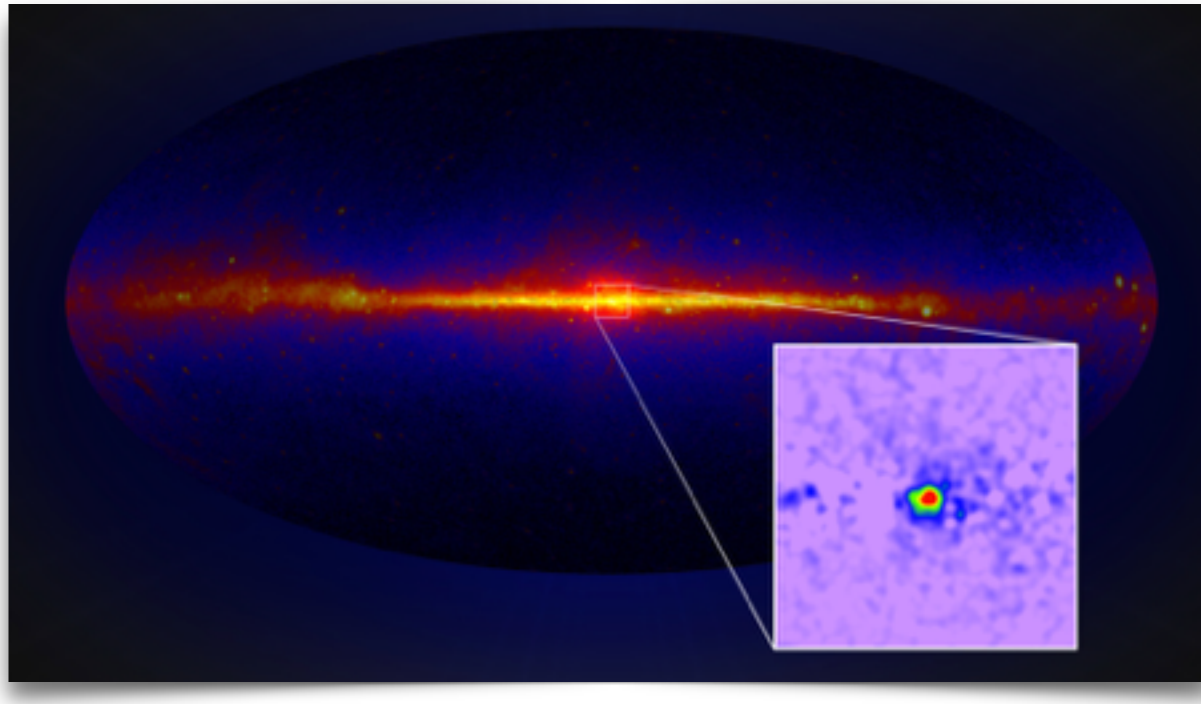
Analysis Tools/Strategies for $H \rightarrow 2a \rightarrow 4b$ Search in Low a Mass Regime

Mazin Khader
University of Illinois at Urbana Champaign

USLUA Lightning Round
November 4, 2016

Theoretical Motivation

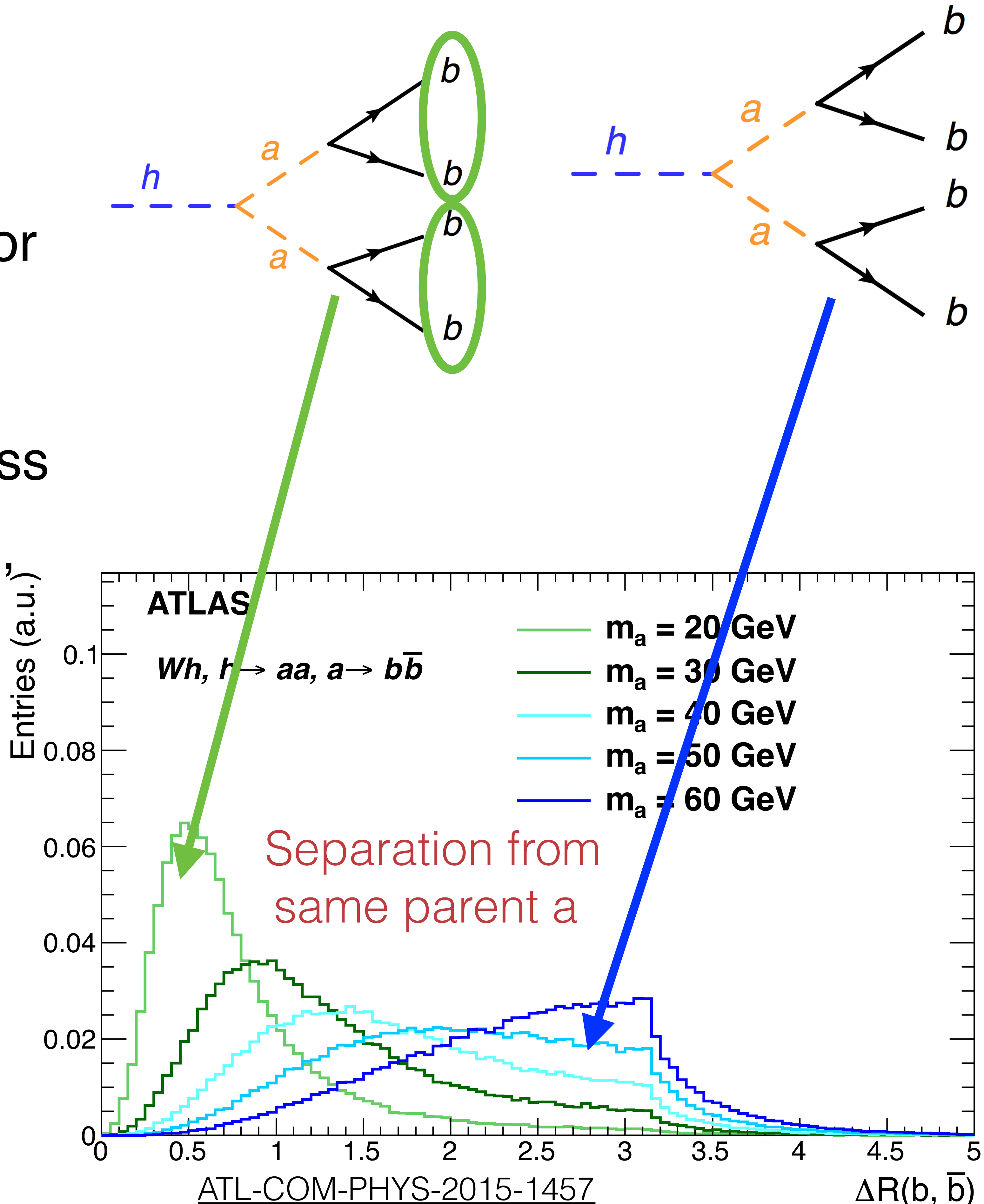
- After the Higgs discovery, next effort has been to see if it fits into the Standard Model (SM)
- Exotic decays in the SM constrained to 34% at 95% C.L.
  - Higgs could serve as a potential portal to new physics!
  - Simple extension of SM→Higgs decay to **two** new spin-zero particles, a
- Theories with a are consistent with gamma ray excess in Galactic Center!
  - Serves as a mediator between dark matter and SM
- Solves other open questions!
  - Matter/anti-matter asymmetry explained with electroweak baryogenesis
  - Helps the naturalness problem of the Higgs boson mass



http://fermi.gsfc.nasa.gov/science/eteu/dm/

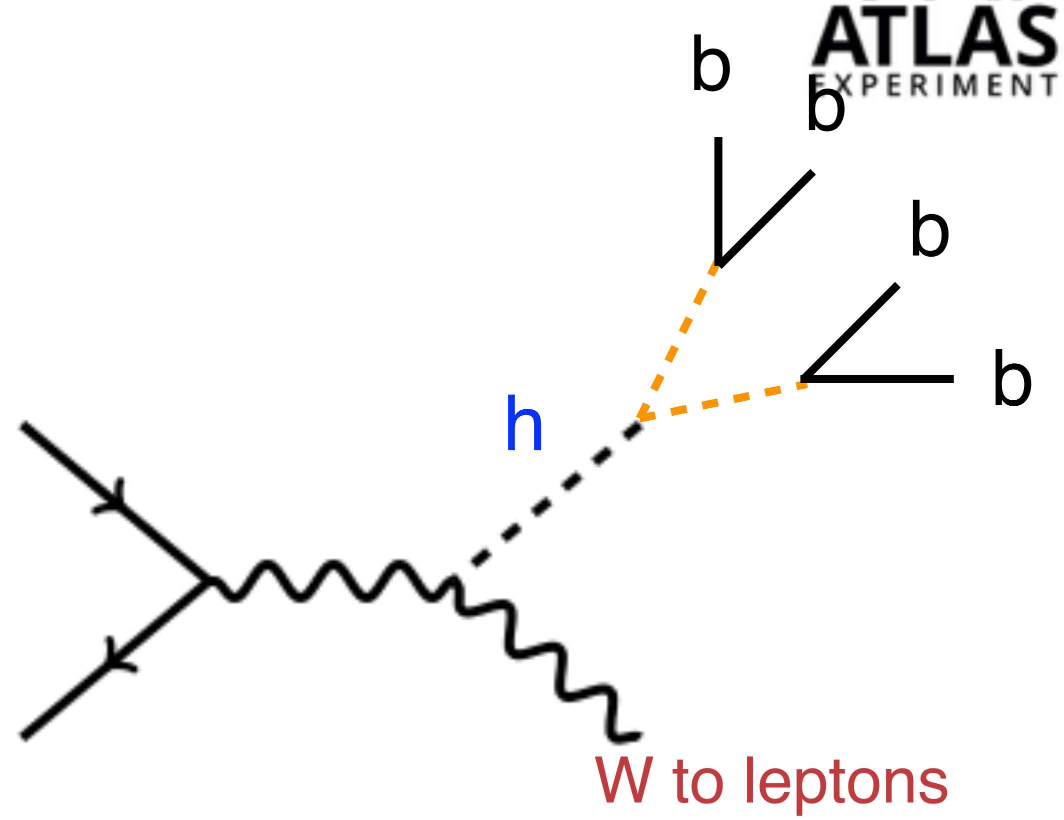
Signal Overview

- For most models, **a** → bb is the dominant decay mode for m_a above ~10 GeV
- The kinematics of the b-quarks depend on the **a** mass
  - As the **a** mass decreases, the b-quarks are more collimated
- The b-quarks tend to have very **low pT**



