Hyperon Polarization at NICA/MPD

Elizaveta Nazarova[1] et al.

«Vorticity and Polarization in Heavy-Ion Collisions»

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

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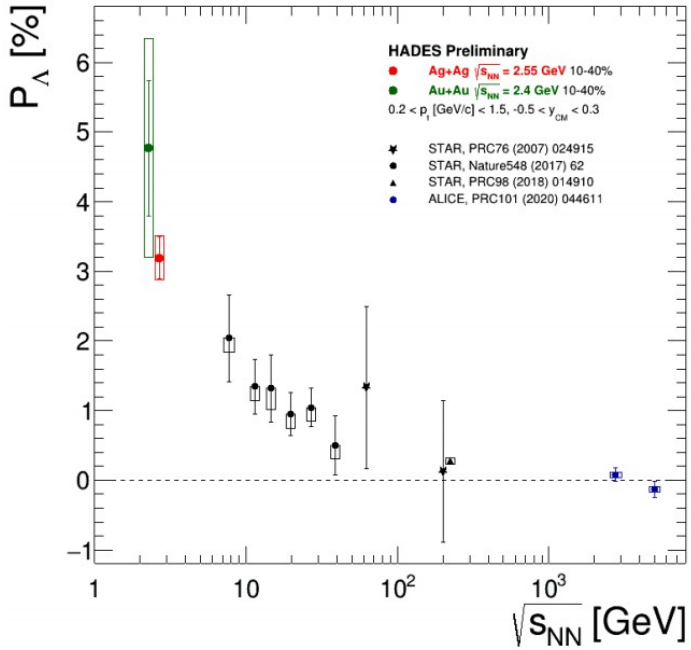
[1] Joint Institute of Nuclear Research, Dubna, Russia

Outline

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

Introduction

- Predicted[1] and observed[2,3] global polarization signals rise as the collision energy is reduced:
  - NICA energy range will provide new insight
- $\Lambda(\bar{\Lambda})$ - splitting of global polarization
- Comparison of models, detailed study of energy and kinematical dependences, improving precision
- Probing the vortical structure with new observables[4,5]



[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] O. Teryaev and R. Usubov, Phys. Rev. C 92, 014906 (2015)
[5] M. A. Lisa et al., Phys. Rev. C 104, 011901 (2021)

Introduction

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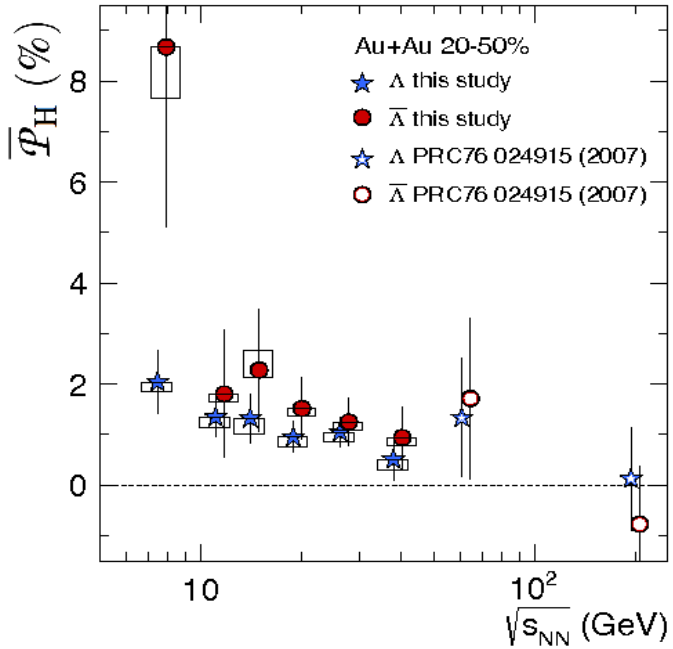

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Global hyperon polarization

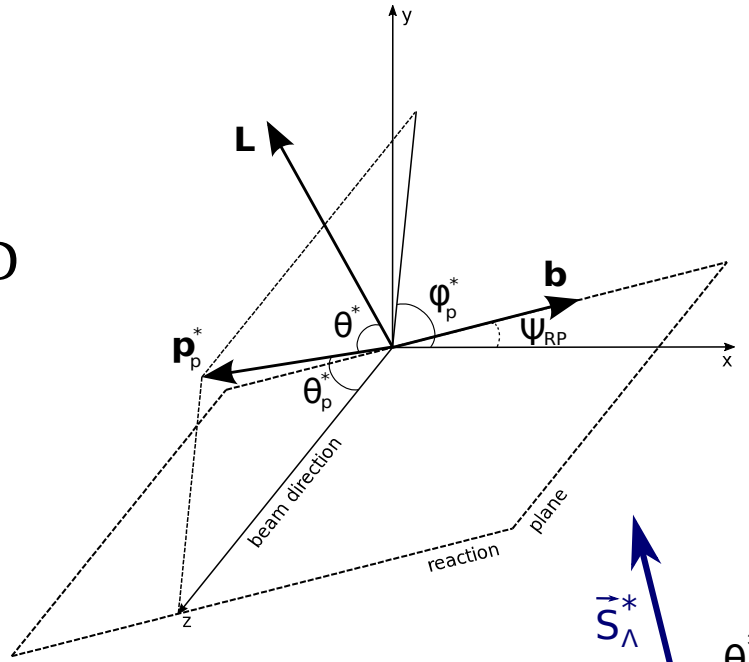
- w.r.t. reaction plane
- Emerges in HIC due to the system angular momentum[1,2]
- Sensitive to parity-odd characteristics of QCD medium and QCD anomalous transport
- Measured through the weak decay:

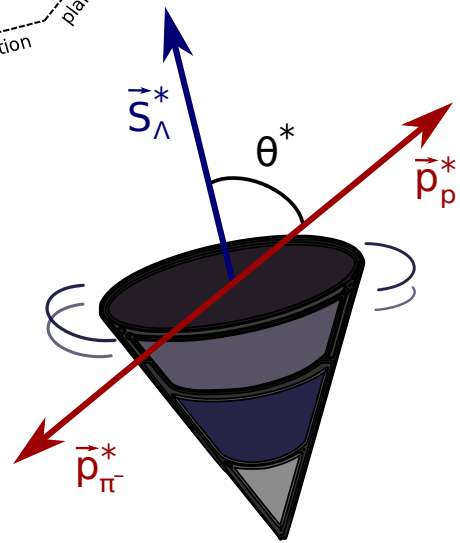
$$\Lambda \to p + \pi^-$$

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

$$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} \simeq 0.732 \quad \text{(Updated value[3])}$$

- * — 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)
[3] Ablikim M, et al., Nature Phys. 15:631 (2019)

Global hyperon polarization

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

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

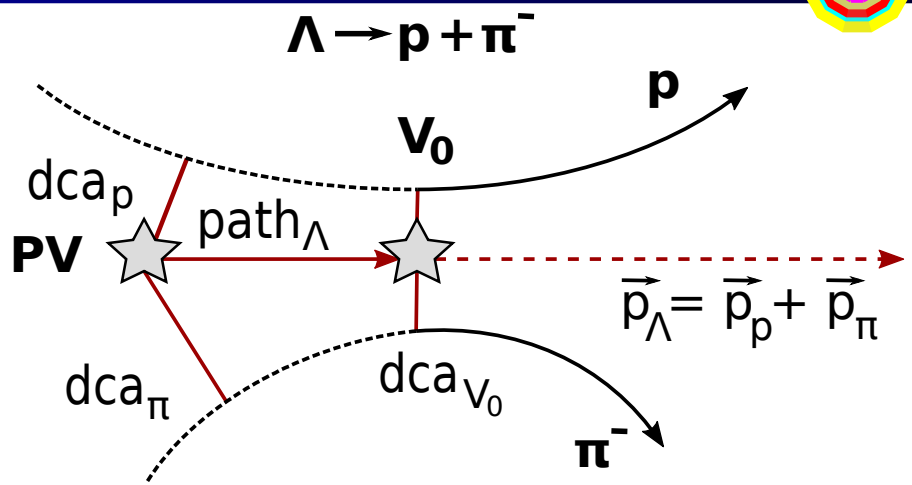
- φ^* — azimuthal angle of decay particle

→ Determine centrality

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

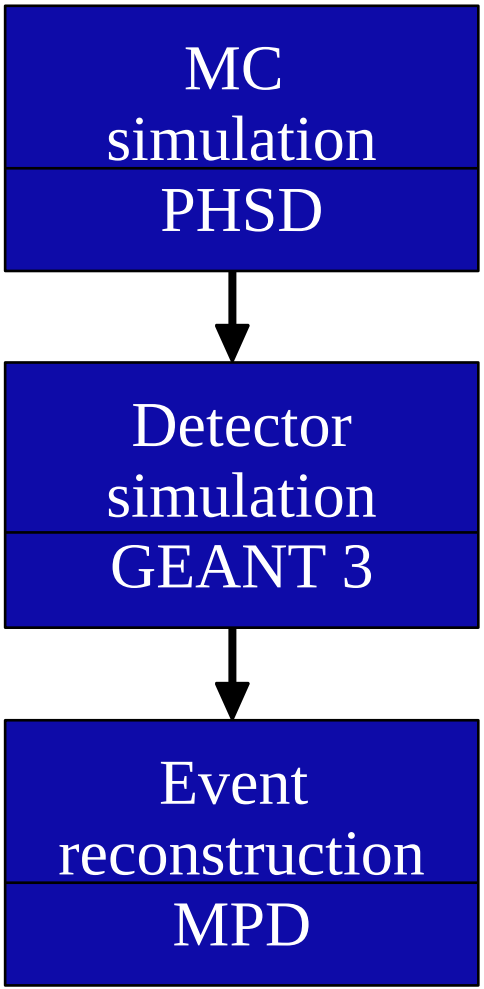
→ Reconstruct Lambda

→ Global polarization



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

Analysis technique

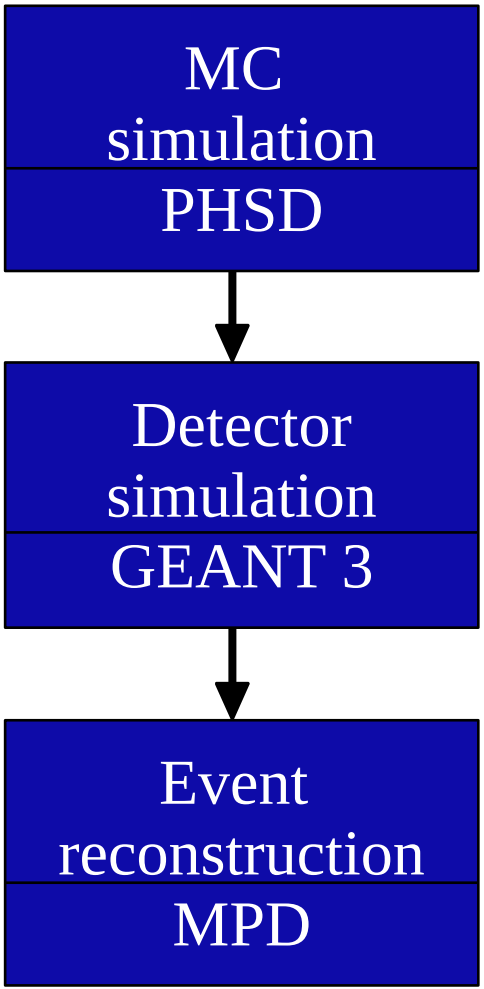


- MC simulation using PHSD generator[1]
  - Bi-Bi @ 9GeV, 10M MB events, b [0,12]fm (request 23)
  - Global hyperon polarization
    - Thermodynamical (Becattini) approach[2]
    - Higher polarization for $\bar{\Lambda}$ (w.r.t. Λ)

[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 using PHSD generator[1] (new)
  - Bi-Bi @ 9GeV, 10M MB events, b [0,12]fm (request 23)
  - Global hyperon polarization
    - Thermodynamical (Becattini) approach[2]
    - Higher polarization for $\bar{\Lambda}$ (w.r.t. Λ)

- MC simulation using PHSD generator[1] (previous)
  - Au-Au @ 7.7GeV, 1.4M MB events, b [0,16]fm
  - Global hyperon polarization
    - Thermodynamical (Becattini) approach[2]

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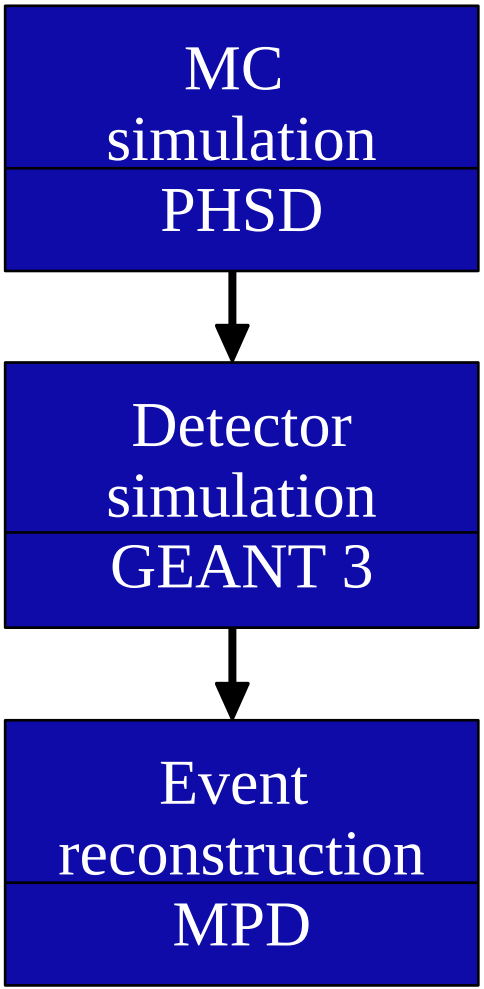
[1] W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

[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 (<u>can be turned on/off</u>)
  - $\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = 1 + \alpha_\Lambda |\vec{P}_\Lambda| \cos\theta^*$ (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

