Global polarization of lambda hyperon in the MPD experiment at NICA energies

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OUTLINE

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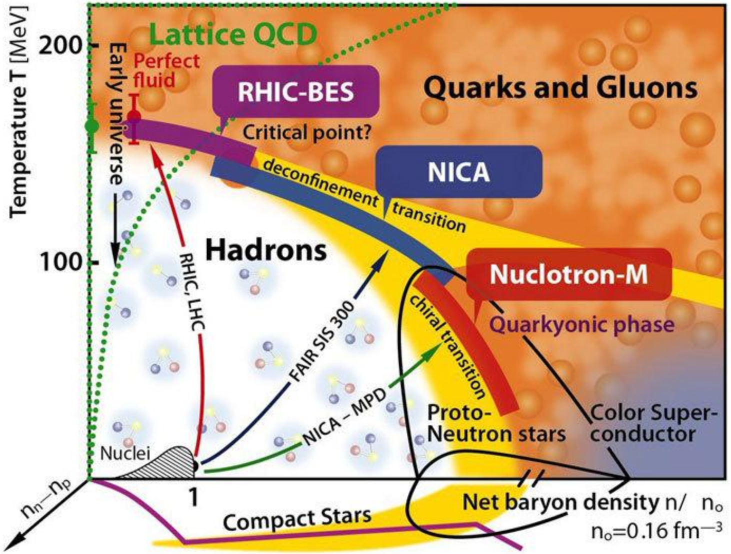
  - QCD phase diagram
  - Heavy ion collisions
  - Global polarization
- MPD in Fix-Target Mode (FXT)
  - Dataset
  - Enhanced Λ production via the afterburner
- Measurement of the P_Λ using QnTools framework
- Results
- Summary and outlook

QCD phase diagram

[1] Phys.Part.Nucl. 56 (2025) 3, 921-927

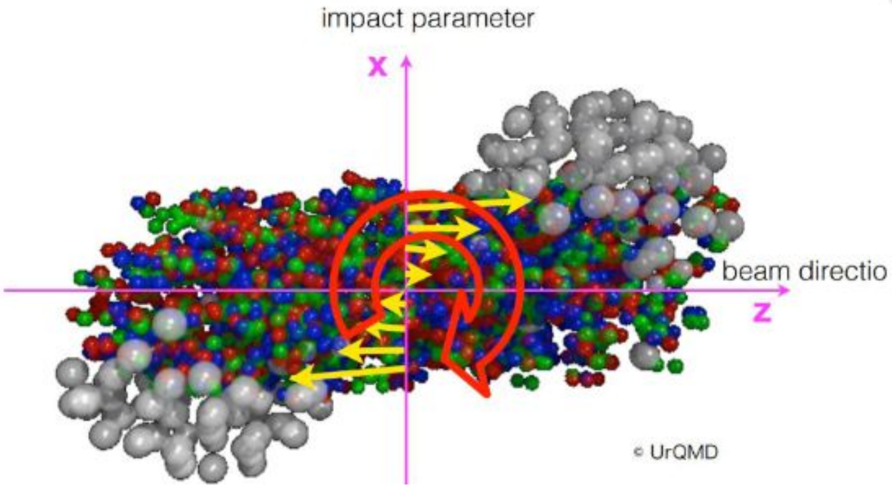
- MPD in **Fixed-Target (FXT) mode**, extending energy coverage to $\sqrt{s_{NN}} \approx 2.3–3.5$ GeV [1]
- Provides access to the region of **high net-baryon density** in the QCD phase diagram
- Enables studies of bulk matter properties, anisotropic flow, strangeness production, and **spin effects**



Complements MPD collider program, ensuring **energy coverage overlap** with HADES, SPS, RHIC-BES, and FAIR

Heavy ion collisions

- **Non-central** heavy-ion collisions create orbital angular momentum [1,2].
- Part of this angular momentum is transferred to the medium, creating **vorticity** [1]
- Global polarization of Λ and anti-Λ hyperons arises from the coupling of spin to this vorticity [3].
- Measurements provide insight into the spin dynamics and **transport properties of QCD matter**.



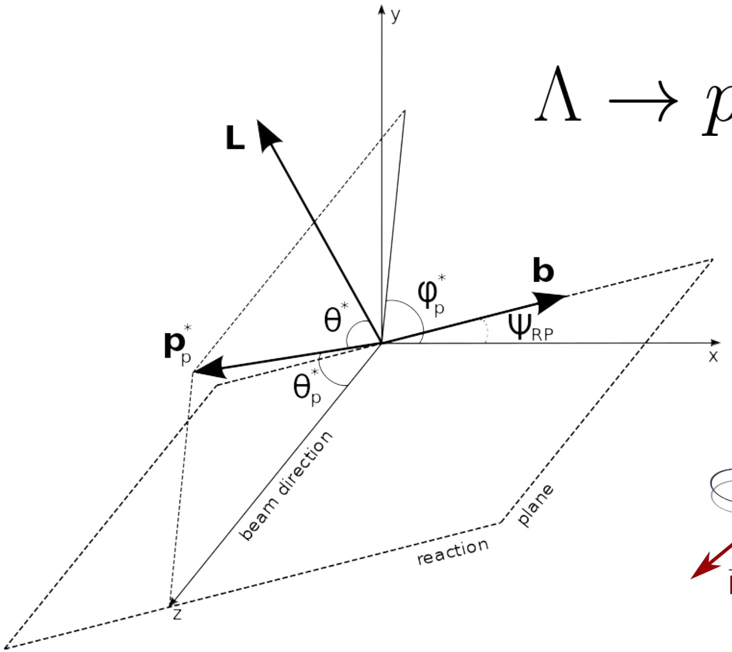
[1] Z. Liang, X. Wang, PRL 94, 102301 (2005)
[2] L. Adamczyk et al., Nature 548, 62 (2017)
[3] The STAR Collaboration., Nature 548, 62–65 (2017)

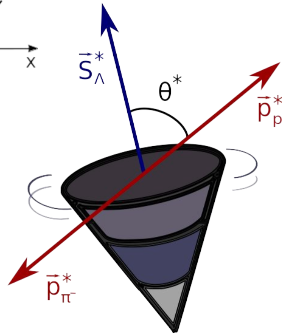
Global polarization

- Weakly decaying hyperons (Λ, anti-Λ) violate parity [1].
- The angular distribution of the daughter baryon is correlated with the hyperon spin [1,2].
- The correlation strength is determined with the **decay parameter**[4]:

