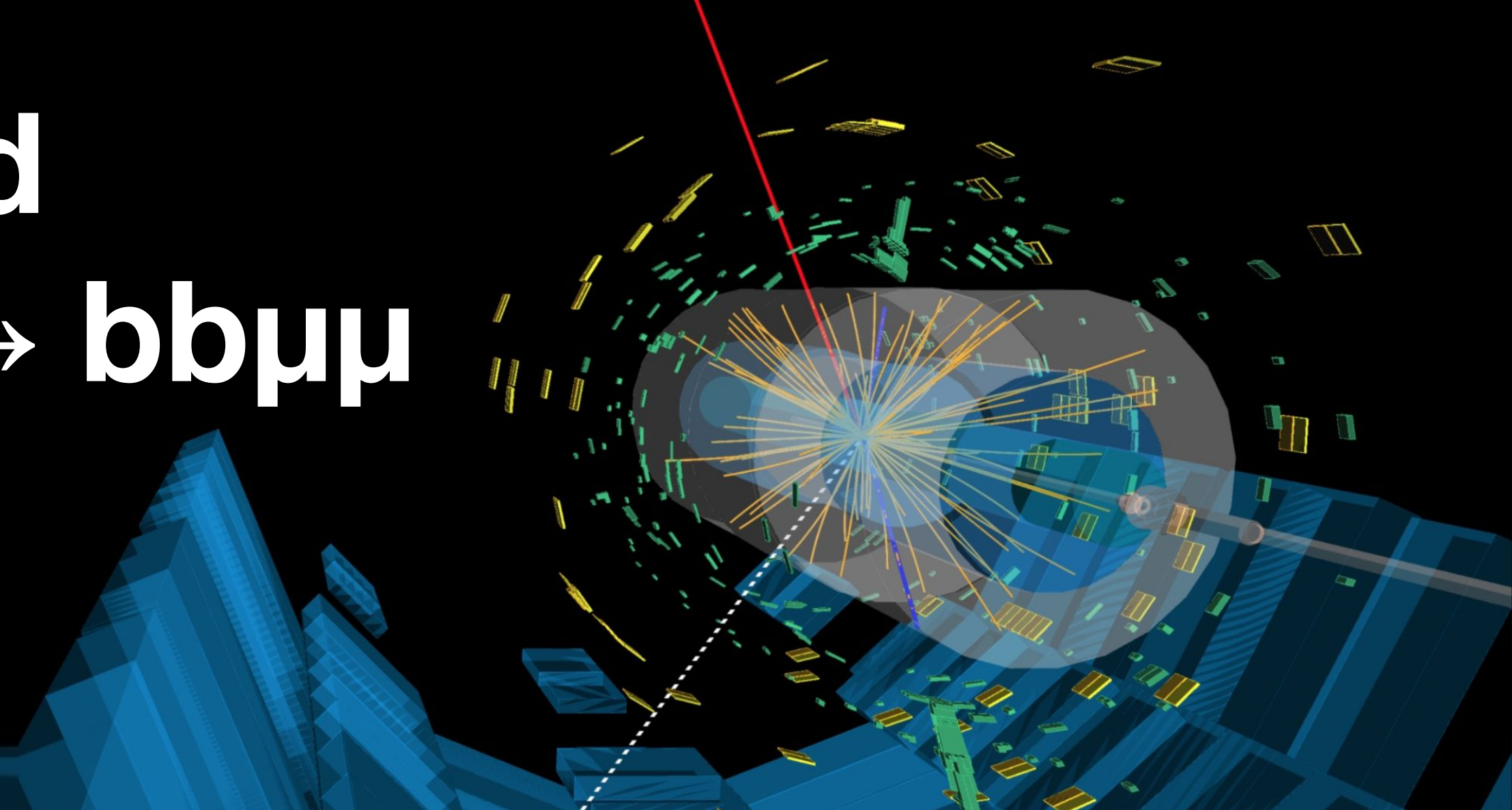


# Machine Learning Optimization for Likelihood-Based Reconstruction in the Exotic Higgs Decay $pp \rightarrow H \rightarrow Za \rightarrow bb\mu\mu$

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## Introduction & Theoretical Motivation

- The Higgs boson gives rise to the Higgs field – the **mechanism by which elementary particles acquire mass**
- Higgs bosons are known to have many decays with different final states, and we study them to understand the underlying mechanics of this field
- We propose the Higgs decay  $pp \rightarrow H \rightarrow Za \rightarrow bb\mu\mu$ :