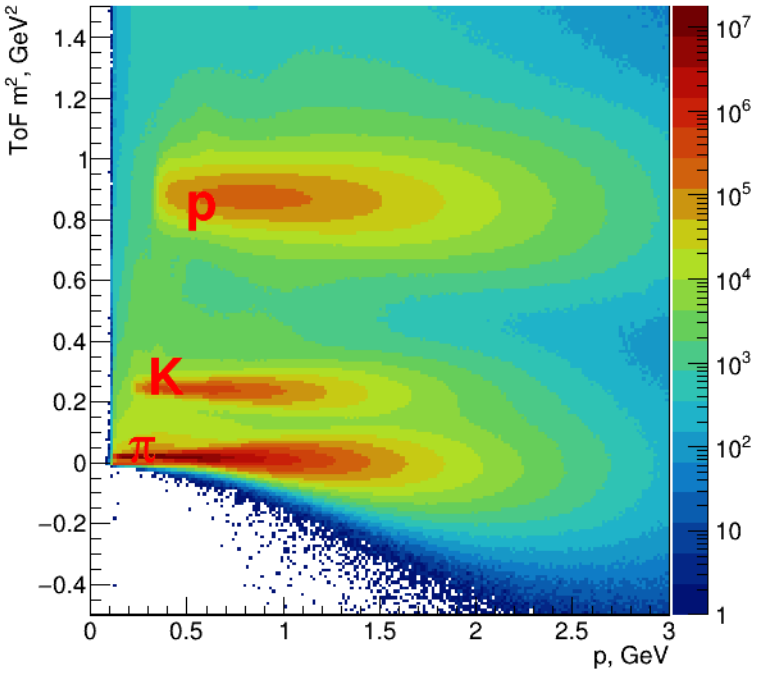
↓

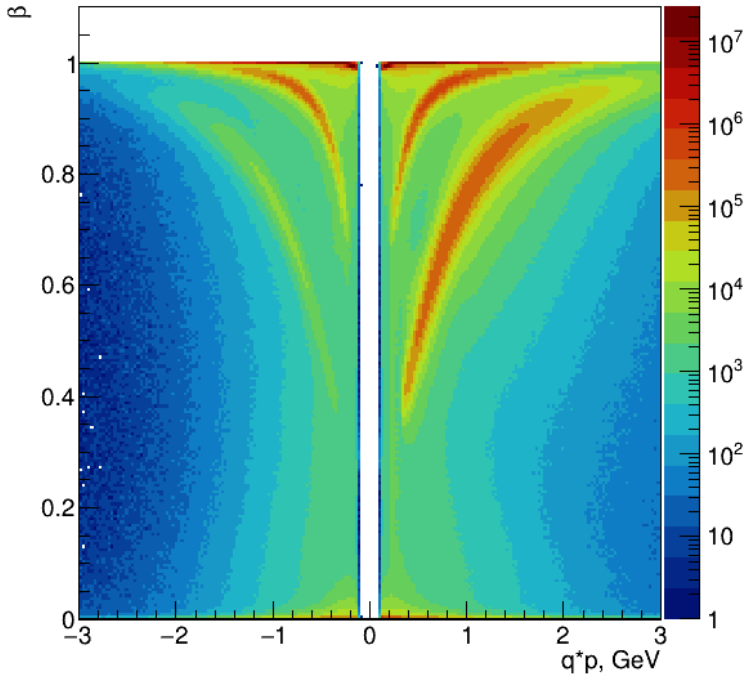
Detector simulation
GEANT 3

↓

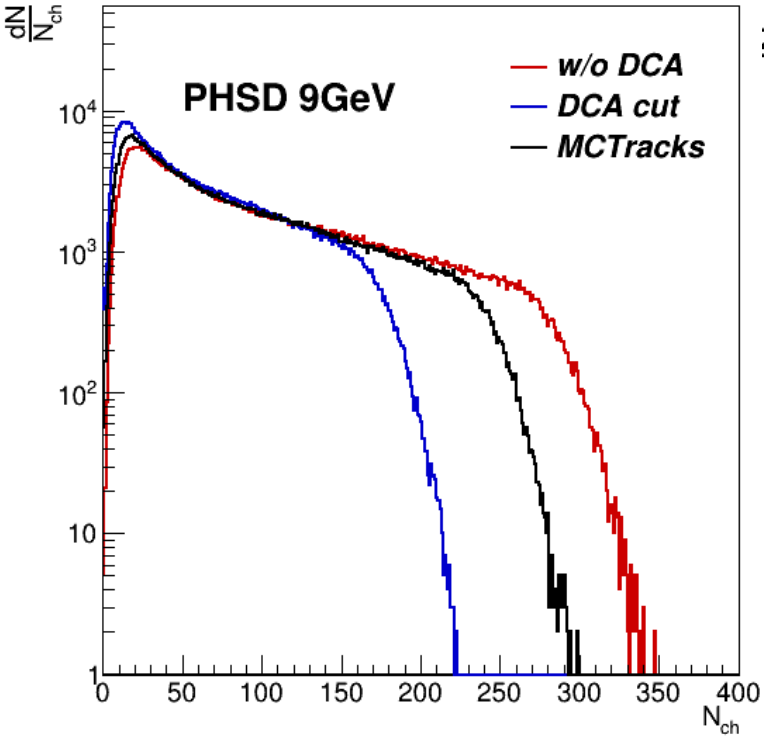
Event reconstruction
MPD

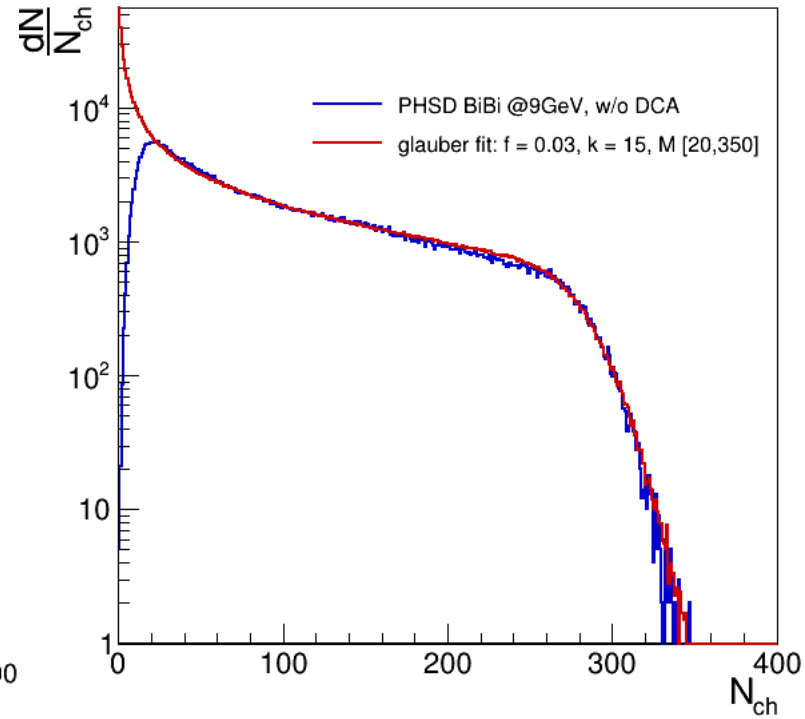
- Event reconstruction
  - Centrality and Event Plane determination
  - Realistic PID
  - Reconstruction of Λ hyperons via their weak decay





Centrality determination

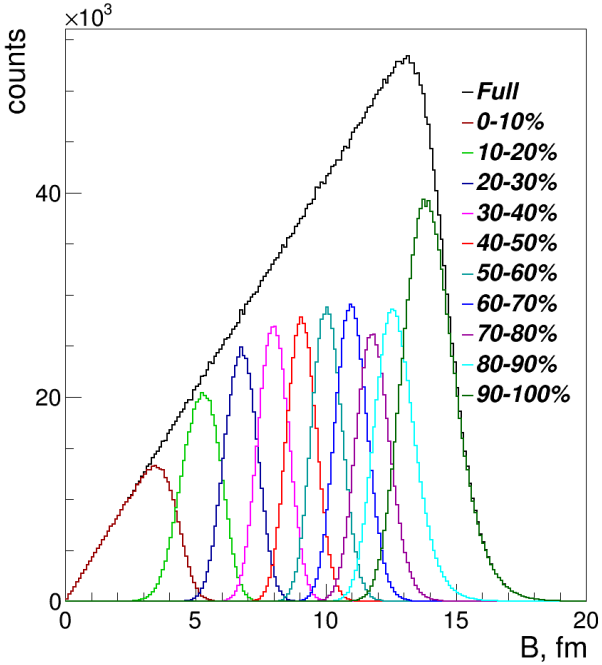


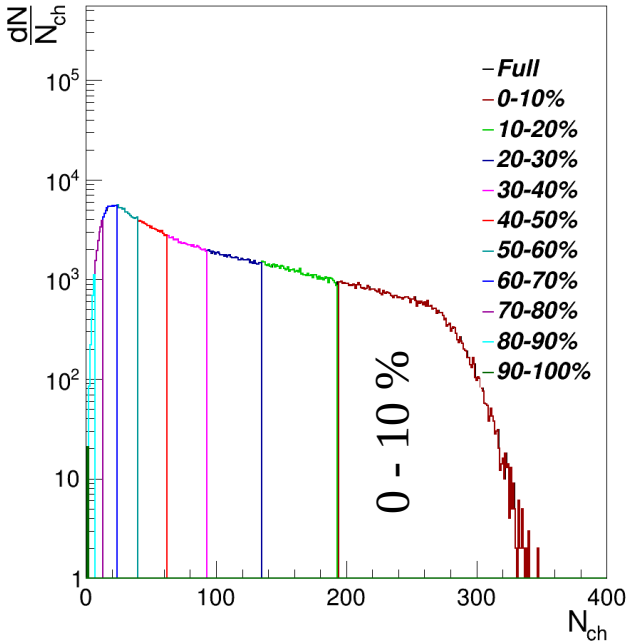


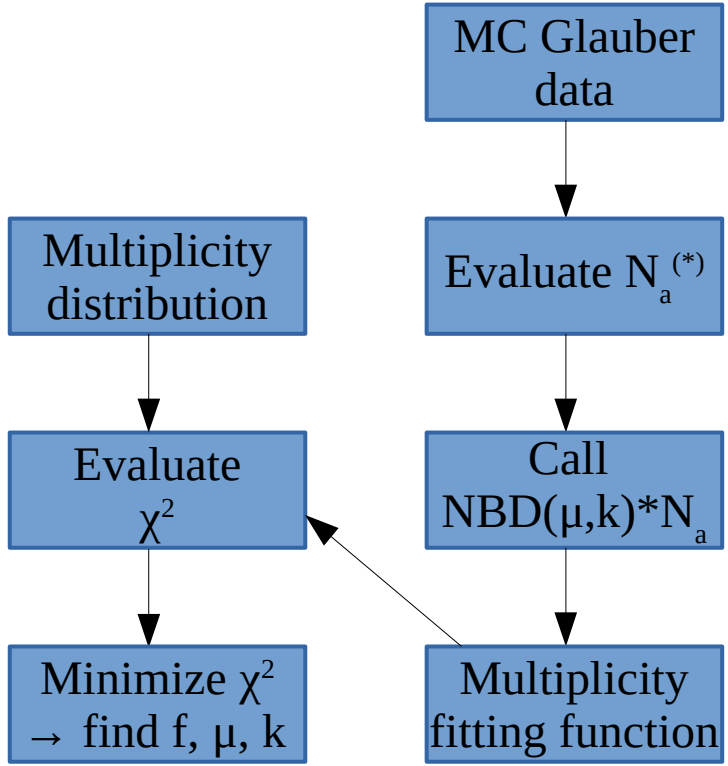
- MC-Glauber based centrality framework[1]
- Selection criteria:
  - 500k events
  - $|\eta| < 0.5$
  - $|p_T| > 0.15$ GeV
  - $N_{hits} > 16$
  - $|DCA| < 0.5$ cm (optional)
  - 10%-centrality bins

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

Centrality determination



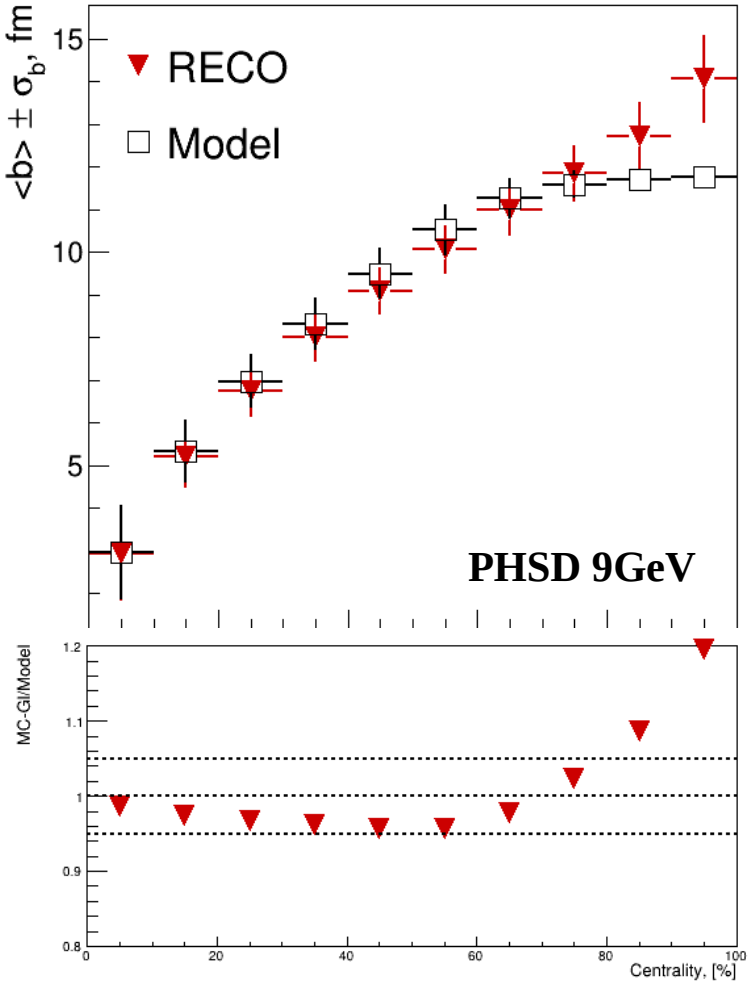




[1] P. Parfenov et al, NRNU MEPhI for the MPD collaboration (https://github.com/FlowNICA/CentralityFramework)

