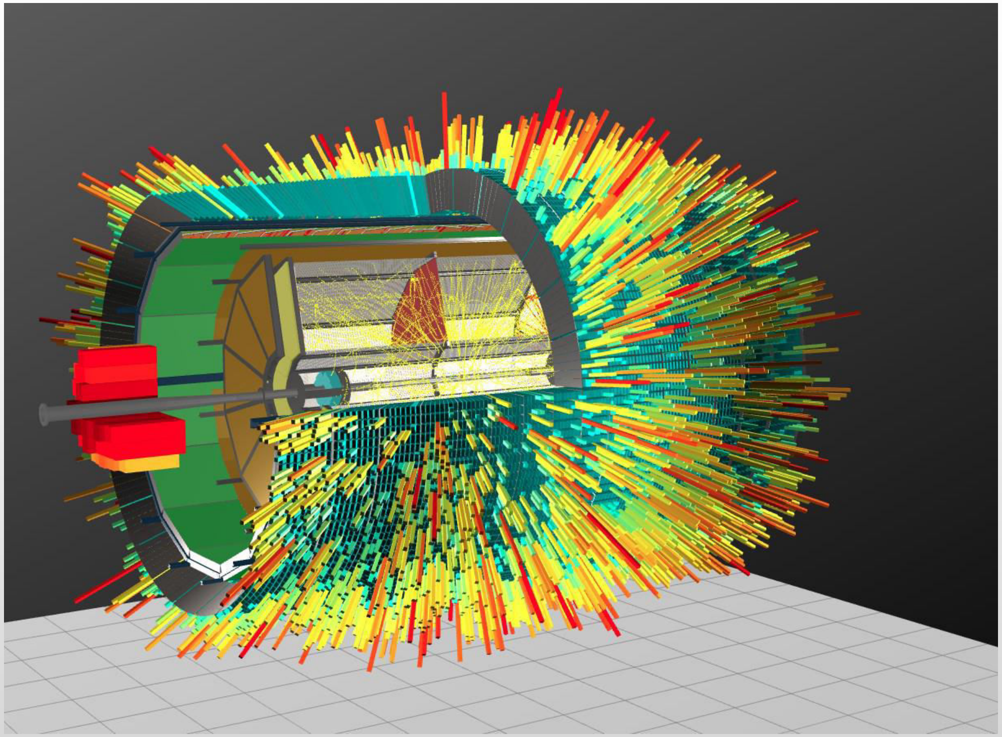
Unique possibilities of the MPD

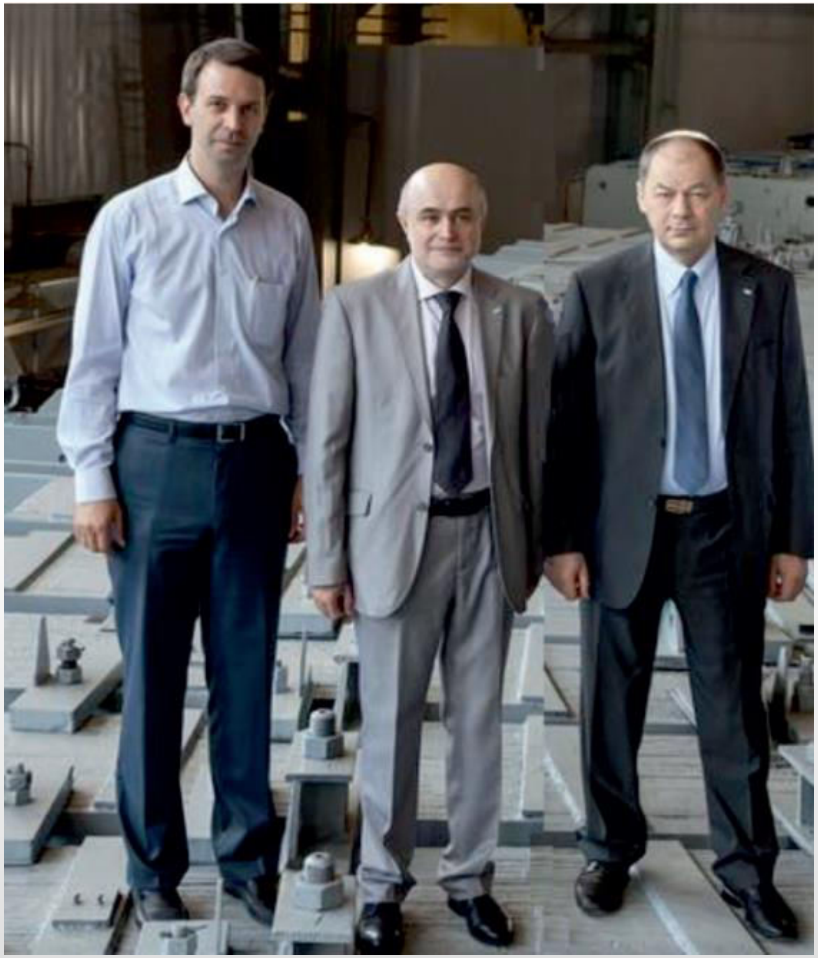
V. Riabov for the MPD Collaboration



Megascience projects in Russia

- A class of unique scientific installations in the Russian national project "Science": large-scale and very expensive international research complexes that are technologically ahead of all existing analogues in the world --> the main idea is the acquisition of new fundamental knowledge, the applied use is desirable, but secondary:
  - ✓ NICA in Dubna – study of heavy ion collisions in the region of maximum baryon densities
  - ✓ PIK reactor in Gatchina - a powerful source of neutrons
  - ✓ Tokamak in Troitsk
  - ✓ Fourth-generation synchrotron radiation source in Protvino
  - ✓ Center for research of extreme light fields in Nizhny Novgorod
  - ✓ Accelerator complex with colliding electron-positron beams in Novosibirsk
  - ✓ Ring photon source in Siberian
  - ✓ Synchrotron on Russky Island

Beginning of NICA

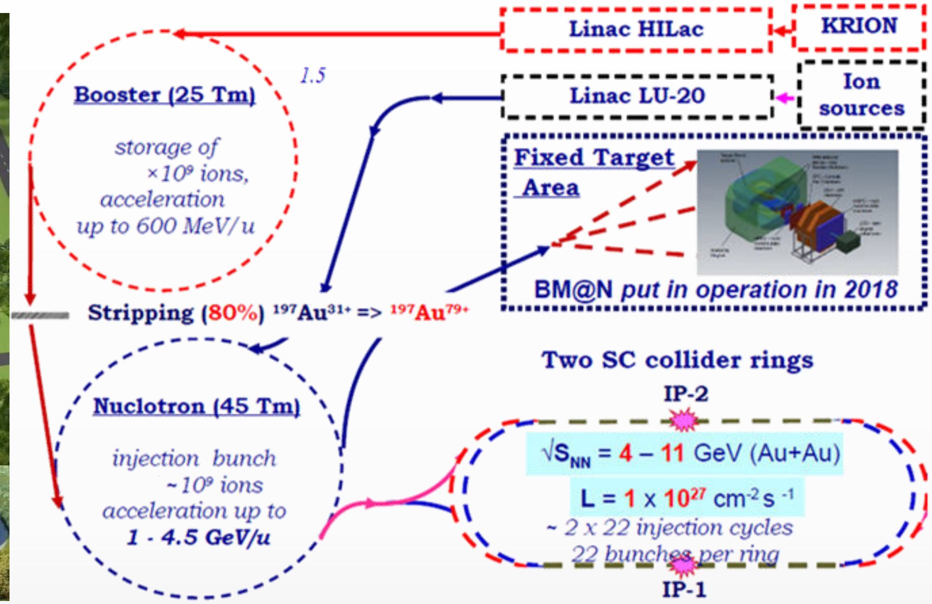


NICA project leaders

- Laboratory of High Energy Physics was established in 2008 by initiative of A. N. Sisakyan to implement the NICA project under the leadership of V. D. Kekelidze, G. V. Trubnikov and A. S. Sorin. Much attention was paid to this project by the director JINR V. A. Matveev

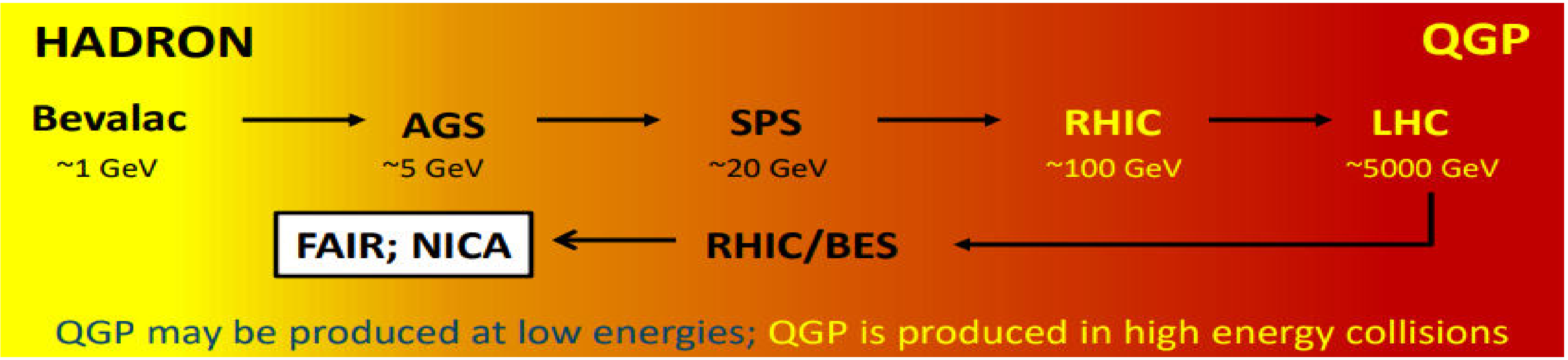
- The session of the Committee of Plenipotentiary Representatives held in Astana identified this project as the flagship in the seven-year development plan of the Institute for 2010–2016. Successful implementation the project continued in the next seven years - in 2017–2023

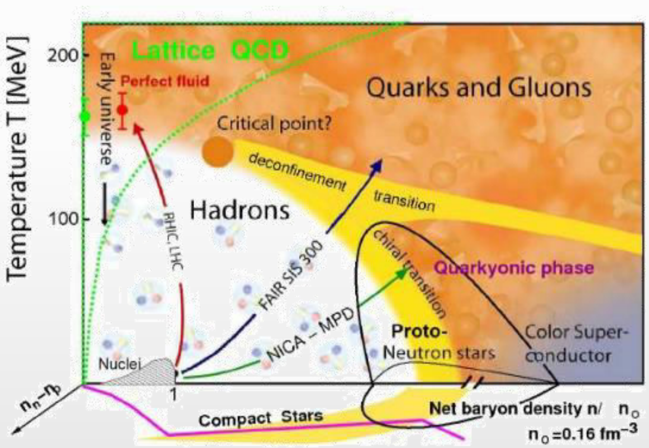
NICA Project



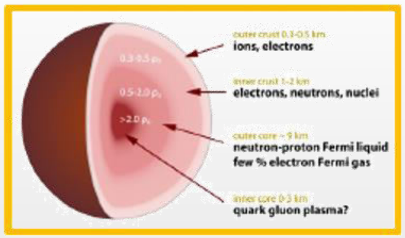
- ❖ The first megascience project in Russia in 30+ years, which is approaching its full commissioning:
  - ✓ already running in the fixed-target mode – BM@N
  - ✓ start of operation in collider mode in 2023-2024 – MPD and later SPD
- ❖ Lots of infrastructure built from scratch (ion source, booster, collider and transfer lines, cryogenics, electricity, etc.) → huge effort and dedication by JINR management and the team involved in different/difficult economical and political times
- ❖ The project is approaching the most interesting times with first data taking with beams in the collider

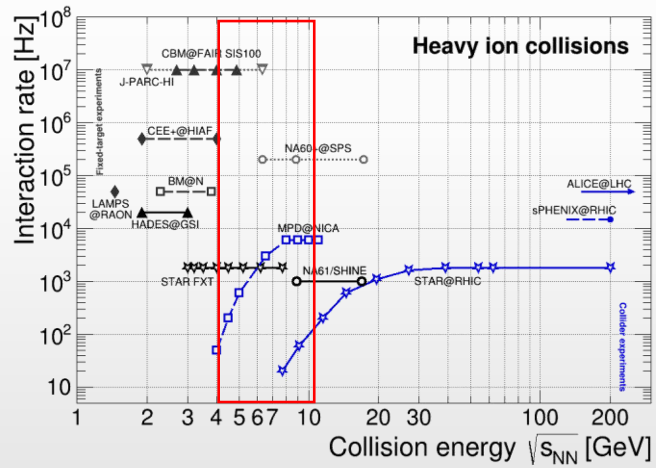
Relativistic heavy-ion collisions





high baryon densities
→ inner structure of
compact stars





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

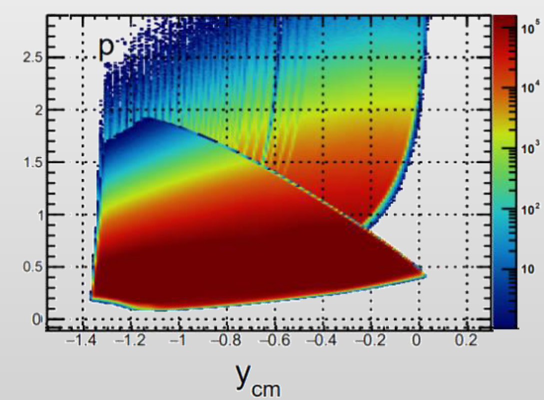
RHIC BES program

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

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

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

Au+Au @ 3.9 GeV



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 → simplified extraction of physical signals

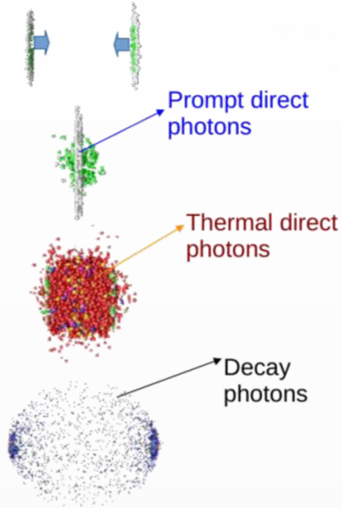
- Continuously develop physical program based on the recent advancements in the field:
  - ✓ identified particle spectra and ratios, collective flow and femtoscopy, production of strangeness and hypernuclei net-proton fluctuations, global polarization of hyperond and spin alignment of vector mesons, dilepton continuum and LVMs, etc.

- Work in close cooperation with theoreticians to look for new signals/observables including those unique for the MPD

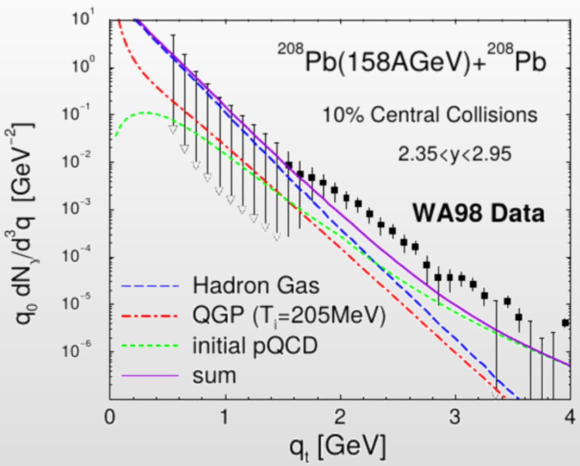
Physical programs of the MPD ($\sqrt{s_{NN}}$ = 4-11 GeV) and BM@N ($\sqrt{s_{NN}}$ = 2.3-3.5 GeV) are bound and should be realized in close cooperation

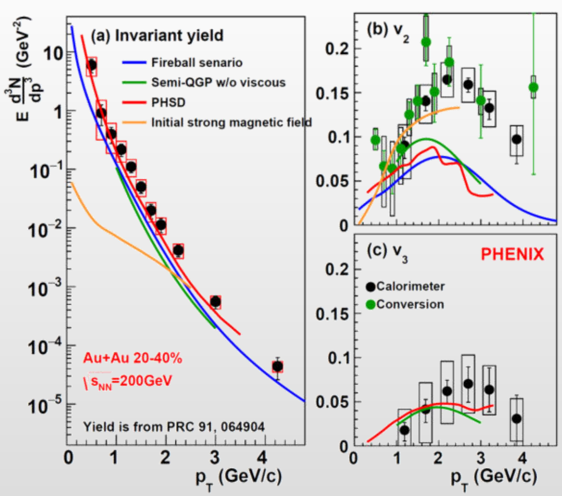
Direct photons

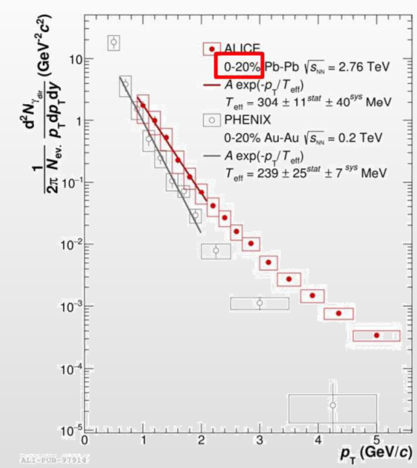
- Direct photons – photons not from hadronic decays.
- Produced throughout the system evolution (thermal + prompt) :
  - ✓ penetrating probe
  - ✓ low-E - most direct estimation of the effective system temperature
  - ✓ high-E - hard scattering probe
- Direct photons in A-A collisions:
  - ✓ LHC, PbPb @ 2.76 and 5 TeV
  - ✓ RHIC, Au-Au(CuCu) @ 62-200 GeV
  - ✓ SPS, PbPb @ 17.2 GeV
- No measurements at NICA energies: yields and flow vs. p_T and centrality