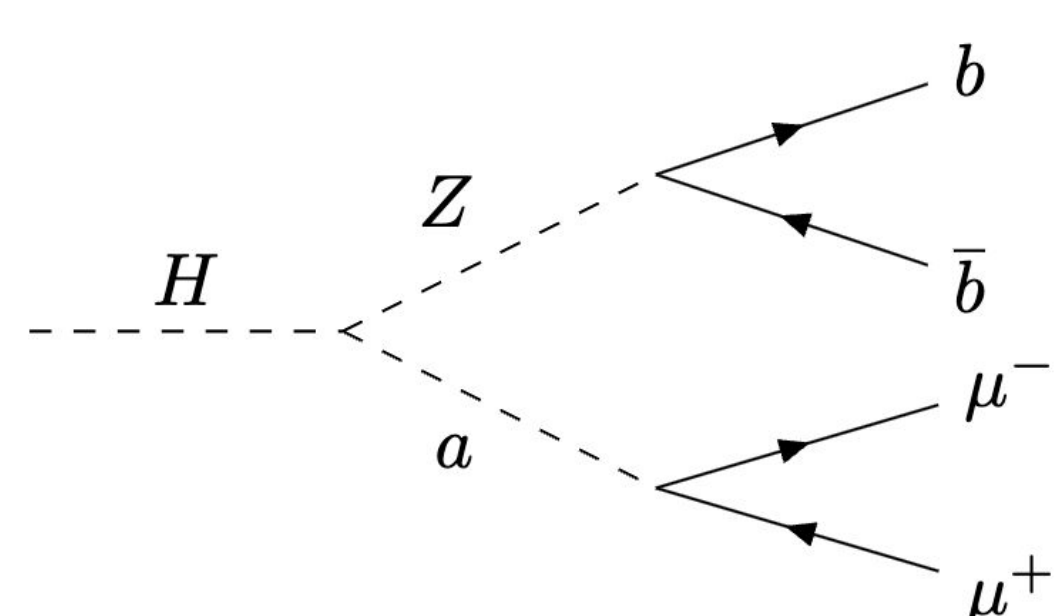


Figure 1.  $H \rightarrow Za \rightarrow bb\mu\mu$  Decay

- This decay introduces a new particle ‘a’, which is a **hypothetical pseudoscalar boson** predicted to exist by some Beyond the Standard Model (BSM) theories
- Theories that support this decay investigate intriguing topics including the properties of dark matter and the question of **baryon (matter-antimatter) asymmetry**

## Data Collection at the LHC

- Particle beams **accelerated to extremely high energies** are made to collide at four points around the LHC, which correspond to four particle detectors
- Here, we present **proton-proton collision data collected in ATLAS Run 3** at a center-of-mass energy of  $\sqrt{s} = 13.6$  TeV

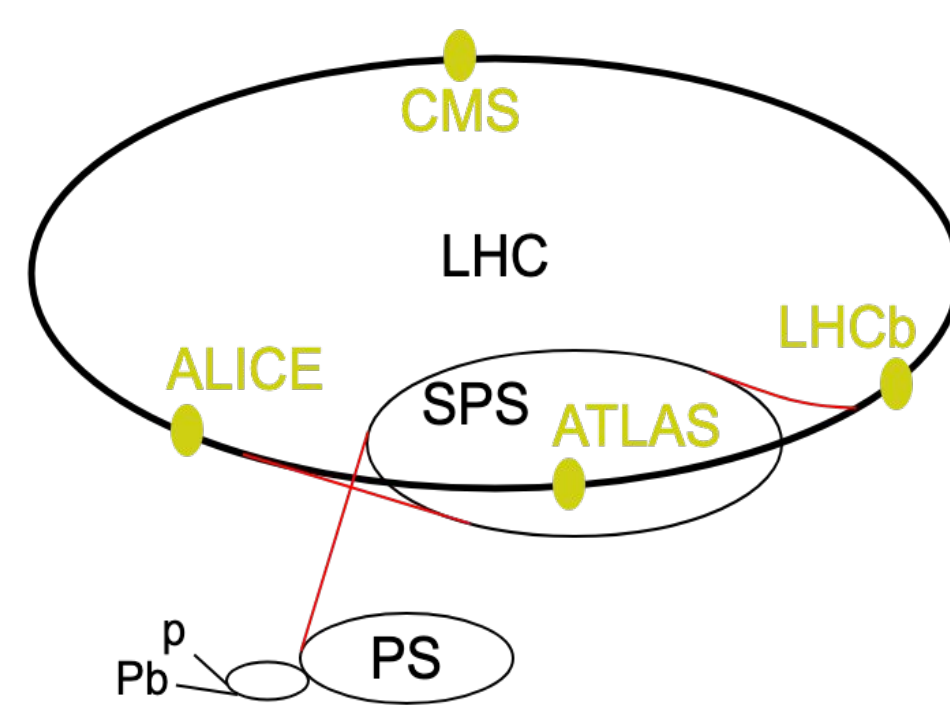


Figure 2. LHC Map [CERN]

