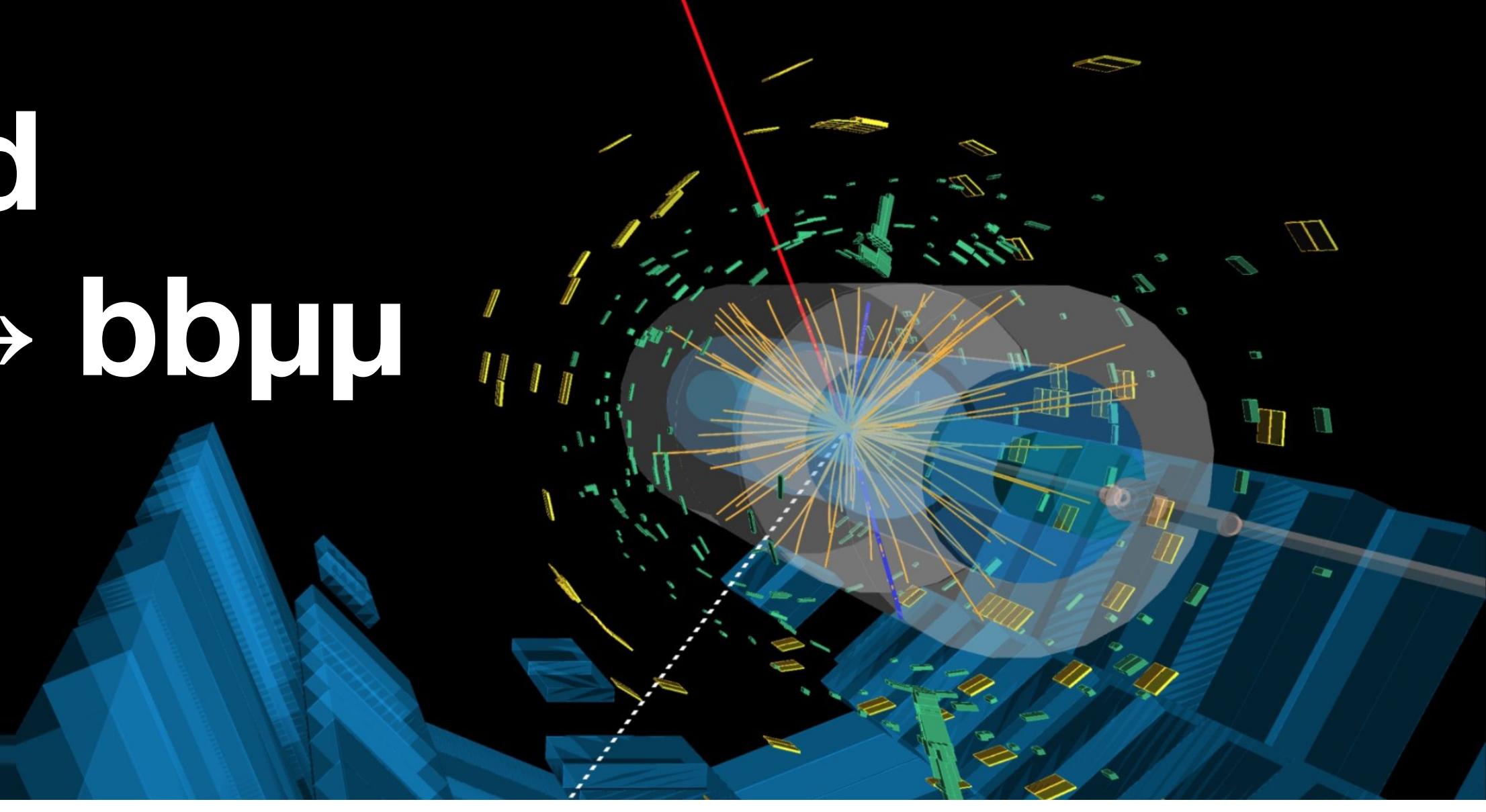




Machine Learning Optimization for Likelihood-Based Reconstruction in the Exotic Higgs Decay $pp \rightarrow H \rightarrow Za \rightarrow bb\mu\mu$

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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 $pp \rightarrow H \rightarrow Za \rightarrow bb\mu\mu$:

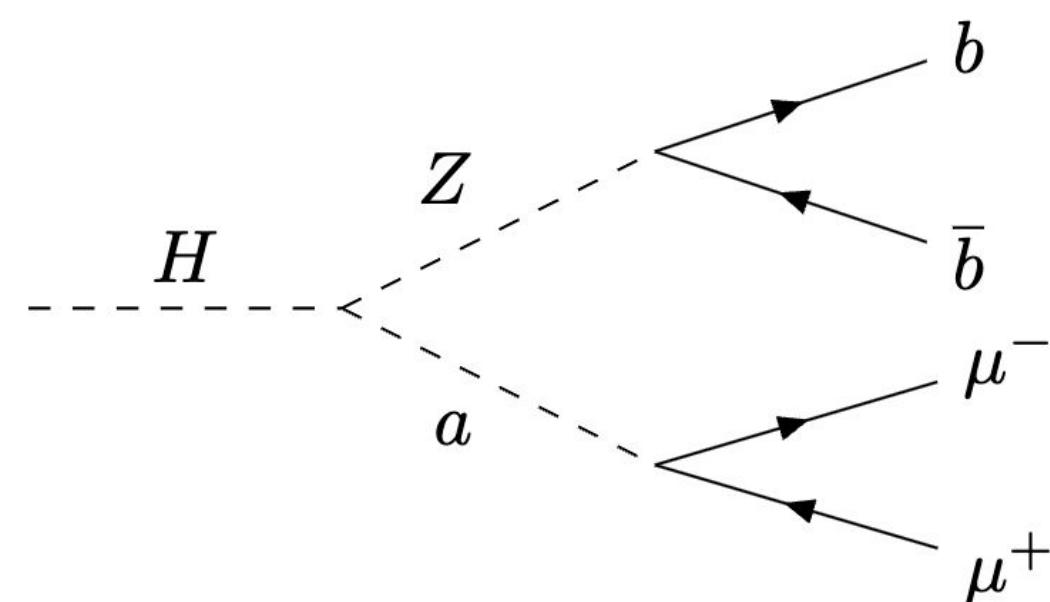


Figure 1. $H \rightarrow Za \rightarrow bb\mu\mu$ Decay

- 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

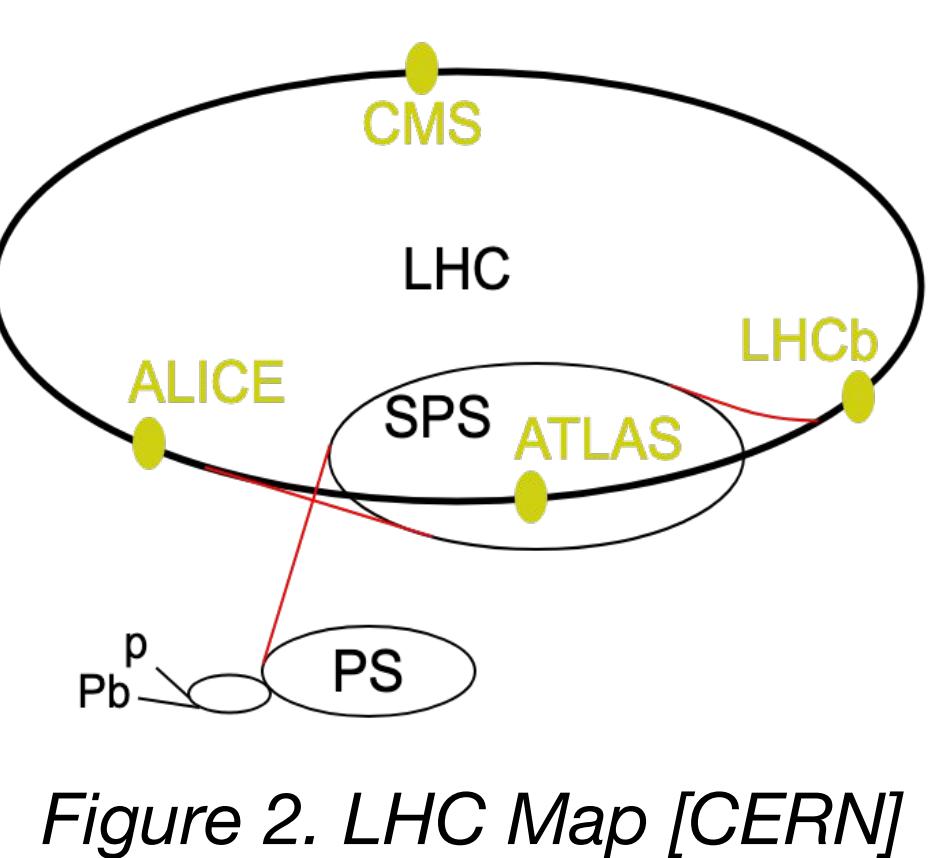


Figure 2. LHC Map [CERN]