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

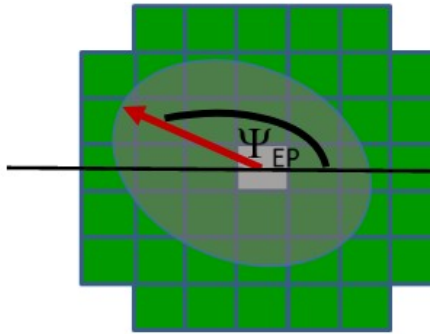
Centrality determination



- Completed calibration of centrality
  - Full analysis for 10%-centrality bins
  - 4 intervals of centrality chosen (0-10%, 10-20%, 20-50%, 50-100%), for comparison with previous results
- Choice of b [0,12]fm reduces amount of events without interaction (~1% compared to ~20% we had with b [0,16]fm)
- Agreement within ~5% for impact parameter
  - Except for the last two centrality bins (80-90%, 90-100%)
  - Excluded them from the main analysis

Event plane determination

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



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

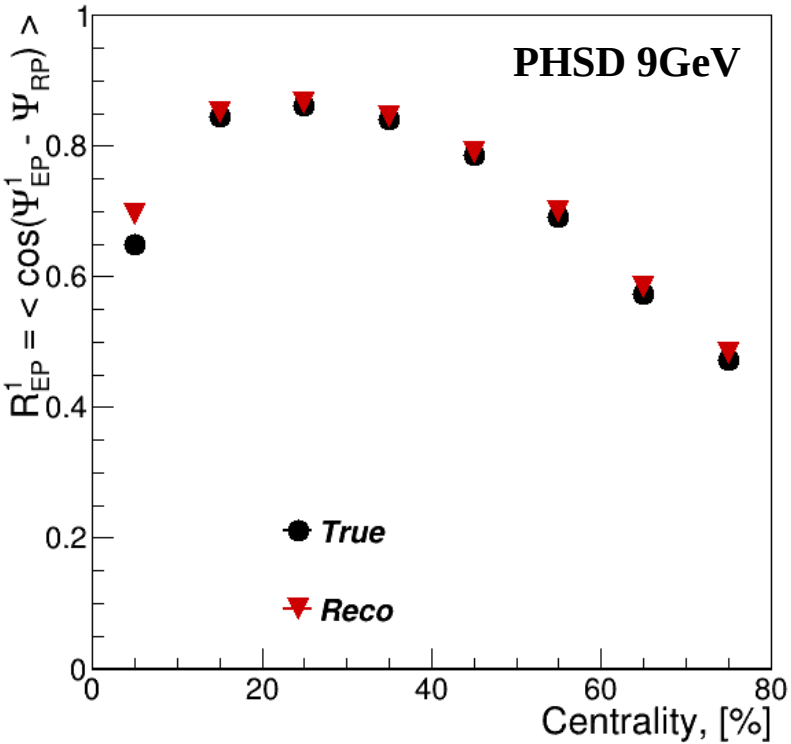
$\mathrm{w}_i = p_{\mathrm{T}i} / p_{\mathrm{T}\mathrm{total}}$ (TPC)

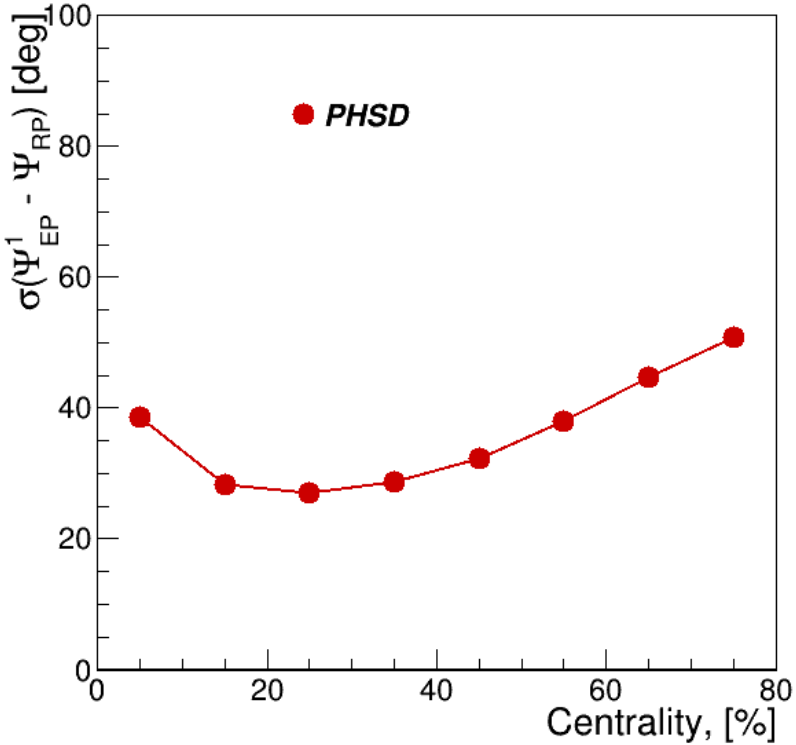
- Event plane resolution can be calculated as:
  - $R_{\mathrm{EP}}^{k} = \langle \cos(k(\Psi_{\mathrm{EP}}^{n} - \Psi_{\mathrm{RP}})) \rangle$ (w.r.t. reaction plane angle from the model)
  - $R_{\mathrm{EP}}^{k} = \sqrt{\left\langle \cos(k(\Psi_{\mathrm{EP,R}}^{n} - \Psi_{\mathrm{EP,L}}^{n})) \right\rangle}$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

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

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

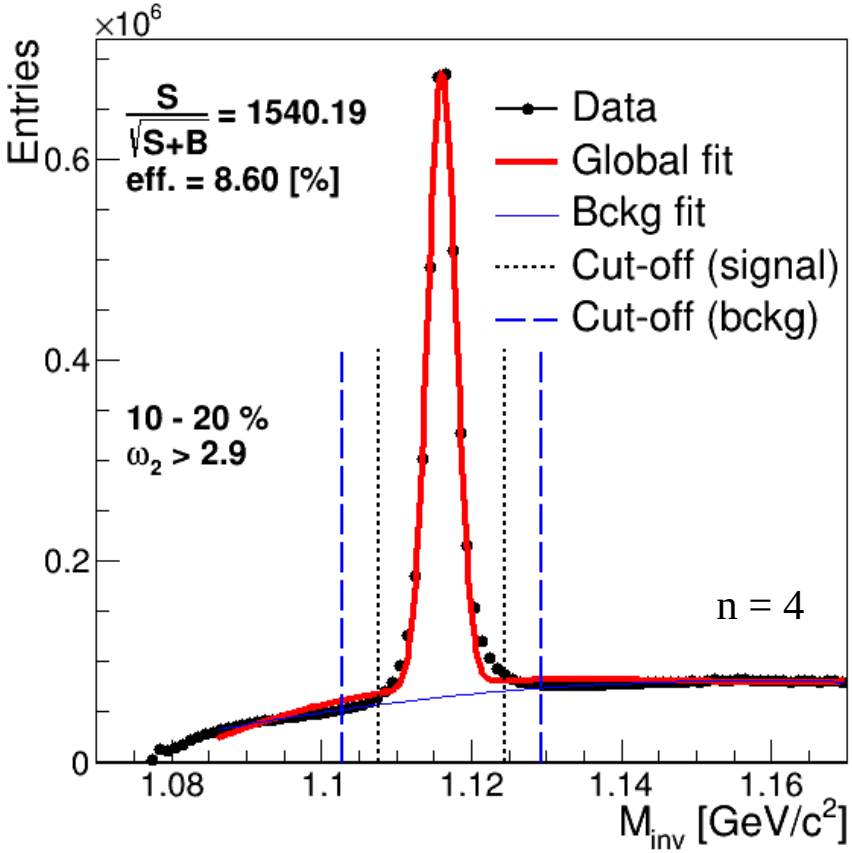
Event plane determination





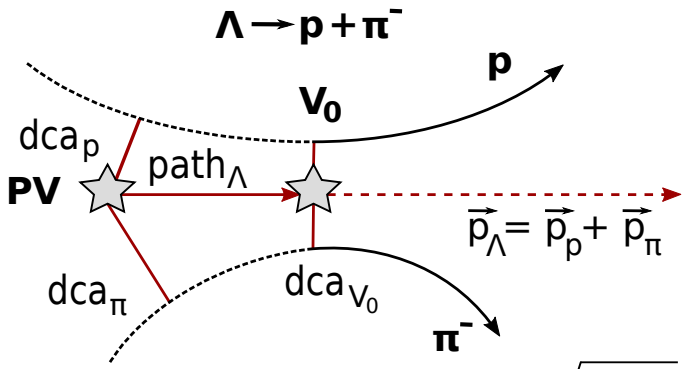
- 1-st order event plane resolution determined using FHCal
- Checked via 2 methods
  - Sub-event resolution method
  - Gaussian fit of distribution ($\Psi_{EP} - \Psi_{RP}$)

Lambda reconstruction



Fitting procedure:

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



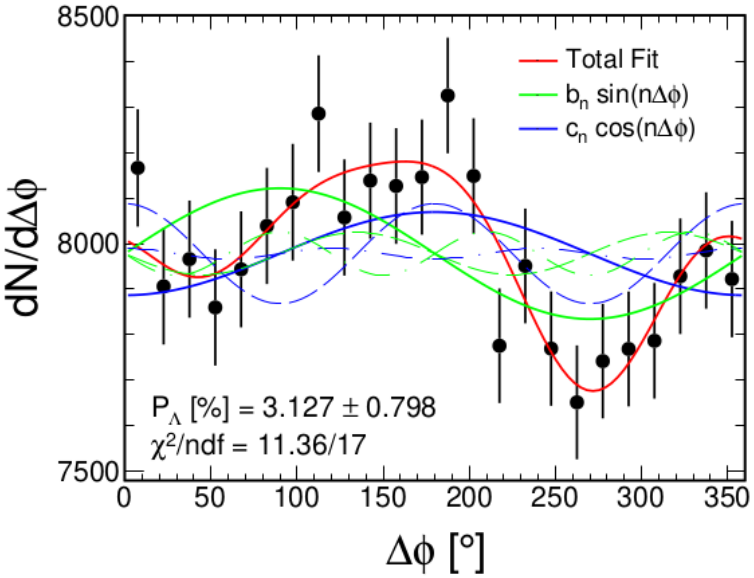
$$f(x) = p_0 \exp\left(\frac{(-0.5(x-p_1))^2}{p_2^2}\right) + p_3(L_0 + p_4 L_1 + p_5 L_2 + p_6 L_3 + p_7 L_4)$$

$$\omega_2 = \ln \frac{\sqrt{\chi^2_\pi \chi^2_p}}{\chi^2_\Lambda + \chi^2_{V_0}}$$

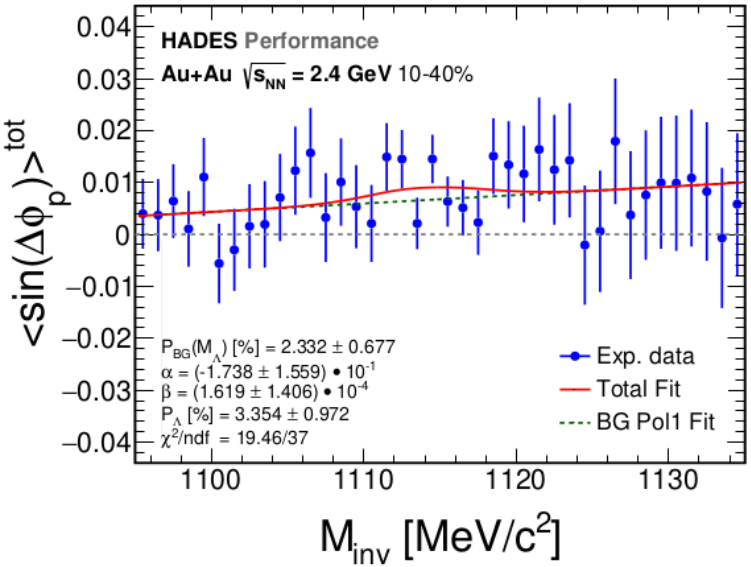
Global polarization reconstruction

Two methods of extracting global polarization (based on results by HADES)

- «Event plane» method
  - $\Delta\phi_p^*$ - extraction method
  - Net amount of Λ in each bin of $\Delta\phi_p^*$
  - Distribution of $N_\Lambda(\Delta\phi_p^*)$
- «Invariant mass» method
  - $\langle \sin(\Delta\phi_p^*)\rangle_{\mathrm{TOT}}(M_{inv})$ in bins of M_{inv}
  - Signal and Background fractions
  - Assumtion of linear shape of BG (M_{inv})

