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Development of an event generator for antihyperon-hyperon pair production in antiproton-proton collisions

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Abstract

This project work or study is aimed for developing a lightweight Monte-Carlo (MC) event generator for hyperon pair production in antiproton-proton collisions, and mainly demonstrate it in one of the hyperon decay reaction channels for them, which is $\bar{p} + p \longrightarrow \bar{\Lambda} + \Lambda \longrightarrow \bar{p}\pi^+ + p\pi^-$. The prototype of this external MC event generator we present here is done by the software framework of ROOT. Compare to the corresponding framework of embedded MC event generators that is currently used in the PANDA experiment at FAIR, PandaRoot, it would be more convenient and accessible for quickly testing of new models or formalisms on synthetic data, especially for study topics about polarisation and spin observables. The event generator was benchmarked primarily in its physics performance by studying angular distributions in final states, which are mainly constructed by kinematic relations of 4-momentum vectors in different reference frames for all mother and daughter particles , and consistency check between reference frames.

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1 Introduction

The current event generators for the PANDA [1] experiment at FAIR [2] are currently embedded into its software framework, PandaRoot [3]. While this can be very convenient for the PandaRoot user when running a full Monte Carlo simulation, it is also very resource-demanding. Furthermore, it requires compiling a large software package with a complex dependency tree. Thus, it becomes a difficult task to quickly test new models and formalisms on synthetic data, especially for those study topics about polarisation and spin observables. In particular for $\Lambda \to p\pi^-$ there is a relation to test the polarisation by measuring the angular distribution of the proton [4]

$$I(cos\theta_p) = \frac{1}{4\pi}(1 + \alpha_\Lambda P_n cos\theta_p) \tag{1.1}$$

which would concerns about testing the angular and momentum distribution of the final states, for instance.

This issue was addressed in this project by developing a lightweight event generator for hyperon pair production in antiproton-proton collisions, and mainly demonstrated in the specific reaction channel of $\bar{p} + p \longrightarrow \bar{\Lambda} + \Lambda \longrightarrow \bar{p}\pi^+ + p\pi^-$.

The process will require generating angular distribution for the final state particles in the hyperon rest frame as well as calculating their absolute momentum from mass difference of the hyperon and its daugther particles. From the generated quantities the 4-momentum vectors will constructed and then transformed into the center-of-mass frame of the reaction.

Some major background of physics and software tools involved in this project is presented in this introduction chapter, including the the specific properties of hyperons, a brief introduction to the PANDA experiment at FAIR, as well as a brief introduction to ROOT [5], FairRoot [6], PandaRoot, and the general idea of event generator. The relations of kinematics of 4-vectors as the methodology to construct the event generator, is introduced in the next chapter. The framework of this external event generator and some discussion about that is presented in the 3^{rd} chapters of this report . A conclusion and outlook is given in the final chapter.

1.1 Hyperon Physics and $\overline{\text{p}}$p collisions

A branch of physics research and studies that concering hyperons, namely, is called hyperon physics. Broadly speaking, it can be at least related to the field of particle physics, nuclear physics, and astrophysics.

The study obejects, hyperons, is in the category of matter called baryons. From the point of view of constituent quarks, they are similar to the baryons that is more familiar by most of the people, protons and neutrons. If we make a comparison of hyperons with protons and neutrons, they all have three quarks. But the main difference is that, unlike protons and neutrons which contains only u quarks or d quarks, the hyperons contains at least one s quark, and sometimes with c quark as well (The latter case is mostly called charmed hyperon in order to distinguish). In other word, what we are referring is at least one of the u or d quark is replaced by s quark in the case of neutron or proton. That is, the baryons that contains strange quarks is the interest that mostly considered in this branch of physics research field, and obviously sometimes it can be called strangeness physics more specifically. And the letters Y and $\overline{\text{Y}}$ are usually used to denote hyperons and anti-hyperons, respectively.

A list of typical hyperons is summarised below.

Y	q	$c\tau$ (cm)	T (s)	M (GeV/c^2)	Decay
Λ	uds	7.89	2.632×10^{-10}	1.116	$p\pi^-$ (63.9%)
					$n\pi^0$ (35.8%)
Σ^+	uus	2.404	8.018×10^{-11}	1.189	$p\pi^0$ (51.57%)
					$n\pi^+$ (48.31%)
Σ^0	uds	2.22×10^{-9}	7.4×10^{-20}	1.193	$\Lambda\gamma$ (100%)
Σ^-	dds	4.434	1.479×10^{-10}	1.197	$n\pi^-$ (99.848%)
Ξ^0	uss	8.71	2.0×10^{-10}	1.315	$\Lambda\pi^0$ (99.524%)
Ξ^-	dss	4.91	1.639×10^{-10}	1.322	$\Lambda\pi^-$ (99.887%)
Ω^-	sss	2.461	8.21×10^{-11}	1.672	ΛK^- (67.8%)
					$\Xi^0\pi^-$ (23.6%)
					$\Xi^-\pi^0$ (8.6%)

Table 1.1: Strange ground state hyperons. The name of hyperon, its quark content, mean decay length, mean lifetime, mass, and main decay with branching ration are shown, and they are denoted by Y, q, $c\tau$, T, M, and Decay. Data from [7].

The hyperon , is the lightest in mass amongs them, and also its decay process is important since there are some other hyperons would decay to it and a meson.

In general, since hyperons constains at least one strange quark, it is much more heavier in mass, this type of particles is less well-studies, and it is relatively long-lived paricles, compare to nucleons (protons or neutrons). Thus some physics puzzles might be figured out through the studies of hyperons, for example, topics about asymmetries between matter and antimatter, CP asymmetry and initial conditions in big bang, some reaction and mechanics of neutron star that heavily related to strange quarks.

There are several possible ways to produce hyperons (pair). One of them would be using anti-proton proton collision (annihilation), since provides a greater cross section to produce anti-hyperon hyperon pair [1], when compare to other possibles like production from positron-electron.

1.2 $\overline{\text{P}}$ANDA experiment at FAIR

The acronym "$\overline{\text{P}}$ANDA" or "PANDA" stands for "antiProton ANihilation at DArmstadt". The PANDA Experiment will be one of the key experiments at the Facility for Antiproton and Ion Research (FAIR) which is under construction and currently being built on the area of the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany. The central part of FAIR is a synchrotron complex providing intense pulsed ion beams (from p to U). Antiprotons produced by a primary proton beam will then be filled into the High Energy Storage Ring (HESR) which collide with the fixed target inside the PANDA Detector.

1.2.1 FAIR

"FAIR" stands for "Facility for Antiproton and Ion Research in Europe". Currently the international accelerator facility FAIR, one of the largest research projects worldwide, is being built in Darmstadt, Germany. At FAIR, matter that usually only exists in the depth of space will be produced in a lab for research. Scientists from all over the world will be able to gain new insights into the structure of matter and the evolution of the universe from the Big Bang to the present. FAIR is under construction at GSI Helmholtzzentrum für Schwerionenforschung. Its existing accelerator facilities will become part of FAIR and will serve as first acceleration stage.

