Status of the MPD experiment at NICA

P. Parfenov (JINR, NRNU MEPhI) for the MPD Collaboration

The 7th international conference on particle physics and astrophysics
ICPPA-2024, NRNU MEPhI, Moscow
22-25 October 2024

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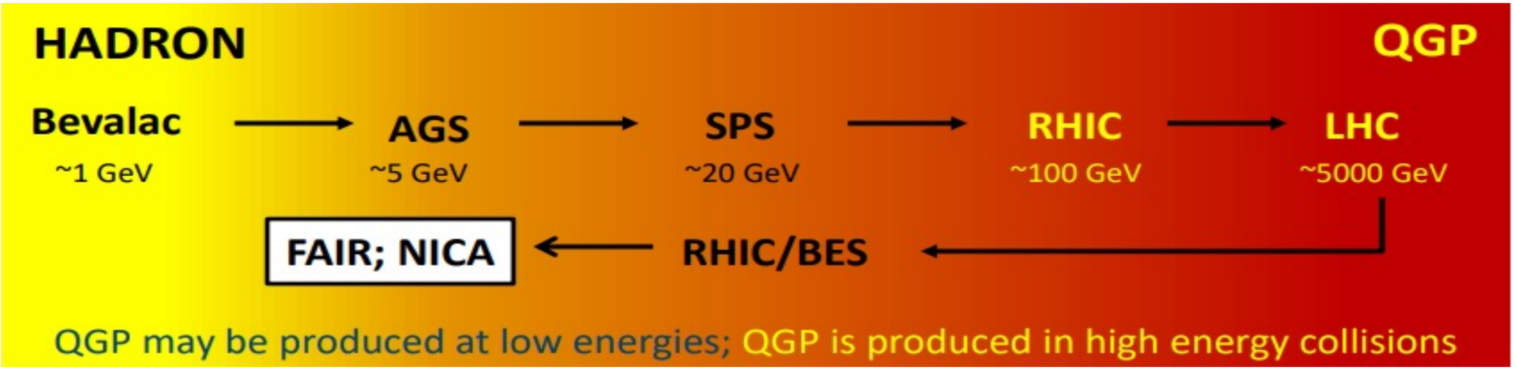
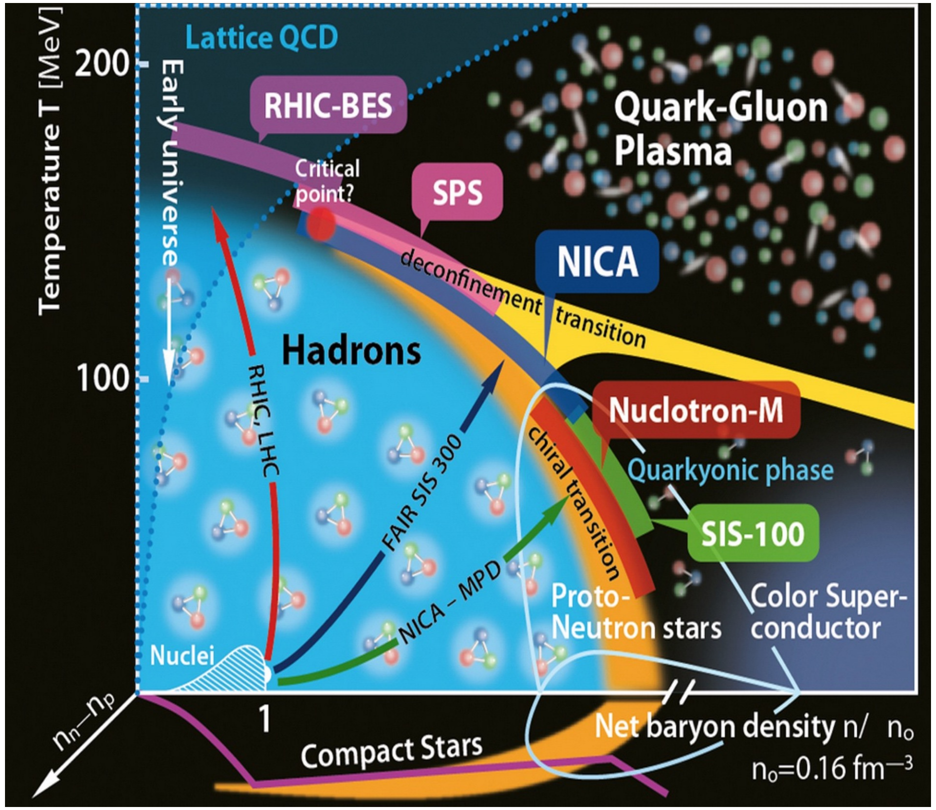
Relativistic heavy-ion collisions



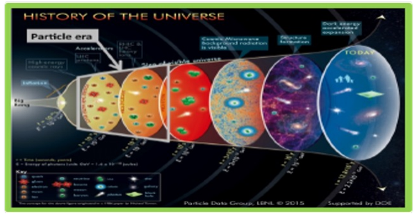
<u>1970s-2000s</u> – nuclear equation of state (EoS), search for the quark-gluon plasma (QGP)
<u>2005s</u> – QGP formation was observed at RHIC and it behaves as almost perfect liquid
<u>2005-2010s</u> – LQCD predicts crossover phase transition at top RHIC and LHC (high T, $\mu_B \approx 0$)

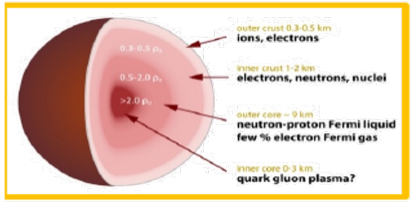
<u>Since 2010s</u> – Beam energy scans to study QCD phase diagram: search for the 1st order phase transition and CEP at Intermediate T, high μ_B



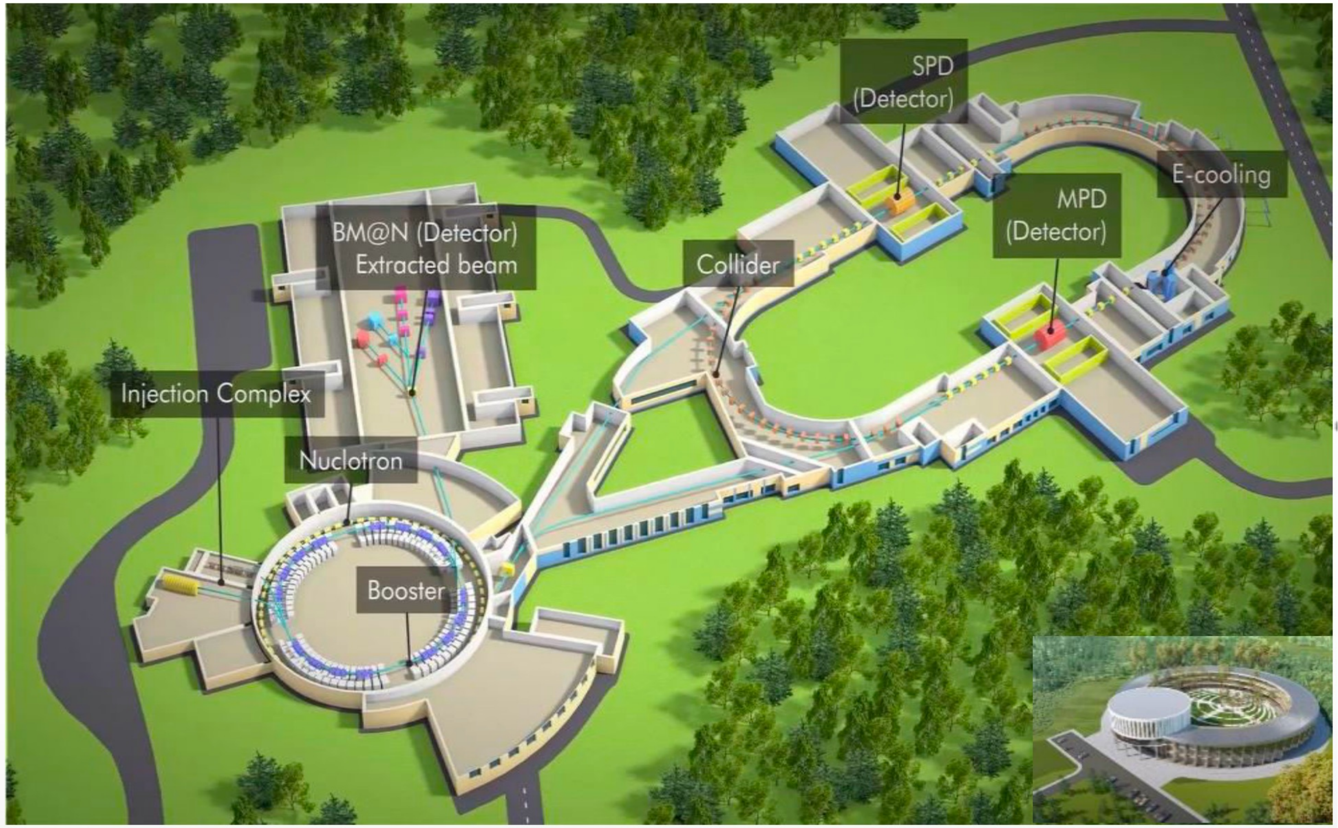
Relativistic heavy-ion collisions allows us to study QCD phase diagram

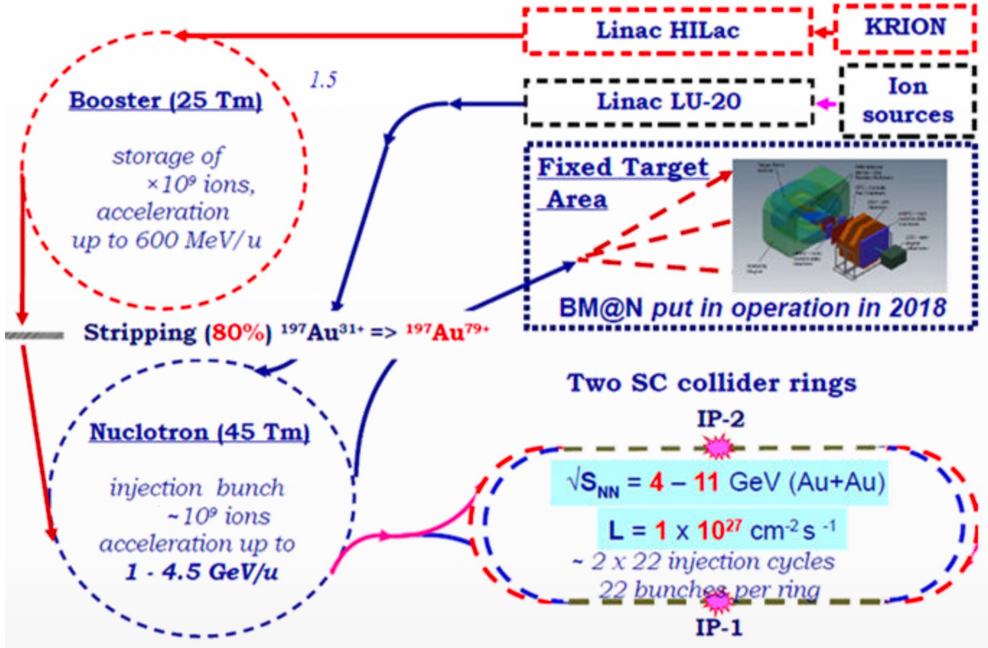
- **High beam energies ($\sqrt{s_{NN}}$>100 GeV):**
  - High T, $\mu_B \approx 0$
  - Evolution of the early Universe
- **Low beam energies (2.4<$\sqrt{s_{NN}}$<11 GeV):**
  - Intermediate T, high μ_B
  - Inner structure of the compact stars, neutron star mergers





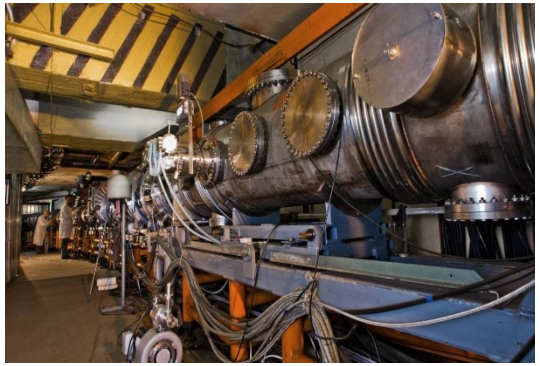
NICA Project at JINR





Booster

Nuclotron



- **Megascience project in Russia, which is approaching its full commissioning:**
  - **Baryonic Matter at Nuclotron (BM@N) –** fixed-target experiment, first physics run Xe+CsI 2022-2023
  - **Multi-Purpose Detector (MPD) –** start of operation in 2025-2026
  - **Spin Physics Detector (SPD) –** operating on polarized deuterons later on

MPD experiment at NICA

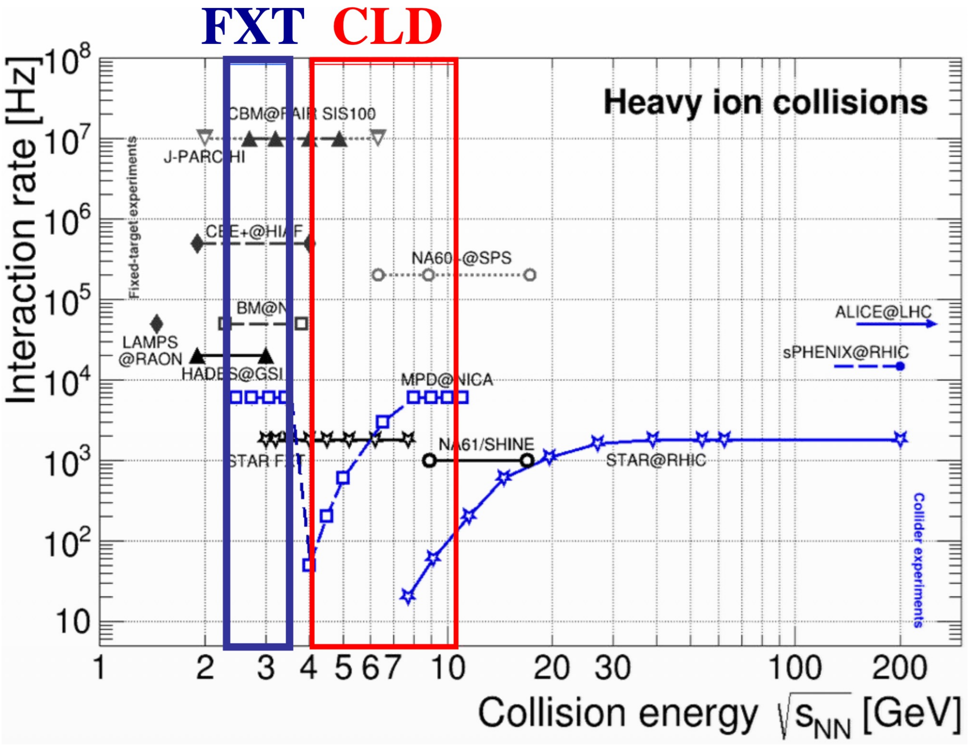
Main subsystems at Stage-I:

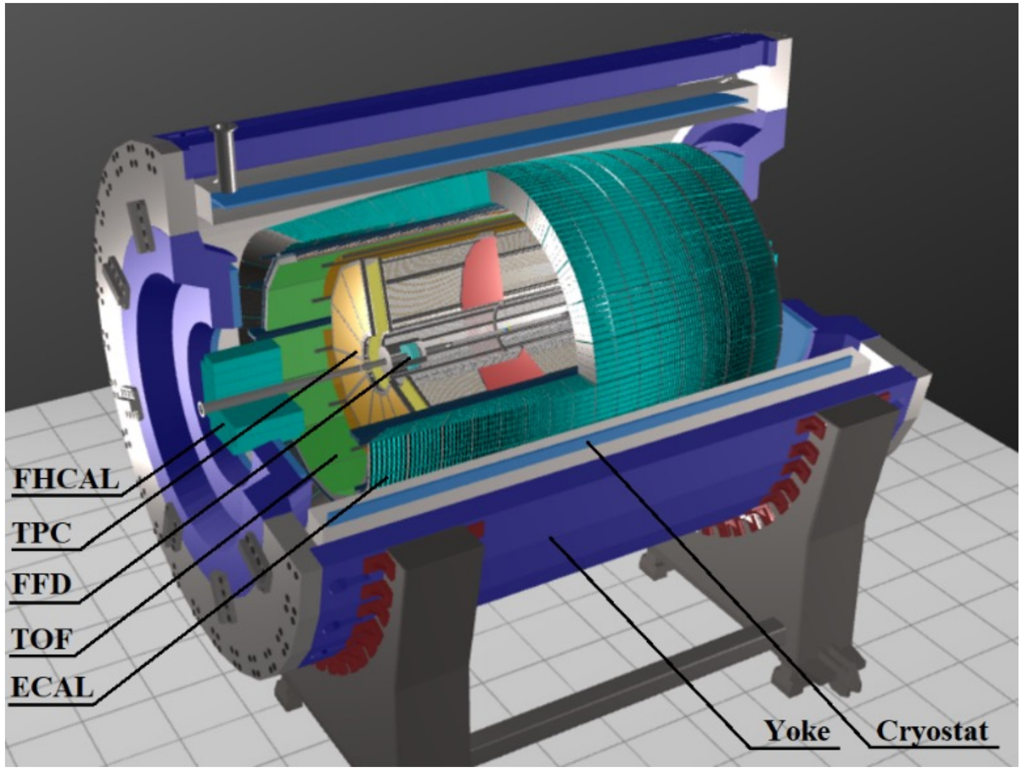
TPC ($|\eta| \leq 1.6$): charged particle tracking + momentum reconstruction + dE/dx identification

TOF ($|\eta| \leq 1.4$): charged particle identification

ECal ($2.9 < |\eta| < 1.4$): energy and PID for $\gamma/e^{\pm}$

FHCal ($2 < |\eta| < 5$) and **FFD** ($2.9 < |\eta| < 3.3$): event triggering + event geometry





Expected beams at the first year(s) of operation (Stage-I):

- MPD-CLD: Xe/Bi+Xe/Bi at $\sqrt{s_{NN}} \sim 7$ GeV
- MPD-FXT: Xe/Bi +W at $\sqrt{s_{NN}} \sim 3$ GeV

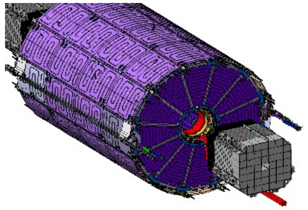
Beam energy overlap: HADES, STAR BES, NA61/SHINE and future CBM

MPD subsystem status (I)

Solenoid Magnet and cryogenics

- Test cooling performed to 70°K in March 2024
- Start of cooling to LHe and magnetic field measurements in the second half of the 2024
- Magnetic field mapper is ready

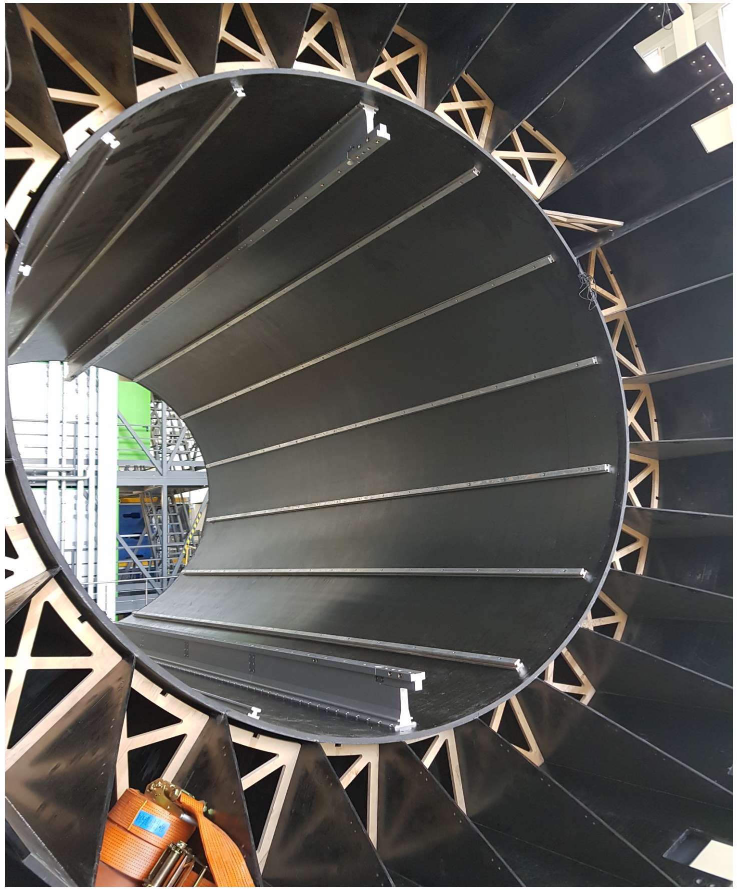
TPC – Time Projection Chamber



- TPC cylinders, central membrane, service wheels, rails, readout chambers, gas system – ready; TPC gas volume assembly and HV/leakage tests – ongoing
- TPC + ECAL cooling systems commissioned in early 2025

