Searches for HH in the bbbb final state in ATLAS

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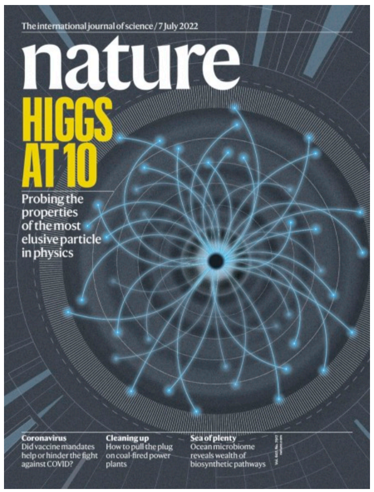
21 Sep 2022

10 years after Higgs boson discovery

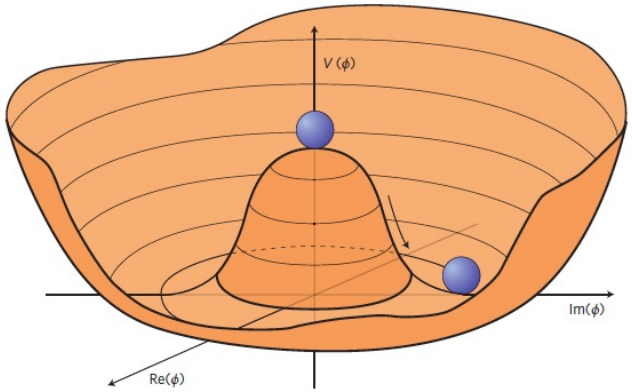
- We've just celebrated the 10 years anniversary of the Higgs boson discovery.



- In the past 10 years:
  - We've measured its mass, CP…
  - We've observed its coupling to many other standard model particles.
- But the self-coupling of the Higgs boson has not been observed yet.
- We still don't know the full picture of the Higgs potential.

The Higgs potential

The Higgs boson self-coupling is directly related to the shape of the Higgs scalar field potential.



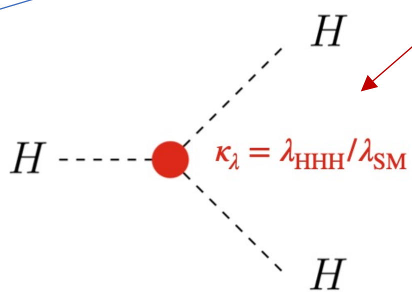
The potential energy of the Higgs field

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

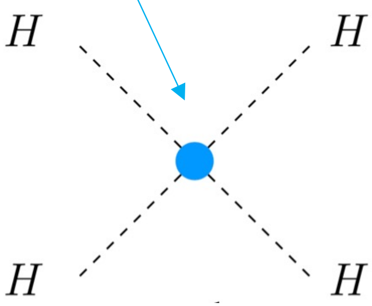
Expand around the minimum

$$\lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4 + \cdots$$

Mass term



Trilinear coupling

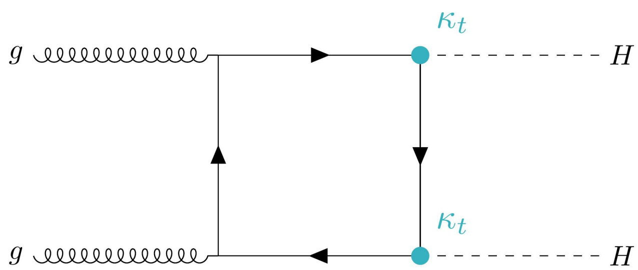


Quartic coupling: still out of reach

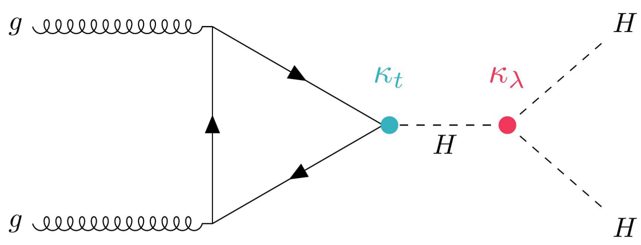
HH production provides direct access to the Higgs boson self-coupling.

HH production

ggF NNLO σ ≈ 31.05 fb

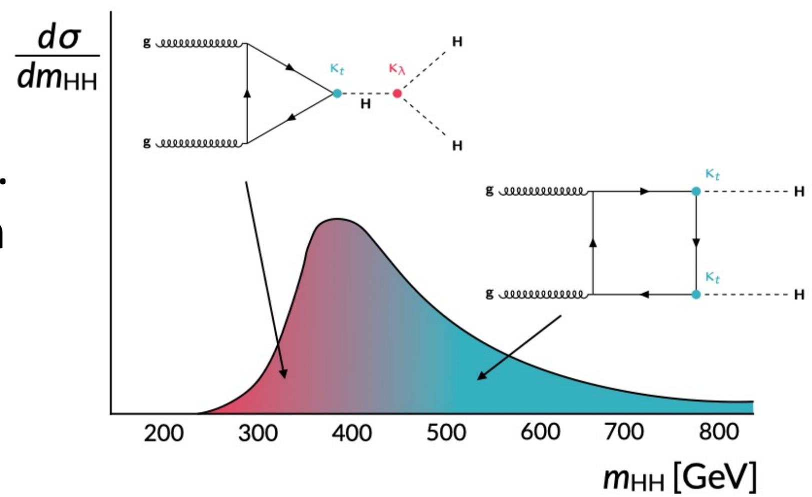


Box diagram



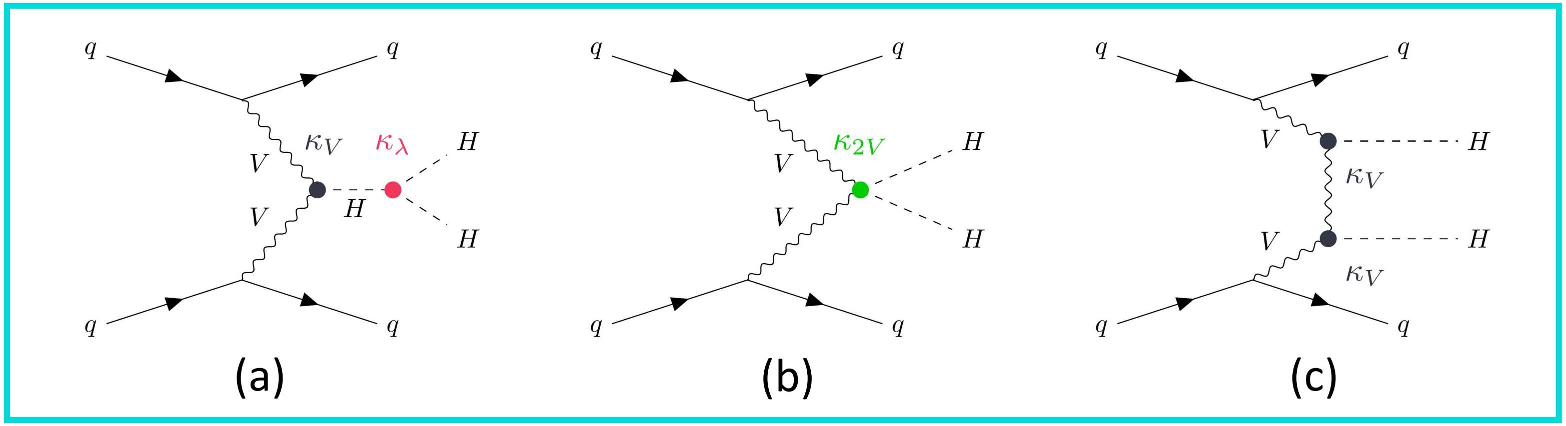
Triangle diagram

- Dominant SM HH production process.
- "Triangle" diagram sensitive to κ_λ.
- Destructive interference between "box" and "triangle" diagram → small SM cross section.



HH production

VBF N3LO σ ≈ 1.73 fb



- Second-leading HH production process.
- Diagram (b) is sensitive to the HHVV coupling κ_{2V}.
- In SM, exact cancellation occurs between (b) and (c).
- When κ_V and κ_{2V} deviate from their SM value, the cross-section grows linearly with the centre-of-mass energy of the incoming vector bosons, providing a smoking gun signature for BSM physics.

Decay channels

- Wide range of possible final states.
- No golden channel. Trade off between large signal event rate and low background.

- bbbb:
  - The most abundant final state, providing high statistics for analysis.
  - Full hadronic final state. Challenge from large multi-jet background.

