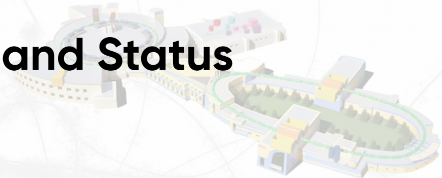
Initial Physics Performance and Status of the MPD at NICA



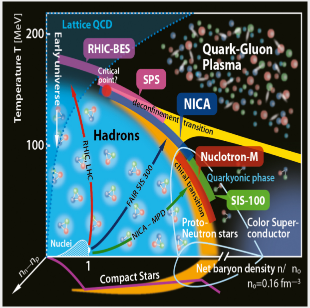
Ivonne Maldonado* for the MPD Collaboration

*ivonne.alicia.maldonado@gmail.com

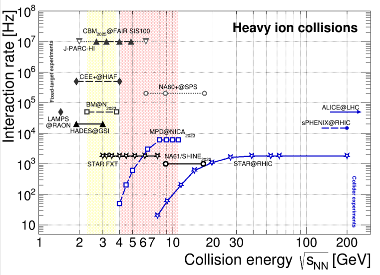
The **20th International Conference on Hadron Spectroscopy and Structure (HADRON 2023)**

Genova, Italy. June 5th–9th, 2023

NICA: Unique and complementary

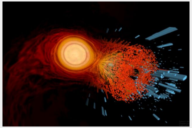


- At $\mu_B \sim 0$, smooth crossover (lattice QCD + data)
- At large μ_B, we expect 1st order phase transition $\rightarrow$ QCD critical point
- Thermal model indicates that highest baryon density is achieved at NICA energy
- Energy range $\sqrt{s_{NN}} < 6$ GeV $\rightarrow$ most appropriate to search CEP



T. Galatyuk, Nucl.Phys. A982(2019);
https://github.com/tgalatyuk/interaction_rate_facilities

Neutron stars mergers → similar density and temperature achieved by HIC at NICA.



Lukas R. Weih & L. Rezzolla (GUF)/CERN

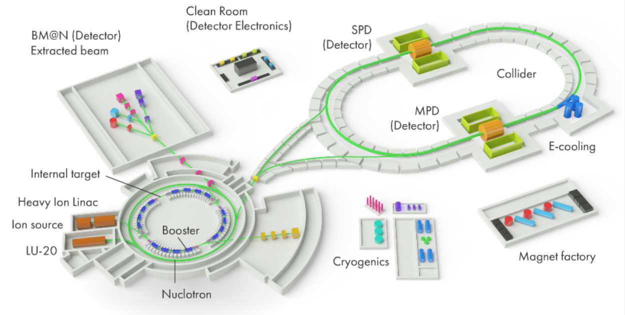
BM@N and MPD will study QCD Medium at extreme net baryon densities.
Many ongoing (NA61/Shine, STAR-BES) and future experiments (CBM at FAIR) in the same energy range

MPD at NICA Complex in Dubna

- Two injection chains
  - Ion sources ($A/Z \leq 3$) $\rightarrow$ LINAC LU-20 (5 MeV/u) $\rightarrow$ Nuclotron
  - ESIS KRION sources ($A/Z \leq 6$) $\rightarrow$ HILAc (3.24 MeV/u) $\rightarrow$ Booster
- SC Booster synchrotron

  injection up to $2 \cdot 10^9$ accelerated up to ~ 600 MeV/u ions of $^{197}Au^{31+}$
- Nuclotron synchrotron

  injection up to $1 \cdot 10^9$ ions accelerated up to $1 - 4.5$ GeV/n
  - → BM@N
- Two Collider superconducting storage rings
  - MPD
  - SPD



Collider. Parameters for 45 T·m, 11 GeV/u for Au^{79+}

Ring circumference (m)	503.4	Luminosity (cm^{-2}s^{-1})	10^{27}
Number of bunches	22	RMS bunch length (m)	0.6
β (m)	0.35	Energy in CM (GeV)	$4 - 11$
RMS $\Delta\rho/\rho$ (10^{-3})	1.6	IBS growth time (s)	1800

Progress of civil construction

Status of the collider construction

- In June 2022, all the collider dipole magnets were installed and mechanically adjusted in the collider tunnel, connected by pairs to each other.
- The assembly of the collider is postponed until completion of the engineering infrastructure mounting that is expected during this year.

