JOINT INSTITUTE FOR NUCLEAR RESEARCH

DZHELEPOV LABORATORY OF NUCLEAR PROBLEMS

FINAL REPORT ON THE START PROGRAME

Feasibility Study of Measurement of $\eta_c \to p\bar{p}$ at SPD Experiment

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Participation period:
September 15th - November 10th
Summer Session 2024

Dubna, 2024

Contents

Abstract

This preliminary study examines the possibility of obtaining measurements $\eta_c \to p\bar{p}$, from proton-proton collisions at energy $\sqrt{s} = 27$ GeV in the context of Spin Physics Detector, SPD, at its final stage. By employing Monte Carlo simulations alongside the spdroot framework we propose the analysis between background and signal decay channels for $\eta_c \to p\bar{p}$ studying kinematic parameters; invariant mass, transverse momentum, polar angle distributions, momentum distribution, Feynman-x spectra, and cosine of the angle α between p and $\bar{p}$. Previous studies, with only Pythia8 event generator, suggest signal/background ratio of 10^{-3}.

In this preliminary study, we conducted a realistic simulation considering both, the event generation and detector response of the SPD. Future work will expand upon these findings using the lxui cluster from JINR-MLIT.

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Dr. Amaresh Datta, for giving me the opportunity to visit JINR and collaborate with SPD team. And I cannot express in words how grateful I am for having met so many caring and supportive people during these two months, starting with Amaresh and Igor with a special acknowledgment to the cheerful friends like: Leira, Visnu, lovely people like Alaa and Mostafa, all of them were kind people whom I wish I had met earlier. The UC staff, caring, welcoming people like Elena Karpova and Anya Zubova, who guided me throughout the entire program,

From the bottom of my heart
thank you to all of them.

1 Introduction

The *Spin Physics Detector* (SPD) is a proposed experiment at the *Nuclotron based Ion Collider fAcility* (NICA) at the **Joint Institute for Nuclear Research** (JINR) in Dubna, Russia. It is a multi-purpose experiment designed to study nucleon spin structure in the three dimensions. With capabilities to collide polarized protons and deuterons with center of mass energy up to 27 GeV and luminosity up to $10^{32} cm^{-2} s^{-1}$ for protons.

Figure 1: General Layout of SPD

The SPD will make cross-section and asymmetry measurements of several hadronic processes sensitive to various (unpolarized and polarized) gluon distributions inside the nucleons and help in the understanding the spin structure of the basic building blocks of visible matter. [1].
The SPD will operate at medium energy ranges, up to 10 GeV in the initial stage and up to 27 GeV in the later stage, that are complementary to the present and future experiments. [2]

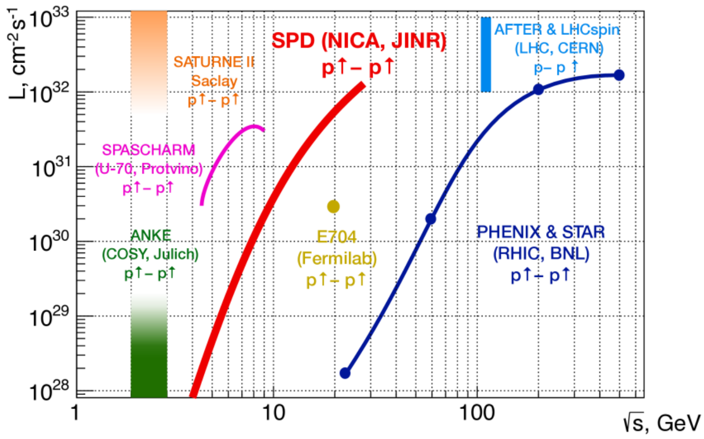


Figure 2: General Layout of SPD

Estimations of the expected event rates are evaluated for p-p collisions at $\sqrt{s} = 27$ [GeV] and $\sqrt{s} = 13.5$ [GeV] for the projected integrated luminosity 1.0 and 0.1 fb^{-1} , respectively that corresponds effectively to one year of data taking or 10^7 [s]. The results are listed in Figure 2. [2]

Probe	$\sigma_{27\,\mathrm{GeV}}$, nb ($\times$BF)	$\sigma_{13.5\,\mathrm{GeV}}$, nb ($\times$BF)	$N_{27\,\mathrm{GeV}}$, 10^6	$N_{13.5\,\mathrm{GeV}}$ 10^6
Prompt-γ ($p_T > 3$ GeV/c)	35	2	35	0.2
J/ψ	200	60		
$\to \mu^+\mu^-$	12	3.6	12	0.36
$\psi(2S)$	25	5		
$\to J/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$	0.5	0.1	0.5	0.01
$\to \mu^+\mu^-$	0.2	0.04	0.2	0.004
$\chi_{c1} + \chi_{c2}$	200			
$\to \gamma J/\psi \to \gamma\mu^+\mu^-$	2.4		2.4	
η_c	400			
$\to p\bar{p}$	0.6		0.6	
Open charm: $D\bar{D}$ pairs	14000	1300		
Single D-mesons				
$D^+ \to K^-2\pi^+$ ($D^- \to K^+2\pi^-$)	520	48	520	4.8
$D^0 \to K^-\pi^+$ ($\bar{D}^0 \to K^+\pi^-$)	360	33	360	3.3

Figure 3: Expected cross-section and counts for each of the gluon probes per one effective year of SPD running. Detector acceptance and reconstruction efficiency are not taken into account.

The scope of this work is to study the feasibility to generate charmed $\eta_c \to p\bar{p}$ for signal and background events in the context of first Stage of SPD experiment.

To fulfill this issue we will use the method of Monte Carlo Simulation (MC simulation) working with SpdRoot framework which works with Pythia 8 as MC event generator, GEANT4 to simulate the interaction of primary events with SPD detector and finaly cern-root for data analysis [5].

