Study of global hyperon polarization at MPD

Elizaveta Nazarova[1] et al.

«Vorticity and Polarization in Heavy-Ion Collisions»

VIII-th Collaboration Meeting of the MPD Experiment at the NICA Facility

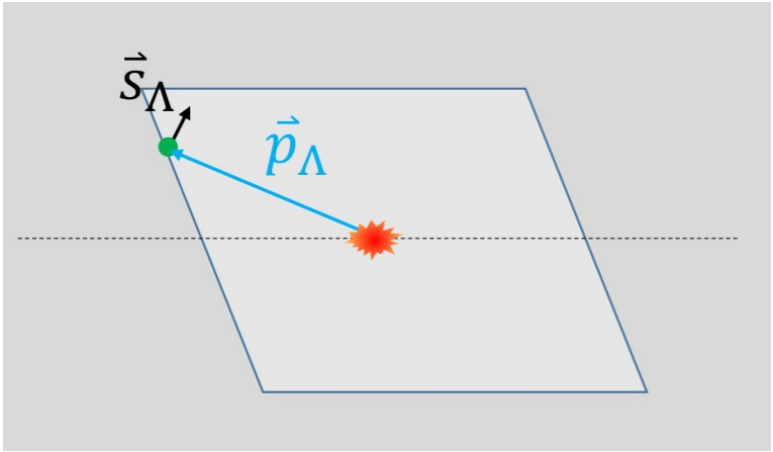
14.10.2021

[1] Joint Institute of Nuclear Research, Dubna, Russia

Outline

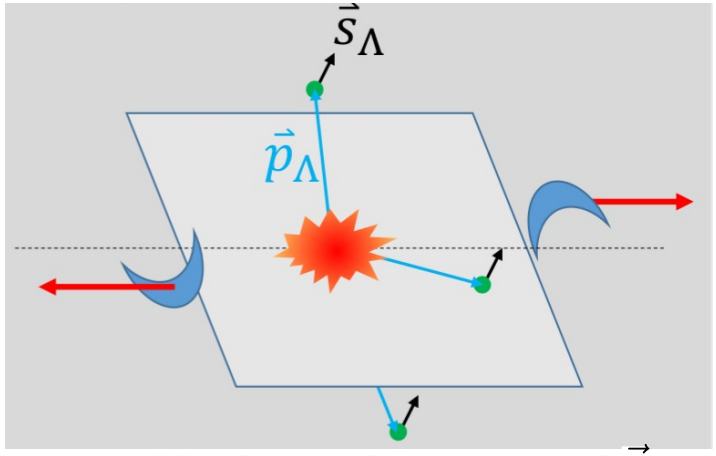
- Introduction
- Motivation
- Analysis technique
  - Simulation
  - Centrality determination
  - Event plane determination
  - Lambda reconstruction
  - Global polarization measurement
- Results
- Conclusions

- Transverse (inclusive) polarization*
  - 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
  - w.r.t reaction plane
  - Emerges in HIC due to the system angular momentum
  - Allows to study characteristics of QCD medium



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

* studied in Phys.Part.Nucl.Lett. 18 (2021) 4, 429-438

Global hyperon polarization

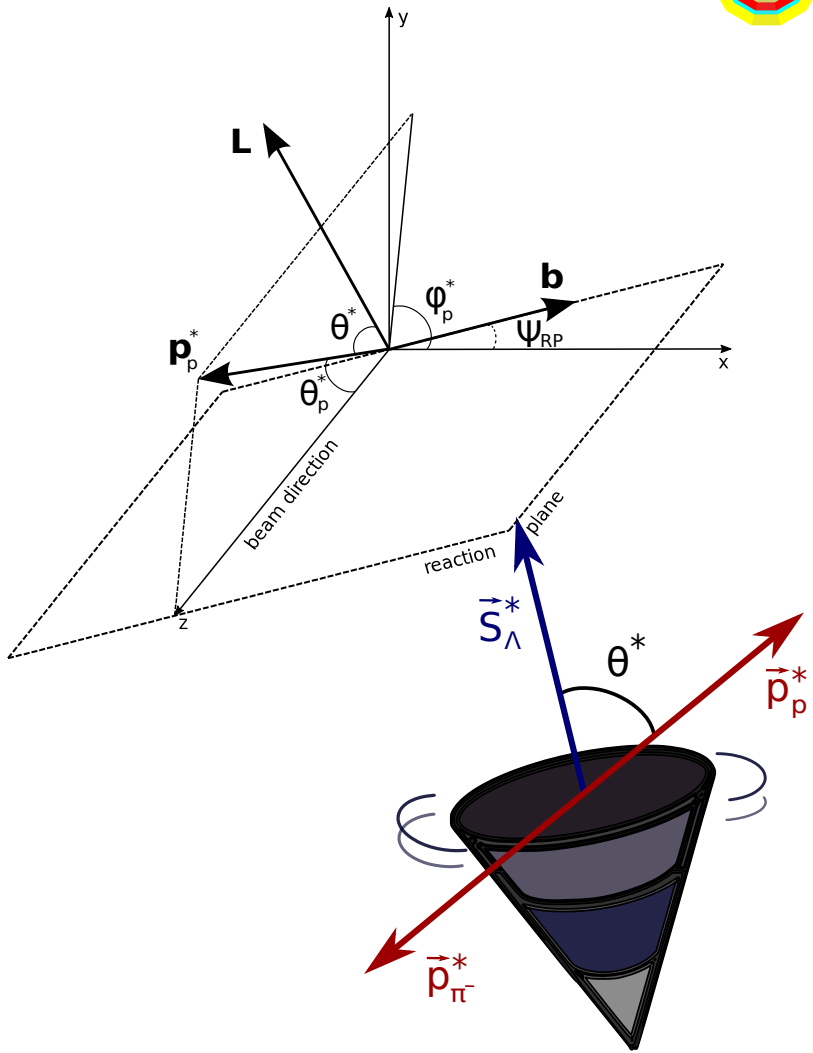
- w.r.t. reaction plane
- Emerges in HIC due to the system angular momentum[1,2]
- Sensitive to parity-odd characteristics of QCD medium and QCD anomalous transport
- Measured through the weak decay:

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

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = 1 + \alpha_{\mathrm{H}} |\vec{P}_{\mathrm{H}}| \cos\theta^*$$

$$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} \simeq 0.732$$

- * — denotes hyperon rest frame (e.g. Λ)



[1] Z. Liang, X. Wang, PRL 94, 102301 (2005)
[2] L. Adamczyk et al., Nature 548, 62 (2017)

Global hyperon polarization

- θ^* — angle between the decay particle and polarization direction

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

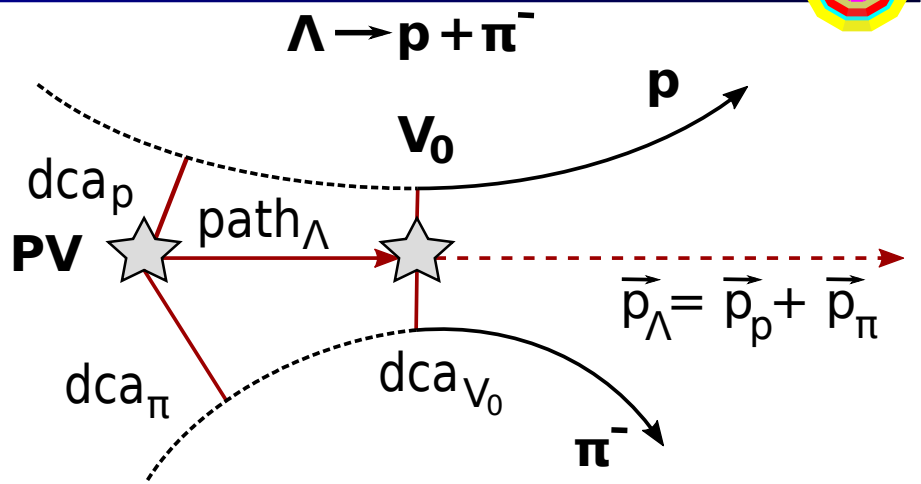
- φ^* — azimuthal angle of decay particle

→ Determine centrality

→ Determine event plane $(\Psi^1_{\mathrm{EP}}, R^1_{\mathrm{EP}})$

→ Reconstruct Lambda

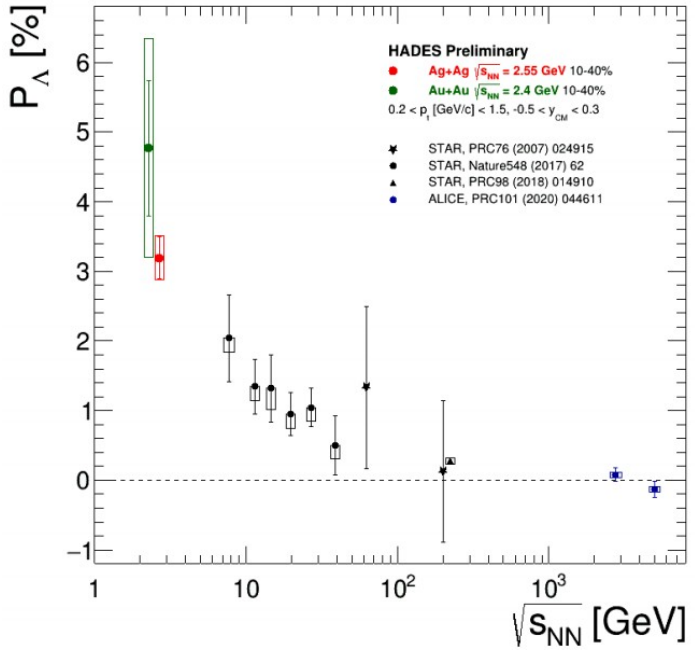
→ Global polarization



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

Motivation

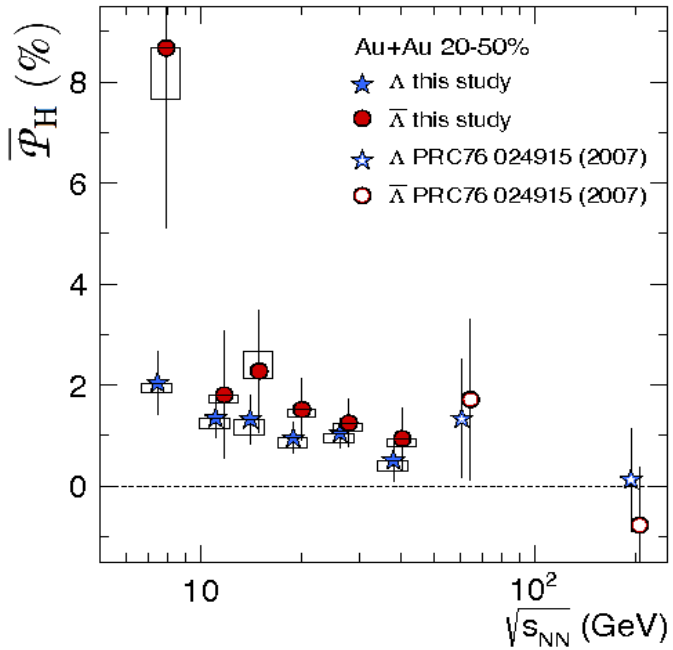
- Predicted[1] and observed[2,3] global polarization signals rise as the collision energy is reduced:
  - NICA energy range will provide new insight
- New value of decay asymmetry α_Λ found[4] (BES-III)
- $\Lambda(\bar{\Lambda})$ - splitting of global polarization (could be explained by the Core-Corona model, see talk by I. Maldonado)
- Comparison of models, detailed study of energy and kinematical dependences, improve precision
- Probing the vortical structure with new observables[5,6]



[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 2021
[4] Ablikim M, et al., Nature Phys. 15:631 (2019)
[5] O. Teryaev and R. Usubov, Phys. Rev. C 92, 014906 (2015)
[6] M. A. Lisa et al., Phys. Rev. C 104, 011901 (2021)

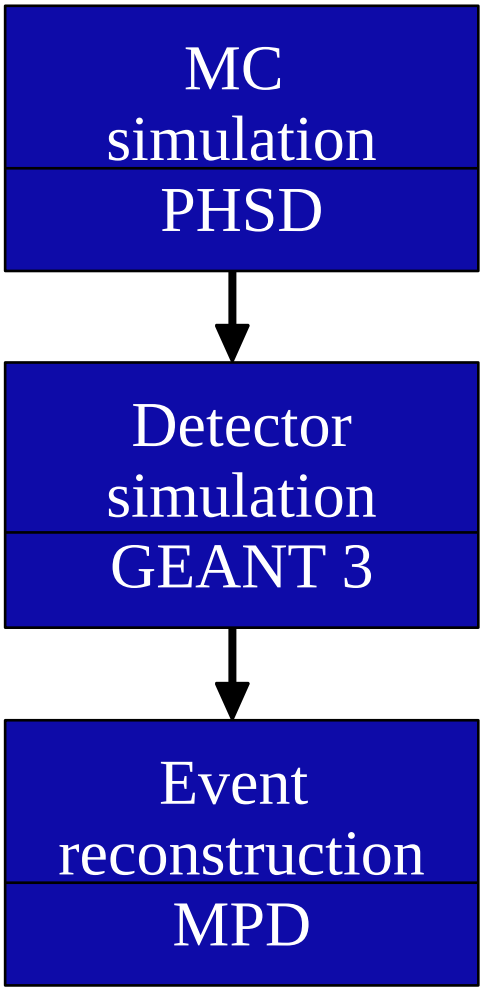
Motivation

- Predicted[1] and observed[2,3] global polarization signals rise as the collision energy is reduced:
  - NICA energy range will provide new insight
- New value of decay asymmetry α_Λ found[4] (BES-III)
- $\Lambda(\bar{\Lambda})$ - splitting of global polarization (could be explained by the Core-Corona model, see talk by I. Maldonado)
- Comparison of models, detailed study of energy and kinematical dependences, improve precision
- Probing the vortical structure with new observables[5,6]



[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 2021
[4] Ablikim M, et al., Nature Phys. 15:631 (2019)
[5] O. Teryaev and R. Usubov, Phys. Rev. C 92, 014906 (2015)
[6] M. A. Lisa et al., Phys. Rev. C 104, 011901 (2021)

