Probing dense nuclear matter by heavy-ion collision experiments at NICA

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on behalf of NICA

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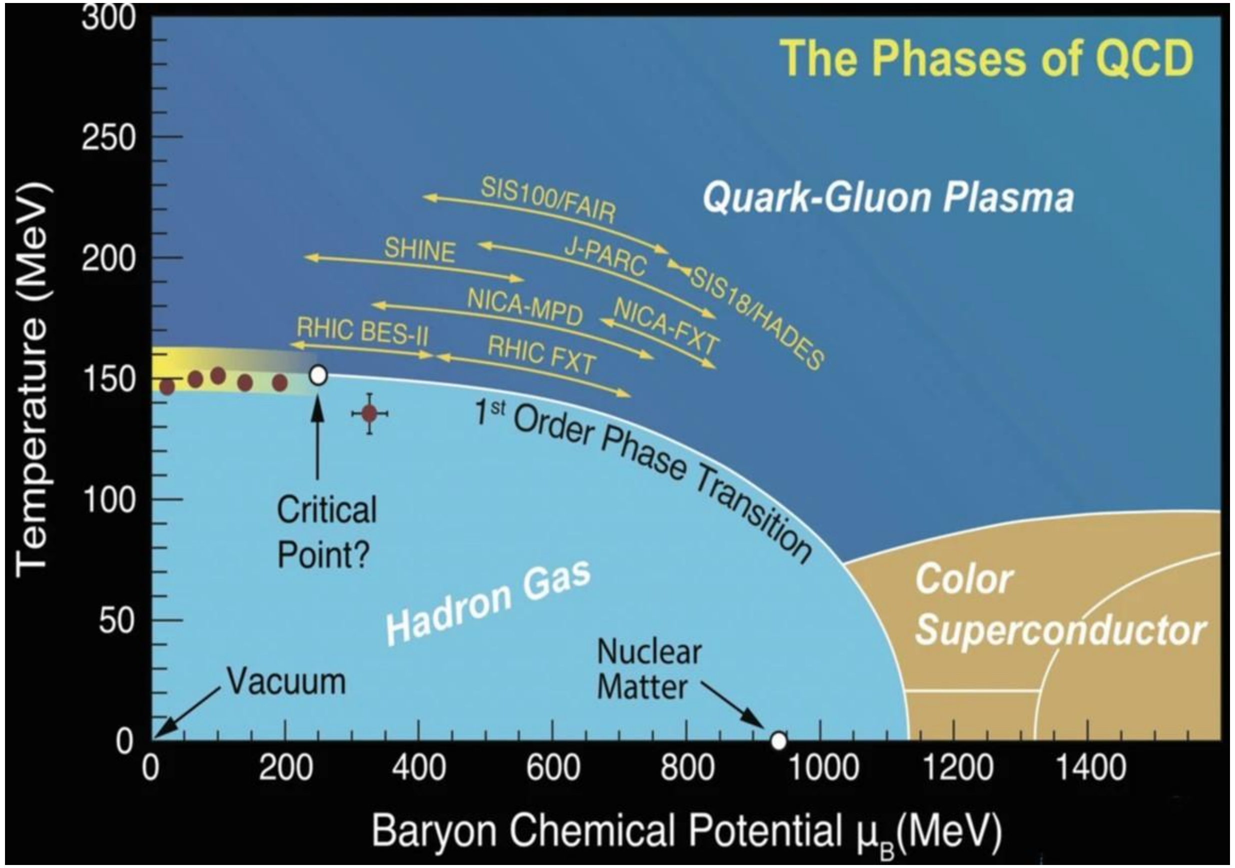
OUTLINE

- Introduction
- NICA accelerator complex: status and prospects
- Detectors for heavy-ion physics at NICA
- Recent results in A+A collisions from NICA
- Summary

Heavy-ion collisions and QCD phase diagram

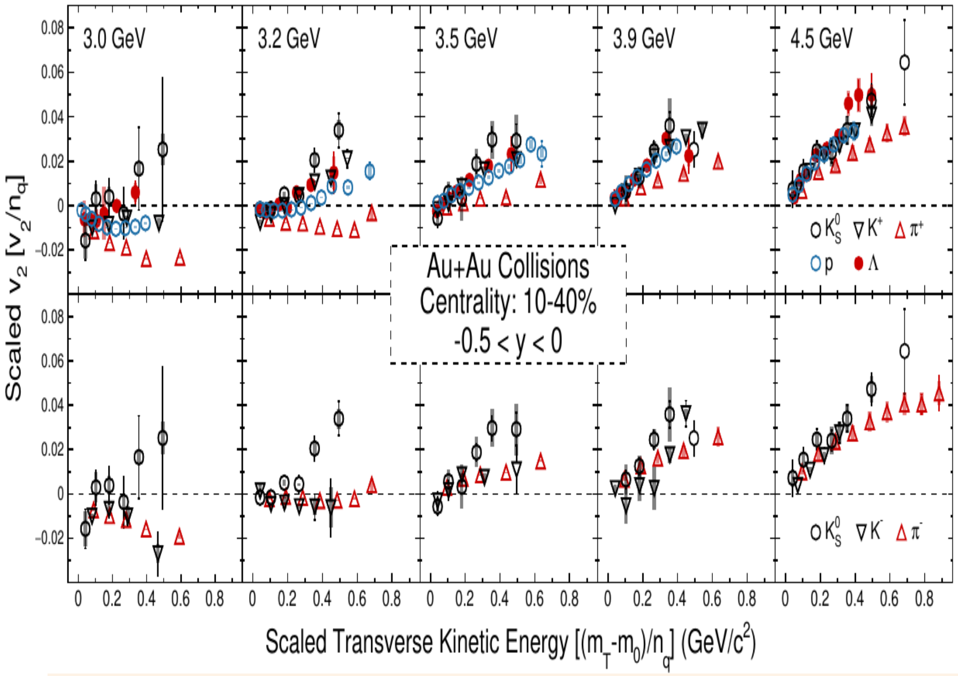


- **QCD phase diagram**: rich structure and variety of conditions. Theoretically probed by lattice QCD and effective models, experimentally by heavy-ion collisions. Location of CEP and 1st order PT is one among major goals
- **NICA niche**: moderate-temperature and high-density domain. High μ_B region is poorly explored, results from HIC have implications for nuclear physics and astrophysics
- Several running and future experimental programs worldwide (RHIC, SPS, FAIR, NICA, HIAF)

Nuclear matter in the high-μ_B region

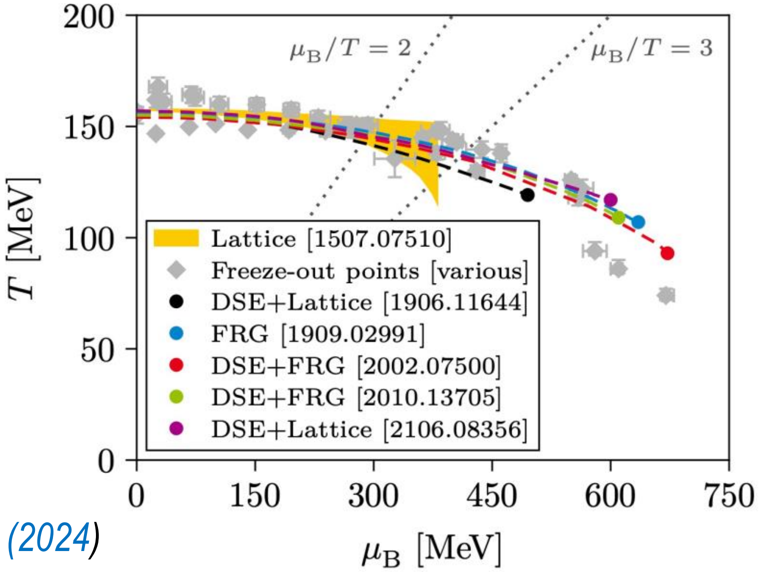
- Low energies: baryons and baryon resonances are dominant *dof*, in-medium effects play a role in hadroproduction
- Higher energies: transition from baryon-rich to meson-dominated matter and QGP droplets can be formed

STAR Collab., arXiv:2504.02531v1



A gradual onset of NCQ scaling is observed, emergence of partonic collectivity at 5 GeV

- LQCD results:
  1) T_{crit} < 135 MeV
  2) HG_to_QGP transition is a crossover at $\mu_B/T<4$
- CEP location might be in the region of T and μ_B achievable at NICA



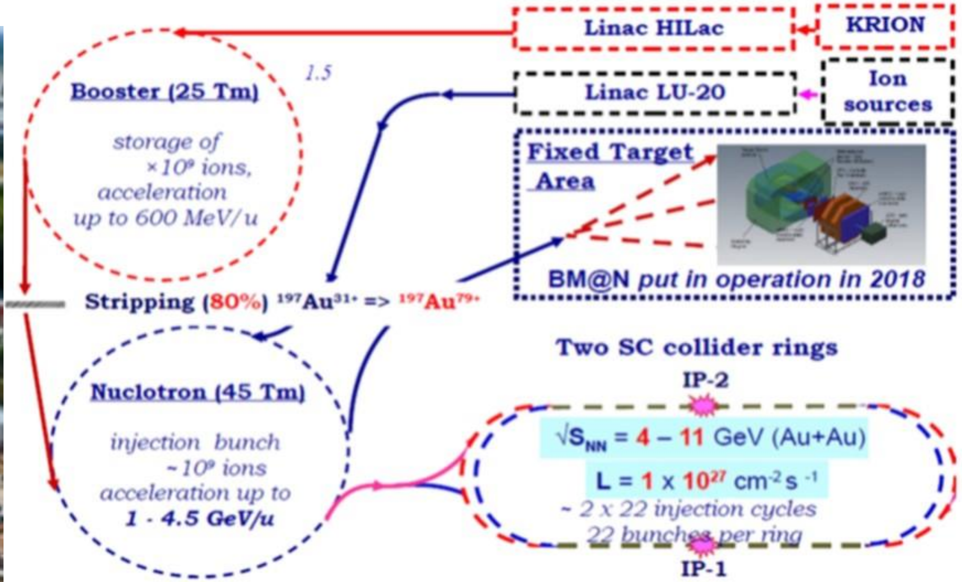
Phys. Rev. D 110, 094006 (2024)

Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	F. Karsch et al.
Summary	**495 - 654**	**100 - 119**

(μ_c, T_c) = (495 - 654, 100 - 119) MeV → $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

- Multiplicities, <pT>, azimuthal anisotropies are sensitive to EOS. Cumulants of conserved quantities and particle ratios are suggested to be sensitive to the QCD critical point. In-medium potentials: resonances and (hyper)nuclei.
- Experimental strategy: vary collision energy and system size to probe different trajectory across phase diagram

NICA – Nuclotron-based Ion Collider fAcility (JINR, Dubna)



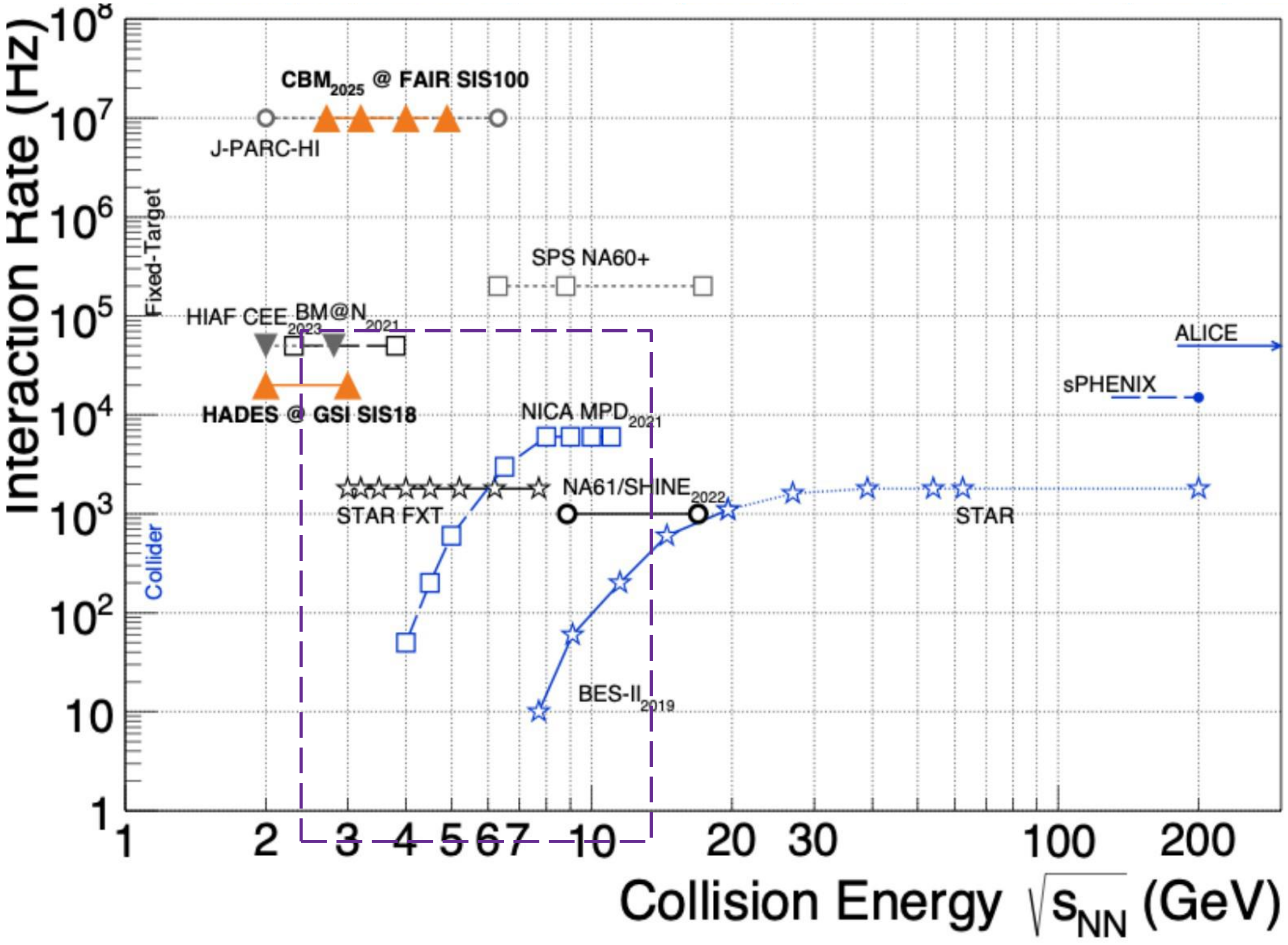
Z/A	$\sqrt{s}$ (GeV)	L (cm^{-2} c^{-2})
1 (protons)	27	10^{32}
0.5 (light nuclei)	13	10^{28}
~0.4 (heavy nuclei)	11	10^{27}

- NICA is approaching full commissioning, all infrastructure elements are ready (cryo, electricity, water, etc.)
- Fixed target mode is fully functional, ion beams up to to ^{124}Xe (E/A=0.5-4.5 GeV) are provided by Nuclotron,
- The (fixed-targed) BM@N experiment has taking data (collisions with C, Ar and Xe beams are recorded)
- Collider and MPD detector commissioning : 2025 onwards

Beam species at NICA and event rates

- Many beam combinations at NICA, a beam energy and system-size scan will be performed
- A high event rate in the region of the max. baryonic density: up to 7 kHz for Au+Au collisions

Beam	Beam intensity (particle / cycle)		
	Current	Ion source type	at NICA
p	$3\cdot10^{10}$	Duoplasmotron	$5\cdot10^{12}$
d	$3\cdot10^{10}$	--- „ ---	$5\cdot10^{12}$
^{4}He	$8\cdot10^{8}$	--- „ ---	$1\cdot10^{12}$
d↑	$2\cdot10^{8}$	SPI	$1\cdot10^{10}$
^{7}Li	$8\cdot10^{8}$	Laser	$5\cdot10^{11}$
^{11,10}B	$1\cdot10^{8}$	--- „ ---	
^{12}C	$1\cdot10^{9}$	--- „ ---	$2\cdot10^{11}$
^{24}Mg	$2\cdot10^{7}$	--- „ ---	
^{14}N	$1\cdot10^{7}$	ESIS (“Krion-6T”)	$5\cdot10^{10}$
^{40}Ar	$1\cdot10^{9}$	--- „ ---	$2\cdot10^{11}$
^{56}Fe	$2\cdot10^{6}$	--- „ ---	$5\cdot10^{10}$
^{84}Kr	$1\cdot10^{4}$	--- „ ---	$1\cdot10^{9}$
^{124}Xe	$1\cdot10^{4}$	--- „ ---	$1\cdot10^{9}$
^{197}Au	-	--- „ ---	$1\cdot10^{9}$
^{209}Bi	-	--..--	--



