Search Into Dark Matter by Investigating Jets Produced in Proton Collisions

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Background

Cosmological observations have proven that dark matter (DM) not only exists but constitutes 27% of the universe[1]. DM is expected to be electrically neutral, have mass, interact weakly with Standard Model (SM) particles, and be stable [2]. DM cannot be directly detected in collider experiments. If DM particles are produced via a mediator when protons collide, the DM itself would be invisible to the detector, but it can be searched for in other ways.

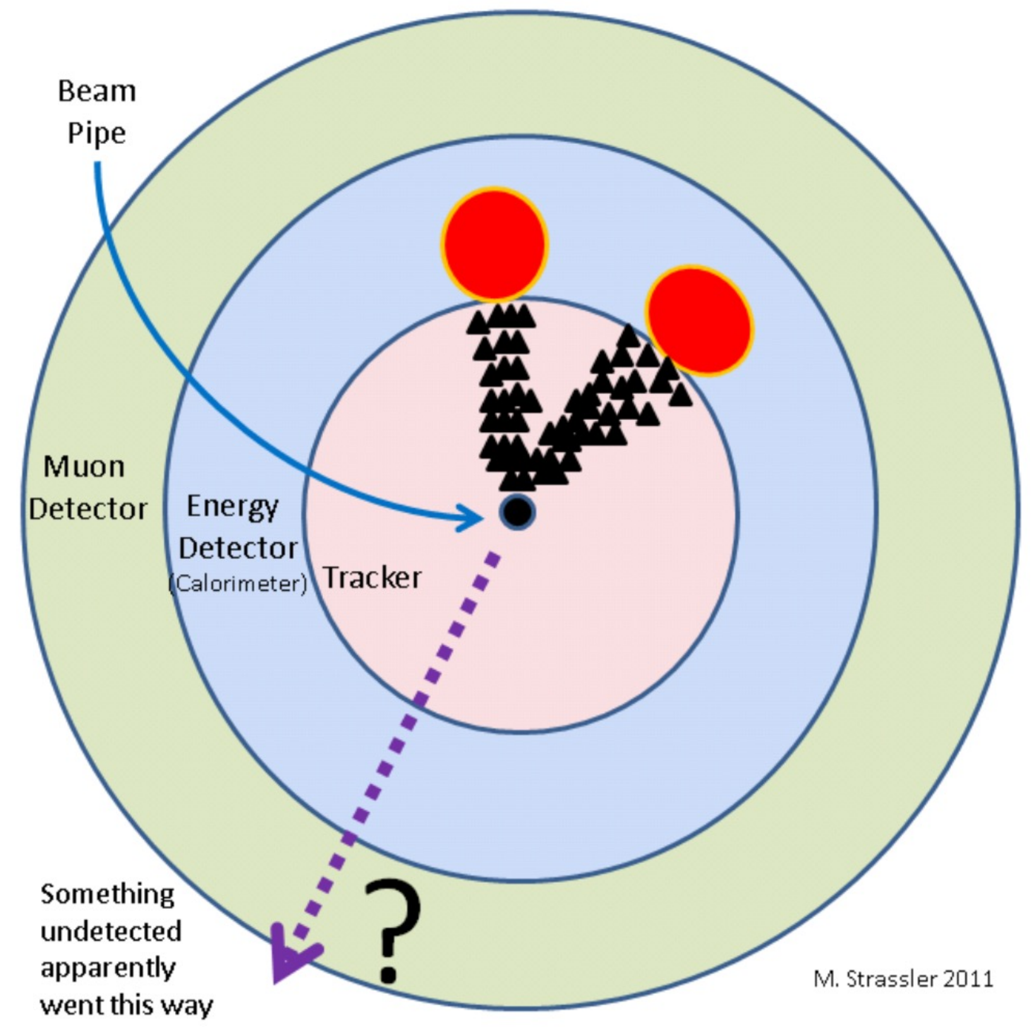


Figure 1: Momentum imbalance in particle collisions indicates the presence of undetectable particles [3]. Since in LHC collisions, the net momentum perpendicular to the beam is zero, any momentum imbalance in the transverse plane must be due to missing particles.

