Are pair of Higgs bosons more interesting than just one?

Louis D'Eramo,
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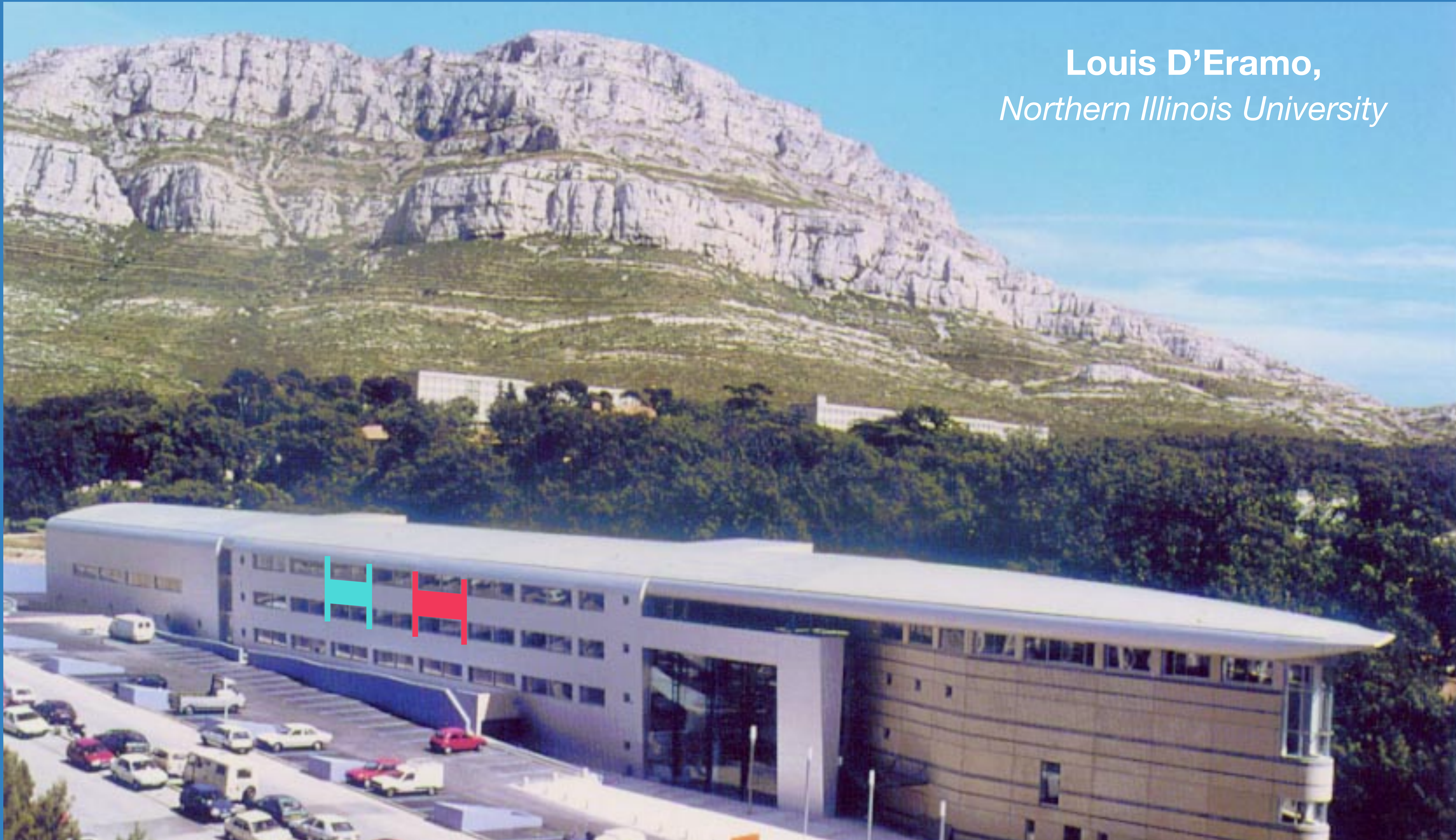

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Investigating the Higgs potential

The full expression of the Higgs potential is encoded with parameters μ and λ as:

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

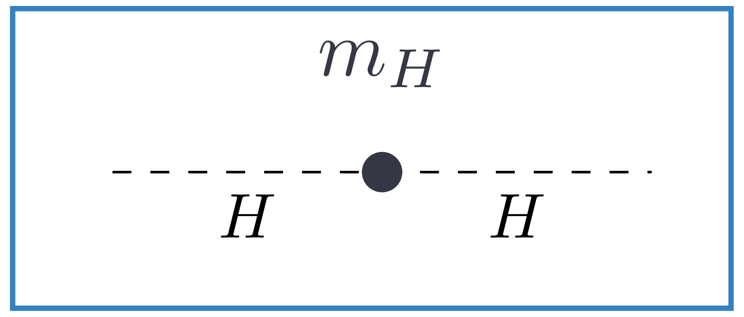
When linearising the Higgs field after the EWSB around the vacuum expected value ν one gets:

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

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.



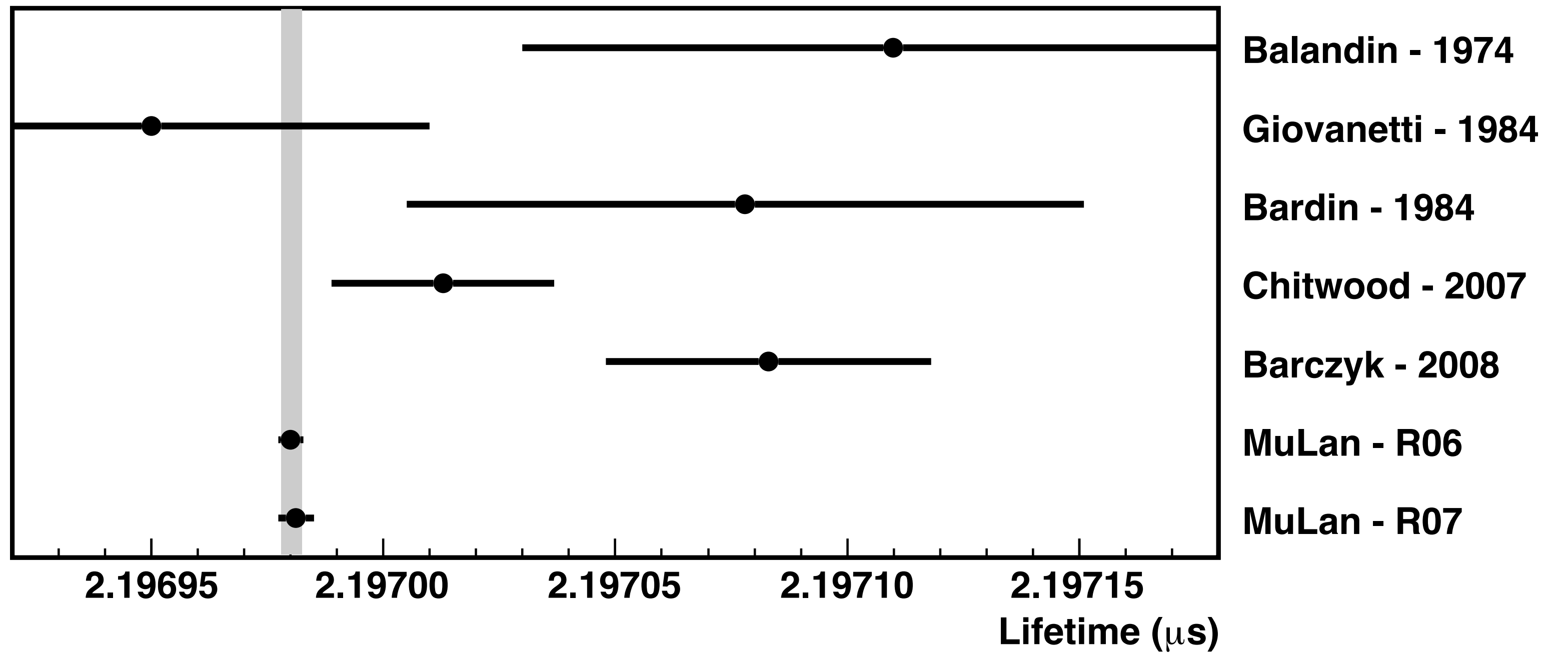
- The first piece of information came from the Higgs boson discovery:
  - Existence of a new particle with couplings according to prediction from EWSB;
  - First measurement of Higgs mass:

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

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

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

1010.0991



- From most precise MuLan experiment:

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

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

$\hookrightarrow \lambda \sim 0.13$

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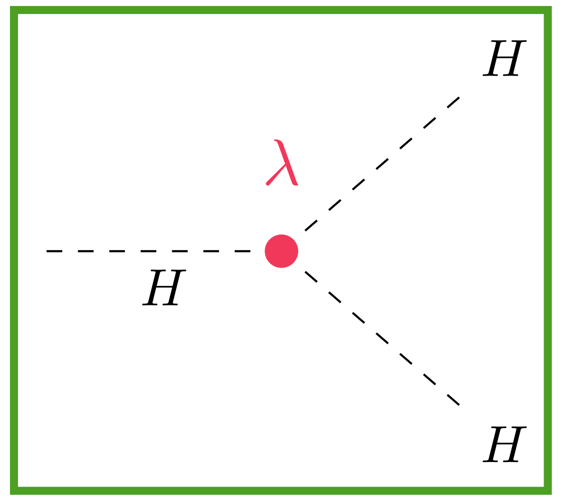
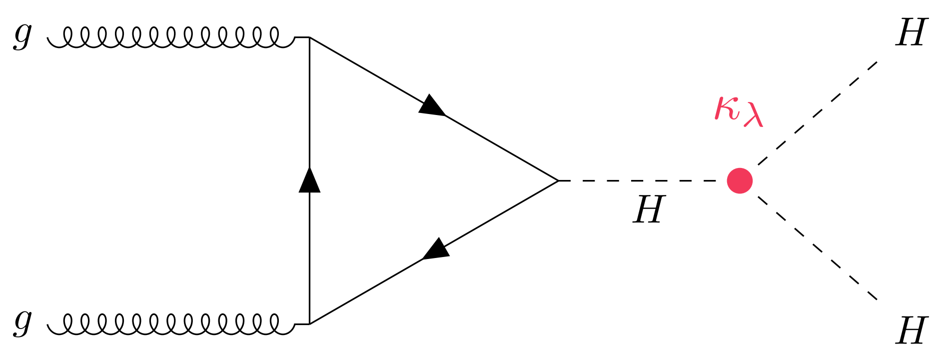
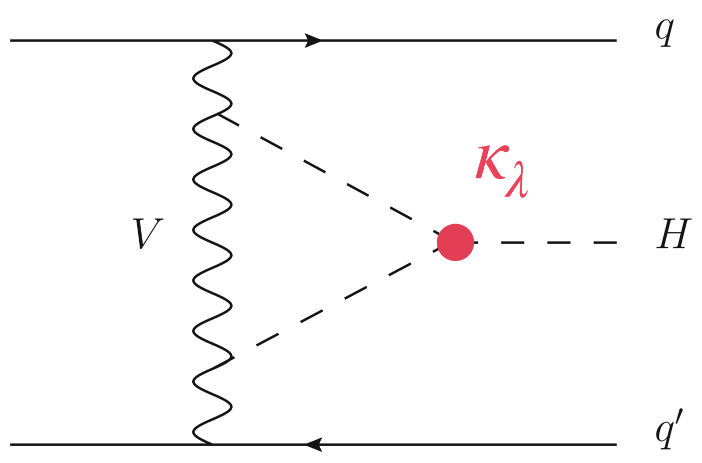
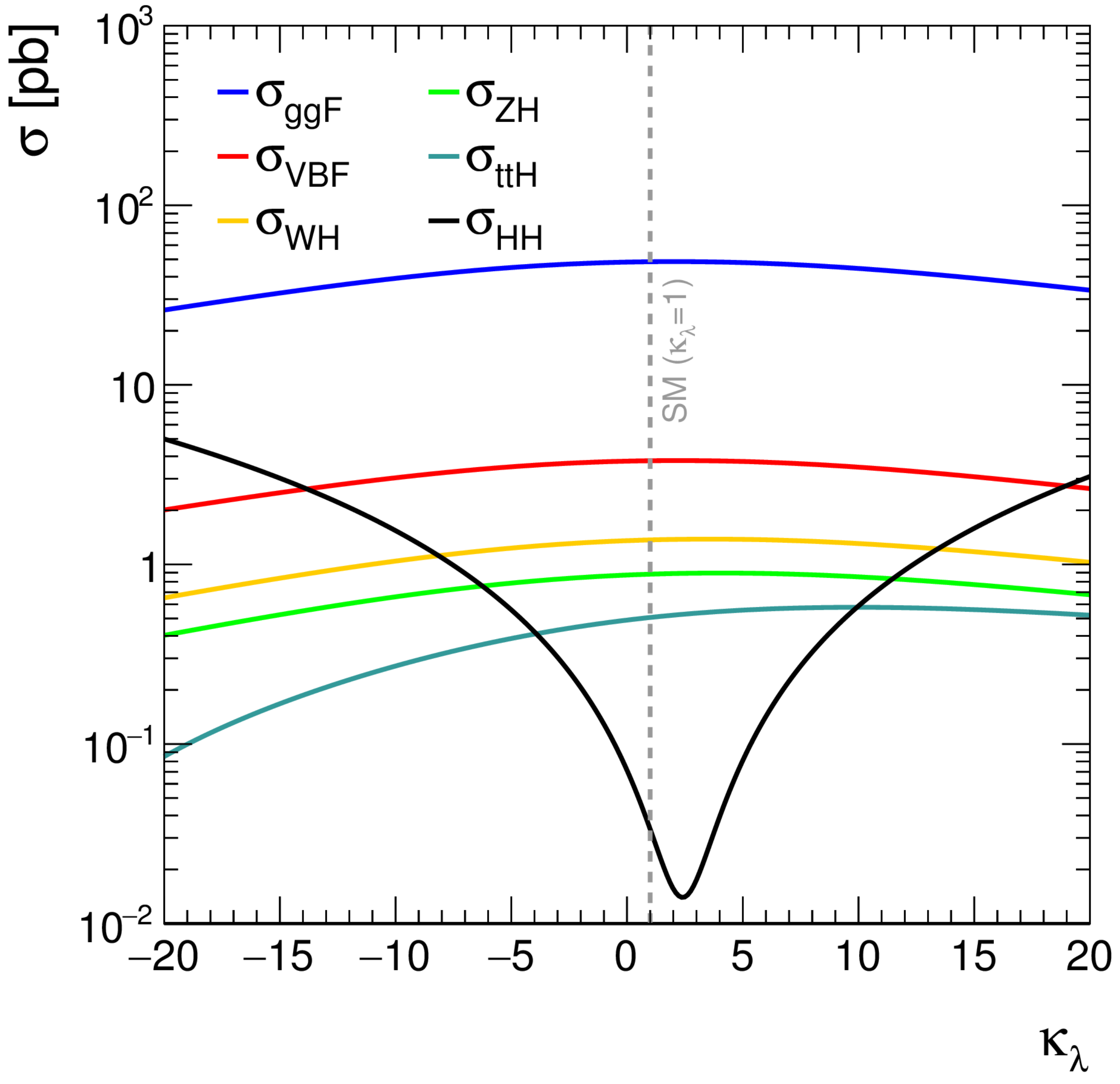


- Direct access to λ through Higgs pair creation:
  - Coupling strength denoted as $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$
  - At tree level: production of pair of Higgs bosons →strong effect on XS.
  - At loop level: effect on the single Higgs cross-section and deviations in kinematics.







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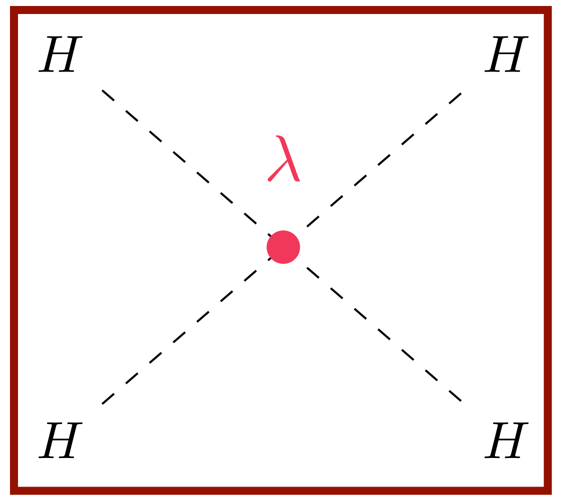
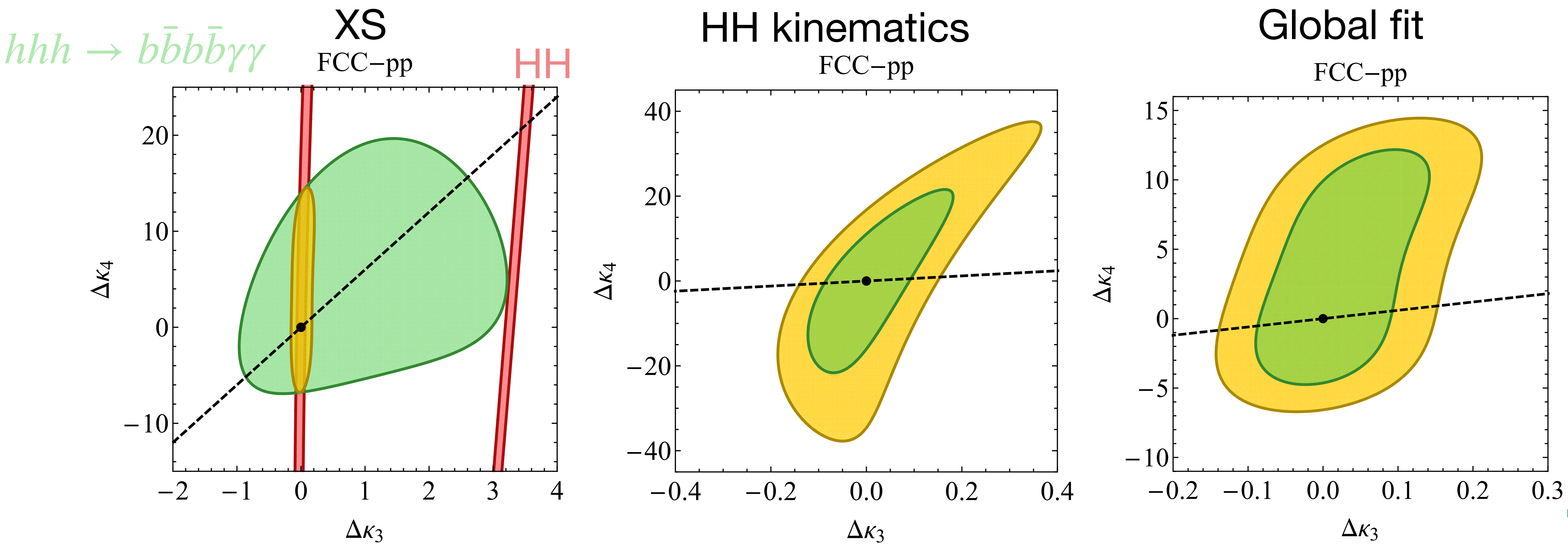


- Quartic interaction even rarer :
  - At tree level: very mild effect on XS and kinematic distributions.
  - At loop level: similar constraints obtained on XS, but stronger effect kinematics.
  - No strong constraints even with FCC 100 TeV collider ($\kappa_4 \in [-3,13]$) or the CLIC 3000 GeV ($\kappa_4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



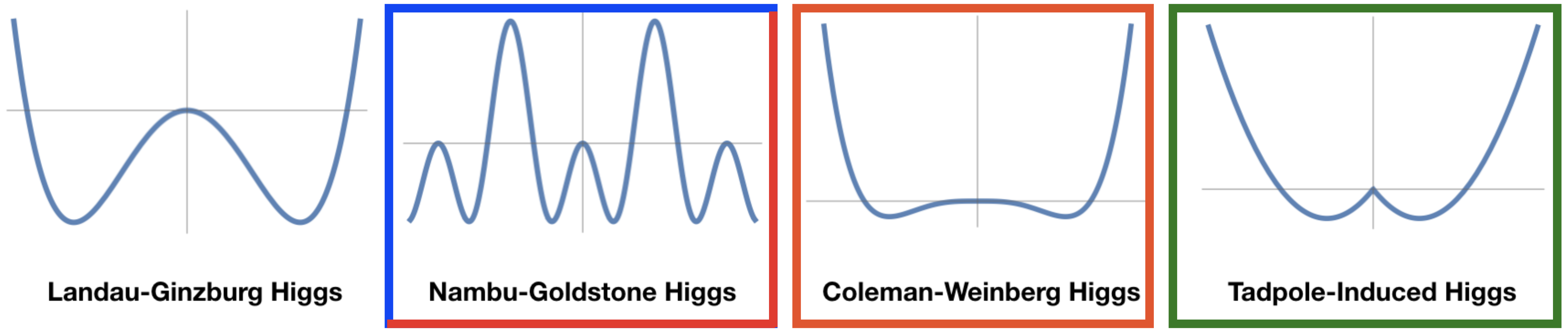
1810.04665

Exploring alternative scenarios

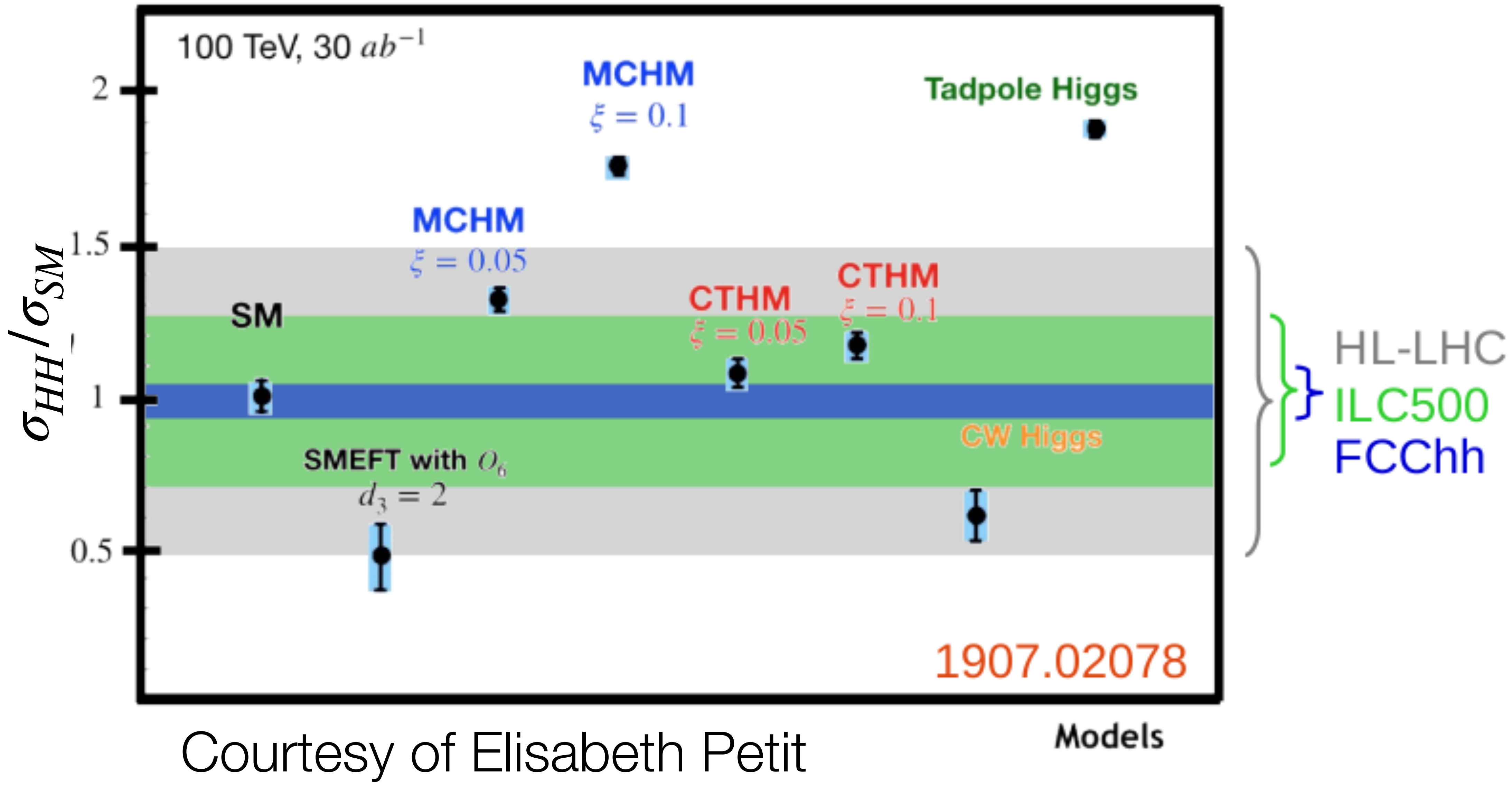
The measurement of the Higgs potential is answering the fundamental question of its nature.
Several other models can show a non zero vacuum expected value with a different second order contribution:

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

- 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

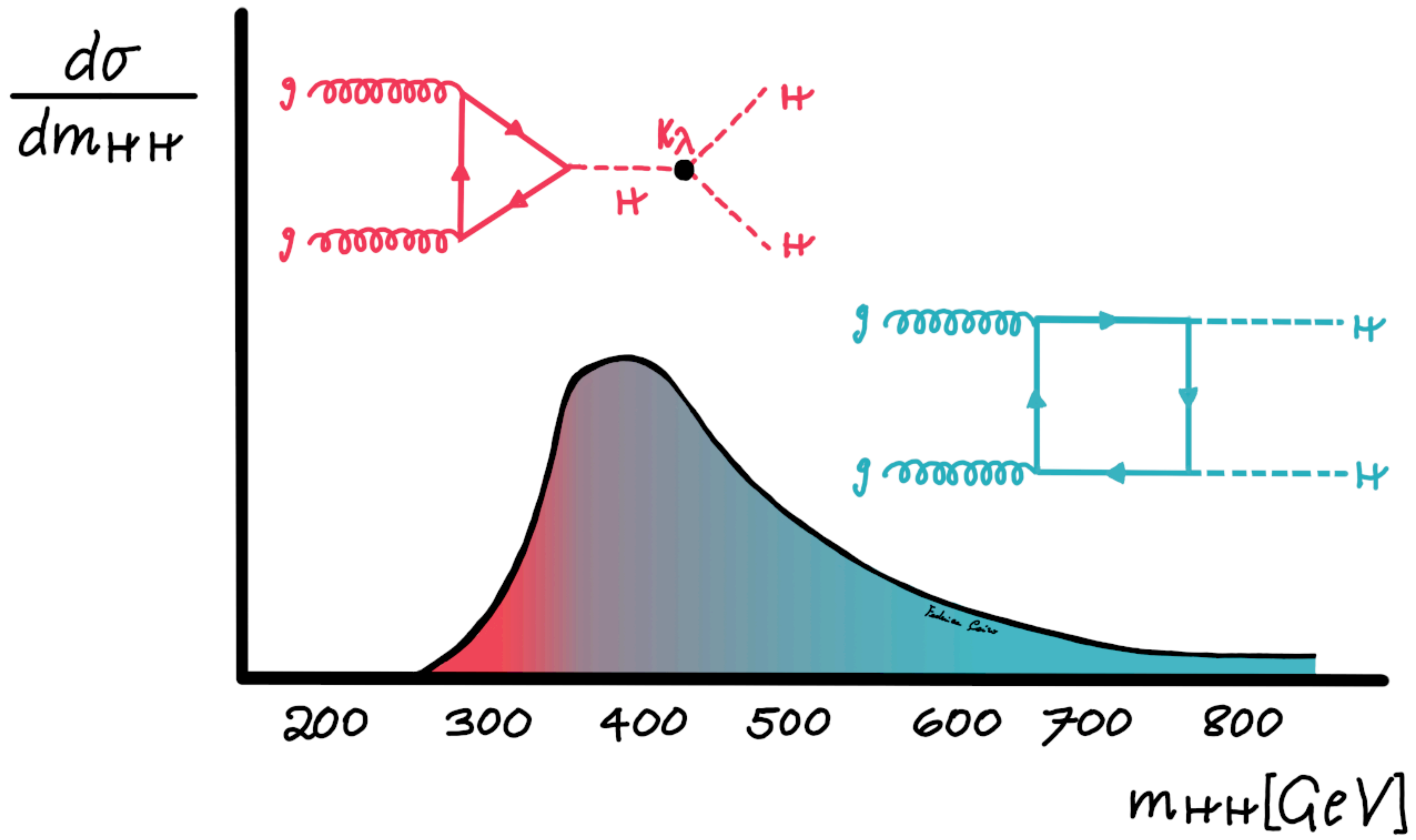


minimal composite Higgs model/
composite twin Higgs model :
different coupling to top quark

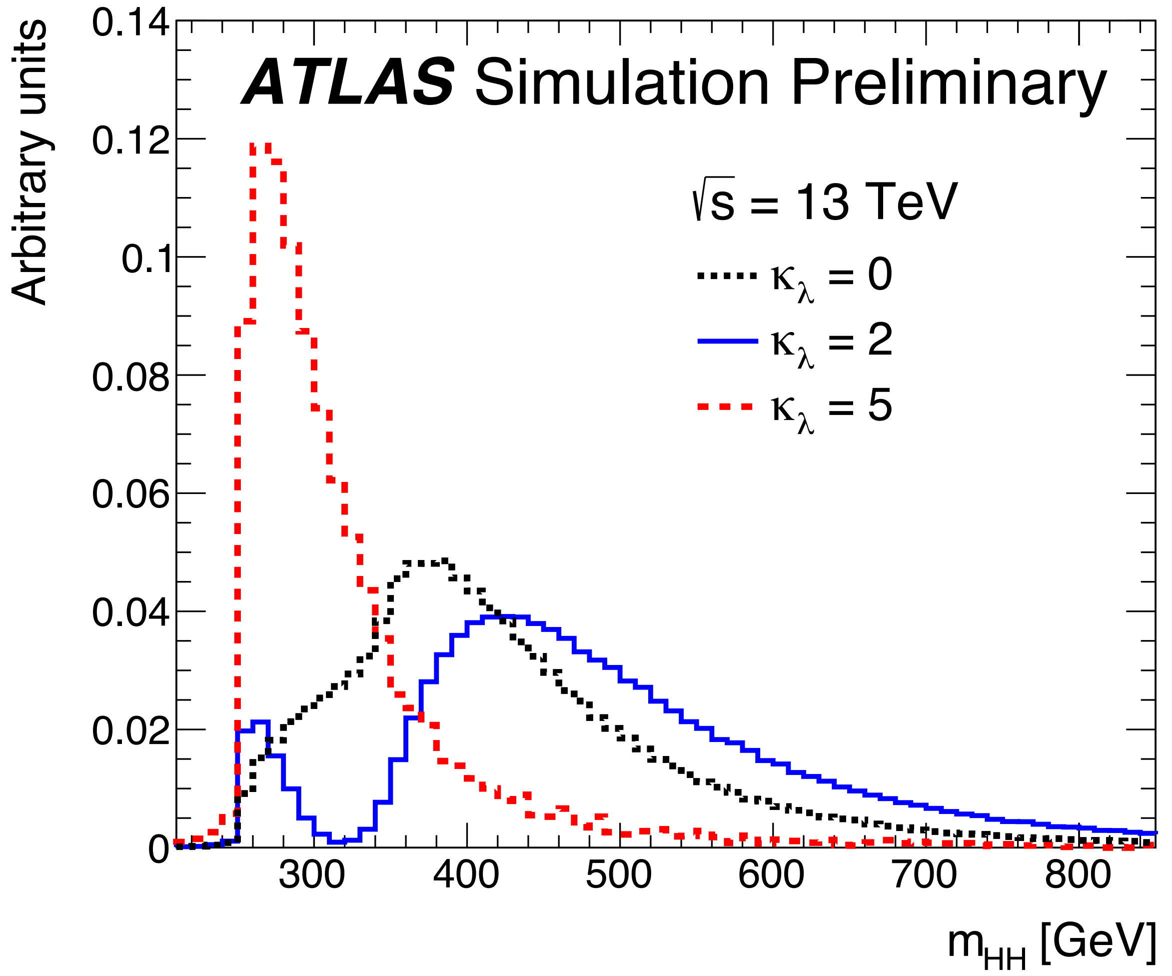


Courtesy of Elisabeth Petit

How are Higgs pairs produced?

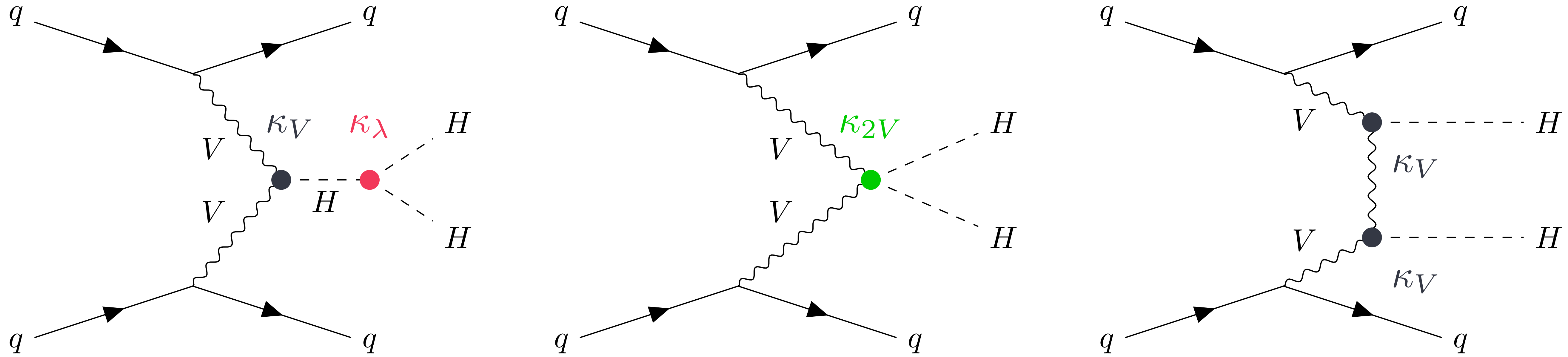


- **gluon-gluon Fusion (ggF):** $\sigma_{HH}^{ggF} = 31.02$ fb
  - Destructive interference between triangle and box diagrams makes the cross-section tiny (1000x smaller than single Higgs).
  - Low masses essential to constrain trilinear coupling κ_λ
  - m_{HH} shape very dependent on the κ_λ



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

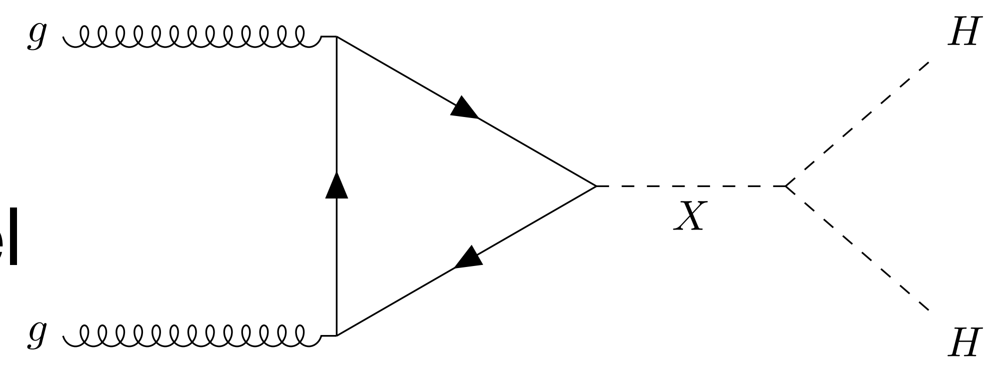
Second order contribution to total production, but direct handle to vector boson coupling modifiers κ_{2V} and κ_V:



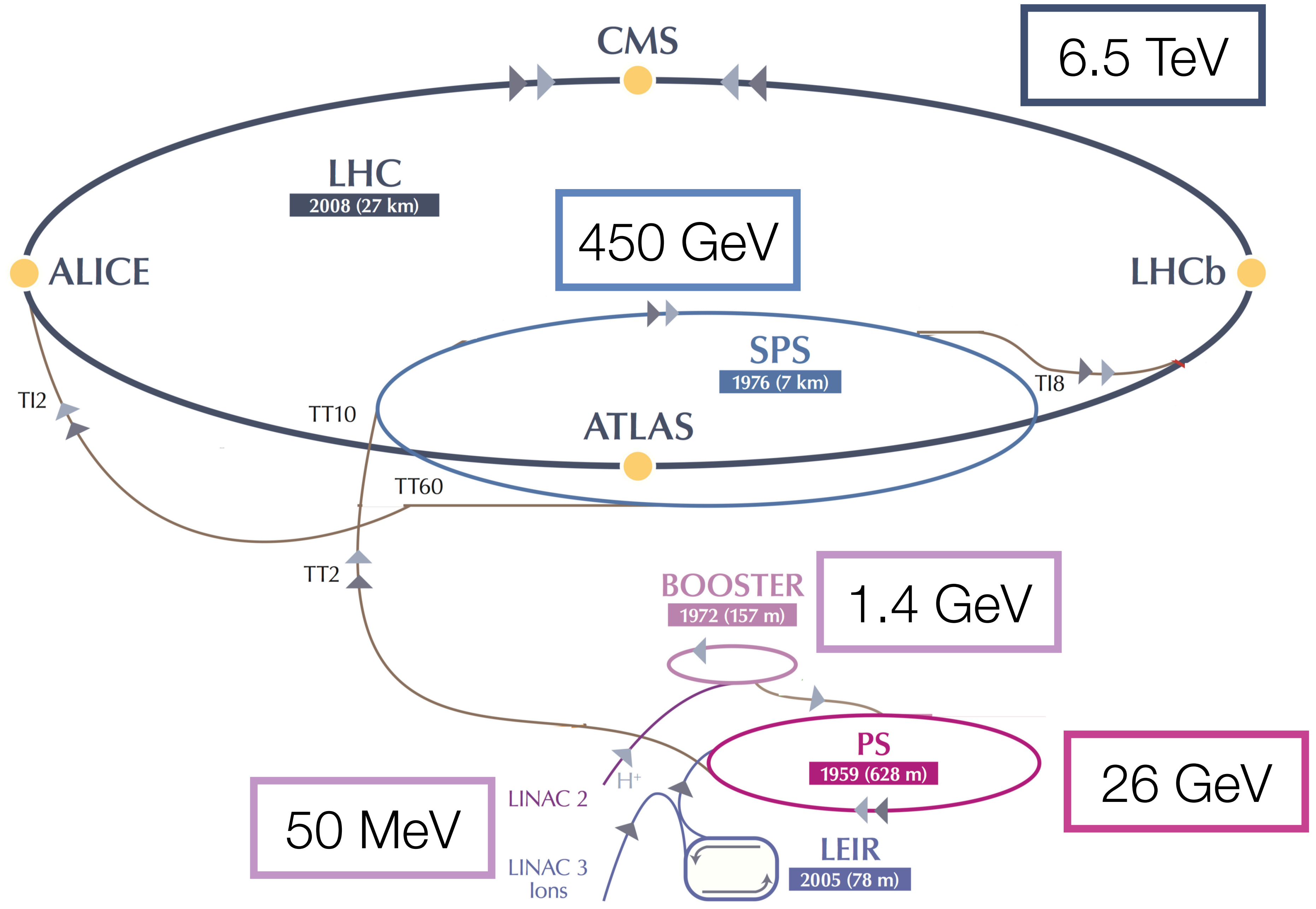
- **BSM resonances:**

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 ?

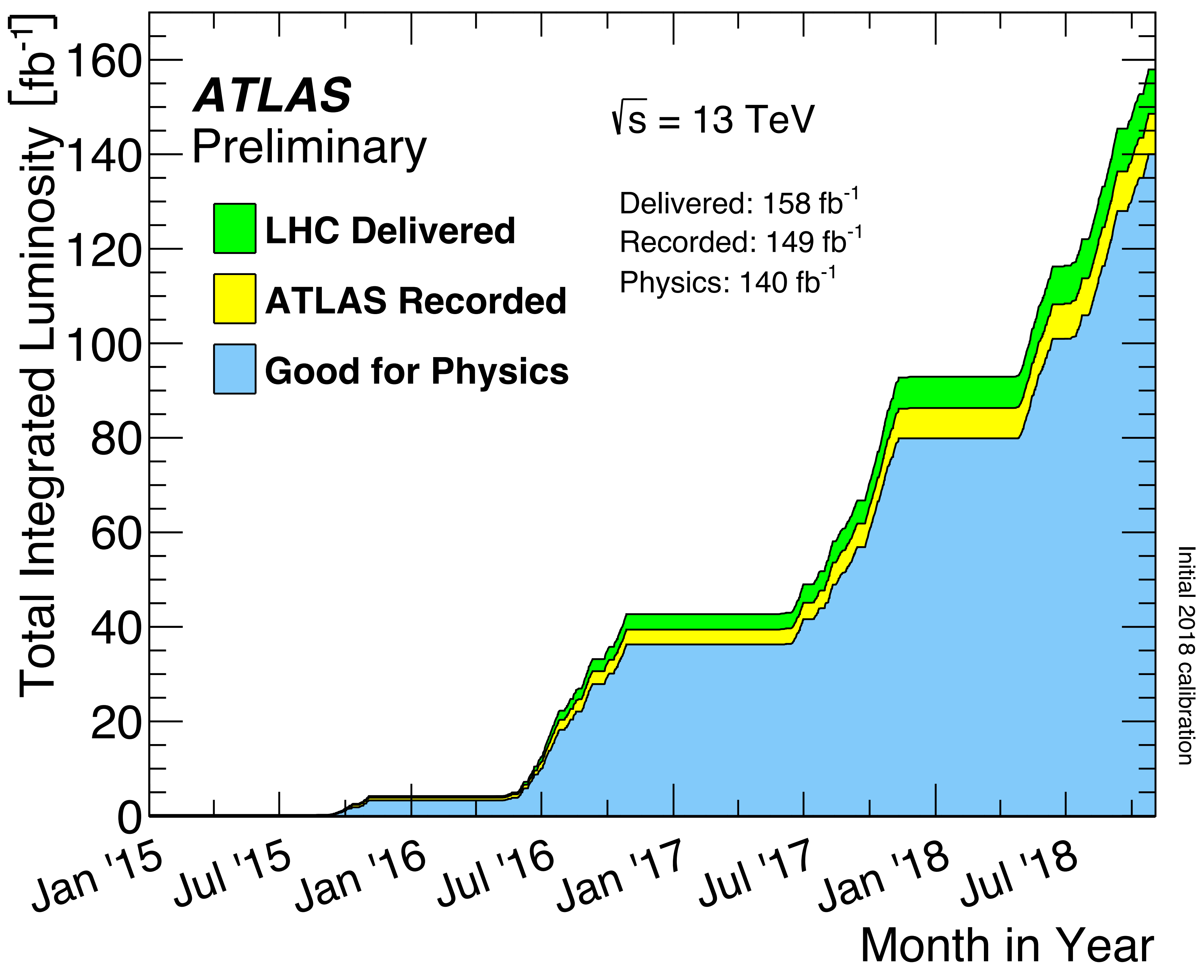


Located under the French Swiss Border, the **Large Hadron Collider** is the final piece of a staged acceleration chain allowing high luminosity **proton-proton** collisions.

