Current status of the global hyperon polarization analysis at MPD

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MPD Polarization Meeting
«Vorticity and Polarization in Heavy-Ion Collisions»

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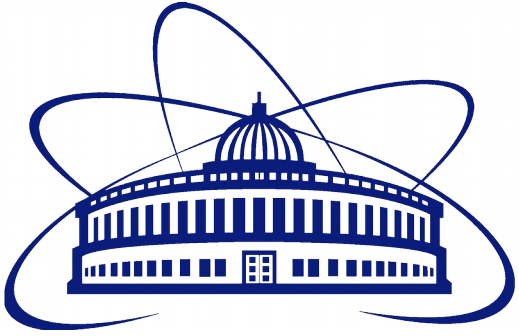


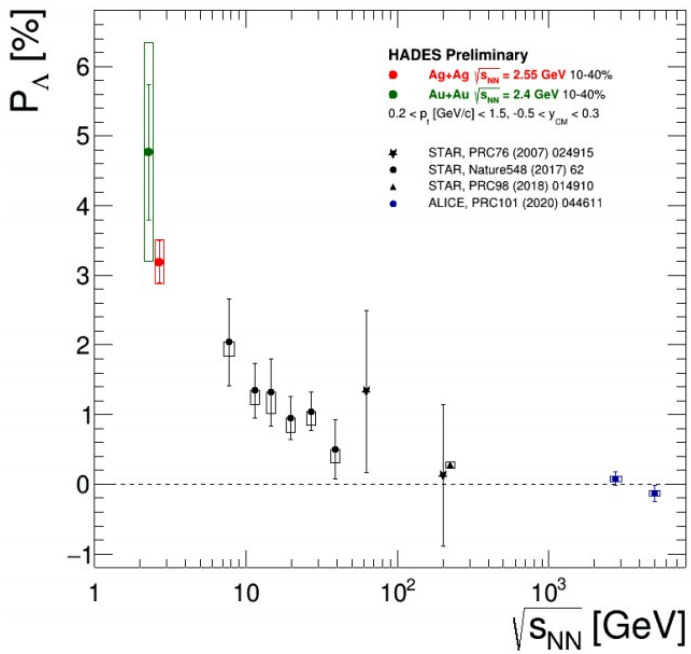
[1] Joint Institute of Nuclear Research, Dubna, Russia

Outline

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

Motivation

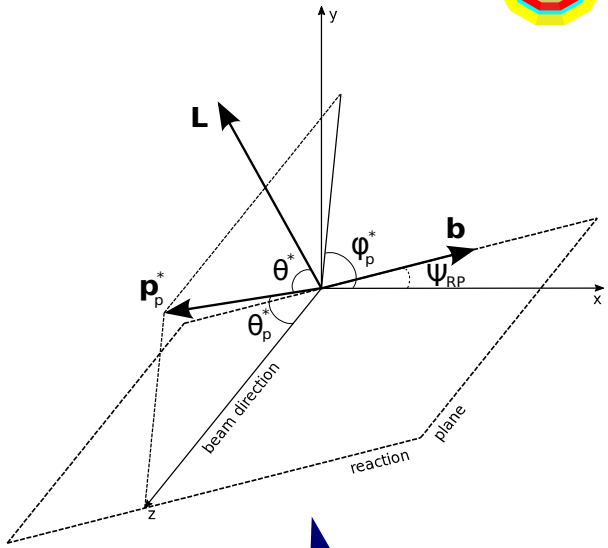
- Predicted[1] and observed[2,3] global polarization signals rise as the collision energy is reduced:
  - NICA energy range will provide new insight
- New value of decay asymmetry α_Λ found in BES-III experiment[4]
  - Effect could be studied at NICA
- $\Lambda(\bar{\Lambda})$-splitting of global polarization,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



[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)

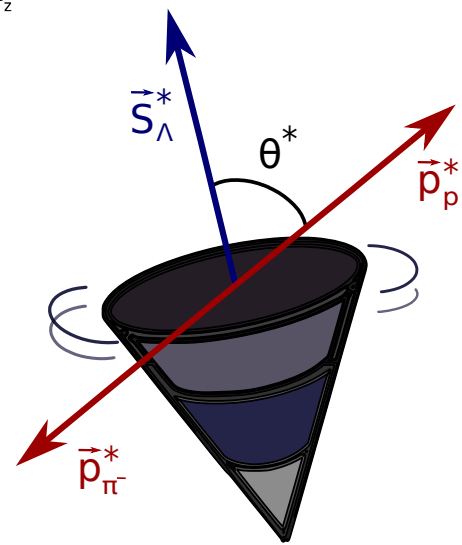
Global hyperon polarization

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



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

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

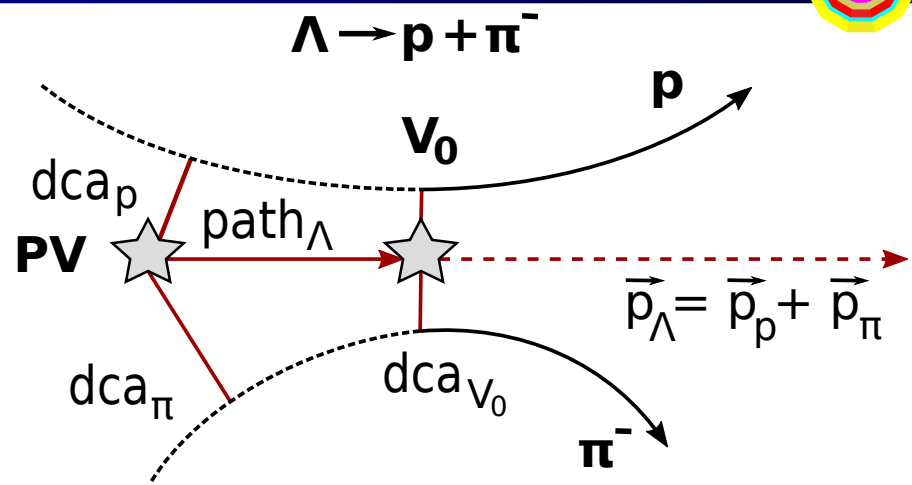


[1] Z. Liang, X. Wang, PRL 94, 102301 (2005)
[2] L. Adamczyk et al., Nature 548, 62 (2017)

Global hyperon polarization

- θ^* — angle between the decay particle and $\vec{n} = \vec{p}_{\text{beam}} \times \vec{p}_{\Lambda}$

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



→ Determine centrality

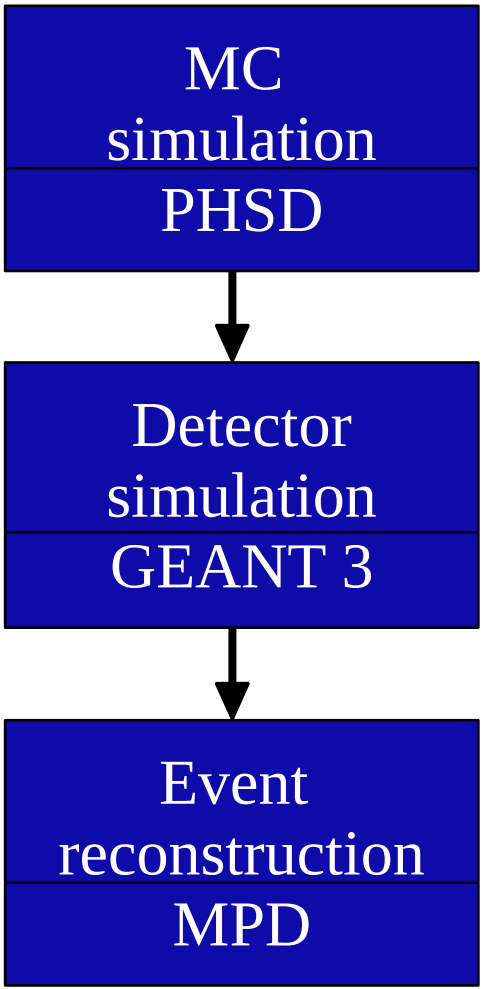
→ Determine event plane $(\Psi^n_{\text{EP}}, R^1_{\text{EP}})$

→ Reconstruct Lambda

→ Global polarization

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

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

[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

MC simulation
PHSD

↓

Detector simulation
GEANT 3

↓

Event reconstruction
MPD

- 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 $P_n > 1$
- 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)
  - $$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = 1 + \alpha_\Lambda |\vec{P_\Lambda}| \cos\theta^*$$