Multi-Purpose Detector (MPD) Collaboration

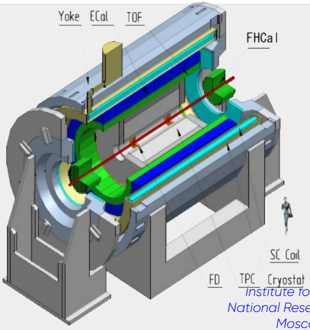
MPD International Collaboration was established in **2018**
to construct, commission and operate the detector

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

Organization

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

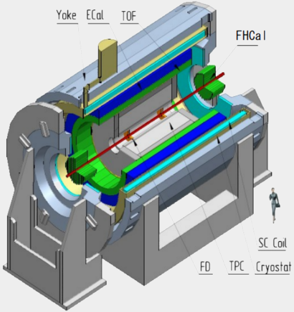
Joint Institute for Nuclear Research
A.Alikhanyan National Lab of Armenia, Yerevan, ***Armenia;***
University of Plovdiv, ***Bulgaria;***
Tsinghua University, Beijing, ***China;***
University of Science and Technology of China, Hefei, ***China;***
Huzhou University, Huzhou, ***China;***
Institute of 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****;*
Benemerita 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;***
Universidad de Sonora, ***Mexico;***
Institute of Applied Physics, Chisinev, ***Moldova;***
Institute of Physics and Technology, ***Mongolia;***
Belgorod National Research University, ***Russia;***
Institute for Nuclear Research of the RAS, Moscow, ***Russia;***
National Research Nuclear University MEPhI, Moscow, ***Russia;***
Moscow Institute of Science and Technology, ***Russia;***
North Osetian State University, ***Russia;***
National Research Center "Kurchatov Institute", ***Russia;***
Peter the Great St. Petersburg Polytechnic University Saint Petersburg, ***Russia****;*
Plekhanov Russian University of Economics, Moscow, ***Russia;***
St. Petersburg State University, ***Russia;***
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***

MPD apparatus

Stage I: TPC, TOF, ECAL, FFD, FHCal



Acceptance

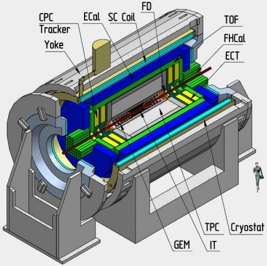
	$\lvert\Delta\phi\rvert$	$\lvert\eta\rvert$
TPC:	$< 2\pi$	≤ 1.6
TOF, EMC:	$< 2\pi$	≤ 1.4
FFD:	$< 2\pi$	$2.9 - 3.3$
FHCal:	$< 2\pi$	$2 - 5$

Beam configuration

- Not-optimal beam optics with wide z-vertex distribution, $\sigma_z \sim 50$cm
- Reduced luminosity($\sim 10^{25}$ 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($A = 209$) → start with Bi+Bi @ 9.2 GeV

Lenght	340 cm
Vessel outer radius	140 cm
Vessel inner radius	27 cm
Default magnetic field	0.5 T
Drift gas mixture	90% Ar + 10% CH4
Maximum Event rate	7 kHz (L = $10^{27} cm^{-2} s^{-1}$)

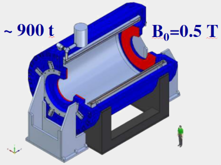
Stage II: ITS + Forward Spectrometers



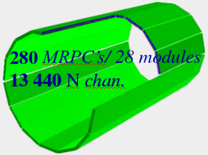
Additional: miniBeBe, MCORD

MPD subsystem in production

SC Solenoid + Iron Yoke



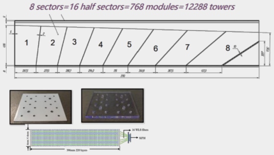
Cool down and power the magnet + magnetic field measurements



TOF

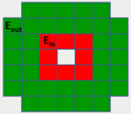
100% of MRPCs(modules) are ready, cosmic tests ongoing.

