Study of Lambda polarization at the MPD

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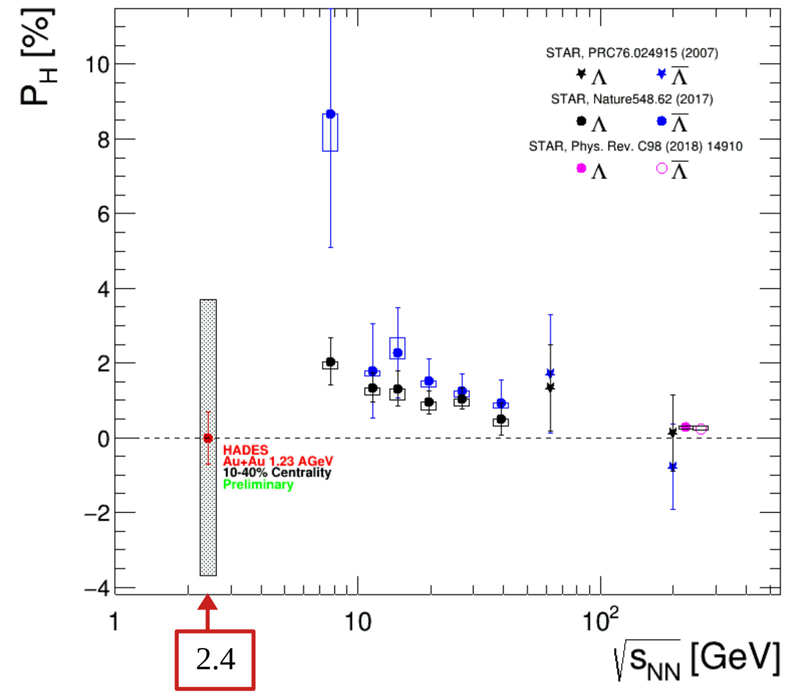
Outline

- Introduction
  - Lambda polarization
  - NICA/MPD experiment
- Analysis method
  - Inclusive polarization
  - Global polarization
- Results
  - Feasibility test of inclusive polarization extraction
  - Study of global hyperon polarization
- Conclusion

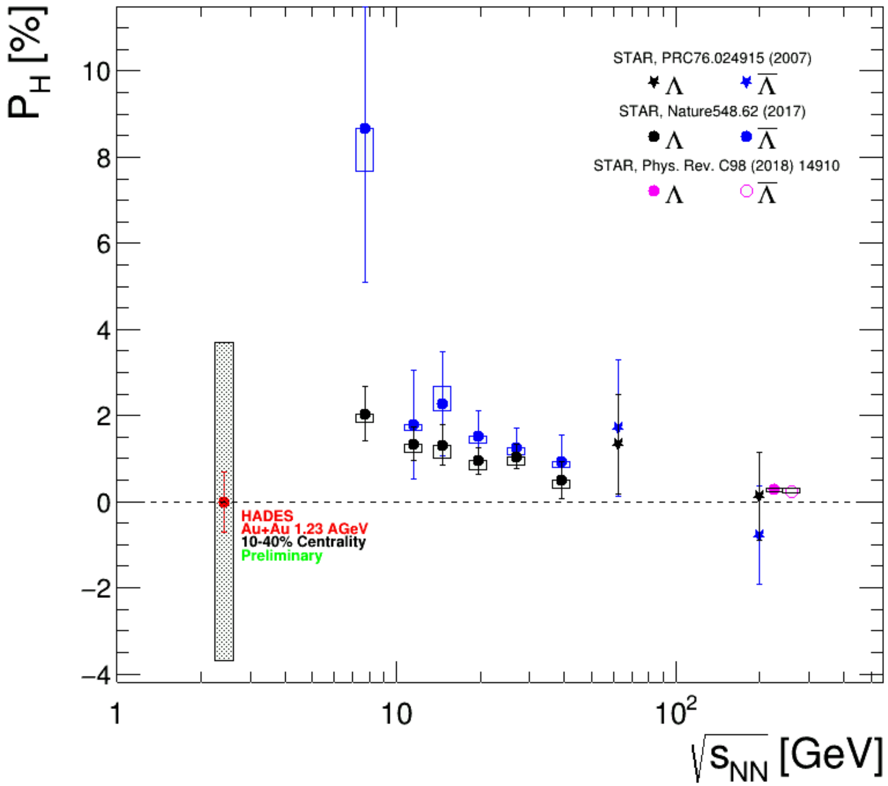
Motivation

- Predicted[1] and observed[2] global polarization signals rise as the collision energy is reduced:
  - NICA energy range will provide new insight
  - Possible drop-off seen at $\sqrt{s_{NN}} = 2.4\,\mathrm{GeV}$ in HADES experiment[3] (preliminary)
- New value of decay asymmetry α_Λ found in BES-III experiment[4]
  - Effect could be studied at NICA
- $\Lambda(\bar{\Lambda})$-splitting of global polarization, connection to the radial flow of $\Lambda(\bar{\Lambda})$

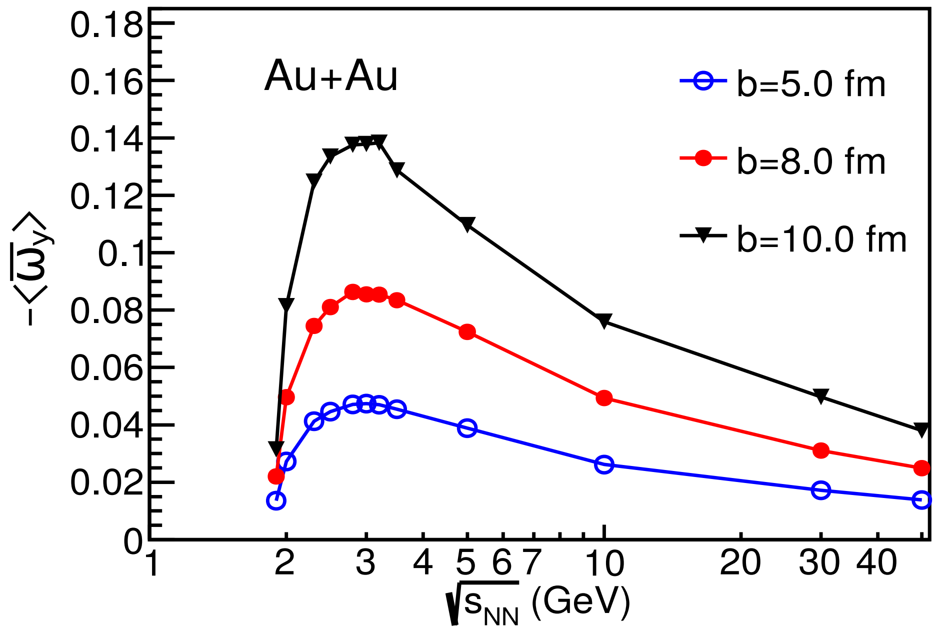


Possible drop-off at low energies?[3]

[1] O. Rogachevsky, A. Sorin, O. Teryaev, Phys.Rev. C 82, 054910 (2010)
[2] J. Adam et al. (STAR Collaboration), Phys. Rev. C 98, 014910 (2018)
[3] F. Kornas for the HADES Collaboration, SQM 2019, Bari, Italy (11.06.19)
[4] Ablikim M, et al., Nature Phys. 15:631 (2019)



Initial thermal vorticity at mid rapidity



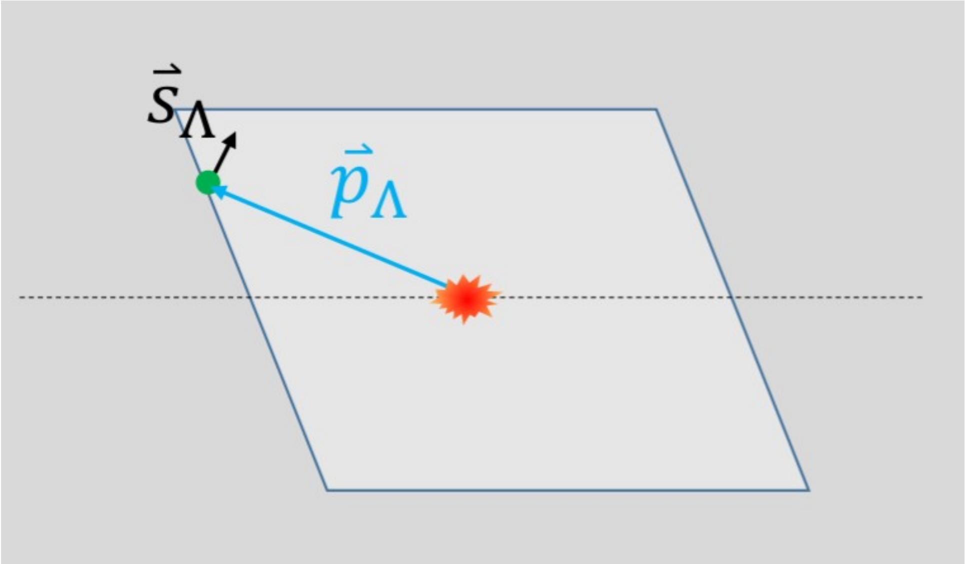
[1] Xian-Gai Deng, Xu-Guang Huang, Yu-Gang Ma, Song Zhang, Phys.Rev.C 101 (2020) 6, 064908

- Preliminary result from HADES collaboration
  - Possible drop-off at low energy (1.23 AGeV)
  - What we might see at NICA/MPD?
- Recent studies were done to estimate low-energy dependence of thermal vorticity using UrQMD[1] and 3FD[2] models
  - If polarization is proportional to vorticity, might give an estimate

[2] Y. B. Ivanov, V. D. Toneev and A. A. Soldatov, Phys. Rev. C (2019) 100, 014908

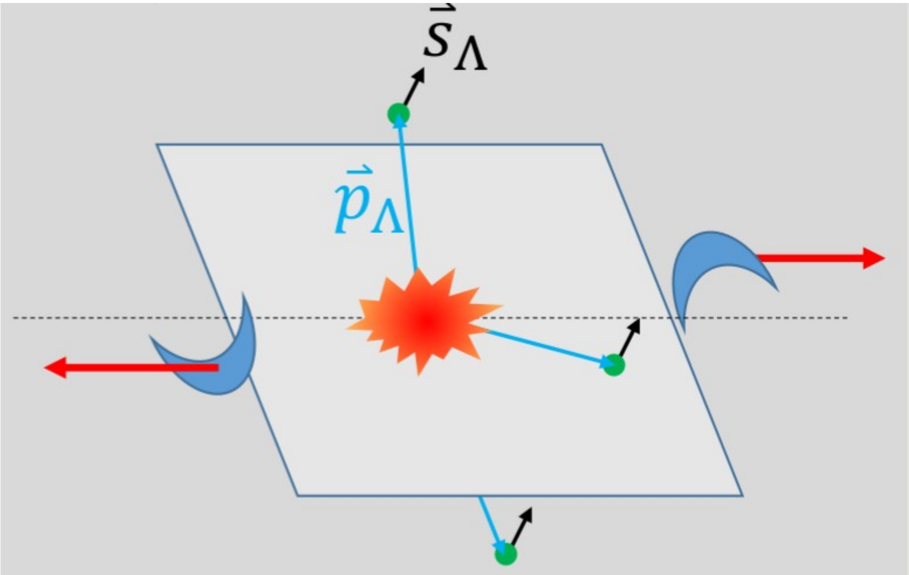
$\Lambda(\bar{\Lambda})$ hyperon polarization

- Inclusive polarization[3,4]
  - w.r.t scattering (production) plane
  - Measured in pp and pA collisions
  - In HIC can be diluted due to the rescattering in the QCD medium



Spanned by beam direction and $\vec{p}_\Lambda$

- Global polarization[1,2]
  - w.r.t reaction plane
  - Emerges in HIC due to the system angular momentum
  - Sensitive to parity-odd characteristics of QCD medium and QCD anomalous transport



Spanned by beam direction and $\vec{b}$

[1] Z. Liang, X. Wang, PRL 94, 102301 (2005)
[2] L. Adamczyk et al., Nature 548, 62 (2017)
[3] A. Lesnik et al., Phys. Rev. Lett. 35, 770 (1975)
[4] G. Bunce et al., PRL 36, 1113 (1976)

$\Lambda(\bar{\Lambda})$ hyperon polarization

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  - w.r.t reaction plane
  - Emerges in HIC due to the system angular momentum
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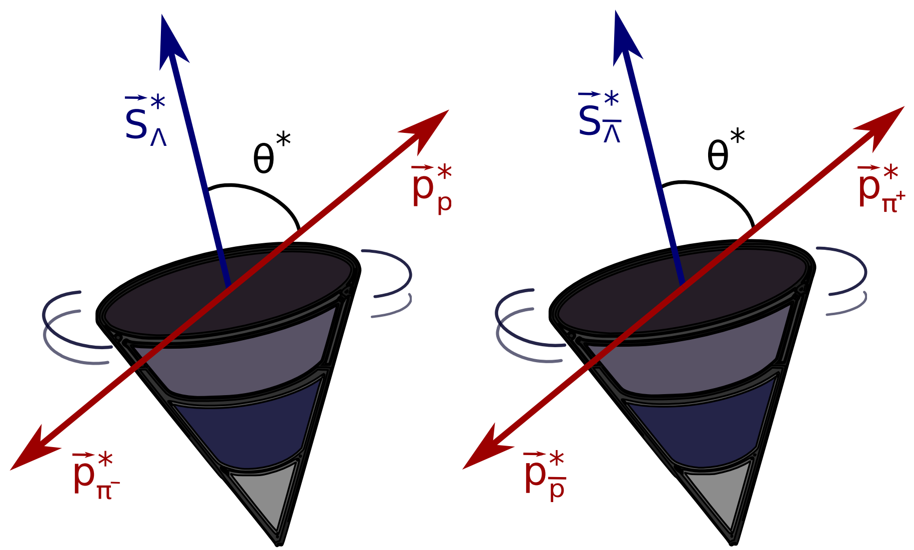
Can be measured through the weak decay: $\Lambda \to p + \pi^-$

$$\bar{\Lambda} \to \bar{p} + \pi^+$$

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = 1 + \alpha_\Lambda P_\Lambda \cos\theta^*$$

* indicates the scattering plane

$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} \simeq 0.642$ (decay asymmetry)



[1] Z. Liang, X. Wang, PRL 94, 102301 (2005)
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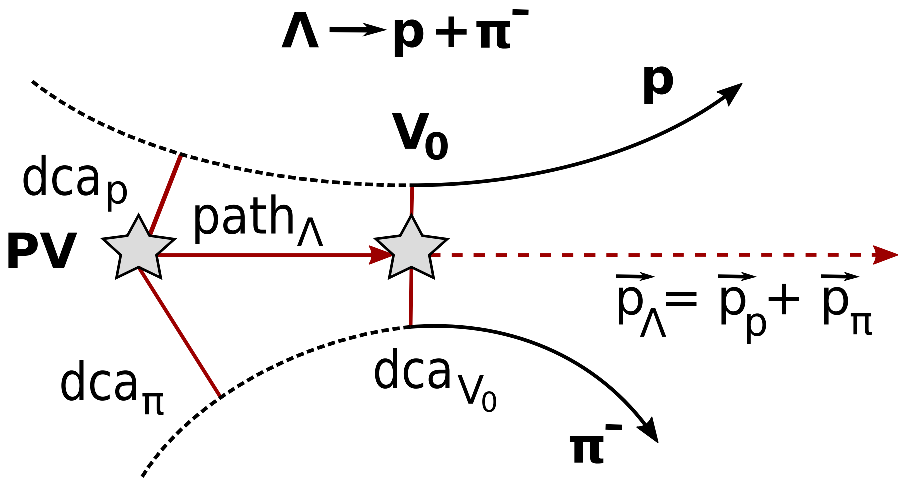
$\Lambda(\bar{\Lambda})$ hyperon polarization



- PV — primary vertex
- V_0 — vertex of hyperon decay
- dca — distance of closest approach
- path — decay length

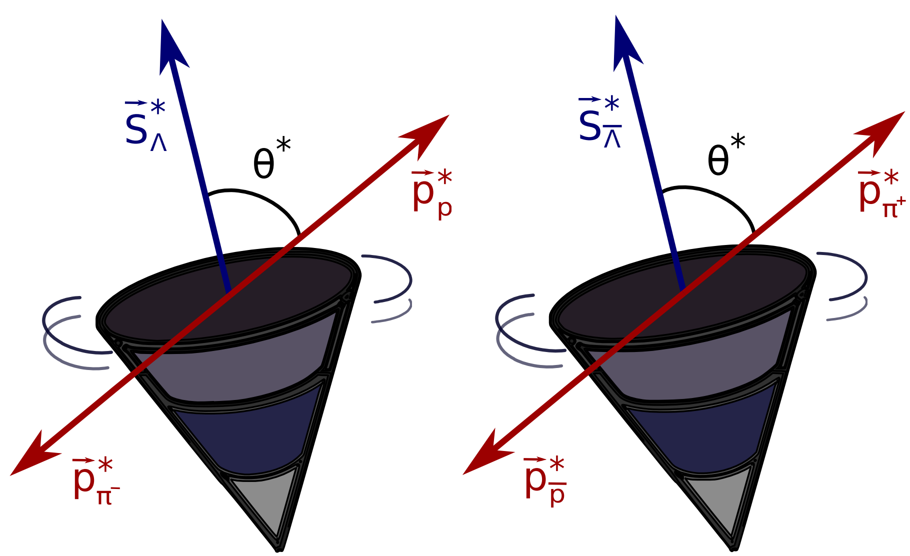
$$\frac{dN}{d\cos\theta^*} = 1 + \alpha_\Lambda P_\Lambda \cos\theta^*$$

- θ^* — angle between the decay particle and $\vec{n} = \vec{p}_{\mathrm{beam}} \times \vec{p}_\Lambda$
- P_Λ — inclusive polarization (w.r.t. production plane of Λ)

