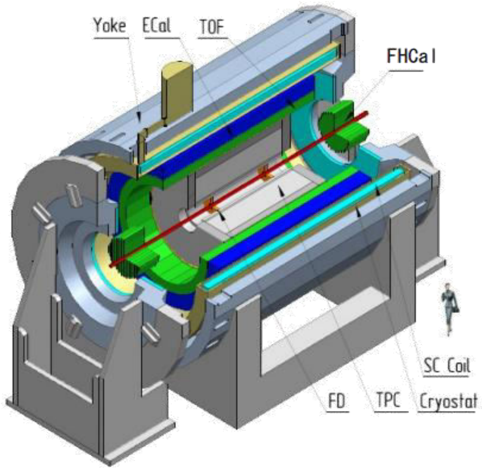
Status and preparations for the first physics with the MPD

Victor Riabov for the MPD Collaboration

MPD at NICA

❖ One of two experiments at NICA collider to study heavy-ion collisions at $\sqrt{s_{NN}}$= 4−11 GeV



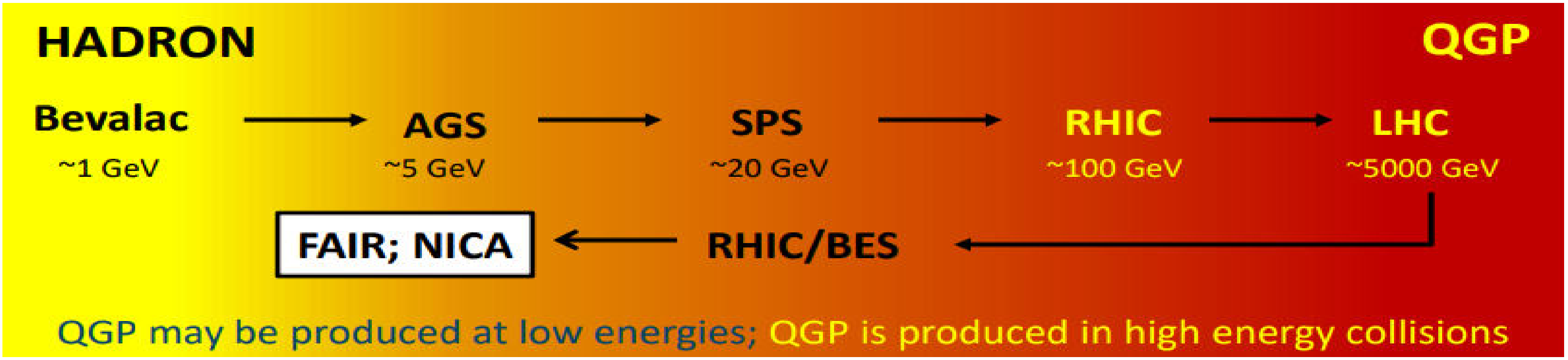
Stage- I

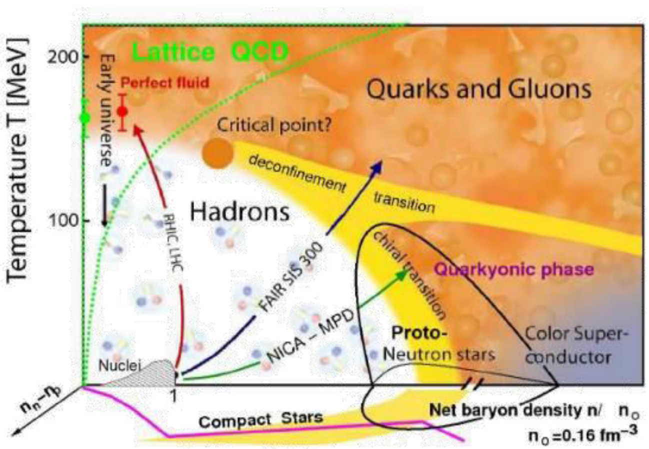
TPC: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.6$
TOF, EMC: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.4$
FFD: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$
FHCAL: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

❖ Expected beam configuration in first year(s) of operation:

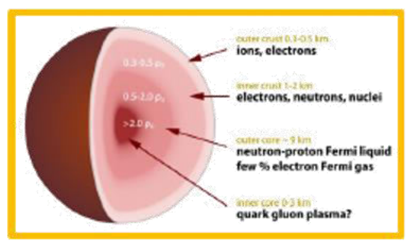
- ✓ not-optimal beam optics with wide z-vertex distribution, σ_z ~ 50 cm
- ✓ reduced luminosity (~10^{25} is the goal for 2023) → collision rate ~ 50 Hz
- ✓ collision system available with the current sources: C (A=12), N (A=14), Ar (A=40), Fe (A=56), Kr (A=78-86), Xe (A=124-134), Bi (A=209)
- ✓ First beams: Bi+Bi in 2025

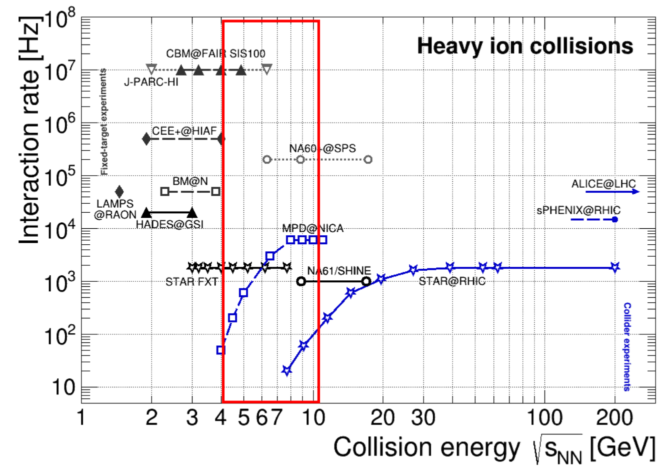
Relativistic heavy-ion collisions





high baryon densities
→ inner structure of
compact stars





- ❖ At μ_B ~ 0, smooth crossover (lattice QCD calculations + data)
- ❖ At large μ_B, 1st order phase transition is expected → QCD critical point
- ❖ BM@N and MPD will study QCD medium at extreme net baryon densities
- ❖ Many ongoing (NA61/Shine, STAR-BES) and future experiments (CBM) in ~ same energy range

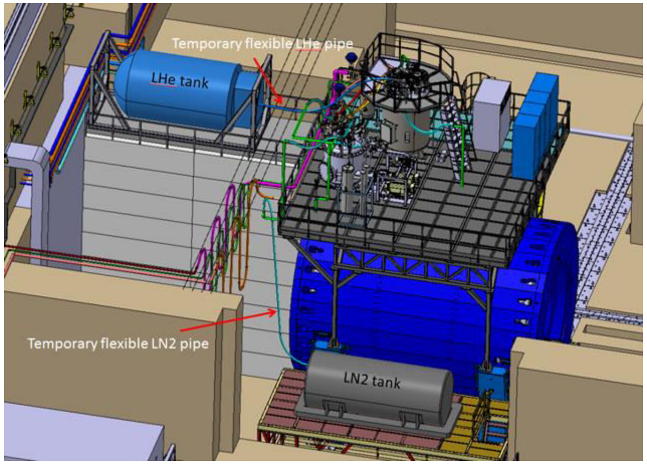
Activities in the MPD Hall

Top platform (cryogenics, power supplies, control system)

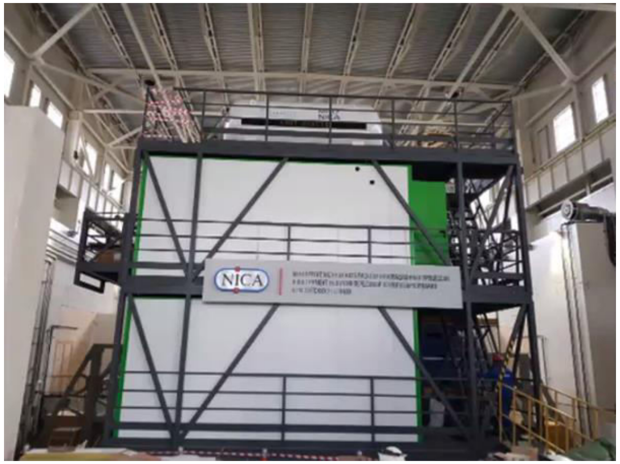
Chimney

Cryogenic platform

Temporary scheme of Solenoid cooling



Thermostable rooms, LN tank



Cryogenic pipes

- Yoke, TRIM coils, top platform, chimney assembled, ongoing tests of the refrigerators and control Dewar
- Pipes, LN2 tanks, LHe pipe, heaters and other equipment re-ordered in Russia and delivered
- Cooling to LN and LHe temperatures by the end of 2023

Time Projection Chamber (TPC)

- ❖ TPC cylinders, central membrane and service wheels are ready, final vessel assembly by the end of 2023
- ❖ Read-out chambers (ROCs) - 24 tested chambers in stock + 4 tested spare chambers

- ❖ Gas system ready – testing
- ❖ TPC FE electronics status:
  - ✓ 65% manufactured (967 pc)
  - ✓ no more problems with components → 100% available

- ❖ On critical path:
  - ✓ TPC rails prod./inst. – October-November, 2023
  - ✓ TPC cooling system – (INP BSU, Belarus) – FEE cooling ready by November, 2023; thermostabilization panels by September, 2024

❖ TPC installation in the MPD: end of 2024

Time-of-Flight (TOF)

- ❖ The production of MRPC detectors was completed in September 2022, (107%) chambers
- ❖ TOF modules are assembled → long-term cosmic ray tests
- ❖ Electronics & cables, HV distribution modules, installation equipment - in stock
- ❖ Started assembly of the TOF gas system in the MPD hall in September 2022 → finished in summer, 2023

Storage of tested TOF modules

TOF installation bench in LHEP

- ❖ The equipment for installing the modules in the MPD is ready for use and stored in the laboratory

- ❖ TOF installation in the MPD: September, 2024

Electromagnetic calorimeter (ECAL)

- Sampling calorimeter with projective geometry (70 tons):
  - ✓ 25 sectors (50 half-sectors); 2400 modules; 38,400 “shashlyk”-type Pb-Sc towers with segmentation of 4x4 cm^2
- 1600 modules (66%) have been produced (800 in Russia + 800 in China)
- Production of additional 400 modules in Russia is ongoing, use Russian-made WLS fibers → 83% in total
- Mass production of half-sectors in JINR by international team, 18 half-sectors assembled

