Exploring the Unknown with Higgs boson pairs

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The Plan

Theoretical Background: Why study Higgs pair production?

Experimental Overview: How to approach the problem

Latest results from ATLAS

- Highlight: $HH \rightarrow bbbb$ decay channel

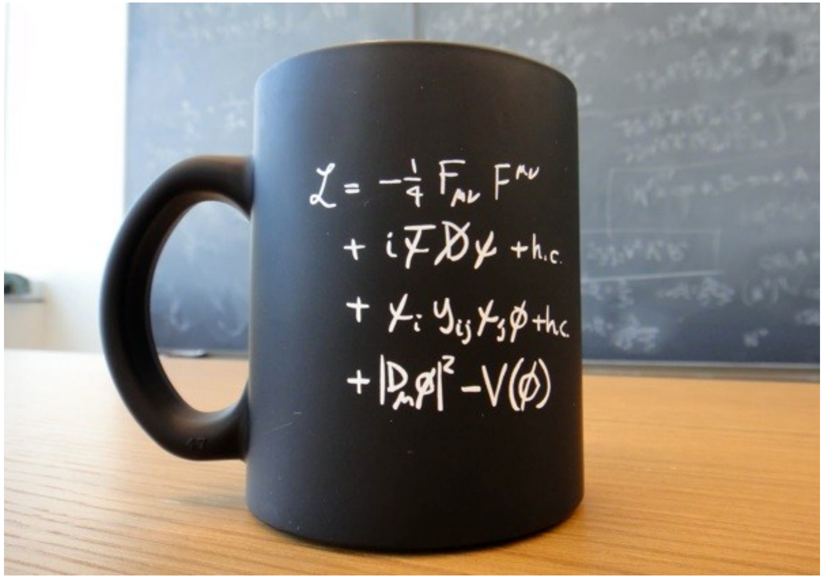
Outlook: HL-LHC and beyond

Our current knowledge

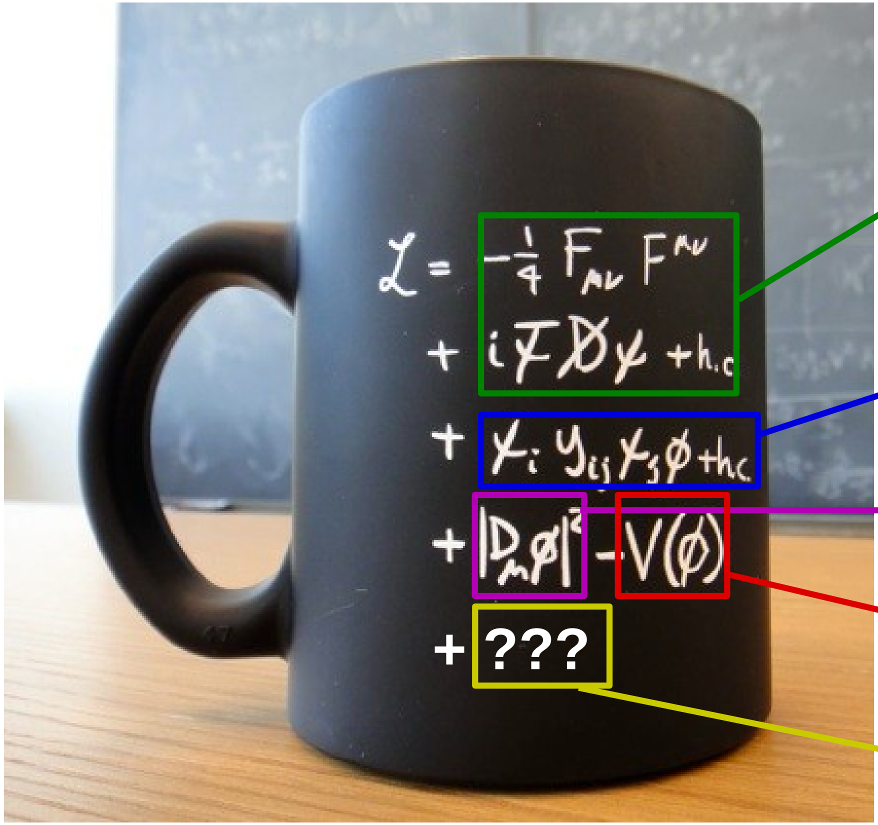
Plenty of reasons to think the SM is incomplete

- Dark matter, antimatter asymmetry, gravity, theoretical “problems” (naturalness), etc…

Let’s start with a zoomed-out look at what we know:



Our current knowledge



Gauge bosons and their interactions with fermions.
Very precisely measured.

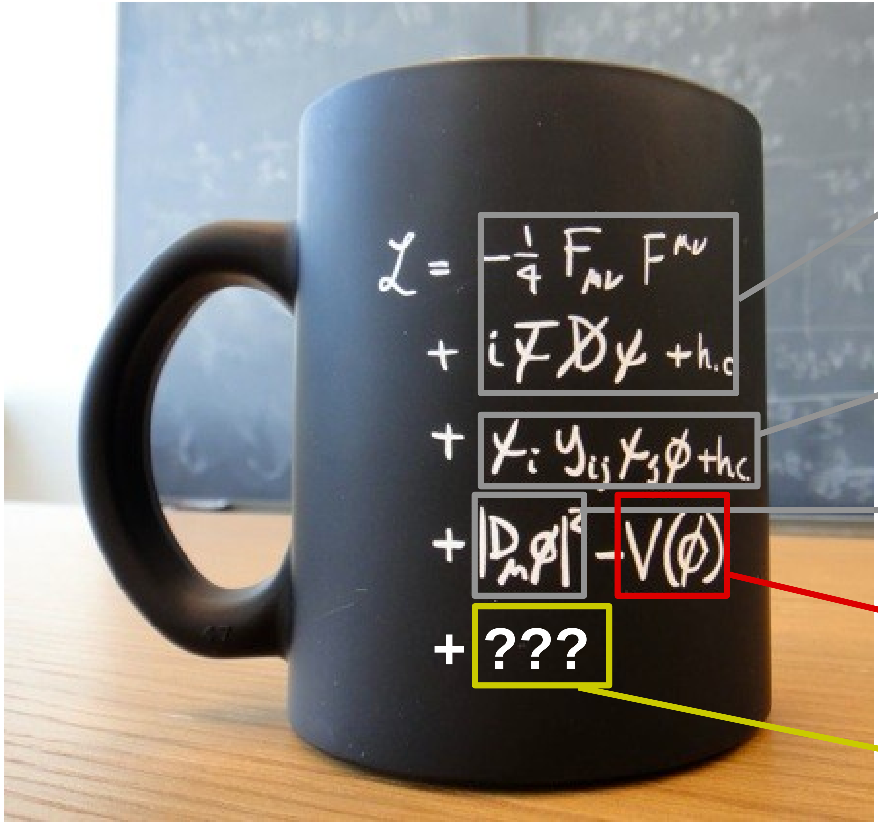
Higgs interactions with fermions.
Fairly well-measured for heavy fermions only.

Higgs electroweak interactions (and propagator).
Precisely measured (mostly).

Higgs potential.
Mostly unexplored!

New fields?

Our current knowledge



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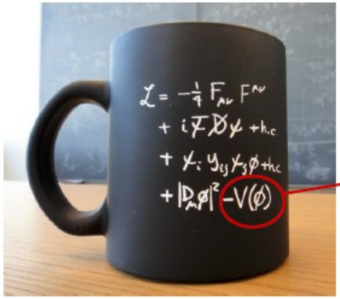
Higgs potential.
Mostly unexplored!

Higgs pair production is a direct probe of both of these!

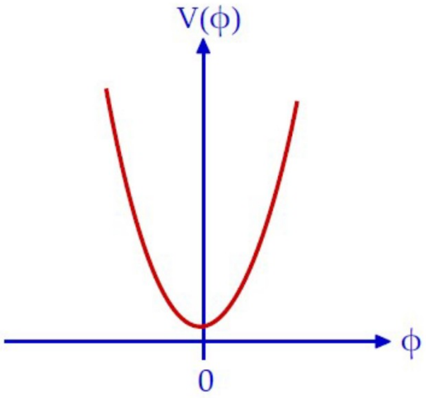
New fields?

The Higgs Potential

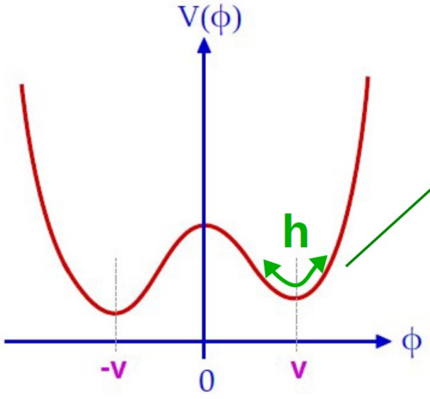


SM predicts the shape of the potential...

$V(\phi) = \mu^2\phi^2 + \lambda\phi^4$ (simplified)



All particles massless

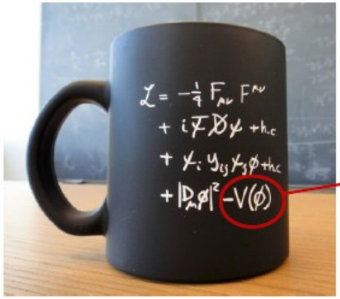


Particle masses proportional to v

Curvature of the minimum corresponds to the Higgs boson mass.

The Higgs Potential

SM predicts the shape of the potential…



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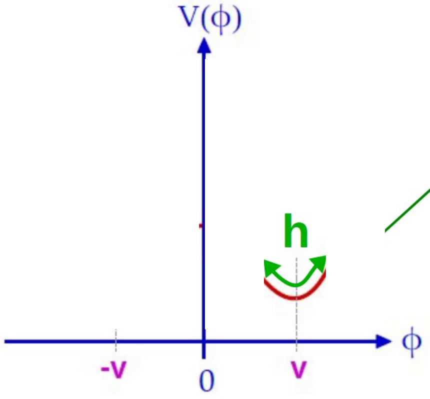


Particle masses proportional to v

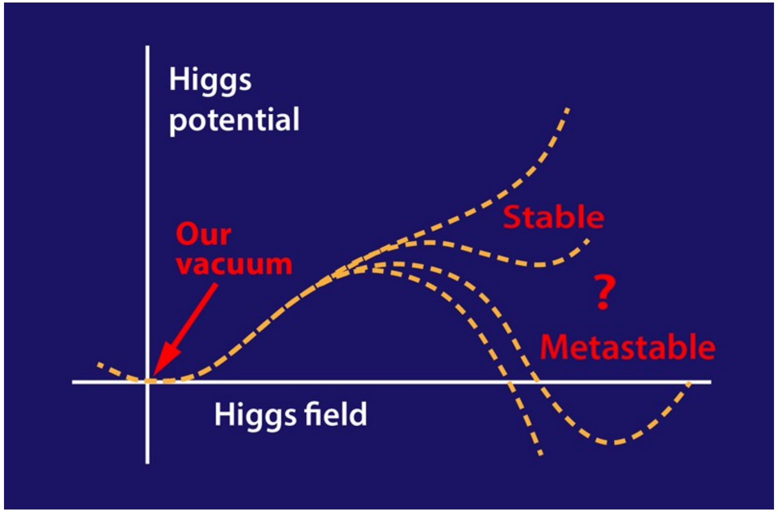
Curvature of the minimum corresponds to the Higgs boson mass.

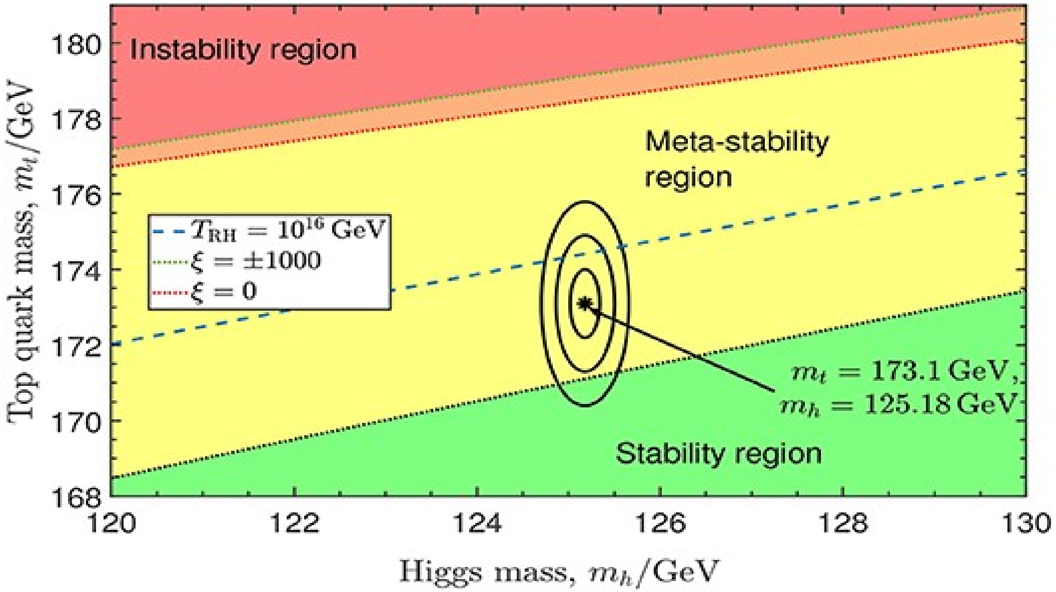
And that's all we've measured of it!
Constraints on the global structure are very loose.

The Higgs Potential

Vacuum stability depends on the Higgs potential!

It's currently not known whether the SM vacuum is stable or metastable. We're close to the edge

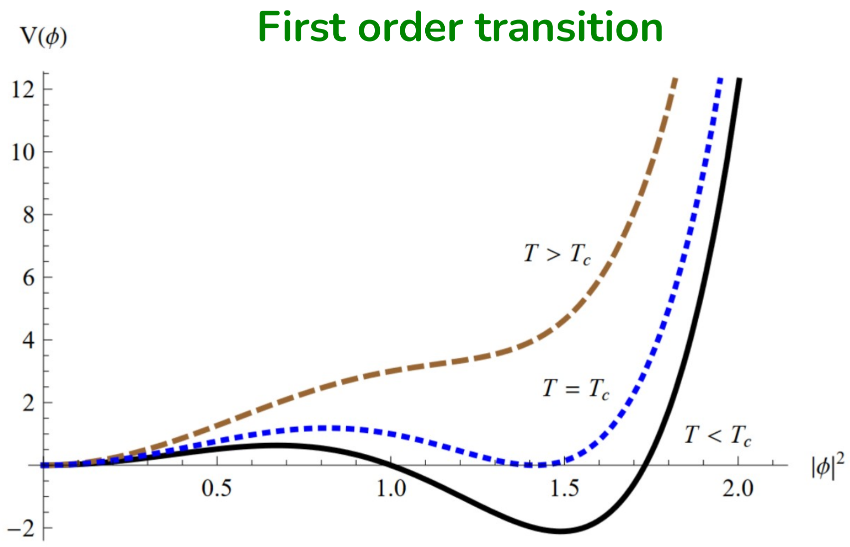




The Electroweak Phase Transition

The Higgs potential also determines the nature of the EW phase transition in the early universe

- At high temperature, **<ϕ> = 0** and baryon number can be violated
- Implications for baryogenesis, which is still poorly understood



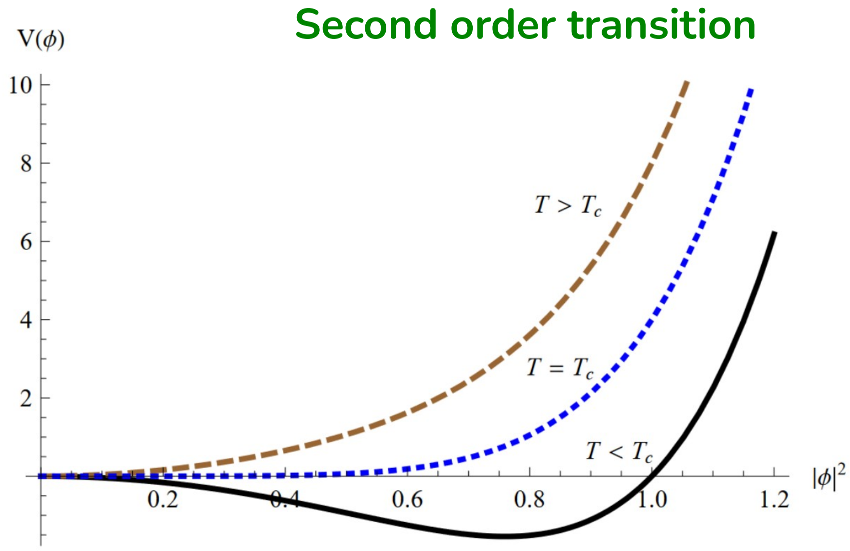
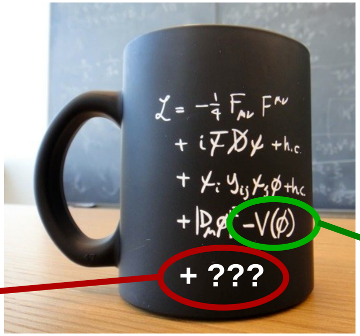


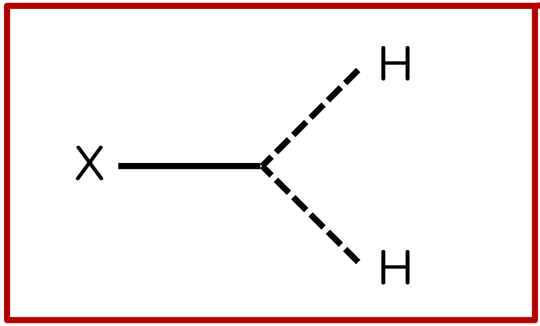
Image: A. Banerjee

Higgs interactions with new fields?

