Progress in hyperon polarization analysis at NICA/MPD

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

19.04.2022

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

Outline

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

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- Analysis technique
  - Simulation
  - Centrality determination
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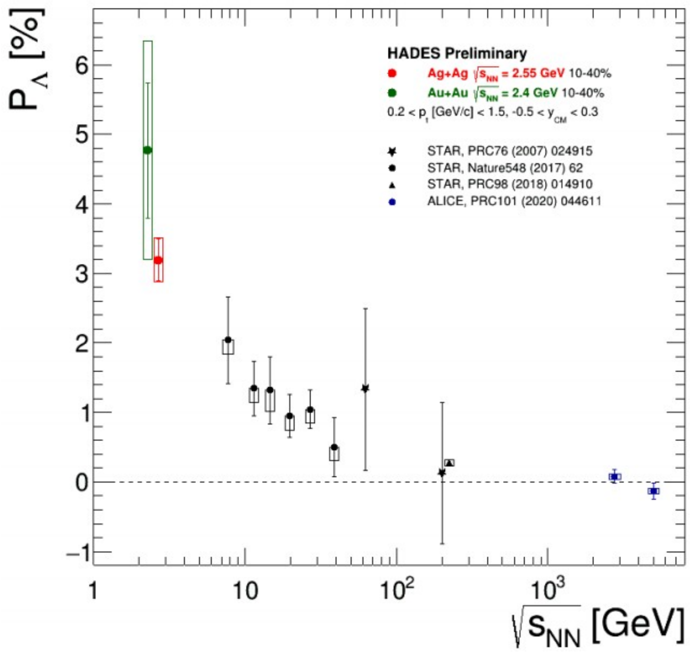
  - Lambda reconstruction
  - Global polarization measurement
- Results
- Conclusions

Compared to the previous results

- 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)

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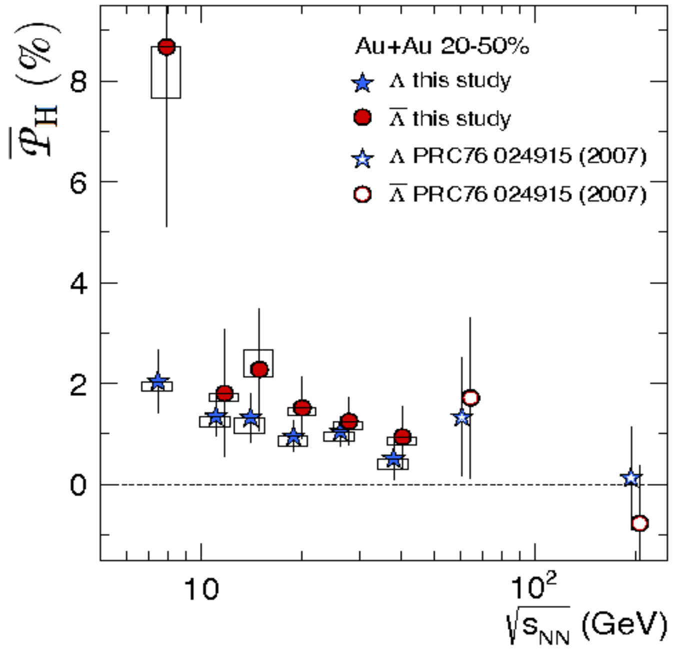

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Global hyperon polarization

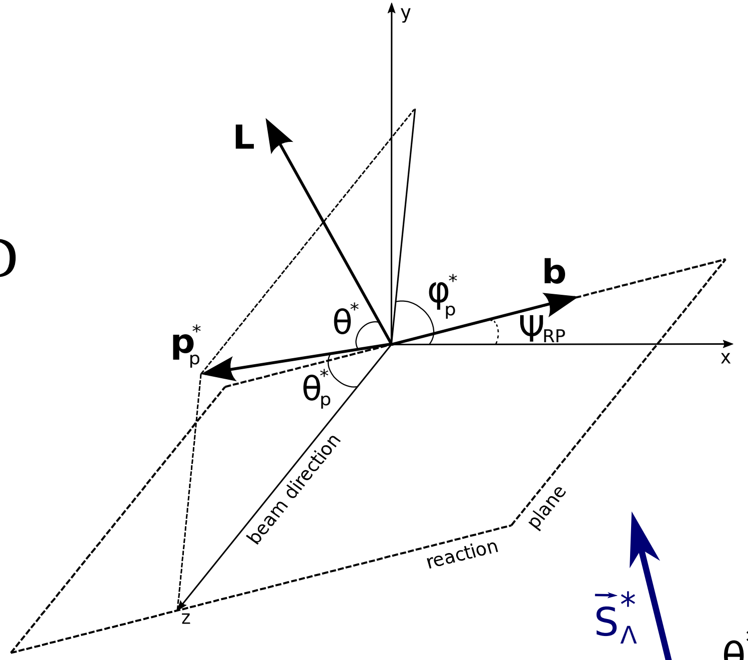
- w.r.t. reaction plane
- Emerges in HIC due to the system angular momentum[1,2]
- Sensitive to parity-odd characteristics of QCD medium and QCD anomalous transport
- Measured through the weak decay:

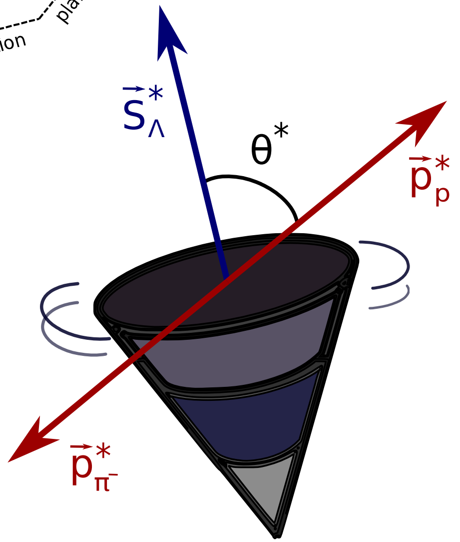
$$\Lambda \to p + \pi^-$$

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

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

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

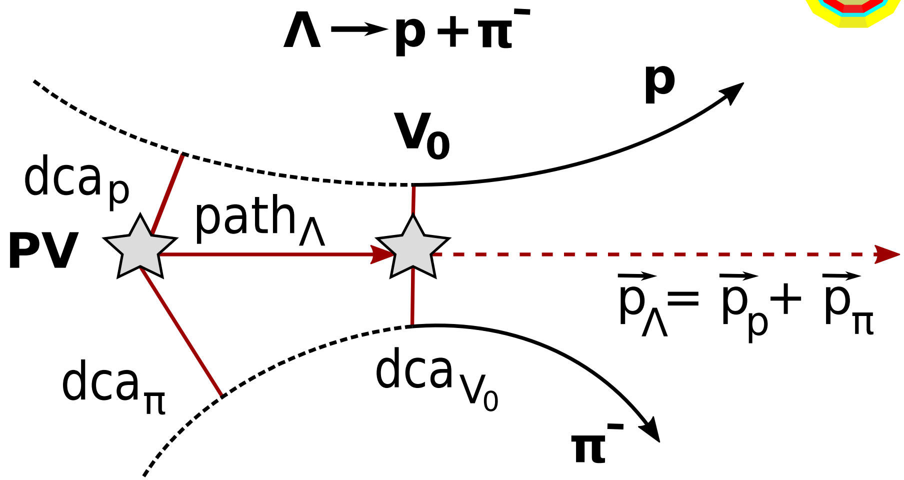
- φ^* — azimuthal angle of decay particle

→ Determine centrality

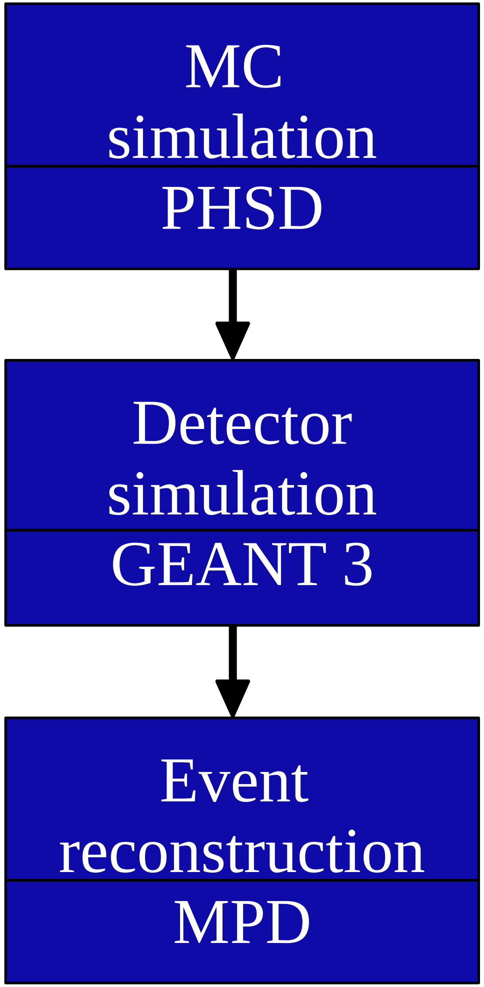
→ Determine event plane ($\Psi^1_{\rm EP}, R^1_{\rm EP}$)

→ Reconstruct Lambda

→ Global polarization



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



- 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]

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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

MC simulation
PHSD

↓

Detector simulation
GEANT 3

↓

Event reconstruction
MPD

- 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]

- 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

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Analysis technique

MC simulation
PHSD

↓

Detector simulation
GEANT 3

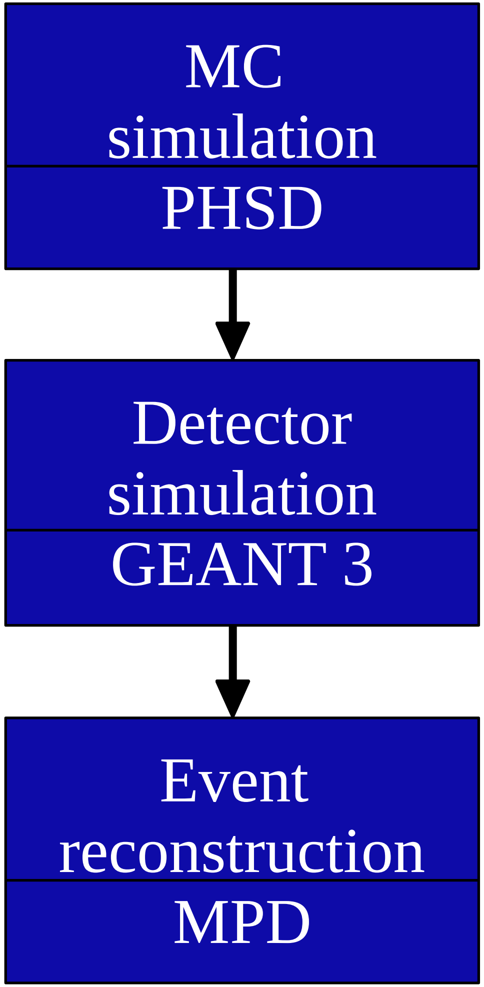
↓

Event reconstruction
MPD

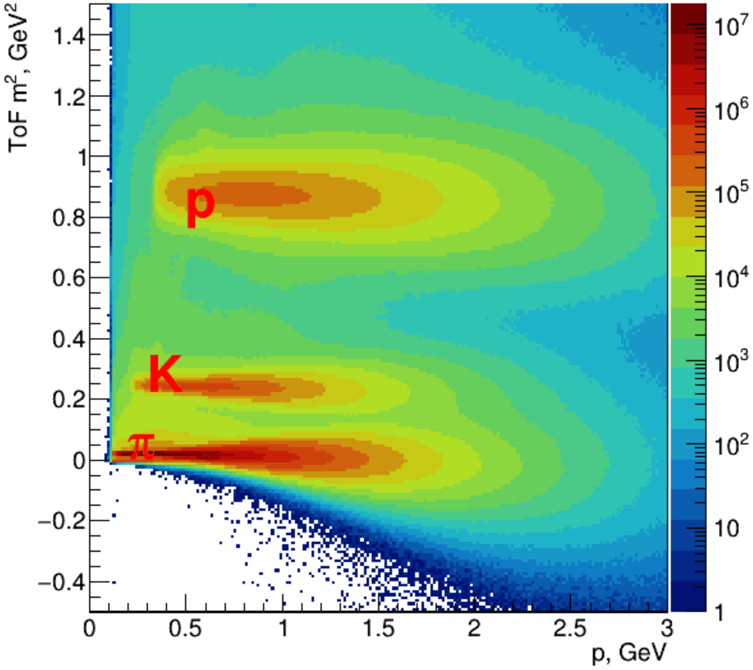
- Detector simulation
  - Transfer of hyperon polarization vector $\mathbf{P} = \{P_x, P_y, P_z\}$ from generator data (PHSD) to MCTracks
  - Accounts for non-unitary length of the vector (weight)
  - Polarization set to zero $\mathbf{P} = \{0,0,0\}$ if $P_n > 1$ (calculation of thermal vorticity is 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 (can be turned on/off)
  - $\frac{dN}{d\cos\theta^*} = 1 + \alpha_\Lambda |\vec{P}_\Lambda| \cos\theta^*$ (recall)

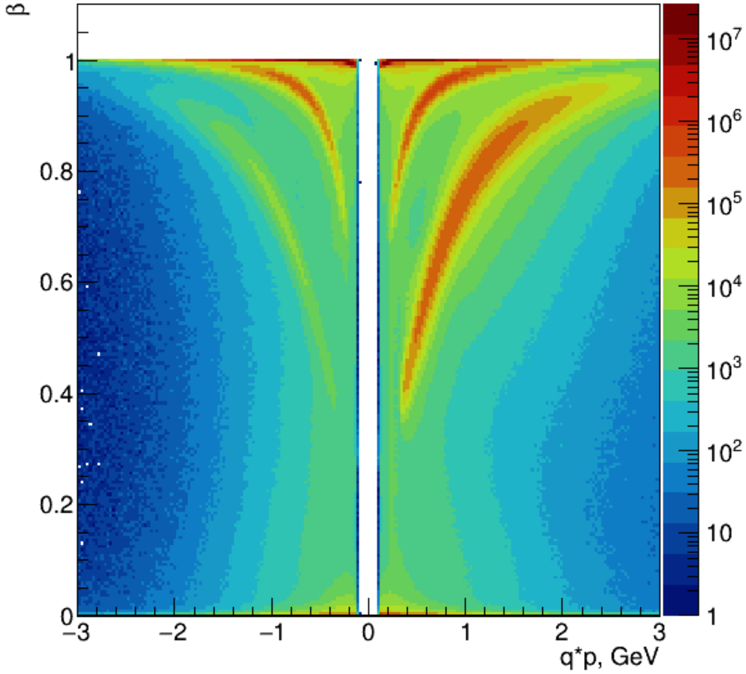
[1] $\Xi^+(\Xi^-)$, Ξ^0, Σ^0 decays ($C_{\Xi^-} = 0.927$, $C_{\Xi} = 0.9$, $C_{\Sigma} = -1/3$)