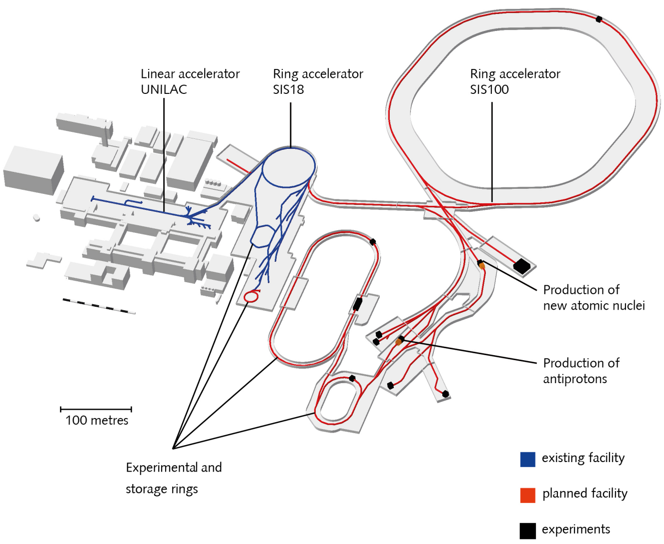

Figure 1.1: The Accelerator Facility of FAIR [2]

1.2.2 $\overline{\text{P}}$ANDA

For the envisaged experimental program a nearly full coverage of the solid angle together with good particle identication and high energy and angular resolutions for charged particles and photons are mandatory. The proposed detector is subdivided into the target spectrometer (TS) consisting of a solenoid around the interaction region and a forward spectrometer (FS) based on a dipole to momentum-analyze the forward-going particles. The combination of two spectrometers allows a full angular coverage, it takes into account the wide range of energies and it still has sufficient flexibility, so that individual components can be exchanged or added for specific experiments.

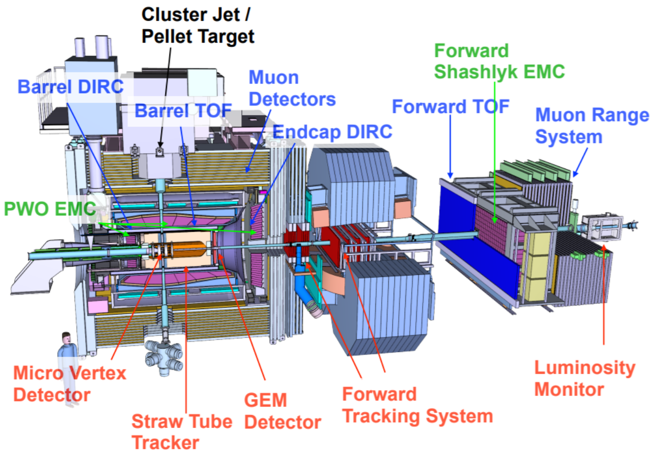

Figure 1.2: The Detector of PANDA [1]

1.3 The current tools for simulation and analysis: PandaRoot

There is a currently using but also under developing simulation and reconstruction software package for the PANDA experiment that is called PandaRoot, which is initially based on the framework of FairRoot, as the latter one is mainly developed for the future experiments at FAIR. One can also noticed that they are built on the open-source data analysis framework called ROOT which is frequently used in HEP, Nuclear physics, and other disciplines.

The first PandaRoot simulation-reconstruction chain was successfully tested on the PANDA Grid in February 2007. It is in a clear and well-defined structure of framework, as a illustration of Simulation stages within the framework of PandaRoot is shown in Figure 1.3.

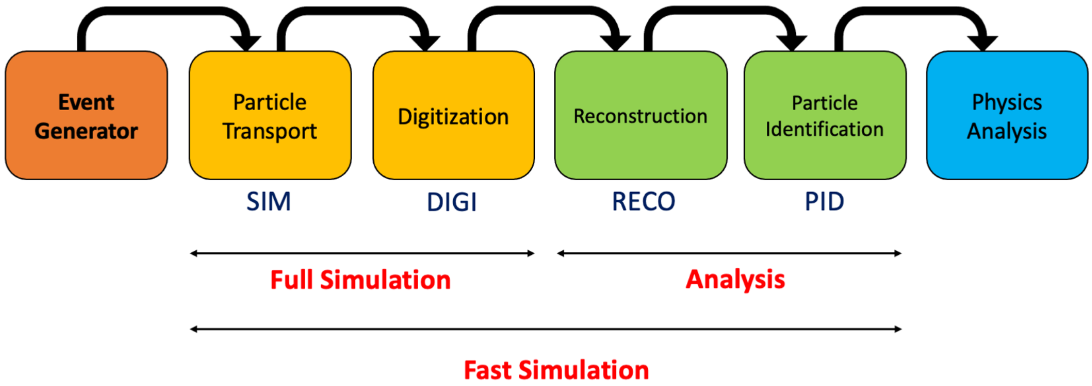

Figure 1.3: Simulation stages within the framework of PandaRoot

Refer to figure 1.3, the basic idea is that there are 6 main stages in the framework of simulation-reconstruction chain [8] in PandaRoot.
The first and the starting point in the simulation stage, the embedded event generators within PandaRoot. They can specific the initial state particle distributions, physics channels and antiproton-proton background reactions, with several complementary event generators can be selected by user, including EvtGen [9], DPM [10], UrQMD [11], and Pythia [12].
The following stage concerns about particle transport through the detector material is simulated with Virtual Monte Carlo, Geant4 [13] or Geant3 [14]. Then the digitization stage the generated MC data is processed to simulate the realistic response of the subdetectors. For the reconstruction stage information provided by the tracking detectors are combined to reconstruct charged tracks and propagate these to the outer subdetectors. For the PID part, probability density functions (p.d.f.) are computed for every track based on different detectors and various particle identification (PID) concepts. It ultimately goes to physics analysis stage, various fitting algorithms for the four momentum and position of the particles as well as particle selection and combination mechanisms are provided.

1.4 Event Generator

Follow by the last section that this is the first part in the structure framework of simulation chain of PandaRoot. The light-weight event generator which we are developing, built on ROOT as a external event generator, as a different approach compare to the original embedded event generator in PandaRoot since the purpose and need of fast-testing formalisms and models for polarisation and spin observables studies on $\bar{Y}Y$ in $\bar{p}p$ annihilation.

1.4.1 Background

The Monte Carlo (MC) Event Generator, or in this report just simply refer it as "event generator", can be known as the software that produces the information of physical quantities of particles in the final state, that as the very-first part or as the preparation process consisted in the whole MC simulation chain, then is ready to go the part of MC simulation, usually particle transport through materials of detectors. In general, the Monte-Carlo Event Generator, can be considered as the software which produces particles in final states for MC simulation Simulates decay chains, Angular distributions, 4-momenta, initial positions, time and PID are passed to transport engine Transport engine simulates interaction of particles from event generator with material of detector.

1.4.2 The External Event Generator developed in this project

External event generator, as its name suggested, can be compiled and ran standalone. This statement is due to the comparison to those embedded event generators, for example, in the case of software framework for PANDA, some event generators like EvtGen or Pythia that can be chosen was embedded into PandaRoot as an integrated framework, which is why we called them embedded event generator. One should once again be aware that, compare to the embedded event generators, that are certainly pros and cons corresponding to these two categories of event generator.

Normally, for the whole matured software framework for the simulation and analysis, the way of embedded is used without so much issues and is especially convenient. Since they are called directly by the macro file, and go into the simulation with the particle transport model. However, the information of output is not stored in a separate file, since it will be too much if this is also kept for the full long-term point of view. Also, when one want to ran the same events again, the event generator has to reproduce them. In order to complement, one can achieve the demand in the other way. namely the external event generator. It produces the output events file independently, generate events once then pass to the part of particle transport, and also run in other parts multiple times on that same events. The most important feature here that we are concerning is, we can set and determine the desired distribution of the event generator, such as angular distribution, without so much difficulties, since mostly the embedded way typically in a heavily dependency in the framework and thus not in a fast and easy way to alter and analyse the distribution itself.

2 Methodology

The main idea is to achieve the production of $\bar{\Lambda}\Lambda$ from the annihilation of $\bar{p}p$, also the dacay products $\bar{p}\pi^+$ and $p\pi^-$ from their 4-momentum equation when considering here the decay of a particle to two daughter particles . Here we focus on the momentum and angular distribution of particles when they are in different reference frame, thus applying the 4-momentum conservation and the Lorentz transformation is needed to do the event generation. We can first generate the angular distribution of $p\pi^-$, and $\bar{p}\pi^+$ in the hyperon and anti-hyperon rest frame, by the 4-momentum conservation and the Lorentz transformation, the corresponding state of them in $\bar{p}p$ centre of mass frame is also generated. Since we have the mass of each particles, the beam momentum in lab system of the beam is set to be 1.64 GeV/c and it is a antiproton beam hit into the stationary proton target experiment. Thus in the event generator we developing follow the relations mentioned above, the momentum vector, angles of The inclination or polar angle, and of azimuth or azimuthal angle, are all generated. The schematic diagram of the kinematics of 4-Vector for all the particles in 3 different reference frame can refer to Figure 2.1.

