Searches for diboson resonances at ATLAS

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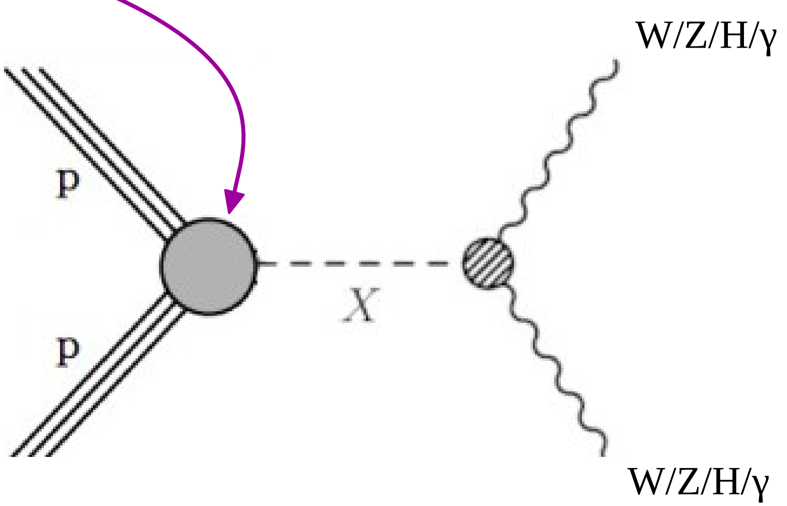
Why dibosons?

Diboson resonances are an extremely generic probe of new physics.

- Predicted by many models: 2HDMs (e.g. SUSY), extra dimensions, etc...

ATLAS has a broad program of diboson searches

- Cover as many final states as possible.
- Try to avoid making strict assumptions about the models.
  - Consider varied production modes and spin hypotheses to ensure wide coverage.
- Aim for maximum reinterpretability.



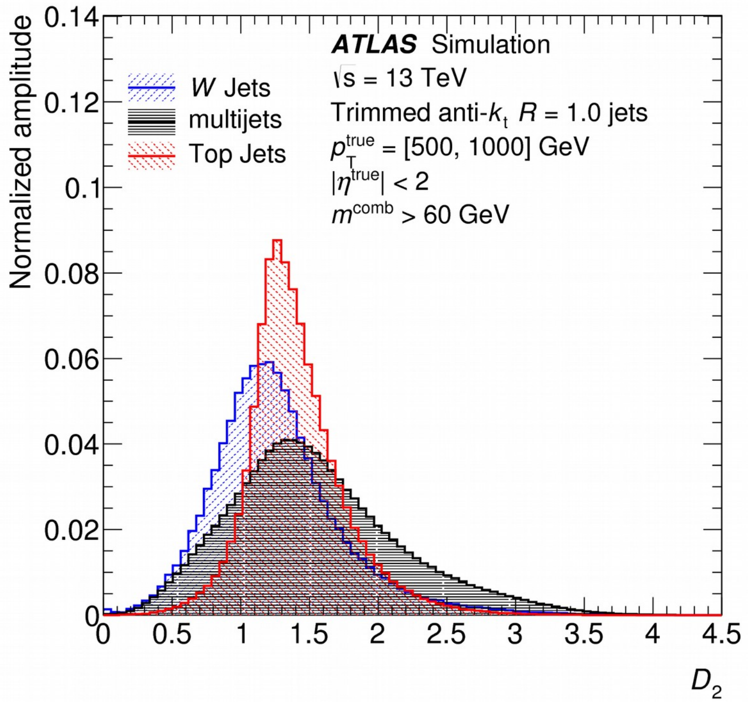
Modern Methods for High Masses

At the multi-TeV scale, use boosted hadronic decays of W/Z/H

- Large branching fraction gives advantage in statistics-limited regime.
- High boost means decay products are collimated into 1 jet

Recent developments in boosted object tagging give large sensitivity improvements!

- Substructure-based taggers for hadronic W, Z, and H decays



D_2 is an **energy correlation ratio**.

For full details, see:
JHEP 06 (2013) 108
JHEP 12 (2014) 009

Eur. Phys. J. C 79 (2019) 375

Modern Methods for High Masses

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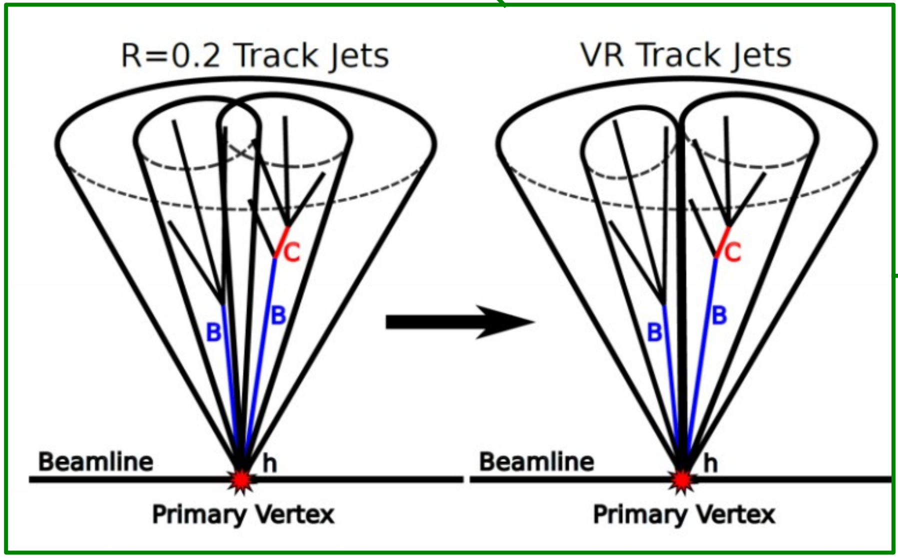
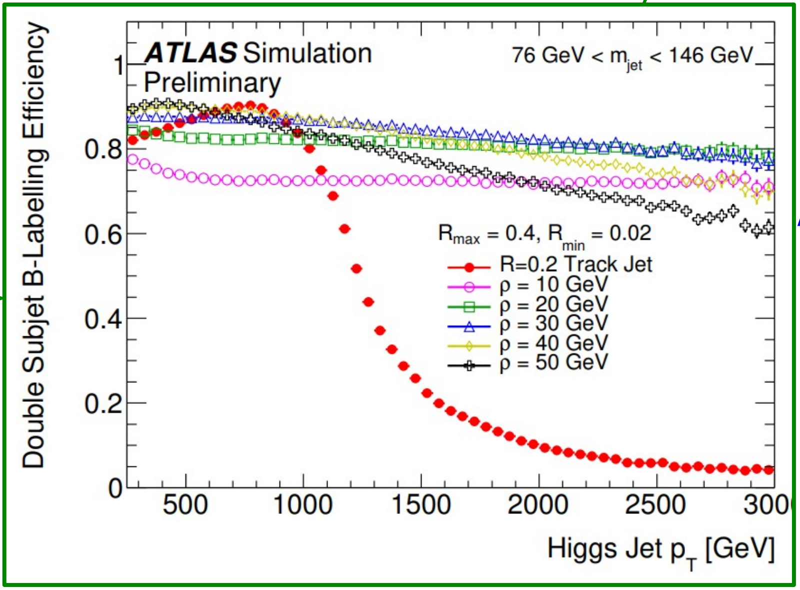
Recent developments in boosted object tagging give large sensitivity improvements!

- Substructure-based taggers for hadronic W, Z, and H decays
- Variable radius track jets newly optimized for b-tagging in dense environments



Boosted H→bb efficiency



Big gain with respect to fixed radius!

ATL-PHYS-PUB-2017-010

What's new from ATLAS?

This talk will discuss the most recent ATLAS diboson results (June-August).

- All use the full ATLAS Run 2 dataset.
- See backup for a summary and links to older results from other channels.

Two new searches for **HH resonances**

- HH → bbbb (ATLAS-CONF-2021-035)
- HH → bbττ (ATLAS-CONF-2021-030) ← Also includes non-resonant interpretations

A search for **Vγ resonances** in the hadronic final state (ATLAS-CONF-2021-041)

A search for **WH resonances** in the lνbb final state (ATLAS-CONF-2021-026)

See also our corresponding Physics Briefings for simple summaries:

https://atlas.cern/updates/briefing/search-heavy-W-bosons (WH→lνbb)
https://atlas.cern/updates/briefing/double-Higgs-to-bottoms(HH→bbbb)
https://atlas.cern/updates/briefing/two-Higgs-better-one (HH→bbττ)

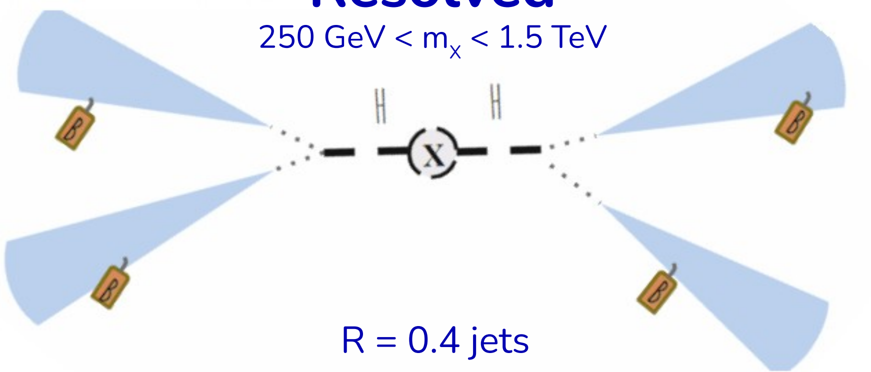
bbbb has the largest branching fraction of any HH final state.

- Best statistics, but a challenging multijet background.
- Data-driven background estimate is needed.

Depending on how heavy the resonance is, we consider decays resulting in 4 distinct jets or 2 collimated ones.

