Determining Trigger Efficiency of VBF Higgs to Bottom/Charm Background Events

SULI/ATLAS Summer 2024 Internship

Zach Gillis

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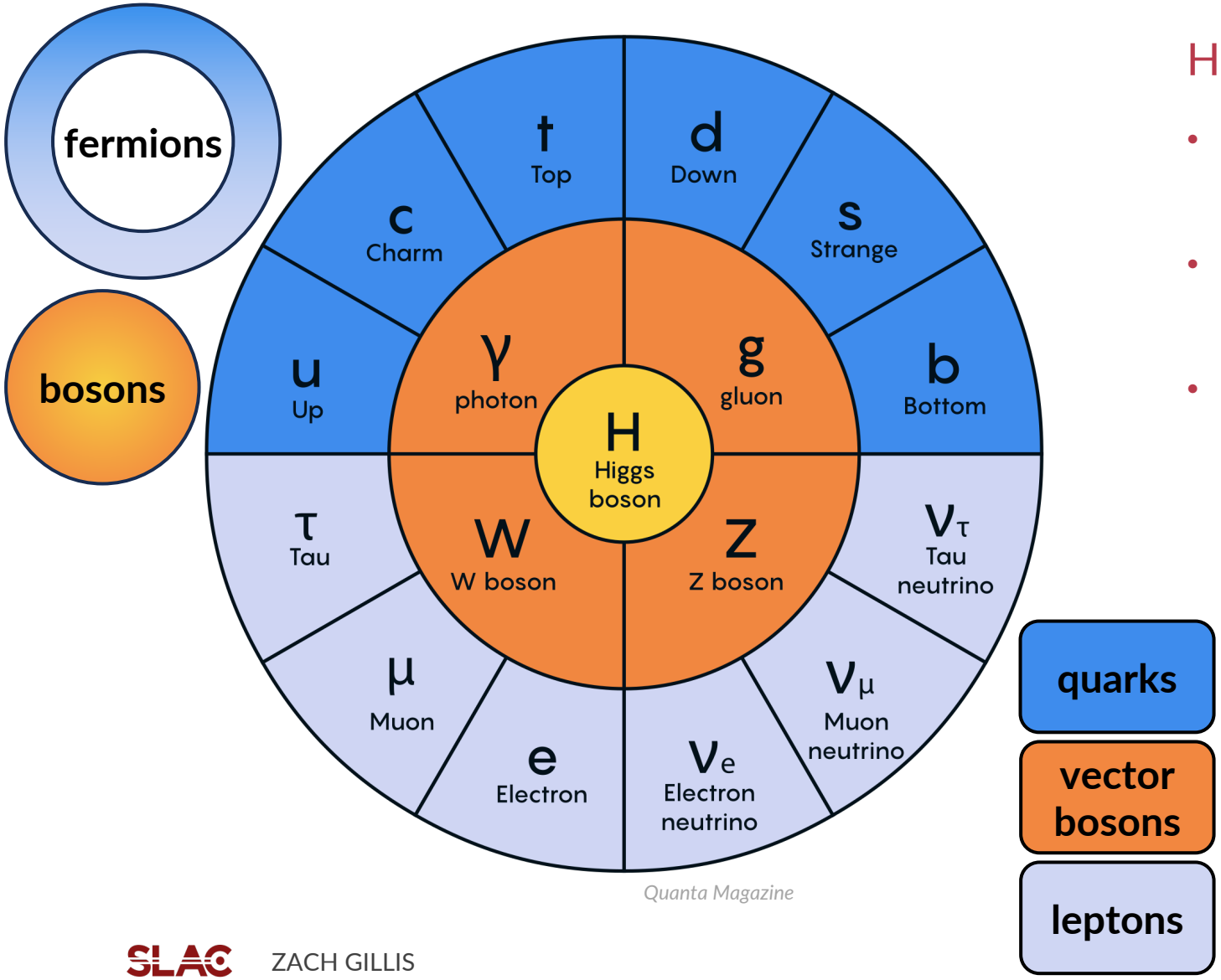
SLAC NATIONAL ACCELERATOR LABORATORY
THE UNIVERSITY OF CHICAGO
Stanford University | U.S. DEPARTMENT OF ENERGY

1

Introduction to the Standard Model & Higgs Boson

Higgs Boson



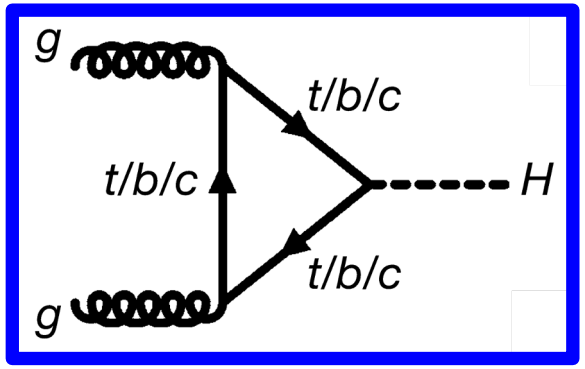
Quanta Magazine

Higgs at the center

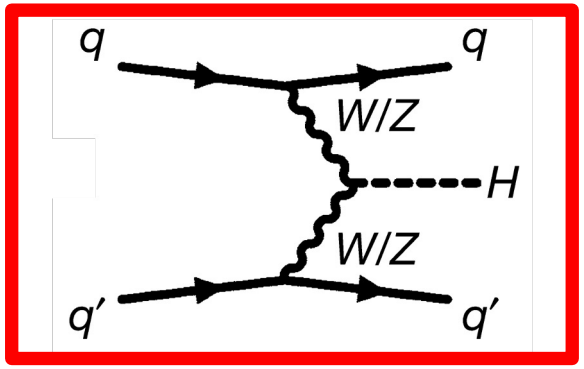
- **All particles get their mass from the Higgs field.** (except neutrinos?)
- Higgs is the only spin-0 particle in the Standard Model & the most recently discovered particle.
- Studying the Higgs may be a path to beyond-SM physics.
  - Does the Higgs decay into beyond-SM particles? [1]
  - Do the Higgs properties align with SM values? [2]

Higgs Boson Production Modes at LHC

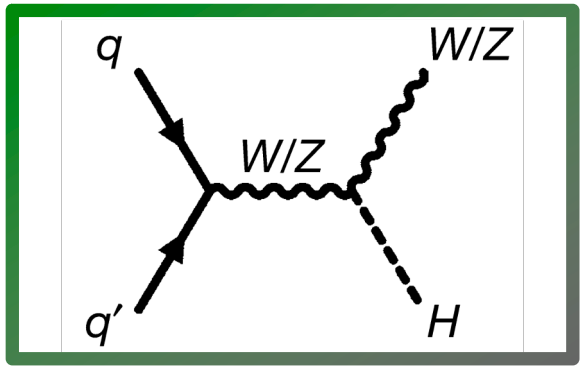
(1) Gluon-gluon fusion



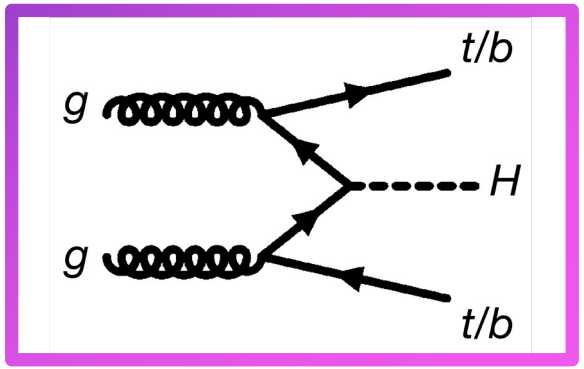
(2) Vector boson fusion



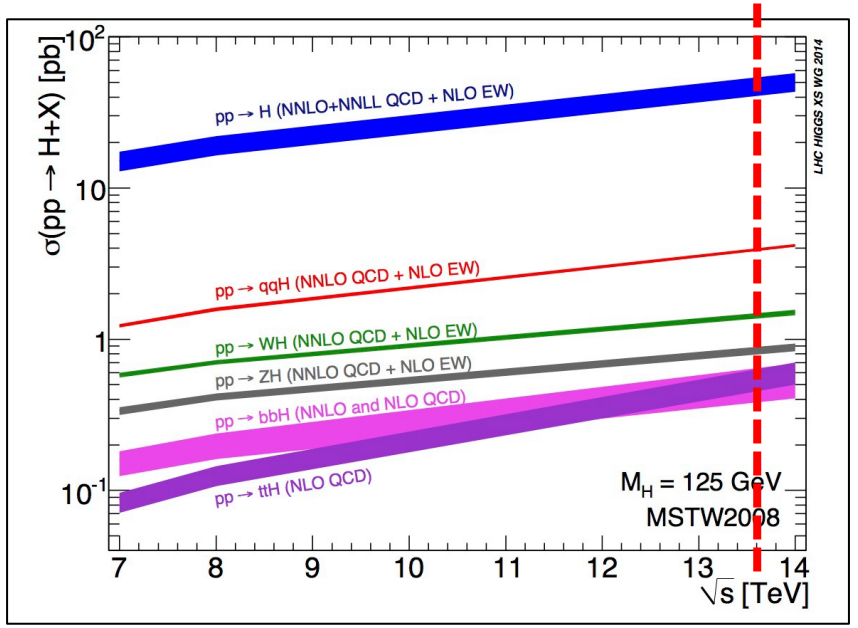
(3) Vector boson associated production



(4) Top/bottom pair associated production



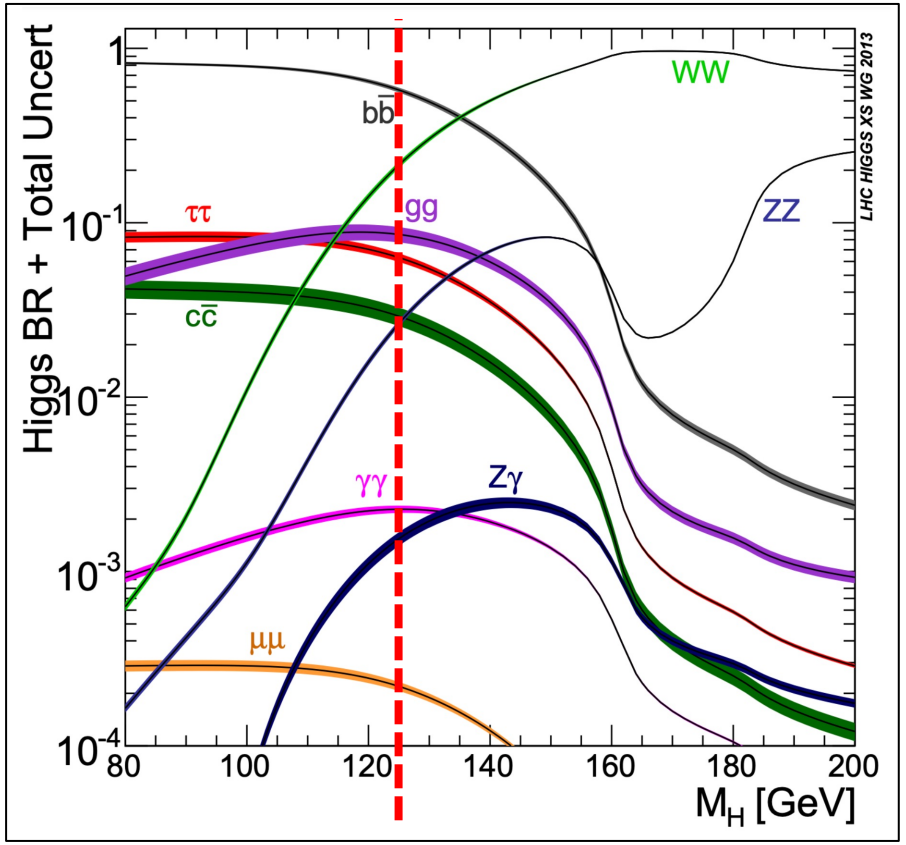
Current run (13.6 TeV)



LHC Higgs XS WG

Higgs Boson Decay Modes

- The Standard Model Higgs decays to:
  - $\boldsymbol{b\bar{b}}$: **57%**
  - W^+W^-: 21%
  - gg: 9%
  - $\tau^+\tau^-$: 6%
  - $\boldsymbol{c\bar{c}}$: **3% – hard to differentiate from $b\bar{b}$**
  - ZZ: 3%
  - Other (incl. $\gamma\gamma$): 1%



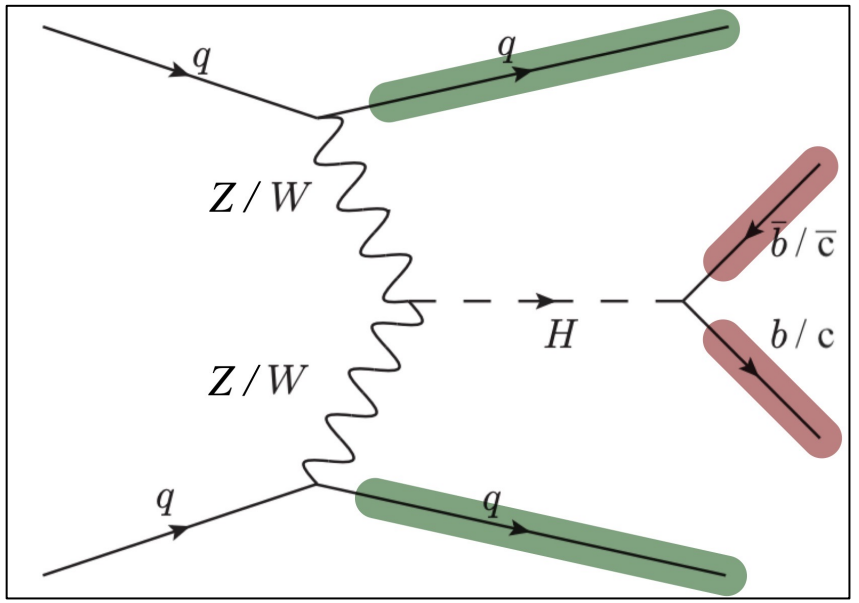
LHC Higgs XS WG

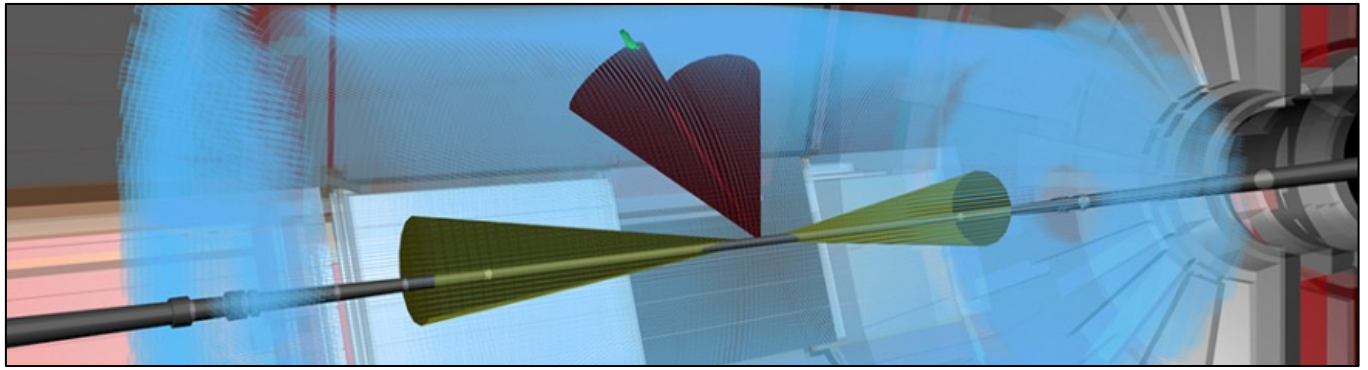
2

VBF H → bb/cc Analysis

Characteristics of VBF H → bb/cc Event

- VBF is the second-largest Higgs production mode in LHC; H → bb is the largest Higgs decay mode.
- Event consists of distinctive VBF-jets with **high invariant mass and high pseudorapidity gap**.
- Event is electroweak in nature, so there are no jets within VBF-jet rapidity gap other than the b/c-jets from Higgs decay.