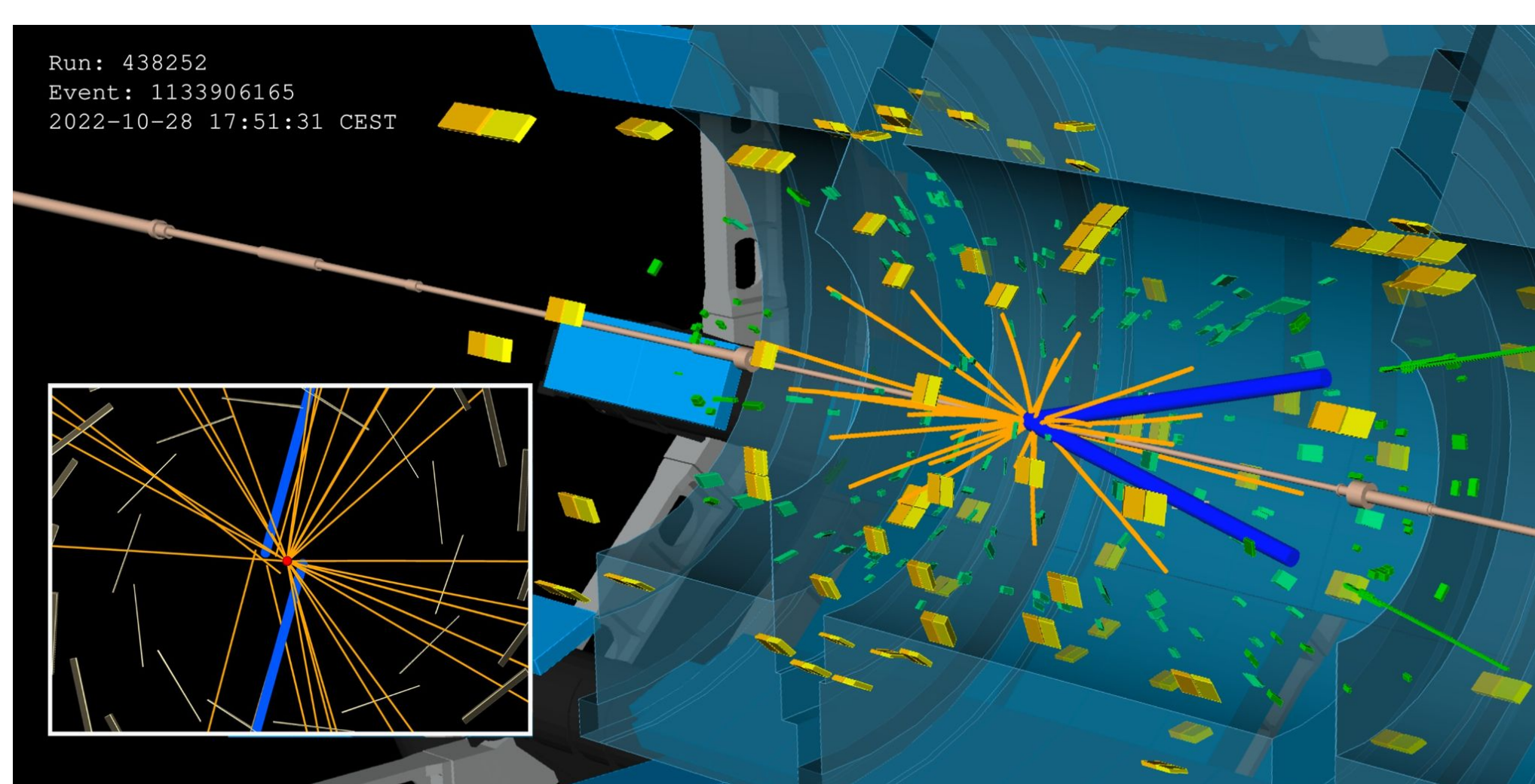


Figure 3. Highest-ever collision energy of 13.6 TeV [ATLAS]

## Dominant Backgrounds: $t\bar{t}$ and Drell-Yan

- Backgrounds are processes or events that mimic the signal of interest by **producing the same final state** – in this analysis,  $t\bar{t}$  and Drell-Yan ( $Z + \text{jets}$ )
- The analysis program utilizes **Monte Carlo analysis** methods to evaluate the signal samples against the dominant backgrounds