MPD subsystem status (II)

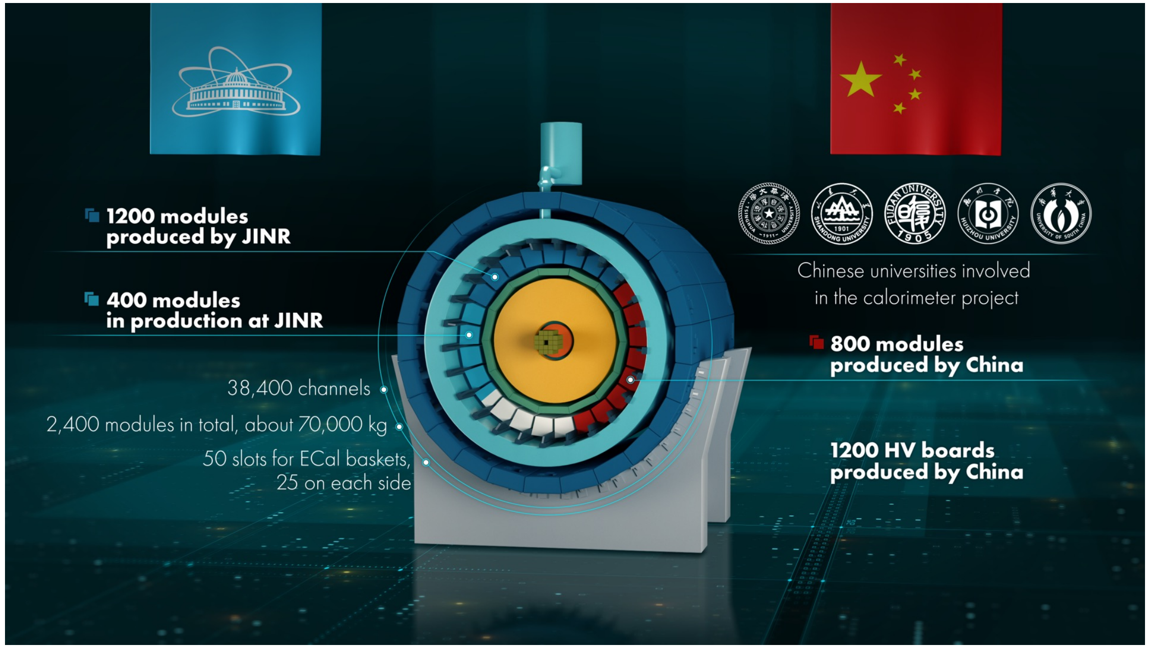
Support structure



Carbon fiber support frame delivered and ready to use

ECAL – Electromagnetic Calorimeter

Produced in consortium with institutes in China



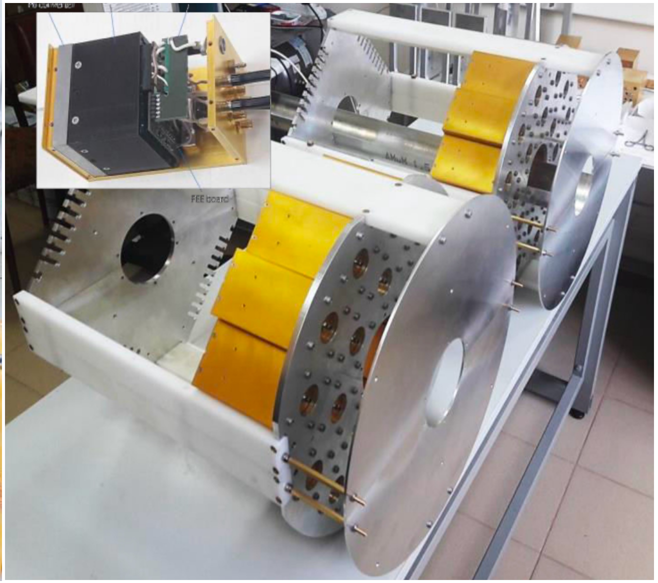
- 2000 (83%) of the calorimeter modules will be ready in 2024
- The remaining 400 (17%) modules will be produced by the April 2025

MPD subsystem status (III)

TOF – Time of Flight

FHCal – Forward Hadron Calorimeter

FFD – Fast Forward Detector



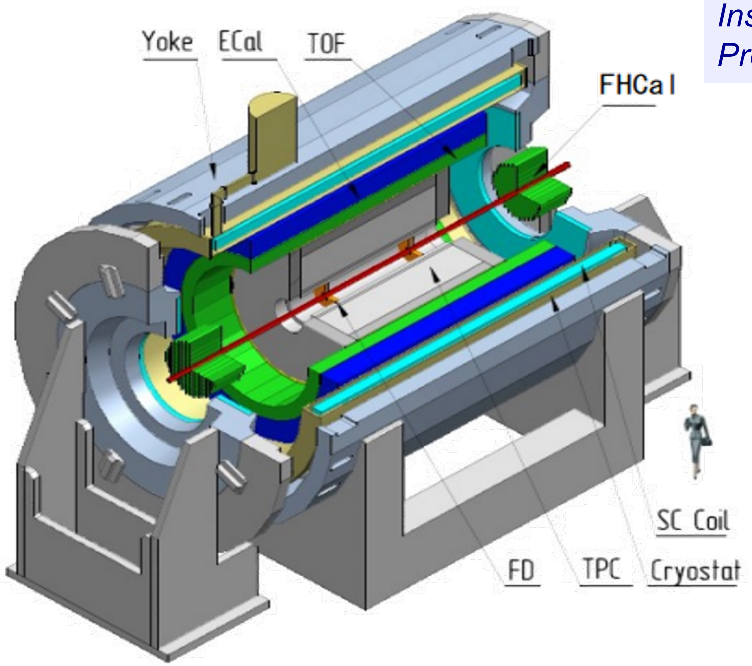
All systems (TOF, FHCal, FFD) are fully produced and ready for installation

Multi-Purpose Detector (MPD) Collaboration

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

12** Countries, **>500** participants, **38** Institutes and **JINR

***Joint Institute for Nuclear Research, Dubna**;*
*A.Alikhanyan National Lab of Armenia, Yerevan, **Armenia;***
*SSI "Joint Institute for Energy and Nuclear Research – Sosny" of the National Academy of Sciences of Belarus, Minsk, **Belarus***
*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**;*
*Universidad de Sonora, **Mexico**;*
*Universidad Michoacana de San Nicolás de Hidalgo, **Mexico***
*Institute of Applied Physics, Chisinev, **Moldova**;*
*Institute of Physics and Technology, **Mongolia**;*



Organization

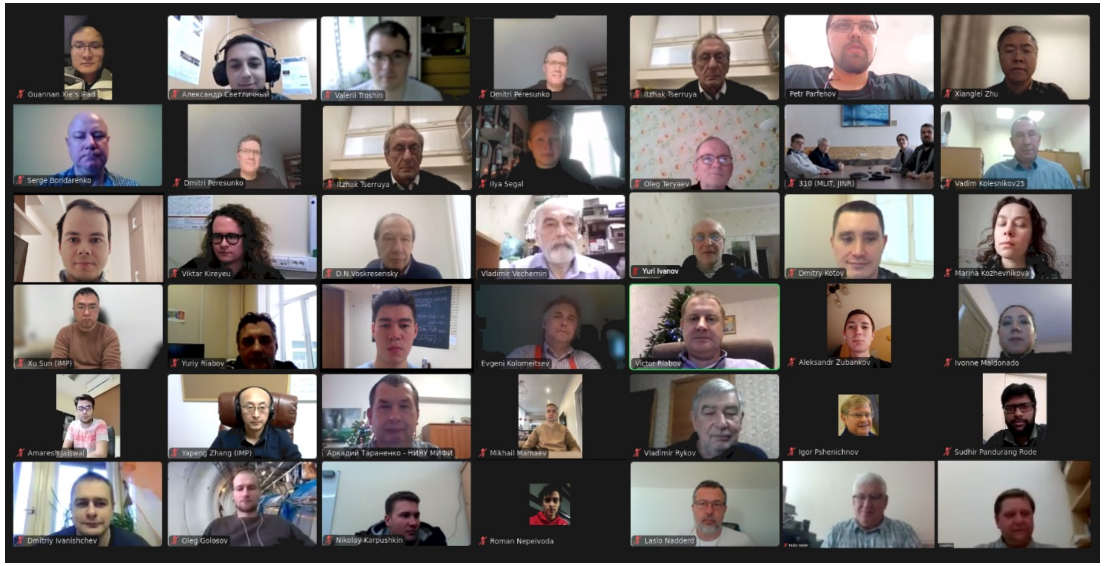
Acting Spokesperson:	***Victor Riabov***
Deputy Spokespersons:	***Zebo Tang, Arkadiy Taranenko***
Institutional Board Chair:	***Alejandro Ayala***
Project Manager:	***Slava Golovatyuk***

https://mpd.jinr.ru/

*Belgorod National Research University, **Russia**;*
*Institute for Nuclear Research of the RAS, Moscow, **Russia**;*
*High School of Economics University, 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***

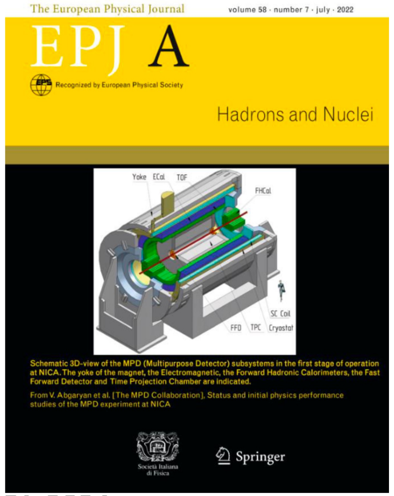
MPD publications, conferences and workshops

- **International Workshop on physics performance studies at NICA**
  - ✓ http://indico.oris.mephi.ru/event/301
  - ✓ 5 workshops since 2019



Over 50 reports at international conferences and workshops

2nd China-Russia Joint Workshop on NICA Facility
indico.jinr.ru/event/4642



Status and initial physics performance studies of the MPD, Eur.Phys.J.A 58 (2022) 7, 140

MPD-related talks and posters at ICPPA-2024

22.10.2024 – posters:

1. G. Fomenko, *Background rejection in ECal detector MPD experiment cosmic test data*
2. P. Gordeev, *Particle identification in MPD at NICA using machine learning*
3. P. Bahtin, *Parameterization of SiPM signals of MPD/ECal*

25.10.2024 – Parallel talks:

1. A. Taranenko, *Study of the beam energy dependence of anisotropic flow using the scaling relations*
2. O. Golosov, *Performance for anisotropic flow measurement of inclusive photons and neutral pions in Bi+Bi collisions at 9.2 GeV with the MPD experiment*
3. M. Mamaev, *The first results for directed flow of protons in Xe+Cs collisions at Ekin=3.8A GeV in the BM@N experiment*
4. V. Kireyeyu, *Probing the nuclear matter equation of state with light nuclei*
5. V. Troshin, *Anisotropic flow measurements of Λ hyperons: performance study for MPD and BM@N experiments at NICA energies*
6. Y. Wang, *Reconstruction of photons and neutral mesons in heavy-ion collisions with MPD at NICA*
7. D. Suvarieva, *A Monte Carlo study of the MPD performance for hyperon selection using machine learning techniques*
8. G. Feofilov, *Challenges for next generation of vertex detectors for collider experiments*
9. M. Martemianov, *Simulation of the total MPD/ECAL setup for cosmic ray calibration*
10. V. Riabov, *Performance of the trigger system of the MPD experiment*
11. A. Ayala, *Recent progress in heavy-ion physics: A theoretical review*
12. V. Kuzmin, *Misalignment influence on the track reconstruction in the MPD TPC*
13. F. Ghazzawi, *Evaluating ML-Accelerated Simulations of the Time Projection Chamber for the MPD Experiment*

MPD physics program

G. Feofilov, P. Parfenov

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

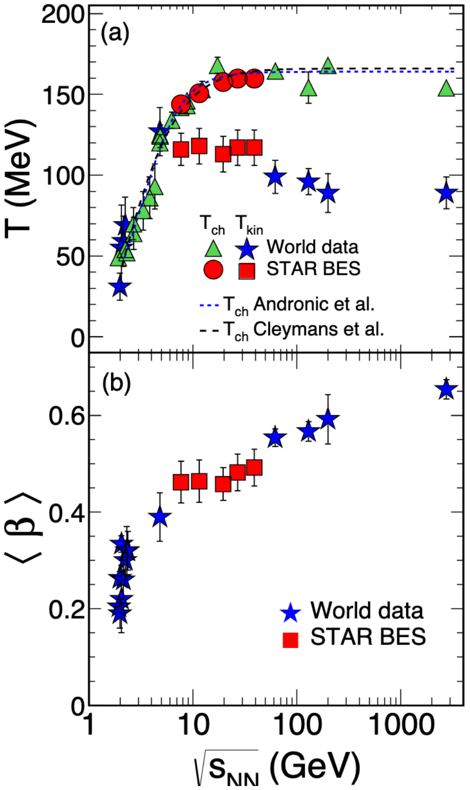
Electromagnetic probes
- Electromagnetic calorimeter meas.
- Photons in ECAL and central barrel
- Low mass dilepton spectra in-medium modification of resonances and intermediate mass region

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

Charged identified hadron production

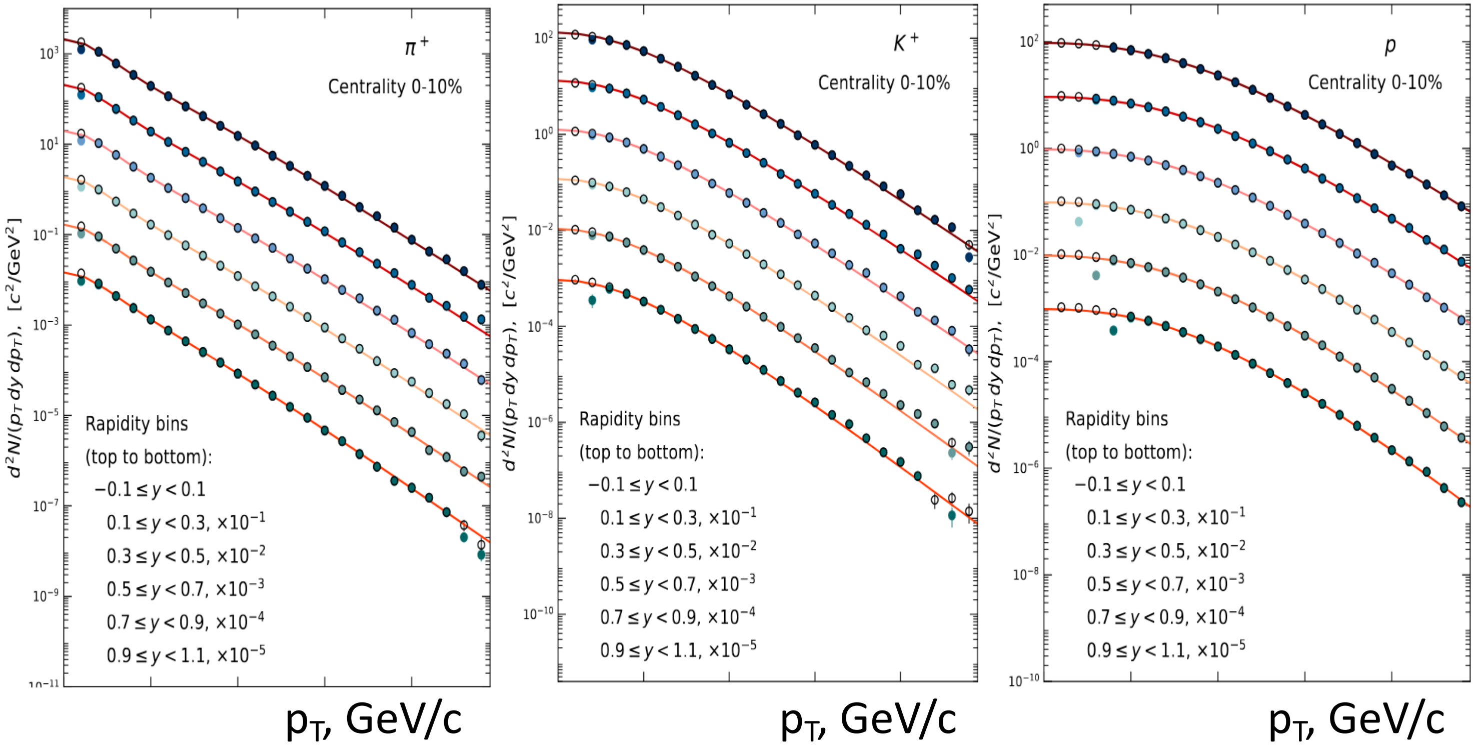
Phys.Rev.C 96 (2017) 4, 044904



Particle yields allow to extract information about (μ_B,T_{ch})

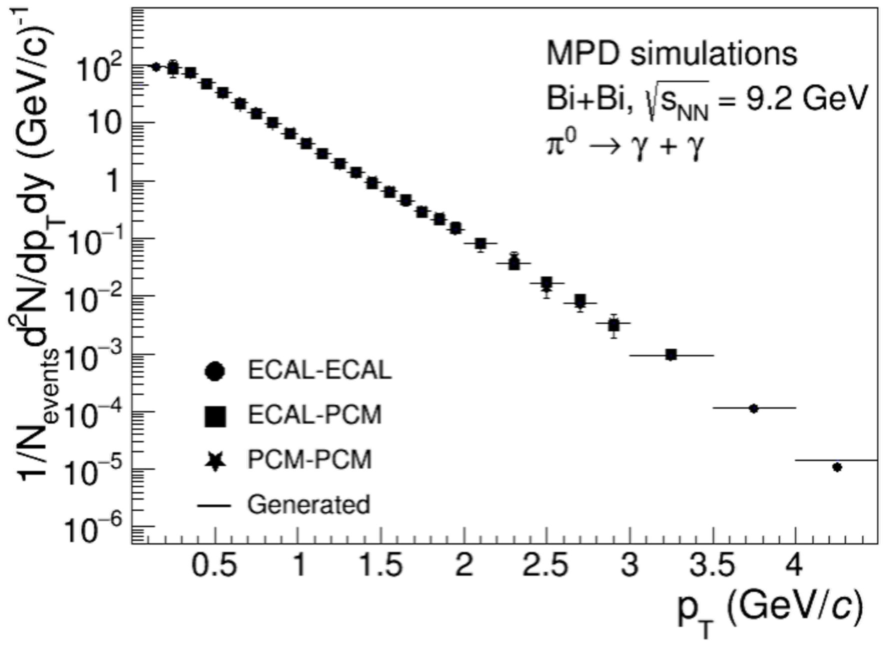
Particle spectra allow to extract information about (<β>,T_{kin})