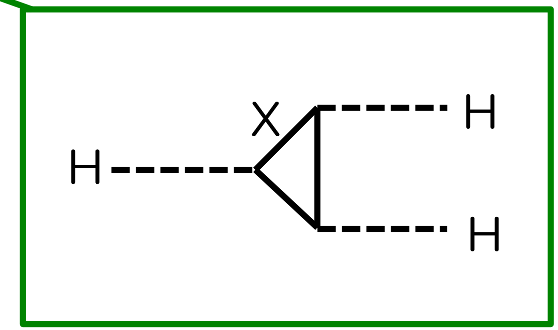
For a BSM theory with a new field X, it's difficult to avoid interactions with H

- Usually only a manually-inserted symmetry will prevent this.
- Example for boson X: $\mathcal{L}_{\text{int}} = g\Phi^{\dagger}\Phi X^{\dagger}X$ (plenty of other structures possible, depending on model)



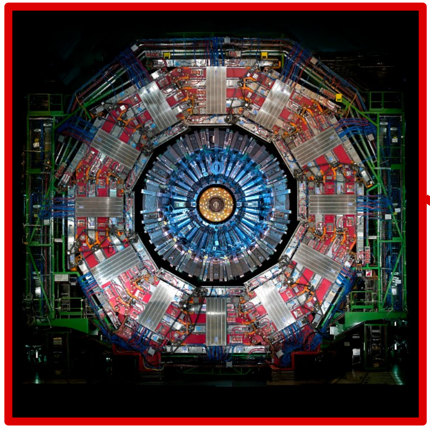


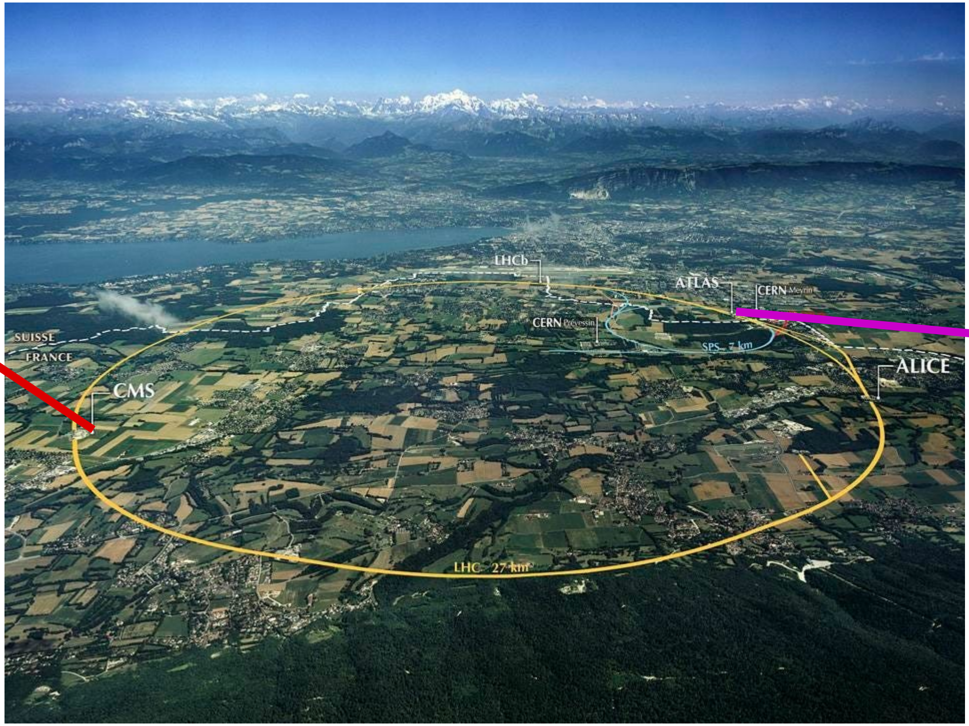
Interactions like this are ubiquitous in BSM models

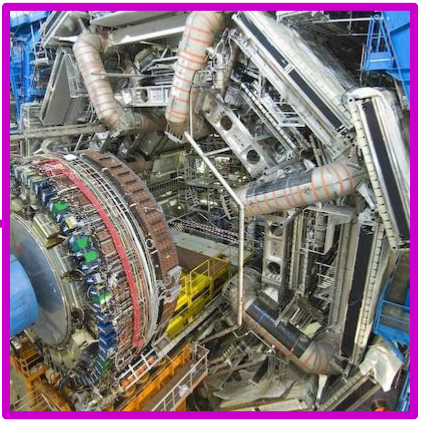


Experimental Overview

ATLAS and CMS are the only experiments currently able to probe Higgs pair production



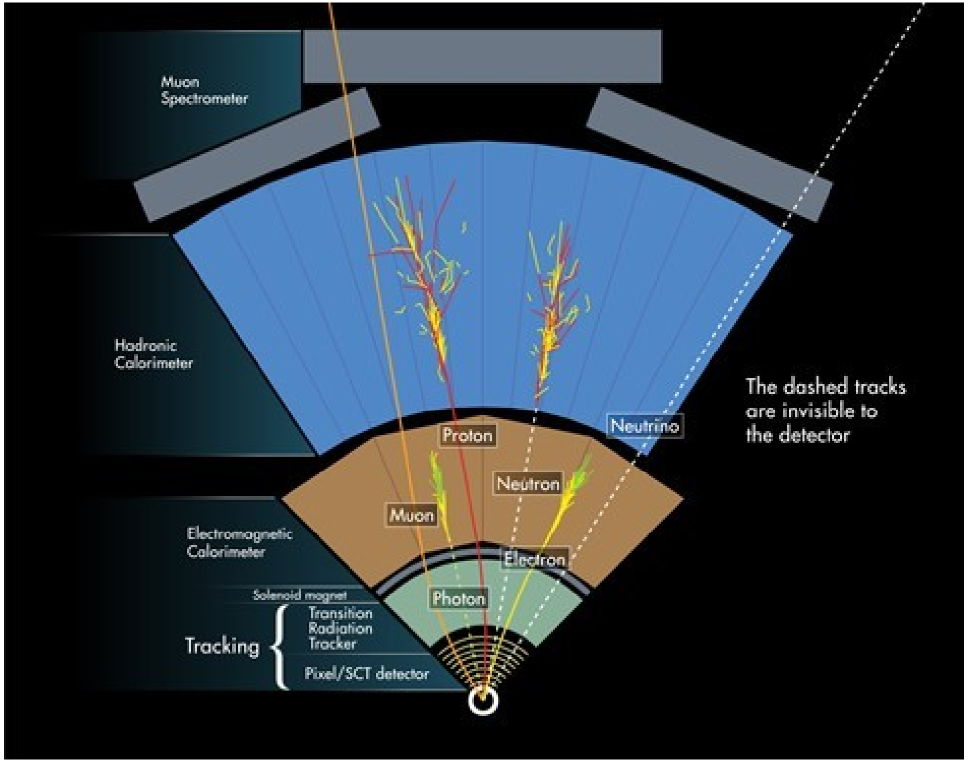




Experimental Overview

Proton-proton collisions at 13 TeV* can produce HH pairs, which promptly decay.

- Decay products are then measured by the detectors



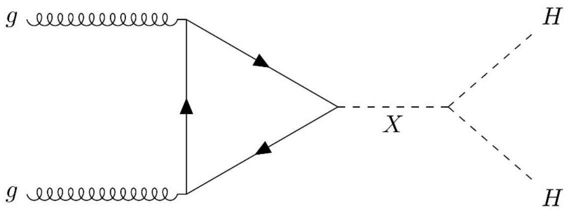
Wide range of detector technologies allows particle ID and momentum measurements for:

- Electrons
- Muons
- Hadronic taus
- Photons
- Jets (with flavor tagging)

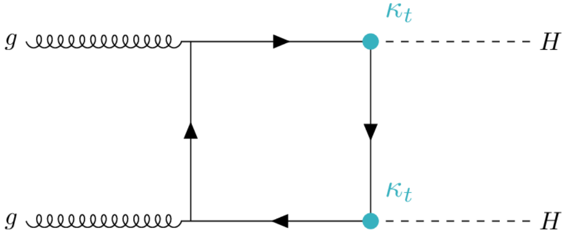
*Now 13.6 TeV in the new run, but no HH results from this yet

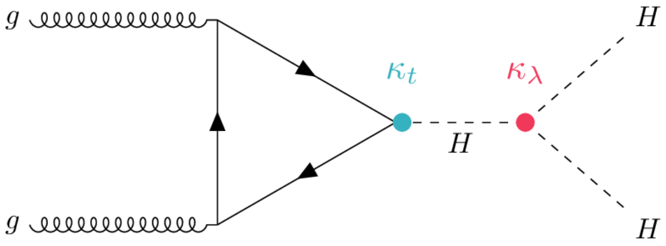
HH production modes at LHC

Resonant (BSM)

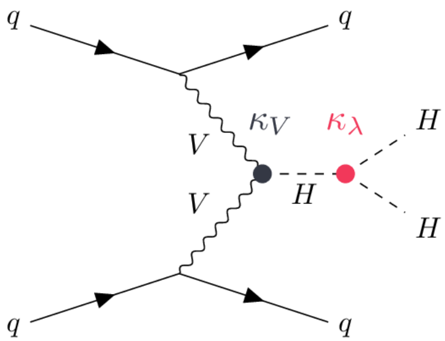


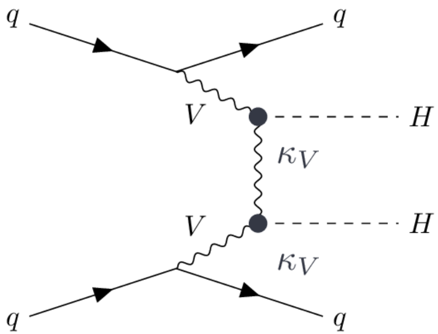
Gluon Fusion

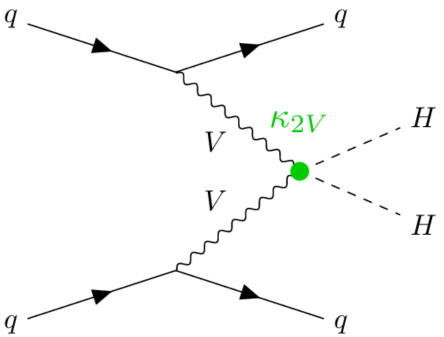




Vector Boson Fusion







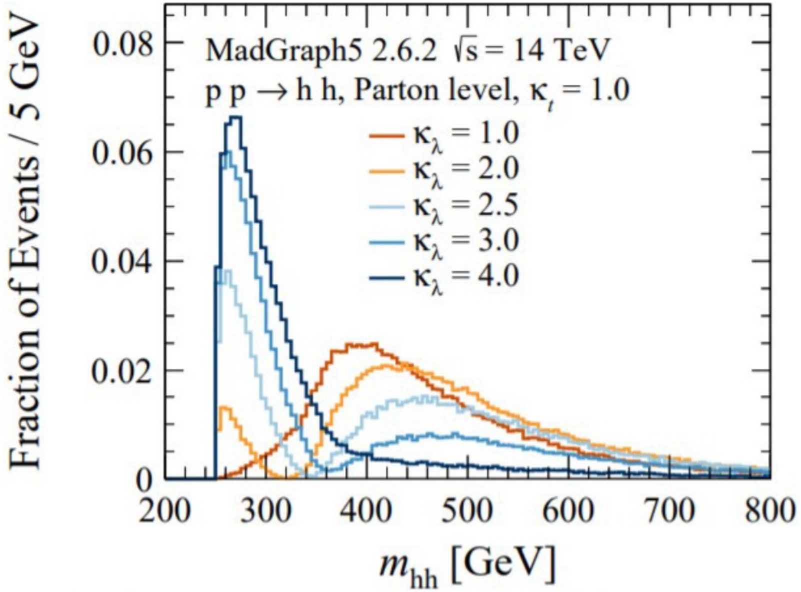
Non-resonant interference

Resonant searches are effectively "bump hunts" in the m_{HH} spectrum.

Non-resonant is more subtle: destructive interference between production diagrams results in complex effects in m_{HH}.

Non-resonant

(Measure Higgs potential)



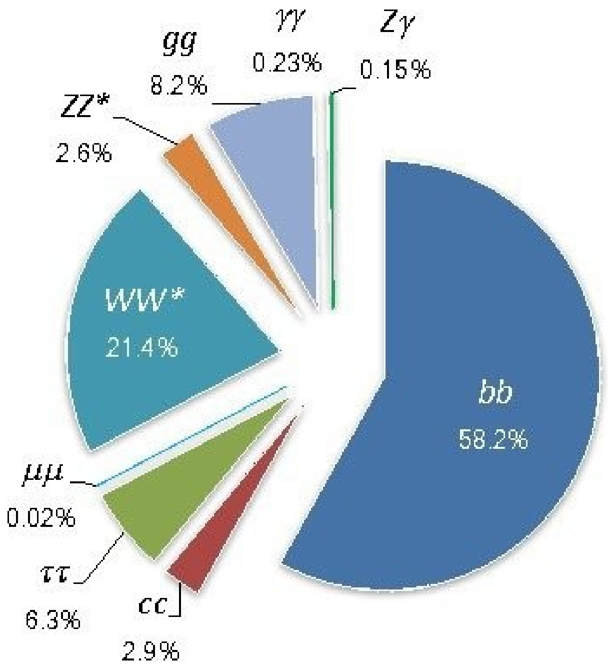
HH invariant mass spread over a wide range, with shape varying substantially with λ

HH decay channels

We're looking for the decay products of 2 Higgs bosons.

This presents a choice:
Which decays to look at?

SM Higgs boson branching ratios



HH decay channels

Which decay modes to search in?

- HH is known to be **very rare**, so high branching ratios are good.
- But, these channels also have the most background. **Complicated trade-off.**
- It turns out that some of the best are bbγγ, bbττ, and bbbb.

