Search for a Standard Model Higgs decaying to a four lepton plus missing transverse momentum final state via dark boson decay

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Motivation

- Standard Model (SM) has deficiencies
    - Many free parameters, no DM or DE, (anti)matter paradox, hierarchy problem, strong CP problem, no gravity …
- Many dark matter models that:
    - providing a candidate for the dark matter (DM) in the universe
    - explain astrophysical “observations” which may have DM interpretation
- This represents an alternative DM scenario to that of Super Symmetry
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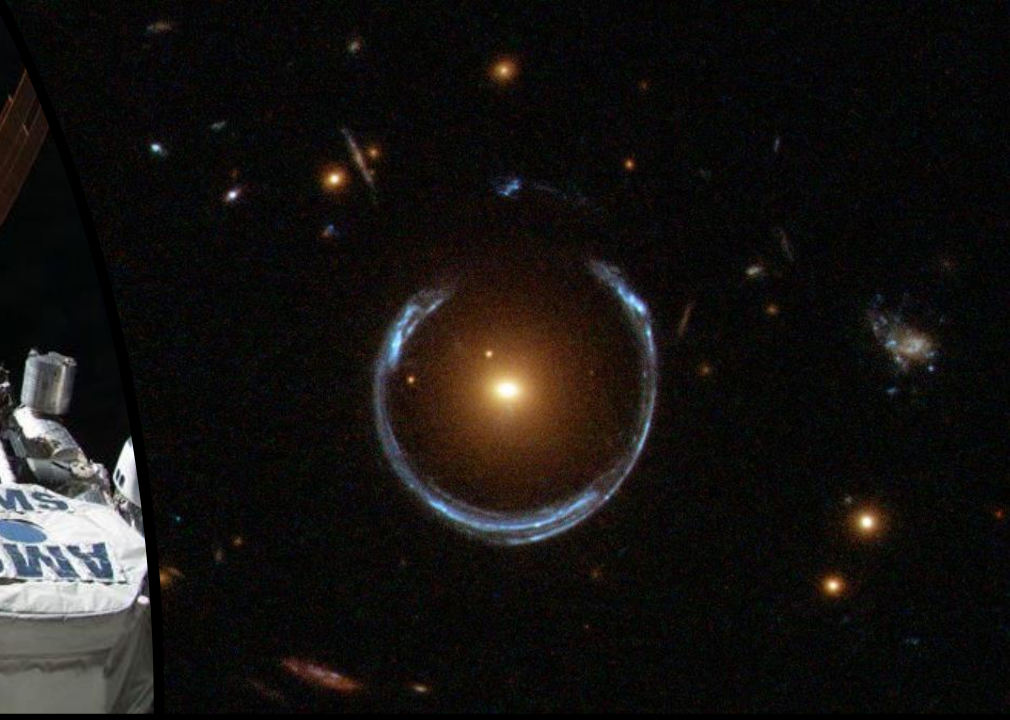
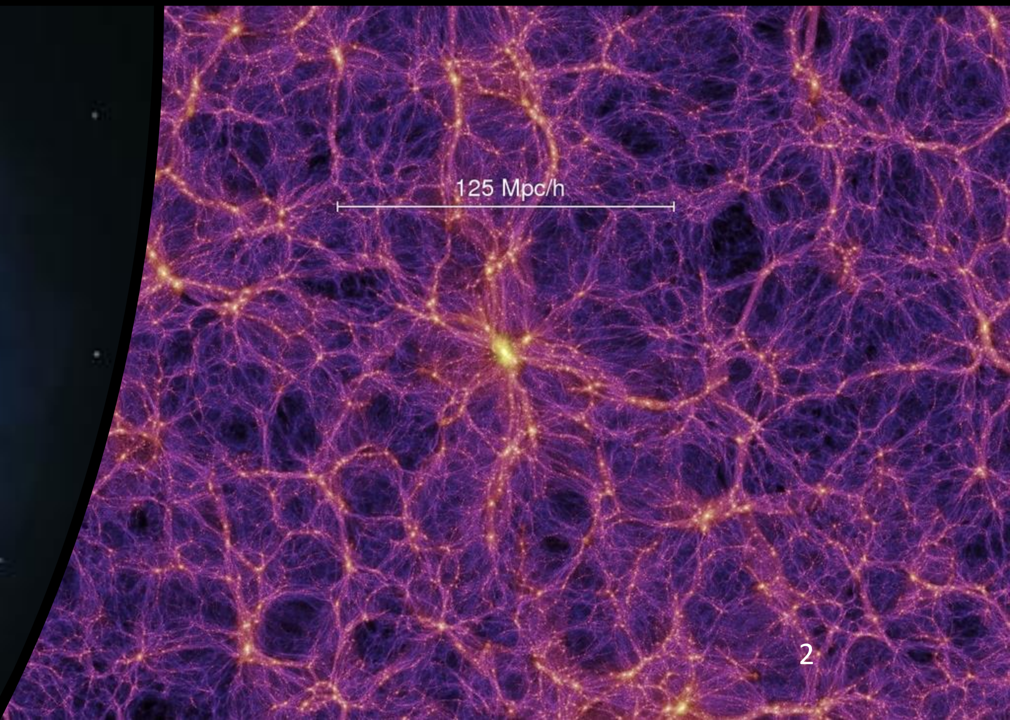
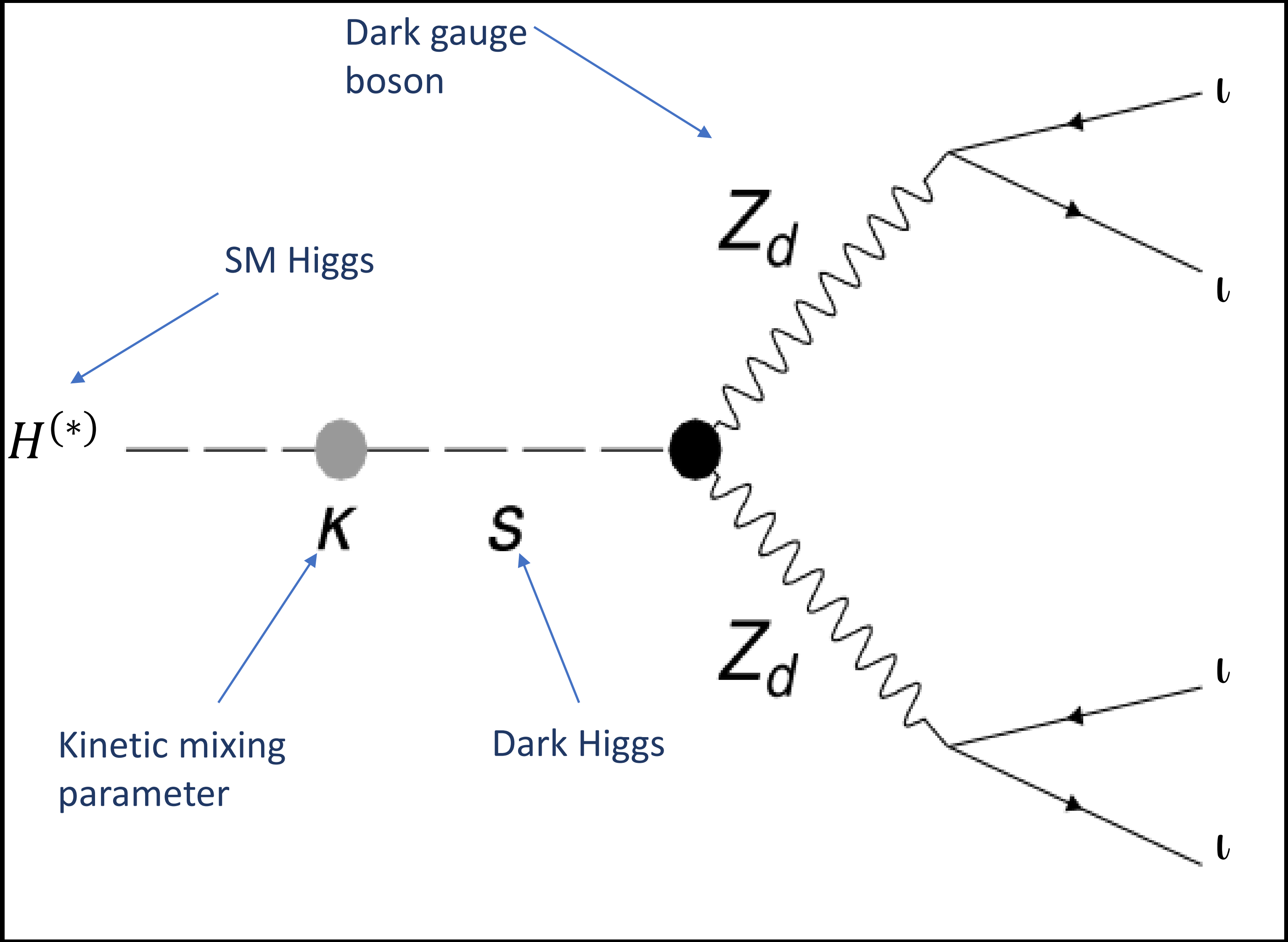