2015 Analysis

- Performed a search for a Higgs produced in association with a W boson with the 2015 data
  - Leptonic decay of W allows us to trigger on the events
  - Paper published in EPJC!
    arXiv:1606.08391



Search for the Higgs boson produced in association with a *W* boson and decaying to four *b*-quarks via two spin-zero particles in *pp* collisions at 13 TeV with the ATLAS detector

The ATLAS Collaboration

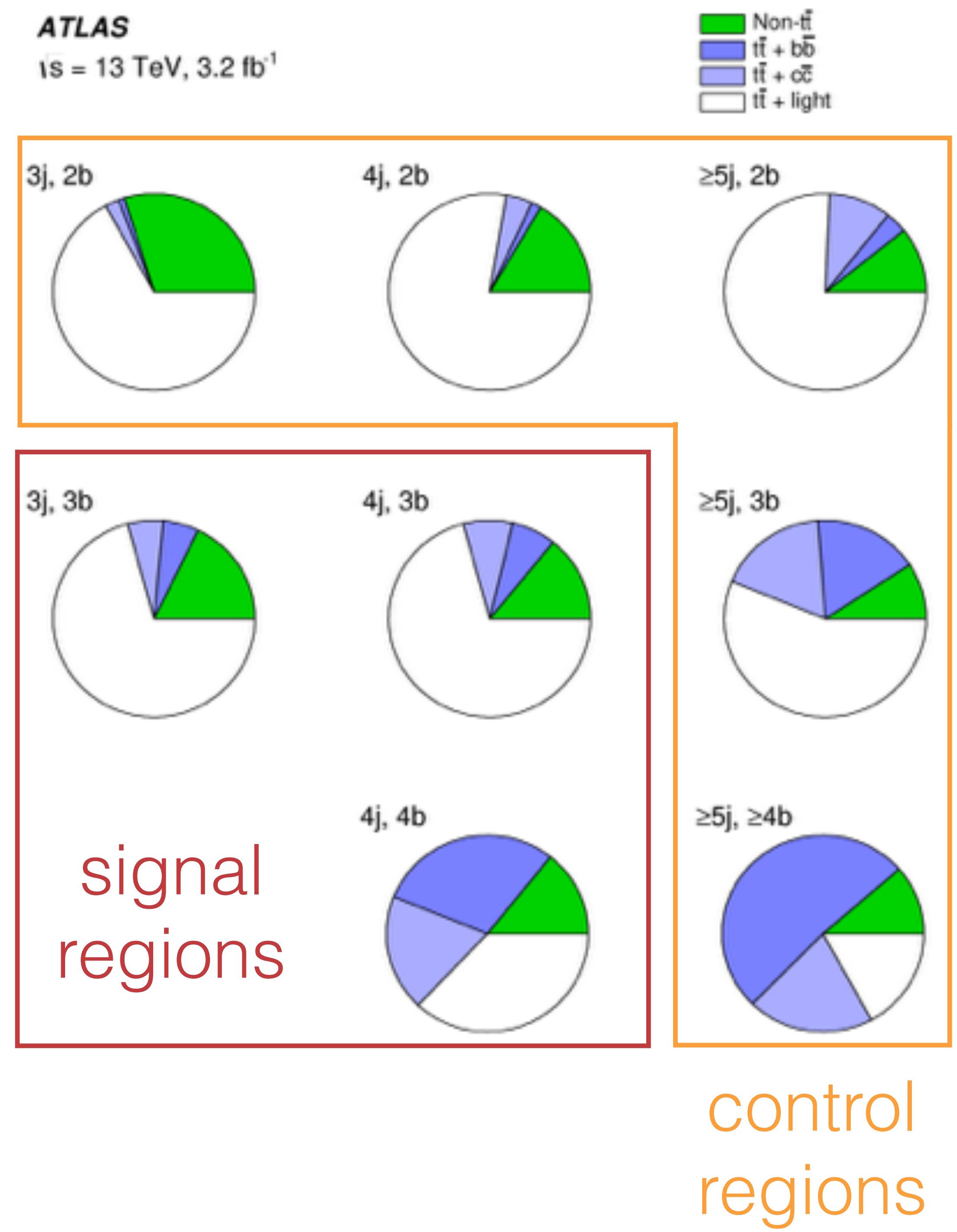
Abstract

This paper presents a dedicated search for exotic decays of the Higgs boson to a pair of new spin-zero particles, $H \to aa$, where the particle a decays to b-quarks and has a mass in the range of 20–60 GeV. The search is performed in events where the Higgs boson is produced in association with a W boson, giving rise to a signature of a lepton (electron or muon), missing transverse momentum, and multiple jets from b-quark decays. The analysis is based on the full dataset of pp collisions at $\sqrt{s} = 13$ TeV recorded in 2015 by the ATLAS detector at the CERN Large Hadron Collider, corresponding to an integrated luminosity of 3.2 fb^{-1}. No significant excess of events above the Standard Model prediction is observed, and a 95% confidence-level upper limit is derived for the product of the production cross section for $pp \to WH$ times the branching ratio for the decay $H \to aa \to 4b$. The upper limit ranges from 6.2 pb for an a-boson mass $m_a = 20$ GeV to 1.5 pb for $m_a = 60$ GeV.

2015 Analysis Strategy

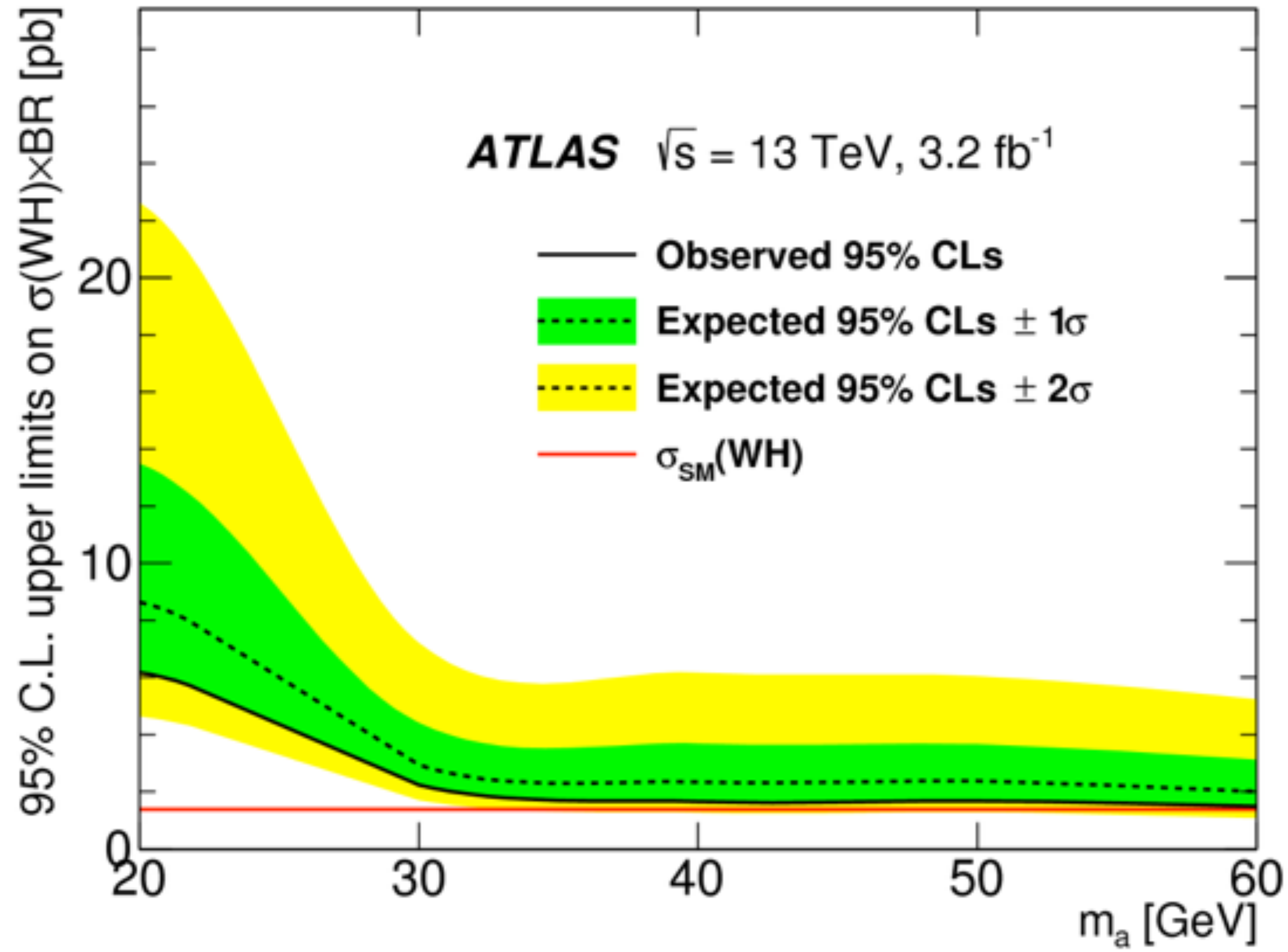
- Defined two sets of regions based on the **jet** and **bjet** multiplicity
  - Signal regions: Where sensitivity to the signal is maximized
  - Control regions: Defined around signal regions to understand the backgrounds
- Performed a profile likelihood fit with the data and MC over all the regions
  - Control regions estimate the main background processes
  - Profile systematic uncertainties