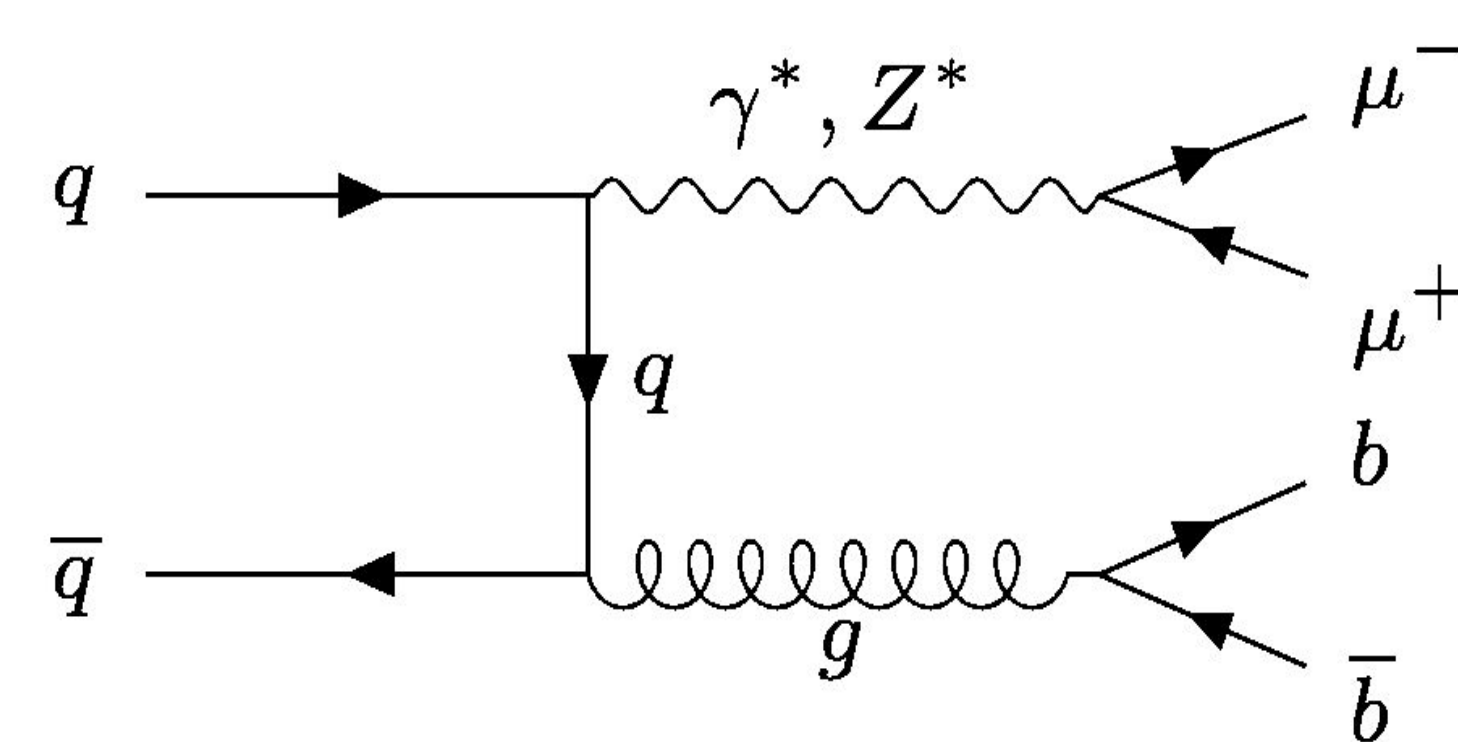


Figure 4. Drell-Yan Process

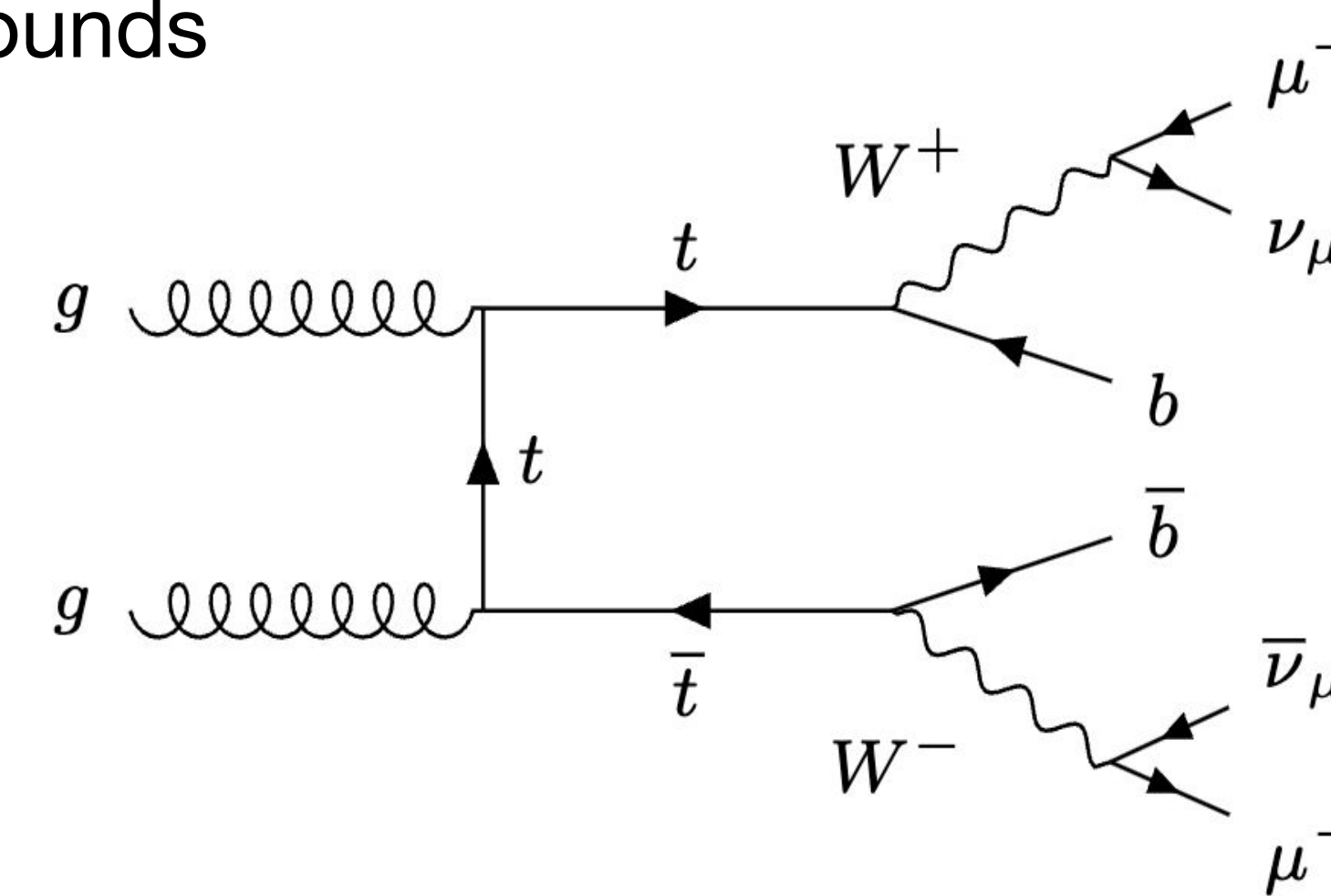


Figure 5.  $t\bar{t}$  Process

- Has an identical final state to  $H \rightarrow Za$
- Background is greatly reduced with the requirement  $10 < m_{\mu\mu} < 65$  GeV
- Final state includes a neutrino pair
- Expected to have **high  $m_T^{\text{miss}}$**  when compared to the sample

## Data & Monte Carlo Comparisons

The effects of a cut are visible after the **kinematic likelihood fitting (KL)**. Here, we compare the pre-fit and post-fit distributions of three mass quantities.

