Search for the Higgs boson decaying to four b-quarks via two spin-zero particles

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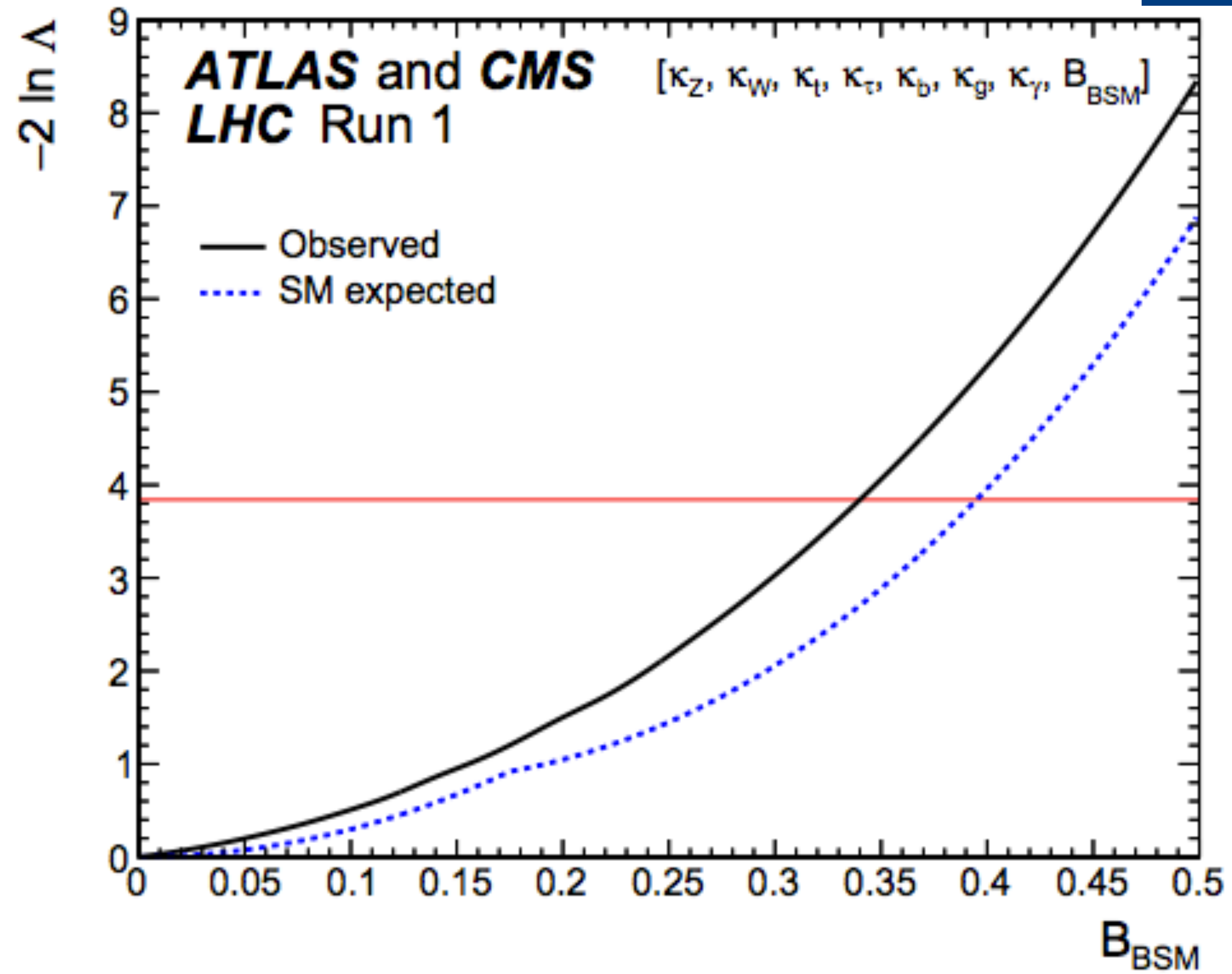
Exotic Higgs Decay Meeting
Nov 7, 2016

Physics motivation

- With the discovery of the Higgs, the next effort has been to see how well it fits into the Standard Model (SM)
- Available measurements constrain exotic decays in the SM to 34% at 95% C.L.
  - Simple extensions of the SM has the Higgs decay to two new spin-zero particles, a

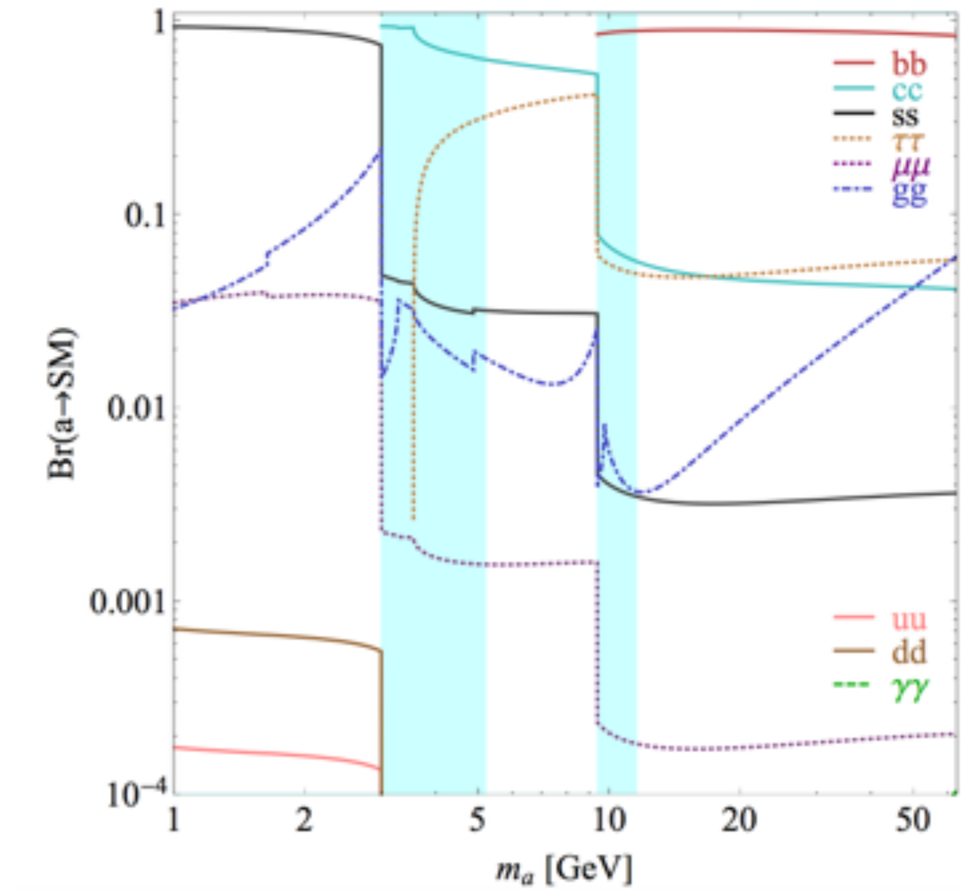


https://arxiv.org/pdf/1606.02266v2.pdf

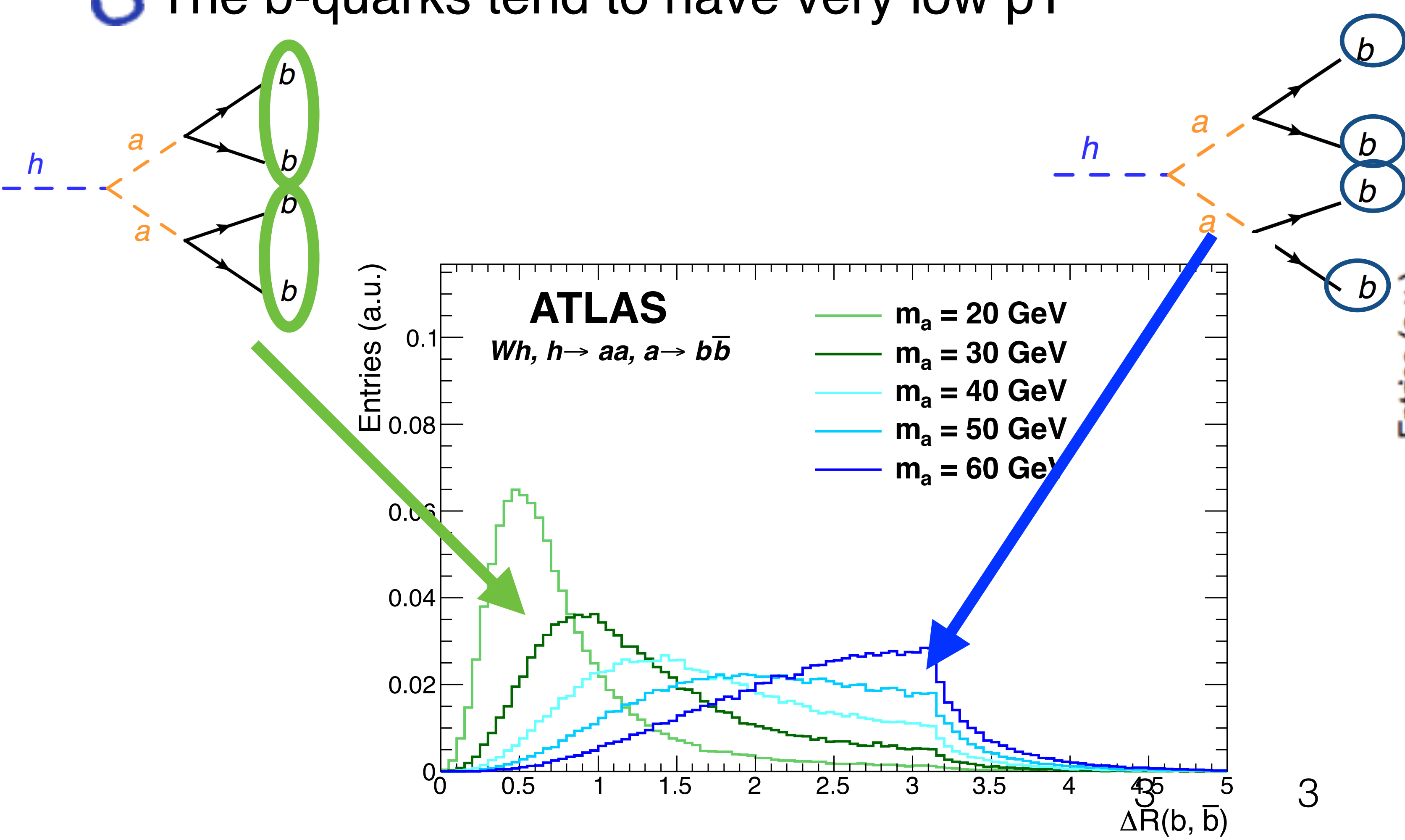
- Spin zero particle can address a few open ended questions in physics:
  - Potential mediator between dark matter and SM particles
  - Allows electroweak baryogensis as explanation of the observed matter/anti-matter asymmetry
  - Alleviate the naturalness problem of the Higgs boson mass

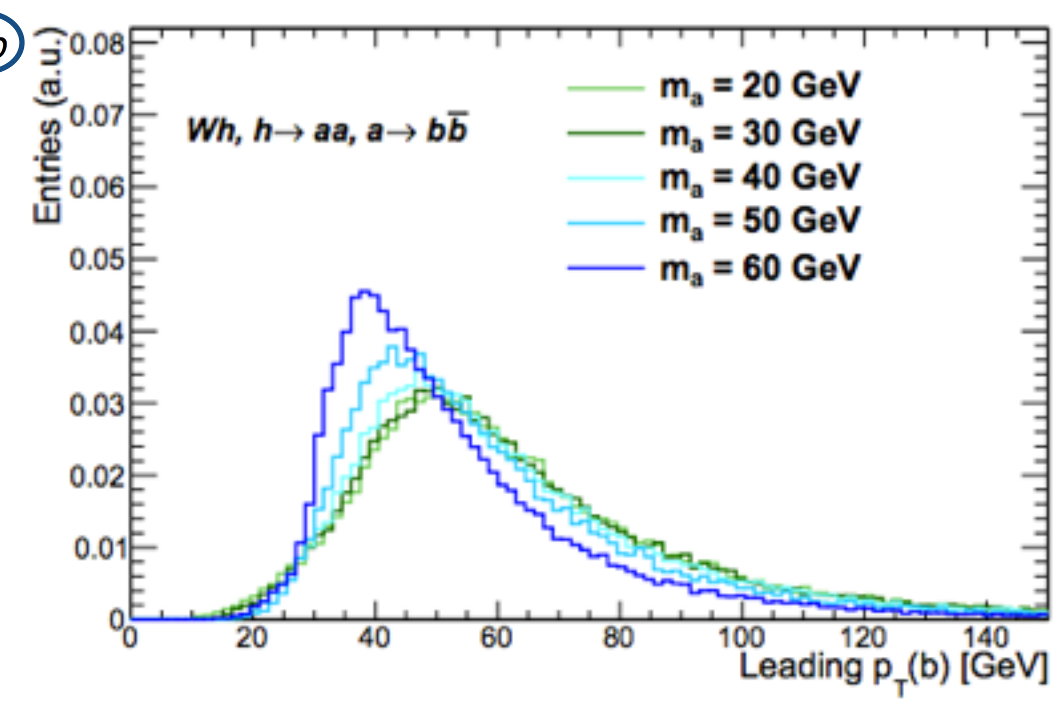
Signal Overview

https://arxiv.org/pdf/1312.4992v5.pdf



- In many models where a contains Yukawa couplings, a → bb is the dominant decay mode above when m_a is above b-pair production threshold
- The kinematics of the b-quarks depend on the spin-zero particle's mass
  - As the spin-zero particle mass decreases, the b-quarks from the same parent tend to be more collimated
- The b-quarks tend to have very low pT

