# The road to first physics with the MPD

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**EuNPC 2022**

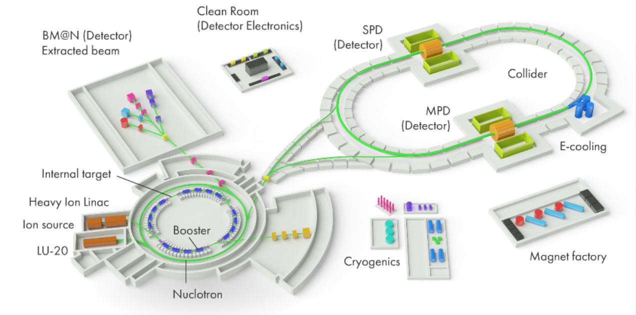
# MPD at NICA Complex in Dubna

- 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 $\sim 600$ 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

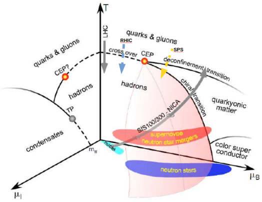
  → BM@N
- Two Collider superconducting storage rings
  - MPD
  - SPD



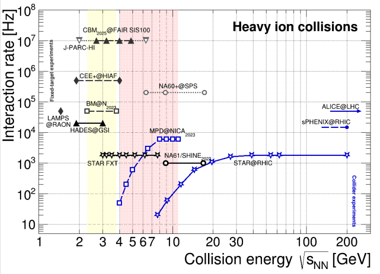

**Collider. Parameters for 45 T·m, 11 GeV/u for $Au^{79+}$**

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

# NICA: Unique and complementary



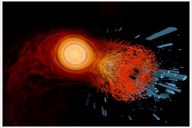

NUPECC Long Range Plan 2017




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

- At $\mu_B \sim 0$, smooth crossover (lattice QCD + data)
- At large $\mu_B$, 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

Neutron stars mergers $\rightarrow$ similar density and temperature achieved by HIC at NICA.



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

**Positioning of the NICA**

| | NA61/SHINE at SPS | CBM at FAIR | STAR BES+FXT at RHIC | MPD + BMN at NICA |
|---|---|---|---|---|
| Coverage of region of transition from baryon to meson dominance (horn) | only higher $\sqrt{s_{NN}}$ | only lower $\sqrt{s_{NN}}$ | Yes (mixing collider and fixed target) | Yes (consistent acceptance) |
| expected luminosity (w.r.t MPD) | lower | higher | lower | reference |
| possibility for system size scan | yes | yes | yes(?) | yes |
| full centrality range | no | yes(?) | yes | yes |
| acceptance type | Fixed target | Fixed target | Collider + fixed target | Collider + fixed target |
| running plan(heavy-ions) | approved for 2021 (per year decision) | beyond 2025 | running conclude in 2021 | 2023 and beyond |
| status at the facility (possible running time) | in competition with many projects (LHC) | CBM one of four main experiments | end of data taking (heavy ion) in 2021 | flagship experiments several months/year |

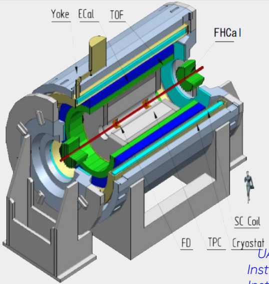
# Multi-Purpose Detector (MPD) Collaboration

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

**10** Countries > 450 participants, **31** institutes and **JINR**

## Organization

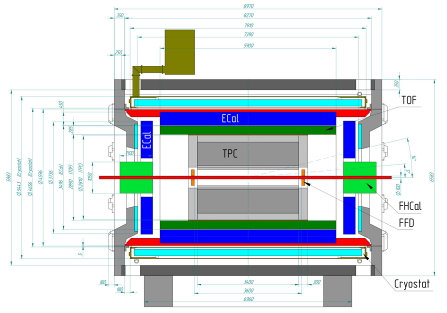
| | |
|---|---|
| Acting Spokesperson: | **Victor Riabov** |
| Deputy Spokesperson: | **Zebo Tang** |
| Institutional Board Chair: | **Alejandro Ayala** |
| Project Manager: | **Slava Golovatyuk** |