$$\alpha_\Lambda \approx -\alpha_{\bar{\Lambda}} \approx 0.732$$

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



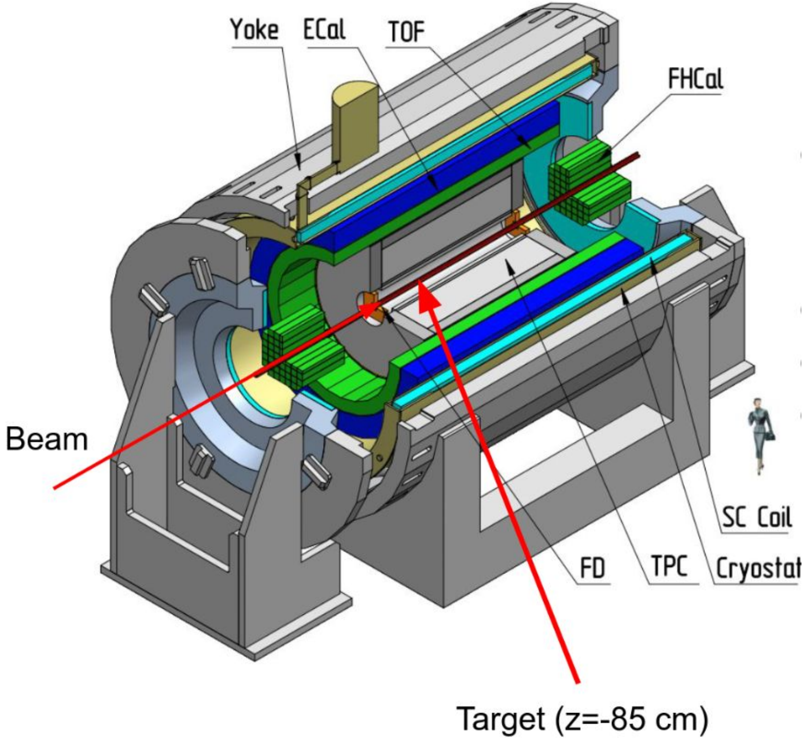


$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_\mathrm{H}|\vec{P}_\mathrm{H}|\cos\theta^*\right)$$ [2]

$\vec{P}_H$ global polarization

[1] Z. Liang, X. Wang, PRL 94, 102301 (2005)
[2] B. I. Abelev, et al., Phys. Rev. C 76, 024915 (2007)
[3] O. Teryaev and R. Usubov, Phys. Rev. C 92, 014906 (2015)
[4] Ablikim M, et al., Nature Phys. 15:631 (2019)

MPD in Fixed-Target Mode (FXT)

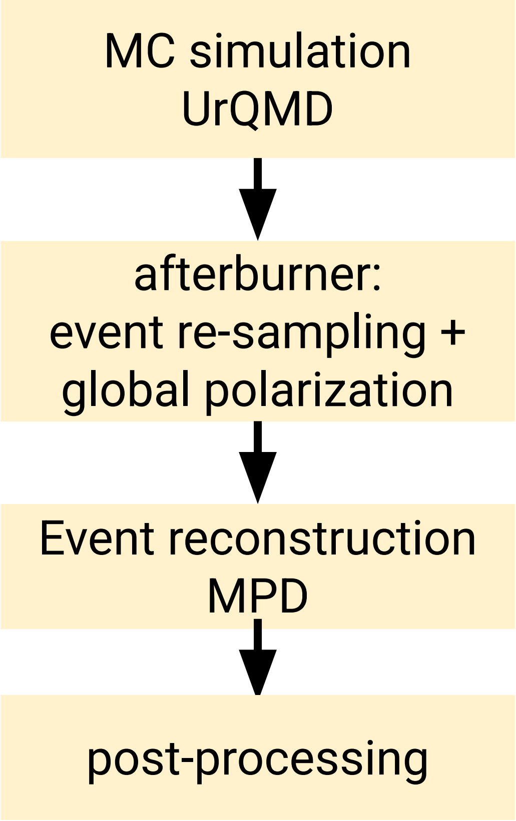


- Model used: UrQMD 3.4:
  - Xe+Xe, $E_{kin} = 2.5\ AGeV\ (\sqrt{s_{NN}} = 2.87\ GeV)$
- point-like target at z = -85 cm, y = 1 cm
- GEANT4 transport
- Enhanced Λ production (via UniGen afterburner)
  - 5 additional Λ hyperons per event
  - Realistic v_1, v_2, P_Λ parameterizations

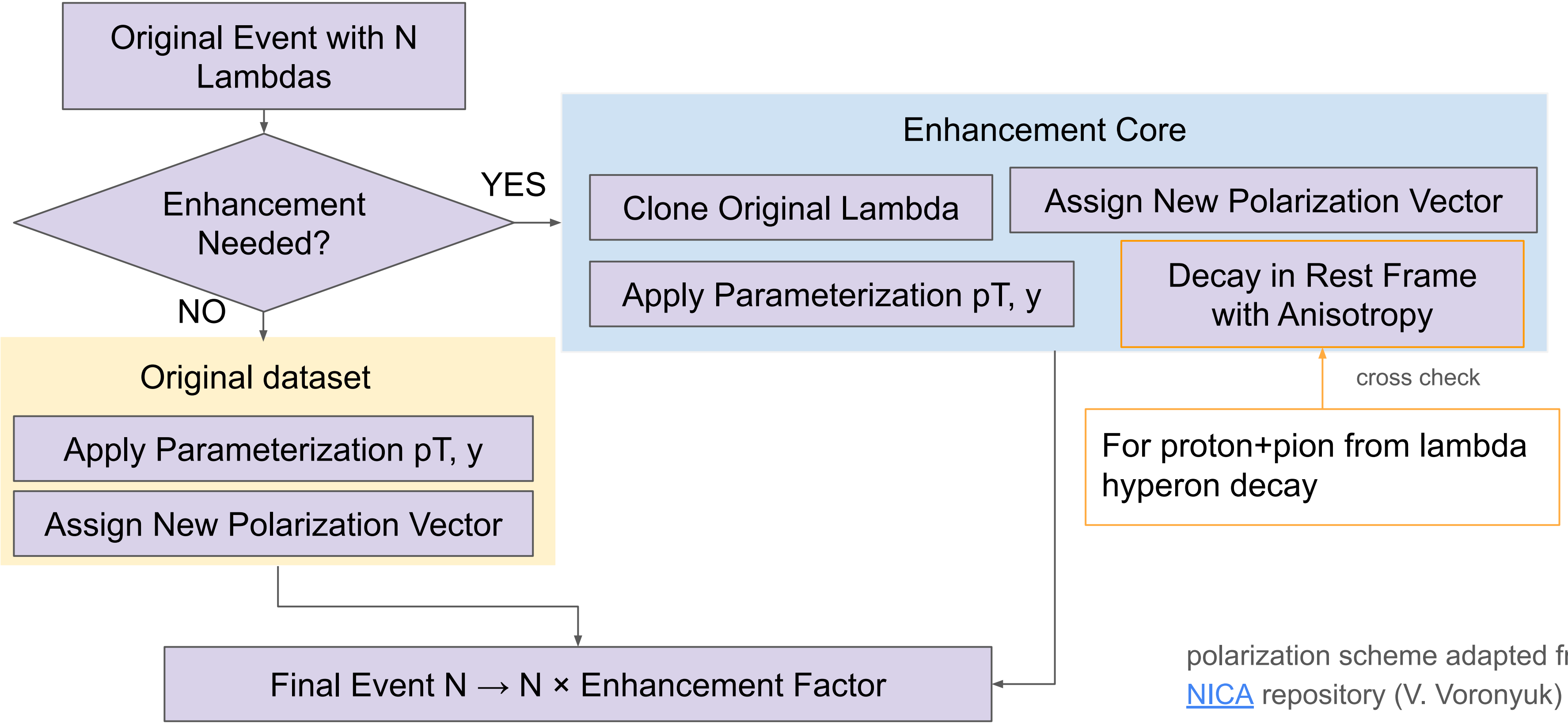
Enhanced production is necessary to obtain statistically significant results w/o modeling a huge amount of data.

Dataset

1. UrQMD Xe+Xe @ 2.87 GeV, 10M events, UniGen format
2. Global hyperon polarization generated from the afterburner $\mathbf{P} = \{P_x, P_y, P_z\}$
3. Enhanced statistics with 5 additional Λ hyperons per event



How event re-sampling works in the afterburner



polarization scheme adapted from [NICA](#) repository (V. Voronyuk)

Selection criteria

- **Event selection:**
  - Centrality based on the impact parameter
- **Track selection:**
  - $N_{hits} > 10$
  - proton/π^- selection based on charge
  - **lambda candidates selection:**
    - dca < 1 cm
    - L > 2.5 cm
    - L/dL > 20
    - $\chi^2_{geo} < 100$
    - $\chi^2_{topo} < 100$
    - $\chi^2(p) > 60$
    - $\chi^2(\pi-) > 200$

Flow vectors

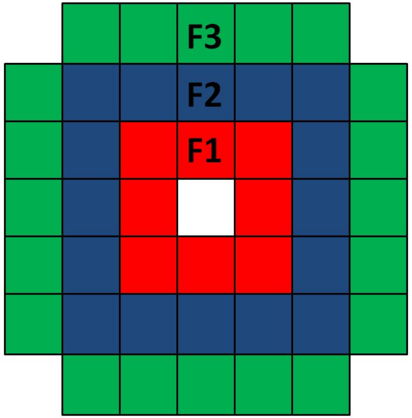
From momentum of each measured particle define a u_n-vector in transverse plane: $u_n = e^{in\phi}$

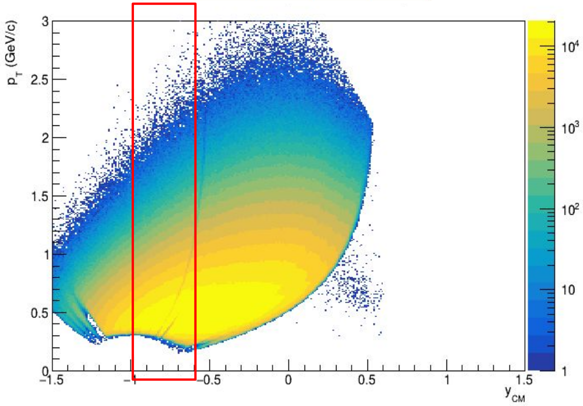
where φ is the azimuthal angle
Sum over a group of u_n-vectors in one event forms Q_n-vector:

$$Q_n = \frac{\sum_{k=1}^{N} w_n^k u_n^k}{\sum_{k=1}^{N} w_n^k} = |Q_n| e^{in\Psi_n^{EP}}$$

ψ_n^{EP} is the event plane angle

FHCal module rings as subevents





Additional subevent from tracks not pointing at FHCal:
Tp: p; -1.0<y<-0.6;

Flow methods for P_Λ calculation

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

Tested in HADES: M Mamaev et al 2020 PPNuclei 53, 277–281
M Mamaev et al 2020 J. Phys.: Conf. Ser. 1690 012122

P in scalar product (SP) method:

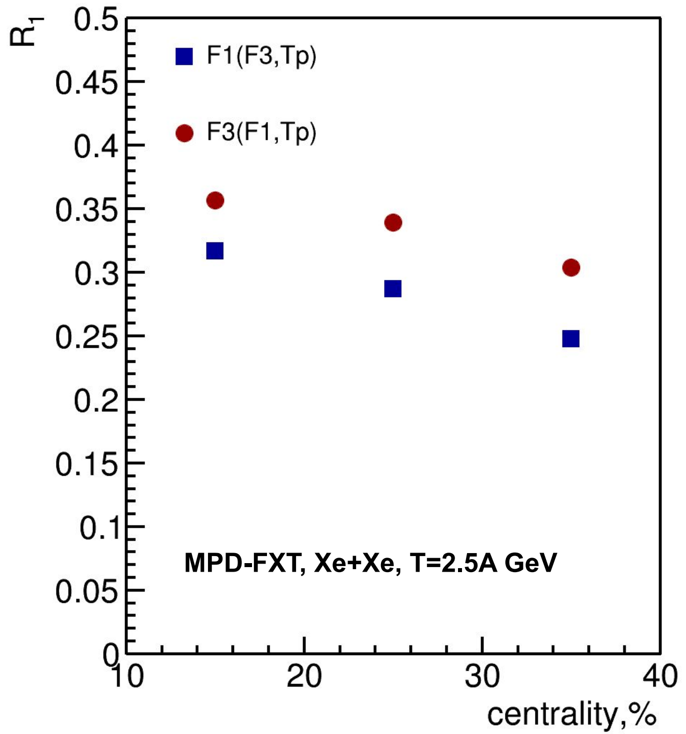
$$P = \frac{8}{\pi\alpha}\frac{\langle u_1 Q_1^{F1}\rangle}{R_1^{F1}}$$ **using xy/yx components!**

Where R_1 is the resolution correction factor

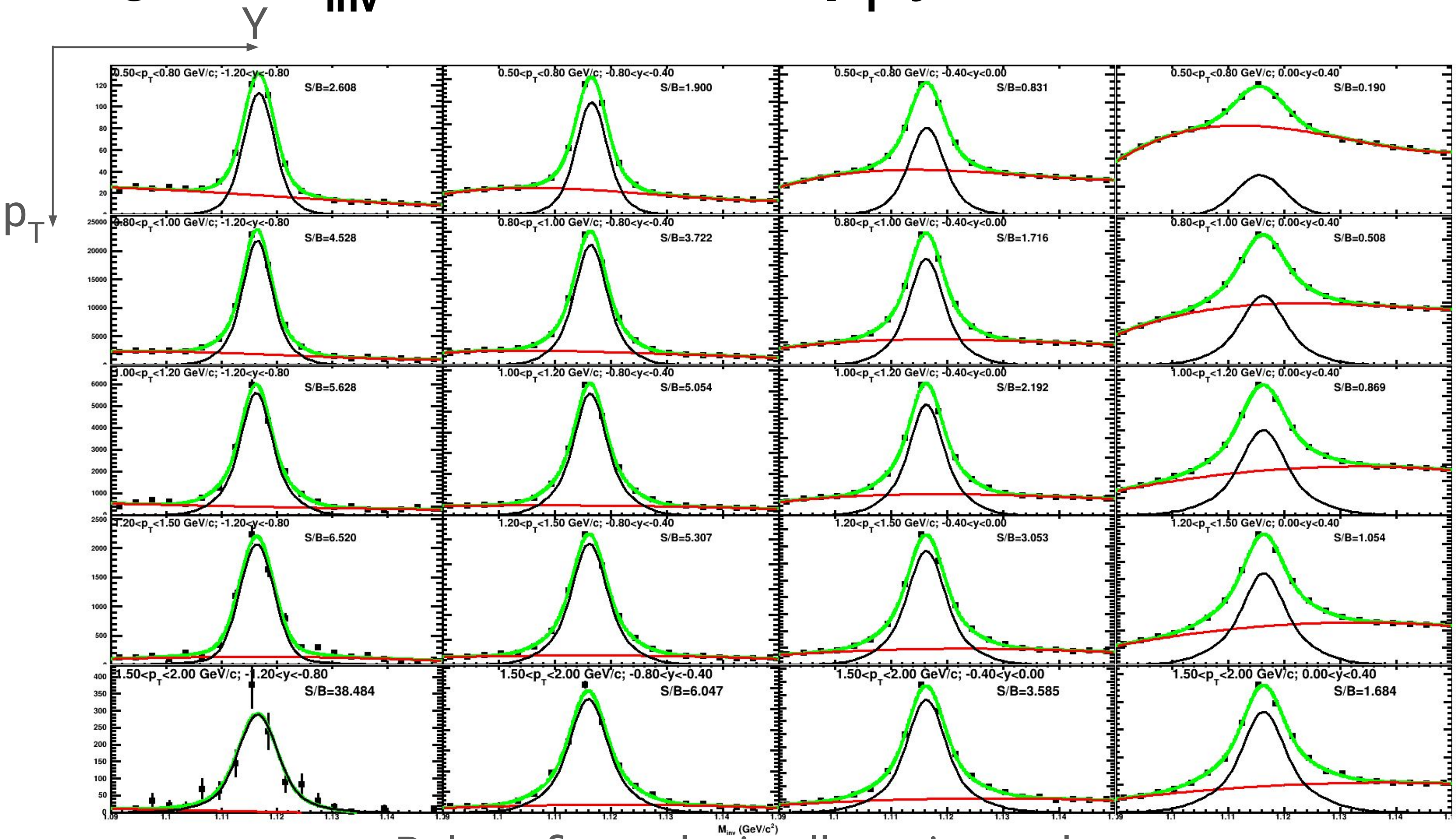
$$R_1^{F1} = \langle \cos(\Psi_1^{F1} - \Psi_1^{RP})\rangle$$

Symbol "F1(F3,Tp)" means R_1 calculated via (3S resolution):

$$R_1^{F1(F3,Tp)} = \frac{\sqrt{\langle Q_1^{F1}Q_1^{F3}\rangle\langle Q_1^{F1}Q_1^{Tp}\rangle}}{\sqrt{\langle Q_1^{F3}Q_1^{Tp}\rangle}}$$

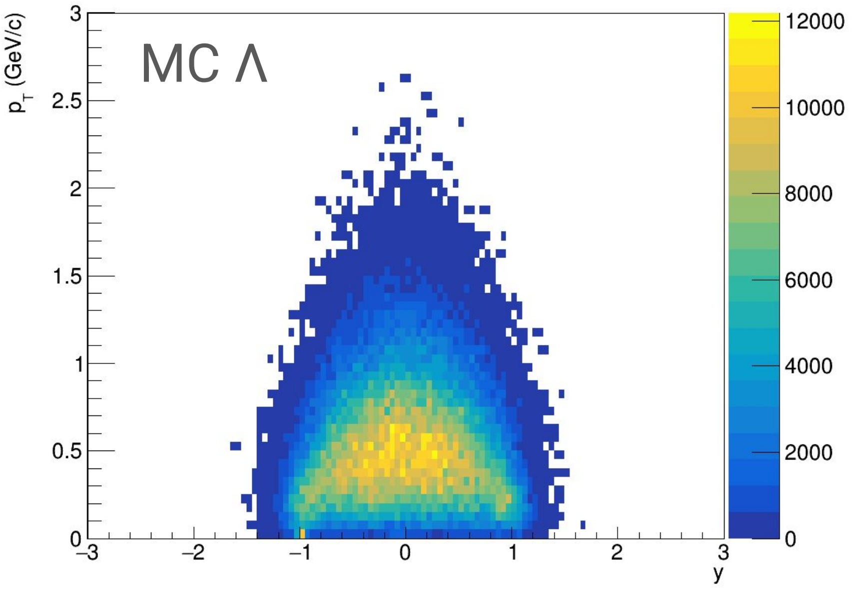


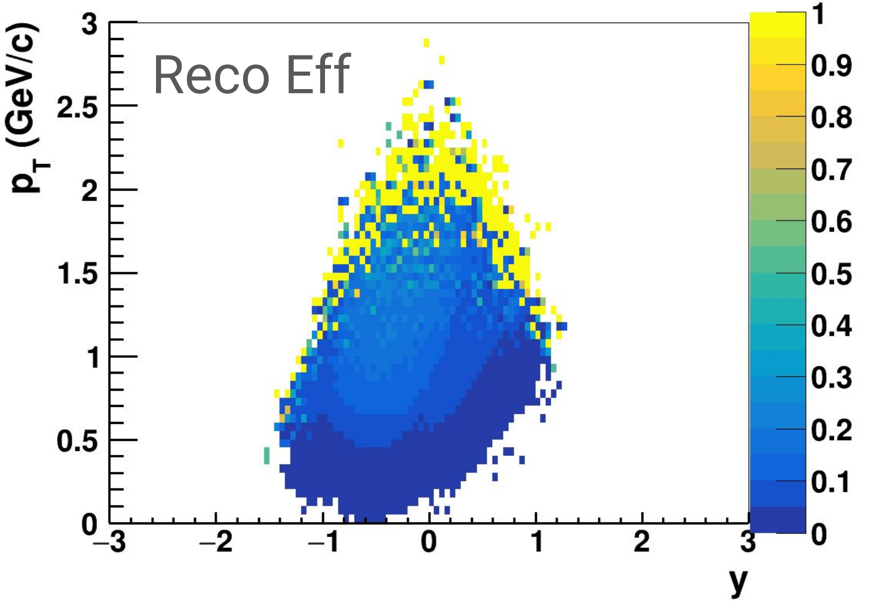
Fitting the m_{inv} distributions in p_T-y bins



Robust fit results in all p_T-y intervals

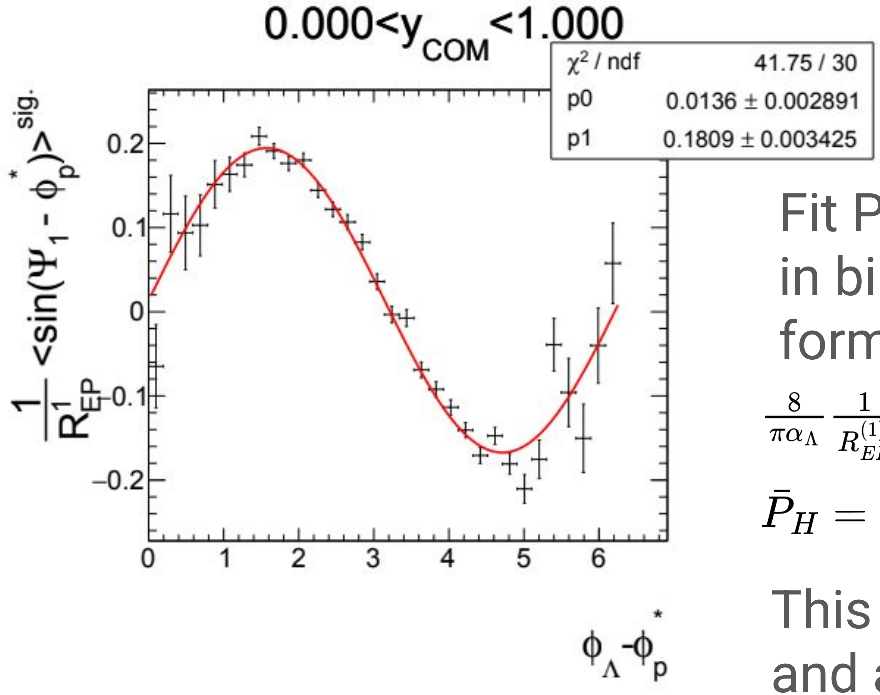
Λ hyperon reconstruction efficiency





MPD-FXT acceptance covers midrapidity for Λ reconstruction in CM

Generalized inv. mass fit method



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

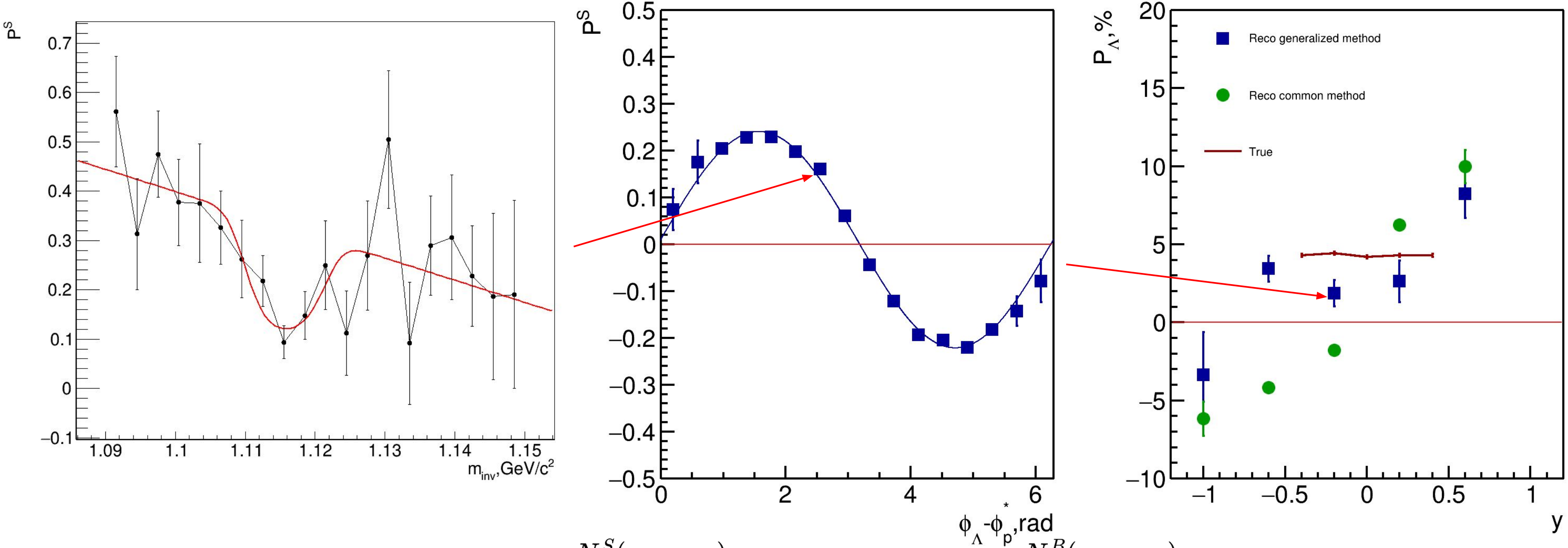
Fit $P^S = \langle \sin(\Psi_{RP} - \varphi_p^*) \rangle^S$ in bins of $\varphi_\Lambda - \varphi_p^*$ for $\eta>0$, $\eta<0$ using formula:

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

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

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

P of Λ hyperons of Xe+Xe at E_{kin}=2.5 AGeV for MPD-FXT



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

- Strong effect of FXT mode, generalized method is essential
- At this moment there are some discrepancies between “reco” and “true” results - investigation is in progress…

SUMMARY AND OUTLOOK

- Global polarization of Λ hyperons measured in MPD-FXT Xe+Xe collisions at 2.5 AGeV
  - Enhanced lambda production via the UniGen afterburner
  - Applied generalized invariant mass fit method to correct for v_1 and acceptance effects
- Observed discrepancy between reconstructed and MC results

Outlook:

- Investigate reconstruction efficiency and other systematic effects. Possible effects from lambda enhancement
- Future milestone: Analyze Xe+W collisions, get predictions for the first results from the MPD-FXT

Cut's dictionary

$\chi^2_{prim}(1;2)$	dca	L	L/dL	χ^2_{geo}	χ^2_{topo}	$\cos_{topo}$
χ^2 of daughter particle to primary vertex ----------------- Cut off primary tracks	Distance between daughter tracks in their closest approach ----------------- Cut off candidates are built from tracks located far away from each other	Length of interpolated track from secondary to primary vertex ----------------- Cut off short-length candidates	Distance between primary and secondary vertices divided by error ----------------- Cut off short-length candidates	χ^2 of daughter tracks in their closest approach ----------------- Cut off candidates are built from tracks located far away from each other	$\chi^2$of the mother track to the primary vertex ----------------- Cut off very distant secondary vertex	Cosine of the angle between reconstructed mother's momentum and radius vector beginning in the primary vertex ----------------- Quality of candidate

$\chi^2(p)>60$
$\chi^2(\pi^-)>200$

dca<1 cm

L>2.5 cm

L/dL>20

$\chi^2_{geo}<100$

$\chi^2_{topo}<100$

$\cos_{topo}>0.995$

KFParticle provides plenty of cuts for candidates selection

UNIGEN FORMAT

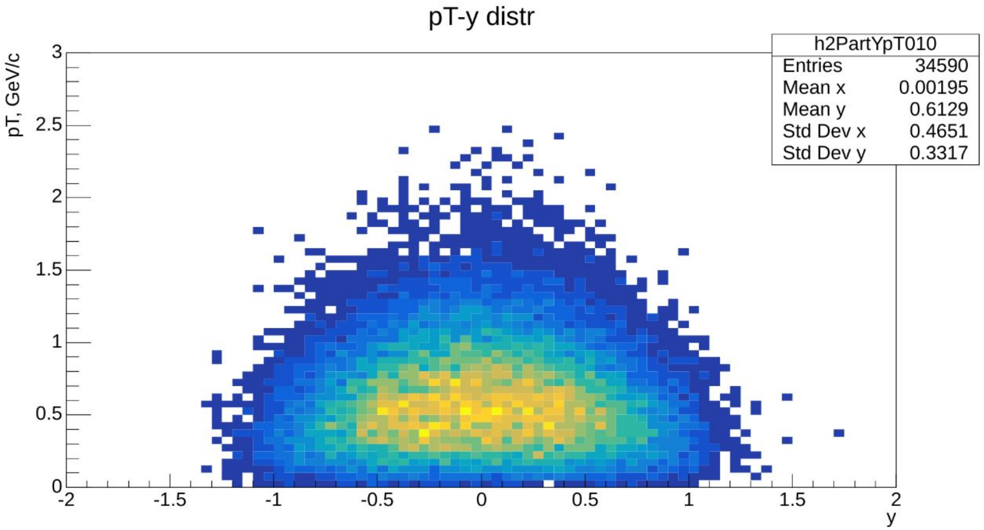
Code available in MPDROOT repository (dev branch)

TFile
├── **URun** run/header metadata
└── **TTree** "events" sequence of UEvent objects
└── **UEvent** one collision snapshot (can be time-stepped)
└── **TClonesArray<UParticle>** particles in that snapshot

- **URun**: generator name, beam/target parameters (A, Z, momentum), impact parameter range, cross section, requested number of events.
- **UEvent**: : event number, impact parameter value, reaction plane angle, optional. Holds the **list of particles**.
- **UParticle**: Stores information about **a single particle**. PDG code, momentum (px, py, pz, E), space-time coordinates (x, y, z, t)...

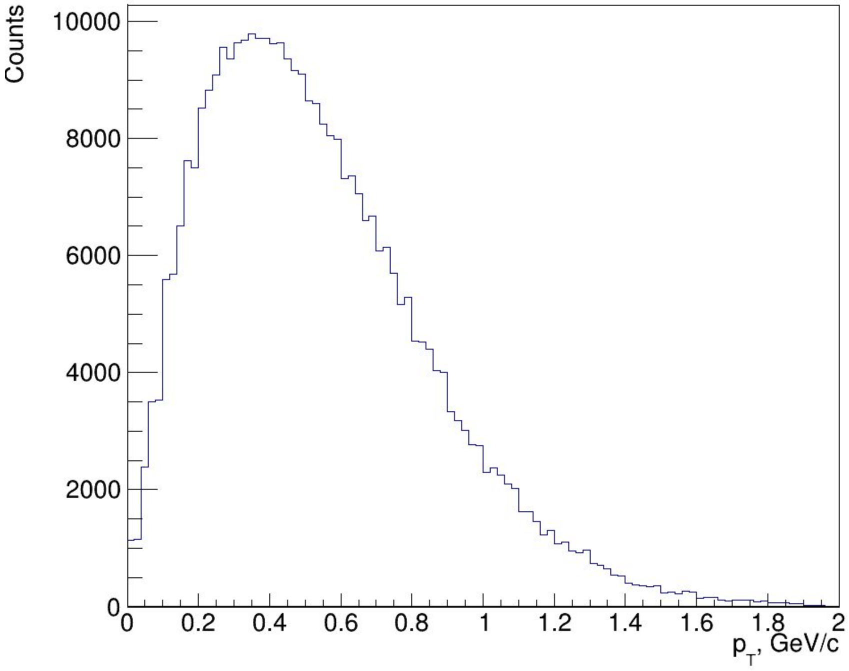
Lambda parameterization

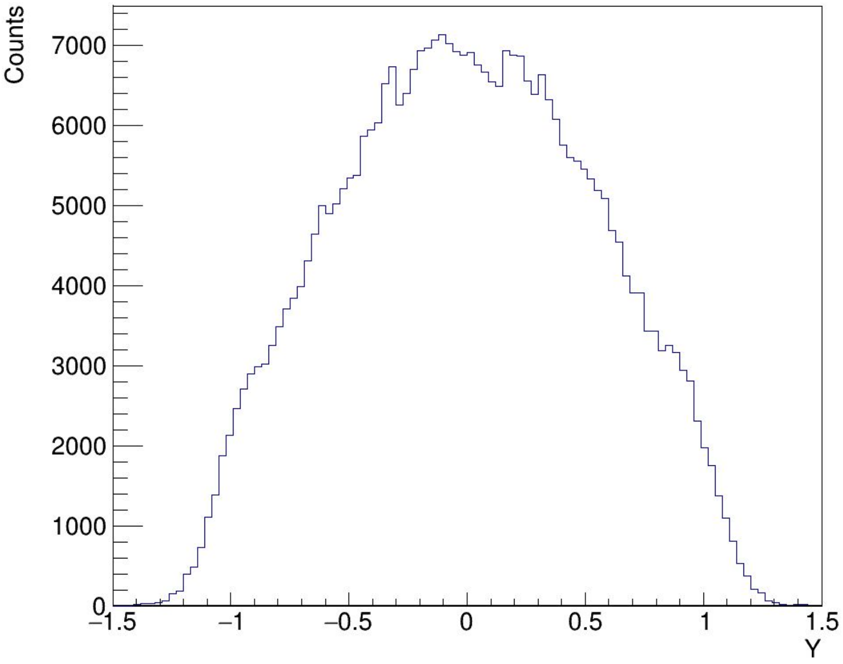
- Directed flow (v1) parametrized as a function of √sNN, centrality, pT, and y
- Elliptic flow (v2) obtained from function get_V2(sNN, centrality, pT, y)
- Flow coefficients constrained: -1 ≤ v1 ≤ 1
- Azimuthal angle φ generated according to probability density:
- f(φ) ~ 1 + 2*v1*cos(φ) + 2*v2*cos(2φ)
- Implementation available in repository: read_unigen_root.cpp



pT and rapidity (y) sampled from 2D histogram:
h_pt_y->GetRandom2(lambda_y, lambda_pT, rand)

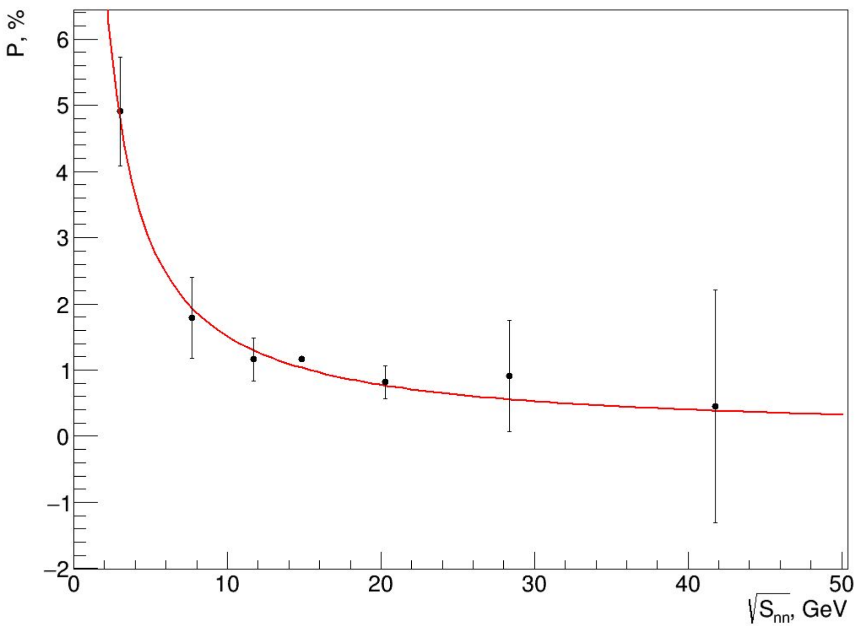
Lambda from model

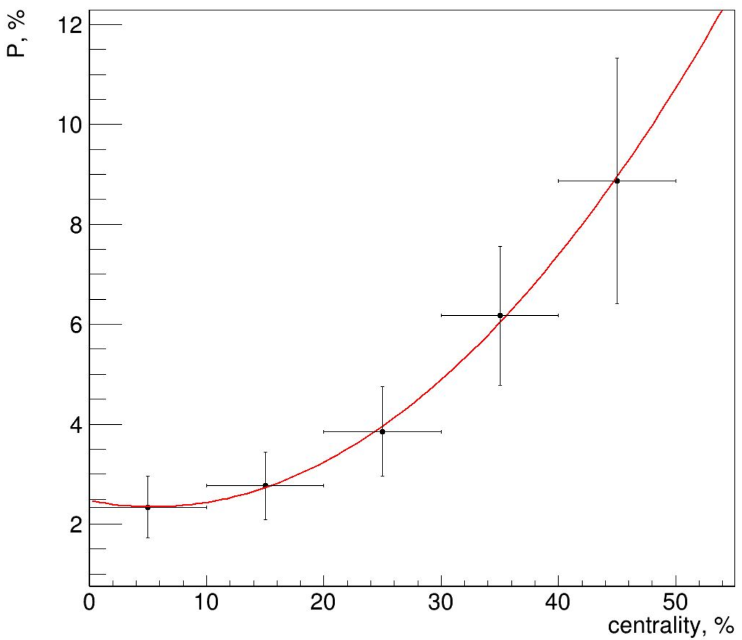




Mean number of lambda in each event <Nlamb>= 328 000 / 1M event

Global polarization parameterization





P(E,cent)=(2.8569/$E^{0.955513}$)*(2.4702-0.0461*cent+0.0042*$cent^2$)

Uniform distribution in p_T-y

Global Polarization

Phys.Rev.C 104 (2021) L061901, 2021.
Global Polarization for 3 GeV

P(E), centrality 20-50%
P(cent), centrality 0-50%, pT>0.7, -0.2<y<1
P(pT), centrality 0-50%, -0.2<y<1
P(y), centrality 0-50%, pT>0.7

Directed flow

Phys.Lett.B 827 (2022) 137003, 2022.
Directed flow for 3 GeV

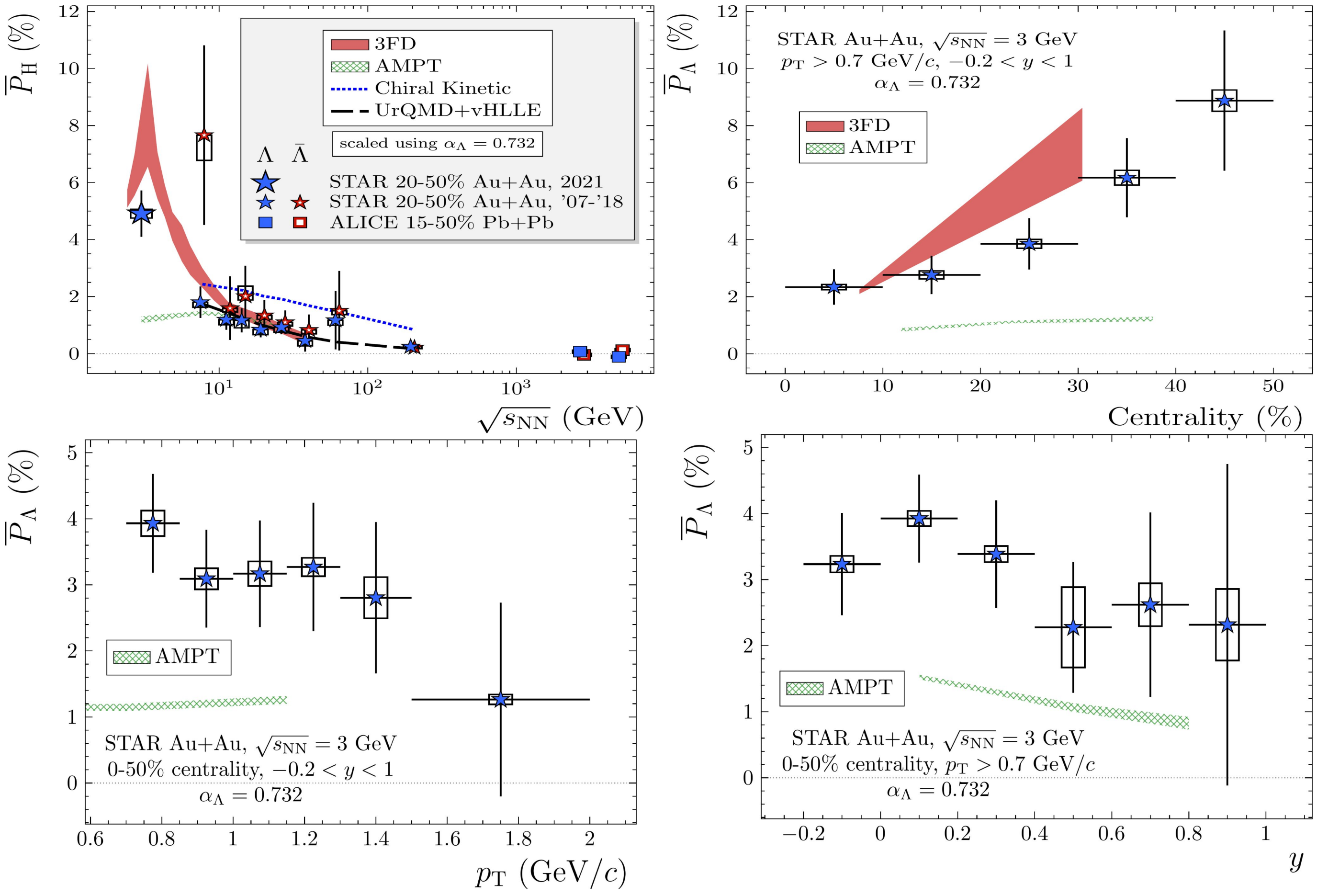
v1(y), centrality 10-40%, 0.4<pT<2
v2(y), centrality 10-40%, 0.4<pT<2

Phys.Rev.Lett. 130 (2023) 212301, 2023.
Directed flow for 3 GeV

v1(y), centrality 5-40%, 0.4<pT<0.8

JHEP 10 (2024) 139, 2024.
Production for 3 GeV

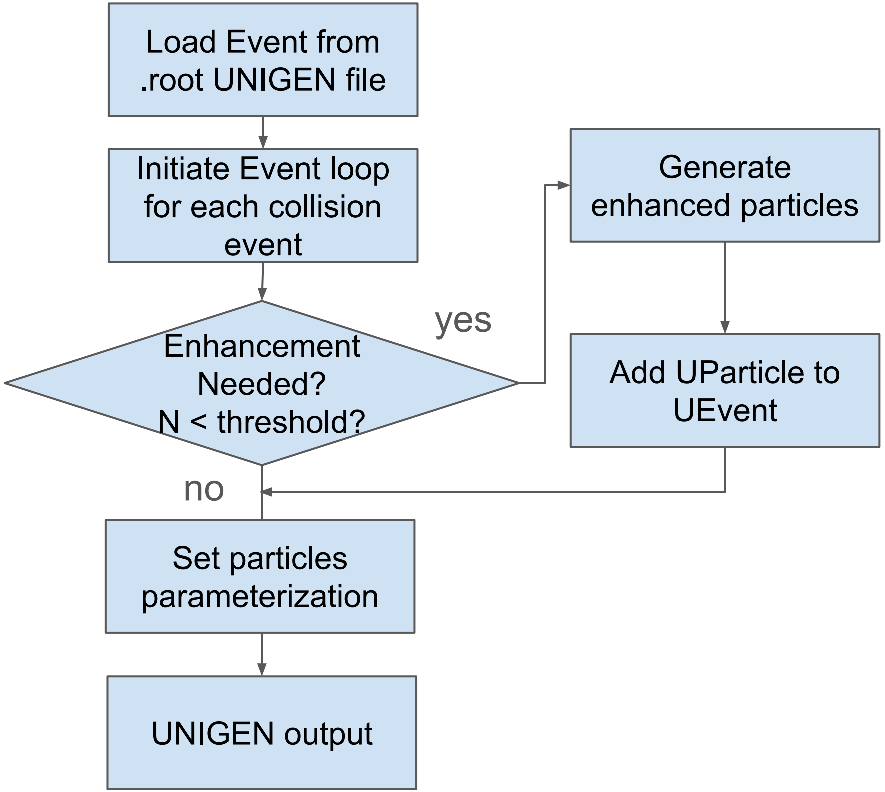
dN/dy, for diff centrality bins
<pT>(Npart), at midrapidity
dN(pT,y,cent)



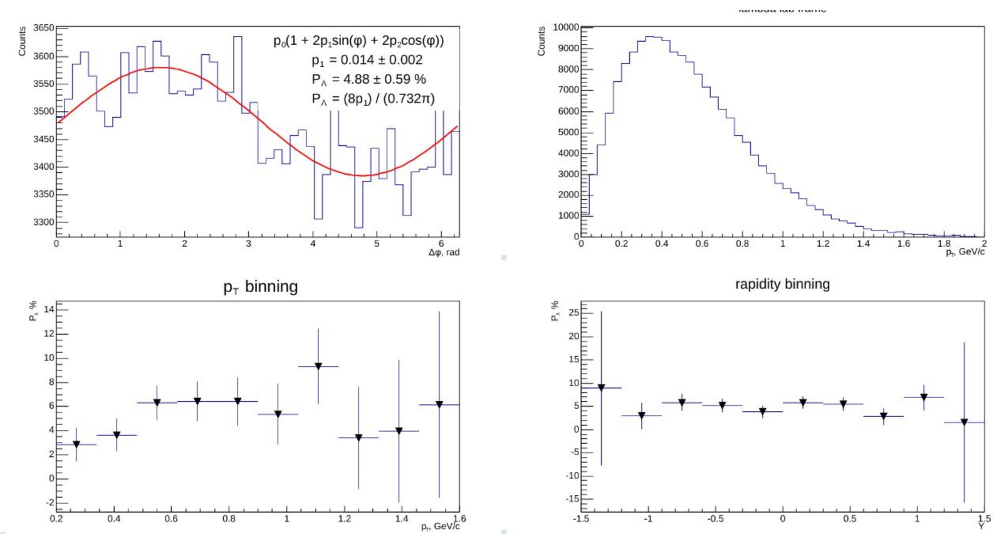
3FD
AMPT
Chiral Kinetic
UrQMD+vHLLE
scaled using $\alpha_\Lambda = 0.732$
Λ $\bar{\Lambda}$
STAR 20-50% Au+Au, 2021
STAR 20-50% Au+Au, '07-'18
ALICE 15-50% Pb+Pb
$\overline{P}_H$ (%)
$\sqrt{s_{NN}}$ (GeV)
STAR Au+Au, $\sqrt{s_{NN}} = 3$ GeV
$p_T > 0.7$ GeV/c, $-0.2 < y < 1$
$\alpha_\Lambda = 0.732$
3FD
AMPT
$\overline{P}_\Lambda$ (%)
Centrality (%)
AMPT
STAR Au+Au, $\sqrt{s_{NN}} = 3$ GeV
0-50% centrality, $-0.2 < y < 1$
$\alpha_\Lambda = 0.732$
$\overline{P}_\Lambda$ (%)
p_T (GeV/c)
AMPT
STAR Au+Au, $\sqrt{s_{NN}} = 3$ GeV
0-50% centrality, $p_T > 0.7$ GeV/c
$\alpha_\Lambda = 0.732$
$\overline{P}_\Lambda$ (%)
y

AFTERBURNER GENERAL WORKFLOW

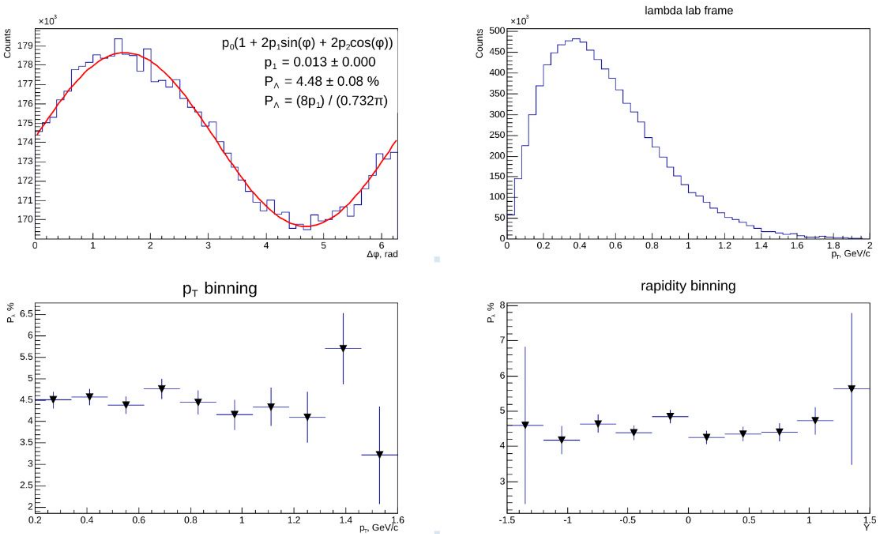
- Each particle is used as a template to generate new ones
- New statistically independent particles preserve original correlations
- Output format identical to the input (Unigen)
- Enhanced UParticles with fMate = -9 (enhanced) and fMate = -15 (added)



Comparison



enhancement = 0



enhancement = 50
(+ added lambda in each event)

EVENT RE-SAMPLING FOR Λ POLARIZATION

- Scheme adapted from NICA repository (V. Voronyuk)
- Polarization measured via proton azimuthal angle in Λ rest frame
- Re-sampling improves statistical precision of polarization measurements