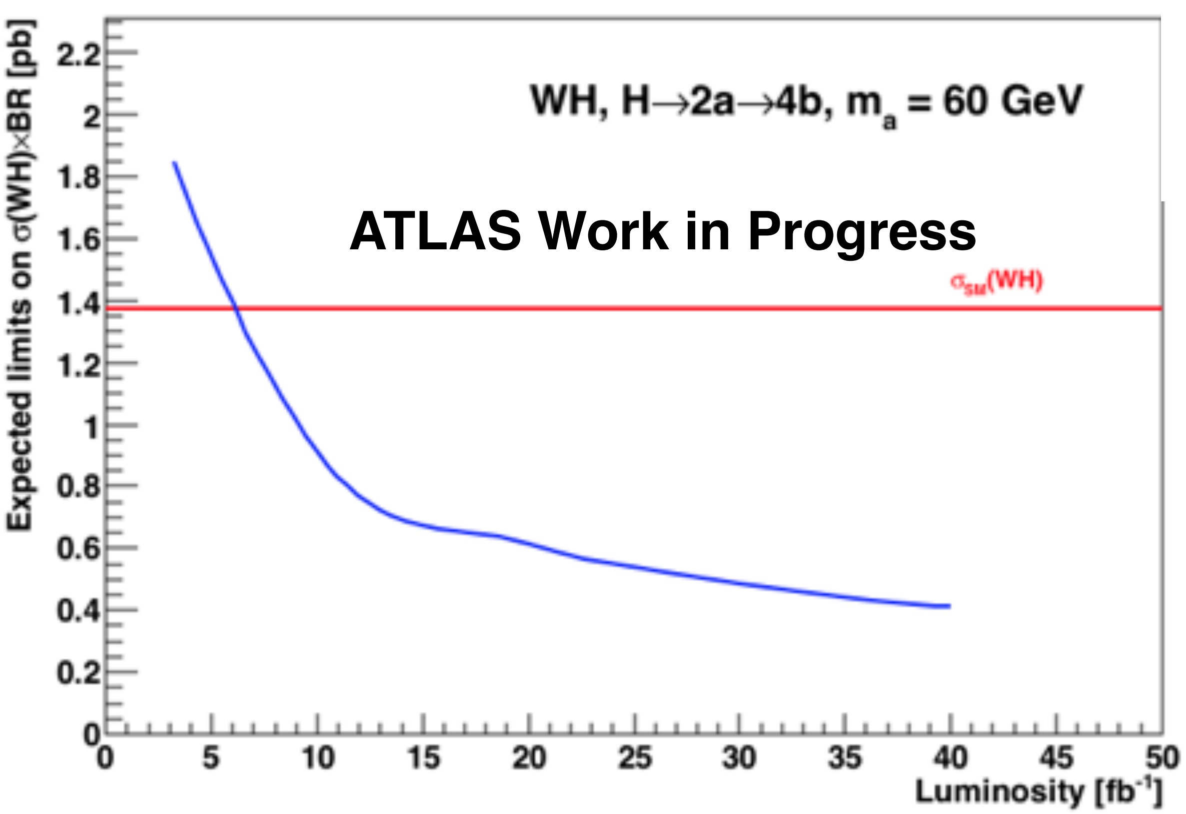
N_{jet} and $N_{b\text{-}jet}$ regions



2015 Analysis Results

- No excess was found in the signal regions
- Limits were set on σ(WH)×BR
  - Close to cross section of WH production in the SM

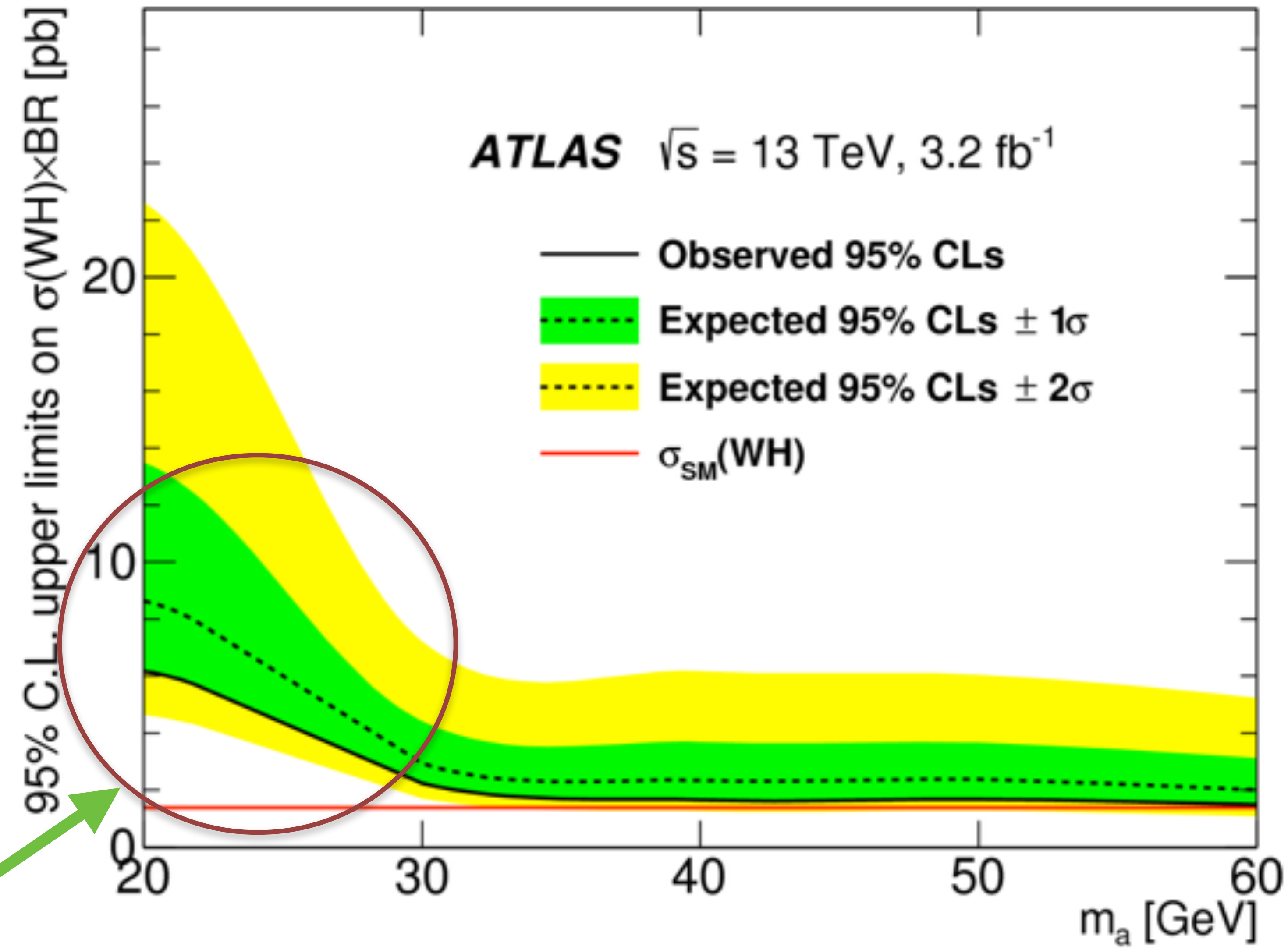


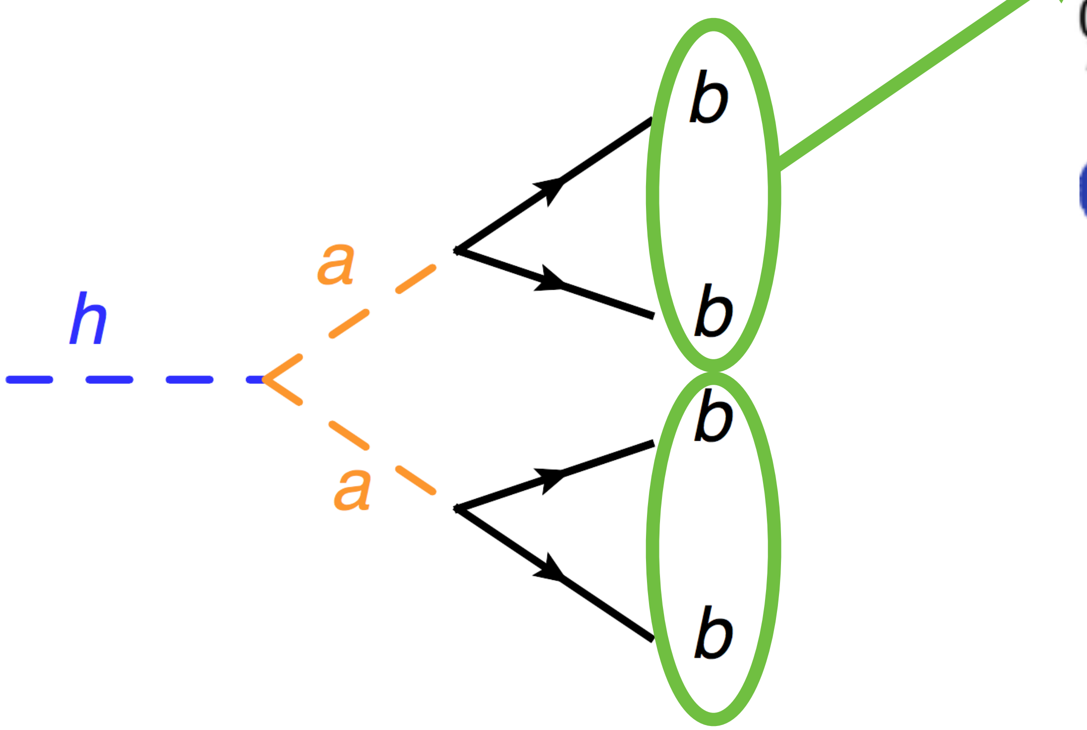


- Limiting factor in the analysis is statistics
  - Better expected sensitivity with more data

2015 Analysis Results

- No excess was found in the signal regions
- Limits were set on σ(WH)×BR
  - Close to cross section of WH production in the SM