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

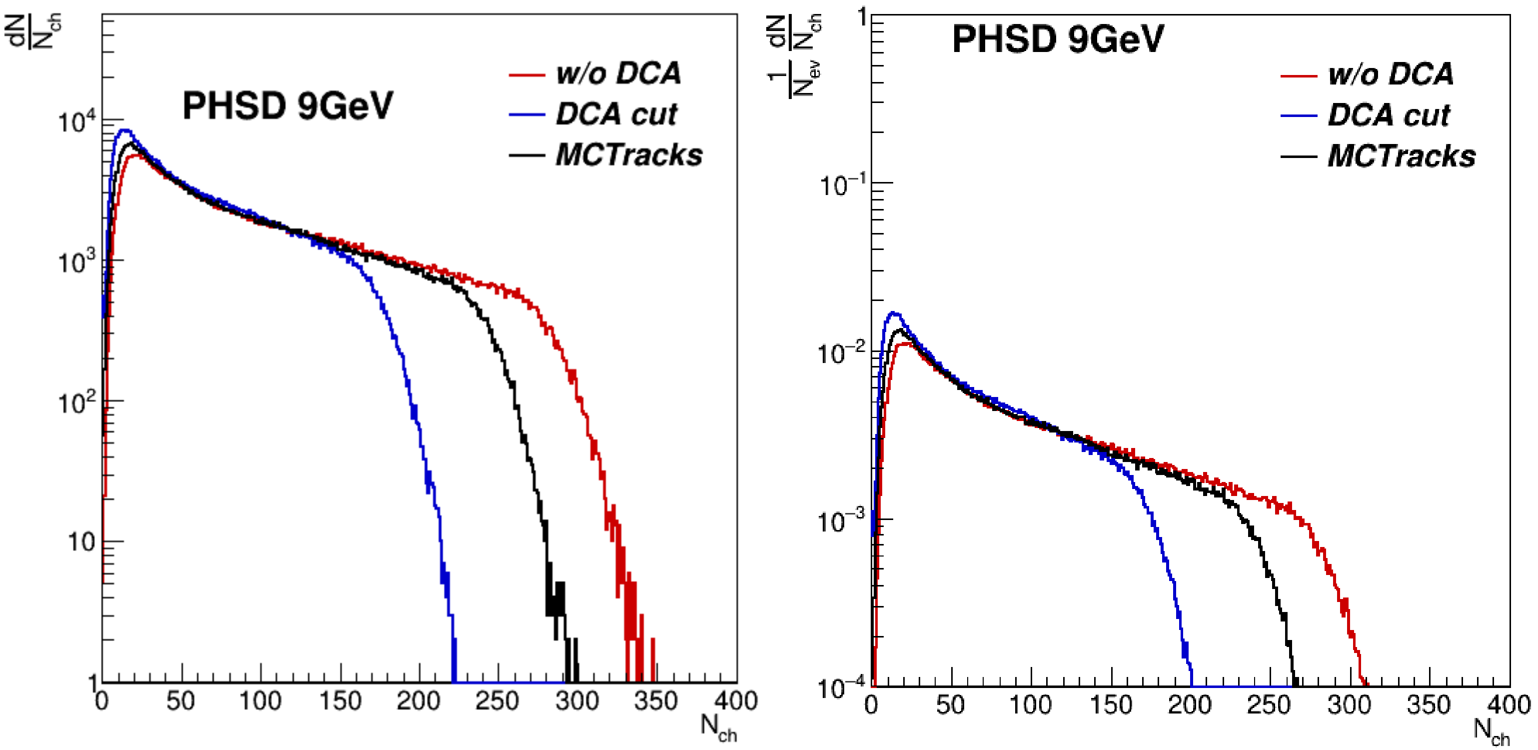


- Event reconstruction
  - Centrality and Event Plane determination
  - Realistic PID
  - Reconstruction of Λ hyperons via their weak decay





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)

DCA comparison in Back-Up

- MC-Glauber based centrality framework[1]

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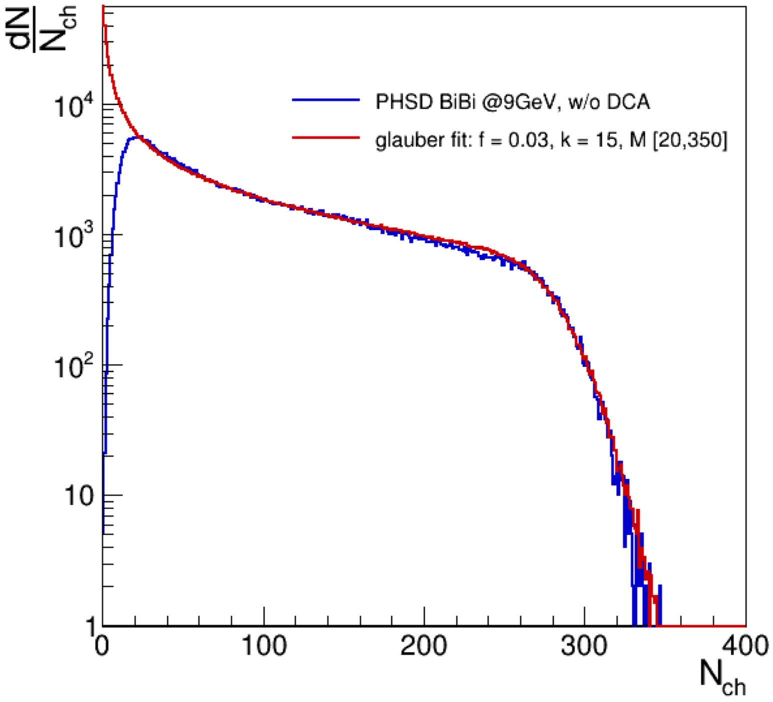
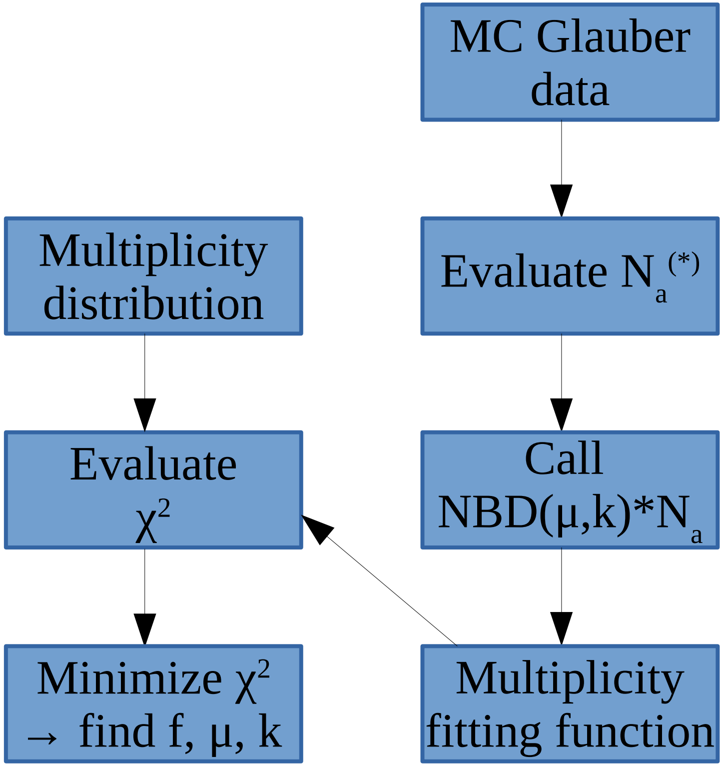


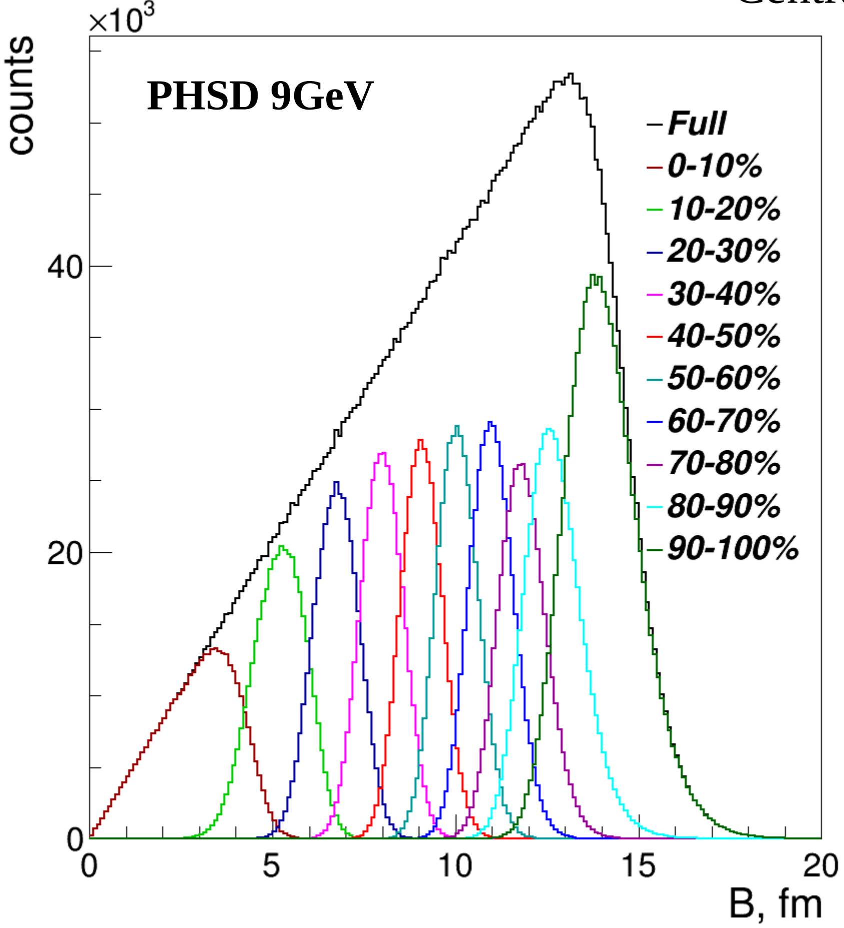


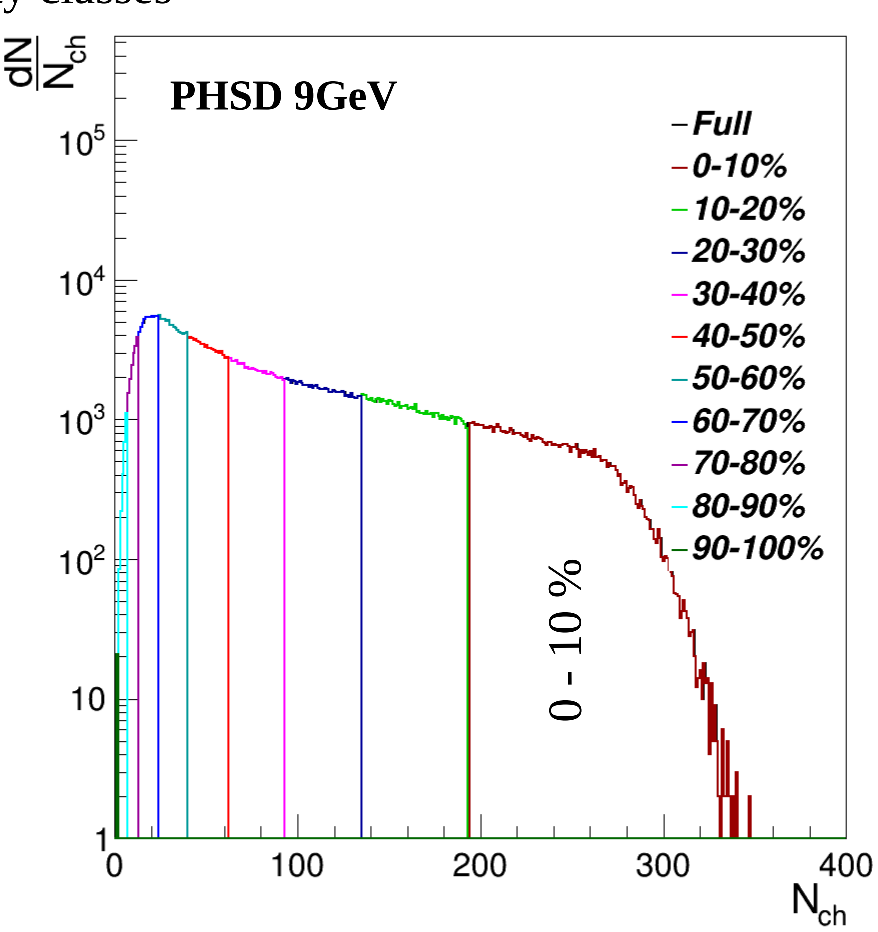
[1] P. Parfenov et al, NRNU MEPhI for the MPD collaboration (https://github.com/FlowNICA/CentralityFramework)

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

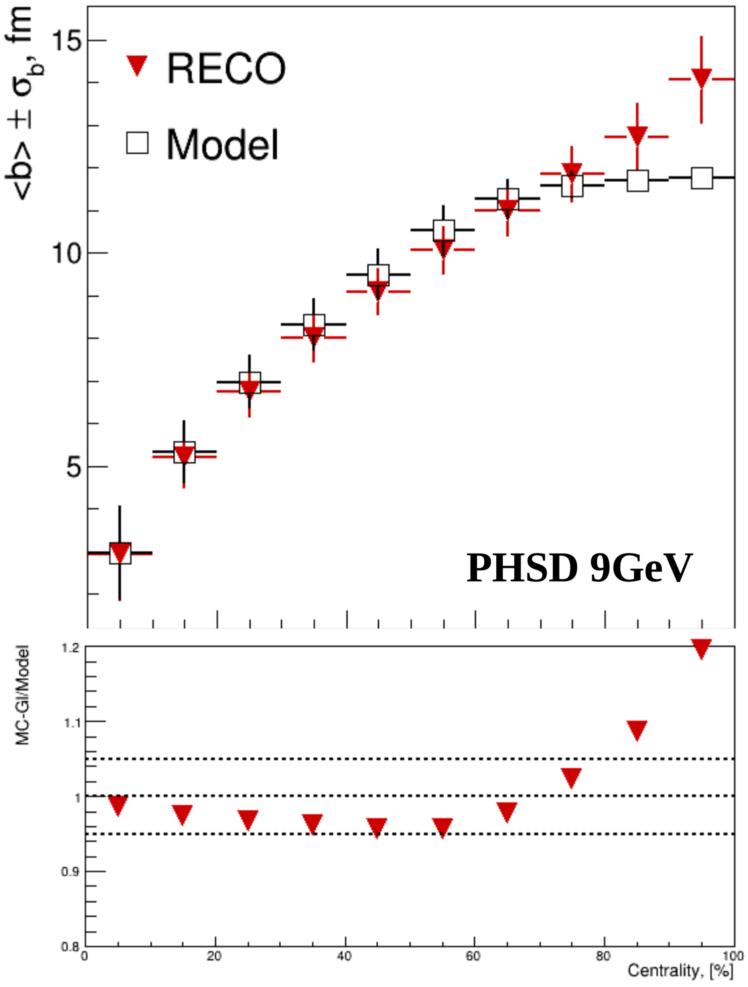
Centrality determination

Centrality classes





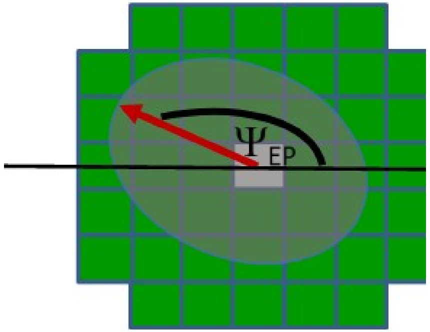
Centrality determination



- Completed calibration of centrality
  - Full analysis done for 10%-centrality bins
  - 4 intervals of centrality chosen for analysis (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:
  - $\Psi^n_{\mathrm{EP}} = \frac{1}{n}\arctan\frac{Q_y}{Q_x}$
  - $Q_y = \Sigma_i \mathrm{w}_i \sin(n\phi_i)$
  - $Q_x = \Sigma_i \mathrm{w}_i \cos(n\phi_i)$



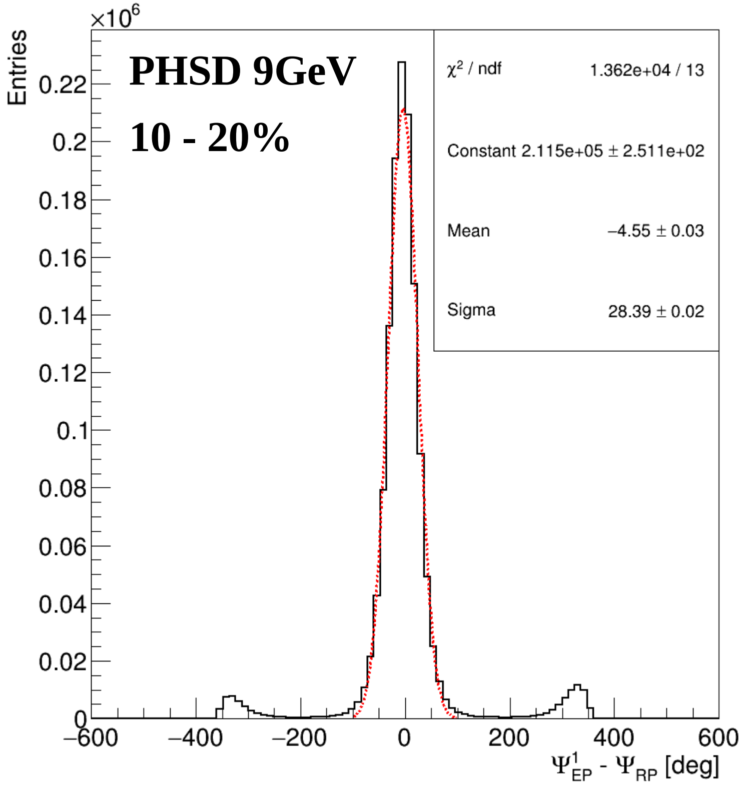
$\mathrm{w}_i = E_i/E_{\mathrm{total}}$ (FHCal)