Bi+Bi, $\sqrt{s_{NN}}$=9.2 GeV

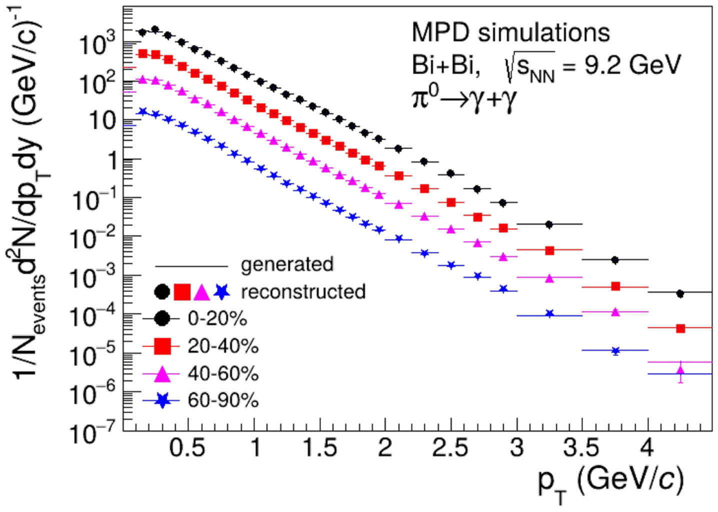


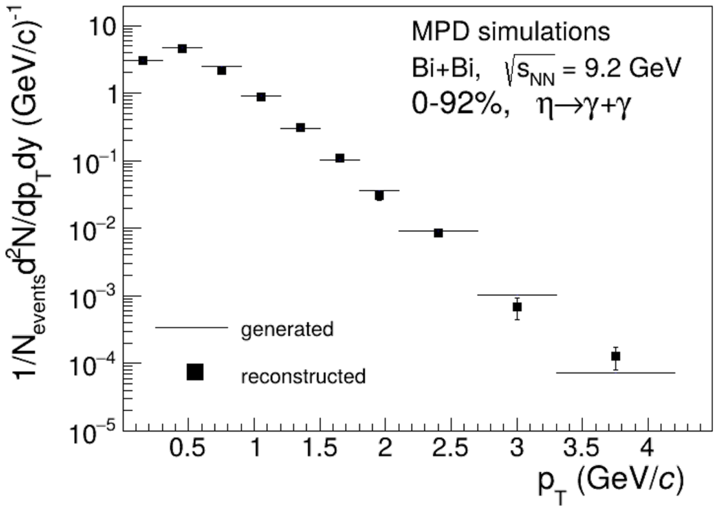
- Probe freeze-out conditions, collective expansion, hadronization mechanisms, strangeness production, parton energy loss, etc. with particles of different masses, quark contents/counts → **requirements on MPD acceptance and PID capabilities**
- **Charged hadrons**: large (~70% of π/K/p) and uniform acceptance + excellent PID capabilities of TPC and TOF from p_T~0.1 GeV/c

Neutral identified hadron production



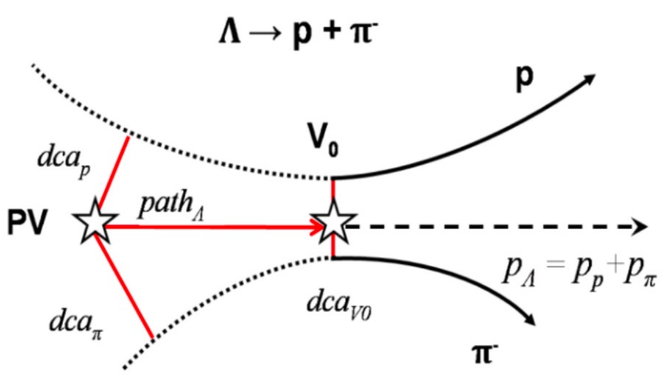
BiBi@9.2 GeV (UrQMD), 50 M events → full event/detector reconstruction

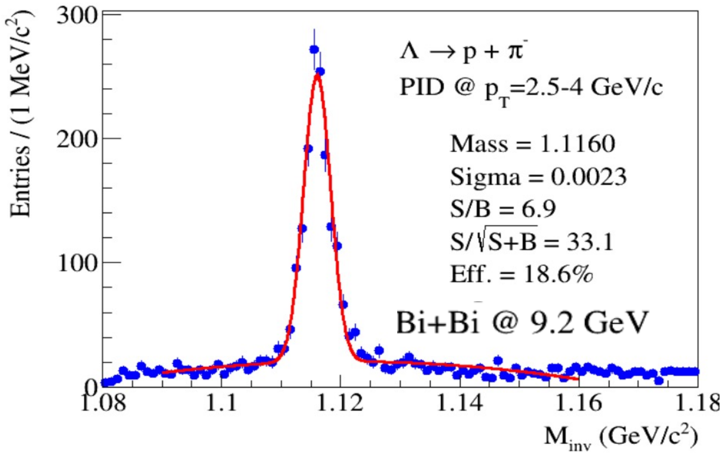


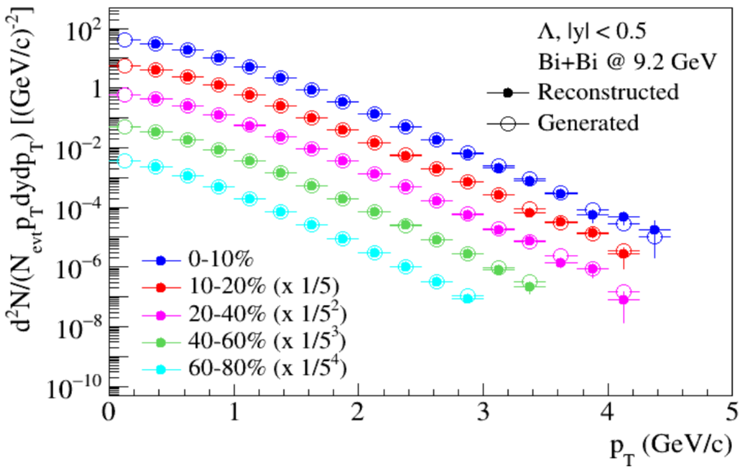


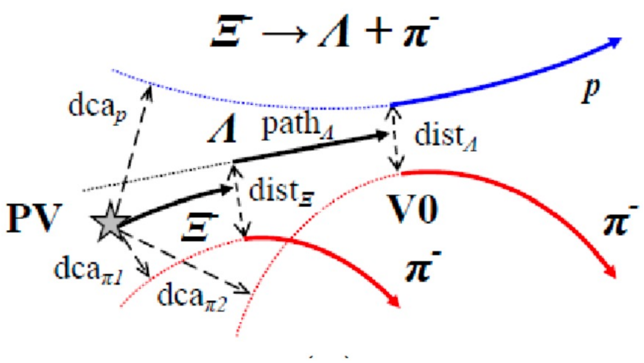
- MPD will be able to measure differential production spectra, integrated yields and $\langle p_T \rangle$, particle ratios, multiplicity distributions for a variety of identified hadrons ($\pi, K, \eta, \omega, \rho$, …)
- Neutral mesons ($\pi^0, K_S, \eta, \omega, \eta'$) : ECAL reconstruction + photon conversion method (PCM)
- Will be helpful to extend p_T ranges of charged particle measurements and assess systematics

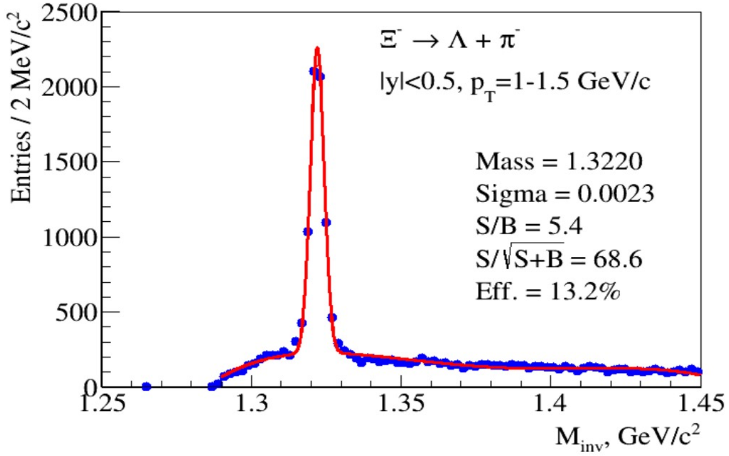
Hyperon production

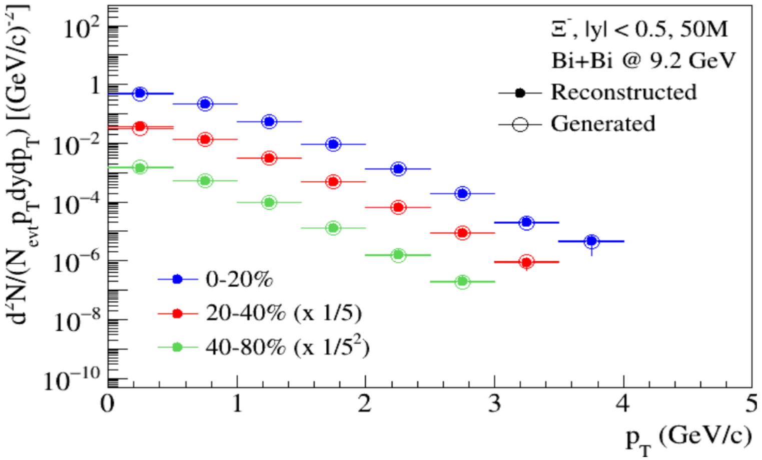






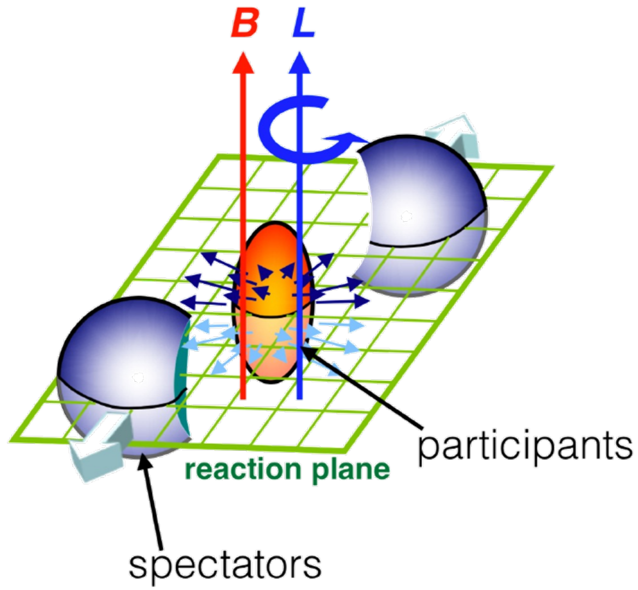






- Strangeness enhancement is considered to be a signature of the QGP formation with no consensus on the dominant mechanisms of strangeness enhancement – precise measurements are needed in pp, pA, AA
- Strange baryons can be reconstructed with a good level of significance (S/B ratios) with PID using TPC+TOF and different topology selections

Global polarization of Λ hyperons P_Λ



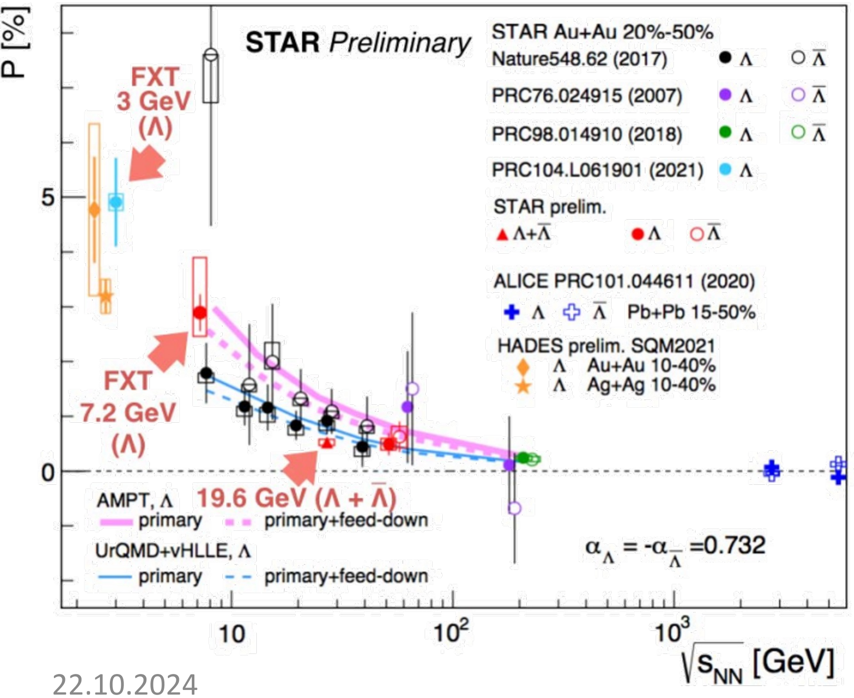
Can be defined as: $\frac{dN}{d\cos(\phi_\Lambda - \phi_p^*)} = \frac{1}{2}\left(1 + \alpha_\Lambda |P_\Lambda| \cos(\phi_\Lambda - \phi_p^*)\right)$

Invariant mass fit method can be used to measure P_Λ:

$$P^{obs}(m_{inv}, p_T) = P^{sig}(p_T)\frac{N^{sig}(m_{inv}, p_T)}{N^{tot}(m_{inv}, p_T)} + P^{bg}(m_{inv}, p_T)\frac{N^{bg}(m_{inv}, p_T)}{N^{tot}(m_{inv}, p_T)}$$

$$\frac{8}{\pi \alpha_\Lambda R_{EP}} P^{sig}(p_T) = \mathbf{P_\Lambda} + c \sin(\phi_\Lambda - \phi_p^*)$$

α_Λ - hyperon decay const., R_{EP} - EP resolution, ϕ_Λ, ϕ_p^* - azimuthal angles of Λ, p



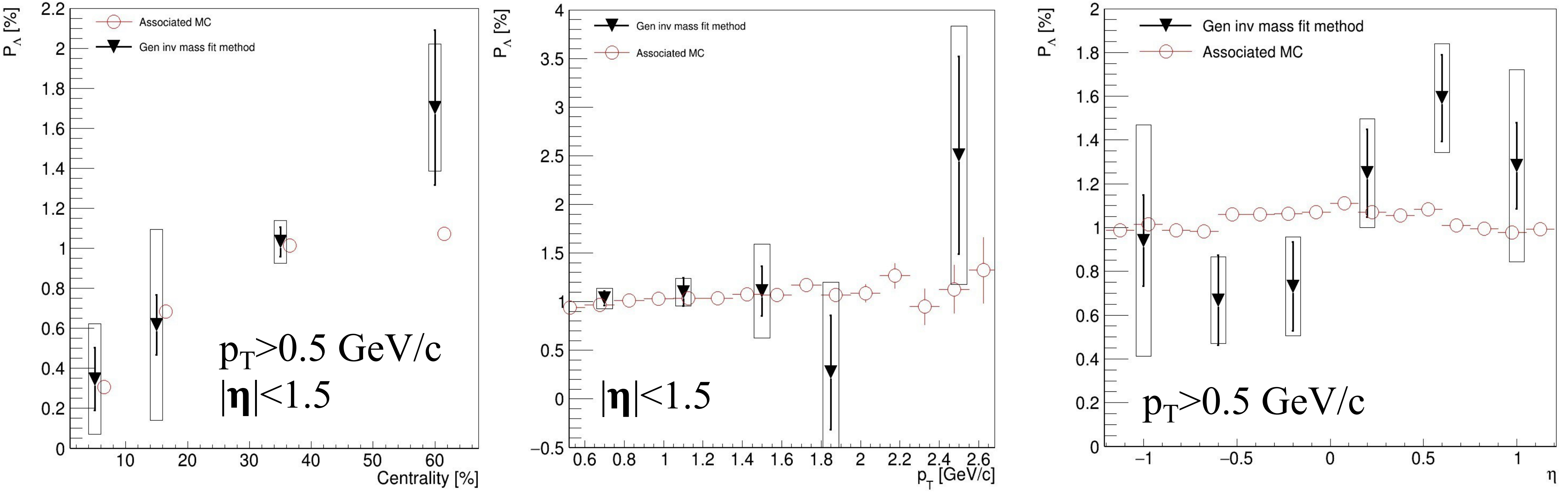
Focus is to see the effect of large angular momentum and magnetic field in heavy-ion collisions

- Global polarization of hyperons experimentally observed, decreases with $\sqrt{s_{NN}}$
  - reproduced by AMPT, 3FD, UrQMD+vHLLE

P_Λ at **NICA:** **<u>extra points in the energy range 2-11 GeV</u>**
centrality, p_T and rapidity dependence of polarization,
not only for Λ, but other (anti)hyperons (Λ, Σ, Ξ)

Global polarization P_Λ in MPD

Performance study of the hyperon global polarization measurements with MPD at NICA, Eur.Phys.J.A 60 (2024) 4, 85



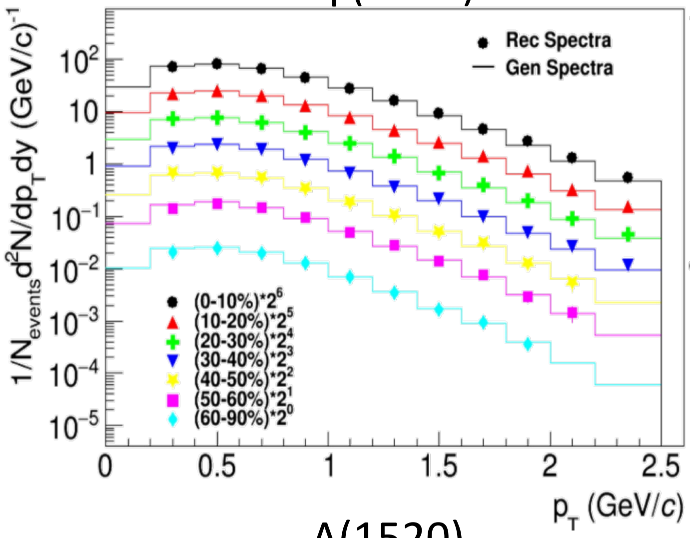
Good performance of MPD for P_Λ measurements

More statistics needed for differential (p_T,**η**) measurements and other hyperons

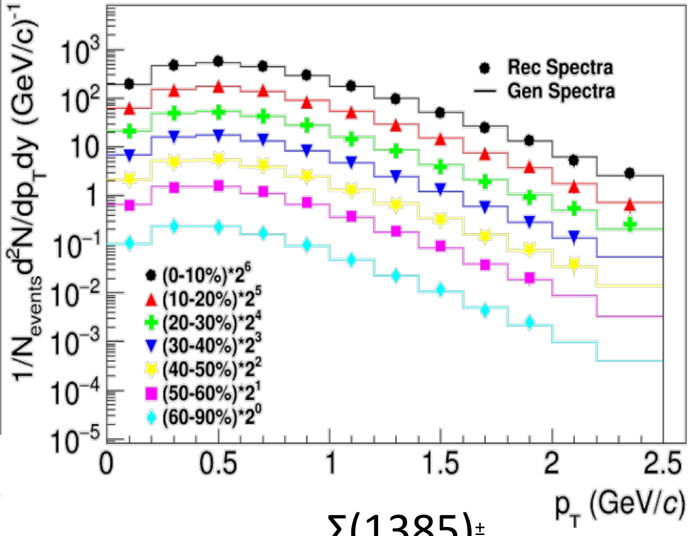
First results are to be expected at ~100M events

Resonance production in MPD

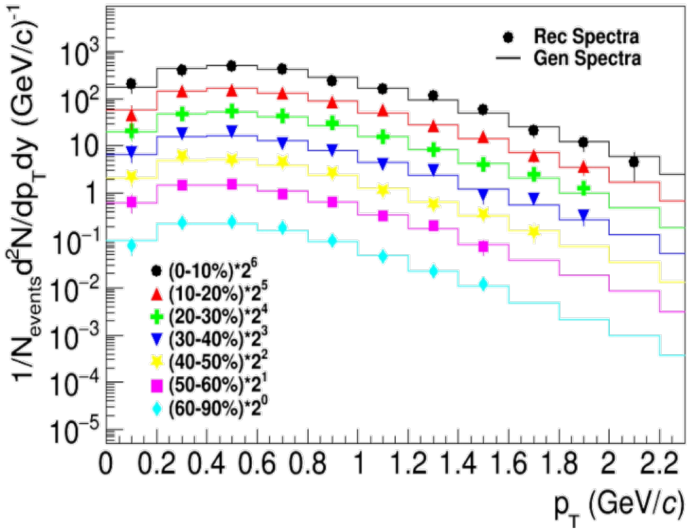
ϕ(1020)