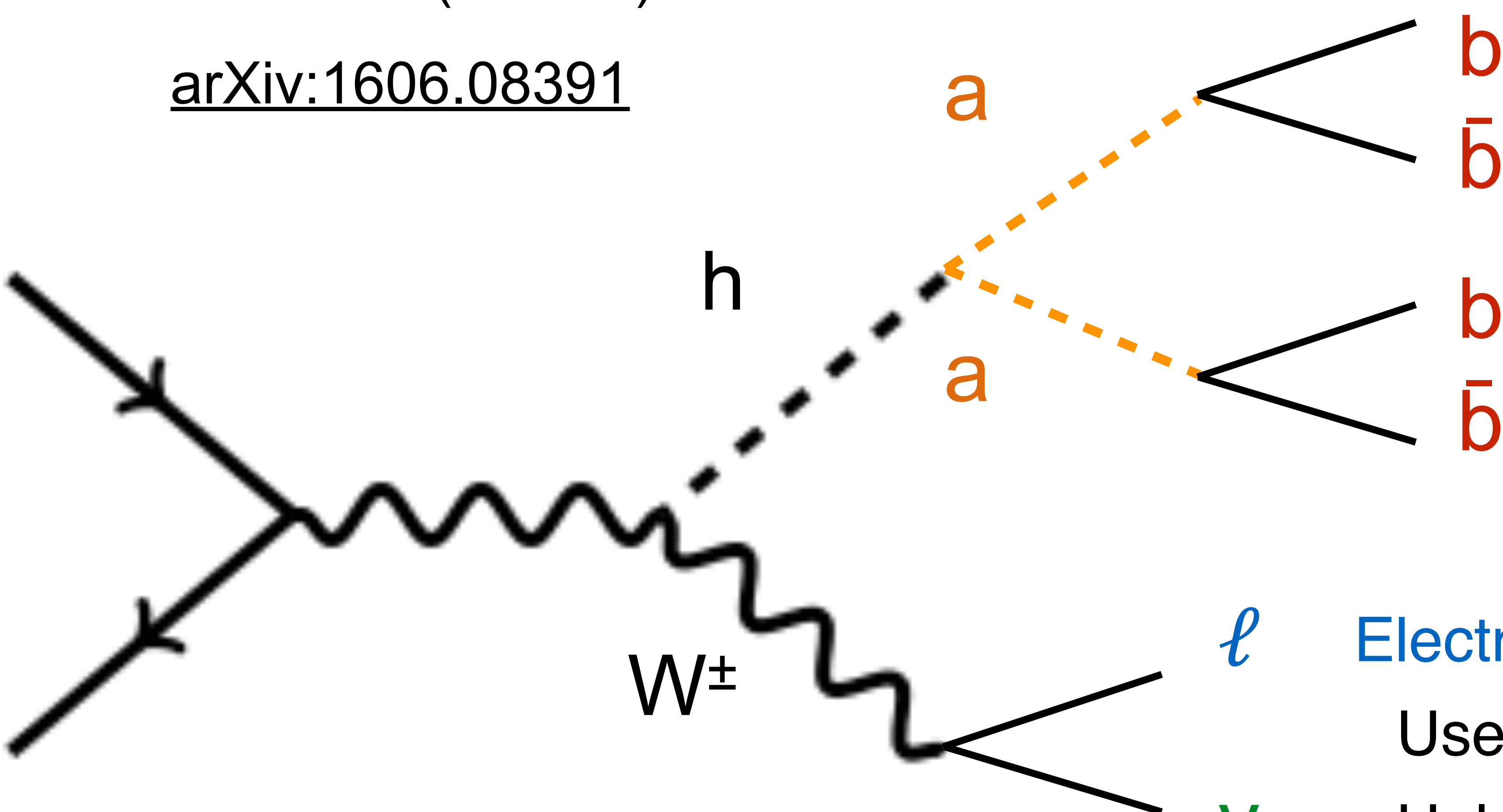




Experimental Signature

- Search for $h \to aa \to bbbb$ in association with a W boson
  - Paper published in EPJC using 2015 data (3.2 fb^{-1})

    arXiv:1606.08391



Jets

B-quarks in jets found with b-tagging, at 77% efficiency working point

Electrons or Muons

Used to trigger

Help distinguish from multi-jet backgrounds

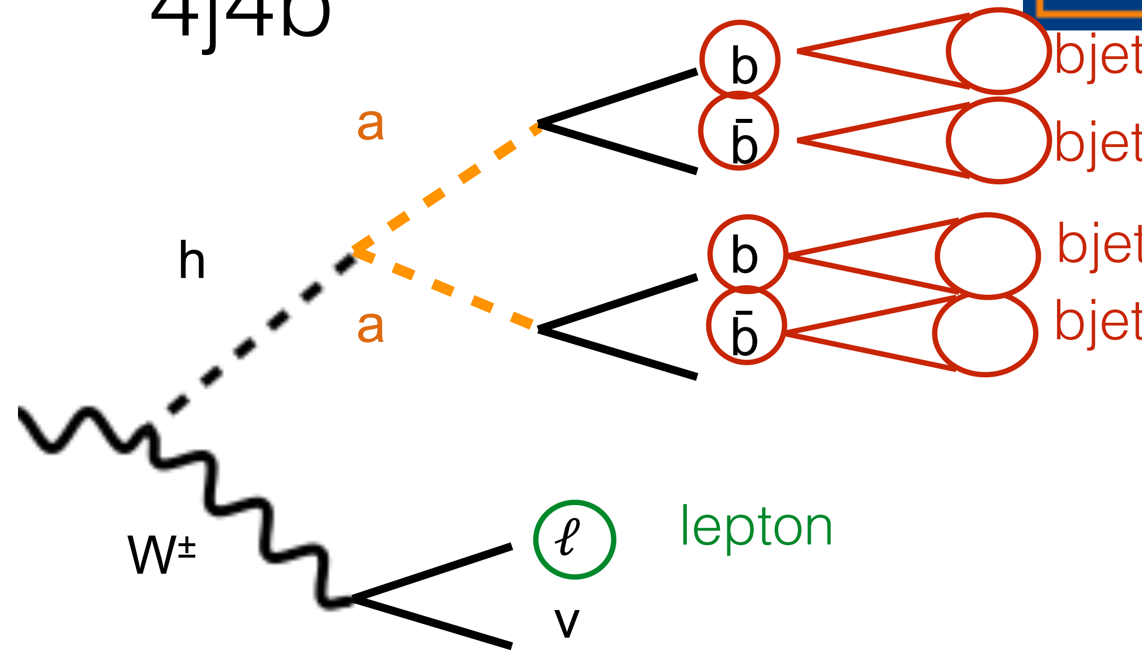
Missing Transverse Energy

Also help distinguish from multi-jet

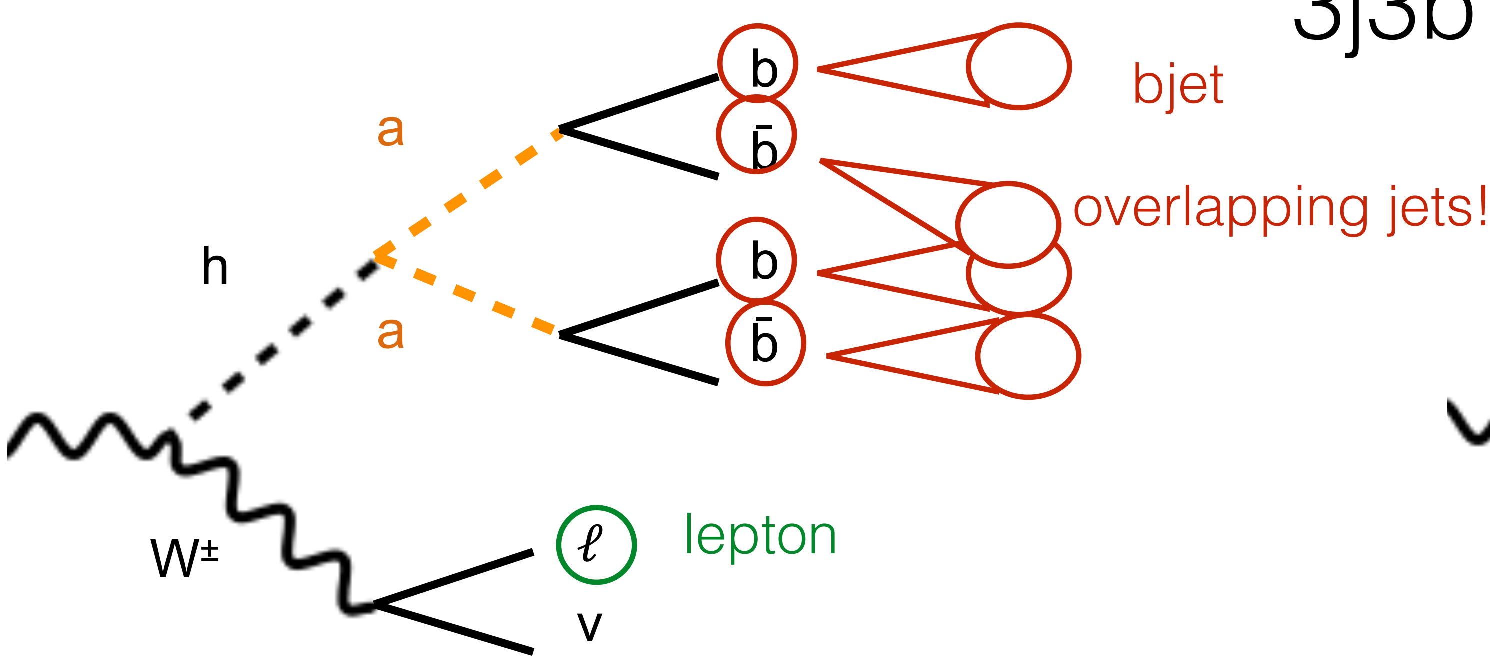
Signal Regions

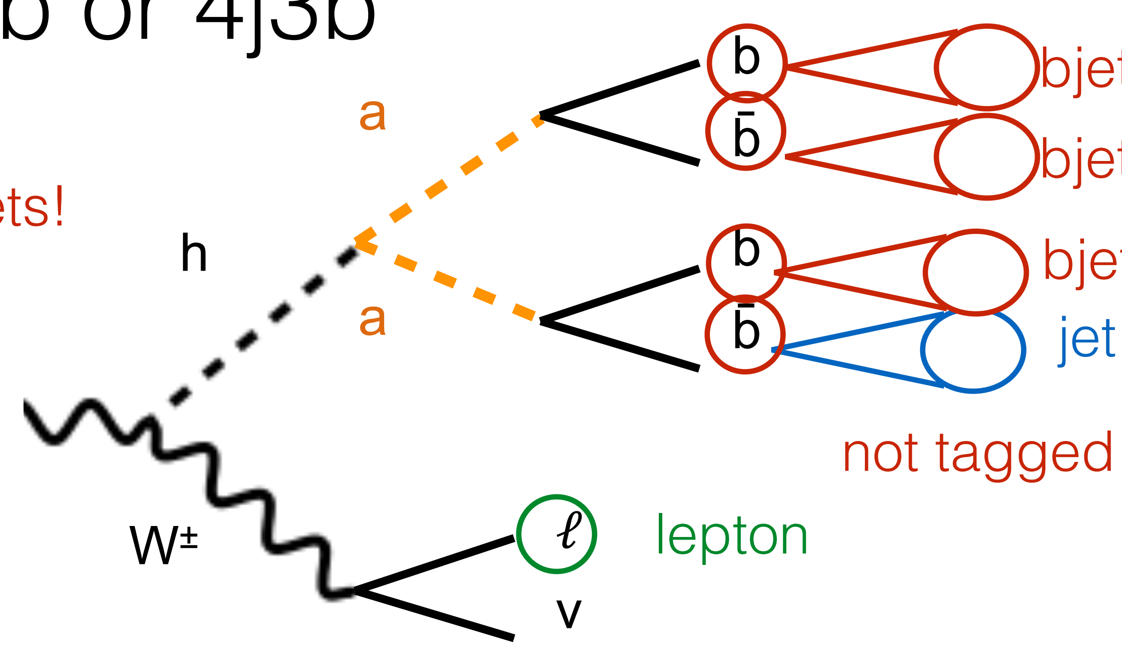
- Signal regions: one lepton and 3 or 4 jets with 3 or 4 b-tags
  - Mistags and possible b-parton overlaps affect b-jet multiplicity