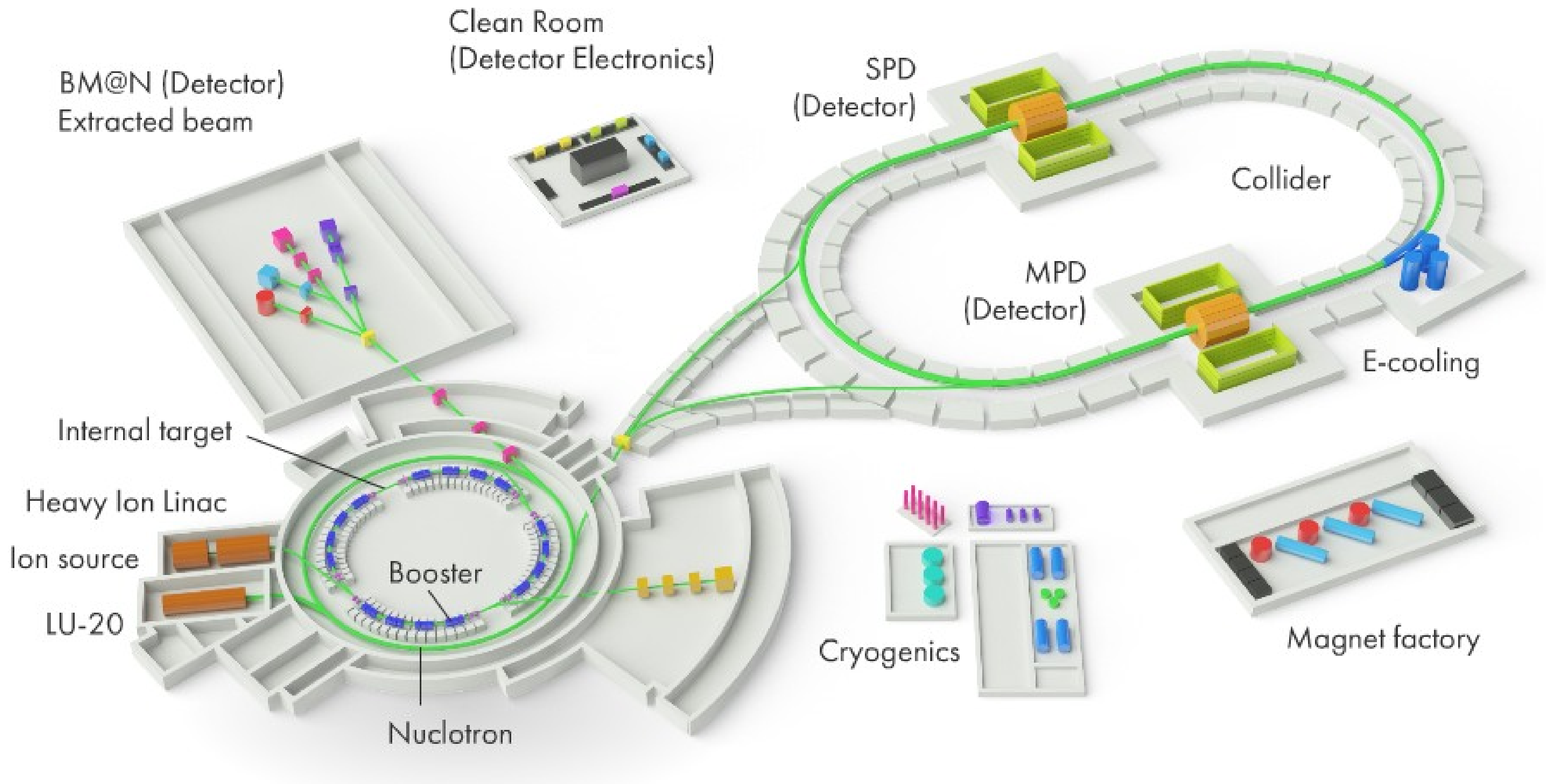
- In the case of global polarization one needs to calculate event plane and account for its resolution (R^1_{EP}):

$$\overline{P}_{\Lambda/\bar{\Lambda}} = \frac{8}{\pi\alpha}\frac{1}{R^1_{\mathrm{EP}}}\left\langle \sin(\Psi^1_{\mathrm{EP}} - \phi^*_p)\right\rangle$$

- ϕ^*_p is the azimuthal angle of p



NICA complex

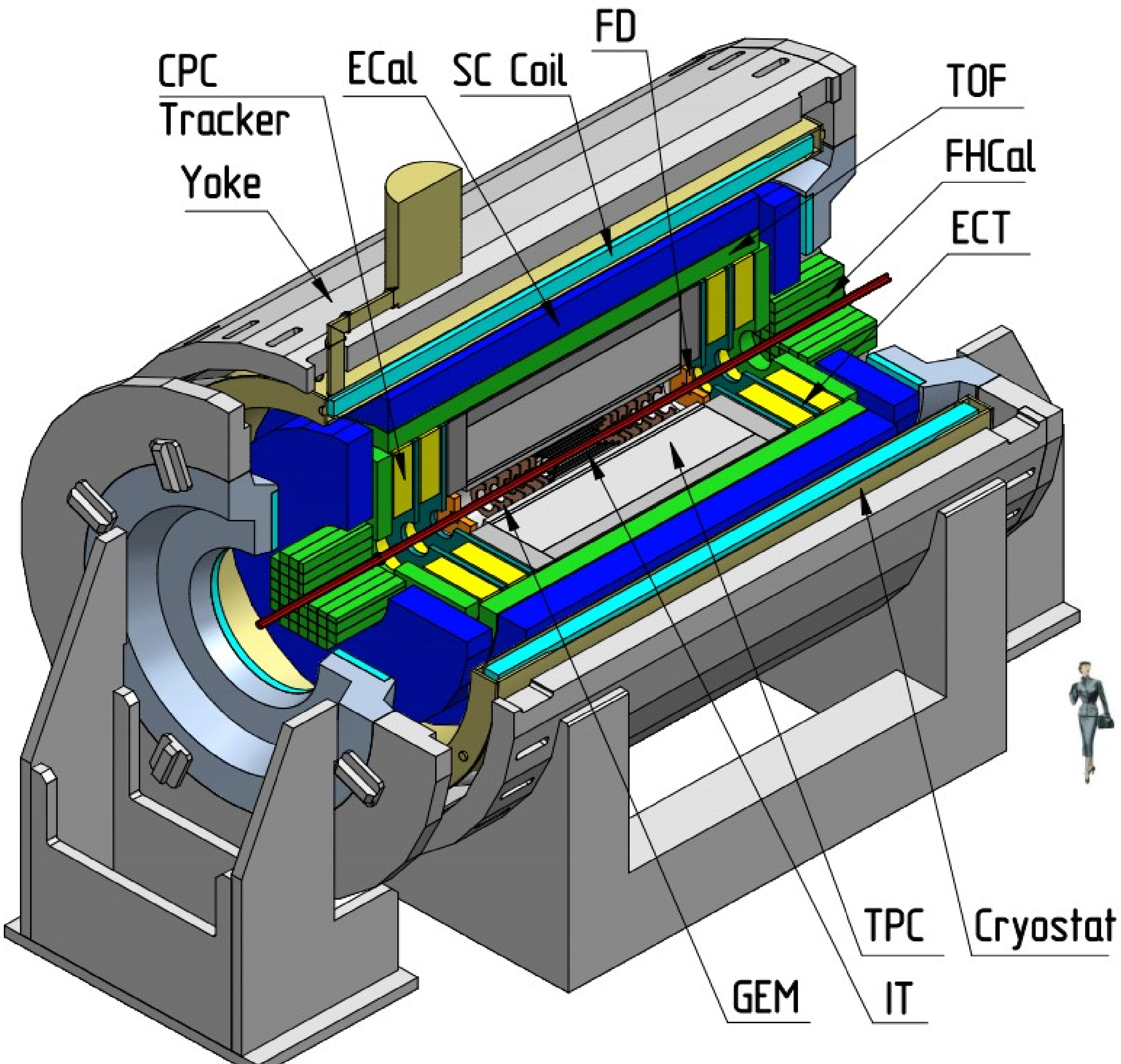


- Beams:
  - p (d) →
  - Au →
- Luminosity:
  - $L = 10^{32}\ cm^{-2}s^{-1}$
  - $L = 10^{27}\ cm^{-2}s^{-1}$

MPD detector

Multi-Purpose Detector (MPD)

- energy and system size scan from 4 to 11 GeV (HI beams) to measure a variety of signals



- 2π acceptance in azimuth
- 3-D tracking (TPC)
- Powerful PID (TPC, TOF, ECAL):
  - π/K up to 1.5 GeV/c
  - K/p up to 3 GeV/c
  - γ, e: $0.1 < p < 3$ GeV/c
- High event rate
  - Up to ~ 6 kHz

- Stage I:
  - TPC, TOF, ECAL, FHCAL, FFD
- Stage II:
  - IT (ITS) + EndCap (CPC, Straw, TOF, ECAL)

Analysis method

- Inclusive polarization
- Data: MC simulation using DCM-QGSM generator[1]
  - Au-Au, $\sqrt{s_{NN}} = 9\,\mathrm{GeV}$, ~100000 events, b=0 fm
  - Inclusive Λ polarization (transverse to the scattering plane)
    - DeGrand-Markkanen-Miettinen approach[2]
    - No $\bar{\Lambda}$ polarization
- Track selection criteria:
  - Number of TPC hits: $N_{hits} > 10$
  - $|\eta| < 1.3$

$$\mathrm{P} = -\left(\frac{12p_T}{\Delta x_0 \mathrm{M}^2}\frac{1-\xi(x)}{(1+3\xi(x))}\right)^2$$

$$\xi(x) = \frac{1-x}{3} + 0.1x,\ x = p_\Lambda/p_{\mathrm{beam}}$$

$$\mathrm{M}^2 = \left[\frac{m_{\mathrm{D}}^2 + p_{T\mathrm{D}}^2}{1-\xi(x)} + \frac{m_{\mathrm{s}}^2 + p_{T\mathrm{s}}^2}{\xi(x)} - (m_\Lambda^2 + p_T^2)\right]$$

[1] V.D. Toneev, K.K. Gudima, Nucl. Phys. A 400, 173 (1983)
[2] T.A. Degrand, J. Markkanen, H.I. Miettinen, Phys. Rev. D: Part. Fields 32, 2445 (1985)

Analysis method

MC simulation
DCM-QGSM

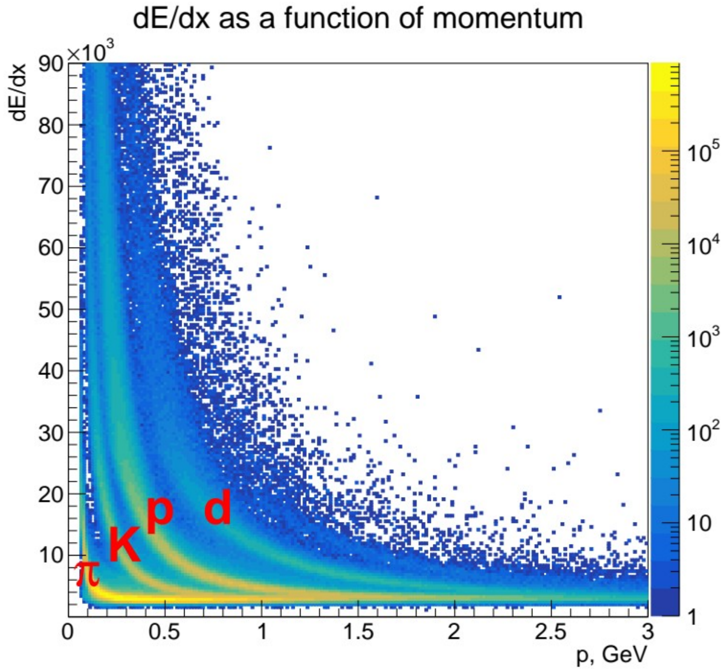
Detector simulation
GEANT 3

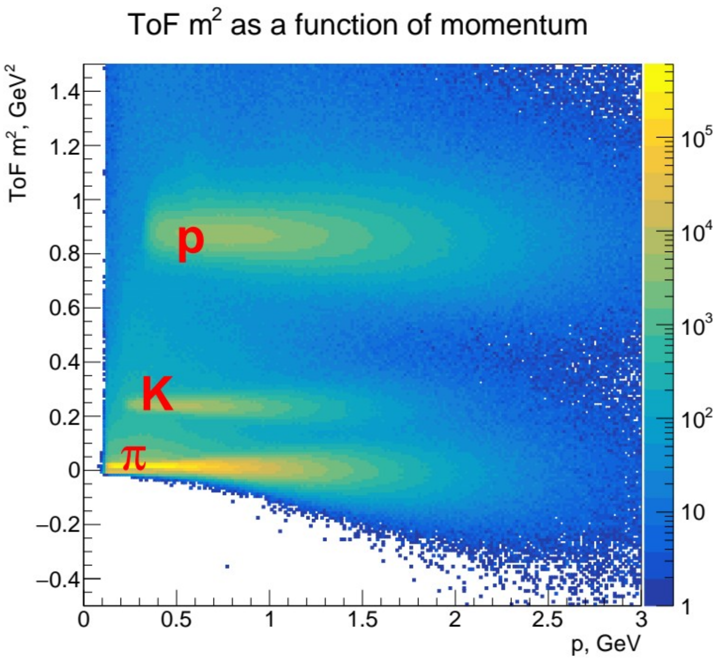
Event reconstruction
MPD

$\Lambda(\bar{\Lambda})$ reconstruction
Analysis

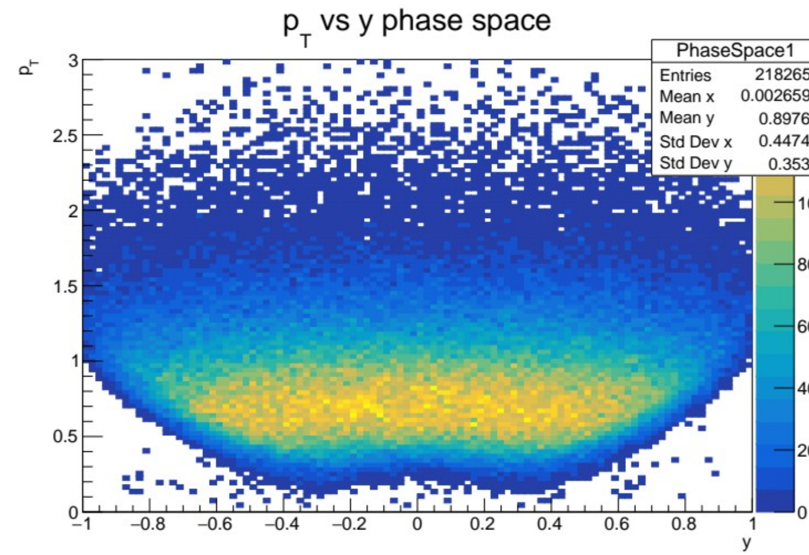
- Realistic Monte-Carlo simulation using DCM-QGSM generator (inclusive Λ polarization)
- Simulation of polarization effects in the detector via GEANT 3 (anisotropic decay of Λ hyperons) — can be switched on/off to study the effect
- Event reconstruction using realistic PID within mpdroot framework
- $\Lambda(\bar{\Lambda})$ reconstruction through the weak decay channel ($\Lambda \rightarrow p + \pi^-$)

