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Evaluation of prospects for hypernuclei studies with MPD at NICA

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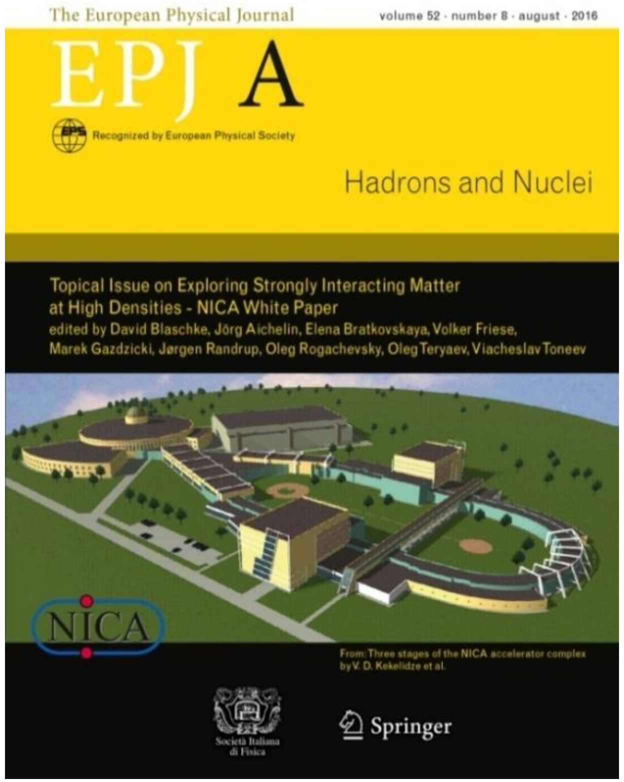
Outline

- NICA project and MPD detector geometry
- Hypernuclei in HIC
- New track reconstruction performance
- New *dE/dx* parameterization in TPC (Garfield++)
- New PID performance in TPC & TOF
- Realistic reconstruction of hypernuclei
- Summary

NICA complex and NICA physics



- New flagship project at JINR (Dubna)
- Based on the technological development of the Nuclotron facility
- Optimal usage of the existing infrastructure
- Modern facility incorporating new technological concepts

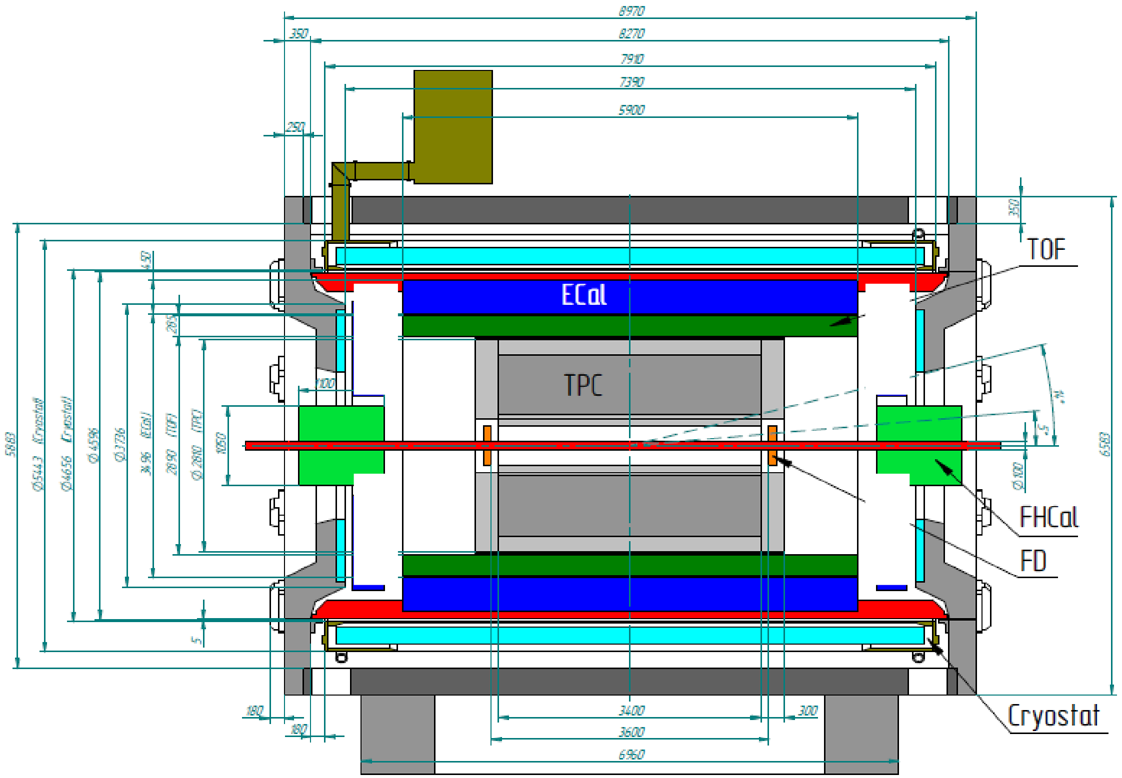
Experimental strategy: energy and system size scan to measure a variety of signals systematically changing collision parameters (energy, centrality, system size). Reference data (i.e. $p+p$) will be taken in the same experimental conditions

NICA parameters:

Beams: *p*, *d*, … $^{197}Au^{79+}$
Collision energy: 4-11 GeV (nuclei)
Luminosity: 10^{27} cm^{-2}s^{-1} (*Au*), 10^{32} cm^{-2}s^{-1} (*p*)
2 Interaction points: MPD and SPD
Fixed target: 1-6A GeV beams

- *Bulk properties, EOS:* particle yields & spectra, ratios, femtoscopy, flow
- *In-Medium modification of hadron properties:* dileptons and resonances
- *Deconfinement (chiral) phase transition at high r_B:* strangeness, Chiral Magnetic (Vortical) effect
- *QCD Critical Point:* event-by-event fluctuations and correlations
- *YN, YY interactions in nuclear matter:* hypernuclei

Multi-Purpose Detector @ NICA



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

Stage 1:

Magnet: 0.5 T superconductor
Tracking: TPC
Particle ID: TOF, ECal, TPC
T0, Triggering: FD
Centrality, Event plane: FHCal

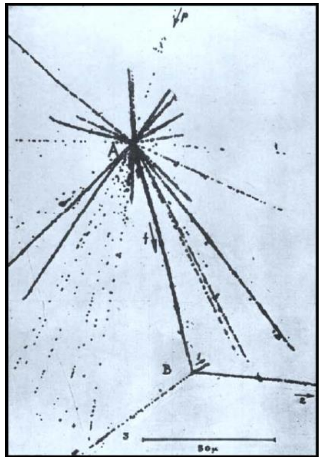
Requirements to the apparatus:

- Hermeticity, homogenous acceptance: 2π in azimuthal angle
- Highly efficient 3-D track reconstruction, high resolution vertexing
- Powerful PID: π/K up to 1.5 GeV/c, K/p up to 3 GeV/c, ECAL for γ, e
- Careful event characterization: impact parameter & event plane reconstruction
- Minimal dead time, event rate capability up to ~ 6 kHz

HIC: Hypermatter production

Hypernuclei – strange nuclear systems (S = -1, -2, …)

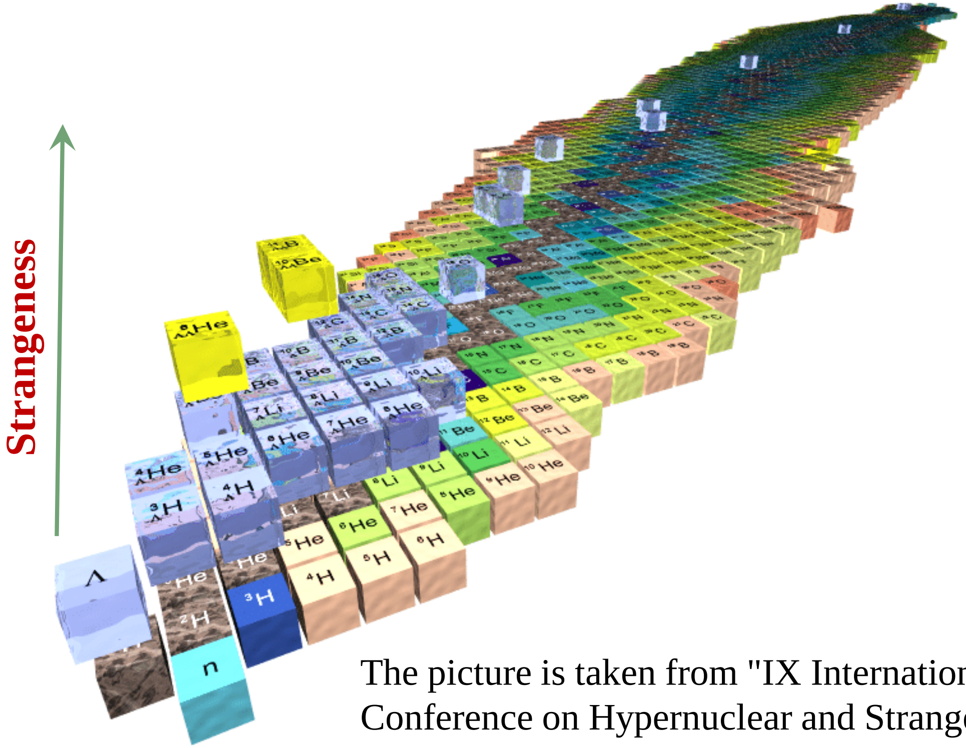
- Contain one (or more) hyperons (*Λ*, *Σ* or *Ξ*) instead of a nucleon
- Give access to the third dimension of the nuclear chart (strangeness)
- Lifetimes close to free *Λ* (weak decay)
- Precise information on *YN* interaction: nuclear EOS, astrophysics
- Hypernuclei ground, excited states and life times: critical assessments for QCD calculations and model predictions
- Production mechanism of bound states with hyperons: coalescence versus spectators-participants interactions, exotic states, dibaryons



The first hypernuclear measurement by Danysz and Pniewski in 1952 from a cosmic ray emulsion event.

No hyperon target available. No hyperon beam available. However, *YN* and *YY* interaction can be investigated: hypernuclei is micro-laboratory with protons, neutrons and hyperon

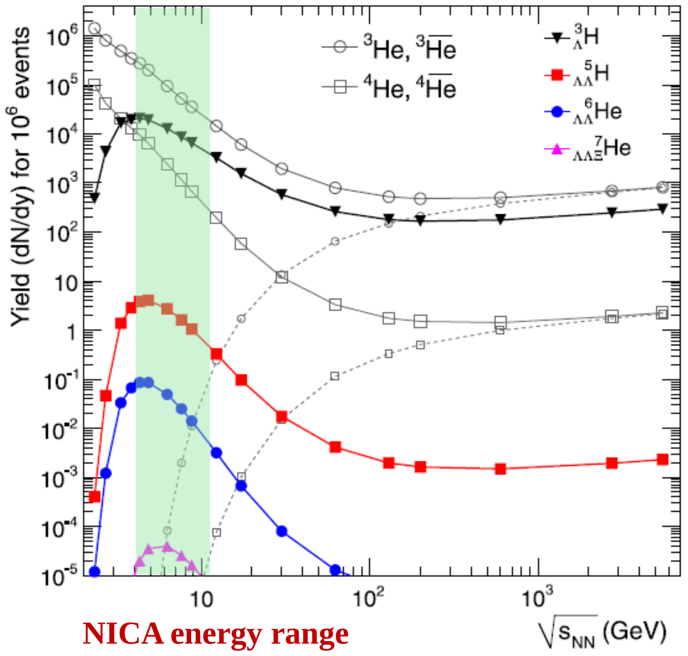
Duality: Nuclear ⟷ Particle Physics



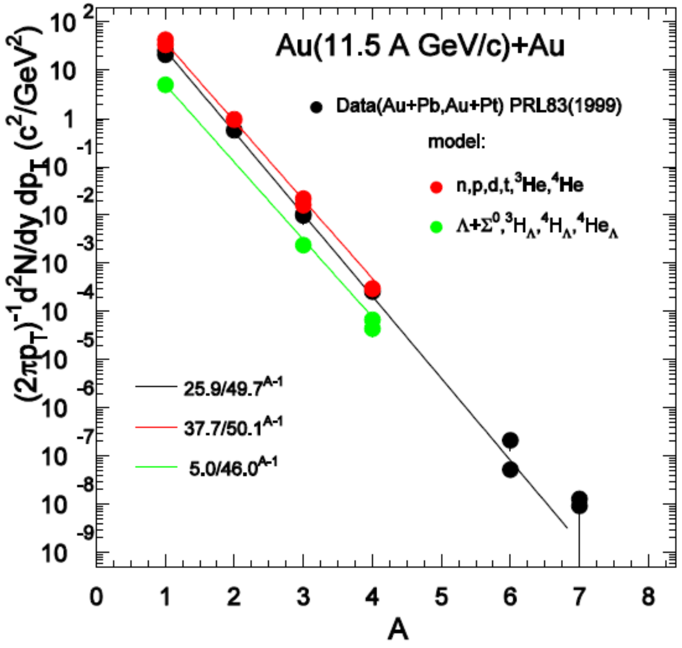
The picture is taken from "IX International Conference on Hypernuclear and Strange Particle Physics" at Johannes Gutenberg-Universität Mainz.