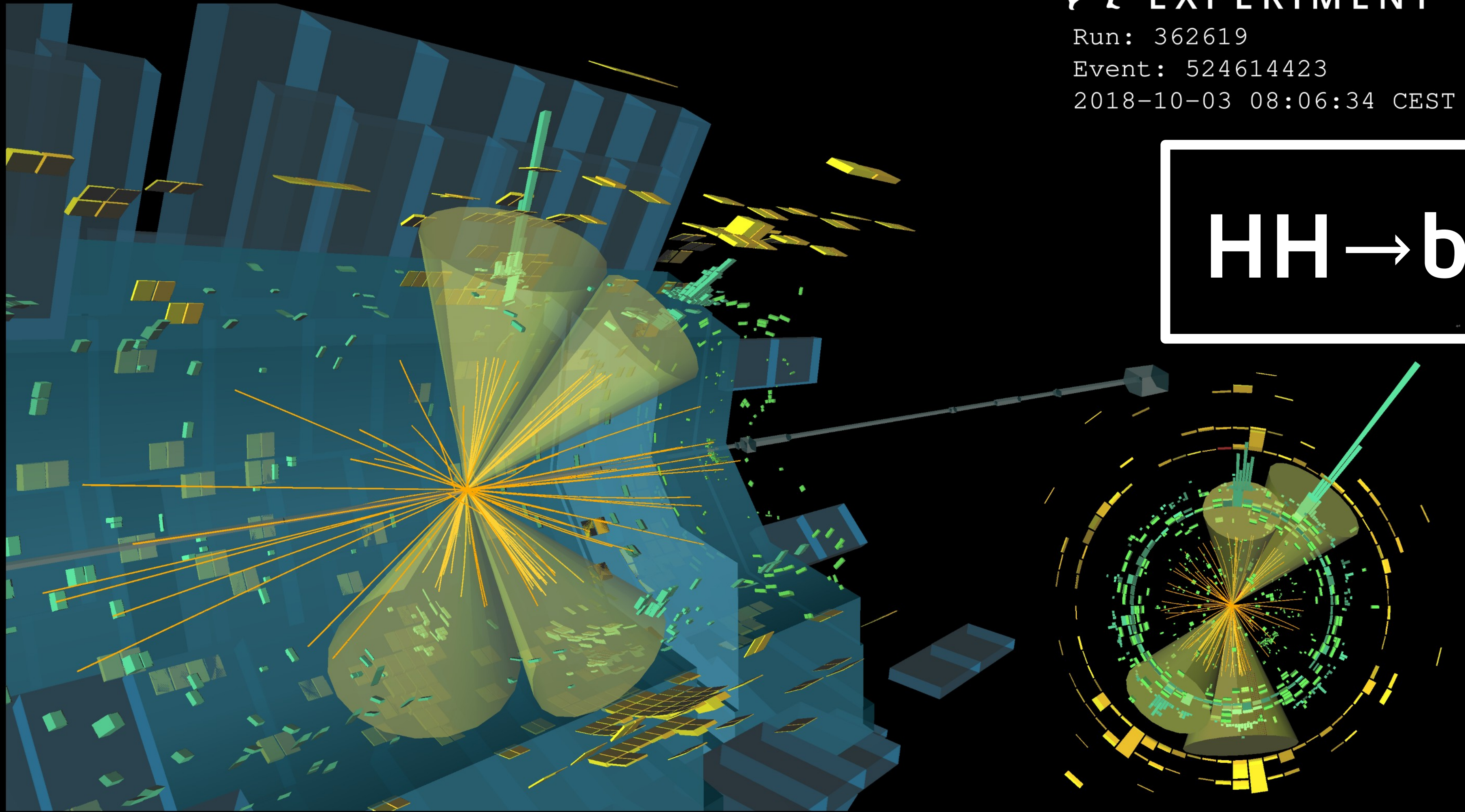
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Resonant: Phys. Rev. D 105 (2022) 092002

Non-resonant: arxiv:2301.03212

ATLAS EXPERIMENT

HH→bbbb



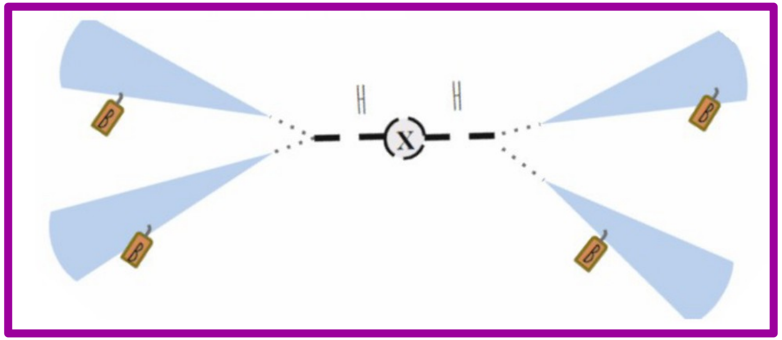
HH→bbbb: Overview

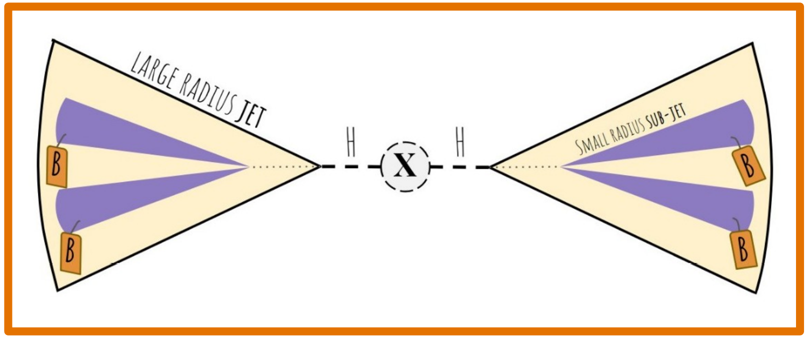
bbbb has the highest branching fraction (~34% in SM), but the largest background

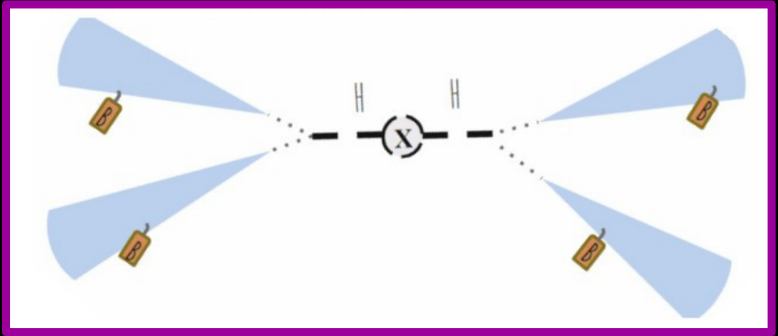
- QCD cross sections are big, even for 4 jets after b-tagging requirements!
- Top pairs also contribute background (5-10%).

Depending on the Higgs boson momenta, the detector signature can be 4 "resolved" jets or 2 merged ("boosted") ones.

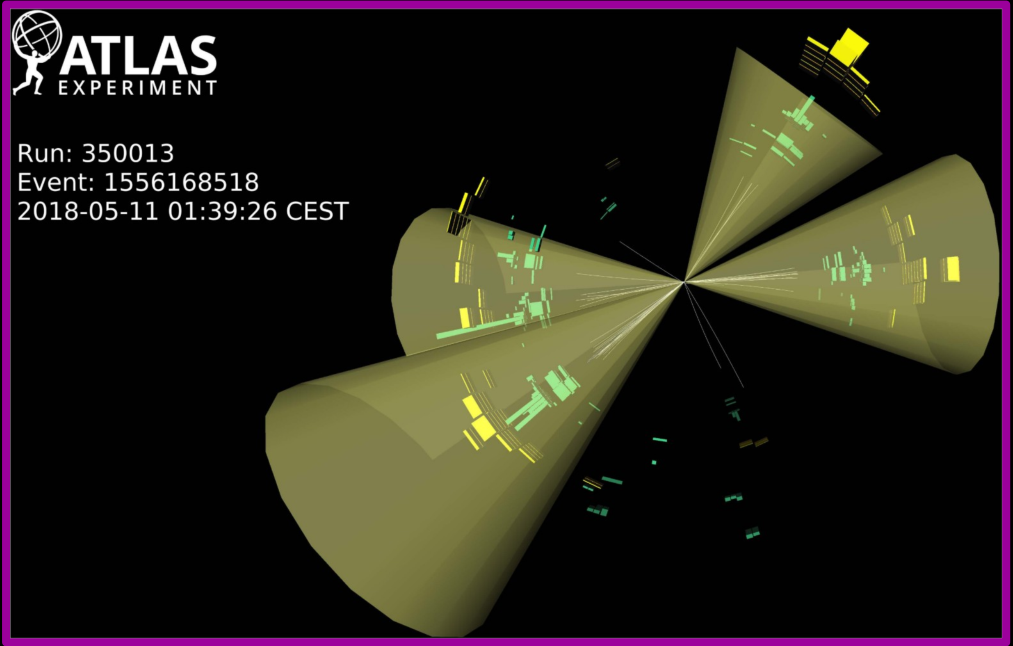
- Include the boosted channel for resonance searches, for mass coverage up to **5 TeV**.

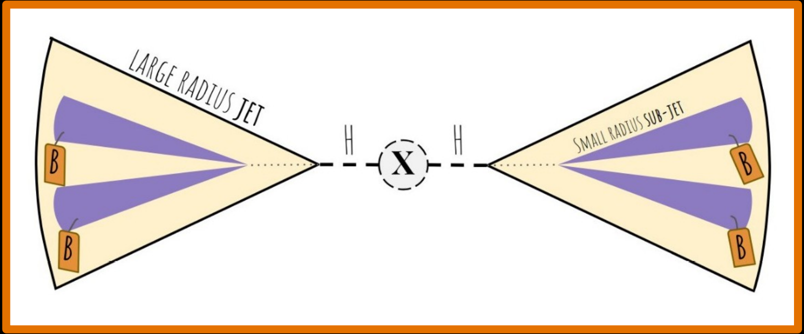




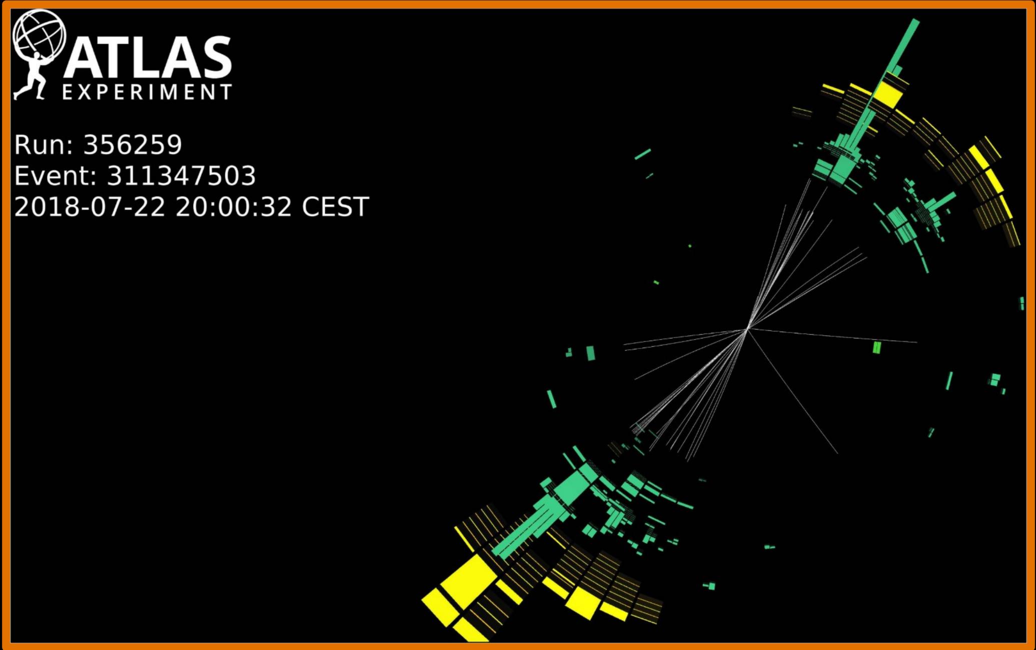


Resolved





Boosted



ATLAS HH→bbbb: Resolved Channel

1. Select events with 4 b-tagged jets* (p_T >40 GeV, so we can trigger on them)

2. Pair these jets into 2 Higgs boson candidates

3. Construct a signal region based on the *H* candidate masses

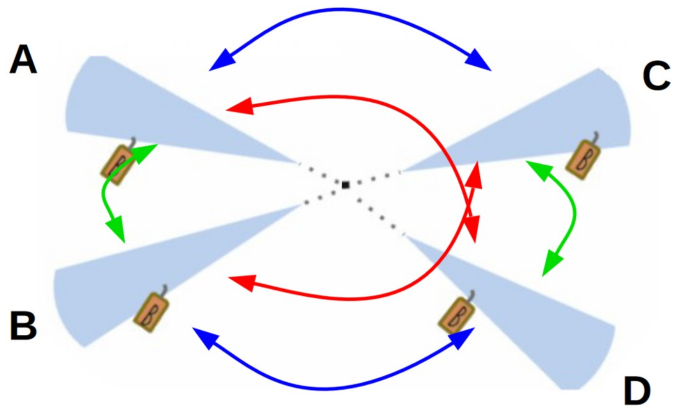
- Also construct adjacent "control" and "validation" regions for estimating background

4. Construct a background model and fit m_{HH} spectrum

- Use events with only 2 jets b-tagged to construct estimate

*Anti-k_t clustering, R=0.4, Particle Flow inputs. 77% eff. b-tagging WP

ATLAS HH→bbbb: Jet Pairing



3 possible pairings

(AB) (CD)

(AC) (BD)

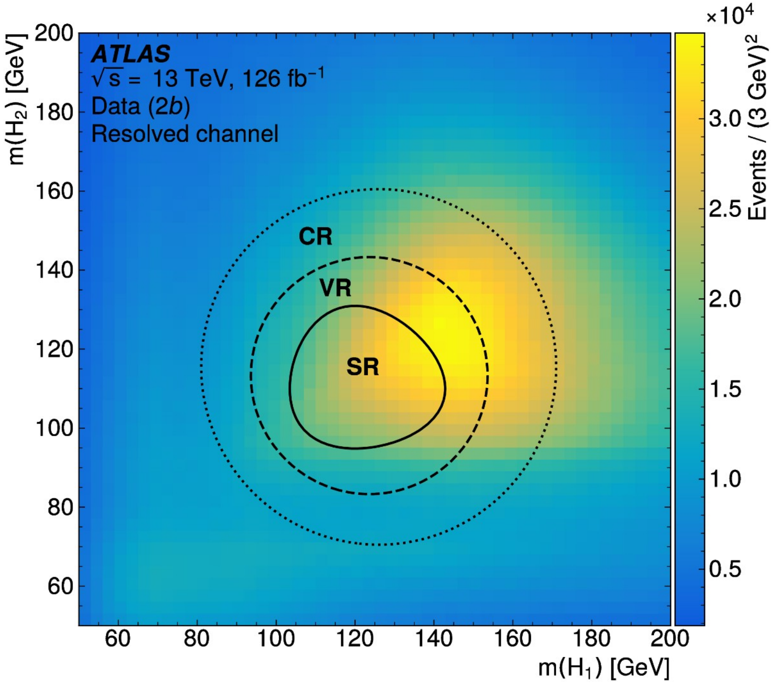
(AD) (BC)

Ambiguity in resolving which jet came from which Higgs

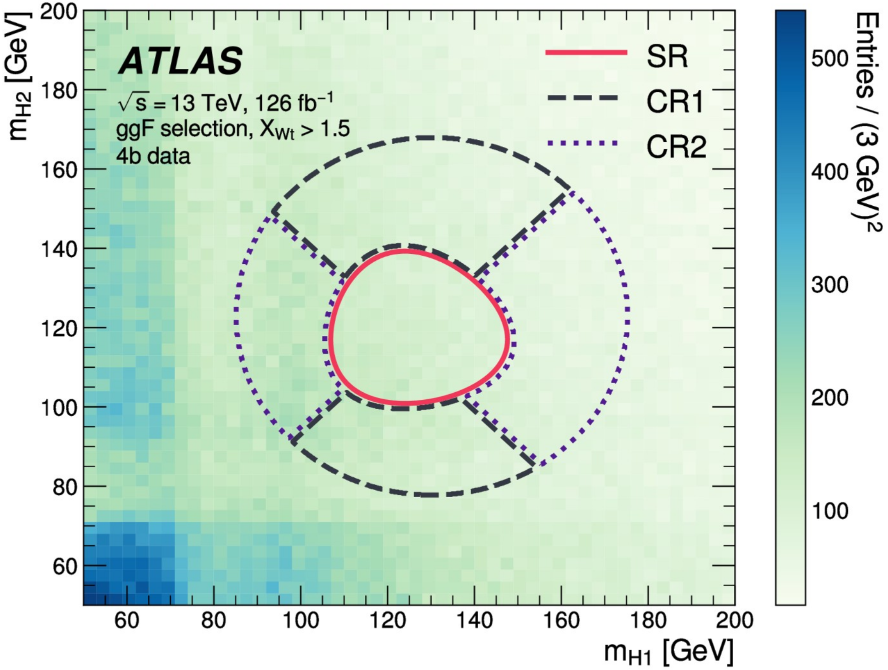
- Choose pairing which gets masses as close to 125 GeV as possible? Major background bias!
- Resonant search: Use a boosted decision tree with angular variables as input features
- Nonresonant search: Simply minimize ΔR_{jj} for H_1.

