Многофункциональный детектор MPD для исследования сильновзаимодействующей материи на коллайдере NICA

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ЛФВЭ ОИЯИ (Дубна)

Для MPD Коллаборации

XIII Черенковские чтения “Новые методы в экспериментальной ядерной физике и физике частиц”

Москва, ФИАН, 14 апреля 2020 г.

Содержание

- Комплекс NICA в ОИЯИ
- Программа по тяжелым ионам на детекторе MPD
- Статус проекта (ускорительный комплекс, детектор, результаты моделирования)
- Заключение

“NAUKA” NATIONAL PROJECT

Decree of the President of RF № 204 on 7 May, 2018

TIMELINE: 01.10.2018 – 31.12.2024

GOALS AND TARGETS:

1. Ensuring the presence of the Russia among the 5 leading countries engaged in R&D in priority areas of science and technology development.
2. Ensuring the attractiveness of employment in Russia for Russian and foreign leading scientists and distinguished young researchers.
3. Advanced increase of internal R&D expenditures using all possible sources in comparison with the growth of the gross domestic product of the country.

FEDERAL PROJECTS INCLUDED IN THE “NAUKA” PROJECT:

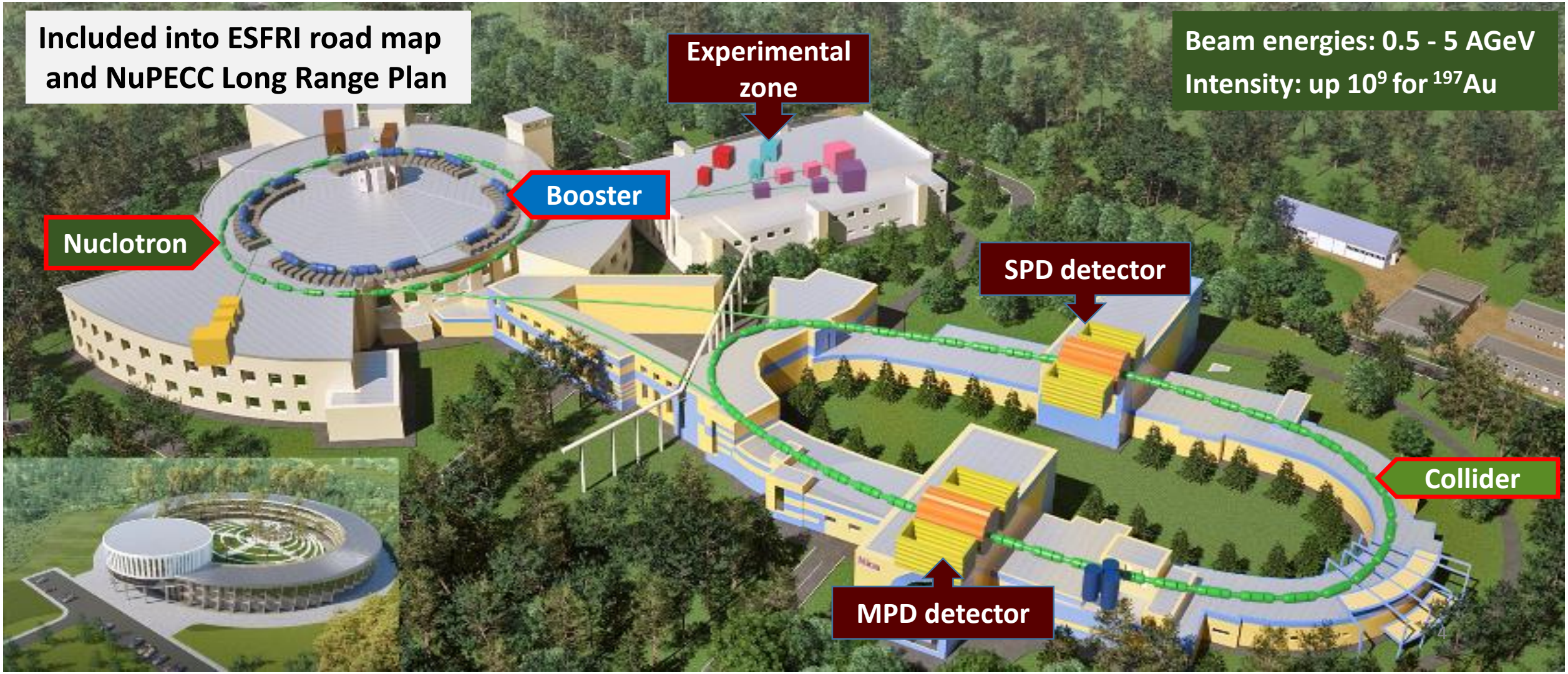
- Development of the scientific and industrial cooperation.
- Development of the advanced infrastructure for R&D in Russia.
- Development of the human resources for R&D.

2020	Establishing 4 world-class international mathematical centers. Establishing 3 world-class genomic research centers. Beginning of international research at the megascience facility of the International Center for Neutron Research (based on the PIK high-flux reactor).
2021	Establishing 3 world-class research centers for R&D in priority fields of scientific and technological development.
	Holding of 29th World Mathematical Congress (St. Petersburg)
2022	**Beginning of international research at the megascience facility “The complex of superconducting rings on colliding heavy ion beams – NICA”.**

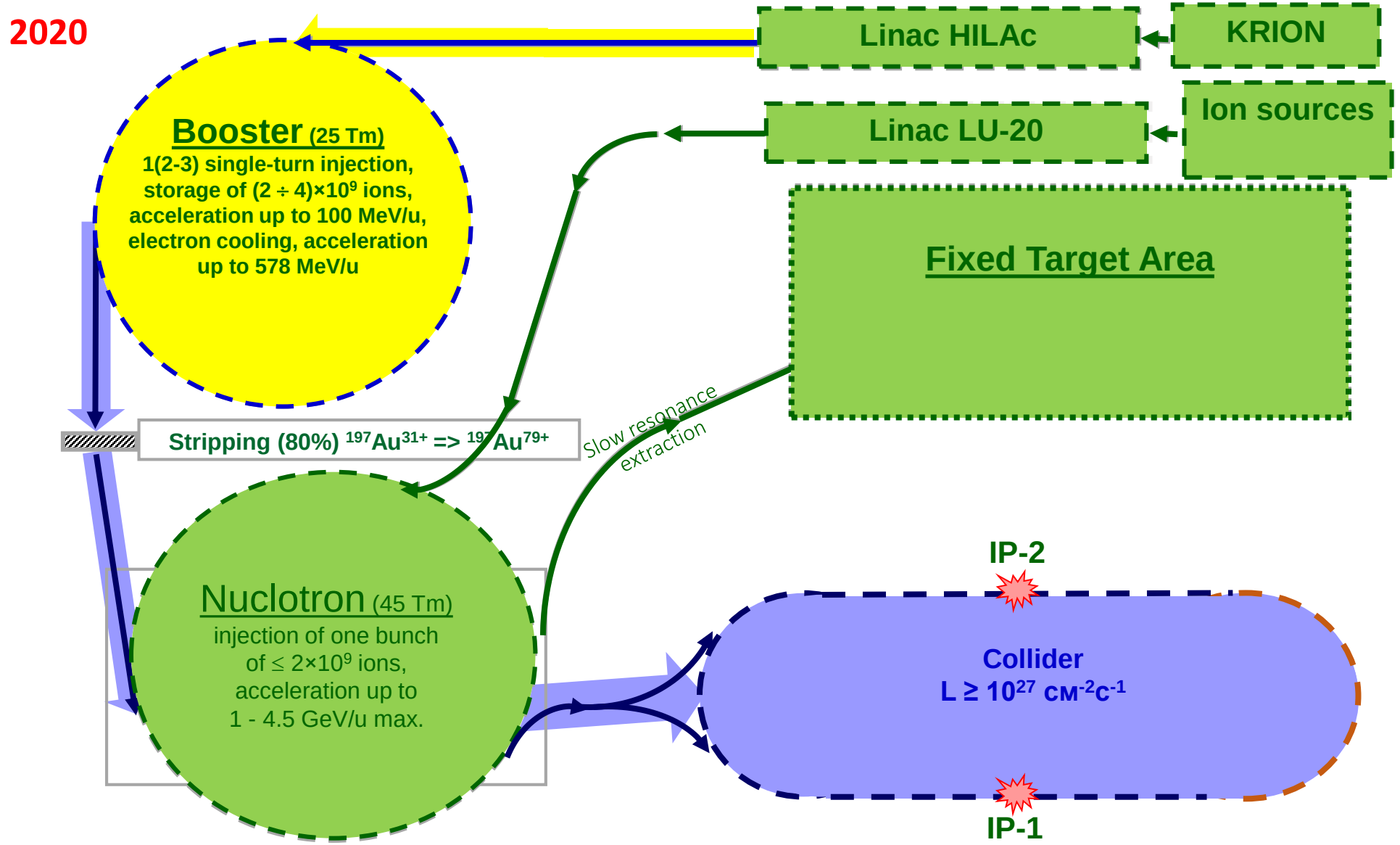
Начало экспериментов на коллайдере NICA – 2022 г.

