Search for Long-Lived Dark Photons & ATLAS Detector Upgrades

Connor Stewart, Columbia University

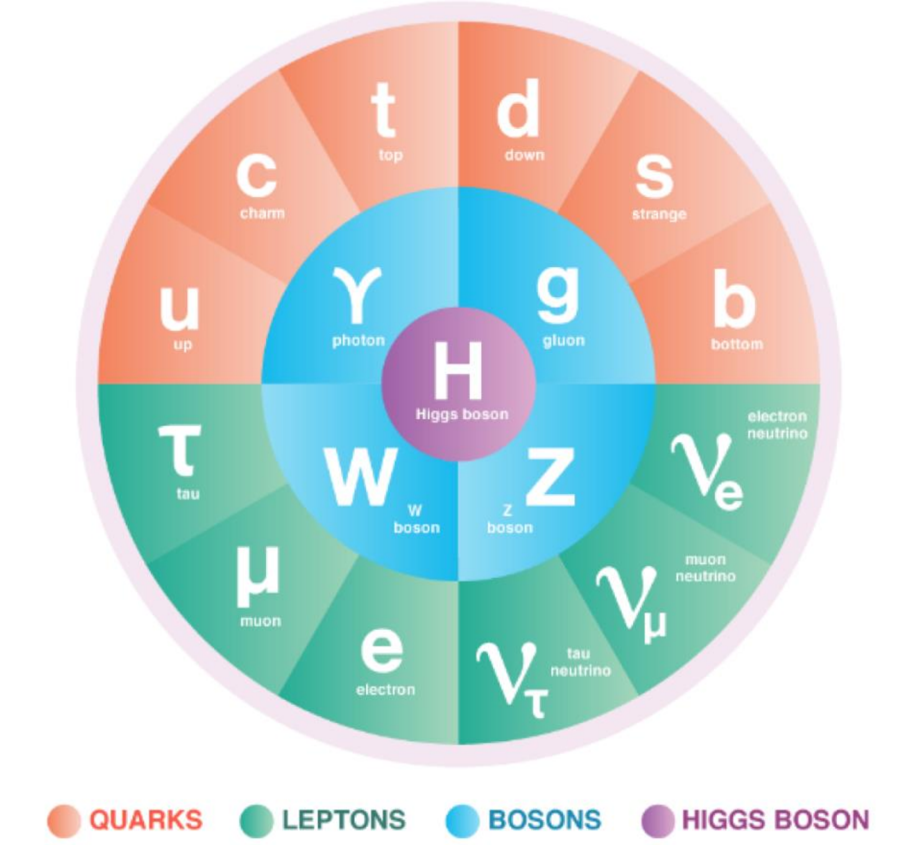
Nevis Laboratories
Columbia University

ATLAS Experiment

Introduction

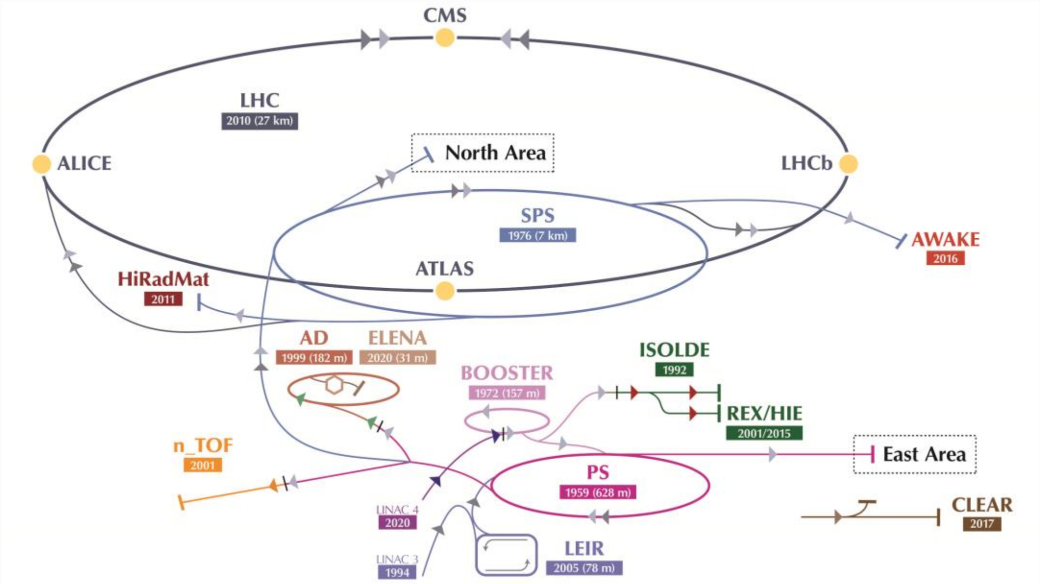
The Standard Model and Beyond

- Describes elementary particles and phenomena
- Classifies particles as:
  - Fermions: Quarks and leptons, coming in 3 generations, 1^{st} generation fermions make up stable particles
  - Bosons: Force carriers and the Higgs boson
- Still incomplete, with dark matter being one thing not accounted for despite making up 27% of the universe

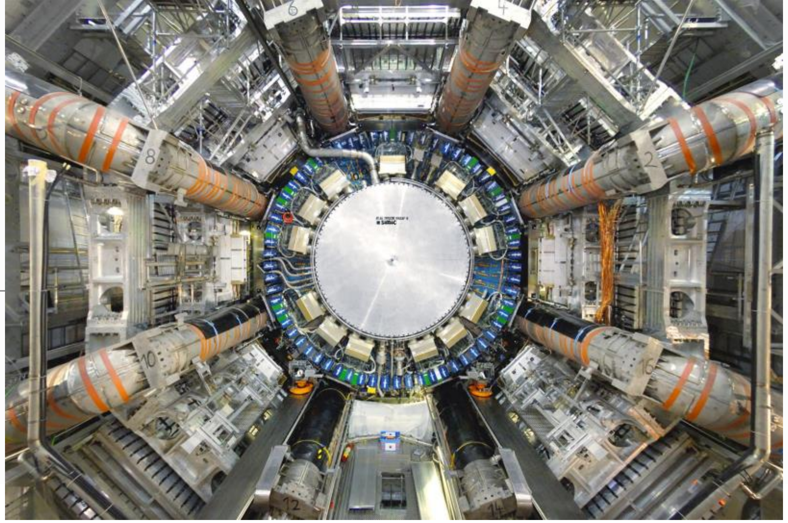


The Large Hadron Collider (LHC)

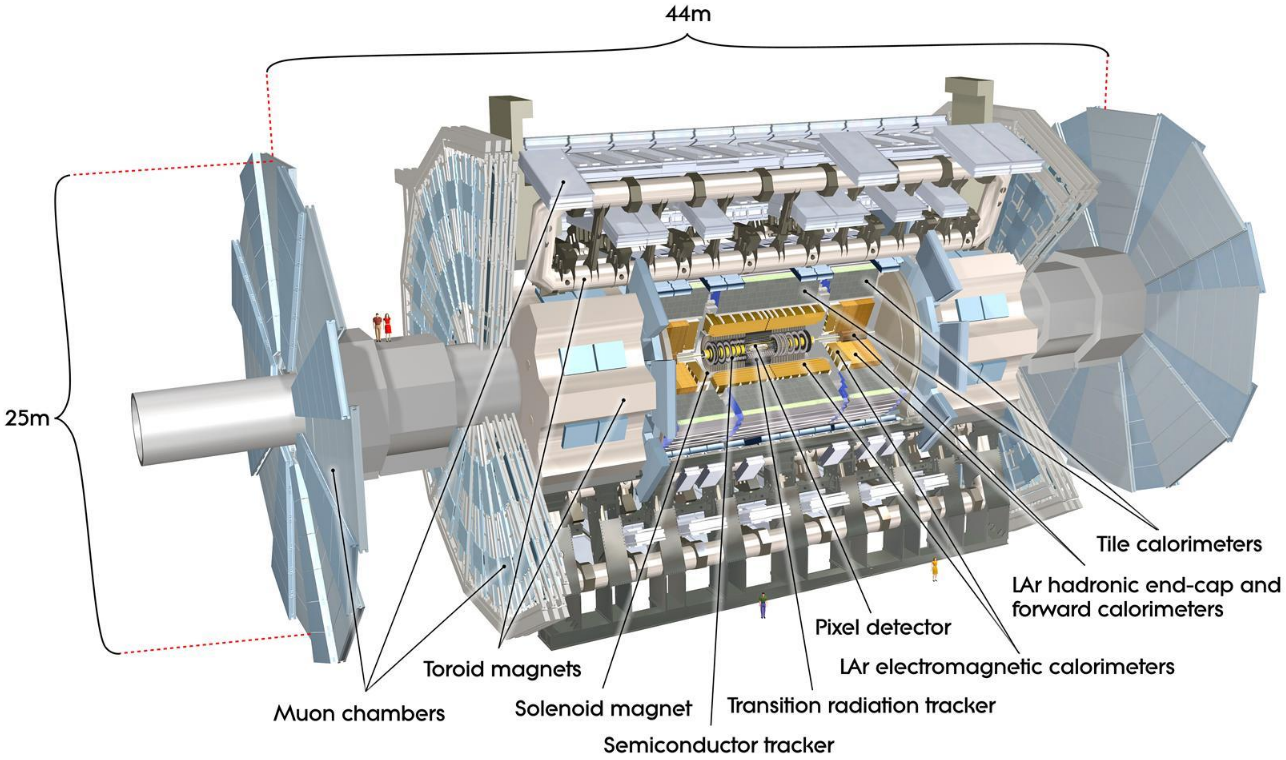
- Particle accelerator at CERN capable of proton-proton collisions at $\sqrt{s} = 14$ TeV
- Its tunnels are 27 km long under the French-Swiss border in Geneva
- Largest and highest-energy particle accelerator in the world



