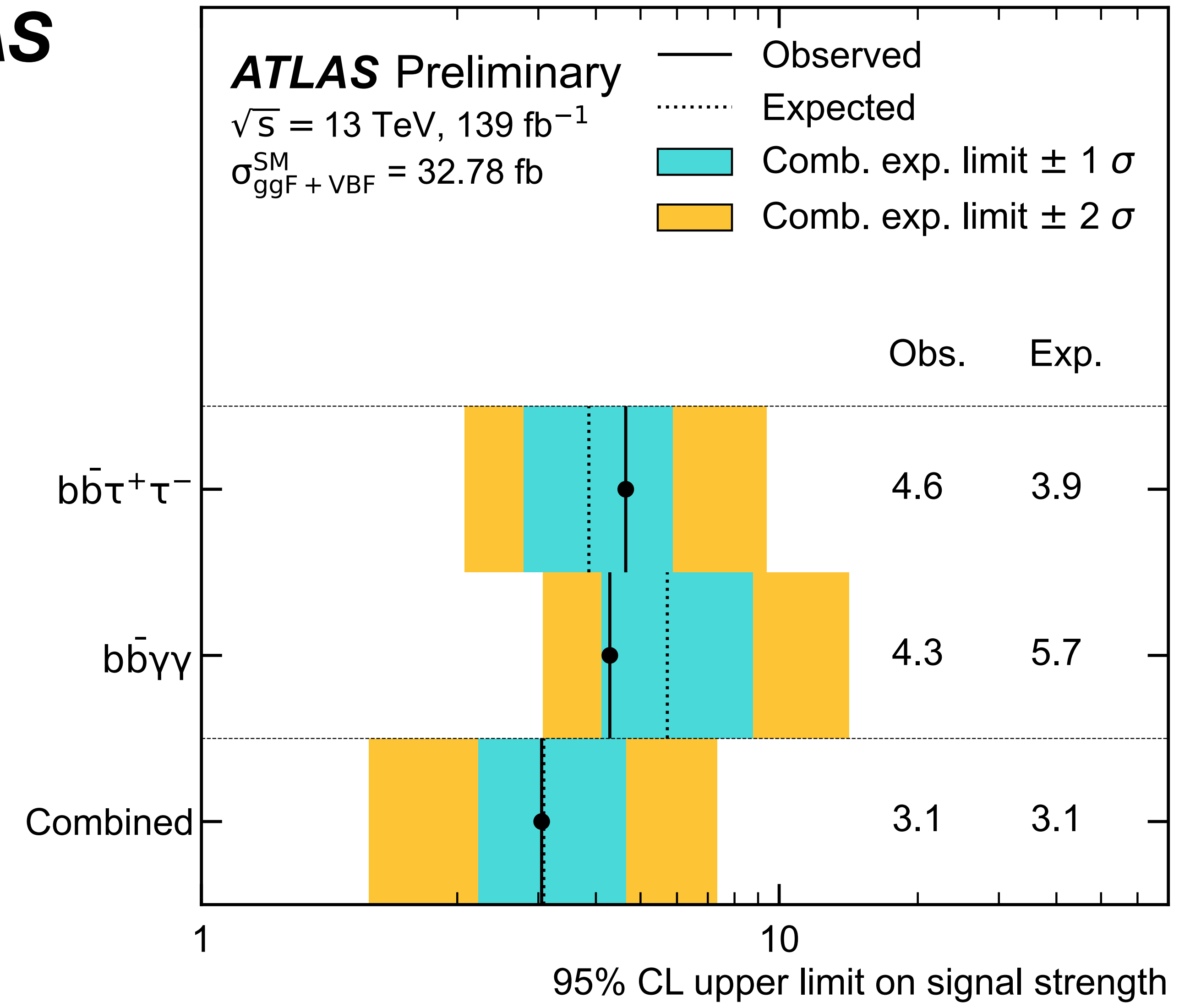
First look at **VBF**: $HH \rightarrow b\bar{b}b\bar{b}$

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

Conclusion

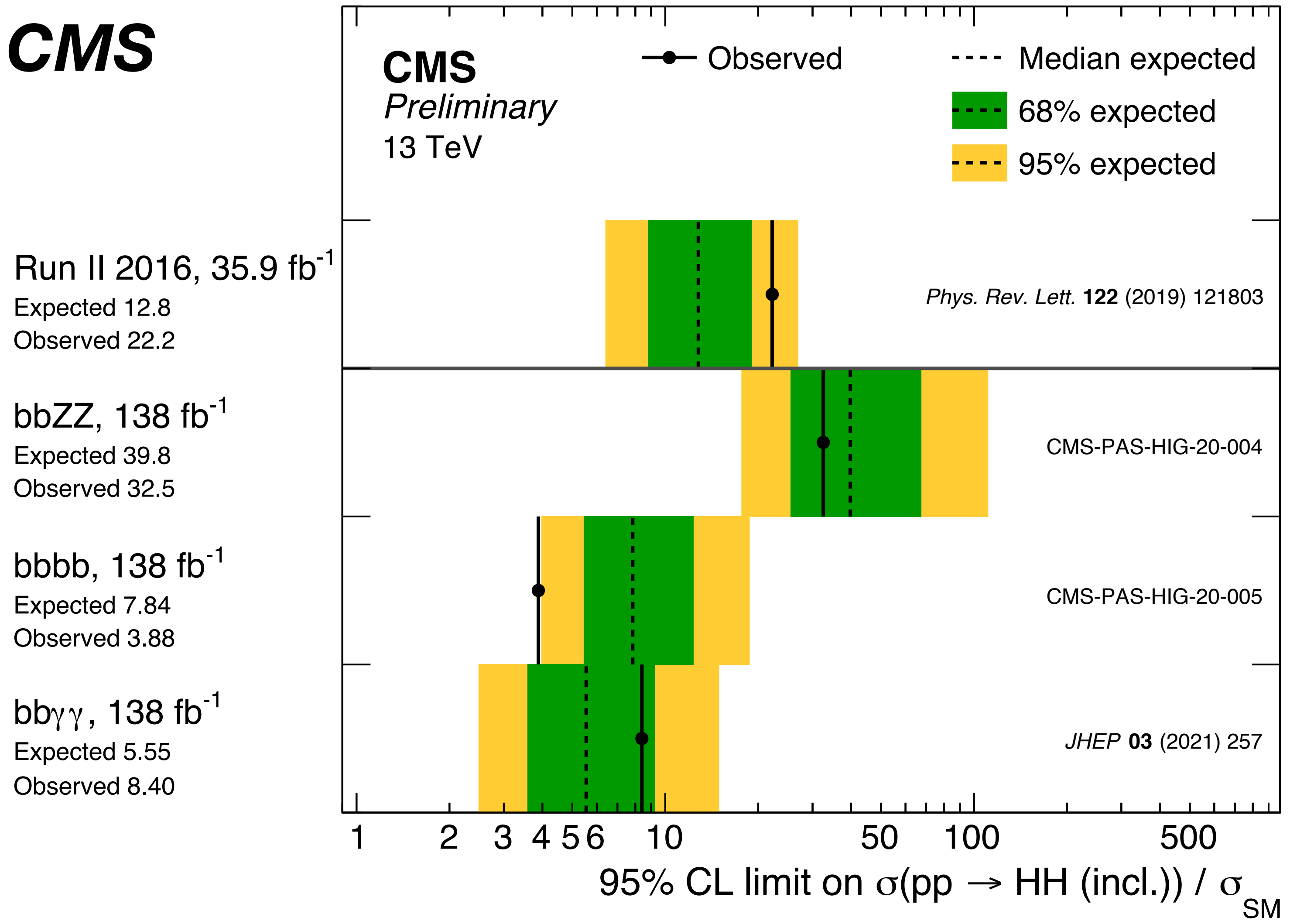
Combinaison: $\mathscr{L} = 36\text{fb}^{-1}$ Phys. Lett. B 800 (2020) 135103

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.

CMS



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

First measurement of σ_{HH}^{VBF}
observed (expected) limit is:

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

ATLAS **Resolved**
840 (550) times the SM prediction.

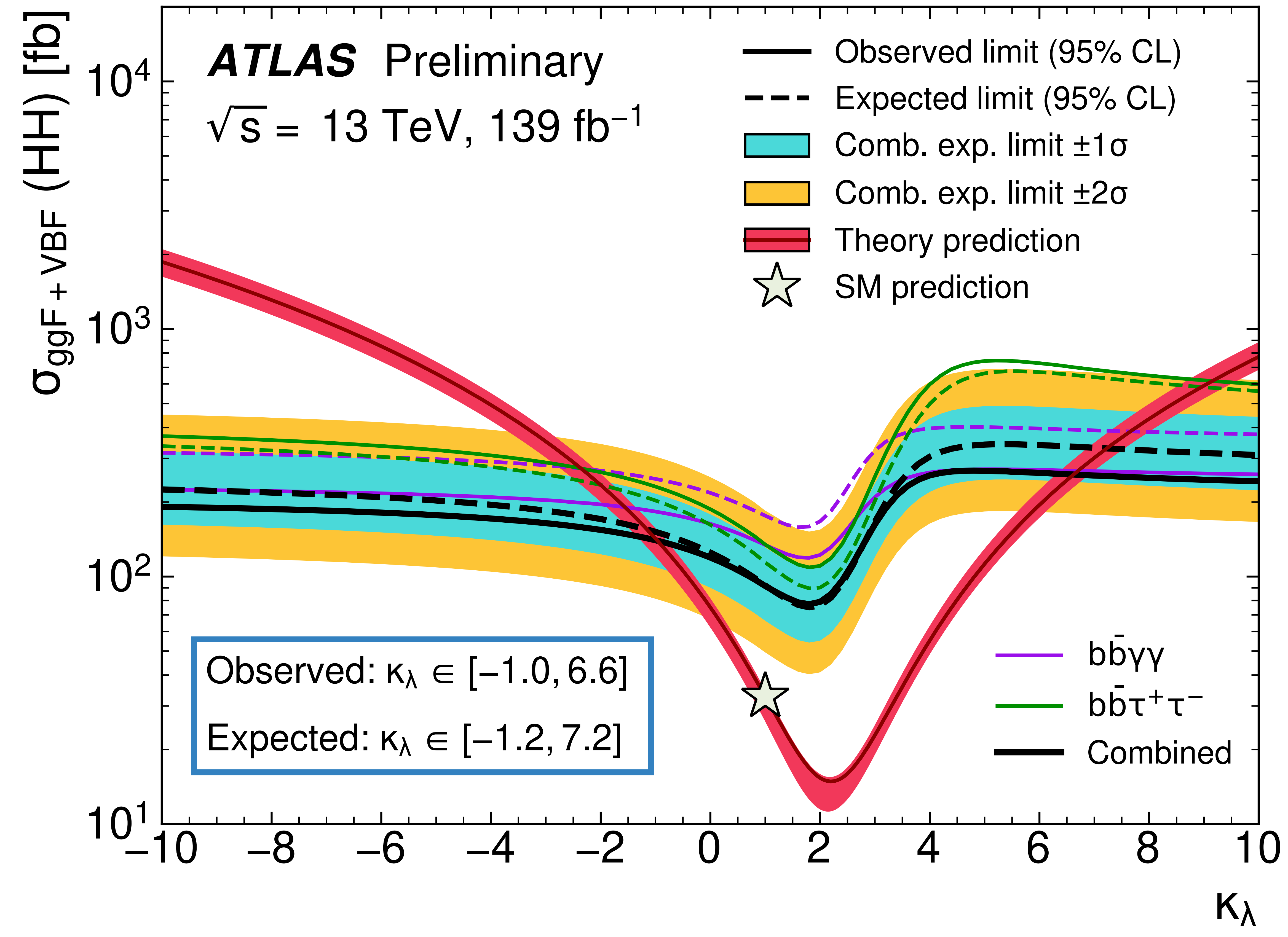
CMS **Boosted**
226 (412) times the SM prediction.