***Joint Institute for Nuclear Research***
*AANL, Yerevan, **Armenia;***
*University of Plovdiv, **Bulgaria;***
*Tsinghua University, Beijing, **China;***
*USTC, Hefei, **China;***
*Huzhou University, Huizhou, **China;***
*Institute of Nuclear and Applied Physics, CAS, Shanghai, **China;***
*Central China Normal University, **China;***
*Shandong University, Shandong, **China;***
*IHEP, Beijing, **China;***
*University of South China, **China;***
*Three Gorges University, **China;***
*Institute of Modern Physics of CAS, Lanzhou, **China;***
*Tbilisi State University, Tbilisi, **Georgia;***
*FCFM-BUAP (Heber Zepeda) Puebla, **Mexico;***
*FC-UCOL (Maria Elena Tejeda), Colima, **Mexico;***
*FCFM-UAS (Isabel Dominguez), Culiacán, **Mexico;***
*ICN-UNAM (Alejandro Ayala), Mexico City, **Mexico;***
*UAM-I (Luis Hernandez), Mexico City, **Mexico;***
*Institute of Applied Physics, Chisinev, **Moldova;***
*Institute of Physics and Technology, **Mongolia;***
*Belgorod National Research University, **Russia;***
*INR RAS, Moscow, **Russia;***
*MEPhI, Moscow, **Russia;***
*Moscow Institute of Science and Technology, **Russia;***
*North Osetian State University, **Russia;***
*NRC Kurchatov Institute, ITEP, **Russia;***
*Kurchatov Institute, Moscow, **Russia;***
*St. Petersburg State University, **Russia;***
*SINP, Moscow, **Russia;***
*PNPI, Gatchina, **Russia;***
*Vinča Institute of Nuclear Sciences, **Serbia;***
*Pavol Jozef Šafárik University, Košice, **Slovakia***

# MPD apparatus

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

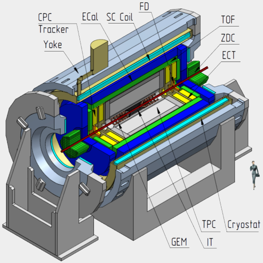



| Lenght | 340 cm |
|---|---|
| Vessel outer radius | 140 cm |
| Vessel inner radius | 27 cm |
| Default magnetic field | 0.5 T |
| Drift gas mixture | 90% Ar + 10% CH4 |
| Maximum Event rate | 7 kHz (L = $10^{27}\,cm^{-2}s^{-1}$) |

**Stage II:** ITS + Forward Spectrometers

**Acceptance**

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



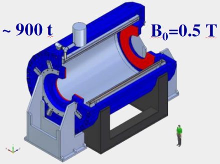

Beam configuration

- Not-optimal beam optics with wide z-vertex distribution, $\sigma_z \sim 50$cm
- Reduced luminosity($\sim 10^{25}$ is the goal for 2023)$\rightarrow$ collision rate $\sim 50$ 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($A = 209$) $\rightarrow$ start with Bi+Bi @ 9.2 GeV in 2023-2024

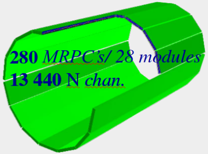
**Additional:** miniBeBe, MCORD

# MPD subsystem in production

## SC Solenoid + Iron Yoke



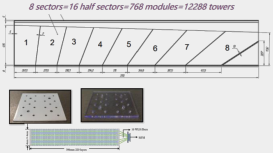

Goal is to cool down and power the magnet + magnetic field measurements are to be expected for the middle of 2023




## TOF

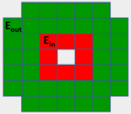
94(60)% of MRPCs(modules) are ready, mass production and tests ongoing.

## ECAL (projective geometry)



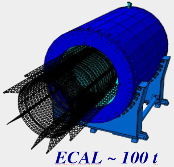

38400 towers
16/25 sectors will be produced for stage-I, production of remaining modules is possible by 2024

## FHCal



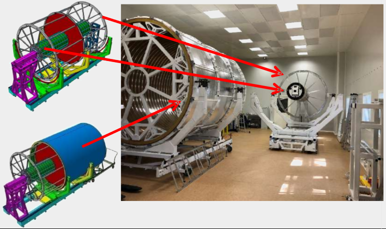

Forward detectors - are in advanced state of production(electronic and integration)

## Support structure

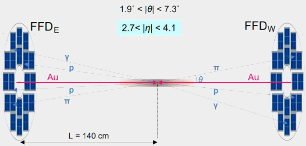



made of carbon fiber sagite $\sim 5$ mm, 0.13 $X_0$
Will be ready in Dec. 2022

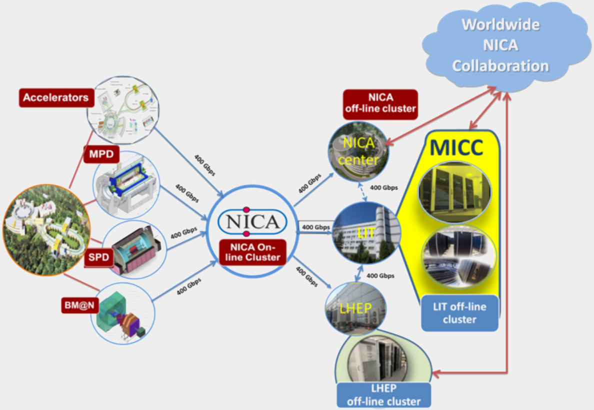
## TPC central tracking detector



## FFD



# Computing Resources for the MPD




- Software framework MpdRoot → extend FairRoot classes and FairSoft packages (ROOT, BOOST, GEANT)
- 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 Status and plan

- 2022:
  preparation of the SC magnet for cooling
- 2023:
  cooling the magnet and MF measurents
  installation of the support frame and detectors
- 2024:
  MPD commissioning
  first run with Bi+Bi @ 9.2 GeV, ~ 50-100 M events for alignment calibration and physics
- 2025 and beyond:
  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.)

# 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

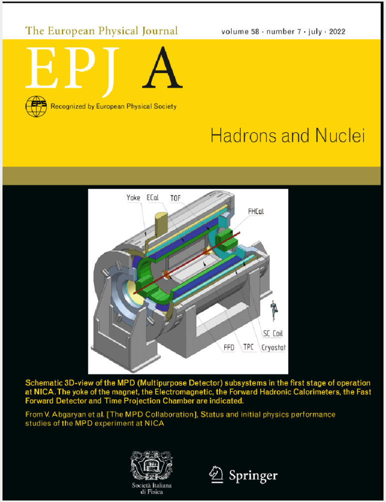
V. Kolesnikov, Xianglei Zhu
**Spectra of light flavor and hypernuclei**
- Light flavor spectra
- Hyperons and hypernuclei
- Total particle yields and yield ratios
- Kinematic and chemical properties of the event
- Mapping QCD Phase Diagram

K. Mikhailov, A. Taranenko
**Correlations and Fluctuations**
- Collective flow for hadrons
- Vorticity, $\Lambda$ polarization
- E-by-E fluctuation of multiplicity, momentum and conserved quantities
- Femtoscopy
- Forward-Backward correlations
- Jet-like correlations

V. Riabov, Chi 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

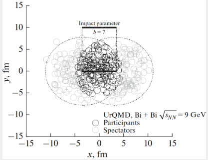
# MPD paper



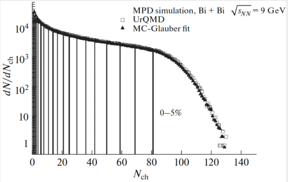

- First collaboration paper recently published in EPJA **Status and initial physics performance studies of the MPD experiment at NICA**, Eur.Phys.J.A 58 (2022) 7, 140

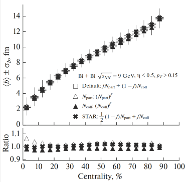
# Centrality and reaction plane determination