The ATLAS Detector



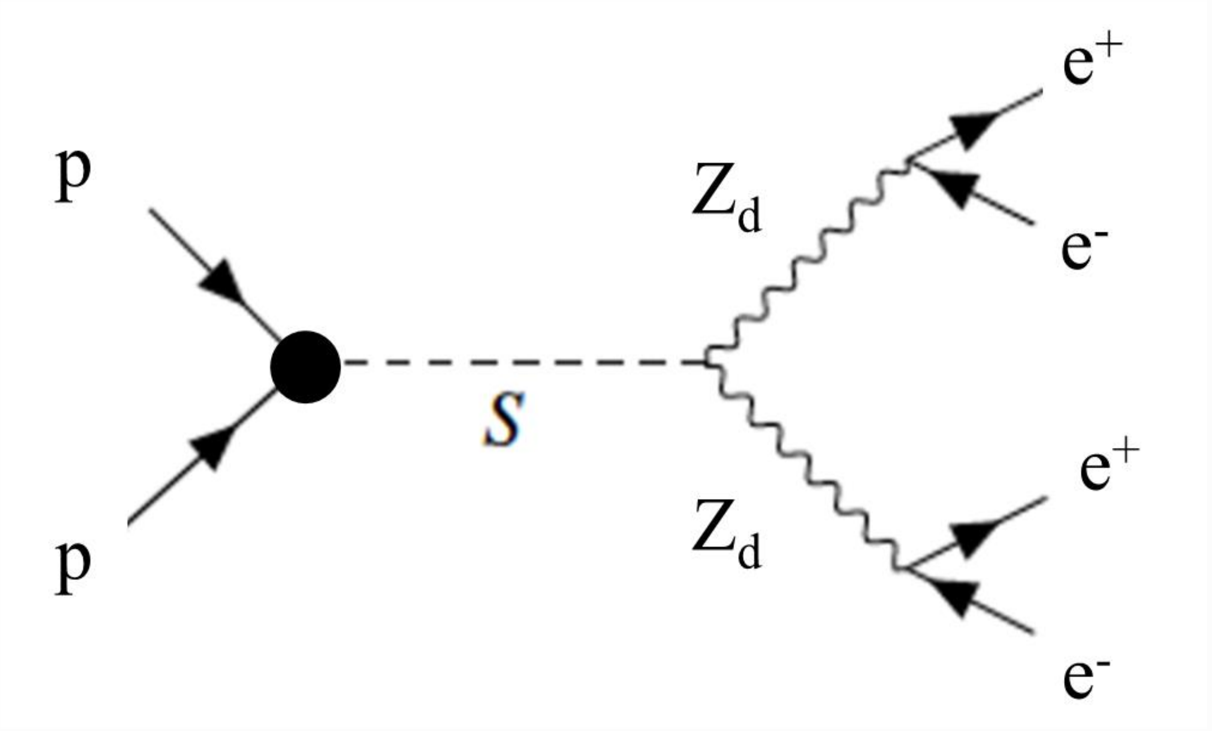
- One of 2 general purpose detectors at the LHC
- Weighs over 7000 tons and sees over 1,000,000,000 collisions per second
- Comprised of an inner detector, electromagnetic and hadronic calorimeters, and a muon spectrometer



Mass Resolution Study in Long-Lived Dark Photons Search

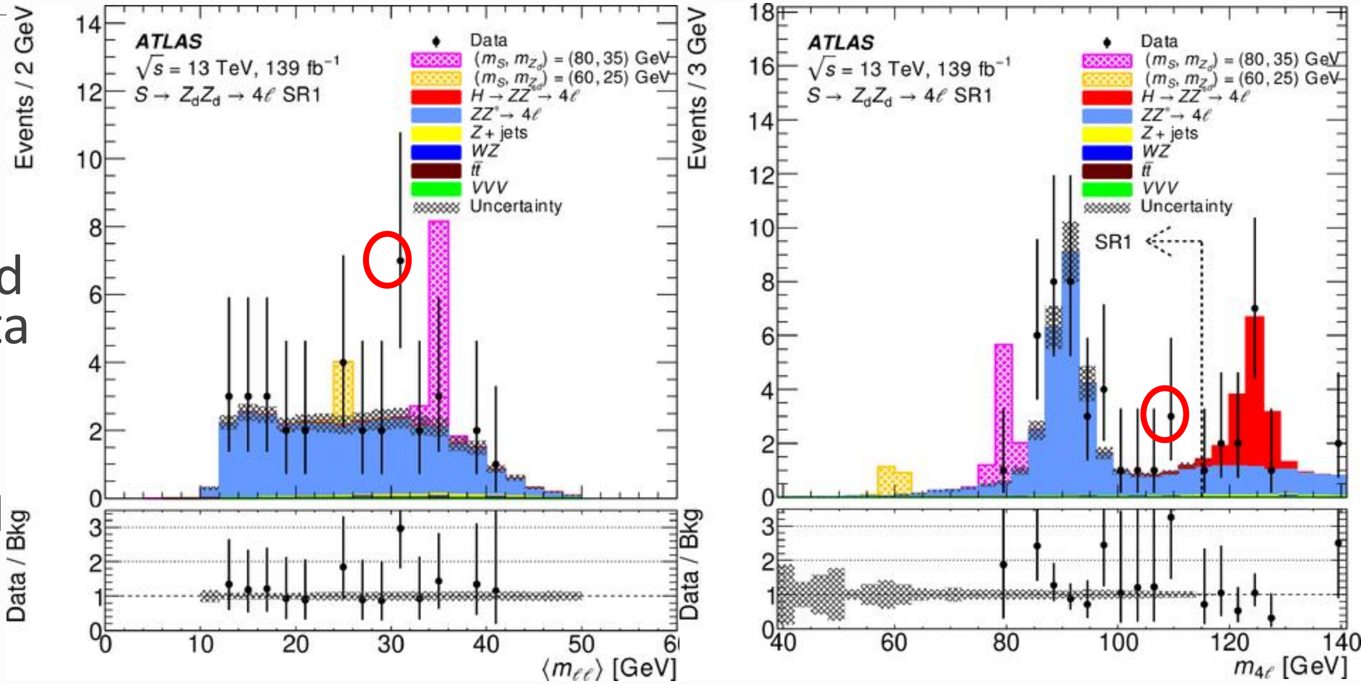
The Hidden Abelian Higgs Model (HAHM)

- One possible dark matter theory
- Proposes the existence of "dark photons" (Zd) which decay from a Higgs-like scalar (S) and into a 4-SM-fermion final state
  - We are interested specifically in the 4-electron final state
- The dark photons can have lifetimes to the order of picoseconds/nanoseconds (long-lived) if their coupling with SM fermions is small
- The parameters of this theory are S mass, Zd mass, and the lifetime of the dark photons



Prompt Dark Photons Search

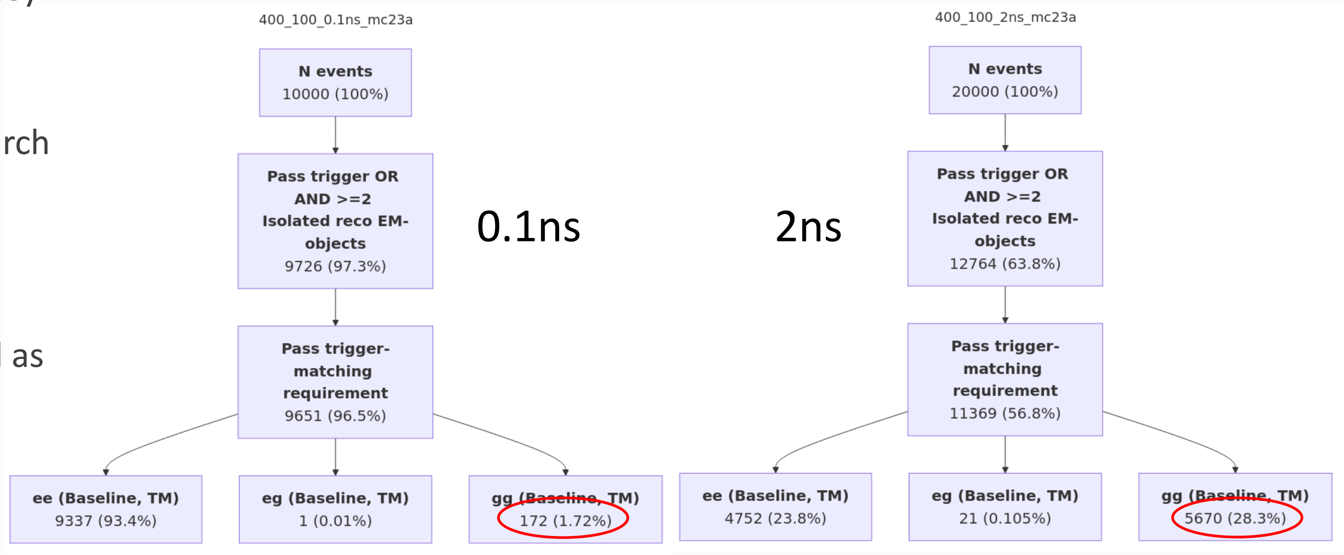
- A search for prompt dark photons (not long-lived) has already been conducted
- Filled-in histograms represent simulated background, the dots represent the data
  - $m_{\ell\ell}$ and $m_{4\ell}$ are the proxies for Zd and S masses respectively
- The data found agreement with the SM and set limits on the dark photon possibilities
- Found a small (1.6σ) excess around mS=110 GeV and mZd=30 GeV
  - This makes this mass point of special interest in the current long-lived search