$HH \rightarrow b\bar{b}\gamma\gamma$ **Resolved**
225 (208) times the SM prediction.

$\frac{\sigma(pp\rightarrow HH)}{\sigma_{SM}}$ at 13 TeV		Partial Run 2 (2015-16)		Ful 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		

Conclusion

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



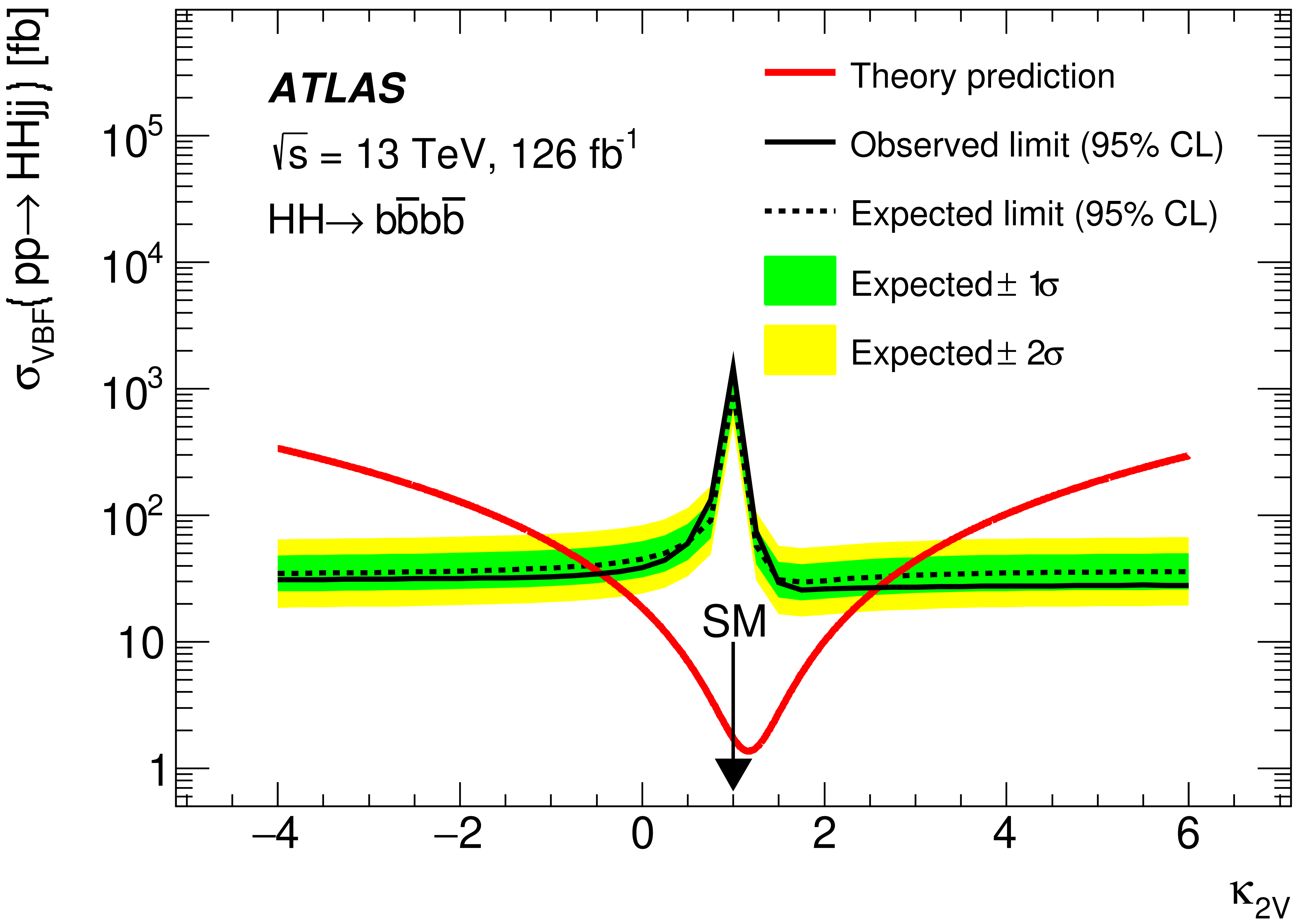
Best limit set so far on κ_λ so far.

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

Limits are set on the κ_{2V} coupling modifier to:

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

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



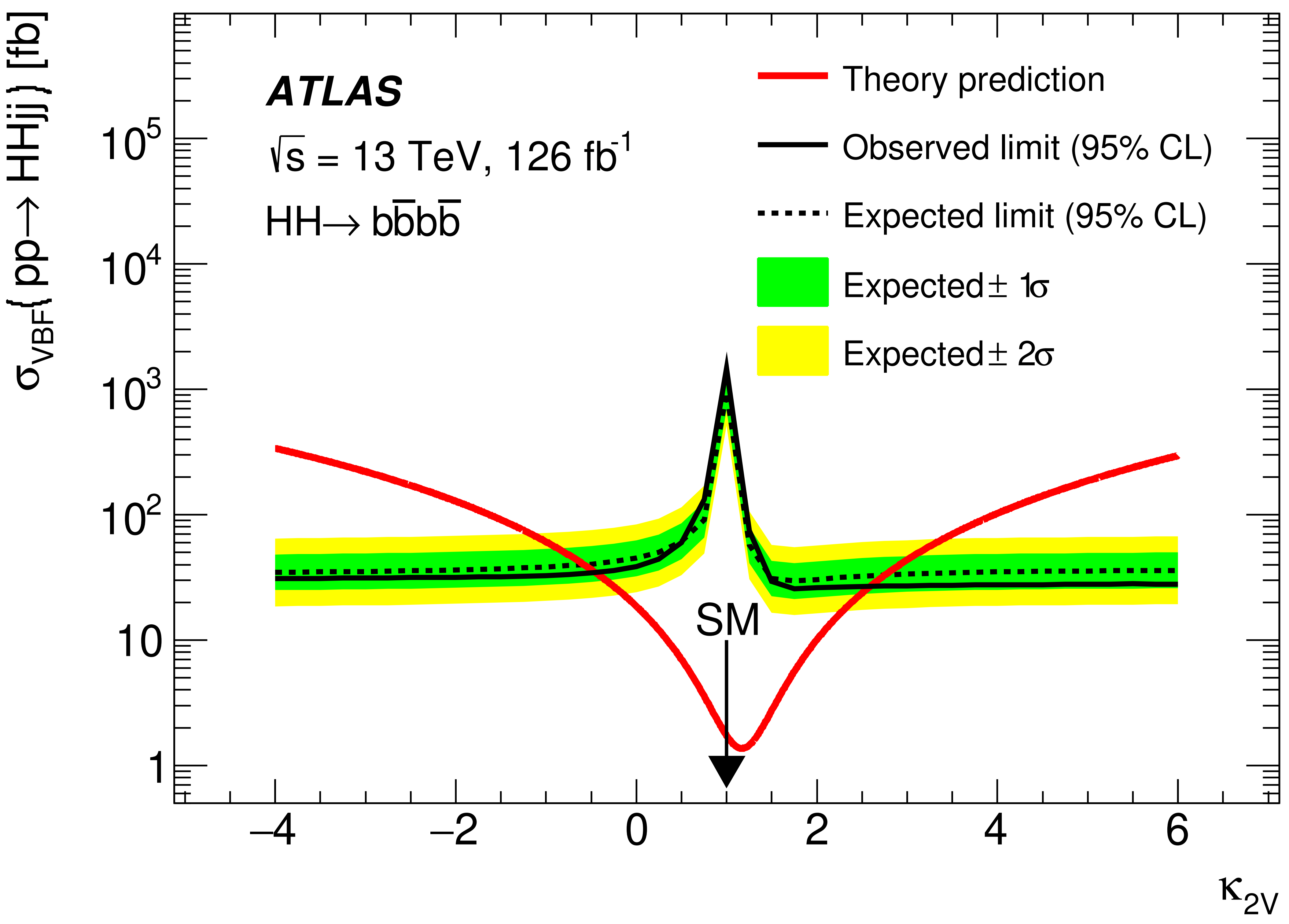
Conclusion

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

Limits are set on the κ_{2V} coupling modifier to:

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

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

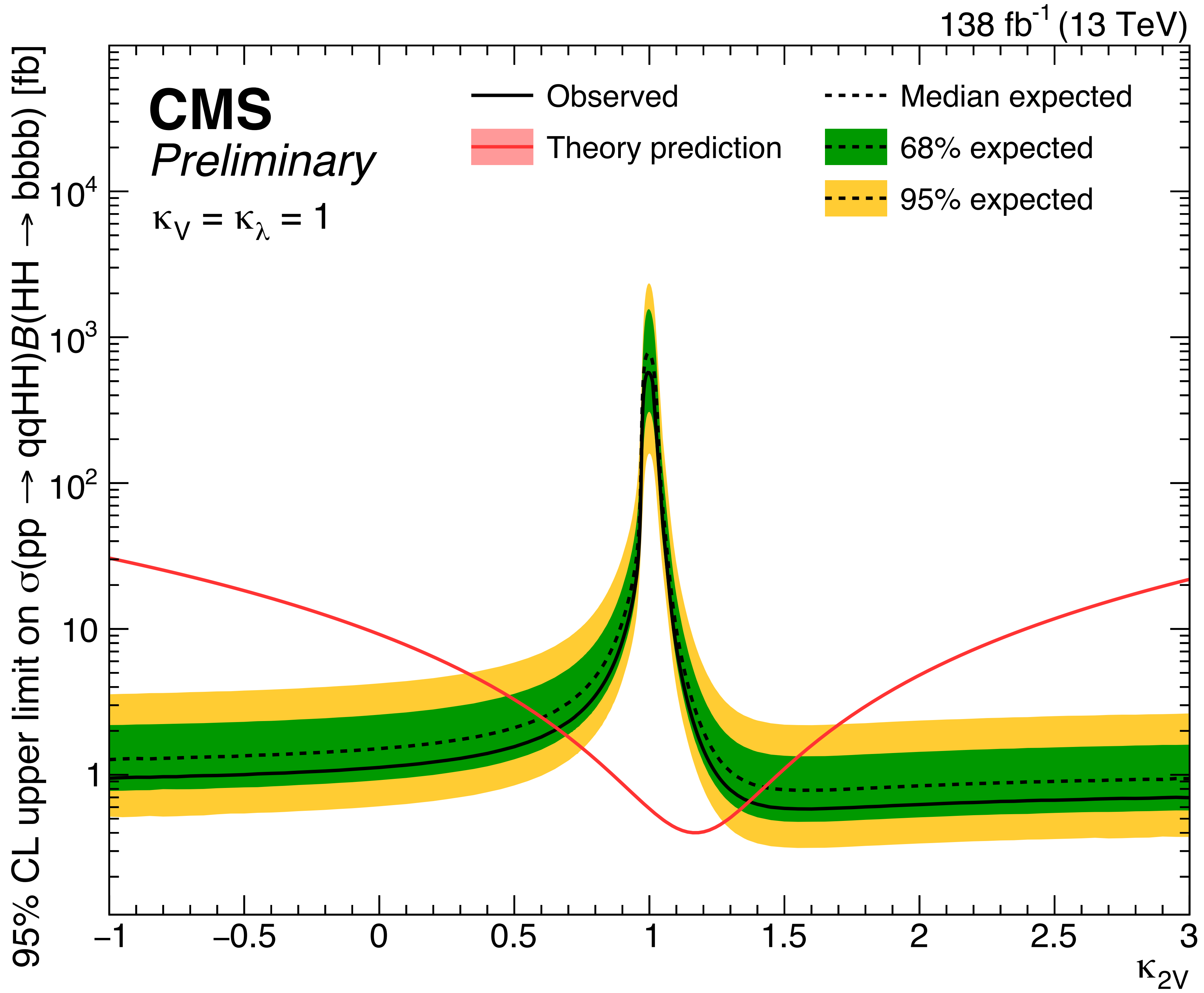


CMS $b\bar{b}b\bar{b}$ Boosted CMS-PAS-B2G-21-001

Several results are now including the κ_{2V} measurement, the best measurement is:

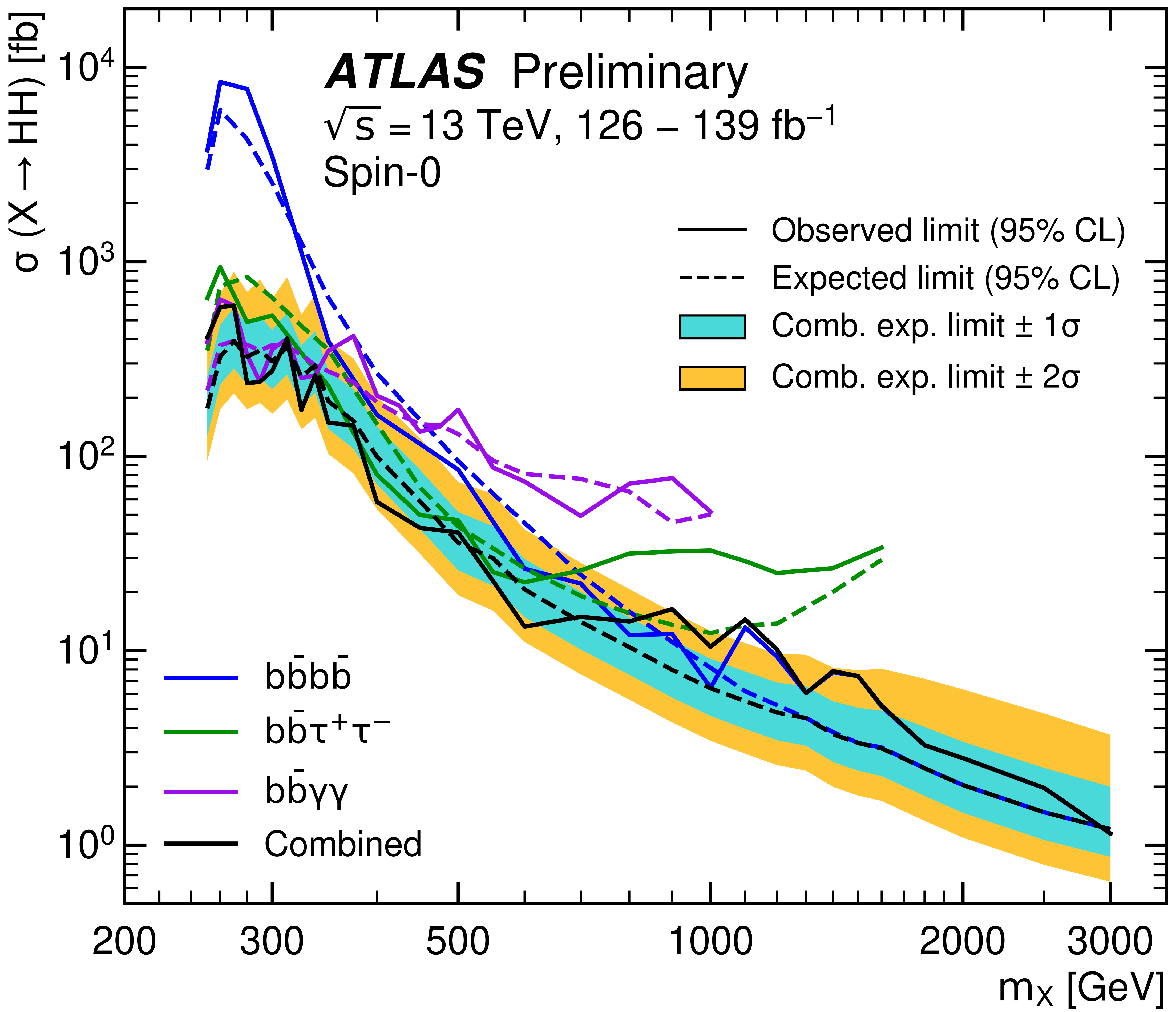
$0.6 < \kappa_{2V} < 1.4$ observed,

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

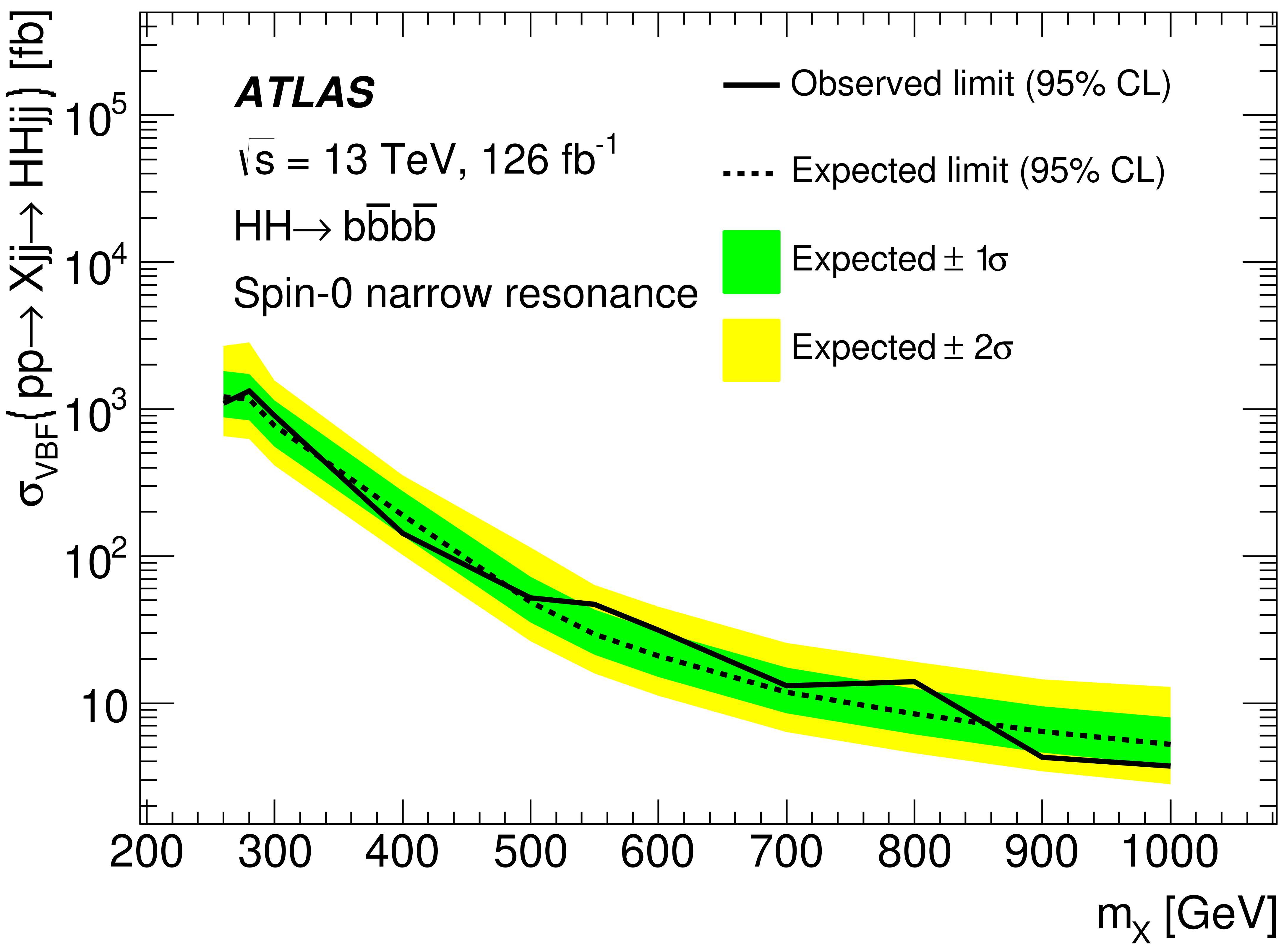


Conclusion

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

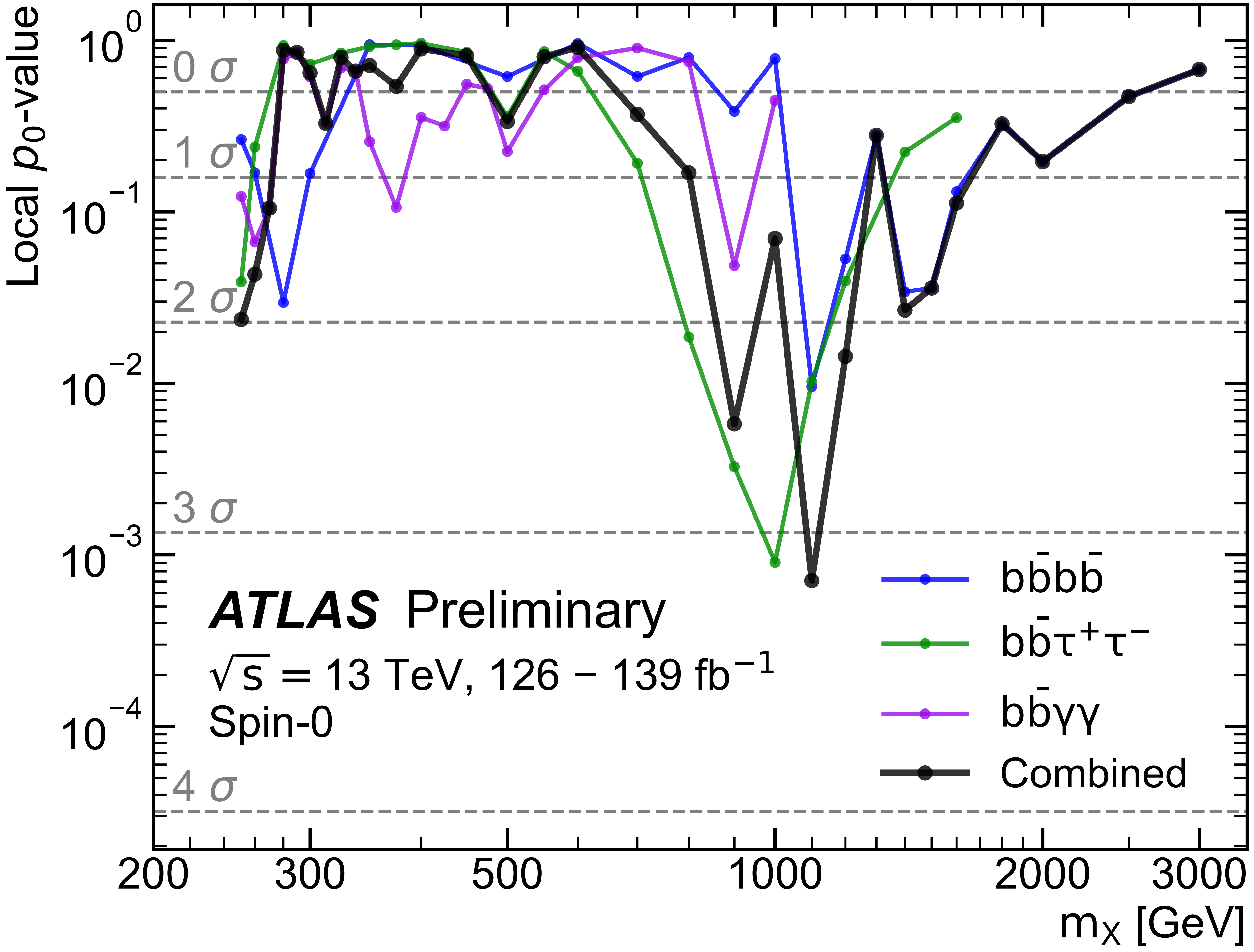


First look at **VBF**: $b\bar{b}b\bar{b}$ final state



Conclusion

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



