Analysis of global polarization of Lambda within MPD framework

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

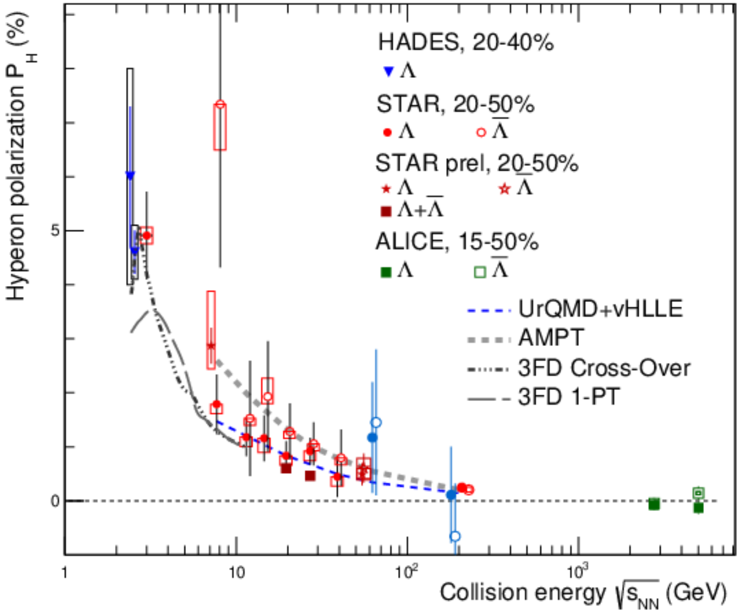
11.04.2023

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

Outline

- Introduction
- Analysis technique
  - Simulation
  - Event reconstruction
  - Lambda reconstruction
  - Global polarization measurement
- Realization within the mpdroot train framework
- Results
- Conclusions & Outlook

- 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 using various observables[4,5,6]



S. Singha, EPJ Web Conf. 276 (2023) 06012

[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] E. Nazarova et al., Phys.Part.Nucl.Lett. 18 (2021) 4, 429-438
[5] O. Teryaev and R. Usubov, Phys. Rev. C 92, 014906 (2015)
[6] M. A. Lisa et al., Phys. Rev. C 104, 011901 (2021)

Introduction

- Predicted[1] and observed[2,3] global polarization signals rise as the collision energy is reduced:
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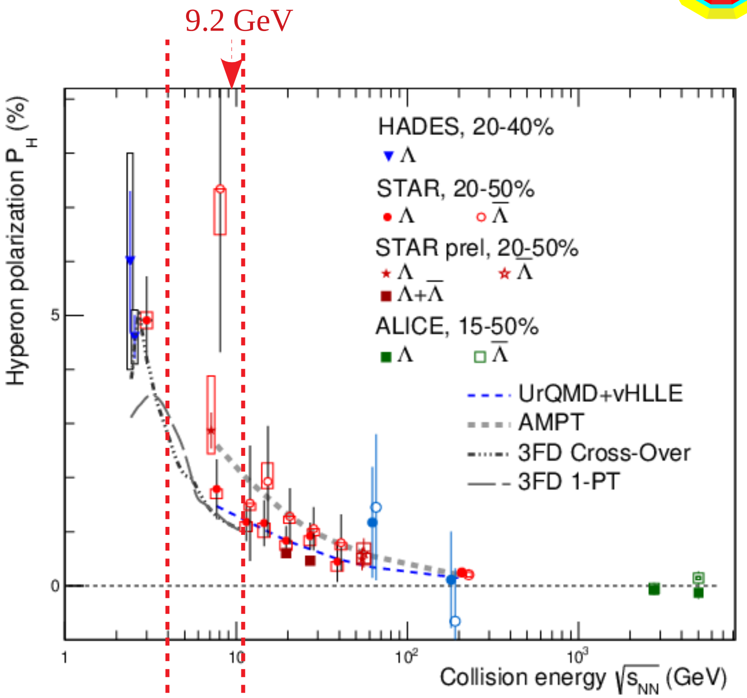

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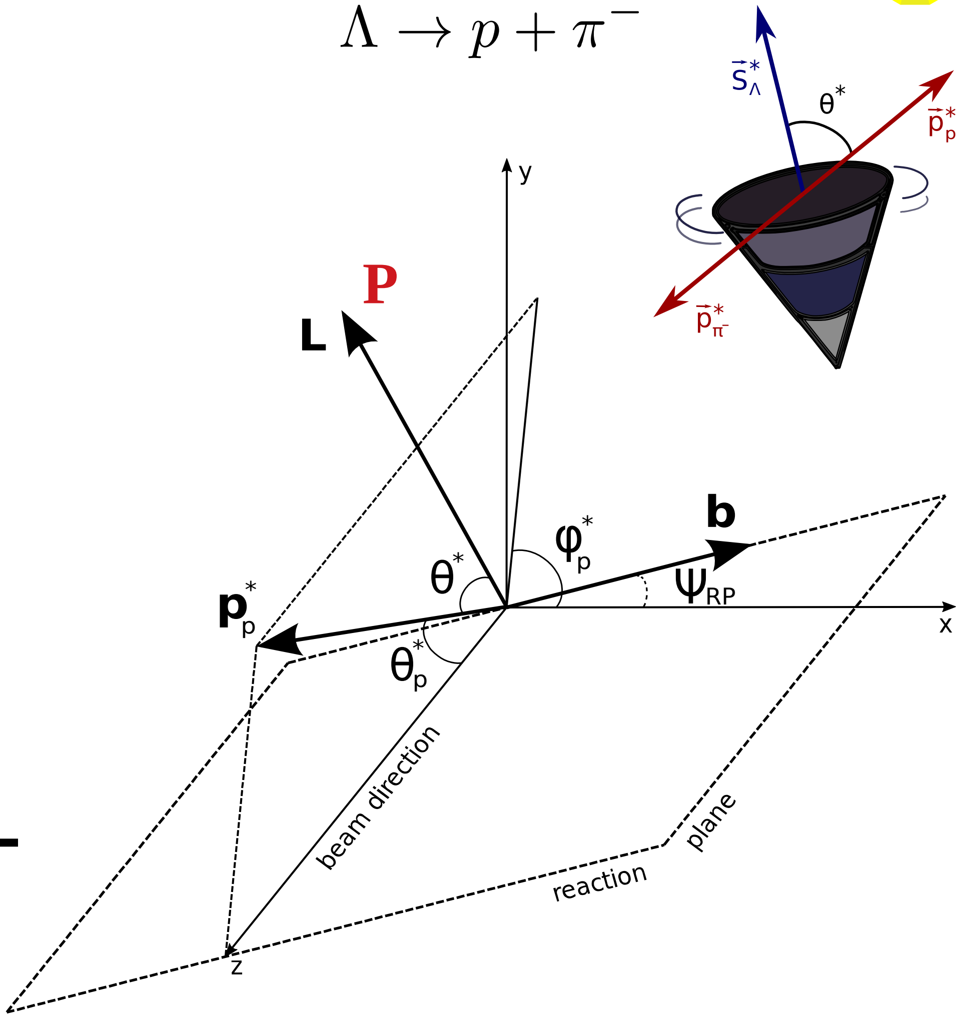
Global hyperon polarization

- w.r.t. reaction plane (RP)
- Emerges in HIC due to the system angular momentum[1,2]
- Measured through the weak decay (1)

