Lambda global polarization studies with MPD

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«Vorticity and Polarization in Heavy-Ion Collisions»

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

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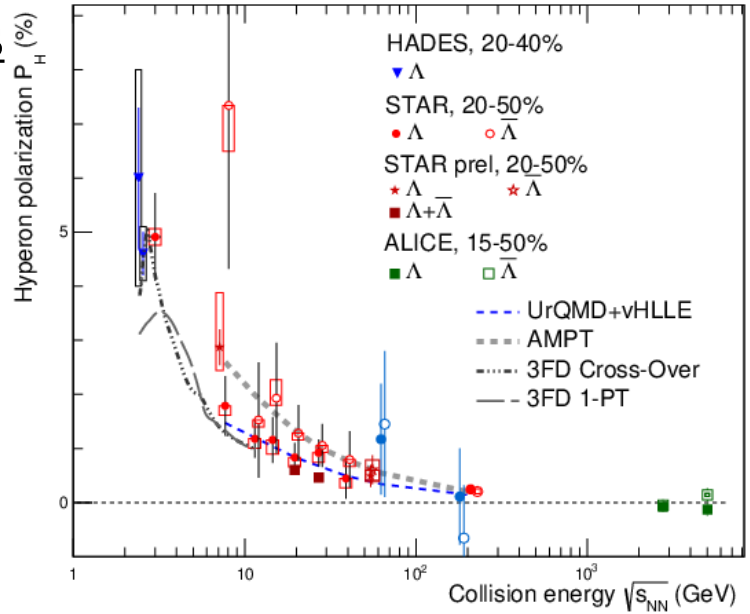
[1] Joint Institute of Nuclear Research, Dubna, Russia

Outline

- Introduction
- Analysis technique
  - Simulation
  - Event reconstruction
  - Lambda reconstruction
  - Global polarization measurement
- Implementation within the centralized MPD framework
- Results
- Conclusions & Outlook

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 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

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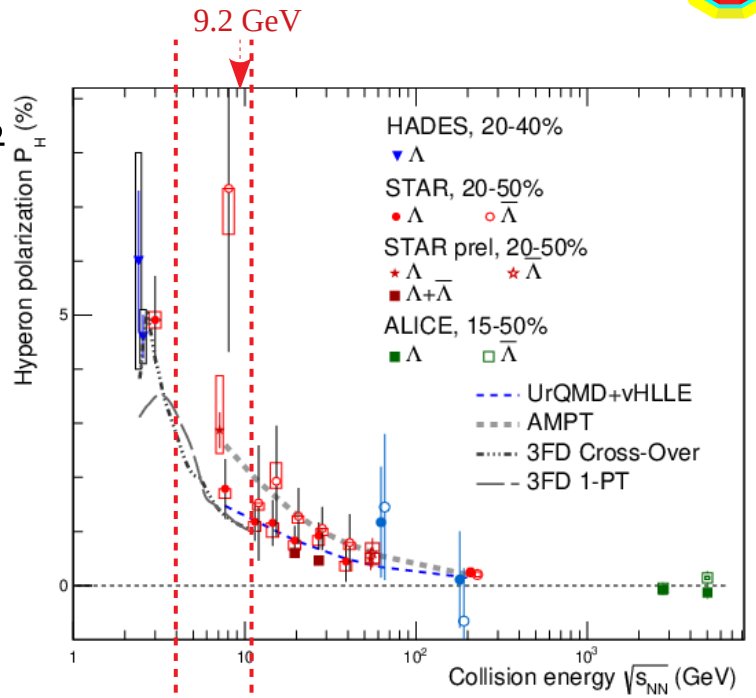

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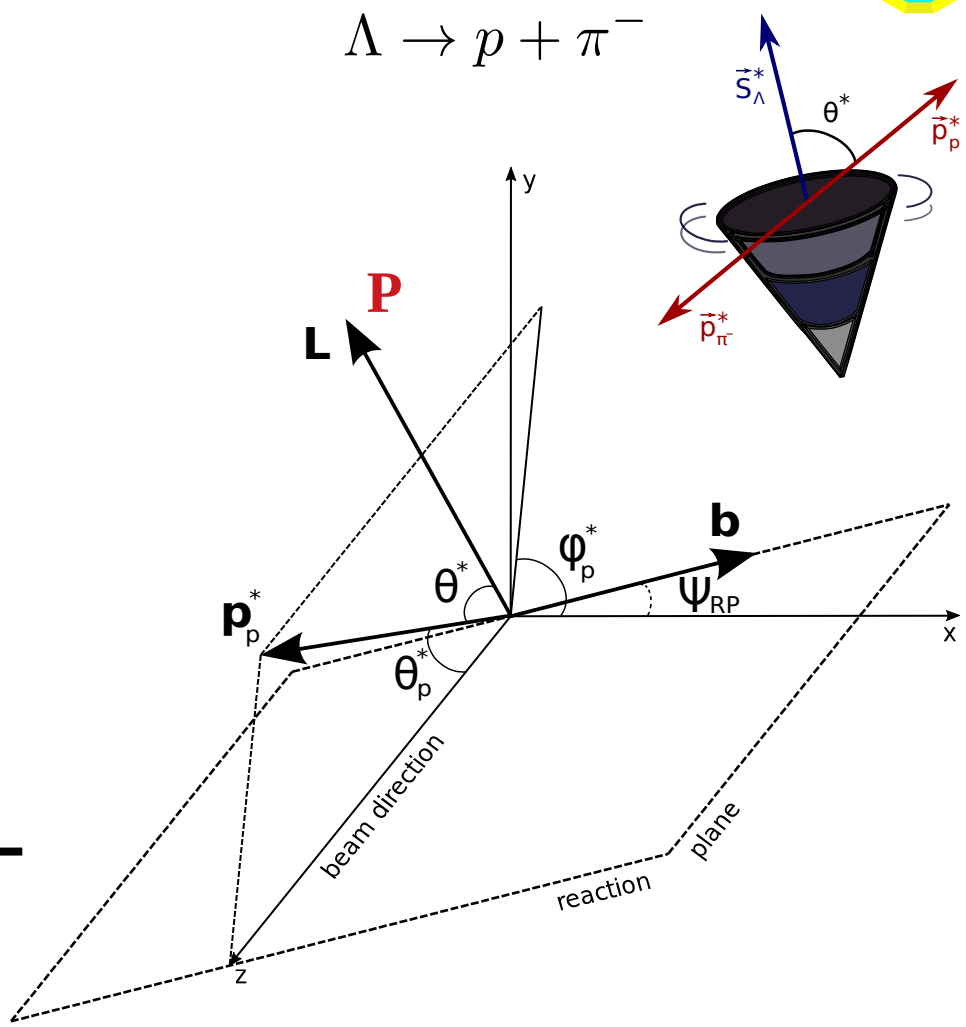
Global hyperon polarization

- 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])

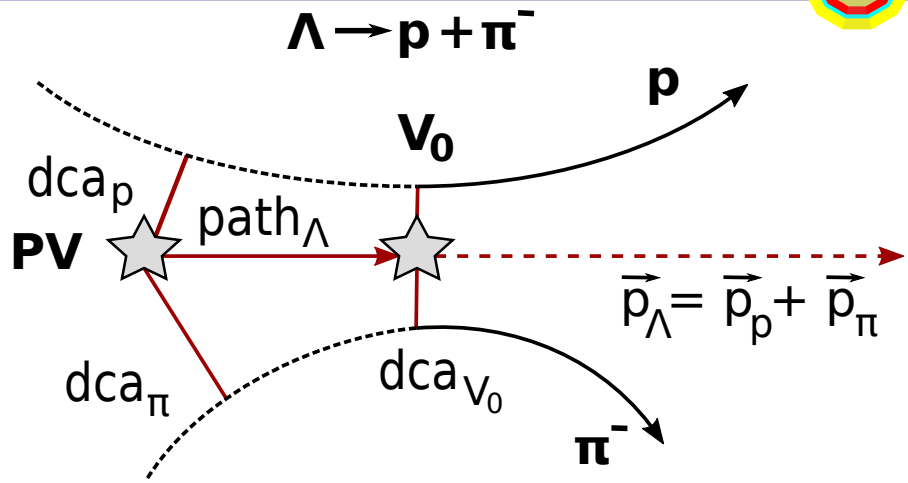


[1] Z. Liang, X. Wang, PRL 94, 102301 (2005)
[2] L. Adamczyk et al., Nature 548, 62 (2017)
[3] Ablikim M, et al., Nature Phys. 15:631 (2019)

Global hyperon polarization

- 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 $(\Psi^1_{\mathrm{EP}}, R^1_{\mathrm{EP}})$

→ 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
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]
    - Hyperon polarization vector ($\mathbf{P} = \{P_x, P_y, P_z\}$)
    - Higher polarization for $\bar{\Lambda}$ (w.r.t. Λ)

See detailts in talk by V. Voronyuk

[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

MC simulation
PHSD

↓

Detector simulation
GEANT 4

↓

Event reconstruction
MPD

- Detector simulation
  - 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))