4j4b



3j3b or 4j3b

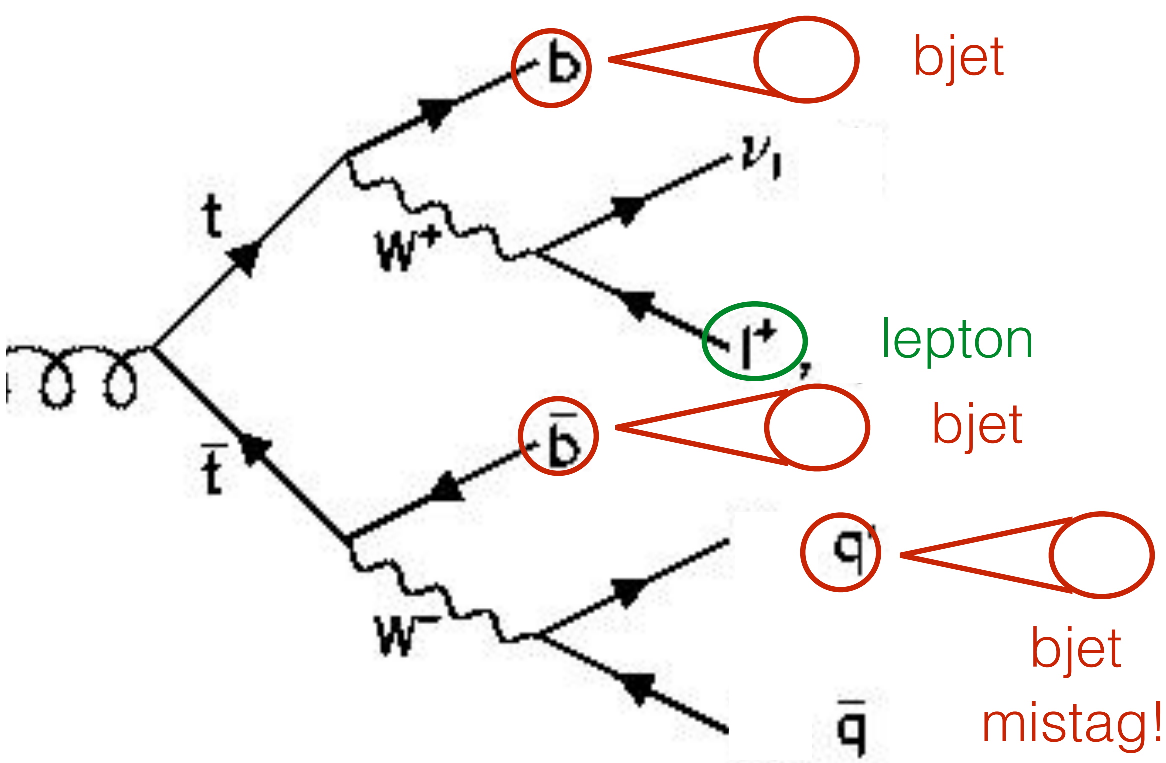




Backgrounds

- Main background process: $t\bar{t}$
- Semileptonic $t\bar{t}$ events can look like the signal signature and enter signal regions
  - Lepton comes from one W
  - b-jets come from top decays and mistagged hadronic W decay products

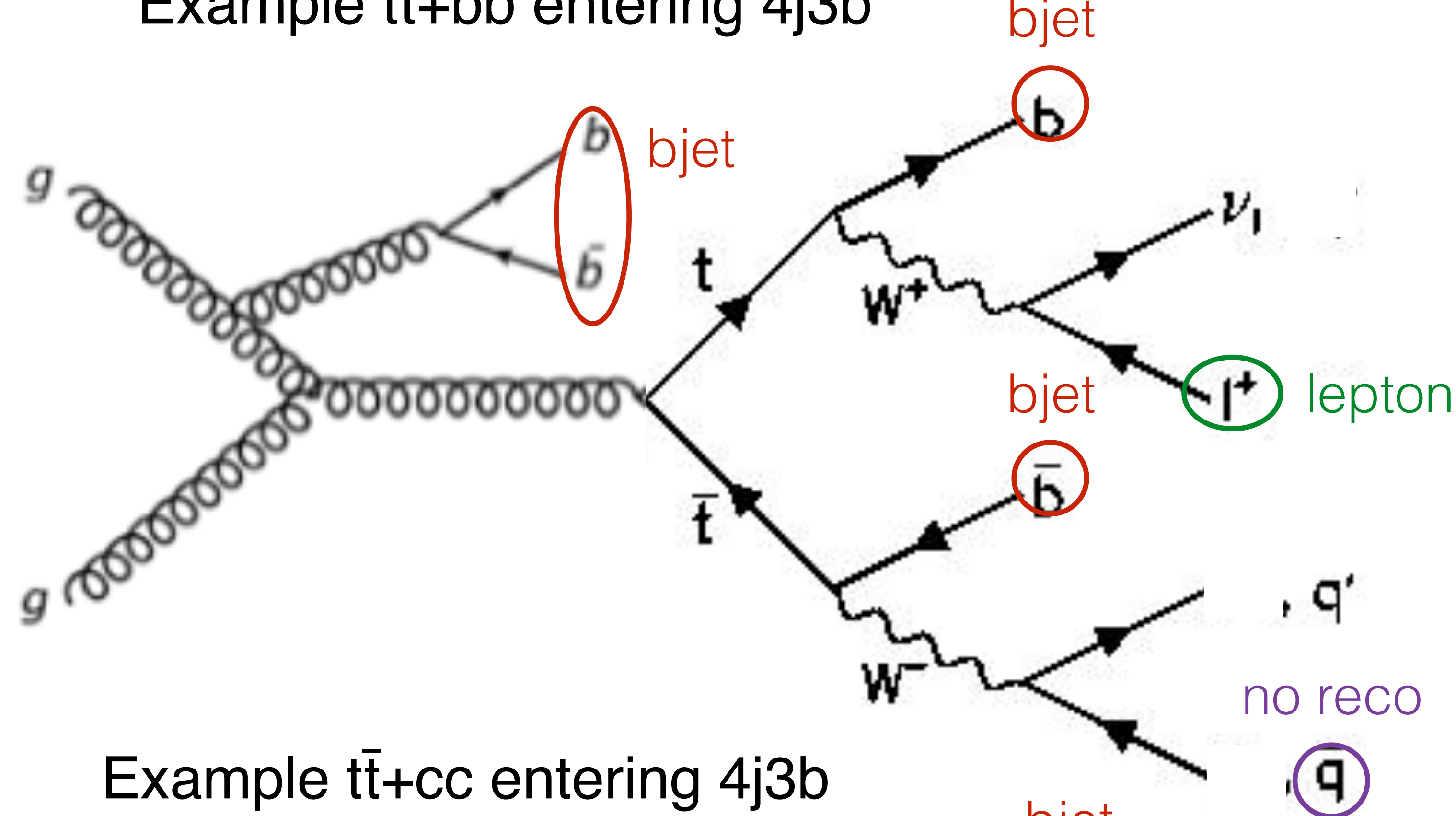
Example $t\bar{t}$ entering 4j3b



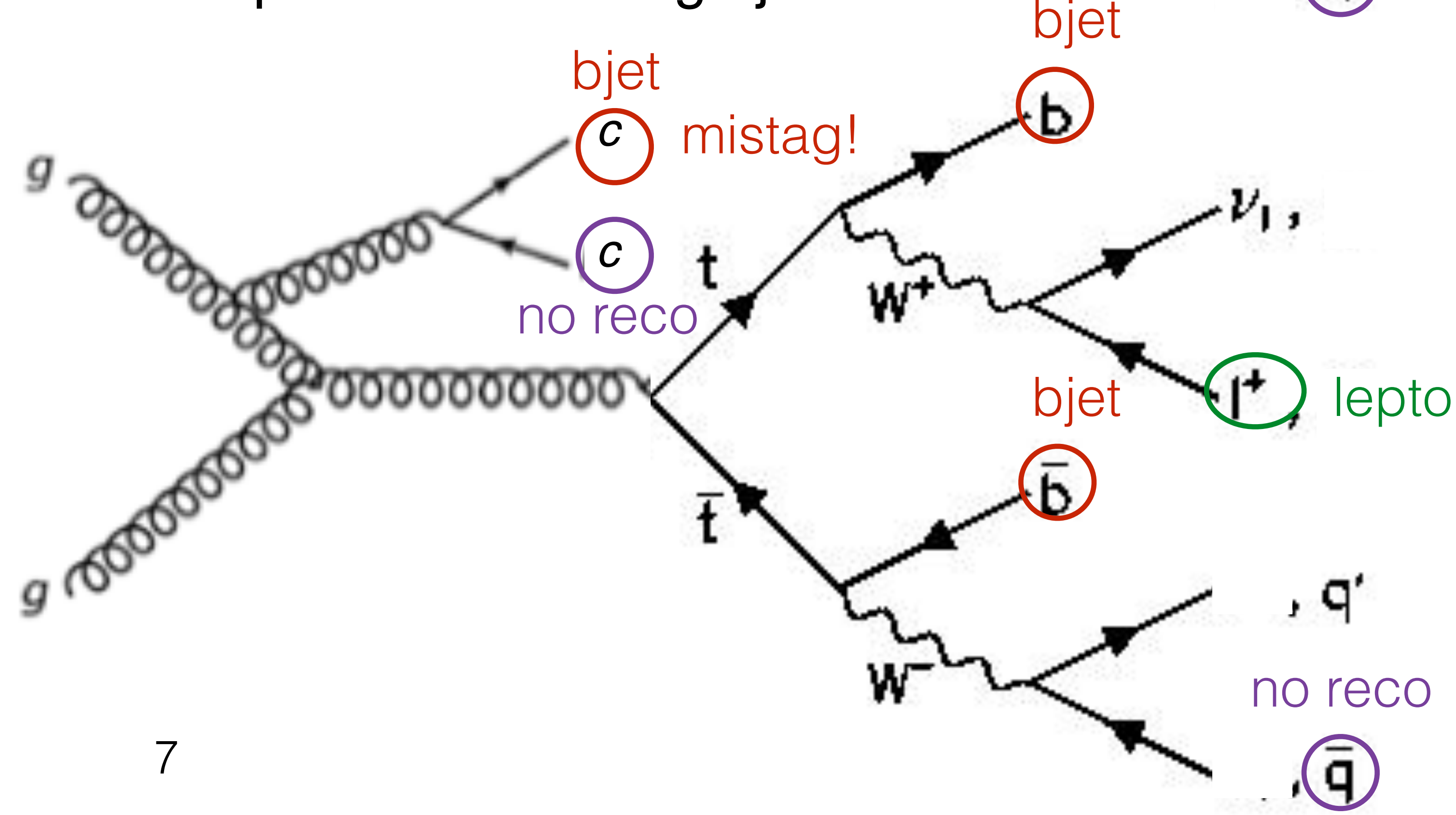
Backgrounds

- Additional radiation in $t\bar{t}$ events can cause them to be classified into signal regions
  - $t\bar{t}$+bb leads to more b-jets
  - $t\bar{t}$+cc can lead to more b-jets through mistags