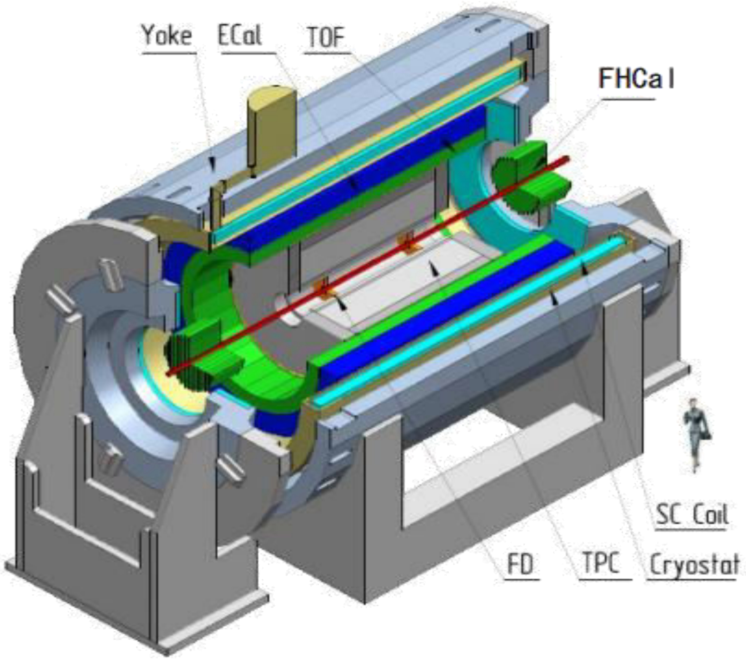
Half-sectors at different stages of assembly

- ECAL installation in the MPD: August, 2024

Multi-Purpose Detector (MPD) Collaboration

MPD** International Collaboration was established in **2018
to construct, commission and operate the detector

11** Countries, **>500** participants, **35** Institutes and **JINR



Organization

Acting Spokesperson:	***Victor Riabov***
Deputy Spokespersons:	***Zebo Tang, Arkadiy Taranenko***
Institutional Board Chair:	***Alejandro Ayala***
Project Manager:	***Slava Golovatyuk***

***Joint Institute for Nuclear Research**;*
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*University of Plovdiv, **Bulgaria;***
*Tsinghua University, Beijing, **China**;*
*University of Science and Technology of China, Hefei, **China**;*
*Huzhou University, Huzhou, **China**;*
*Institute of Nuclear and Applied Physics, CAS, Shanghai, **China**;*
*Central China Normal University, **China**;*
*Shandong University, Shandong, **China**;*
*University of Chinese Academy of Sciences, Beijing, **China**;*
*University of South China, **China**;*
*Three Gorges University, **China**;*
*Institute of Modern Physics of CAS, Lanzhou, **China**;*
*Tbilisi State University, Tbilisi, **Georgia**;*
*Institute of Physics and Technology, Almaty, **Kazakhstan**;*
*Benemérita Universidad Autónoma de Puebla, **Mexico**;*
*Centro de Investigación y de Estudios Avanzados, **Mexico**;*
*Instituto de Ciencias Nucleares, UNAM, **Mexico**;*
*Universidad Autónoma de Sinaloa, **Mexico**;*
*Universidad de Colima, **Mexico**;*
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*Belgorod National Research University, **Russia**;*
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*National Research Center "Kurchatov Institute", **Russia**;*
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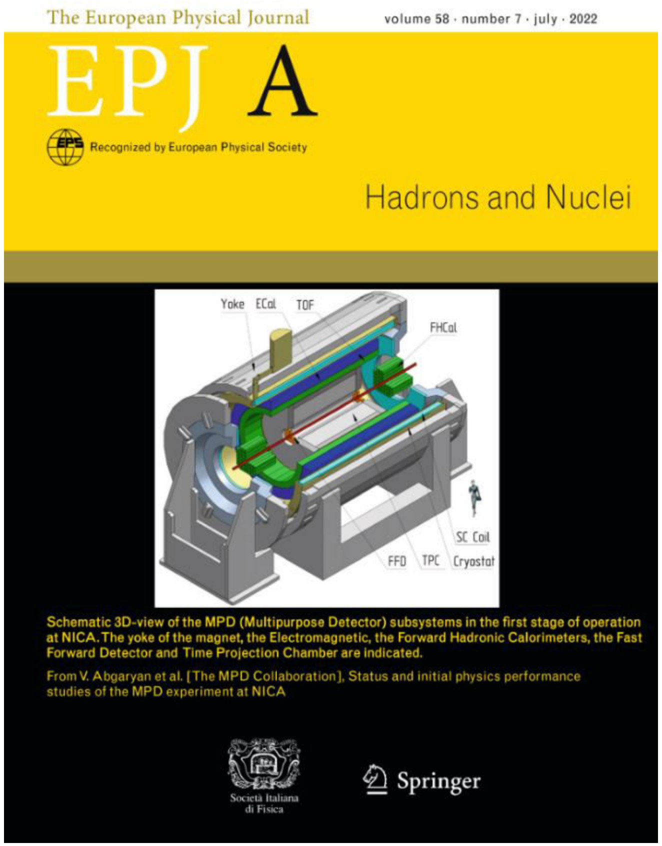
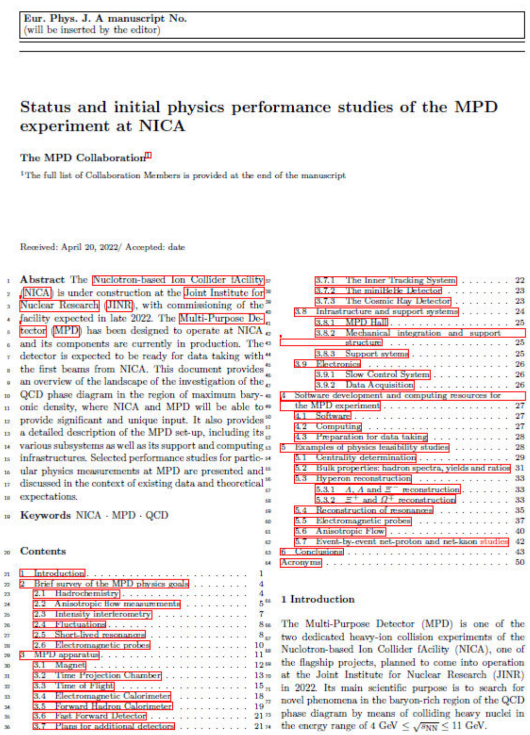
*Skobeltsyn Institute of Nuclear Physics, Moscow, **Russia**;*
*Petersburg Nuclear Physics Institute, Gatchina, **Russia**;*
*Vinča Institute of Nuclear Sciences, **Serbia**;*
*Pavol Jozef Šafárik University, Košice, **Slovakia***

Collaboration activity

- MPD publications: over 200 in total for hardware, software and physics studies (SPIRES)
- MPD @ conferences: presented at all major conferences in the field
- First collaboration paper recently published EPJA (~ 50 pages): Eur.Phys.J.A 58 (2022) 7, 140

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





Eur. Phys. J. A manuscript No.
(will be inserted by the editor)

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

The MPD Collaboration[1]

[1]The full list of Collaboration Members is provided at the end of the manuscript

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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.

Keywords NICA · MPD · QCD

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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 of colliding heavy nuclei in the energy range of 4 GeV $\leq \sqrt{s_{NN}} \leq$ 11 GeV.

MPD physics program

G. Feofilov, A. Aparin

Global observables
- Total event multiplicity
- Total event energy
- Centrality determination
- Total cross-section measurement
- Event plane measurement at all rapidities
- Spectator measurement

V. Kolesnikov, Xianglei Zhu

Spectra of light flavor and hypernuclei
- Light flavor spectra
- Hyperons and hypernuclei
- Total particle yields and yield ratios
- Kinematic and chemical properties of the event
- Mapping QCD Phase Diag.

K. Mikhailov, A. Taranenko

Correlations and Fluctuations
- Collective flow for hadrons
- Vorticity, Λ polarization
- E-by-E fluctuation of multiplicity, momentum and conserved quantities
- Femtoscopy
- Forward-Backward corr.
- Jet-like correlations

D. Peresunko, Chi Yang

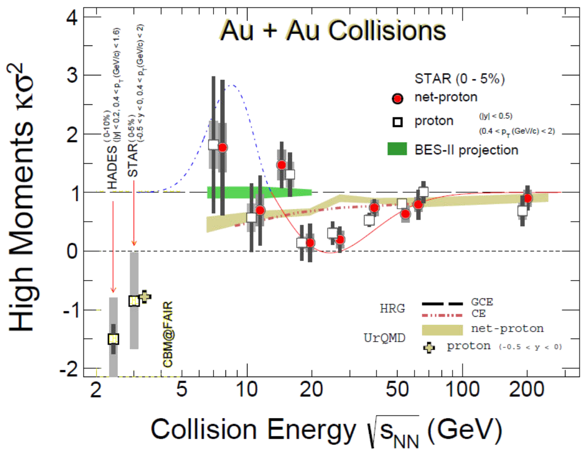
Electromagnetic probes
- Electromagnetic calorimeter meas.
- Photons in ECAL and central barrel
- Low mass dilepton spectra in-medium modification of resonances and intermediate mass region

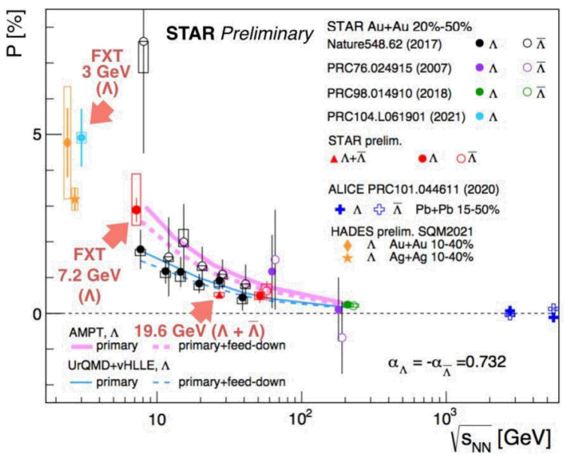
Wangmei Zha, A. Zinchenko

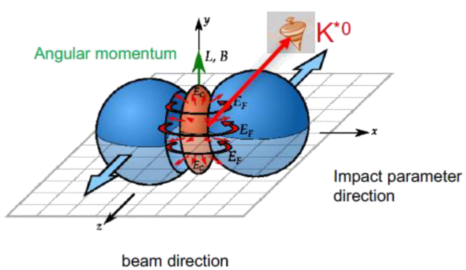
Heavy flavor
- Study of open charm production
- Charmonium with ECAL and central barrel
- Charmed meson through secondary vertices in ITS and HF electrons
- Explore production at charm threshold

Hot topics

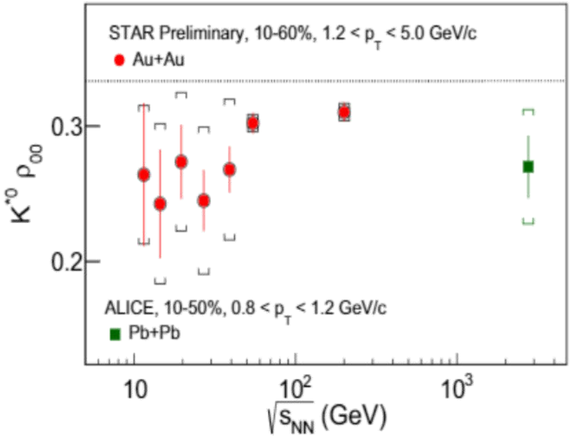
- Critical fluctuations for (net)proton/kaon multiplicity distributions
- Global hyperon polarization in mid-central A+A collisions (Λ, Ξ, Ω)
- Spin alignment of vector mesons (K^*(892), ϕ(1020))