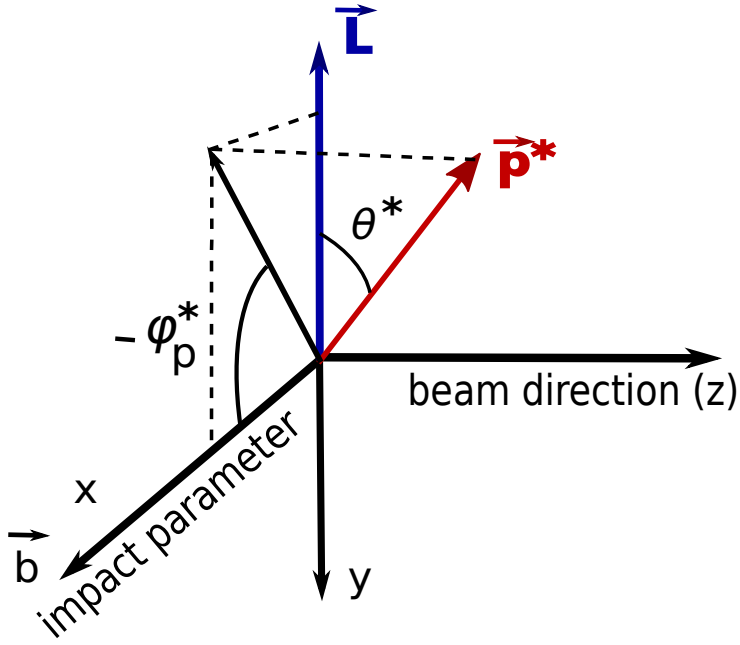


$$\Delta\phi_p^* = \Psi_{\mathrm{EP}}^1 - \phi_p^*$$



Global polarization reconstruction

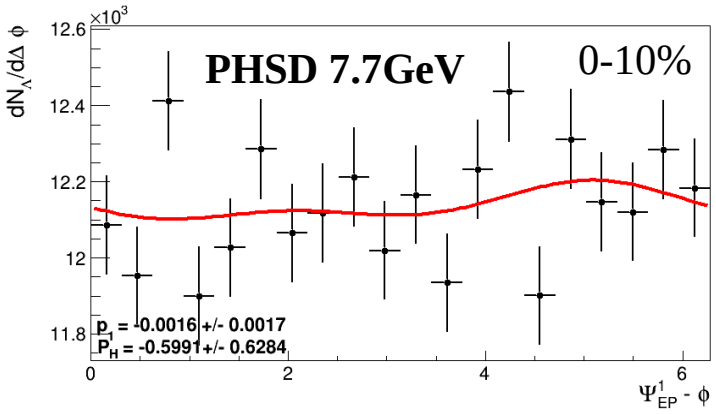
- Obtained invariant mass distribution in bins of $\Delta\phi_p^* = \Psi_{\mathrm{EP}}^1 - \phi_p^*$
  - Net amount of Λ in each bin
  - Distribution of $N_\Lambda(\Delta\phi_p^*)$
- Fit of the distribution[1] to get $\langle \sin(\Delta\phi_p^*) \rangle \rightarrow P_\Lambda$
  - «Event plane» method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

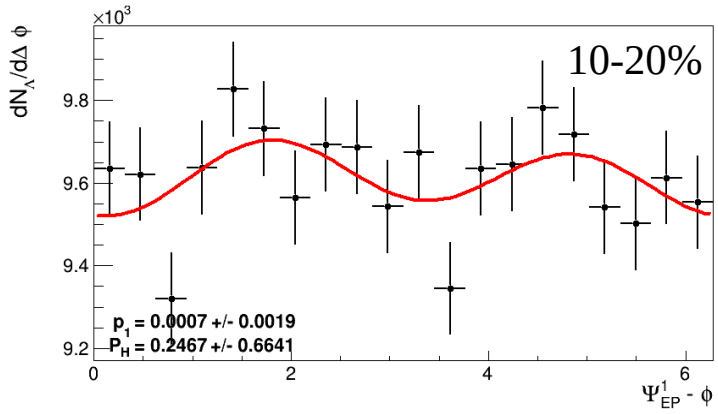


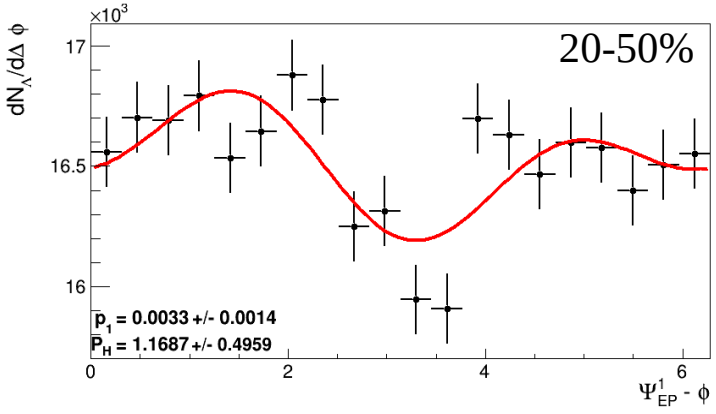
$$\overline{P}_{\Lambda/\bar{\Lambda}} = \frac{8}{\pi\alpha}\frac{1}{R_{\mathrm{EP}}^1}\left\langle \sin(\Psi_{\mathrm{EP}}^1 - \phi_p^*) \right\rangle$$ (recall)

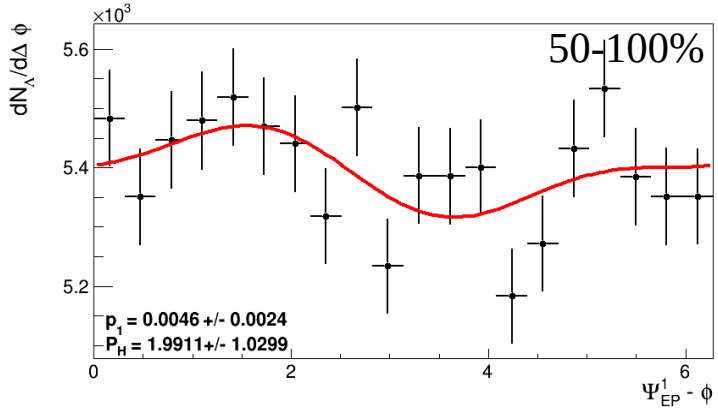
[1] $$\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi_p^*} = p_0(1 + 2p_1\sin(\Delta\phi_p^*) + 2p_2\cos(\Delta\phi_p^*) + 2p_3\sin(2\Delta\phi_p^*) + 2p_4\cos(2\Delta\phi_p^*) + \ldots)$$

Results (previous)









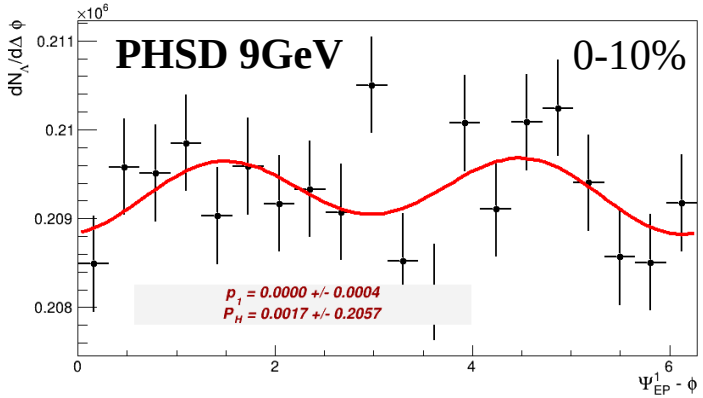
$$P_\Lambda = \frac{8}{\pi \alpha_\Lambda} \frac{p_1}{R^1_{\mathrm{EP}}}$$

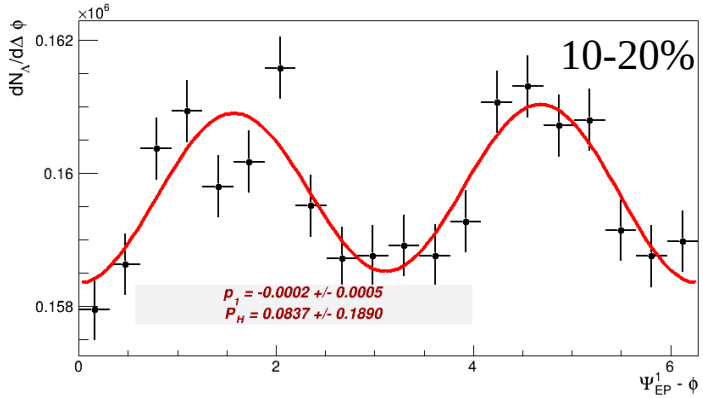
$$\alpha_\Lambda \simeq 0.732$$

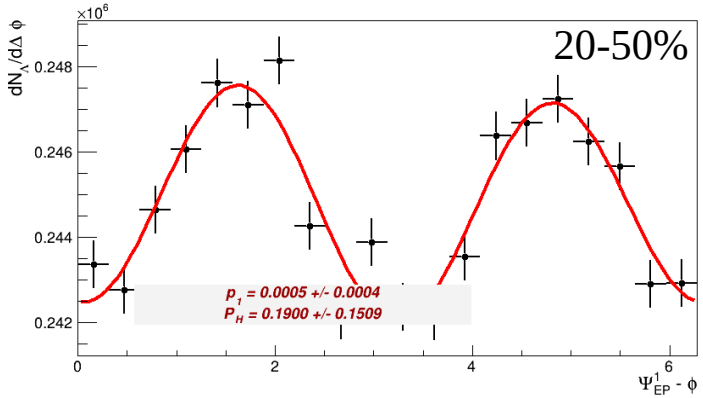
	20-50%
N_Λ	3.3* 10^5
p_0	(1.6 +/- 3.3)* 10^4
$p_1/10^{-4}$	33.02+/- 14.01
$p_2/10^{-4}$	44.03 +/- 13.93
$p_3/10^{-4}$	-3.26 +/- 13.95
$p_4/10^{-4}$	-52.39 +/- 14.00

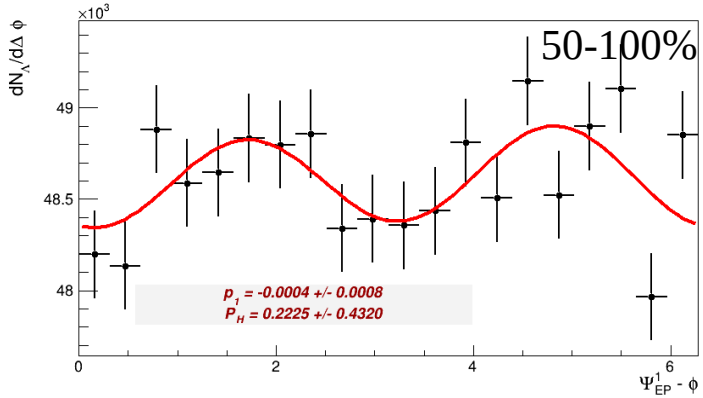
$$\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi^*_p} = p_0(1 + 2p_1 \sin(\Delta\phi^*_p) + 2p_2 \cos(\Delta\phi^*_p) + 2p_3 \sin(2\Delta\phi^*_p) + 2p_4 \cos(2\Delta\phi^*_p) + ...)$$

Results (new)









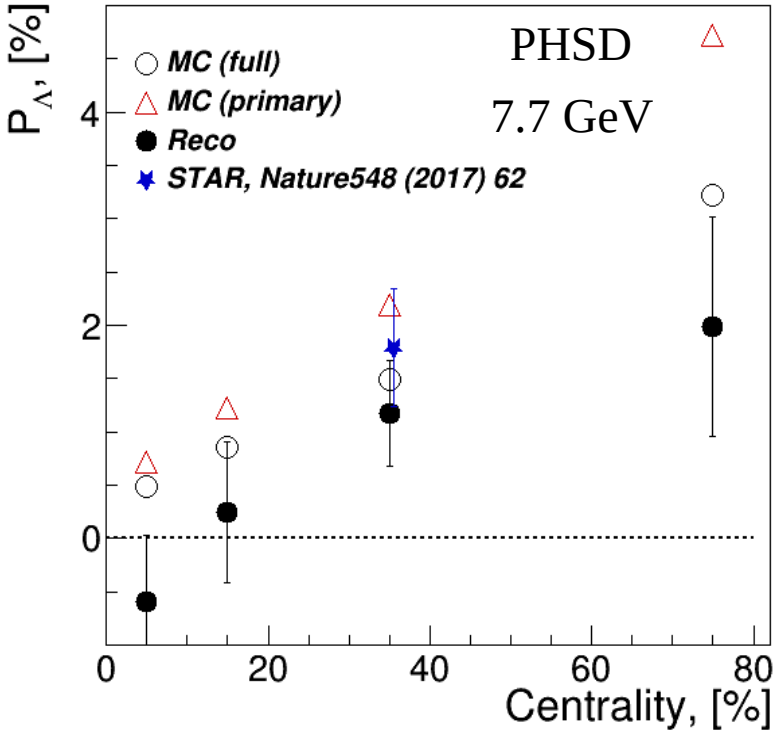
$$P_\Lambda = \frac{8}{\pi \alpha_\Lambda} \frac{p_1}{R^1_{\mathrm{EP}}}$$

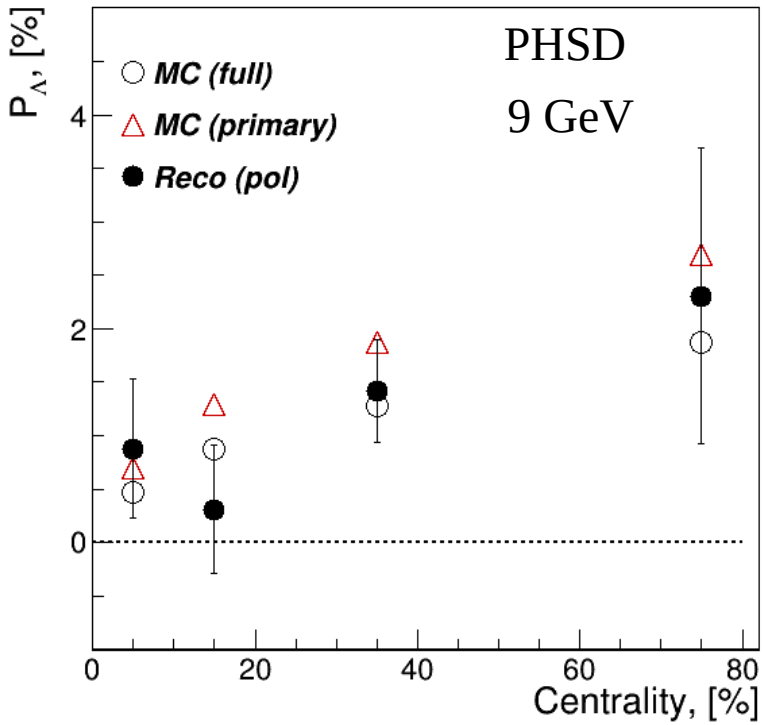
$$\alpha_\Lambda \simeq 0.732$$

	20-50%
N_Λ	4.9* 10^6
p_0	(2.5 +/- 1.3)* 10^5
$p_1/10^{-4}$	4.57+/- 3.63
$p_2/10^{-4}$	4.39 +/- 4.61
$p_3/10^{-4}$	-7.62 +/- 3.62
$p_4/10^{-4}$	-51.52 +/- 3.62