NICA – Nuclotron-based Ion Collider fAcility

- Chain of accelerators providing ion beams (from *p* to Au) for fundamental physics studies & applied research
- Modern detectors for study dense nuclear matter and spin phenomena (MPD, SPD, BM@N)
- Experimental zone with beam lines for fundamental and applied research
- Factory with cryogenic infrastructure for production, testing and supply superconducting elements



NICA accelerator complex: scheme and status

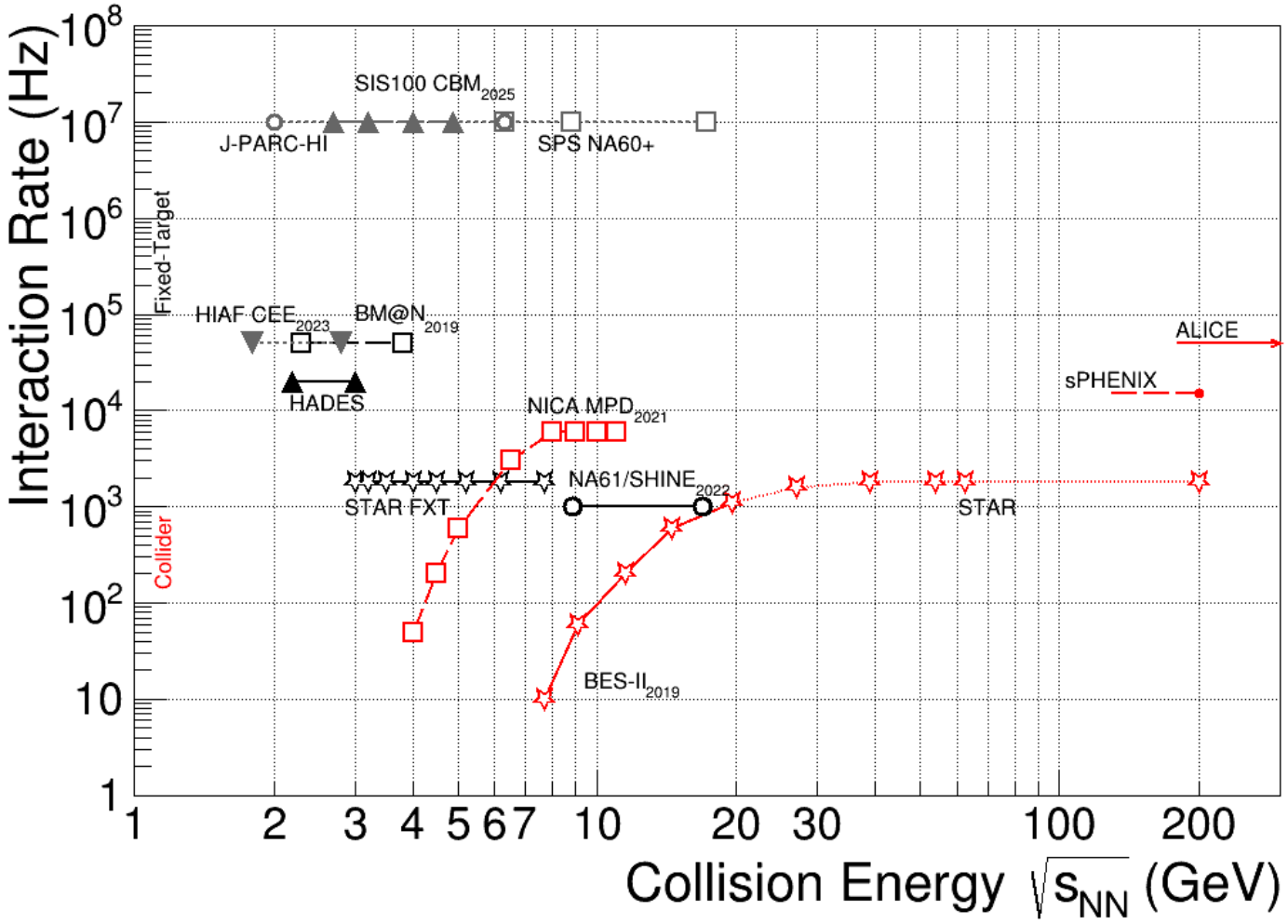


work in progress	assembly	commissioned / existing

NICA beam intensities and event rates

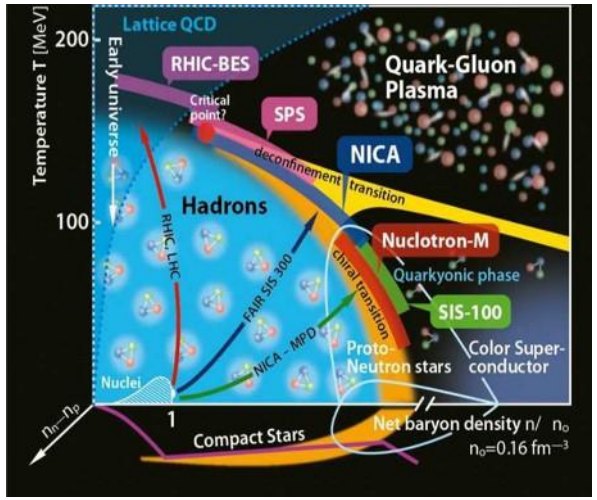
Beam	Beam intensity (particle / cycle)		
	Current	Ion source type	at NICA
p	$3 \cdot 10^{10}$	Duoplasmotron	$5 \cdot 10^{12}$
d	$3 \cdot 10^{10}$	--- ,, ---	$5 \cdot 10^{12}$
^{4}He	$8 \cdot 10^{8}$	--- ,, ---	$1 \cdot 10^{12}$
d↑	$2 \cdot 10^{8}$	SPI	$1 \cdot 10^{10}$
^{7}Li	$8 \cdot 10^{8}$	Laser	$5 \cdot 10^{11}$
^{11,10}B	$1 \cdot 10^{8}$	--- ,, ---	
^{12}C	$1 \cdot 10^{9}$	--- ,, ---	$2 \cdot 10^{11}$
^{24}Mg	$2 \cdot 10^{7}$	--- ,, ---	
^{14}N	$1 \cdot 10^{7}$	ESIS ("Krion-6T")	$5 \cdot 10^{10}$
^{40}Ar	$1 \cdot 10^{9}$	--- ,, ---	$2 \cdot 10^{11}$
^{56}Fe	$2 \cdot 10^{6}$	--- ,, ---	$5 \cdot 10^{10}$
^{84}Kr	$1 \cdot 10^{4}$	--- ,, ---	$1 \cdot 10^{9}$
^{124}Xe	$1 \cdot 10^{4}$	--- ,, ---	$1 \cdot 10^{9}$
^{197}Au	-	--- ,, ---	$1 \cdot 10^{9}$