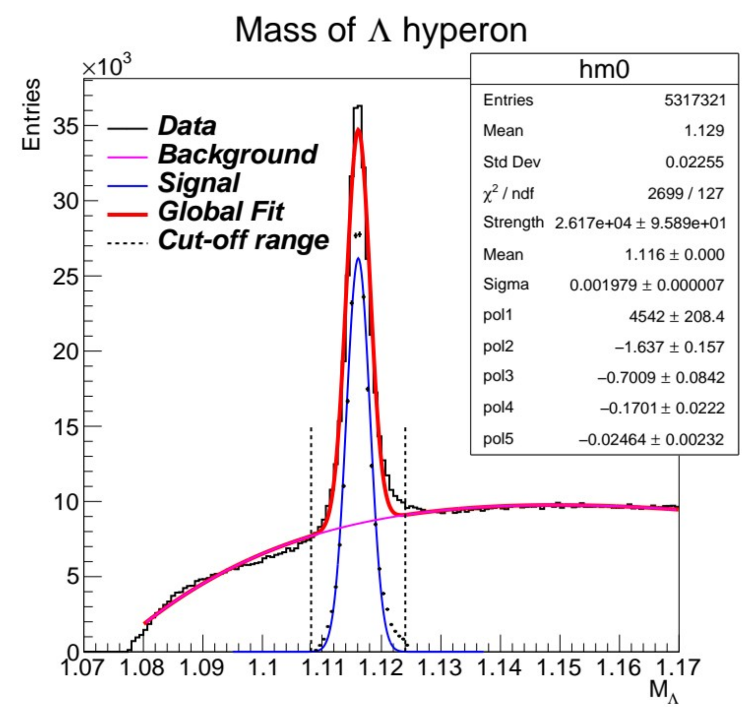
MPD PID for the analysis





Phase space for Λ hyperon

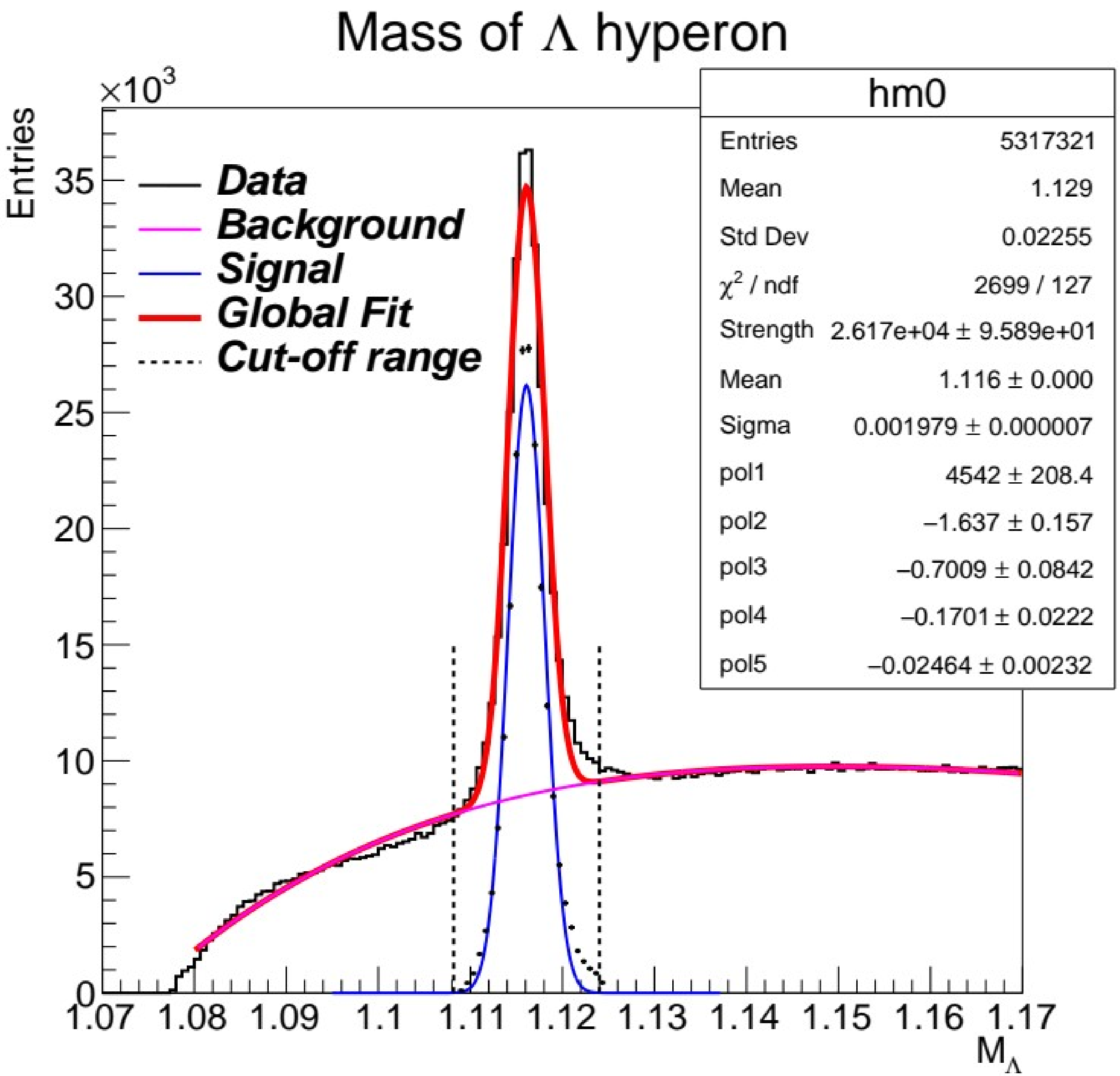


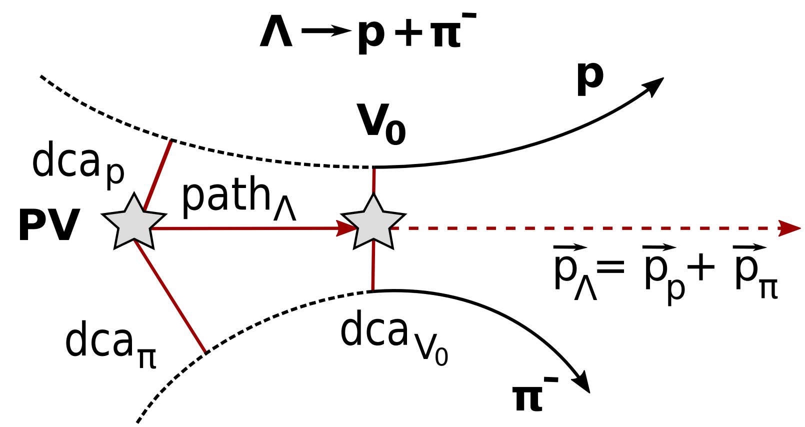


$$\Lambda \rightarrow p + \pi^-$$

Invariant mass distribution of Λ hyperon

Results



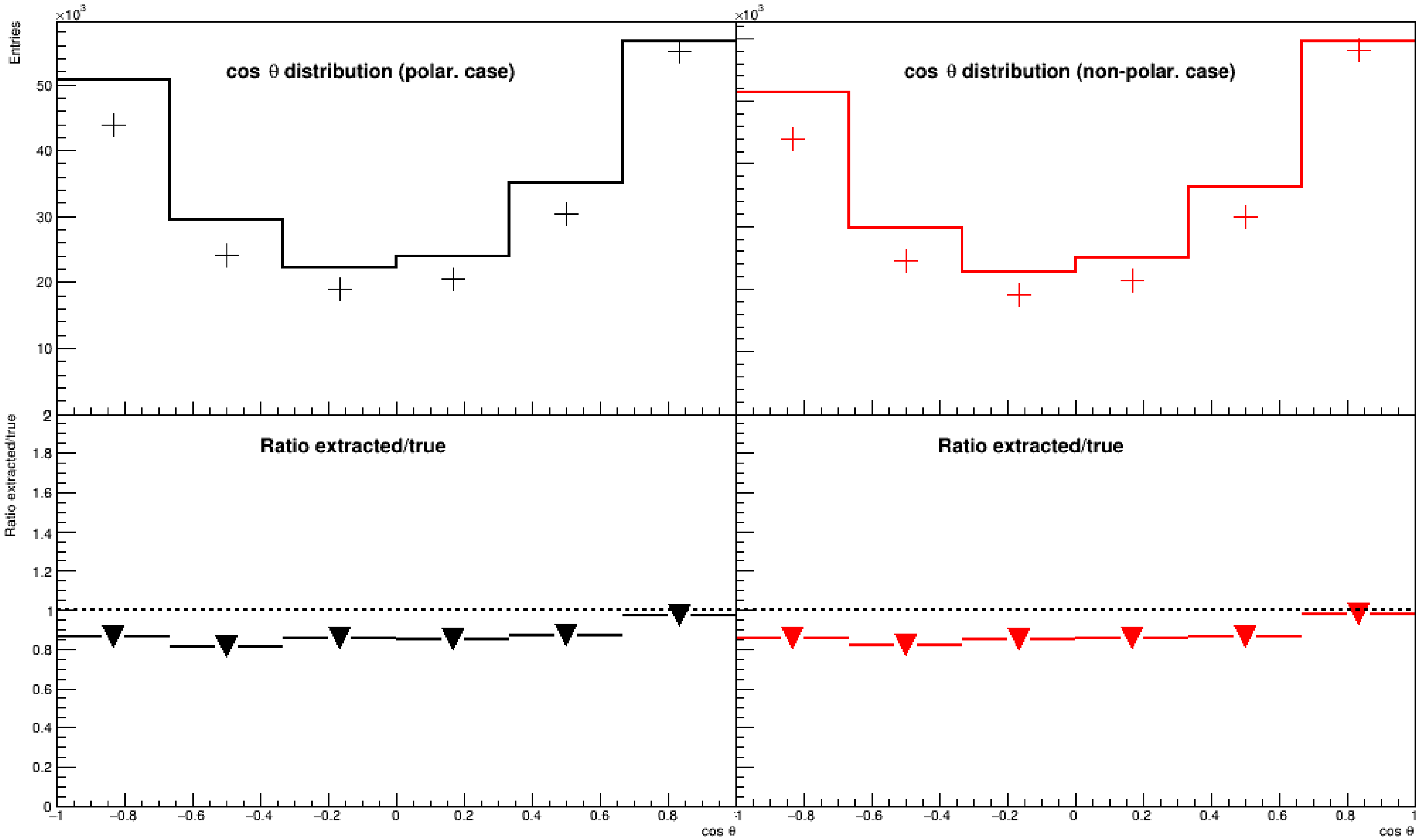


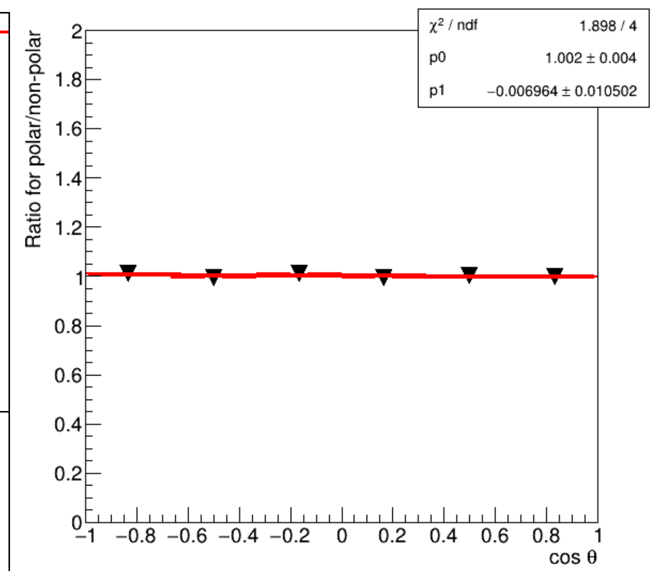
Fitting function:

- Gauss for signal
- Legendre polynomials (L_n) for Background
- Cut-off: $\langle M_\Lambda \rangle \pm 4\sigma$
- DCA and track-separation cuts

$$f(x) = [0]\exp\left(\frac{(-0.5(x-[1]))^2}{[2]^2}\right) + [3](L_0 + [4]L_1 + [5]L_2 + [6]L_3 + [7]L_4)$$

Results





Check of the extraction technique

Comparison of extracted angular distributions (from invariant mass) with the true distributions (for «polarized» and «non-polarized» case)
→ shows detector acceptance effects

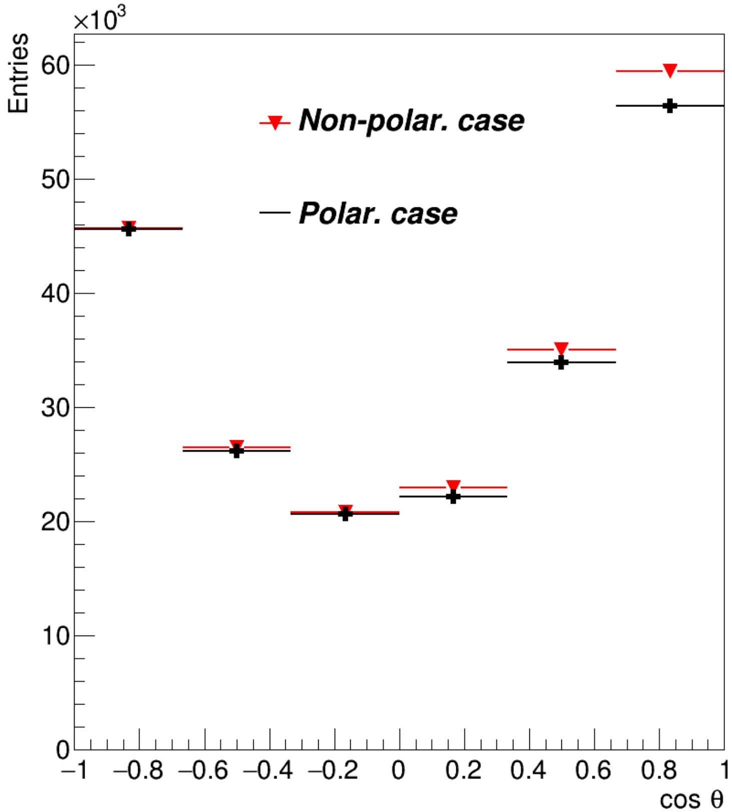
Extracted (polarized case)

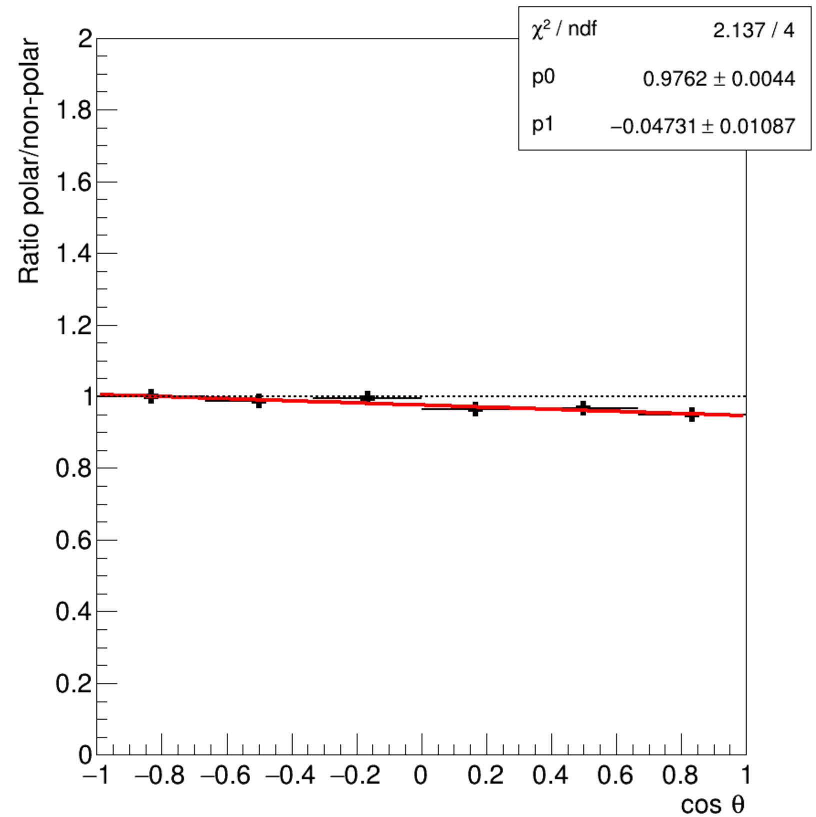
Extracted (non-polarized case)

True (polarized case)

True (non-polarized case)

Results





Accounting for detector acceptance

↓

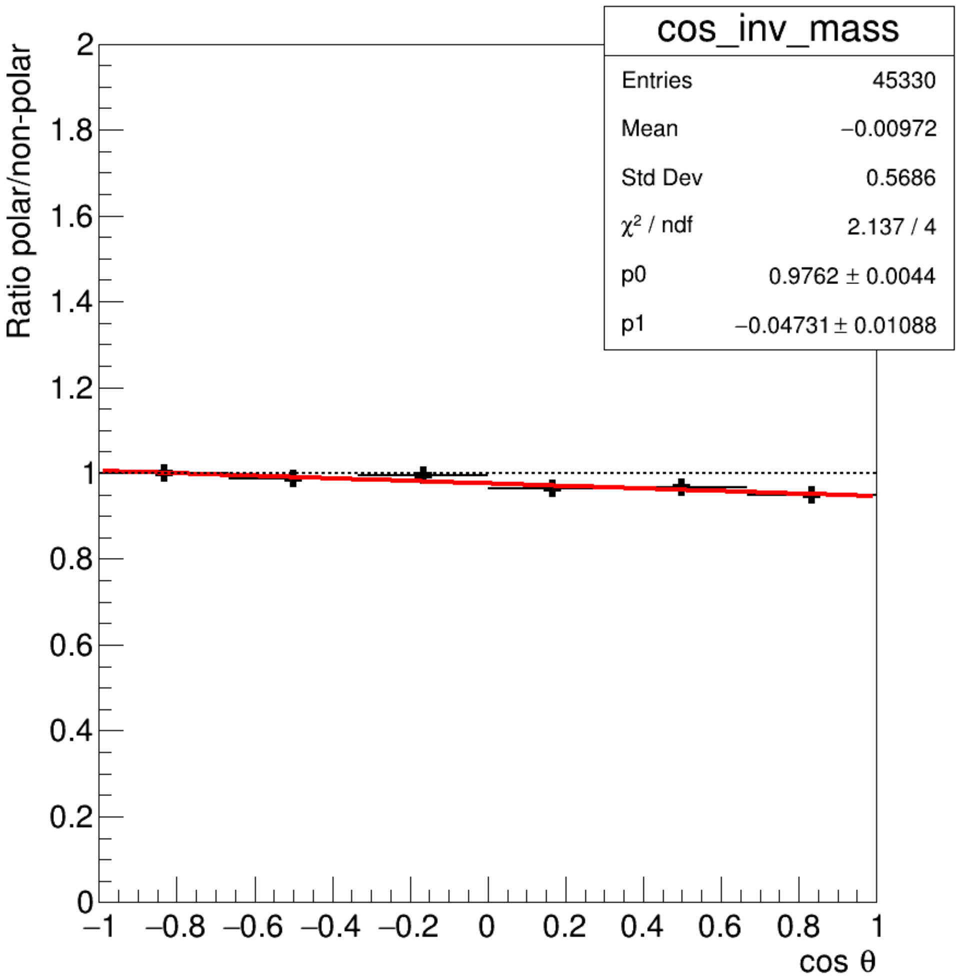
Net effect of polarization

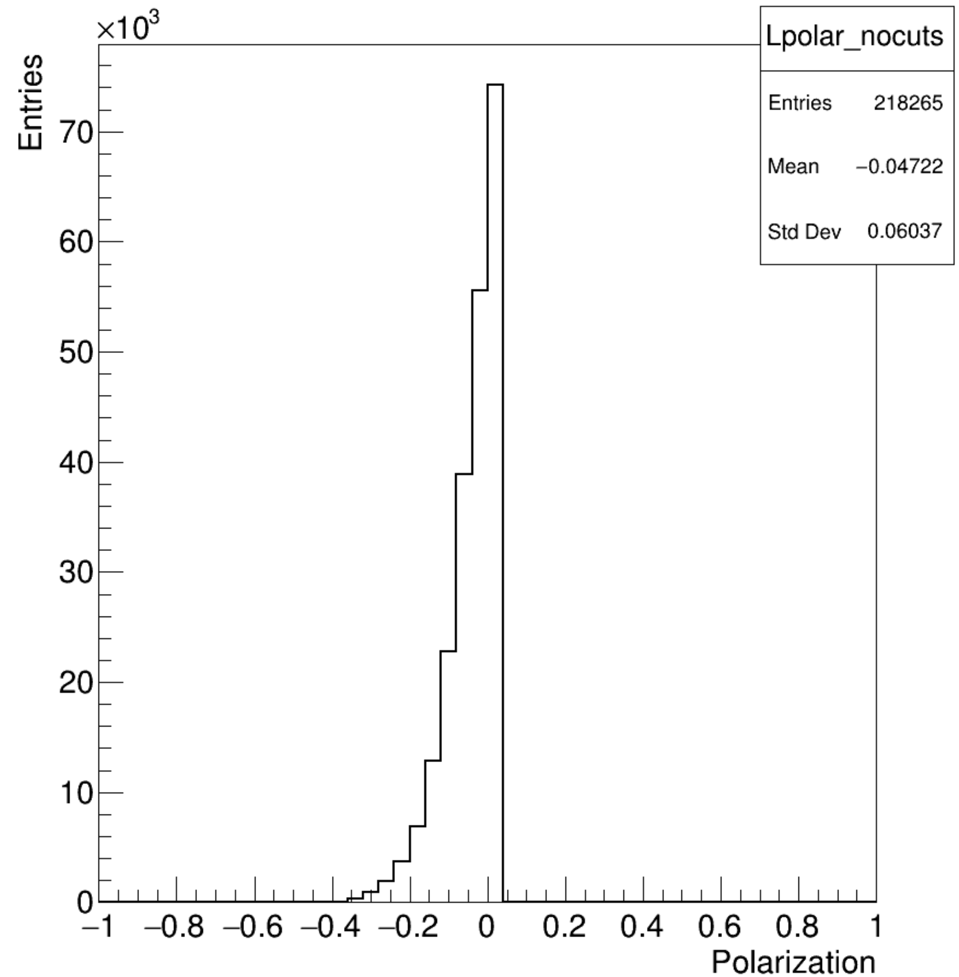
Dividing extracted angular distributions obtained from polarized/non-polarized case (with or w/o anisotropic decay)