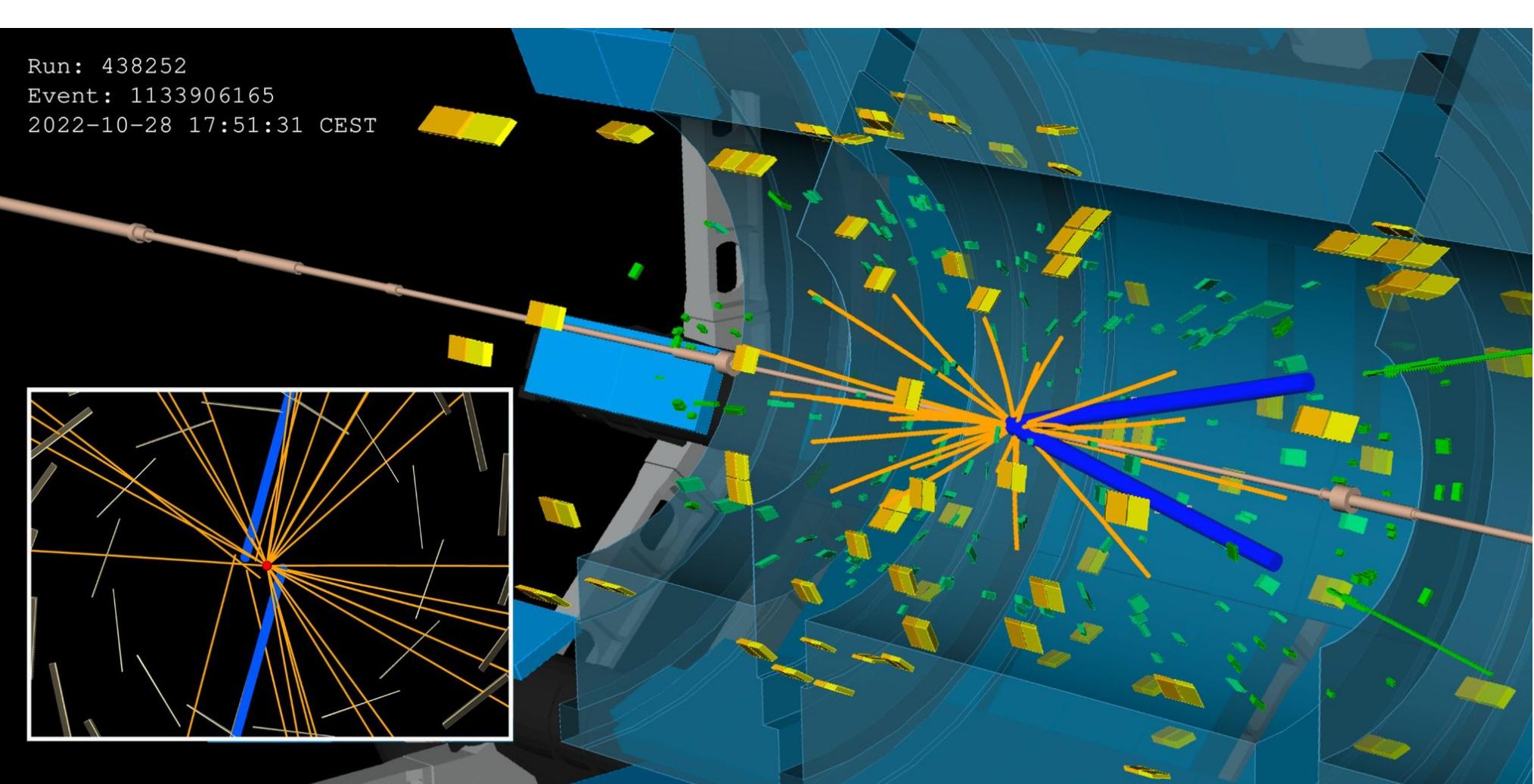


Figure 3. Highest-ever collision energy of 13.6 TeV [ATLAS]

Dominant Backgrounds: ttbar and Drell-Yan

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

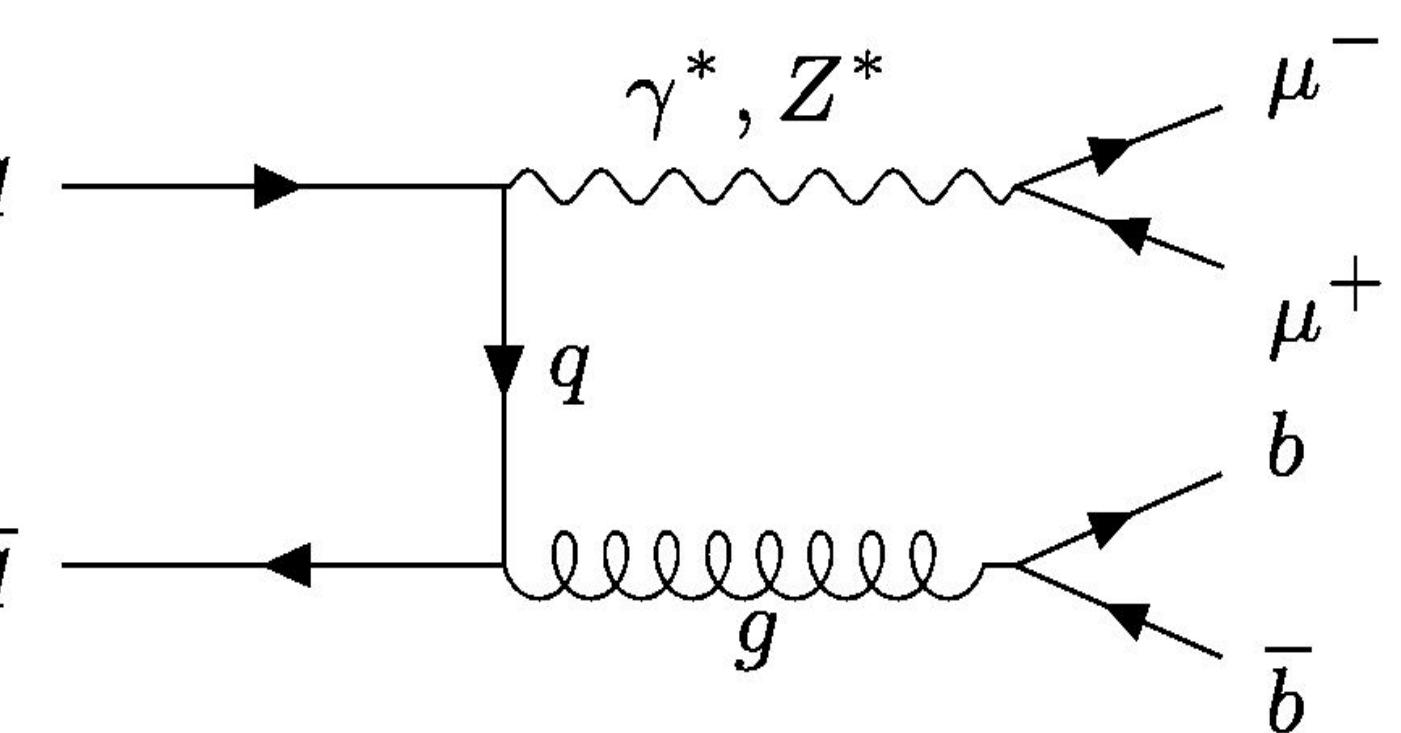


Figure 4. Drell-Yan Process

- 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^{miss} when compared to the sample