Example $t\bar{t}$+bb entering 4j3b



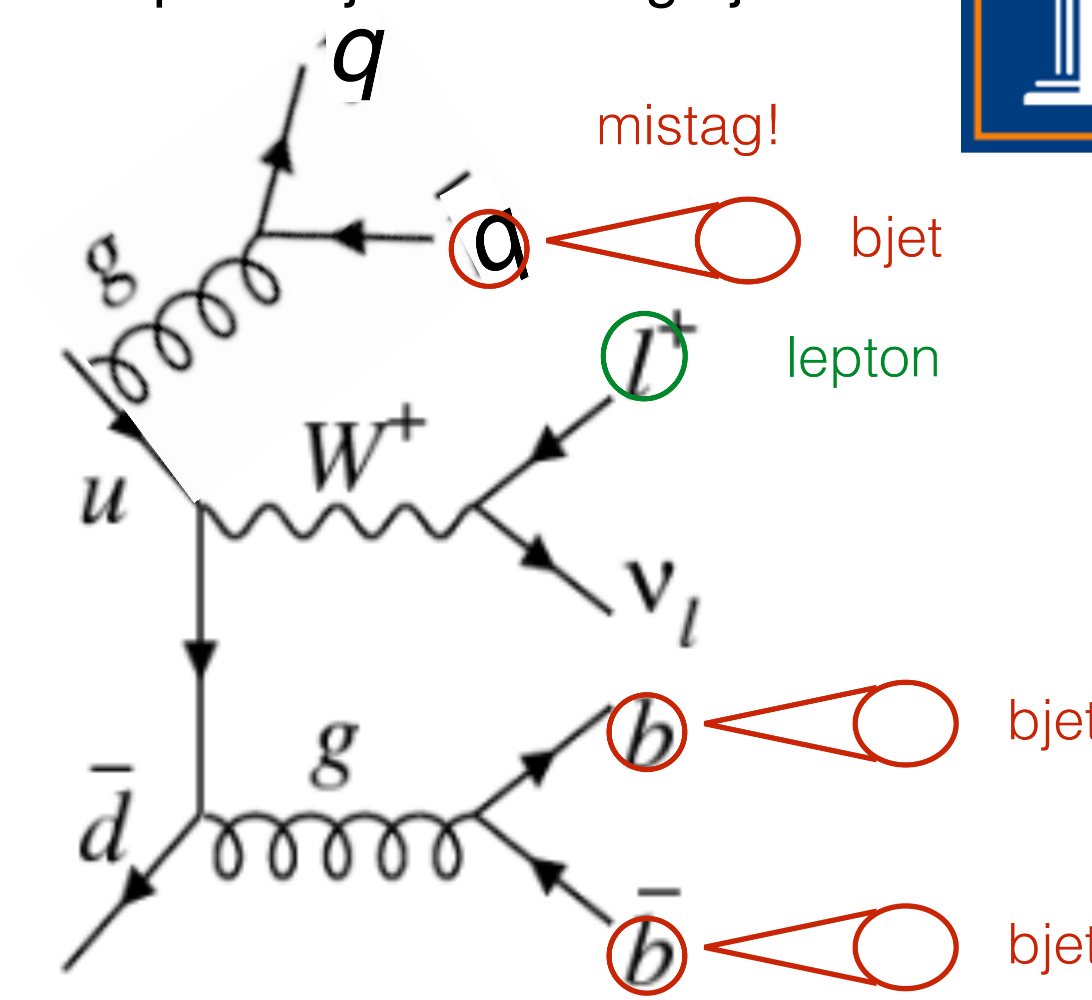
Example $t\bar{t}$+cc entering 4j3b



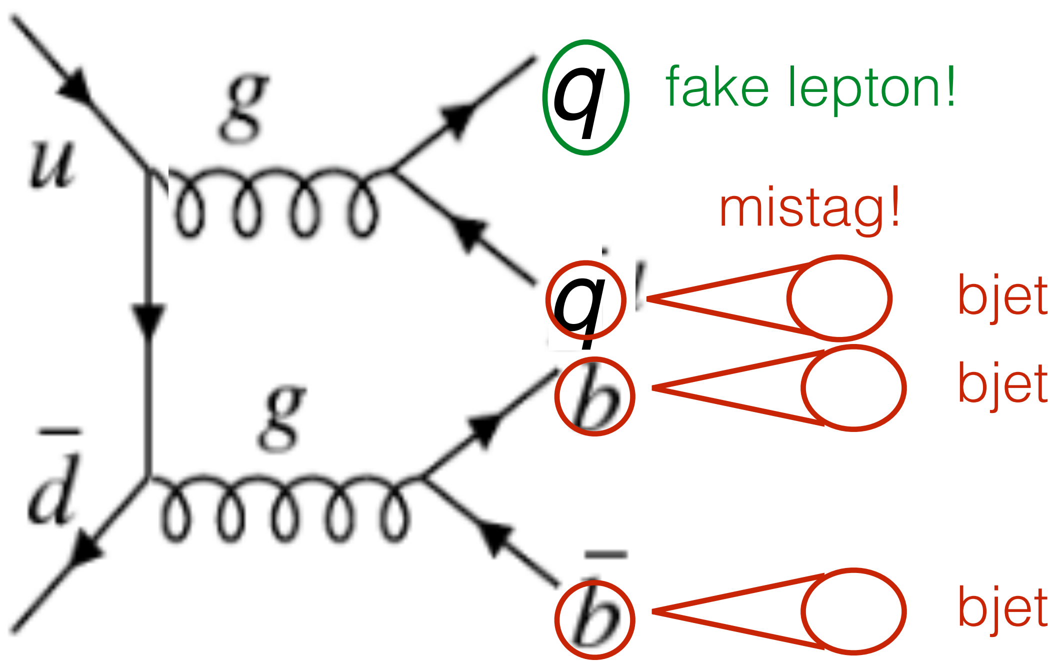
Backgrounds

- Additional background: W+jets
  - Lepton comes from one W
  - Jets from additional QCD processes in event
    - Radiative g →bb
    - Other radiation leading to mistags

Example W+jets entering 4j3b



Example multijet entering 3j3b



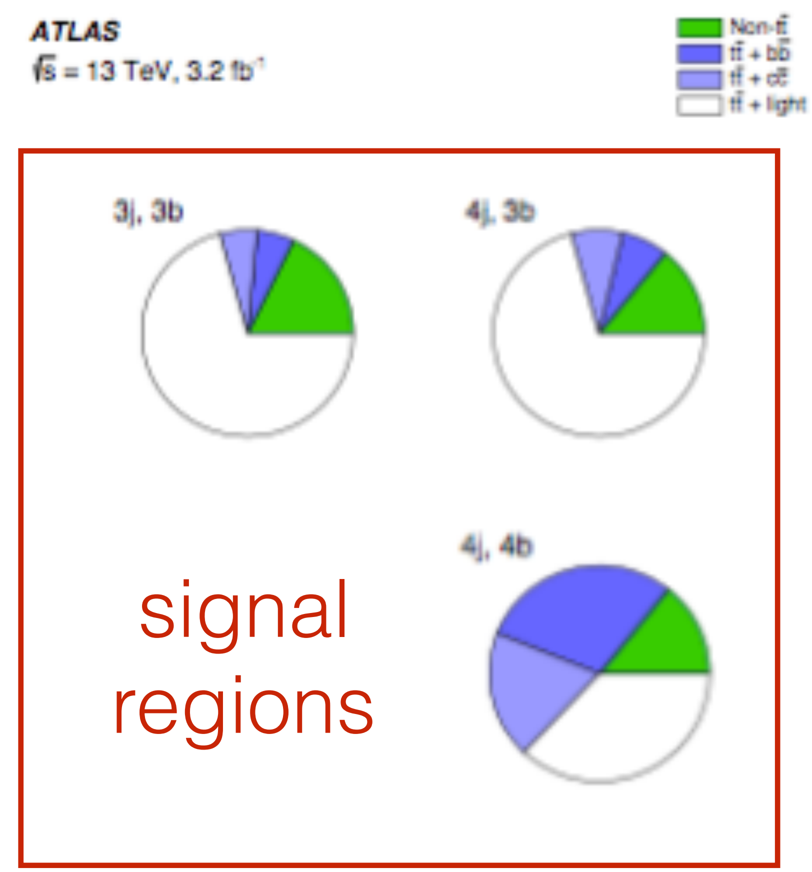
- Additional background: Multijet
  - Jets can "fake" a lepton in the detector
  - Many jets from QCD processes

Signal and Background Separation

- Significant amount of background events in signal regions
  - Strong effort to understand background estimations necessary
- Maximize separation of signal and background using multivariate method
  - Exploit kinematic differences between signal and backgrounds using a BDT

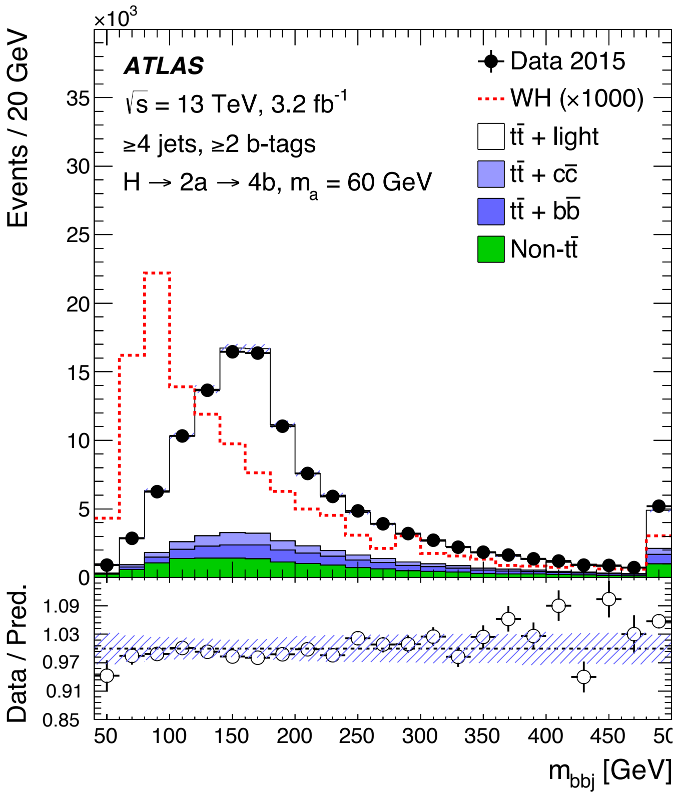
	3j3b	4j3b	4j4b
Signal Yields	10 ± 2	9 ± 1	3 ± 1
Total Background	1640 ± 58	4270 ± 130	165 ± 15