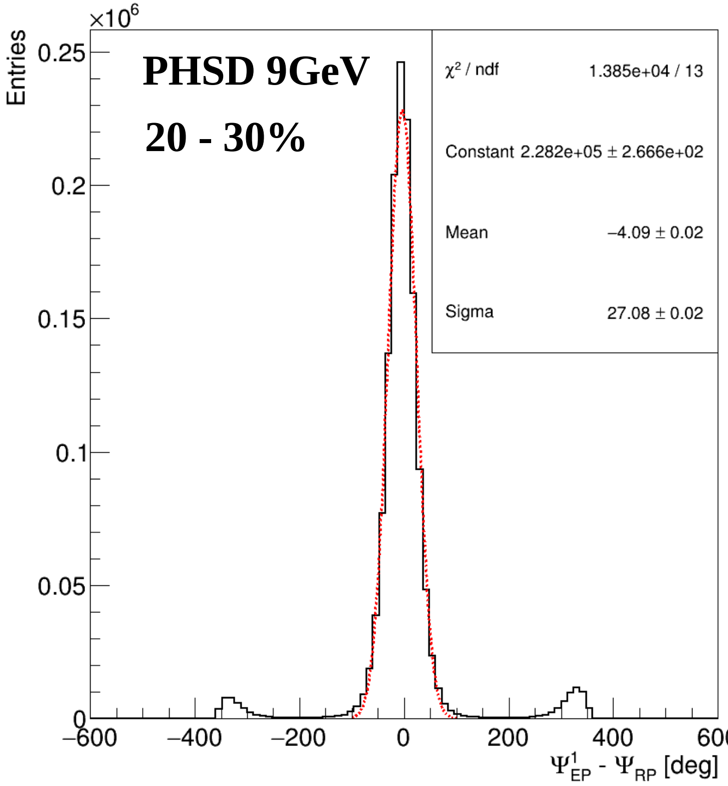
$\mathrm{w}_i = p_{\mathrm{T}i}/p_{\mathrm{Ttotal}}$ (TPC)

- 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)
  - $R^k_{\mathrm{EP}} = \sqrt{\left\langle\cos(k(\Psi^n_{\mathrm{EP,R}} - \Psi^n_{\mathrm{EP,L}}))\right\rangle}$ (sub-event resolution method[1])

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

Event plane determination

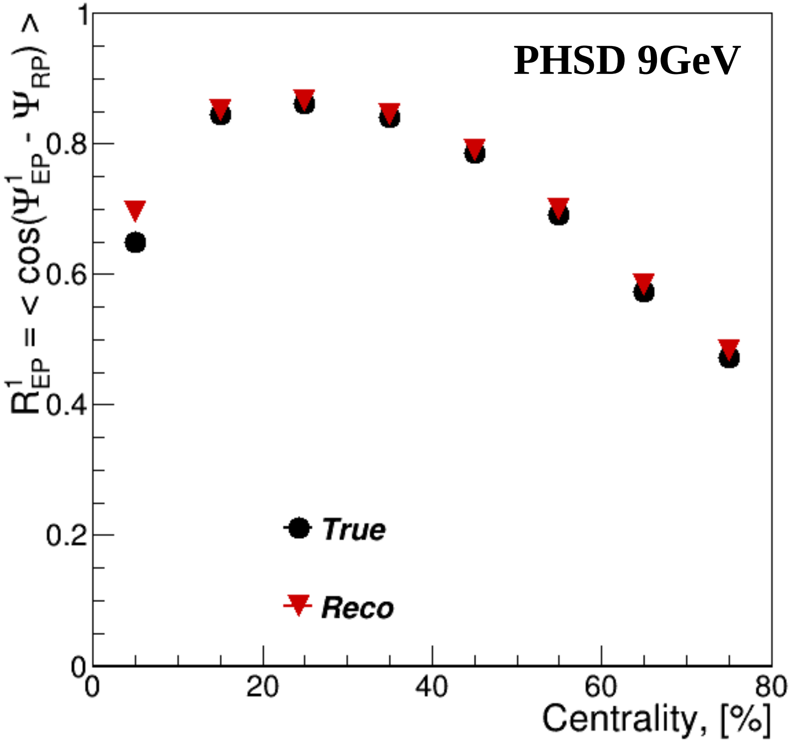


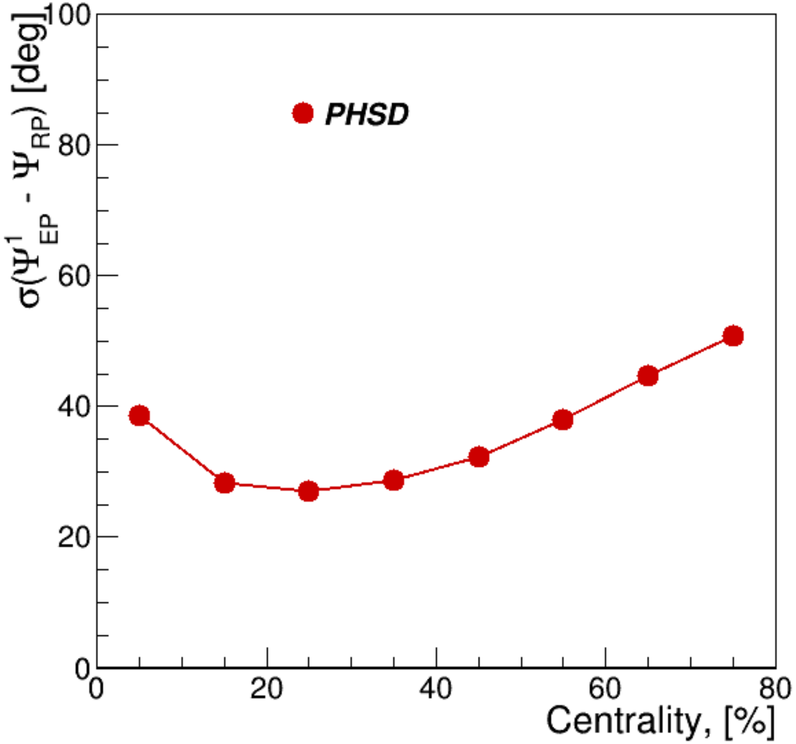


- Difference between EP and RP angles
  - Gaussian fit
  - Max. resolution of ~ 27 deg.
  - Centered at 0

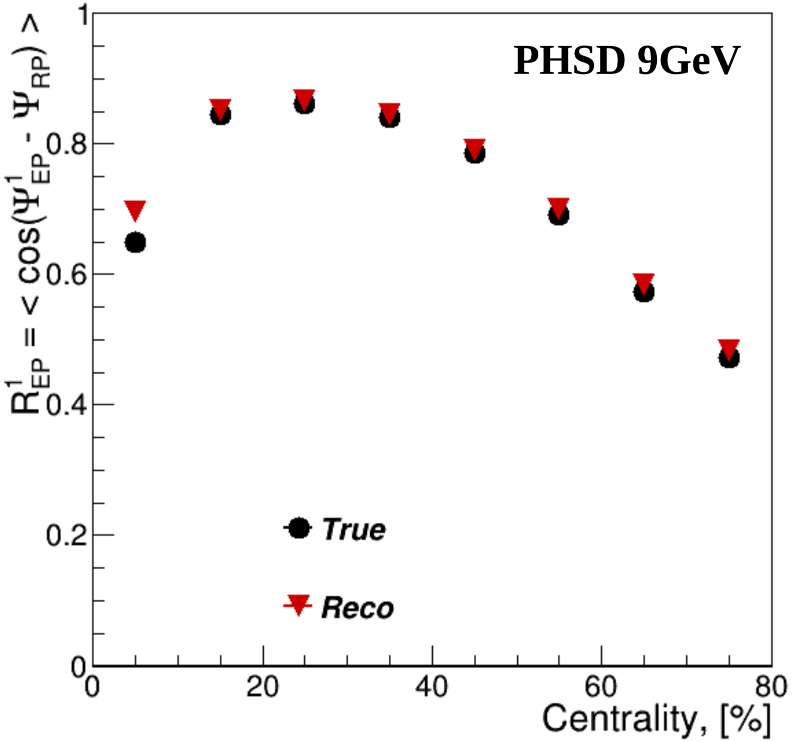
$$R^k_{\mathrm{EP}}(sub) = \frac{\sqrt{\pi}}{2\sqrt{2}}\chi \exp\left(-\chi^2/4\right)\left[I_{(k-1)/2}(\chi^2/4) + I_{(k+1)/2}(\chi^2/4)\right]$$

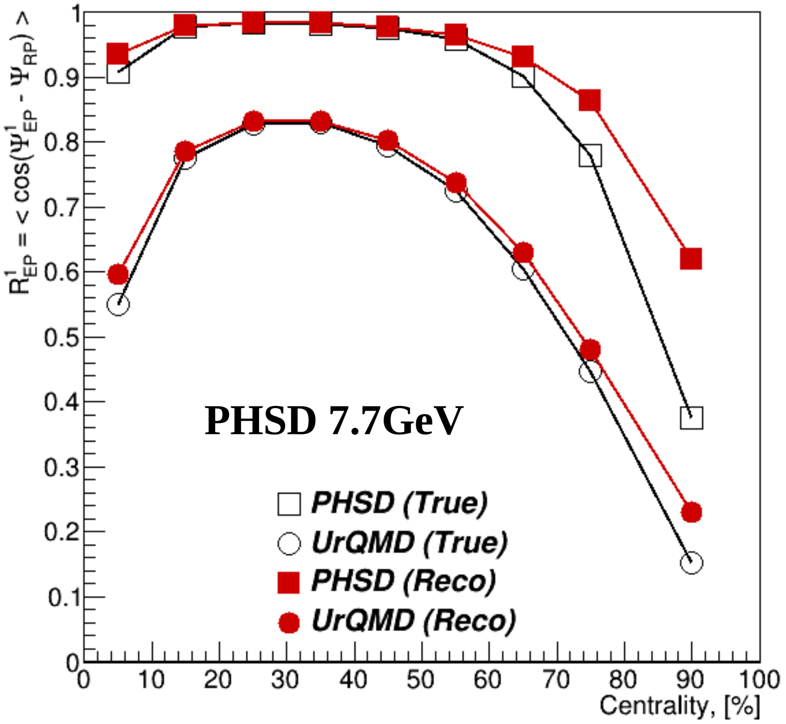
Event plane determination



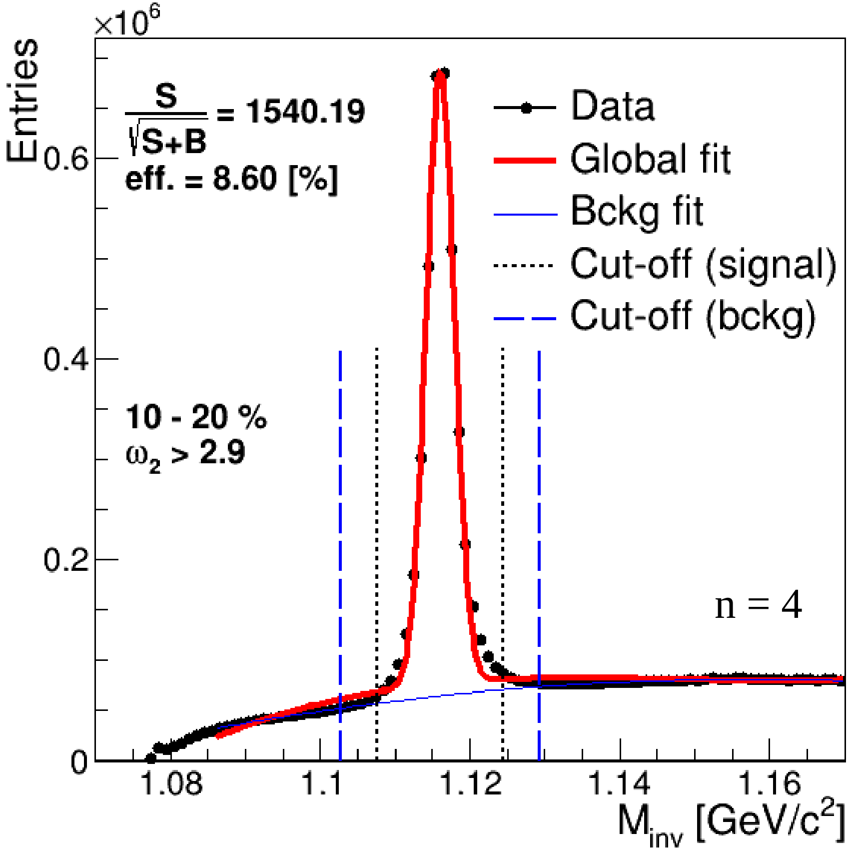


- Event plane and its resolution determined using FHCal
- Checked via 2 methods



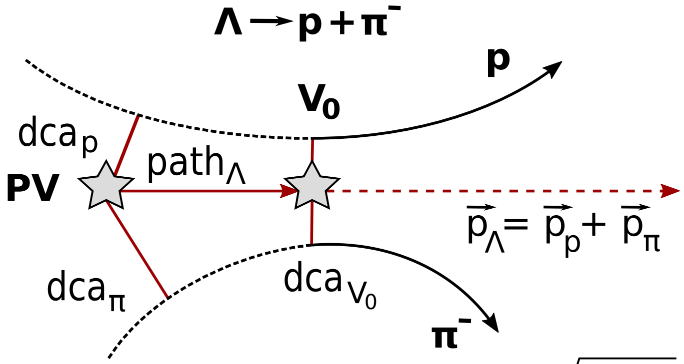


- Event plane and its resolution determined using FHCal
- Reasonable behaviour compared to the previous results



Fitting procedure:

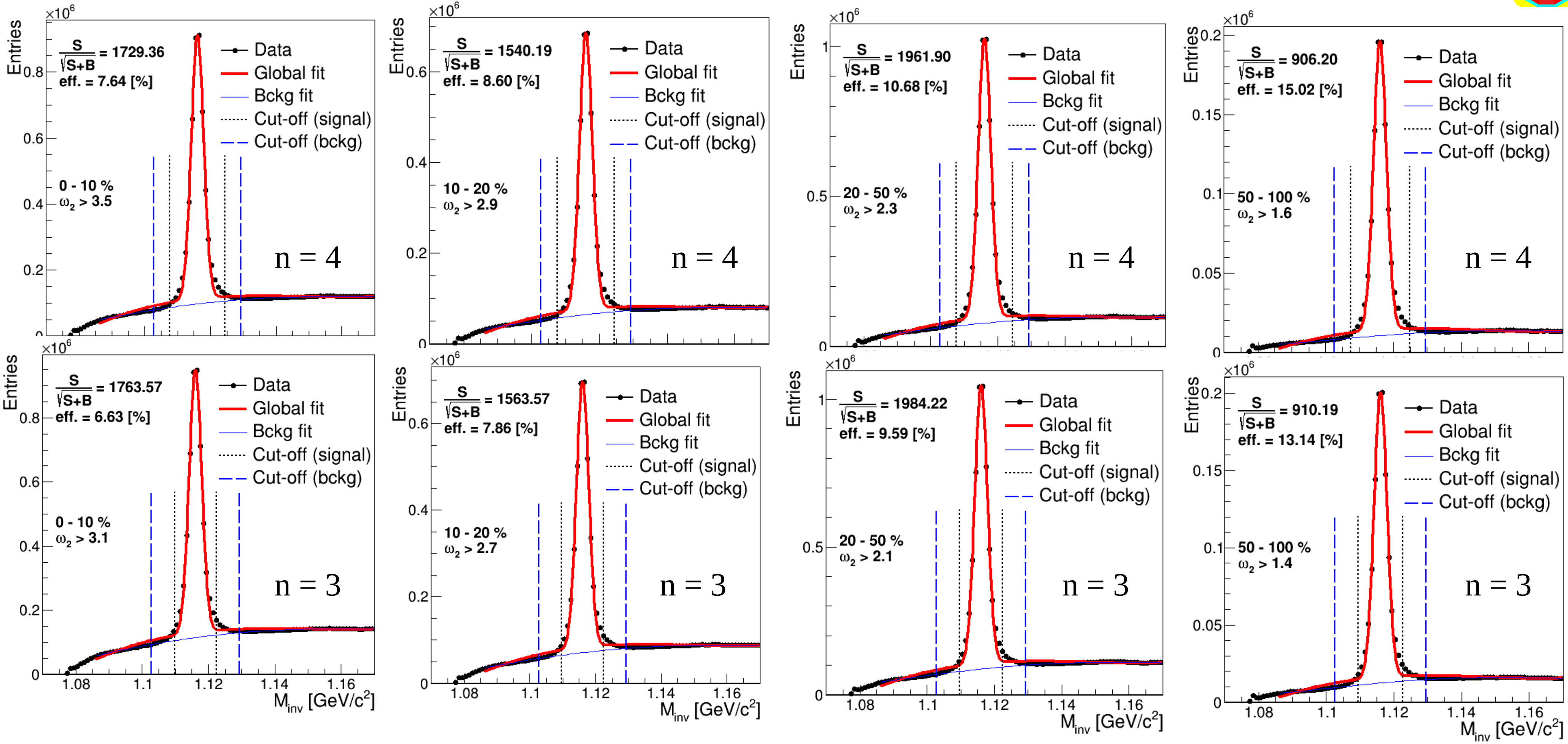
- Global fit (Gauss + Legendre polynomials)
- Background fit in sidebands (± 7σ)
- Cut-off: $<M_\Lambda> \pm n^*\sigma$
- ω_2 cut based on maximum significance (for each centrality bin)



