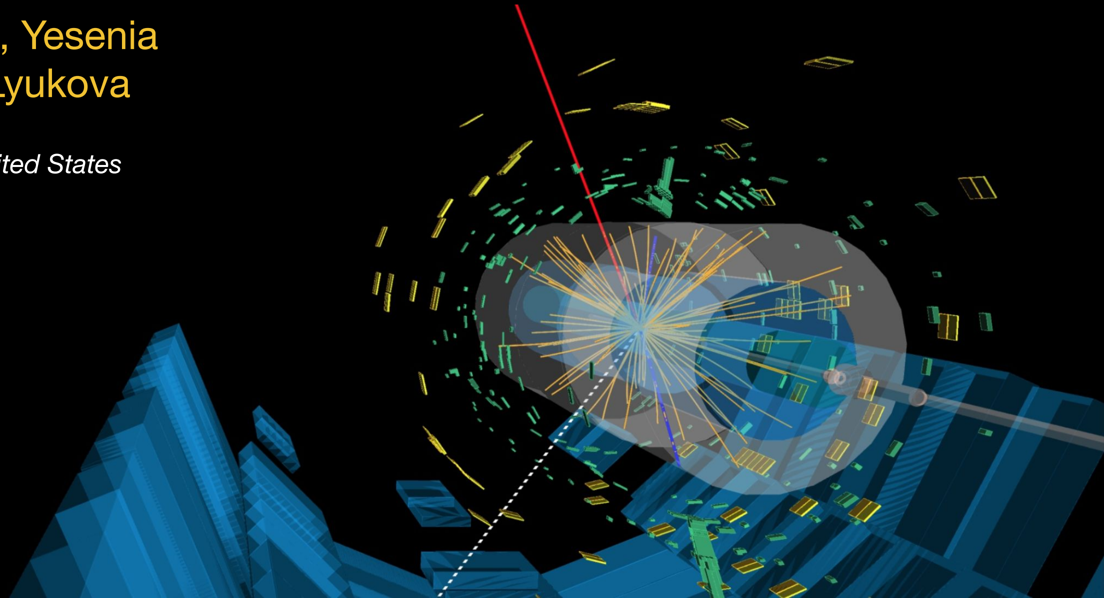
Machine Learning Optimization for Likelihood-Based Reconstruction in the Exotic Higgs Decay $pp \to H \to Za \to bb\mu\mu$

Alo Chakravarty, John Hobbs, Yesenia Hernandez-Jimenez, Mars Lyukova

Stony Brook ATLAS Group New York, United States



Contents

Intro / Background

Background: H → Za → bbμμ Decay Mode

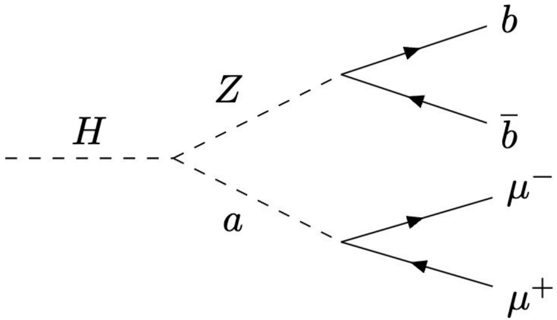


Figure 1. H → Za → bbμμ Decay

- Possible decay mode which introduces the ‘a boson’
  - Hypothesized pseudoscalar light-like particle
- Appears in NMSSM theories as a popular dark matter candidate
- Theorized to couple to the Higgs – This decay is thus an offshoot of the H → aa → bbμμ analysis

H → aa vs. H → Za

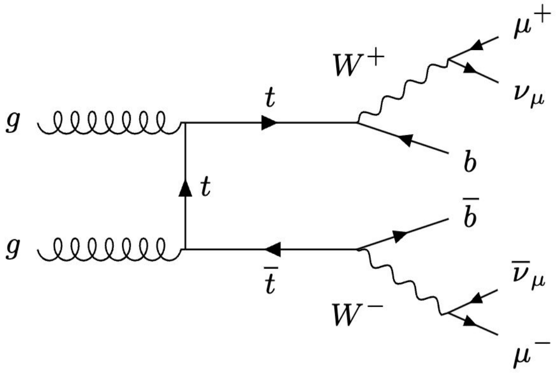
- Introduces a mass difference between Z and a
- Reconstruction to Higgs suggests physics beyond the Standard Model
- Mass difference is manifested experimentally in our kinematic likelihood fitting algorithm (KLFitter)
- Constraint: m_bb - m_uu = delta_m, with delta_m = m_Z - m_a