2 Spin Physics Detector, SPD

The SPD detector system will have complete 4 coverage in solid angle. The design includes a barrel part and two end-caps. In the barrel part, the SPD will feature a solenoid magnet providing a field up to 1.2 T at the interaction point. The magnetic field provides charge separation of the particle tracks and also helps in determination of the charged particle momentum.[1]

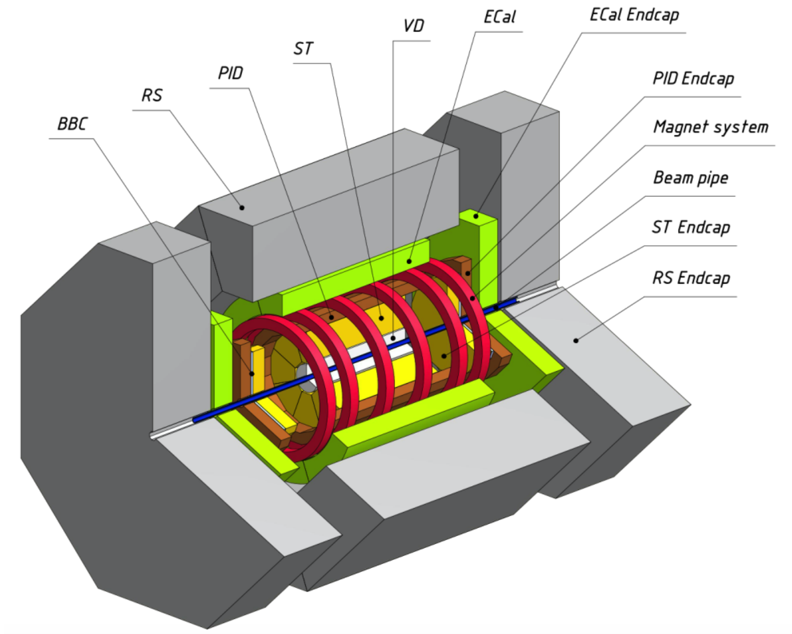


Figure 4: General Layout of SPD

2.1 Physics Stage I

In the initial stage NICA will provide proton beams up to 5 GeV with collision luminosity up to $10^{31} cm^{-2}s^{-1}$ for the pp collisions and up to 4.5 GeV/n (per nucleon) deuteron beams with collision luminosity up to $10^{30} cm^{-2}s^{-1}$ for the first few years.

The SPD will take advantage of the low energies at the initial stage to look for compelling and interesting physics effects in pp, dd and possibly in the light nuclei collisions. [1]

2.2 Physics Stage II

For stage II when NICA will reach its full potential of luminosity $10^{32} cm^{-2}s^{-1}$for the pp collisions), energy and polarization capacities, the SPD will focus primarily on making measurements of observables from polarized pp and dd collisions that are sensitive to the gluon distributions inside nucleons.At peak luminosities, one year of data at the SPD will correspond to integrated luminosities of 1.0 and 0.1 fb^{-1} respectively for p-p collisions at$\sqrt{s} = 27$ and $\sqrt{s} = 13.5$ GeV.[4]

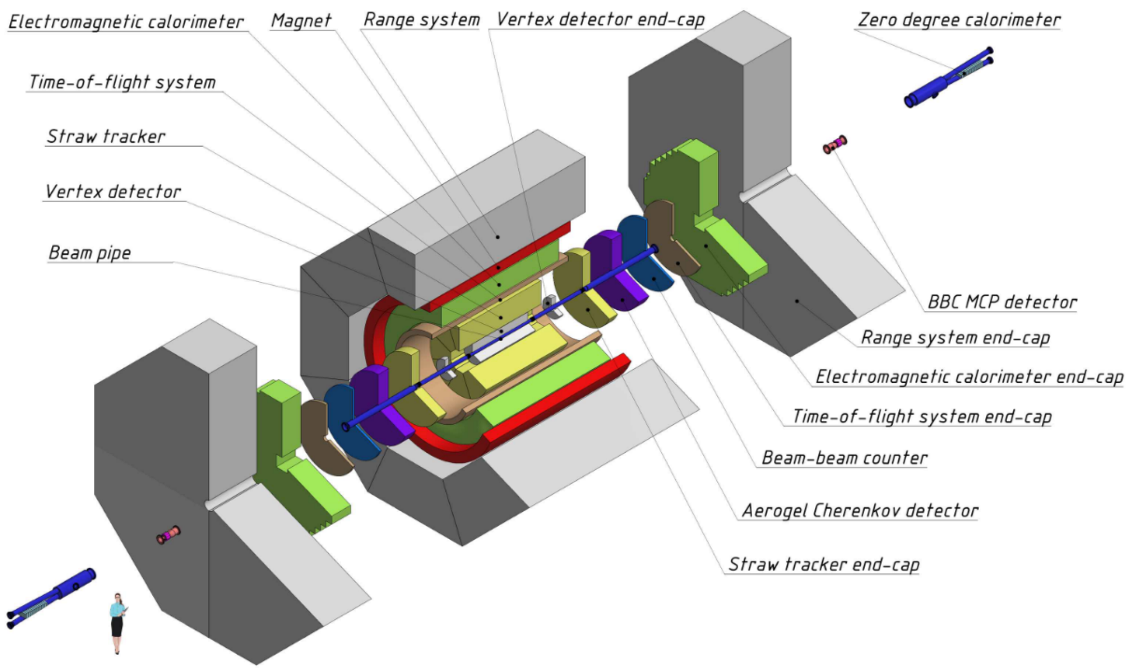


Figure 5: Second Stage of SPD

Going outward from the aluminium beam-pipe, the detectors in the barrel part of the SPD at this stage will include :

- An improved silicon vertex detector detector (DSSD).
- Straw tracker (TS).Tracking system will provide a momentum resolution $\frac{\delta p_T}{p_T} =$ 2% for 1 GeV/c momentum tracks.