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

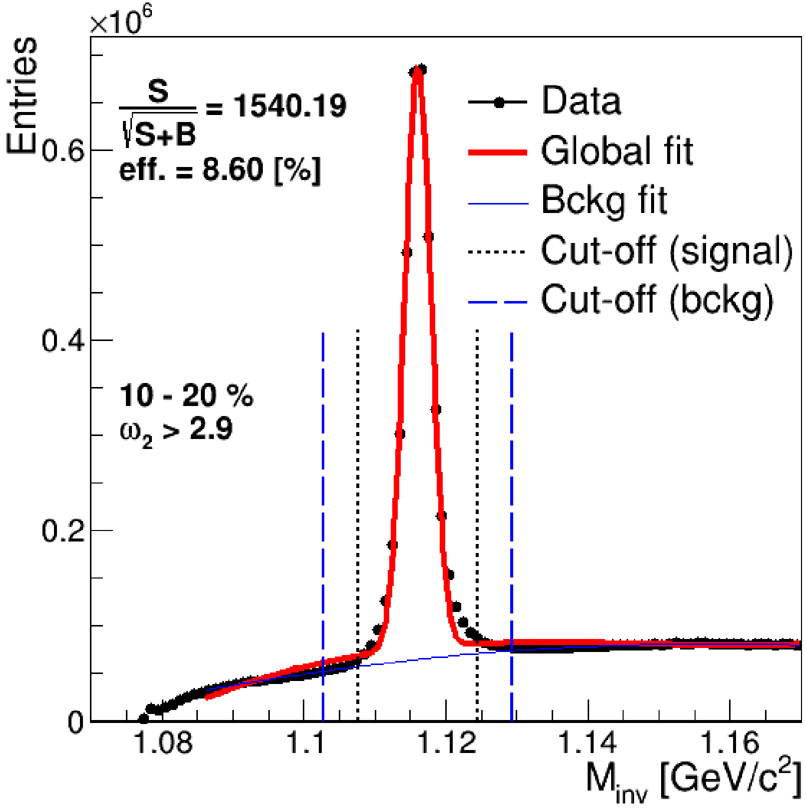
$$f(x) = p_0 \exp\left(\frac{(-0.5(x-p_1))^2}{p_2^2}\right) + p_3(L_0 + p_4L_1 + p_5L_2 + p_6L_3 + p_7L_4)$$

Lambda reconstruction



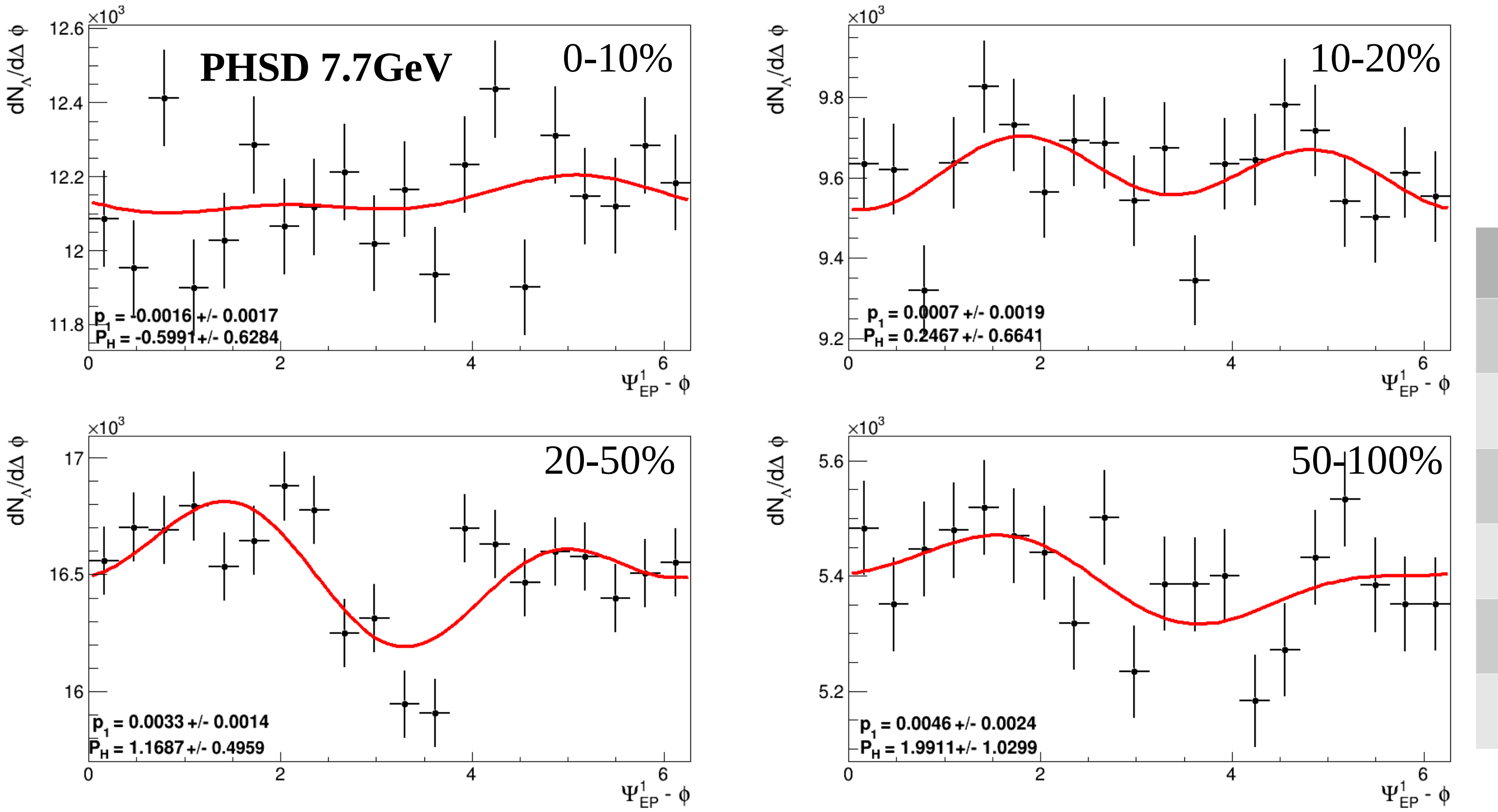
Global polarization reconstruction

- Obtained 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[1] to get $\langle\sin(\Delta\phi_p^*)\rangle \rightarrow P_\Lambda$
  - «Event plane» method (p_n — fit parameters)
  - $P_\Lambda = \frac{8}{\pi\alpha_\Lambda}\frac{p_1}{R_{\rm EP}^1}$



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

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



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

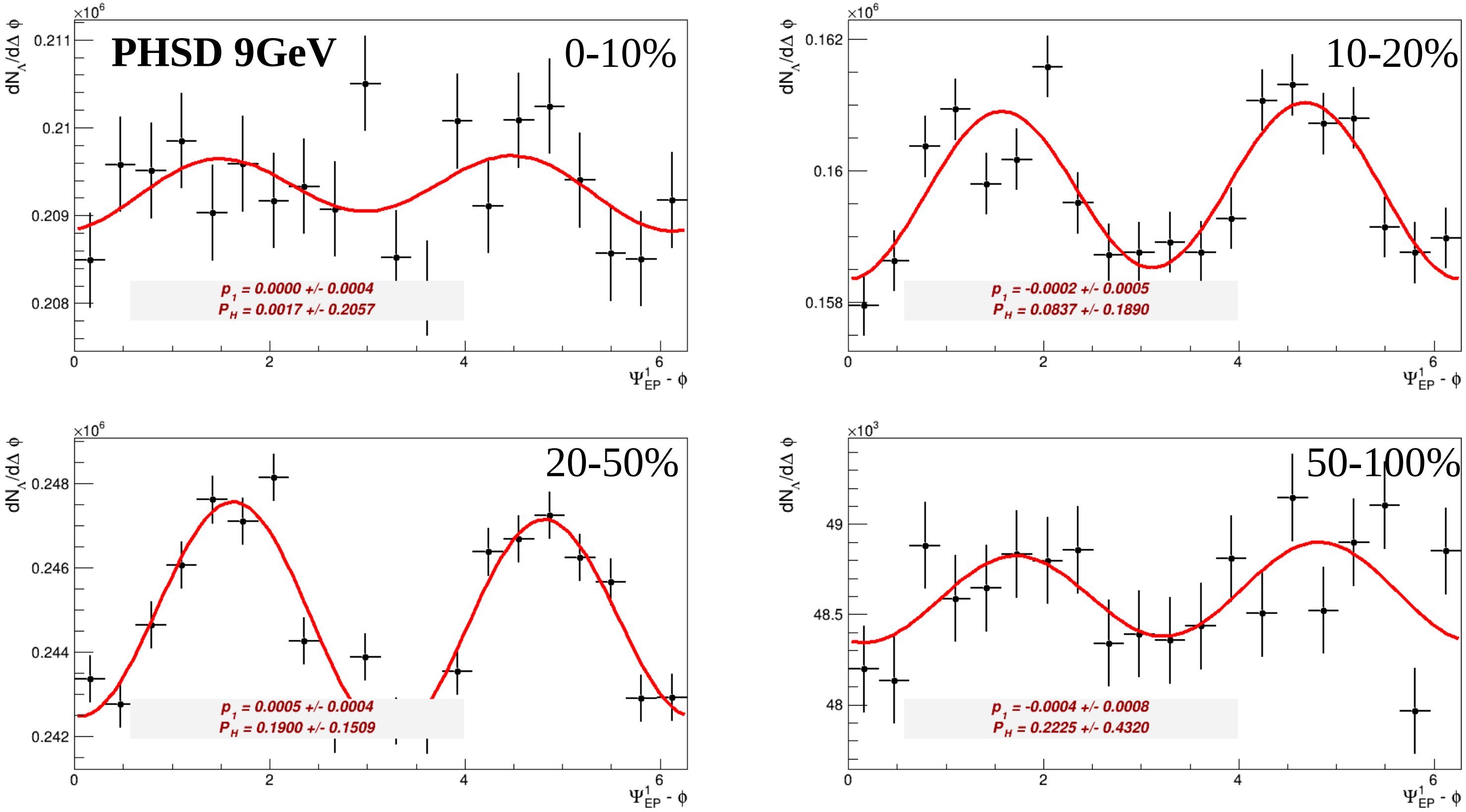
$$\alpha_\Lambda \simeq 0.732$$

	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

p_1 and p_2 are of the same magnitude order!

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

Results (new)

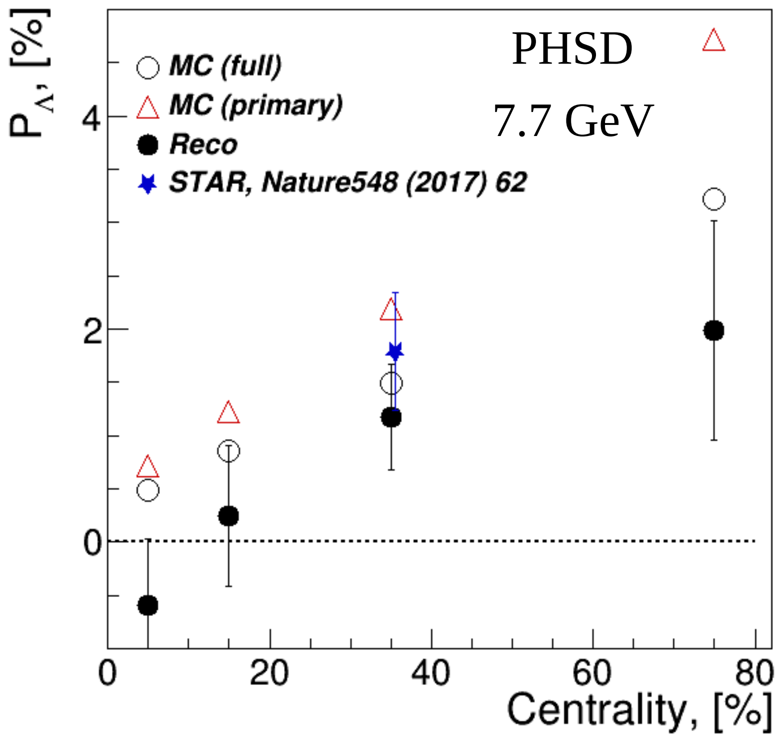


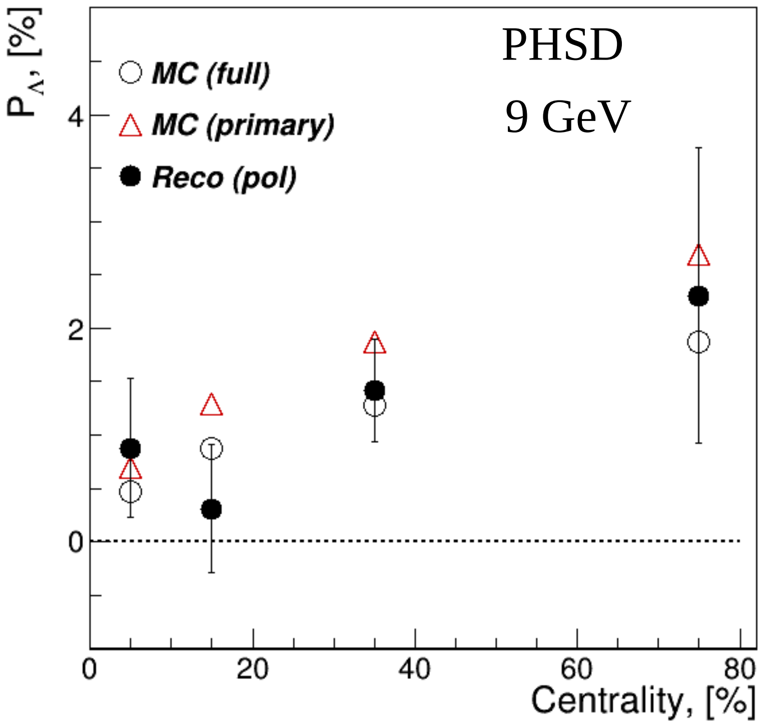
$$P_\Lambda = \frac{8}{\pi\alpha_\Lambda}\frac{p_1}{R^1_{\mathrm{EP}}}$$

$$\alpha_\Lambda \simeq 0.732$$

	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

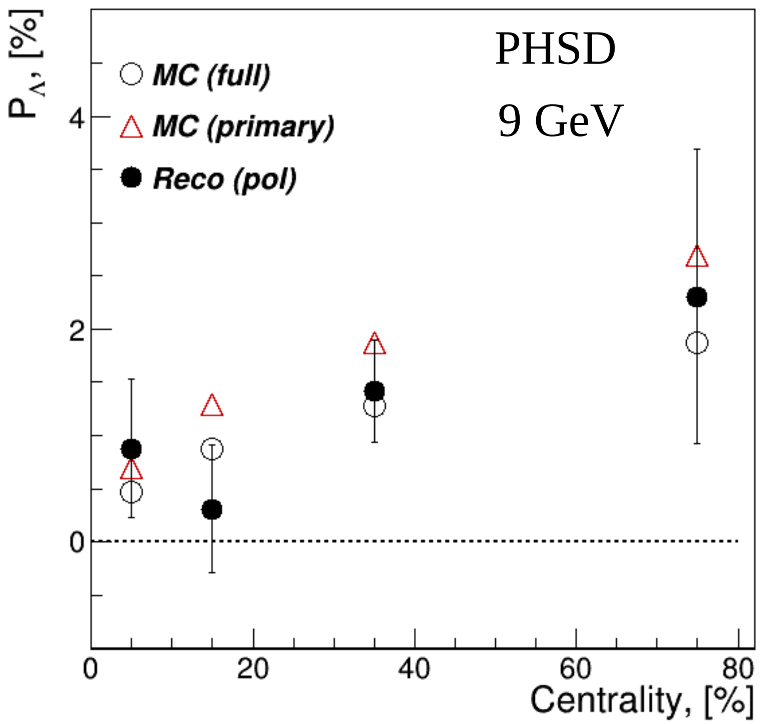
$$\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi^*_p} = p_0(1 + 2p_1\sin(\Delta\phi^*_p) + 2p_2\cos(\Delta\phi^*_p) + 2p_3\sin(2\Delta\phi^*_p) + 2p_4\cos(2\Delta\phi^*_p) + ...)$$

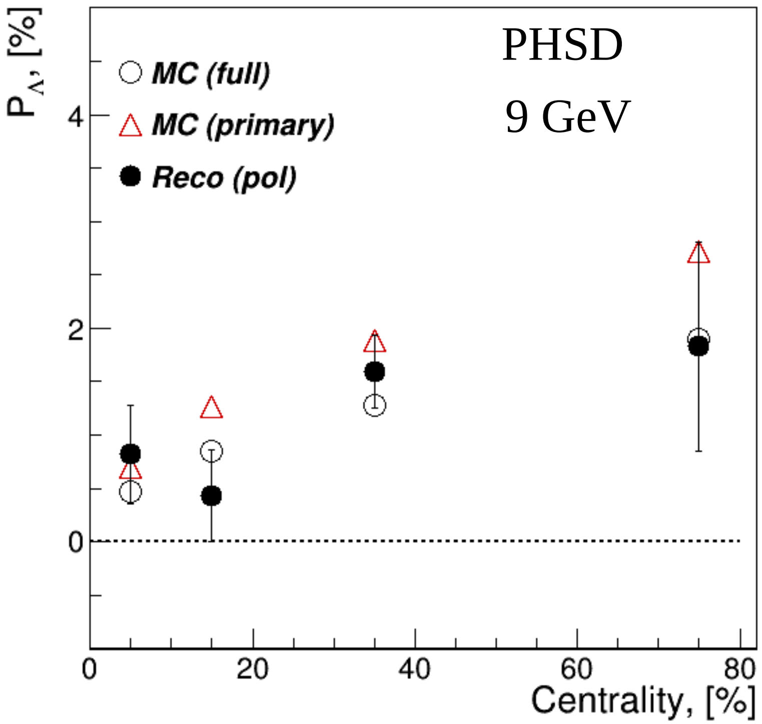




- (left) Previous result (PHSD ~1M events, @ 7.7 GeV)
- (right) New result with ~1M events, PHSD @ 9 GeV
- The results seem similar, but ...