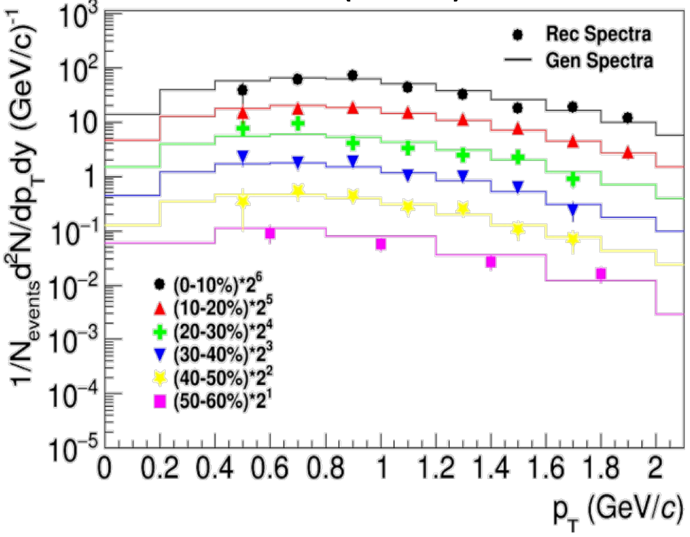
K*(892)^0



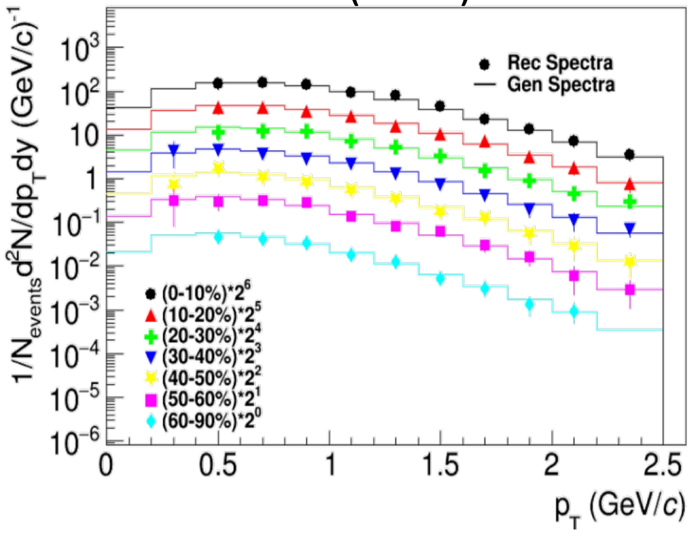
K*(892)$^\pm$



Λ(1520)



Σ(1385)$^\pm$



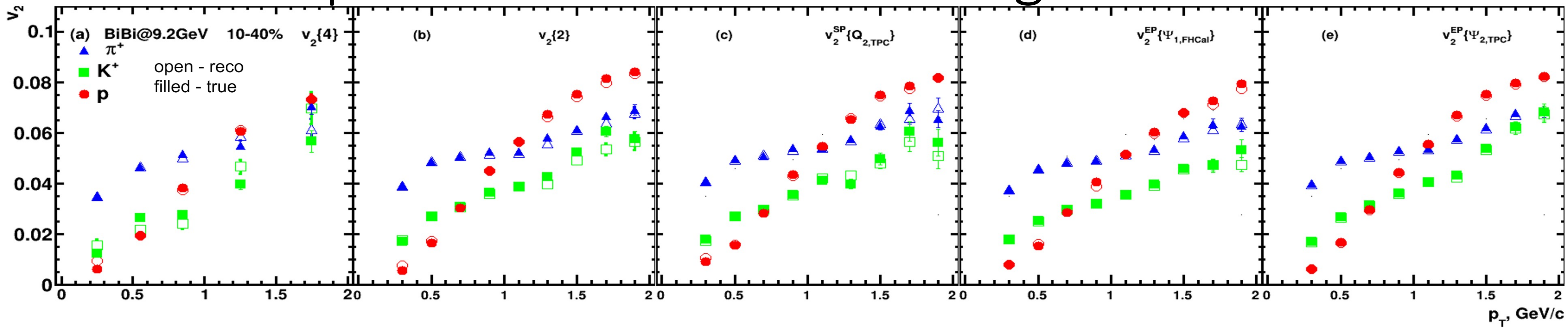
Short-lived resonances are sensitive to rescattering and regeneration in the hadronic phase

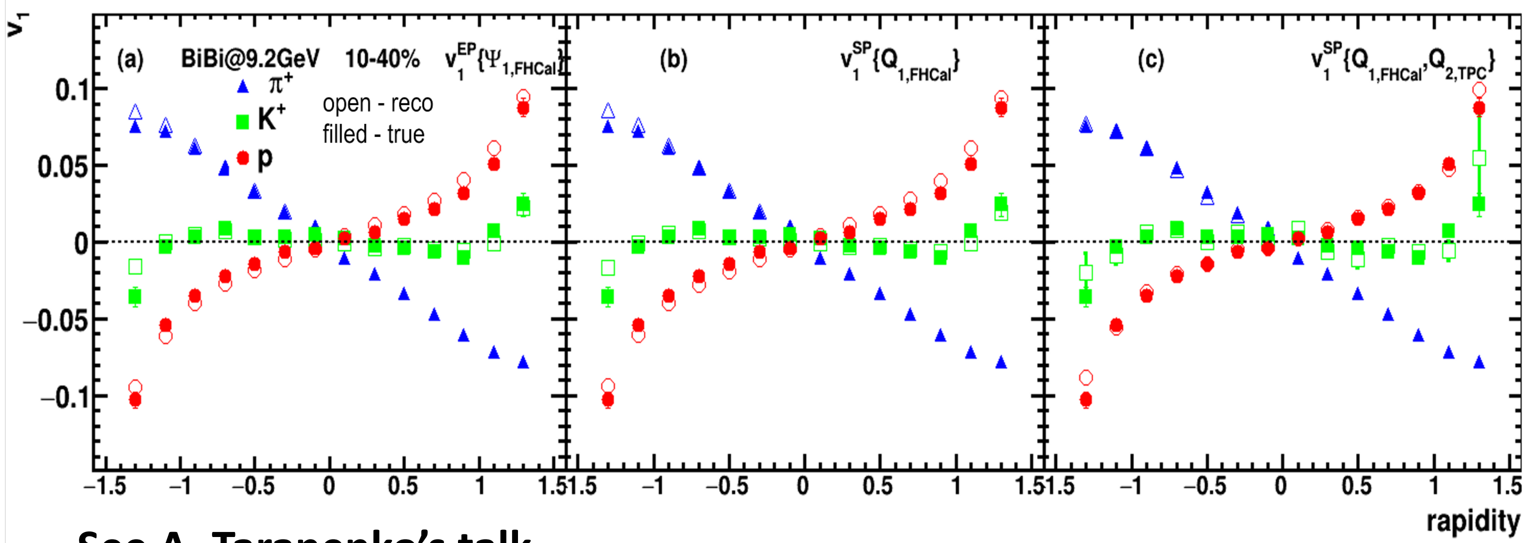
Most realistic approach to data analysis, centrality dependence

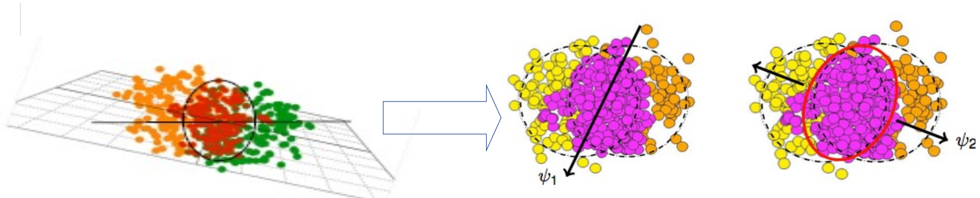
MPD is capable of resonance reconstruction using TPC and TOF for PID and selection based on the topology of the decay

First measurements are feasable with 10M events

Anisotropic flow of identified charged hadrons







v_1 - directed flow v_2 - elliptic flow

$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

$$v_n = \langle \cos[n(\phi - \Psi_{RP})] \rangle$$

See A. Taranenko's talk

Good performance for flow measurements for all methods used (EP, SP, Q-cumulants)

Anisotropic flow of V0 particles

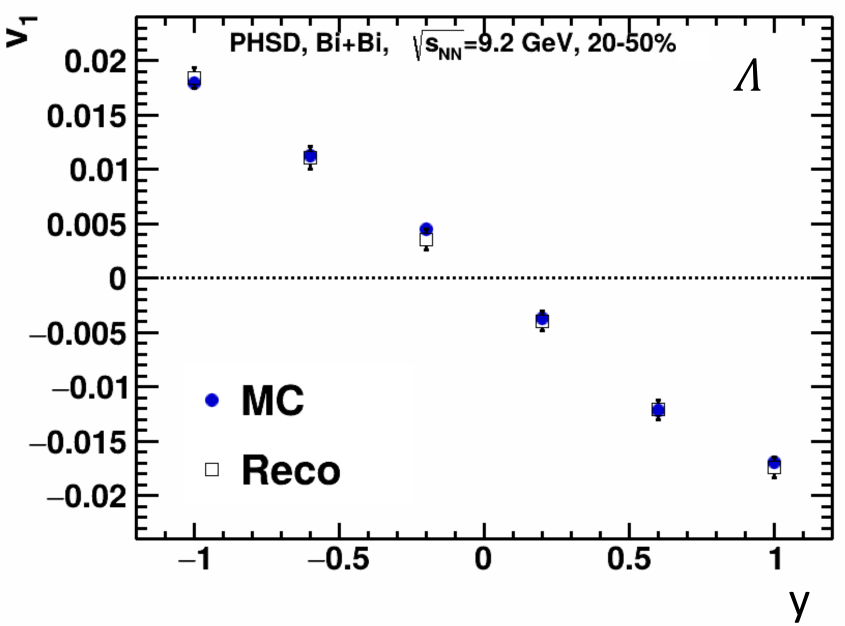
Differential flow can be defined using the following fit:

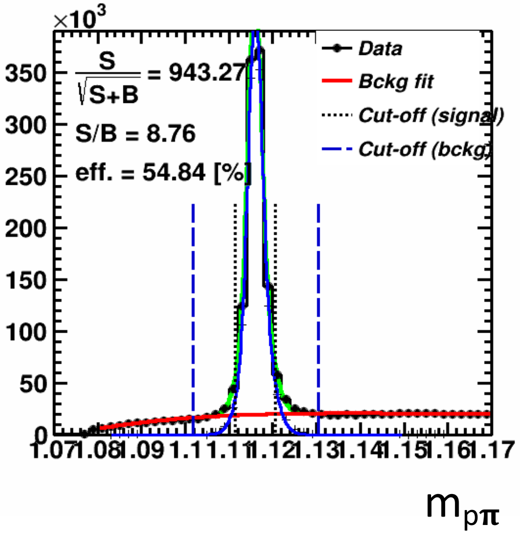
$$v_n^{SB}(m_{inv}) = v_n^S \frac{N^S(m_{inv})}{N^{SB}(m_{inv})} + v_n^B(m_{inv}) \frac{N^B(m_{inv})}{N^{SB}(m_{inv})}$$

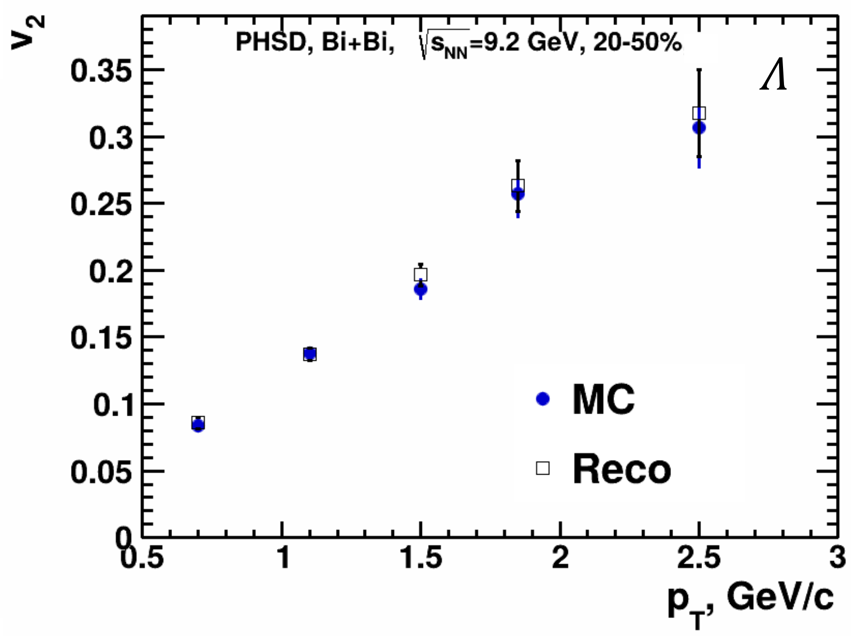
where:

- v_n^S - signal anisotropic flow (set as a parameter in the fit)
- $v_n^B(m_{inv})$ - background flow (set as polynomial function)
- $N^{SB}(m_{inv})$ - m_{inv} distribution (signal + background)
- $N^S(m_{inv})$ - m_{inv} signal distribution
- $N^B(m_{inv})$ - m_{inv} background distribution

See V. Troshin's talk



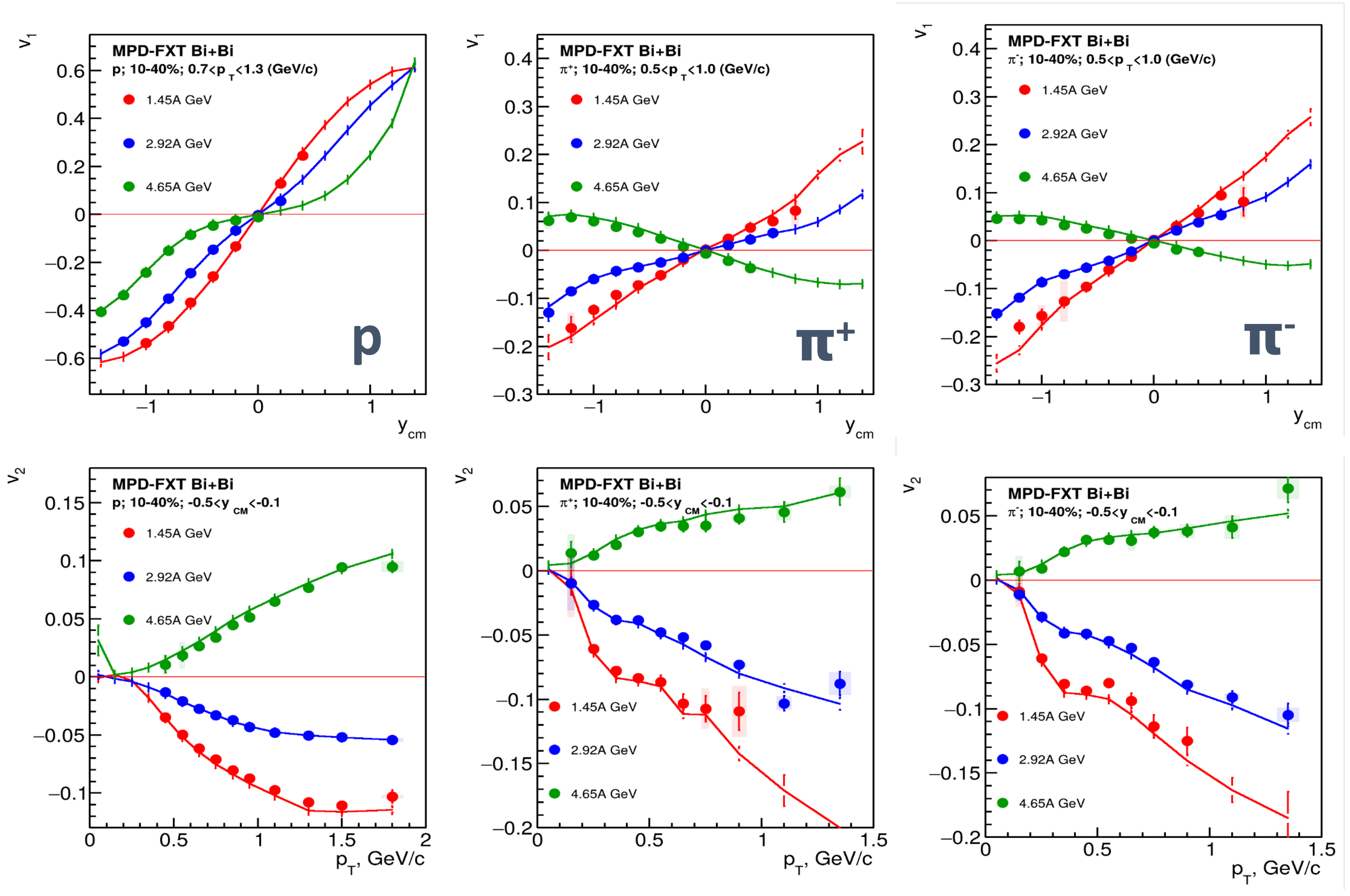




Good performance for v_1, v_2 using invariant mass fit and event plane methods

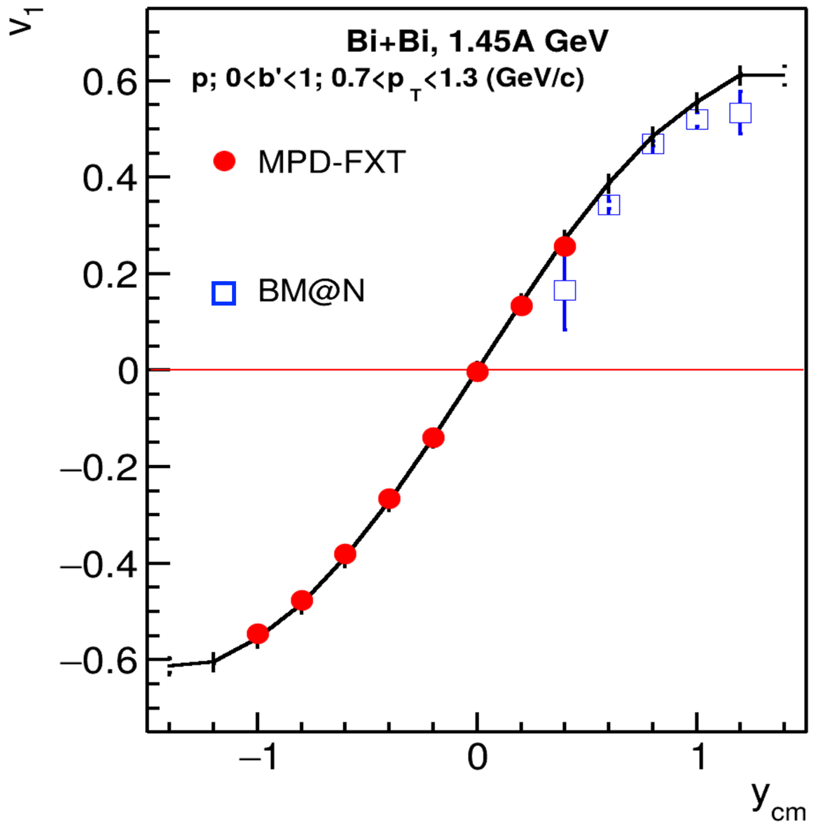
Anisotropic flow in MPD-FXT

- ❖BiBi @ 2.5, 3.0 and 3.5 GeV (UrQMD mean-field, fixed-target mode)
- ❖Realistic PID (TPC+TOF); efficiency corrections; centrality by TPC multiplicity



Reconstructed v_1 & v_2 are quantitatively consistent with truly generated signals

MPD vs. BM@N performance



MPD and BM@N complete each other with a small overlap

Measurement techniques were tested on experimental data from BM@N **– see talks of M. Kapishin and M. Mamaev**

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 published. Second paper under preparation

- ➢First operations of the MPD detector are expected at the end of 2025
- ➢MPD will provide a unique opportunity for investigating properties of strongly-interacting matter at high baryon densities
  - ✓to map the QCD phase diagram
  - ✓to search for phase transition and the Critical End Point

Backup

MPD Strategy

- ❖ MPD strategy–high-luminosity scans in **energy** and **system size** to measure a wide variety of signals:
  - ✓ order of the phase transition and search for the QCD critical point → structure of the QCD phase diagram
  - ✓ hypernuclei and equation of state at high baryon densities → inner structure of compact start, star mergers
- ❖ Scans to be carried out using the **same apparatus** in the same configuration/geometry with all the advantages of collider experiments:
  - ✓ maximum phase space, minimally biased acceptance, free of target parasitic effects
  - ✓ correlated systematic effects for different systems and energies → search for non-monotonic behavior of signals
- ❖ Continuously develop physical program based on the recent advancements in the field:
  - ✓ identified particle spectra and ratios, collective flow and femtoscopy, production of strangeness and hypernuclei net-proton fluctuations, global polarization of hyperond and spin alignment of vector mesons, dilepton continuum and LVMs, etc.
- ❖ Work in close cooperation with theoreticians to look for new signals/observables including those unique for the MPD

See more in: **Status and initial physics performance studies of the MPD experiment at NICA, Eur.Phys.J.A 58 (2022) 7, 140**

Physical programs of the MPD ($\sqrt{s_{NN}}$ = 2.3-11 GeV) and BM@N ($\sqrt{s_{NN}}$ = 2.3-3.5 GeV) are bound and should be realized in close cooperation

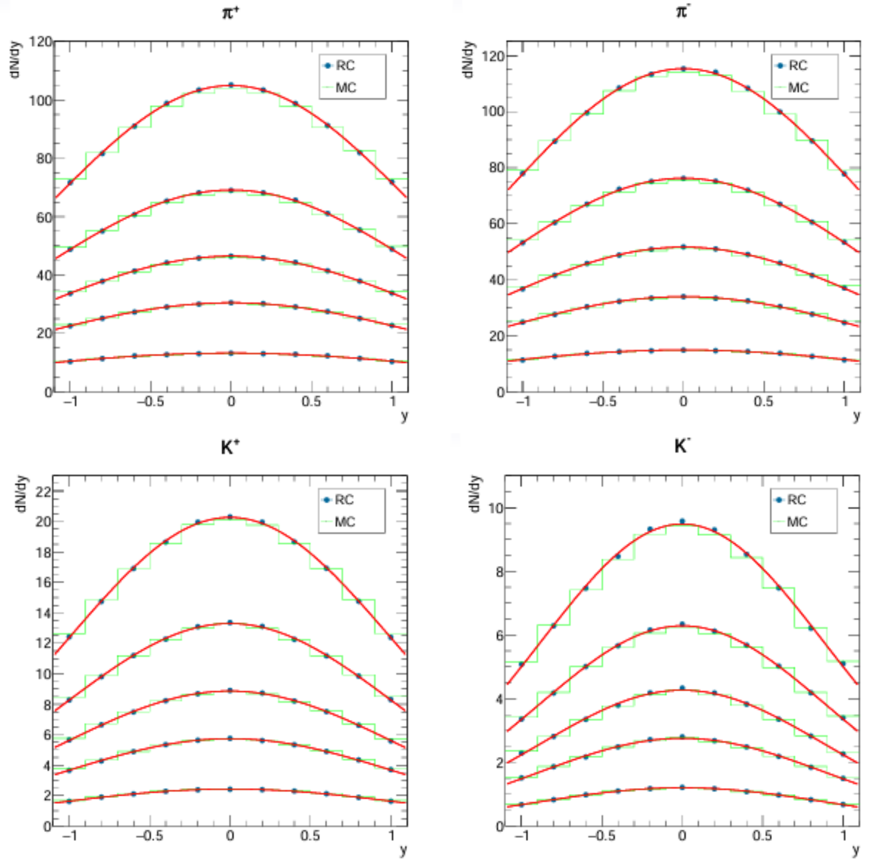
MPD schedule

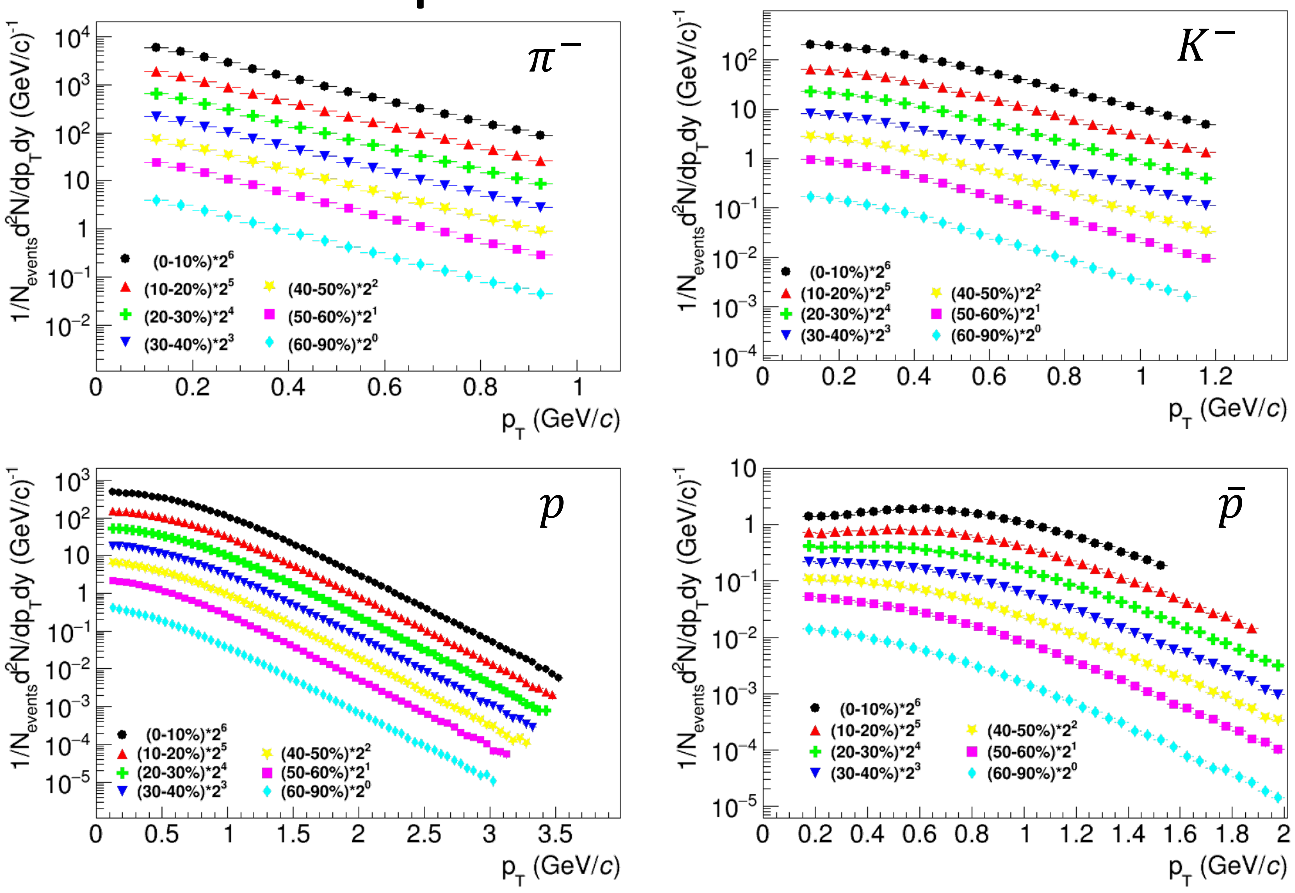
	Year 2024	
1	October 15th. - November 22th	Cooling down of the Solenoid to the working temperature 4K
2	November 25th	Readiness to switching on Solenoid Power Supplies Cooling water supplying in the Central distributor system of bld. 17 (MPD) must be ready
3	November 25th - December 15th	Solenoid Safety regimes of emergent energy evacuation working out Development of algorithms of cooling on base of experience with manual regime
4	December 15th – December 30th	Installation Magnetic Field Mapper, Calibration, preparation for measurements of Field
5	November 20th – December 20th	Installation FHCal into poles
6	December 20th	TPC mechanical body is assembled, leak test and HV test are finished
7	December 30th	TPC/Ecal Cooling system is commissioned
8	December 30th	Production of Ecal half sectors (modules) are finished
	Year 2025	
9	January 15th - April 30th	Magnetic field measurements on nominals: 0.2T, 0.3T, 0.4T, 0,45T, 0.5T, 0,55T
10	May 5th - May 8th	Support Frame installation
11	May 12th – August 30th	Installation ECal sectors
12	June 16th – August 30th	Installation TOF modules (access from both sides)
13	September 1st – November 23d	TPC installation
14	June 2d – November 23d	Cabling
15	November 24th – December 14th	Beam pipe installation
16	December 22d	Moving on the beam line
17	December 30th	Commissioning

Selected publications from the MPD Collaboration

1. **Status and initial physics performance studies of the MPD experiment at NICA, *Eur.Phys.J.A* 58 (2022) 7, 140**
2. Mamaev, M.; Taranenko, A. Toward the System Size Dependence of Anisotropic Flow in Heavy-Ion Collisions at $\sqrt{s_{NN}}$ = 2–5 GeV. *Particles* **2023**, *6*, 622-637
3. Segal, I. Centrality Determination in Heavy-Ion Collisions Based on Monte-Carlo Sampling of Spectator Fragments. *Particles* **2023**, *6*, 568-579
4. Kireyeu, V.; Kolesnikov, V.; Zinchenko, A.; Vasendina, V.; Mudrokh, A. Prospects for the (Hyper)Nuclei Study in the Nica Energy Range. *Particles* **2023**, *6*, 399-404
5. Blau, D.; Peresunko, D. Direct Photon Production in Heavy-Ion Collisions: Theory and Experiment. *Particles* **2023**, *6*, 173-187
6. Luong, V.B.; Idrisov, D.; Parfenov, P.; Taranenko, A. Elliptic Flow and Its Fluctuations from Transport Models for Au+Au Collisions at sNN = 7.7 and 11.5 GeV. *Particles* **2023**, *6*, 17-29
7. Parfenov, P. Model Study of the Energy Dependence of Anisotropic Flow in Heavy-Ion Collisions at $\sqrt{s_{NN}}$ = 2–4.5 GeV. *Particles* **2022**, *5*, 561-579
8. Peresunko, D. Approaches to Measuring Direct Photon Yield in A–A Collisions. *Particles* **2022**, *5*, 188-197
9. E. Kryshen et. al., Thermal Photon and Neutral Meson Measurements Using the Photon Conversion Method in the MPD Experiment at the NICA Collider, *Phys.Part.Nucl.* 52 (2021) 4, 669-674

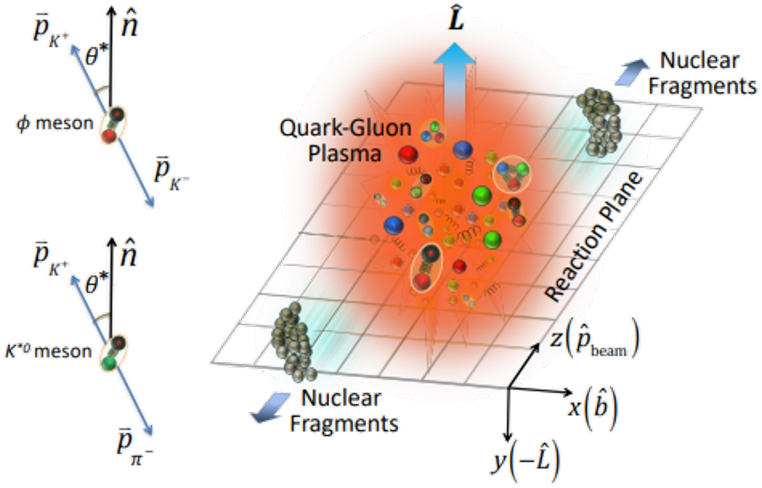
Charged identified hadron production

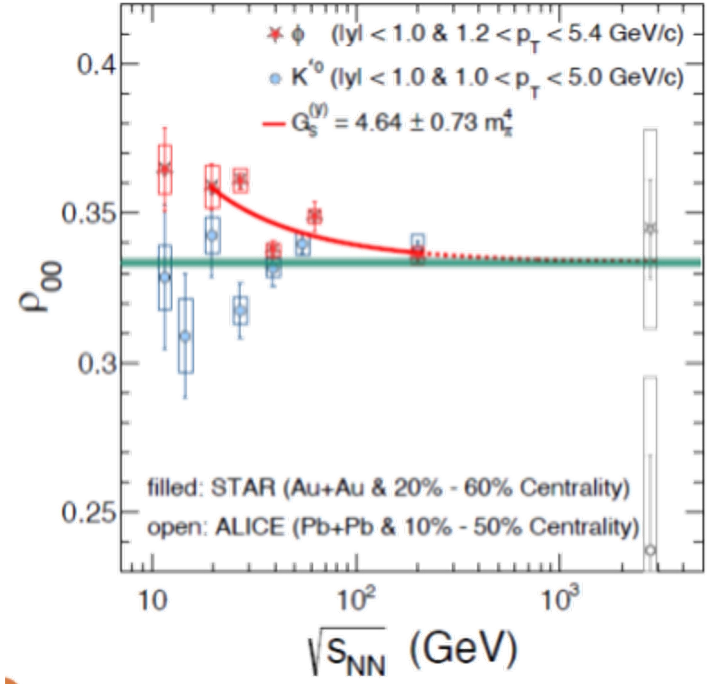




- Probe freeze-out conditions, collective expansion, hadronization mechanisms, strangeness production ("horn" for K/π), parton energy loss, etc. with particles of different masses, quark contents/counts
- Charged hadrons: large (~70% of π/K/p) and uniform acceptance + excellent PID capabilities of TPC and TOF down to p_T~0.1 GeV/c

Polarization of vector mesons: K*(892) and ϕ





- Light quarks can be polarized by $|\bar{J}|$and $|\bar{B}|$
- If vector mesons are produced via recombination their spin may align
- Quantization axis:
  - ✓ normal to the production plane (momentum of the vector meson and the beam axis)
  - ✓ normal to the event plane (impact parameter and beam axis)

- Measured as anisotropies:

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

$\rho_{0,0}$ is a probability for vector meson to be in spin state = 0 →
$\rho_{0,0}$ = 1/3 corresponds to no spin alignment

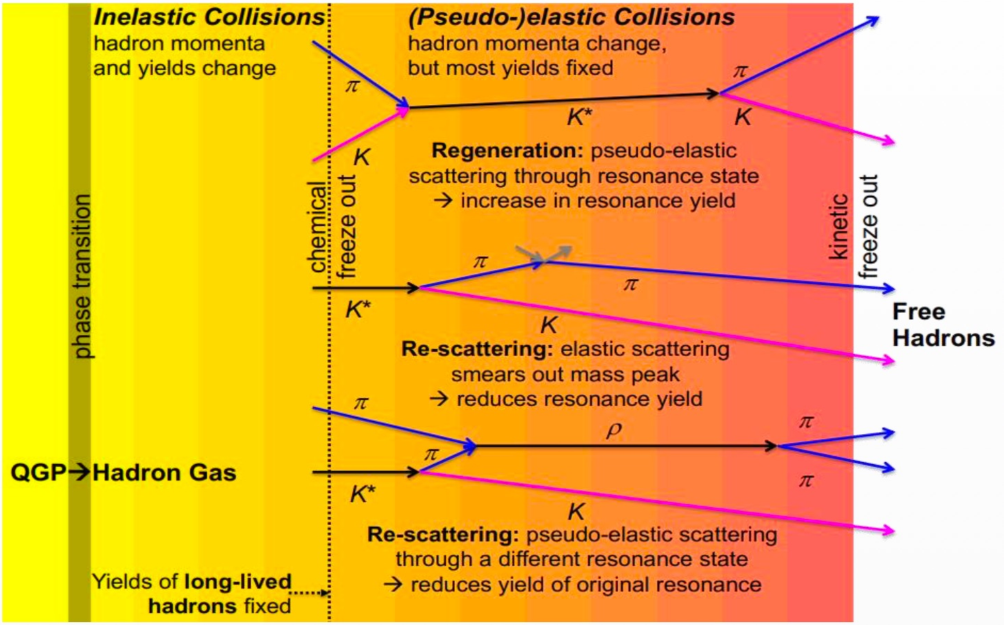
- Measurements at RHIC/LHC challenge theoretical understanding → ρ_{00} can depend on multiple physics mechanisms (vorticity, magnetic field, hadronization scenarios, lifetimes and masses of the particles)

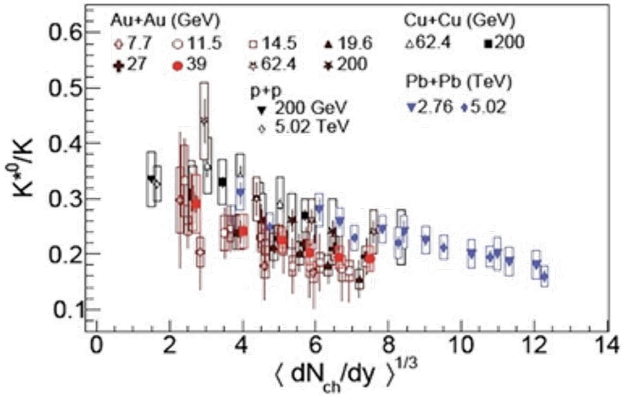
MPD: extend measurements in the NICA energy range, $\sqrt{s_{NN}}$ < 11 GeV

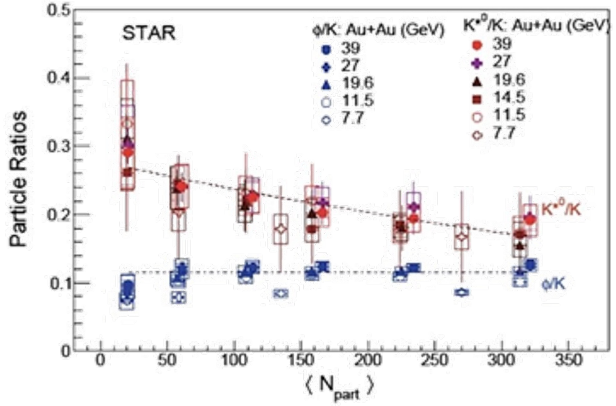
Hadronic resonances

❖ Short-lived resonances are sensitive to rescattering and regeneration in the hadronic phase

	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
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$







❖ Properties of the hadronic phase are studied by measuring ratios of resonance yields to yields of long-lived particles with same/similar quark contents: ρ/π, K^*/K, ϕ/K, Λ*/Λ, $\Sigma^{*\pm}/\Sigma$ and Ξ^{*0}/Ξ

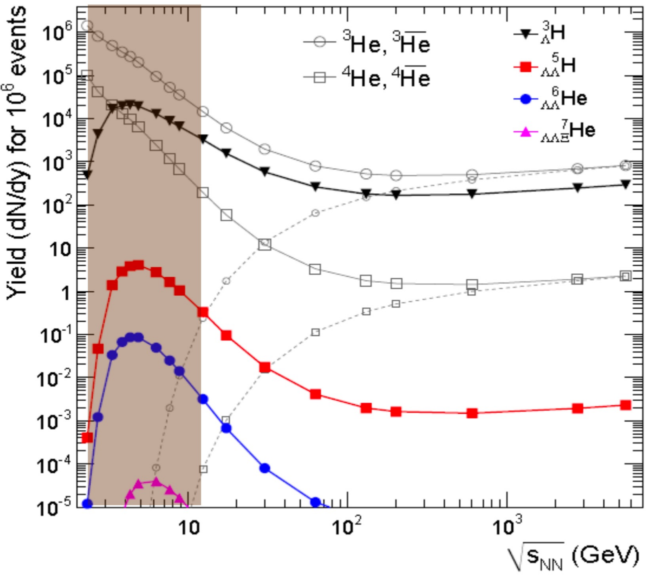
❖ Measurements in a wide energy range $\sqrt{s_{NN}}$= 7-5000 GeV support the existence of a hadronic phase that lives long enough (up to τ ~ 10 fm/*c*) to cause a significant reduction of the reconstructed yields of short-lived resonances

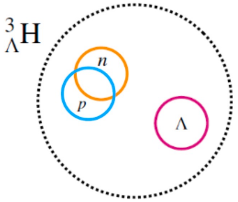
❖ All model predictions for early stages must be filtered through the hadronic phase

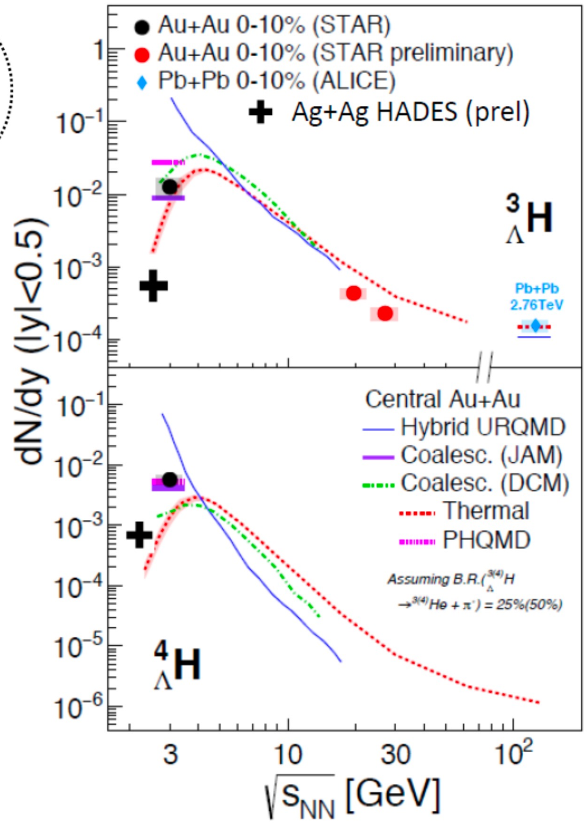
Precise measurements at NICA are needed to validate description of the hadronic phase in models

Hypernuclei production

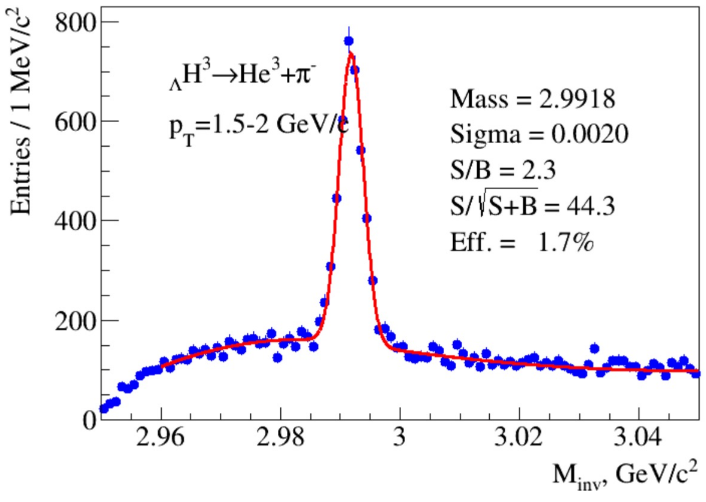
A. Andronic et al, PLB 697 (2011) 203

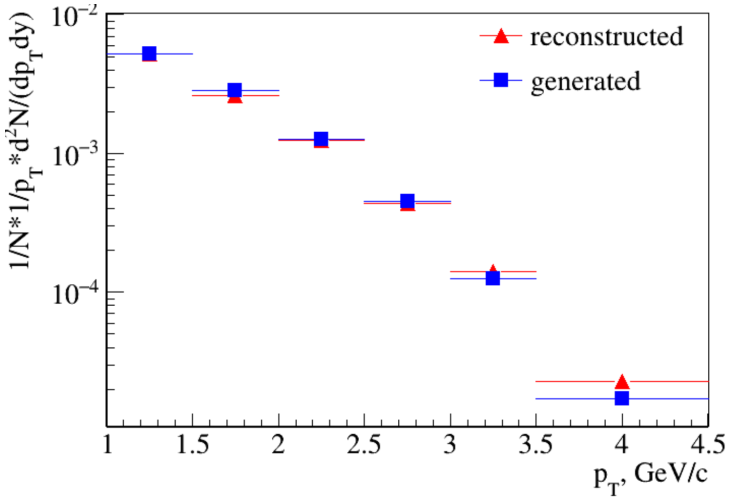


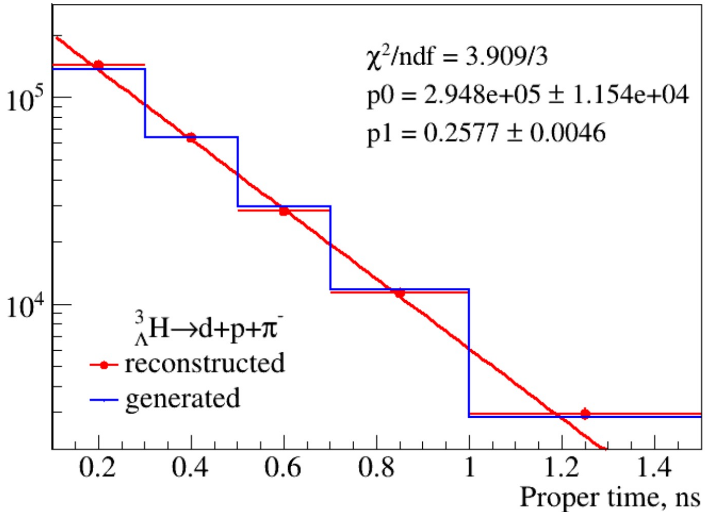




- Hypernuclei measurements may shed light on their production mechanism (statistical hadronisation, coalescence) – there are few data on the production of hypernuclei in heavy-ion collisions
- Statistical models predict enchanced hypernuclei production at NICA energies – more hypernuclei are available for measurements
- Yields and lifetimes from the models are well reproduced in MPD performance studies with 40M events for ${}^{3}_{\Lambda}H$

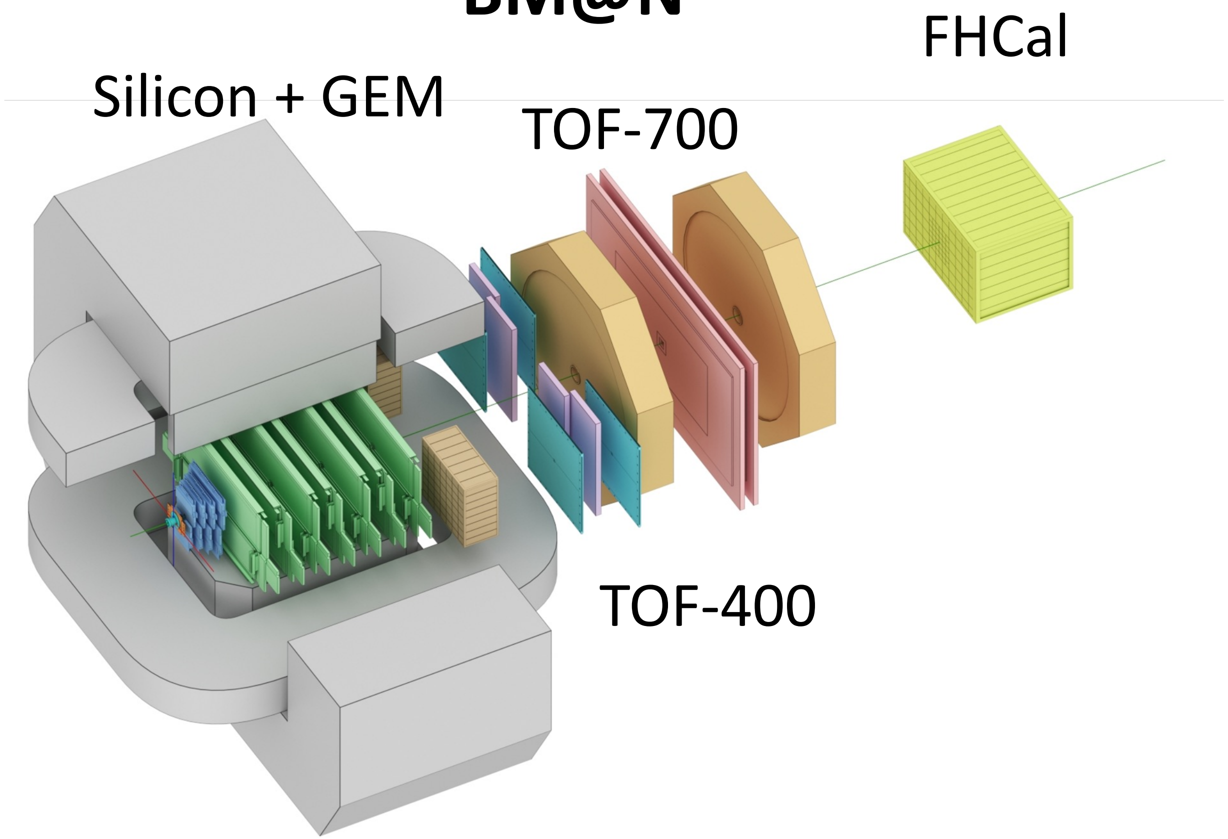




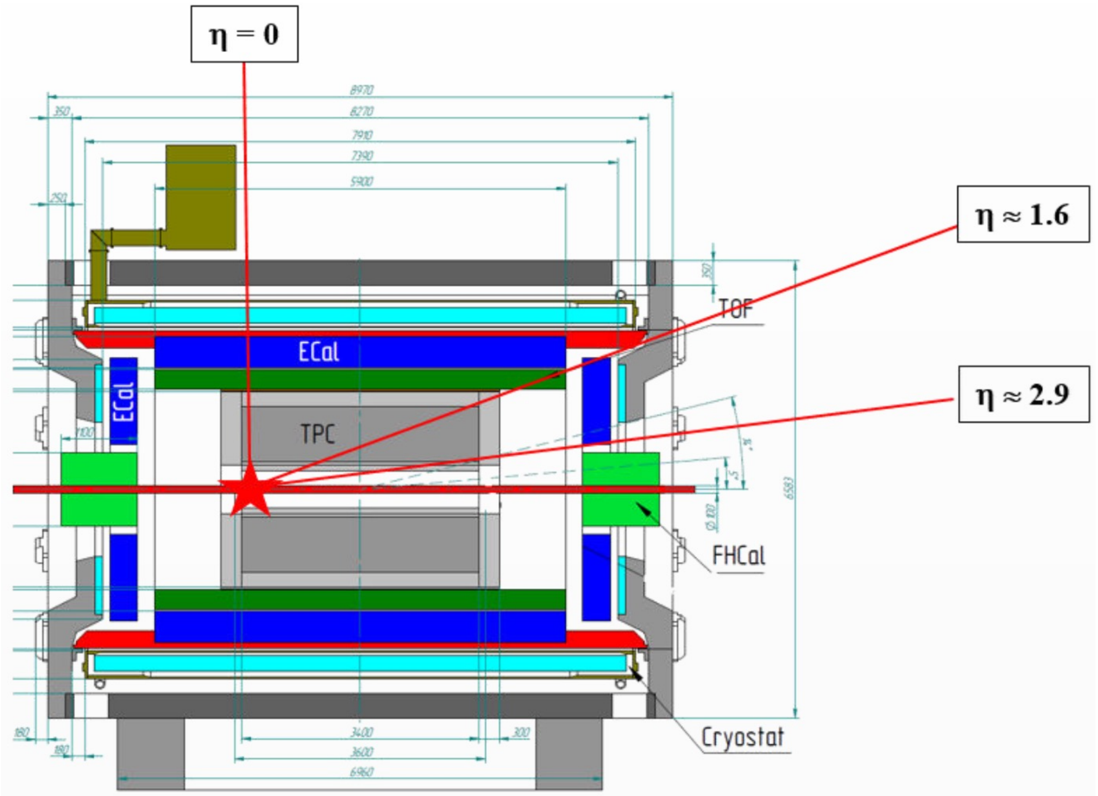


The BM@N and MPD-FXT experiments

BM@N



MPD-FXT

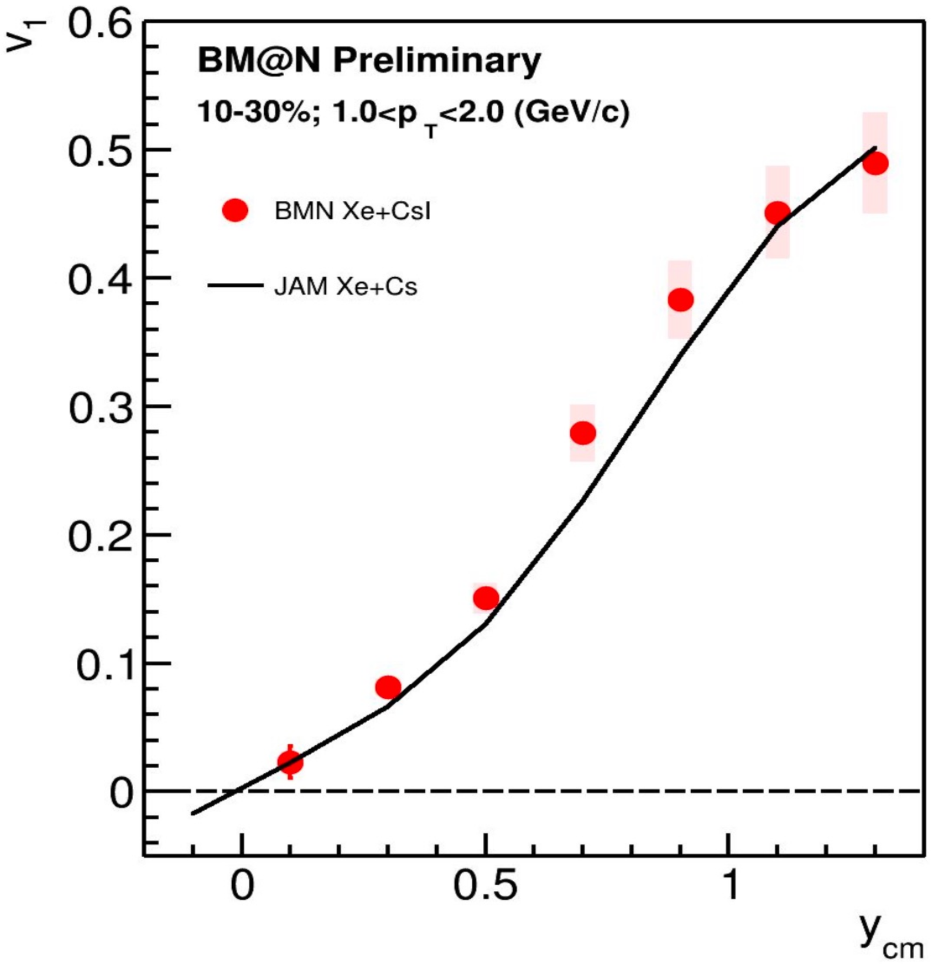


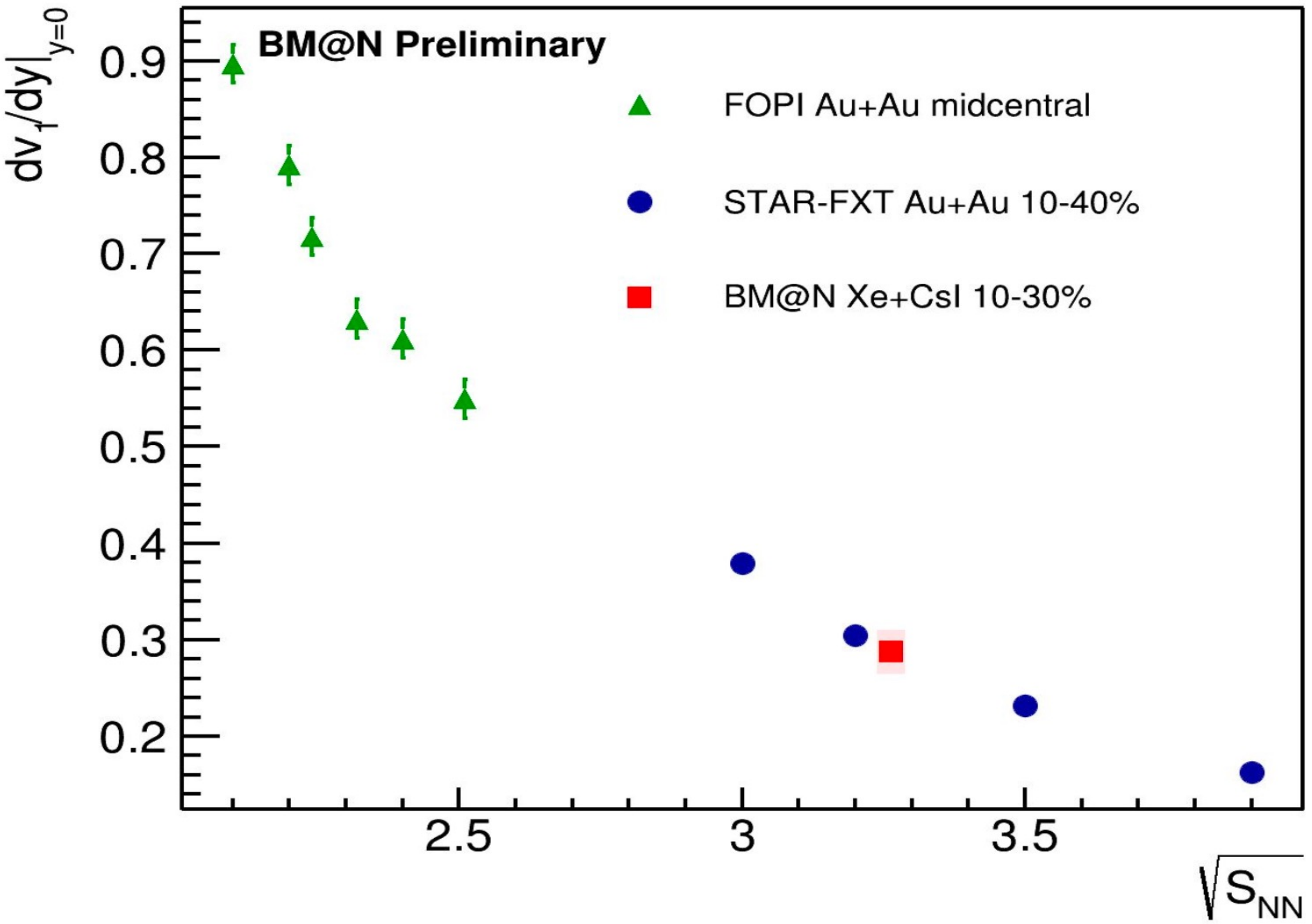
Detectors used for anisotropic flow measurements:

- **Tracking system:** FSD+GEM (BM@N); TPC (MPD-FXT)
- **PID:** TOF-400, TOF-700 (BM@N); TPC, TOF (MPD-FXT)
- **EP measurements:** FHCal (BM@N), FHCal (MPD-FXT)

First results from the Xe run at BM@N

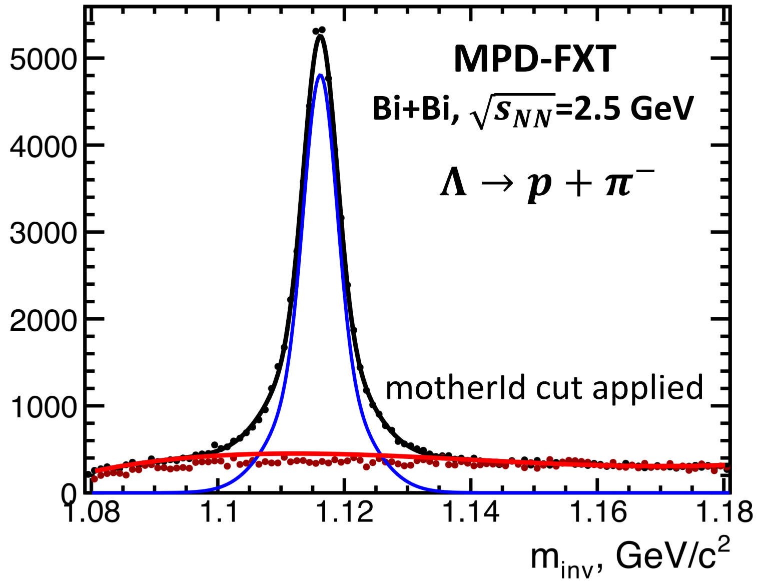
See M. Mamaev's talk

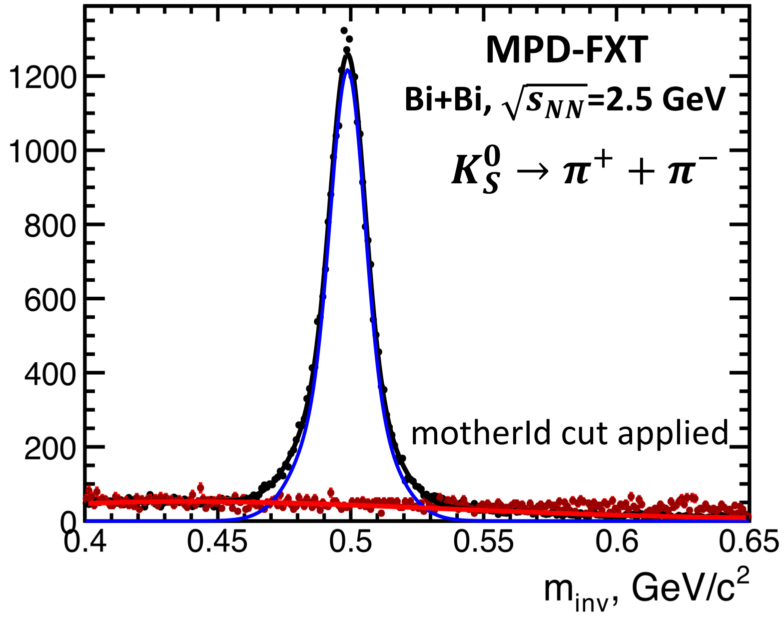




- **All measurement**

V0 selection: PFSimple





PFSimple: interface for the KFParticle package

KFParticle: package developed for complete reconstruction of short-lived particles

- Successfully used in many experiments
- Based on the Kalman filter mathematics
- Independent in the sense of experimental setup (collider, fixed target)

First tests for Λ, K_S^0 from the MPD-FXT production are ready:

- Basic topological cuts:

$$\chi^2_{topo} < 50, \chi^2_{geo} < 50, L > 3\ cm, \frac{L}{dL} > 5\ cm$$

- Signal extraction: sideband fits, rotation background were tested

PFSimple is already available as a module in the cvmfs

EOS for high baryon density matter

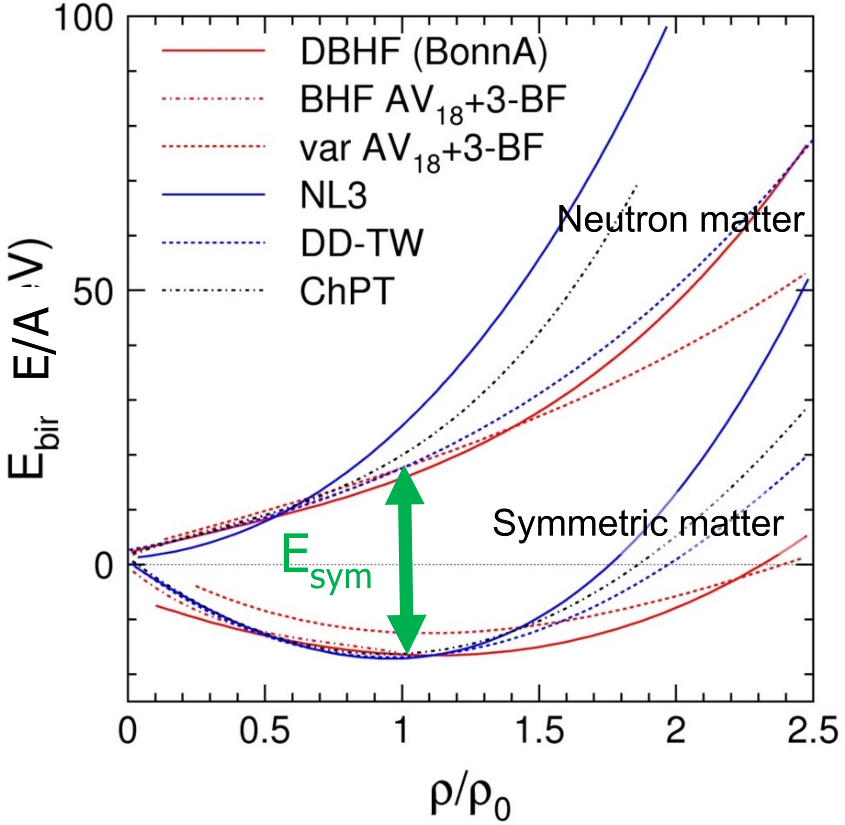
The binding energy per nucleon: $E_A(\rho,\delta) = E_A(\rho,0) + E_{sym}(\rho)\delta^2 + O(\delta^4)$

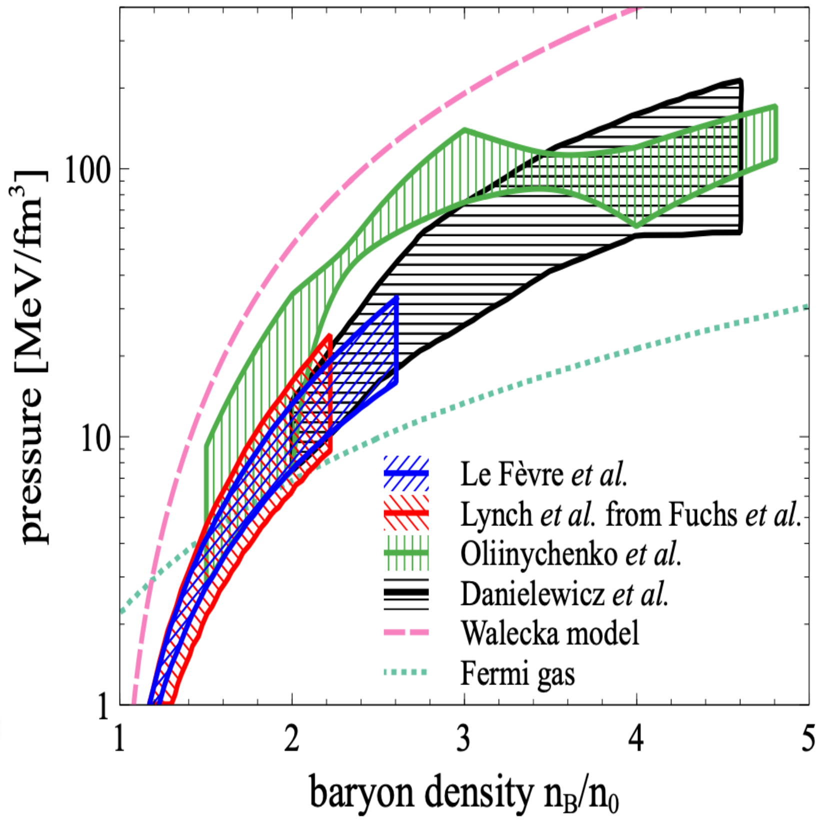
Isospin asymmetry:

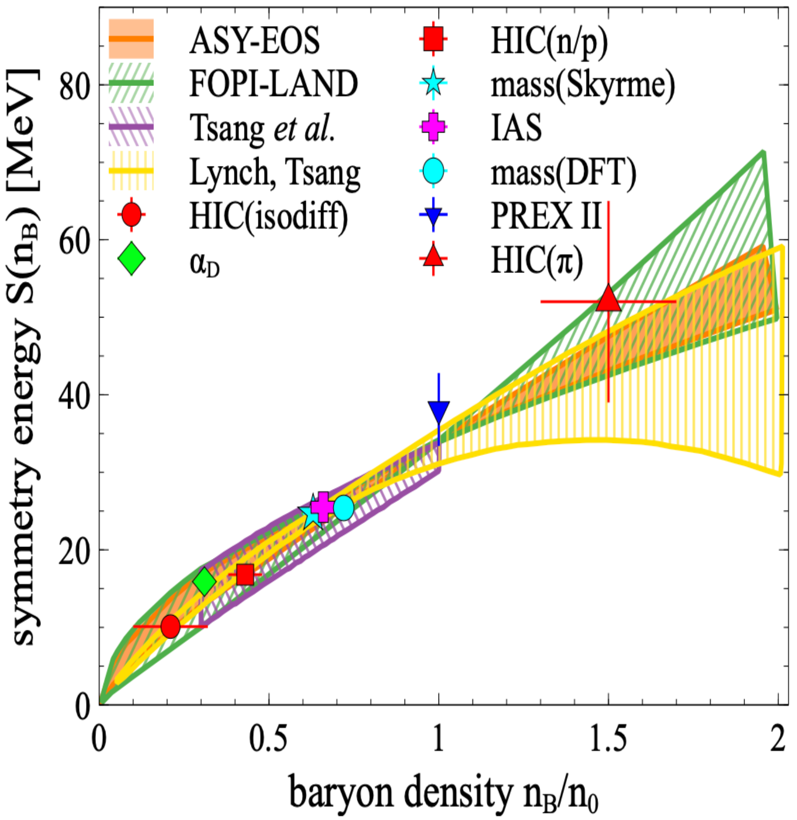
$\delta = (\rho_n - \rho_p)/\rho$

Symmetric matter

Symmetry energy





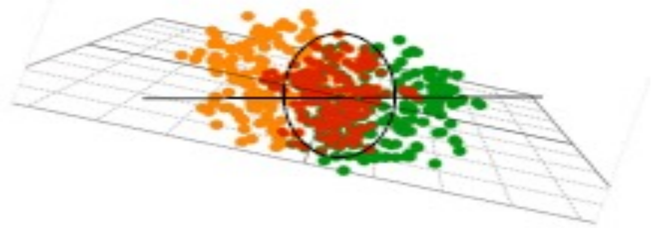


Ch. Fuchs and H.H. Wolter, EPJA 30 (2006) 5

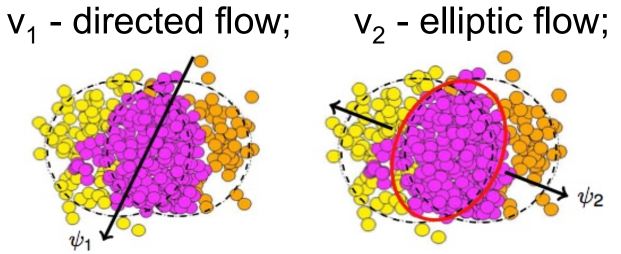
A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080

New data is needed to further constrain transport models with hadronic d.o.f.

Anisotropic flow



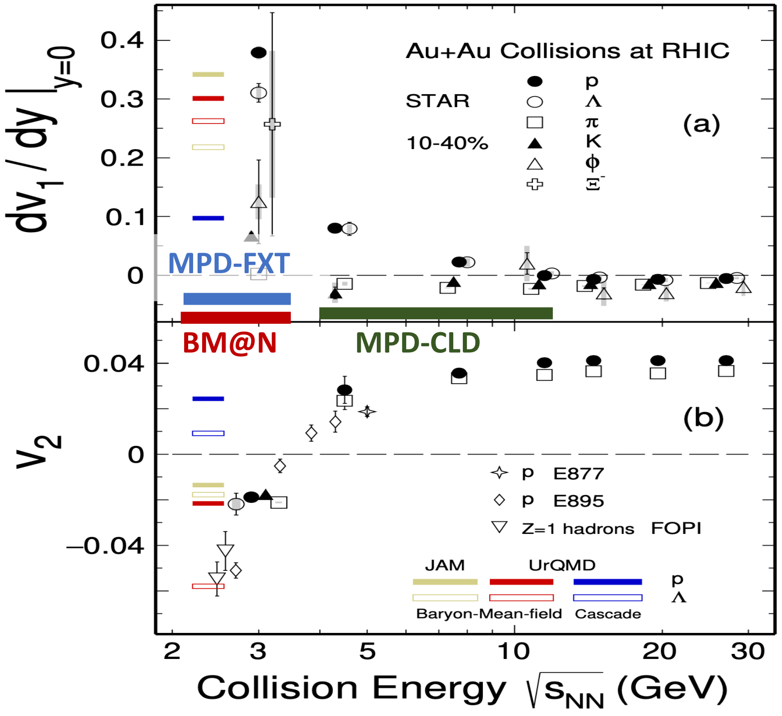
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$



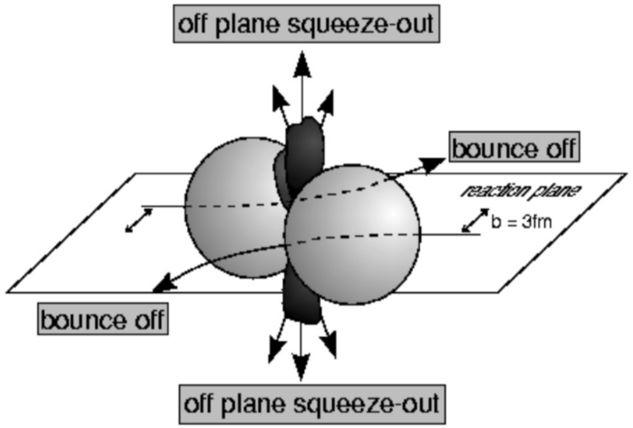
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

$$v_n = \langle \cos[n(\phi - \Psi_{RP})]\rangle$$

STAR, Phys.Lett.B 827 (2022) 137003



Initial eccentricity (and its attendant fluctuations) ϵ_n drive momentum anisotropy v_n with specific viscous modulation



See A. Taranenko's talk

At Nuclotron-NICA:

Strong energy dependence of dv_1/dy and v_2 at $\sqrt{s_{NN}}$=2-11 GeV

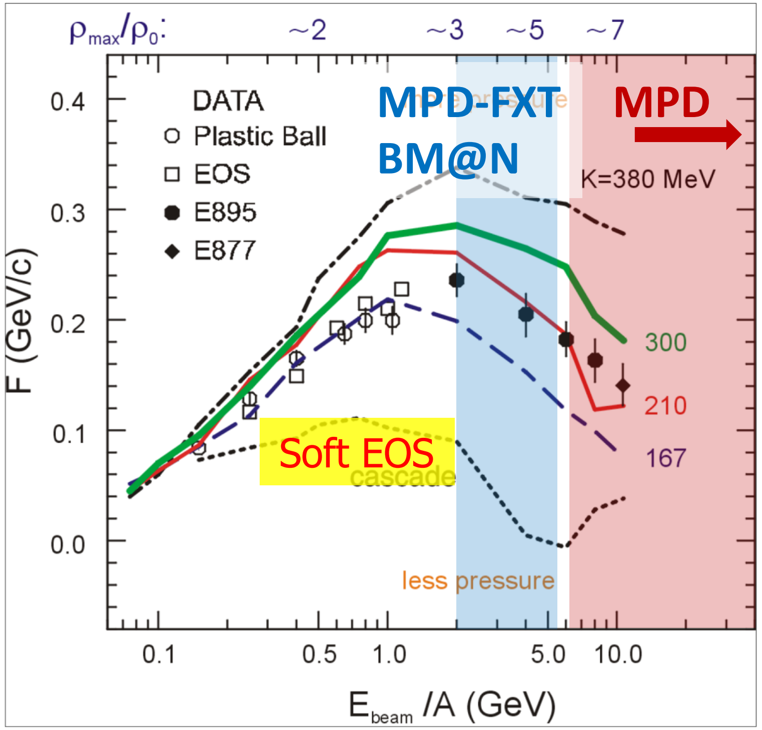
Anisotropic flow at Nuclotron-NICA energies is a delicate balance between:

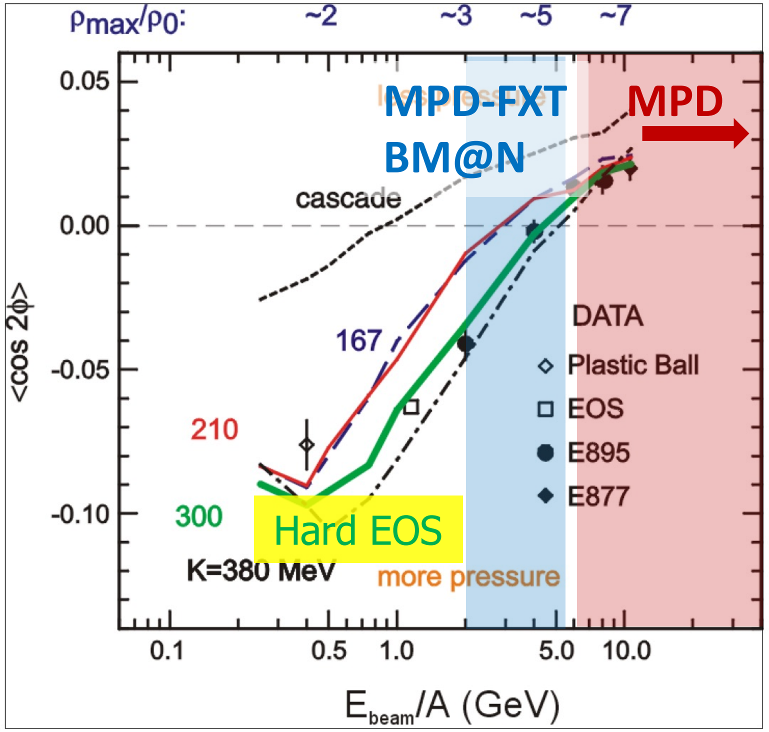
I. **The ability of pressure developed early in the reaction zone** $(t_{exp} = R/c_s)$

II. **The passage time for removal of the shadowing by spectators** $(t_{pass} = 2R/\gamma_{CM}\beta_{CM})$

Sensitivity of the collective flow to the EOS

P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592





$$F = \left. \frac{d\langle p_x/A\rangle}{d(y/y_{cm})} \right|_{y/y_{cm}=1}$$

$$v_2 \equiv \langle \cos(2(\varphi - \Psi_{RP})) \rangle$$

$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n(\phi - \Psi_n)\right]\right)$$

$$v_n = \langle \cos[n(\phi - \Psi_{RP})] \rangle$$

Anisotropic flow sensitive to the EoS

EoS extraction: define incompressibility

$$K_0 = 9\rho^2 \frac{\partial^2 (E_A)}{\partial \rho^2}$$

Discrepancy in the interpretation:

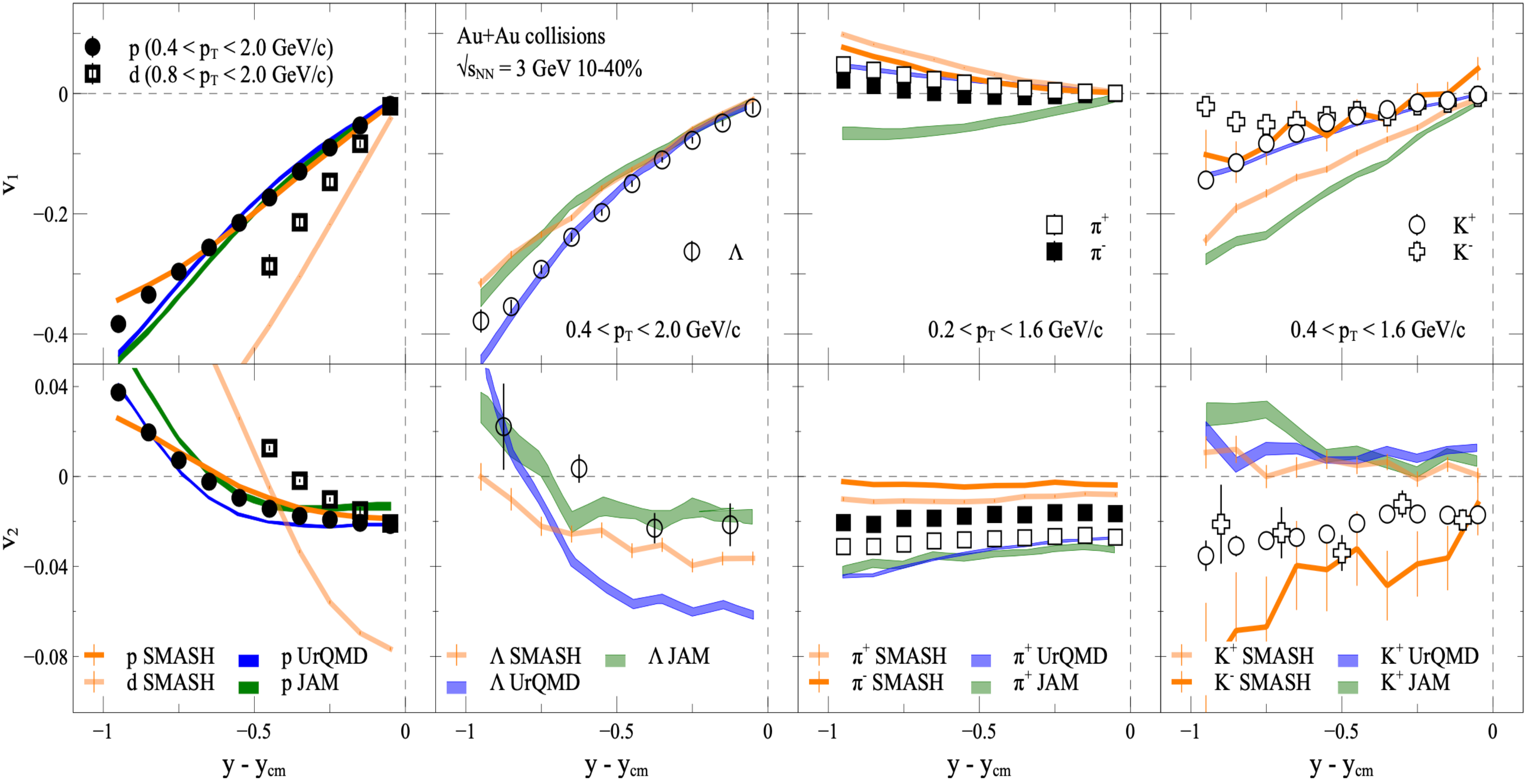
- v_1 suggests soft EoS (K_0≈210 MeV)
- v_2 suggests hard EoS (K_0≈380 MeV)

New measurements using new data and modern analysis techniques might address this discrepancy

Additional measurements are essential to clarify the previous results

$v_{1,2}(y)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data

A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080



Model description of v_n:

- Good overall agreement for v_n of protons
- v_n of light nuclei is not described
- v_n of Λ is not well described
  - **nucleon-hyperon** and **hyperon-hyperon** interactions
- Light mesons (π,K) are not described
  - No mean-field for mesons

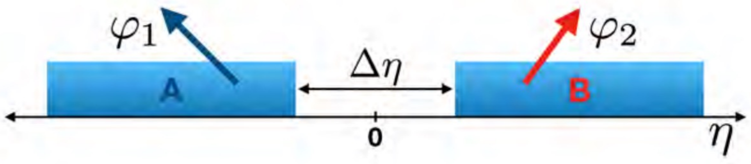
Models have a huge room for improvement in terms of describing v_n

Methods for v_n measurements in MPD-CLD

- **Sub-event 2-particle Q-cumulants v2{2}:**

Δη=0.1 is applied between 2 sub-events A, B to suppress non-flow

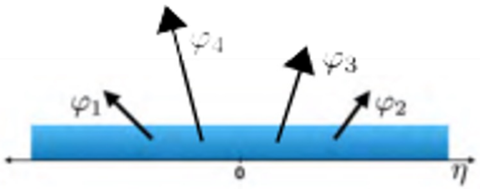
$$Q_n = \sum_{i=1}^{M} e^{in\phi} \qquad \langle 2 \rangle_{a|b} = \frac{Q_{n_a} Q^*_{n,b}}{M_a M_b} \qquad v_2\{2\} = \sqrt{\langle\langle 2 \rangle\rangle_{a|b}}$$



- **4-particle Q-cumulants v2{4}**

$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)} \qquad v_2\{4\} = \sqrt[4]{2\,\langle\langle 2 \rangle\rangle^2 - \langle\langle 4 \rangle\rangle}$$

$$\langle 4 \rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2\Re[Q_{2n} Q^*_n Q^*_n] - 4(M-2)\,|Q_n|^2 - 2M(M-3)}{M(M-1)(M-2)(M-3)}$$



- **Event plane method:** Δη=0.1

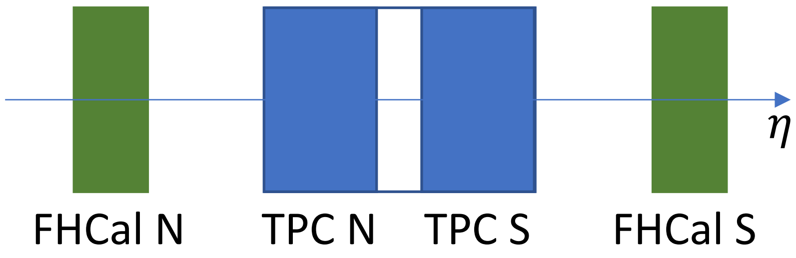
$$Q_{n,x} = \sum_i w_i \cos(n\phi_i) \qquad Q_{n,y} = \sum_i w_i \sin(n\phi_i)$$

$$\Psi_n^{EP} = \frac{1}{n} \tan^{-1}\left(\frac{Q_{n,y}}{Q_{n,x}}\right) \qquad v_n = \frac{\langle \cos[n(\phi - \Psi_n^{EP})] \rangle}{\sqrt{\langle \cos[n(\Psi_{n,a} - \Psi_{n,b})] \rangle}}$$

Here: $\boldsymbol{\omega_i}$ - $p_{T,i}$ transverse momentum of the i-th track in the TPC

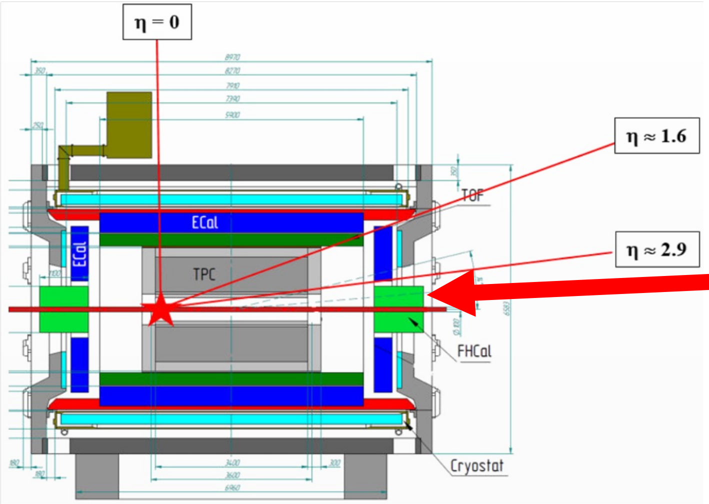
$\boldsymbol{\varphi_i}$ - azimuthal angle of the i-th track in the TPC

Ψ_n- event plane angles

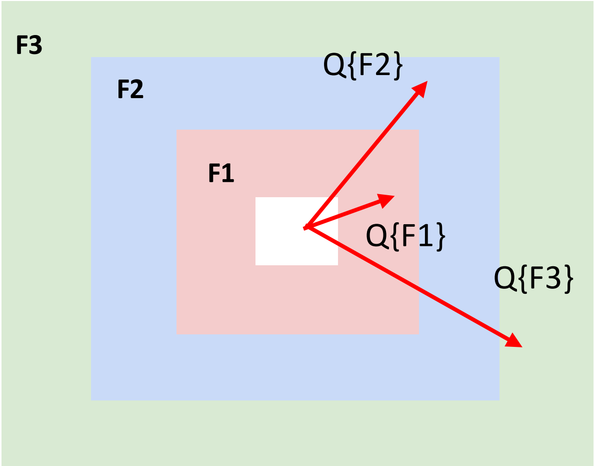


Method's details described in PRC 83 (2011), 044913 , EP method: Phys.Rev.C 77 (2008) 034904

Flow vectors for MPD-FXT case



Modules of FHCal divided into 3 groups



From momentum of each measured particle define a u_n-vector in transverse plane:

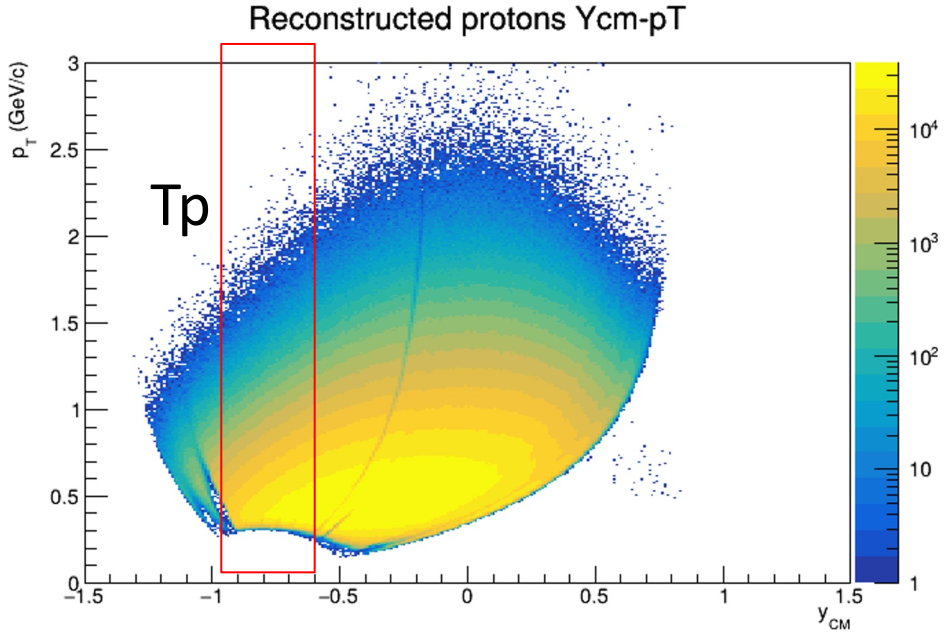
$$u_n = e^{in\phi}$$

where ϕ is the azimuthal angle

Sum over a group of u_n-vectors in one event forms Q_n-vector:

$$Q_n = \frac{\sum_{k=1}^{N} w_n^k u_n^k}{\sum_{k=1}^{N} w_n^k} = |Q_n| e^{in\Psi_n^{EP}}$$

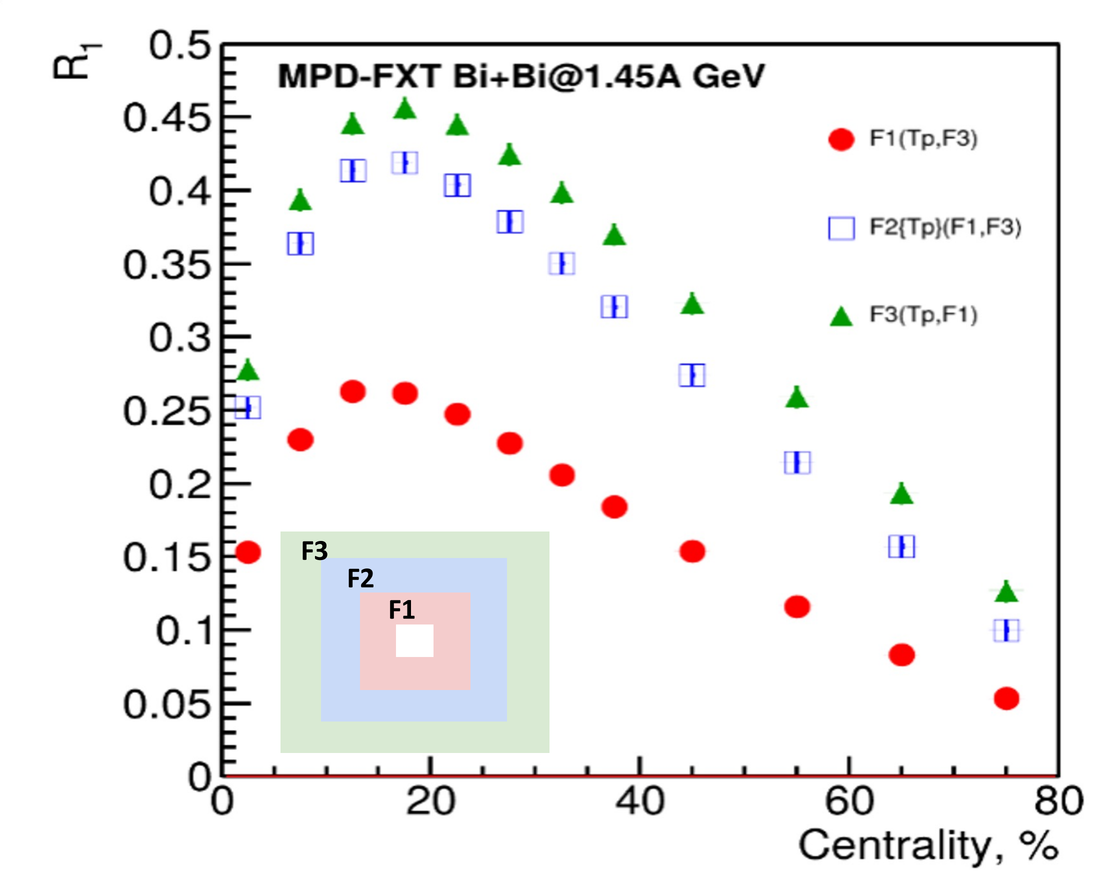
Ψ_n^{EP} is the event plane angle



Additional subevents from tracks not pointing at FHCal:
Tp: p; -1.0<y<-0.6;

Flow methods for v_n calculation

Tested in HADES: M Mamaev et al 2020 PPNuclei 53, 277–281
M Mamaev et al 2020 J. Phys.: Conf. Ser. 1690 012122



Scalar product (SP) method:

$$v_1 = \frac{\langle u_1 Q_1^{F1} \rangle}{R_1^{F1}} \qquad v_2 = \frac{\langle u_2 Q_1^{F1} Q_1^{F3} \rangle}{R_1^{F1} R_1^{F3}}$$

Where R_1 is the resolution correction factor

$$R_1^{F1} = \langle \cos(\Psi_1^{F1} - \Psi_1^{RP}) \rangle$$

Symbol “F2(F1,F3)” means R_1 calculated via (3S resolution):

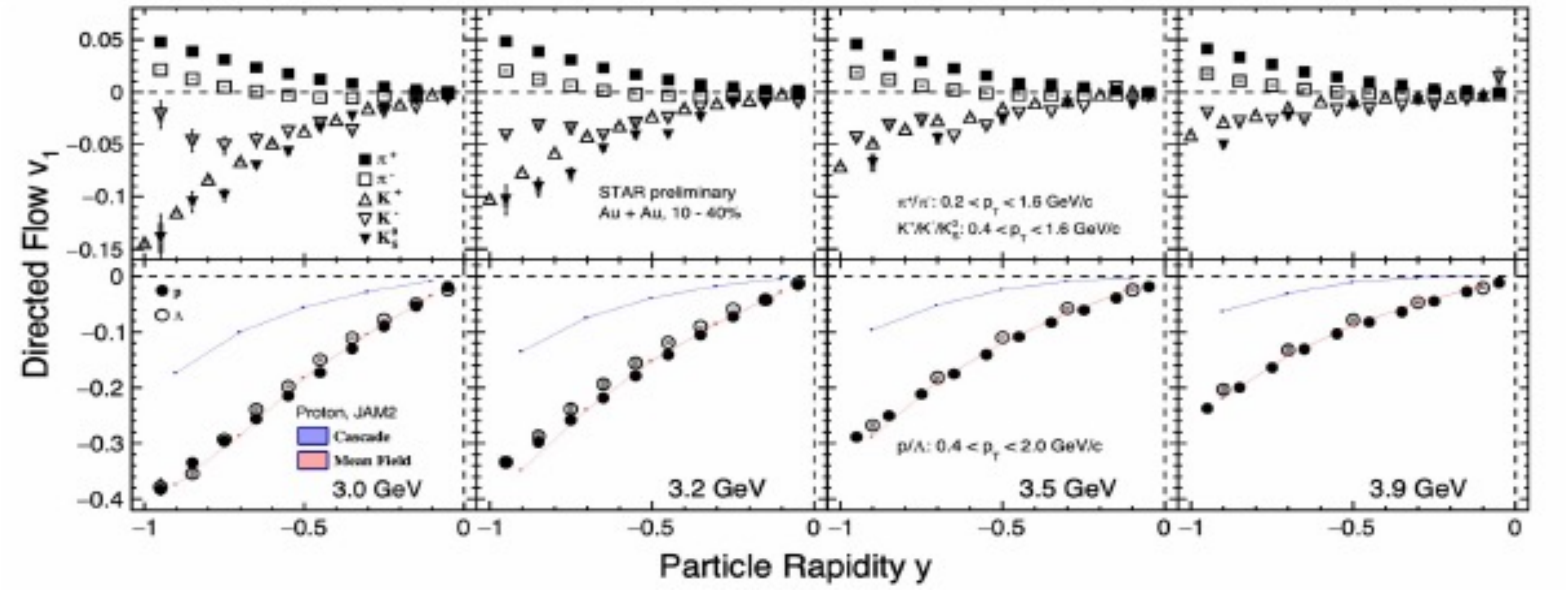
$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

Symbol “F2{Tp}(F1,F3)” means R_1 calculated via (4S resolution):

$$R_1^{F2\{Tp\}(F1,F3)} = \langle Q_1^{F2} Q_1^{Tp} \rangle \frac{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{Tp} Q_1^{F1} \rangle \langle Q_1^{Tp} Q_1^{F3} \rangle}}$$

New STAR results from BES-II

Results from QM 2023

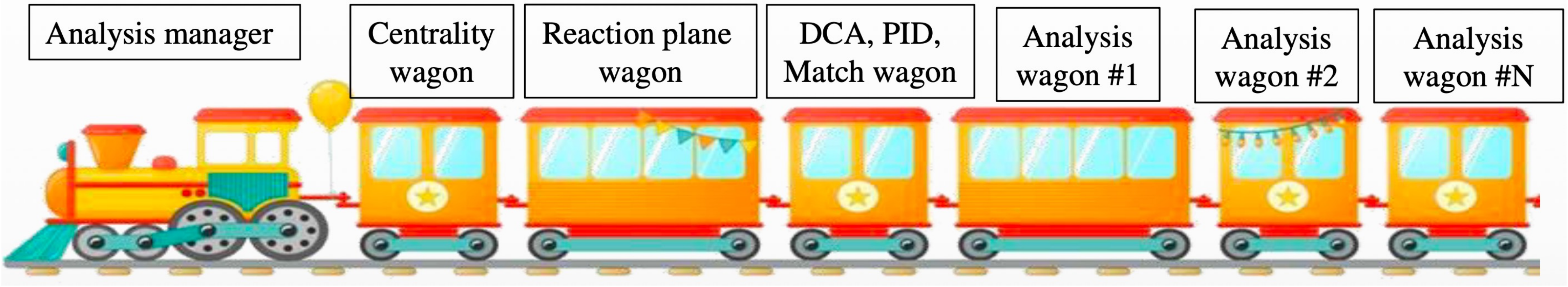


New preliminary results from STAR BES-II were presented at QM-2023 for Au+Au at $\sqrt{s_{NN}}$=3, 3.2, 3.5, 3.9 GeV

Feasibility studies: centralized analysis framework

Physics feasibility studies are done using centralized large-scale MC productions
Requirements for the analysis framework:
- Consistency of approaches and results across the collaboration – robust crosscheck of the analysis
- Ability to easily implement analysis in the framework – modular structure of the software, code standartization
- Easy data storage and reduced number of I/O operations – execution of the modules in one sequence

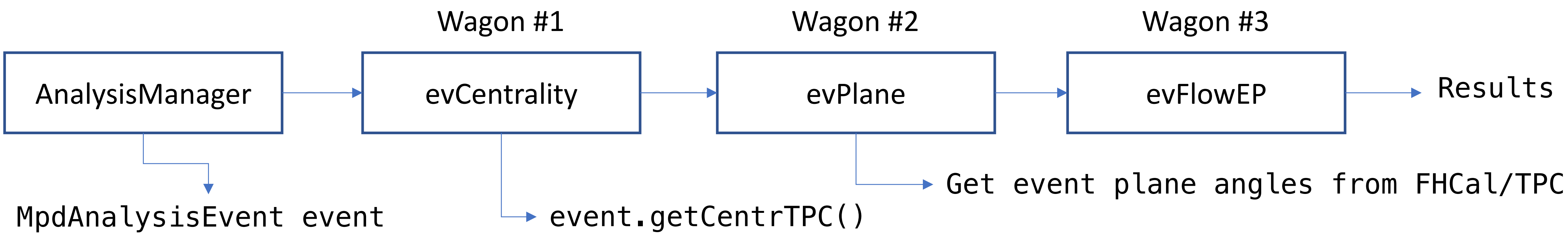
Solution: Analysis Train



- First Analysis Train runs started in September 2023 – regular runs on request
- Continuous development:
    - Improvements to the current analysis wagons (improved PID parameters)
    - Implementation of the new wagons

Analysis Train became a new standard for physics (feasibility) studies in MPD

Flow measurements in MPD-CLD: evFlowEP wagon



Directed flow:

$$v_1 = \frac{<cos(\phi - \Psi_1^{EP})>}{Res(\Psi_1)}$$

Elliptic flow:

$$v_2(\Psi_2) = \frac{<cos[2(\phi - \Psi_2^{EP})]>}{Res(\Psi_2)} \quad v_2(\Psi_1) = \frac{<cos[2(\phi - \Psi_{1,FHCal}^{EP})]>}{Res(\Psi_1)}$$