https://arxiv.org/abs/2410.16781

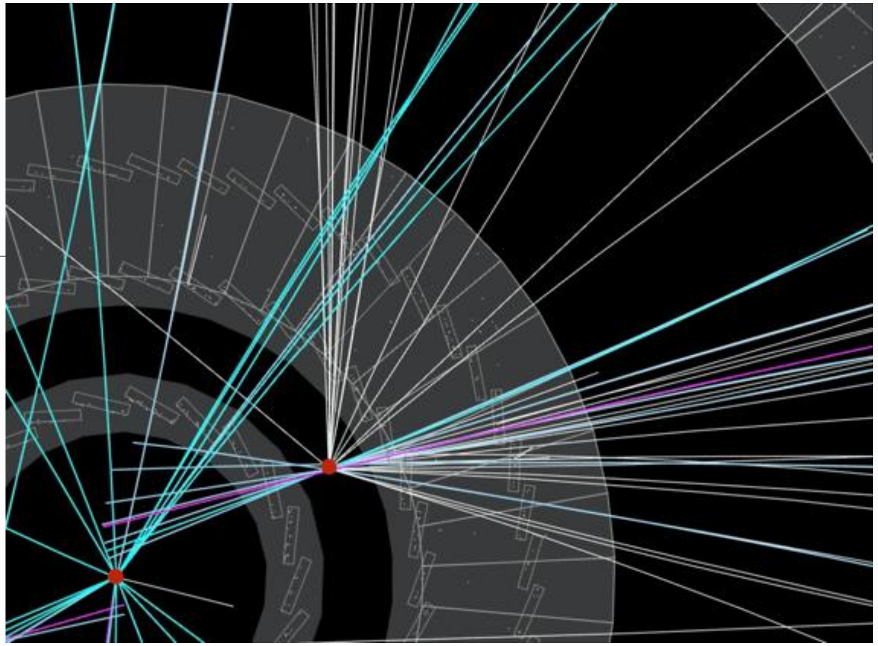
Long-Lived Dark Photons Search

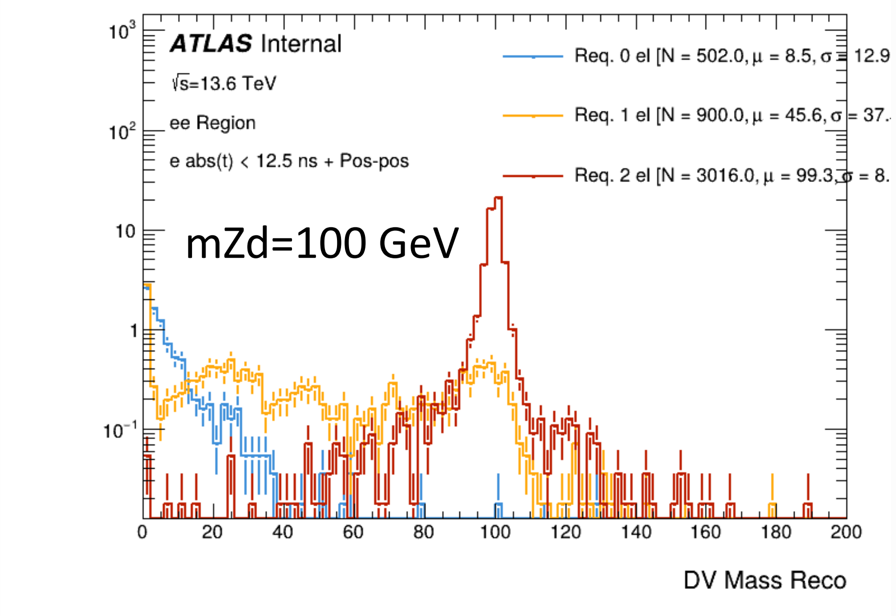
- The lifetime of long-lived particles allows the possibility that they move from the primary vertex before decaying at a displaced vertex (DV), resulting in displaced electrons
  - These could thus evade the limits of the prompt search and explain the relative faintness of the signal in the prompt search
  - We only require at least two objects instead of all four
- Our analysis looks at the "*ee* channel" with two reconstructed electrons
  - Displacement can lead to electrons being mis-reconstructed as photons, so others are working on the "γγ channel" for this case which can become increasingly important for longer lifetimes, with increased displacements leading to higher probabilities to miss the charged track in the inner detector
- We look at simulated signals with mS between 60 and 600 GeV, mZd between 10 and 290 GeV, and Zd lifetime values of 0.1, 0.5, 2, and 10 ns
  - This means we can also investigate the slight excess observed in the prompt search



Displaced Vertexing

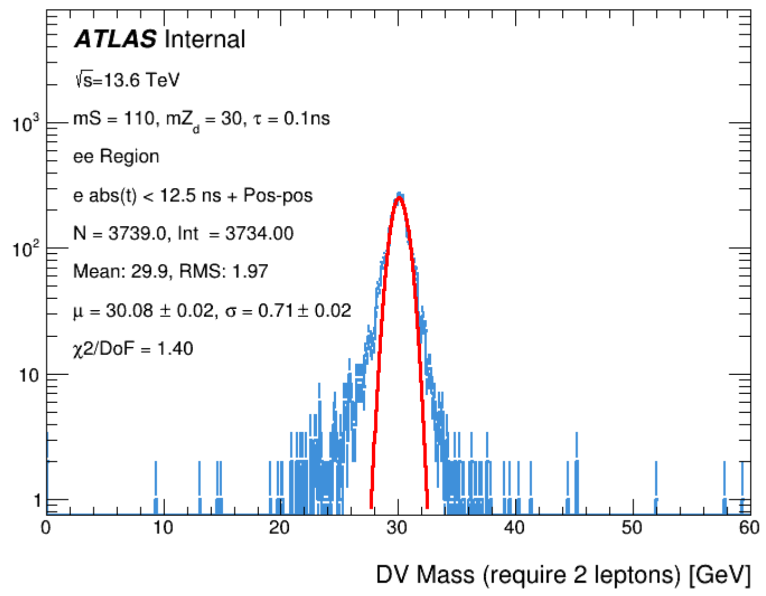
- Displaced Vertices (DVs) are where particle tracks meet which are far away from the primary vertex where collisions occur
- DV-matched electrons are electrons which are reconstructed and traced back to a DV
- Others have worked on optimizing an algorithm to sort candidate DVs based on charged particle tracks
- The reconstructed mass of the DVs heavily relies on the number of matched reconstructed electrons
  - The following study measuring how well the DV mass is reconstructed focuses on the (ideal) case with 2 reconstructed electrons per DV

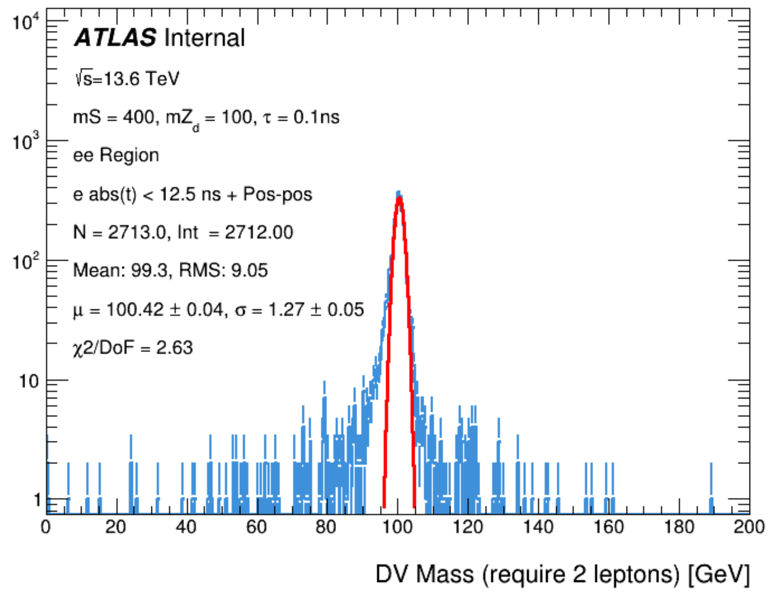




Mass Resolution Study

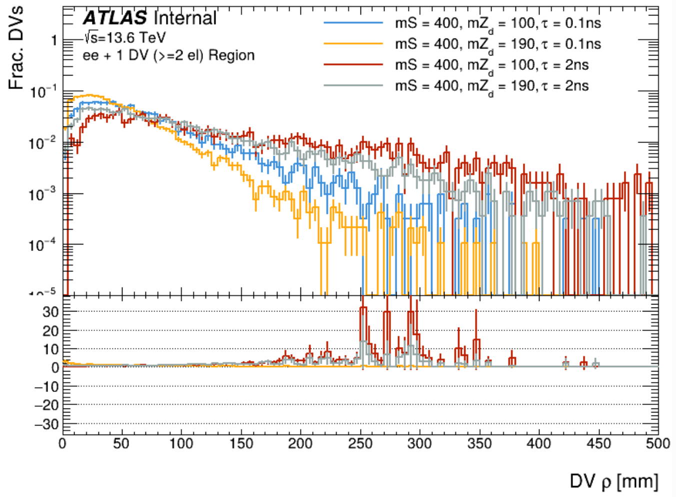
- My work involves studying the DV mass resolution
  - This means plotting the masses of DVs in Monte Carlo simulated signals and finding σ of a truncated gaussian fit
  - The fit is performed iteratively to focus on the core and account for non-gaussian tails
- The better (narrower) a signal's mass resolution is, the better we can reconstruct the mass of the Zd and therefore the better we can discriminate the signal from the background