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

[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

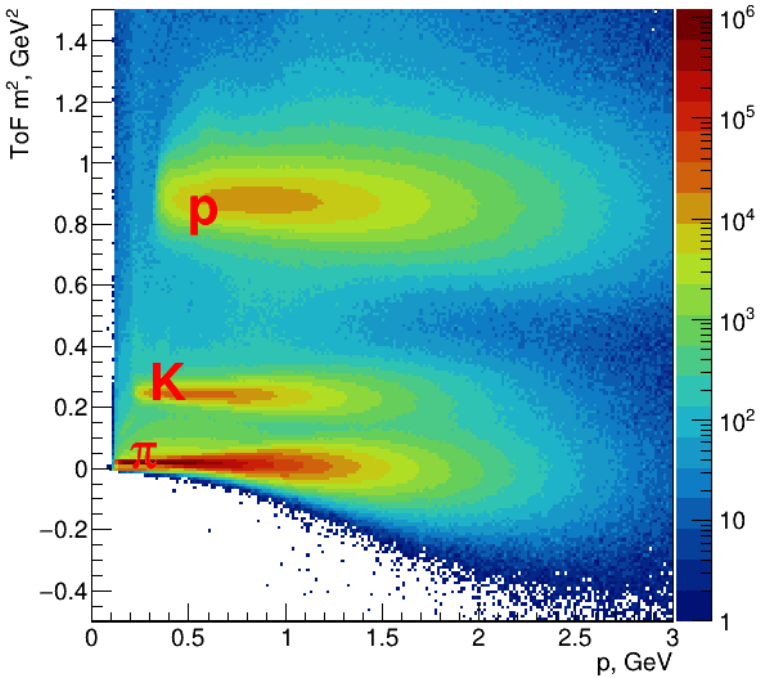
Analysis technique

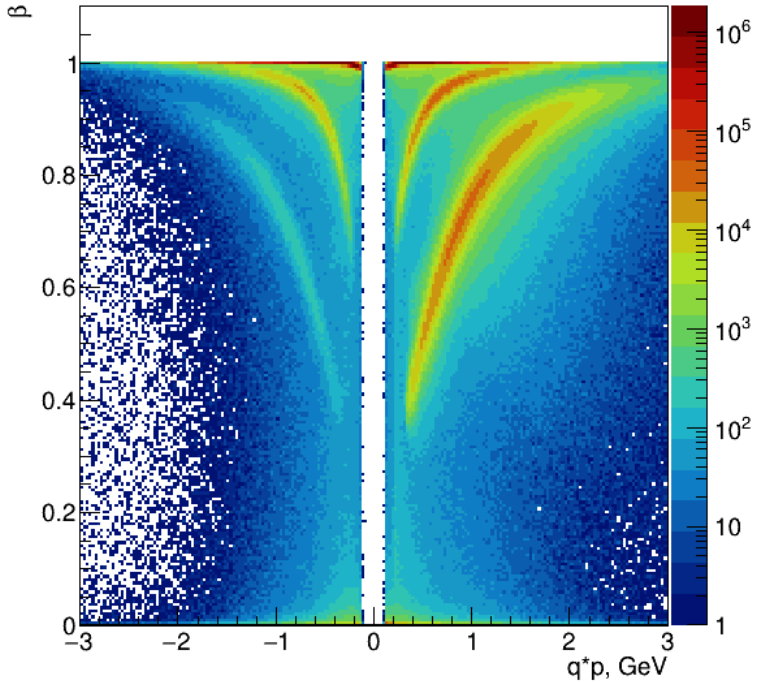
MC simulation
PHSD

Detector simulation
GEANT 3

Event reconstruction
MPD

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

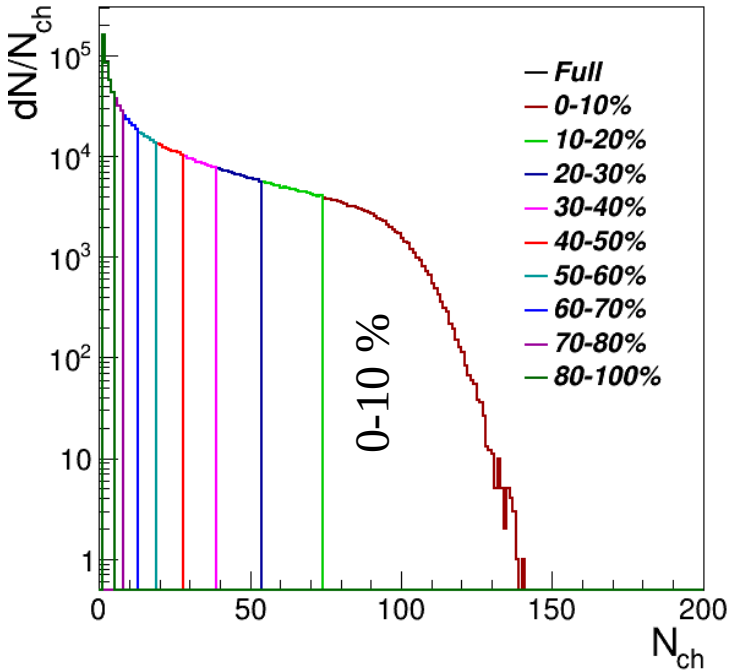


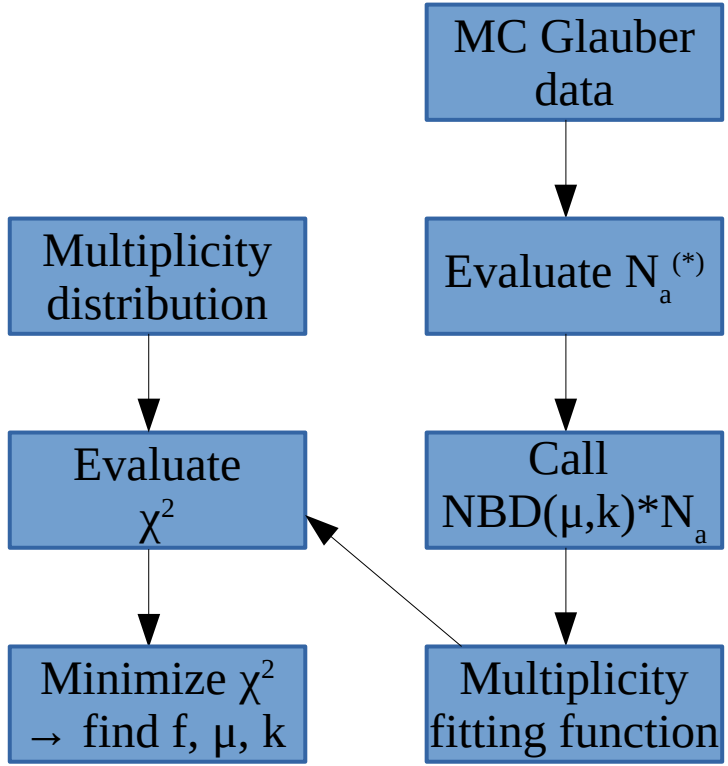


Centrality determination

- 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

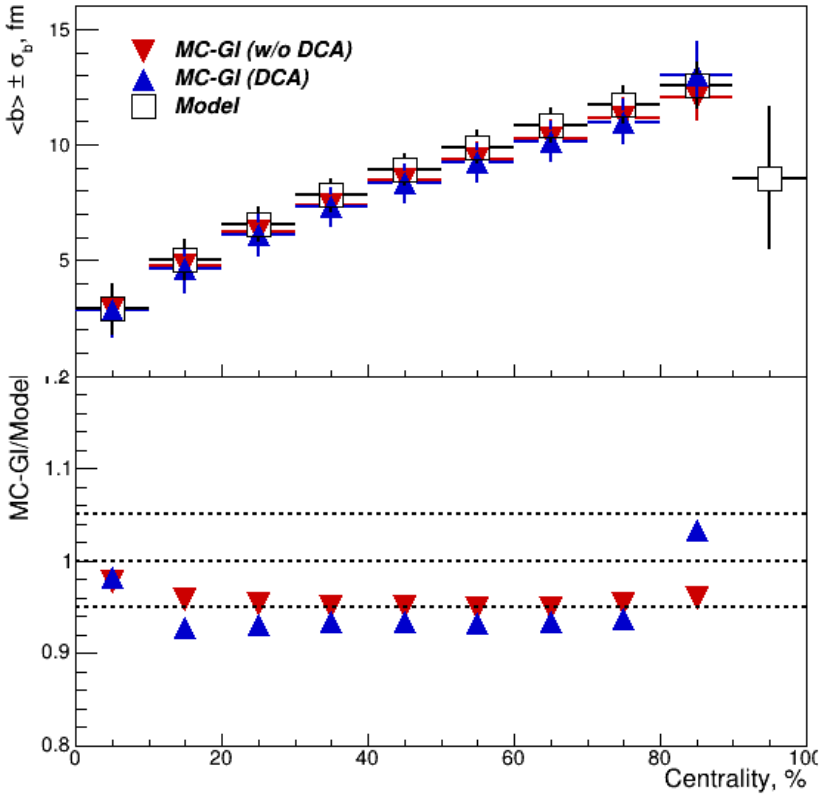




[1] P. Parfenov et al, NRNU MEPhI for the MPD collaboration (https://github.com/FlowNICA/CentralityFramework)

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

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)
  - $R^k_{\mathrm{EP}} = \left\langle \cos(k(\Psi^n_{\mathrm{EP,R}} - \Psi^n_{\mathrm{EP,L}})) \right\rangle$ (sub-event resolution method[2])

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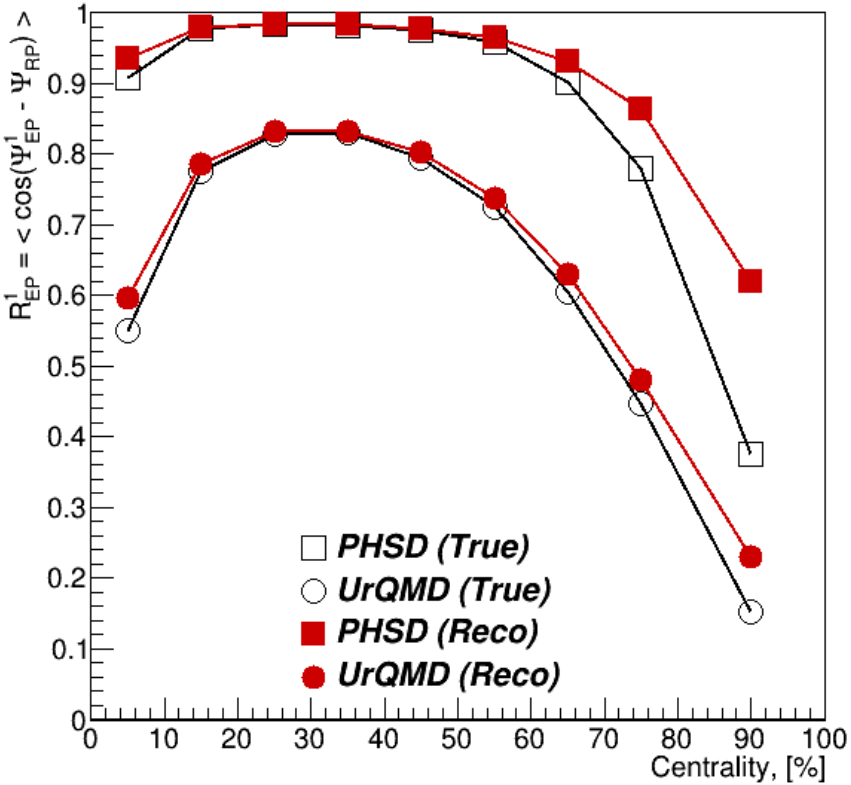
[1] J. Barrette et al. (E877 Collaboration) Phys. Rev. C56, 3254 (1997)

