

SWITCHED AT BIRTH

Born Lepton Assignment of
Semi-Leptonic $t\bar{t}H(\rightarrow \mu\mu)$ Events

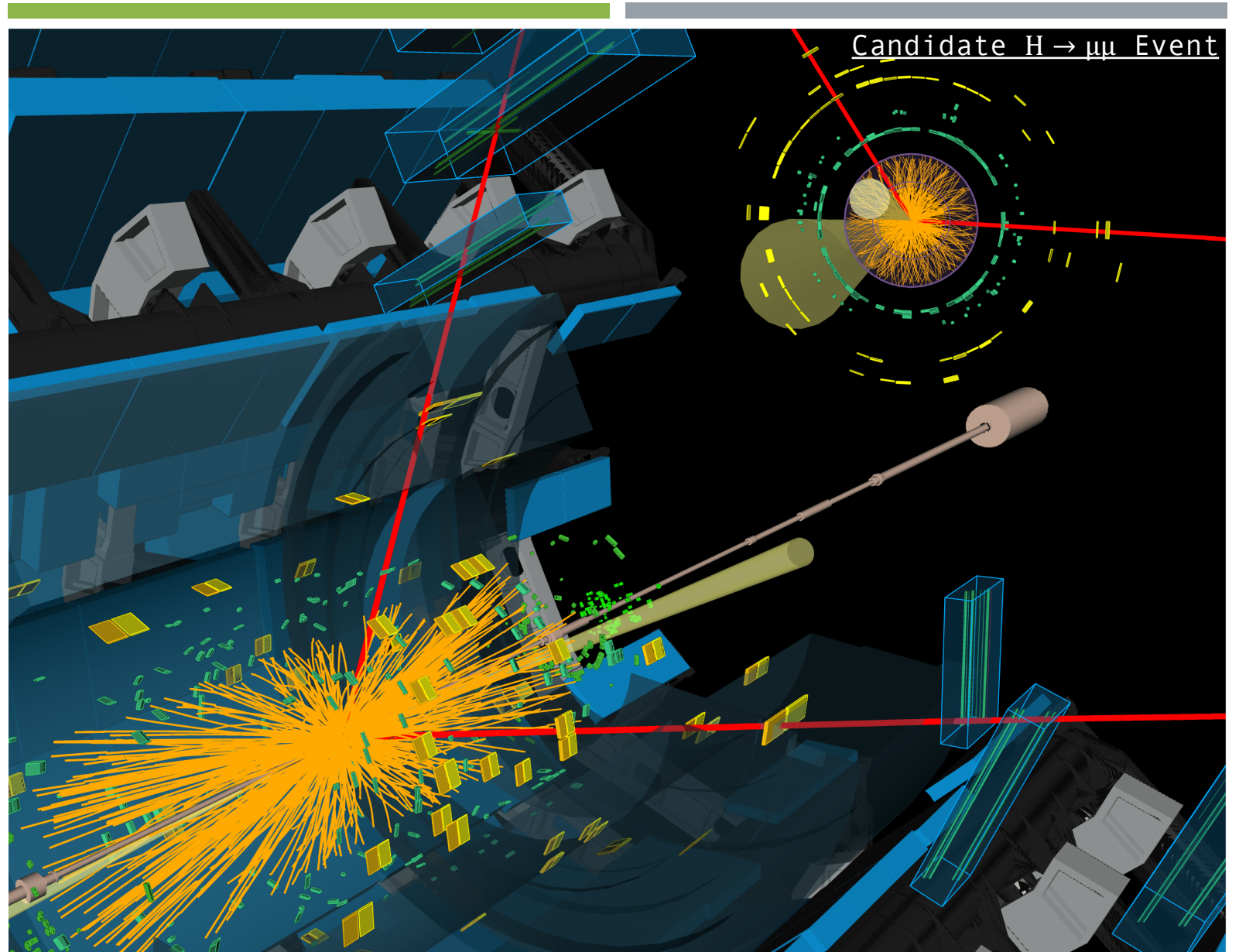
Ian Ramirez-Berend

CAP Congress

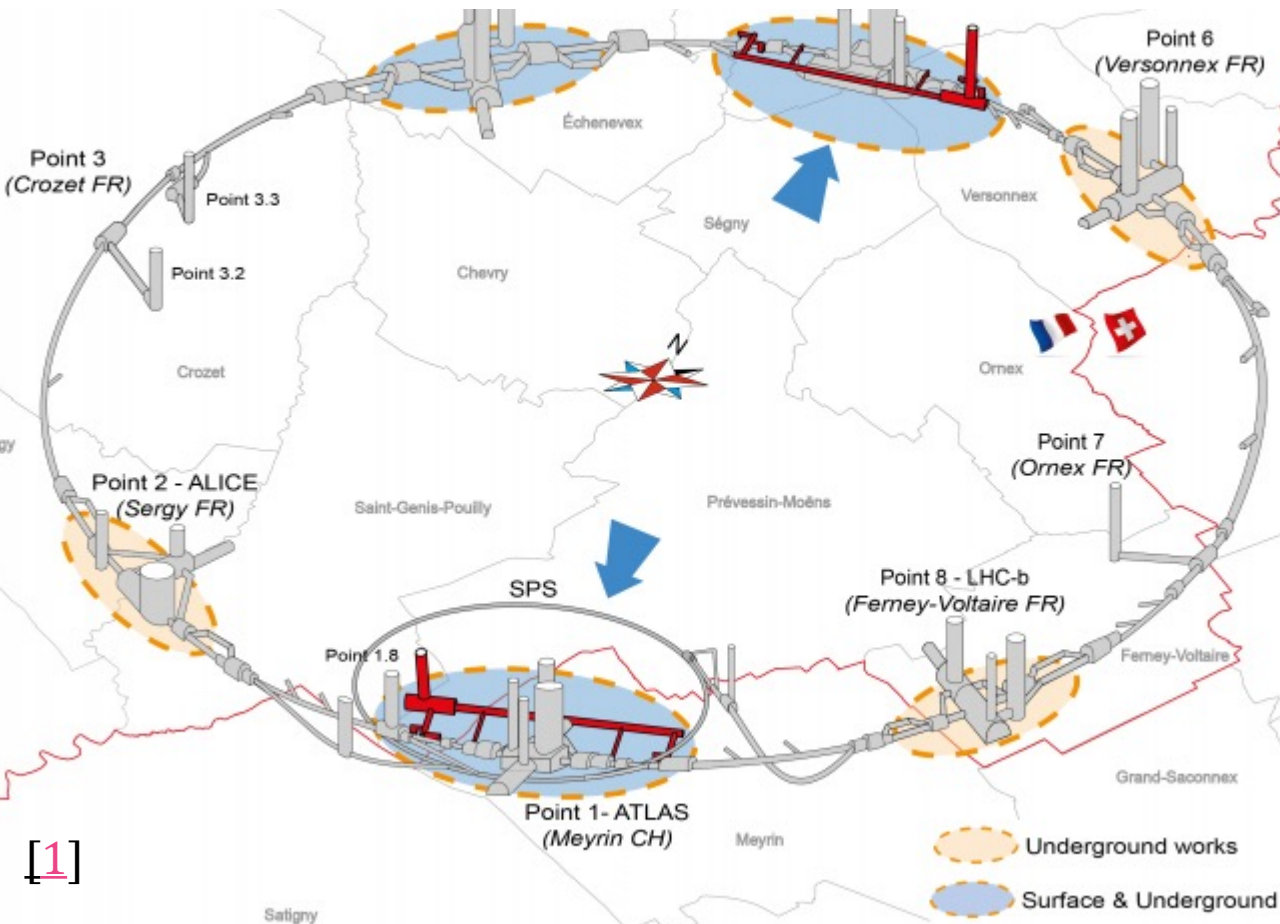
23 June 2026



Carleton
ATLAS

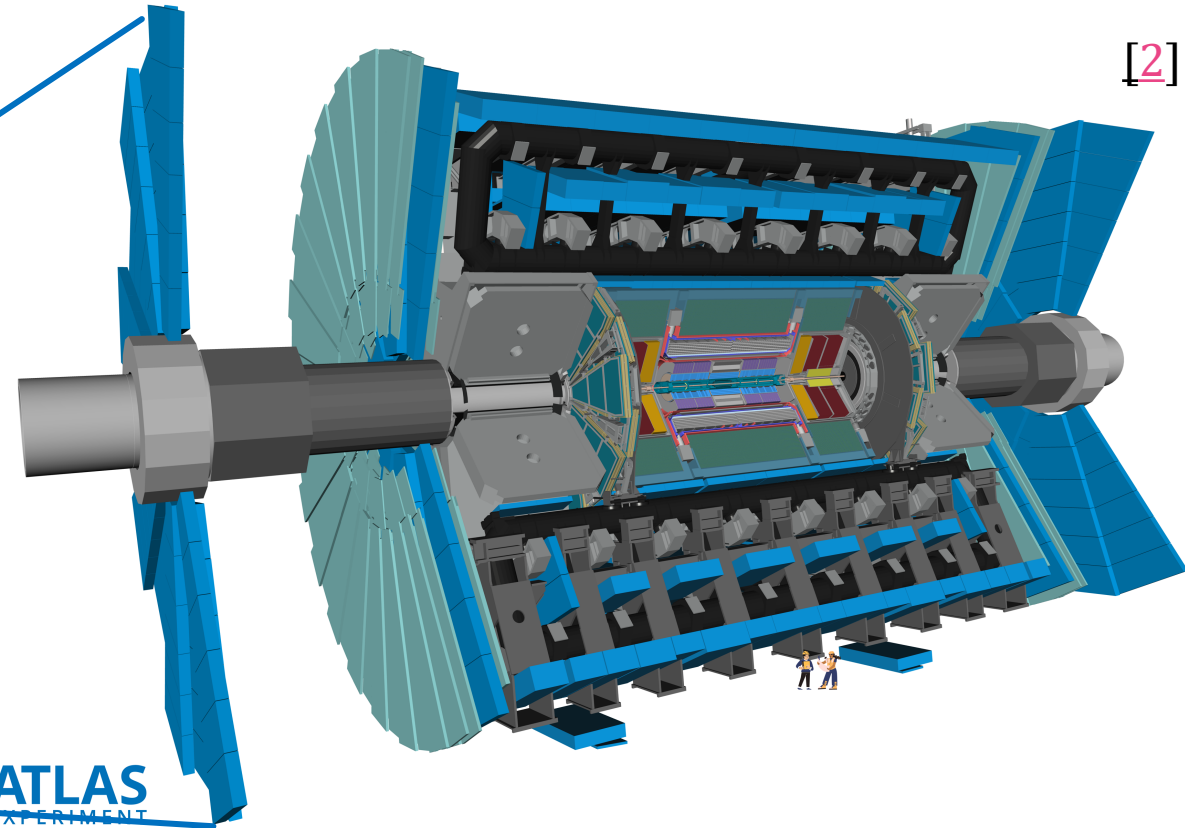
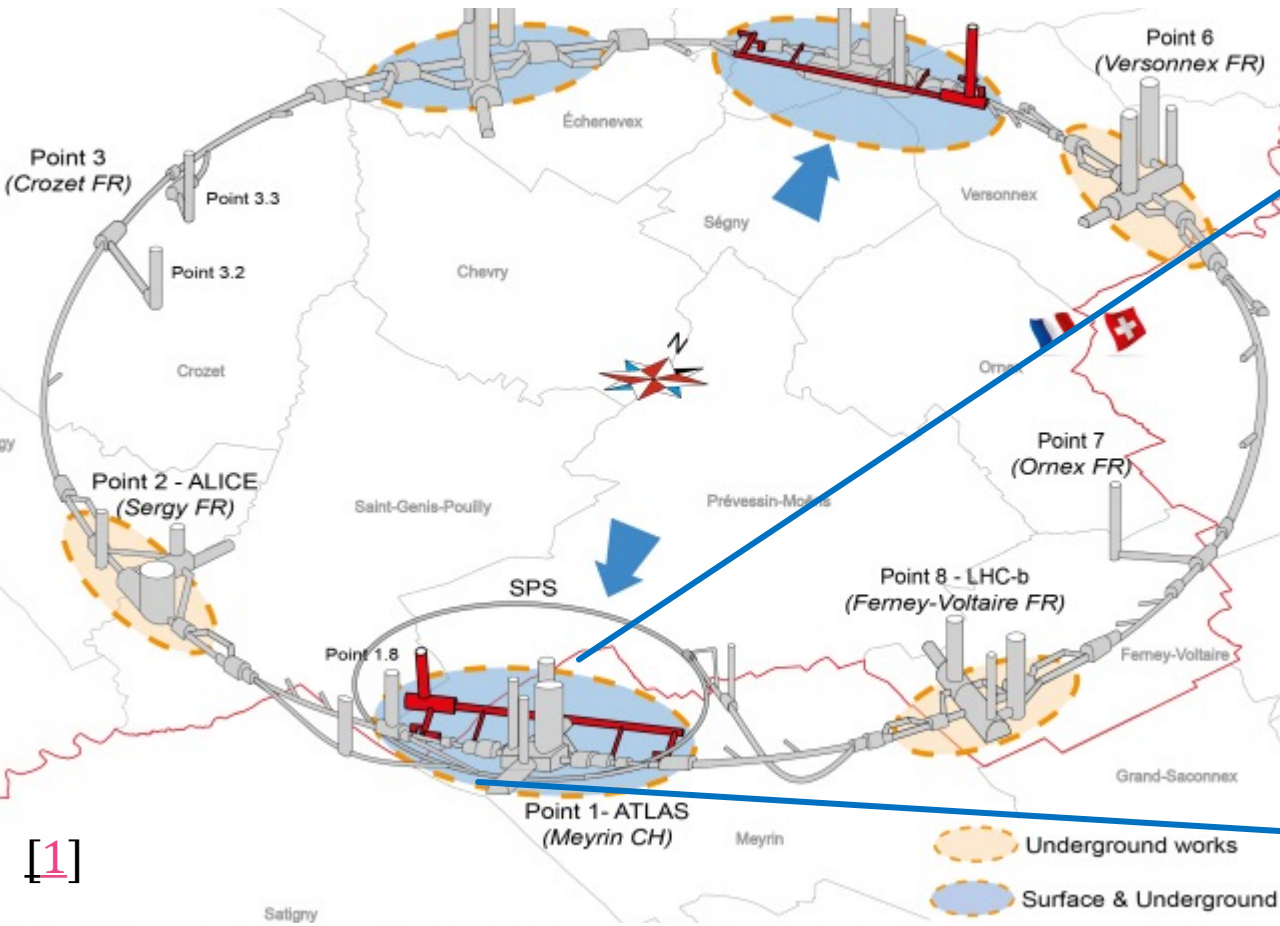


THE LARGE HADRON COLLIDER (LHC)



- World's largest particle accelerator
- Accelerates bunches of protons to $0.999999c$
- Collides them at very high energy $\sqrt{s} = 13.6 \text{ TeV}$
- Only machine capable of producing the Higgs boson
 - Higgs boson discovered by LHC experiments in 2012

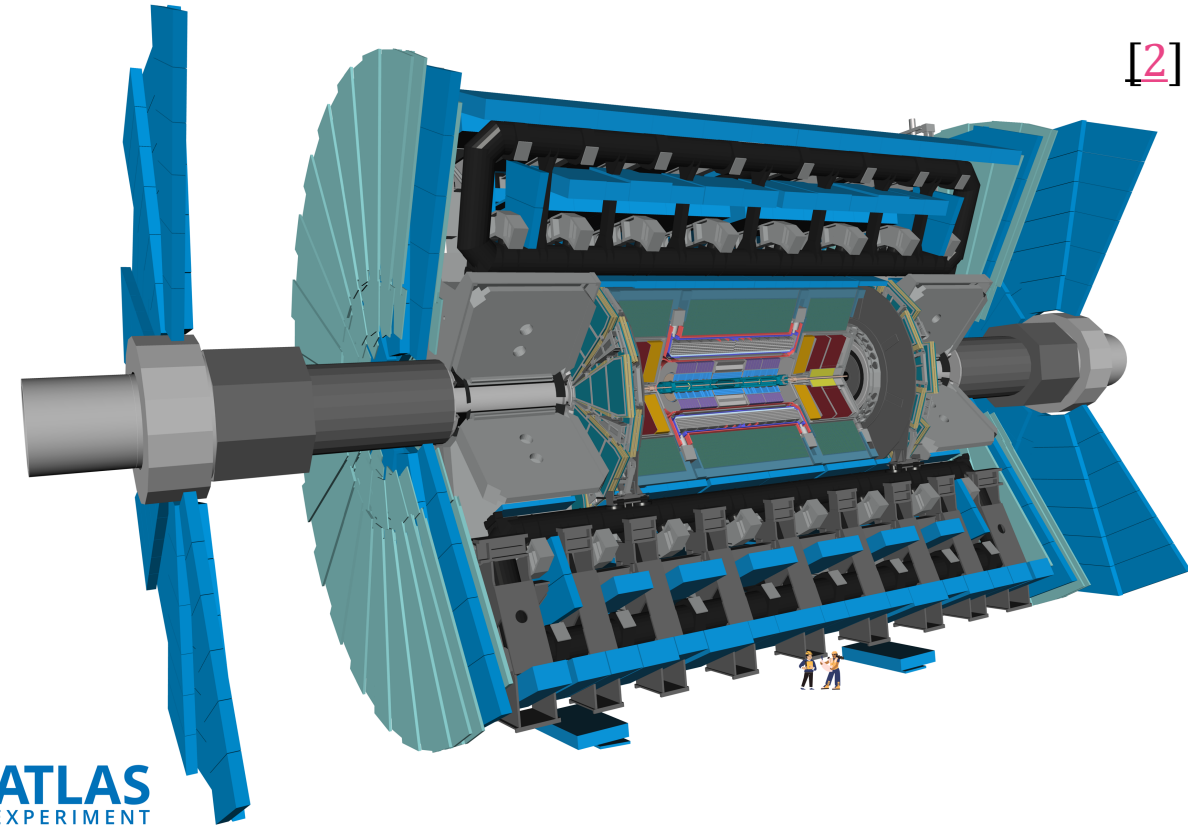
THE LHC + ATLAS



THE ATLAS DETECTOR

- Largest experiment on the LHC
- General purpose detector: designed to fully measure the particles produced in proton-proton collisions

Three layers of subdetectors:



[2]

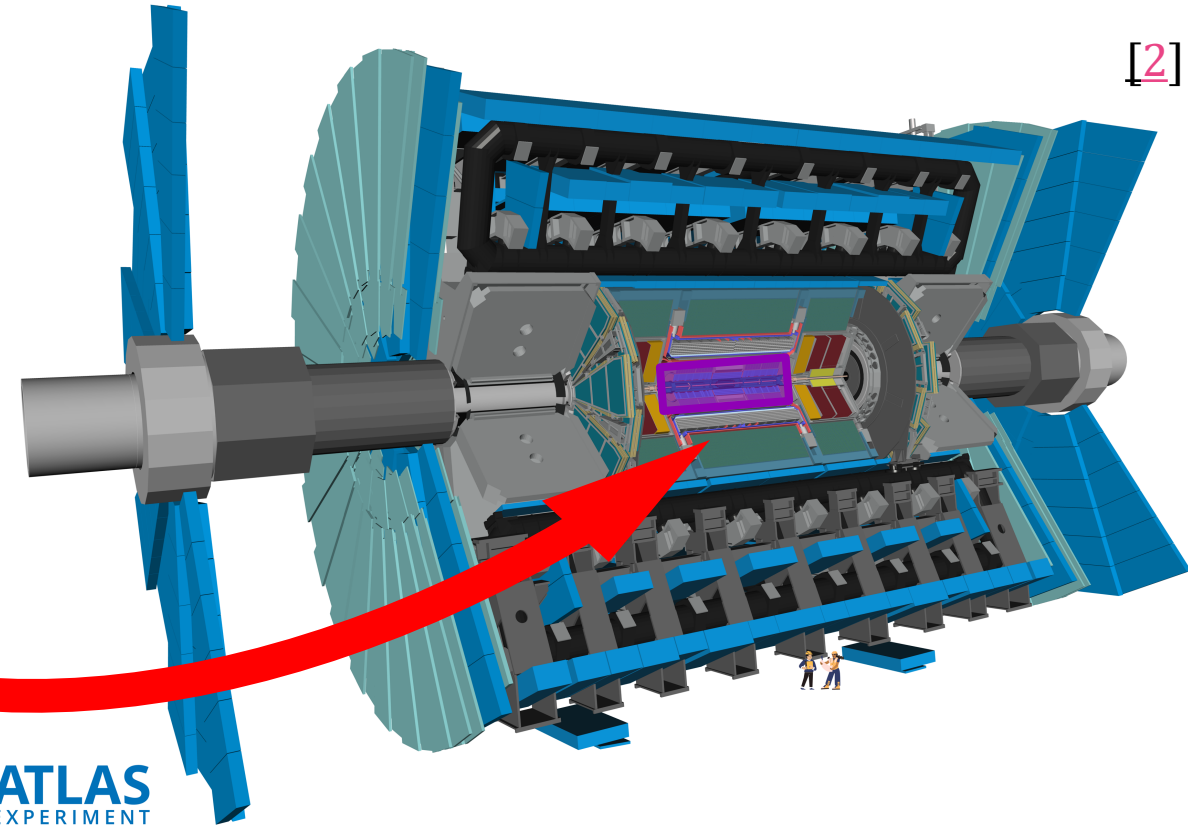


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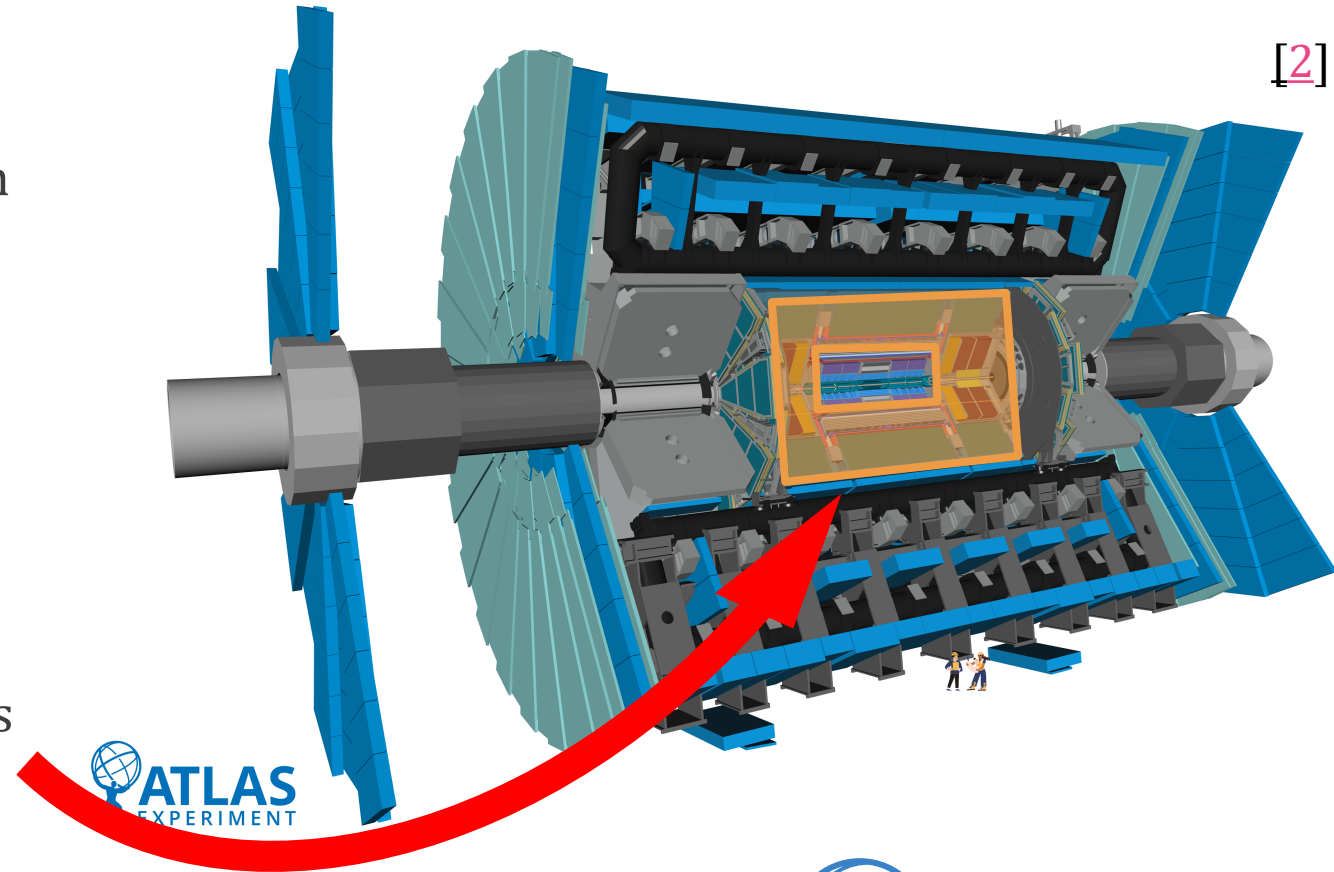


