Исследование глобальной поляризации лямбда гиперонов в столкновениях тяжелых ядер в эксперименте MPD.

Трошин В.[1,2], Парфенов П.[1,2],Колесников В.[1,2], Тараненко А.[1,2], Теряев О.[1] , Воронюк В.[1],

Зинченко А.[1]

(1- ОИЯИ, 2 - НИЯУ МИФИ)

Научная сессия секции ядерной физики ОФН РАН

1-5 апреля 2024

Работа поддержана Министерством науки и высшего образования РФ,
проект "Фундаментальные и прикладные исследования на
экспериментальном комплексе класса мегасайенс NICA"
№ FSWU-2024-0024

Outline

- Introduction
- $\Delta\varphi$-method
- Generalized invariant mass fit method
- Results
- Summary

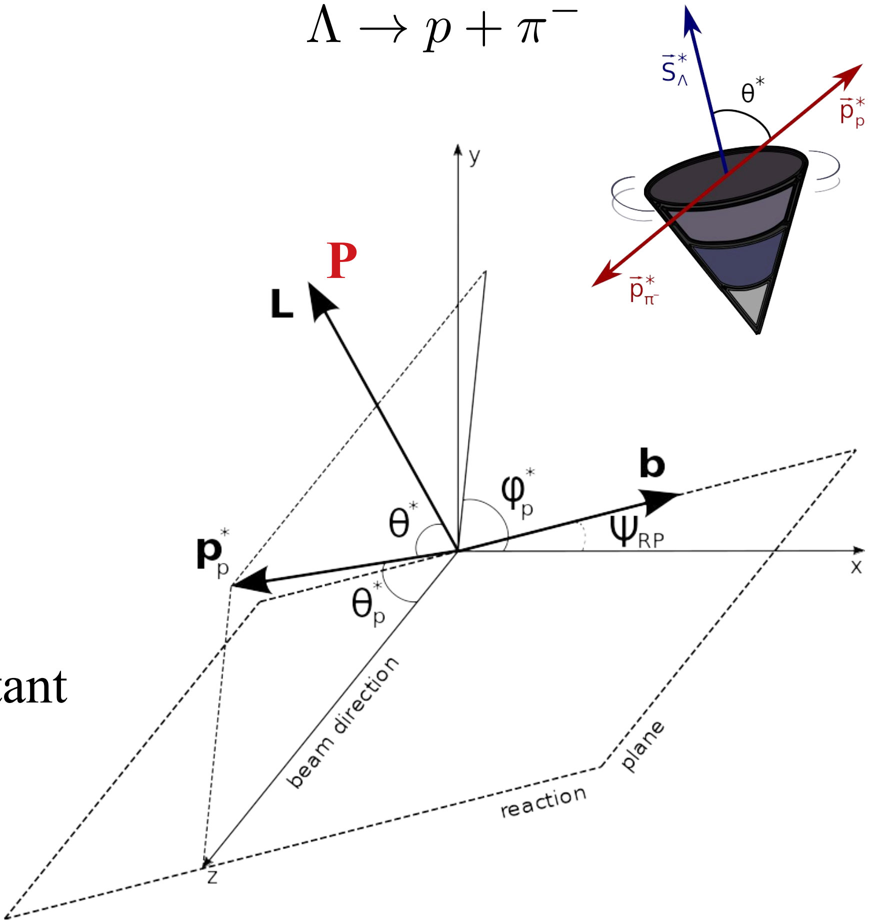
Global hyperon polarization

- w.r.t. reaction plane (RP)
- Emerges in HIC due to the system angular momentum
- Measured through the weak decay:

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

- * — denotes hyperon rest frame
- θ^* — angle between the decay particle(proton) and polarization direction
- $\alpha_\Lambda \simeq -\alpha_{\bar{\Lambda}} \simeq 0.732$ - hyperon decay constant

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

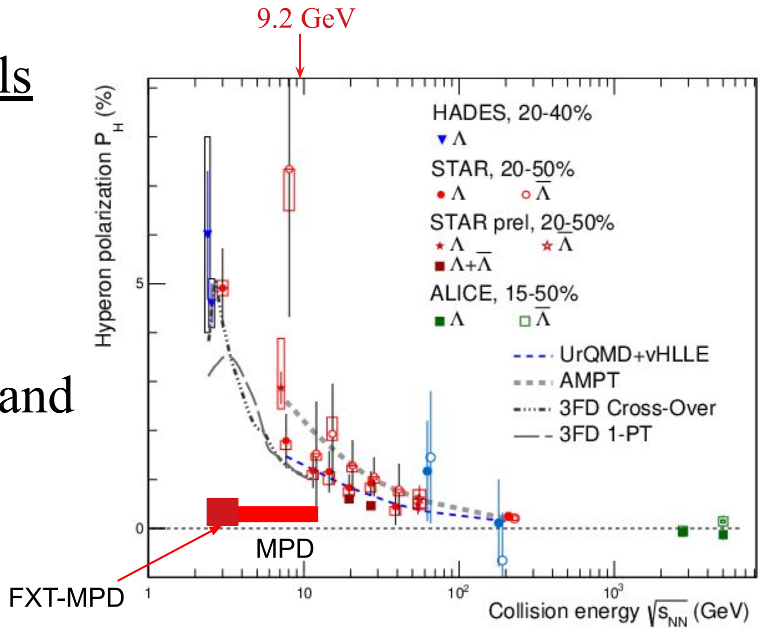


Global Polarization at Nuclotron-NICA energies

- Predicted and observed <u>global polarization signals rise</u> 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

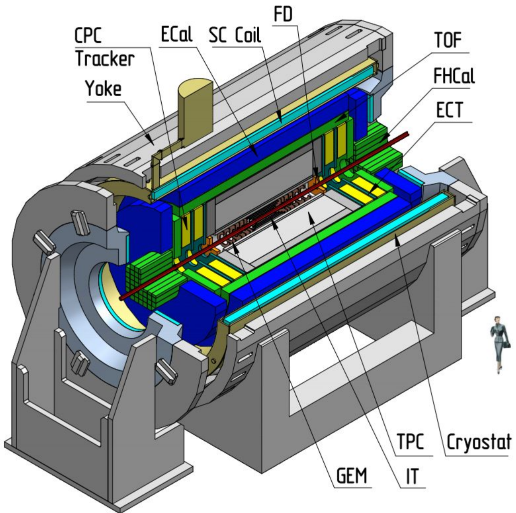


S. Singha, EPJ Web Conf. 276 (2023) 06012

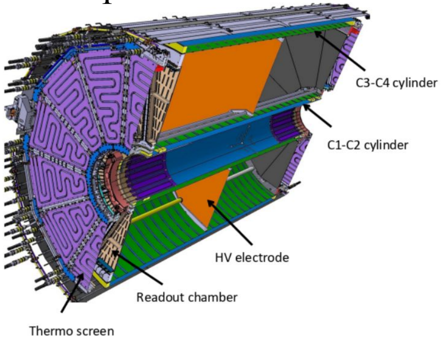
J. Adam et al. (STAR Collaboration), Phys. Rev. C 98, 014910 (2018)
O. Teryaev and R. Usubov, Phys. Rev. C 92, 014906 (2015)