- Accounts for the detector acceptance → shows net effect due to polarization of Λ hyperons

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = 1 + \alpha_\Lambda P_\Lambda \cos\theta^*$$

Results



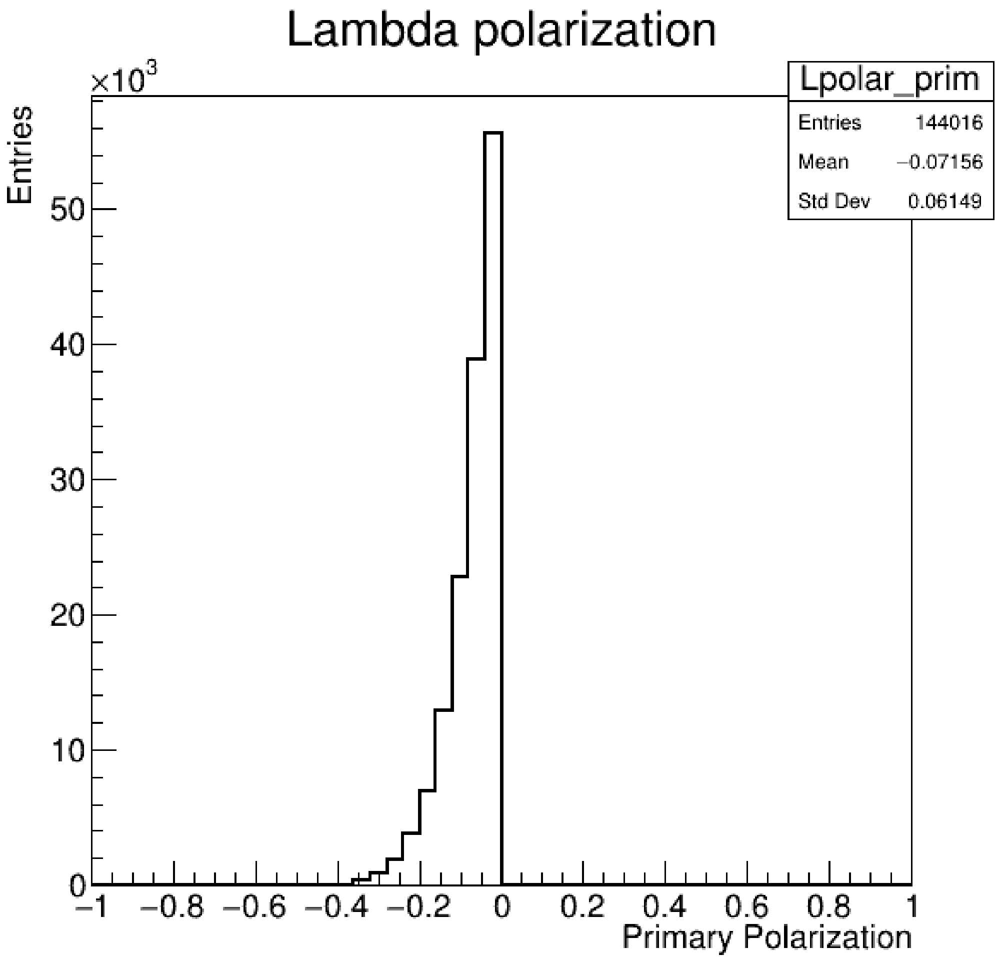


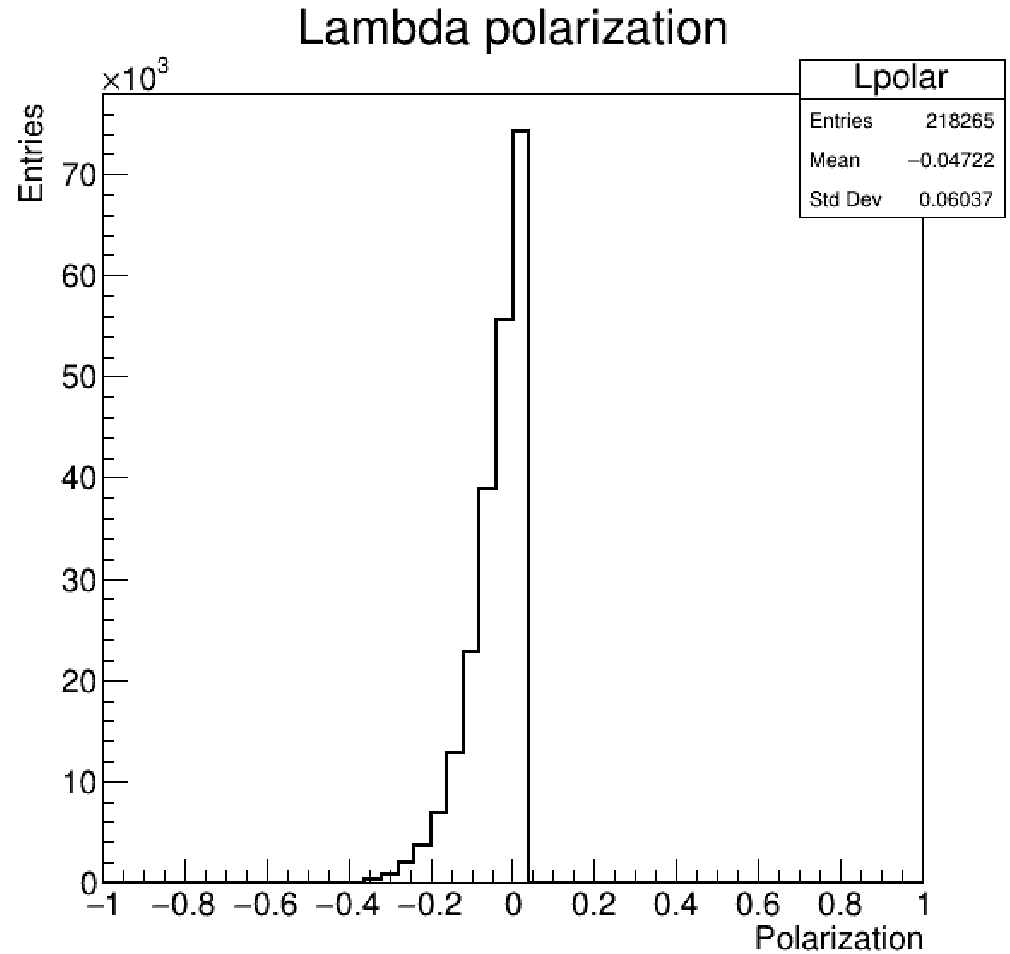
p_1 (slope parameter) → extracted polarization value:

- $p_1 = -0.04731 \pm 0.01088$

$\langle P \rangle$ (mean polarization) → true mean polarization (full Λ):

- $\langle P \rangle = -0.0472 \pm 0.00013$





<P> (mean polarization) → true mean polarization is smeared towards 0 due to non-polarized secondary Λ:

- $<P> =$ -0.0471 $\pm$ 0.00013 (full)
- $<P> =$ -0.0714 $\pm$ 0.00016 (only primary Λ)

Major contributions from decays:

$\Sigma^* \to \Lambda\pi \quad \Xi \to \Lambda\pi$

$\Sigma^0 \to \Lambda\gamma$

Study of global polarization

- Data: MC simulation using PHSD generator[1]
  - Au-Au, $\sqrt{s_{NN}} = 7.7$ GeV, ~1.5M MB events
  - Global $\Lambda(\bar{\Lambda})$ polarization
    - Thermodynamic (Becattini) approach[2]
- Track selection criteria for reconstruction:
  - Number of TPC hits: $N_{hits} > 10$
  - $|\eta|<1.3$

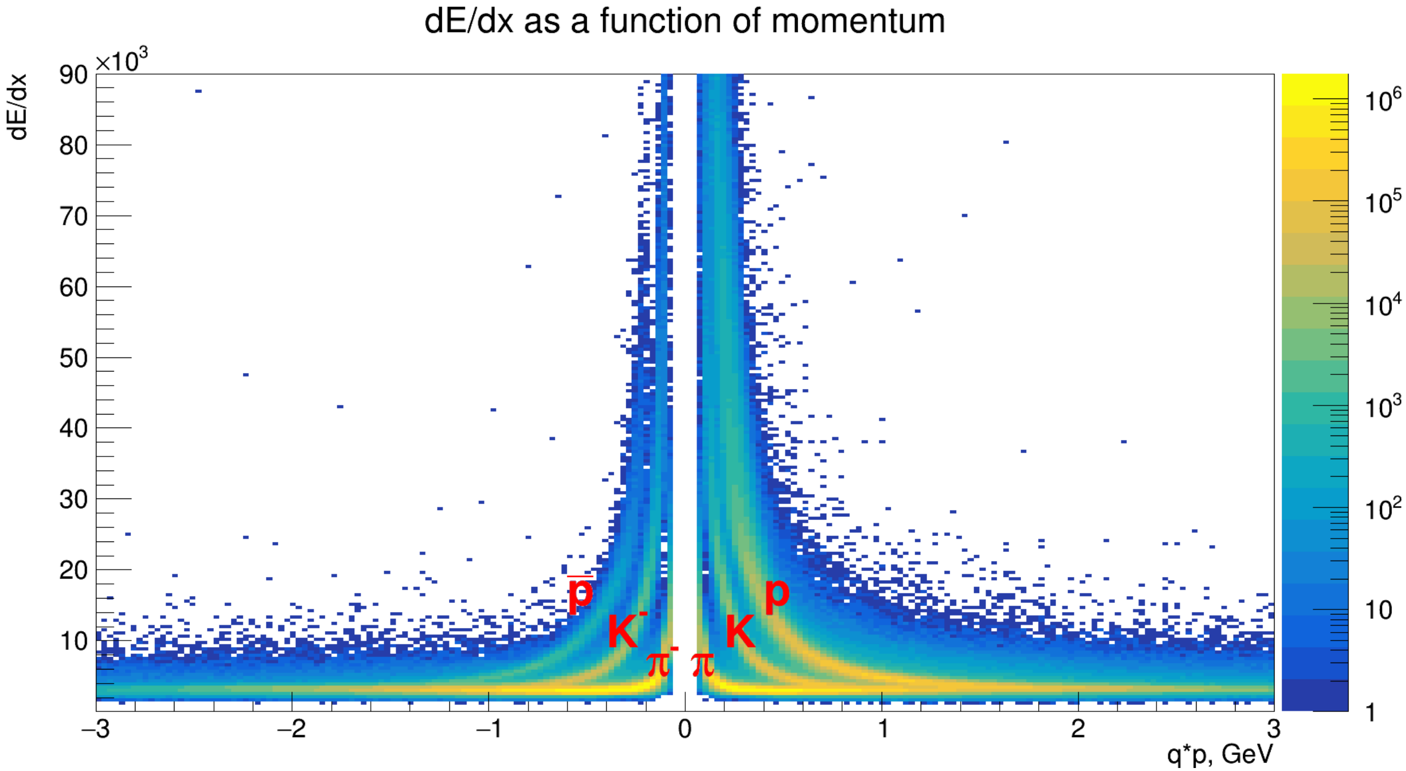
$$\boxed{\overline{P}_{\Lambda/\bar{\Lambda}} = \frac{8}{\pi\alpha}\frac{1}{R^1_{\mathrm{EP}}}\left\langle \sin(\Psi^1_{\mathrm{EP}} - \phi^*_p)\right\rangle}$$

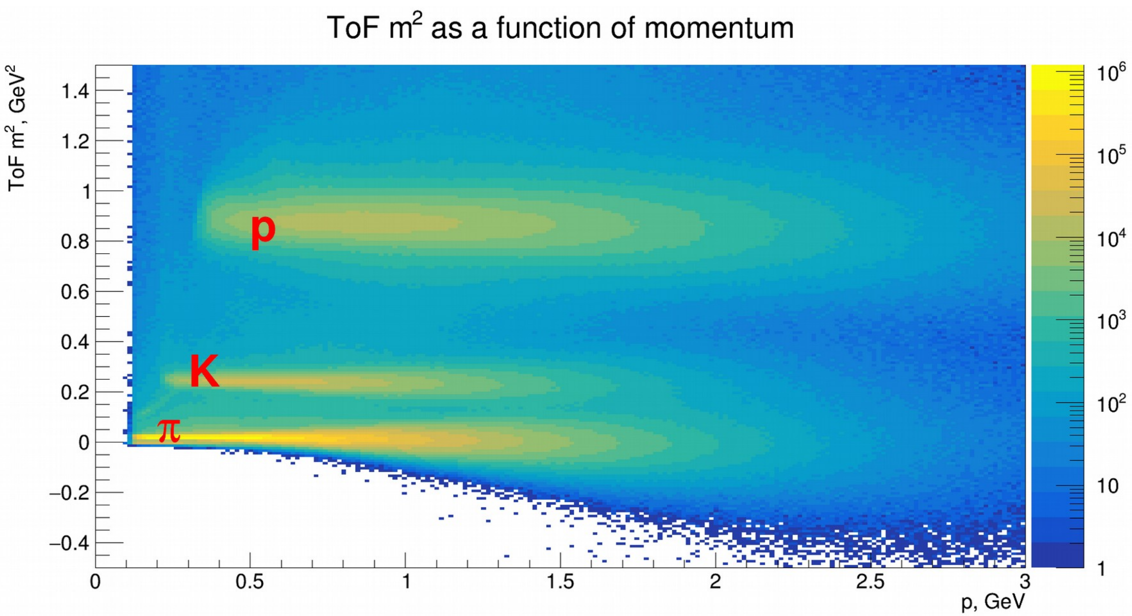
→ Need to calculate: Ψ^1_{EP} and R^1_{EP}

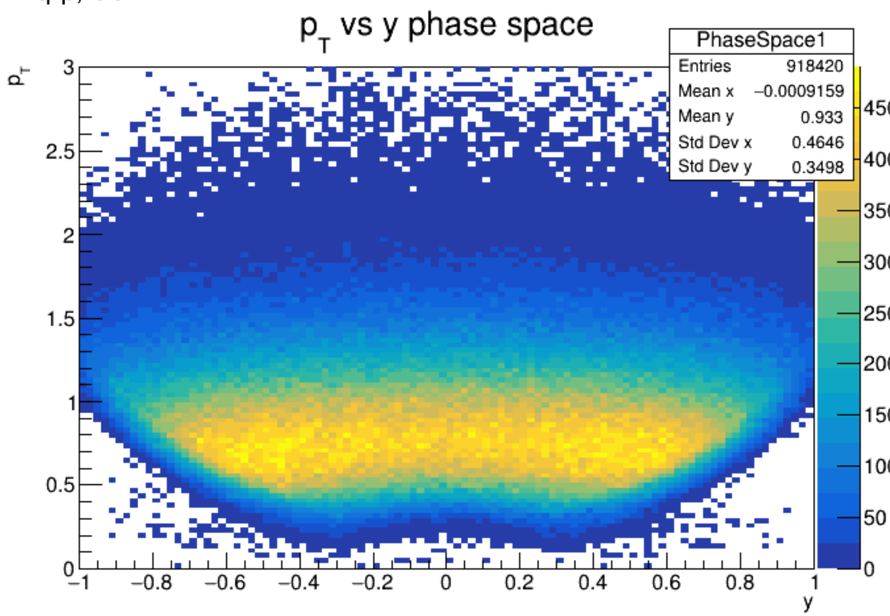
[1] W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

[2] F. Becattini, V. Chandra, L. Del Zanna, E. Grossi, Ann. Phys. 338 (2013) 32

PID performance for the dataset

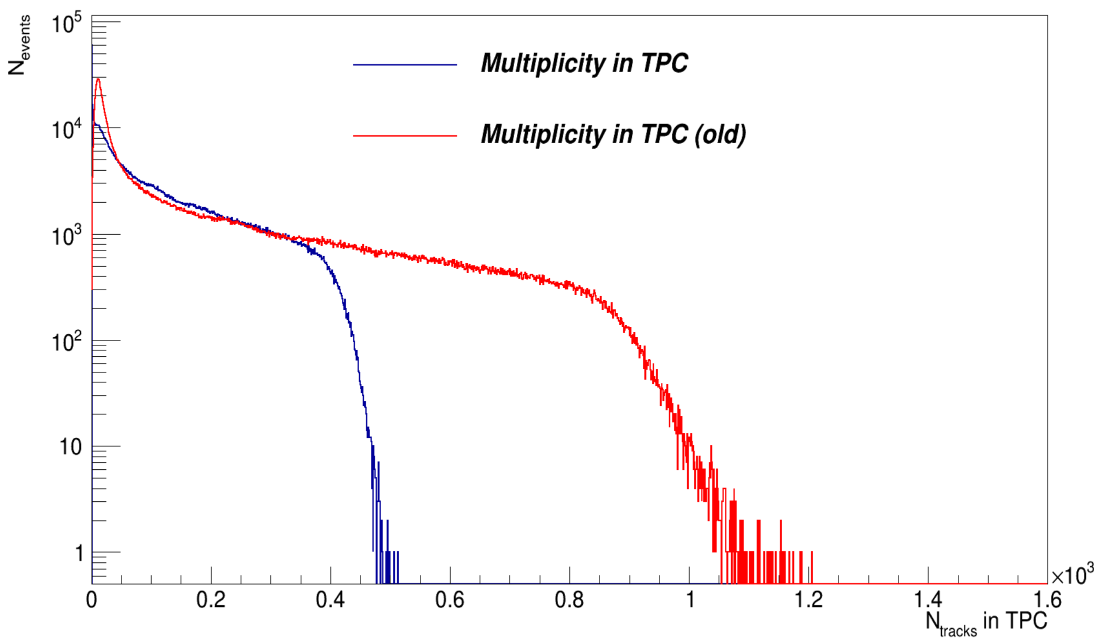






Centrality determination (TPC)