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

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

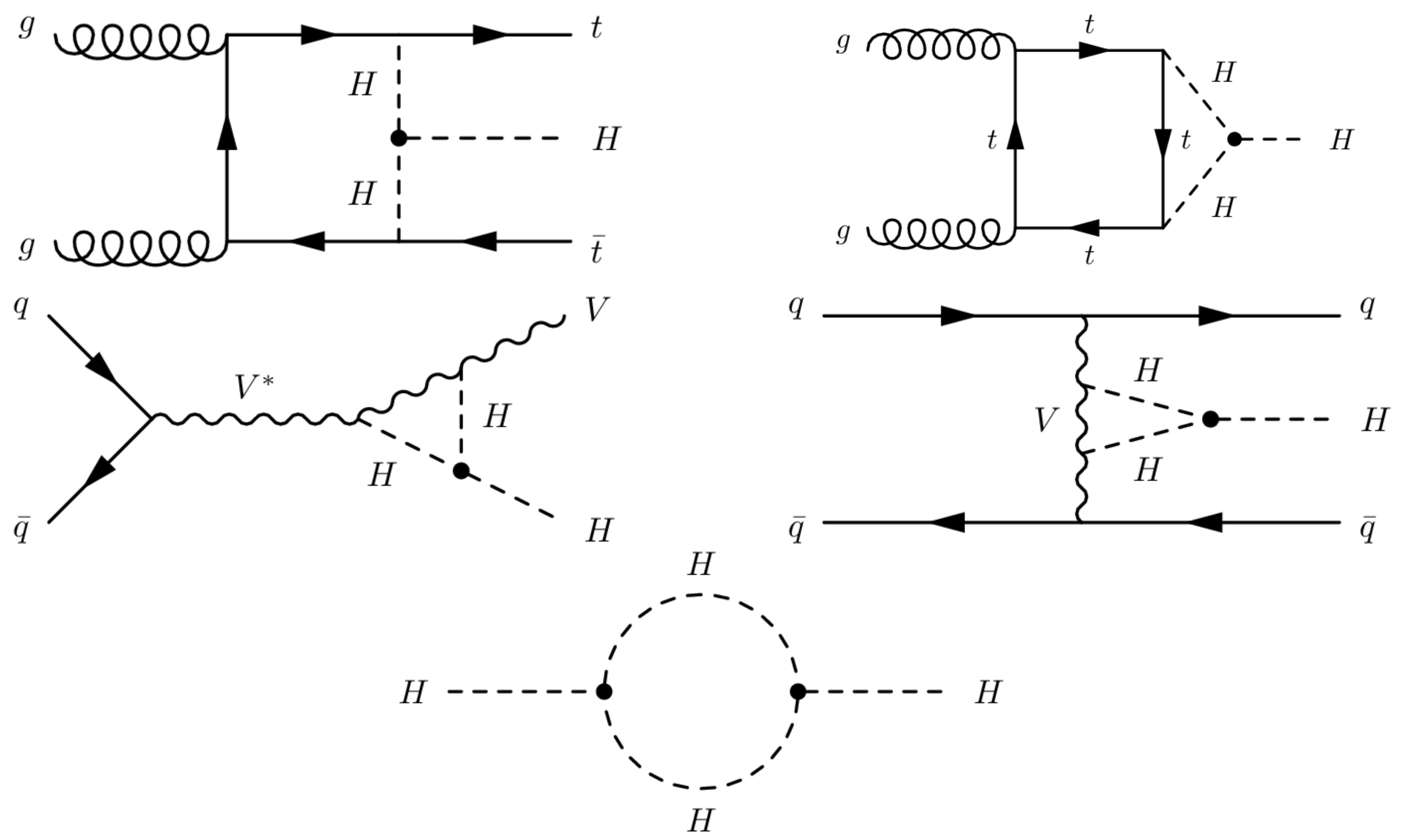
* The global significance accounts for a look-elsewhere effect with a trial factor (see Eur. Phys. J. C 70, 525–530 (2010))

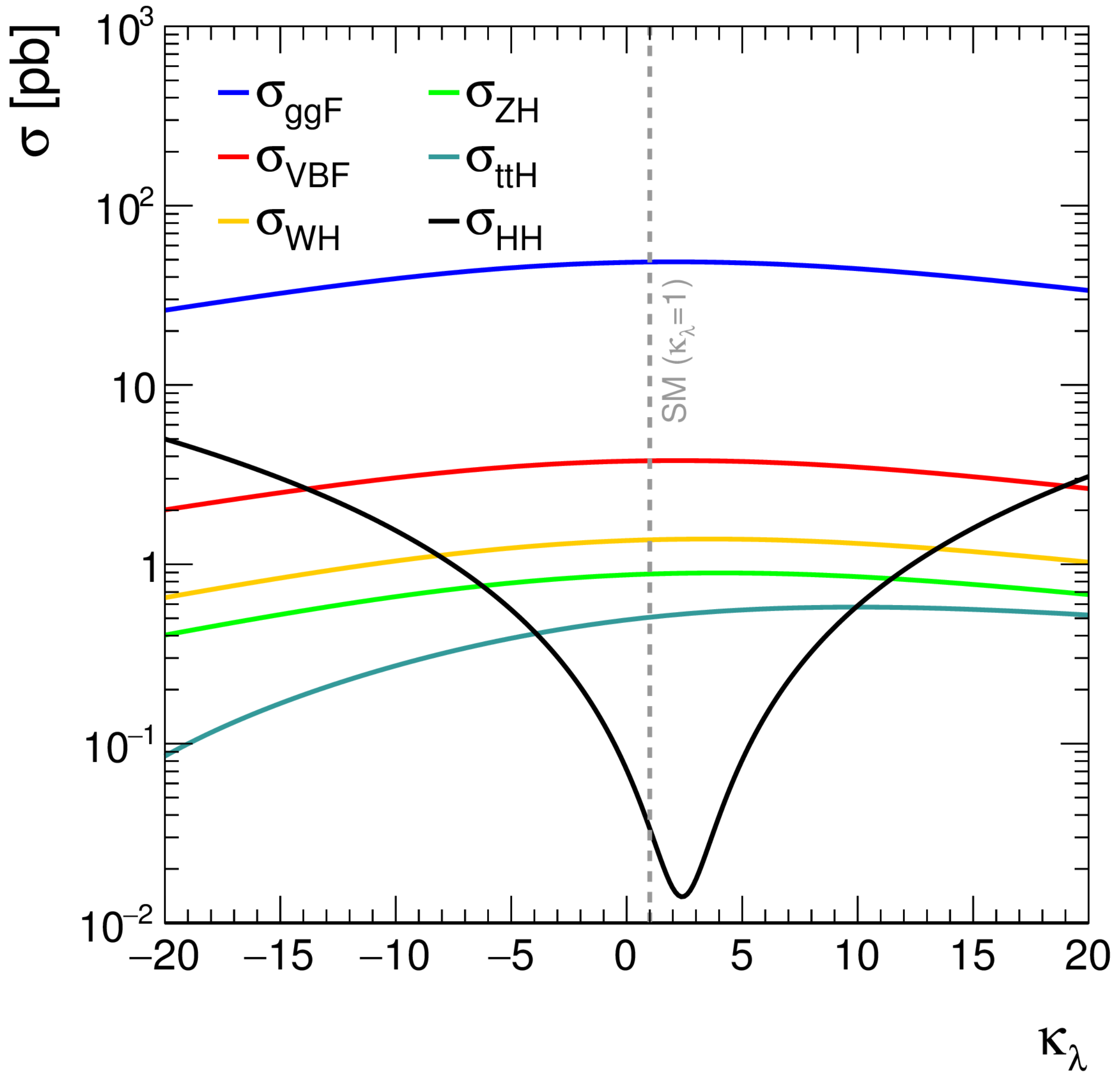
ATLAS EXPERIMENT

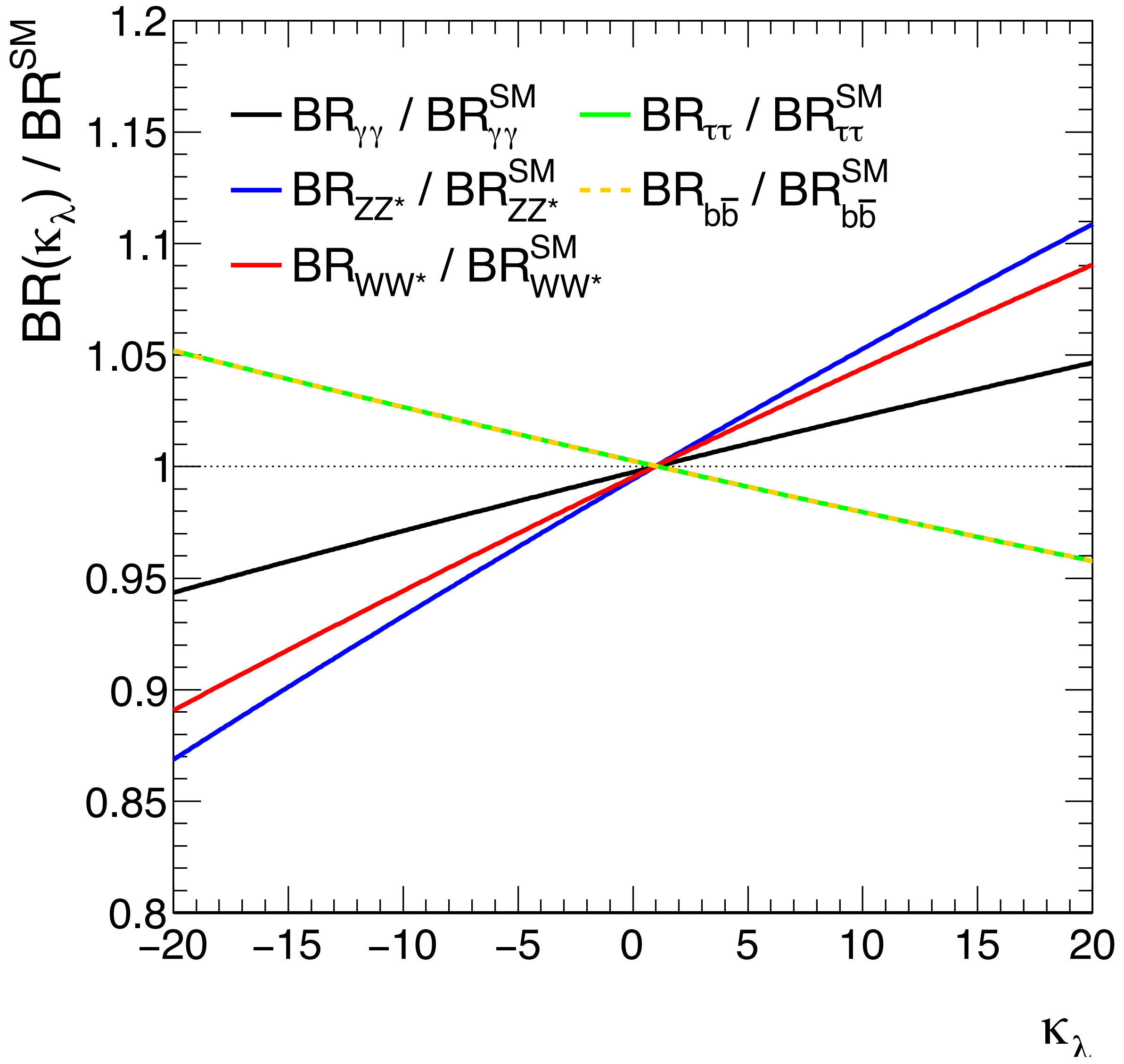
Thanks for your attention.