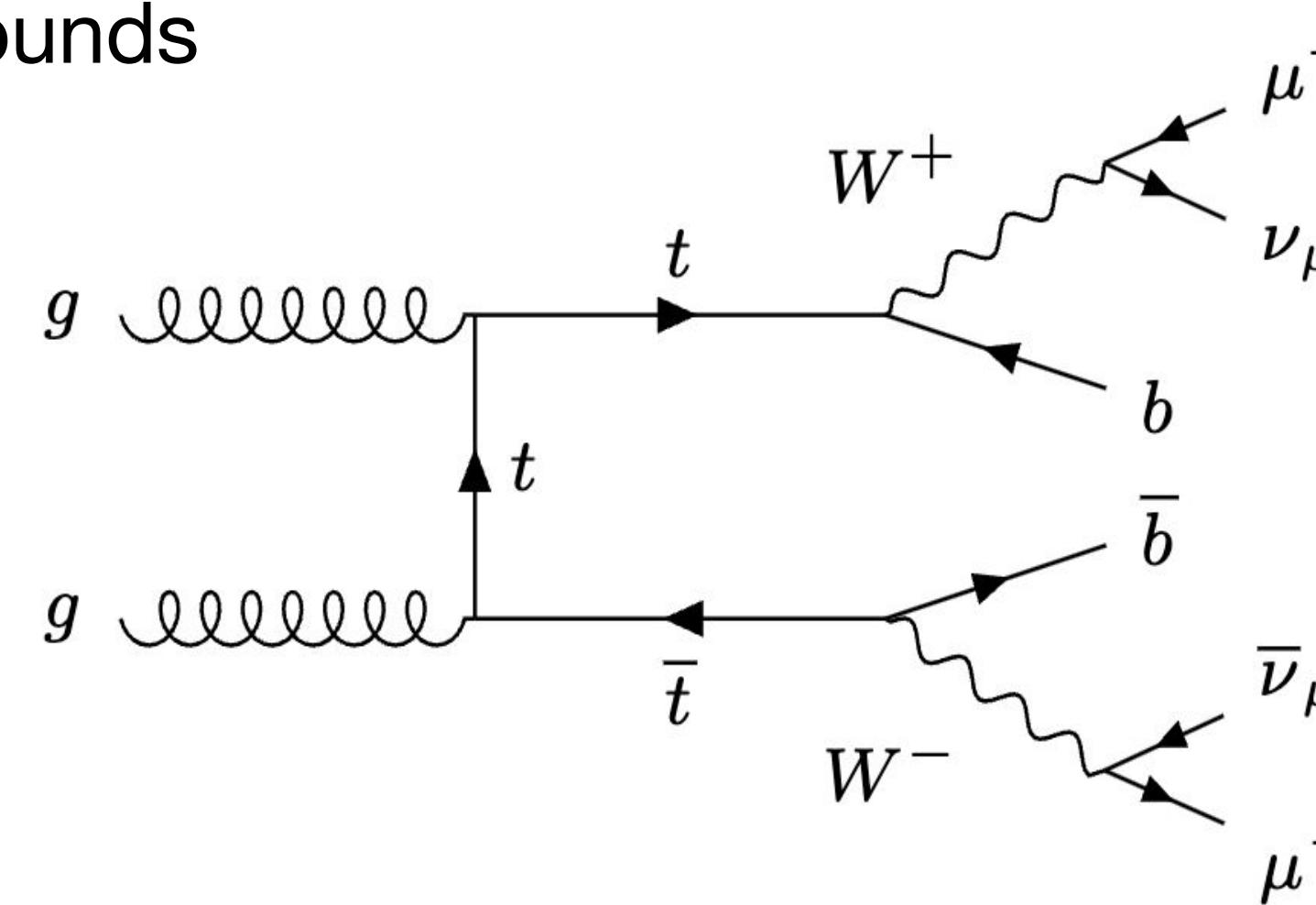


Figure 5. ttbar Process

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 ~80 GeV
- Implement mass cuts to significantly reduce background by confining to a tight (± 3 GeV) mass window

Signal-Background Improvement Results

$\sqrt{s}=13.6 \text{ TeV}, L=29 \text{ fb}^{-1}$	$m_a=18 \text{ GeV}$	$m_a=25 \text{ GeV}$	$m_a=30 \text{ GeV}$	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 $\eta < 2.47$	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
$N_b = 2$ & $p_T^b >= 20 \text{ GeV}$	5.51 ± 0.08	6.93 ± 0.09	10.44 ± 0.11	40298.40 ± 52.38	10479.21 ± 81.00
$10 < m_{\mu\mu} < 65 \text{ GeV}$	5.51 ± 0.08	6.93 ± 0.09	10.44 ± 0.11	36196.17 ± 49.64	9774.91 ± 78.14
$E_T^{\text{miss}} < 60 \text{ GeV}$	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
$E_T^{\text{miss}} \geq 60 \text{ GeV}$	0.25 ± 0.02	0.31 ± 0.02	0.37 ± 0.02	22176.59 ± 38.86	530.65 ± 11.93

Figure 12. Analysis Cutflow

- We observe a dramatic decrease in both backgrounds for all mass signals with the implementation of the mass cuts
- 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