At the Large Hadron Collider (LHC), hadrons are collided at velocities approaching the speed of light, and several layers of detectors reconstruct the particles and jets that emerge. Jets are sprays of particles that result from quarks and gluons at very high energies radiating more particles, essentially creating a cascade of particles in a narrow cone. Some heavier particles, such as Z-bosons, are highly unstable and decay immediately, in which case only the stable decay products are directly detected.

Introduction

DM particles cannot be directly measured; however, they can be detected indirectly via lack of momentum conservation. Neutrinos, which are already in the SM, also cannot be detected because they have zero electric or color charge and thus don't interact via either the electromagnetic or strong nuclear force. So the challenge is then discriminating neutrinos from DM, both invisible. This research investigates one method of doing so by using correlations between the mass of the invisible and visible system. Since in proton collisions, neutrinos are predominantly produced via an intermediate Z-boson, the mass of the invisible system in neutrino events will be near the Z-boson mass, while potential DM events will have masses at least twice the DM mass (because they are produced in pairs) and generally higher. In order to quickly investigate potential correlations, simulated samples of 2 muons (μ) are used instead of 2 neutrinos (ν), because the physics of Z → $\mu\mu$ very nearly matches that of Z → $\nu\nu$, but the interactions involving muons are readily available.

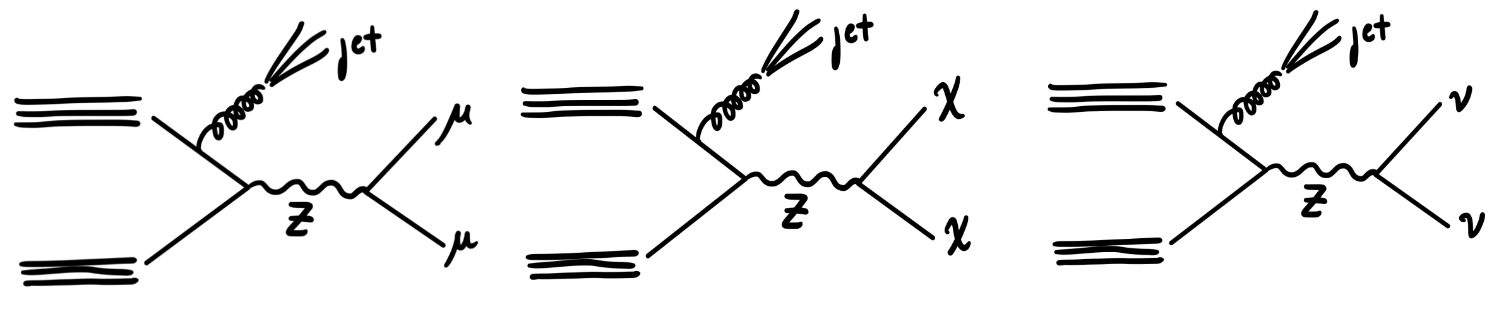


Figure 2: Feynman diagrams of pp decaying to $\mu\mu$, $\chi\chi$, $\nu\nu$ via intermediate Z boson

The investigation specifically looks at the properties of jets produced in Z → $\mu\mu$ interactions, and their relationships with the dimuons produced. The analysis is also performed with a cut applied to the dimuon invariant transverse momentum ($p_{T\mu\mu}$) to mimic missing transverse energy (MET).

Materials

The project uses ROOT, a C++ based CERN framework[4], to analyze computer simulated particle collision data. CERN has a large database of files that can be used to generate different processes involving particles with specified properties, and these options can then be used to simulate particle collisions. Simulated events can then be converted into a ROOT readable format, called a TRUTH derivation. The TRUTH derivation preserves certain properties based on which level is specified. For this project, the TRUTH1 derivation is used, as this level preserves jet information.