Phys.Rev. C94 (2016) no.6, 064901







Simultaneous description of the large photon yields and flow is a challenge for theoretical models at RHIC and the LHC → "direct photon puzzle"

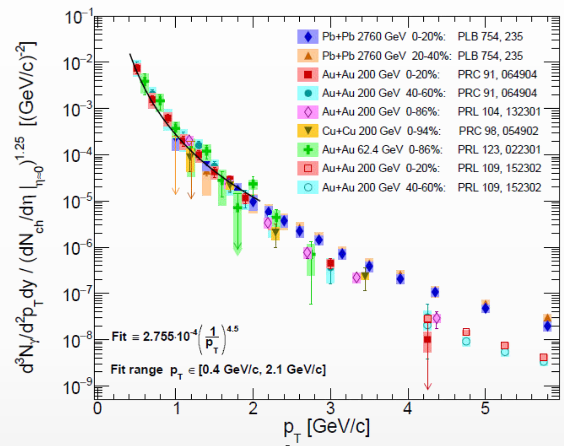
Direct photon yields at NICA

Estimation of the direct photon yields @NICA

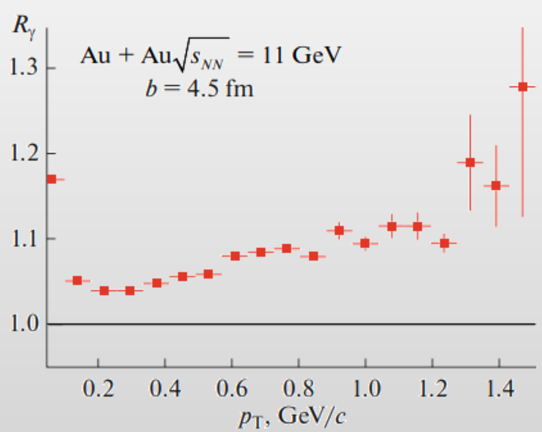
model calculations

empirical scaling

- ✓ UrQMD v3.4 with hybrid model (3+1D hydro, bag model EoS, hadronic rescattering and resonances within UrQMD)
- ✓ each cell have Ti, Ei, μbi:
  - T is high – QGP phase (Peter Arnold, Guy D. Moore, Laurence G. Yaffe, JHEP 0112:009 2001)
  - T is low – HG phase (Simon Turbide, Ralf Rapp, Charles Gale, Phys.Rev.C69:014903,2004)
  - T is intermediate – mixed phase
- ✓ integrate over all cells and all time steps
- ✓ calculations reproduce hydro calculations for the SPS

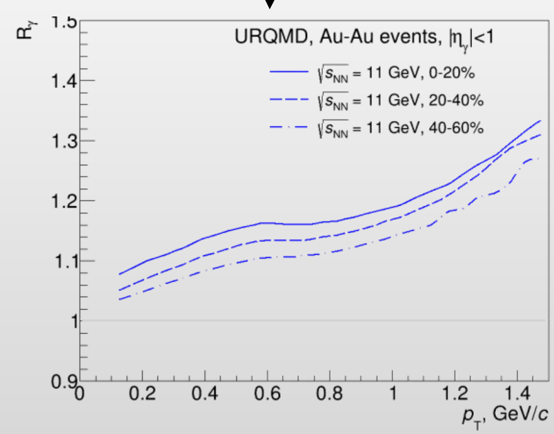


Physics of Particles and Nuclei, 2021, Vol. 52, No. 4, pp. 681–685



$$R_\gamma = \frac{\gamma_{\rm inc}}{\gamma_{\rm decay}} = \frac{\gamma_{\rm inc}/\pi^0}{\gamma_{\rm decay}/\pi^0_{\rm param}}$$

$$\gamma_{\rm direct} = \left(1 - \frac{1}{R_\gamma}\right) \cdot \gamma_{\rm inc}$$

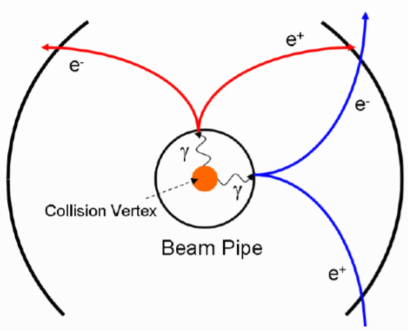


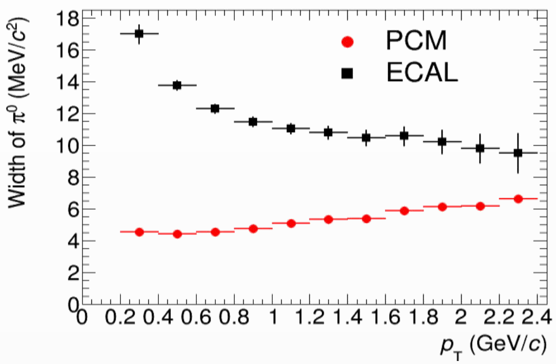
❖ Non-zero direct photon yields are predicted with Rγ ~ 1.05 – 1.15 and v2 ~ 0.5% at top NICA energy

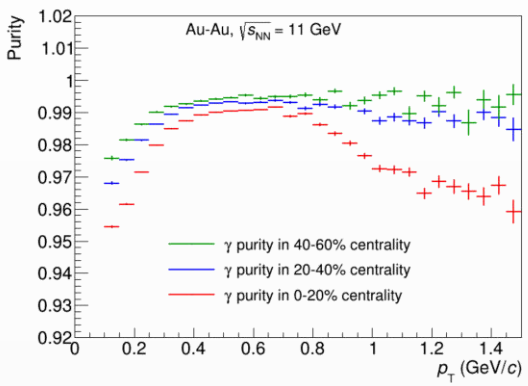
Prospects for the MPD

- Photons can be measured in the ECAL or in the tracking system as e^+e^- conversion pairs (PCM)

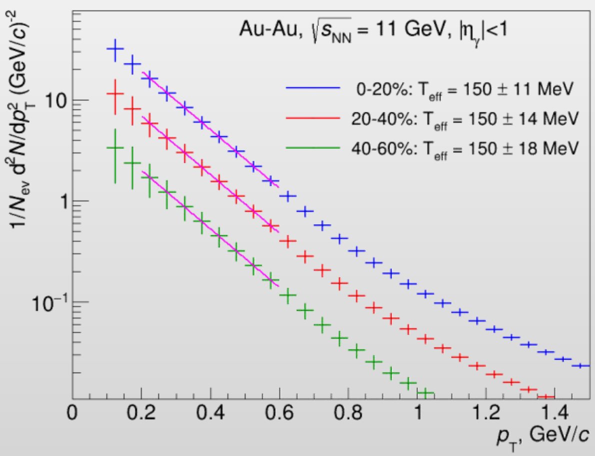
beam pipe (0.3% X_0) + inner TPC vessels (2.4% X_0)







- Main sources of systematic uncertainties for direct photons:
  - ✓ detector material budget → conversion probability
  - ✓ π^0 reconstruction efficiency
  - ✓ p_T-shapes of π^0 and η production spectra



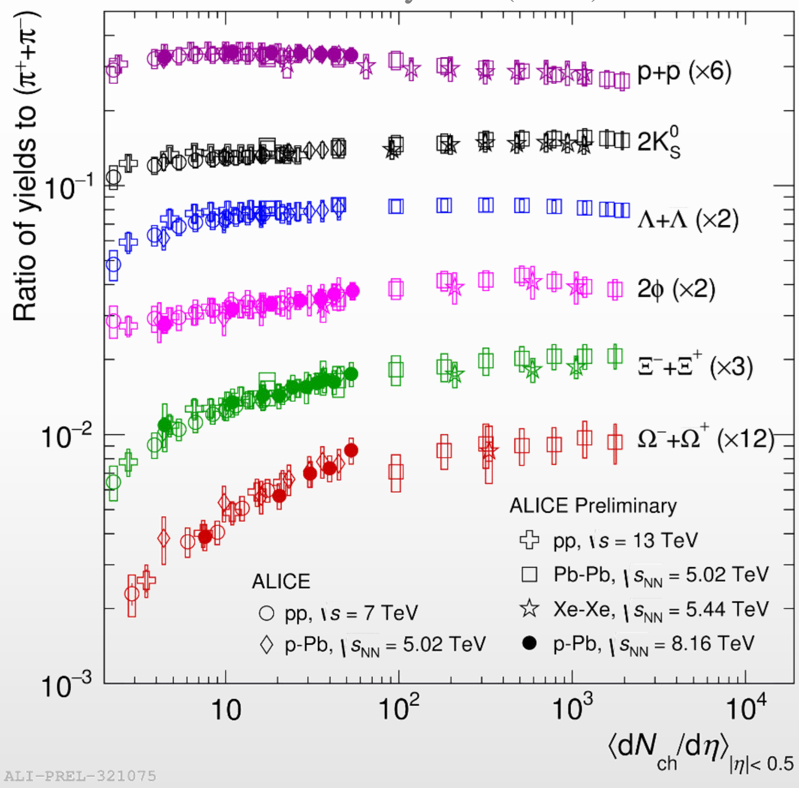
- ✓ ECAL and PCM for photon reconstruction and measurement of neutral mesons (background)
- ✓ With $R\gamma$ ~ 1.1 and $\delta R\gamma/R\gamma$ ~ 3% → uncertainty of T_{eff} ~ 10%
- ✓ Development of reconstruction techniques and estimation of needed statistics are in progress

→ potentially, MPD can provide <u>unique measurements</u> for direct photon production in the NICA energy range

Strangeness production: pp, p-A, A-A

- Since the mid 80s, strangeness enhancement is considered as a signature of the QGP formation
- Experimentally observed in heavy-ion collisions at AGS, SPS, RHIC and LHC energies

Nature Phys. 13 (2017) 535



|S| = 0

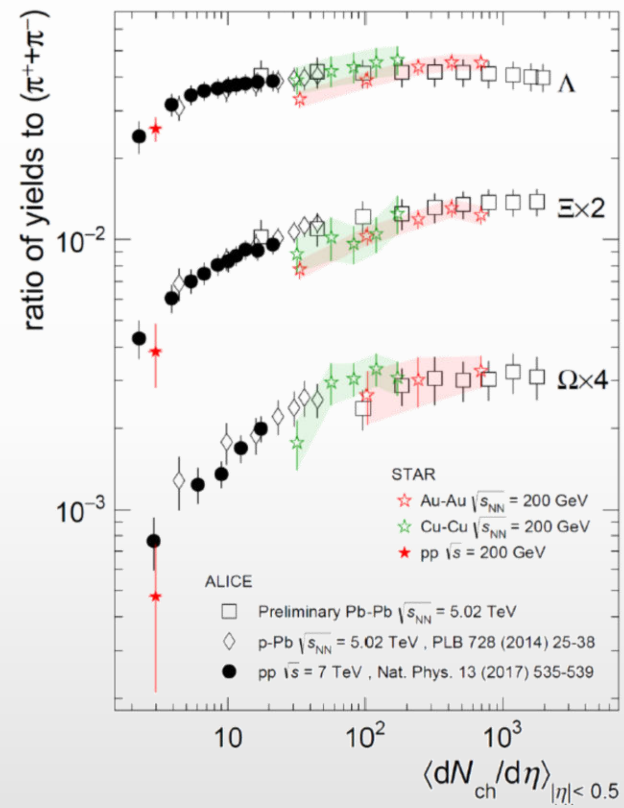
|S| = 1

|S| = 1

|S| = 0 (hidden)

|S| = 2

|S| = 3

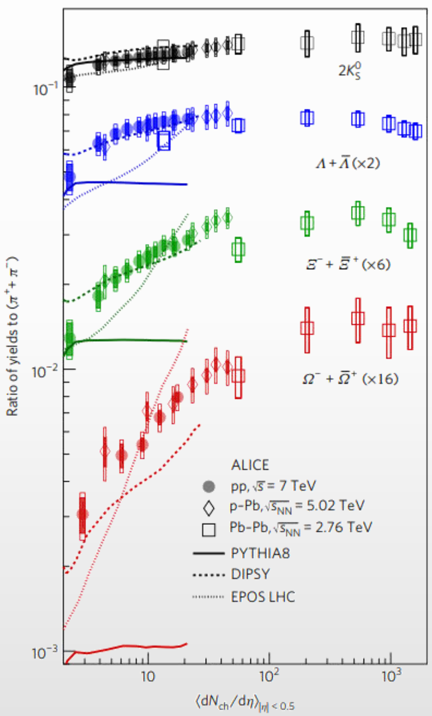


- Smooth evolution vs. multiplicity in pp, p-A and A-A collisions at LHC energies
- Strangeness enhancement increases with strangeness content and particle multiplicity
- STAR @ RHIC measurements in pp, A-A are in agreement with ALICE @ LHC at similar $<dN_{ch}/d\eta>$

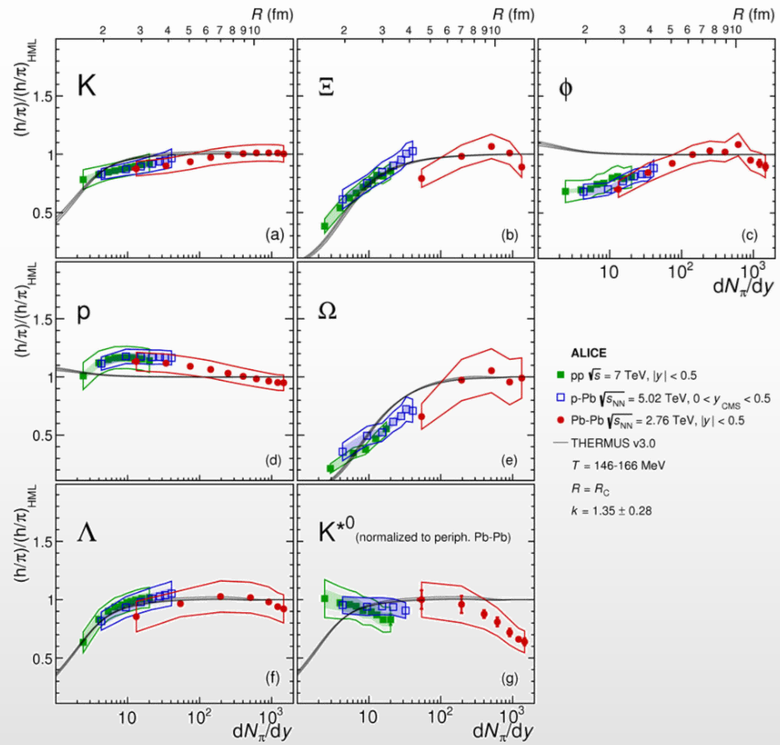
Origin of enhancement

- Origin of the strangeness enhancement in small/large systems is still under debate:
  - ✓ 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)

Nature Physics volume 13, pages535–539 (2017)



V. Vislavicius, A. Kalweit, arXiv:1610.03001

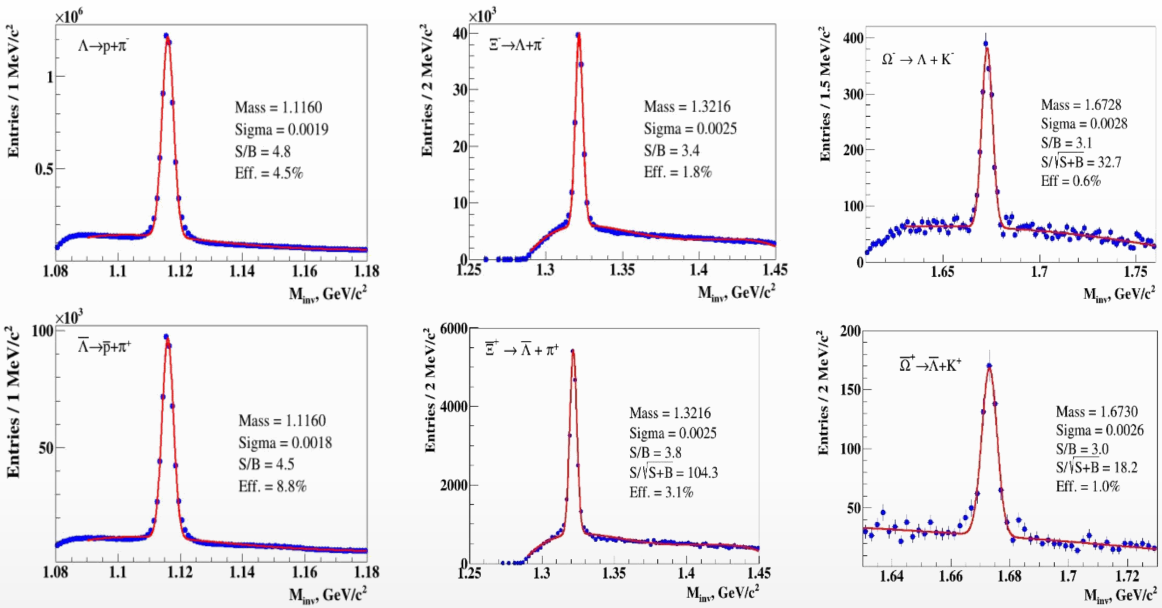


- System size scan for (multi)strange baryon and meson production is a key to understanding of strangeness production → <u>unique capability of the MPD</u> in the NICA energy range