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

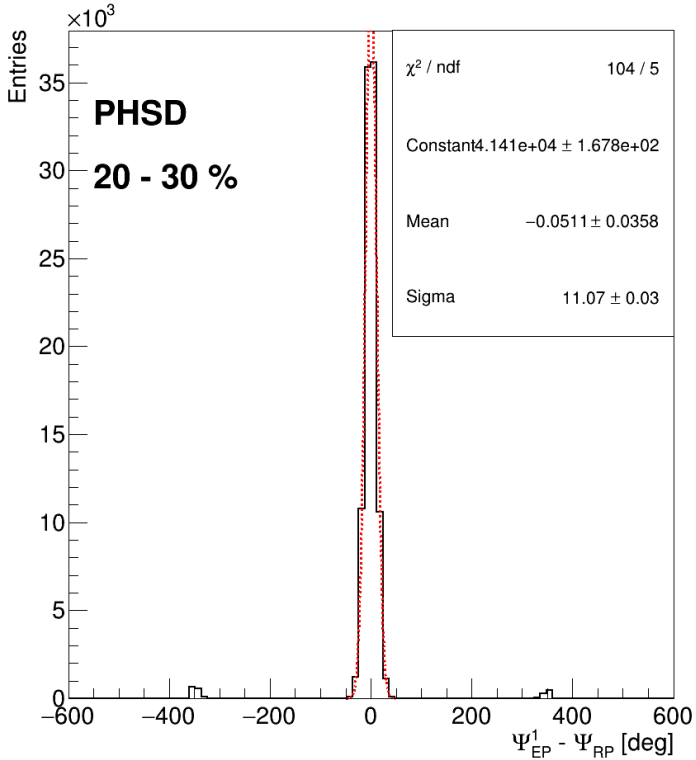
Event plane determination

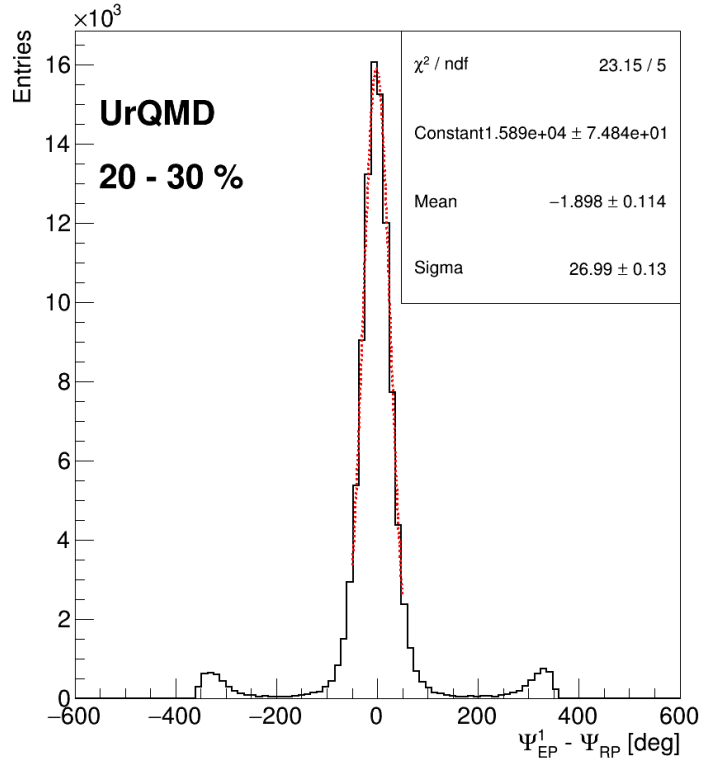


- Event plane and resolution determined using FHCal
- PHSD gives higher resolution values w.r.t. URQMD model
- Effect not understood yet

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

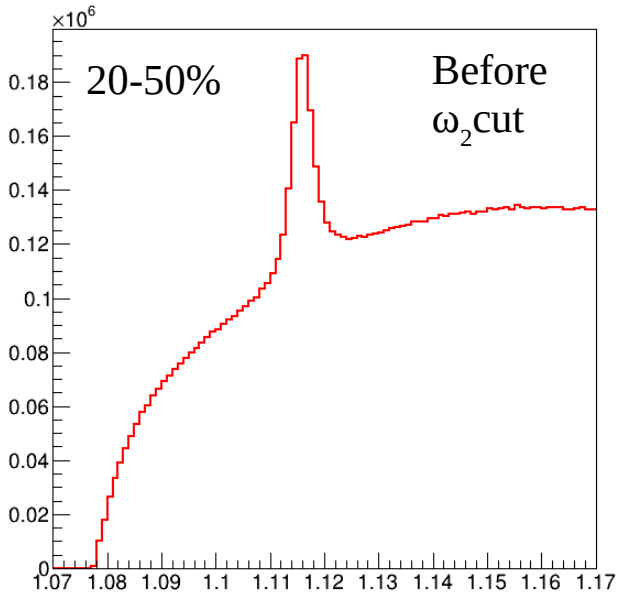
Event plane determination





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

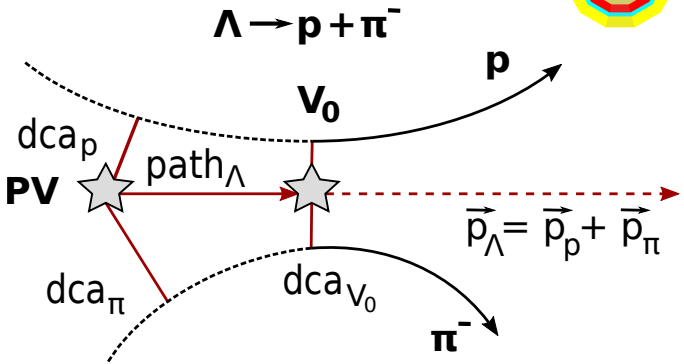
Lambda reconstruction

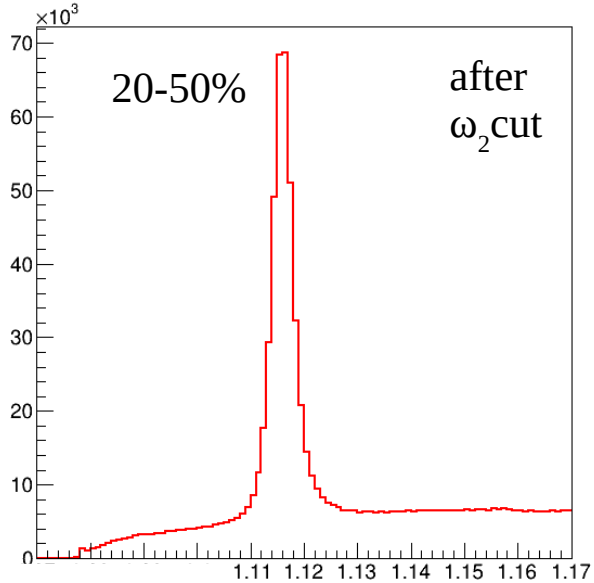


$$\omega_2 = \ln \frac{\sqrt{\chi_\pi^2 \chi_\mathrm{p}^2}}{\chi_\Lambda^2 + \chi_{\mathrm{V}_0}^2}$$

Fitting procedure:

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

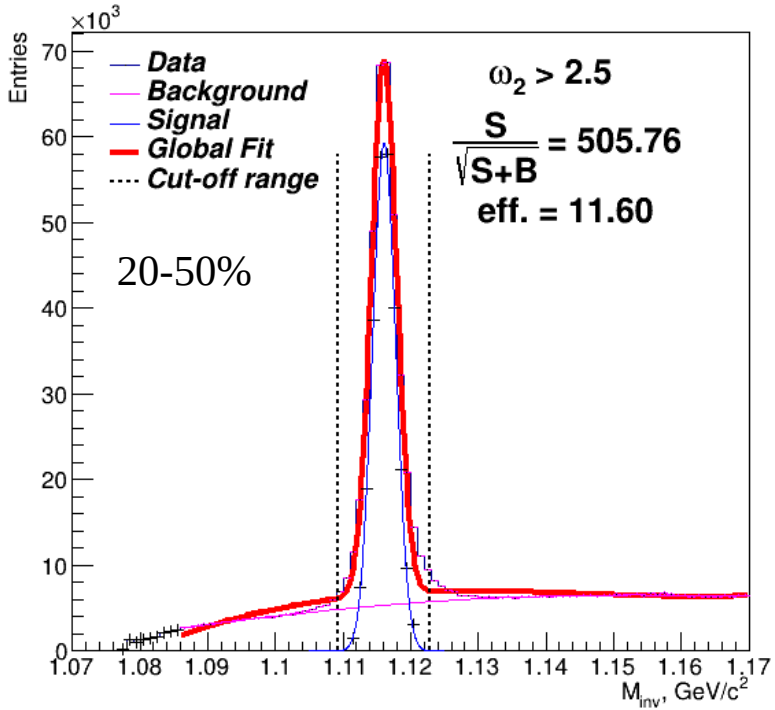




$$f(x) = [0]\exp\left(\frac{(-0.5(x-[1]))^2}{[2]^2}\right) + [3](L_0 + [4]L_1 + [5]L_2 + [6]L_3 + [7]L_4)$$

Global polarization reconstruction

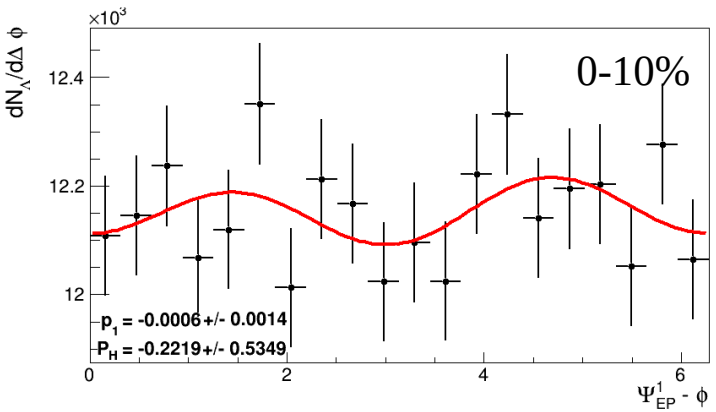
- Obtained invariant mass distribution in bins of $\Delta\phi_p^* = \Psi_{\mathrm{EP}}^1 - \phi_p^*$
  - Net amount of Λ in each bin
  - Distribution of $N_\Lambda(\Delta\phi_p^*)$
- Fit of the distribution[1] to get $\langle \sin(\Delta\phi_p^*) \rangle \rightarrow P_\Lambda$
  - «Event plane» method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

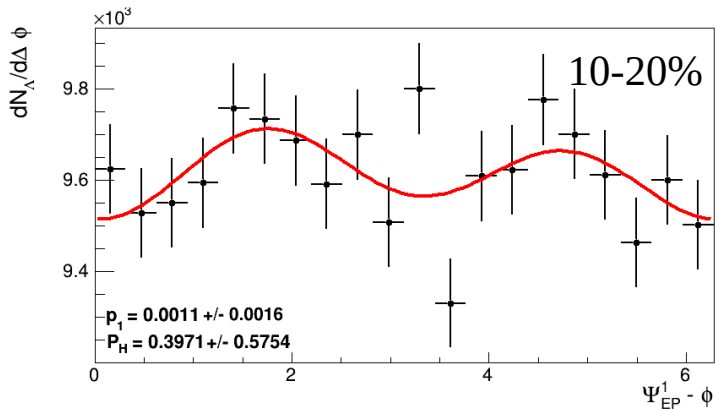


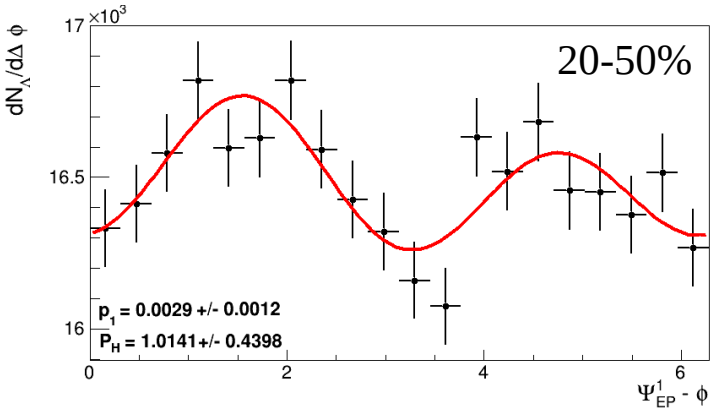
$$\overline{P}_{\Lambda/\bar{\Lambda}} = \frac{8}{\pi\alpha}\frac{1}{R_{\mathrm{EP}}^1}\left\langle \sin(\Psi_{\mathrm{EP}}^1 - \phi_p^*) \right\rangle$$