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.

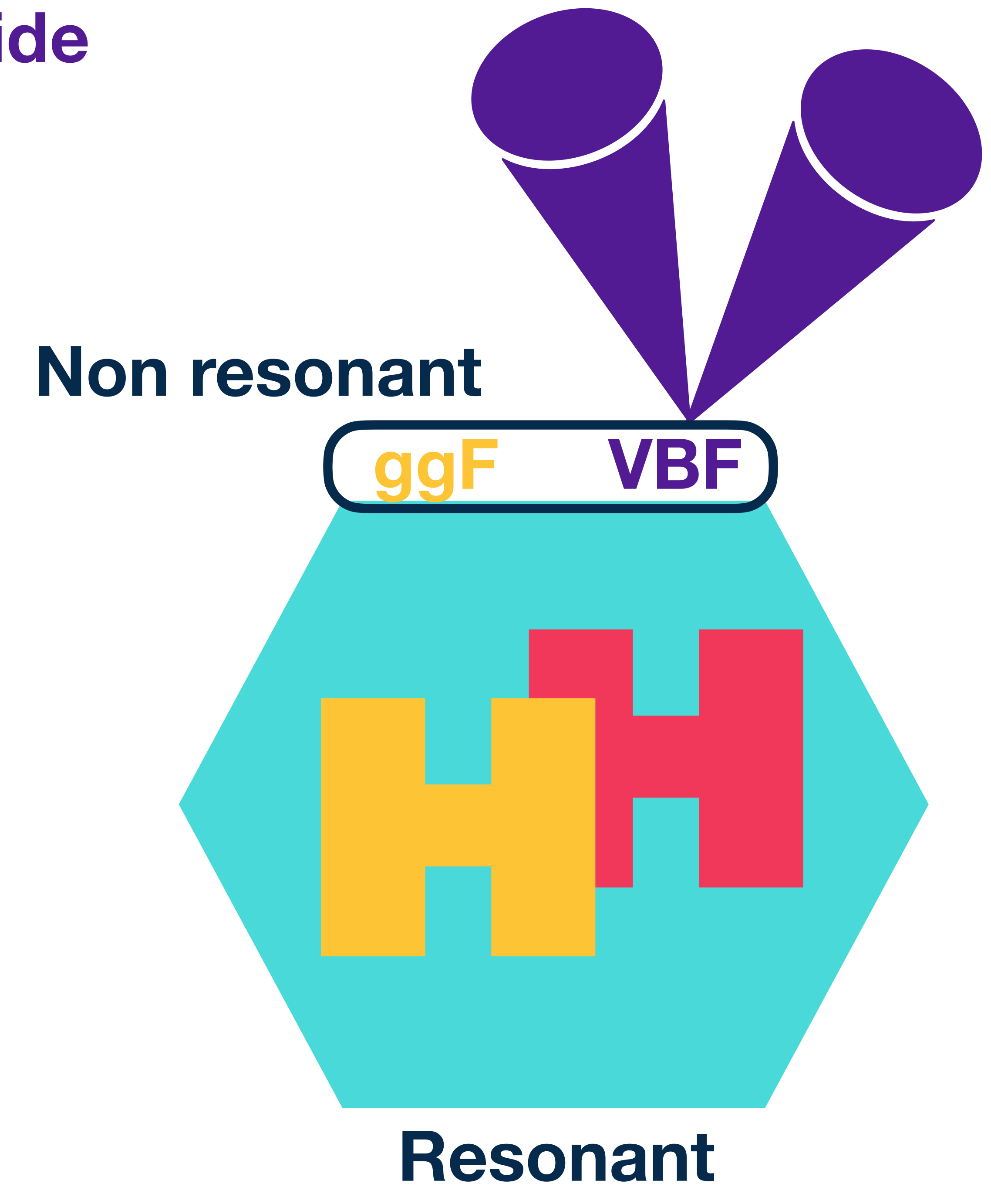
	N_H	N_{HH}
Run-1	512 000	200
Run-2	6 800 000	4 300
Run-3*	7 700 000	5 000
HL-LHC*	165 000 000	110 000

*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**.

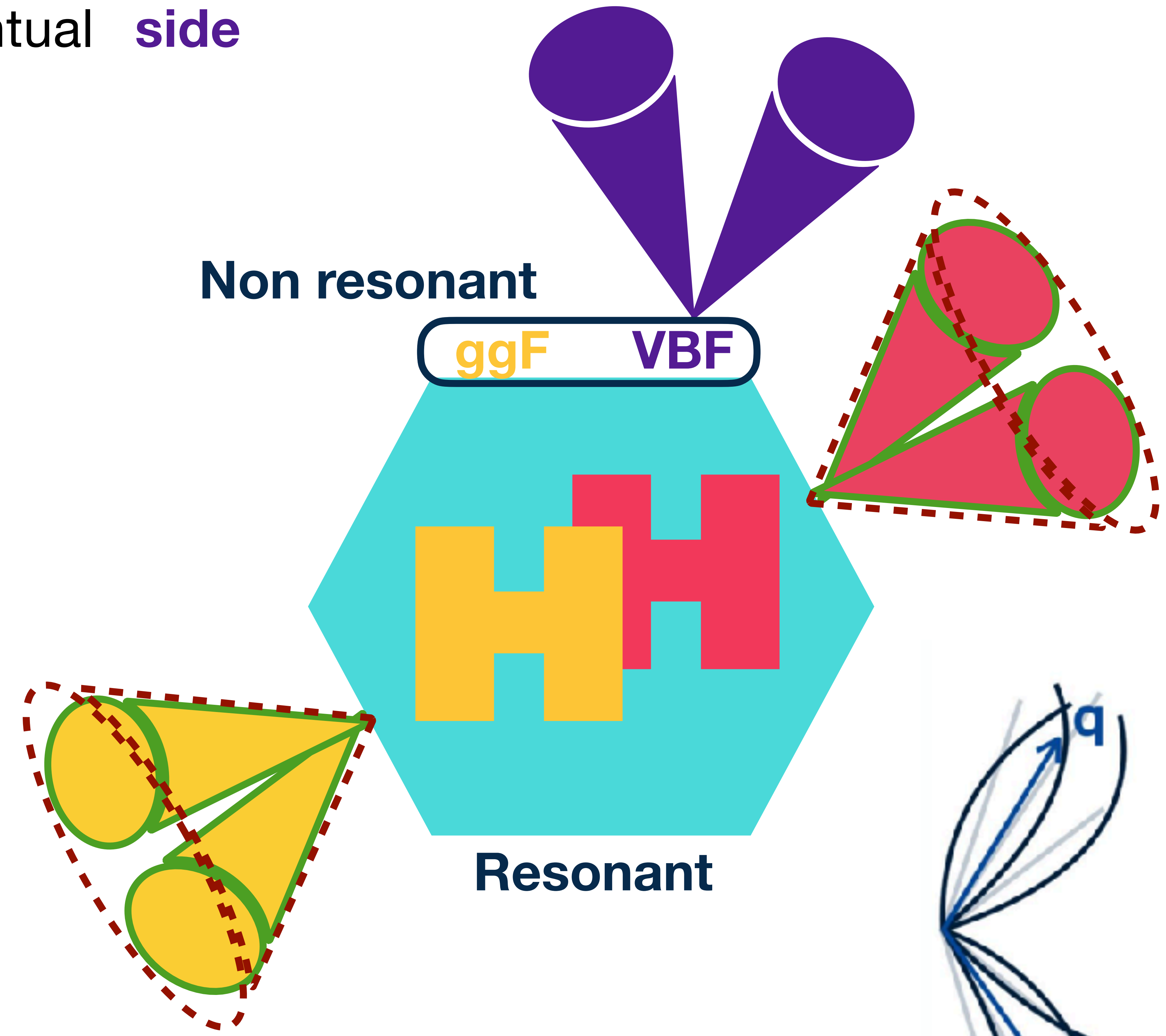


How to look for Higgs pairs?

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

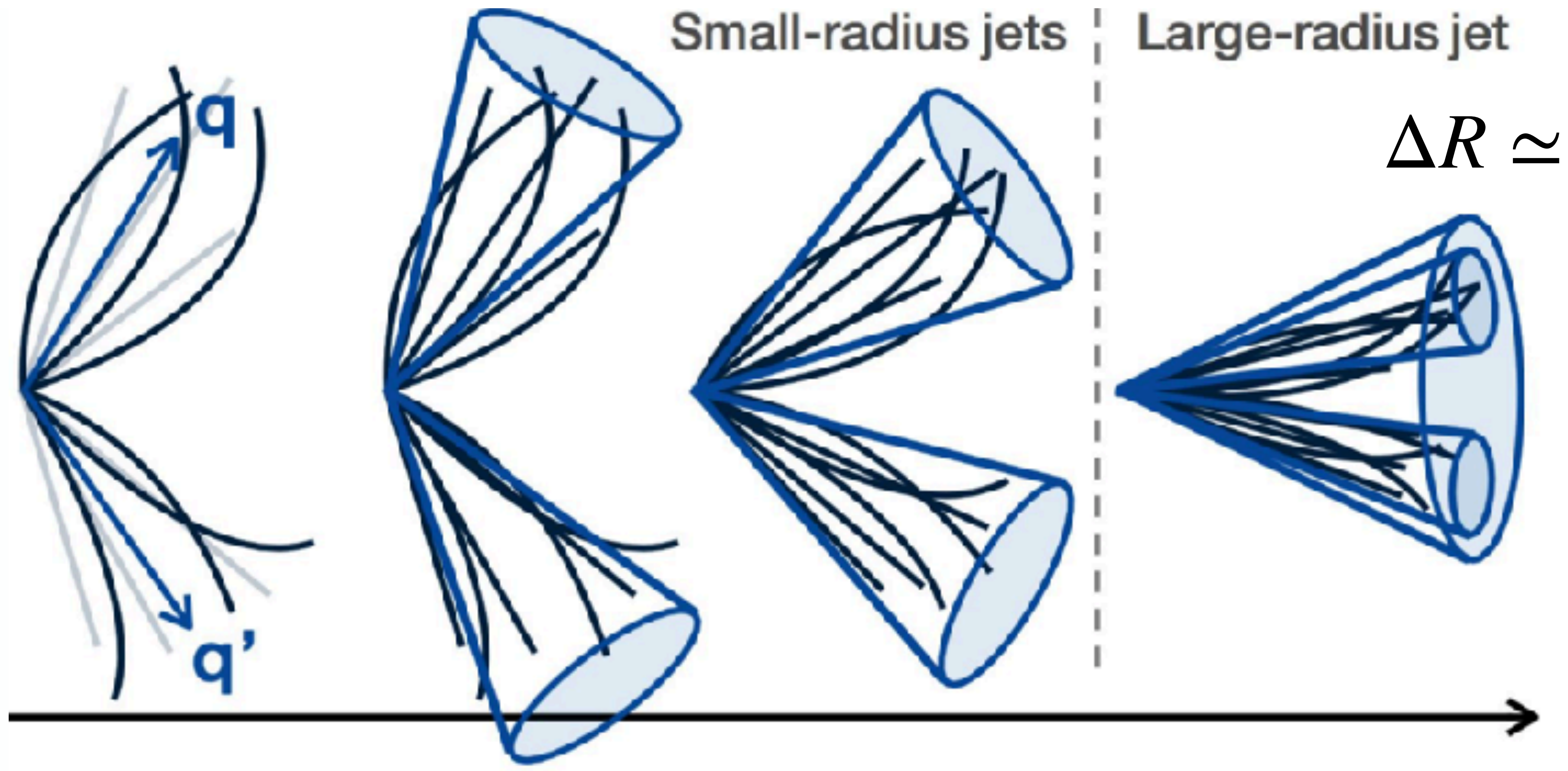
Experimentally only the **decay products** of the Higgs bosons can be **measured**. They define the **strategy** of the analysis:

- 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:

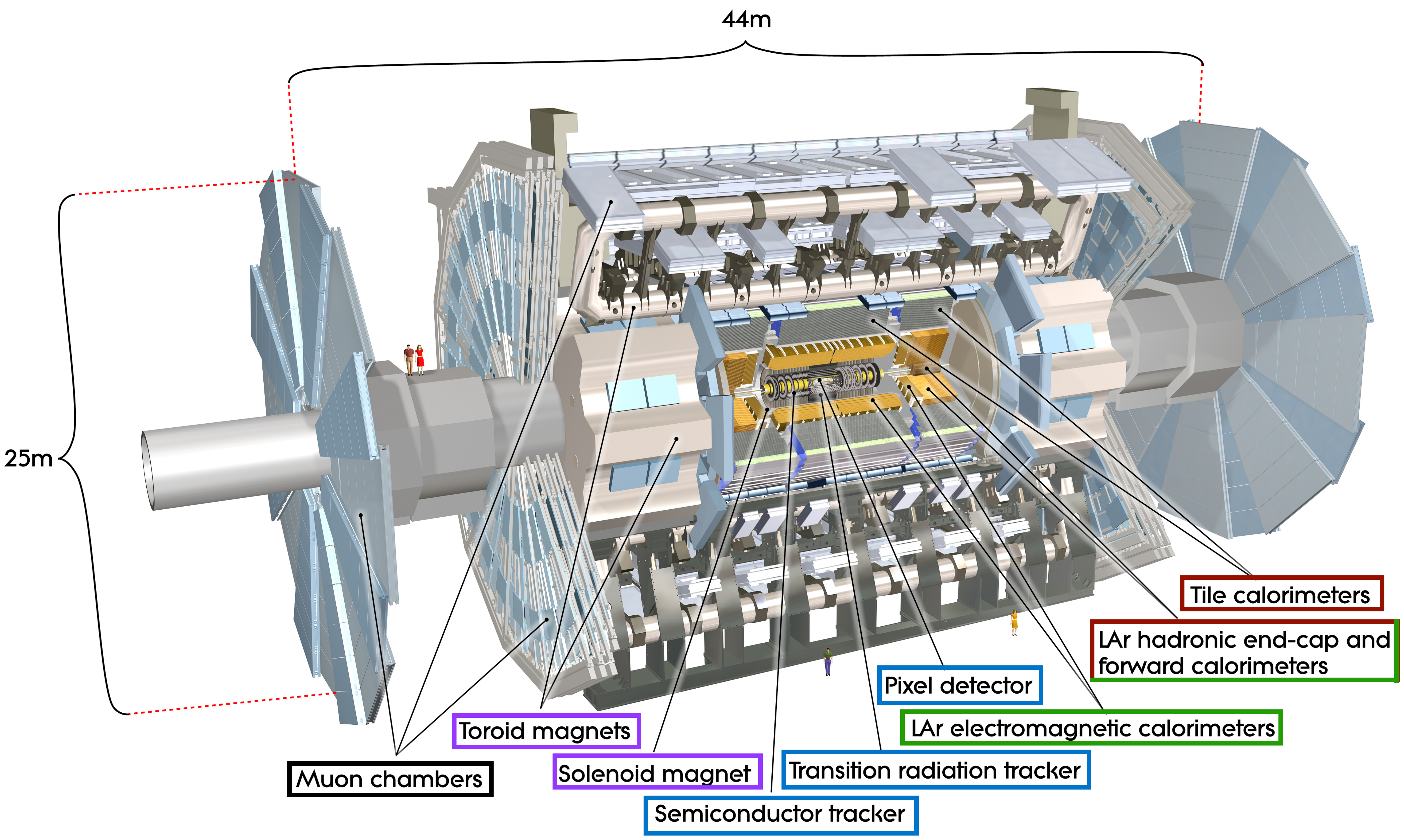
- **Resolved**: two single objects can be reconstructed, aiming at low m_{HH}.
- **Boosted**: one object is reconstructed with dedicated sub-structure analysis.



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

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?

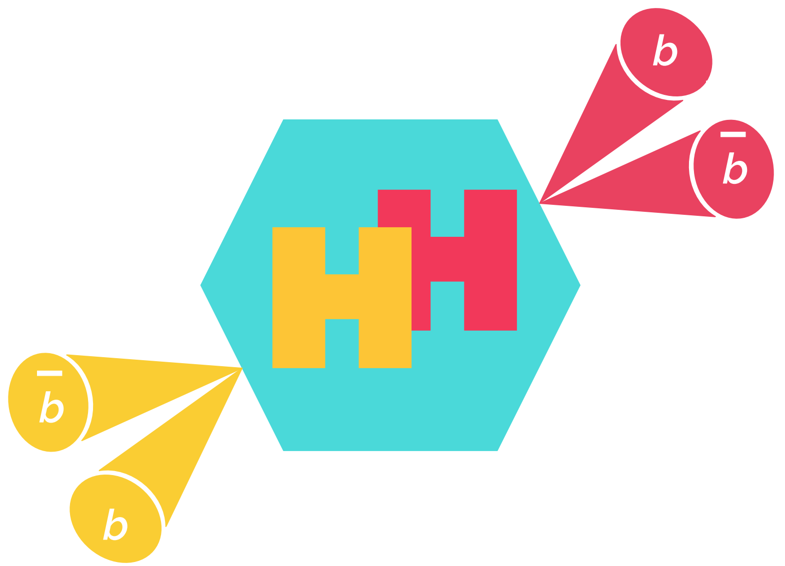
No clear *Golden channel*, but several promising signatures:

$BR(HH \to XXYY)$

	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**.



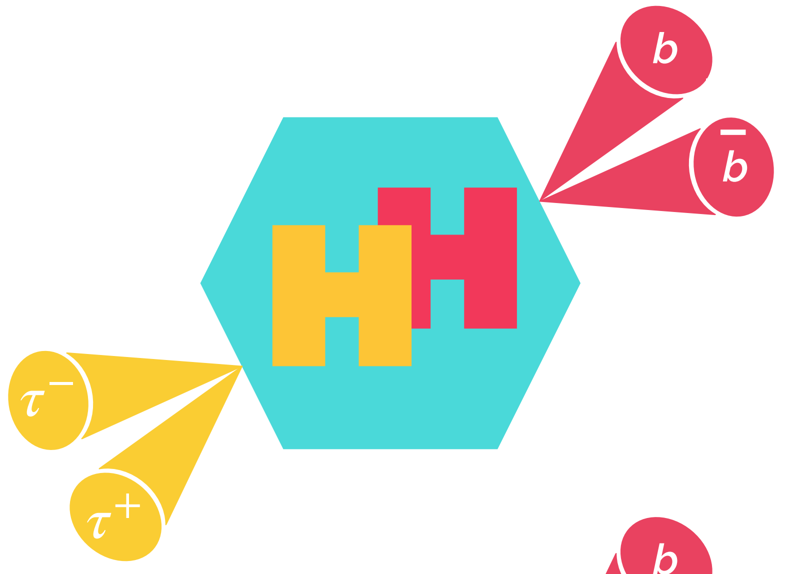
$HH \to b\bar{b}b\bar{b}$

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

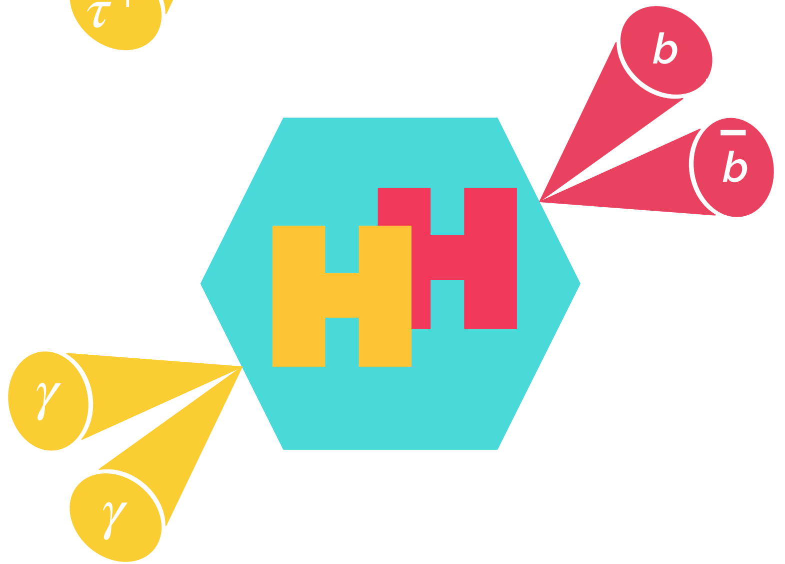


$HH \to b\bar{b}\tau^+\tau^-$

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

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

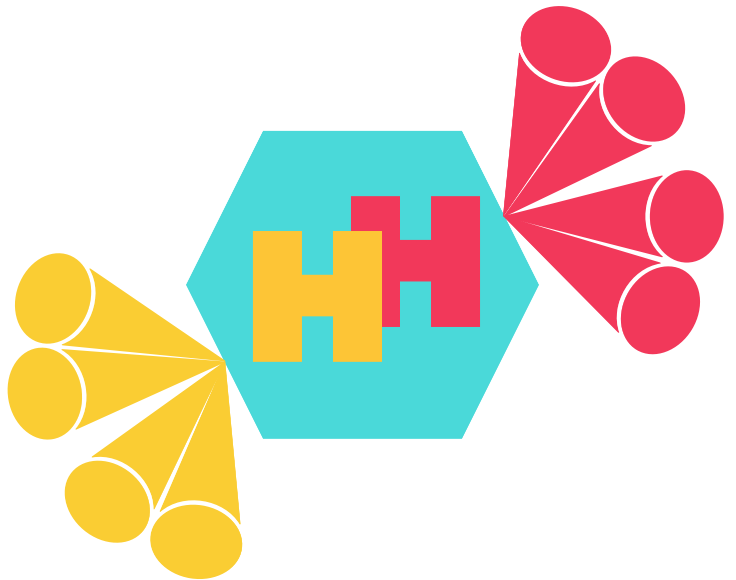
Boosted: $\mathscr{L} = 139\text{fb}^{-1}$ JHEP 11 (2020) 163



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

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

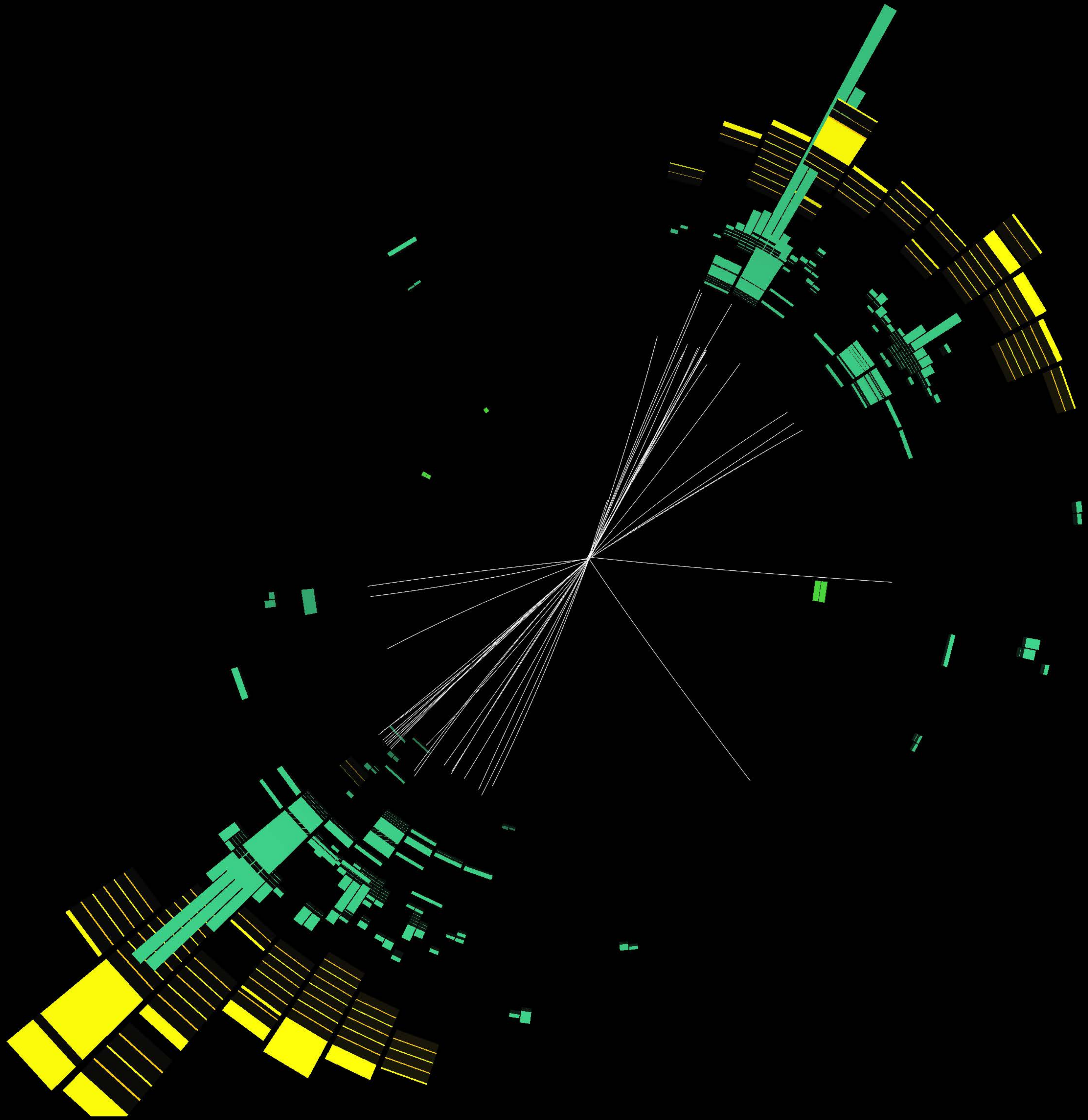
$b\bar{b}l\nu q\bar{q}$: $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 04 (2019) 092

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

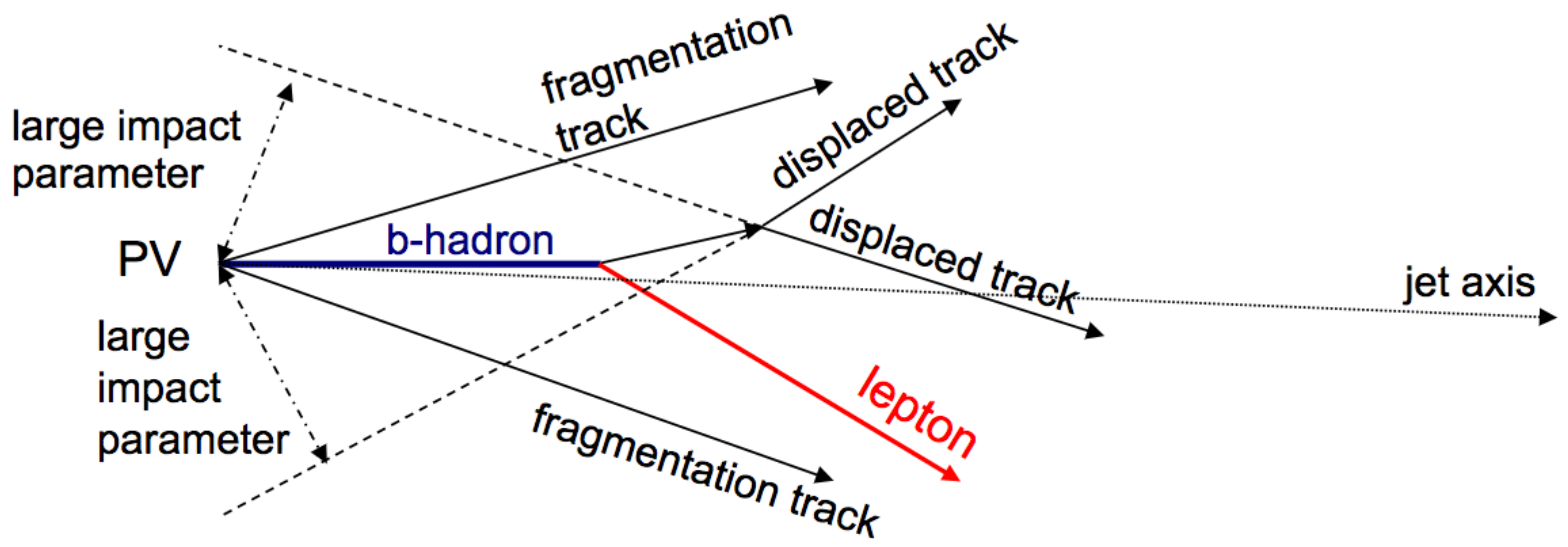
$HH \to b\bar{b}b\bar{b}$



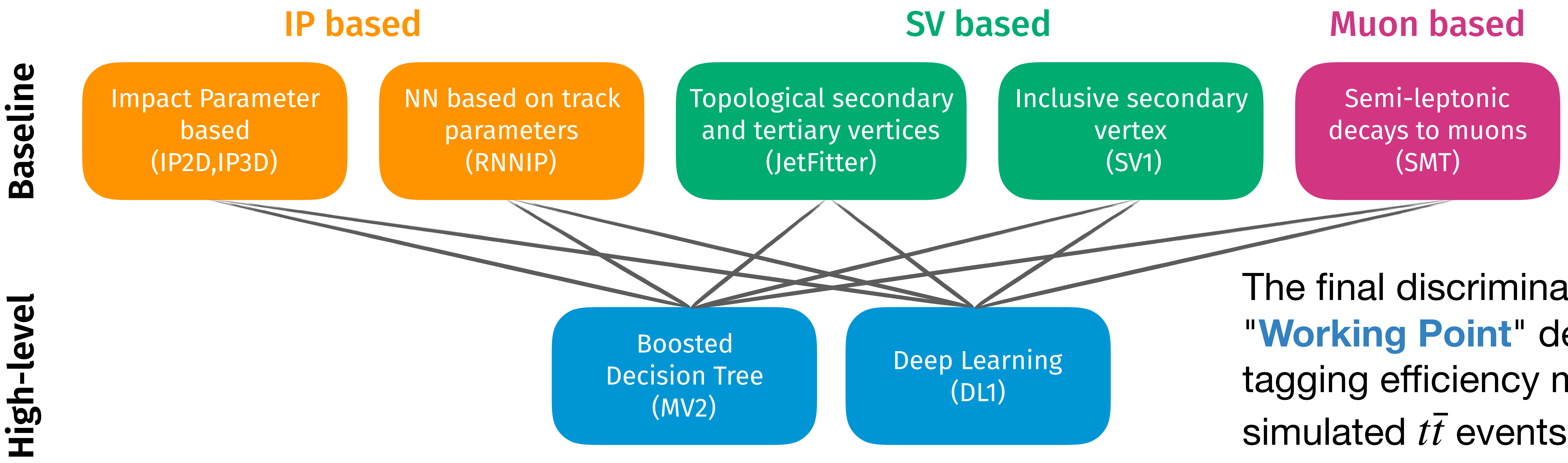
How to identify b-jets

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.

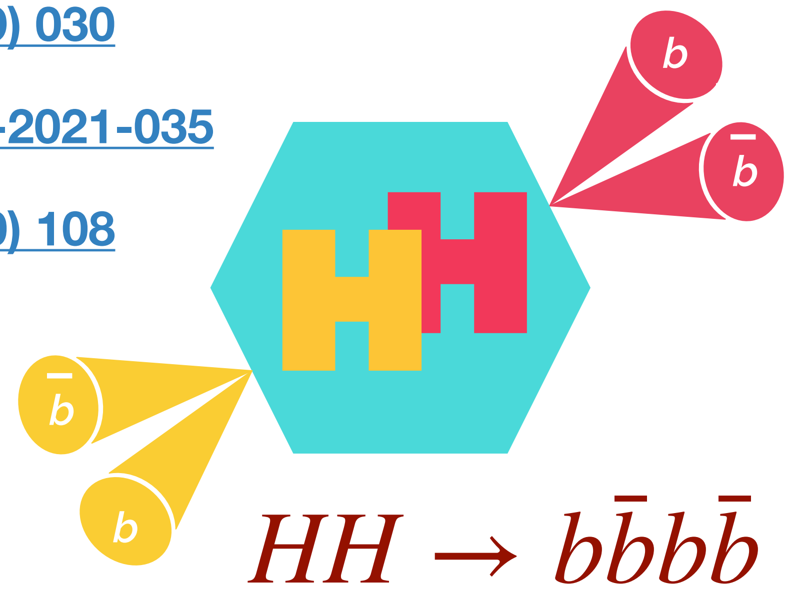
Dedicated **energy corrections** are also applied to account for the soft muon as well as energy mis measurements.

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

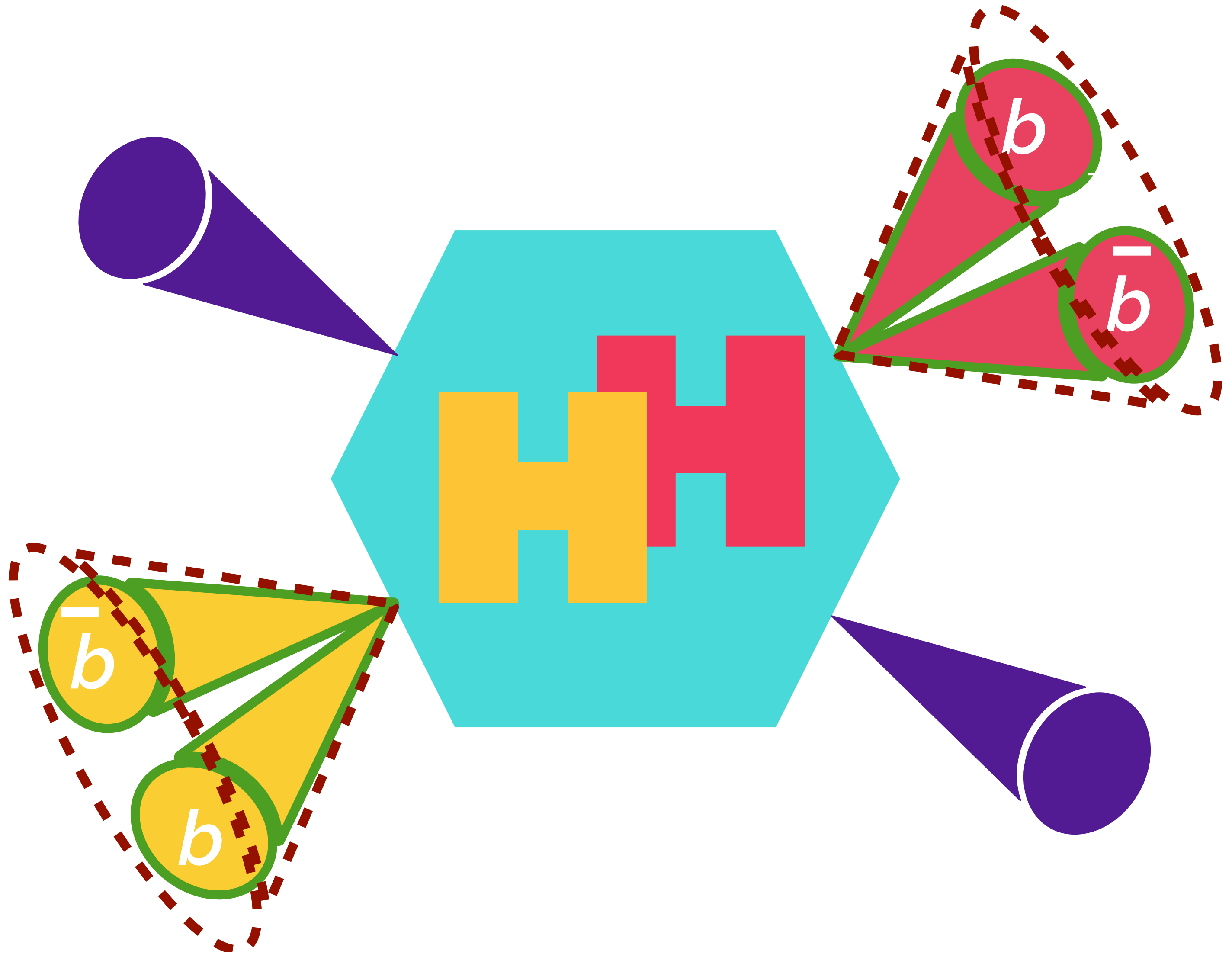


$HH \to b\bar{b}b\bar{b}$

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.



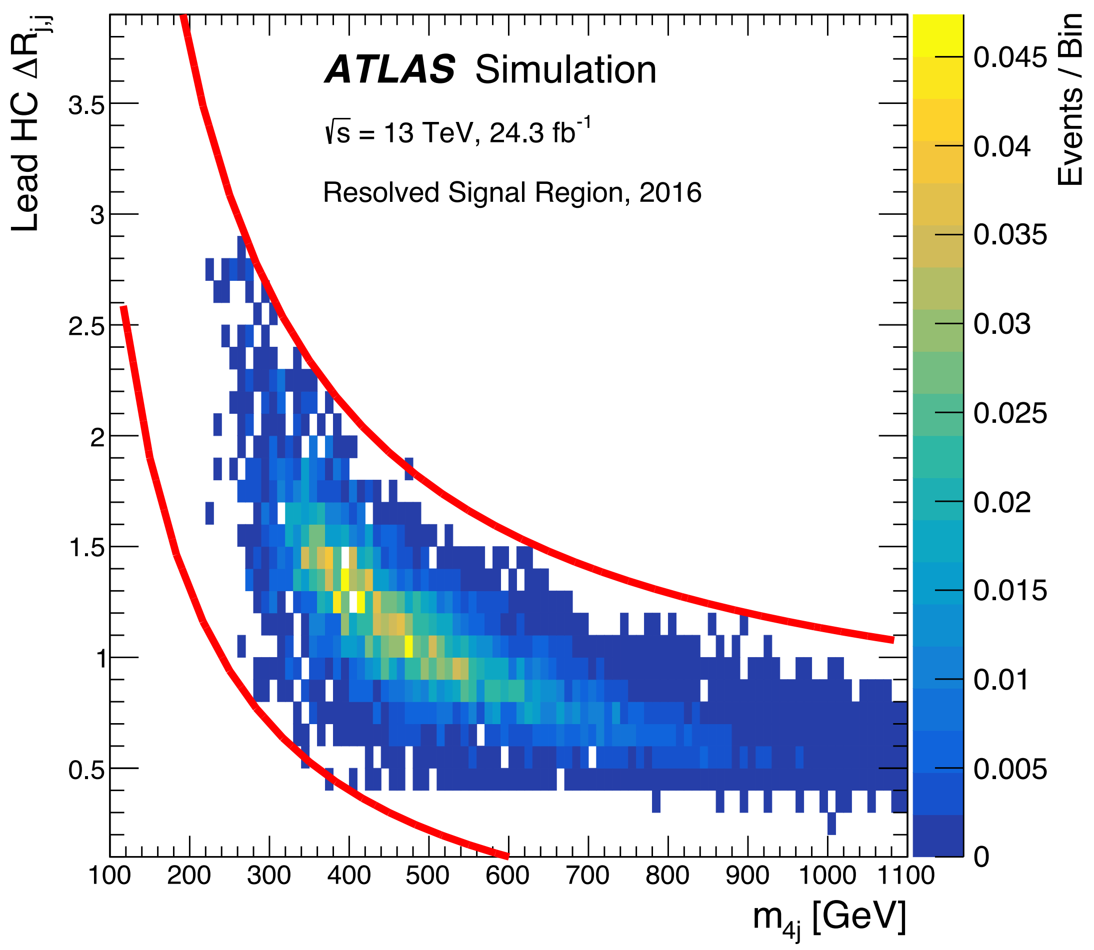
VBF **Non resonant / Resonant**

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

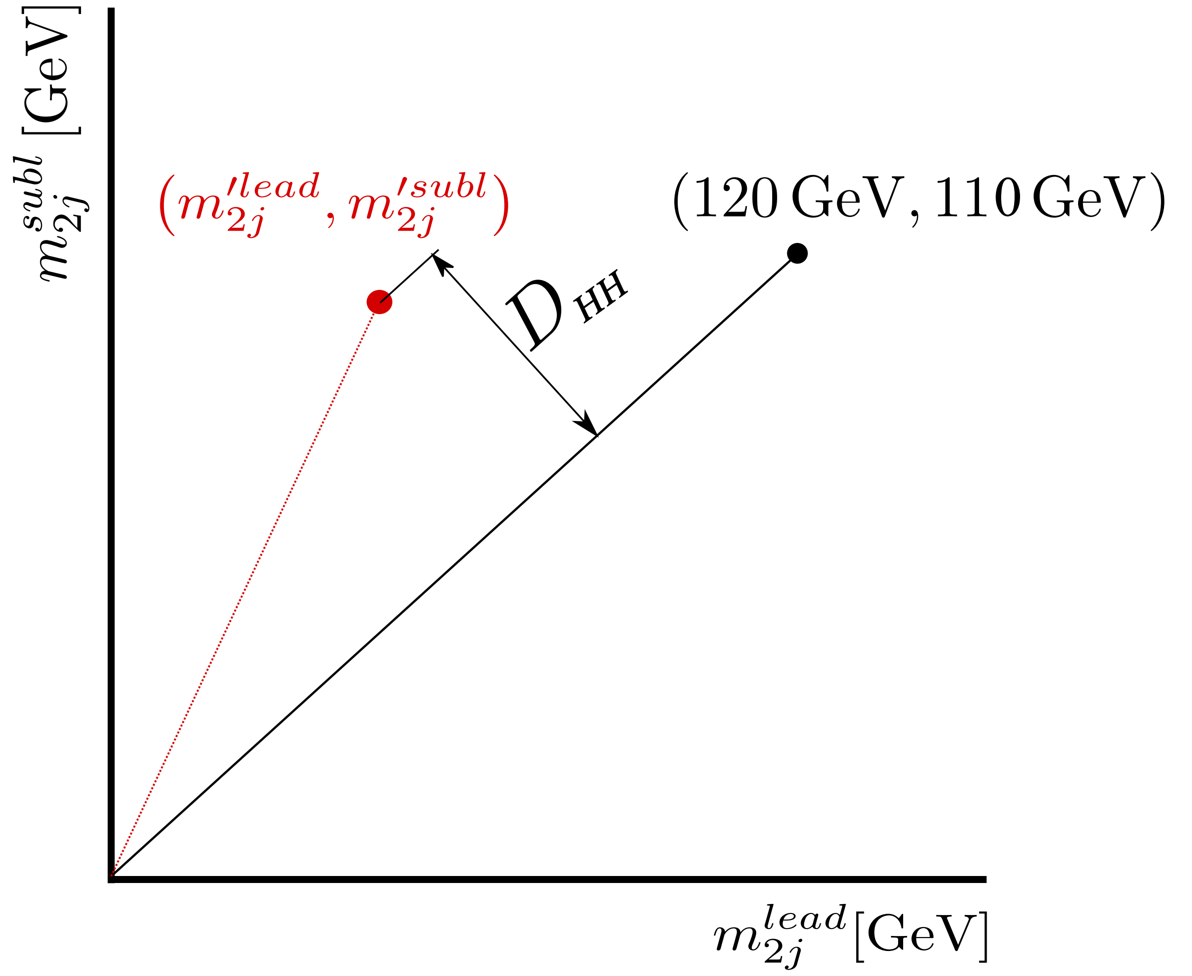
VBF jets:
- At least 2 forward jets with opposite η sign.