## Centrality with TPC multiplicity



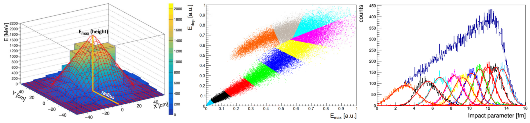

- MC Glauber approach to extract b
- MC Glauber compatible with Bayesian inversion method (Γ-fit)
- Similar results with different event generators and energies



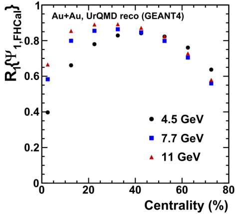




- Centrality estimation consistent with STAR → good for cross checks between experiments

## 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

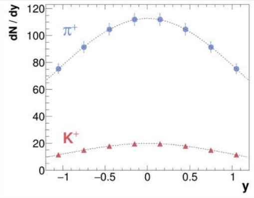


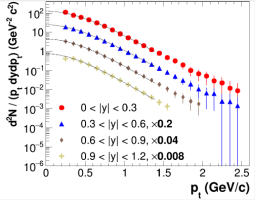

$$\Psi_{EP} = Atan\left(\frac{\sum_i E_i sin(\phi_i)}{\sum_i cos(\phi_i)}\right)$$

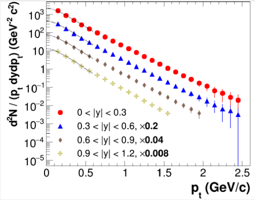
Acta Physica Polonica B 14 (2021) 3, 503-506,Particles 4 (2021) 2, 275-287, Phys.Part.Nucl.Lett. 19 (2022) 5, 489-492

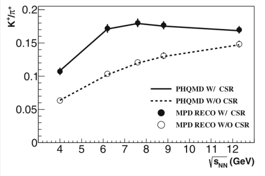
# Bulk Properties: hadron spectra, yields and ratios

- 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



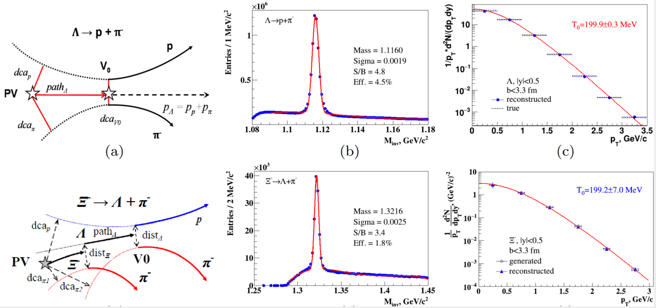

- MPD provides large phase-space coverage for identified pions and kaons (> 70% of the full phasespace at 9 GeV)
- Hadron spectra can be measured from $p_T = (0.1)0.2$ to $2.5$ GeV/c (for $\pi$)
- Extrapolation to full $p_T$-range and to the full phase space can be performed exploiting the spectra shapes (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 $\phi$(1020)



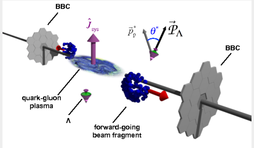

Acta Phys. Pol. B Proc. Suppl. 14, 529 (2021)

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

# Global Polarization

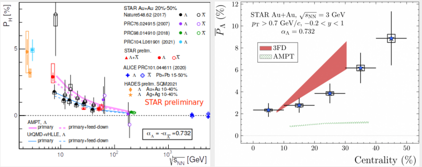
- Global polarization decrease with $\sqrt{s_{NN}}$
- Transport models used to reproduce global polarization are: AMPT, 3FD, UrQMD+vHLLE

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)

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




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

## Global Polarization

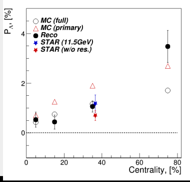
$$\mathcal{P} = \frac{8}{\pi\alpha_H}\frac{\langle sin(\Psi_{EP} - \phi_p)\rangle}{R_{EP}}$$