Resolved

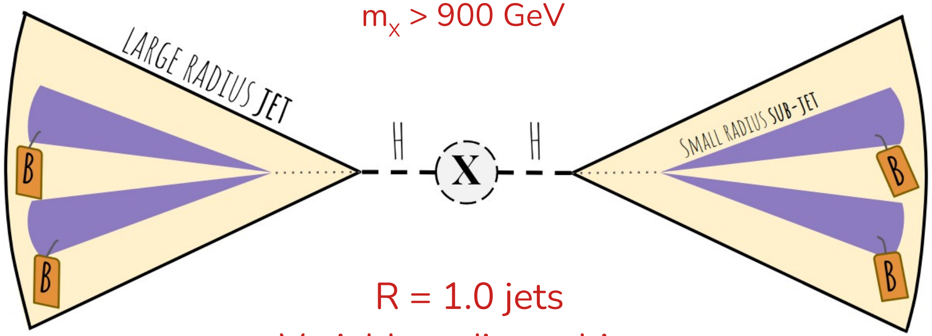
250 GeV < m_X < 1.5 TeV



R = 0.4 jets

Boosted

m_X > 900 GeV

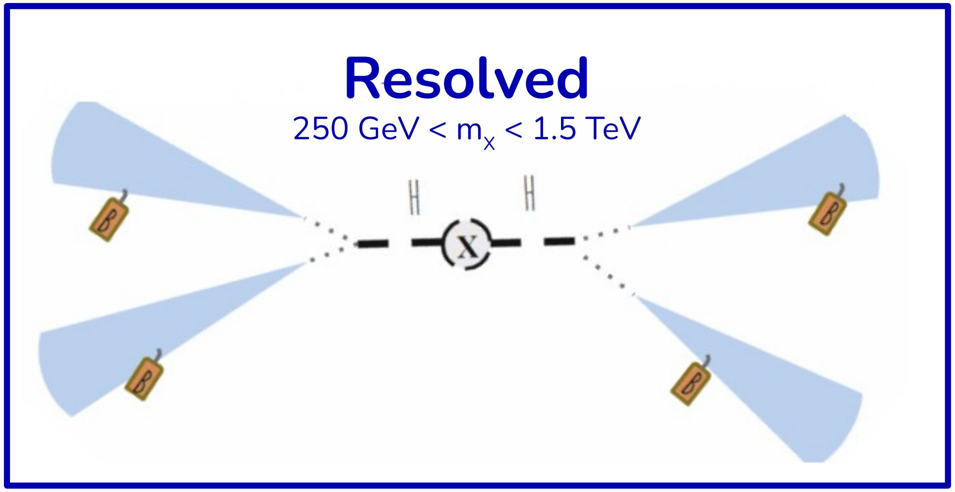


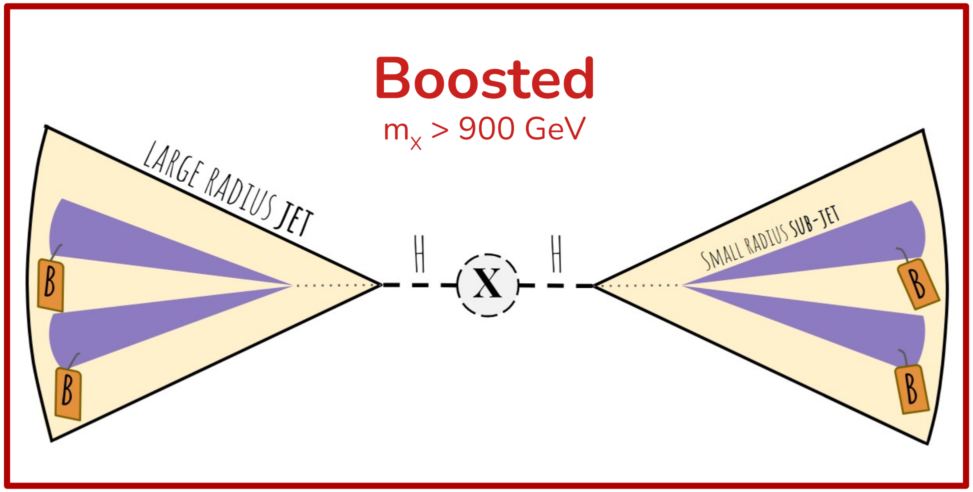
R = 1.0 jets

Variable radius subjets

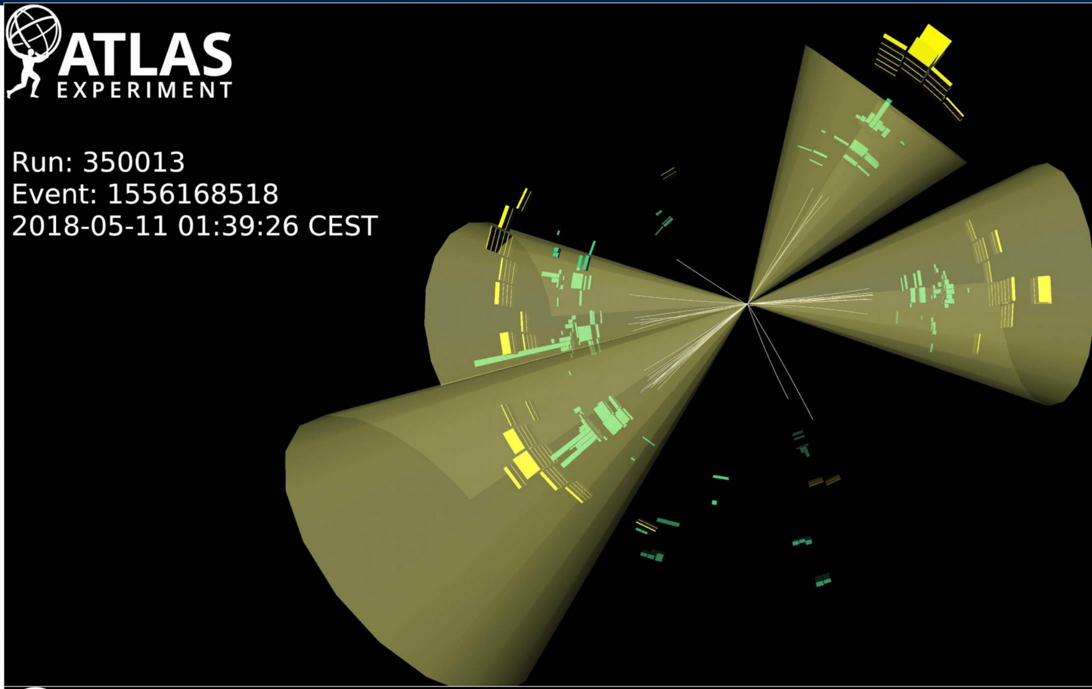
Sketches by S. Paredes Saenz

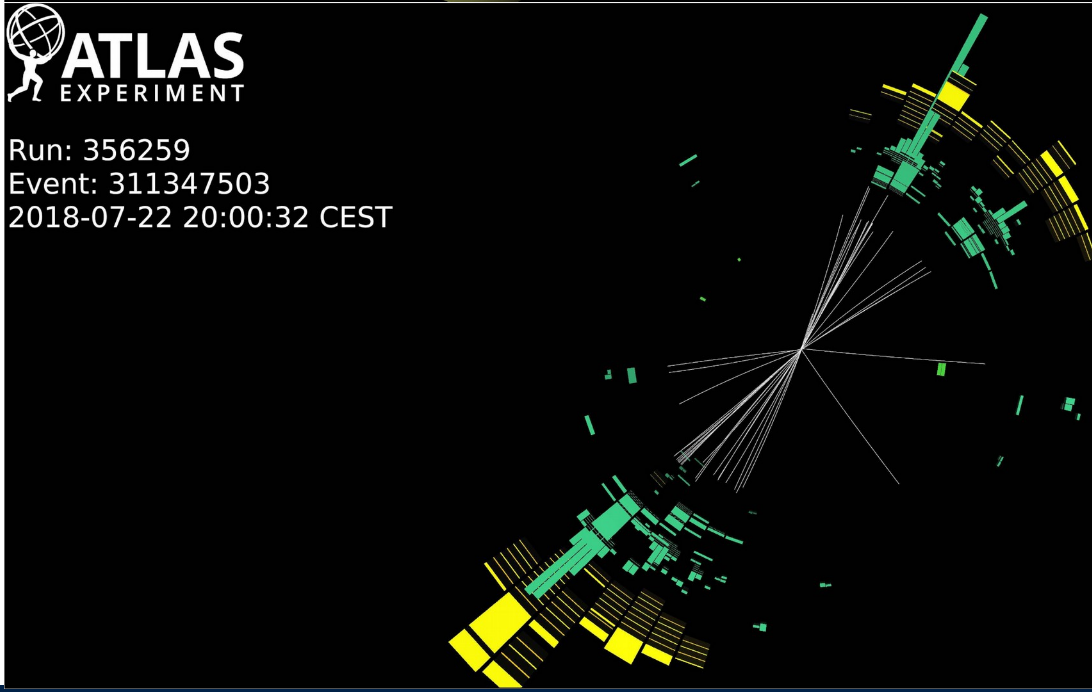
HH → bbbb





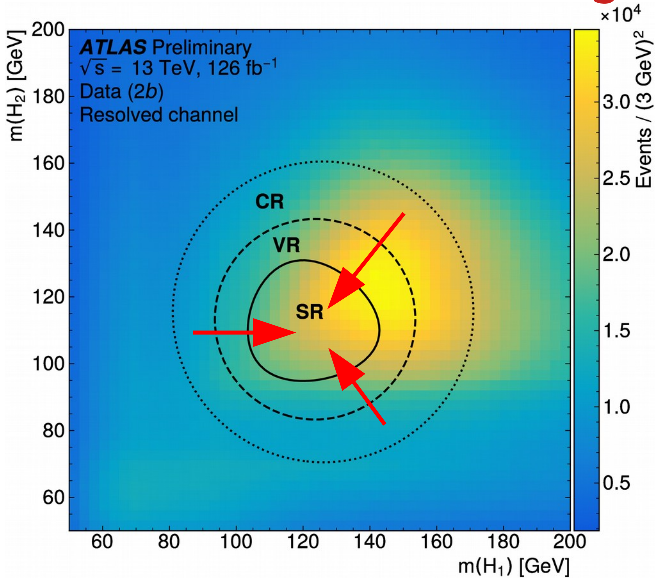
Sketches by S. Paredes Saenz



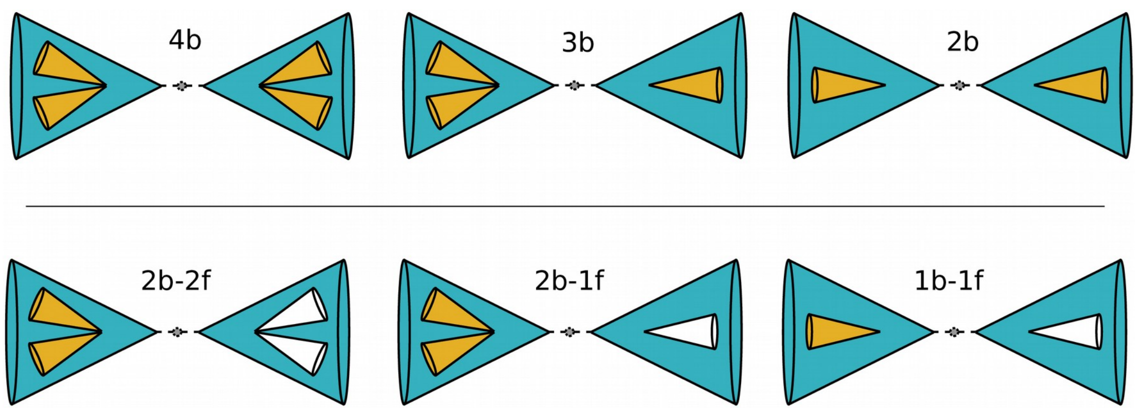


HH → bbbb

Resolved data with 2 b-tags



Categorize boosted events based on subjet b-tagging



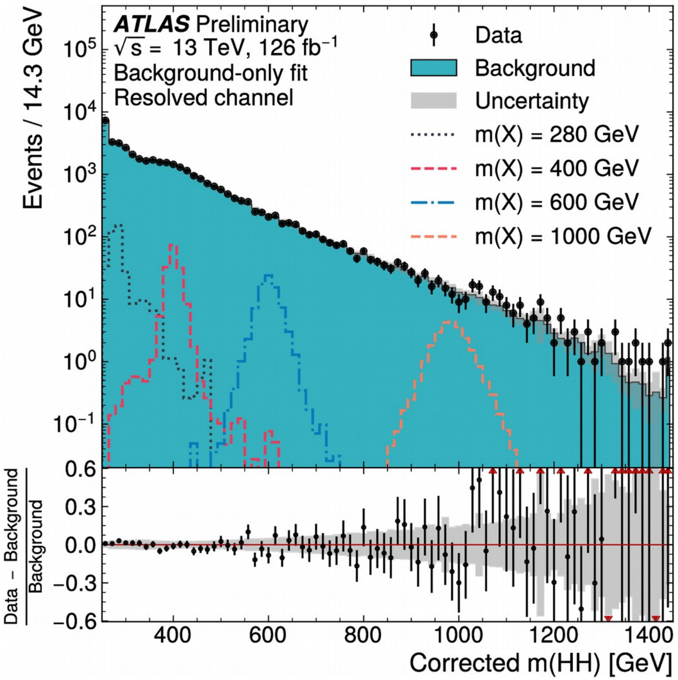
Center SR on Higgs mass peak in m_{H1}-m_{H2} plane.

- Jet pairs for the resolved channel are chosen by a boosted decision tree

Estimate background from data with fewer b-tags.

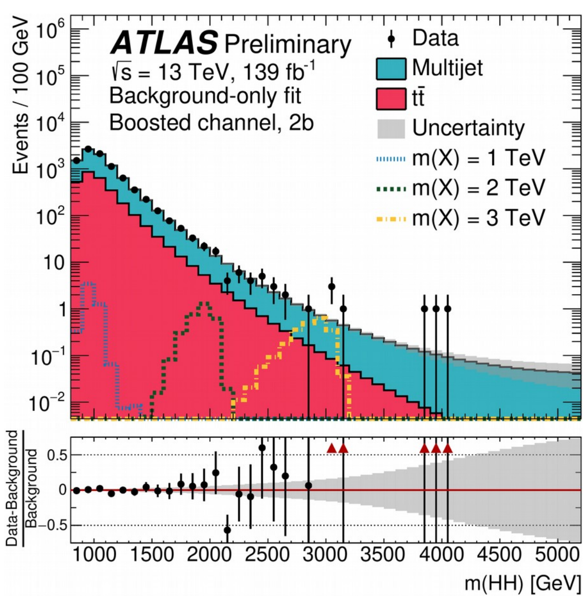
- Reweight low-tag data to replicate high-tag kinematics.
- Use control region in m_{H1}-m_{H2} plane to derive this reweighting.
- Validation region used to check background estimate and derive systematics.