- Adapting the technique developed in the flow group
  - https://git.jinr.ru/nica/mpdroot/-/tree/dev/macro/physical_analysis/Flow
- Centrality determination through TPC:
  - $|\eta|<1.5$
  - $0 < p_T < 3$
  - DCA calibrations
  - Track multiplicity in TPC → centrality of the event



Division into 10-% centrality intervals

- 0 - 10 %
- 10 - 20 %
- 20 - 30 %
- 30 - 40 %
- 40 - 50 %
- 50 - 60 %
- 60 - 70 %
- 70 - 80 %
- 80 - 90 %
- 90 - 100 %

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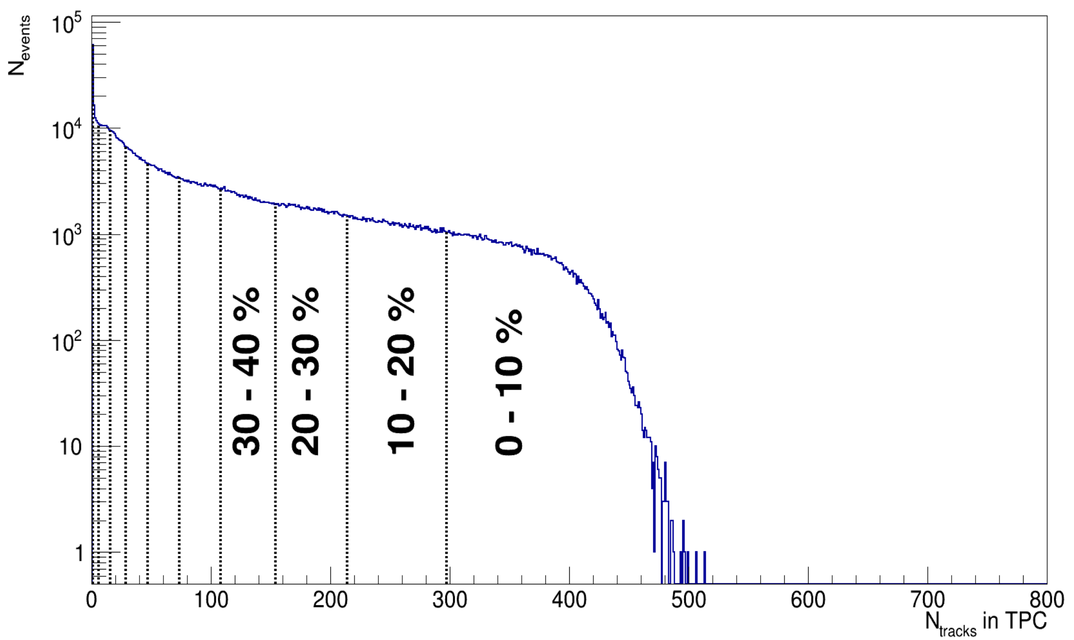
Event with multiplicity $N_{tr} \pm \sigma_N$ have impact parameter in range of $b \pm \sigma_b$



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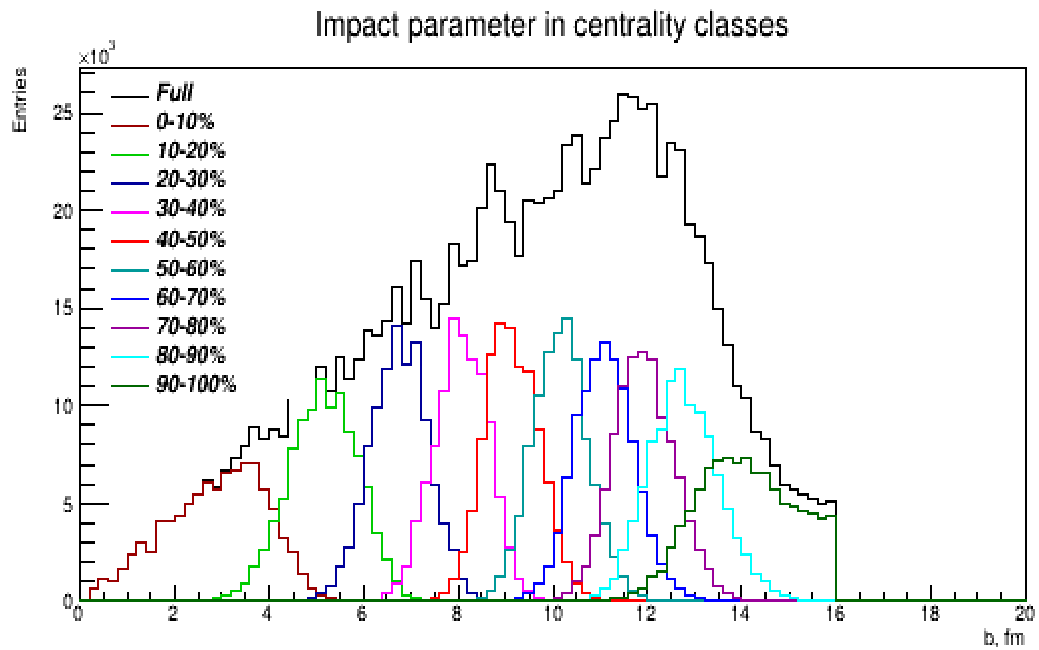

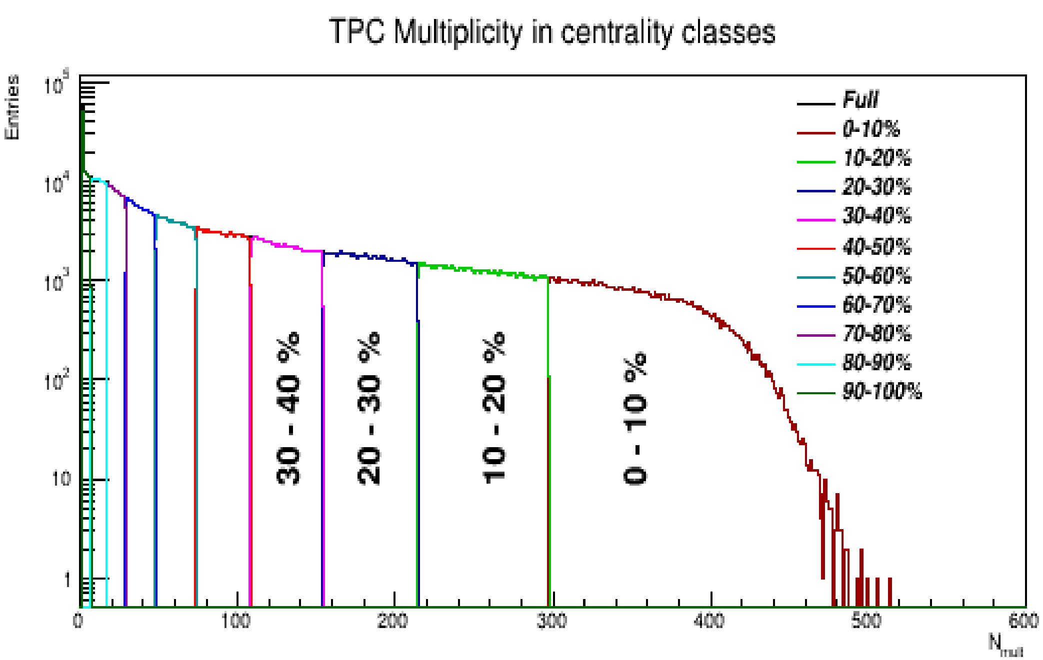

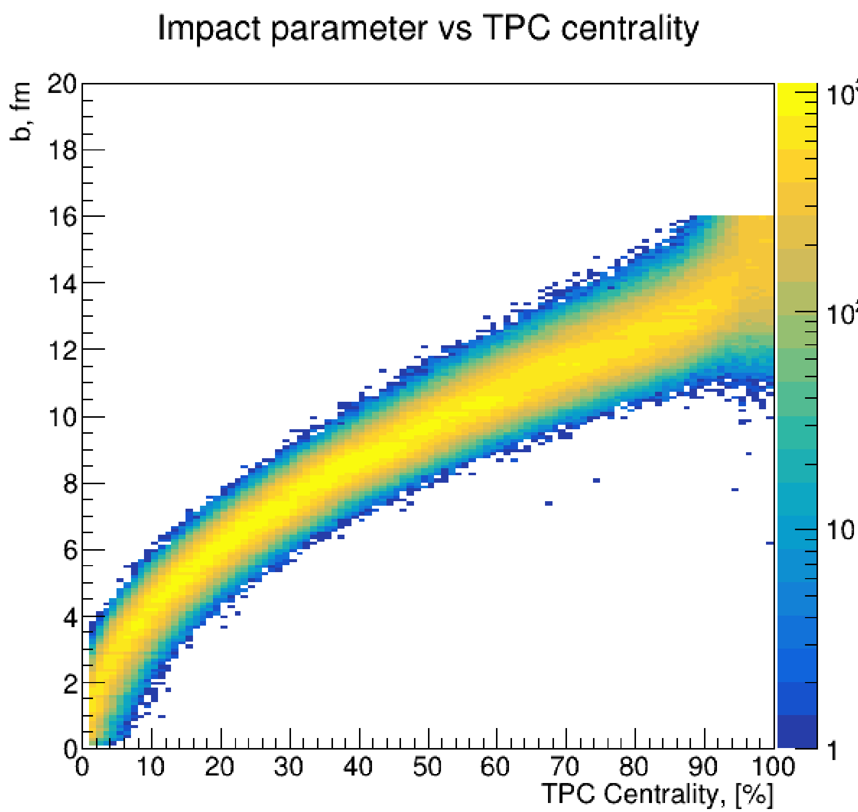

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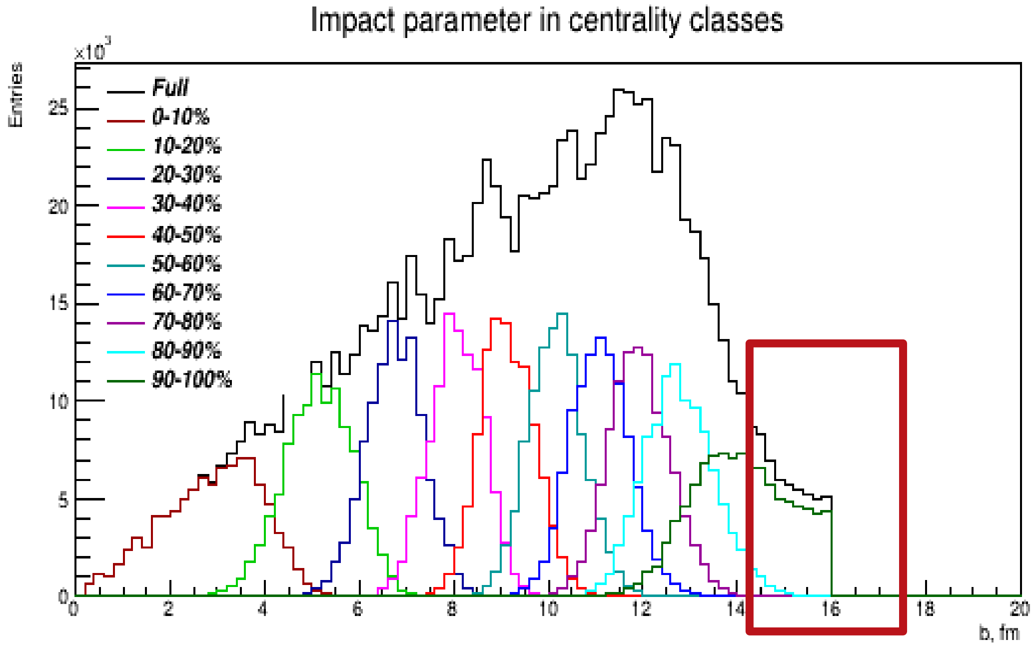

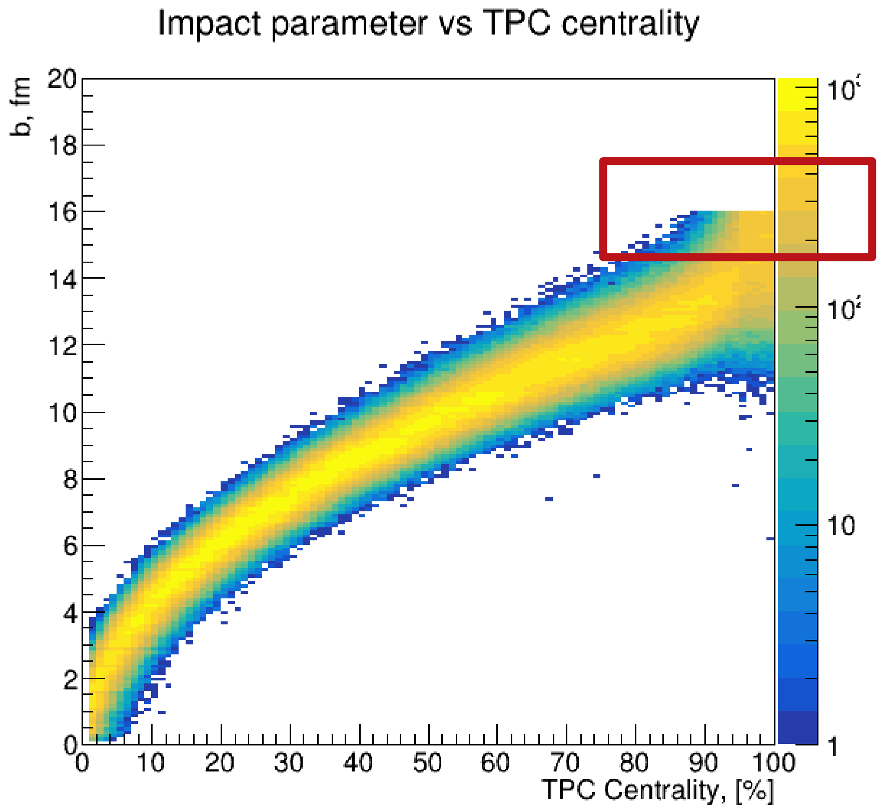

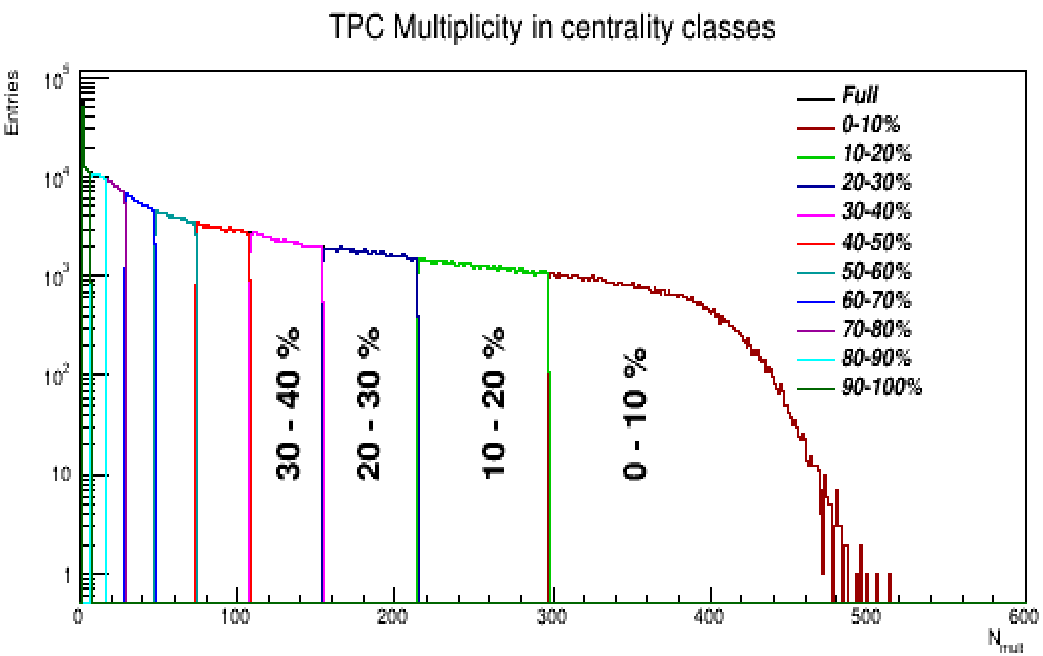

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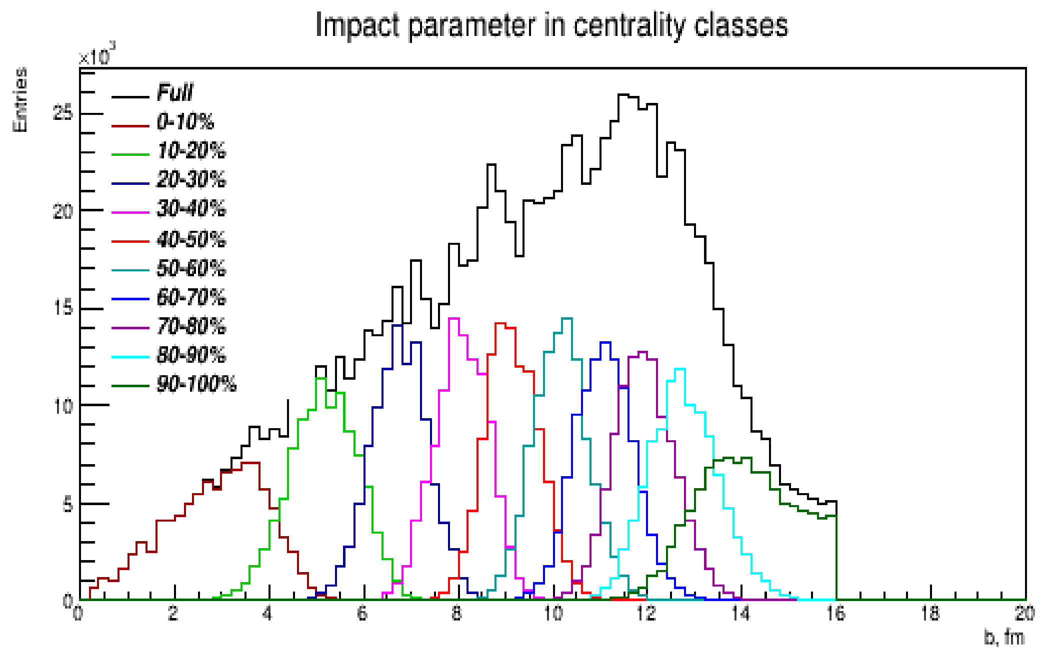