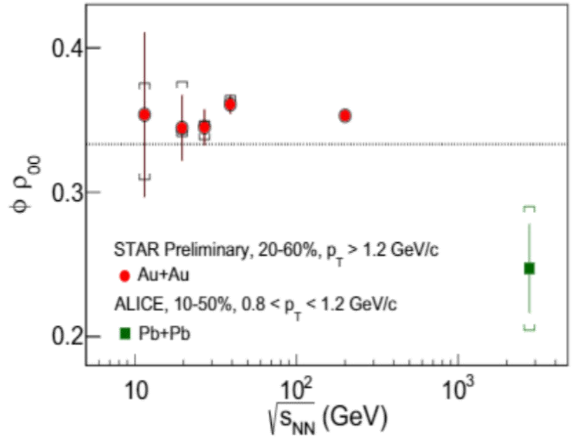






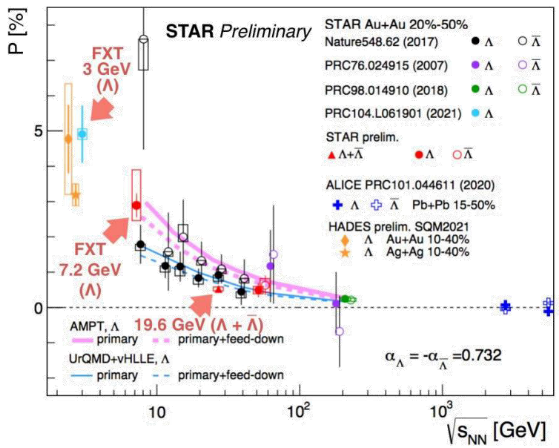
$$\frac{dN}{dcos\theta} = N_0\left[1 - \rho_{0,0} + cos^2\theta\left(3\rho_{0,0} - 1\right)\right]$$

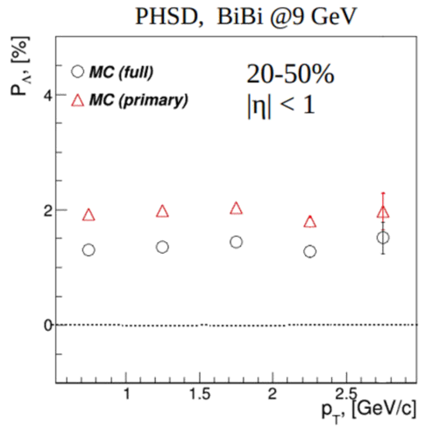


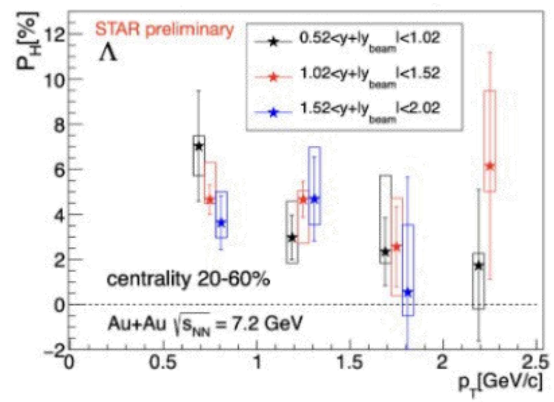


Hyperon global polarization

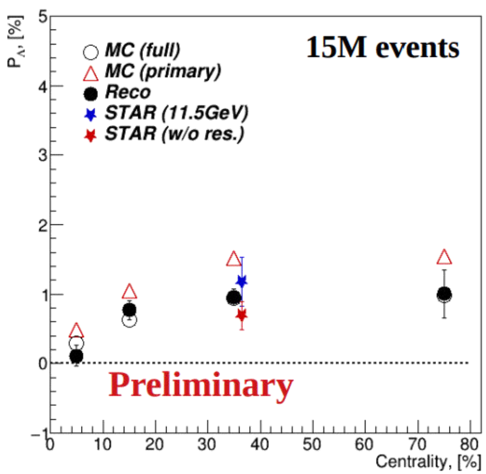
- BiBi@9.2 GeV (PHSD), 15 M events → full event/detector simulation and reconstruction
- Global hyperon polarization (thermodynamical Becattini approach [1]) by the event generator → reproduce at generator level basic features measured by STAR







- Reconstruction of Λ global polarization, work in progress, BiBi@9.2 GeV:



- Analysis performed using 'Polarization wagon' of the Analysis Train
- Measured polarization is consistent with the generated one
- First global polarization measurements for $\Lambda/\bar{\Lambda}$ will be possible with ~ 10M data sampled events

[1] F. Becattini, V. Chandra, L. Del Zanna, E. Grossi, Ann. Phys. 338 (2013) 32

Charged identified light hadrons

- Probe freeze-out conditions, collective expansion, hadronization mechanisms, strangeness production ("horn" for K/π), parton energy loss, etc. with particles of different masses, quark contents/counts
- Charged hadrons: large and uniform acceptance + excellent PID capabilities of TPC and TOF

0-5% central AuAu@9 GeV (PHSD), 5 M events → full event/detector simulation and reconstruction

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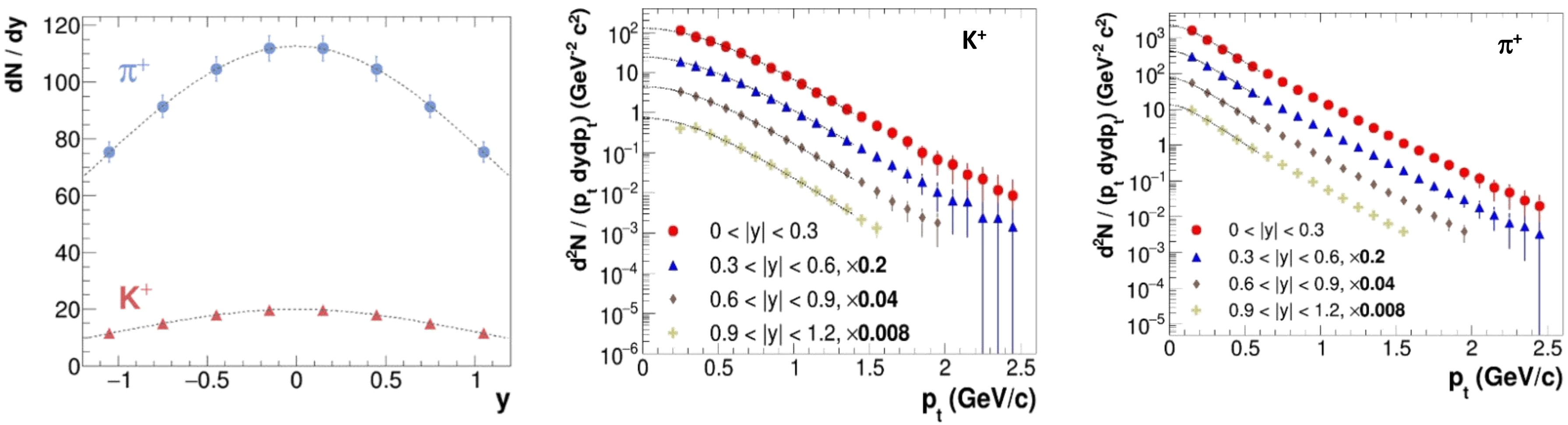
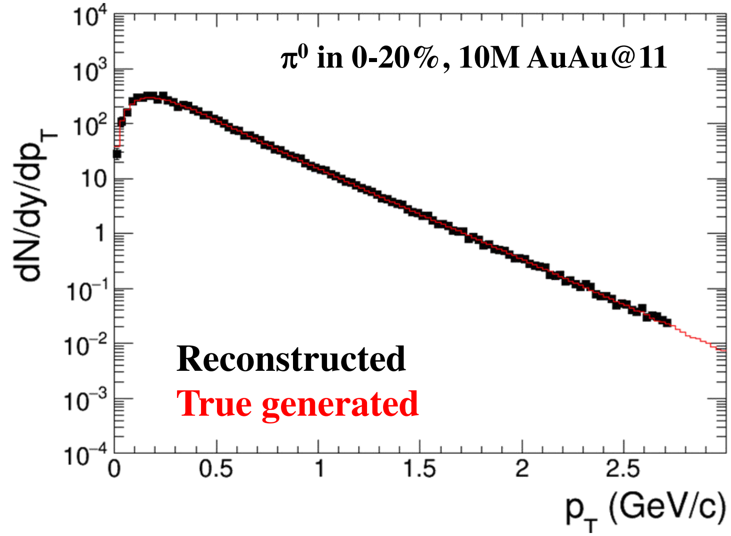


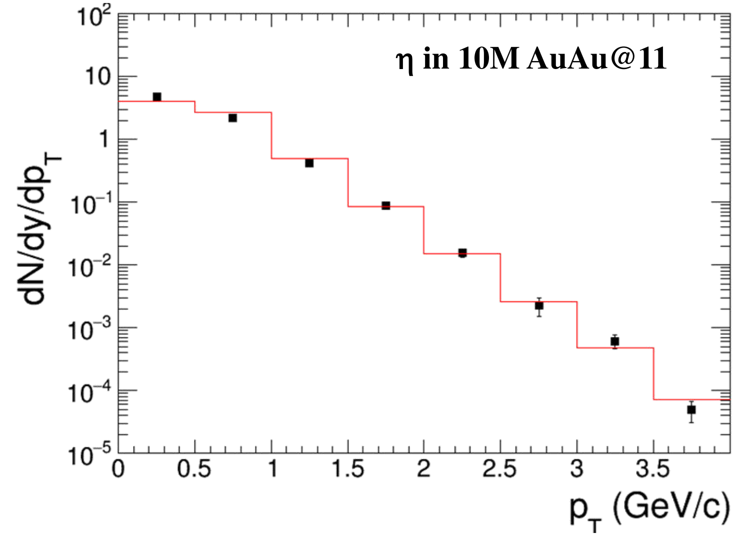
✓ sample ~ 70% of the π/K/p production in the full phase space
✓ hadron spectra are measured from p_T ~ 0.1 GeV/c

Neutral identified light hadrons

❖ Neutral mesons (π^0, η, K_s, ω, η'): ECAL reconstruction + photon conversion method (PCM)

AuAu@11 GeV (UrQMD), 10M events → full event/detector simulation and reconstruction





✓ extend p_T ranges of charged particle measurements
✓ different systematics

MPD will be able to measure differential production spectra, integrated yields and <p_T>, particle ratios for a wide variety of identified hadrons (π, K, η, ω, p, η')