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

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

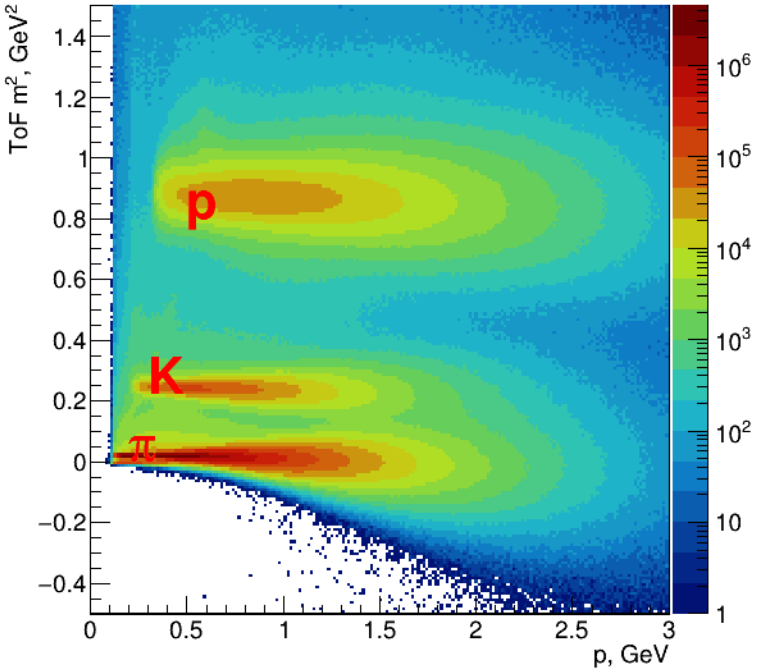
[2] F. Becattini et al., Phys.Rev.C 95 (2017) 5, 054902

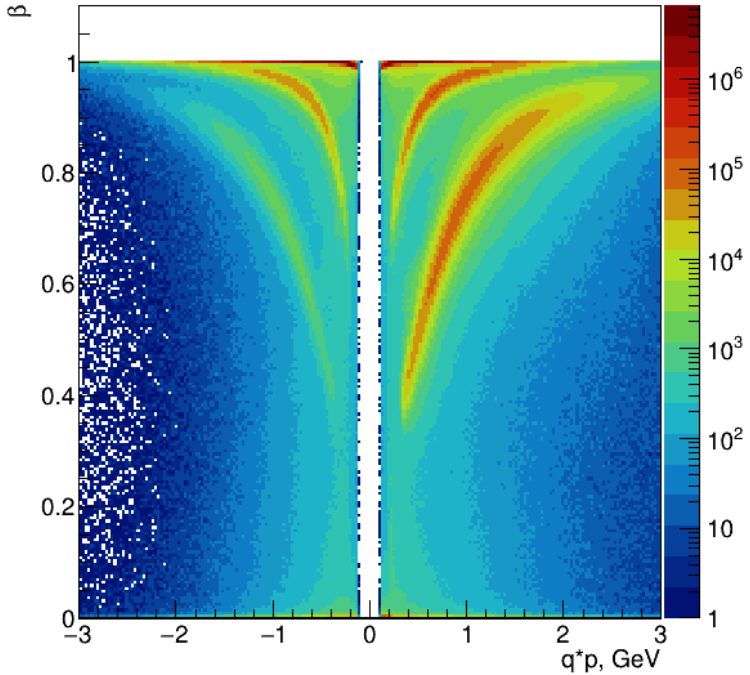
MC simulation
PHSD

Detector simulation
GEANT 4

Event reconstruction
MPD

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





Implementation within the MPD framework

- MC analysis
- Reco analysis

- Incorporating the code for hyperon global polarization analysis into the centralized MPD train framework
- Utilizing Centrality and Event Plane wagons
- Events are processed one-by-one by each wagon, that modify and/or analyze the data
- All wagons have similar structure → provide consistency among all analyses