- Time-of-flight (TOF) detector for particle identification with a timing resolution of 50 ps and π/K separation for charged tracks up to 1.5 GeV/c momentum.
- Beam-beam counter (BBC), that will provide local polarimetry, luminosity control
- Electromagnetic calorimeter for the determination of photon energies with an energy resolution of $\frac{\delta E}{E} = \frac{\%5}{\sqrt{E}} \oplus \%1$ and electron/positron identification .
- Range system (RS)

End-caps of the the SPD detector system in far forward and backward positions that will provide local polarimetry, luminosity control and event selection criteria for elastic collisions at stage silicon vertex detector, straw tracker, BBC, TOF detector, Aerogel detector for extending the π/K separation up to 2.5 GeV/c momentum, electromagnetic calorimeter and ZDC.[1]

2.3 Charmonium production

The SPD will measure light and charm meson productions near the production threshold. Of particular interest is the charmonium (J/ψ) and the (η_c) formation near threshold for pp and dd collisions at the first stage. In stage II, charmonia productions are dominated by gluon-gluon fusion process, making their cross-sections and asymmetries particularly sensitive to gluons inside protons, η_c is of special interest as TMD factorization is proven for its production, connectiong its transverse asymmetries to the Gluon Sivers Function.[1]

3 Monte Carlo Simulation

For the MC simulation the spdroot framework was used, which mainly uses Pythia8[1] for the event generation, GEANT4 [2] was used to simulate the SPD detectors, and ROOT[3] for data analysis.

Figure 6: Workflow MC simulation

Firstly, events were generated by Pythia8, followed by the reconstruction of final track states and momentum distributions, with an outcome of daughter particles stored in output root files. Subsequently, the generated events interact with GEANT4 reconstruction of the SPD detectors, interacting with various detector components including BBC, ST, and TOF for both barrel and end caps. Finally, the output was saved and analyzed using ROOT.
This study excluded the use of ECAL and RS for the barrel, as well as aerogel and zero-degree calorimeter for the end caps.
In pythia8, the event generator does not allow hadronization of $c\bar{c}$ to η_c meson. We, therefore, studied the production of J/ψ mesons and their decay into $p\bar{p}$.
The main goal of this study is to analyze the ratio between signal and background events. A signal event is considered a charmonium mother particle J/ψ forced to decay into $p\bar{p}$ daughter particle. A background event considers every decayed $\bar{p}$ daughter particle without taking into account if it is a product of a charmonium mother particle J/ψ, in other words, all random combinations of p and $\bar{p}$.
Signal and background events were simulated to establish a comparative framework between the next parameters: invariant mass, transverse momentum, polar angle distributions, momentum distribution, Feynman-x spectra, and cosine of the angle α between p and $\bar{p}$. See the scripts used in this report on Appedinx.

[1] General-purpose Monte Carlo event generator.
[2] Geometry ANd Tracking version 4
[3] General-purpose framework for analyzing large amounts of data, developed by CERN

3.1 Event Generation

For the Event generation of signal events the next parameters were used:

```
// Setup for p-p collision in second stage
P8gen->SetBeam(2212, 2212, 27.);

// Production processes J/psi
P8gen->SetParameters("Charmonium:gg2ccbar(3S1)[3S1(1)]g = on,off");
P8gen->SetParameters("Charmonium:gg2ccbar(3S1)[3S1(8)]g = on,off");
P8gen->SetParameters("Charmonium:qg2ccbar(3S1)[3S1(8)]q = on,off");
P8gen->SetParameters("Charmonium:qqbar2ccbar(3S1)[3S1(8)]g = on,off");
P8gen->SetParameters("Charmonium:gg2ccbar(3S1)[1S0(8)]g = on,off");
P8gen->SetParameters("Charmonium:qg2ccbar(3S1)[1S0(8)]q = on,off");
P8gen->SetParameters("Charmonium:qqbar2ccbar(3S1)[1S0(8)]g = on,off");
P8gen->SetParameters("Charmonium:gg2ccbar(3S1)[3PJ(8)]g = on,off");
P8gen->SetParameters("Charmonium:qg2ccbar(3S1)[3PJ(8)]q = on,off");
P8gen->SetParameters("Charmonium:qqbar2ccbar(3S1)[3PJ(8)]g = on,off");

// Jpsi decays to p+ p-
P8gen->SetParameters("443:OneChannel= 1 1 0 2212 -2212");

//To run
primGen->AddGenerator(P8gen);
run->SetGenerator(primGen);

// Gaussian beam Z-position 30 [cm] width in beam direction
primGen->SetTarget(0., 30.);
primGen->SmearGausVertexZ(kTRUE);
```

For the creation of background events the subsequent parameters were employed. Observe that there exists no decay channel thus every particle, in a $p - p$ collision will be produced:

```
// Setup for p-p collision in second stage

P8gen->SetBeam(2212, 2212, 27.);

// Production processes J/psi
P8gen->SetParameters("SoftQCD:all = on");

//To run
primGen->AddGenerator(P8gen);
run->SetGenerator(primGen);

// Gaussian beam Z-position 30 [cm] width in beam direction
primGen->SetTarget(0., 30.);
primGen->SmearGausVertexZ(kTRUE);
```

And as we mention before, we only will use BBC, TOF and TS.

```
        run->AddModule(ts_barrel);
        run->AddModule(ts_ecps);
        run->AddModule(tof_barrel);
        run->AddModule(tof_ecps);

        run->AddModule(bbc);
```