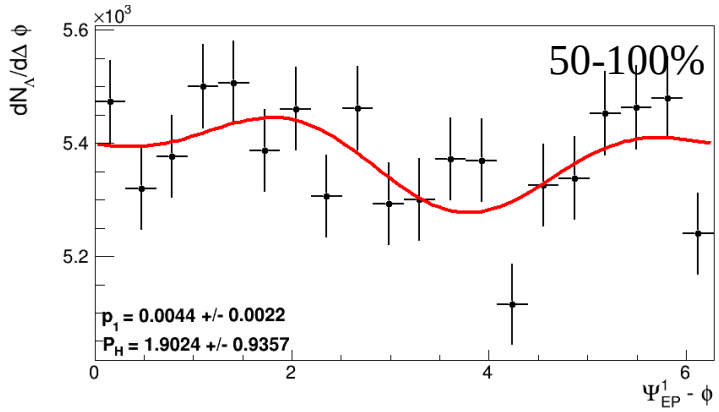
[1] $$\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi_p^*} = [0](1 + 2[1]\sin(\Delta\phi_p^*) + 2[2]\cos(\Delta\phi_p^*) + 2[3]\sin(2\Delta\phi_p^*) + 2[4]\cos(2\Delta\phi_p^*) + \ldots)$$

Results









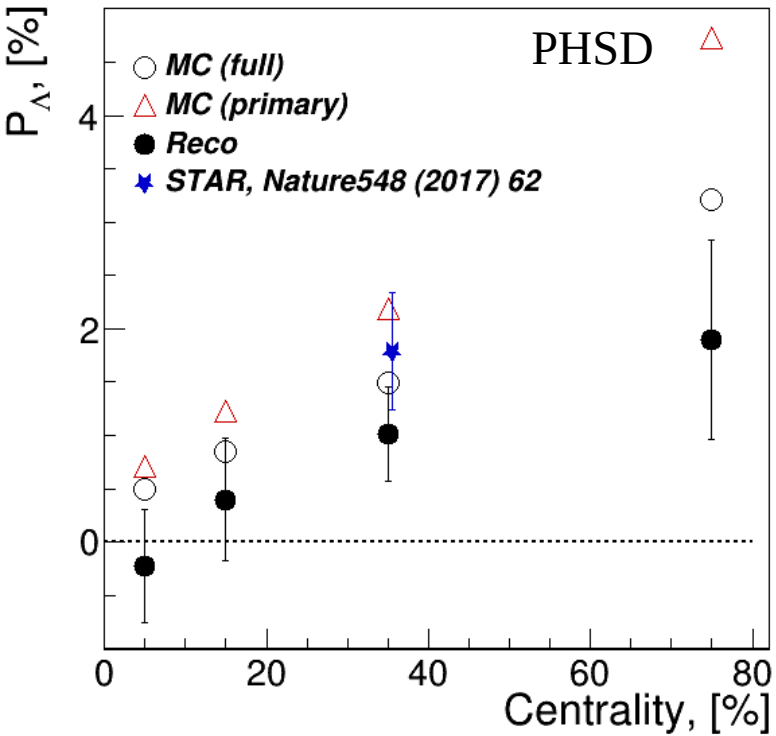
$$P_\Lambda = \frac{8}{\pi \alpha_\Lambda} \frac{p_1}{R^1_{\mathrm{EP}}}$$

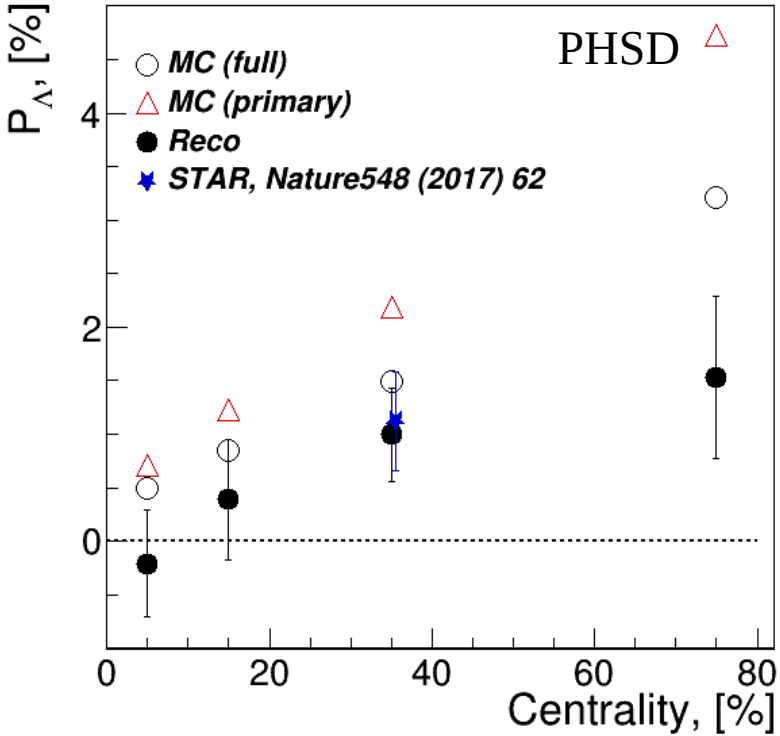
$$\alpha_\Lambda \simeq 0.732$$

$$N_\Lambda \sim 2 * 10^5$$

$$\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi^*_p} = [0](1 + 2[1]\sin(\Delta\phi^*_p) + 2[2]\cos(\Delta\phi^*_p) + 2[3]\sin(2\Delta\phi^*_p) + 2[4]\cos(2\Delta\phi^*_p) + ...)$$

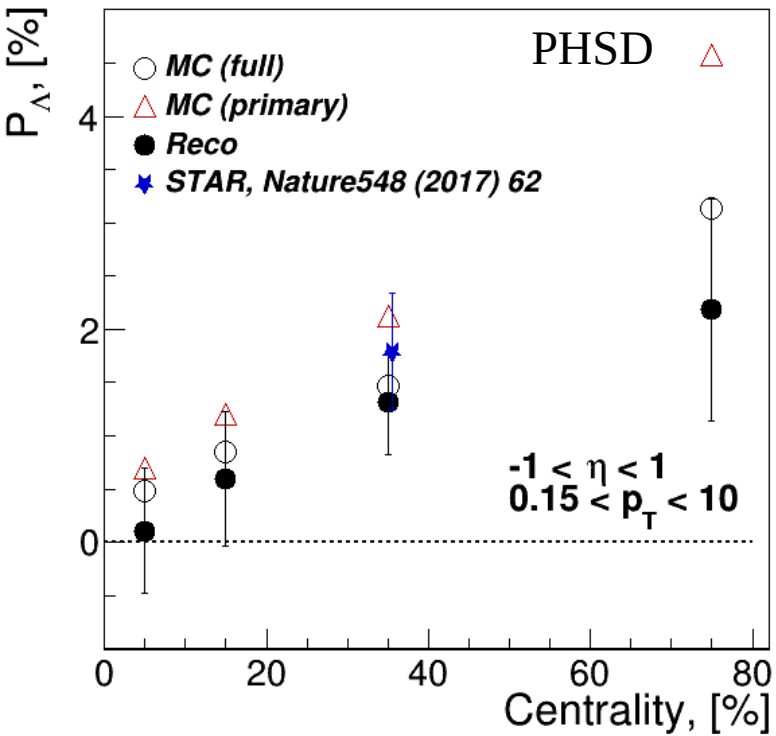
Results

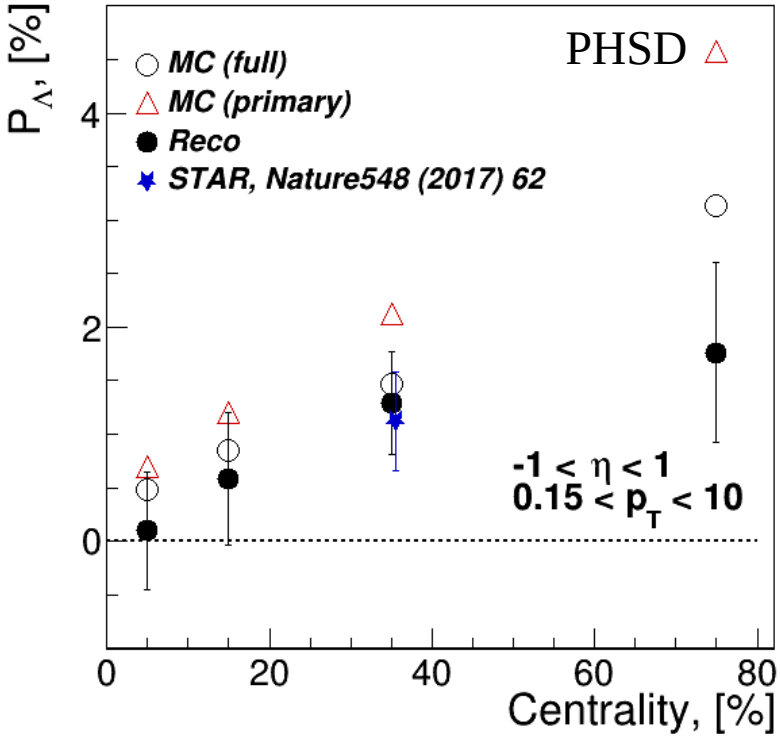




- STAR measurement is corrected for the new value of decay asymmetry
- (left) corrected for EP resolution (right) no resolution correction
- Feed-down from decays lowers polarization value

