Cross-PWG Meeting of the MPD Collaboration
JINR, Dubna, Russia
28 June 2022

Perspectives of hypernuclei study at NICA/MPD from realistic Monte Carlo simulation

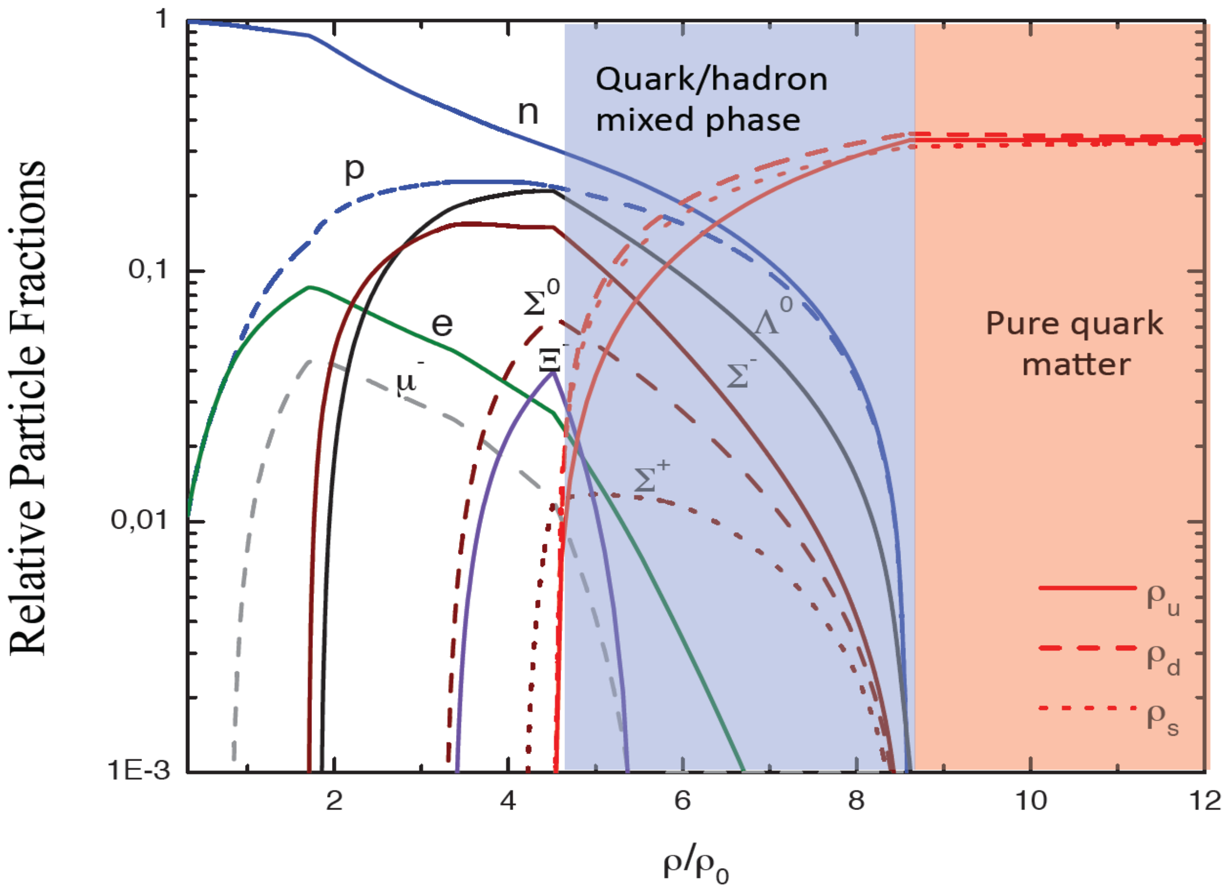
V. Kireyeu, V.Kolesnikov, A.Mudrokh, I.Rufanov, V.Vasendina, A.Zinchenko
PWG2

Outline

- Motivation
- PHQMD generator
- Track reconstruction performance
- dE/dx simulation in TPC
- PID
- Realistic reconstruction of hypernuclei:
  - ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$
  - ${}^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$
  - ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$
  - ${}^{4}_{\Lambda}He \rightarrow {}^{3}He + p + \pi^{-}$
- Summary and Plans

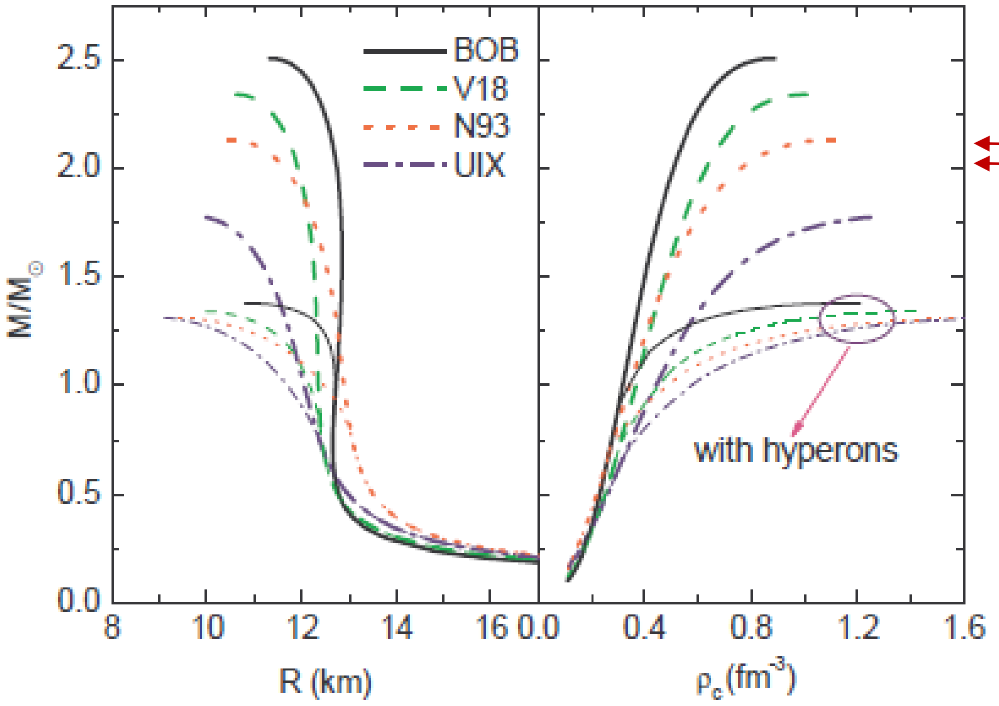
Hypermatter: intro

- Nuclear matter EOS is of importance for QCD, nuclear physics and astrophysics
- Only NN potential are very well determined from scattering experiments
- Hyperons appear in the core of neutron stars (NS) at approx. twice the normal nuclear density
- In a new chemical composition, due to attractive YN potentials, the EOS becomes softer
- New balance among the (inward) gravitational force and (outward) thermal + Fermi degenerate pressure impacts the mass-radius (M-R) relation for NSs



M. Orsaria et al, Phys. Rev. C 89, 015806 (2014)

Hypermatter in stellar objects: hyperon puzzle



EoS becomes soft with hyperons → change in the M-R relation

2.17+/-0.11 (PSR J0740+662)
2.01±0.04 (PSR J0348+0432)

Contradiction with recent measurements for Millisecond Pulsar (MSP) masses

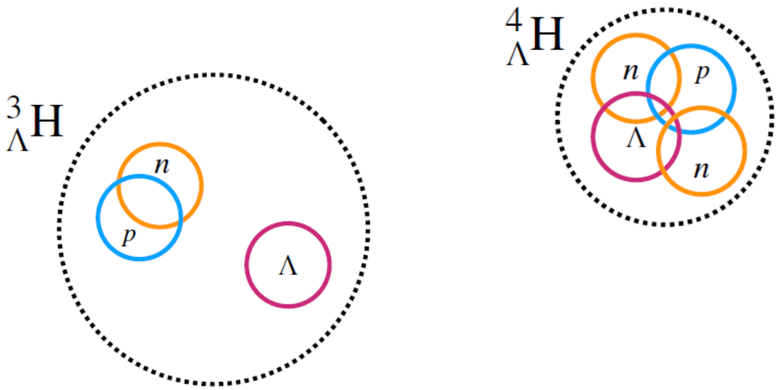
Hyperon Puzzle in NSs!

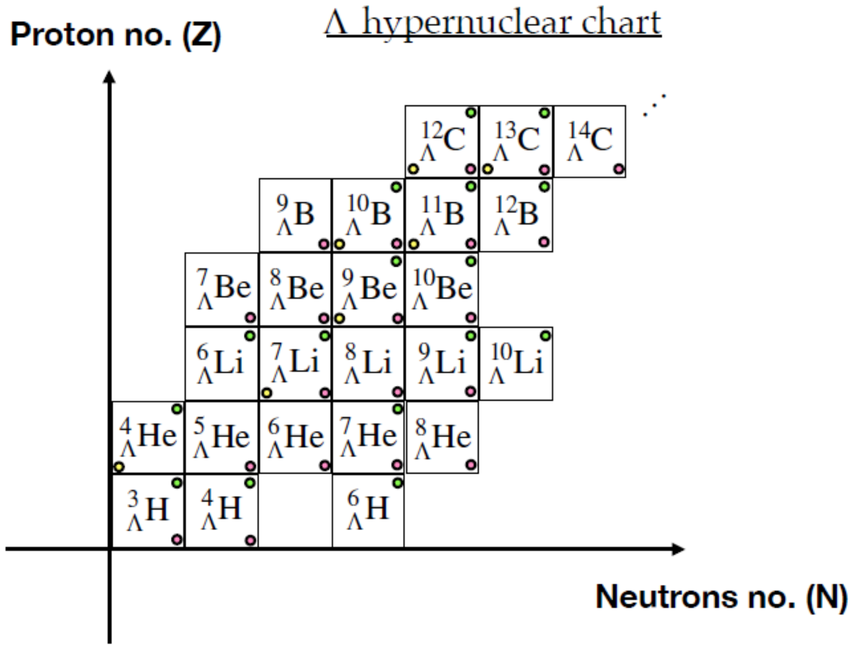
Proper description of the underlying hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions in dense QCD medium is needed → hypernuclei offer the possibility.

Hypernuclei in heavy-ion collisions

- ❑ No chance to get YN or YY scattering data from the experiments (hyperon decay)
- ❑ High multiplicity heavy-ion collisions provide a number of methods to do the job: two-particle correlations and hypernuclei

Hypernuclei are nuclei containing at least one hyperon



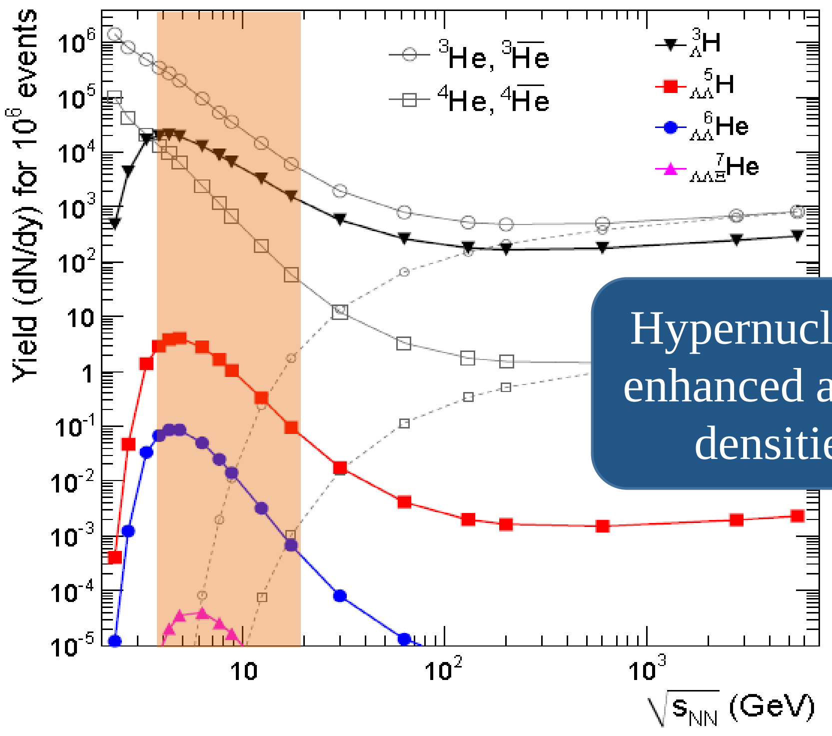


- ❑ Λ hypernuclear chart: 40+ Λ-hypernuclei
- ❑ Attractive Λ potential with a depth of about 30 MeV
- ❑ Very few ΛΛ-hypernuclei (mainly from Ξ^- capture reactions in emulsions), ΛΛ weakly attractive(?)
- ❑ Precise measurements of binding energies, lifetimes and branching ratios can give tighter constrains → **NICA!**

Hypernuclei: why NICA?

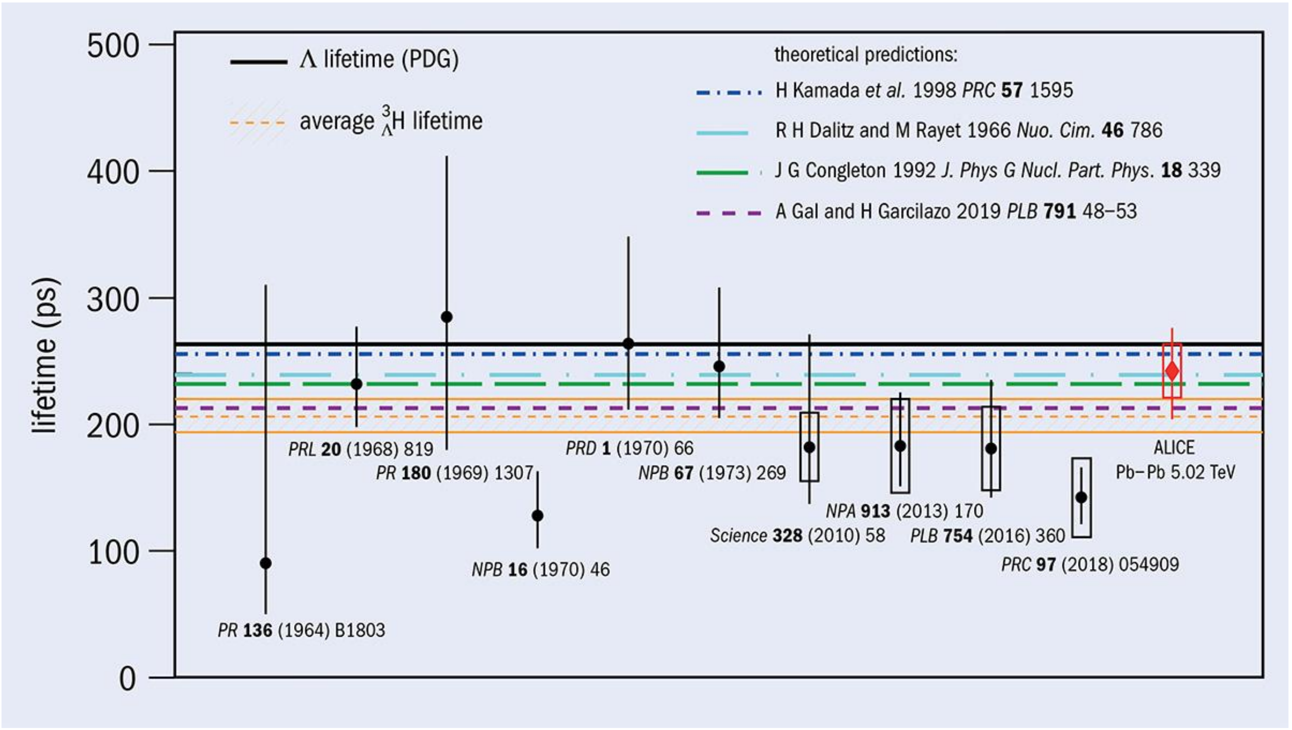
- Maximum in baryon density and in relative strangeness production favorsformation of strange nuclear clusters
- Thermal model predicts an enhanced hypernuclear production within the NICA energy range: at the nominal luminosity even double hypernuclei are feasible

A. Andronic et al, PLB697 (2011) 203



Hypernuclei production enhanced at high baryon densities (NICA)

S. Acharya et al. (ALICE Collaboration) Phys. Lett. B 797 (2019) 134905



Hypertriton lifetime – more data to reduce current uncertainty

To study hypernuclei, MPD detector must be able to detect and identify light nuclei in a wide rapidity range as well to have a good capability for precise secondary vertex reconstruction

PHQMD generator

The goal: to develop a **unified n-body microscopic transport approach** for the description of heavy-ion dynamics and dynamical cluster formation from low to ultra-relativistic energies

Realization: combined model **PHQMD = (PHSD & QMD) & SACA**

Parton-Hadron-Quantum-Molecular Dynamics

↓

Initialization à propagation of baryons:
QMD (Quantum-Molecular Dynamics)

↓

Propagation of partons (quarks, gluons) and mesons
+ collision integral = interactions of hadrons and partons (QGP)
from PHSD (Parton-Hadron-String Dynamics)

↓

Clusters recognition:
SACA (Simulated Annealing Clusterization Algorithm)
vs. MST (Minimum Spanning Tree)

J. Aichelin et al.,
Phys. Rev. C 101, 044905
& arXiv:1907.03860

Cluster recognition: Minimum Spanning Tree (MST)

R. K. Puri, J. Aichelin, J.Comp. Phys. 162 (2000) 245-266

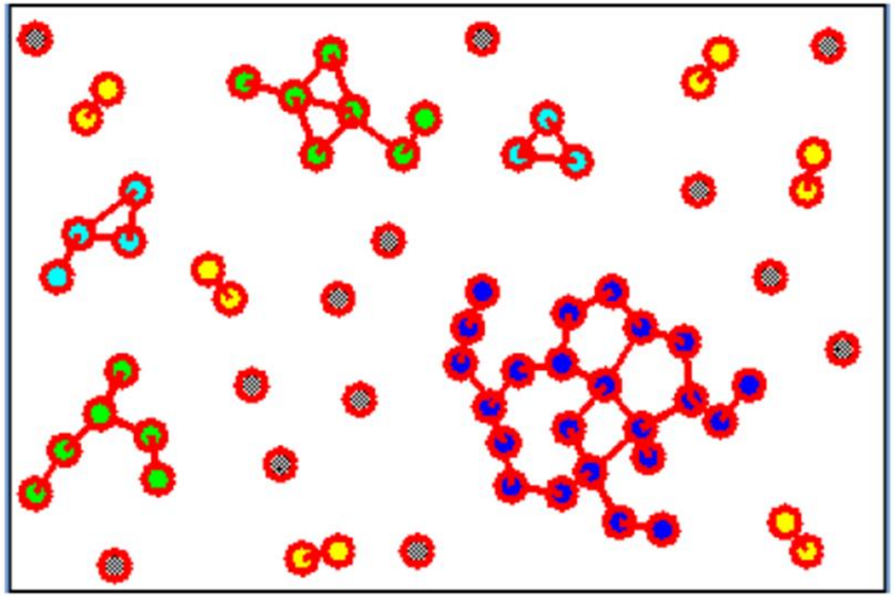
The Minimum Spanning Tree (MST) is a cluster recognition method applicable for the (asymptotic) final states where coordinate space correlations may only survive for bound states.

The MST algorithm searches for accumulations of particles in coordinate space:

1. Two particles are "bound" if their distance in coordinate space fulfills

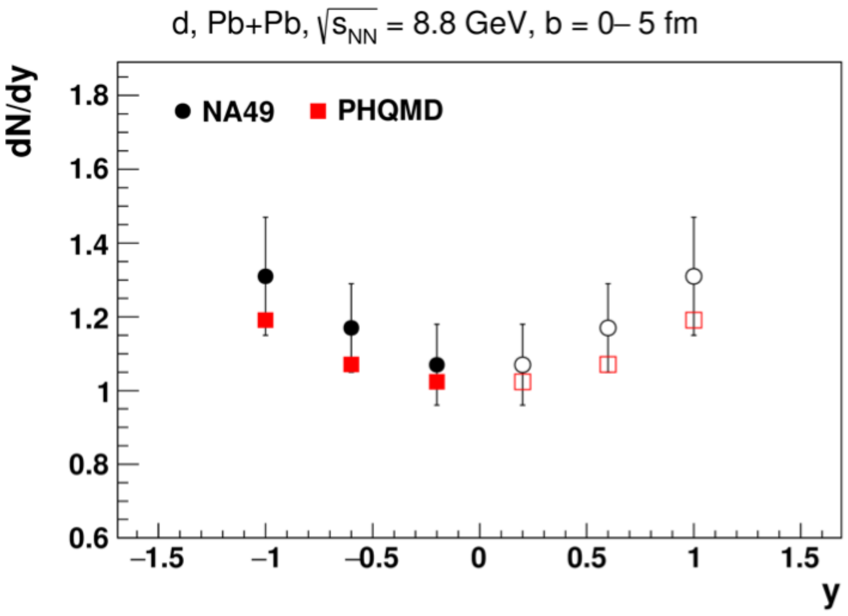
$$|\mathbf{r}_i - \mathbf{r}_j| \leq 4.0\ fm$$

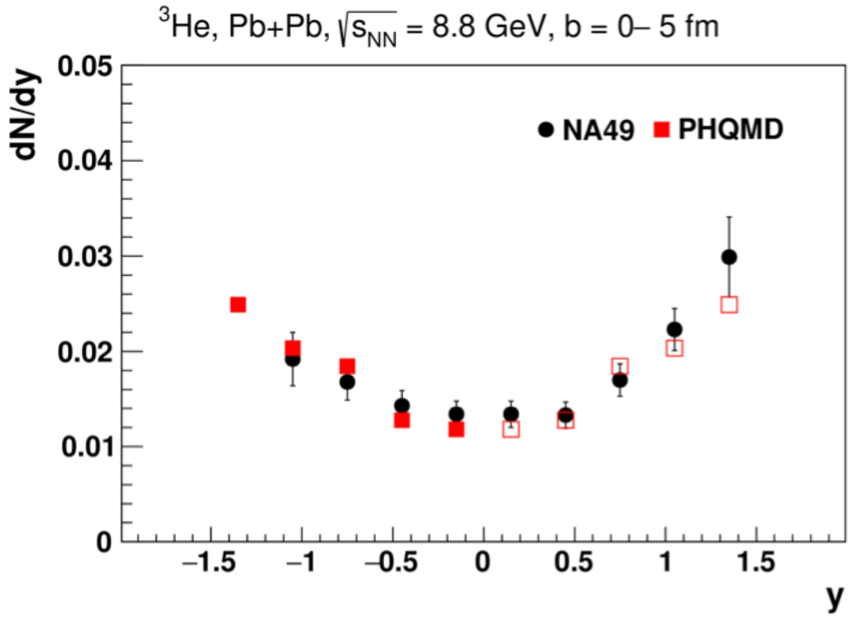
2. Particle is bound to a cluster if it bounds with at least one particle of the cluster.

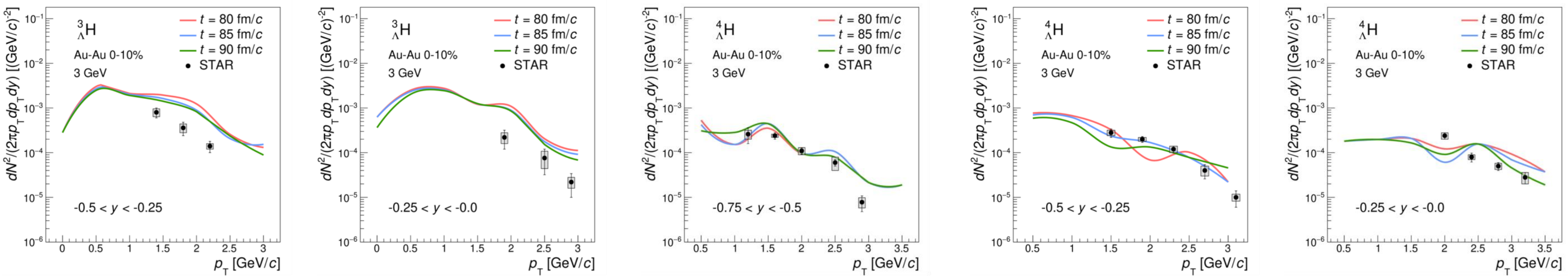


Inclusion of an additional momentum cuts (coalescence) lead to a small changes: particles with large relative momentum are mostly not at the same position (V. Kireyeu, Phys. Rev. C 103, 054905)

PHQMD generator







S. Glassel et al., Phys. Rev. C 105, 014908 & arXiv:2106.14839

Main objectives:

Tests of MPD performance for hypernuclei reconstruction with a new generator PHQMD and realistic detector simulation and reconstruction

Software development: Towards a realistic simulation of the MPD / NICA

- Realistic description of the response of detectors, development, implementation and optimization of algorithms for reconstruction of signals in detectors
- Realistic track reconstruction procedure in TPC
- Description of ionization losses in TPC gas based on Garfield ++ simulations that are consistent with STAR data
- New realistic identification of electrons, hadrons and light nuclei in TPC and TOF software

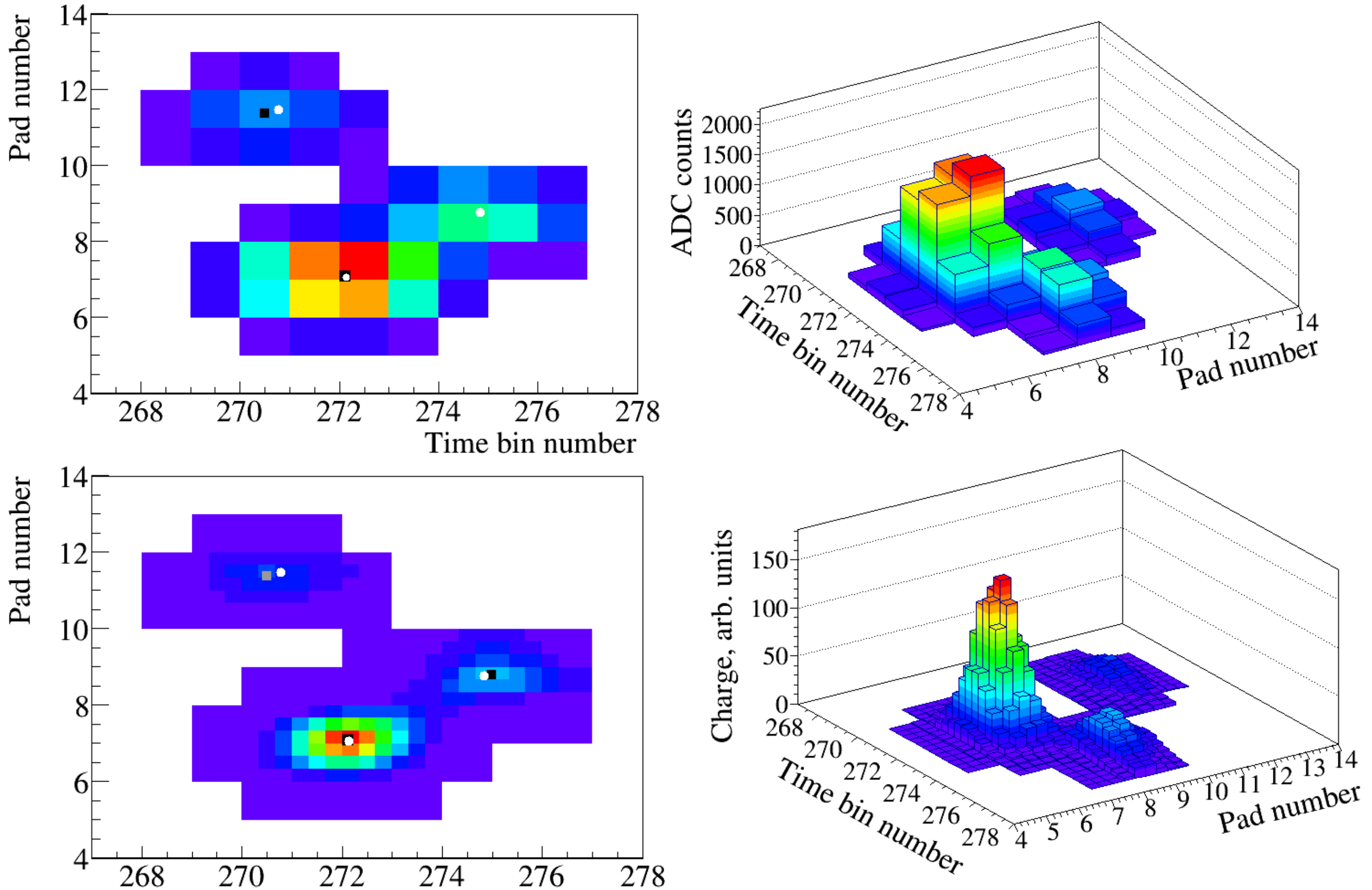
Software requirements for hypernuclei reconstruction:

- High-quality reconstruction of the tracks of hadrons and light nuclei
- Good reconstruction of primary and secondary vertices
- High efficiency of identification of both hadrons and light nuclei

Cluster topologies and MLEM procedure

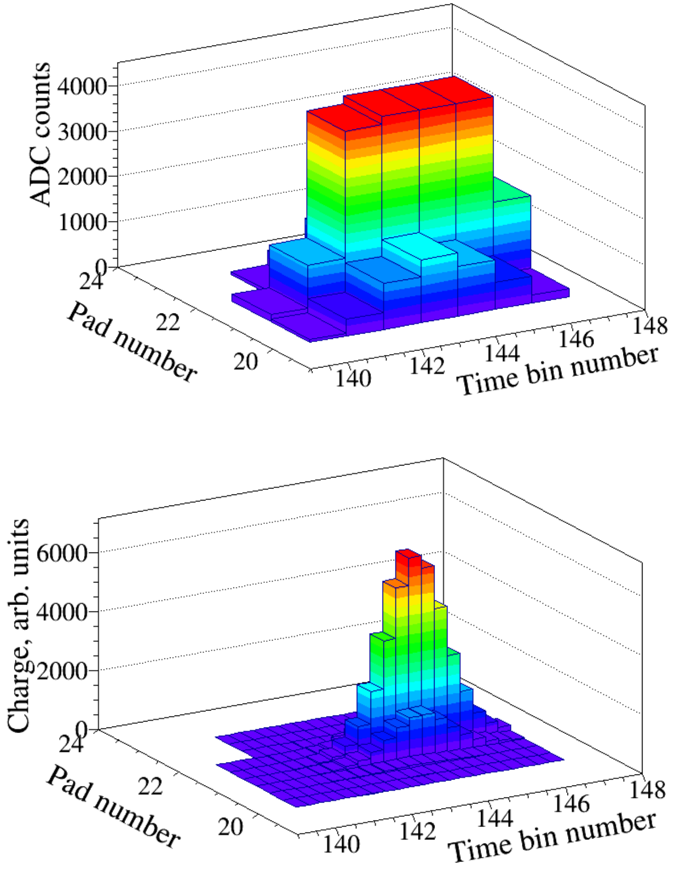
Maximum Likelihood - Expectation Maximization procedure

3D view of a cluster with overflows



before

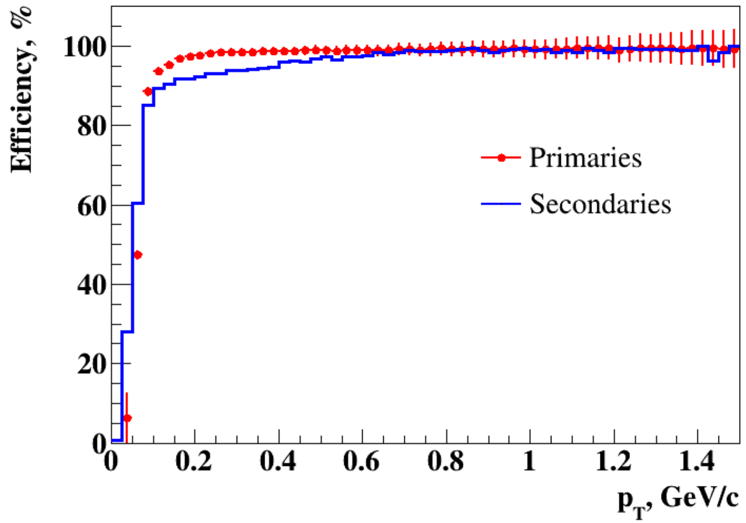
after MLEM

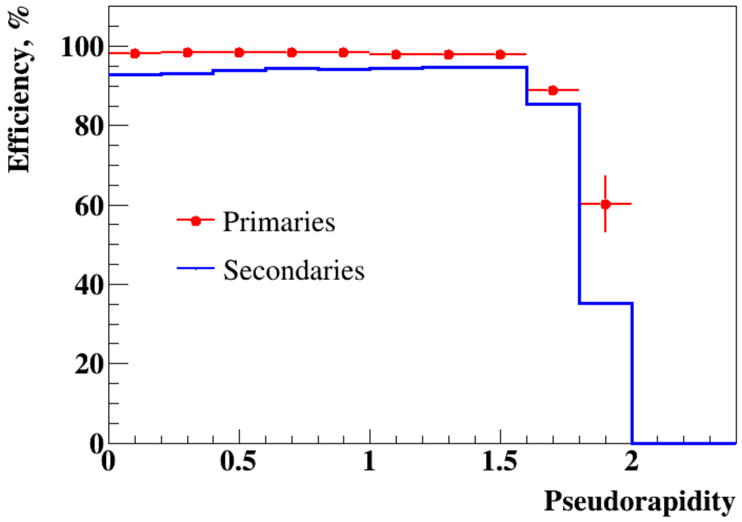


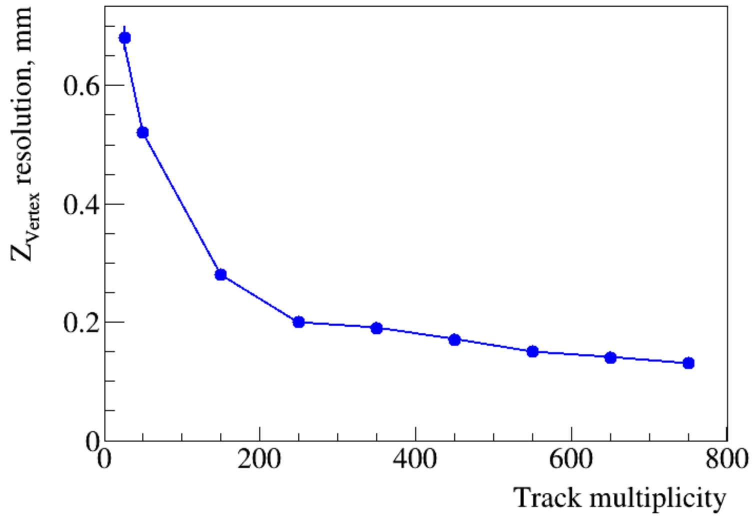
True hit coordinates - ○, Reconstructed hit coordinates - ■. On the top left plot one hit has not been reconstructed.
Bottom - 2D and 3D views of the same precluster after the MLEM procedure.

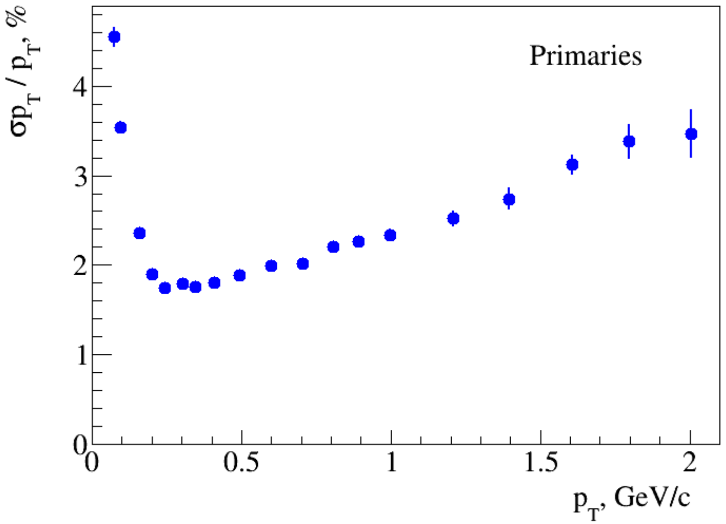
Top - ADC output: charge loss because of overflows;
Bottom - signal recovery using undistorted measurements from the tails after MLEM procedure.

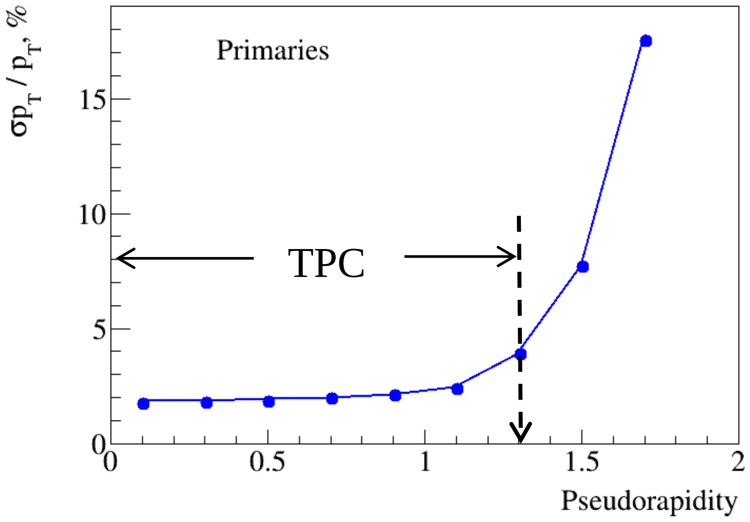
Realistic MPD simulation and reconstruction

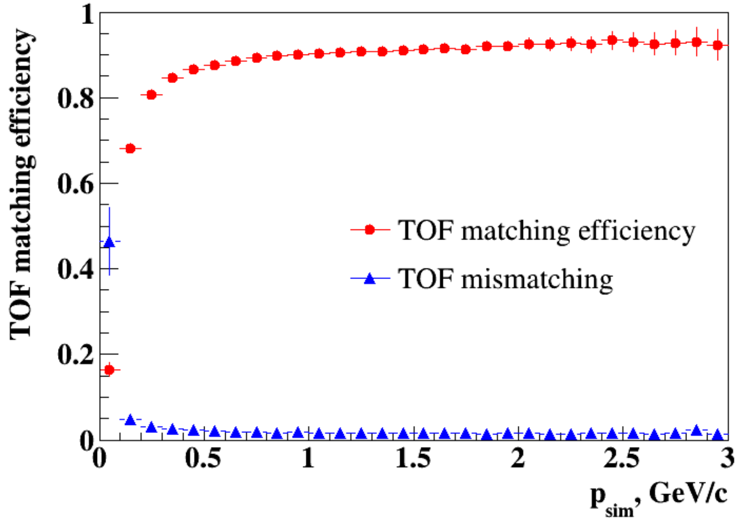




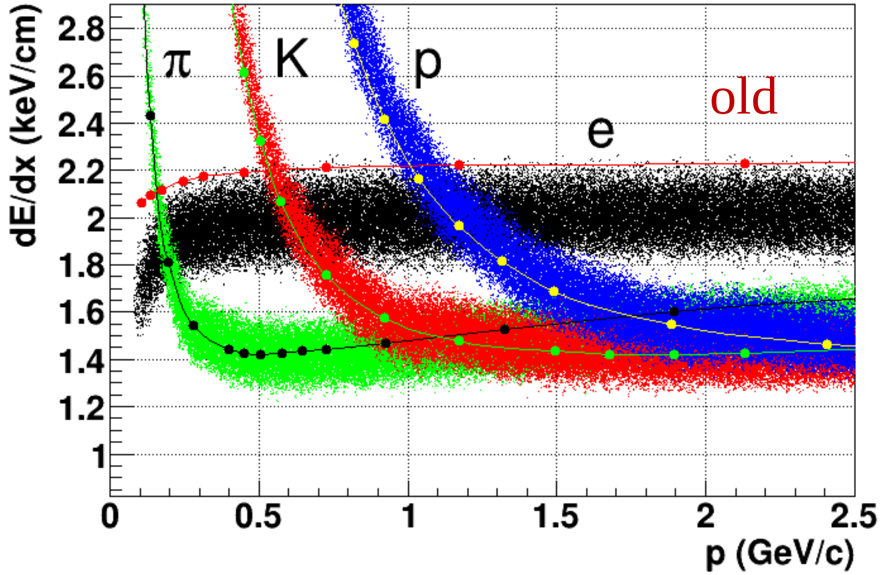


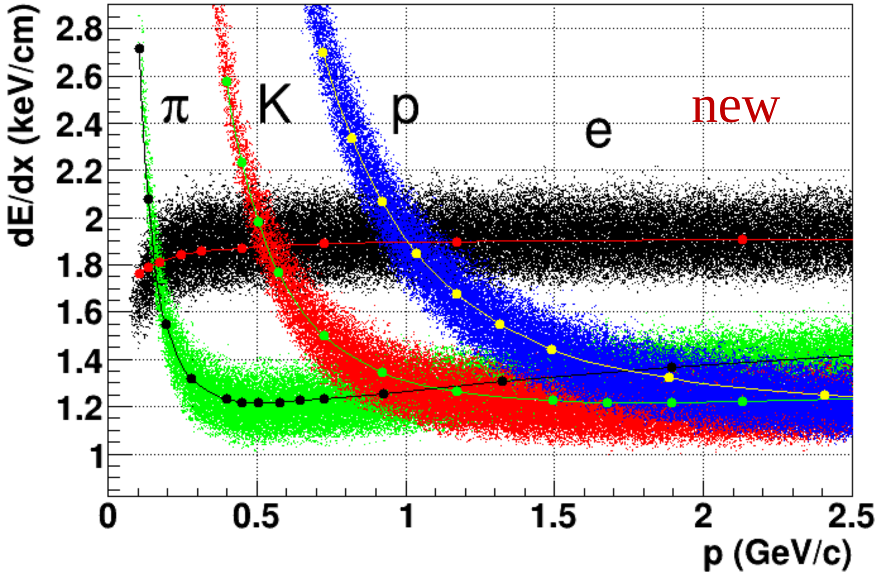






dE/dx simulation in TPC





dE/dx vs momentum for TPC/MPD
Box generator (*e*, *π*, *K*, *p*);
Curves – STAR standard function
(Bichsel`s functions)
[NIM A558 (2006) 419-429]

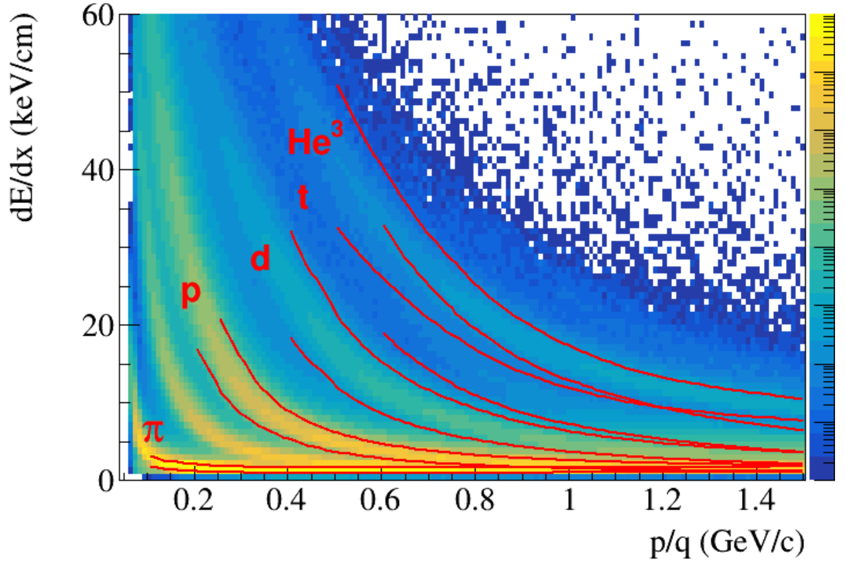
	ALICE	STAR	MPD
Gas	85% *Ne* mix	P10	P10
N rows x pitch (mm):			
Inner pads	64 x 7.5 mm	13 x 12 mm	26 x 12 mm
Outer pads	64 x 10 mm	32 x 20 mm	27 x 18 mm
Outer-2 pads	32 x 32 mm	–	–
P10 mixture – 90% *Ar*, 10% methane			

Data vs MC with old parameterization *dE/dx* in GEANT3:

- ❑ Essentially (~20%) underpredicts relativistic rise of the ionization energy loss as seen from comparison of pion and electron bands
- ❑ Overpredicts energy loss at low momentum (protons at *p*<1 GeV/c)
- ❑ Gives shifted momentum of intersections of electron and other particles bands
- ❑ Gives distorted input for realistic PID

New *dE/dx* parametrization (Garfield++) in GEANT gives a good agreement with STAR data

PID performance in TPC & TOF



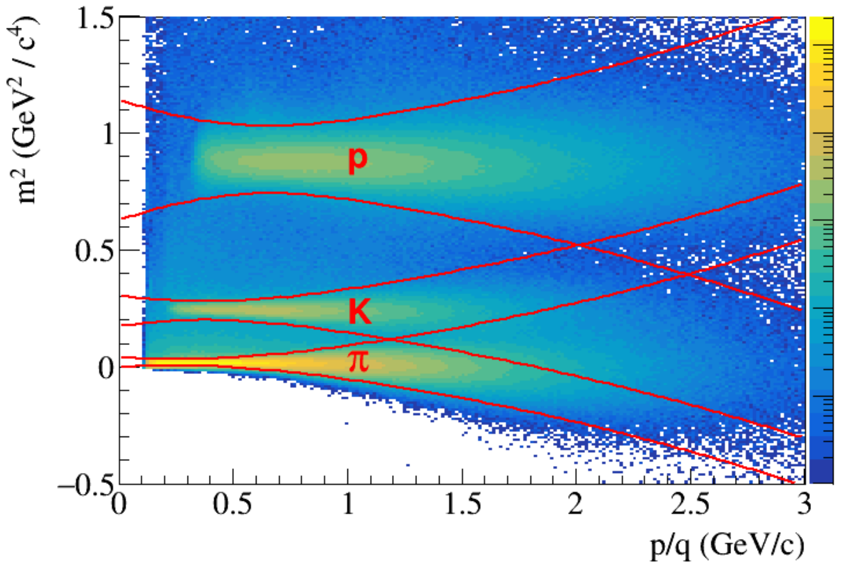
dE/dx vs momentum in TPC and
m^2 vs momentum in TOF
(Red lines ±3σ)

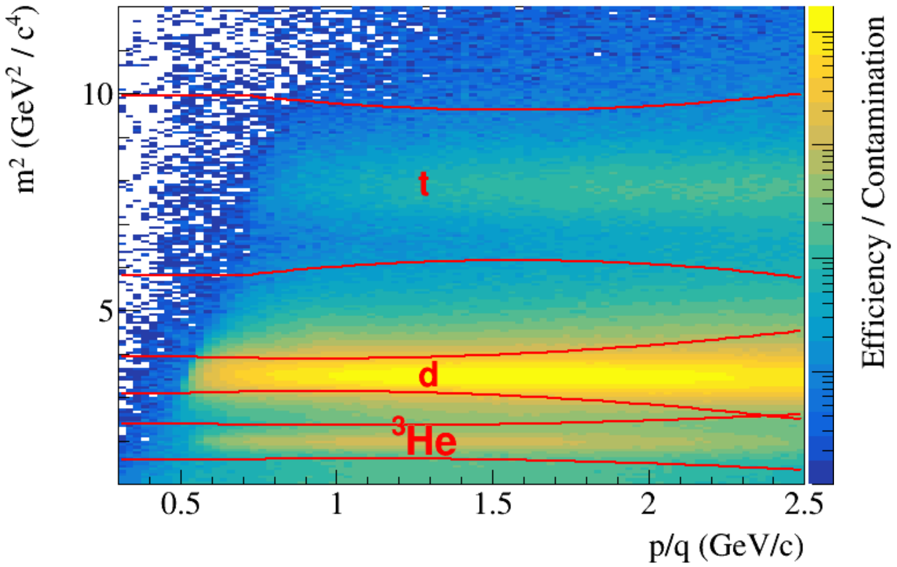
Mass square calculated using the measurements of magnetic rigidity (*p/q*), time-of-flight (*T*) and trajectory length (*L*):

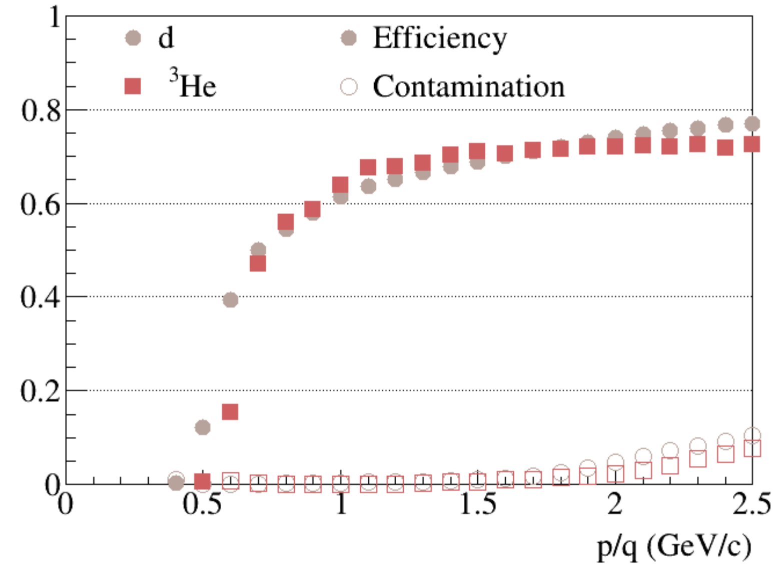
$$m^2 = p^2\left(\frac{c^2T^2}{L^2} - 1\right)$$

Selection criteria for events and identified tracks:

1. $|Z_{PV}| < 50$ cm
2. Primaries particles
3. $N_{TPC\_hits} \geq 27$
4. $|\eta| < 1.3$



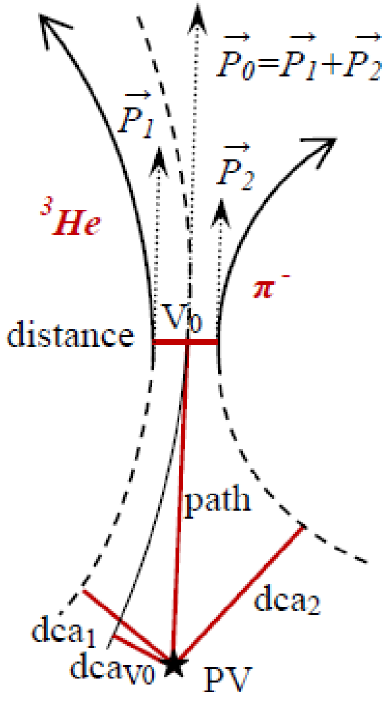




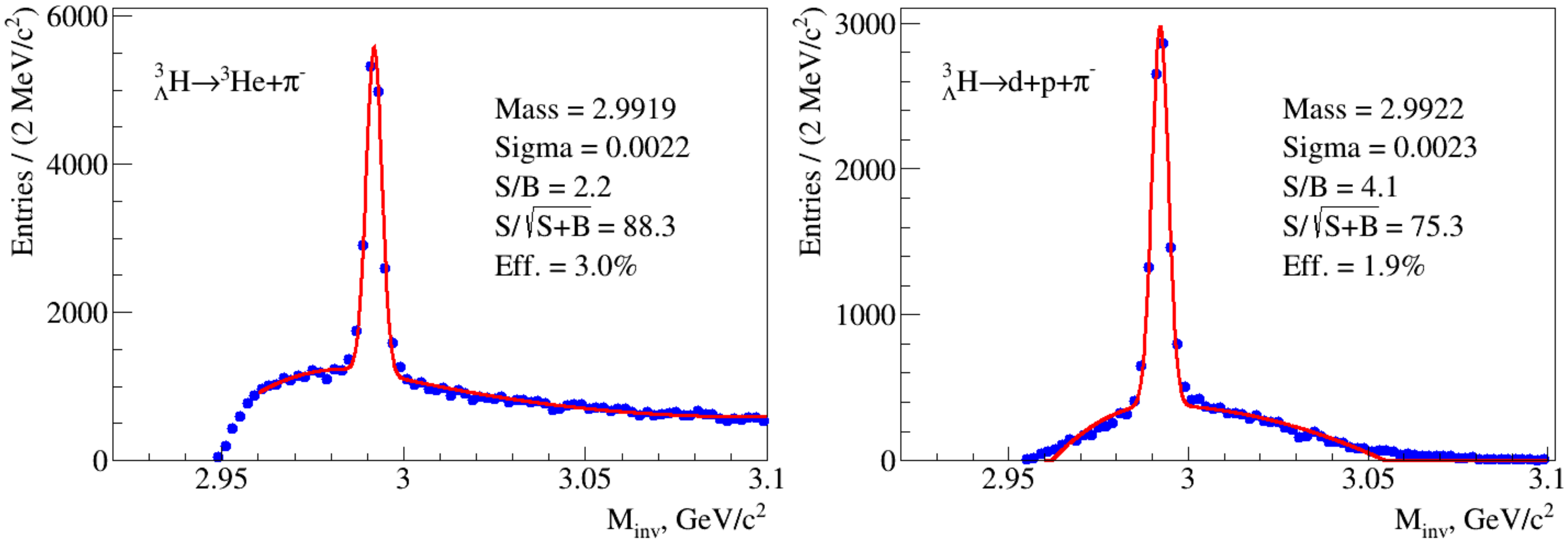
Data set

- **Generator:** PHQMD, Bi+Bi @9.2 GeV, 40M min. bias events & Bi+Bi @8.8 GeV, 15M min. bias events
- **Detectors:** TPC and TOF
- **Cluster / hit reconstruction:** precluster finder *(group of adjacent pixels in time bin – pad space*) ; hit finder *("peak-and-valley" algorithm either in time bin – pad space (for simple topologies) or in time-transverse coordinate pixel space after Bayesian unfolding (for more complicated topologies))* → COG around local maxima
- **Track reconstruction:** two-pass Kalman filter with track seeding using outer hits (*1st pass*) or leftover inner hits (*2nd pass*)
- **Track acceptance criterion:** $|\eta| < 1.3$, $N_{TPC\_hits} \geq 10$ (for reconstructed tracks)
- **Particle Identification:** *dE/dx* in TPC & m^2 in TOF, $N_{TPC\_hits} \geq 20$ (for identified tracks)
- **Vertex reconstruction:** Kalman filter based formalism working on MpdParticle objects

Hypertriton reconstruction



Bi+Bi @ 9.2 GeV, min. bias, 40M



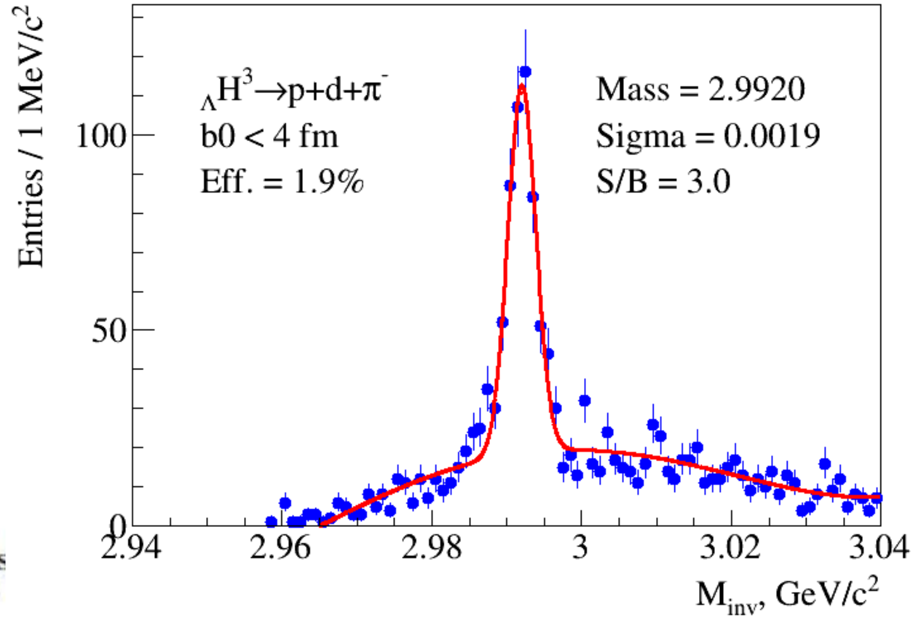
Mesonic decay of $_{\Lambda}H^3$: Event topology

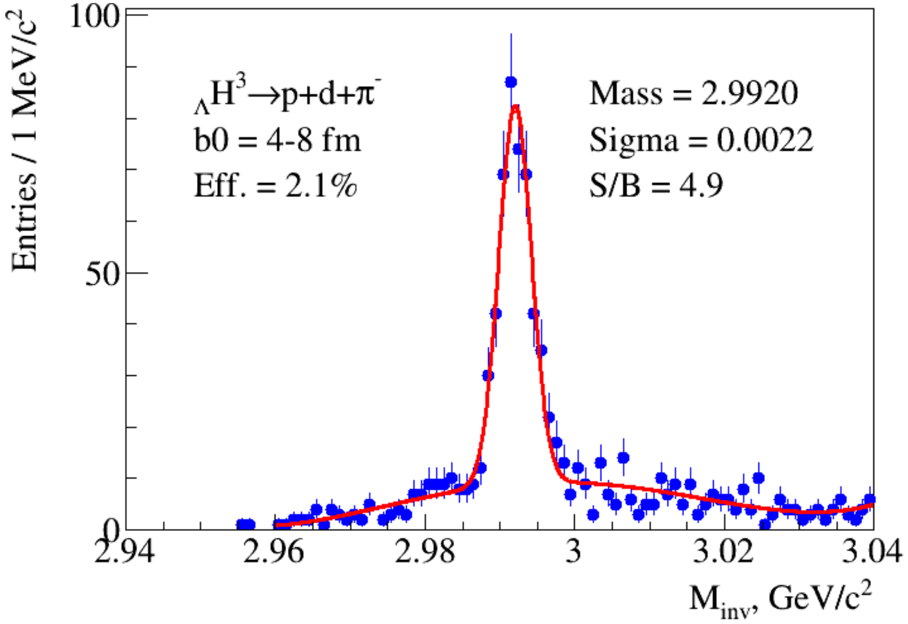
- PV – primary vertex
- V_0 – vertex of hyperon decay
- dca – distance of the closest approach
- path – decay length

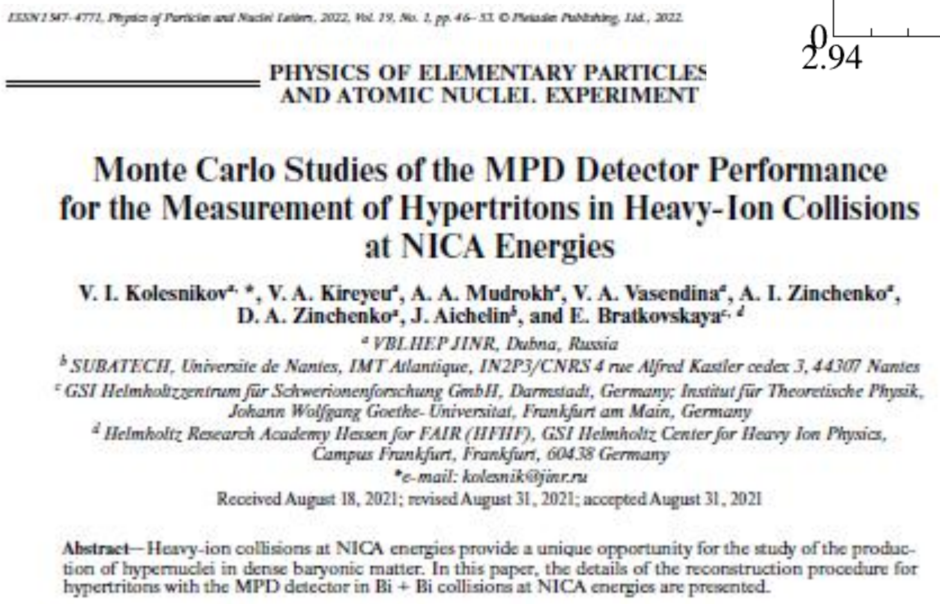
Decay channel	Branching ratio	Decay channel	Branching ratio
$\pi^{-} + {}^{3}He$	**24.7%**	$\pi^{-} + p + p + n$	1.5%
$\pi^{0} + {}^{3}H$	12.4%	$\pi^{0} + n + n + p$	0.8%
$\pi^{-} + p + d$	**36.7%**	$d + n$	0.2%
$\pi^{0} + n + d$	18.4%	$p + n + n$	1.5%

Testing reconstruction efficiency in centrality bins

Bi+Bi @ 8.8 GeV,
15M min. bias events







ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2022, Vol. 19, No. 1, pp. 46–53. © Pleiades Publishing, Ltd., 2022.