3.2 Detector simulation and event reconstruction

In this segment, one must exercise caution to activate the GEANT4 simulation modules of the chosen detectors exclusively to prevent errors in data acquisition and storage for inputs and outputs of Monte Carlo truth data, MC Thuth.
As an illustration, the subsequent reference is made to TS; vertex and track reconstruction of Straw tracker:

```
 //-------------------------------------------------------//
 // [INNER (VERTEX) TRACKING SYSTEM (ITS) HIT PRODUCER]
 // Input: mc-event, mc-particles, its-points
 // Output: mc-its-hits

SpdItsMCHitProducer* its_hits_producer = new SpdItsMCHitProducer();

//its_hits_producer->SetHitProductionMetod(1);  // 0,1 (default: 0)

//its_hits_producer->SaveHits(false); // default: true

its_hits_producer->SetVerboseLevel(1);

Run->AddTask(its_hits_producer);

//-------------------------------------------------------//
// [STRAW TRACKING SYSTEM (BARREL+CAPS) HIT PRODUCER]
// Input: mc-event, mc-particles,
//          ts-barrel-points and/or ts-endcaps-points
// Output: mc-ts-hits

SpdTsMCHitProducer* ts_hits_producer = new SpdTsMCHitProducer();

ts_hits_producer->SetHitType('v');  // 'v'=(R) (default), 'w'=(R,Z)

//ts_hits_producer->SaveHits(false);  // default: true

ts_hits_producer->SetVerboseLevel(1);

Run->AddTask(ts_hits_producer);
```

3.3 Data Analysis

For the analysis, we separate, for convenience, into 2 scripts; analysis and comparison data. For the analysis and storing data we used ROOT to save parameters such as invariant mass, transverse momentum, p_T of daughter particles, polar angle distributions, momentum distribution, Feynman-x spectra [xF], cosine of the α between $p - \bar{p}$. Equivalent parameters for J/ψ mother particles also were taking account. Using the *Tree* class of ROOT we stored above mention parameters in *branches* and saved them in a root file to be, subsequently, plotted, scaled, set the cuts for filtered background data, and presented in the comparison script.
Next an illustration of the analysis script.

```
//create output file and tree
TFile* outputFile = TFile::Open("output.root", "RECREATE");
TTree* dataTree = new TTree("jpsiData", "Processed J/psi parameters");

 dataTree->Branch("pMom_s", &pMom_s, "pMom_s/F");
 dataTree->Branch("pbarMom_s", &pbarMom_s, "pbarMom_s/F");
 dataTree->Branch("pxF_s", &pxF_s, "pxF_s/F");
 dataTree->Branch("pbarxF_s", &pbarxF_s, "pbarxF_s/F");
 dataTree->Branch("pTheta_s", &pTheta_s, "pTheta_s/F");
 dataTree->Branch("pbarTheta_s", &pbarTheta_s, "pbarTheta_s/F");
 dataTree->Branch("pTranfMom_s", &pTranfMom_s, "pTranfMom_s/F");
...
 while( (IT->NextEvent()) && (ne_total < events_max) )
 {
    ...
        //Store the p and pbar in p and pbar
  int pdg = mctrack->GetParticlePdg();
  if ( pdg == 2212 ) //for proton
         {
          fitted_pprot = true;
          pMom_s= p3.Mag2();
          pxF_s=p3.Z()/(27/2) ;
          pTheta_s=pprot.Theta()*180/TMath::Pi();
          pTranfMom_s = pprot.Pt();
         }
  if ( pdg == -2212 ) //for antiproton
        {
        fitted_ppbar = true;
        pbarMom_s= p3.Mag2();
        pbarxF_s=p3.Z()/(27/2);
        pbarTheta_s=ppbar.Theta()*180/TMath::Pi();
        pbarTranfMom_s = ppbar.Pt();
        }
    dataTree->Fill(); //to save in the tree
 }
```

Next an illustration of the comparation script.

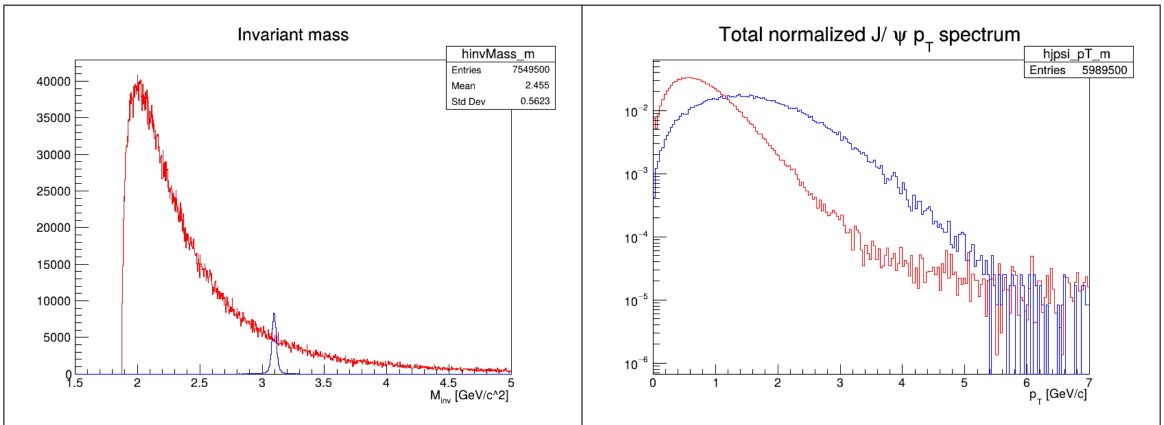
```
TH1D* hinvMass_m = new TH1D("hinvMass_m",
"Invariant Mass; M_{inv} [GeV/c^2]", 100, 1, 7);
...
  TFile* background = TFile::Open("reco_output.root");
  TTree* backgroundTree = (TTree*) background->Get("jpsiData");

  minbiasTree->SetBranchAddress("invMass_m",   &invMass_m);
  hinvMass_m->Scale(1.0/hinvMass_s->GetEntries());
...

gStyle->SetOptStat(11);
TCanvas* c = new TCanvas("canvas", "Canvas", 1300, 900);
c->cd(1);
hinvMass_m->SetMarkerColor(kRed);
hinvMass_m->SetLineColor(kRed);
hinvMass_m->Draw("hist");
c->Print("output.pdf");
```

4 Results

In this initial investigation, we produce approximately 120k for Signal events and approximately 2.7 M for background events for the subsequent diagrams; red denotes background and blue is for signal events. The mass resolution of the signal peak was determined to be ≈ 30 MeV. The next parameters were compared:



(a) (b)

Figure 7: In (a) invariant mass distribution for signal and background events. In (b) total transverse momentum distributions for $p\bar{p}$ in signal and background events

Afterward, we compared th invariance mass and momentum of proton and antiproton events.