NICA : status of the accelerator complex

NICA HILINAC : operational, ions up to ^{124}Xe, work for heavier specie ongoing

NICA Booster : operational, beams up to Xe E/A ~ 600 MeV

NUCLOTRON : operational, beams from p to Xe E/A – 0.5-4.5 GeV

NICA Collider : assembled; commissioning; vacuum, cryo, power, quench protection tests

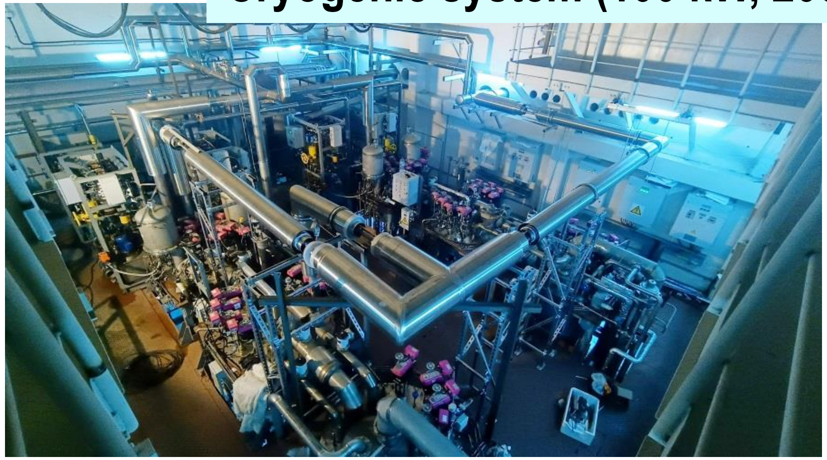
NICA : status of infrastructure and engineering systems

Detector buildings and engineering systems

Power stations (up to 100 MW)

Water cooling system

Cryogenic system (100 kW, 2000 l/h He at 4.5K)



BM@N detector at NICA

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Full Length Article

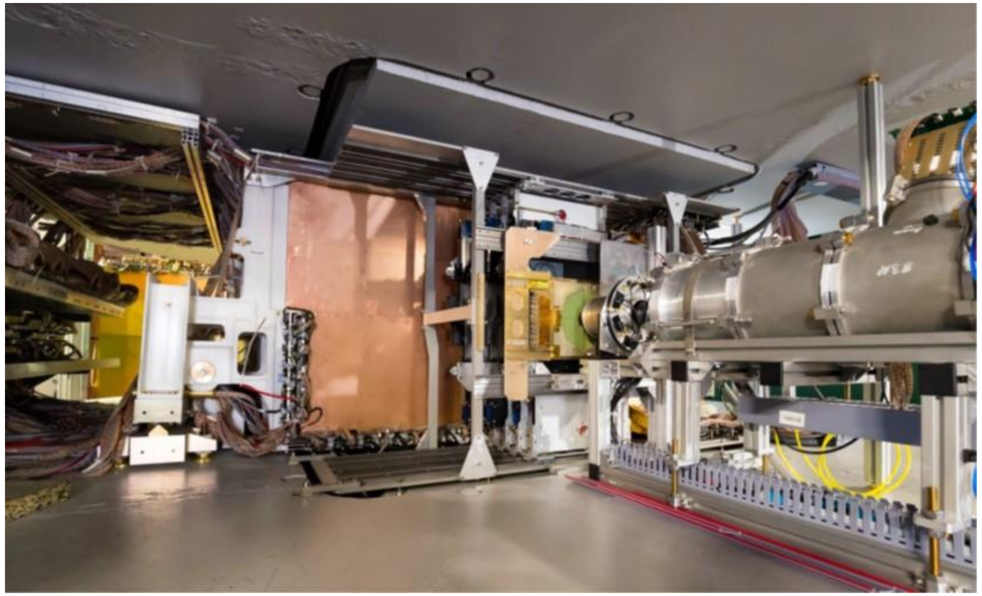
The BM@N spectrometer at the NICA accelerator comp

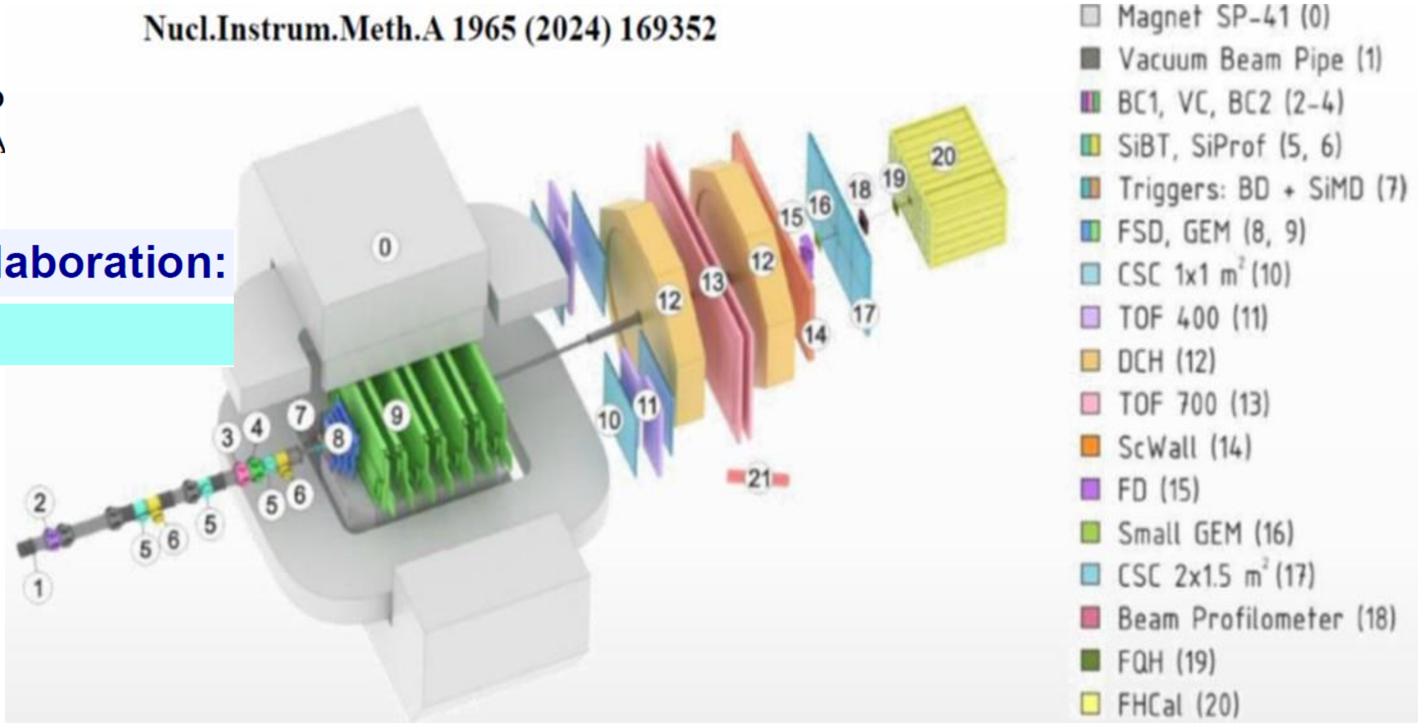
S. Afanasiev [a], G. Agakishiev [a], E. Aleksandrov [a], I. Aleksandrov [a], P. A

Nucl.Instrum.Meth.A 1965 (2024) 169352

Baryonic Matter at Nuclotron (BM@N) Collaboration:

5 Countries, 13 Institutions, 214 participants





FSD, GEM, CSC, DCH: charged particle tracking + momentum measurements

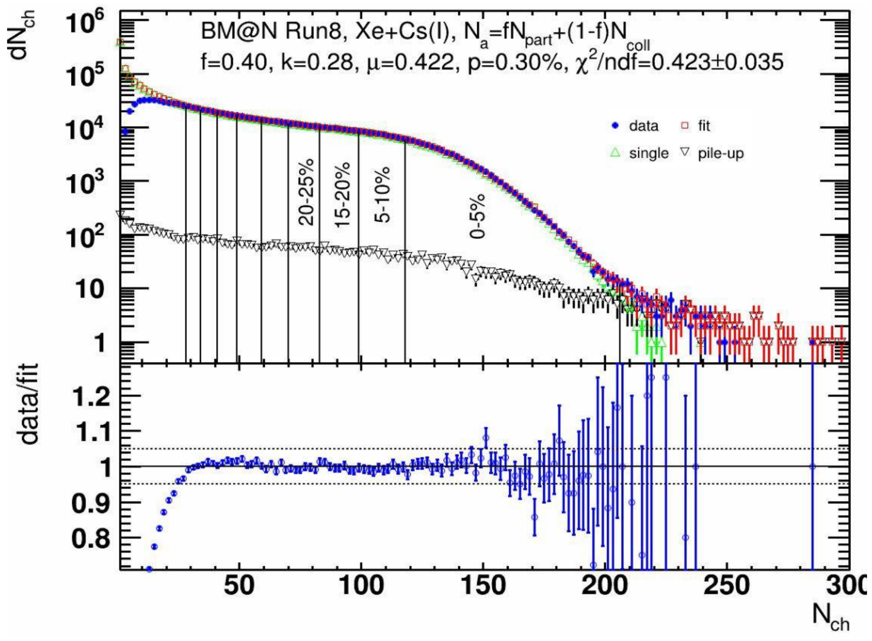
TOF400, TOF700: charged particle identification by m^2/β

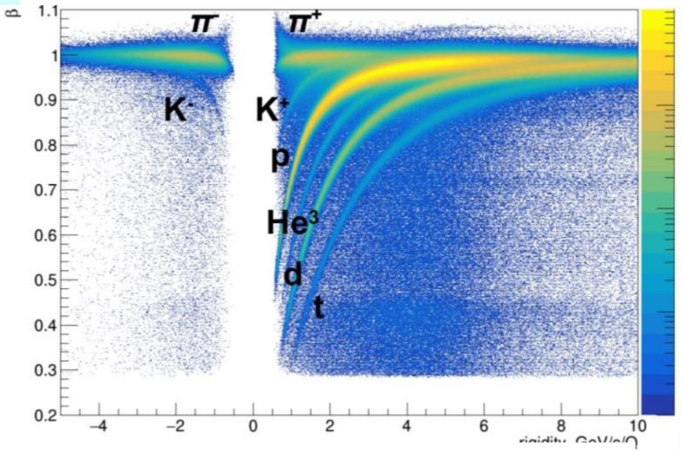
FQH, FHCAL: event geometry, event centrality

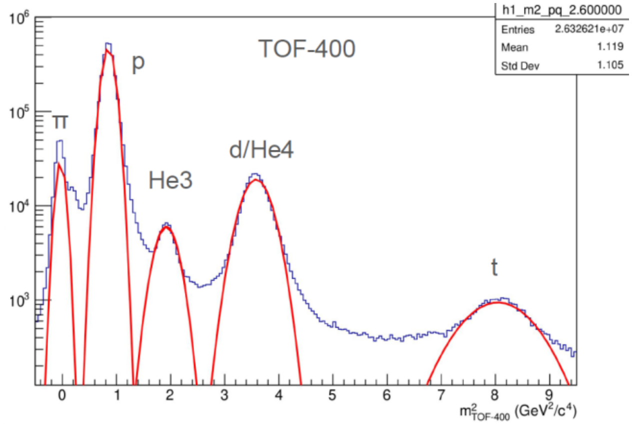
BM@N: data taking campaign and detector performance

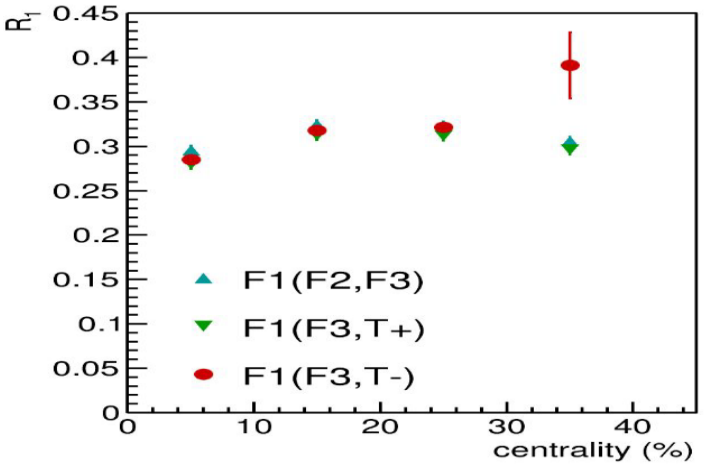
- Centrality by charged track multiplicity, pileup rejection (residual pileups ~1%)
- Event plane by azimuthal distribution of spectators in FHCAL
- Particle ID by Time Of Flight
- Good phase-space coverage in the forward hemisphere for hadrons

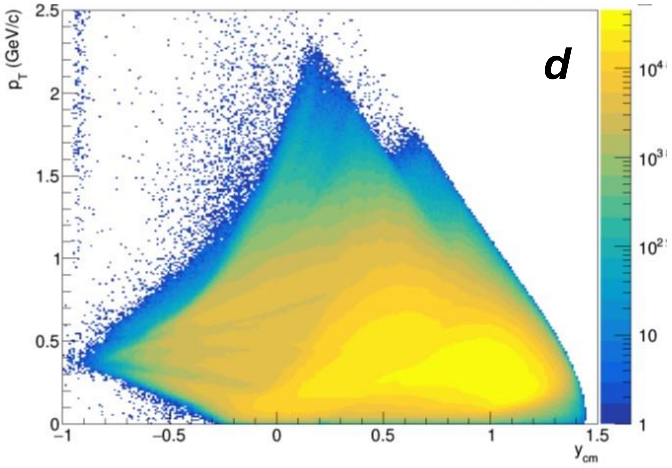
Data	$\sqrt{s}$ (GeV)	# Events
^{12}C + C, Al, Cu, Pb	4, 4.5	25M
^{40}Ar + C, Al, Cu, Sn, Pb	3.1	20M
^{124}Xe + CsI	3.3	500M