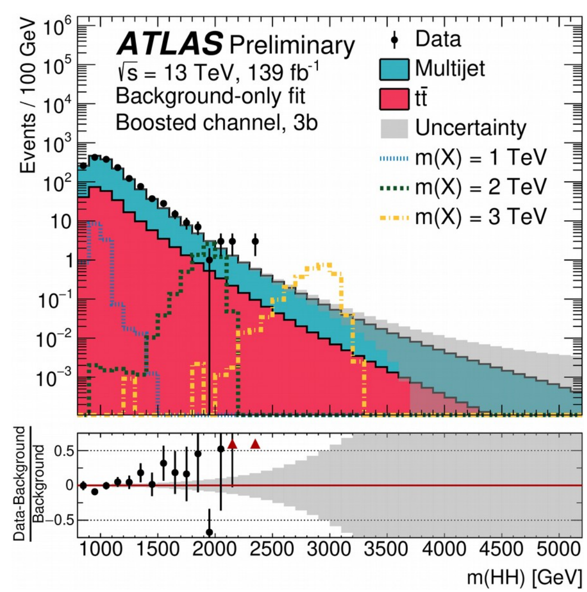
HH → bbbb: Results

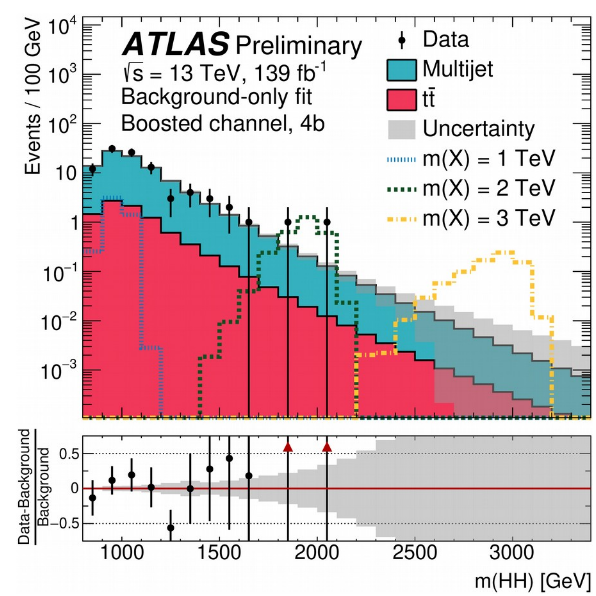


No statistically significant excess anywhere.

- Biggest deviation from background prediction is at 1100 GeV
  - Global significance is 1.0σ (1.2σ) for spin-0 (spin-2) signal model.



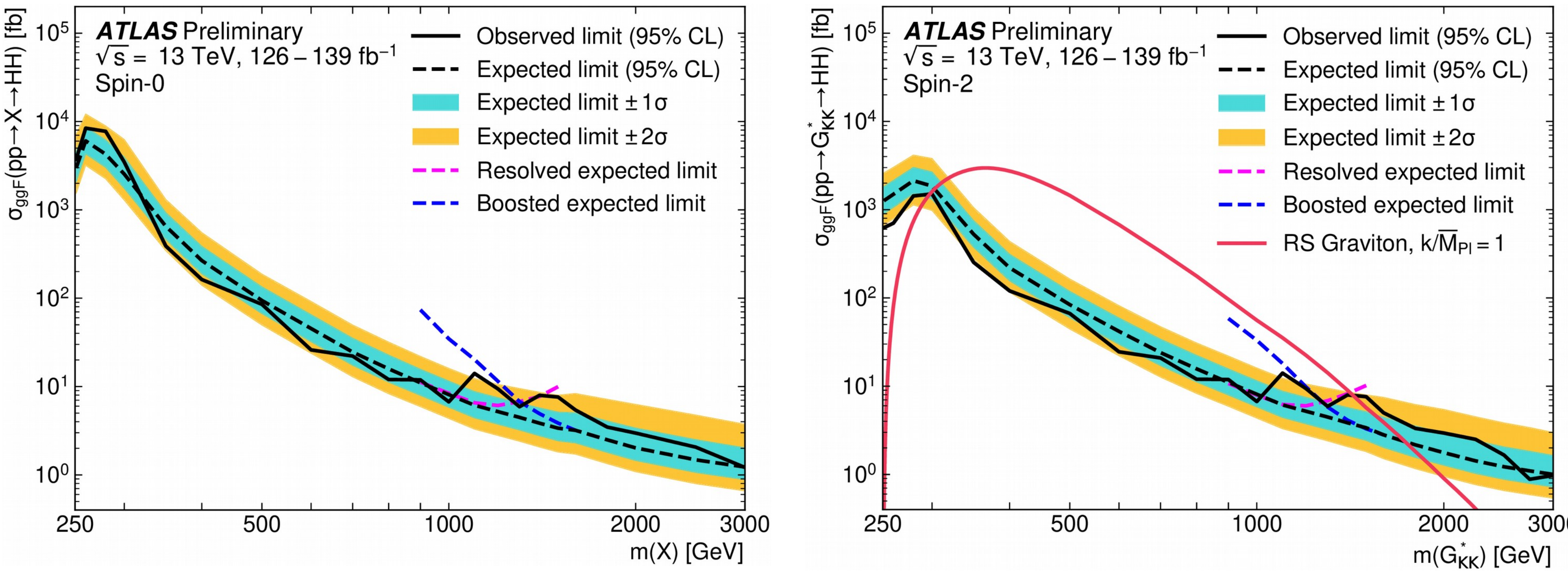




HH → bbbb: Results

Set upper limits on cross section for resonant HH production

- Spin 0 signal model: Generic narrow resonance produced in ggF.
- Spin 2 signal model: Randall-Sundrum graviton with $k/M_{Pl} = 1$
    - Wider than detector resolution (3-13% of mass, depending on m_G).

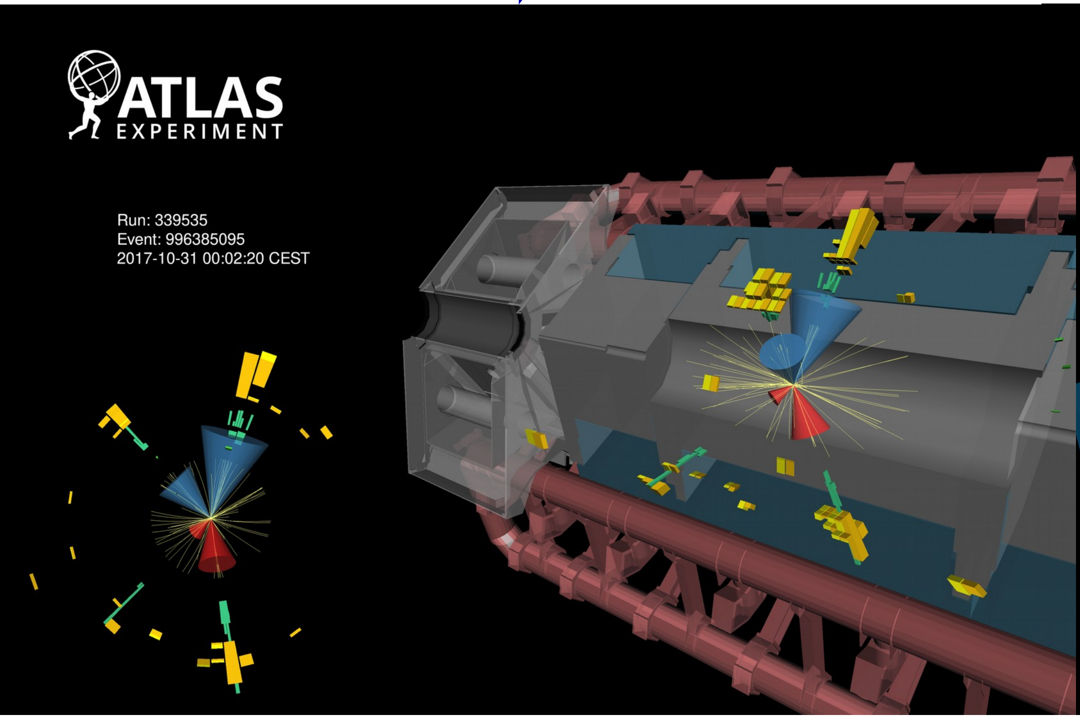


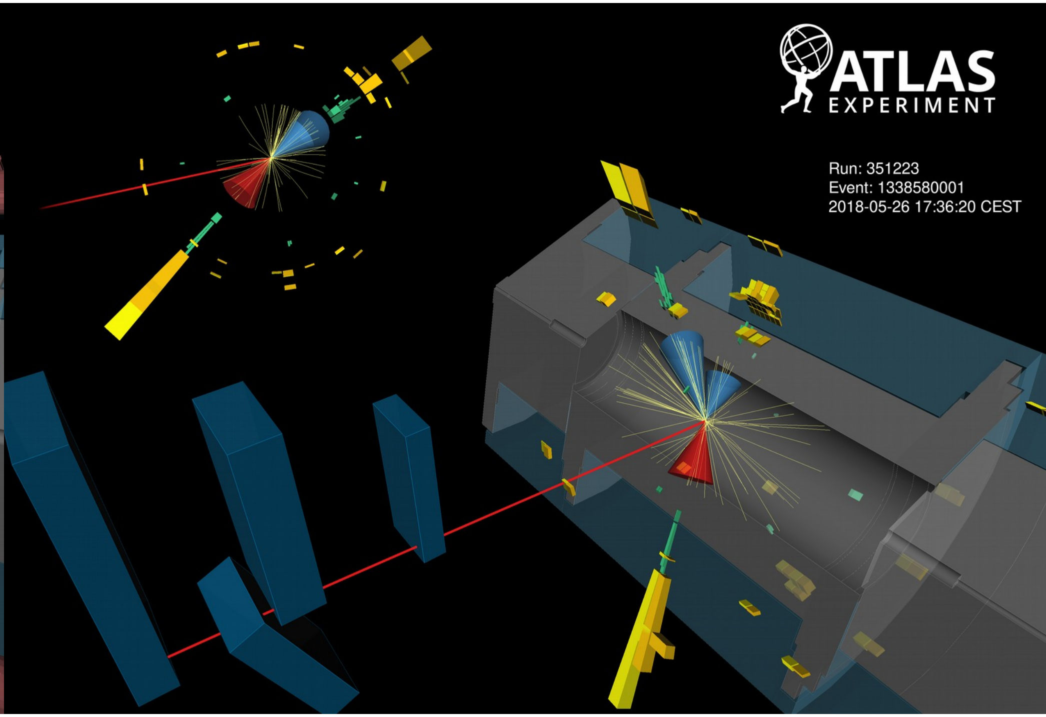
Statistically limited. Background extrapolation uncertainties also relevant to a lesser extent.

HH → bbττ

bbττ has a lower branching ratio than bbbb, but also lower backgrounds.

- Use both fully hadronic and semileptonic decay channels.





= b-jet

= hadronic τ

= muon

HH → bbττ

Select events and classify into 4 categories

$\tau_{had}\tau_{had}$ SR
$\tau_{lep}\tau_{had}$ SR: single lepton trigger
$\tau_{lep}\tau_{had}$ SR: lepton+τ trigger
Z+heavy flavor CR

Signal-enriched data

Use neural network to construct discriminant in each category from kinematic variables.

Parameterized on m_X.

Fit m_{ll} spectrum to constrain Z+heavy flavor background

MC for true τ background estimation

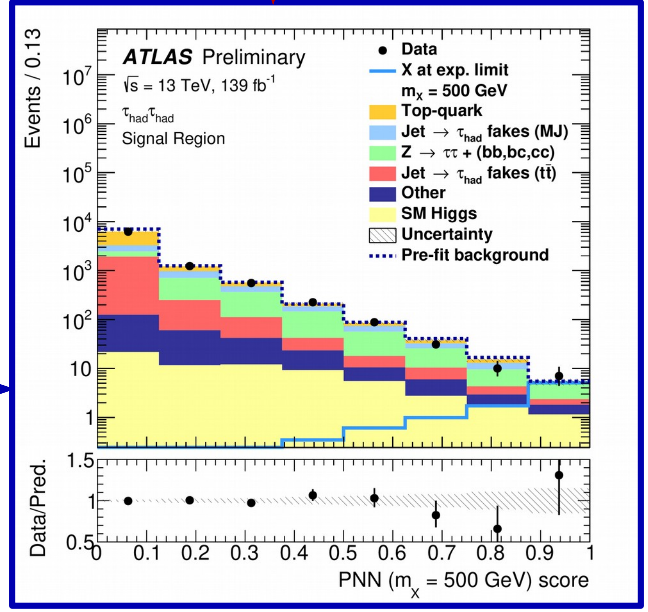
Z + heavy flavor
Top pair production
Other small backgrounds

Floating normalization

Data-driven fake τ background estimation

Multijet
Top pair production

Background estimate

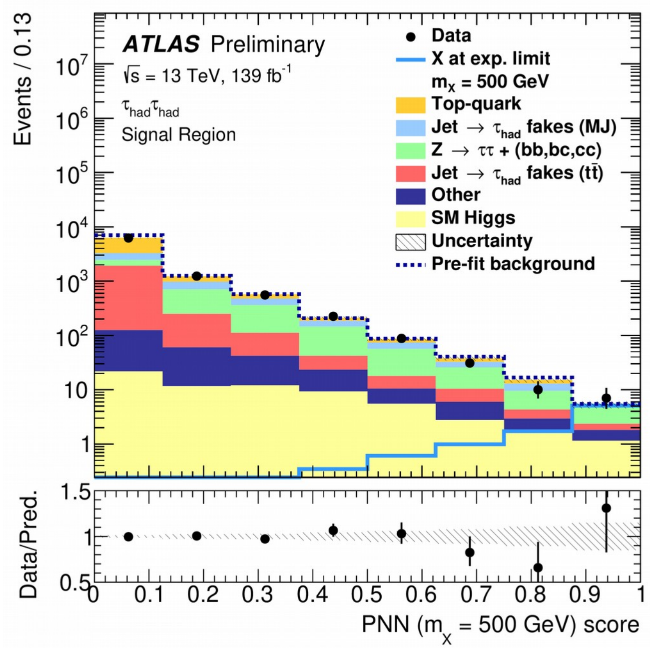


HH → bbττ: Results

These plots show a representative example: a 500 GeV signal

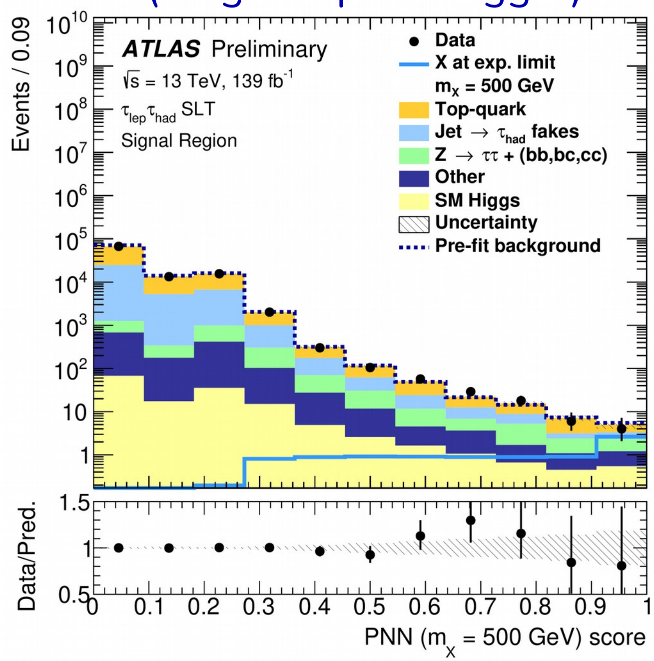
- In this example, m_X is set to 500 GeV for the parameterized NN.
- Each signal mass has different NN performance and therefore a different background shape.