ECAL (projective geometry)



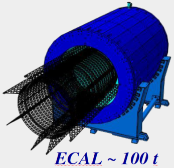
38400 towers
66-83% of the whole detector will be produced for Stage-I

FHCal



Forward detectors - are in advanced state of production(electronic and integration)

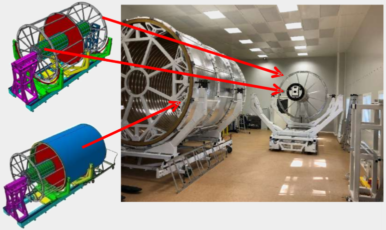
Support structure



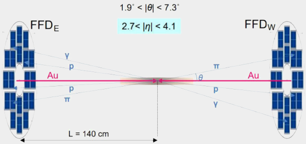
ECAL ~ 100 t

made of carbon fiber sagite ~ 5 mm, 0.13 X_0

TPC central tracking detector



FFD



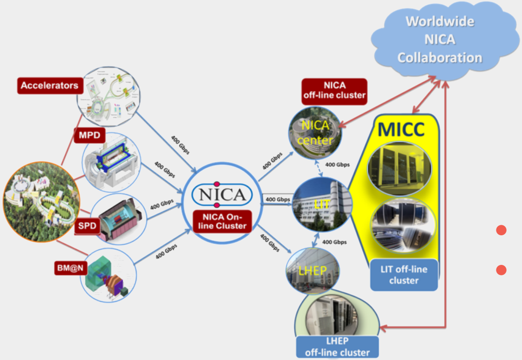
MPD Status and plan

- **2023:**
  preparation for Vacuum test of Solenoid with Cryostat. Solenoid cooling down.
- **2024:**
  Supplying the current to the solenoid and Correction coils. MF measurements. Support frame and detectors installation. Cabling and Installation of beam pipe.
- **2025:**
  Move the MPD on Collider beam line and Commisioning.
- **beyond:**
  MPD commissioning first run with Bi+Bi @ 9.2 GeV, ~ 50-100 M events for alignment calibration and physics. Au+Au @ 11 GeV, design luminosity system size and collision energy scans

- Preparation of the MPD detector and experimental program is ongoing, all activities are continued
- All components of the MPD 1-st stage detector are in advanced state of production (subsystems, support frame, electronics platforms, LV/HV, control systems, cryogenics, cabling, etc.)

Schedule of the MPD-NICA is significantly affected by the current geopolitical situation (suspension of collaboration with CERN and Polish & Czech Republic member institutions, economic sanctions and problems with supplies of many components from companies).

Computing Resources for the MPD



- Software framework MpdRoot - object oriented set of tools to simulate, transport and reconstruct MC events within MPD experiment
  - Centralized Analysis Framework

- Main technological elements at VBLHEP and LIT
- LIT NICA part of MICC → connection with computing complexes of other organizations involved in NICA Complex
- DIRAC → infrastructure enables integration of heterogeneous computing resources at multiple sites

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 Diagram

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 correlations
- Jet-like correlations