BACK-UP

Single Higgs constrains

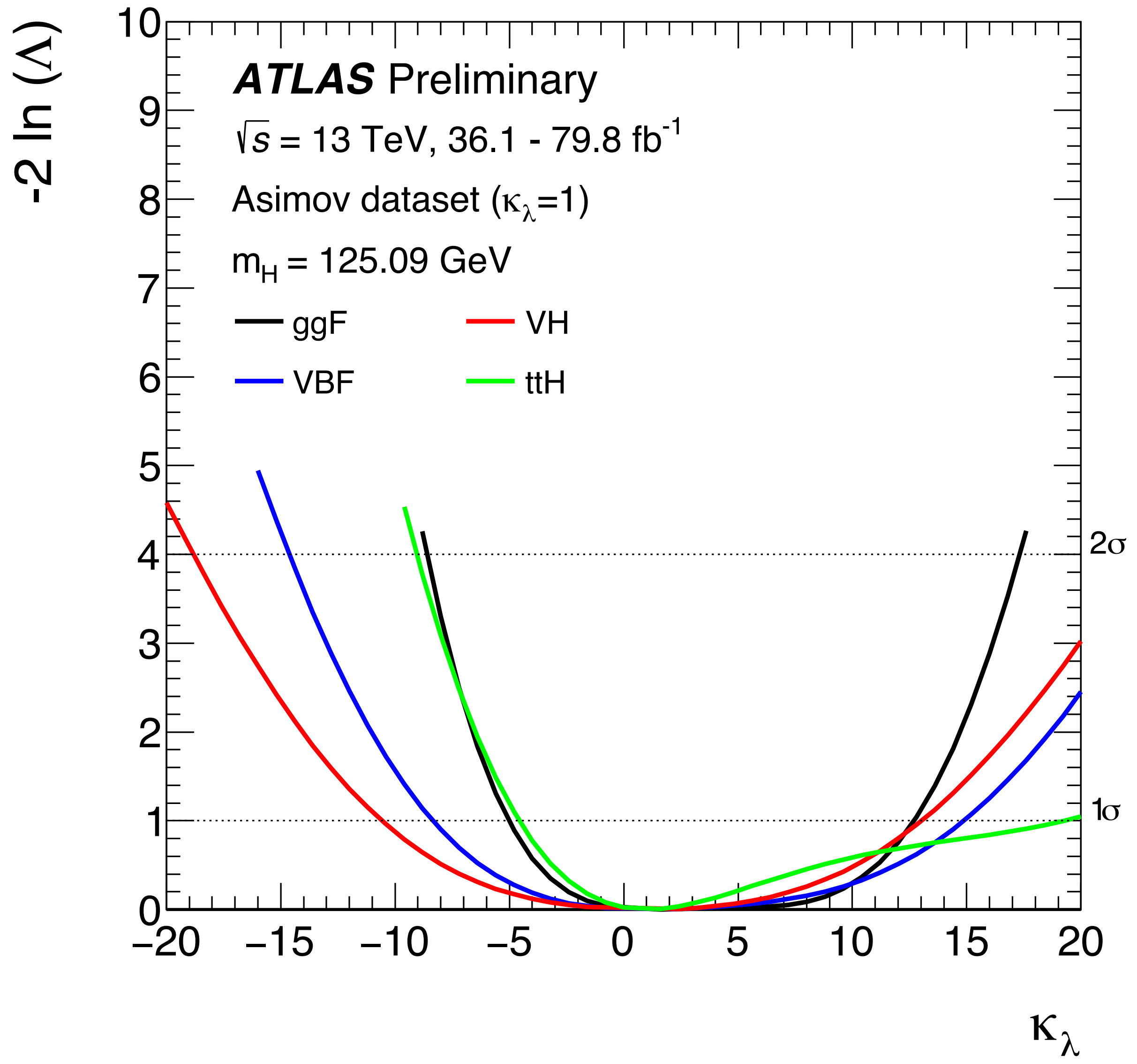


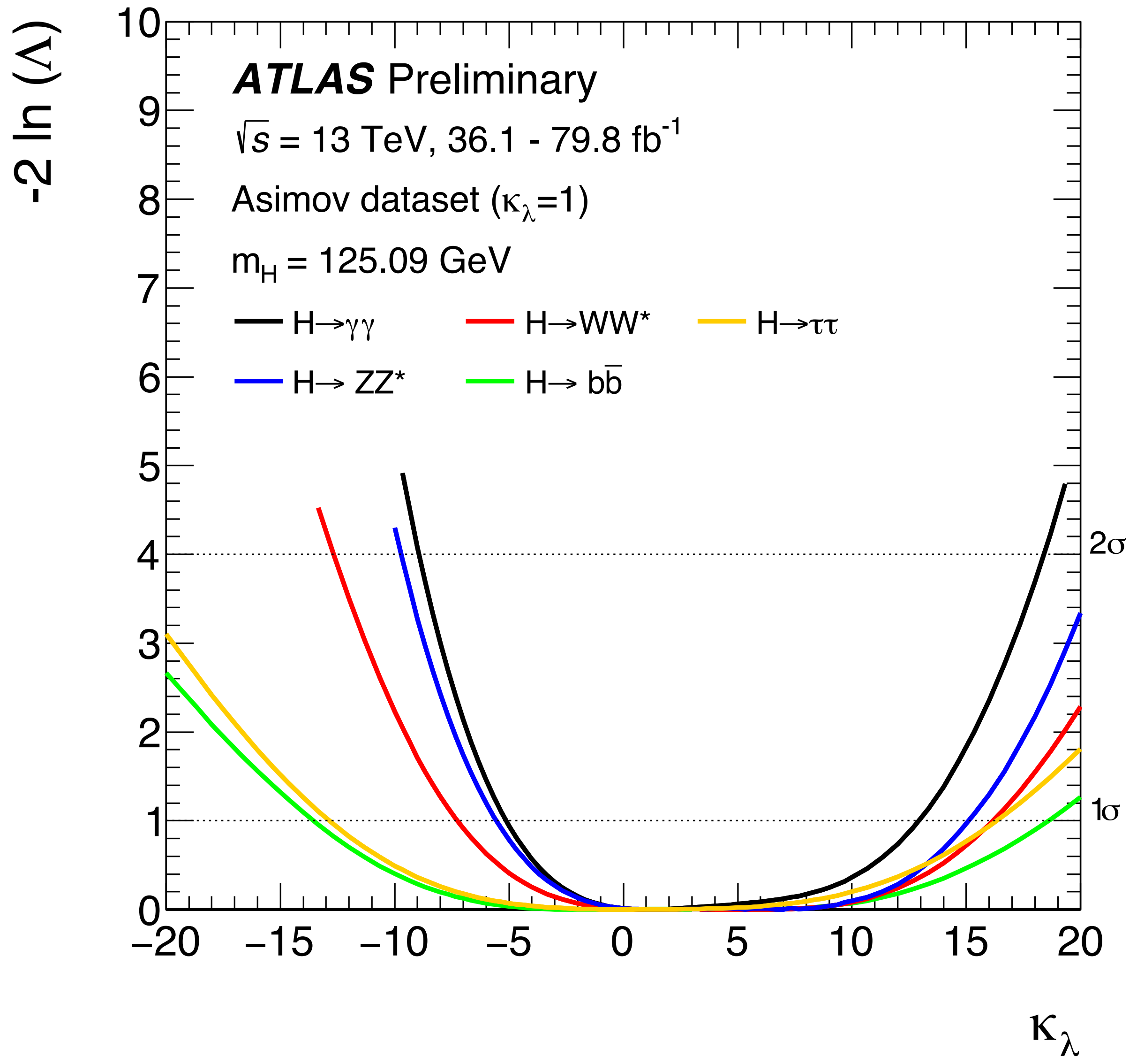


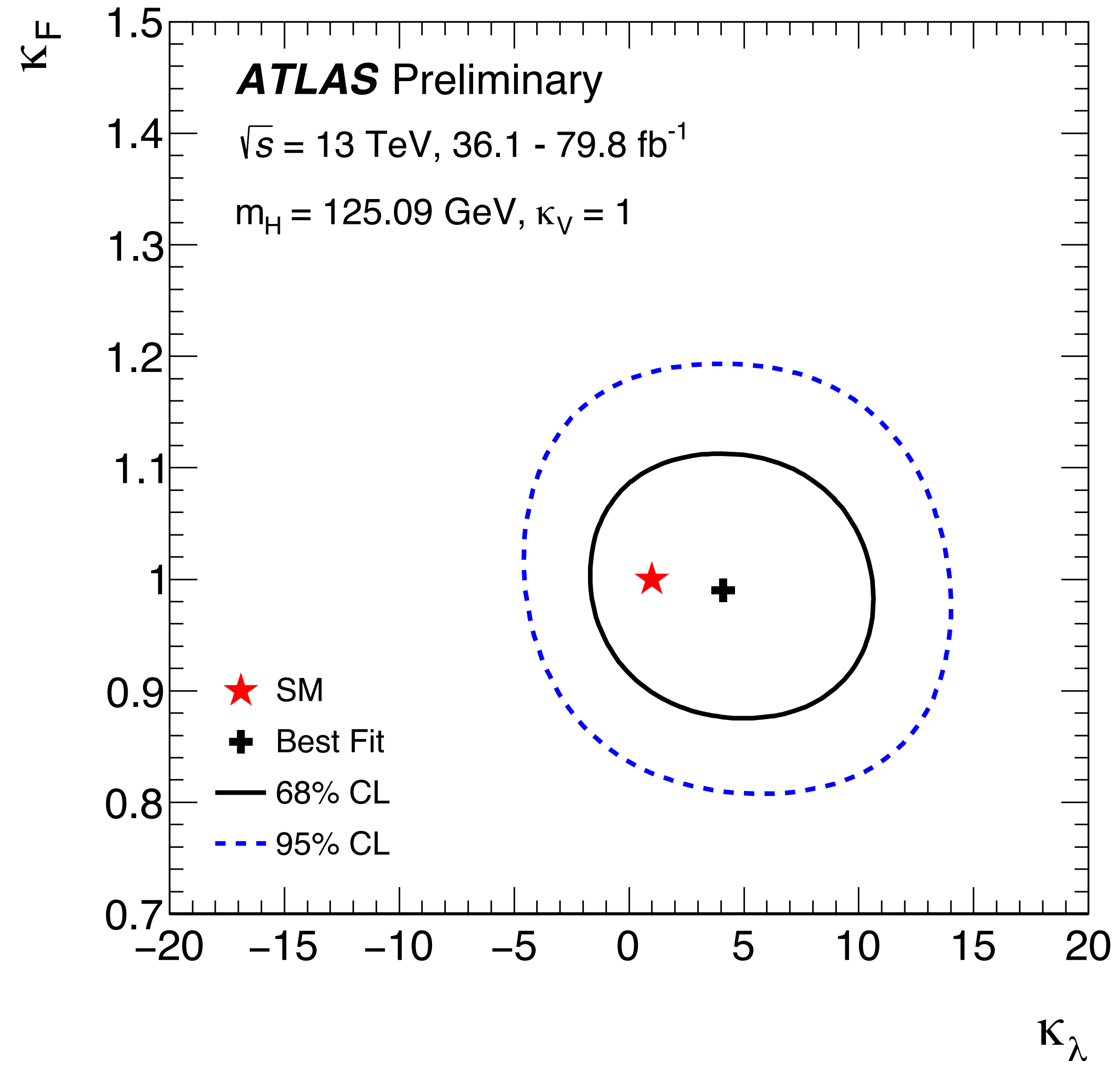


[ATL-PHYS-PUB-2019-009]