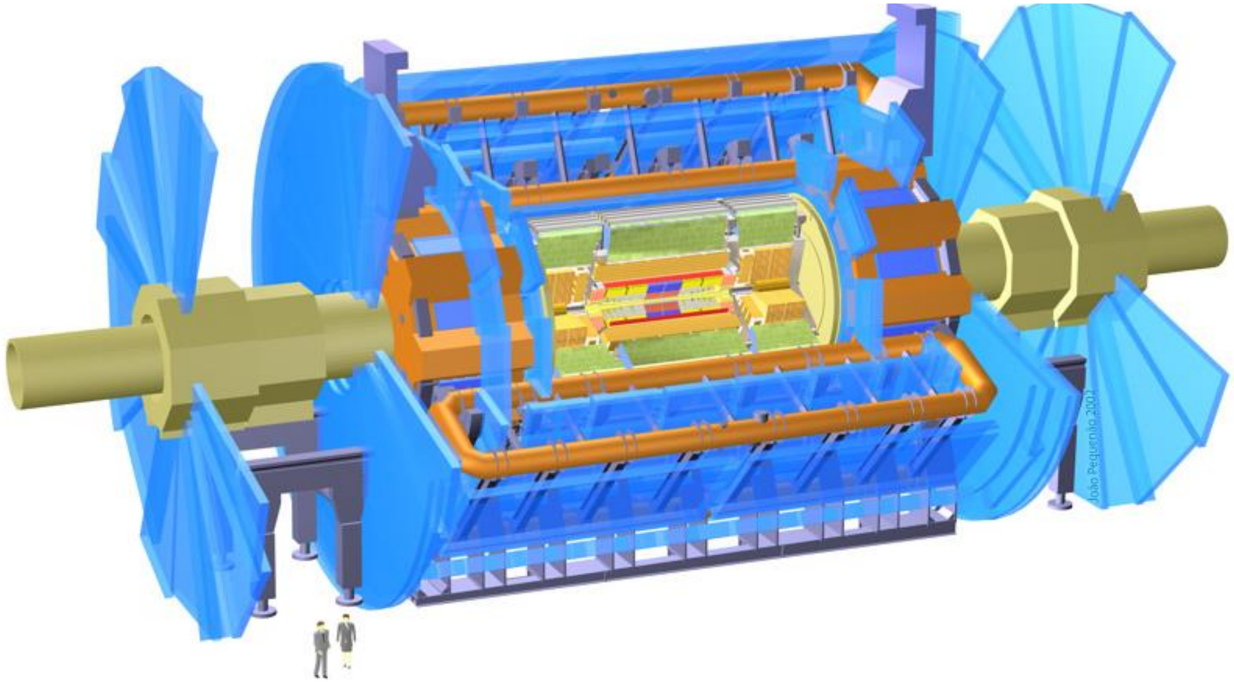


Hidden Abelian Higgs Model

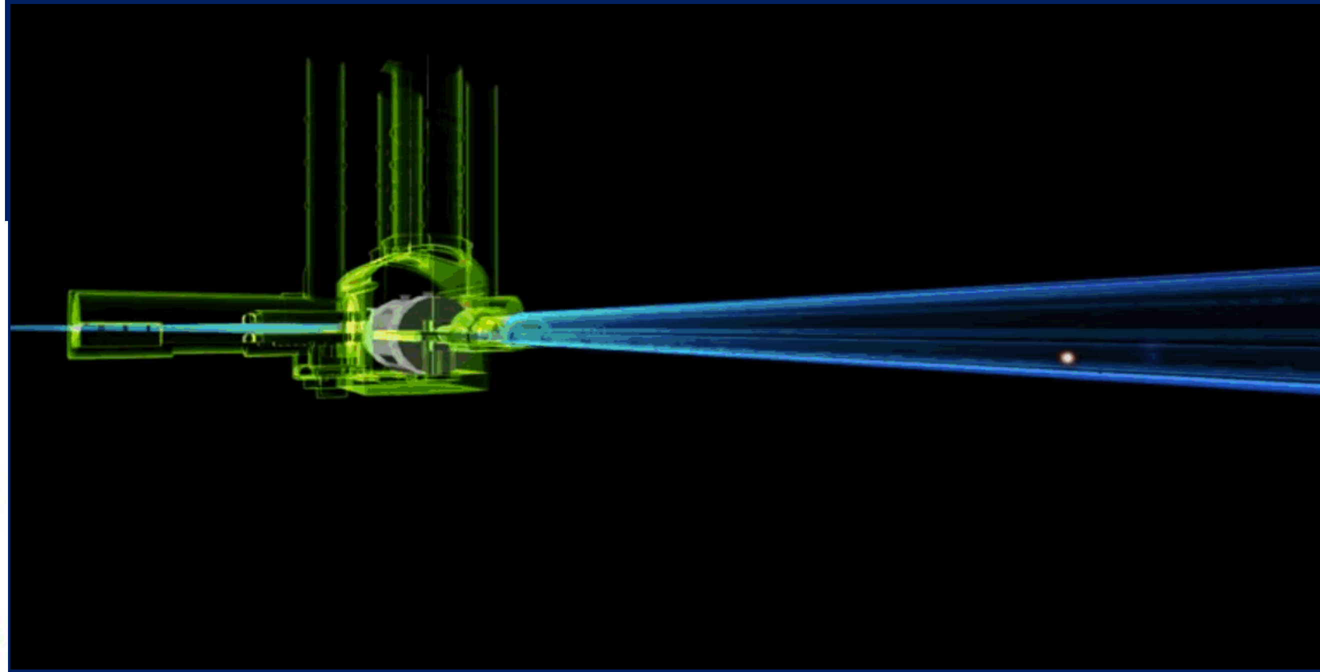
- Possibility of extending the Standard model using Hidden Abelian Higgs model (HAHM)
- Mixing between the dark Higgs and the SM Higgs via the the mixing parameter κ. This happens when the dark Higgs mechanism spontaneously breaks the $U(1)_d$ gauge symmetry
- We look for four lepton final state (4u, 4e, 2e2u)



ATLAS EXPERIMENT



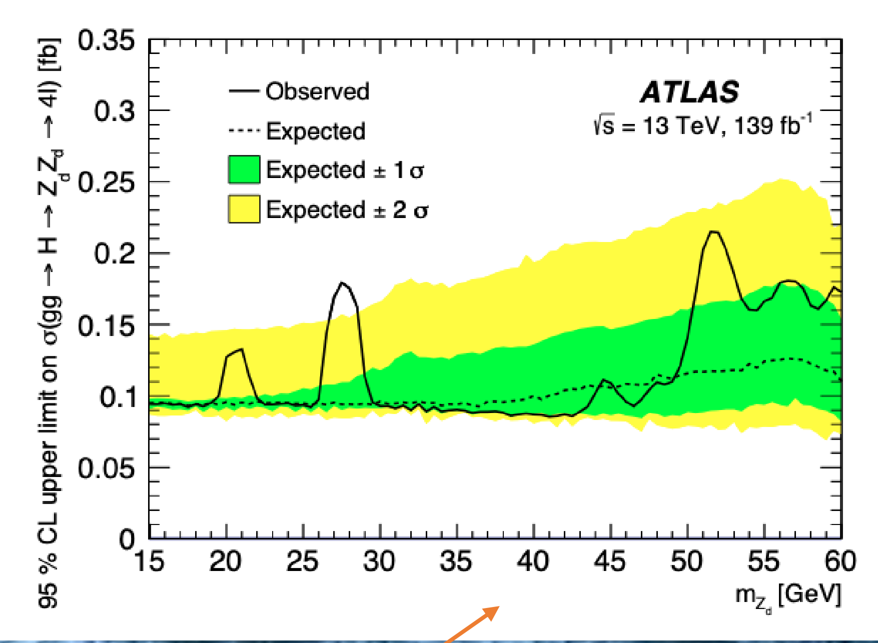
- General purpose detectors designed to find the Higgs boson and other physics that may deviate from the Standard Model
- Takes a snapshot of every collision that occurs at the interaction point

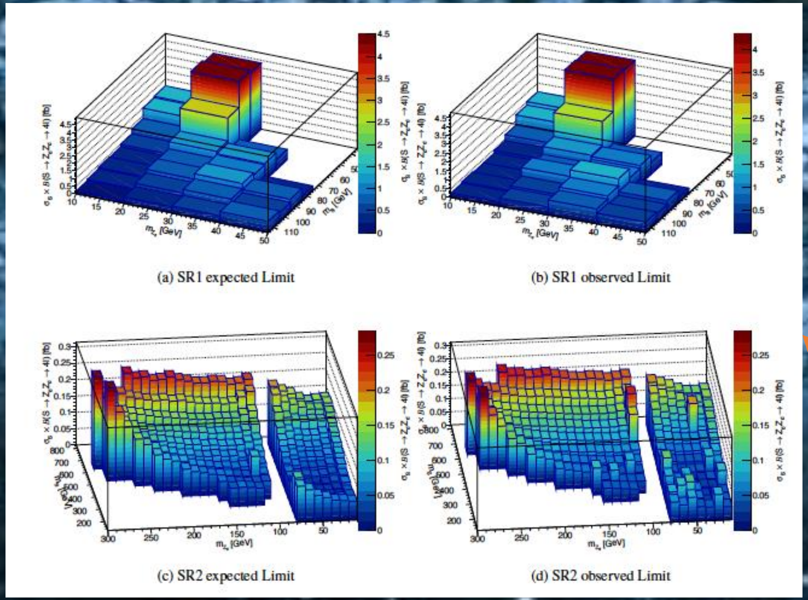


- Consists of the inner detector, the electromagnetic calorimeter, the hadronic calorimeter and the muon spectrometer
- Inner detector used to detect direction, momentum and charge of electrically charged particles
- Electromagnetic and hadronic calorimeters are used to measure energy of particles
- Muon spectrometer measures the momentum of muons

Motivation

- The High Mass and Additional Scalar analyses produced significant bumps around 30 GeV.
- In addition, CMS analysis similar to the HM analysis also showed bumps around 30 GeV.