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = \frac{1}{2}(1 + \alpha_{\mathrm{H}}|\vec{P}_{\mathrm{H}}|\cos\theta^*) \quad (1)$$

- * — denotes Lambda rest frame
- θ^* — angle between the decay particle and polarization direction
- $\alpha_\Lambda \simeq -\alpha_{\bar{\Lambda}} \simeq 0.732$ (Value updated in 2019[3])

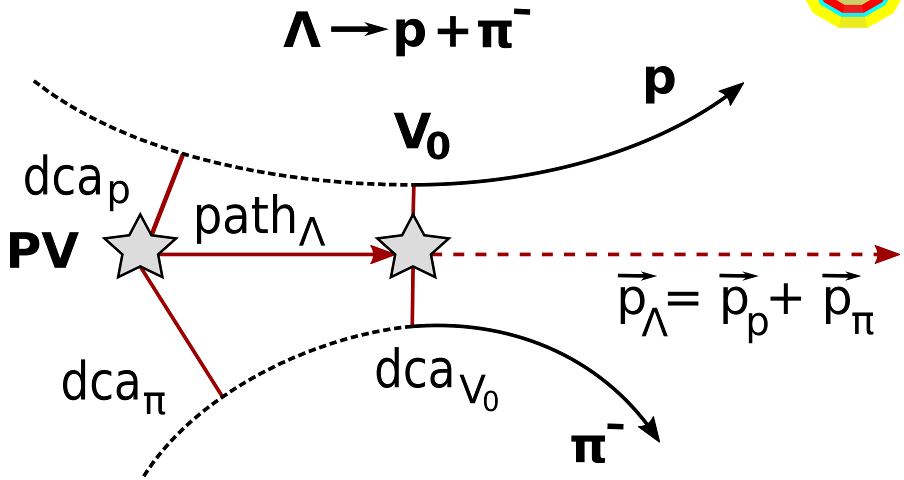
$\Lambda \to p + \pi^-$



[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)

- Polarization can be measured using the azimuthal angle of proton in Lambda rest frame φ^*

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



→ Determine centrality

→ Determine event plane (Ψ^1_{EP}, R^1_{EP})

→ Reconstruct Lambda

→ Global polarization

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

MC simulation
PHSD
↓
Detector simulation
GEANT 4
↓
Event reconstruction
MPD

- MC simulation using PHSD generator[1,2,3]
  - Bi-Bi @ 9.2GeV, 15M MB events, b [0,12]fm (request 30)
  - Global hyperon polarization
    - Thermodynamical (Becattini) approach[4]
    - 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] N.S. Tsegelnik, E.E. Kolomeitsev, V. Voronyuk, Phys.Rev.C 107 (2023) 3, 034906
[3] N Tsegelnik, E. Kolomeitsev, V. Voronyuk, Particles 2023, 6, 373-384
[4] F. Becattini, V. Chandra, L. Del Zanna, E. Grossi, Ann. Phys. 338 (2013) 32

Analysis technique

MC simulation
PHSD

↓

Detector simulation
GEANT 4

↓

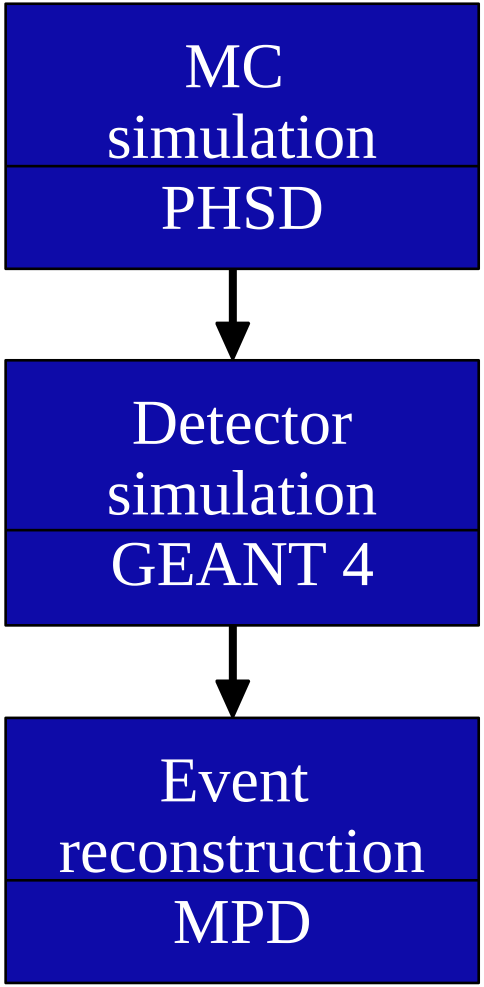
Event reconstruction
MPD

- <u>Detector simulation</u>
  - Transfer of polarization vector **P** = $\{P_x, P_y, P_z\}$ from generated data to the detector simulation
  - Rotation w.r.t. to generated reaction plane
  - Spin direction of hyperons is randomized according to the probability (length of the vector |**P**|)
- Transfer of polarization during hyperon decays[1,2] (feed-down effect)
  - $\mathbf{S}^*_D = C\mathbf{S}^*_P$;
  - Spin direction randomized based on the feed-down constant
- Anisotropic decay of Λ hyperons (following eq. (1))

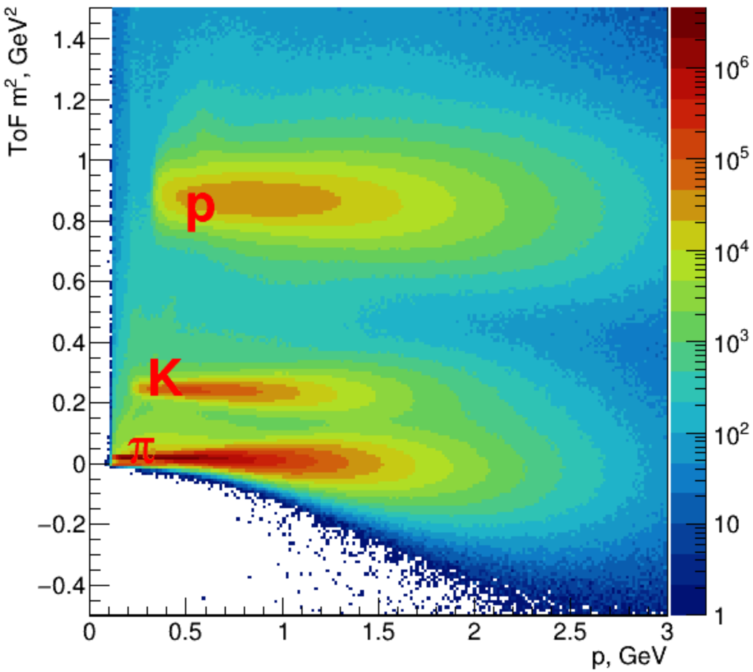
$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1 + \alpha_H |\vec{P}_H| \cos\theta^*) \quad (1)$$