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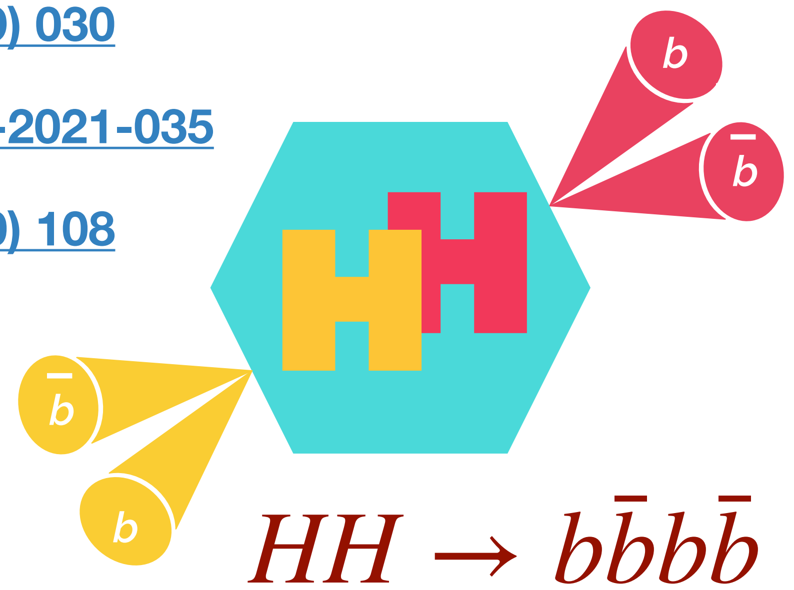


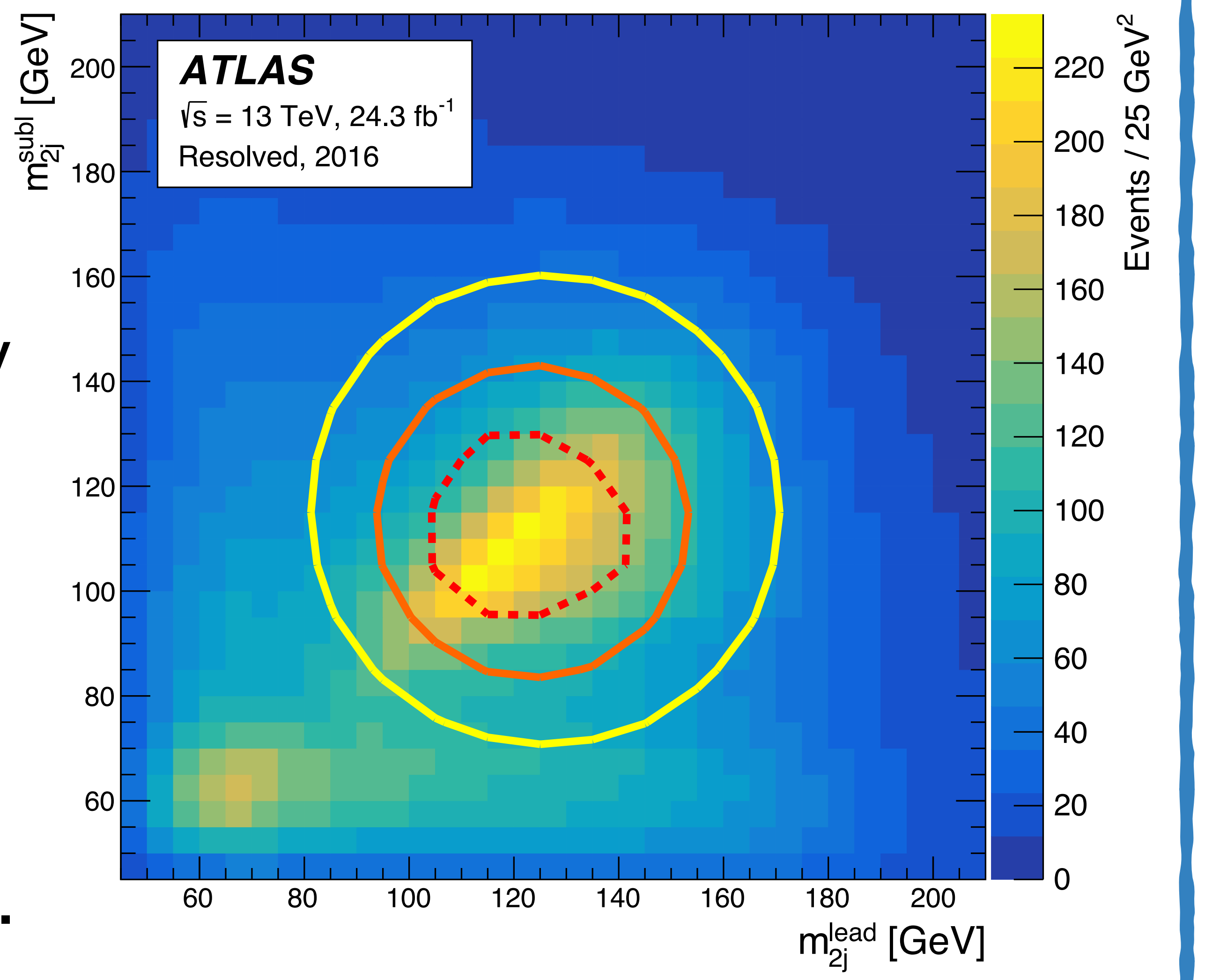
ggF

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.



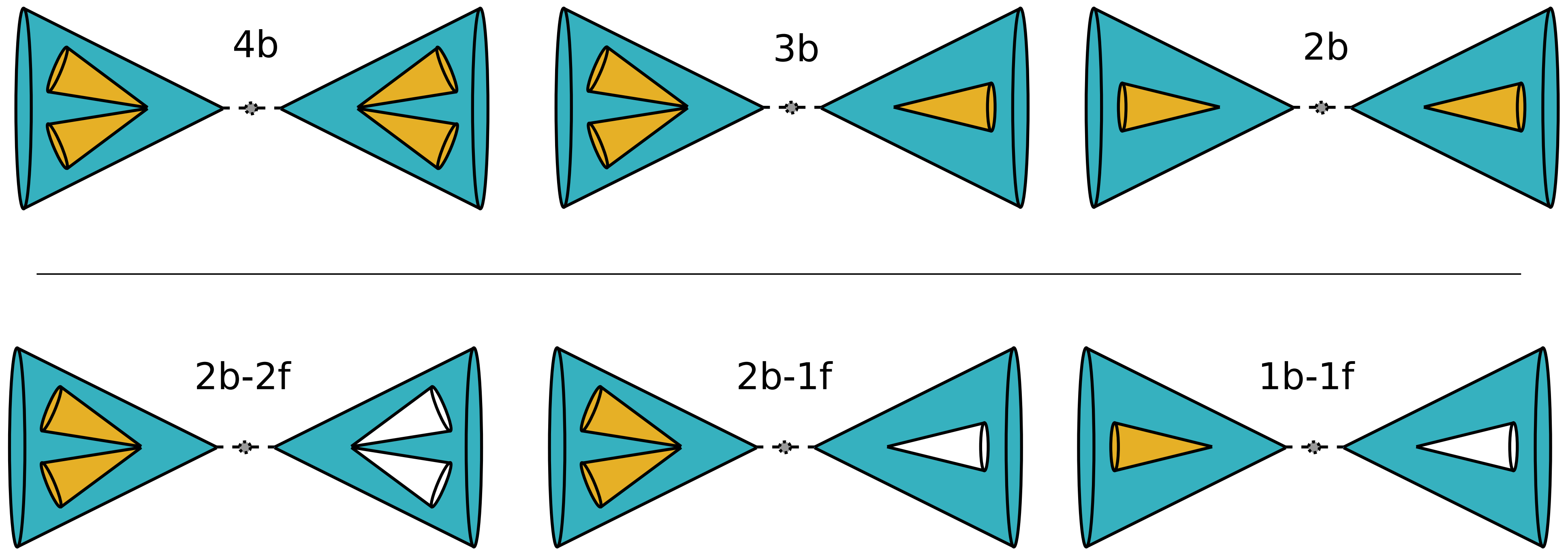
Boosted: **Resonant**

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

Main backgrounds:

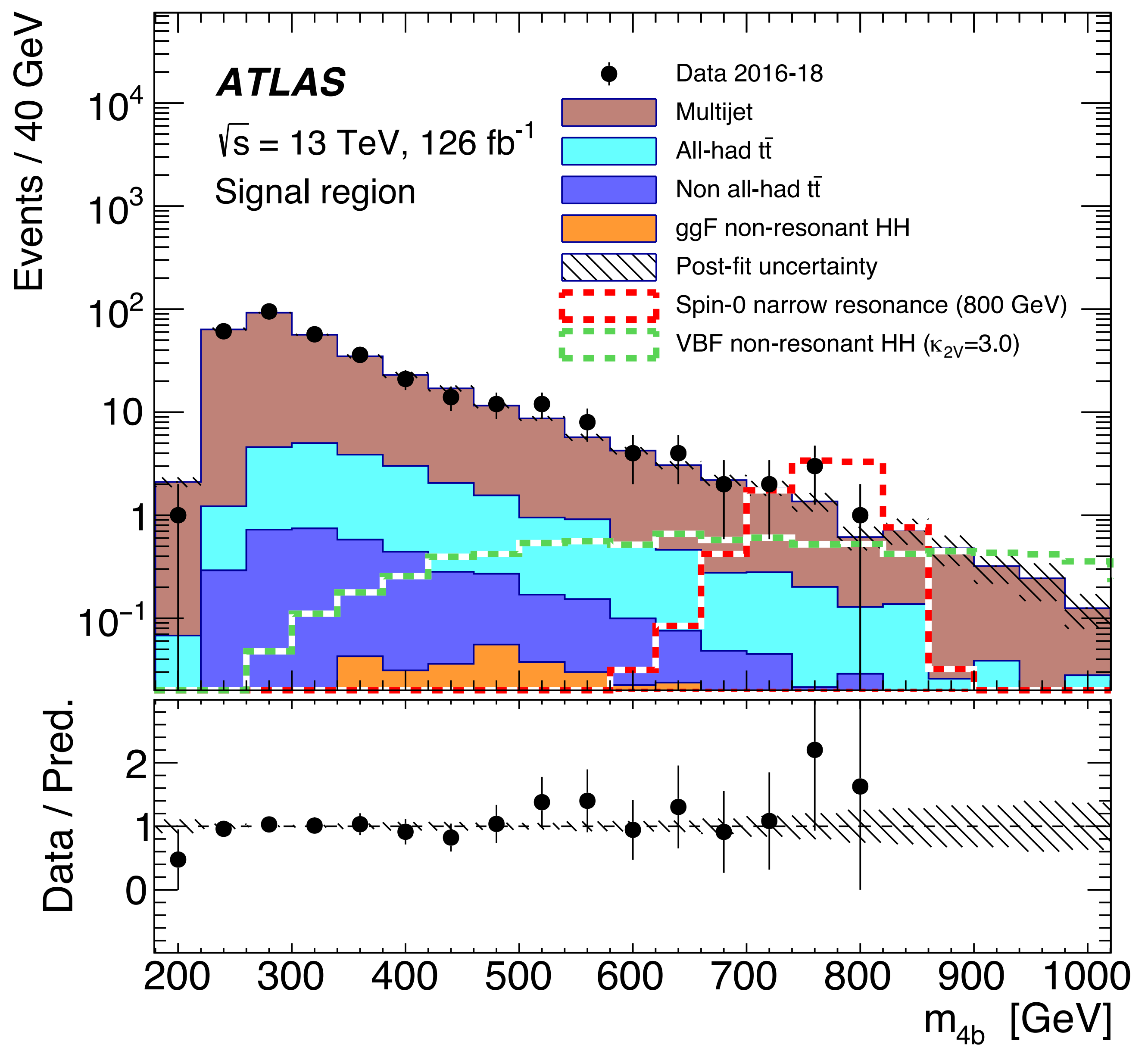
$t\bar{t}$ and multi-jets contribute:

- 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

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

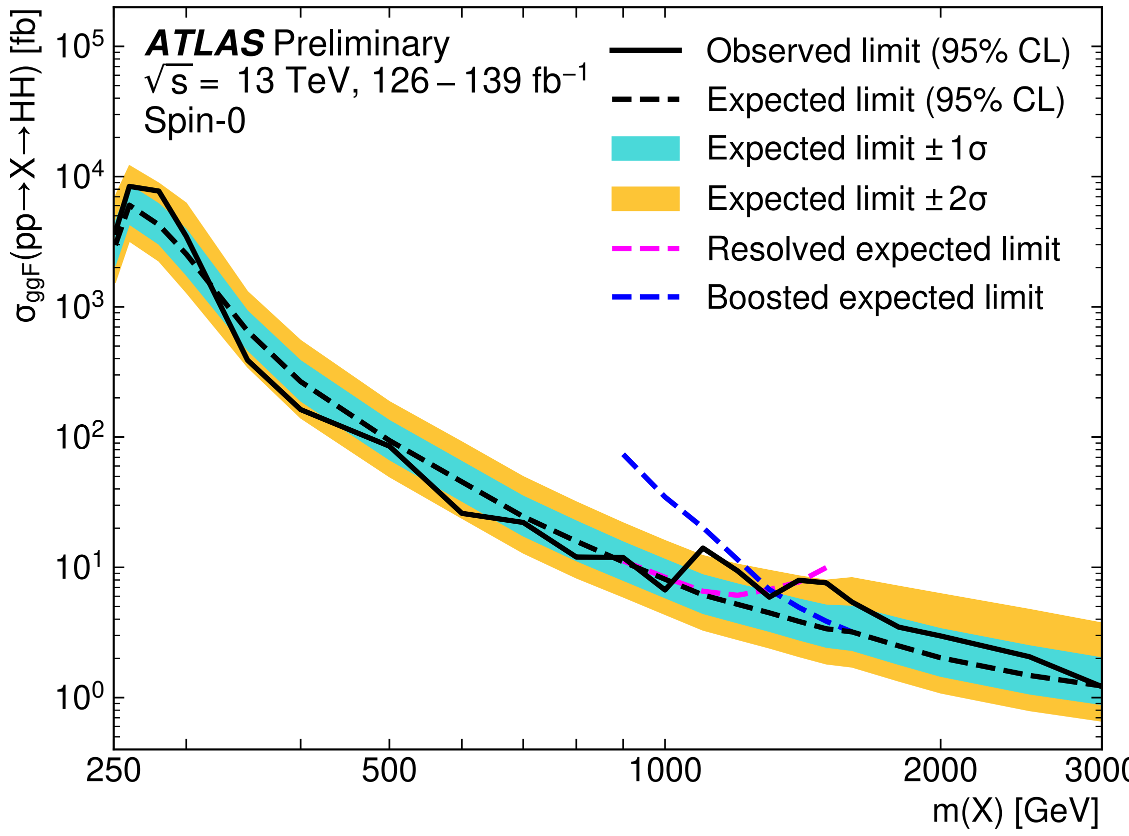
ggF — No significant excess found

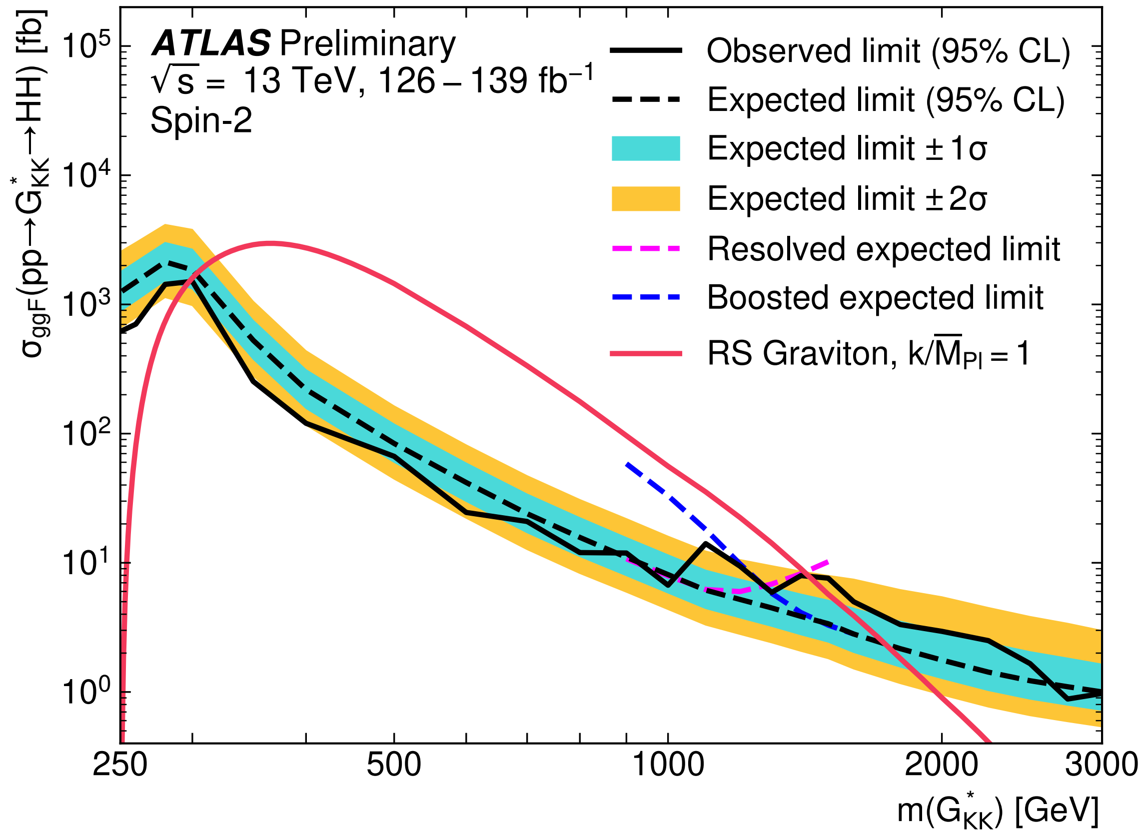
Non-resonant Resolved

$\sigma_{HH}^{ggF} \times BR(HH \to b\bar{b}b\bar{b})$ observed (expected) limit is 12.9 (14.8) times the SM prediction.

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

Limits set on $\sigma(X/G_{KK} \to HH \to b\bar{b}b\bar{b})$:
Most significant excess is found at 1.1 TeV with a local (global) significance of 2.6 σ (1.0 σ).



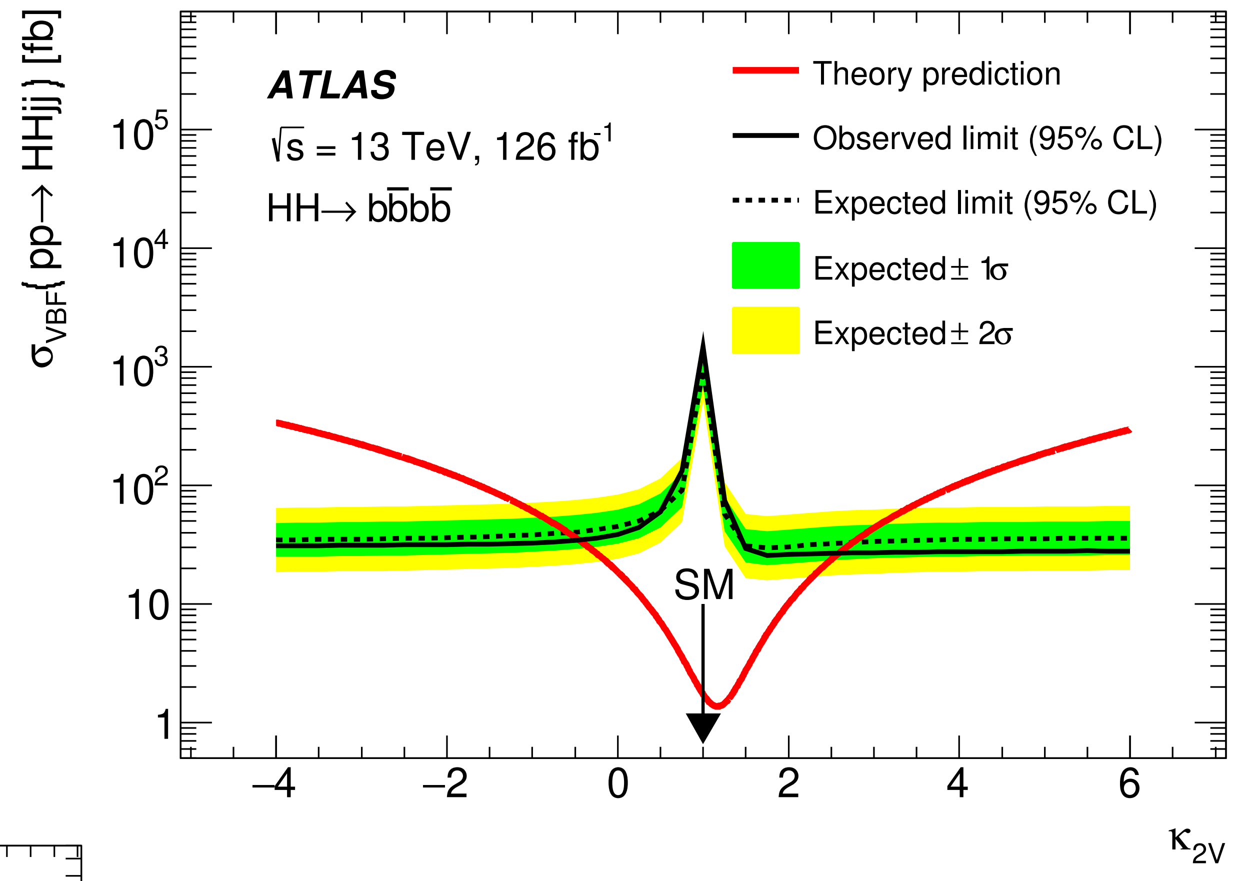


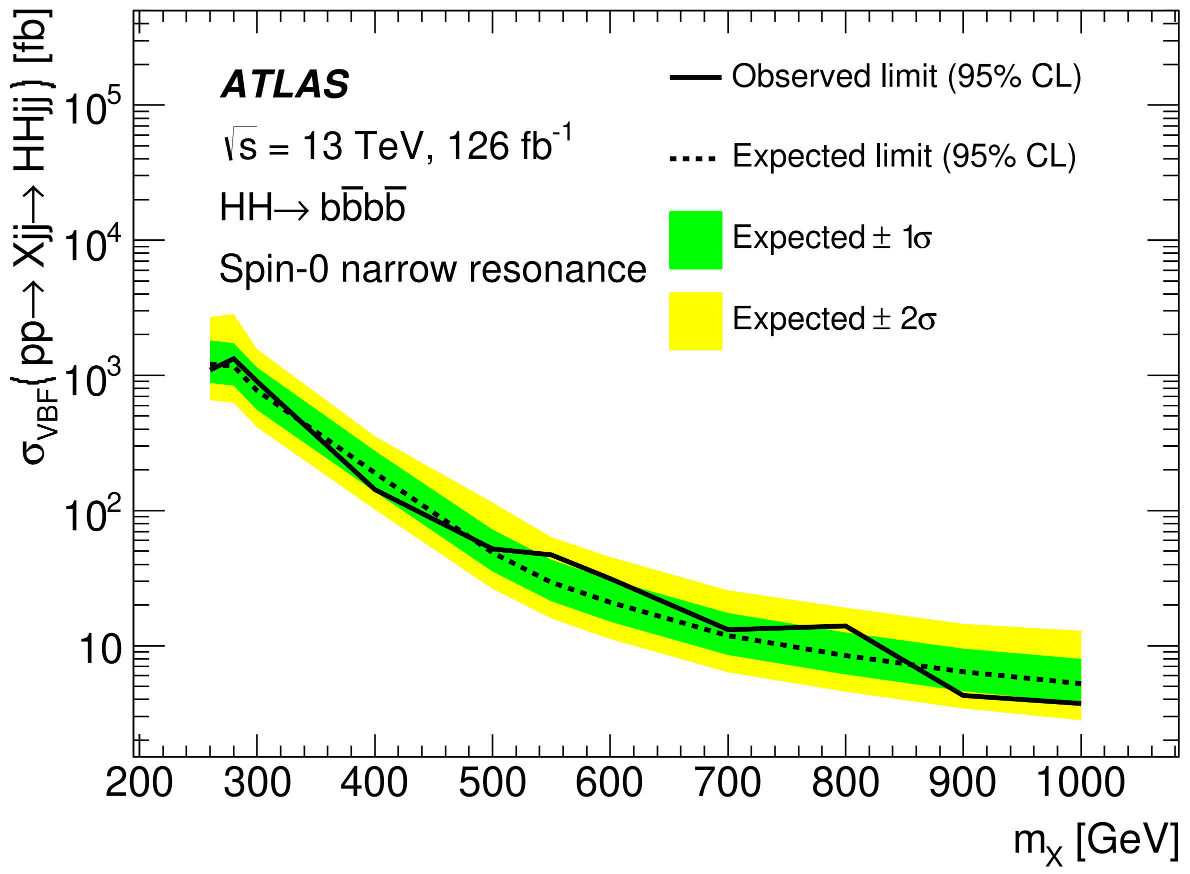
VBF — No significant excess found

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).





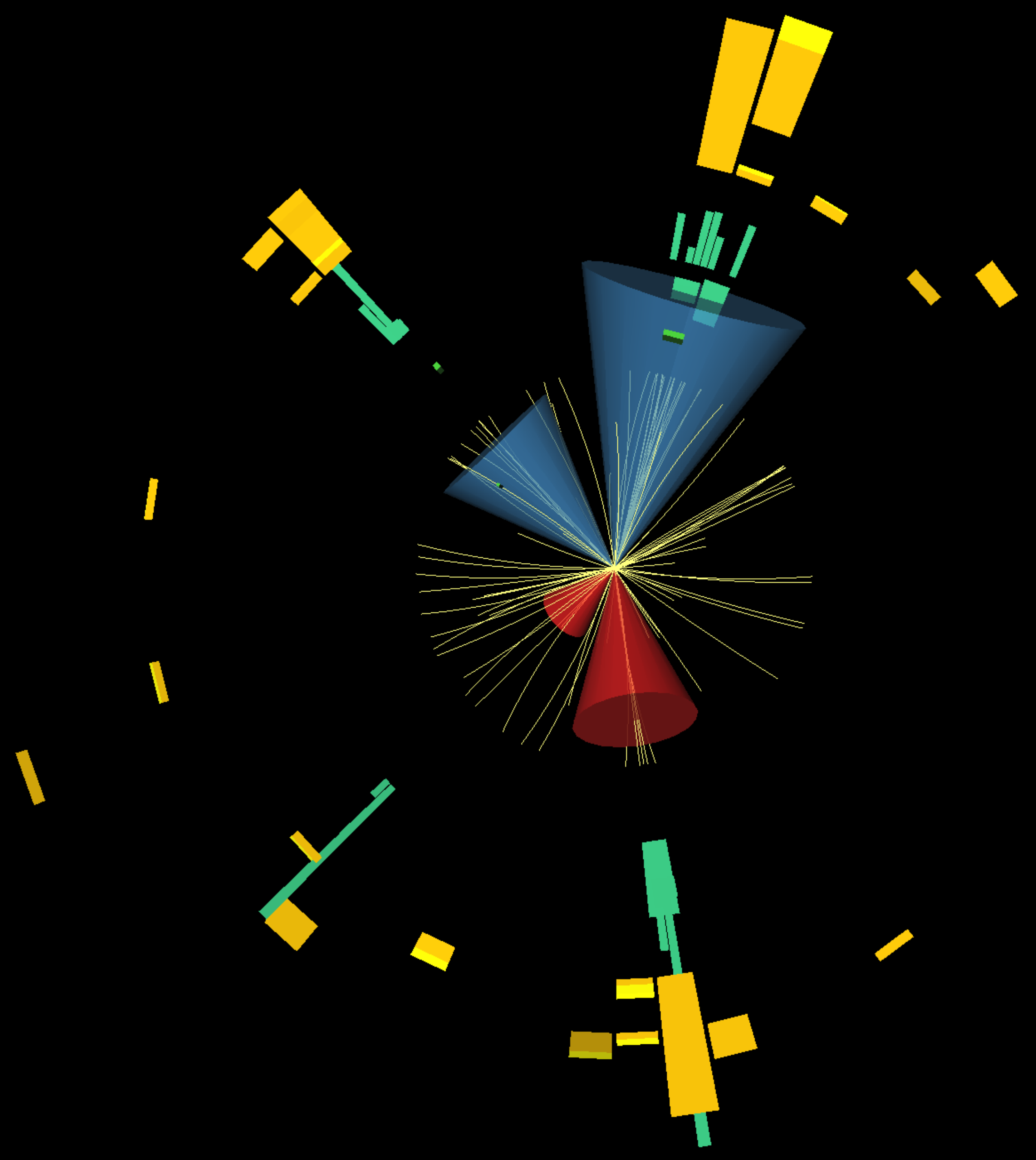
Resonant

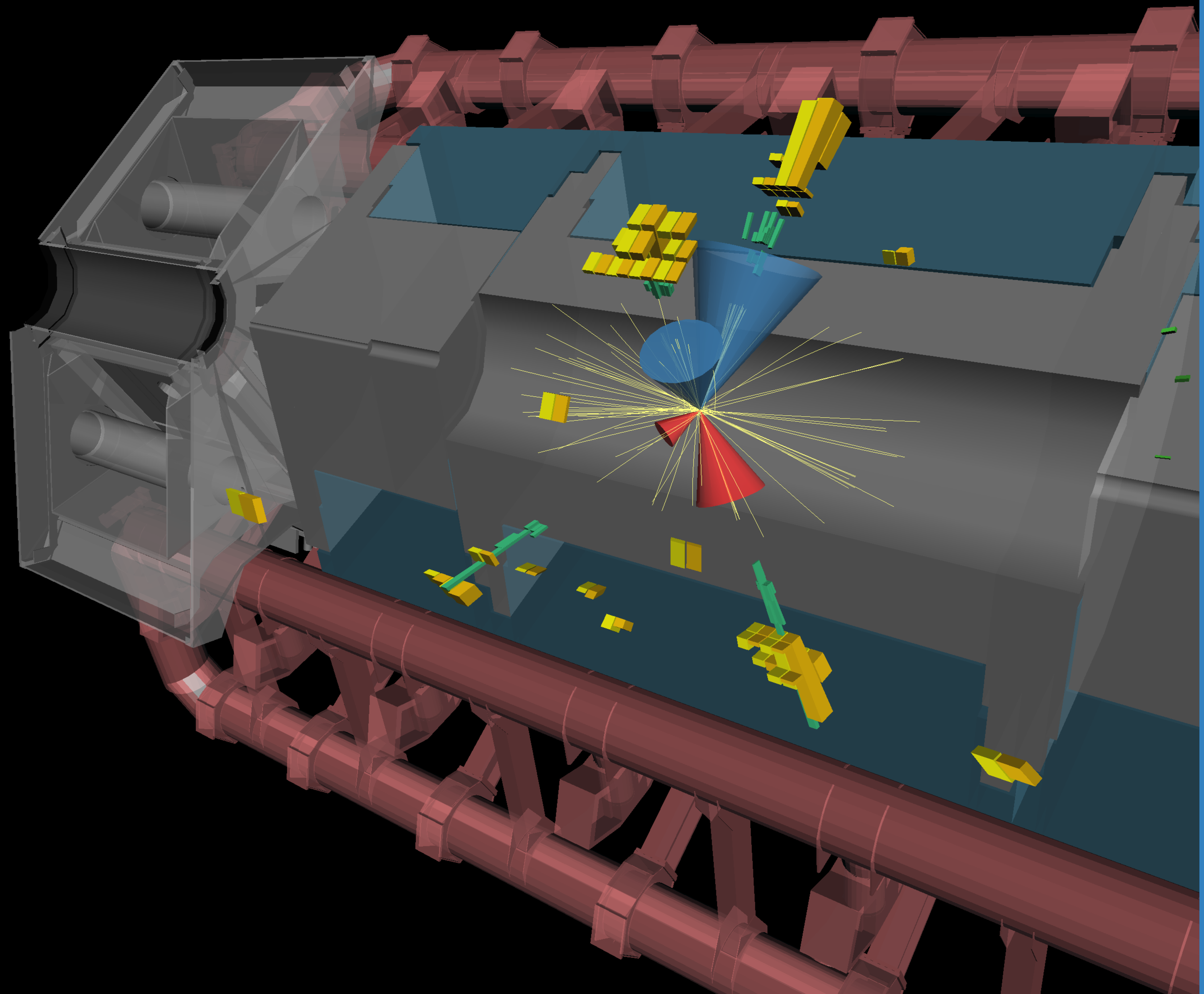
Limits set on $\sigma_{VBF}(X \to HH)$ where X is either a narrow- or broad-width scalar resonance

ATLAS EXPERIMENT

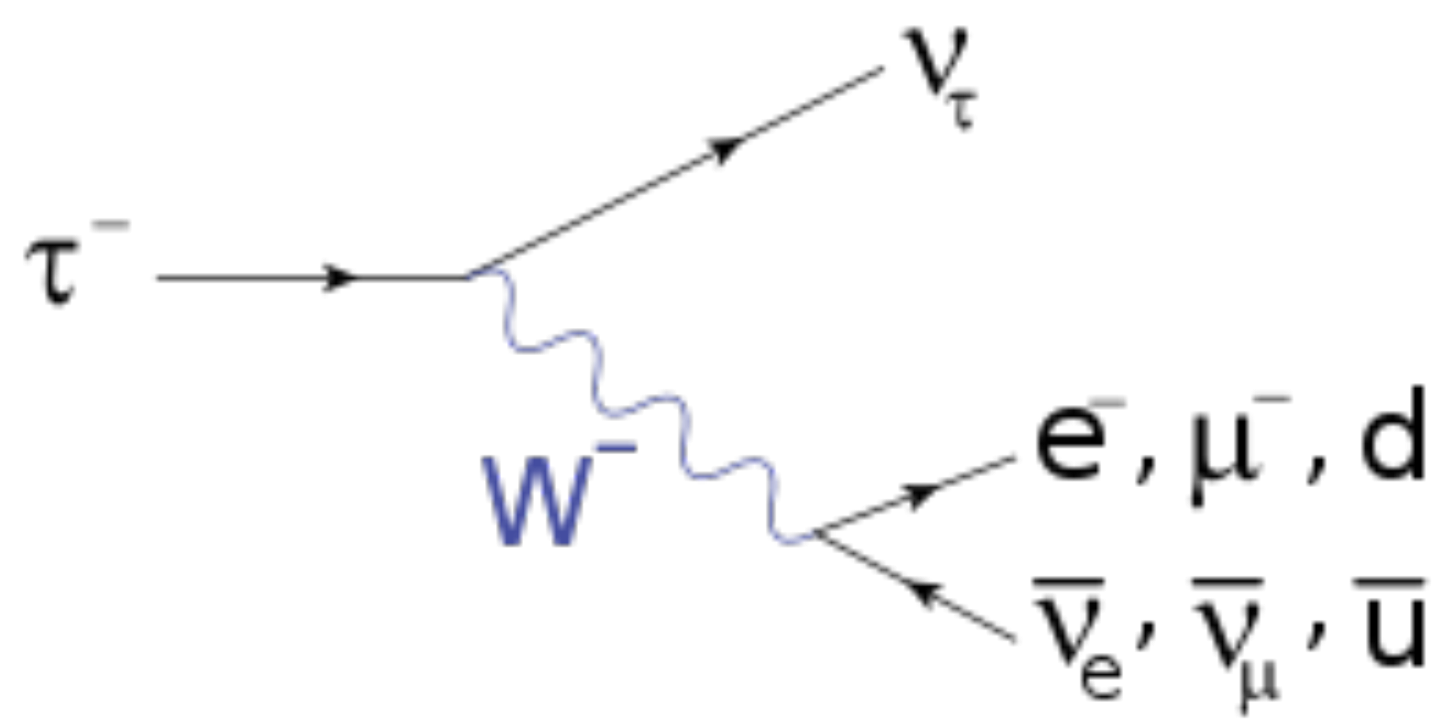
$HH \rightarrow b\bar{b}\tau^{+}\tau^{-}$

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



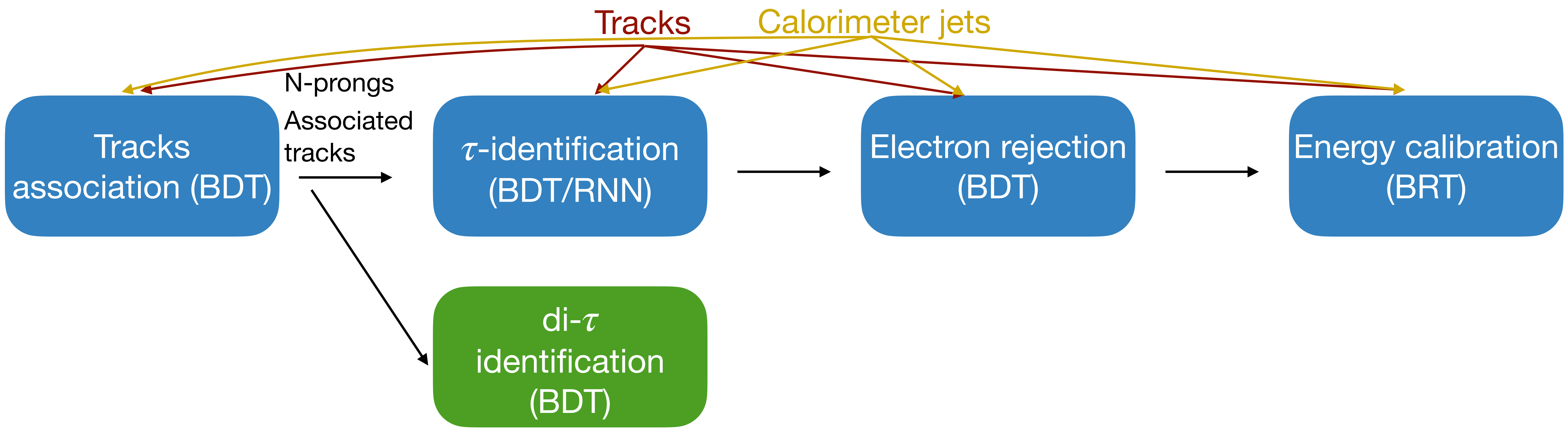


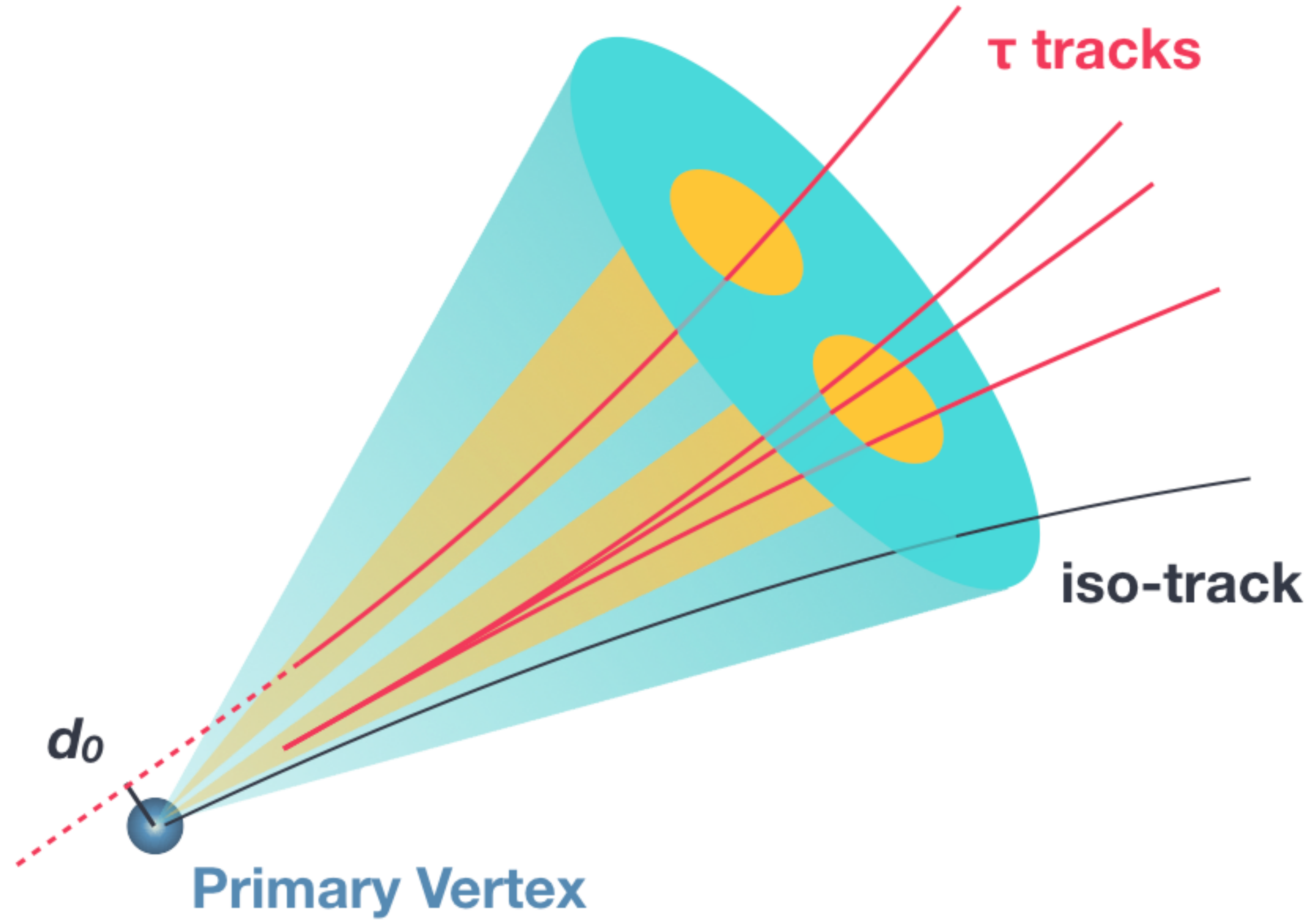
How to reconstruct tau leptons ?



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.



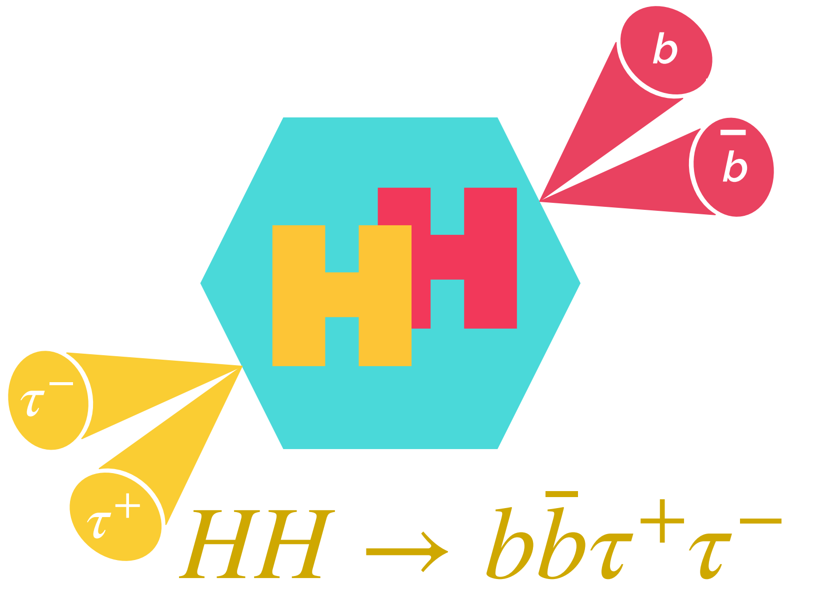


In **boosted topologies**, the reconstructed jets are closer to each other. A dedicated BDT is therefore trained to account for **smaller radius jets** and the **specific topologies**. No additional energy correction was found to be needed in these cases.