First measurements will be possible with a few million sampled heavy-ion events

Short-lived resonances - I

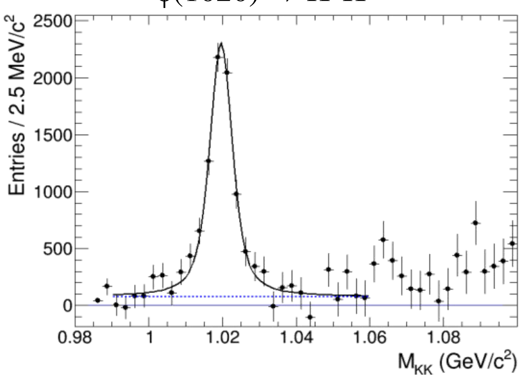
❖ Resonances probe reaction dynamics and particle production mechanisms vs. system size and $\sqrt{s_{NN}}$:
✓ hadron chemistry and strangeness production, lifetime and properties of the hadronic phase, spin alignment of vector mesons, flow etc.

increasing lifetime ⟶

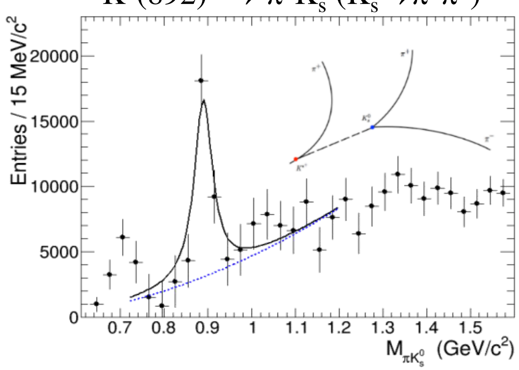
	ρ(770)	K^*(892)	Σ(1385)	Λ(1520)	Ξ(1530)	φ(1020)
cτ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

❖ BiBi@9.2 GeV (UrQMD) after mixed-event background subtraction: *Phys.Scripta* 96 (2021) 6, 064002

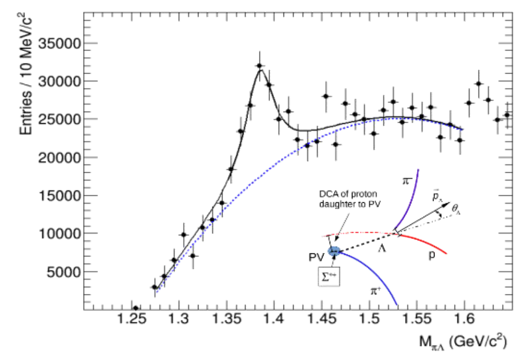
$\phi(1020) \to K^+K^-$



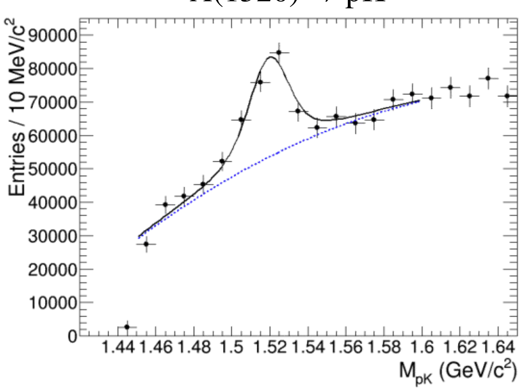
$K^*(892)^\pm \to \pi^\pm K_s$ ($K_s \to \pi^+\pi^+$)



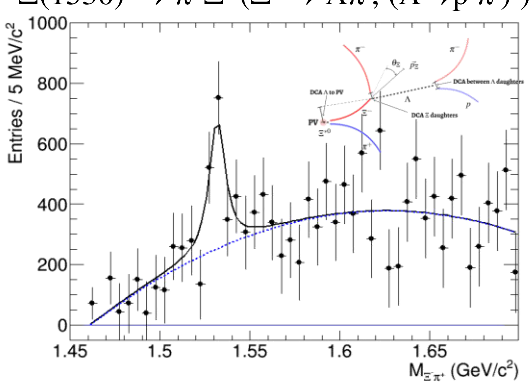
$\Sigma(1385)^\pm \to \pi^\pm\Lambda$ ($\Lambda \to p\pi$)



$\Lambda(1520) \to pK^-$



$\Xi(1530)^0 \to \pi^+\Xi^-$ ($\Xi^- \to \Lambda\pi^-$, ($\Lambda \to p\ \pi^-$))

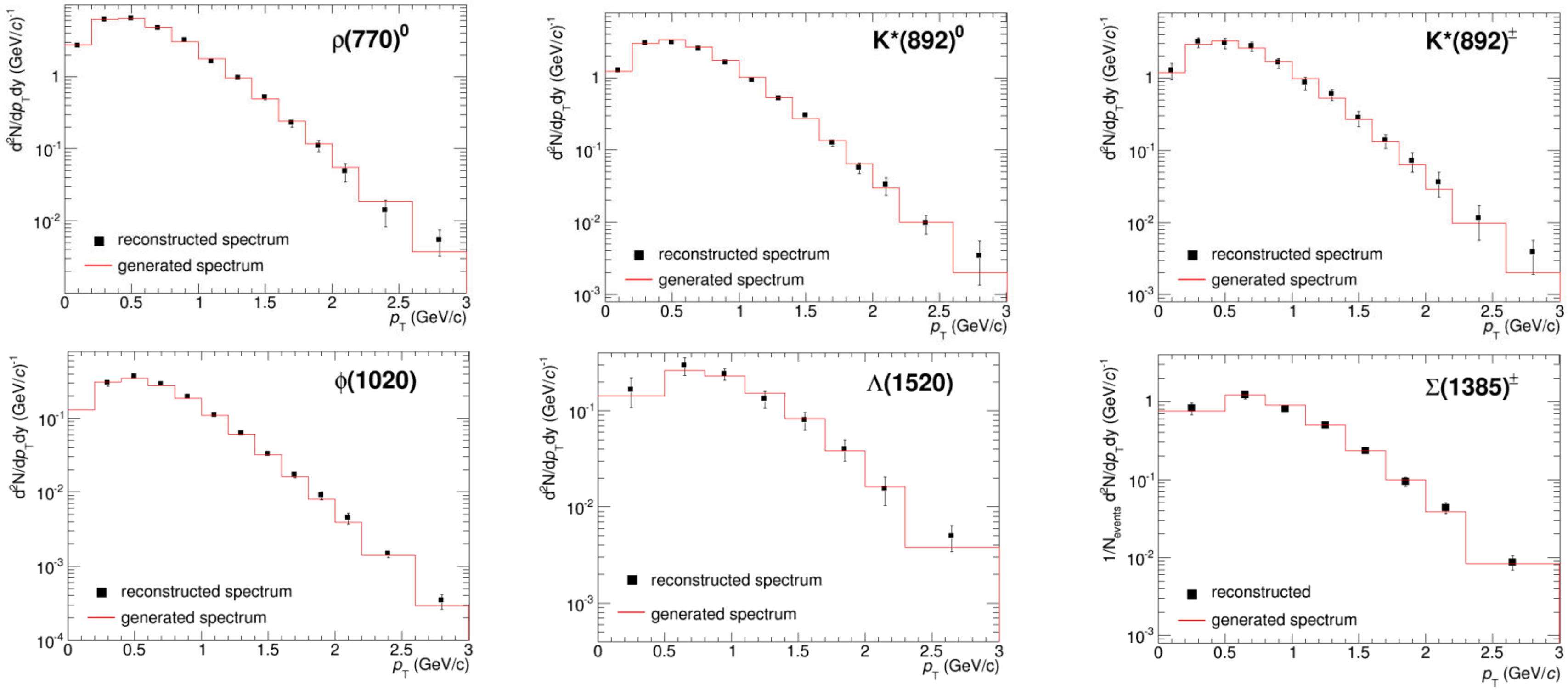


✓ MPD is capable of reconstruction the resonance peaks in the invariant mass distributions using combined charged hadron identification in the TPC and TOF

✓ decays with weakly decaying daughters require additional second vertex and topology cuts for reconstruction

Short-lived resonances - II

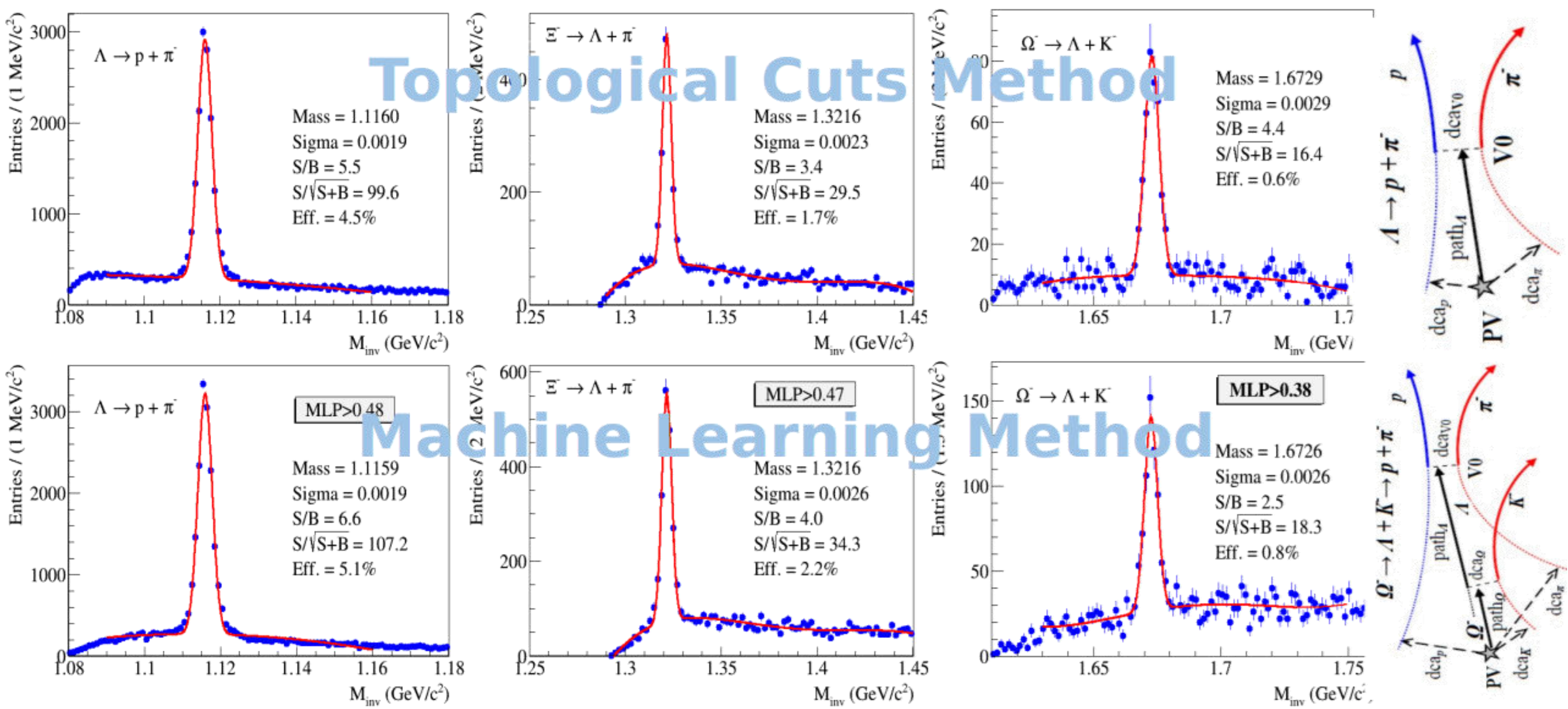
- ❖ Full chain simulation and reconstruction, p_T ranges are limited by the possibility to extract signals, $|y| < 1$