MPD detector

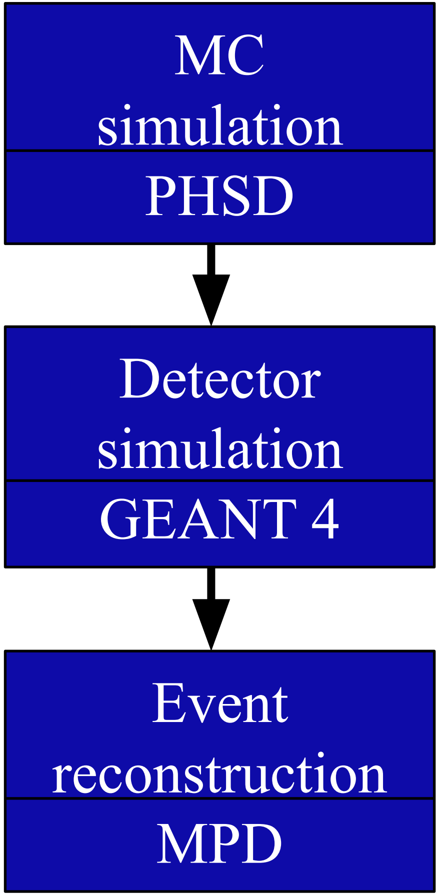
- 4π spectrometer designed to work at high luminosity in the energy range of the NICA collider (4-11 GeV)
- Capable of detecting of charged hadrons, electrons and photons.
- Precise 3-D tracking system and a high-performance particle identification system based on the time-of-flight measurements and calorimetry.
- Forward Hadron Calorimeter (FHCal) allow to reconstruct projectile and target spectator symmetry planes



Time Projection Chamber (TPC) is a main tracking detector, overlapping pseudorapidity region $|\eta| < 1.5$ with high particle reconstruction efficiency for $p_T > 0.1$ GeV/c



Monte-Carlo simulation



- MC simulation using PHSD generator

N.S. Tsegelnik, E.E. Kolomeitsev, V. Voronyuk, Phys.Rev.C 107 (2023) 034906
N.S. Tsegelnik, E.E. Kolomeitsev, V. Voronyuk, Particles 2023, 6, 373-384

  - **Bi-Bi @ 9.2GeV, 15M MB events, b [0,12]fm**
  - Global hyperon polarization
    - Thermodynamical (Becattini) approach

F. Becattini, et. al. Ann. Phys. 338 (2013) 32

    - Hyperon polarization vector ($\mathbf{P} = \{P_x, P_y, P_z\}$)

- Transfer of polarization during hyperon decays (feed-down effect)
- Anisotropic decay of Λ hyperons:

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

Measurements of global hyperon polarization

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

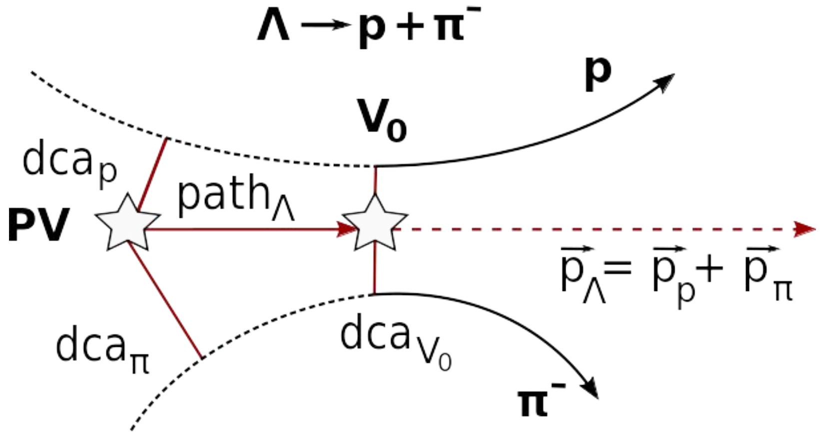
$$\overline{P}_{\Lambda/\bar{\Lambda}} = \frac{8}{\pi\alpha}\frac{1}{R^1_{\mathrm{EP}}}\left\langle \sin(\Psi^1_{\mathrm{EP}} - \phi^*)\right\rangle$$