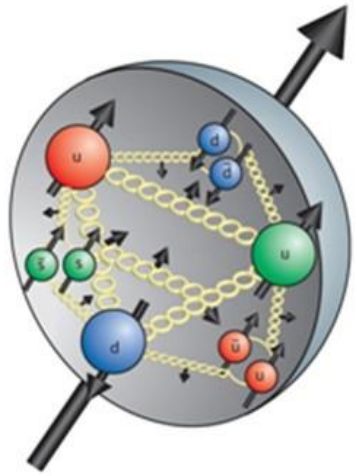
NICA will provide the largest luminosity in the region of high baryon density (collider mode). Typical event rate - up to 7 kHz

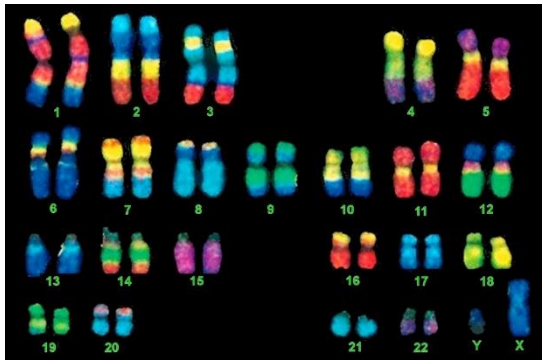


Физ. Программа для MPD детектора.

Scientific pillars of the NICA program







Heavy-ion program

Probing of fundamental laws of physics with heavy-ion collisions:

- Formation of new state of matter (QGP)
- Properties of physical vacuum
- Origin of particle mass
- Properties of massive stellar objects (neutron stars)

Spin physics program

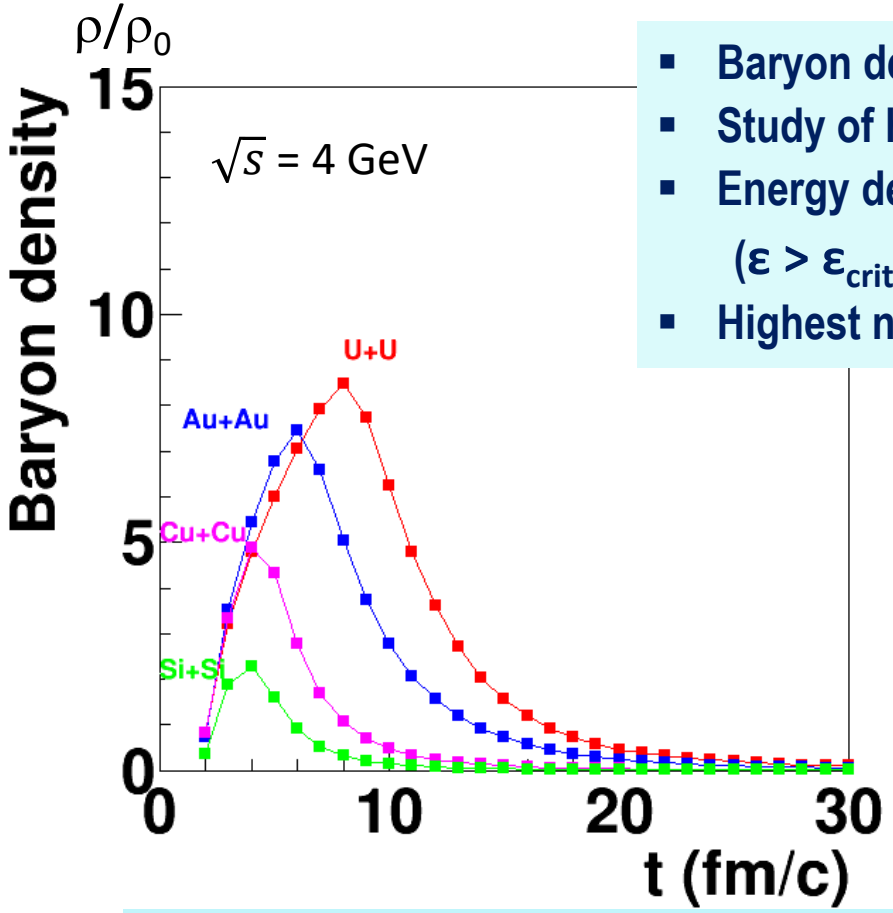
New comprehensive studies with polarized beams to:

- Resolve nucleon spin crisis
- New precise measurements of the nucleon Parton Distribution Functions

Program of applied research

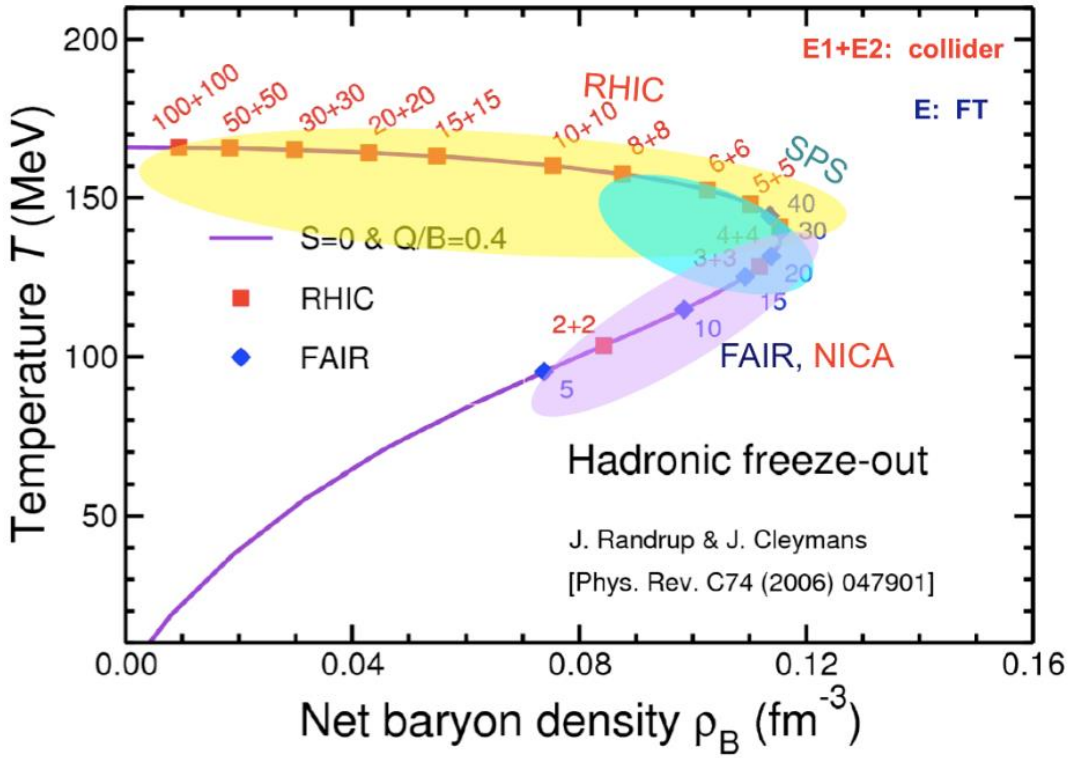
- Development of universal charged particle accelerators
- Universality of operating modes & increasing limiting parameters of superconducting magnets
- Radiation hardness and modification of materials
- Radiobiology research with heavy-ion beams