Implementation in the Breit-Wigner function:

```
// Breit-Wigner of a->bb
int option = 0;
if (option == 0) {
  vecci.push_back(BCMath::LogBreitWignerRel(tlv_fit_ahad.M(), tlv_meas_alep.M() + m_dmass, 0.5));
} else if (option == 1) {
  vecci.push_back(BCMath::LogBreitWignerRel(tlv_fit_higgs.M(), 125, 0.5));  // comp2
}
```

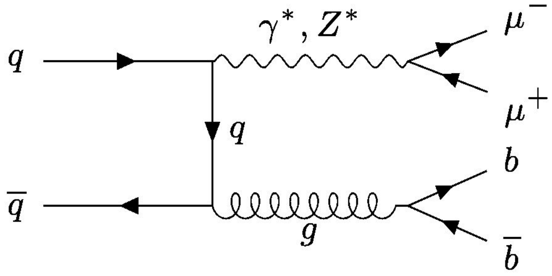
Dominant Background Processes

ttbar:



- Reconstruct to a pair of gluons
- Final state includes a pair of indetectible neutrinos
- Expected to have a high E_T^{miss} compared to signal
- ttbar is greatly reduced with the cut $E_T^{miss} < 60$ GeV

Drell Yan:



- Reconstruct to a quark-antiquark pair
- Expected to have a dimuon mass less than 10 GeV and greater than 65 GeV
- Drell Yan is greatly reduced with the cut 10 GeV $< m_{\mu\mu} <$ 65 GeV

Introduce event selection (cuts)

Project Goal: Improve the Signal-Background Ratio

Core question: Can we isolate enough signal to say if the $H \rightarrow Za$ decay is viable?

Project goal: Reduce background while maintaining as much signal as possible
$\rightarrow$ Improve the Signal:Background ratio

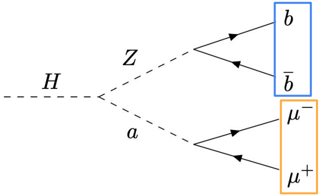
Methods

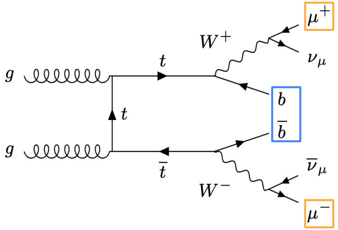
Method: Event Selection

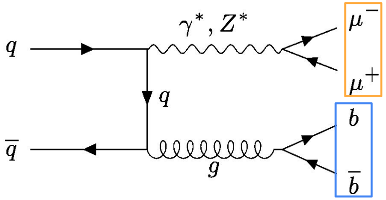
Implement cuts that only signal should pass through → based on properties of the processes themselves

Basic physical cuts: specific to the bbμμ final state

Trigger	Unprescaled single or dilepton trigger match
Muons	$N_\mu = 2$ Opposite Sign (OS) $10 < m_{\mu\mu} < 65$ GeV
***b*-jets**	$p_T^b > 20$ GeV $N_b = 2$







Base cut
Single OR Dilepton Trigger Match
$N_\mu = 2$
OS Muons
Muons $\eta<2.47$
Muons Isolation Loose_VarRad
$N_b == 2$ & $p_T{}^b >= 20$ GeV
$10 < m_{\mu\mu} < 65$ GeV
$E_T{}^{miss} < 60$ GeV

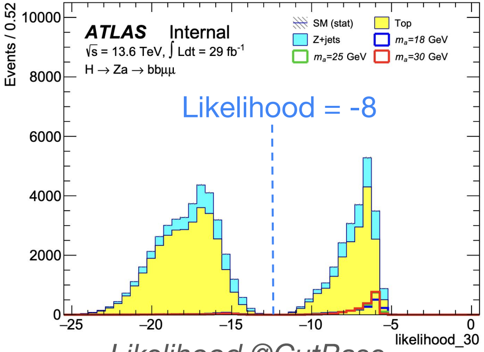
} Background control cuts

New Methods for Event Selection

ATLAS EXPERIMENT

Step 1: Mass-Specific Likelihood

- Likelihood_18 > -8
  Likelihood_25 > -8
  Likelihood_30 > -8



Likelihood @CutBase

Step 2: Tight Mass Window

- Confine the signal and background to a tight ± 3 GeV mass window around a target ‘a’ mass
- Analysis previously ran over all background, while signal mass peaks precisely