ATLAS HH→bbbb: Event Selection

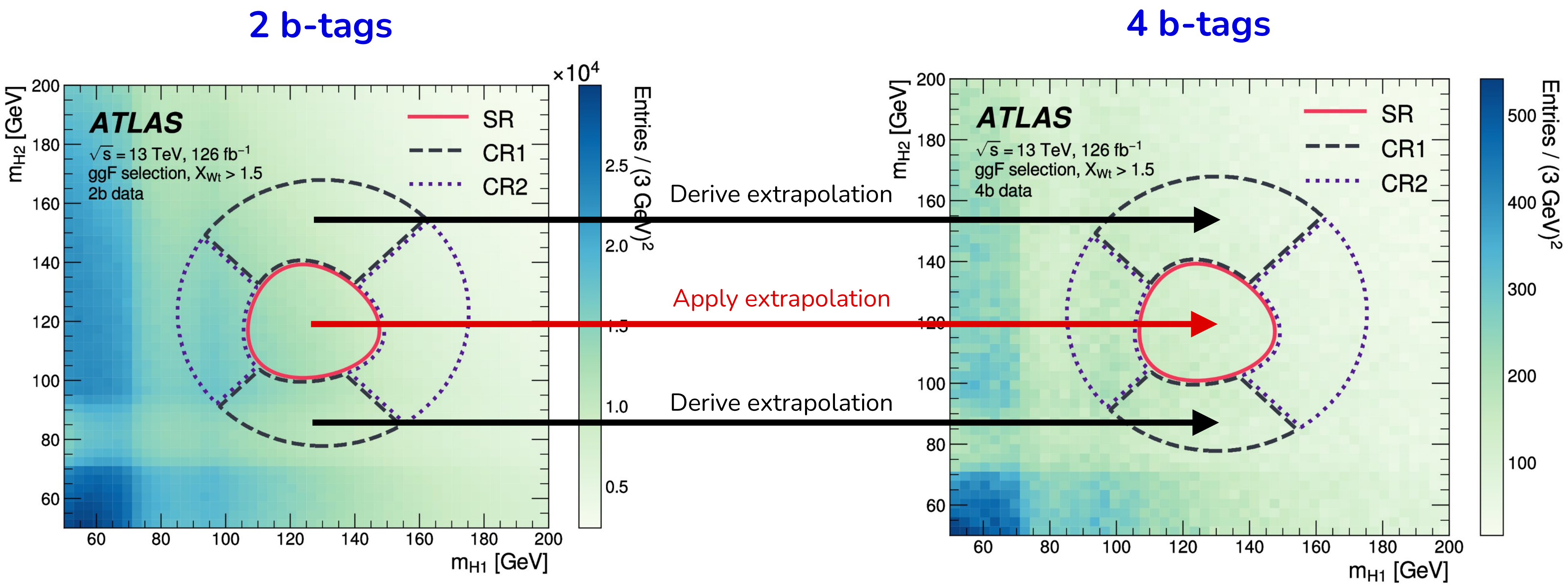
Resonant Analysis



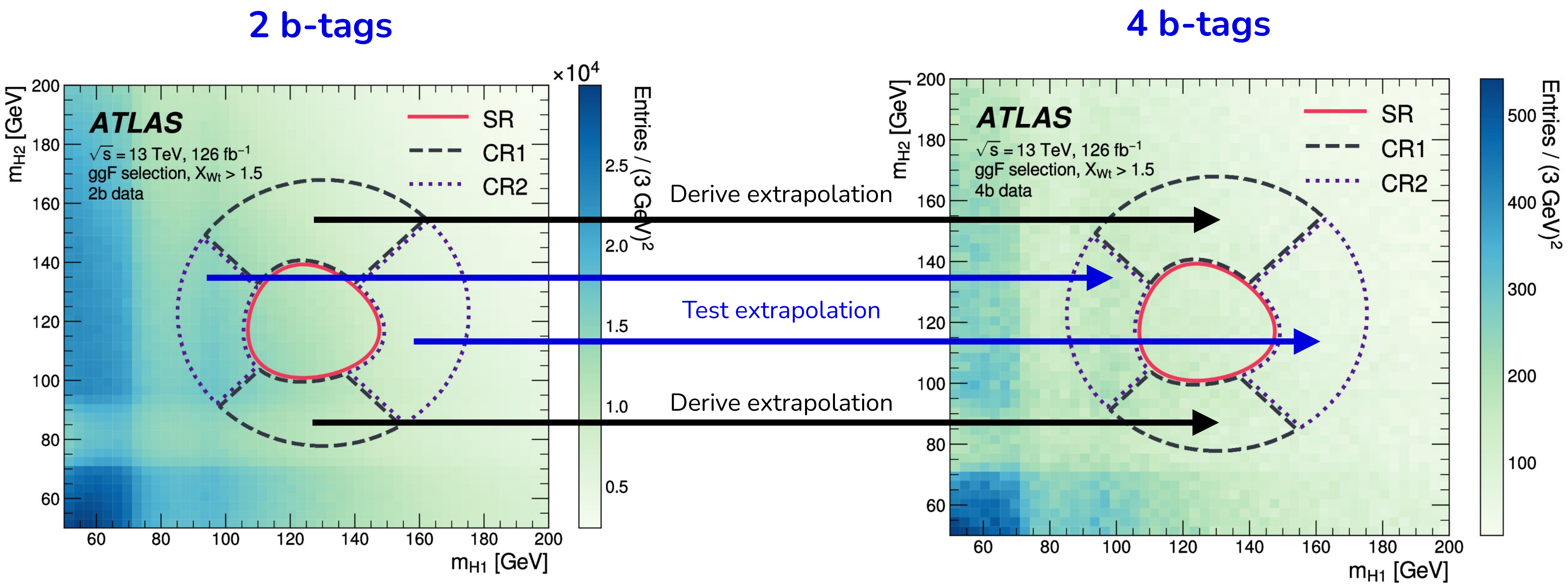
Non-resonant Analysis



ATLAS HH→bbbb: Background Model



ATLAS HH→bbbb: Background Model



HH→bbbb: Background Reweighting

2b distributions don't look exactly like 4b distributions.

- Derive a kinematic reweighting in CR to apply to 2b "SR"

This is a density ratio estimation problem: find ***w(x)***, where

$$w(\vec{x}) = \frac{p_{4b}(\vec{x})}{p_{2b}(\vec{x})}$$

Neural network can "learn" the solution by minimizing:

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

x are a a set of kinematic variables

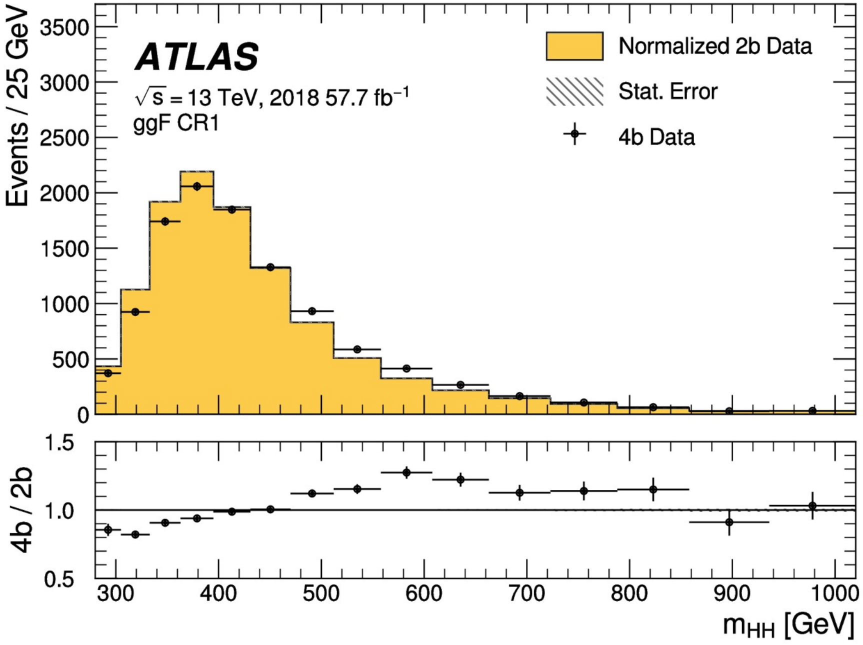
HH→bbbb: Background Reweighting

The full list of reweighting variables...

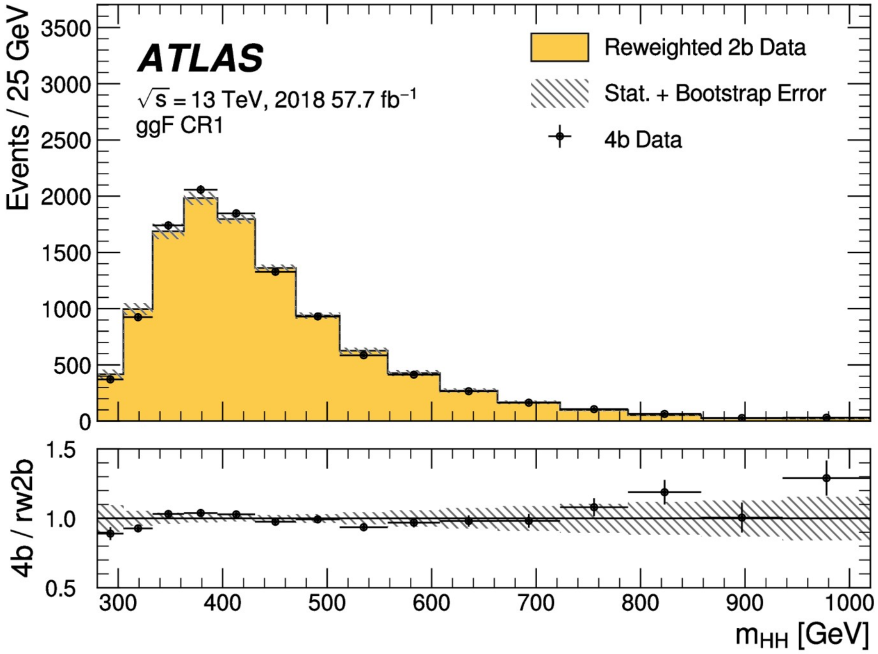
ggF	VBF
1. $\log(p_{\mathrm{T}})$ of the 2nd leading Higgs boson candidate jet 2. $\log(p_{\mathrm{T}})$ of the 4th leading Higgs boson candidate jet 3. $\log(\Delta R)$ between the closest two Higgs boson candidate jets 4. $\log(\Delta R)$ between the other two Higgs boson candidate jets 5. Average absolute η value of the Higgs boson candidate jets 6. $\log(p_{\mathrm{T}})$ of the di-Higgs system 7. ΔR between the two Higgs boson candidates 8. $\Delta\phi$ between jets in the leading Higgs boson candidate 9. $\Delta\phi$ between jets in the subleading Higgs boson candidate 10. $\log(X_{Wt})$ 11. Number of jets in the event 12. Trigger class index as one-hot encoder	1. Maximum di-jet mass out of the possible pairings of the four Higgs boson candidate jets 2. Minimum di-jet mass out of the possible pairings of the four Higgs boson candidate jets 3. Energy of the leading Higgs boson candidate 4. Energy of the subleading Higgs boson candidate 5. Second smallest ΔR between the jets in the leading Higgs boson candidate (out of the three possible pairings for the leading Higgs candidate) 6. Average absolute η value of the four Higgs boson candidate jets 7. $\log(X_{Wt})$ 8. Trigger class index as one-hot encoder 9. Year index as one-hot encoder (for years inclusive training)

HH→bbbb: Background Reweighting

Before Reweighting



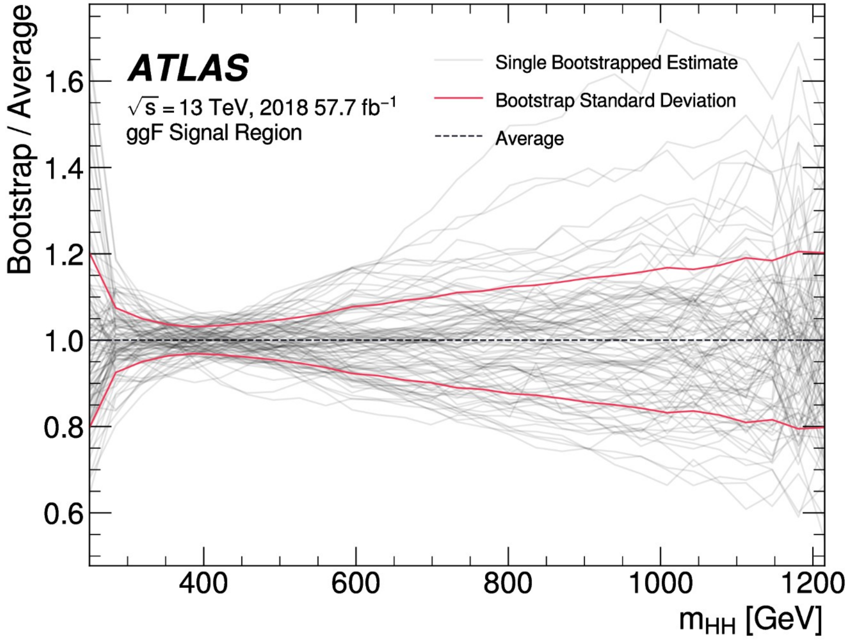
After Reweighting



HH→bbbb: Background Reweighting

In practice, we construct an ensemble of reweighting functions

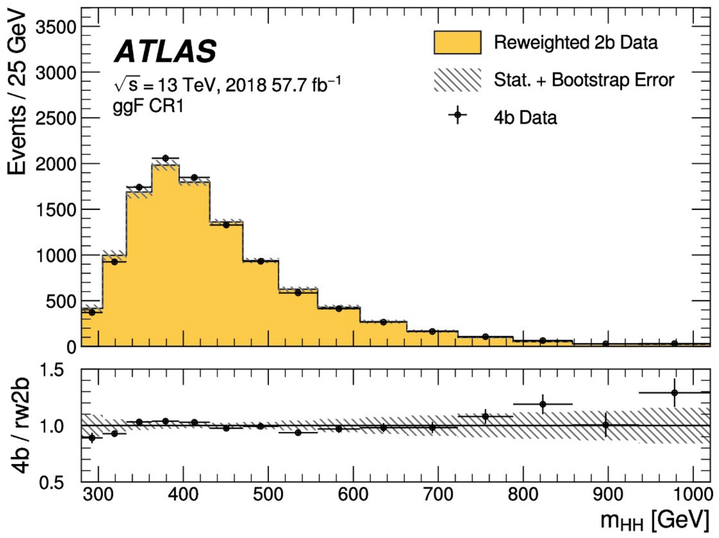
- Build training sets by sampling with replacement ("bootstrap" method)
- Average distribution is nominal estimate, spread gives stat. uncertainty