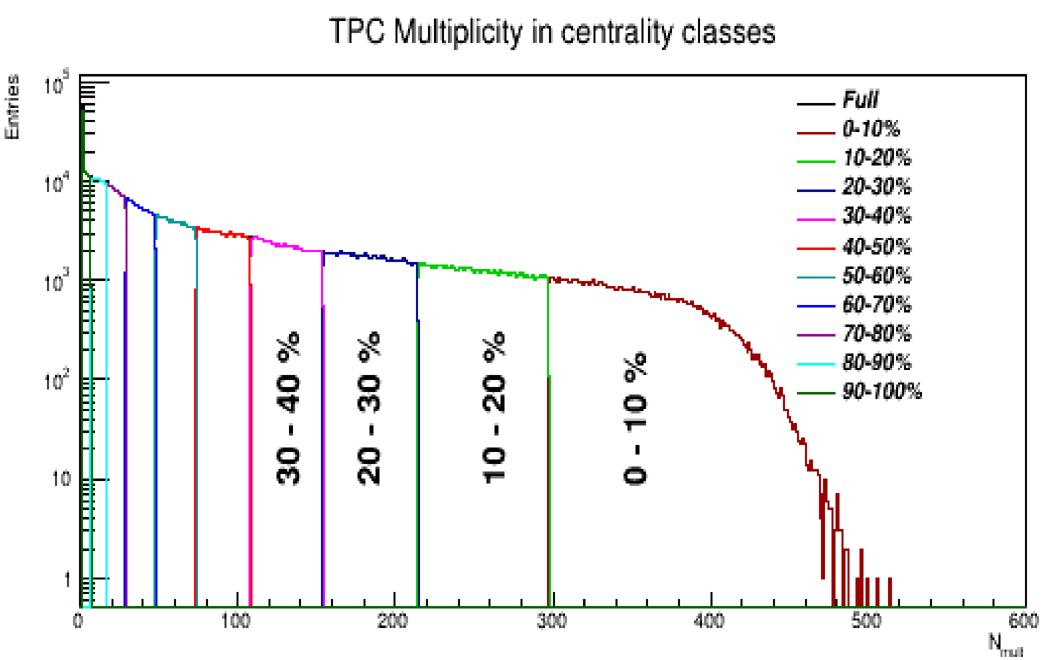

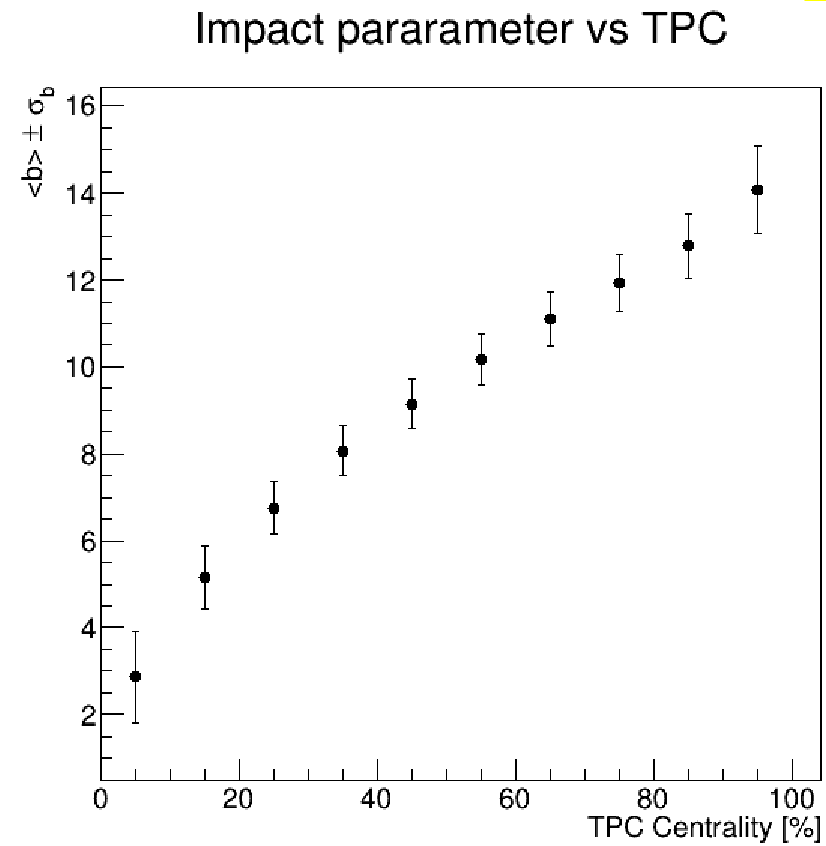

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Event plane determination

- Event plane angle can be measured as:
  - $\Psi_{\mathrm{EP}}^{n} = \arctan\dfrac{Q_y}{Q_x}$
  - $Q_y = \Sigma_i \mathrm{w}_i \sin(n\phi_i)$
  - $Q_x = \Sigma_i \mathrm{w}_i \cos(n\phi_i)$

$$\mathrm{w}_i = \begin{cases} -E_i,\ -p_{\mathrm{T}i} & \text{if } \eta < 0 \\ E_i,\ p_{\mathrm{T}i} & \text{if } \eta > 0 \end{cases}$$

«-» appears only for 1st-order EP!

- Respectively, within the flow group implementation:
  - $\mathrm{w}_i = E_i/E_{\mathrm{total}}$ (for the TPC Event plane)
  - $\mathrm{w}_i = p_{\mathrm{T}i}/p_{\mathrm{Ttotal}}$ (for the FHCal Event plane)

- Event plane resolution can be calculated as:
  - $R_{\mathrm{EP}}^{1} = \left\langle \cos(n(\Psi_{\mathrm{EP}}^{1} - \Psi_{\mathrm{RP}})) \right\rangle$ (w.r.t. reaction plane angle from the model)
  - $R_{\mathrm{EP}}^{1} = \left\langle \cos(n(\Psi_{\mathrm{EP,R}}^{1} - \Psi_{\mathrm{EP,L}}^{1})) \right\rangle$ (sub-event resolution) ⟶

⟶ Can be used to estimate experimental resolution[1]

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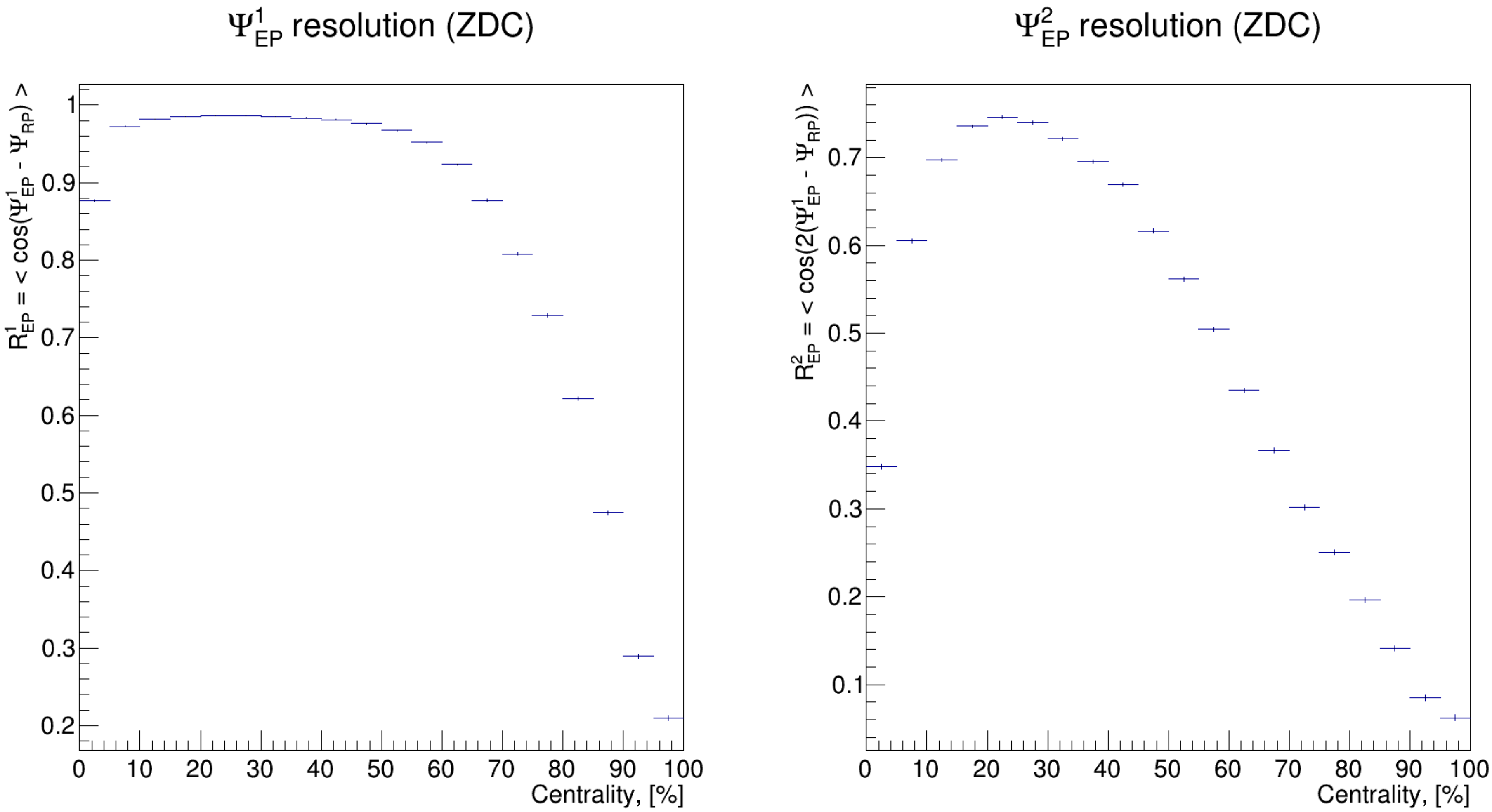
[1] A. M. Poskanzer , S. Voloshin Phys.Rev. C (1998) 58. pp. 1671–1678

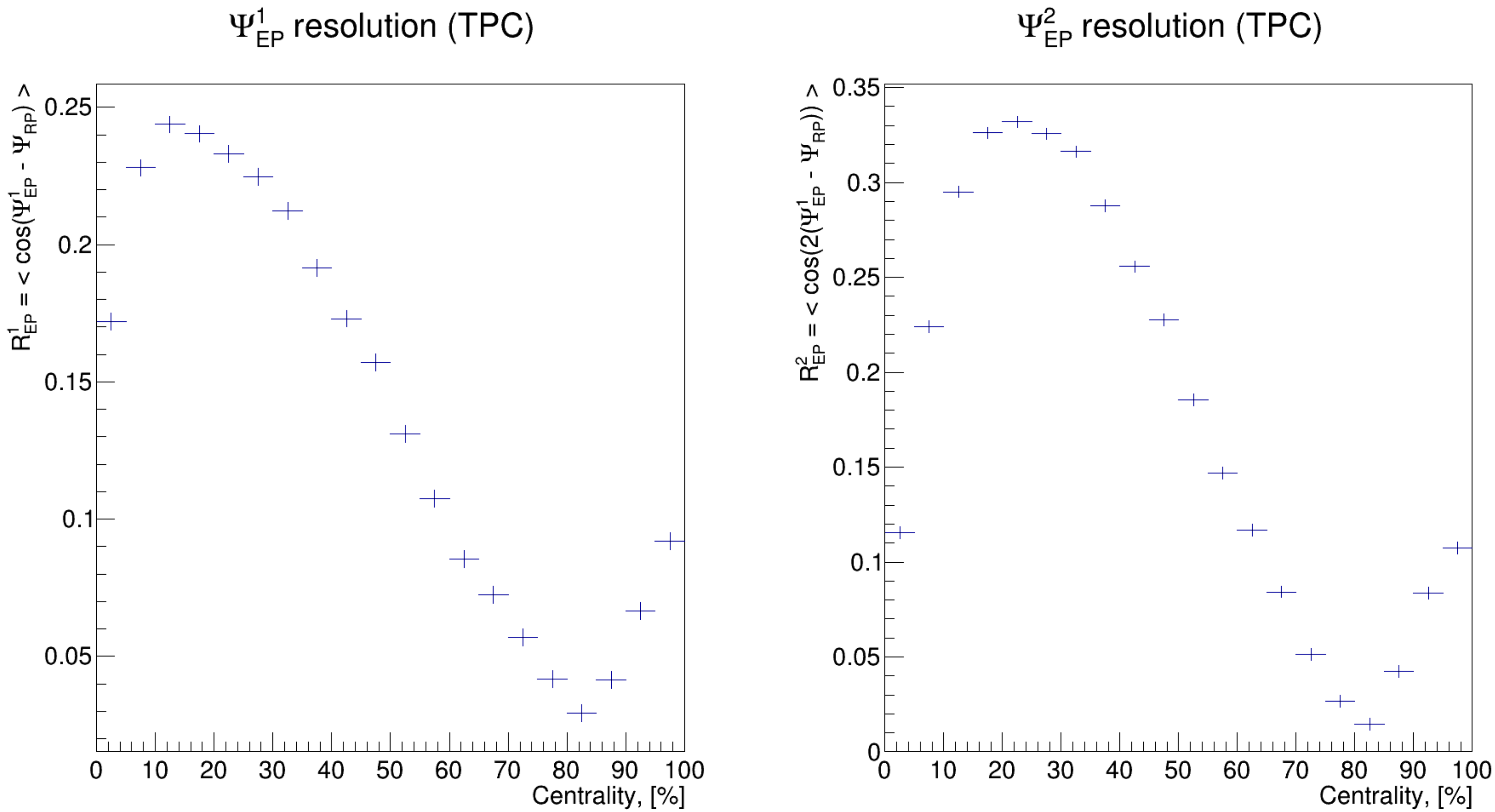
Event plane determination (ZDC)



- Centrality is calculated via TPC multiplicity
- Event Plane angle through FHCal
- Dependence of resolution R^n on TPC centrality is shown as TProfile

→ Need to estimate experimental resolution (using sub-event resolution)

Event plane determination (TPC)



- Centrality is calculated via TPC multiplicity
- Event Plane angle through TPC
- Dependence of resolution R^n on TPC centrality is shown as TProfile

⟶ Need to estimate experimental resolution (using sub-event resolution)

Conclusions

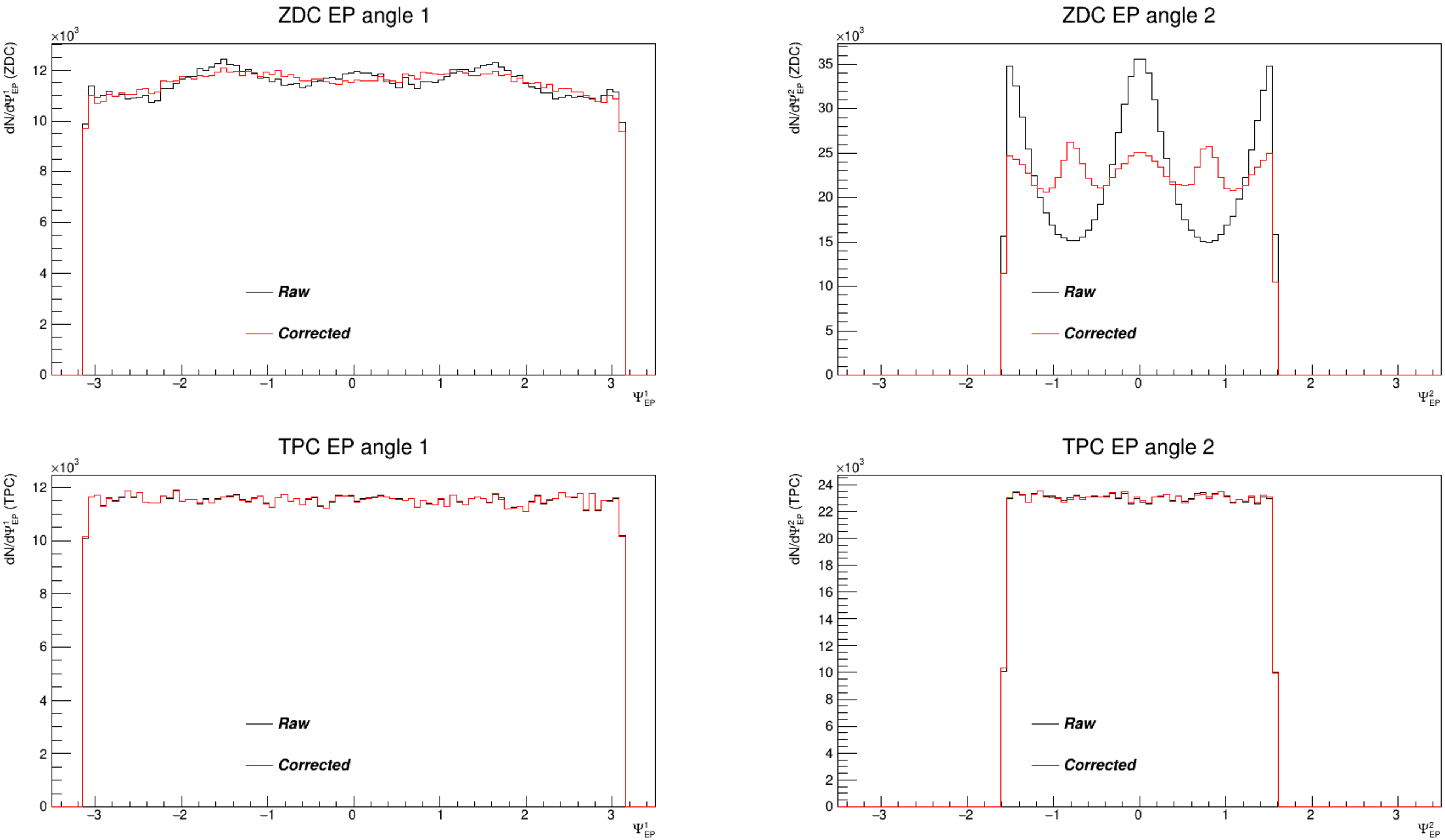
- Feasibility test of inclusive polarization extraction within the framework of the MPD experiment
  - Good sensitivity of the detector to inclusive Λ polarization
  - Reasonable extraction of Λ-hyperons via the weak decay
  - Upper limit on the value of inclusive Λ polarization
- Outlook
  - Study the technique in different regions of p_T (x)
  - Properly account for secondary Λ-hyperons
  - Estimate dilution effects due to rescattering in the QCD medium

