CERN Summer Students

REPORT

September 2019

Background study for the search for long-lived particles produced in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ that decay to two displaced hadronic jets in the muon spectrometer at the ATLAS detector

Julie Munch Torndal

Supervisor:
Cristiano Alpigiani E-mail: cristiano.alpigiani@cern.ch

Introduction

In particle physics our current understanding is described by the Standard Model (SM) with great precision and great success. It was completed in 2012 with the discovery of the Higgs particle. Since then no new discoveries have proven the inaccuracy of the model even though it is well known that the SM is unsuccessful in describing Dark Matter, Matter-Antimatter Asymmetry and the Hierarchy problem. The paradigm has to change. The question now is where to look next. Several Beyond the Standard Model (BSM) theories have been proposed but none have been proven. Some BSM theories allows for or requires long-lived particles (LLPs). The life-times ($c\tau$) of LLPs can range from 100 μm to $10^6 - 10^8$ m where the upper limit is set by the Big Bang Nucleosynthesis limit.

In extending the Standard Model, long lived particles (LLPs) can be introduced through a hidden sector that weakly couples to the SM [1]. They are neutral and can therefor not be detected directly. Figure 1 shows a Feynman diagram of the process where LLPs decay into displaced hadronic jets. Here a SM field mediated by a scalar boson (e.g. the Higgs) couples to a hidden sector field, where a scalar boson Φ decays into a pair of neutral, hidden-sector scalars, s. The lifetime of the scalars can depend on the coupling strength. A weak coupling will result in long lifetimes hence long-lived particles. These will then decay to a pair of SM heavy quarks which can be detected by ATLAS.[1]

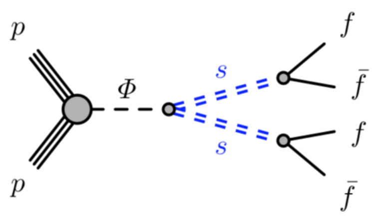


Figure 1 Feynman diagram for the scalar boson decaying into displaced hadronic jets [1]

This report focuses on LLP decays reconstrubcted in the muon spectrometer of the ATLAS detector at LHC. To claim a discovery it is crucial to now the background accurately so that the LLPs can be distinguished. Here the background will be studied using a data driven method that uses *zero bias* data, which is signal free, to determine the expected number of events that have two vertices that resembles both scalars decaying in the muon spectrometer.

[1] It is also a possibility that the lifetimes are too long to be detected.

Experimental Setup

In this analysis, data recorded by the ATLAS detector during 2015, 2016, 2017, and 2018 have been used. The ATLAS coordinate system is defined such that the origin is located at the nominal interaction point of pp collisions with the z-axis following the beam direction such that $(x, y, z) = (0, 0, s)$ as seen in figure 2 where s is the designed trajectory. The x-axis points inwards to the center of the LHC ring and the y-axis points upwards. The x-y plane is also known as the transverse plane with coordinates (r, ϕ), where ϕ is the aximuthal angle around the z-axis. The pseudorapidity is defined as

$$\eta = -\ln\tan\left(\frac{\theta}{2}\right) \tag{1}$$

It's more appropiate to use because it is a quantity that is invariant under boosts along the z-axis. The angular distance is given by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ [1].

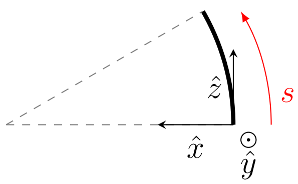


Figure 2 : Designed trajectory for the protons

The ATLAS detector is a multipurpose detector. It consists of an inner tracking detector (ID) which is surrounded by the electromagnetic and hadronic calorimeters, and outermost is the Muon Spectrometer (MS). An overview of the detector can be found in Appendix in figure 3. The ID measures the directions and momenta of the charged particles, and the calorimeters measure the energies of the electrons, photons, and hadrons. Almost all the energy will be deposited in the calorimeters although sometimes excess energy from jets will punch through to the MS (punch-through jets). The muon is the only SM charged particle that cannot be stopped by the calorimeter system. In the MS the muons are deflected with a magnetic field in the barrel provided by a toroid magnet system. By deflecting the muons, the momentum can be measured using separate trigger and high-precision chambers. The monitored drift tube chambers (MDTs) are used for reconstructing the track. Separate trigger chambers are used for a faster readout. Resistive plate Chambers (RPCs) are used in the barrel and Thin Gap Chambers (TGCs) are used in the endcap. If there is sufficient activity, these selects a muon region of interest (RoI). Candidate events for decays of LLPs in the MS are selected by a Muon RoI Cluster trigger, which requires three muon RoIs in the barrel and four muon RoIs in the endcap within a $\Delta R = 0.4$ cone. Sometimes the punch-through jets reach the MS and fake a displaced vertex that look exactly like the expected signal. This is the main background.

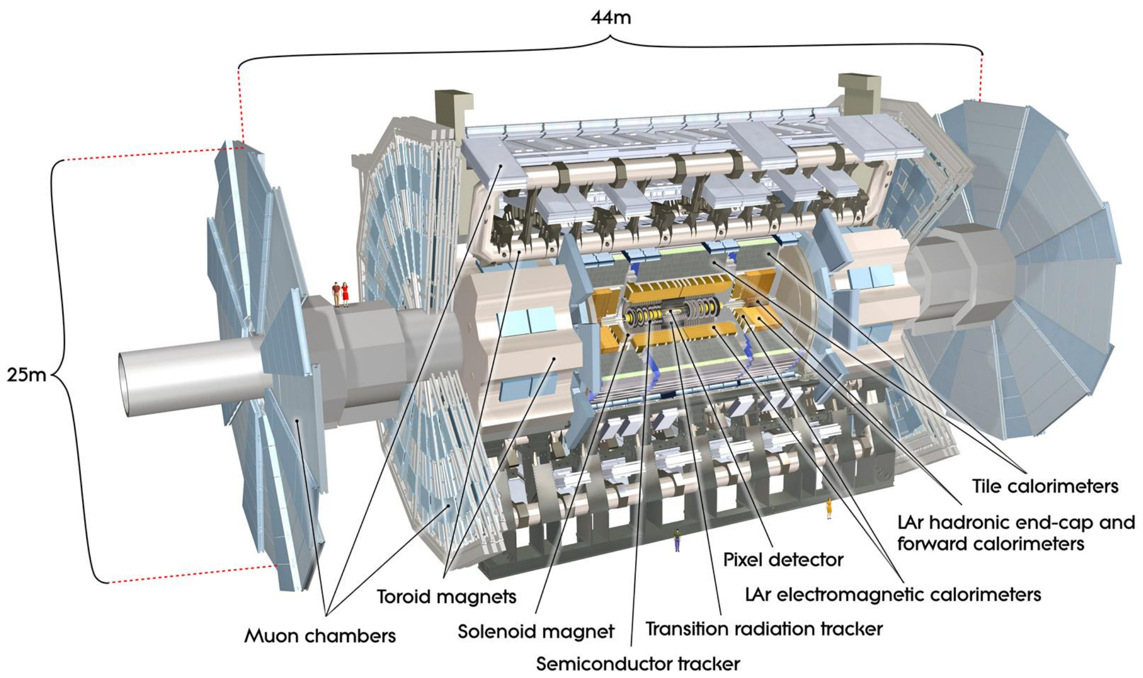


Figure 3 ATLAS detector overview [CERN-GE-0803012-01]

Analysis

The search for LLPs is a search for excesses in the data indicating their existence, hence it is crucial to know the background accurately. A high rejection of background can be obtained by requiring that both hidden-sector scalars decay in the MS. Hence, the signature of an LLP is two isolated, displaced vertices. It is distinct from any SM decay. The expected background assuming no LLPs is the number of expected events with two isolated MS vertices. It can be calculated from the following

$$N[2 \text{ MS Vertices}] = N[1 \text{ MS Vertex}] \times P[\text{MS Vertex}] \tag{2}$$

where $N[1 \text{ MS Vertex}]$ is the number of events containing one isolated MS vertex and $P[\text{MS Vertex}]$ is the probability of finding a vertex in events not selected by the muon RoI trigger. This calculation assumes that the probability of finding a single MS vertex is uncorrelated to finding a second [2].

Data Sets

In the following analysis two data sets were used. The first one contains *zero bias* events. It is used to determine the probability in eq. 2 since not all backgrounds can be properly simulated. The zero bias data is acquired with a special *zero-bias* trigger that fires one LHC revolution after a bunch crossing has occurred. Because of the delay no *pp* collisions are occurring when the zero-bias trigger is fired so only background events will be recorded. The zero bias data is recorded during the same periods of time as the signal trigger ensuring that it has the correct run conditions. However, the zero bias trigger fires much less frequently so the luminosty is much smaller. The second data set is from the main stream i.e *pp* collision data. It was recorded by the ATLAS detector during 2015, 2016, 2017, and 2018 data taking periods using $\sqrt{s}$ =13 TeV. This will be used to estimate the number of events containing one isolated MS vertex. The total integrated luminosity is 143 fb^{-1}.