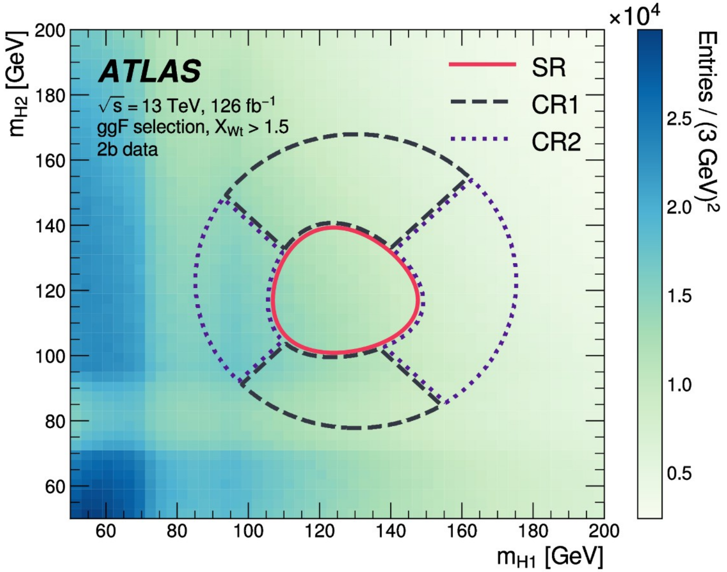


HH→bbbb: Systematic Uncertainties

Several more uncertainties on background model considered (besides detector & theory):

- Non-closure of the reweighting in the CR used to derive it
- Extrapolation from CR to SR (estimated using alternate reweightings derived in other regions)
- Residual non-closure when tested using 3b event selection



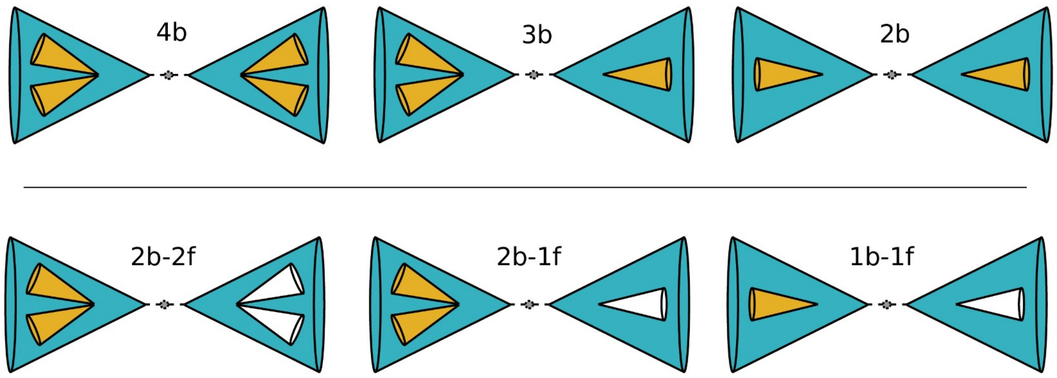


HH→bbbb: Boosted Channel

Select events with 2 large-*R* jets* (one with $p_T > 450$ GeV, so we can trigger on it)

b-tag them using variable-radius subjets constructed from their associated tracks

- At very high resonance masses, even these get merged. Therefore, also keep events with only 2 or 3 b-tagged subjets in their own separate categories.



“Low-tag” control samples for background modeling

*Anti-k_t clustering, R=1.0, locally-calibrated calorimeter cluster inputs, trimmed (R=0.2, 5% threshold)

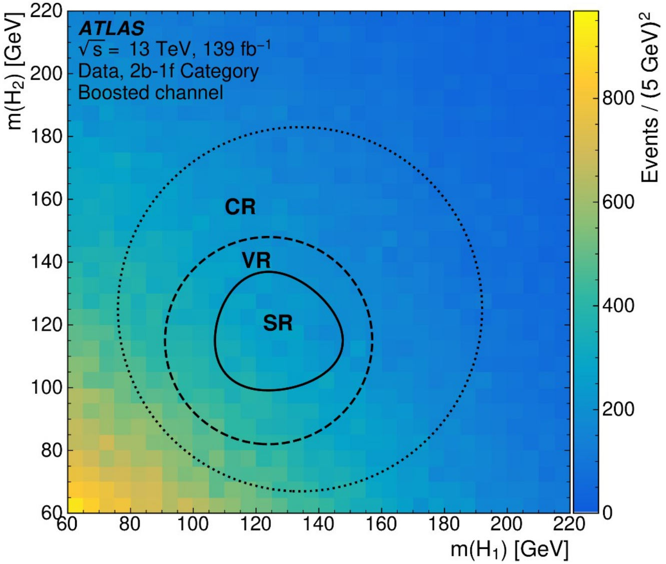
HH→bbbb: Boosted Channel

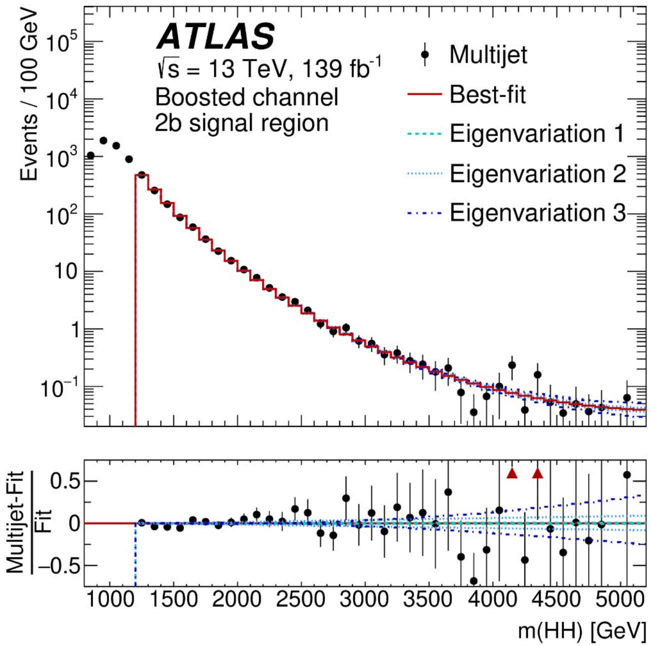
Top pair background more significant in the boosted channel.

- Model explicitly with MC, and subtract this off for the multijet estimate

Kinematic reweighting only needed in 2b selection (statistics)

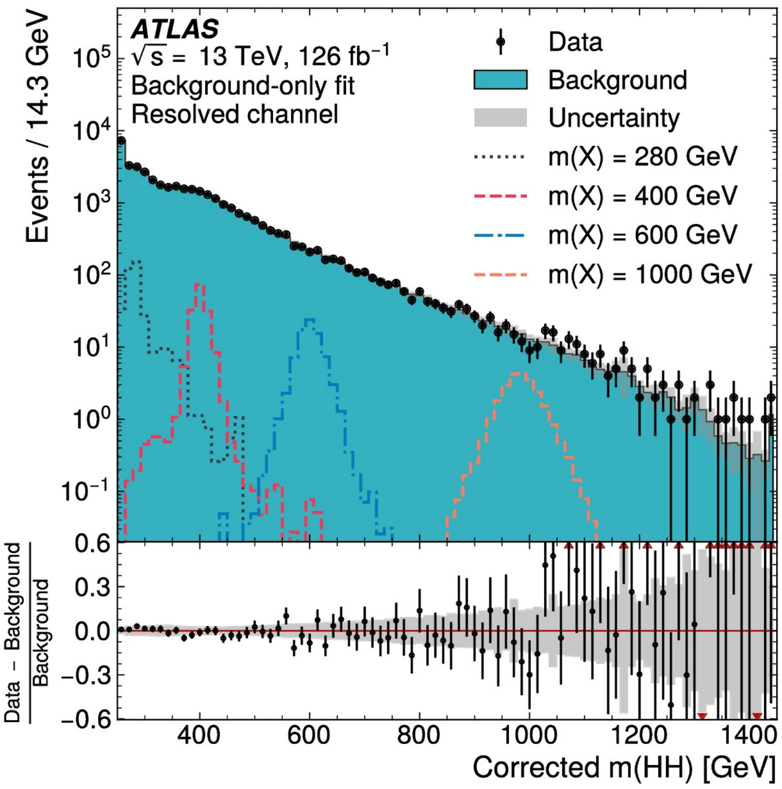
Fit analytic function to m_{HH} tails to smooth bkgd estimate

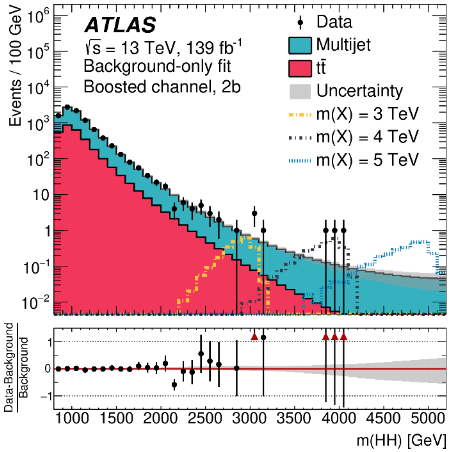


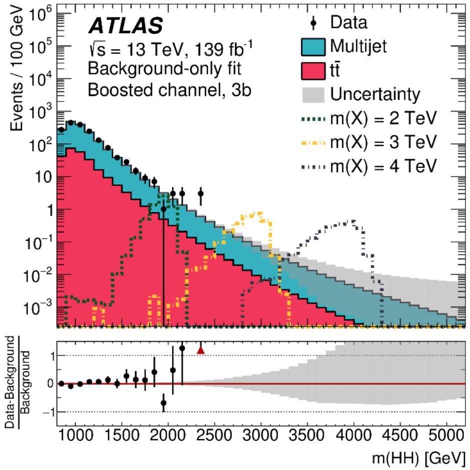


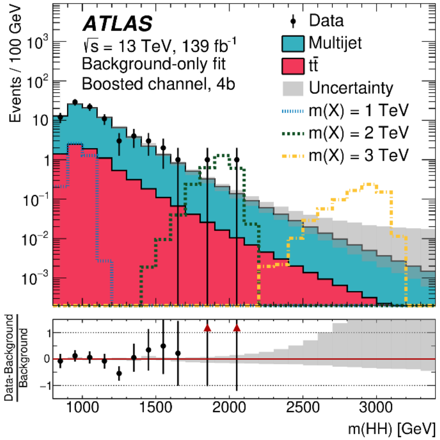
HH→bbbb: Resonant Results

Data consistent with background.



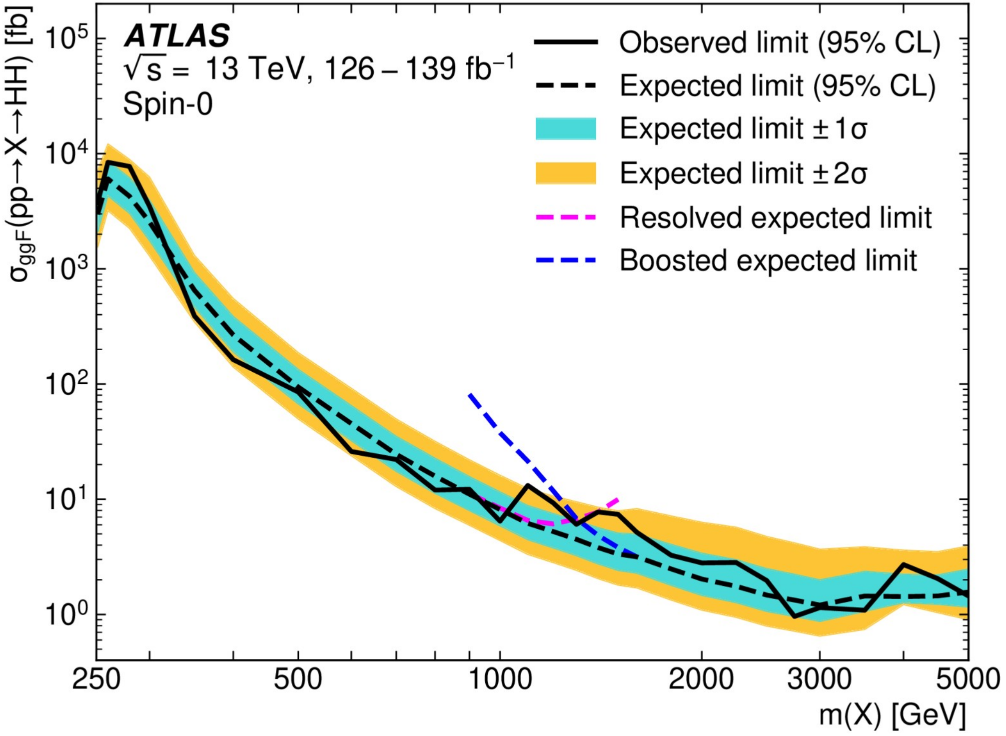


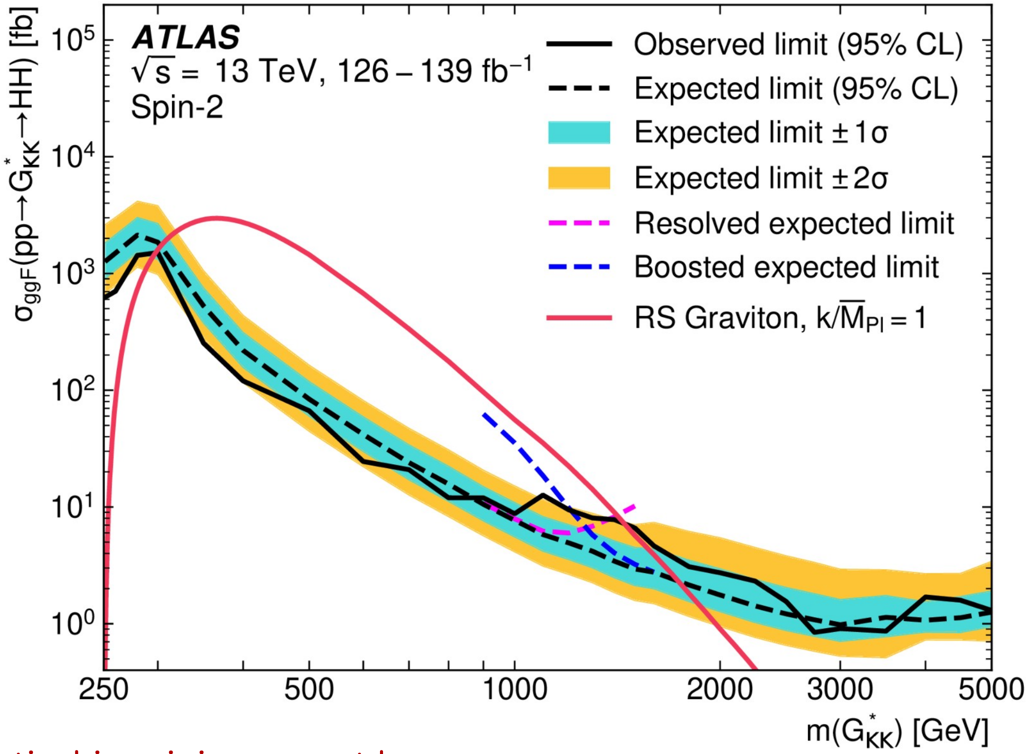




HH→bbbb: Resonant Results

Set cross section limits on benchmark models: generic narrow scalar produced in ggF, and RS graviton

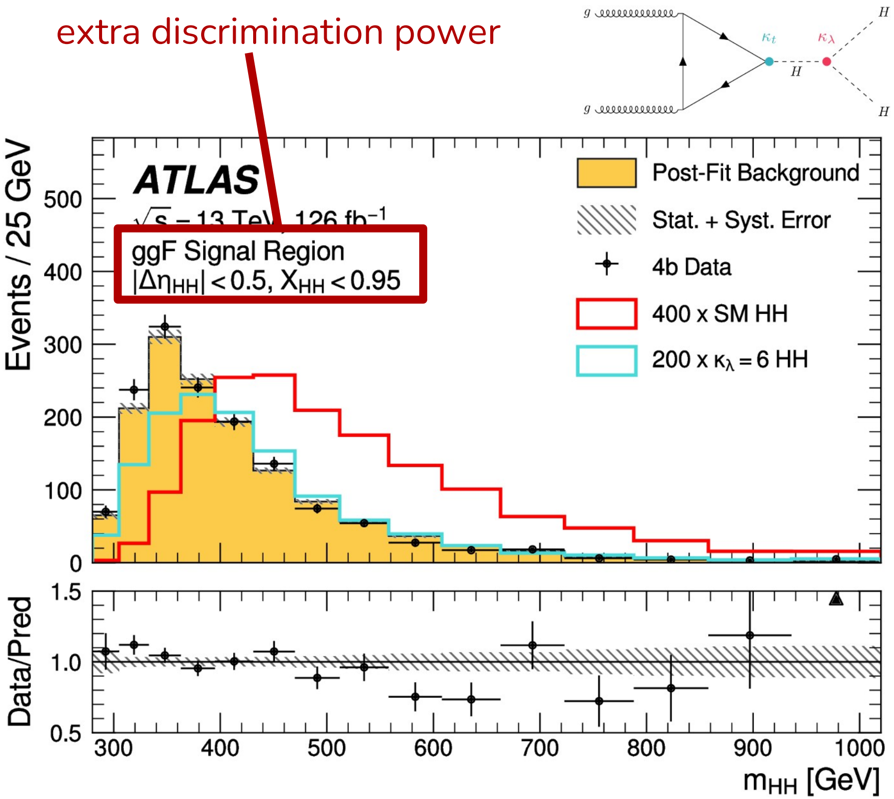




Dominant uncertainties are statistical in origin, even at low mass.