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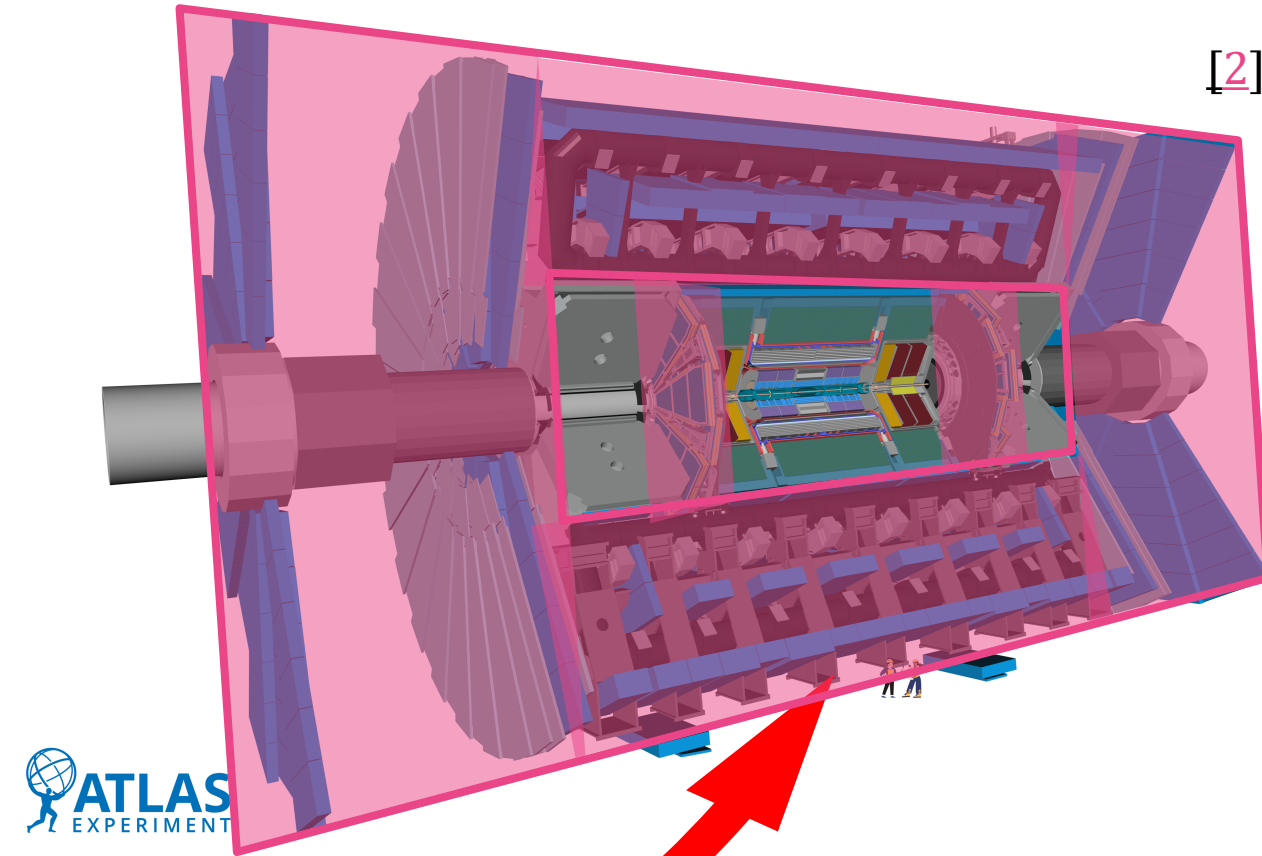
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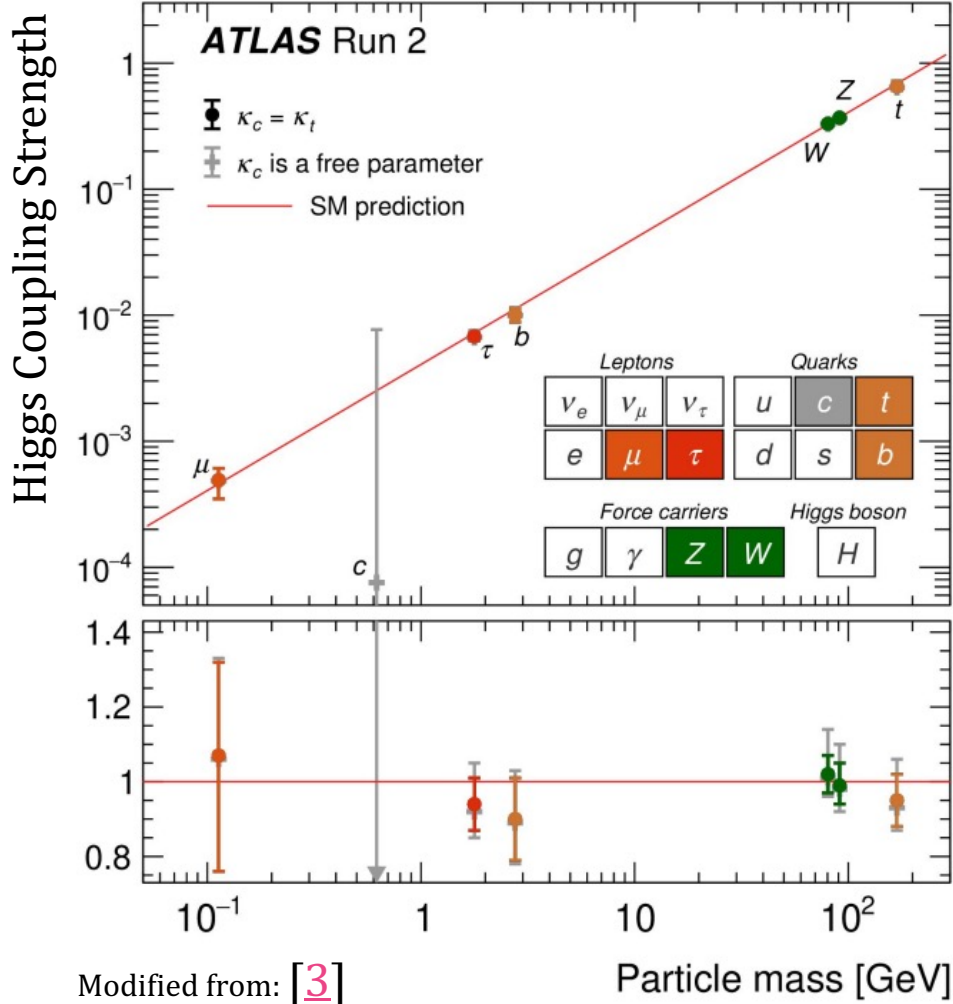
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Three layers of subdetectors:

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3. **Muon Spectrometers:** measure the trajectory and momentum of muons that escape the calorimeter

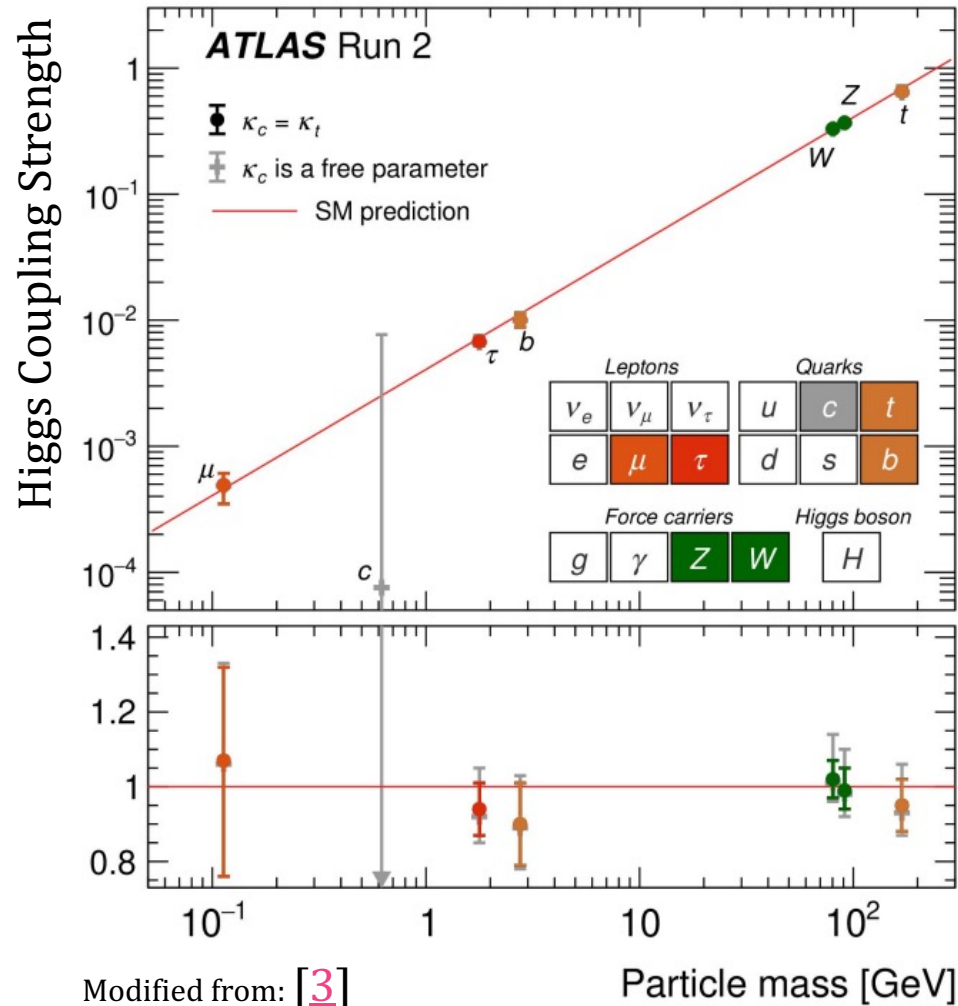


OVERVIEW: THE HIGGS BOSON



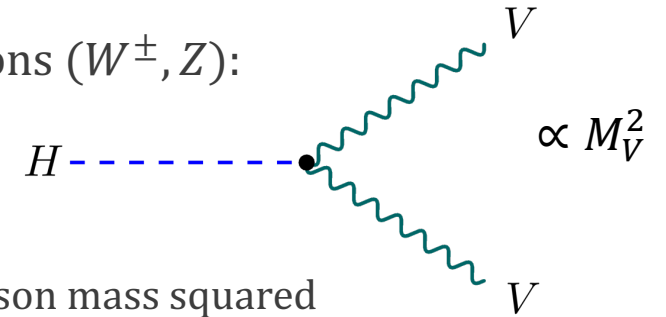
Higgs couples to particles based on mass:

OVERVIEW: THE HIGGS BOSON



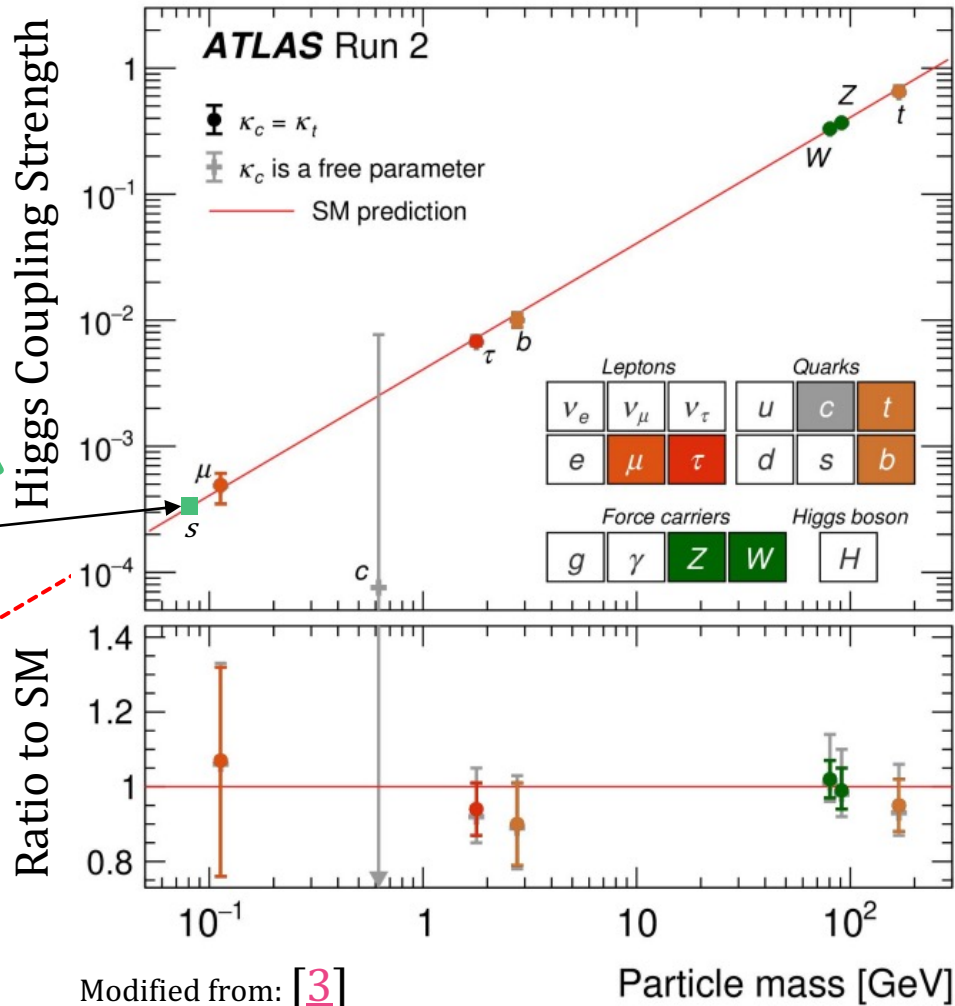
Higgs couples to particles based on mass:

- Massive Vector Bosons (W^\pm, Z):



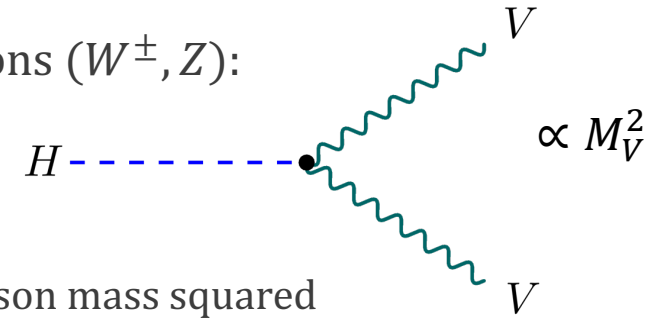
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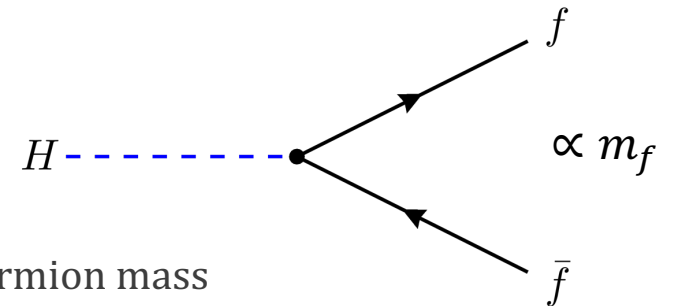
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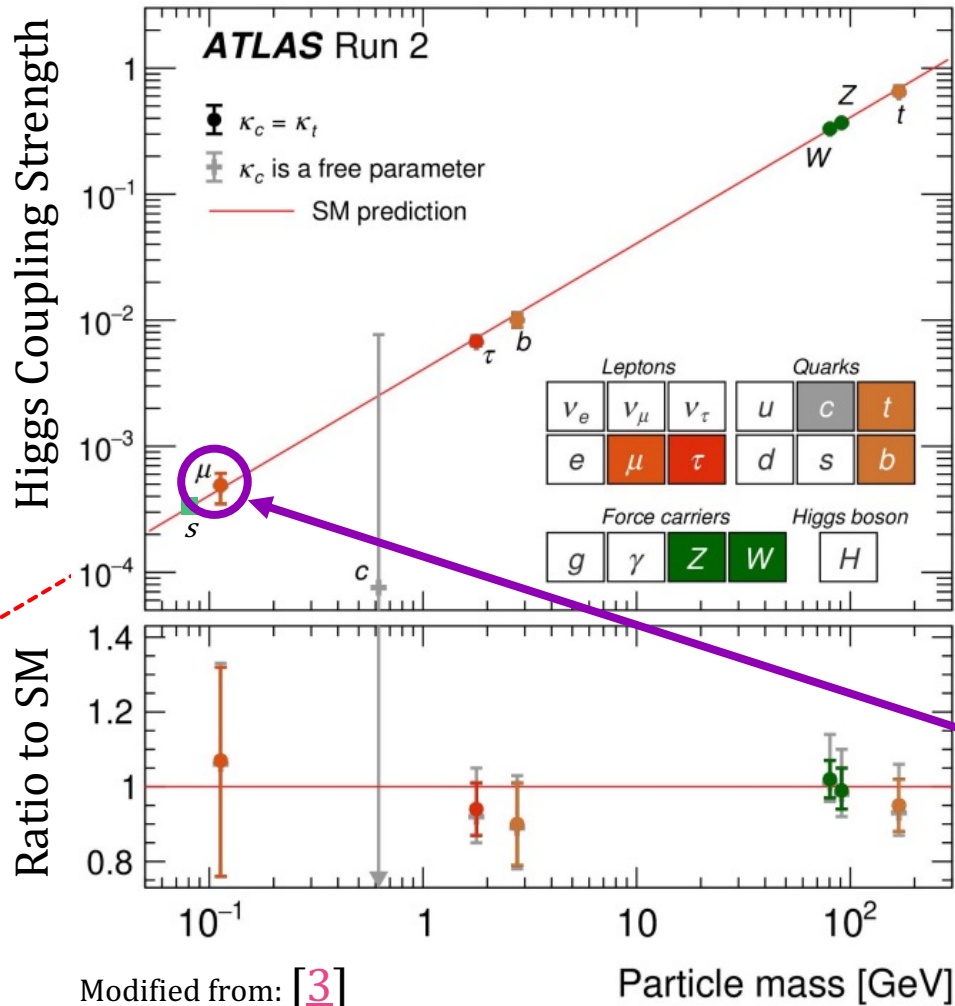
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- Fermions:



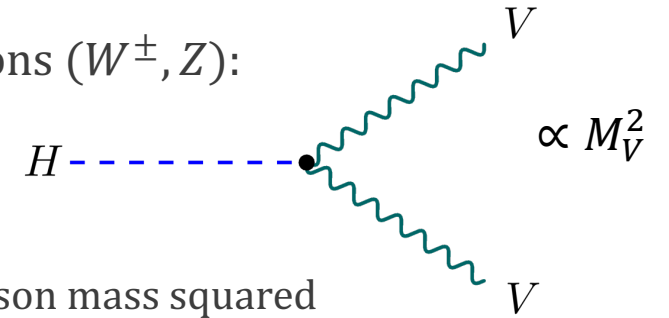
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HIGGS DECAY TO MUONS



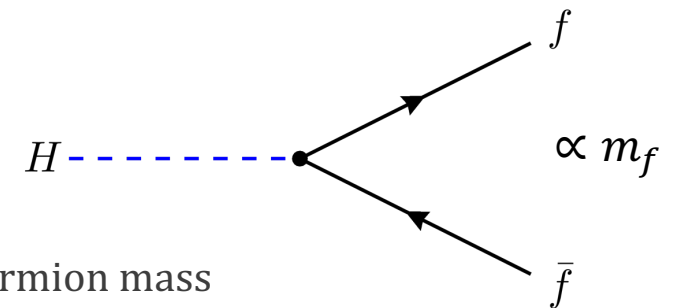
Higgs couples to particles based on mass:

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- Proportional to boson mass squared

- Fermions:



- Proportional to fermion mass

- Higgs decay to two muons is extremely rare

- Branching ratio: 0.022%

- Best candidate to measure Higgs coupling to 2nd Generation fermion

HIGGS BOSON PRODUCTION AT THE LHC

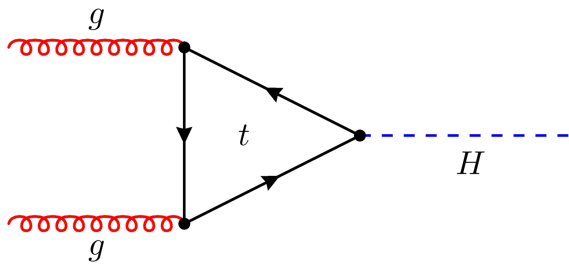
Four Main Production Modes:



HIGGS BOSON PRODUCTION AT THE LHC

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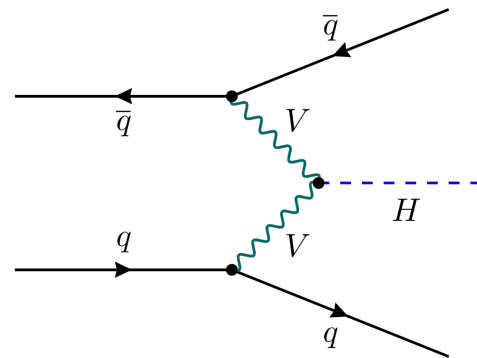
Gluon-Gluon Fusion (ggF)
~87 % of events



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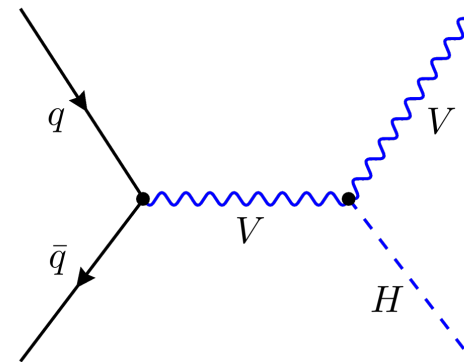
Vector Boson Fusion (VBF)
~7% of events



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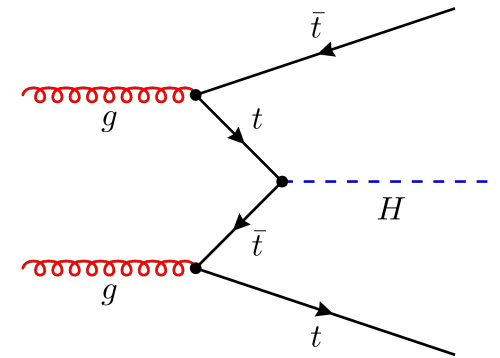
Associated Production with
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~4% of events



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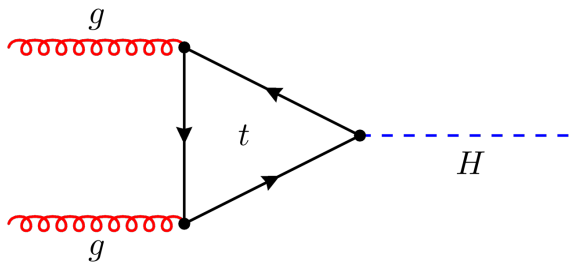
Associated Production with
Top Quarks (ttH)
~1% of events



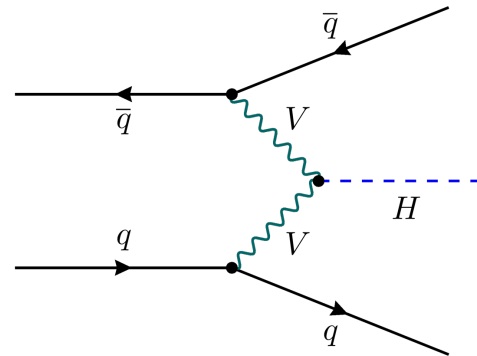
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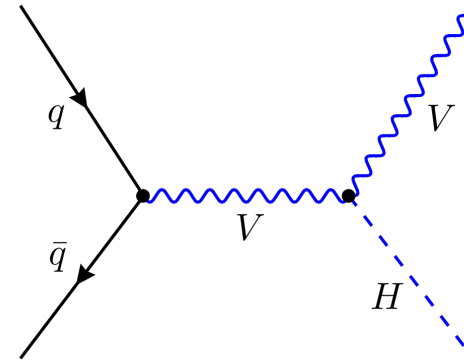
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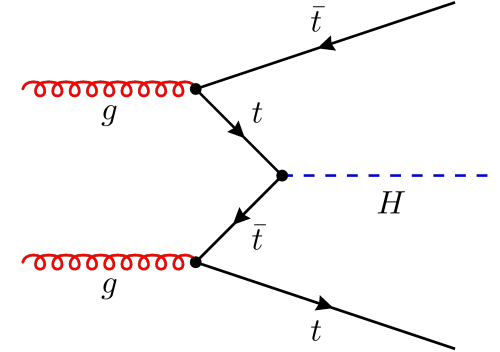
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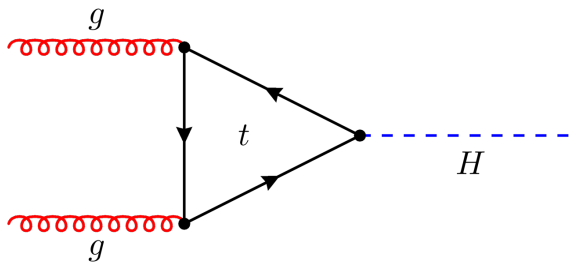


Analysis sorts events by production mode then categorizes using machine learning

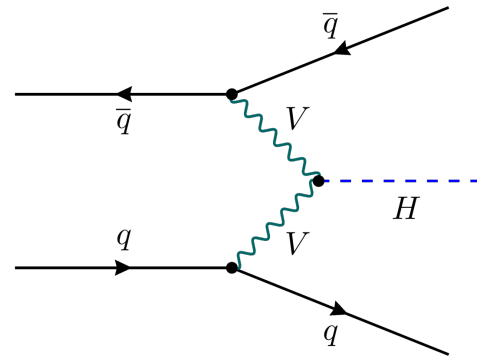
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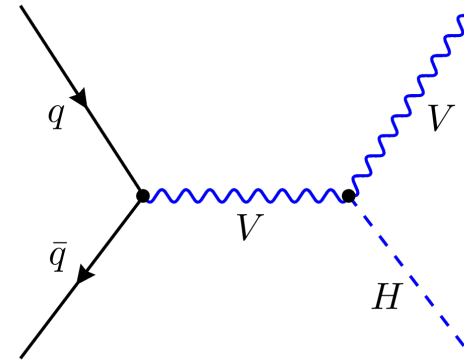
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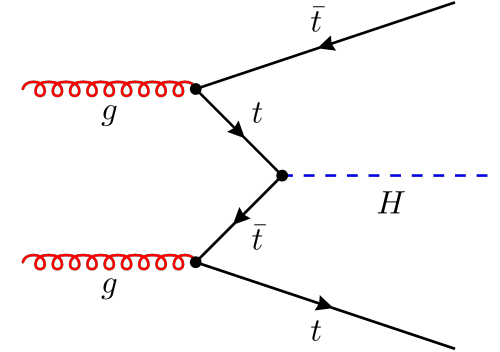
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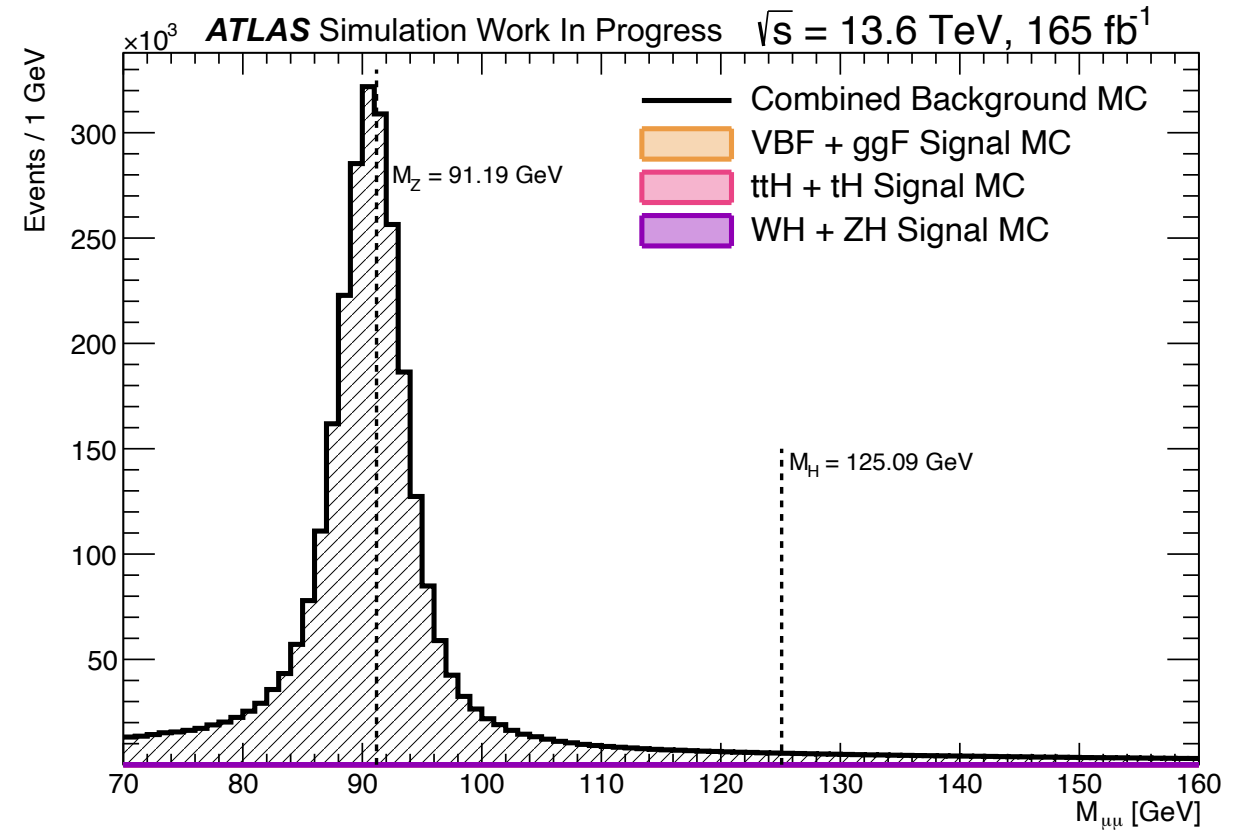
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← Similarity to Background