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



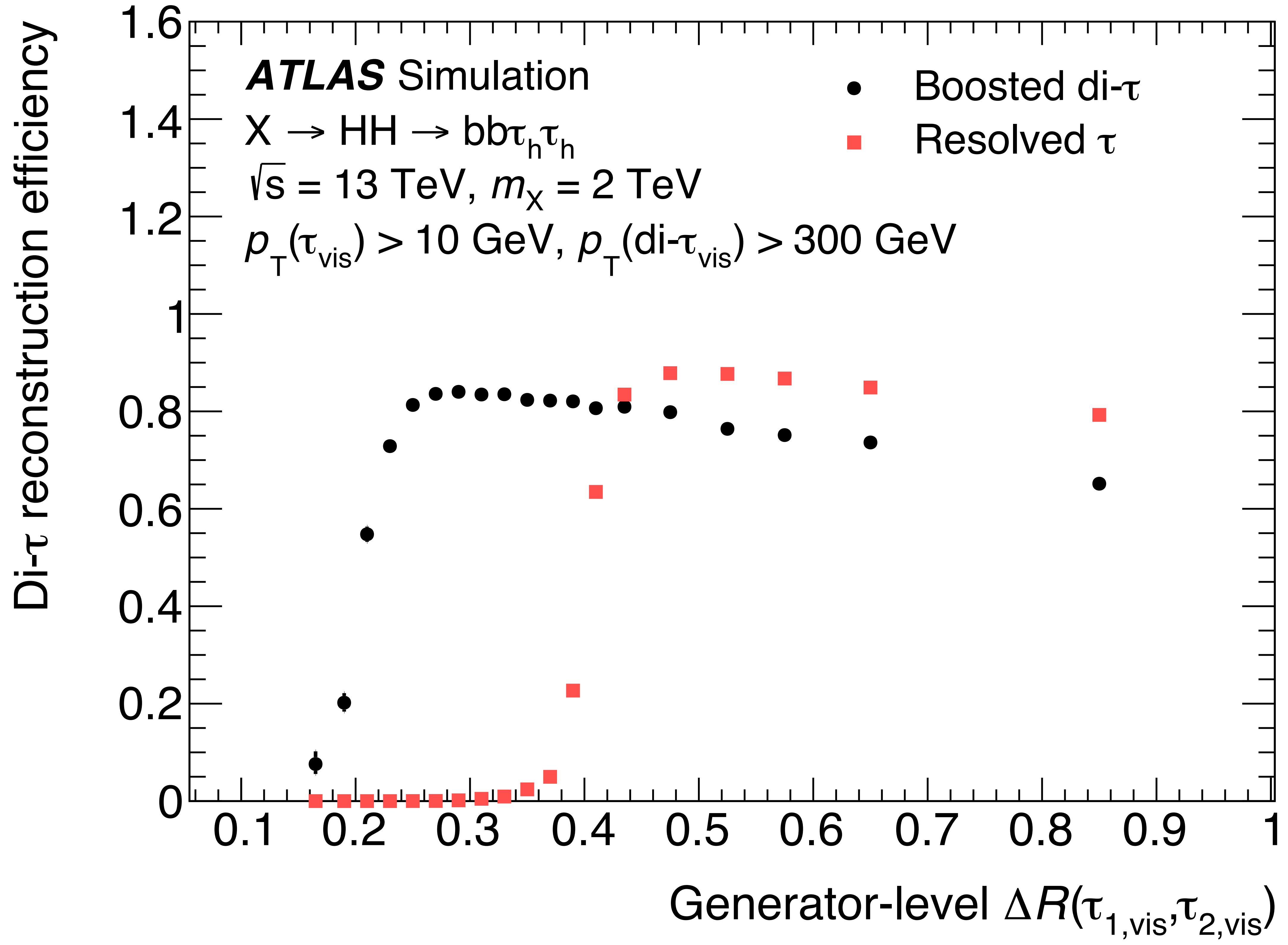




Bbtautau Boosted

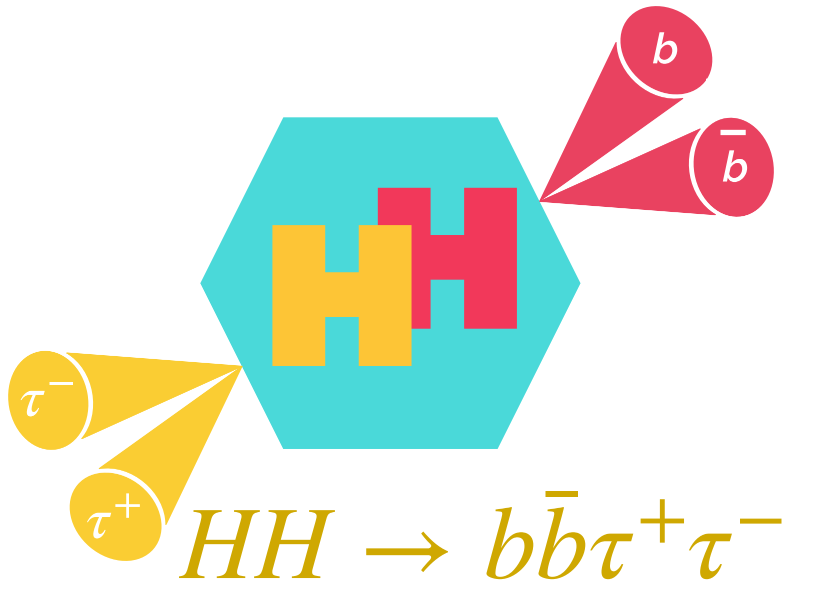
$HH \rightarrow b\bar{b}\tau^+\tau^-$

Boosted di-tau BDT identification:



Variable	Definition
$E^{\mathrm{sj}_1}_{\Delta R<0.1}/E^{\mathrm{sj}_1}_{\Delta R<0.2}$ and $E^{\mathrm{sj}_2}_{\Delta R<0.1}/E^{\mathrm{sj}_2}_{\Delta R<0.2}$	Ratios of the energy deposited in the core to that in the full cone, for the sub-jets sj_1 and sj_2, respectively
$p_{\mathrm{T}}^{\mathrm{sj}_2}/p_{\mathrm{T}}^{\mathrm{LRJ}}$ and $(p_{\mathrm{T}}^{\mathrm{sj}_1}+p_{\mathrm{T}}^{\mathrm{sj}_2})/p_{\mathrm{T}}^{\mathrm{LRJ}}$	Ratio of the p_{T} of sj_2 to the di-τ seeding large-radius jet p_{T} and ratio of the scalar p_{T} sum of the two leading sub-jets to the di-τ seeding large-radius jet p_{T}, respectively
$\log(\sum p_{\mathrm{T}}^{\text{iso-tracks}}/p_{\mathrm{T}}^{\mathrm{LRJ}})$	Logarithm of the ratio of the scalar p_{T} sum of the iso-tracks to the di-τ seeding large-radius jet p_{T}
$\Delta R_{\max}(\mathrm{track}, \mathrm{sj}_1)$ and $\Delta R_{\max}(\mathrm{track}, \mathrm{sj}_2)$	Largest separation of a track from its associated sub-jet axis, for the sub-jets sj_1 and sj_2, respectively
$\sum[p_{\mathrm{T}}^{\mathrm{track}}\Delta R(\mathrm{track}, \mathrm{sj}_2)]/\sum p_{\mathrm{T}}^{\mathrm{track}}$	p_{T}-weighted ΔR of the tracks matched to sj_2 with respect to its axis
$\sum[p_{\mathrm{T}}^{\text{iso-track}}\Delta R(\text{iso-track}, \mathrm{sj})]/\sum p_{\mathrm{T}}^{\text{iso-track}}$	p_{T}-weighted sum of ΔR between iso-tracks and the nearest sub-jet axis
$\log(m^{\mathrm{tracks,\,sj}_1}_{\Delta R<0.1})$ and $\log(m^{\mathrm{tracks,\,sj}_2}_{\Delta R<0.1})$	Logarithms of the invariant mass of the tracks in the core of sj_1 and sj_2, respectively
$\log(m^{\mathrm{tracks,\,sj}_1}_{\Delta R<0.2})$ and $\log(m^{\mathrm{tracks,\,sj}_2}_{\Delta R<0.2})$	Logarithms of the invariant mass of the tracks with $\Delta R < 0.2$ from the axis of sj_1 and sj_2, respectively
$\log(\lvert d^{\mathrm{sj}_1}_{0,\text{lead-track}}\rvert)$ and $\log(\lvert d^{\mathrm{sj}_2}_{0,\text{lead-track}}\rvert)$	Logarithms of the closest distance in the transverse plane between the primary vertex and the leading track of sj_1 and sj_2, respectively
$n^{\mathrm{sj}_1}_{\mathrm{tracks}}$ and $n^{\text{sub-jets}}_{\mathrm{tracks}}$	Number of tracks matched to sj_1 and to all sub-jets, respectively

Bbtautau Resolved



BDT input variables:

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

Impact of systematics on SM limit:

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

Non resonant limits per channel:

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

BDTs

ggF: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-016

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

Non Resonant

Variable	Definition
Photon-related kinematic variables	
$p_T/m_{\gamma\gamma}$	Transverse momentum of the two photons scaled by their invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudo-rapidity and azimuthal angle of the leading and sub-leading photon
Jet-related kinematic variables	
b-tag status	Highest fixed b-tag working point that the jet passes
p_T, η and ϕ	Transverse momentum, pseudo-rapidity and azimuthal angle of the two jets with the highest b-tagging score
$p_T^{b\bar{b}}$, $\eta_{b\bar{b}}$ 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^{miss} and ϕ^{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 ΔR 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 ΔR between the two b-tagged jets
N_{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 ΔR between the di-photon and the b-tagged jets system

