UNIVERSITY OF CAMBRIDGE

TRINITY HALL CAMBRIDGE

An experimental perspective on tri-Higgs production

Bill Balunas

University of Cambridge

HHH Workshop
14 July 2023

Introduction

HHH production is interesting for a variety of reasons

- Won't go in detail on motivation: see other talks at this workshop!

No experimental study of HHH has been produced to date.

- Complex final states, potentially difficult-to-model backgrounds at LHC
- Very small cross sections

Today I'll discuss what experimentalists view as some of the main issues

- Final state considerations
- Lessons learned from HH analyses (the most similar done so far): mainly ATLAS perspective
- Main practical challenges and ideas for overcoming them
- Relevant questions for theorists

Disclaimer: I’m a member of ATLAS, but this is not a standard “ATLAS talk”. All views expressed are my own and I’m not speaking on behalf of the Collaboration today.

That said, my views are based on experience with HH at ATLAS, and I will refer to some past results for context and lessons learned.

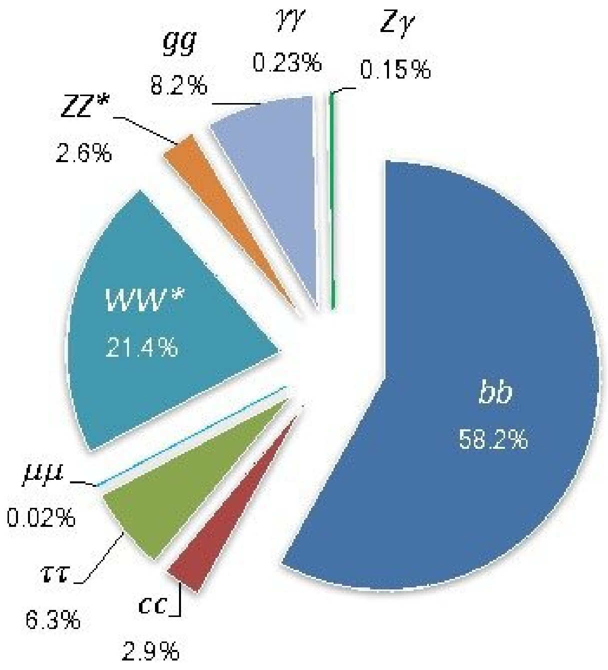
- Obviously, I will **only** be referring to material which is public (See ATLAS’s Public Results page for reference).

Decay channels

To look for HHH, we'd need to study the decay products of 3 Higgs bosons.

Many combinations are possible, each requiring a different experimental approach.
Which ones to look at?

SM Higgs boson branching ratios



Decay channels: HH

Look to HH for guidance

- ATLAS and CMS have found that bbγγ, bbττ, and bbbb are currently the most sensitive.
- Signal rate generally too small in channels without H→bb decay.
- bbγγ and, to a lesser extent, bbττ, are statistically-limited with the current LHC dataset. Also true for bbbb in resonant searches.

	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%

Seems to imply that HHH→bbbbXX is a good starting point

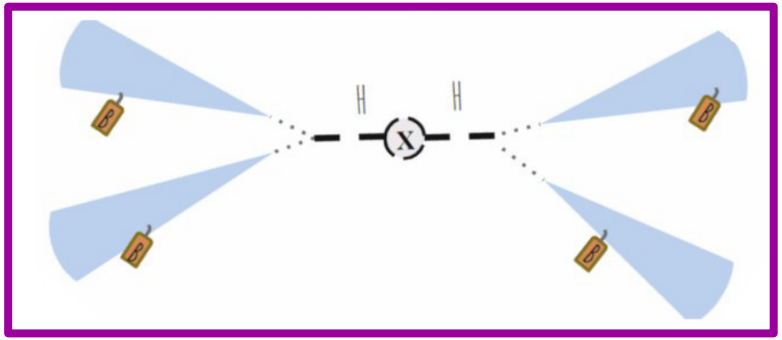
HH→bbbb: a brief review

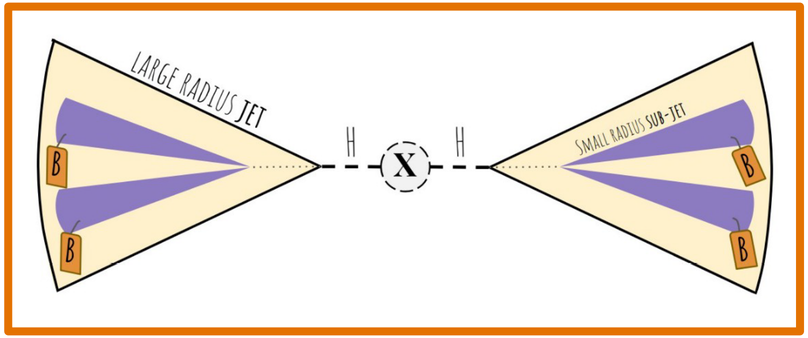
bbbb has the highest branching fraction (~34% in SM), but the largest background