THE PROBLEM: BACKGROUNDS

- Many other LHC processes result in two muon final states
- Main background: Drell-Yan Process
$$pp \rightarrow Z \rightarrow \mu\mu$$
- $M_{\mu\mu}$ = Reconstructed mass of two muons
 - Dominated by Z mass peak at $\sim 91\text{GeV}$

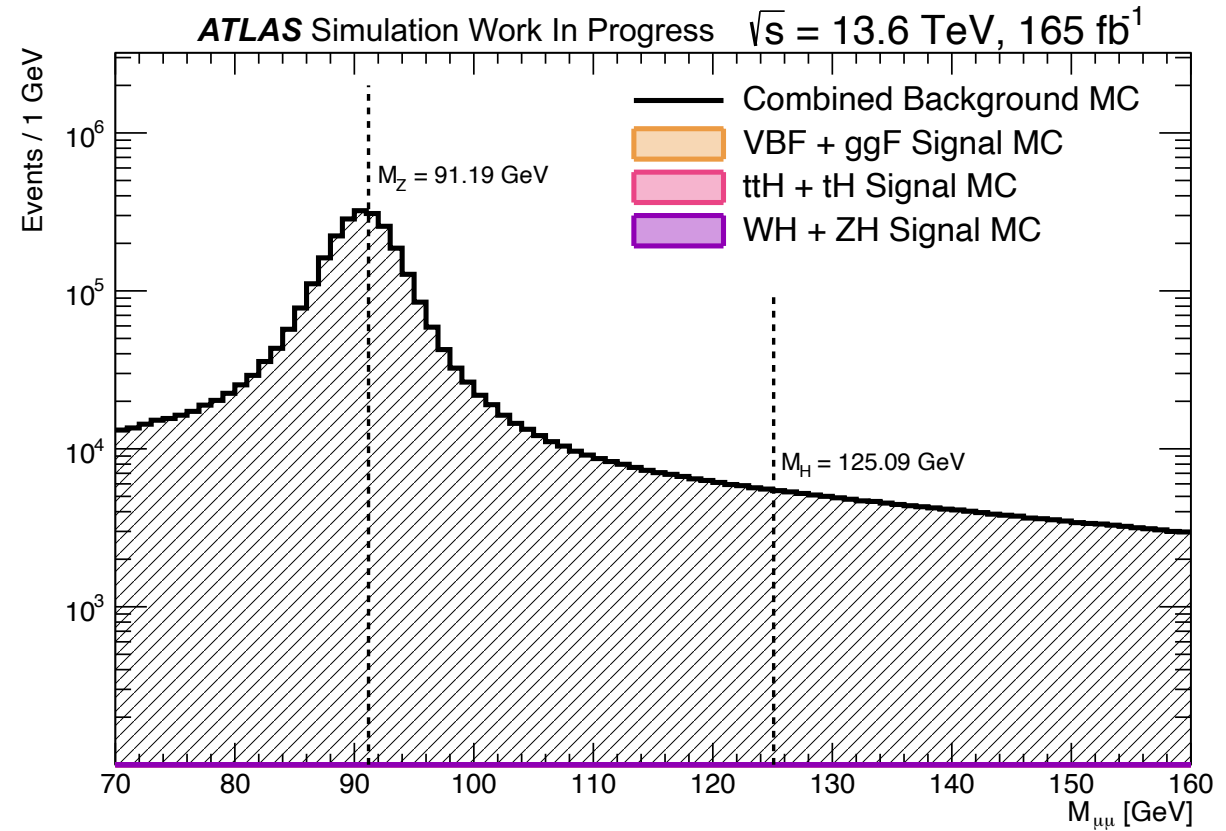


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Other backgrounds with dimuon final states:

- **Diboson:** W^+W^- , $W^\pm Z$, ZZ
 - More important in VH categories
- **Top Quark:** $t\bar{t}$, tW , $t\bar{b}$
 - More important in ttH category

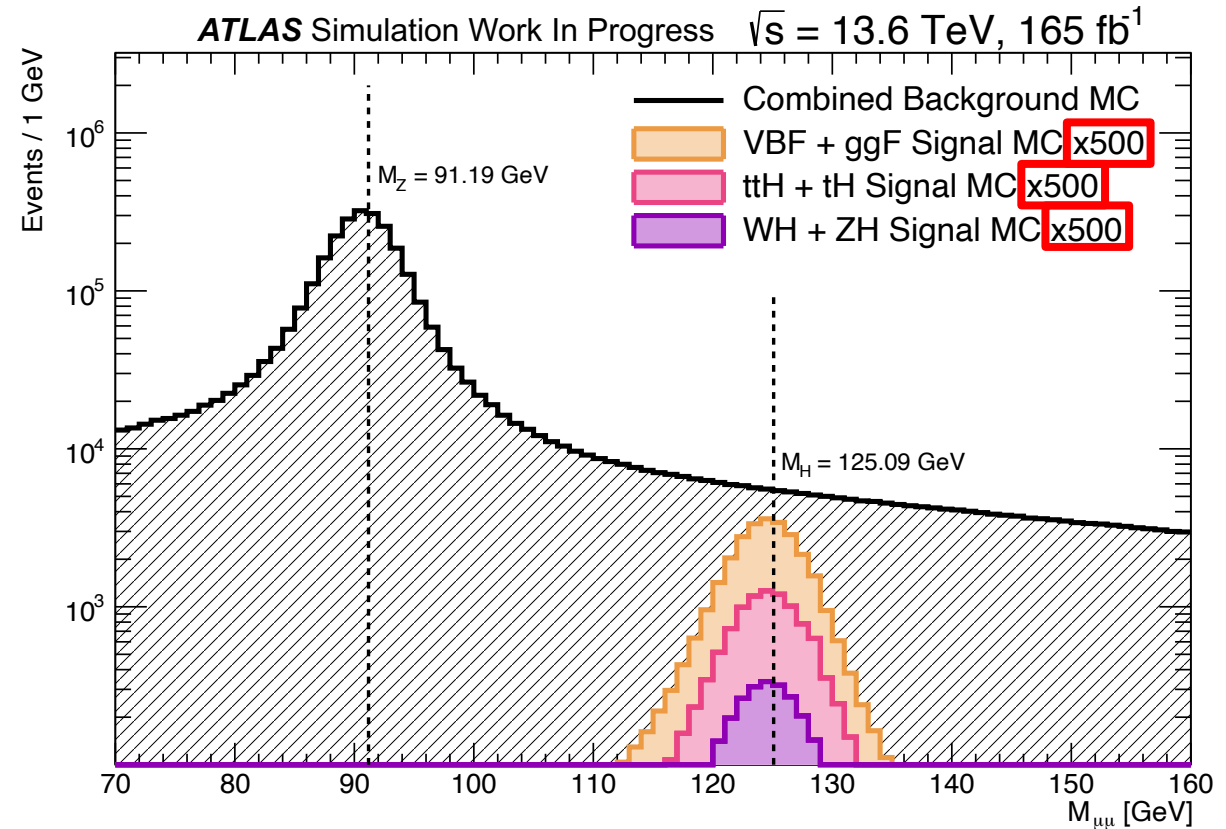


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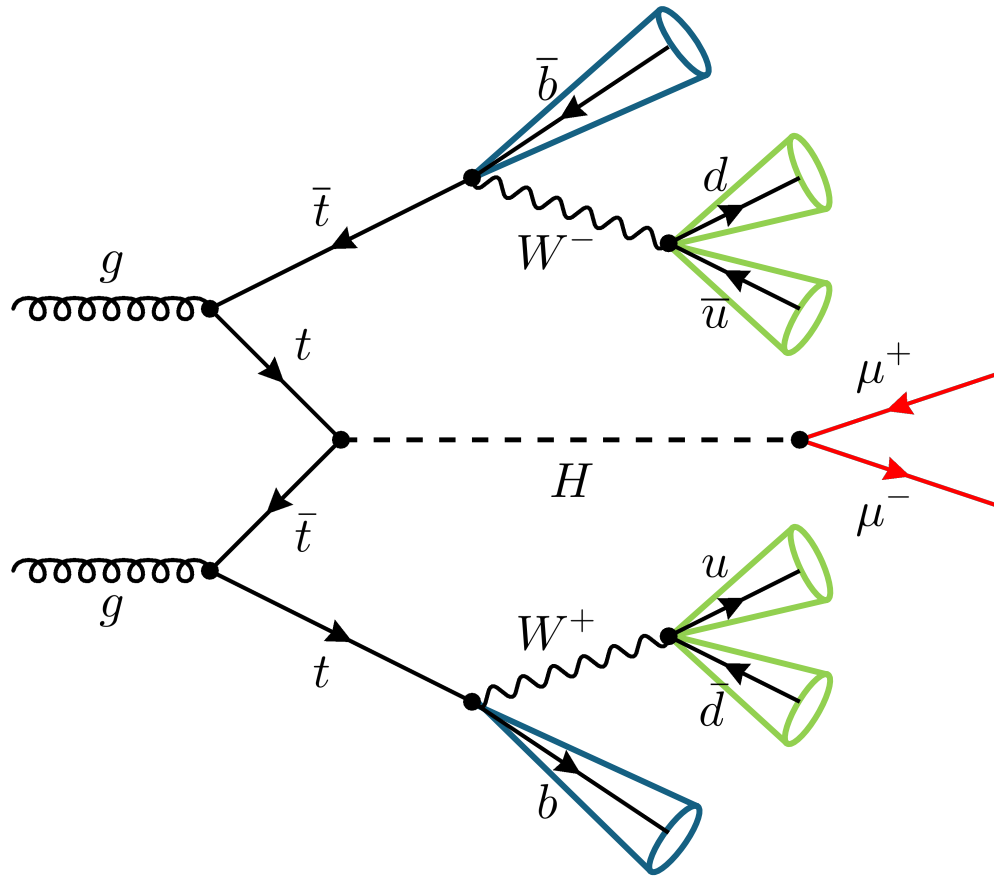
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- Top Quark: $t\bar{t}$, tW , $t\bar{b}$
 - More important in ttH category
- Higgs contribution is very small, becomes a 'bump-hunt'
 - Focus on ttH, easier to separate from main backgrounds

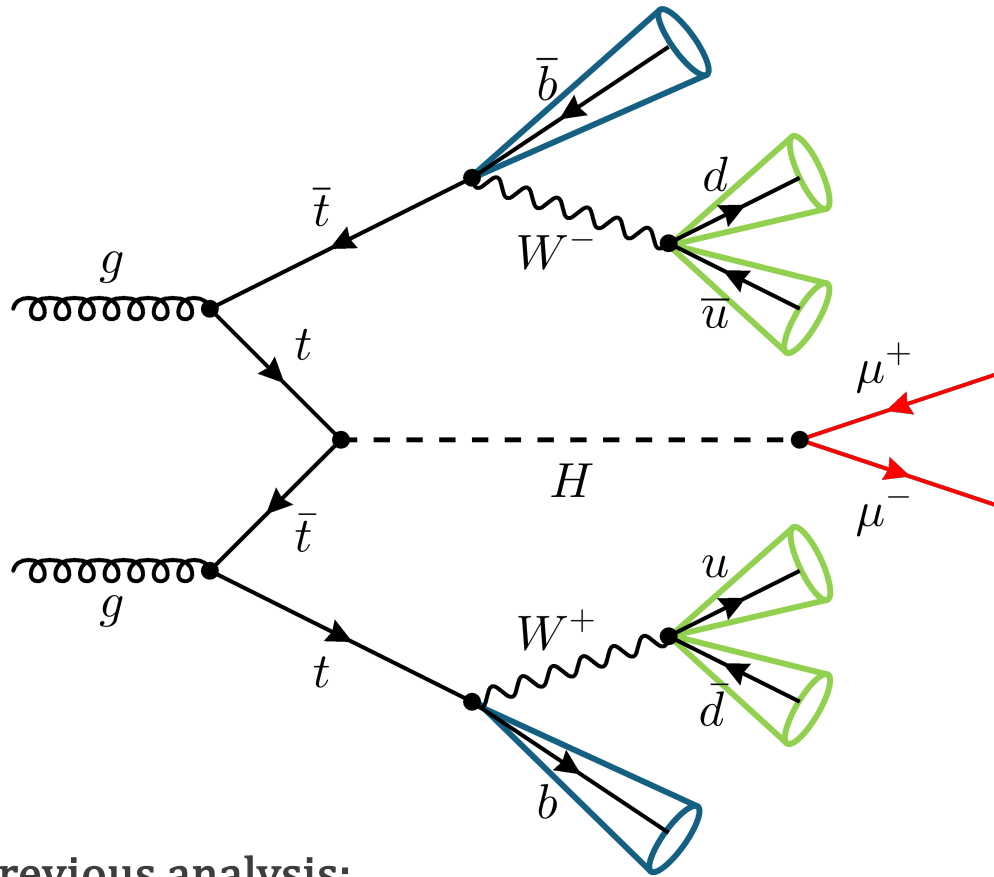


MUON ASSIGNMENT IN ttH EVENTS



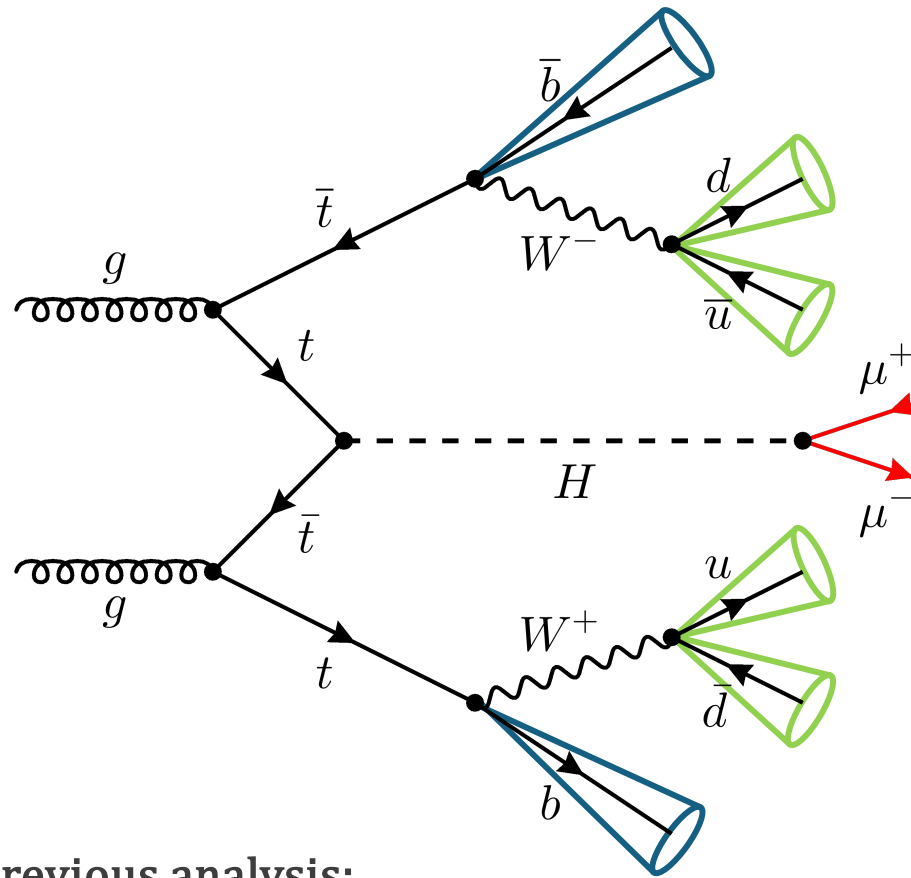
- Higgs Boson is neutral:
need two muons with opposite electric charge

MUON ASSIGNMENT IN ttH EVENTS

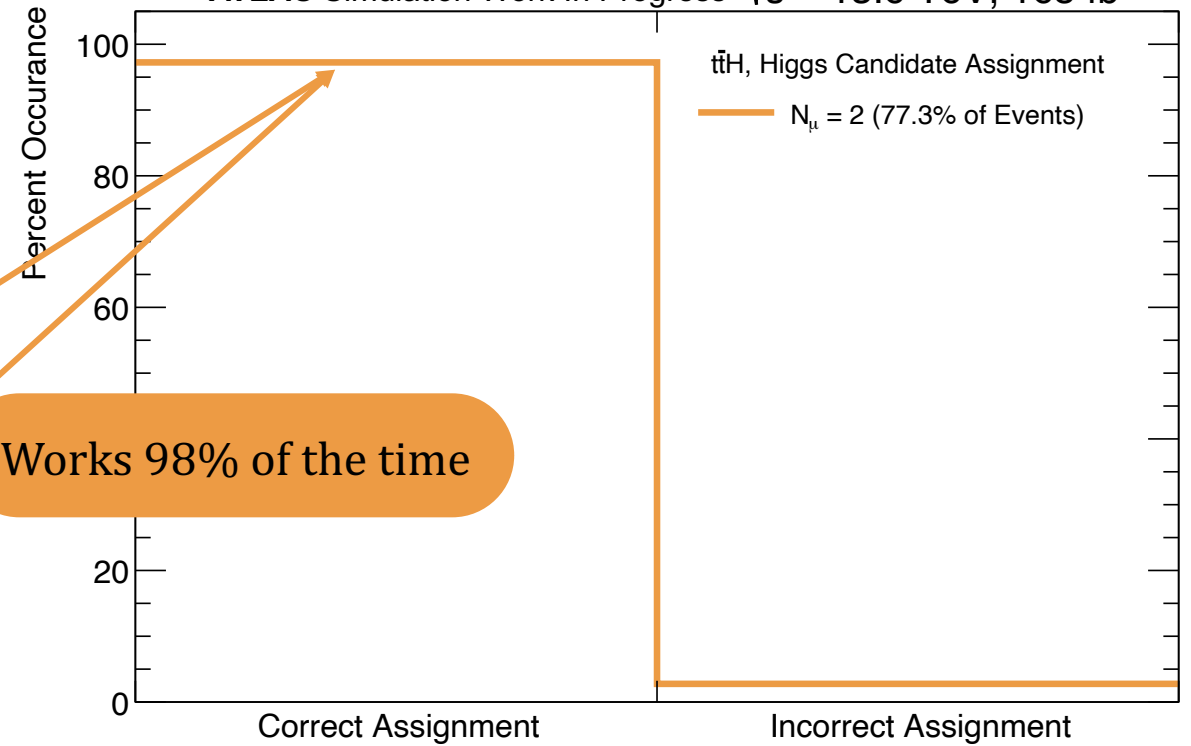


- In previous analysis:
take two muons with
highest transverse momentum (p_T)

MUON ASSIGNMENT IN $t\bar{t}H$ EVENTS

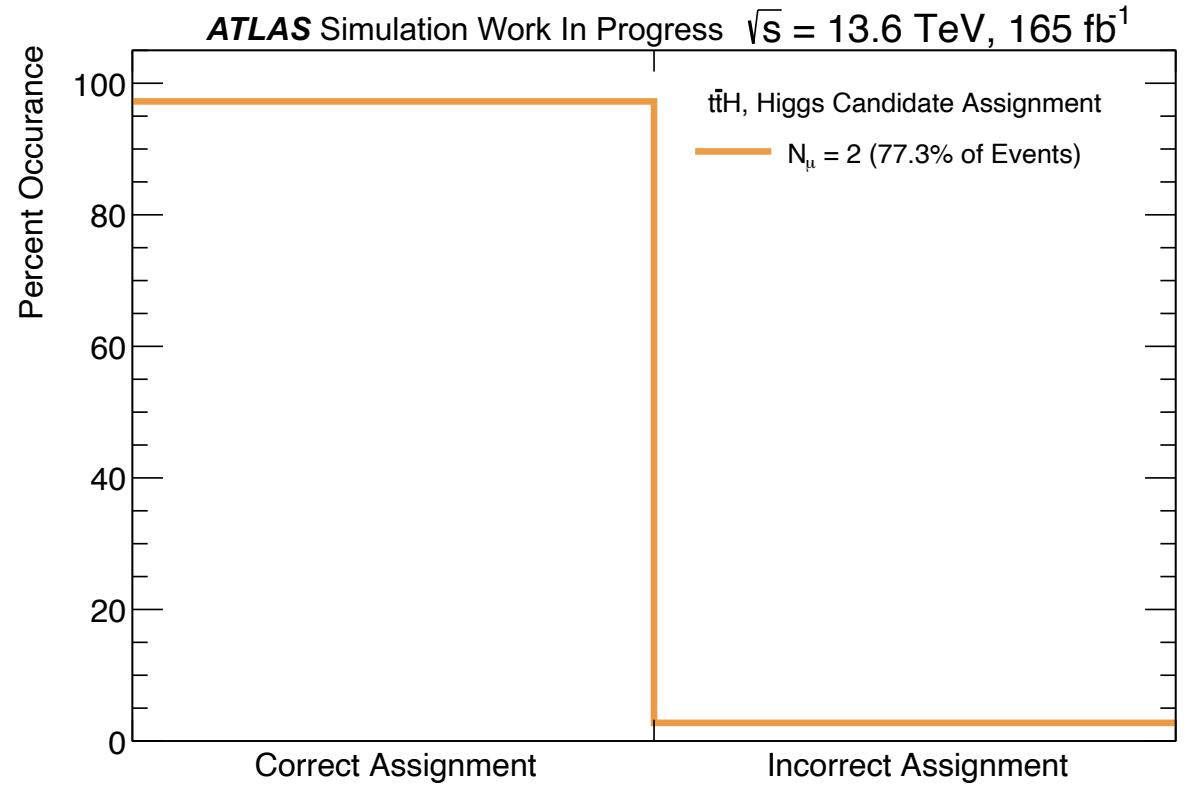
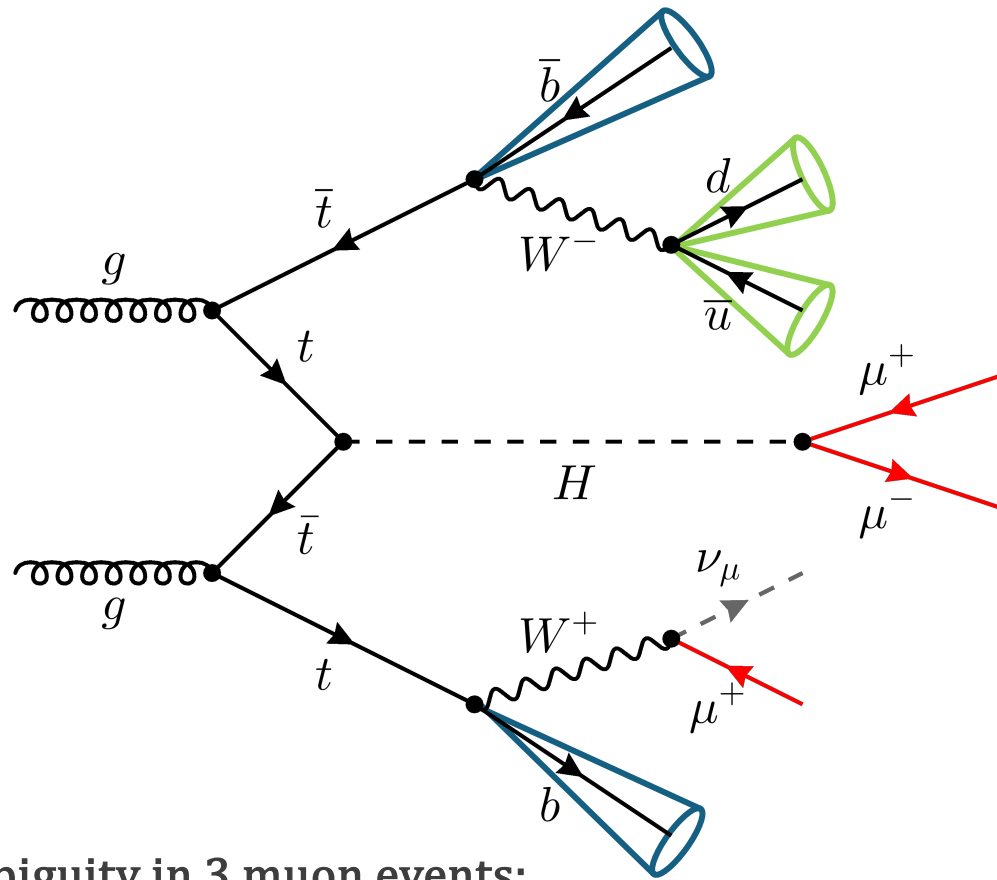


ATLAS Simulation Work In Progress $\sqrt{s} = 13.6 \text{ TeV}, 165 \text{ fb}^{-1}$