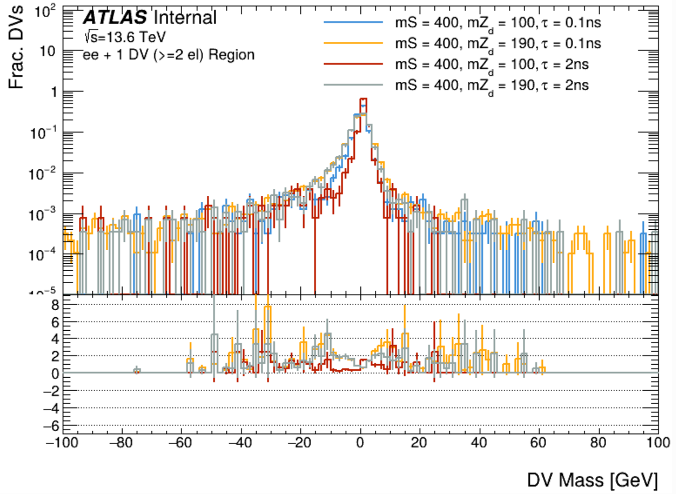




Looking Across Lifetimes/Masses

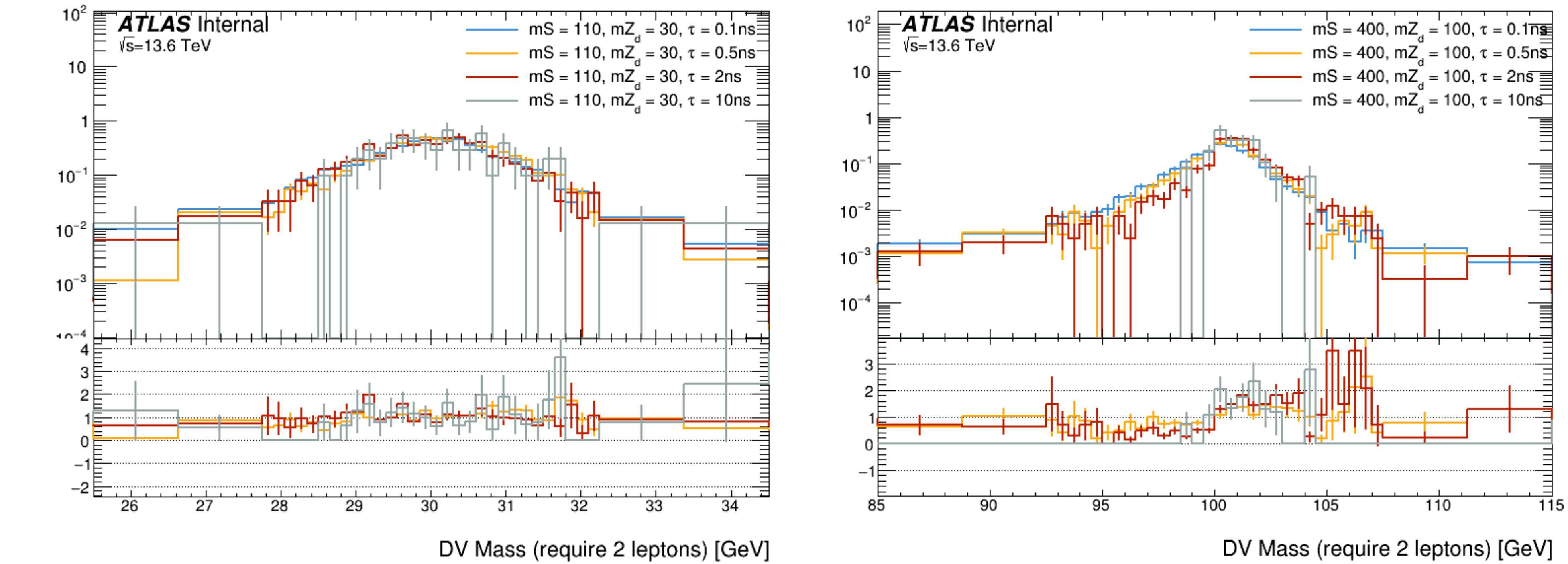
- We have Monte Carlo signal samples across 17 mass points each with 4 lifetimes
- We must account for differences in mass and in lifetime when performing the analysis
- Our studies showed that the mass resolution does not depend on lifetime (see next slide)





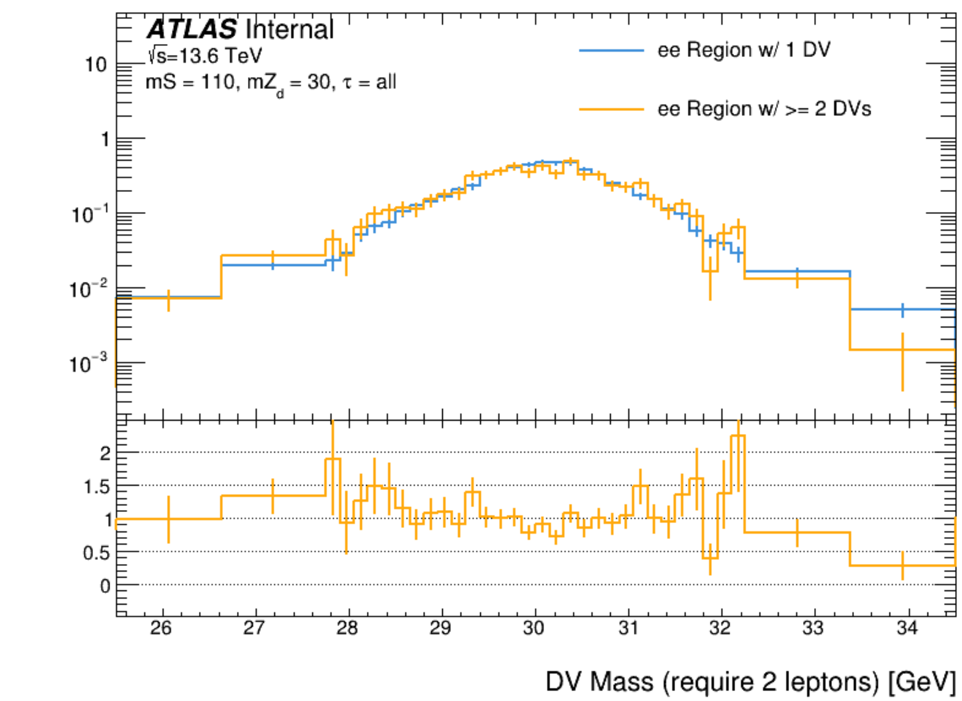
Resolution Dependence on Zd Lifetime

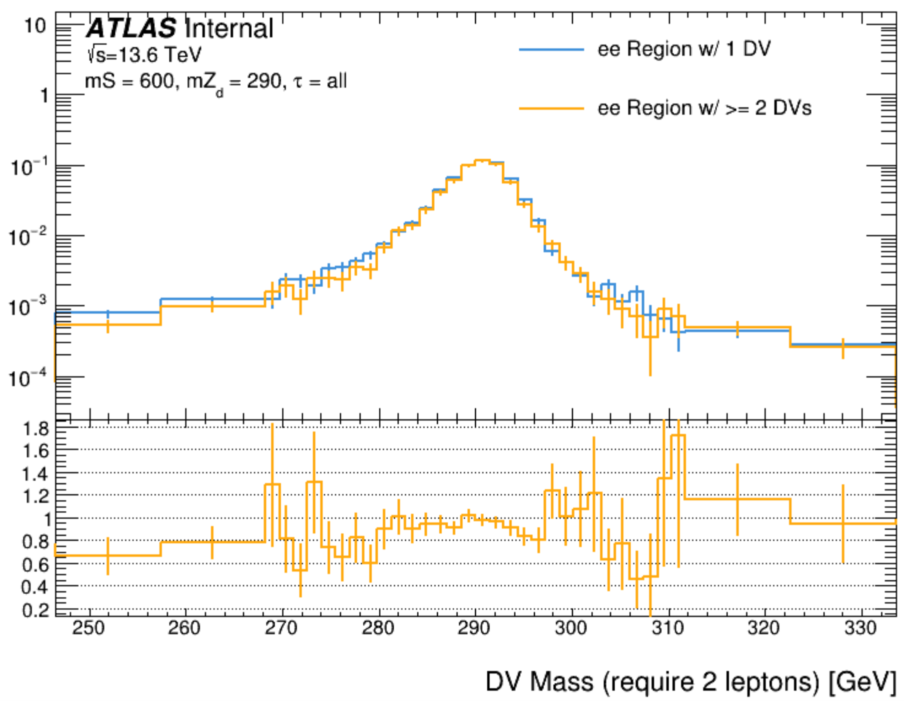
- First overlaid and normalized the mass histograms for all lifetimes on the same plot for each mass point
- There did not appear to be significant difference between the lifetimes, which justifies using the combined signals from all lifetimes together for this analysis
  - Instead, increasing lifetime just decreases the number of reconstructed DVs