Large branching ratio

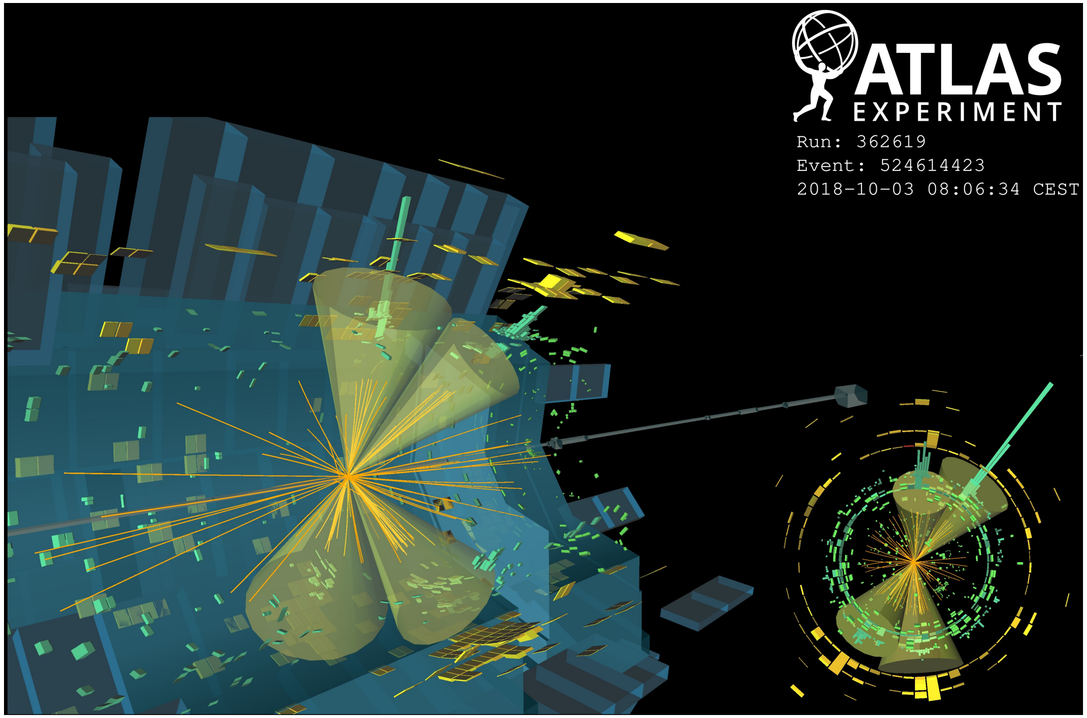
Clean signature

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

Branching ratio of HH decay channels

Non-resonant HH→4b

ATLAS-CONF-2022-035



Analysis outline

Trigger

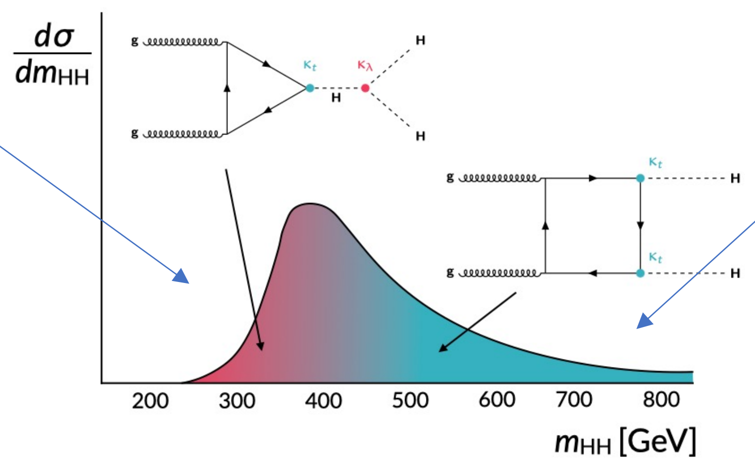
- Use a combination of two multi-jet triggers for complementary acceptance across m_{HH}.
- Analysis operates on trigger turn-on region.
- Separate events into two trigger classes by offline cuts to avoid trigger scale factor ambiguity.

2b2j

- 2 b-tagged jets (35 GeV) + 2 extra jets (35 GeV).
- Important for low m_{HH} events.

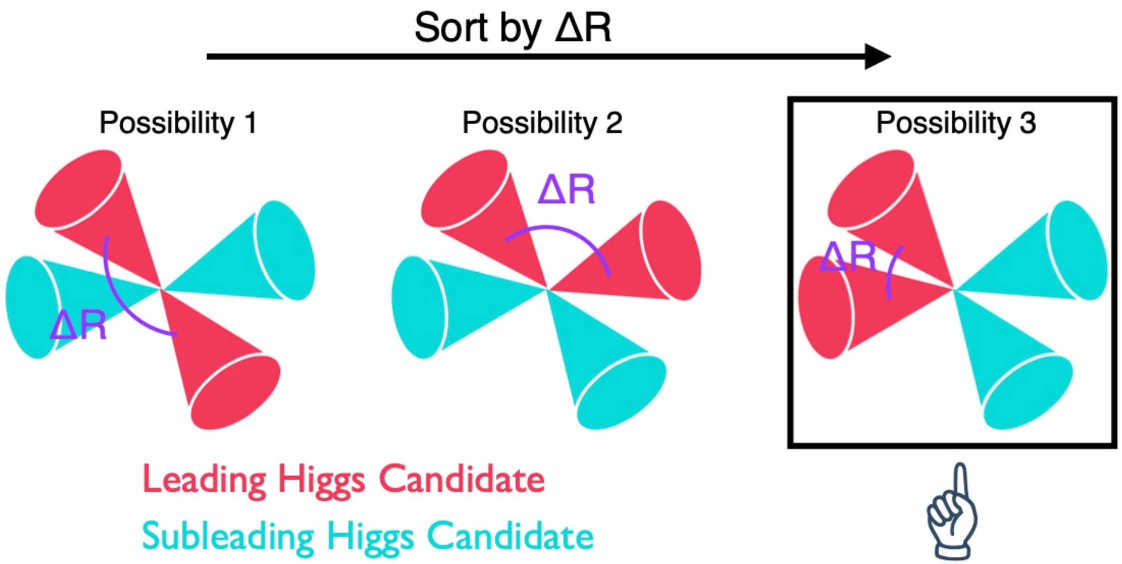
2b1j

- 2 b-tagged jets (55 GeV) + 1 extra jet (100 – 150 GeV).
- Important for high m_{HH} events.



Jet pairing strategy

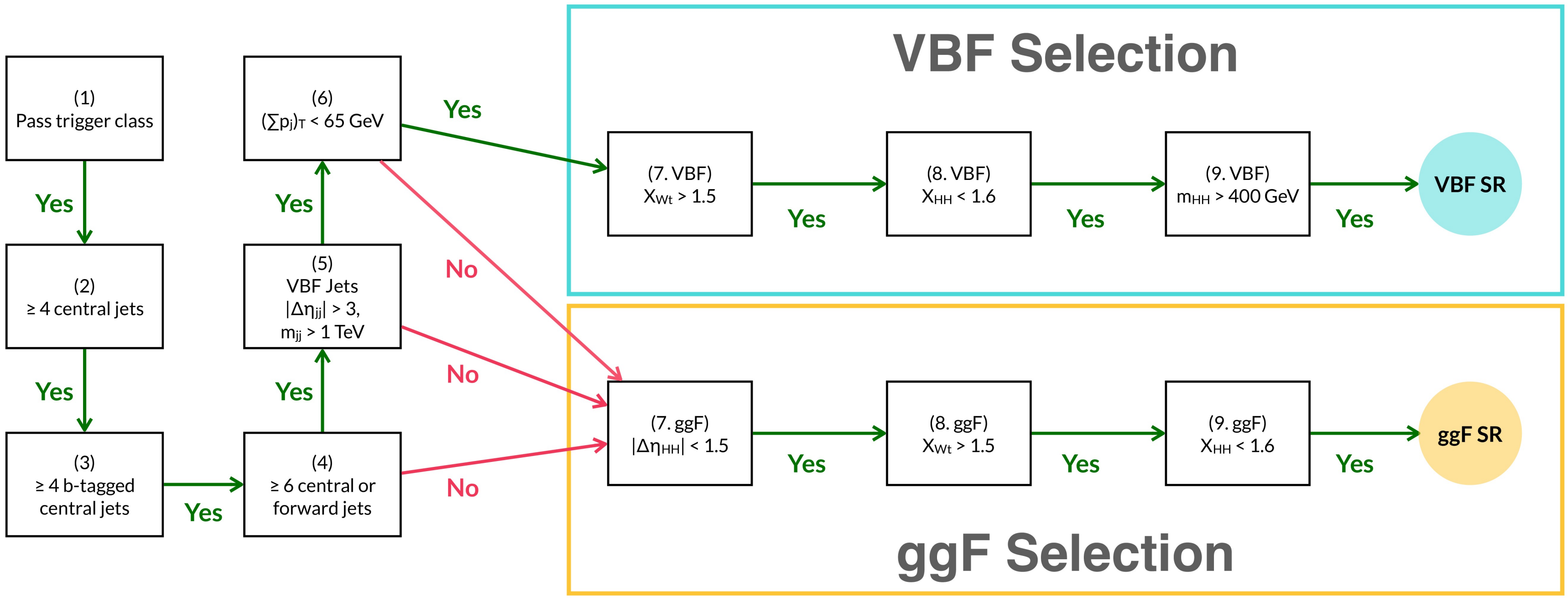
- Pair the four Higgs Candidate jets to reconstruct the two Higgs Bosons.
  - Strategy: Choose the pair that minimize the ΔR of the two jets of the leading Higgs candidate.



  - Minimum-ΔR strategy uses no mass information in the pairing, resulting in relative smooth m_{H1}-m_{H2} mass plan and easier background estimation.