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

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

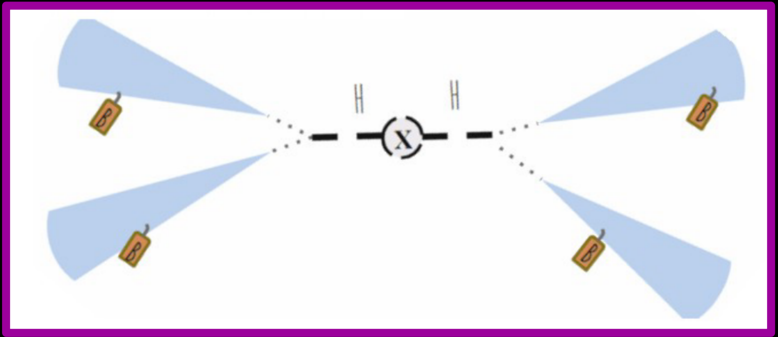
- With HHH, we could have any number of H→bb decays merged. Mainly relevant for heavy resonances

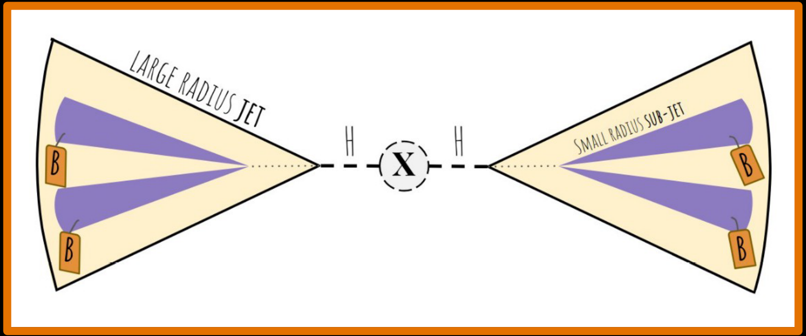




Resonant: Phys. Rev. D 105 (2022) 092002

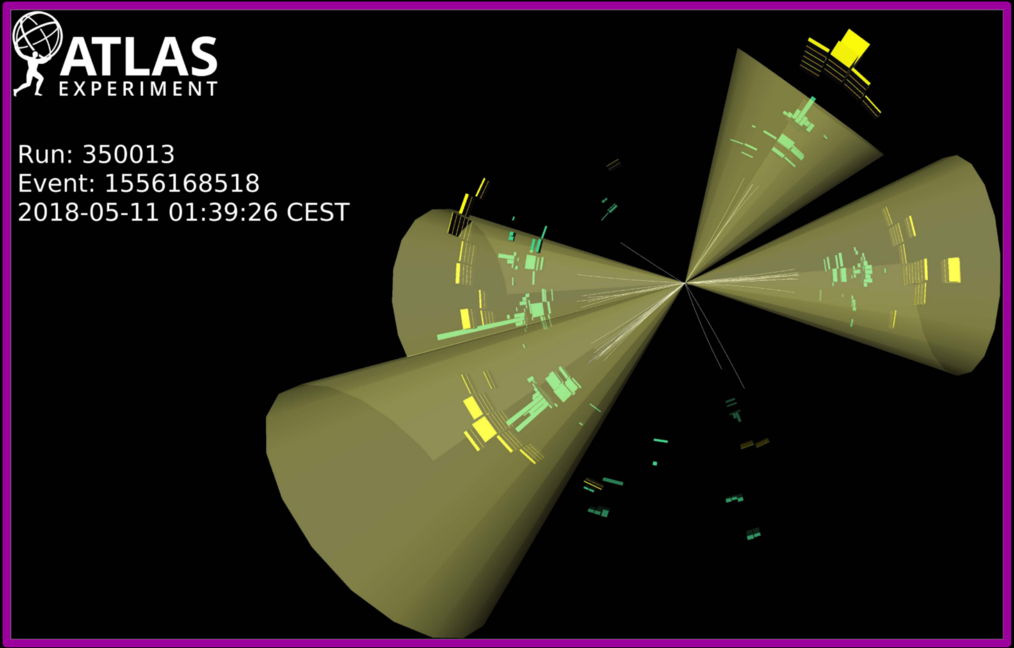
Non-resonant: arxiv:2301.03212

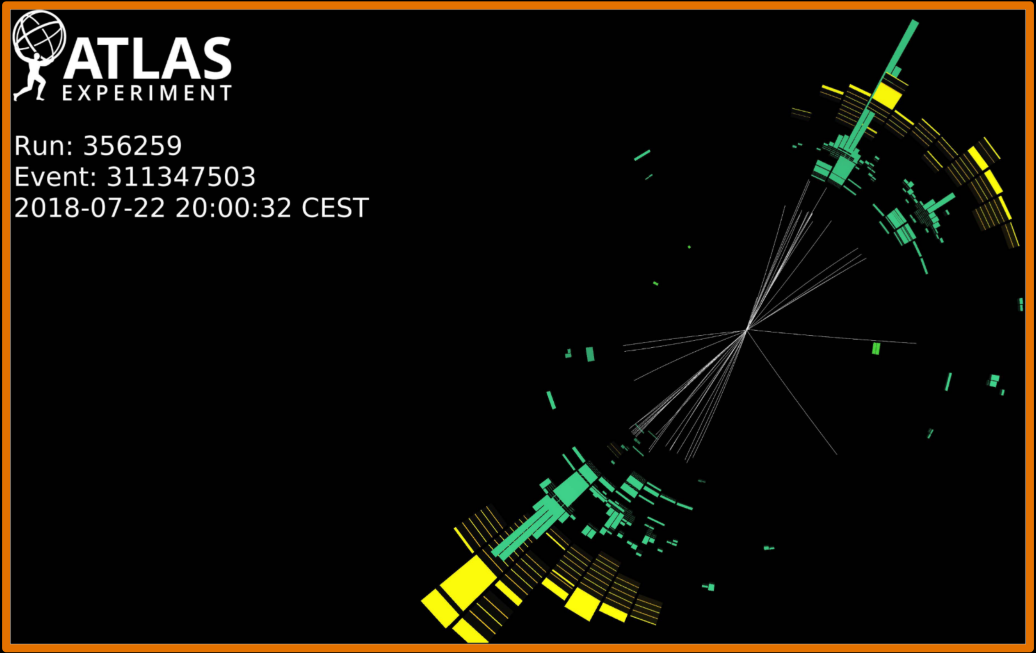




Resolved

Boosted





HH→bbbb: ATLAS overview

1. Select events with 4 b-tagged jets (p_T >40 GeV, so trigger can catch event)

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

A word on triggers

1. Select events with 4 b-tagged jets (p$_T$ >40 GeV, so trigger can catch event)

2. Pair these je

3. Construct a s