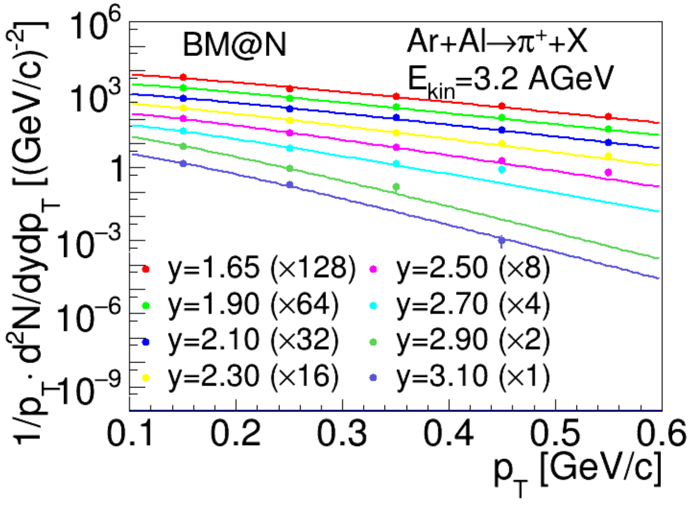


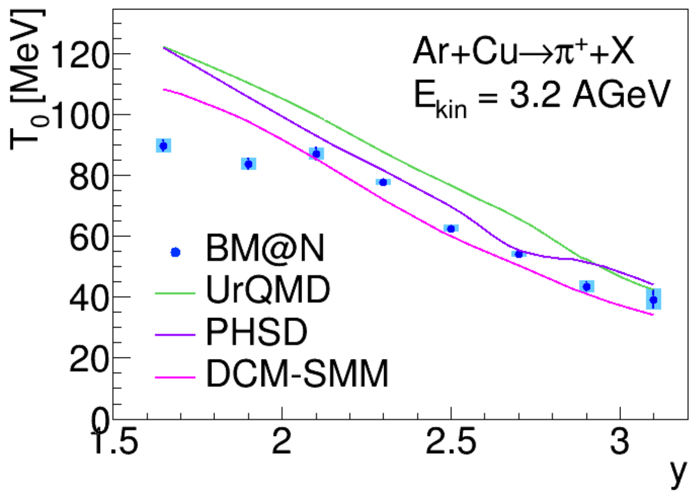


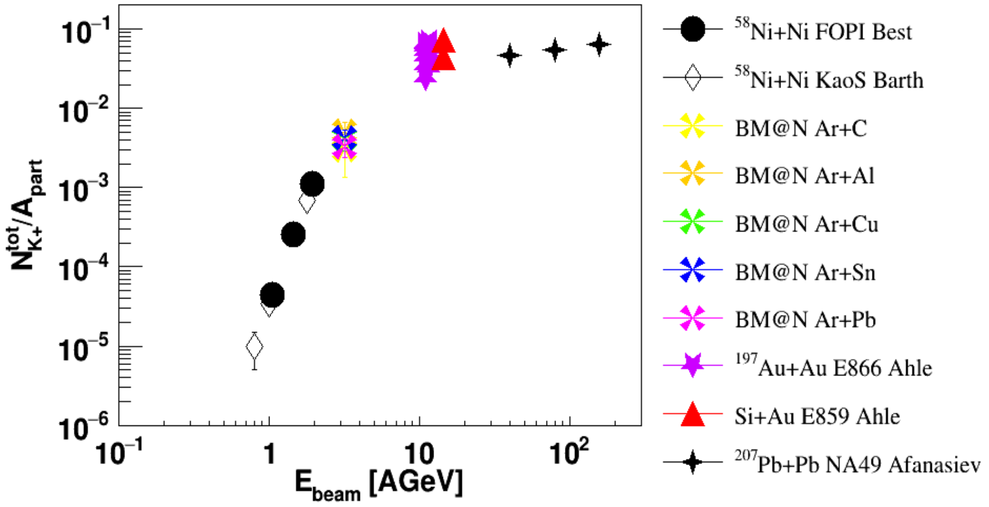
BM@N: results on π^+ and K^+ production in Ar+A at 3.2A ГэВ

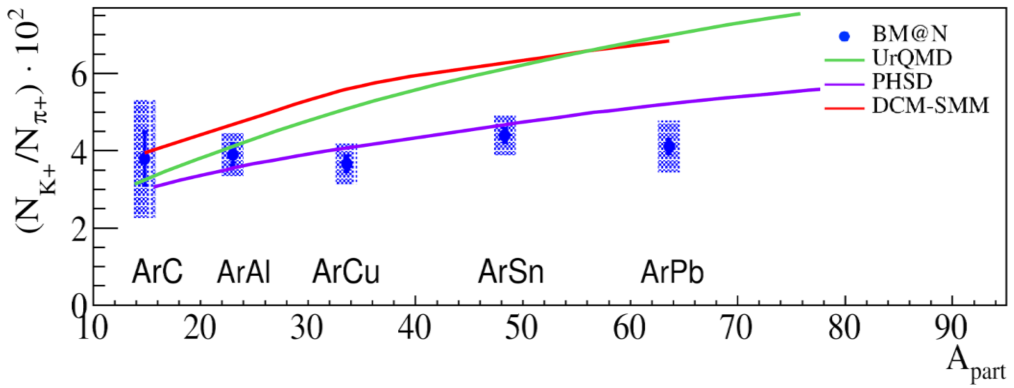
- 0-80% Ar+A(C,Al,Cu,Sn,Pb) collisions
- pT-spectra, yields and ratios of pions and kaons

BM@N Collab. JHEP 07 (2023) 174









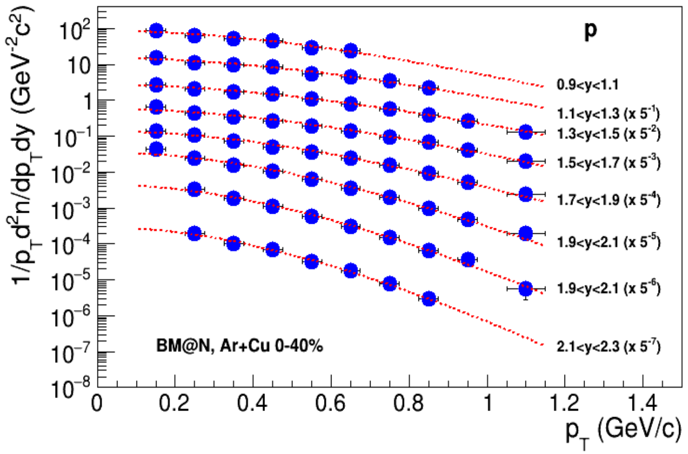
- Max. radial expansion at midrapidity
- Fast rising trend for kaon multiplicity at BM@N energies
- K/π-ratio shows a weak system size dependence in Ar+A

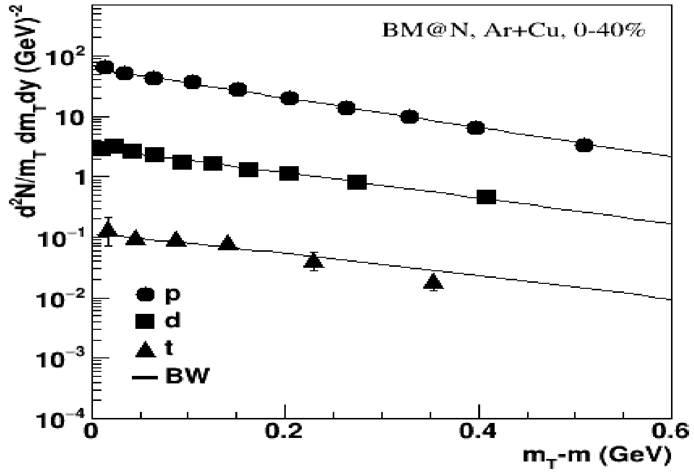
BM@N: results on *p, d, t* in Ar+A at 3.2A ГэВ

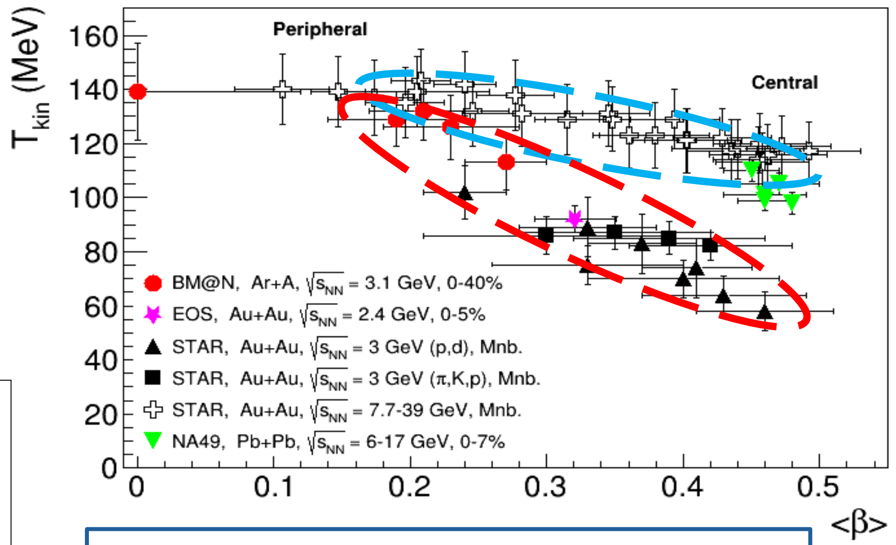
BM@N Collab., arXiv:2504.02759

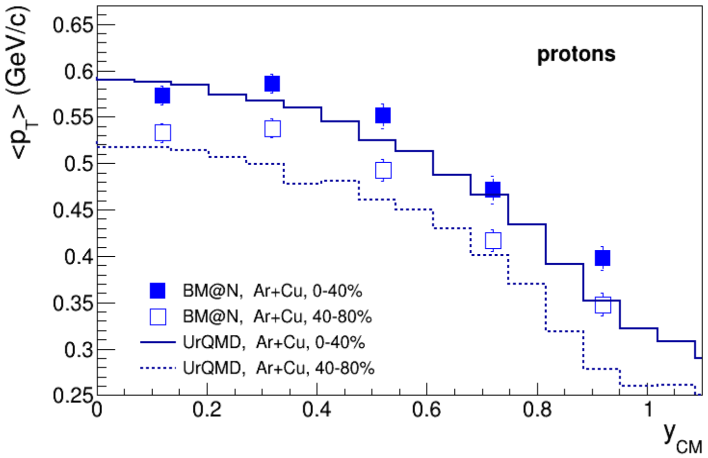
$$\frac{d^2N}{m_T dm_T dy} = Norm(y)\int_0^R m_T K_1\left(\frac{m_T\cosh\rho(r)}{T}\right) I_0\left(\frac{p_T\sinh\rho(r)}{T}\right) rdr$$

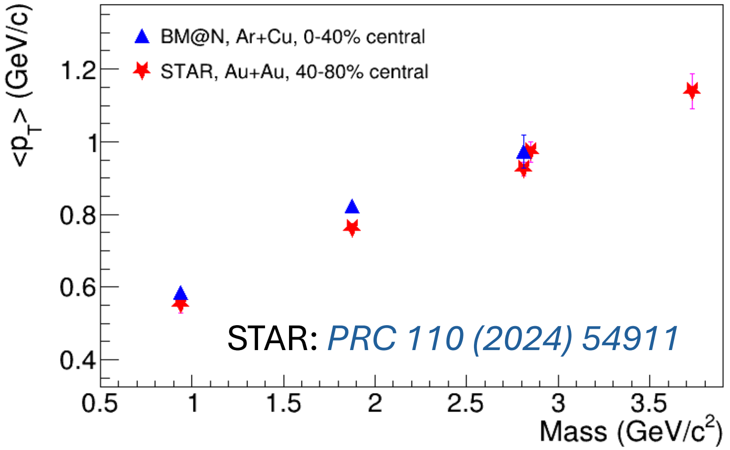
PRL75 (1995) 2662; PRC94, 044906 (2016);
PRC 96 (2017) 4, 044904; Acta Phys. Pol. B16, 1 (2023);











- BW fits (*p+d+t*): ***T*** ~ 115-140 MeV, <**β**> ~ 0.2-0.25 for 0-40% Ar+A
- A change in the (T-β)-trend for √*s* < 6 GeV → different EOS?

More data to confirm this trend!

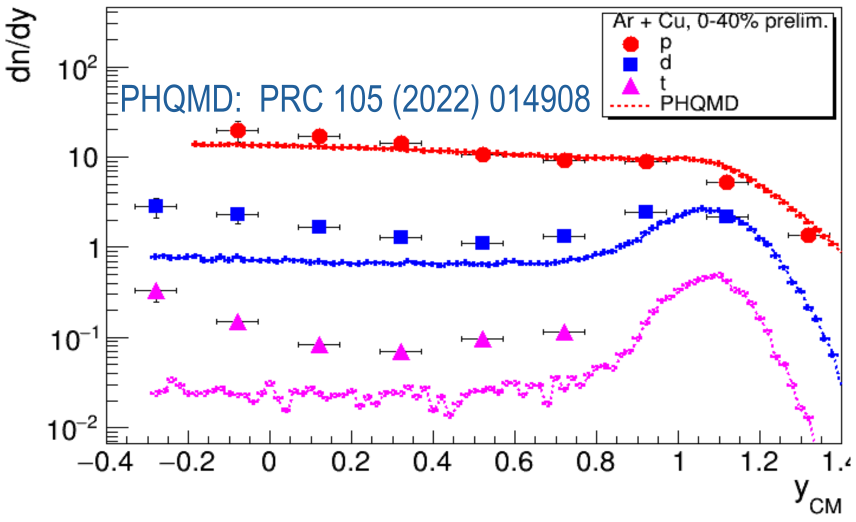
- <pT> rises with particle mass and has the maximum at midrapidity (max. compression)
- Models reproduce qualitatively rapidity dependence → test pT-generation mechanism?
- <pT> in Ar+Cu (0-40%) and Au+Au (40-80%) agree → <pT> is defined by the size of the overlapping region?

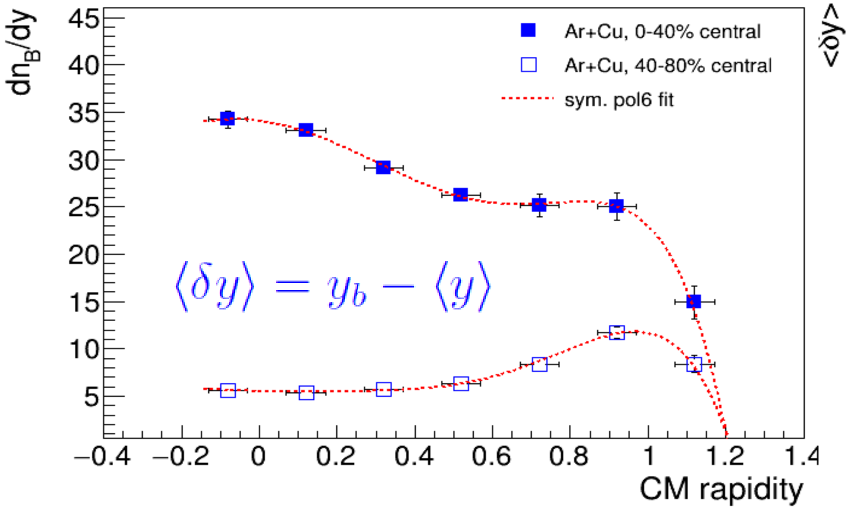
BM@N results: rapidity spectra and losses in Ar+A at 3.2A ГэВ

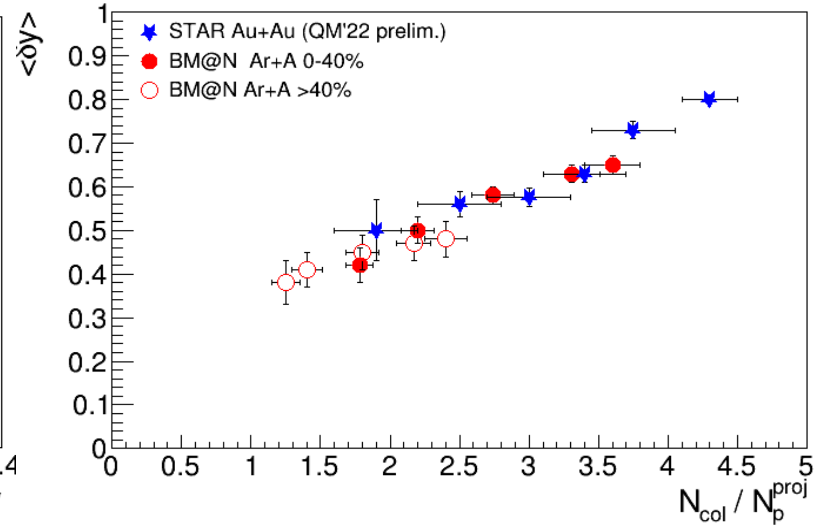
- Rapidity distributions of produced baryons are essential to quantify the momentum loss by the incoming nucleons, to estimate the initial energy and baryon density in the produced matter, and to tune model predictions

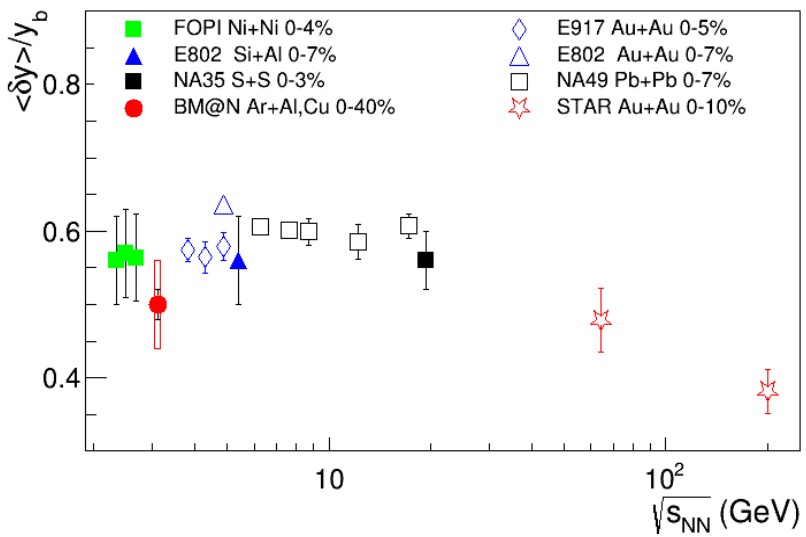
BM@N Collab., arXiv:2504.02759

$$\frac{dn_B}{dy} = (1+\alpha(y))\frac{dn_p}{dy} + \beta\frac{dn_d}{dy} + \gamma(1+\alpha(y)^{-1})\frac{dn_t}{dy},$$







