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Muon Mayhem: Searching for Z in A Pool of Decay

**Abstract**

This research addresses CERN confirmation of Z boson's existence years ago. This investigation uses a real-world dataset of proton-proton collisions corresponding to the same data measured by the LHC. The invariant mass of resulting muon-antimuon pairs are first filtered and plotted. Then, the upper boundary on permitted isolation values for either muon is decreased until only one mass window is prominent. Next, thistogram’s bin heights is fitted to a PDF that infers the fraction signal Z boson decay events within this dataset. The isolation is finally tweaked to maximize this signal fraction and its certainty, and the coinciding mass value should be approximately that of the Z boson. The most optimal peak in mass measurements occurred within the 70-110 GeV range. The signal fraction is maximized to 99.9999 ± 0.1102 % when the upper isolation boundary is < 0.085, and the coinciding mass value is 90.9341 ± 0.0238 GeV. This is approximately equal to Z’s true mass of ≈ 91.2 GeV, demonstrating this research successfully developed a method to filter only signal events from the dataset.

**Introduction**

From smashing together rocks to now subatomic particles, humanity has progressed far in understanding physics. Only a few decades ago did CERN confirm the existence of the Z boson, which along with W, is responsible for the weak force that governs particle decay. However, confirming Z’s existence was no simple task. While these proton-proton collisions produce Z, they may also produce a pair of b-quarks via an intermediate gluon; and in both cases the resulting particles immediately decay into a muon-antimuon pair. This made it difficult because the The Large Hadron Collider (LHC) could only detect the resulting muons, not Z itself. However, CERN discovered muon-antimuon events with high isolation corresponded to b-quark decay. They realized the fraction of signal events to background can be maximized if they only considered events with muons of low isolation, and this exclusion helped CERN confirm Z even with the collider’s physical limitations.

In order to dive into CERN’s investigation, the invariant mass of muon-antimuon pairs must first be measured. Consistent measurements within any explicit mass window should correspond to the weight of the preceding particle(s), whether it be a Z boson or a pair of b-quarks. The b-quark decay can be excluded from this data by narrowing the permitted isolation values of considered muons. However, constricting this boundary too much will likely increase the uncertainty of Z's mass window since there may be too few collision events remaining. Here, curve-fitting a PDF to the mass measurements is needed. This will be used to find the fraction of signal, Z boson, events to background, b-quark, events; and this fraction and its corresponding certainty can be further maximized by fine-tweaking the isolation upper boundary. If these constraints yield a prominent mass window centered about the Z boson, then it is certain nearly all plotted events correspond to Z decay and that the signal fraction is most optimal.

**Method**

This investigation uses a historical dataset from CERN of proton-proton collisions measured by the LHC. This dataset contains approximately 300,000 collision events, most of which depict the resulting muon-antimuon pair. Each event tabulates the number of detected muons, their charges, isolation values, as well as their four-momenta in modified polar coordinates. The combined invariant mass of the muon-antimuon pair will be calculated using the following equation:

Where represents each muon’s three-momenta. The energy of an individual muon will be determined from the length of its four-momenta vector:

The combined invariant masses across all muon-antimuon events will then be plotted on a histogram in Python.

Next, the upper bound on permitted isolations will start high and narrow down to exclude most b-quark decay events. This exclusion is expected to be most significant around the b-quark’s mass range and least significant in Z’s mass range. Given that the b-quark was theorized and confirmed in the 1970s, and CERN’s experiment to confirm Z was in the 1980s, it can be assumed that the mass of the b-quark is already known to be ≈ 4.18 GeV. Therefore, mass measurements between 0-10 GeV should diminish as the upper isolation boundary becomes more narrow, and this should be visible in the corresponding histograms. On this topic, the mass of the Z boson is presently known to be ≈ 91.2 GeV. While this should not be used to guide the investigation for Z, it can however be used to confirm the results during discussion.

The isolation values of most muons in the dataset seemingly fall within the range of 0 and 2. The upper bound therefore decreases exponentially starting from 1, then to .5, and finally to .1. Note that the isolation boundary will discount a collision event if either of the two muons has an isolation higher than bound. A finer constriction on isolation may be necessary if the .1 boundary still yields multiple potential mass windows.