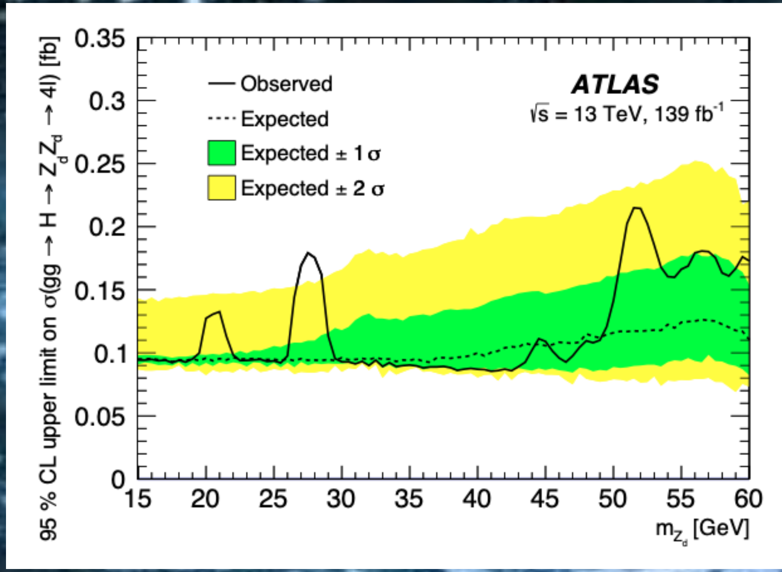
High mass limits

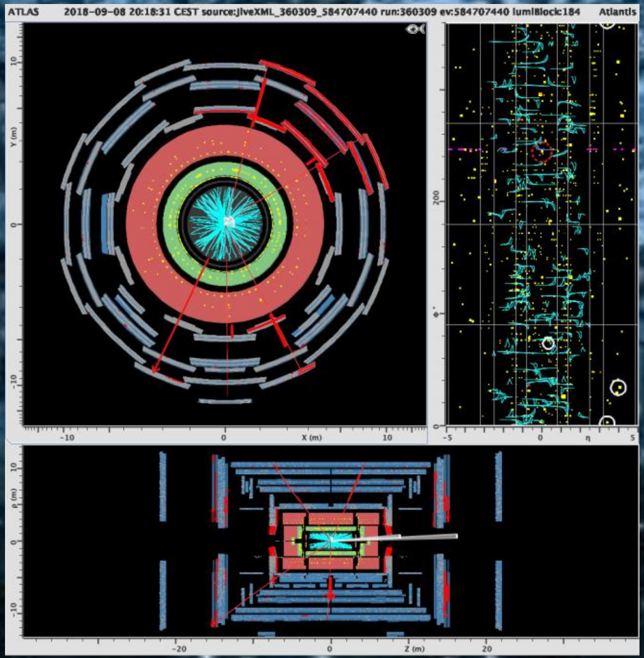
Additional scalar limits

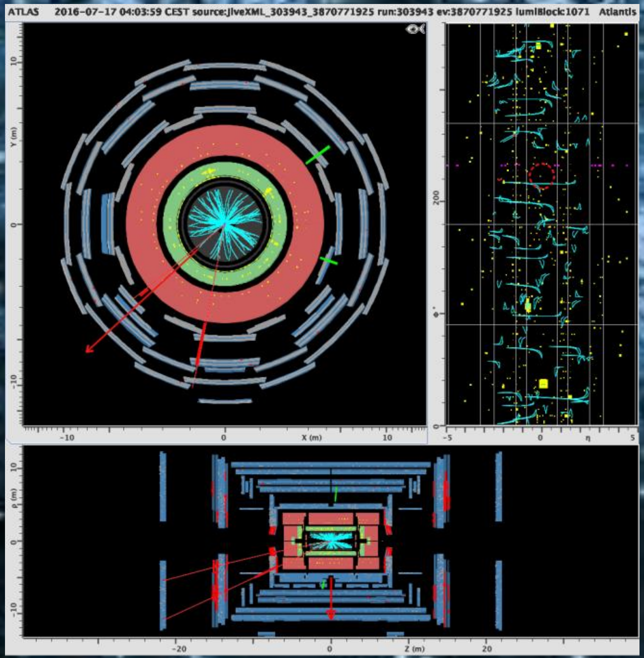
Motivation

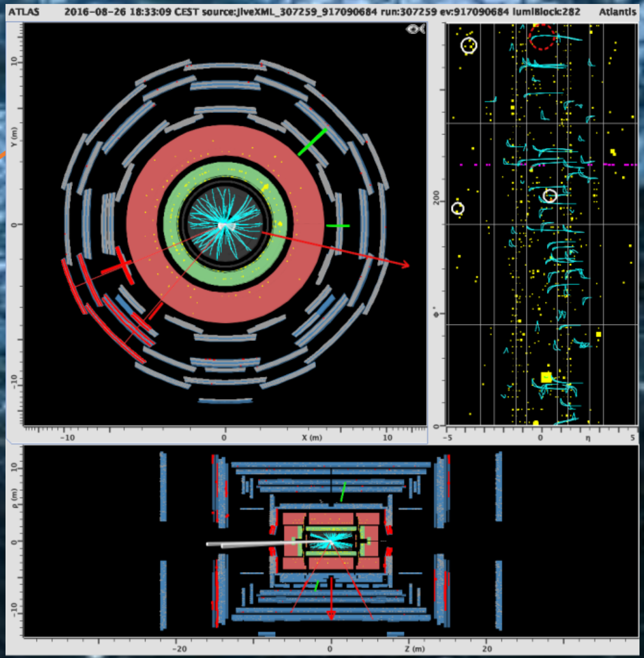
High mass Events

- When looking at the event displays of the events corresponding to the bumps, we noticed that there is a significant amount of missing energy