- ❖ Reconstructed spectra match the generated ones within uncertainties
- ❖ First measurements for resonances will be possible with accumulation of ~ 10^7 Bi+Bi events
- ❖ Measurements are possible starting from ~ zero momentum → sample most of the yield
- ❖ Measurements of $\Xi(1530)^0$ are very statistics hungry

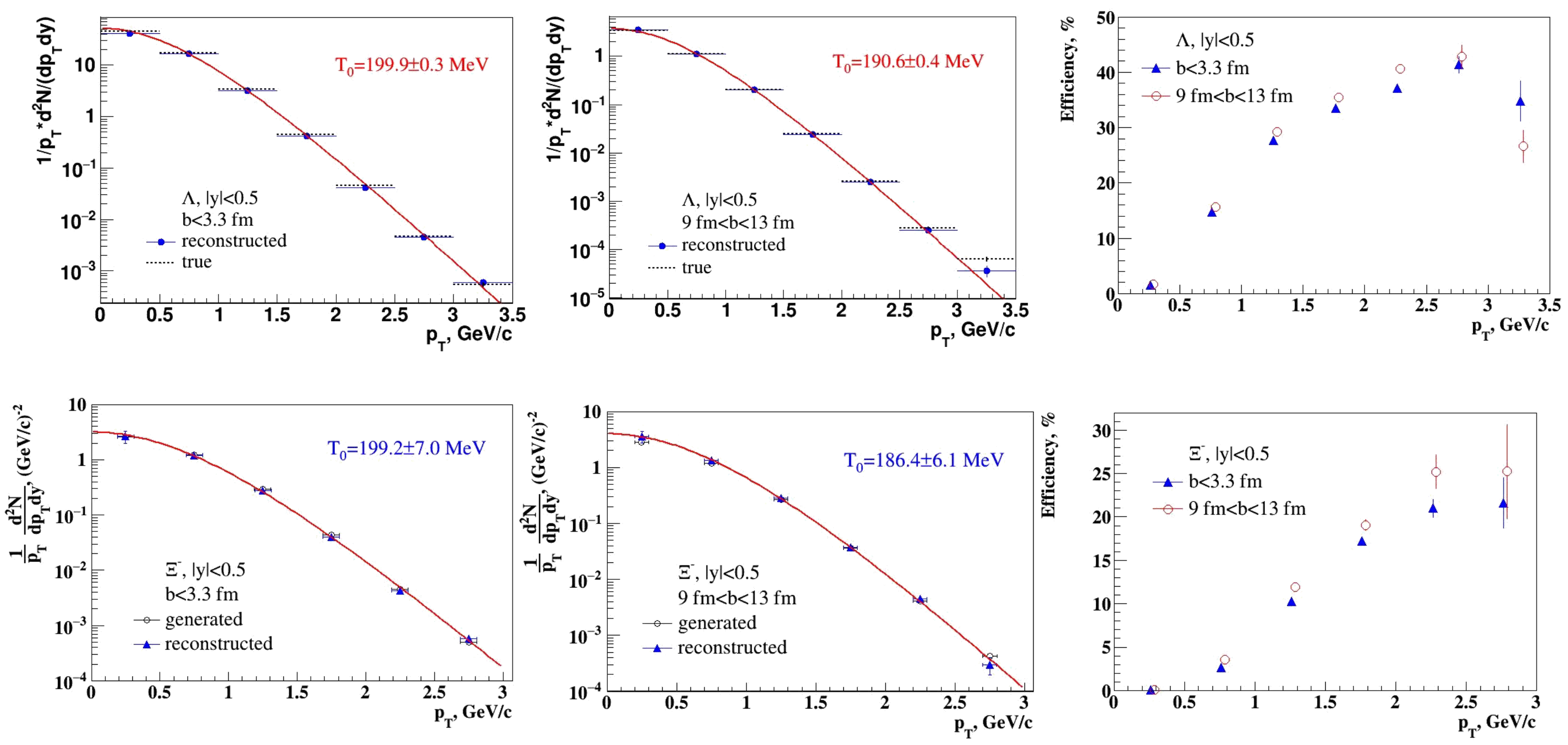
Weak decays of strange baryons - I

- Strangeness production probes the EoS, phase boundaries and onset of deconfinement
- Antibaryon-to-baryon ratios at intermediate momenta are sensitive to CEP (a falling trend in contrast to a constant behavior in the scenario without CEP)
- BiBi@9.2 GeV (PHSD):



Strange baryons can be reconstructed with good S/B ratios using charged hadron identification in the TPC&TOF and different decay topology selections

Weak decays of strange baryons - II

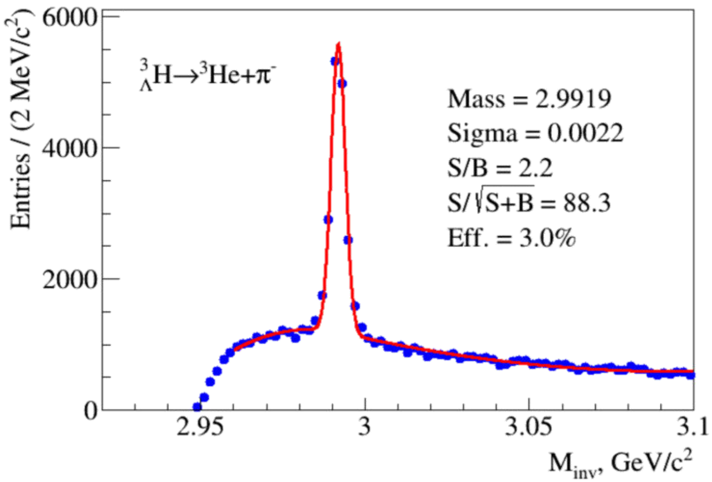


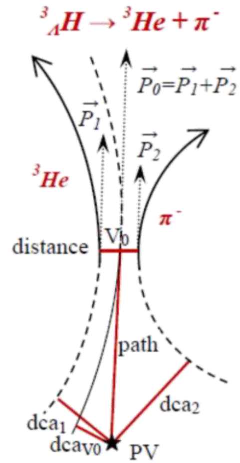
- ❖ Capability to reconstruct baryon yields down to low momenta with reasonable efficiencies
- ❖ High-p_T reach is limited by statistics
- ❖ Reconstructed spectra are consistent with the generated ones → MC closure test passed

Reconstruction of hypertritons

BiBi@9.2 GeV (PHQMD), 40 M events → full event/detector simulation and reconstruction

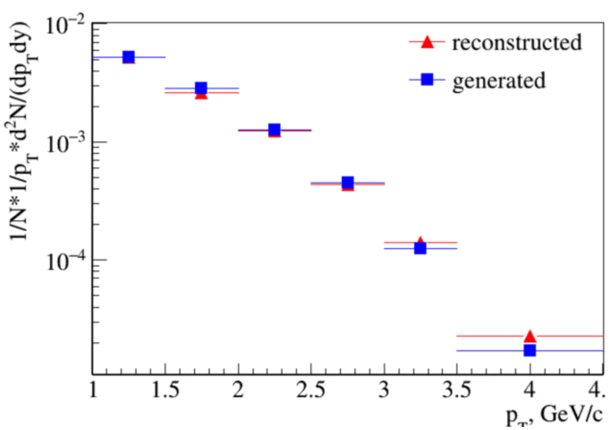
Phys.Part.Nucl.Lett. 19 (2022) 1, 46-53



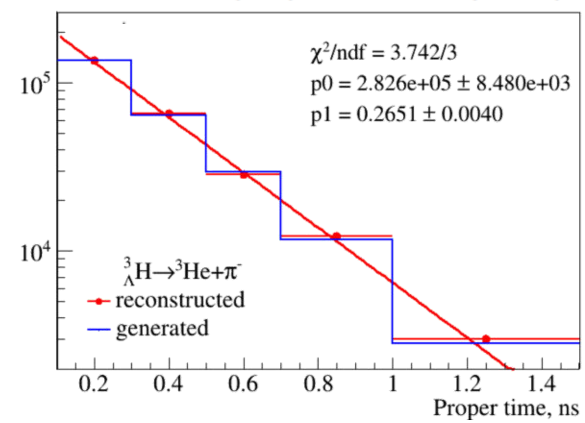


Decay channel	Branching ratio	Decay channel	Branching ratio
$\pi^- + {}^3He$	**24.7%**	$\pi^- + p + p + n$	1.5%
$\pi^0 + {}^3H$	12.4%	$\pi^0 + n + n + p$	0.8%
$\pi^- + p + d$	**36.7%**	$d + n$	0.2%
$\pi^0 + n + d$	18.4%	$p + n + n$	1.5%

Spectrum is reconstructed up to p_T=4.5 GeV/c

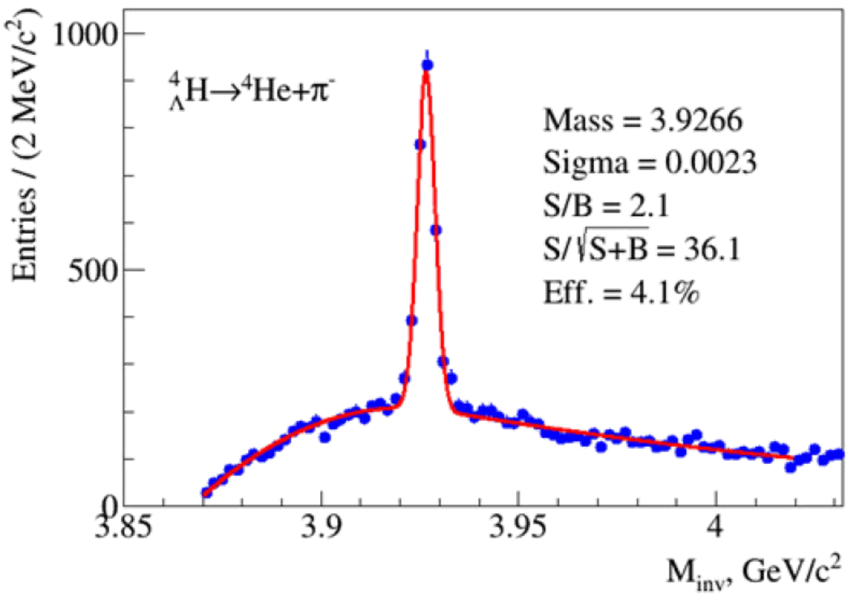


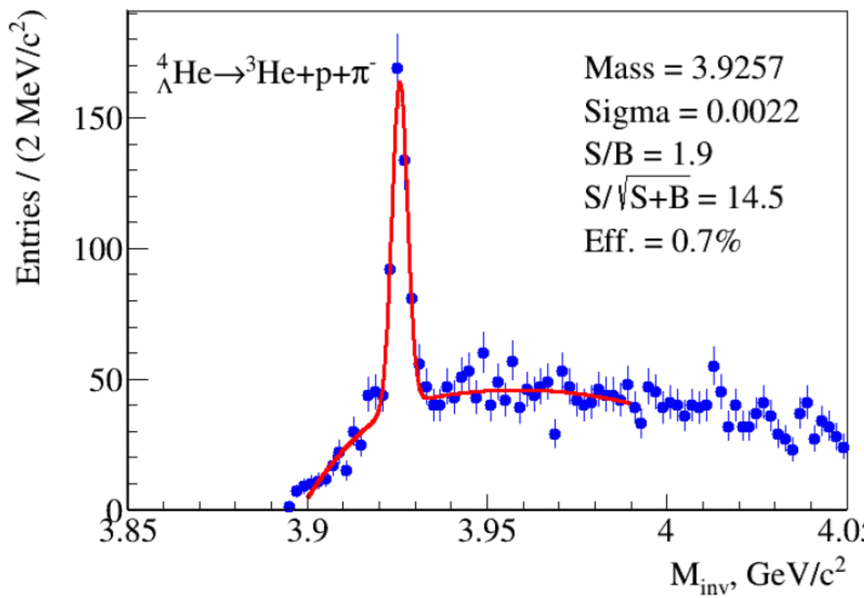
$$N(\tau) = N(0)\exp\left(-\frac{\tau}{\tau_0}\right) = N(0)\exp\left(-\frac{ML}{cp\tau_0}\right),$$