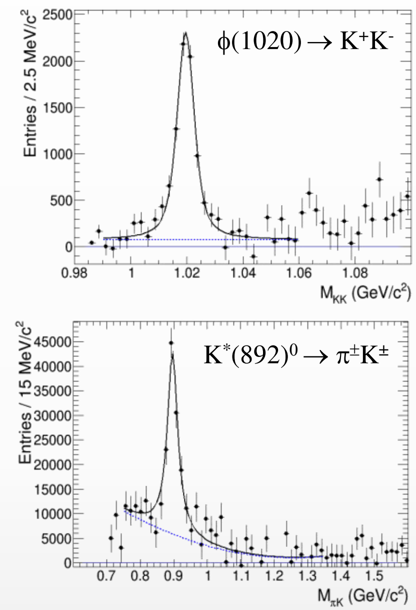
MPD performance

AuAu@11 GeV (PHSD), 10 M events

BiBi@9.2 GeV (UrQMD), 10 M events



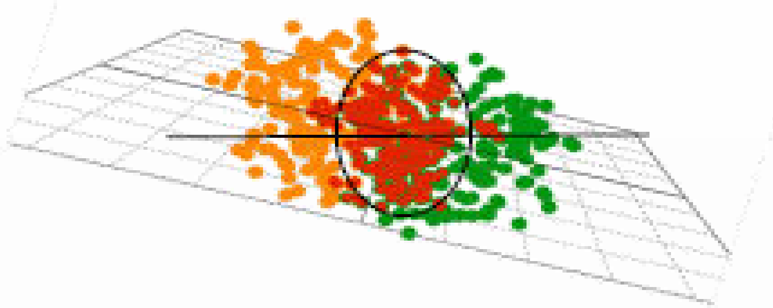
Acta Physica Polonica B 14 (2021) 3, 529-532

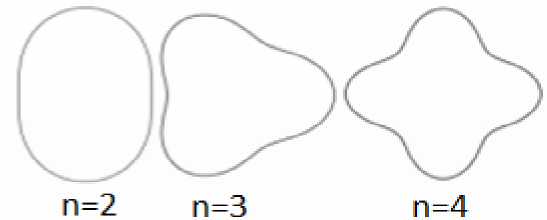


Phys.Scripta 96 (2021) 6, 064002

MPD has capabilities to measure production of charged π/K/p, (multi)strange baryons and resonances in pp, p-A and A-A collisions using charged hadron identification in the TPC&TOF and different decay topology selections

Anisotropic flow at RHIC/LHC



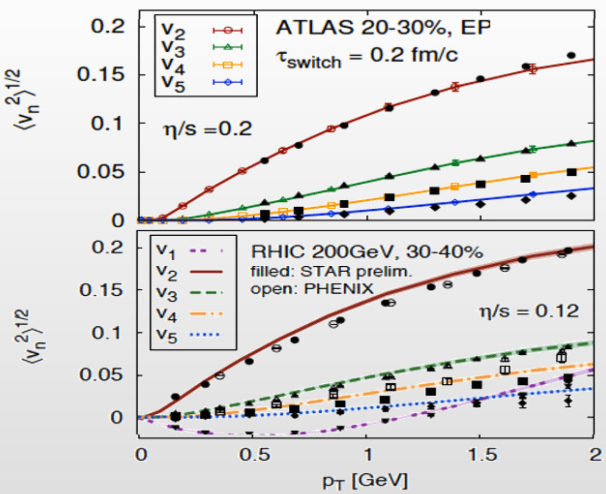


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

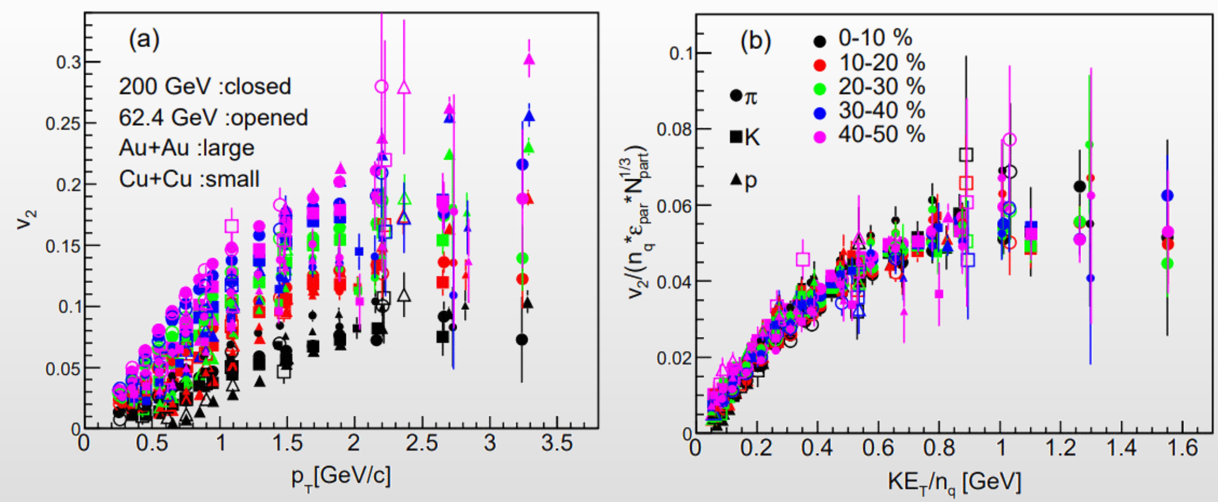
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

❖ Initial eccentricity and its fluctuations drive momentum anisotropy v_n with specific viscous modulation

Gale, Jeon et al., Phys. Rev. Lett. 110, 012302



Phys.Rev.C 92 (2015) 3, 034913

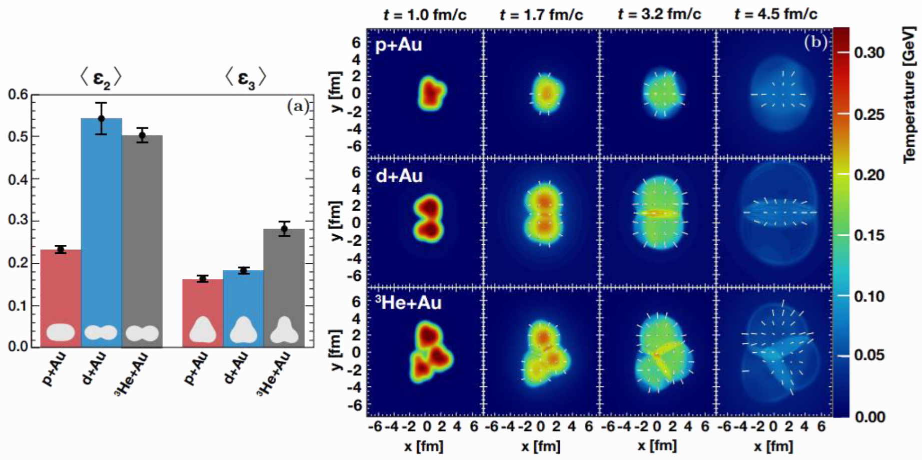


❖ Evidence for a dense perfect liquid found at RHIC/LHC (M. Roirdan et al., Scientific American, 2006)

❖ System size scan (A-A) is an important part of systematic study (initial geometry → flow harmonics)

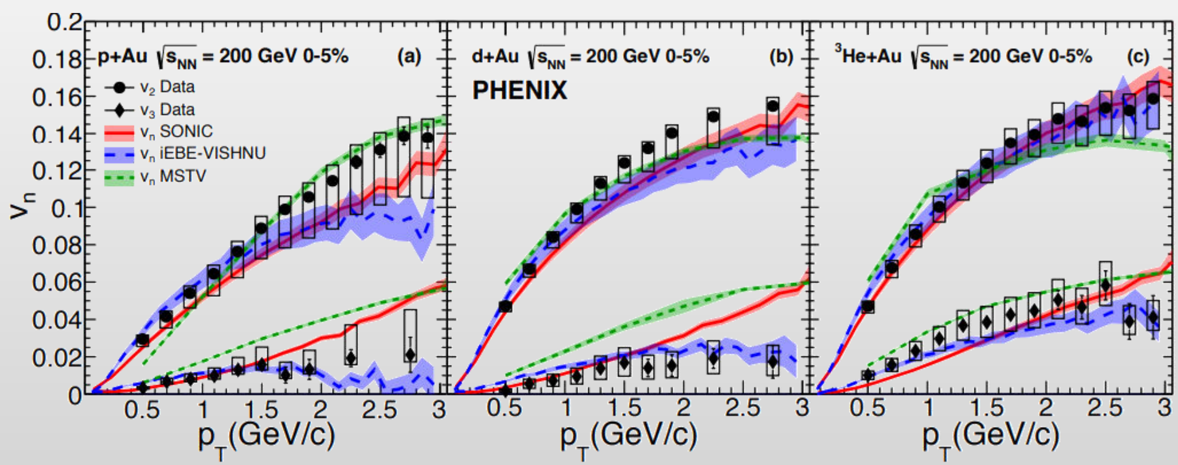
Small system scan at RHIC

Nature Phys. 15 (2019) 3, 214-220

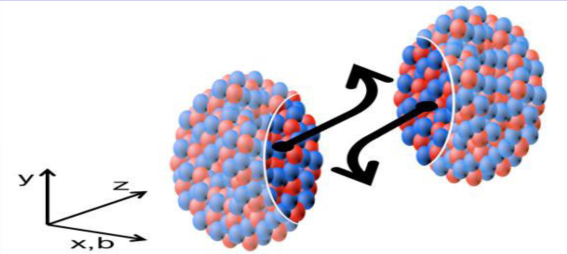


p-Au, d-Au and ^{3}He-Au @ 200 GeV by PHENIX

- Measurements demonstrate that the v_n's are correlated to the initial geometry
- Hydrodynamical models, which include the formation of a short-lived QGP droplet, provide a simultaneous description of these measurements

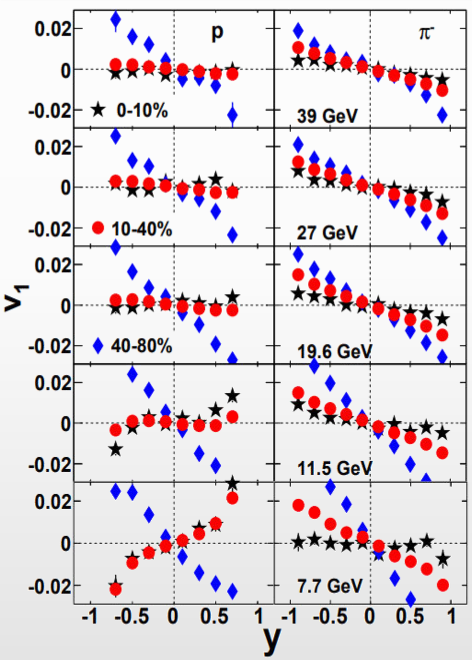


Beam energy dependence



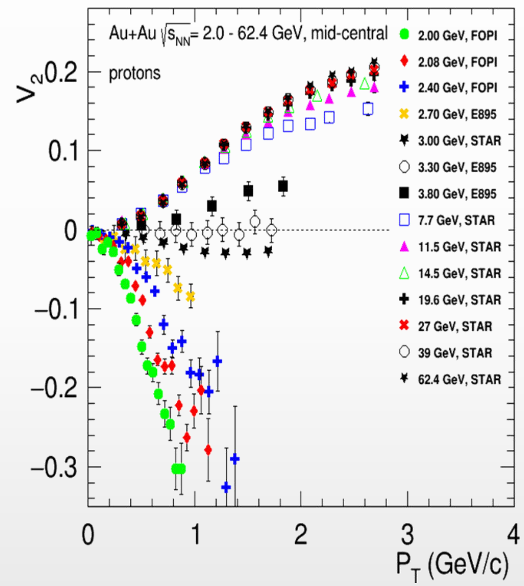
- Generated during the nuclear passage time (2R/γ) – sensitive to EOS
- RHIC @ 200 GeV (2R/γ) ~ 0.1 fm/c
- AGS @ 3-4.5 GeV (2R/γ) ~ 9-5 fm/c
- v_1 and v_2 show strong centrality, energy and species dependence

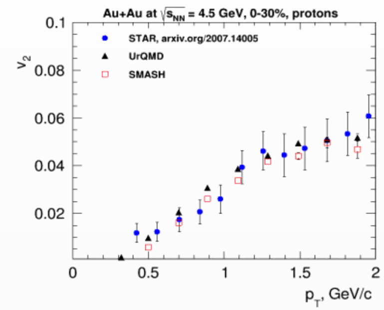
Phys.Rev.Lett. 112 (2014) 16, 162301

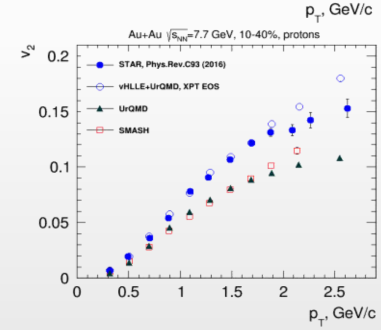


✓ models do not reproduce measurements

EPJ Web Conf. 204 (2019) 03009







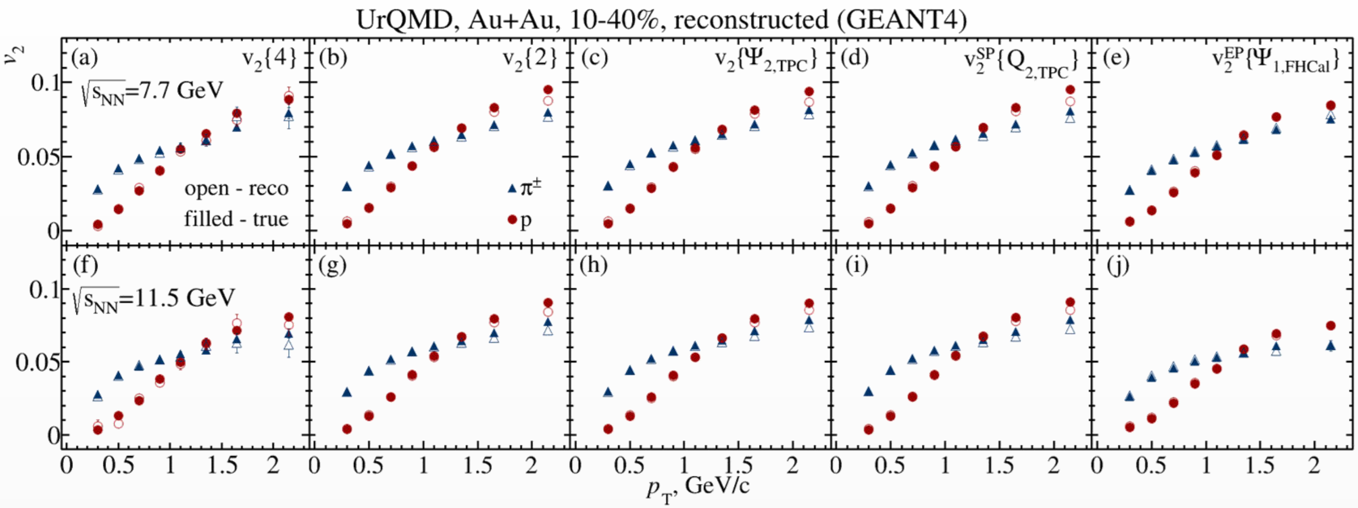
✓ $\sqrt{s_{NN}}$ ~ 3-4.5 GeV, pure hadronic models reproduce v_2 (JAM, UrQMD) → degrees of freedom are the interacting baryons

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

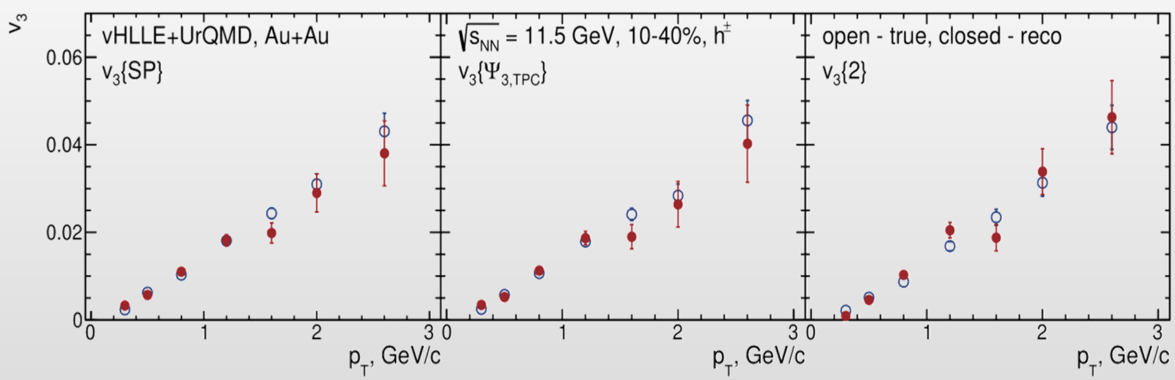
System size scan for flow measurements is vital for understanding of the medium transport properties and onset of the phase transition → unique capability of the MPD in the NICA energy range