Event selection

- central jets: $|\eta| < 2.5$ and $p_T > 40$ GeV
- forward jets: $2.5 < |\eta| < 4.5$ and $p_T > 30$ GeV



Top-veto discriminant

$$X_{Wt} = \sqrt{\left(\frac{m_W - 80.4\ \text{GeV}}{0.1\ m_W}\right)^2 + \left(\frac{m_t - 172.5\ \text{GeV}}{0.1\ m_t}\right)^2}$$

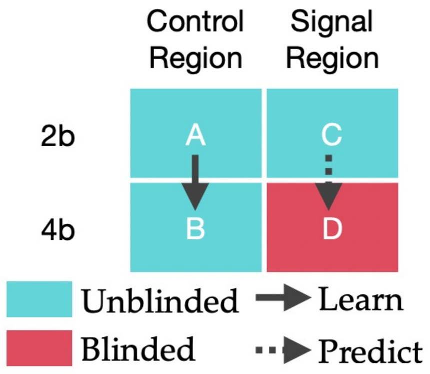
HH discriminant

$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\ \text{GeV}}{0.1\ m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\ \text{GeV}}{0.1\ m_{H2}}\right)^2}$$

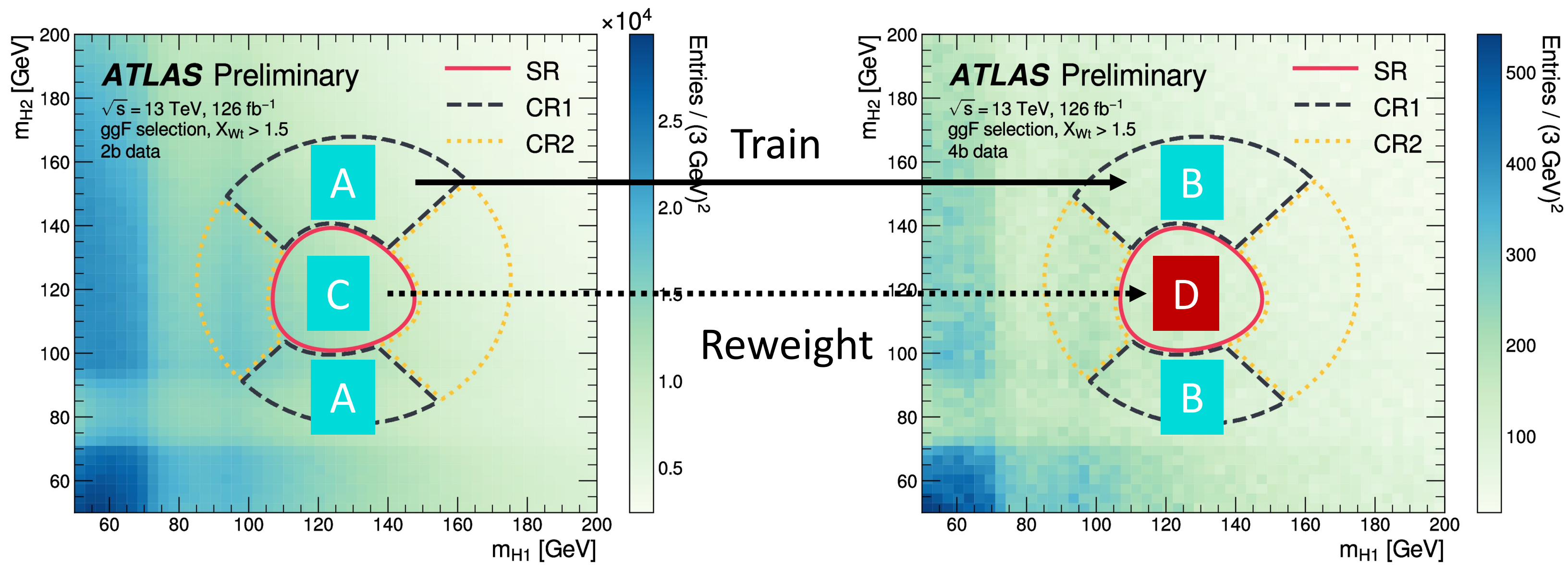
Background estimation

- Use data-driven background estimation due to the difficulty in modelling multi-jet process in MC.
- Kinematic reweighting 2b→4b using a neural network with loss function:

$$\mathcal{L}(w(\vec{x})) = \int d\vec{x} \left[\sqrt{w(\vec{x})}\, p_{2b}(\vec{x}) + \frac{1}{\sqrt{w(\vec{x})}}\, p_{4b}(\vec{x}) \right]$$



The reweighting function $w(\vec{x}) = \frac{p_{4b}(\vec{x})}{p_{2b}(\vec{x})}$ is obtained by minimizing the loss function.

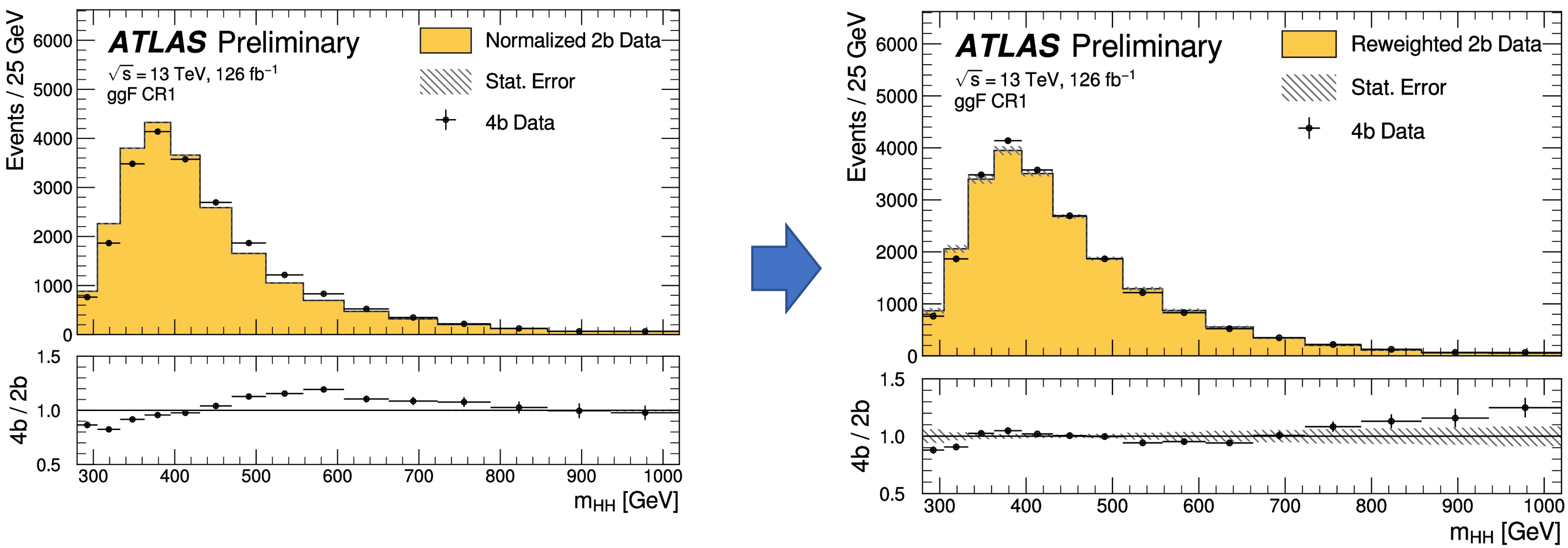


2b mass plane

4b mass plane

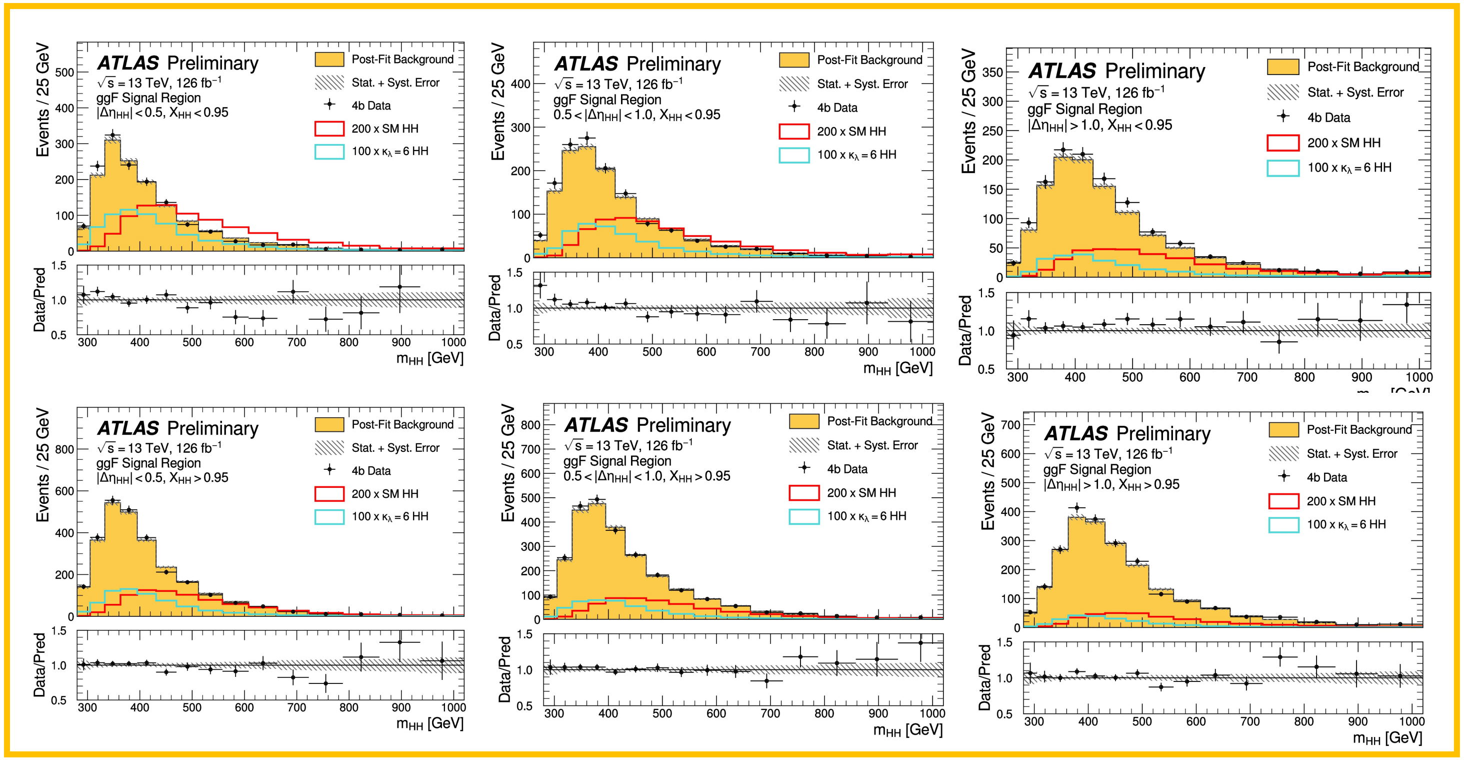
Background estimation performance

- m_{HH} before and after reweighting in CR1 where the neural network is trained.