Event Selection

To ensure a good selection of the events and to minimize background different criteria are applied. For the baseline criteria only quality events that have a primary vertex and are complete will be chosen. The barrel region is in the magnetic field region while the endcap is outside as mentioned above. The two regions require different techniques to reconstruct a vertex so to ensure vertex reconstruction efficiency the overlap region between the barrel and endcap is excluded. Otherwise a vertex might be reconstructed twice and fake a 2 MS vertex event. The barrel region is defined so that the decay length in the transverse plane meets the boundary $3\,\mathrm{m} < L_{xy} < 8\,\mathrm{m}$ and that $|\eta| < 0.7$. The endcap region is defined so that $L_{xy} < 8\,\mathrm{m}$, the decay length in the longitudinal plane meets the boundary $5\,\mathrm{m} < |L_z| < 15\,\mathrm{m}$, and that $1.3 < |\eta| < 2.5$. For efficiency a sufficient number of hits in the MDT is required such that $300 \leq n_{MDT} < 3000$ and for the number of hits in RPC and in TGC it is required that $n_{RPC} \geq 250$ and $n_{TGC} \geq 250$ in the barrel and endcap respectively. Finally, to reject background from jets that punch through to the MS and deposit energy the vertices are required to be isolated. To ensure high quality jets only those with a high transverse momentum above 30 GeV are used to compute the isolation. Vertices with jets that lie within an isolation cone size of $\Delta R = 0.3$ and $\Delta R = 0.6$ for the barrel and endcap respectively are not isolated and will be discarded because they can be created by a punch-through jet. For track isolation, tracks with high and low transverse momentum, p_T, are treated separately because some jets have most of their energy in a single hadron, while others can consist of multiple low-p_T tracks [1]. High-p_T tracks are required to have $p_T > 5\,\mathrm{GeV}$ and lie outside the same isolation cone as for the jets to pass the isolation criteria. For low-p_T tracks they are not isolated if the vector-sum of all tracks within a cone of $\Delta R < 0.2$ is $|\sum \vec{p}_T| < 10\,\mathrm{GeV}|$. For counting the number of single MS vertex events in the main stream data it is required that only *one* MS vertex events are chosen, that they pass the muon RoI cluster trigger and that the vertex is matched to a RoI Cluster i.e. $\Delta R(\text{vertex, cluster}) < 0.4$

Results

In the zero bias data 51 good isolated vertices were found in 161332954 events. 49 were found in the endcap and 2 in the barrel. The probability of finding a good, isolated vertex due to background is then

$$P[\text{MS Vertex}] = 51/161332954 = 3.16 \cdot 10^{-7} \tag{3}$$

In the main stream data 932088 events passed the selection described above. Here 167274 of those were found in the barrel and 764814 in the endcap. Using equation 2 the number of expected background events in 2015, 2016, 2017, and 2018 data is

$$N[2 \text{ MS Vertices}] = 3.16 \cdot 10^{-7} \cdot 932088 = 0.29 \tag{4}$$

Discussion and Conclusion

From the above result less than one event in 2015, 2016, 2017, and 2018 data is expected to have two displaced MS vertices. The number is not completely accurate as the systematic uncertainty have not been accounted for but the expected background seems to be very low. The 2 MS Vertex search seems to be very successful at rejecting background. In Appendix several plots have been included for illustrating the data. Table 1 shows the cutflow for the data. It illustrates the different criteria described above. The final count is the total number of events, the baseline count is the number of events that passes the baseline criteria, the MuVtx trigger count is the number of events that also passes the MuVtx trigger, the good selection count is the number of events that also passes the good selection criteria, and the isolation count is the number of events that passes all the previous criteria as well as being isolated. It is also specified which of these are in the barrel and in the endcap.

In appendix plots for two other types of data have been included. One is from dijet MC that contains simulated QCD events and can be used to study punch-through jets. This approach would not consider all the other backgrounds but it could provide better statitics for punch-through jets, which are the main source of background. The other type of data included is from the late stream. This could be an alternative approach to using zero bias data. The late stream is also recorded during the same run times and triggered when bunch crossings are empty. However, the cutflow shows an unexpected asymmetry between the left and right side of the detector. It is also apparent from the plots. The results from the main stream and the zero bias data does not indicate any similar asymmetry.

In conclusion the background is estimated to be very low where the number of expected background events in 2015, 2016, 2017, and 2018 data was found to be

$$N[\text{2 MS Vertices}] = 0.29 \tag{5}$$

The 2 MS vertex search requires that *both* scalars have lifetimes that lead to them decaying in the MS. But they might have very different lifetimes such that only one of the LLPs would decay in the MS. By requiring additional criteria other 1 MS vertex searches could be explored but they do not have the same advantage with the high rejection of background.

References

[1] ATLAS Collaboration (2019) Search for long-lived particles produced in pp collisions at $\sqrt{s}$ =13 TeV that decay into displaced hadronic hets in the ATLAS muon spectrometer. arXiv:1811.07370 [hep-ex]

[2] C. Alpigiani et al. (2018) Search for long–lived, weakly interacting particles produced in proton–proton collisions at $\sqrt{s}$ =13 TeV that decay to displaced hadronic jets in the muon spectrometer of the ATLAS detector ATL-COM-PHYS-2017-279 (ATLAS Note)

Appendix

Cutflow

Table 1 :

	Main Stream	**Zero Bias**	**MC**	**Late Stream**
Final count	8779383	42527828	8623113	5736988
Baseline count	8779383	42525539	8622922	5728329
MuVtx trigger count	8737573		8221196	
Good selection count	6478301	141	7260135	1703
Isolation count	932088	51	4836	1688
Barrel count	167274	2	4740	585
left	84845	1		177
right	82429	1		408
Endcap count	764814	49	96	1103
left	382424	28		129
right	382390	21		974
Asymmetry in barrel	0.014±0.002	–		-0.40±0.04
Asymmetry in endcap	0.00004±0.0011	0.14±0.14		-0.766±0.019

Assymmetry is calculated using

$$A = \frac{N_{\text{left}} - N_{\text{right}}}{N_{\text{left}} + N_{\text{right}}} \tag{6}$$

For Late Stream 2015 no events passed the baseline criteria.

For Late Stream 2016 the asymmetry is found to be

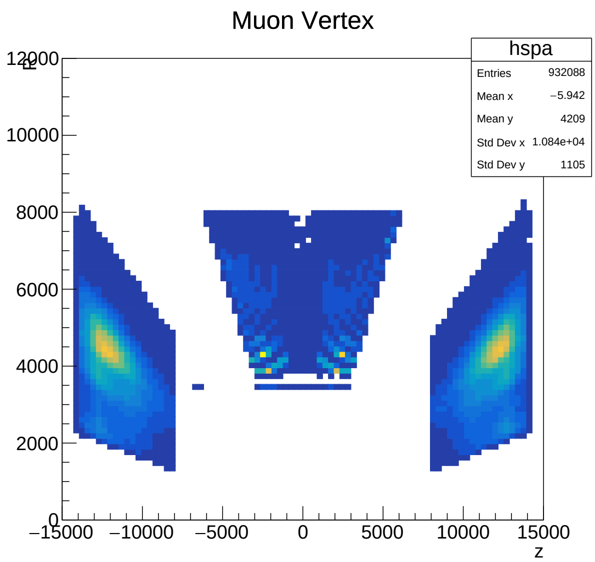
$$A_{\text{barrel}} = \frac{136 - 358}{136 + 358} = -0.45 \pm 0.04 \tag{7}$$

$$A_{\text{endcap}} = \frac{102 - 913}{102 + 913} = -0.799 \pm 0.019 \tag{8}$$

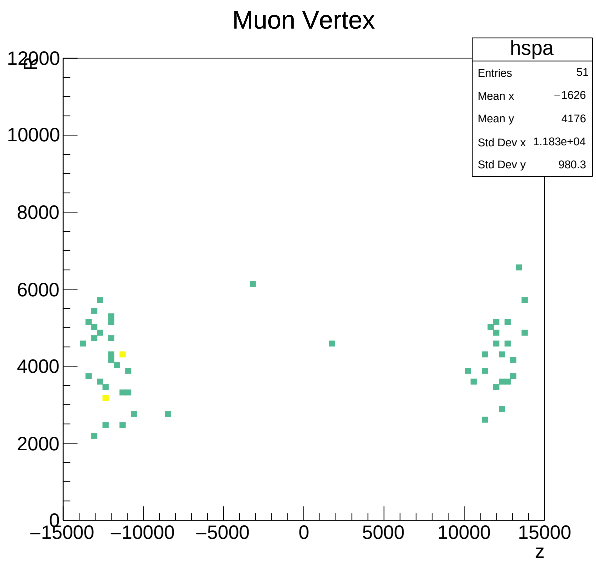
For Late Stream 2017 the asymmetry is found to be

$$A_{\text{barrel}} = \frac{41 - 50}{41 + 50} = -0.10 \pm 0.10 \tag{9}$$

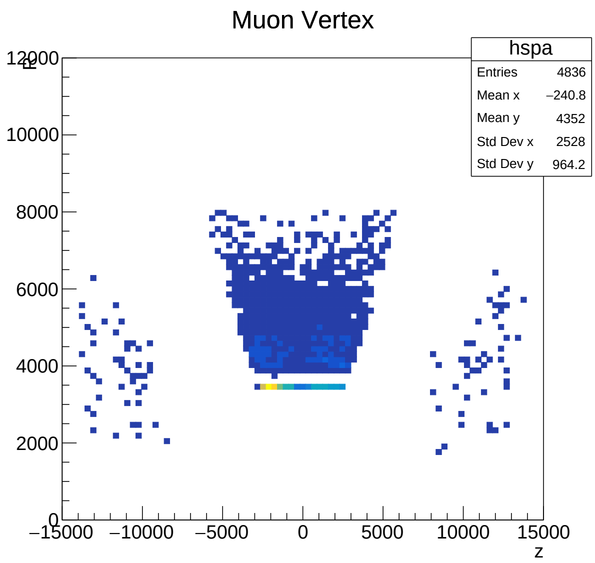
$$A_{\text{endcap}} = \frac{28 - 61}{28 + 61} = -0.37 \pm 0.10 \tag{10}$$