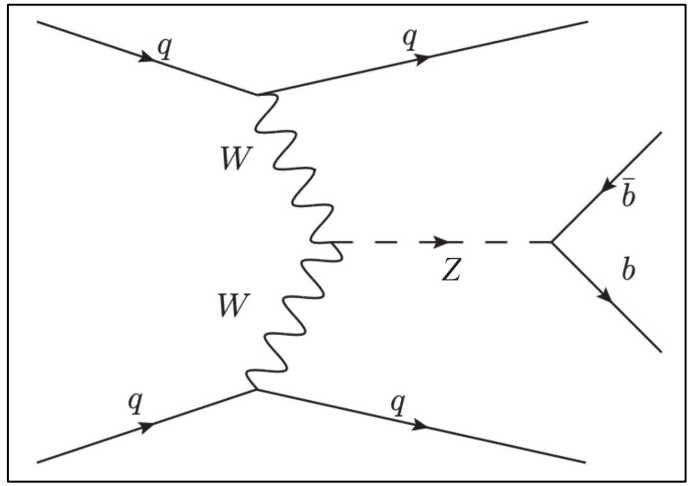


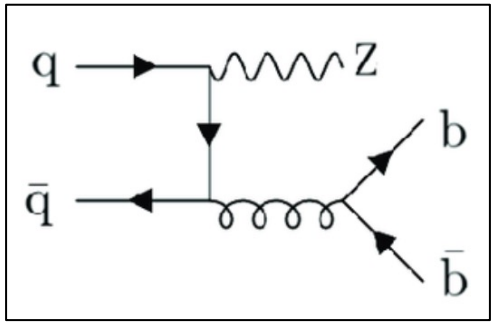
CMS

Event Background

What is background?

- Backgrounds are other physics events that have a similar detector signature, needs to be subtracted from data to yield accurate event statistics





Background in VBF H → bb/cc analysis

- Primary background is from QCD multijets, handled through data-driven methods
- This project focuses on Z → bb + jets background
  - b-jet energy resolution is limited ⇒ bb-dijet mass distributions from Z and Higgs decays overlap significantly (Z, Higgs have similar masses).
  - Monte Carlo estimates of this background are not accurate enough, will be reweighed

Defining Control Region

Why do we need a control region?

- A control region is a well-known phase space with an orthogonal output to the signal region
  - Necessary to study trigger efficiency in the signal region without referencing SR data
- Required to study trigger efficiency, get scale factors for SR MC, and transport factors to reweigh background.

Signal versus control region

Signal region

$H \rightarrow bb$ + jets
$Z \rightarrow bb$ + jets

- ≥ 4 jets
- Passes VBF trigger
- ≥ 1 VBF-candidate jet
  - Jet $p_T > 75$ GeV
  - $|\eta| < 4.5$
  - $m_{jj} > 1200$ GeV
  - $\Delta\eta_{jj} > 4$
  - $\Delta\phi_{jj} < 2$
- 2 b-tagged jets from Higgs/Z decay

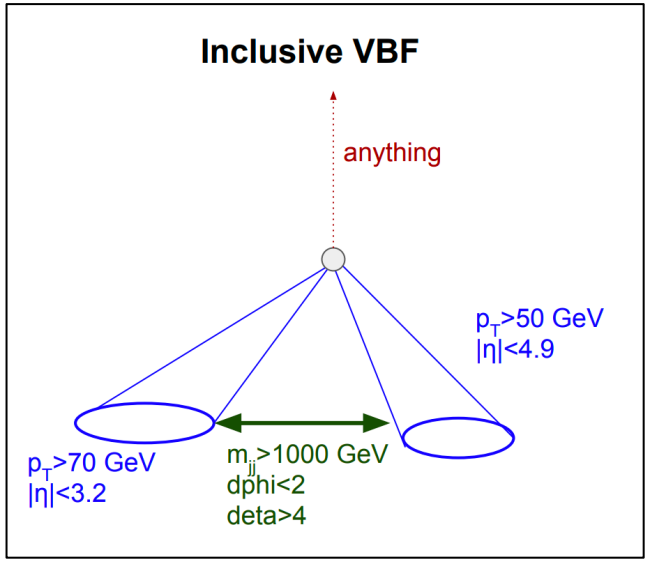
Control region

$Z \rightarrow \mu^+\mu^-$ + jets

- ≥ 2 jets
- Passes VBF trigger
- ≥ 1 VBF-candidate jet
- 2 muons from Z decay
  - $p_T > 10$ GeV, $|\eta| < 2.7$
  - 2 muons satisfying SFOS requirements
  - For ≥ 2 muons, select pair closest to Z mass.

Event Trigger

- Far too many events occur than can be recorded
- The trigger system determines which events are interesting and should be saved
- Inclusive VBF trigger selects events with 2 VBF jets, which have distinctly high invariant mass and pseudorapidity gap.



ATLAS Trigger System

Level-1 Trigger (L1)

40 MHz → 100 kHz

Hardware trigger that processes all events, working with select calorimeter and muon spectrometer data

High-Level Trigger (HLT)

100 kHz → 1.5 kHz

Software trigger that runs event reconstruction algorithms using full detector information

Trigger Efficiency

What is trigger efficiency?

- Trigger efficiency is the proportion of events meeting selection criteria that actually pass trigger
- Trigger efficiency informs the parameters of analysis kinematic phase space and the scale factor for SR MC.

Trigger studies for this analysis

- Goal is to determine the VBF trigger efficiency within the control region

$$\text{trig. eff.} = \frac{\#\text{ events passing VBF \& loose muon triggers}}{\#\text{ events passing loose muon trigger}}$$

- Events matched with eventNumber
- VBF trigger: HLT_j70_j50a_j0_DJMASS1000j50dphi200x400deta_L1MJJ_500_NFF
- Loose muon trigger (single muon trigger): HLT_mu24_ivarmedium_L1MU14FCH

Project Outline

My contribution

1. Validate control region event selections
    - Create kinematic MC event histograms for signal and control regions; determine if distributions are expected
    - Compare MC 22 & 23 distributions for validation
2. Determine the trigger efficiency (w.r.t. kinematic variables) within the control region in both data and MC (only leading order events for now)
    - Use the “loose” muon trigger to flag $Z \rightarrow \mu^{+}\mu^{-}$ + jets events
    - See which among these are flagged by the VBF trigger

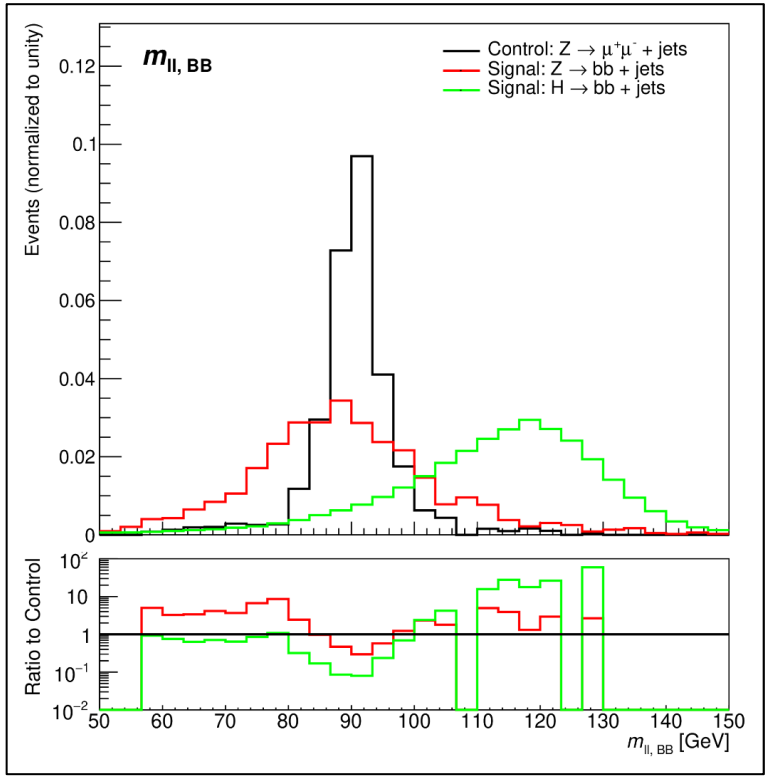
3

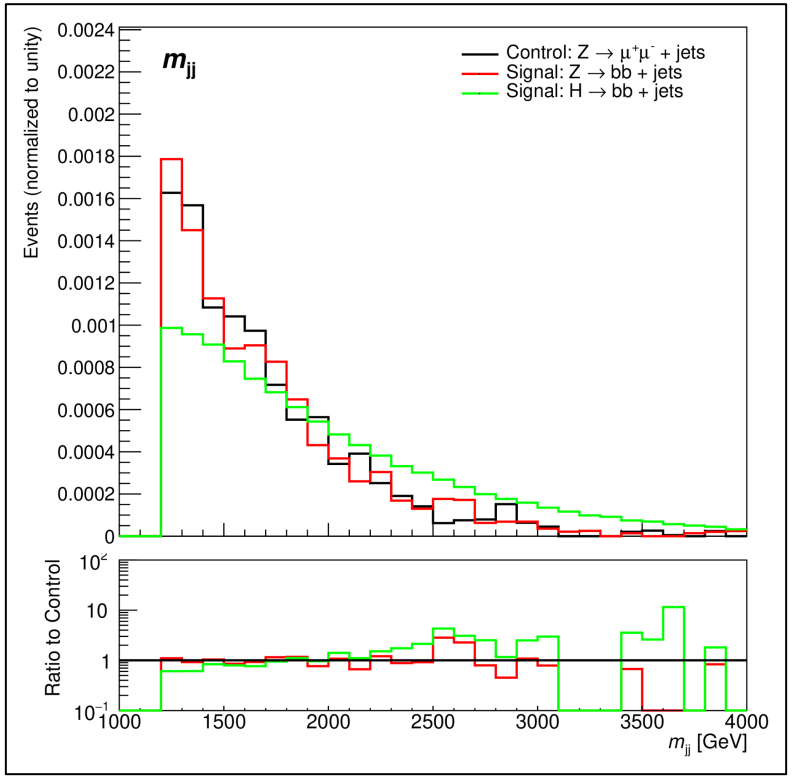
Control Region Validation

Control Region Validation

Invariant mass

- Less resolution in bb masses than dilepton mass: jets have lower detector resolutions than muons
- Jet mass distribution for H → bb + jets skews rightward: non-VBF jets (QCD events) included in Z events