$\tau_{had}\tau_{had}$ category



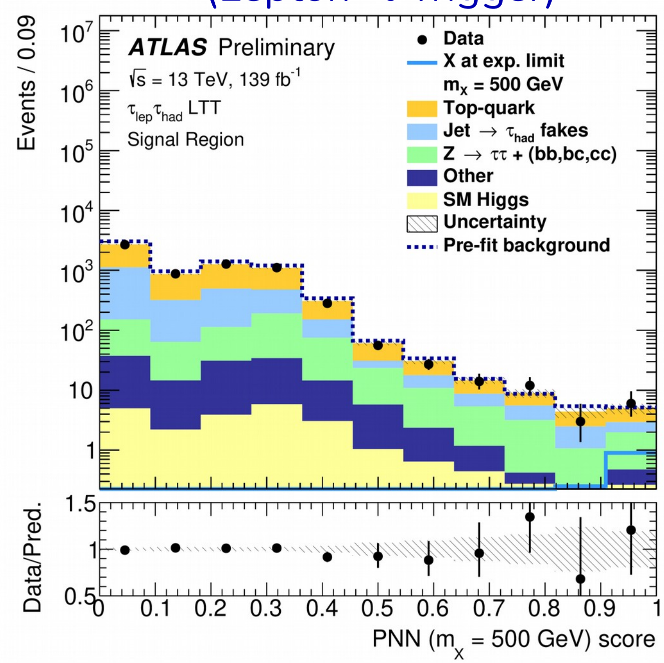
$\tau_{lep}\tau_{had}$ category

(Single Lepton Trigger)



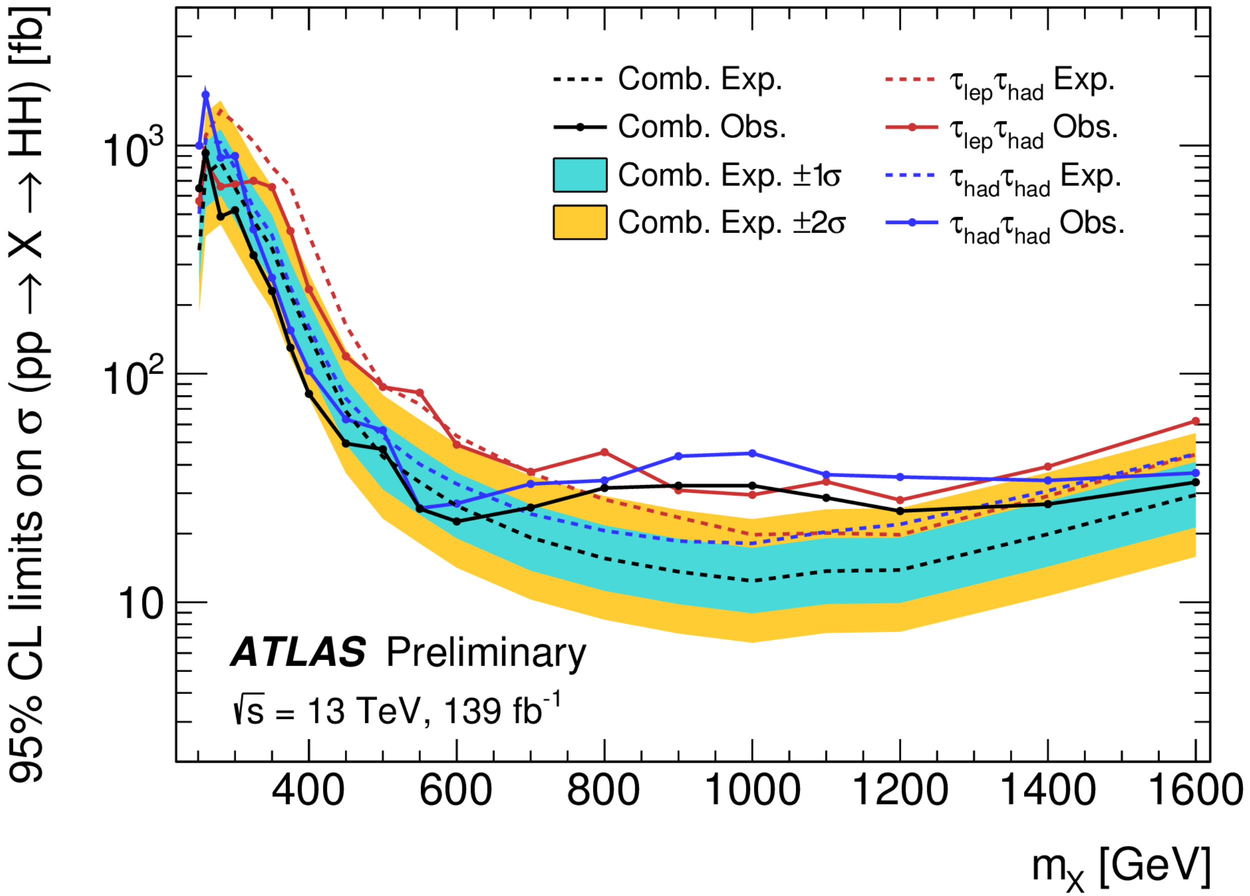
$\tau_{lep}\tau_{had}$ category

(Lepton+τ Trigger)



HH → bbττ: Results

Set upper limits on HH production cross section via a narrow spin-0 resonance

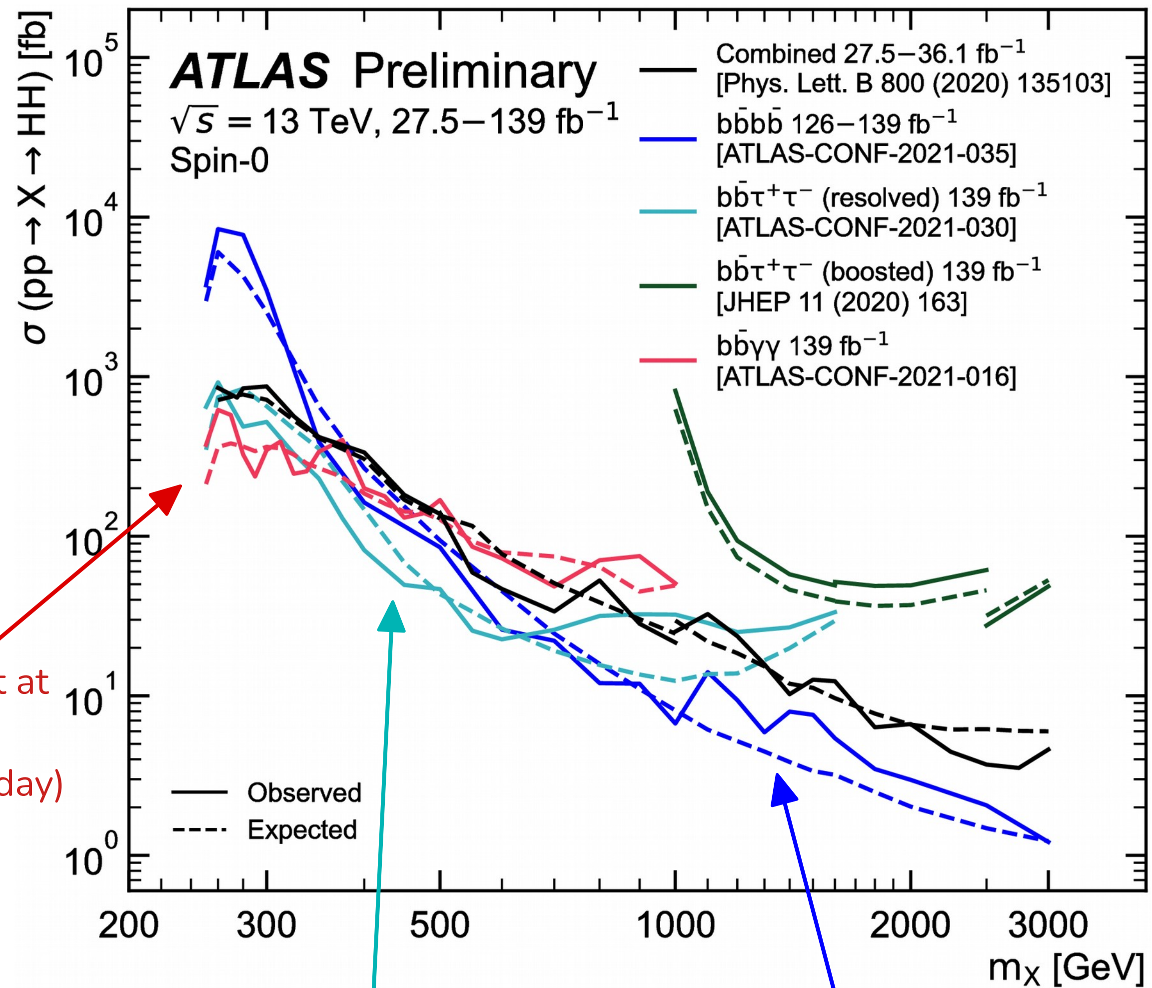


Broad excess in the 700-1200 GeV range.

– Most significant signal hypothesis is 1000 GeV: 2.0σ global

HH: Summary of current limits

Assumptions for this plot: Resonance is narrow, spin-0, and produced in ggF.



bbγγ strongest at low mass (not featured today)

bbττ strongest at medium mass

bbbb strongest at high mass

Factor ~5 improvement over previous results at high mass!

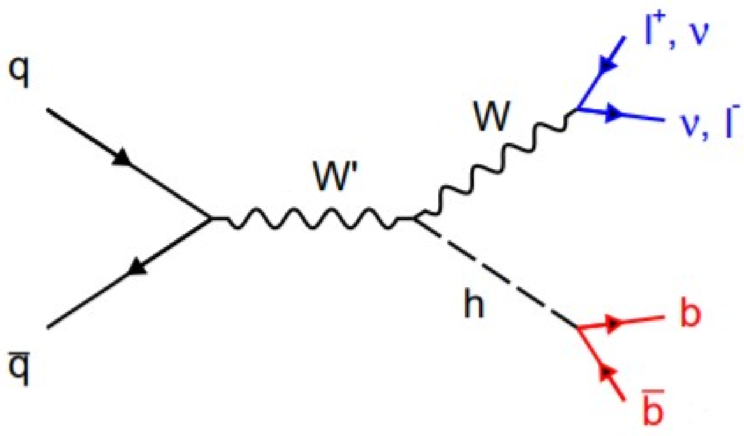
Increased dataset accounts for 2x.