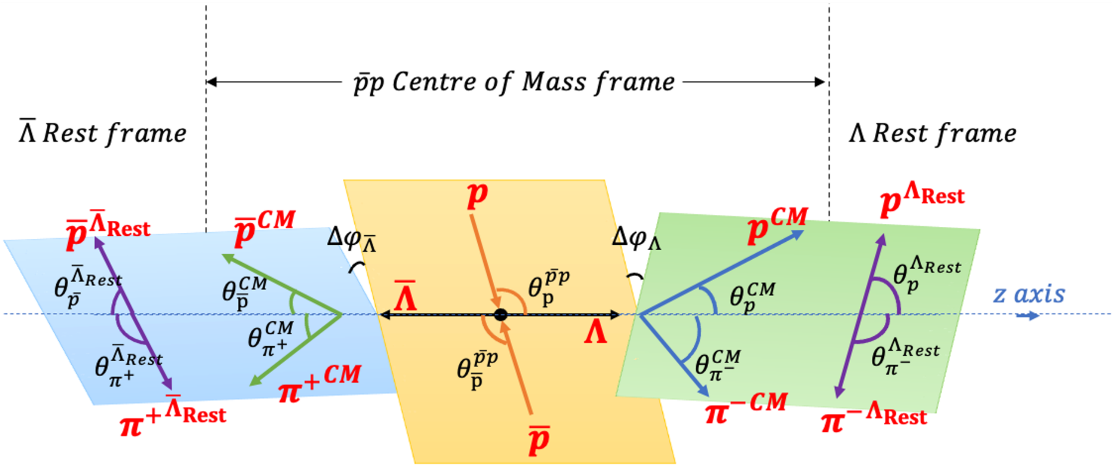

Figure 2.1: Schematic Diagram of the reaction in CM frame and Rest frame

2.1 Kinematics of 4-Vector

Recall for a 4-momentum p_A^2 , In natural unit, it can be written as

$$p_A^2 \equiv E_A^2 - \boldsymbol{p}_A^2 = m_A^2 \tag{2.1}$$

where E is energy, $\boldsymbol{p}$ is the 3 momentum, and m is the mass. In the case for a scattering process of two particles into two particles, e.g. $p_A + p_B = p_C + p_D$, it is then

$$\begin{pmatrix} E_A \\ p_{A_x} \\ p_{A_y} \\ p_{A_z} \end{pmatrix} + \begin{pmatrix} E_B \\ p_{B_x} \\ p_{B_y} \\ p_{B_z} \end{pmatrix} = \begin{pmatrix} E_C \\ p_{C_x} \\ p_{C_y} \\ p_{C_z} \end{pmatrix} + \begin{pmatrix} E_D \\ p_{D_x} \\ p_{D_y} \\ p_{D_z} \end{pmatrix} \tag{2.2}$$

Now for considering the decay of a mother particle with mass M to two daughter particles of mass m1 and m2 in the rest frame of the parent particle. This implies $p_1^2 = m_1^2$ and $p_2^2 = m_2^2$. By the 3-momentum conservation, the two daughter particles must be emitted back to back in the parent rest frame , we can choose the parameters to be two angles θ and φ defining the direction of one of the daughters. Using the 4-momentum conservation, $P = p_1 + p_2$, in parent's rest frame and thus $P = (M, \mathbf{0})$, rewrite $p_2 = P - p_1$ we get

$$p_2^2 = (P - p_1)^2 = P^2 - 2P \cdot p_1 + p_1^2 \tag{2.3}$$

and the mass

$$m_2^2 = M^2 - 2ME_1 + m_1^2 \tag{2.4}$$

The energy of the daughter particels can be solved

$$E_1 = \frac{M^2 + m_1^2 - m_2^2}{2M} \tag{2.5}$$

and using the relation of $E_2 = M - E_1$ in this case parent's rest frame

$$E_2 = \frac{M^2 + m_2^2 - m_1^2}{2M} \tag{2.6}$$

The momentum form $|\boldsymbol{p_1}| = \sqrt{E_1^2 - m_1^2}$ and obtains

$$|\boldsymbol{p_1}| = \frac{\sqrt{(M^2 + m_1^2 - m_2^2)^2 - 4M^2 m_1^2}}{2M} = \frac{\sqrt{(M^2 - m_1^2 - m_2^2)^2 - 4m_1^2 m_2^2}}{2M} \tag{2.7}$$

Notice that the it is symmetric under the interchange of daughter particle 1 and 2. Thus, it would be an identical result $|\boldsymbol{p_1}| = |\boldsymbol{p_2}|$, as we expected from the conservation of 3 momentum.

2.2 Hyperon and Anti-hyperon Rest Frame

In these 2 reference frame which is the final state particles, it is first constructed in ROOT by applying the 4-momentum relation mentioned above. Λ and $\bar{\Lambda}$ is at rest, with the $p\pi^-$ and $p\pi^+$ are going in the back-to-back direction in their reference frame of rest frame of hyperon and antihyperon, respectively. Since we already know the mass of particles, then the corresponding energy and 3-momentum vector for the specific polar angle, and azimuthal angle that generated in each event are calculated and stored.

2.3 $\overline{\text{p}}$p Centre of Mass Frame

Refer to Figure 2.1 again. After the final state particles in $\bar{\Lambda}$ and Λ are generated, including polar angle, azimuthal angle, and component of momentum vector, then it is the time to do the Lorentz transformation.

2.3.1 Lorentz Boost

In the situation of boosting daughter particles from parent rest frame, which means that this time Λ and $\bar{\Lambda}$ are not in rest but moving, that is they are the CM frame of the system antiproton-proton.
We take the example of $\Lambda \to p\pi^-$ to illustrate the calculation. In this case, several relations should be considered and thus update the components of momenta, and not affect the energy . If we consider Λ be moving along the +z direction and assume the decay happens in the x–z plane with p_p being the proton momenta. In the Λ rest frame, using the results of Section 2.1 and apply the boost, where the quantity with upper * (asterisk) symbol denotes the value in original mother particle rest frame.

$$\begin{cases} p^*_{p_x} = p^*_p sin\theta^* \\ p^*_{p_z} = p^*_p cos\theta^* \end{cases} \tag{2.8}$$

Similarly we have

$$\begin{cases} p^*_{\pi^-_x} = -p^*_{p_x} \\ p^*_{\pi^-_z} = -p^*_{p_z} \end{cases} \tag{2.9}$$

While the energy of them can also be found

$$\begin{cases} E^*_p = \frac{m^2_\Lambda + m^2_p - m^2_\pi}{2m_\Lambda} \\ E^*_\pi = m_\Lambda - E^*_p \end{cases} \tag{2.10}$$

Considering

$$E_\Lambda = \sqrt{p_\Lambda^2 + m_\Lambda^2} \tag{2.11}$$

Also the γ factor and velocity

$$\gamma_\Lambda = \frac{E_\Lambda}{m_\Lambda} \tag{2.12}$$

$$v_\Lambda = \frac{p_\Lambda}{E_\Lambda} \tag{2.13}$$

Ultimately the Lorentz transformation (LT) can be done by multiply the factors we got above

$$\begin{cases} p_{p_x} = p^*_{p_x} \\ p_{p_z} = \gamma_\Lambda (p^*_{p_x} + v_\Lambda E^*_p) \\ tan\theta_p = \frac{p_{p_x}}{p_{p_z}} \end{cases} \tag{2.14}$$

and simlarily for the other daughter particle

$$\begin{cases} p_{p_{\pi^-}} = p^*_{p_{\pi^-}} \\ p_{p_{\pi^-}} = \gamma_\Lambda (p^*_{p_{\pi^-}} + v_\Lambda E^*_{\pi^-}) \\ tan\theta_{\pi^-} = \frac{p_{p_{\pi}^-}}{p_{\pi_z^-}} \end{cases} \tag{2.15}$$

So that the updated new angles θ_p and θ_{π^-} are calculated from applying the LT relation. The hyperon side is presented as an example above, and it is the same principle that is worked out for the antihyperon side, which generated new angles of $\theta_{\bar{p}}$ and θ_{π^+}, for which we assume the angular distribution in the final state for each side are generated independently.