PHYSICS OF ELEMENTARY PARTICLES AND ATOMIC NUCLEI. EXPERIMENT

Monte Carlo Studies of the MPD Detector Performance for the Measurement of Hypertritons in Heavy-Ion Collisions at NICA Energies

V. I. Kolesnikov[a], *, V. A. Kireyeu[a], A. A. Mudrokh[a], V. A. Vasendina[a], A. I. Zinchenko[a], D. A. Zinchenko[a], J. Aichelin[b], and E. Bratkovskaya[c, d]

[a] VBLHEP JINR, Dubna, Russia
[b] SUBATECH, Universite de Nantes, IMT Atlantique, IN2P3/CNRS 4 rue Alfred Kastler cedex 3, 44307 Nantes
[c] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany; Institut für Theoretische Physik, Johann Wolfgang Goethe- Universitat, Frankfurt am Main, Germany
[d] Helmholtz Research Academy Hessen for FAIR (HFHF), GSI Helmholtz Center for Heavy Ion Physics, Campus Frankfurt, Frankfurt, 60438 Germany
*e-mail: kolesnik@jinr.ru

Received August 18, 2021; revised August 31, 2021; accepted August 31, 2021

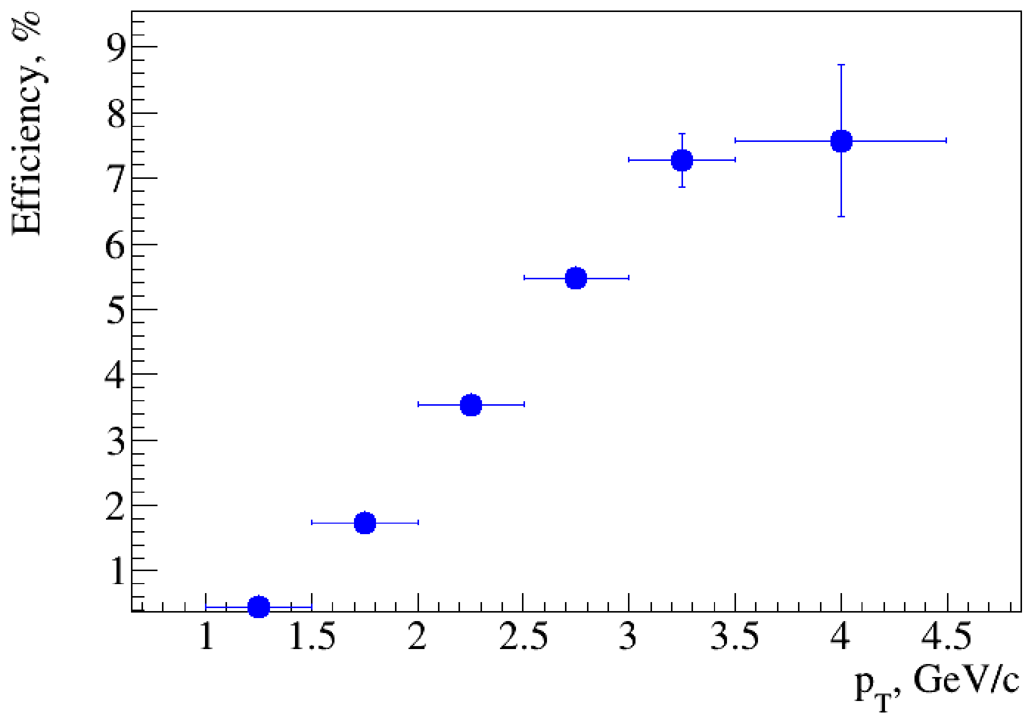
Abstract—Heavy-ion collisions at NICA energies provide a unique opportunity for the study of the production of hypernuclei in dense baryonic matter. In this paper, the details of the reconstruction procedure for hypertritons with the MPD detector in Bi + Bi collisions at NICA energies are presented.

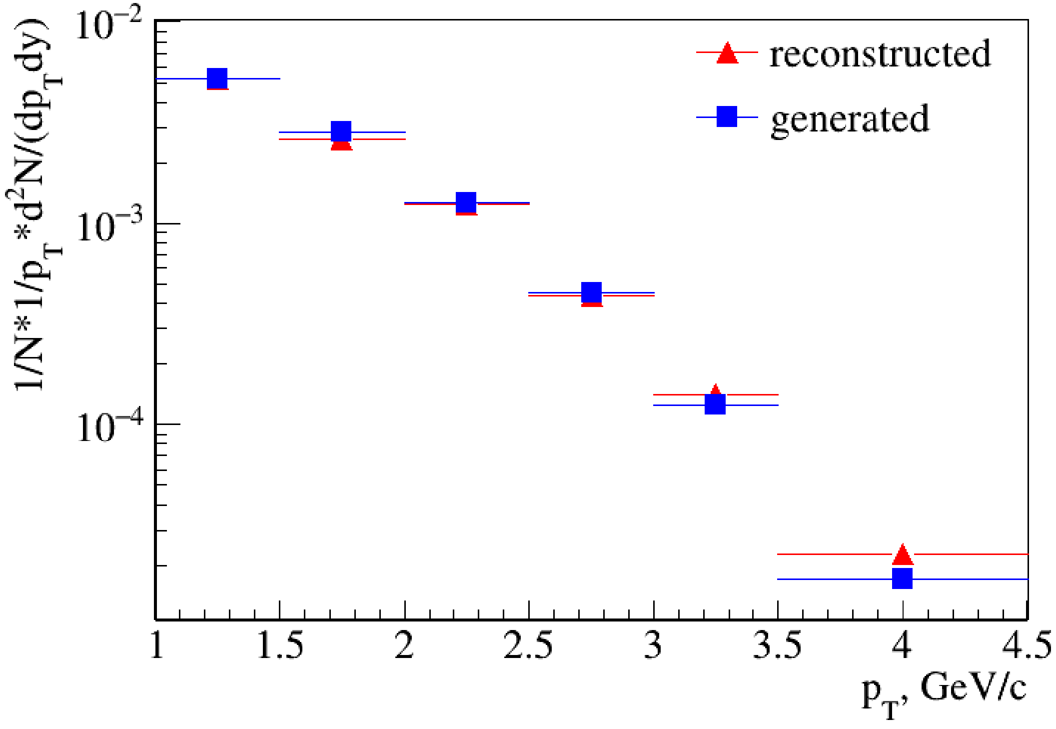
- Two centrality intervals, all pT-bins
- 3-prong decay mode of hypertritons

Efficiency and S/B-ratio is lower in more central collisions

pT-spectrum of hypertritons

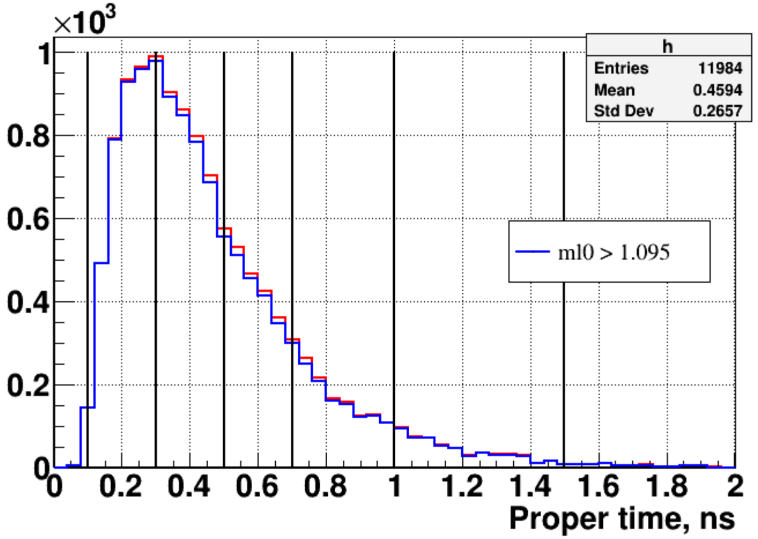
Bi+Bi @ 9.2 GeV, min. bias, 40M





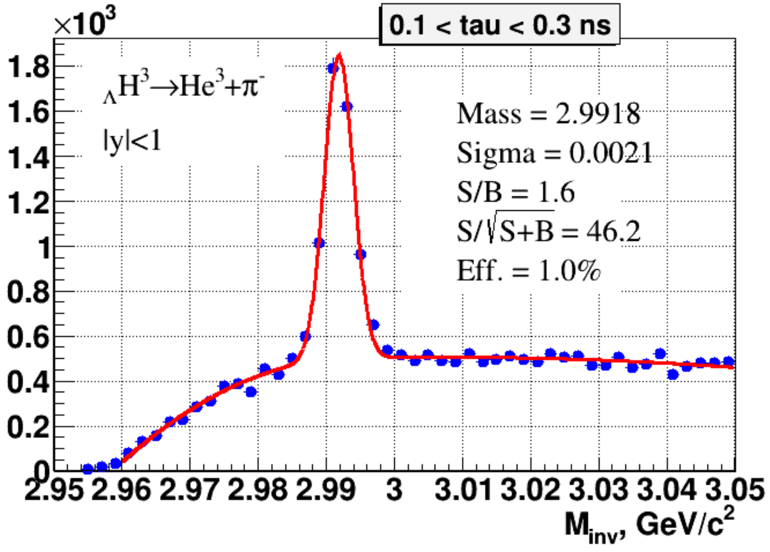
- Invariant spectrum is reconstructed up pT=4.5 GeV/c
- Rapidity density can be obtained in minbias Bi+Bi collisions (with a proper fit function)

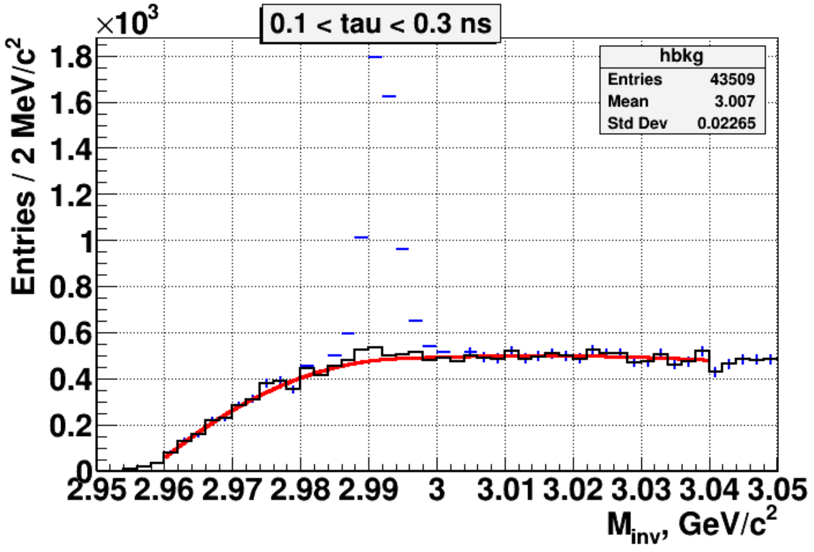
Hypertriton lifetime analysis

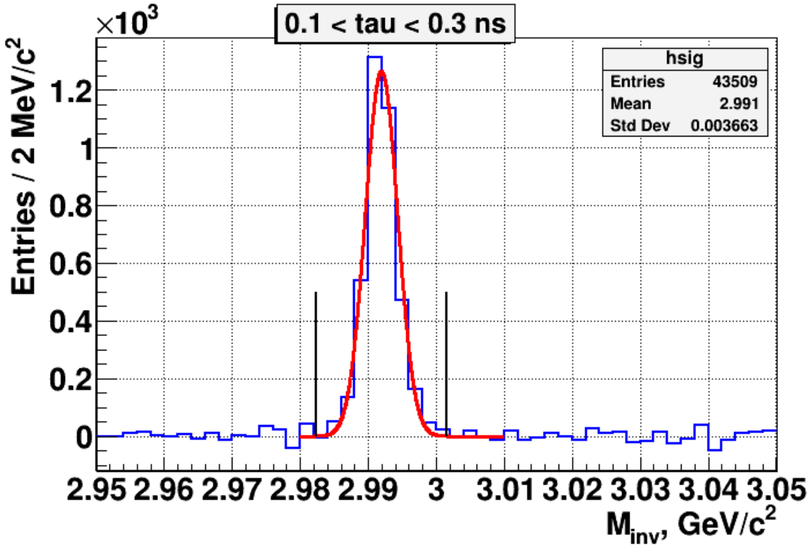


- Large event statistics allows extraction of the lifetime
- Hypertritons are reconstructed in several cτ bins
- The yields are extracted similarly