MPD performance: v_2 for π/p, v_3 for $h^{\pm}$

AuAu@7.7 GeV (UrQMD), 15 M events → full event/detector simulation and reconstruction



AuAu@11.5 GeV (vHLLE + UrQMD), 15 M events → full event/detector simulation and

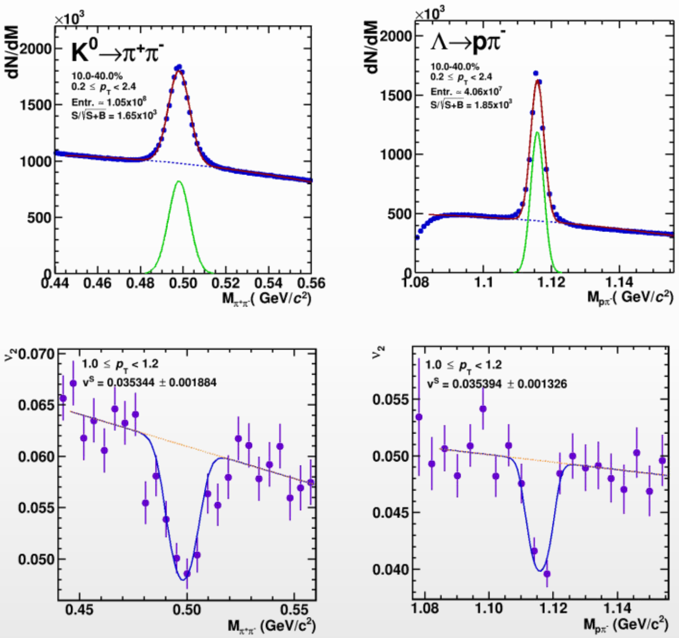


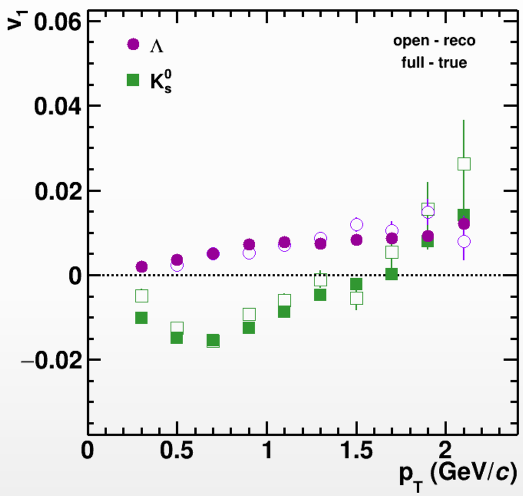
- Reconstructed and generated v_2 of pions and protons and v_3 of charged hadrons are in good agreement
- Models show that higher harmonic ripples are more sensitive to the existence of a QGP phase

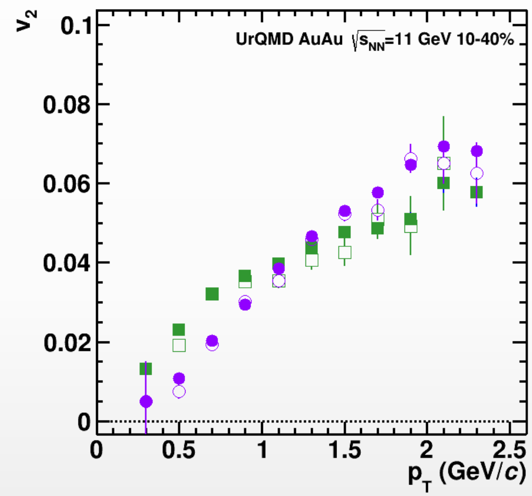
Collective flow for V0 (K^0_s and Λ)

AuAu@11 GeV (UrQMD), 25 M events → full event/detector simulation and reconstruction

$$v_2^{SB}(m_{inv},p_T) = v_2^S(p_T)\frac{N^S(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)} + v_2^B(m_{inv},p_T)\frac{N^B(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)}$$





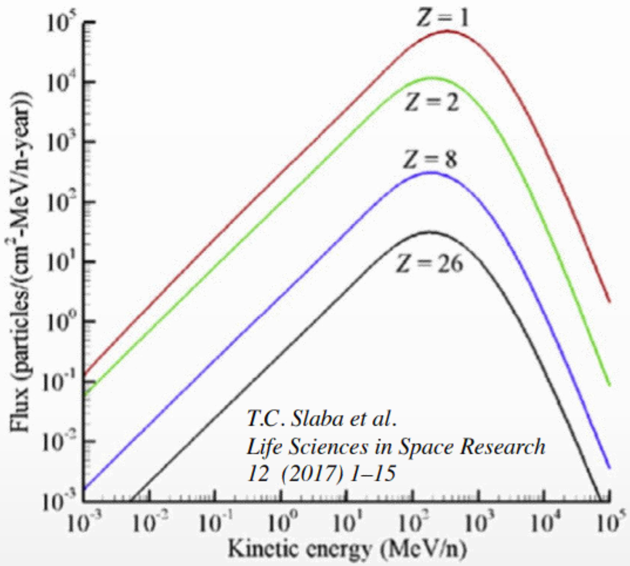


- Differential flow signal extraction using invariant mass fit method
- Reasonable agreement between reconstructed and generated v_n signals for K^0_s and Λ

MPD has capabilities to measure different flow harmonics for a wide variety of identified hadrons in pp, p-A and A-A collisions

High-energy heavy-ion reaction data

- Galactic Cosmic Rays composed of nuclei (protons, … up to Fe) and E/A up to 50 GeV
- These high-energy particles create cascades of hundreds of secondary, etc. particles

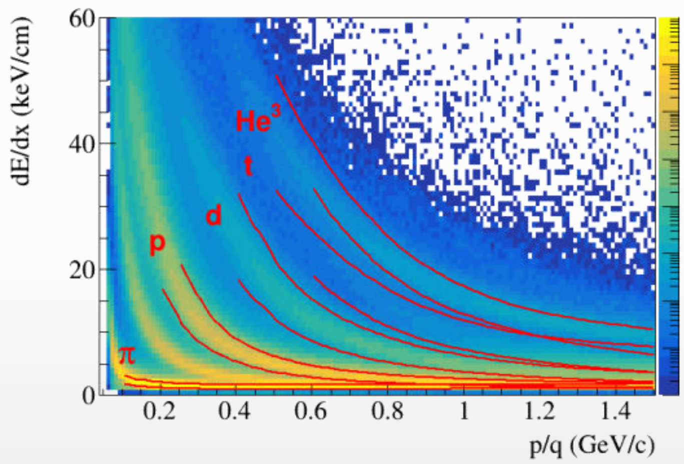


- Cosmic rays are a serious concern to astronauts, electronics, and spacecraft.
- The damage is proportional to Z^2, therefore the component due to ions is important
- Damage from secondary production of p, d, t, ^{3}He, and ^{4}He is also significant
- Need input information for transport codes for shielding applications (Geant-4, Fluka, PHITS, etc.):
  - ✓ total, elastic/reaction cross section
  - ✓ particle multiplicities and coellecense parameters
  - ✓ outgoing particle distributions: $d^2N/dEd\Omega$

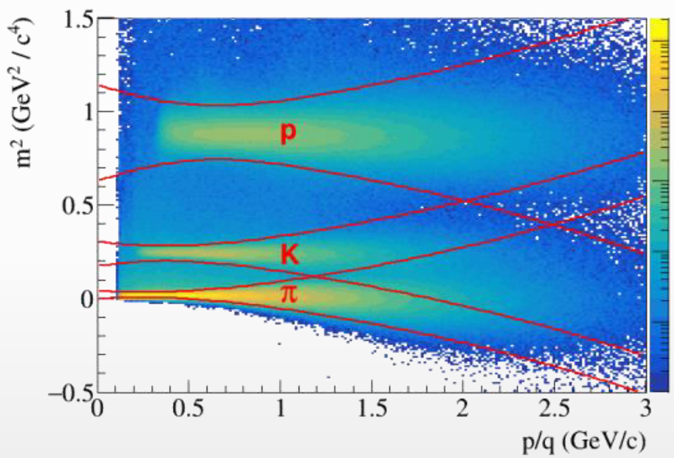
High energy heavy ion reaction data

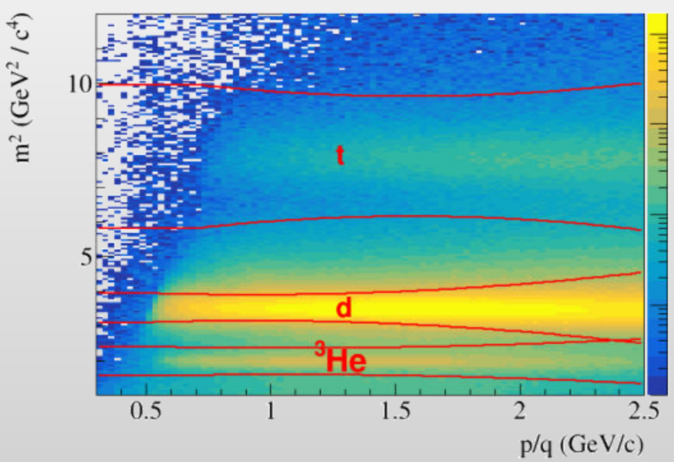
- NICA can deliver different ion beam species and energies:
  - ✓ Targets of interest (C = astronaut, Si = electronics, Al = spacecraft) + He, C, O, Si, Fe, etc.
- No data exist for projectile energies > 3 GeV/n

dE/dx vs momentum in TPC



m2 vs. momentum in TOF





MPD has excellent light fragment identification capabilities in a wide rapidity range → <u>unique capability of the MPD</u> in the NICA energy range

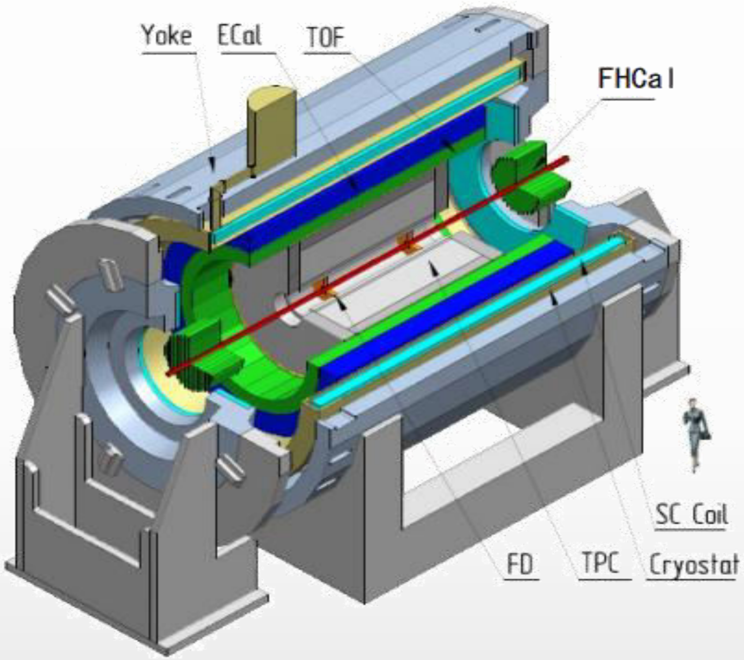
Multi-Purpose Detector (MPD) Collaboration

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**;*
*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***

NICA

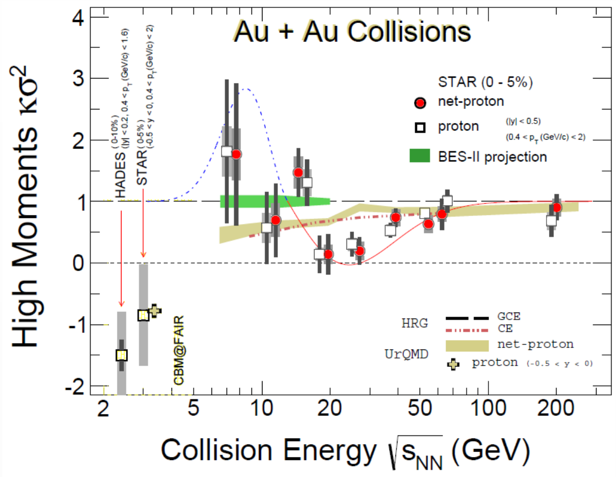
Summary

- ❖ NICA is the first megascience project in Russia in 30+ years, which is approaching its commissioning
- ❖ NICA will provide unique results on the structure of the QCD phase diagram, provide insight into inner structure of compact start and neutron star mergers

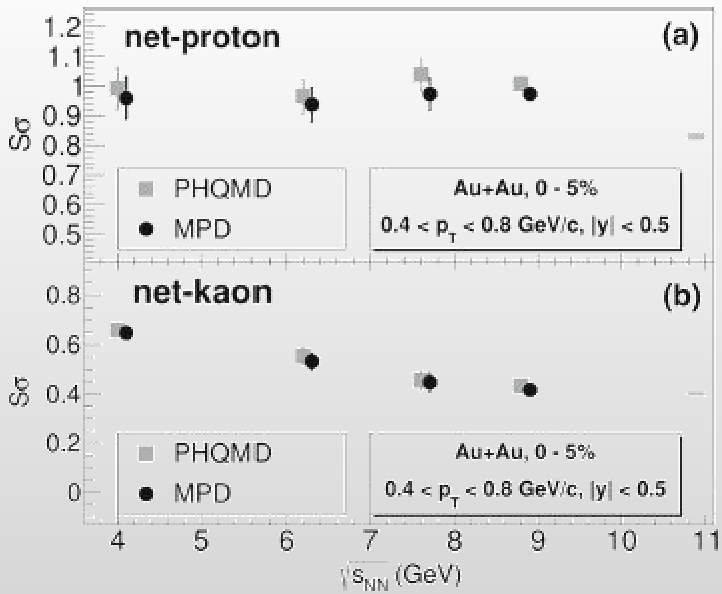
Happy birthday and many years to come !!!

Critical fluctuations

- Ratio of the 4th-to2nd moment of the (net)proton multiplicity distribution:
  - ✓ non-monotonic behavior → deviation from non-critical dynamic baseline close to CEP ???
  - ✓ need significant improvement of statistical precision and systematic uncertainties + extra points in the NICA energy range



AuAu@11 (UrQMD), 5-50·10^4 events→ full event/detector simulation and reconstruction

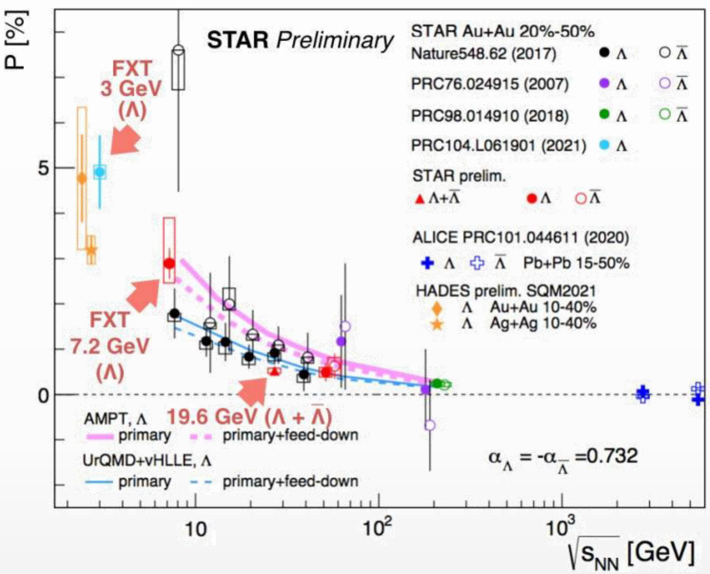


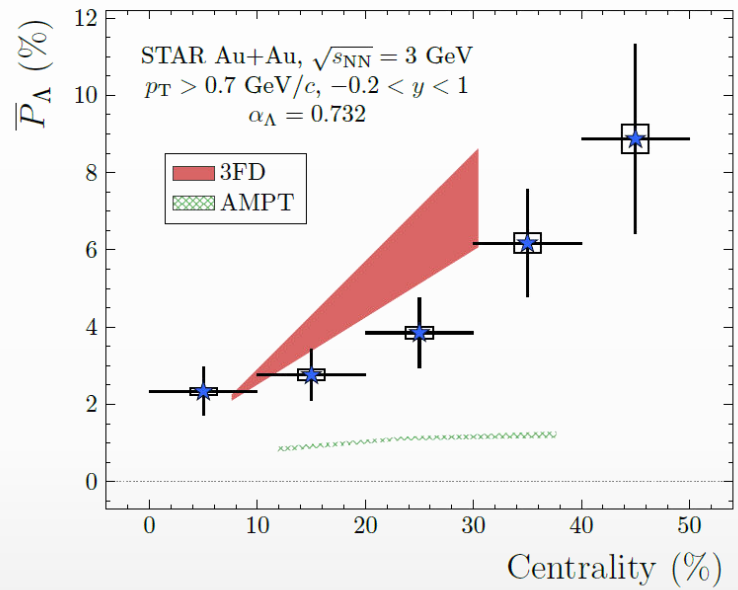
Effective skewness Sσ for net-protons (a) and net-kaons (b) in Au+Au interactions at several collision energies are reproduced

Global hyperon polarization

- Global hyperon polarization measurements in mid-central A+A collisions at $\sqrt{s_{NN}}$= 3-5000 GeV

STAR, Phys.Rev.C, 104(6):L061901, 2021



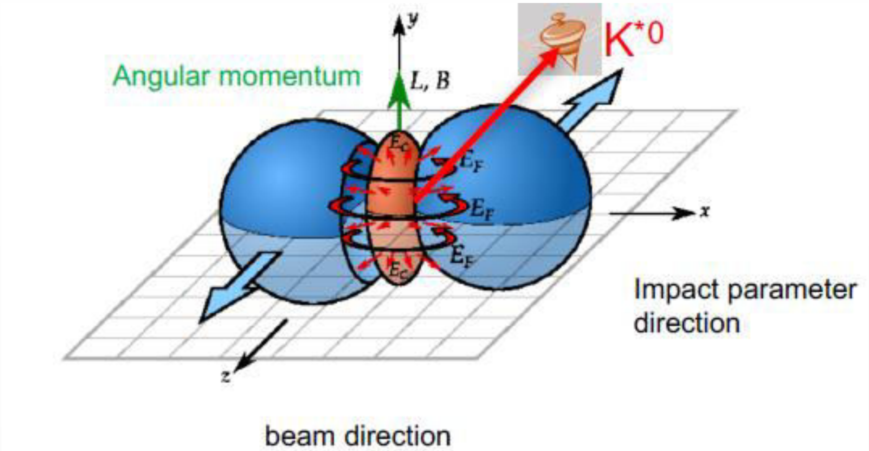


- Global polarization of hyperons experimentally observed, decreases with $\sqrt{s_{NN}}$
- Hint for a Λ-$\bar{\Lambda}$ difference, magnetic field, $P_{\Lambda} \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_{\Lambda} B}{T}, \quad P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_{\Lambda} B}{T}$?
- Feed down from Σ(1385) → Λπ, Σ^0 →Λγ; Ξ→Λπ reduces polarization by ~ 10-20%
- Energy dependence of global polarization is reproduced by AMPT, 3FD, UrQMD+vHLLE
- AMPT with partonic transport strongly underestimates measurements at $\sqrt{s_{NN}}$ = 3 GeV → hadron gas?