   – Also construct ... kground

4. Construct a b

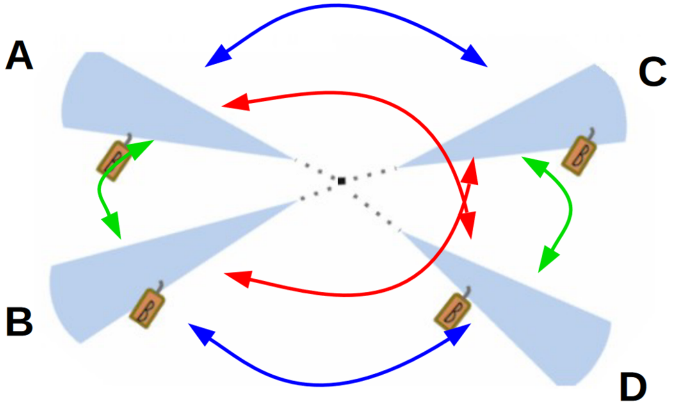
   – Use events wi

Triggering can be a major challenge, especially in fully hadronic final states!

Most SM HH→4b events fail this criterion. HHH searches will face similar issues, depending on decay channel.

Maggie will discuss this in more detail tomorrow.

HH→bbbb: Jet Pairing



3 possible pairings

(AB) (CD)

(AC) (BD)

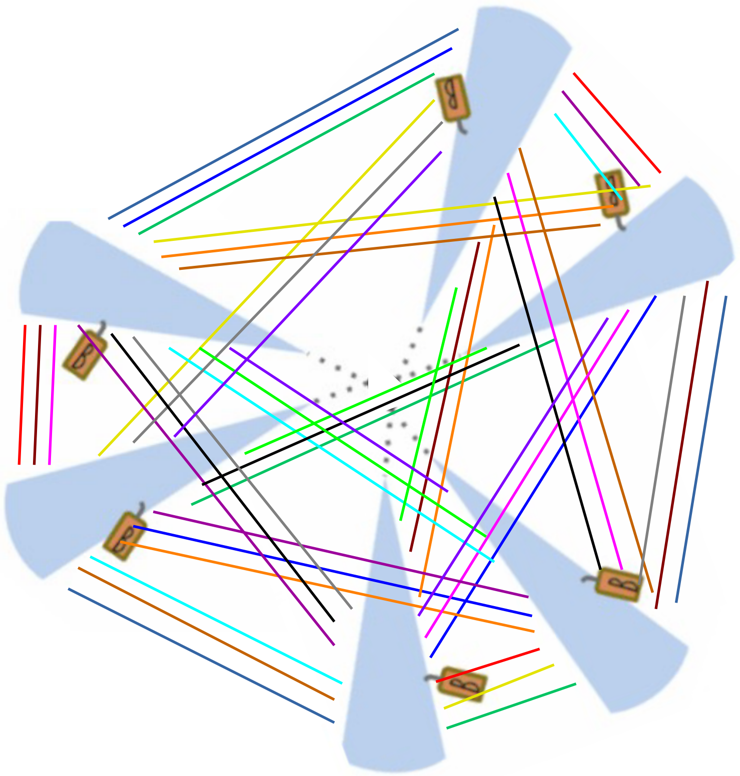
(AD) (BC)

Ambiguity in resolving which jet came from which Higgs

- Choose pairing which gets masses as close to 125 GeV as possible? Works, but biases background!
- ATLAS resonant search: Use a boosted decision tree with angular variables as input features
- ATLAS nonresonant search: Simply minimize ΔR_{jj} for leading H.