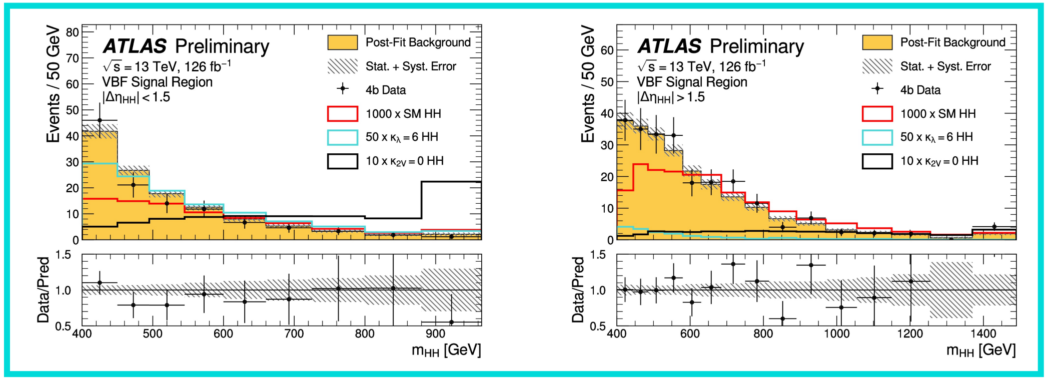


- Reweighting improves the agreement with 4b events.

Categorization



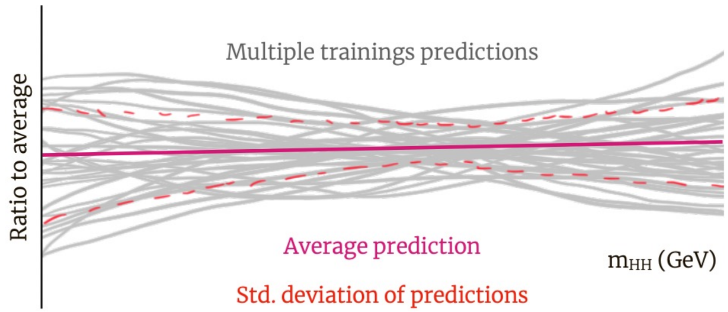
ggF:
2D categorization
in $\Delta\eta_{HH}$ and X_{HH}



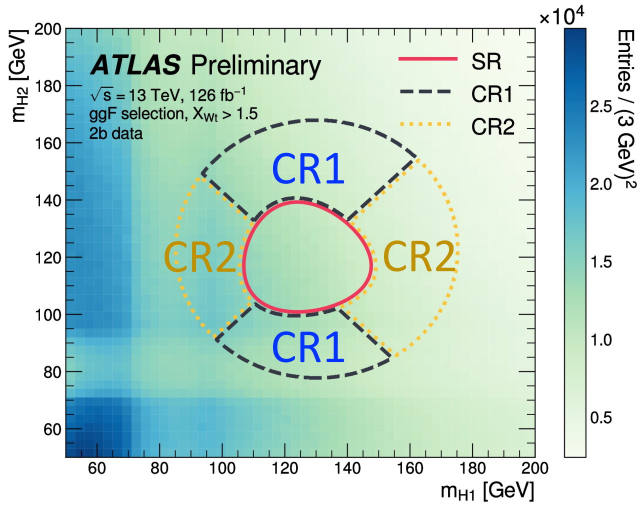
VBF:
1D categorization
in $\Delta\eta_{HH}$

Systematic uncertainties

- Background estimation uncertainty is the most important source of experimental uncertainty.
  - 2b statistics: Limited statistics of 2b events in SR.
  - Bootstrap: Variation of NN training
  - CR1 VS CR2: CR2 provides independent training with different interpolation assumption.
  - 3b1f: Replace 4b events by 3b1f in background estimation and use the non-closure as systematic.
- Background estimation also validated in reversed $\Delta\eta_{HH}$ region and shifted signal region.



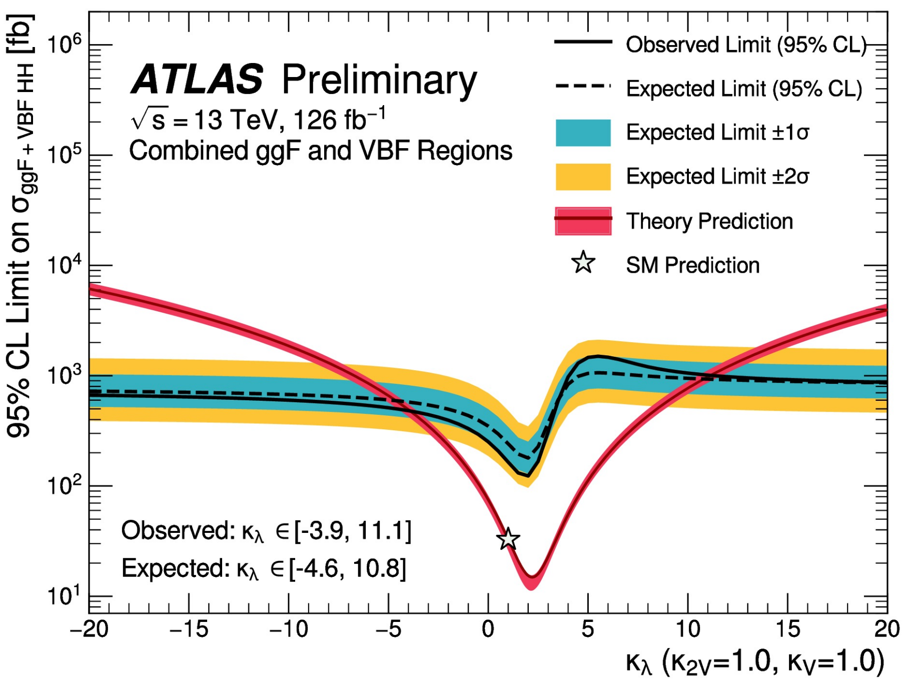
Bootstrap



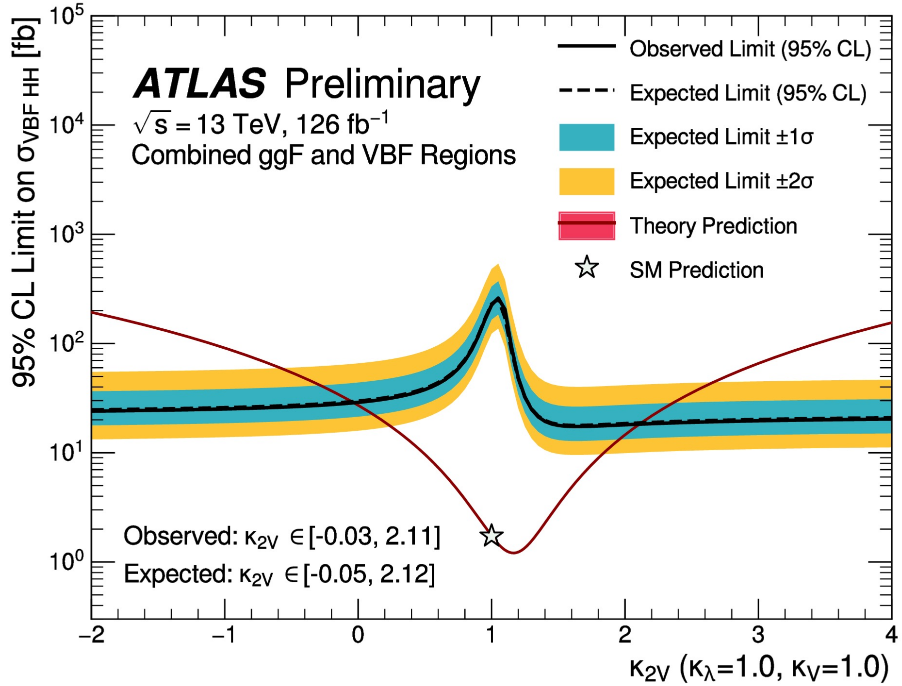
CR1 VS CR2

Results

κ_λ



κ_{2V}



- No evidence for a HH(bbbb) signal is found.
- Observed (expected) upper limit on the cross section for ggF+VBF production is set to 5.1 (8.1) times the SM prediction.