Nuclear matter at NICA energies



- Baryon density in heavy-ion collisions: 3-7ρ_0
- Study of hadroproduction in dense (predominantly baryonic) matter at low NICA energies
- Energy density above the critical value for deconfinement phase transition ($\varepsilon > \varepsilon_{crit}$= 0.7 GeV/fm^3) in central Au+Au at the top energy
- Highest net-baryon density: favors deconfinement and chiral symmetry restoration (CSR)

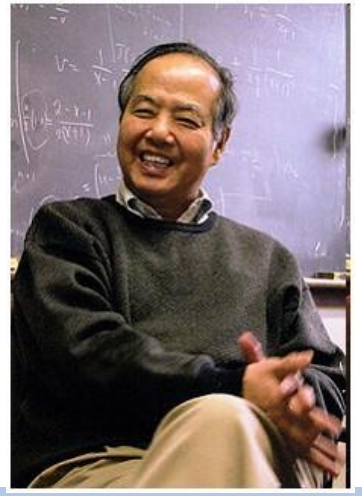
A fundamental understanding of the QCD phase diagram is still lacking and the main goal of the NICA experimental program is to map out the QCD phase diagram and try to establish the properties of the different phases



NICA/MPD physics program program (White Paper)

***Experimental strategy**: energy and system size scan to measure a variety of signals systematically changing collision parameters (energy, centrality, system size). Reference data (i.e. p+p) will be taken in the same experimental conditions*

Physics targets for the exploration of the QCD phase diagram accessible to NICA and possible observables for a "mixed phase" in the release of the "NICA White Paper" as a Topical Issue of the EPJ A (July 2016).

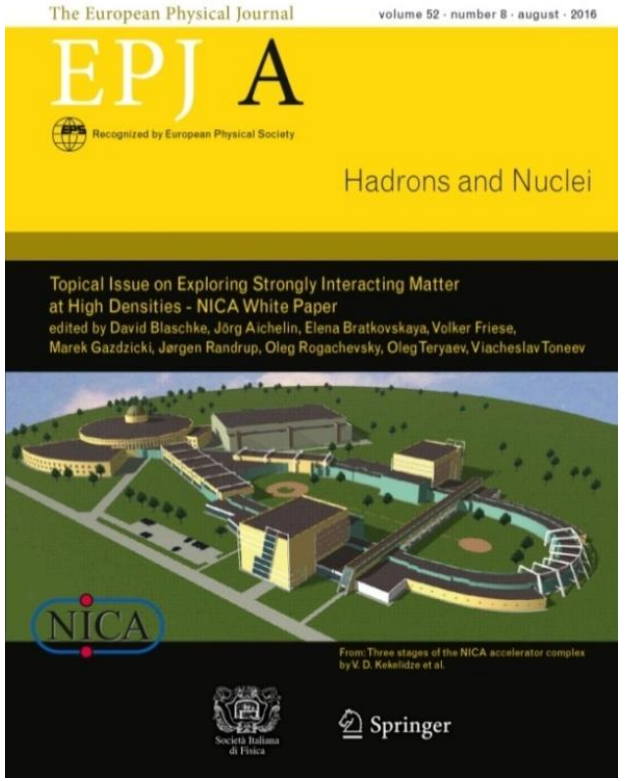


T.D.Li: *"The NICA heavy ion collider will be a very major step towards the formation of a new phase of quark-gluon matter."*

White Paper Contributions:

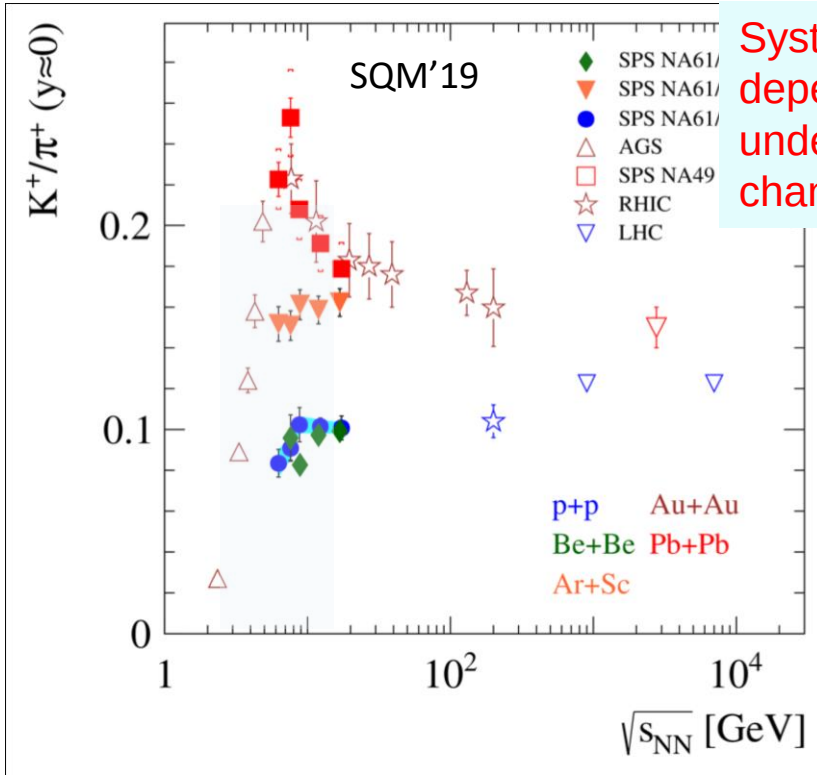
111 *contributions,*
188 *authors from* **70** *centers in* **24** *countries*

- Modification of the QCD vacuum at high baryon densities,
- Indication of Chiral Symmetry Restoration
- Deconfinement phase transition and properties of the mixed phase
- QCD phase diagram and search for the Critical End Point
- Bulk properties, nuclear EOS and its hyperon sector