After a single window coincides with Z, it can be assumed most b-quark decay events are excluded. This exclusion can be further optimized by curve-fitting the histogram to a PDF. The PDF will consist of a signal function that coincides with a Z decay, as well as a background function that coincides with b-quark decay. This signal function will be a convolution of both a Gaussian distribution and the Lorentz distribution, termed Voigt profile, and is defined as:

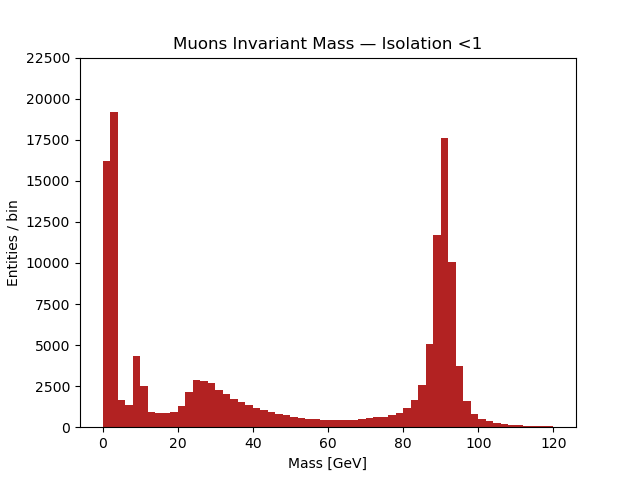
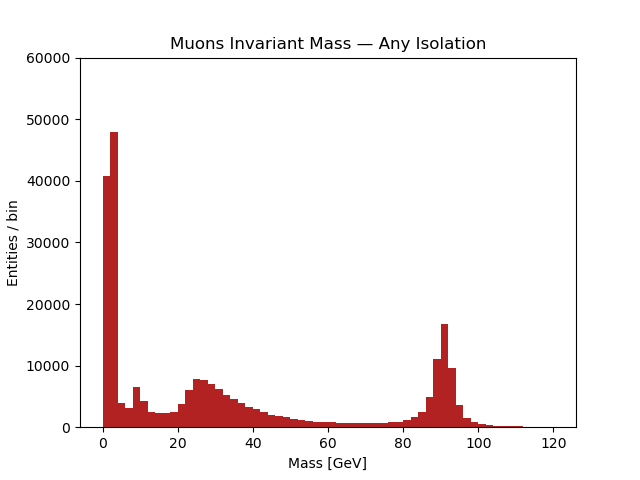
Where is the Faddeeva function . and are both defined as:

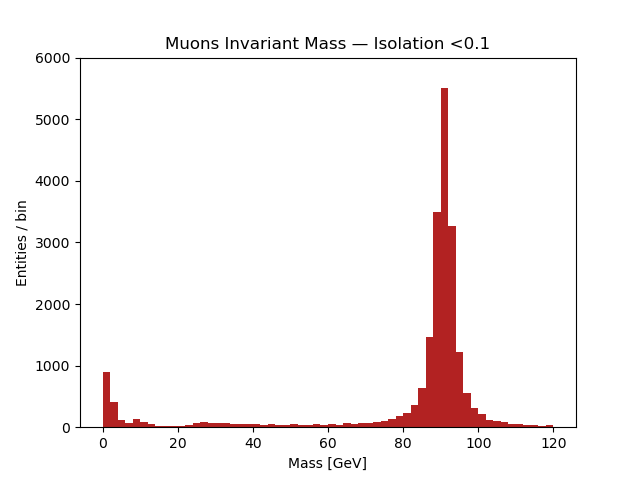
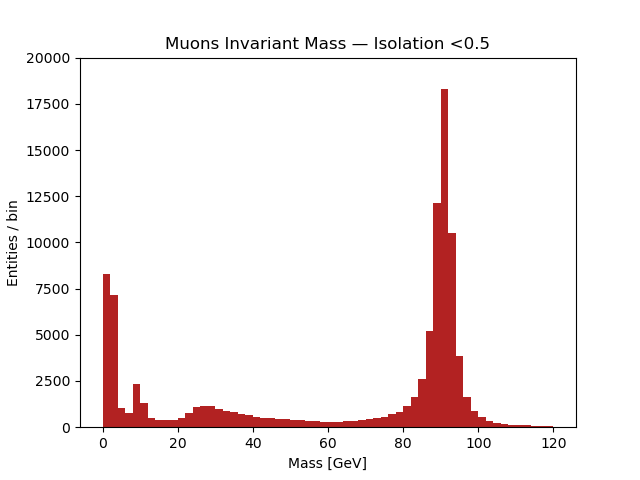
On the other hand, the function representing background b-quark decay will be a falling exponential, defined as:

Both signal and background functions will be combined into a more advanced PDF for SciPy’s curve\_fit() to properly parametrize:

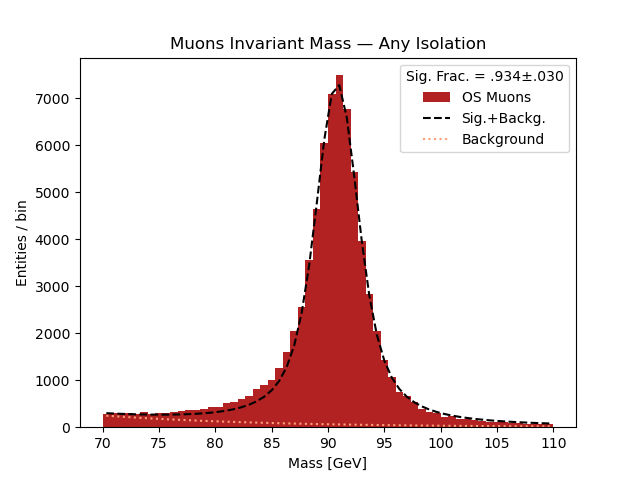
Where A represents the normalization constant, s represents the signal fraction, and and represent the x-shift needed to center the PDF about Z’s mass. Fortunately, curve\_fit() also provides the uncertainty in each calculated parameter, making it easy to fully maximize the signal fraction and certainty.

**Results**

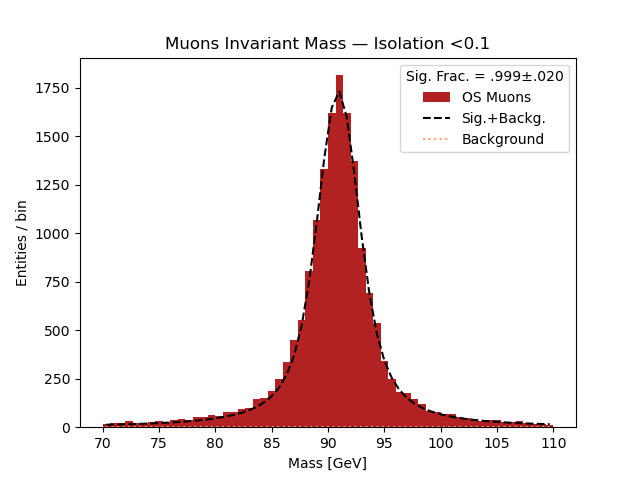
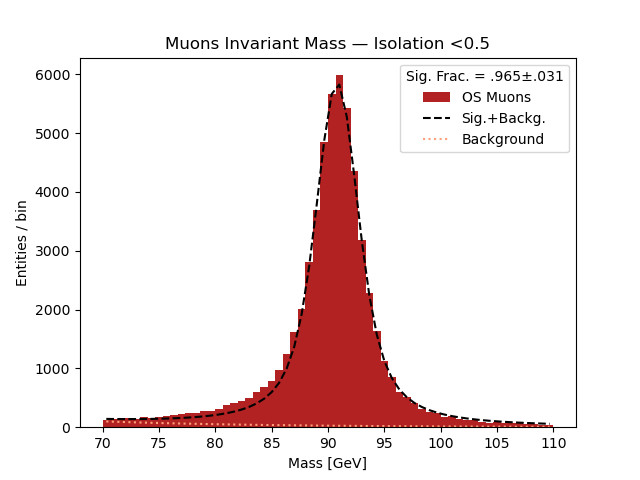


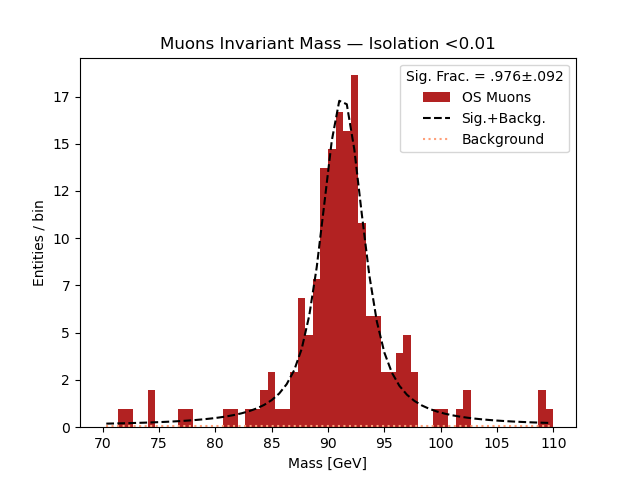
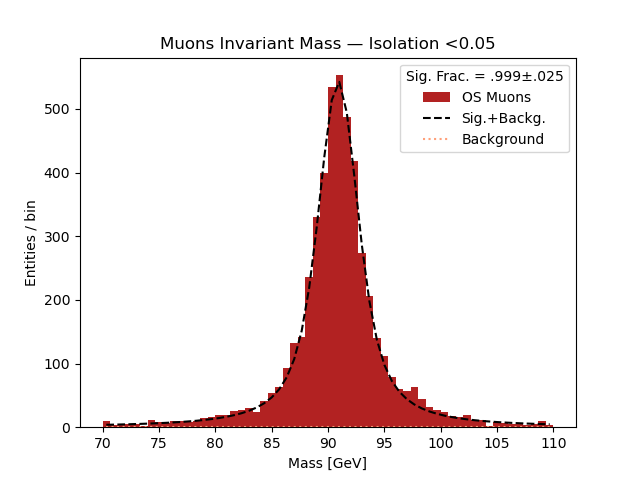