2.3.2 Lorentz Rotation

Since it is usually align the beam and target particles in the z-aixs for the convenience of setting and calculation, the orientation of the 4-vector we generated in previous progress have to rotate. That is to perform the Lorentz rotation. After the rotation then we can imagine if we keep the definition of the angles still starting from z-axis, the relative difference of the values of angles remains, but the actually values of angles in this rotated frames would be altered, that is in the point of view when the beam and target in the z-axis, as shown in Figure 2.2 below.

To perform the rotation, the relation of angles in spherical coordinates

$$\begin{cases} x = rcos\varphi sin\theta \\ y = rsin\varphi sin\theta \\ z = rcos\theta \end{cases} \tag{2.16}$$

Also the rotation matrix can be considered to perform this operation.

$$R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta & -sin\theta \\ 0 & sin\theta & cos\theta \end{pmatrix} \tag{2.17}$$

$$R_y = \begin{pmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{pmatrix} \tag{2.18}$$

$$R_z = \begin{pmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{2.19}$$

And in general

$$R = R_z(\alpha)R_y(\beta)R_x(\gamma) \tag{2.20}$$

where $\alpha, \beta, and \gamma$ are arbitrary angles in a general rotation in 3 dimension. After that using these relations in spherical coordinates and one can do the rotation for both θ and φ in the point of view when beam and target particle is in the z-axis as shown in the right-half of the Figure 2.2.

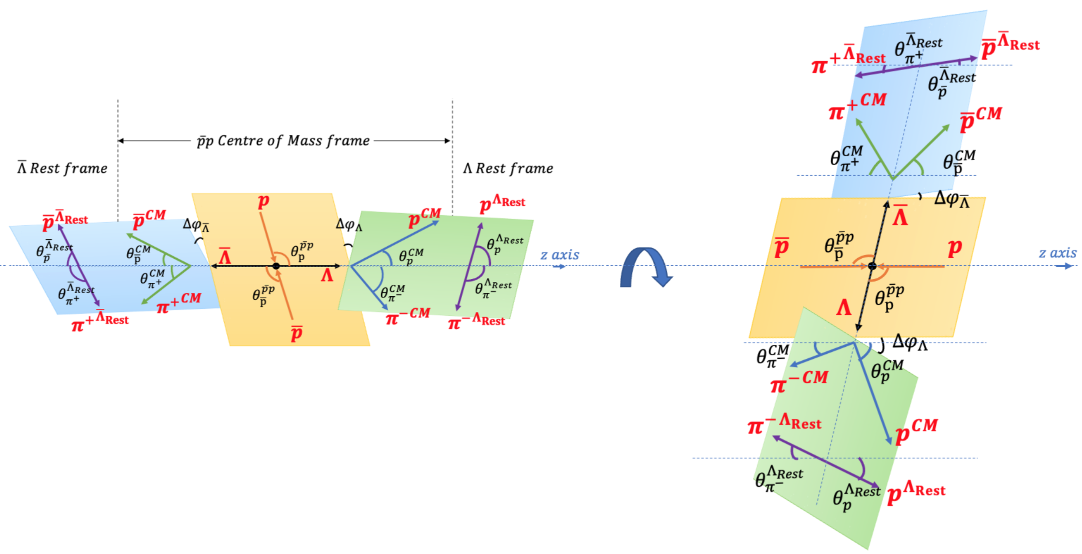

Figure 2.2: Schematic Diagram of the reaction in CM frame and Rest frame after rotation to align beam of antiproton to z-axis

3 The framework of Event Generator for reaction $\bar{p} + p \to \bar{\Lambda} + \Lambda$

In this chapter, using the corresponding methodology and physics relations presented in chapter 2, the idea, progress, and results of this external event generator is discussed.

m_Λ	m_p	m_{π^-}	p_{beam}
1.115 GeV/c^2	0.9383 GeV/c^2	0.1396 GeV/c^2	1.64 GeV/c

Table 3.1: Mass of Λ, mass of proton, and mass of π^-, also the momentum of beam $\bar{p}$ in $\bar{p}p$ lab frame

The Table 3.1 list the input parameters, mass of proton (same as antiproton), π^- (same as π^+) and beam momentum in $\bar{p}p$ lab frame, that are used for calculating in the external event generator. An ROOT macro C++ file "TestLbarLGen.cpp" is developed, that can be run on ROOT to do and give the output root file that can be used as external event generator. The ROOT macro can be found publicly om my GitHub, which is in this url: https://github.com/shenvitor/llbar_EventGenerator

3.1 ROOT Tree format

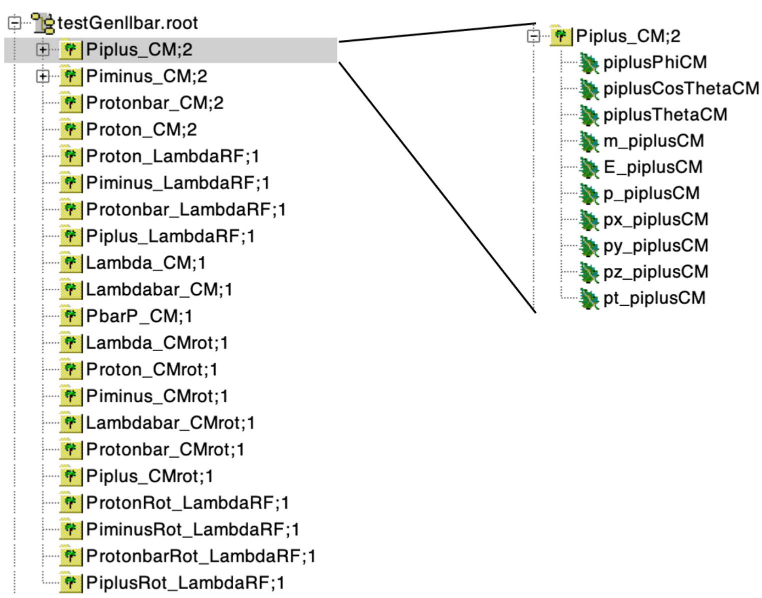

Figure 3.1: The output of root tree format file of the external event generator

Refer to Figure 3.1. The result of the event generator is outputed a root file named "testGenllbar.root" which is after performed a root macro file named "TestLbarLGen.cpp" that I have developed the actual coding for running in the ROOT framework, based on the general idea and method introduced in chapter 2.
The tree section named according to the particle's name and the reference frame that it belongs to.
In the hyperon rest frame: "Proton_LambdaRF" and "Piminus_LambdaRF".
In the anti-hyperon rest frame: "Protonbar_LambdaRF" and "Piplu_LambdaRF".
In the CM frame of $\bar{p}p$ system: "Proton_CM", "Piminus_CM", "Protonbar_CM", "Piplu_CM", "Lambda_CM", "Lambdabar_CM".
And also the "PbarP_CM" storage the random angles of the beam in the CM frame. After all, applying the rotation so that all of the tree section except the "PbarP_CM", got their new updated values in the beam z-axis oriented reference frame. Then they named with "Rot" or "rot": "ProtonRot_LambdaRF", "PiminusRot_LambdaRF", "ProtonbarRot_LambdaRF", "PipluRot_LambdaRF", "Proton_CMrot", "Piminus_CMrot", "Protonbar_CMrot", "Piplu_CMrot", "Lambda_CMrot", and "Lambdabar_CMrot".
For each tree section, there are some branches. The branches contain the corresponding physical quantities distribution for that particular tree section. Refer to Figure 3.1, there are distribution of φ angles, value of $Cos(\theta)$, θ angles, mass, energy, magnitude of momentum, x, y ,z component of momentum, and also transverse component of momentum.