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

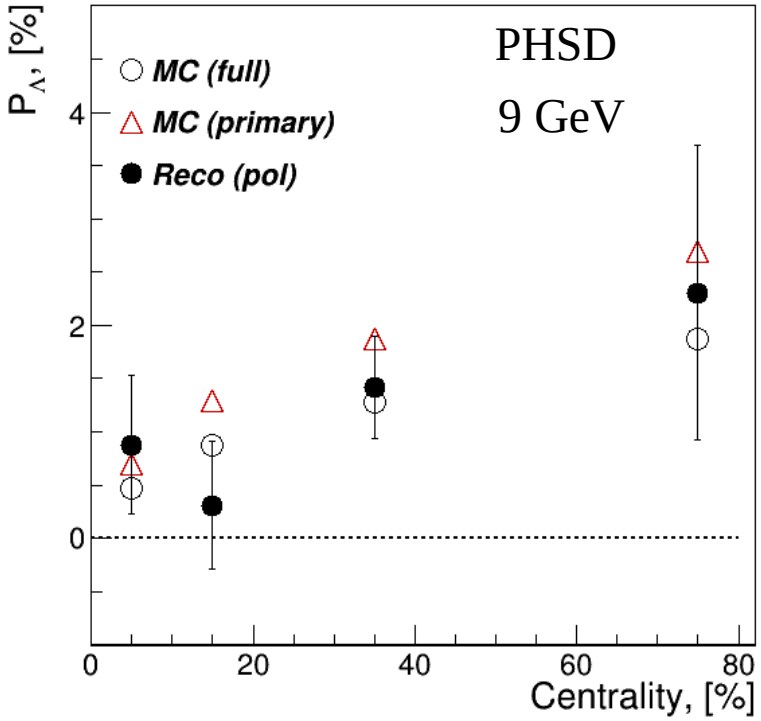
Results

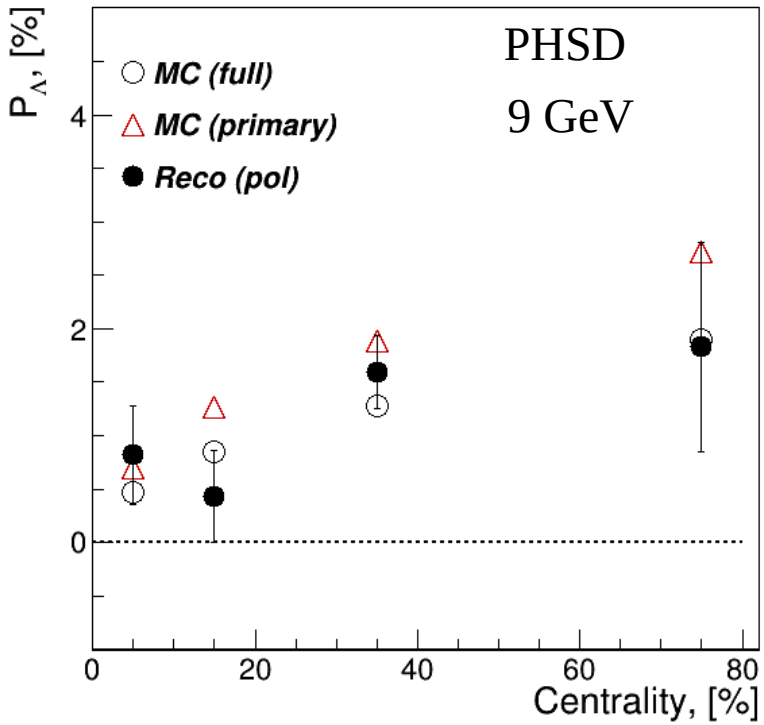




- (left) Previous result (PHSD ~1M events, @ 7.7 GeV)
- (right) New result with ~1M events, PHSD @ 9 GeV
- The results seem similar, but ...

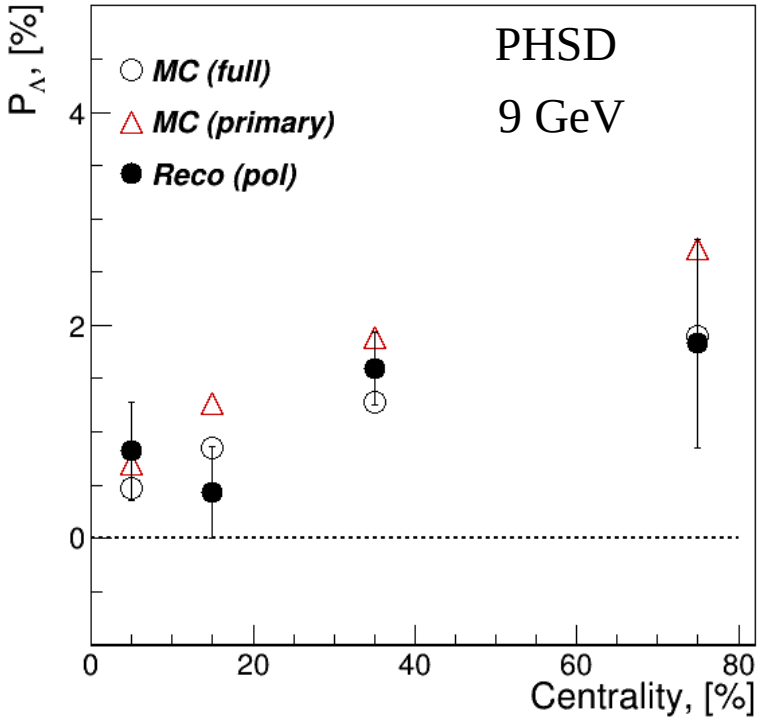
Results

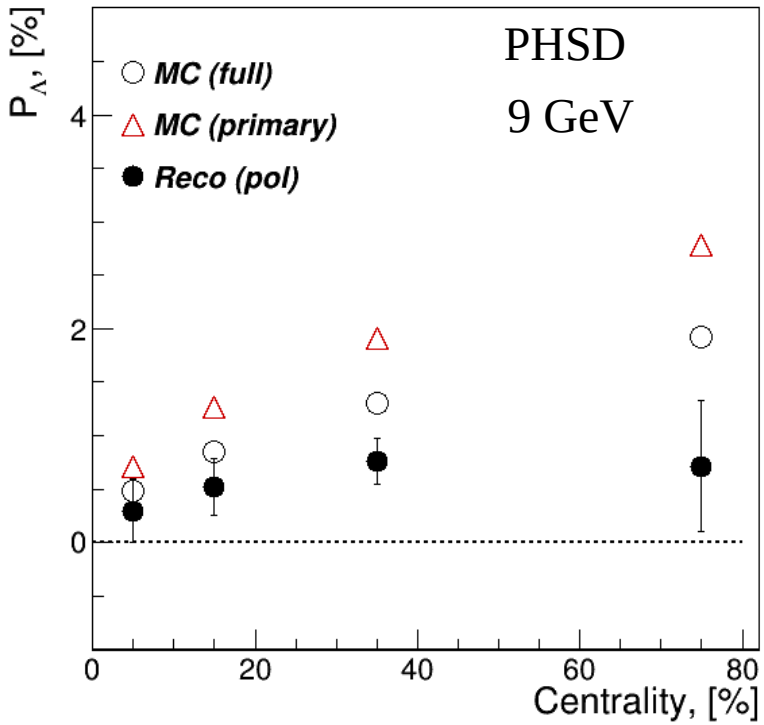




- (left) PHSD @ 9 GeV, ~1M events
- (right) PHSD @ 9 GeV, ~2M events
- When we increase statistics, the picture starts to change

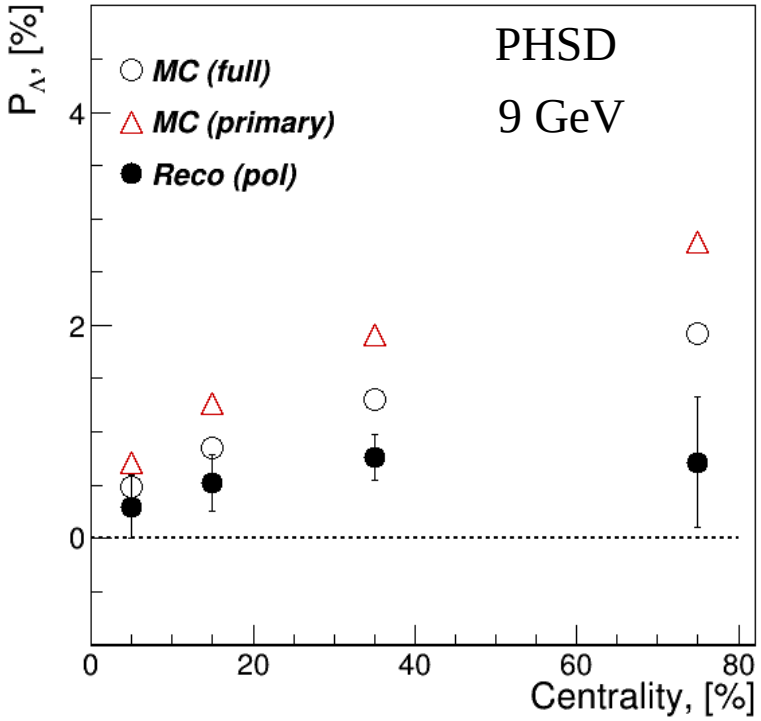
Results

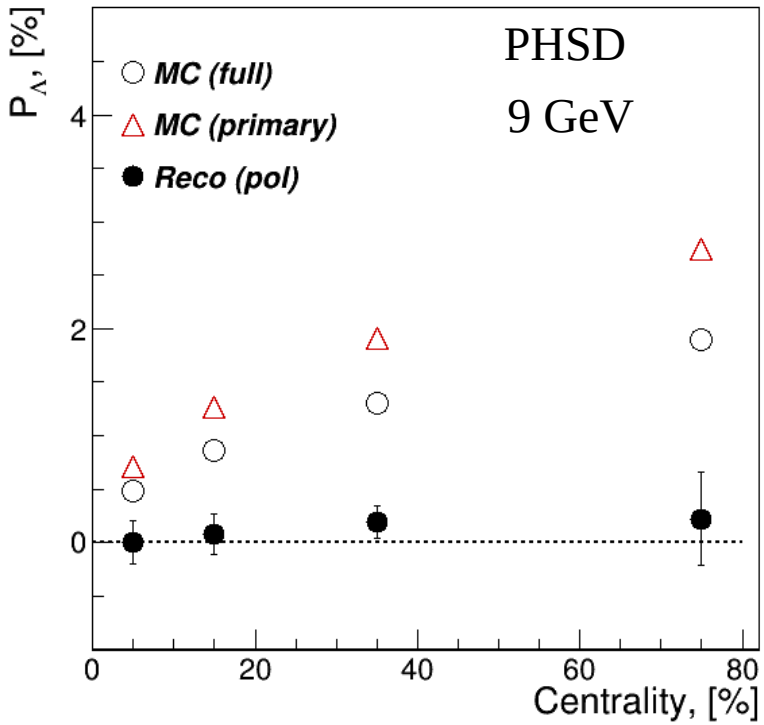




- (left) PHSD @ 9 GeV, ~2M events
- (right) PHSD @ 9 GeV, ~5M events
- Not only the errors are decreasing, but the value of polarization

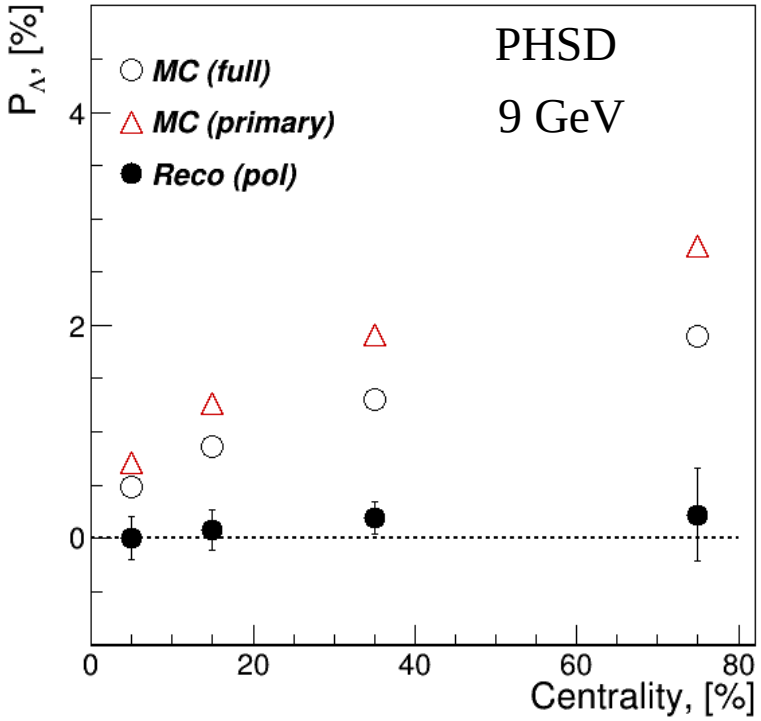
Results

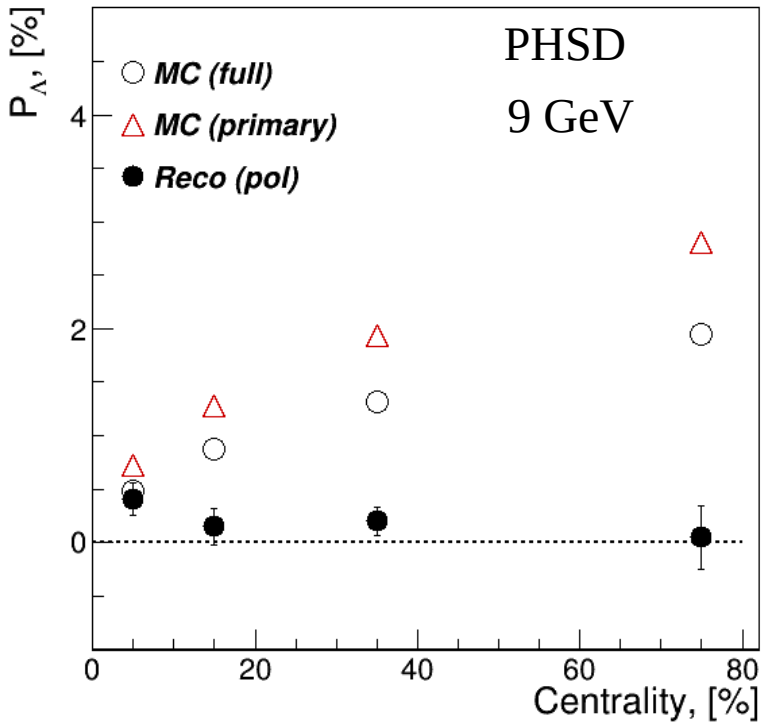




- (left) PHSD @ 9 GeV, ~5M events
- (right) PHSD @ 9 GeV, ~10M events
- Not only the errors are decreasing, but the value of polarization
- For the full sample, the reconstructed value is consistent with 0