Conclusions

- Study of global hyperon polarization extraction within the framework of the MPD experiment
  - Adapted available technique from the flow group (centrality calculation via TPC, event plane determination via TPC & FHCal)
  - Event plane resolution w.r.t. centrality from TPC
  - Added PID reconstruction for $\bar{\Lambda}$ (needs to checked)
- Outlook
  - Further tests on the centrality and EP determination
  - Corrections for the EP angles
  - Estimate of the experimental EP resolution (using sub-event EP)
  - Add centrality determination through FHCal (possibly combined FHCal + TPC multiplicity)
  - Choose the best method to avoid possible correlations with the analysis

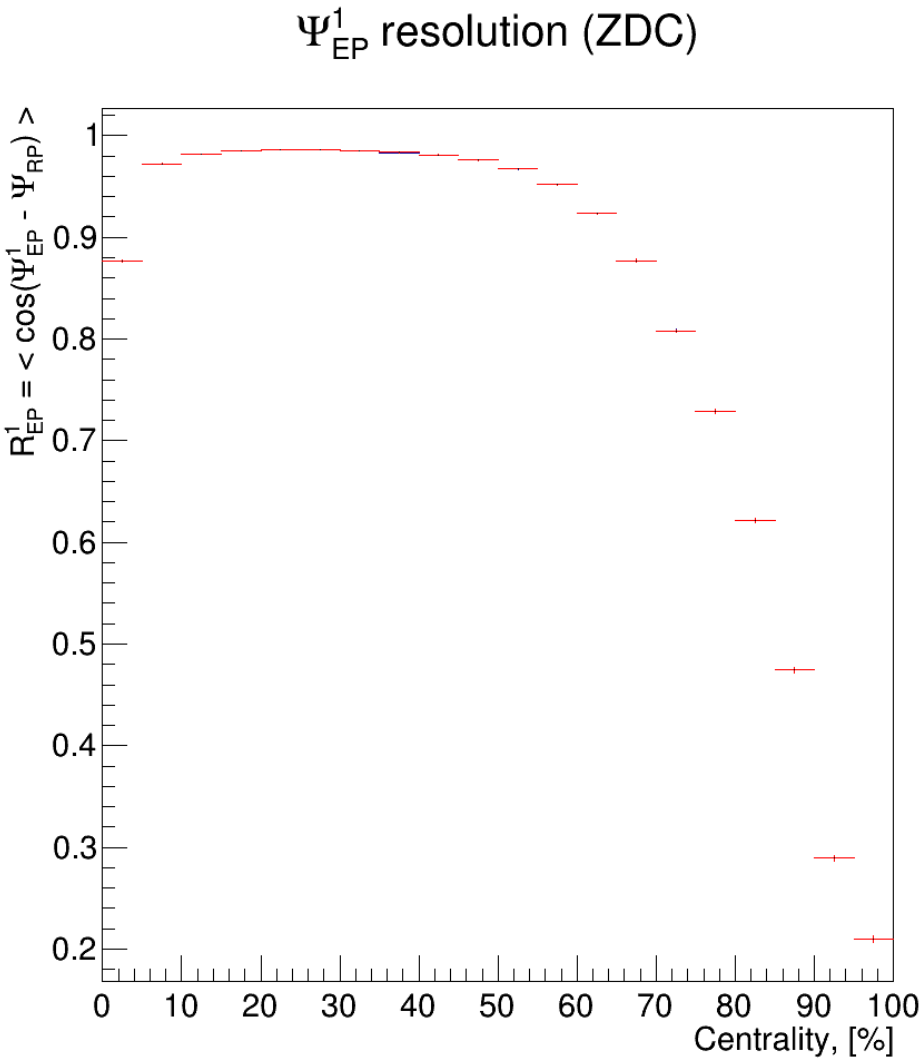
Thank you for your attention!

Back Up

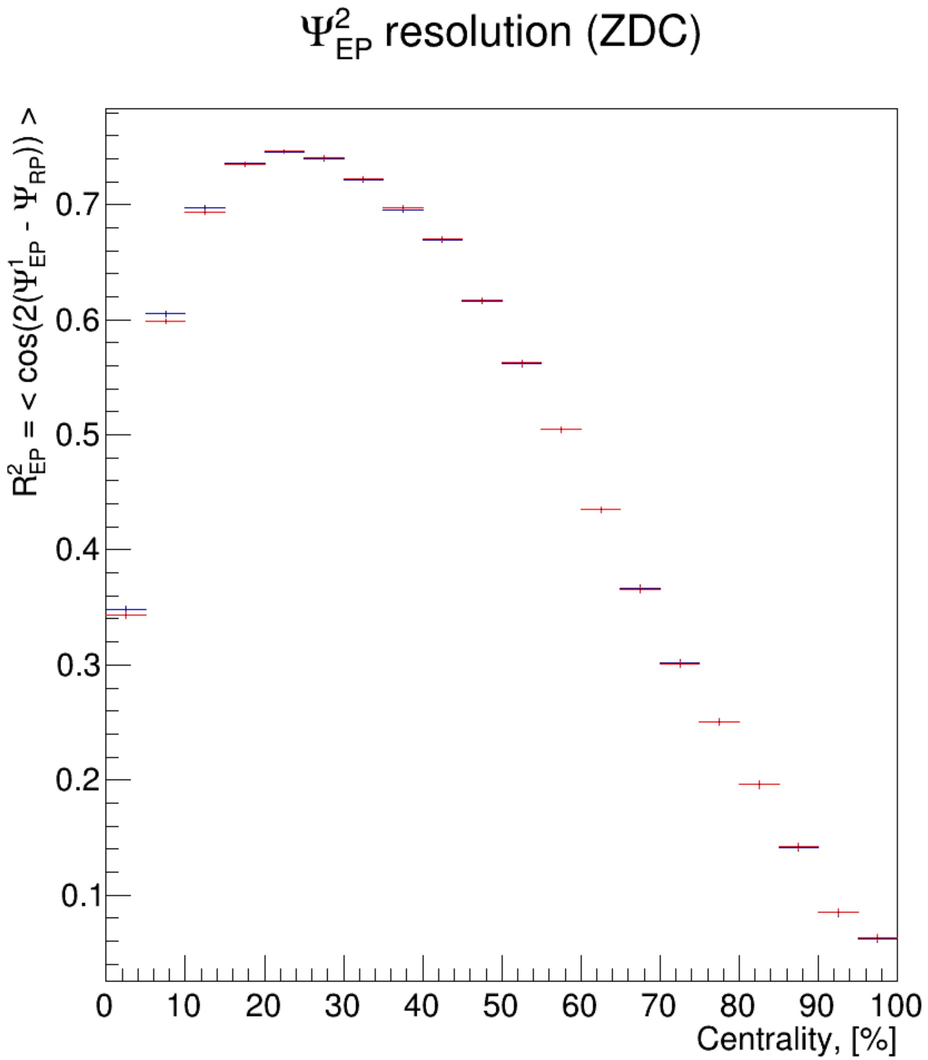


$$\Psi^* = \Psi + \Sigma_n \frac{2}{n}(-\langle \sin n\Psi \rangle \cos n\Psi + \langle \cos n\Psi \rangle \sin n\Psi)$$

Back Up

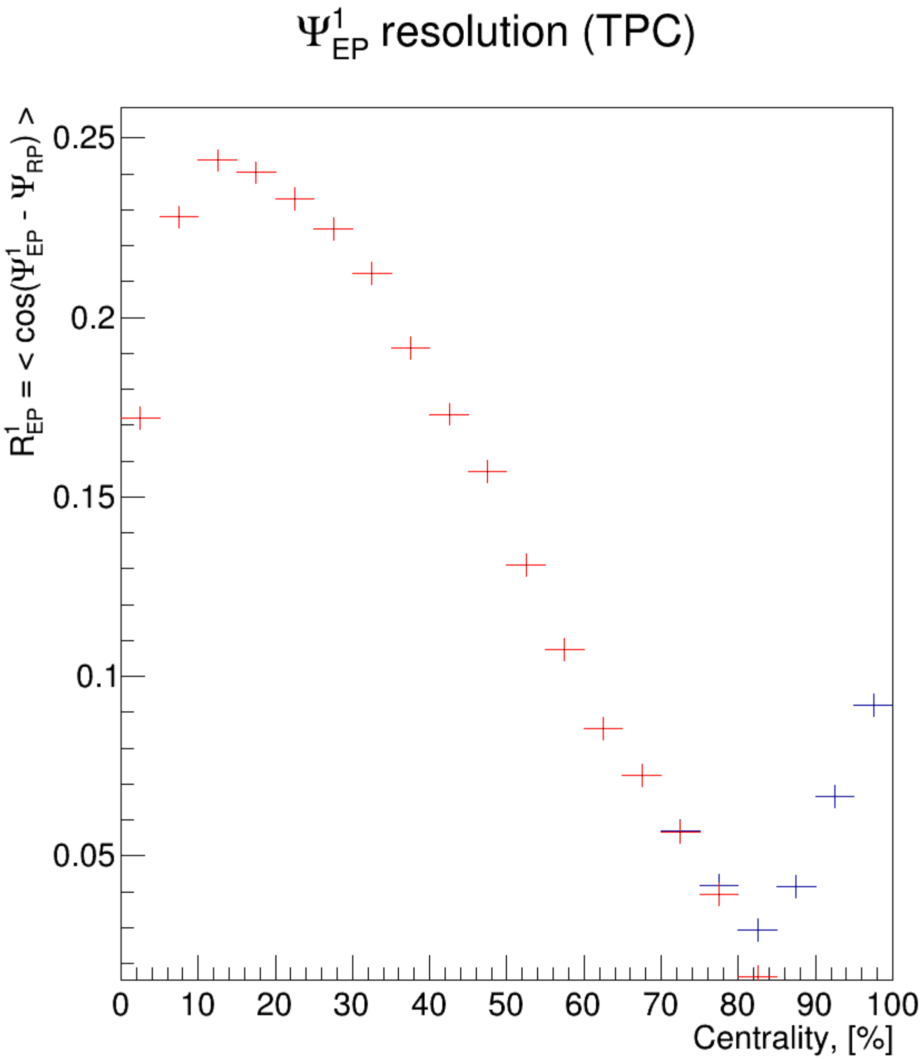


Ψ^1_{EP} resolution (ZDC)
$R^1_{EP} = < cos(\Psi^1_{EP} - \Psi_{RP}) >$
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100
Centrality, [%]

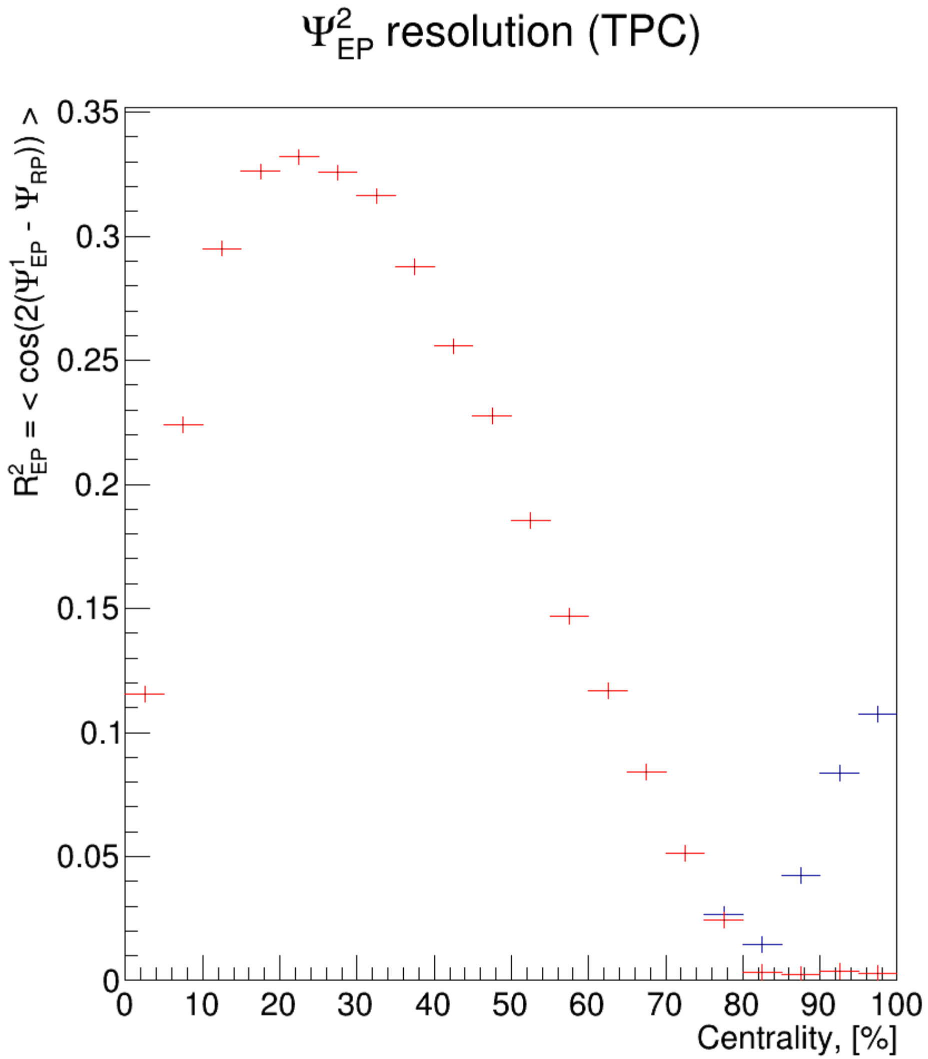


Ψ^2_{EP} resolution (ZDC)
$R^2_{EP} = < cos(2(\Psi^1_{EP} - \Psi_{RP})) >$
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
10
20
30
40
50
60
70
80
90
100
Centrality, [%]

Back Up

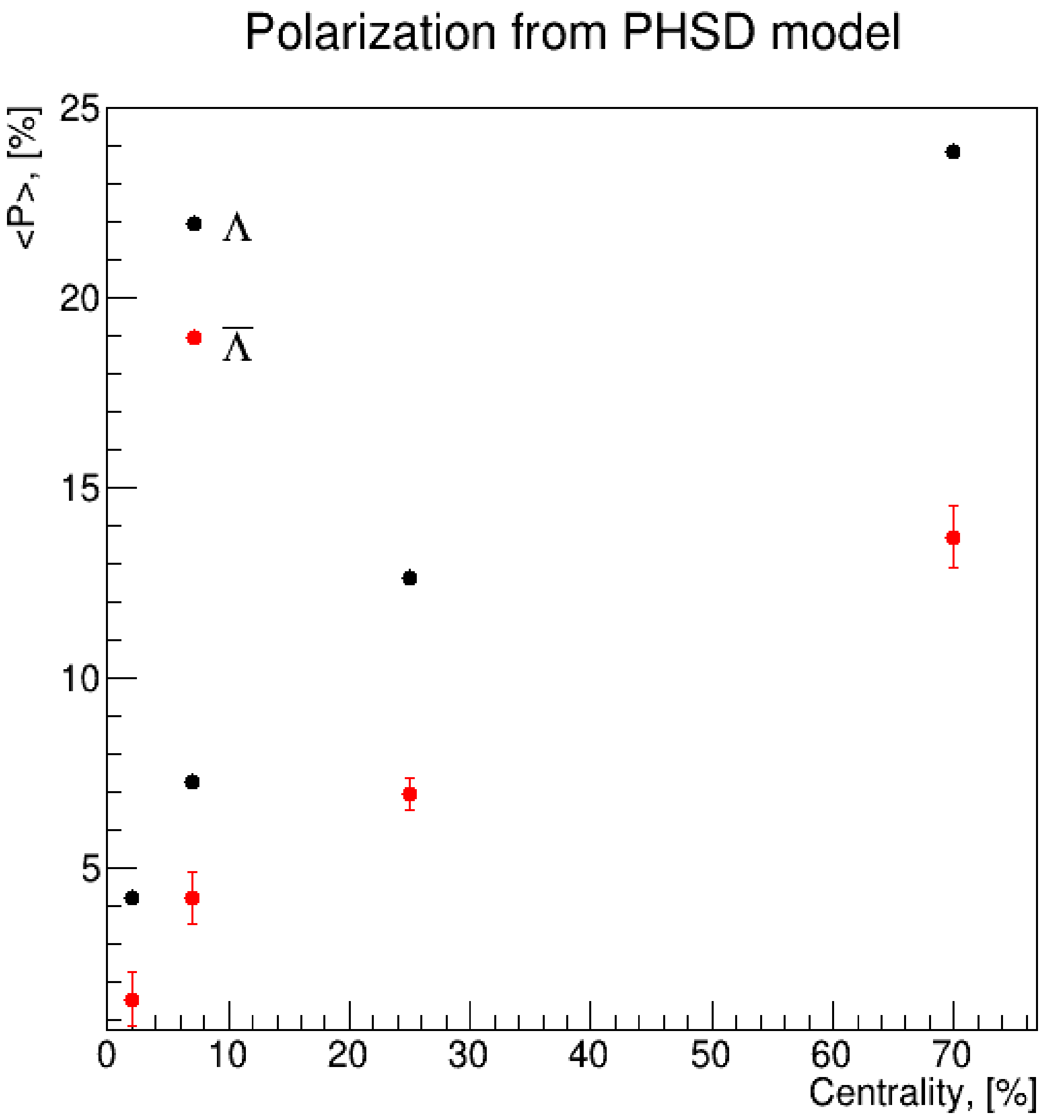


Ψ^1_{EP} resolution (TPC)
$R^1_{EP} = < cos(\Psi^1_{EP} - \Psi_{RP}) >$
0.25
0.2
0.15
0.1
0.05
0
10
20
30
40
50
60
70
80
90
100
Centrality, [%]