3.2 Test for uniform distribution

At first the distribution of $Cos(\theta)$ and φ for the particles in hyperon and antihyperon rest frame is generated in uniform distribution (by using the TRandom3 in ROOT). As shown in Figure 3.2.

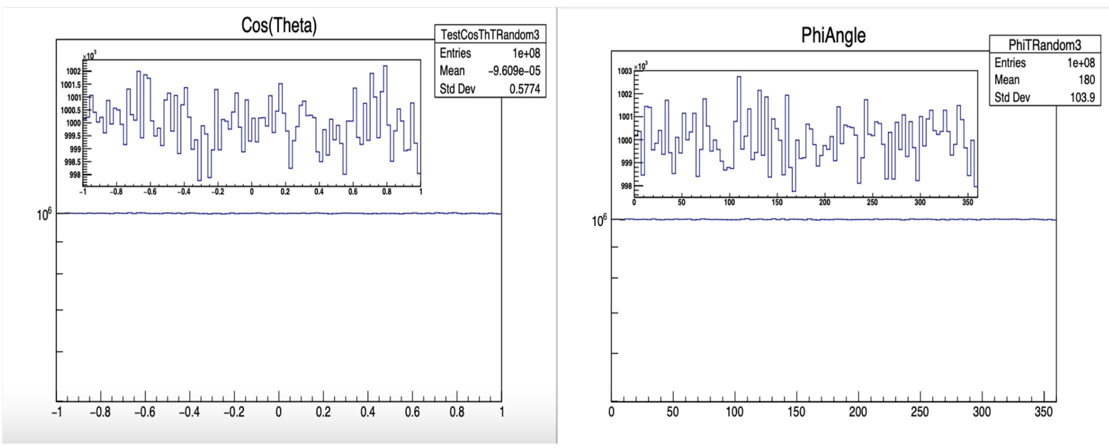

Figure 3.2: Testing uniform distribution

This will apply the the distribution of $Cos(\theta)$ and φ of the $p\pi^-$ in Λ rest frame and the $p\pi^+$ in $\bar{\Lambda}$ rest frame. The intuitive reason that we setting the distribution of $Cos(\theta)$ in the final state particles can be considered the from the cross section relation. Especially when we consider the decay, the solid angles Ω that is subtended by a ring of radius r from θ to $\theta + d\theta$, the area of the whole spherical shell of radius r is $2\pi r^2 sin\theta d\theta$ and with the surface area of sphere is $4\pi r^2$, thus

$$d\Omega = \frac{dA}{r^2} = 2\pi sin\theta d\theta = -2\pi d(cos\theta) \tag{3.1}$$

It means that the linearity relations of the solid angle and value of $cos(\theta)$, which means that we are assuming that this test for the decay is in the isotropic distribution.

3.3 Generation of physics quantities

We shall focus on and check the generated distribution of angles for all the particle in $\bar{p}p \to \bar{\Lambda}\Lambda \to p\pi^- + \bar{p}\pi^+$ in hyperon and antihyperon rest frame, then CM frame of $\bar{p}p$ after Lorentz boost, and also the rotation of orientation for all of them.
The distribution of φ, $cos\theta$, and θ of different particles in various reference frame is presented in this section.

3.3.1 Angular distribution in hyperon and antihyperon rest frame

Refer to Figure 3.3 and 3.4. In the rest frame of Λ and $\bar{\Lambda}$, for the production particles of $p\pi^-$ and $\bar{p}\pi^+$, these quantities of uniform distribution of angle φ and value of $cos\theta$ are first generated independently.
That is also the case in the following presented results of generation. From left to right, the first column is about angle φ, the second column is about $cos\theta$, and the third column is about θ angle.
Also notice that, the isotropic setting of φ angle here will not affect here after the LT transformation and rotation, it is kept for checking it remains isotropic as shown its validity of the generation. That in our following results, but these are keep as the record for the development of further possible extend of this project when using a different model and assumption in the future studies.

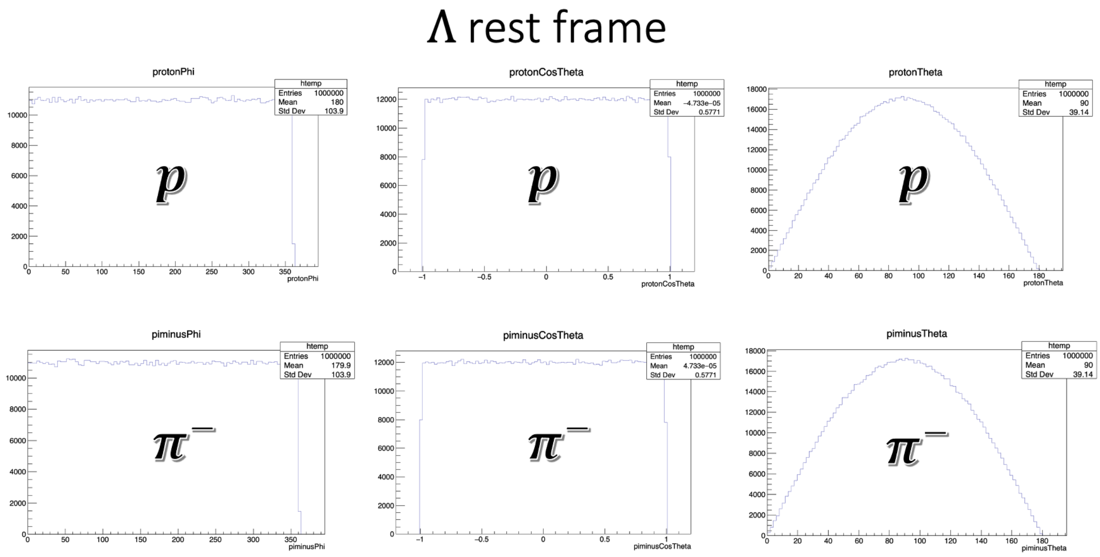

Figure 3.3: The distribution of φ, $cos\theta$, and θ of p and π^- at hyperon rest frame

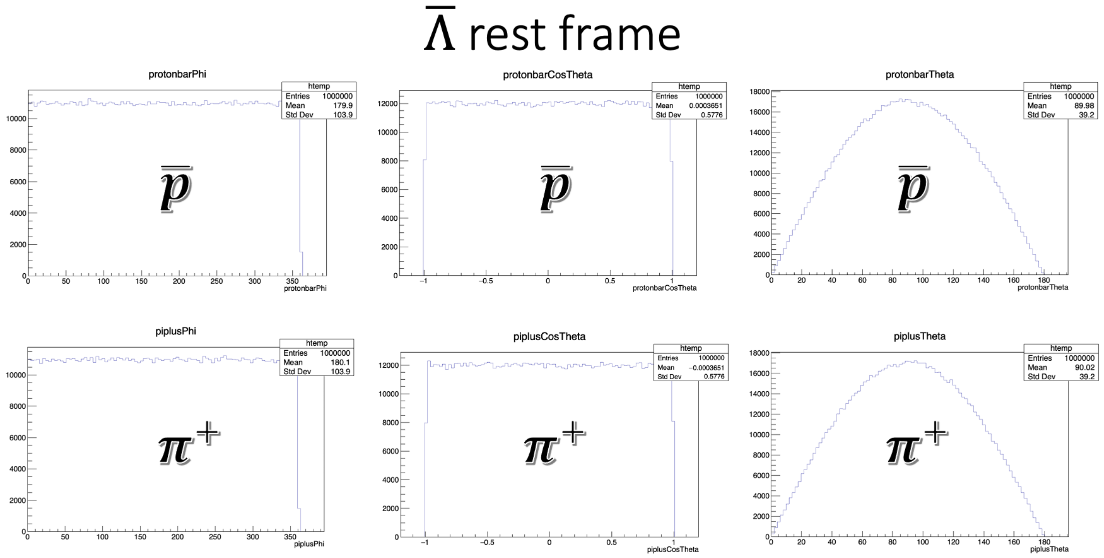

Figure 3.4: The distribution of φ, $cos\theta$, and θ of $\bar{p}$ and π^+ at antihyperon rest frame