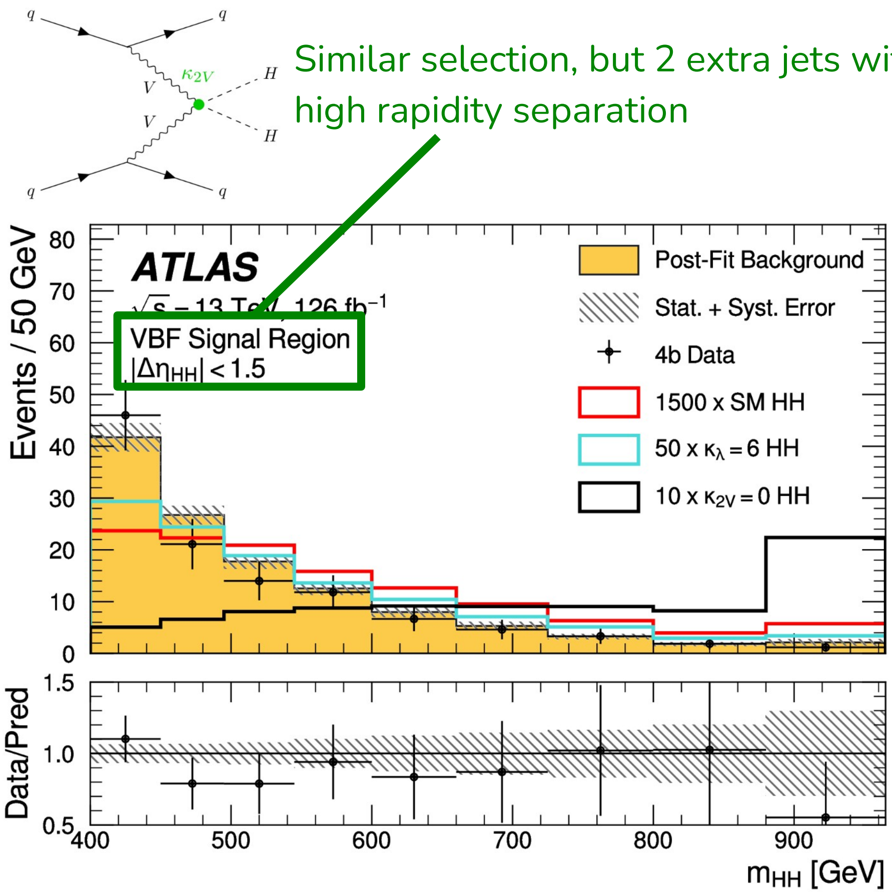
HH→bbbb: Non-Resonant Results

Categorize by kinematic variables for extra discrimination power

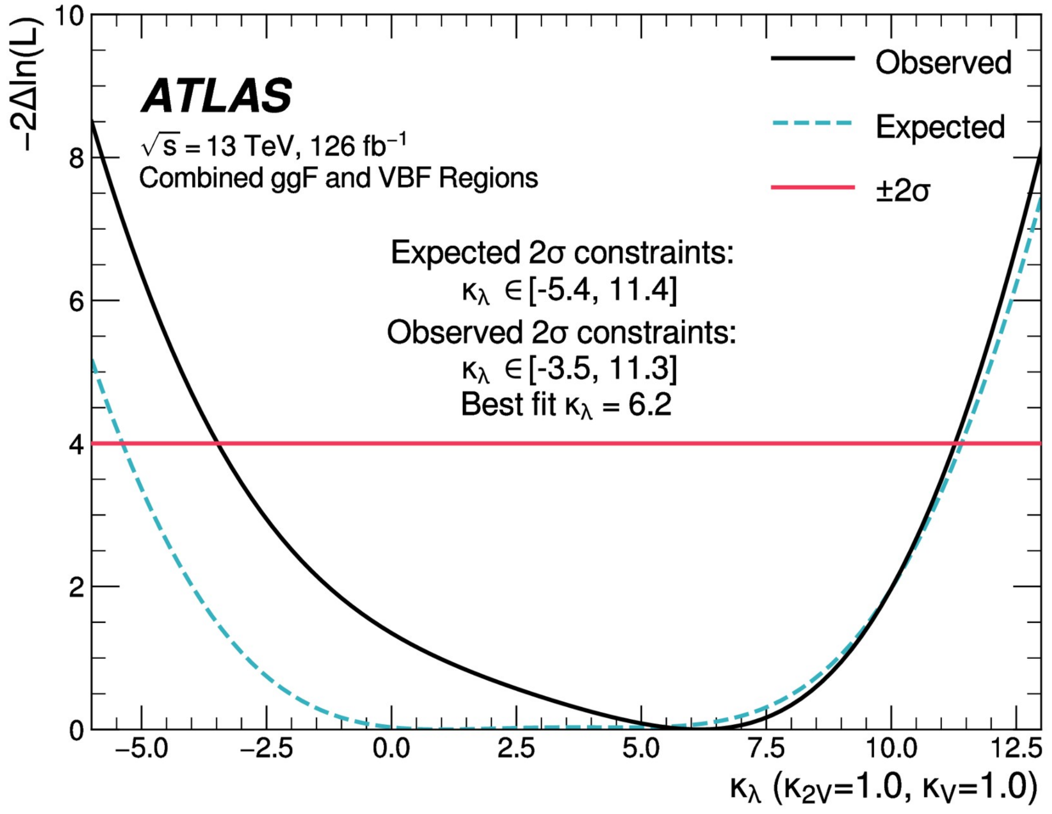


X_{HH} = distance from SR center in units of mass "resolution"

Similar selection, but 2 extra jets with high rapidity separation



HH→bbbb: Non-Resonant Results

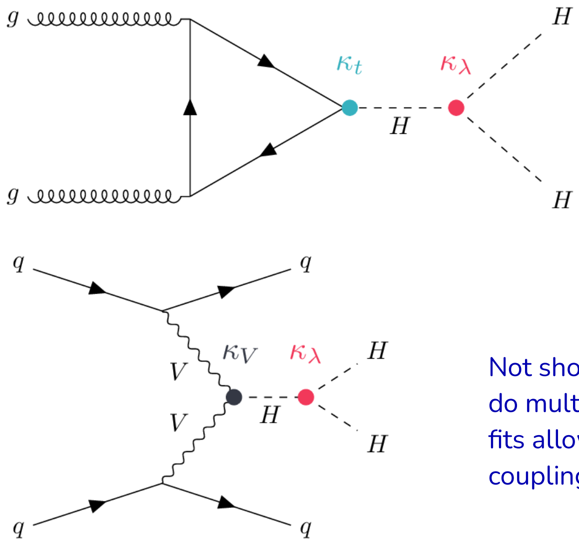


Effective Field Theory interpretation.

- Set limits on HHH vertex, holding other interactions fixed to SM ("kappa framework")

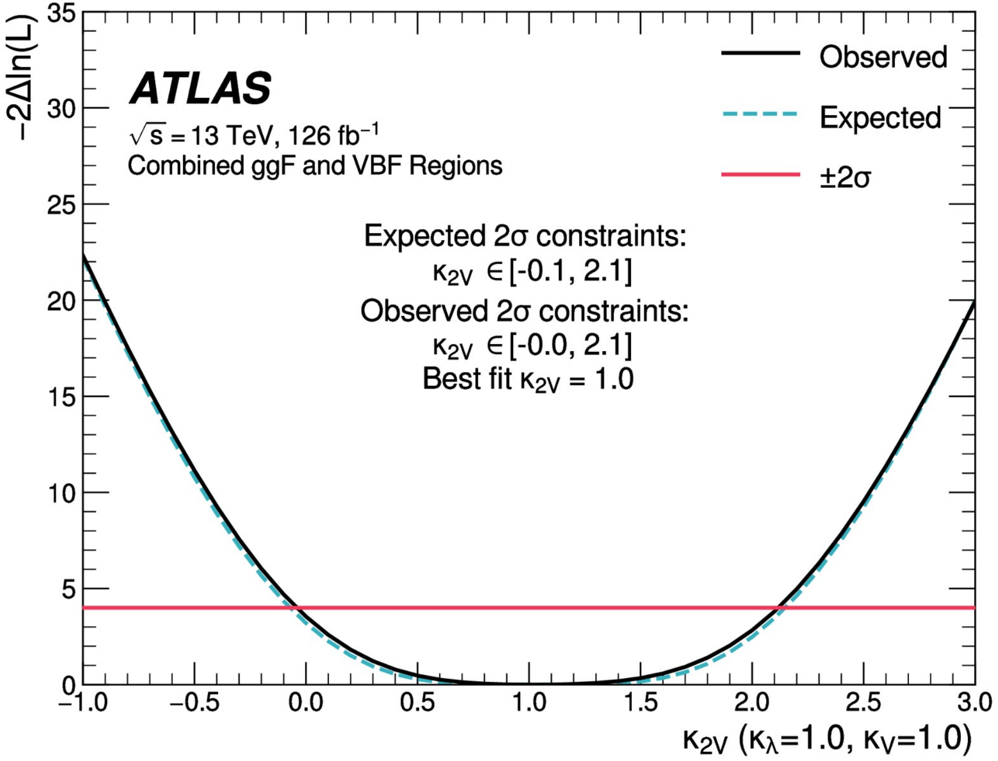
Also set signal strength limit:

- 5.4 (8.1 expected) times SM cross section excluded



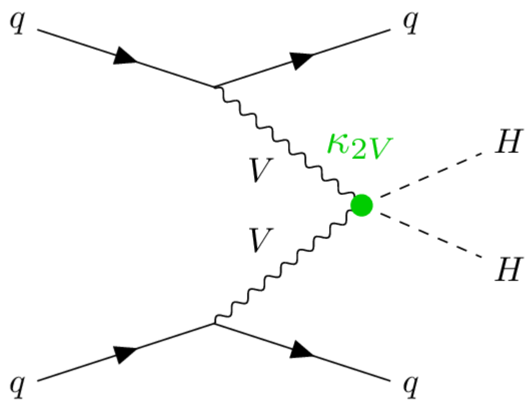
Not shown here: can also do multi-parameter EFT fits allowing other couplings to float too

HH→bbbb: Non-Resonant Results



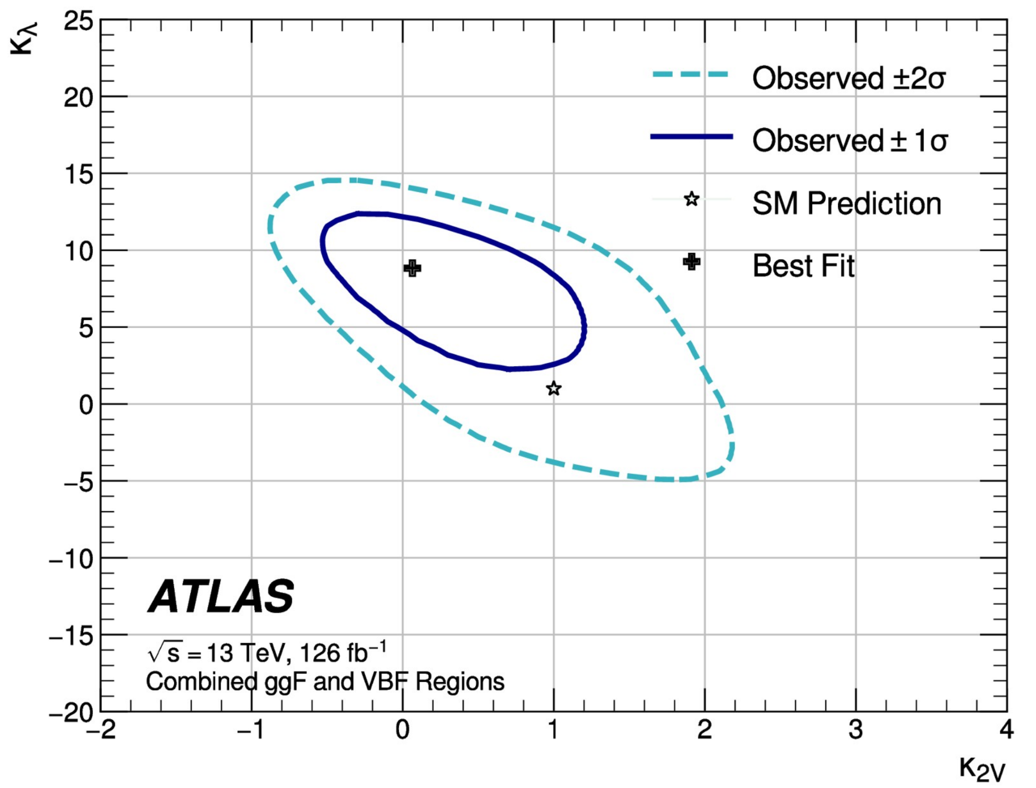
Also set limit on HHVV vertex

- In SM, this is tied to HVV vertex. This provides a check on that assumption.