D. Peresunko, C. Yang

Electromagnetic probes

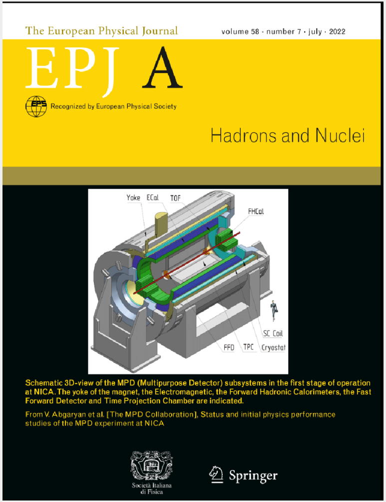
- Electromagnetic calorimeter measurement
- Photons in ECAL and central barrel
- Low mass dilepton spectra in-medium modification of resonances and intermediate mass region

Wangmei Zha, A. Zinchenko

Heavy flavor

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

MPD paper



The European Physical Journal volume 58 · number 7 · july · 2022

EPJ A

Recognized by European Physical Society

Hadrons and Nuclei

Schematic 3D-view of the MPD (Multipurpose Detector) subsystems in the first stage of operation at NICA. The yoke of the magnet, the Electromagnetic, the Forward Hadronic Calorimeters, the Fast Forward Detector and Time Projection Chamber are indicated.

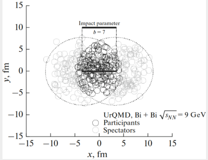
From V. Abgaryan et al. [The MPD Collaboration], Status and initial physics performance studies of the MPD experiment at NICA

Società Italiana di Fisica Springer

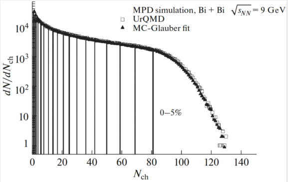
- First collaboration paper recently published in EPJA **Status and initial physics performance studies of the MPD experiment at NICA**, Eur.Phys.J.A 58 (2022) 7, 140

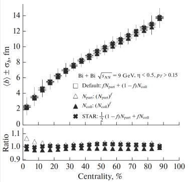
Centrality and reaction plane determination

Centrality with TPC multiplicity



- MC Glauber approach to extract b
- MC Glauber compatible with Bayesian inversion method (Γ-fit)
- Similar results with different event generators and energies

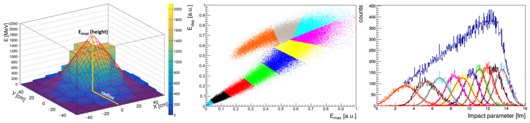




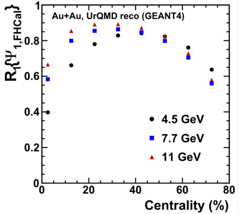
- Centrality estimation consistent with STAR → good for cross checks between experiments

Acta Physica Polonica B 14 (2021) 3, 503-506,Particles 4 (2021) 2, 275-287, Phys.Part.Nucl.Lett. 19 (2022) 5, 489-492

Centrality with FHCal



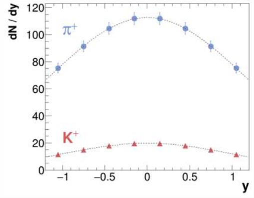
Two dimensional linear fit of the energy deposition in FHCal modules, to extract the correlation between the maximum energy and the deposited energy in 10% centrality classes

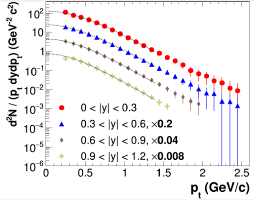


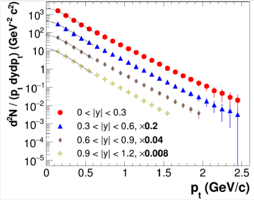
$$\Psi_{EP} = Atan\left(\frac{\sum_i E_i sin(\phi_i)}{\sum_i cos(\phi_i)}\right)$$

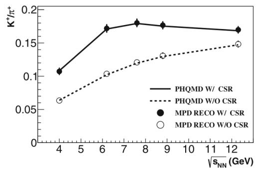
Bulk Properties: hadron spectra, yields and ratios

- Particle spectra, yields and ratios are sensitive to bulk fireball properties and phase transformations in the medium
- Uniform acceptance and large phase coverage are crucial for precise mapping of the QCD phase diagram