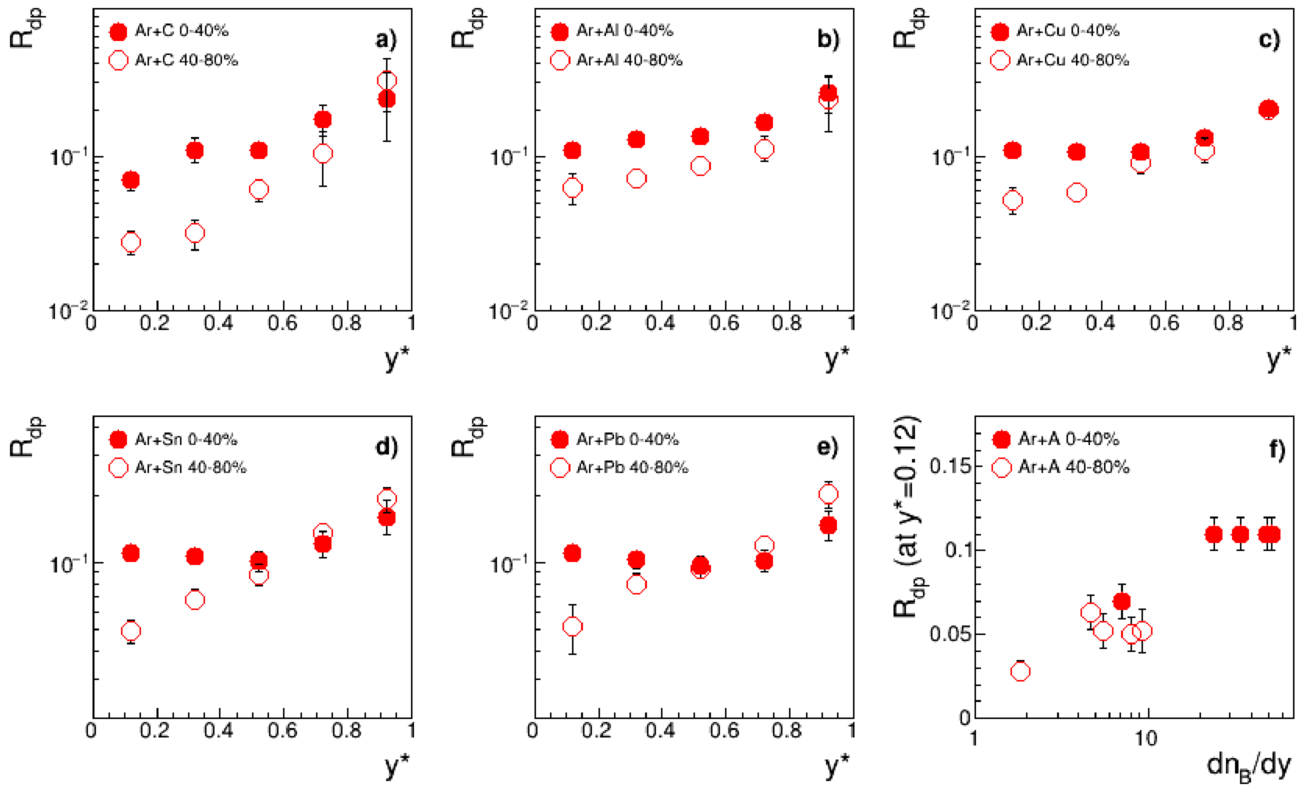


- ***d,t***: a large deficit near mifrapidity in models, coalescence produces too few clusters (indication of feeddown from excited states?)
- <*δy*> rises with the target mass and centrality due to increase in the number of multiple interactions in the overlap region
- <*δy*> scales with the beam rapidity in medium-size A+A over a broad energy range

BM@N results: particle ratios in Ar+A at 3.2A ГэВ

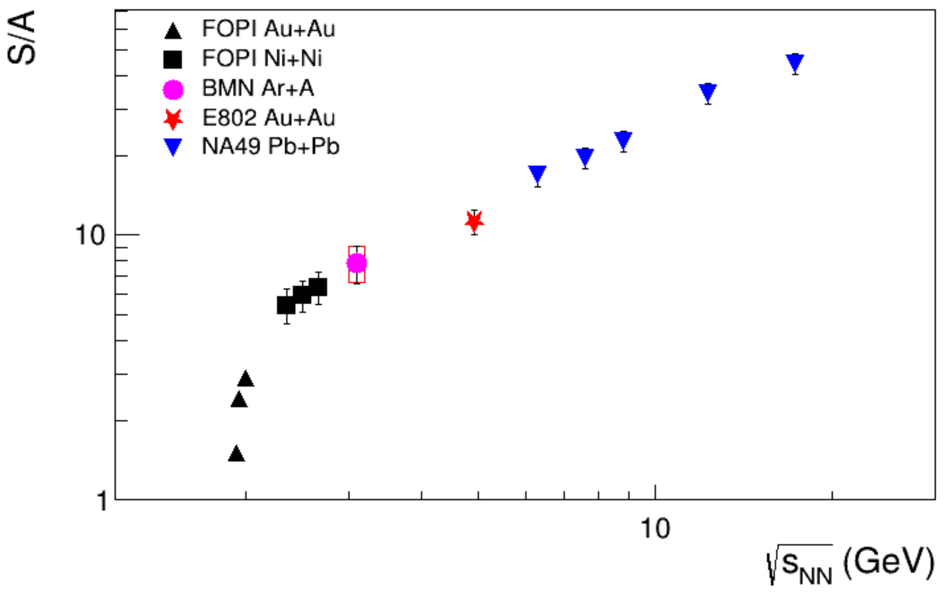
- ❑ R_{dp} is related to the baryon phase-space density and entropy-per-baryon in the source

BM@N Collab., arXiv:2504.02759



L.P.Csernai and J. I. Kapusta, Phys. Rep. 131, 4 (1986) 223–318

$$\frac{S_N}{A} = 3.945 - \ln R_{dp} - \frac{1.25 R_{dp}}{1 + R_{dp}}$$



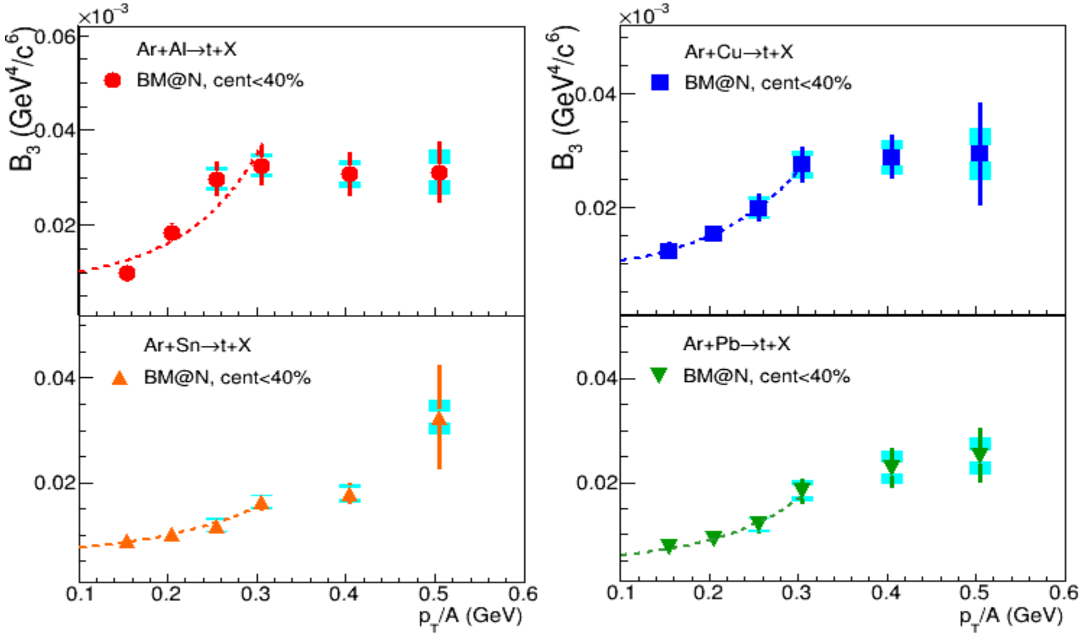
- R_{dp} rises towards the beam rapidity, the rise is stronger in peripheral Ar+A (increase of the contribution from nuclear fragmentation or/and the baryochemical potential plays a role)
- R_{dp} indicates a plateau in central Ar+A in addition to midrapidity R_{dp} saturation in central Ar+A
- S/A ~ 8.0 in central Ar+A (midrapidity value) and increases steady with collision energy

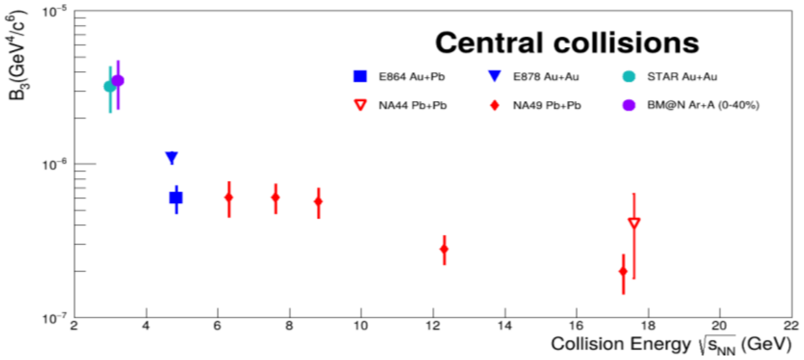
BM@N results: particle ratios in Ar+A at 3.2A ГэВ

- Coalescence parameter B_A is related to the homogeneity volume in the source
- A peak structure in the excitation function of O_{pdt} (~ relative neutron density fluctuations) as a probe of the QCD phase diagram structure (phase transition and CEP) – *K.J.Sun et al, Phys. Lett. B 781, 499 (2018)*

BM@N Collab., arXiv:2504.02759

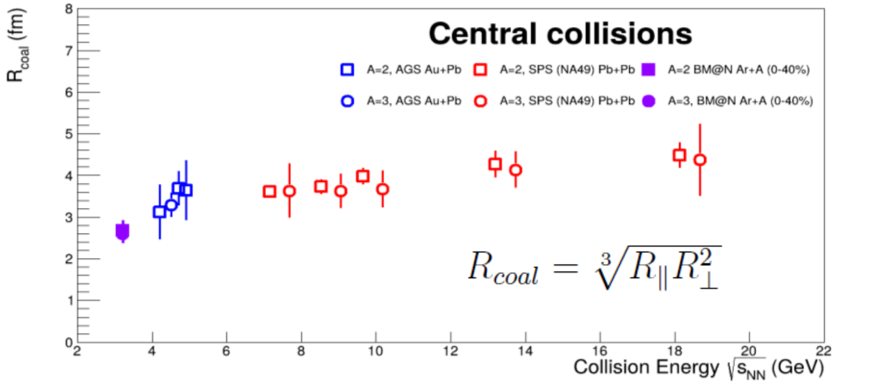
$$E_A d^3N_A/d^3p_A = B_A (E_p d^3N_p/d^3p)^Z (E_n d^3N_n/d^3p)^{A-Z}_{|p=p_A/A}$$

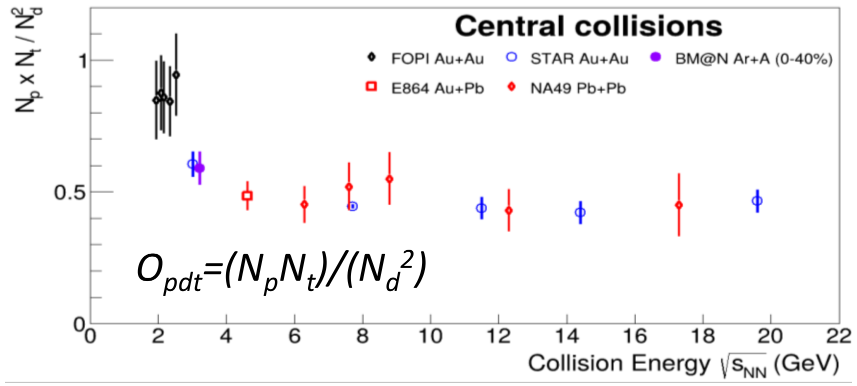




Using prescription for R_{coal} from:

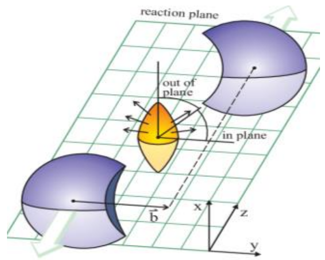
R. Scheibl and U. Heinz, Phys. Rev. C 59, 1585 (1999).





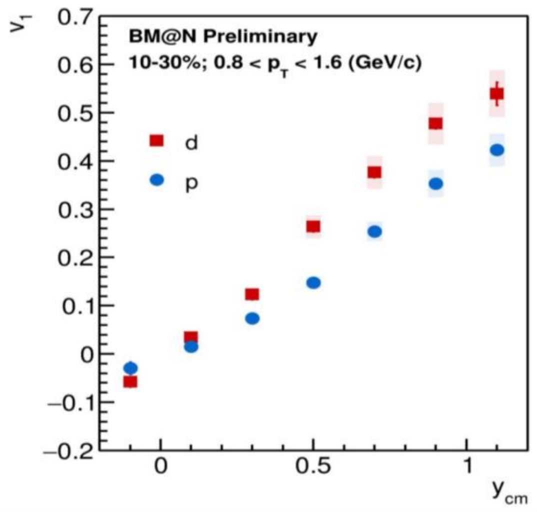
- BM@N results from 0-40% central Ar+A follow the general trend of the excitation function for B_A and O_{dpt}

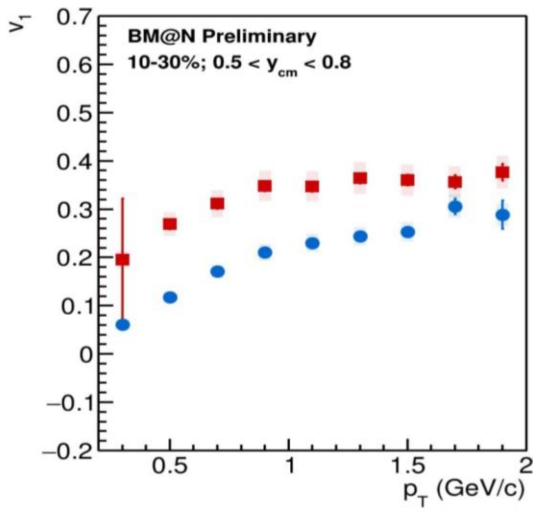
BM@N results on directed flow in Xe+CsI at E/A=3.8 GeV