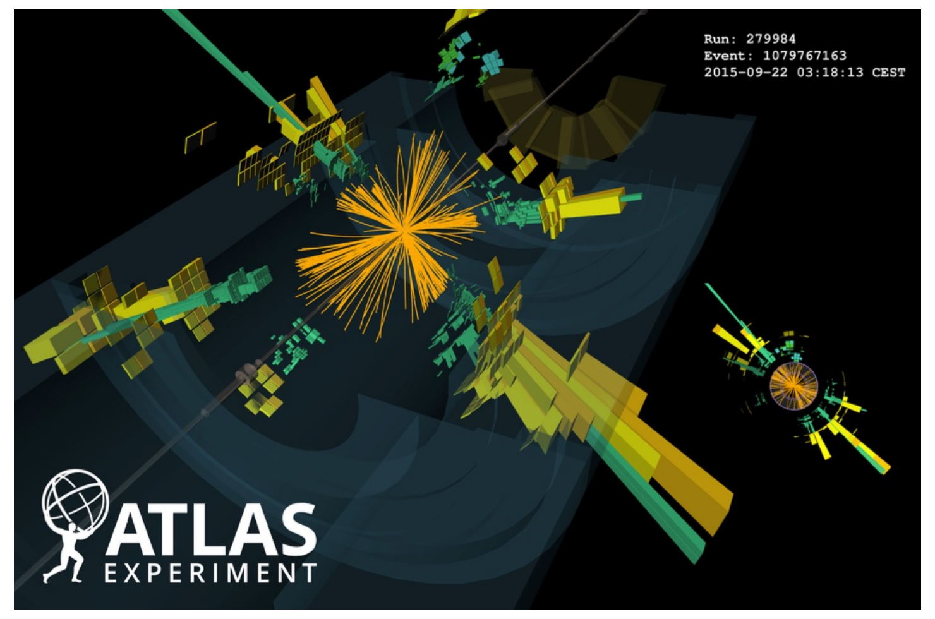


Figure 3: Jets produced from pp collisions [5]

Methodology

The analysis is performed on various files containing simulated particle data. One sample is a simulation of the full Z boson mass distribution expected in data. Since it is unweighted, the sample is dominated by dimuons coming from a Z boson, hence the peak in dimuon invariant mass at 90 GeV (the mass of Z). Thus, samples at higher dimuon masses are generated, which have greater luminosity in specific dimuon mass ranges. These are generated Drell-Yan (proton-proton collisions) samples that produce dimuons in each event. Configurations are used to specify the mass range. Code to plot the variables of interest is then run on files containing the generations using ROOT.