- Main macro to start the train (example):

```
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

Implementation within the MPD framework

- **Centrality Wagon** (see V. Riabov report at Cross-PWG)
- Calculates centrality based on TPC multiplicity
- Return 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 FFD||FHCal trigger (assessed based on event track multiplicity using efficiency file)
- Event centrality (float in [0-91]) is available for all other wagons in the train: event.getCentrTPC();
- For global polarization analysis we used **4** or **7** bins of centrality

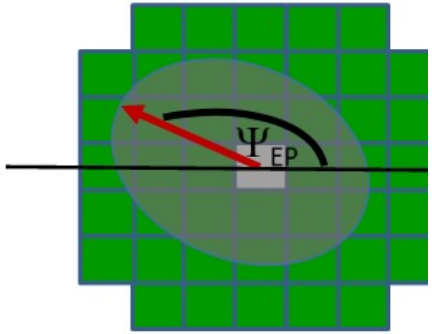
- Selection criteria:
  - $|\eta| < 0.5$
  - $|p_T| > 0.1$ GeV
  - $N_{hits} > 10$
  - $|DCA| < 2.0$
  - Cuts on empty events and vertex, trigger efficiency

0-10%, 10-20%, 20-50%, 50-100%

0-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%

Implementation within the MPD framework

- **Event Plane Wagon** (see P. Parfenov report at Cross-PWG)
- 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 via subevent method[1])
- Option to use EP corrections (reduce possible bias from non-uniform detector acceptance)



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

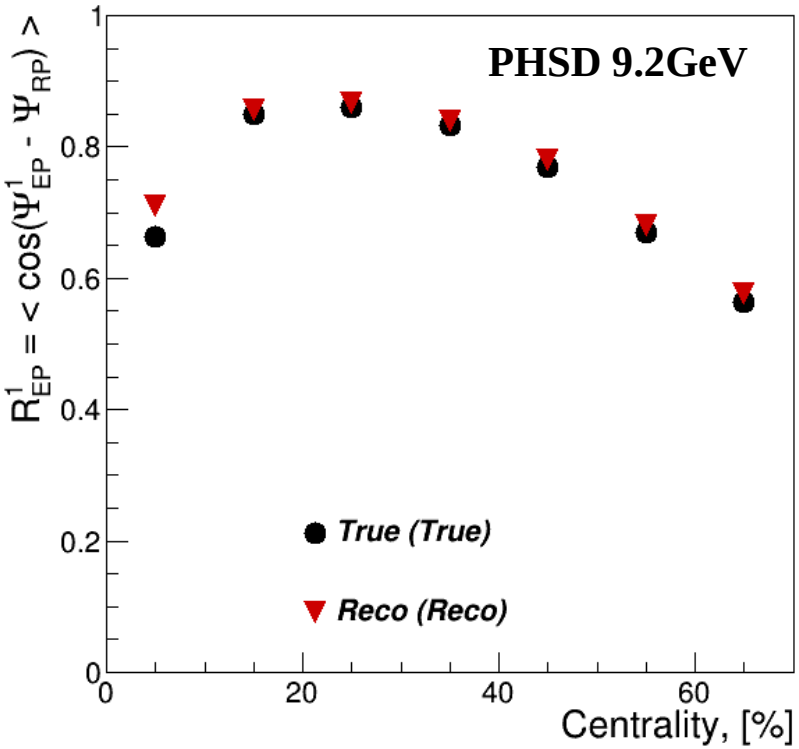
$$Q_y = \Sigma_i \mathrm{w}_i \sin(n\phi_i)$$

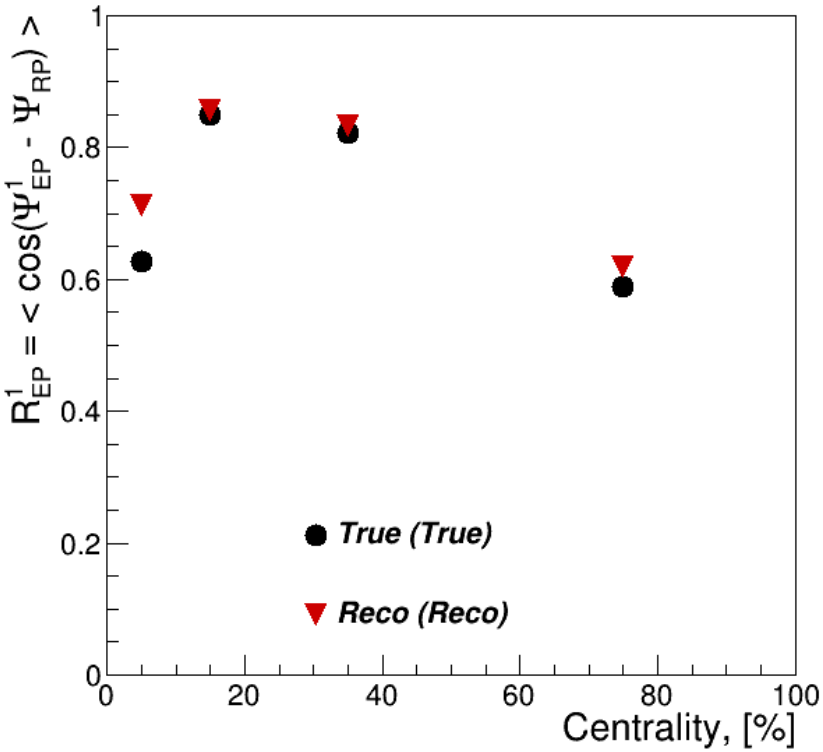