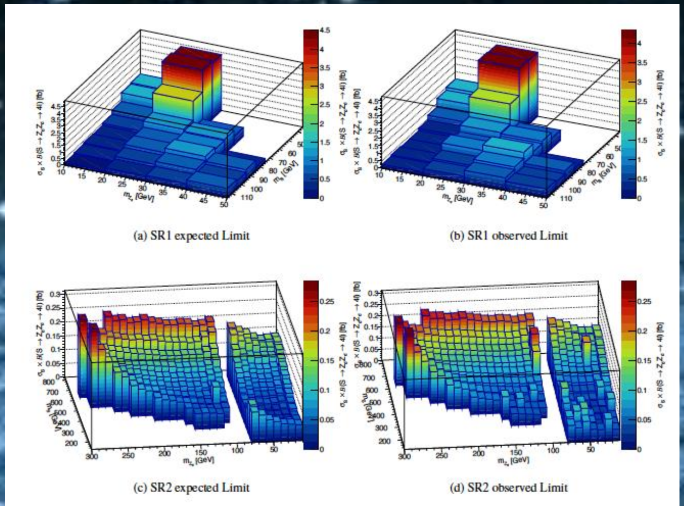






Motivation

Additional scalar Events



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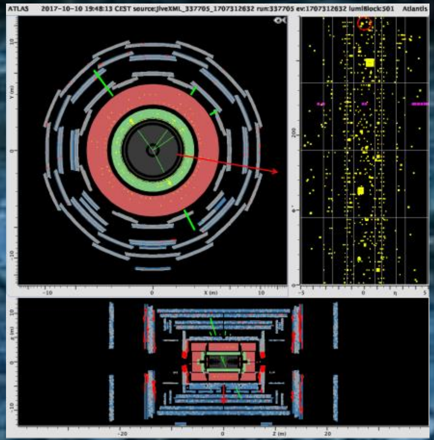
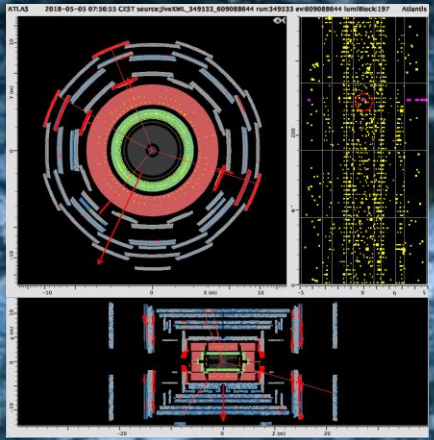
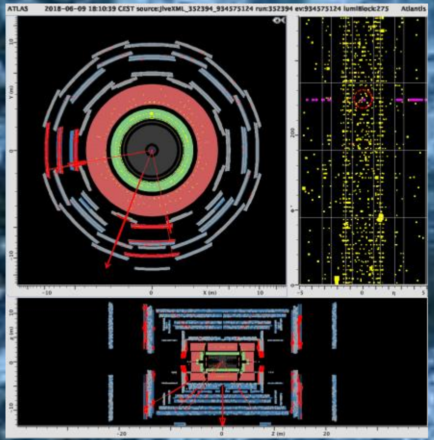
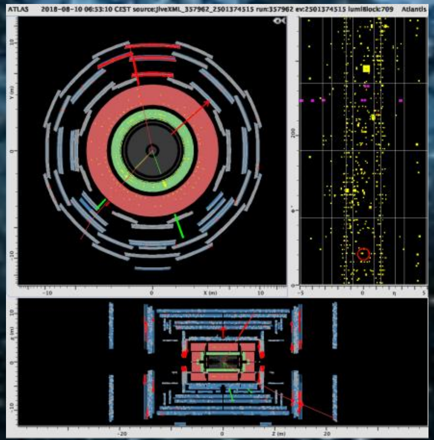
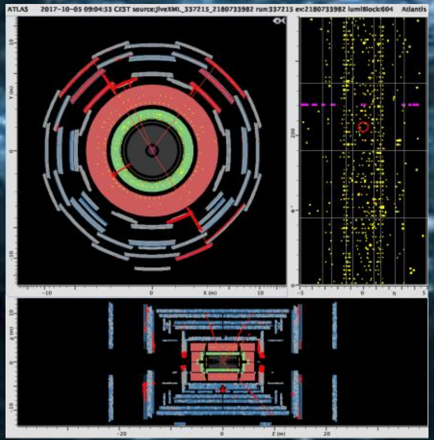




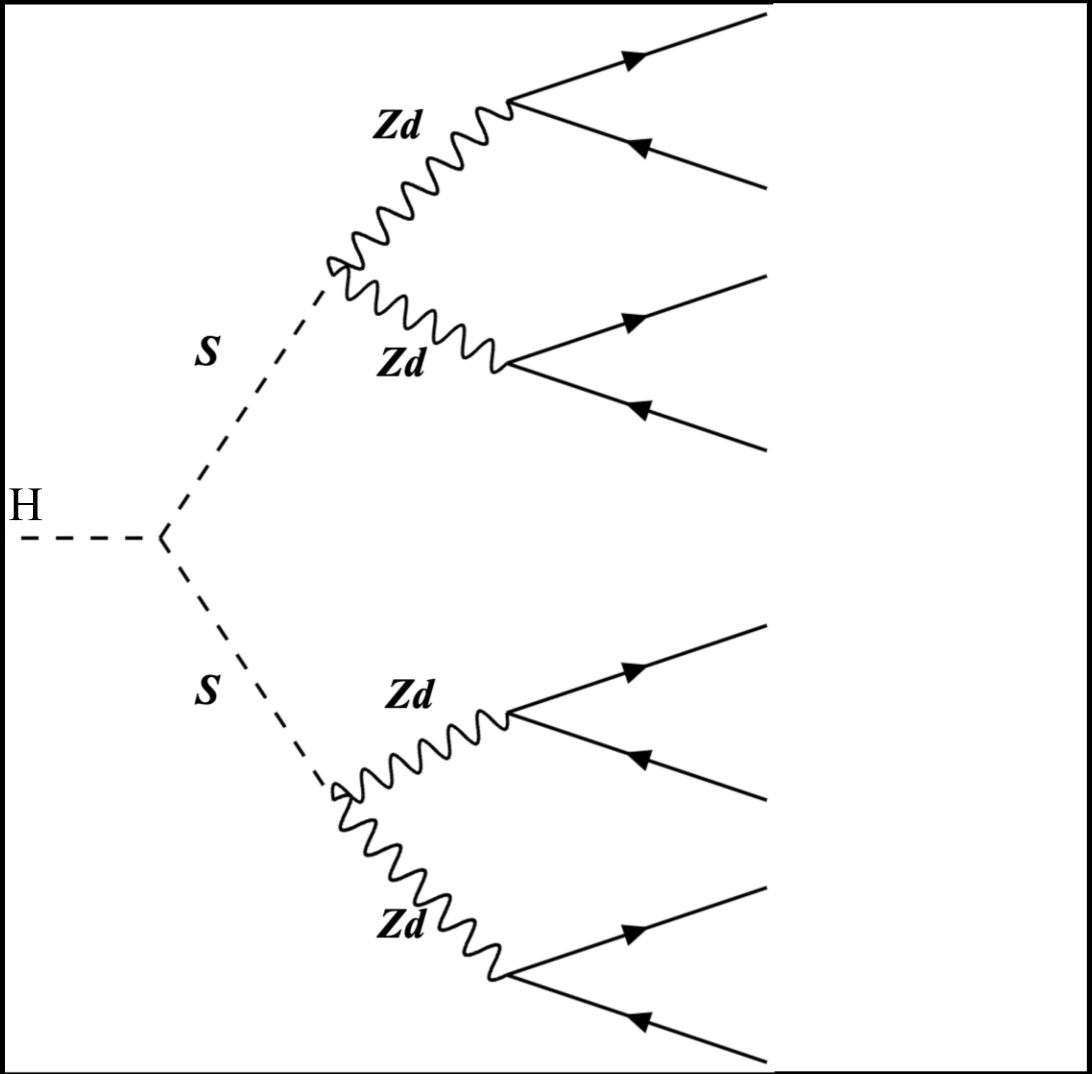






Hidden Abelian Higgs Model

- Altered the event generation code originally intended for 4l final state.
- Decay model final state goes to eight
- In our case, the signal we are looking for is where one of the scalars decays to a four neutrino final state while the other scalar goes to 4u, 4e or 2e2u



Possible decays

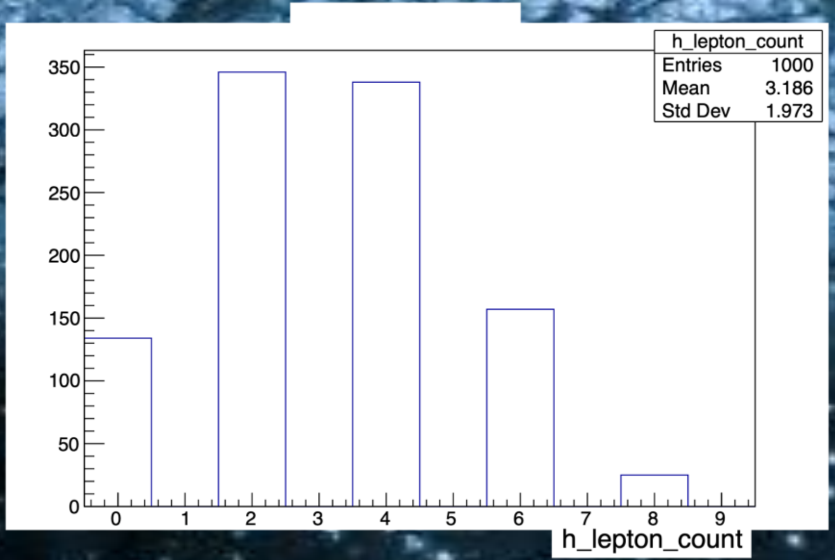
- Explore the number of combinations of the final state that are possible in this channel and found that there are eight possibilities
- Did a calculation of the probability of observing certain combinations
- Generated 1000 events to see which events are observed

Different configurations of final state leptons

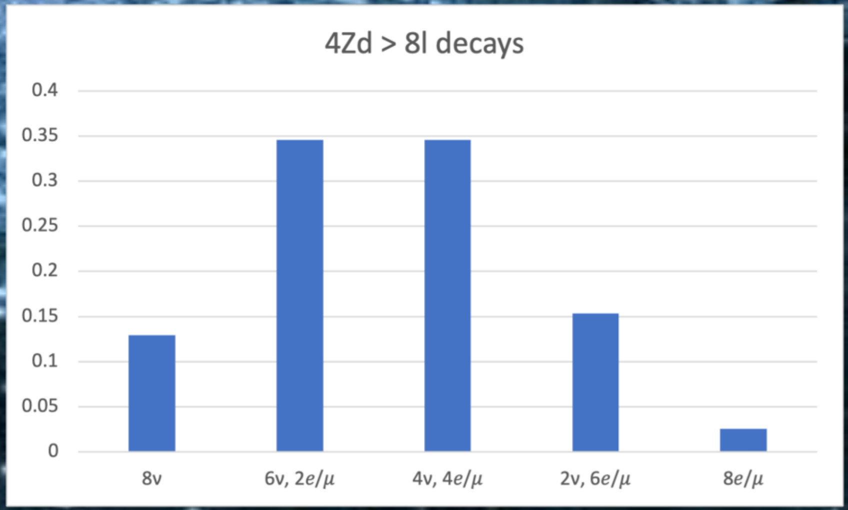
- 8ν
- 6ν, $2e/\nu$
- 4ν, $4e/\nu$
- 2ν, $6e/\nu$
- $8e/\nu$

For this analysis, we will concentrate on the 4ν, $4e/\mu$ configuration.