→ Determine centrality

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

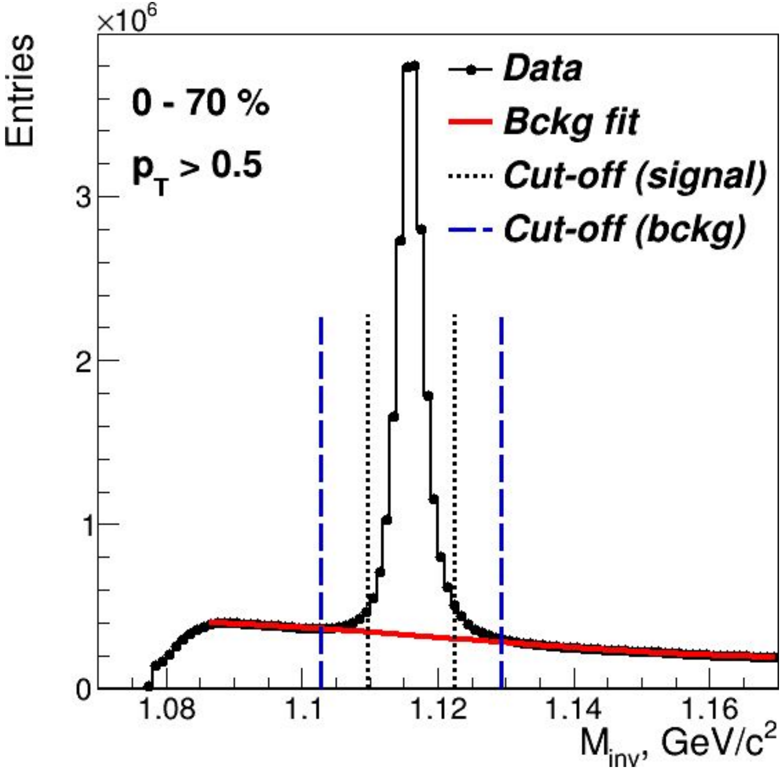
→ Reconstruct Lambda

→ Measure global polarization



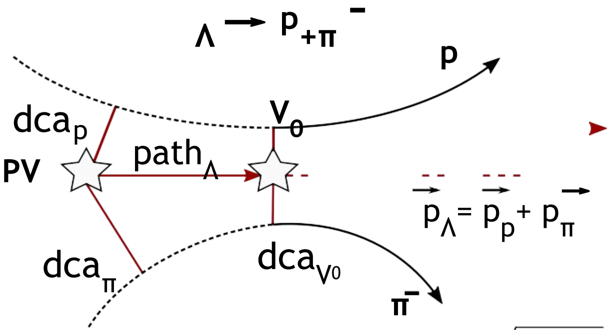
- PV — primary vertex
- V_0 — vertex of hyperon decay
- dca — distance of closest approach
- path — decay length

Λ selection



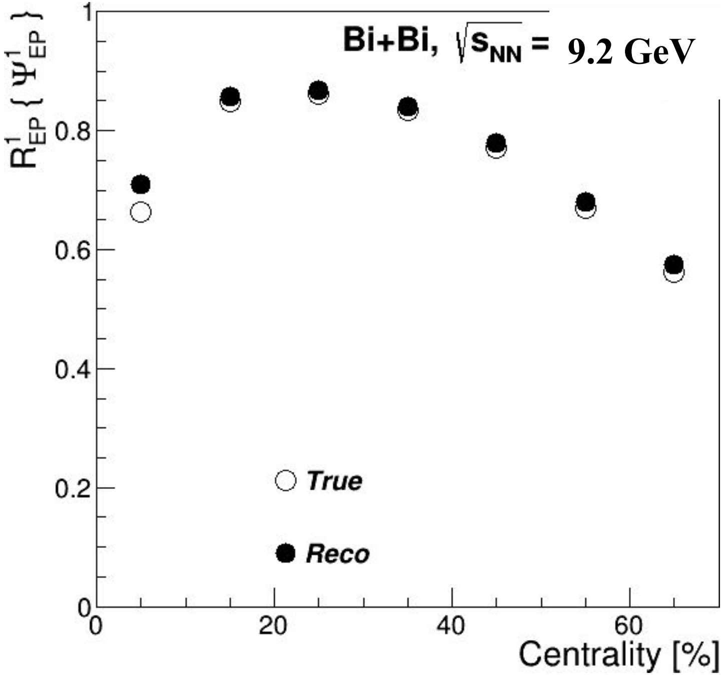
Fitting procedure (sideband method):

- Global fit (Gauss + Legendre polynomials)
- Background fit in sidebands (± 7σ)
- Signal Cut-off: <M>± 3σ
- Λ selection criteria:
  - «ω»-selection (1 parameter)
  - «χ»-selection (5 parameters)



$$\omega_2 = \ln \frac{\sqrt{\chi_\pi^2 \chi_p^2}}{\chi_\Lambda^2 + \chi_{V_0}^2}$$

Event Plane (EP) measurements



- Good performance for EP measurements using FHCal is observed for PHSD model Bi+Bi at 9.2 GeV

  True: w.r.t. reaction plane (RP) angle

  Reco: determined using sub-event method

$$R_1 = \langle \cos(\Phi_1^F - \Psi^{RP}) \rangle$$

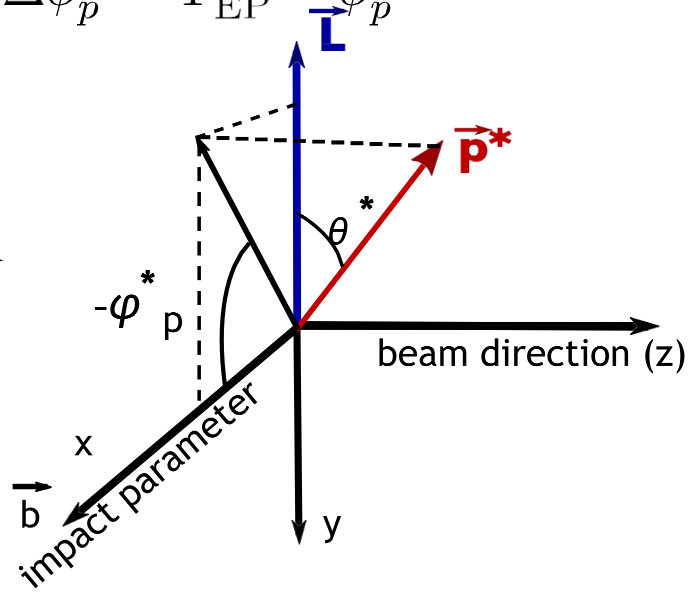
$$R_1(\Phi_1(F_N, F_S)) = \sqrt{\langle \cos(\Phi_1^{F_N} - \Phi_1^{F_S}) \rangle}$$

$$\chi \rightarrow \sqrt{2}\chi$$ - approximation to full event

$$R_n(\Phi_n) = \frac{\sqrt{(\Pi)}}{2\sqrt{(2)}} \chi e^{-\frac{\chi^2}{4}} [I_{(n-1)/2}(\frac{\chi^2}{4}) + I_{(n+1)/2}(\frac{\chi^2}{4})]$$