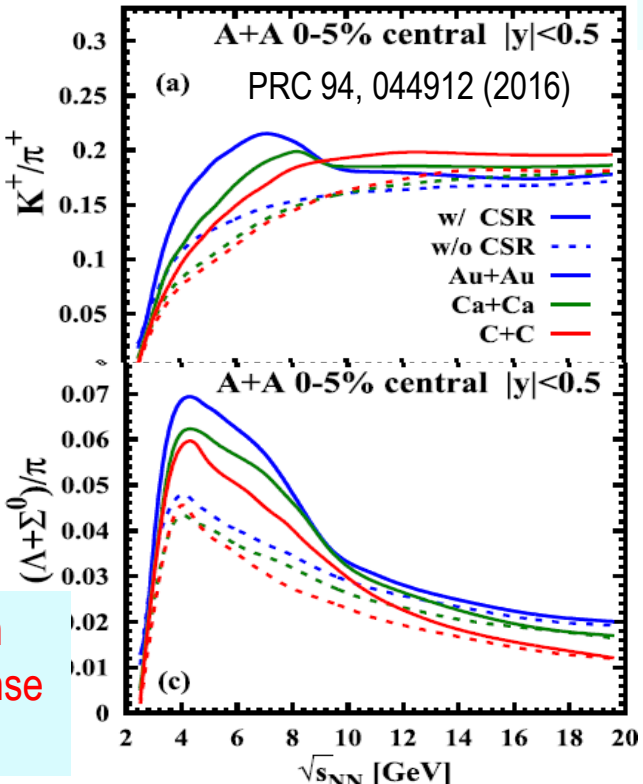


NICA/MPD physics cases: strangeness production

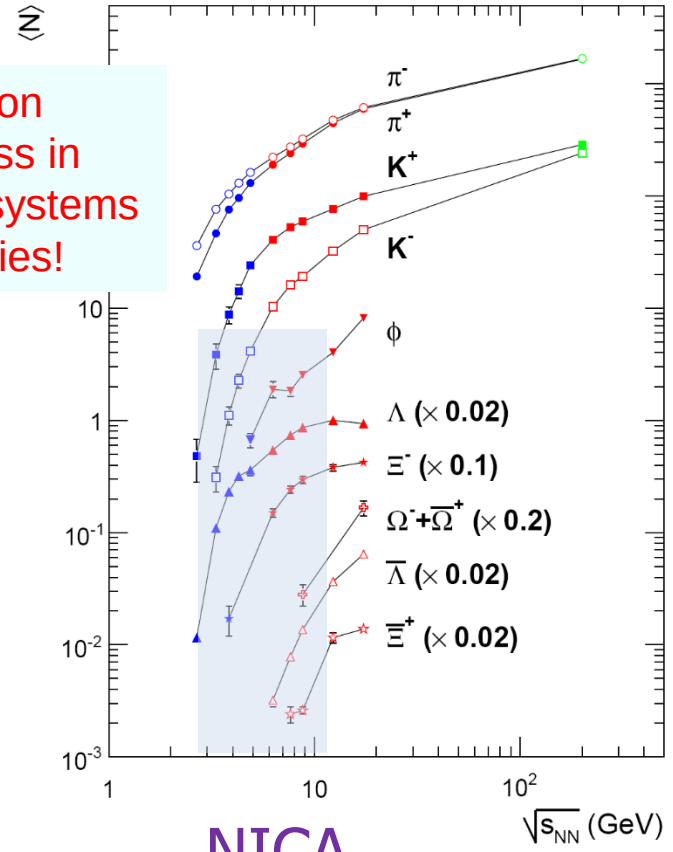
- Excitation function of hadrons, including strangeness (yields, spectra, and ratios)
- Nuclear matter EOS, in-medium effects, and chemical equilibration can be probed
- Hyperons sensitive to early stage and phase transformations in QCD medium
- Non-monotonic strangeness-to-entropy ratio seen in heaviest systems (phase transformation?)



System size of the energy dependence is not fully understood. The largest changes at NICA!



Lack of data on multistrangeness in different collision systems at NICA energies!

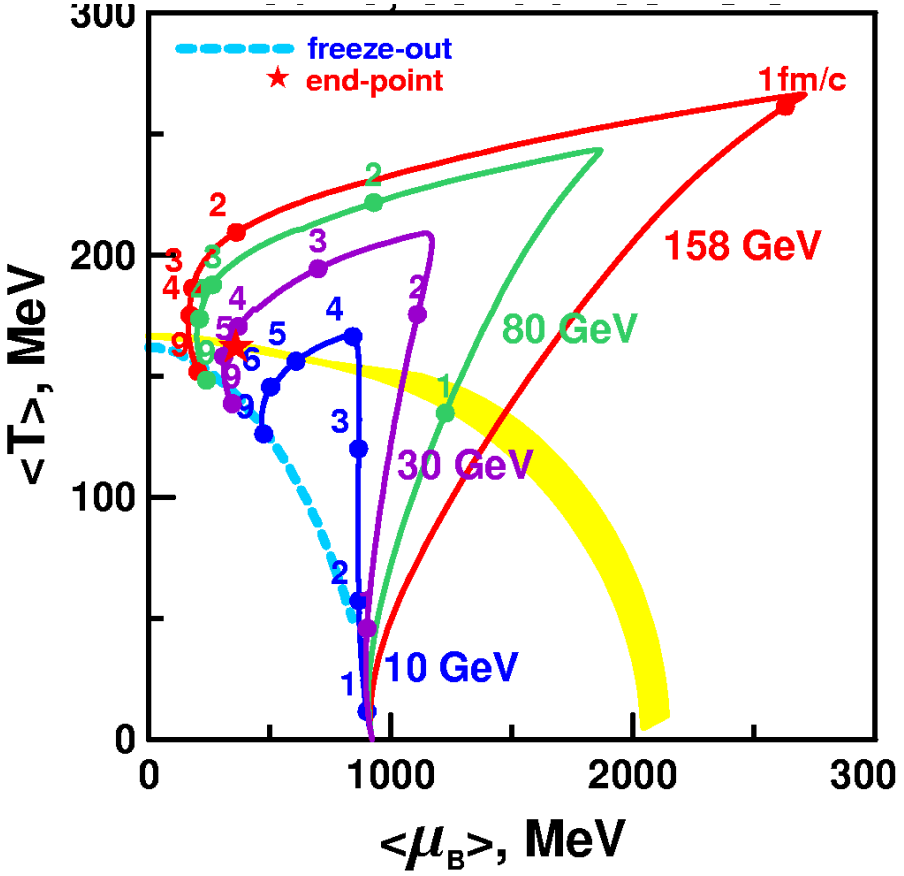


NICA

Theory predicts the largest effect for the hadron ratios due to chiral symmetry restoration in dense matter at NICA energies!

Search for the QCD Critical End Point (CEP) at MPD

Trajectories calculated by a 3-fluid hydrodynamics model Toneev & Ivanov



If the trajectory is in the vicinity of the critical endpoint – abnormal fluctuations can be observed

Observables - event-by-event fluctuations:

- **multiplicity, charge number**
- **particle ratios**
- **mean pT, azimuthal angle**
- **baryon number**

Searching for the CEP is very important:

High Risk,

but potentially also

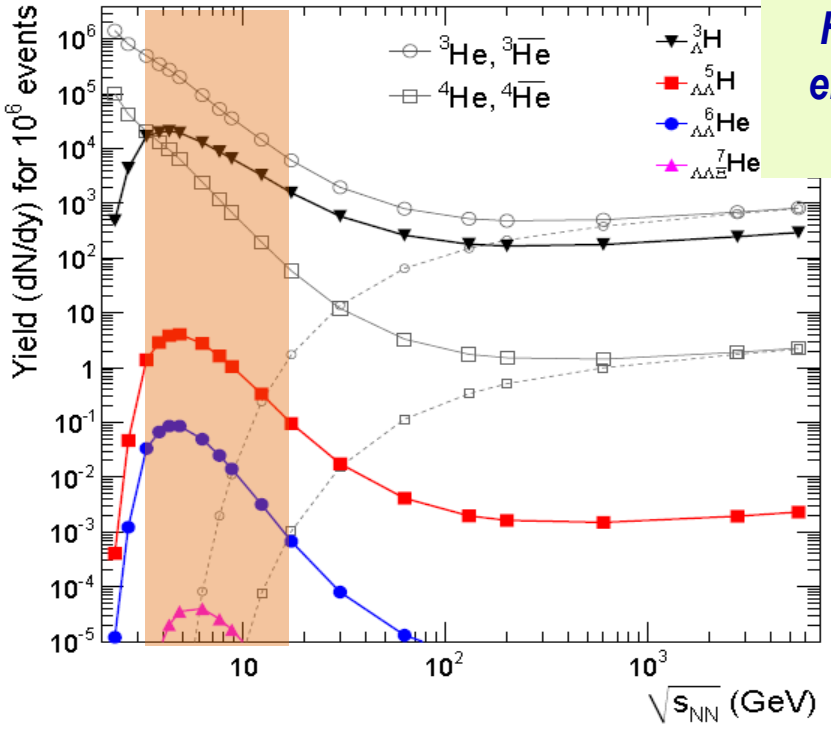
High Return !