Analysis technique

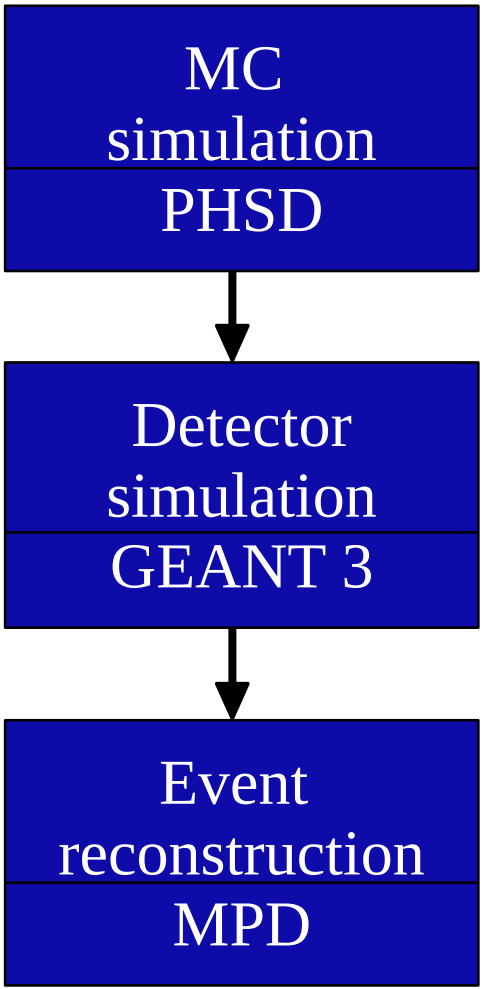


- MC simulation using PHSD generator[1]
  - Au-Au @ 7.7GeV, 1.4M MB events, b [0,16]fm
  - Global hyperon polarization
    - Thermodynamical (Becattini) approach[2]
- Dataset for comparison (UrQMD):
  - Au-Au @ 7.7GeV, 1.4M MB events (request 9), b [0,16]fm
  - No polarization in dataset (calculation of vorticity is required)

[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

Analysis technique



- Detector simulation
  - Transfer of hyperon polarization vector **P** = {P_x,P_y,P_z} from generator data (PHSD) to MCTracks
  - Accounts for non-unitary length of the vector (weight)
  - Polarization set to zero **P** = {0,0,0} if $P_n > 1$ (calculation of thermal vorticity is unreliable)
- Transfer of polarization during hyperon decays[1] (feed-down)
  - $\mathbf{S}^*_D = C\mathbf{S}^*_P$
  - D — daughter, P — parent, C — coefficient[2]
- Anisotropic decay of Λ hyperons (can be turned on/off)
  - $\frac{dN}{d\cos\theta^*} = 1 + \alpha_\Lambda |\vec{P}_\Lambda| \cos\theta^*$ (recall)

[1] $\Xi^+(\Xi^-)$, Ξ^0, Σ^0 decays ($C_{\Xi^-} = 0.927$, $C_\Xi = 0.9$, $C_\Sigma = -1/3$)

[2] F. Becattini et al., Phys.Rev.C 95 (2017) 5, 054902

Analysis technique

MC simulation
PHSD

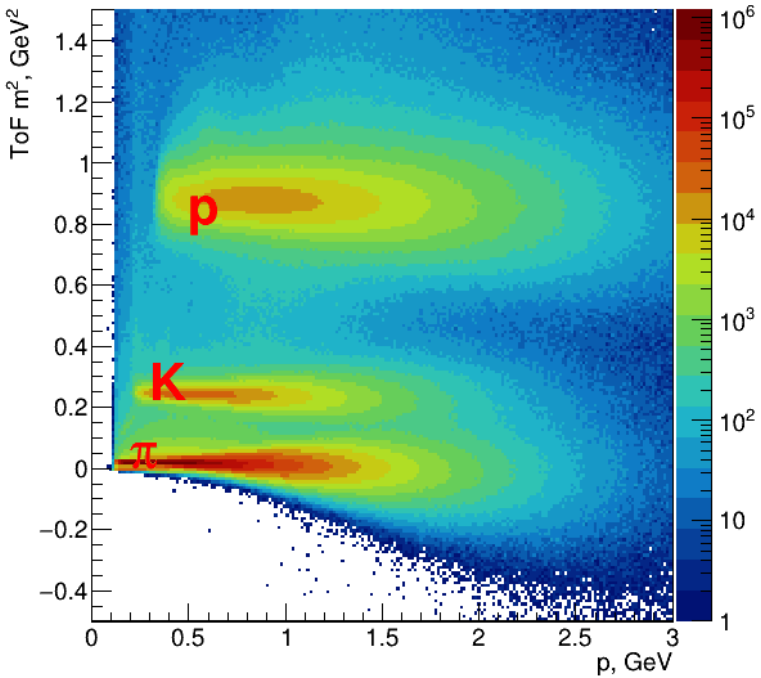
↓

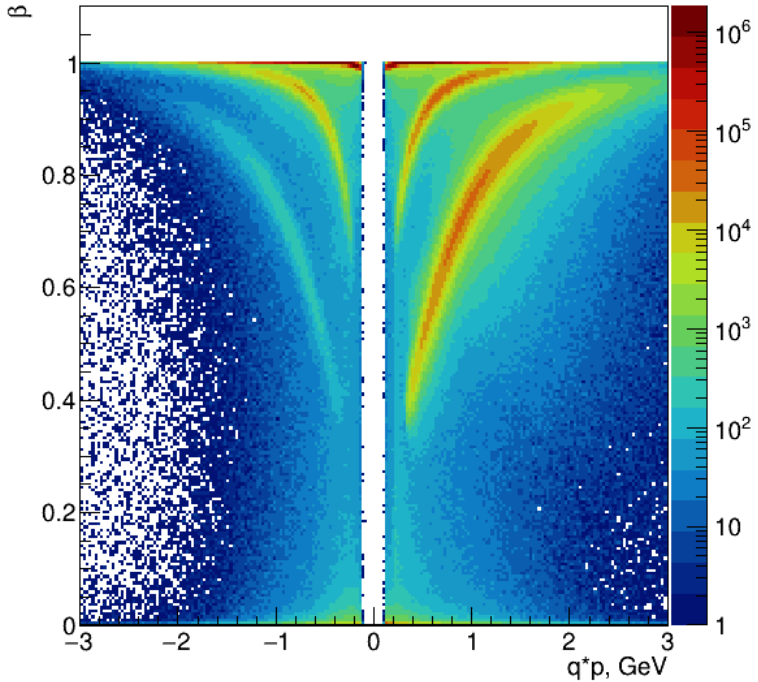
Detector simulation
GEANT 3

↓

Event reconstruction
MPD

- Event reconstruction
  - Centrality and Event Plane determination
  - Realistic PID
  - Reconstruction of Λ hyperons via their weak decay

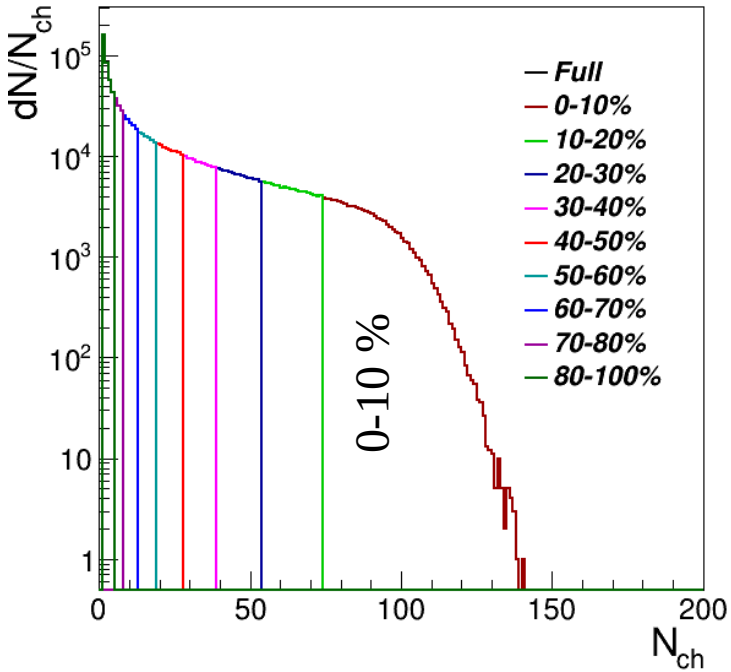


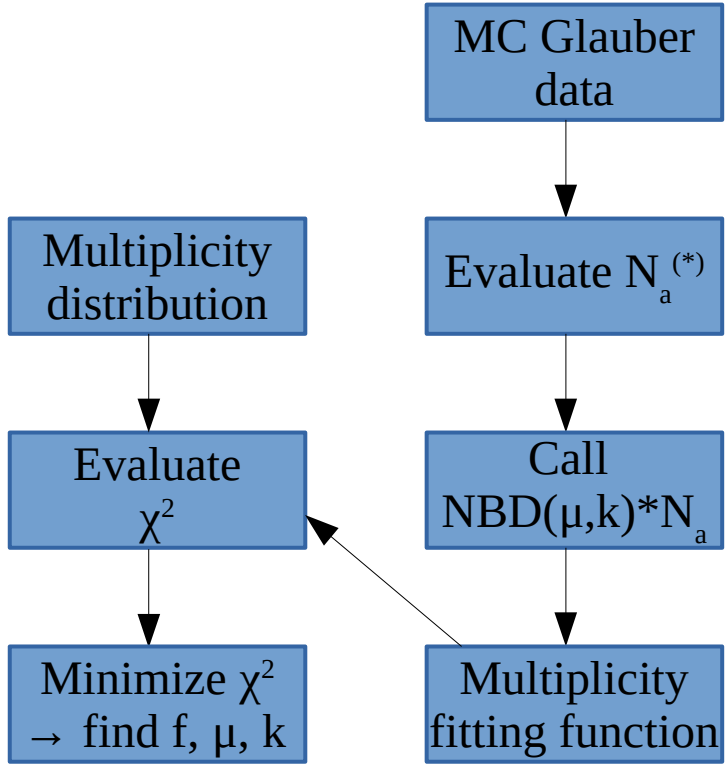


Centrality determination

- MC-Glauber based centrality framework[1]

- Selection criteria:
  - 500k events
  - $|\eta| < 0.5$
  - $p_T > 0.15$ GeV
  - $N_{hits} > 16$
  - $|DCA| < 0.5$ cm (optional)
  - 10%-centrality bins

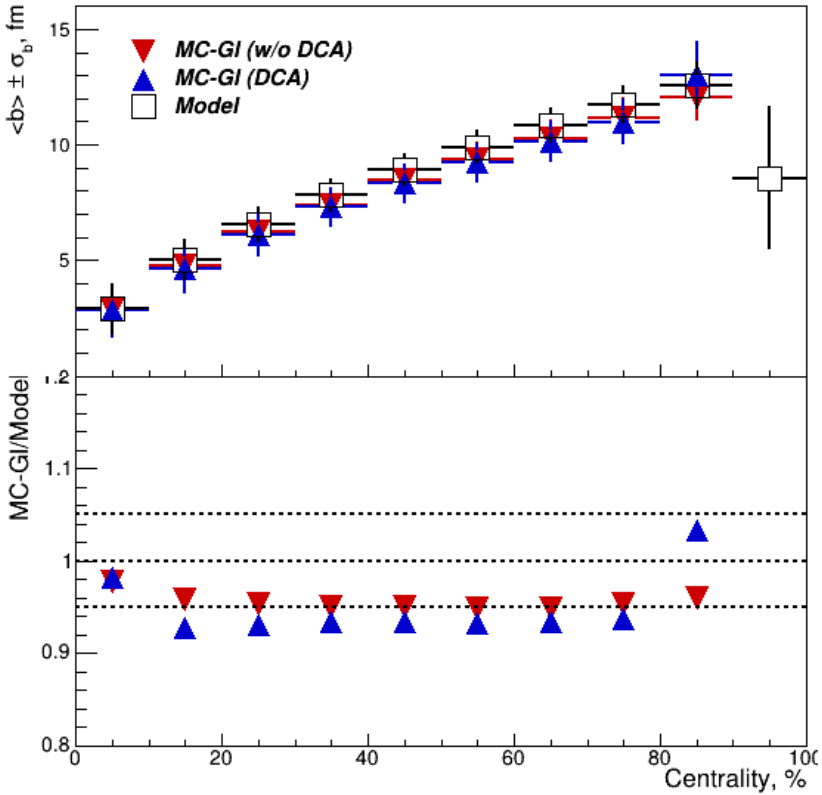




[1] P. Parfenov et al, NRNU MEPhI for the MPD collaboration (https://github.com/FlowNICA/CentralityFramework)

$$^{(*)}N_a = fN_{\text{part}} + (1-f)N_{coll}$$

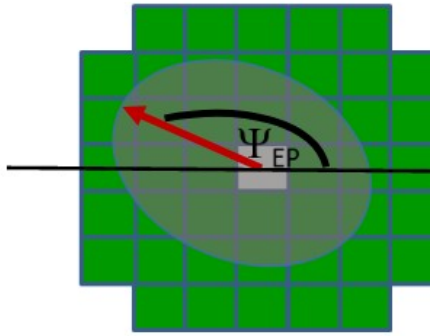
Centrality determination



- Last interval (90-100%) not determined correctly
  - Combined into 80-100%
  - 4 intervals of centrality chosen for analysis (0-10%, 10-20%, 20-50%, 50-100%) for comparison
- ~300k events discarded due to zero multiplicity in TPC
- Agreement within ~5% for impact parameter
  - Better agreement w/o DCA cut

Event plane determination

- Event plane angle can be measured as:
  - $\Psi^n_{\mathrm{EP}} = \frac{1}{n}\arctan\frac{Q_y}{Q_x}$
  - $Q_y = \Sigma_i \mathrm{w}_i \sin(n\phi_i)$
  - $Q_x = \Sigma_i \mathrm{w}_i \cos(n\phi_i)$



$\mathrm{w}_i = E_i/E_{\mathrm{total}}$ (FHCal)

$\mathrm{w}_i = p_{\mathrm{T}i}/p_{\mathrm{T}\mathrm{total}}$ (TPC)

- EP correction[1]: $\Psi^n_{\mathrm{cor}} = \Psi^n + \sum_n^4 \frac{2}{n}(-\langle \sin n\Psi^n \rangle \cos n\Psi^n + \langle \cos n\Psi^n \rangle \sin n\Psi^n)$

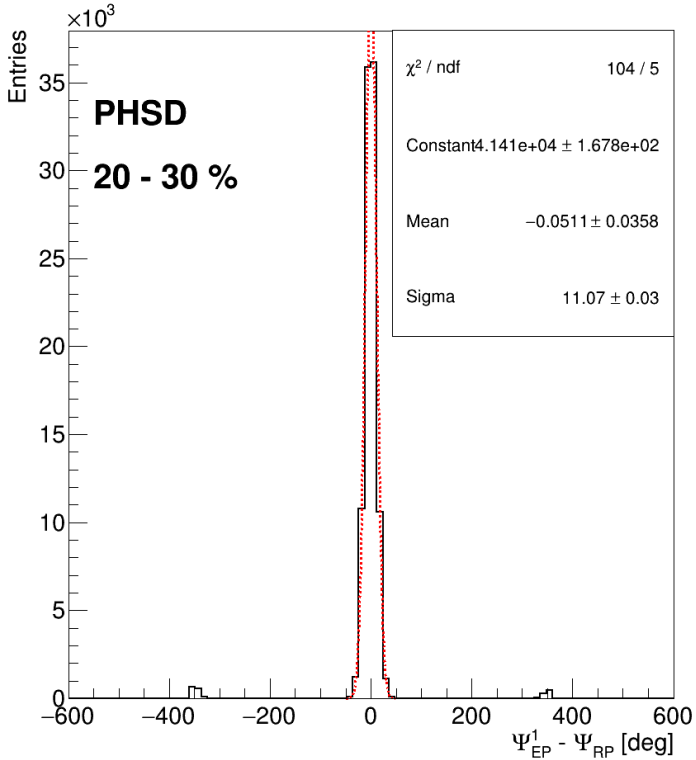
- Event plane resolution can be calculated as:
  - $R^k_{\mathrm{EP}} = \langle \cos(k(\Psi^n_{\mathrm{EP}} - \Psi_{\mathrm{RP}})) \rangle$ (w.r.t. reaction plane angle from the model)
  - $R^k_{\mathrm{EP}} = \sqrt{\left\langle \cos(k(\Psi^n_{\mathrm{EP,R}} - \Psi^n_{\mathrm{EP,L}})) \right\rangle}$ (sub-event resolution method[2])