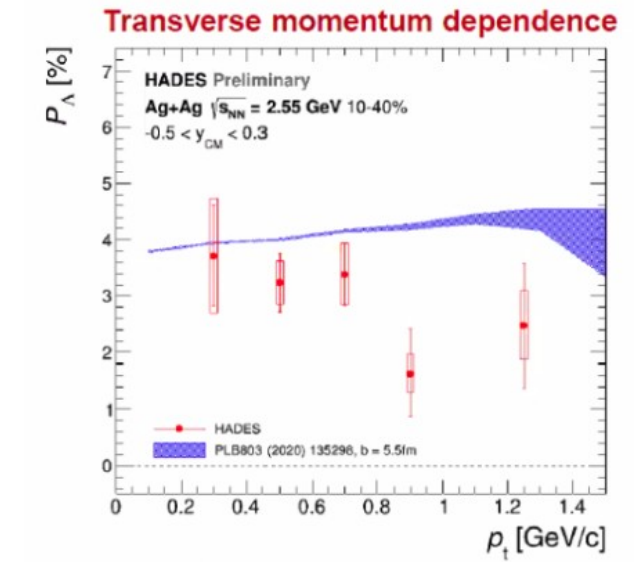
Results

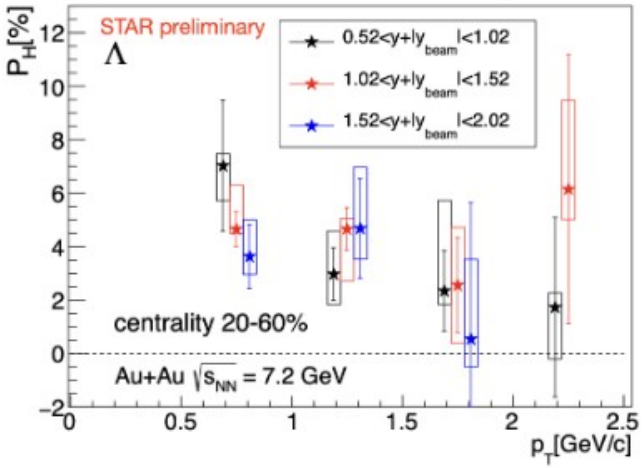




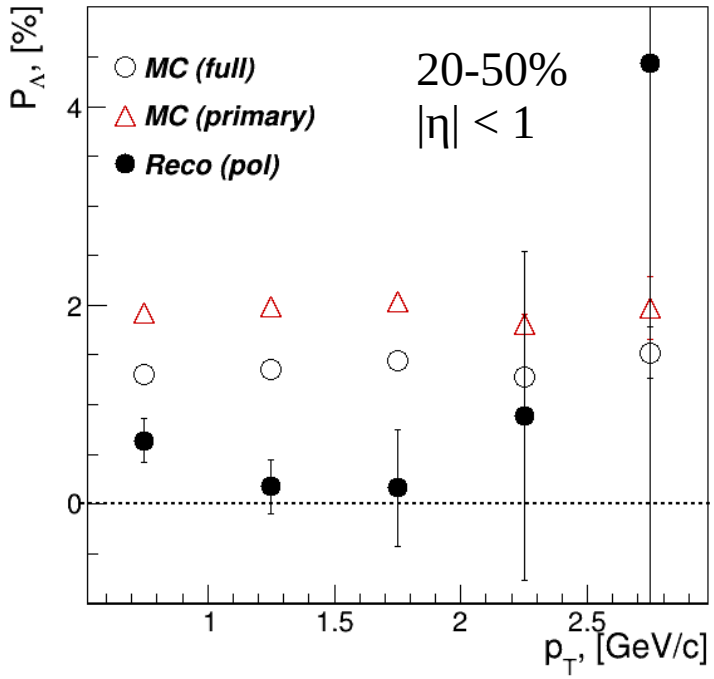
- (left) PHSD @ 9 GeV, ~10M events, using $\Delta\phi_p^* = \Psi_{\mathrm{EP}}^1 - \phi_p^*$
- (right) PHSD @ 9 GeV, ~10M events, using $\Delta\phi_p^* = \Psi_{\mathrm{RP}} - \phi_p^*$

Results



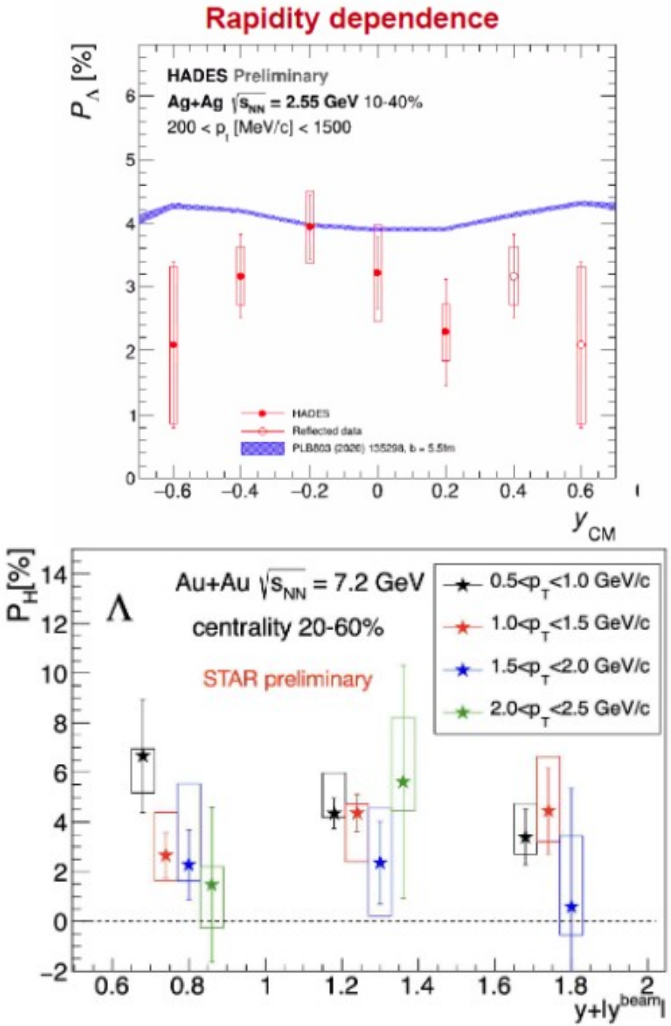


PHSD, BiBi @9 GeV

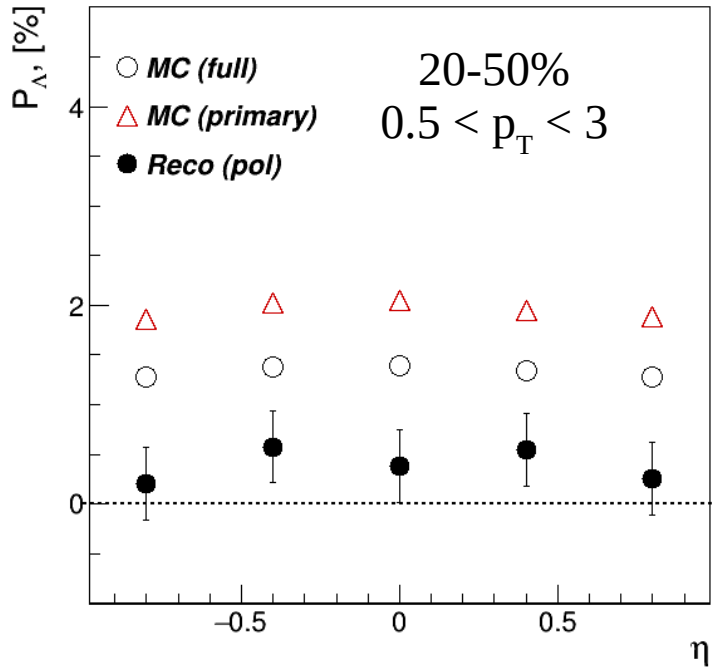


- Rapidity and transverse momentum dependences of global polarization of Lambda
  - STAR collaboration, SQM2021 (e-Print: 2108.10012)
  - HADES collaboration, SQM2021
- No significant y and p_T dependence within uncertainties

Results



PHSD, BiBi @9 GeV



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  - HADES collaboration, SQM2021
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Conclusions

- Feasibility study of the global polarization measurement with PHSD
  - Sample with increased statistics: Bi-Bi @ 9GeV, 10M MB events, b [0,12]fm
  - Official production (request 23)
- Compared with our previous results from the testing sample (Au-Au @ 7.7GeV, 1.4M MB events, b [0,16]fm)
  - Better results with centrality and EP resolution determination
  - Unexpected behaviour of extracted global polarization values
- Detailed study is necessary

Outlook

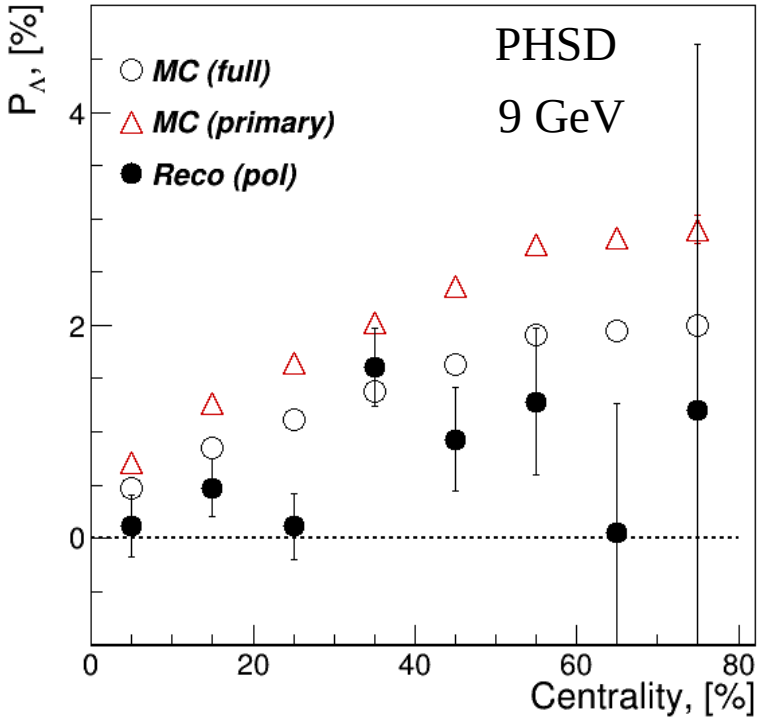
- Ongoing studies:
  - Using MCTracks information, extract polarization with the EP method

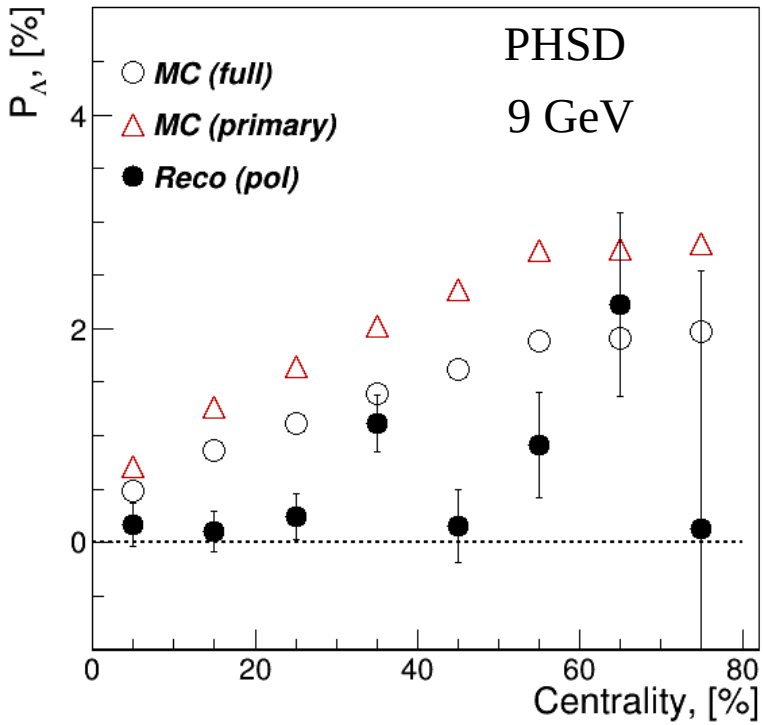
    (Exact number of Lambda and MC polarization)
  - Re-check the polarization transfer with the new mpdroot version
  - Check the implementation of the EP method (Lambda reconstruction, fitting procedure, number of bins)
- Implement the «Invariant mass» method
  - How to cross-check?
- Background contribution to polarization
- Anti-Lambda polarization extraction

The End

Thank you for your attention!