Experimental challenge: fluctuation signal may be suppressed due to final state interactions that washed out the signal. True CEP signal should show consistency in several observables!

NICA/MPD physics cases: hypernuclei in A+A collisions

- Precise information on Y-N interaction: nuclear EOS, astrophysics
- Hypernuclei ground, excited states and life times: critical assessments or QCD calculations and model predictions
- Production mechanism of bound states with hyperons: coalescence versus spectators-participants interactions

A. Andronic et al, PLB697 (2011) 203



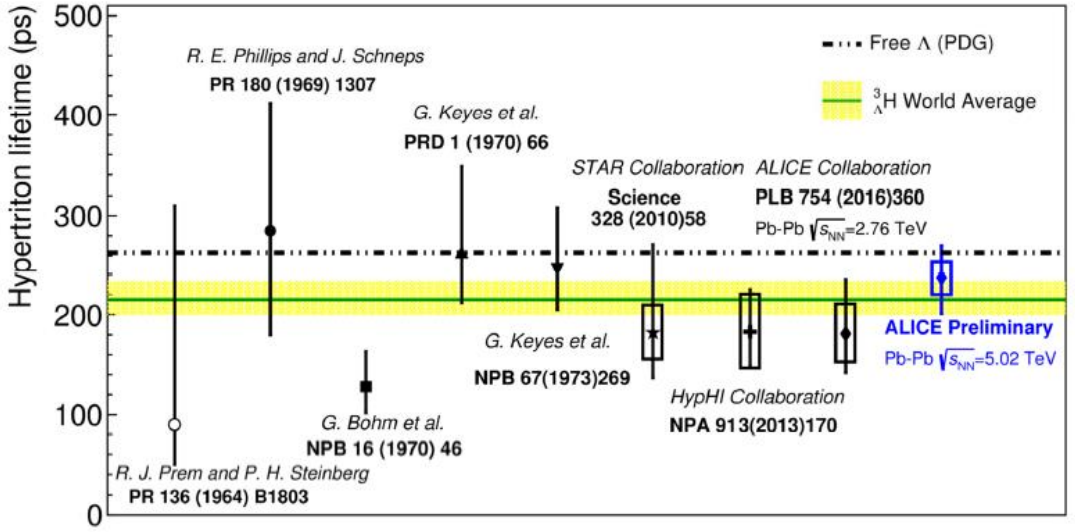
Hypernuclei production enhanced at high baryon densities (NICA)

Hypernuclei yields @ NICA:

Au+Au collisions @ 4 GeV

rate 7 kHz, efficiency ~ 1%

Hyper-nucleus	Yield/week
$_\Lambda{}^3$H	$1 \cdot 10^5$
$_{\Lambda\Lambda}{}^5$H	20



Hypertriton lifetime puzzle → more precision reducing current uncertainty needed!

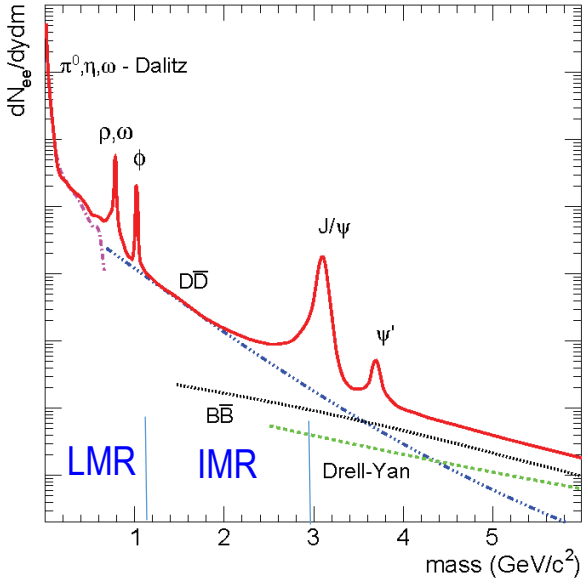
To study hypernuclei, MPD detector must be able to detect and identify light nuclei in a wide rapidity range as well to have a good capability for precise secondary vertex reconstruction

MPD physics: dileptons

Dileptons and photons ideally suited to probe the properties of dense QCD matter:

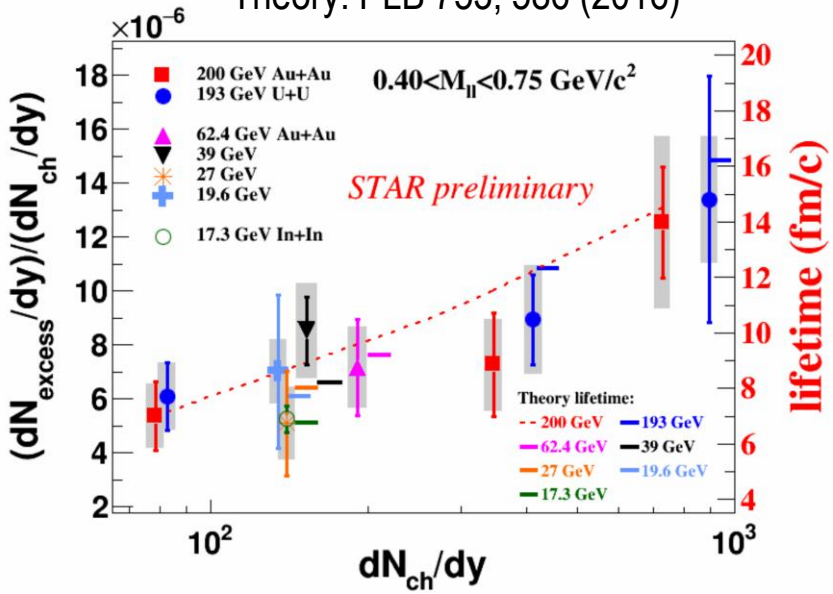
- ✓ provide time-integrated picture of the collision dynamics
- ✓ penetrating probes – no strong interactions in the medium
- ✓ emission is sensitive to the overall fireball lifetime, baryon density and T

Spectrum of dileptons

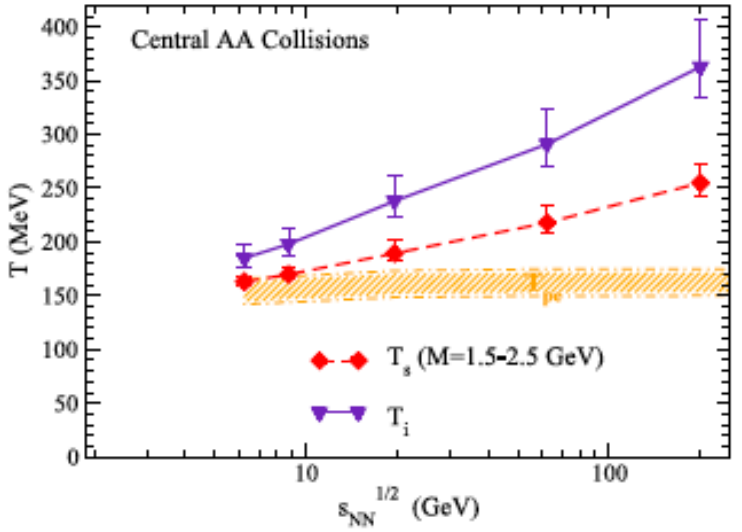


- **LMR:** In-medium modification (resonance melting prior to CSR) + thermal radiation from HG
- **IMR:** QGP thermal radiation + heavy-flavor contribution

Theory: PLB 753, 586 (2016)

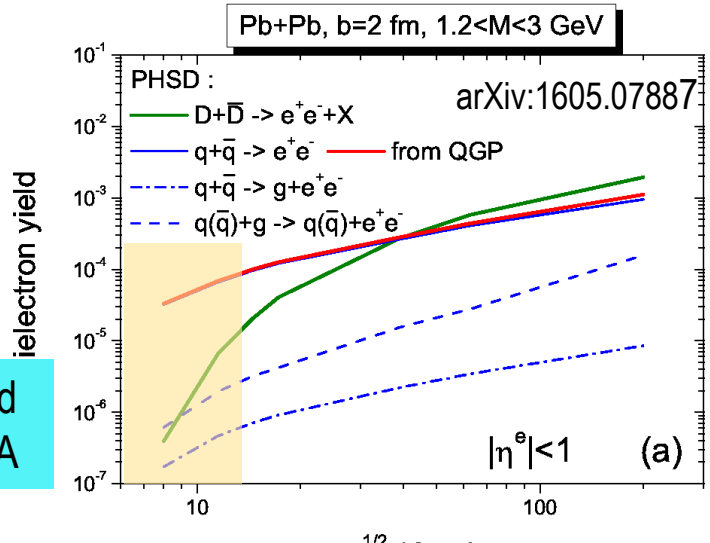


- The thermal radiation integrated in the LMR tracks the fireball lifetime



- The gap between initial Ti and measured Ts decreased towards NICA energies

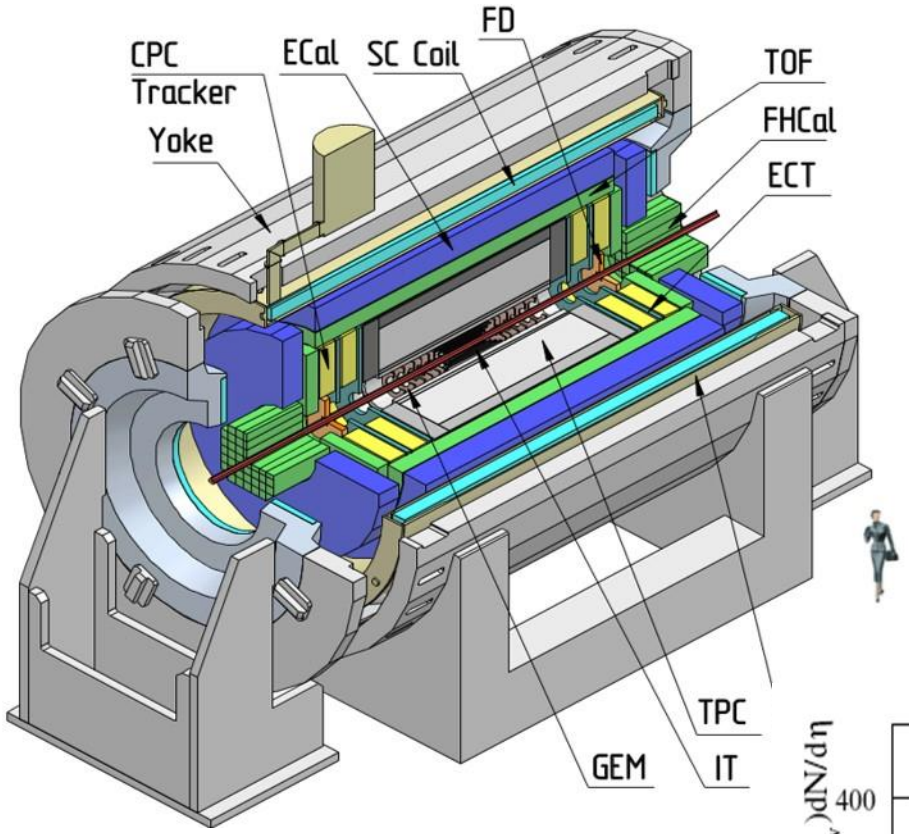
- Small contribution from correlated charm in dilepton spectra at NICA



MPD детектор.

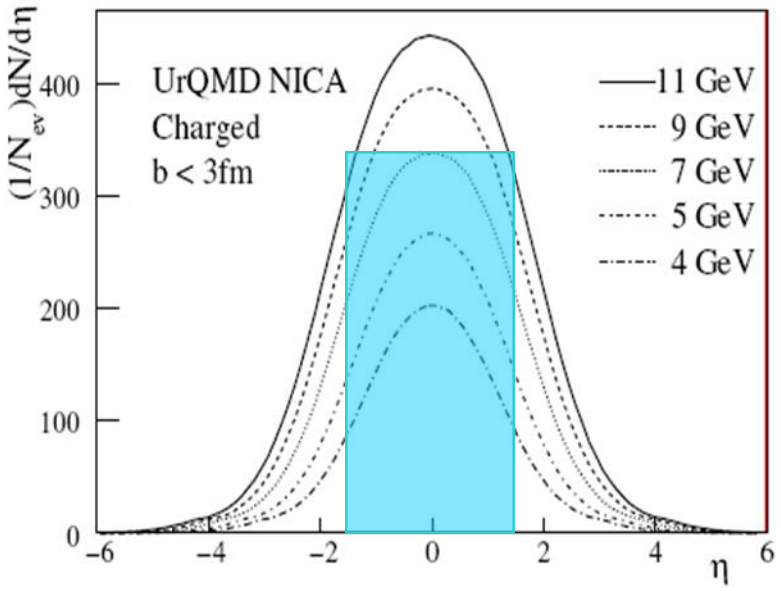
Конструкция, подсистемы и статус производства