The rest is due to improved methods, especially **VR track jets** for b-tagging**.**

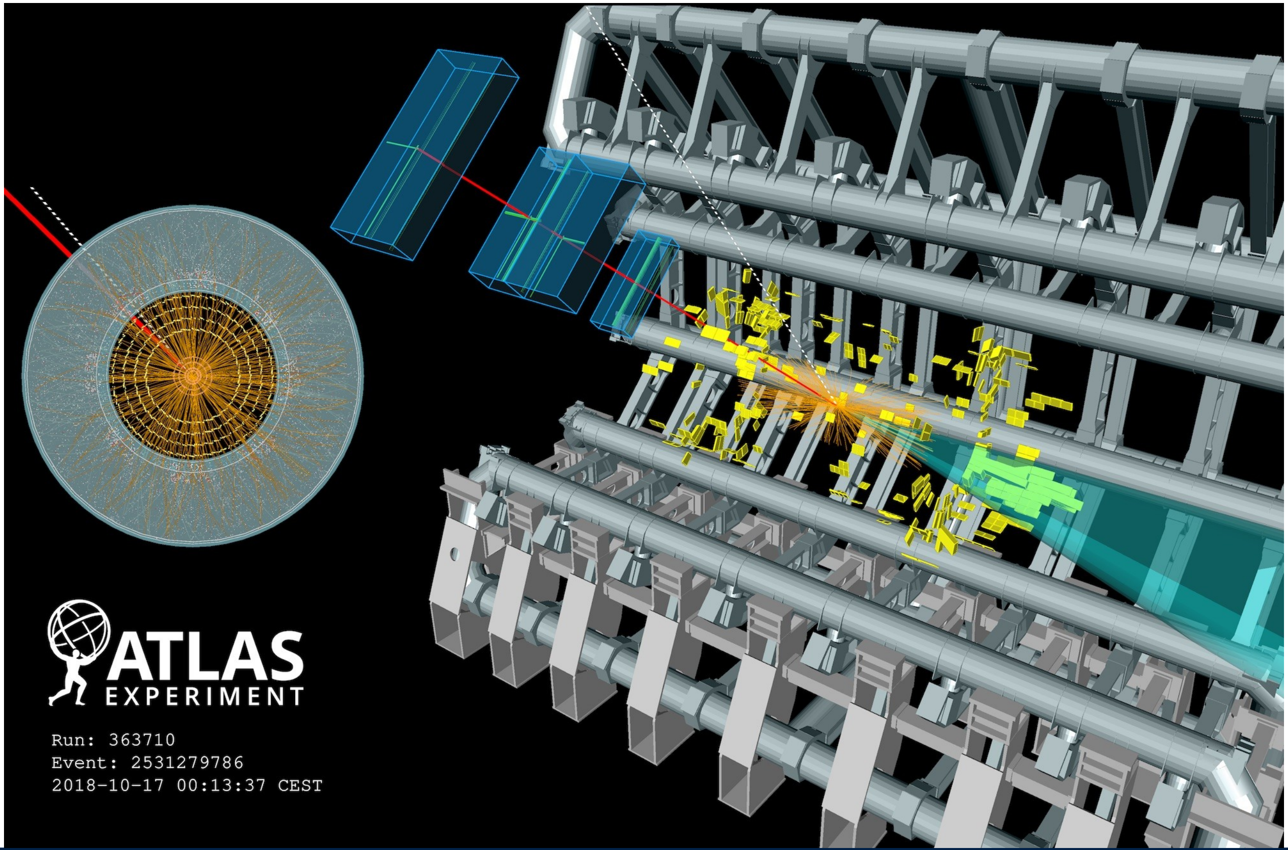
WH → lνbb

Search for WH → lνbb decays in both resolved and merged topologies

- Simultaneous fit of 4 categories: (resolved, merged) x (1-tag, 2-tag)
- Use variable radius track jets for the merged to extend sensitivity at high mass



An event from the merged 1 b-tag signal region



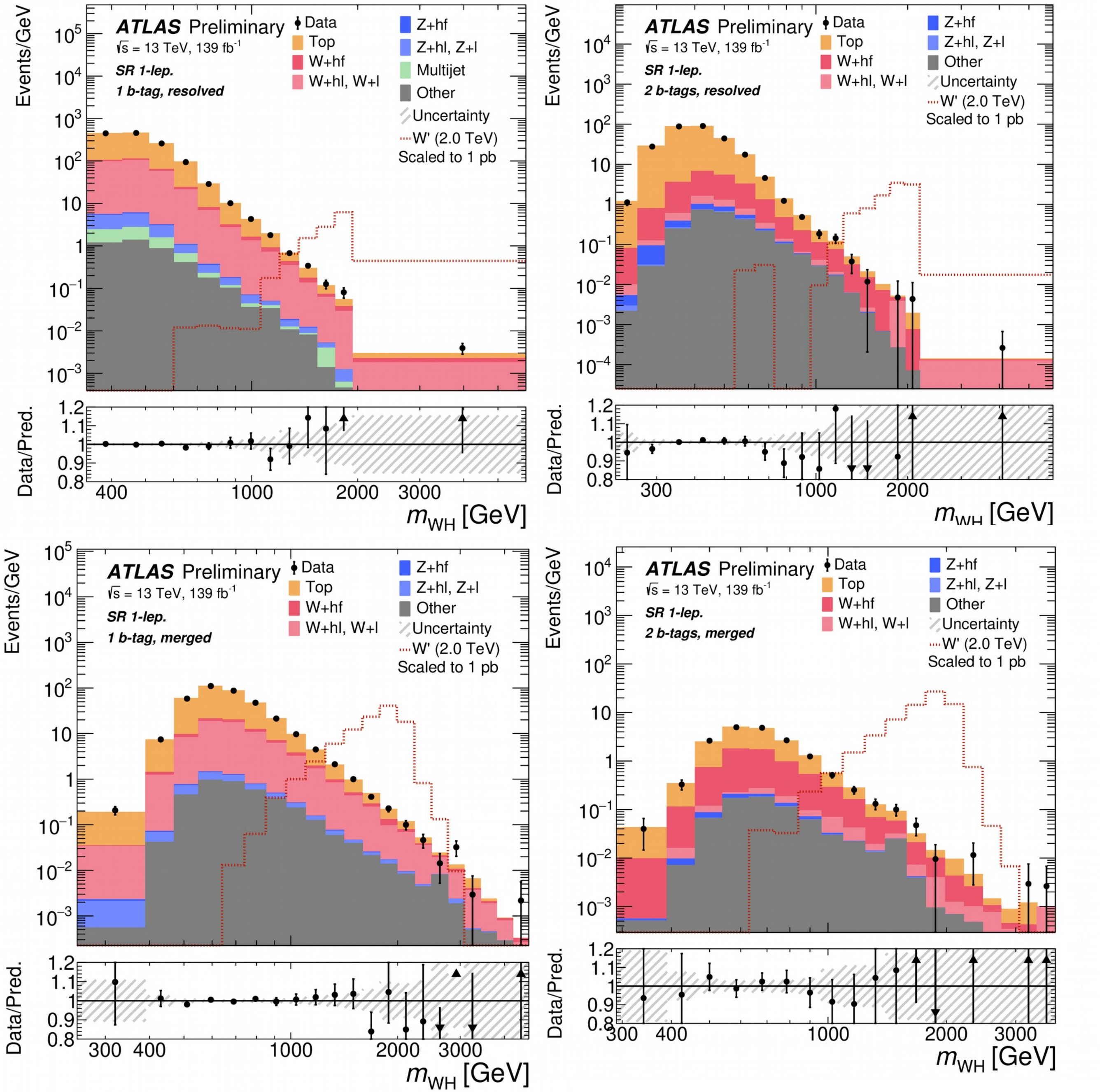
WH → lνbb

Search for bumps in WH mass spectrum

- Estimate neutrino momentum z component by constraining lν system to the W pole mass

Background estimate:

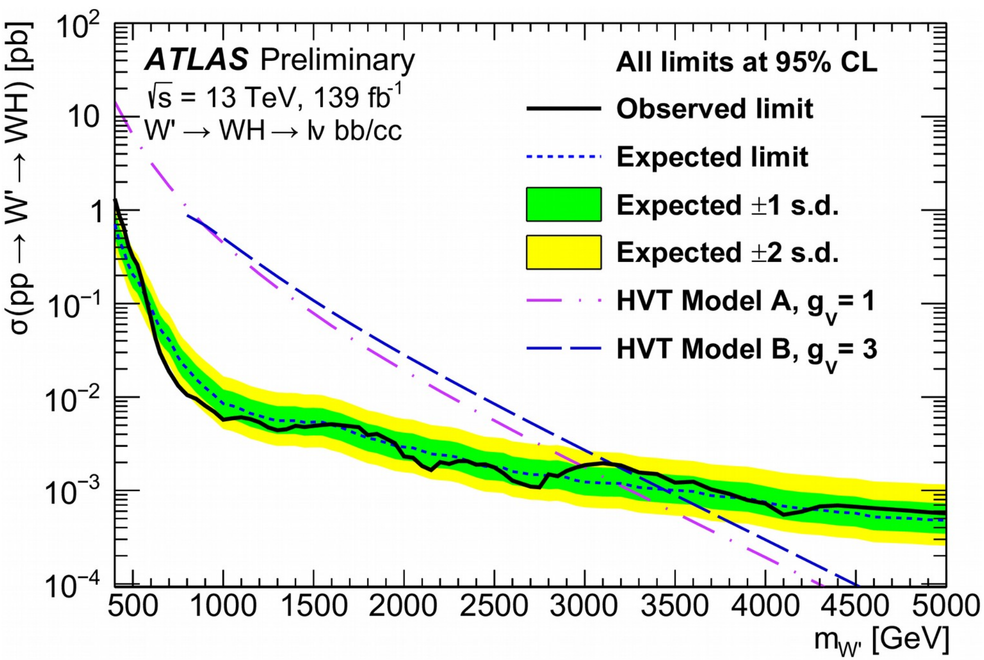
- Top, W + jets
  MC-based: constrain normalization using m_H sideband
- Multijet
  Data-driven: invert lepton isolation to define control region
- Others: small, use MC

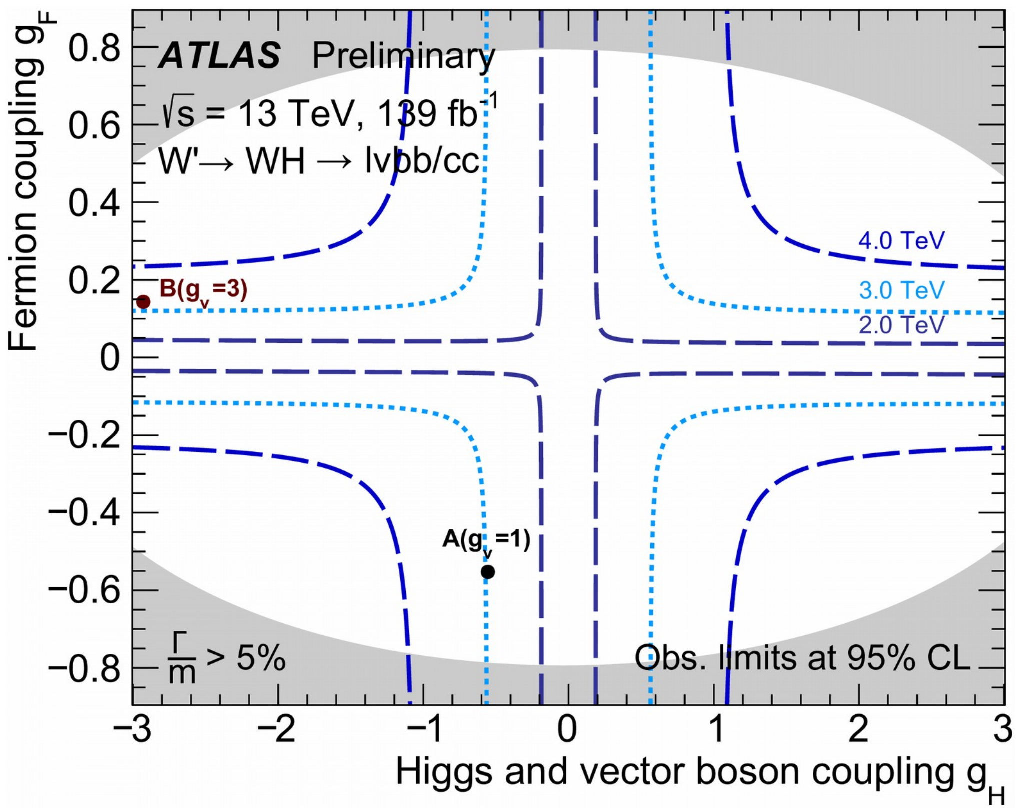


WH → lνbb: Results

Set upper limits on cross section based on narrow spin-1 resonance

- Heavy Vector Triplet model is used as benchmark
  - New $SU(2)_L$ vector field added to SM, minimal coupling structure.
- Limits also interpreted in terms of couplings for this model.





Sensitivity is limited by statistics over most of the mass range.