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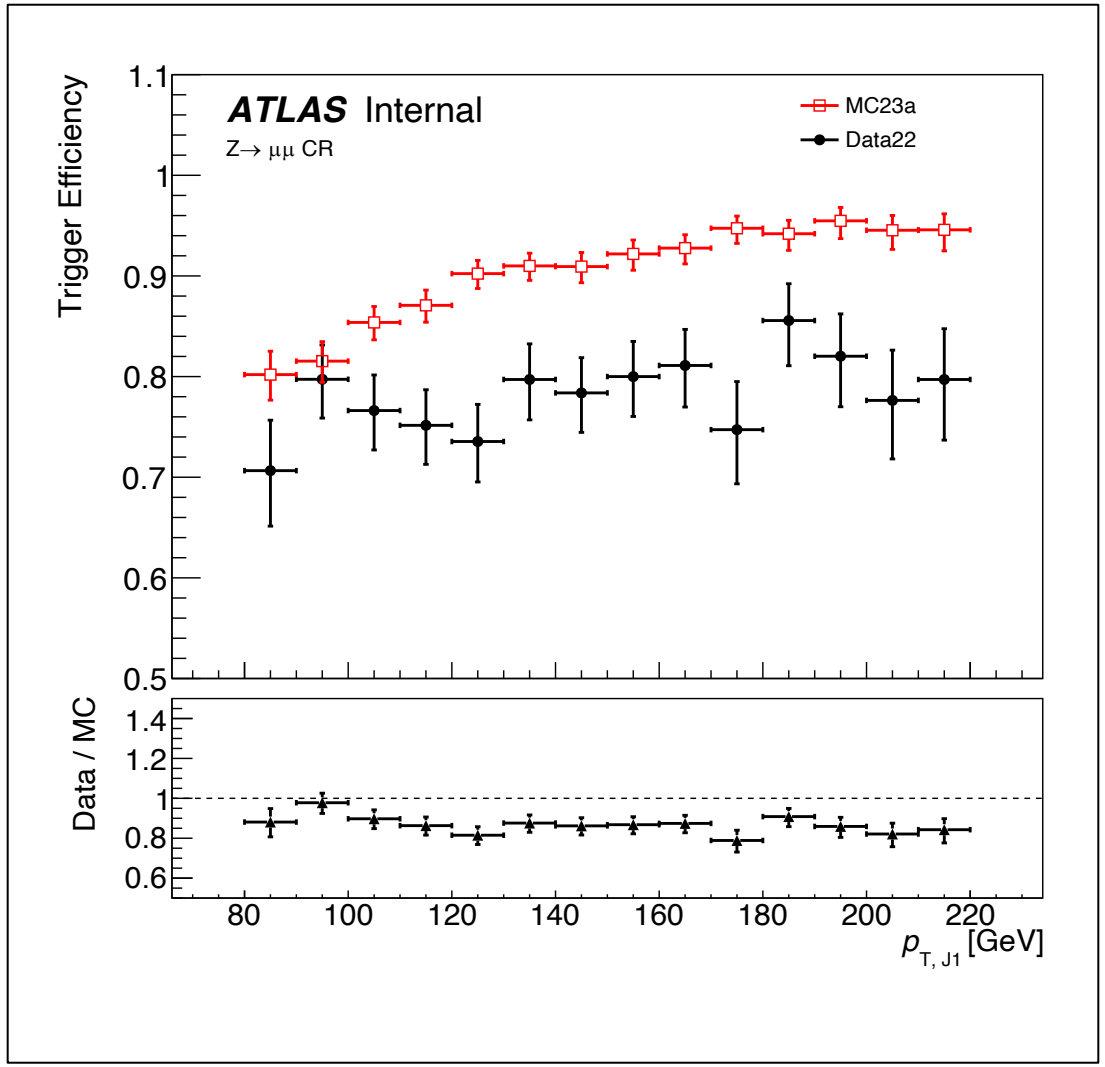
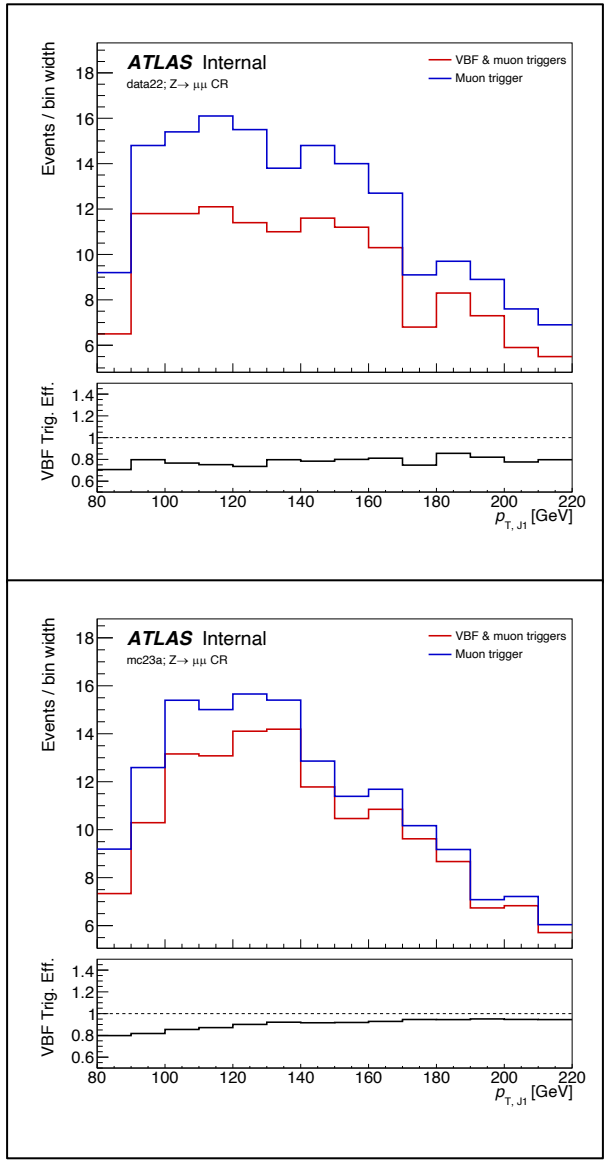
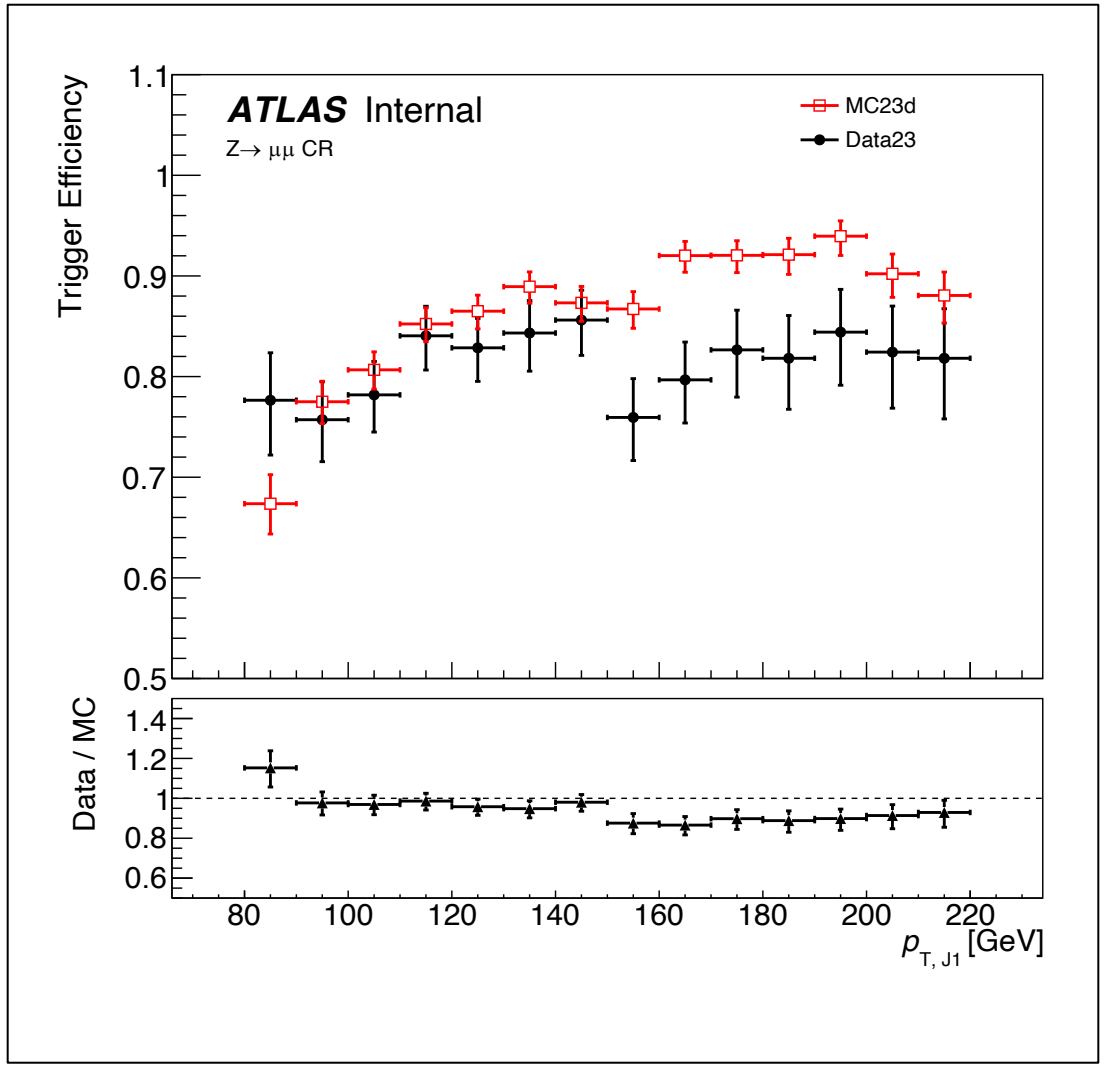
Trigger Efficiency

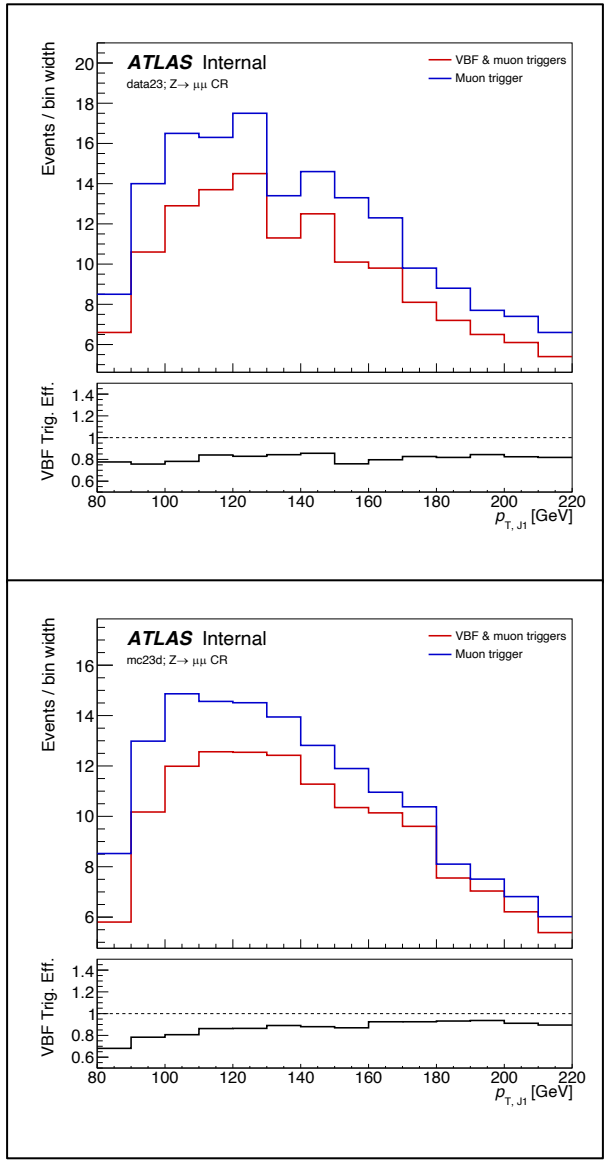
Trigger Efficiency in Data & MC, $p_{T,\,J1}$, MC23a/Data22





Trigger Efficiency in Data & MC, $p_{T,\,J1}$, MC23d/Data23





Conclusion

- Defined and validated control region
- Determined VBF trigger efficiency in MC and data within control region
- Will allow accurate reweighing of signal region trigger efficiency in MC

Acknowledgements

Mentors

- Prajita Bhattarai
- Caterina Vernieri

Program

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- SULI Program
- SLAC National Accelerator Laboratory

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References

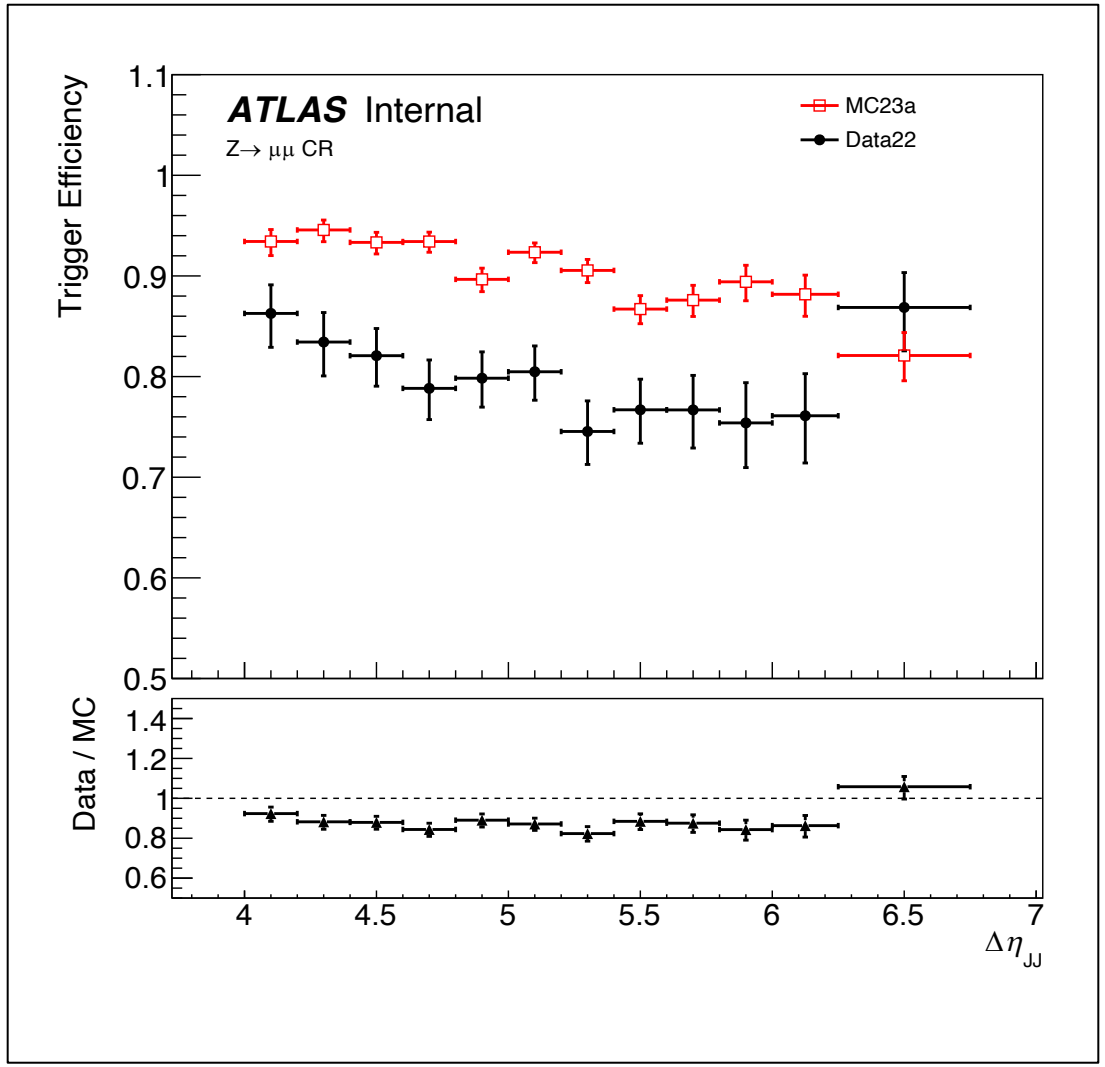
1) *Looking for the invisible with the higgs boson*. ATLAS. (n.d.-b). https://atlas.cern/updates/briefing/invisible-Higgs-search

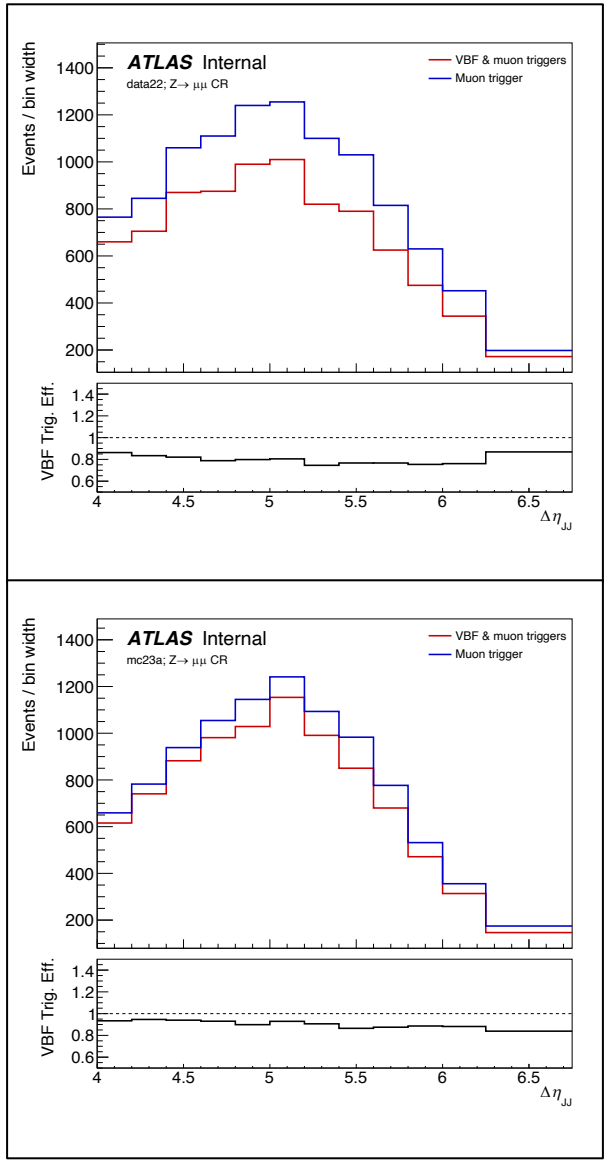
2) Leney, K. (2024, June). *Seeing double (Higgs bosons)*. Lecture.