❖ First measurements for hypertriton will be possible with accumulation of ~ 50 M BiBi@9.2 events

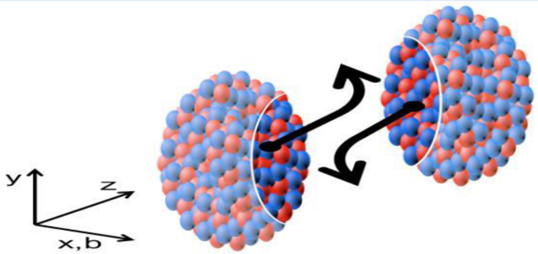
Heavier hypernuclei





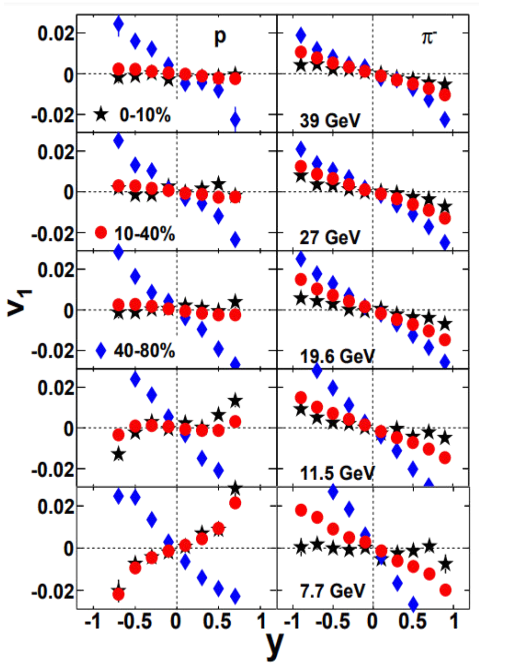
- Monte Carlo events enriched with hypernuclei distributed by (η-p_T) phase space predicted by PHQMD
- Signals for heavier hypernuclei can be reconstructed with the equivalent statistics of ~140 M events

Collective flow at NICA energies



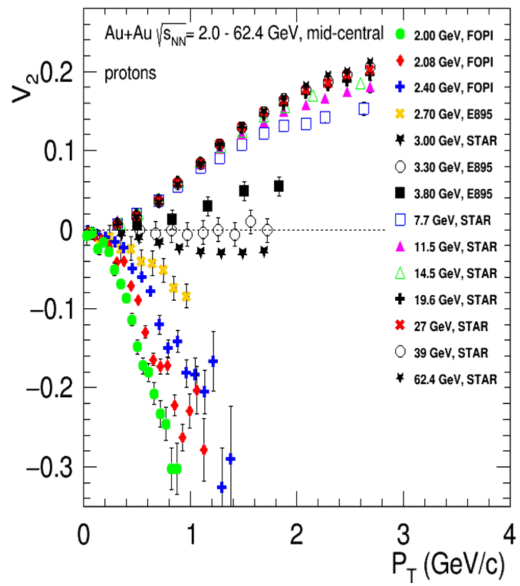
- Generated during the nuclear passage time (2R/γ) – sensitive to EOS
- RHIC @ 200 GeV (2R/γ) ~ 0.1 fm/c
- AGS @ 3-4.5 GeV (2R/γ) ~ 9-5 fm/c
- v_1 and v_2 show strong centrality, energy and species dependence

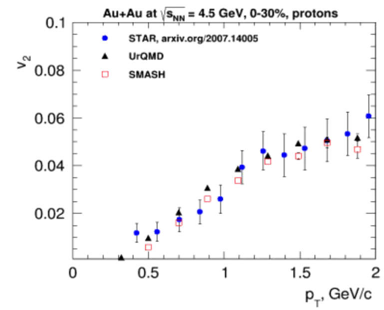
Phys.Rev.Lett. 112 (2014) 16, 162301

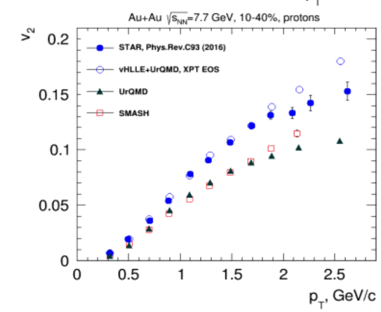


✓ models do not reproduce measurements

EPJ Web Conf. 204 (2019) 03009







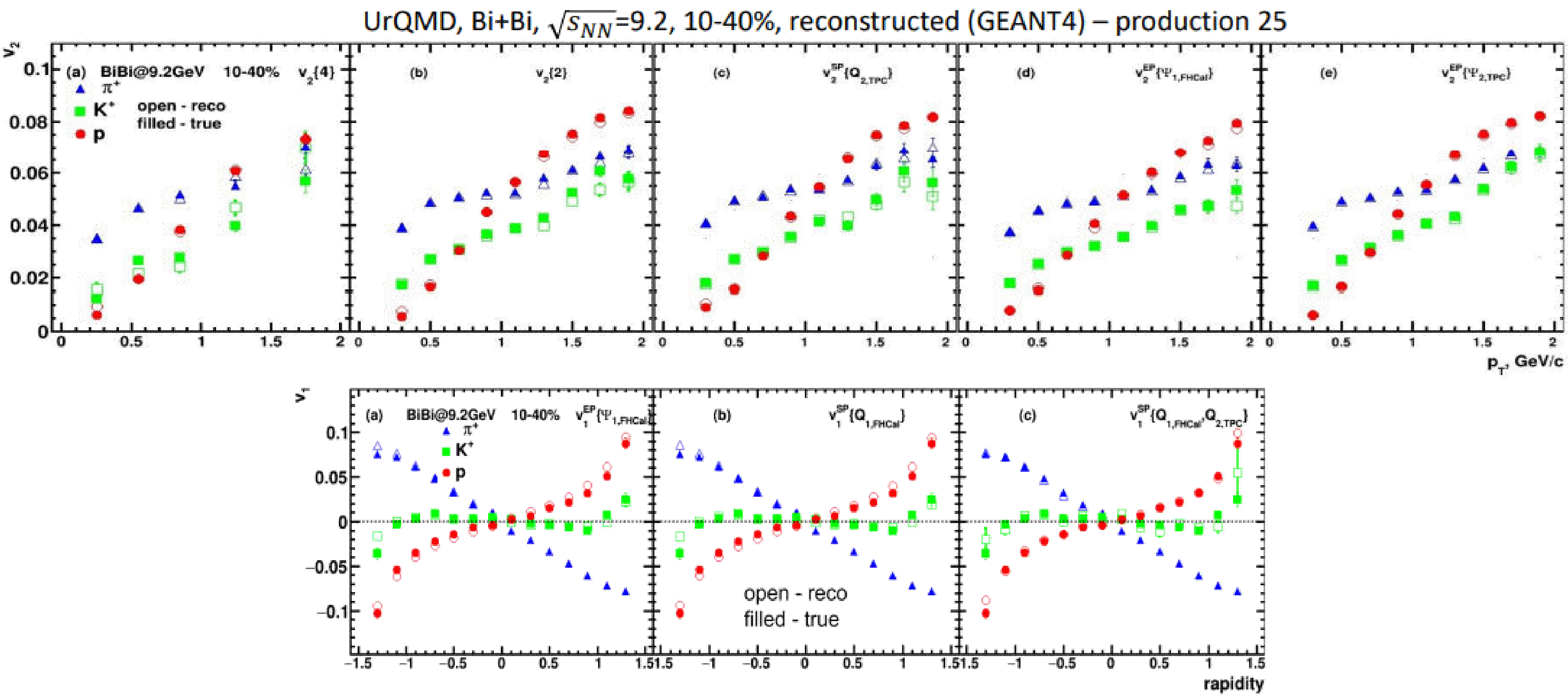
✓ $\sqrt{s_{NN}}$ ~ 3-4.5 GeV, pure hadronic models reproduce v_2 (JAM, UrQMD) → degrees of freedom are the interacting baryons

✓ $\sqrt{s_{NN}} \geq 7.7$ GeV, need hybrid models with QGP phase (vHLLE+UrQMD, AMPT with string melting,…)

System size scan for flow measurements is vital for understanding of the medium transport properties and onset of the phase transition

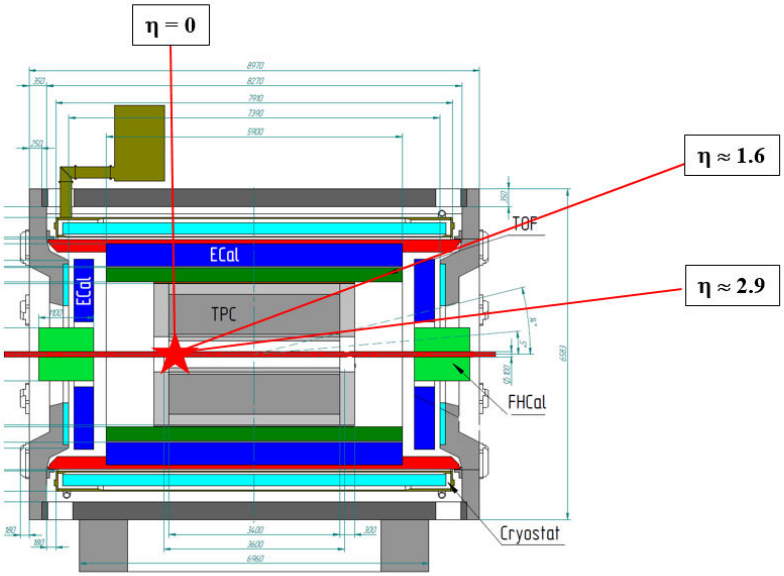
Performance for v_1, v_2 of identified hadrons