Similar methods could presumably be used in HHH final states with 4b plus some other decay

HHH→6b: Jet Pairing



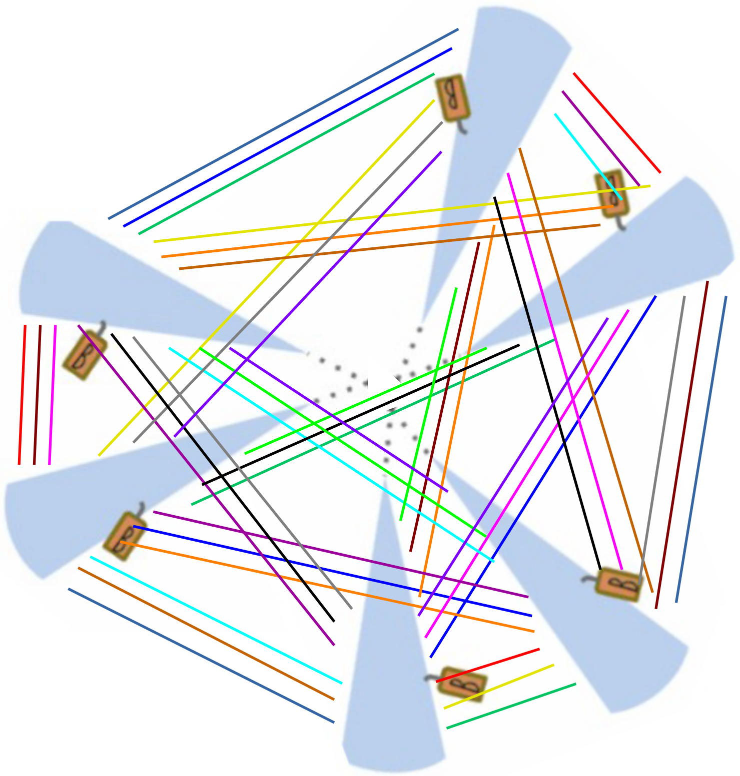
With 6 jets, there are 15 ways to pair them into Higgs boson candidates

- Grows combinatorially if there are any additional jets, e.g. from ISR/FSR

Higher jet multiplicity means events tend to be somewhat isotropic

- Unless the jets have high p_T, each pair must have a wide opening angle for m=125 GeV.
- Event needs a lot of energy for the 3 Higgses to be clearly separated. Mainly only common if we're considering heavy HHH resonances
  - If resonance is heavy enough, the jets from each H can merge

HHH→6b: Jet Pairing



Several approaches are possible

- BDT or NN based pairing, like ATLAS HH→4b?
- More sophisticated ML algorithms, e.g. permutation-invariant attention networks (see SPANet, 2106.03898)?
- Maybe simple minimization of mass deviation from 125 GeV is actually OK (efficiency worth the bias trade-off), especially if background is small?
- Maybe don't need to assign a jet pairing at all? May have implications for background estimation…

How to optimize pairing definition/algorithm?

- SM HHH has very different kinematics from models with (or without!) resonances
- Within resonant models, there's dependence on mass, whether there's a multiply-resonant structure, etc.

Background estimation challenges

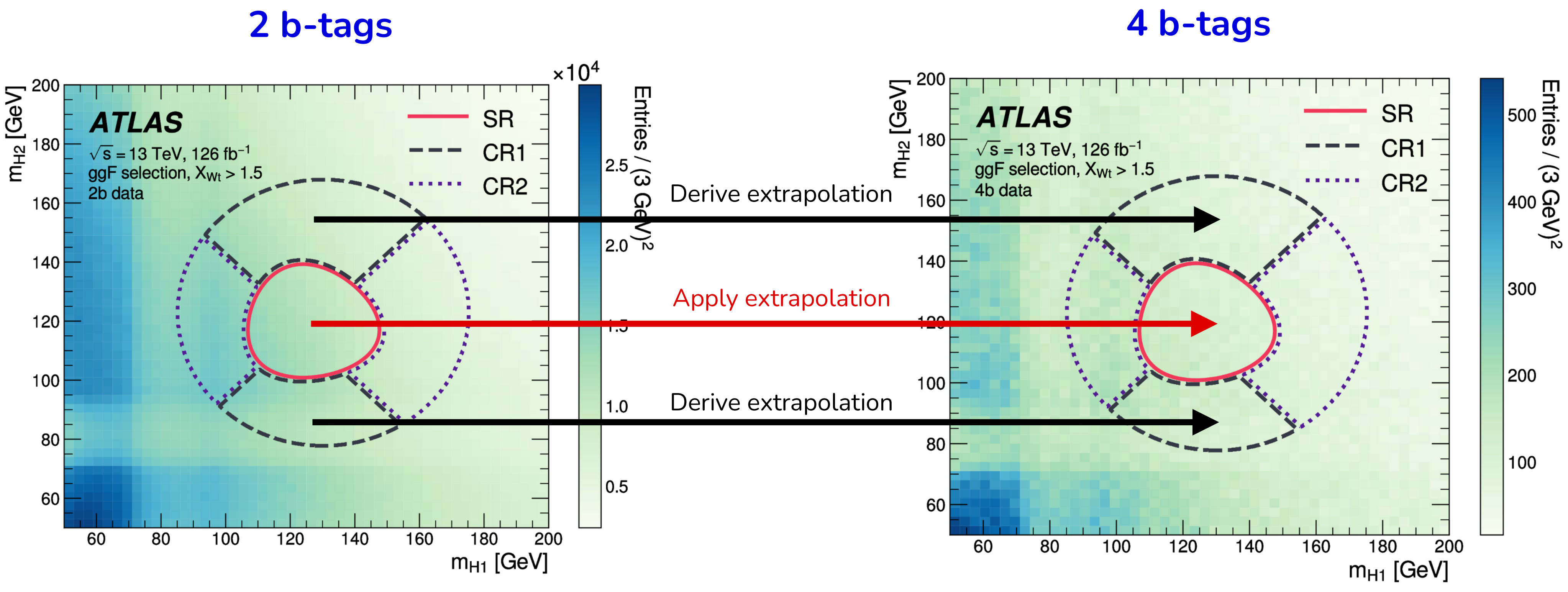
Final states with high multiplicities (*especially* of hadronic objects) have hard-to-model backgrounds

- Even simulating 2→4 QCD with sufficient accuracy and statistics to model the background for HH→4b is currently infeasible.
- HH→bbττ (with hadronic τ decays) has a significant background from “fake” τ’s (misidentified jets). Very hard to model in simulation!
- These headaches will only get worse with 6 objects in the final state!