$c\tau = cML/p$ (c-speed of light, M-hypertriton mass, L-track length)



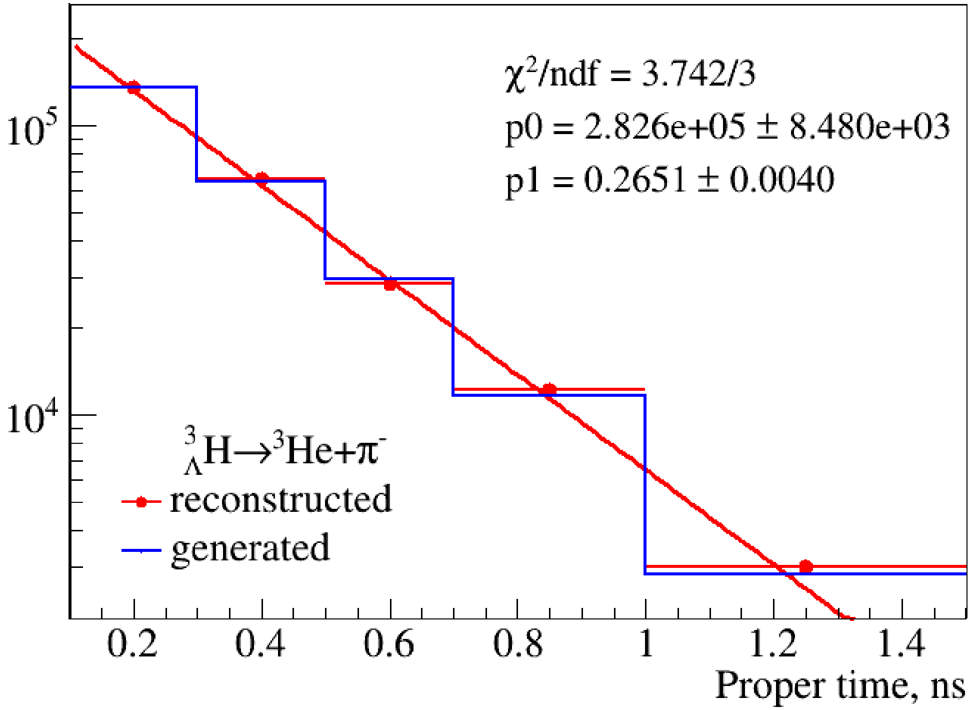


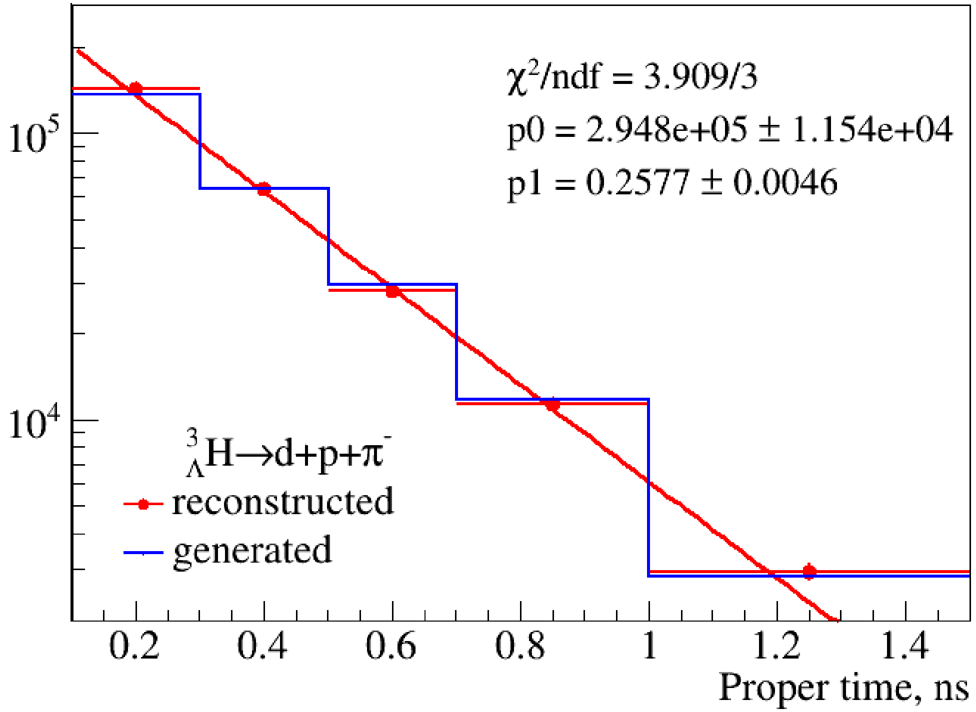


Hypertriton lifetime

Bi+Bi @ 9.2 GeV, min. bias, 40M
b0 < 12 fm, τ = [0.1 – 1.5] ns

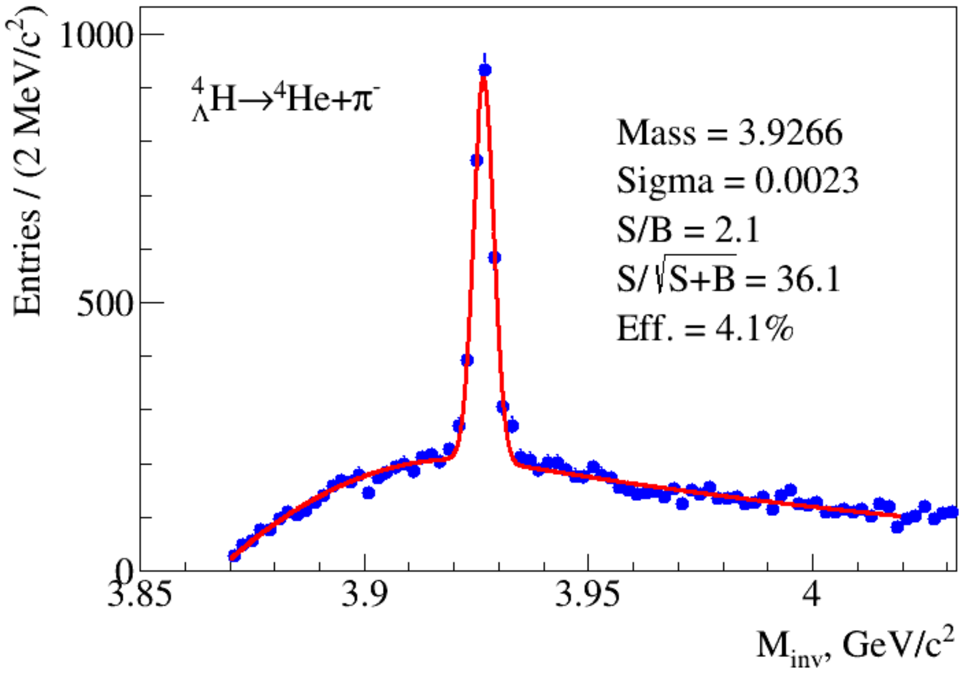
$$N(\tau) = N(0)\exp\left(-\frac{\tau}{\tau_0}\right) = N(0)\exp\left(-\frac{ML}{cp\tau_0}\right),$$



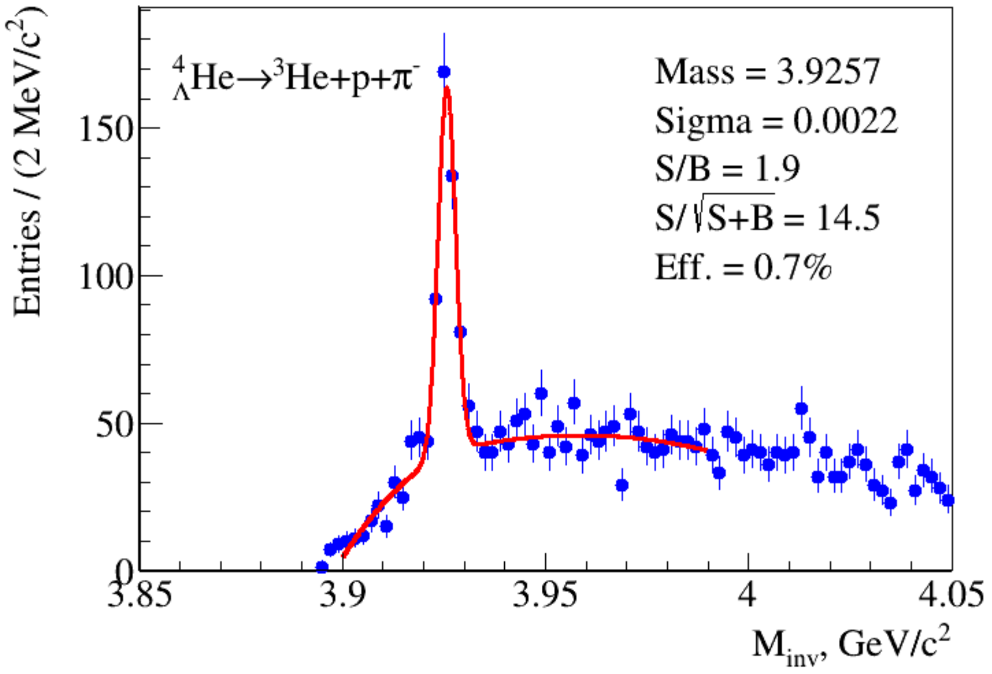


Results for different decay modes are consistent

$^{4}_{\Lambda}H$ and $^{4}_{\Lambda}He$ reconstruction



Branching ratio: 75%



Branching ratio: 32%

Signal embedding technique: The Monte Carlo event sample was enriched by signal particles (hypernuclei), distributed according to the η-p_T phase space given by the PHQMD generator

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

Summary and Plans

- The MPD reconstruction and identification packages have been tested using hypernuclei as a testing tool
- Clear peaks of $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$ and $^{4}_{\Lambda}He$ in invariant mass spectrum have been obtained
- $^{3}_{\Lambda}H$ pT-spectrum has been obtained
- $^{3}_{\Lambda}H$ decay time has been extracted

Plans: Test of Machine Learning Methods for particle identification and hypernuclei selection at NICA/MPD