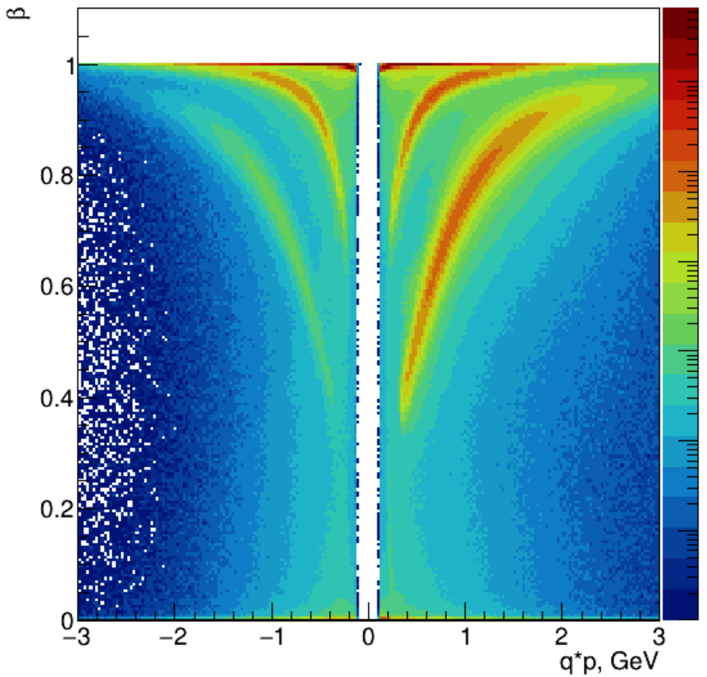
[1] $\Xi^+(\Xi^-)$, Ξ^0, Σ^0 decays ($C_{\Xi^-} = 0.927$, $C_{\Xi} = 0.9$, $C_{\Sigma} = -1/3$)

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

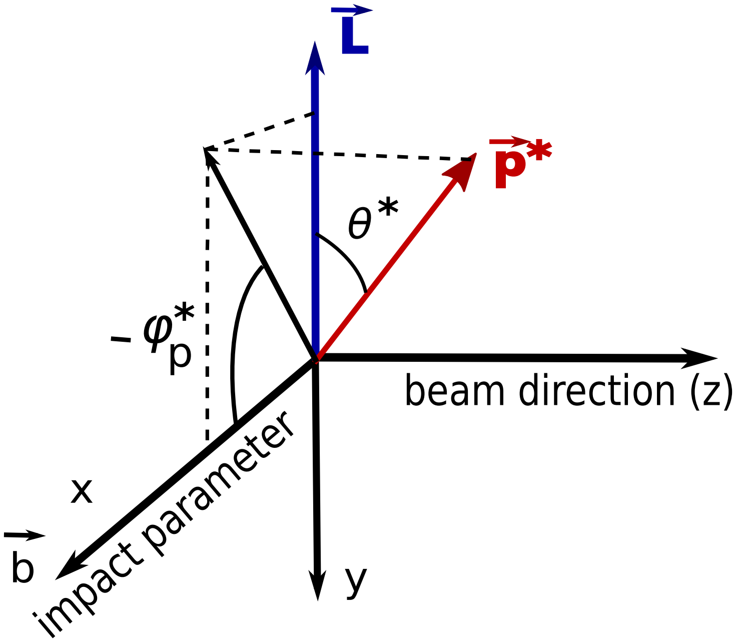


- <u>Event reconstruction</u>
  - Centrality calibration - TPC multiplicity
  - Event plane determination (Ψ^1_{EP}, R^1_{EP}) - via FHCal
  - Lambda reconstruction - PID
  - Global polarization extraction - EP method





- Obtain 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 $\langle \sin(\Delta\phi_p^*) \rangle \to P_\Lambda$
  - «Event plane» method (p_n — fit parameters)
  - $P_\Lambda = \frac{8}{\pi\alpha_\Lambda}\frac{p_1}{R_{\mathrm{EP}}^1}$
  - Can be used for testing of both Reco and MC tracks within the simulation



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

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

Realization within the mpd train framework

- Moving the analysis into the MPD train framework: events are processed one-by-one by each wagon, that modify and/or analyze the data
- Preliminary version of GlobalPolarization wagon:

```
void RunAnalyses (){
   gROOT->LoadMacro("mpdloadlibs.C");
   gROOT->ProcessLine("mpdloadlibs()");
   MpdAnalysisManager man("ManagerAnal",-1);
   man.InputFileList("list.txt");
   man.ReadBranches("*");
   MpdCentralityAll pCentr("pCentr","pCentr");
   man.AddTask(&pCentr);
   MpdEventPlaneAll pEP("pEP","pEP");
   man.AddTask(&pEP);
   MpdGlobalPolarization
     pGlobalPol("pGlobalPol","pGlobalPol");
   man.AddTask(&pGlobalPol);
   man.Process();
}
```

Centrality wagon

EP wagon

Polarization wagon

Input (config) file

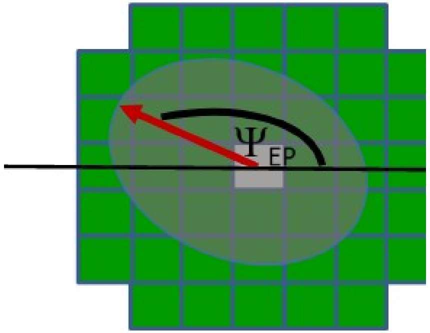
output file

Realization within the mpd train framework

- **Centrality Wagon**
- Calculates centrality based on TPC multiplicity for each accepted event
- Returns centrality ‘-1’ for rejected events (not included in the further analysis):
  - empty events
  - events with no vertex by TPC
  - events with reconstructed vertex |z-vertex-TPC| > 130 cm
  - events that failed to fire the FFD||FHCL trigger (assessed based on event track multiplicity using efficiency file)
- Event centrality is available for all other wagons in the train: event.getCentrTPC();
- Centrality is provided as a float in the range [0-91] for accepted events

- Selection criteria:
  - $|\eta| < 0.5$
  - $|p_T| > 0.1$ GeV
  - $N_{hits} > 10$
  - $|DCA| < 2.0$
  - Cuts on empty events and vertex, trigger efficiency

- **Event Plane Wagon**
- Calculates 1st-order EP angle via FHCal, 2nd-order EP angle via TPC
  - Can be accessed in other wagons (e.g. for FHCal):
  - event.fMpdEP.GetPhiEP_FHCal_F_all() → Full
  - event.fMpdEP.GetPhiEP_FHCal_N_all() → η < 0
  - event.fMpdEP.GetPhiEP_FHCal_S_all() → η < 0
- Corresponding EP resolutions can be calculated using the provided information (within the analysis using subevent method[1])
- Option to use EP corrections (reduce possible bias from non-uniform detector acceptance)