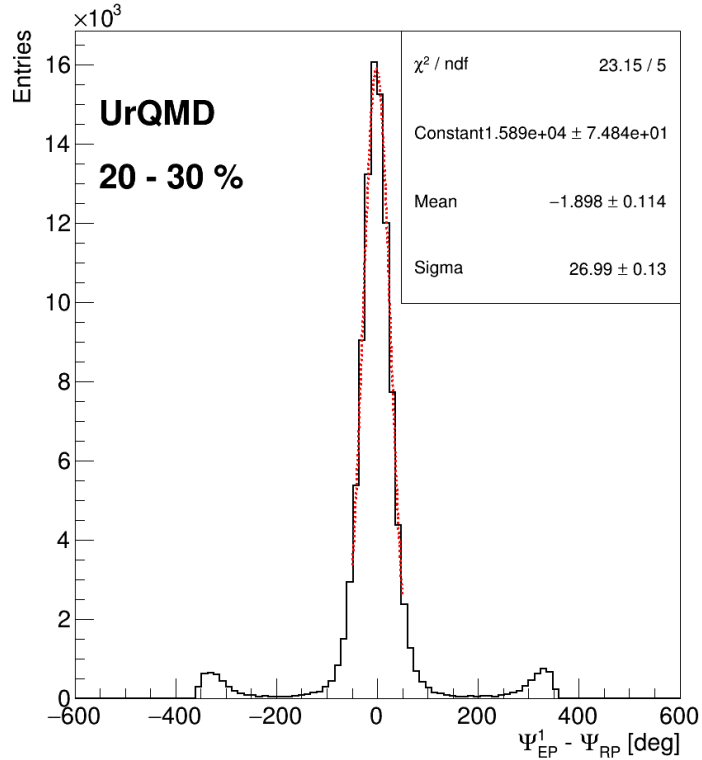
---

[1] J. Barrette et al. (E877 Collaboration) Phys. Rev. C56, 3254 (1997)

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

Event plane determination

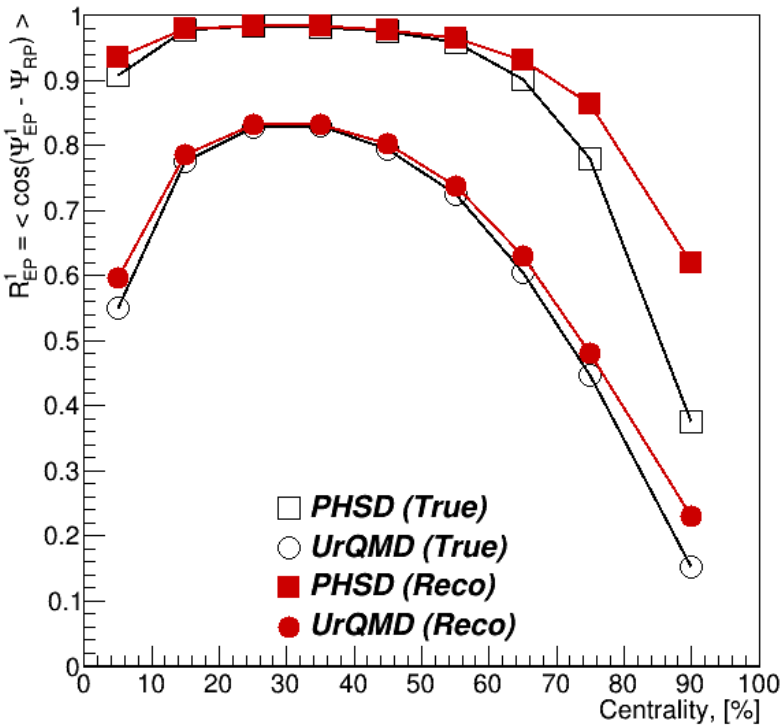


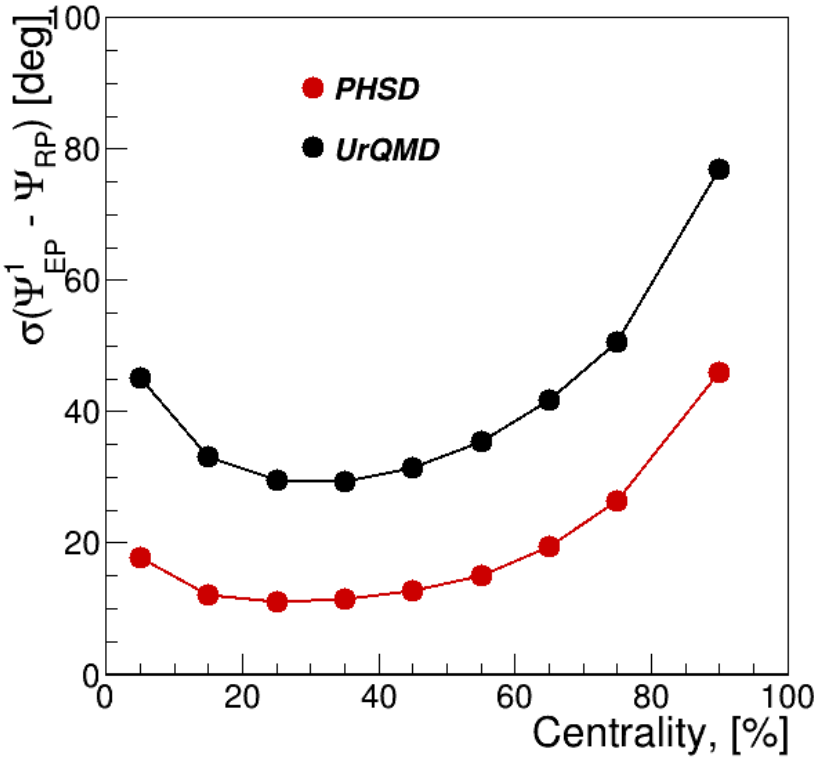


- Difference between EP and RP angles
  - Gaussian fit
  - Resolution of ~ 27 deg. for UrQMD and ~ 11 deg. for PHSD
  - Centered at 0

$$R^k_{\mathrm{EP}}(sub) = \frac{\sqrt{\pi}}{2\sqrt{2}}\chi \exp\left(-\chi^2/4\right)\left[I_{(k-1)/2}(\chi^2/4) + I_{(k+1)/2}(\chi^2/4)\right]$$

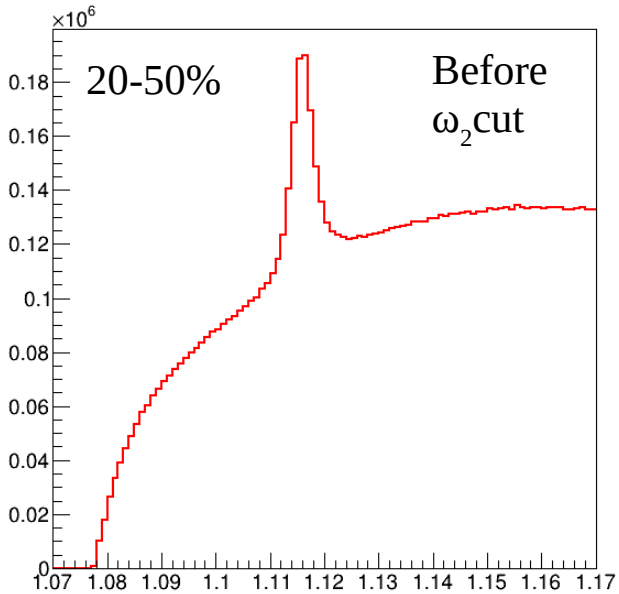
Event plane determination





- Event plane and resolution determined using FHCal
- PHSD gives higher resolution values w.r.t. URQMD model
- Effect not understood yet

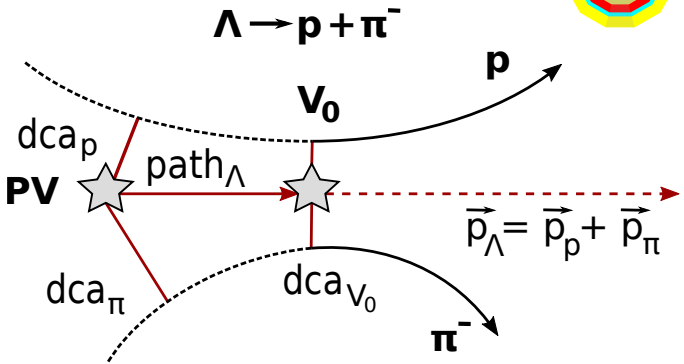
Lambda reconstruction

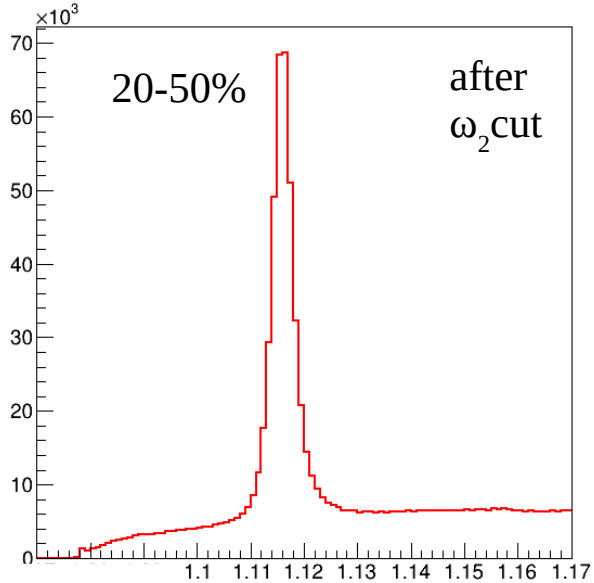


$$\omega_2 = \ln \frac{\sqrt{\chi_\pi^2 \chi_\mathrm{p}^2}}{\chi_\Lambda^2 + \chi_{\mathrm{V}_0}^2}$$

Fitting procedure:

- Global fit (Gauss + Legendre polynomials)
- Background fit in sidebands ($\pm\ 7\sigma$)
- Cut-off: $<\mathrm{M}_\Lambda> \pm\ 4\sigma$
- ω_2 cut based on maximum significance (for each centrality bin)

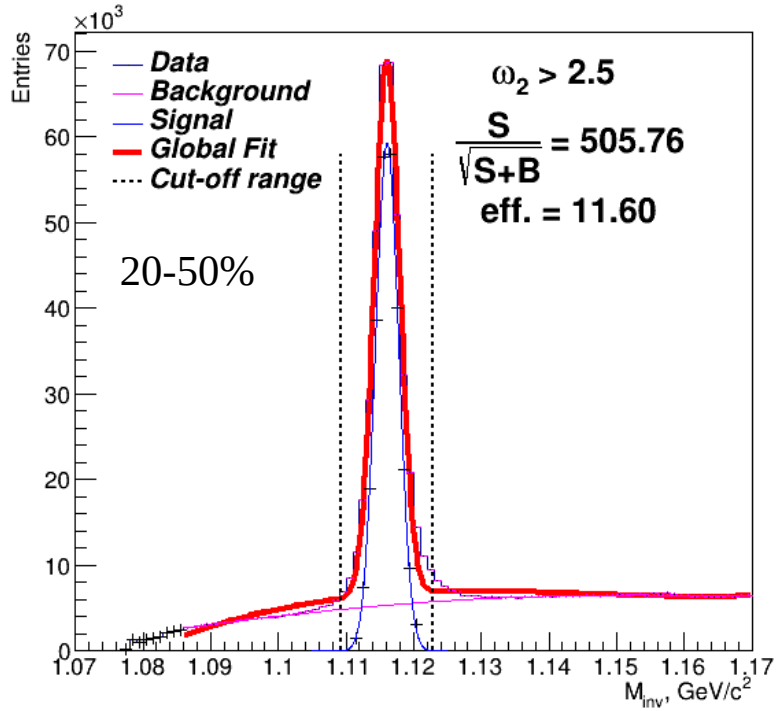




$$f(x) = p_0 \exp\left(\frac{(-0.5(x-p_1))^2}{p_2^2}\right) + p_3(L_0 + p_4 L_1 + p_5 L_2 + p_6 L_3 + p_7 L_4)$$

Global polarization reconstruction

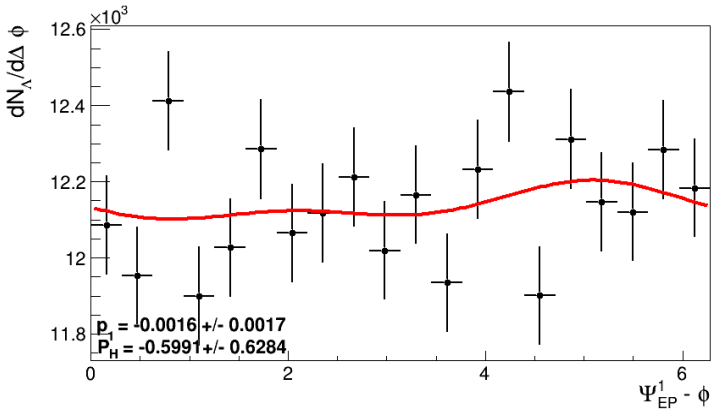
- Obtained invariant mass distribution in bins of $\Delta\phi_p^* = \Psi_{\mathrm{EP}}^1 - \phi_p^*$
  - Net amount of Λ in each bin
  - Distribution of $N_\Lambda(\Delta\phi_p^*)$
- Fit of the distribution[1] to get $\langle \sin(\Delta\phi_p^*) \rangle \rightarrow P_\Lambda$
  - «Event plane» method (p_n — fit parameters)
  - $P_\Lambda = \dfrac{8}{\pi\alpha_\Lambda}\dfrac{p_1}{R_{\mathrm{EP}}^1}$