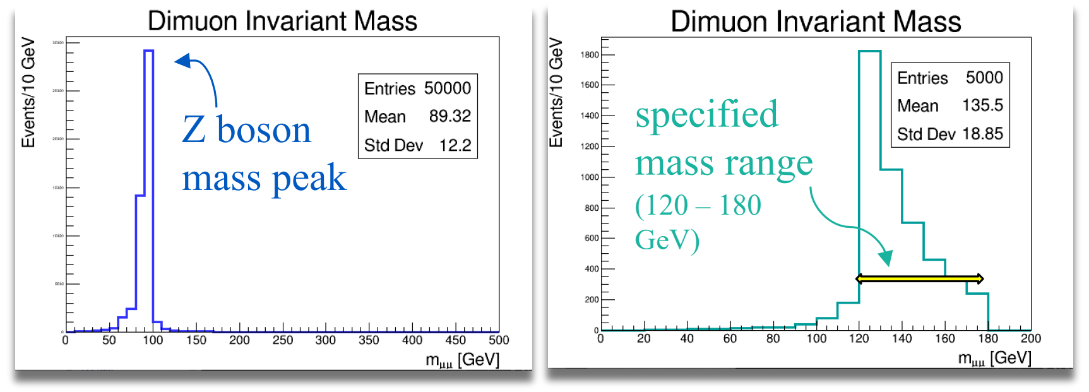
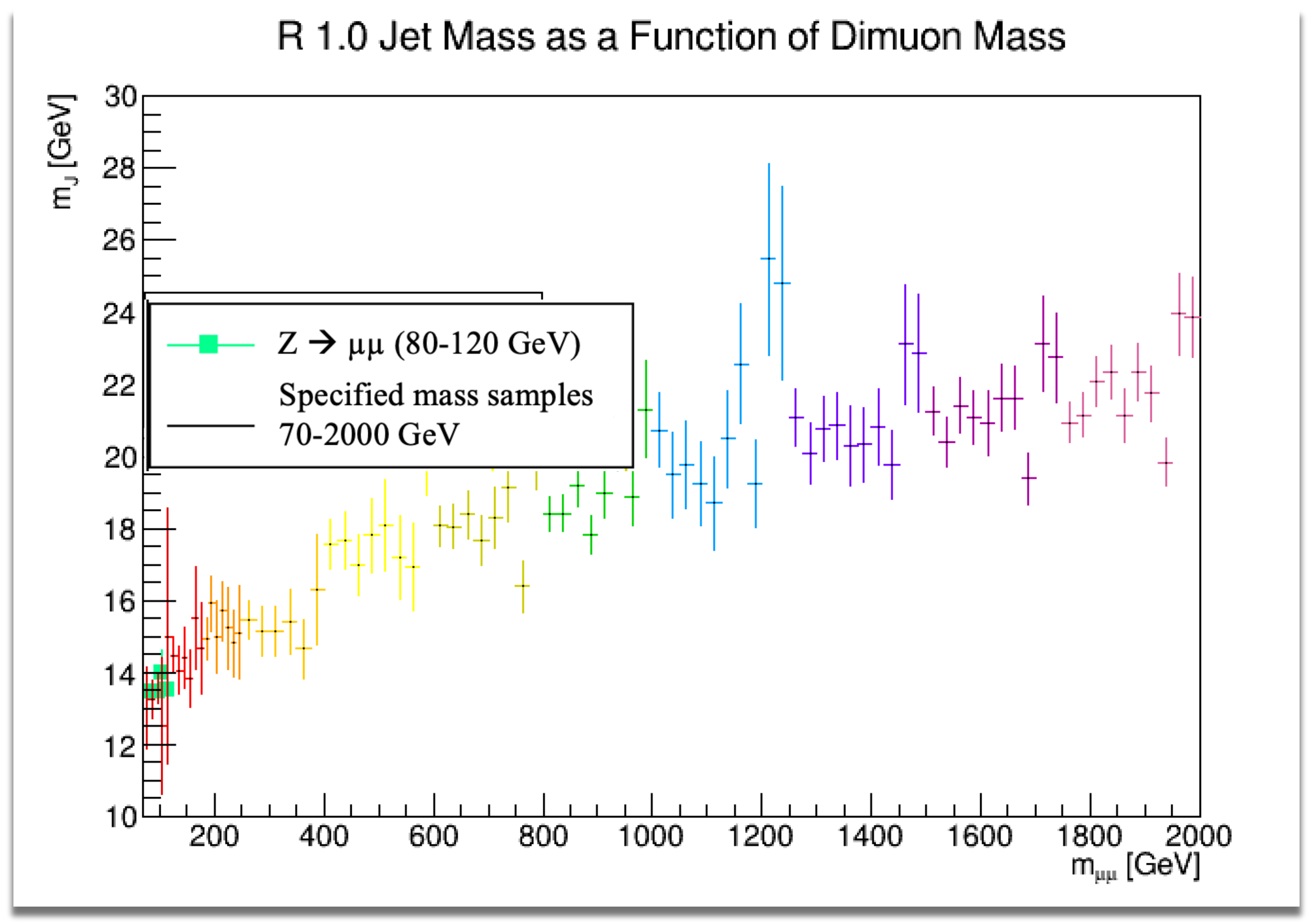