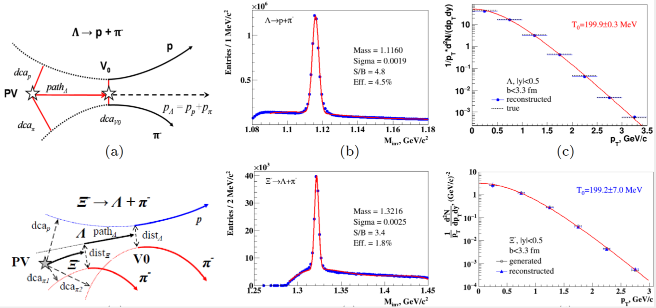
- MPD provides large phase-space coverage for identified pions and kaons (> 70% of the full phasespace at 9 GeV)
- Hadron spectra can be measured from $p_T = (0.1)0.2$ to 2.5 GeV/c (for π)
- Extrapolation to full p_T-range and to the full phase space can be performed exploiting the spectra shapes (see BW fits for p_T-spectra and Gaussian for rapidity distributions)

Hyperon Reconstruction

- Strangeness enhancement is considered as a signature of the QGP formation Rafelski, Phys. Rep. 88(1982)331, Rafelski, Múller, P.R.Lett. 48(1982)1066
- Experimentally observed in HIC at AGS, SPS, RHIC and LHC energies.
- Differential measurements (vs. pT, multiplicity, event shape, energy balance) of strange baryons are needed in different collision systems (pp, pA, AA) at NICA energies

No consensus on the dominant strangeness enhancement mechanisms:

- strangeness enhancement in QGP contradicts with the observed collision energy dependence
- strangeness suppression in pp within canonical suppression models reproduces most of results except for ϕ(1020)

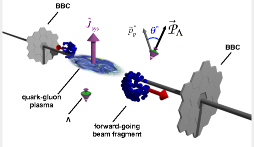


Acta Phys. Pol. B Proc. Suppl. 14, 529 (2021)

- Strange baryons can be reconstructed with good S/B ratios using charged hadron identification in the TPC and TOF and different decay topology selections. And different techniques like TMVA. https://doi.org/10.3390/particles6020027

Global Polarization

Large angular momentum and strong magnetic field formed in mid-central heavy-ion collisions → Vorticity to the QGP and polarization of particles in the final state



Nature 548,62-65(2017)

Λ and $\bar{\Lambda}$ polarization can be measured by its self analyzing charged decay → preferential emission of p is along spin direction.

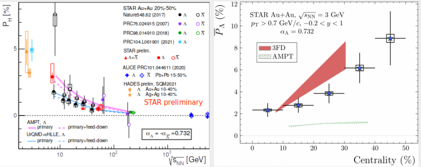
Global Polarization

$$\mathcal{P} = \frac{8}{\pi\alpha_H}\frac{\langle sin(\Psi_{EP} - \phi_p)\rangle}{R_{EP}}$$

with the Λ decay parameter $\alpha_\Lambda = 0.732 \pm 0.014$ Nature Phys. 15 (2019) 631-634)), the event plane angle Ψ_{EP}, the azimuthal angle of decay proton ϕ_p in the Λ rest frame and the resolution of the event plane angle R_{EP}

Phys.Rev.C 76,024915(2007); 95,039906(E)(2017)

- Global polarization decrease with $\sqrt{s_{NN}}$
- Transport models used to reproduce global polarization are: AMPT, 3FD, UrQMD+vHLLE



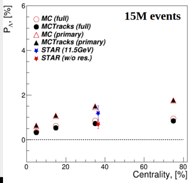
Kosuke Okubo, QM022 - STAR, Phys.Rev.C, 104(6):L061901, 2021

MPD will cover $\sqrt{s_{NN}} = 4 - 11$ GeV as a function of centrality, p_T and Y not only for Λ but other hyperons($\bar{\Lambda}$, Ξ, $\bar{\Xi}$, Σ, $\bar{\Sigma}$).