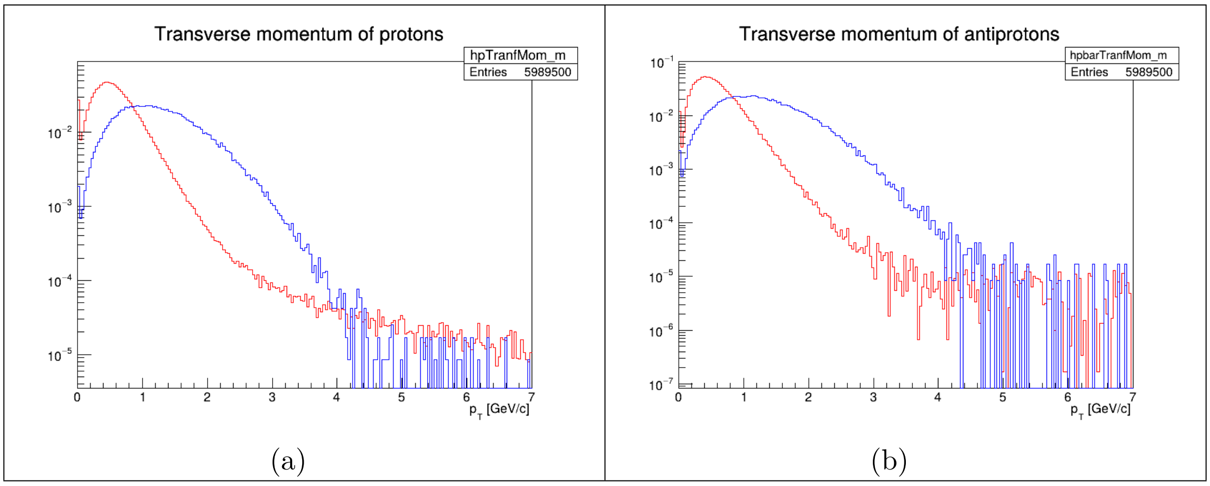


Figure 8: Transverse momentum distributions in signal and background for protons in (a) and (b) for antiprotons.

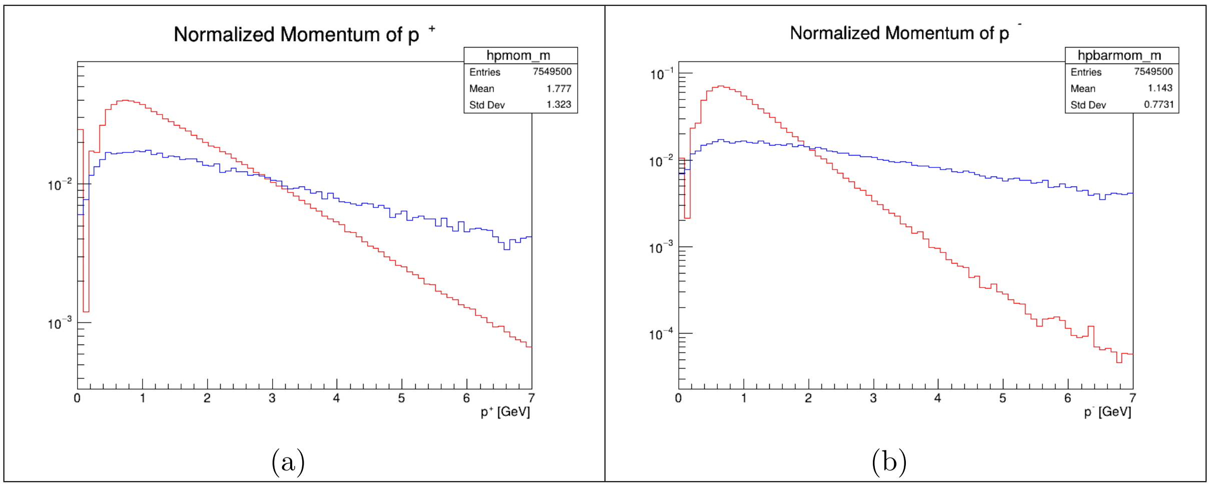


Figure 9: Momentum distributions of protons (8a) and antiprotons (8b) in signal and background events.

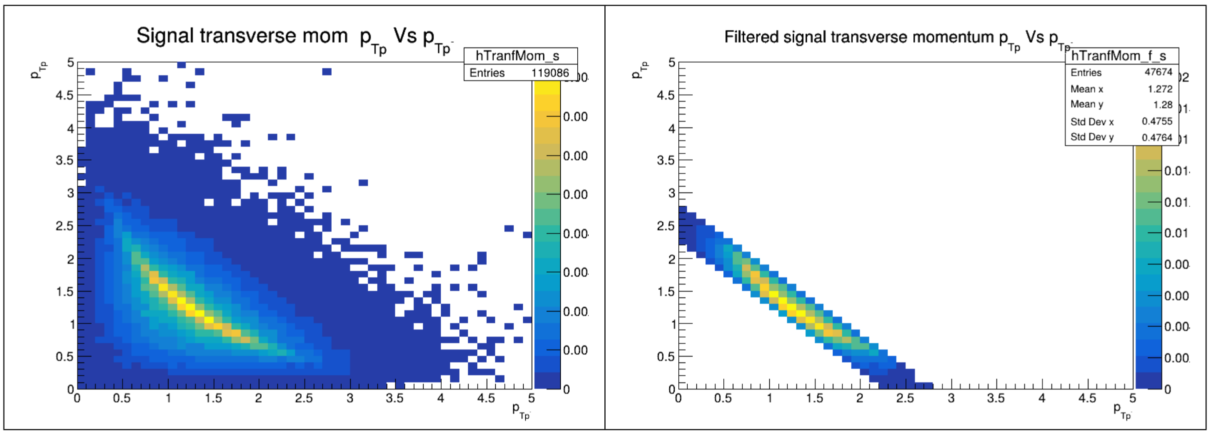


Figure 10: In (a) $\bar{p}$ Vs p Signal event transverse momentum distributions. In (b) The transverse distribution with a cut off applied.