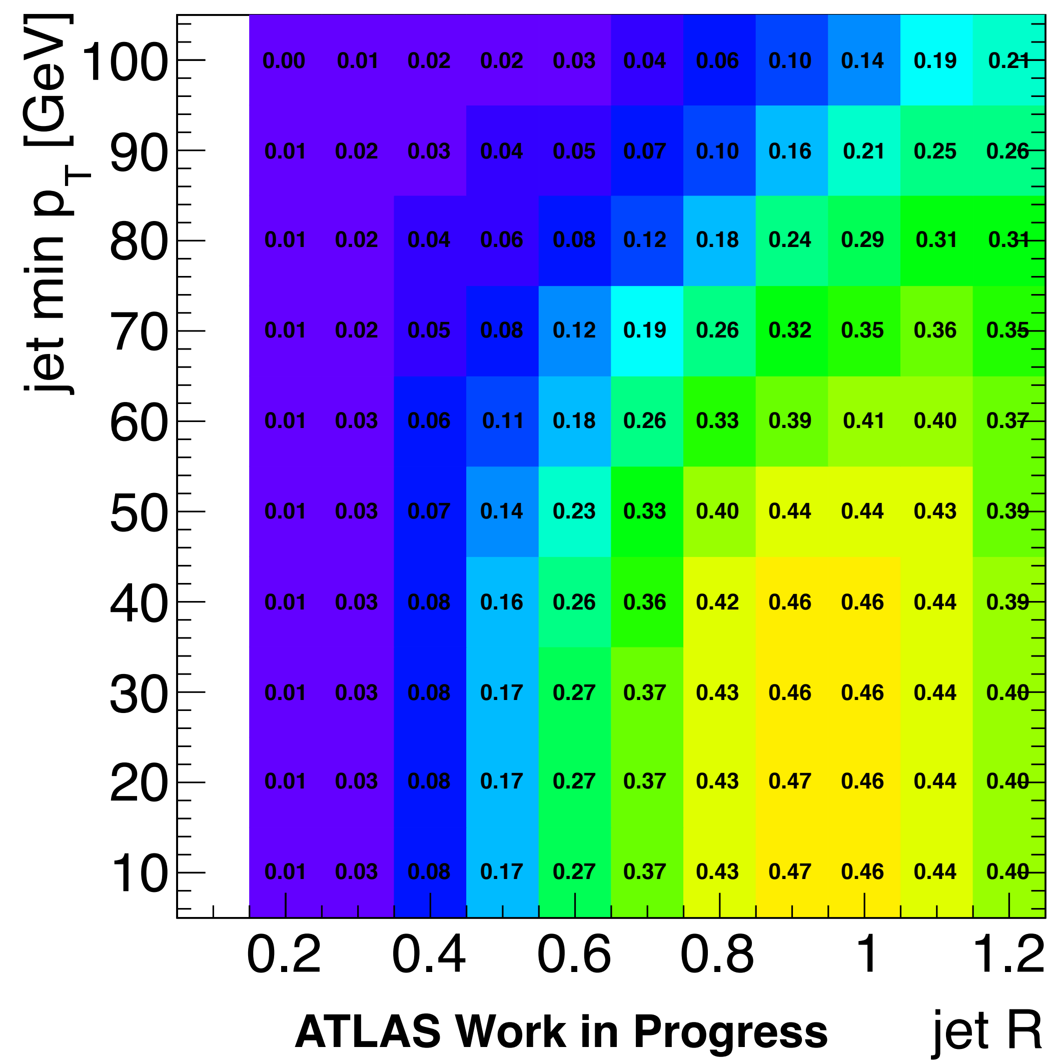


- Weaker limits set for mass of 20 GeV as expected due to the collimating b-quarks
  - Indicates that the analysis strategy of finding b-jets is not optimal

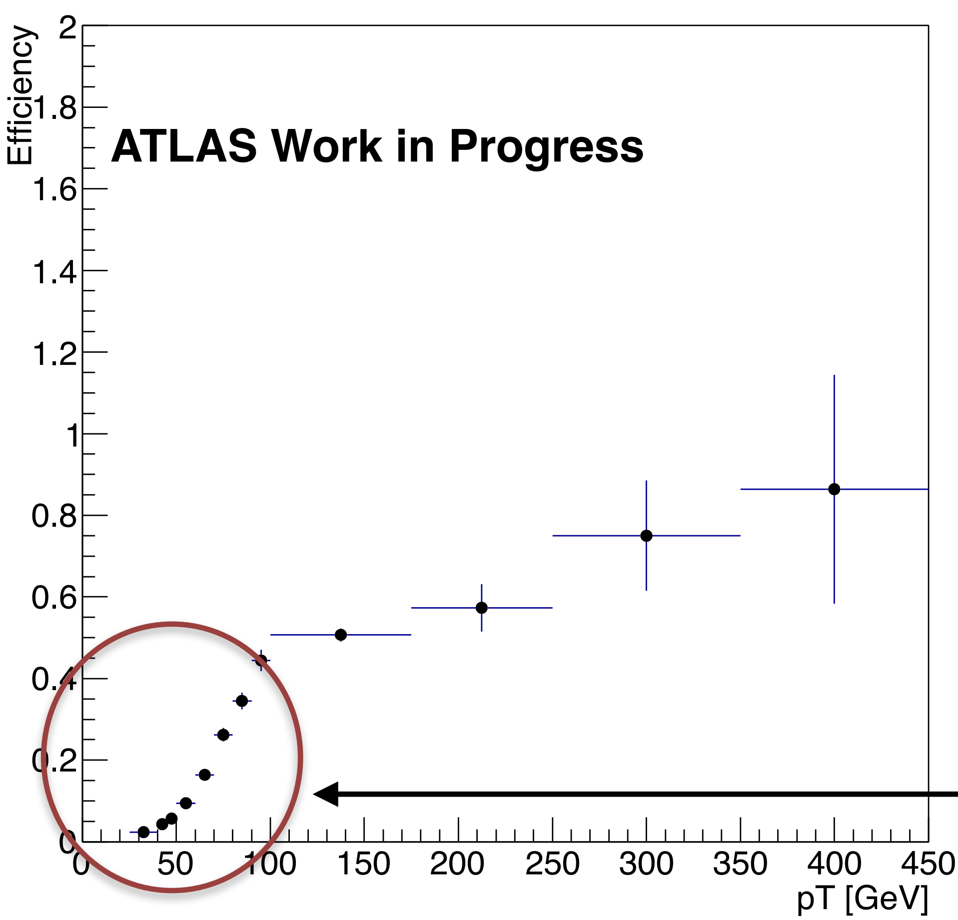
Strategy for Low Spin-Zero Mass

- Instead of looking for 3 or 4 single b-tagged jets → 2 large jets with 2 b-quarks
- Looked at signal efficiency for events with 2 jets each with 2 b-quarks truth matched
  - Signal acceptance increases with **larger jets** and **lower pT** thresholds
- Need to double b-tag the large jets!

Signal efficiency @ m=20 GeV



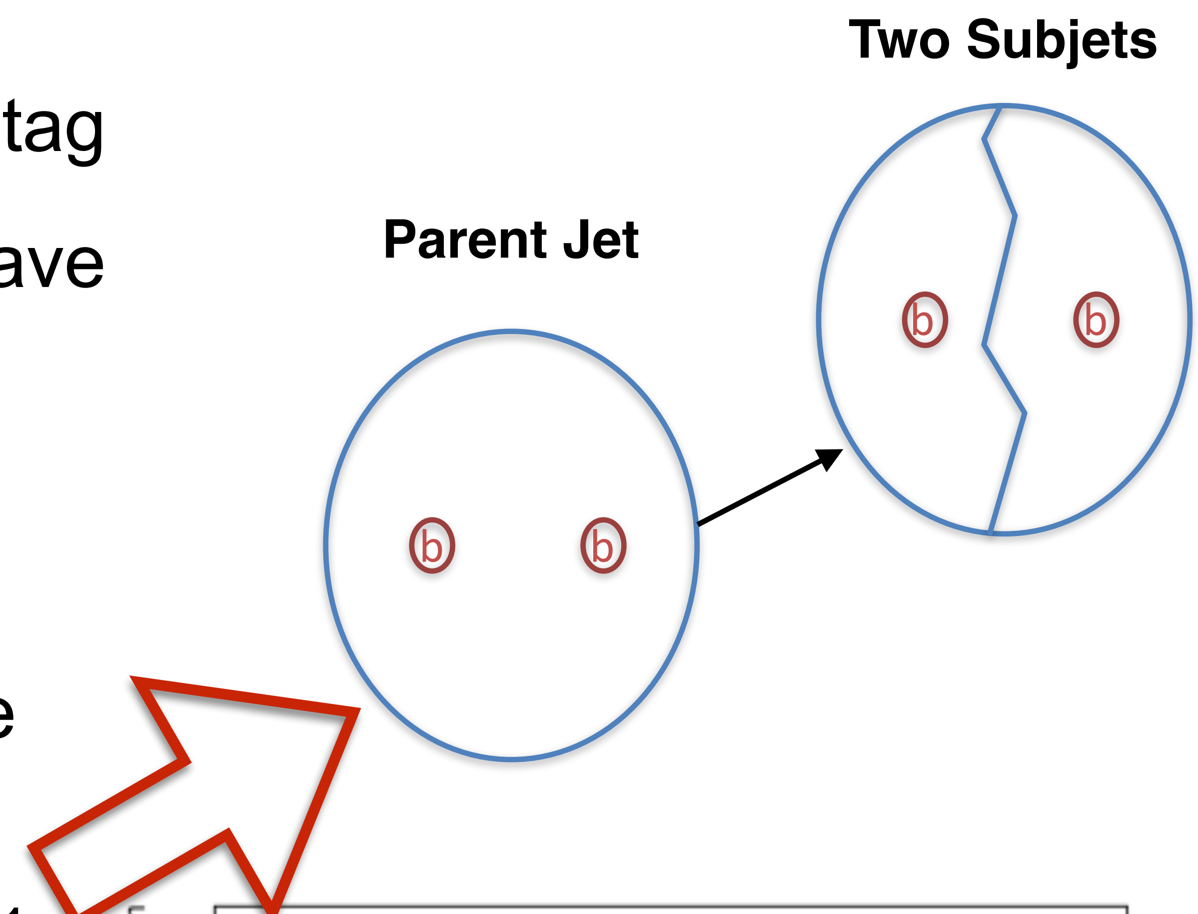
Efficiency of Two R = 0.2 Track Jets Matched to Large Jet