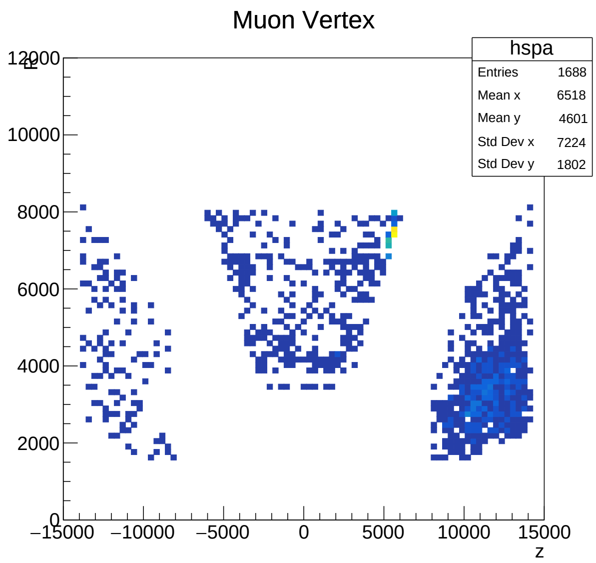
(a) Main Stream



(b) Zero Bias

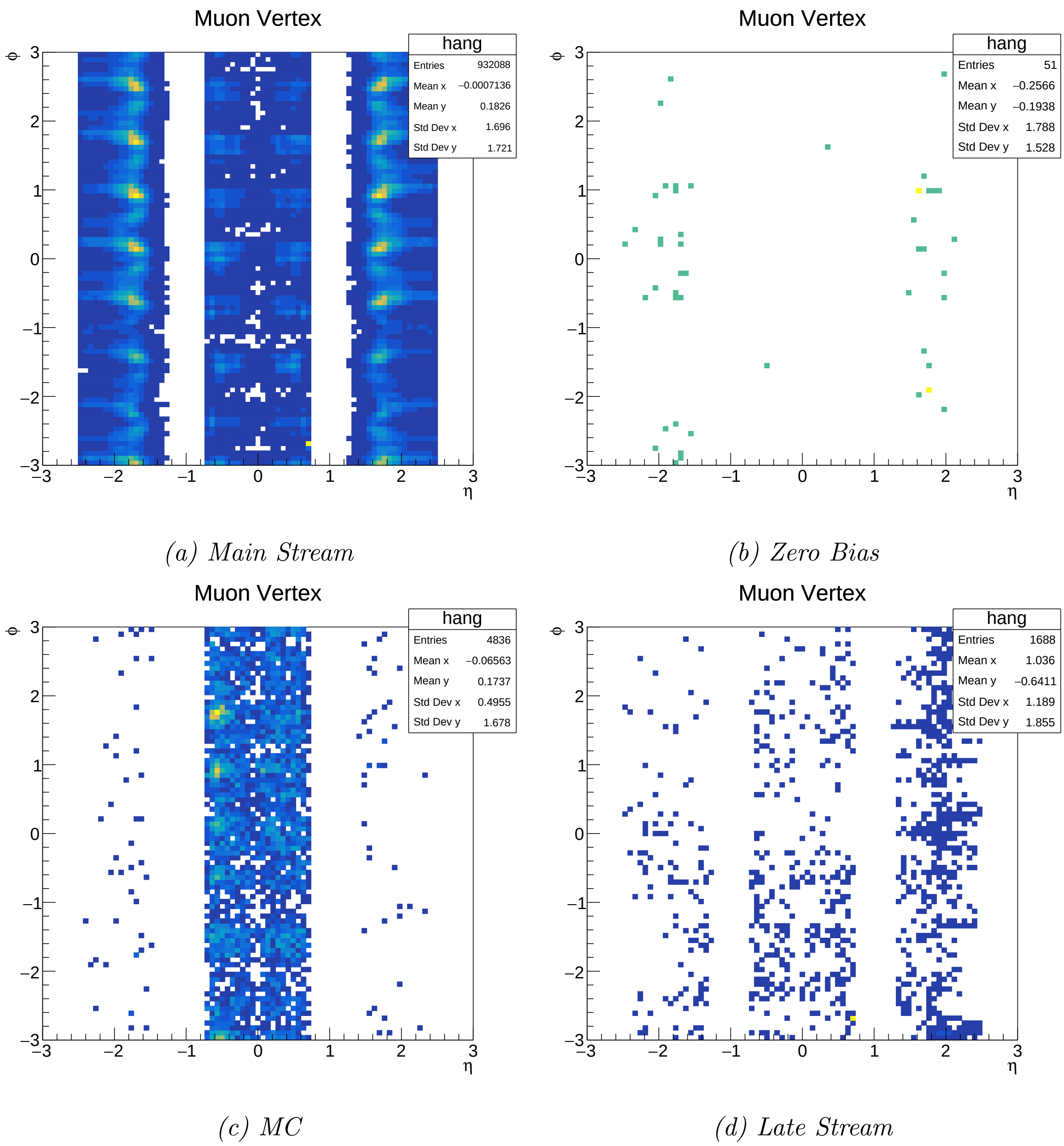


(c) MC



(d) Late Stream

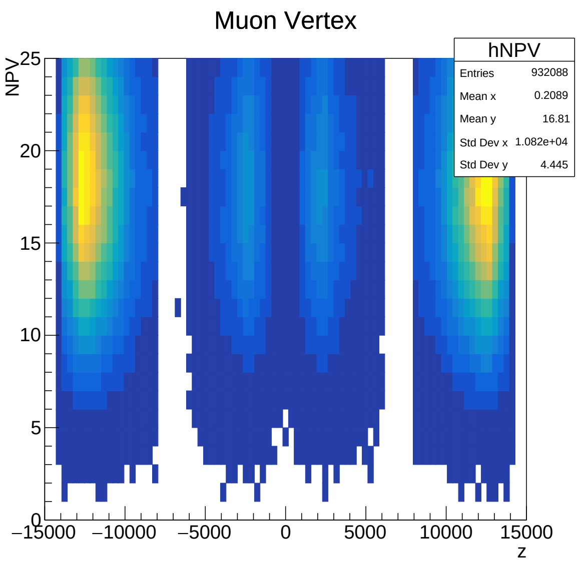
Figure 4 : R vs. z in vertex



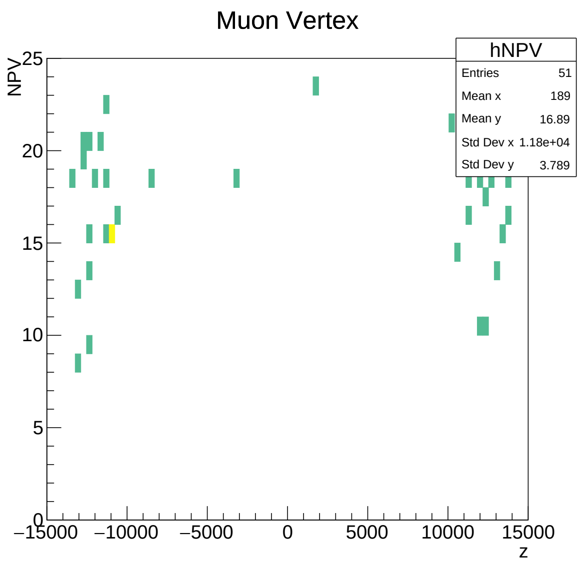
(a) Main Stream *(b) Zero Bias*

(c) MC *(d) Late Stream*

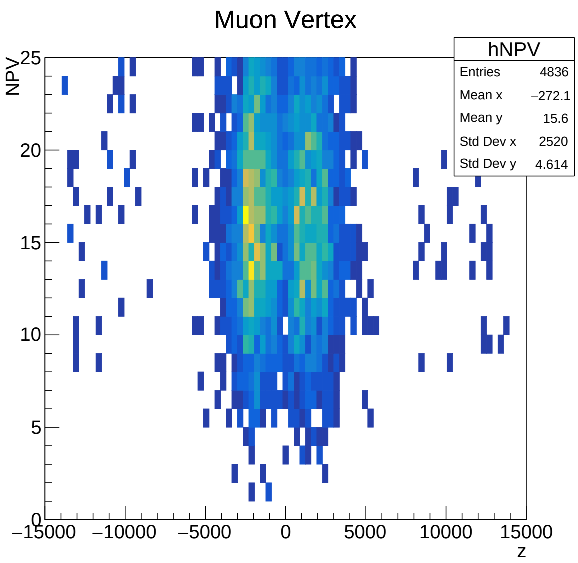
Figure 5 : ϕ vs. η in vertex



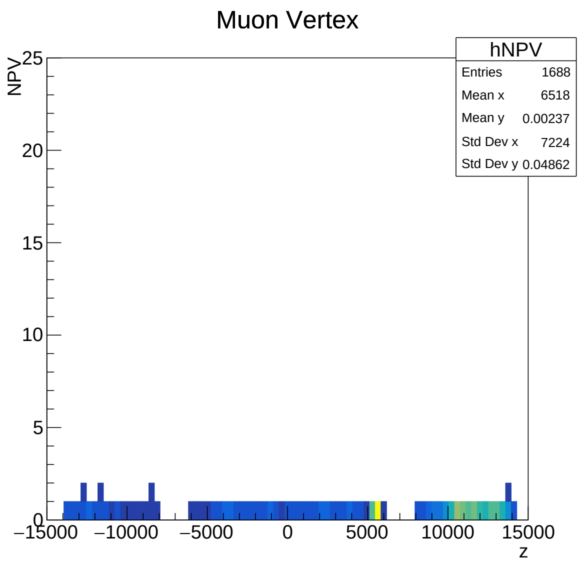