HIC: Multy-hypernuclear production

Statistical model:
A.Andronic, P.Braun-Munzinger, J.Stachel, H.Stocker
Physics Letters B 697 (2011)



DCM-QGSM model:
K.Gudima, V.Toneev



Expected yields for Stage'2 ($L=10^{27}$ $cm^{-2}s^{-1}$):

$^{3}_{\Lambda}H$ for MPD (10 weeks) @ 5 GeV: $\mathbf{9 \cdot 10^5}$
$^{4}_{\Lambda}He$ for MPD (10 weeks) @ 5 GeV: $\mathbf{1 \cdot 10^5}$

- ***In heavy-ion reactions:*** production of hypernuclei through coalescence of Λ with light fragments
- ***Maximal yield*** predicted for $\sqrt{s_{NN}}$ = 4-5 GeV (statistical model)

➡ NICA energy range is ideally suited for the search of (double) hypernuclei

Main goal:

Realistic hypernuclei reconstruction with NEW realistic MPD performance

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METHODS
OF PHYSICAL EXPERIMENT

Evaluation of the MPD Detector Capabilities for the Study of the Strangeness Production at the NICA Collider[1]

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Abstract—One of the main tasks of the NICA/MPD physics program is the study of the strangeness production in nuclear collisions. In this paper the MPD detector performance is presented for measurements of K_S^0-mesons, $\Lambda(\bar{\Lambda})$-hyperons and hypertritons in central Au + Au collisions at NICA energies.

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1. INTRODUCTION

The primary goal of the NICA (Nuclotron-based Ion Collider fAcility) heavy-ion program [1] is the study of the properties of nuclear matter under extreme conditions. At sufficiently high temperature and baryon density achieved in central collisions of relativistic nuclei, a transition into a state of deconfined quarks and gluons - quark gluon plasma (QGP) is expected. In the dense nuclear matter, the deconfinement phase transition might be accompanied by a restoration of chiral symmetry due to melting of the quark condensate [2–4]. Recent results on hadro-production from the CERN SPS [5] and RHIC [6] indicate that the onset of the deconfinement is likely to be observed in cental A+A collisions at energies $\sqrt{s}$ > 7A GeV. Moreover, the analysis of the thermodynamic freeze-out parameters extracted from the data over a wide energy range performed in [7] reveals that the net-baryon density in central collisions of heavy ions has a maximum in the energy range from $\sqrt{s}$ = 5A to 9A GeV. So, the energy range of the NICA collider (4 < $\sqrt{s}$ < 11A GeV)

detecting both the hadronic (π, K, p, Λ, Ξ, Ω) and non-hadronic (e, γ) probes.

Study of (anti)hyperon production is of particular interest because of several reasons. First of all, the strangeness enhancement in heavy-ion collisions relative to proton induced reactions has been proposed as a signature for the deconfinement. The expected increase of the strange particle production in a QGP phase is due to both the lower threshold of the $s\bar{s}$-pair production and the addition of gluon fragmentation channels [11]. It was also established experimentally that this strangeness enhancement is stronger for particles with higher strangeness content [12, 13].

Secondly, since the hadronic cross-sections of multi-strange hyperons are small, additional rescattering effects in the dense hadronic matter for strange hadrons are not so important as for other hadrons. Thus, measured phase-space distributions of strange hyperons reveal important characteristics of the fireball at the early stages of the system evolution. Moreover, it has recently been observed by the STAR experiment that the characteristic azimuthal anisotropy

The first hypernuclei simulation with early version of MPD and simplified track reconstruction in TPC

Software development:

Towards a realistic simulation of the MPD / NICA

- Realistic description of the response of detectors, creation and configuration 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

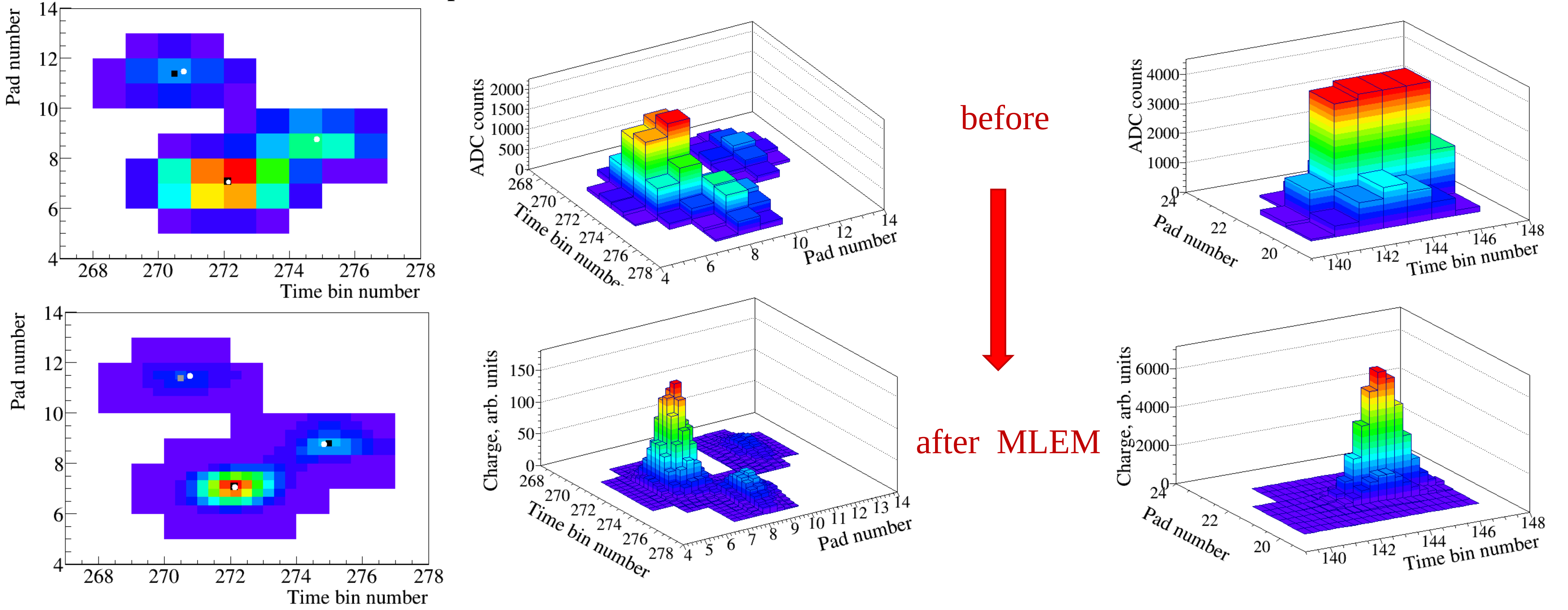
Software requirements for hypernuclei simulation:

- Qualitative reconstruction of the tracks of hadrons and light nuclei
- Good recovery of primary and secondary vertex
- High efficiency of identification of both hadrons and light nuclei

Cluster topologies and Maximum Likelihood - Expectation Maximization procedure

2D and 3D views of a precluster of three tracks

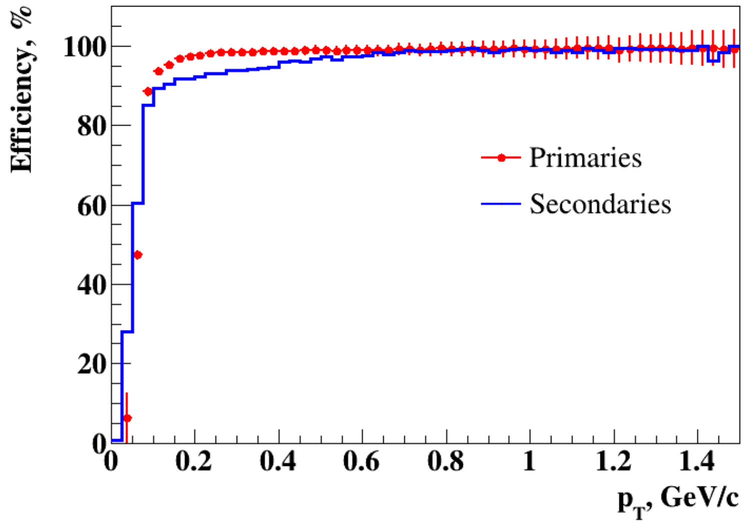
3D view of a cluster with overflows

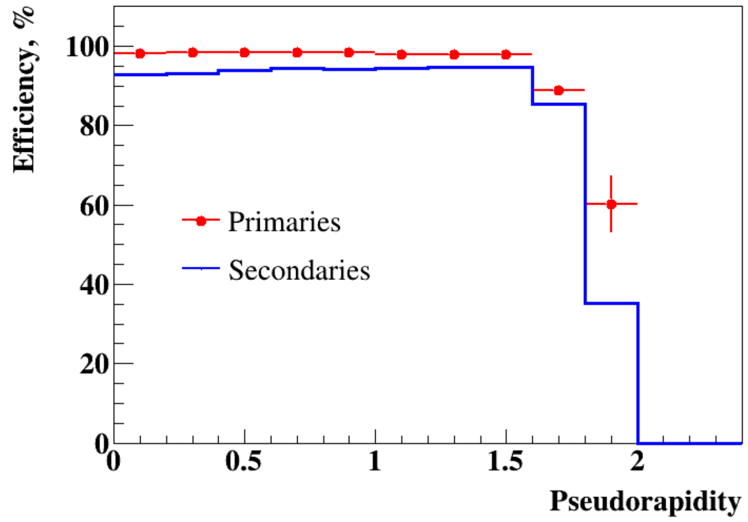


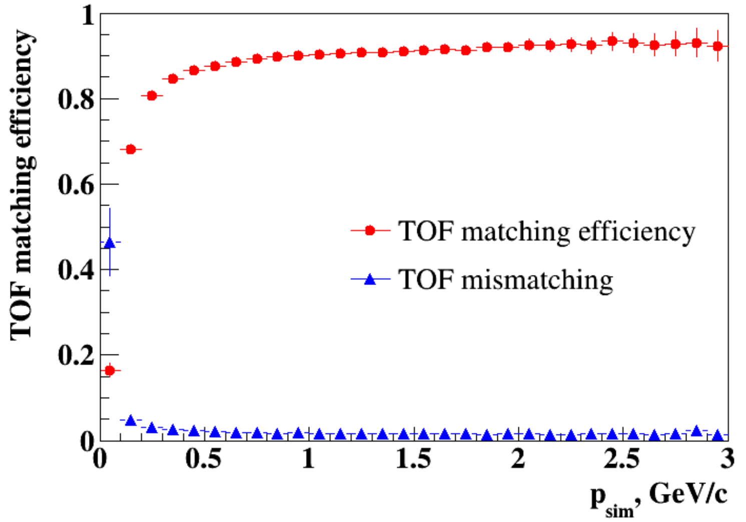
True hit coordinates - ○, Reconstructed hit coordinates - ■. On the top left plot one hit has not been reconstructed.
Bottom - 2D and 3D views of the same precluster after the MLEM procedure.

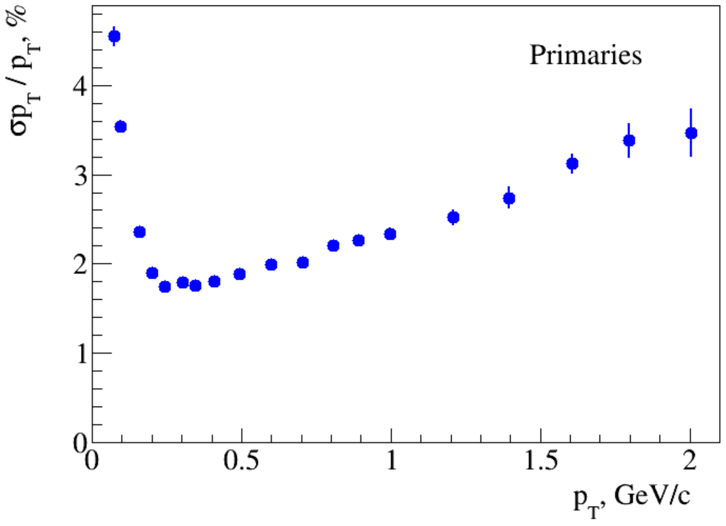
Top - ADC output: charge loss because of overflows;
Bottom - signal recovery using undistorted measurements from the tails after MLEM procedure.