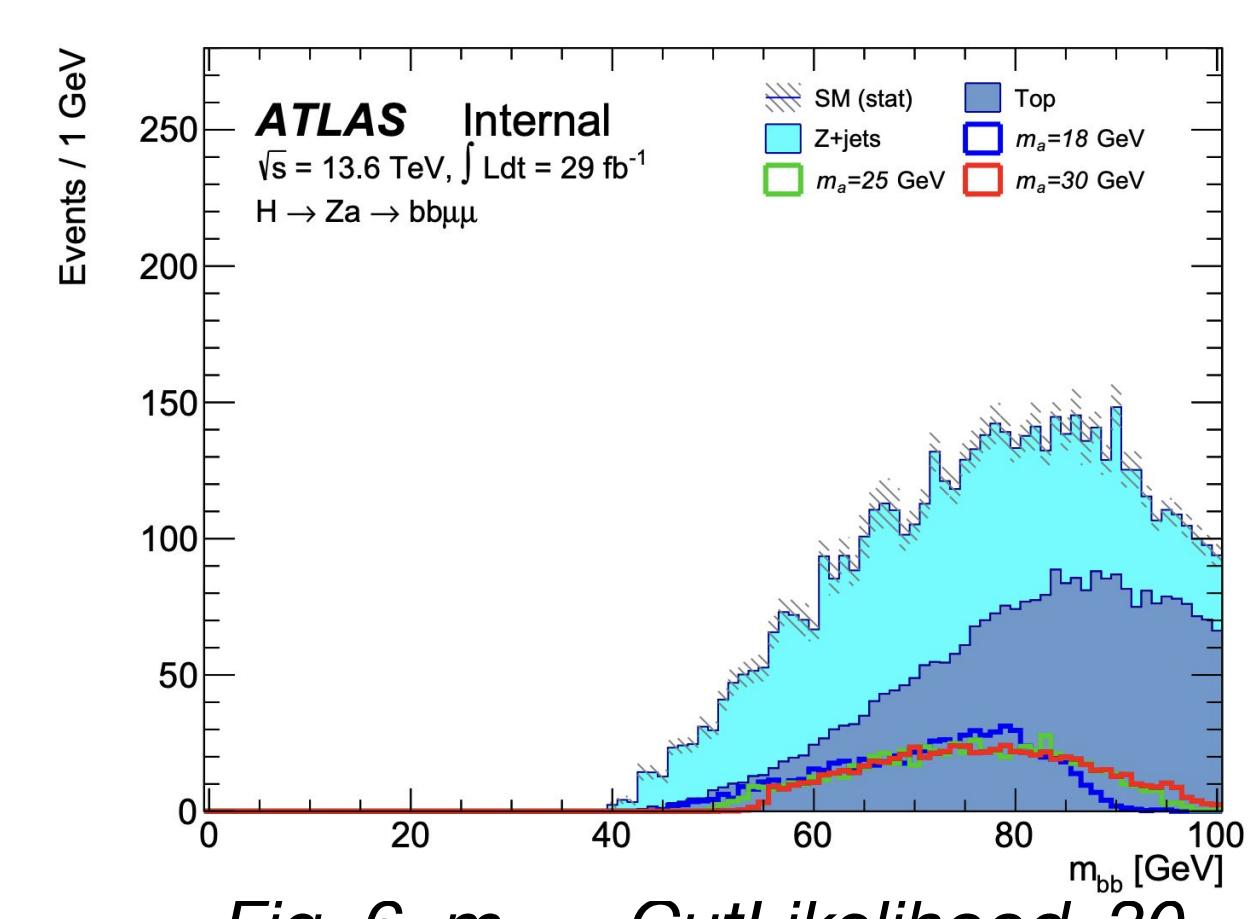


Fig. 6. m_{bb} - CutLikelihood_30

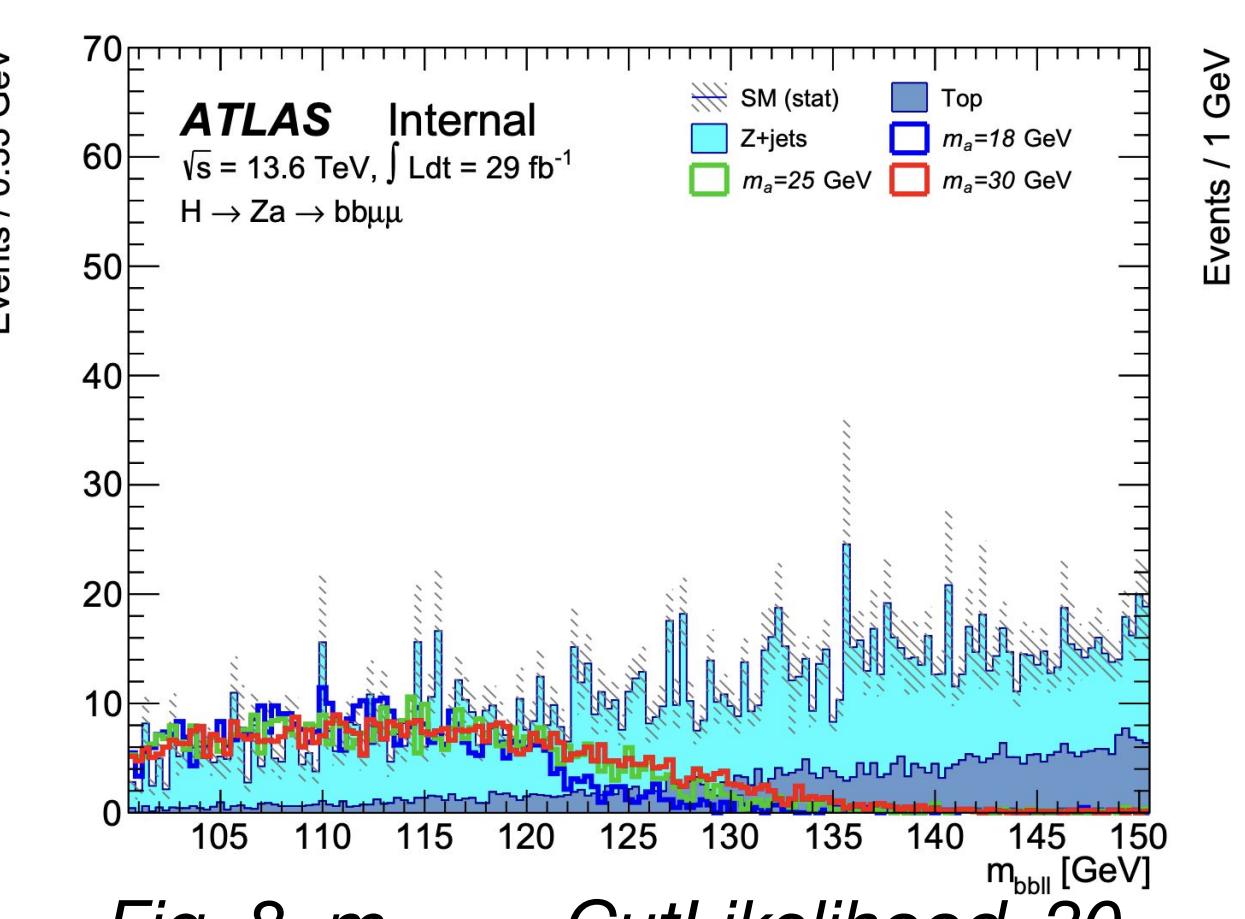


Fig. 8. $m_{bb\mu\mu}$ - CutLikelihood_30