3.3.2 Angular distribution in $\bar{p}p$ CM frame

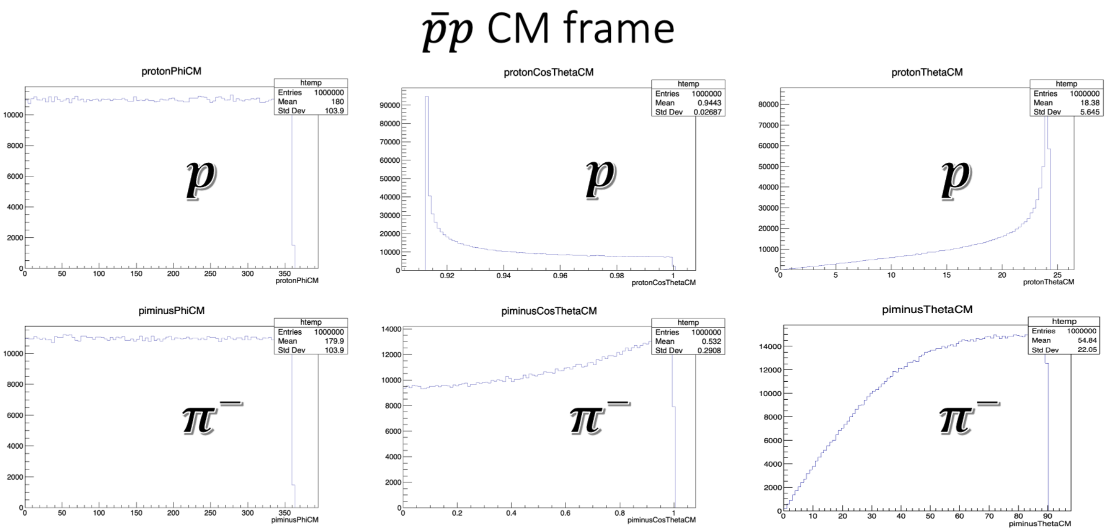

Figure 3.5: The distribution of φ, $cos\theta$, and θ of p and π^- at $\bar{p}p$ CM frame

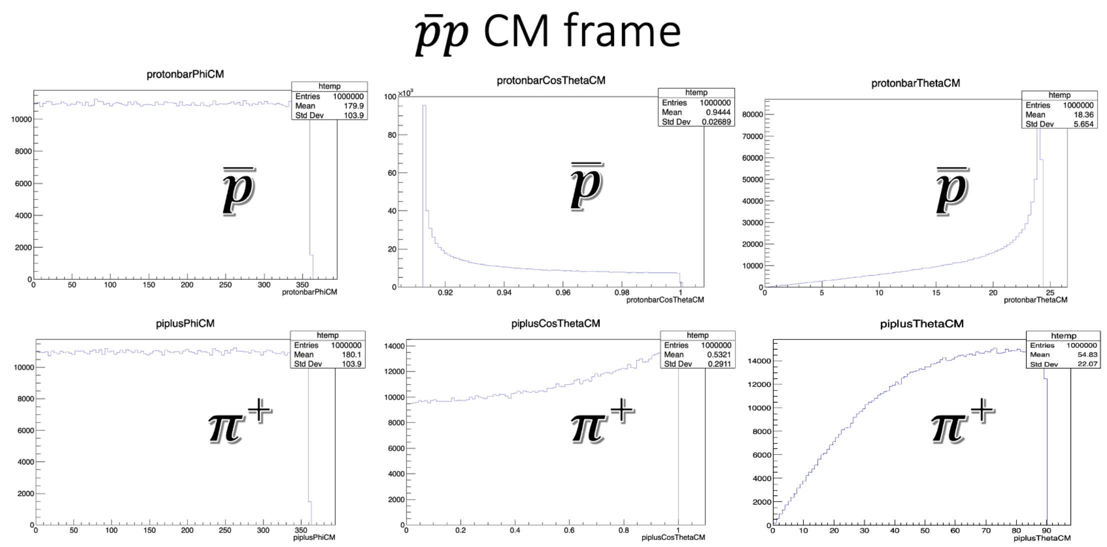

Figure 3.6: The distribution of φ, $cos\theta$, and θ of $\bar{p}$ and π^+ at $\bar{p}p$ CM frame

While the distribution of θ angle is also kept for the record of consistency check, the focus here is to look for the distribution of $cos\theta$, from the setting desired distribution, to the LT transformed frame and rotated or beam aligned frame.
Refer to Figure 3.5 and 3.6. They are showing the distribution after the Lorentz transformation that go to Centre of Mass frame, as shown that, these daughter particles (proton, π^-, antiproton, and π^+) shows the typical distribution pattern under the assumption of isotropic distribution in the mother particle rest frame .

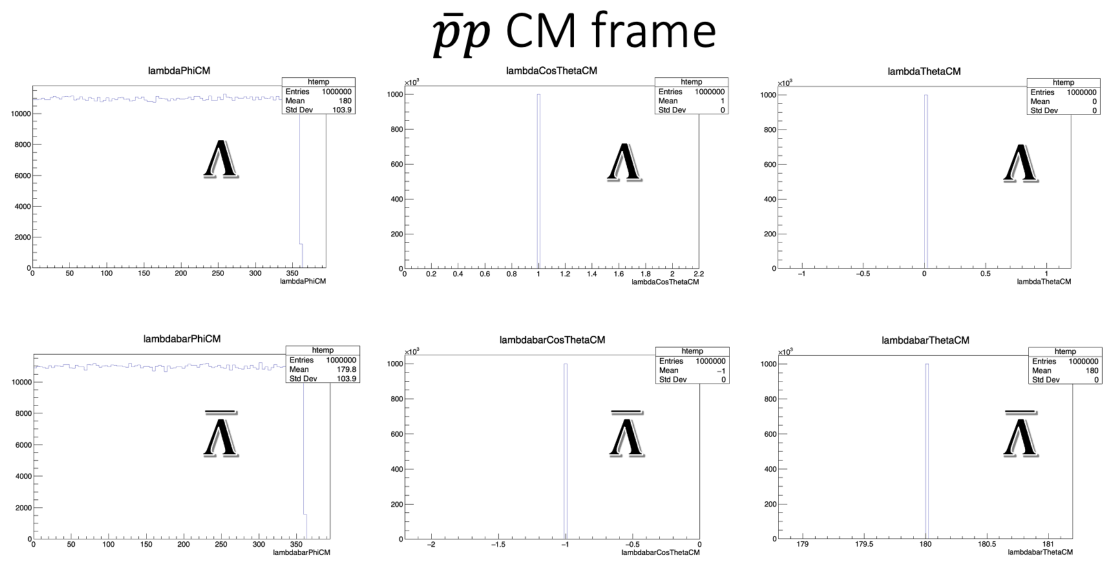

Figure 3.7: The distribution of φ, $cos\theta$, and θ of Λ and $\bar{\Lambda}$ at $\bar{p}p$ CM frame

Refer to Figure 3.7. That is the antihyperon-hyperon pair, $\bar{\Lambda}\Lambda$, in the CM frame. As we introduce in the chapter 2, we assume initially the generation of them are align with the z-axis, thus we can notice their $cos\theta$ value are 1 and -1, respectively.