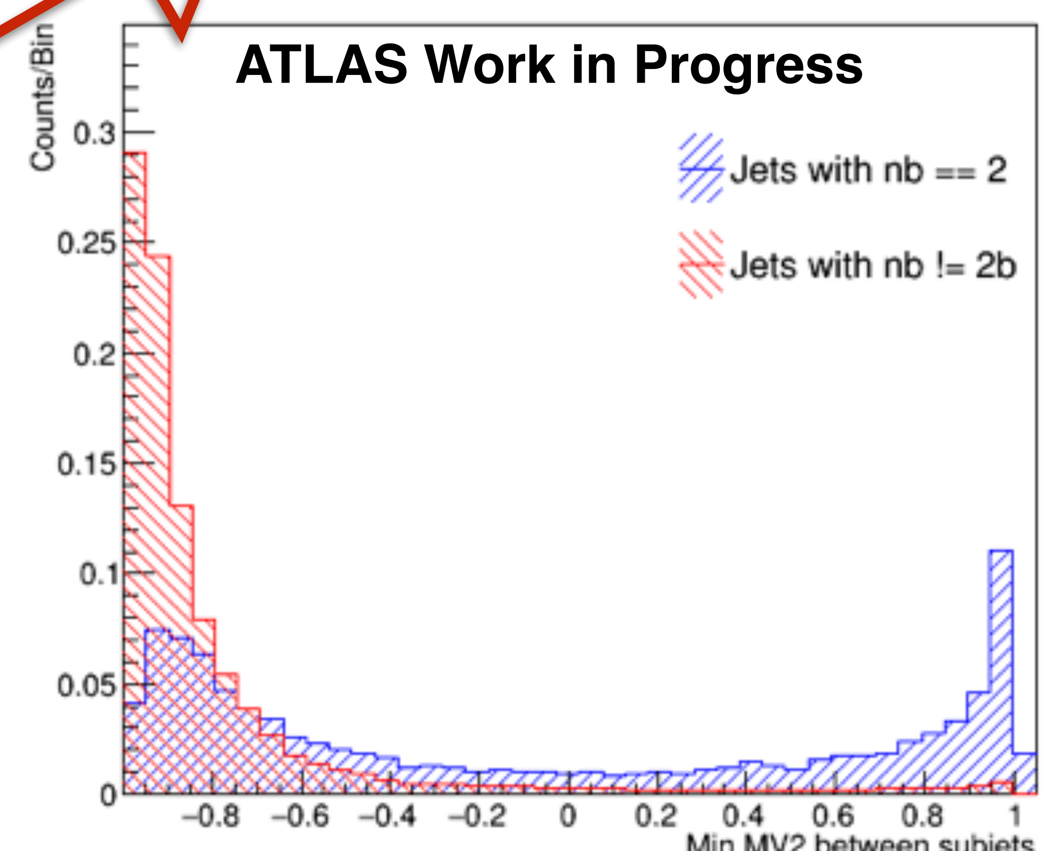


- Current double b-tagging reconstructs 0.2 radius track jets, b-tags them, and matches them to **large jets**
  - Due to the low pT of our signal, the second track jet usually **does not get reconstructed**.

Double B-Tagging

- Need an alternative method to double b-tag
- Collaborating with SLAC, who already have useful existing tools!
- "Build" two subjets from jet's **clustering history**
  - **Guarantees** that subjets will be made for each jet!
  - Ideally, each subjet will each contain 1 b-quark
- Use subjets to compute variables and feed them to a **BDT**
  - Example input: minimum value of the single b-tagging output between the two subjets

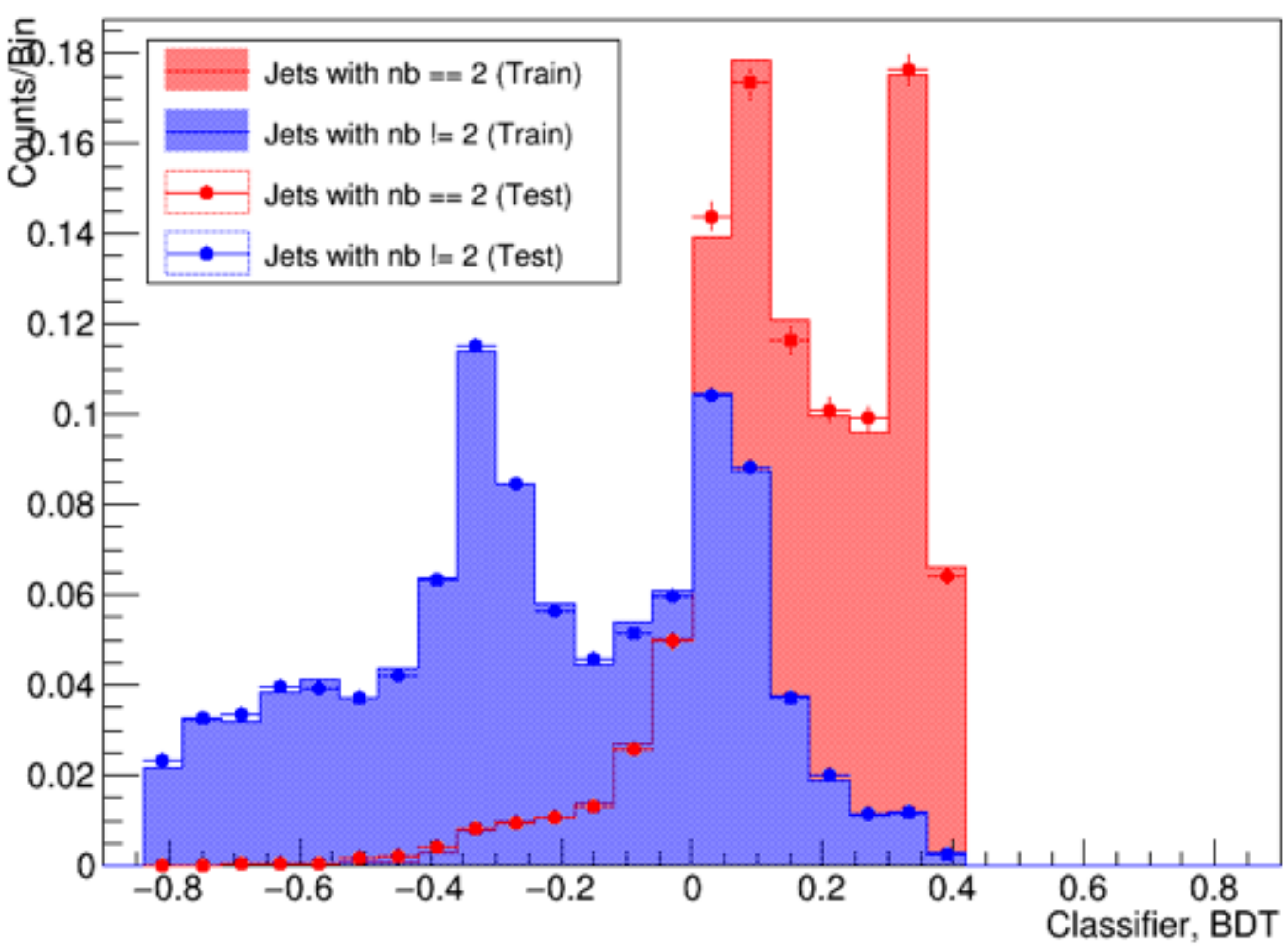




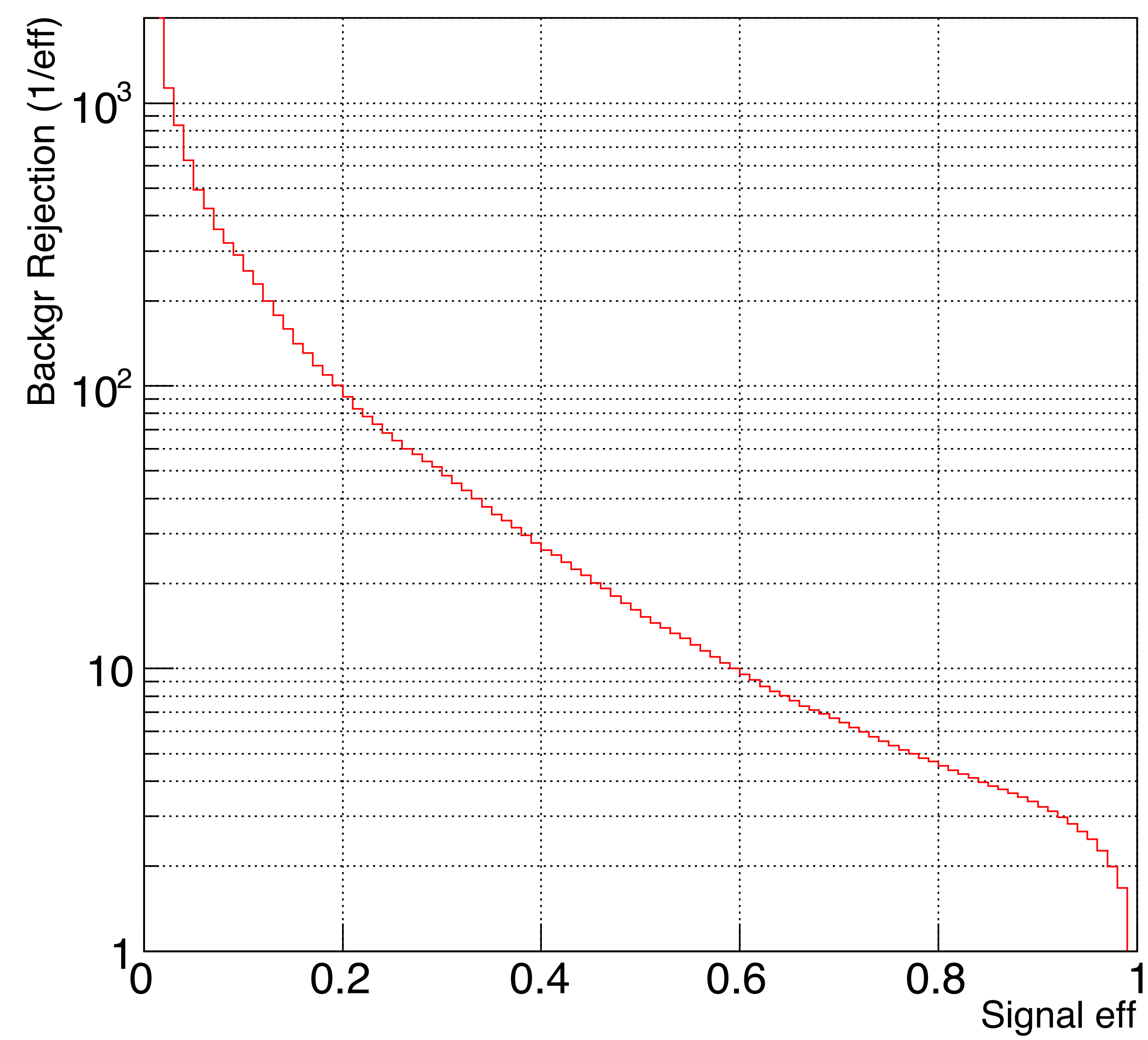
Preliminary Look at BDT Performance

- BDT output combining b-tagging and kinematic information from subjets
- Comparing **jets with 2 b-quarks** vs **jets with 0 or 1 b-quark**
- A promising first look, there are still many improvements and optimizations under investigation