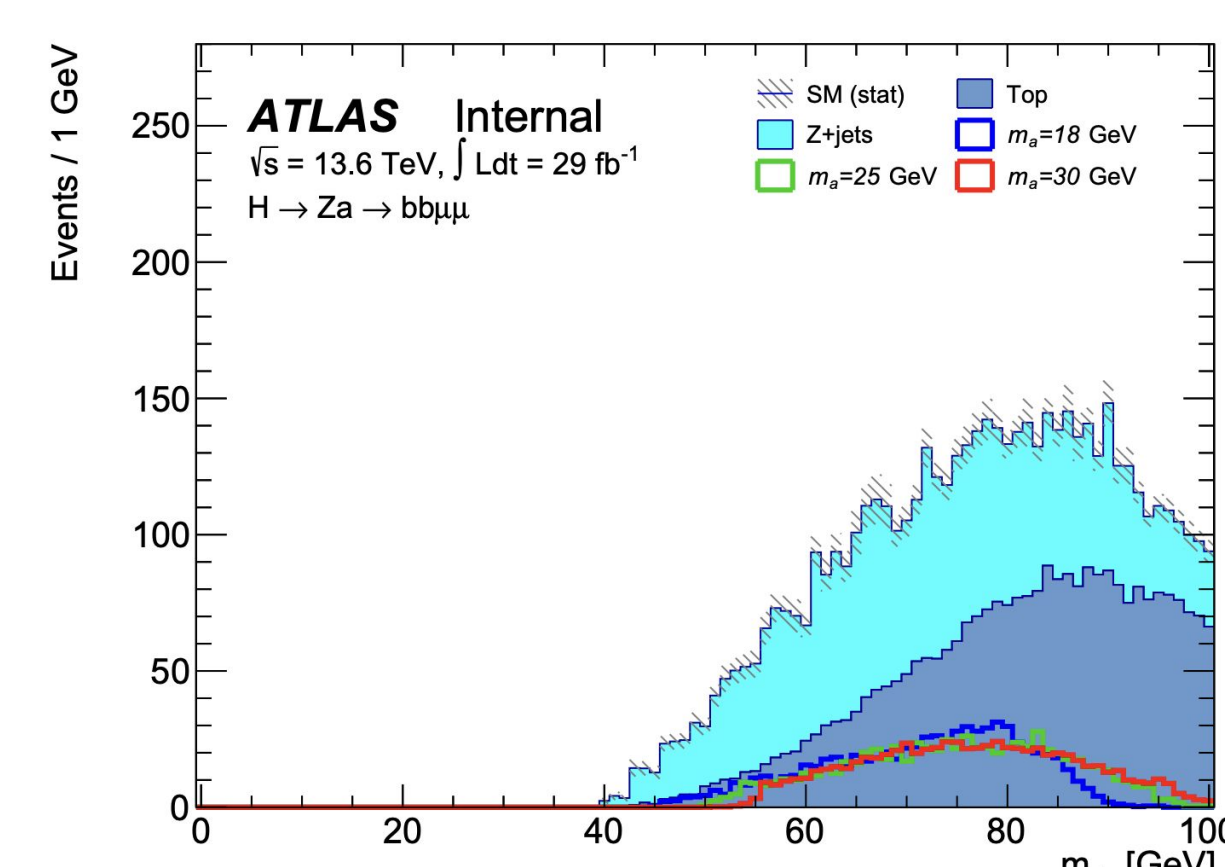


Fig. 6.  $m_{bb}$  - CutLikelihood\_30

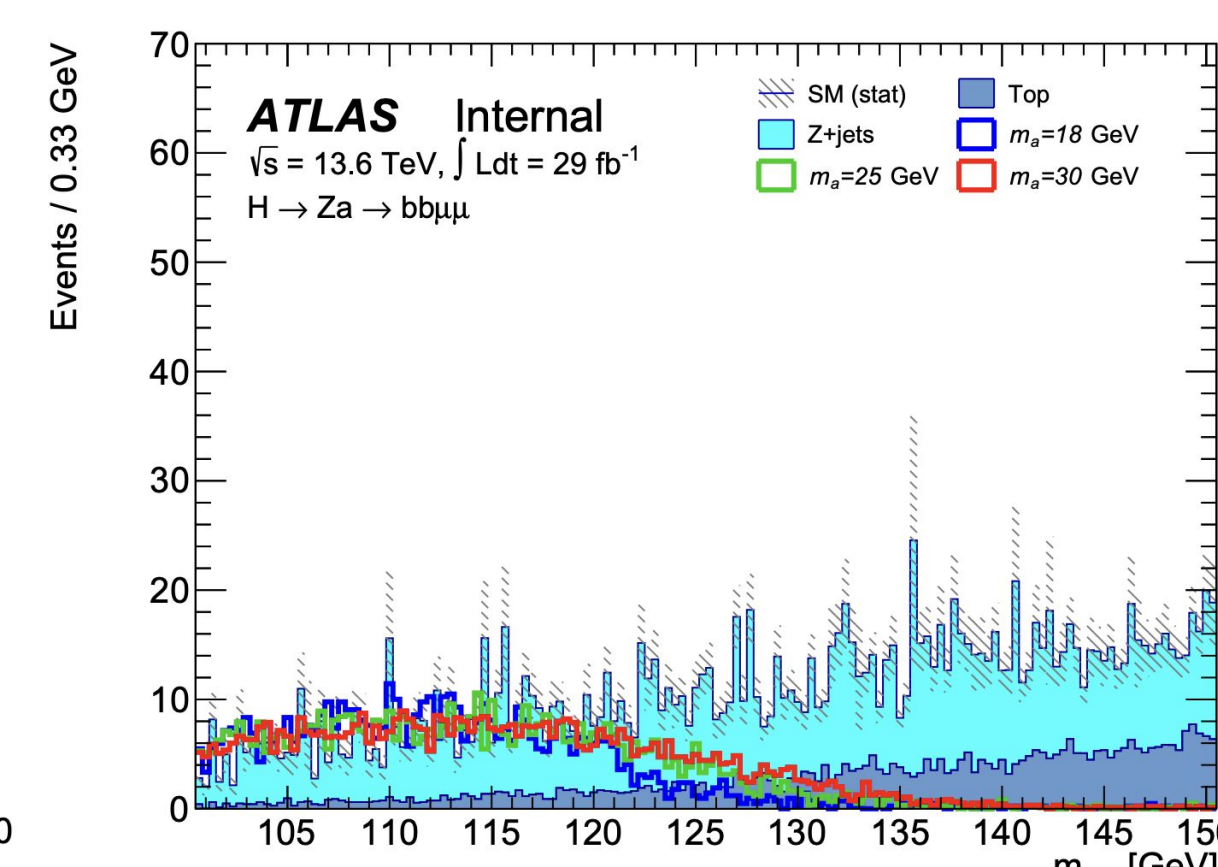


Fig. 8.  $m_{bb\mu\mu}$  - CutLikelihood\_30

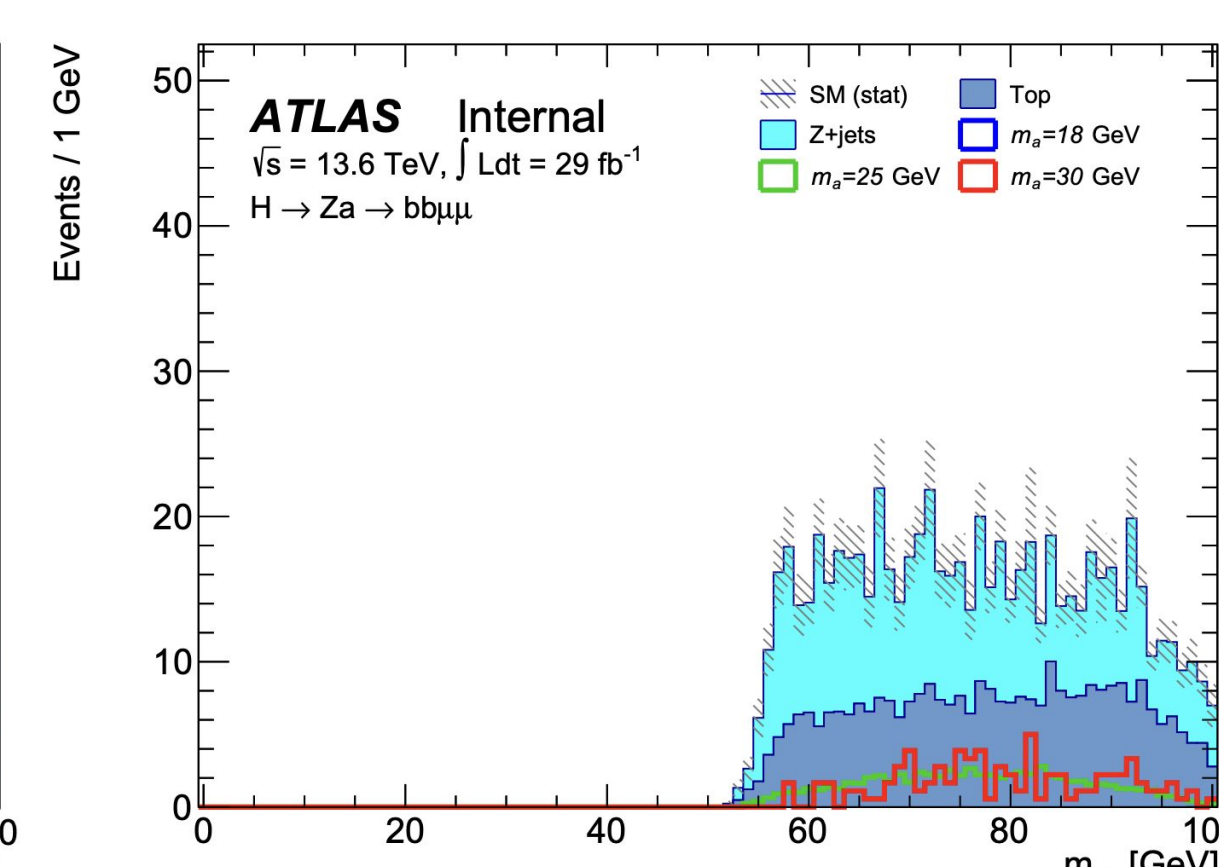


Fig. 10.  $m_{bb}$  - CutMass\_25

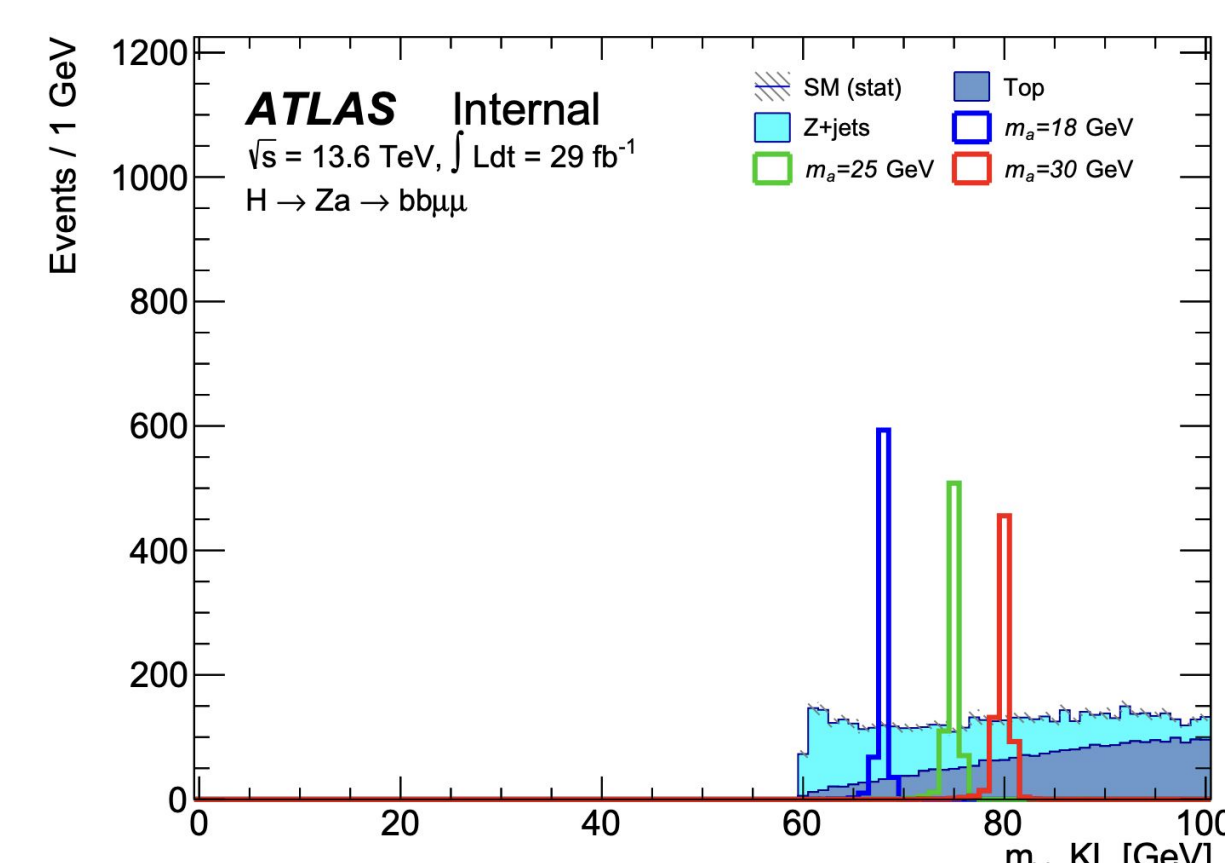


Fig. 7.  $m_{bb\_KL}$  - CutLikelihood\_30

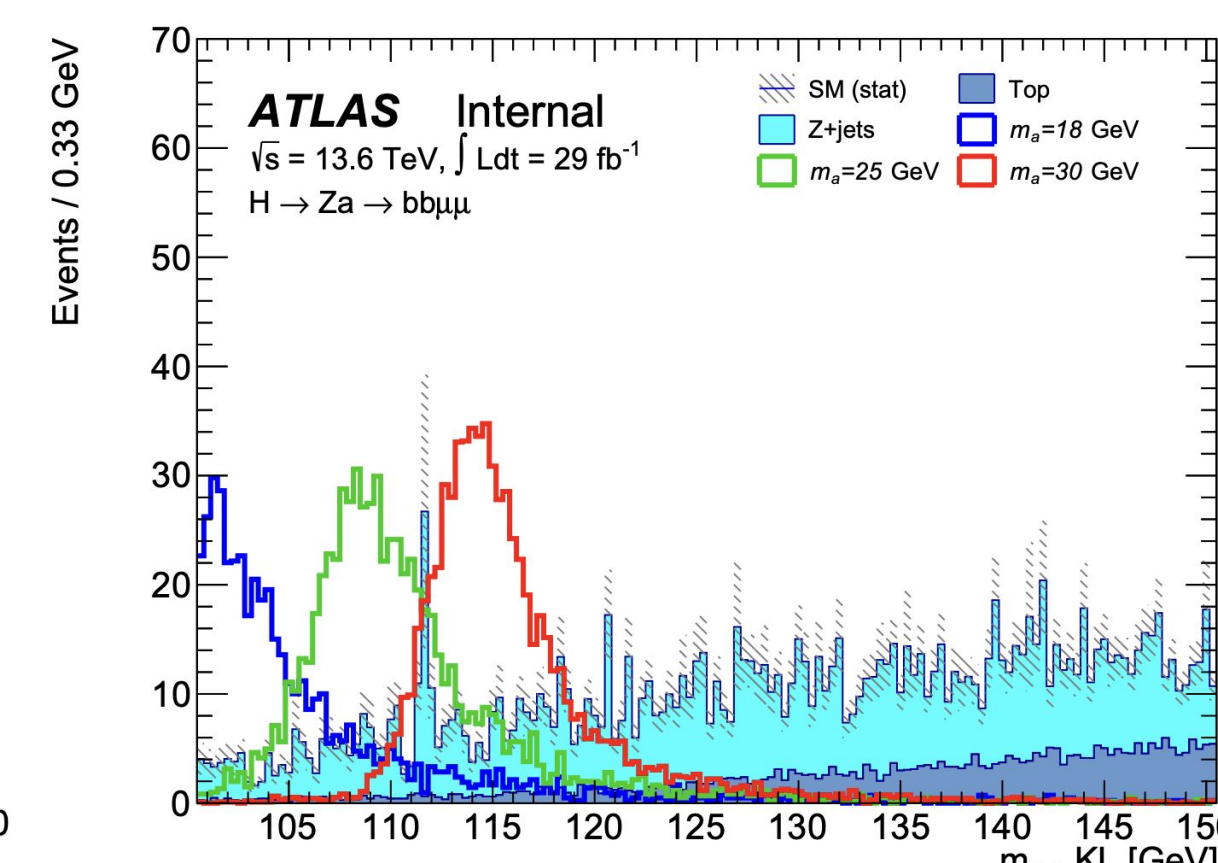


Fig. 9.  $m_{bb\mu\mu\_KL}$  - CutLikelihood\_30

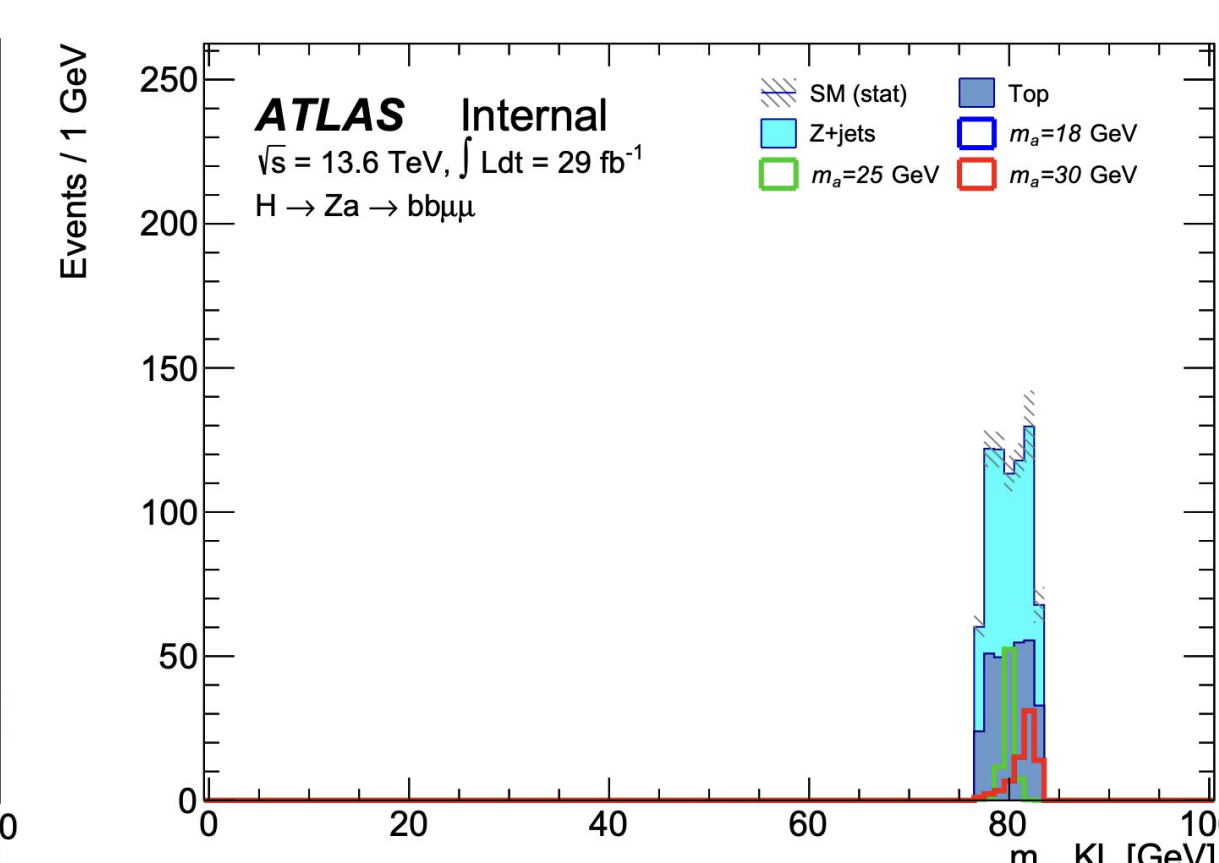


Fig. 11.  $m_{bb\_KL}$  - CutMass\_25

- Dijet mass at Likelihood cut (30 GeV): peaks at 80 GeV  $\rightarrow$  reconstructs Z boson