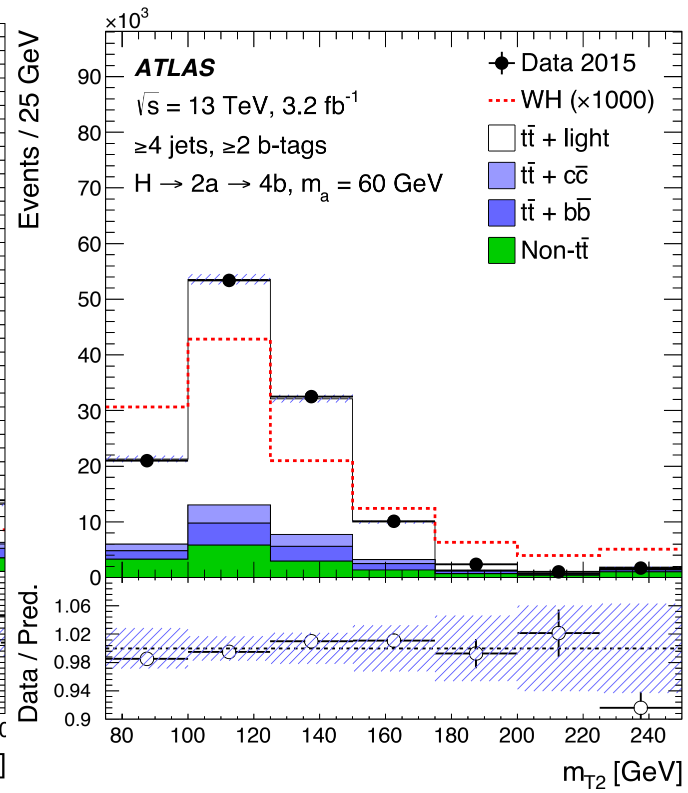
N_{jet} and $N_{b\text{-}jet}$ regions

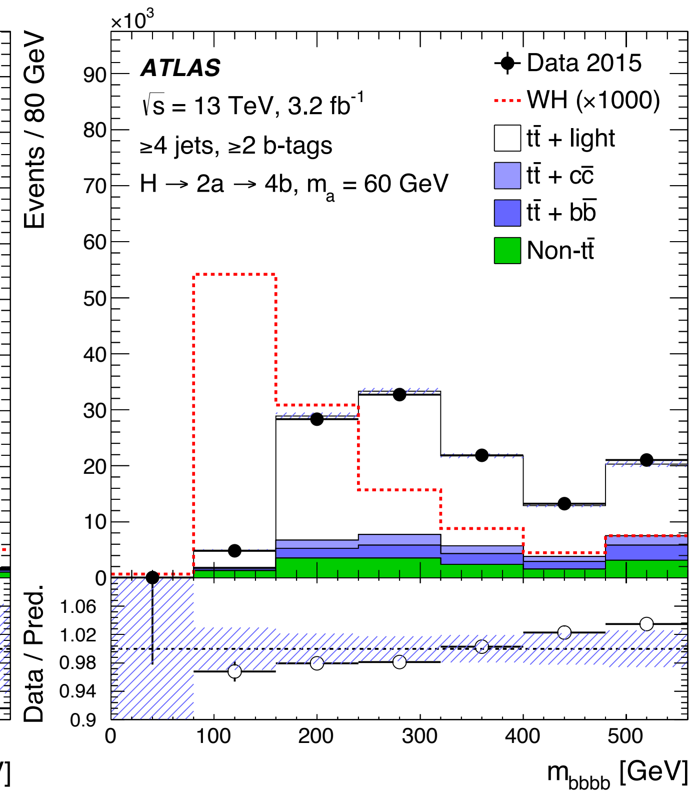


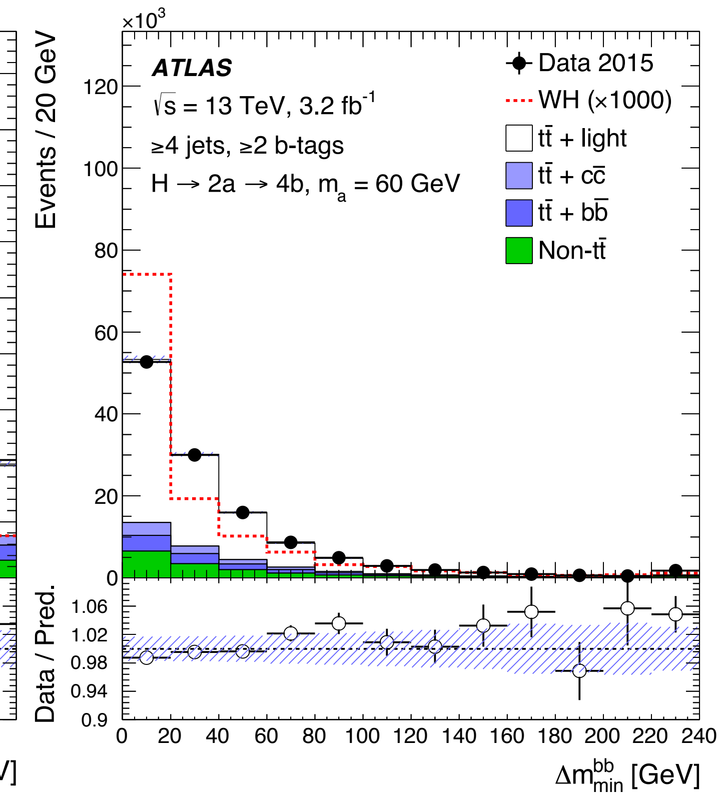
BDT Discriminant

Inclusive Regions

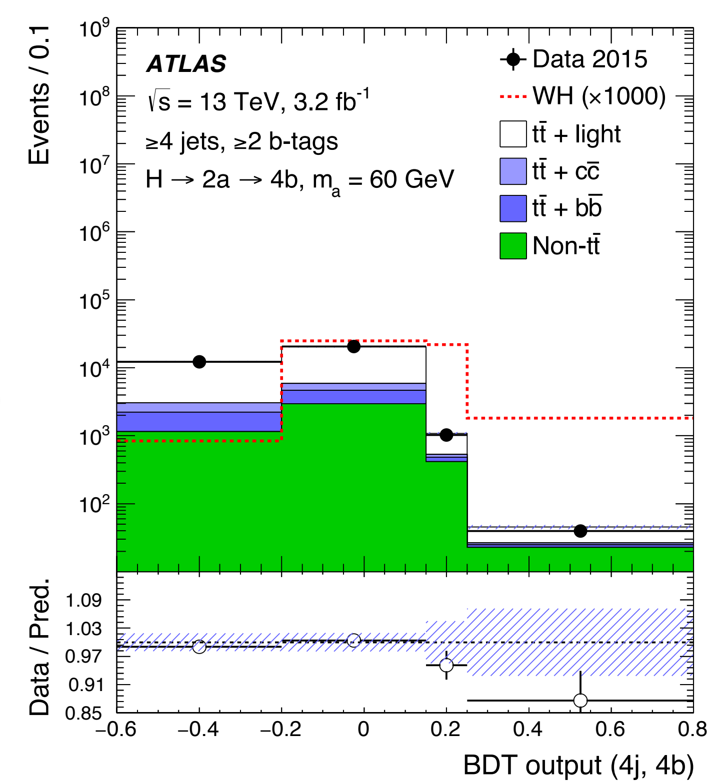








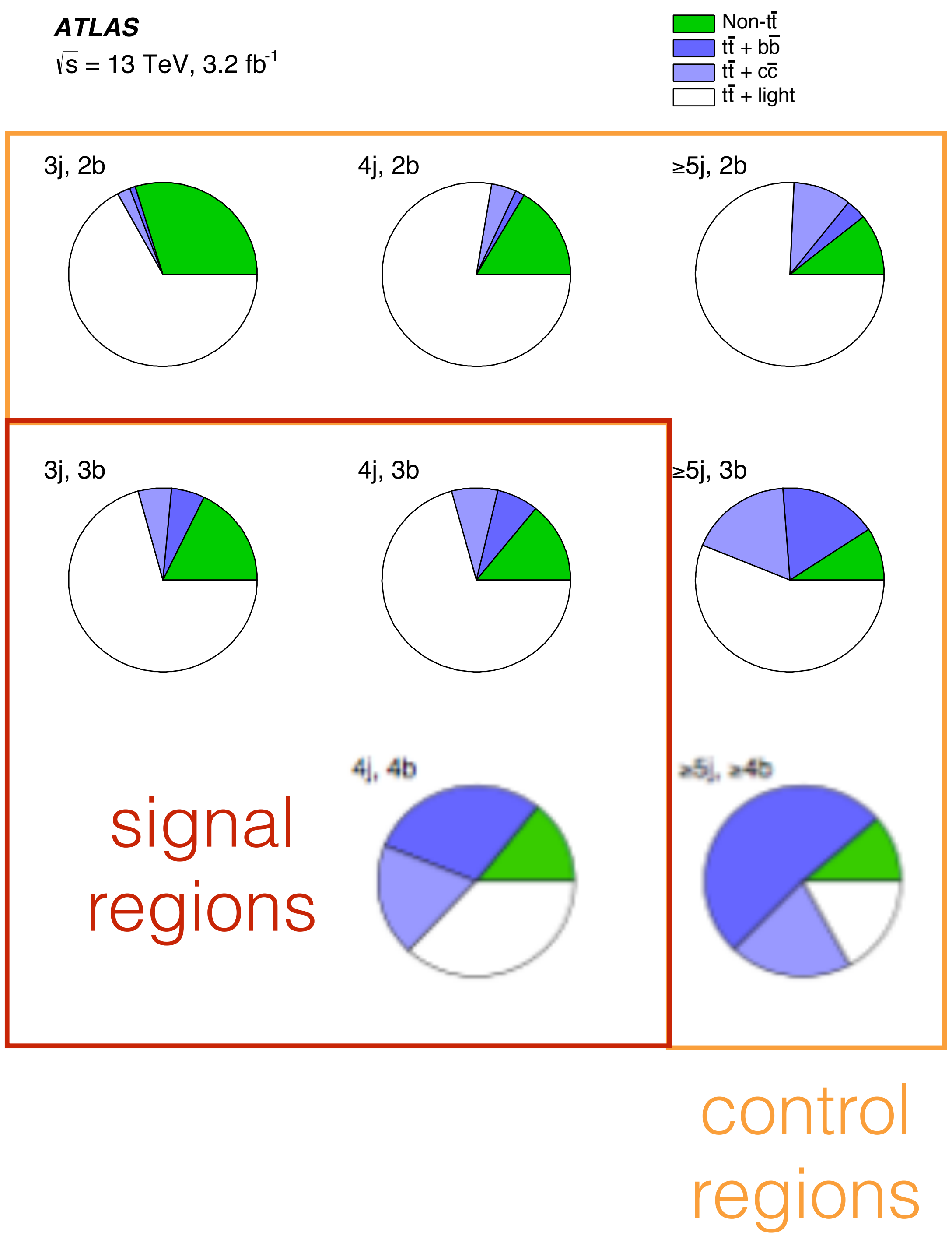
- The top 5 variables combined into a BDT
  - Variables physics motivated
- Different BDTs are trained specifically for each signal region
- With BDT inputs well modeled, we can trust the BDT output
- BDT output allows for optimal separation between signal and backgrounds
  - Signal tends to have higher BDT values while backgrounds have lower BDT values



Control Regions

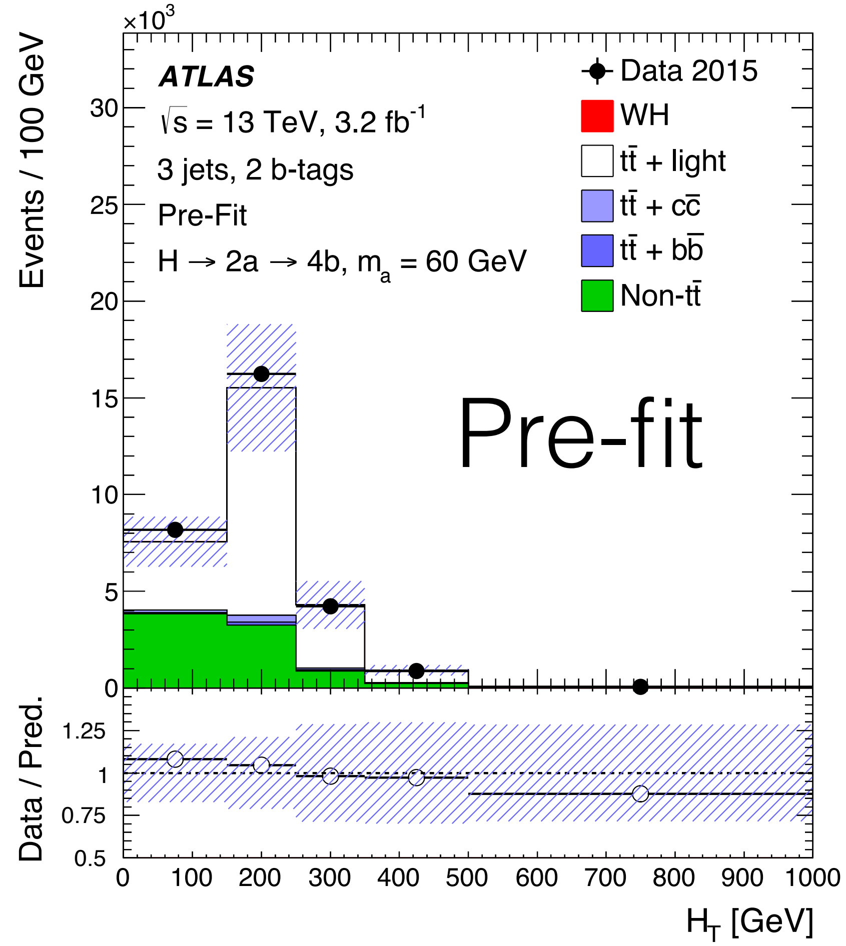
- In order to understand background modeling in the signal regions, control regions are defined
  - Defined as close to the signal regions as possible with different jet and b-tag multiplicities
  - Overestimation (underestimation) of backgrounds could result in removal (creation) of an excess!
- No single, dominating background in each control region, the combination of all of them allows control over the background processes