ATLAS Work in Progress

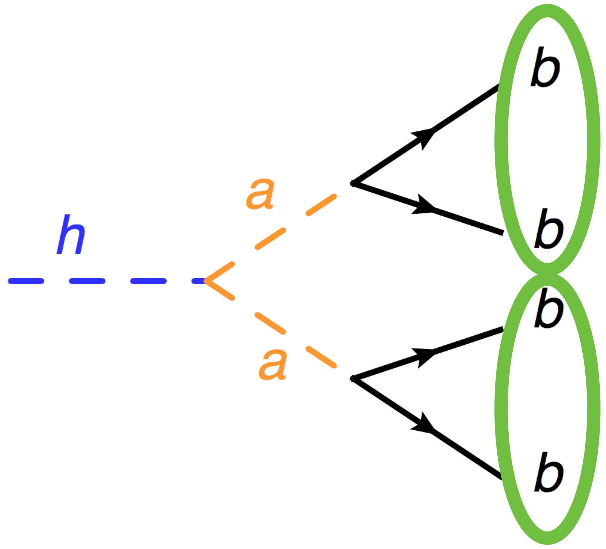


ATLAS Work in Progress

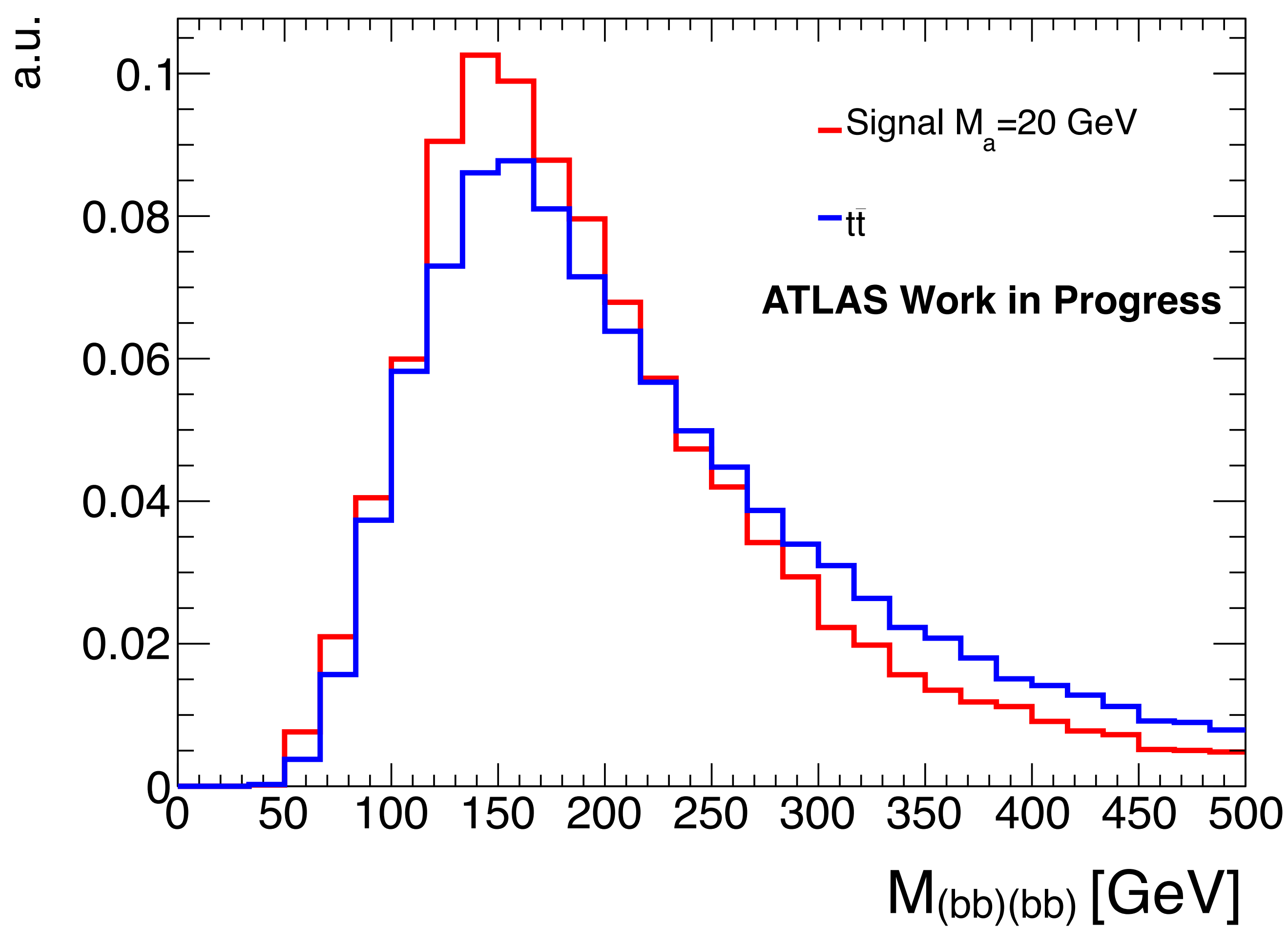


Reconstructing the Higgs Mass

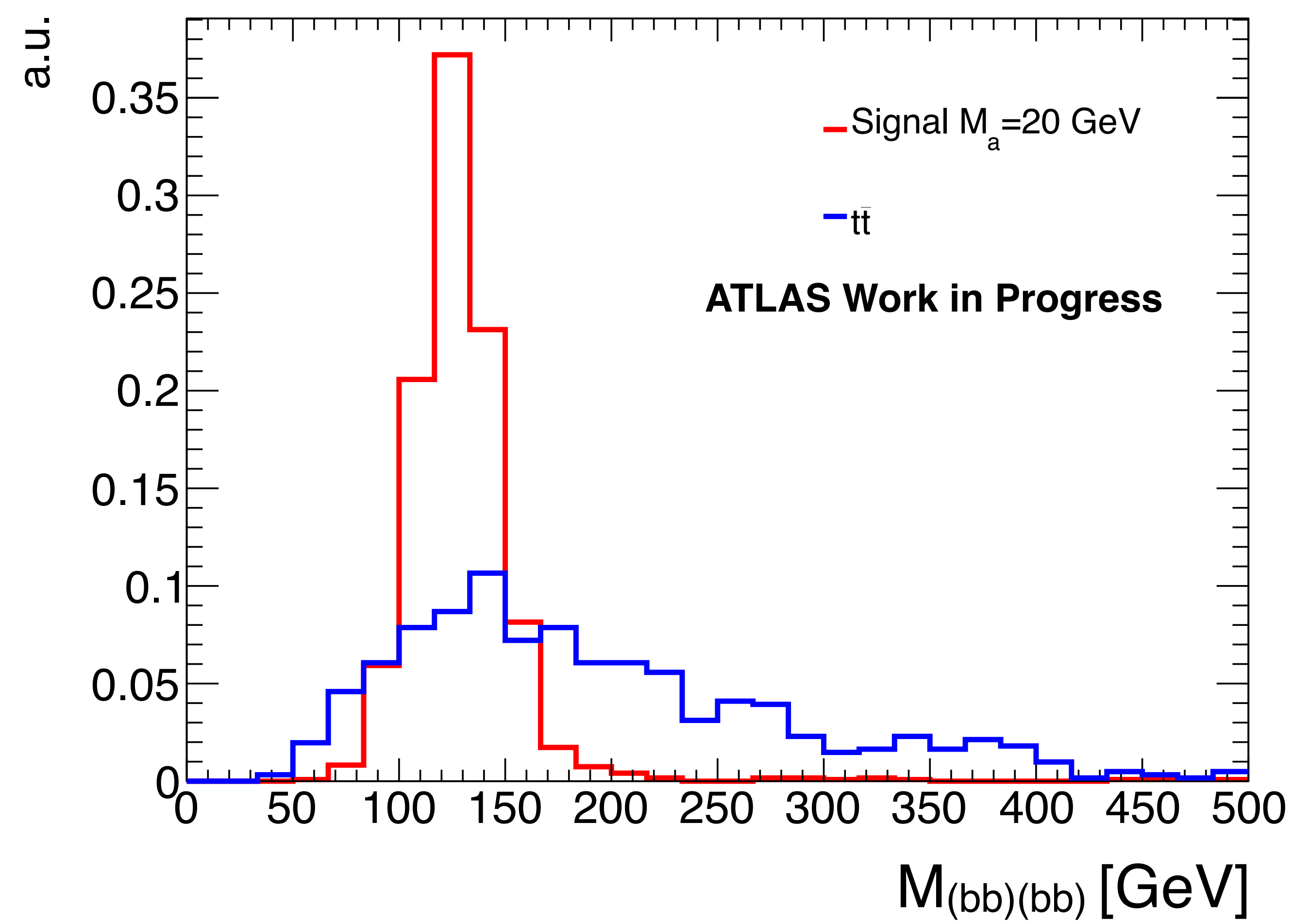
- As a validation of the BDT, reconstruct the invariant mass of two "double b-tagged", large radius jets
  - If working correctly, expect to find a **peak at the mass of the Higgs** for the signal