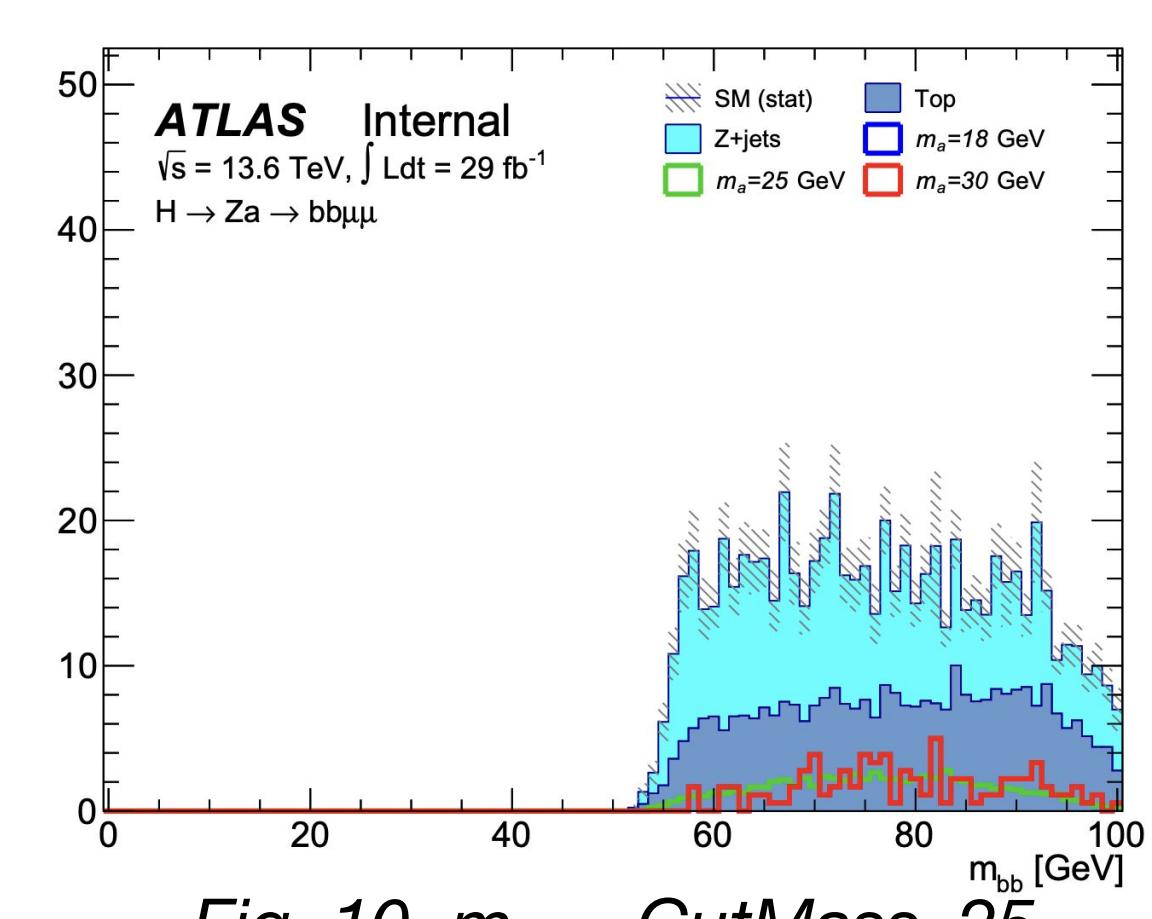


Fig. 10. m_{bb} - CutMass_25

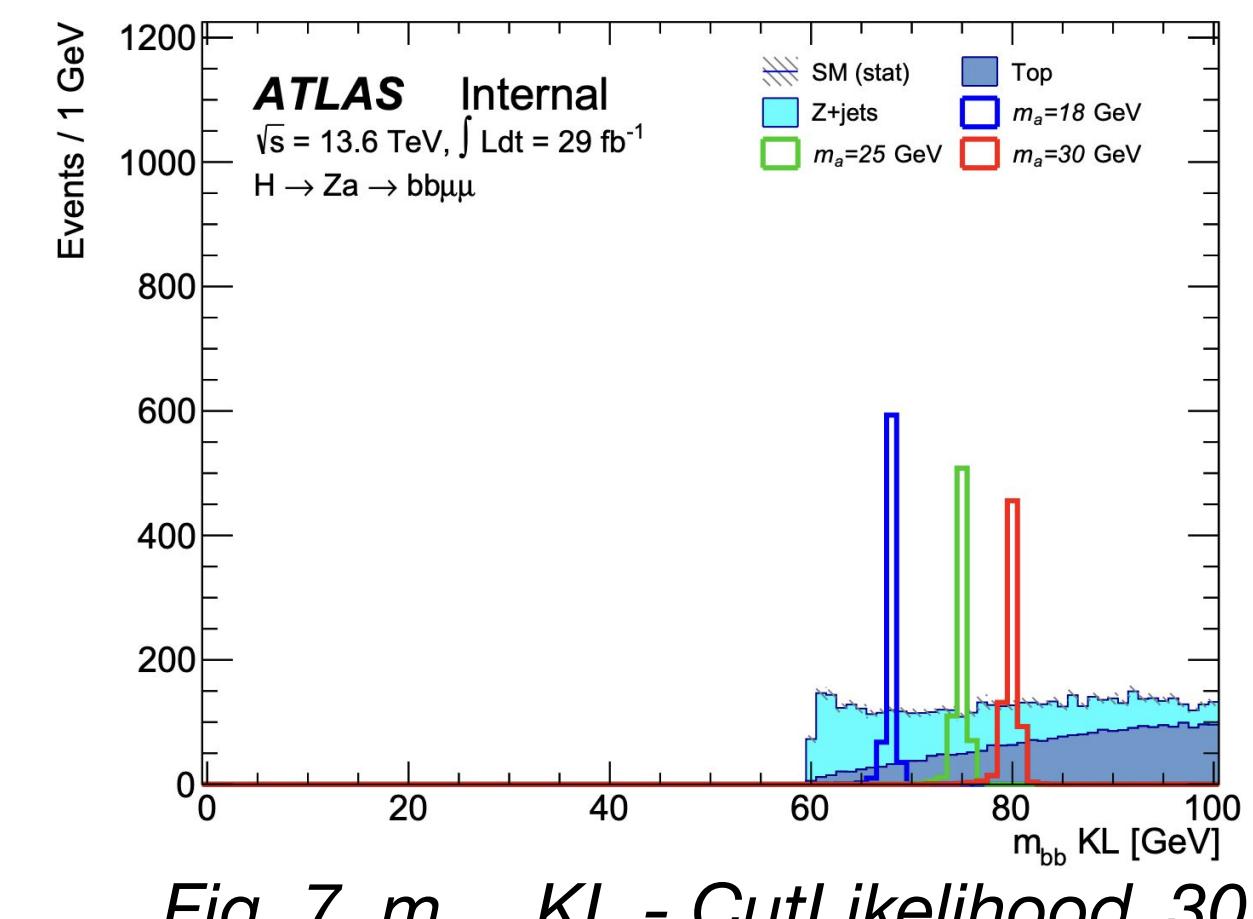


Fig. 7. m_{bb-KL} - CutLikelihood_30

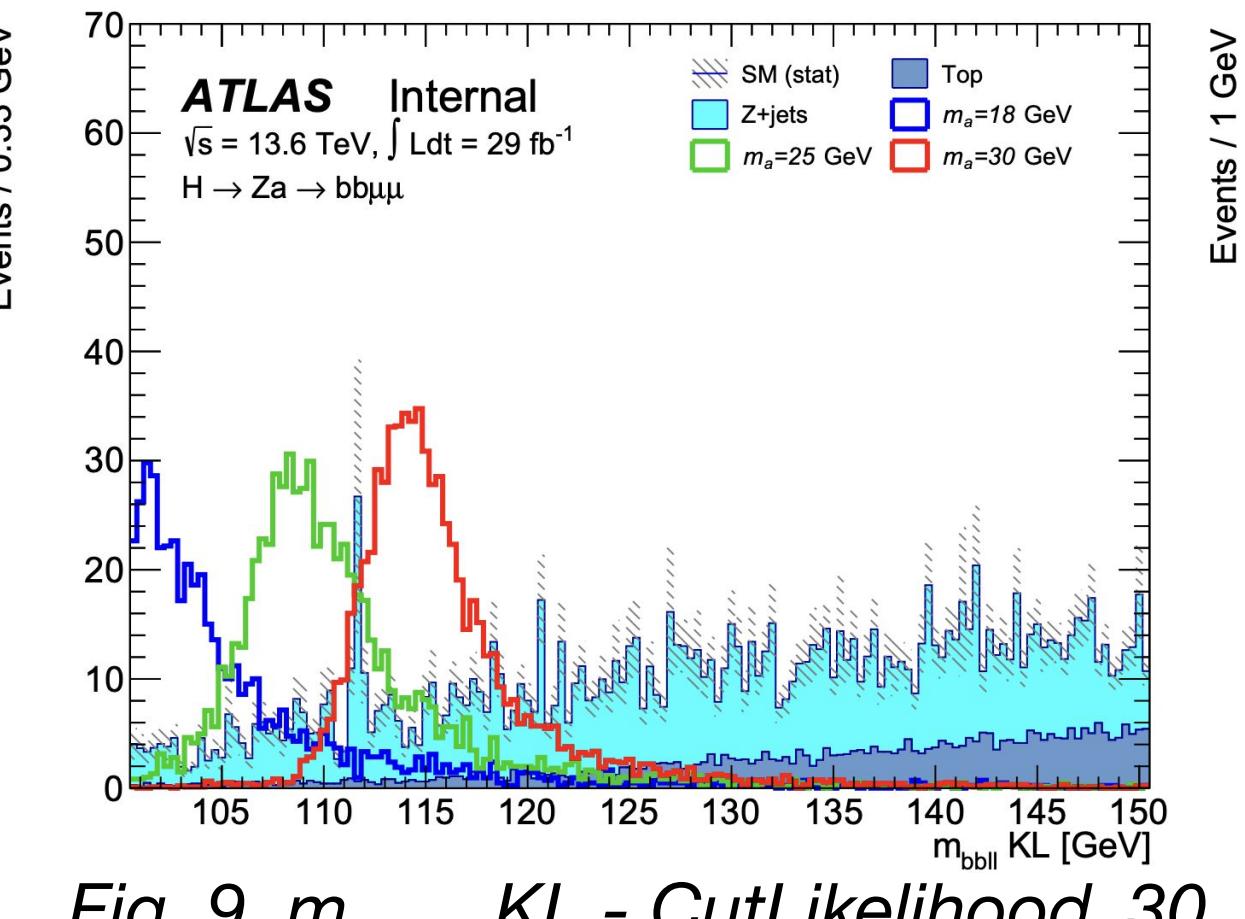