MPD: extra points in the energy range 3-10 10 GeV with small uncertainties; centrality, p_T and rapidity dependence of polarization not only for Λ, but other (anti)hyperons (Λ, Σ, Ξ)

Polarization of vector mesons: $K^{*}(892)$ and ϕ

Non-central heavy-ion collisions:

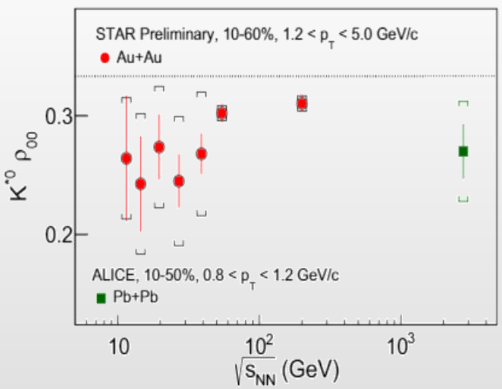


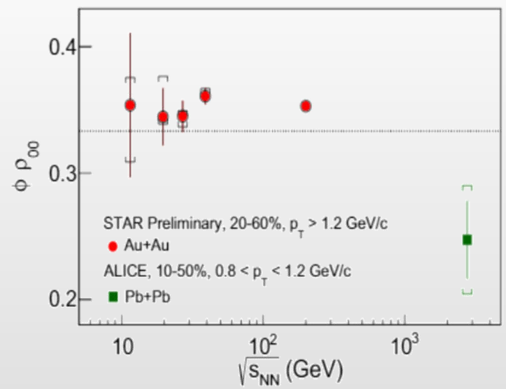
- Light quarks can be polarized by $|\bar{J}|$and $|\bar{B}|$
- If vector mesons are produced via recombination their spin may align
- Quantization axis:
  - ✓ normal to the production plane (momentum of the vector meson and the beam axis)
  - ✓ normal to the event plane (impact parameter and beam axis)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

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

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

NPA 1005 (2021) 121733





- 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)

BACKUP

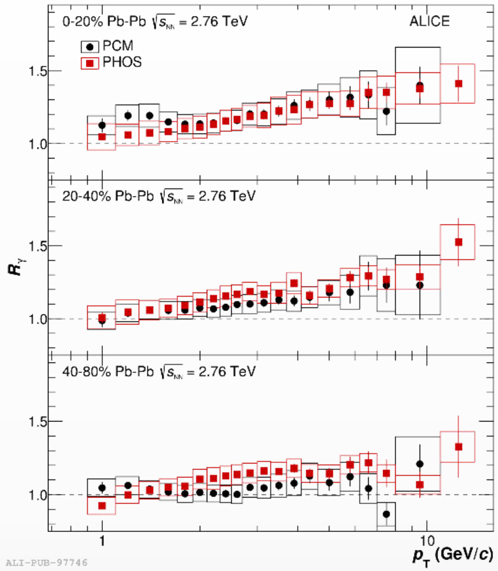
Positioning of the MPD

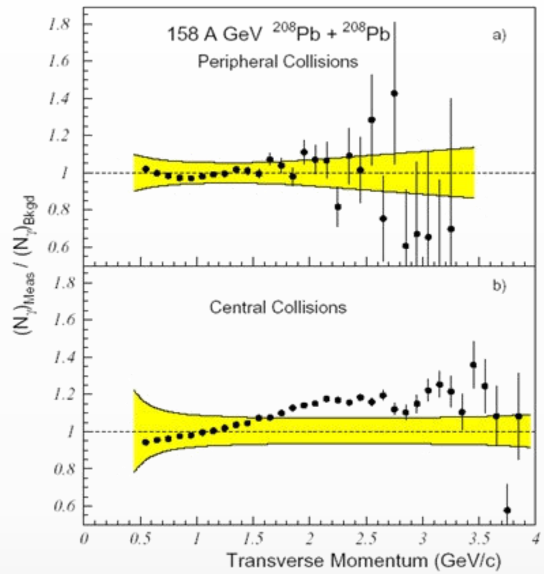
❖ Many experiments to study a similar physics case in the same decade

	NA61/SHINE at SPS	CBM at FAIR	STAR BES+FXT at RHIC	MPD + BM@N 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 concluded 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 datataking (heavy-ion) in 2021	flagship experiments several months/year

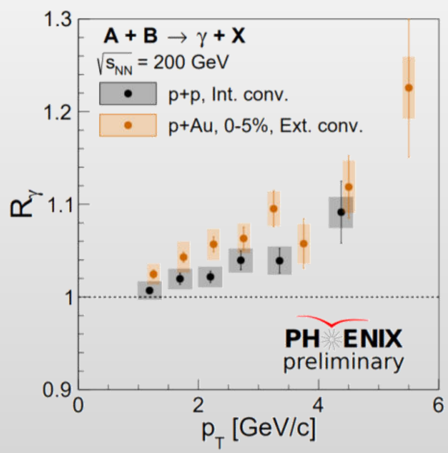
Comparison to higher energies

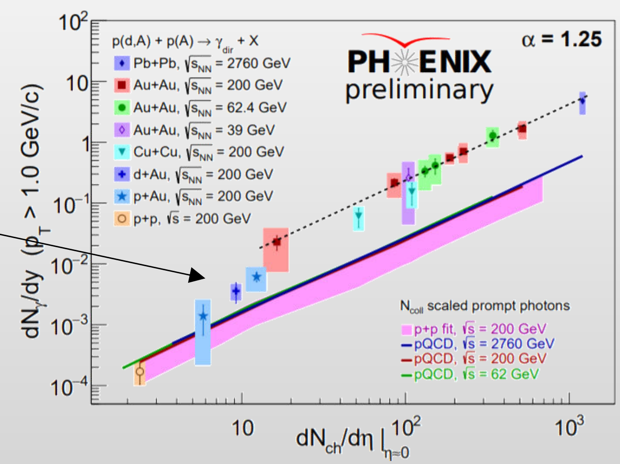
- Rγ ~ 1.05-1.2 in heavy-ion collisions at SPS/RHIC/LHC, $\sqrt{s_{NN}}$ = 17.2-2760 GeV





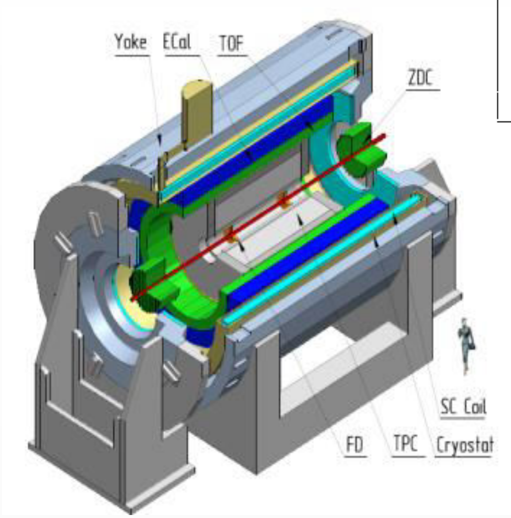
- Rγ ~ 1.05 is on the verge of experimental measurability (PHENIX in pp/pA@200, ≥ 2σ)





Multi-Purpose Detector

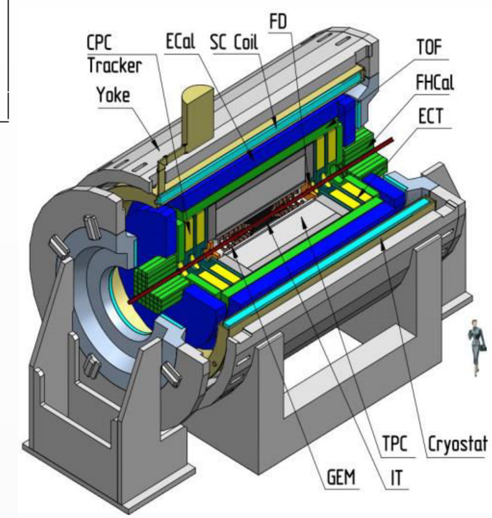
Stage- I



Length	340 cm
Vessel outer radius	140 cm
Vessel inner radius	27 cm
Default magnetic field	0.5 T
Drift gas mixture	90% Ar+10% CH_4
Maximum event rate	7 kHz ($L = 10^{27}$ cm^{-2}s^{-1})

upgrade

Stage- II



TPC: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.6$

TOF, EMC: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.4$

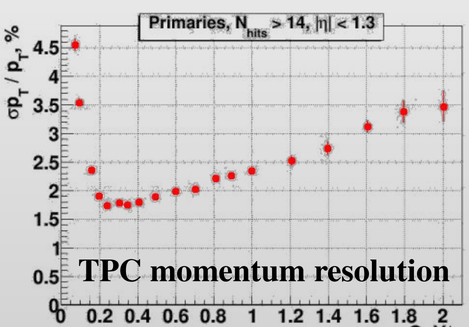
FFD: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$

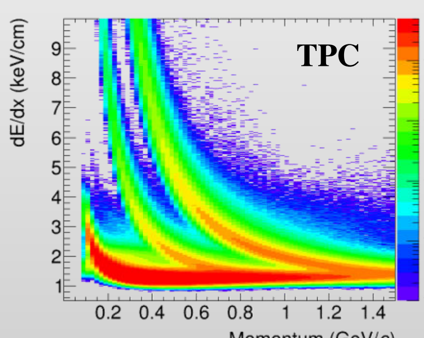
FHCAL: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

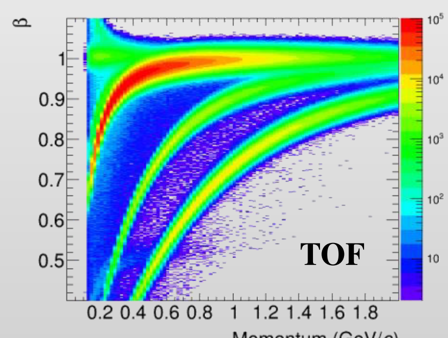
+ ITS (heavy-flavor measurements)

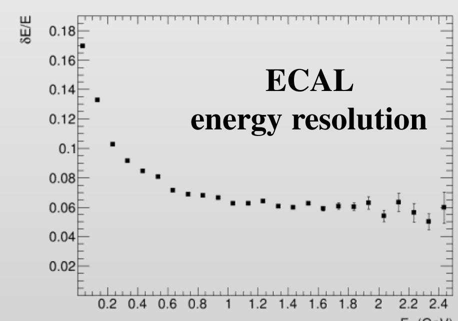
+ forward spectrometers

Au+Au @ 11 GeV (UrQMD + full chain reconstruction)





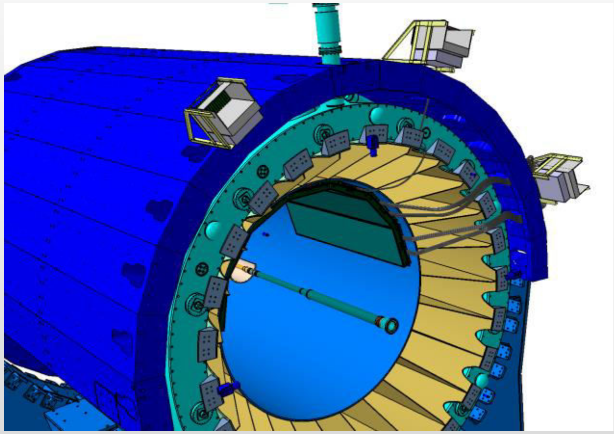




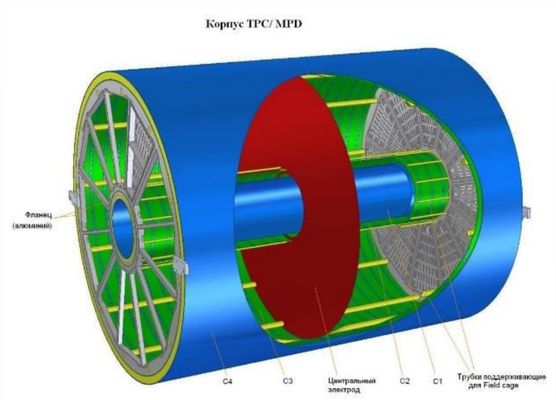
Support Frame for detectors inside of the Solenoid

The structure of Support Frame is made of carbon fiber which allows for deformation less than 3 mm under load with detectors (~80 T).
Producer - The Central Research Institute for Special Machinery, Khotkovo, Moscow region is a leading Russian enterprise in design and production of structures on the basis of advanced polymer composite materials for rocket & space engineering, transport, power, petrochemical machinery and other industries.