Results





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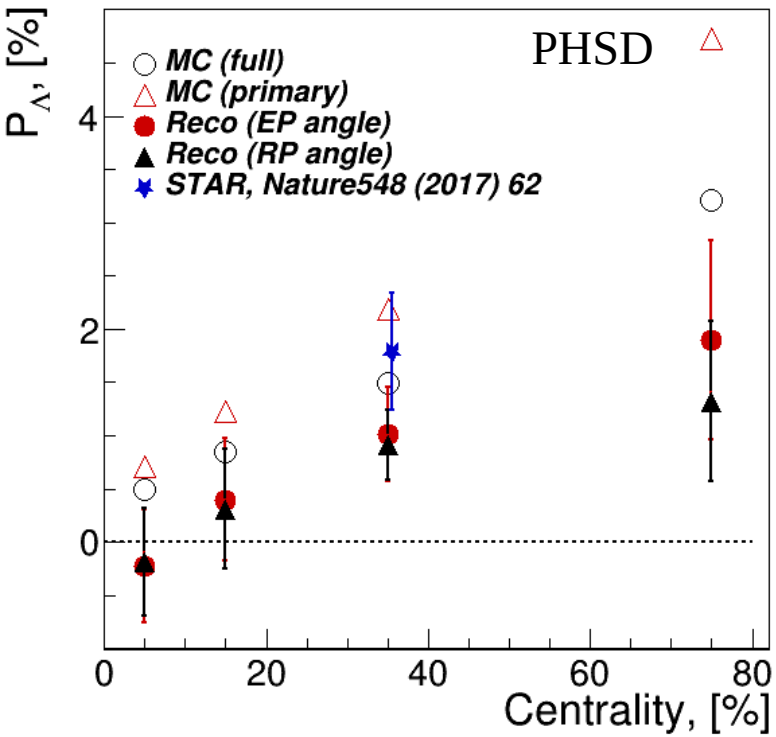
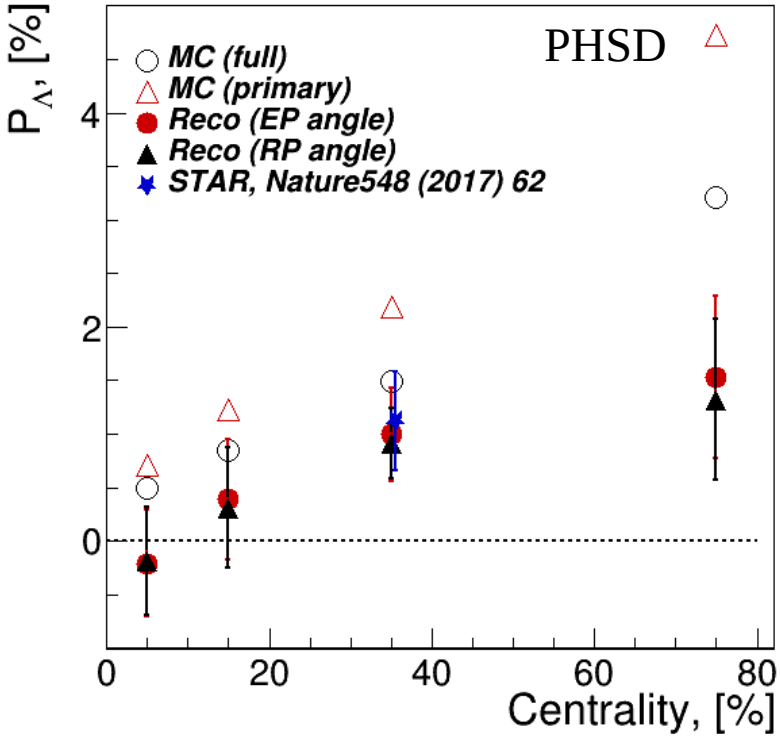


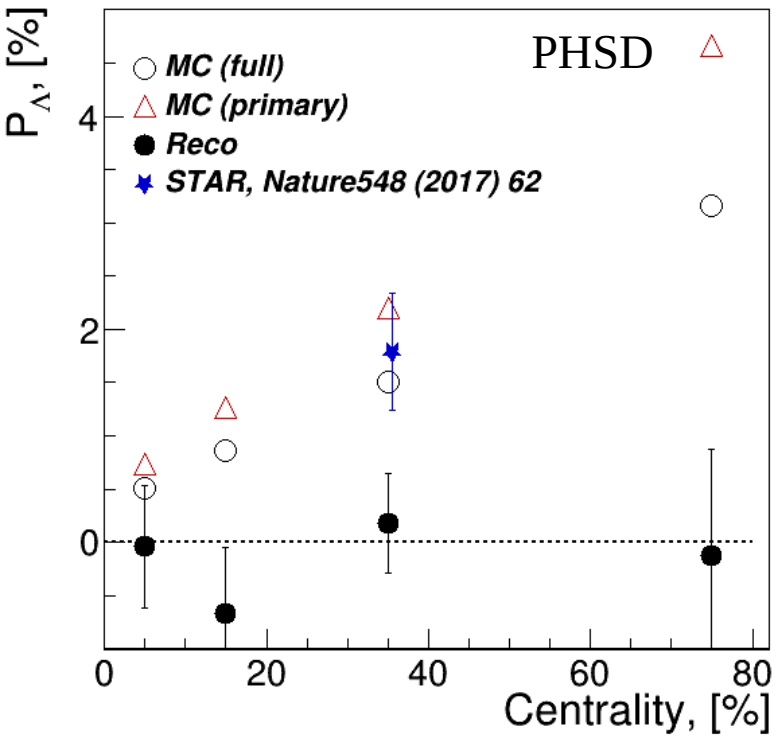


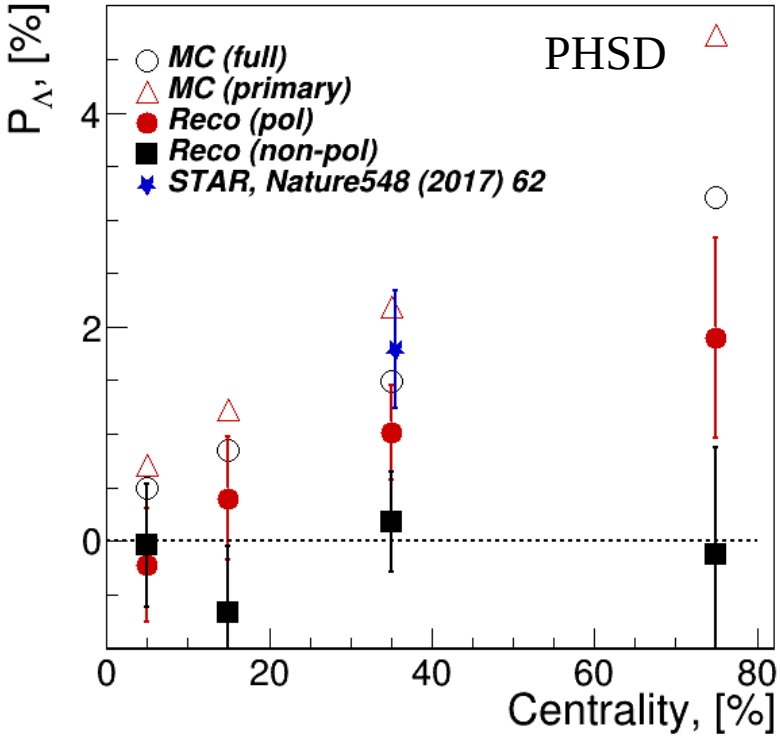
- Measurement w.r.t. RP angle (no resolution required)
- (left) corrected for EP resolution
- (right) no resolution correction

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

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

Results





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

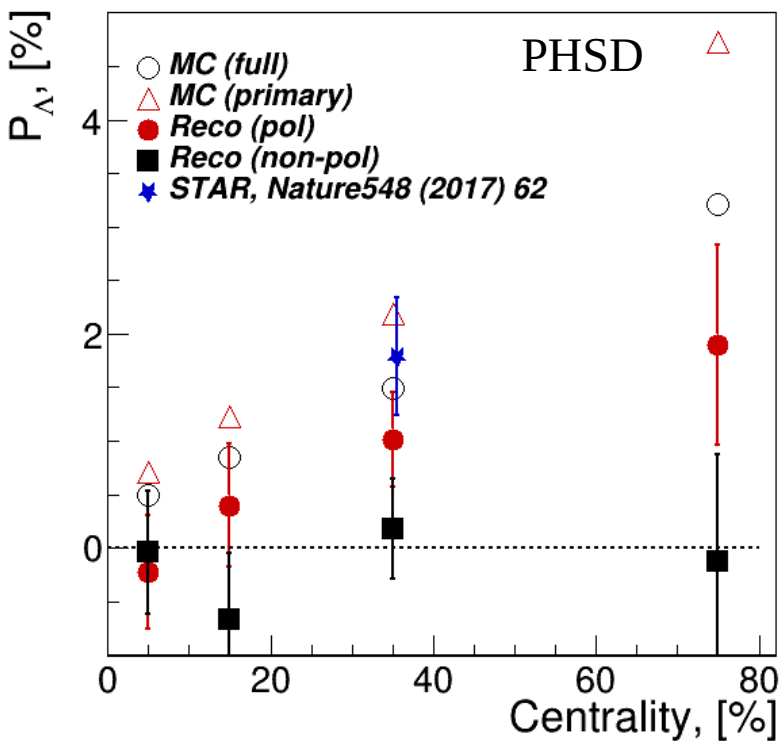
$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = 1 + \alpha_\Lambda |\vec{P}_\Lambda| \cos\theta^*$$

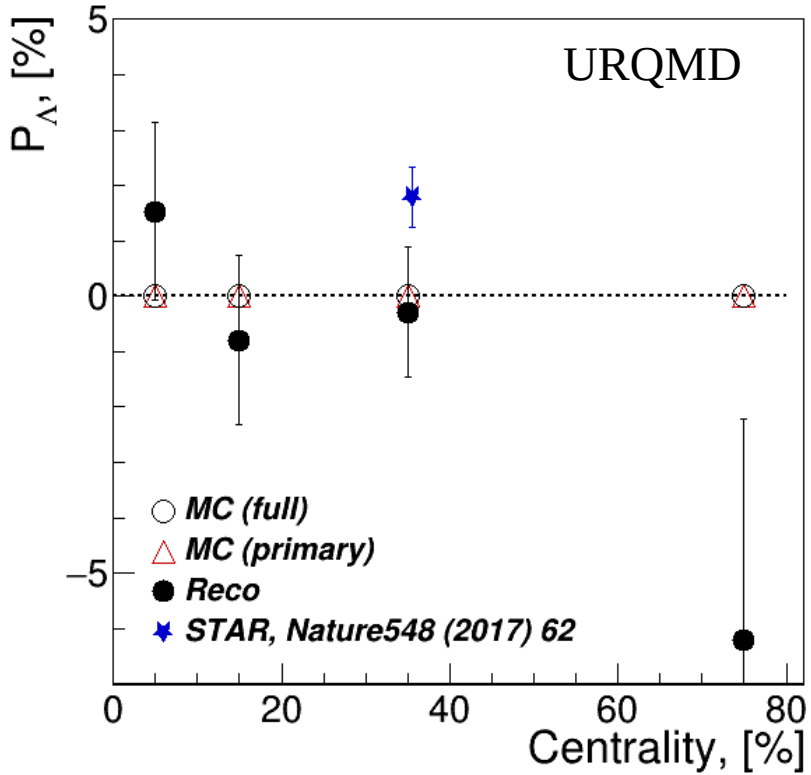
Conclusions

- 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

The End

Thank you for your attention!