- 4-body mass at Likelihood cut (30 GeV): peaks at 115 GeV  $\rightarrow$  reconstructs Higgs
- Dijet mass at Mass cut (25 GeV): notice **significant background reduction**

Note: We reconstructed the Z mass to be 80 GeV, rather than 90 GeV, motivated by the observed position of the pre-fit mass peak out of concerns of biasing results. This results in a desired dijet reconstruction of 80 GeV and Higgs reconstruction of 115 GeV. This discrepancy will be studied as part of future work.

## Machine Learning BDT and Event Selection

- Current work involves the implementation of an ML boosted decision tree (BDT)
- After implementation, we train the BDT to be optimized for the  $bb\mu\mu$  final state
- The BDT we use is modified from that developed for the  $H \rightarrow aa \rightarrow bb\mu\mu$  decay
- Basic physical cuts: oppositely charged muons,  $m_a \approx m_\mu$  with  $10 \text{ GeV} < m_{\mu\mu} < 65 \text{ GeV}$ ,  $p_T^b$  is above 20 GeV

- Introduce mass-specific likelihood cuts to improve signal isolation and achieve dijet mass peaks at  $\sim 80$  GeV
- Implement mass cuts to significantly reduce background by confining to a tight ( $\pm 3$  GeV) mass window

## Signal-Background Improvement Results

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

Figure 12. Analysis Cutoff

- We observe a dramatic decrease in both backgrounds for all mass signals with the implementation of the mass cuts
- $\rightarrow$  For the **25 GeV** signal, the **background decreases by  $\sim 92.03\%$  for  $t\bar{t}$  and  $\sim 86.84\%$  for  $Z + \text{jets}$**
- $\rightarrow$  This success extends to the other two mass signals:

**18 GeV:** 94.35%  $t\bar{t}$  reduction, 82.46%  $Z + \text{jet}$  reduction

**30 GeV:** 90.12%  $t\bar{t}$  reduction, 87.79%  $Z + \text{jet}$  reduction

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