❖ UrQMD, BiBi@9.2 GeV

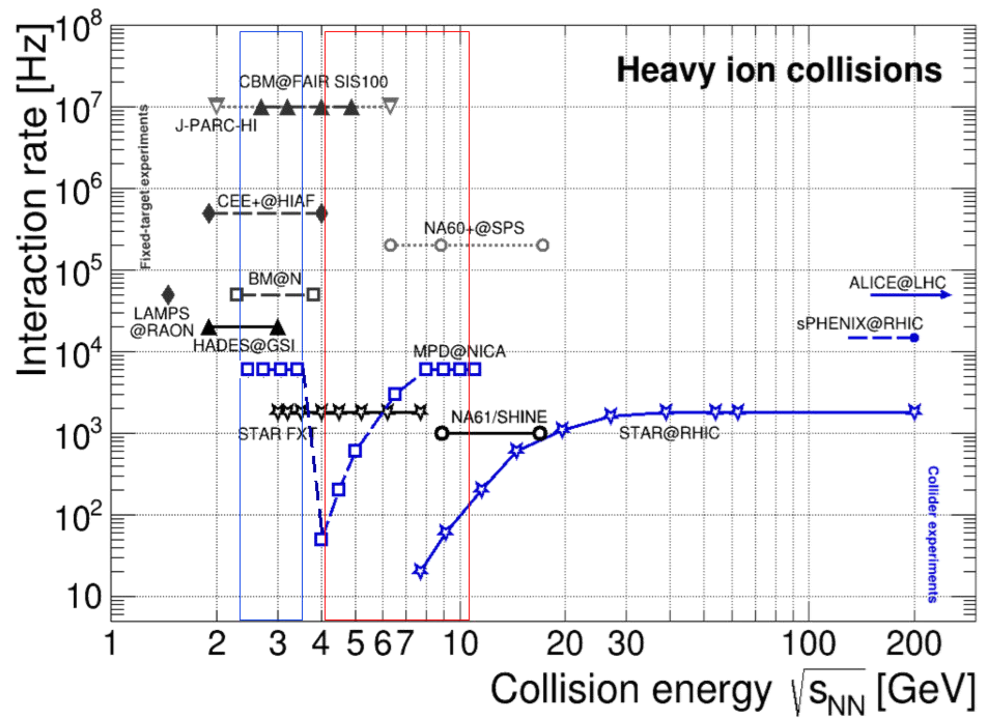


- Reconstructed and generated v_1 and v_2 for identified hadrons are in good agreement for all methods

Running in the fixed-target mode



E_{beam}	$\sqrt{s_{NN}}$ collider mode	$\sqrt{s_{NN}}$ FXT mode	η_{CM}	CMS coverage
2.0	4	2.4	0.7	-0.7; 0.9 (2.2)
5.5	11	3.5	1.23	-1.23; 0.37 (1.67)



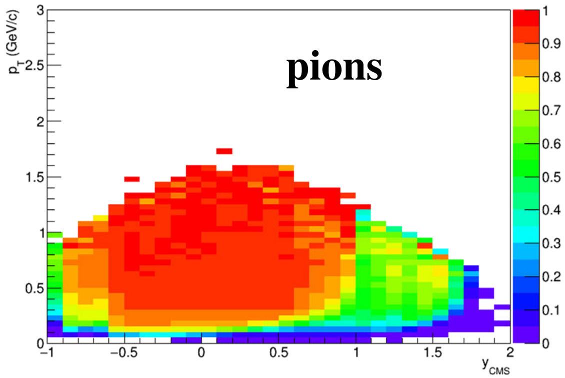
- ❖ Fixed-target mode: one beam + thin wire (~ 100 μm) close to the edge of the MPD central barrel:
  - ✓ extends energy range of MPD to $\sqrt{s_{NN}}$ = 2.4-3.5 GeV (overlap with HADES, BM@N and CBM)
  - ✓ solves problem of low event rate at lower collision energies (only ~ 50 Hz at $\sqrt{s_{NN}}$ = 4 GeV at design luminosity)
  - ✓ backup start-up solution (too low luminosity, only one beam, etc.)

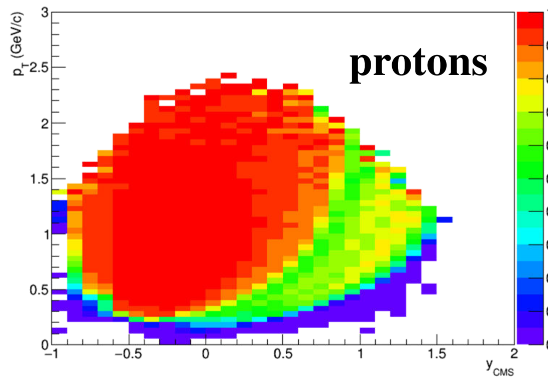
Detector performance in FXT mode

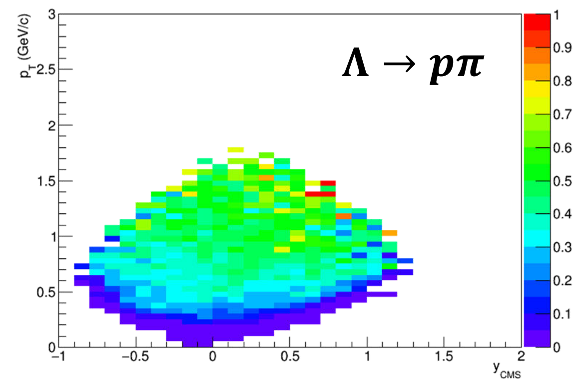
- Existing trigger system is even more efficient compared with the collider mode (FFD + FHCAL + TOF)
- MPD detector provides good enough acceptance for identified hadrons at midrapidity (y_{CMS} ~ 0):

✓ E = 2 A·GeV

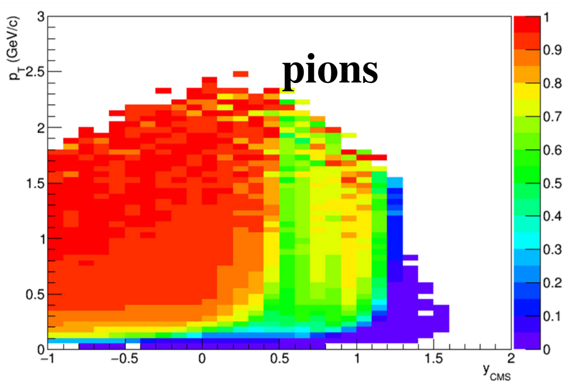
Track selections: N_{hits} > 10; DCA < 2 cm; Primary particles ($R_{production}$ < 1 cm)

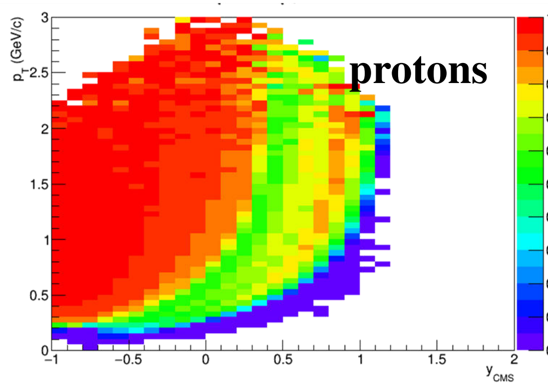


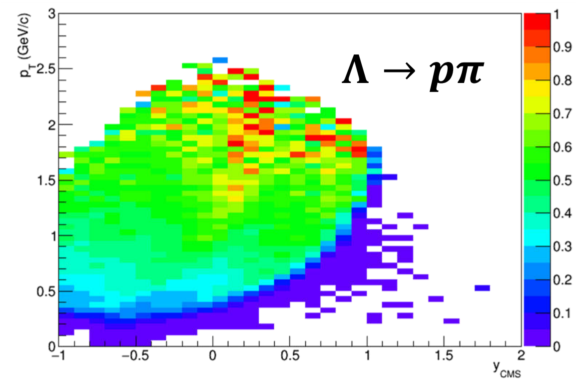




✓ E = 5.5 A·GeV







MPD detector is able to run in the fixed-target mode in the default configuration

Summary

- ❖ Preparation of the MPD detector and experimental program is continued
- ❖ Commissioning and start of data taking → 2025
- ❖ Further program will be driven by the physics demands and NICA capabilities

BACKUP

RHIC BES program

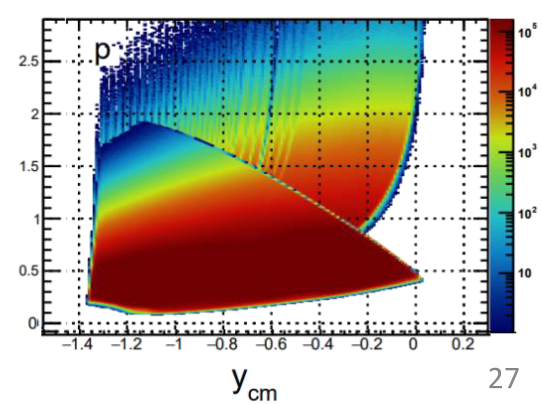
- Data taking by STAR at RHIC: 3 < $\sqrt{s_{NN}}$ < 200 GeV (750 < μ_B < 25 MeV)

Au+Au Collisions at RHIC

Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	200	380 M	25 MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	11.5	157 M	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	9.2	160 M	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	7.7	104 M	420 MeV		Run-21	11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
						12	3.0 (3.85)	2000 M	750 MeV	-1.05	Run-18, 21

- A very impressive and successful program with many collected datasets, already available and expected results
- Limitations:
  - ✓ Au+Au collisions only
  - ✓ Among the fixed-target runs, only the 3 GeV data have full mid-rapidity coverage for protons (|y| < 0.5), which is crucial for physics observables