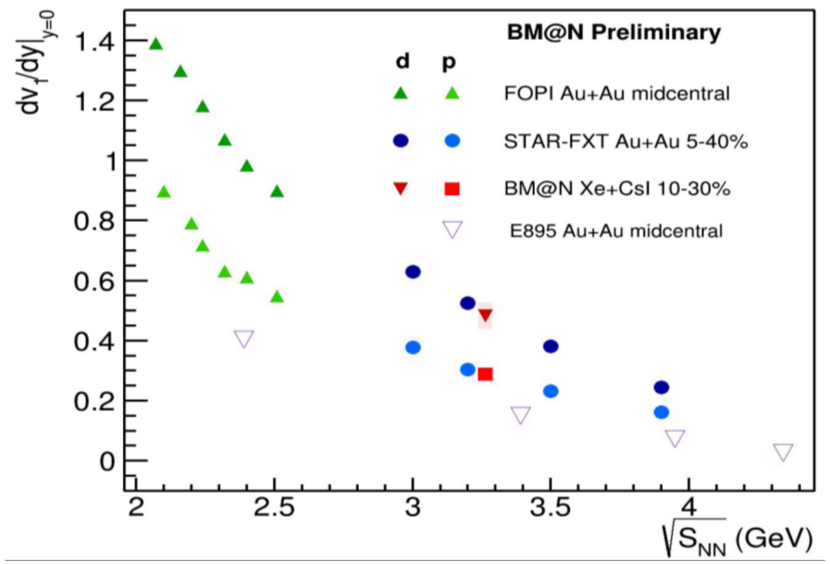


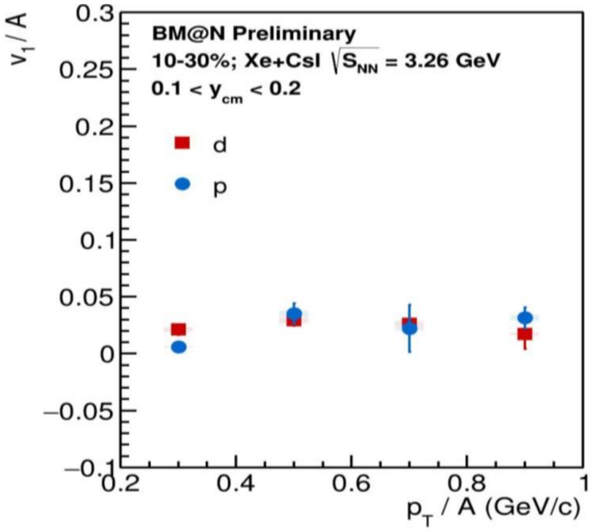
- Initial spatial asymmetry is transformed into particle momentum anisotropy
- Fourier coefficients v_n are sensitive to the matter compressibility providing access to medium properties (dof, viscosity and EOS)

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_{RP}))\right) \qquad v_n = \langle \cos(n(\phi - \Psi_{RP}))\rangle$$



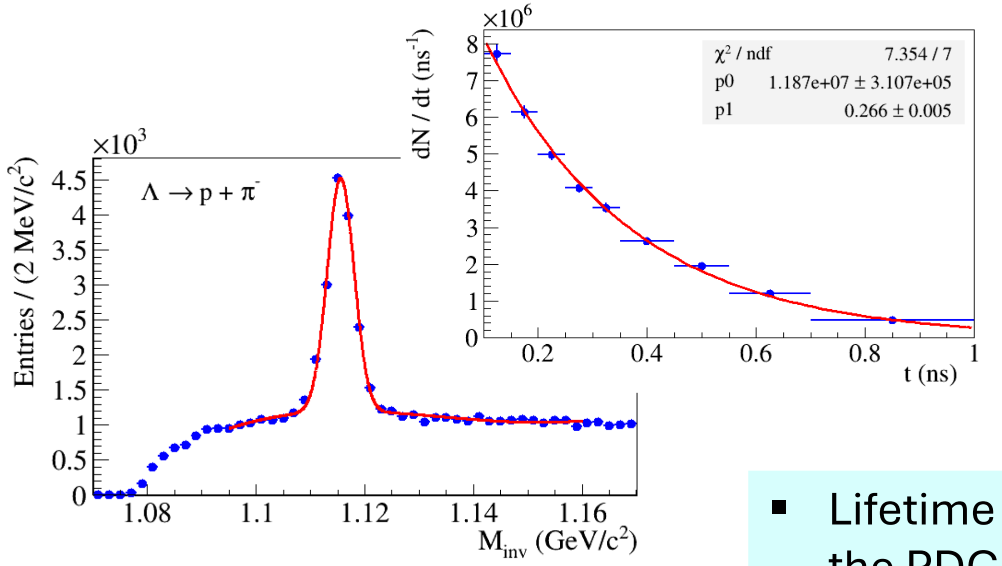


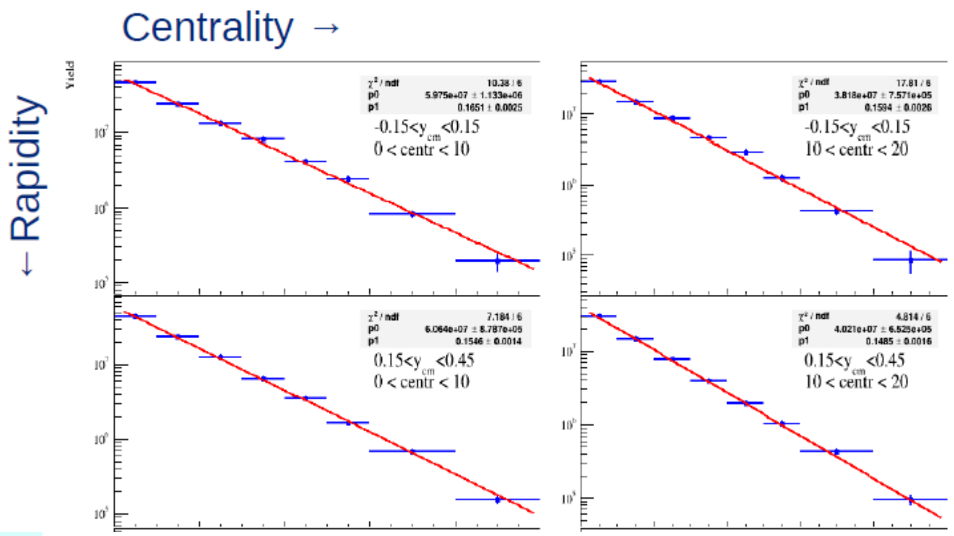




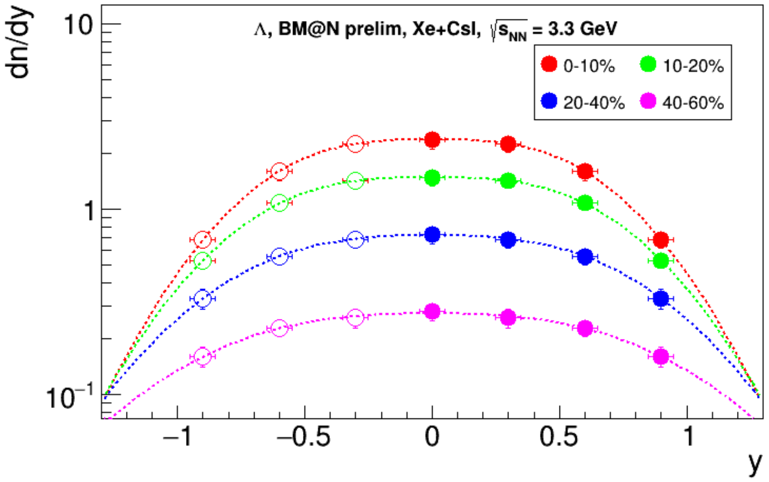
- v_1 increases with particle mass in mid-central Xe+CsI
- v_1 follows the scaling with mass number (as expected in a coalescence approach $v_{n,A}(Ap_t) = Av_n(p_t)$)
- dv_1/dy close to linear scaling with mass, BM@N results follow the world data trend

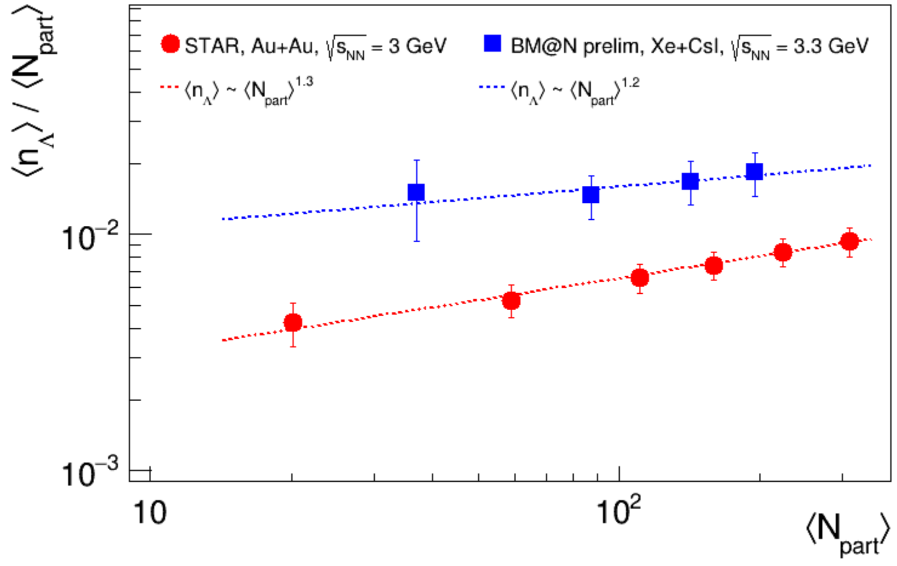
BM@N results on Λ production in Xe+CsI at E/A=3.8 GeV





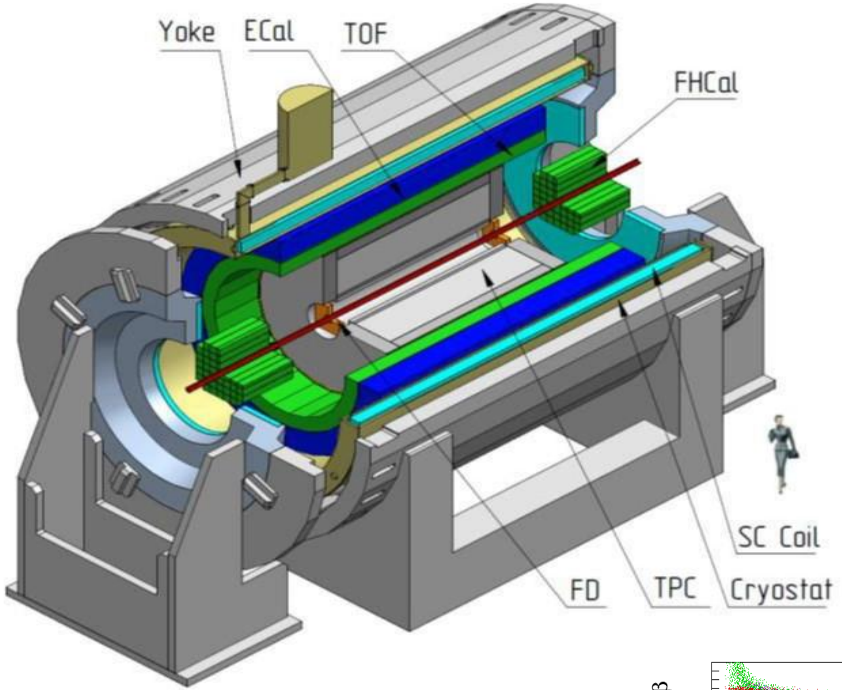
- Lifetime in agreement with the PDG value
- $<n_\Lambda>$ increases stronger than linear with N_{part} → energy accumulation in sequential NN collisions?
- A reduction of the rise with N_{parti} in Xe+CsI relative to Au+Au (higher energy and a smaller system)



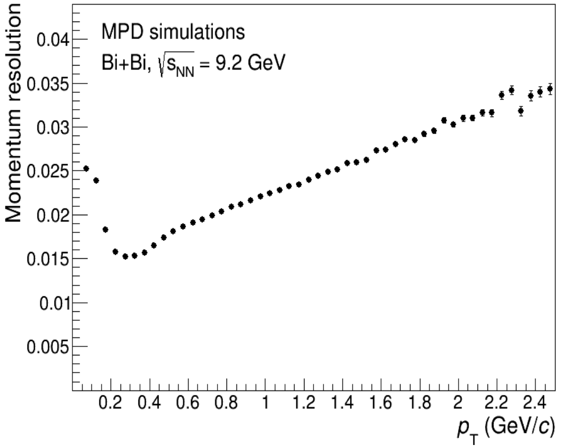


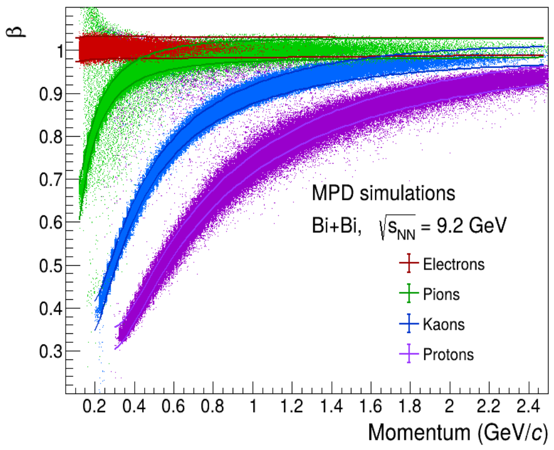
Multi Purpose Detector (MPD) detector at NICA

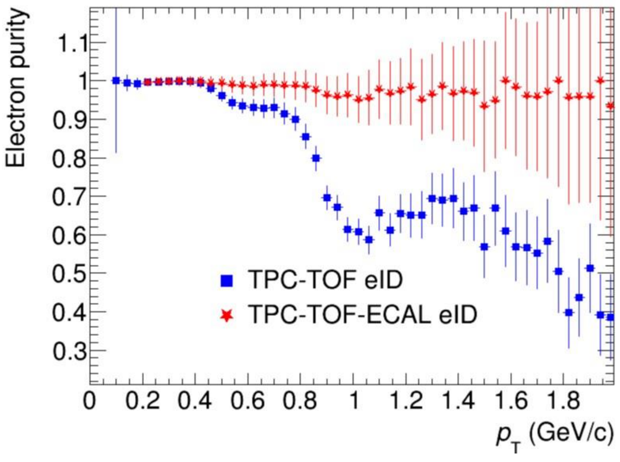
MPD Collaboration: 12** Countries, **>500** participants, **38** Institutes and **JINR

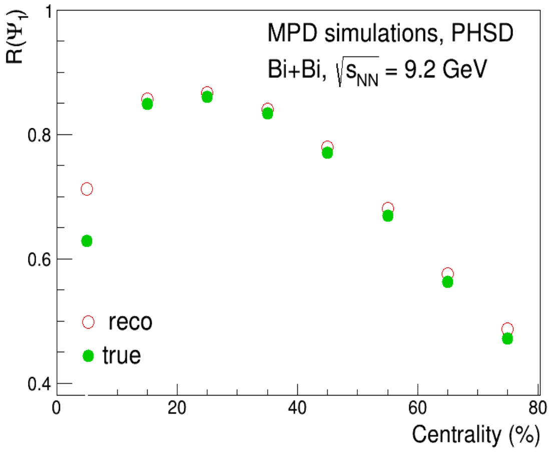


- Uniform acceptance (barrel |y| < 1.5), full azimuth
- 3D tracking, combined PID (dE/dx + TOF and ECAL for e/γ)
- Precise event characterization and event plane (FHCAL)
- Fast timing and triggering (FFD)
- Upgrades (>2028) with central and endcap tracker + PID at |y|>1.5)



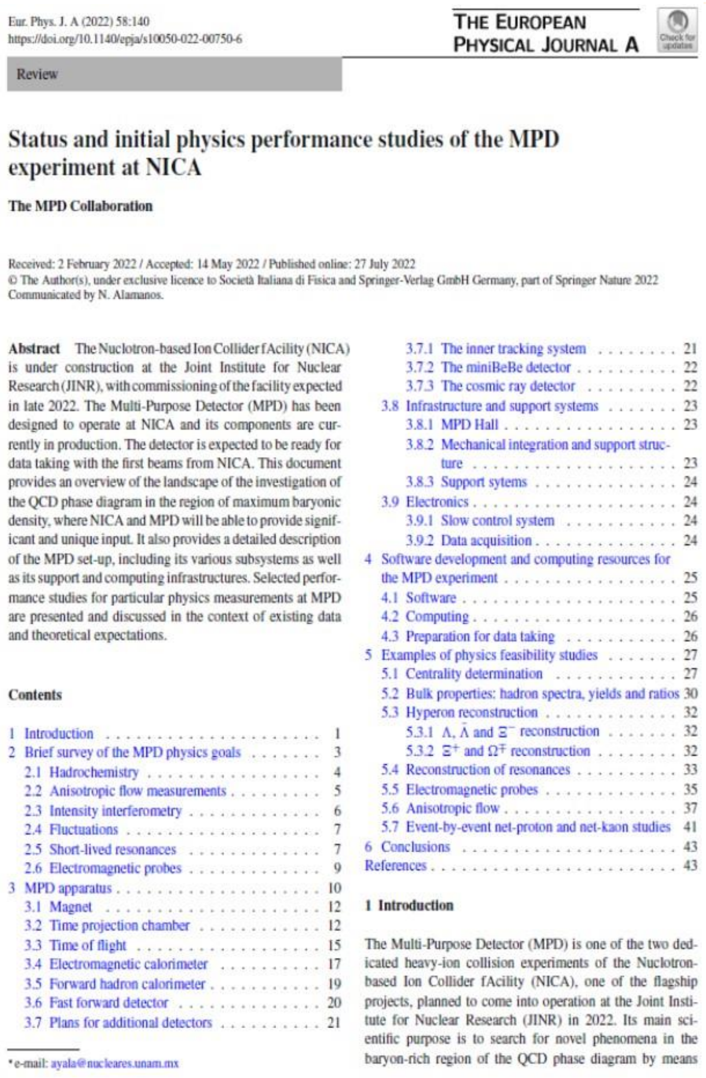






MPD physics objectives

***Experimental strategy**: energy and system size scan to measure a large variety of signals systematically changing collision parameters (energy, centrality, system size). Uniform acceptance of the setup is an advantage.*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THE EUROPEAN PHYSICAL JOURNAL A

Review

Status and initial physics performance studies of the MPD experiment at NICA

The MPD Collaboration

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Communicated by N. Alamanos.