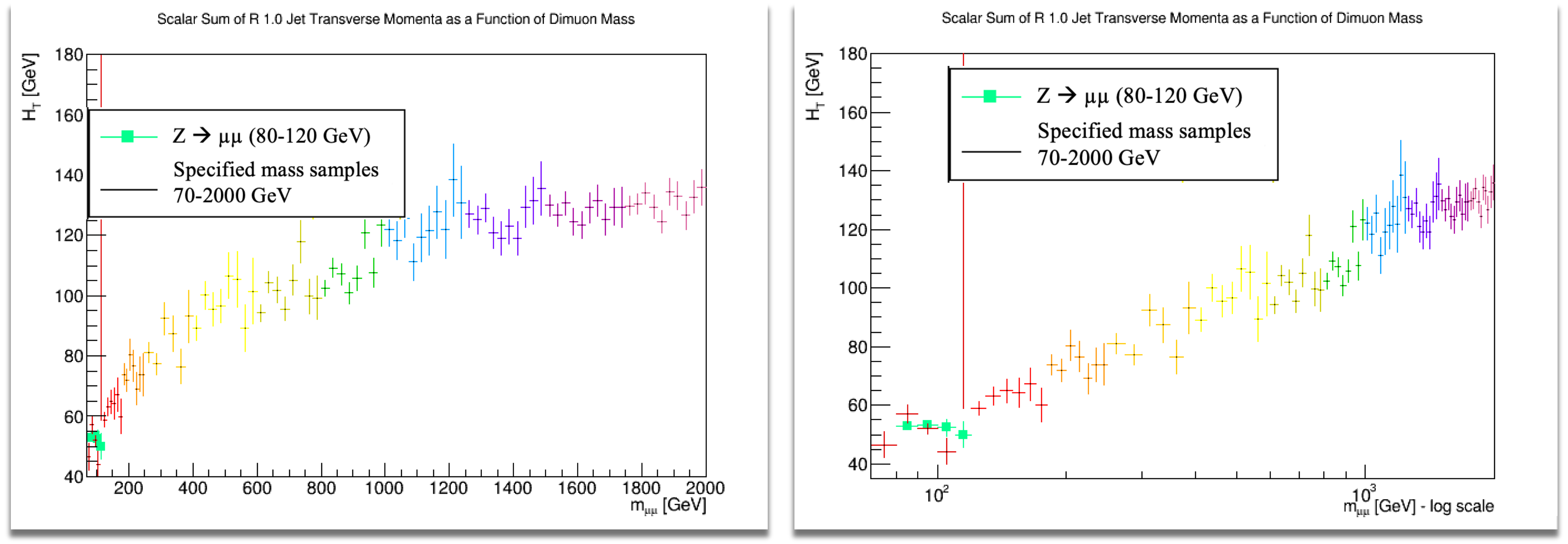
Figure 4: Plots of dimuon invariant mass for original sample with full distribution (left) and dedicated higher mass sample of 120 – 180 GeV (right)

Results

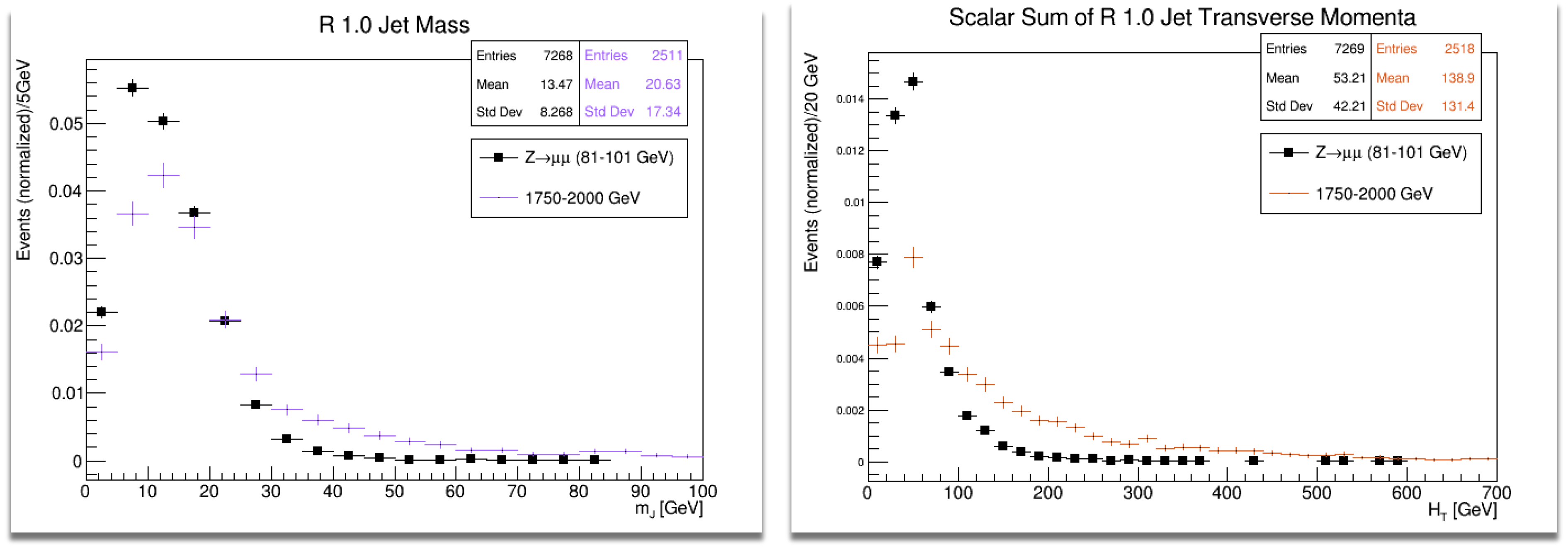
Profile of 2 dimensional histograms of the mass of the leading jet (jet with highest transverse momentum) in an event as functions of the dimuon invariant mass (magnitude of the sum of the four-momentum vectors for the 2 muons). Each color corresponds to the plot for a sample of a specified mass range, which are then combined in the same profile along with the original sample. Use of a profile allows to more clearly visualize the relationship between the 2 variables.