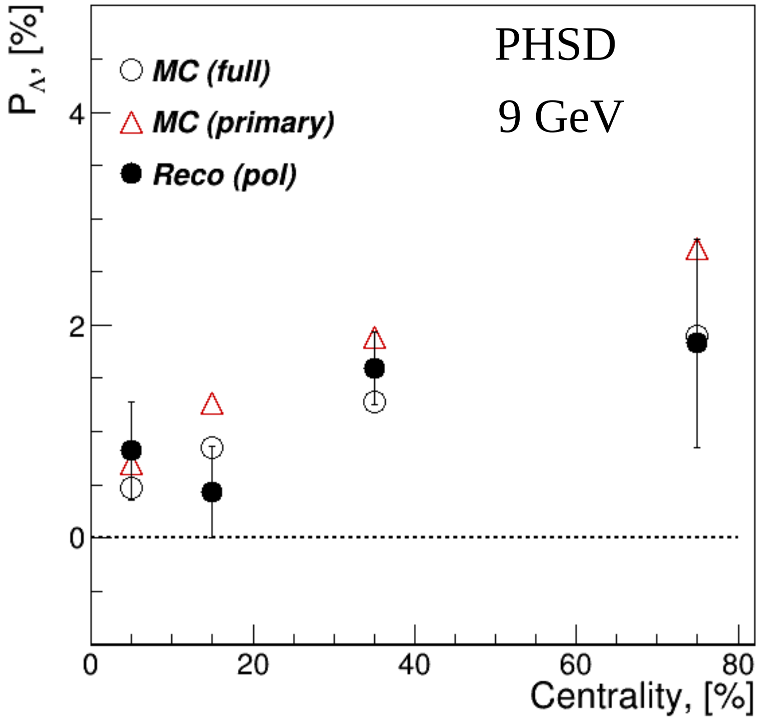
Results

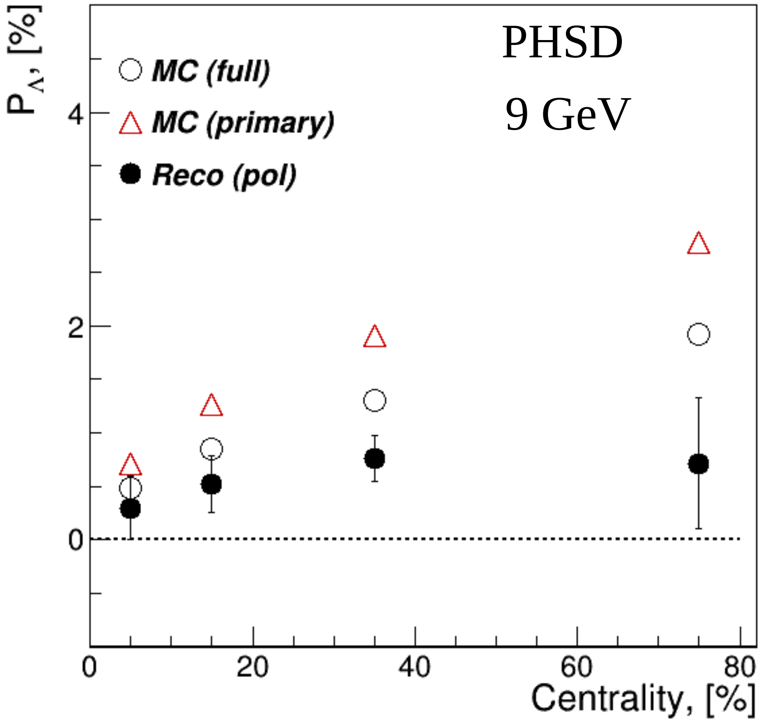




- (left) PHSD @ 9 GeV, ~1M events
- (right) PHSD @ 9 GeV, ~2M events
- When we increase statistics, the picture starts to change

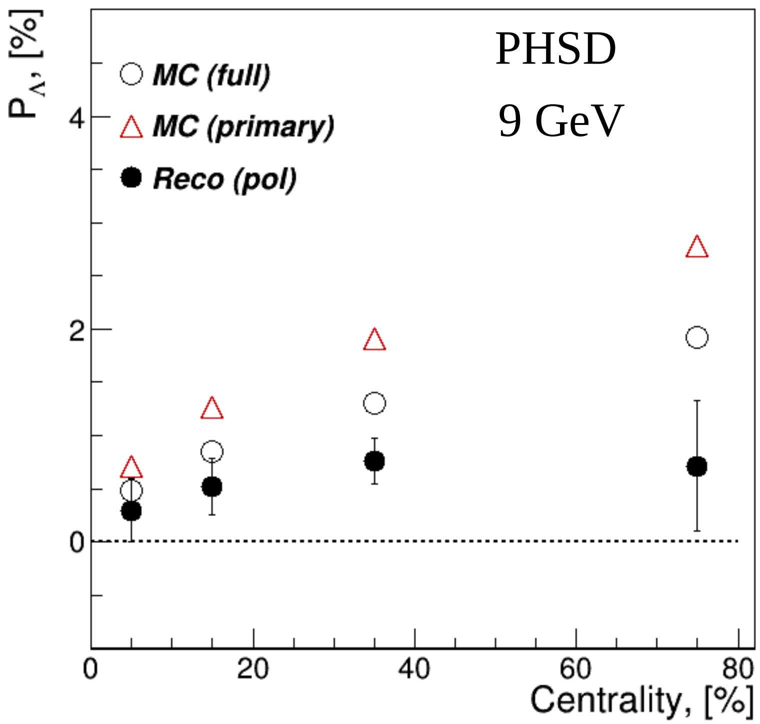
Results

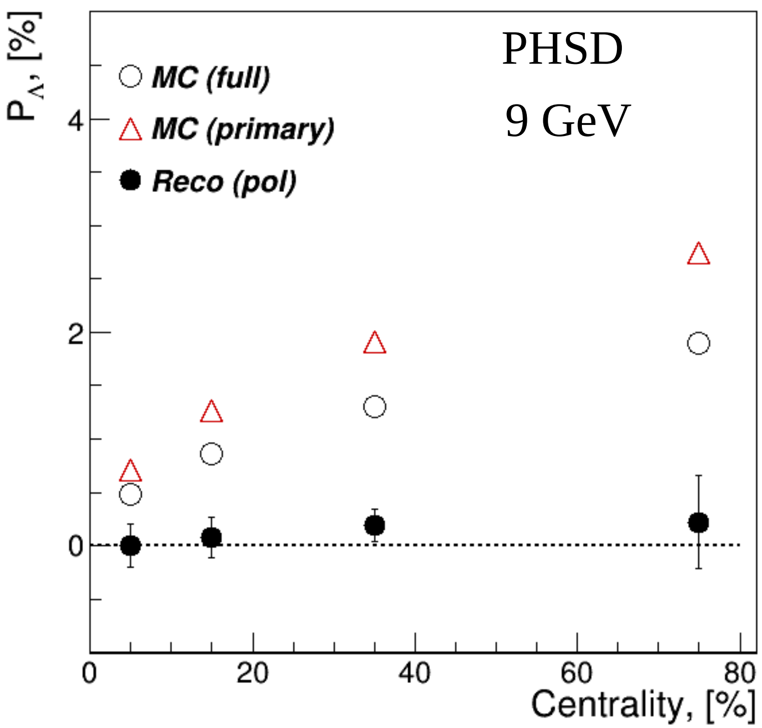




- (left) PHSD @ 9 GeV, ~2M events
- (right) PHSD @ 9 GeV, ~5M events
- Not only the errors are decreasing, but the value of polarization

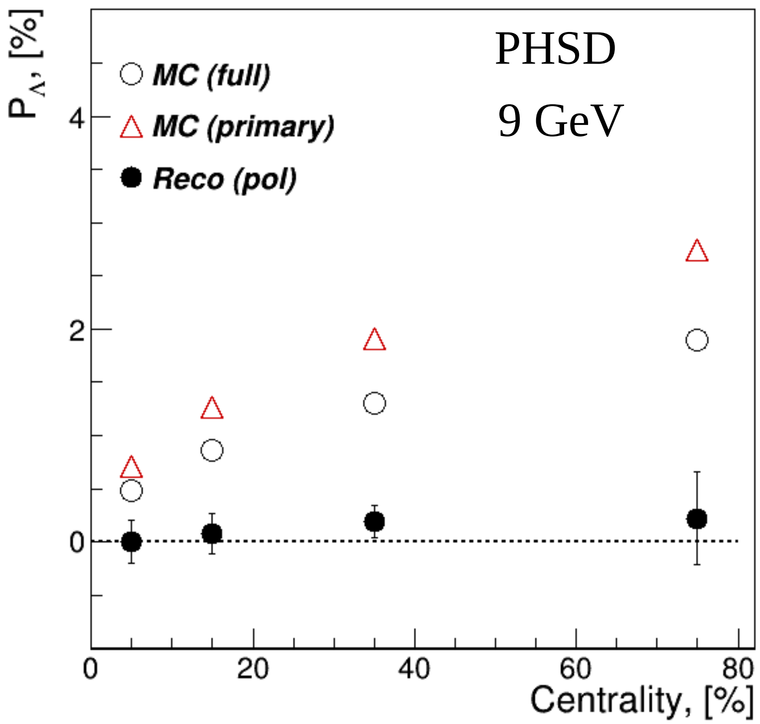
Results

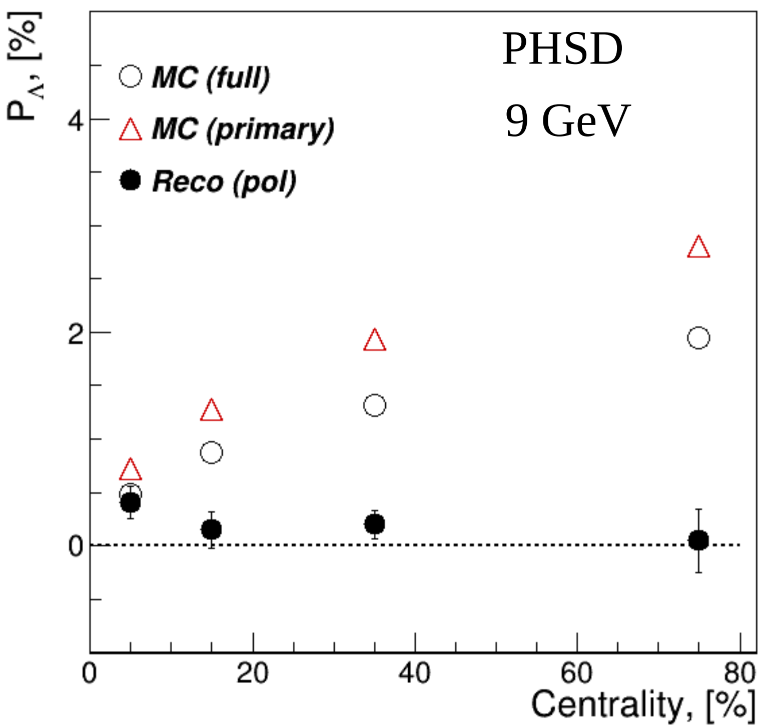




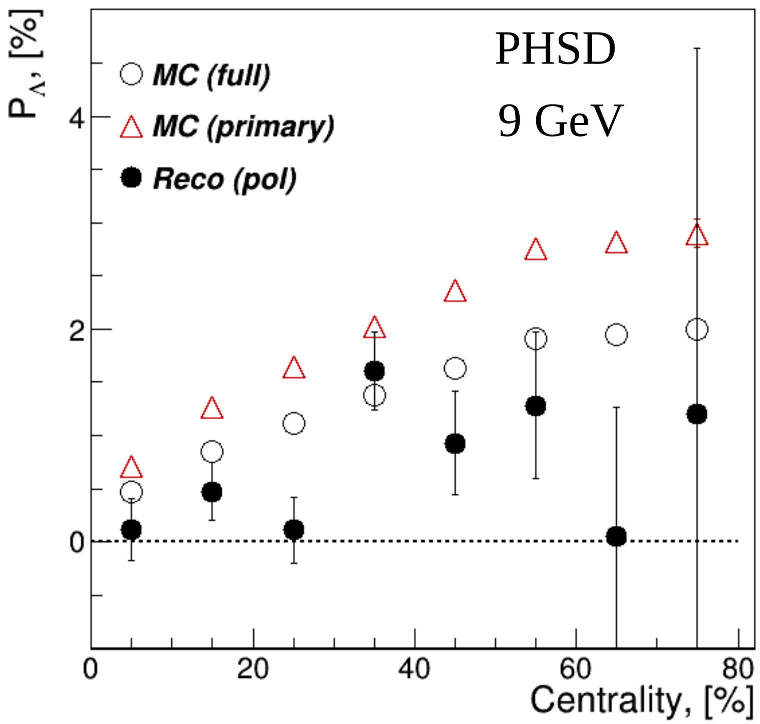
- (left) PHSD @ 9 GeV, ~5M events
- (right) PHSD @ 9 GeV, ~10M events
- Not only the errors are decreasing, but the value of polarization
- For the full sample, the reconstructed value is consistent with 0