Abstract The Nuclotron-based Ion Collider fAcility (NICA) is under construction at the Joint Institute for Nuclear Research (JINR), with commissioning of the facility expected in late 2022. The Multi-Purpose Detector (MPD) has been designed to operate at NICA and its components are currently in production. The detector is expected to be ready for data taking with the first beams from NICA. This document provides an overview of the landscape of the investigation of the QCD phase diagram in the region of maximum baryonic density, where NICA and MPD will be able to provide significant and unique input. It also provides a detailed description of the MPD set-up, including its various subsystems as well as its support and computing infrastructures. Selected performance studies for particular physics measurements at MPD are presented and discussed in the context of existing data and theoretical expectations.

Contents

1 Introduction

The Multi-Purpose Detector (MPD) is one of the two dedicated heavy-ion collision experiments of the Nuclotron-based Ion Collider fAcility (NICA), one of the flagship projects, planned to come into operation at the Joint Institute for Nuclear Research (JINR) in 2022. Its main scientific purpose is to search for novel phenomena in the baryon-rich region of the QCD phase diagram by means

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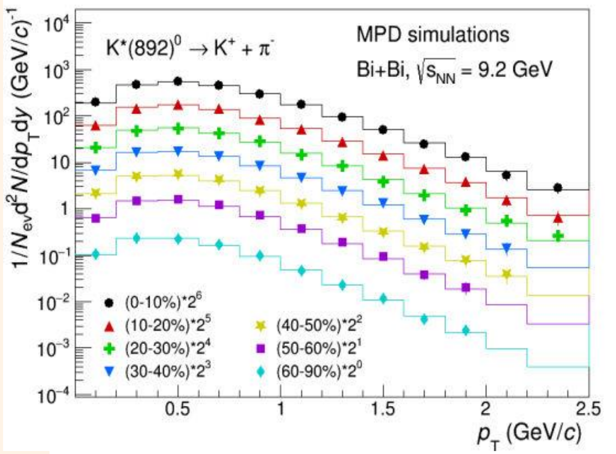
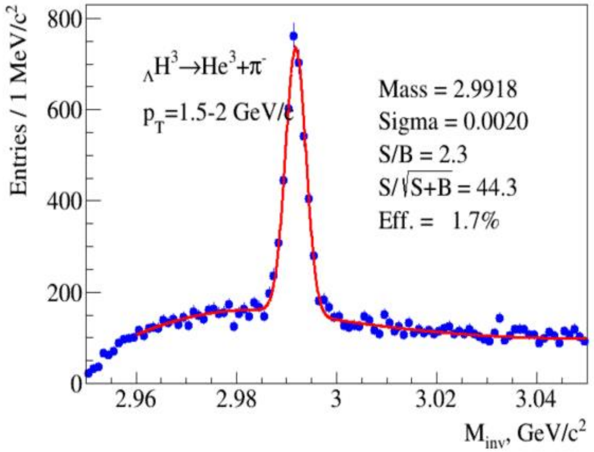
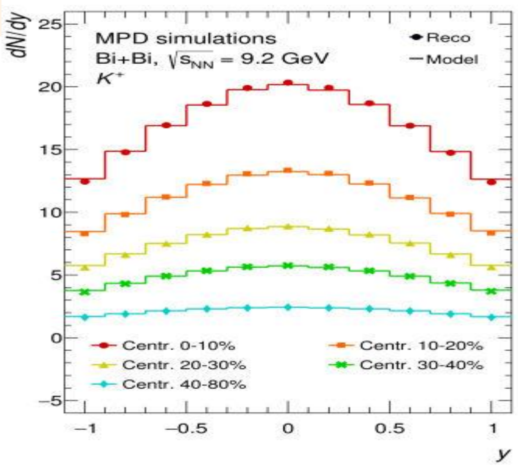
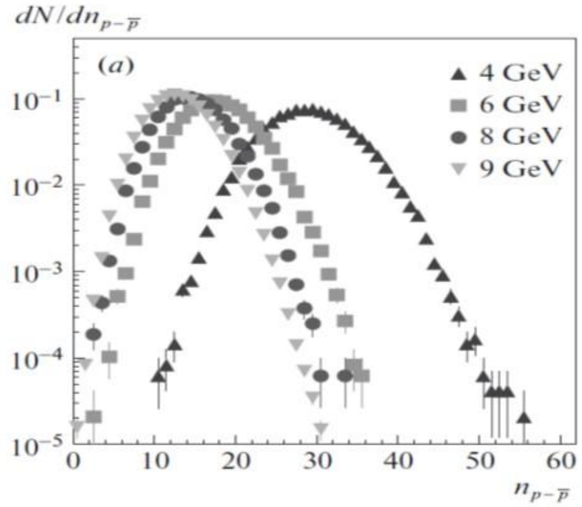
MPD Tasks and Observables:

- ***Bulk properties, EOS, phase diagram mapping***
  particle yields & spectra, femtoscopy, flow
- ***In-Medium modification of hadron properties***
  LM and IM dilepton production, resonances
- ***Phase transition at high ρ_B***
  (Multi)strangeness production
- ***QCD Critical Point***
  event-by-event fluctuations and correlations
- **EOS @ NS densities, in-medium Λ-N potentials**
  hypernuclei



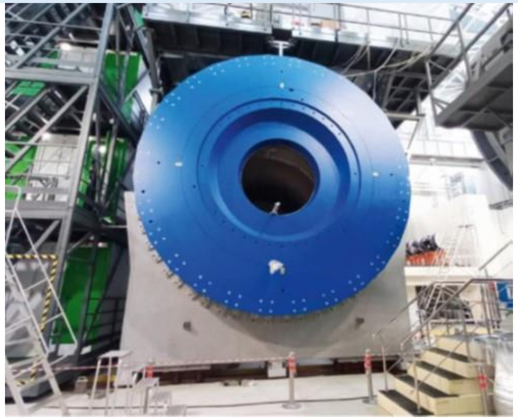




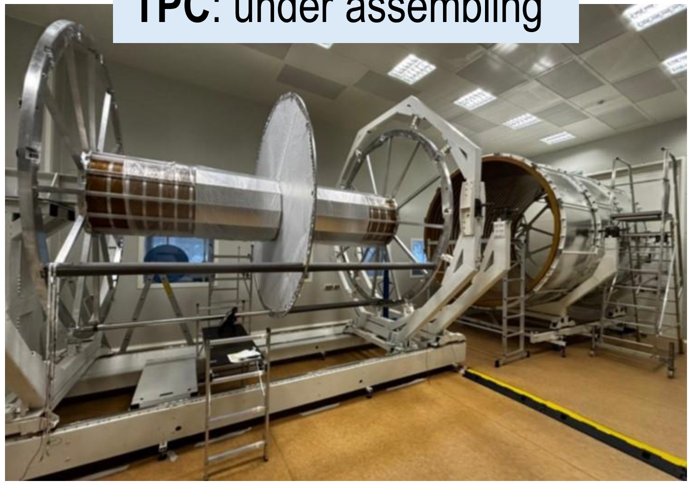


MPD detector: status of subsystems

Magnet: at 4.2 K, under magnetic field measurements

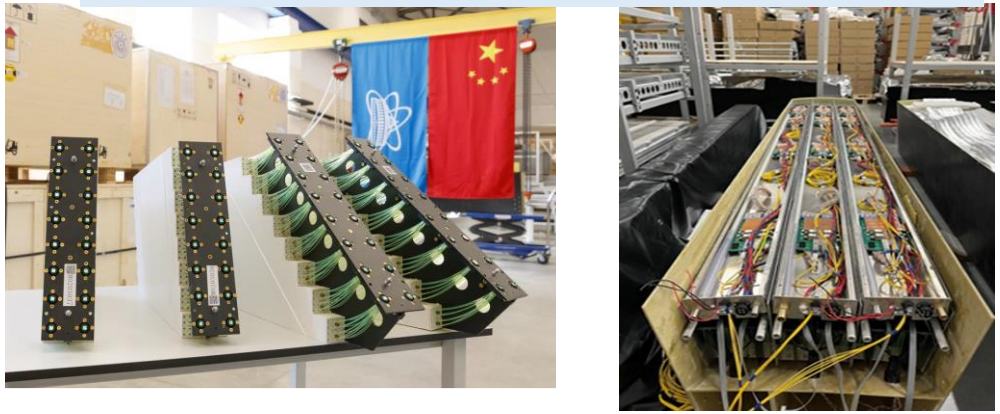


TPC: under assembling



FHCAL: test installation in the magnet pole

ECAL: 85% of modules will be installed in 2025



TOF: MRPC modules are subject of cosmic ray tests

Fully assembled detector - by the end of 2025, commissioning with beams in 2026

MPD : status of infrastructure and assembling tooling

- Cryogenics, cabling, piping, cooling, electronics etc.
- Tooling for installation of MPD subsystems

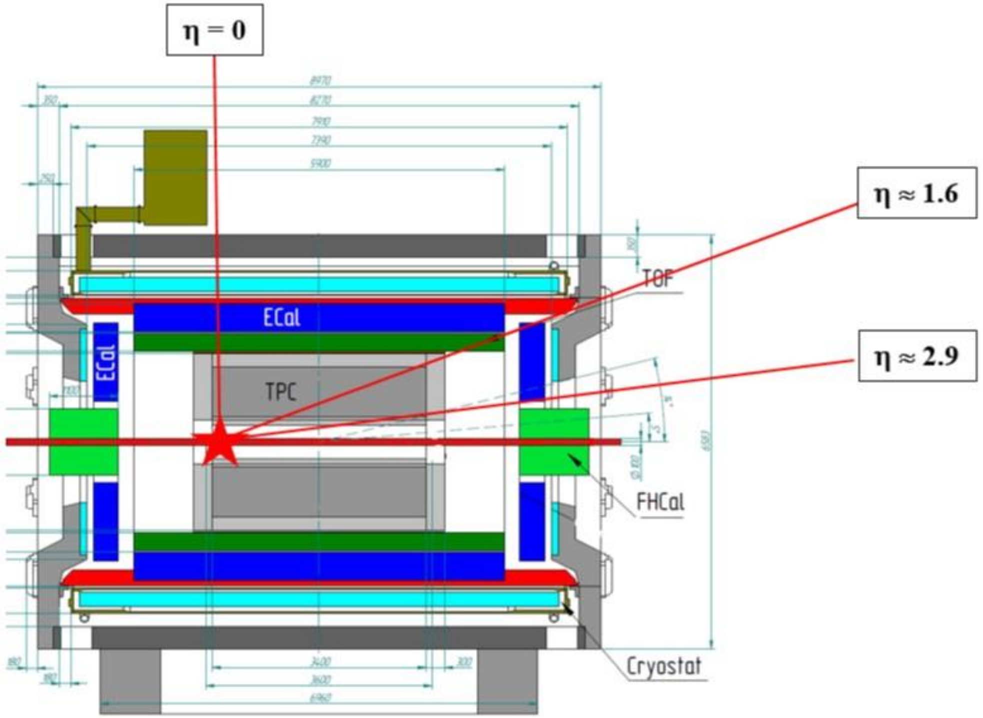
Fiber support frame

TOF installation bench

NICA/MPD tasks during the commissioning phase (2025-26)

NICA FirstDay parameters:

- ^{124}Xe, E_{beam} 3.4A GeV, Luminosity up to 10^{26}
- Collider (CLD) and Fixed target (FXT) operation modes at MPD start-up $\sqrt{s}$ = 7 (CLD) 3 (FXT) GeV



Estimated data set volume 50-100 MEvents

- After MPD assembly, specific calibration and alignment runs (laser and cosmic data for TPC, TOF, ECAL) start.
- MPD in the RUN position – beam tuning and start of data taking

MPD tasks during the First Day data taking:

- Estimation of the triggering efficiency, event centrality classes, momentum resolution, reaction plane
- Estimate of total charged particle multiplicity density and total transverse energy
- Measurement of basic observables robust against less precise particle ID: elliptic and directed flow, particle/antiparticle ratios, two-pion interferometry, spectra and yield of hyperons via secondary vertex reconstruction w/o PID

After calibration of the PID response and TPC-TOF matching:

Continuation with the complete physics program of MPD with identified hadrons: identified particle spectra, yields and ratios, reconstruction of hyperons and resonances with final efficiency, correlation and fluctuation measurements, etc.

MPD feasibility study (CLD)

- Physics feasibility studies using large-scale Monte Carlo productions
- Develop physics program, analysis methods and algorithms

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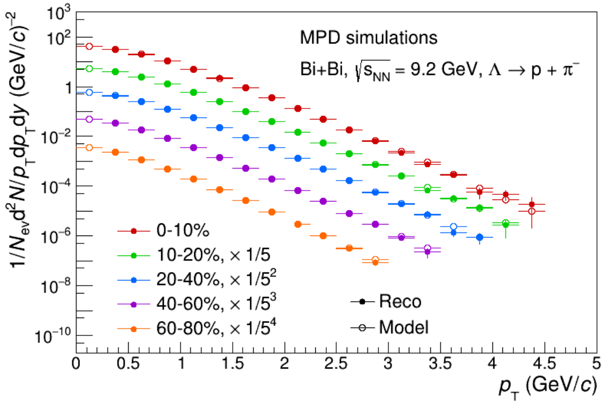
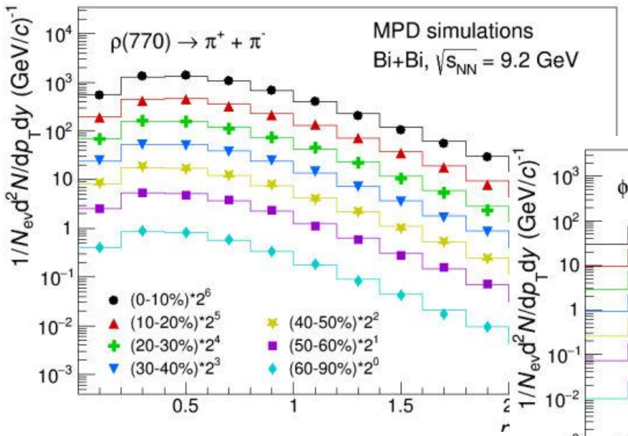
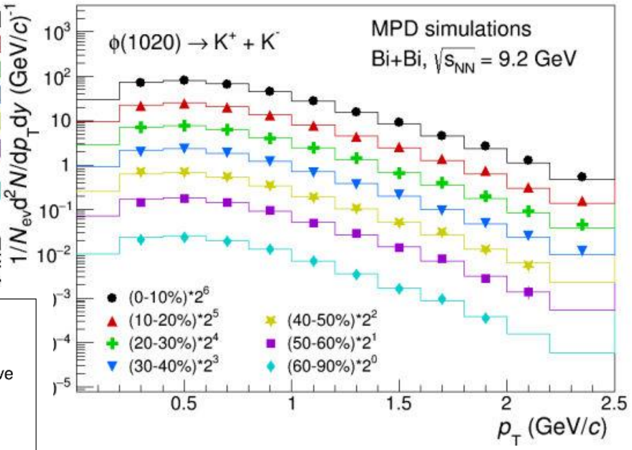
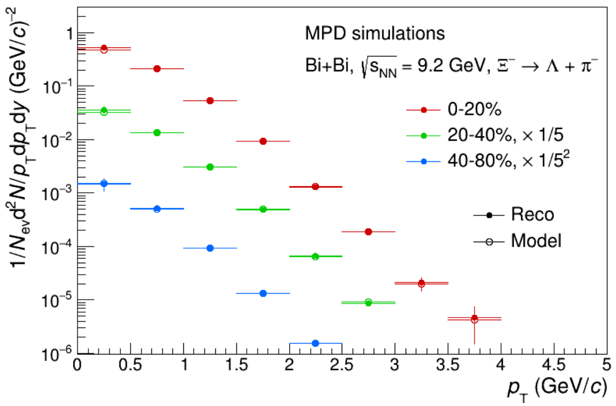
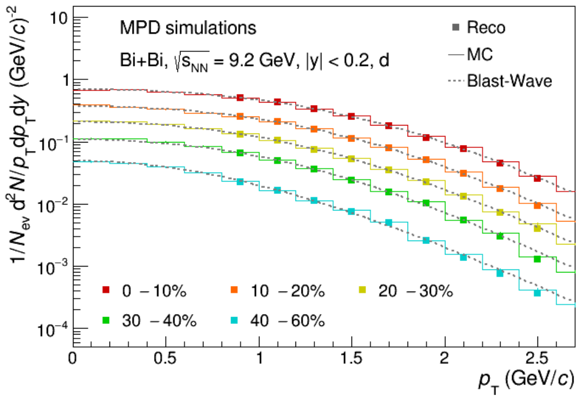
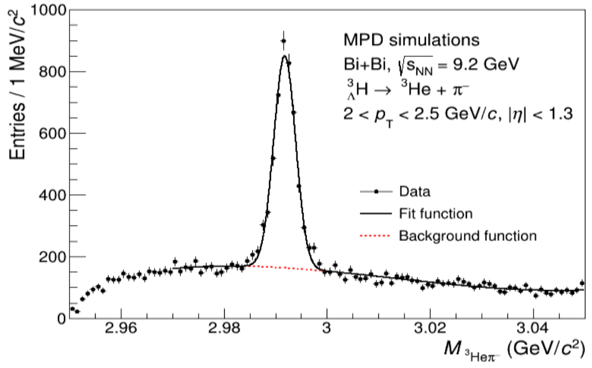