$$Q_x = \Sigma_i \mathrm{w}_i \cos(n\phi_i)$$

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

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

Event plane resolution





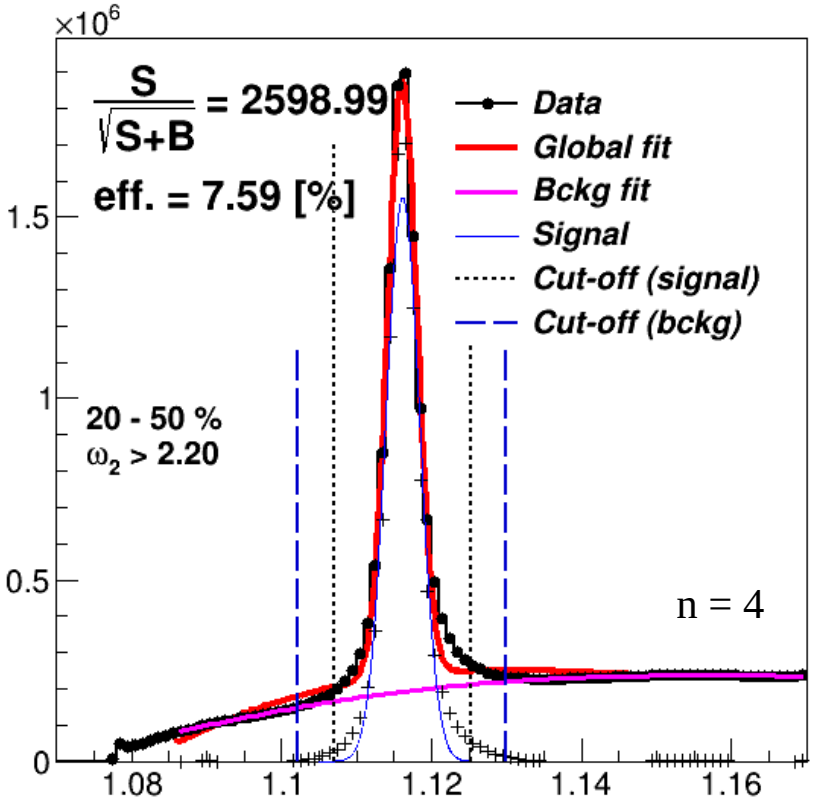
- 1-st order EP resolution using FHCal (for 7 or 4 bins of centrality)
- True: w.r.t. RP angle
- Reco: determined using subevent method[1]

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

Implementation within the MPD framework

- **Global Polarization Wagon**
- MC polarization → check simulation and extraction method
  - Using information from MCTracks, 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 → feasibility study of Lambda polarization
  - Obtains topology selection cuts for Lambda reconstruction («selection» option)
  - 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 extraction using EP method

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)

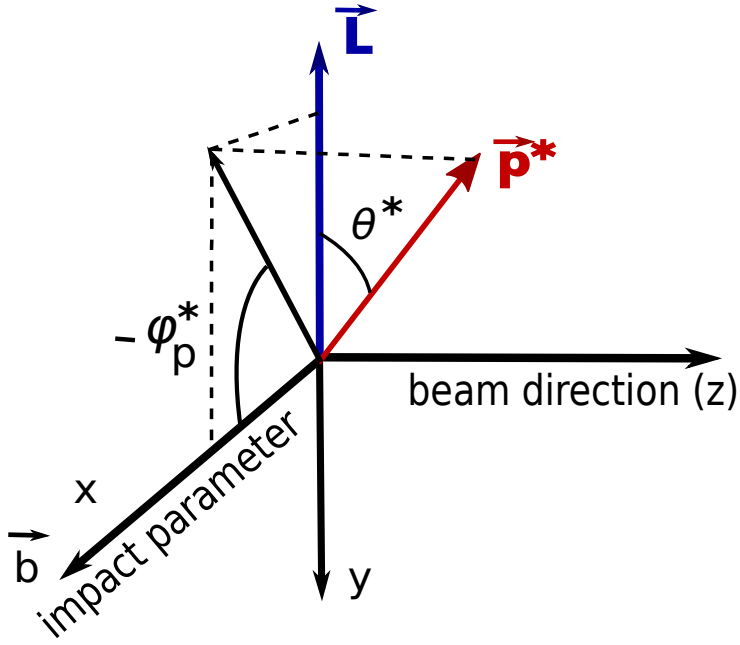
	ω_2	Significance
0-10%	3.6	2315.98
10-20%	3.0	2043.82
20-50%	2.2	2598.99
50-100%	1.7	1166.78

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

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

Global polarization reconstruction

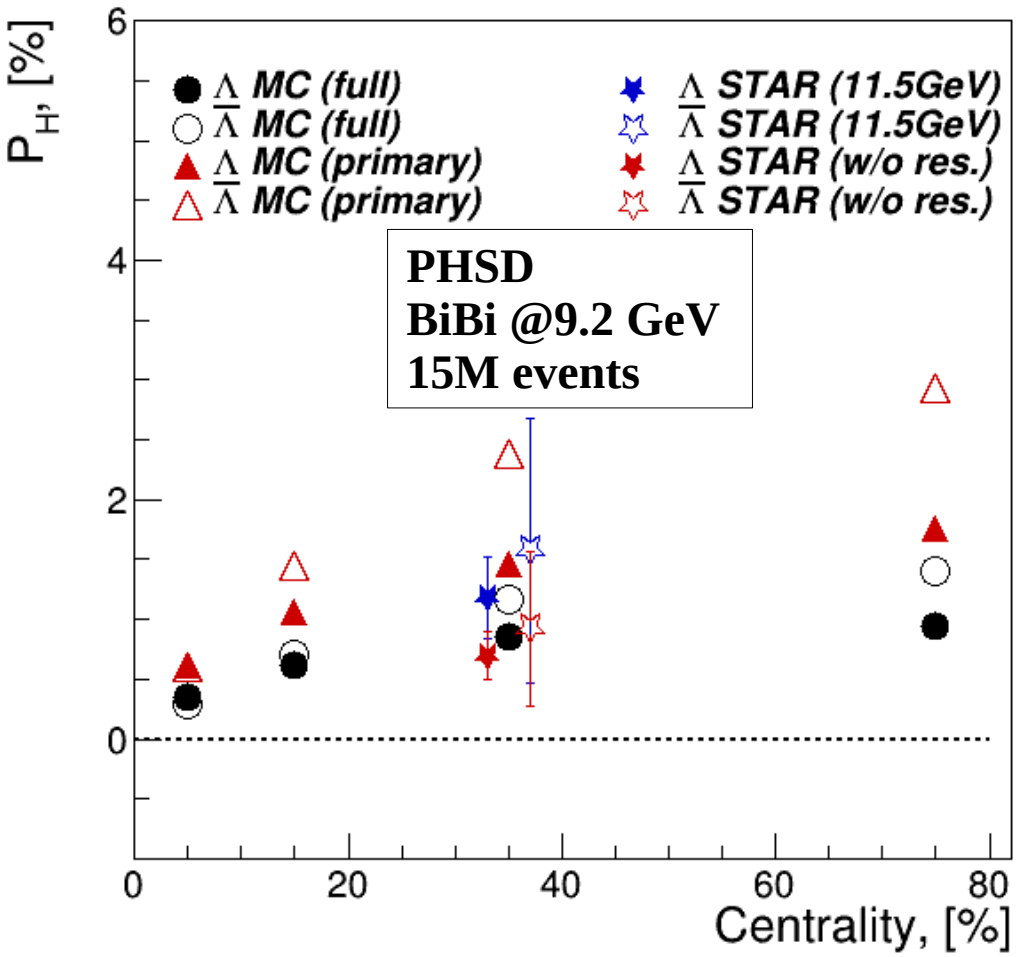
- Obtain invariant mass distribution in bins of $\Delta\phi_p^* = \Psi_{\mathrm{EP}}^1 - \phi_p^*$