Event count



Probability calculation



Possible decays

- Found that P(4e/μ,4ν) ≈ 0.35
- Within the case of observing 4e/μ,4ν, there are a few more combinations of final states
- Generated 1000 events to see which events are observed, where P(4-4) = 0.1152, P(2-2-2-2) = 0.2304

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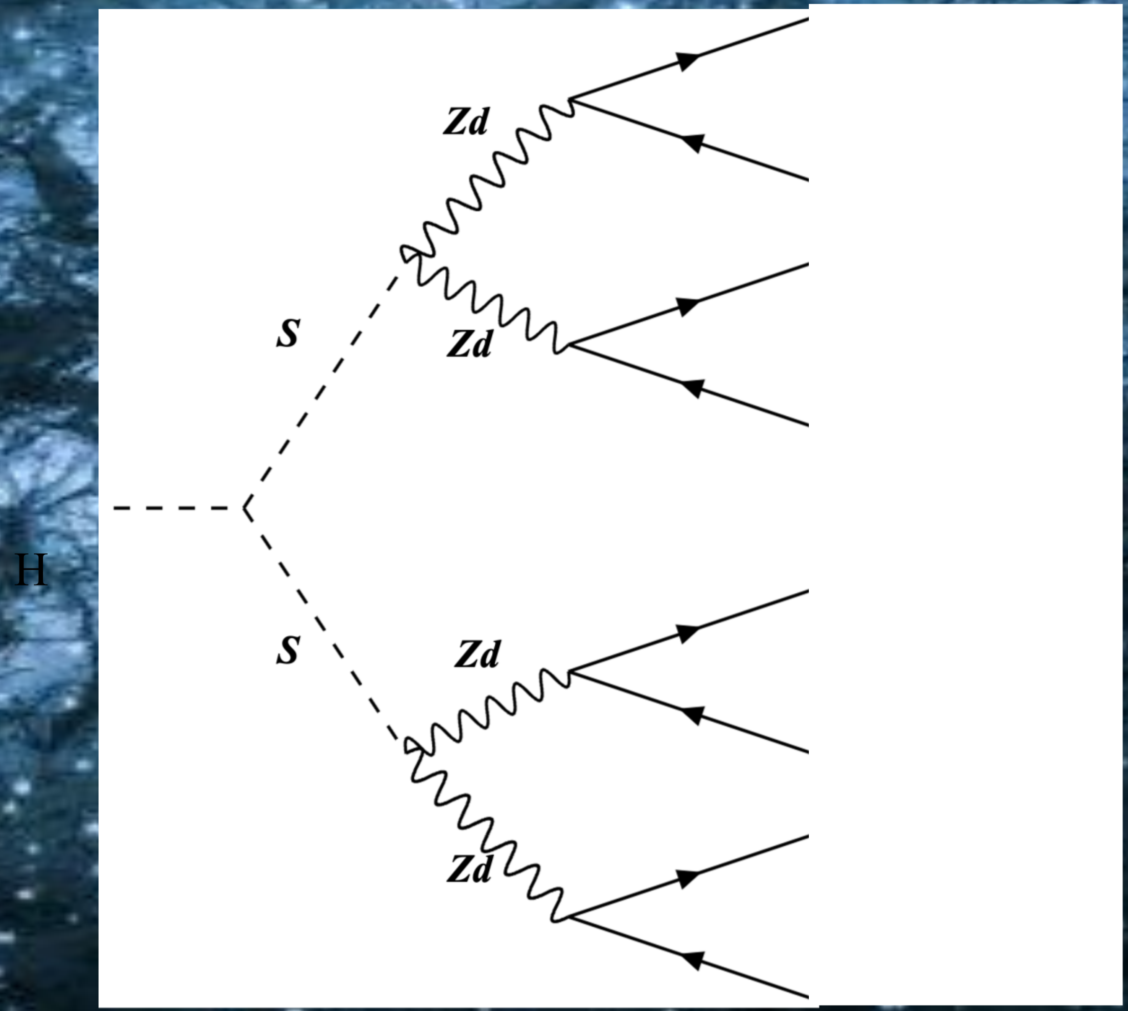
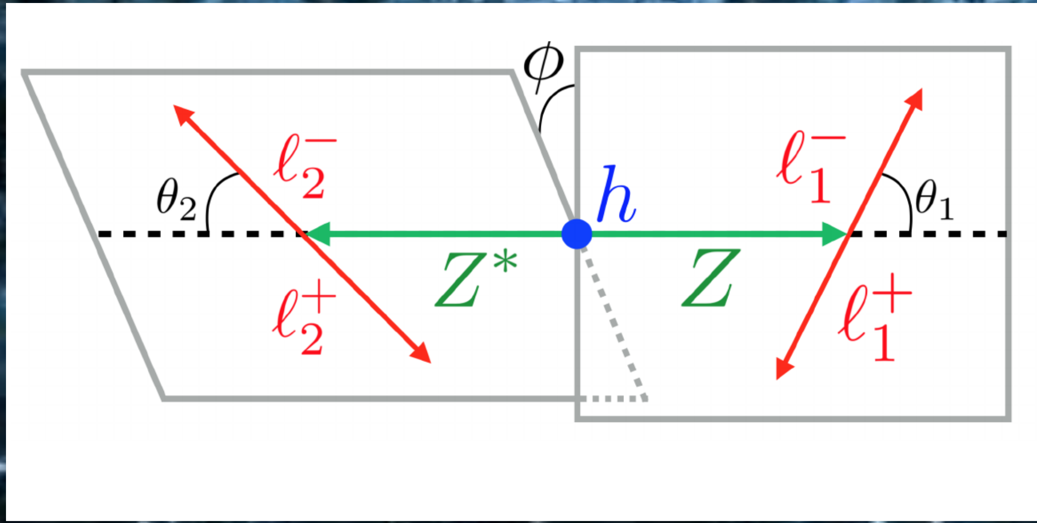
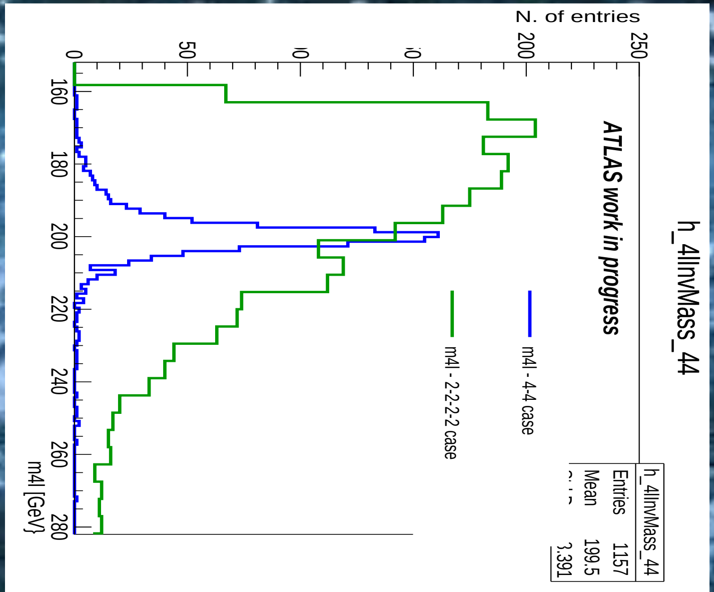


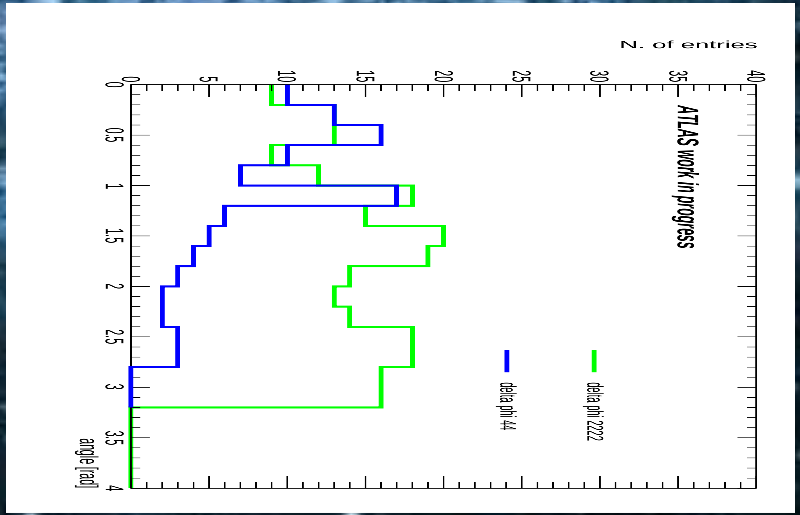
Discriminate between 2222 and 44 case

- Unlike the 4-4 case, the visible lepton pairs in the 2-2-2-2 case do not reconstruct to an Higgs-like particle. We therefore need a cut to discriminate the 2-2-2-2 events from the 4-4 case
- Generated 1000 events where H = 800 GeV and S = 200GeV
- Therefore formulated a few ways to find a discriminator which include:
    - Comparing the distributions of the angle ϕ formed by the planes lepton pairs decaying from Z_d in the reference frame of one of the S particles.