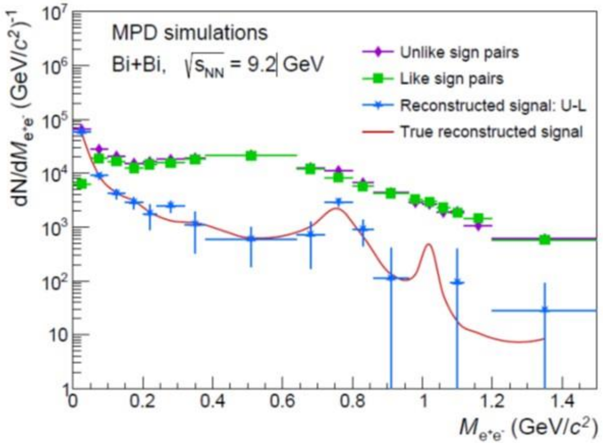


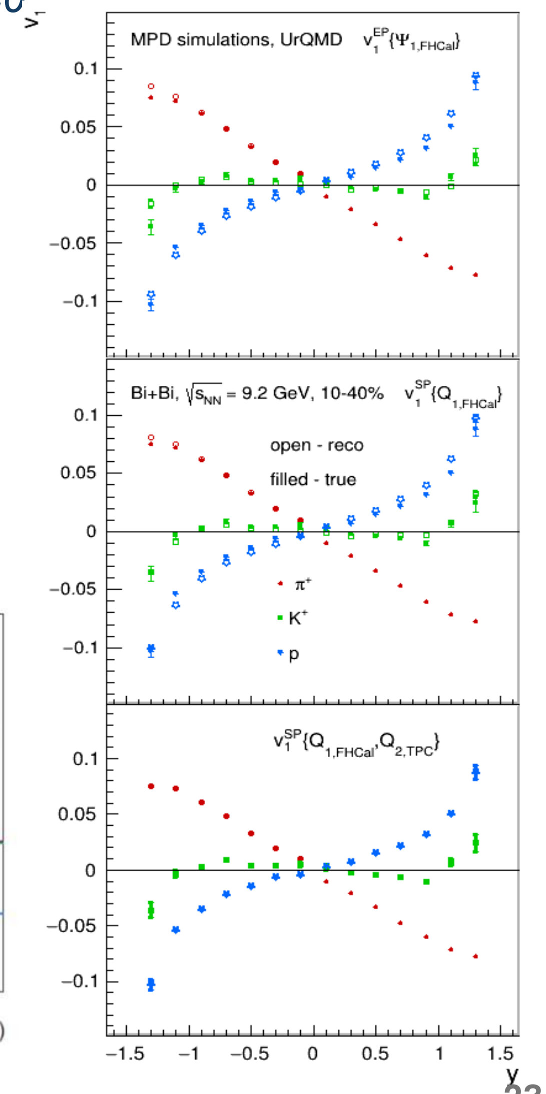












Summary

- NICA collider and MPD detector is close to the commissioning phase

- Experimental data for C+A, Ar+A, Xe+CsI collisions are recorded by the BM@N experiment at the Nuclotron accelerator (NICA complex, JINR). Production of charged hadrons, hyperons and light nuclei is under study.

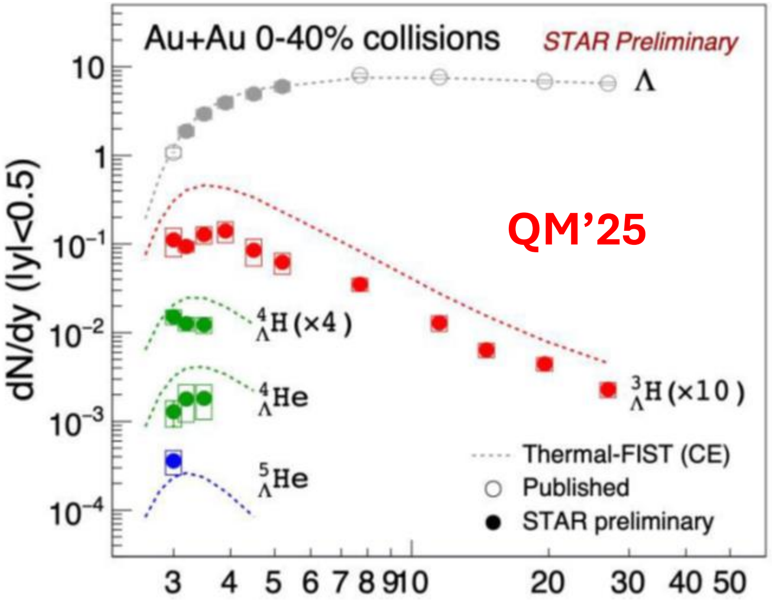
- **^{40}Ar+A collisions**: pT-spectra, rapidity distributions, ratios of hadrons are obtained in centrality selected events over the forward rapidity range:
  - K^+/π^+ ratio indicates a weak system-size dependence in Ar+A collisions
  - $<\delta y>$ for baryons grows with the system size and scales with y_{beam} within the NICA energy range
  - d/p-ratio indicates a saturation near midrapidity, entropy per baryon S/A is estimated
  - Coalescence parameters and source radii for deuterons and tritons are compared to world data
  - O_{pdt} – ratio in Ar+A collisions at 3.1 GeV follows the overall excitation function trend
- **^{124}Xe+CsI collisions (BM@N prelim.):**
  - v_1 increases with particle mass for *p,d and* follows the scaling with mass number (coalescence)
  - dv_1/dy is close to a linear scaling with mass, BM@N results follow the world data trend
  - $<n_\Lambda>$ increases stronger than linear with N_{part}

Thank you for your attention!

Spares

Nuclear matter in the high-μ_B region : (hyper)nuclei

- Light (hyper)nuclei : weekly bound objects are copiously formed in hot and dense matter, max. production rates at 3 GeV
- Yields and ratios allow testing reaction dynamics, momentum-space correlations, and dynamical fluctuations (CEP)
- YN and YY potential are crucial for the nuclear matter EOS at high density (nuclear physics and astrophysics)
- Models reproduce the trend of the hypernuclei excitation function, but overestimate the yields
- Hyperon dof makes EoS for neutron stars softer and the max NS radius smaller → in contradiction with observations



- Relative neutron density fluctuation related to spinodal instability at CEP

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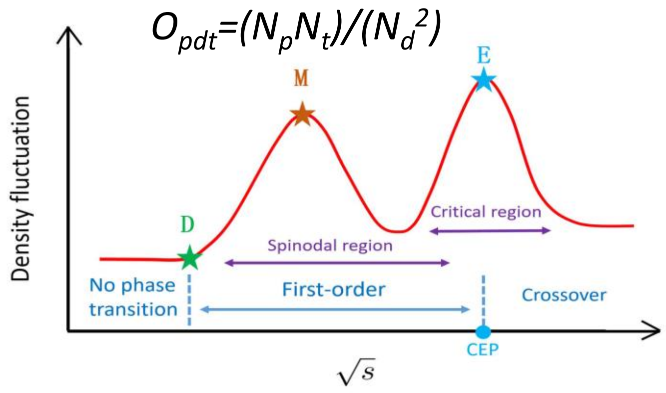

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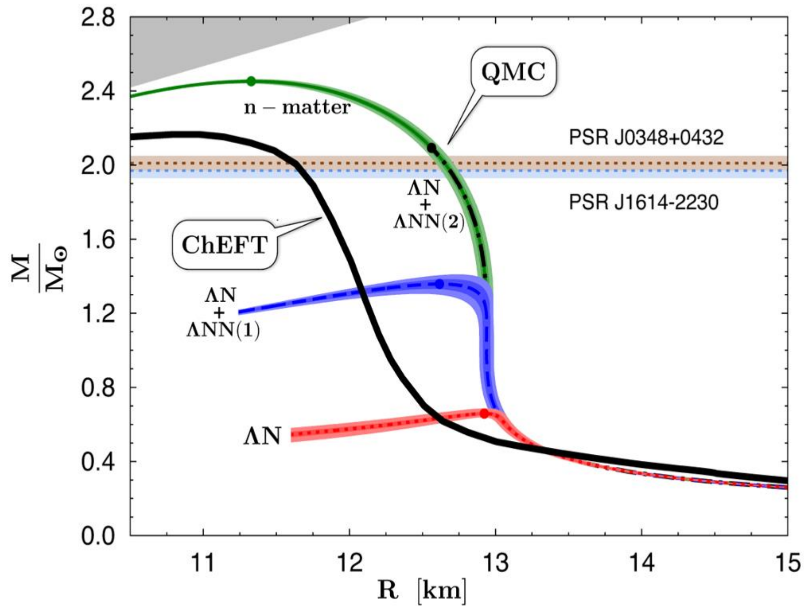
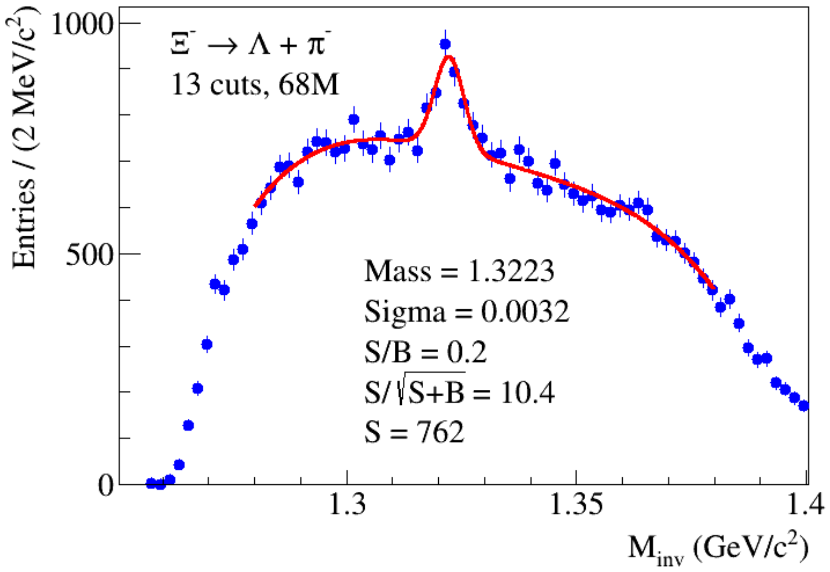
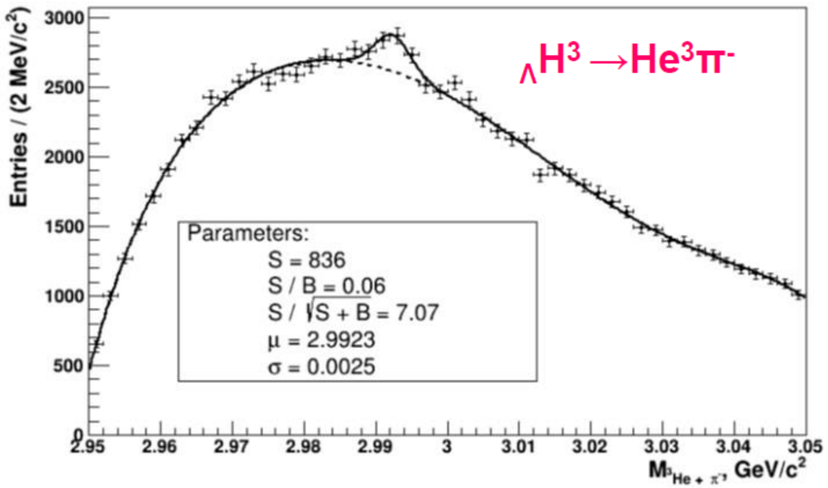
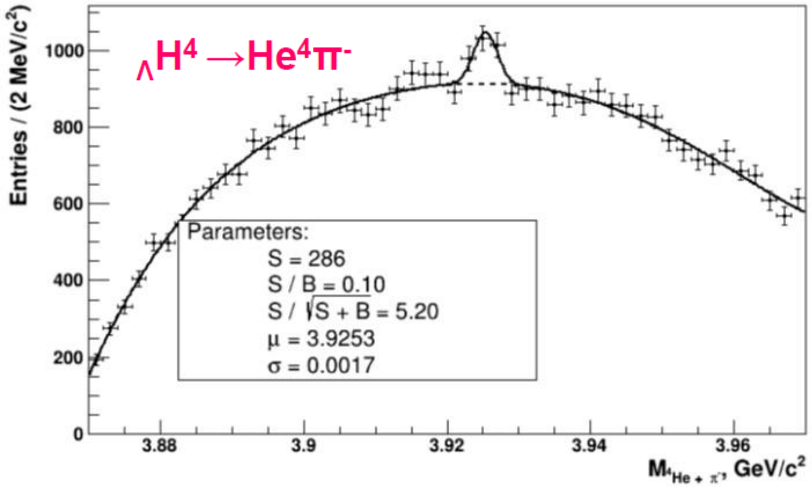


New data on (hyper)nuclei yields and ratios, binding energies, lifetimes, branching ratios are needed to provide tighter constrains to EOS, to observe signals on critical phenomena and provide input for models