Backup

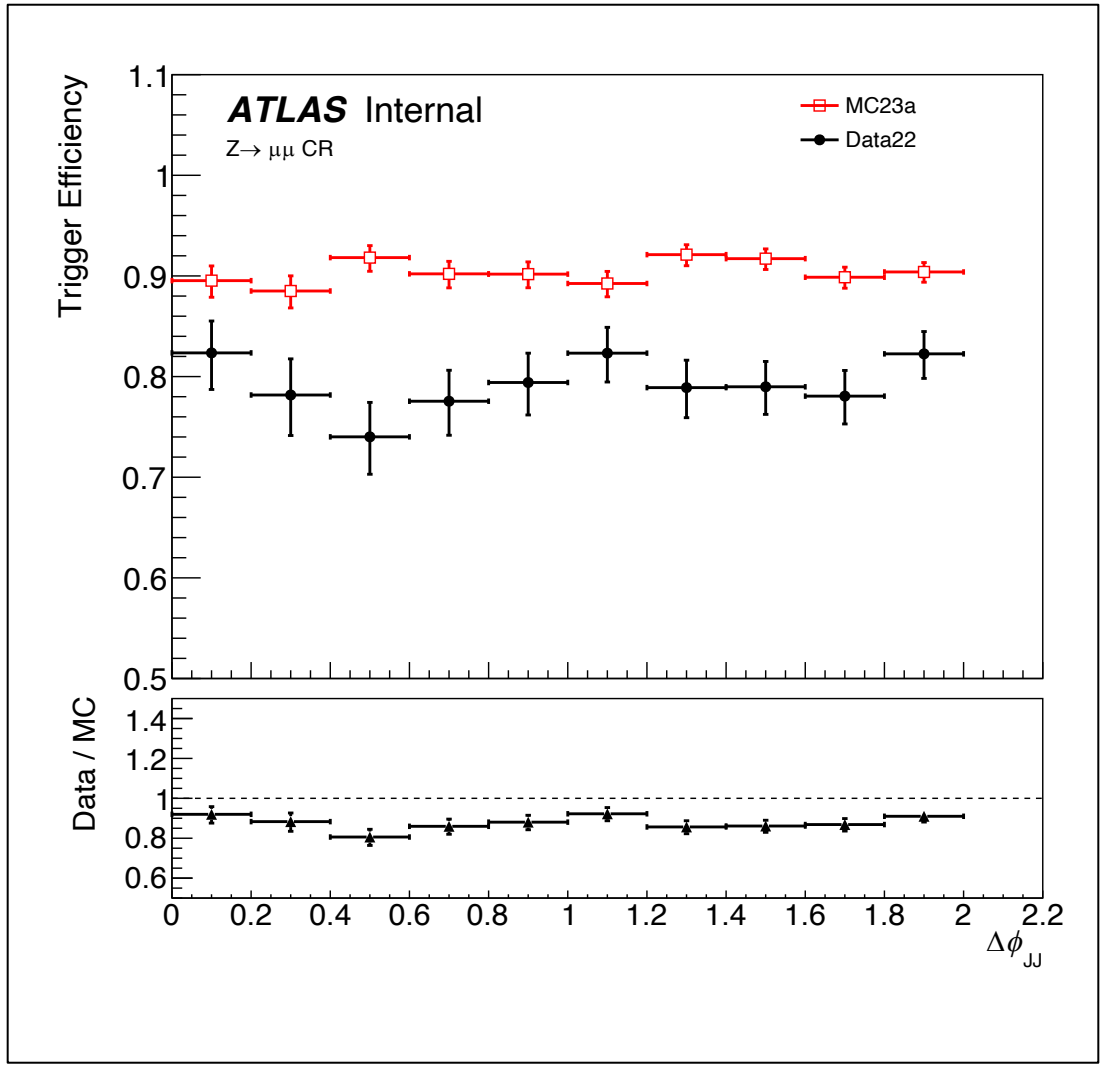
Trigger Efficiency in MC23a/Data22

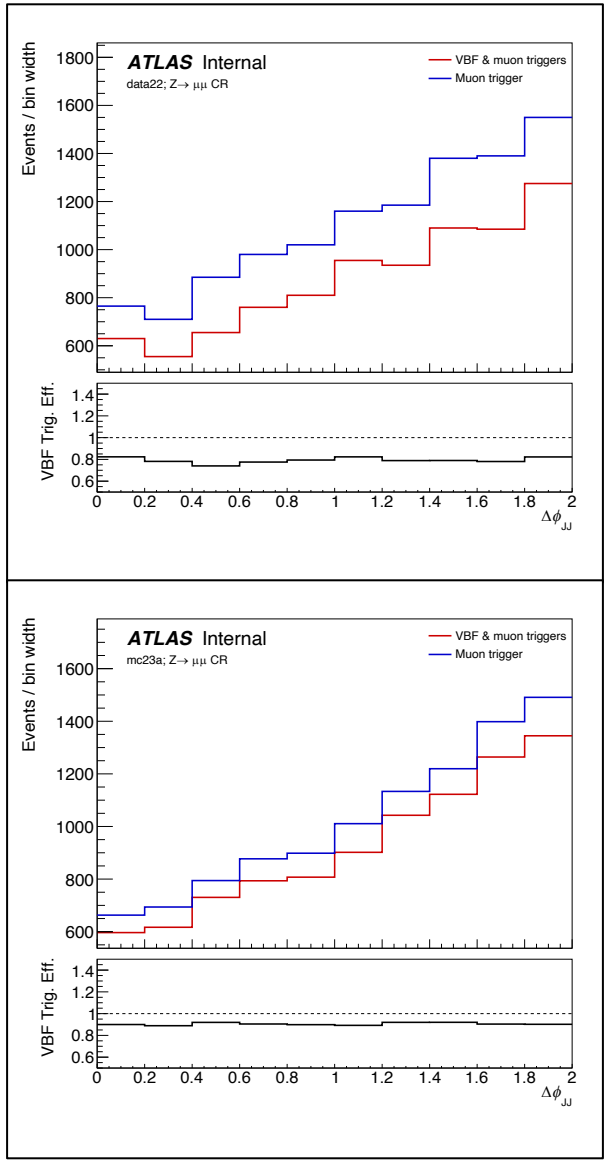
Trigger Efficiency in Data & MC, $\Delta\eta_{JJ}$



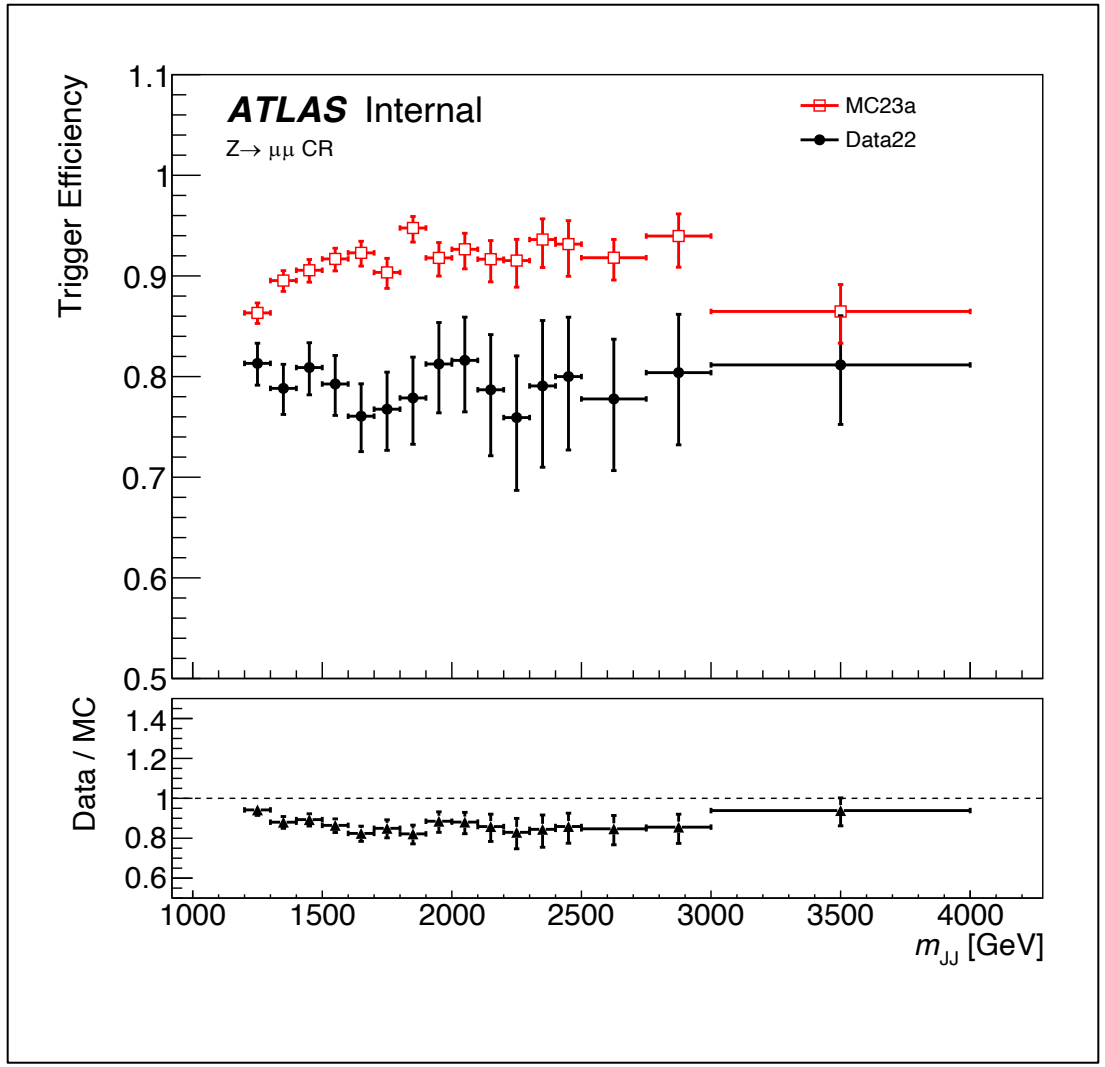


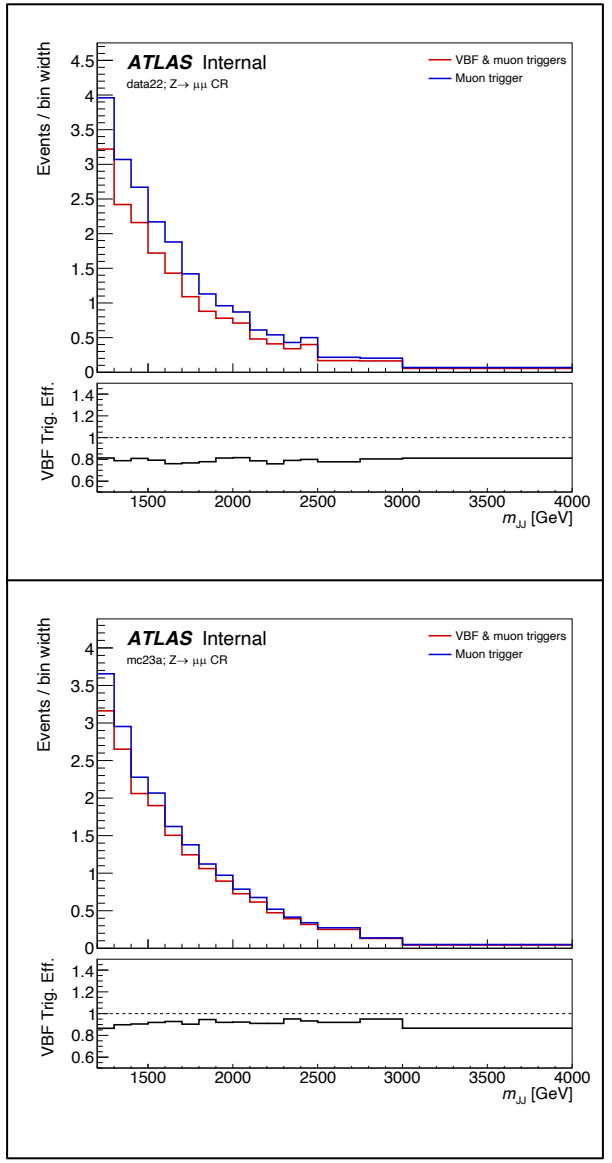
Trigger Efficiency in Data & MC, $\Delta\Phi_{JJ}$