Usual solution to these issues is a data-driven background estimate

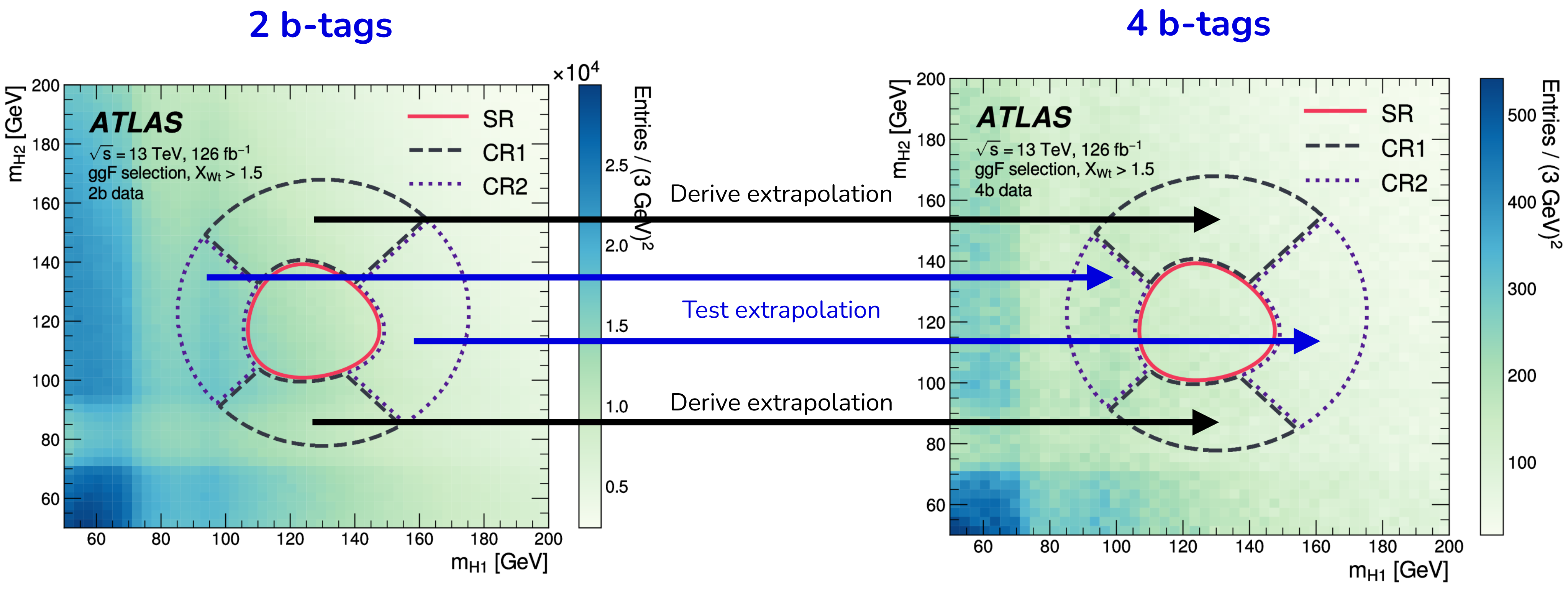
- Construct a control sample in the real data and make assumptions to extrapolate to “signal region”.
- These assumptions will need to be checked and come with meaningful uncertainties (on the distributions which are ultimately fit – invariant masses, etc.).

ATLAS HH→bbbb: Background model



Assumption: mapping from 2b → 4b kinematics is the same in the CR and the SR

ATLAS HH→bbbb: Background model



Validate with an independent data sample, use this to help estimate uncertainties

Background estimation challenges

Any experimental HHH study in the near future will almost certainly need to use some form of data-driven background model

- **Challenge:** How to construct a control sample which is enriched in background, but kinematically very similar to the main sample/"signal region"?
- **Challenge:** How to validate this background model and estimate meaningful uncertainties associated with it?
- Answers will depend on the final state and analysis strategy…

Example: QCD is flavor-agnostic, so its kinematics should be largely independent of whether the jets are b-tagged. Can look at events with non-b-tagged jets.

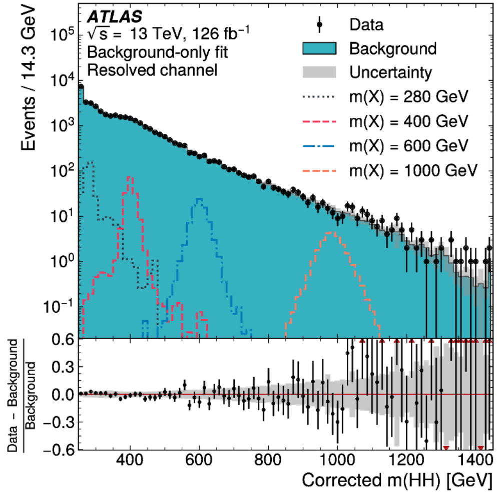
- "Largely", but not *exactly*, because the proton PDF has much more light flavor than bottom, and sometimes the initial state flavor is correlated with the final state flavor.
- Need to understand the size of this effect, which will require a *different* independent sample.