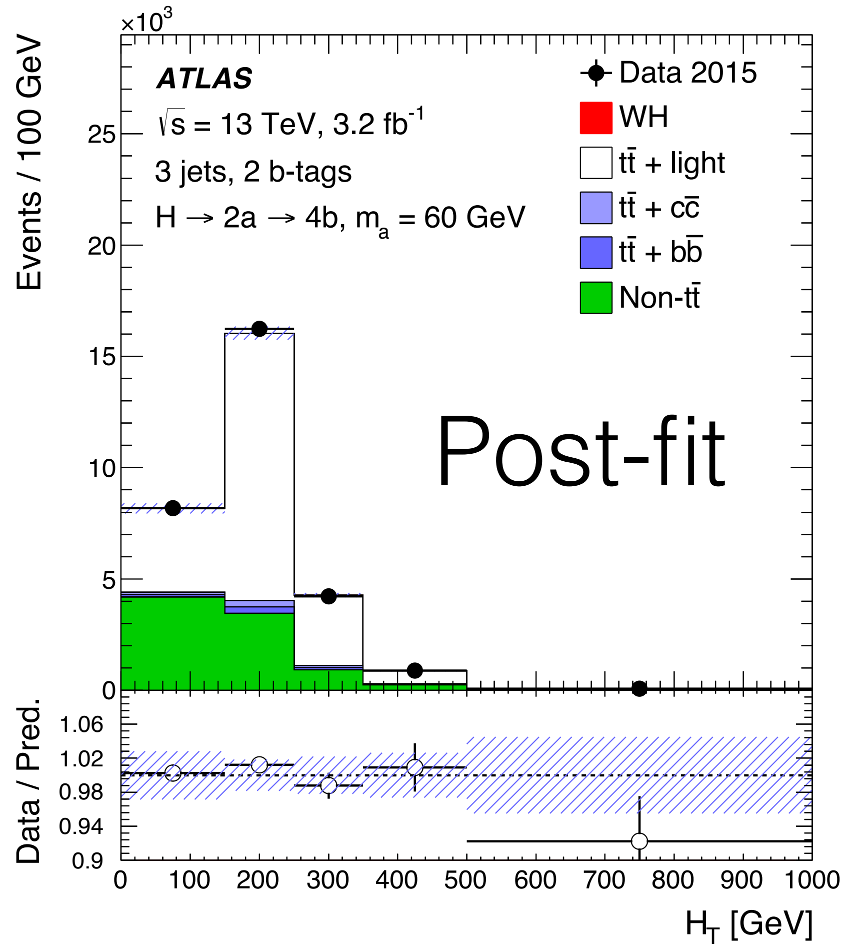
N_{jet} and $N_{b\text{-}jet}$ regions



Profile Likelihood Fit

- Perform profile likelihood fit to data/MC in control and signal regions simultaneously
  - Control regions estimate the main background processes
  - Profile systematic uncertainties
- Variables fed into fit →different distributions depending on the region
  - Control regions: Σ jet pT
  - Signal regions: BDT output
- Main systematic uncertainties
  - $t\bar{t}$ normalization and modeling
  - Uncertainties related to b-tagging
- Good agreement between data/MC in the control regions
  - Total systematic uncertainty constrained



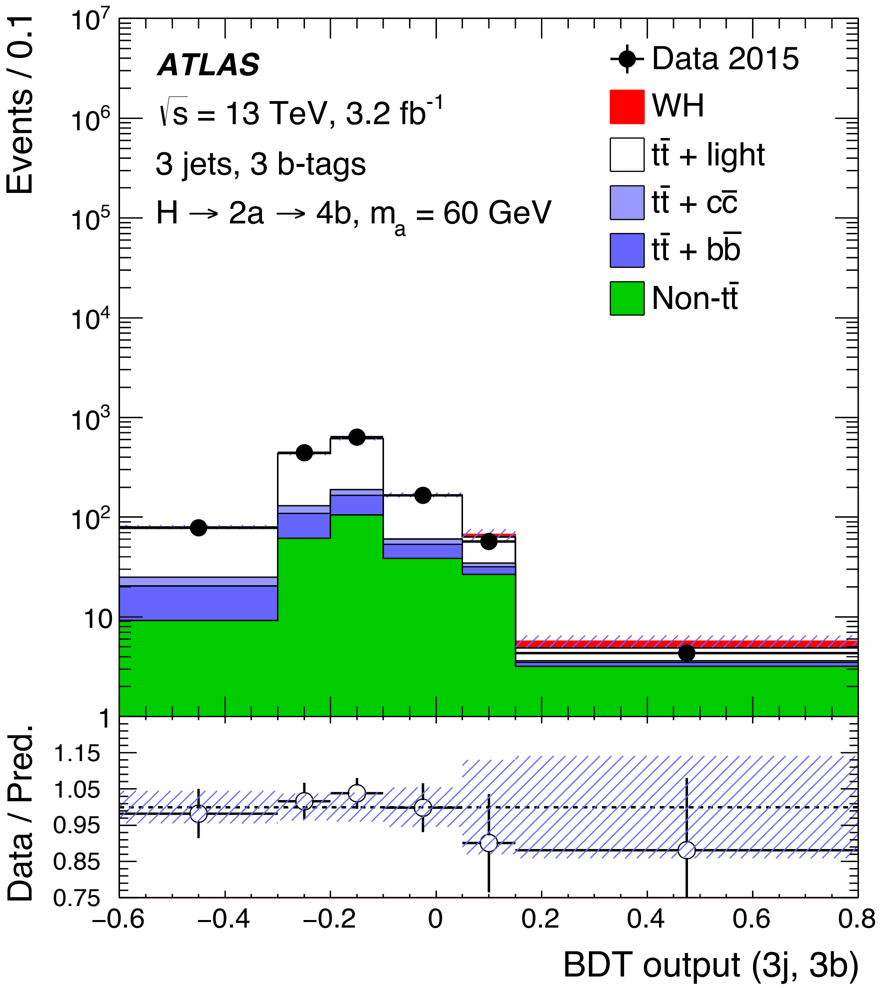


Data/MC Comparisons - Signal Regions

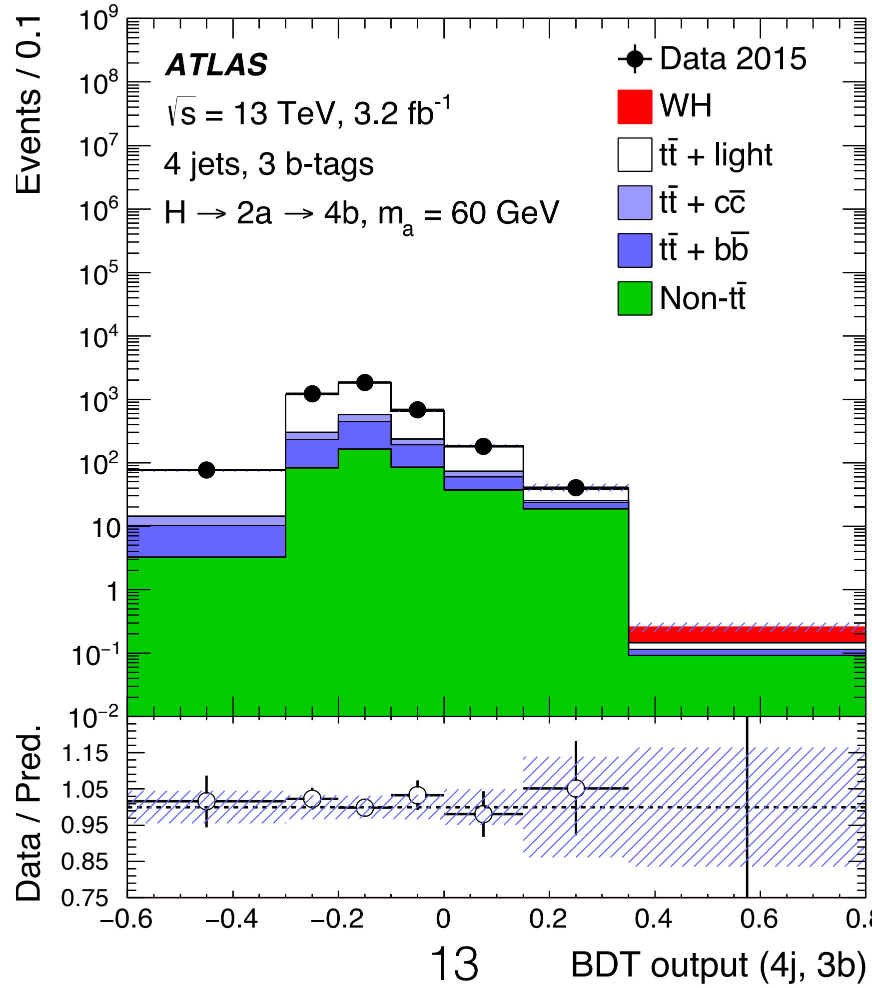
- Ensuring the background modeling is correct in control regions, the data in the signal regions can be studied
- Most sensitive region - 4j4b

	3j3b	4j3b	4j4b
Signal Yields	10 ± 2	9 ± 1	3 ± 1
Total Background	1640 ± 58	4270 ± 130	165 ± 15
Data	1646	4302	166