PHSD simulation of 15M events for Bi+Bi at $\sqrt{s_{NN}} = 9.2$ GeV

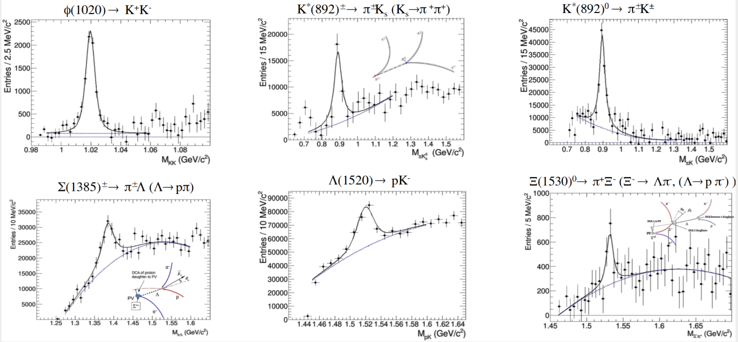
Full event/detector simulation and reconstruction

First global measurements for $\Lambda/\bar{\Lambda}$ will be possible with ~ 10M data sampled events



Reconstruction of resonances

- Resonances are best suited to probe density and lifetime of the late hadronic phase of HI collisions
- Suppression of short-lived resonances was observed in central HI collisions at SPS, RHIC and LHC → dominance of re scattering over regeneration → consistent with existence of a long enough hadronic phase → hadronic phase lifetime ~ 10 fm/c
- Hadronic phase affects most of observables measured in the final state (flow, correlations, yields, etc.)
- Measurements for resonances are vital to cross check the hadronic phase models

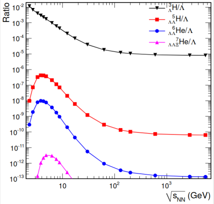


Phys.Scripta 96 (2021) 6, 064002

- MPD is capable of reconstruction the resonance peaks in the invariant mass distributions using combined charged hadron identification with TPC and TOF
- Decays with weakly decaying daughters require additional second vertex and topology cuts for reconstruction
- **First measurements for resonances will be possible with accumulation of ~ 10 M of Bi+Bi events**

Reconstruction of hypertritons

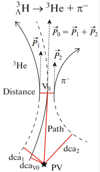
- Hyper nuclei measurement provides information about production mechanism, Y-N potential, strange sector of nuclear EoS
- It has strong implications for astronuclear physics, since are expected in the inner core of neutron stars
- Production mechanism can be described by different phenomenological models: statistical hadronization (SHM) and coalescence
- Models predict enhanced hypernuclear production at NICA, double hypernuclei are reachable

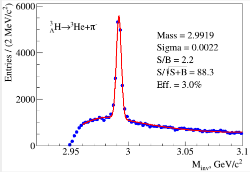


Phys.Lett.B697:203-207,2011

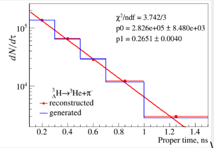
First measurements for hypertriton will be possible with 50M Bi+Bi @ 9.2 events

Phys.Part.Nucl.Lett. 19 (2022) 1, 46-53, https://doi.org/10.3390/physics5020028





Hypertriton reconstruction allows extraction of its lifetime τ



$$
\begin{aligned}
N(\tau) &= N(0)\,exp(-\frac{\tau}{\tau_0}) \\
&= N(0)\,exp(-\frac{ML}{cp\tau_0})
\end{aligned}
$$

where τ is the proper time, L is the decay distance, p is the particle momentum, M is the hypertriton rest mass and c is the speed of light