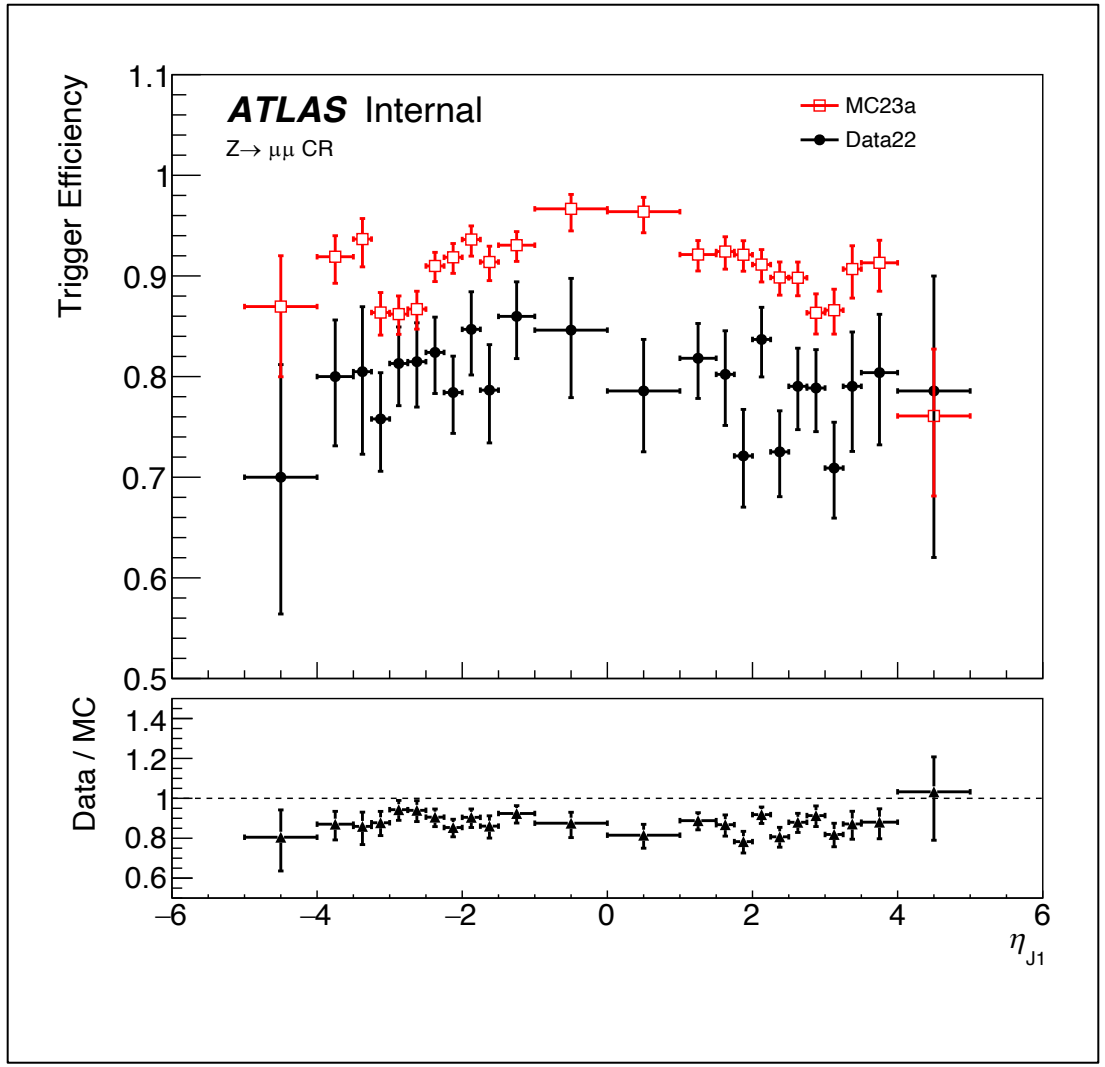


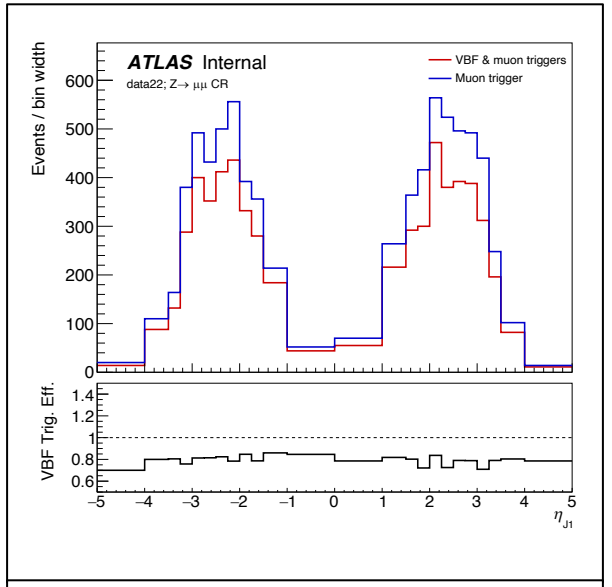
Trigger Efficiency in Data & MC, m_{JJ}

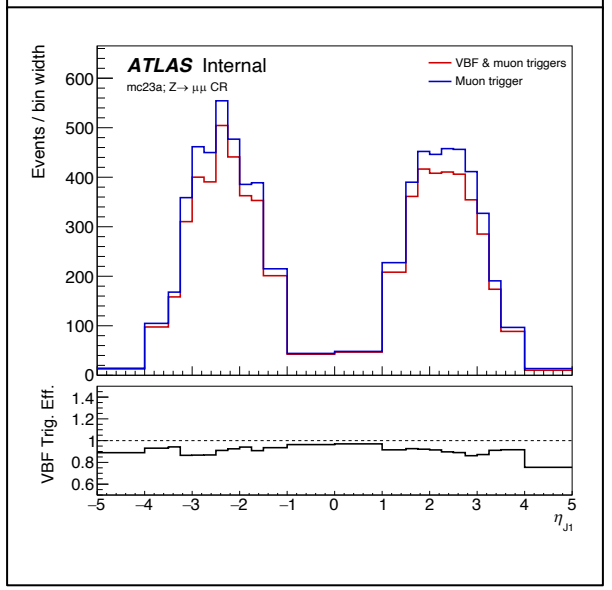




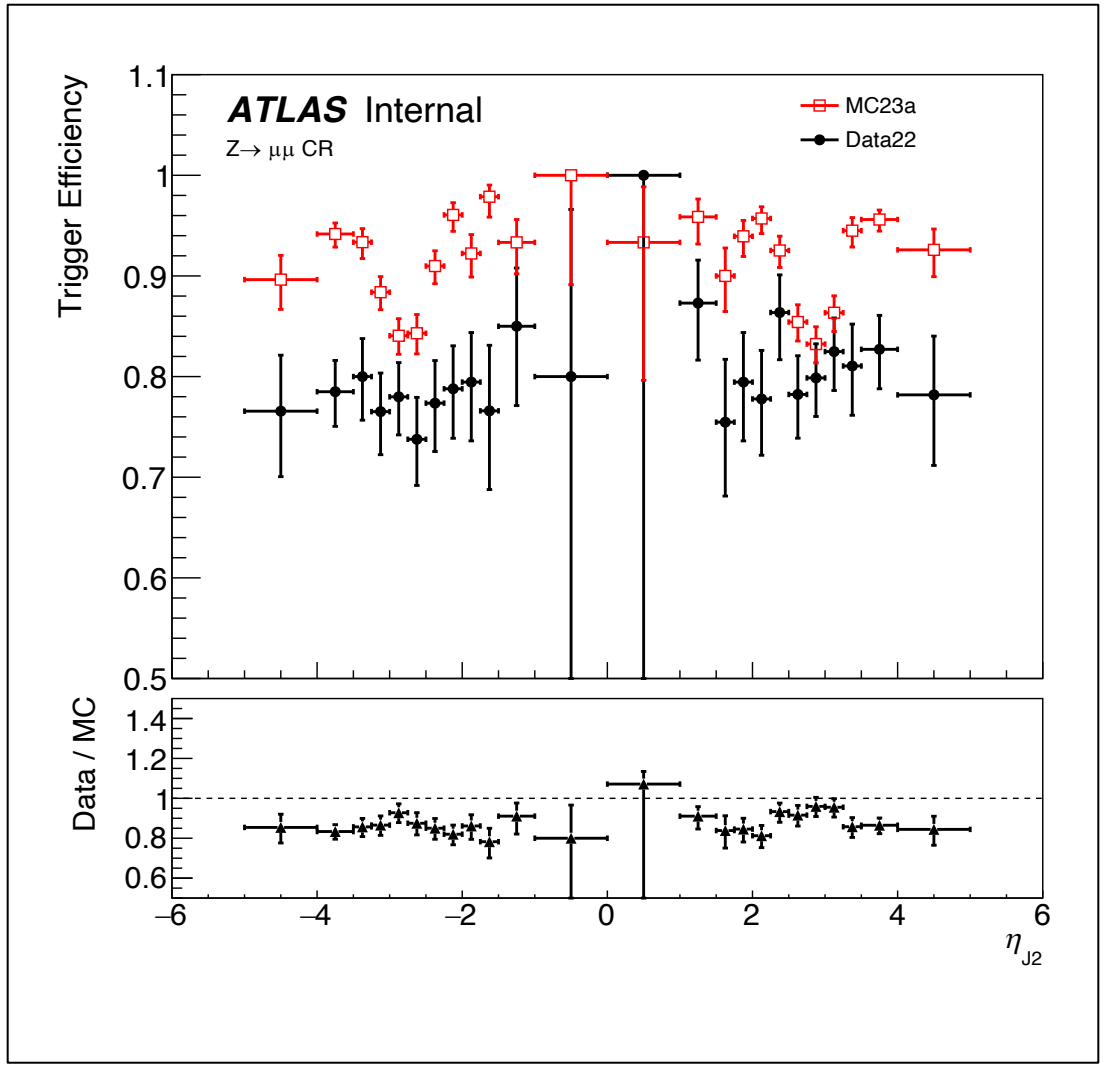
Trigger Efficiency in Data & MC, η_{J1}

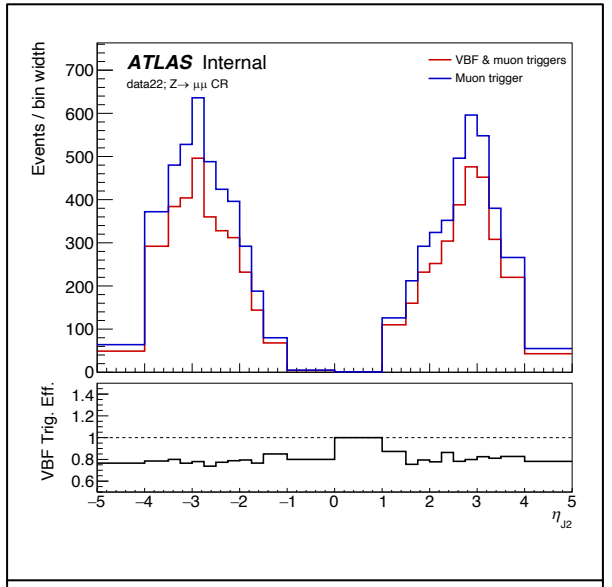


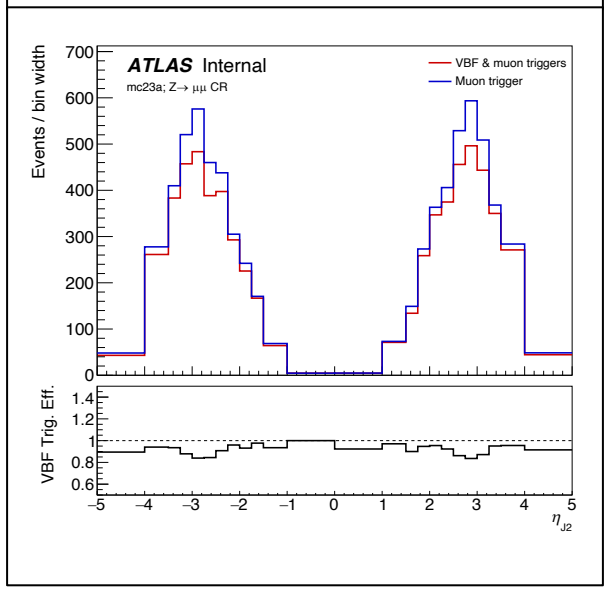




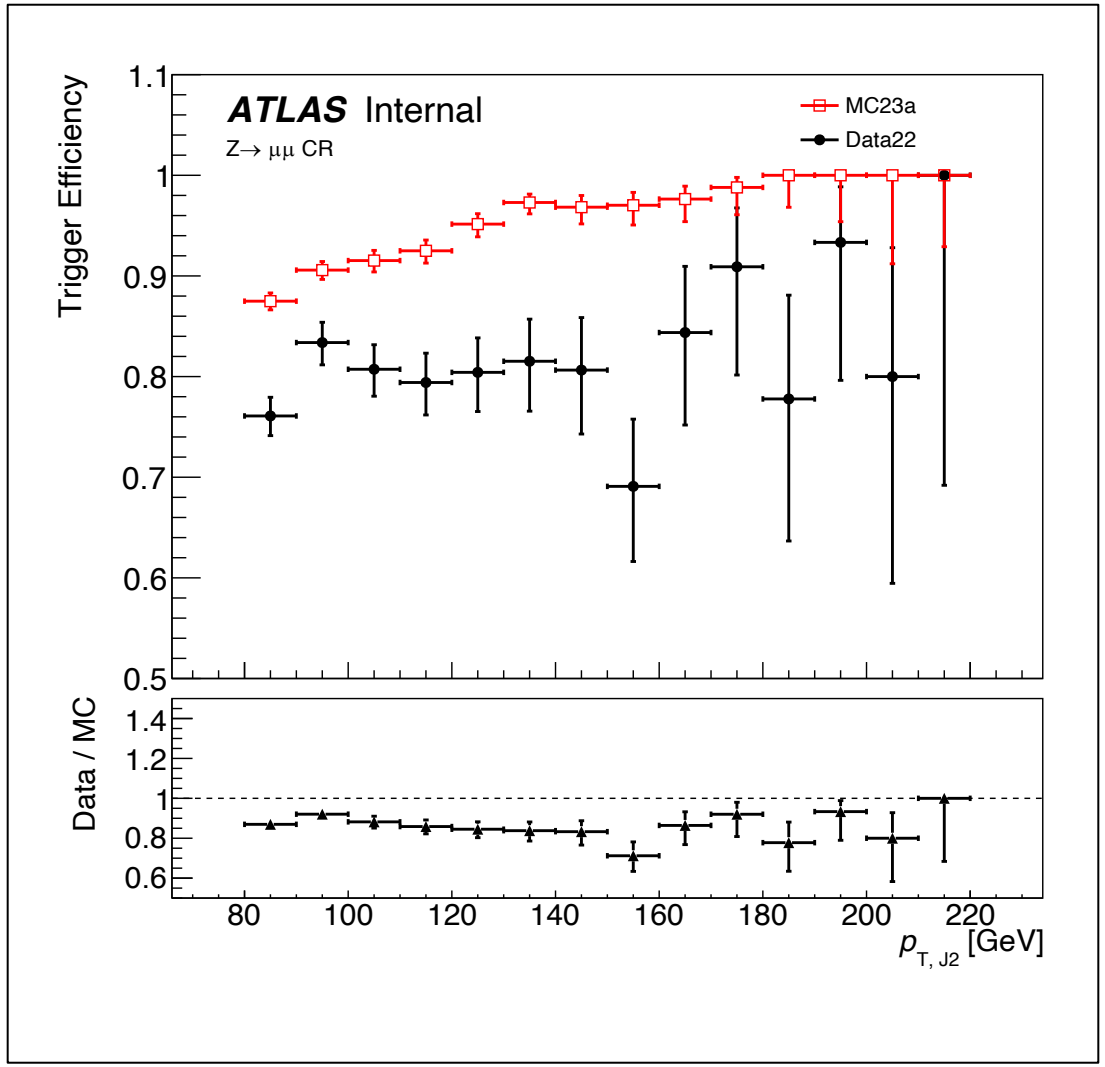