(a) Main Stream



(b) Zero Bias

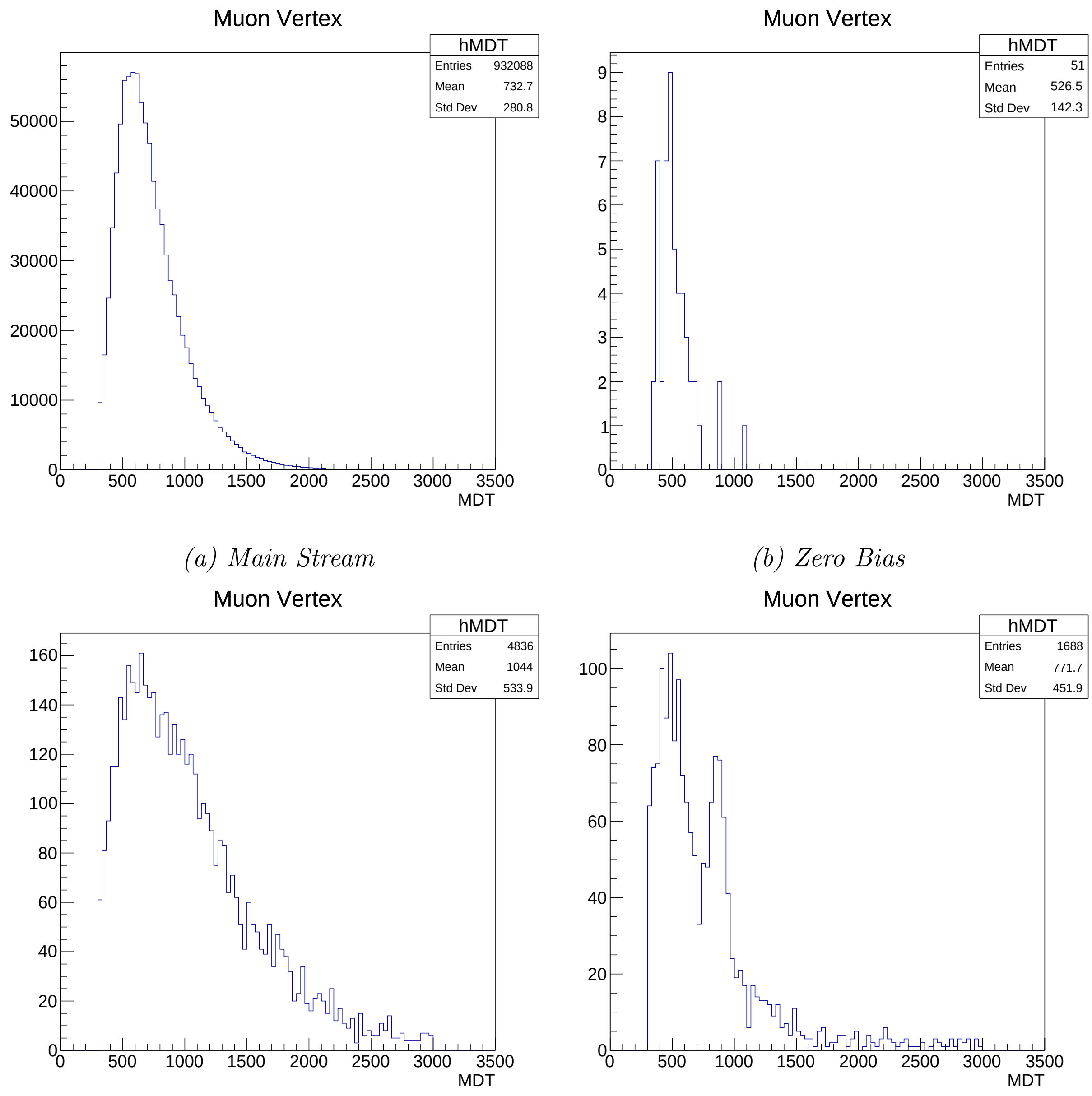


(c) MC



(d) Late Stream

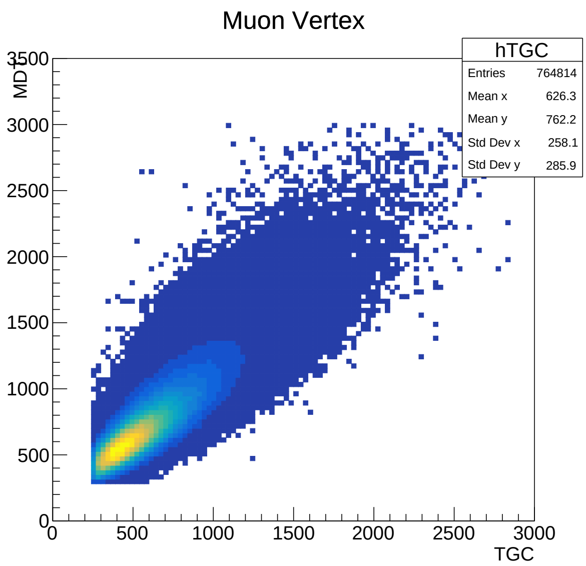
Figure 6 : NPV vs. z



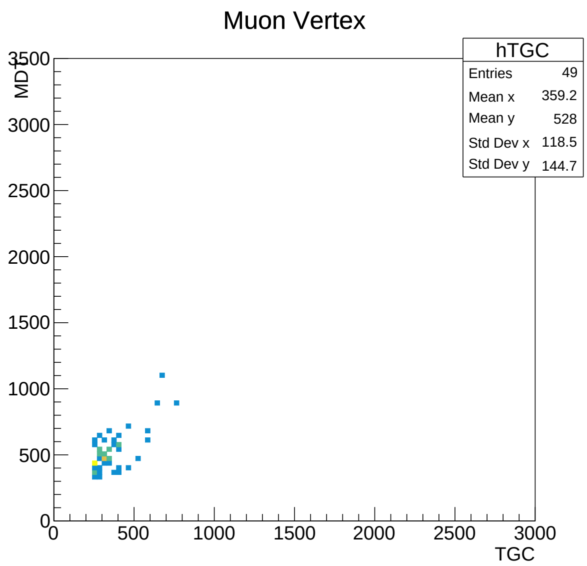
(a) Main Stream *(b) Zero Bias*

(c) MC *(d) Late Stream*

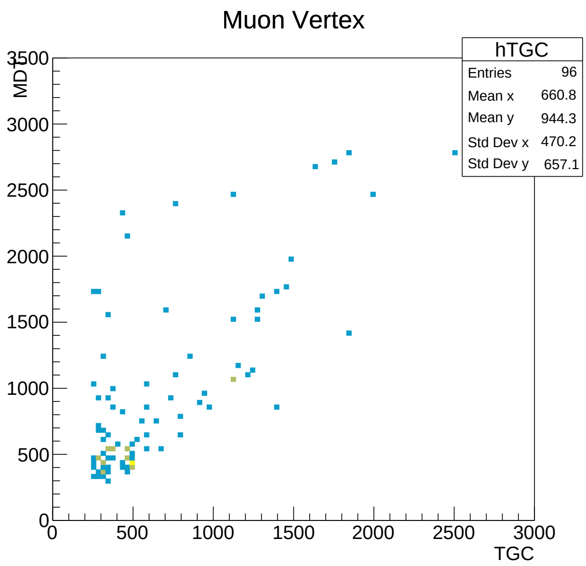
Figure 7 : MDT distribution



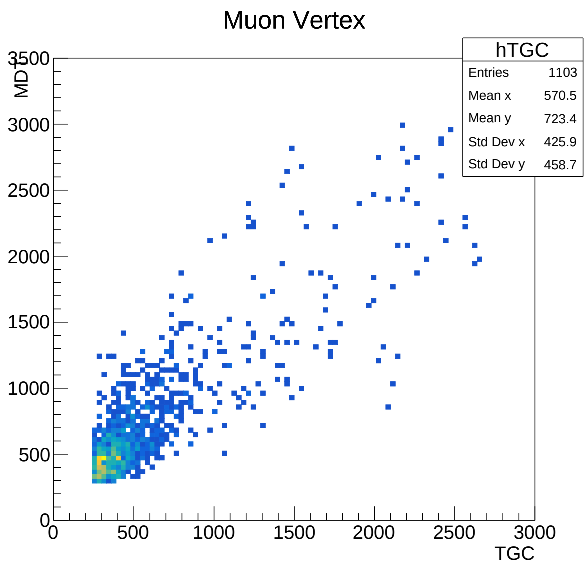
(a) Main Stream



(b) Zero Bias