Resolution Dependence on Number of Reconstructed DVs per Event

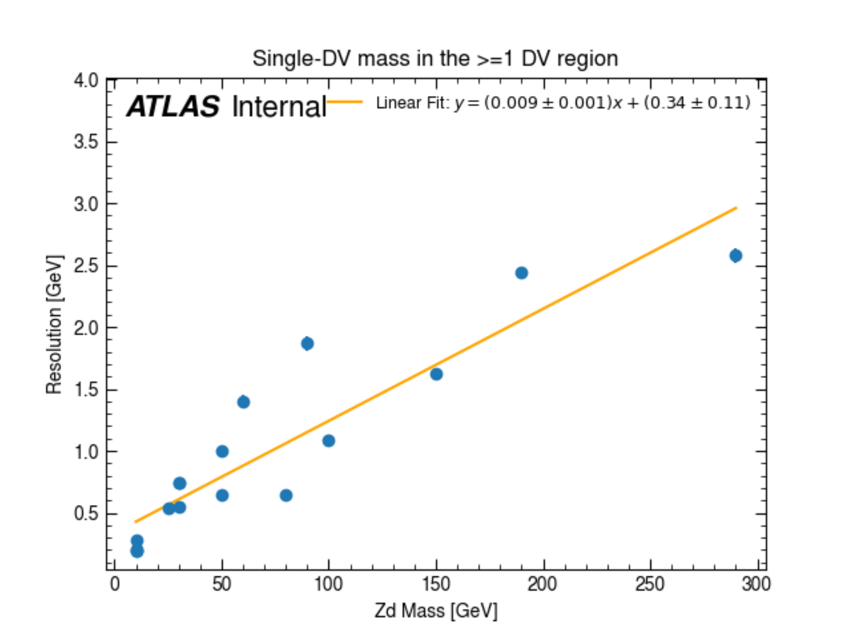
- There are cases where only 1 DV is detected per event, and others where we have at least 2 DVs, so we must look at these differently too in case there is a difference, as we're less likely to mistakenly pair electrons from different DVs if there are 2 reconstructed compared to if there is only 1
- Next overlaid and normalized the mass histograms for both regions
- Again, did not see a significant difference so we can focus on the combined region with at least 1 DV

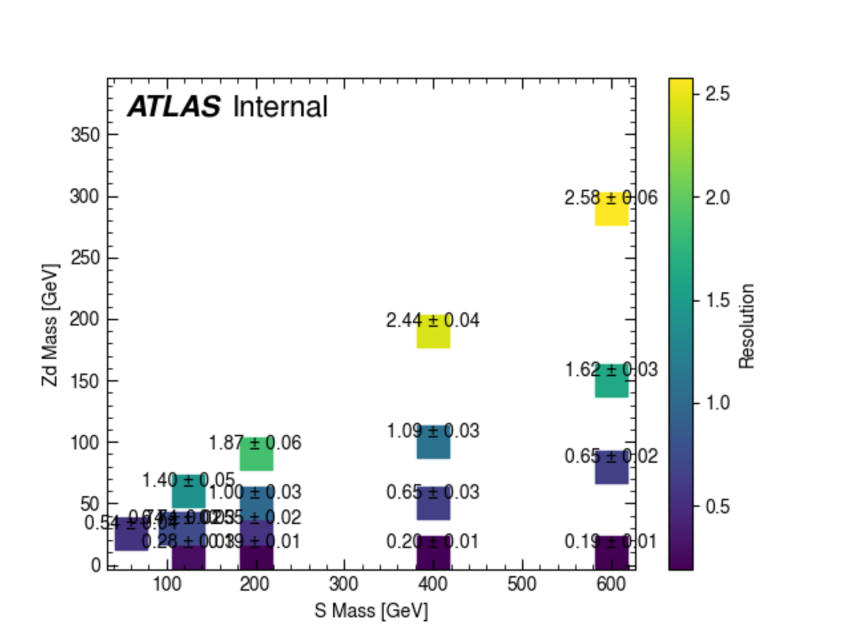




Mass Resolution Versus Zd Mass

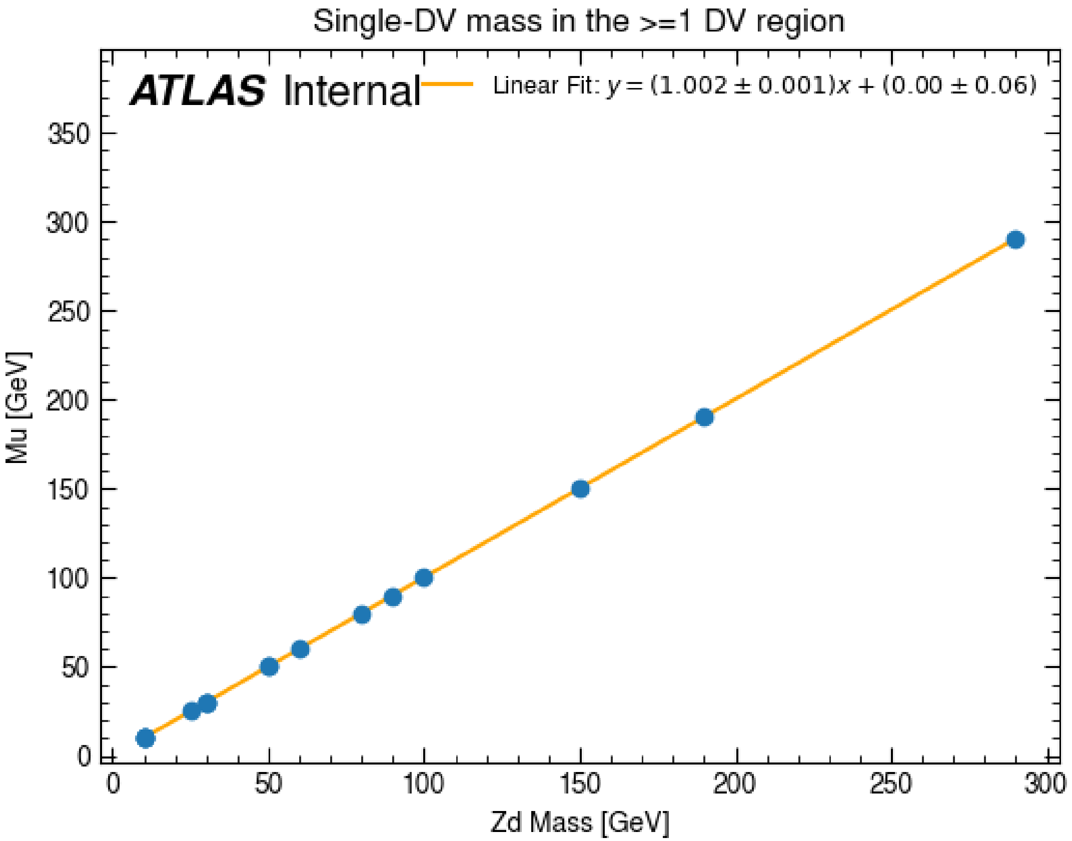
- Plotted, fitted, and retrieved the resolution for each mass point in this combined region
- Resolution follows a linear trend against mZd with a slope of .01
- Resolution also increases with smaller effect against mass splitting for a fixed mZd
  - This effect of mass splitting can explain the variation around the fit in the plot against mZd





Mu (Mean) vs Dark Photon Mass

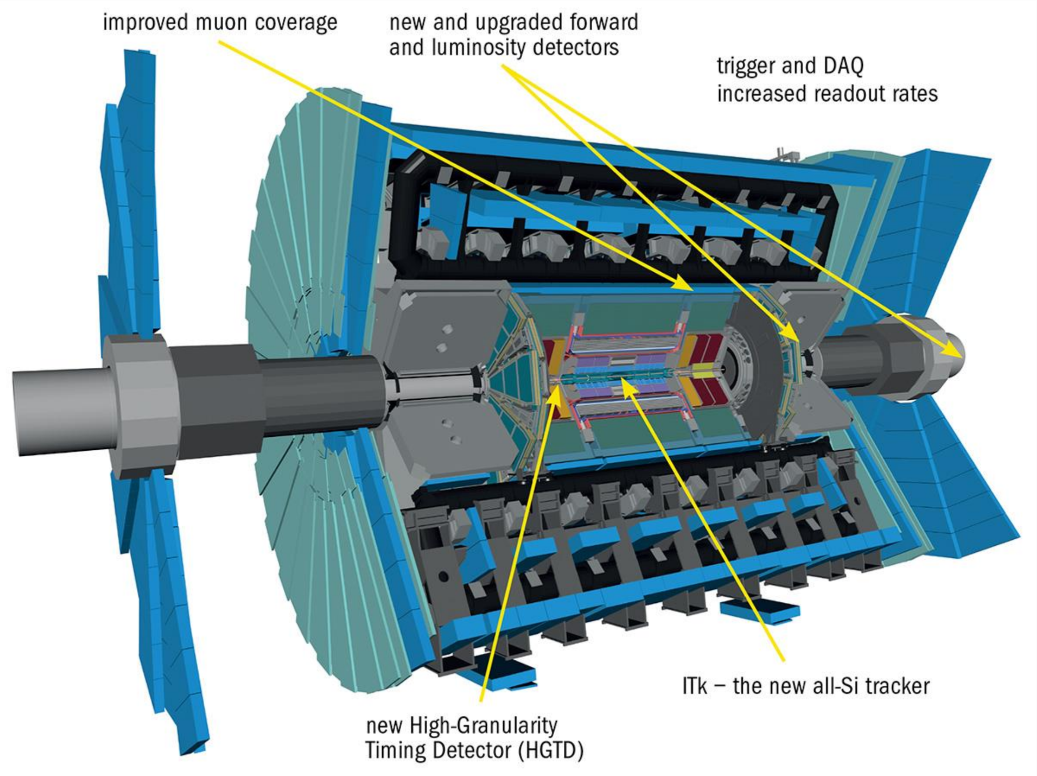
- To confirm linearity, the μ values of the gaussian distributions were also plotted against mZd
- Shows there is no observed bias in the reconstructed mass versus the truth mass, with a slope of 1 and an offset of 0