  - Net amount of Λ in each bin
  - Distribution of $N_\Lambda(\Delta\phi_p^*)$
- Fit of the distribution[1] to get $\langle \sin(\Delta\phi_p^*) \rangle \rightarrow P_\Lambda$
  - «Event plane» method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



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

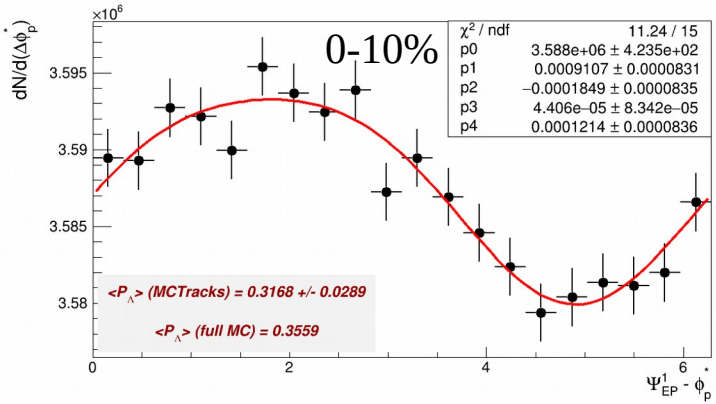
[1] $$\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi_p^*} = p_0(1 + 2p_1 \sin(\Delta\phi_p^*) + 2p_2 \cos(\Delta\phi_p^*) + 2p_3 \sin(2\Delta\phi_p^*) + 2p_4 \cos(2\Delta\phi_p^*) + \ldots)$$

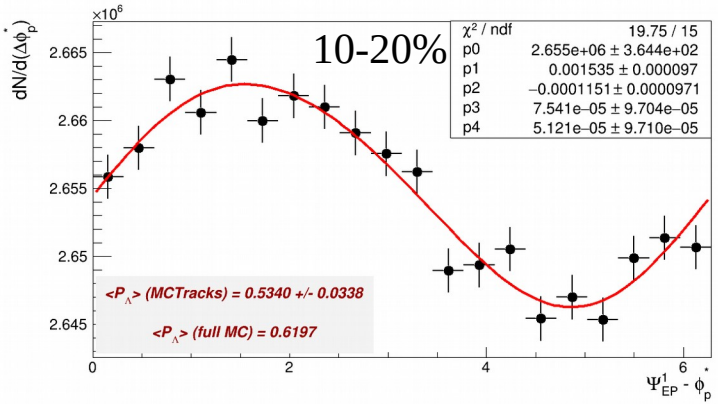
Results (MC, Lambda/ALambda polarization)

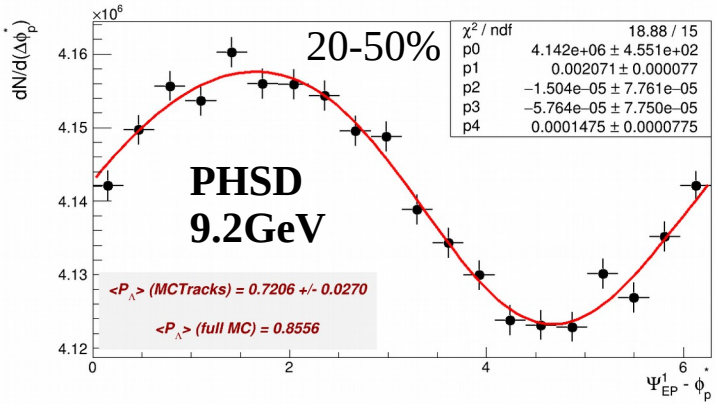


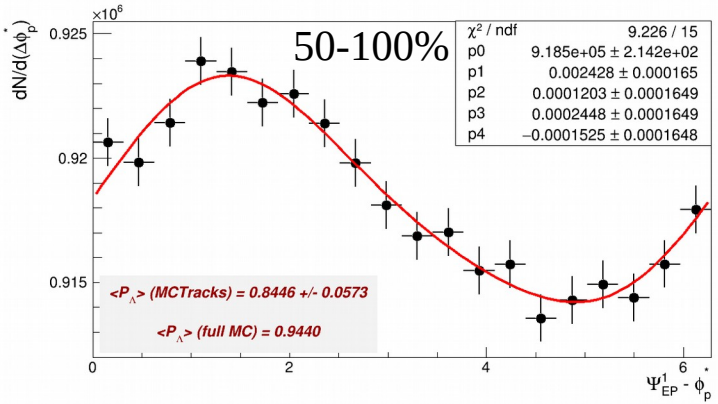
- Polarization of $\bar{\Lambda}$ is higher than that of Λ
- Feed-down effects decrease full polarization values (primary + secondary hyperons)
- Model values of polarization can be extracted as mean value of P_y distribution ($-|P_y|$)
- EP method can be used to measure polarization from both MC and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

Results (MC, Lambda)









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

$$\alpha_\Lambda \simeq 0.732$$

$$\Delta\phi^*_p = \Psi^1_{\mathrm{RP}} - \phi^*_p$$

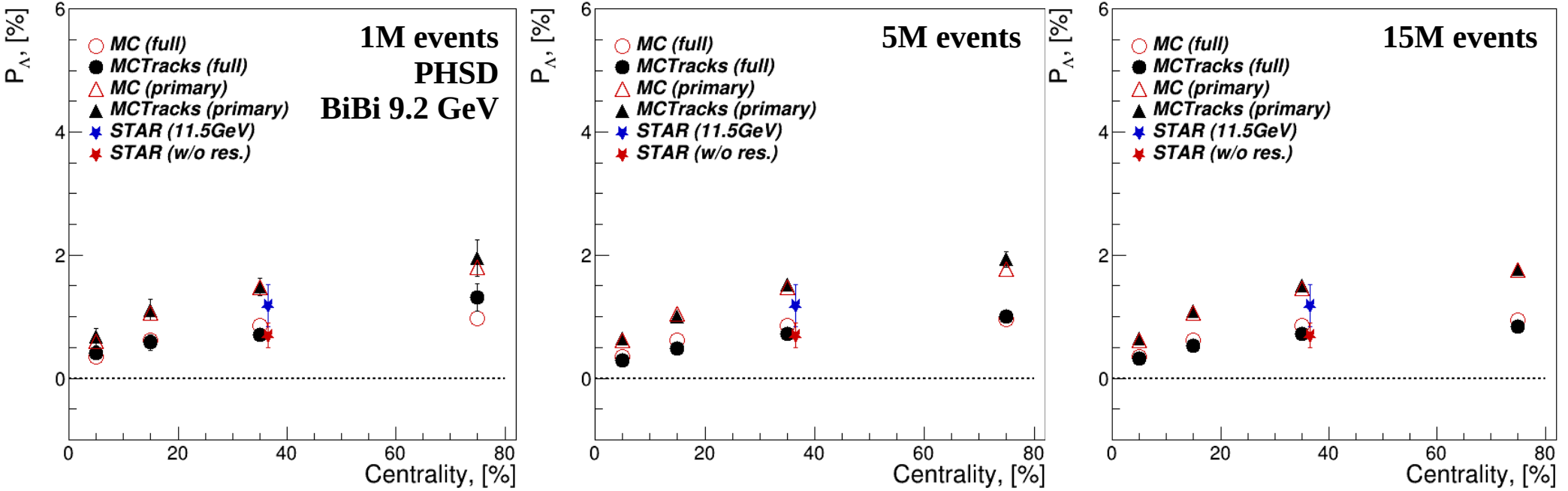
	N_Λ
0-10%	$7.2 * 10^7$
10-20%	$5.3 * 10^7$
20-50%	$8.3 * 10^7$