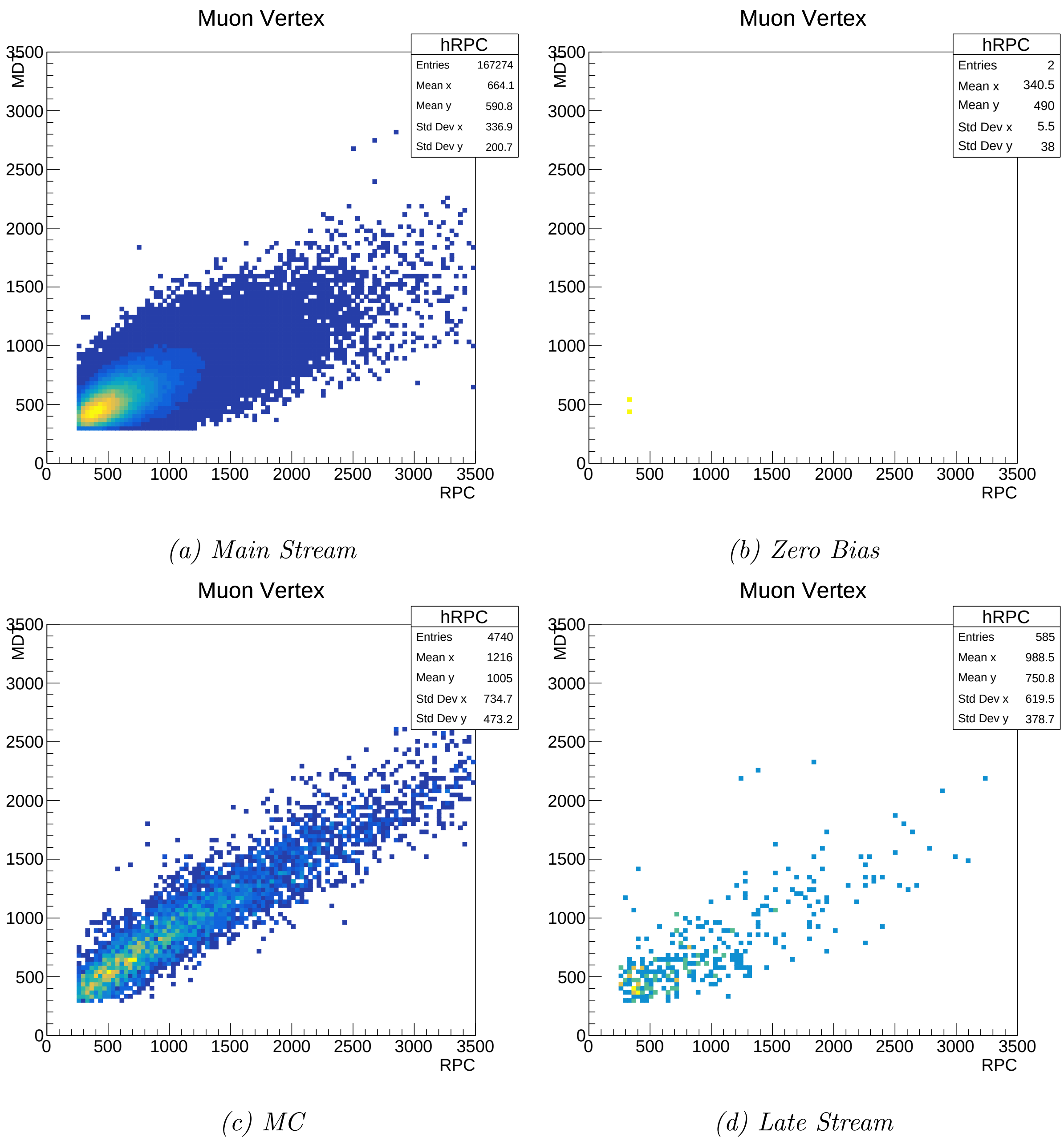


(c) MC



(d) Late Stream

Figure 8 : MDT vs. TGC



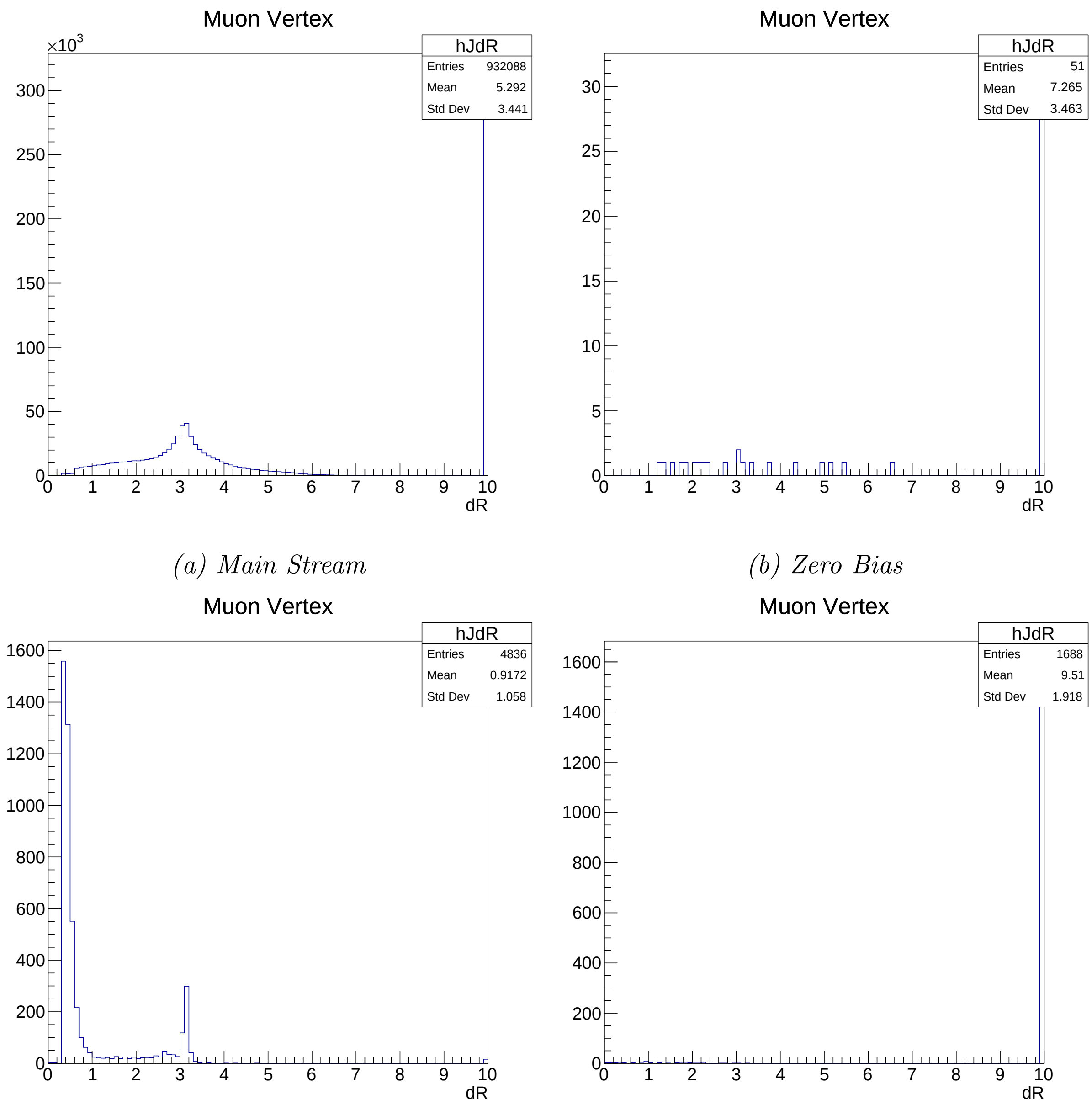
(a) Main Stream

(b) Zero Bias

(c) MC

(d) Late Stream

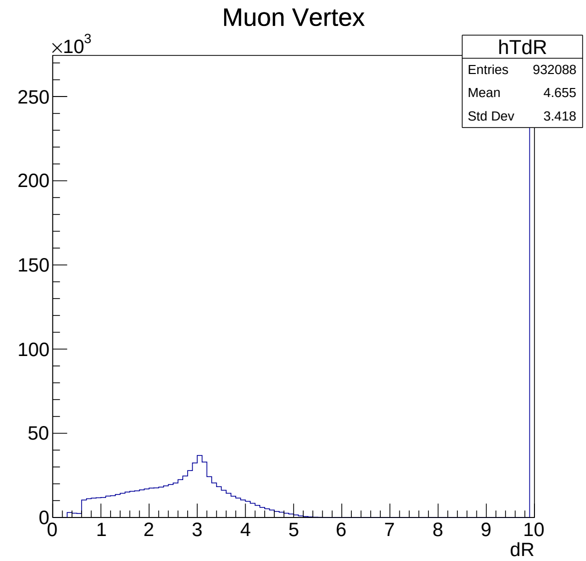
Figure 9 : MDT vs. RPC



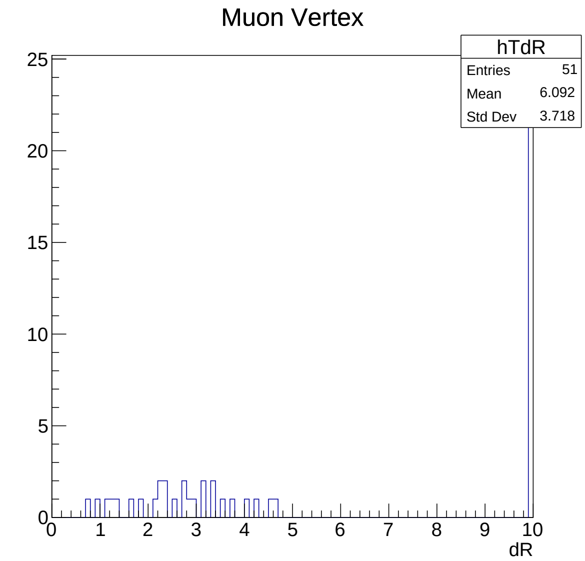
(a) Main Stream *(b) Zero Bias*

(c) MC *(d) Late Stream*

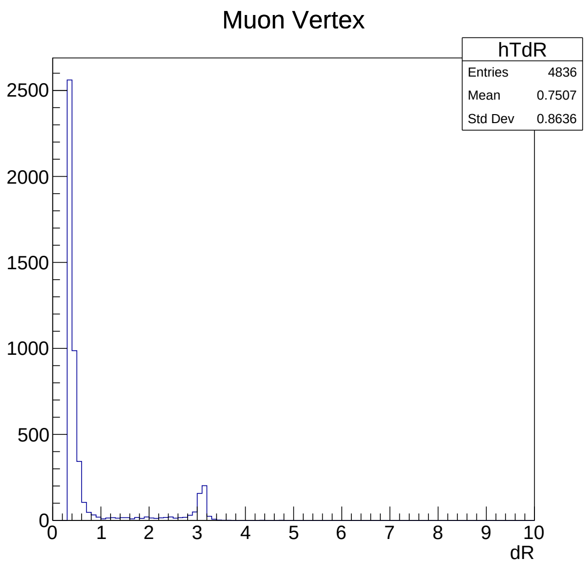
Figure 10 : ΔR distribution for jets