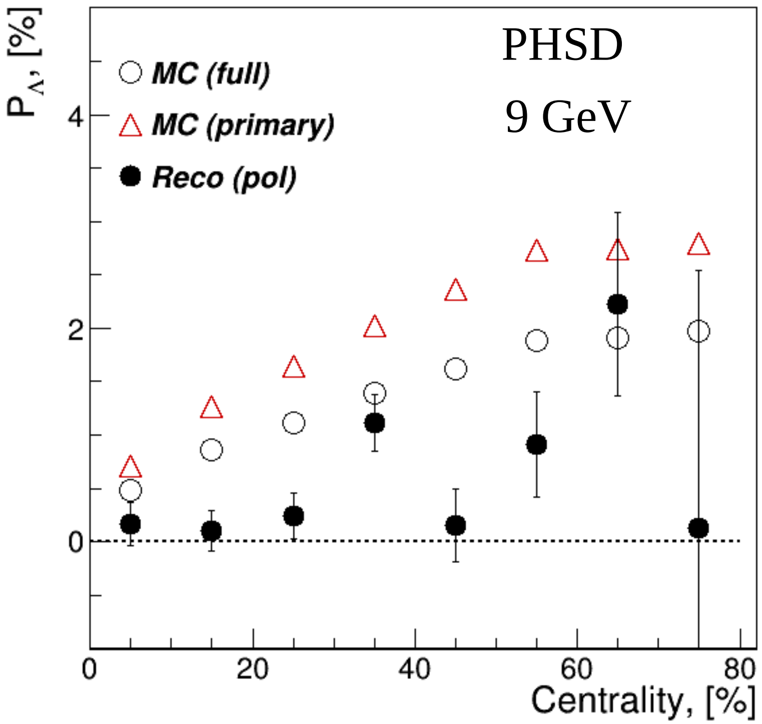
Results





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





- (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

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

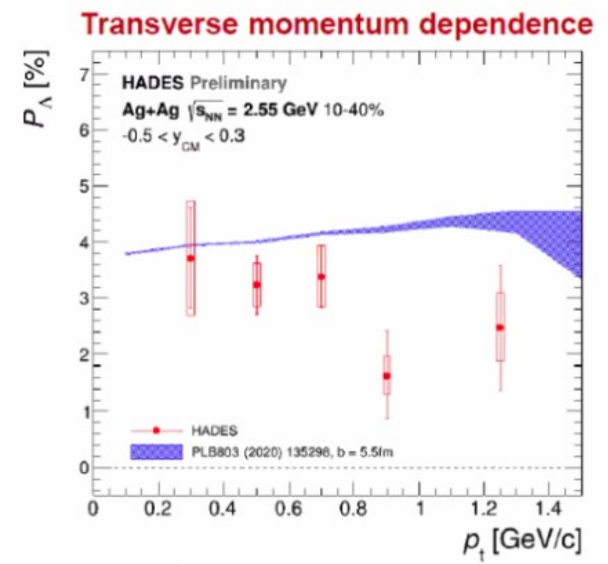
	0-10%	10-20%	20-50%	50-100%
N_{events}	1.3* 10^6	1.4* 10^6	4.2* 10^6	3.0* 10^6
N_Λ (full)	4.4* 10^6	3.3* 10^6	4.9* 10^6	1.0* 10^6
N_Λ (5M)	2.1* 10^6	1.6* 10^6	2.4* 10^6	0.5* 10^6

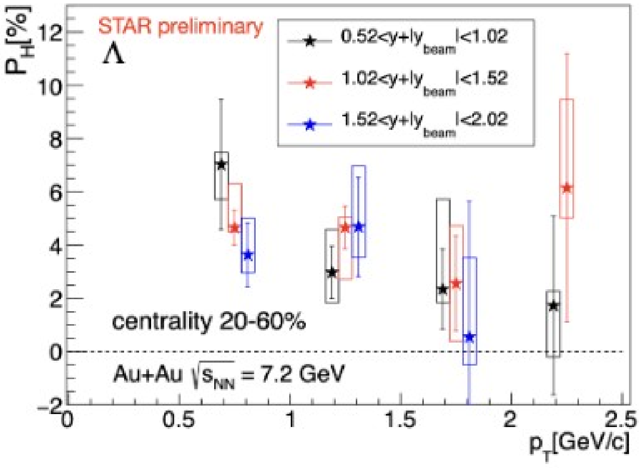
PHSD @7.7 GeV

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

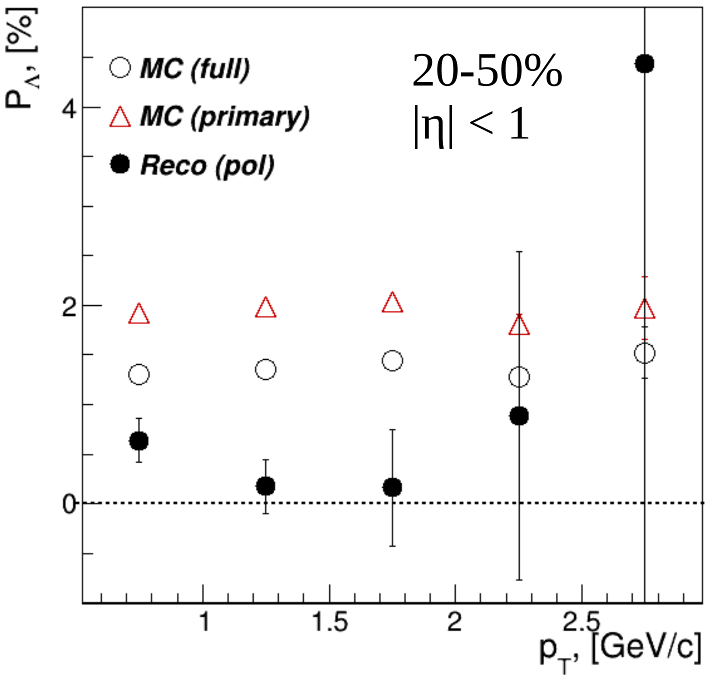
HADES
Au-Au @1.23 AgeV
Ag-Ag @1.58 AGeV

	10-40%
N_Λ (Au)	1.5* 10^5
N_Λ (Ag)	1.1* 10^6

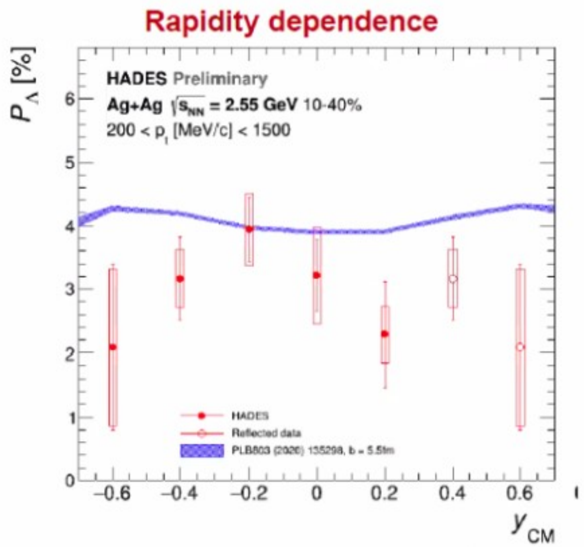


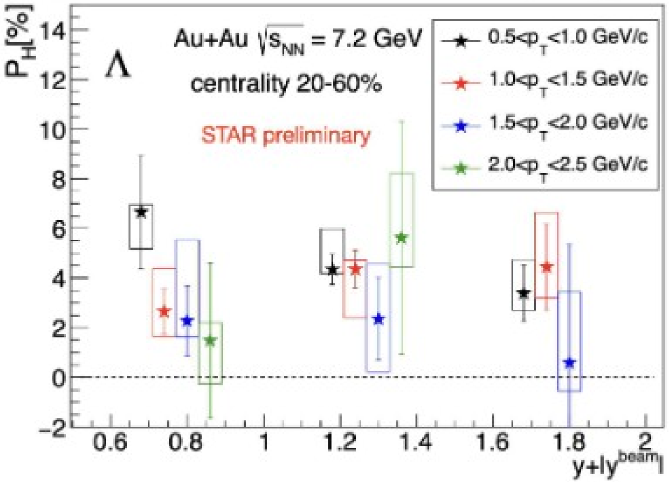


PHSD, BiBi @9 GeV

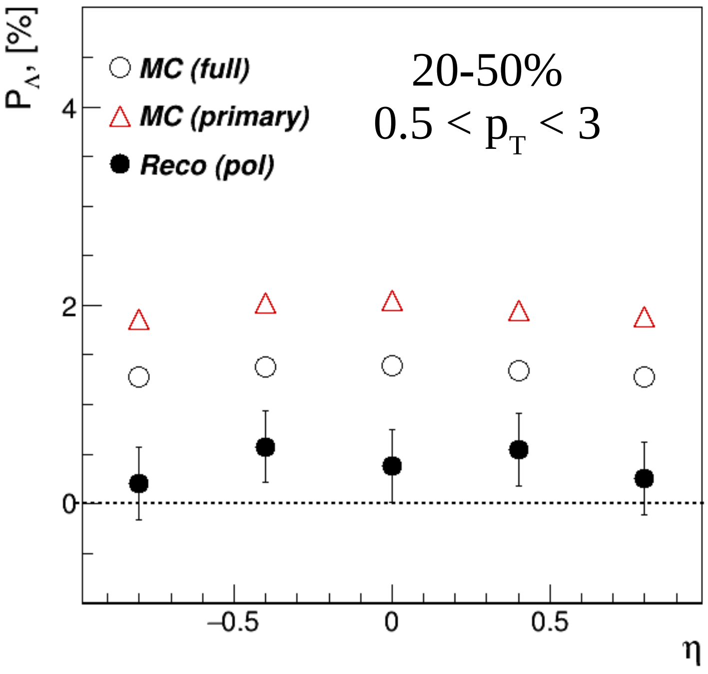


- Rapidity and transverse momentum dependences of global polarization of Lambda
  - STAR collaboration, SQM2021 (e-Print: 2108.10012)
  - HADES collaboration, SQM2021
- No significant y and p_T dependence within uncertainties





PHSD, BiBi @9 GeV



- Rapidity and transverse momentum dependences of global polarization of Lambda
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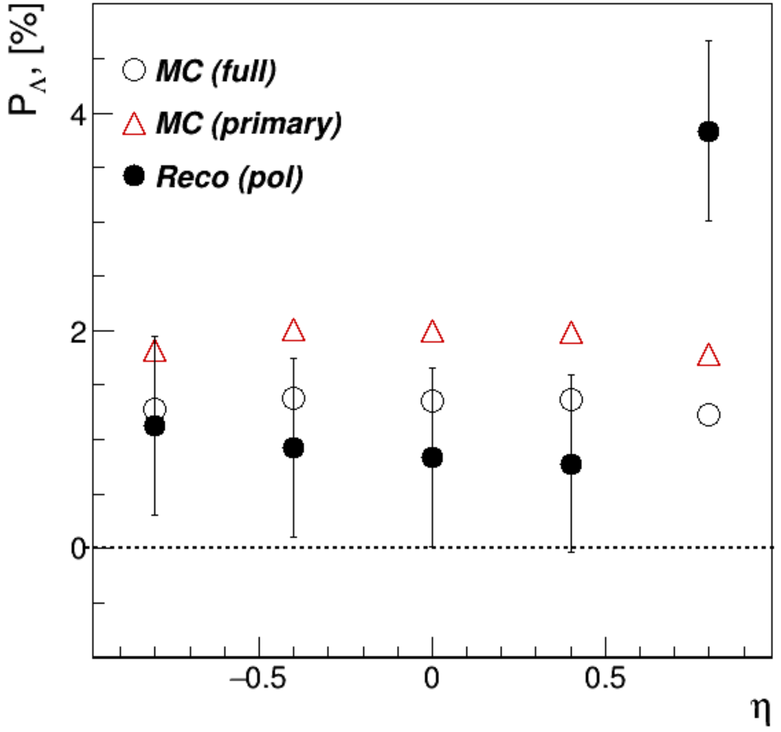
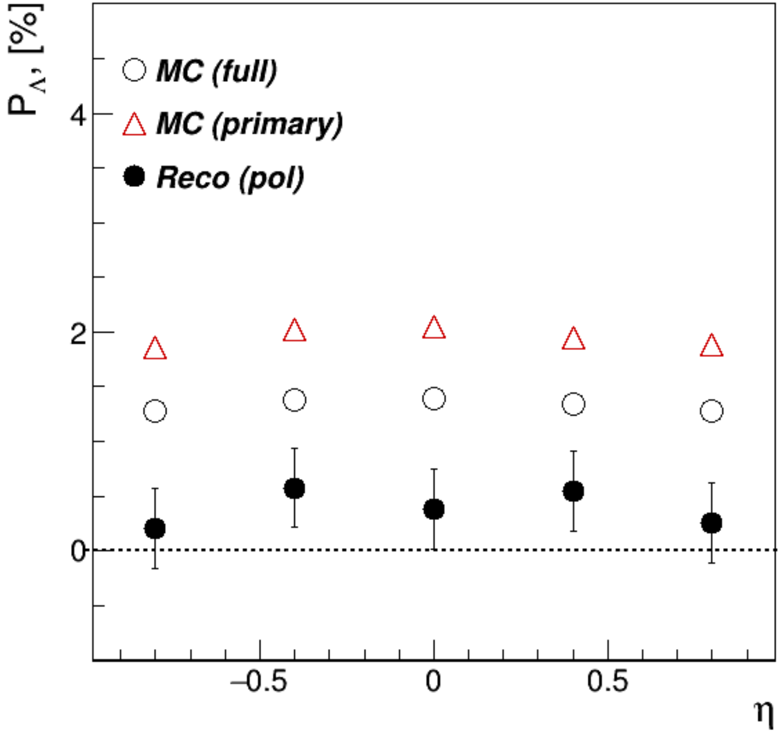
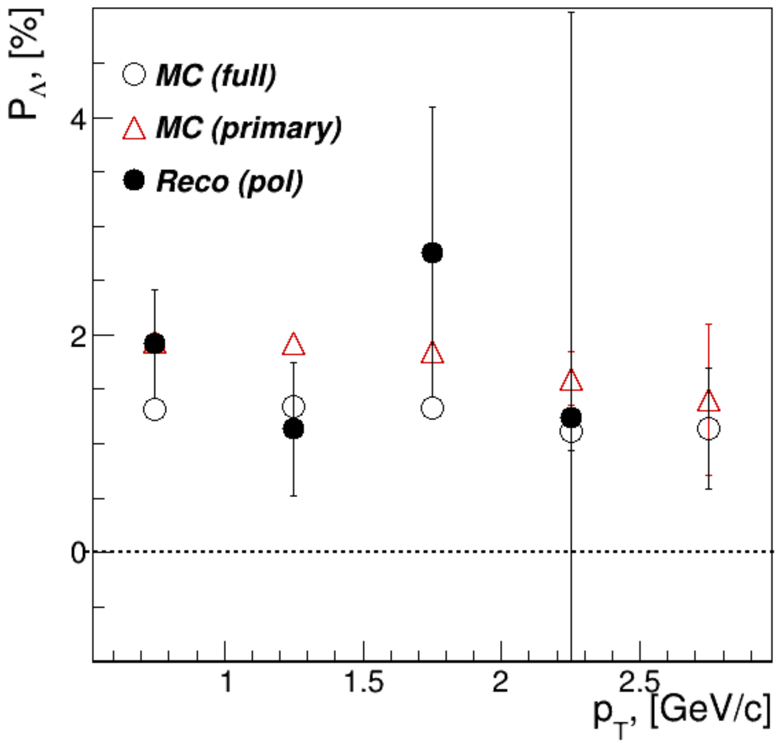
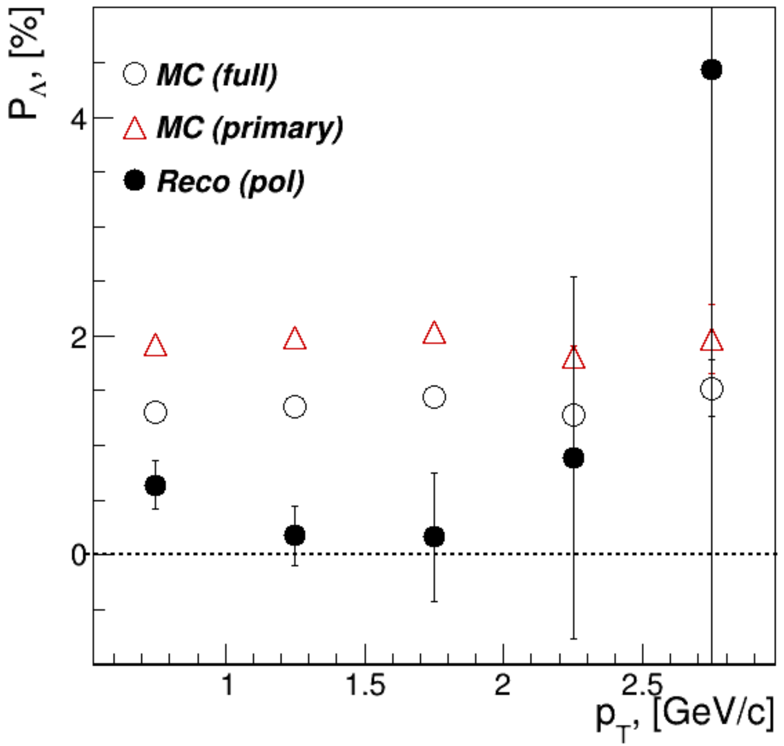