50-100%	$1.8 * 10^7$

$$R^1_{\mathrm{EP}} = 1$$

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

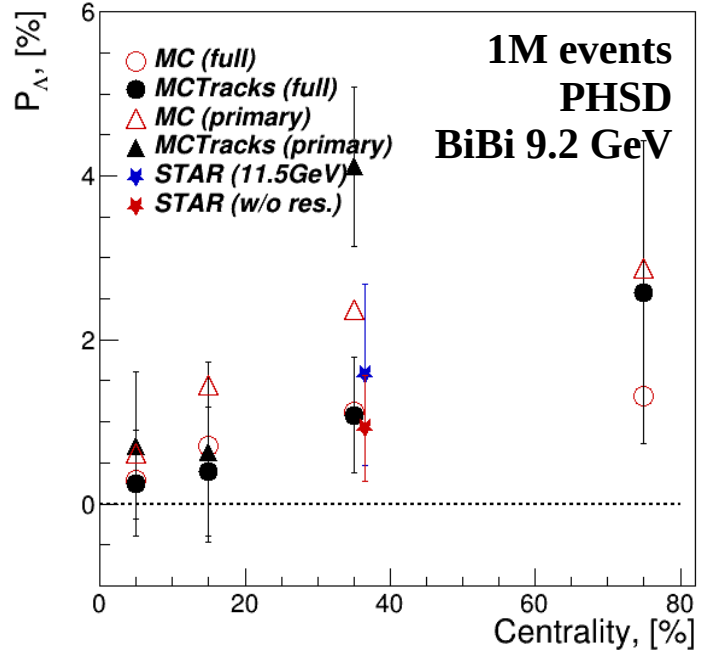
$$\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi^*_p} = p_0(1 + 2p_1 \sin(\Delta\phi^*_p) + 2p_2 \cos(\Delta\phi^*_p) + 2p_3 \sin(2\Delta\phi^*_p) + 2p_4 \cos(2\Delta\phi^*_p) + \ldots)$$

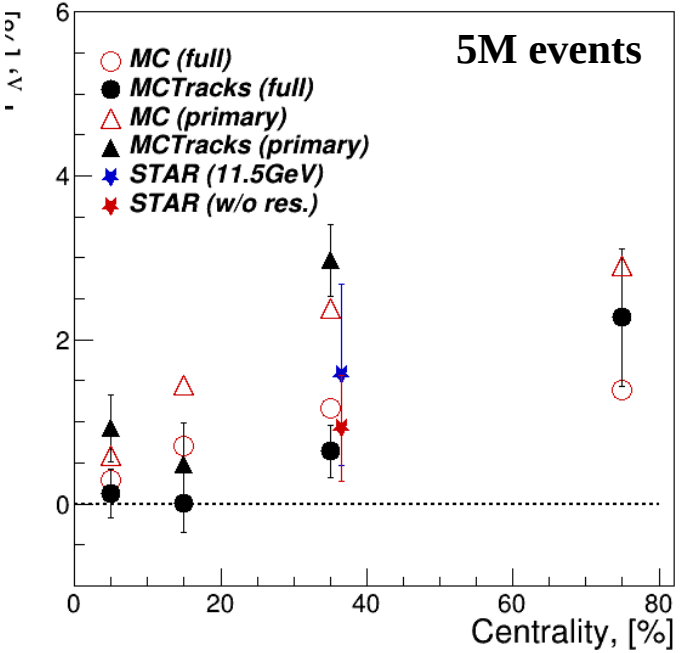
Results (MC, Lambda)

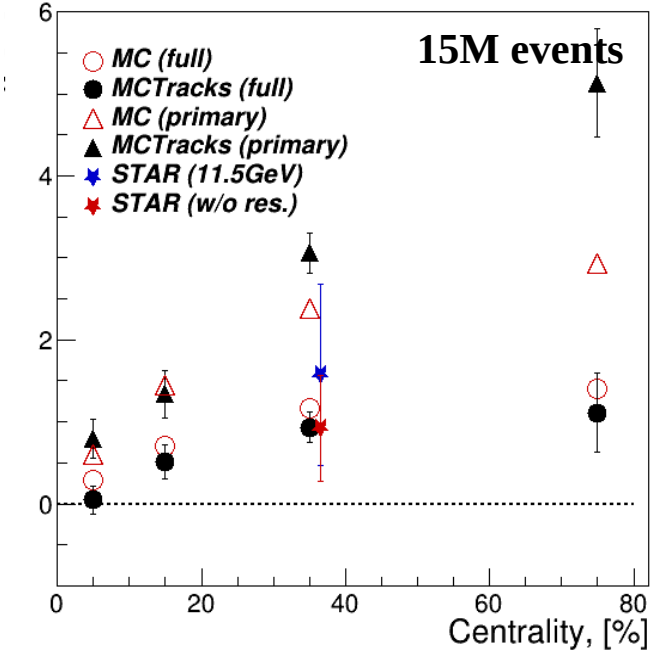


- Testing the EP method of polarization extraction on the MCTracks
- Model value of polarization (MC) compared with the one calculated through the angular distribution (MCTracks)
- Using RP angle instead of EP angle
- Results are consistent and in good agreement

Results (MC, ALambda)

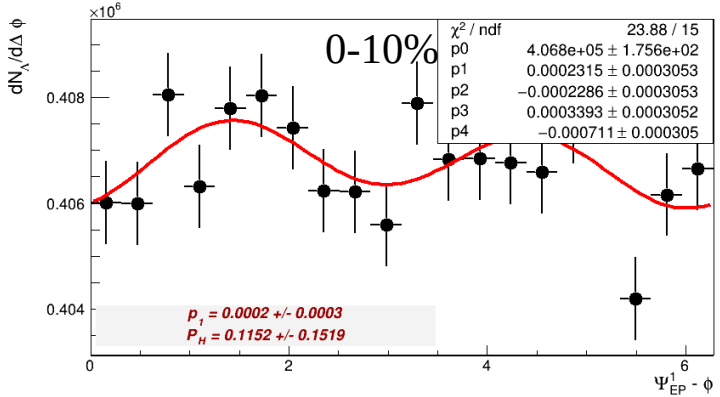


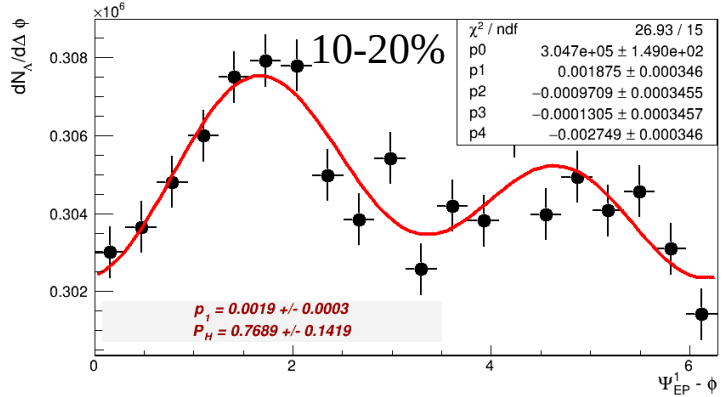


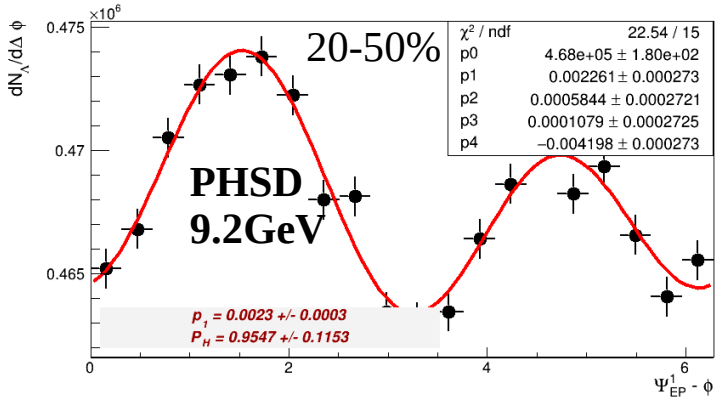


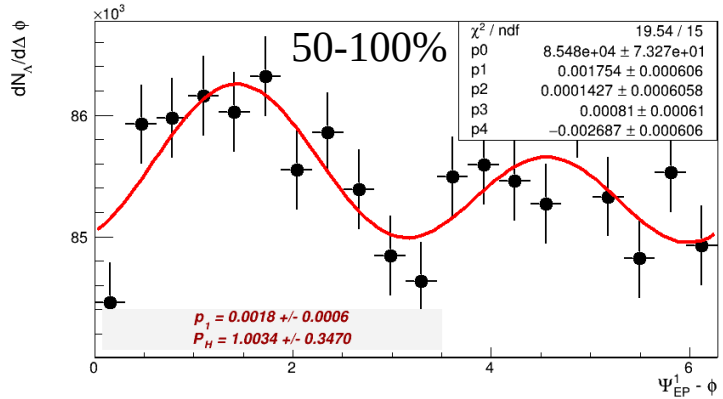
- Testing the EP method of polarization extraction on the MCTracks
- Model value of polarization (MC) compared with the one calculated through the angular distribution (MCTracks)
- Using RP angle instead of EP angle
- Results are consistent and in good agreement (statistics for ALambda is lower)

Results (Reco, Lambda)









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$$\alpha_\Lambda \simeq 0.732$$