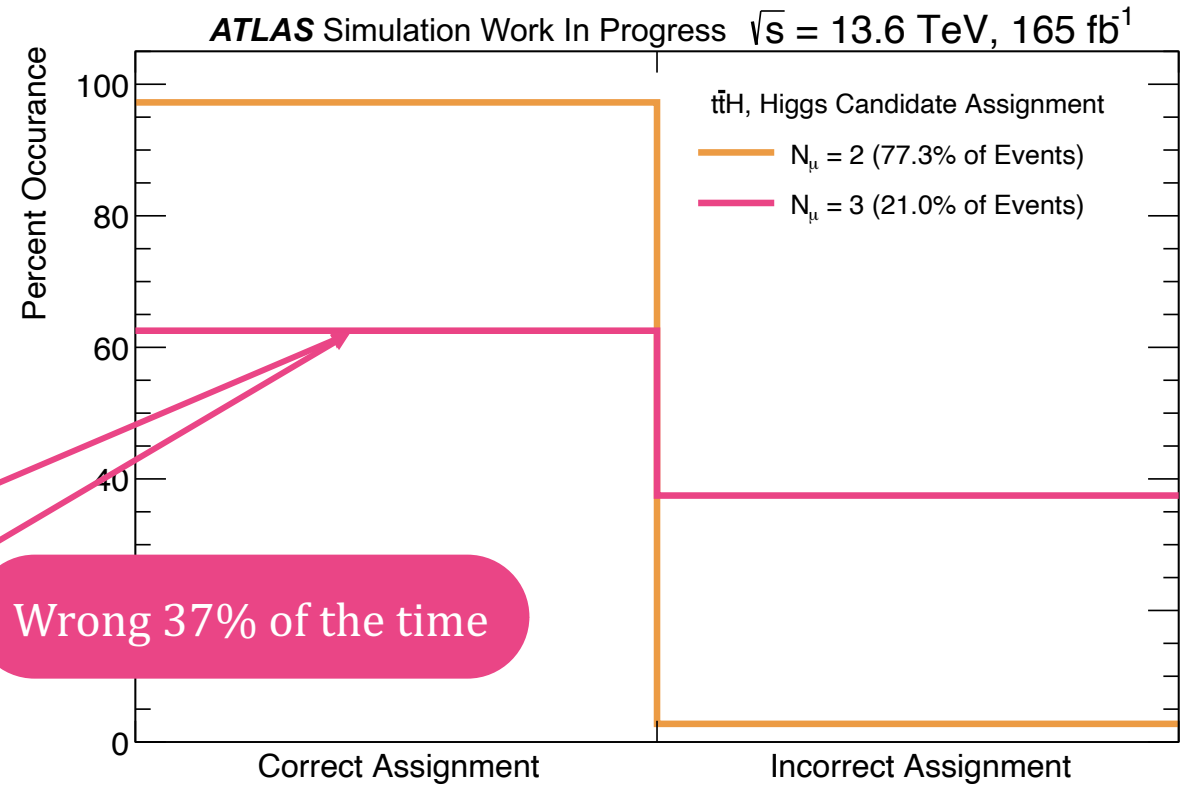
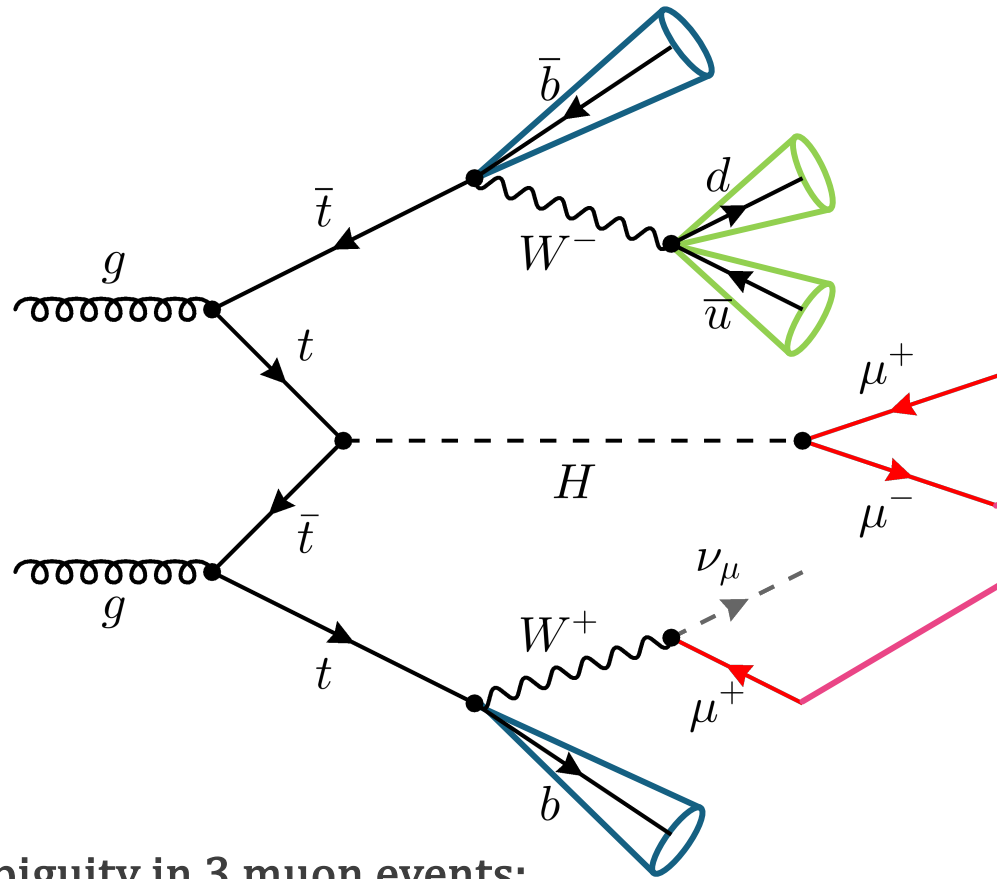
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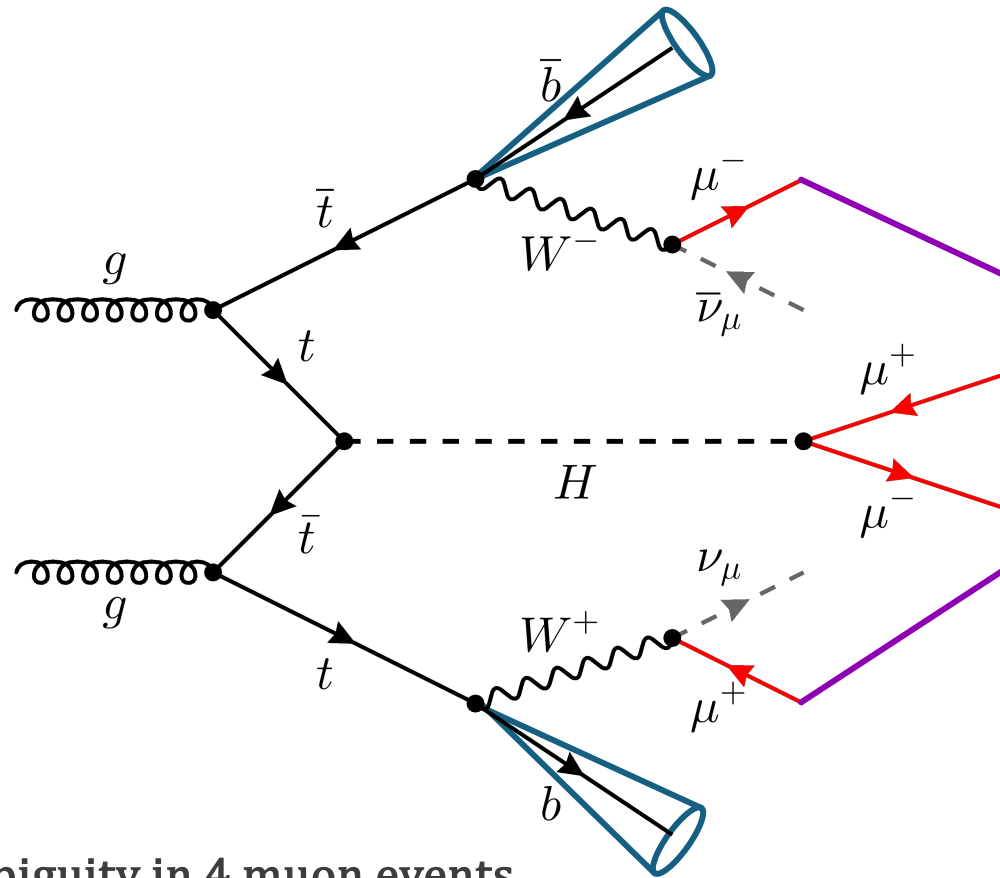
- Ambiguity in 3 muon events:
Probability of selecting correctly drops

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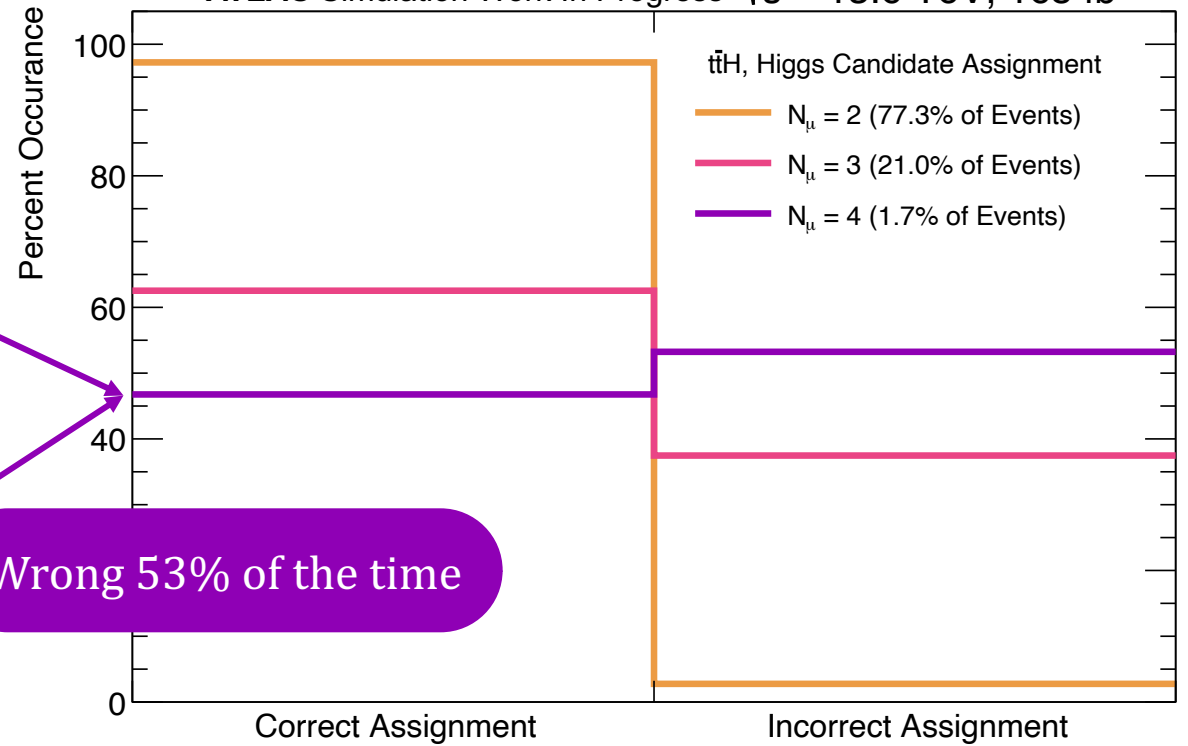


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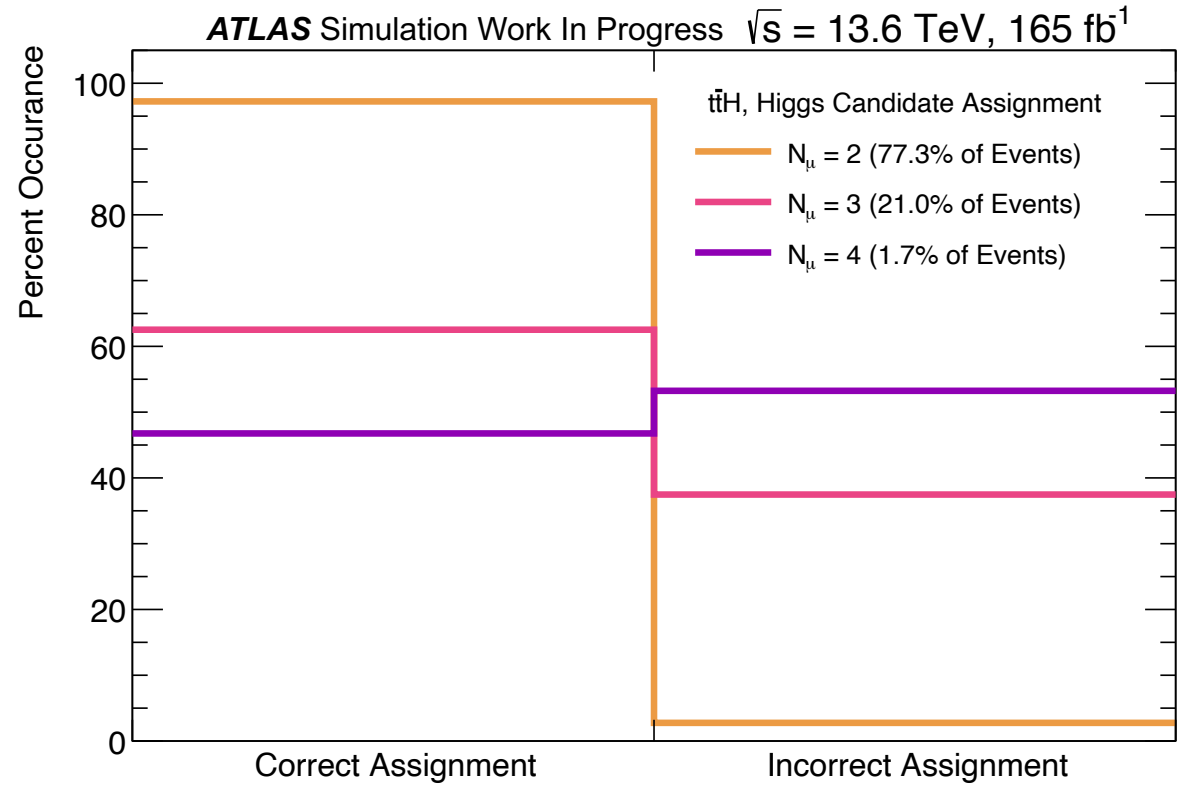
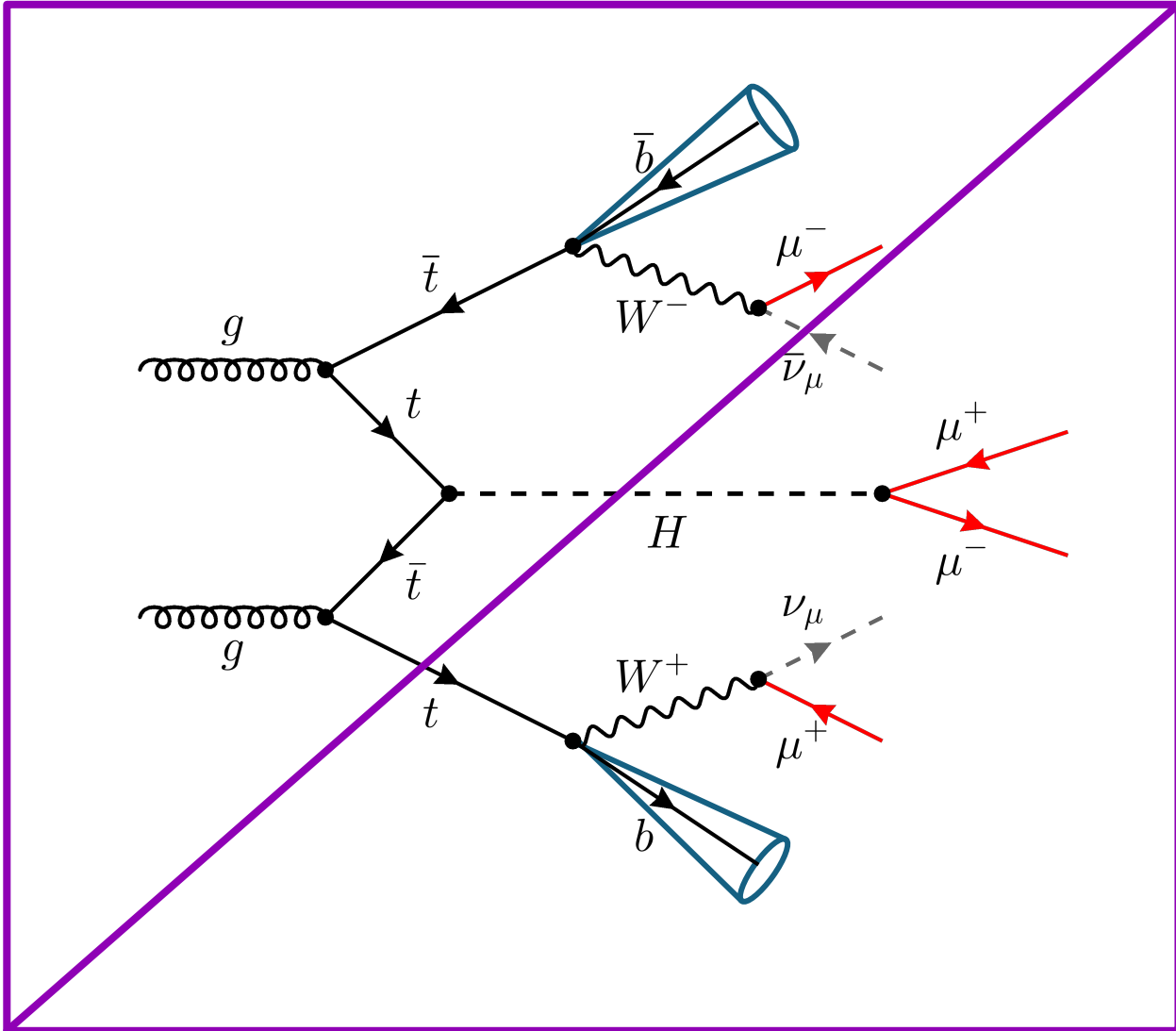
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Wrong 53% of the time

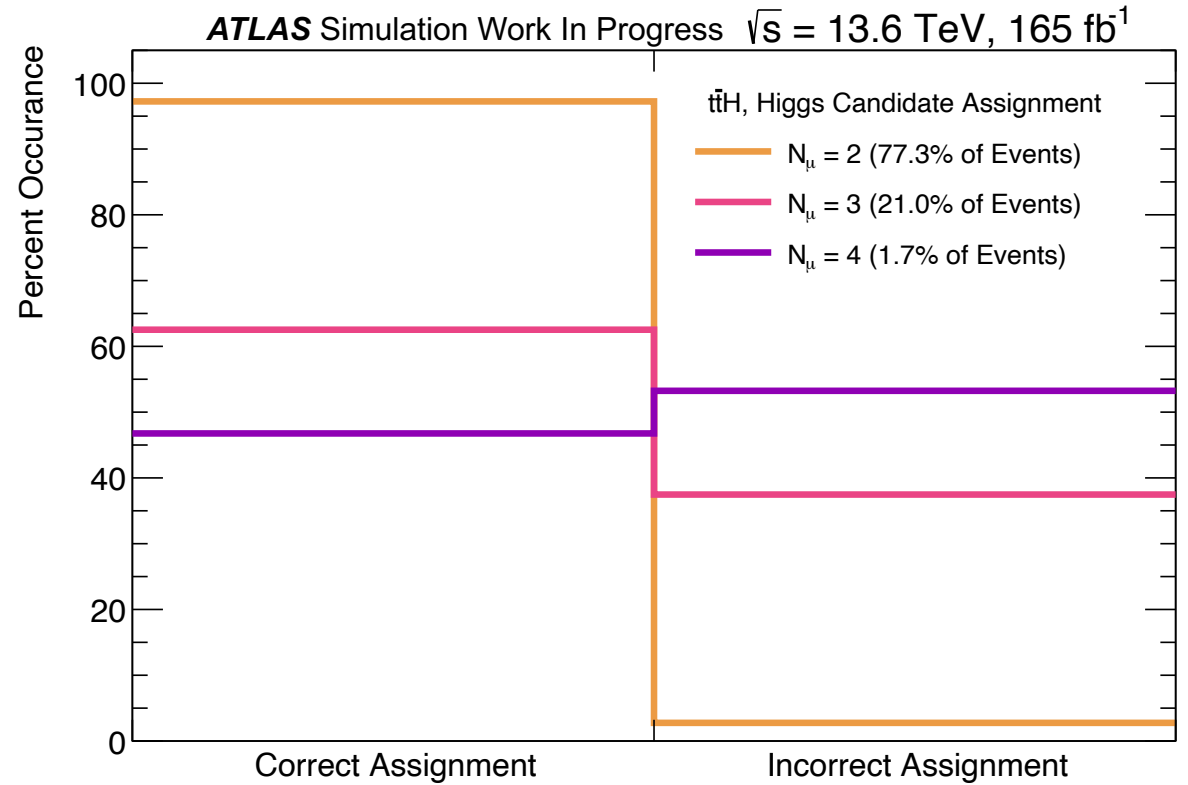
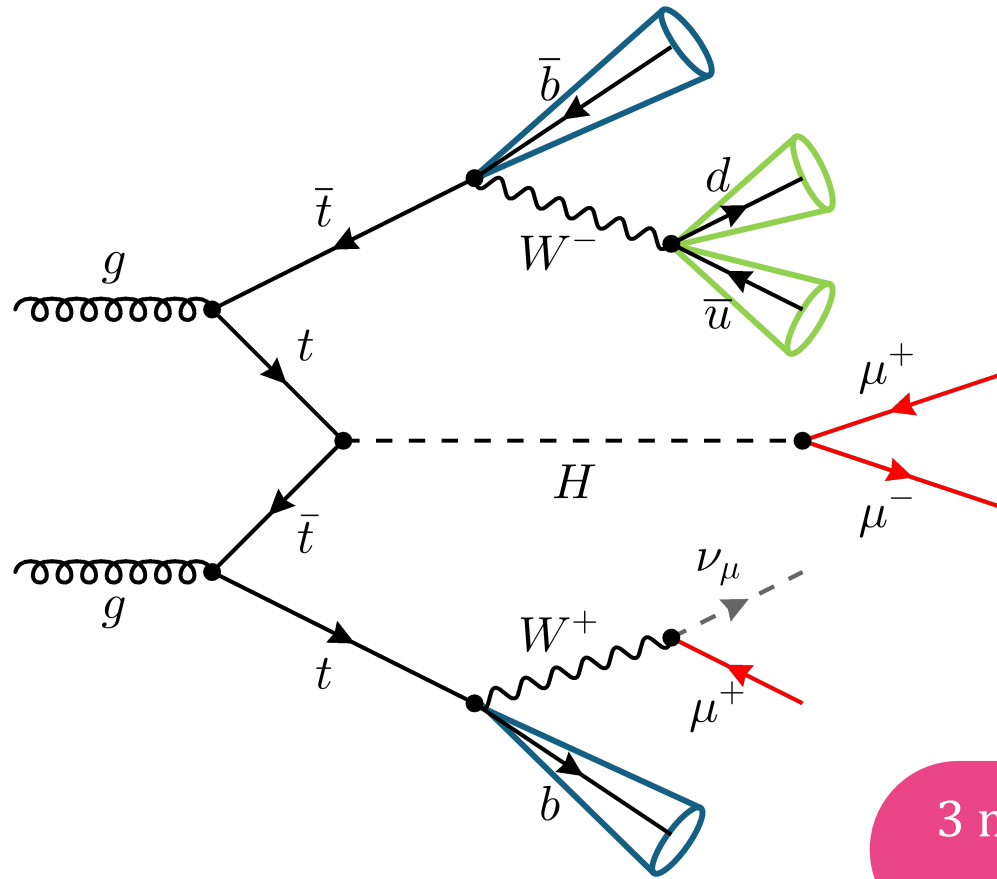
- Ambiguity in 4 muon events

MUON ASSIGNMENT IN ttH EVENTS



4 muon events are very rare
Impact on $t\bar{t}H$ category is small

MUON ASSIGNMENT IN $t\bar{t}H$ EVENTS

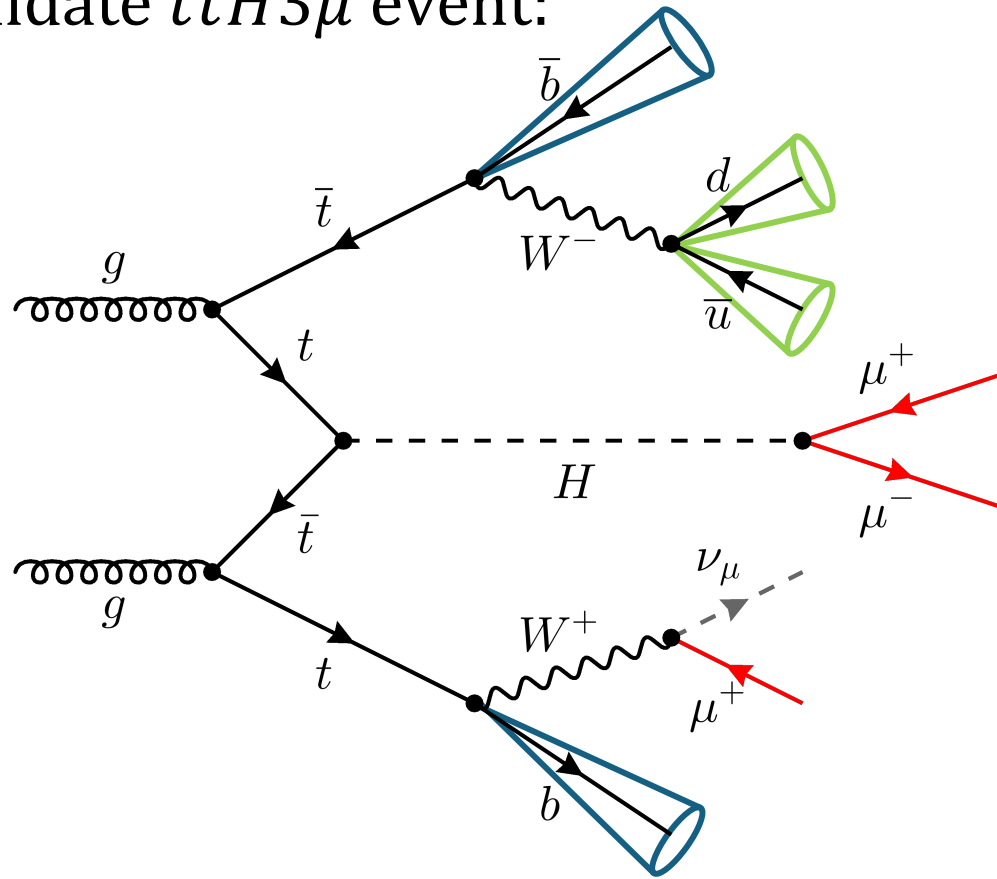


3 muon events are common enough to have a big impact on $t\bar{t}H$

Goal: fix muon assignment in $t\bar{t}H3\mu$ events

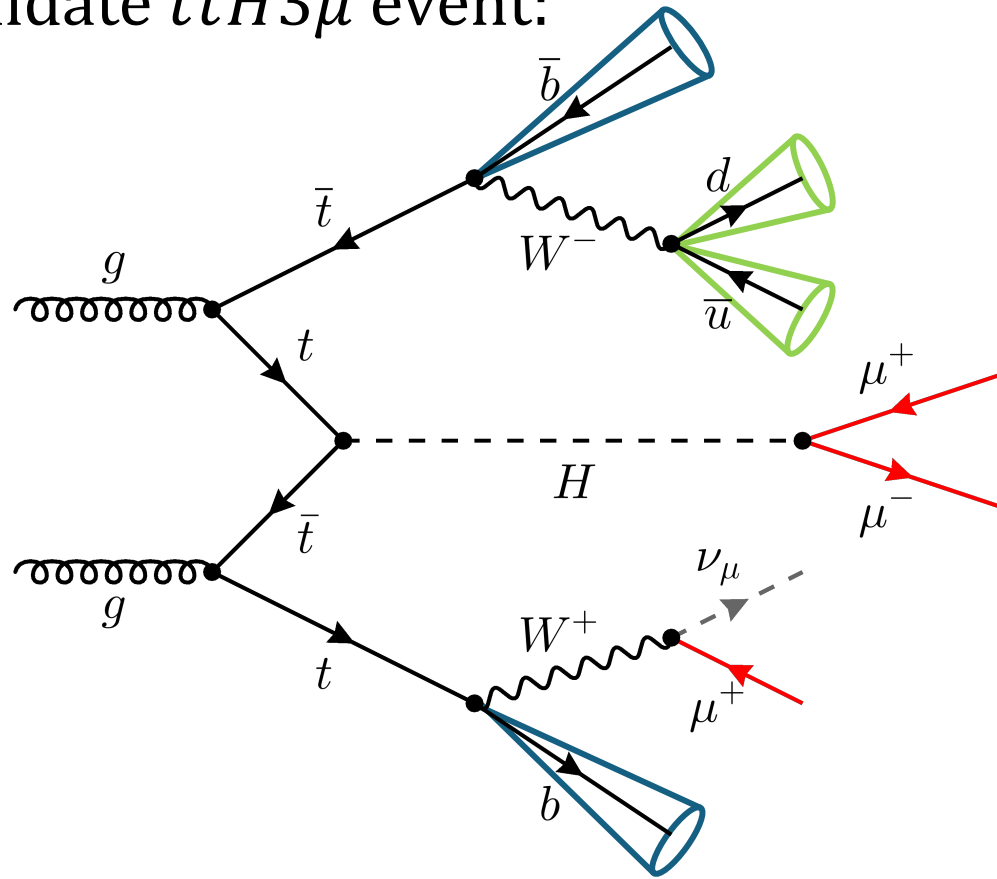
AMBIGUITY IN 3 MUON EVENTS

Candidate $t\bar{t}H3\mu$ event:

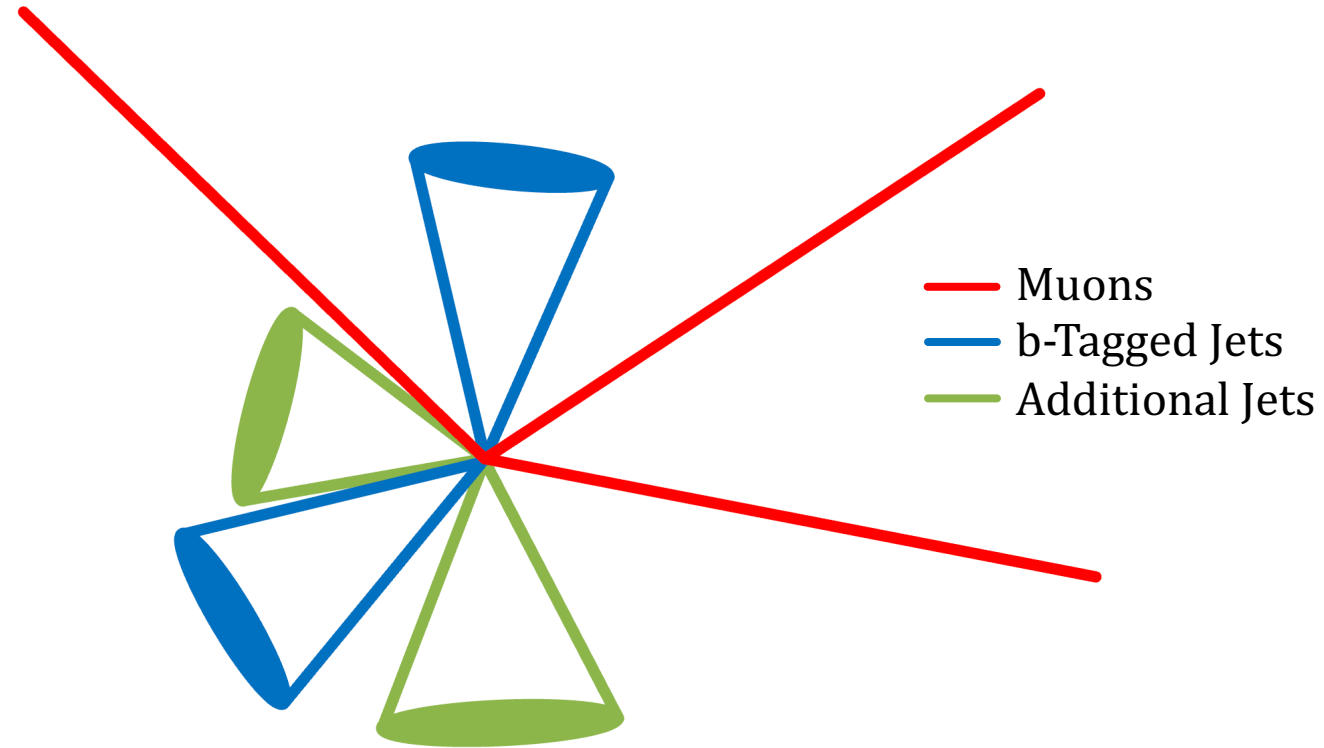


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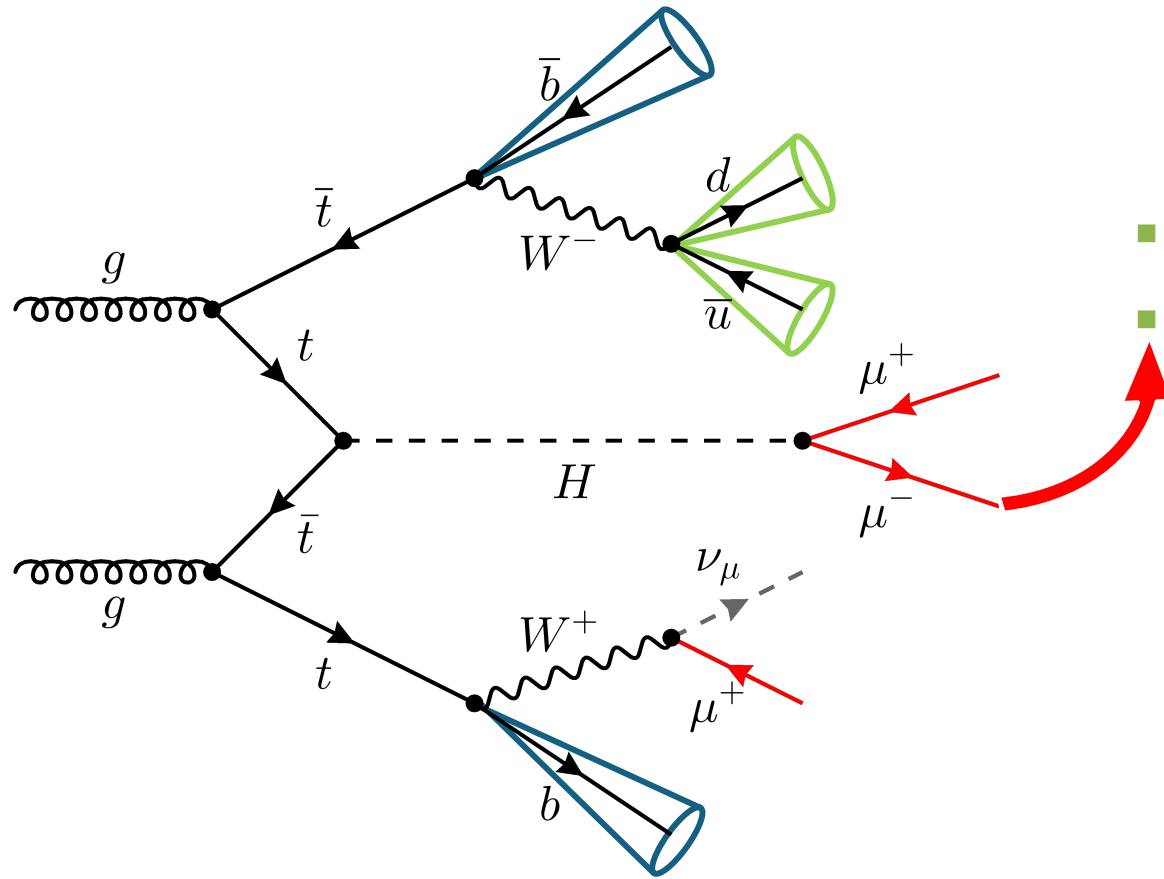
Candidate $t\bar{t}H3\mu$ event:



What the ATLAS detector 'sees'

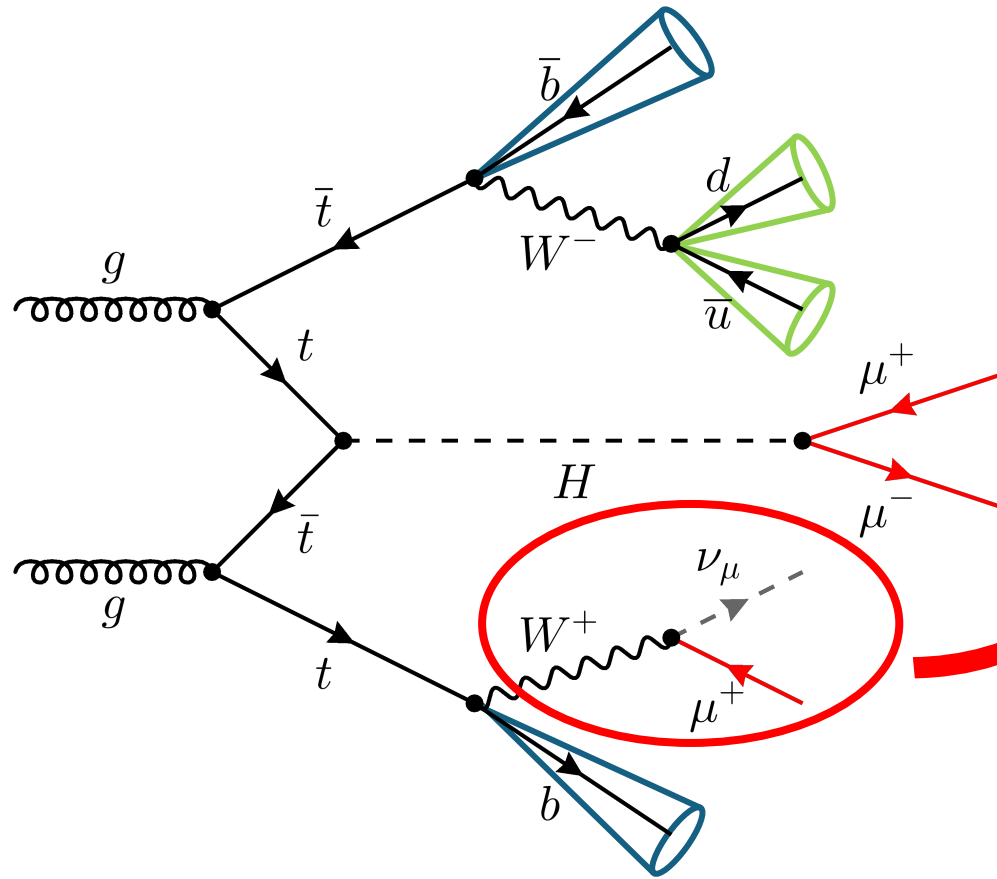


FIXING THE MUON ASSIGNMENT



- Only ambiguity from muons with same electric charge
- Opposite signed muon must be from the Higgs

FIXING THE MUON ASSIGNMENT

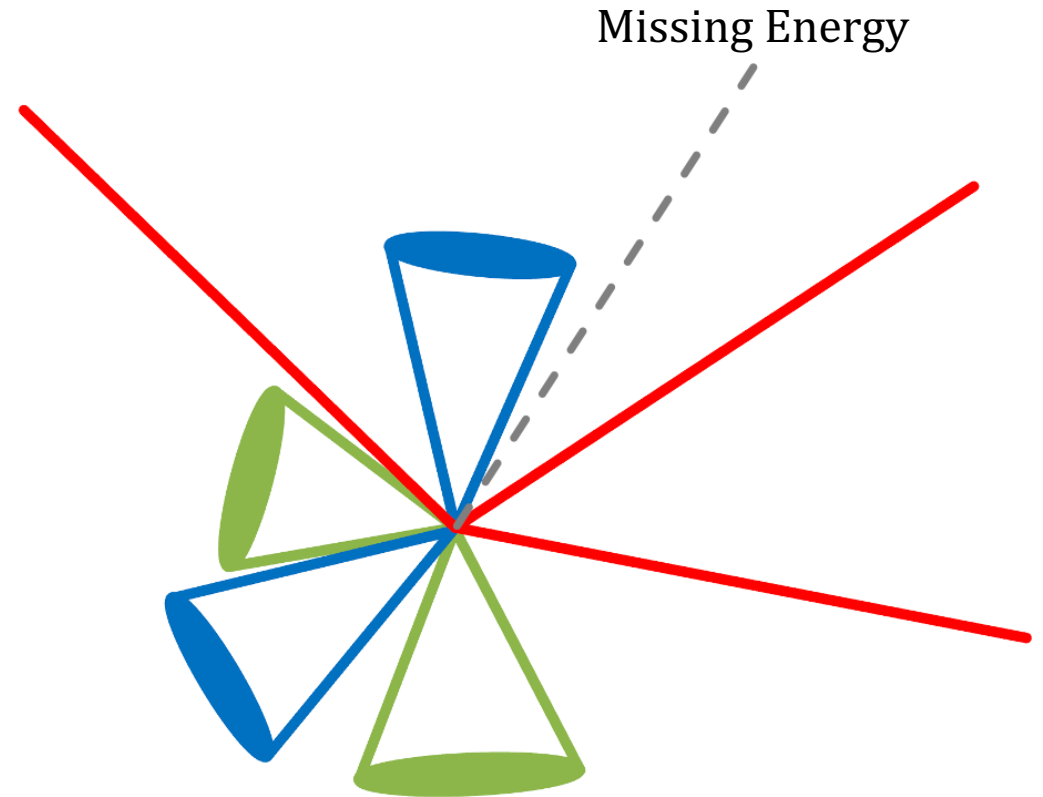


- Only ambiguity from muons with same electric charge
- Opposite signed muon must be from the Higgs
- Use the information from $W \rightarrow \mu + \nu$ decay to select the non-Higgs muon by reconstructing the mass of the W

FIXING THE MUON ASSIGNMENT

$W \rightarrow \mu + \nu$ Decay

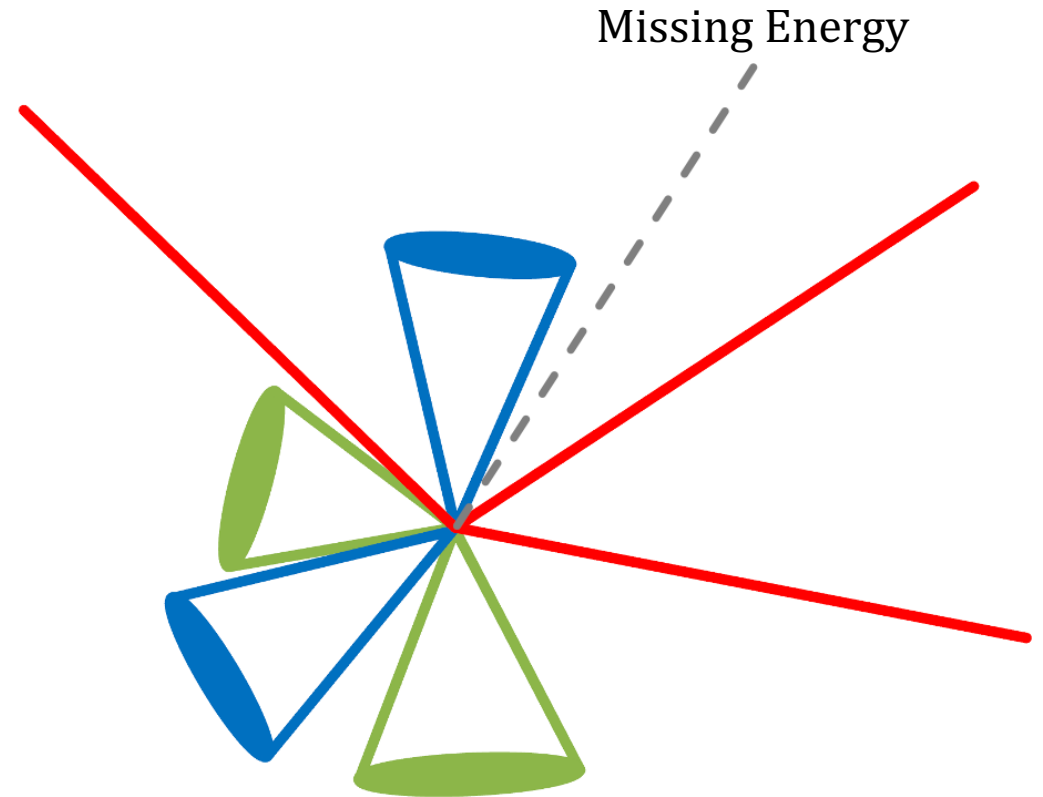
- Neutrino gives missing energy signature in ATLAS detector



FIXING THE MUON ASSIGNMENT

$W \rightarrow \mu + \nu$ Decay

- Neutrino gives missing energy signature in ATLAS detector
- To reconstruct the W, need neutrino momentum vector
- Can solve a quadratic equation to obtain \vec{p}_ν
 - Full details in backup



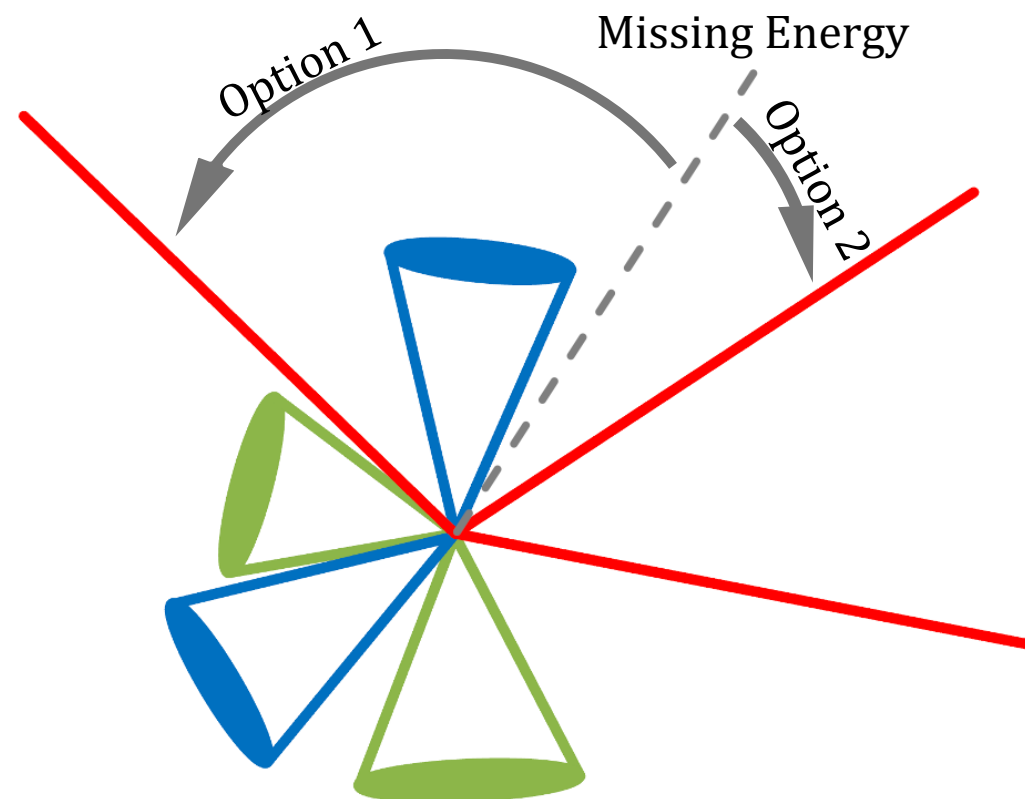
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Three Key Steps:

1. Solve equation for each ambiguous (same charge) muon



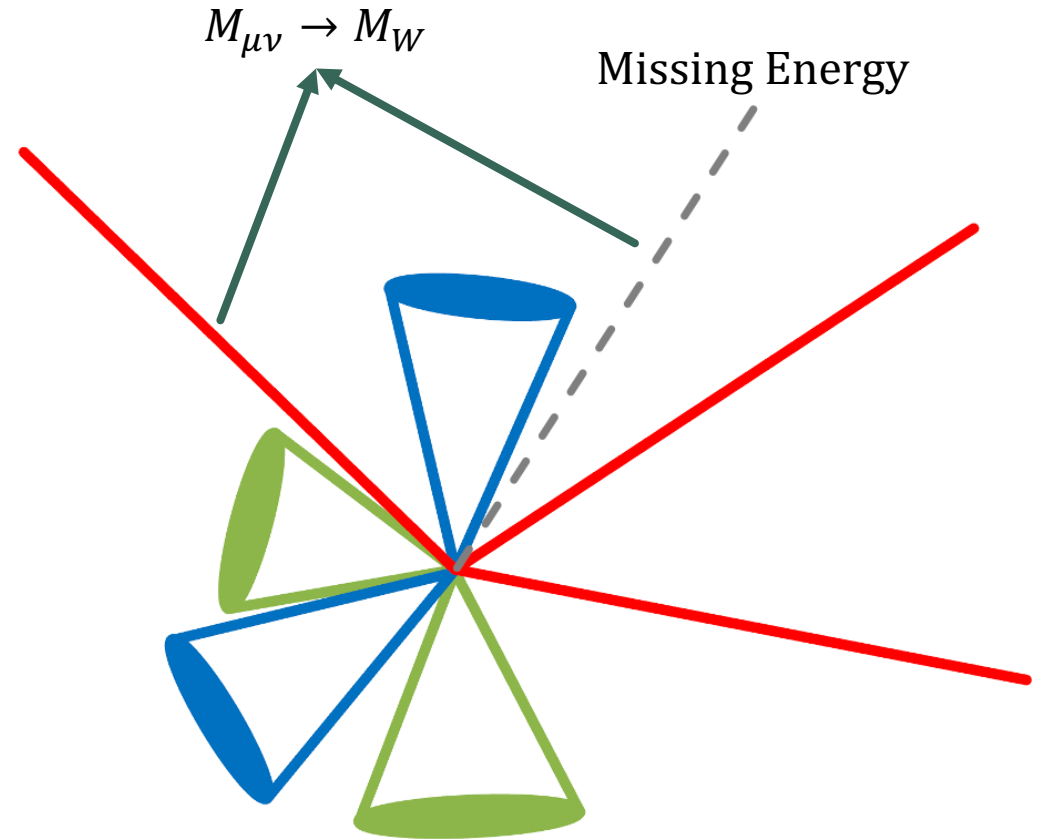
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2. Pick the $\mu + \nu$ pair that gives a mass closest to the W mass



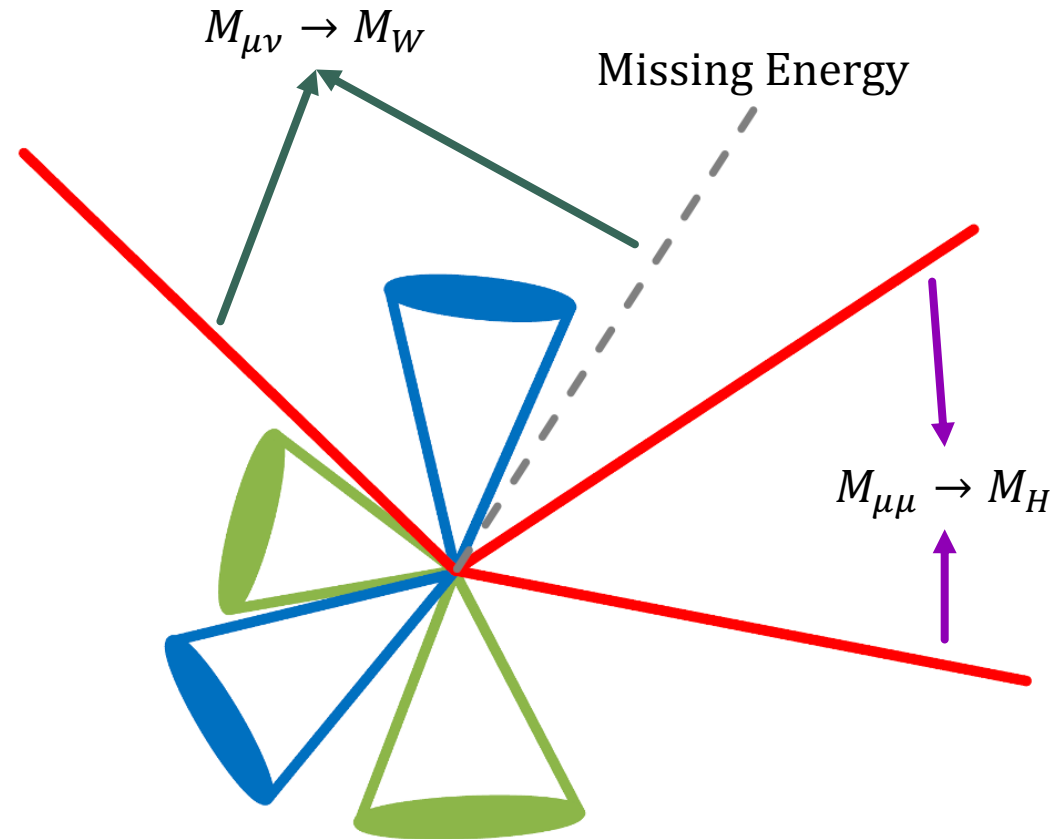
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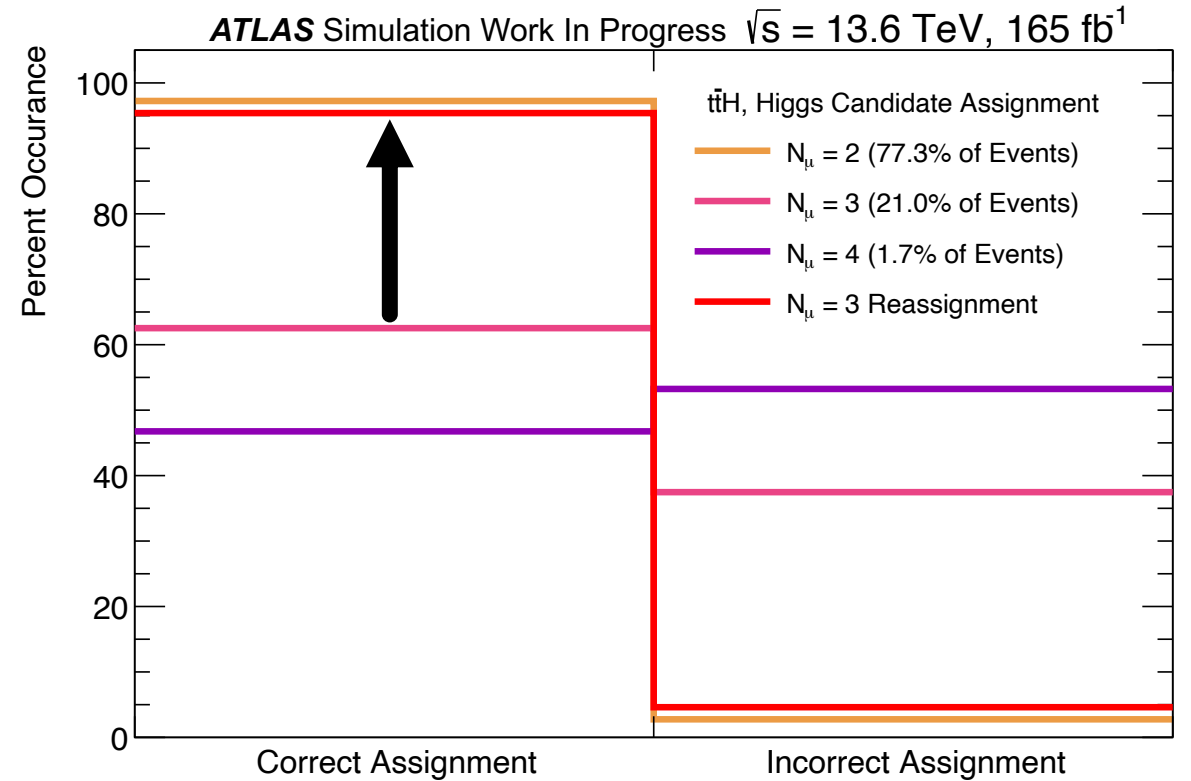
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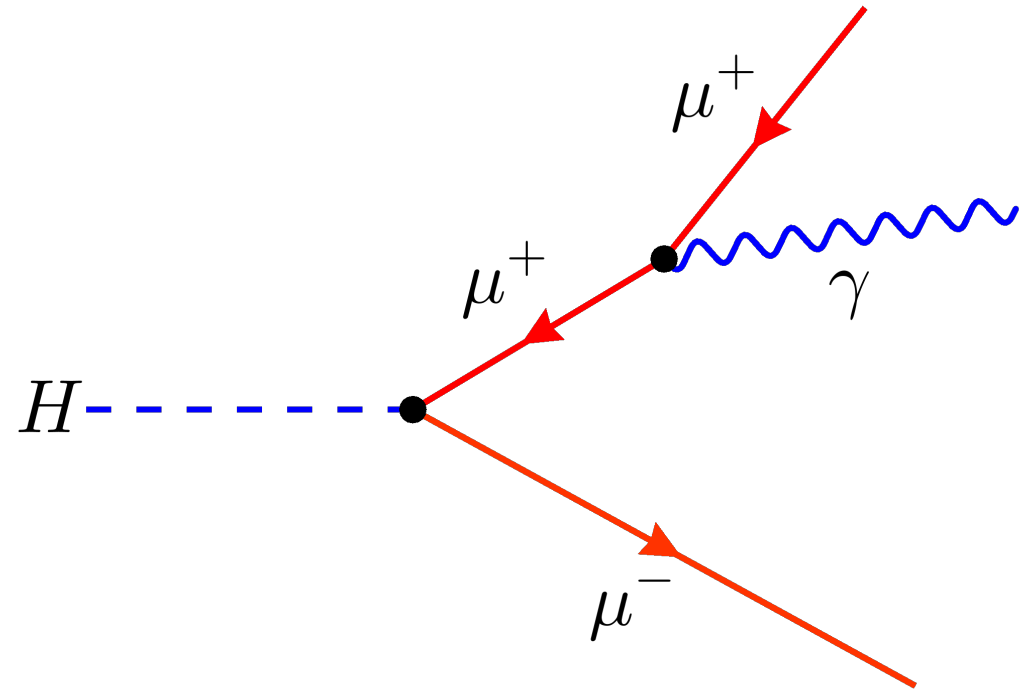
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Increase correct assignment
probability to 95%