H





Discriminate between 2222 and 44 case

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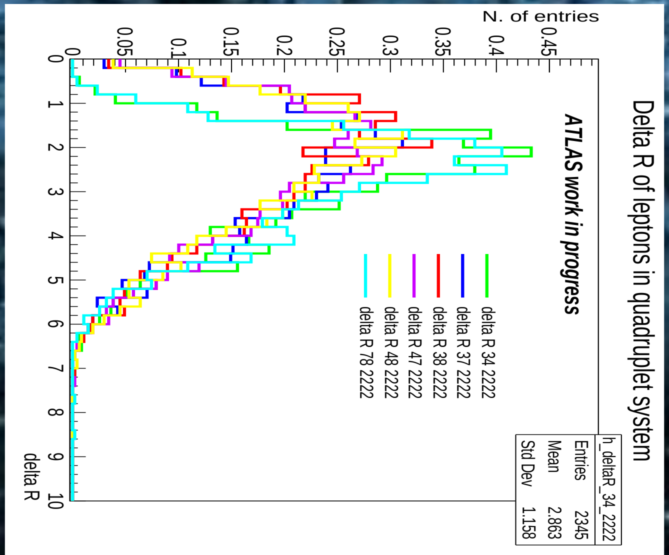
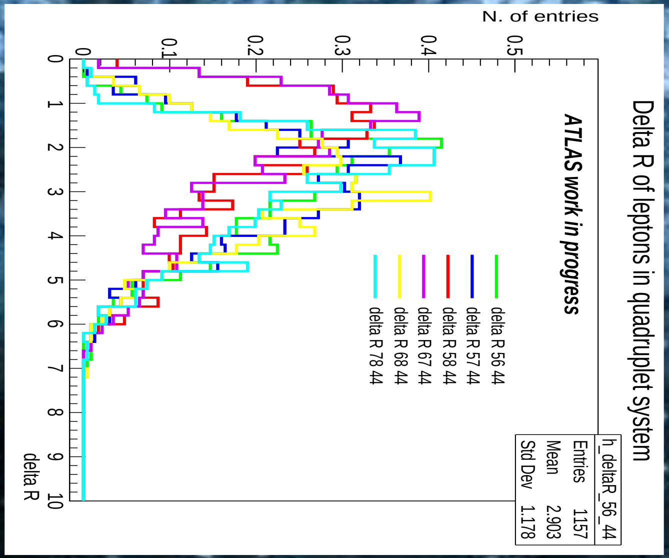
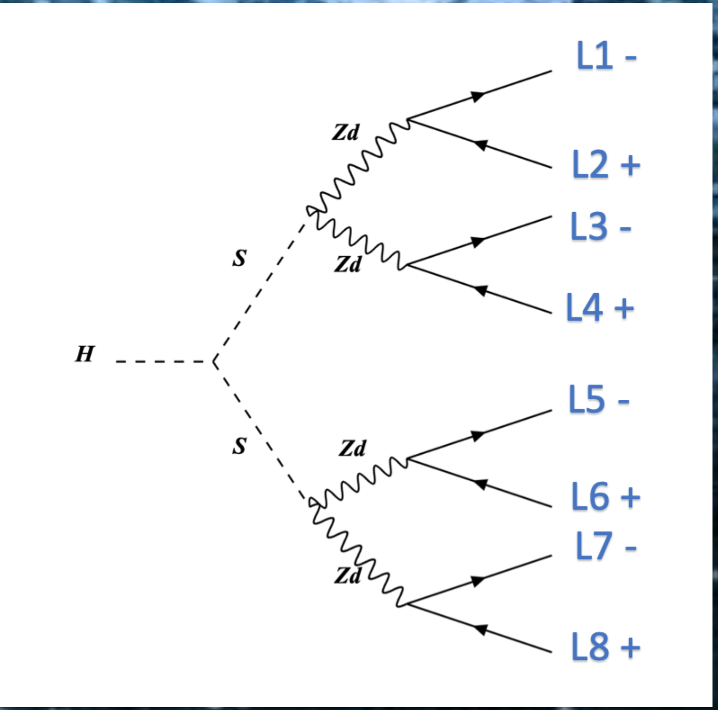
- Therefore formulated a few ways to find a discriminator which include:
    - Comparing the angular distance between the visible leptons in each case
    - Compare the angular distance between the Zd's that are reconstructed using the visible leptons
    - Calculated the angular distance using the following equation:
        - $\Delta R = \sqrt{\Delta\eta^2 + \Delta\emptyset^2}$







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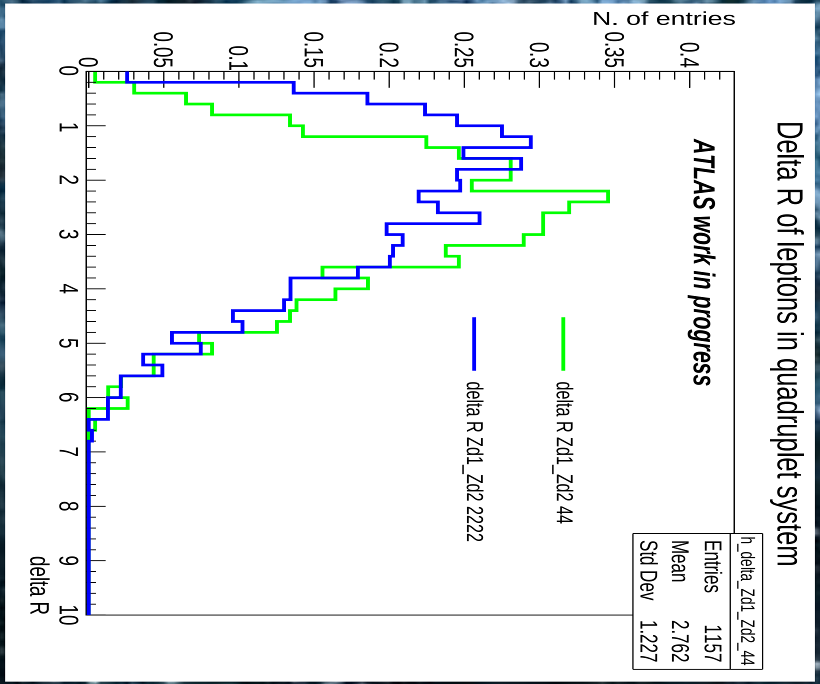
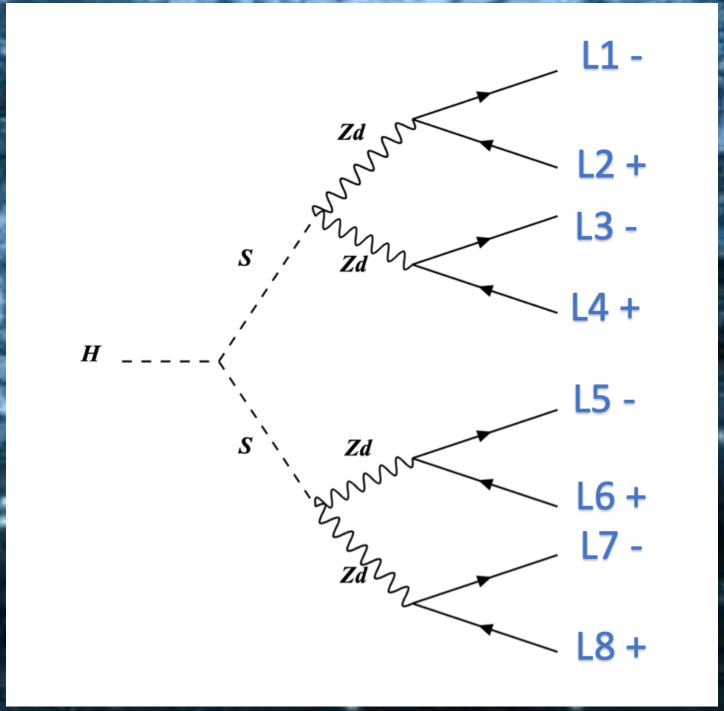


H



Conclusion

- No clear discriminator has been identified however there are some distinct shapes for each case
- Future plan is to use these discriminators to construct a boosted decision tree that tested as a discriminator