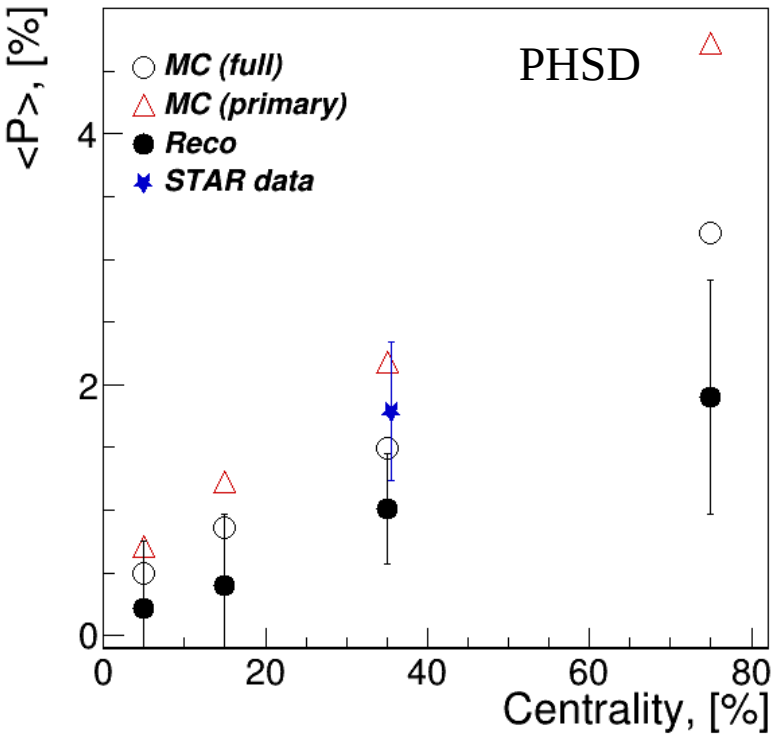


$N_\Lambda \sim 5 * 10^4$ (URQMD)

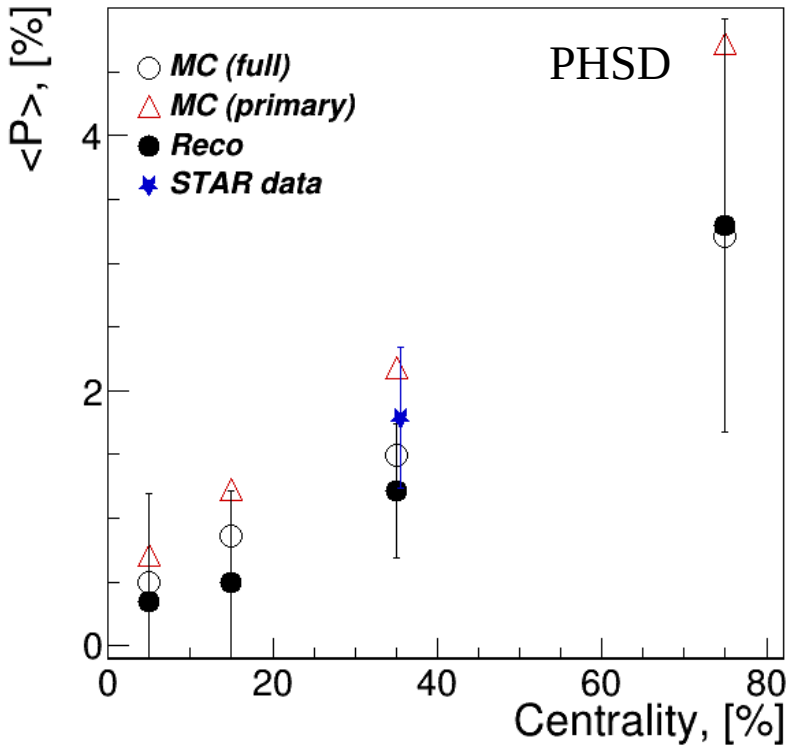
$N_\Lambda \sim 2 * 10^5$ (PHSD)