Fig. 9. $m_{bb\mu\mu-KL}$ - CutLikelihood_30

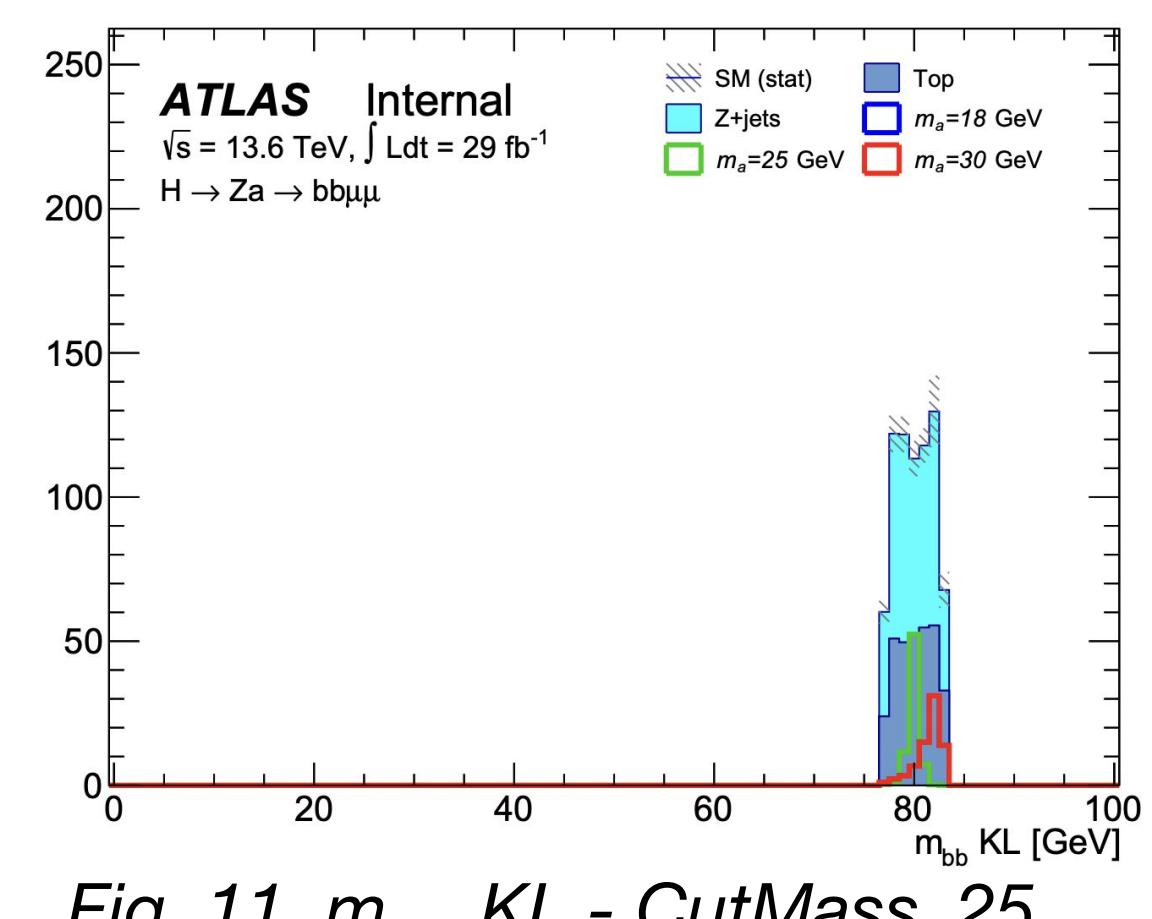


Fig. 11. m_{bb-KL} - CutMass_25

- Dijet mass at Likelihood cut (30 GeV): peaks at 80 GeV → reconstructs Z boson
- 4-body mass at Likelihood cut (30 GeV): peaks at 115 GeV → 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.

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