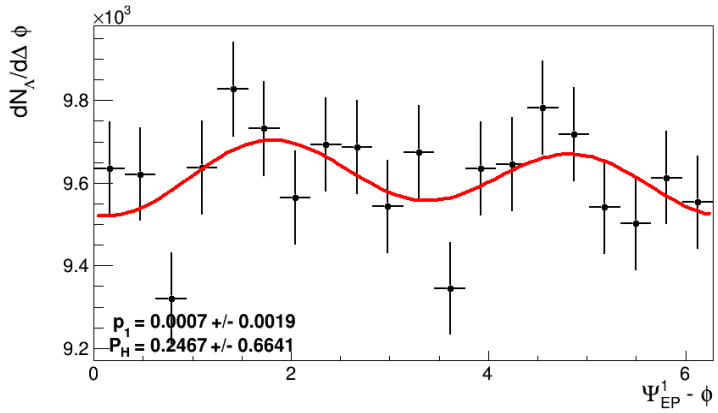


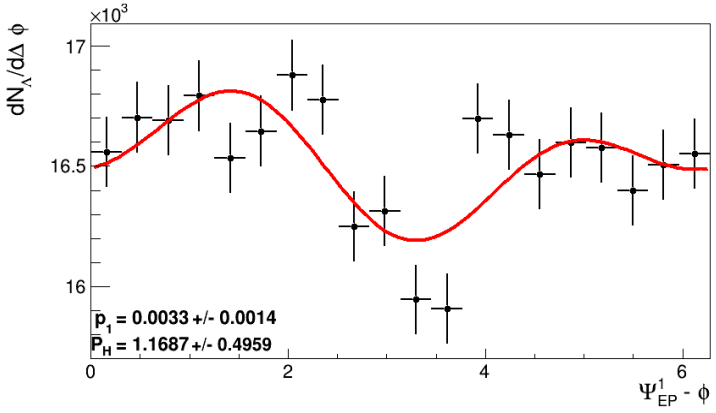
$$\overline{P}_{\Lambda/\bar{\Lambda}} = \frac{8}{\pi\alpha}\frac{1}{R_{\mathrm{EP}}^1}\left\langle \sin(\Psi_{\mathrm{EP}}^1 - \phi_p^*) \right\rangle$$ (recall)

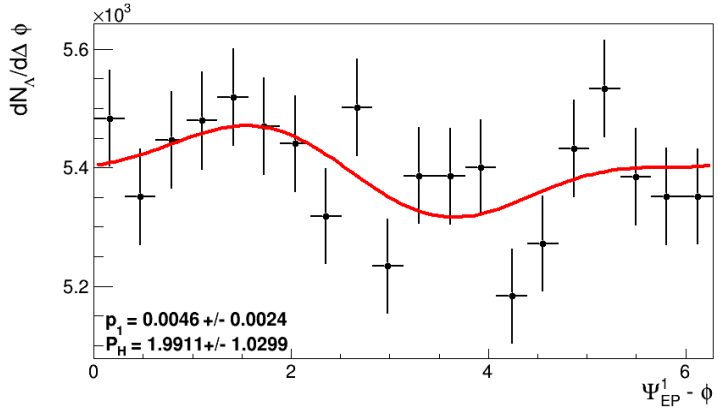
[1] $$\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi_p^*} = p_0(1 + 2p_1\sin(\Delta\phi_p^*) + 2p_2\cos(\Delta\phi_p^*) + 2p_3\sin(2\Delta\phi_p^*) + 2p_4\cos(2\Delta\phi_p^*) + \ldots)$$

Results









$$P_\Lambda = \frac{8}{\pi \alpha_\Lambda} \frac{p_1}{R^1_{\mathrm{EP}}}$$

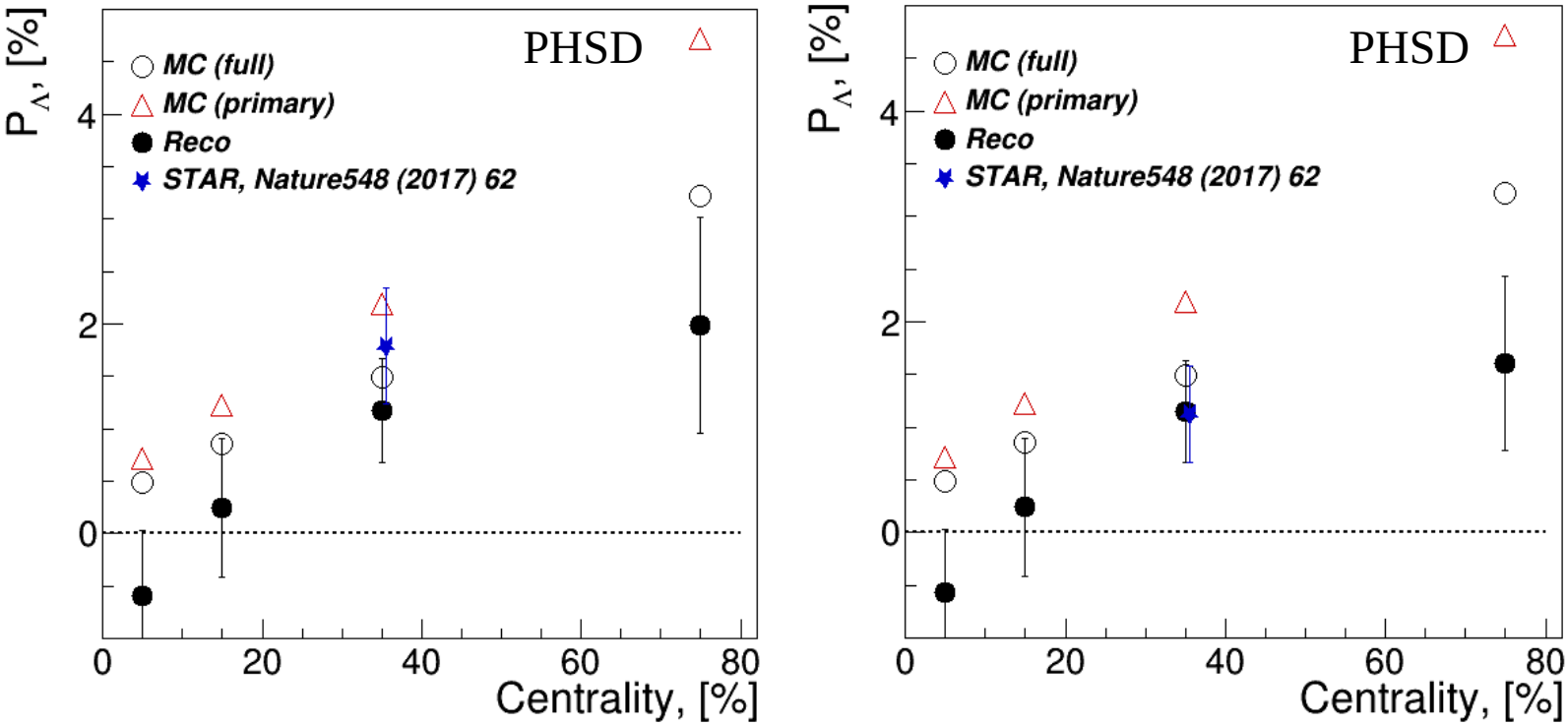
$$\alpha_\Lambda \simeq 0.732$$

	20-50%
N_Λ	3.3* 10^5
p_0	(1.6 +/- 3.3)* 10^4
$p_1/10^{-4}$	33.02+/- 14.01
$p_2/10^{-4}$	44.03 +/- 13.93
$p_3/10^{-4}$	-3.26 +/- 13.95
$p_4/10^{-4}$	-52.39 +/- 14.00

p_1 and p_2 are of the same magnitude order!

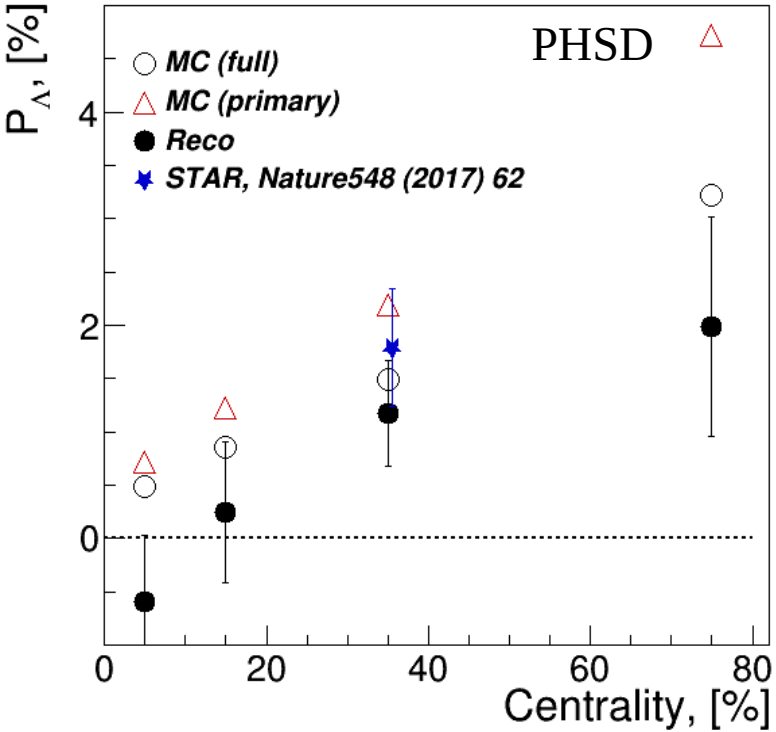
$$\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi^*_p} = p_0(1 + 2p_1 \sin(\Delta\phi^*_p) + 2p_2 \cos(\Delta\phi^*_p) + 2p_3 \sin(2\Delta\phi^*_p) + 2p_4 \cos(2\Delta\phi^*_p) + ...)$$

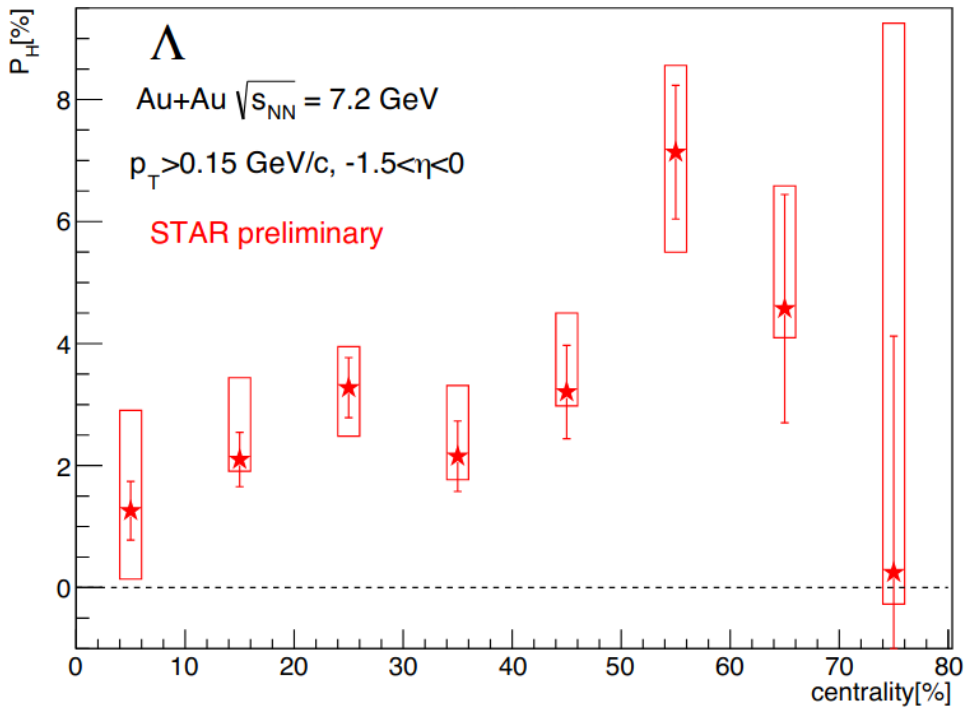
Results



- STAR measurement is corrected for the new value of decay asymmetry
- (left) corrected for EP resolution (right) no resolution correction
- Feed-down from decays lowers polarization value
- Need to estimate background contribution to polarization

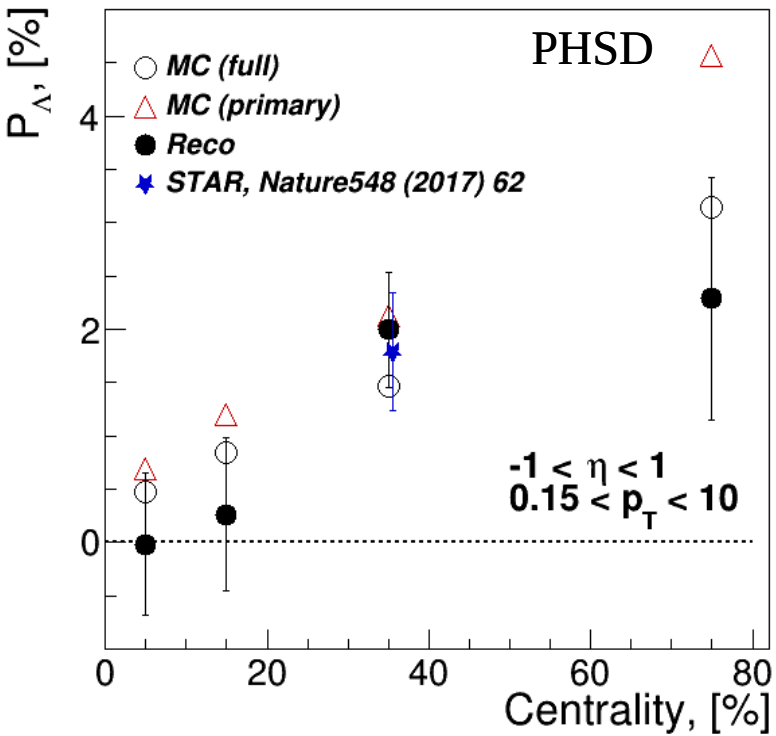
Results

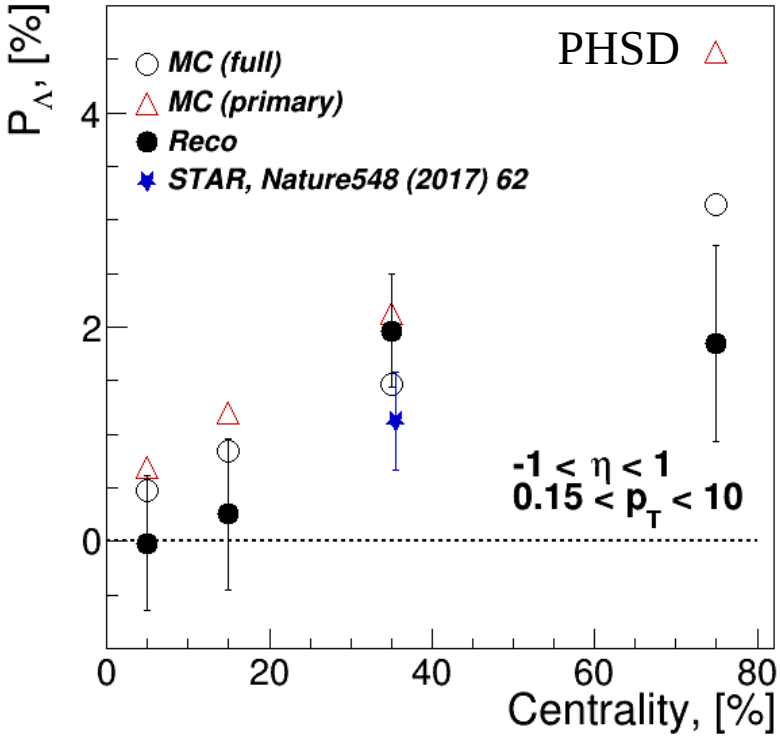




- Centrality dependence of global polarization agrees with the recently reported preliminary results from STAR collaboration