Trigger Efficiency in Data & MC, η_{J2}

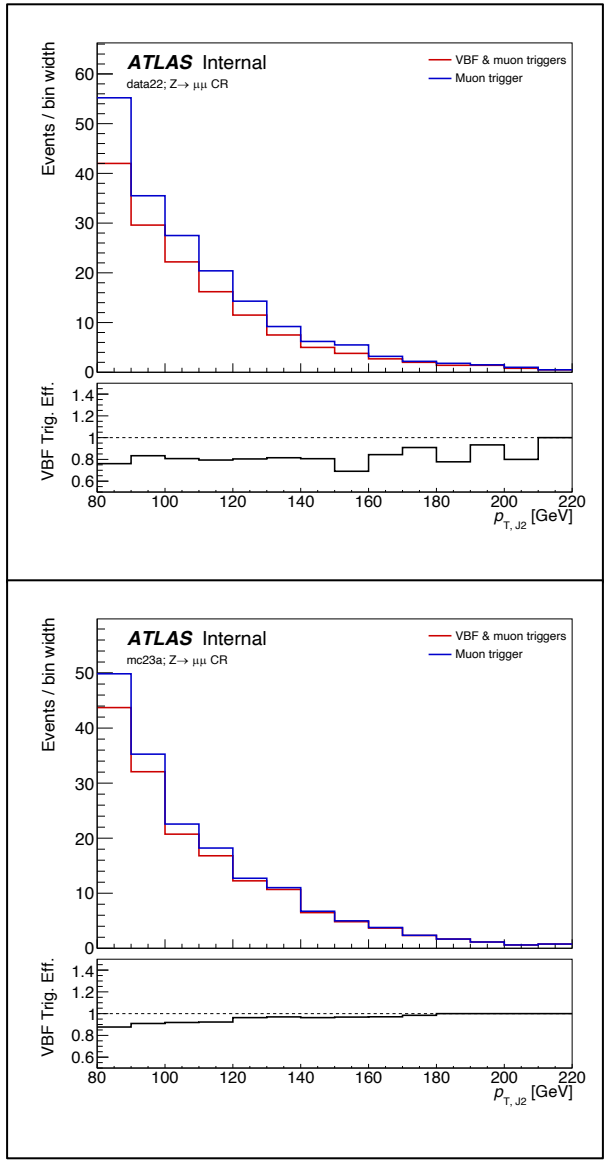






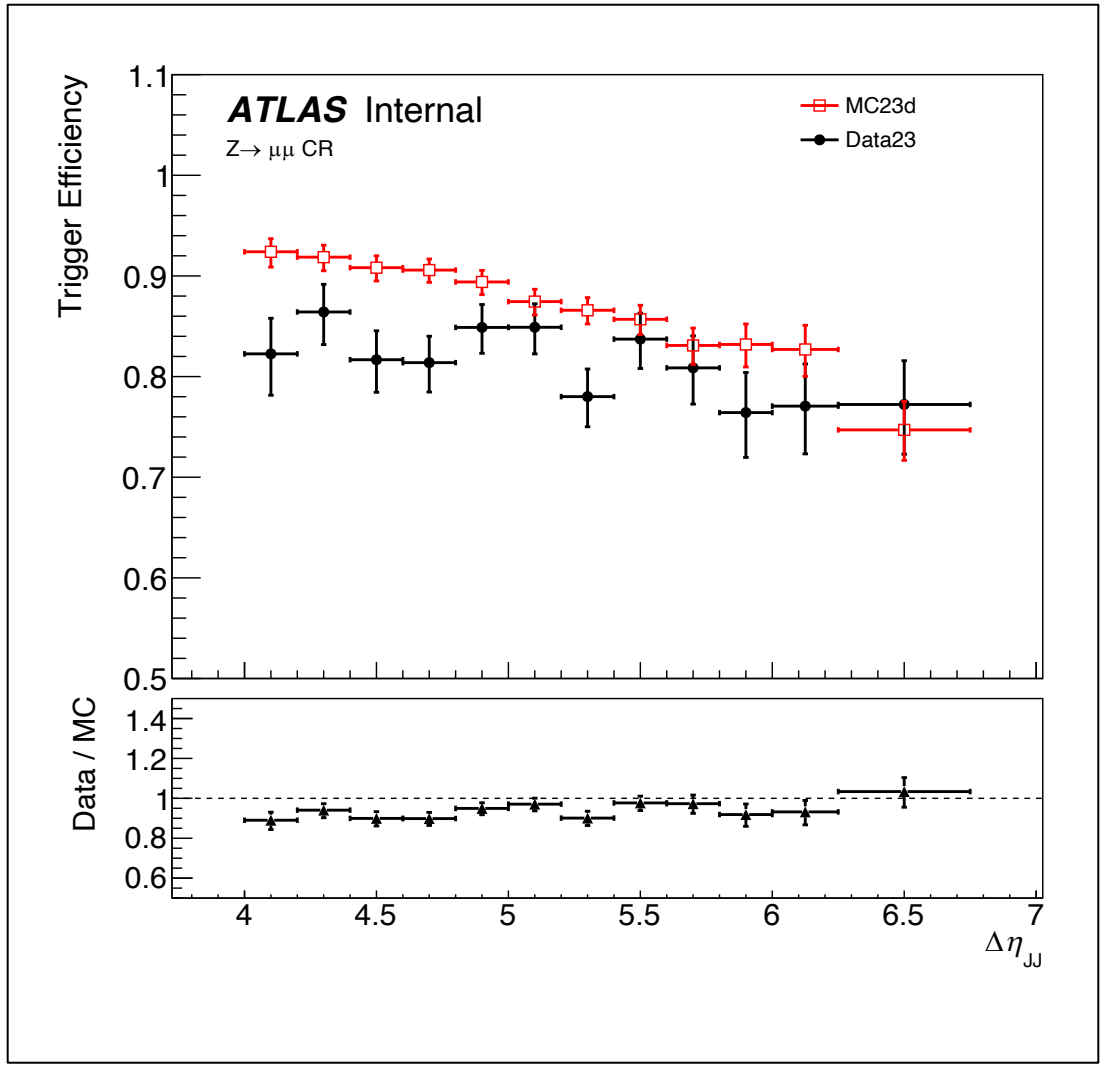
Trigger Efficiency in Data & MC, $p_{T,\,J2}$

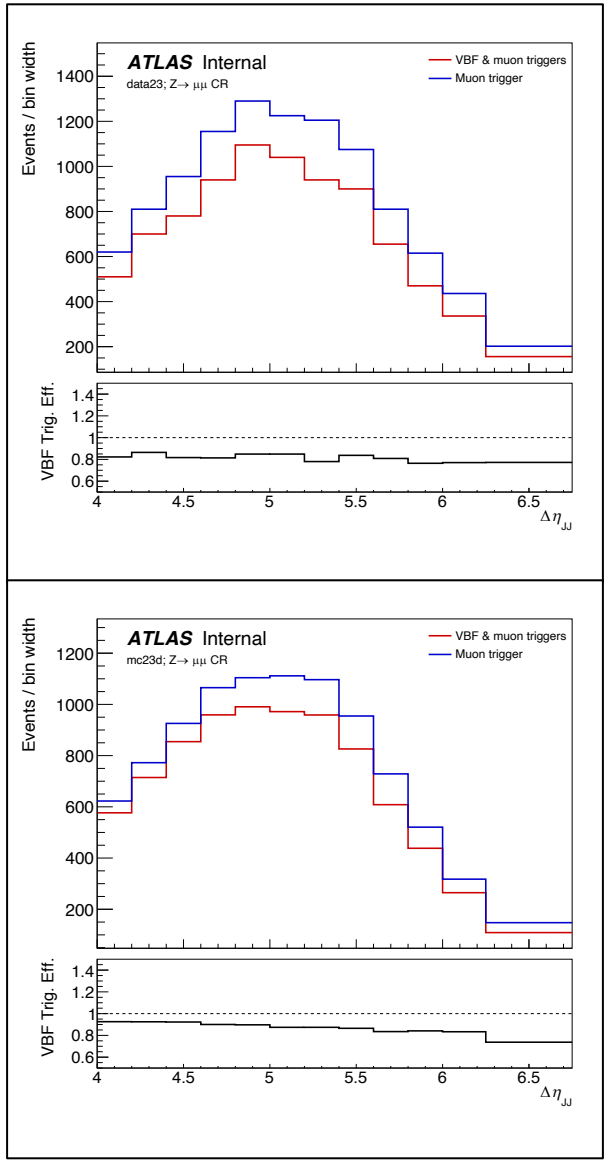




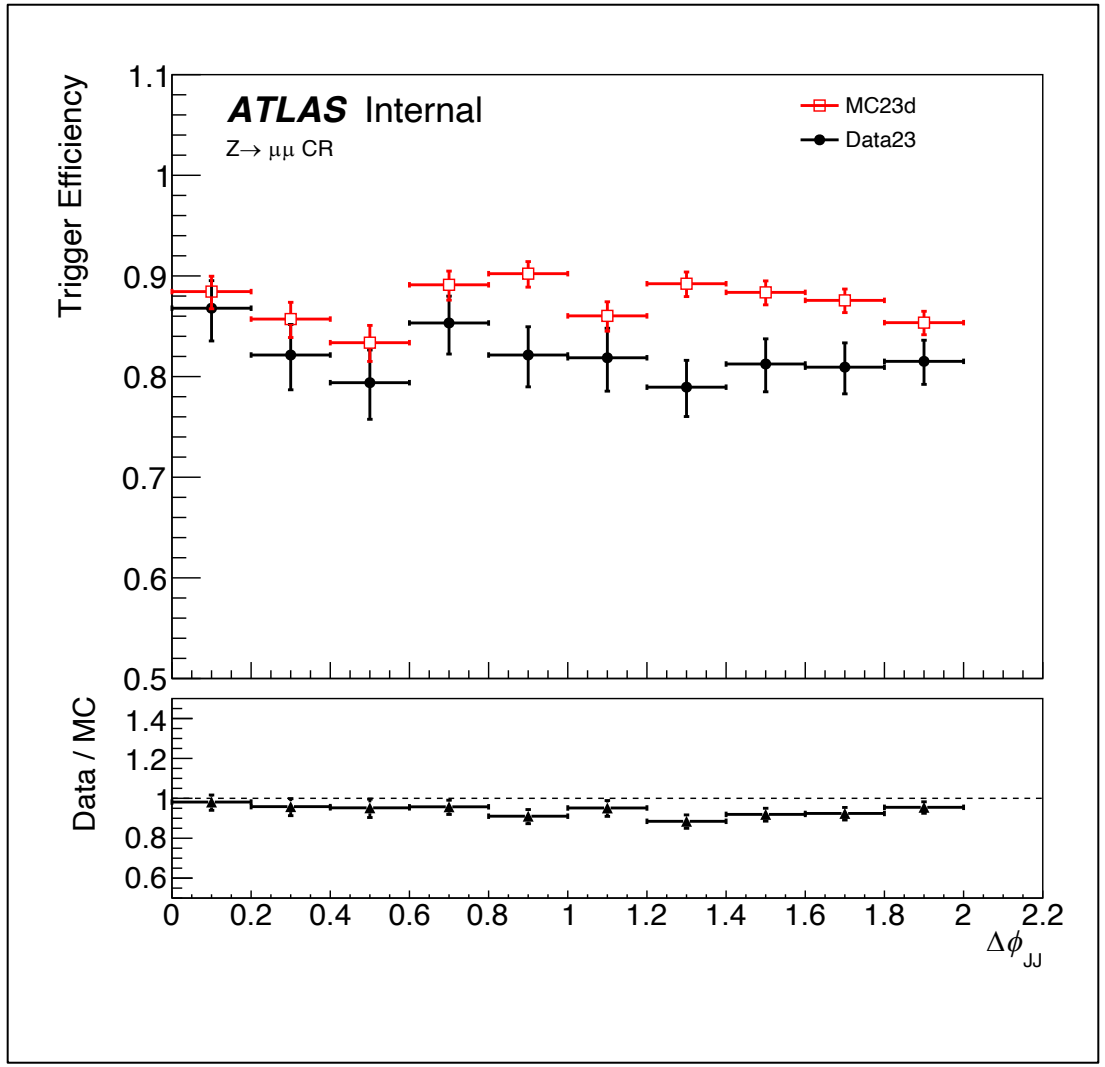
Trigger Efficiency in MC23d/Data23

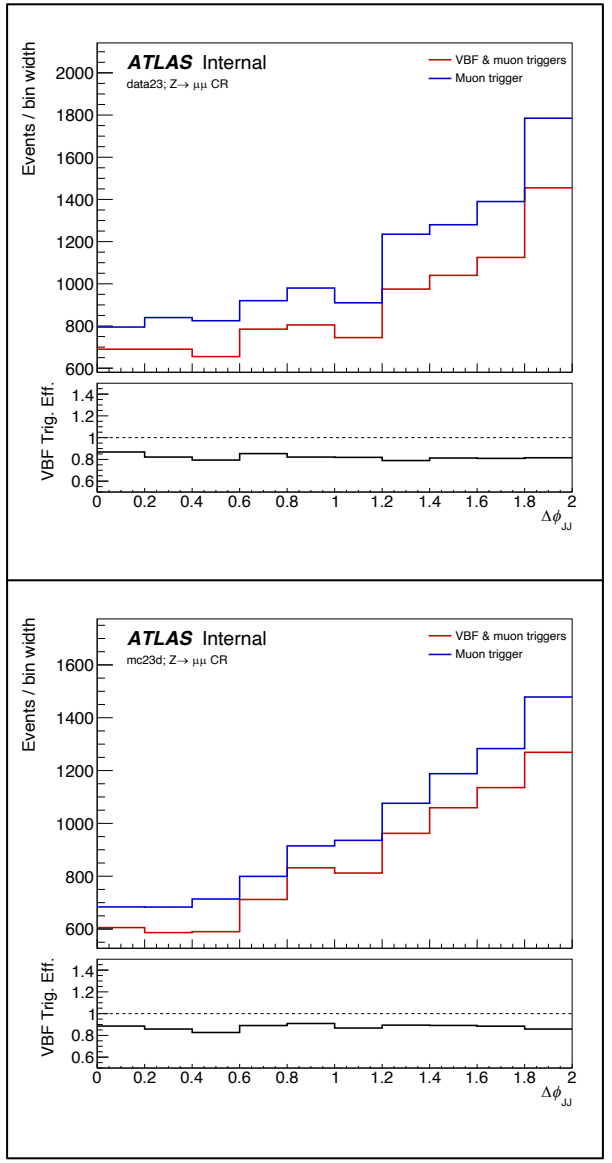
Trigger Efficiency in Data & MC, $\Delta\eta_{JJ}$