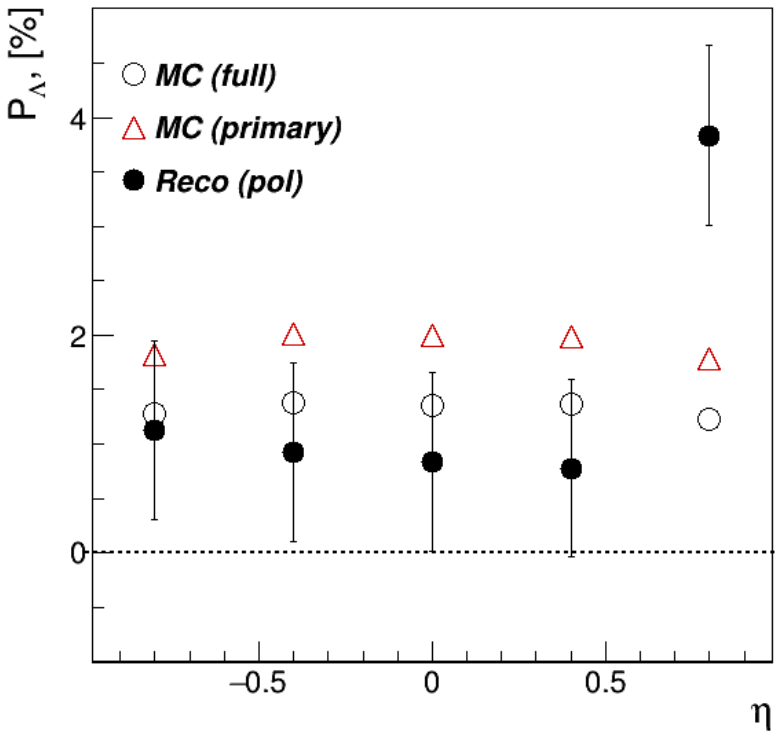
Back Up: Results

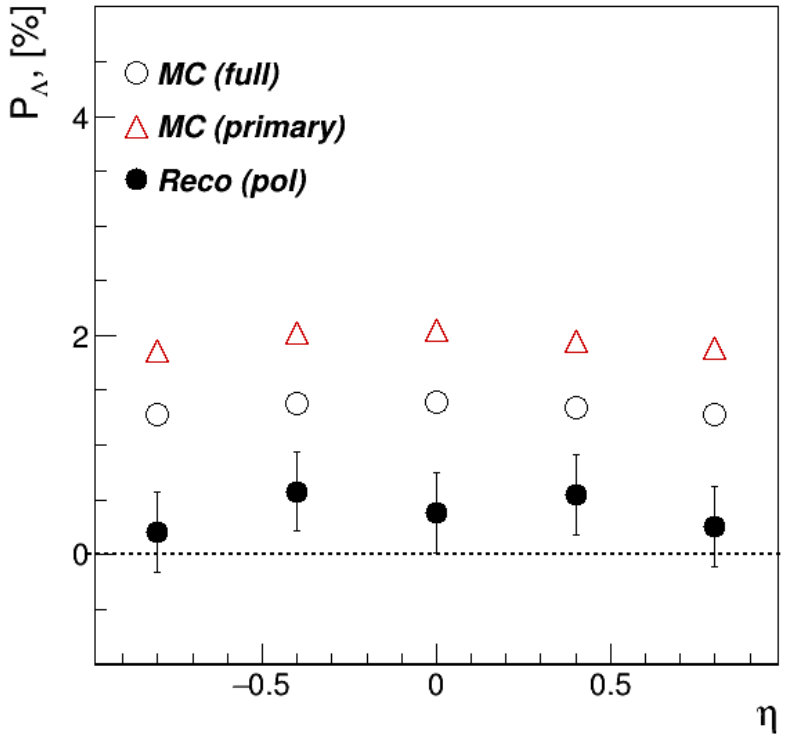




- (left) PHSD @ 9 GeV, ~5M events
- (right) PHSD @ 9 GeV, ~10M events
- Not only the errors are decreasing, but the value of polarization
- For the full sample, the reconstructed value is consistent with 0

Results





- (left) PHSD @ 9 GeV, ~2M events
- (right) PHSD @ 9 GeV, ~10M events

Back Up: Overview of statistics

	0-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	90-100%
N_{events}	$1.3* 10^6$	$1.4* 10^6$	$1.4* 10^6$	$1.4* 10^6$	$1.4* 10^6$	$1.5* 10^6$	$1.2* 10^6$	$3.7* 10^5$	$7.5* 10^4$	$1.8* 10^3$
N_{Λ}	$4.4* 10^6$	$3.3* 10^6$	$2.4* 10^6$	$1.6* 10^6$	$1.0* 10^6$	$0.6* 10^6$	$0.3* 10^6$	$0.5* 10^5$	-	-

PHSD @9 GeV

	0-10%	10-20%	20-50%	50-100%
N_{events}	$1.3* 10^6$	$1.4* 10^6$	$4.2* 10^6$	$3.0* 10^6$
N_{Λ} (full)	$4.4* 10^6$	$3.3* 10^6$	$4.9* 10^6$	$1.0* 10^6$
N_{Λ} (5M)	$2.1* 10^6$	$1.6* 10^6$	$2.4* 10^6$	$0.5* 10^6$

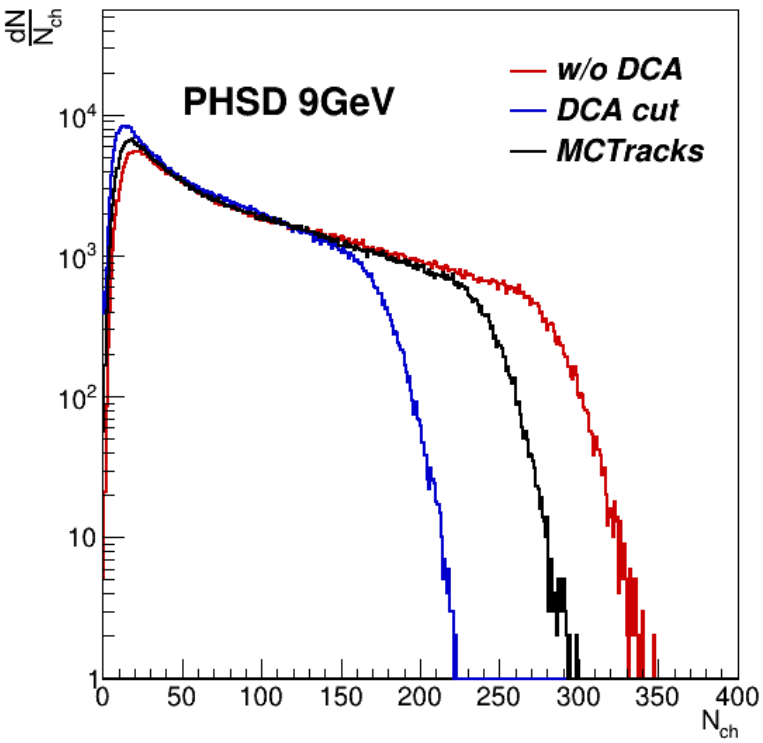
PHSD @7.7 GeV

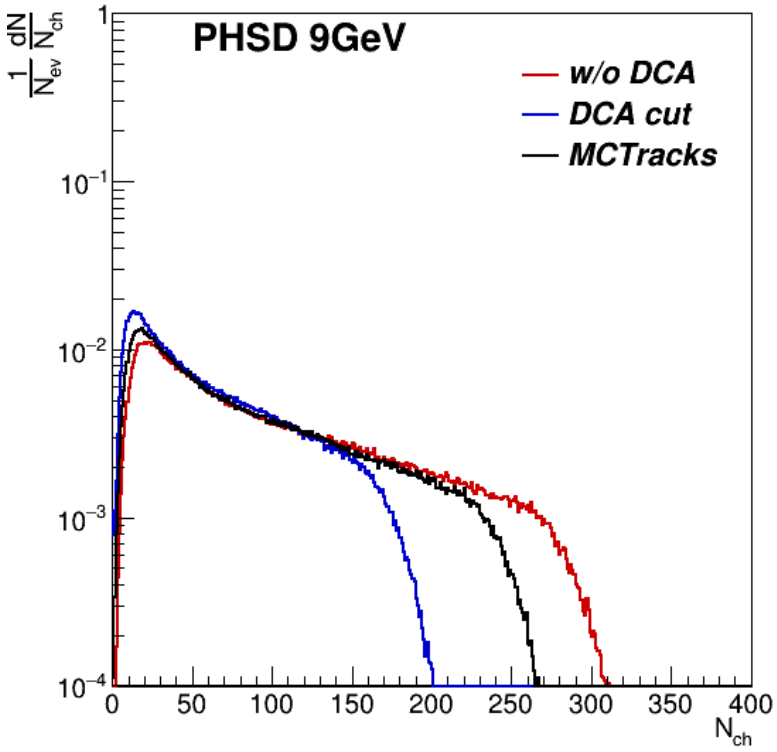
	20-50%
N_{events}	$2.9* 10^6$
N_{Λ}	$3.3* 10^5$

HADES
Au-Au @1.23 AgeV
Ag-Ag @1.58 AGeV

	10-40%
N_{Λ} (Au)	$1.5* 10^5$
N_{Λ} (Ag)	$1.1* 10^6$

Back Up: Multiplicity in TPC





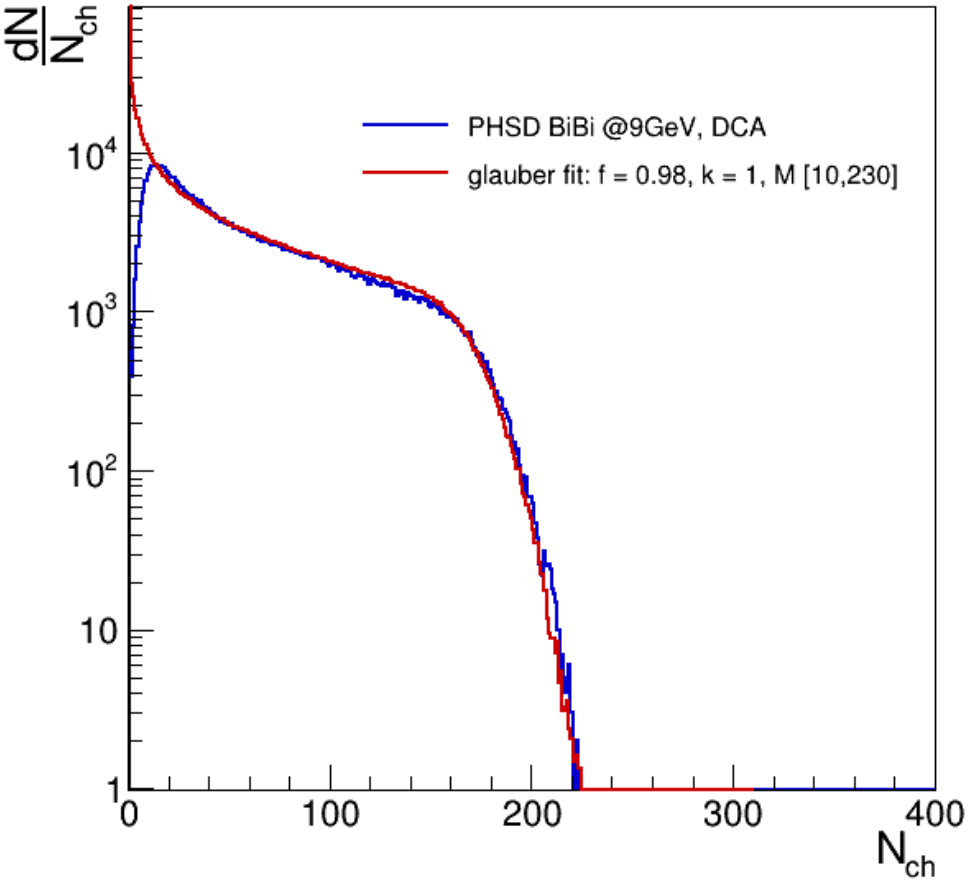
- MC-Glauber based centrality framework[1]
- Selection criteria:
  - 500k events
  - $|\eta| < 0.5$
  - $|p_T| > 0.15$ GeV
  - $N_{hits} > 16$
  - $|DCA| < 0.5$ cm (optional)
  - 10%-centrality bins

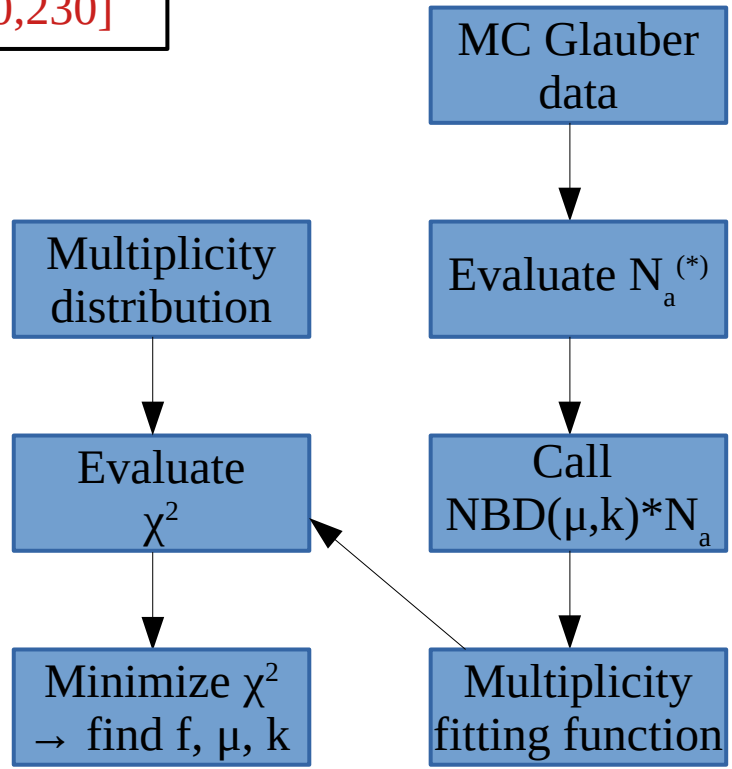
[1] P. Parfenov et al, NRNU MEPhI for the MPD collaboration (https://github.com/FlowNICA/CentralityFramework)

Back Up: Centrality determination

$f = 0.98$, $\mu = 0.43$, $k = 1$, $\chi^2 = 15.32 \pm 0.36$

DCA cut, M [10,230]