HH→bbbb: Non-Resonant Results

Can consider scenarios where both couplings are modified



HH→bbττ

arXiv:2209.10910

(accepted in JHEP)

ATLAS EXPERIMENT

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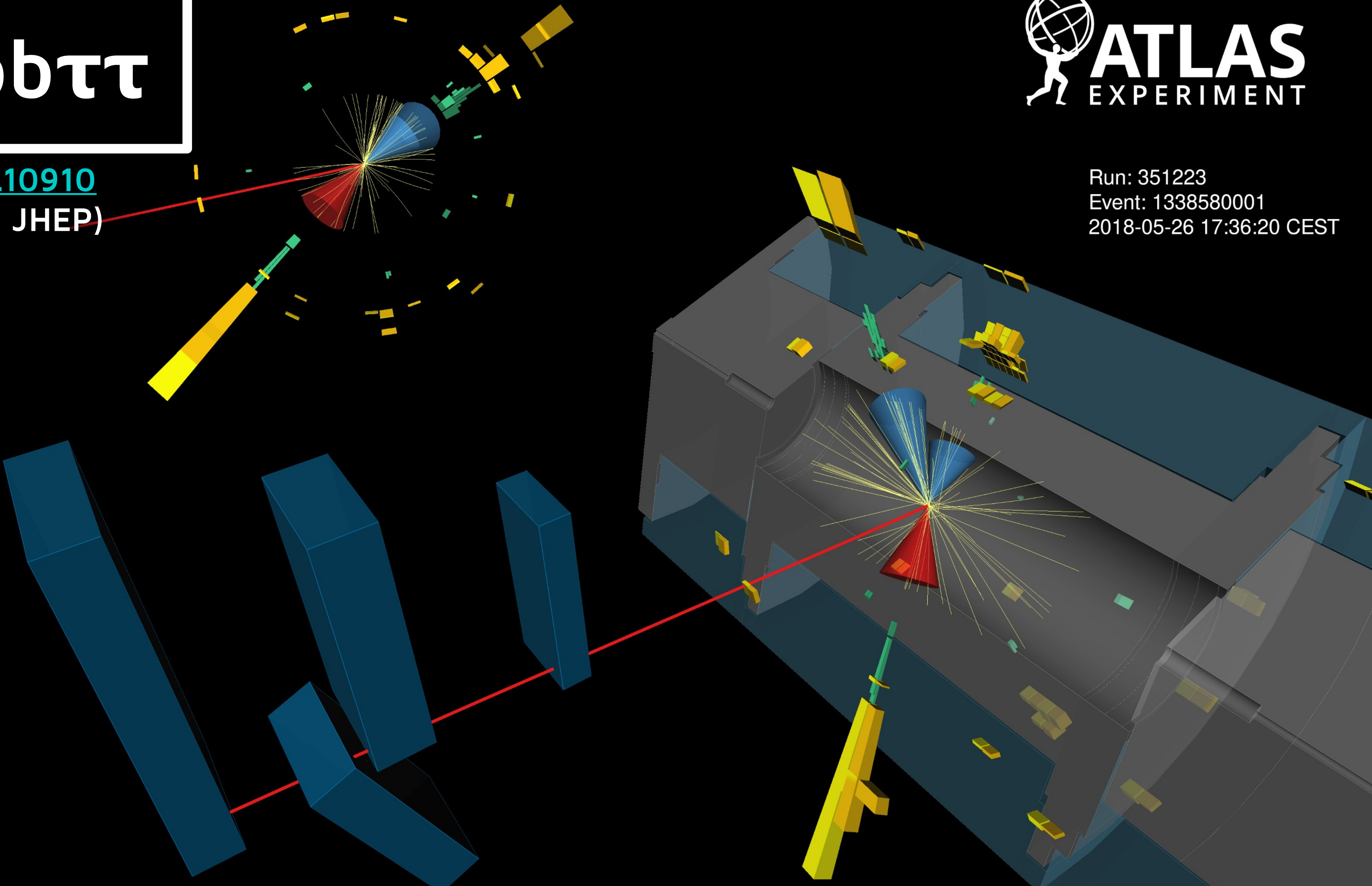
Event: 1338580001
2018-05-26 17:36:20 CEST



$HH \to bb\tau\tau$: Overview

Lower branching fraction (~7.3% in SM) than bbbb, but more manageable backgrounds

- We consider the semi-leptonic ($\tau_{lep}\tau_{had}$) and fully-hadronic ($\tau_{had}\tau_{had}$) cases in this search.

Method: Select signal-like events using object-based cuts, then use an MVA to construct a discriminant, which we then fit.

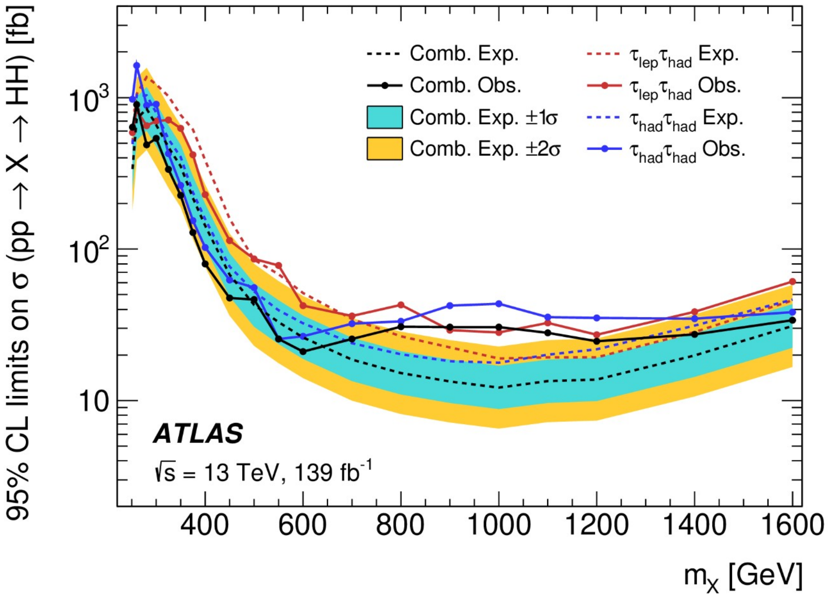
- Various BDT and NN architectures used for resonant/non-resonant interpretations

Mix of Monte Carlo and data-driven background modelling

- "Fake" hadronic taus are tricky, use fake-enriched control region to estimate from data

HH→bbττ: Results

Data consistent with background. Set cross section limits on narrow scalar resonance



Comparable sensitivity between $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$

Statistical uncertainties dominate the sensitivity (but systematics not quite negligible)

Excess at ~1 TeV has a global significance of **2.0σ**

Non-resonant: Cross sections above 4.7 (3.9 expected) times the SM excluded

HH→bbγγ

ATLAS EXPERIMENT

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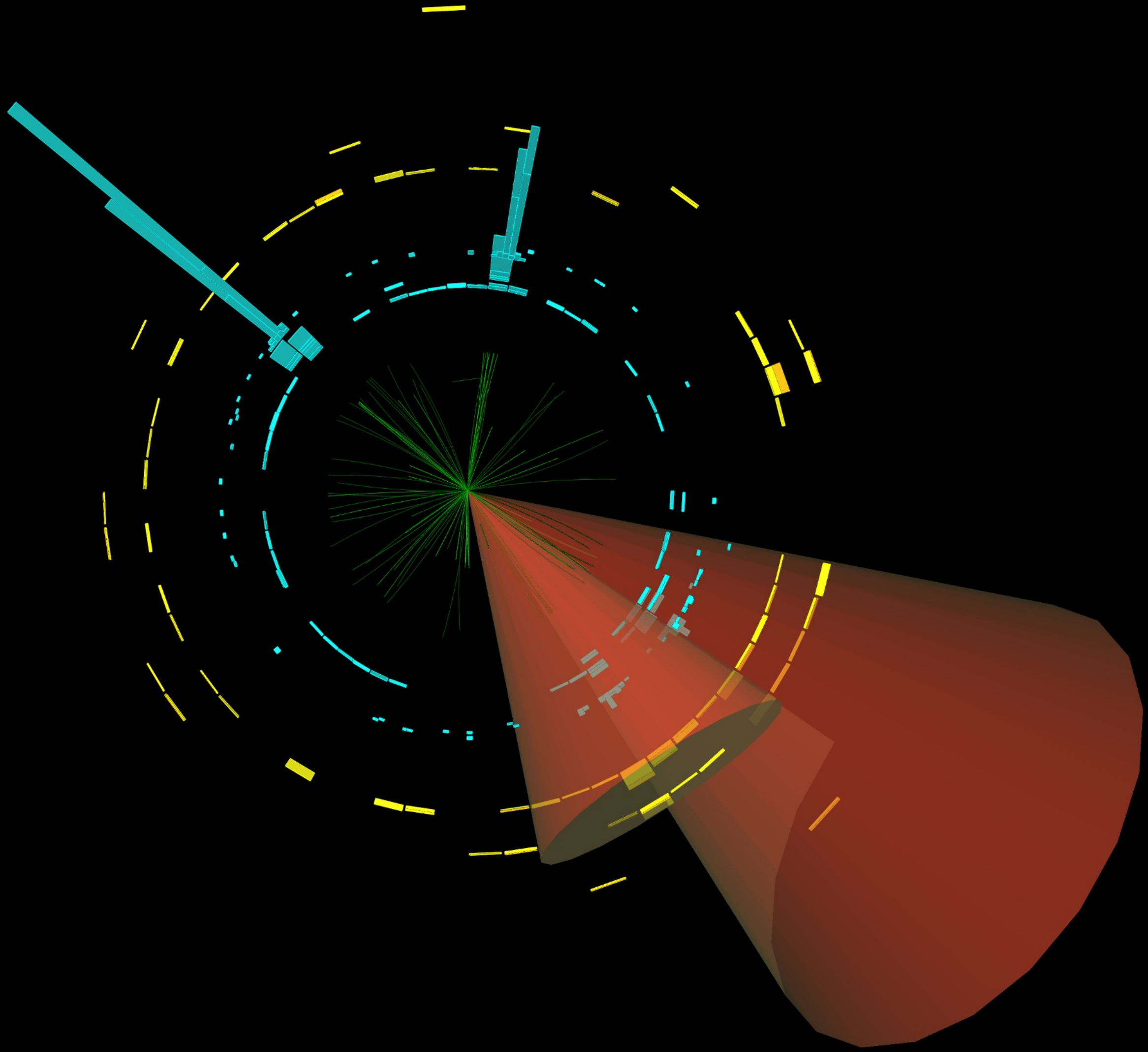
2017-07-17 23:58:15 CEST



Phys. Rev. D 106 (2022) 052001

HH→bbγγ: Overview

The bbγγ final state is very clean, but has low branching fraction (~0.26% in SM)

- Very statistically limited, and will remain so for a long time to come
- Photon triggers allow good reach to low masses

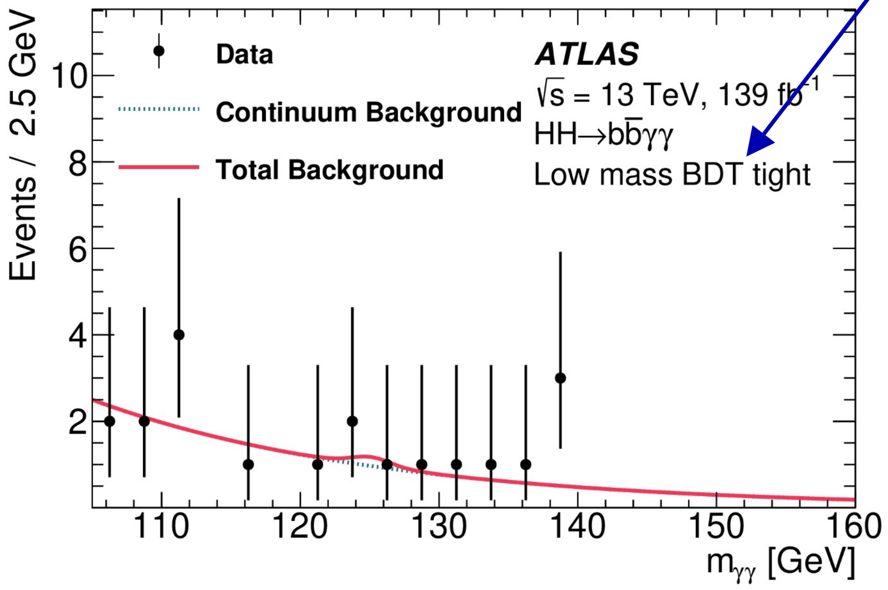
Method: Use two BDTs to cut away background, then fit the $m_{\gamma\gamma}$ distribution

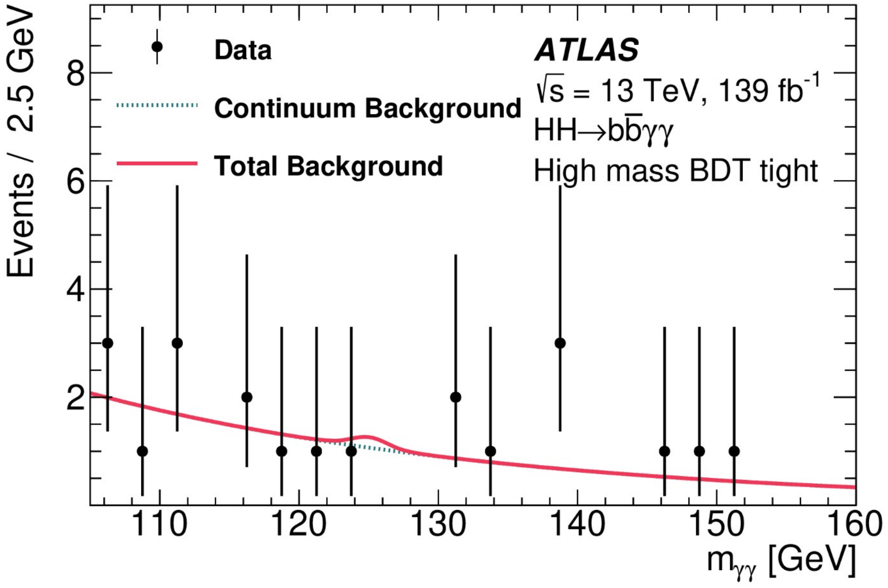
- One to discriminate vs. H→γγ and one to discriminate vs. everything else (smooth $m_{\gamma\gamma}$)
- H→γγ background taken from MC simulation
- "Continuum" γγ background modeled as an exponential function in $m_{\gamma\gamma}$

HH→bbγγ: Results

Data are consistent with the background model.

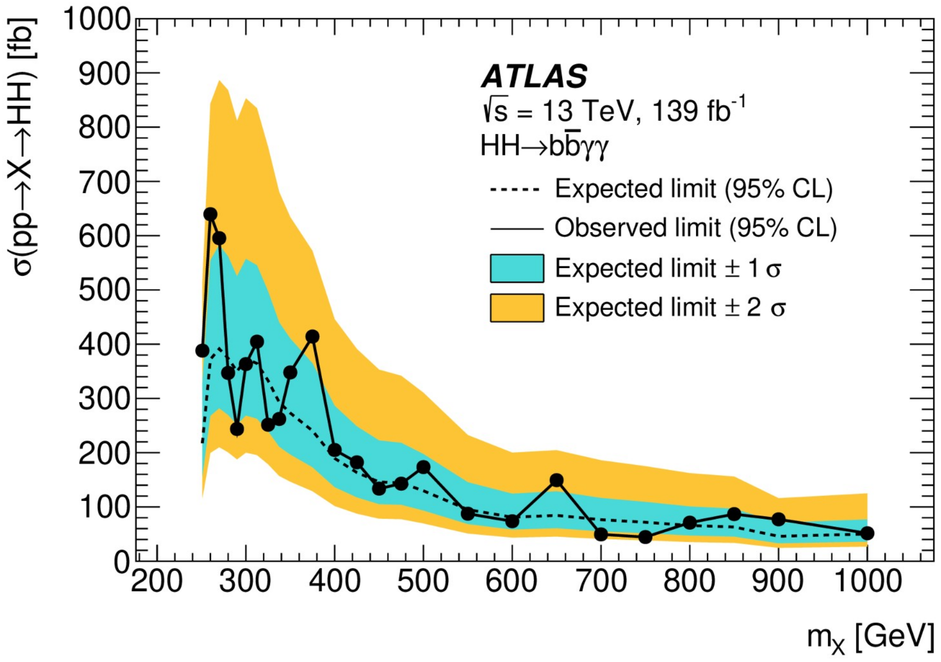
Several kinematic categories to improve discrimination power