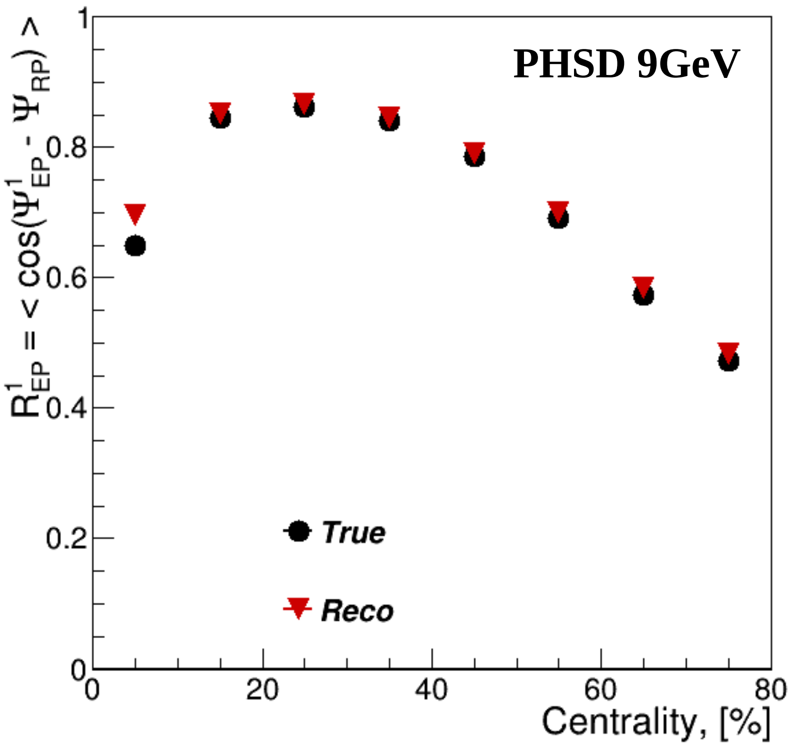
$$\Psi^{n}_{\mathrm{EP}} = \frac{1}{n}\arctan\frac{Q_y}{Q_x}$$

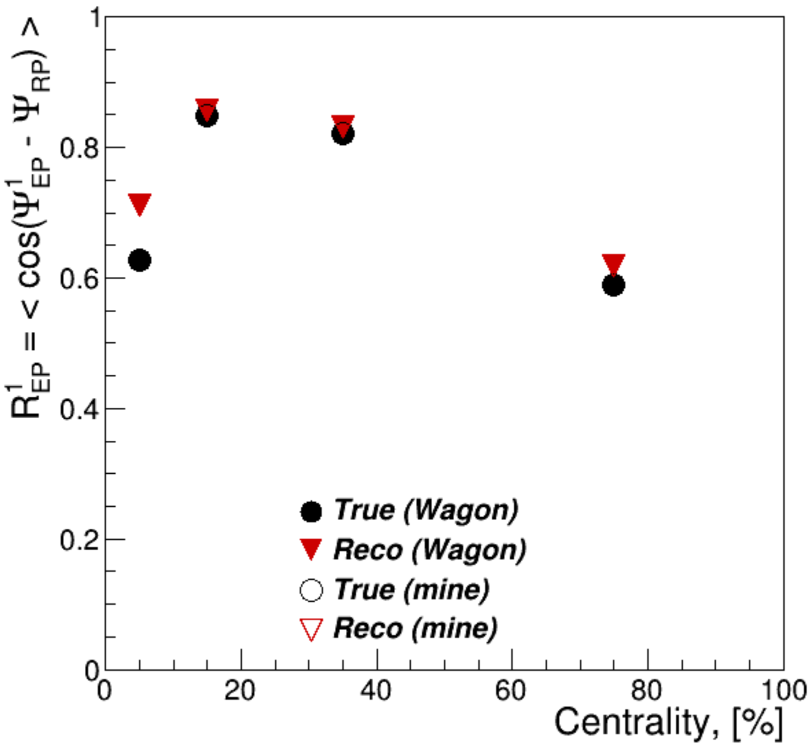
$$Q_y = \Sigma_i \mathrm{w}_i \sin(n\phi_i)$$

$$Q_x = \Sigma_i \mathrm{w}_i \cos(n\phi_i)$$

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

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

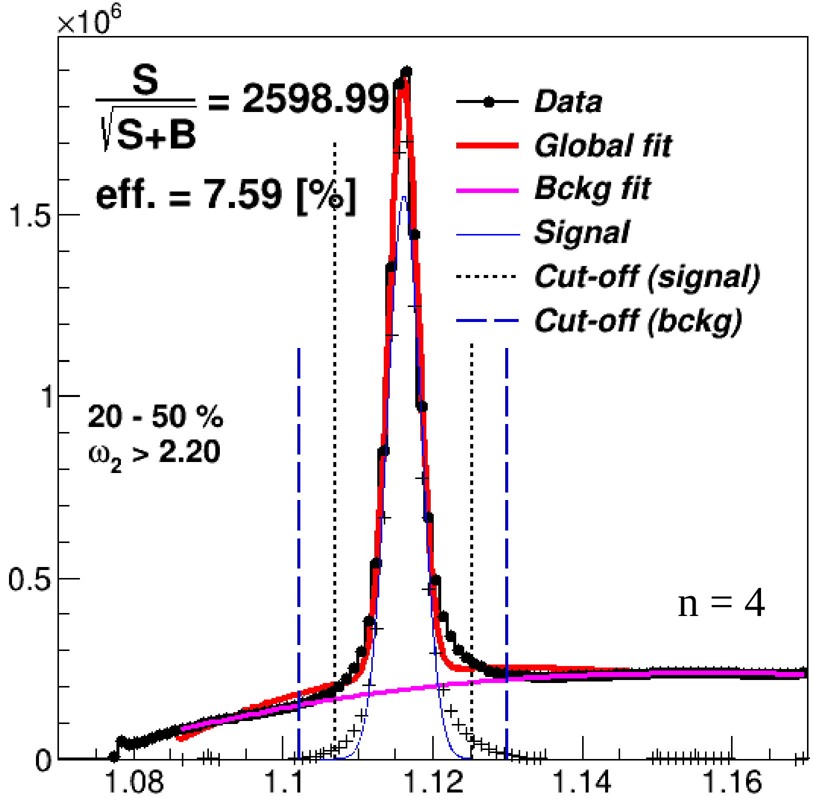




- 1-st order event plane resolution determined using FHCal
- (left) true and reconstructed resolution for 7 centrality bins
- (right) comparison of EP resolution coming from the EP wagon and calculated in my code (for 4 centrality bins)

Realization within the mpd train framework

- **Global Polarization Wagon**
- MC polarization test
  - Using information from MCTracks branch, obtains MC distribution of global polarization for Lambda/ALambda
  - Obtains angular distribution of protons from Lambda using either RP or EP angle, which can be fitted to extract polarization
- RECO polarization
  - Obtains topology selection cuts for Lambda reconstruction («selection»)
  - Currently done for ω_2 selection («omega»), plan to add multidimensional selection based on dca or chi values
  - The obtained file with selection values needs to be used in the second iteration of the train («analysis») to obtain the required distributions for polarization



Fitting procedure:

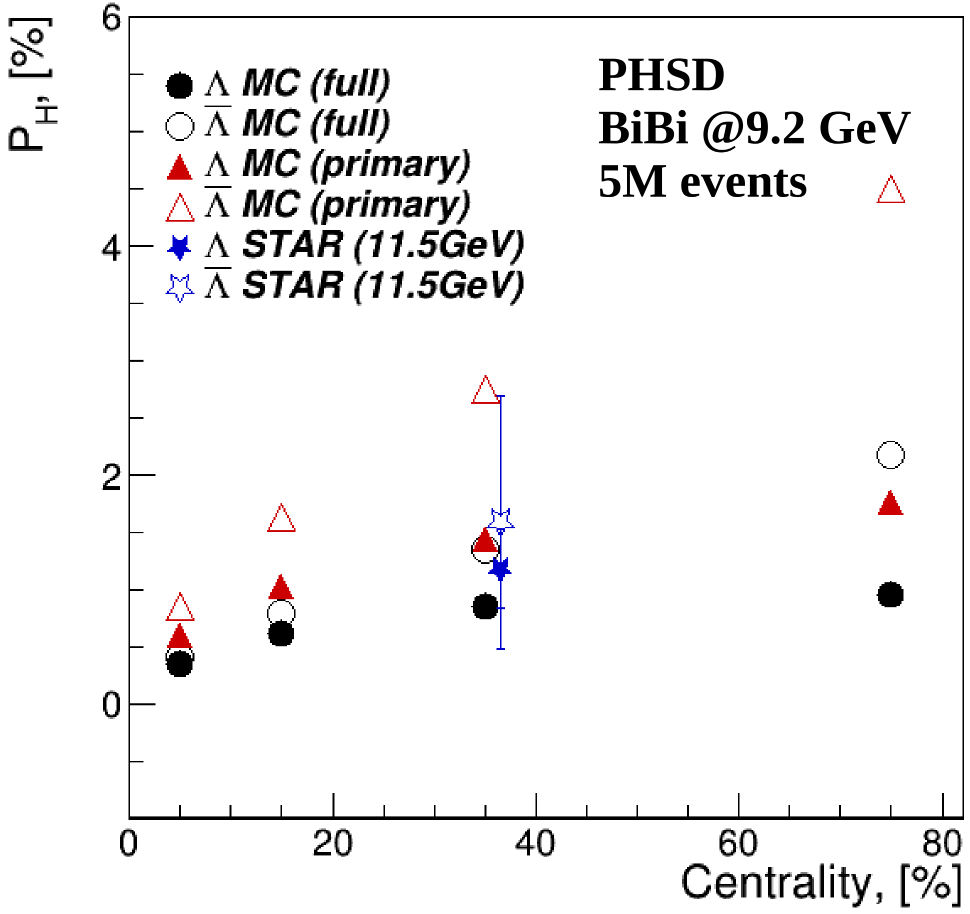
- Global fit (Gauss + Legendre polynomials)
- Background fit in sidebands ($\pm$ 7σ)
- Cut-off: $\langle M_\Lambda \rangle \pm n^*\sigma$
- ω_2 cut based on maximum significance (for each centrality bin)

	ω_2	Significance
0-10%	3.6	2315.98
10-20%	3.0	2043.82
20-50%	2.2	2598.99
50-100%	1.7	1166.78

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

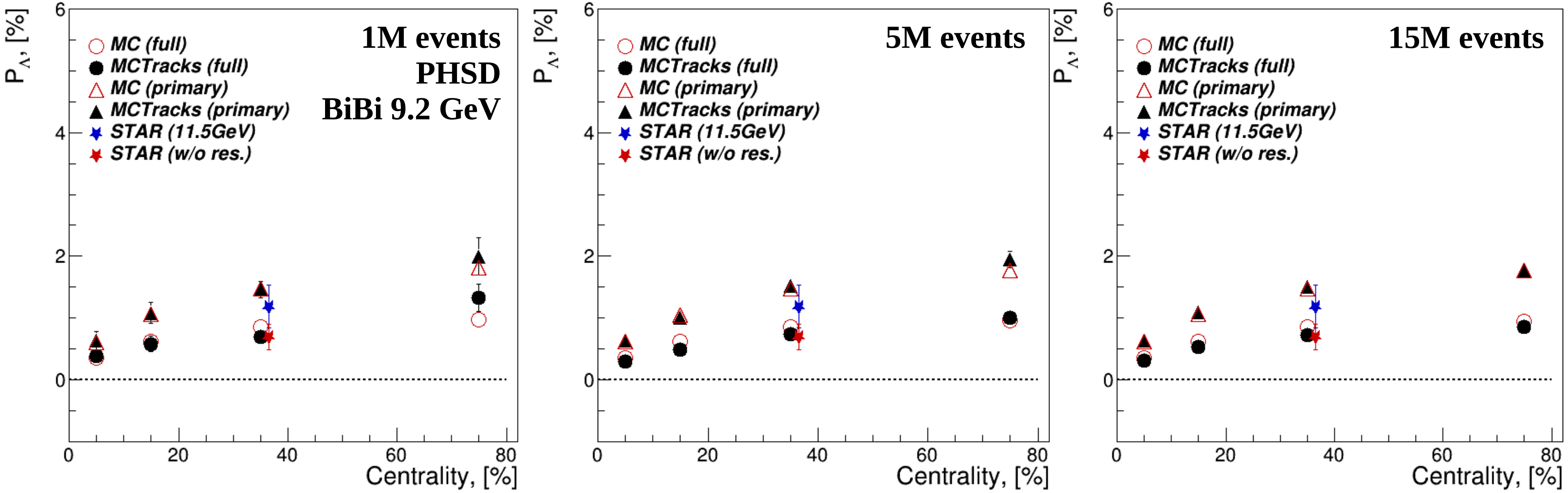
$$f(x) = p_0 \exp\left(\frac{(-0.5(x-p_1))^2}{p_2^2}\right) + p_3(L_0 + p_4 L_1 + p_5 L_2 + p_6 L_3 + p_7 L_4)$$

Results (MC, Lambda/Alambda polarization)



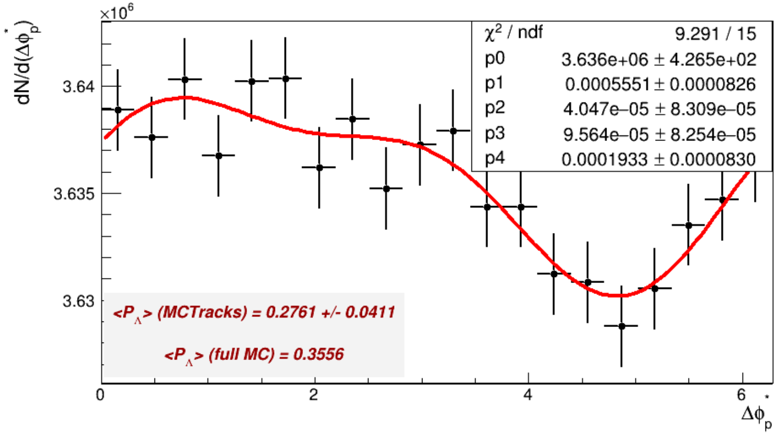
- Polarization of $\bar{\Lambda}$ is higher than that of Λ
- Feed-down effects decrease full polarization values (primary + secondary hyperons)
- Model values of polarization can be extracted as mean value of P_y distribution ($-|P_y|$)
- EP method can be used to measure polarization from both MC and Reco tracks

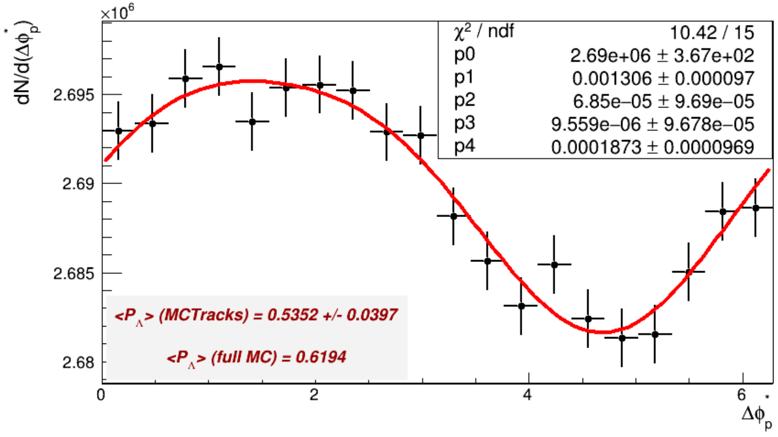
Results (MC, Lambda)