Anisotropic flow

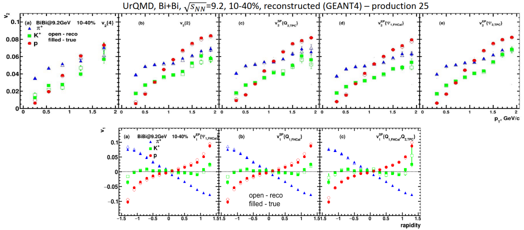
Flow has high sensitivity to the transport properties of the QCD matter: EoS, speed of sound (c_s), specific viscosity (η/s), etc.

$$\frac{dN}{d\phi} = \frac{N}{2\pi}(1 + \sum 2v_n cos(n(\phi - \Psi_n)))$$

with $v_n = \langle cos(n(\phi - \Psi_n))\rangle$

v_1 and v_2 for identified hadrons

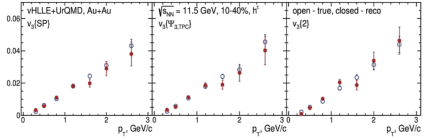
UrQMD events for Bi+Bi @ 9.2 GeV measured at mid-centrality 10-40%



MPD detector is able to provide detailed differential measurements of directed and elliptic flows with high accuracy.

Higher harmonics v_3

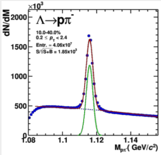
Results for Au+Au @ 11.5 GeV (vHLLE + UrQMD), 15M events → full event/detector simulation and reconstruction

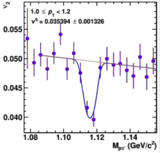


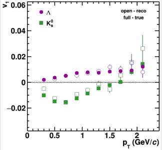
Models show that higher harmonic ripples are more sensitive to the existence of a QGP phase

Collective flow for V0 (K^0_s and Λ)

Results for Au+Au @ 11 GeV (UrQMD), 25M events → full event/detector simulation and reconstruction



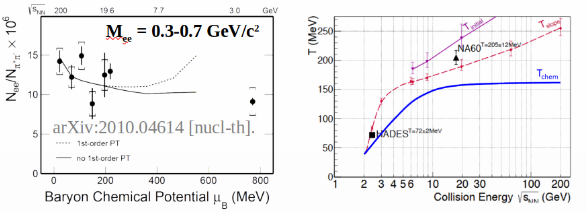




Differential flow signal extraction using invariant mass fit method

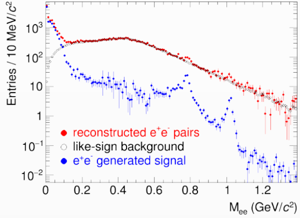
Dielectron studies

- HBT measurements for identical particles
- Yield and flow of e^+e^- pairs:
  - probe deconfinement and chiral symmetry restoration
  - effective temperature



T. Galatyuk et al., Eur. Phys. J. A 52 (2016) 131; R. Rapp and H. v. Hess, PLB 753 (2016) 586
J.Cleymans et al. 2006 Phys. Rev. C73, 034905
NA60: H. Specht, AIP Conf. Proc. 1322 (2010) 160; HADES: Nature Physics 15 (2019) 1040

BiBi@9.2 GeV (UrQMD+PHSD), 10 M events → full event/detector simulation and reconstruction



- S/B (integrated in 0.2 -1.5 GeV/c) 5~10%
- Methods to improve S/B ratio with a minimal penalty for pair reconstruction are being developed
- Meaningful measurements for e^+e^- continuum and LVMs would require $\sim 10^8$ events, first observations will be possible with ~ 50 M events

Summary

- MPD collaboration is steadily coming to final integration of the detector and first data taking on the beams from NICA
- Physics program for the first years of MPD data taking is formulated and the first physics paper was recently published
- MPD will provide a unique opportunity for investigating properties of nuclear matter at maximal densities to map the QCD phase diagram, to search for phase transition and the Critical End Point
- First operations of the MPD detector are expected with cosmic studies.
- Comissioning and start of data taking with Bi + Bi collisions at $\sqrt{s_{NN}} = 9.2$ GeV at the NICA complex is expected at 2025

GRACIAS