Front End Board Upgrades for the ATLAS Liquid Argon Calorimeter

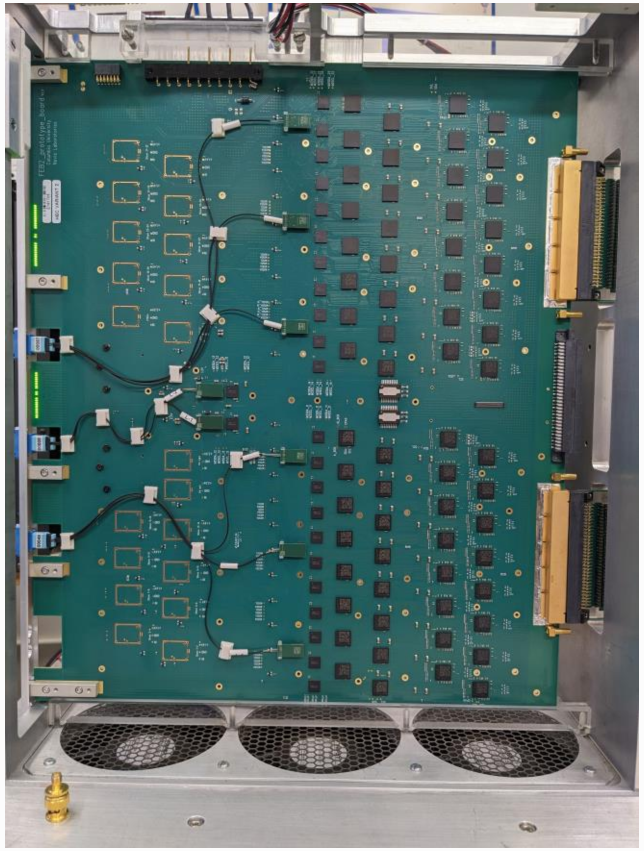
The High Luminosity LHC (HL-LHC)

- The LHC will soon be upgraded to the High Luminosity LHC which will produce a much higher (up to 10X) rate of particle collisions than we do now
- The larger rate of collisions will require upgrades to ATLAS and other detectors in order to handle the larger amount of events



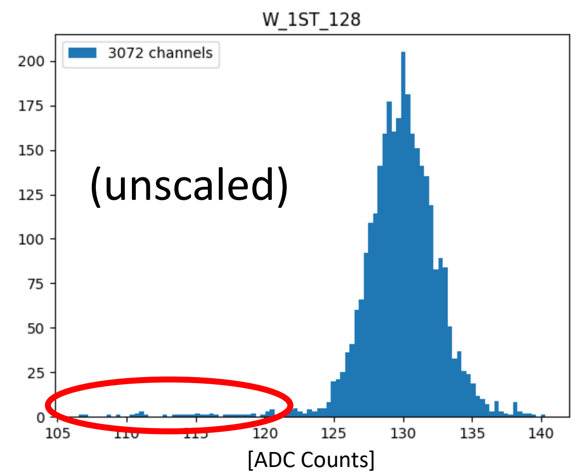
The Front-End Board 2 (FEB2)

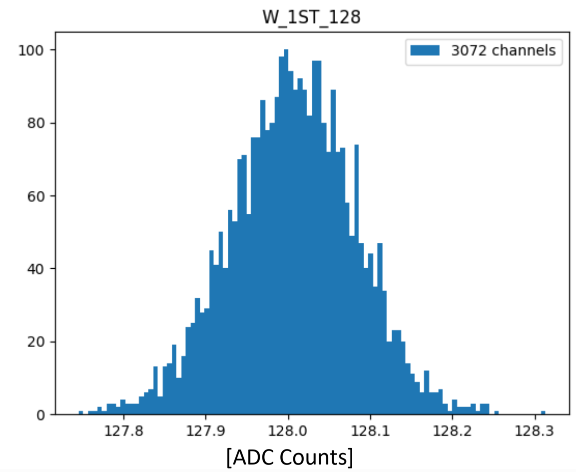
- One necessary upgrade is to the LAr Calorimeter, and Columbia is developing the new Front-End Boards which digitize the signals from the produced currents
  - The upgrade will require 1524 boards to read out all the ~200k channels of the LAr calorimeter
- These boards include custom designed COLUTA analog-to-digital (ADC) ASIC chips which digitize the LAr calorimeter signals to convert the measured (analog) voltage into binary (digital) numbers



Calibration Constant Histograms

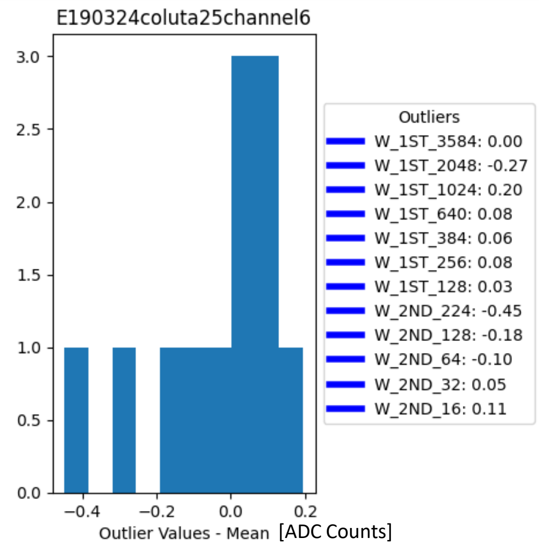
- Each board has 32 COLUTA chips and each chip has 8 channels, each with their own set of calibration constants
- The chips are robotically tested standalone at UT Austin and in Saclay (Paris) and sorted for constants within 20% of the mean
  - Our goal is to identify an acceptable range for a chip's constants to be within to use for quality control testing, and to test the chips we receive in situ to cross check that they are satisfactory
- For each of the constants, we plot the distribution of the values across all channels
- Some of the constants are offset by a scaling factor, which when accounted for makes the distribution thinner
  - Scaling the constants makes the histograms go from having many non-gaussian outliers to having a much cleaner shape

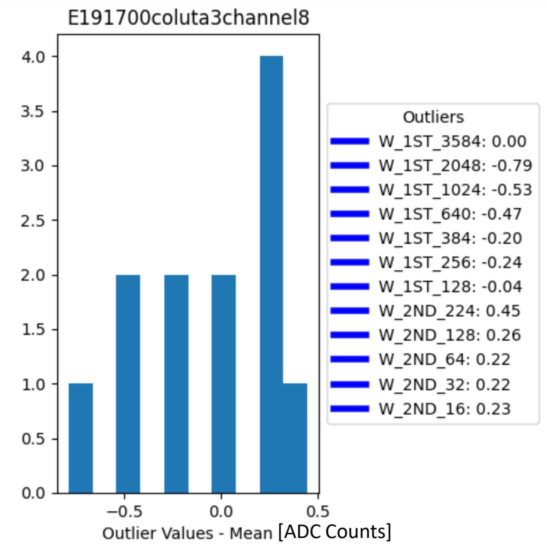




Calibration Constant Outlier Analysis

- For these distributions, channels were identified if their unscaled constants had any values which were outliers ($\pm 5\sigma$)
- The difference between these unscaled outliers and the mean were then plotted, with many of the plots looking almost identical
- Taking these constants which were unscaled outliers and scaling them before plotting, the pattern went away, and the differences became small
  - This tells us that the scaling and sorting done at UT Austin/Saclay is working and our constants are within an acceptable range, since constants which are outliers while unscaled are no longer outliers after scaling





Next Steps

Dark Photon Search

- The results of these DV mass reconstruction studies will be used to search for a signal over background in 2-lepton DV events
- We are performing similar studies for the 1-matched-lepton case to optimize how to treat those events
- We've plotted the MC signals for the 0 matched lepton case
  - Now we're ready to start looking at data in the 0 matched lepton case since it's not our signal region

FEB2

- The boards will soon go into mass production and quality control (QC) will be run on them
- The QC process will use these distributions of constants to help determine if a chip is up to quality