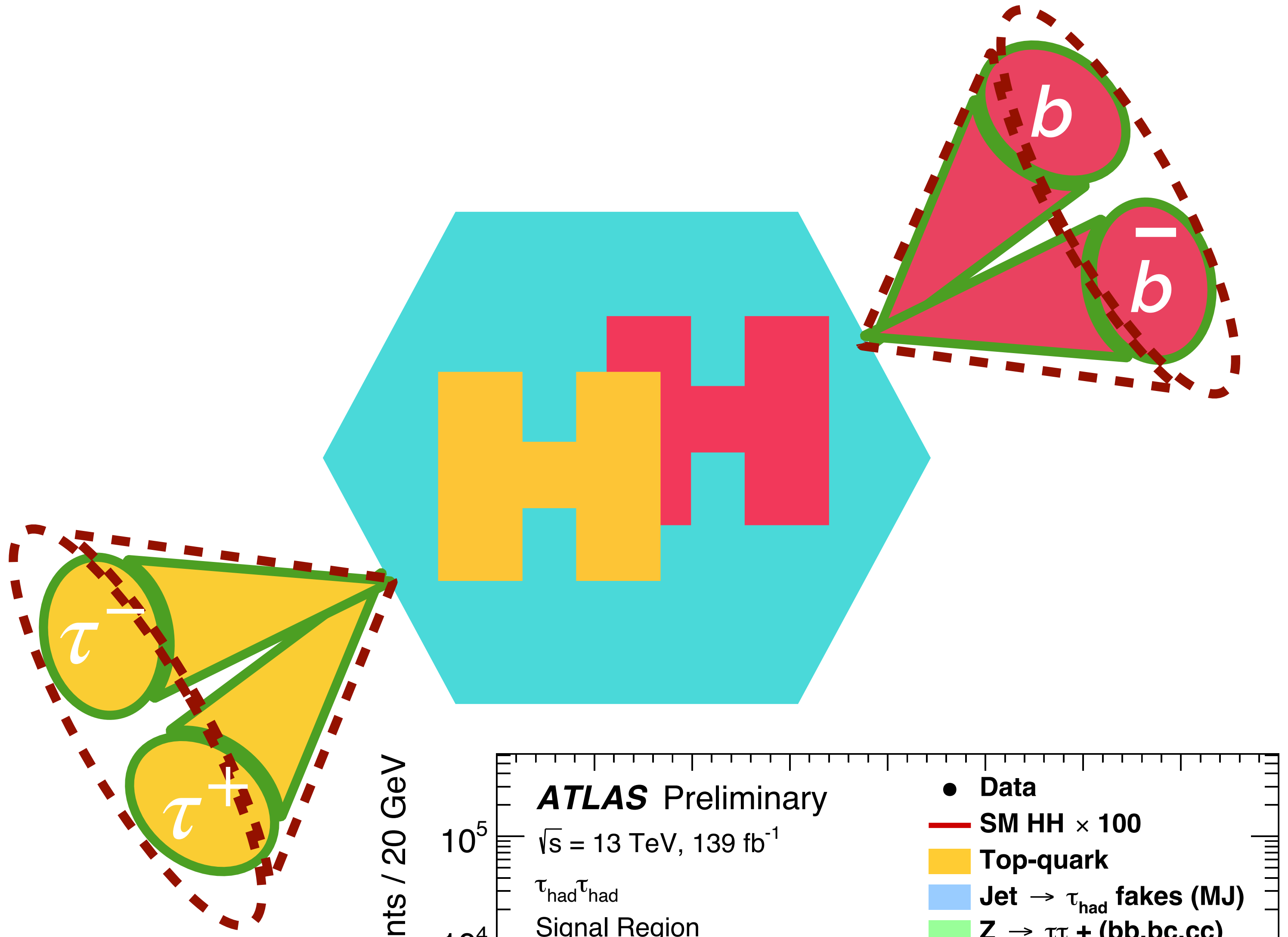
Strategy

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:

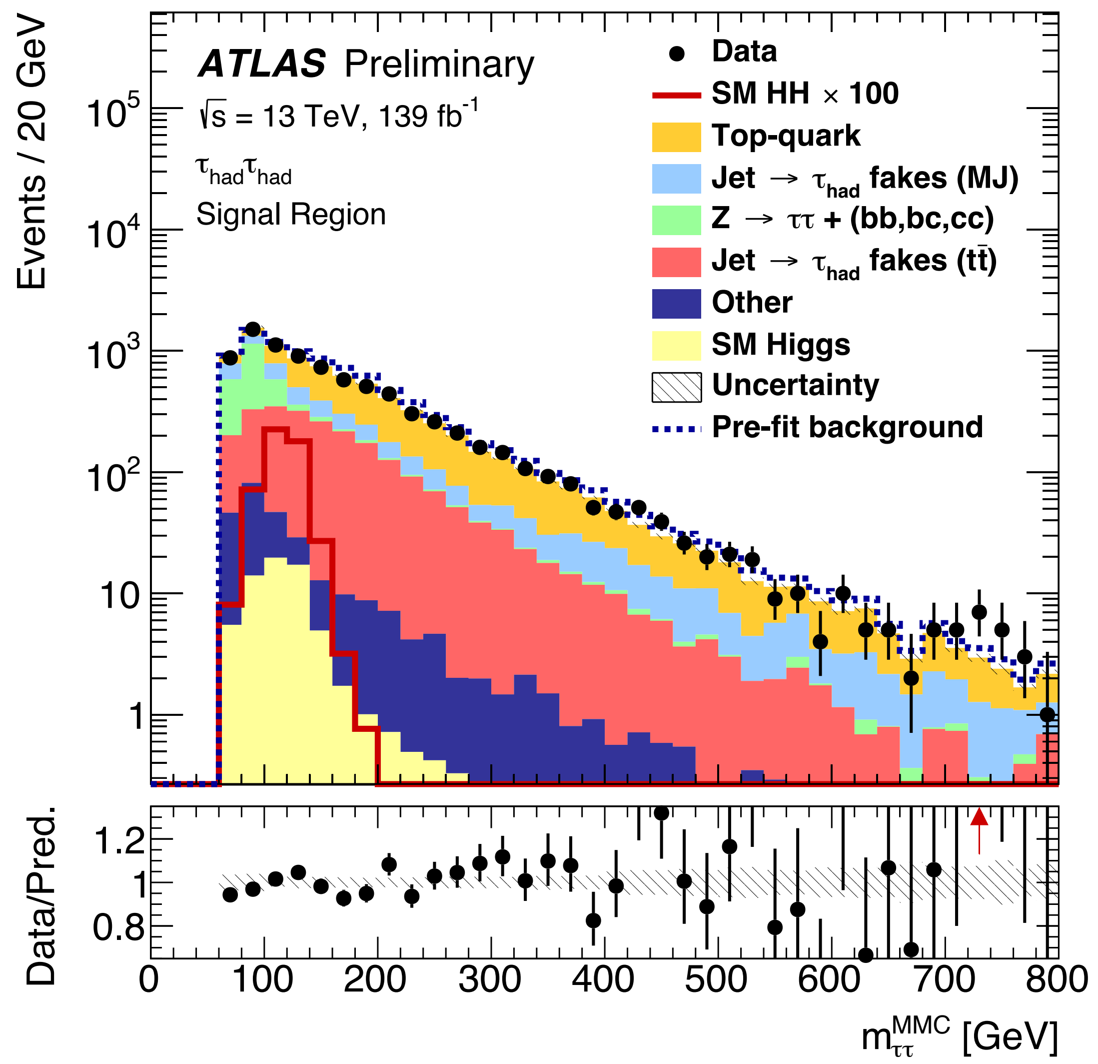


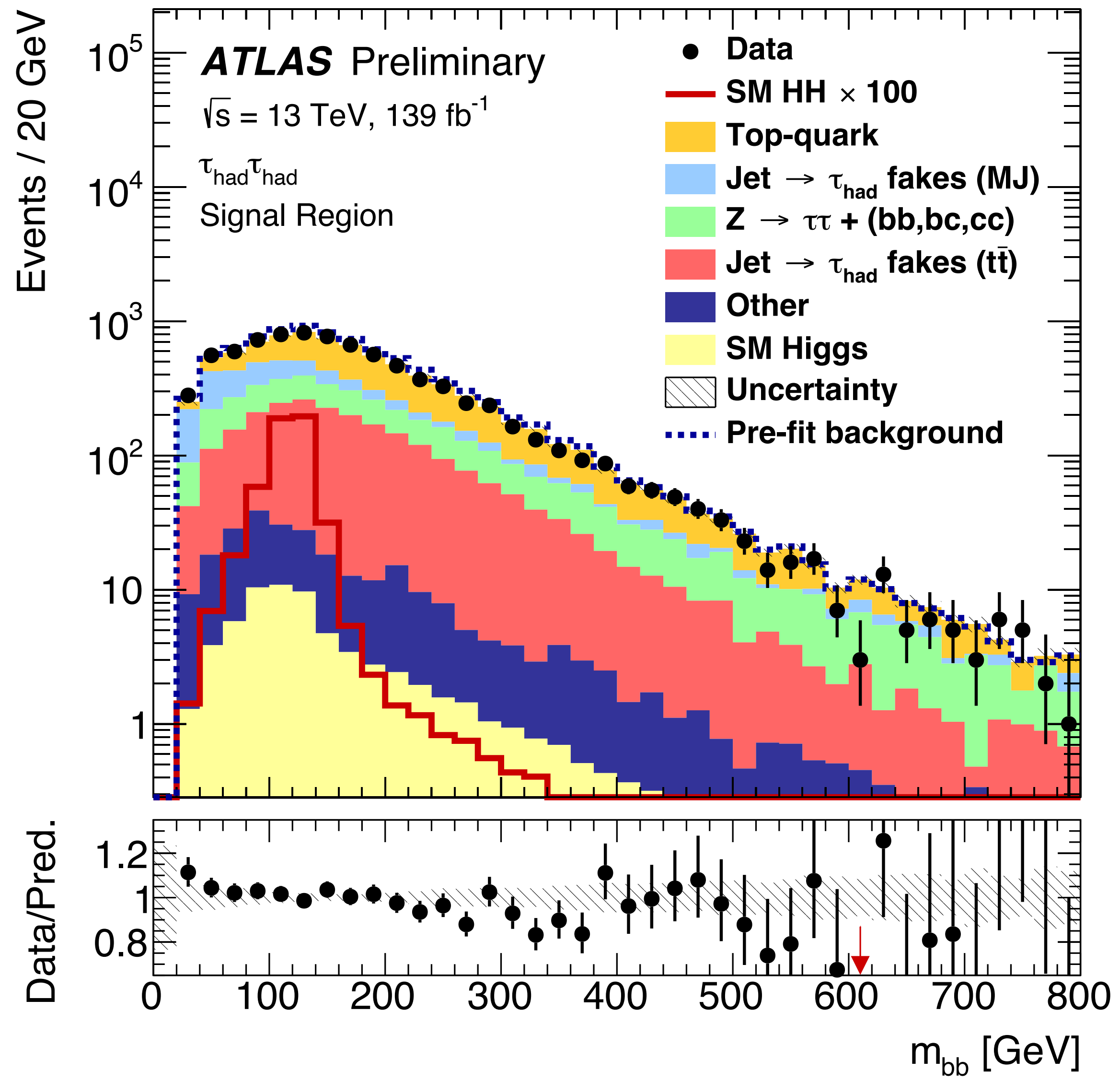
Resolved:
Exactly 2 b-jets
Boosted:
- ≥ 1 extra large R jet;
- 2 variable radius b-tagged jets inside.

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 :
- ≤ 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

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

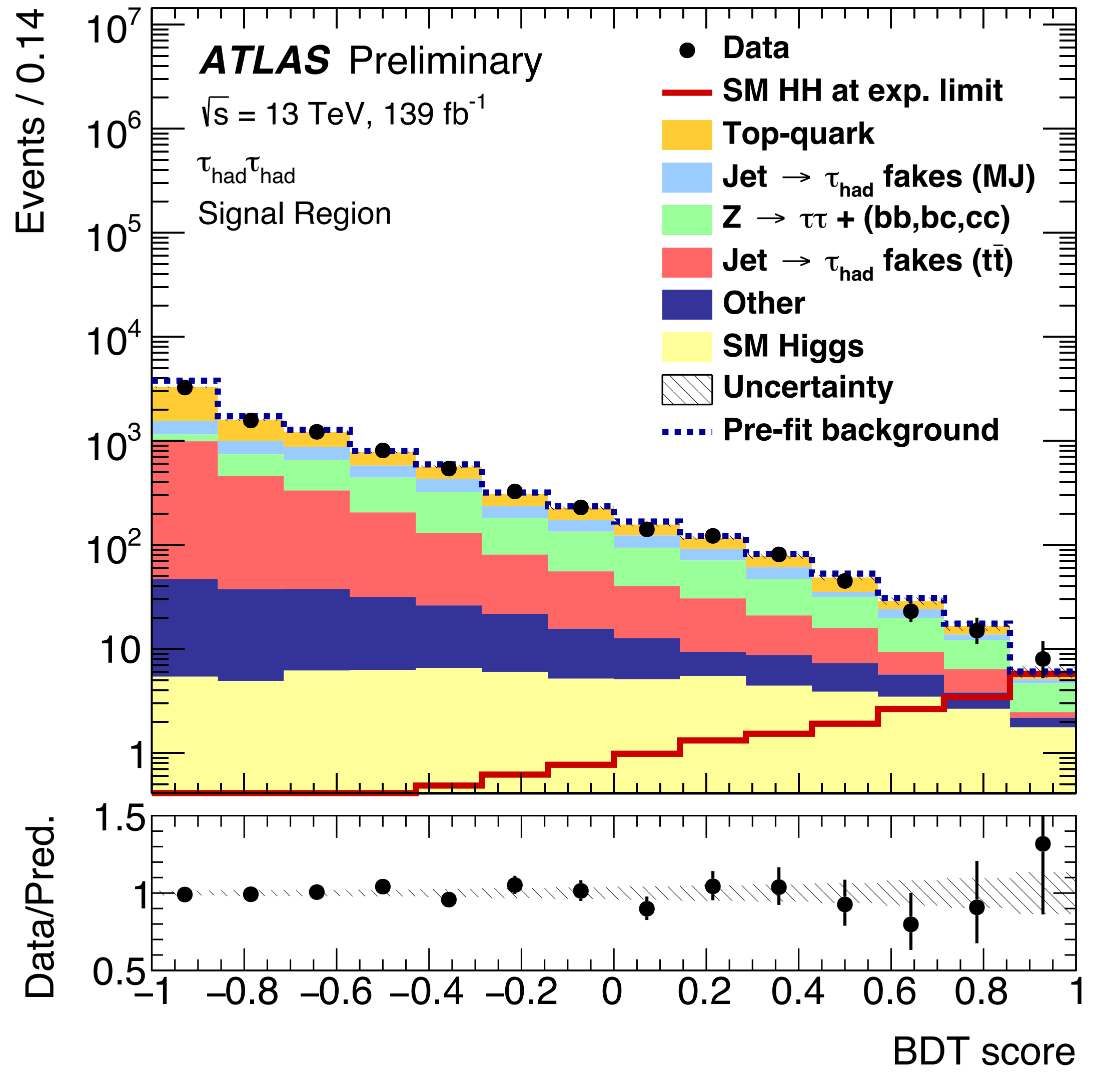
Resolved:

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.

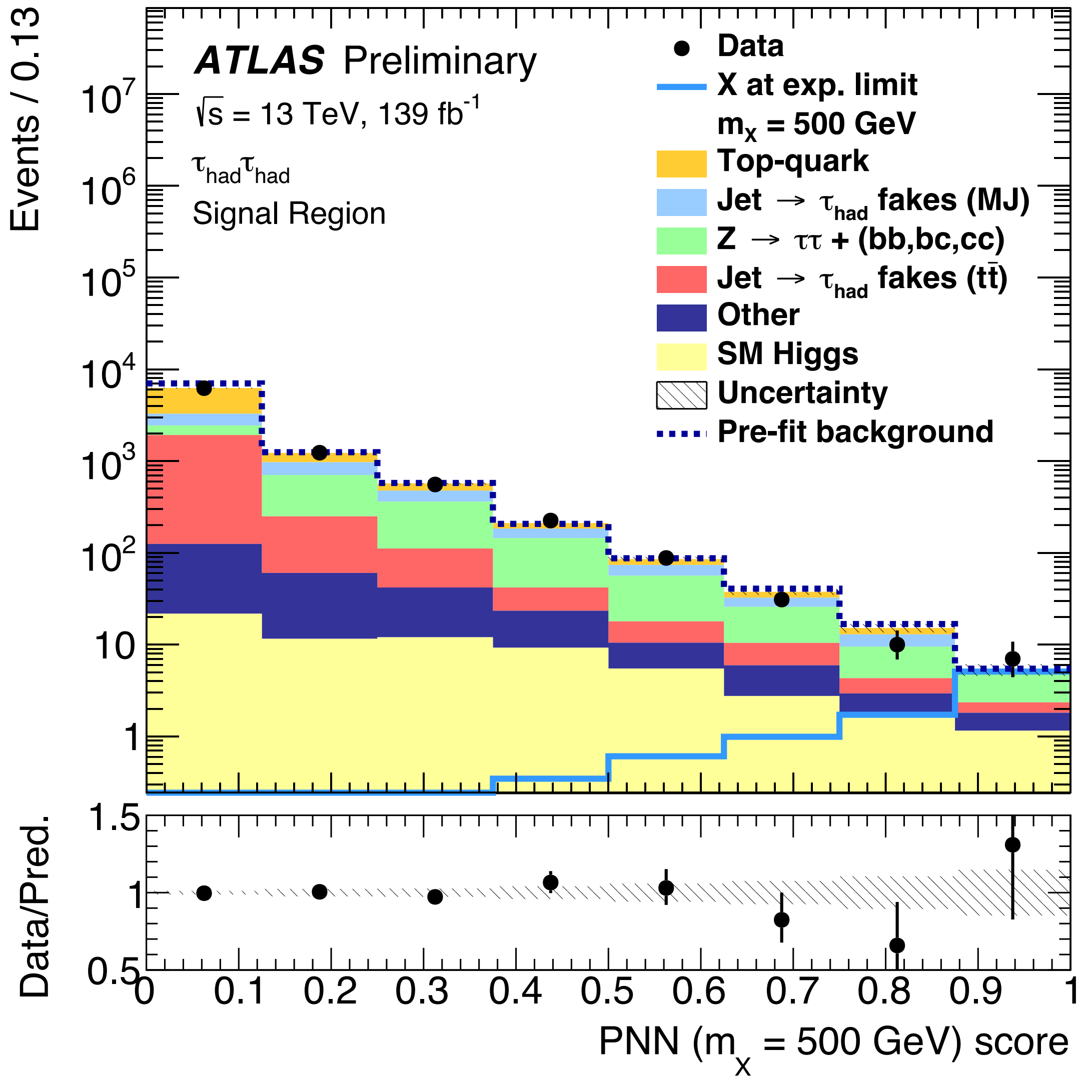
Non-resonant

- 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

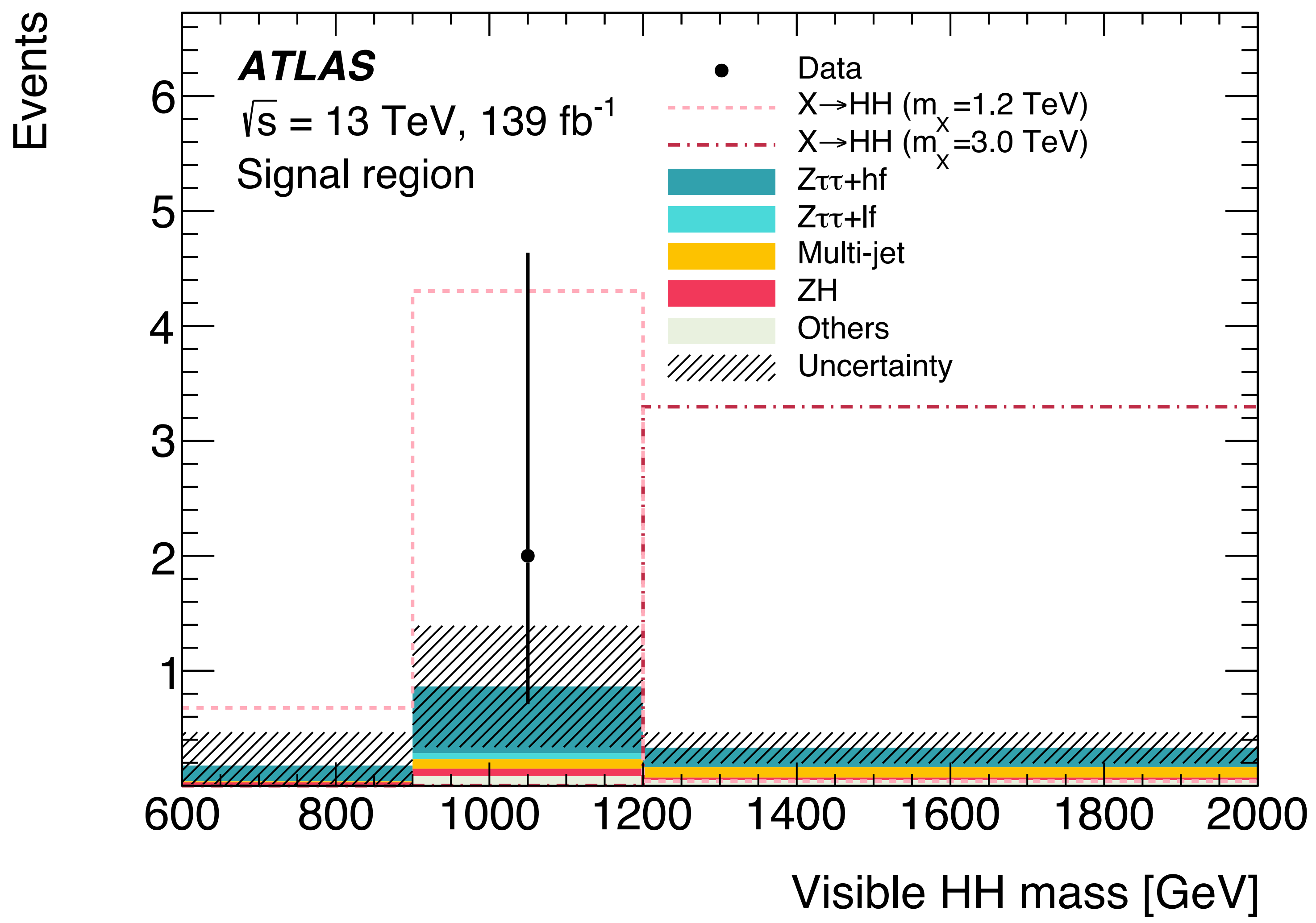


dedicated Control Regions for:

$t\bar{t}$, $Z \rightarrow \tau\tau$, 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:

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

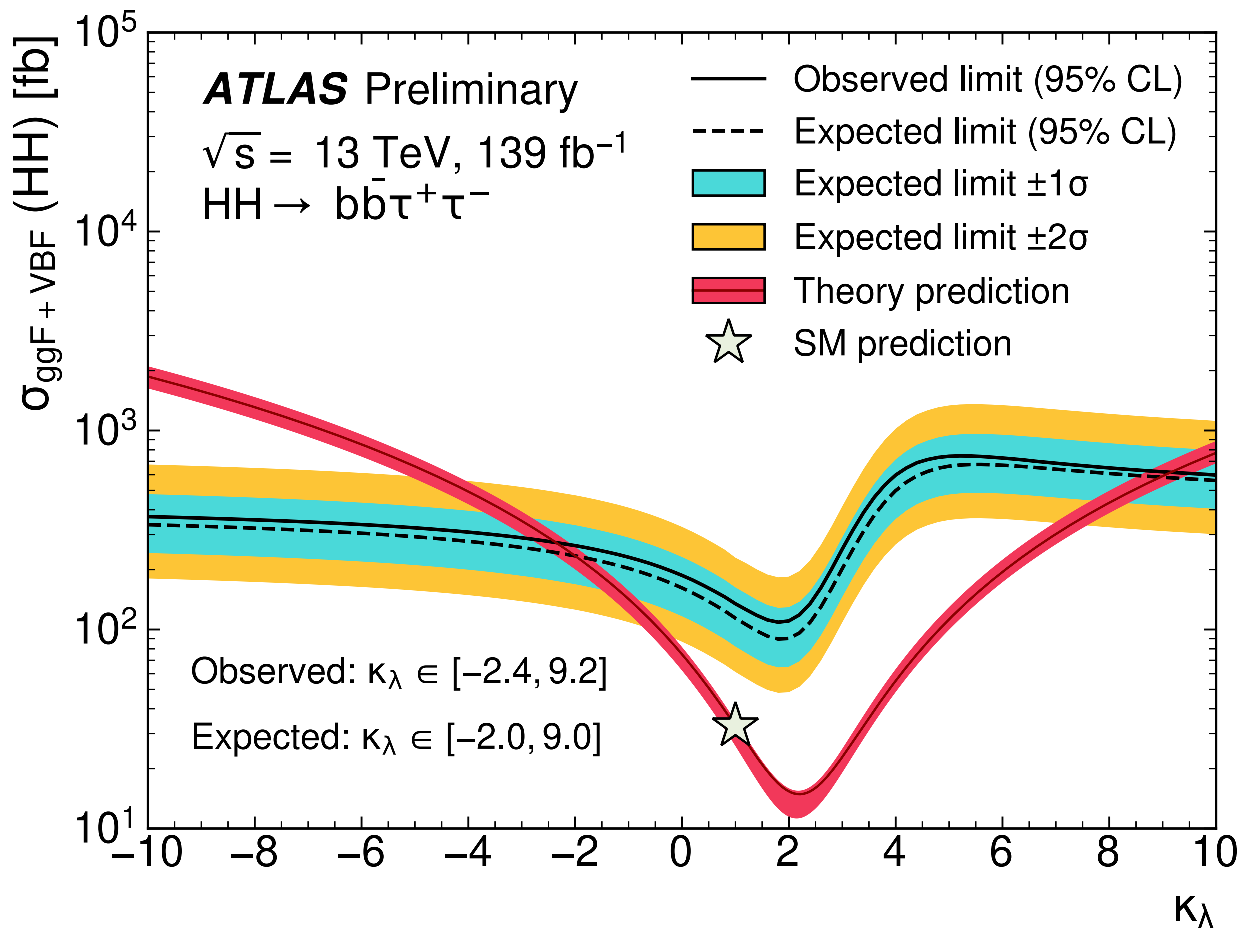
Results

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

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

Resolved:

Non-resonant No significant excess found

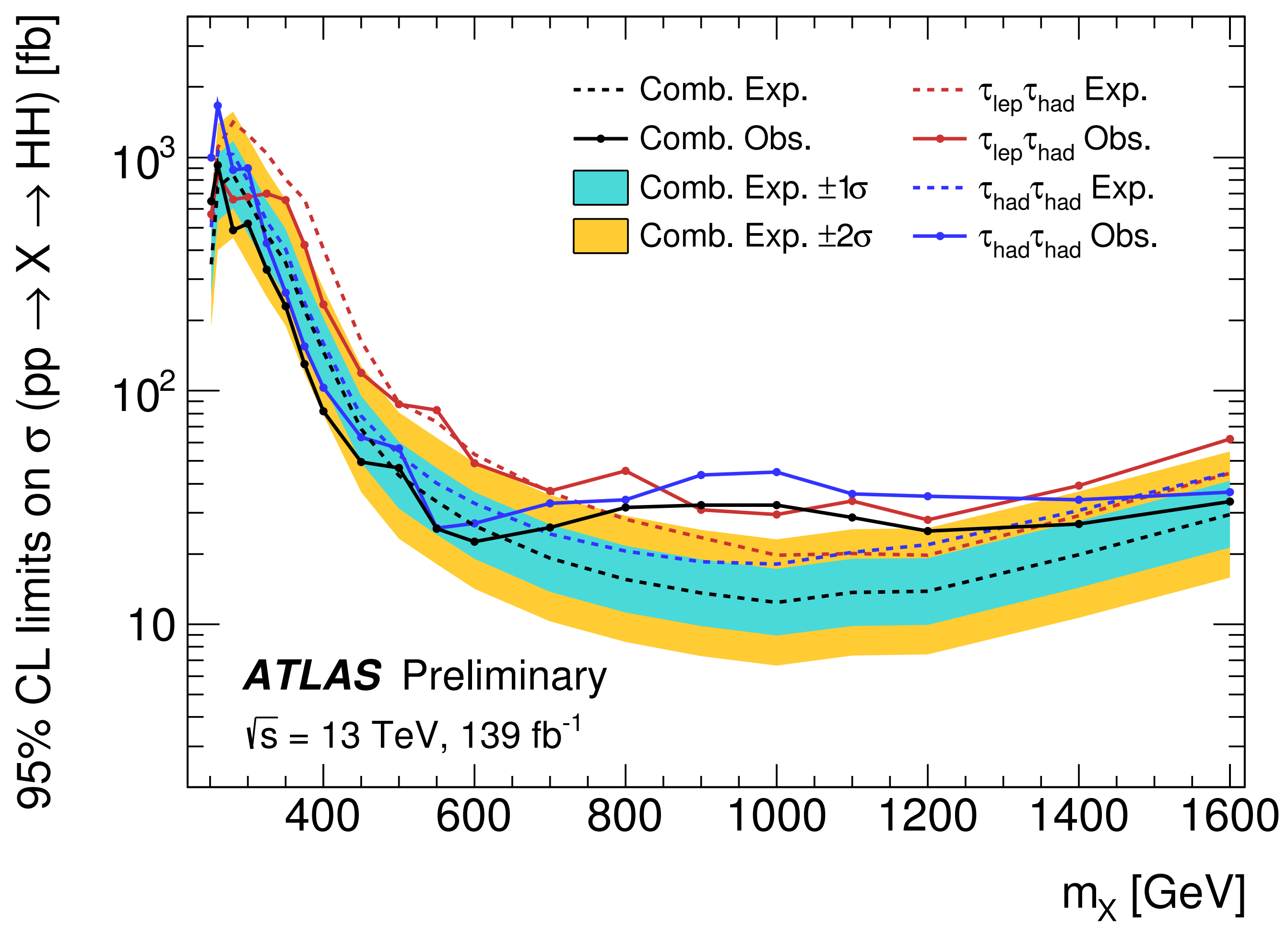


$\sigma_{HH}^{ggF+VBF}$ **observed (expected)** limit is **4.7 (3.9)** times the SM prediction.

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

Resonant

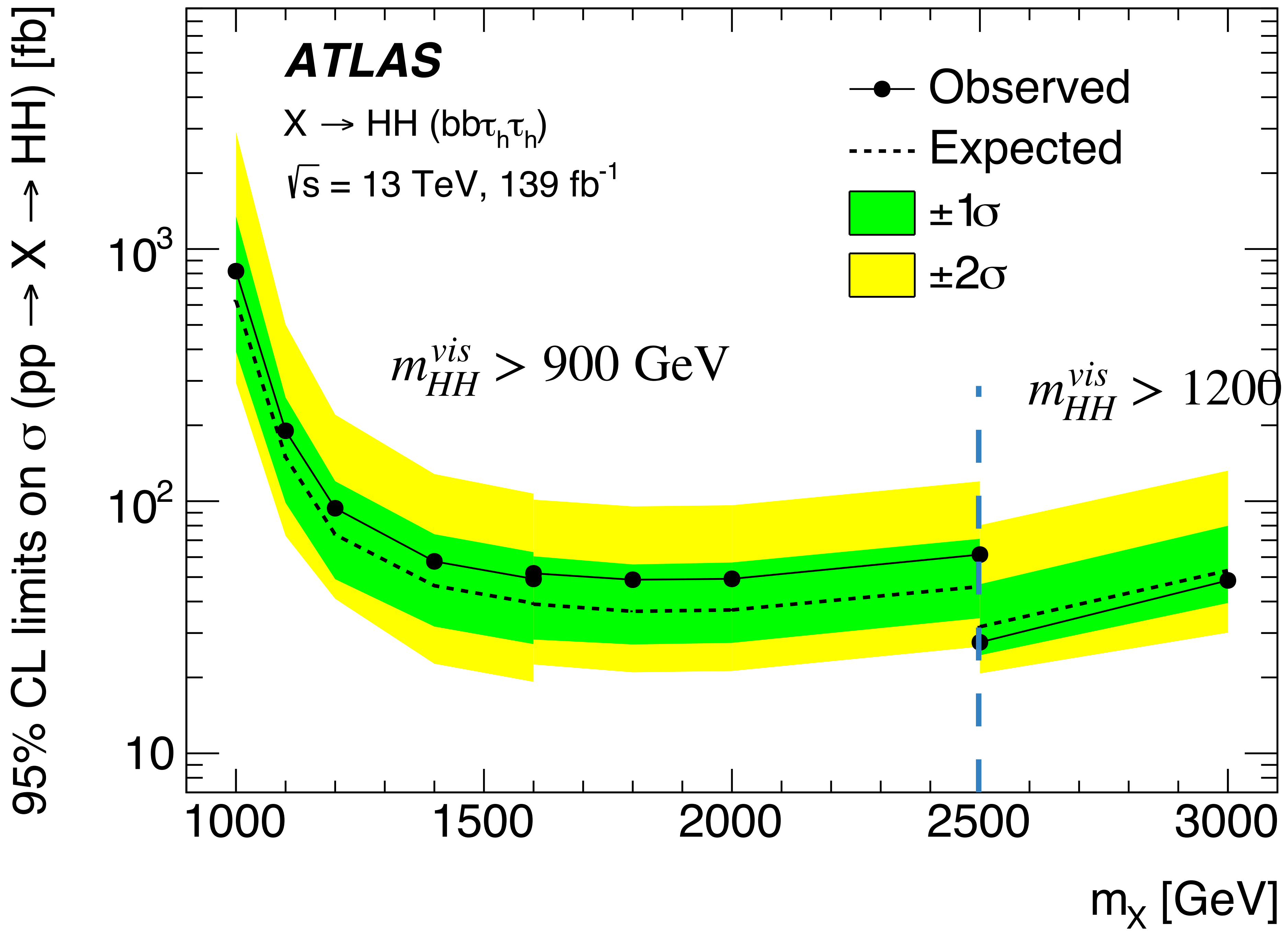
Highest deviation form the SM prediction seen at 1 TeV with a local (global) significance of 3.0σ (2.0)σ.



Boosted: No significant excess found

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

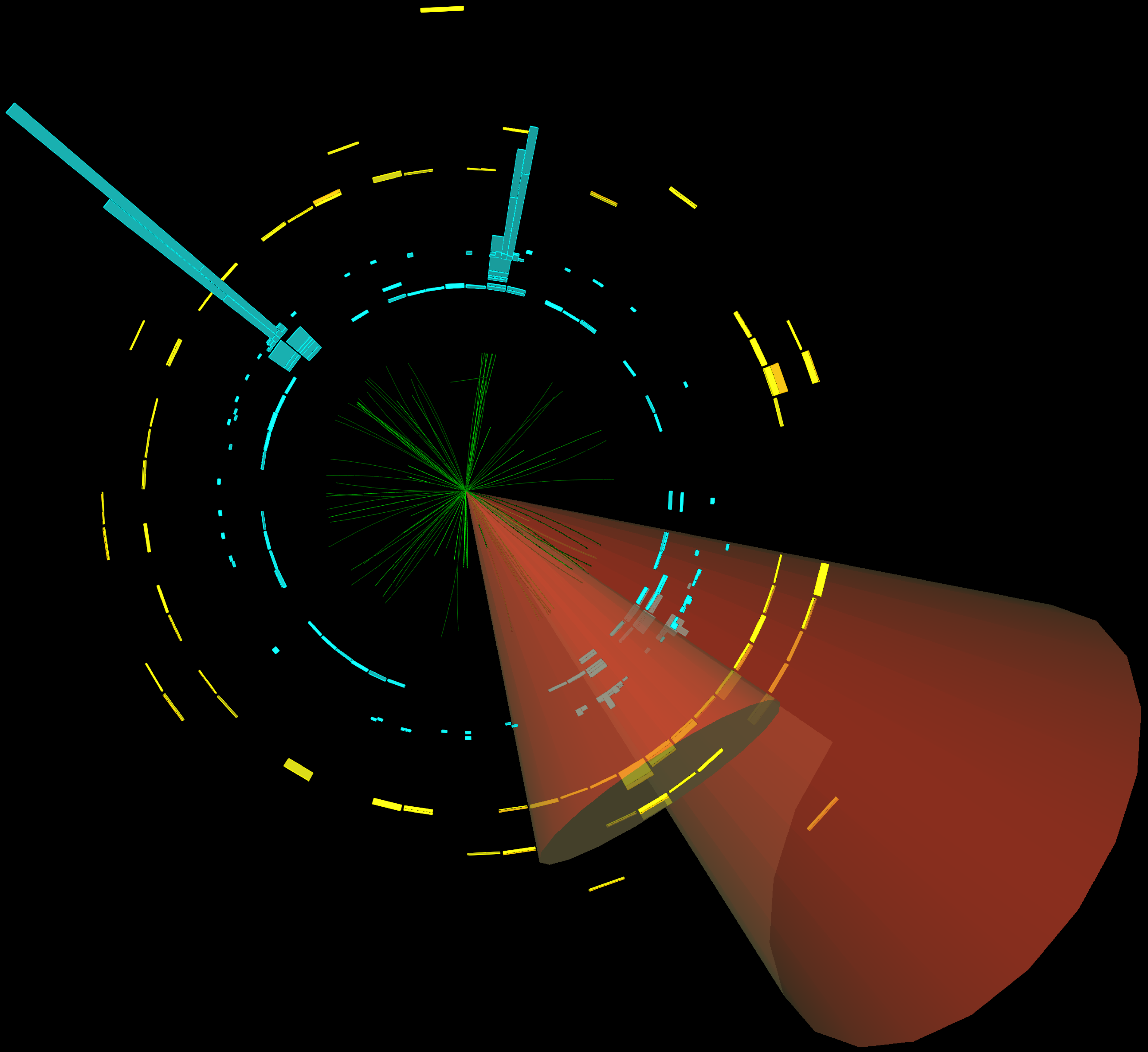
- Two regimes based on the cut on m_{HH}^{vis}



ATLAS
EXPERIMENT

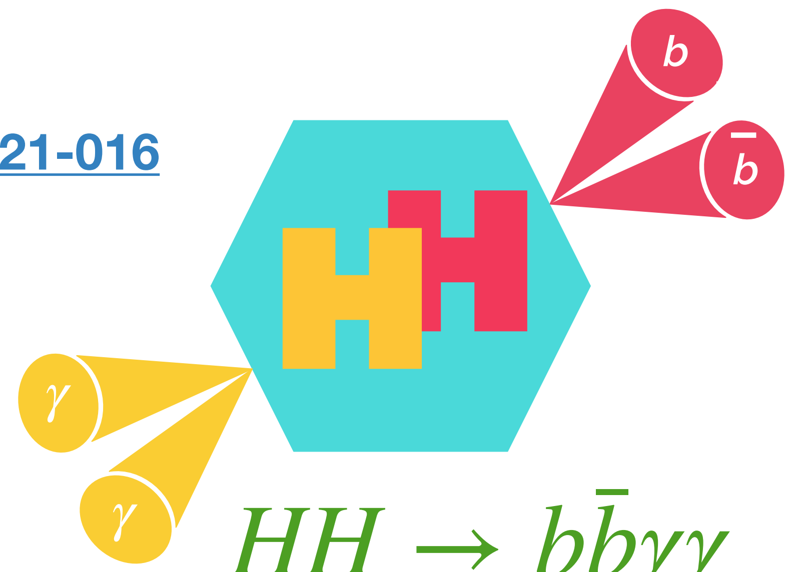
Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST

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

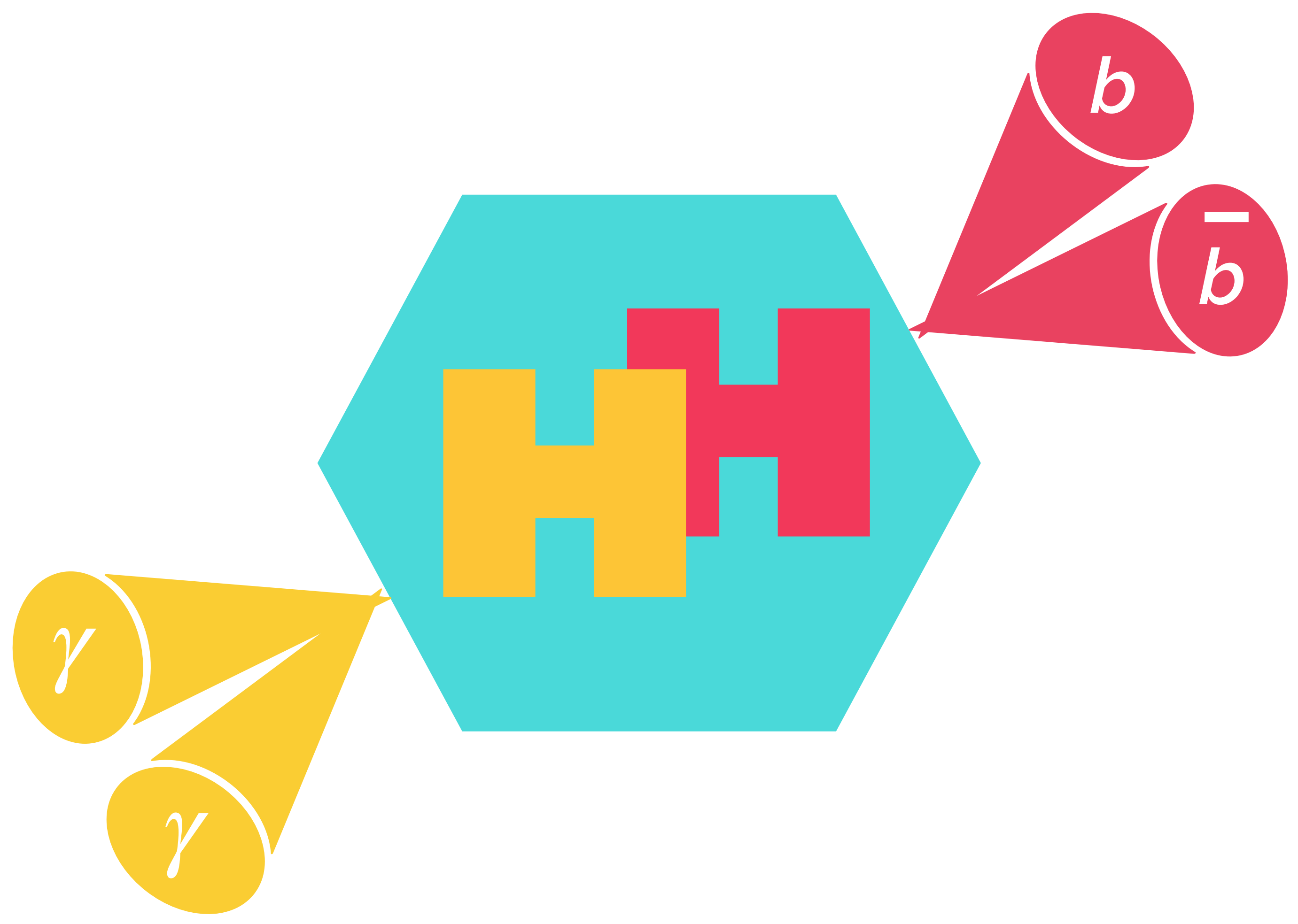


Strategy

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

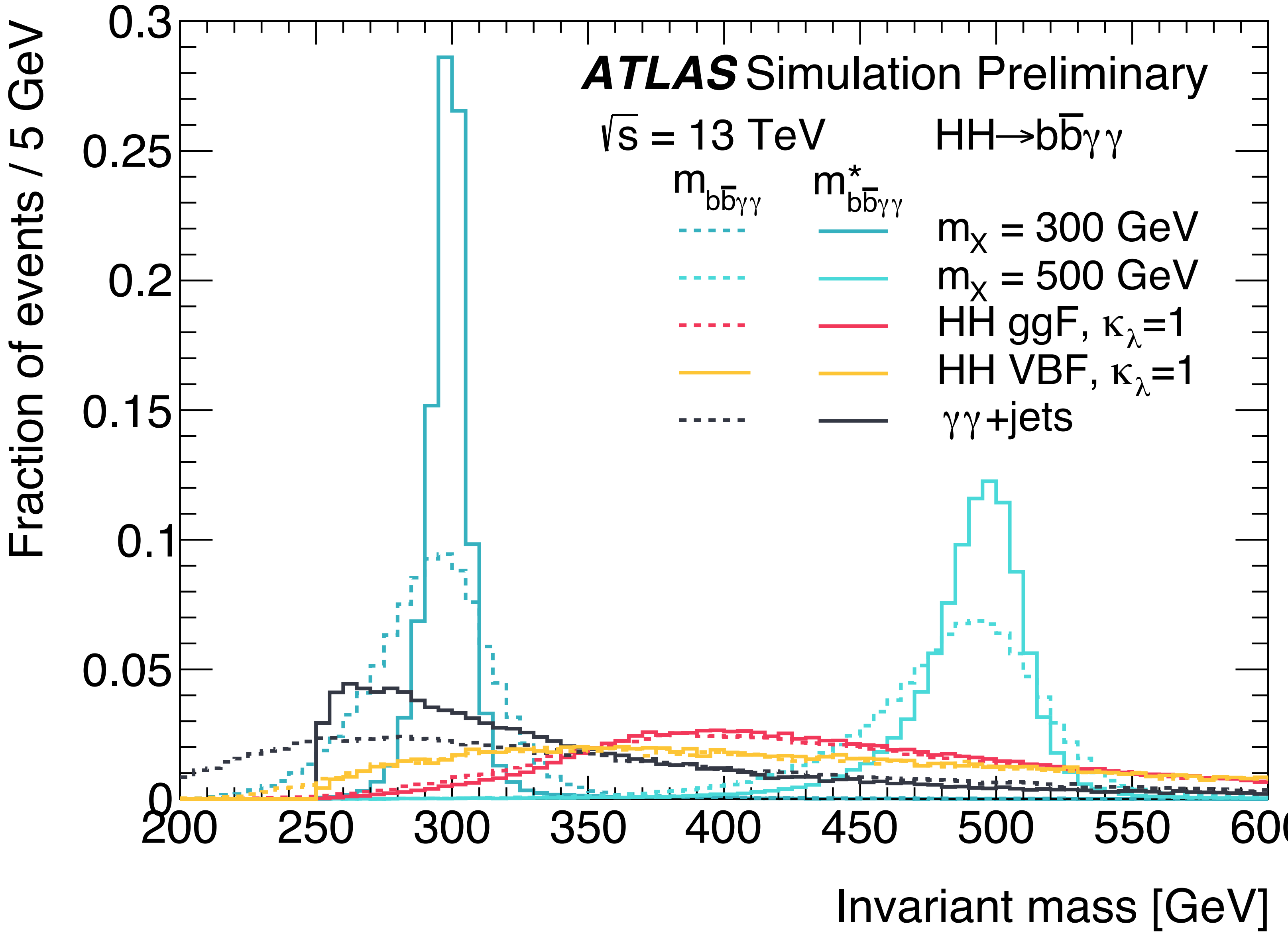


$HH \rightarrow b\bar{b}\gamma\gamma$



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

- Exactly 2 High quality photons;
- No lepton.