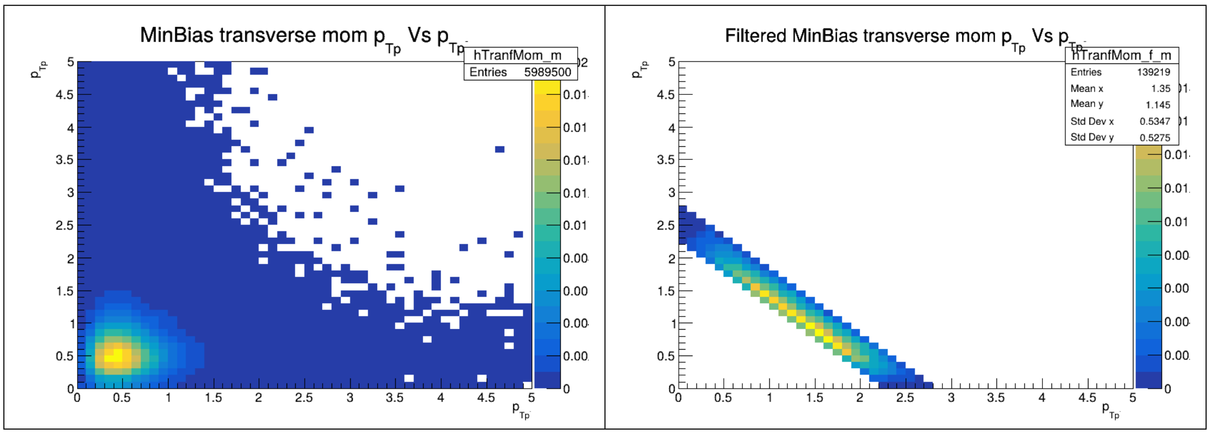


Figure 11: In (a) $\bar{p}$ Vs p Signal event transverse momentum distributions. In (b) The transverse distribution with a cut off applied.

Polar angle distribution for p and $\bar{p}$ and cosine of angle α:

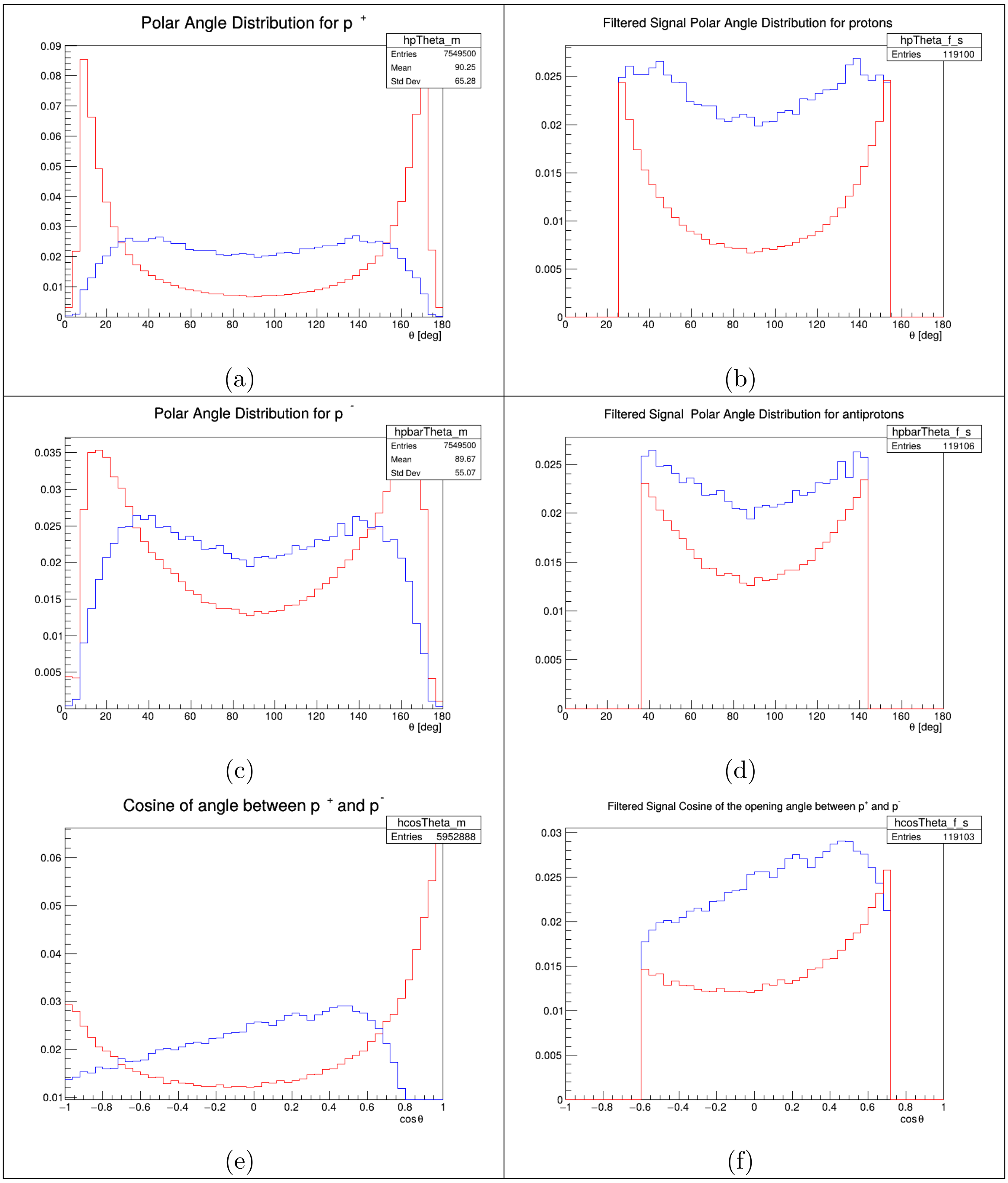


Figure 12: Polar angle distributions (in degrees) for protons (12a) and antiprotons (12c) in signal and background events. A cut off were applied for for Polar Angle distribution in (12 b) and for antiproton in (12d).