Δφ-method

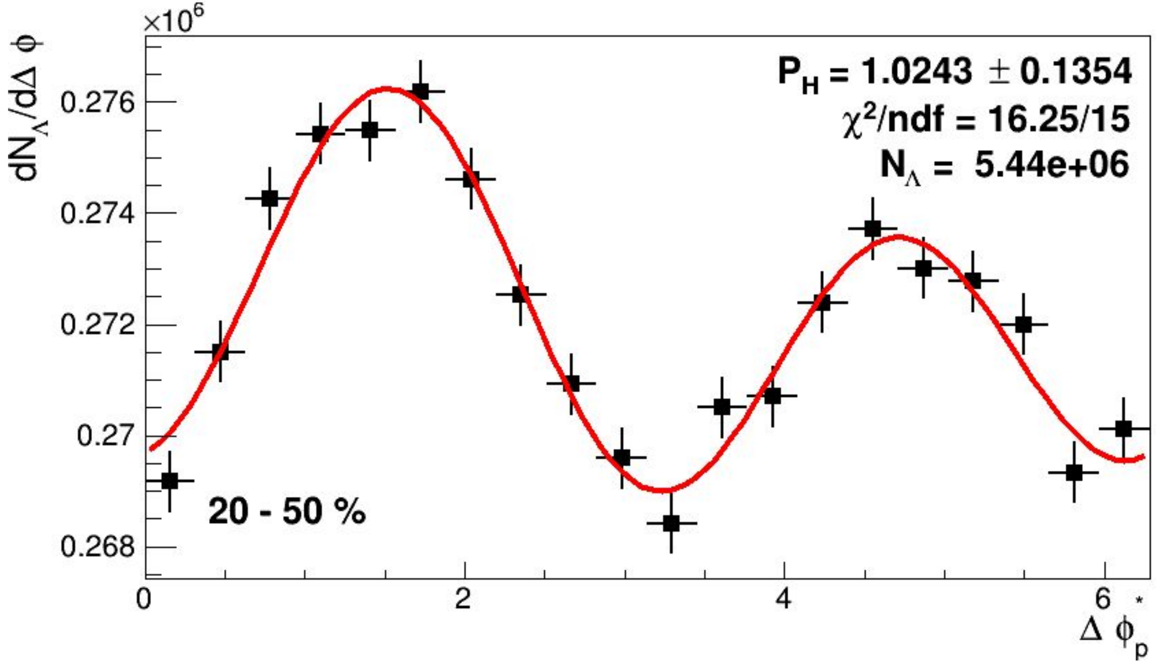
- Obtain invariant mass distribution in bins of $\Delta\phi_p^* = \Psi_{\rm EP}^1 - \phi_p^*$
  - Net amount of Λ in each bin
  - Distribution of $N_\Lambda(\Delta\phi_p^*)$
- Fit of the distribution to get $\langle \sin(\Delta\phi_p^*) \rangle \longrightarrow P_\Lambda$
  - $dN/d\Delta\varphi_P^*$
  - $P_\Lambda = \frac{8}{\pi\alpha_\Lambda}\frac{p_1}{R_{\rm EP}^1}$



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

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

Δφ-distribution: centrality 20-50%



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

$$\alpha_\Lambda \simeq 0.732$$

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

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

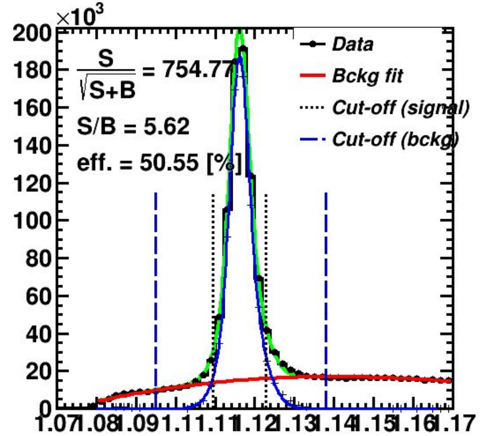
Inv. mass fit method

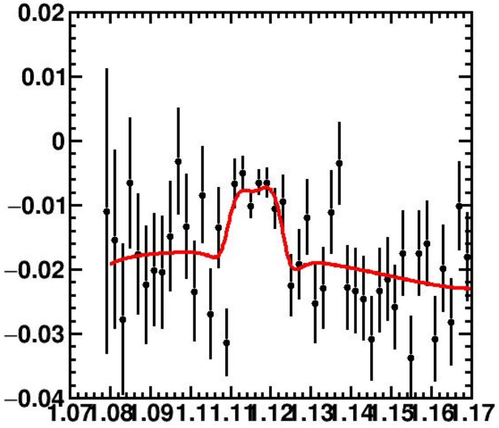
- Use invariant mass distribution
- Calculate Sig/All, Bg/All ratios
- Fit <sin(Ψ_{EP} - φ_p^*)> as a function of inv. mass:

$$P^{SB}(m_{inv}, p_T) = P^S(p_T)\frac{N^S(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)} + P^B(m_{inv}, p_T)\frac{N^B(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)}$$

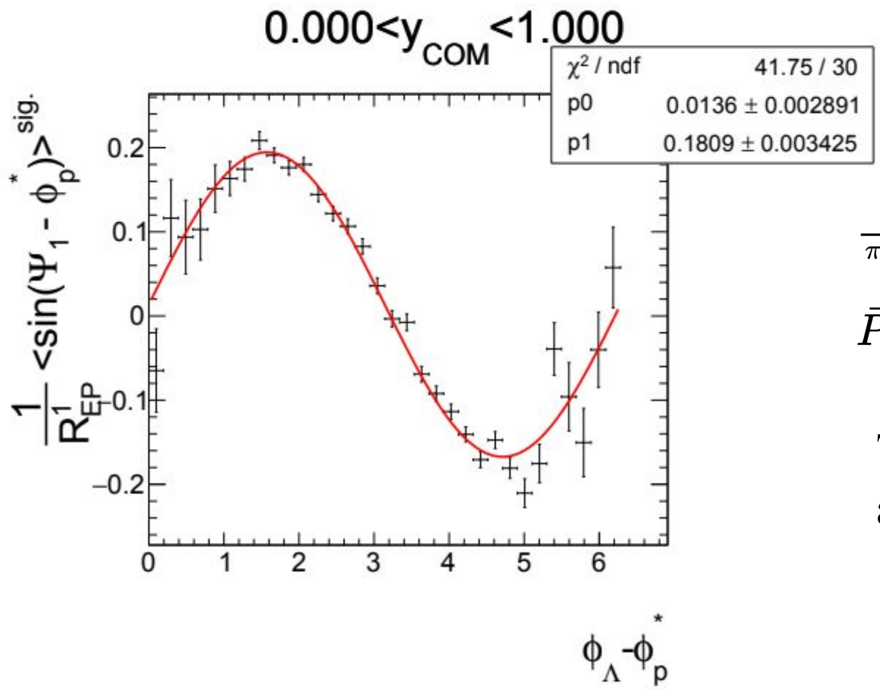
- Use $P^S(p_T)$ = <sin(Ψ_{RP} - φ_p^*)>^{S} to find P_H:

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





Generalized inv. mass fit method



M.S. Abdallah et al. (STAR Collaboration), Phys. Rev. C 104, L061901 (2021)