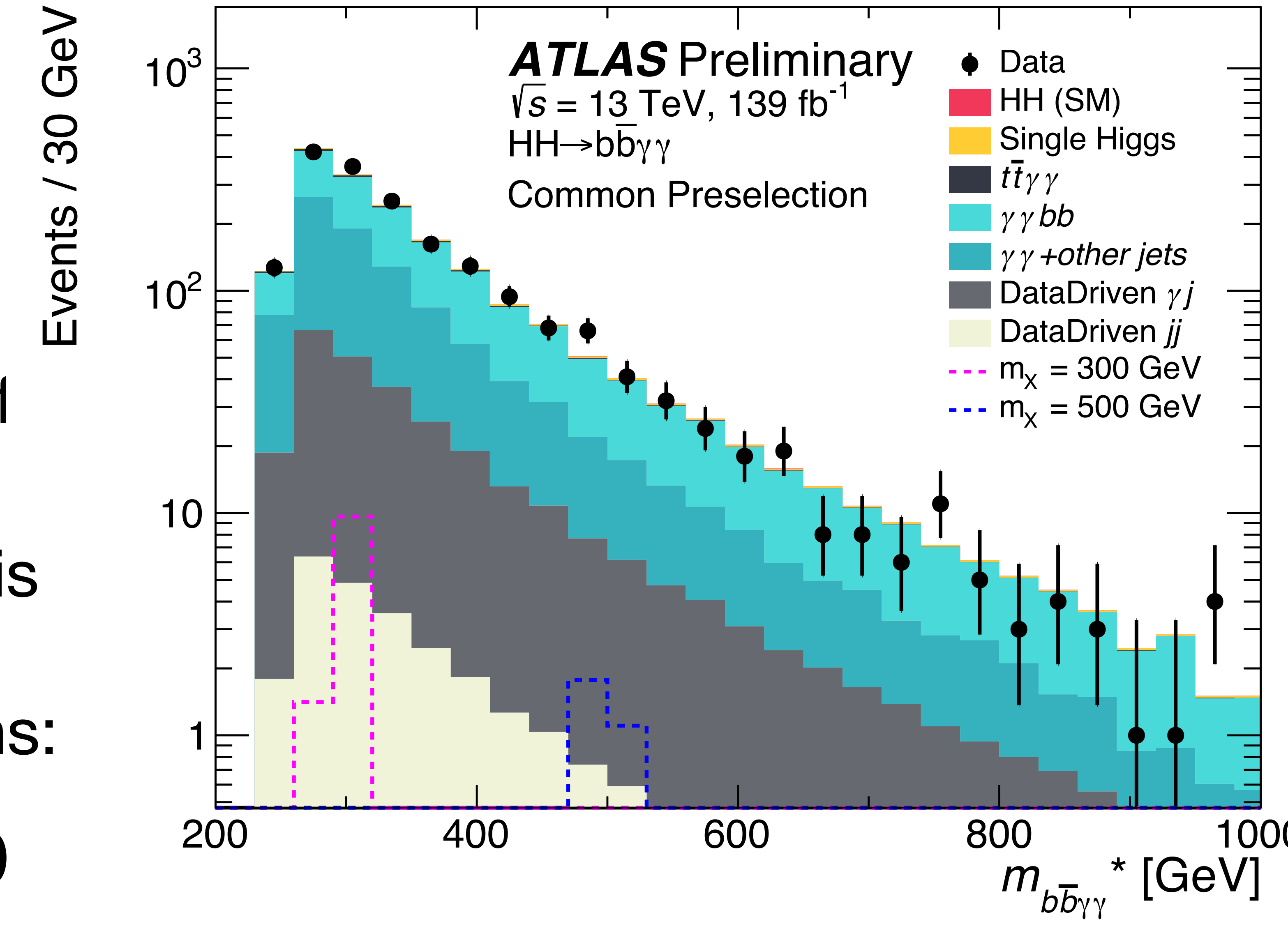


While the $m_{\gamma\gamma}$ variable is now used for the fit, the HH invariant mass $m_{b\bar{b}\gamma\gamma}$ is still useful for both the:

- 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?

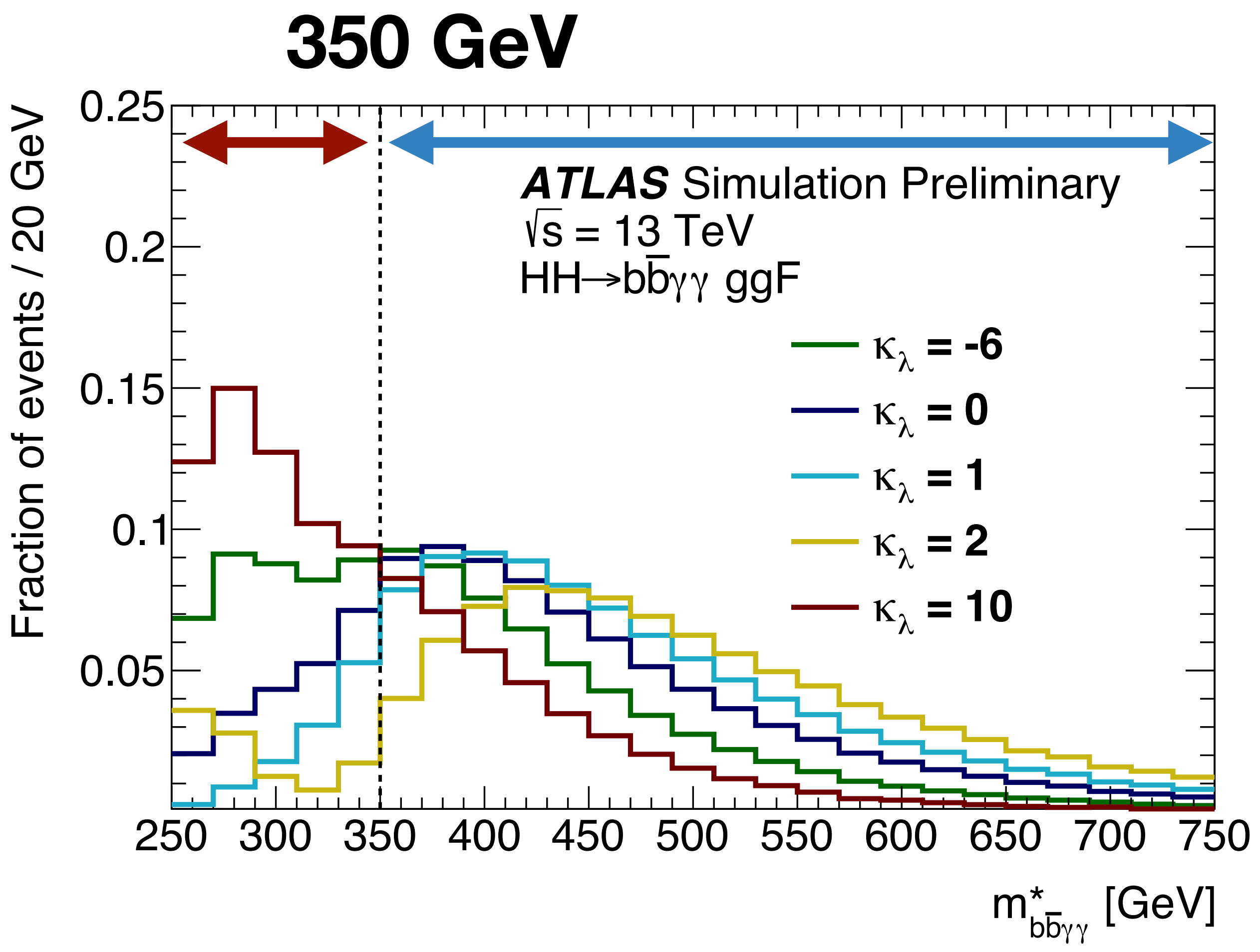
ggF: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-016

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

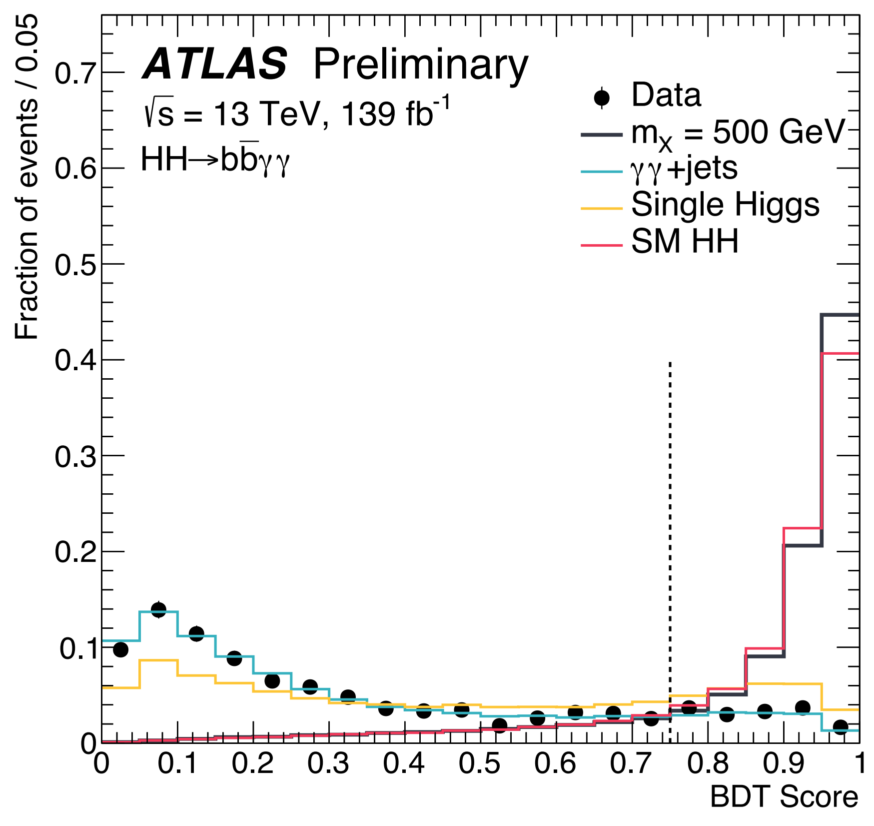
Non Resonant :

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.

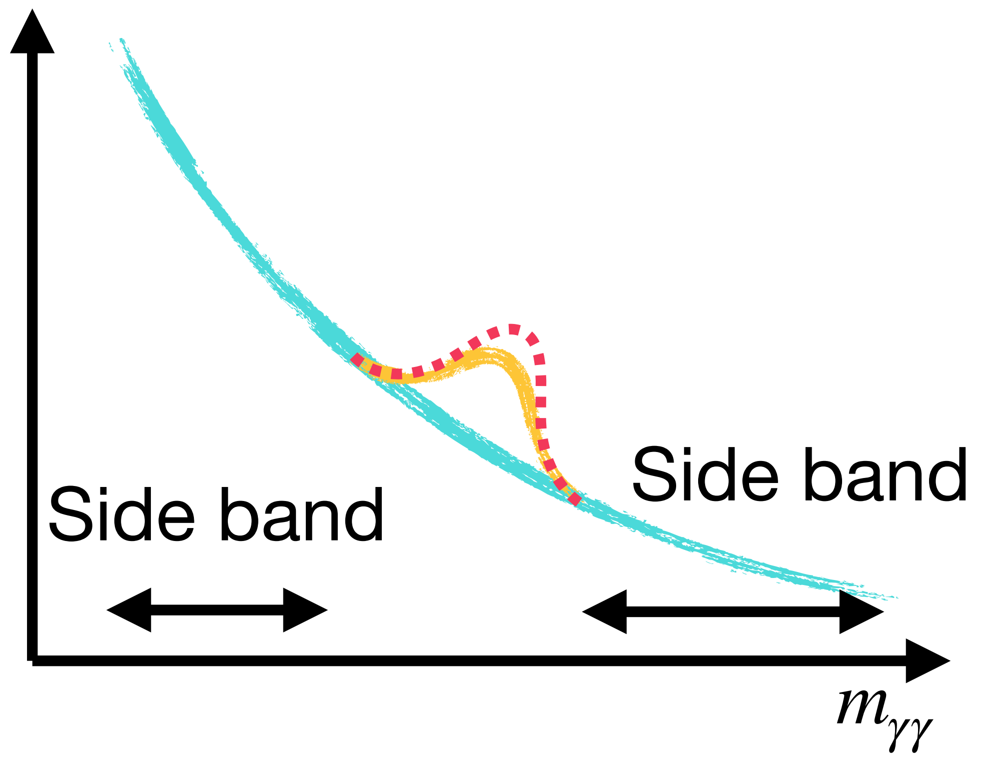


Resonant:



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.

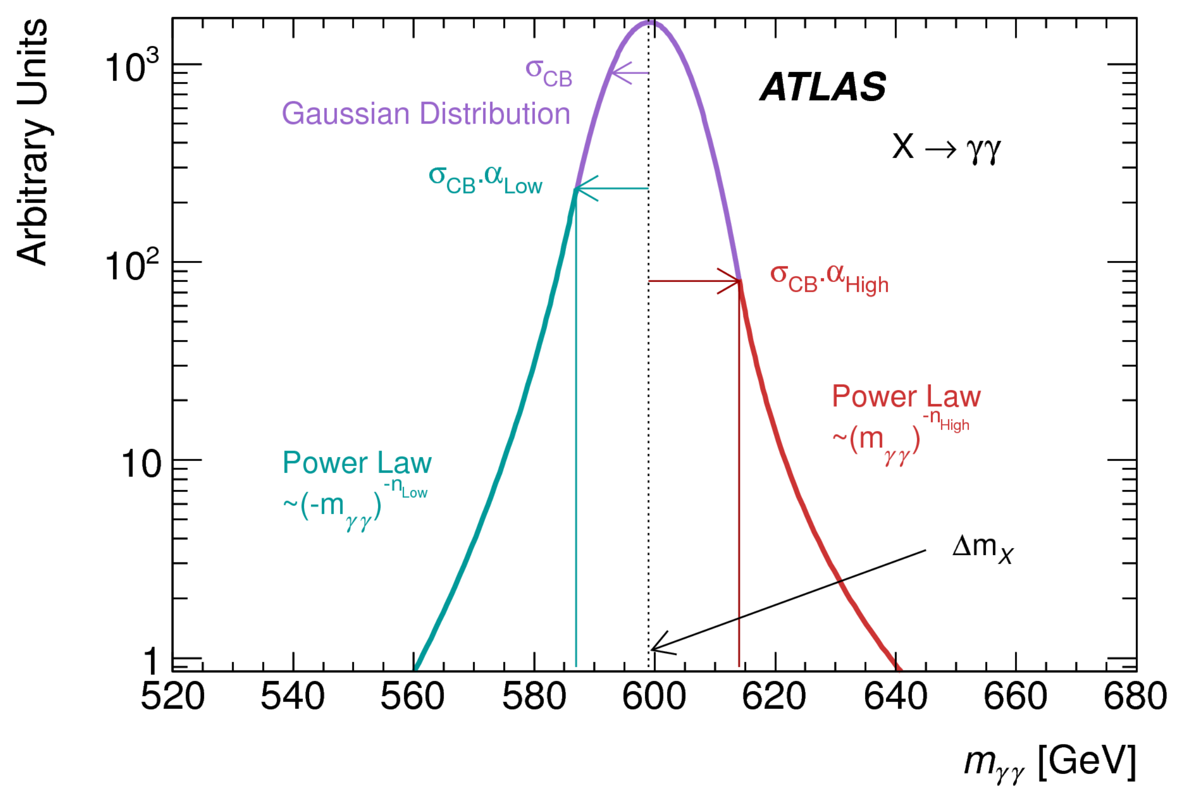
The background and signal processes are modelled thanks to **functional forms** used in the final fit:



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

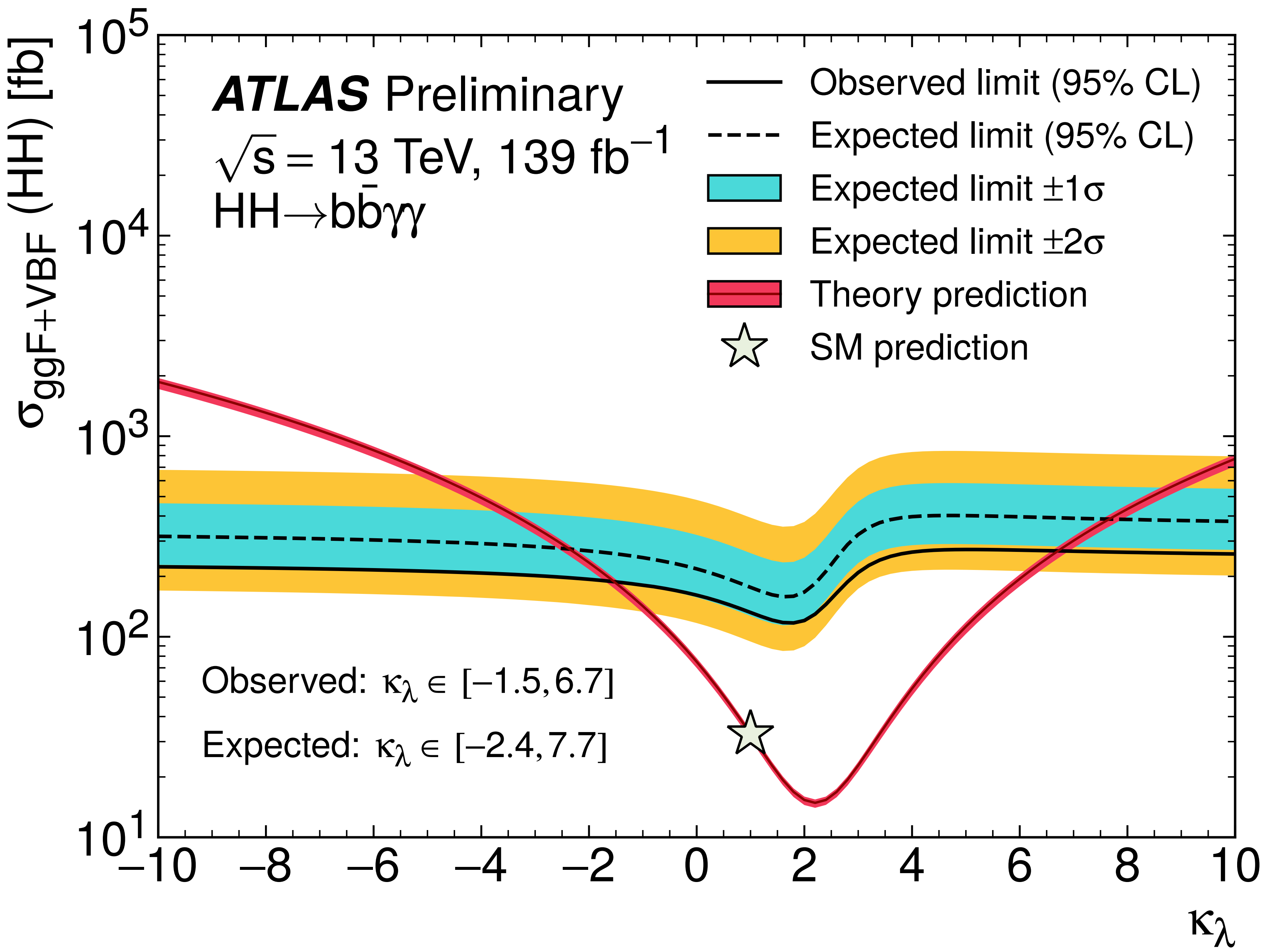
$HH \rightarrow b\bar{b}\gamma\gamma$

Non Resonant

No significant excess found

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

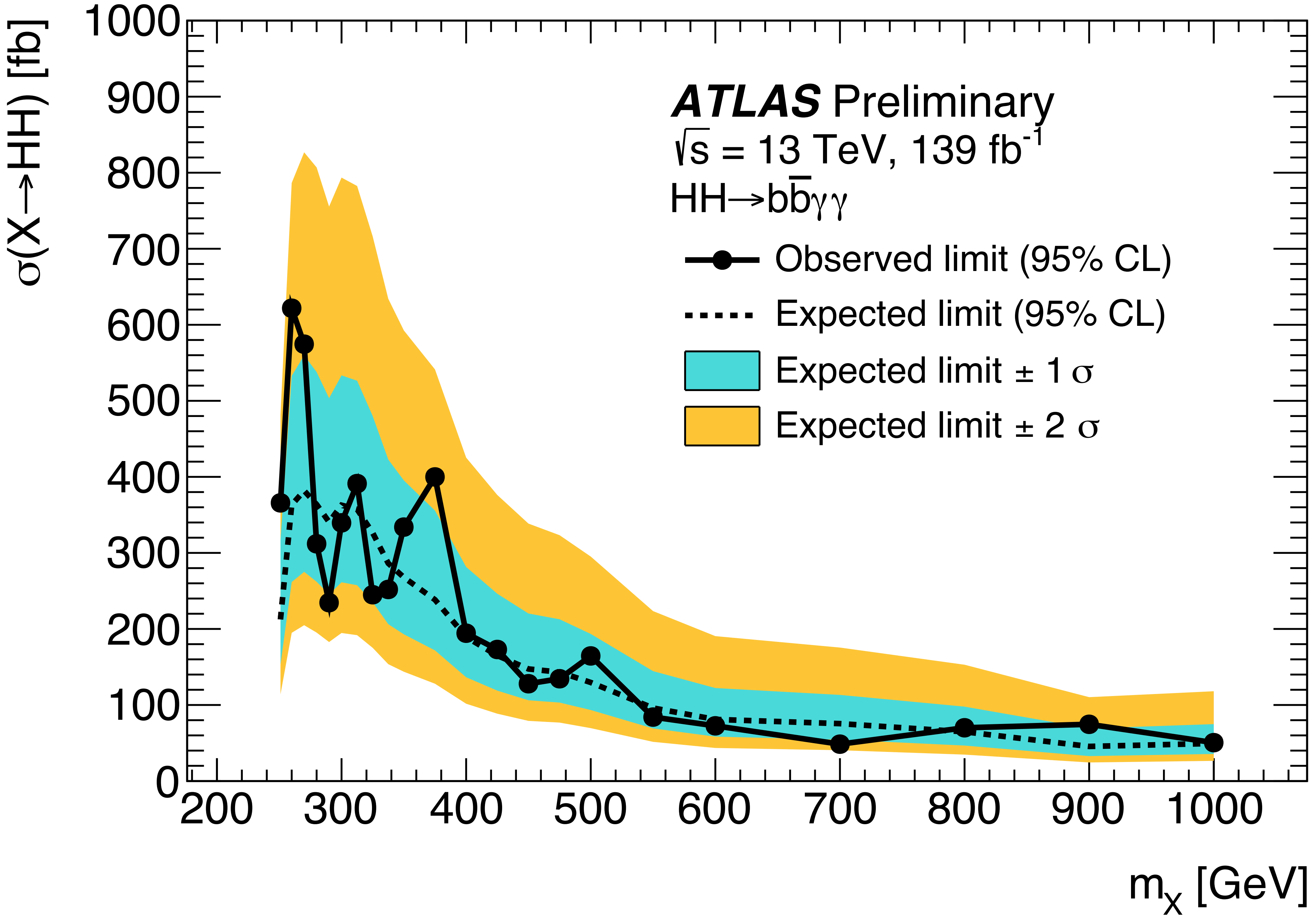
- *Best result* from single channel *observed to date;*
- Statistically dominated.
- Limits are set on κ_λ: $-1.5 < \kappa_\lambda < 6.7$ observed
  $-2.4 < \kappa_\lambda < 7.7$ expected.

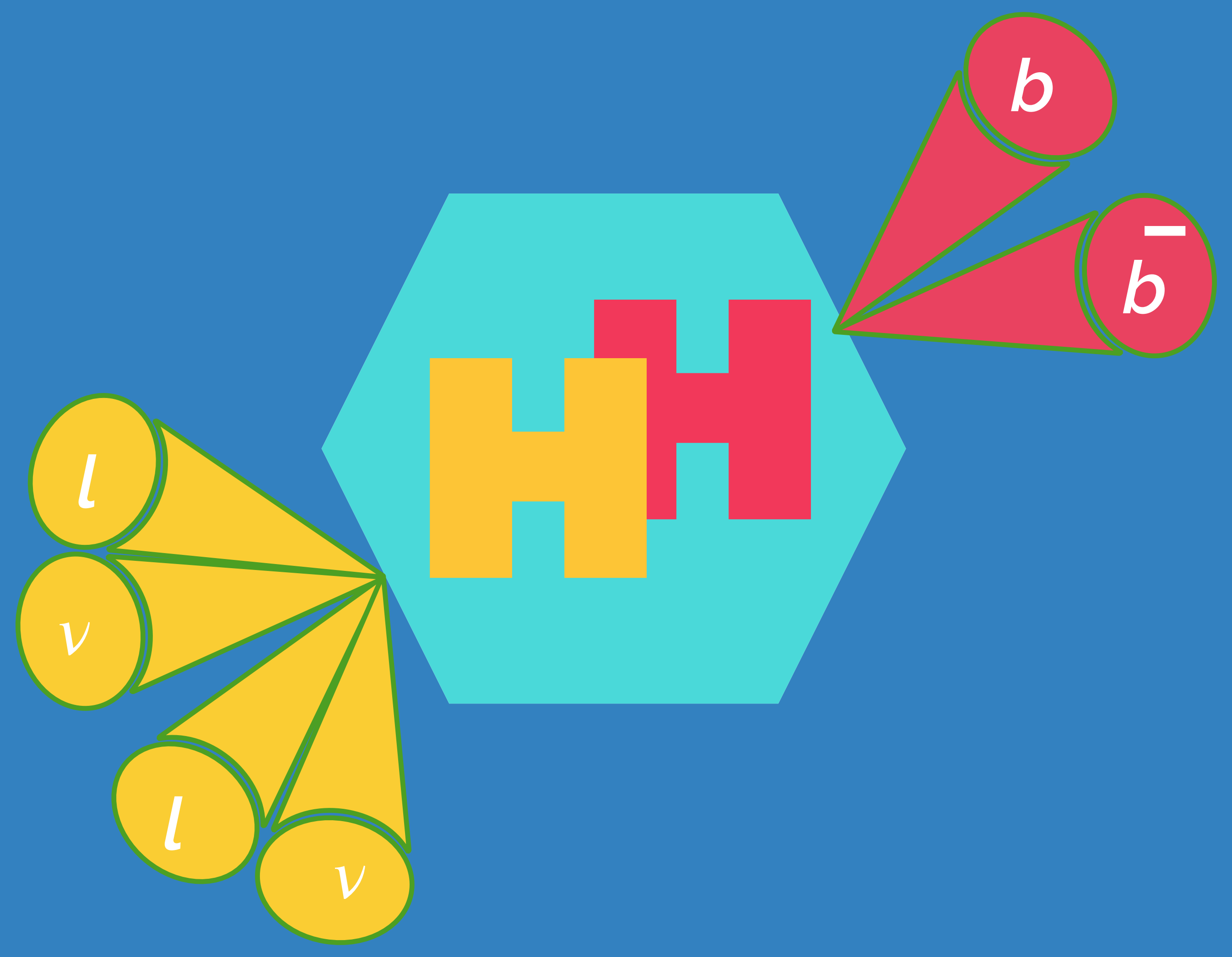


Resonant:

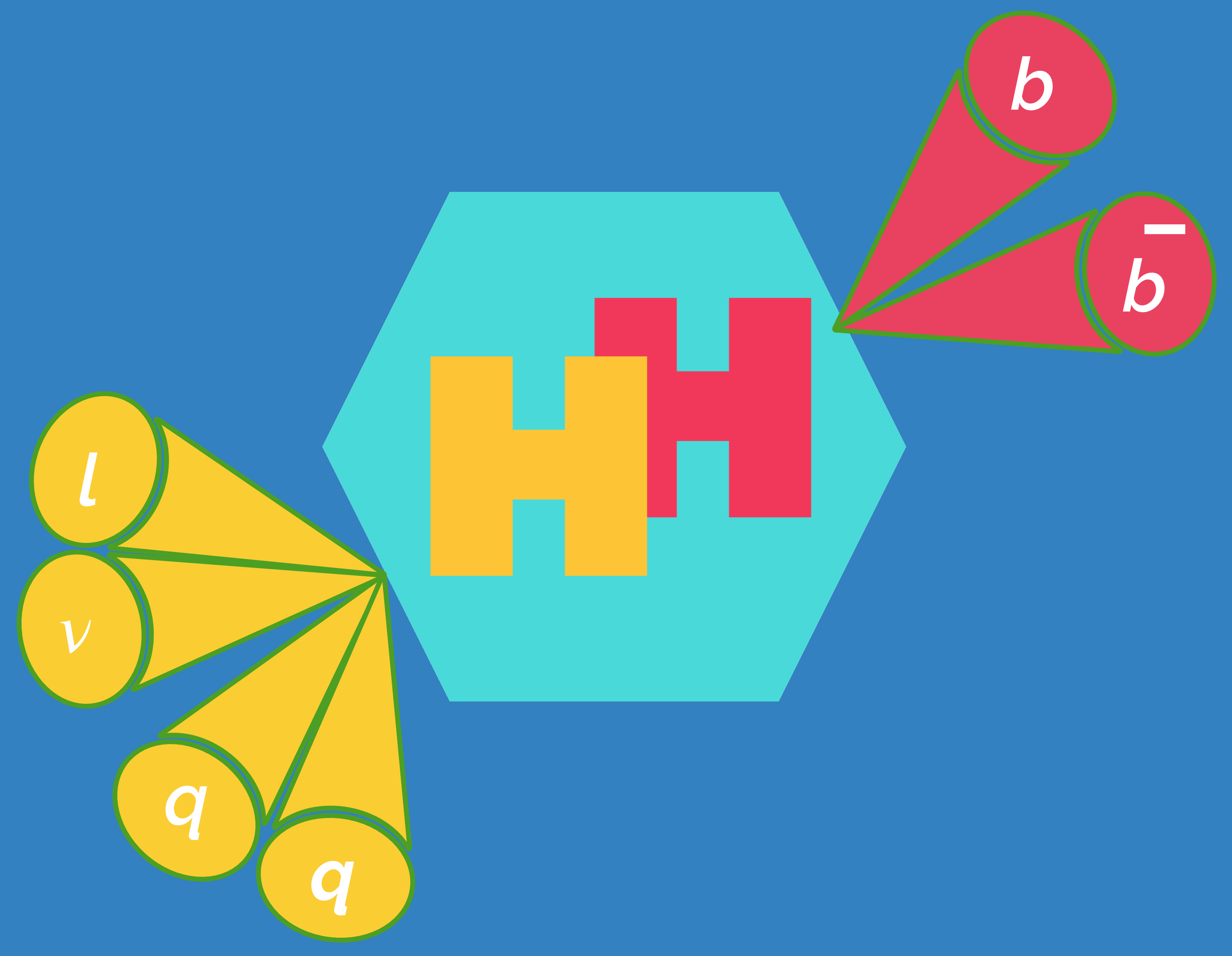
No significant excess found

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

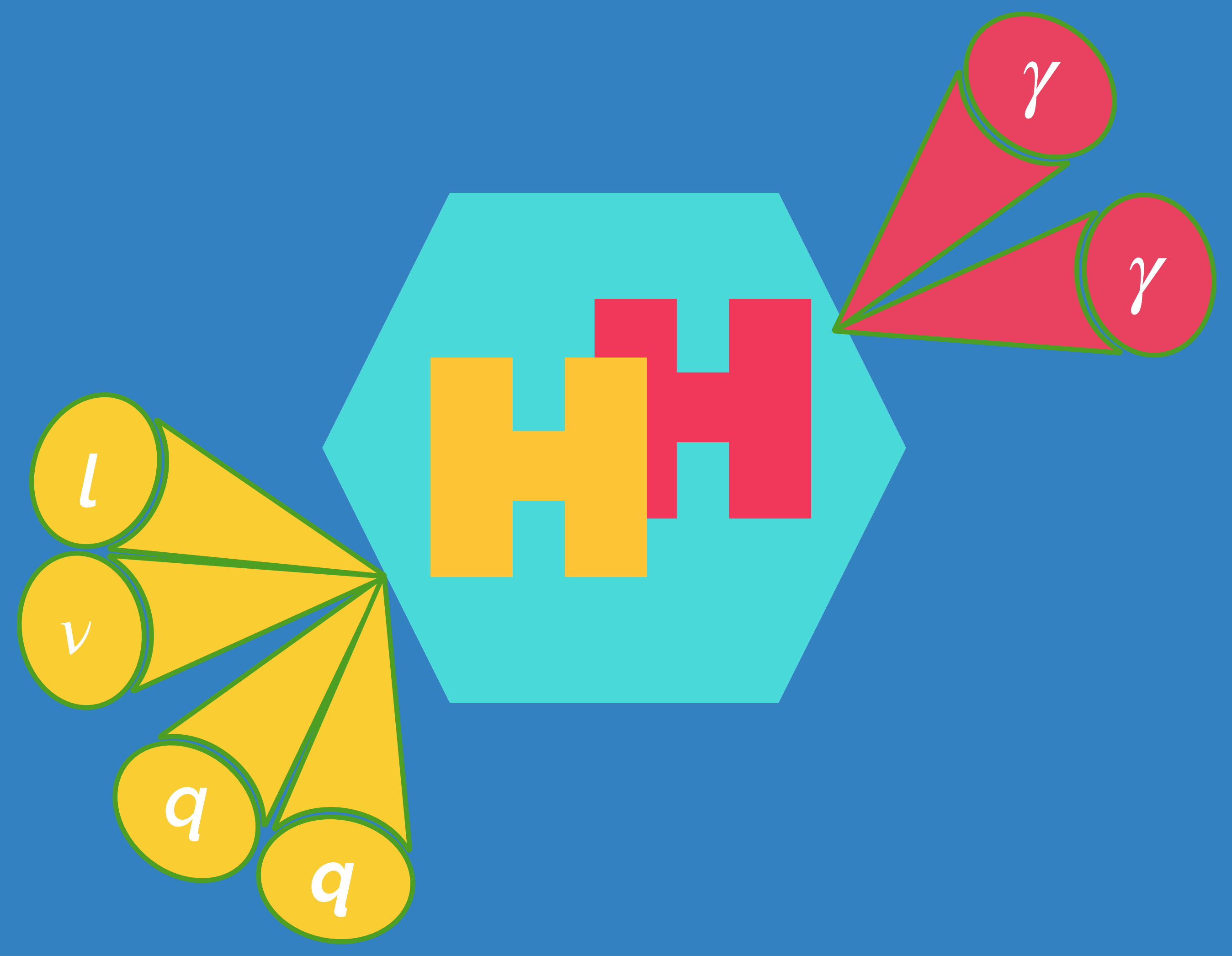




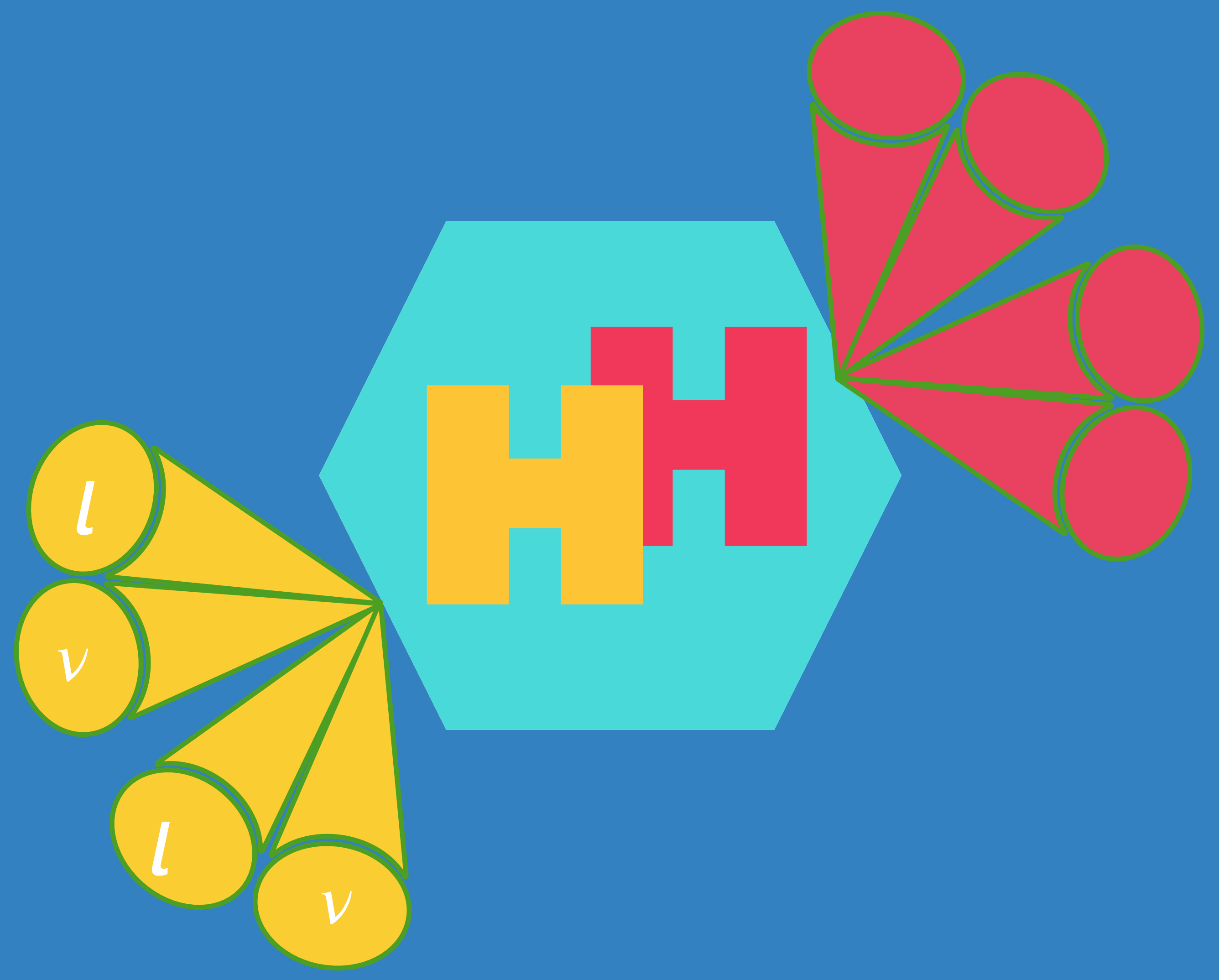
b
$\bar{b}$
l
ν
l
ν



b
$\bar{b}$
l
ν
q
q



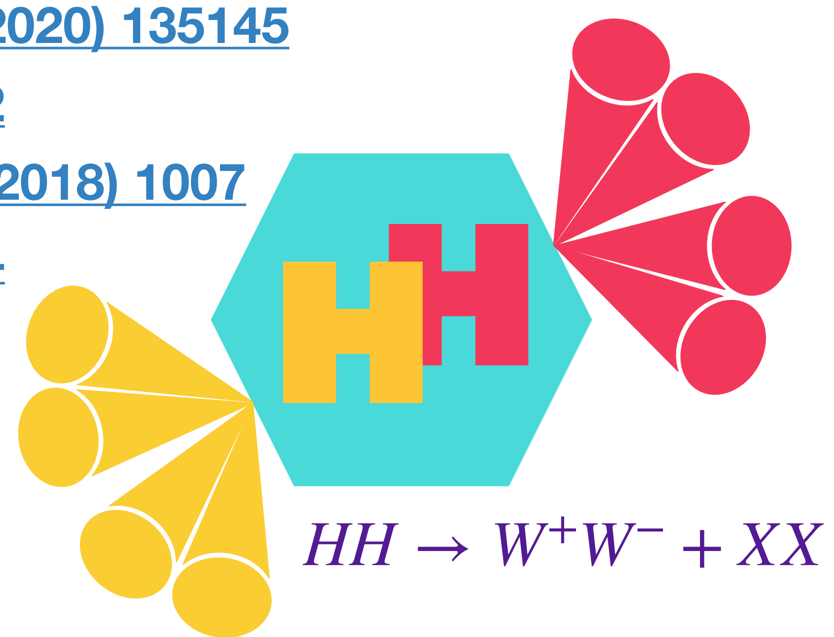
γ
γ
l
ν
q
q



l
ν
l
ν

Selection

$b\bar{b}l\nu l\nu$ final state : $\mathscr{L} = 139\text{fb}^{-1}$ — Phys. Lett. B 801 (2020) 135145
$b\bar{b}l\nu q\bar{q}$ final state : $\mathscr{L} = 36\text{fb}^{-1}$ — JHEP 04 (2019) 092
$\gamma\gamma WW^*$ final state : $\mathscr{L} = 36\text{fb}^{-1}$ — Eur. Phys. J. C 78 (2018) 1007
WW^*WW^* final state : $\mathscr{L} = 36\text{fb}^{-1}$ — JHEP 05 (2019) 124