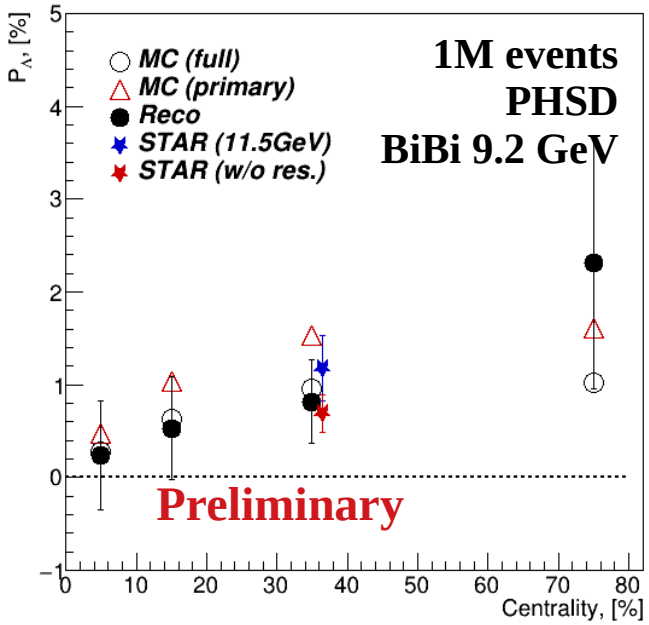
$$\Delta\phi^*_p = \Psi^1_{\mathrm{EP}} - \phi^*_p$$

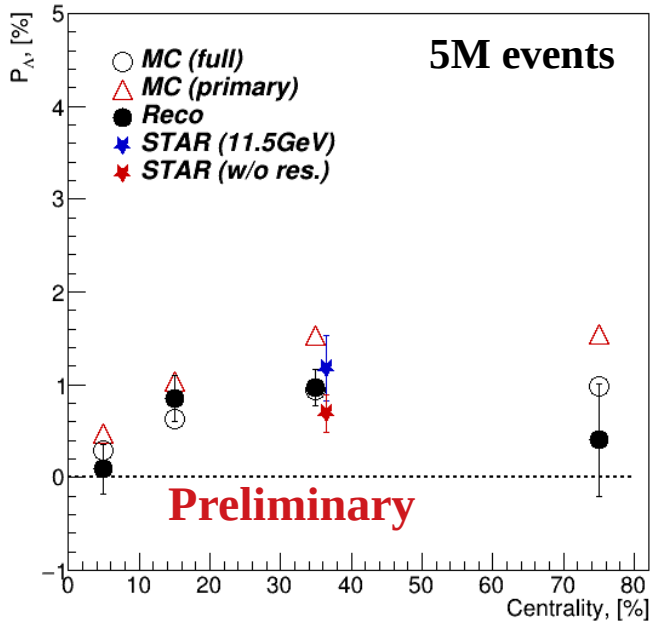
	N_Λ
0-10%	7.7* 10^6
10-20%	5.8* 10^6
20-50%	8.9* 10^6
50-100%	1.6* 10^6

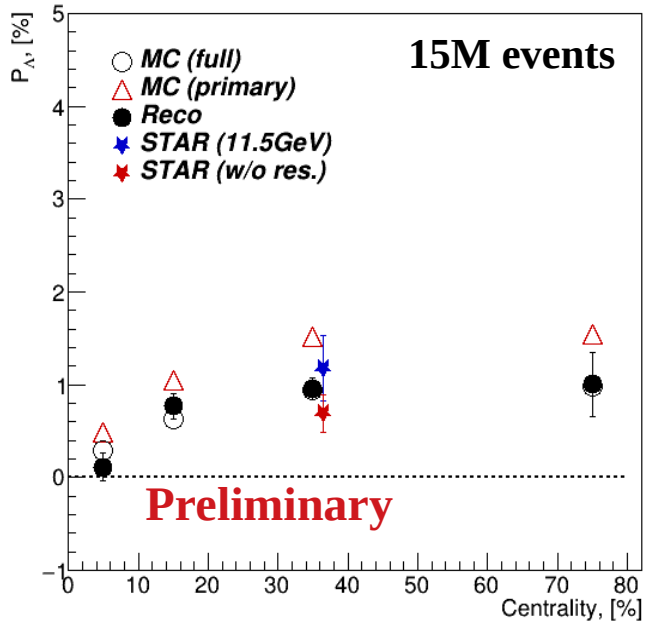
- Anisotropy is clearly visible in the angular distribution
- Statistics for Reco Lambda is sufficient for extracting polarization in 4 centrality bins

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

Results (Reco, Lambda)







- 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 Lambda/ALambda polarization using official centralized MC production:
  - Request 30: PHSD, Bi-Bi @9.2GeV, 15M MB events, b [0,12]fm
  - Good agreement between reconstructed and model values of polarization → preparation of obtained results for publication
- Implementation of the analysis within the MPD train framework
  - First version of the global polarization wagon for calculation of MC or RECO polarization is ready → will be added to mpdroot
  - Utilizes Centrality and Event Plane wagons
  - Lambda reconstruction using 1D topology selection (ω_2 parameter) based on maximum significance → ongoing work on adding different selection options, as well as another method of polarization extraction

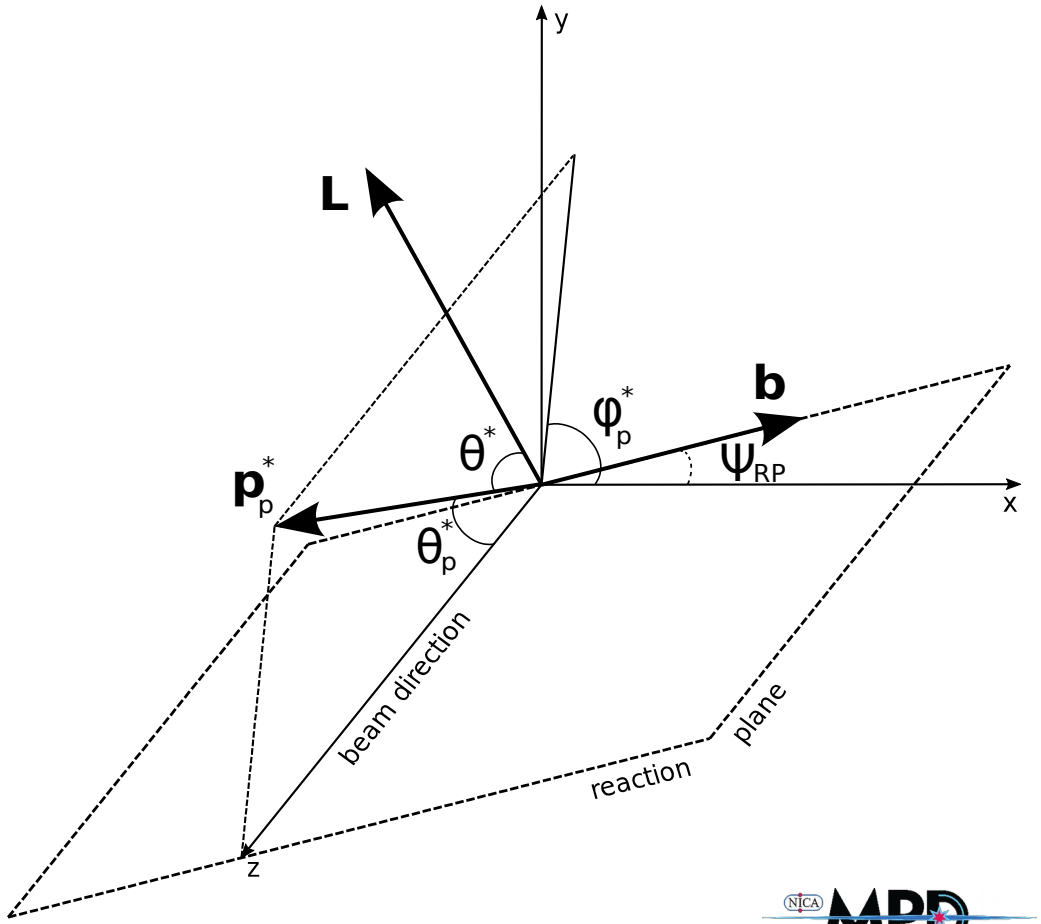
Thank you for your attention!

Back Up: Anisotropic decay of Lambda