Fit $P^S = \langle\sin(\Psi_{RP} - \varphi_p^*)\rangle^S$ in bins of $\varphi_\Lambda - \varphi_p^*$ for $\eta>0$, $\eta<0$ using formula:

$$\frac{8}{\pi\alpha_\Lambda}\frac{1}{R_{EP}^{(1)}}\langle\sin(\Psi_1-\phi_p^\star)\rangle^{sig} = \overline{P_\Lambda}^{true} + cv_1\sin(\phi_\Lambda-\phi_p^\star)$$

$$\bar{P}_H = \frac{1}{2}[\bar{P}_H(\eta>0)+\bar{P}_H(\eta<0)]$$

This fit corrects effects of directed flow and acceptance contributions to P_H

We use generalized inv. mass fit method further in this work

Systematics

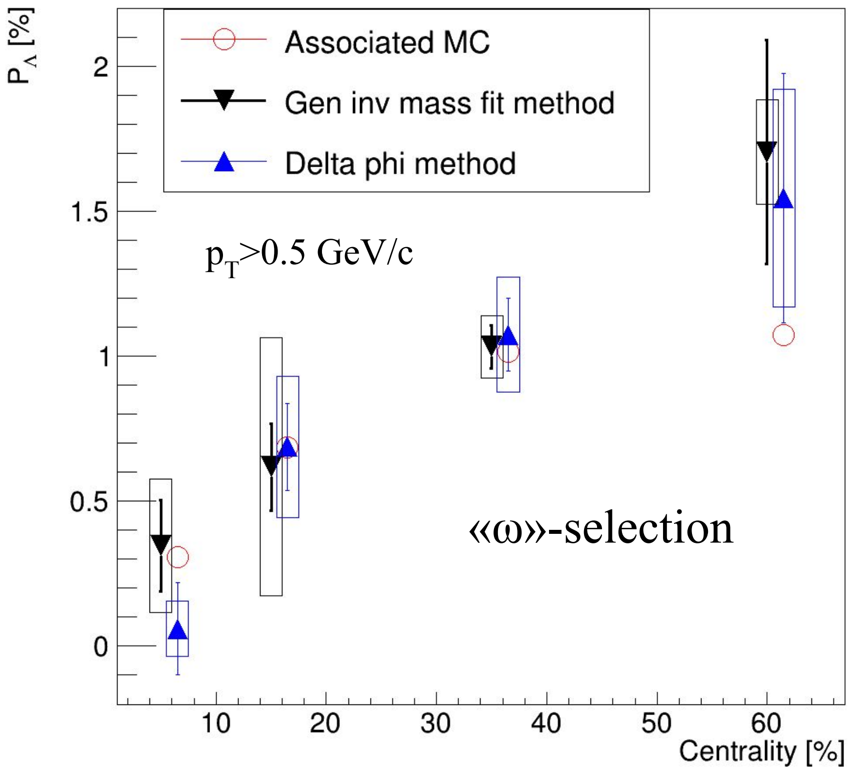
For Δφ-method:

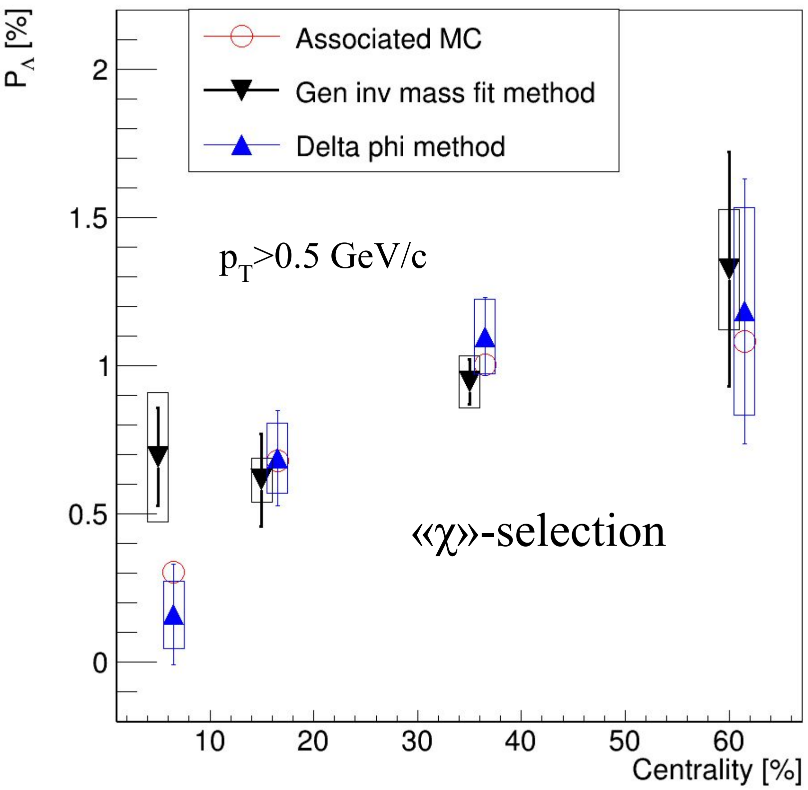
- σ for fitting signal at all distributions: 3± 0.5σ
- Resolution: comparison of 2-sub event and 3-sub event
- Δφ bins: 20±4
- Bg polarization: fit the Bg in Δφ bins instead of Sig

For Gen inv mass fit method:

- σ for fitting signal at all distributions: 3± 0.5σ
- Resolution: comparison of 2-sub event and 3-sub event
- $\varphi_{\Lambda} - \varphi_{p}^{*}$ bins: 16±4
- Bg polarization: fit the $\langle \sin(\boldsymbol{\Psi}_{RP} - \varphi_{p}^{*}) \rangle$ with *pol0* and *pol1*