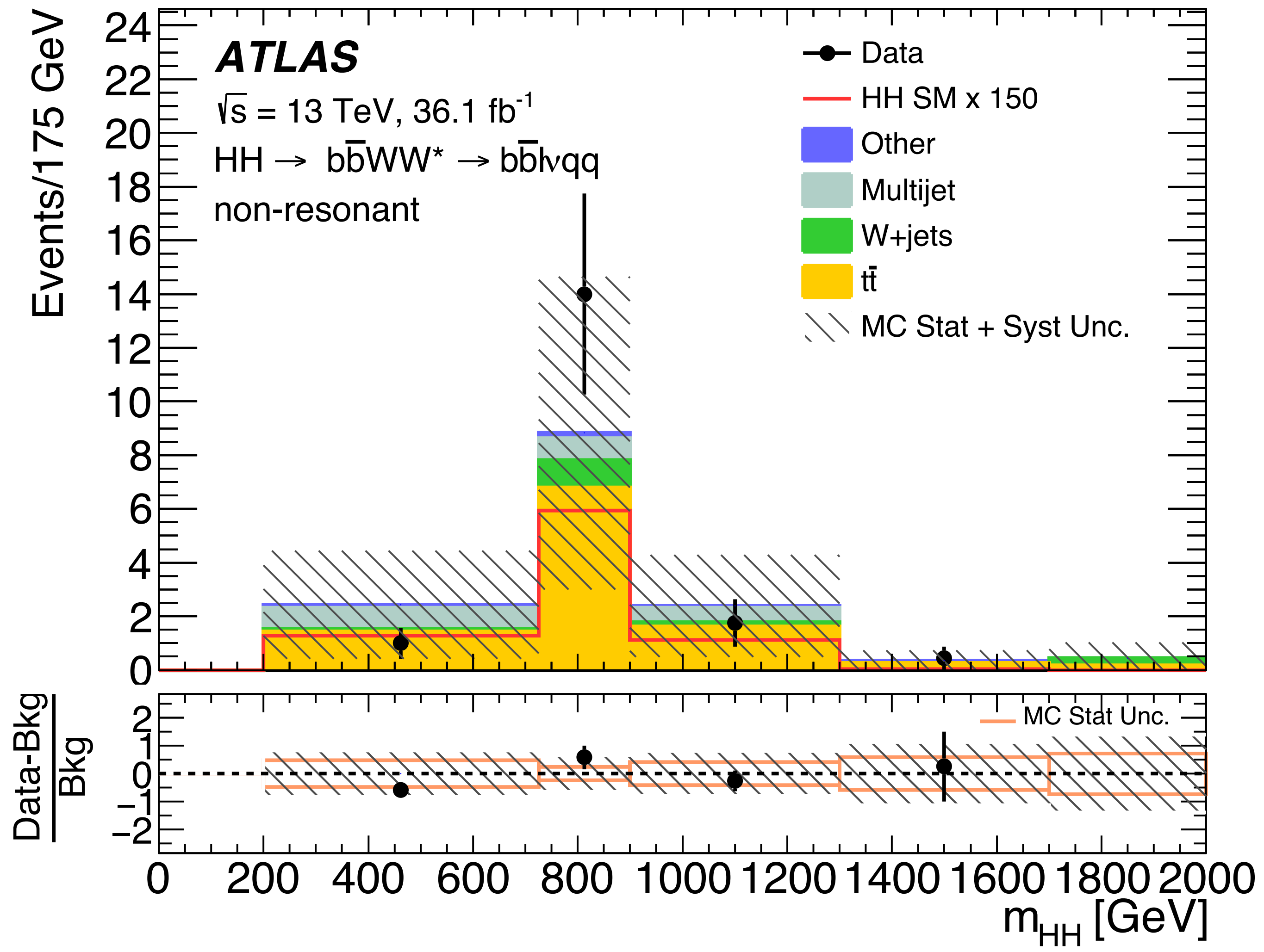
$HH \rightarrow W^+W^- + XX$

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

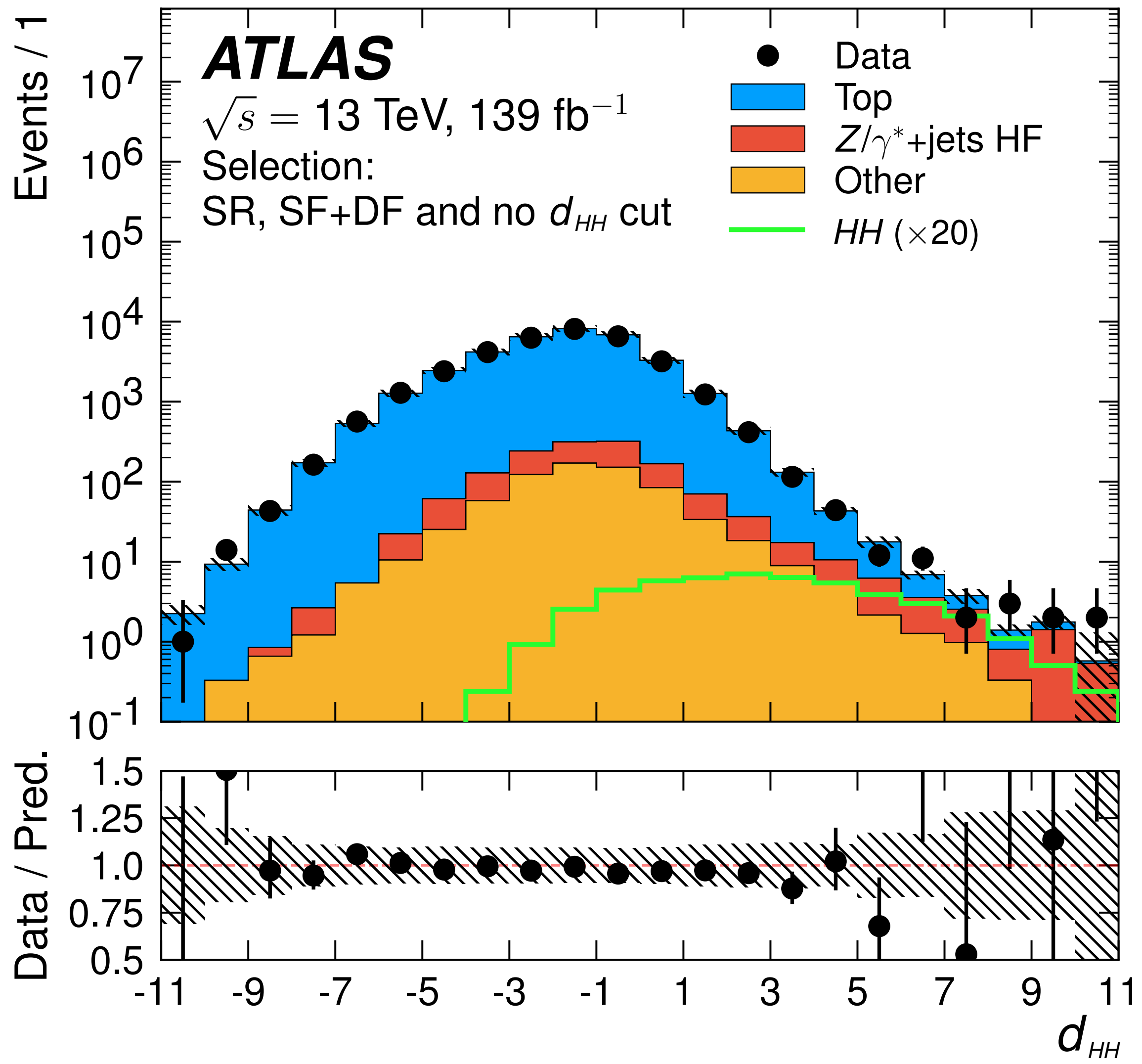
$H \rightarrow WW^* \rightarrow l\nu q\bar{q}$:
- Resolved/Boosted:
  - ≥ 1 high quality lepton.
  - ≥ 2 additional jets, pair chosen with minimising $\Delta R(jet, jet)$
  - Kinematic fit to find the neutrino momentum assuming $m_H = 125$ GeV



Fit: m_{HH} in different categories

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

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

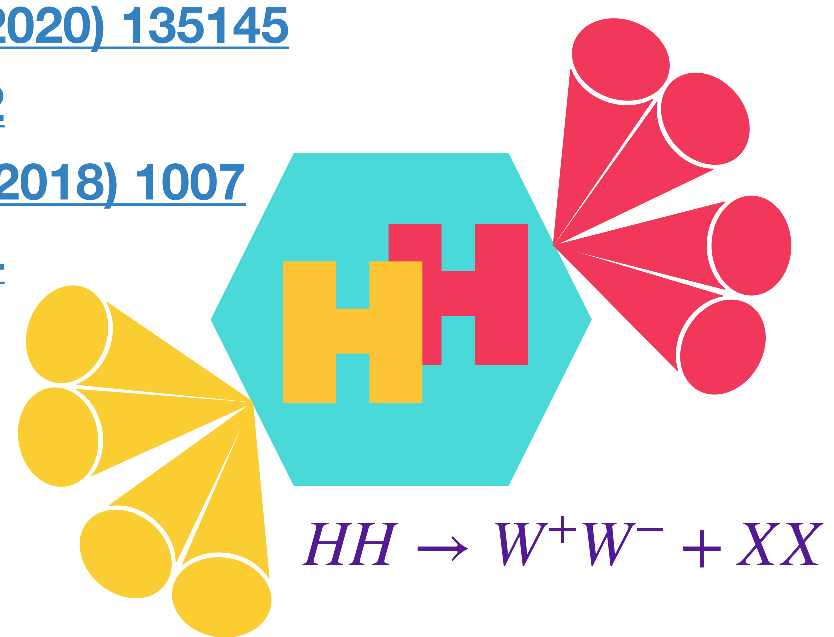


- $H \rightarrow b\bar{b}$:
  - Exactly 2 b-tagged jets
- $H \rightarrow WW^* \rightarrow l\nu l\nu$:
  - Exactly 2 opposite charge high quality leptons.
  - Categories: based on flavour.
- *Deep neural Network:*
  - To remove dominant backgrounds

Fit: single bin in different categories

Results

$b\bar{b}l\nu l\nu$ final state : $\mathscr{L} = 139\text{fb}^{-1}$ — Phys. Lett. B 801 (2020) 135145
$b\bar{b}l\nu q\bar{q}$ final state : $\mathscr{L} = 36\text{fb}^{-1}$ — JHEP 04 (2019) 092
$\gamma\gamma WW^*$ final state : $\mathscr{L} = 36\text{fb}^{-1}$ — Eur. Phys. J. C 78 (2018) 1007
WW^*WW^* final state : $\mathscr{L} = 36\text{fb}^{-1}$ — JHEP 05 (2019) 124

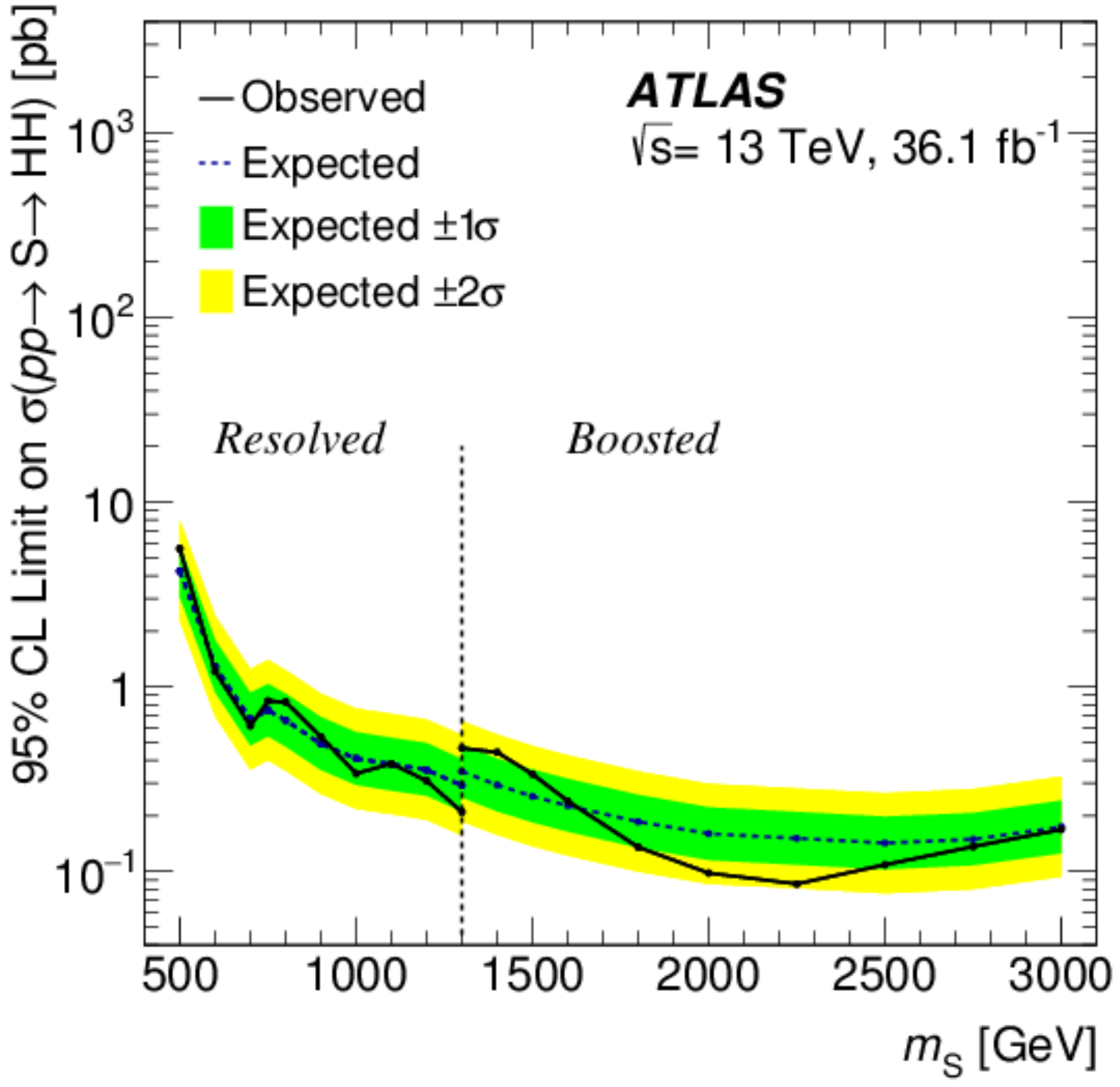


$b\bar{b}l\nu q\bar{q}$ final state

Non-resonant Resolved

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

Resonant: Resolved Boosted

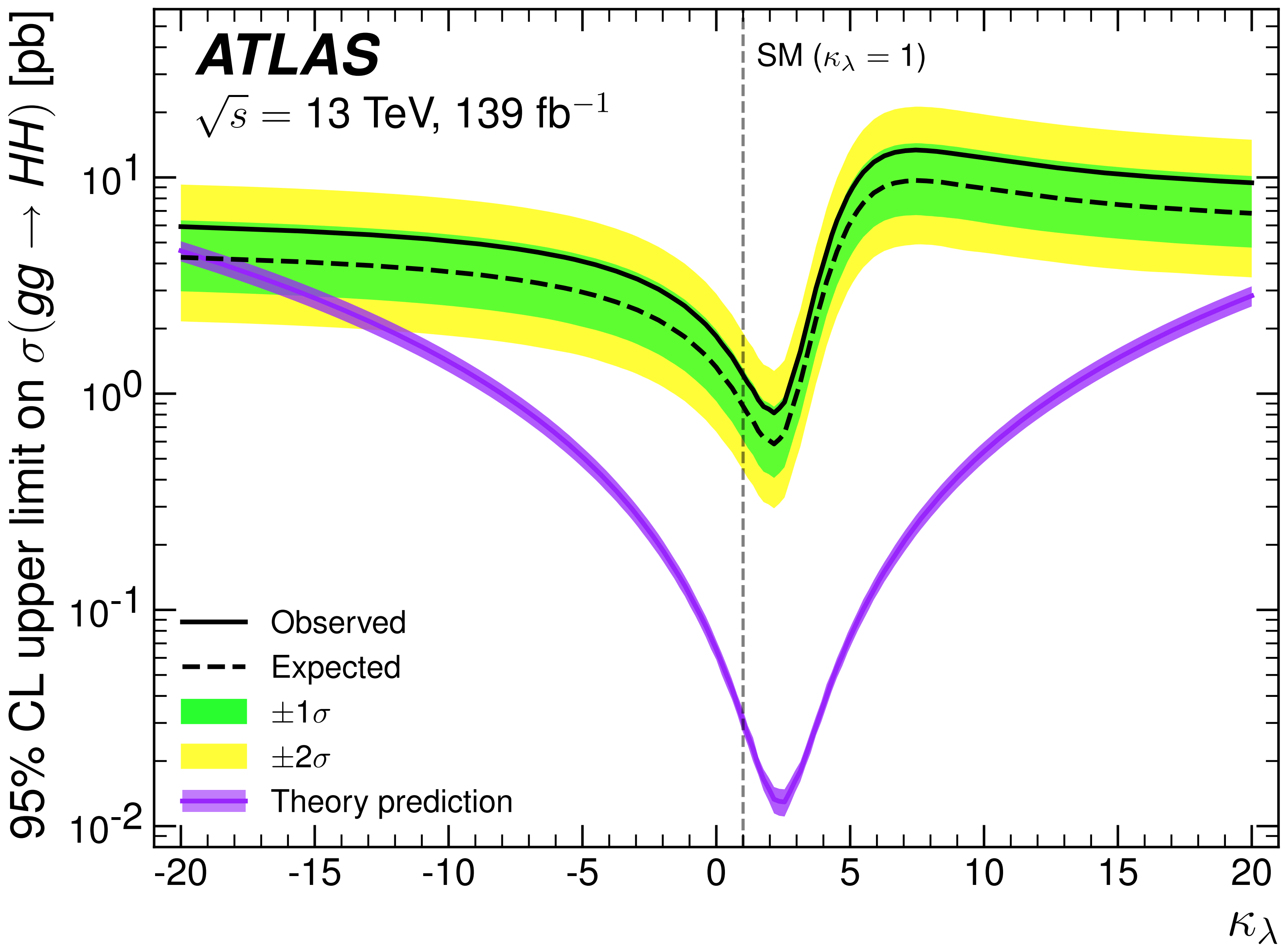


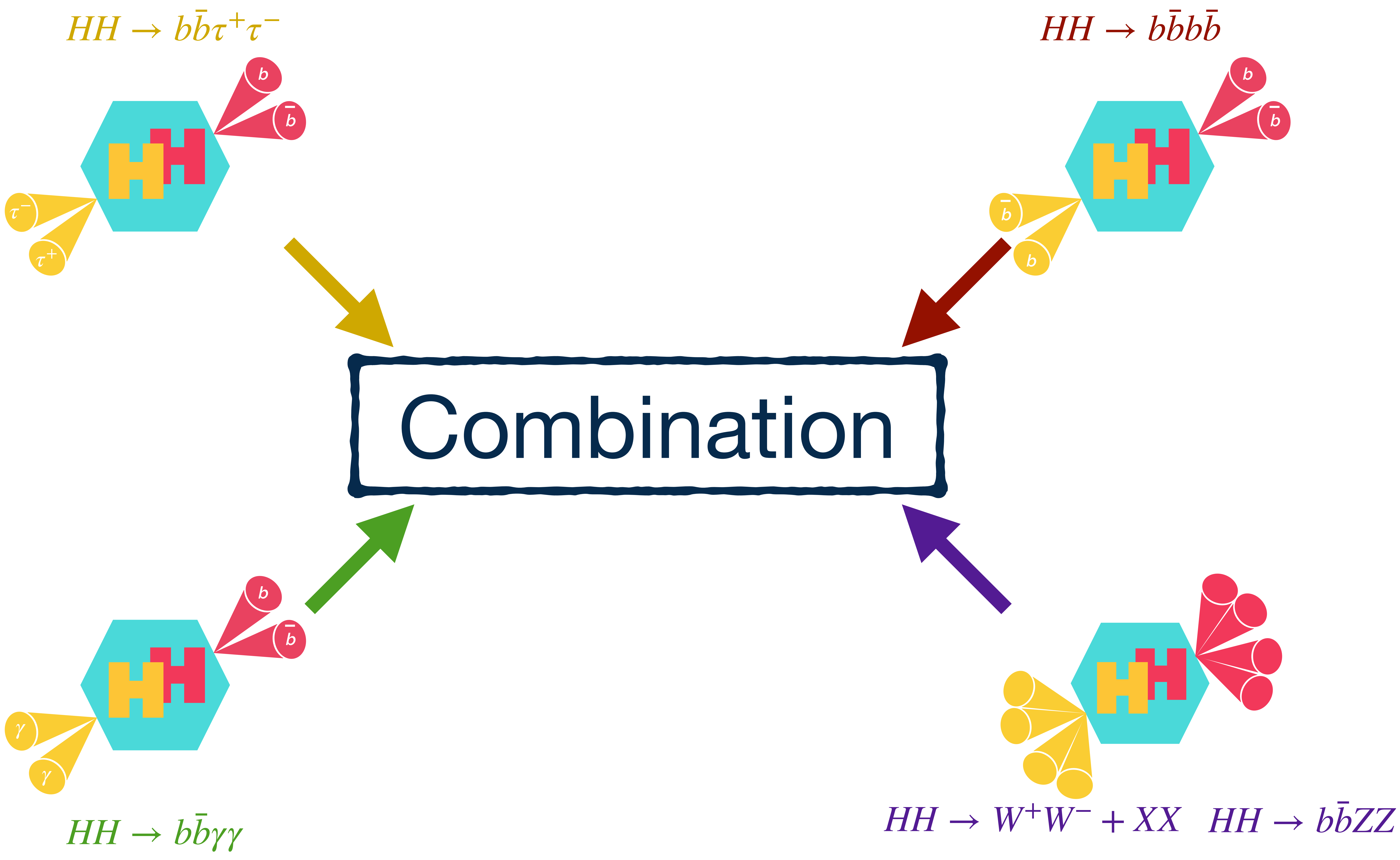
Limits set on $\sigma(X \to HH)$ where X is a narrow-width scalar resonance

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

Non-resonant

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



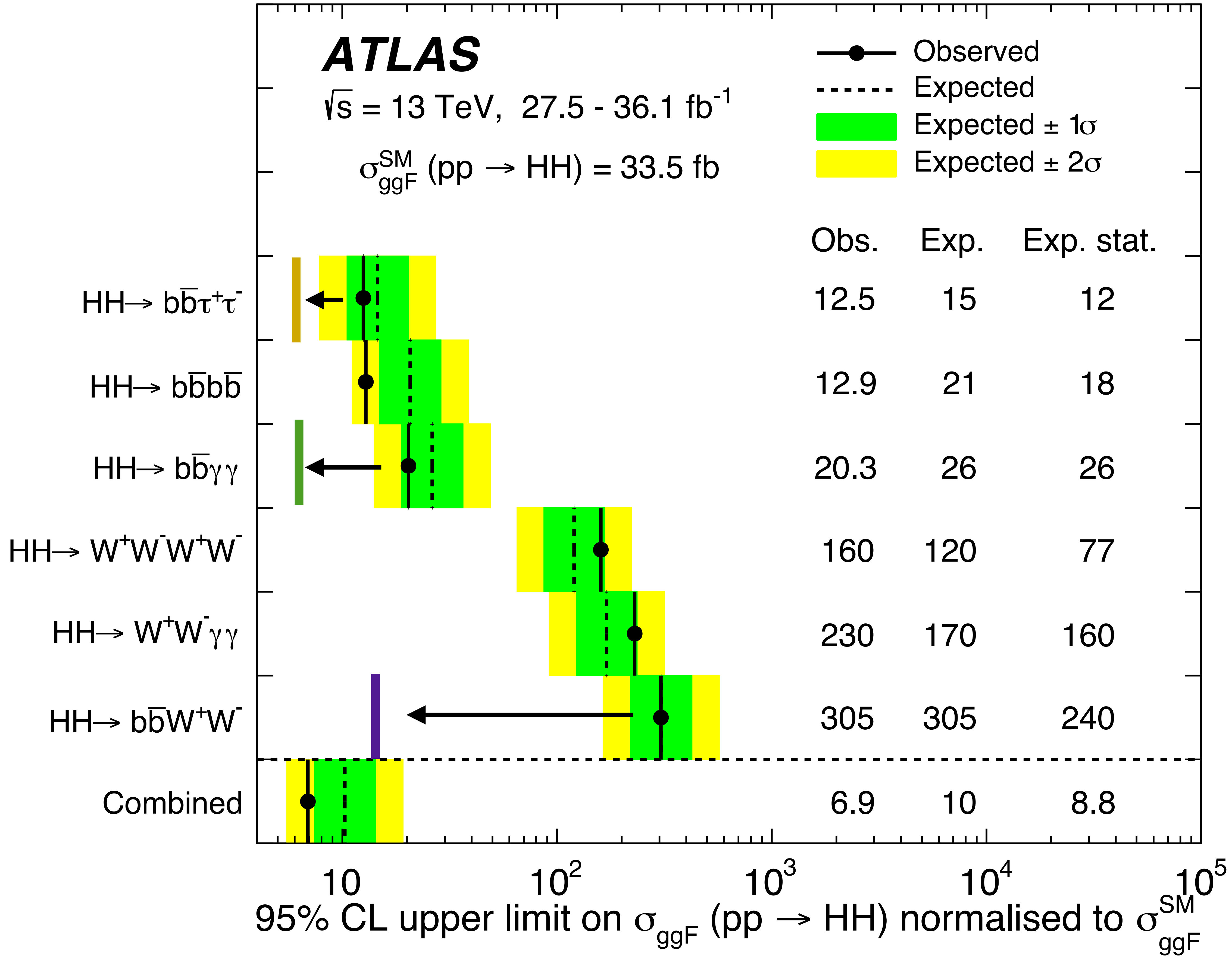


$HH \to b\bar{b}\tau^+\tau^-$
$HH \to b\bar{b}b\bar{b}$
Combination
$HH \to b\bar{b}\gamma\gamma$
$HH \to W^+W^- + XX$ $HH \to b\bar{b}ZZ$

Conclusion

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

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

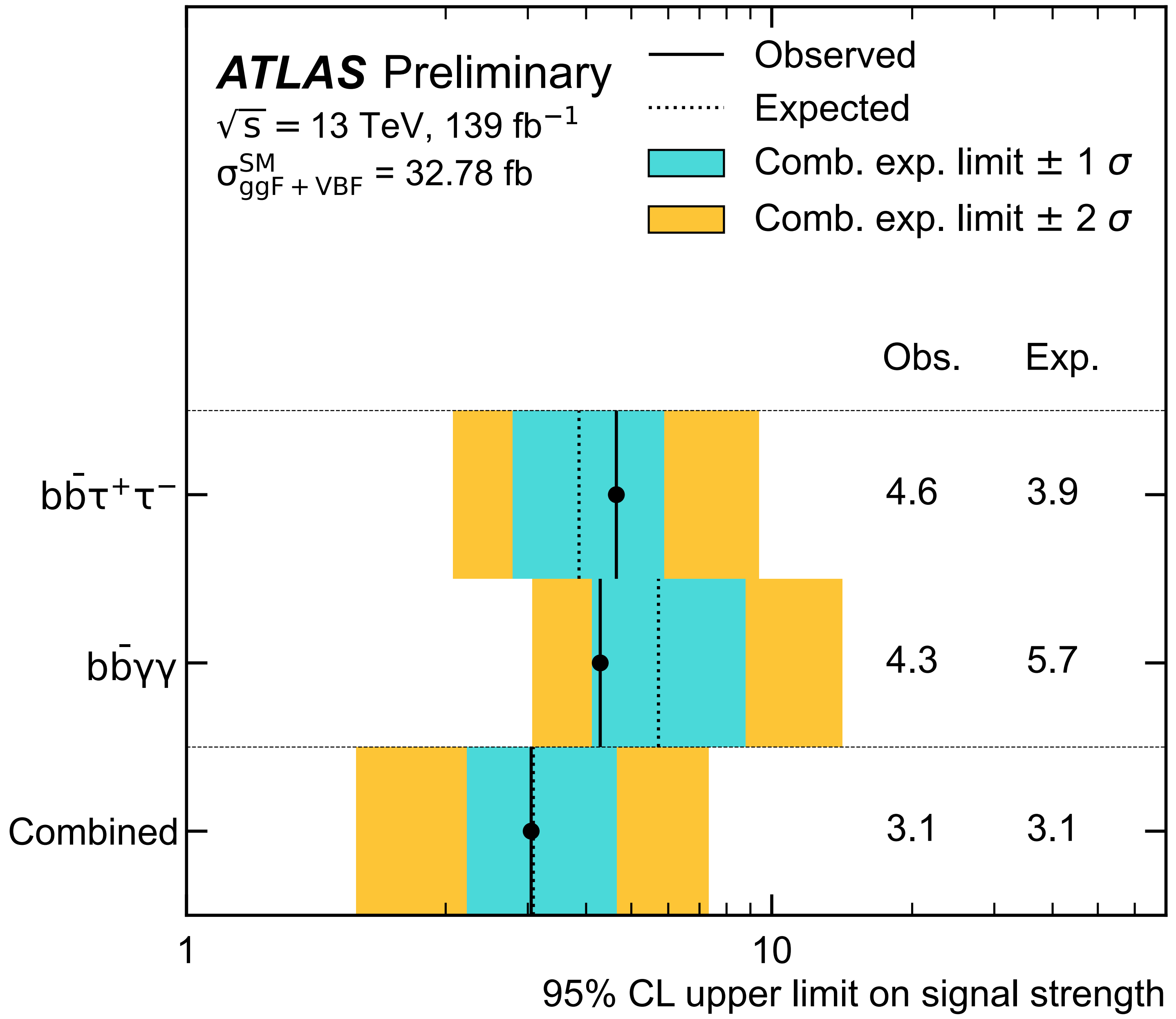


Additional results with $\mathscr{L} = 139\text{fb}^{-1}$:

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

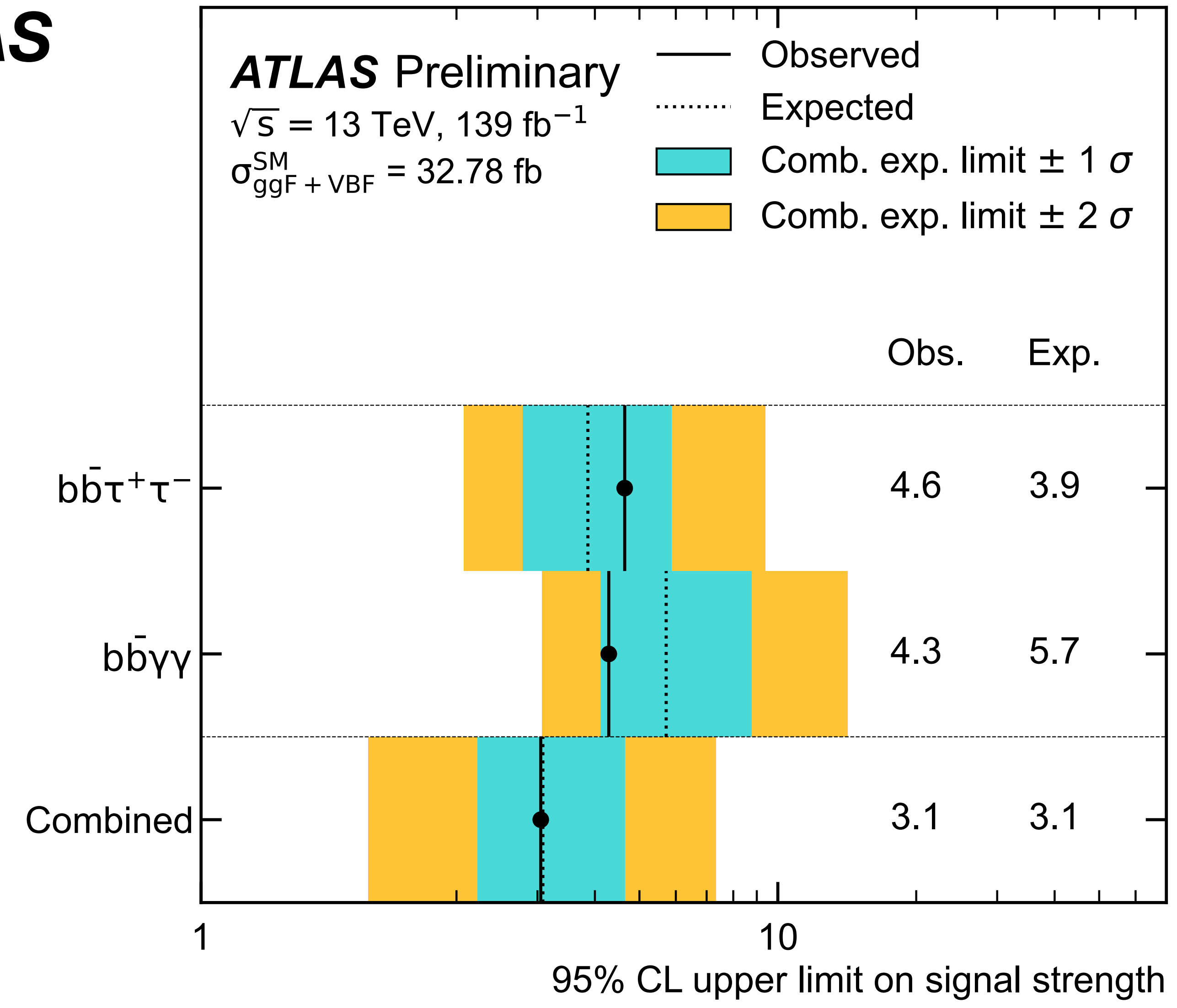
First look at **VBF**: $HH \rightarrow b\bar{b}b\bar{b}$

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

Conclusion

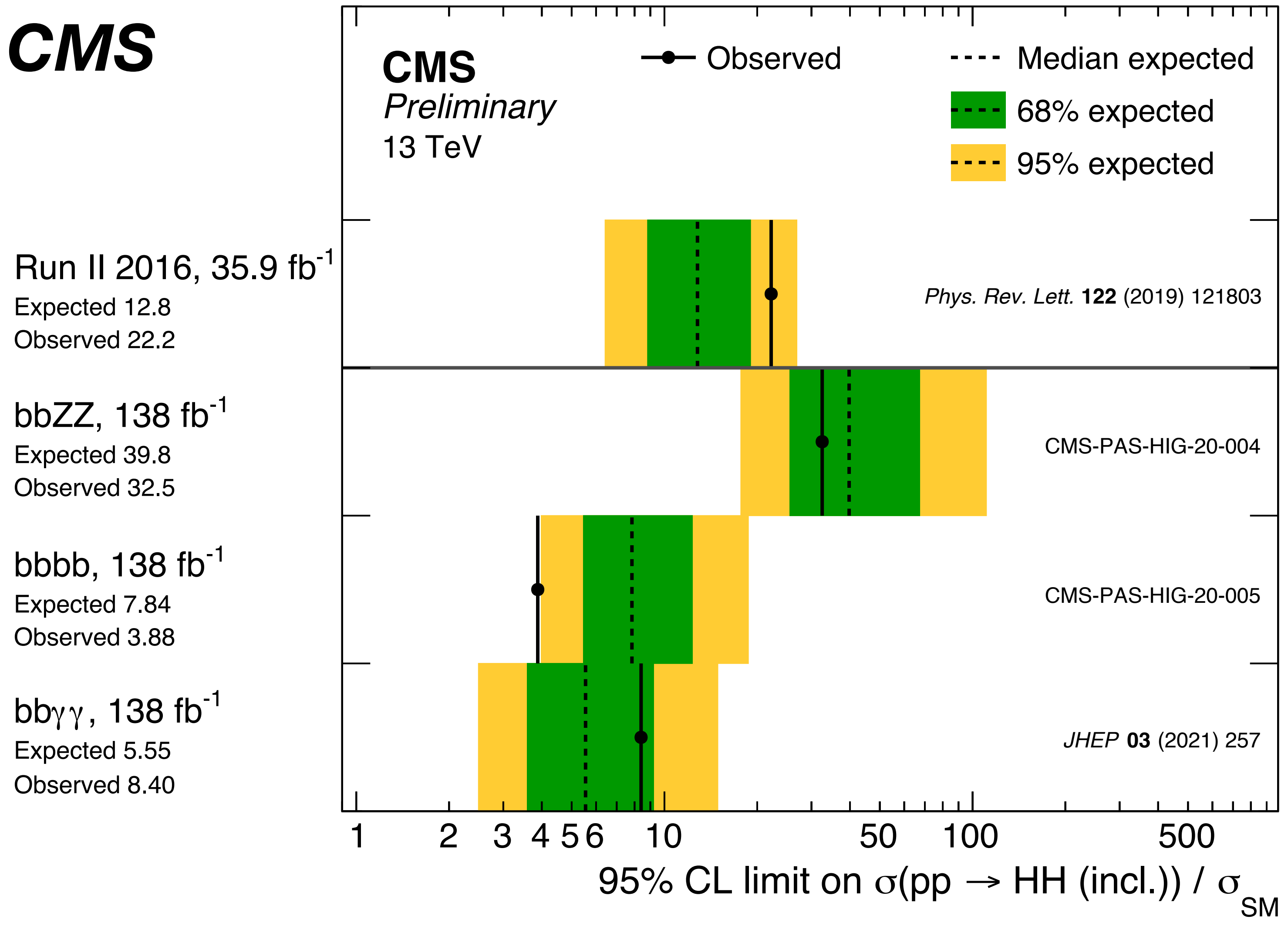
Combinaison: $\mathscr{L} = 36\text{fb}^{-1}$ Phys. Lett. B 800 (2020) 135103

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:

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

ATLAS **Resolved**

840 (550) times the SM prediction.

CMS **Boosted**

226 (412) times the SM prediction.

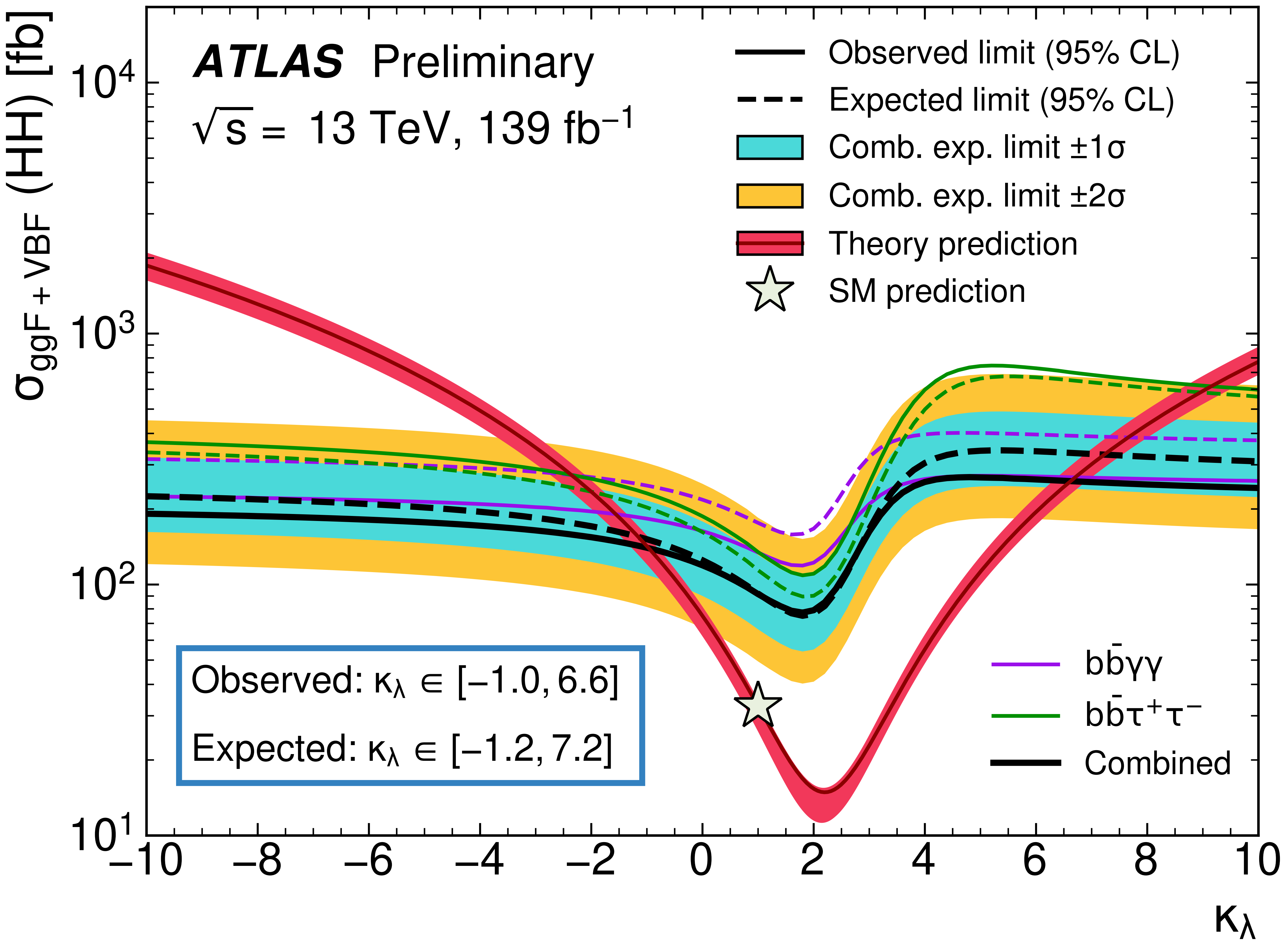
$HH \to b\bar{b}\gamma\gamma$ **Resolved**

225 (208) times the SM prediction.