FINAL STATE RADIATION (FSR)

- Because muons have charge, can sometime lose energy by radiating a photon
 - Changes final state to be: $H \rightarrow \mu\mu\gamma$

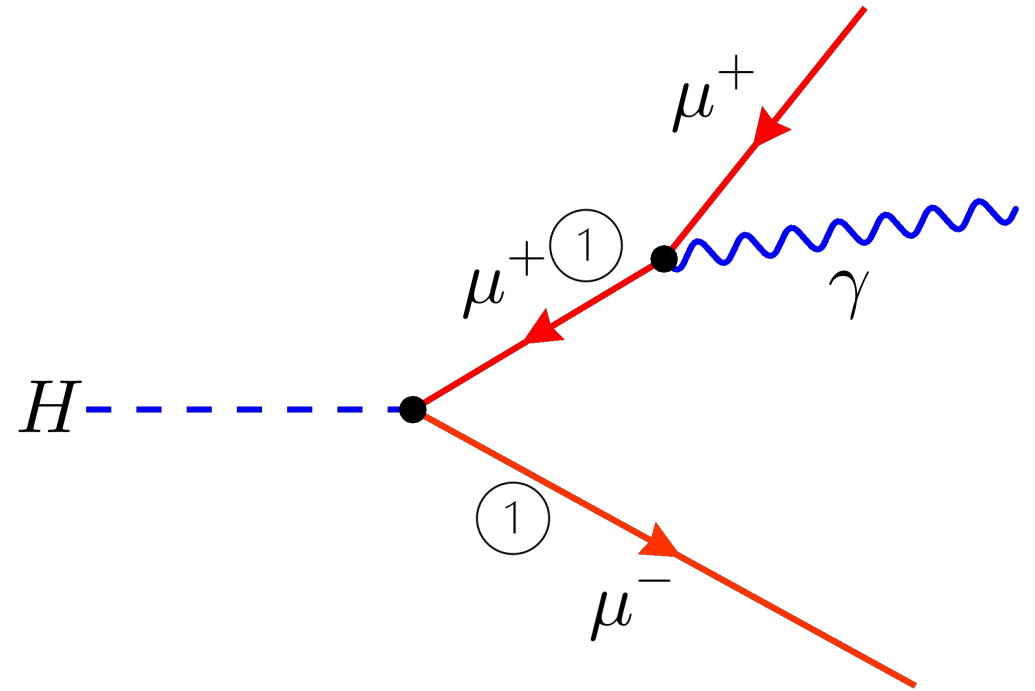


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In events with Final State Radiation we have:

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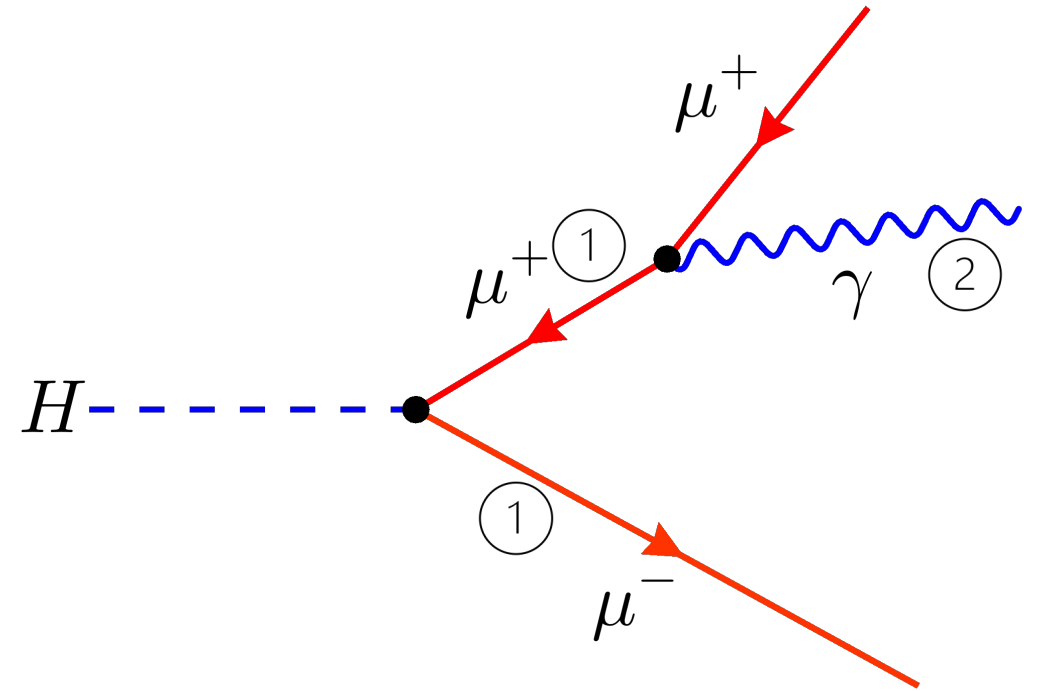


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In events with Final State Radiation we have:

1. **Born Muons:** come directly from the Higgs decay, before FSR
2. **FSR Photons:** radiated from the muon, taking some energy



FINAL STATE RADIATION (FSR)

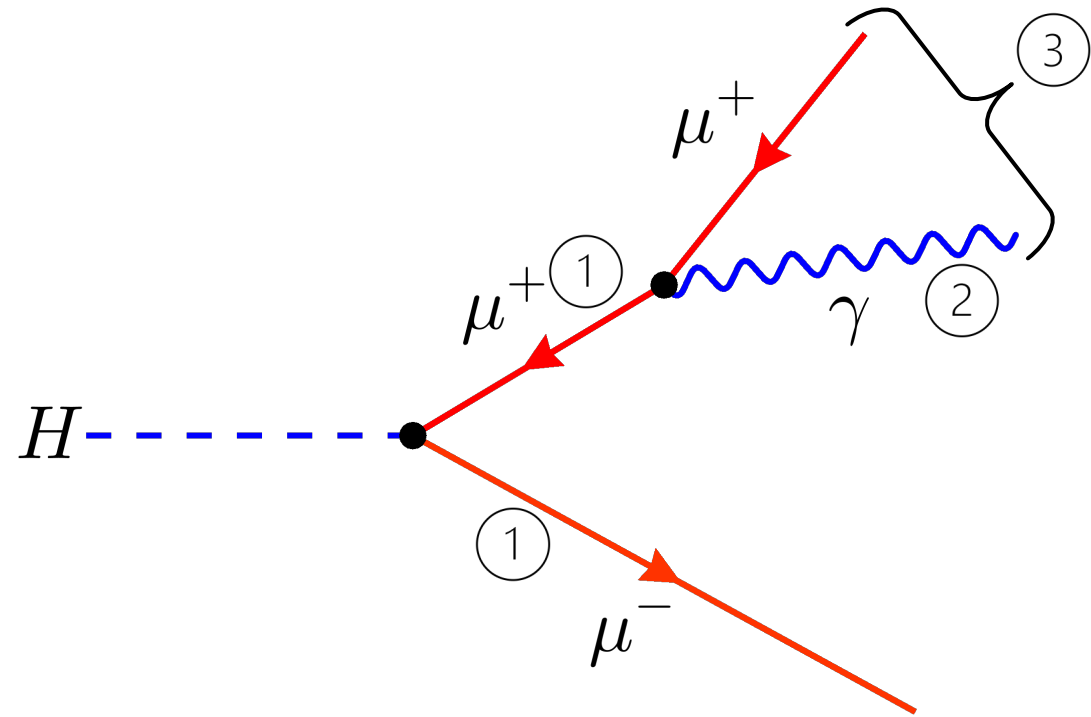
- Because muons have charge, can sometime lose energy by radiating a photon
 - Changes final state to be: $H \rightarrow \mu\mu\gamma$

In events with Final State Radiation we have:

1. **Born Muons:** come directly from the Higgs decay, before FSR
2. **FSR Photons:** radiated from the muon, taking some energy
3. **FSR Recovery:** the reconstructed muon with the FSR photon energy added back

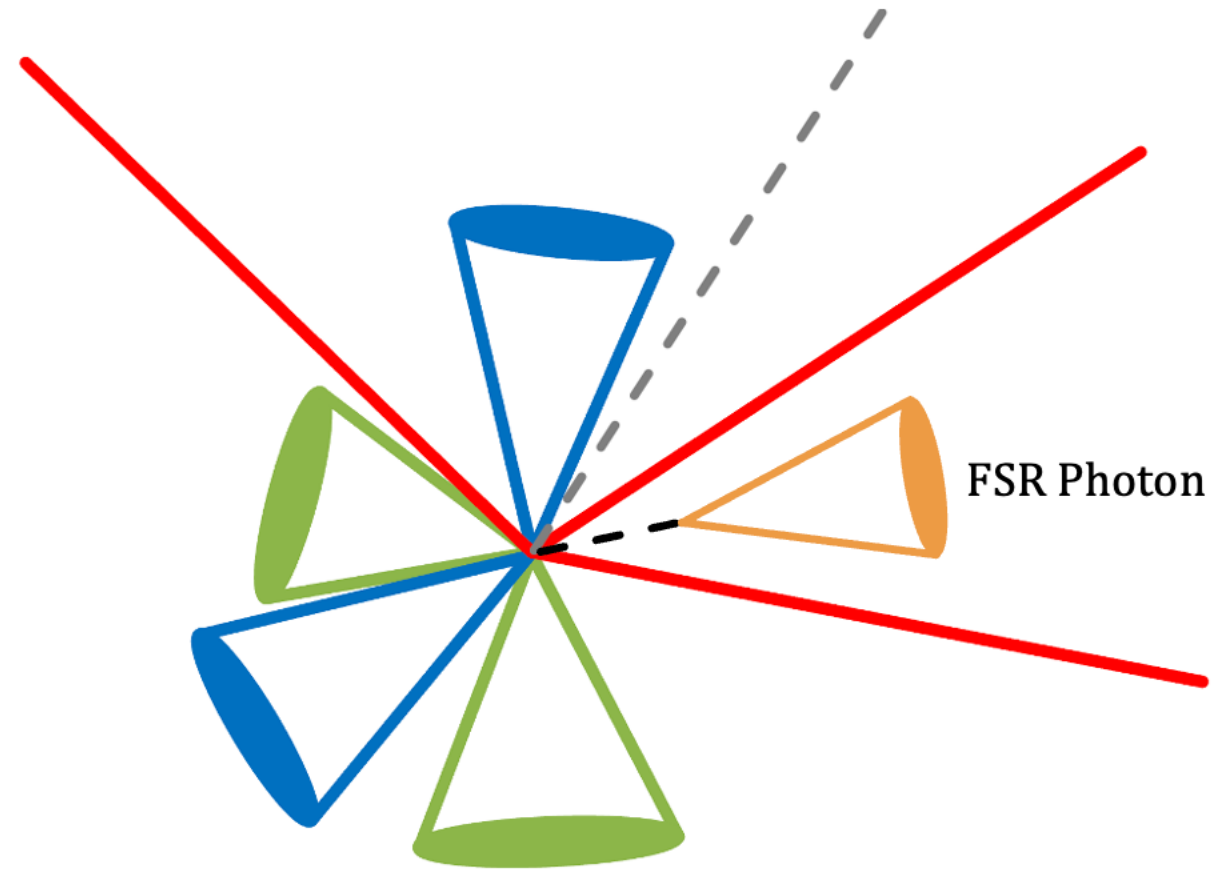
- If FSR recovery is not done, the reconstructed mass of the two muons will be less than the Higgs boson mass (125 GeV):

$$M_{\mu\mu} < M_H$$



SWITCHED AT BIRTH

- Reconstructed FSR photon must be matched to a muon

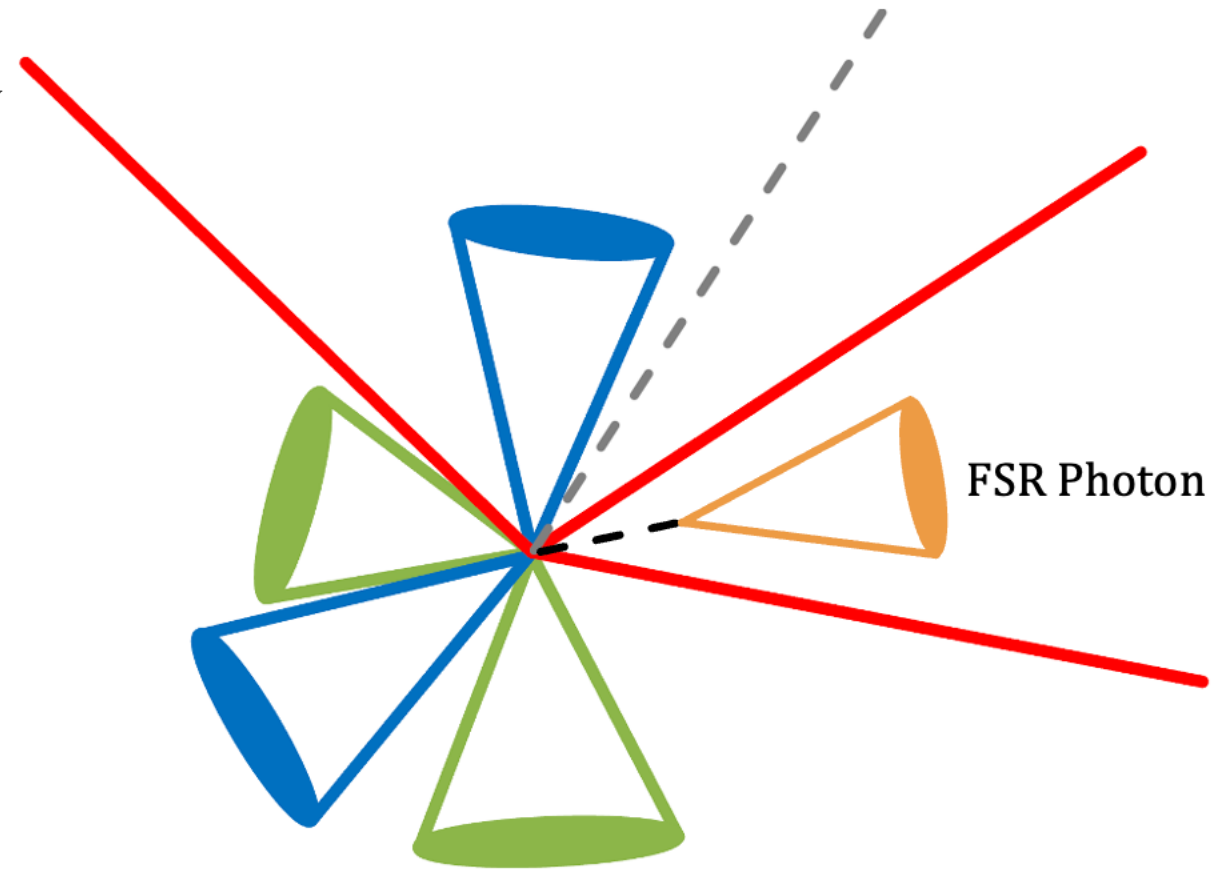


SWITCHED AT BIRTH

- Reconstructed FSR photon must be matched to a muon
- If muon assignment is wrong, FSR recovery will add energy to wrong born muon
- Reconstructed mass of the two muons + FSR gives mass different from Higgs

$$M_{\mu\mu(\gamma)} \neq M_H$$

- FSR recovery not done in previous analysis due to ambiguity of multi-muon final states



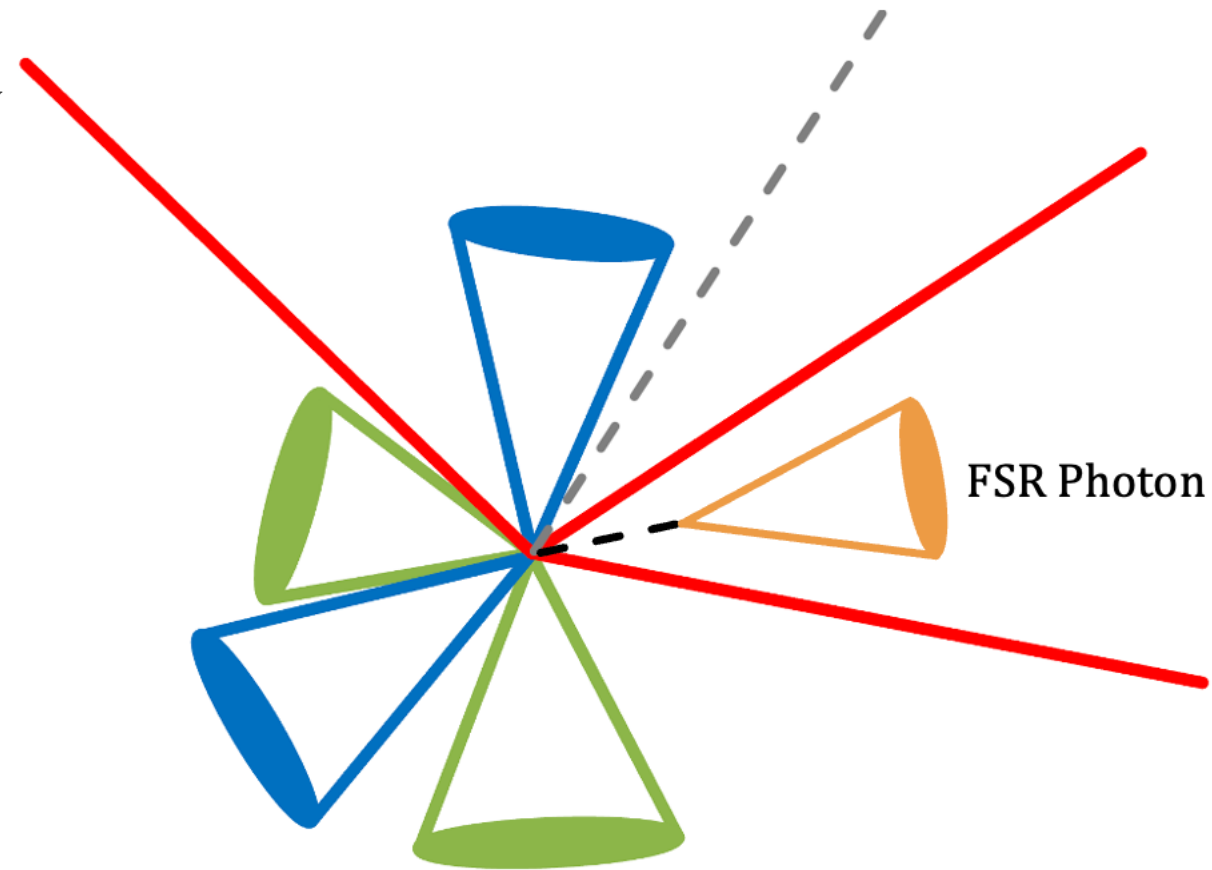
SWITCHED AT BIRTH

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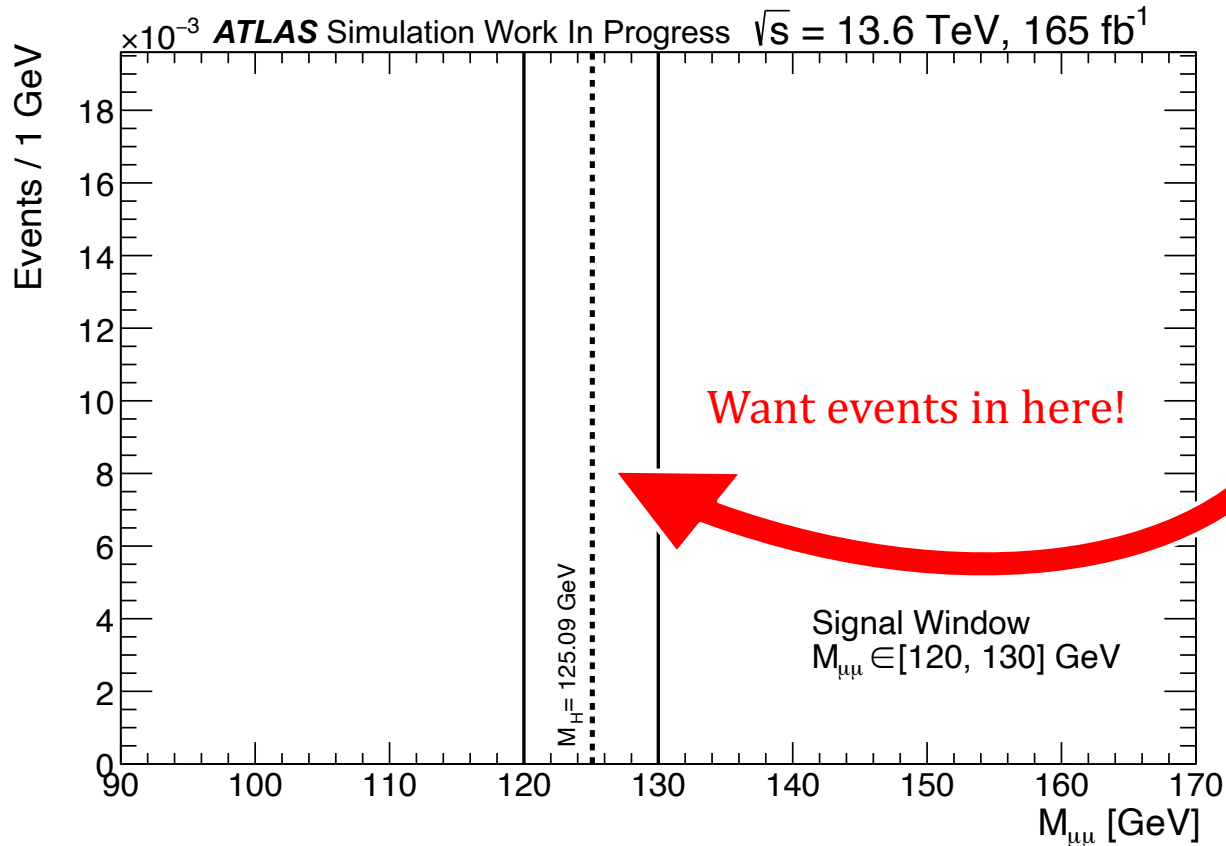
$$M_{\mu\mu(\gamma)} \neq M_H$$