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

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

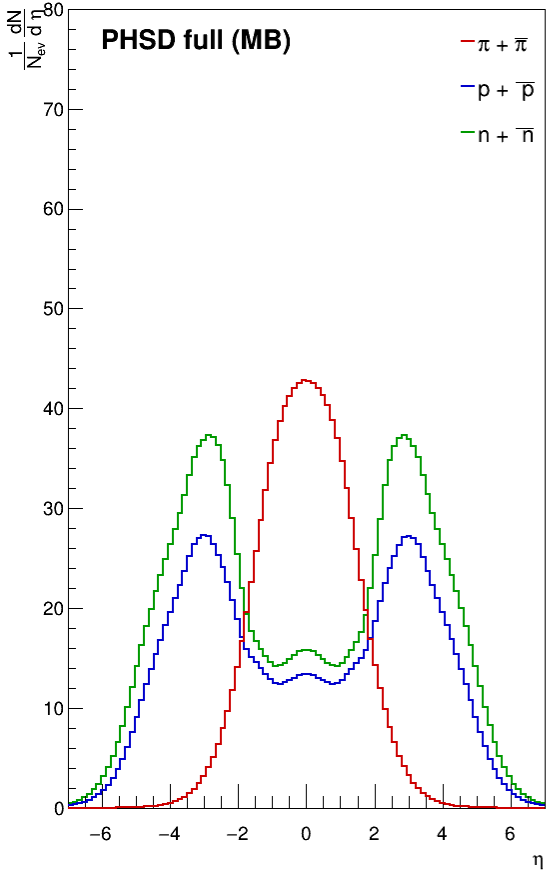


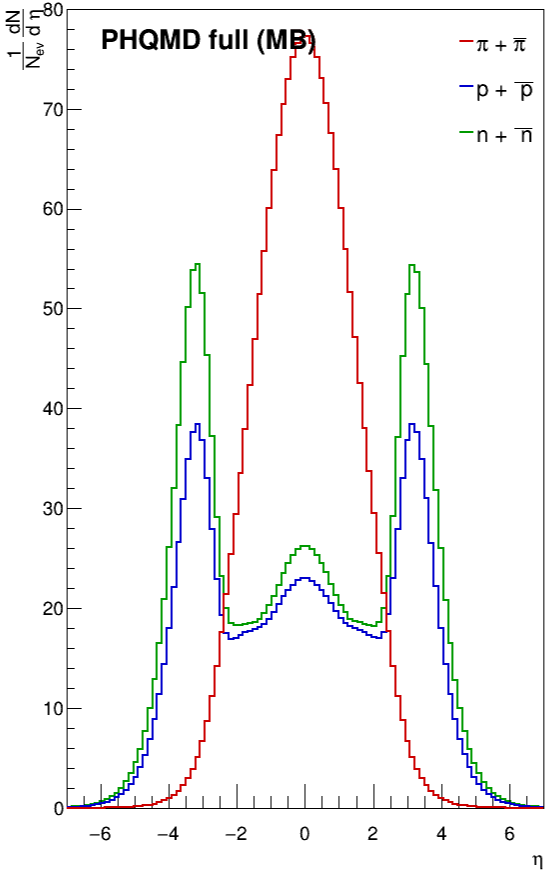
Using PHSD EP resolution values

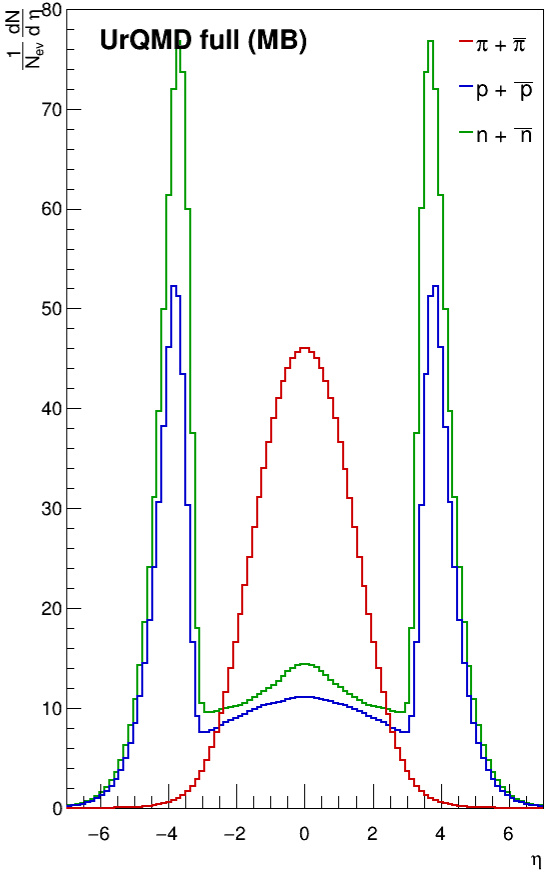


Using UrQMD EP resolution values

Back Up

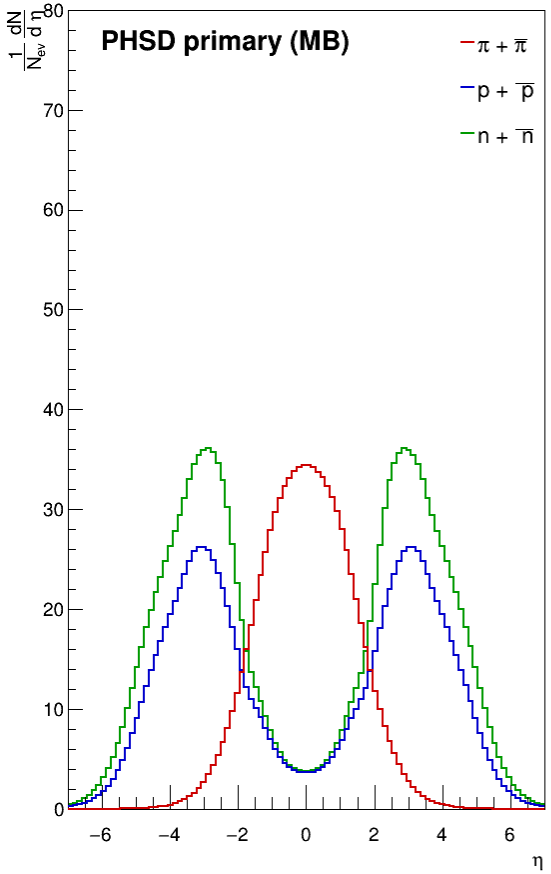


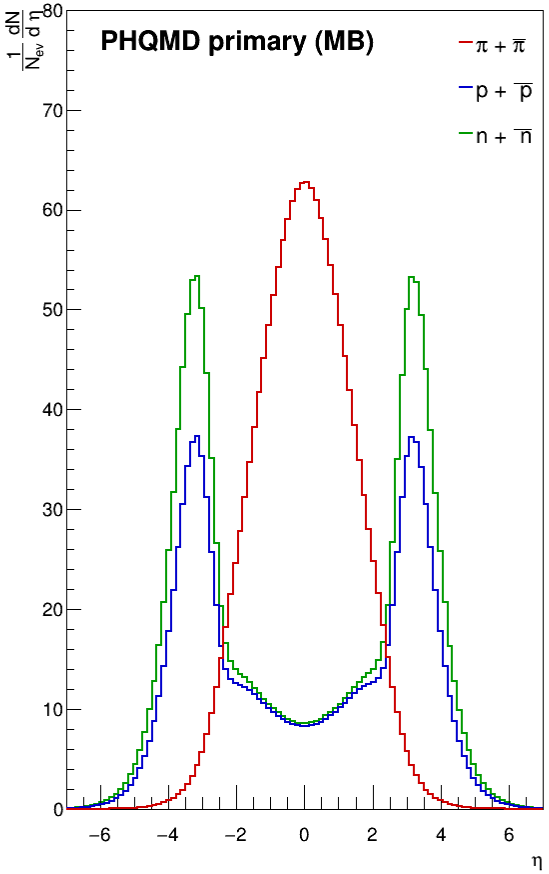


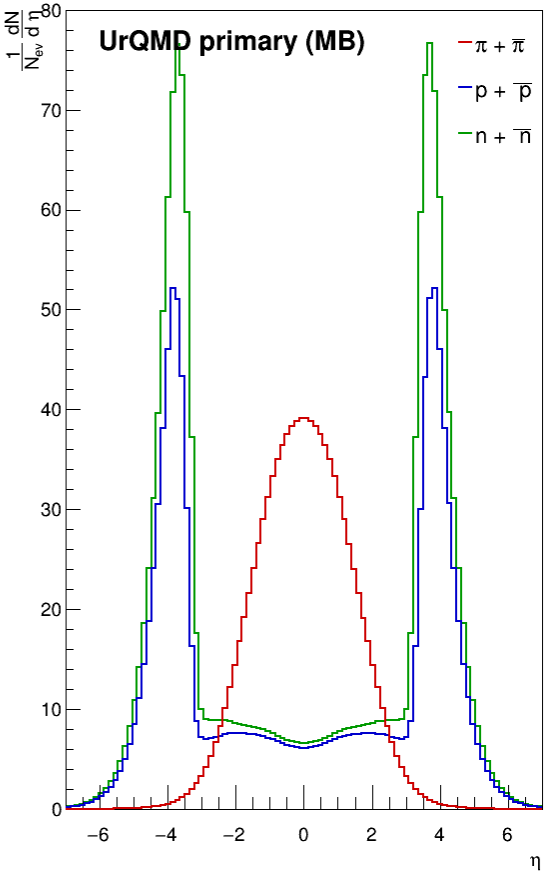


$2 < |\eta| < 5$ region corresponds to FHCal

Vertex cut of 50cm

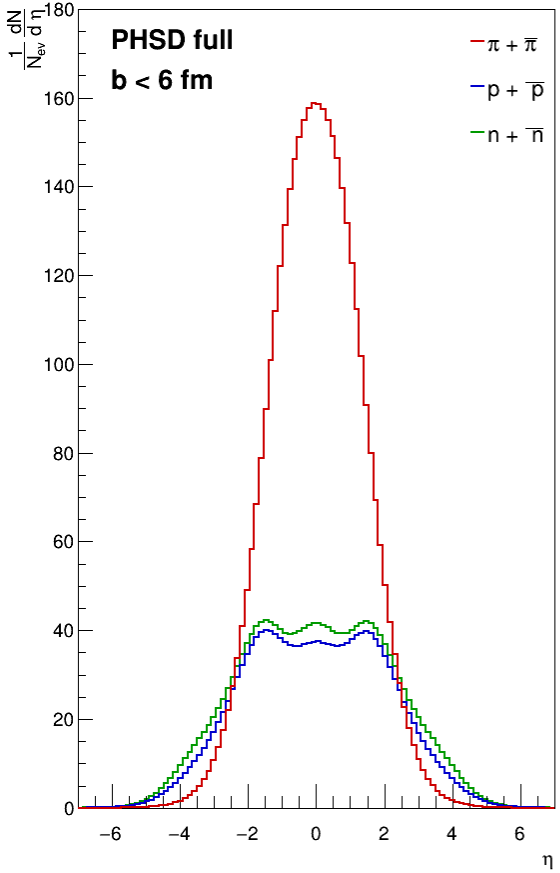


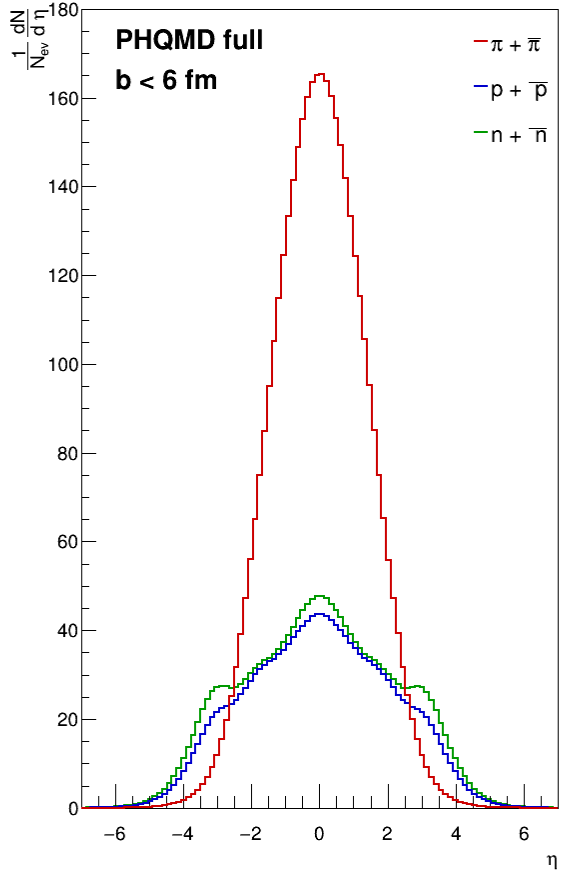


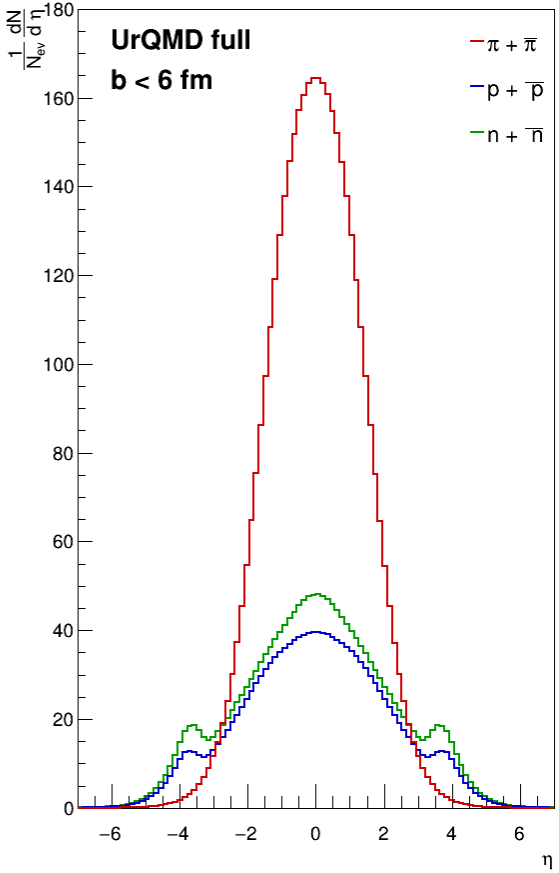


$2 < |\eta| < 5$ region corresponds to FHCal

Back Up