$\frac{\sigma(pp\to HH)}{\sigma_{SM}}$ 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		

Conclusion

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



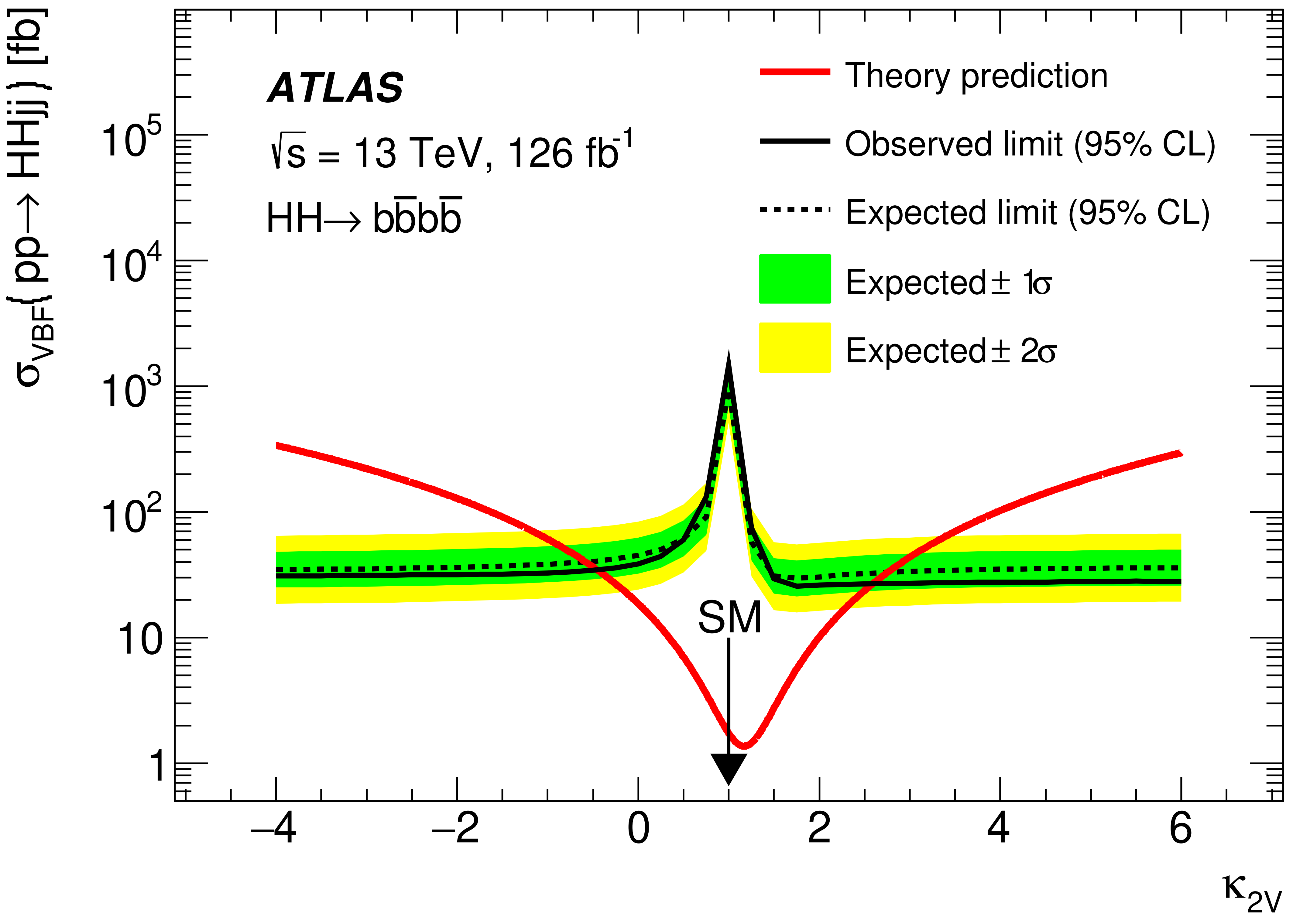
Best limit set so far on κ_λ so far.

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,

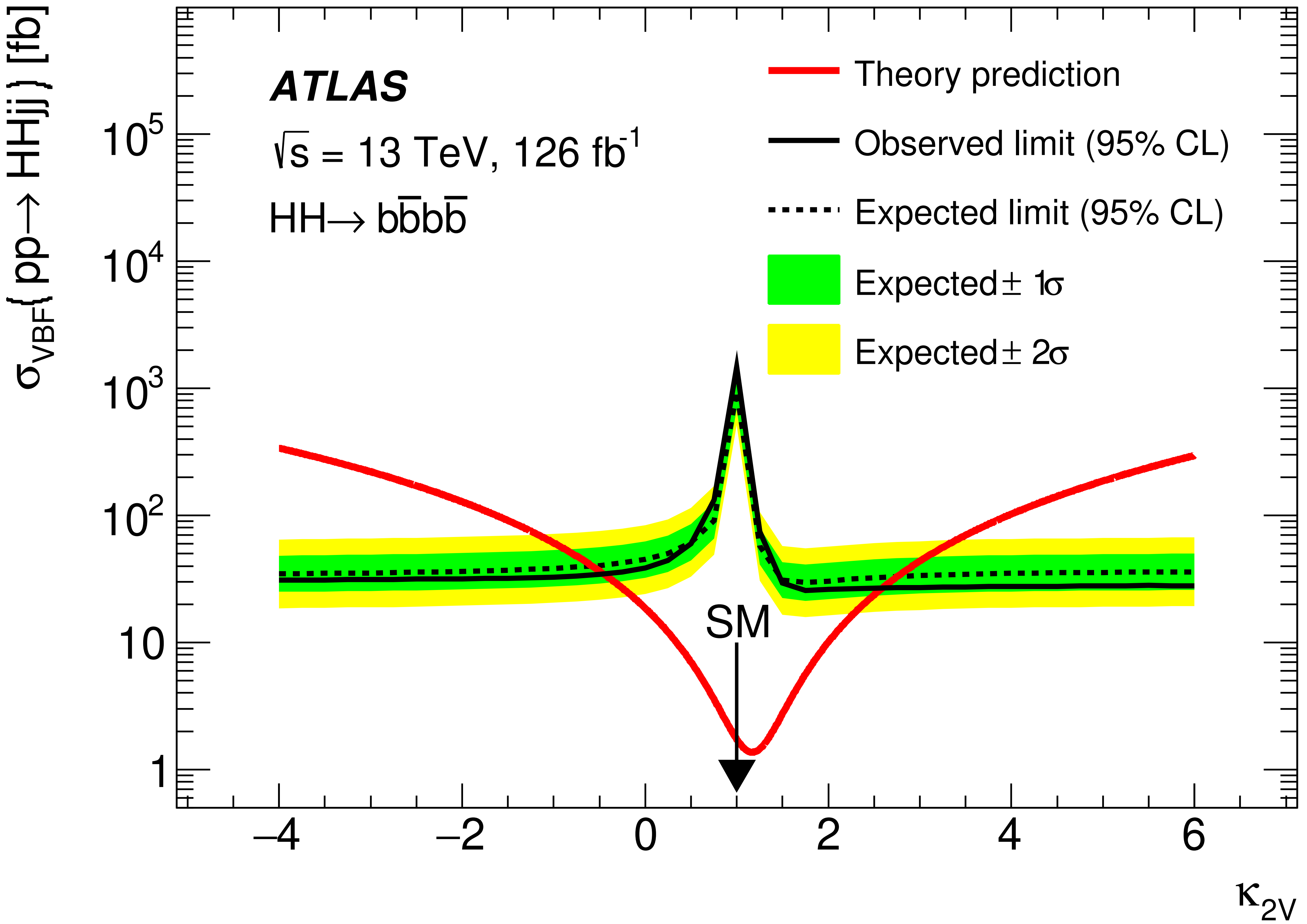
$-0.6 < \kappa_{2V} < 2.7$ expected.



Conclusion

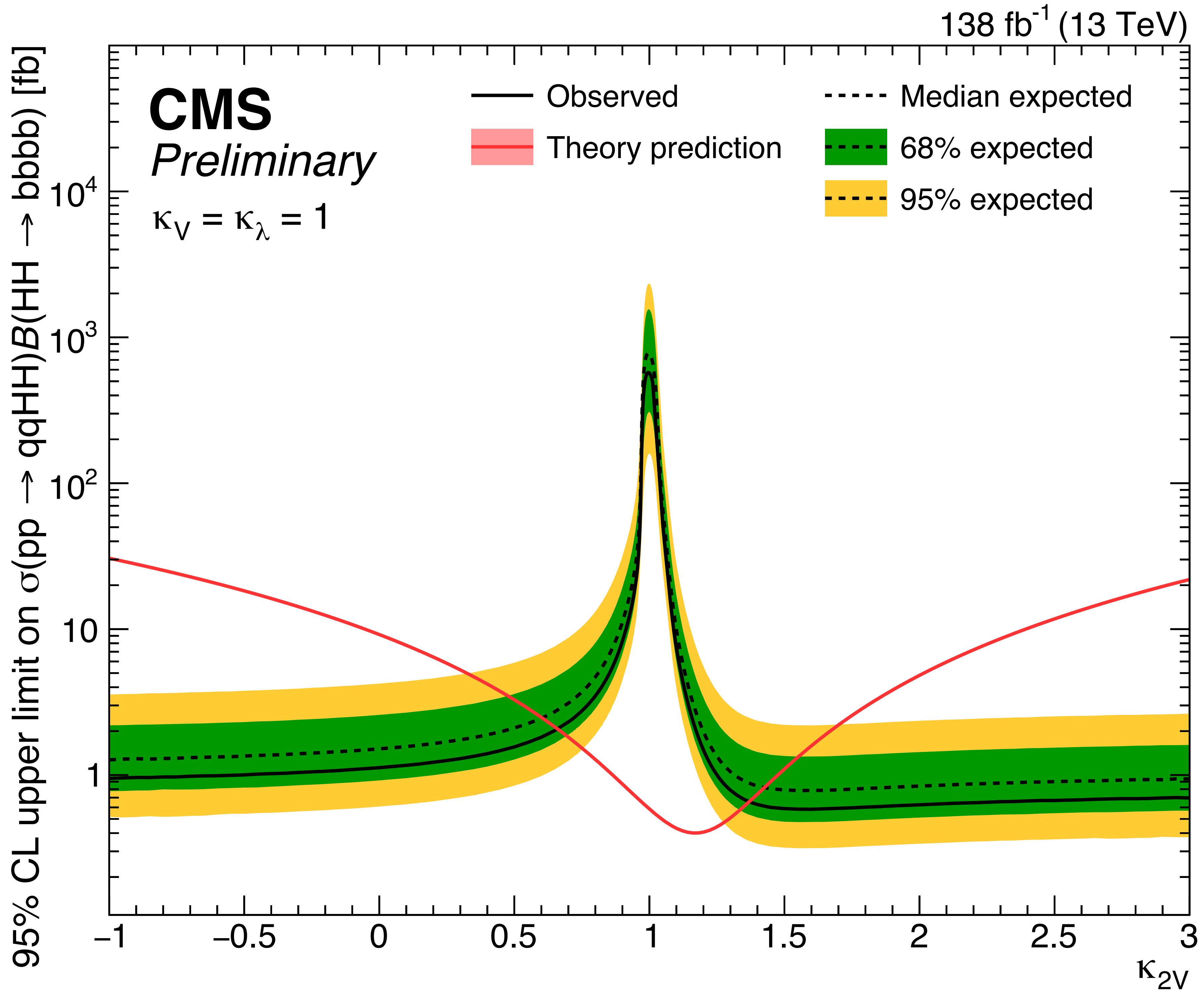
ATLAS $b\bar{b}b\bar{b}$ final state

Limits are set on the κ_{2V} coupling modifier to:
$-0.4 < \kappa_{2V} < 2.6$ observed,
$-0.6 < \kappa_{2V} < 2.7$ expected.



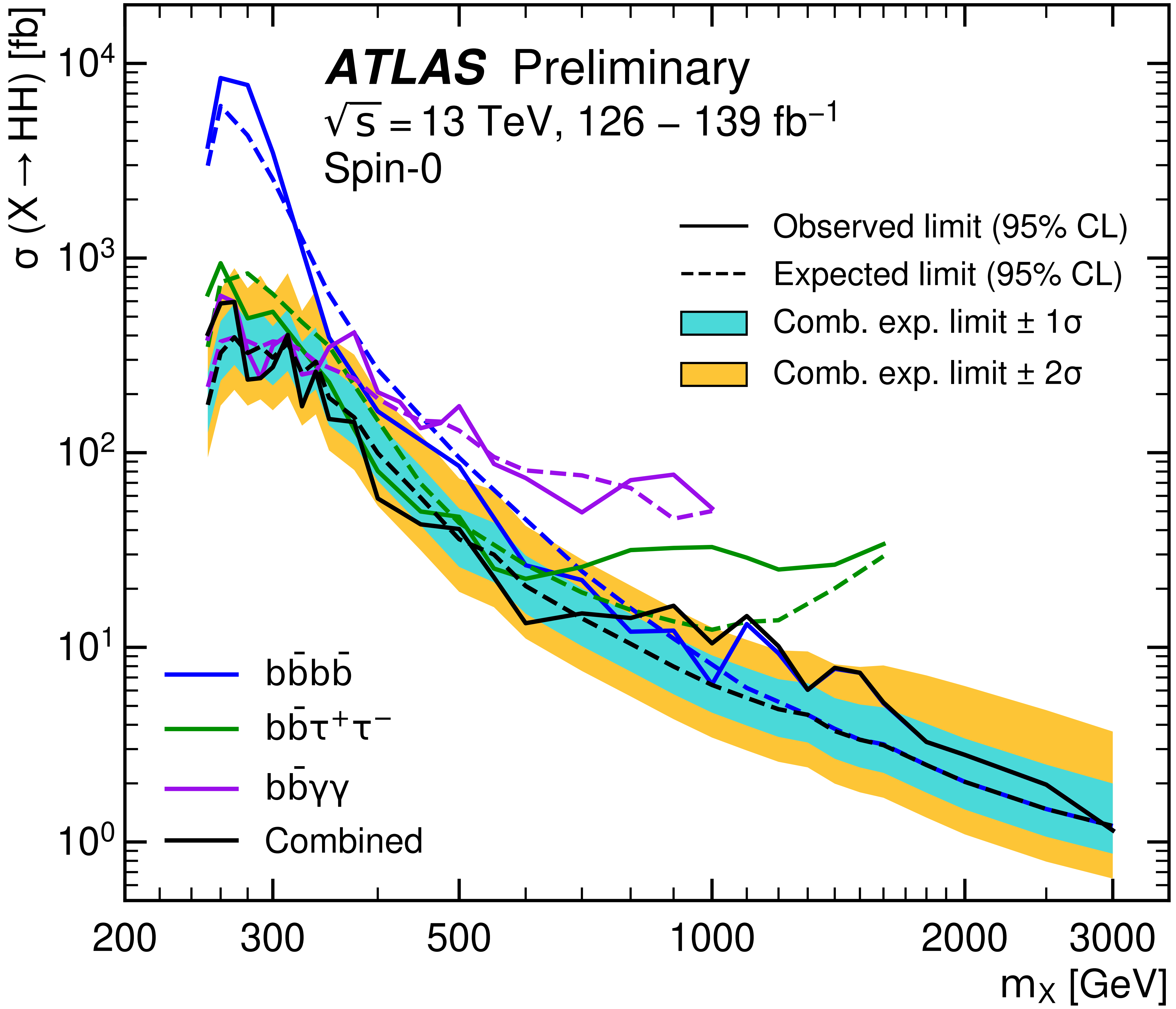
CMS $b\bar{b}b\bar{b}$ Boosted CMS-PAS-B2G-21-001

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.

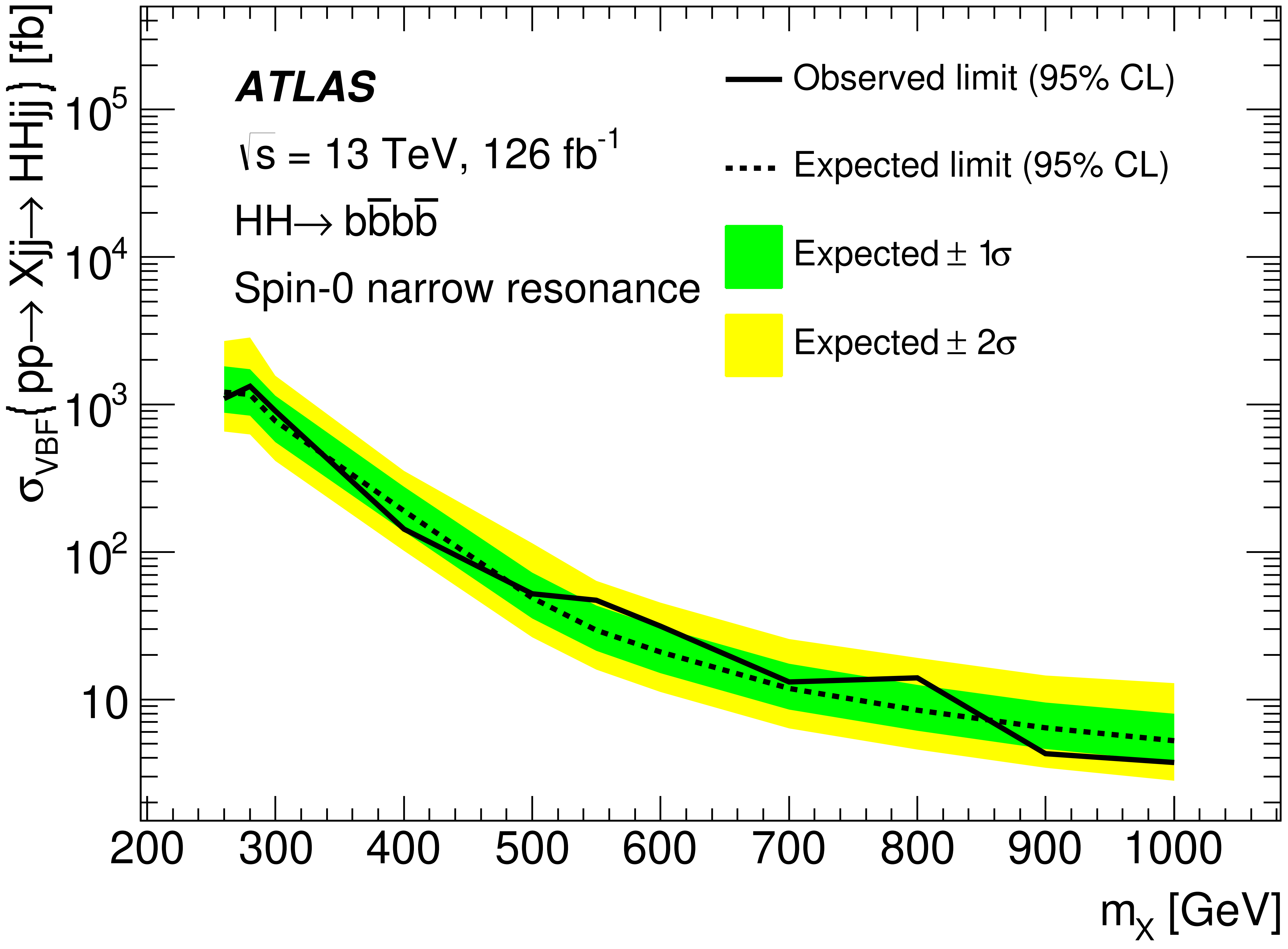


Conclusion

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

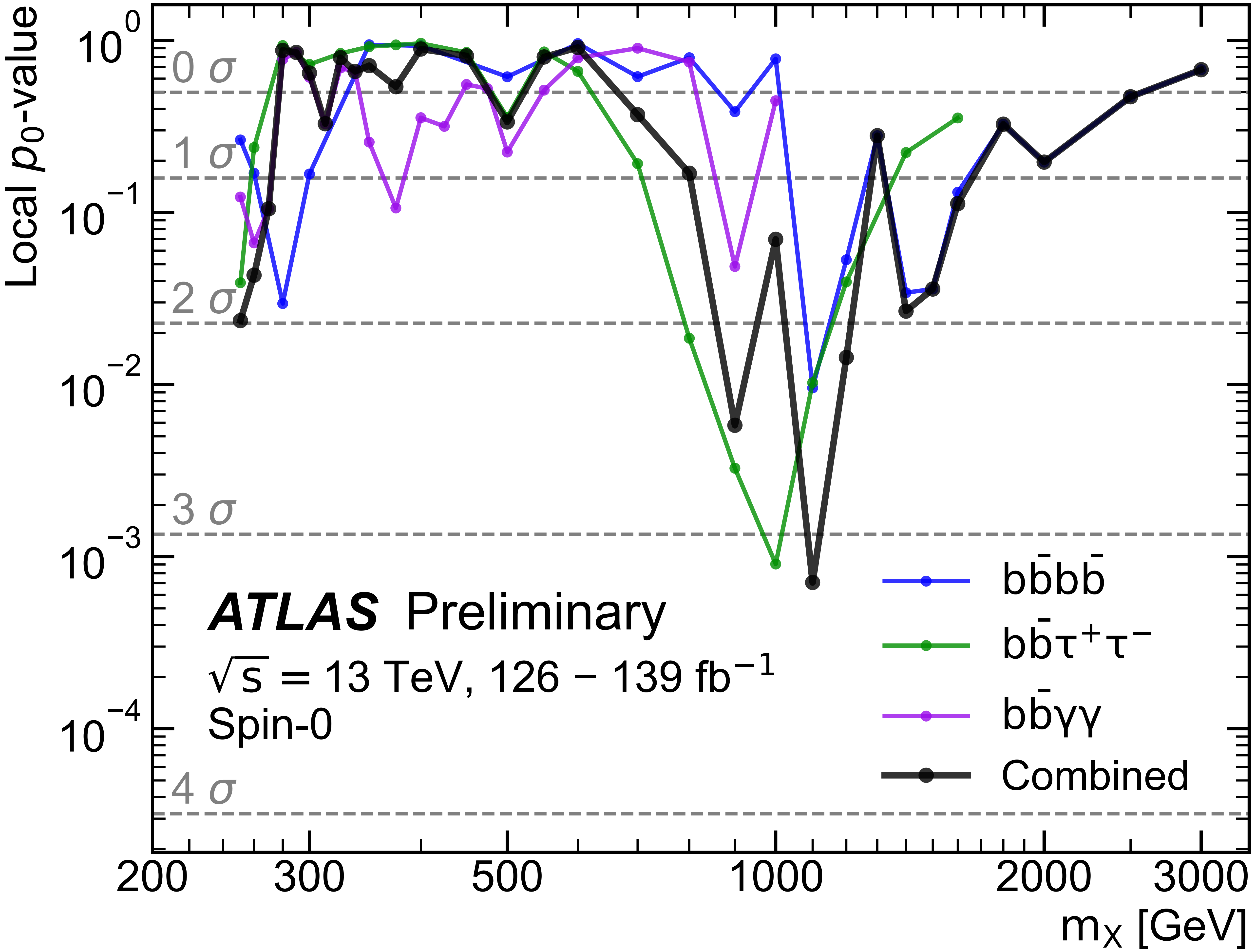


First look at **VBF**: $b\bar{b}b\bar{b}$ final state



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.

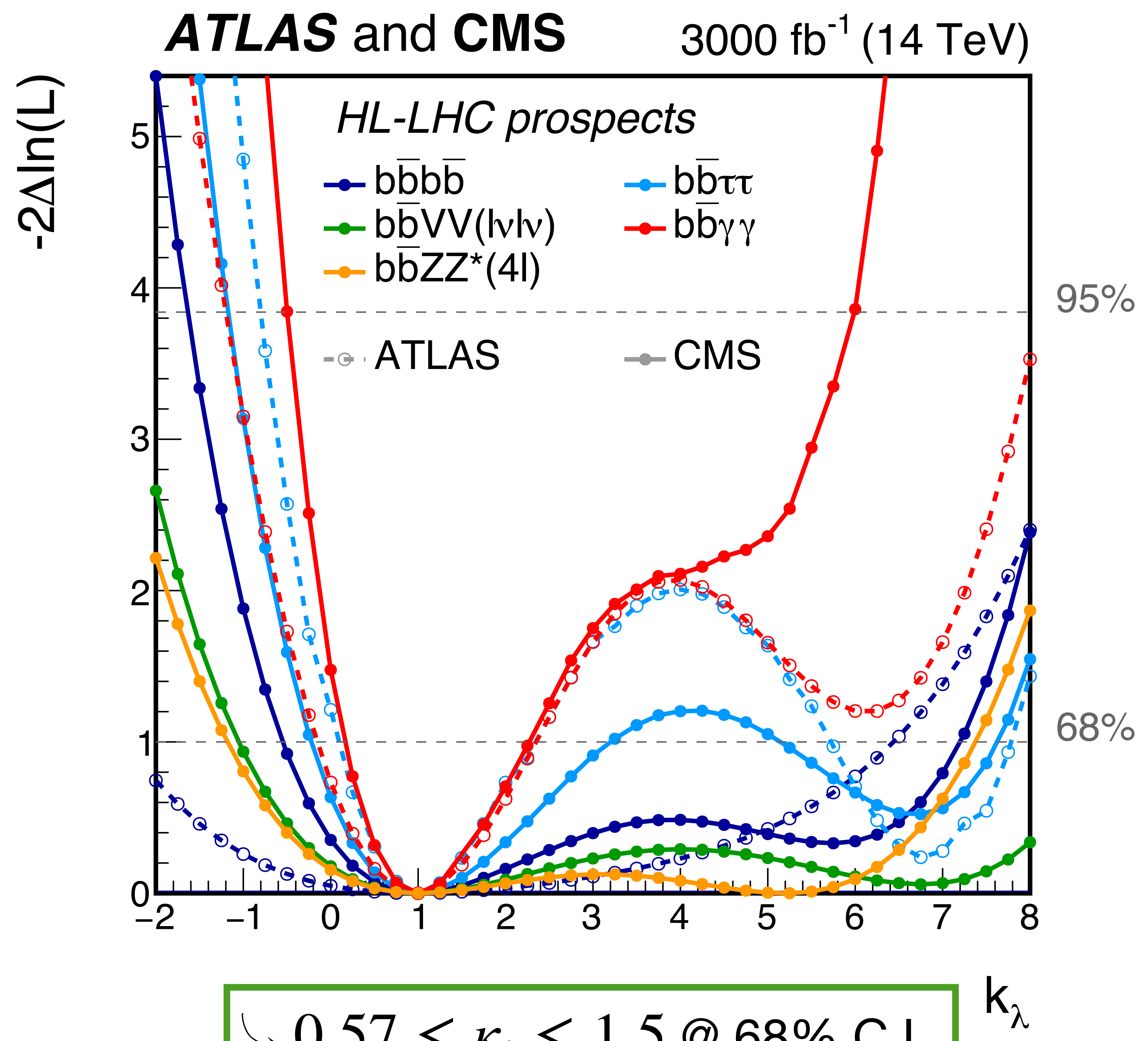
Post-credit scene: a look into the future

The story is not over yet : the **High Luminosity** phase of the LHC aims at collecting more than **90%** of the total LHC dataset.

CERN has published a Yellow Report summarising the extrapolation of the partial Run-2 results:

- Including special consideration for the systematics
- Some re-optimisation from the published partial Run-2 results

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to bbbb$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



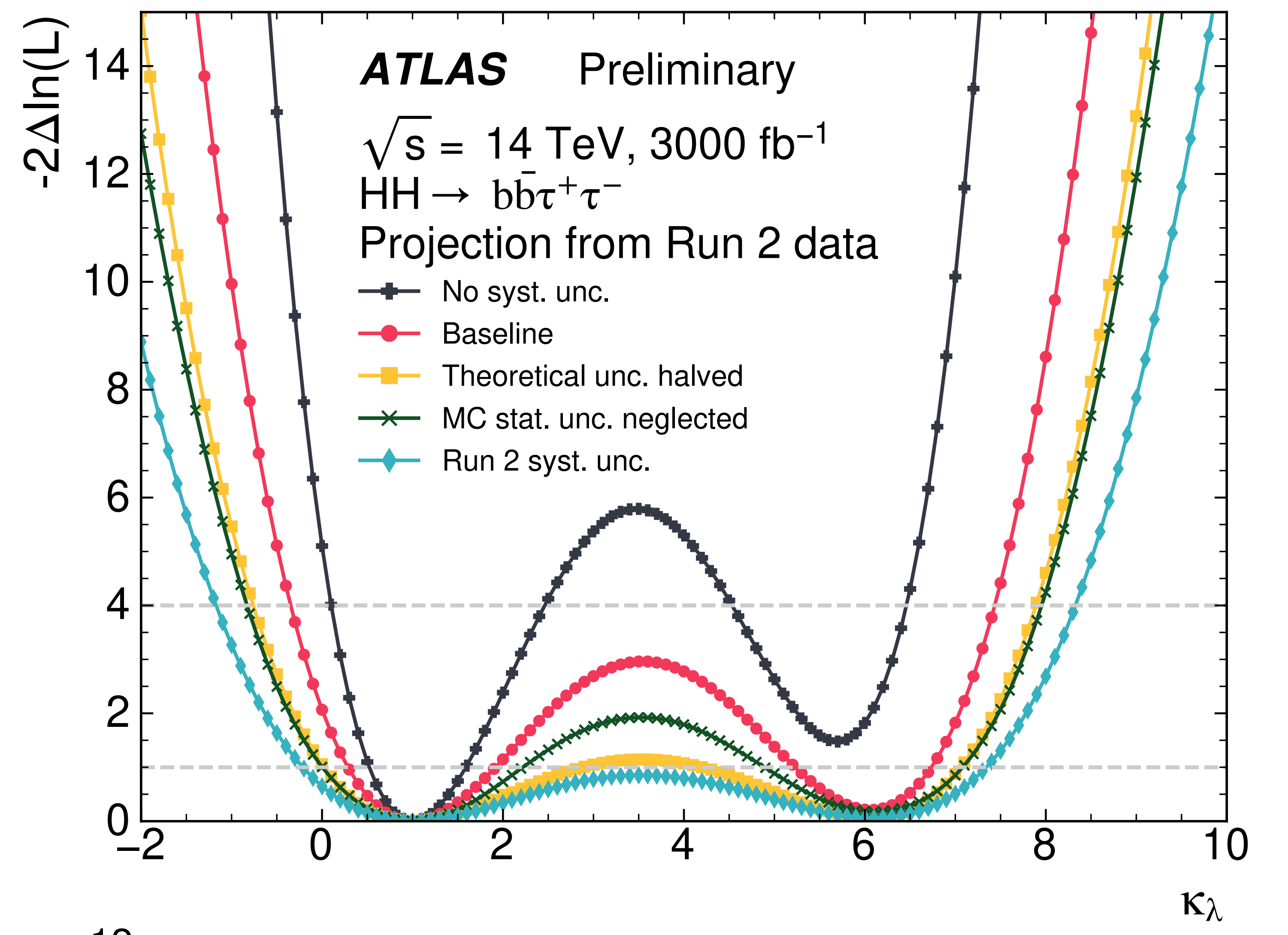
$\hookrightarrow 0.57 \leq \kappa_\lambda \leq 1.5$ @ 68% C.L.

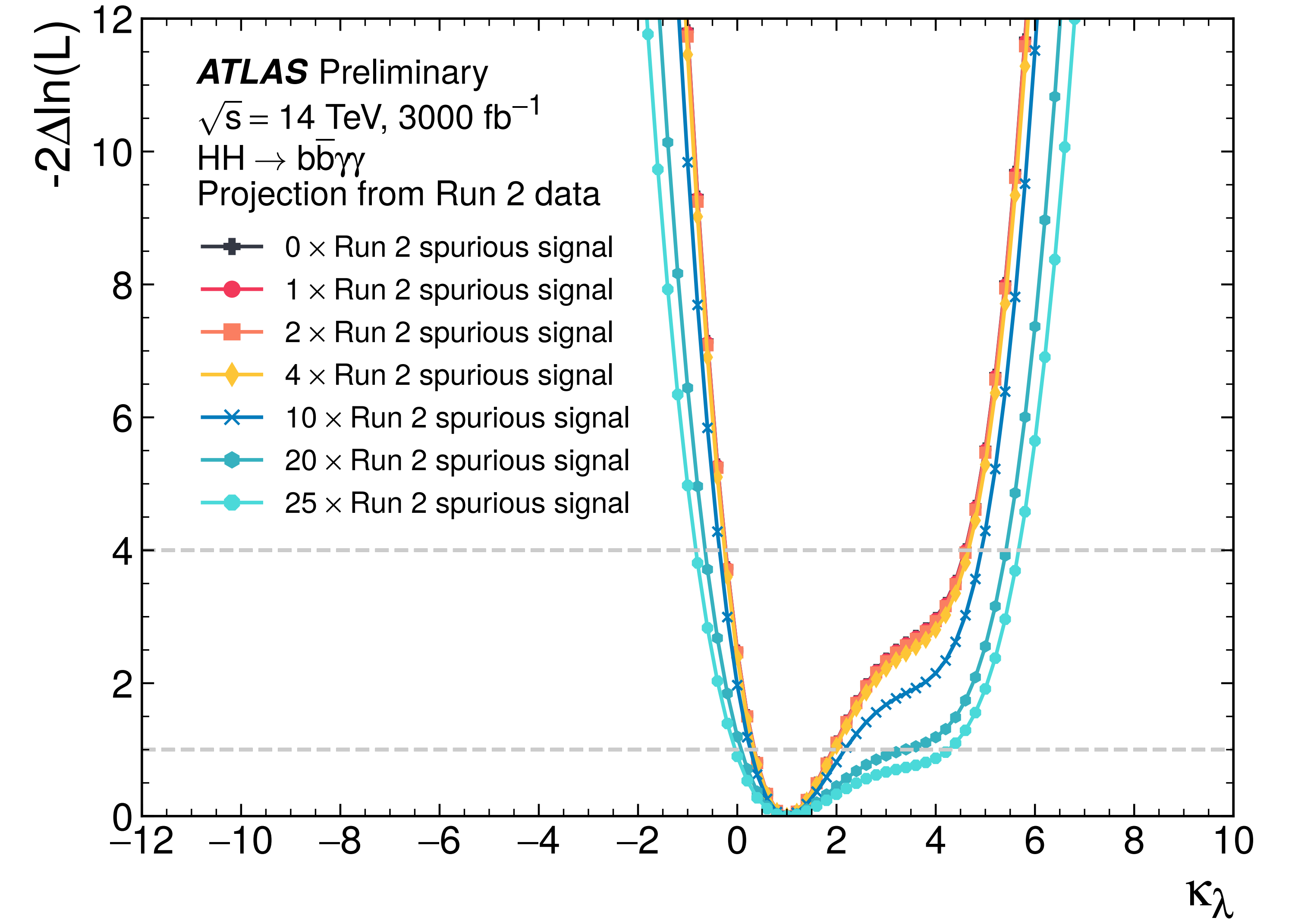
Post-credit scene: a look into the future

Since then we have updated greatly the analysis, improving far beyond the luminosity gain.
From the ATLAS side both $HH \to b\bar{b}\tau^+\tau^-$ (ATL-PHYS-PUB-2021-044) and $HH \to b\bar{b}\gamma\gamma$ (ATL-PHYS-PUB-2022-001) have released recent results :

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5 **4.0**	1.6	2.1 **2.8**	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1 **2.3**	1.8	2.0 **2.2**	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

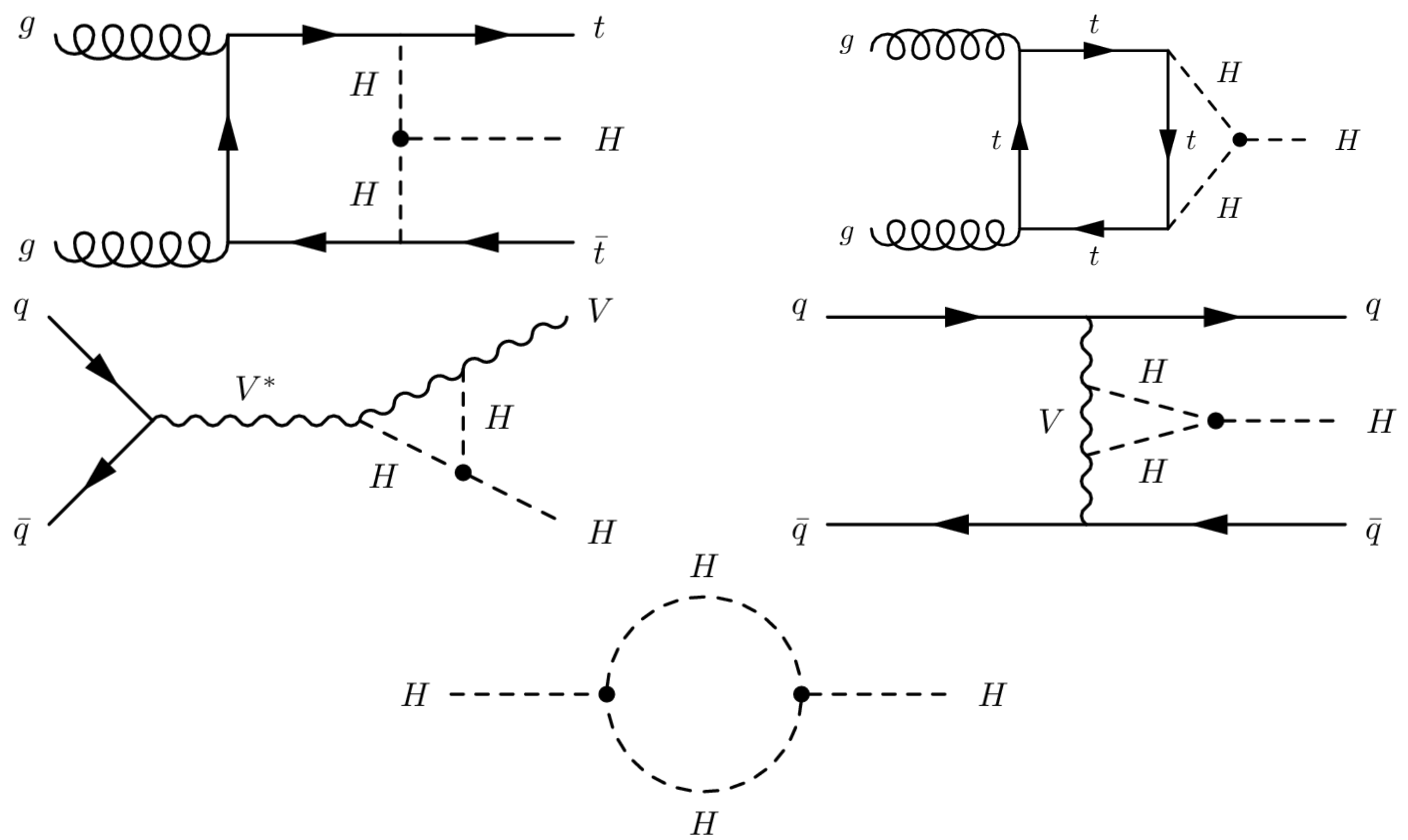
The **gains** are mostly explained by the improved selection and reconstruction techniques.
The limitations mainly arise from the **theoretical uncertainties** on single Higgs production and top-related backgrounds, as well as the modelling of the diphoton one.