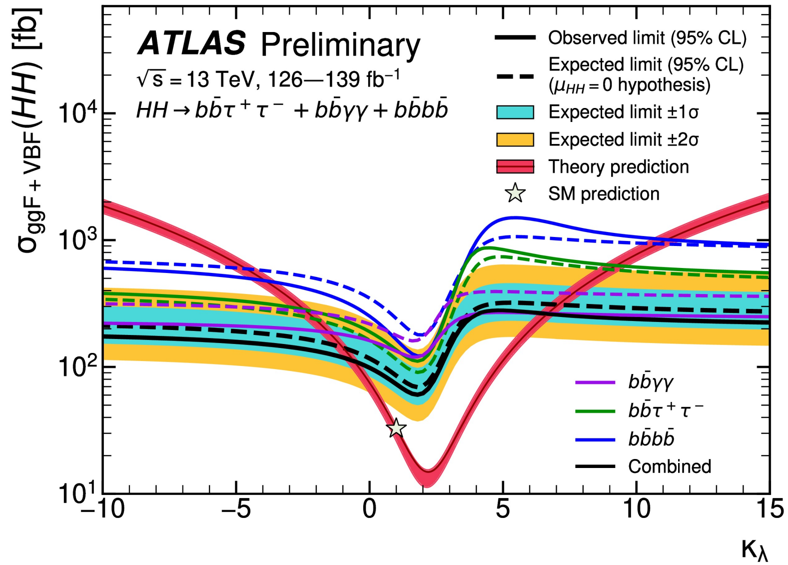
Combination

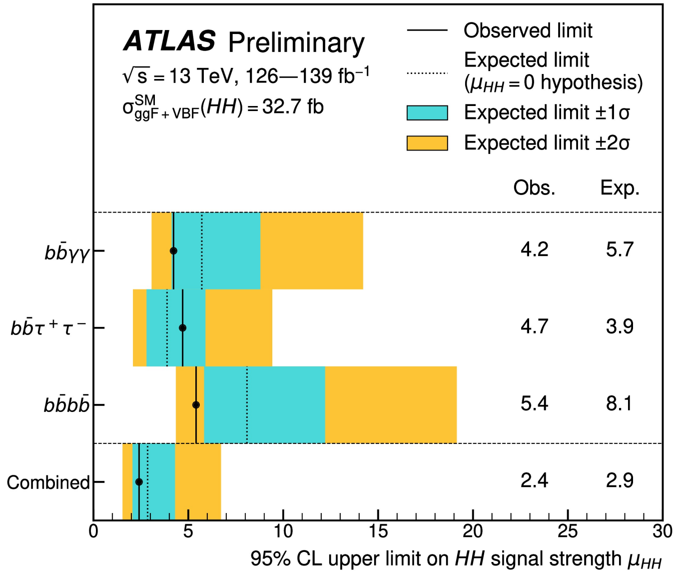
[ATLAS-CONF-2022-050]

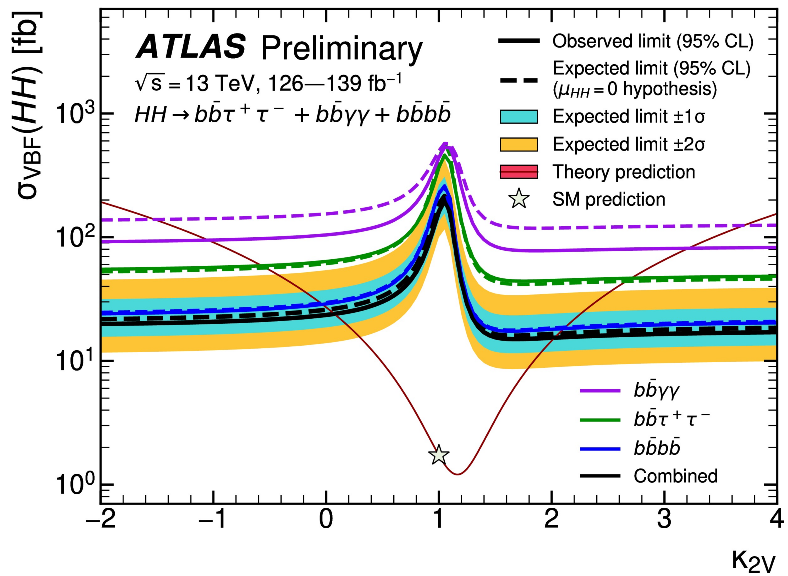
- Combining with bbγγ and bbττ channels gives strong constraints on HH production.

$$\mu_{HH} = \sigma^{HH}_{ggF+VBF}/\sigma^{HH,SM}_{ggF+VBF} = 2.4\ (2.9) \times SM$$

Observed (expected) constraint on κ_λ:
$-0.6 < \kappa_\lambda < 6.6$ $(-2.1 < \kappa_\lambda < 7.8)$
Observed (expected) constraint on κ_{2V}:
$0.1 < \kappa_{2V} < 2.0$ $(0.0 < \kappa_{2V} < 2.1)$

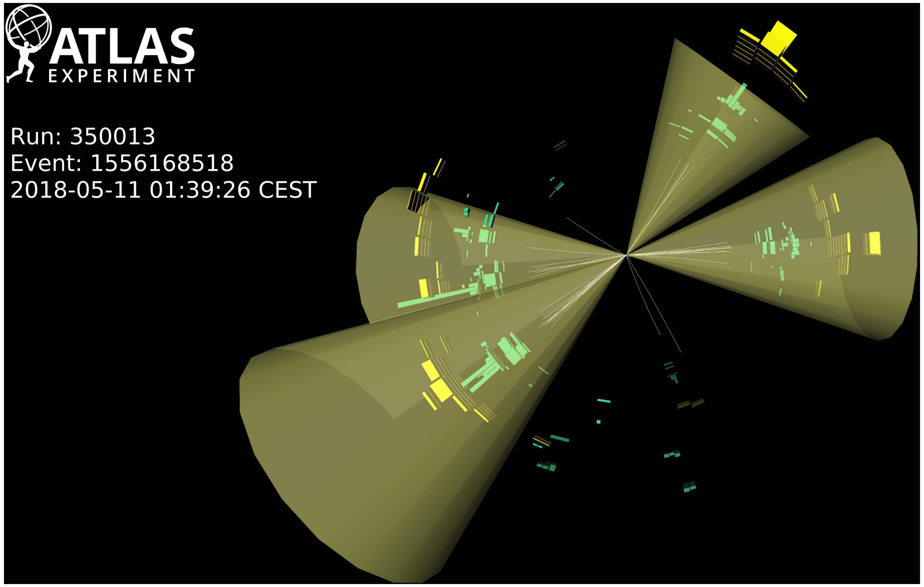


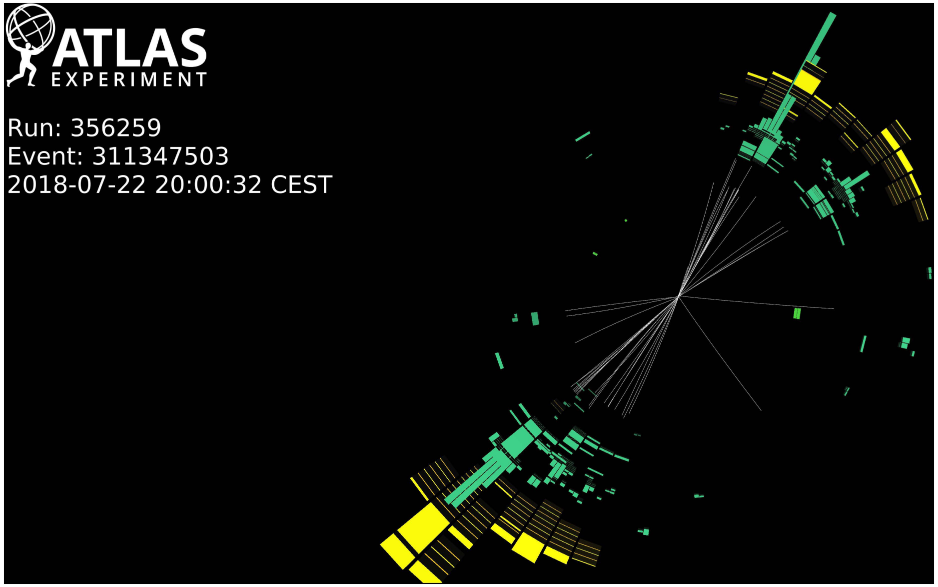




Resonant HH→4b

[Phys. Rev. D 105, 092002]

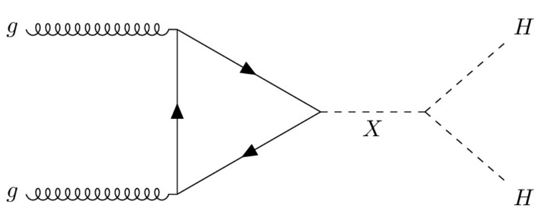




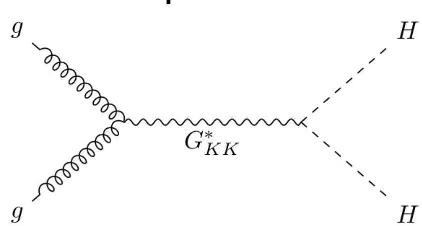
Resonant HH – a window to probe new physics

- Some BSM physics scenarios predict new resonances decaying to standard-model-like Higgs pairs.
- Two benchmark models:
  - Generic spin-0 resonance (e.g. 2HDM and MSSM) with negligible width.
  - Spin-2 gravitons (Randall-Sundrum models) with model dependent width.
- Only ggF production mode is considered.