Likelihood cut definition:

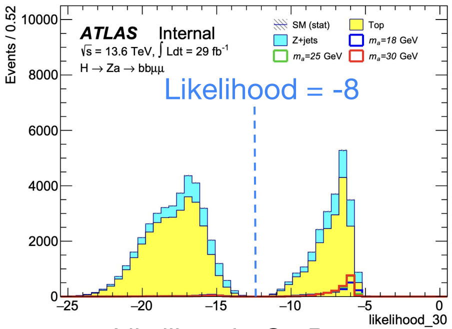
```
+CutLikelihood_18 {
  <.cutExpression = "[$(likelihood_18)] > -8.", .title="Likelihood_18 $ > -8$">
```

Mass cut definition:

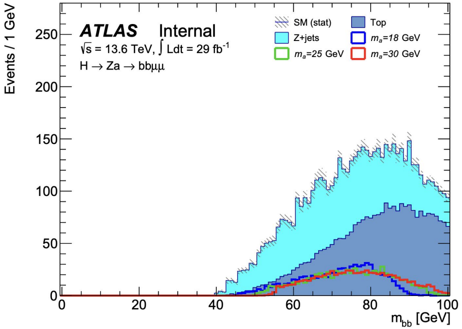
```
+CutLikelihood_18 {
  <.cutExpression = "[$(likelihood_18)] > -8.", .title="Likelihood_18 $ > -8$">
  # NEW MASS CUT
  +CutMass_18      {
    <.cutExpression = "(([$(Mll)]/1000 > 15) && ([$(Mll)]/1000 < 21))", .title="$ 15 < m_{\mu\mu} < 21 $">
  } # CutMass_18
```