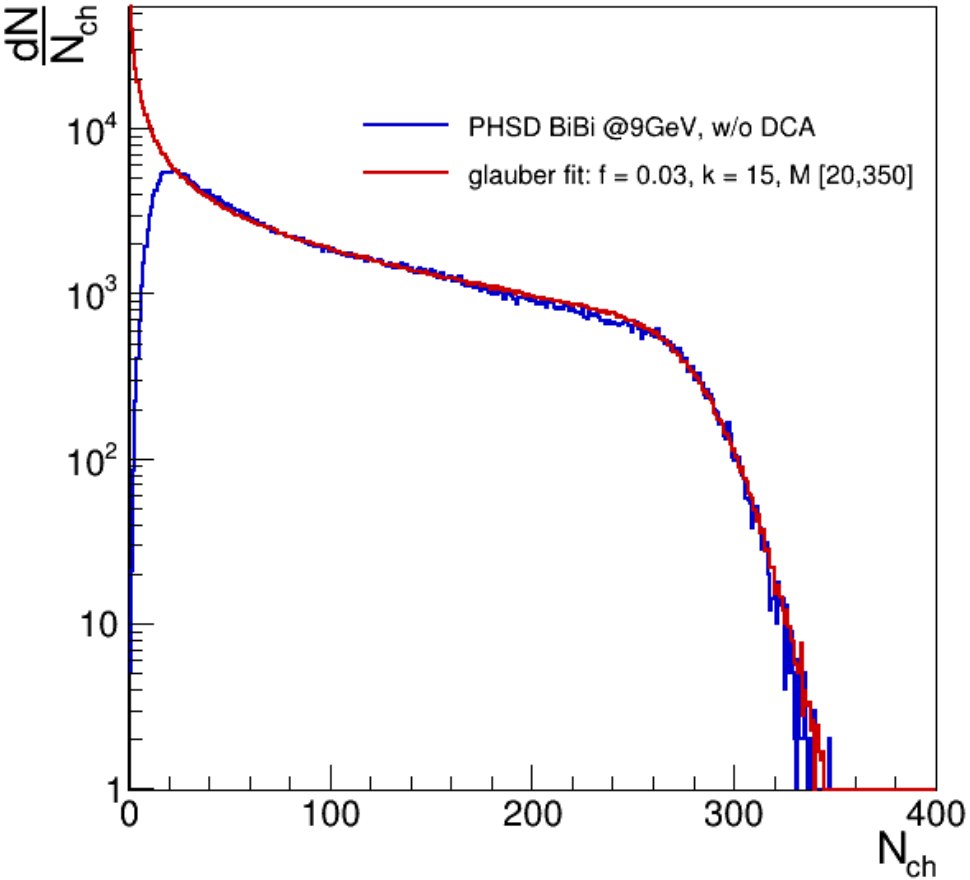


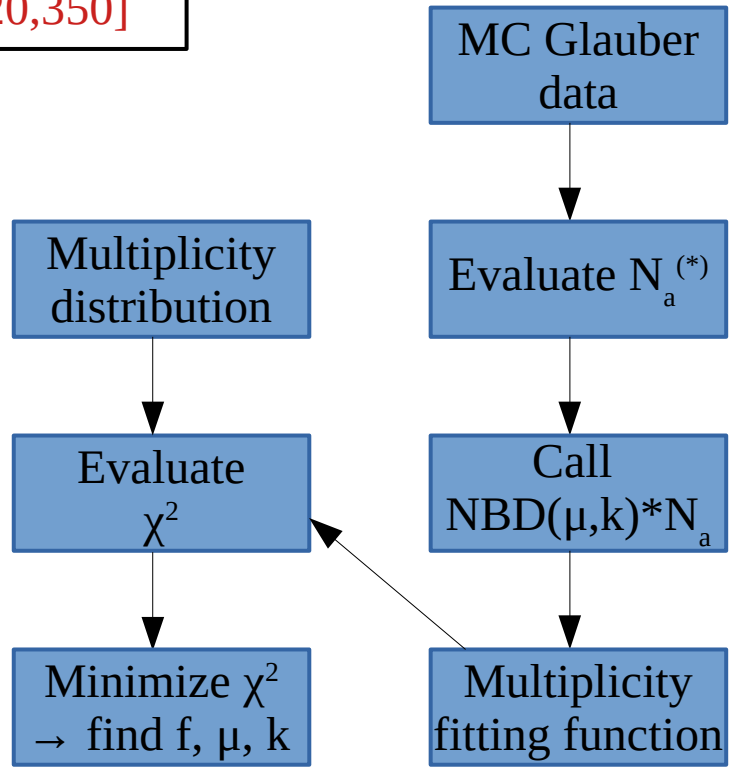
$$^{(*)}N_a = fN_{\text{part}} + (1-f)N_{coll}$$

Back Up: Centrality determination

$f = 0.03$, $\mu = 0.31$, $k = 15$, $\chi^2 = 3.65 \pm 0.11$

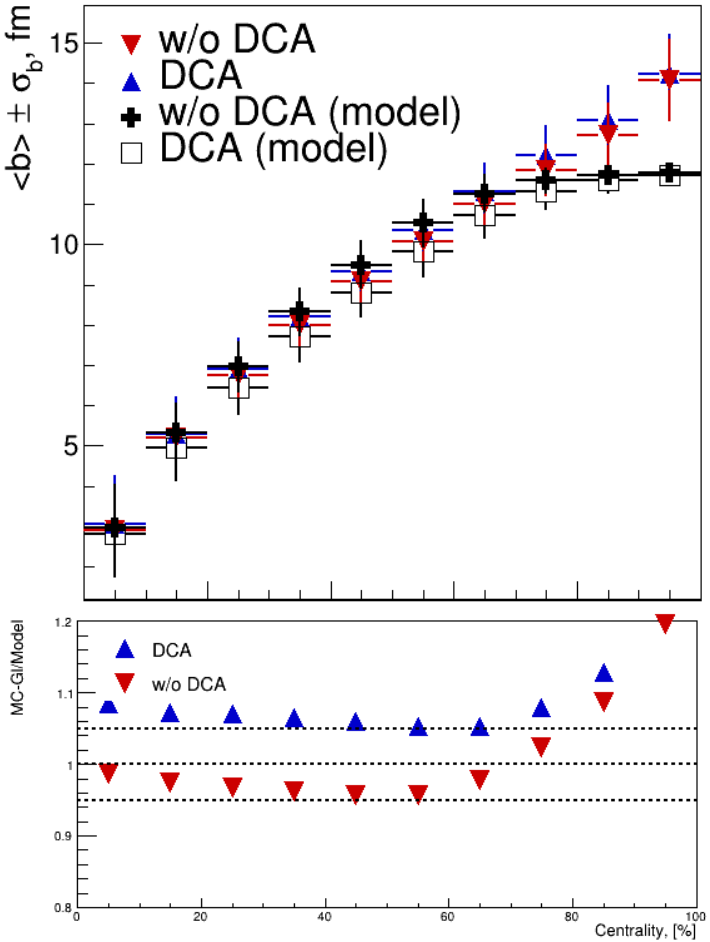
w/o DCA, M [20,350]



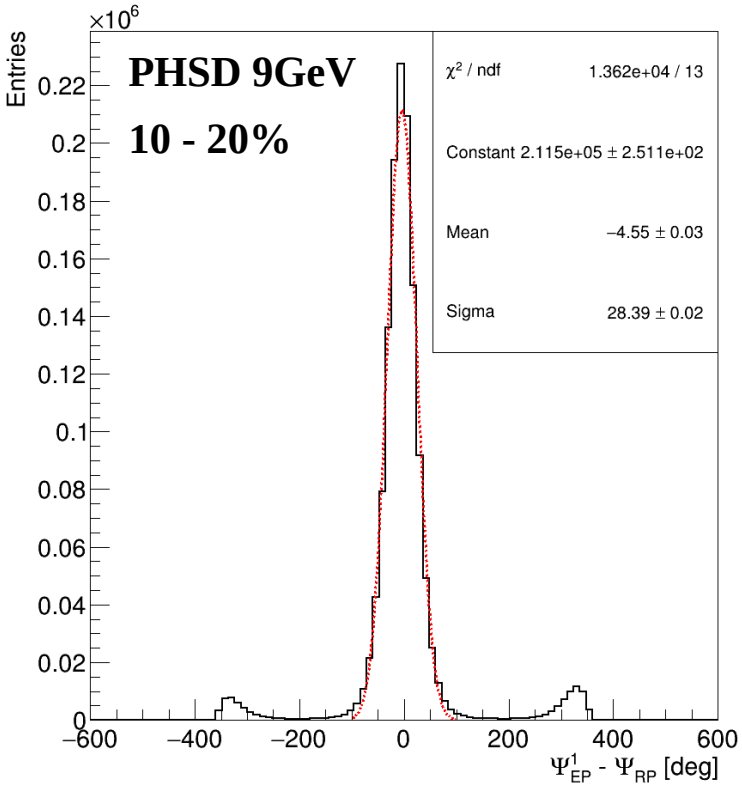


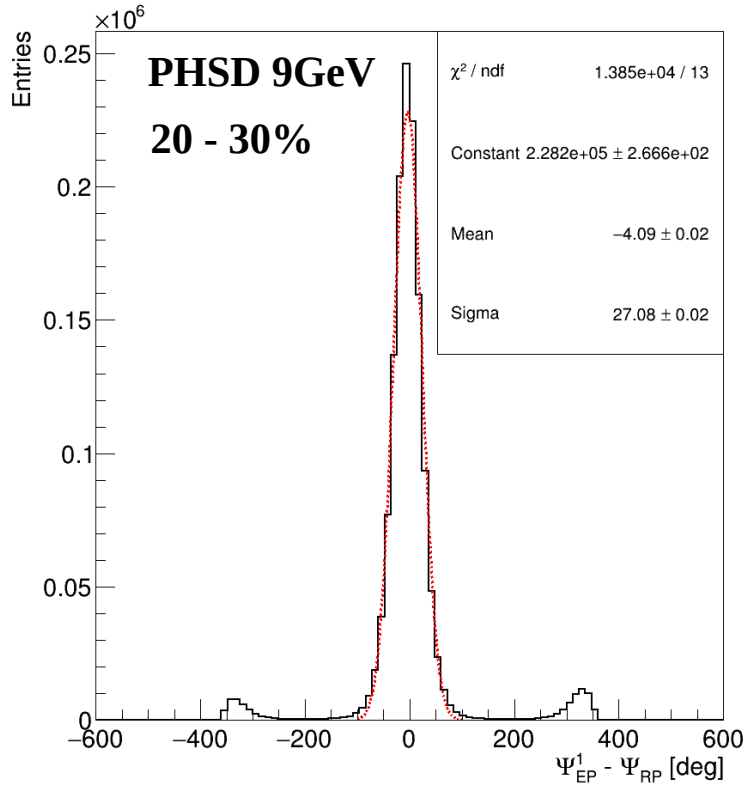
$$^{(*)}N_a = fN_{\text{part}} + (1-f)N_{coll}$$

Back Up: Average impact parameter



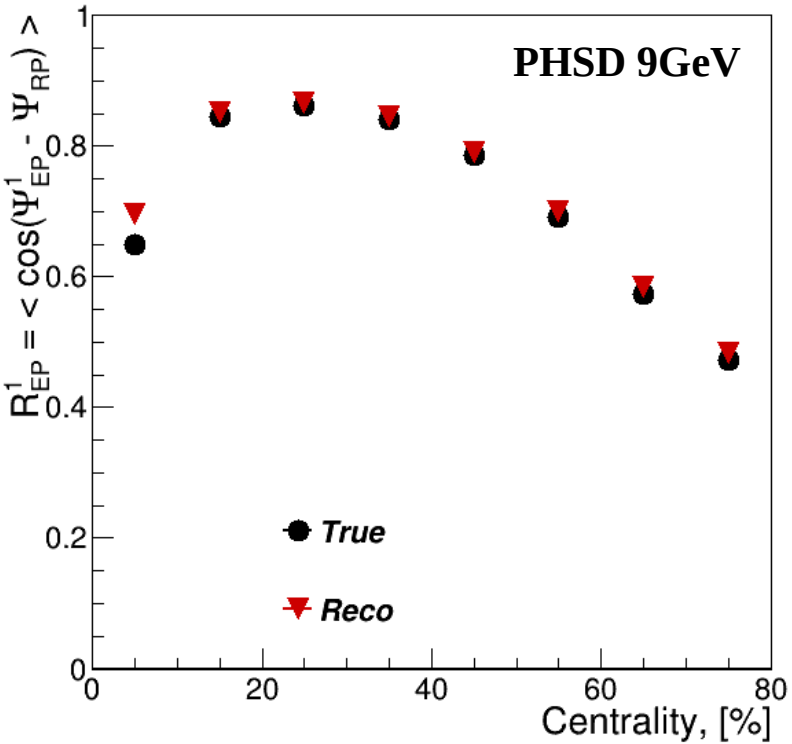
Back Up: Event plane determination

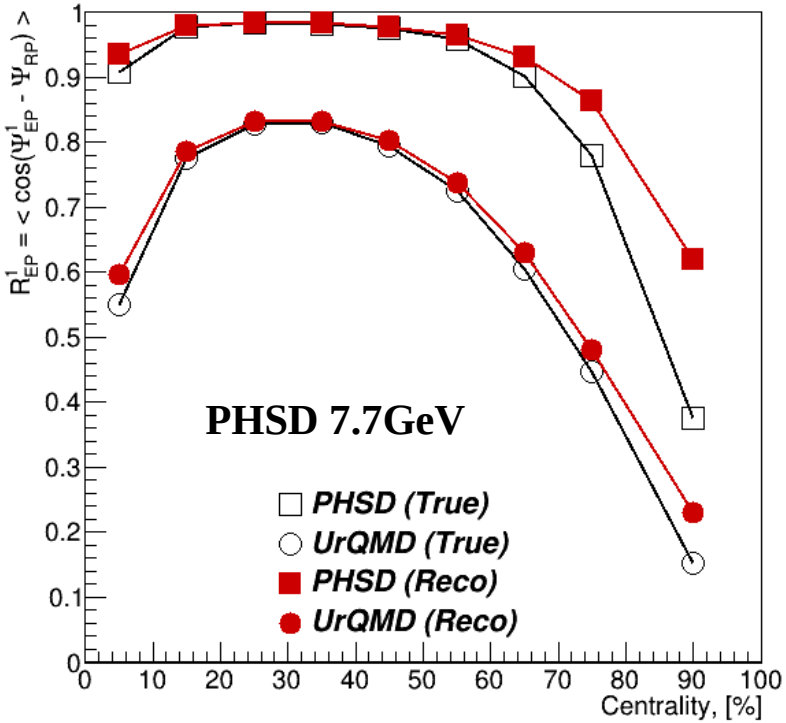




- Difference between EP and RP angles
  - Gaussian fit
  - Max. resolution of ~ 27 deg.
  - Centered at 0

Back Up: Event plane determination





- Event plane and its resolution determined using FHCal
- Reasonable behaviour compared to the previous results

Back Up: Lambda reconstruction