Spin 0

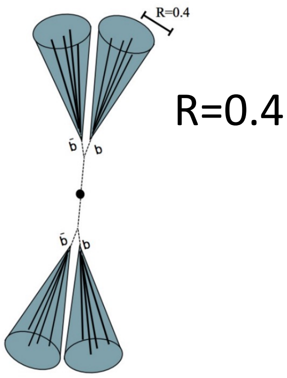


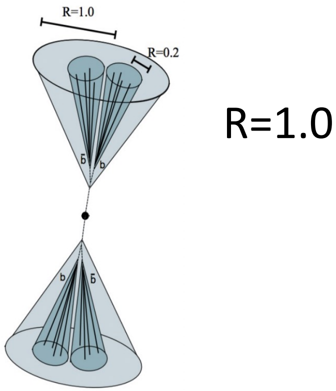
Spin 2



Analysis strategy

- Resolved + boosted analysis channels to cover a wide resonances mass range:

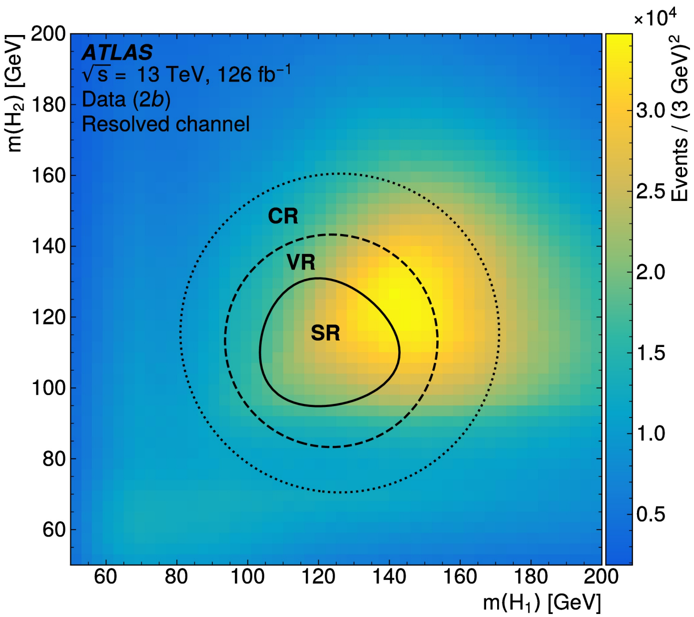


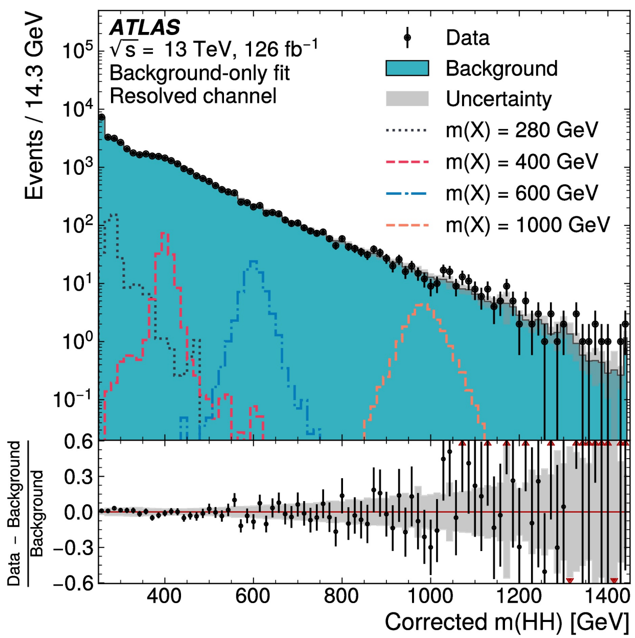


- More triggers for acceptance in a wide mass range:
  - Resolved: a combination of 2b2j + 2bj1 + 2bH_T + 1j triggers; more complicated trigger classes to resolve scale factor ambiguity.
  - Boosted: single large-R jet trigger, operating on trigger plateau.

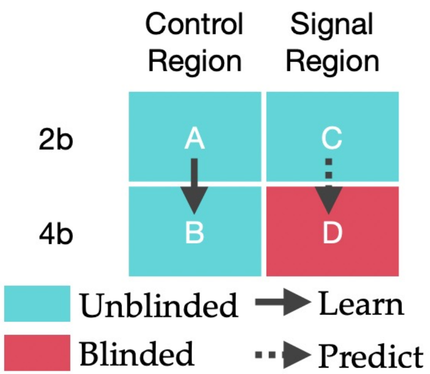
- Pairing: use BDT pairing in the resolved channel.

Analysis strategy - resolved



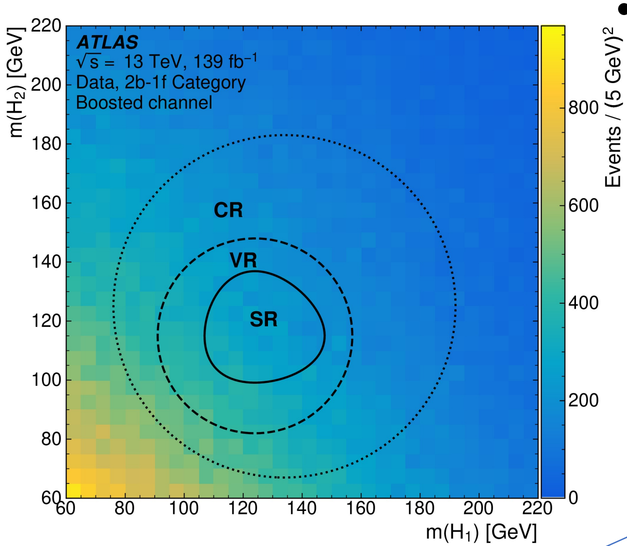


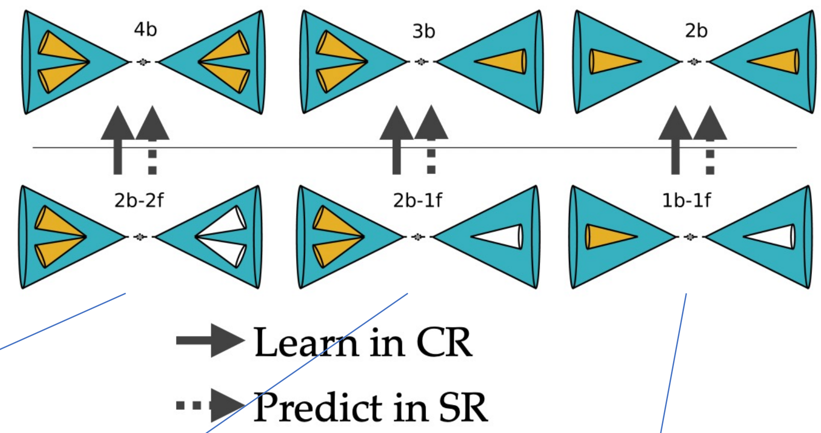
- Similar background estimation strategy as the non-resonant analysis.
- Circular CR due to the non-uniformity of the mass plane from BDT pairing.

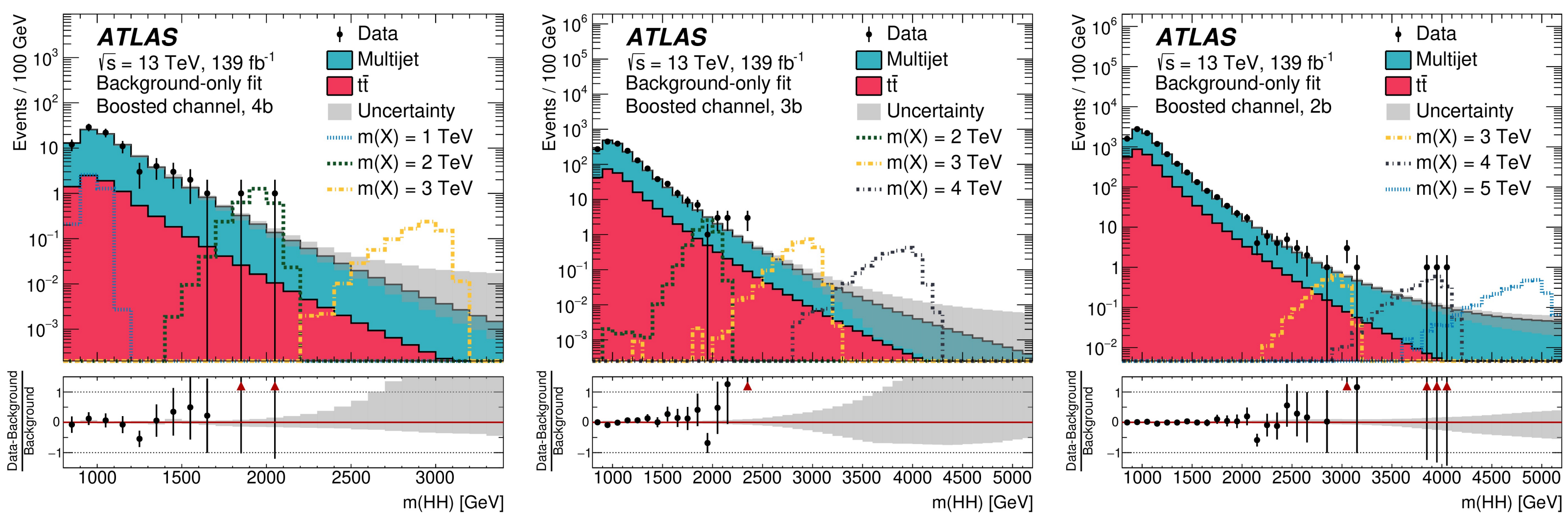


Analysis strategy - boosted

- Low-tag to high-tag reweighting for multi-jet background.
- MC-based estimation for ttbar background.