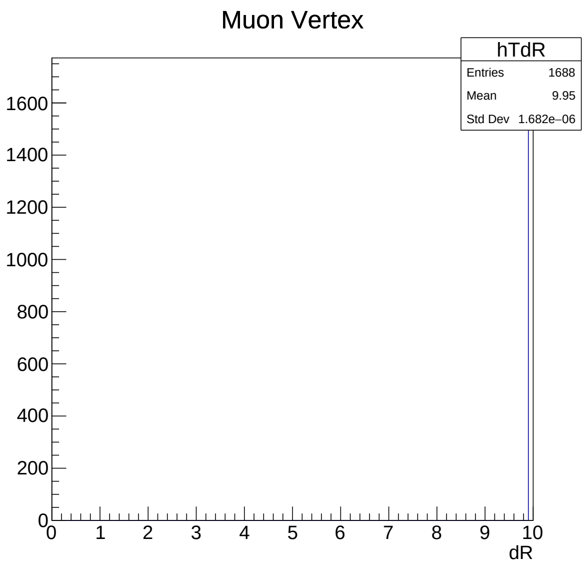
(a) Main Stream



(b) Zero Bias

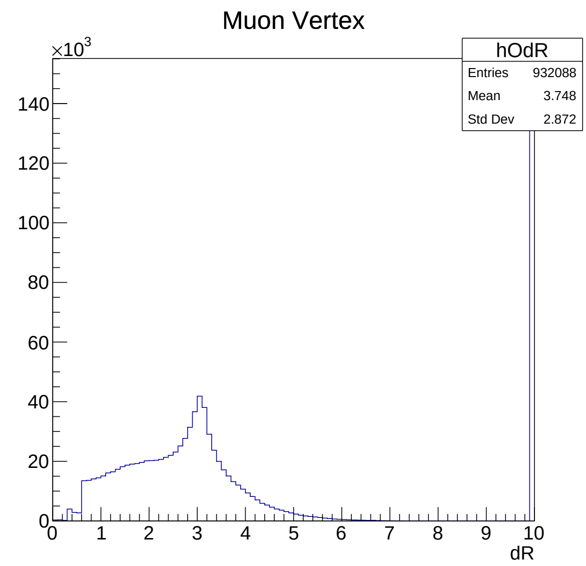


(c) MC

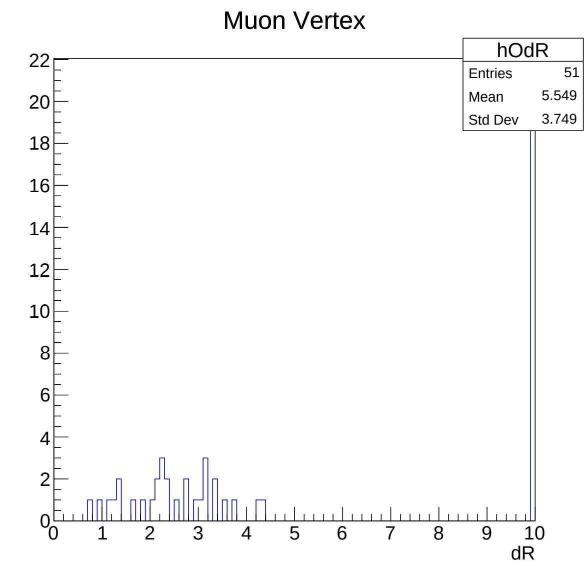


(d) Late Stream

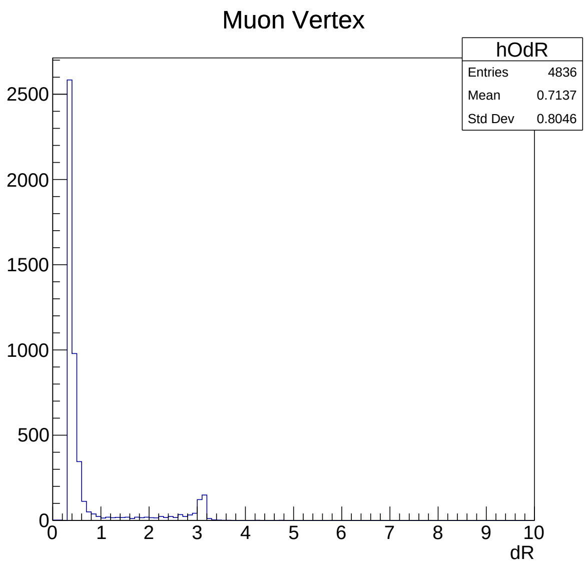
Figure 11 : ΔR distribution for track



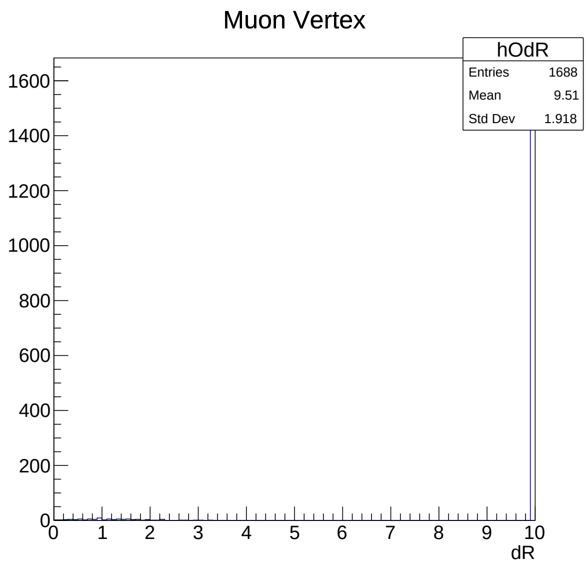
(a) Main Stream



(b) Zero Bias

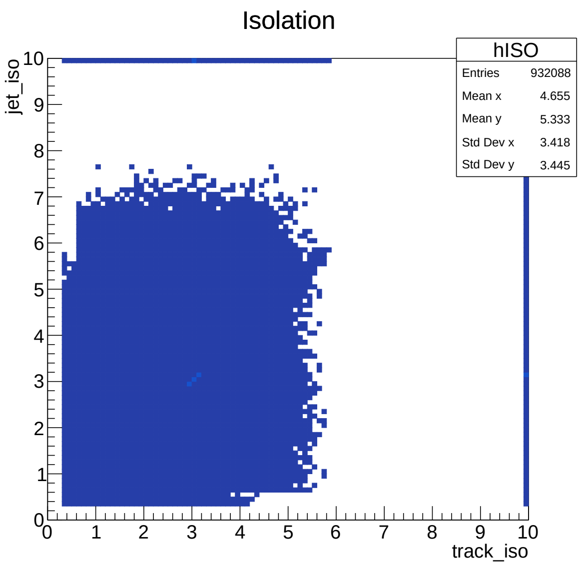


(c) MC