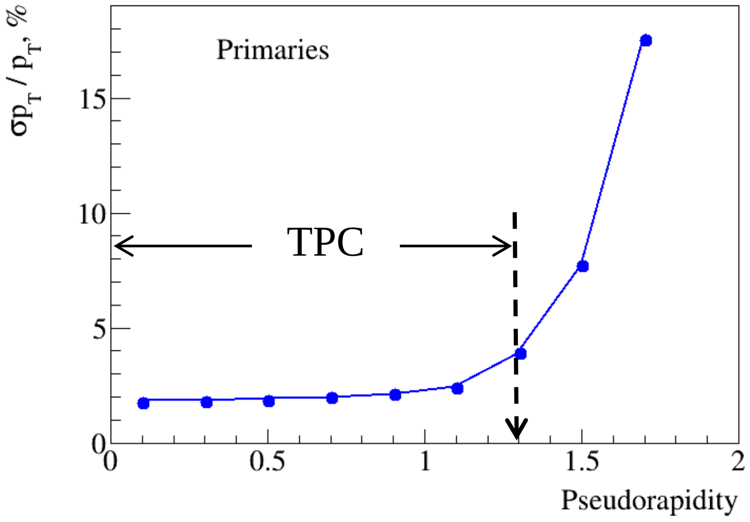
Realistic MPD simulation and reconstruction

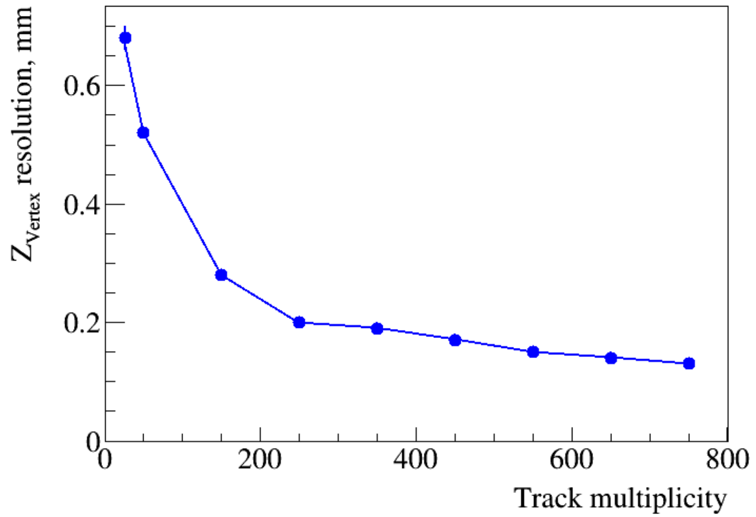




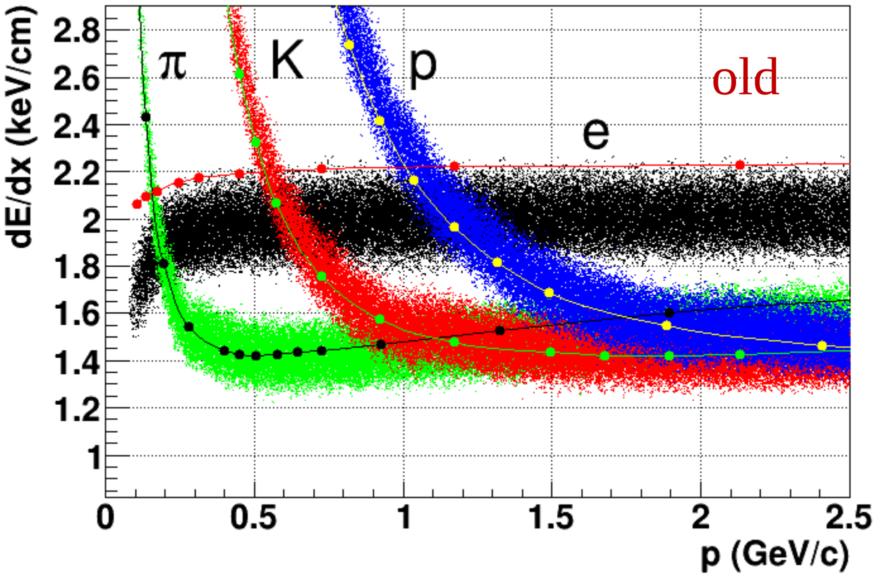


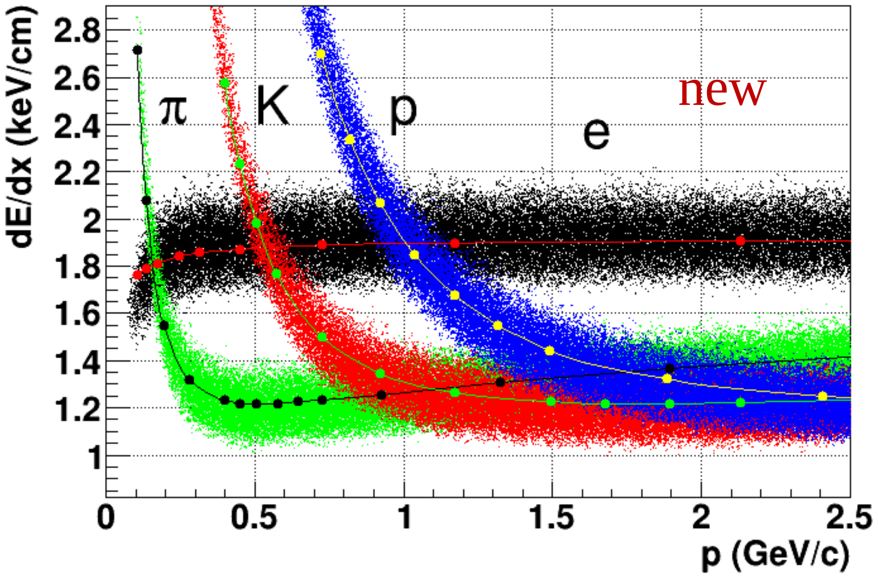






New *dE/dx* performance in TPC





More details in I.Rufatov`s talk

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

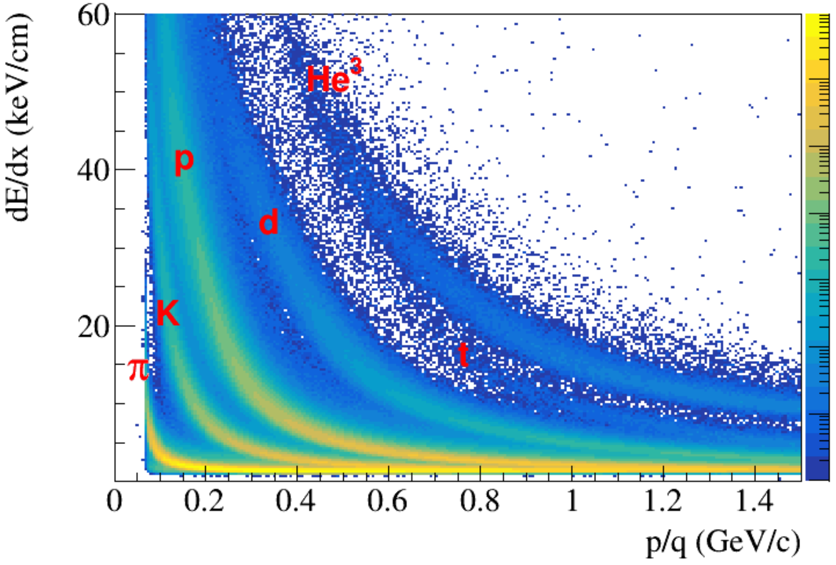
	ALICE	STAR	MPD
Gas	85% *Ne* mix	P10	P10
N rows x pitch (mm):			
Inner pads	64 x 7.5 mm	13 x 12 mm	26 x 12 mm
Outer pads	64 x 10 mm	32 x 20 mm	27 x 18 mm
Outer-2 pads	32 x 32 mm	–	–
P10 mixture – 90% *Ar*, 10% methane			