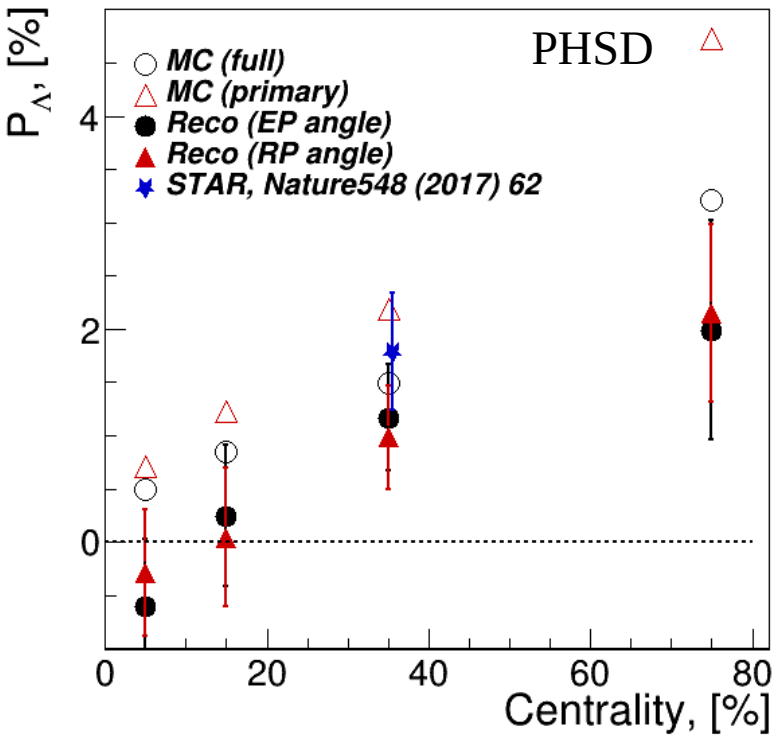
Results

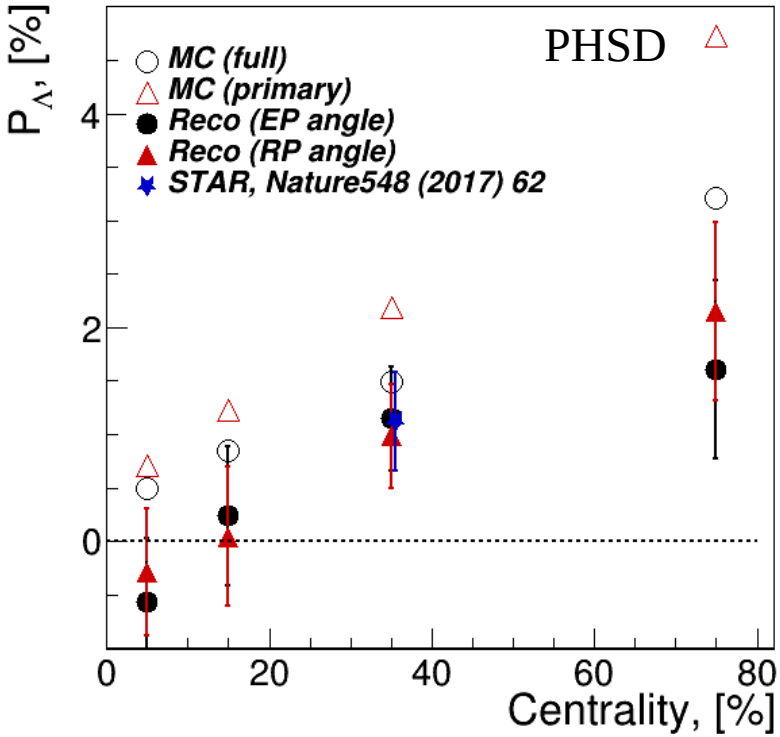




- STAR measurement is corrected for the new value of decay asymmetry
- (left) corrected for EP resolution (right) no resolution correction
- Feed-down from decays lowers polarization value

Results



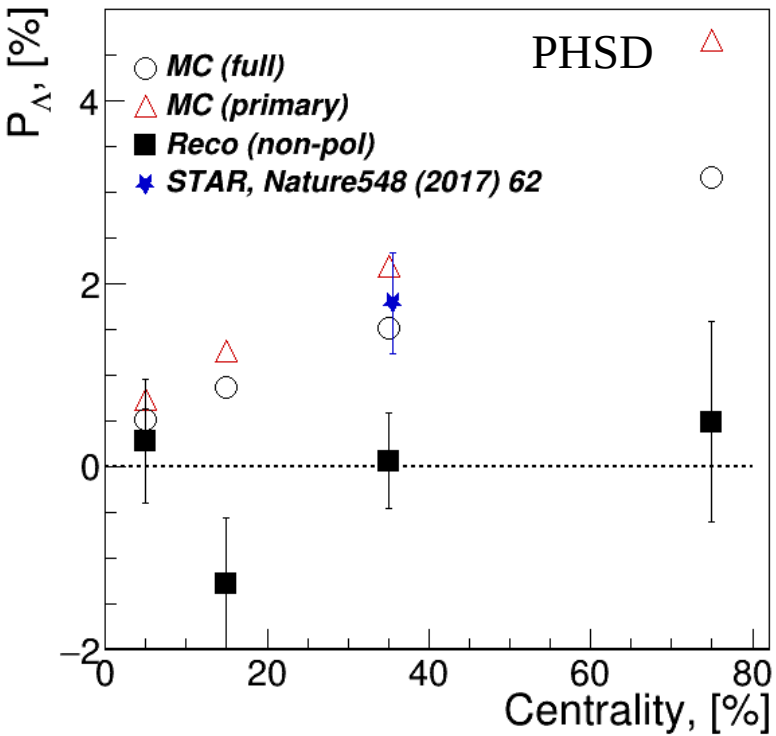


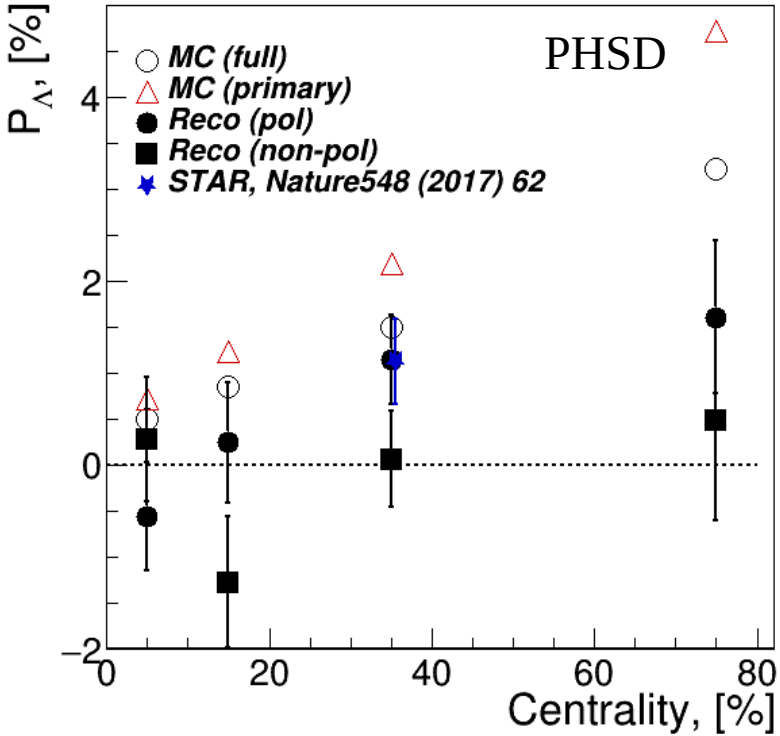
- Measurement w.r.t. RP angle (no resolution required)
- (left) corrected for EP resolution
- (right) no resolution correction

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

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

Results





- STAR measurement is corrected for the new value of decay asymmetry
- Non-polarized sample — can be obtained by disabling anisotropic decay of Lambda*

* $\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = 1 + \alpha_\Lambda |\vec{P}_\Lambda| \cos\theta^*$

Conclusions

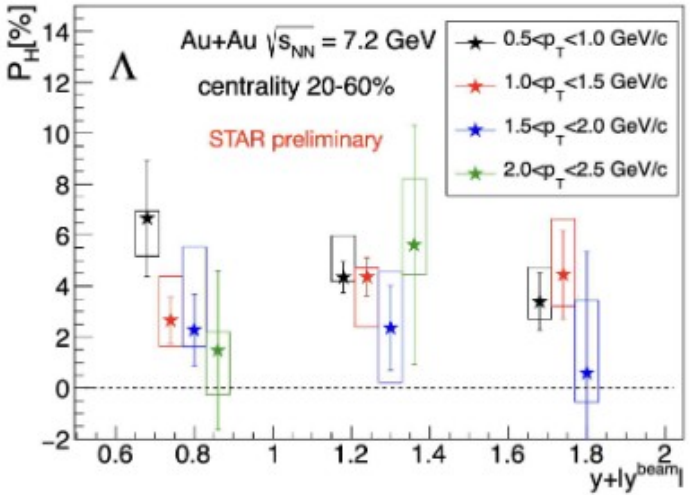
- Implemented transfer of polarization to secondary Lambda
- Realized event plane method for global polarization measurements
  - ➢ Question about PHSD Event Plane resolution remains
- Measurements agree within error bars with the model value, as well as the experimental data from STAR collaboration
  - ➢ Exception in the peripheral region
- Arises due to the anisotropic decay of Lambda, incorporated in the detector simulation

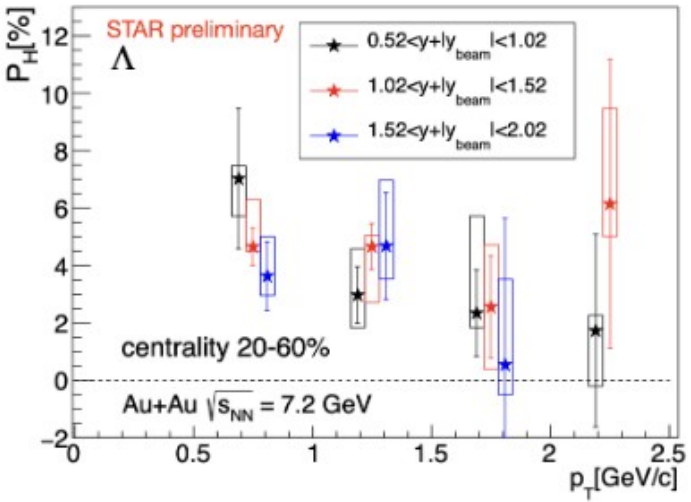
Outlook

- Estimate background contribution to global polarization
- Differential measurement of polarization and estimation of systematics
  - Increased statistics required
- Realize alternative method of polarization extraction
- Include anisotropic decay for other Hyperons in the detector simulation
  - Study global polarization of other hyperons
- Include different models for the simulation

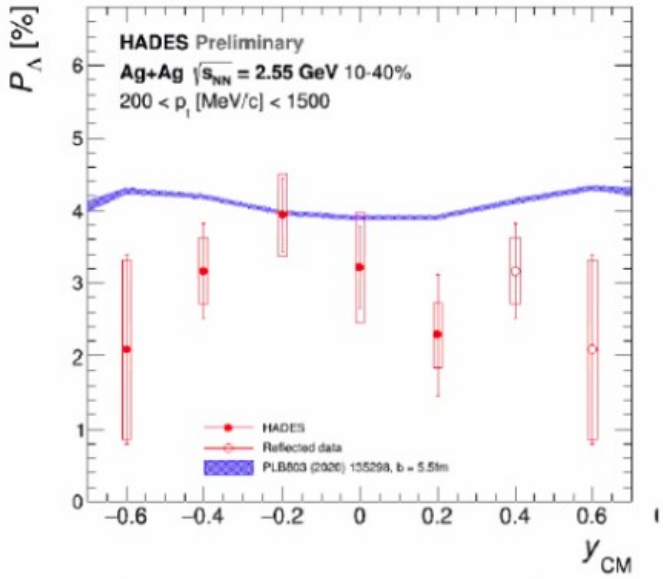
Thank you for your attention!