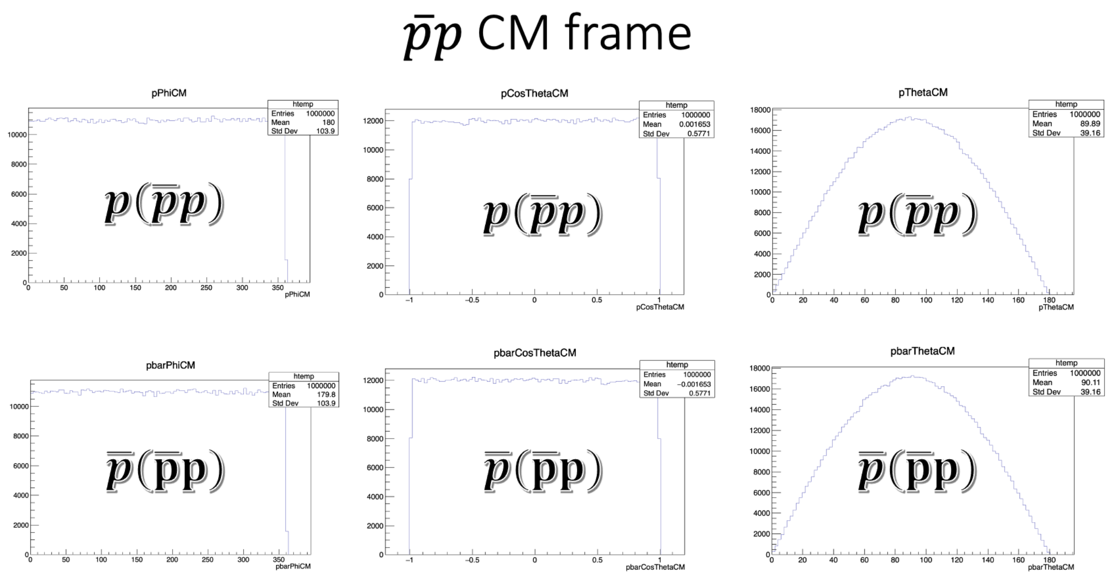

Figure 3.8: The distribution of φ, $cos\theta$, and θ of $\bar{p}p$ at $\bar{p}p$ CM frame

Refer to Figure 3.8. The distribution of angles for the beam and target, $\bar{p}p$, are also needed to generate. Since these values of distribution, are later use for the rotation that for having the orientation of beam-target align with z-axis perspective.

3.3.3 Angular distribution in $\bar{p}p$ CM frame after rotation

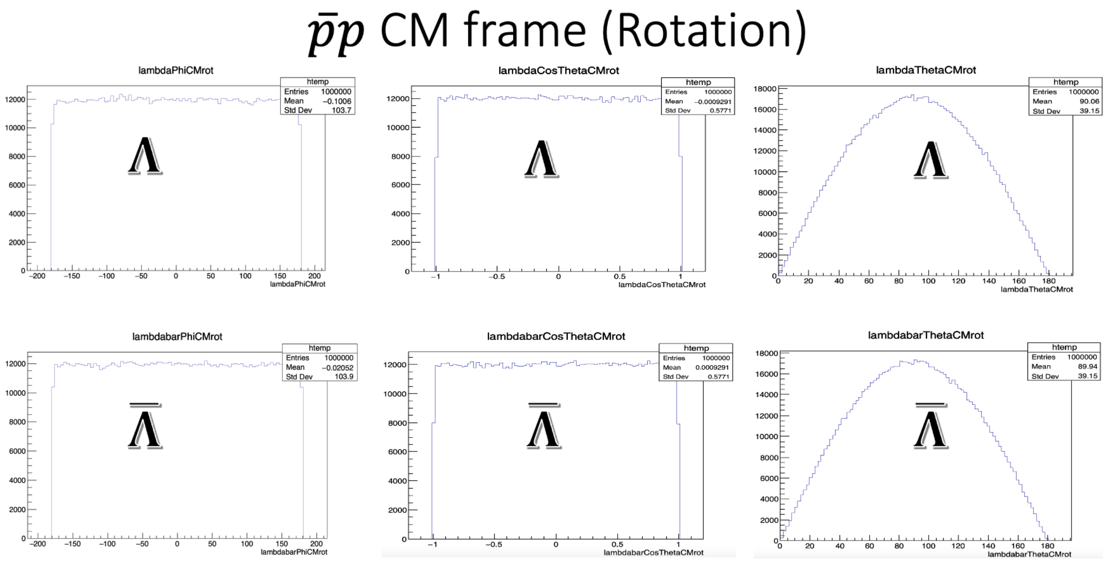

Figure 3.9: The distribution of φ, $cos\theta$, and θ of Λ and $\bar{\Lambda}$ at $\bar{p}p$ CM frame after the rotation

Refer to Figure 3.9. As expected, it is the isotropic results are given out. It shows the result of distribution after applying the rotation for the $\bar{\Lambda}\Lambda$. That is to use the generated distribution of angles of beam-target previously, and then perform this operation based on the methodology of spherical relations and rotation introduced in chapter 2.

The Figure 3.10 and 3.11 gives the results of distribution of daughter particles in $\bar{p}p$ Centre of Mass frame. As we can view them as in comparison, daughter particle pair proton π^- and daughter particle pair antiproton π^+ are going to the opposite direction in this CM frame, since mother particles Λ and $\bar{\Lambda}$ are so. And the value of $cos\theta$ distribution tells this story successfully. While the change after rotation is due to still using the definition of θ value from the z-axis, and as we rotate them, the values altered as we can realise it here accordingly.

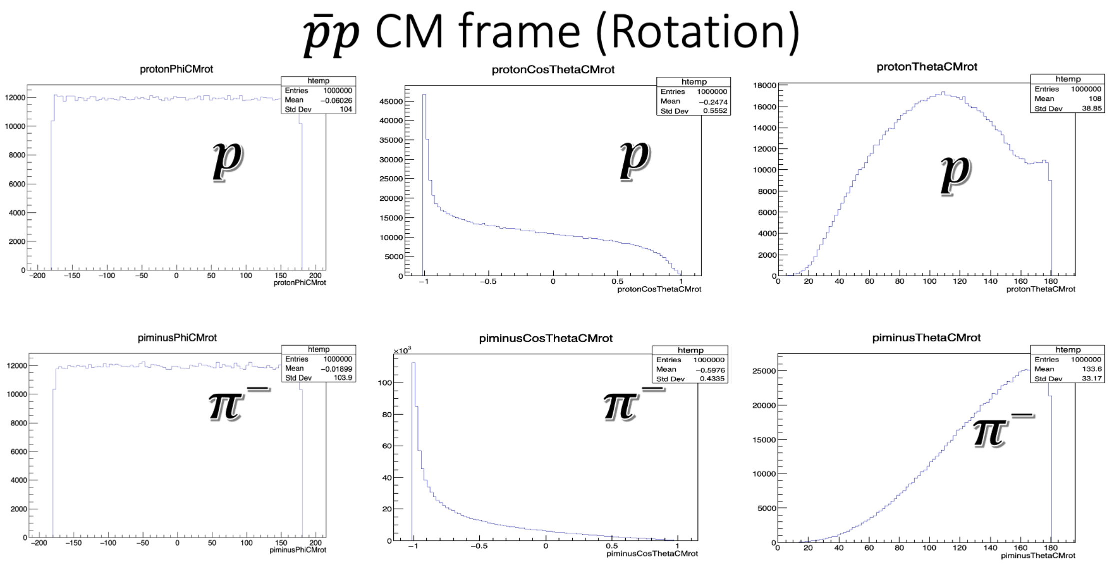

Figure 3.10: The distribution of φ, $cos\theta$, and θ of and π^- at $\bar{p}p$ CM frame after the rotation