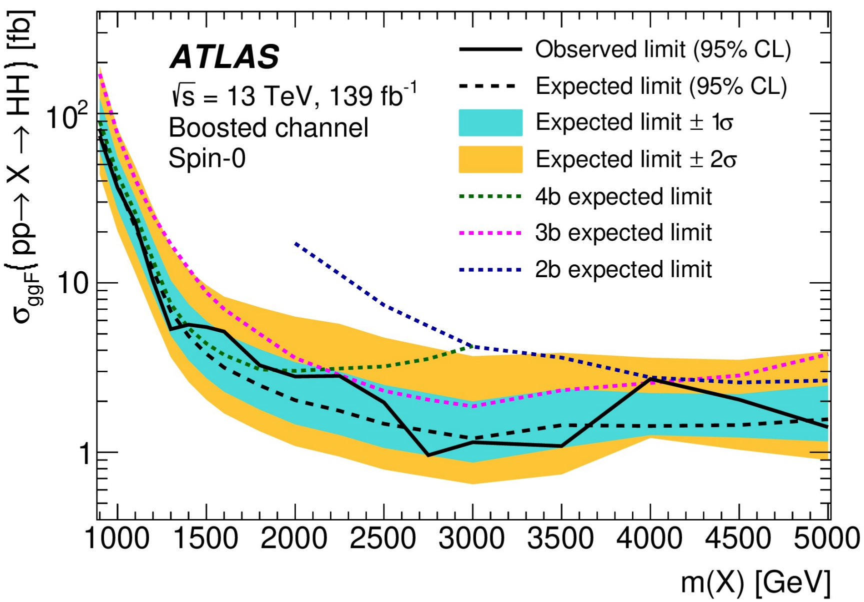




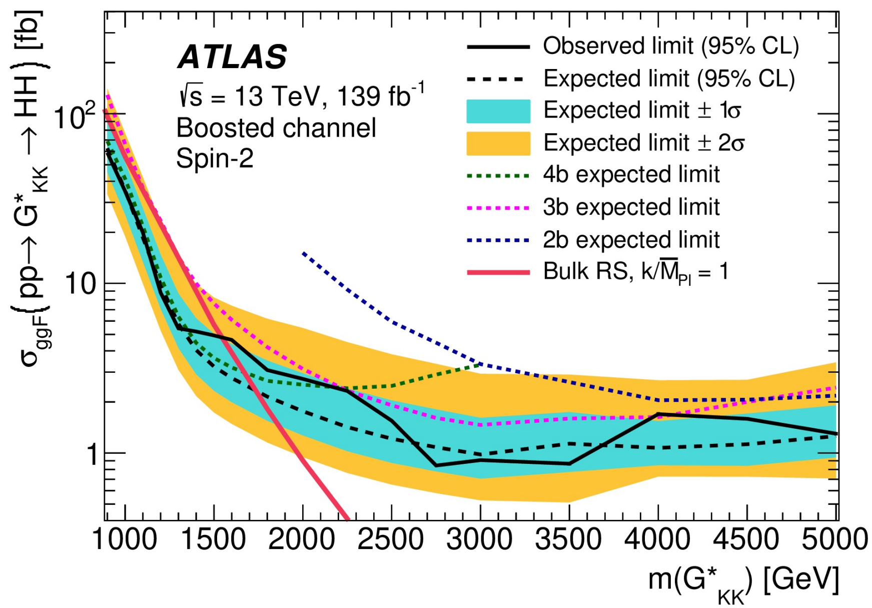


Results – boosted only

Spin 0

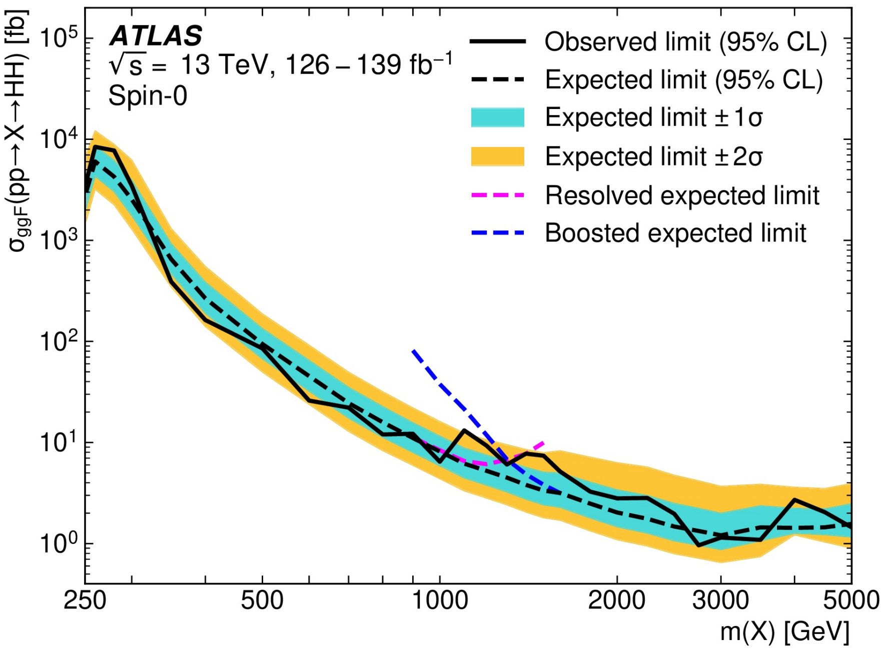


Spin 2

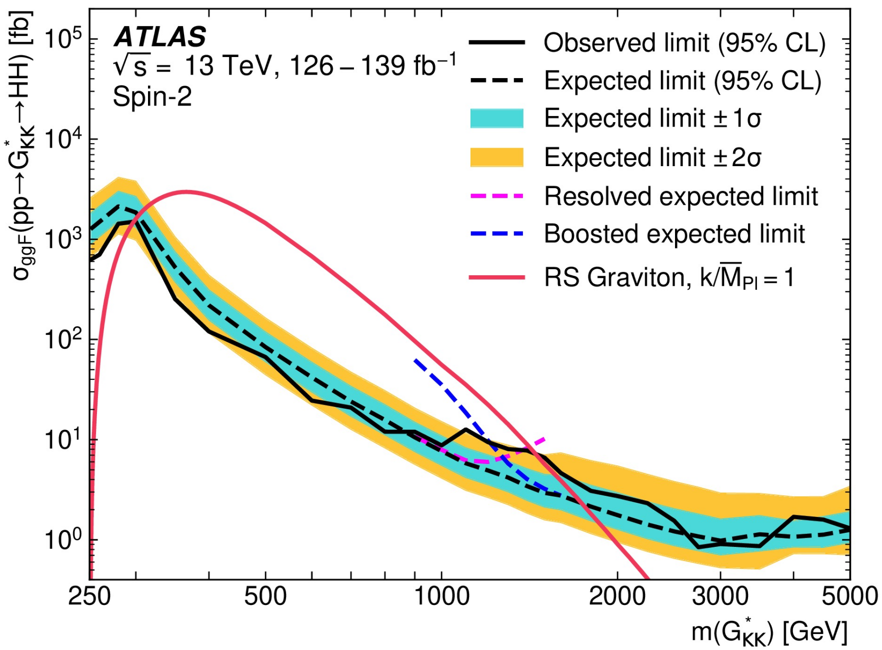


Results – resolved + boosted

Spin 0



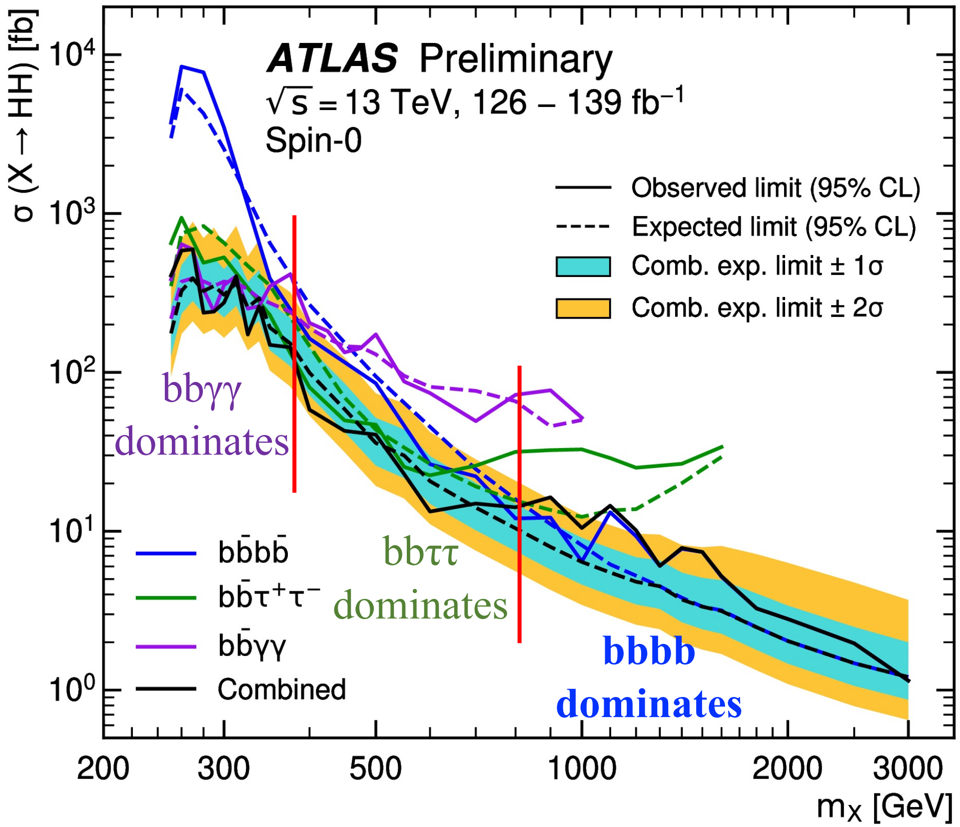
Spin 2



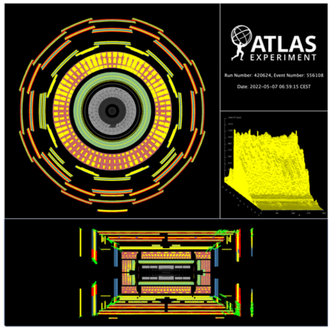
Results – HH combination

ATLAS-CONF-2021-052

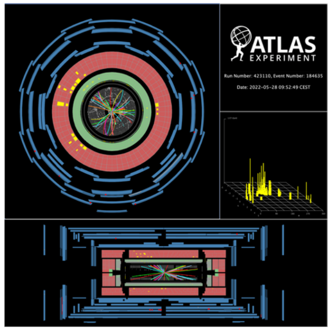
- Combining with bbγγ and bbττ channels.
- Complementarity between channels allows to obtain optimal exclusion limits on spin-0 ggF X→HH cross section across m_X.