Results

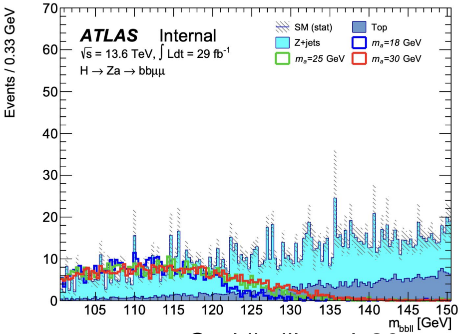
Monte Carlo Comparisons



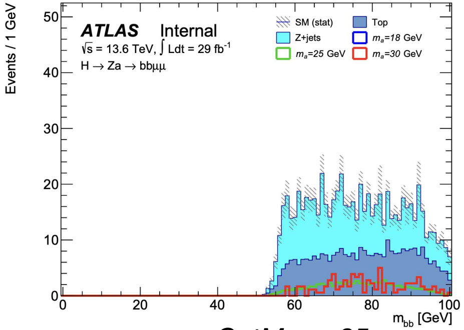
Likelihood - CutBase



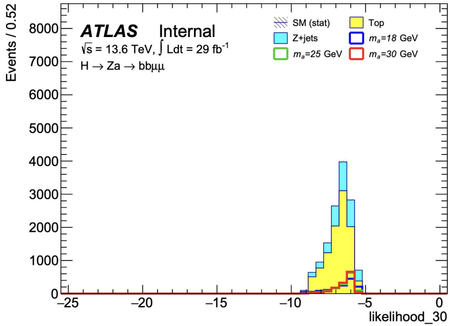
m_{bb} - CutLikelihood_30



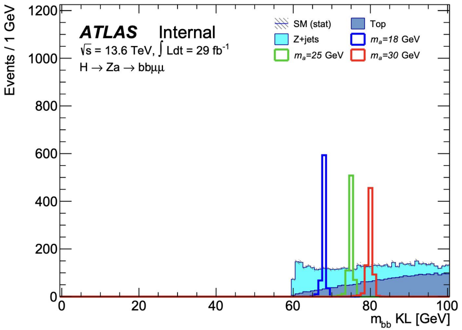
$m_{bb\mu\mu}$ - CutLikelihood_30



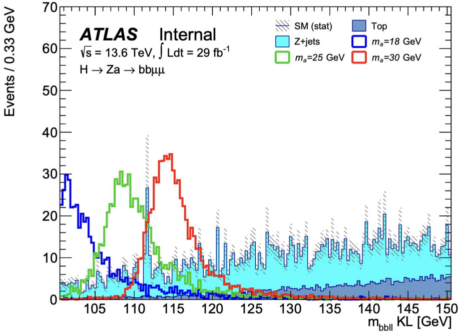
m_{bb} - CutMass_25



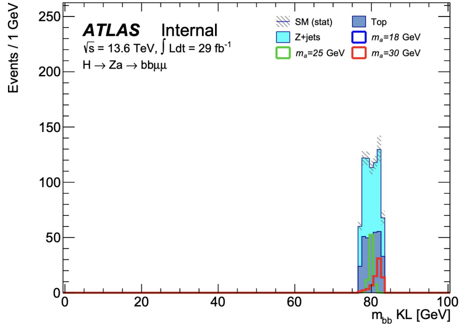
Likelihood - CutLikelihood_30



m_{bb}_KL - CutLikelihood_30



$m_{bb\mu\mu}$_KL - CutLikelihood_30



m_{bb}_KL - CutMass_25

Numerical Results via Cutflow

$\sqrt{s}$=13.6 TeV, L=29 fb^{-1} $\mu\mu$(2022)	m_a=18 GeV	m_a=25 GeV	m_a=30 GeV	Top	Z+jets
Base cut	47.83 ± 0.25	66.21 ± 0.29	81.45 ± 0.32	50229.25 ± 58.49	11272.15 ± 105.48
Single OR Dilepton Trigger Match	23.52 ± 0.17	29.27 ± 0.19	42.98 ± 0.23	47585.02 ± 56.93	12718.06 ± 87.27
$N_\mu = 2$	22.71 ± 0.17	28.17 ± 0.19	41.73 ± 0.23	47410.63 ± 56.82	12659.28 ± 86.87
OS Muons	22.36 ± 0.17	27.89 ± 0.19	41.57 ± 0.23	46758.69 ± 56.43	12578.88 ± 86.63
Muons η<2.47	22.24 ± 0.17	27.77 ± 0.19	41.38 ± 0.23	46582.58 ± 56.32	12507.77 ± 86.42
Muons Isolation Loose_VarRad	18.43 ± 0.15	22.68 ± 0.17	34.32 ± 0.21	42491.73 ± 53.79	10859.25 ± 81.61
N_b == 2 & p_T^b >= 20 GeV	5.51 ± 0.08	6.93 ± 0.09	10.44 ± 0.11	40298.40 ± 52.38	10479.21 ± 81.00
$10 < m_{\mu\mu} < 65$ GeV	5.51 ± 0.08	6.93 ± 0.09	10.44 ± 0.11	36196.17 ± 49.64	9774.91 ± 78.14
$E_T^{miss} < 60$ GeV	5.26 ± 0.08	6.63 ± 0.09	10.07 ± 0.11	14019.59 ± 30.89	9244.27 ± 77.23
Likelihood_18 > -8	4.25 ± 0.07	5.27 ± 0.08	7.48 ± 0.10	4076.47 ± 16.64	3012.77 ± 44.55
$15 < m_{\mu\mu} < 21$	4.23 ± 0.07	0.02 ± 0.00	0.00 ± 0.00	230.13 ± 3.95	528.43 ± 16.25
Likelihood_25 > -8	4.05 ± 0.07	5.48 ± 0.08	8.23 ± 0.10	4010.56 ± 16.51	3137.25 ± 46.44
$22 < m_{\mu\mu} < 28$	0.00	5.44 ± 0.08	0.16 ± 0.01	319.83 ± 4.66	412.76 ± 18.41
Likelihood_30 > -8	3.72 ± 0.07	5.37 ± 0.08	8.43 ± 0.10	3922.11 ± 16.33	3178.53 ± 47.13
$27 < m_{\mu\mu} < 33$	0.00	0.00 ± 0.00	8.32 ± 0.10	387.68 ± 5.13	388.01 ± 20.05
$E_T^{miss} \geq 60$ GeV	0.25 ± 0.02	0.31 ± 0.02	0.37 ± 0.02	22176.59 ± 38.86	530.65 ± 11.93

Figure 12. Analysis Cutflow

➔ For the **25 GeV** signal, the background decreases by ~92.03% for ttbar and ~86.84% for Z+ jets

➔ This success extends to the other two mass signals:
18 GeV: 94.35% ttbar reduction, 82.46% Z+ jet reduction
30 GeV: 90.12% ttbar reduction, 87.79% Z+ jet reduction