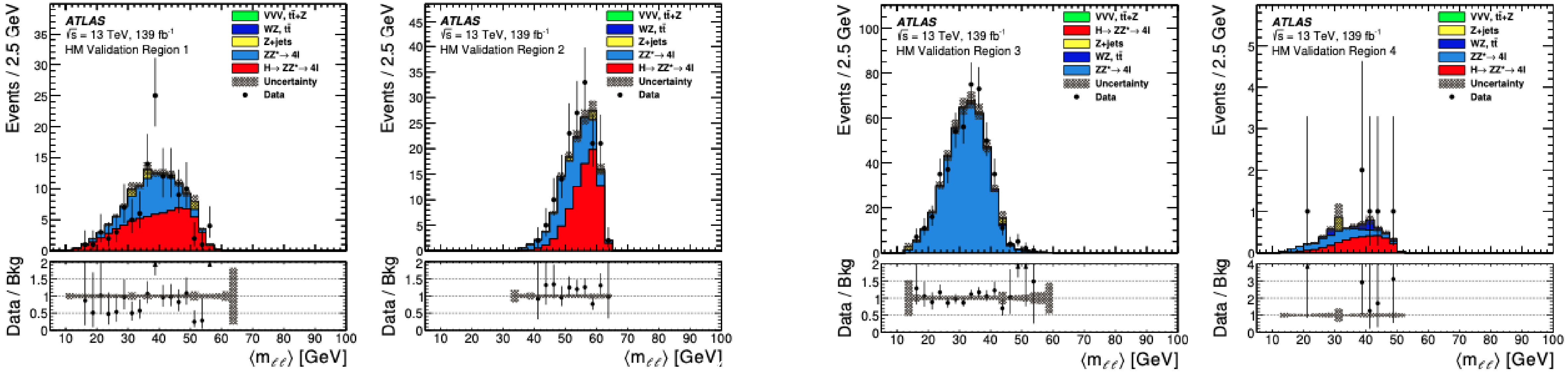
Event selection

- Final state objects of interest are electrons and muons
- Electron must be within central region of the detector
- Muons must be within acceptance region of muon spectrometer
- Look for quadruplet containing two Same Flavor Opposite Sign lepton pairs. Quadruplet with smallest lepton pair mass difference is chosen
- Leptons in quadruplet must be isolated from other deposits in the Inner Detector and Calorimeter
- Invariant mass of quadruplet must be within Higgs window
- Quadruplet masses must comply with signal region requirement

	$H \to Z_d Z_d \to 4\ell$ ($\ell = e, \mu$)
Mass range	15 GeV $< m_{Z_d} <$ 60 GeV
Baseline electrons	$p_T >$ 7 GeV and $\lvert\eta\rvert < 2.47$ Loose identification with an IBL hit $\lvert z_0 \sin\theta\rvert < 0.5$ mm
Baseline muons	$p_T >$ 5 GeV (15 GeV if calo-tagged) and $\lvert\eta\rvert < 2.7$ Loose identification $\lvert z_0 \sin\theta\rvert < 0.5$ mm and $d_0 < 1$ mm (except for standalone muons)
Quadruplet selection	Require at least one quadruplet consisting of two pairs of same-flavour opposite-sign leptons Three leading-p_T leptons satisfying $p_T >$ 20 GeV, 15 GeV, 10 GeV Number of calorimeter-tagged muons plus number of standalone muons not greater than 1 At least one lepton in the quadruplet responsible for firing at least one trigger For di-lepton triggers, all leptons of the trigger must match leptons in the quadruplet Define pairs m_{12} and m_{34} such that $\lvert m_{12} - m_Z\rvert < \lvert m_{34} - m_Z\rvert$ $\Delta R(\ell, \ell') > 0.10\,(0.20)$ for same-flavour (different-flavour) leptons in the quadruplet
Quadruplet ranking	Select quadruplet with smallest $\Delta m_{\ell\ell} = \lvert m_{12} - m_{34}\rvert$
Event Selection	
Isolation impact parameter	Track and calorimeter isolation Excluding tracks/clusters from other leptons in the quadruplet $d_0/\sigma_{d_0} < 5$ for electrons and $d_0/\sigma_{d_0} < 3$ for muons
$m_{4\ell}$	115 GeV $< m_{4\ell} <$ 130 GeV
Z-veto	10 GeV $< m_{12,34} <$ 64 GeV
Heavy-flavour veto	Reject event if $m_{12,34,14,23}$ in: ($m_{J/\Psi}$ − 0.25 GeV) to ($m_{\Psi(2S)}$ + 0.30 GeV), or ($m_{\Upsilon(1S)}$ − 0.70 GeV) to ($m_{\Upsilon(3S)}$ + 0.75 GeV)
Signal region	$m_{34}/m_{12} > 0.85 - 0.1125 f(m_{12})$

Background estimate

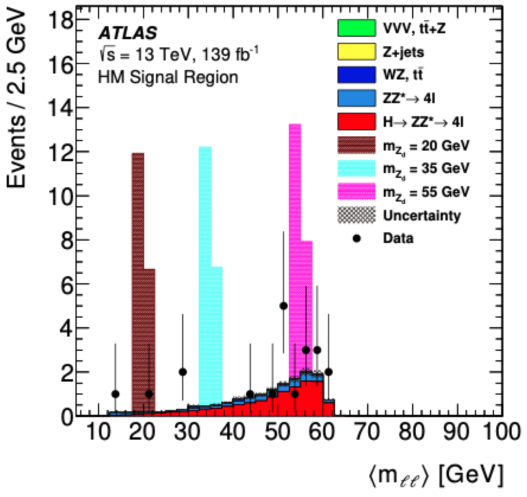
- VR1:Invert the Z-Veto requirement so that $m_{14,23} \geq 75\ GeV$ and signal region requirement is removed
- VR2: Requirement on four invariant mass pairings is removed and replaced with $m_{12} \geq 64\ GeV$
- VR3: Invert Higgs boson mass window and signal region requirement
- VR4: Invert signal region and require all four dilepton mass requirements to be $m_{ll} < 55\ GeV$

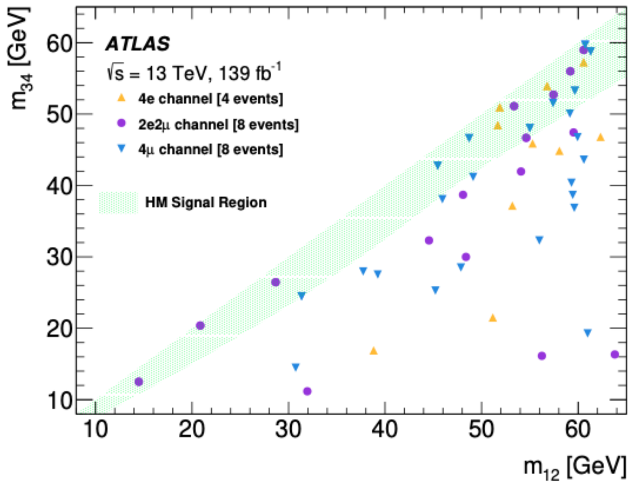


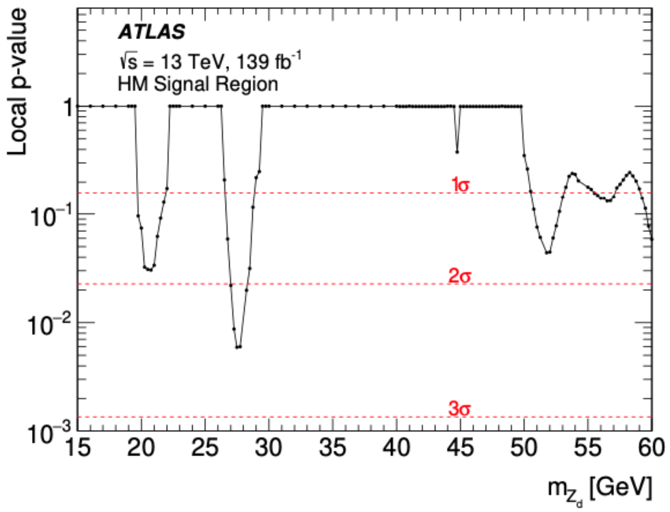
(a) (b) (c) (d)

Results

- Pre-fit background distributions together with data are shown on the left plot. Expected signal histograms are stacked on top of background and normalized with $\sigma(pp \rightarrow H \rightarrow Z_d Z_d \rightarrow 4l)$
- Total of 20 events are observed with a total predicted background of 15±1.3 events
- Used profile likelihood $-2log\left[\frac{L(\mu=0,\hat{\hat{\theta}})}{L(\mu,\hat{\theta})}\right]$ as the test statistic
- Biggest deviation observed at 28 GeV corresponding to a significance of 2.5σ