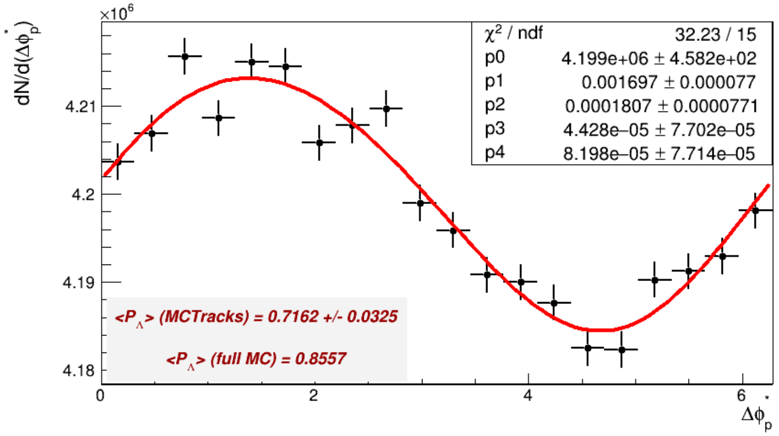


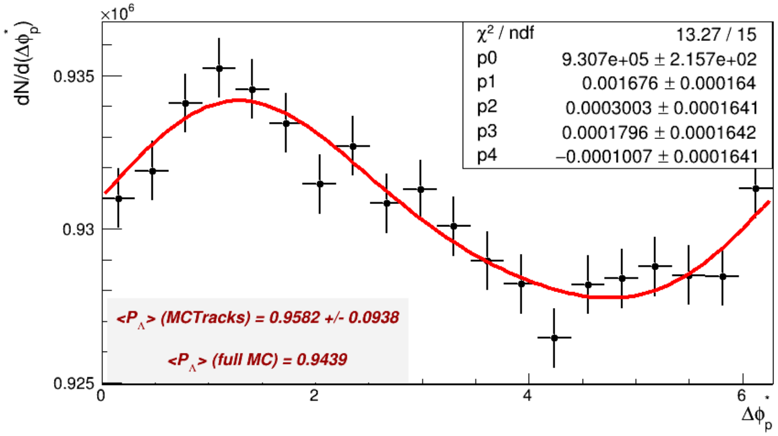
- Testing the EP method of polarization extraction on the MCTracks
- Model value of polarization (MC) compared with the one calculated through the angular distribution (MCTracks)
- Using RP angle instead of EP angle
- Results are consistent and in good agreement

Results (MC, Lambda)



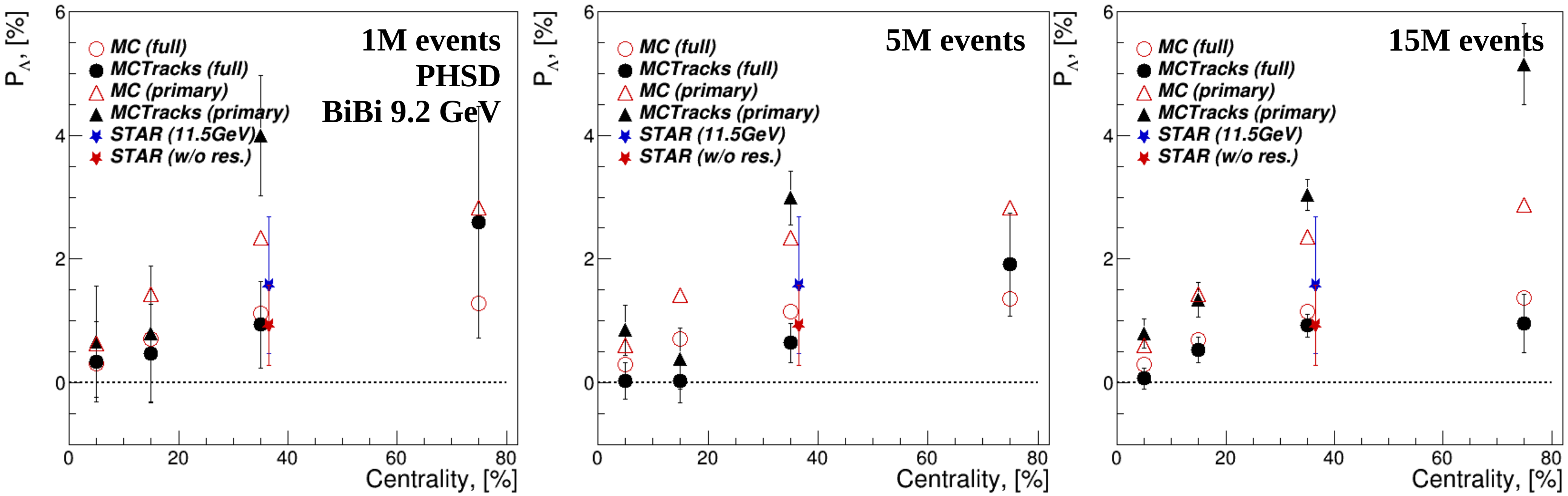






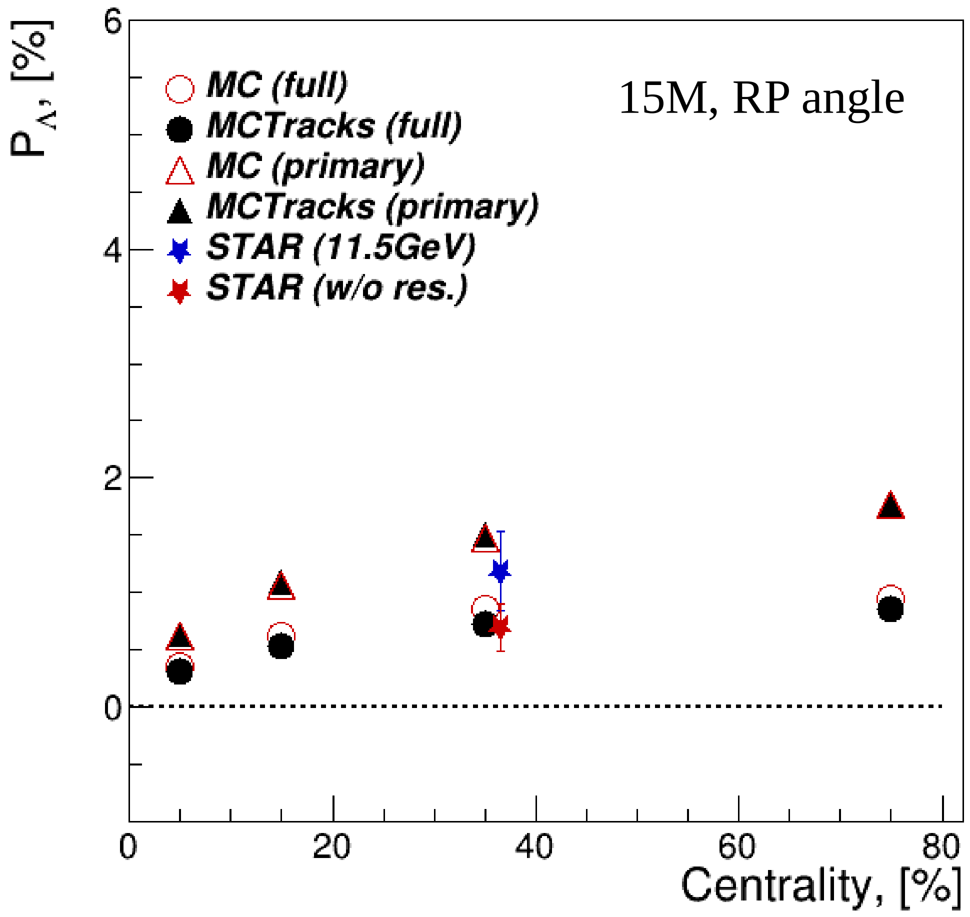
- Anisotropy is clearly visible in the angular distribution
- Good agreement between values calculated via fitting procedure and mean polarization