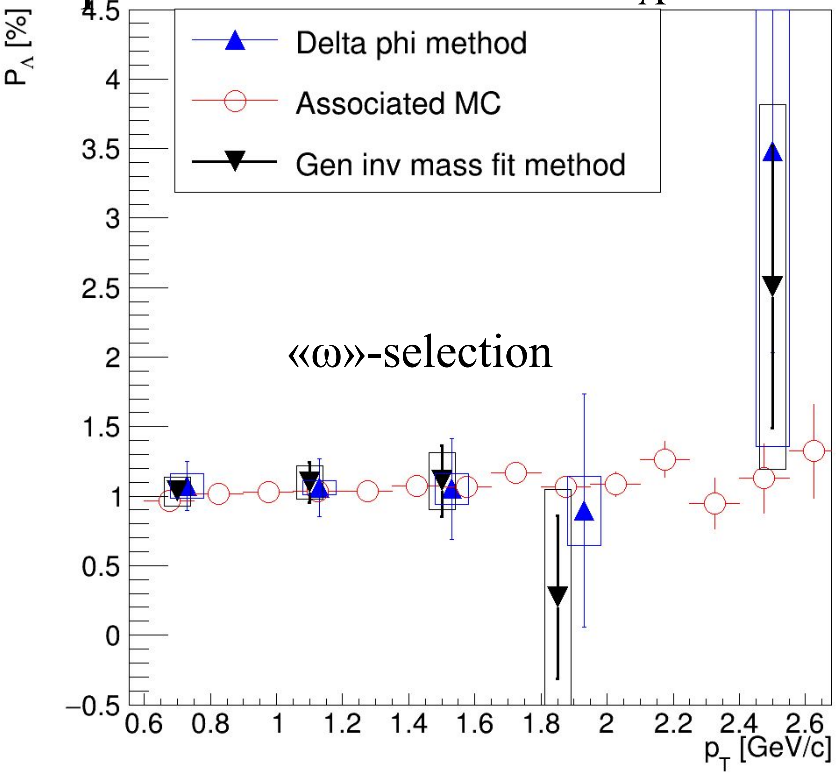
Centrality dependence of P_Λ

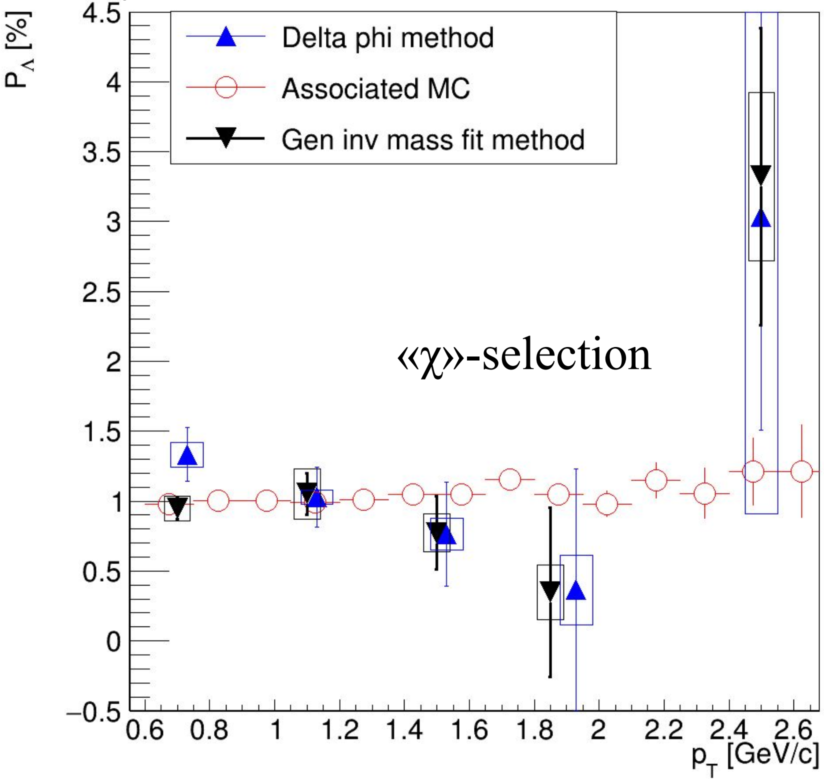




Both methods have a good agreement with Associated MC

p_T - dependence of P_Λ for centrality 20-50%

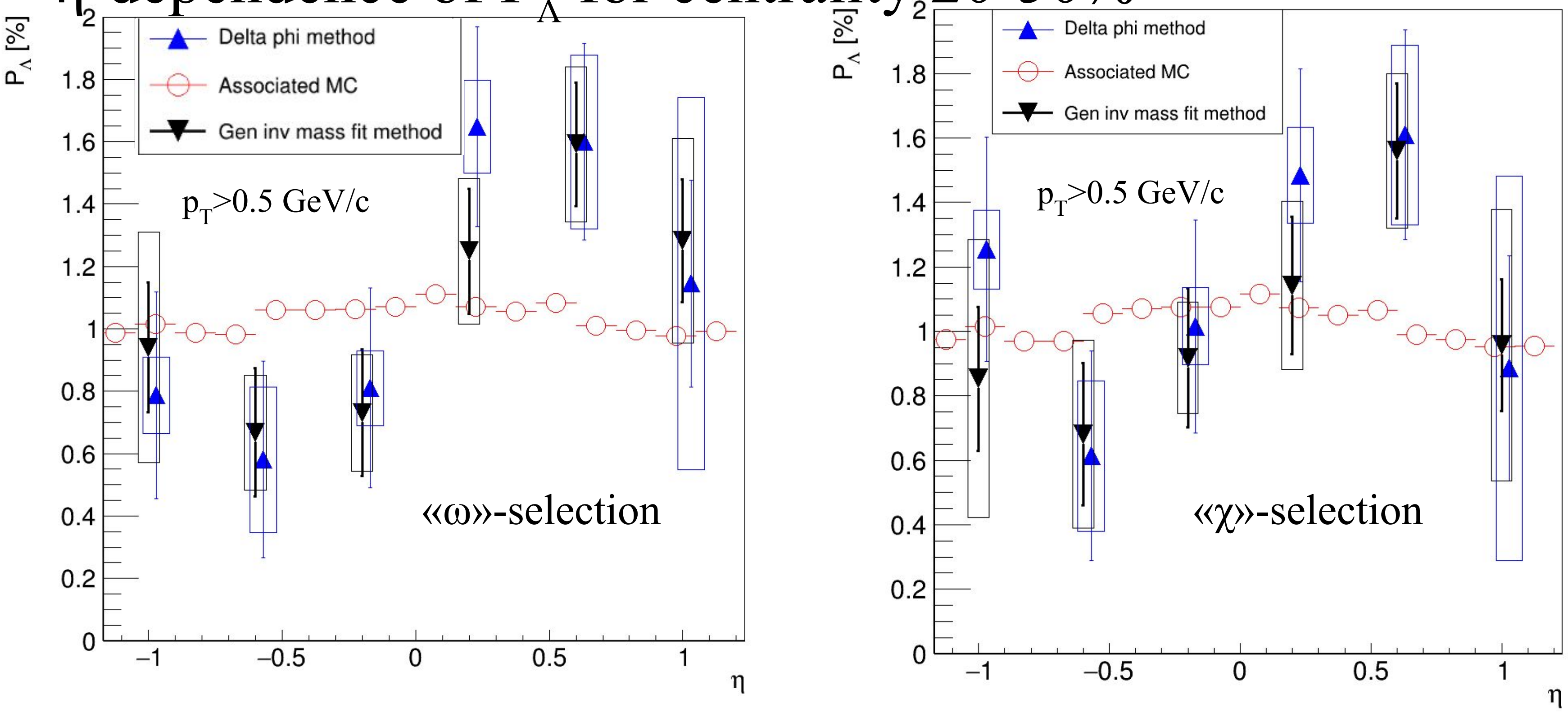




Both methods have a good agreement with Associated MC

Need more statistics to study high p_T region

η-dependence of P_Λ for centrality 20-50%



Both methods have an agreement with Associated MC
Need more statistics to study η-dependence