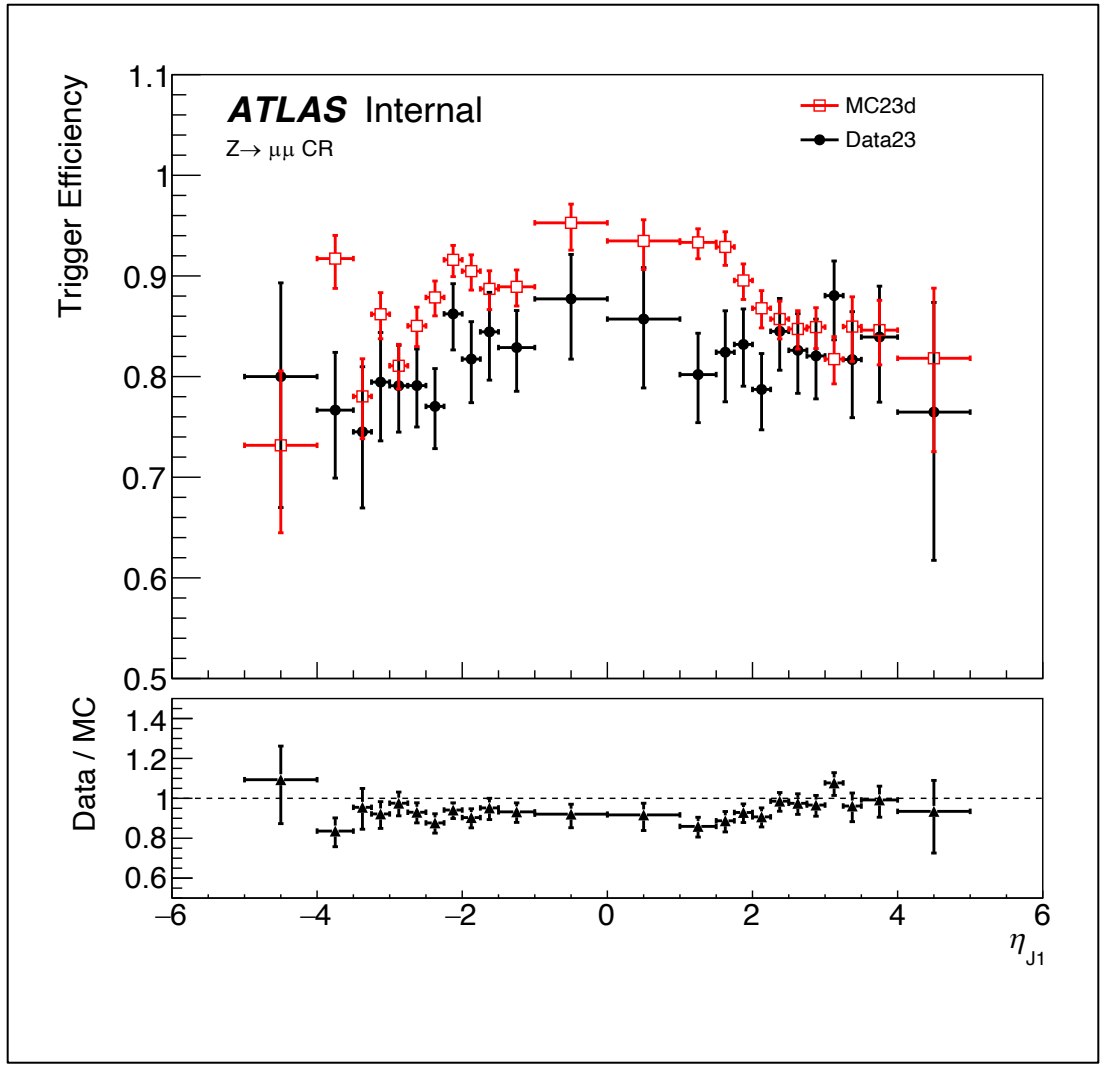


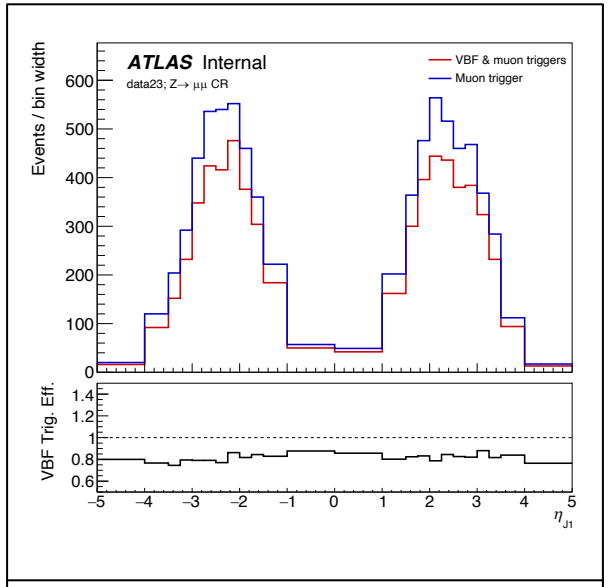
Trigger Efficiency in Data & MC, $\Delta\Phi_{JJ}$