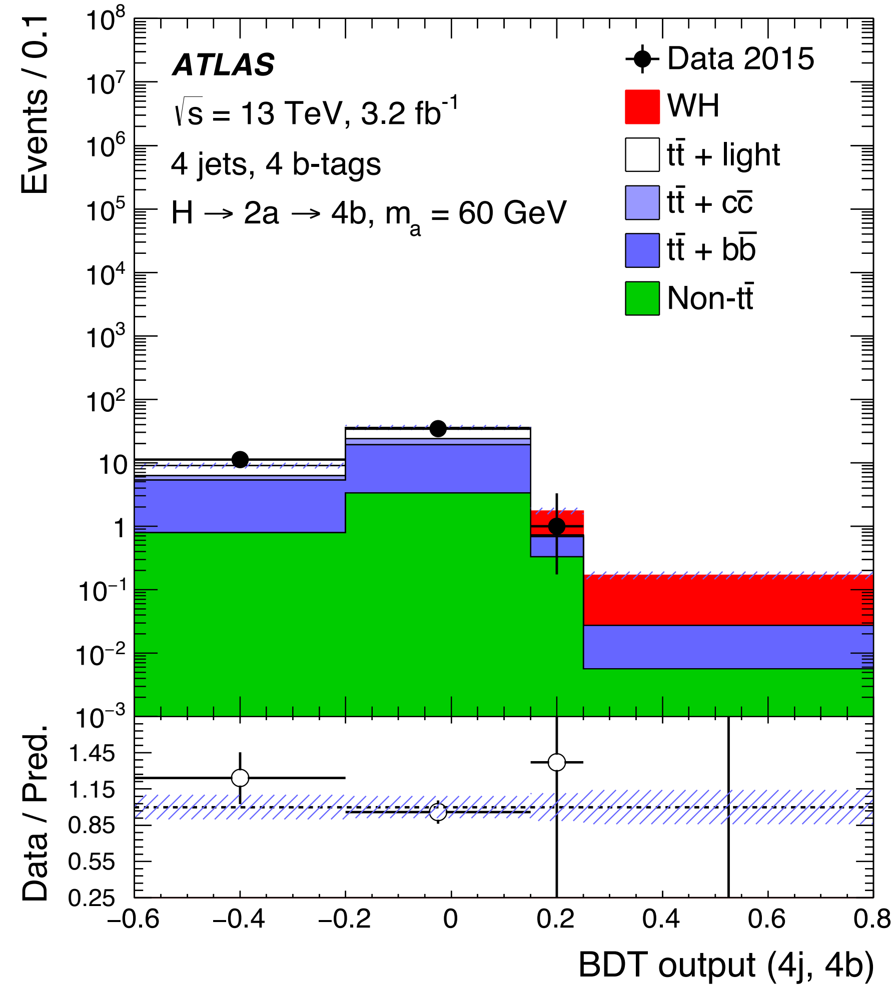
3j3b



4j3b

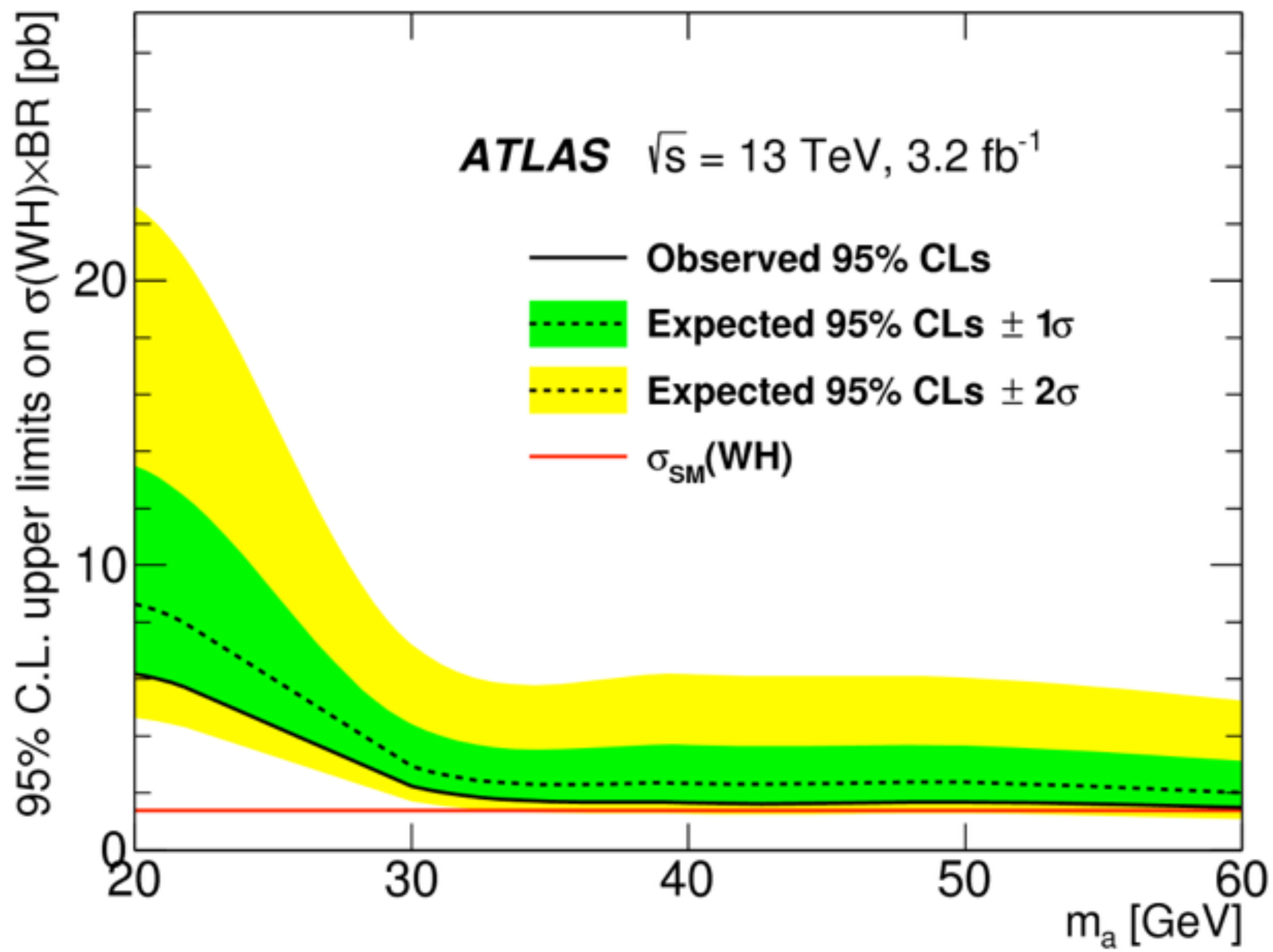


4j4b

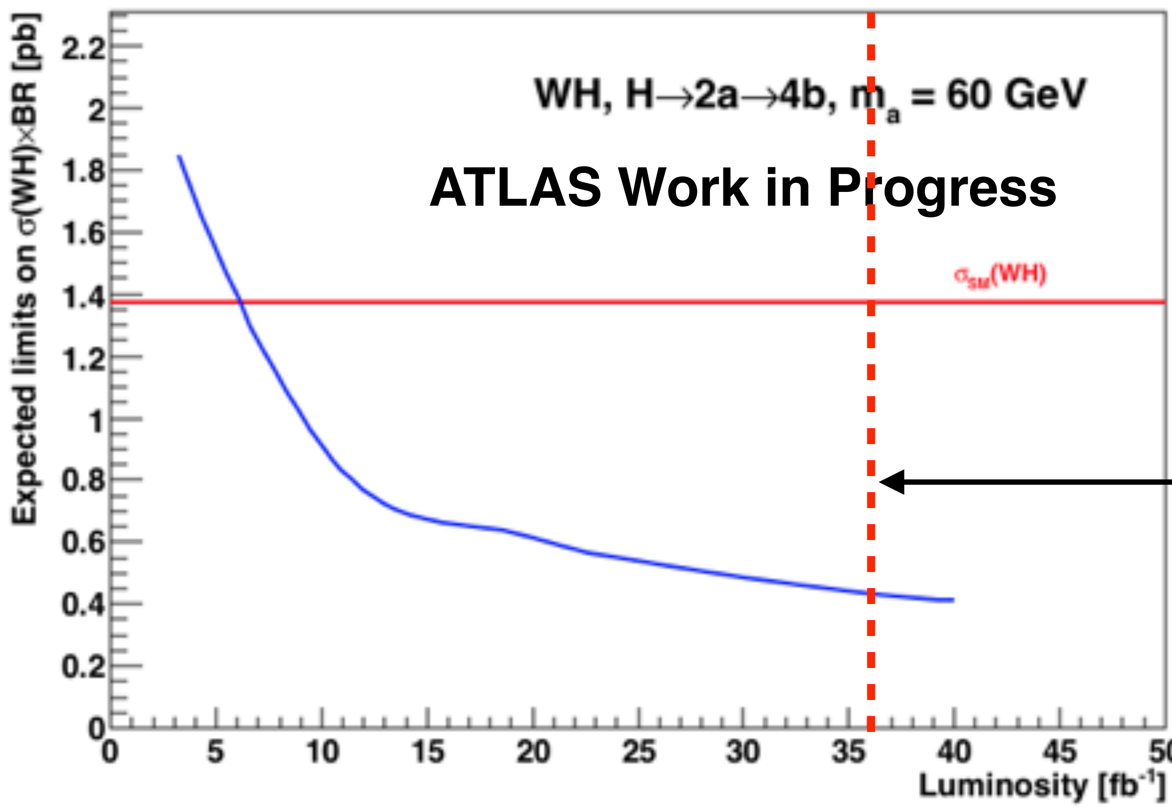


h→aa→bb̄bb̄: Limits

- Since no significant excess is observed in the signal regions, set limits on $\sigma(WH) \times \mathrm{BR}(H \to aa) \times \mathrm{BR}(a \to b\bar{b})^2$
  - Close to the SM cross section for WH production

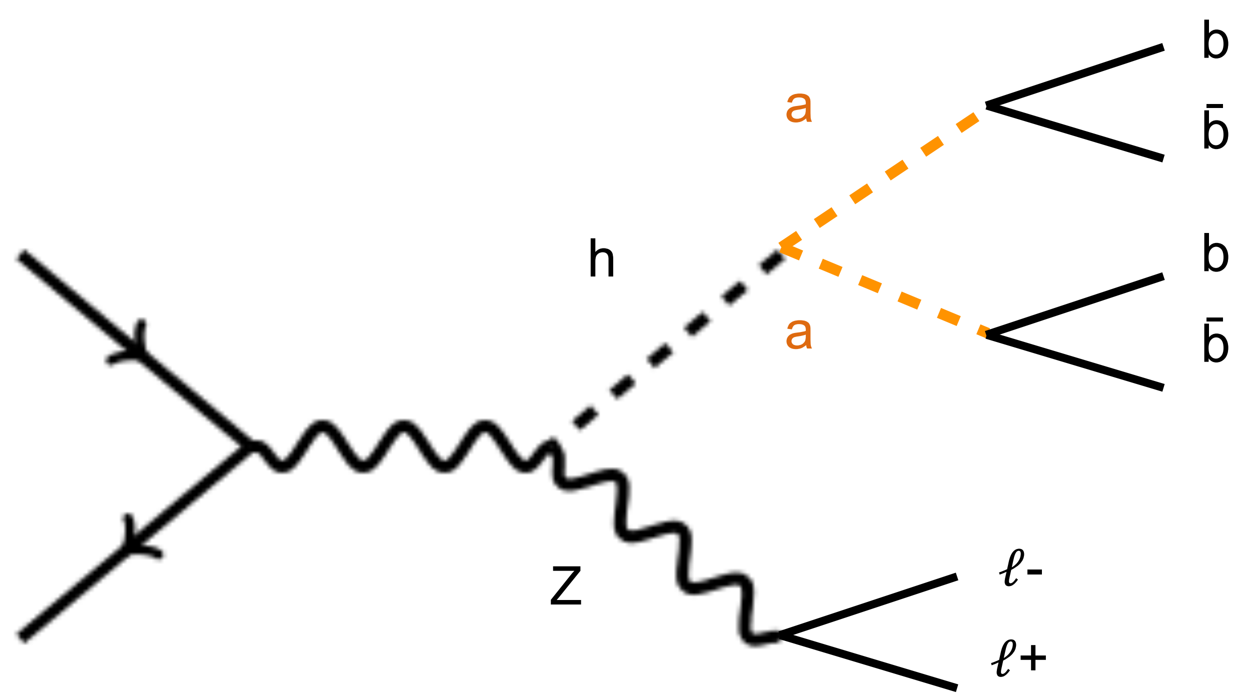


$h \to aa \to b\bar{b}b\bar{b}$: Improvements



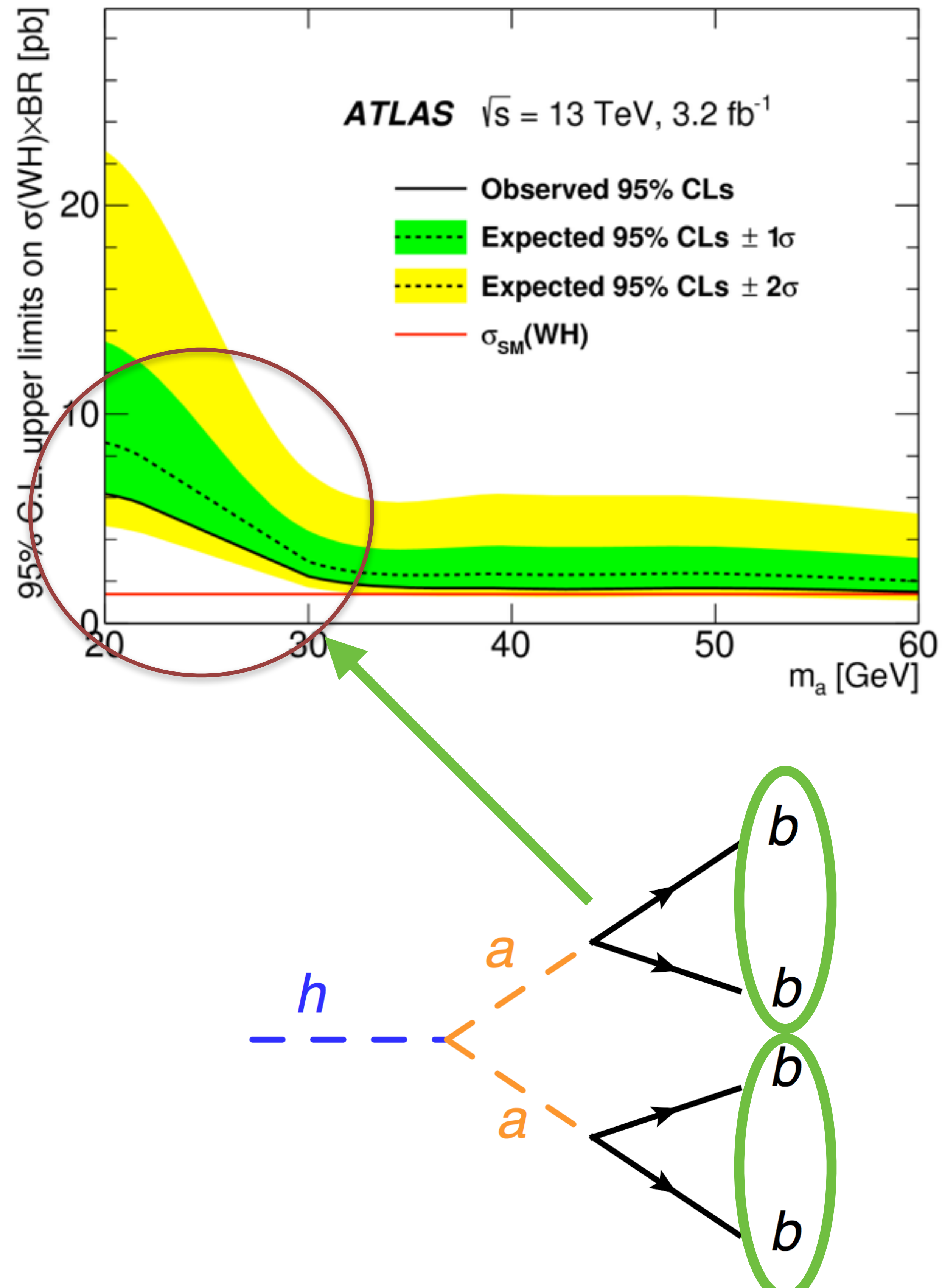
- Major limiting factor in the analysis is statistics
  - Better expected sensitivity with more data
  - Currently gathered 36 fb^{-1} of data for 2015+2016