Limits and interpretation

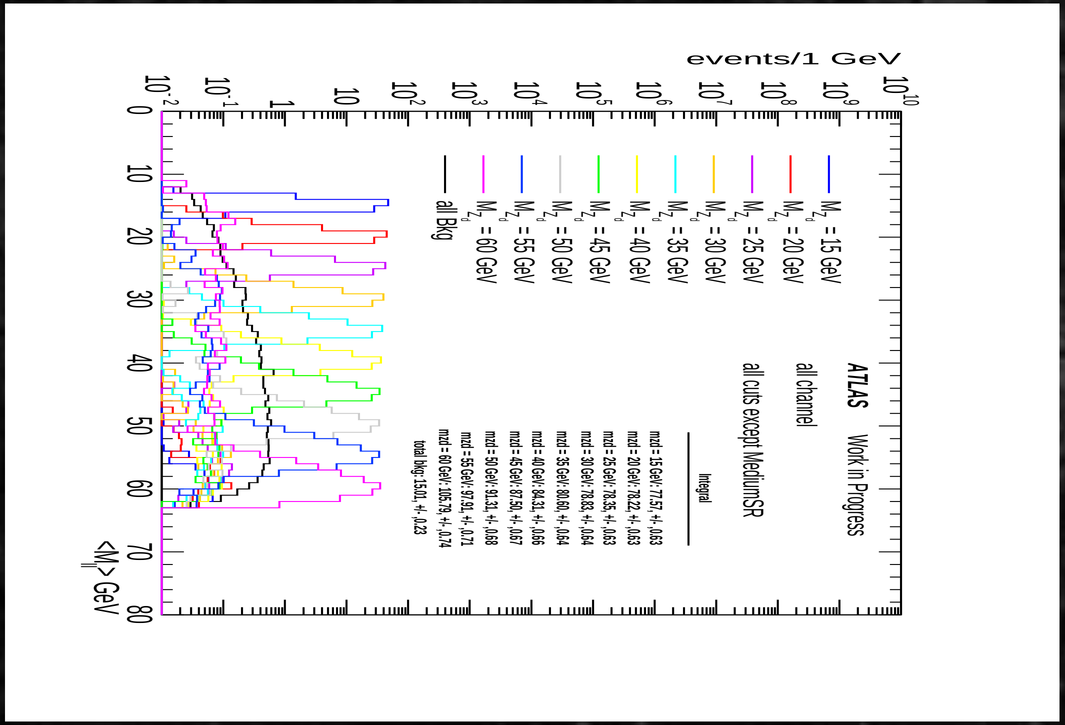
- No significant excesses observed. Therefore, we derive model independent limits based on fiducial regions
- Fiducial region selections designed to mimic full event selection
- These are used to factorized effects of event selection into largely model-independent efficiency and model dependent acceptance
- Efficiency is used to find the model independent cross-section limit which is converted into model dependent cross-section limit using the acceptance

	$H \to Z_d Z_d \to 4\ell$ ($\ell = e, \mu$)
Mass range	15 GeV < m_{Z_d} < 60 GeV
Electrons	p_T > 7 GeV $\lvert\eta\rvert$ < 2.5
Muons	p_T > 5 GeV $\lvert\eta\rvert$ < 2.7
Quadruplet	Three leading-p_T leptons satisfying p_T > 20 GeV, 15 GeV, 10 GeV
	ΔR > 0.10(0.20) between same-flavour (different flavour) leptons
	m_{34}/m_{12} > 0.85 - 0.1125 $f(m_{12})$
	10 GeV < $m_{12,34}$ < 64 GeV For 4e and 4μ channels: 5 GeV < $m_{14,23}$ < 75 GeV
	Reject event if $m_{12,34,14,23}$ in either: ($m_{J/\psi}$ − 0.25 GeV) to ($m_{\psi(2S)}$ + 0.30 GeV), or ($m_{\Upsilon(1S)}$ − 0.70 GeV) to ($m_{\Upsilon(3S)}$ + 0.75 GeV)

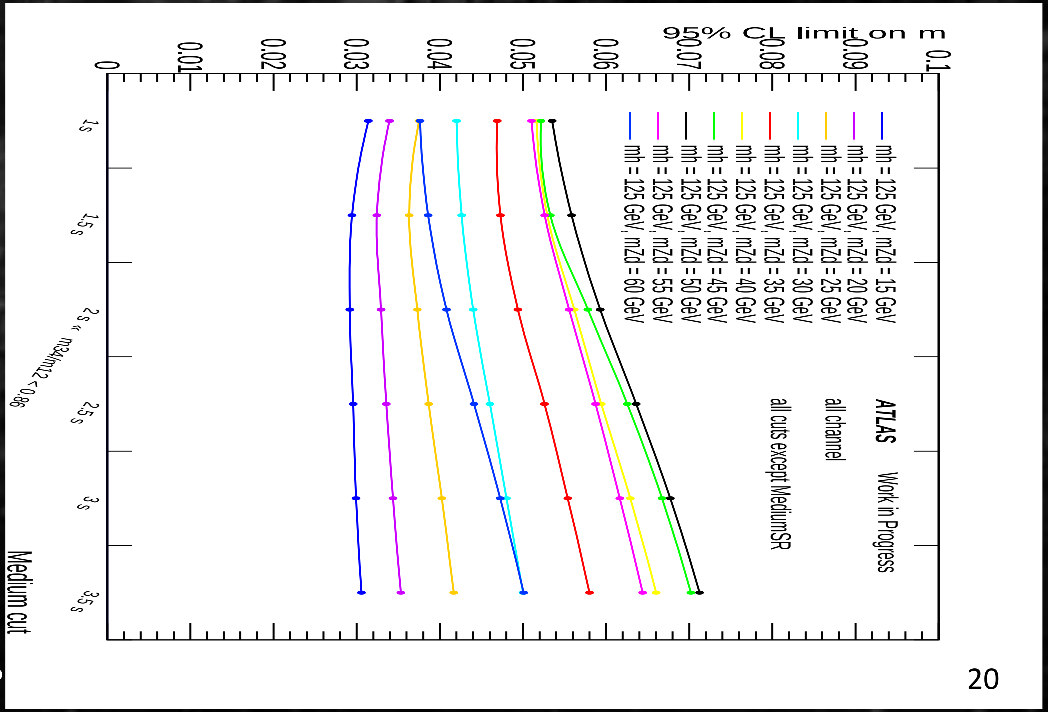
Thank you

Modification to Signal Region

- Background shape formed after applying all cuts except MSR cut with signals for various values of m_{Z_d} superimposed.

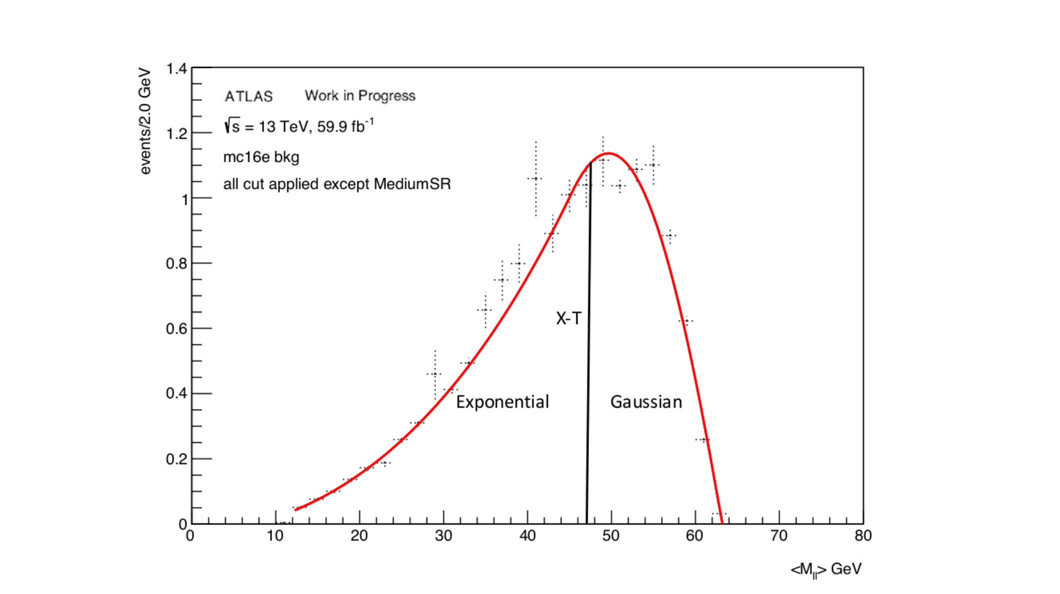


- In the model independent context, MSR can be broadened in the low mass region because of the small background.
- A study shows that increasing the MSR from 2σ to 3.5σ will increase the signal yield more than background for low m_{Z_d} masses while slightly less so for high m_{Z_d} masses. So a wider signal region is possible for the lower m_{Z_d} masses .



Modification to Signal Region

- Construct a modulated signal region using the shape of the background that will have a 3.5σ width from m_{Z_d} = 10GeV and decrease to 2σ at m_{Z_d} = 64 GeV. The background can be represented by a function consisting of an exponential attached to a Gaussian peak.



Function is given by:

$$F(x_i) = \begin{cases} B_1 + B_2(x_i - X) + he^{\frac{-(x_i - X)^2}{2\sigma^2}} & x_i > X - T \\ B_1 + B_2(x_i - X) + he^{\frac{-T(2x_i - 2X + T)}{2\sigma^2}} & x_i < X - T \end{cases}$$

- This function is then used to construct a modulating function using the following formula:

$$f(m_{12}) = 1 - \frac{F(m_{12}) - F(10)}{F(49.64) - F(10)}$$

Where:

$$f(m_{12}) = \begin{cases} 1 & m_{12} = 10GeV \\ 0 & m_{12} > 49.64GeV \end{cases}$$

Which gives the new Signal Region: