Perspectives for the study of hyperon and hypernuclei production in heavy-ion collisions at NICA/MPD

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VBLHEP, JINR

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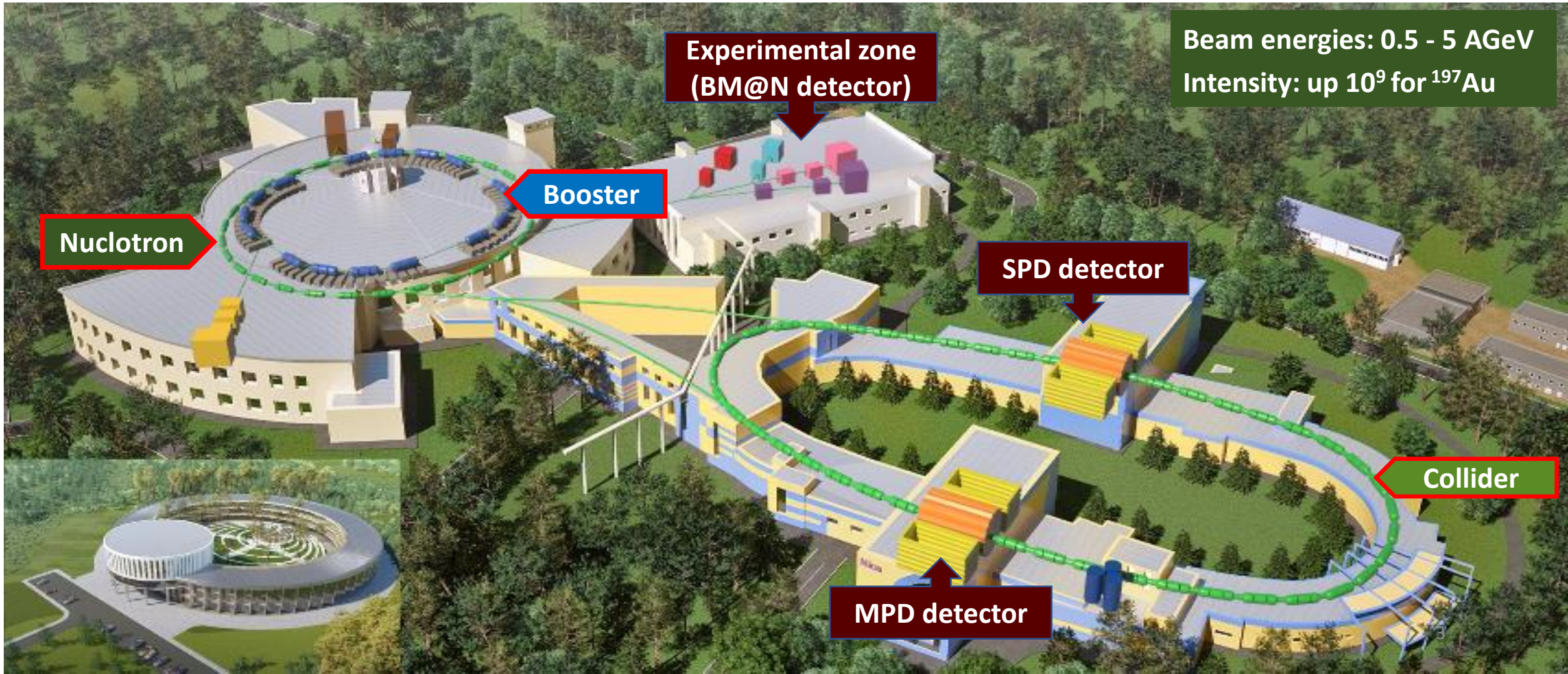
OUTLINE

- Introduction:
  - NICA/MPD physics cases : strangeness and hypernuclei
- MPD detector performance studies:
  - Λ-hyperon reconstruction
  - Results for cascades
  - Hypertriton reconstruction
- Summary

NICA – Nuclotron-based Ion Collider fAcility

- Chain of accelerators providing ion beams (from *p* to Au) for fundamental physics studies & applied research
- Modern detectors for study dense nuclear matter and spin phenomena (MPD, SPD, BM@N)
- Experimental zone with beam lines for physics study and applied research
- Cryogenic infrastructure for production, testing and supply superconducting elements



NICA/MPD physics. Tasks and Observables

***Experimental strategy**: energy and system size scan to measure a large variety of signals systematically changing collision parameters (energy, centrality, system size). Reference data (ip+p) will be taken in the same experimental conditions.*

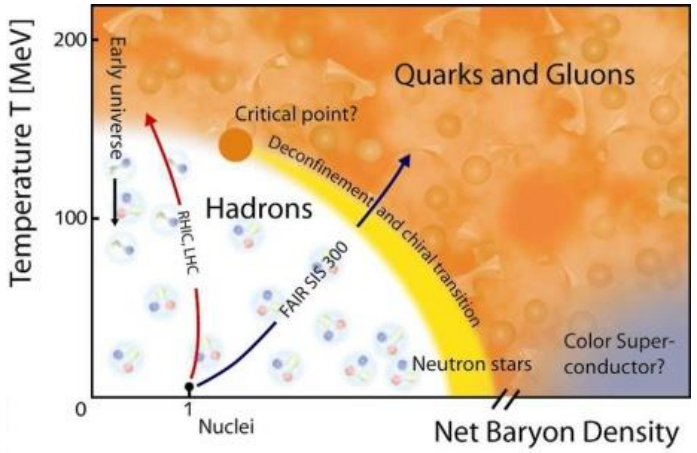
Bulk properties, EOS
particle yields & spectra, ratios, femtoscopy, flow
measure: *γ, π, K, p, Λ, Ω, (anti)particles, light nuclei*

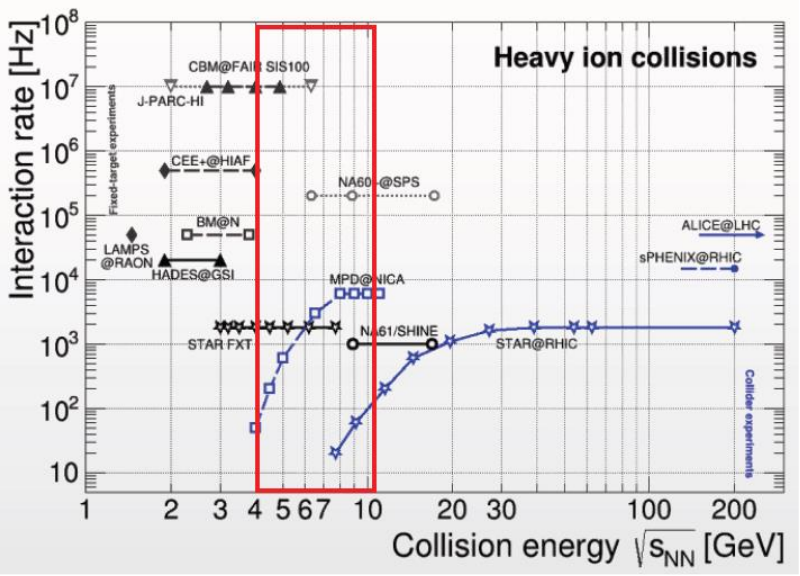
In-Medium modification of hadron properties
onset of low-mass dilepton enhancement
measure: *ρ, ω, ϕ → e+e-*

Deconfinement (chiral) phase transition at high ρ_B
enhanced strangeness production
Chiral Magnetic (Vortical) effect

QCD Critical Point
event-by-event fluctuations and correlations

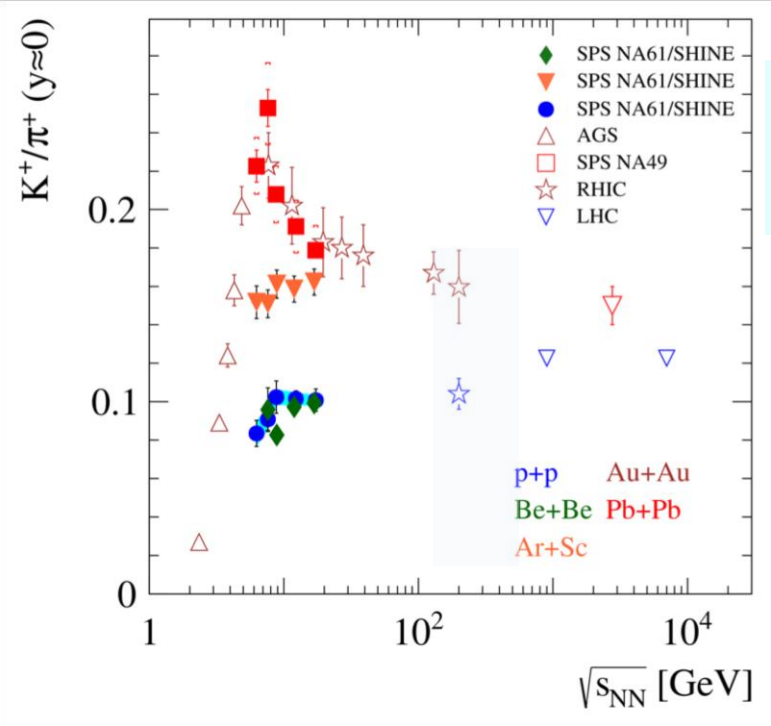
EOS @ NS densities, in-medium Λ-N and Λ-N interactions
hypernuclei



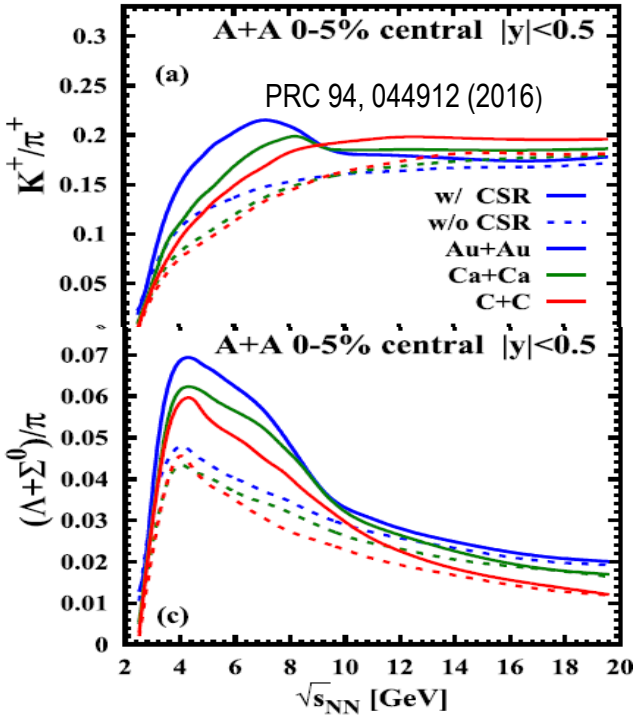


NICA physics cases: strange hadrons

- Excitation function of hadrons, including strangeness (yields, spectra, and ratios)
- Nuclear matter EOS, in-medium effects, and chemical equilibration can be probed
- Hyperons sensitive to early stage and phase transformations in QCD medium
- Non-monotonic strangeness-to-entropy ratio seen in heaviest systems (phase transformation?)

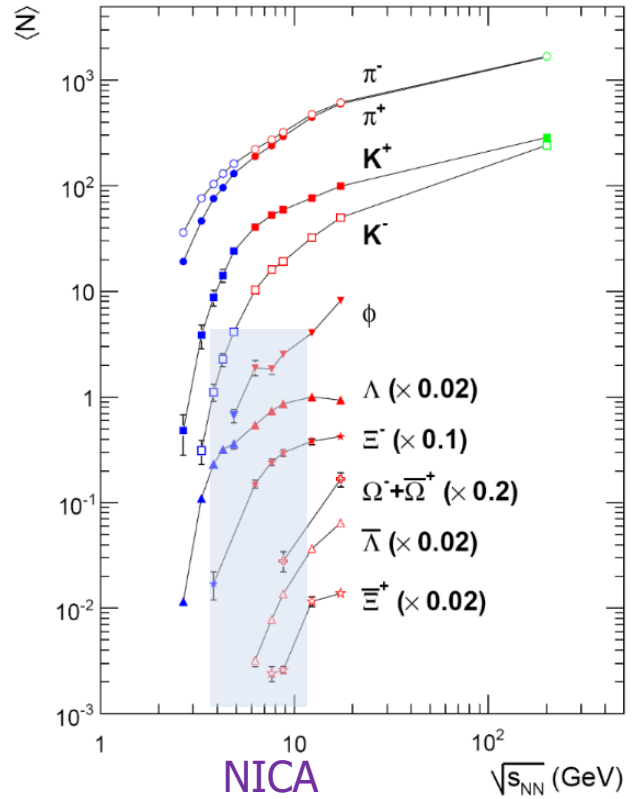


- System size of the energy dependence is not fully understood



- Theory predicts the largest effect for the hadron ratios due to CSR in dense matter at NICA

- Lack of data on multistrangeness in different collision systems @ NICA energies!

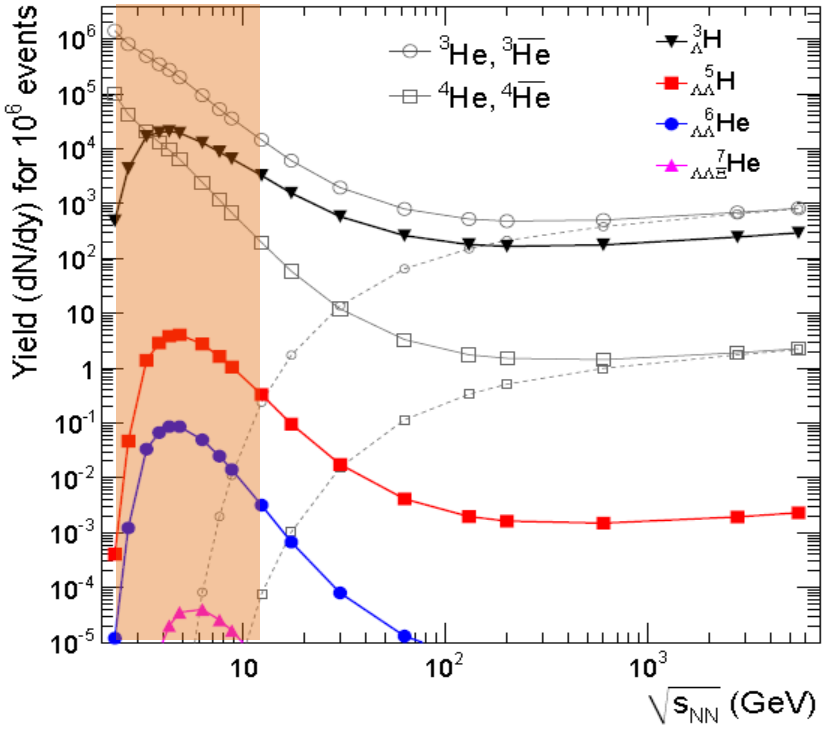


NICA physics cases: hypernuclei

- Nuclear matter EOS is of importance for QCD, nuclear physics and astrophysics
- Only NN potential are very well determined from scattering experiments
- But YN or YY potentials are rather uncertain since such experiments difficult to perform
- High multiplicity heavy-ion collisions provide several methods to do the job: two-particle correlations and hypernuclei

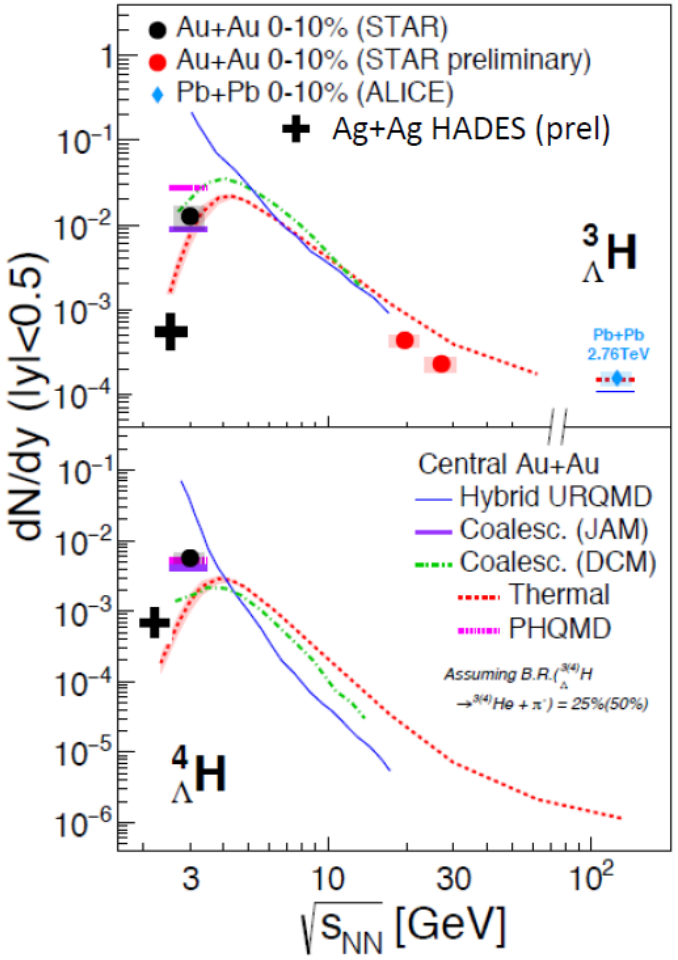
Hypernuclei are nuclei containing at least one hyperon

A. Andronic et al, PLB 697 (2011) 203



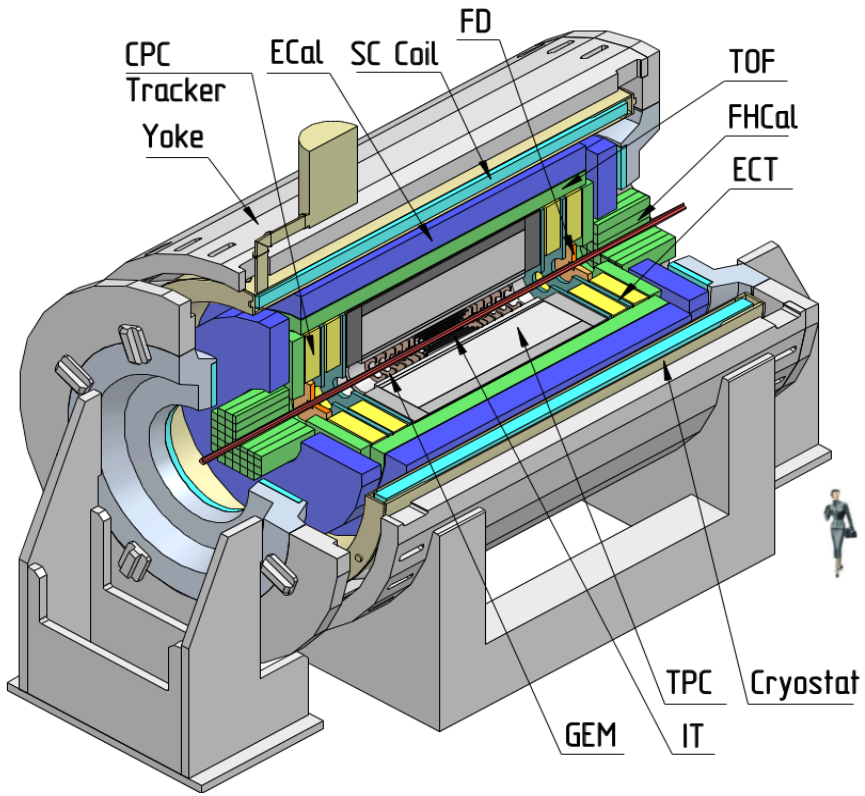
- Few data on the production of hypernuclei in HIC
- Available data leave space for various model predictions (thermal, coalesce, hybrid)
- Further and deeper investigations of the hypernuclear formation mechanisms require additional measurements at different energies and collision systems (**NICA**)

QM'2022

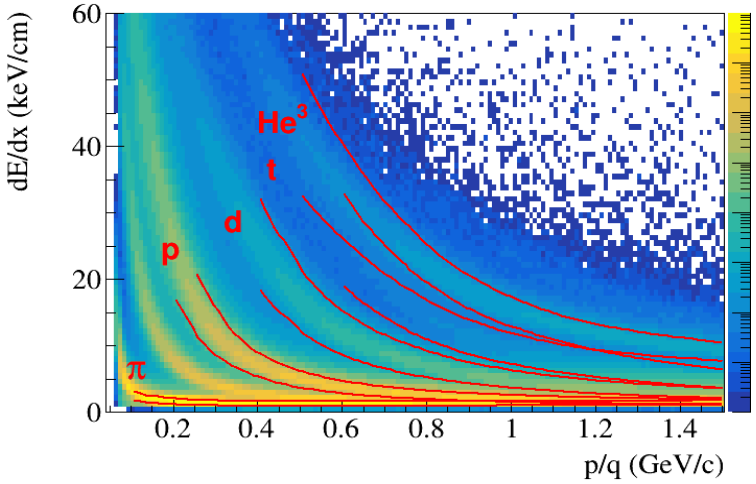


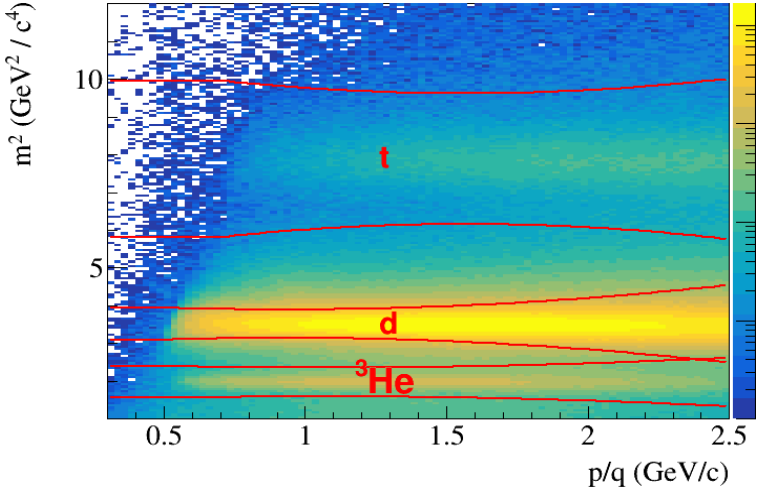
Thermal model predicts an enhanced production of (hyper)nuclei within the NICA energy range

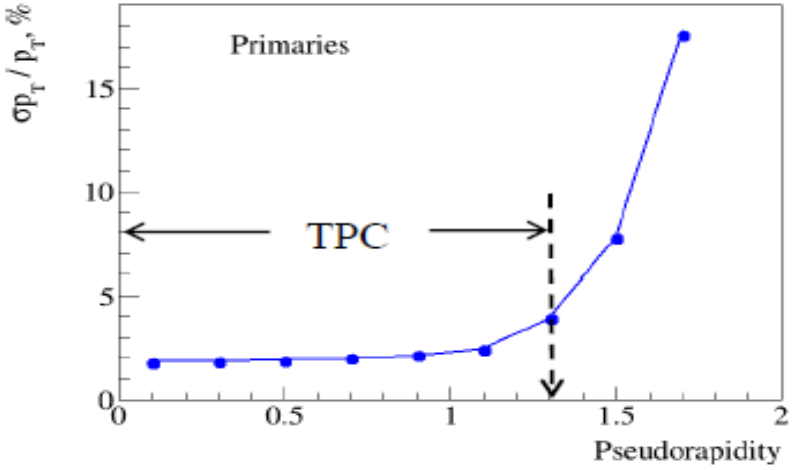
MultiPurpose Detector for A+A collisions @ NICA

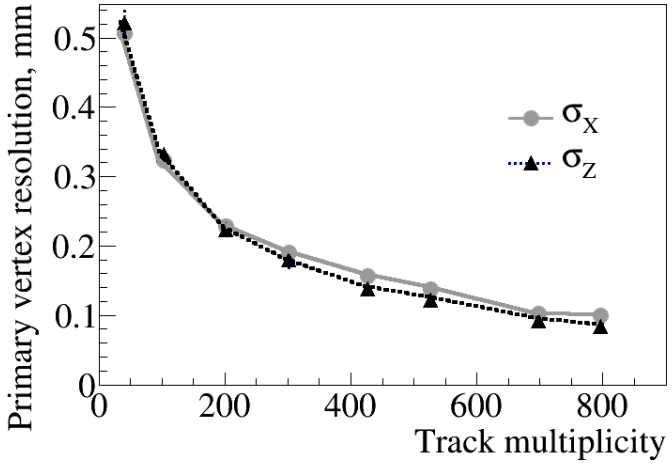


- 3D tracking (TPC), uniform acceptance
- Powerful PID (TPC, TOF, ECAL)
- Precise event characterization (FHCAL)
- Fast timing and triggering (FD)

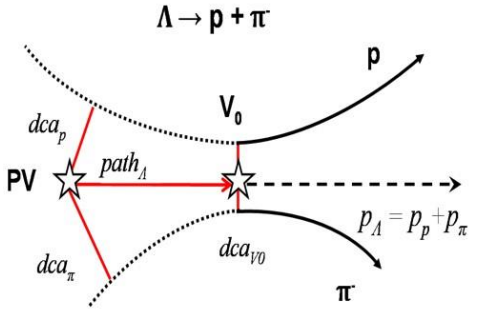






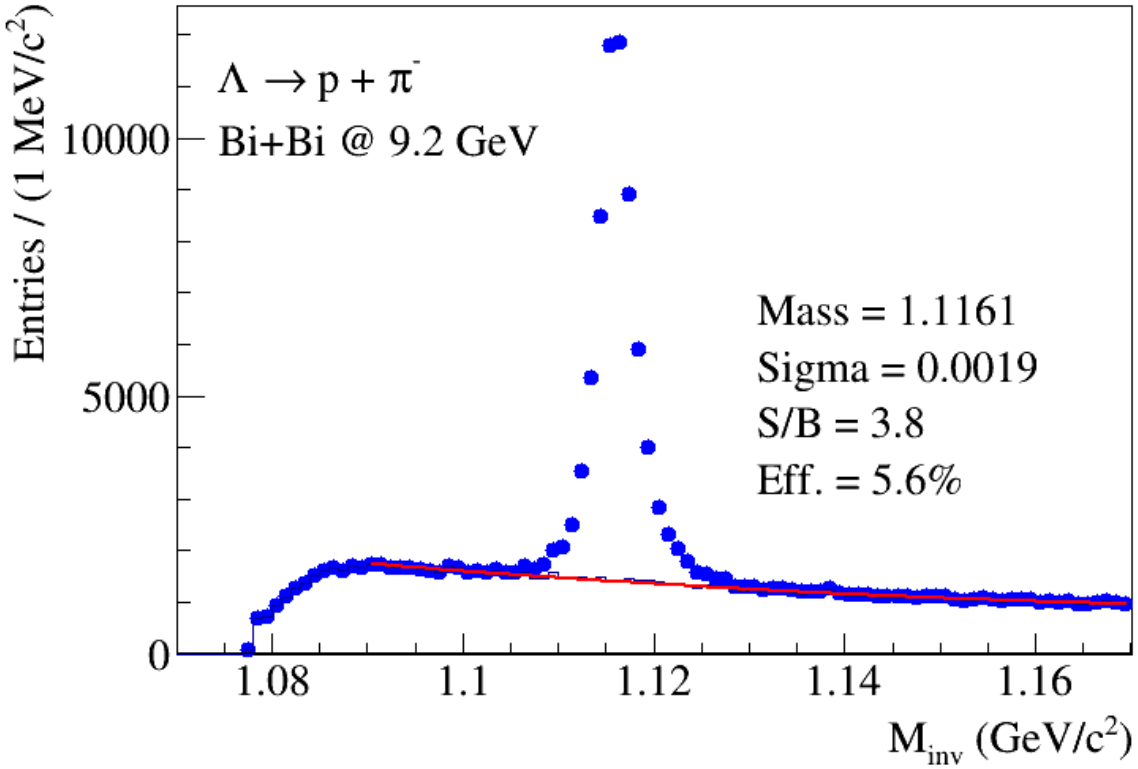


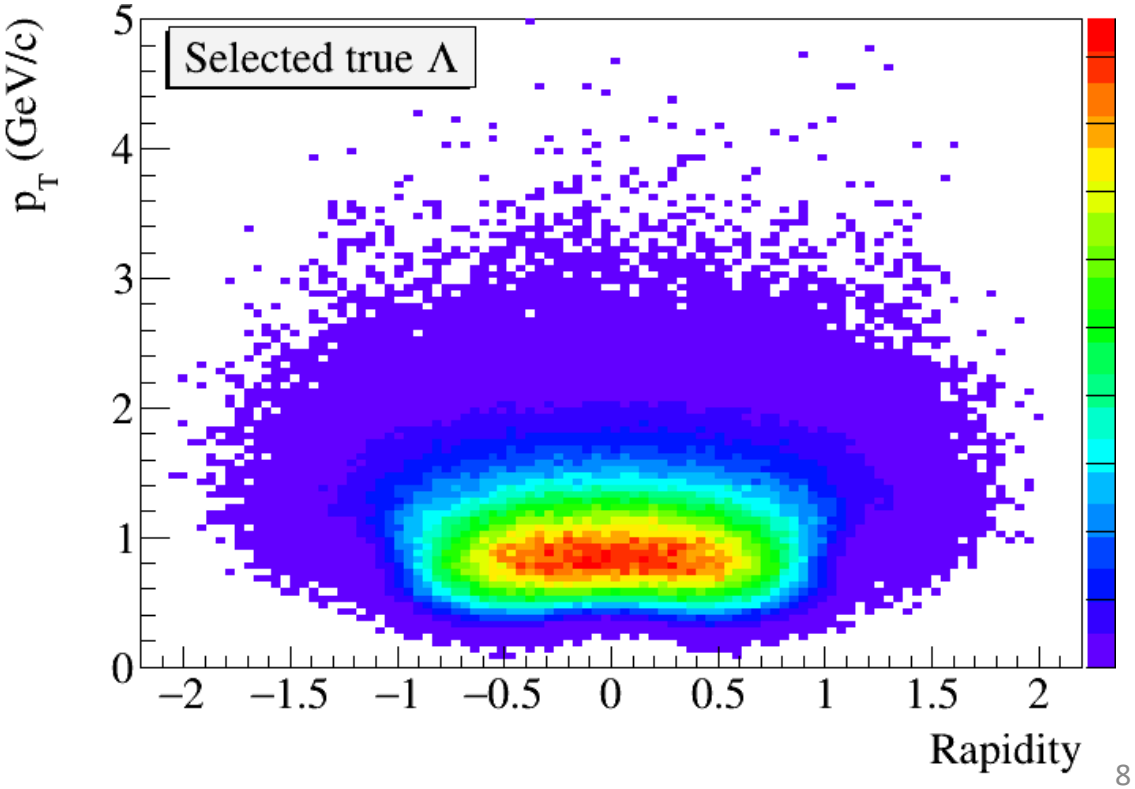
Λ-hyperon reconstruction in MPD



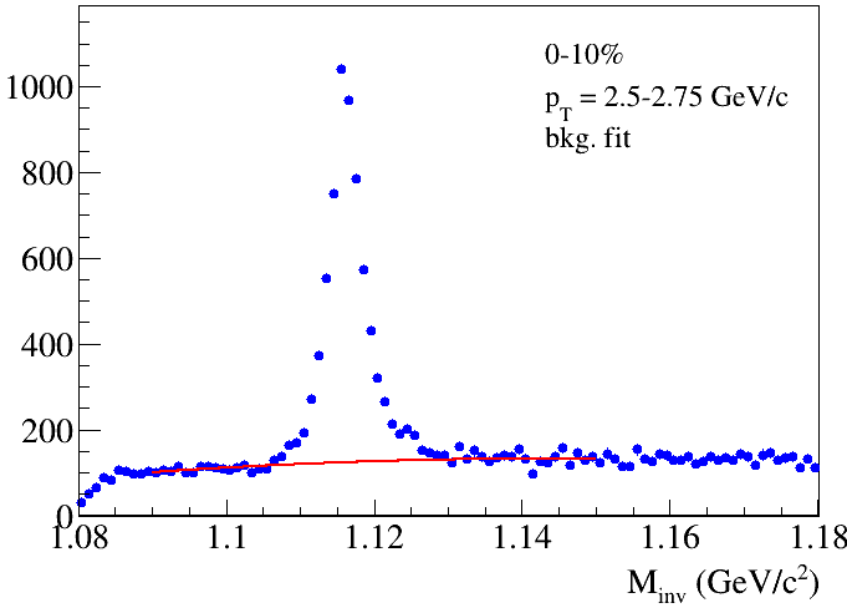
- ✓ **Data set:** Bi+Bi @ 9.2 GeV, 50M Min bias (UrQMD)
- ✓ **PID:** dE/dx+TOF
- ✓ **Selection:** $|y| < 0.5$, $Z_{PV} = \pm 130$ cm
- ✓ **Centrality bins:** TPC multiplicity 0-10%,10-20%,20-40%,40-60%, 60-80%
- ✓ **Hyperon reco**: Secondary vertex finding technique with a set of topological cuts

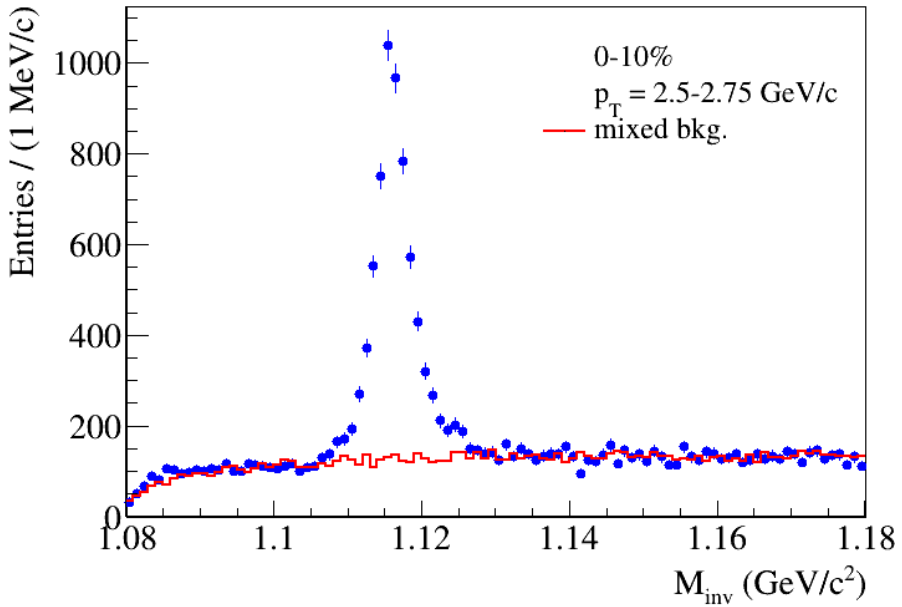
PV *- primary vertex*
V0 ***-*** *vertex of decay*
dca- *distance of closest approach*
path *– decay length*

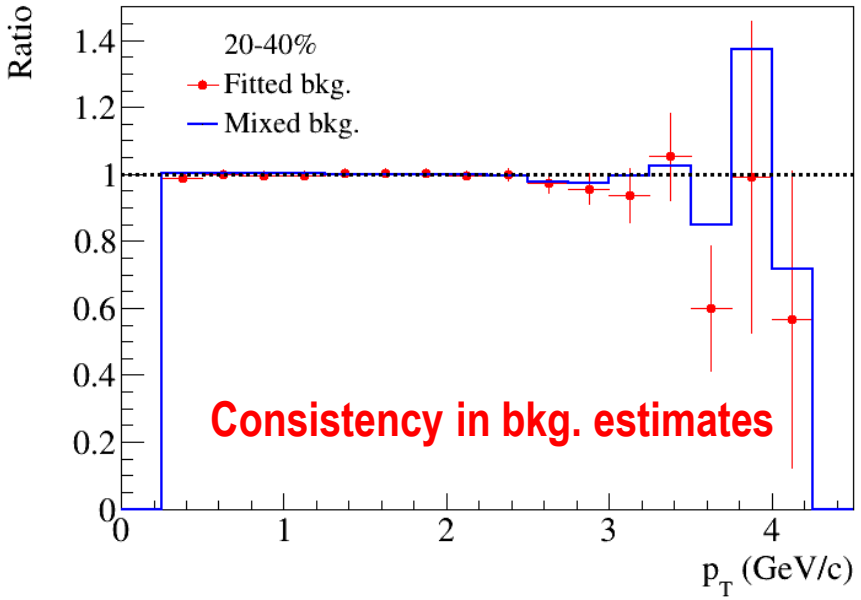




Λ-hyperon reconstruction in MPD: background estimate





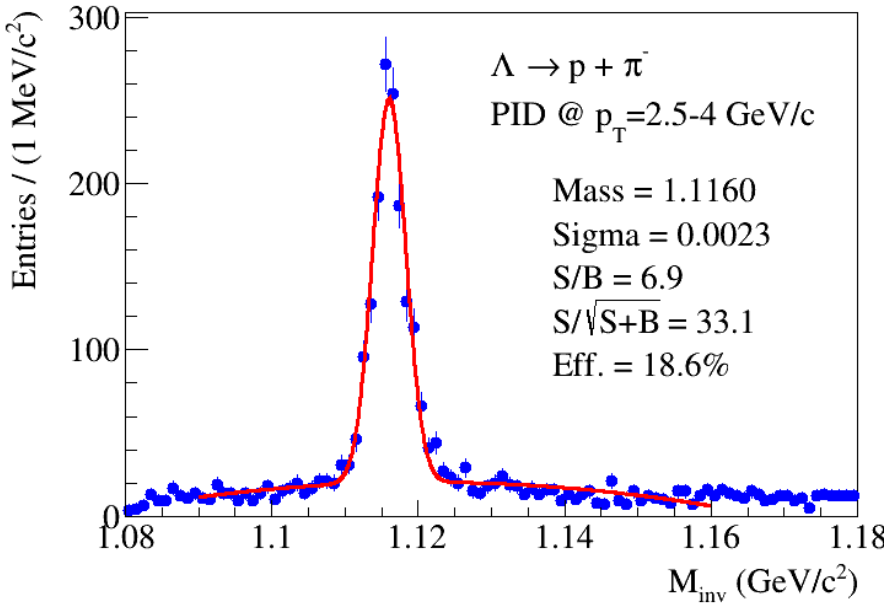


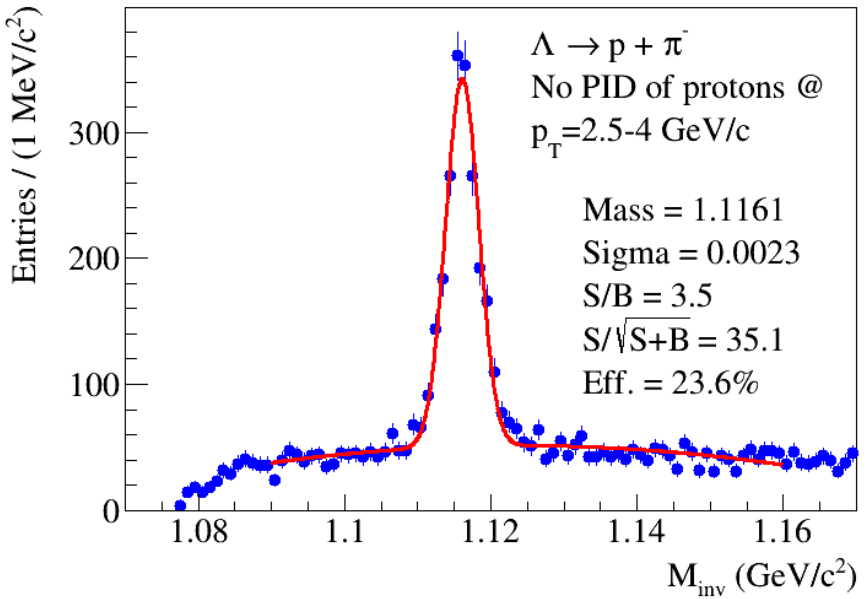
Study of systematic uncertainties and improvements in the analysis chain:

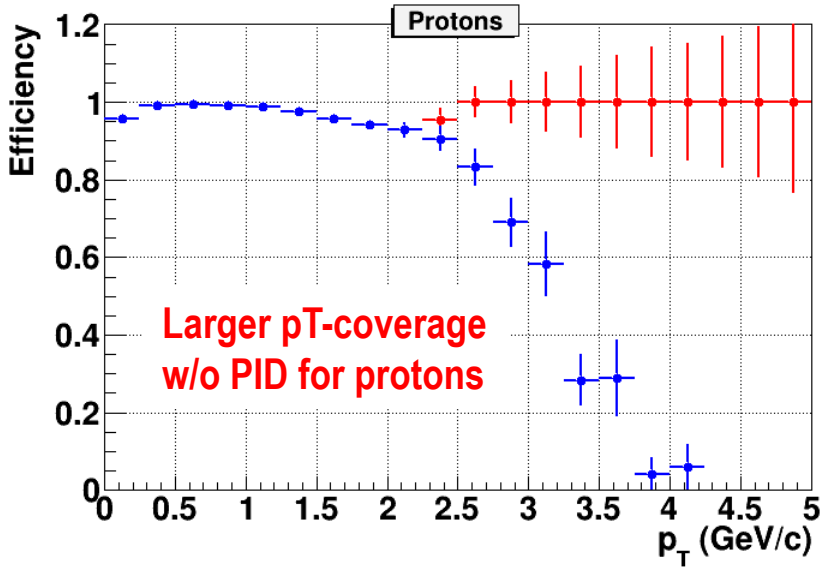
- Background estimates (fit vs mixed background)
- Varying PID modes for high-pT protons
- Testing alternative Machine Learning technique

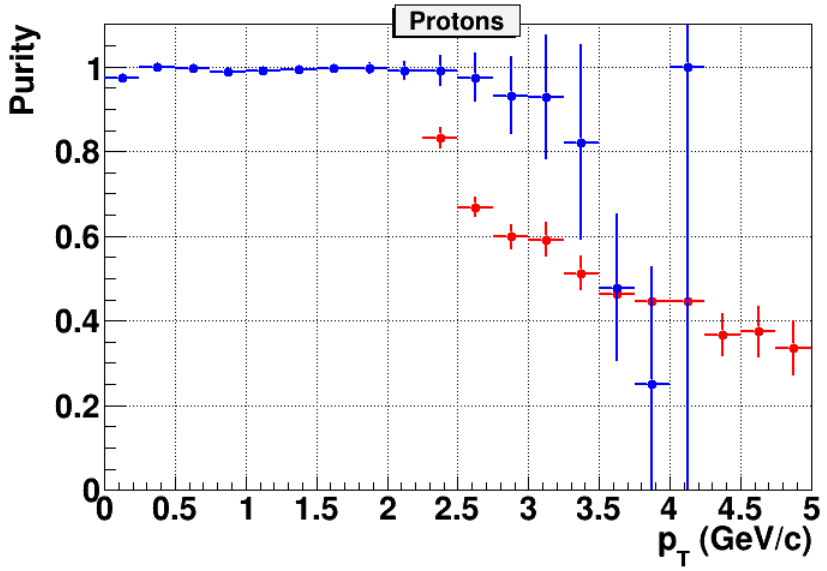
More in talk of D.Suvarieva on Tuesday at 15:50

Λ-hyperon reconstruction at high pT: PID vs pairing of pos. and neg. hadrons





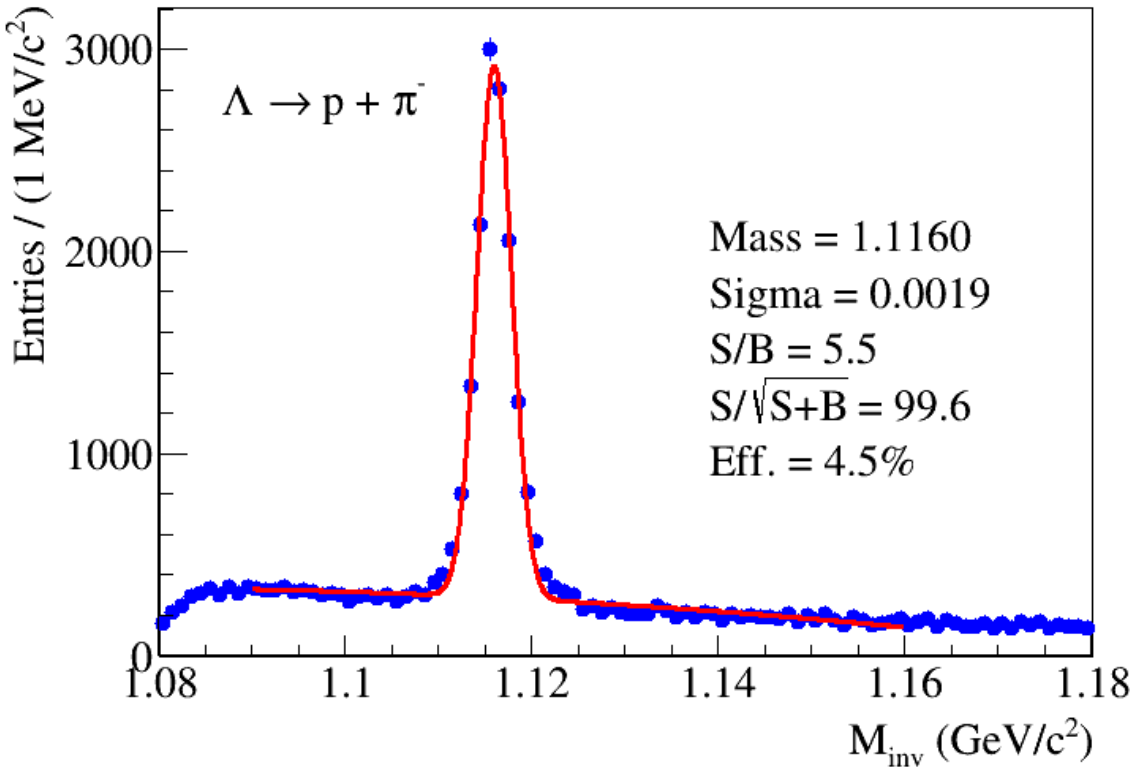




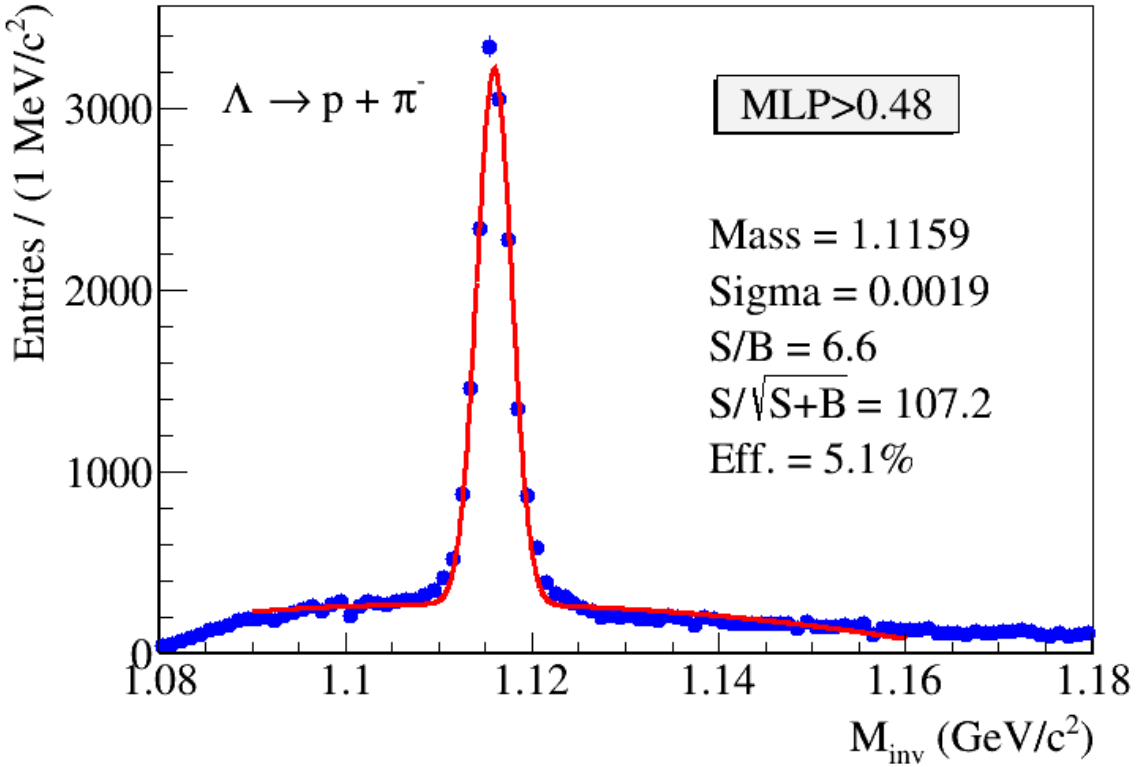
Λ reconstruction: standard method vs TMVA

- ML approach within the Toolkit for Multivariate Data Analysis with ROOT (TMVA)

Standard method of Topological Cuts (6 cuts)

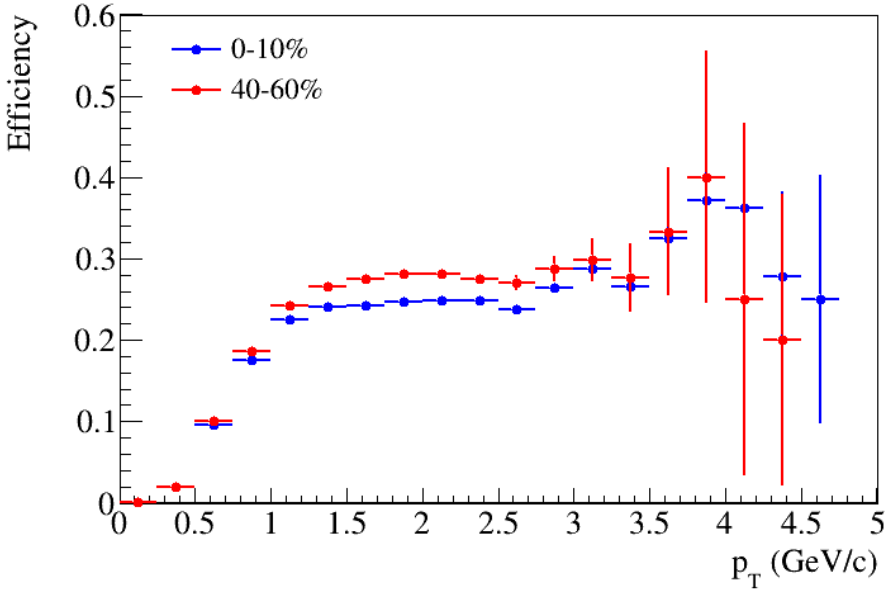


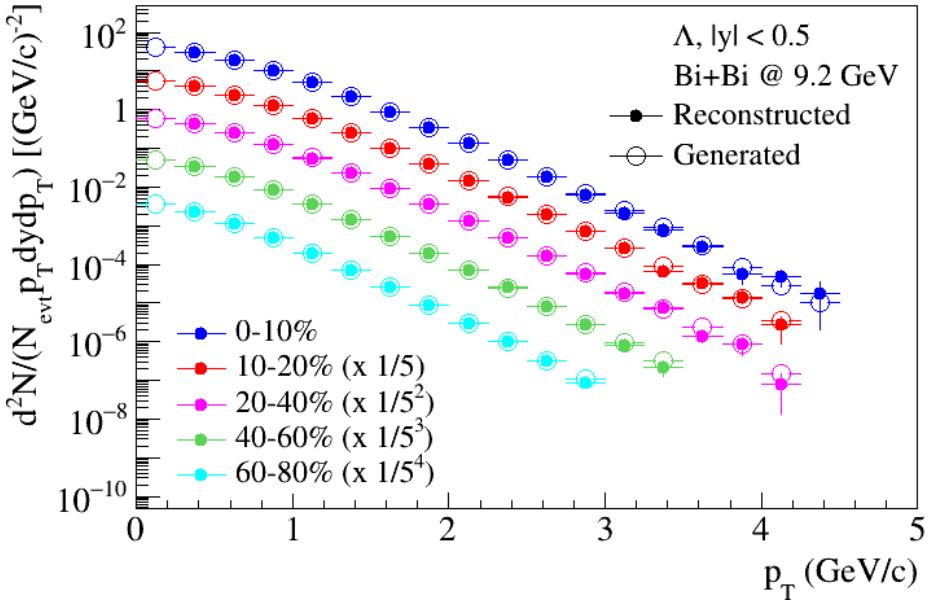
TMVA method (8 cuts)

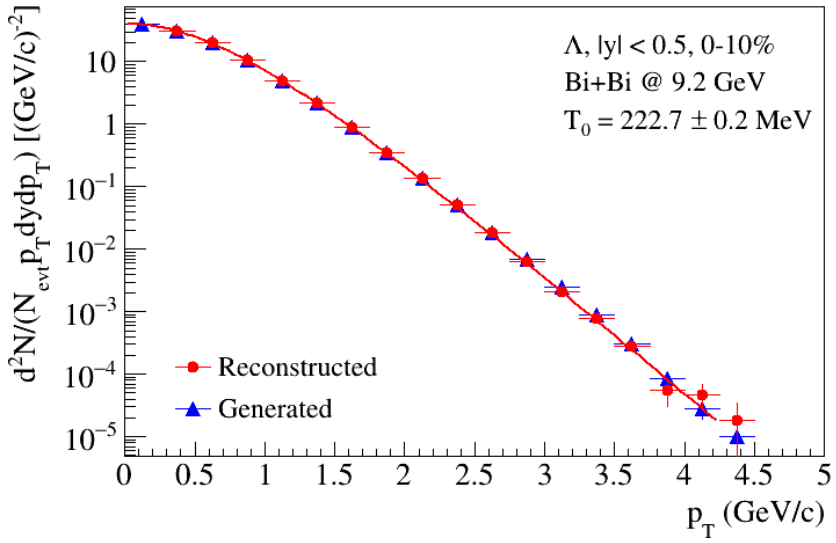


Better Lambda selectivity with TMVA (under tuning)

Λ analysis results: fully corrected invariant pT-spectra in centrality bins

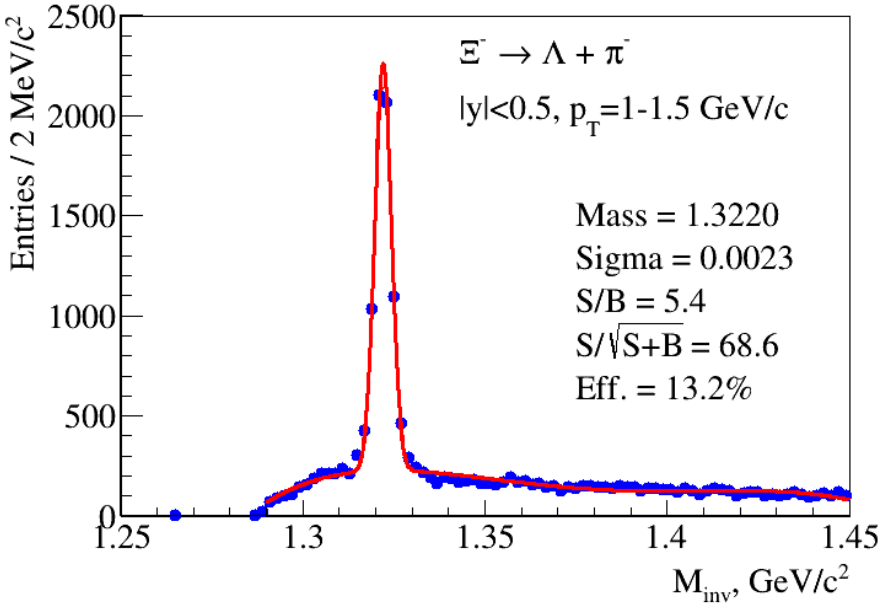


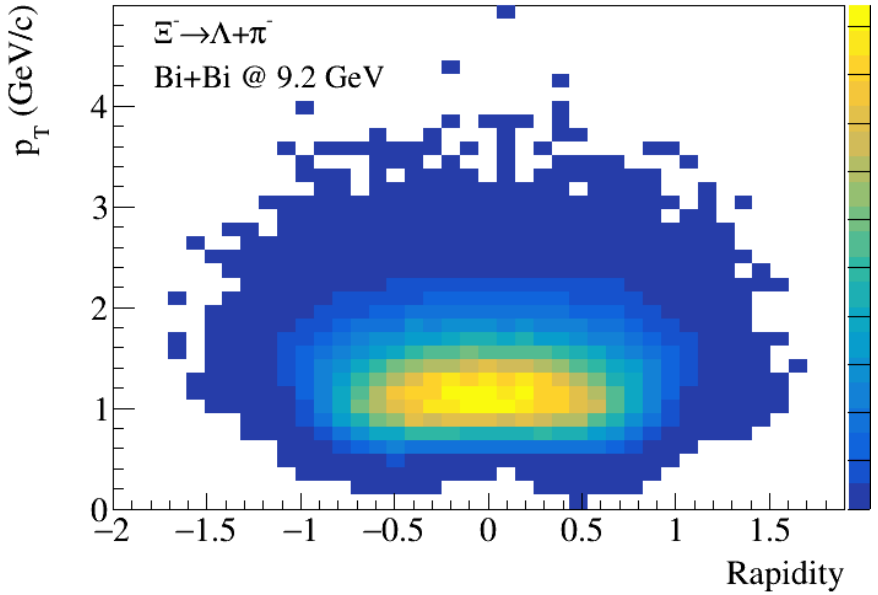




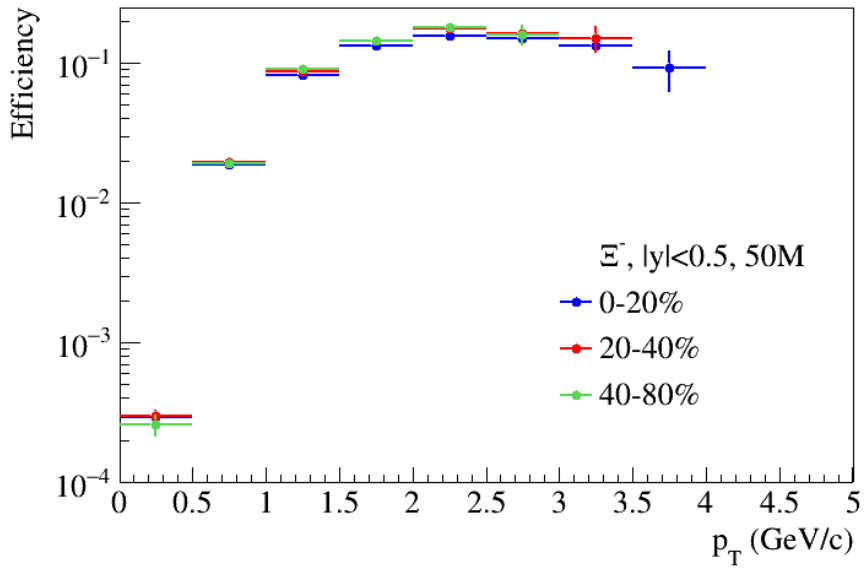
- Invariant pT-spectra of Lambda are reconstructed in several centrality bins
- Reconstructed distributions are consistent with data from model
- Thermal fits applied to data

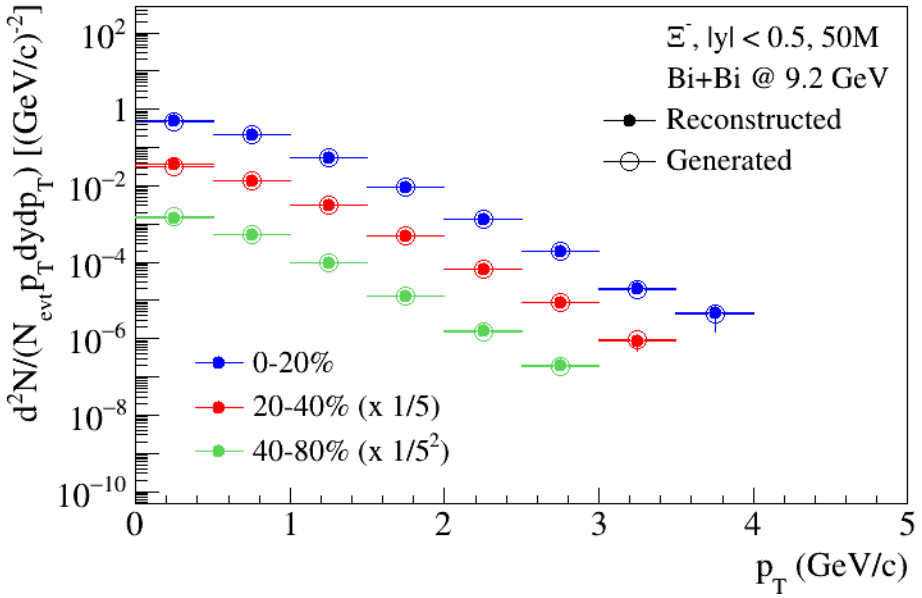
Ξ analysis: efficiency, phase-space and spectra in centrality bins



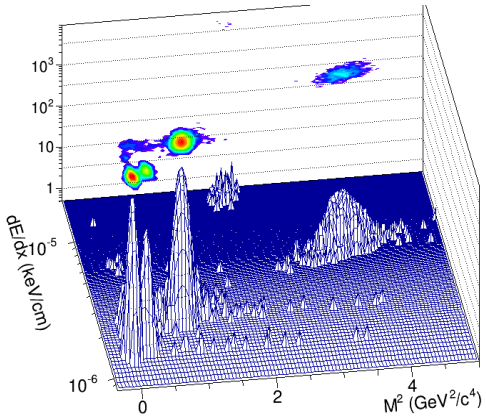


- **Good phase-space coverage for Ξ in MPD**
- **Analysis is ongoing**

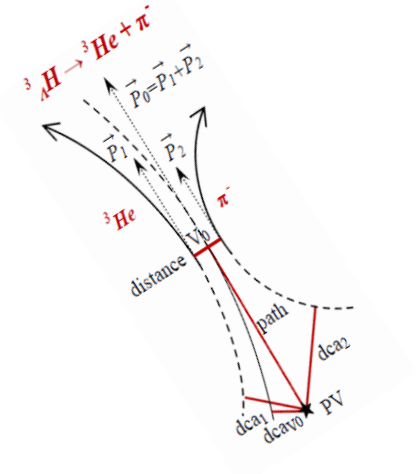


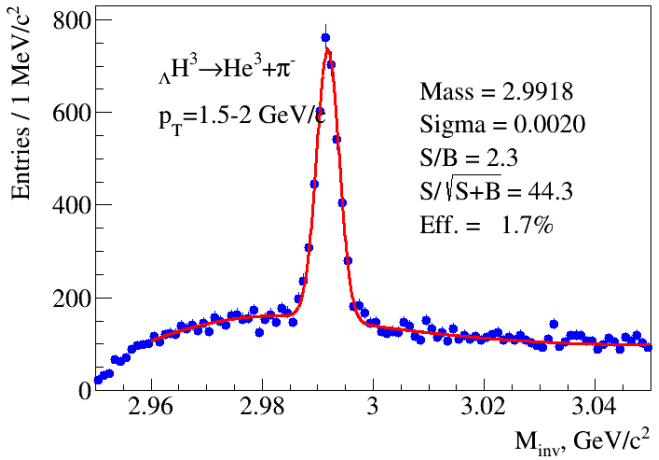


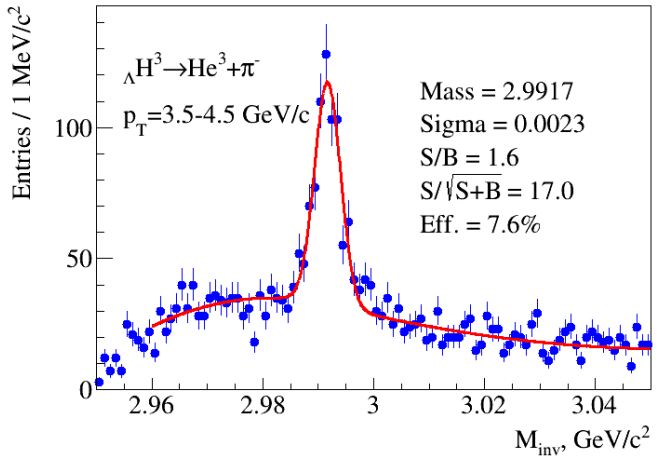
Reconstruction of hypertritons in MPD

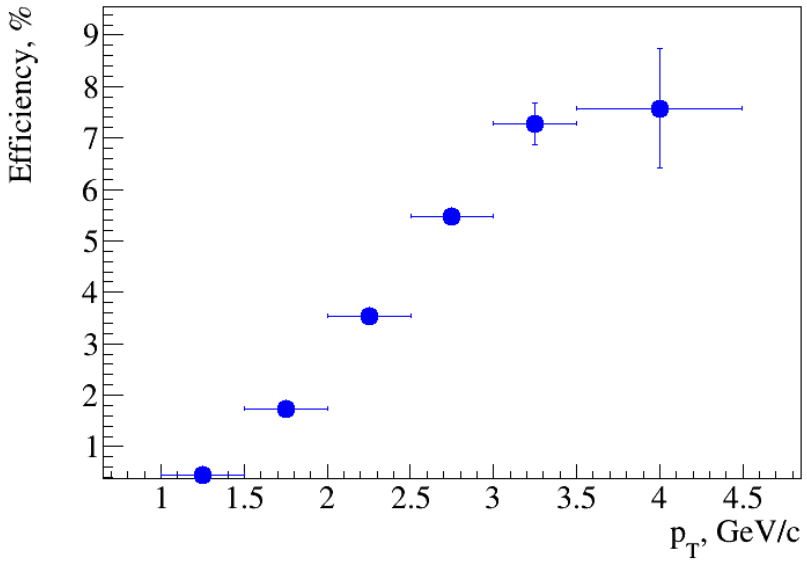


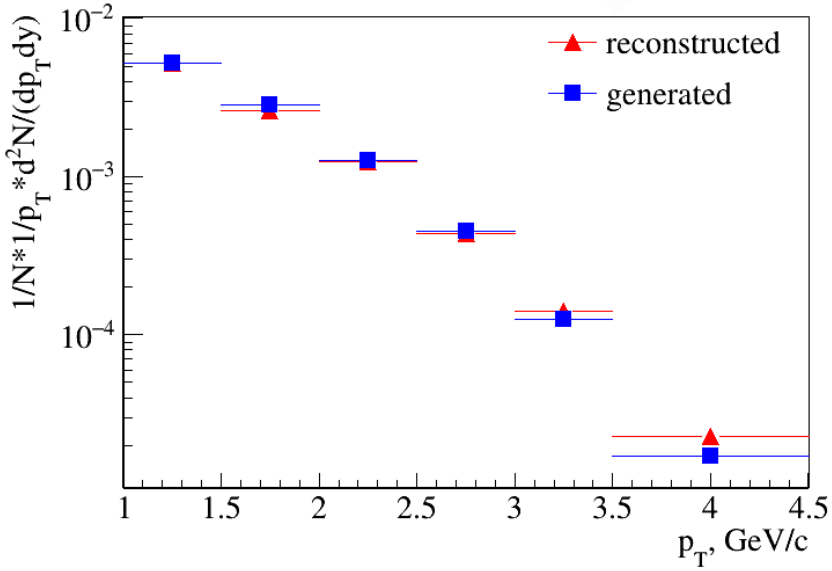
- 40M Events Bi+Bi at 9.2 GeV, |y|<1 (PHQMD model)
- Full event simulation and reconstruction
- A set of topological cuts aimed at maximizing significance







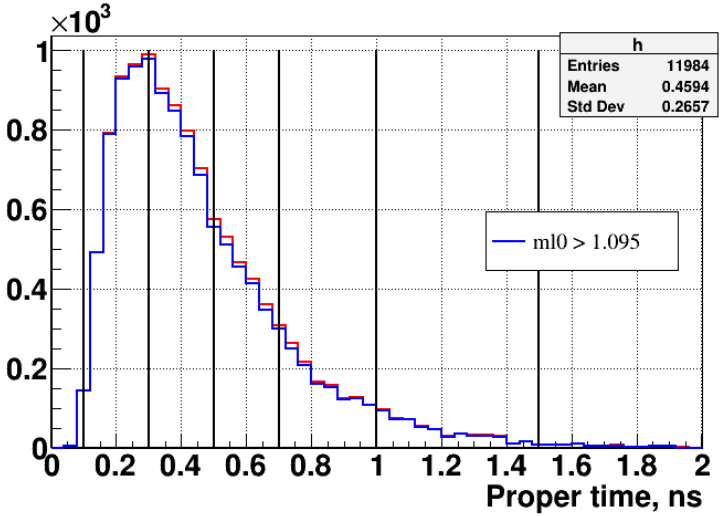


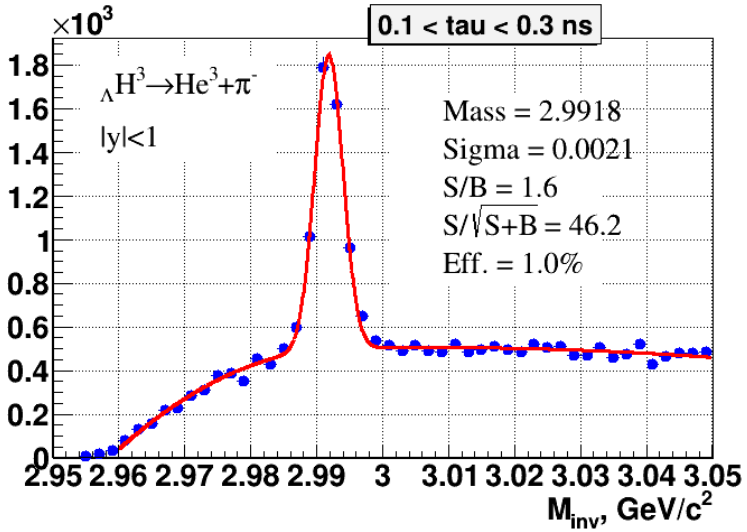


- Invariant spectrum of hypertritons is reconstructed up pT=4.5 GeV/c
- With a larger data sets, pT-spectra and rapidity densities can be obtained in centrality selected Bi+Bi collisions over a large phase space shedding light to the formation details and collective behavior of hypernuclei

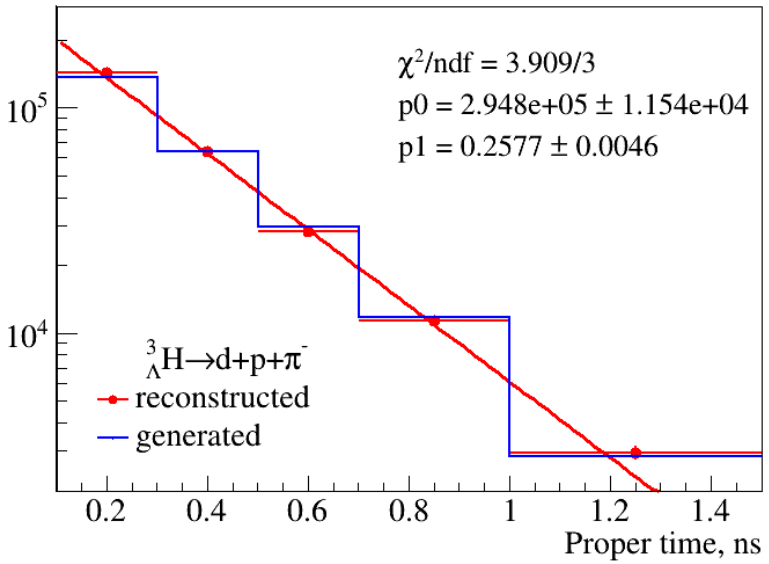
Hypertriton lifetime study

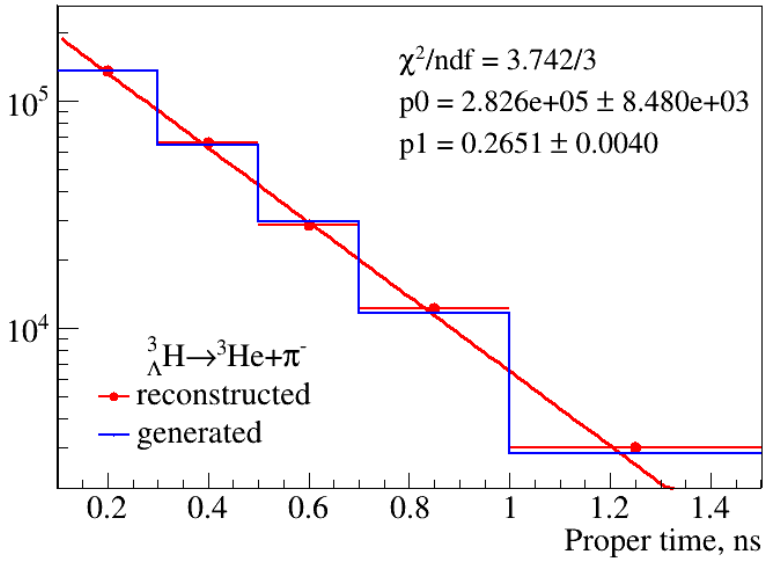
- Hypertritons are reconstructed in several \tau bins
- 2- and 3-prong decay modes were studied separately to estimate systematics





$\tau = ML/p$ (p – momentum, M-hypertriton mass, L-track length)





$$N(\tau) = N(0)\exp\left(-\frac{\tau}{\tau_0}\right) = N(0)\exp\left(-\frac{ML}{cp\tau_0}\right),$$

Results for different decay modes are consistent

Summary

- **Intensive preparations for the start of the MPD physics program at NICA is ongoing**
- **Production of hyperons and hypernuclei is sensitive to the strange sector of the nuclear matter EOS and has implication for nuclear physics and astrophysics**
- **The results of MPD feasibility studies indicate good hyperon and hypernuclei reconstruction performance of the detector**
- **Future high statistics data from NICA/MPD can provide better constrains for hypernuclei production models in the high baryon density regime**

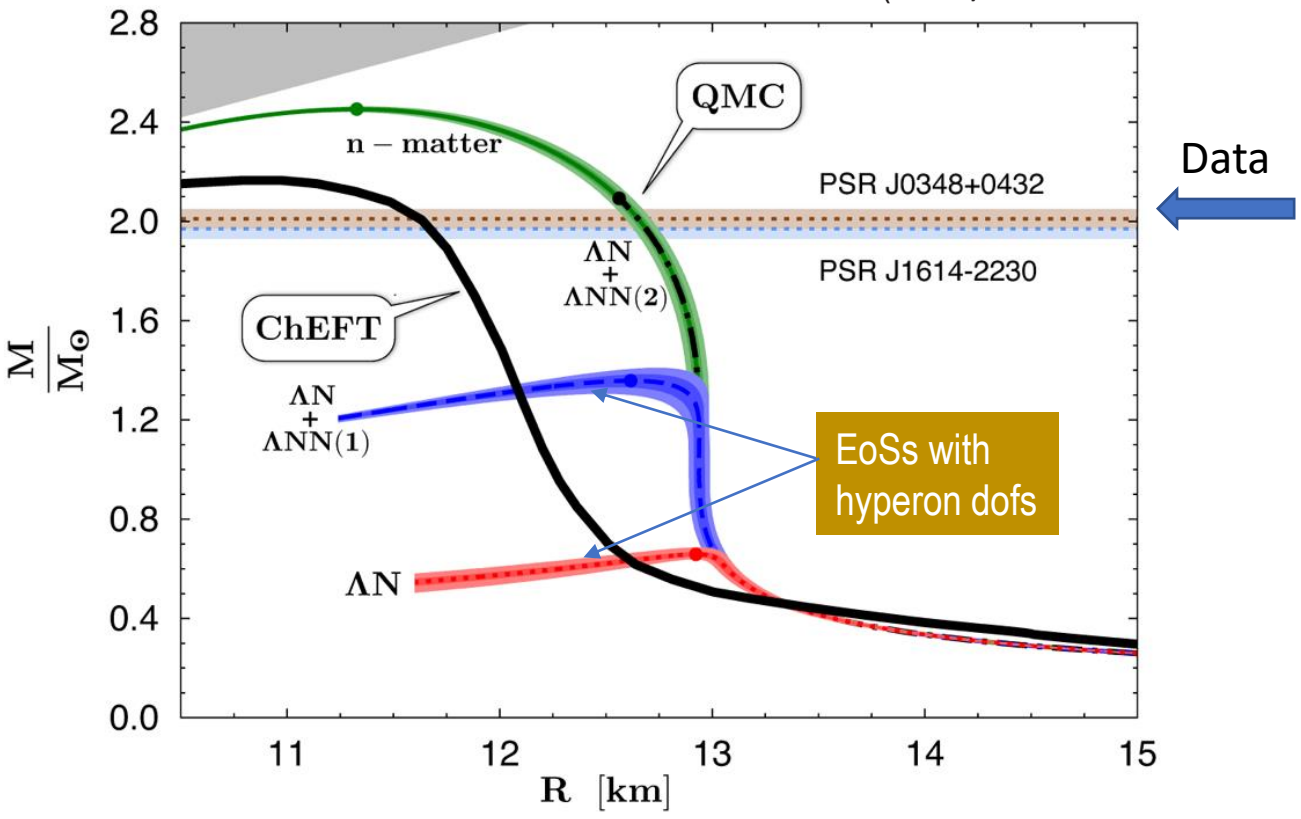
Thank you for listening!

Spares

Strangeness in dense nuclear matter : puzzling behavior

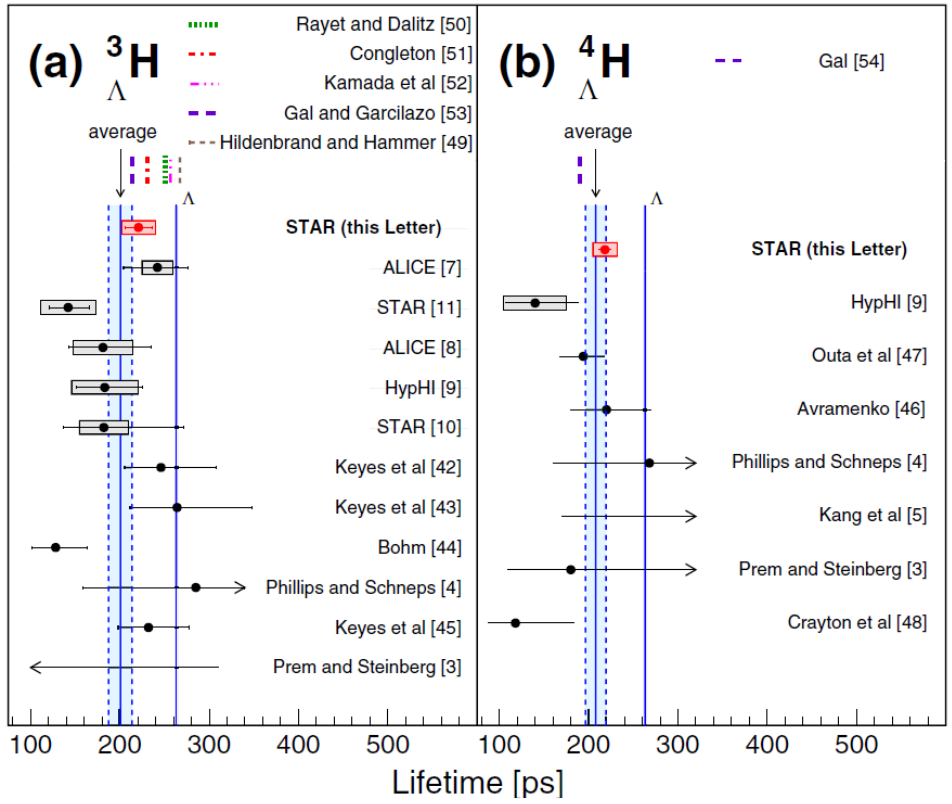
- Hyperons appear in the core of neutron stars (NS) at ~ (2-3)n_0 leading to softening EoS and reducing the max. mass for NSs, but the latter is in contradiction with observations (NS hyperon puzzle)
- Averaged lifetimes of hypernuclei from A+A are shorter than expected from theory (lifetime puzzle)

REVIEWS OF MODERN PHYSICS 88 (2016)



Data

PRL 128, 202301 (2022)



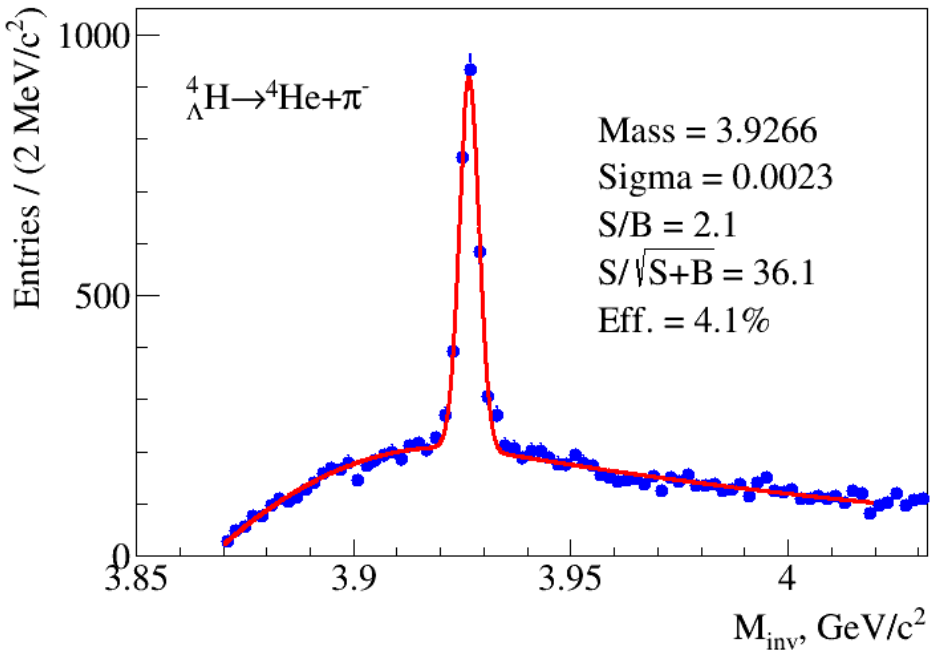
Many open questions on YN (YY, YNN) potentials in dense matter, new data on B_Λ, lifetimes, branching ratios are needed to provide tighter constrains

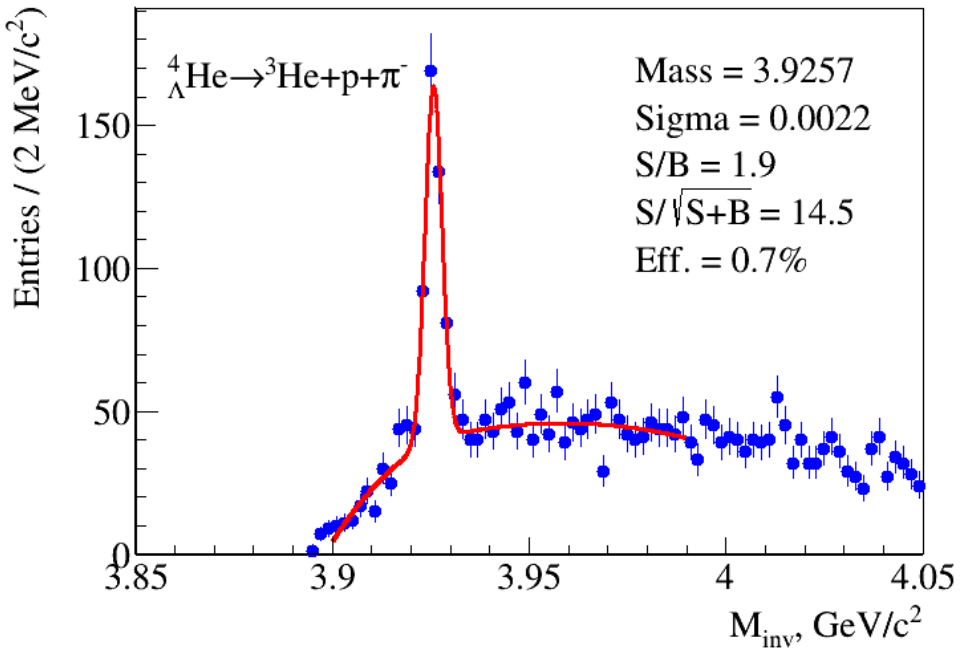
More data are required to reduce current uncertainty (NICA/MPD)

Results for heavier hypernuclei in MPD

- 40Mevents Bi+Bi at 9.2 GeV, b < 12 fm (PHQMD) enriched by signal particles

Equivalent statistics: ~140 M events for $^{4}_{\Lambda}$H and for $^{4}_{\Lambda}$He





Good MPD performance for heavier hypernuclei in Bi+Bi at 9 GeV