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

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

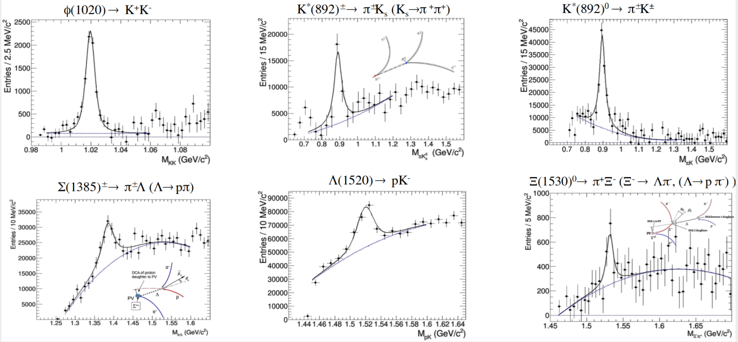
MPD will cover $\sqrt{s_{NN}} = 3 - 10$ GeV as a function of centrality, $p_T$ and $Y$ not only for $\Lambda$ but other hyperons($\bar{\Lambda}$, $\Xi$, $\bar{\Xi}$, $\Sigma$, $\bar{\Sigma}$).

PHSD simulation of 4M 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 $\sim 10$M 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 $\sim 10$ 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

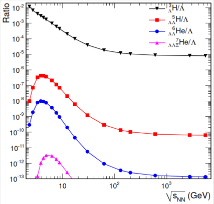



Phys.Scripta 96 (2021) 6, 064002

- 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 $\sim 10$ M of Bi+Bi events**

# Reconstruction of hypertritons

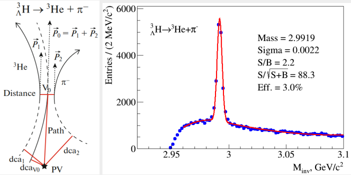
- Hyper nuclei measurement provides information about production mechanism, Y-N potential, strange sector of nuclear EoS
- It has strong implications for astronuclear physics, since are expected in the inner core of neutron stars
- Production mechanism can be described by different phenomenological models: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



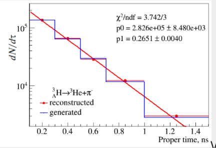

Phys.Lett.B697:203-207,2011

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

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




Hypertriton reconstruction allows extraction of its lifetime $\tau$




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

where $\tau$ 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

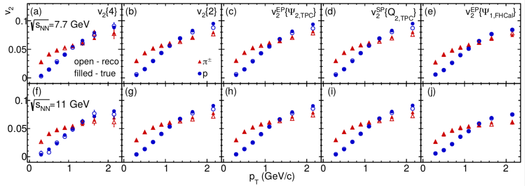
Flow has high sensitivity to the transport properties of the QCD matter: EoS, speed of sound ($c_s$), specific viscosity ($\eta/s$), etc.

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

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

**$v_2$ for pions and protons**

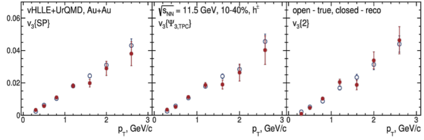
15 M of reconstructed UrQMD events for Au+Au @ 7.7 GeV measured at mid-centrality 10-40%




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

**Higher harmonics $v_3$**

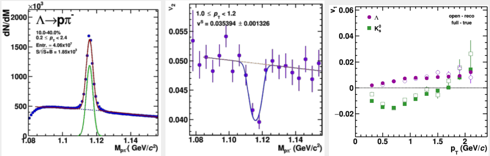
Results for Au+Au @ 11.5 GeV (vHLLE + UrQMD), 15M events → full event/detector simulation and reconstruction




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

**Collective flow for V0 ($K_s^0$ and $\Lambda$)**

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




Differential flow signal extraction using invariant mass fit method

# 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 at the end of 2023 with cosmic studies
- Start of data taking with Bi + Bi collisions at $\sqrt{s_{NN}} = 9.2$ GeV at the NICA complex is expected at 2024

# GRACIAS


IX Collaboration Meeting of the MPD Experiment at the NICA Facility