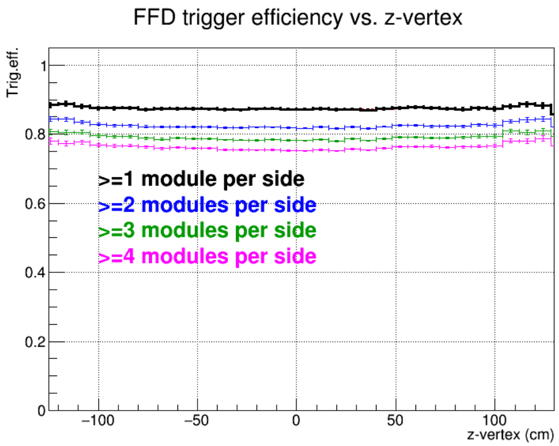
Au+Au @ 3.9 GeV

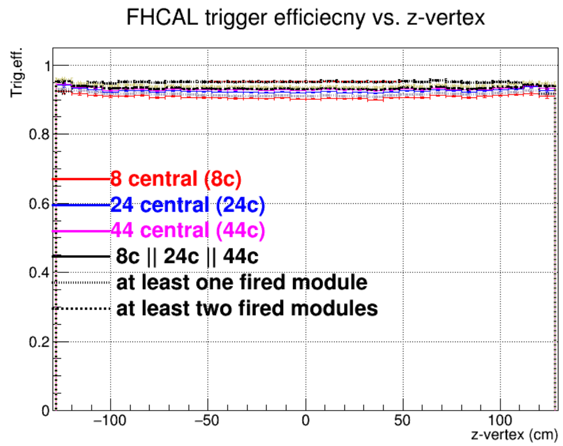


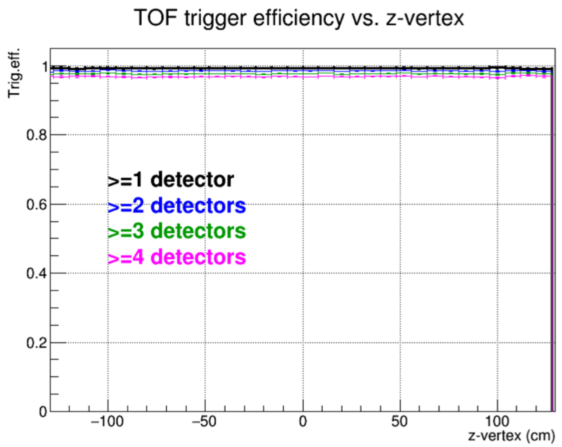
Trigger simulation, BiBi@9.2 GeV

- Trigger system consists of FFD (2.7 < |η| < 4.1), FHCAL (2 < |η| < 5) and TOF (|η| < 1.5)
- MPD trigger system challenges at NICA energies:
  - ✓ low multiplicity of particles produced in heavy-ion collisions
  - ✓ particles are not ultra-relativistic (even the spectator protons)
- DCM-QGSM-SMM, BiBi@9.2: trigger efficiency is 87-98% for different trigger configuration

- FFD trigger definition:
  - ✓ at least one fired module per side
  - ✓ meaningful times, 0 < time $_{E,W}$ < 50 ns
  - ✓ reconstructed z-vertex, |z-vertex| < 140 cm
- FHCAL trigger definition:
  - ✓ at least one fired module per side
  - ✓ meaningful times, 0 < time $_{E,W}$ < 50 ns
  - ✓ reconstructed z-vertex, |z-vertex| < 150 cm
- TOF trigger definition:
  - ✓ at least one fired MRPC



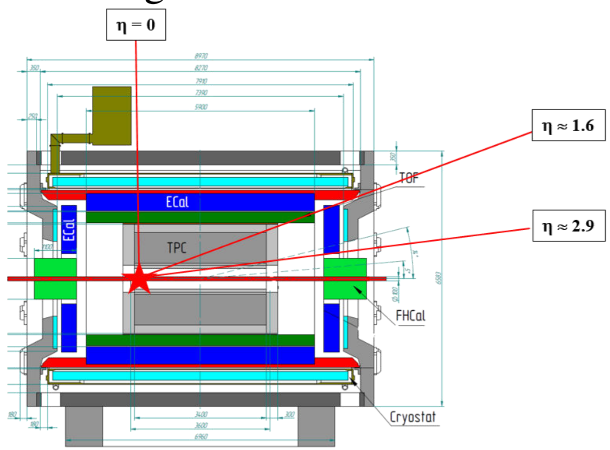




- Trigger system of the MPD based on FFD, FHCAL and TOF detectors provides high efficiency in HIC
- Simulation of the MPD trigger system is now included in the Analysis Train
- A dedicated wagon in the Analysis Train provide centrality for all analyses based on TPC multiplicity
- Light collision systems: ~ 50% for C+C, vanishingly small for d+d

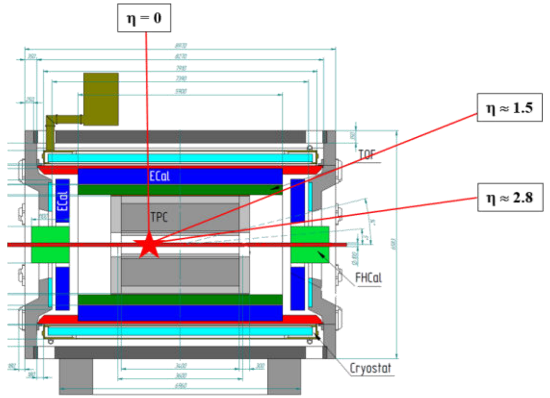
Fixed target configurations

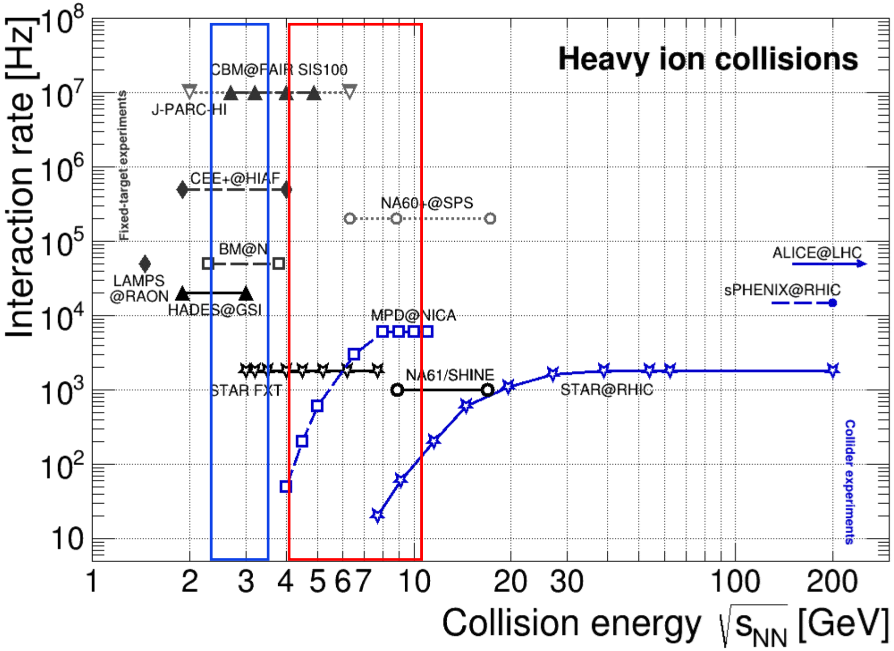
- With a target located at z = -150 cm



E_{beam}	$\sqrt{s_{NN}}$ collider mode	$\sqrt{s_{NN}}$ FXT mode	η_{CM}	CMS coverage
2.0	4	2.4	0.7	-0.7; 0.9 (2.2)
5.5	11	3.5	1.23	-1.23; 0.37 (1.67)

- With a target located at z = -115 cm



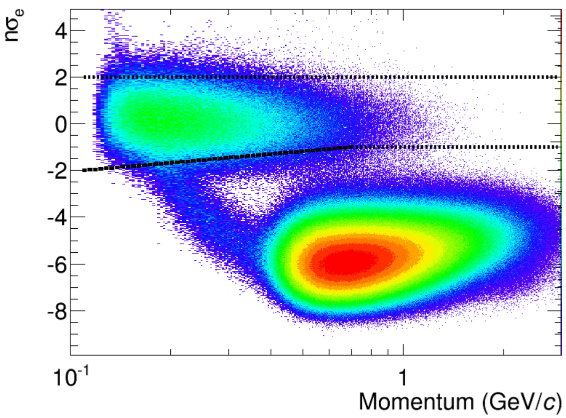


- In heavy-ion collisions:
  - ✓ MPD trigger system based on the FFD, FHCAL and TOF provides high efficiency in the FXT mode
  - ✓ potential problems with online T0 and vertex at lower beam energies

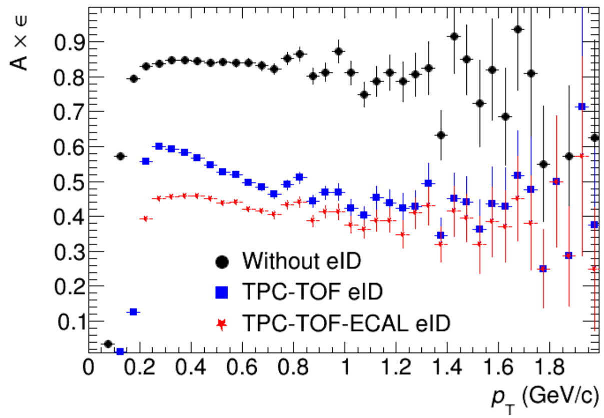
(Di)electrons

- Dielectron spectra are sensitive probes of the deconfinement and the chiral symmetry restoration
- AuAu@11 GeV (UrQMD for background & PHQMD for signal)

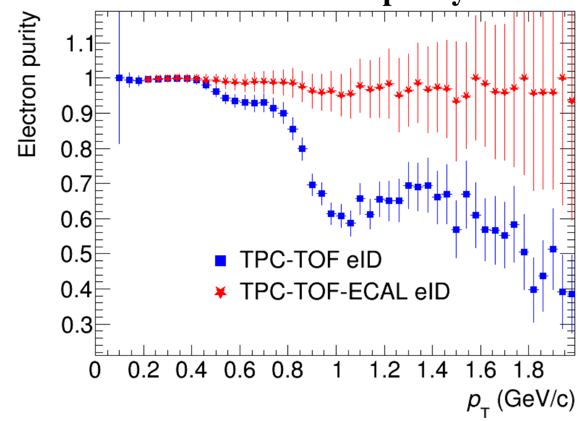
$n\cdot\sigma_e^{TPC}$ with $2\sigma_e$ PID in the TOF

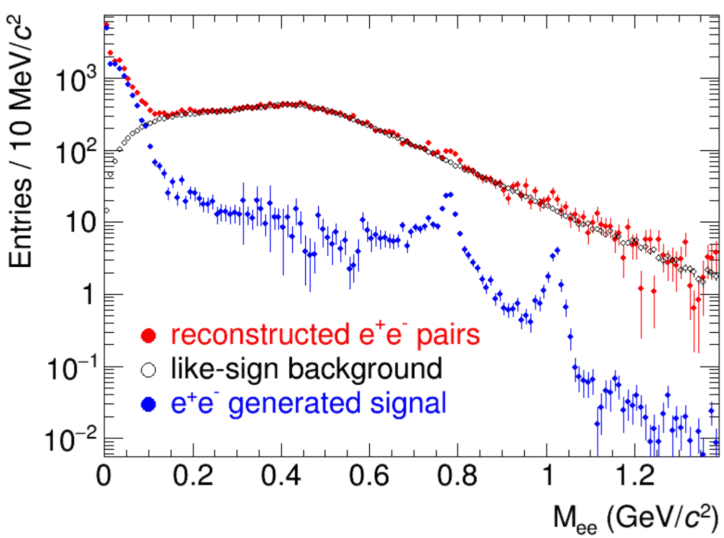


Efficiency of e-track reconstruction



Electron purity





- S/B (integrated in 0.2-1.5 GeV/c^2) ~ 5-10%
- Methods to improve S/B ratio while preserving reasonable efficiency for the pairs are being developed and matured