Fitting & Interpretation

Experimentalists need to compare the data to different hypotheses (SM, varied couplings, BSM models...) with some statistical test. How best to structure this?

HH→bbbb

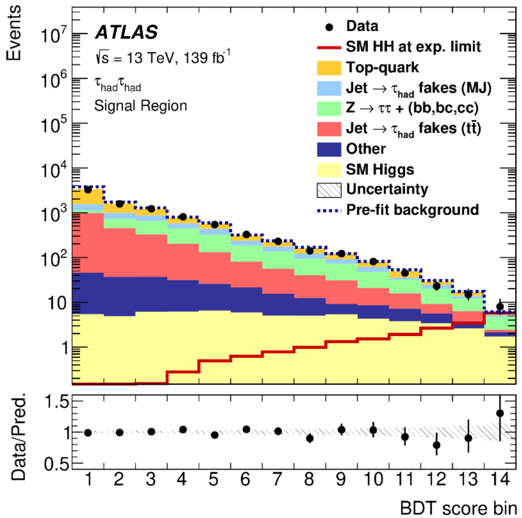
Phys. Rev. D 105 (2022) 092002



Fit multi-H invariant mass distribution?

HH→bbττ

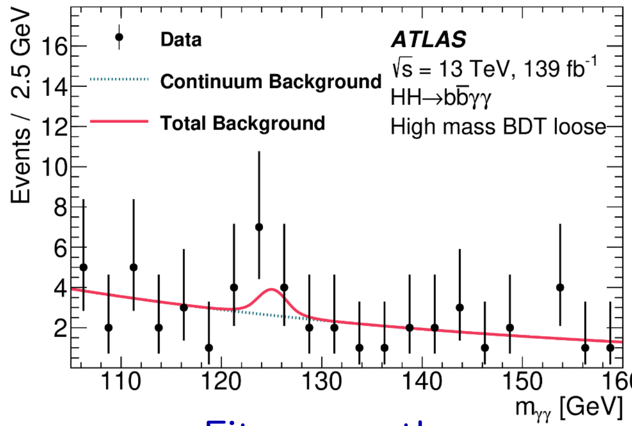
JHEP 07 (2023) 040



Fit some ML-based discriminant?

HH→bbγγ

Phys. Rev. D 106 (2022) 052001



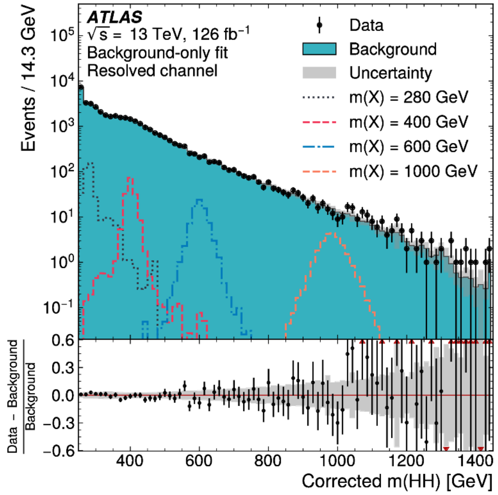
Fit some other kinematic variable?

Fitting & Interpretation

Experimentalists need to compare the data to different hypotheses (SM, varied couplings, BSM models…) with some statistical test. How best to structure this?

HH→bbbb

Phys. Rev. D 105 (2022) 092002



Fit multi-H invariant mass distribution?

HH→bbττ

- Clear physical interpretation, especially for resonance searches.
- Also try to fit intermediate resonance for Y→XH→HHH (e.g. TRSM and similar models)?
- May be challenging at low masses where trigger effects are relevant.
- Sensitivity for nonresonant interpretations may vary depending on the models being considered

Fit some ML-based discriminant?

Fit some other kinematic variable?

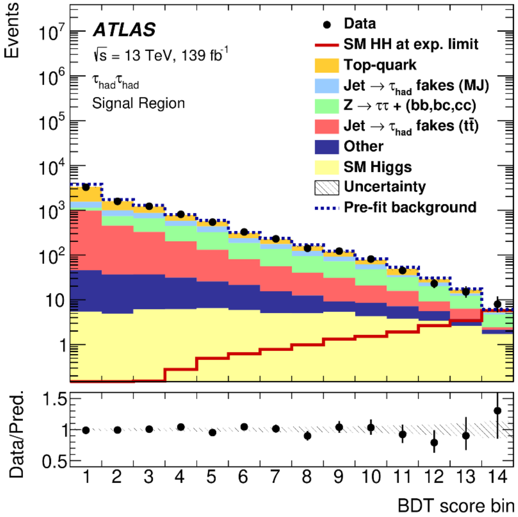
Fitting & Interpretation

Experimentalists need to compare the data to different hypotheses (SM, varied couplings, BSM models…) with some statistical test. How best to structure this?

- Will have best nominal sensitivity, by construction
- Systematic uncertainties may be difficult to understand
- May be very sensitive to model on which the ML algorithm is optimized. Loss of generality?
- Can be difficult to interpret the distributions physically, especially for theorists who want to re-interpret.