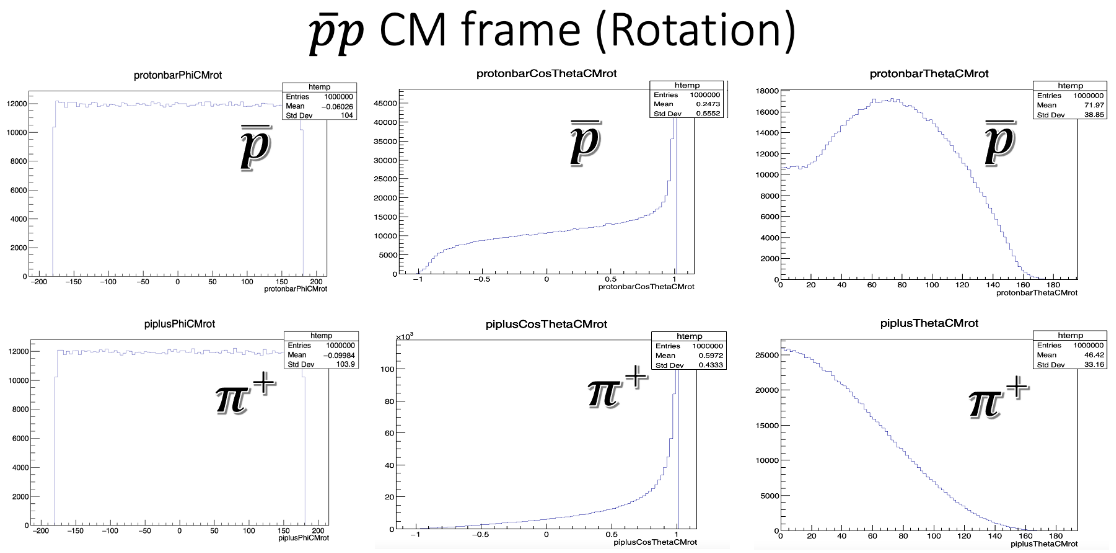

Figure 3.11: The distribution of φ, $cos\theta$, and θ of $\bar{p}$ and π^+ at $\bar{p}p$ CM frame after the rotation

3.3.4 Angular distribution in hyperon and antihyperon rest frame after rotation

Finally, refer to Figure 3.12 and 3.13. Since after rotation, there are extra values of angles needed to add up, when we comparing them and expressed them in the original axis representation. And this is the same principle for all of the change of the value for the distribution that after the rotation for the z-axis orientation of the beam particle.

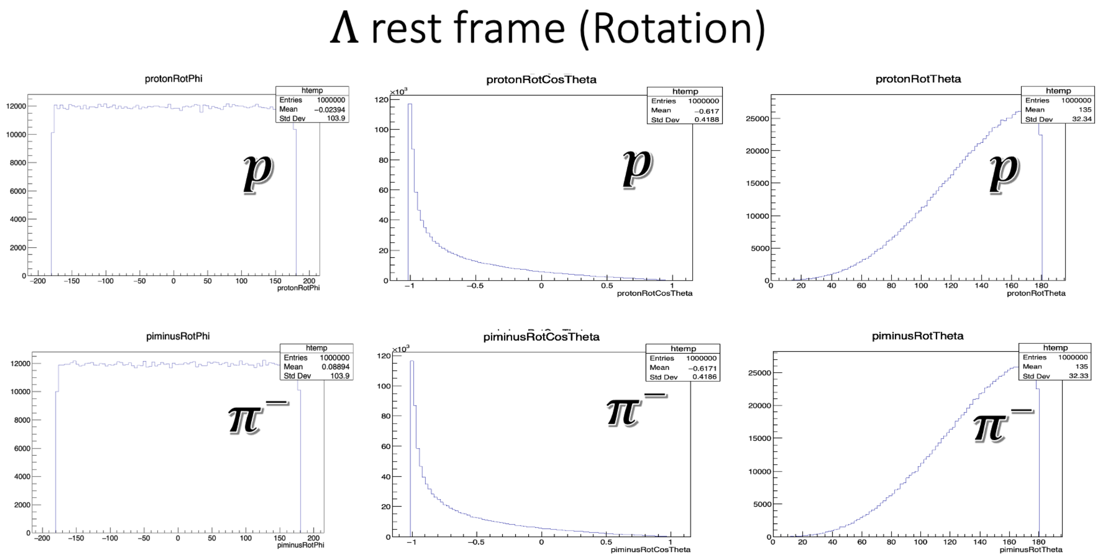

Figure 3.12: The distribution of φ, $cos\theta$, and θ of p and π^- at hyperon rest frame after the rotation

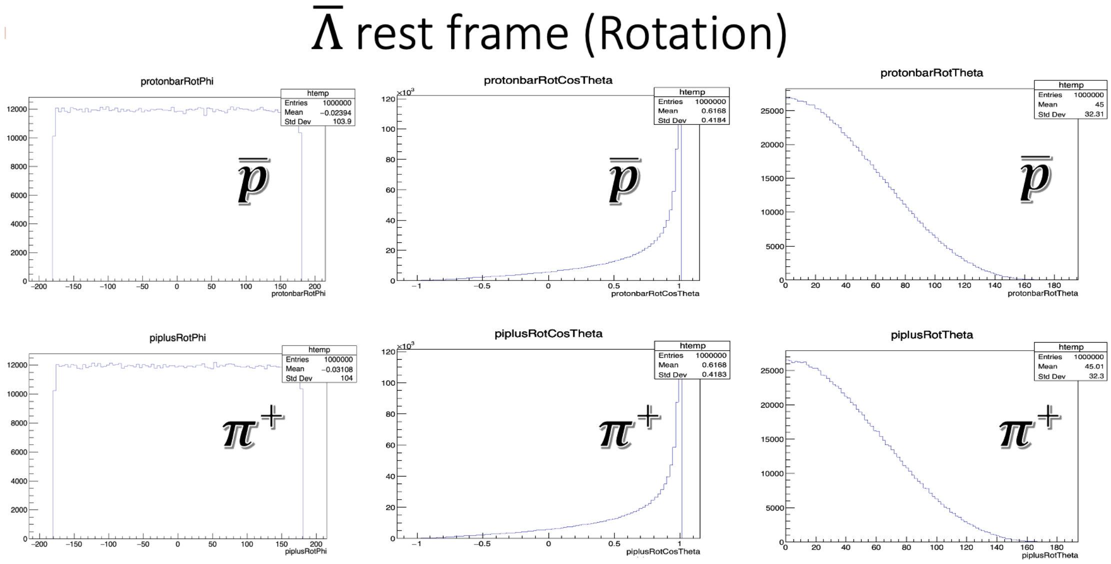

Figure 3.13: The distribution of φ, $cos\theta$, and θ of $\bar{p}$ and π^+ at antihyperon rest frame after the rotation

4 Conclusion & Outlook

In this project report, a prototype of external Monte-Carlo Event Generator for the antihyperon-hyperon pair productionin antiproton-proton annihilation, in particular for the reaction of $\bar{p} + p \longrightarrow \bar{\Lambda} + \Lambda \longrightarrow \bar{p}\pi^{+} + p\pi^{-}$, based on their simplified kinematics relations of 4-vectors, is developed and presented.

This external MC event generator is built on ROOT, compare to embedded event generator used in PandaRoot, it can be more accessible and convenient to achieve the need of quickly testing models and formalisms about polarisation and spin-observables studies for antihyperon-hyperon pair productionin antiproton-proton annihilation. To implement the desired distribution related to some testing models of spin-observables through the external event generator, with further studies and tests of the implementation, for example [15], [16] ,that we would want to investigate, would be the most probably next future extend of this project.

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