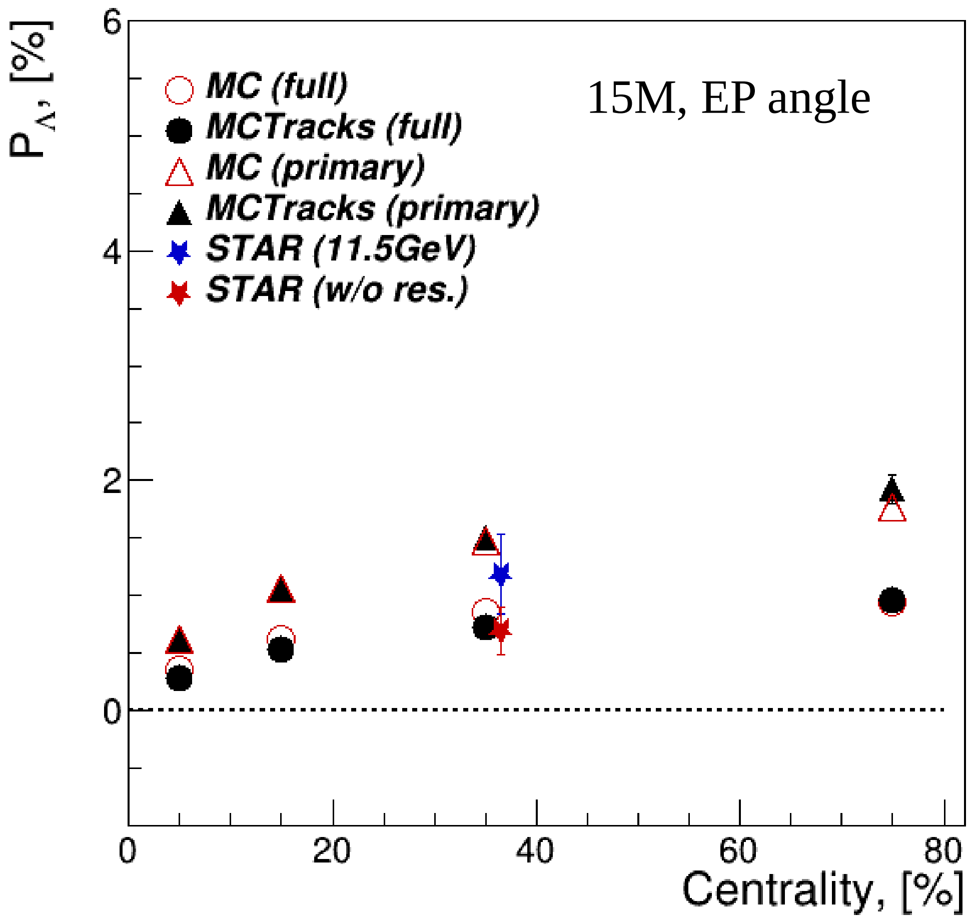
Results (MC, ALambda)



- Testing the EP method of polarization extraction on the MCTracks
- Model value of polarization (MC) compared with the one calculated through the angular distribution (MCTracks)
- Using RP angle instead of EP angle
- Results are consistent and in good agreement (but statistics for ALambda is lower)