Back Up

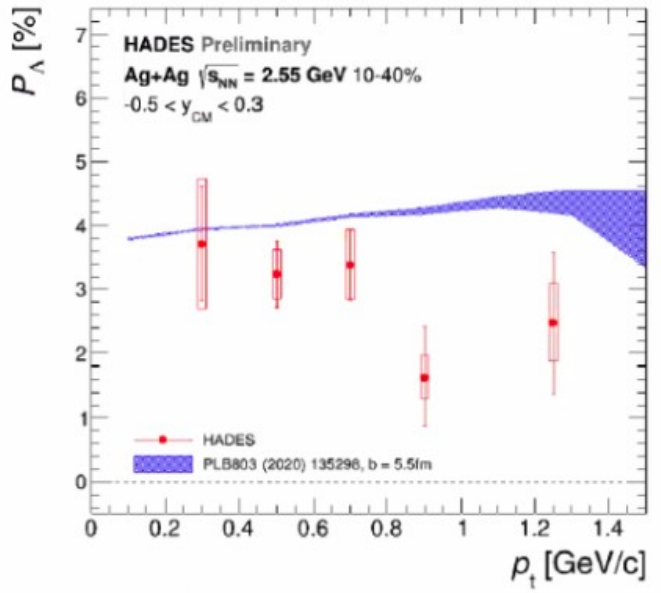




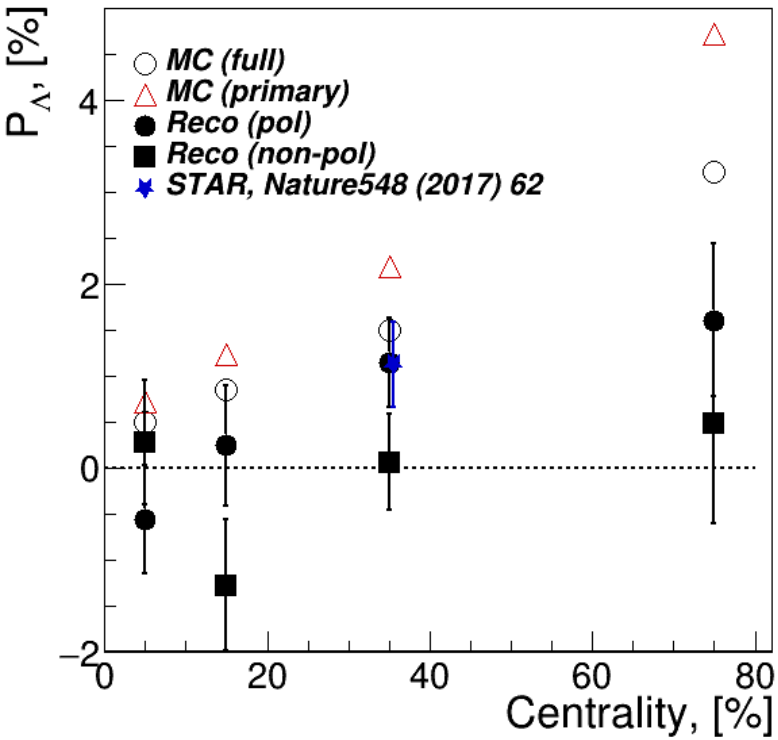
Rapidity dependence

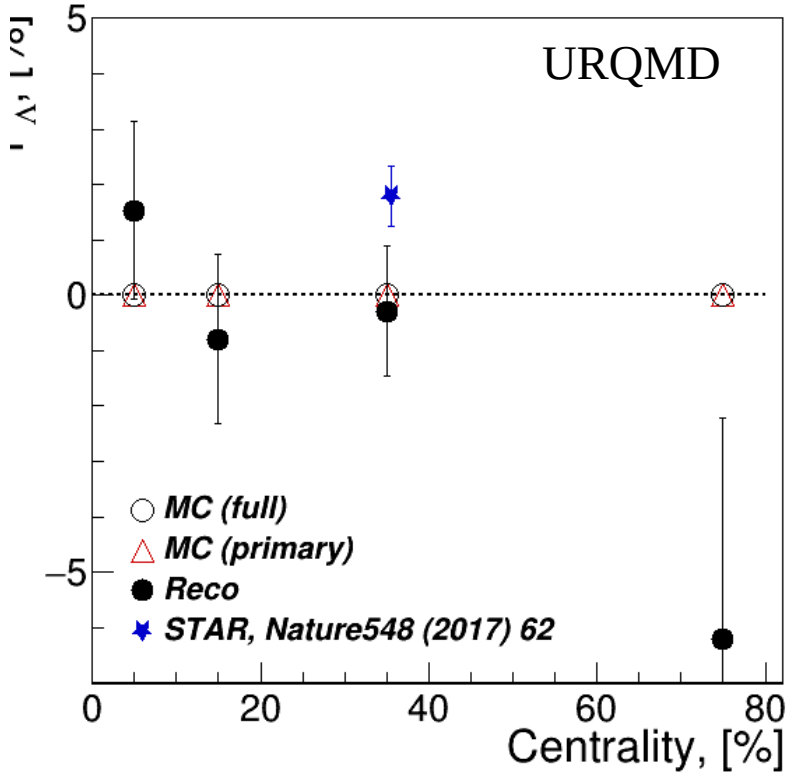


Transverse momentum dependence



- Rapidity and transverse momentum dependences of global polarization of Lambda
  - STAR collaboration, SQM2021 (e-Print: 2108.10012)
  - HADES collaboration, SQM2021
- No significant y and p_T dependence within uncertainties



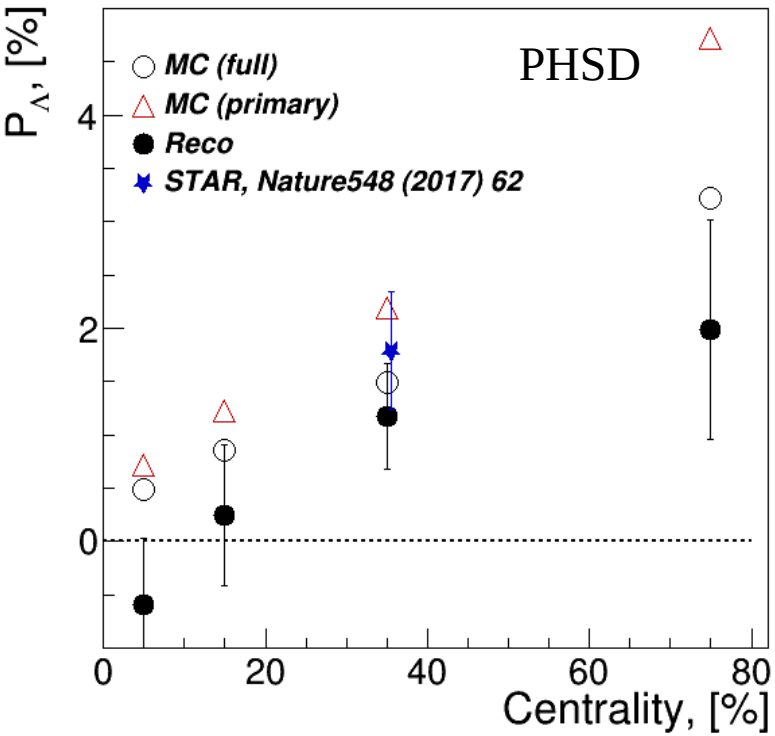


$N_\Lambda \sim 5 * 10^4$ (URQMD)

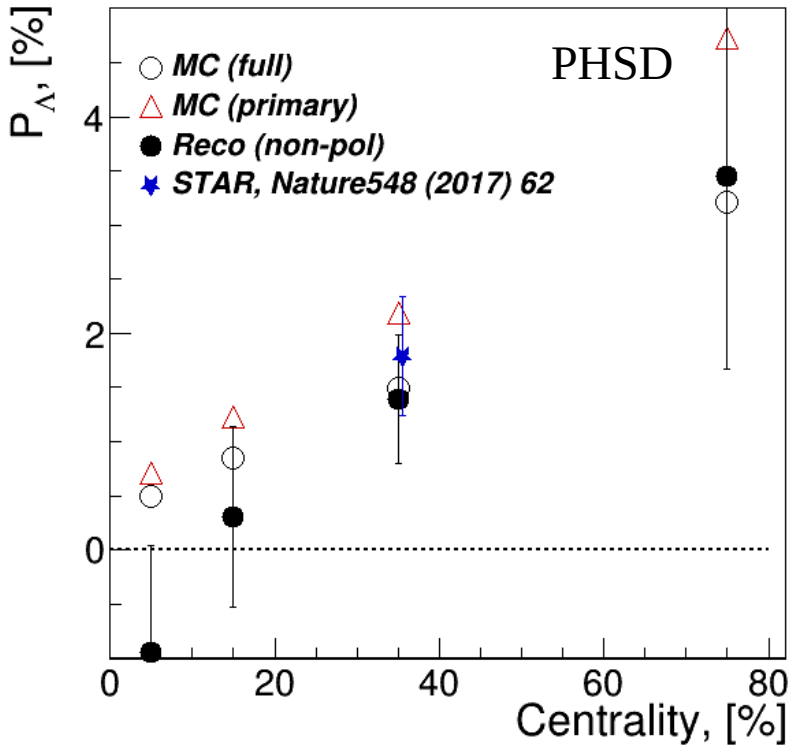
$N_\Lambda \sim 2 * 10^5$ (PHSD)

- STAR measurement is corrected for the new value of decay asymmetry
- Non-polarized sample — can be obtained by disabling anisotropic decay of Lambda*

* $$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = 1 + \alpha_\Lambda |\vec{P}_\Lambda| \cos\theta^*$$



Using PHSD EP resolution values



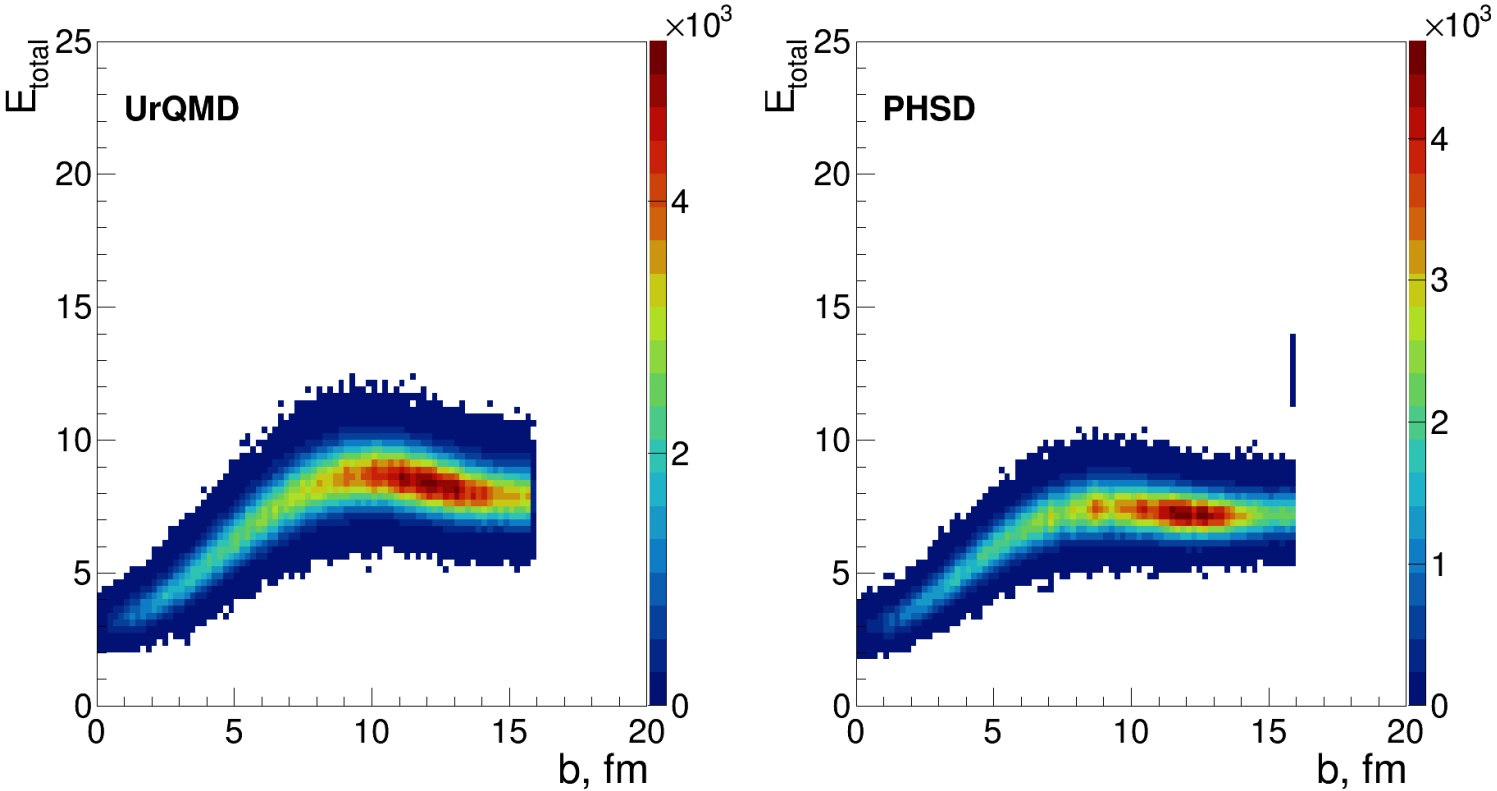
Using UrQMD EP resolution values

Fit parameters for the polarized sample (PHSD dataset)

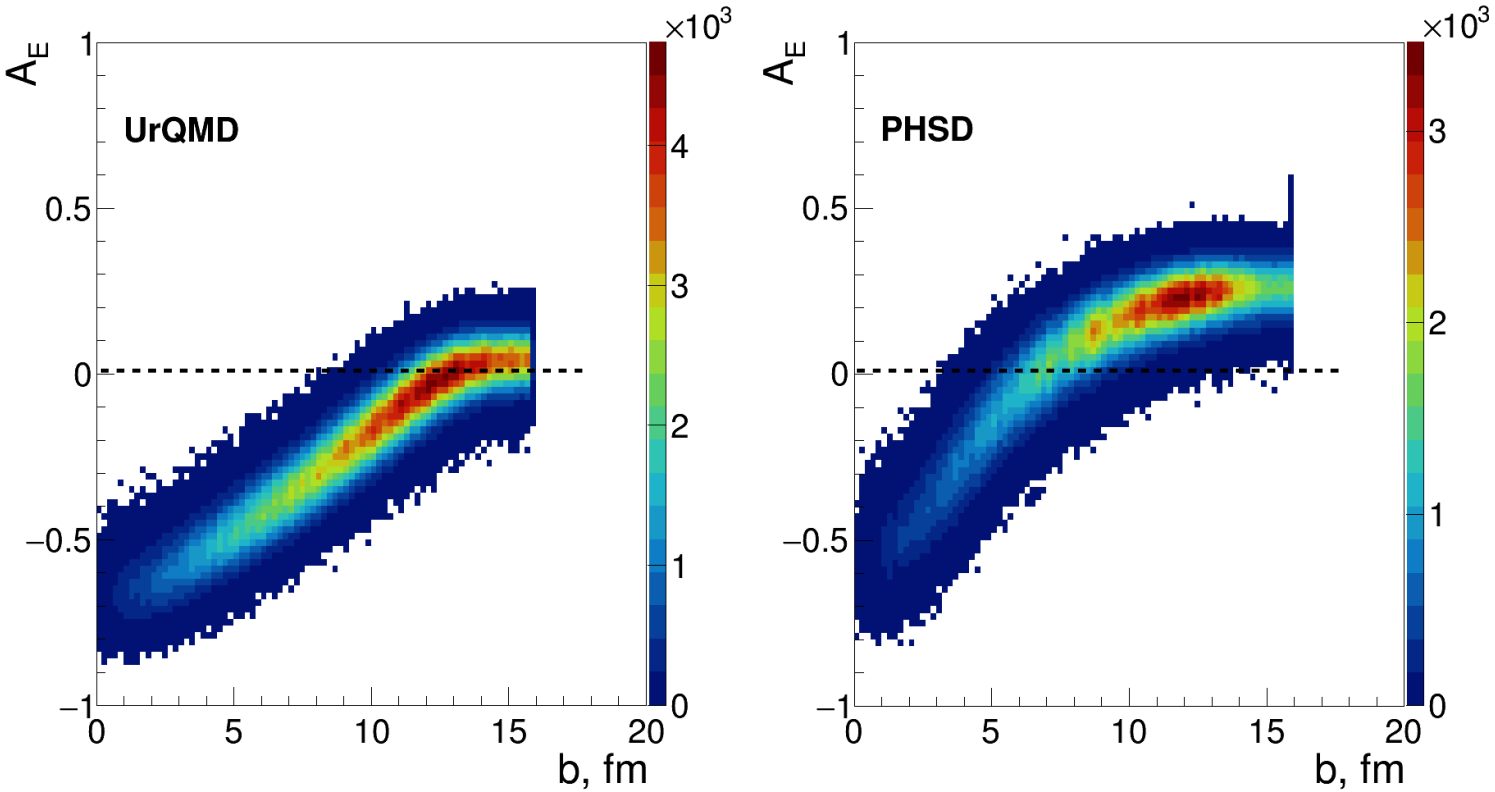
	0-10%	10-20%	20-50%	50-100%
N_Λ	$2.4 \cdot 10^5$	$1.9 \cdot 10^5$	$3.3 \cdot 10^5$	$1.1 \cdot 10^5$
p_0	$1.2 \cdot 10^4$ +/- 29	$1.0 \cdot 10^4$ +/- 25	$1.6 \cdot 10^4$ +/- 33	$0.5 \cdot 10^4$ +/- 18
$p_1/10^{-4}$	-16.14 +/- 16.93	6.95 +/- 18.71	33.02 +/- 14.01	46.13 +/- 23.86
$p_2/10^{-4}$	4.52 +/- 16.78	-11.09 +/- 18.65	44.03 +/- 13.93	31.01 +/- 21.13
$p_3/10^{-4}$	-7.32 +/- 16.92	-13.09 +/- 18.72	-3.26 +/- 13.95	-13.70 +/- 17.60
$p_4/10^{-4}$	-6.74 +/- 16.96	-35.86 +/- 18.61	-52.39 +/- 14.00	-23.41 +/- 23.29

$$\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi_p^*} = p_0(1 + 2p_1\sin(\Delta\phi_p^*) + 2p_2\cos(\Delta\phi_p^*) + 2p_3\sin(2\Delta\phi_p^*) + 2p_4\cos(2\Delta\phi_p^*) + ...)$$