- FSR recovery not done in previous analysis due to ambiguity of multi-muon final states
- Need to ensure the muon selection is correct before FSR recovery
- With fixed selection strategy, can ensure muons are not switched at birth:

$$M_{\mu\mu(\gamma)} \rightarrow M_H$$

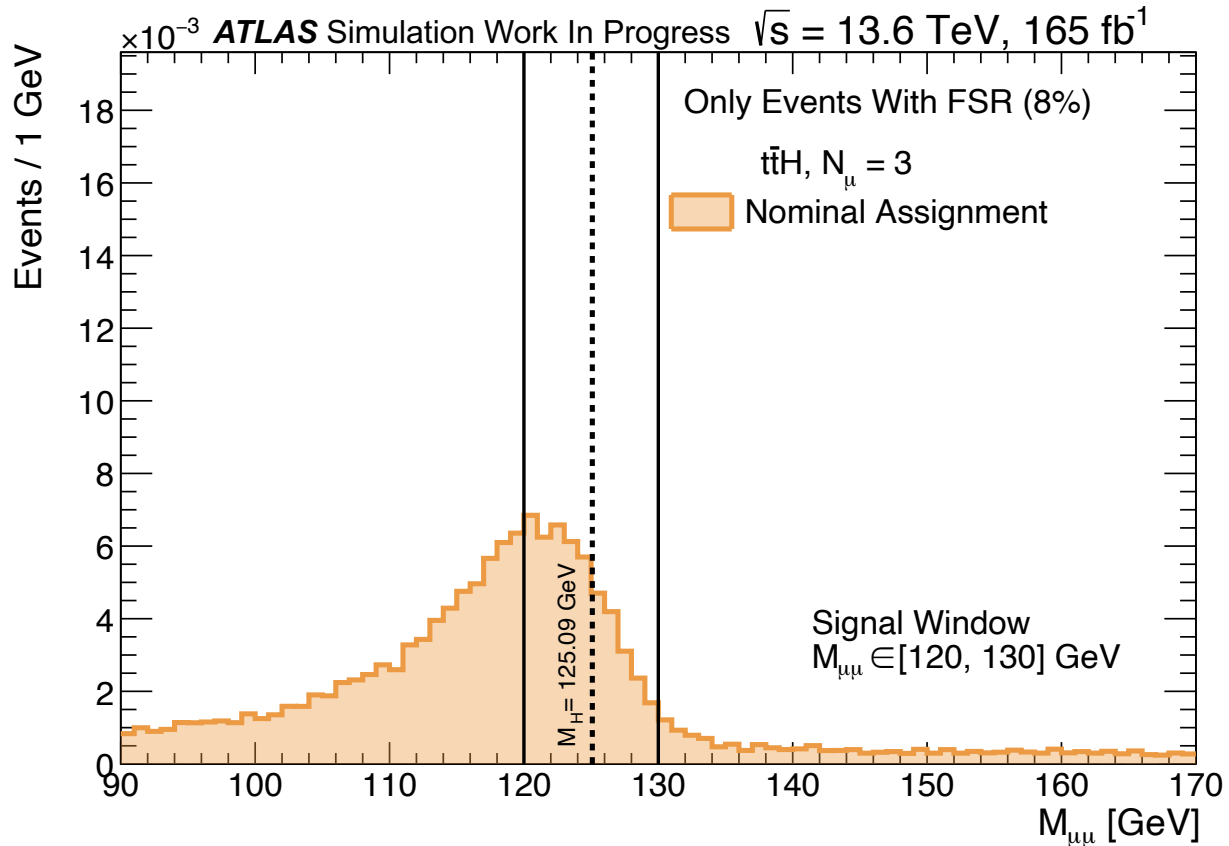


IMPACT ON $t\bar{t}H3\mu$ EVENTS



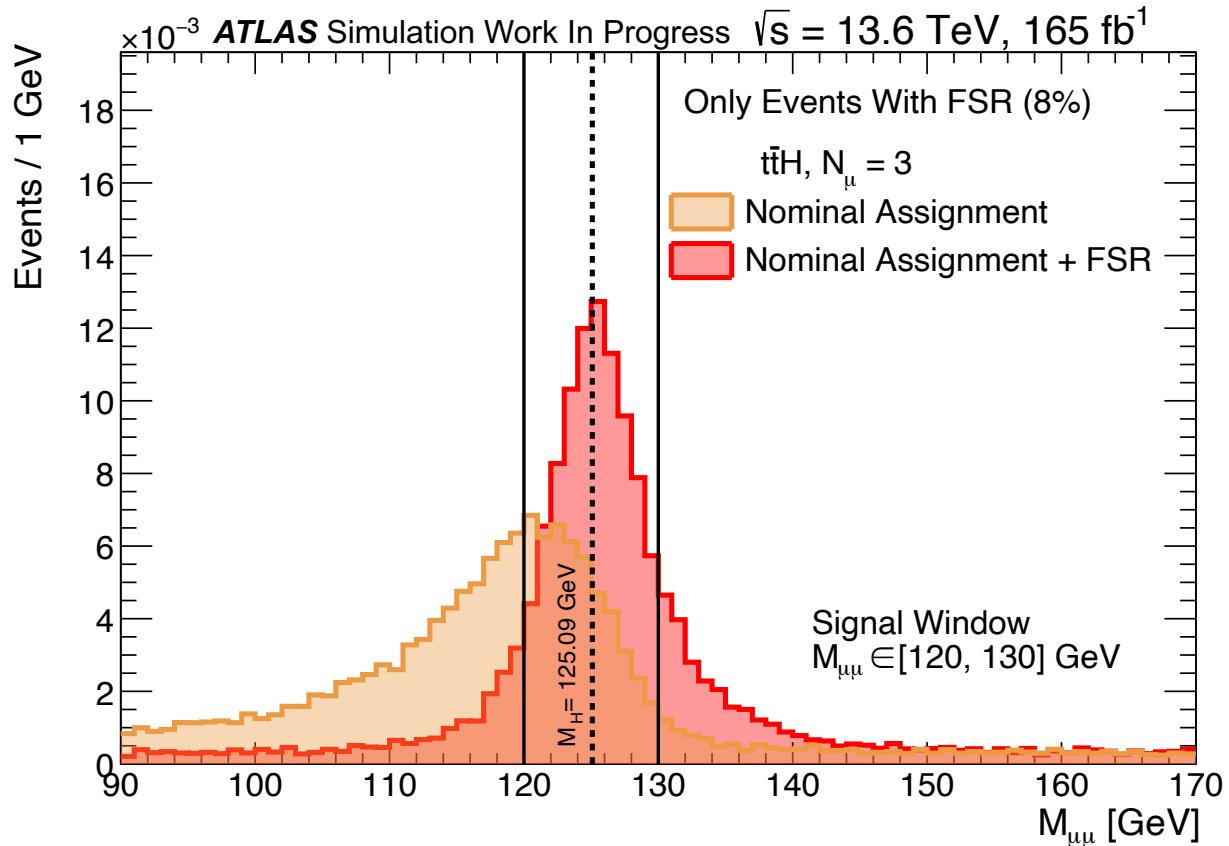
- If the Higgs candidate reconstruction is done properly, we expect to see events in a small window around the actual Higgs mass (125 GeV)

IMPACT ON $t\bar{t}H3\mu$ EVENTS



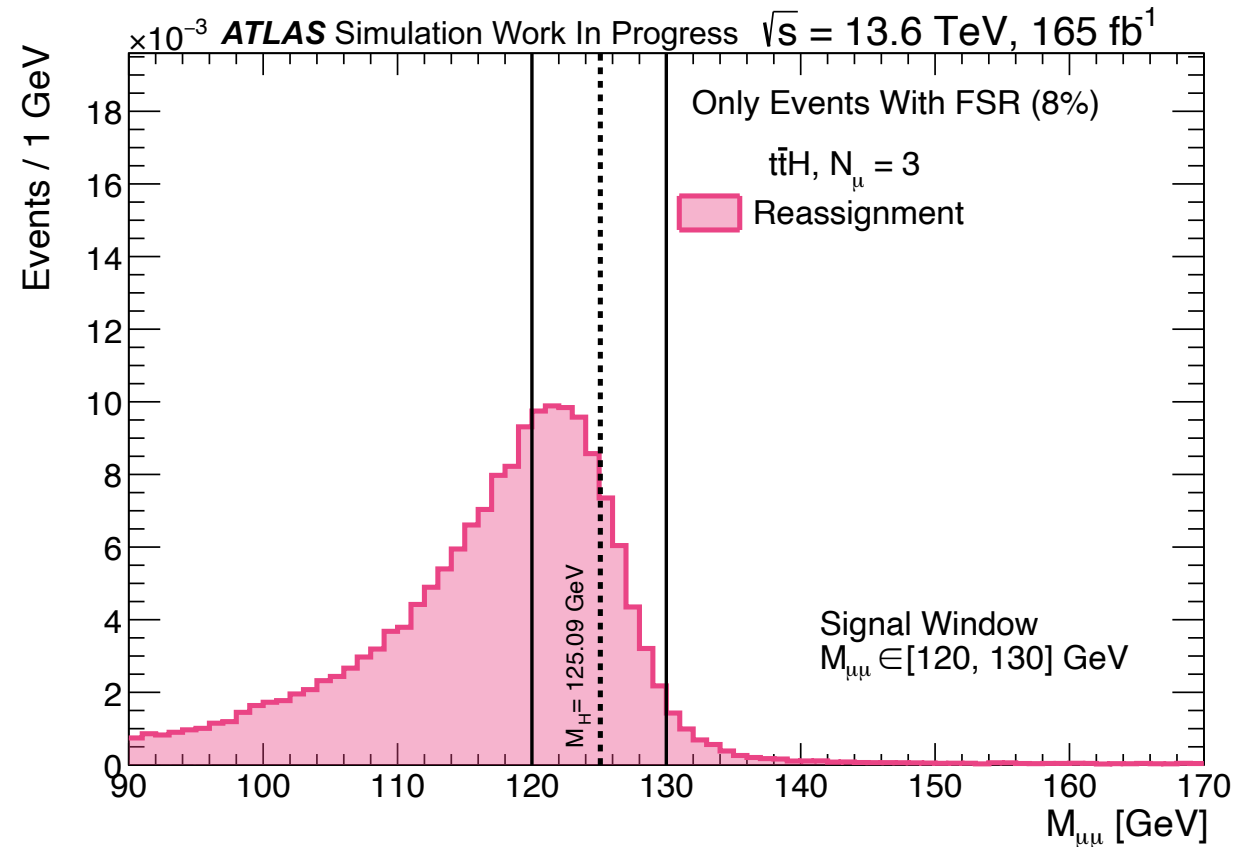
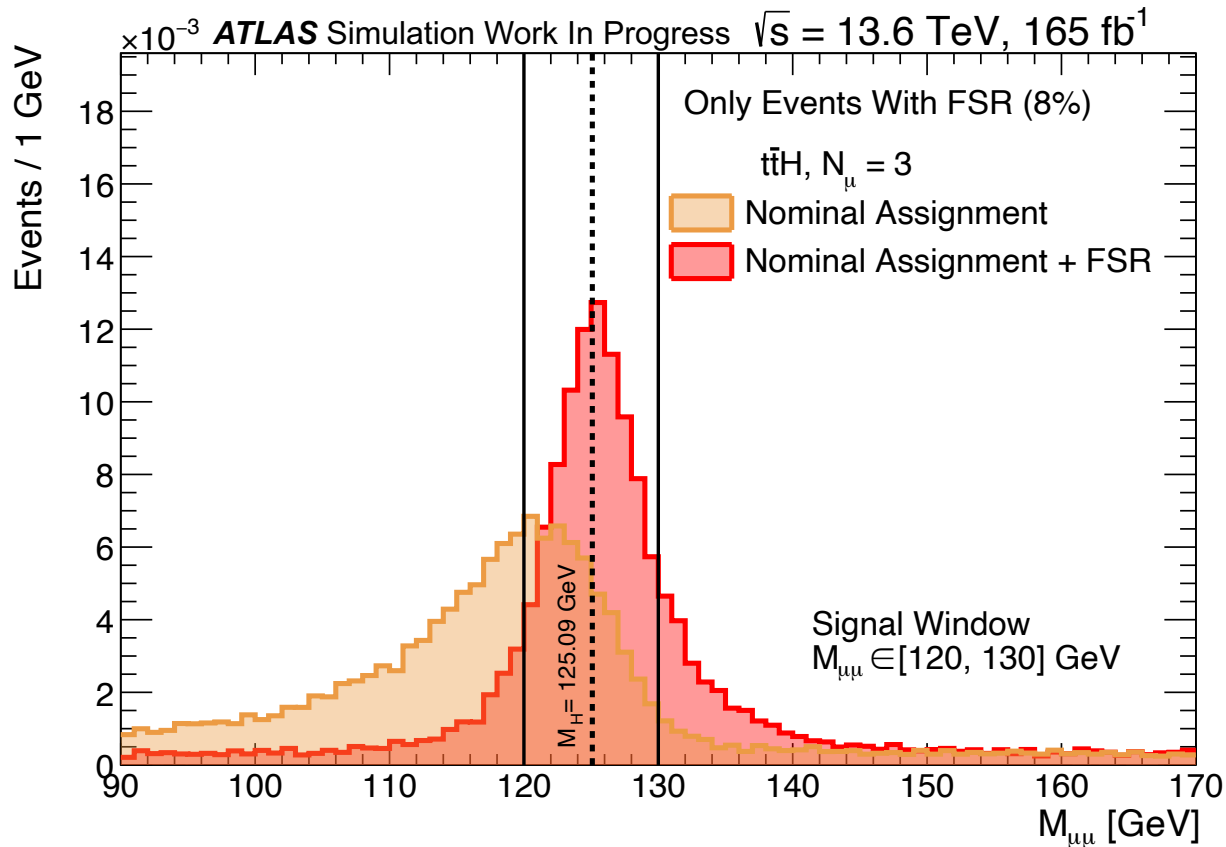
- If we use the nominal muon assignment (two highest p_T muons) and don't do FSR recovery, we see many events end up outside of the window

IMPACT ON $t\bar{t}H3\mu$ EVENTS



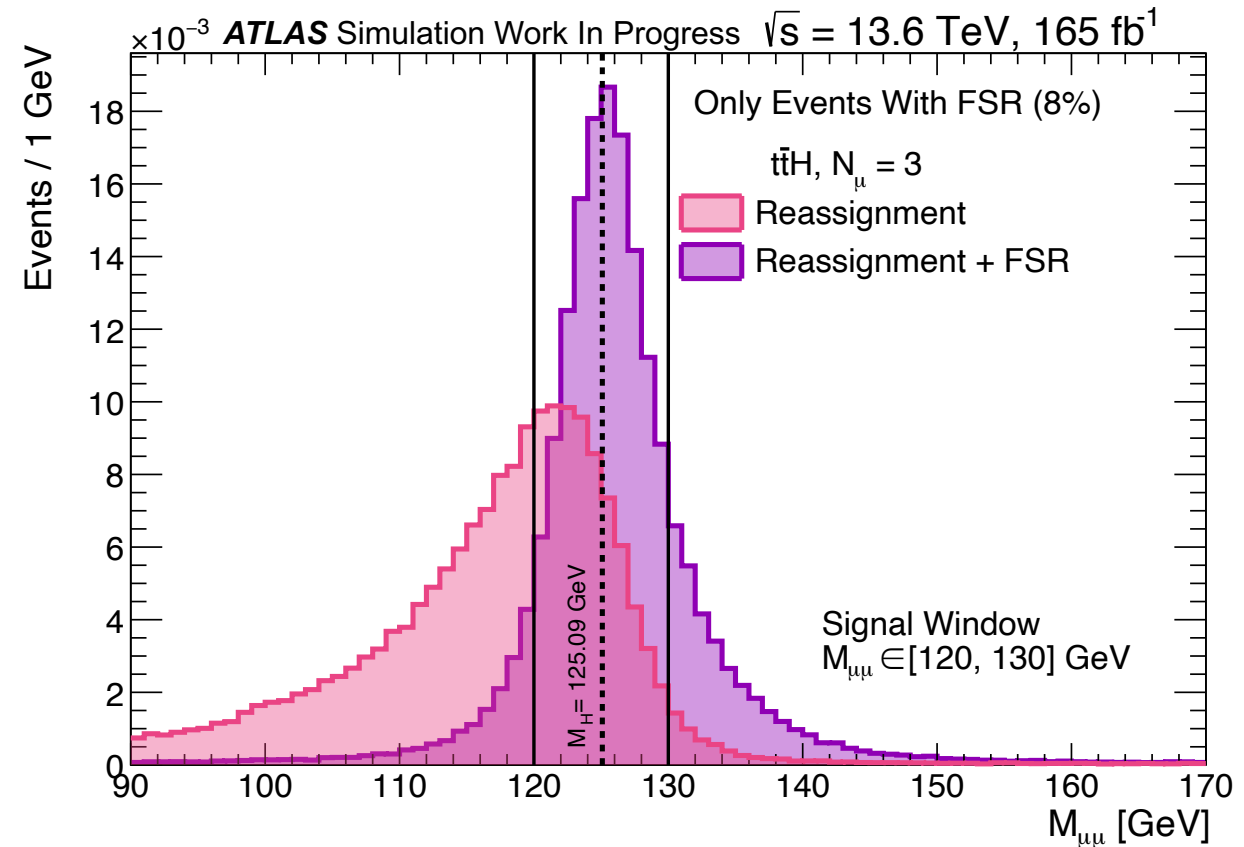
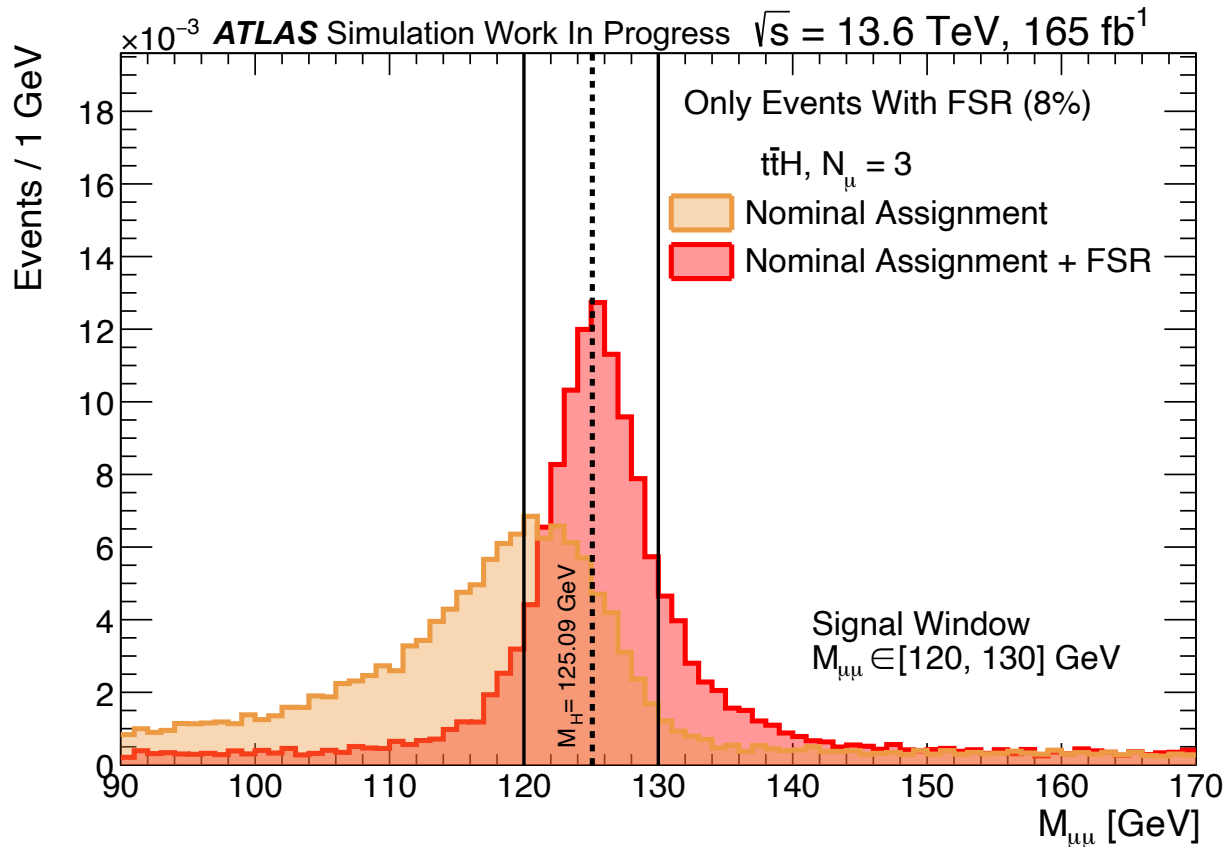
- If we apply FSR recovery, then we get many more events in the window, and the peak is right at the Higgs mass
- Can we do better using the reassigned muons?

IMPACT ON $t\bar{t}H3\mu$ EVENTS



- Get a lot more events in the signal window than with the nominal assignment
- Without FSR recovery we still see many events with lower masses

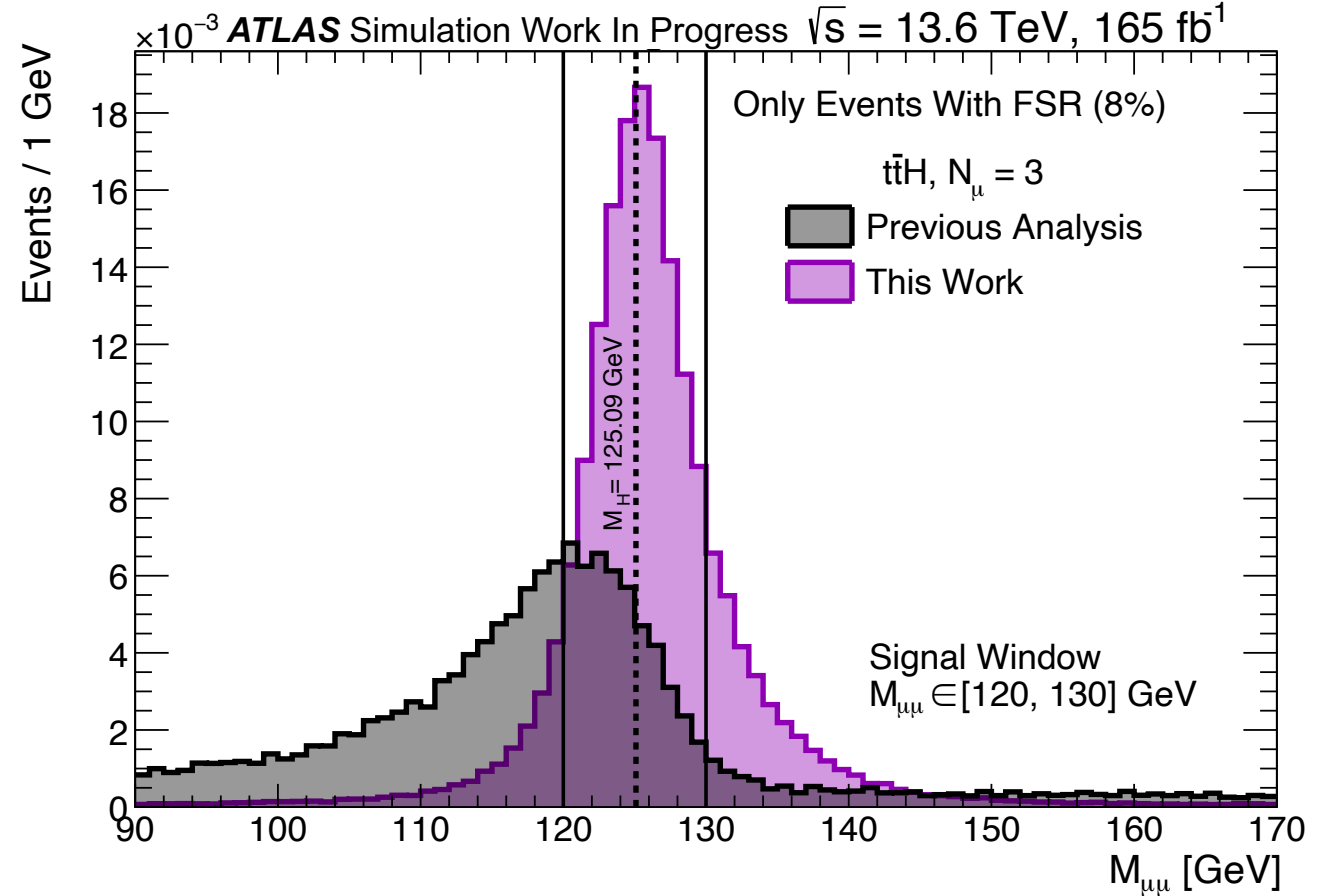
IMPACT ON $t\bar{t}H3\mu$ EVENTS



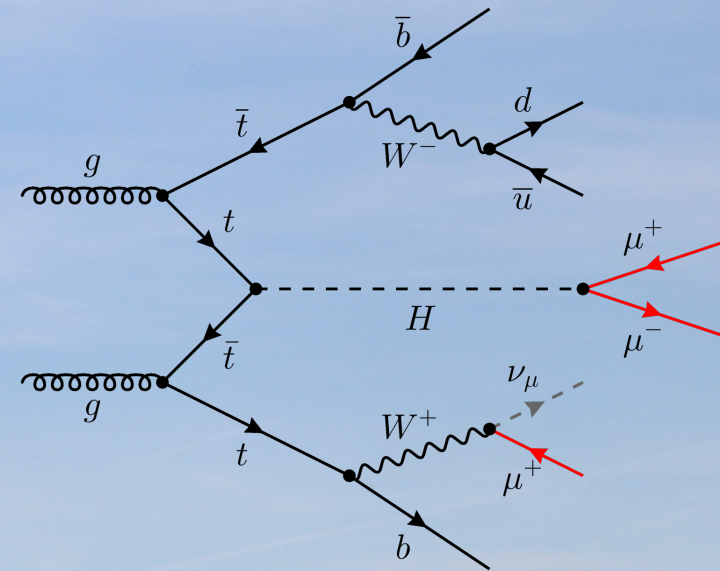
- With corrected muon assignment and FSR recovery, we get an increased signal yield of 160% for events that have an FSR photon reconstructed
- This represents an increase of 56% for all $t\bar{t}H3\mu$ events

CONCLUSIONS

- Fixing the muon assignment in $t\bar{t}H3\mu$:
 - Stops muons being *switched at birth*
 - Allows for FSR recovery
 - Gives a 56% increase in the signal yield
- Many other components to the analysis:
 - Machine learning categorization
 - Spurious signal modelling
 - Statistical analysis + Fit
- Overall gives 21% improvement over previous analysis



Thank You For Listening!



Mt. Blanc:
Z Mass Peak

Le Môle:
Higgs Mass Peak
(x5000)

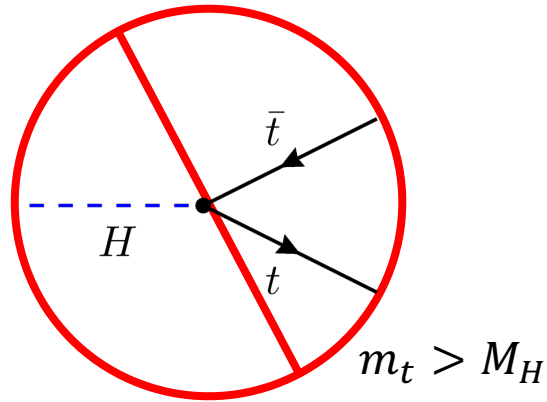


ADDITIONAL MATERIAL

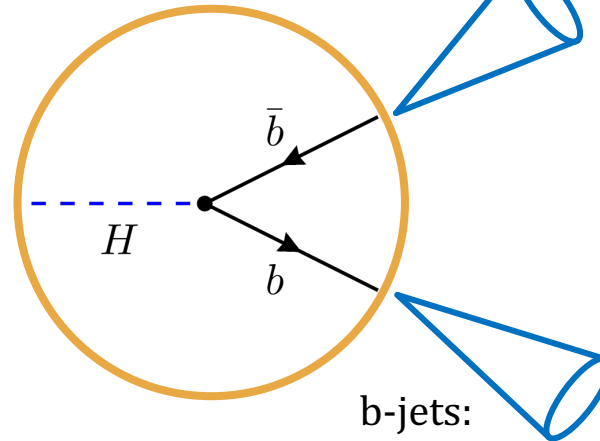


WHY STUDY HIGGS DECAY TO MUONS?