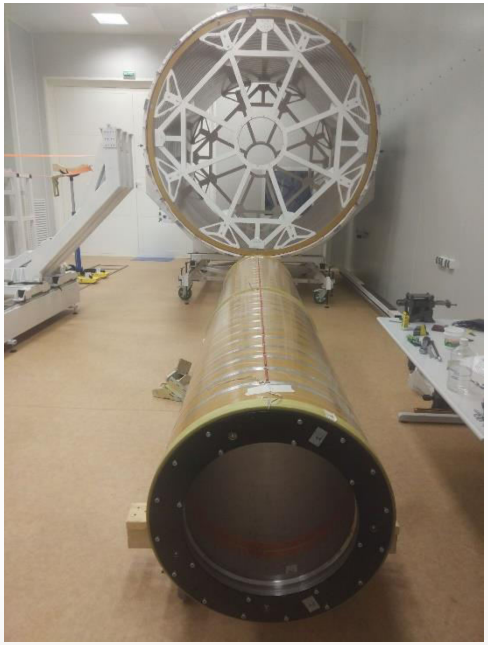
- the Frame will be transported to Dubna in November 2021
- December 2021 (as soon as Magnetic field measurements is finished)
- Representatives of the Company will participate in the process of installation of Support Frame into MPD and its alignment

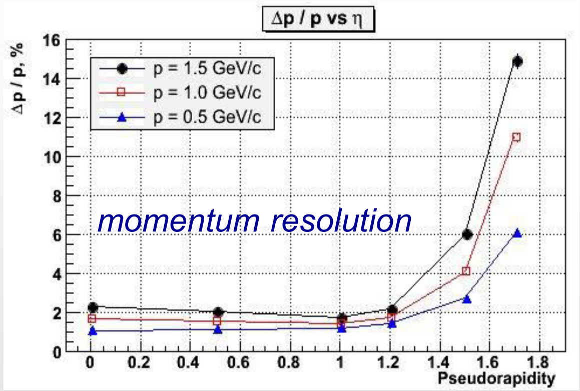


Time Projection Chamber (TPC): main tracker

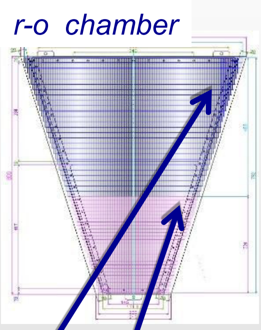


length	*340 см*
outer Radii	*140 см*
inner Radii	*27 см*
gas	*90%Ar+10%CH_4*
drift velocity	*5.45 см / μs;*
drift time	*< 30 μs;*
# R-O chamb.	*12 + 12*
# pads/ chan.	***95 232***
max rate	*< 7kGz (L= 10^{27})*





TPC/MPD Front-end card



Read-Out Chambers (ROCs) are ready and tested (production at JINR)
113 Electronics sets (8%) produced
Two sites (Moscow, Minsk) tested for electronics production
C1-C2 and C3-C4 cylinders assembled
TPC flange under finalization

FE electronics: **FEC64SAM** –
*dual **SAMPA** card (**ALICE** technology)*

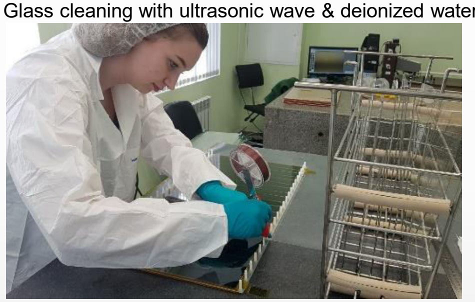
pad structure:
- *rows – 53*
- *large pads 5 × 18 mm^2*
-

MPD Time-of-Flight

Mass production staff: 4 physicists, 4 technicians, 2 electronics engineers
Productivity: ~ 1 detector per day (1 module/2 weeks)

Glass cleaning with ultrasonic wave & deionized water

Automatic painting of the conductive layer on the glass

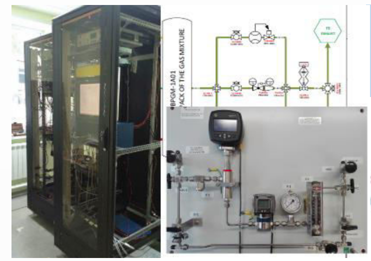


MRPC assembling

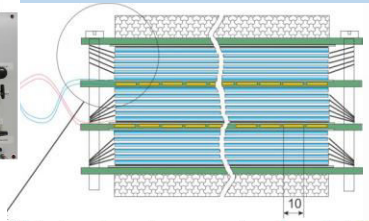
Soldering HV connector and readout pins

	Number of detectors	Number of readout strips	Sensitive area, m²	Number of FEE cards	Number of FEE channels
MRPC	1	24	0.192	2	48
Module	10	240	1.848	20	480
Barrel	280	6720	51.8	560	**13440** (1680 chips)

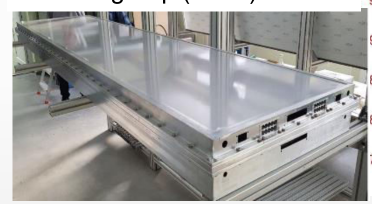
All procedure of detector assembling and optical control is performed in a clean rooms ISO class 6-7.



Dimensions of sensitive area 600 x300 mm^2



TOF gas system:
Responsibility of the Polish group (WUT)



Single detector time resolution: 50ps

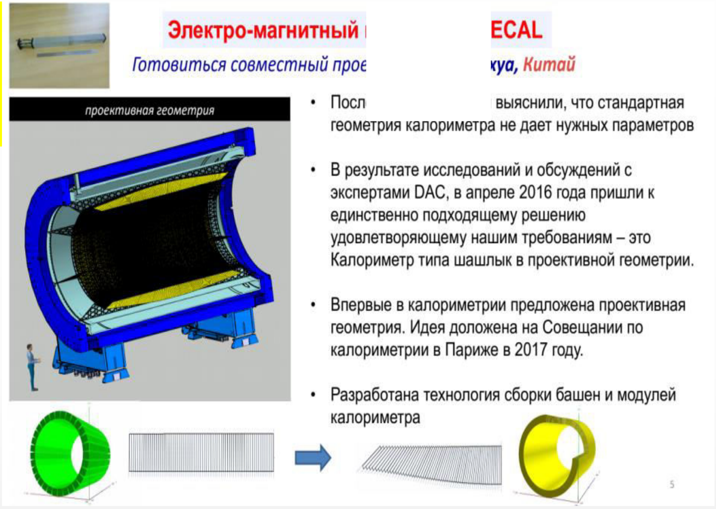
Purchasing of all detector materials completed
So far 40% of all MRPCs are assembled
Assembled half sectors of TOF are under Cosmics tests
Investigation of solutions for detector integration and technical installations

Electromagnetic Calorimeter (ECAL)

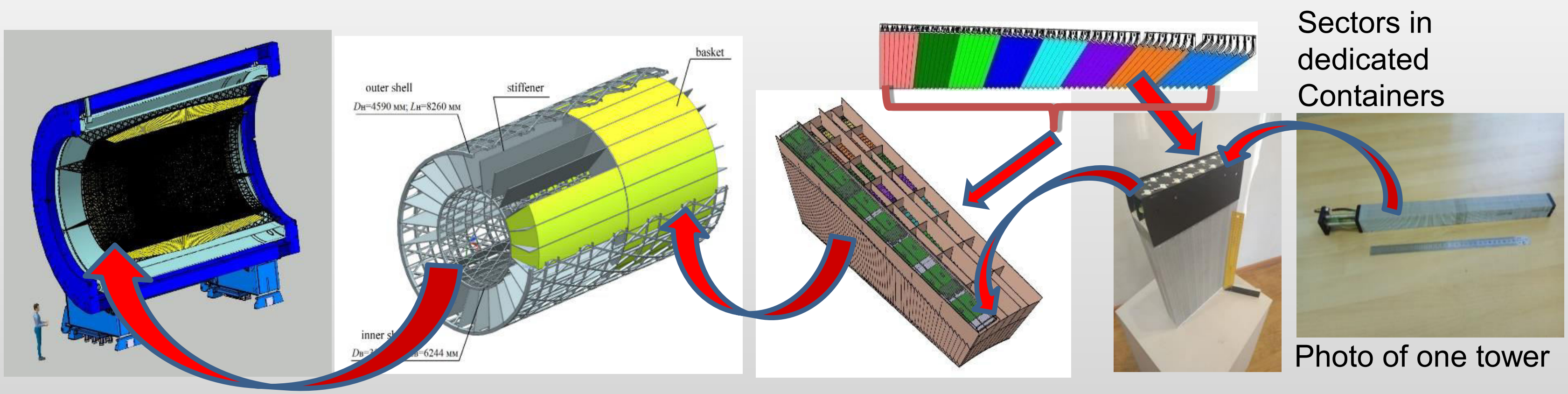
- ❖ *Pb+Sc "Shashlyk"* — *read-out: WLS fibers + MAPD* — *L ~35 cm (~ 14 X_0)*
- ❖ *Segmentation (4x4 cm^2)* — *σ(E) better than 5% @ 1 GeV* — *time resolution ~500 ps*

Barrel ECAL = <u>38400</u> ECAL towers (2x25 half-sectors x 6x8 modules/half-sector x 16 towers/module)

So far ~300 modules (16 towers each) = 3 sectors are produced
Another 3 sectors are planned to be completed by May 2021
Chinese collaborators will produce 8 sectors by the end of 2021
25% of all modules are produced by JINR (production area in Protvino) 75% produced in China, currently funding is secured for approx. 25%



Projective geometry



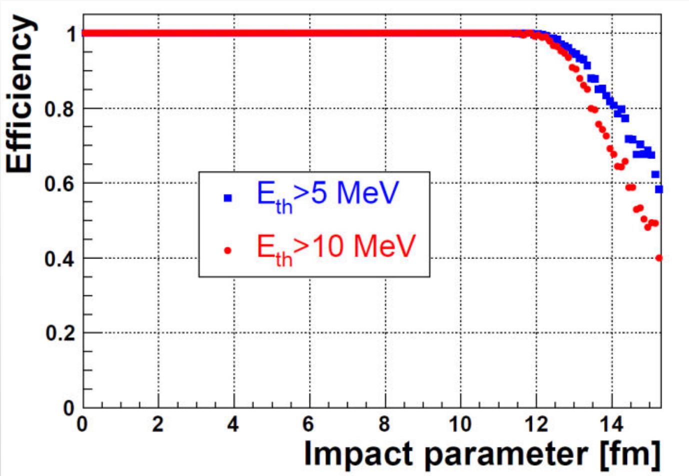
Forward Hadron Calorimeter (FHCal)

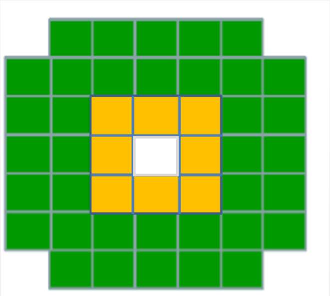
- **All (90+spare) FHCal modules are assembled and are used for the tests.**
- **100 Front-End-Electronics (FEE) boards are produced and tested.**

The activities with modules:

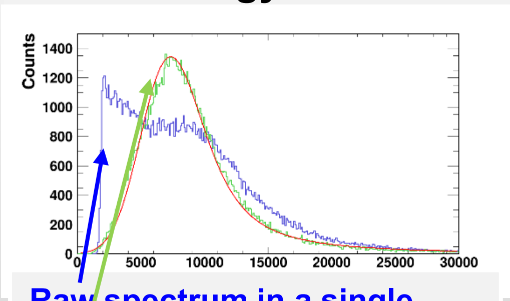
- **Tests with cosmic muons;**
- **Tests of Front-End-Electronics (FEE);**
- **Study of FEE electronic noises;**
- **Development of FHCal trigger;**
- **Development of Slow Control.**

FHCal Trigger efficiency



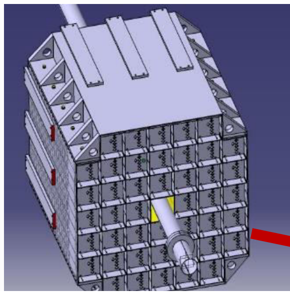


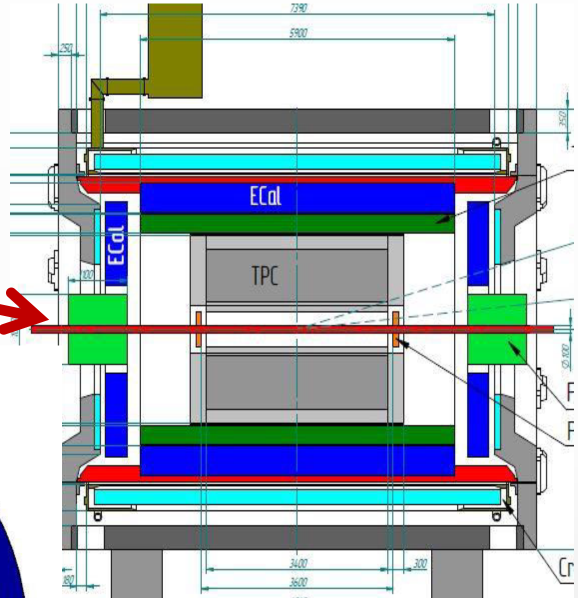
FHCal energy calibration with cosmic

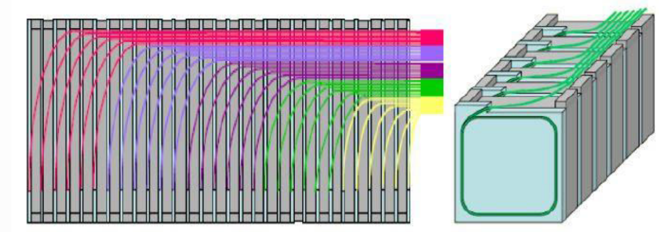


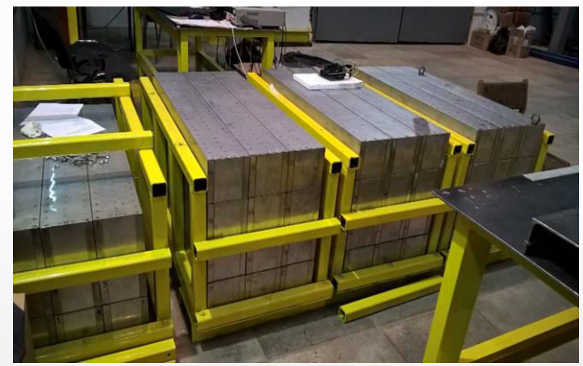
Raw spectrum in a single

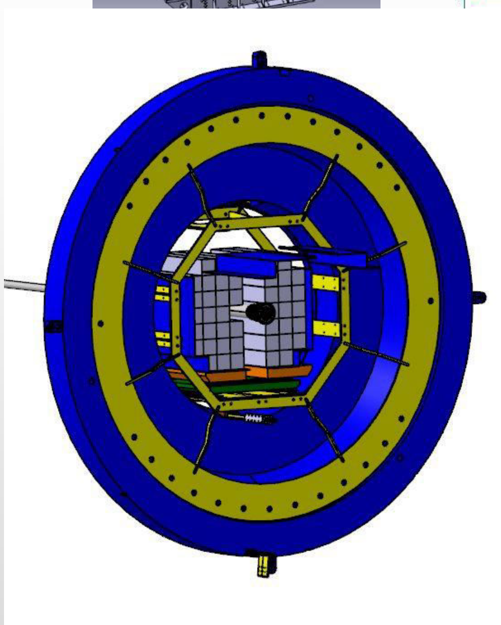
Corrected to the pass length in scintillators





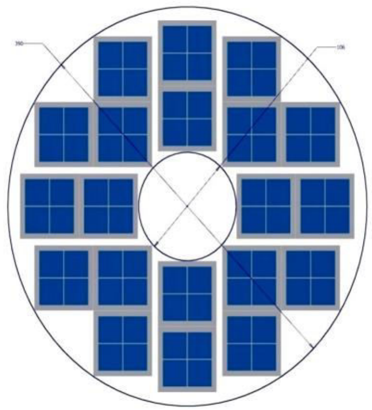


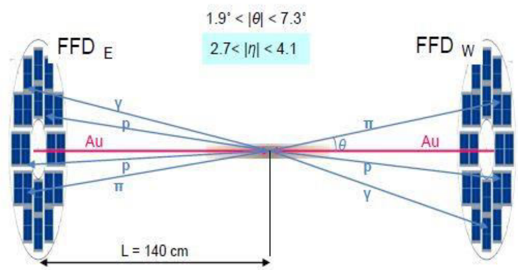




- Two-arms at ~3.2 m from the interaction point.
- Each arm consists of 44 individual modules.
- Module size 150x150x1100cm^3 (42 layers)
- Pb(16mm)+Scint.(4mm) sandwich
- 7 longitudinal sections
- 6 WLS-fiber/MAPD per section
- 7 MAPDs/module

FFD - Fast Trigger L_0 for MPD





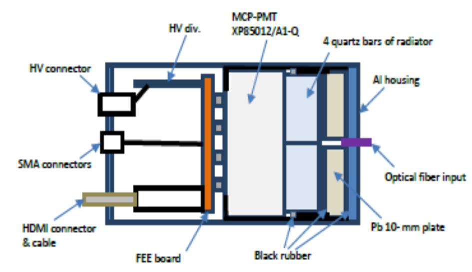


Fig. 4-1. A scheme of the FFD module.