Total energy in FHCal

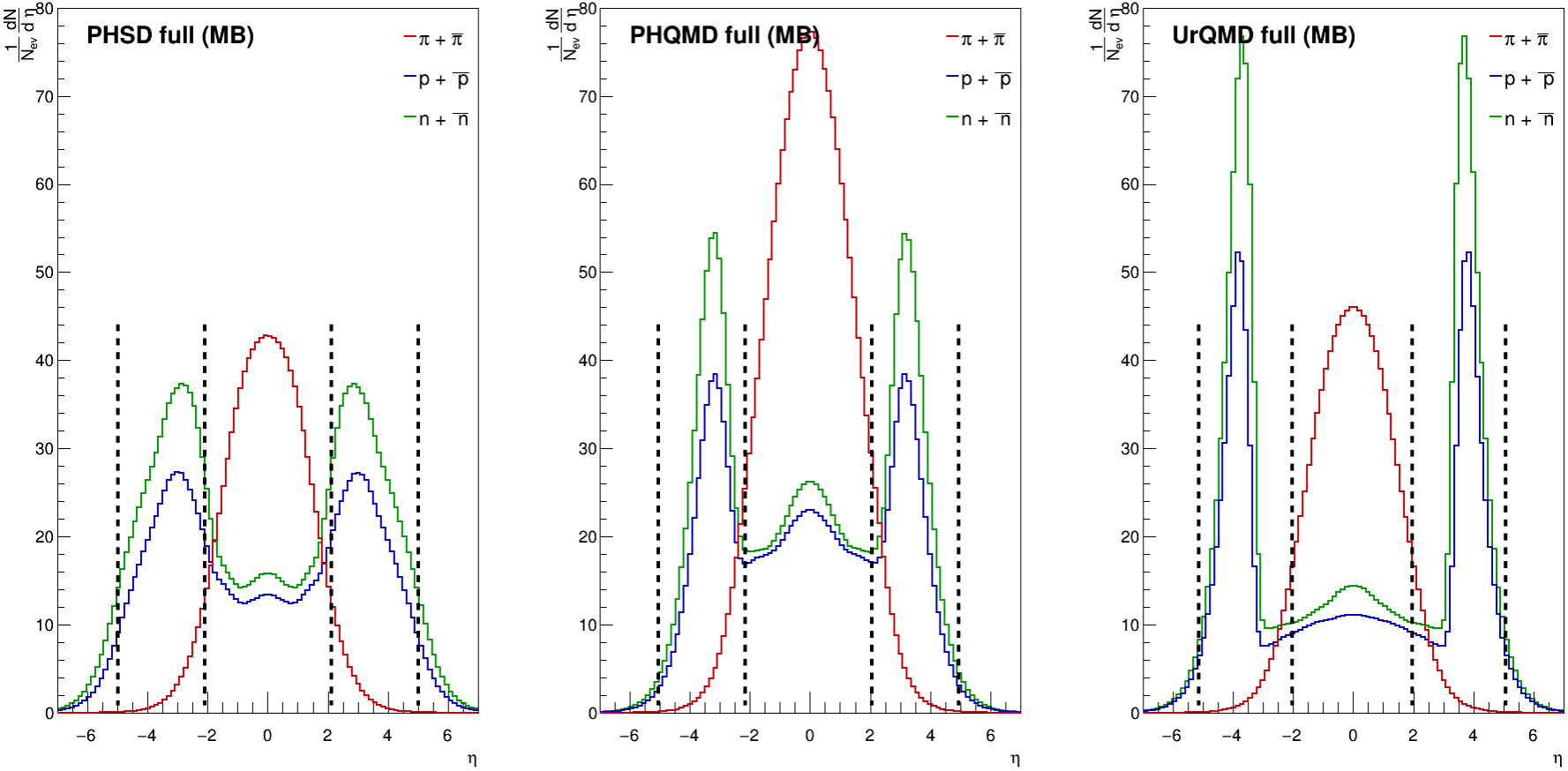


Energy asymmetry in FHCal



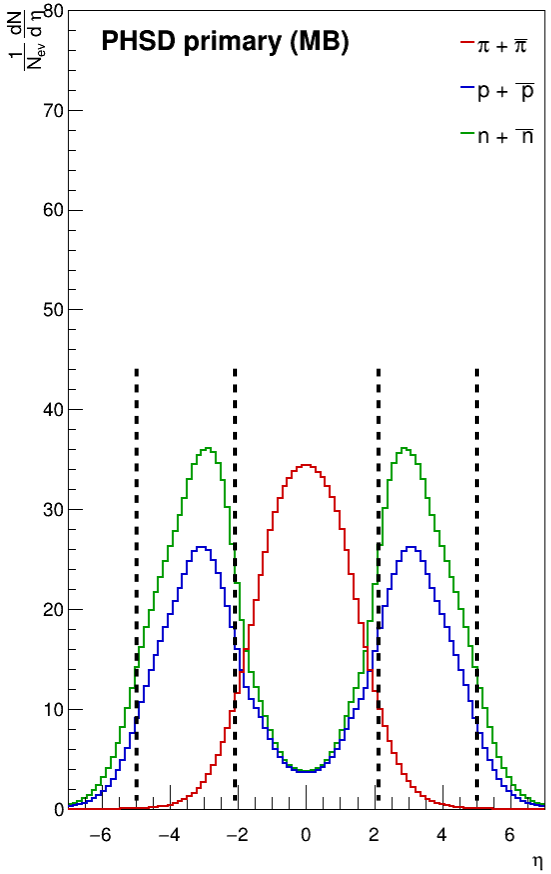
$$A_{\mathrm{E}} = \frac{E_{\mathrm{in}} - E_{\mathrm{out}}}{E_{\mathrm{in}} + E_{\mathrm{out}}}$$