■ Higgs coupling to 3rd Generations:

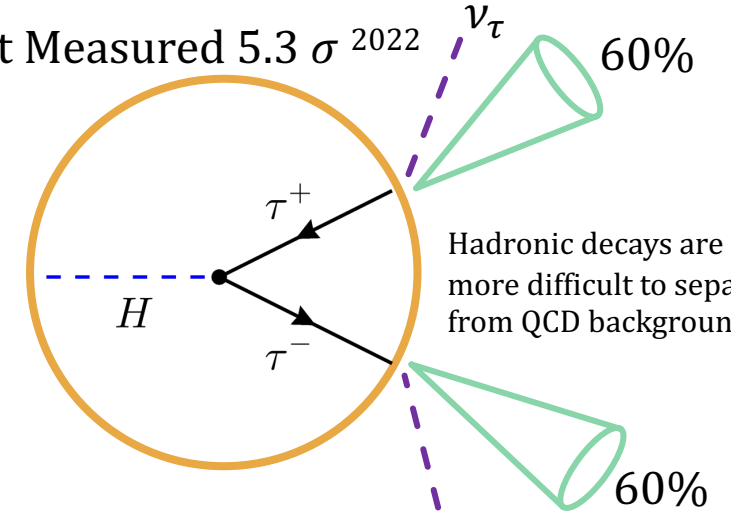


Most Common: BR \sim 58%



b-jets:
Require Flavour Tagging
Hard to differentiate from QCD

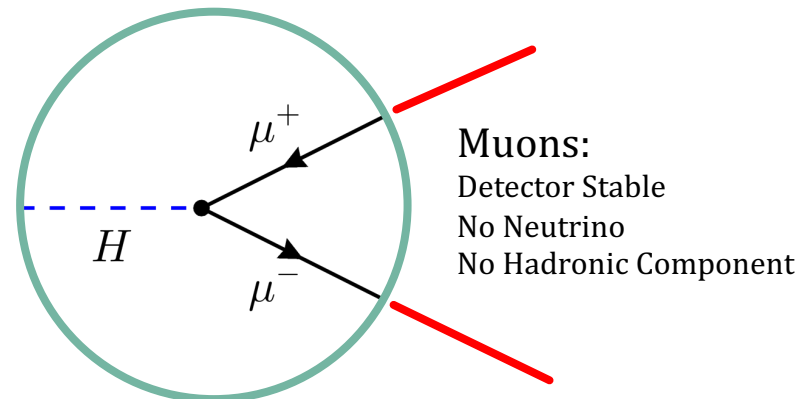
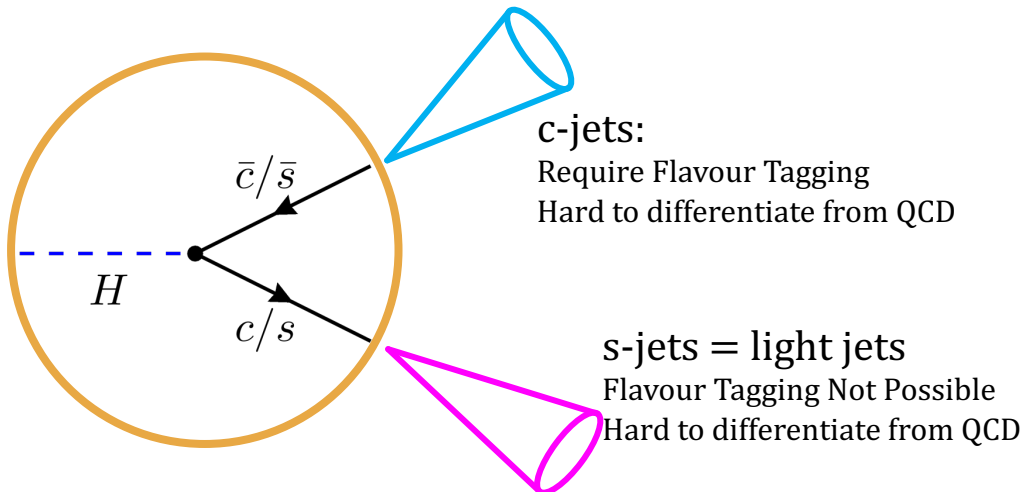
Best Measured 5.3σ 2022



Hadronic decays are more difficult to separate from QCD background

$\bar{\nu}_\tau =$ Missing Energy

■ Higgs coupling to 2nd Generations:



FIXING THE MUON ASSIGNMENT

$W \rightarrow \mu + \nu$ Decay

- Neutrino gives missing energy signature in ATLAS detector
- To reconstruct the W, need neutrino momentum vector
 - Can get \mathbf{p}_x^ν and \mathbf{p}_y^ν from the missing energy, only missing \mathbf{p}_z^ν
 - Can get \mathbf{p}_z^ν by solving a quadratic equation:

$$\zeta \cdot (p_z^\nu)^2 + \psi \cdot p_z^\nu + \xi = 0$$

- Where ζ, ψ, ξ are based on the muon information and the missing energy
- Solve equation for each ambiguous (same charge) muon
- Pick the $\mu + \nu$ pair that gives a mass closest to the W mass by minimizing a χ^2 defined as:

$$\chi^2 = \left(\frac{M_{\mu\mu} - M_H}{\sigma_H} \right)^2 + \left(\frac{M_{\mu\nu} - M_W}{\sigma_W} \right)^2$$

- The other two muons are assigned to the Higgs

$$p_x^\nu = E_T^{\text{miss}} \cdot \cos(\phi^{\text{miss}})$$

$$p_y^\nu = E_T^{\text{miss}} \cdot \sin(\phi^{\text{miss}})$$

$$\zeta = (p_z^\mu)^2 - (E^\mu)^2$$

$$\psi = \omega \cdot p_z^\mu$$

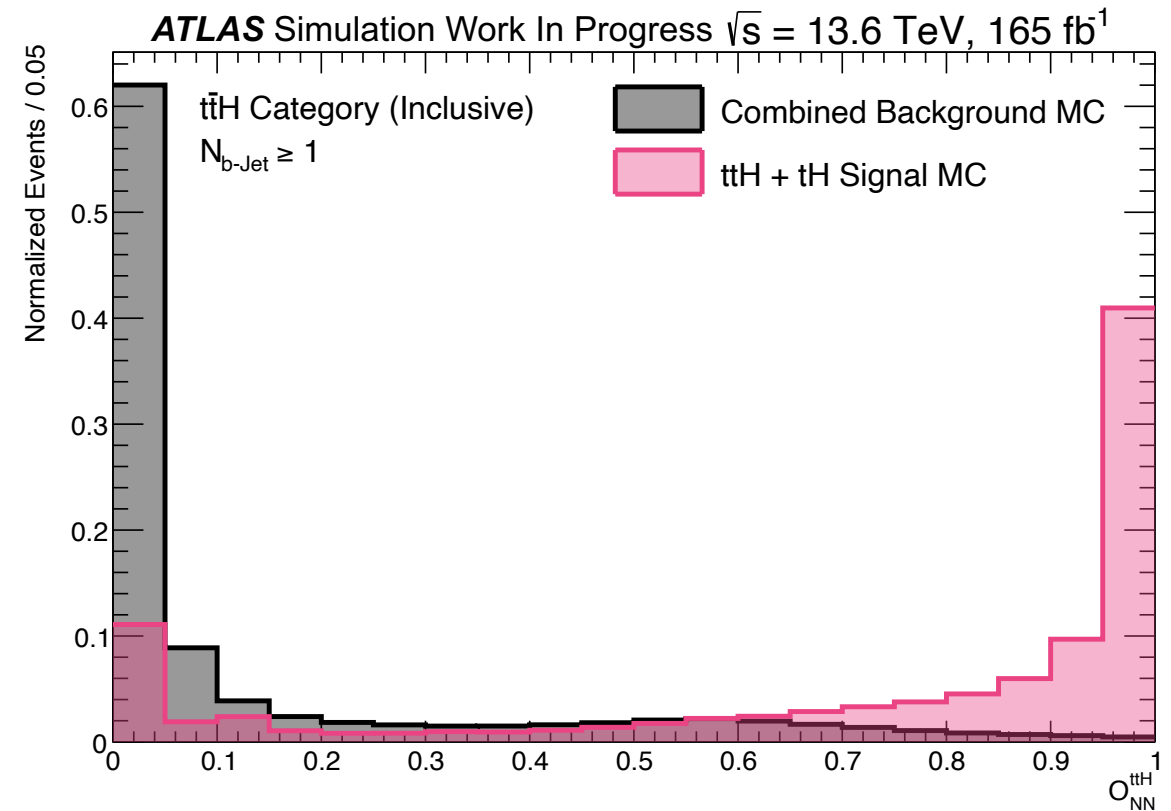
$$\xi = -(E^\mu)^2 \cdot [(p_x^\nu)^2 + (p_y^\nu)^2] + \frac{\omega^2}{4}$$

$$\omega = M_W^2 - m_\mu^2 + 2(p_x^\mu p_x^\nu + p_y^\mu p_y^\nu)$$

MACHINE LEARNING CATEGORIZATION

- Events entering the ttH category (at least 1 b-tagged jet) are then used to train a Neural Network (NN) to separate signal events from background
 - Signal: ttH + tH
 - Background: Top Quark, Drell-Yan, Diboson, Electroweak Z
 - Only category using a NN, all others use Boosted Decision Trees (BDTs)
- ttH NN is trained using Distance Correlation (**DisCo**) loss term which keeps the NN score (O_{NN}^{ttH}) decorrelated from the dimuon invariant mass (with or without FSR recovery depending on the muon assignment)
- Define two categories based on NN score (High, Medium) which optimize the Azimov counting significance:

$$Z_i = \sqrt{2 \left((s_i + b_i) \log \left(\frac{s_i + b_i}{b_i} \right) - s_i \right)}$$



TRAINING VARIABLES

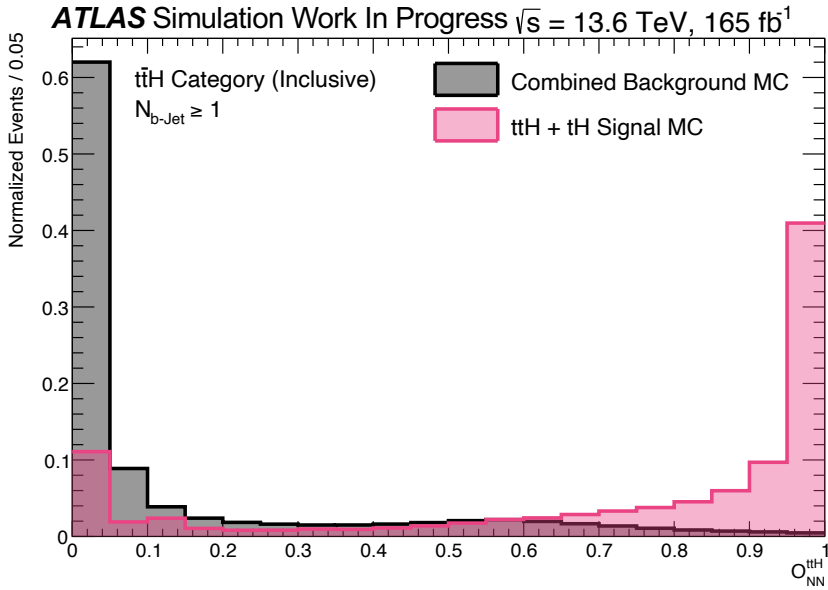
Variable	Description
$p_T^{\mu_1}$	Transverse momentum of the leading muon
$p_T^{\mu_2}$	Transverse momentum of the subleading muon
η_{μ_1}	Pseudorapidity of the leading muon
η_{μ_2}	Pseudorapidity of the subleading muon
ϕ_{μ_1}	Azimuthal angle of the leading muon
ϕ_{μ_2}	Azimuthal angle of the subleading muon
N_{muons}	The number of muons
$\cos \theta^*$	The lepton decay angle $\cos \theta^*$ in the Collins–Soper frame [118]
$p_T^{j_1}$	Transverse momentum of the leading jet
$p_T^{j_2}$	Transverse momentum of the subleading jet
η_{j_1}	Pseudorapidity of the leading jet
η_{j_2}	Pseudorapidity of the subleading jet
$N_{\text{track}}^{j_1}$	Number of tracks in the leading jet with $p_T > 0.5$ GeV
$N_{\text{track}}^{j_2}$	Number of tracks in the subleading jet with $p_T > 0.5$ GeV
m_{jj}	Invariant mass of the dijet system
H_T	Scalar sum of the transverse momentum of all jets
$N_{j\text{-central}}$	Number of central jets ($ \eta < 2.5$)
$N_{b\text{-jet}}$	Number of b -jets (85% WP)

E_T^{miss}	Missing transverse momentum
$N_{\text{electrons}}$	Number of electrons
$p_T^{\ell_3}$	Transverse momentum of the third lepton
$p_T^{\ell_4}$	Transverse momentum of the fourth lepton
m_{sub}	Subleading mass of the third-leading muon and the leading or subleading muon of opposite charge
$m_{\ell_3\ell_4}$	Dilepton mass of the third- and fourth- leading leptons
$\Delta\phi(\ell_3, \ell_4)$	Azimuthal angle between third and fourth leptons
$\Delta\eta(H, \ell_3)$	Pseudorapidity separation between the dimuon system and the third lepton
m_{lep}^t	Transverse mass of leptonic t decay reconstructed from the third leading lepton, \vec{p}_T^{miss} , and a b -jet
m_{had}^t	Mass of hadronic t decay reconstructed from three jets, one of which is a b -jet
m_{lep}^W	Transverse mass of leptonic W decay reconstructed using Equation 6.13
m_{had}^W	Mass of hadronic W decay reconstructed from the two non b -tagged jets used to reconstruct the hadronic t mass

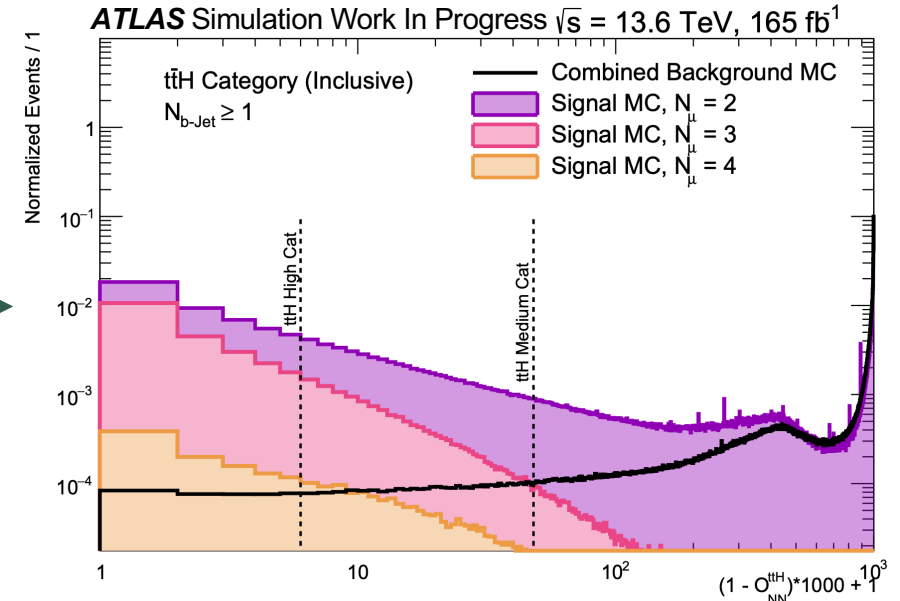
Use the same input features as the previous analysis:

- Many depend on the selected Higgs candidate muons, or on the resulting additional leptons
- After muon reassignment, these must be recalculated

CATEGORY BREAKDOWN

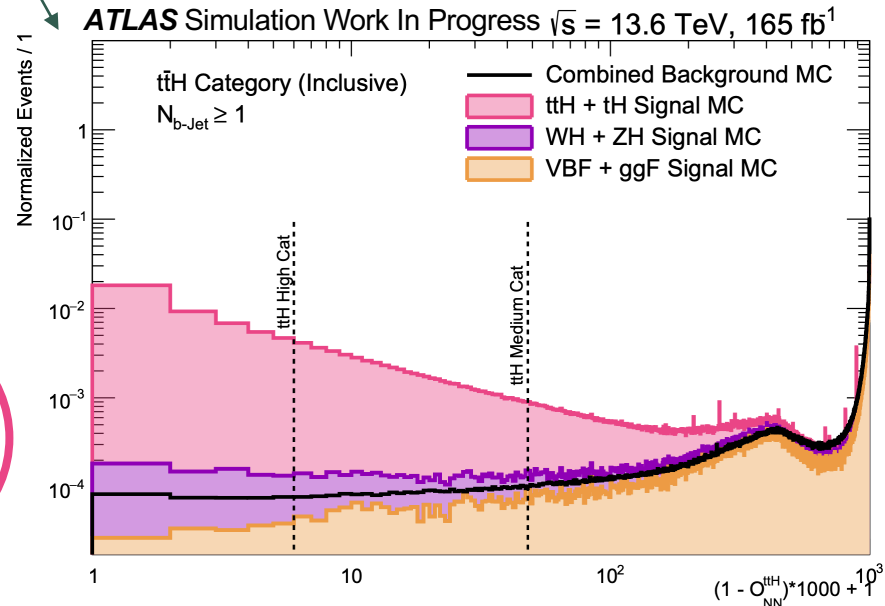


Linear Transform
(for visualization):
 $(1 - O_{NN}^{ttH}) \times 1000 + 1$



Contribution of Top Quark Background:
High Category: 73.6%
Medium: 77.8%

Signal Purity ($ttH + tH + tWH + bbH$):
High Category: 98.7%
Medium Category: 93.4%



Higher lepton
multiplicity events
contribute more at
higher NN scores

MACHINE LEARNING RESULTS

Neural Network Categorization Results

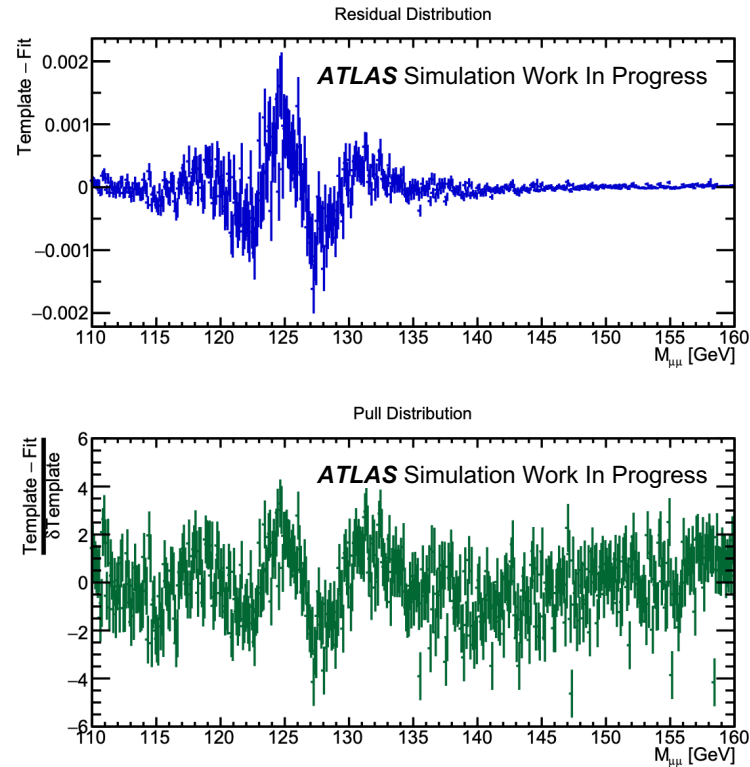
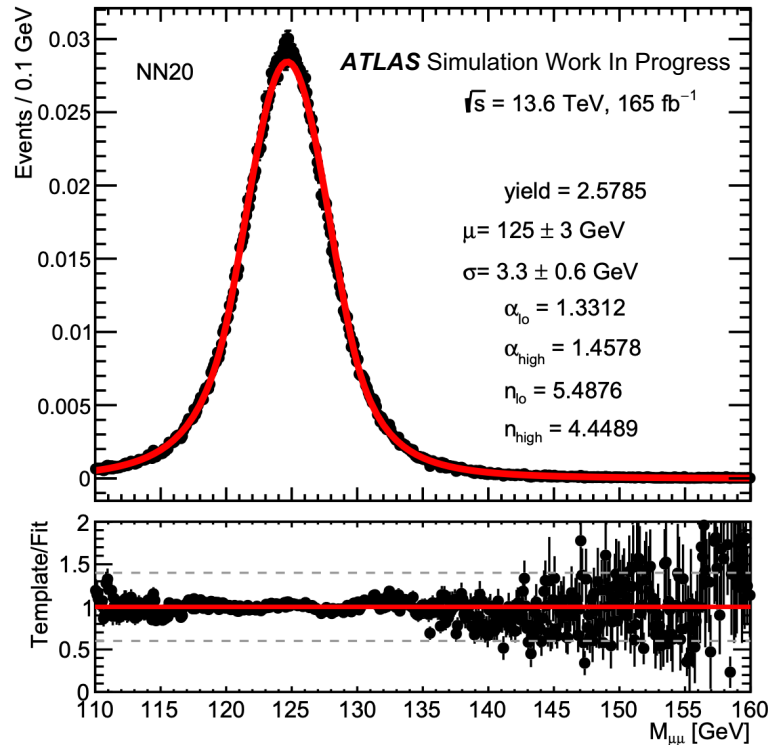
Muons	FSR	Category	Signal	Background	Significance
Nominal	No	High	2.22	53.89	0.300
		Med	3.93	588.57	0.162
		Total:			0.341
Reassign	Yes	High	2.04	31.27	0.360
		Med	3.18	247.12	0.202
		Total:			0.413

Category Optimization Results

- Nominal category corresponds to the muon assignment used in the previous analysis
 - FSR recovery was not performed previously due to ambiguity in multi-muon final states
- With muon reassignment and FSR recovery, we get 21% improvement
 - 9% from FSR recovery
 - 12% from muon reassignment



SIGNAL MODELLING



- Signal Monte-Carlo is fit with a Double-Sided Crystal Ball (DCSB) function
 - Combination of a gaussian core and exponential tails
- Parameters of DCSB fit are used as signal model when testing the Signal+Background fit

ttH High Category:
5% reduction in fit width
compared with previous analysis

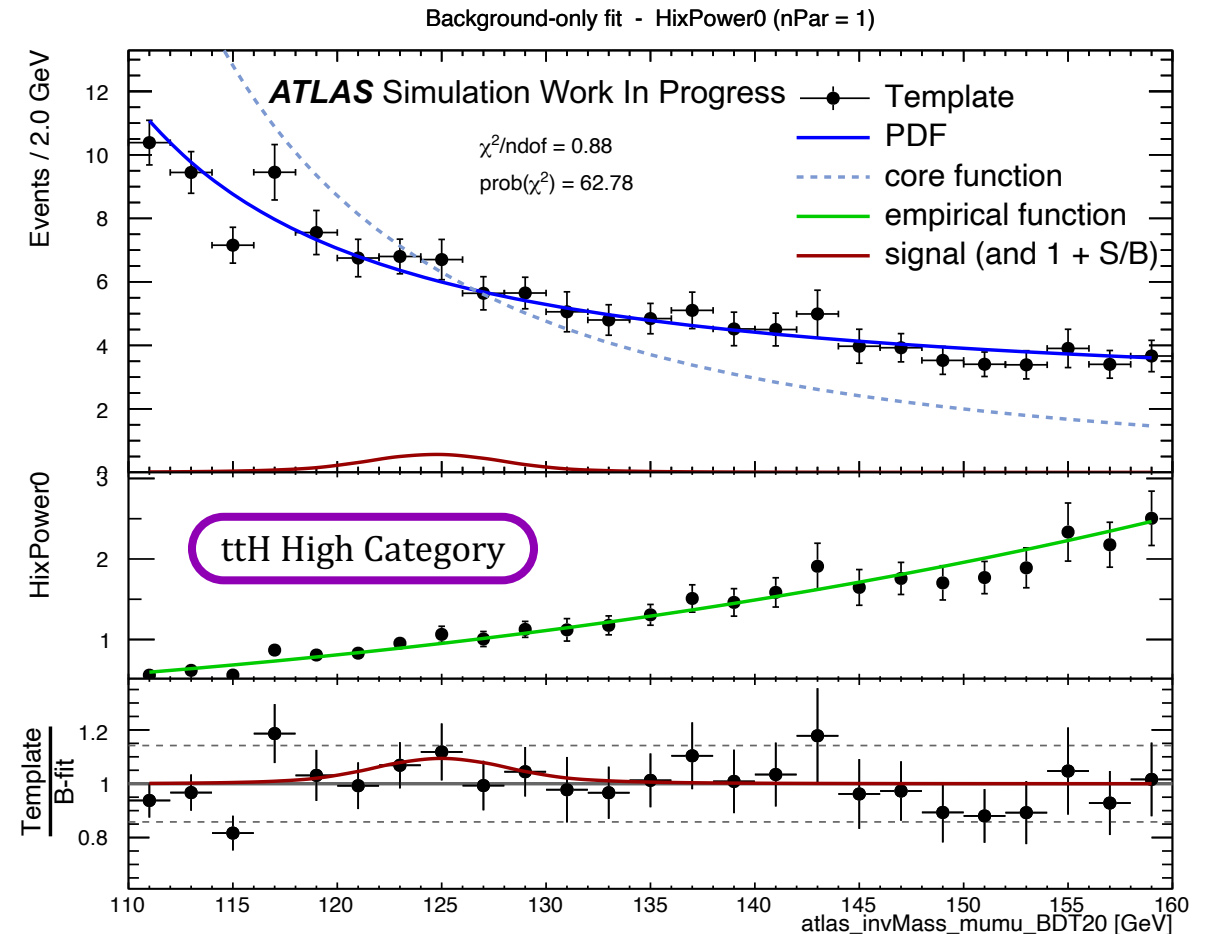
BACKGROUND MODELLING + SPURIOUS SIGNAL

Background Modelling

- Fit a smooth empirical function (power law or exponential) + Drell-Yan Core function
 - Core function used to model the falling tail from Drell-Yan better than simple functions alone
- Signal Model is fit to distribution of events with background model subtracted

Spurious Signal

- Try to fit a signal model to a background only (Monte-Carlo) sample
- If signal-like features are present in the background model then this contributes to spurious signal and must be accounted for



STATISTICAL ANALYSIS RESULTS

ttH Category	Z_{Azimov} (Stat. Only)	Z_{exp} (Stat. Only)	Z_{exp} (Stat. + SS)
Previous Analysis	0.35	0.31	0.29
This Work	0.41	0.36	0.35
Change	+17%	+16%	+21%

Blinded Fit Results

- When moving from counting significance to fit results, see a larger reduction in statistical-uncertainty-only significance
- See a smaller reduction when including Spurious Signal
- Inclusion of muon reassignment and FSR recovery gives 21% improvement on expected significance with SS