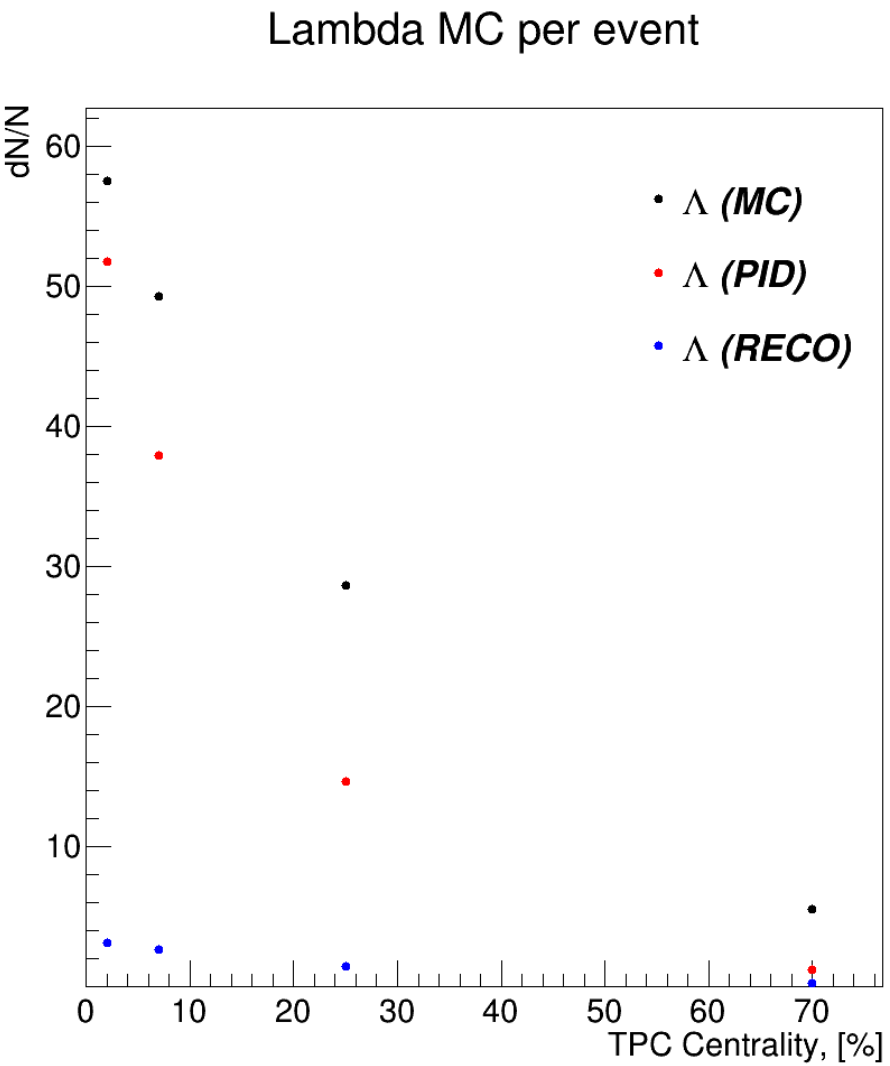
Ψ^2_{EP} resolution (TPC)
$R^2_{EP} = < cos(2(\Psi^1_{EP} - \Psi_{RP})) >$
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
70
80
90
100
Centrality, [%]

Back Up

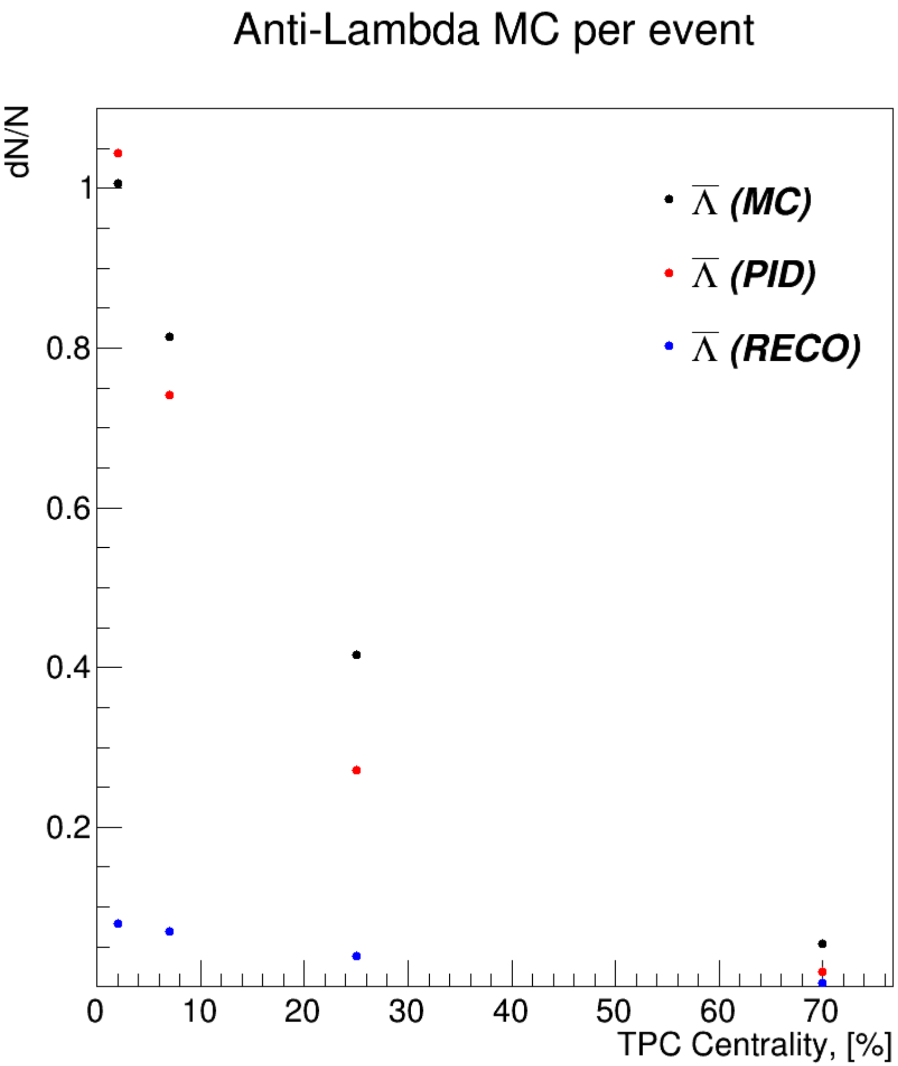


- Mean value of the P_y component of the polarization vector from the PHSD model (MpdMCTrack)
- Should correspond to P_J (P_J = $-P_y$)
- Uncorrrected TPC centrality was used
- Seems to have correct dependence
- Need to finish the full-scale analysis for the final conclusion

Back Up

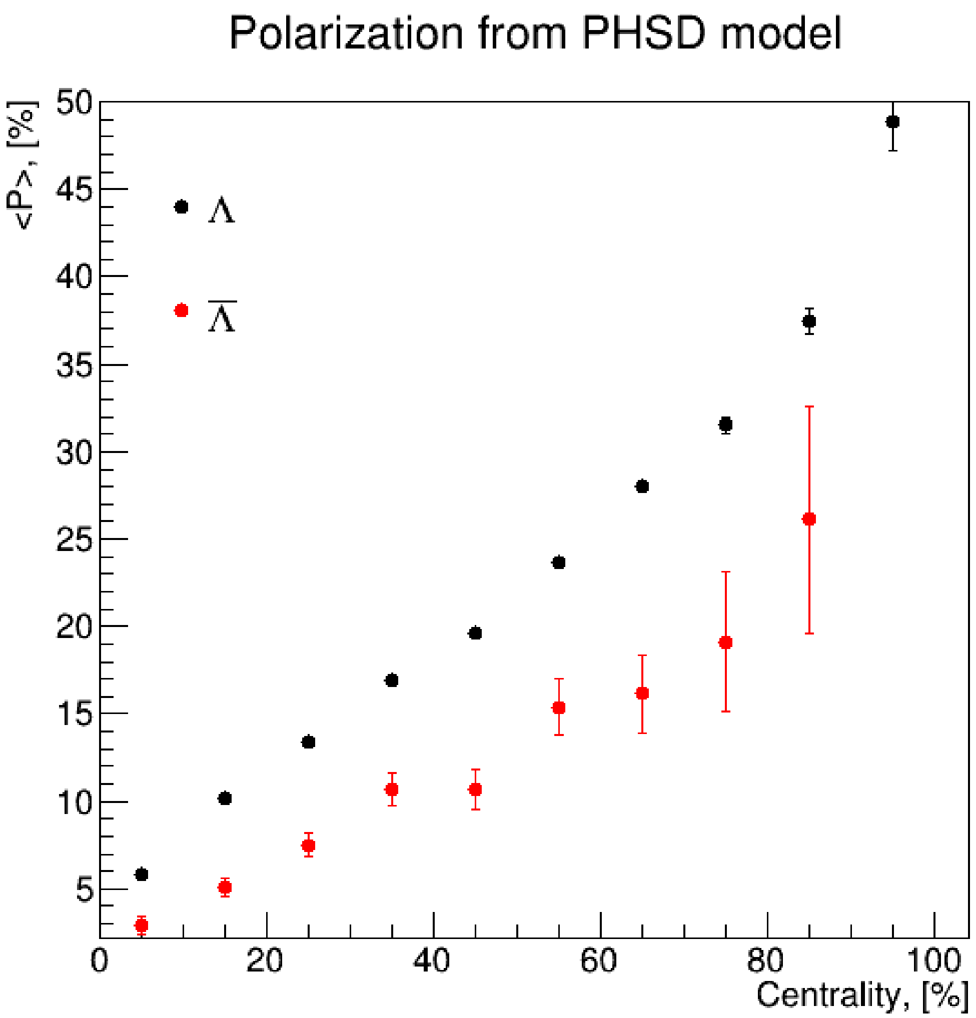


Lambda MC per event
dN/N
60
50
40
30
20
10
0
10
20
30
40
50
60
70
TPC Centrality, [%]
Λ (MC)
Λ (PID)
Λ (RECO)



Anti-Lambda MC per event
dN/N
1
0.8
0.6
0.4
0.2
0
10
20
30
40
50
60
70
TPC Centrality, [%]
$\overline{\Lambda}$ (MC)
$\overline{\Lambda}$ (PID)
$\overline{\Lambda}$ (RECO)

Back Up



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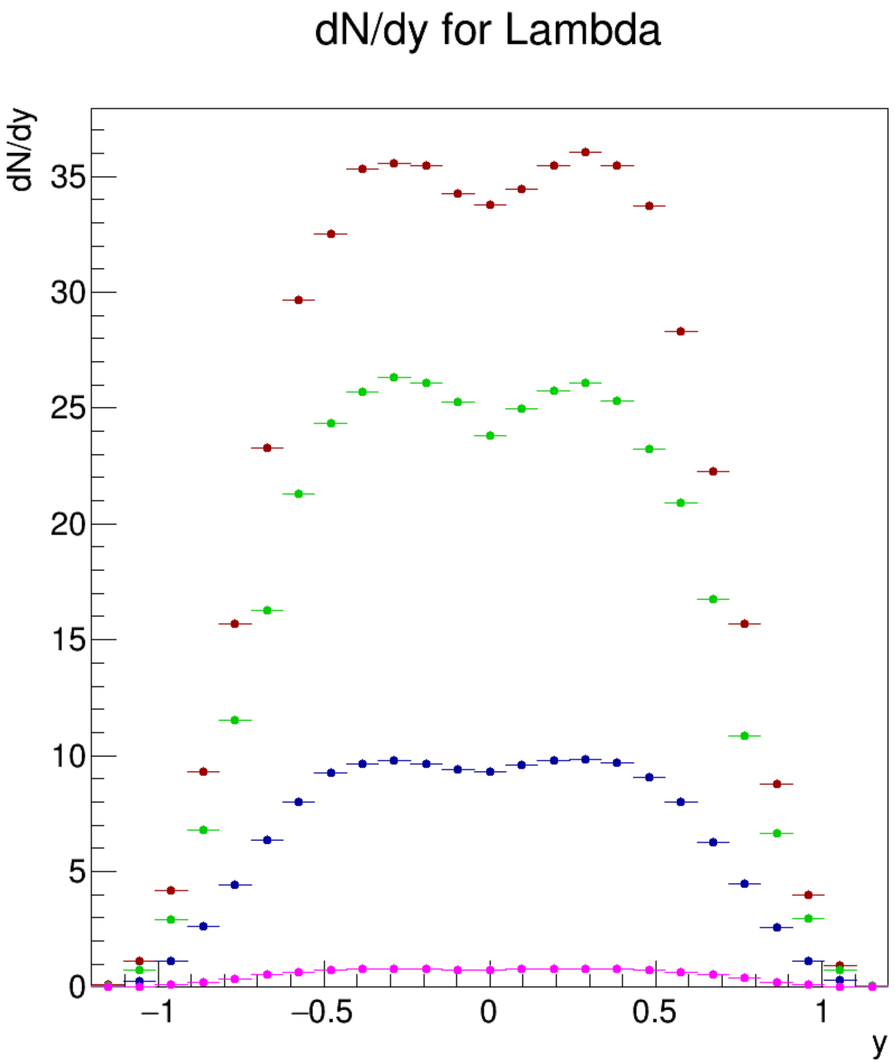

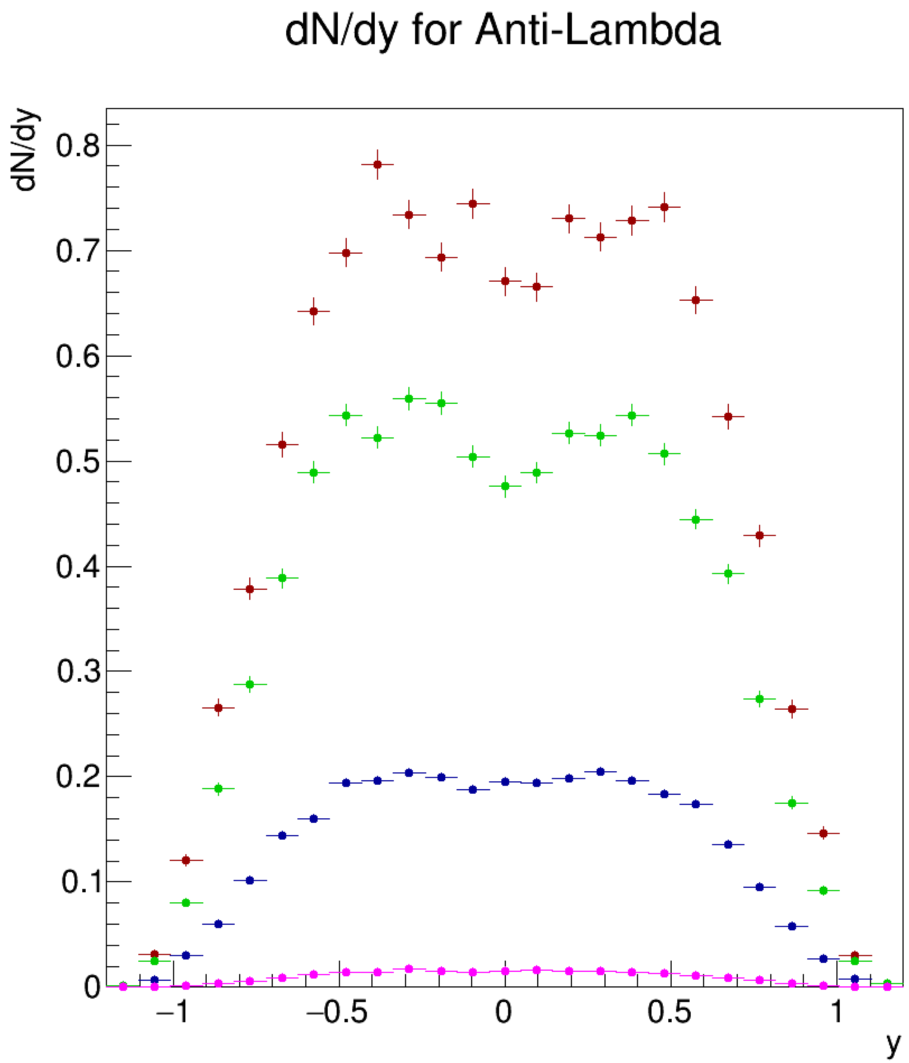

(preliminary)

Analysis method

MC simulation
DCM-QGSM

Detector simulation
GEANT 3

Event reconstruction
MPD

$\Lambda(\bar{\Lambda})$ reconstruction
Analysis

- Realistic Monte-Carlo simulation using DCM-QGSM generator (inclusive Λ polarization)

This is currently done via P_x component of the polar. vector!

- Simulation of polarization effects in the detector via GEANT 3 (anisotropic decay of Λ hyperons) — can be switched on/off to study the effect

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = 1 + \alpha_\Lambda P_\Lambda \cos\theta^*$$

- Event reconstruction using realistic PID within mpdroot framework

- $\Lambda(\bar{\Lambda})$ reconstruction through the weak decay channel $\Lambda \to p + \pi^-$