In summary these cuts, for signal events, are presented in Table 1

Cut to filter data	Parameter	Signal
Cut 1	Polar angle p	$cos(\theta) \in [35, 145]$
Cut 2	Polar angle $\bar{p}$	$cos(\theta) \in [25, 155]$
Cut 3	$cos(\alpha)$	$cos(\alpha) \in [-0.6, 0.7]$
Cut 4	Transverse momentum	$x + y - 2.3 > 0$ and $x + y - 2.8 < 0$

Table 1: Cuts for background events

The main goal of this study was to generate the mass invariance of all $J/\psi \to p\bar{p}$ for both signal and background while implementing a criterion to filter background events as much as possible. For that purpose the filters in Table 1 were applied to filter signal/background invariance mass and reduced background data see Figure 13.

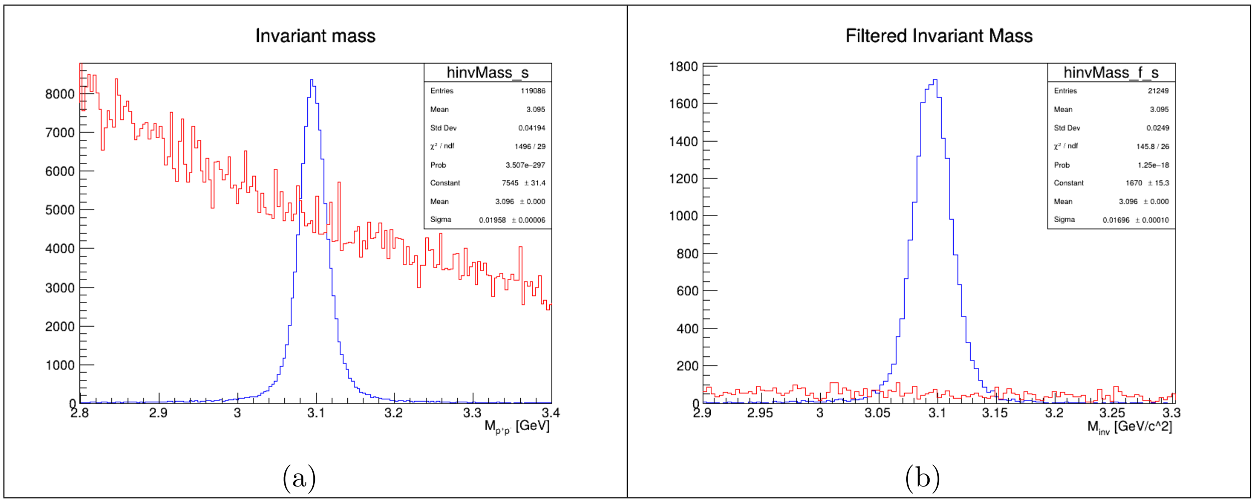


Figure 13: Invariant mass distribution in (a) before applying cuts and (b) after applying Table 1 cuts