Post-fit plots

ggF: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-016

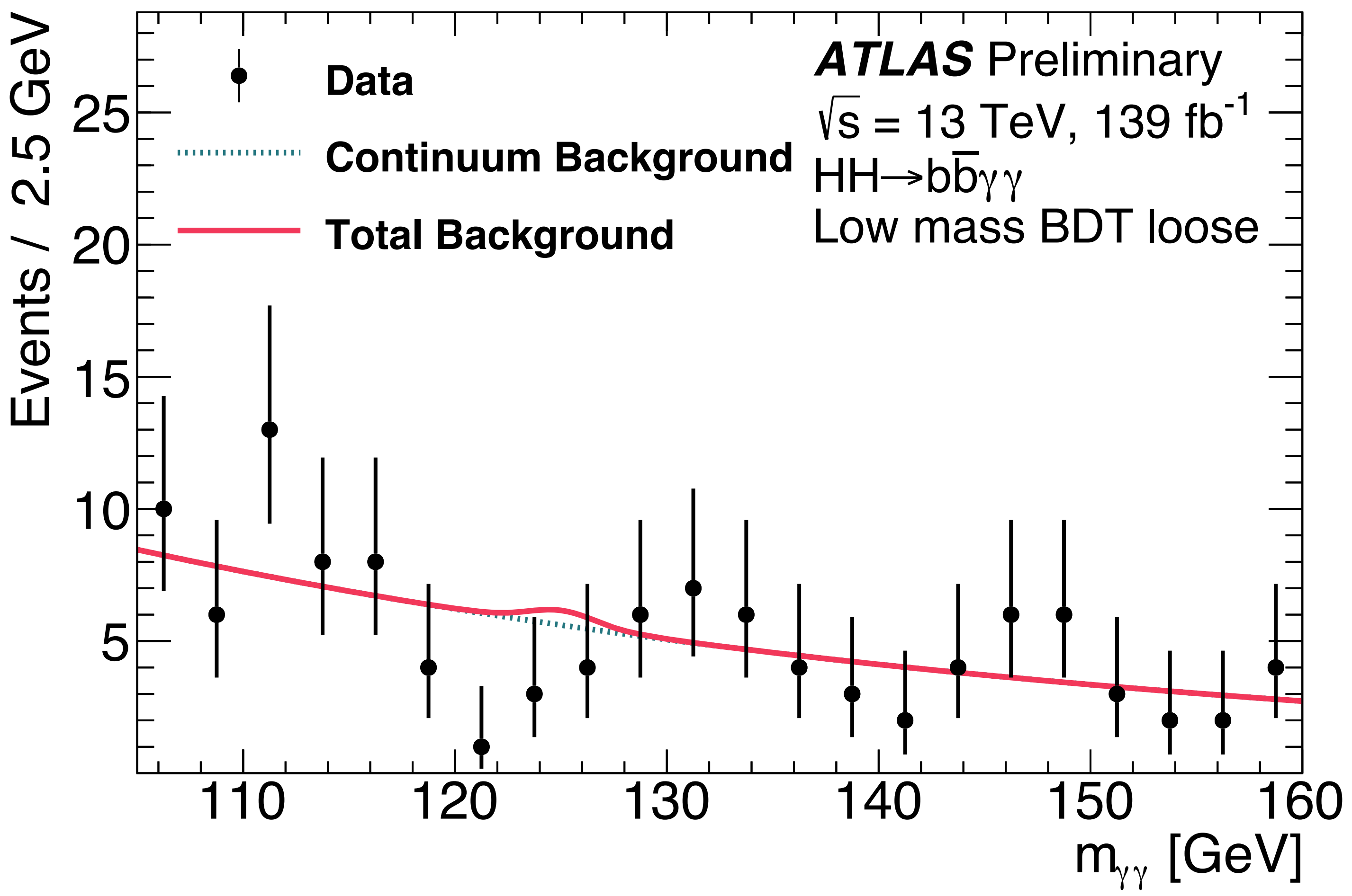
$HH \rightarrow b\bar{b}\gamma\gamma$

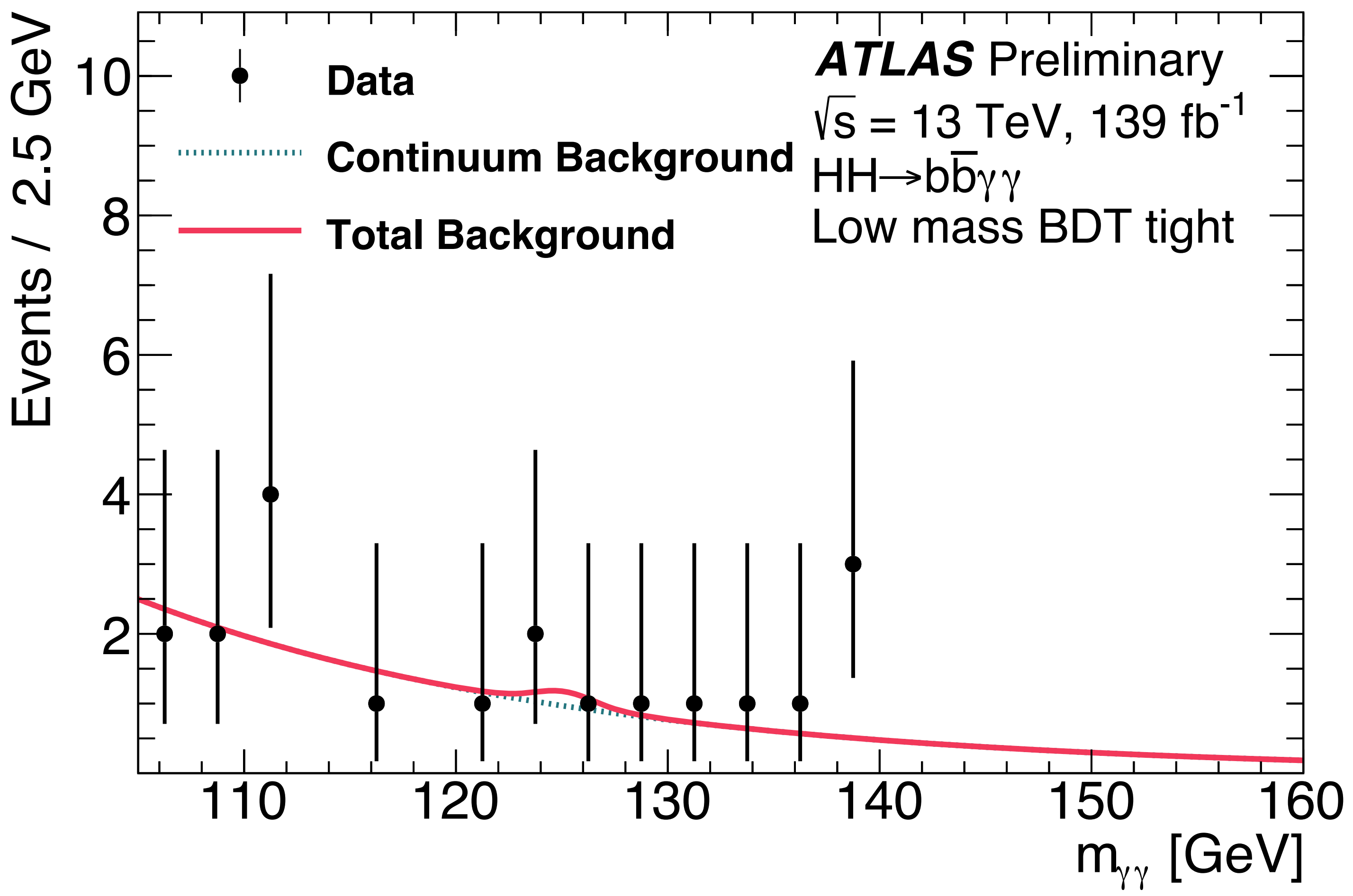
Non Resonant

BDT loose

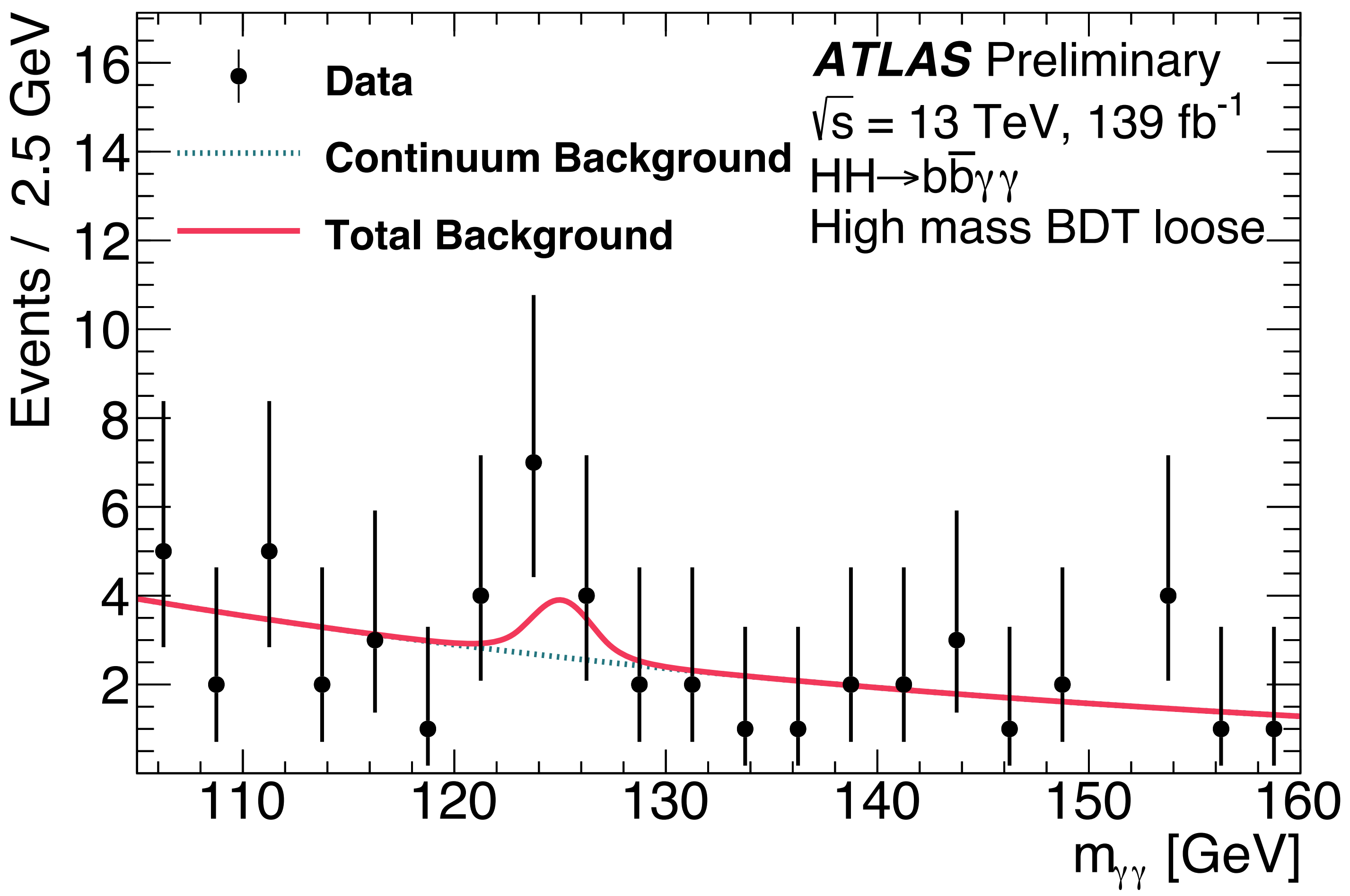
BDT tight

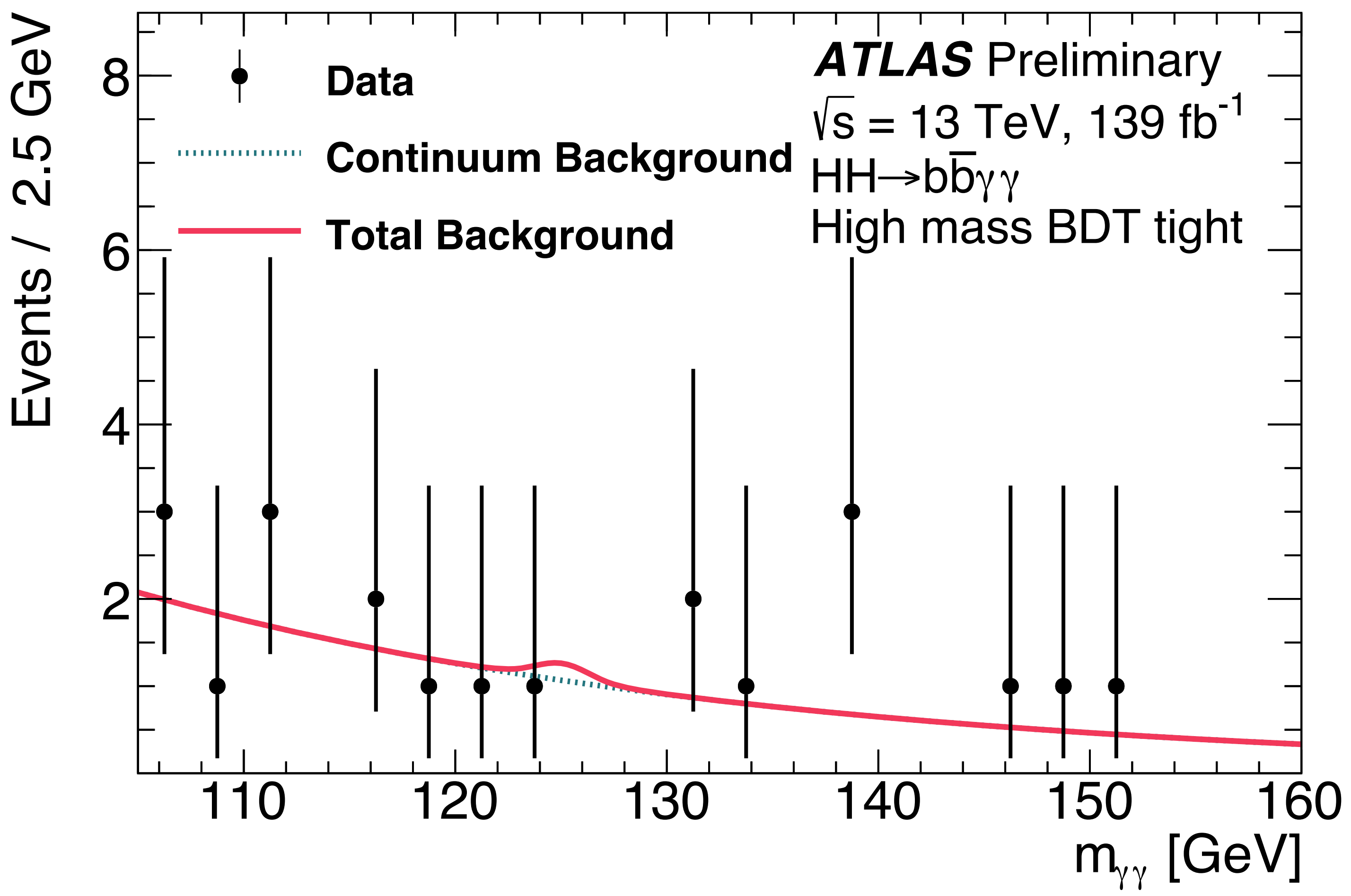
Low mass





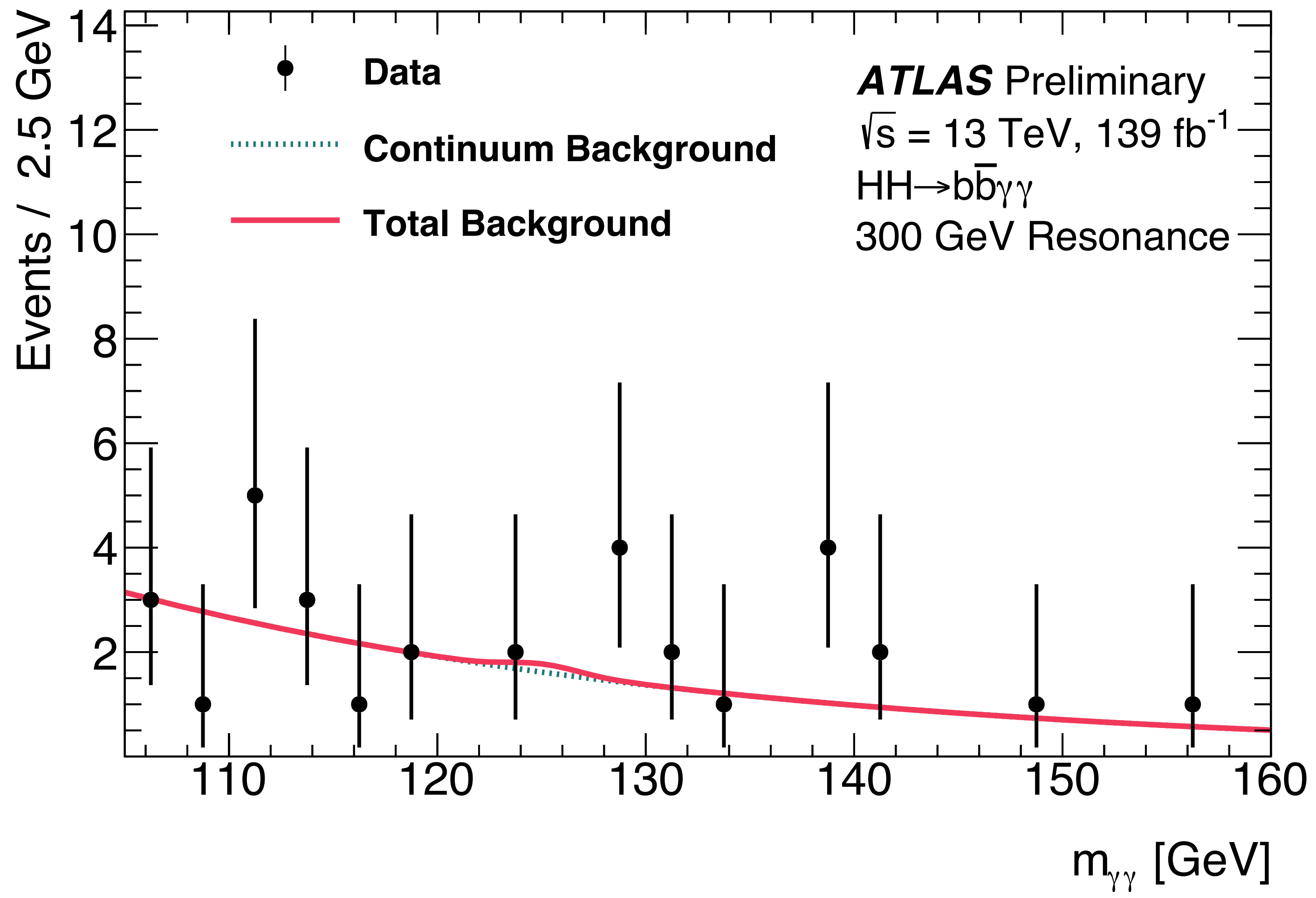
High mass



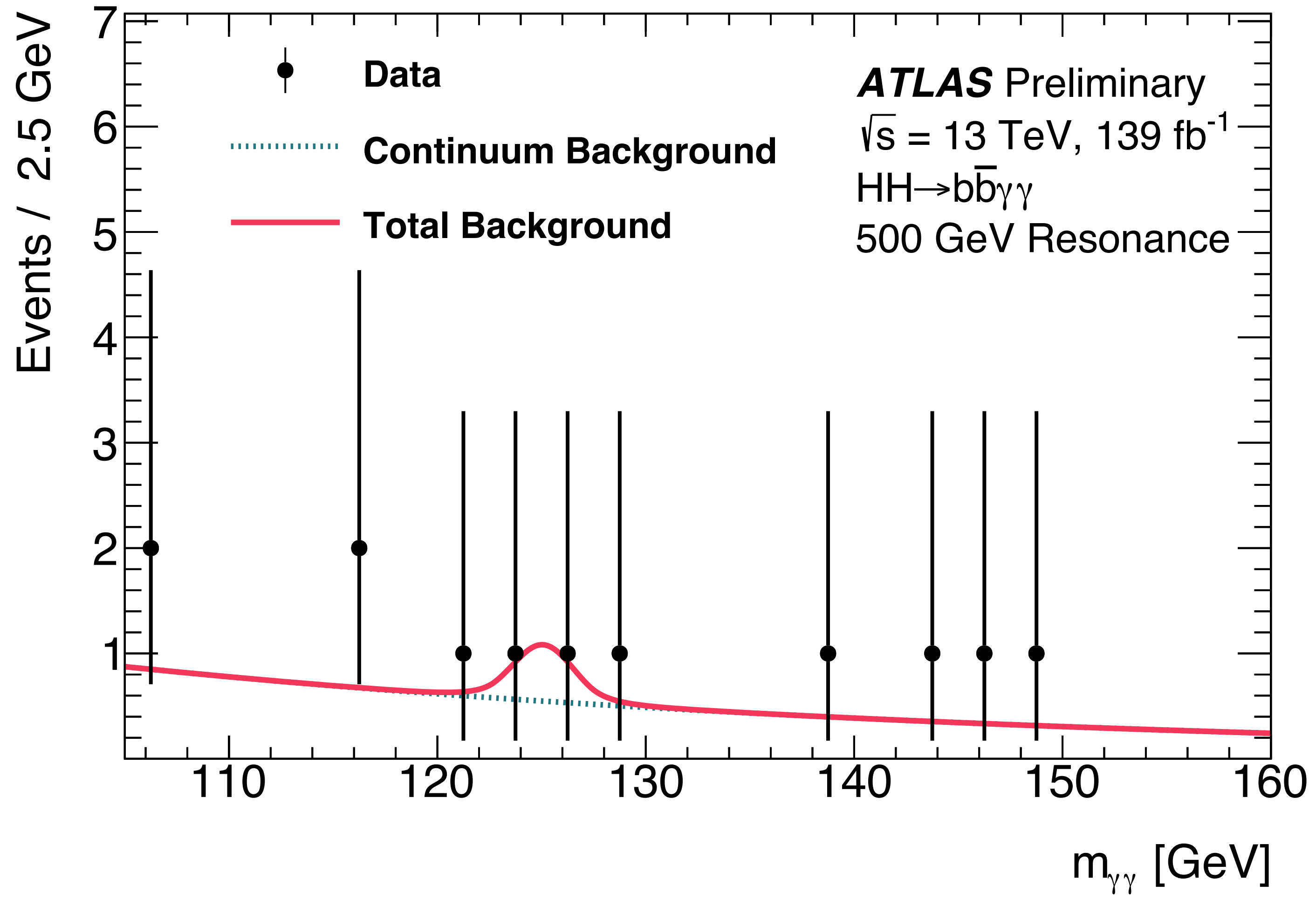


Resonant

Mx = 300 GeV



Mx = 500 GeV



Yields and systematics

ggF: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-016

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

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

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

Comparison to CMS

$\frac{\sigma(pp \to HH)}{\sigma_{SM}}$ at 13 TeV		Partial Run 2 (2015-16)		Ful Run 2 (2015-18)	
		Obs	Exp	Obs	Exp
$HH \to bbyy$	ATLAS	20.3	26	4.1	5.5
	CMS	23.6	18.8	7.7	5.2
$HH \to bb\tau\tau$	ATLAS	12.5	15	4.7	3.9
	CMS	31.4	25.1		
$HH \to bbbb$	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 κ_λ at 95% C.L.		Obs	Exp
$HH \to bbyy$	ATLAS	-1.5 – 6.7	-2.4 – 7.7
	CMS	-3.3 – 8.5	-2.5 – 8.2
$HH \to bbbb$	ATLAS		
	CMS	-2.3 – 9.4	-5.0 – 12.0
Combination *partial Run 2*	ATLAS	-5.0 – 12.0	-5.8 – 12.0
	CMS	-11.8 – 18.8	-7.1 – 13.6
Full Run 2	ATLAS	-1.0 – 6.6	-1.2 – 7.2