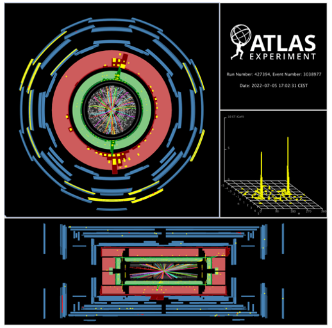
Preparation for LHC Run 3



Run3 beam splashes
(07 May 2022)

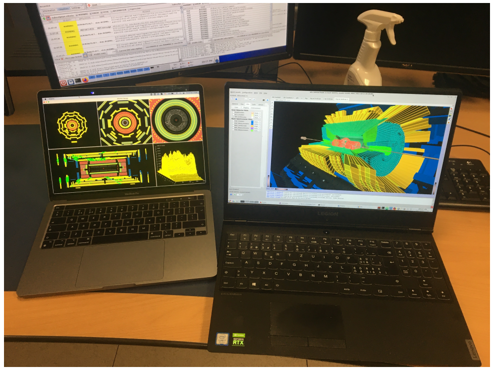


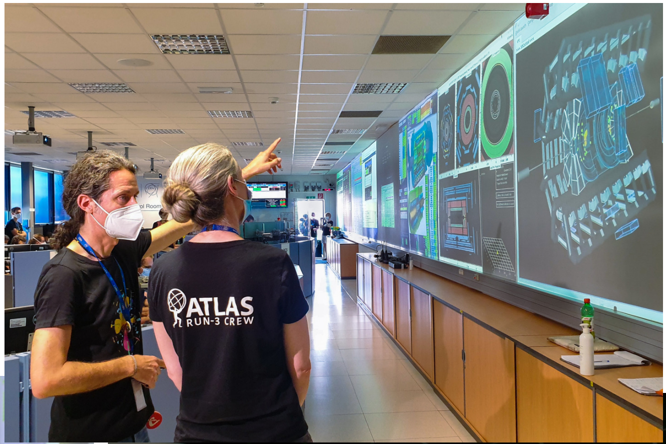
Run3 900 GeV test collisions
(28 May 2022)

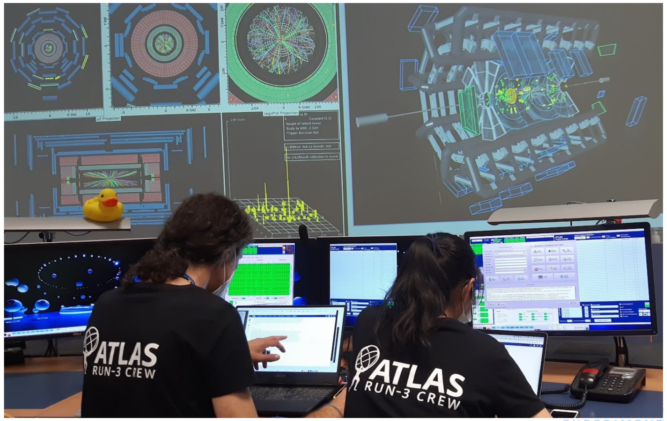


Run3 13.6 TeV collisions
(05 July 2022)

Preparation for LHC Run 3







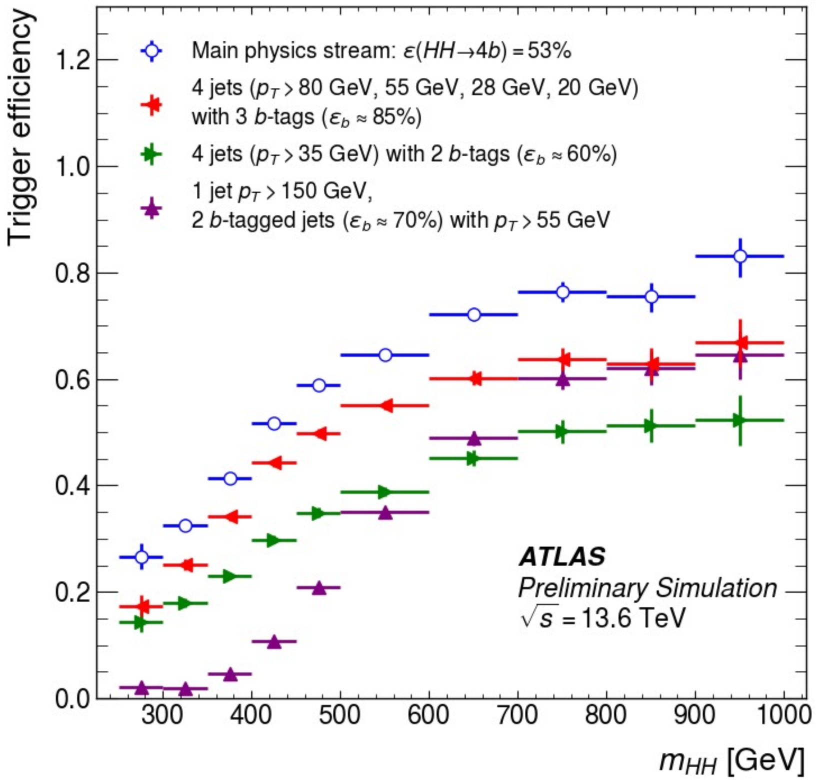
LHC restarted at 13.6 TeV for Run 3

Run 3 trigger improvement

[ATLAS Trigger Public Results]

HH4b triggers reoptimized for Run 3:

- Particle flow reconstruction
- Deep learning neural network b-tagger
- Additional asymmetric 4-jet triggers (2 or 3 b-tagged jets)



Three triggers provide events to the main stream:

- Asymmetric 3b1j trigger (new)
- Symmetric 2b2j trigger (reoptimized)
- 2b1j trigger (reoptimized)

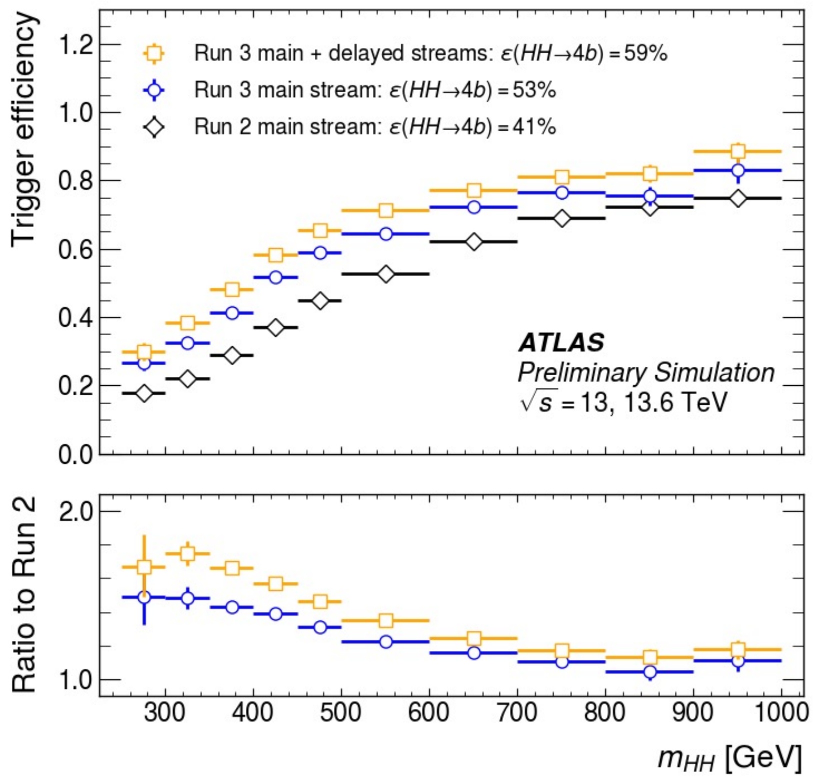
Good coverage across the m_{HH} mass spectrum.
The total combined efficiency for SM HH→4b signal is 53%.

Run 3 trigger improvement

[ATLAS Trigger Public Results]

HH4b triggers reoptimized for Run 3:

- Particle flow reconstruction
- Deep learning neural network b-tagger
- Additional asymmetric 4-jet triggers (2 or 3 b-tagged jets)



Run 3 delayed stream:
- Asymmetric 2b2j

Run 3 main stream:
- Asymmetric 3b1j
- Symmetric 2b2j
- 2b1j

Run 3 eff: 59%

Run 2 main stream:
- Symmetric 2b2j
- 2b1j

Run 2 eff: 41%

The asymmetric 4-jet trigger in Run 3 increase the SM HH→4b signal efficiency from 41% to 59%.

Summary

- Latest ATLAS results on HH→4b searches are presented.
- All results are compatible with SM. No evidence for SM HH→4b yet due to the limited sensitivity. Set the most stringent limits with the full Run 2 dataset.

- Run 3 data taking is on the way.
- Already several improvements foreseen for Run 3. The optimization is still ongoing, to pave ways for the Run 3 analysis.