BM@N: reconstruction of cascades and hypertritons in Xe+CsI

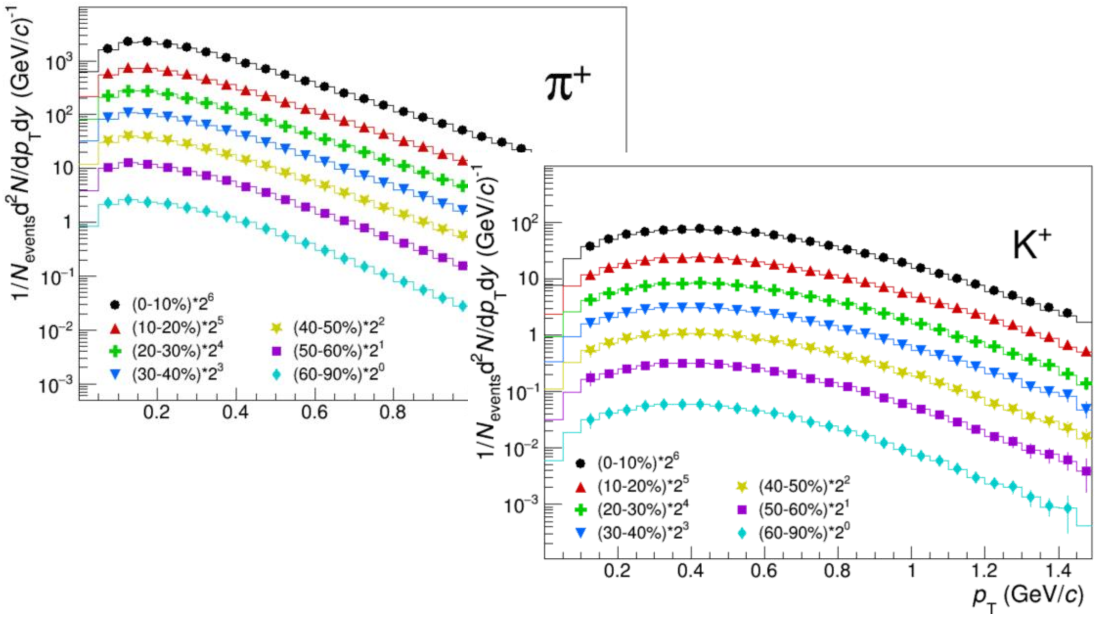


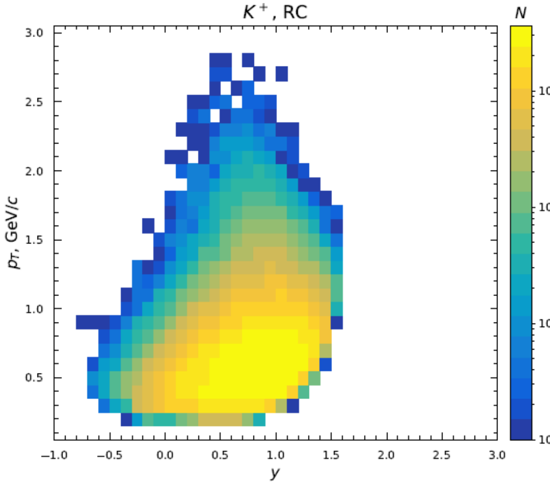


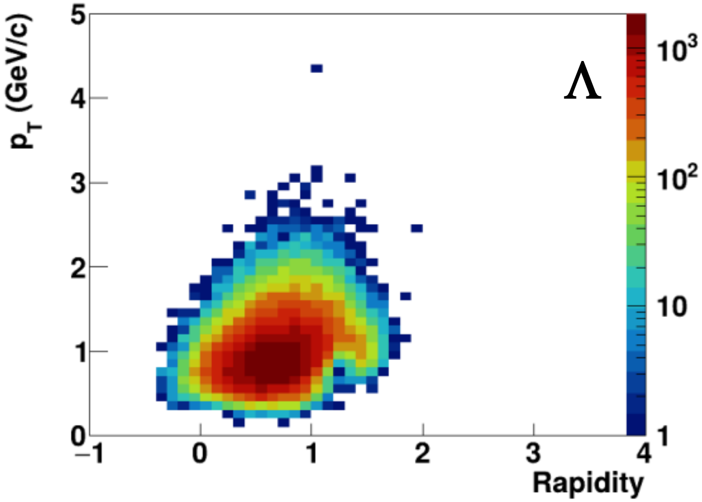


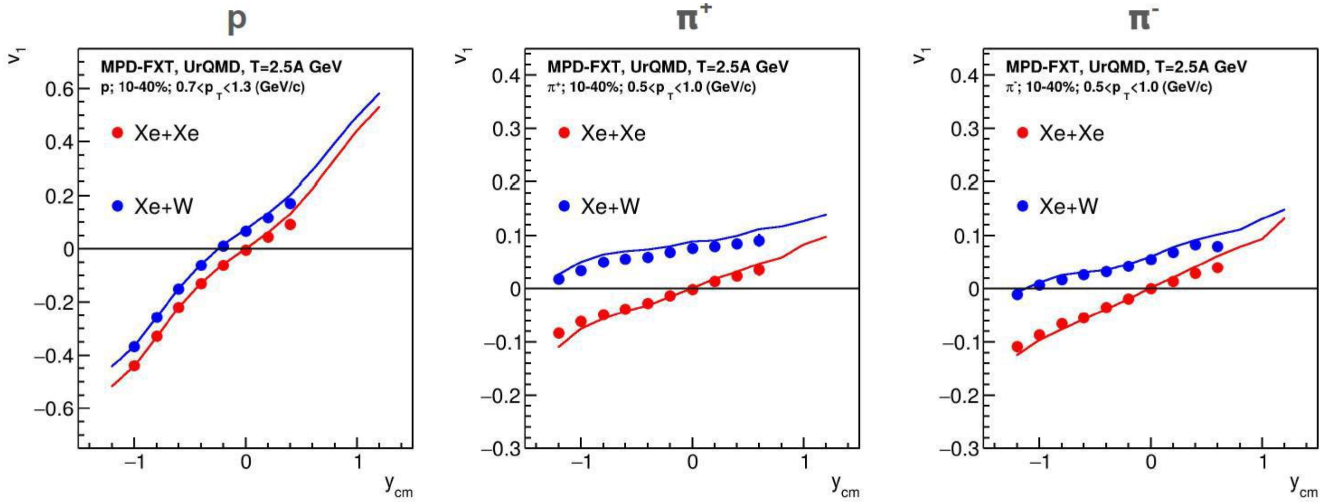
MPD feasibility study (FXT)

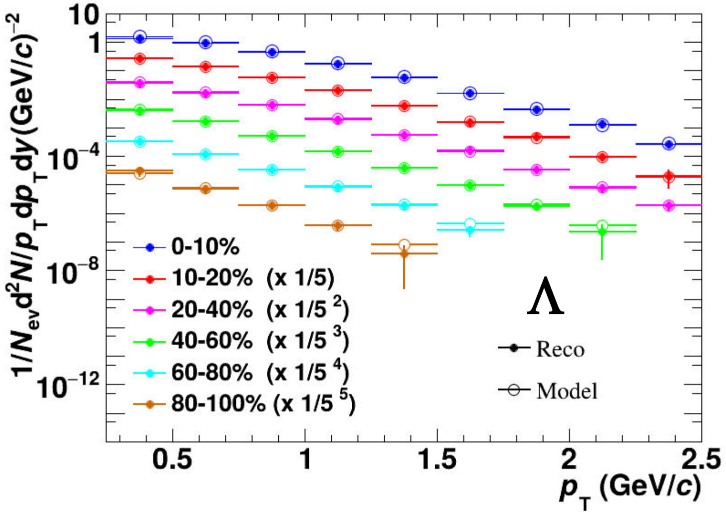
- MPD feasibility studies using large-scale Monte Carlo productions for Xe+W at 3 GeV







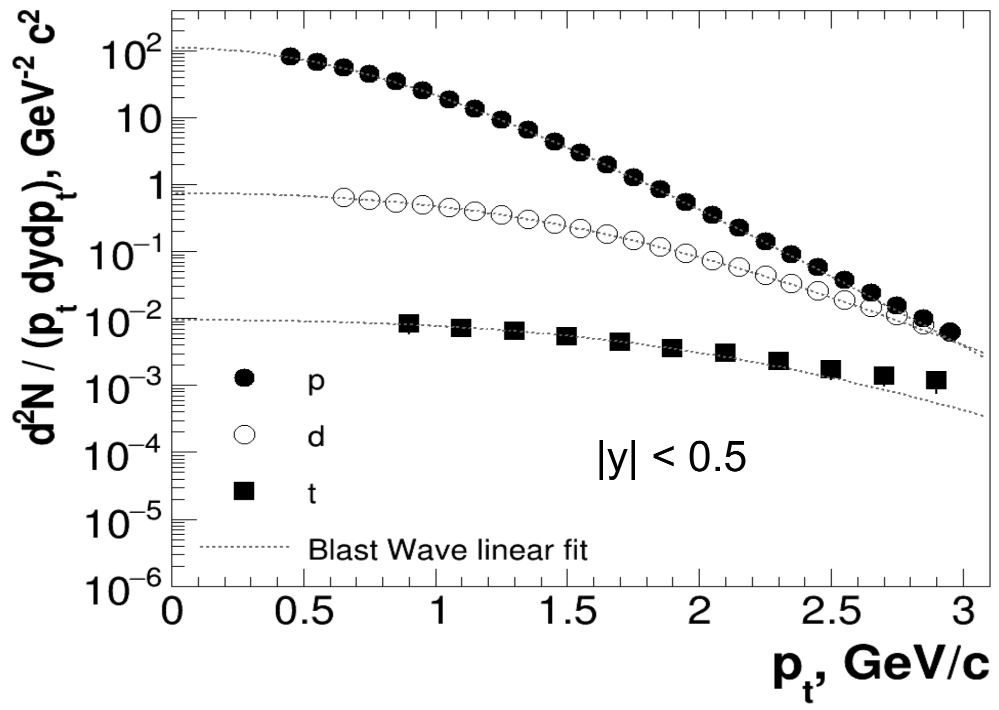


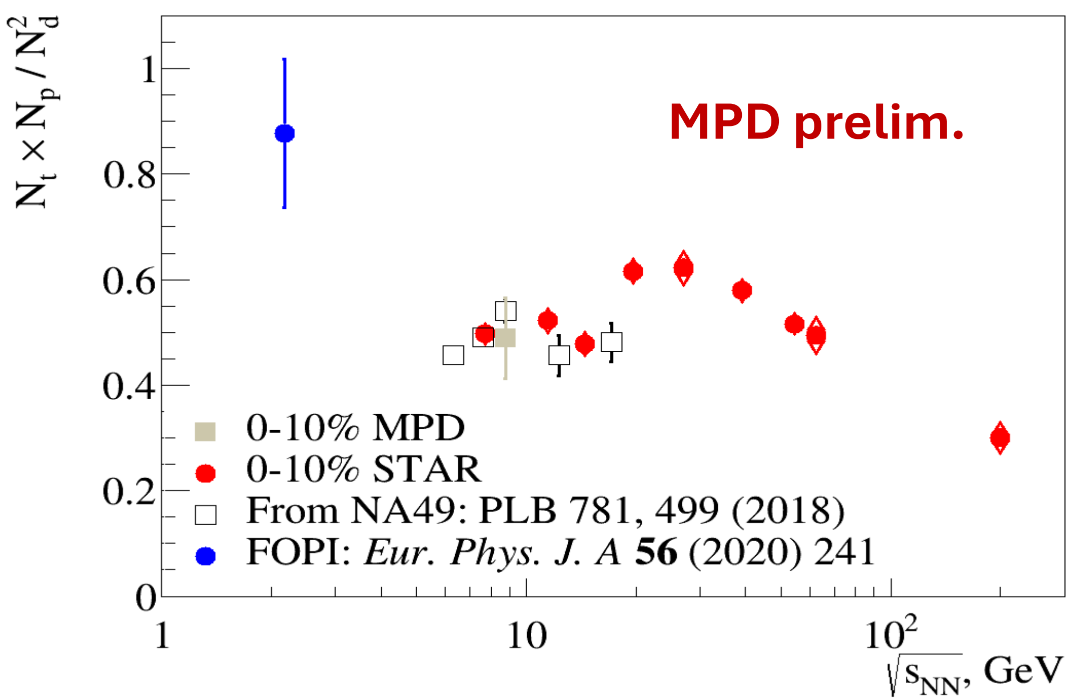


MPD: particle yields ratio in the analysis of density fluctuations

- A peak structure in the excitation function of relative neutron density fluctuations as a probe of the QCD phase diagram structure – *K.J.Sun et al, Phys. Lett. B 781, 499 (2018)*

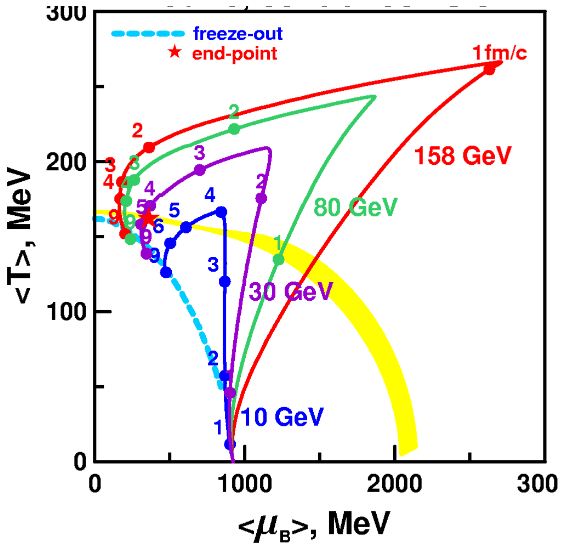
$O_{pdt}=(N_p N_t)/(N_d^2)$

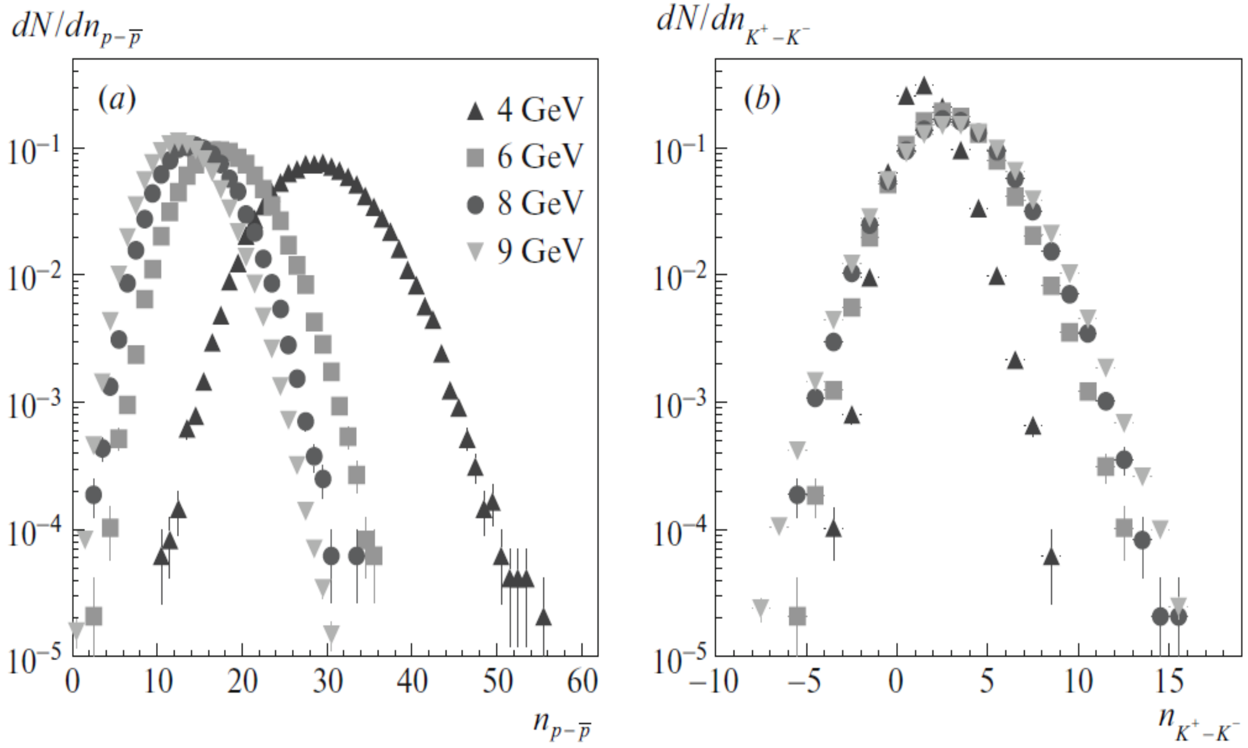




MPD: prospects for CEP search in net-proton and net-strangeness fluctuations

- Moments of event-by-event multiplicity distributions or cumulant ratios are directly compared to susceptibilities, which diverge in the proximity of CEP
- MPD has a large uniform acceptance for hadrons and good per-event PID capability → good prospects for the study strangeness and baryon number fluctuations





effective skewness Sσ for net-protons (a) and net-kaons (б)