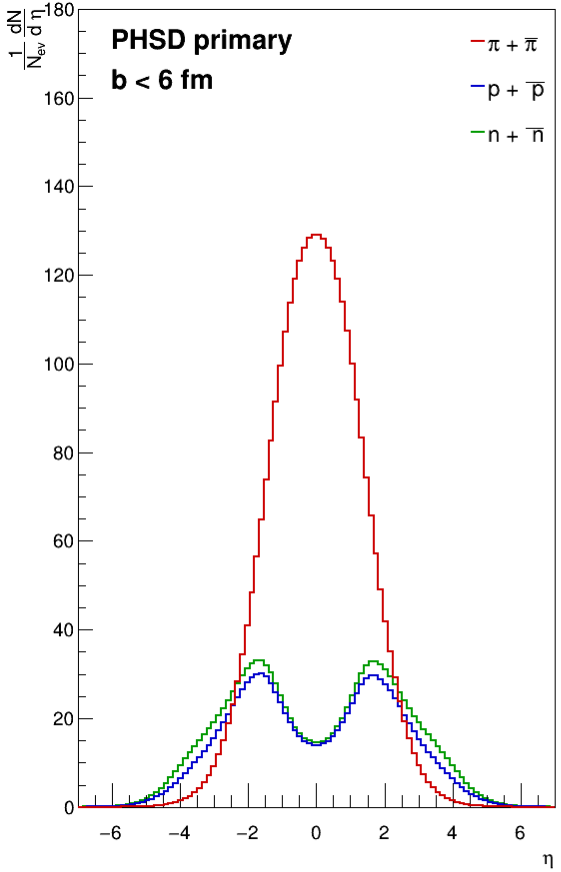


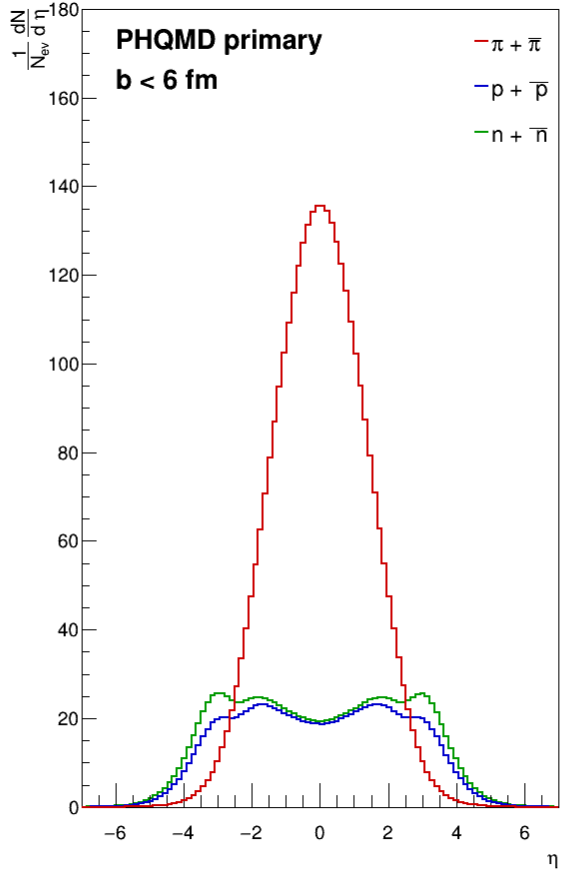


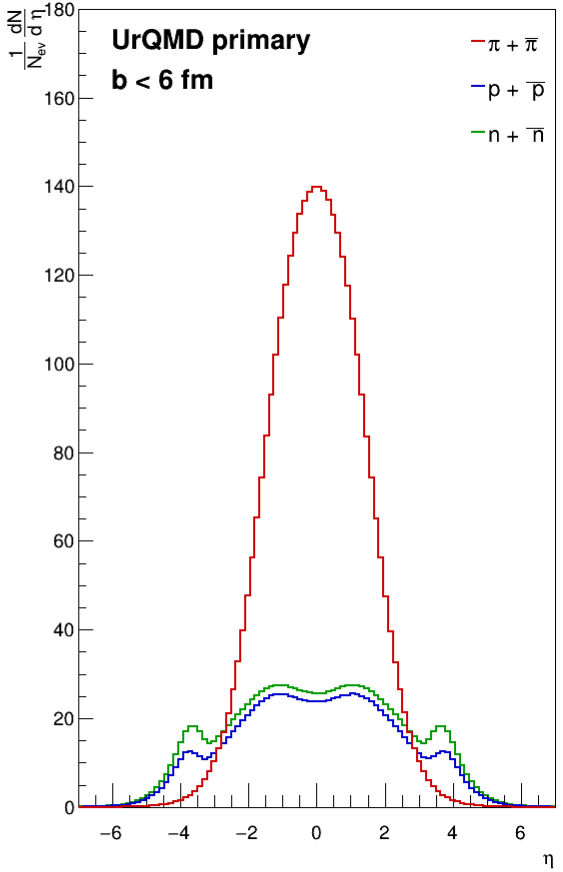


$2 < |\eta| < 5$ region corresponds to FHCal

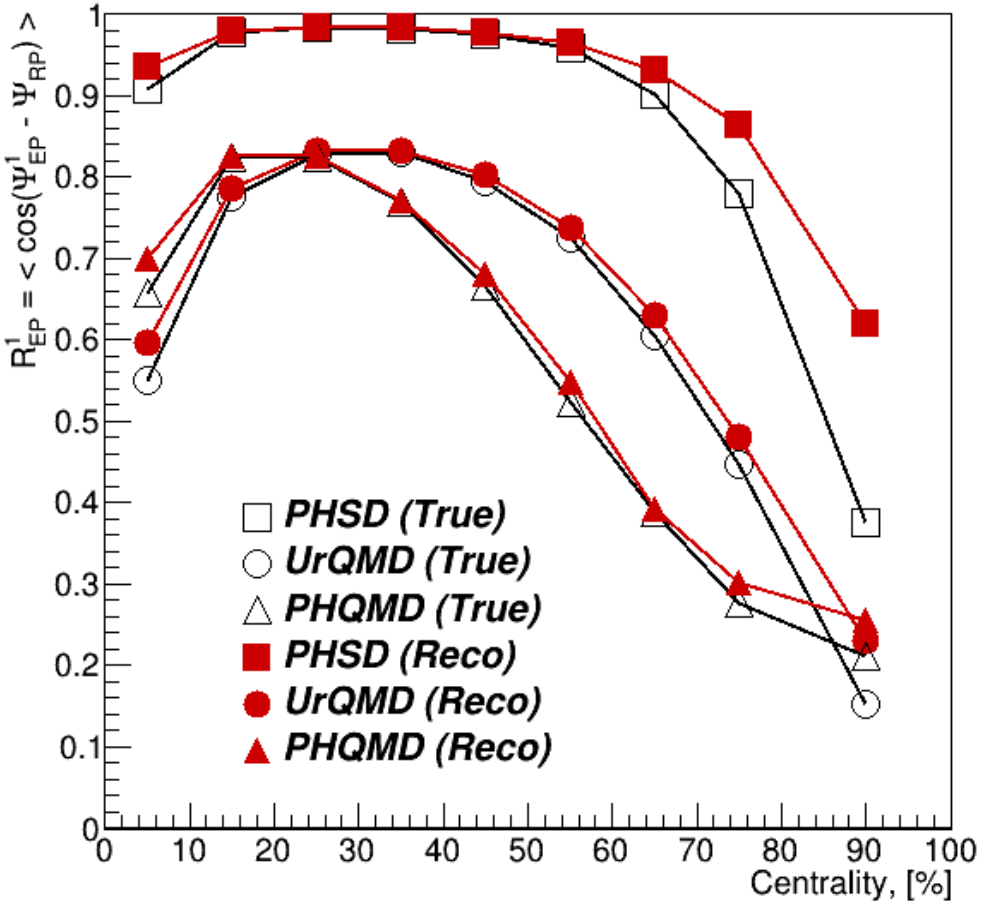
Back Up





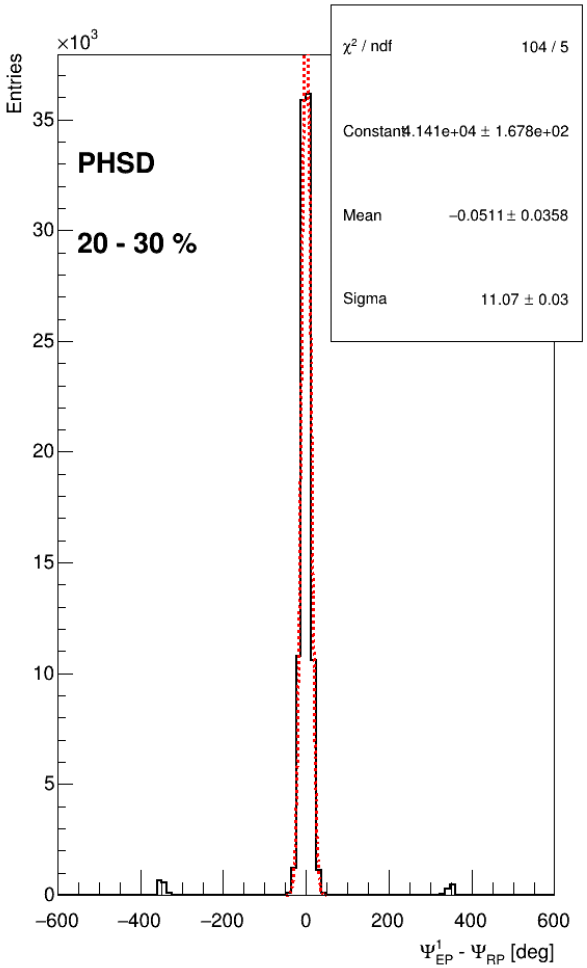


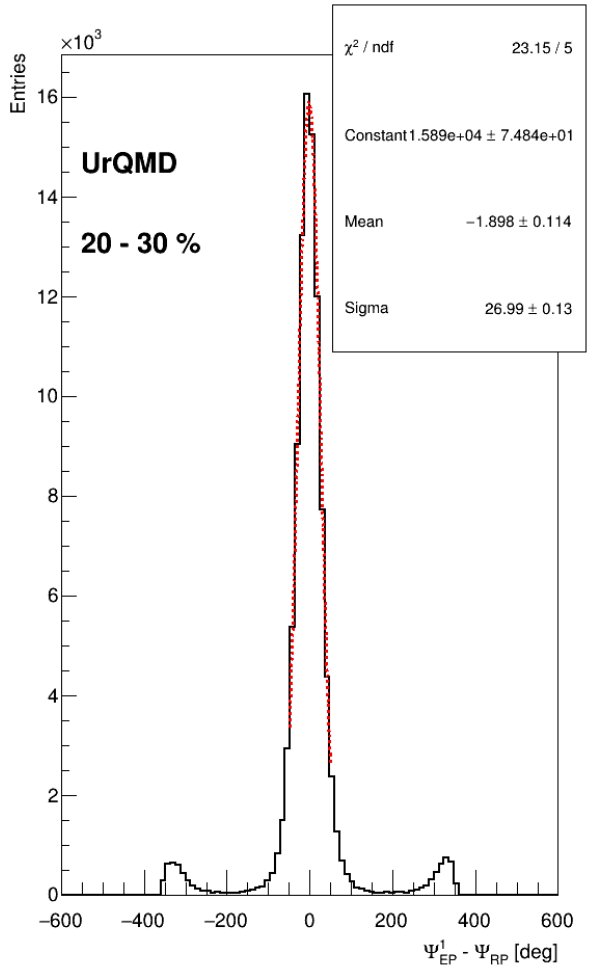
$2 < |\eta| < 5$ region corresponds to FHCal

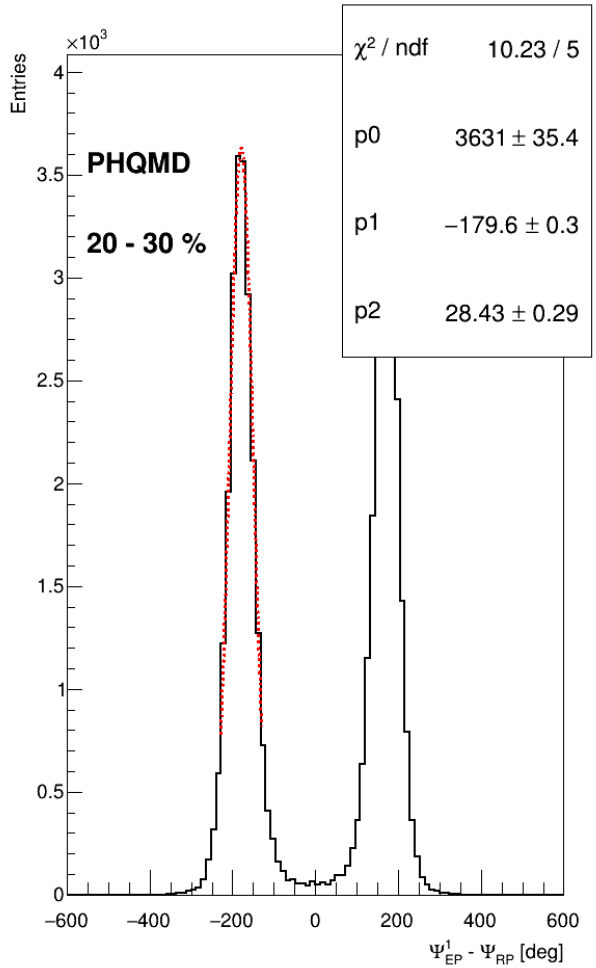


- Comparison of the UrQMD, PHQMD & PHSD models
  - Much lower statistics in the PHQMD sample
  - 1-order EP resolution is similar for UrQMD and PHQMD
  - Feature of the PHQMD model: reaction plane is shifted by 180deg → need to account for the shift in the calculations

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]