Dimuon invariant mass calculation: $m_{\mu\mu} = \parallel \tilde{P}_{\mu\mu} \parallel = \sqrt{(\tilde{P}_{\mu 1} + \tilde{P}_{\mu 2})^2}$



Profiles of the scalar sum of jet transverse momenta, H_T, as functions of dimuon invariant mass. The plot on the left uses a regular scale, on the right uses a logarithmic scale.



One dimensional histograms of jet mass (once again using the leading jet from each event) and H_T. For each plot, the histogram from the original sample with the full Z boson mass distribution is normalized and overlayed with the histogram from the dedicated dimuon mass sample of 1750 – 2000 GeV, which is the highest mass range analyzed.

Conclusion and Next Steps

The results show that there is a nontrivial correlation between jet mass as well as the scalar sum of jet transverse momenta and the dimuon invariant mass. Since the samples generated do not contain sufficient events with $p_{T\mu\mu}$ values above the $p_{T\mu\mu}$ cut to be able to analyze, a next step would be to generate and analyze samples with greater luminosity at higher $p_{T\mu\mu}$ values.

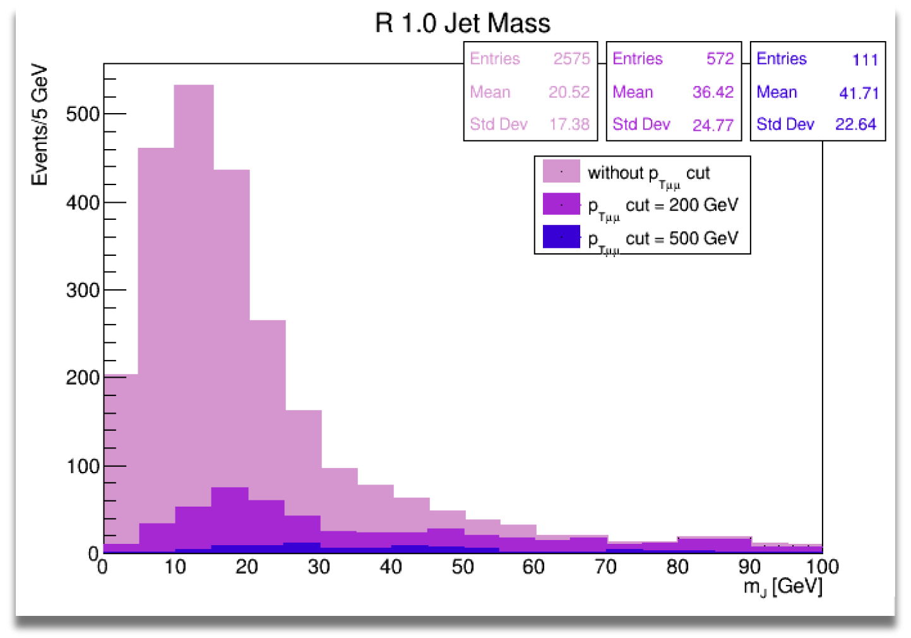


Figure 5: Plots of jet mass from generated sample of $m_{\mu\mu}$ = 1750 – 2000 GeV with and without $p_{T\mu\mu}$ cuts. Very few events remain after the $p_{T\mu\mu}$ cuts (sample contains 5000 events total).

Further, samples of Z → $\chi\chi$ would be simulated, and the m_J and H_T distributions for those samples would be compared to the distributions for Z → $\nu\nu$ to assess improvement in the analysis sensitivity from using simulated samples of DM.

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[1] NASA, *Dark Energy, Dark Matter* (2023) https://science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy
[2] D. Blas, *Introduction to dark matter* (2019) https://conference.ippp.dur.ac.uk/event/785/attachments/3688/4159/Lectures_DM.pdf
[3 , 5] A. Vaidya, ATLAS Experiment, *Jet physics at the LHC, an introduction* (2017)
[4] root.cern homepage