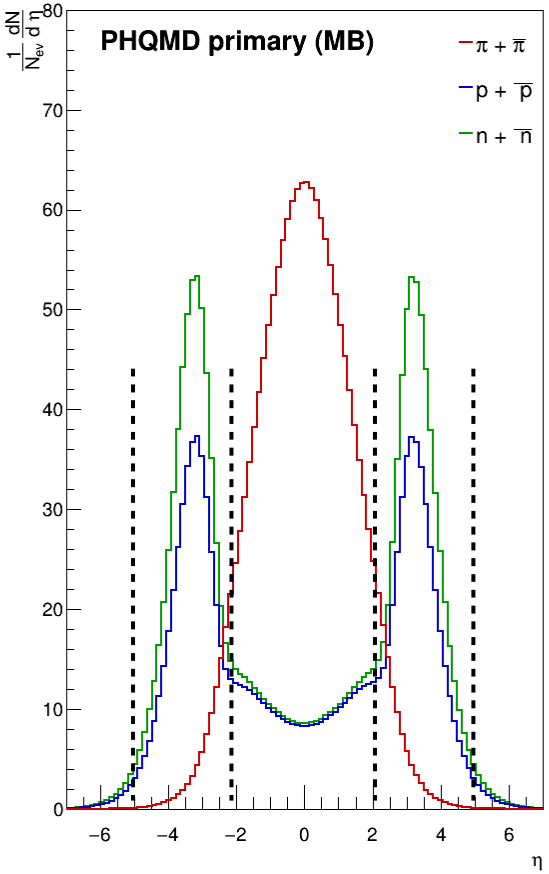
PHQMD dataset with b[0,12] fm

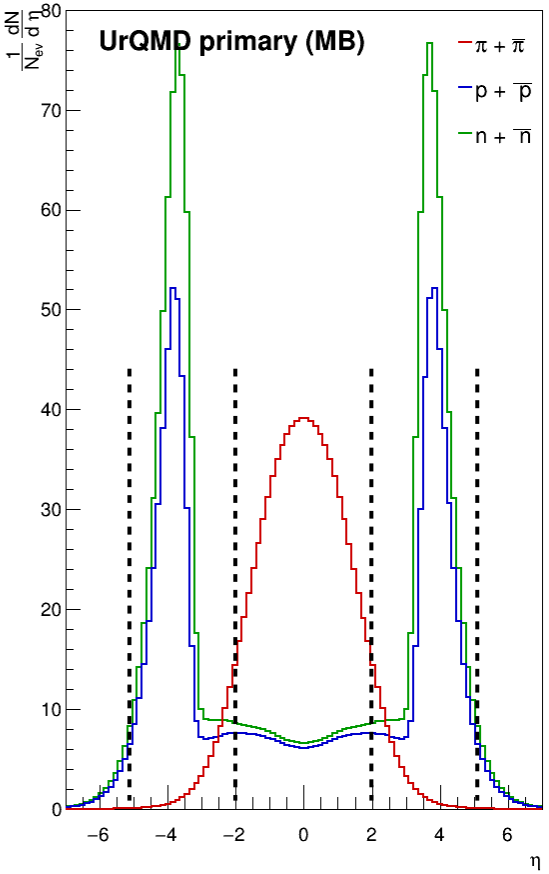


$2 < |\eta| < 5$ region corresponds to FHCal

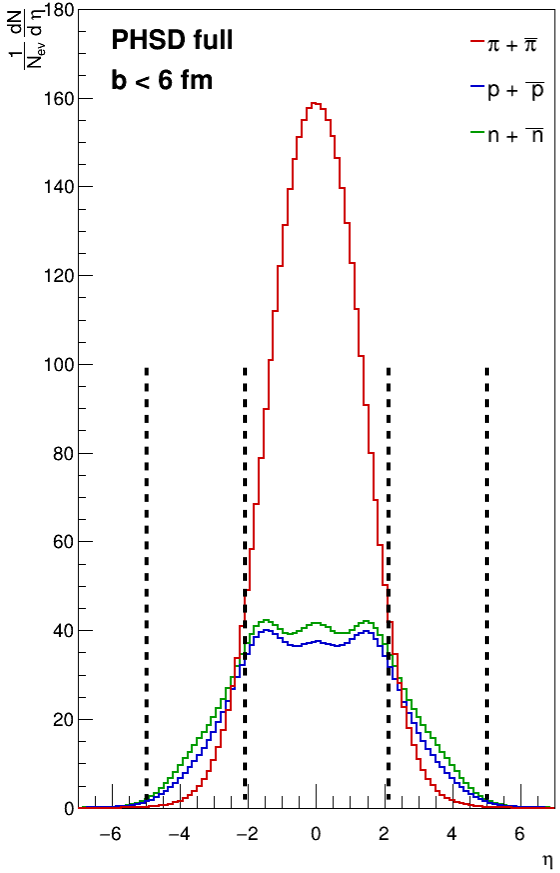
Vertex cut of 50cm

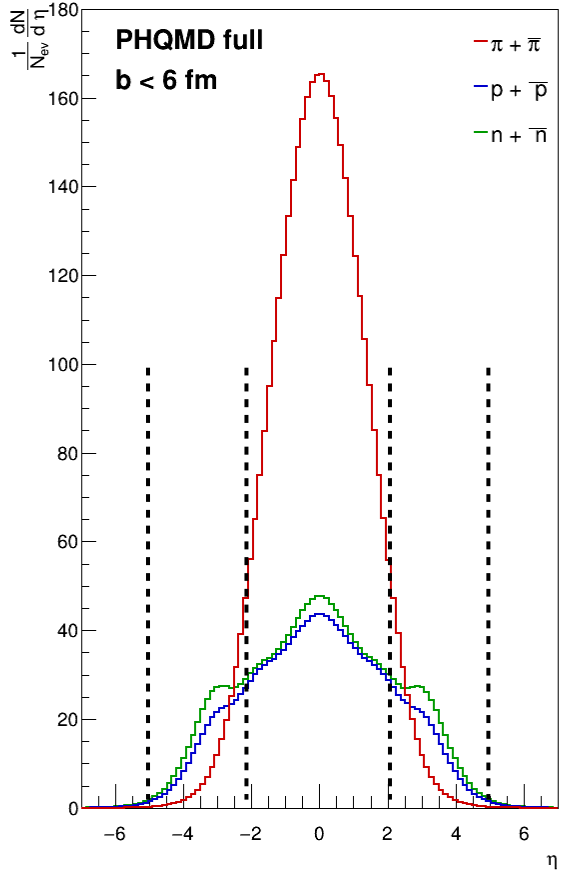


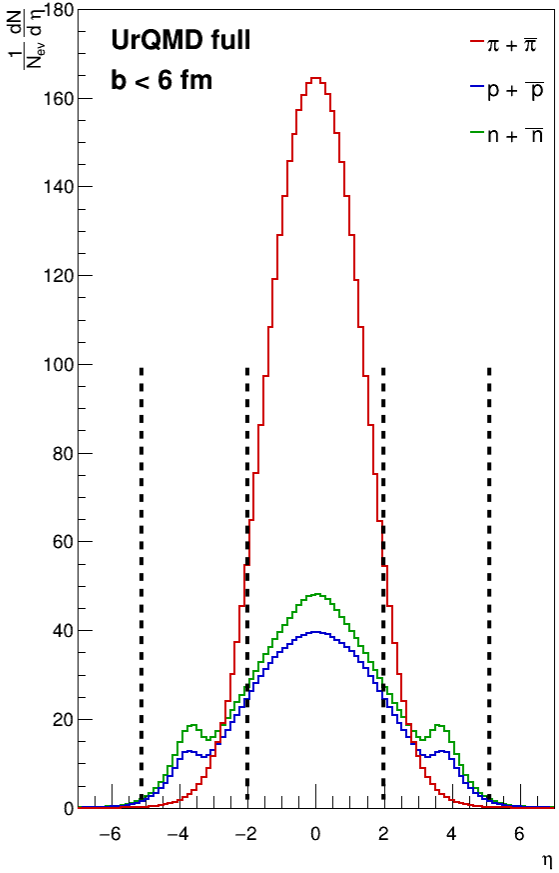




$2 < |\eta| < 5$ region corresponds to FHCal

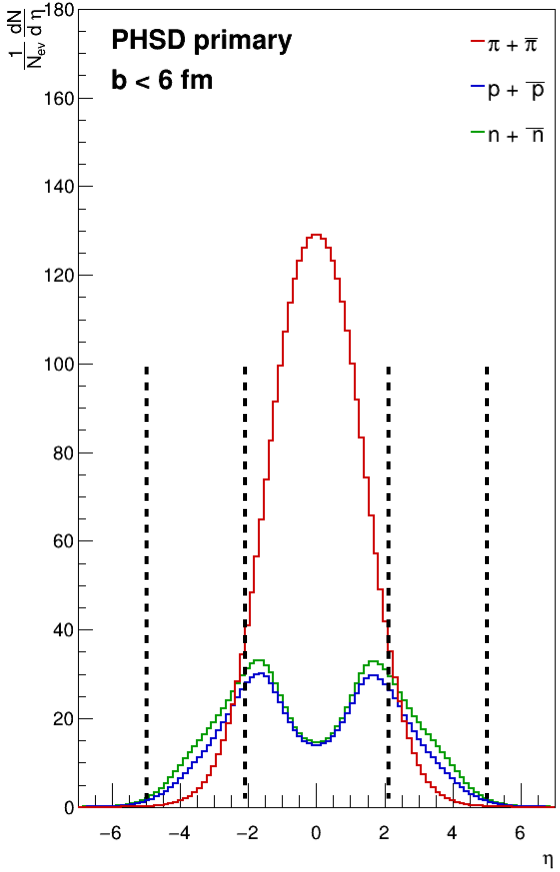


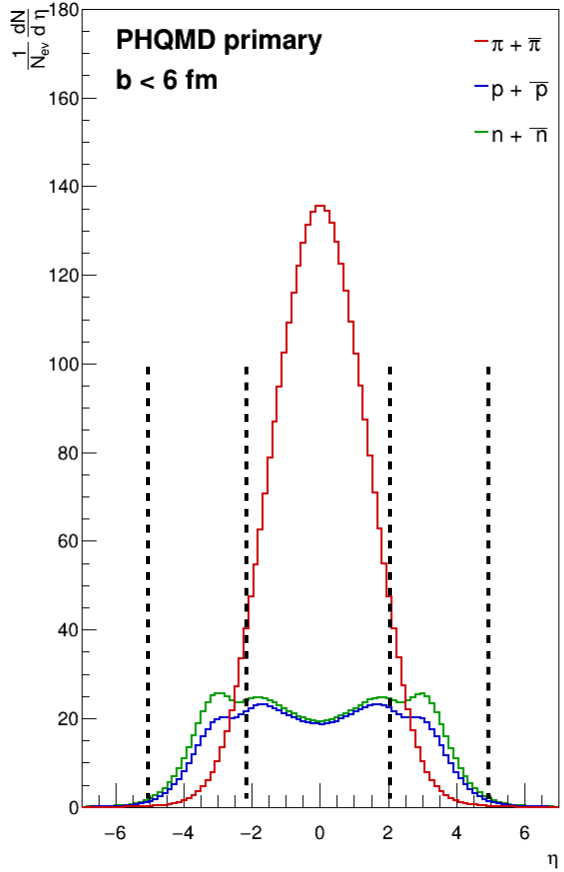


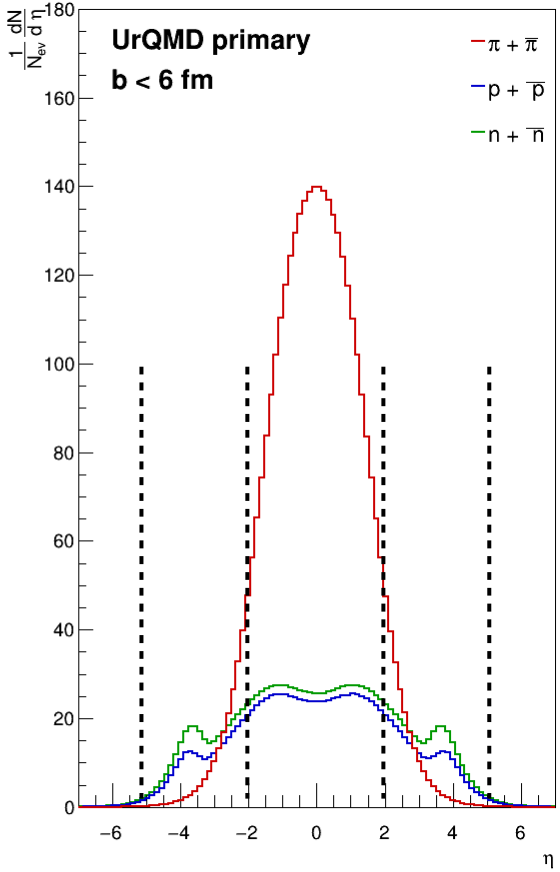


$2 < |\eta| < 5$ region corresponds to FHCal

Back Up

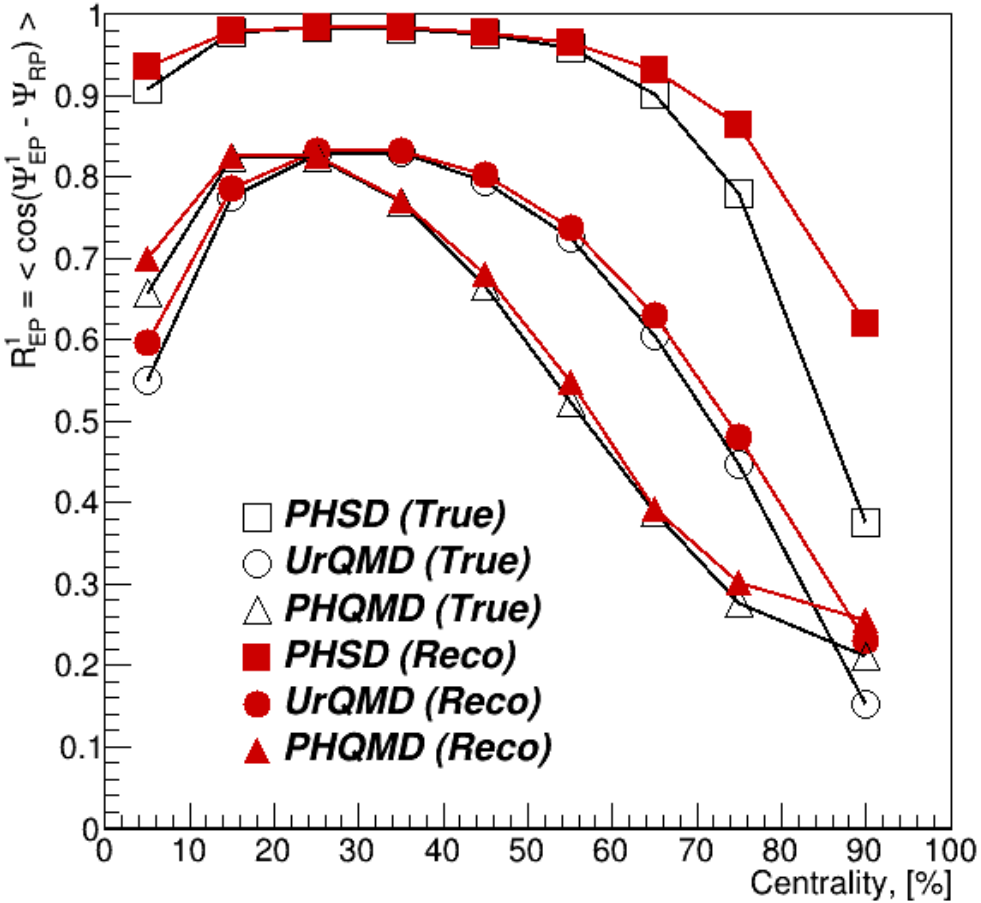






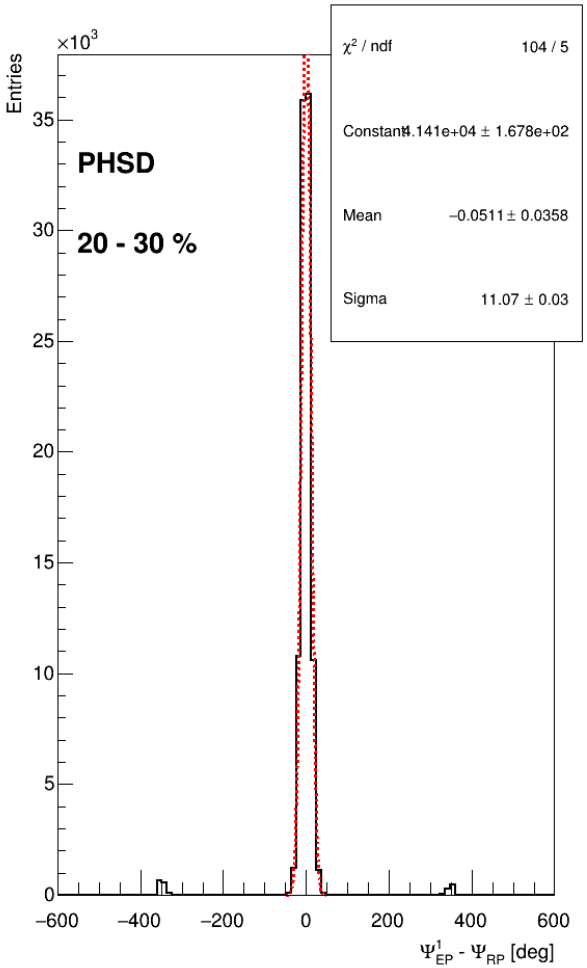
$2 < |\eta| < 5$ region corresponds to FHCal

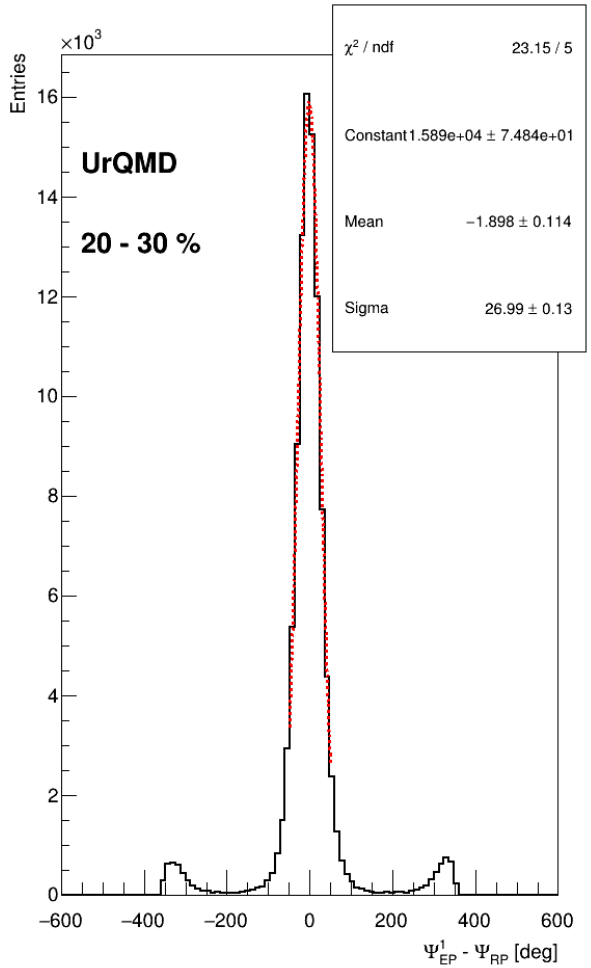
Back Up

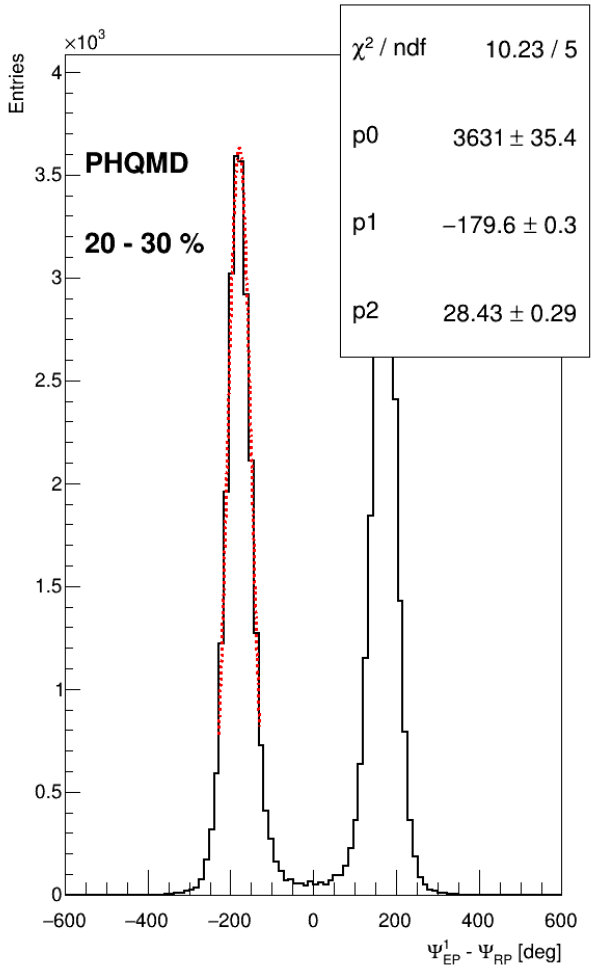


- Comparison of the UrQMD, PHQMD & PHSD models
  - Much lower statistics in the PHQMD sample
  - 1-order EP resolution is similar for UrQMD and PHQMD
  - Feature of the PHQMD model: reaction plane is shifted by 180deg → need to account for the shift in the calculations

Back Up


PHSD
20 - 30 %
χ² / ndf 104 / 5
Constant 4.141e+04 ± 1.678e+02
Mean −0.0511 ± 0.0358
Sigma 11.07 ± 0.03
Entries
×10³
Ψ¹EP - ΨRP [deg]


UrQMD
20 - 30 %
χ² / ndf 23.15 / 5
Constant 1.589e+04 ± 7.484e+01
Mean −1.898 ± 0.114
Sigma 26.99 ± 0.13
Entries
×10³
Ψ¹EP - ΨRP [deg]


PHQMD
20 - 30 %
χ² / ndf 10.23 / 5
p0 3631 ± 35.4
p1 −179.6 ± 0.3
p2 28.43 ± 0.29
Entries
×10³
Ψ¹EP - ΨRP [deg]