Acknowledgements

- Thank you to Professor John Parsons, Professor Georgia Karagiorgi, Professor Reshmi Mukherjee, Amy Garwood, and everyone at Nevis for making this REU possible
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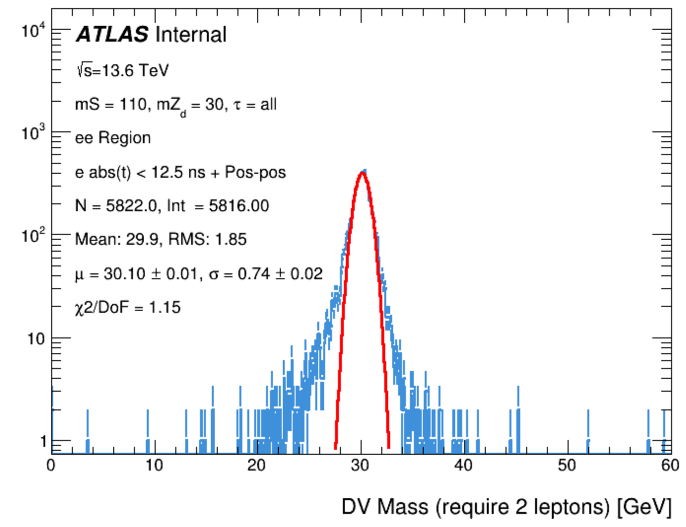
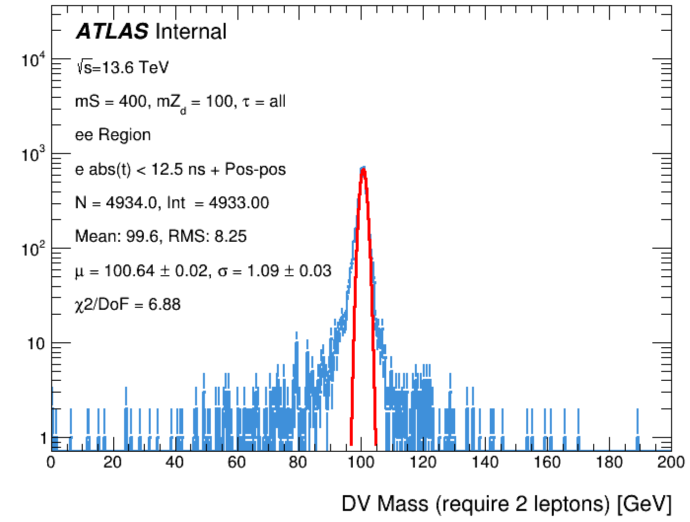
- Thank you to everyone in the Columbia ATLAS Group and all the other REU students for a great Summer
- This material is based upon work supported by the National Science Foundation under Grant No. PHY-2349438.

Backup

Combined Lifetime/Region Mass Histograms

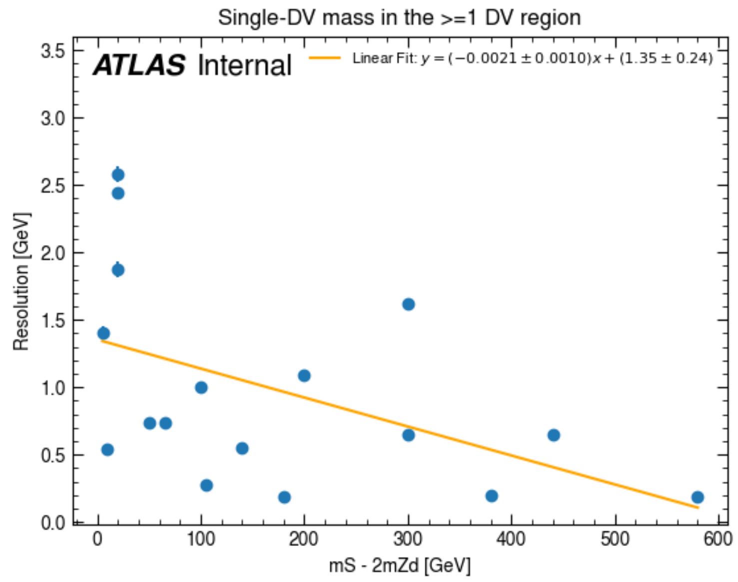
- Plotted the mass histograms of the combined lifetimes in the combined DV region
- Extracted σ of an iterative gaussian fit to these distributions as the mass resolution

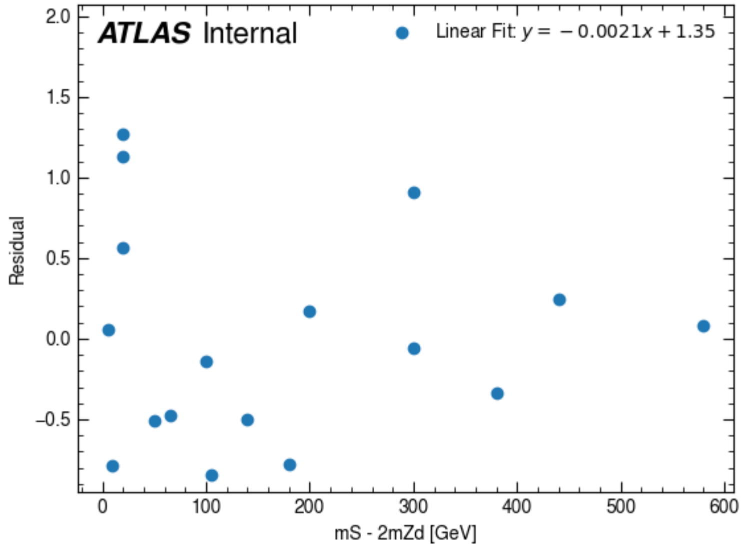




Fitting to mS-2mZd (1D)

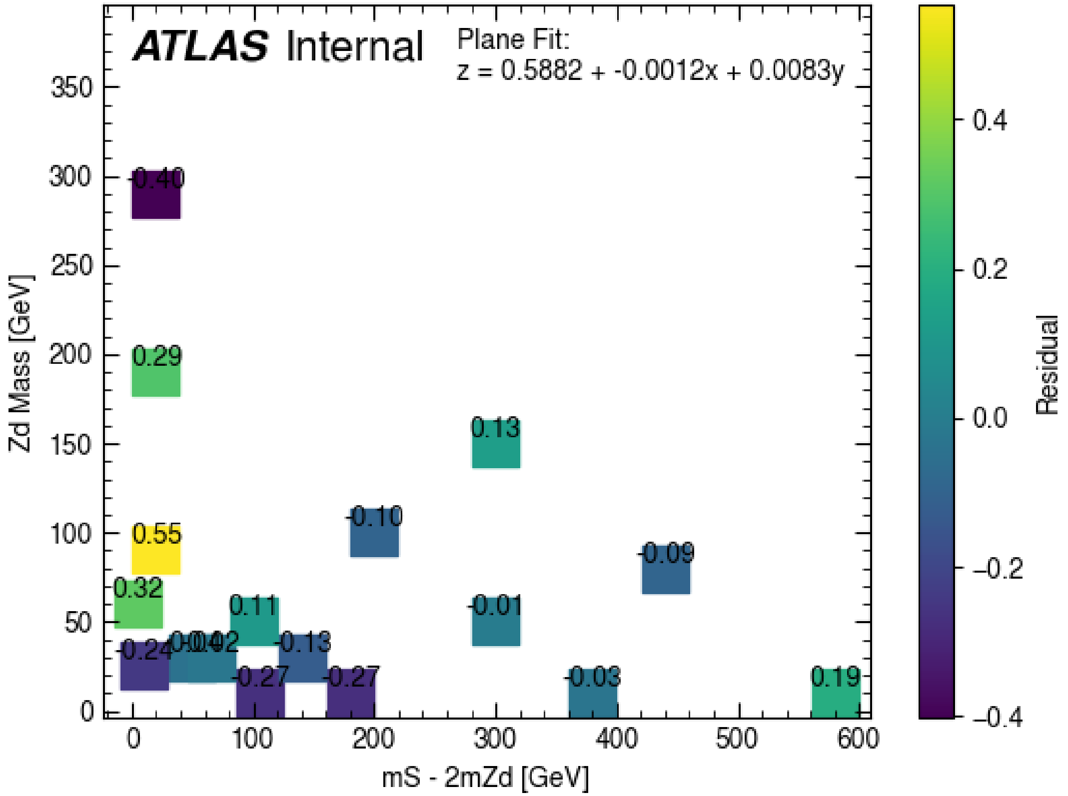
- To account for the dependence on both mS and mZd, plotted resolution against mS-2mZd
  - This was chosen to account for available energy the S particle has for the Zd after producing the two Zds
- Also produced a linear best fit to this plot
  - The residuals from this fit were plotted and seen to be small (less than 1.5 GeV) suggesting a good fit





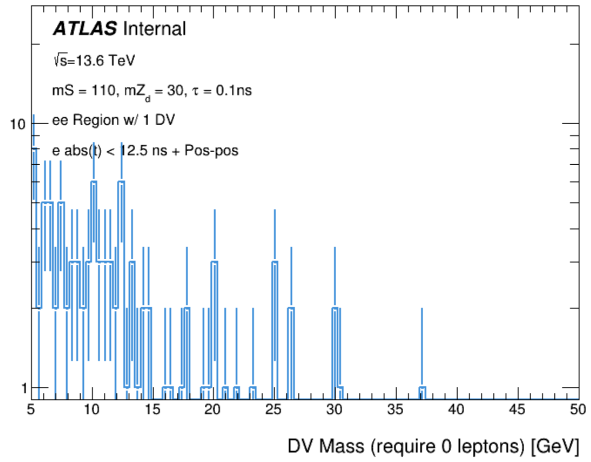
Fitting to mS-2mZd (2D)