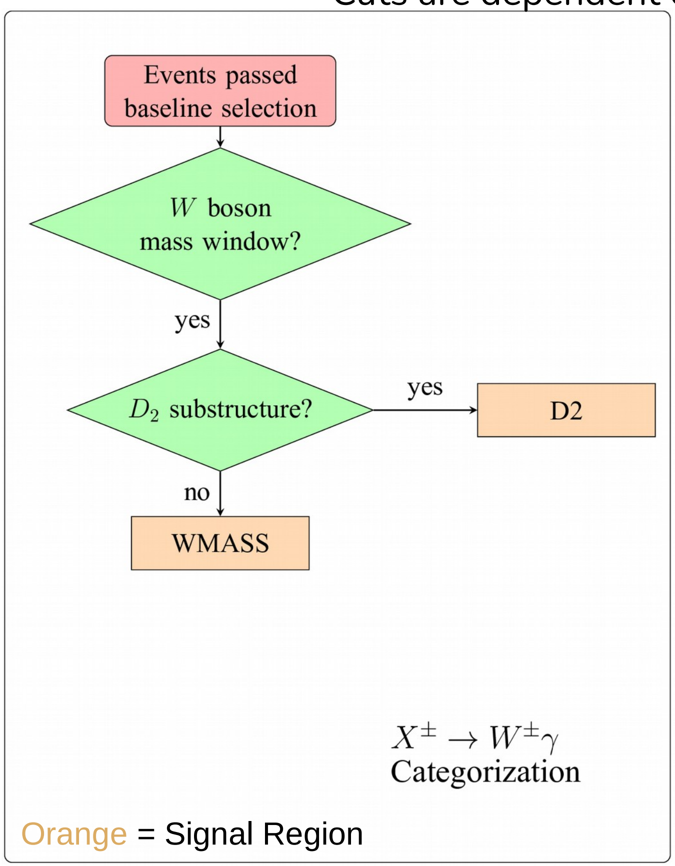
At the lowest masses, modeling uncertainties on the background are dominant.

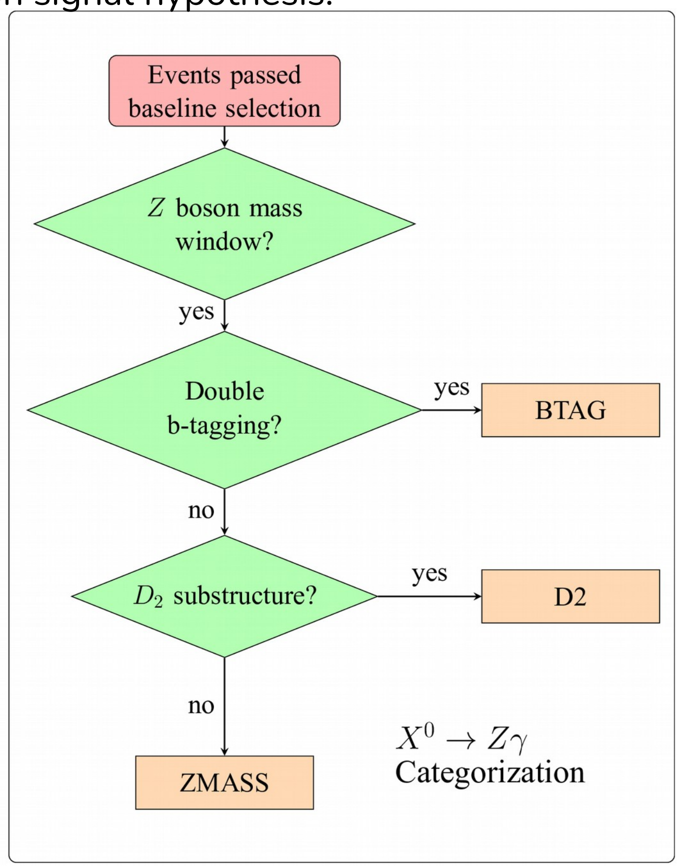
Vγ (boosted hadronic decays)

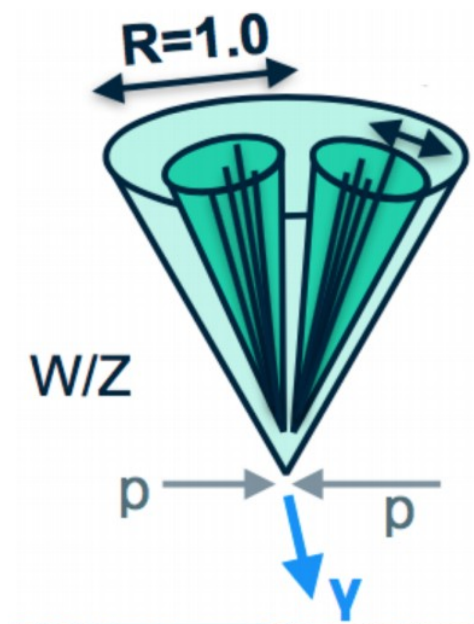
This search focuses on merged topologies from boosted W/Z.

- Identify 2-prong substructure using energy correlation ratios* (D_2).
- Variable radius track jets for Z→bb identification

Split events into orthogonal signal regions.
Cuts are dependent on signal hypothesis.





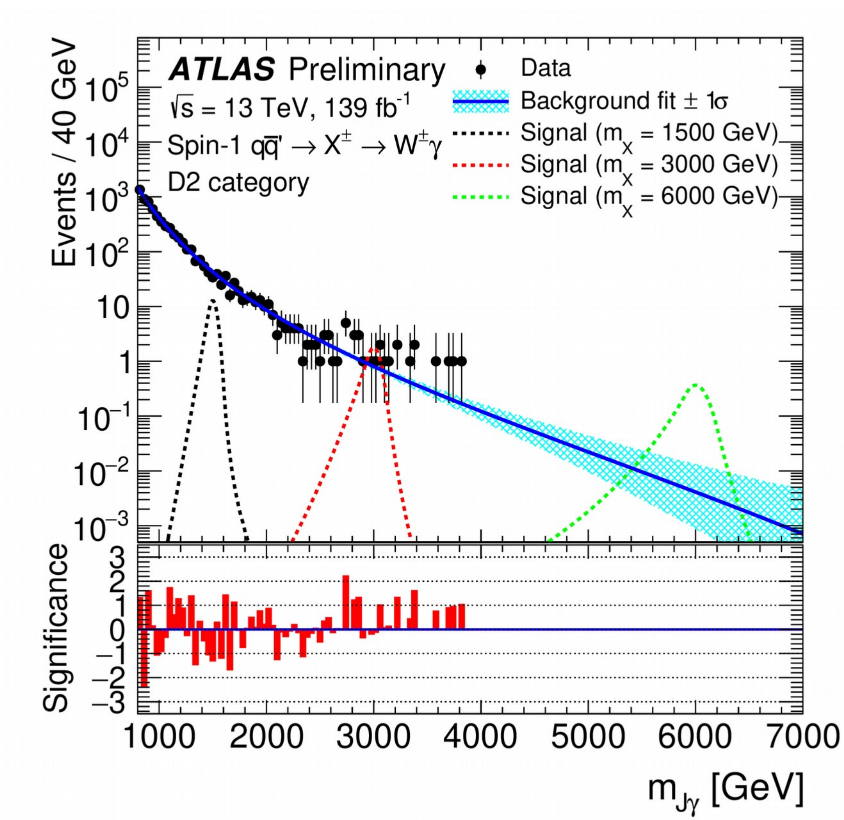


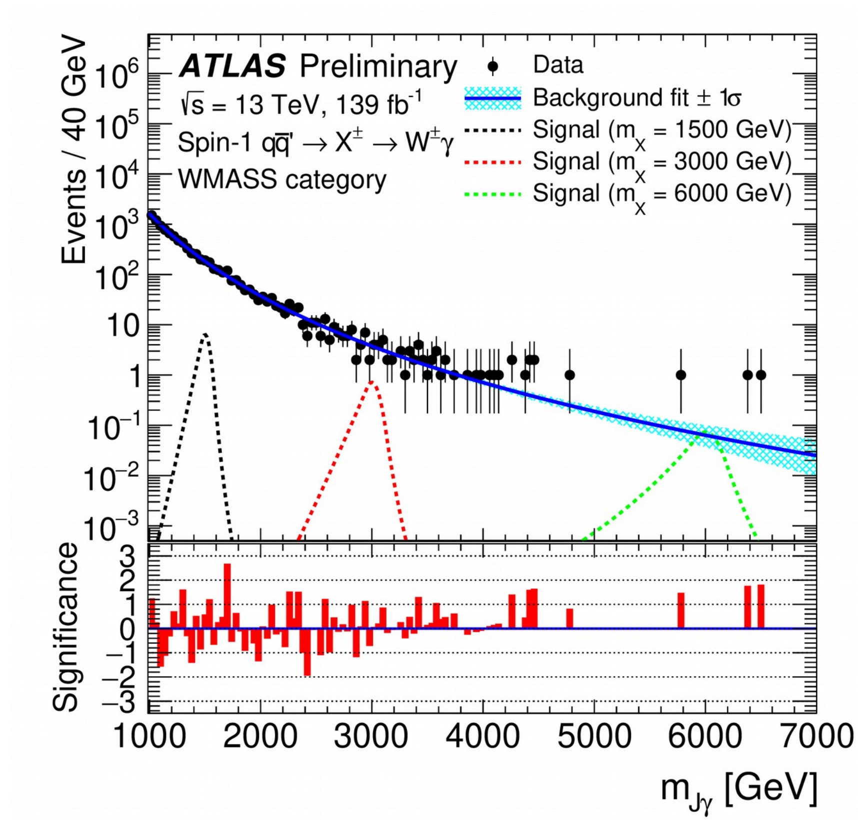
* More info in:
JHEP 06 (2013) 108
JHEP 12 (2014) 009
Eur. Phys. J. C 80 (2020) 1165

Vγ (boosted hadronic decays)

Unbinned likelihood fit of a parametric function to data in each region

- Background modeled as $\mathcal{B}(m_{J\gamma};\boldsymbol{p}) = (1-x)^{p_1} x^{p_2+p_3\log(x)},\ x = m_{J\gamma}/\sqrt{s}$
- “Spurious signal” accounted for with systematics.
- Signal modeled with double-sided Crystal Ball function.

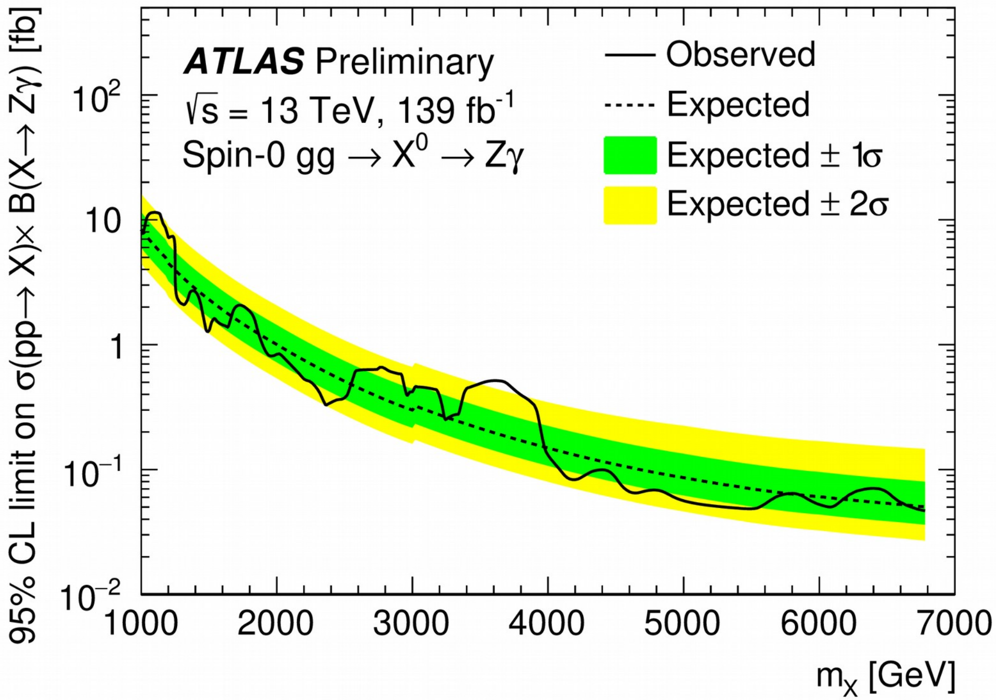


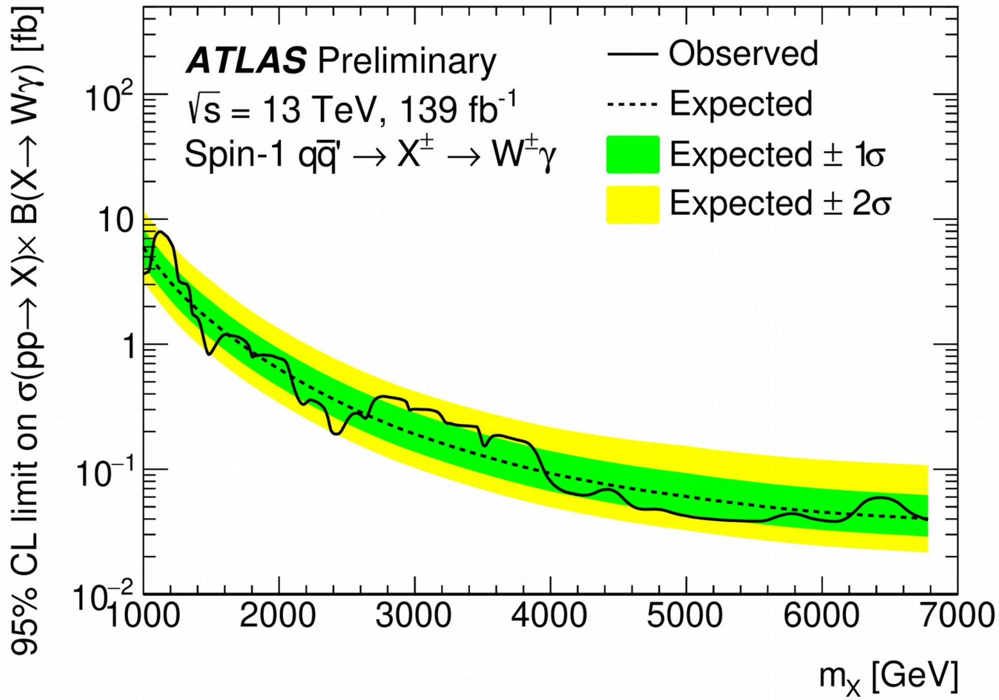


Vγ (boosted hadronic decays): Results

No significant discrepancy from SM observed.