HH→bbττ

JHEP 07 (2023) 040



Fit some ML-based discriminant?

HH→bbγγ

Phys. Rev. D 106 (2022) 052001

Fit some other kinematic variable?

Fitting & Interpretation

Experimentalists need to compare the data to different hypotheses (SM, varied couplings, BSM models…) with some statistical test. How best to structure this?

HH→bbbb

Phys. Rev. D 105 (2022) 092002

HH→bbττ

JHEP 07 (2023) 040

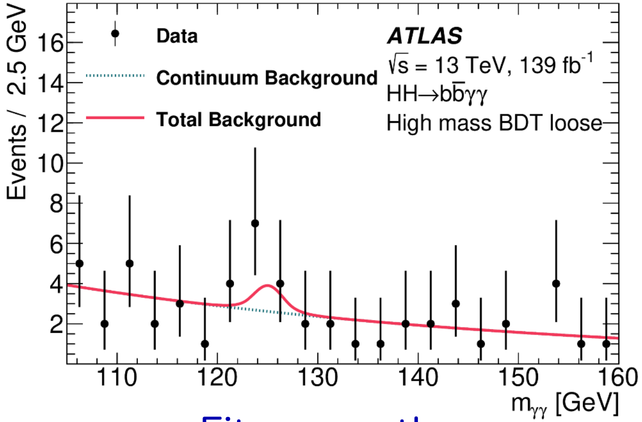
- Sacrifice discrimination power in exchange for simplicity.
- Salient information may be integrated out (if an excess is seen, would need separate studies to characterize it)
- May be worthwhile for very clean final states (e.g. with H→γγ) where statistics effectively only allow a cut-&-count analysis

Fit multi-H invariant mass distribution?

Fit some ML-based discriminant?

HH→bbγγ

Phys. Rev. D 106 (2022) 052001



Fit some other kinematic variable?

Interpretation: discussion points

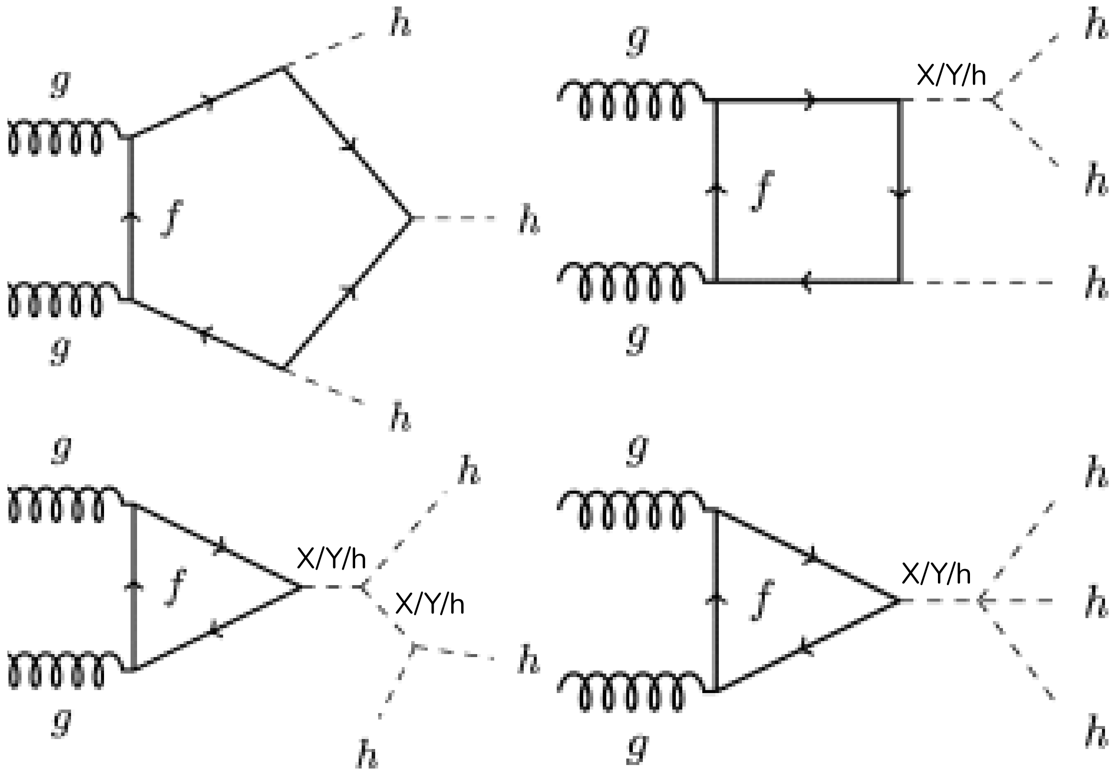
Nonresonant HHH interpretations

- **Simplest method:** Assume SM kinematic shapes and constrain cross section
  - Not necessarily representative of a realistic model, but potentially useful as a benchmark
- **Higgs quartic coupling:** Often quoted as something we can do with HHH.
  - SM value not within reach, even with 100 TeV FCC-pp (see e.g. 1810.04665)
  - Assuming the quartic coupling is independent of the cubic, at what values does it cease being perturbative? Would LHC results be theoretically meaningful in this framework?

Resonant HHH interpretations

- A variety of models predict HHH resonances (see various theory talks at this workshop!)
- Different models have different kinematic structures (intermediate resonances, contributions from non-resonant diagrams, etc.).
- Trade-off between optimizing for a particular model vs. retaining generality
- What about high mass resonances? Extended Higgs sectors often have perturbativity/unitarity issues in this regime...