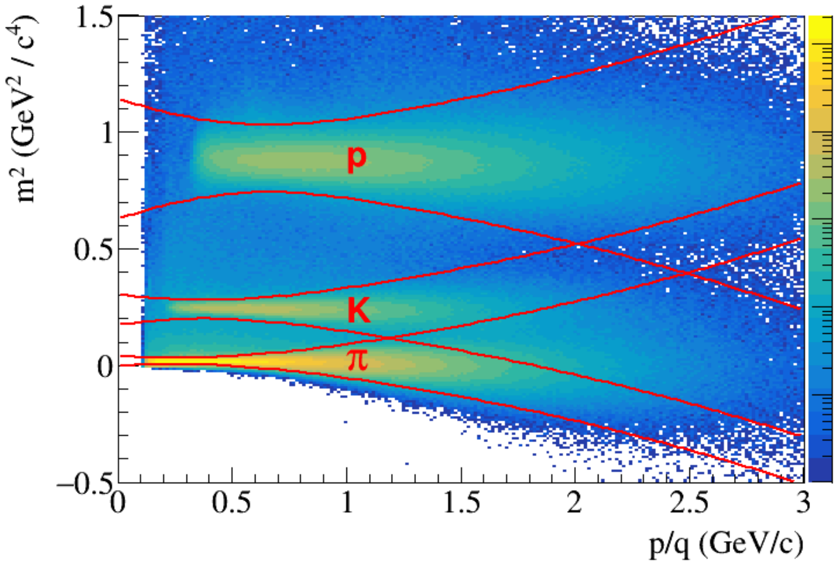
Data vs MC with old parameterization *dE/dx* in GEANT3:

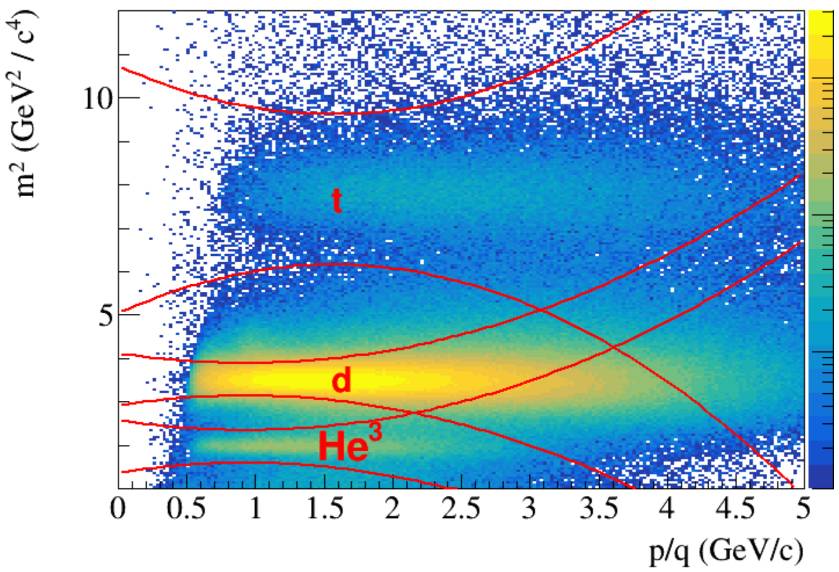
- Essentially (~20%) underpredicts relativistic rise of the ionization energy loss as seen from comparison of pion and electron bands
- Overpredicts energy loss at low momentum (protons at p<1 GeV/c)
- Gives shifted momentum of intersections of electron and other particles bands
- Gives distorted input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

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

New PID performance in TPC & TOF







More details in A.Zinchenko`s talk

dE/dx vs momentum in TPC and
m^2 vs momentum in TOF

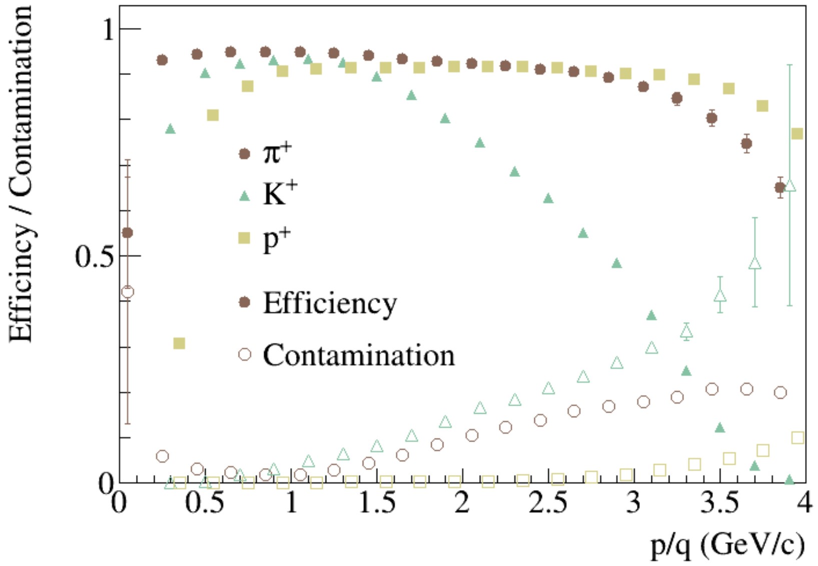
Selection criteria for events and identified tracks:

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

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

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

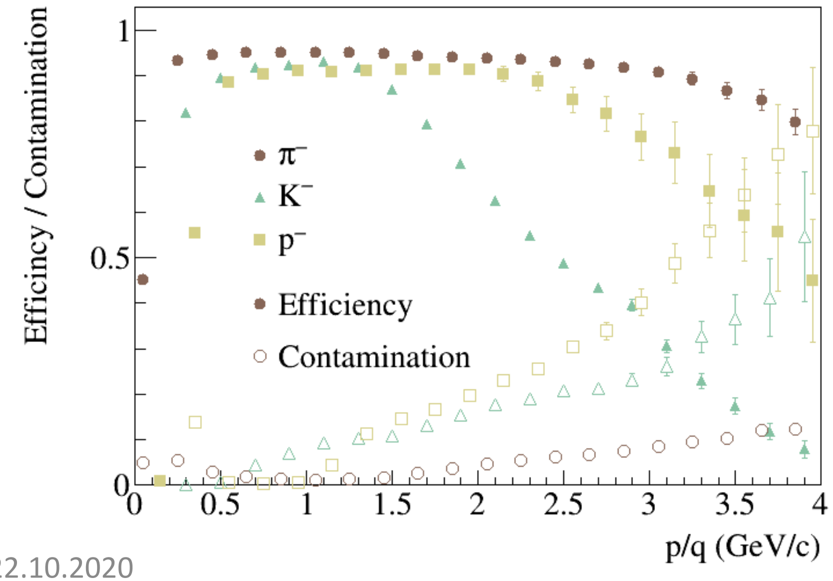
PID: Efficiency and Contamination

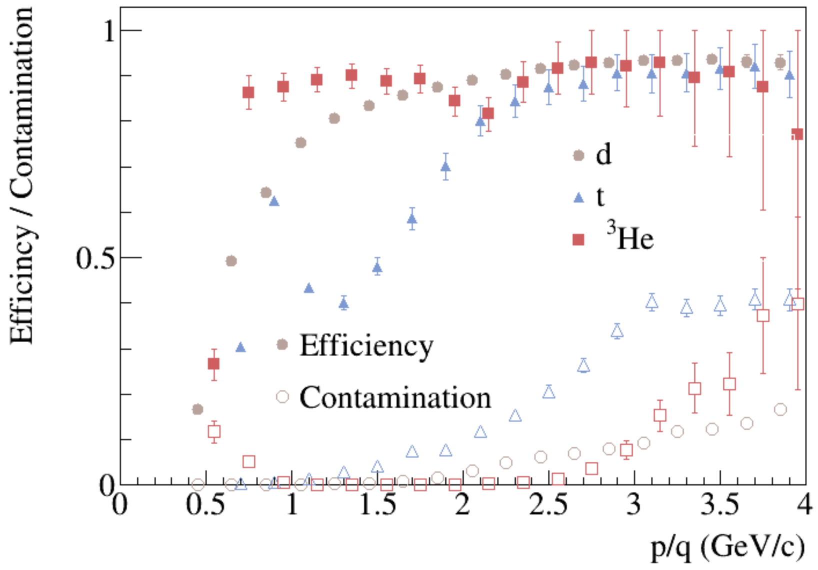


Primaries + secondaries (after GEANT) particles

$$\text{Eff.} = \frac{\text{particles which are correctly identified}}{\text{all particles of a given species (PDG)}}$$

$$\text{Cont.} = \frac{\text{particles which are falsely identified}}{\text{all identified particles of a given species}}$$

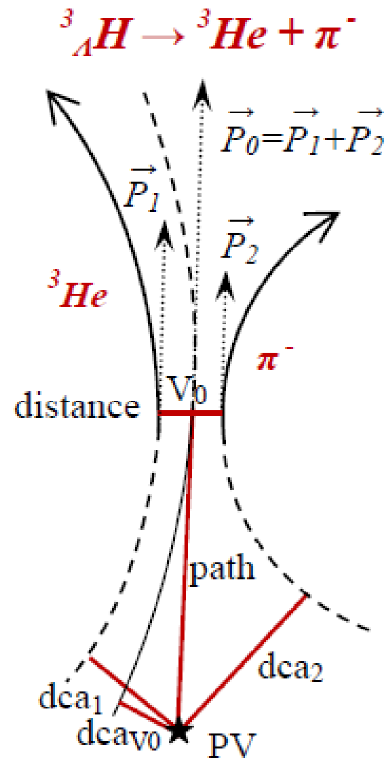


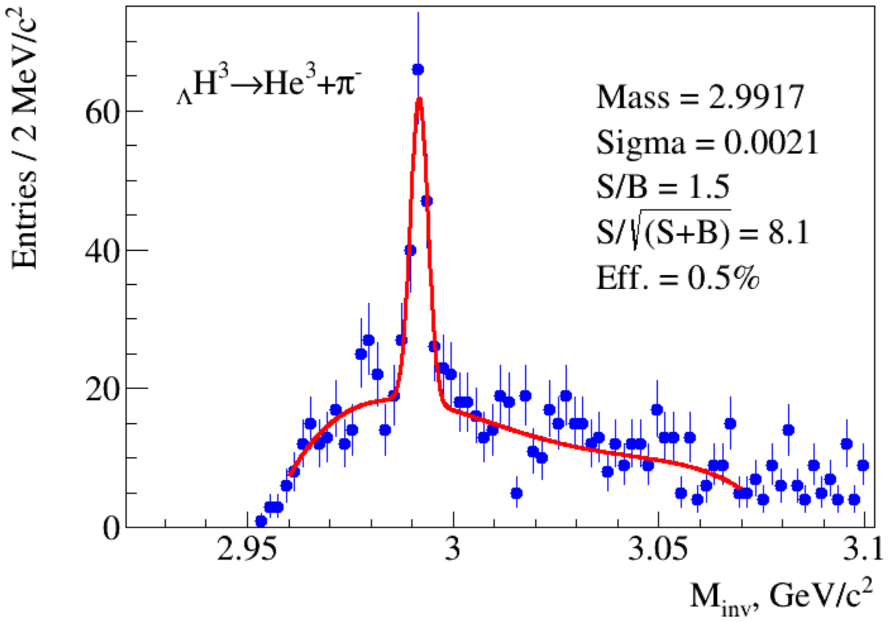


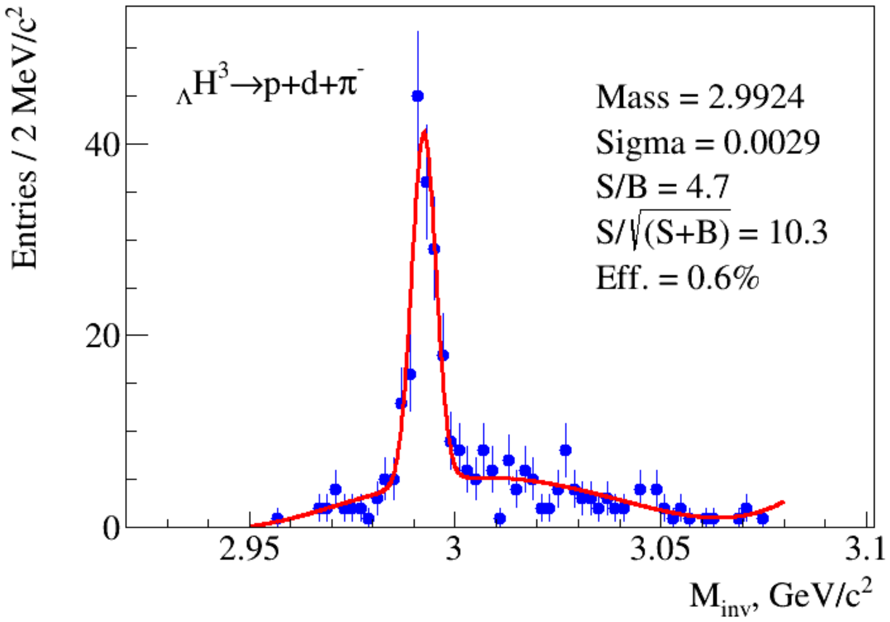
Data set

- **Generators:** DCM-QGSM, Au+Au @ 5 GeV, central, 0.9M 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)
- NEW **energy loss simulation in gas TPC:** with new parameterization in GEANT (Garfield++)
- NEW PID**:** dE/dx in TPC & m^2 in TOF, $N_{TPC\_hits} \geq 27$ (for identified tracks)
- **Vertex reconstruction:** Kalman filter based formalism working on MpdParticle objects