- Set cross section limits over a wide mass range
- Spin 0, 1, and 2 signal models considered.



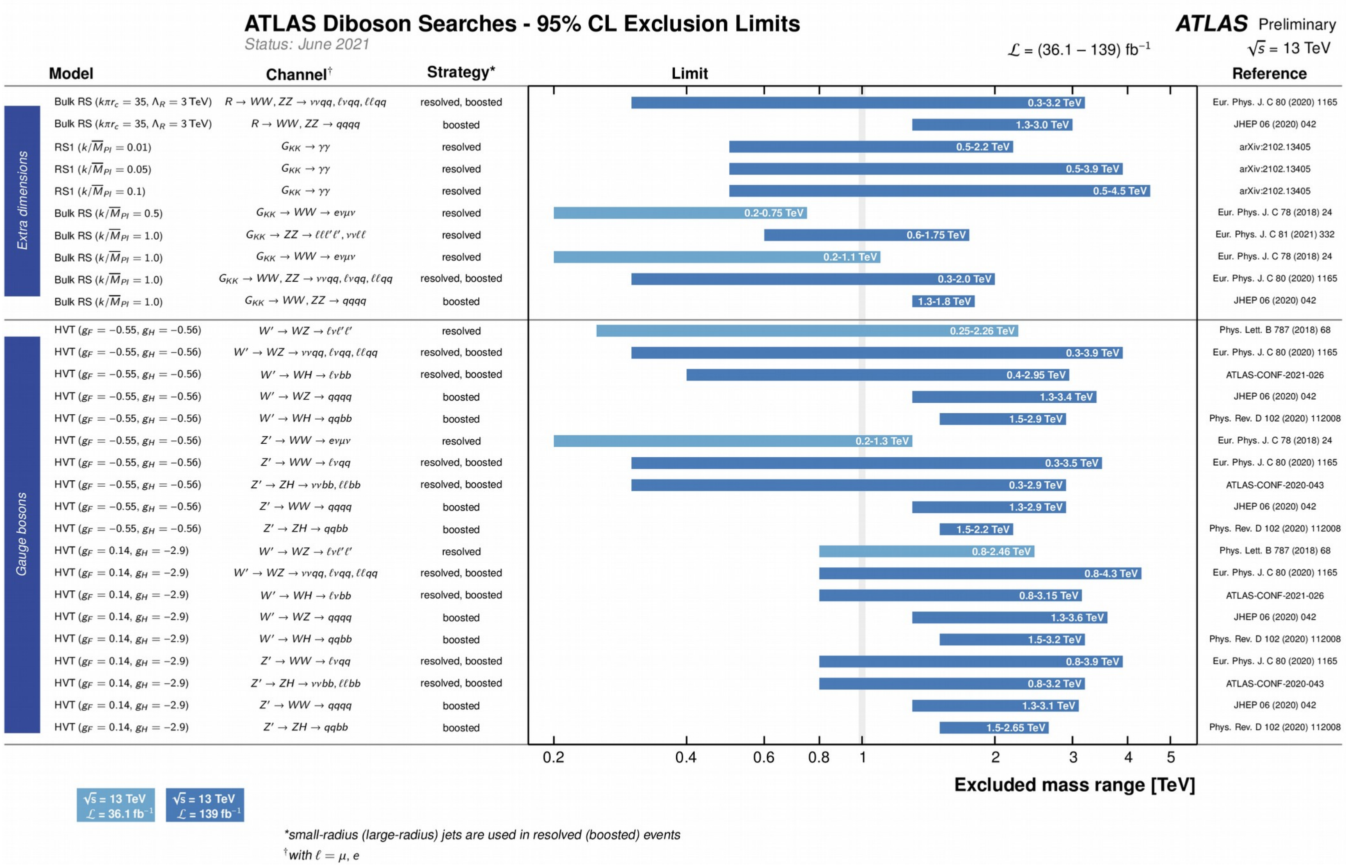


Sensitivity is limited by statistics. Jet calibration uncertainties also relevant in some regions.

Summary

ATLAS continues to probe a wide range of diboson final states.

- All data consistent with the SM so far.
- Developments in reconstruction techniques driving improved sensitivity.



[Link to legible version and other summary plots]

Backup

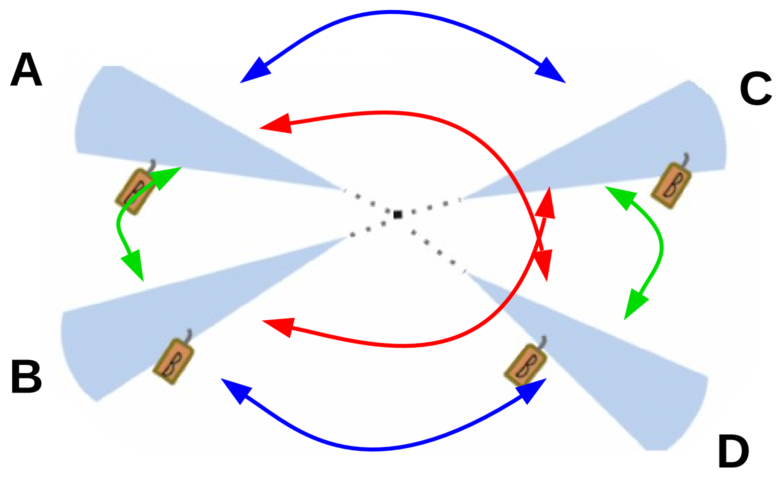
Final State Coverage

	W	Z	H	γ
W	Eur. Phys. J. C 80 (2020) 1165		ATLAS-CONF-2021-026 Phys Rev D 102 (2020) 112008	ATLAS-CONF-2021-041
Z			ATLAS-CONF-2020-043 Phys Rev D 102 (2020) 112008	
H			ATLAS-CONF-2021-016 ATLAS-CONF-2021-030 ATLAS-CONF-2021-035	Phys. Rev. Lett. 125 (2020) 251802
γ				arXiv:2102.13405 (submitted to PLB)

(Symmetric)

Only searches using the full Run 2 dataset are shown.

HH → bbbb: Pairing resolved jets



<u>3 possible pairings</u>

(AB) (CD)

(AC) (BD)

(AD) (BC)

Which jets are paired to form the Higgses?

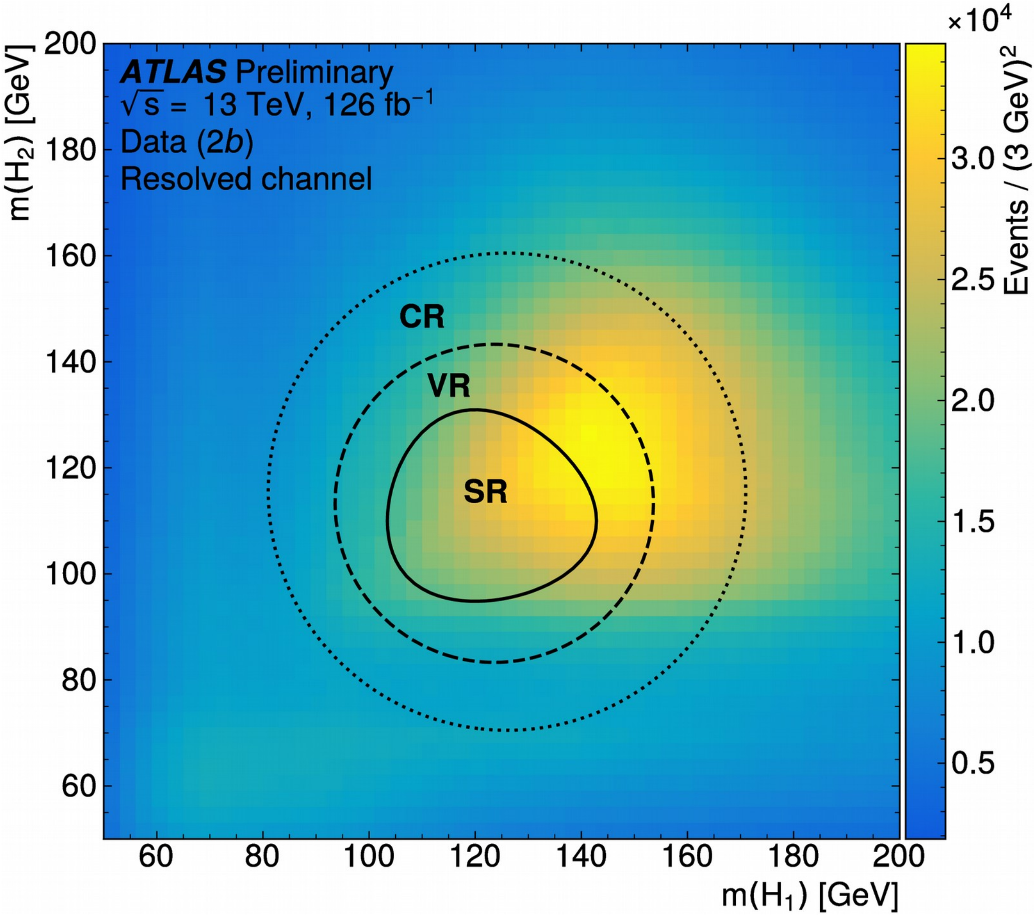
Naive solution: Pick the pair that gives Higgses closest to 125 GeV

- This makes the background also peak there!

In practice, we use machine learning here.

- BDT takes in kinematic information and decides how “signal-like” each pairing is.
- Trained on signal MC to discriminate right pairings from wrong ones.

HH → bbbb: Resolved Region Definitions



SR

$$X_{HH} = \sqrt{\left(\frac{m(H_1) - 120\,\text{GeV}}{0.1 \times m(H_1)}\right)^2 + \left(\frac{m(H_2) - 110\,\text{GeV}}{0.1 \times m(H_2)}\right)^2}. < 1.6$$

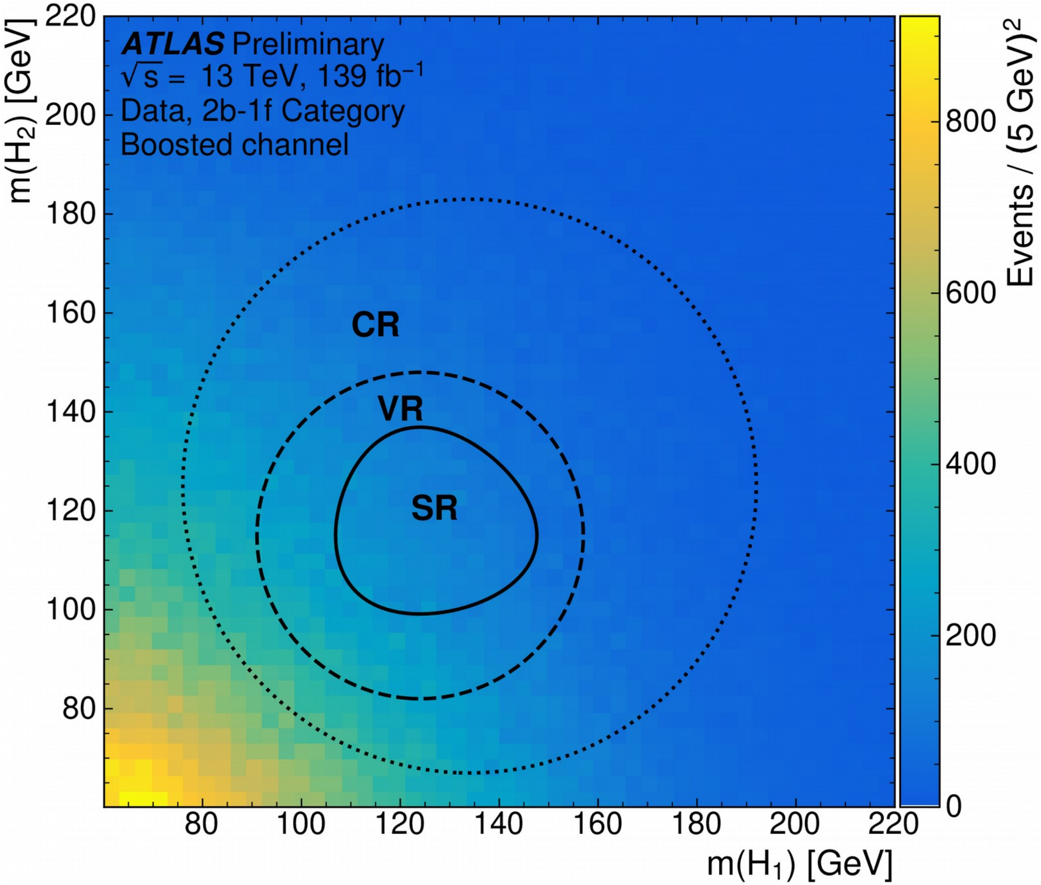
VR

$$R_{HH}^{\text{VR}} \equiv \sqrt{\left(m(H_1) - 1.03 \times 120\,\text{GeV}\right)^2 + \left(m(H_2) - 1.03 \times 110\,\text{GeV}\right)^2} < 30\,\text{GeV}.$$