Summary

- Implementation of generalized invariant mass fit method
  - Gen inv. mass fit method is used in STAR collaboration and takes into account the effects of non-uniform acceptance and v_1 - may be applicable in fixed-target program at MPD
- Both methods have a good agreement with Associated MC
- The statistics size of 15M events is not enough for p_T-η measurements

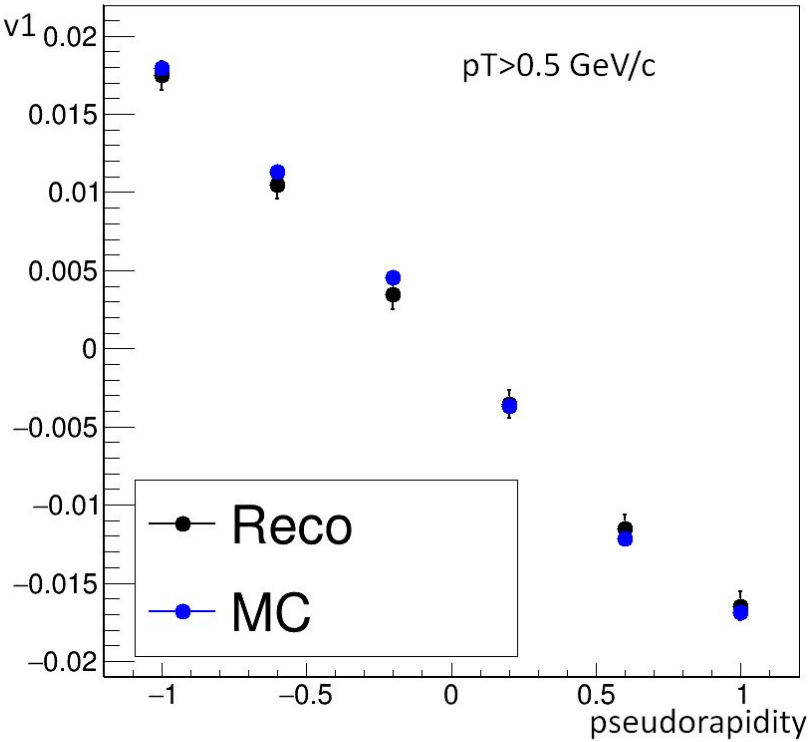
Outlook

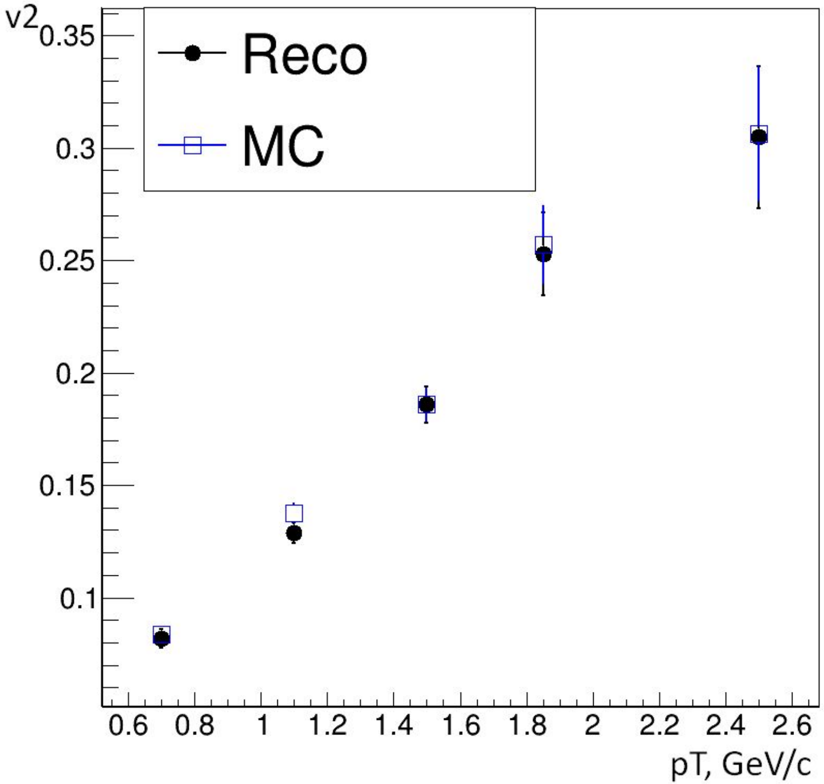
- Analysis of systematics
- $\bar{\Lambda}$-global polarization measurements
- Performance study with larger statistics(30-50M events)

Thank you for your attention!