- Will add ZH production channel
  - Improve sensitivity with additional channel
  - Final signature changes to have two leptons



$h \to aa \to b\bar{b}b\bar{b}$: Low Mass

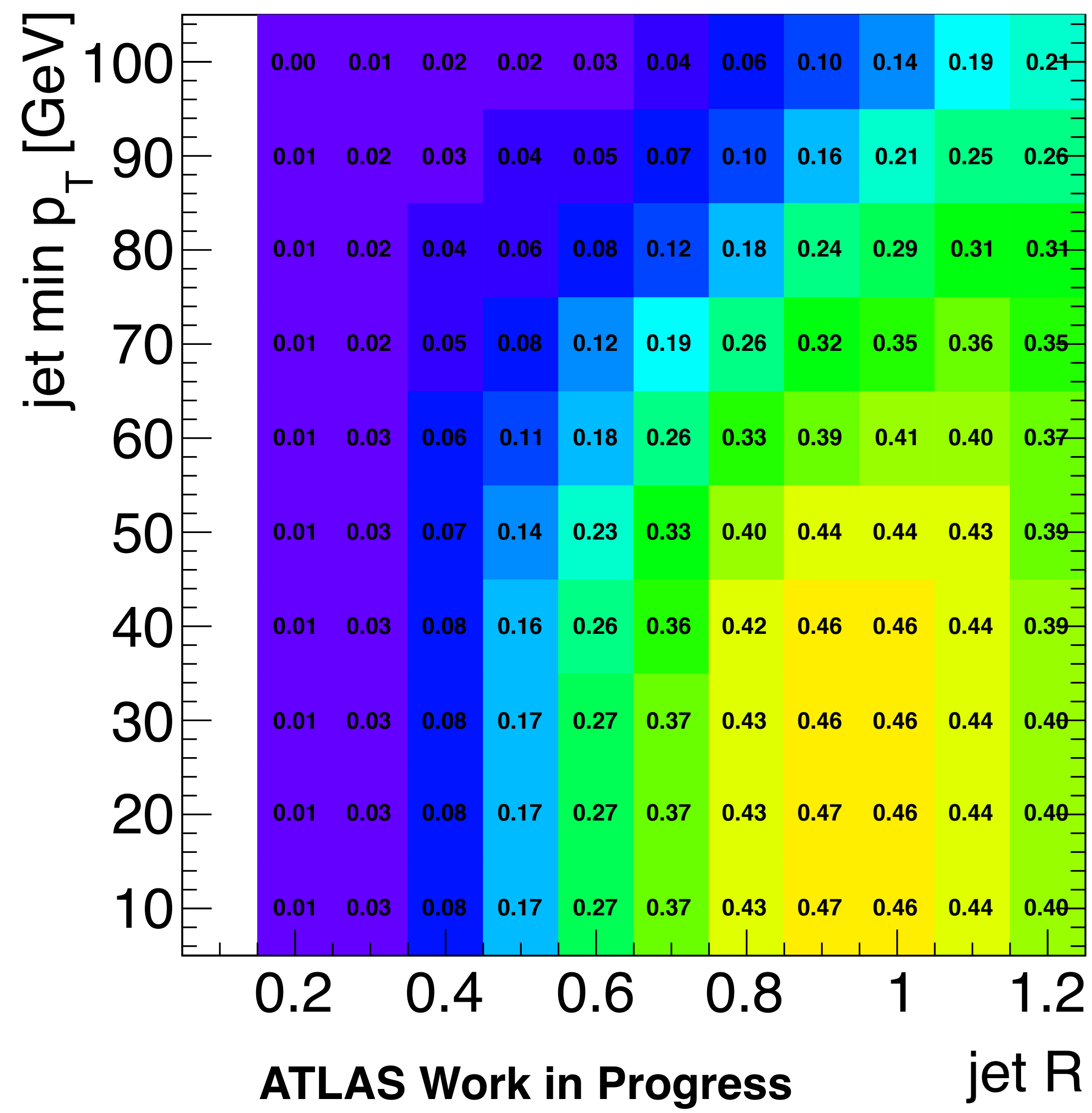
- Limits become weaker as a mass decreases
  - Collimating b-quarks change jet/bjet multiplicity → different final state
  - Need to consider new strategies to optimize for this region



Current Efforts for Low Mass Regime

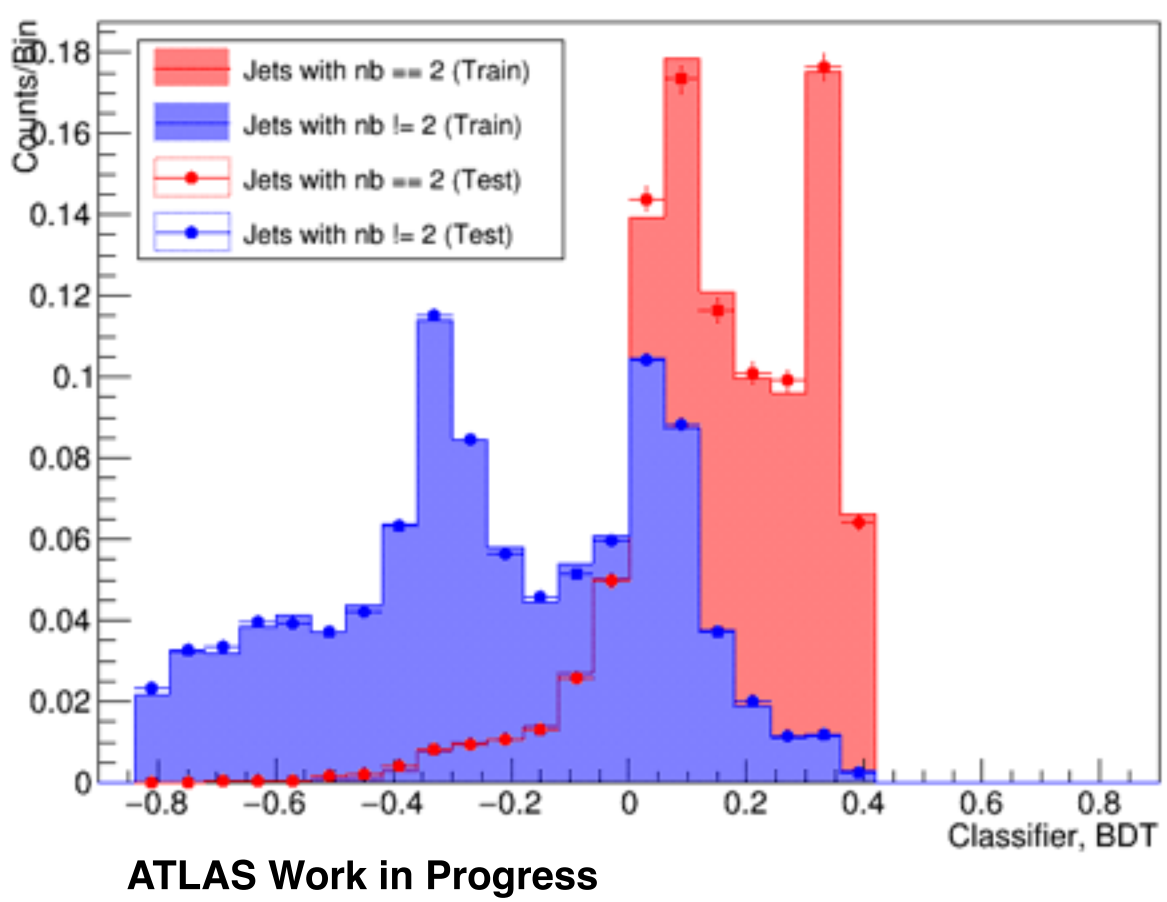
- Instead of looking for 3 or 4 jets with 1 b-parton → 2 large jets with 2 b-partons
- Looked at signal efficiency for events with 2 jets each with 2 b-partons truth matched
  - Signal acceptance increases with **larger jets** and **lower pT** thresholds
  - Looking for 4 jets with 1 b-parton yielded efficiencies ~1% for jets above 20 GeV
- Challenging effort to double b-tag has not been done before in the low pT regime
  - Collaborating with SLAC

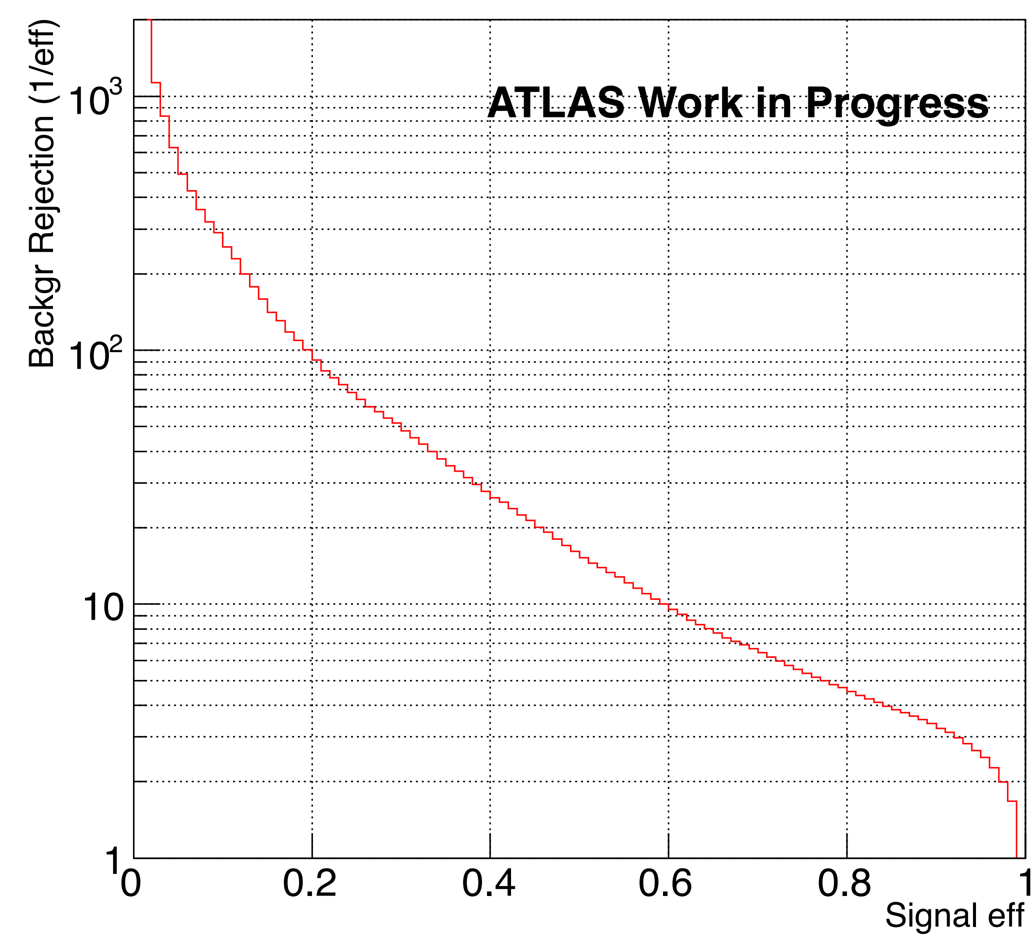
Signal efficiency @ m=20 GeV



Current Efforts for Low Mass Regime

- Investigating how to double b-tag low pT, large radius jets
- First looking at a simple BDT to discriminate jets with 2 b-partons vs jets with 0/1 b-parton
  - Using b-tagging/kinematic information from subjets in large jets as input
- Promising first start, currently working to improve performance





Conclusions/Next Steps

- Search has been done for Higgs decaying to two spin-zero particles decaying to b-pairs in WH production
  - No previous attempt in ATLAS or CMS
  - Analysis using full 2015 data (3.2 fb^{-1}) has been published in EPJC arXiv:1606.08391
    - No significant excess with respect to the SM observed
- Analysis team optimizing for next iteration using full 2015+2016 luminosity (36 fb^{-1})
- Optimizing search to also accommodate the dilepton channel (ZH production)
- Developing new techniques to improve sensitivity in low mass regime

Backup