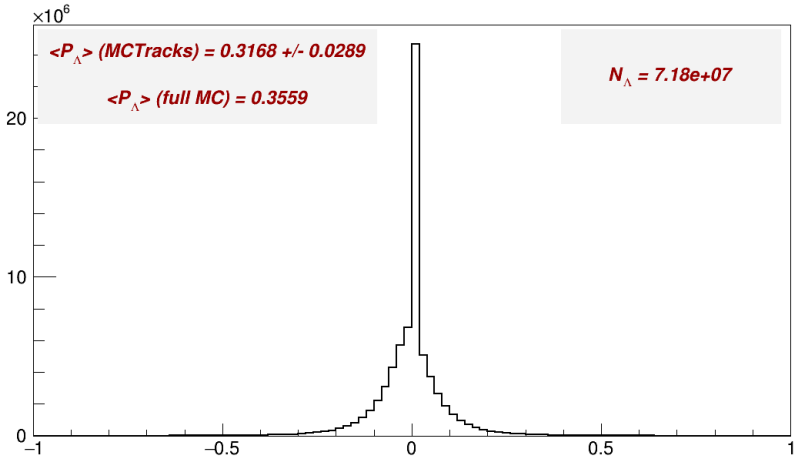
- Calculate random cosθ^* (from (1)) with |P|=1
- $\alpha_{\bar{\Lambda}} = -\alpha_{\Lambda} = 0.732$
- φ^* - random in [0,2π]
- Construct unitary vector of proton
- Rotate it w.r.t. polarization direction
- Boost to the lab frame

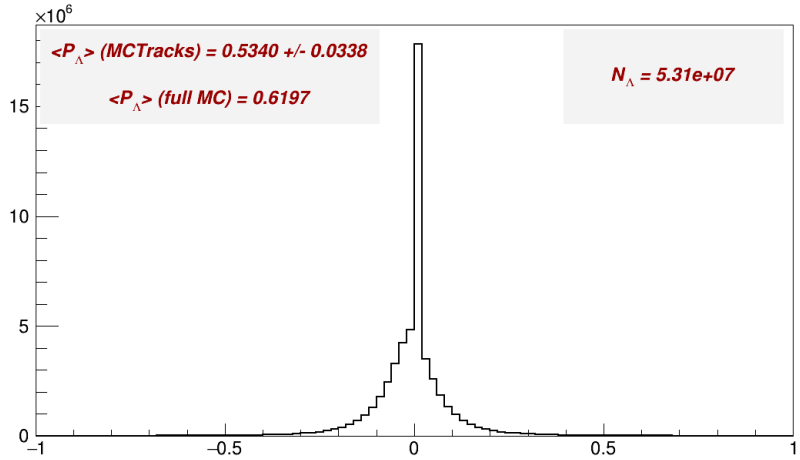
$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = \frac{1}{2}(1 + \alpha_{\mathrm{H}}|\vec{P}_{\mathrm{H}}|\cos\theta^*) \quad (1)$$

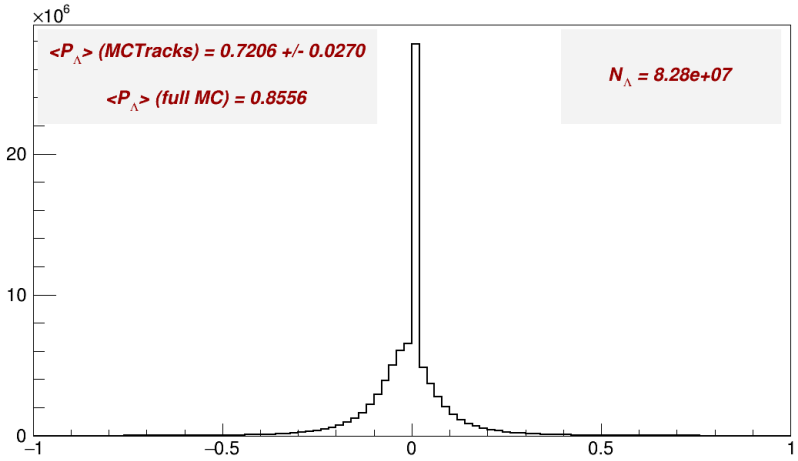
- Testing
  - Model values of polarization: mean value of P_y distribution ($-|P_y|$)
  - EP method used to measure polarization from (MC/Reco tracks)

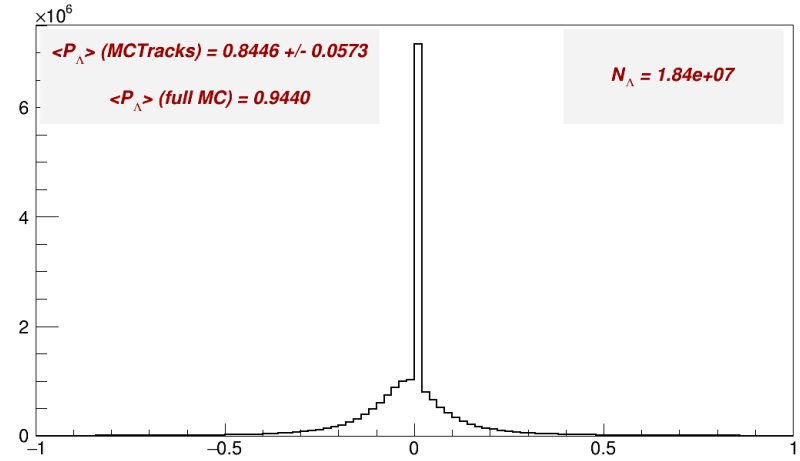


Back Up: P_y distributions (MC, Lambda)

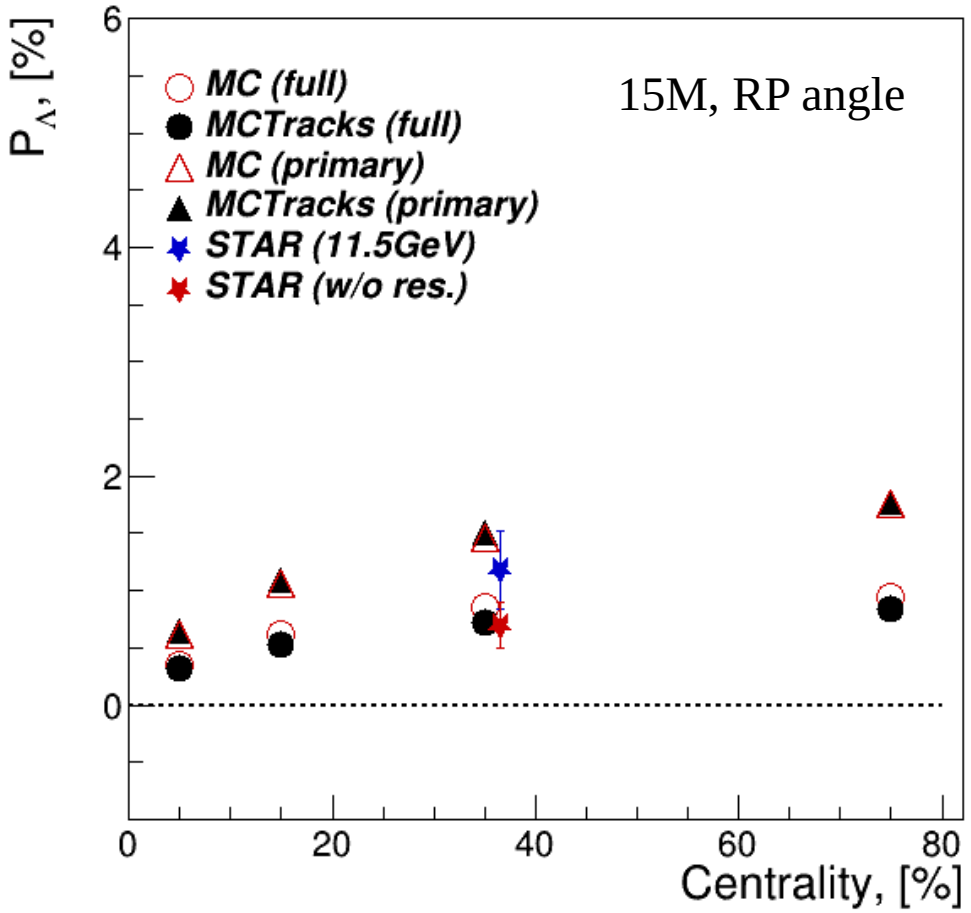


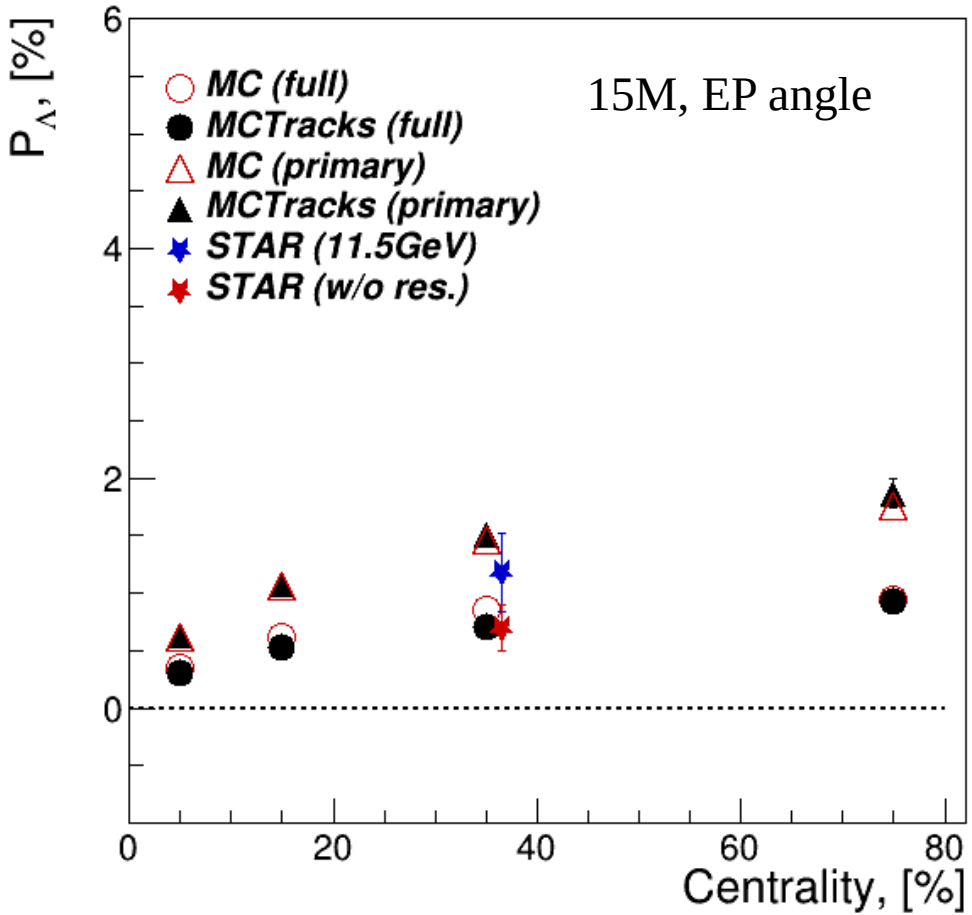






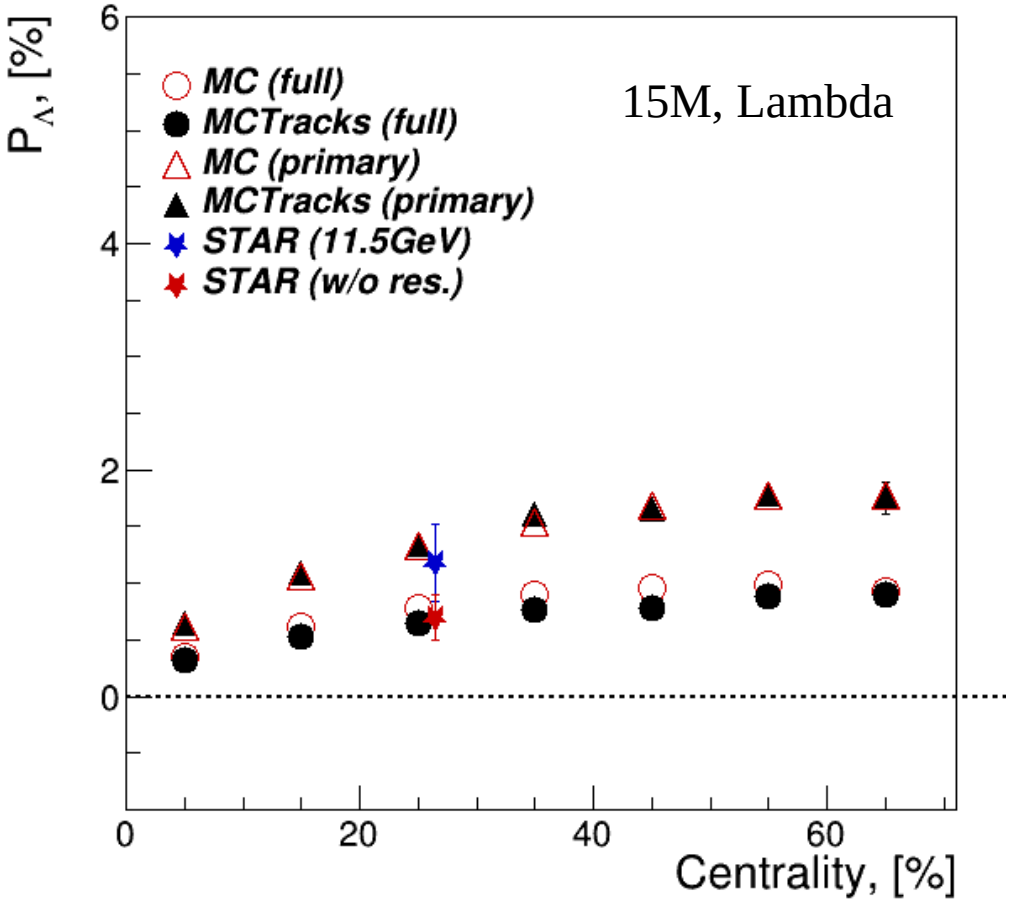
Back Up: Results (MC, Lambda) — RP vs EP angle

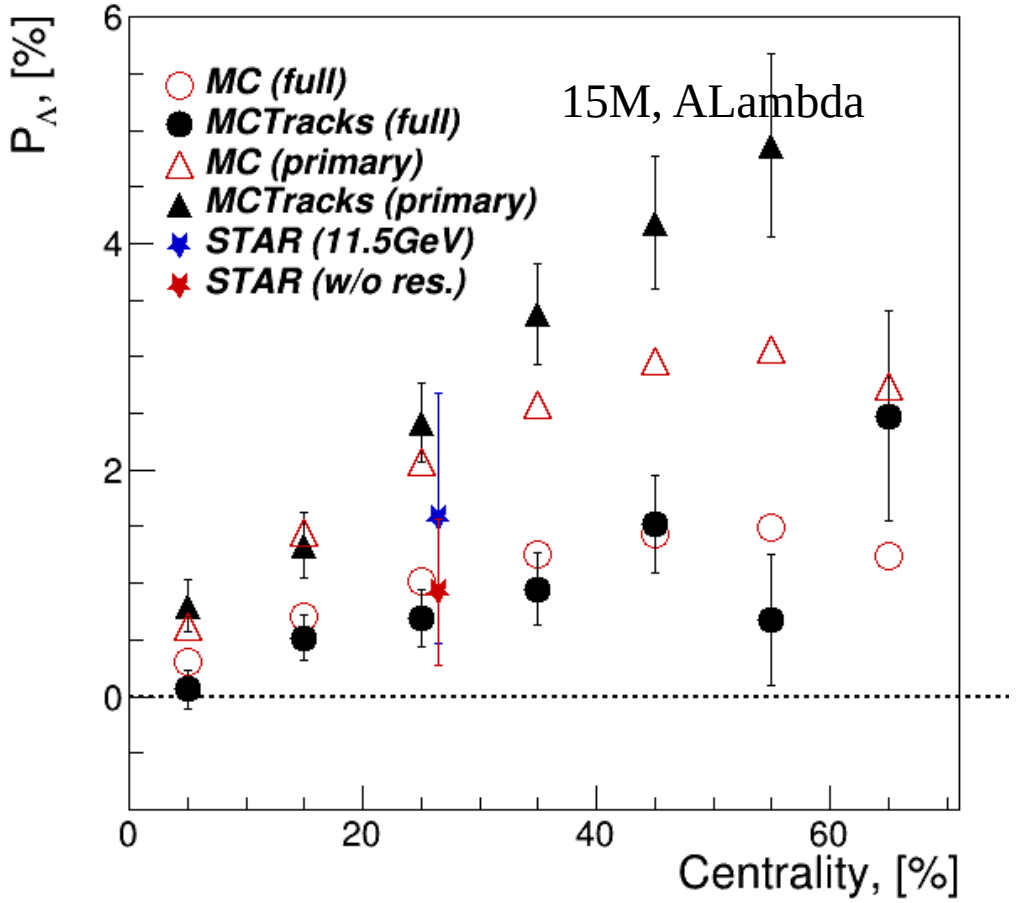




Using EP angle and its resolution instead of RP angle gives consistent results

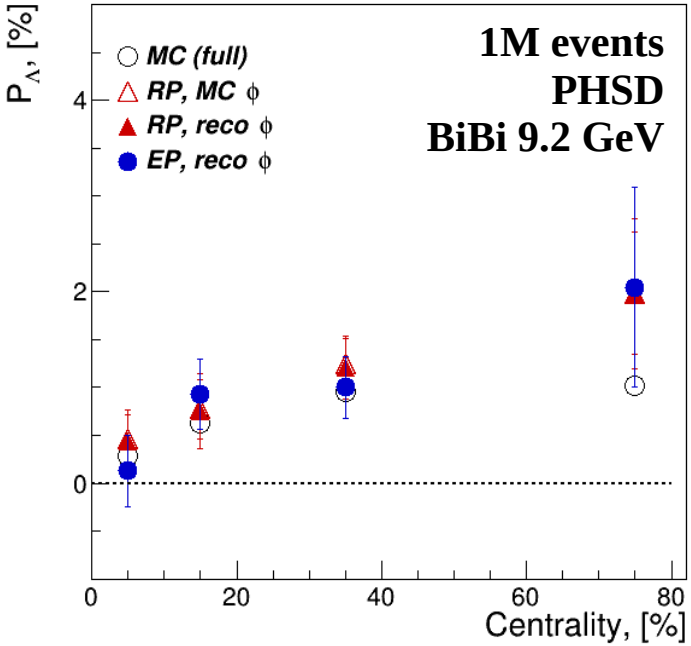
Back Up: Results (MC, Lambda/ALambda)

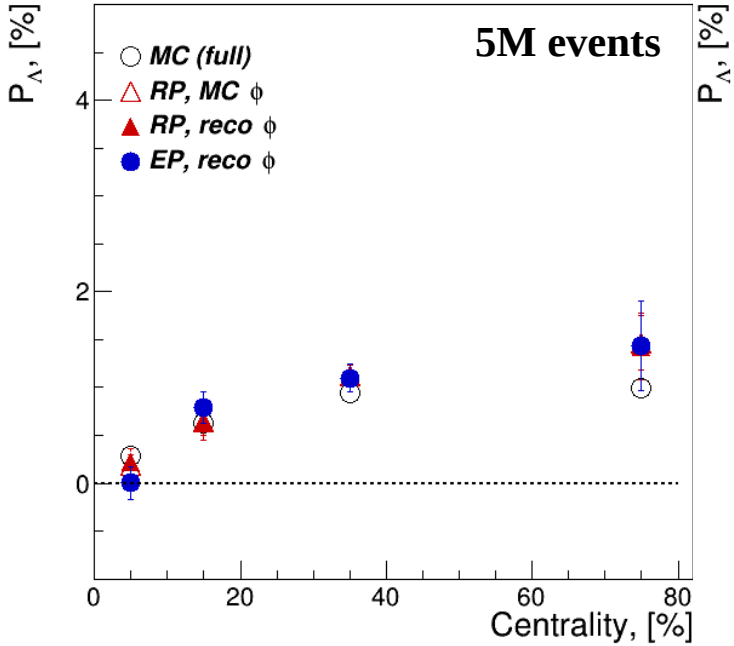


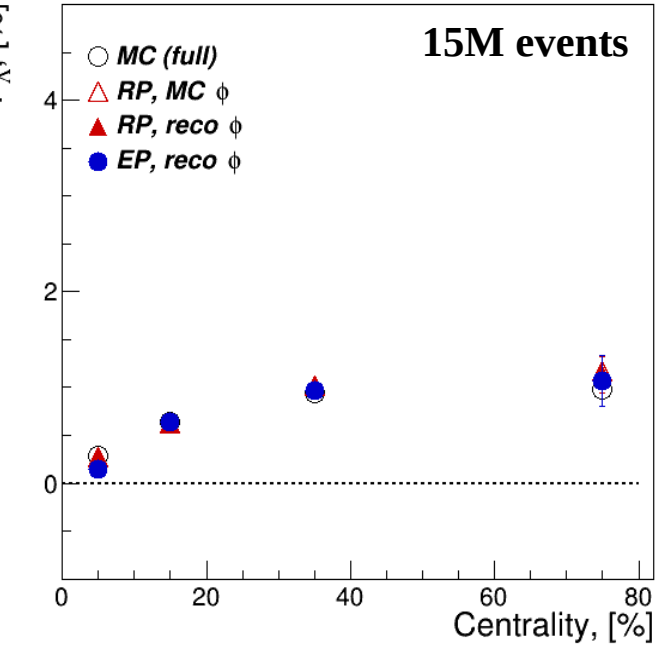


Using RP angle instead pf EP angle. Calculated for 7 centrality bins.

Back Up: 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