Interpretation: discussion points



Example: add 2 scalars to SM (a la TRSM)

All of these diagrams contribute, with both scalar plus the Higgs in the internal propagators. Significant interference!

Relative contributions vary depending on model construction/couplings.

To explore more in discussion sessions?

Summary

HHH hasn't yet been done experimentally – because it's very hard!

- **Best decay channels** not obvious, but some H→bb decays will likely be needed for rate (trade-off vs. background)
  - 6b, 4b2W, 4b2τ, and 4b2γ appear to be good starting points
- **Low signal rates** and **hard-to-model backgrounds** in high-multiplicity states are among the main challenges
- **Design of statistical fits** and **interpretation of results** may be very nontrivial.

The challenges are not insurmountable

- HH analyses at ATLAS & CMS have faced similar ones and produced innovative methods
  - Machine learning algorithms have helped to squeeze out maximum sensitivity
- Data-driven background modelling is likely to be key for any near-term HHH search
- **Excellent detector performance also absolutely crucial:** triggering, flavor tagging…
  - I've glossed over this here because there's a whole session on it tomorrow!

Input from theorists very welcome on what would be valuable from the experiments

Backup

ATLAS HH→bbbb background model

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

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

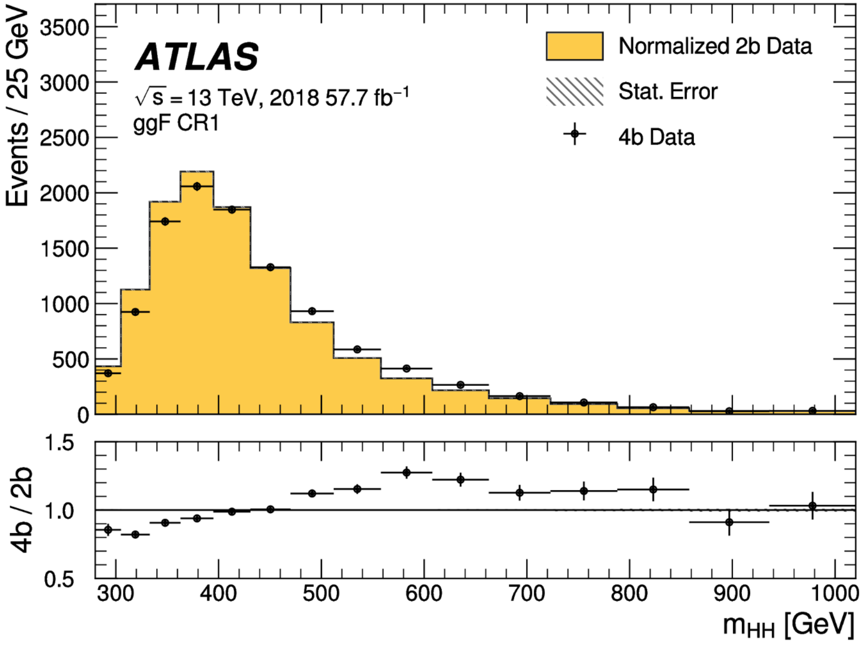
Neural network can "learn" the solution by minimizing:

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

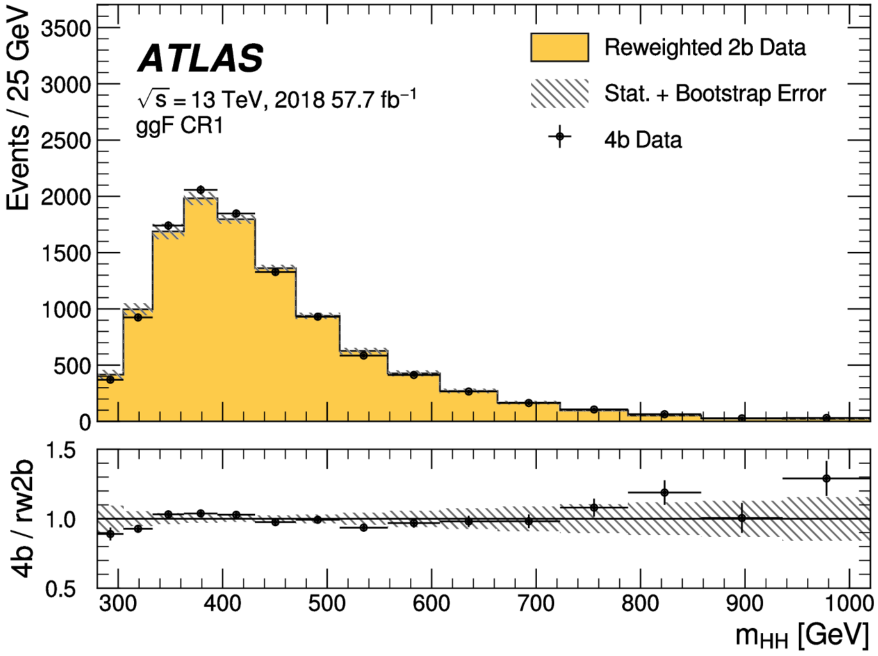
x are a a set of kinematic variables

ATLAS HH→bbbb background model

Before Reweighting



After Reweighting



ATLAS HH→bbbb systematics

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