Method 1 vs. Method 2 in Numbers

ATLAS EXPERIMENT

$\sqrt{s}$=13.6 TeV, L=29 fb^{-1} μμ(2022)	m_a=18 GeV	m_a=25 GeV	m_a=30 GeV	Top	Z+jets
$10 < m_{\mu\mu} < 65$ GeV	5.51 ± 0.08	6.93 ± 0.09	10.44 ± 0.11	36196.17 ± 49.64	9774.91 ± 78.14
Likelihood_18 > -8	4.25 ± 0.07	5.27 ± 0.08	7.48 ± 0.10	4076.47 ± 16.64	3012.77 ± 44.55
$15 < m_{\mu\mu} < 21$	4.23 ± 0.07	0.02 ± 0.00	0.00 ± 0.00	230.13 ± 3.95	528.43 ± 16.25
Likelihood_25 > -8	4.05 ± 0.07	5.48 ± 0.08	8.23 ± 0.10	4010.56 ± 16.51	3137.25 ± 46.44
$22 < m_{\mu\mu} < 28$	0.00	5.44 ± 0.08	0.16 ± 0.01	319.83 ± 4.66	412.76 ± 18.41
Likelihood_30 > -8	3.72 ± 0.07	5.37 ± 0.08	8.43 ± 0.10	3922.11 ± 16.33	3178.53 ± 47.13
$27 < m_{\mu\mu} < 33$	0.00	0.00 ± 0.00	8.32 ± 0.10	387.68 ± 5.13	388.01 ± 20.05
$E_T^{miss} \geq 60$ GeV	0.25 ± 0.02	0.31 ± 0.02	0.37 ± 0.02	22176.59 ± 38.86	530.65 ± 11.93

Analysis Cutflow

CutLikelihood → CutMass

- **18 GeV**: 94.35% ttbar reduction, 82.46% Z+ jet reduction
- **25 GeV**: 92.03% ttbar reduction, 86.84% Z+ jet reduction
- **30 GeV**: 90.12% ttbar reduction, 87.79% Z+ jet reduction

CutLikelihood → CutMass

- **18 GeV**: 99.36% ttbar reduction, 94.59% Z+ jet reduction
- **25 GeV**: 99.12% ttbar reduction, 95.78% Z+ jet reduction
- **30 GeV**: 98.93% ttbar reduction, 96.03% Z+ jet reduction

Machine Learning BDT Implementation

ATLAS EXPERIMENT

- Currently developing and training the BDT
- Implementation steps
  1. Implement new variables
  2. Modify BDT training script to H → Za mode
  3. Run analysis on BDT training script
  4. Take output .xml file and create an alias out of it
  5. Add alias to analyze/visualize scripts
  6. Run analysis on simulation analysis script
  7. Repeat
- Based on BDT training results from H → aa analysis, we expect a 3x reduction in background

New variables:

```
TH1F('diffDRjjDRll'
TH1F('a_ll_phi'
TH1F('a_ll_eta'
TH1F('DPhiaa'
TH1F('DEtaaa'
TH1F('DRaa'
TH1F('DPhi_b0_l0'
TH1F('DEta_b0_l0'
TH1F('DR_b0_l0'
TH1F('DPhi_b0_l1'
TH1F('DEta_b0_l1'
TH1F('DR_b0_l1'
TH1F('DPhi_b1_l0'
TH1F('DEta_b1_l0'
TH1F('DR_b1_l0'
TH1F('DPhi_b1_l1'
TH1F('DEta_b1_l1'
TH1F('DR_b1_l1'
```

Modify BDT training script for H → Za:

```
def runMVA(mva):
    # The object passed here is an instance of TQMVA
    # Name the output .root and .xml files
    name =  "myBDT_a25" + mva.getTagStandardStringDefault("eventSelector","")
```

```
mva.addSignal("/sig/mm/?/?/a25")
mva.addBackground("bkg/mm/?/top")
mva.addBackground("bkg/mm/?/Zjets")
```

Switch to BDT training script:

```
# BDT
MVA: config/MVA/Hbbuu/HbbuuMVA
#MVA; config/MVA/Hbbuu/HbbuuMVA_DYT
```

Immediate and Future Work

Immediate work:

- Finish implementing ML BDT (or extend BDT to other mass signals)

Future work:

- Include smaller backgrounds
- Electronics testing for upgraded boards
- Investigate reconstructed Z mass peak from dijet plots

Thank you for listening!