CR

$$R_{HH}^{\text{CR}} \equiv \sqrt{\left(m(H_1) - 1.05 \times 120\,\text{GeV}\right)^2 + \left(m(H_2) - 1.05 \times 110\,\text{GeV}\right)^2} < 45\,\text{GeV}.$$

HH → bbbb: Boosted Region Definitions



SR

$$X_{HH} = \sqrt{\left(\frac{m(H_1) - 124\,\text{GeV}}{0.1 \times m(H_1)}\right)^2 + \left(\frac{m(H_2) - 115\,\text{GeV}}{0.1 \times m(H_2)}\right)^2} < 1.6$$

VR

$$R_{HH}^{\text{VR}} \equiv \sqrt{(m(H_1) - 124\,\text{GeV})^2 + (m(H_2) - 115\,\text{GeV})^2} < 33\,\text{GeV}.$$

CR

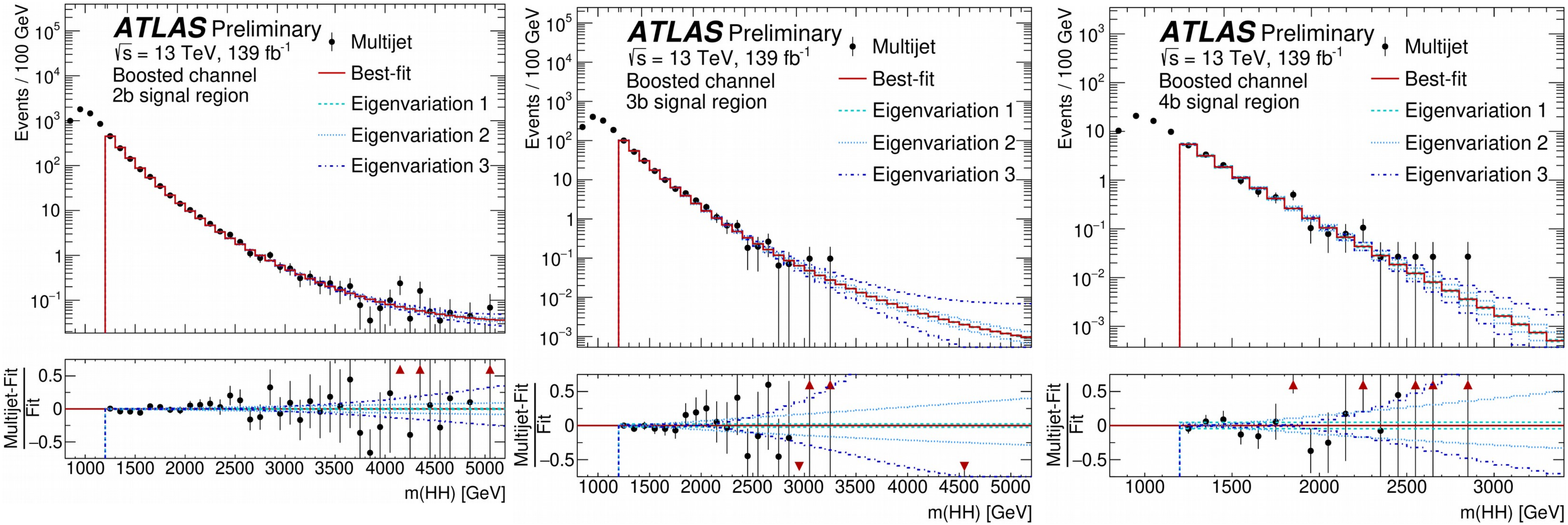
$$R_{HH}^{\text{CR}} \equiv \sqrt{(m(H_1) - 134\,\text{GeV})^2 + (m(H_2) - 125\,\text{GeV})^2} < 58\,\text{GeV}$$

HH → bbbb: Boosted Smoothing Fits

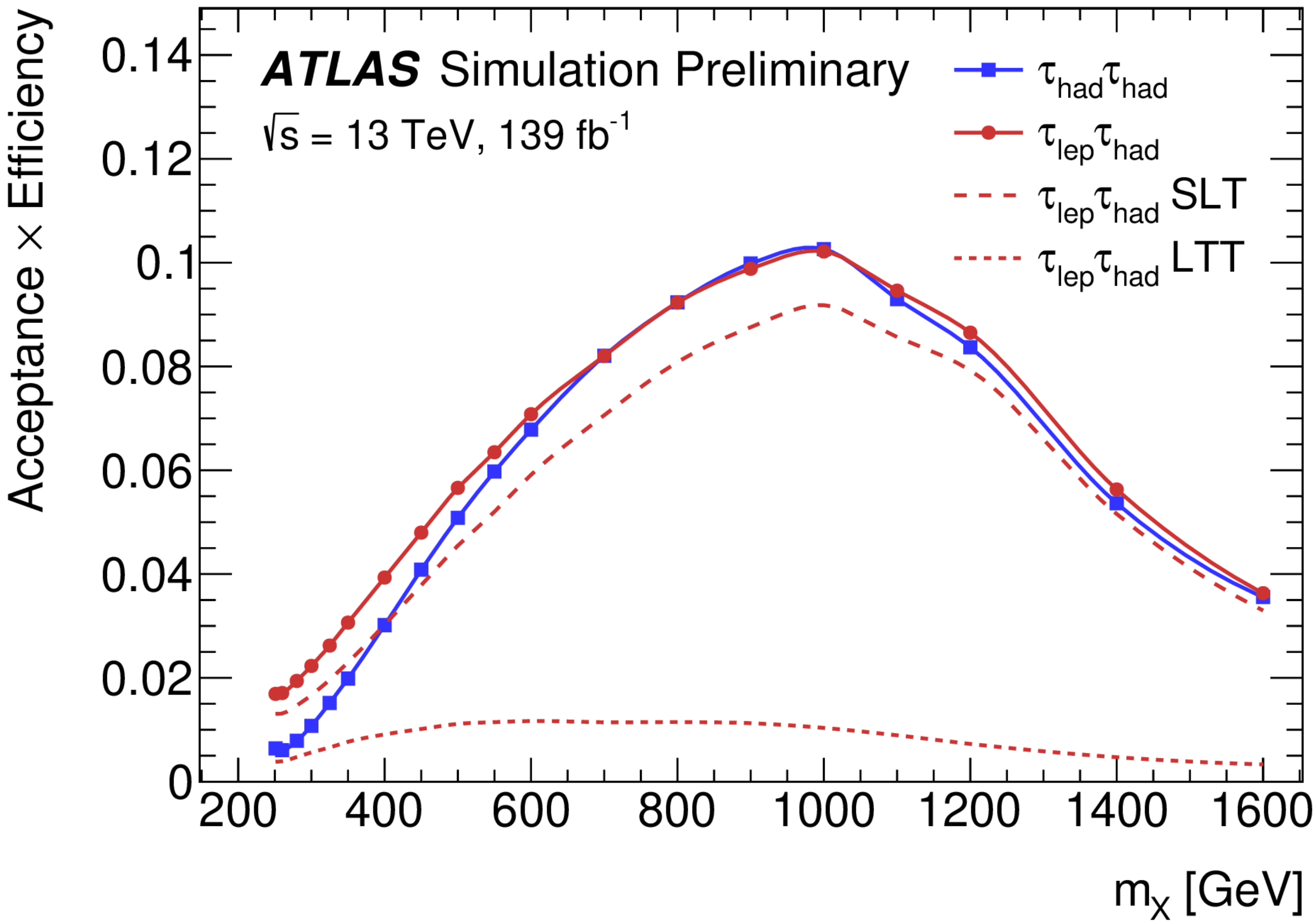
A parametric function is used to smooth the boosted background at high masses:

$$f(x) = \frac{e^{-p_0}}{x^2}(1-x)^{p_1 - p_2 \ln x}$$

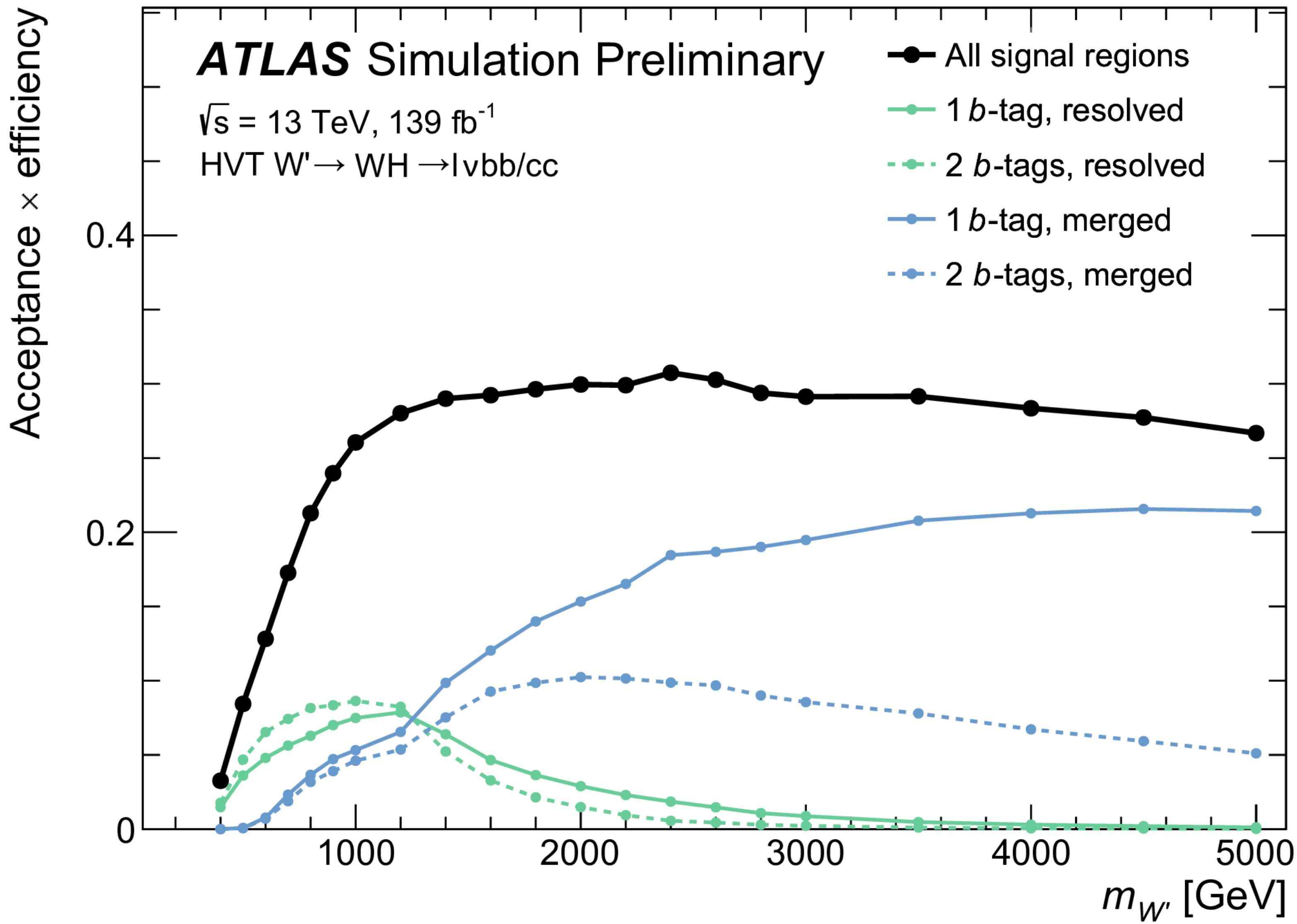
7 alternate functions are used to evaluate dependence on this choice.



HH → bbττ: Signal Acceptance



WH → lνbb: Signal Acceptance



Vγ (boosted): Signal Acceptance