FFD provides information on
- interaction rate (luminosity adjustment)
- bunch crossing region position

15 mm quartz radiator
10 mm Lead converter

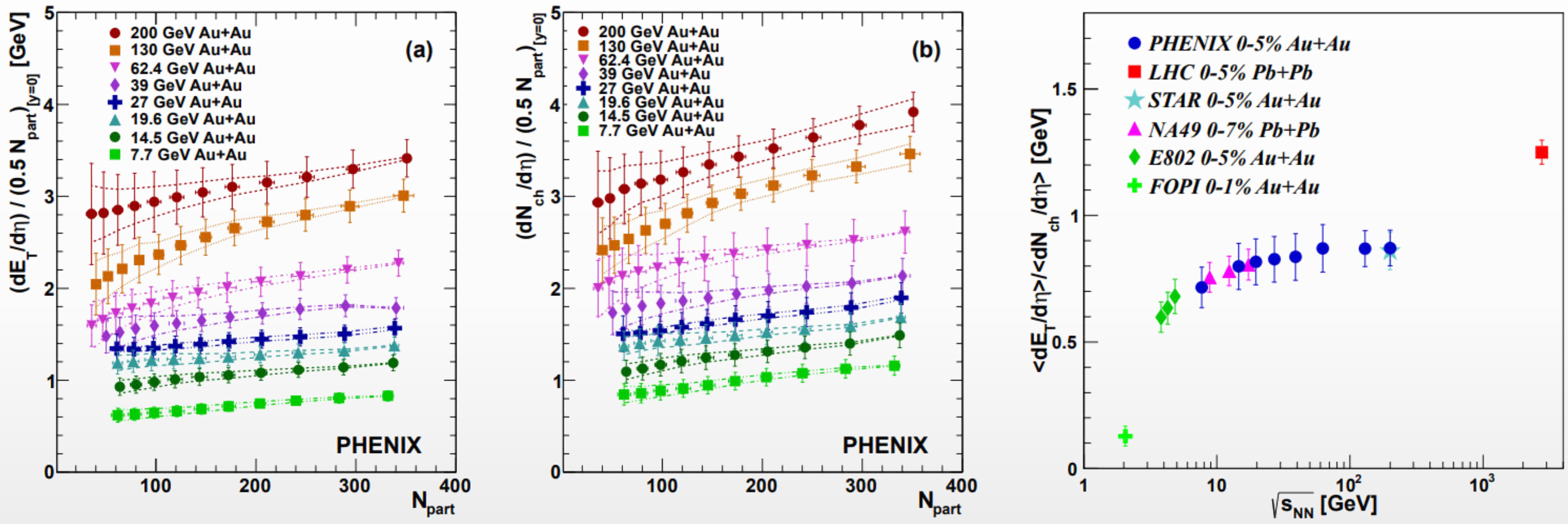
The FFD sub-detector consists of
20 modules based on
Planacon multianode MCP-PMTs
80 independent channels

MPD trigger group is created on the basis of FFD team
Beside FFD we consider the signals from FHCal to be implemented into trigger L0
The FHCal team have produced trigger electronics.
Monte Carlo studies will be used to optimize the properties of the L0 trigger

$dE_T/d\eta$ and $dN_{ch}/d\eta$

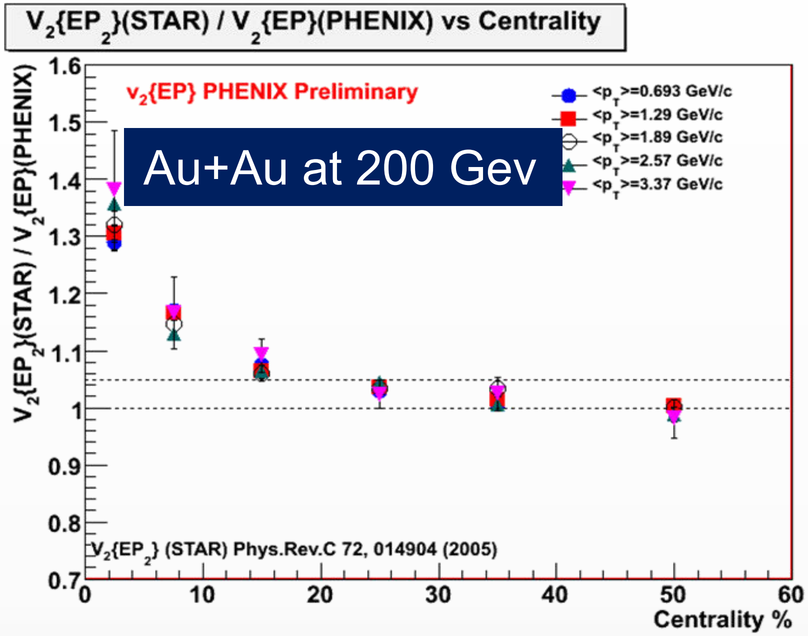
- Transverse energy and charged-particle multiplicity provide characterization of the nuclear geometry of the reaction, sensitive to dynamics of the colliding system (centrality, energy density, etc.)
- E_T/N_{ch} at NICA shows a quick increase of the average transverse mass of the produced particles

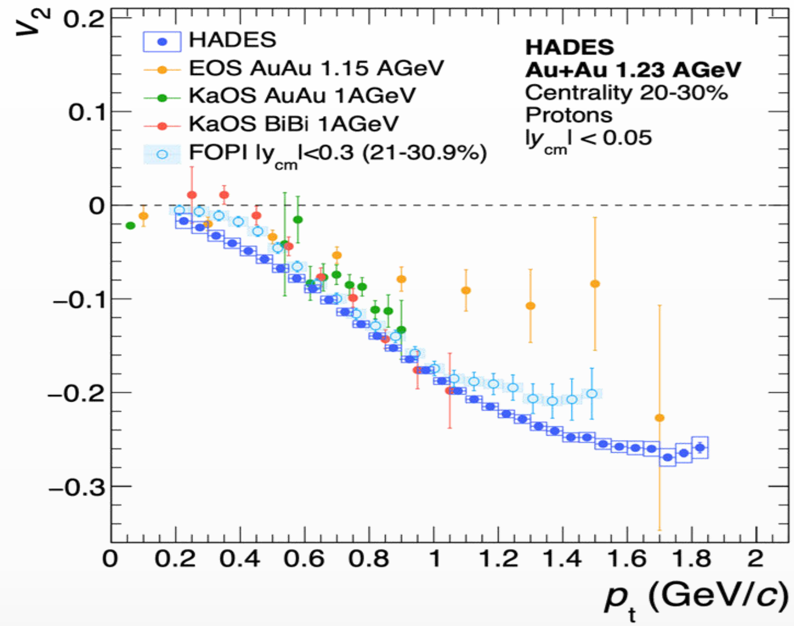
Phys.Rev.C 93 (2016) 2, 024901



- Many references for cross-checks with other experiments
- The measurements will constitute the first physics results from the MPD

Why do we need new measurements at BM@N and MPD?

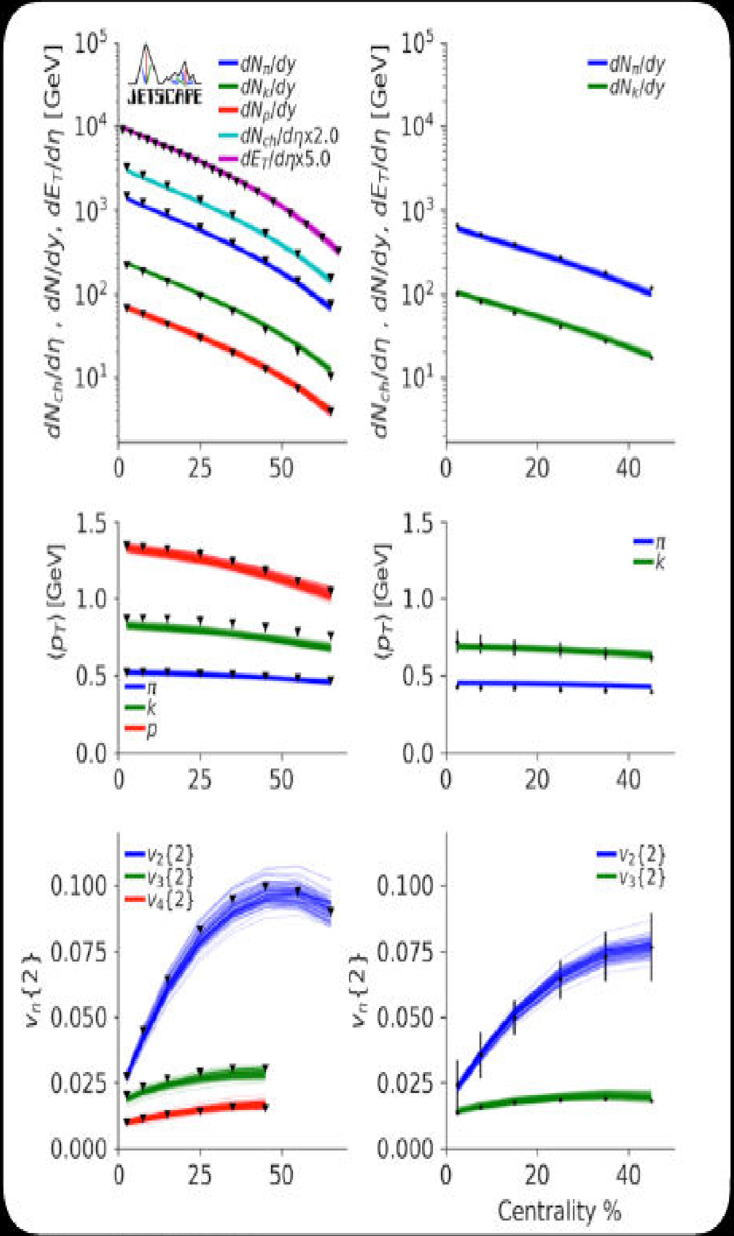




- The main source of existing systematic errors in v_n measurements is the difference between results from different experiments at the same collision energy
- A good measurement should be reproducible; in particular, it should be done in such a way that one can easily compare results from different experiments, using different detectors.

"Eliminating experimental bias in anisotropic-flow measurements of high-energy nuclear collisions", Matthew Luzum, Jean-Yves Ollitrault, Phys.Rev. C87 (2013) 4, 044907

GLOBAL BAYESIAN CONSTRAINTS ON QGP VISCOSITY



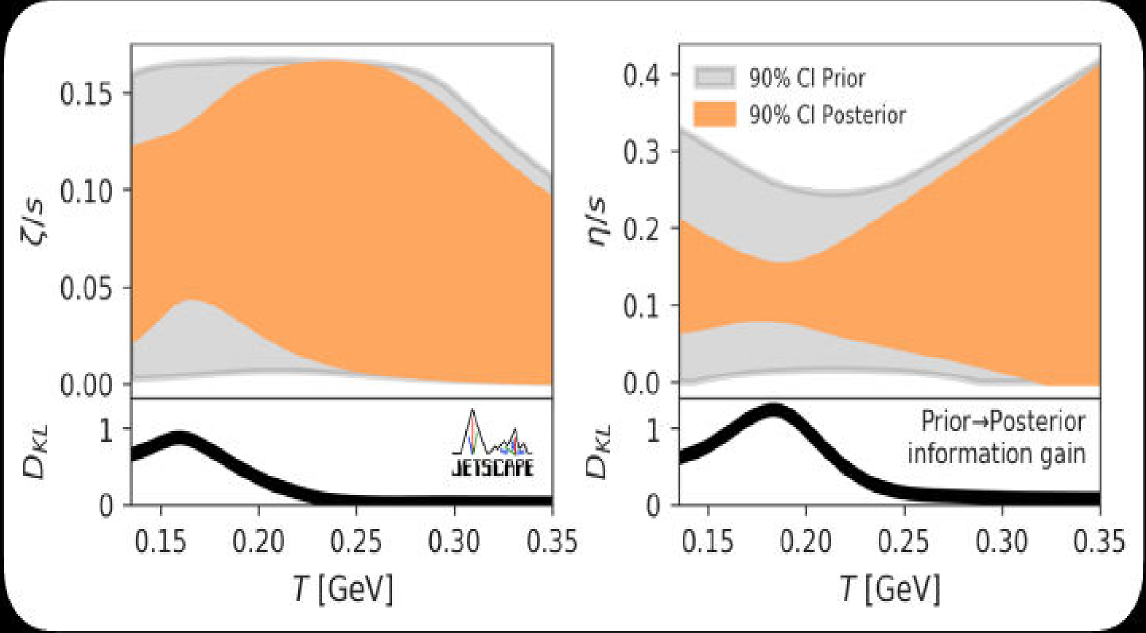
S. Pratt, E. Sangaline, P. Sorensen and H. Wang, Phys. Rev. Lett. 114, 202301 (2015)

J. E. Bernhard, J. S. Moreland, S. A. Bass, J. Liu and U. Heinz, Phys. Rev. C94, 024907 (2016)

J. E. Bernhard, J. S. Moreland and S. A. Bass, Nature Phys. 15, 1113-1117 (2019)

G. Nijs, W. Van Der Schee, U. Gursoy and R. Snellings,
Phys. Rev. Lett. 126, 202301 (2021) & Phys. Rev. C103, 054909 (2021)

D. Everett *et al.* [JETSCAPE], Phys. Rev. Lett. 126, 242301 & Phys. Rev. C103, 054904 (2021)



- Precision hadronic measurements can systematically constrain the QGP viscosity

Elliptic flow measurements using TPC: Scalar product, Event-plane

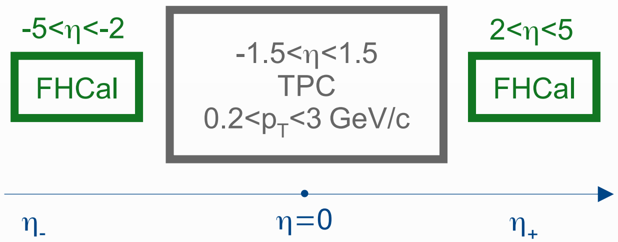
$$u_2 = \cos 2\phi + i \sin 2\phi = e^{2i\phi}$$

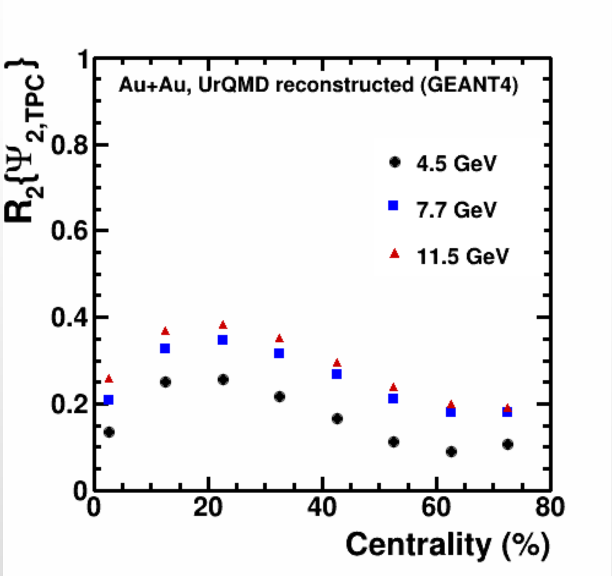
$$Q_2 = \sum_{j=1}^{M} \omega_j u_{2,j}, \; \Psi_{2,\mathrm{TPC}} = \frac{1}{2}\tan^{-1}\left(\frac{Q_{2,y}}{Q_{2,x}}\right)$$

- **Scalar product:** $$v_2^{\mathrm{SP}}\{Q_{2,\mathrm{TPC}}\} = \frac{\langle u_{2,\eta\pm} Q^*_{2,\eta\mp}\rangle}{\sqrt{\langle Q_{2,\eta+} Q_{2,\eta-}\rangle}}$$
- **TPC Event-plane:**

$$v_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} = \frac{\langle \cos\left[2(\phi_{\eta\pm} - \Psi_{2,\eta\mp})\right]\rangle}{\mathrm{R}_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\}}$$

$$\mathrm{R}_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} = \sqrt{\langle \cos\left[2(\Psi_{2,\eta+} - \Psi_{2,\eta-})\right]\rangle}$$





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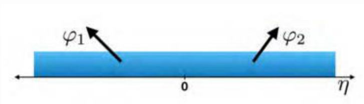
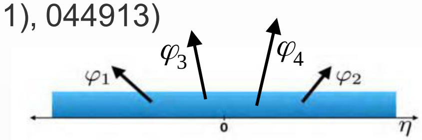
Elliptic flow measurements using TPC: Q-Cumulants

- **Standard Q-Cumulants:** (A. Bilandzic et al., Phys. Rev. C **83** (2011), 044913)





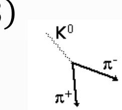
$$\langle 2\rangle_n = \frac{|Q_n|^2 - M}{M(M-1)} \approx v_2^2 + \delta$$

$$\langle 4\rangle_n = \frac{[Q_n]^4 + [Q_{2n}]^2 - 2\Re[Q_{2n}Q_n^*Q_n^*] - 4(M-2)[Q_n]^2 - 2M(M-3)}{M(M-1)(M-2)(M-3)} \approx v_2^4 + 4v_2^2 + 2\delta^2$$

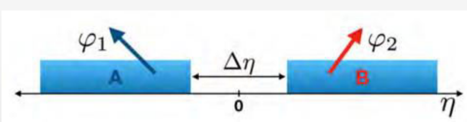
$$v_2\{4\} = \sqrt[4]{2\langle\langle 2\rangle\rangle^2 - \langle\langle 4\rangle\rangle}$$

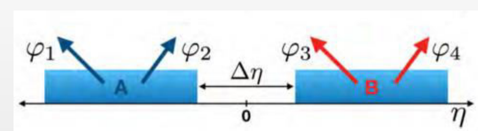
δ – nonflow contribution

- resonance decay
- jets



- **Subevent Q-Cumulants:** (J. Jia et al., Phys. Rev. C **96** (2017), no. 3, (





$$\langle 2\rangle_{a|b} = \frac{Q_{n,a}Q_{n,b}^*}{M_a M_b}, v_2\{2,2-\mathrm{sub}\} = \sqrt{\langle\langle 2\rangle\rangle_{a|b}}$$

$$\langle 4\rangle_{a,a|b,b} = \frac{(Q_{n,a}^2 - Q_{2n,a})(Q_{n,b}^2 - Q_{2n,b})^*}{M_a(M_a-1)M_b(M_b-1)}, v_2\{4,2-\mathrm{sub}\} = \sqrt[4]{2\langle\langle 2\rangle\rangle_{a|b}^2 - \langle\langle 4\rangle\rangle_{a,a|b,b}}$$

Note: In this presentation, all of v_2\{2\} result is obtained by subevent method to suppress non-flow contribution

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Sensitivity of different methods to flow fluctuations

- Elliptic flow fluctuations: $\sigma_{v2}^2 = \langle v_2^2 \rangle - \langle v_2 \rangle^2$
- Assuming $\sigma_{v2} \ll \langle v_2 \rangle$ and a Gaussian form for flow fluctuations
- Fluctuations enhance $v_2\{2\}$ and suppress high-order **Q-Cumulants** compared to $\langle v_2 \rangle$:
- (S. A. Voloshin, A. M. Poskanzer, and R. Snellings, Landolt-Bornstein **23** (2010), 293)

$$v_2\{2\} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v2}^2}{\langle v_2 \rangle} \qquad v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\mathrm{LYZ}\} \approx \langle v_2 \rangle - \frac{1}{2}\frac{\sigma_{v_2}^2}{\langle v_2 \rangle}$$