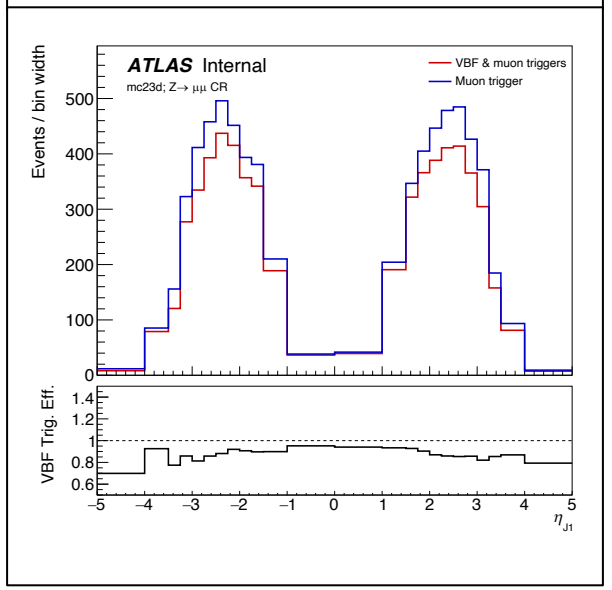




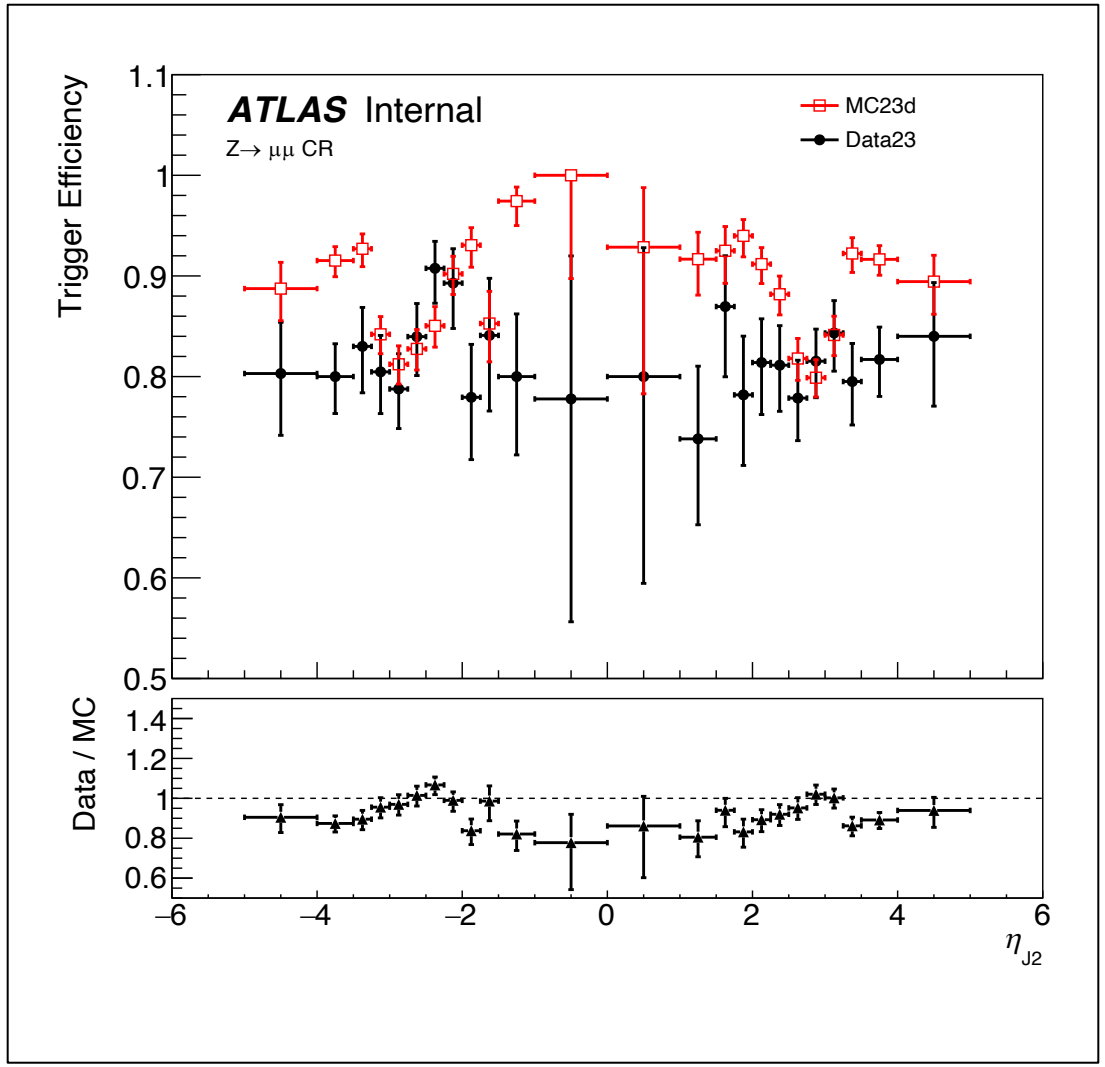
Trigger Efficiency in Data & MC, η_{J1}

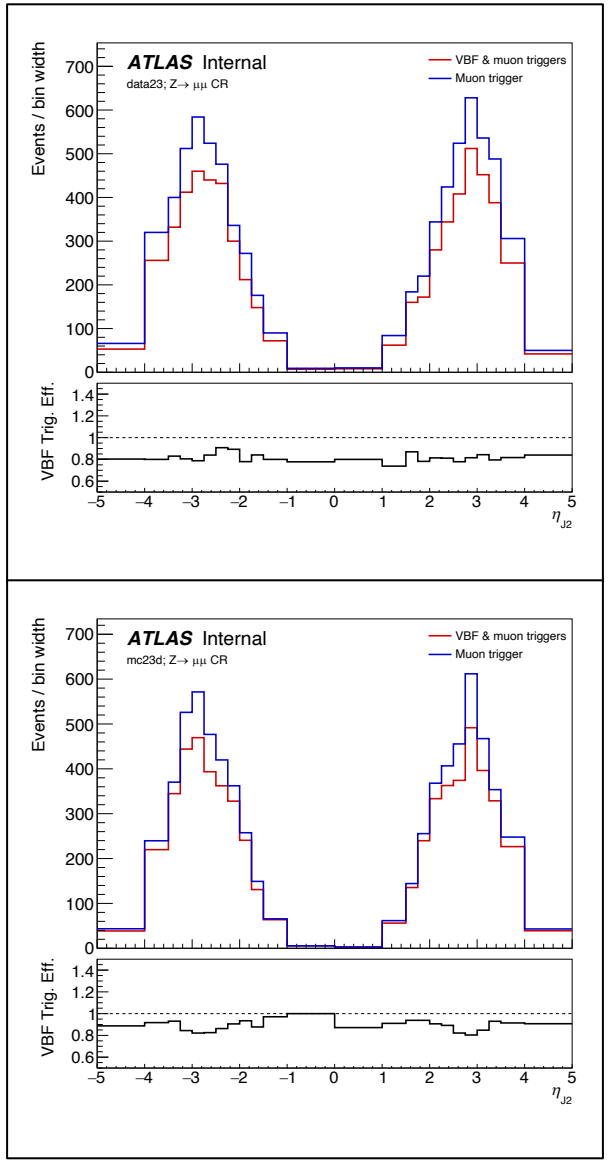




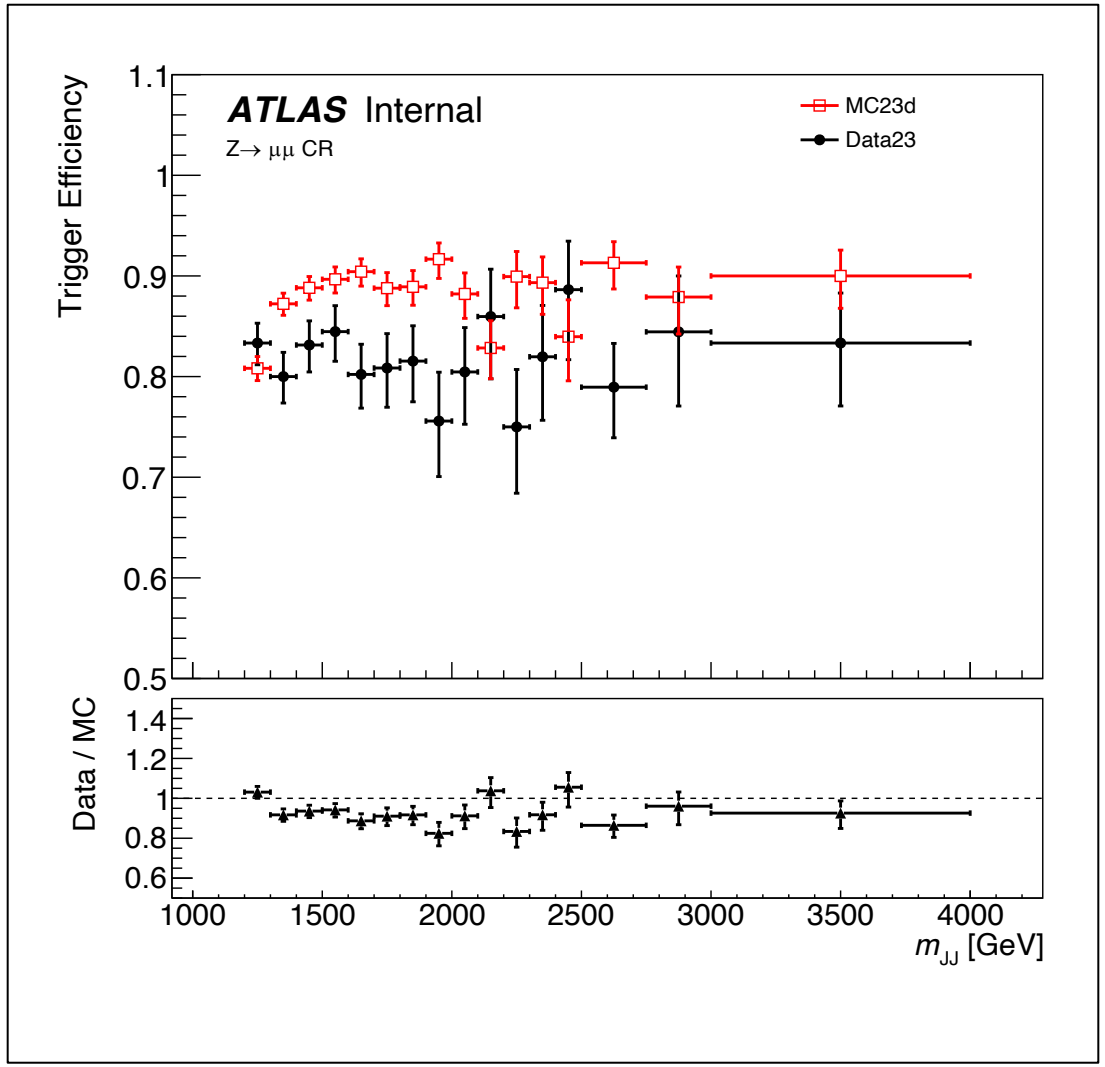


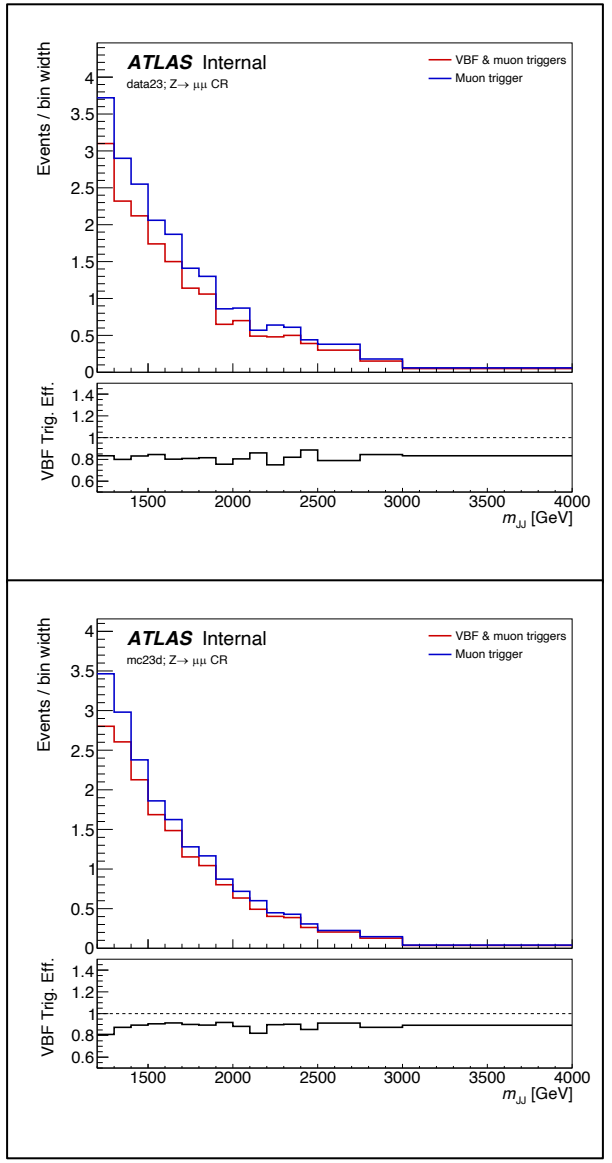
Trigger Efficiency in Data & MC, η_{J2}



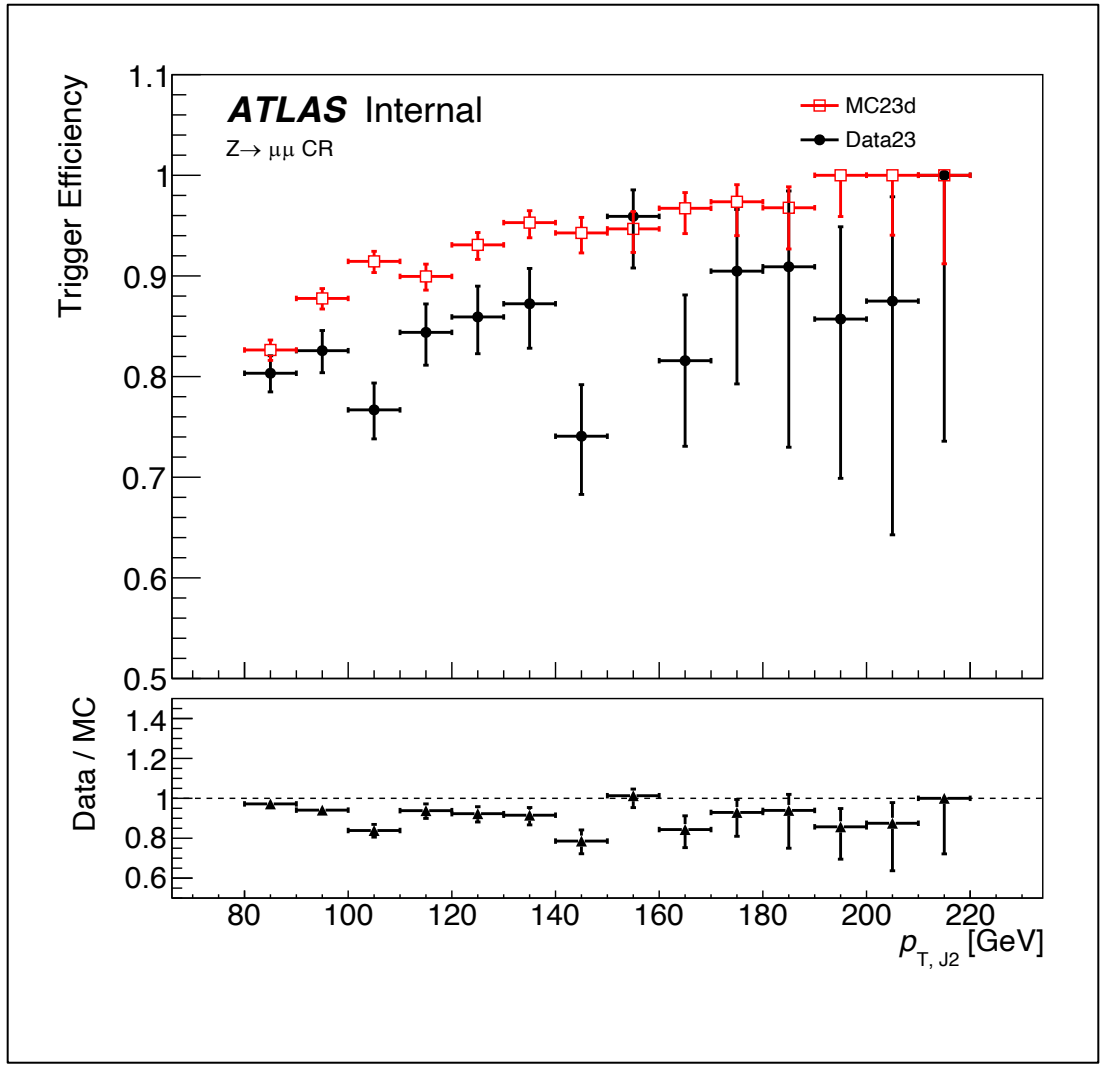


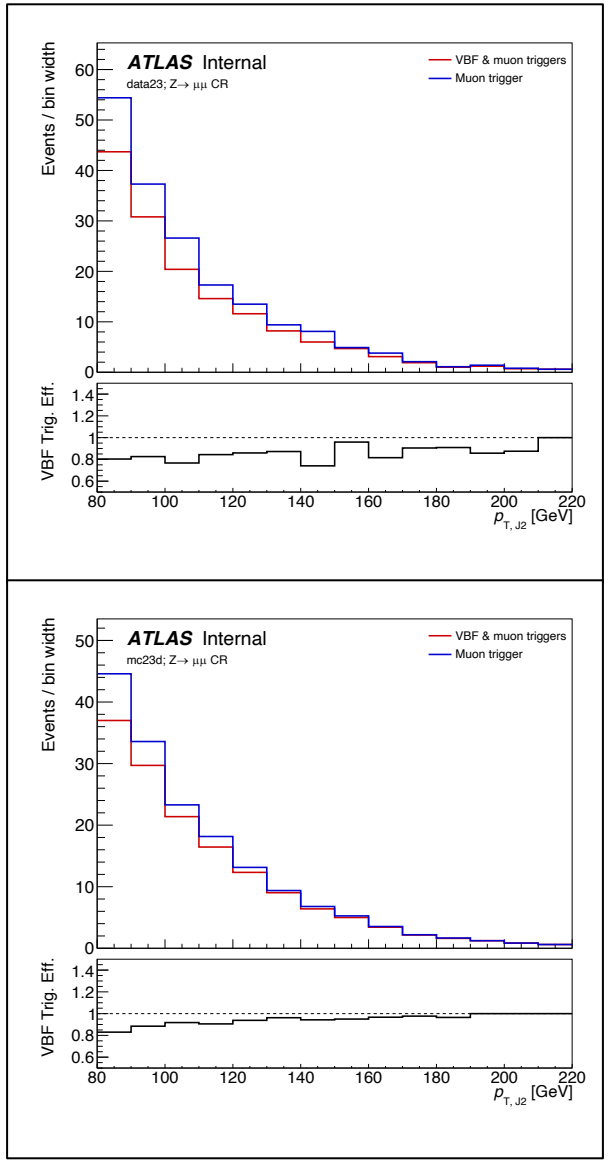
Trigger Efficiency in Data & MC, m_{JJ}





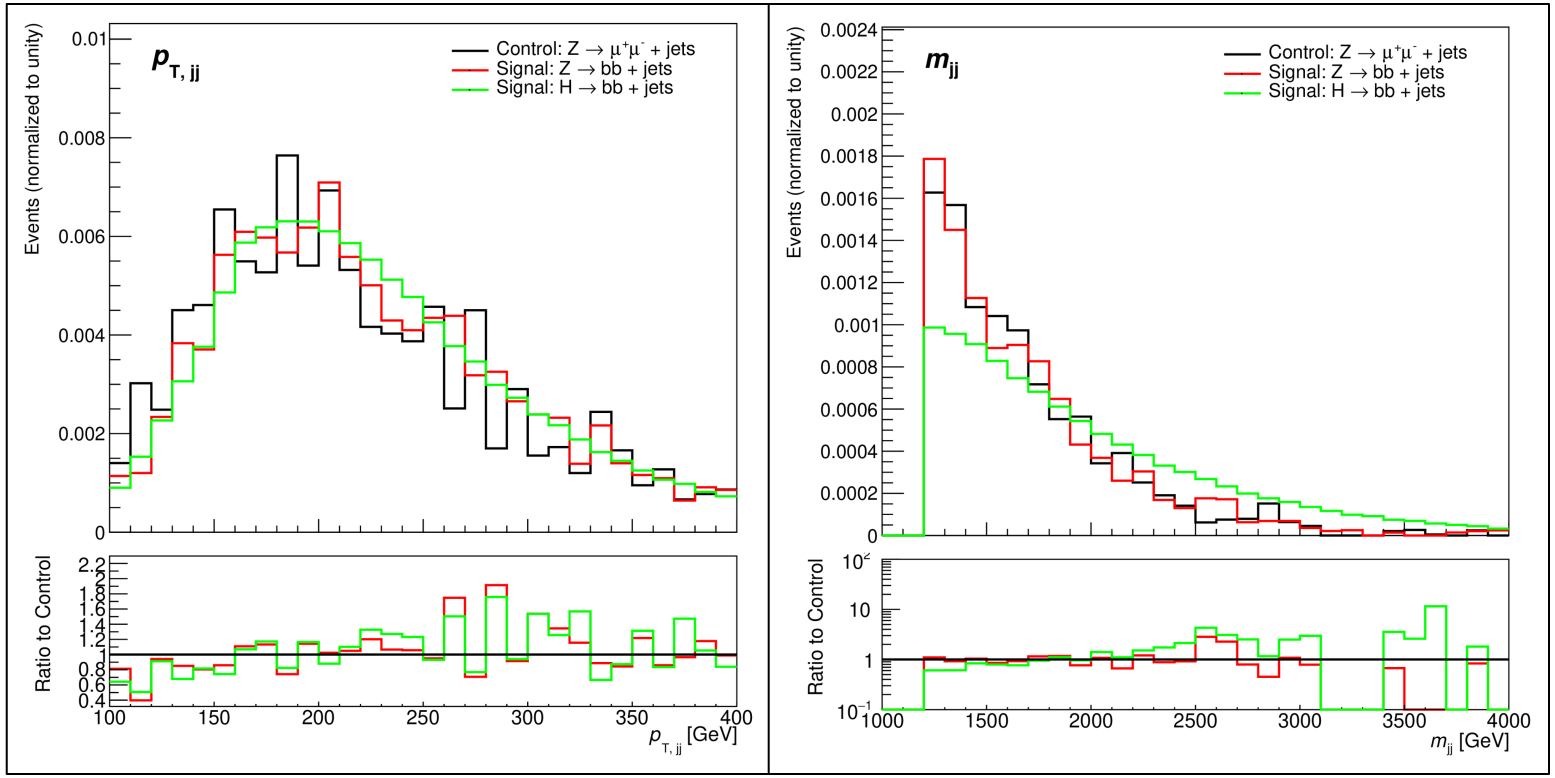
Trigger Efficiency in Data & MC, $p_{T,\,J2}$





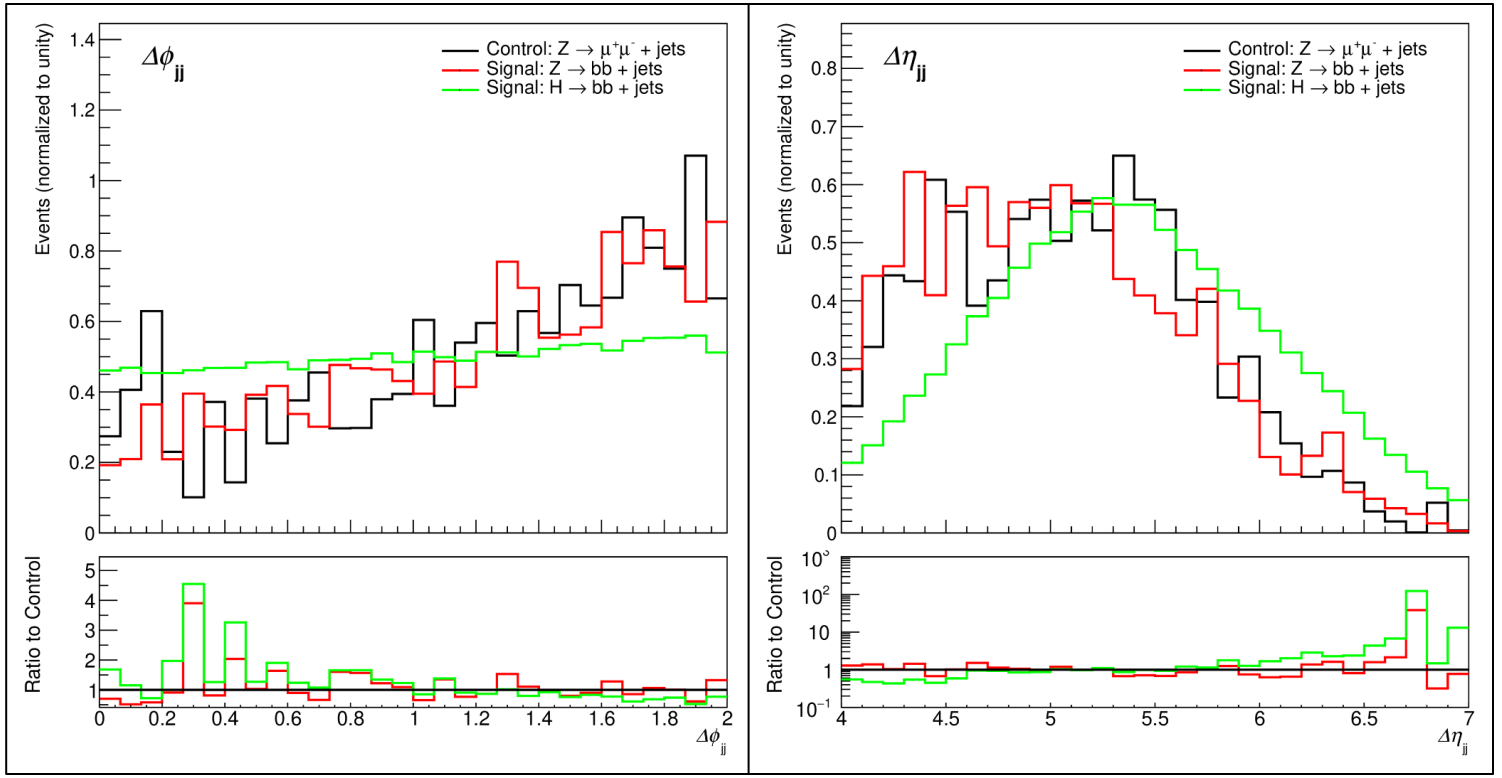
Dijet Kinematics

- Similar distributions between SR and CR
- Dijet mass distributions for Z decays skew leftward: includes non-VBF jets (QCD events)



Dijet Kinematics

- Similar distributions between Z decay events, skewed from H → bb + jets



Central Dijet & Muon Kinematics

- Less resolution in bb-dijet masses: jets have lower detector resolutions than muons
- Dilepton p_T being fixed.