Mass of 2 Leading pT Jets



Mass of 2 Highest BDT Valued Jets Passing BDT Cut



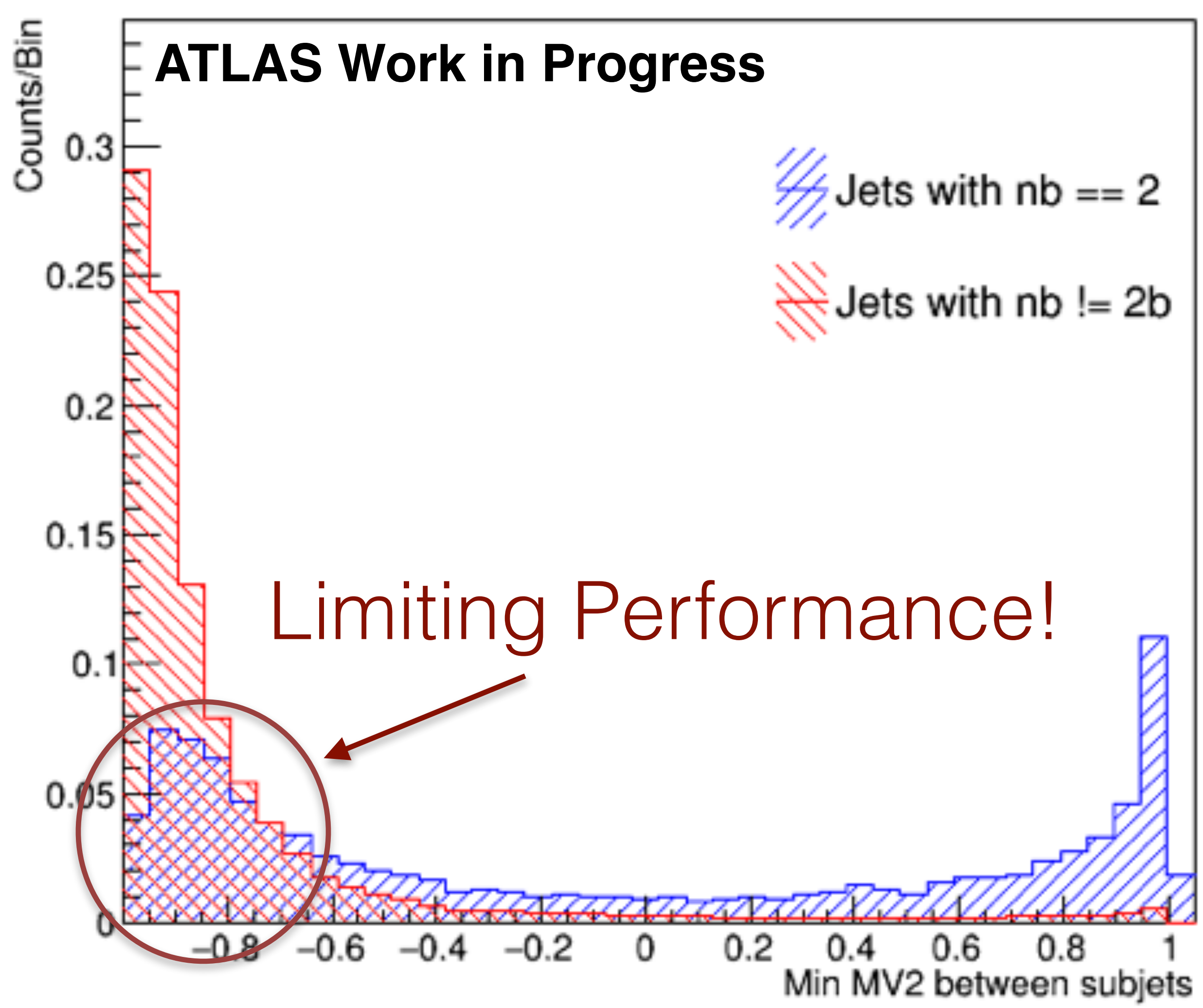
Conclusions/Next Steps

- Analysis with 2015 data has been done searching for exotic Higgs decays in WH production
  - Limits on σ(WH)×BR were set, but a loss in sensitivity was seen when the mass of the spin-zero particle was low
- First look at a new strategy to development a low pT double b-tagger to improve sensitivity for the low mass regime
  - Promising start, many areas to improve on
- Planned Next Steps
  - Optimize performance and calibrate the tagger
  - Prepare for the next iteration of the search to include 2016 data

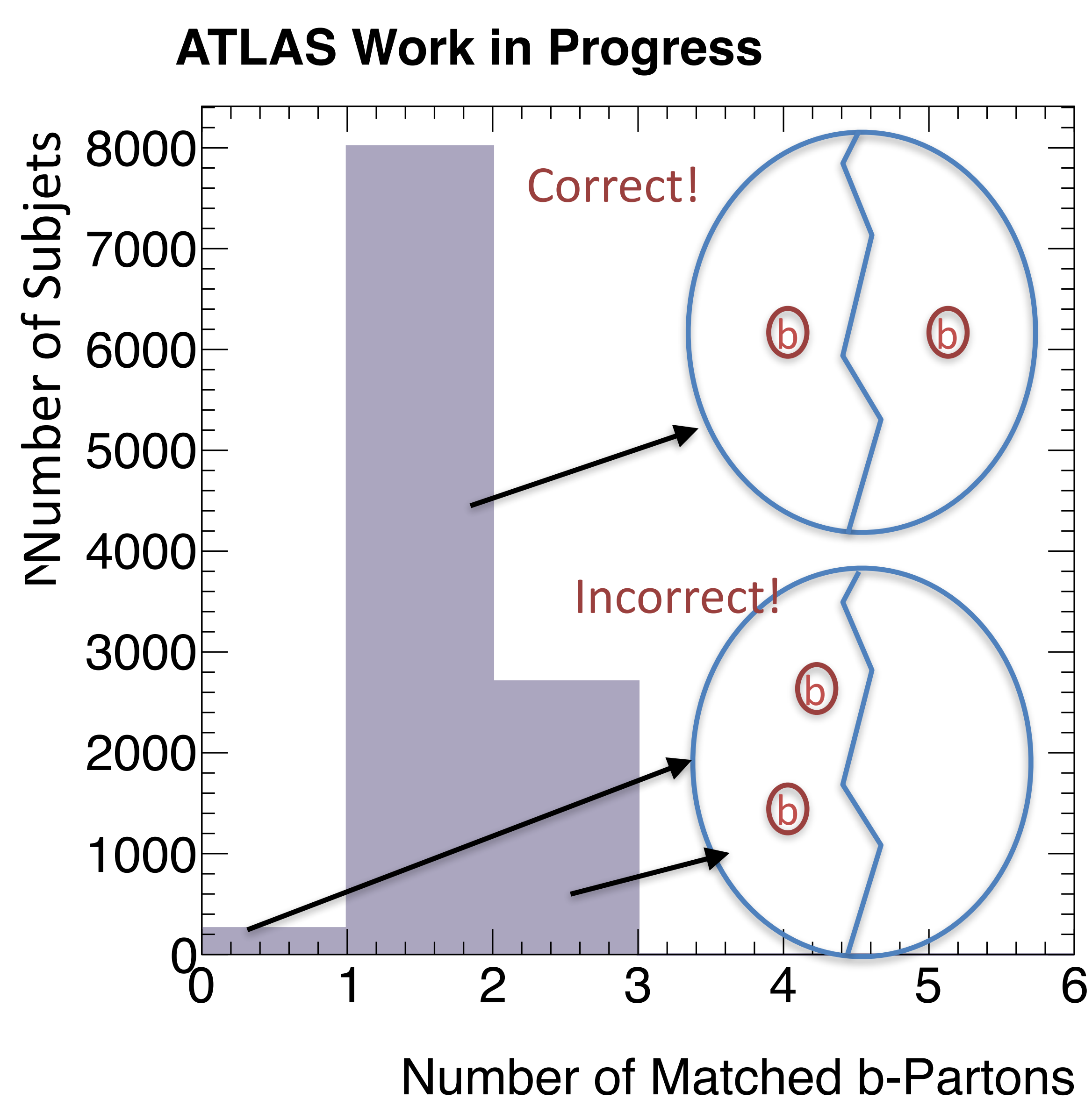
Backup slides

Current Challenges

- The peak in low min MV2 values for jets with 2 b's is currently limiting performance
- First checking if the ExKt algorithm is splitting the jets the correct way
  - Ideally, a jet with two b's will have 1 b in each subjet
- Jets incorrectly split look like jets with 1 b matched