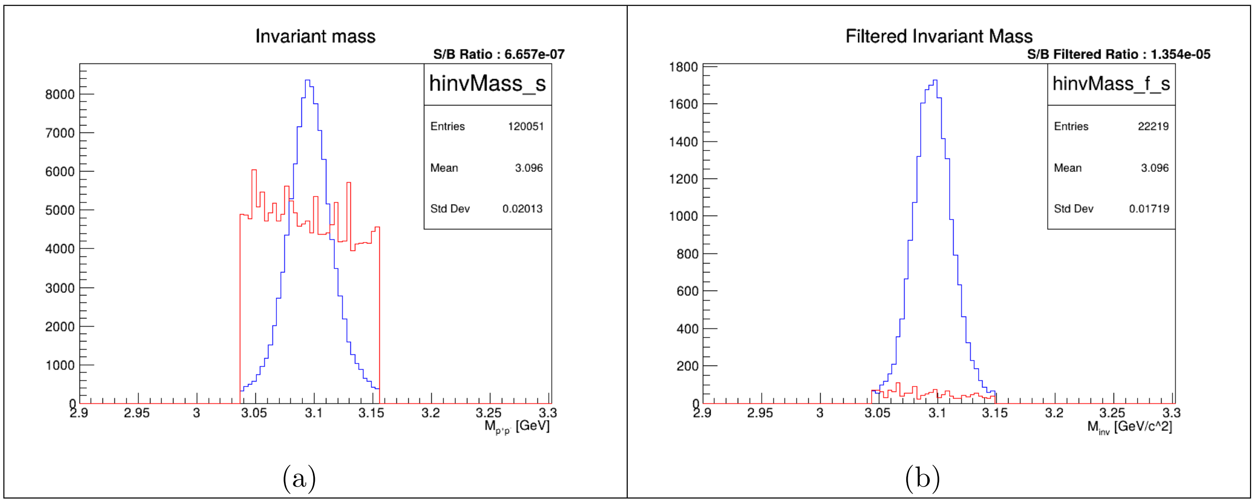
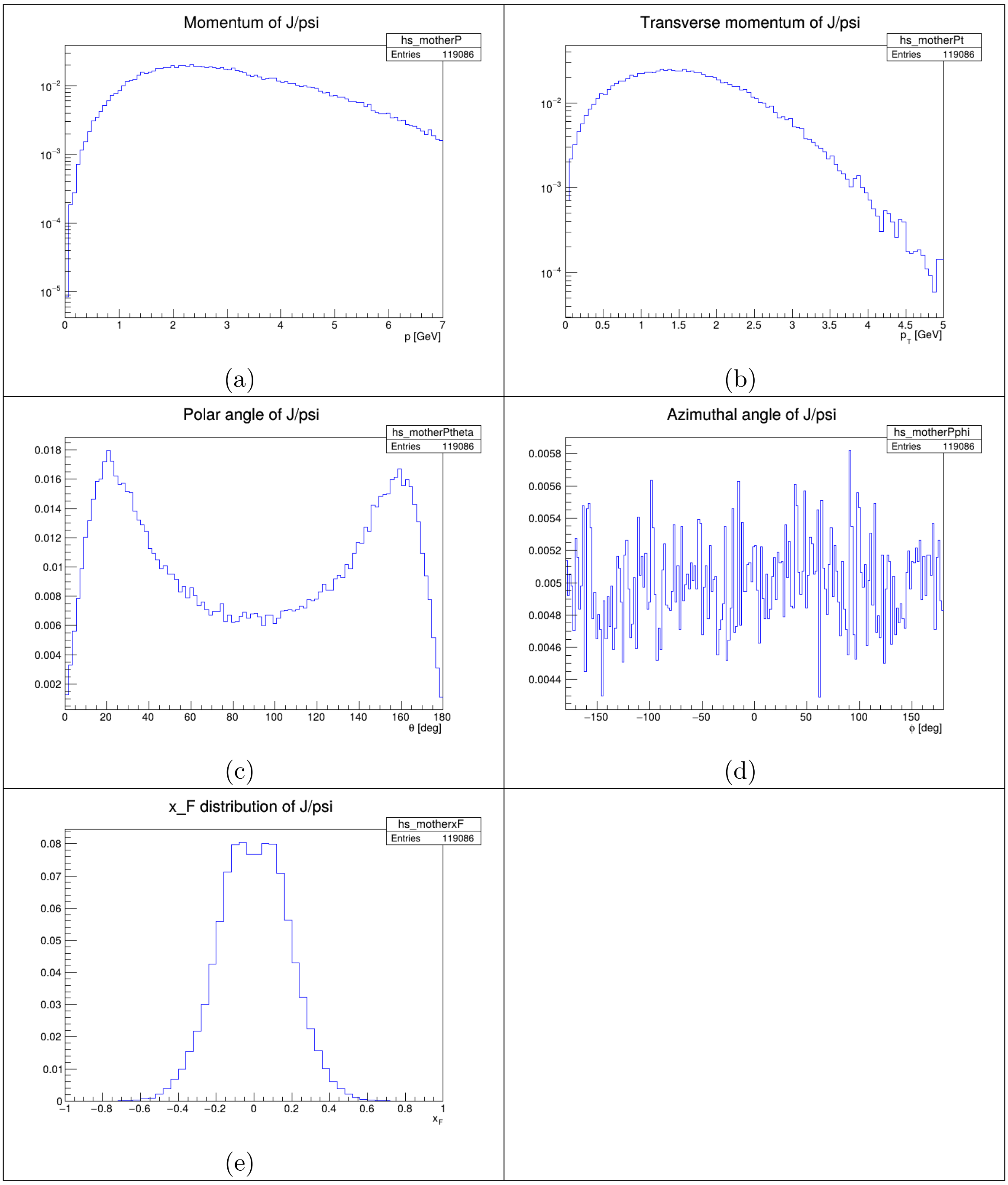


Figure 14: The 3 σ window for Invariant mass distribution and S/B ratio in (a) before applying cuts and (b) after applying Table 1 cuts



(a) (b) (c) (d) (e)

Figure 15: Parameters of J/ψ mother particles . Momentum in (13a), Transverse momentum in (13b), Polar angle θ in (13c), Azimuthal or ϕ angle in (13 d) and x_F in (13e)

5 Conclusions

- Opening angles between daughter particles (Fig 8): signal events have acute angles as can be expected, for the detector setup, whereas background events show obtuse angles.
- Polar angles of daughter particles (Fig 12): signal distributions are predominantly flat, whereas background distributions are significantly peaked at highly forward and backward orientations.
- The comparative before-and-after cuts shown in Figure 13 serve as a prime example of background event filtering because the analysis between forced decays and all random combinations of $p\bar{p}$ it is necessary to study the feasibility of production of charmonia $\eta_c \to p\bar{p}$ in SPD for a whole year of data as Figure 3 exemplify.
- The implemented cuts improved the signal-to-background ratio (S/B), in 3 σ window enhance the analysis. The S/B ratio increased from 10^{-7} before the cuts to 10^{-5} after the cuts. (Fig 14)
- It is essential to note that the present report is a preliminary result, the reason it is that for a whole year of data adquisition in SPD, background events are approximately 38000 B $\approx 10^9$, 400 M of η_c, mother particles to be generated in Pythia8 and to interact with SPD to merely produce a 6×10^5 daughter $p\bar{p}$ particles.
- To study quantitatively signal/background a limit of 10^9 background events and 10^6 signal events is expected to be simulated and analyzed with lxui cluster with further time calculations with JINR's lxui cluster. This preliminary report will be supplemented in future.

6 References

[1] Guskov, A. et al. (2023) 'Probing gluons with the future spin physics detector', Physics, 5(3), pp. 672–687. doi:10.3390/physics5030044.

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[3] D. Amaresh, Feasibility Study of Measurement of $\eta_c \to p\bar{p}$ at SPD Experiment, 2022

[4] Abazov, The Spd Collaboration V. et al. "Technical Design Report of the Spin Physics Detector at NICA." (2024).

[5] Z. Alexey , spdroot, (2024), GitHub repository, https://git.jinr.ru/nica/spdroot

7 Appendix

Figure 16: Google drive folder of scripts