- (left) PHSD @ 9 GeV, ~2M events
- (right) PHSD @ 9 GeV, ~10M events

Results





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

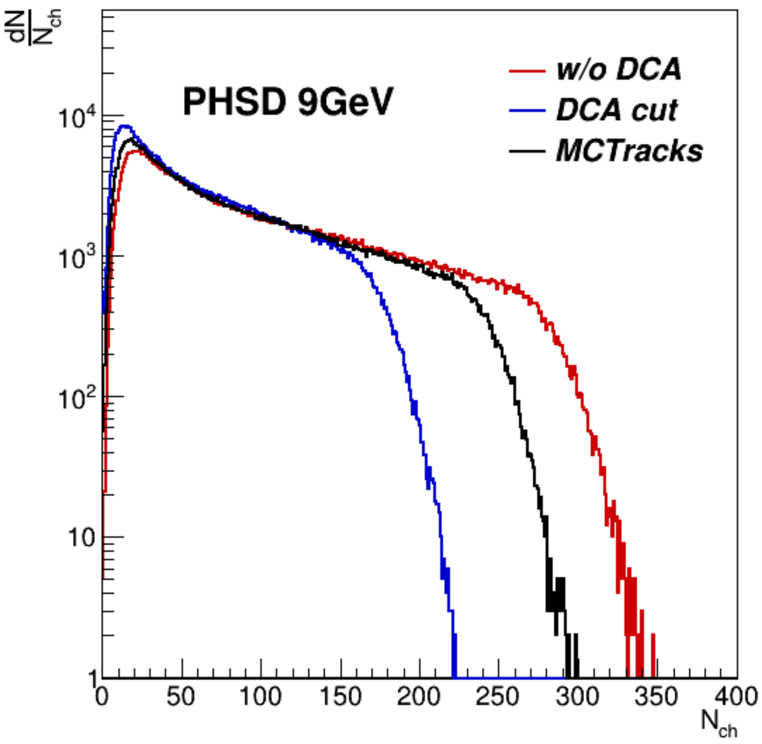
Conclusions

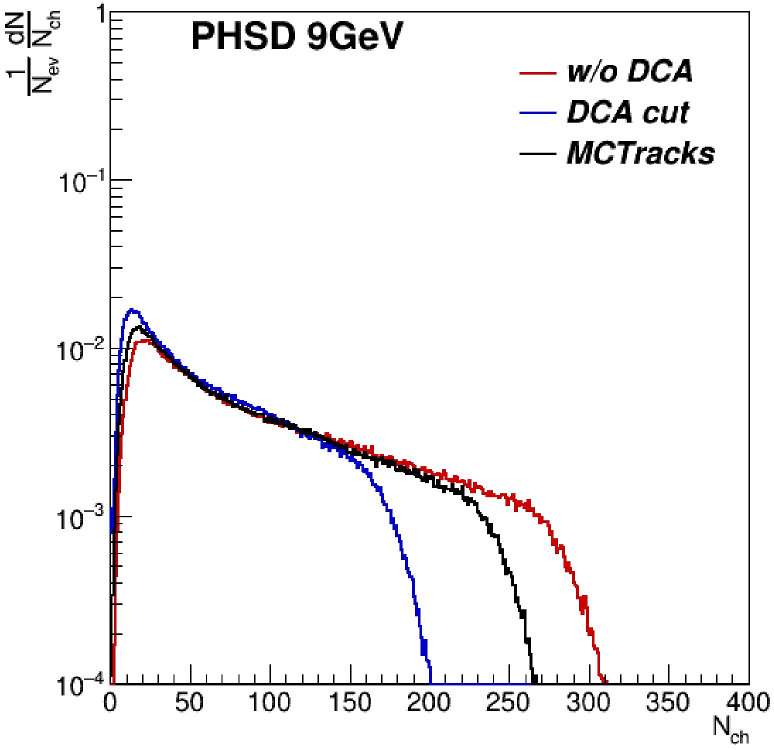
- Feasibility study of the global polarization measurement with PHSD
  - Sample with increased statistics: Bi-Bi @ 9GeV, 10M MB events, b [0,12]fm
  - Official production (request 23)
- Compared with our previous results from the testing sample (Au-Au @ 7.7GeV, 1.4M MB events, b [0,16]fm)
  - Better results with centrality and EP resolution determination
  - Unexpected behaviour of extracted global polarization values
- Outlook
  - Does the method become inapplicable/should be corrected?
  - Is the picture the same with the second method?

The End

Thank you for your attention!

Back Up: Multiplicity in TPC



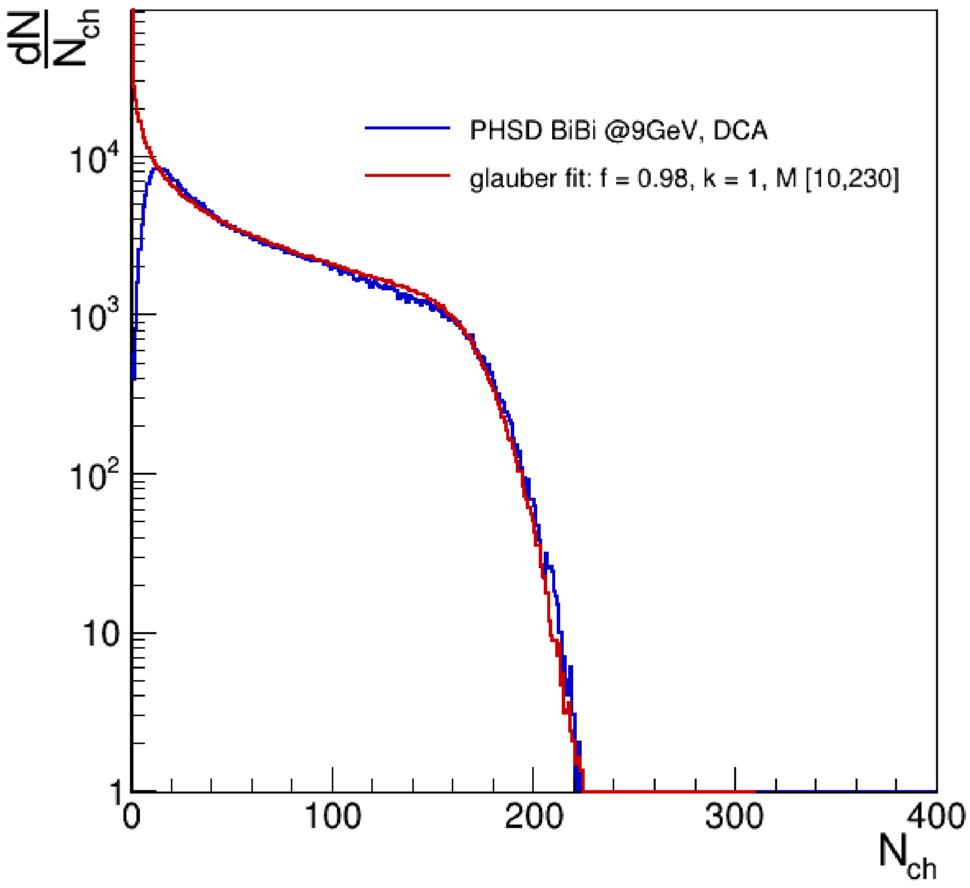


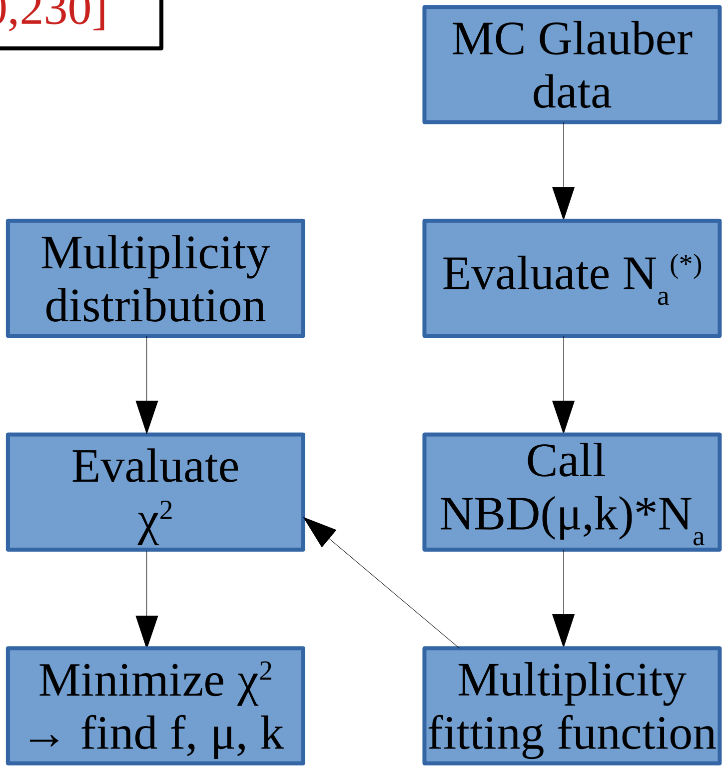
- MC-Glauber based centrality framework[1]
- Selection criteria:
  - 500k events
  - $|\eta| < 0.5$
  - $|p_T| > 0.15$ GeV
  - $N_{hits} > 16$
  - |DCA| < 0.5 cm (optional)
  - 10%-centrality bins

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

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

DCA cut, M [10,230]



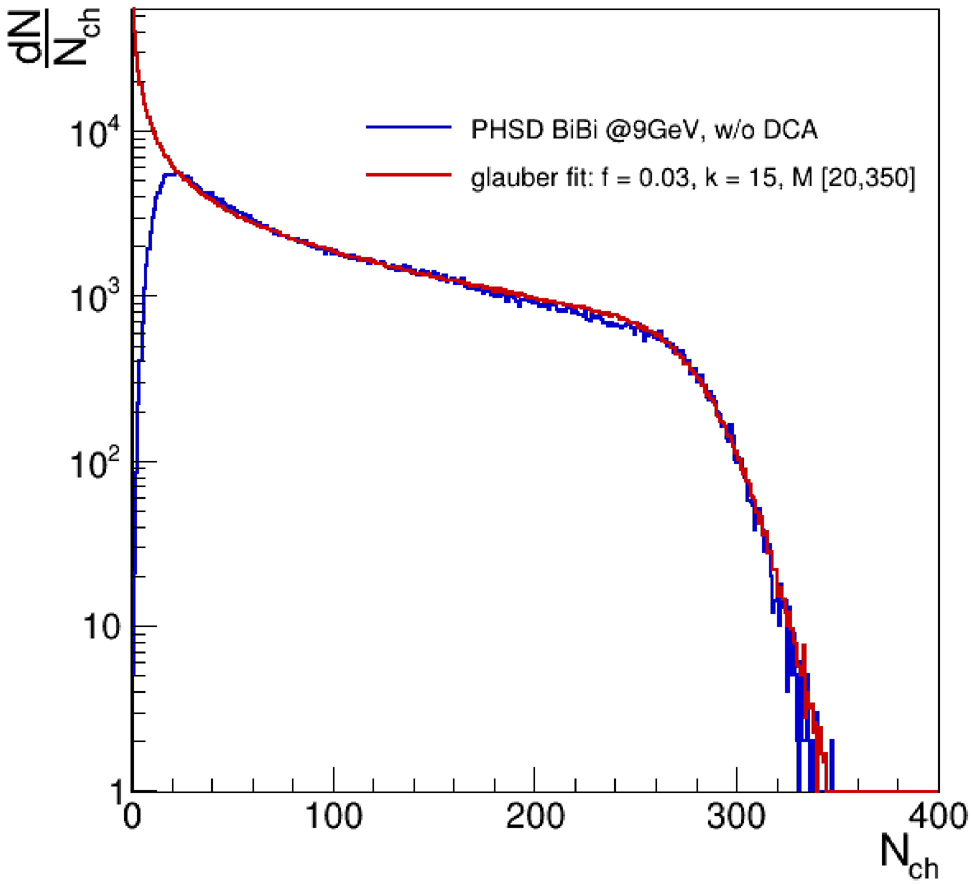


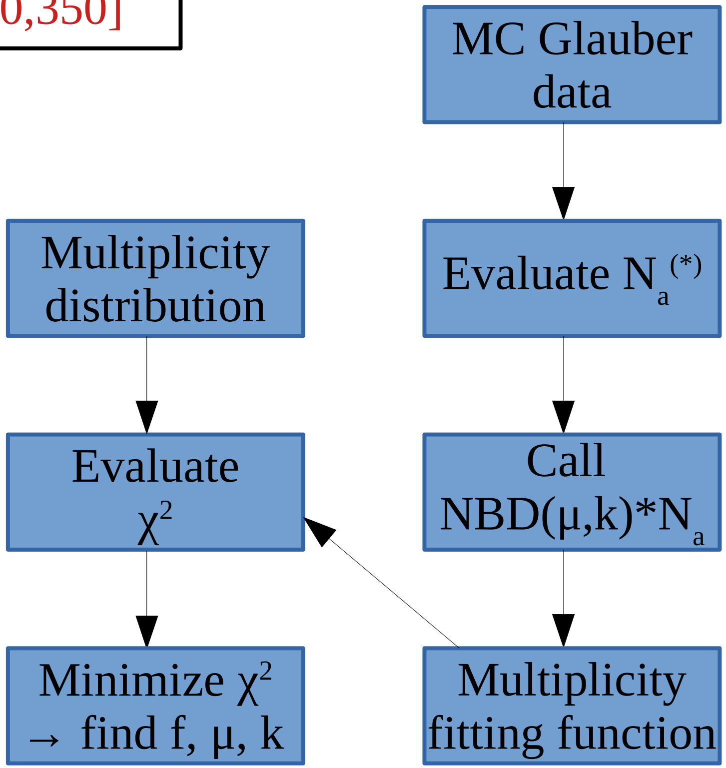
$$^{(*)}N_a = fN_{\text{part}} + (1-f)N_{coll}$$

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]

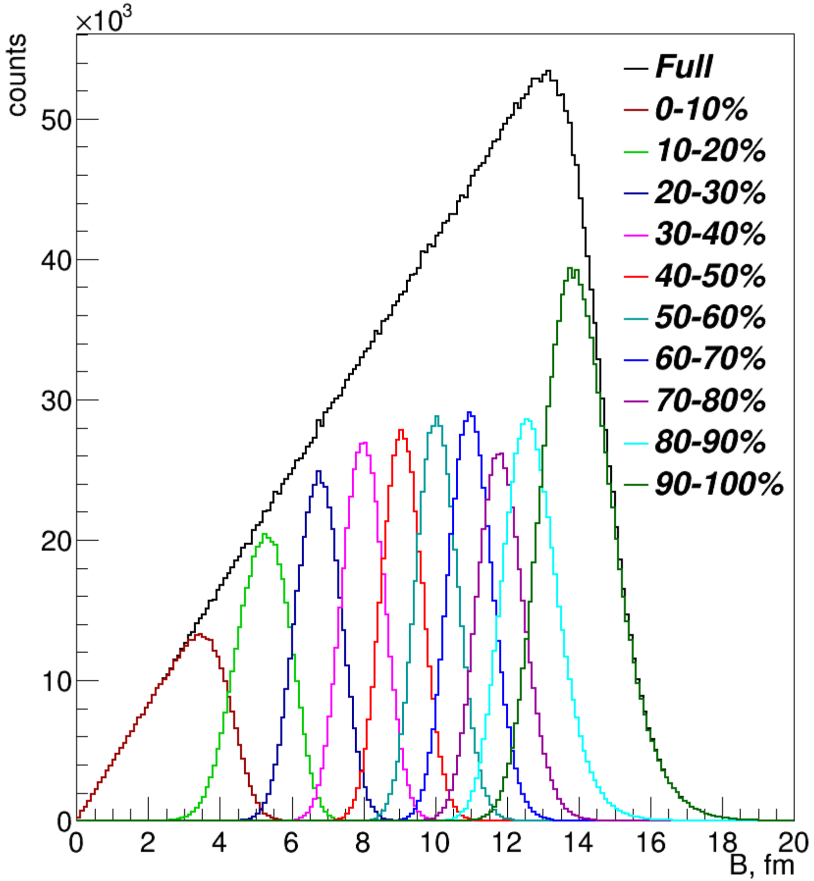




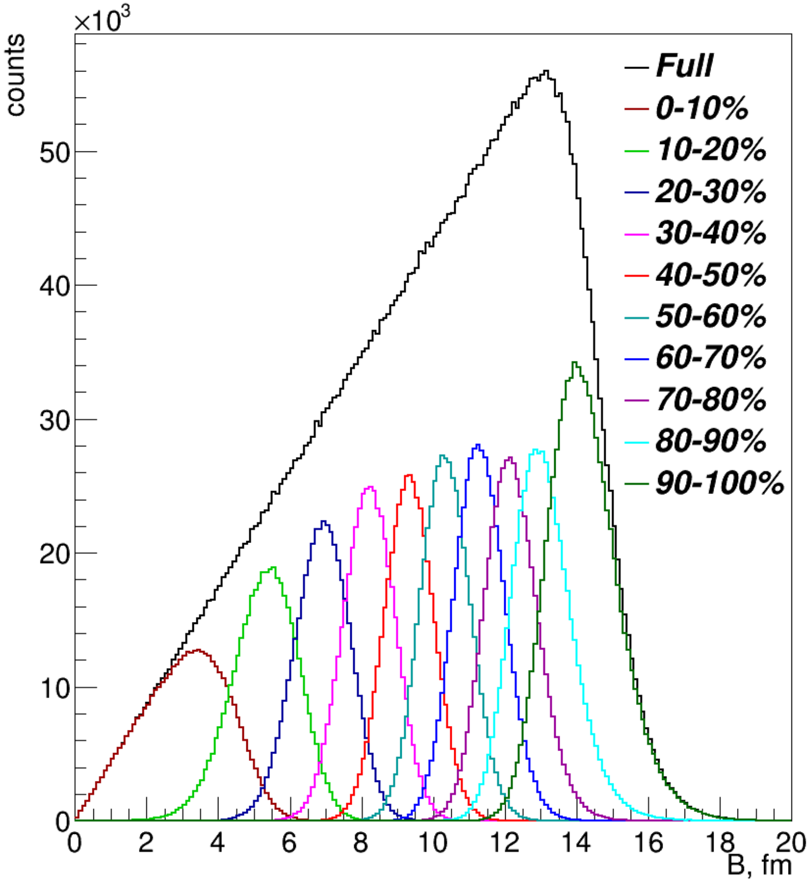
$$^{(*)}N_a = fN_{\text{part}} + (1-f)N_{coll}$$