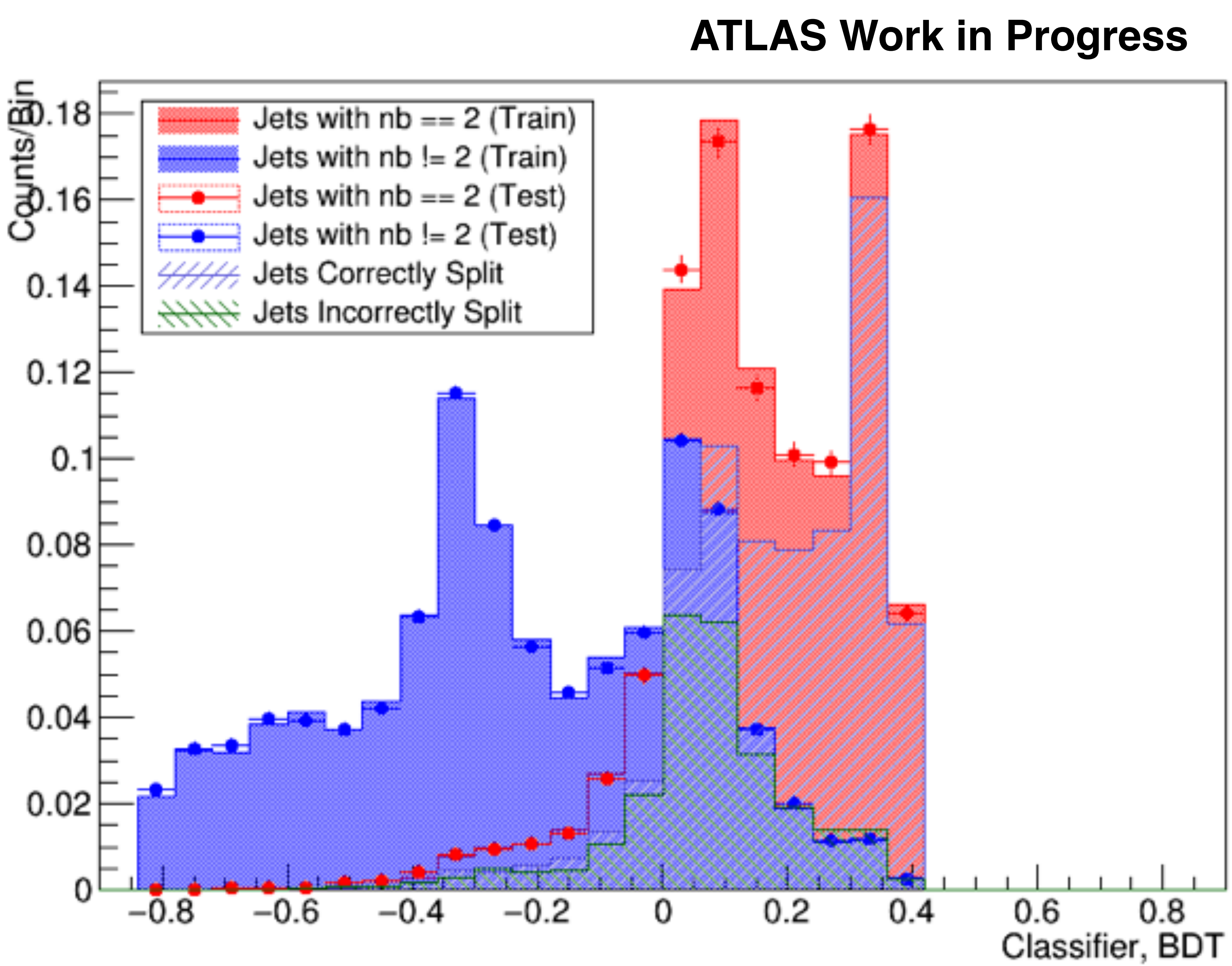


Leading pT Subjet in Jets with 2 b's



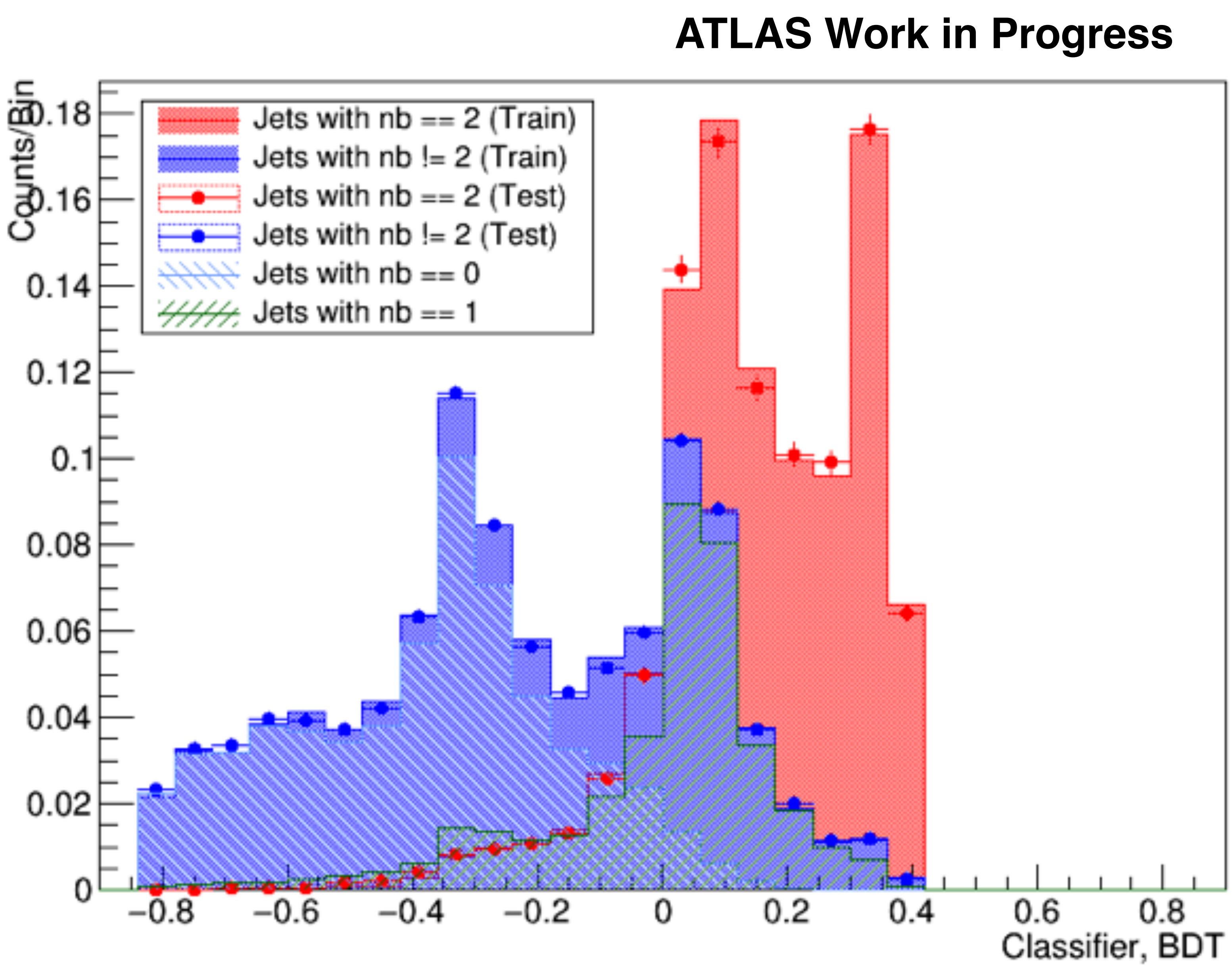
Current Challenges

- Separate BDT output of signal jets (red) with as correctly split (purple) with incorrectly split (green)
- Jets incorrectly split limiting performance as expected



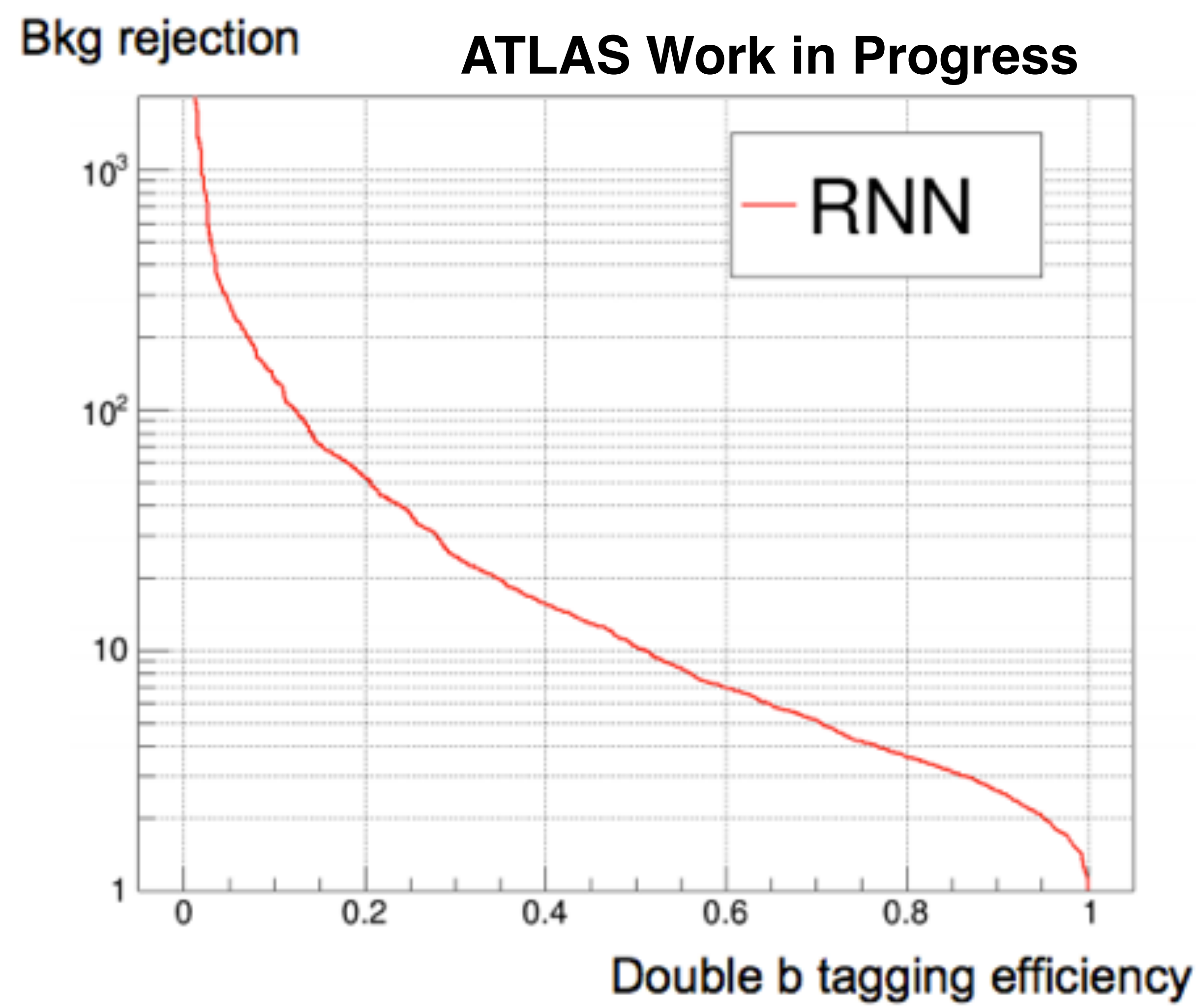
Current Challenges

- Separate BDT output of background jets (blue) with 1 b (green) and 0 b's (light blue)
- Jets with 1 b look like jets with 2 b's incorrectly split



Alternative Methods

- Another approach being explored: Recurrent Neural Network (RNN)
  - Instead of considering tracks as individual objects, treat them as an ordered sequence.
  - Exploit the correlations between tracks.
  - Allows all tracks associated to a jet to be fed as input.



Statistical procedure & systematics

- Profile likelihood fit performed in the TRexFitter framework
  - Fit carefully validated in different configurations: using Asimov dataset and fitting only the control regions.
  - Signal regions blinded until analysis was fully reviewed.
- Systematic uncertainties
  - All object systematics
    - NP sets for electrons and muons (reduced)
    - 18 NP set for JES uncertainties (+1 for JER)
    - E_T^{miss} soft term uncertainties
    - b-tagging and mistag uncertainties
  - Background-related systematics
    - $t\bar{t}$ background uncertainties
      - radHi / radLo uncertainties (Powheg+Pythia6)
      - PS uncertainty (Powheg+Herwig++)
      - Generator uncertainty (aMC@NLO+Herwig++)
      - Sherpa $t\bar{t}+b\bar{b}$ NLO systematics
    - Other background sources
      - Recommended normalization uncertainties
  - Luminosity and pileup

Systematic uncertainty	Type	Components
Luminosity	N	1
Pileup	S	1
Reconstructed Objects		
Electron trigger+reco+ID+isolation	SN	5
Electron energy scale+resolution	SN	2
Muon trigger+reco+ID+isolation	SN	6
Muon momentum scale+resolution	SN	3
Jet energy scale	SN	18
Jet energy resolution	SN	1
Missing transverse momentum	SN	3
b-tagging efficiency	SN	5
c-tagging efficiency	SN	4
Light-jet tagging efficiency	SN	14
Background Model		
$t\bar{t}$ cross section	N	1
$t\bar{t}$+HF: normalization	N	3
$t\bar{t}+b\bar{b}$: NLO Shape	SN	8
$t\bar{t}$ modeling: ISR/FSR	SN	3
$t\bar{t}$ modeling: generator	SN	3
$t\bar{t}$ modeling: parton shower+hadronisation	SN	3
W+jets normalization	N	3
Z+jets normalization	N	3
Single top cross section	N	1
Single top model	SN	1
Diboson normalization	N	1
$t\bar{t}V$ cross section	N	1
$t\bar{t}H$ cross section	N	1
Multijet normalization	N	1
Multijet model	S	1