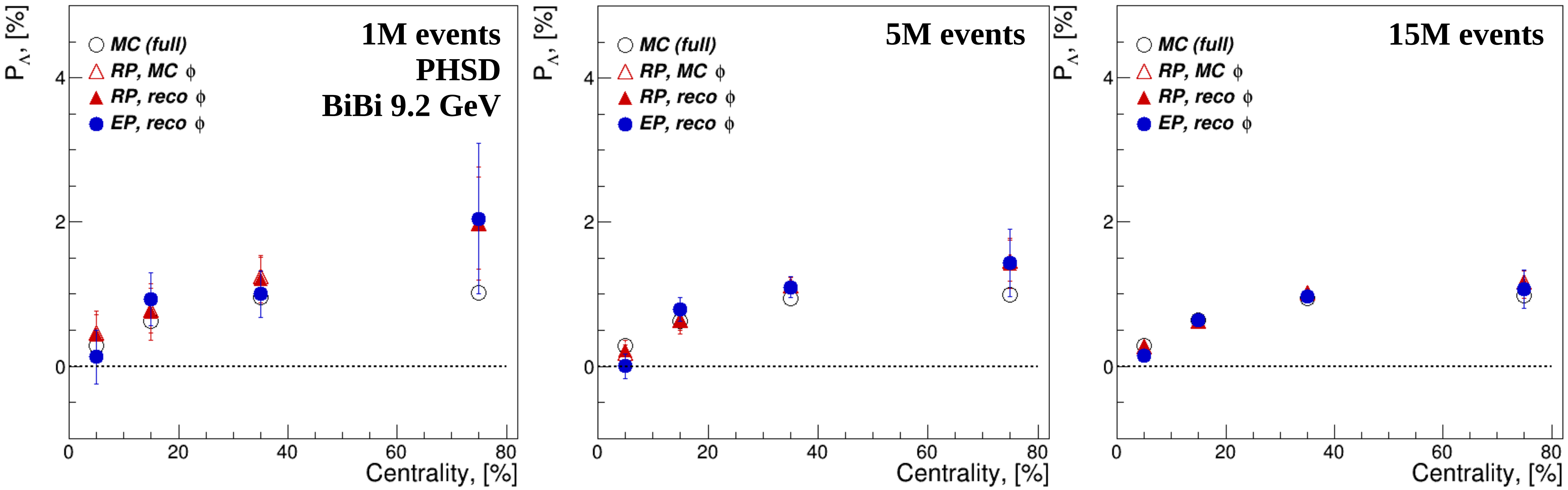
Results (MC, Lambda) — RP vs EP angle



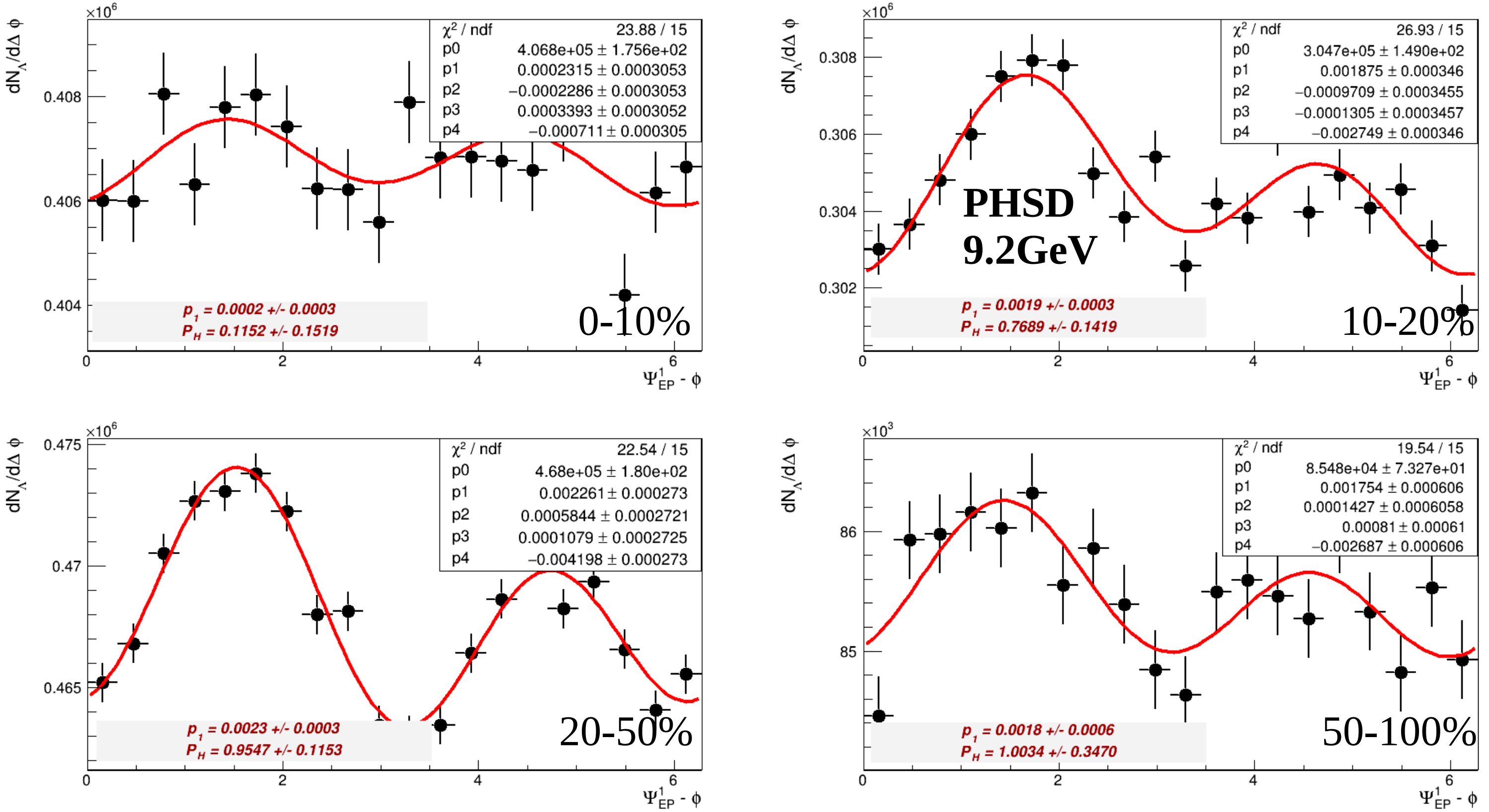


Using EP angle and its resolution instead of RP angle gives consistent results

Results (MCReco, Lambda)



- Fitting of angular distributions for «true» Lambda from Reco
- Using exact azimuthal angle (MC φ), reconstructed angle (reco φ) - with RP angle
- Using reconstructed angle (reco φ) - with EP angle and its resolution
- Consistent results between all choices



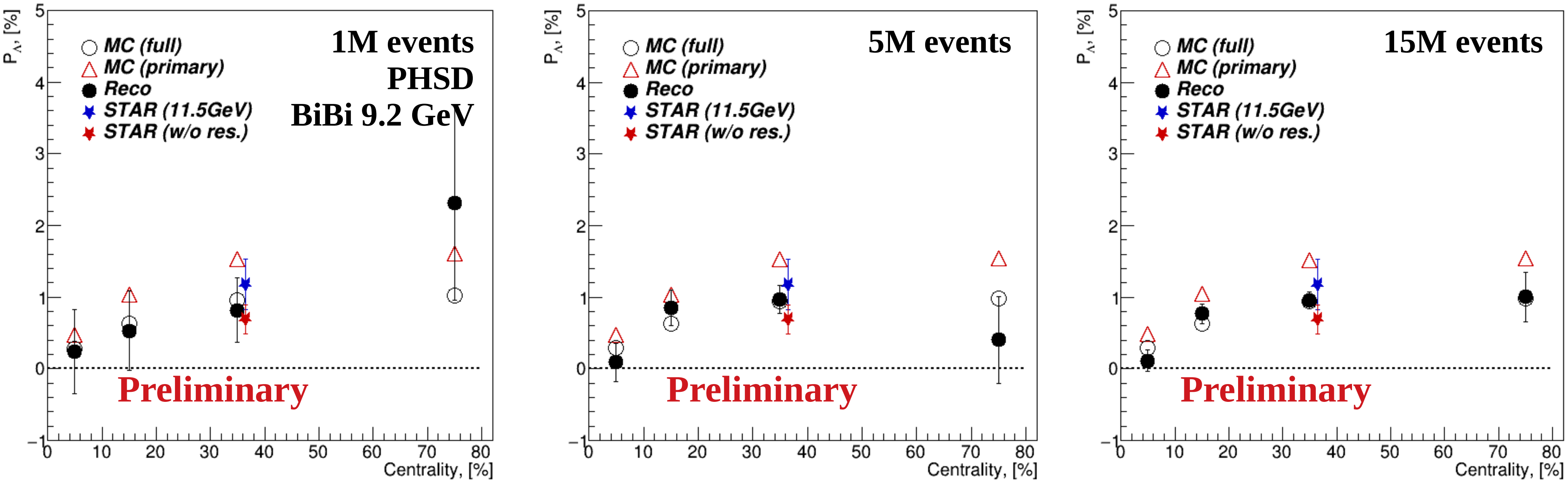
$$P_\Lambda = \frac{8}{\pi \alpha_\Lambda} \frac{p_1}{R^1_{EP}}$$

$$\alpha_\Lambda \simeq 0.732$$

	N_Λ
0-10%	8.1* 10^6
10-20%	6.1* 10^6
20-50%	9.4* 10^6
50-100%	1.7* 10^6

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

Results (Reco)



- Reconstructed polarization values using ω_2 selection for Lambda
- Uncertainties decrease with increasing statistics
- Results are in good agreement with MC values
- 50-100% (50-70%) centrality region: lowest statistics, smallest EP resolution

Conclusions & Outlook

- Feasibility study of global hyperon polarization at MPD
  - Official production (request 30): Bi-Bi @ 9.2GeV, 15M MB events, b [0,12]fm
- Global polarization framework within the MPD train framework
  - Preliminary version for MC tests or RECO polarization
  - Using Centrality and Event Plane wagon
  - Good agreement between reconstructed and MC values of polarization
- Outlook
  - Finalize the framework and results (include different selection options, anti-Lambda reconstruction)
  - Choose what results to include in the paper

The End

Thank you for your attention!