As expected, the 0-10 GeV mass window had a high volume of collision events due to b-quark decay. The number of events in this window decreased drastically as the upper bound on isolation decreased. Conversely, the 70-110 GeV invariant mass window becomes more statistically significant as the isolation boundaries tighten. The Z boson must be somewhere within this 70-110 GeV range since it is not substantially affected by the decreasing isolation.

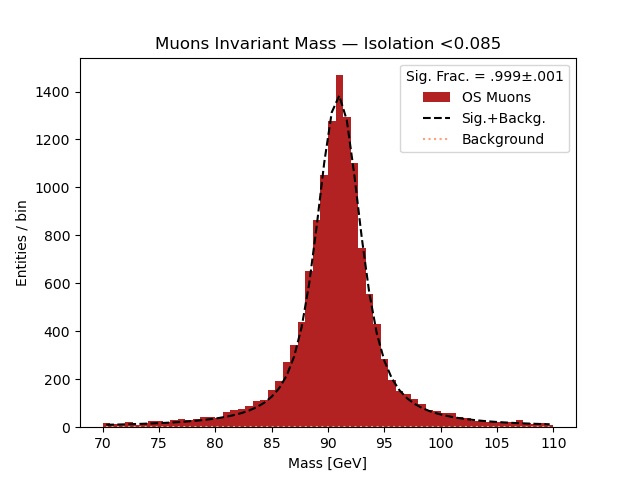


To better understand the influence background measurements have on signal measurements, an unconstricted histogram is plotted within the 70-110 GeV window. The impact of background measurements here is not drastic, as the signal fraction is approximately 93.44 ± 2.9 %. Regardless, the upper bound on isolation must be lessened in order to maximize signal fraction and minimize its uncertainty.

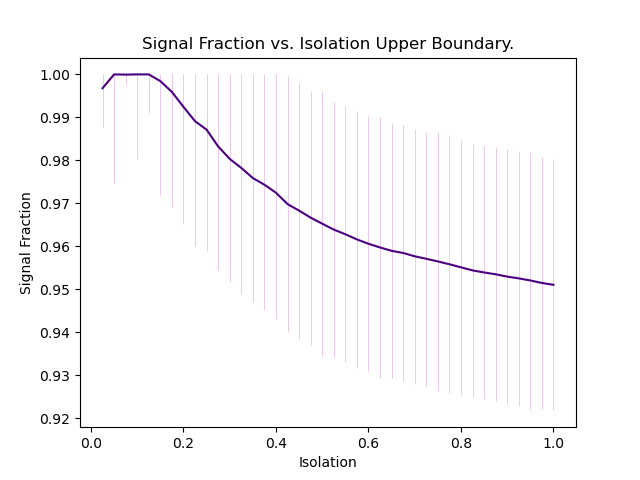




As the isolation boundary decreases, the impact of background events becomes insignificant. However, the case where isolation <.01 is obviously too narrow. This is further supported by the sharp increase in signal fraction uncertainty to ± 9.2 %. The optimal isolation constriction was therefore overpassed.



Using numerical analysis, the most optimal upper bound for isolation is at <.085. This constriction corresponds to a signal fraction of exactly 99.9999 ± 0.1102 %. The mass corresponding to the peak of the PDF is centered at 90.9341 ± 0.0238 GeV.



Plotting isolation’s impact against signal fraction, <.085 is further solidified as the most optimal upper boundary. There, the signal is at its maximum yet slowly decreases as the isolation increases, and, the uncertainty too is at its minimum and increases outside the boundary. However, note the exact isolations 0.050, 0.10, 0.125, 0.450, and 0.90 yielded computational data overflow errors, this may have skewed the results.

**Discussion**

The mass of the Z boson is officially ≈ 91.2 GeV, and the mass value corresponding to the optimal isolation boundary is close to this value. Therefore, it can be asserted that this isolation boundary is optimal, consequently demonstrating that the corresponding near-perfect signal fraction and uncertainty was successfully attained. However, this is not to say this investigation is without its flaws. Certain isolation values yielded a data overflow error that could not be resolved, this may have skewed results. My limited knowledge in how Python stores data unfortunately impeded finding the solution to this problem. Regardless, this error did not occur at the <.085 boundary. Therefore, the extremely high signal fraction obtained at this boundary was likely unaffected by this error.