Hypertriton reconstruction







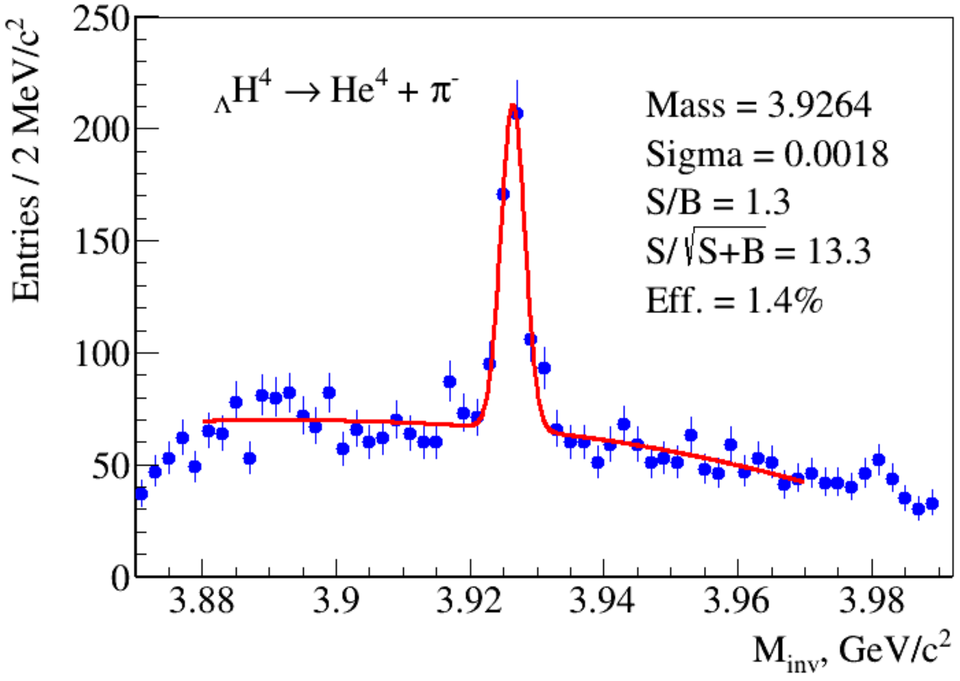
Efficiency = (reconstructed, identified and selected *Hyp* at $|\eta| < 1.3$) / (all generated *Hyp* after GEANT within 50 cm of PV) – ***includes branching ratios, detector acceptance and reconstruction efficiency***

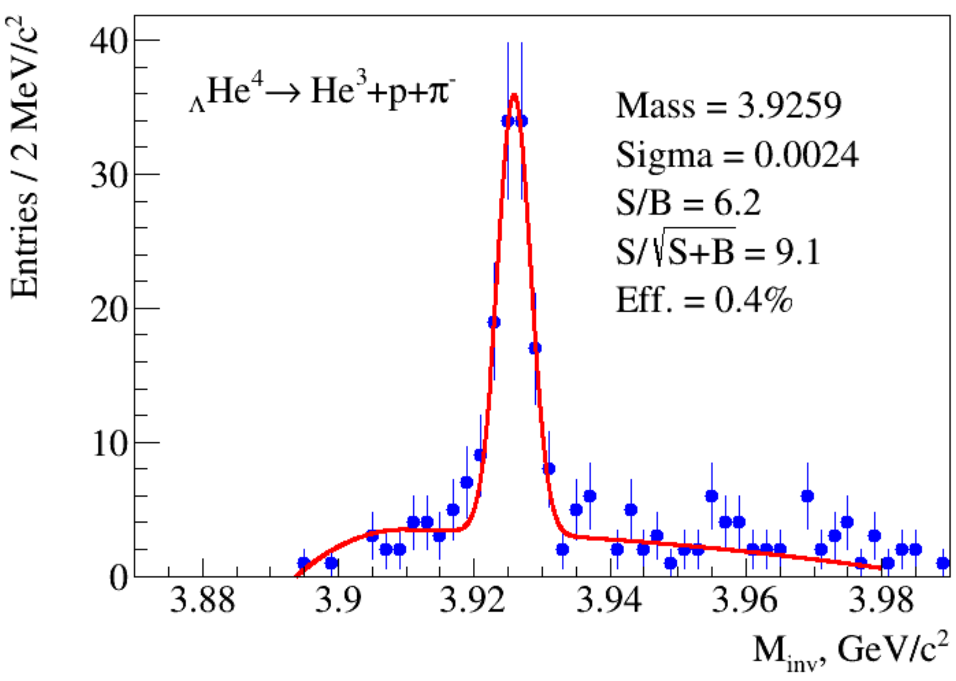
Mesonic decay of $_\Lambda H^3$: Event topology

- 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
$\pi^- + {}^3He$	**24.7%**	$\pi^- + p + p + n$	1.5%
$\pi^0 + {}^3H$	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%

${}_{\Lambda}H^4$ and ${}_{\Lambda}He^4$ 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 y-p_T phase space given by the DCM-QGSM generator

Equivalent statistics: ~20M events for ${}_{\Lambda}H^4$ and ~30M for ${}_{\Lambda}He^4$

Summary

- The updated MPD reconstruction and identification packages have been tested using hypernucleus as a testing tool
- New method with Garfield++ package of track energy loss calculation in gas volume of TPC detector has been tested
- For hadrons and light nuclei the new combined identification, based *dE/dx* in TPC and m^2 in TOF, has been tuned and tested
- Clear peaks of $_{\Lambda}H^3$, $_{\Lambda}H^4$ and $_{\Lambda}He^4$ in invariant mass spectrum have been obtained

The updated results on the yields of hypernuclei have largely confirmed the earlier, rather ideal, estimates and increased the level of reliability of the physical predictions underlying the physical program of the experiment.

The obtained results showed that even the starting version of the MPD setup (TPC+TOF) has good opportunities for studying hypernuclei.

Thank you for attention!