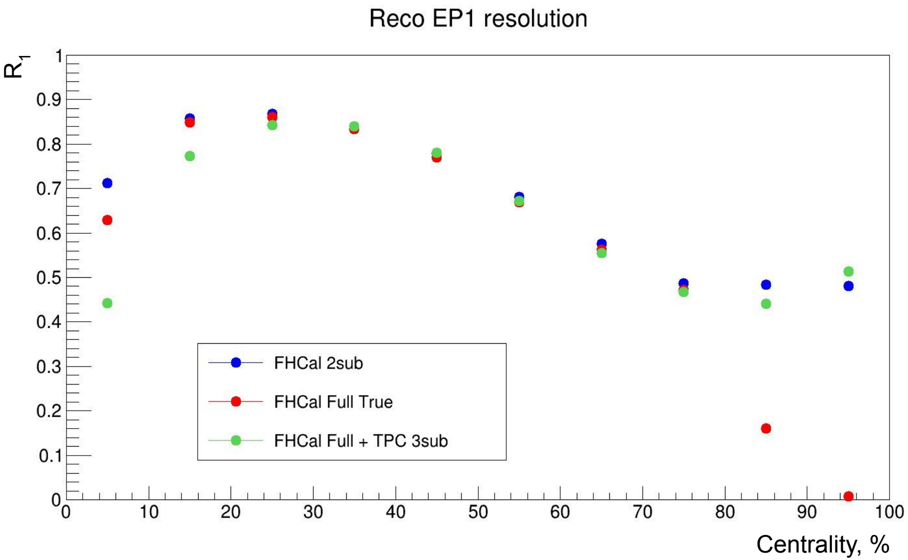
BACKUP

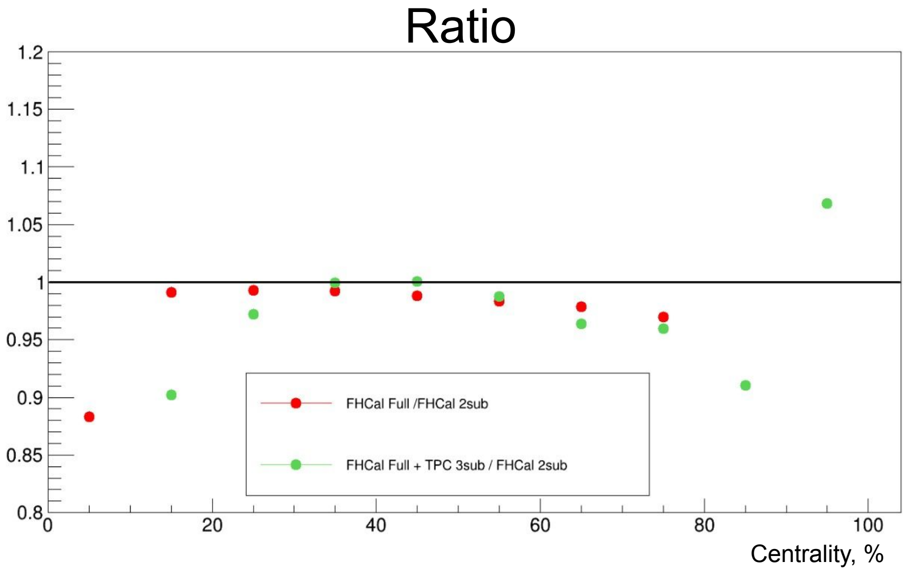
Collective flow





Resolution measurements





$$R_1 = \langle \cos(\Phi_1^F - \Psi^{RP}) \rangle \quad (1)$$

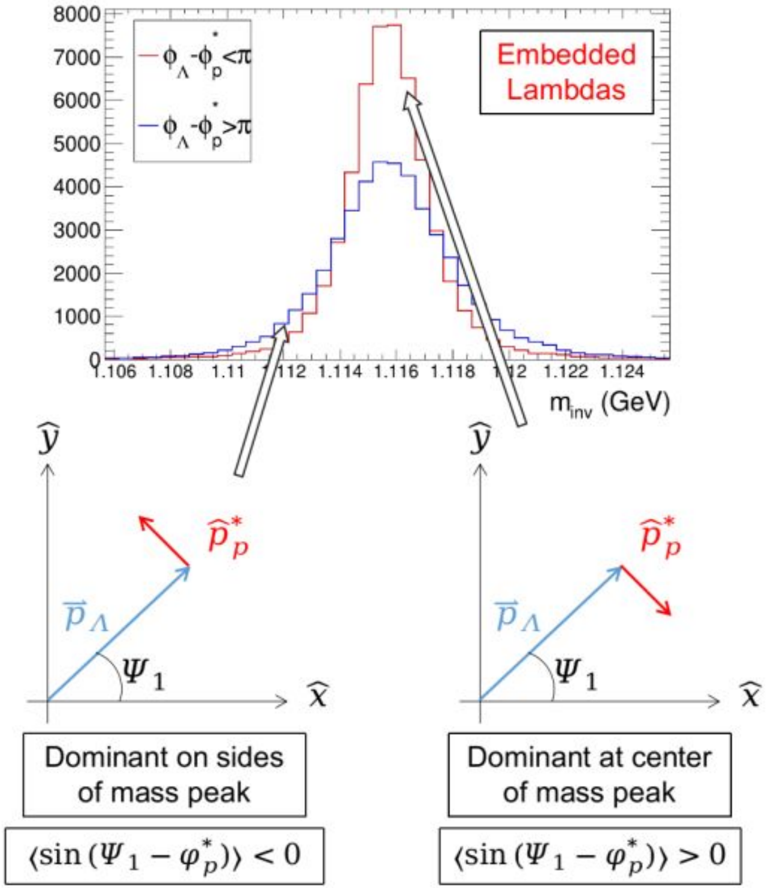
$$R_1(\Phi_1(F_N, F_S)) = \sqrt{\langle \cos(\Phi_1^{F_N} - \Phi_1^{F_S}) \rangle} \quad (2)$$

$$R_1(\Phi_1(T_N, T_S, F)) = \sqrt{\frac{2\langle \cos(\Phi_1^{T_N} - \Phi_1^{T_S}) \rangle \langle \cos(\Phi_1^{T_S} - \Phi_1^{F}) \rangle}{\langle \cos(\Phi_1^{T_N} - \Phi_1^{F}) \rangle}} \quad (3)$$

$$R_n(\Phi_n) = \frac{\sqrt{(\Pi)}}{2\sqrt{(2)}} \chi e^{-\frac{\chi^2}{4}} [I_{(n-1)/2}(\frac{\chi^2}{4}) + I_{(n+1)/2}(\frac{\chi^2}{4})] \quad (4)$$

- FHCal Full True from Eq. (1)
- FHCal 2sub event from Eq.(2)
- FHCal Full + TPC 3sub from Eq.(3)
- F - FHCal, T - TPC, N,S - right and left part of detector
- Eq.(4) - extrapolation to full event

Generalized inv. mass fit method



This method can deal with tracks crossing: daughter particles tracks with opposite charges are bended in the opposite directions in the magnetic field, and these tracks may cross each other -> creates 2 peaks distribution.
Solution: fit Sig with 2 gausses

Warning: with detector asymmetry it would provide the effect of v_1 on the polarization measurements and odd pseudorapidity dependence

M.S. Abdallah et al. (STAR Collaboration),
Phys. Rev. C 104, L061901 (2021)

Examples pseudorapidity