- **TPC EP method**: (M. Luzum et al., Phys. Rev. C **87** (2013) 4, 044907)

$$\langle v_2 \rangle \leq v_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} \leq \sqrt{\langle v_2^2 \rangle} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v2}^2}{\langle v_2 \rangle}$$

- **Scalar product**:

$$v_2^{SP}\{Q_{2,\mathrm{TPC}}\} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v2}^2}{\langle v_2 \rangle}$$

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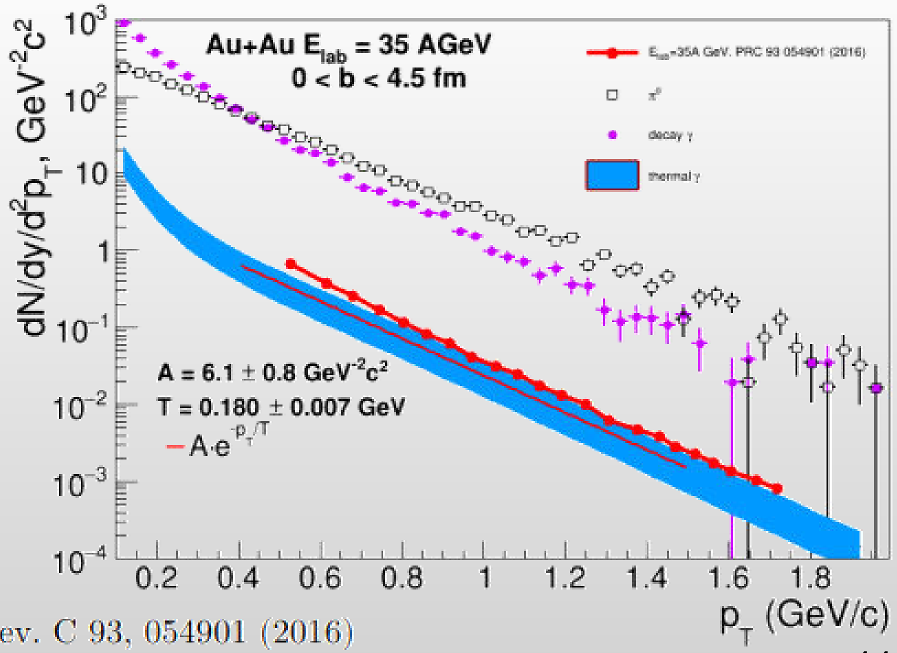
Simulation setup

- ✓ UrQMD v3.4 with hybrid model (3+1d hydro, **bag model** EoS, hadronic rescattering and resonances within UrQMD)
- ✓ π^0 and decay photon spectrum are calculated **within the same simulation**
- ✓ impact parameter range $0<b<9$ fm
- ✓ In hydrodynamical evolution, for each volume we calculate thermal gamma yield based on T, energy density (e), QGP fraction, baryonic chemical potential. We integrate these yields over time (until freeze-out time) and space.
- ✓ Two extreme cases: calculate thermal gamma emission from the volume above freeze-out criterion ($e > e_{freezeout}$), or calculate for all volumes. Reality somewhere in between (all volumes interact during hydro evolution). Comparing these options one can estimate theoretical uncertainties

$$\frac{d^3 N^{\gamma,therm}}{dy\, d^2 k_T} = \int_{\Omega} dV\, dt\, R_\gamma \left| k, T(x), \mu(x), u(x) \right|$$



Why simulations in PRC 93 054901 (2016) and PRC 81 044904 (2010) have almost the same yield despite ~5 times difference in energy (35 vs 158 AGeV)?

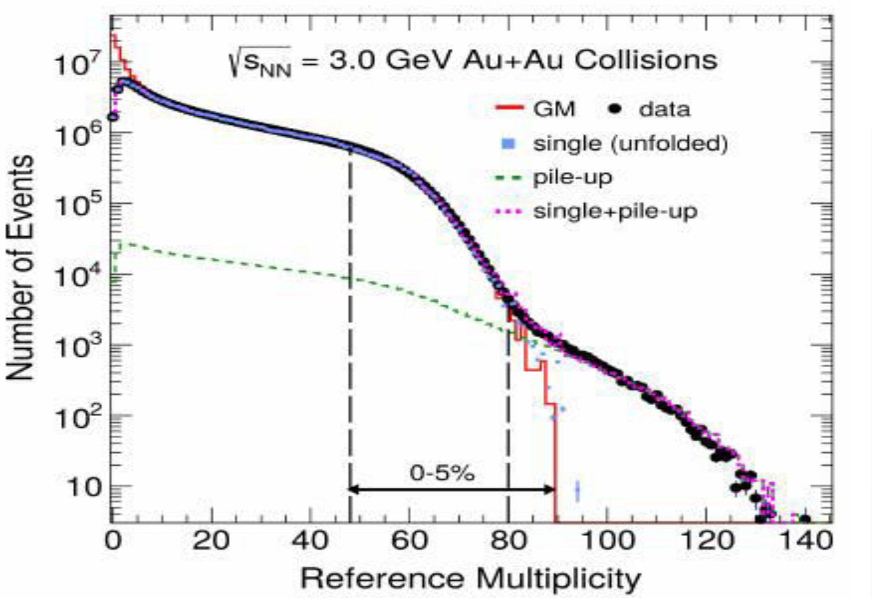
Comparison with S. Endres, H. van Hees, M. Bleicher, Phys. Rev. C 93, 054901 (2016)

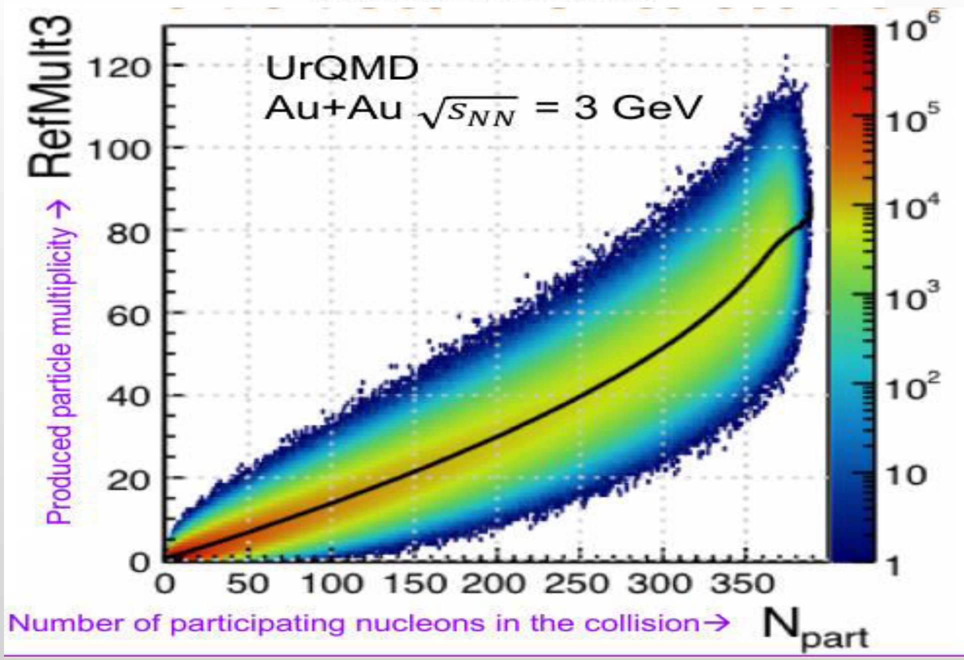
Experimental challenges in fluctuations measurements

Event-by-event identification issues
- Cut based approach
- Identity method
- PSET identity method

Non-dynamical contributions
- E-by-e fluctuations of wounded nucleons
- Depends on centrality selection methods

Contributions from pileup events





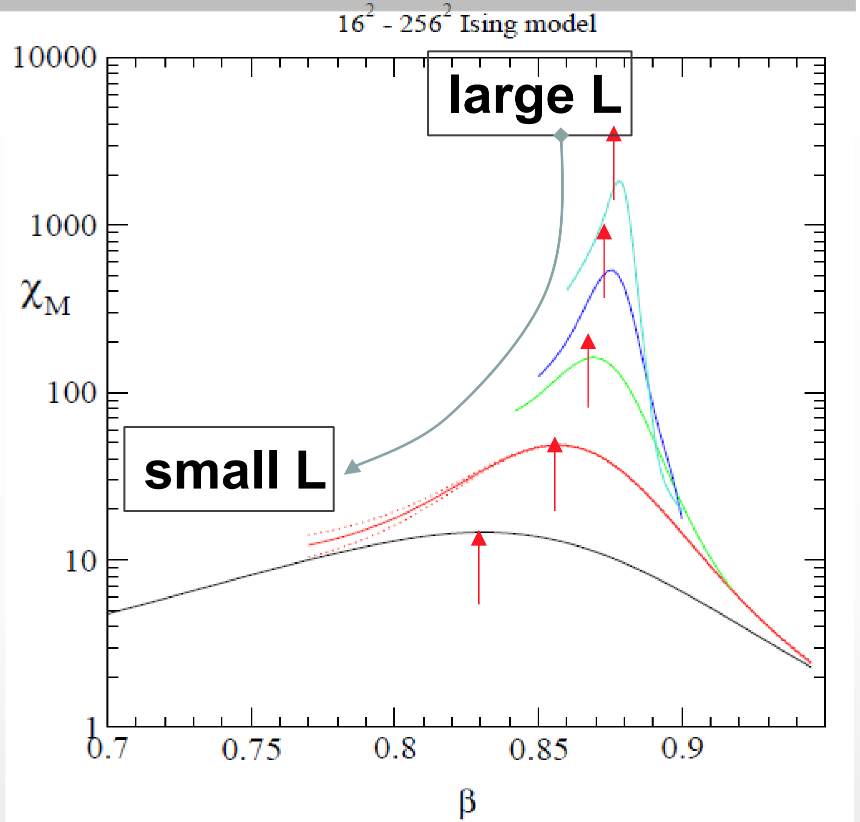
Finite-Size Effects and search for CEP

In HIC, both the size (**L**) and duration of formed system are finite.

Critical behavior changes with L

If the L is too small, the correlation length **ξ** can not be fully developed to cause a phase transition.

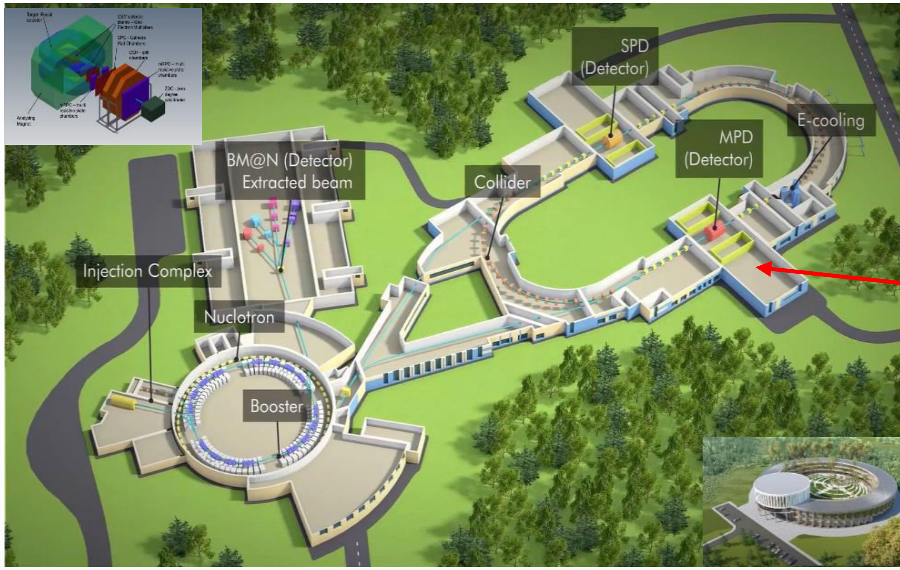
if the correlation length $\xi \sim |T - T_c|^{-\nu} \leq \mathrm{L}$ the finite-size effect is not negligible and only a **pseudo-critical point, shifted from the genuine CEP, is observed.**



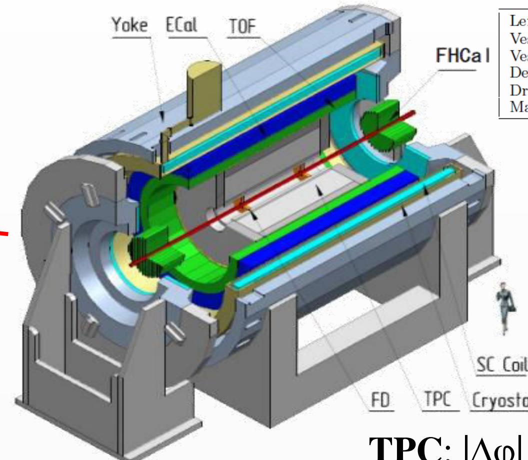
Note change in peak heights positions & widths with L

- ✓ **Finite-size effects have a specific dependencies on size (L)**
- ✓ **The scaling of these dependencies give access to the CEP's location, it's critical exponents and scaling function.**

Megascience projects



Stage- I



Length	340 cm
Vessel outer radius	140 cm
Vessel inner radius	27 cm
Default magnetic field	0.5 T
Drift gas mixture	90% Ar+10% CH_4
Maximum event rate	7 kHz ($L = 10^{27}$ $cm^{-2}s^{-1}$)

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

- ❖ One of two collider experiments at NICA collider to study heavy-ion collisions at $\sqrt{s_{NN}}$= 4−11 GeV
- ❖ Expected beam configuration in Stage-I:
  - ✓ not-optimal beam optics with wide z-vertex distribution, σ_z ~ 50 cm
  - ✓ reduced luminosity (~10^{25} is the goal for 2023) → collision rate ~ 50 Hz
  - ✓ collision system available with the current sources: C (A=12), N (A=14), Ar (A=40), Fe (A=56), Kr (A=78-86), Xe (A=124-134), Bi (A=209) → start with Bi+Bi @ 9.2 GeV in 2023-2024

MPD status and plans

- ❖ 2022:
  - ✓ preparation of the SC magnet for cooling
- ❖ 2023:
  - ✓ cooling the magnet and MF measurement
  - ✓ installation of the support frame and detectors
- ❖ 2024:
  - ✓ MPD commissioning
  - ✓ first run with BiBi@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.)

Schedule of the MPD-NICA is significantly affected by the current geopolitical situation (suspension of collaboration with CERN and Polish & Czech Republic member institutions, economical sanctions and problems with supplies of many components from western companies). The primary goal to have the MPD commissioned by the first beams at NICA collider is preserved.

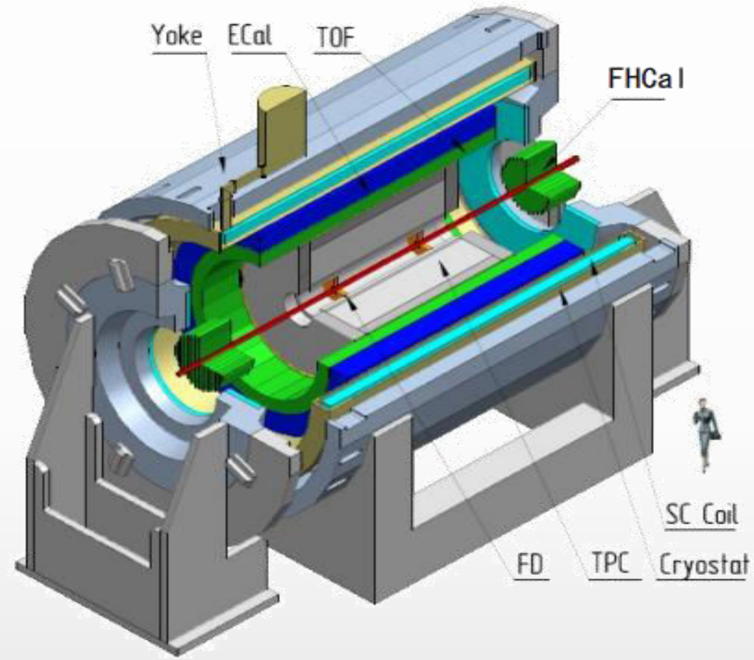
Multi-Purpose Detector (MPD) Collaboration

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****;*
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 physics program

G. Feofilov, A. Aparin

Global observables

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

V. Kolesnikov, Xianglei Zhu

Spectra of light flavor and hypernuclei

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

K. Mikhailov, A. Taranenko

Correlations and Fluctuations

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

V. Riabov, 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

Physics capability studies using centralized Monte Carlo productions:

✓ most advanced event generators

✓ most up-to-date performance of detector subsystems

✓ common detector performance, same event/detector environment for all studies

✓ consistent picture for year-1 running with BiBi@9.2 → second collaboration paper

Collaboration activity

- Many ongoing construction works, theoretical and physics feasibility studies
- MPD publications: over 200 in total for hardware, software and physics studies:
  - ✓ RFBR grant program (now completed) attracted many new Russian institutions in the NICA activities
  - ✓ financial support for participation of Russian institutions in the MPD-NICA is needed for success of the project
- Presented at all major conferences in the field
- First collaboration paper recently published EPJA (~ 50 pages):
  - ✓ Status and initial physics performance studies of the MPD experiment at NICA, Eur.Phys.J.A 58 (2022) 7, 140