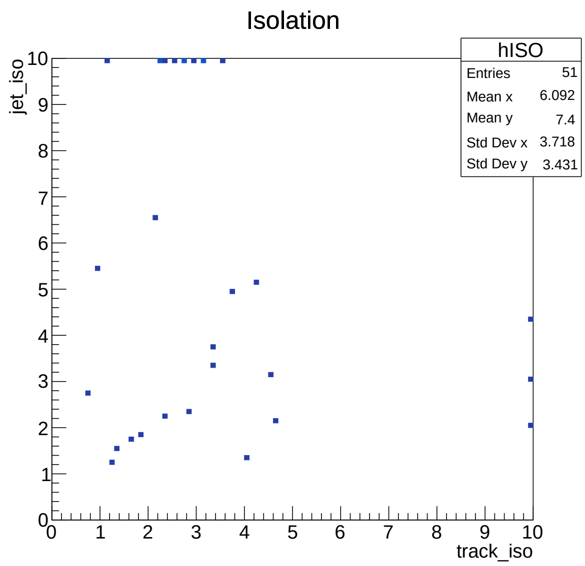


(d) Late Stream

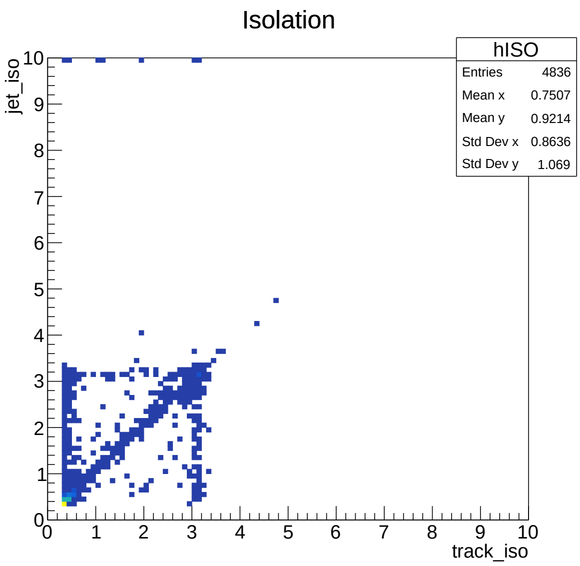
Figure 12 : ΔR distribution for closest object



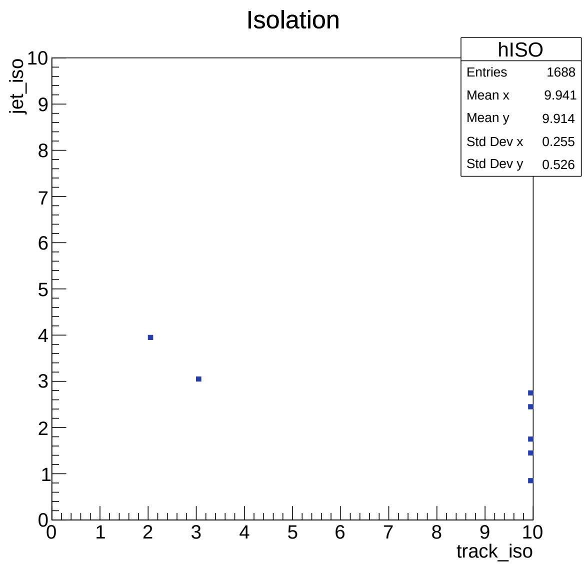
(a) Main Stream



(b) Zero Bias

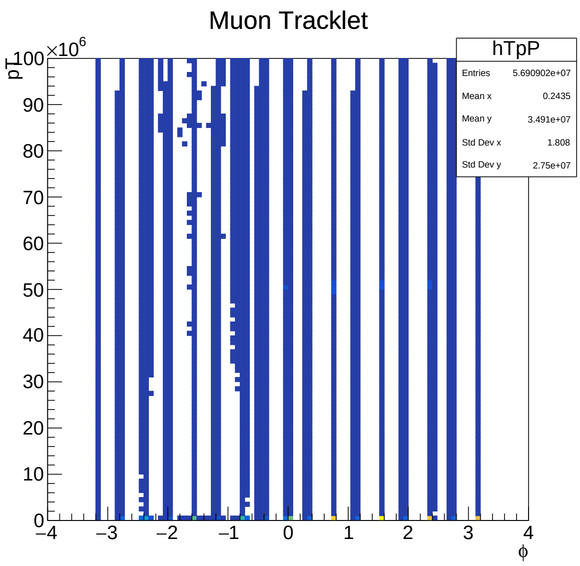


(c) MC

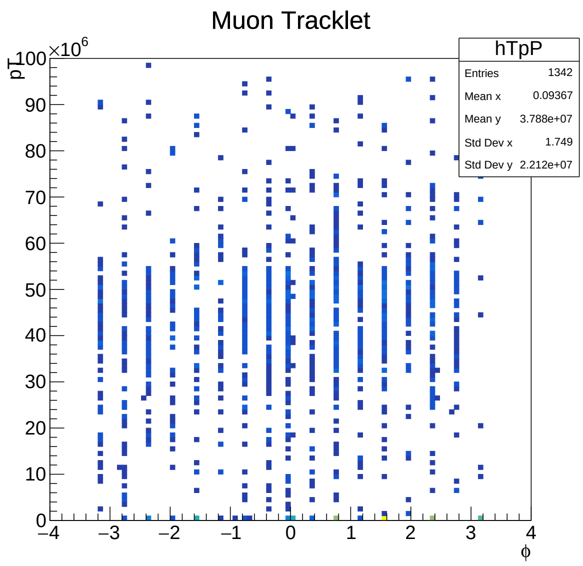


(d) Late Stream

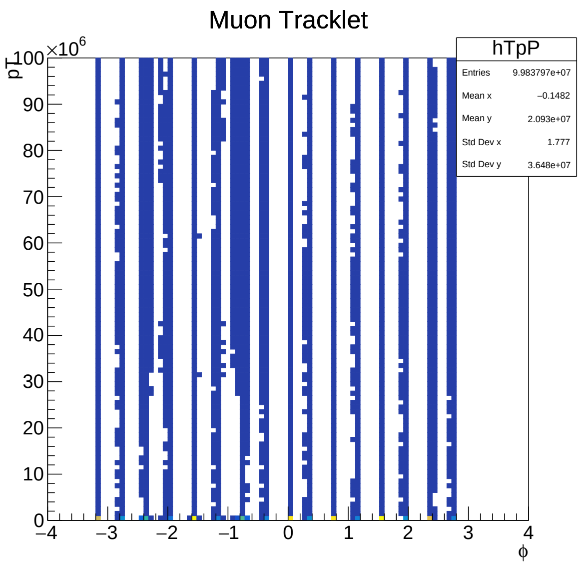
Figure 13 : Isolation for jets vs. isolation for tracks