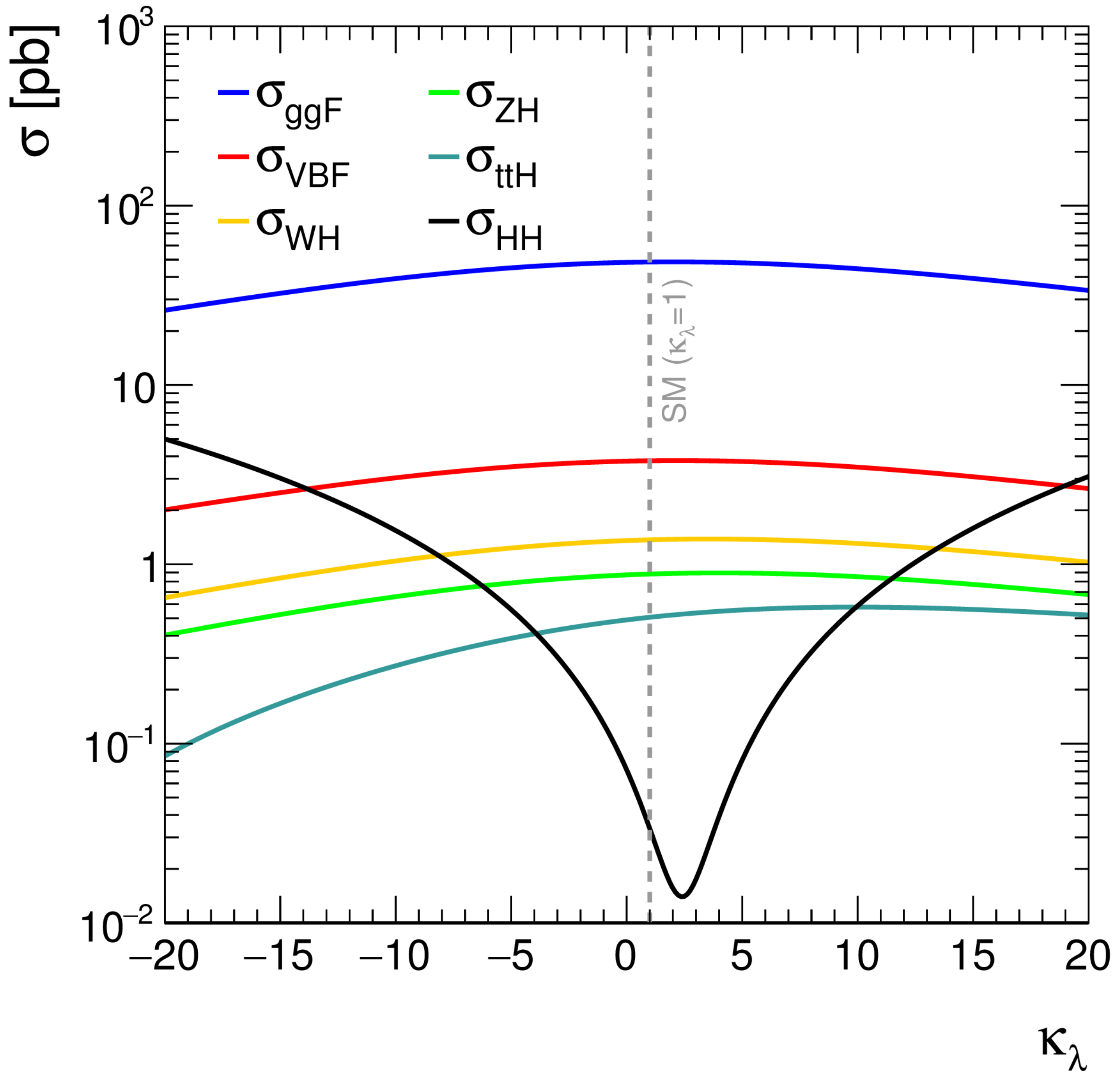


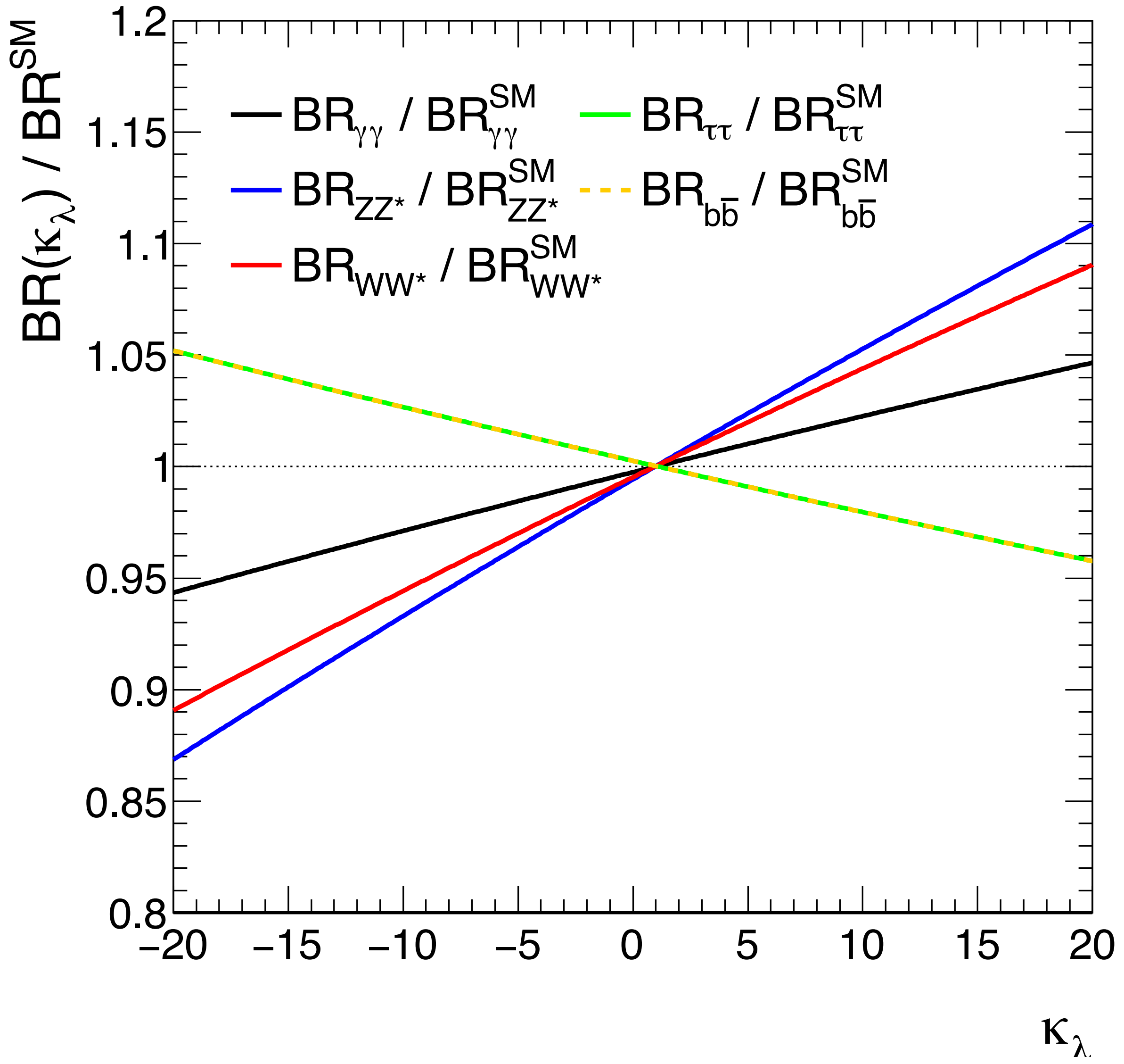


BACK-UP

Single Higgs constrains

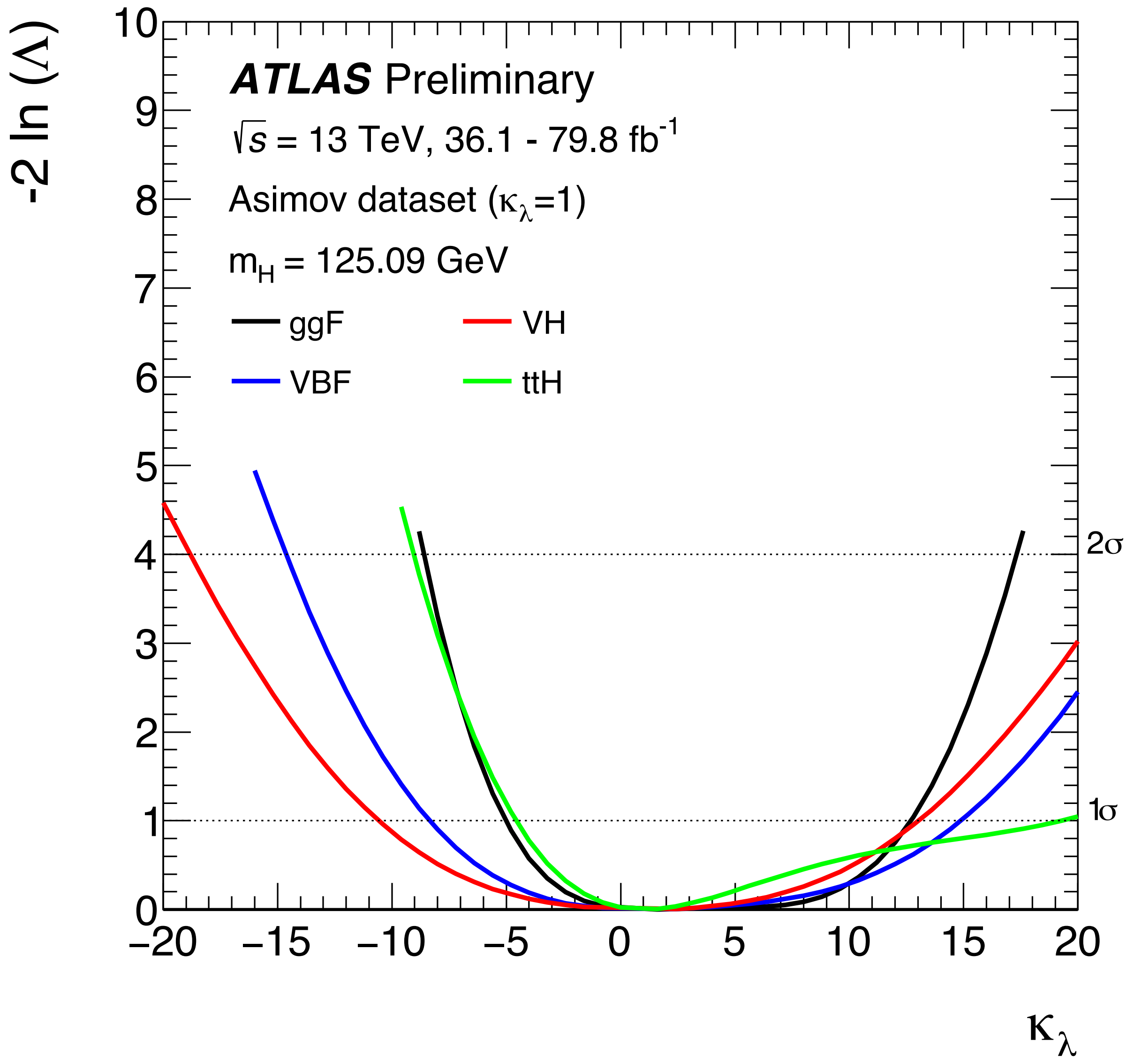


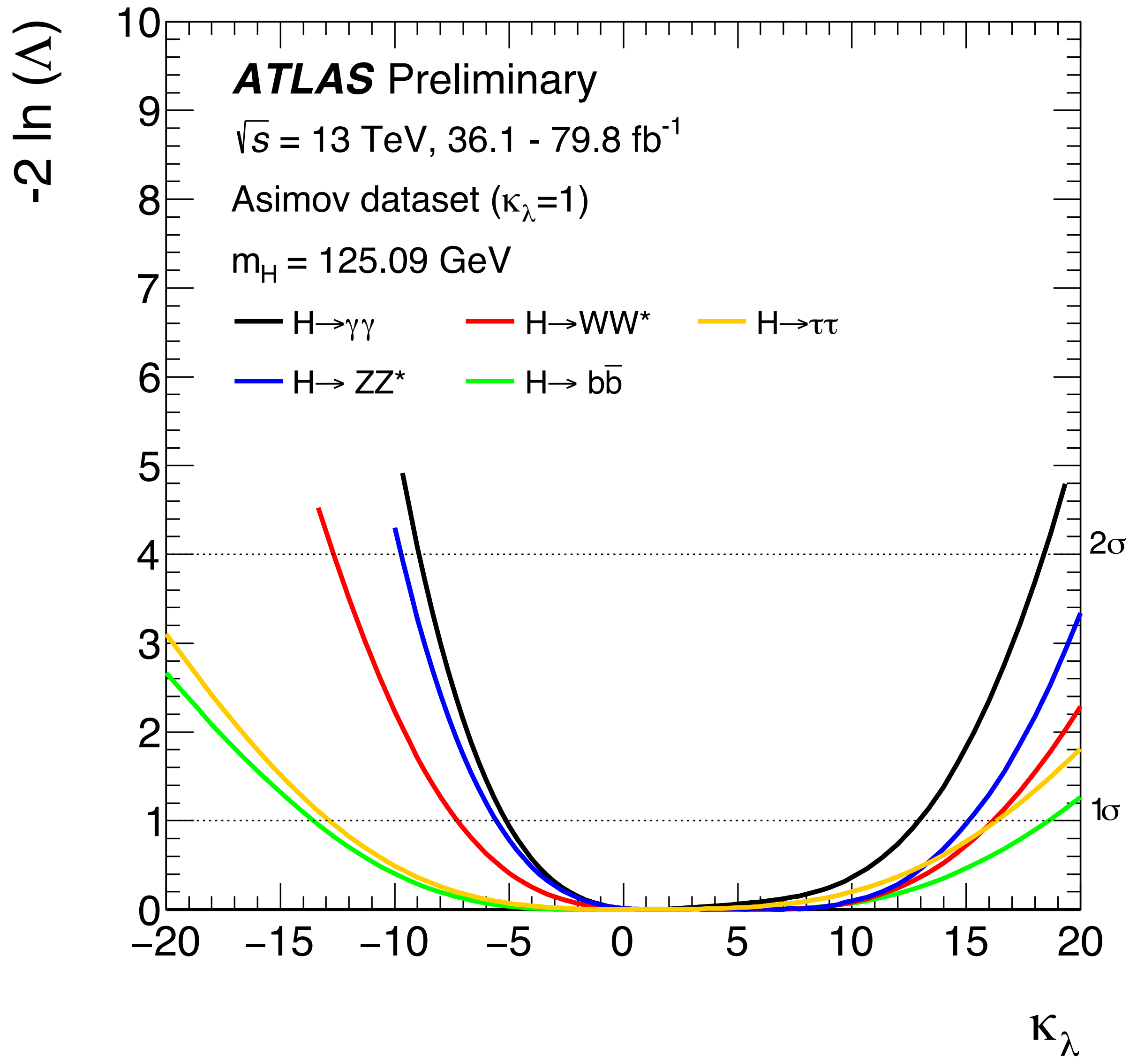


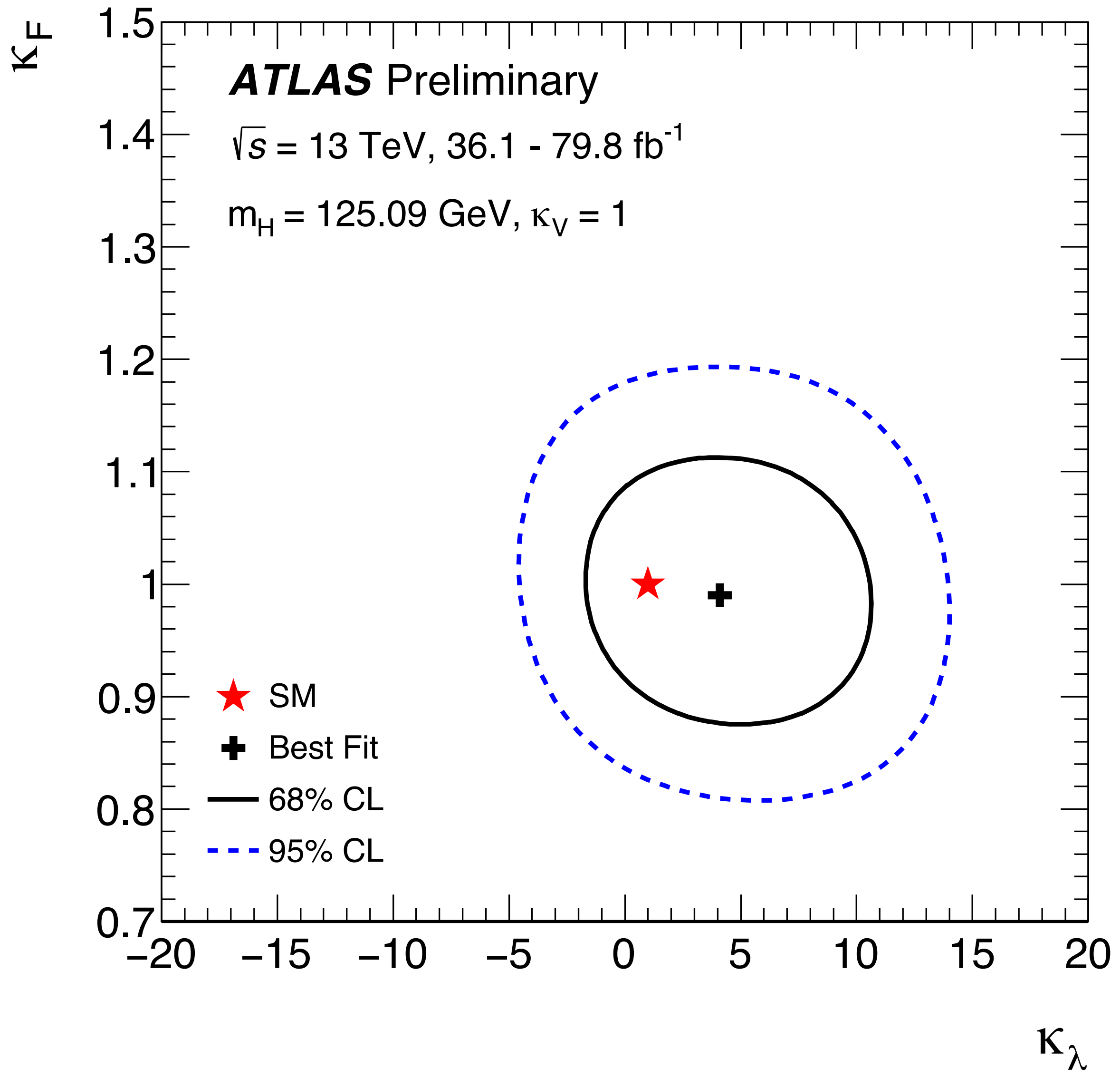


ATL-PHYS-PUB-2019-009

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

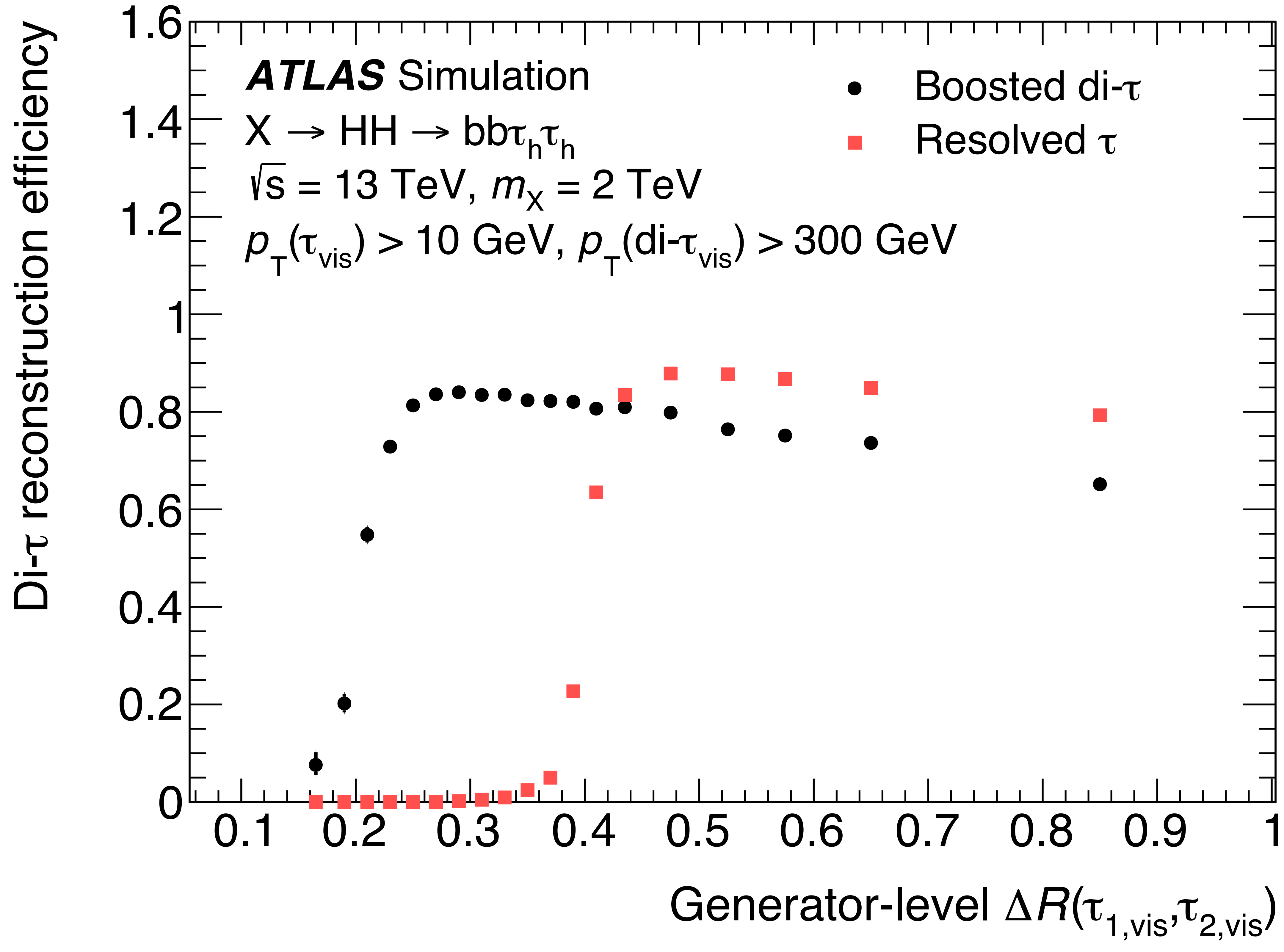






Bbtautau Boosted

Boosted di-tau BDT identification:



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

Non resonant limits per channel:

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

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
$Z \to \tau\tau$	±6.8
SM Higgs	±2.9
Other backgrounds	±0.3

BDTs

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

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

Non Resonant

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

Resonant

Variable	Definition
Photon-related kinematic variables	
$p_{\mathrm{T}}^{\gamma\gamma}$, $y^{\gamma\gamma}$	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	
$m_{b\bar{b}}$, $p_{\mathrm{T}}^{b\bar{b}}$ 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 $N_{b-\mathrm{jets}}$	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

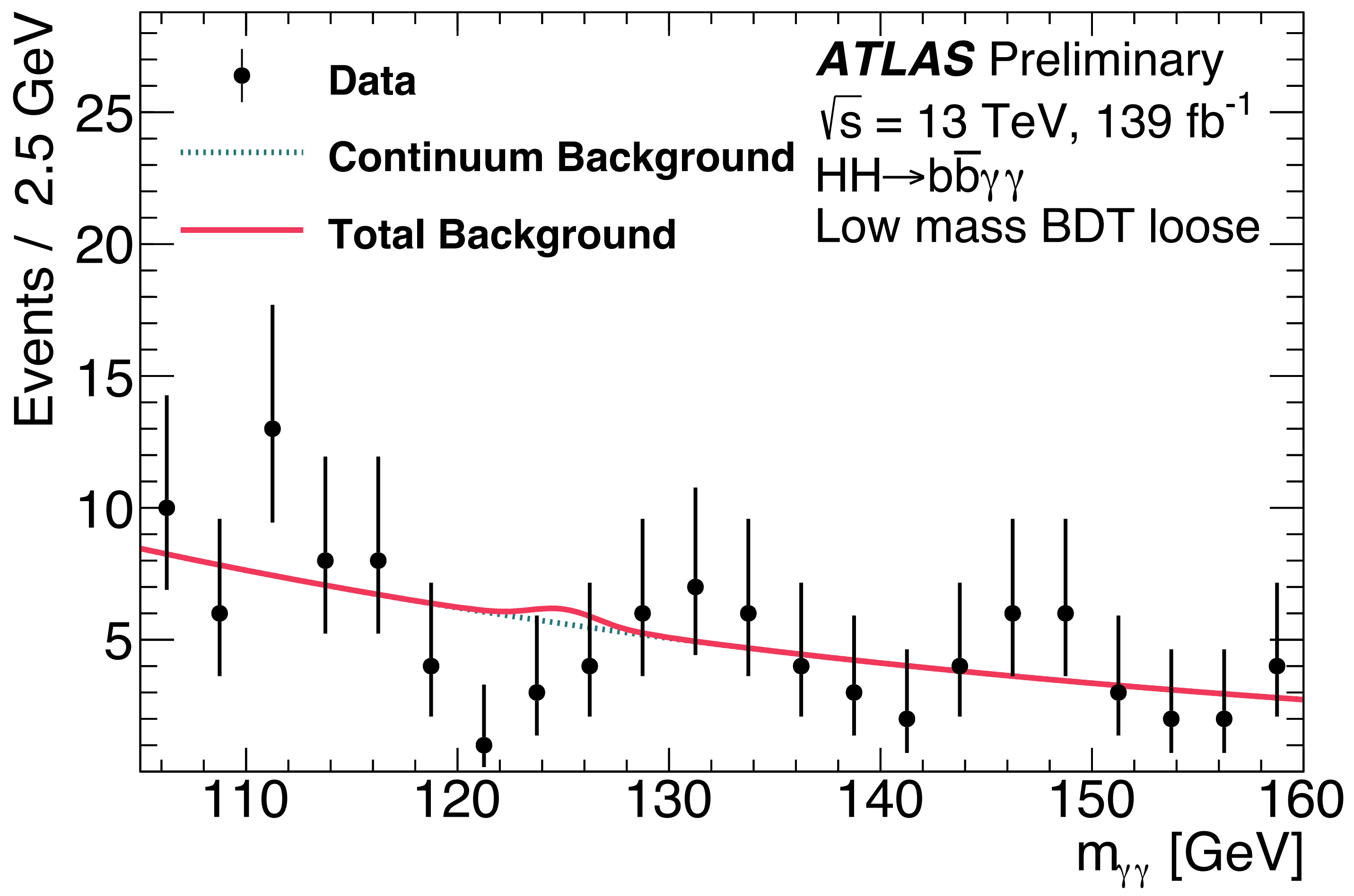
$HH \rightarrow b\bar{b}\gamma\gamma$

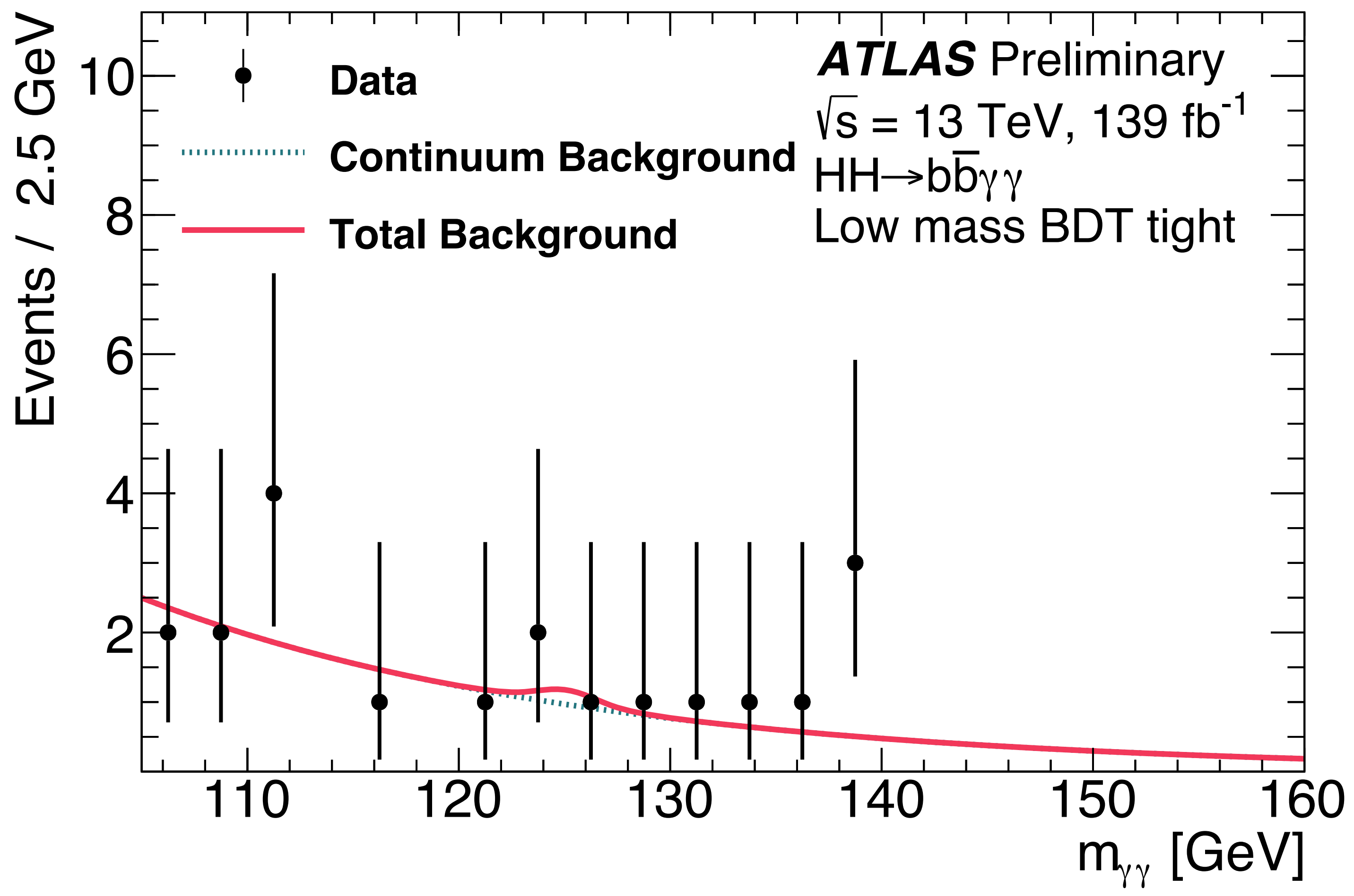
Non Resonant

BDT loose

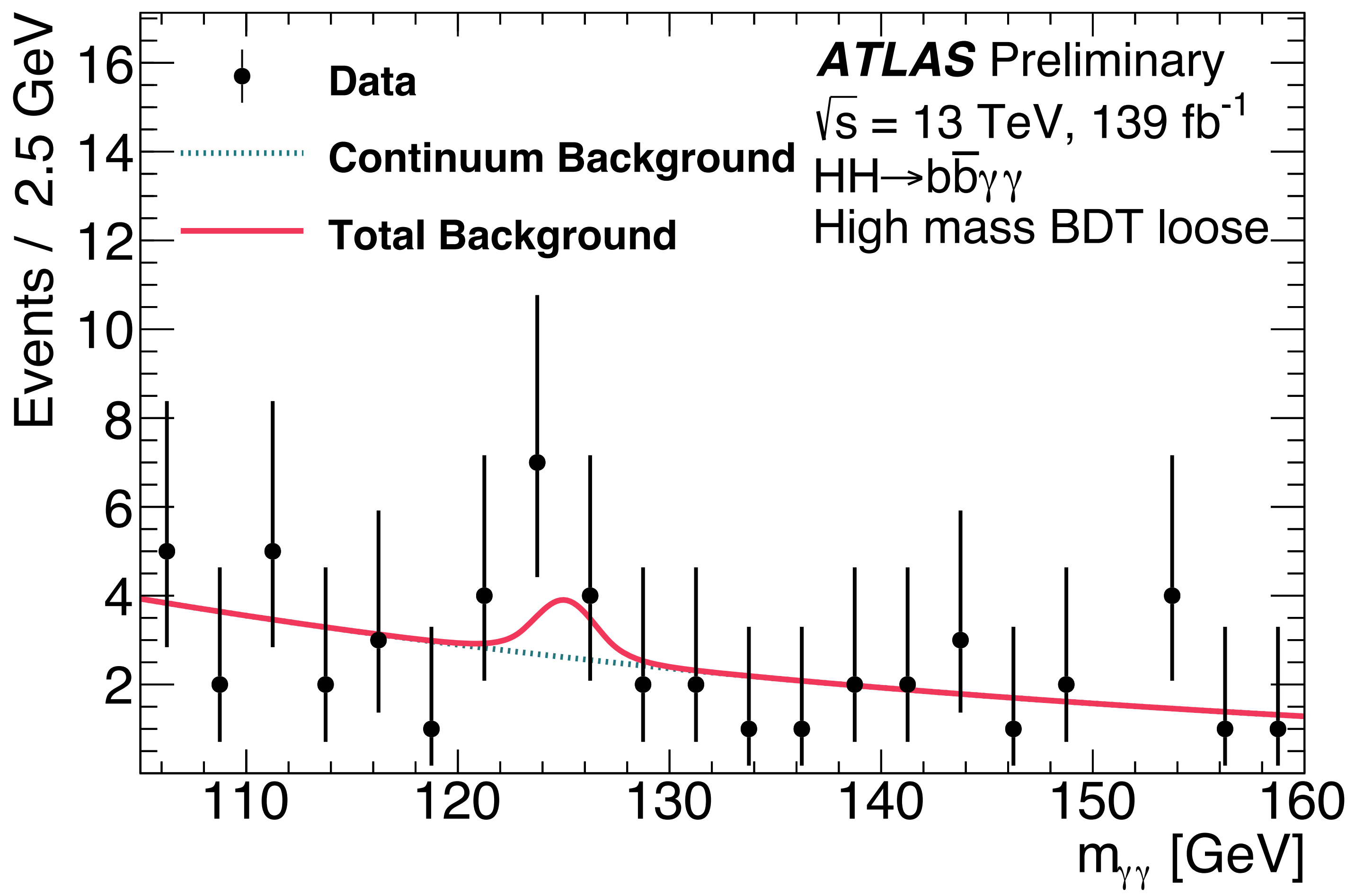
BDT tight

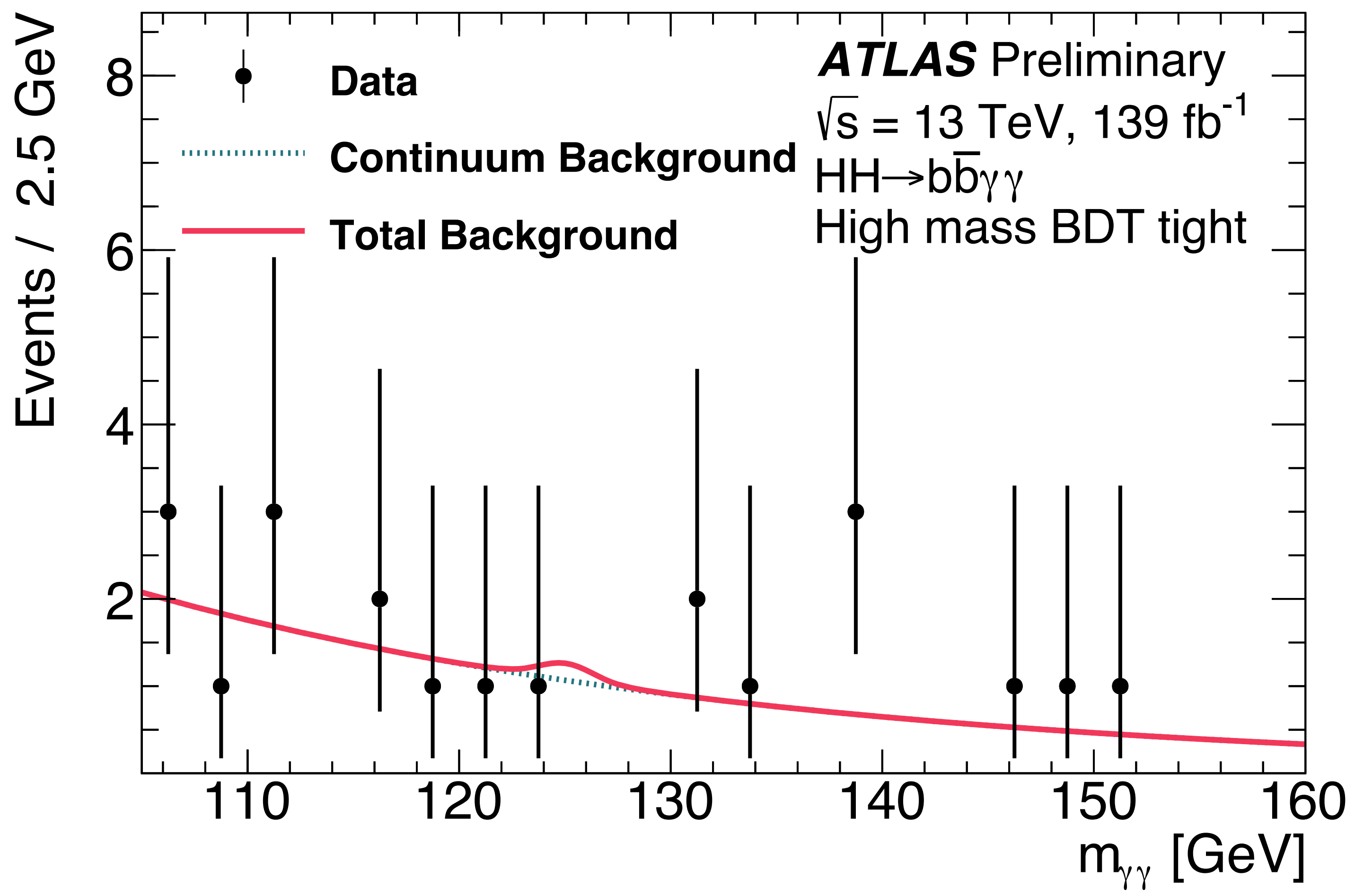
Low mass





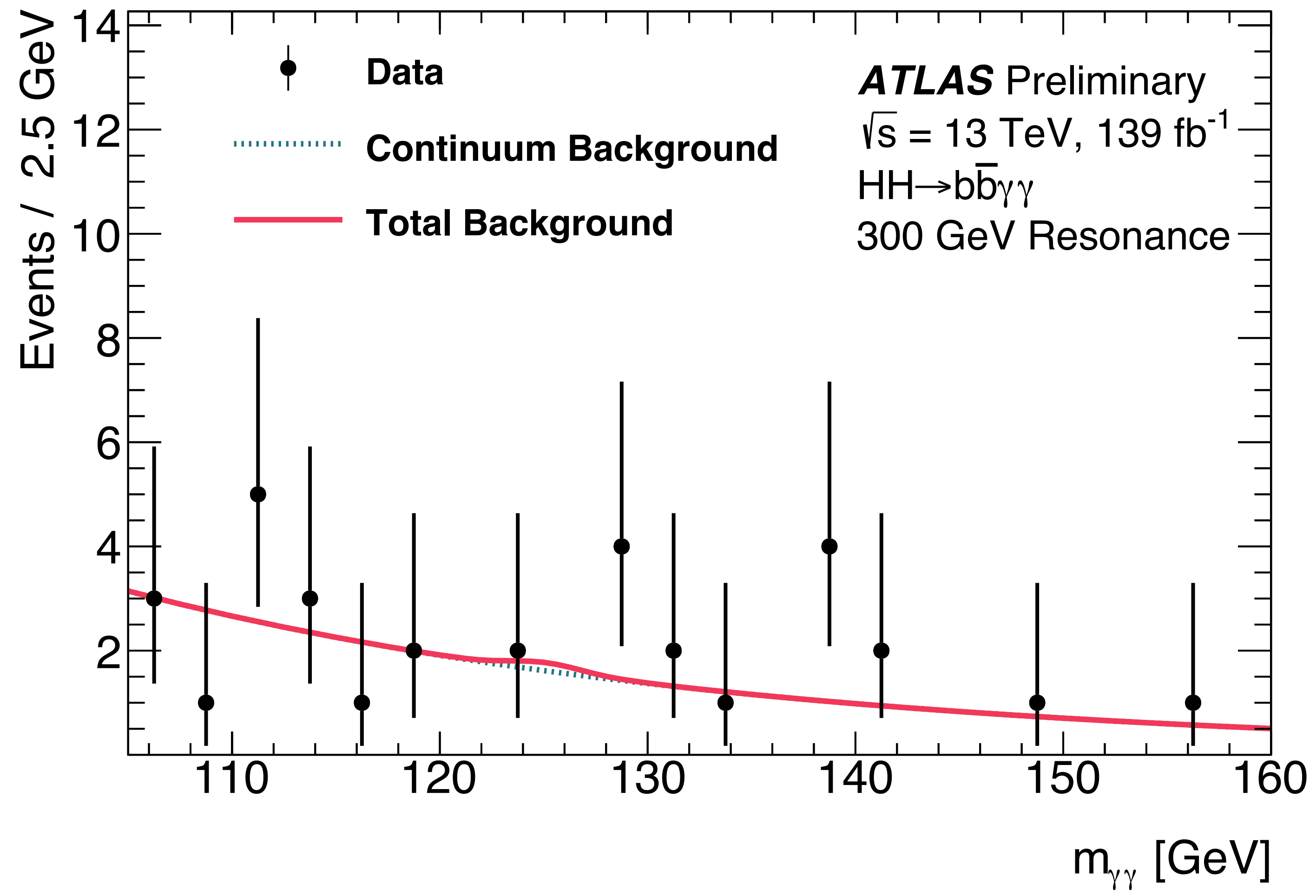
High mass



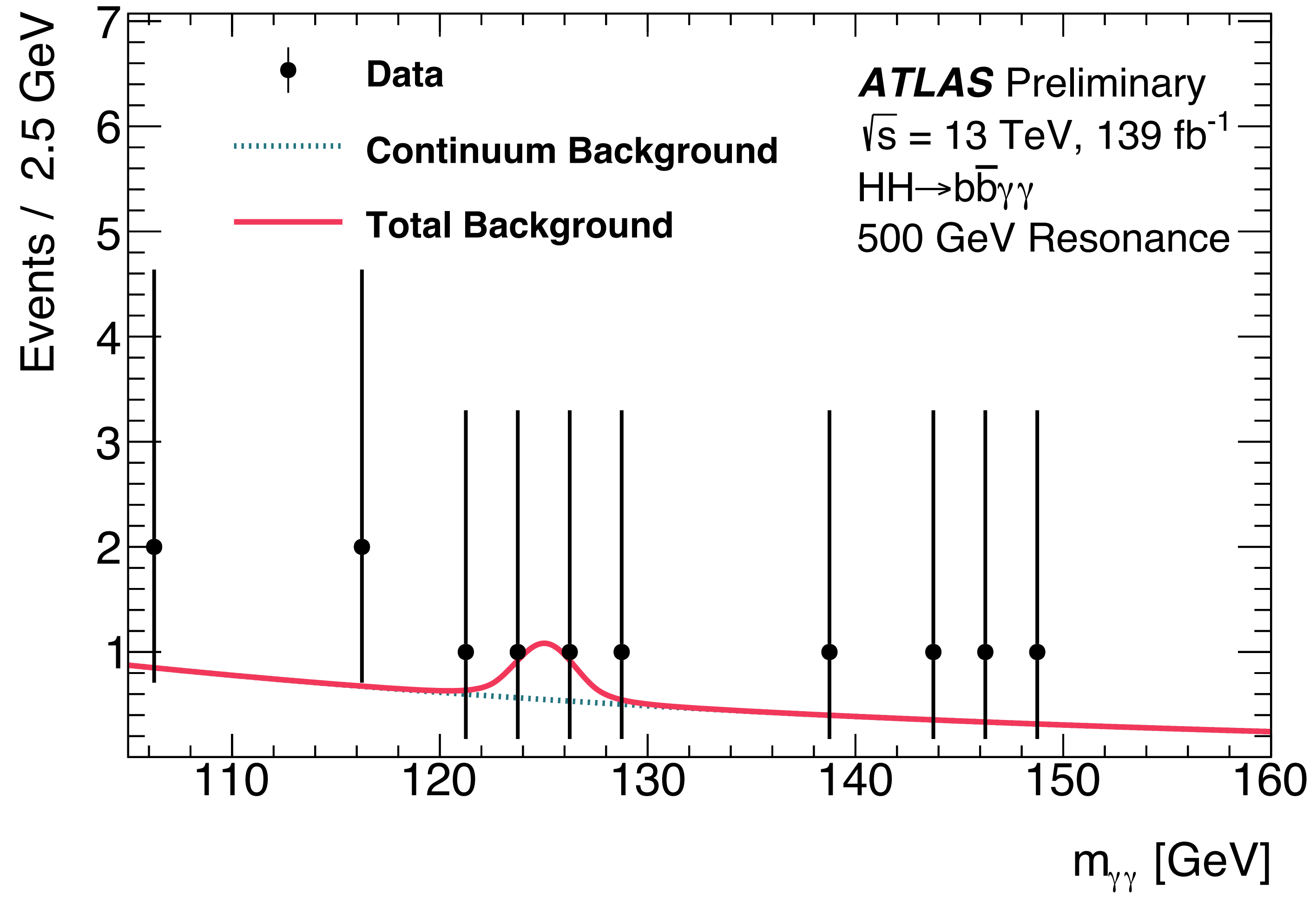


Resonant

Mx = 300 GeV



Mx = 500 GeV



Yields and systematics

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

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

	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