Backup

Mass-Specific Likelihood Implementation

ATLAS EXPERIMENT

1. Observable definition (LikelihoodMbbuu.py)

Hbbuu > Hbbuu > share > observables > Hbbuu > LikelihoodMbbuu.py

```
    # NEW COPIES FOR EACH dmass

    likelihoodMV_18 = LikelihoodMultiVariable("likelihoodMV_18", "BTaggedJets", 62)
    if not TQObservable.addObservable(likelihoodMV_18):
        INFO("Failed to add likelihoodMV_18 observable")
        return False

    likelihoodMV_25 = LikelihoodMultiVariable("likelihoodMV_25", "BTaggedJets", 55)
    if not TQObservable.addObservable(likelihoodMV_25):
        INFO("Failed to add likelihoodMV_25 observable")
        return False

    likelihoodMV_30 = LikelihoodMultiVariable("likelihoodMV_30", "BTaggedJets", 50)
    if not TQObservable.addObservable(likelihoodMV_30):
        INFO("Failed to add likelihoodMV_30 observable")
        return False
```

2. Alias definition (aliases.cfg)

Hbbuu > Hbbuu > share > config > aliases > Hbbuu > aliases.cfg

```
#aliases.likelihood: [VecAT(likelihoodMV,0)]
    # NEW COPIES FOR EACH dmass
aliases.likelihood_18: [VecAT(likelihoodMV_18,0)]
aliases.likelihood_25: [VecAT(likelihoodMV_25,0)]
aliases.likelihood_30: [VecAT(likelihoodMV_30,0)]

#aliases.bjet0_pt_KL: [VecAT(likelihoodMV,1)]
    # NEW COPIES FOR EACH dmass
aliases.bjet0_pt_KL_18: [VecAT(likelihoodMV_18,1)]
aliases.bjet0_pt_KL_25: [VecAT(likelihoodMV_25,1)]
aliases.bjet0_pt_KL_30: [VecAT(likelihoodMV_30,1)]

#aliases.bjet1_pt_KL: [VecAT(likelihoodMV,2)]
    # NEW COPIES FOR EACH dmass
aliases.bjet1_pt_KL_18: [VecAT(likelihoodMV_18,2)]
aliases.bjet1_pt_KL_25: [VecAT(likelihoodMV_25,2)]
aliases.bjet1_pt_KL_30: [VecAT(likelihoodMV_30,2)]

#aliases.Mbbuu_KL: [VecAT(likelihoodMV,3)]
    # NEW COPIES FOR EACH dmass
aliases.Mbbuu_KL_18: [VecAT(likelihoodMV_18,3)]
aliases.Mbbuu_KL_25: [VecAT(likelihoodMV_25,3)]
aliases.Mbbuu_KL_30: [VecAT(likelihoodMV_30,3)]

#aliases.Mbb_KL: [VecAT(likelihoodMV,4)]
    # NEW COPIES FOR EACH dmass
aliases.Mbb_KL_18: [VecAT(likelihoodMV_18,4)]
aliases.Mbb_KL_25: [VecAT(likelihoodMV_25,4)]
aliases.Mbb_KL_30: [VecAT(likelihoodMV_30,4)]
```

3. Cut definition (cuts_Default.def)

```
+Cut2Muons {
        +CutLikelihood_18{
          <.cutExpression = "[$(likelihood_18)] > -8.", .title="Likelihood_18 $ > -8$">
```

3. Cutflow definition (histograms.cfg)

Hbbuu > Hbbuu > share > config > histograms > Hbbuu > histograms.cfg

```
#################################
#
# Cutflow Definition
#
#################################

@CutBase: Njets, NMuons, NbJets, Pt_mu0, Pt_mu1, Eta_mu0, Eta_mu1, P
#@CutISOMuons: Njets, NbJets, dR_ll, dR_jj
@Cut2BSel: Njets, NMuons, NbJets, Pt_mu0, Pt_mu1, Eta_mu0, Eta_mu1,
#@CutLikelihood: Njets, Pt_mu0, Pt_mu1, Eta_mu0, Eta_mu1, Phi_mu0, P

@CutLikelihood_18: Njets, Pt_mu0, Pt_mu1, Eta_mu0, Eta_mu1, Phi_mu0,
@CutLikelihood_25: Njets, Pt_mu0, Pt_mu1, Eta_mu0, Eta_mu1, Phi_mu0,
@CutLikelihood_30: Njets, Pt_mu0, Pt_mu1, Eta_mu0, Eta_mu1, Phi_mu0,

#@CutVR:    Njets, Pt_mu0, Pt_mu1, Eta_mu0, Eta_mu1, Phi_mu0, Phi_mu
#@CutTopCRLikelihood: Njets, Pt_mu0, Pt_mu1, Eta_mu0, Eta_mu1, Phi_m
```