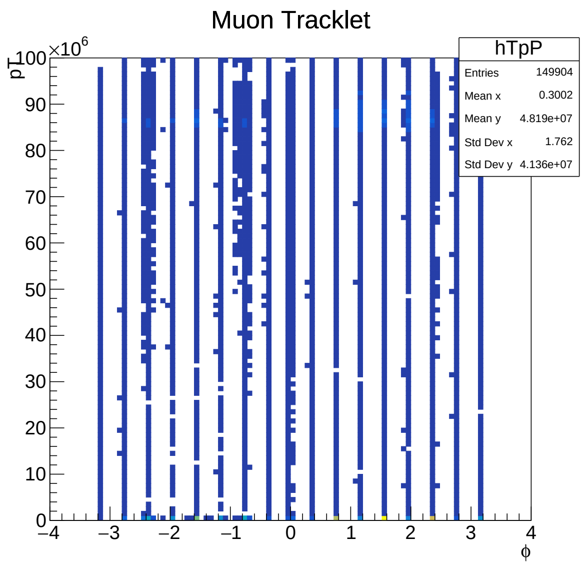
(a) Main Stream



(b) Zero Bias

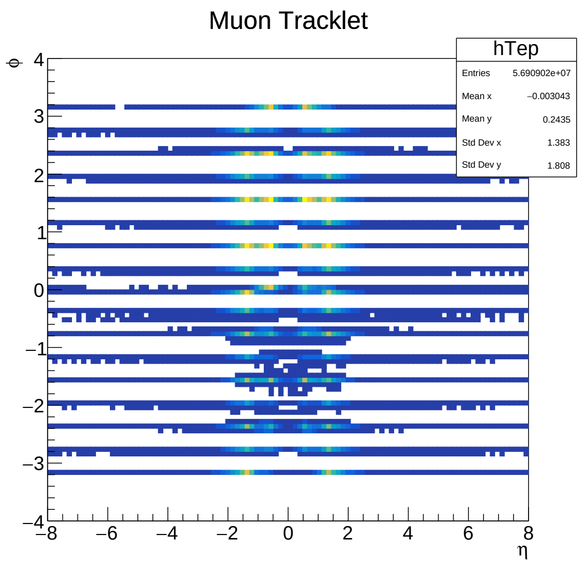


(c) MC

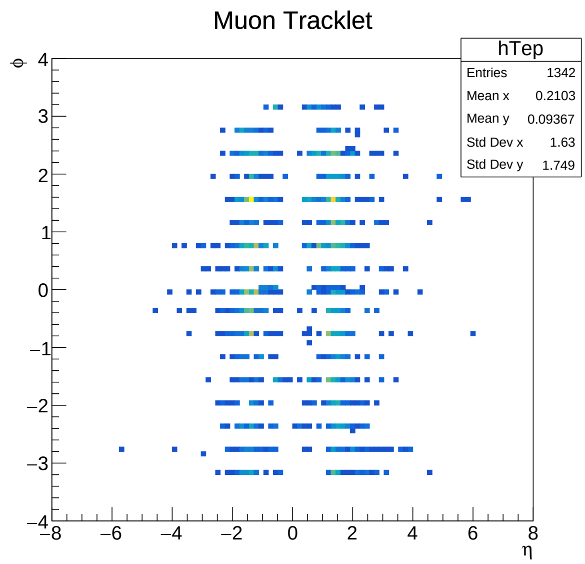


(d) Late Stream

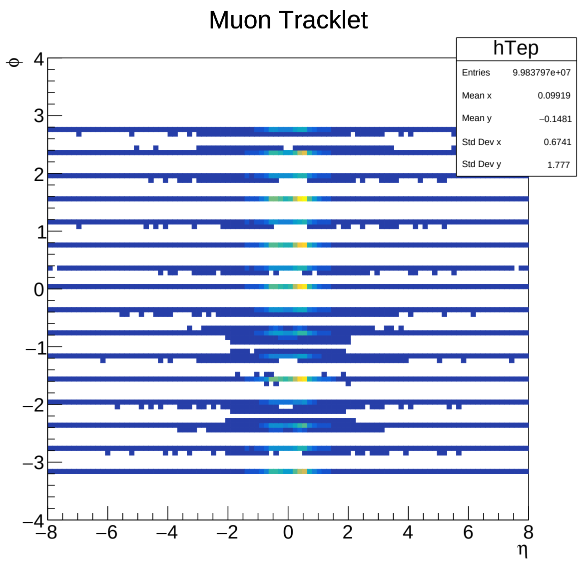
Figure 14 : p_T vs. ϕ for tracklet



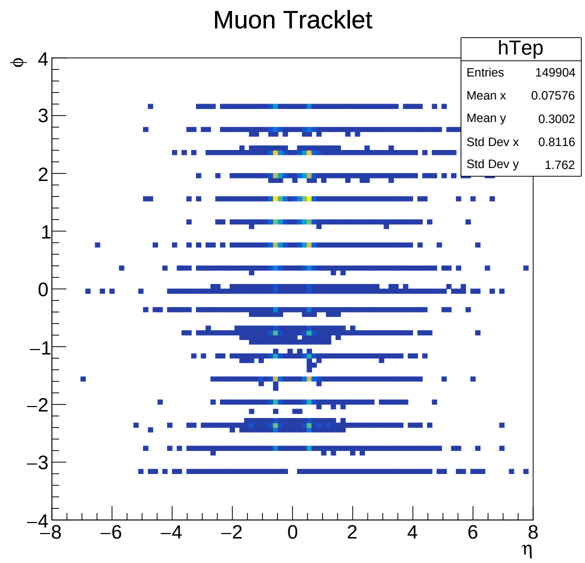
(a) Main Stream



(b) Zero Bias

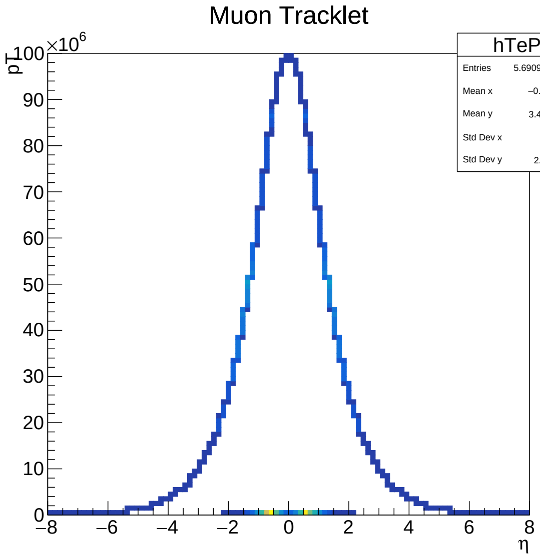


(c) MC

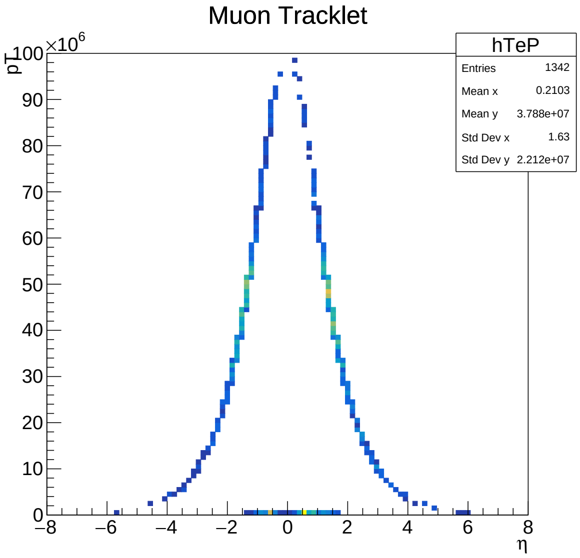


(d) Late Stream

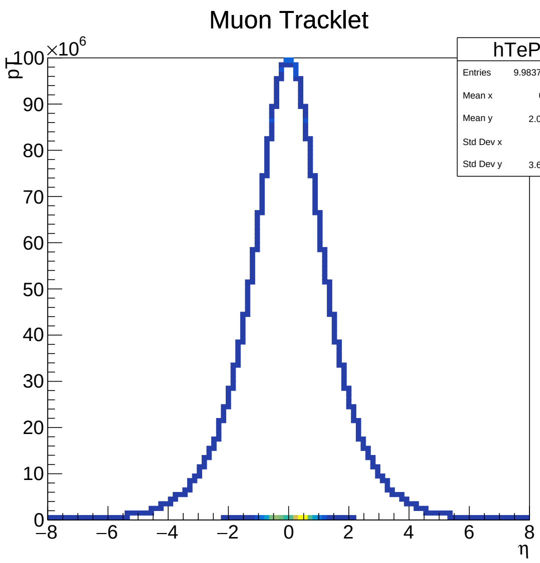
Figure 15 : ϕ vs. η for tracklet



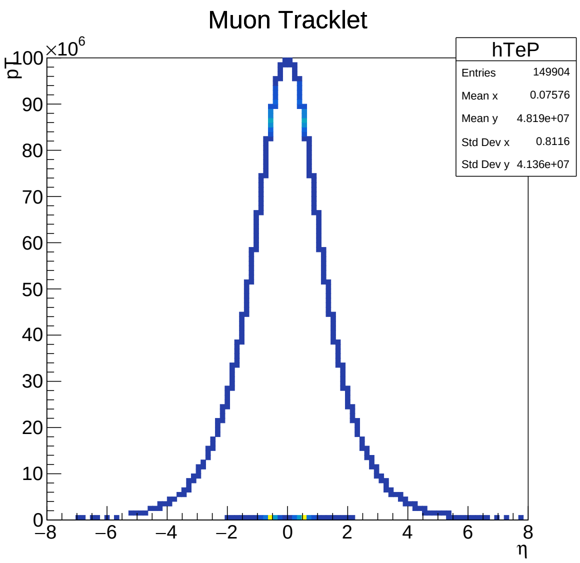
(a) Main Stream



(b) Zero Bias



(c) MC



(d) Late Stream

Figure 16 : p_T vs. η for tracklet