Back Up: Centrality determination

w/o DCA, M [20,350]



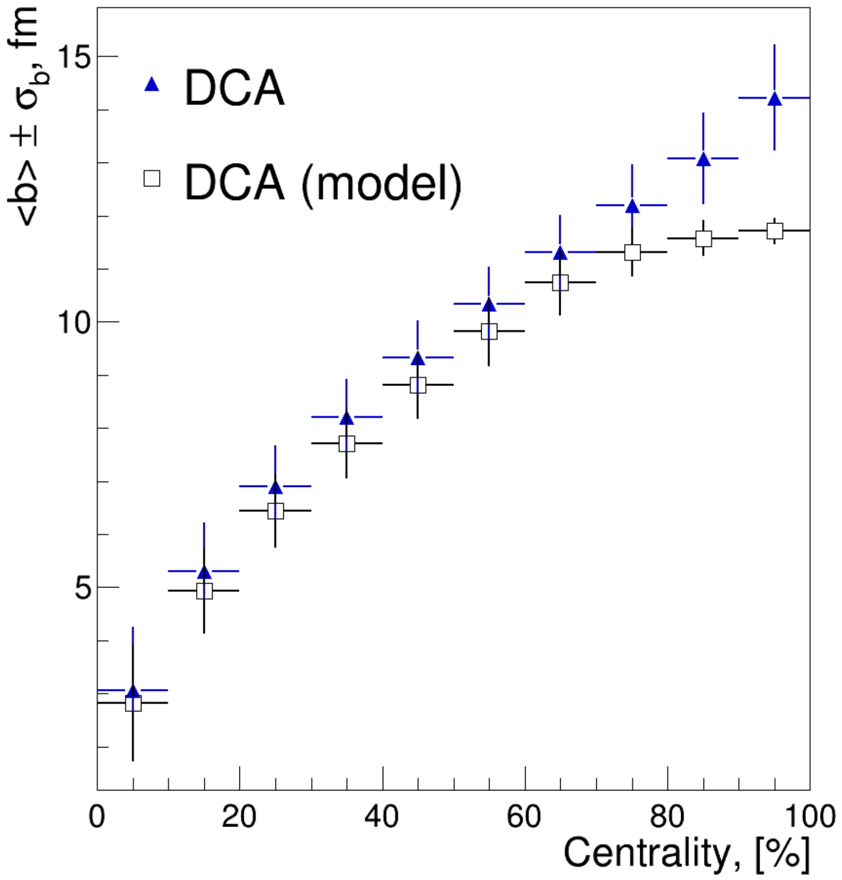
DCA cut, M [10,230]

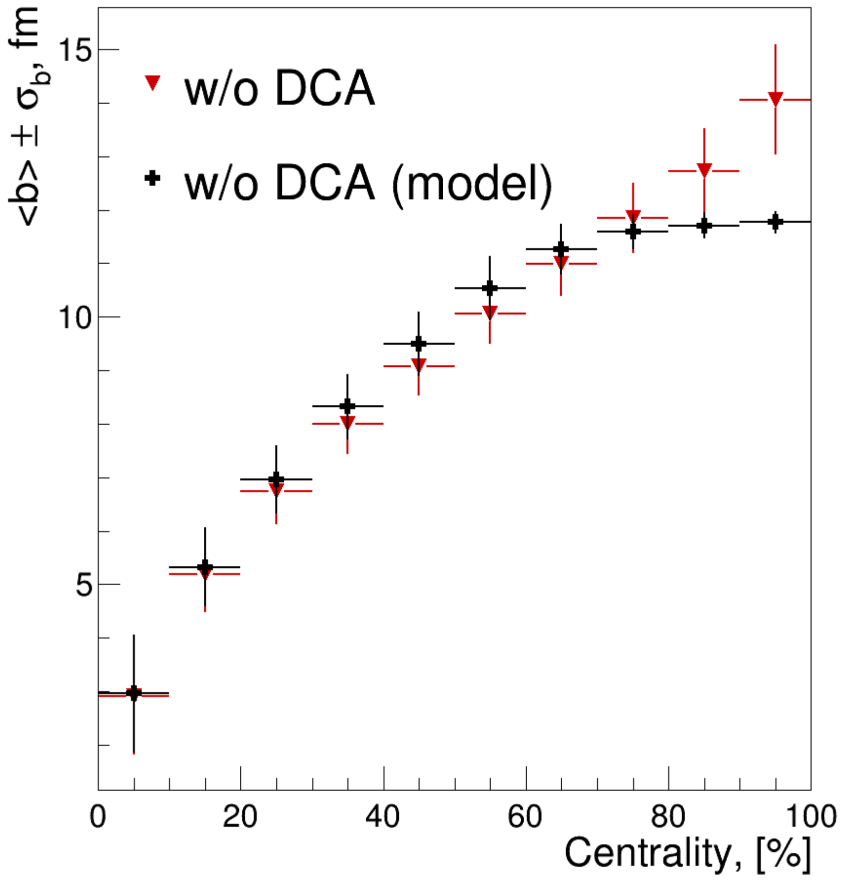


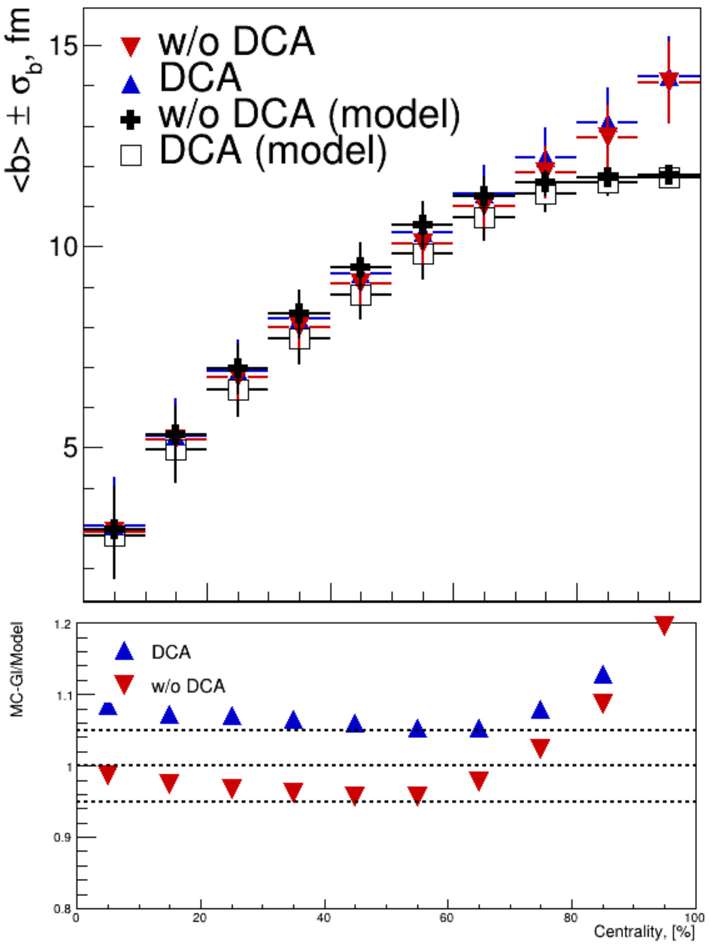
Back Up: Average impact parameter

DCA cut, M [10,230]

w/o DCA, M [20,350]






w/o DCA
DCA
w/o DCA (model)
DCA (model)
<b> ± σ_b, fm
15
10
5
MC-Gl/Model
DCA
w/o DCA
1.2
1.1
1
0.9
0.8
0
20
40
60
80
100
Centrality, [%]

Back Up: Parameters from centrality framework

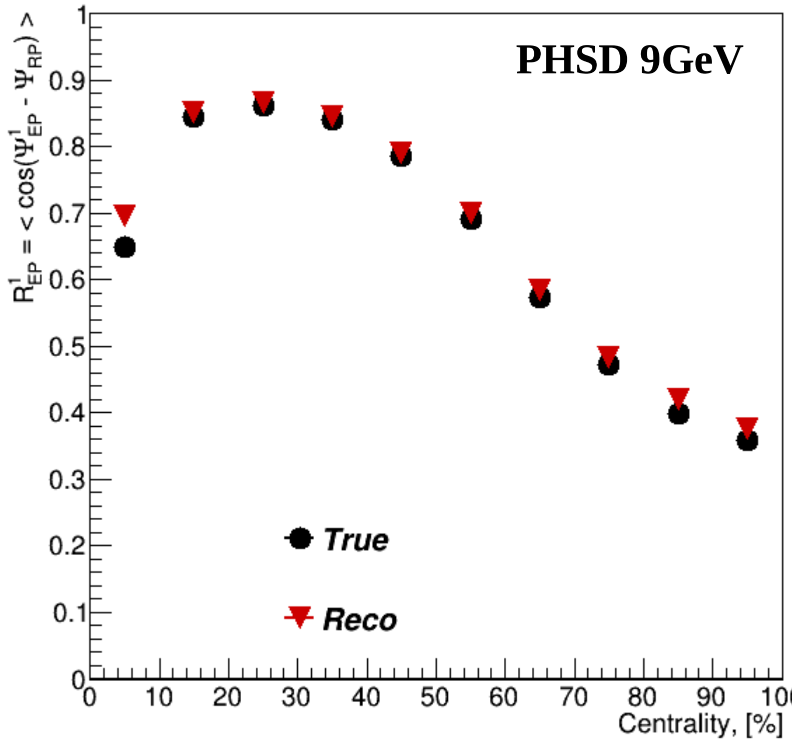
Centrality, %	N_{ch}^{min}	N_{ch}^{max}	$\langle b \rangle$, fm	RMS	b_{min}, fm	b_{max}, fm	$\langle N_{part} \rangle$	RMS	N_{part}^{min}	N_{part}^{max}	$\langle N_{coll} \rangle$	RMS	N_{coll}^{min}	N_{coll}^{max}
0 - 10	127	232	3.06	1.21	1.54	4.28	336.78	37.71	292.83	387.52	748.61	113.62	627.36	890.99
10 - 20	94	127	5.30	0.92	4.28	6.16	254.64	36.00	219.87	292.83	524.17	101.49	434.17	627.36
20 - 30	69	94	6.90	0.78	6.16	7.58	189.45	30.00	162.66	219.87	357.94	79.26	293.21	434.17
30 - 40	49	69	8.20	0.72	7.58	8.78	138.34	25.24	117.29	162.66	237.63	61.37	191.21	293.21
40 - 50	34	49	9.33	0.69	8.78	9.85	98.20	20.73	81.42	117.29	151.55	45.65	118.68	191.21
50 - 60	22	34	10.35	0.69	9.85	10.84	66.94	17.09	53.69	81.42	91.64	33.18	68.90	118.68
60 - 70	13	22	11.31	0.71	10.84	11.75	42.59	13.44	33.20	53.69	50.91	22.41	36.82	68.90
70 - 80	7	13	12.20	0.76	11.75	12.63	25.22	9.95	18.92	33.20	25.98	13.88	18.04	36.82
80 - 90	3	7	13.08	0.87	12.63	13.61	13.68	6.99	9.16	18.92	12.18	8.06	7.69	18.04
90 - 100	1	2	14.22	1.00	13.61	14.97	5.13	3.36	1.02	9.16	3.77	3.13	-0.60	7.69

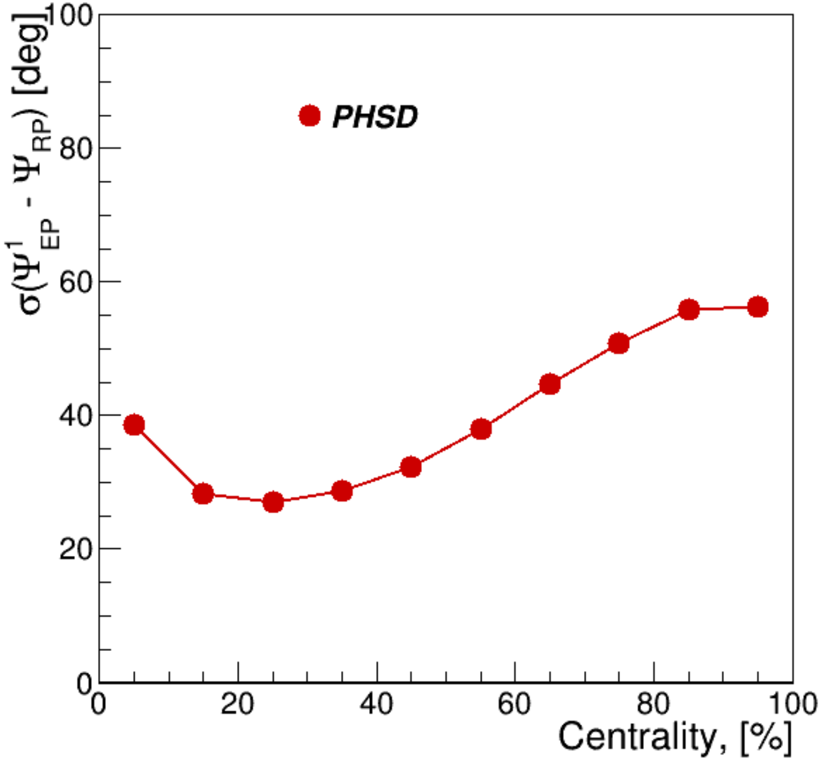
DCA cut, M [10,230]

w/o DCA, M [20,350]

Centrality, %	N_{ch}^{min}	N_{ch}^{max}	$\langle b \rangle$, fm	RMS	b_{min}, fm	b_{max}, fm	$\langle N_{part} \rangle$	RMS	N_{part}^{min}	N_{part}^{max}	$\langle N_{coll} \rangle$	RMS	N_{coll}^{min}	N_{coll}^{max}
0 - 10	193	355	2.92	1.09	1.30	4.18	341.13	33.89	297.02	392.86	767.45	95.49	641.69	916.61
10 - 20	135	193	5.19	0.72	4.18	6.03	259.03	29.90	225.32	297.02	535.50	70.25	447.39	641.69
20 - 30	93	135	6.74	0.61	6.03	7.39	195.95	25.17	169.74	225.32	372.76	54.10	308.16	447.39
30 - 40	62	93	8.00	0.57	7.39	8.54	146.01	21.34	125.37	169.74	253.46	42.14	206.93	308.16
40 - 50	40	62	9.08	0.56	8.54	9.59	106.45	17.91	89.62	125.37	166.85	32.22	133.08	206.93
50 - 60	24	40	10.06	0.57	9.59	10.55	74.98	15.09	61.30	89.62	104.73	24.64	80.42	133.08
60 - 70	13	24	11.00	0.61	10.55	11.41	49.57	12.41	39.76	61.30	60.45	18.15	45.09	80.42
70 - 80	7	13	11.85	0.66	11.41	12.26	31.20	9.73	24.04	39.76	33.01	12.43	23.55	45.09
80 - 90	3	7	12.72	0.81	12.26	13.32	17.82	7.89	12.00	24.04	16.39	8.72	10.53	23.55
90 - 100	1	2	14.06	1.03	13.32	15.03	6.15	4.27	-0.56	12.00	4.61	3.86	-2.99	10.53

Back Up: Event plane determination





- Event plane and its resolution determined using FHCal
- Checked via 2 methods