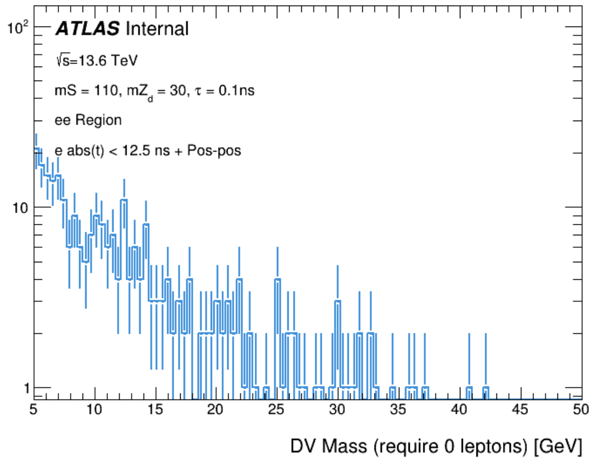
- Also created a 3-dimensional plot of resolution against both mS-2mZd and mZd to account for the effects of both masses
- A plane was fit to the points, and the residuals from this plane were plotted against the two variables

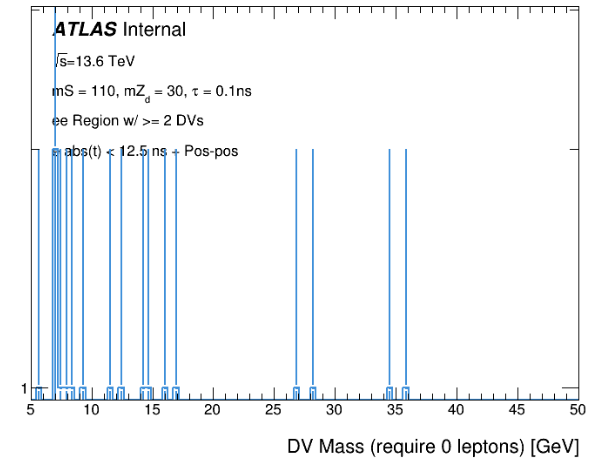


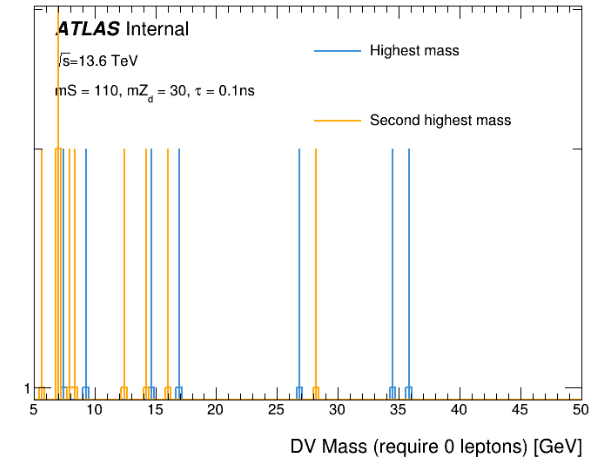
0 Matched Leptons Case

- Also began exploring the case where we have 0 matched electrons
- We're not able to reconstruct anything from these shapes, meaning there's no signal in it
- Therefore since this is a "blinded" search, we can now plot the data in this case without accidentally unblinding since there's no signal anyway



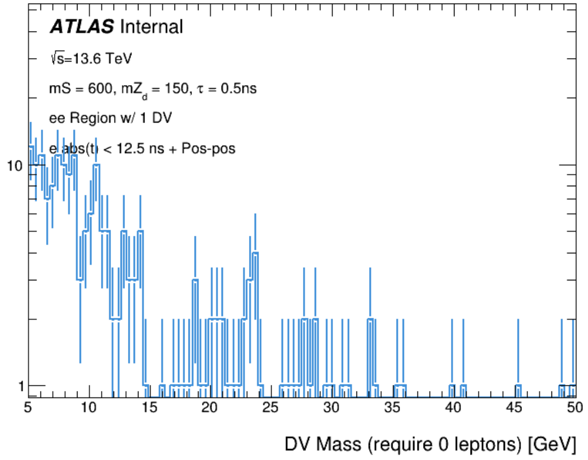


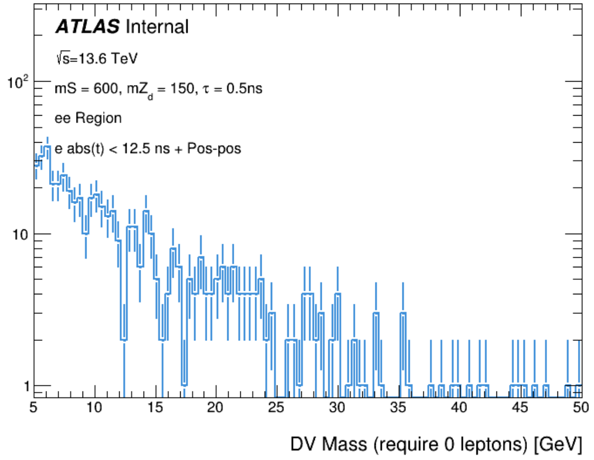


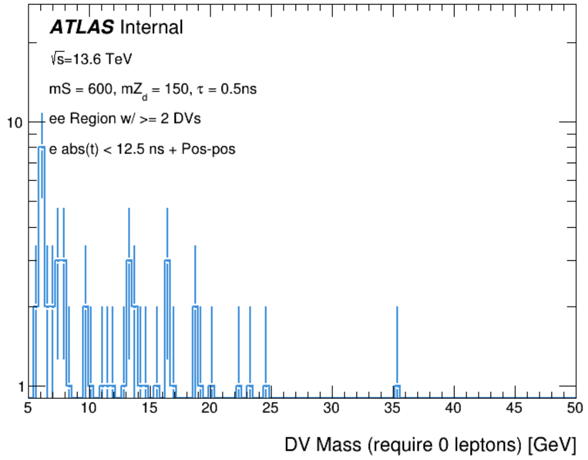


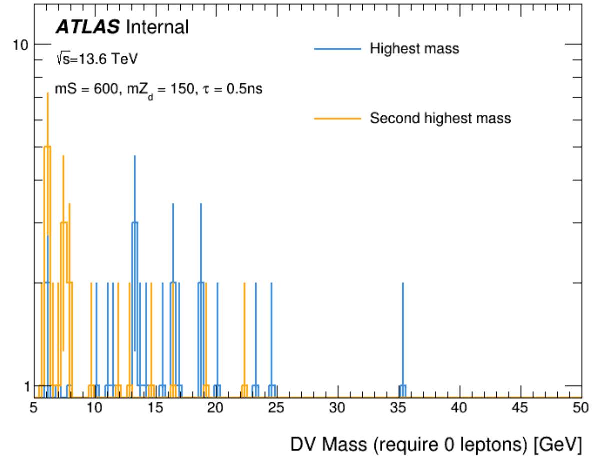
Extra 0 Matched Leptons Plots

- Plots in the various DV regions of the 0 matched lepton case for a different mass point and lifetime



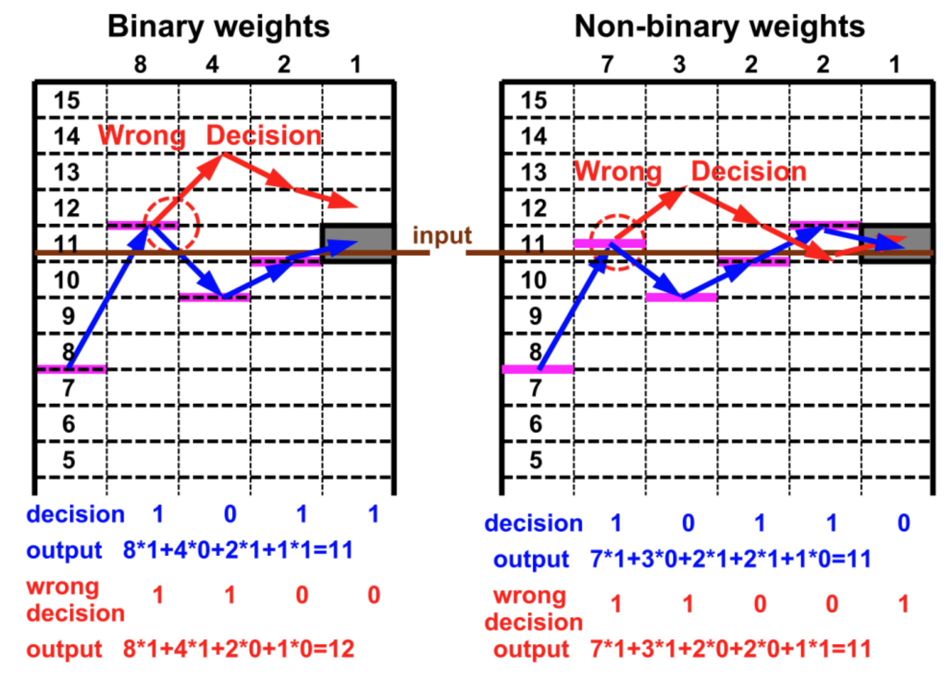






COLUTA ADC ASIC Calibration Constants

- To optimize the speed of the chips, they use non-binary weights (calibration constants) to perform this digitization
  - We are willing to sacrifice some mistakes for speed, and unlike binary weights non-binary weights allow us to correct those mistakes later
- Ideally the weights would be the same among chips, but the capacitors inside them are inconsistent and cause small fluctuations



Detailed Calibration Constant Explanation

- Binary weights (16, 8, 2, 4, 1) can be used to relate our binary and voltage numbers
  - If the voltage is greater than 16, add a 1
  - Then if the voltage is less than 16+8 add a 0
  - If the voltage is greater than 16+4 add a 1, and so on
- These binary weights only have one way to get to a specific number, so to correct mistakes we make for the sake of speed, we use non-binary weights which can recorrect us later