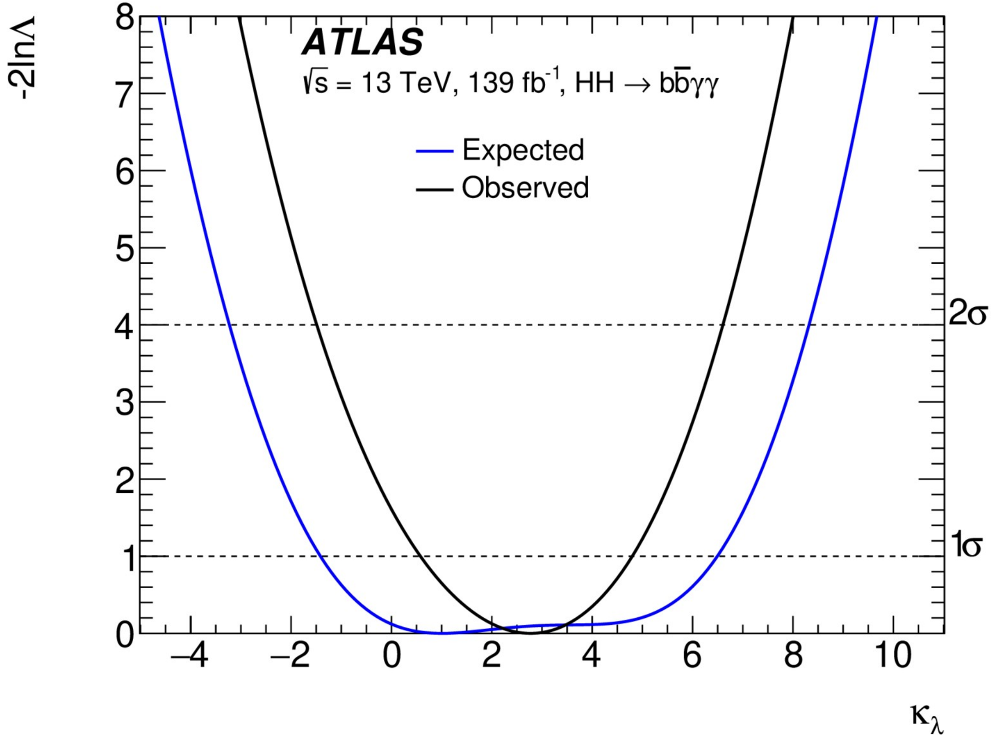


HH→bbγγ: Results

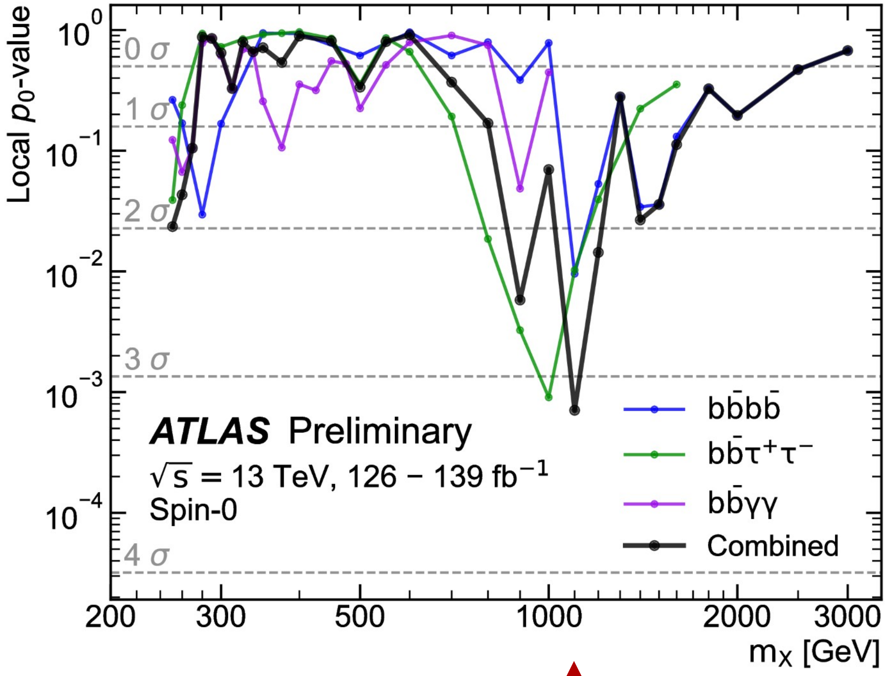
Resonance Search

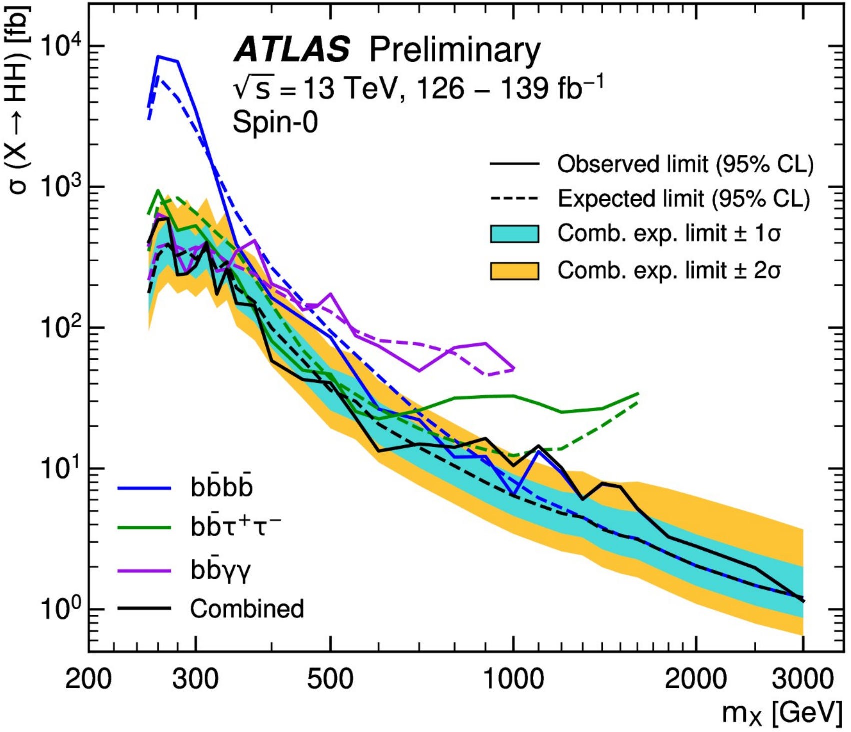


Self-coupling (non-resonant)



Resonant HH: combining channels



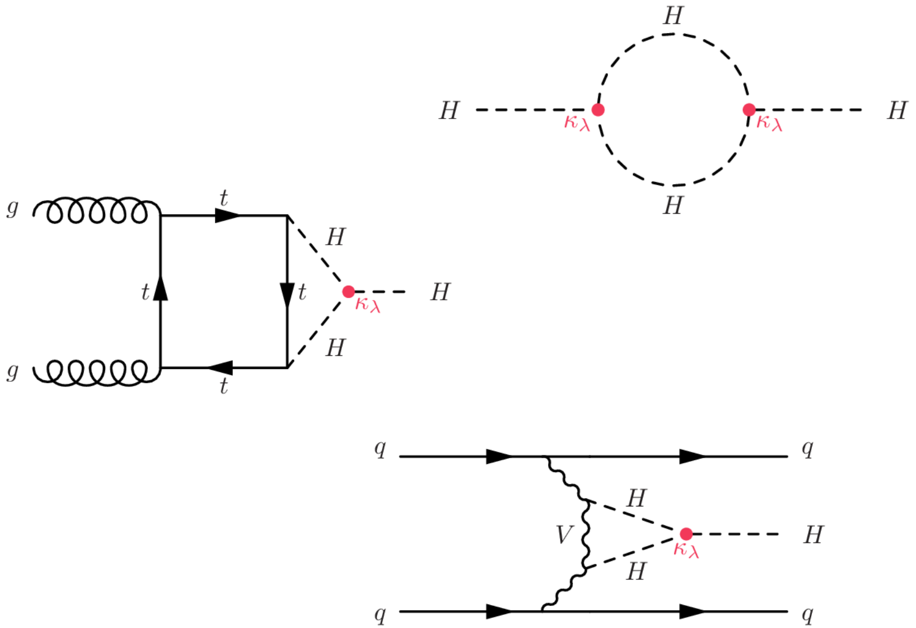


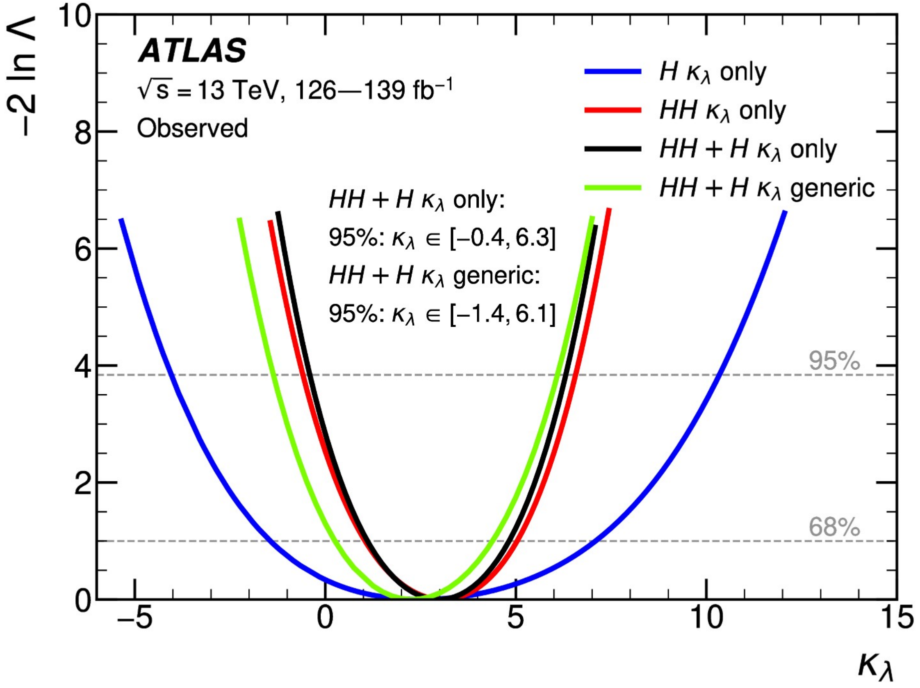
Global significance of largest excess is **2.1σ**

Each of the 3 decay channels is the most sensitive in a different mass range: **good complementarity**

Non-resonant: combining channels

We can combine with single-Higgs channels for maximum sensitivity to the self-coupling

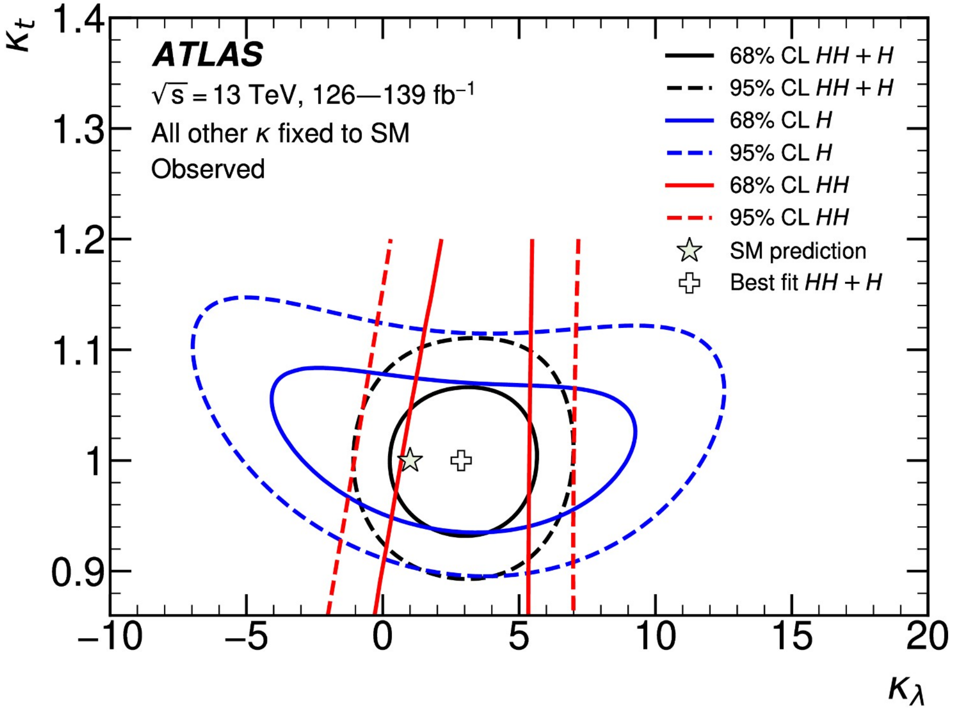


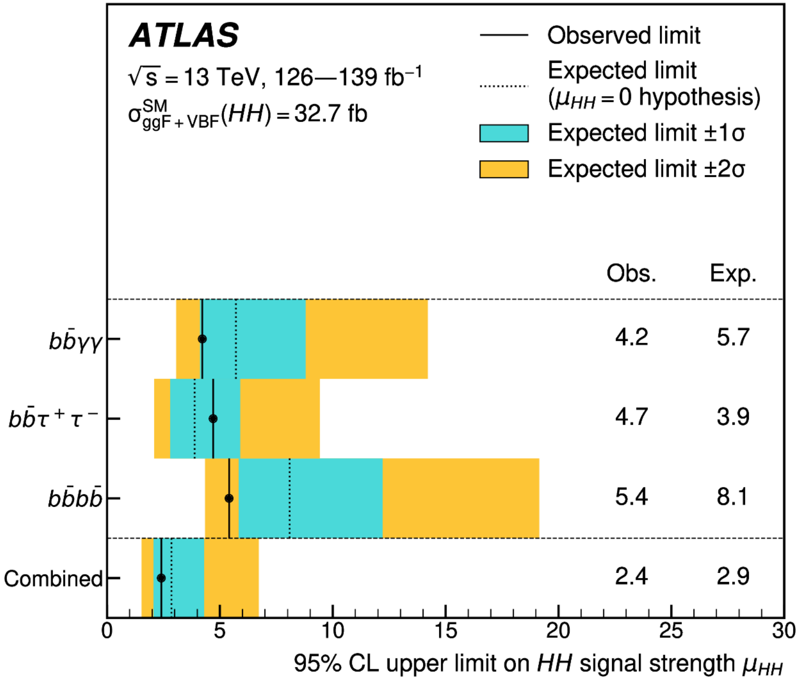


arXiv:2211.01216

Non-resonant: combining channels

Single Higgs channels provide complementary contraints on ttH coupling





arXiv:2211.01216

Looking ahead: the future

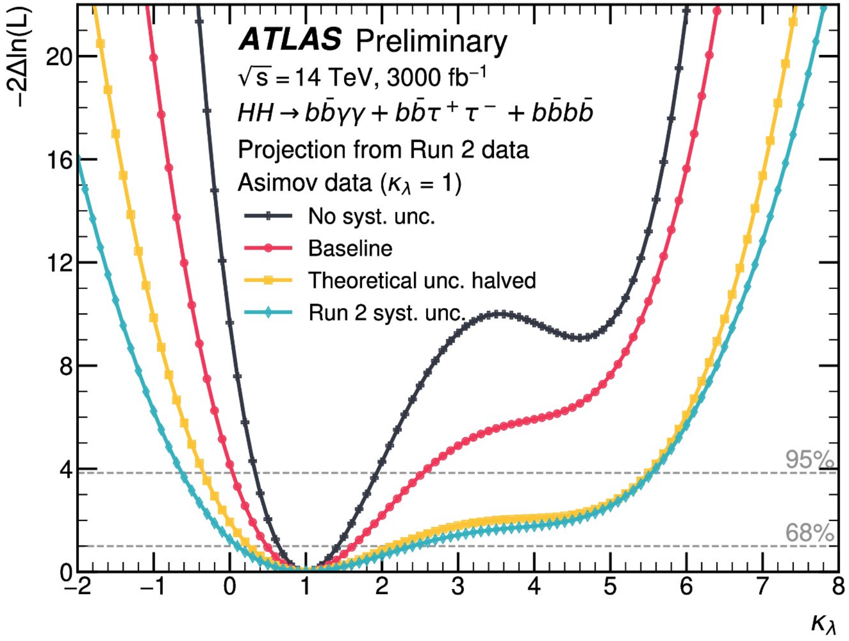
We're transitioning from "search" to "precision measurement" paradigm

Baseline ATLAS HL-LHC projection expects evidence for SM HH production at 3.4σ

- Roughly **5σ** in the limit of small systematic uncertainties
- This assumes current analysis methodology: good chance we'll exceed this!

Future colliders can do even better

- O(10%) precision expected on self-coupling at ILC, FCC-ee. Mainly from single Higgs!



Summary

Higgs pair production gives us a unique probe for physics beyond the SM.

- **Resonant production** lets us directly search for new particles decaying to HH
- **Non-resonant production** lets us search for indirect effects and explore the **Higgs potential**

ATLAS has a broad set of results constraining these processes

- **CMS** has an analogous set of results: methodology varies, but conclusions very similar
- Everything in agreement with SM so far, but sensitivity improving rapidly
  - Will need to get more clever with our methods to keep reducing backgrounds/systematics

This will continue to be a rich area of study for years to come!

- “Observation” of Higgs pair production at LHC not out of the question