MultiPurpose Detector for A+A collisions @ NICA

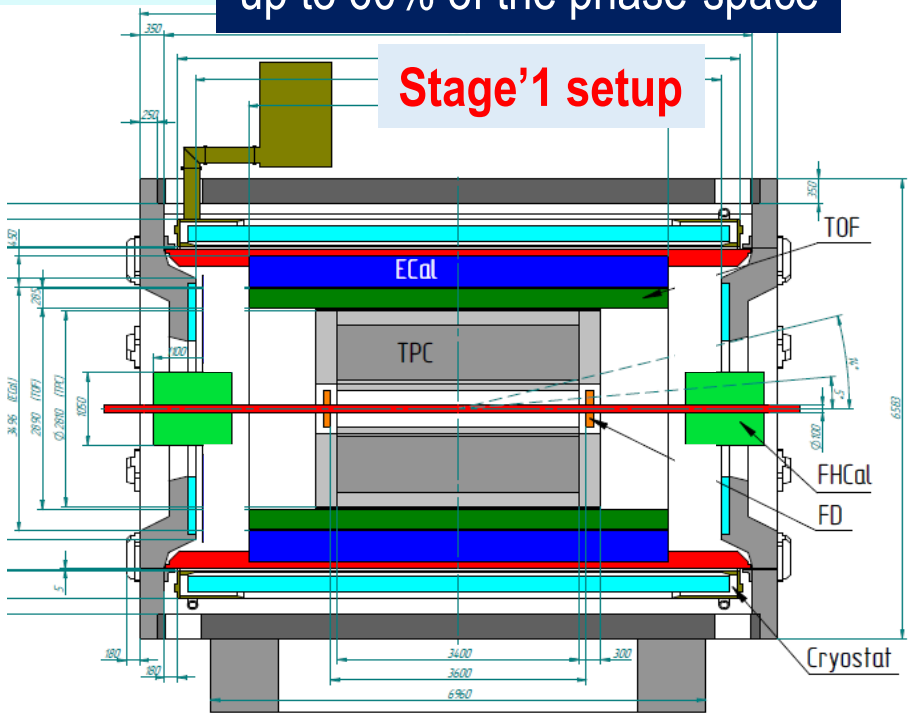


- 3D tracking (TPC,ECT), uniform acceptance, 2π in azimuth
- High resolution vertexing (IT)
- Powerful PID (TPC, TOF, ECAL)
  - π/K up to 2 GeV/c, K/p up to 3 GeV/c
  - γ, e : 0.1<p<3 GeV/c
- Precise event characterization (FHCAL)
- Fast timing and triggering (FFD)
- Low material budget
- High event rate (up to ~ 7 kHz)

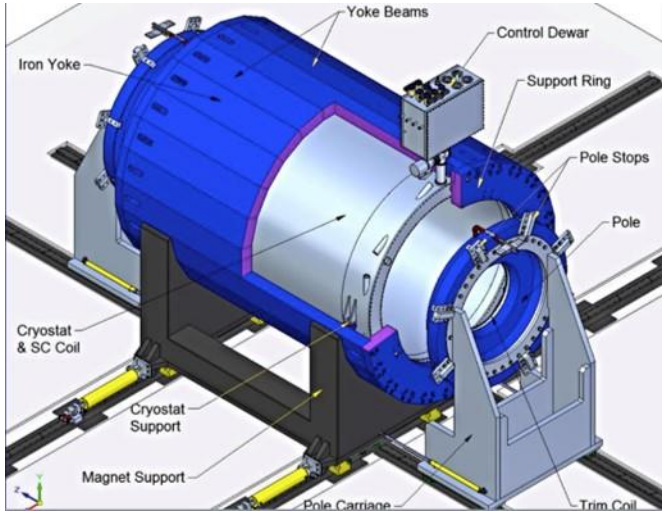
Stage'1 setup – extended midrapidty region (|η|<1.5)
up to 60% of the phase-space



I Stage (barrel part)
II Stage (full configuration)



MPD magnet: design & construction status



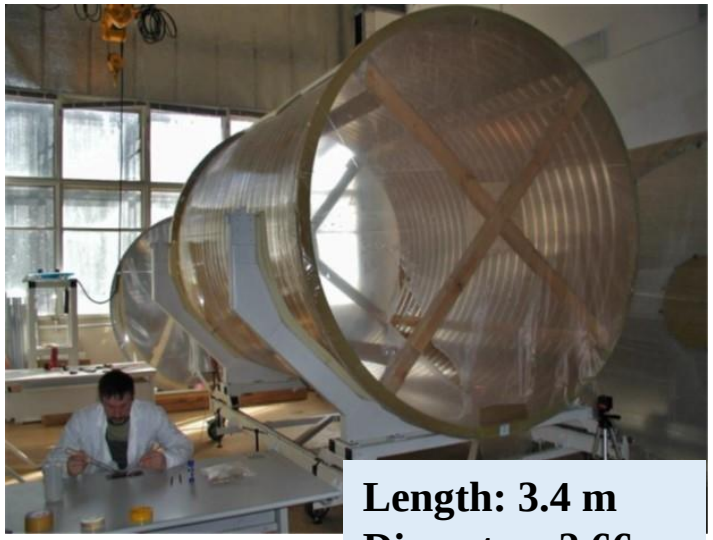
MPD Solenoid production stages (AGS superconductors, Genova, Italy)

Field – up to 0.6 T

Manufacturing	2016 - 2019
Packaging and Transportation	2020

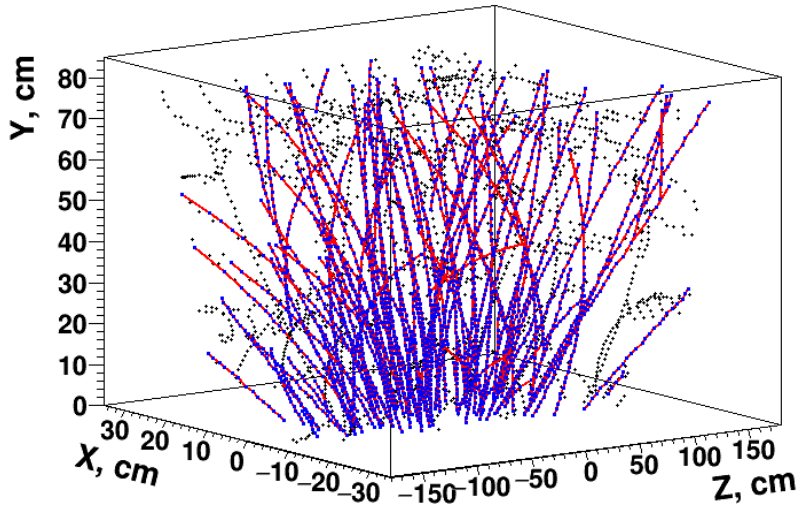
Magnet yoke (VHM, Vitkovice, Cech Rep.) – **delivered**

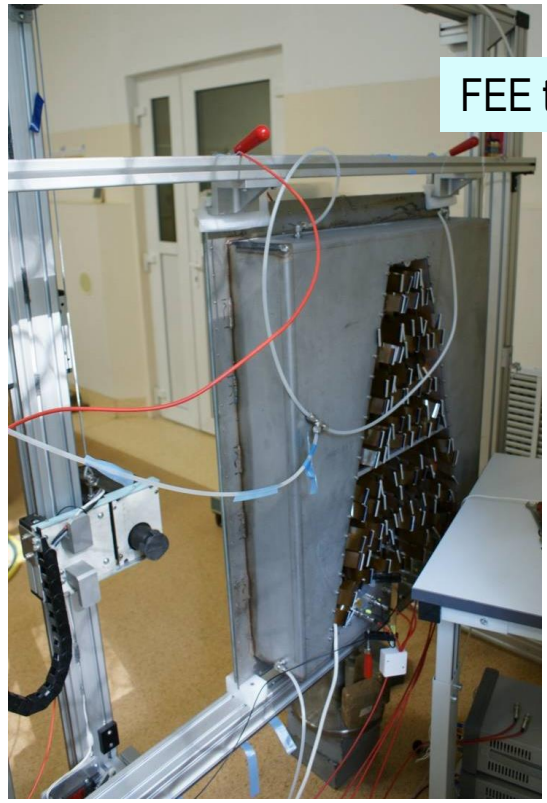
Main tracking in MPD: TPC design & construction status



Length: 3.4 m
Diameter: 2.66 m

Dimentions: 4m x 3m
Rate capability up to 7 kHz
Spatial resolution: $\sigma_{r\phi}$~300 μm, σ_z~ 2 mm
Momentum resolution: $\Delta p/p < 3\%$
dE/dx resolution: < 8%



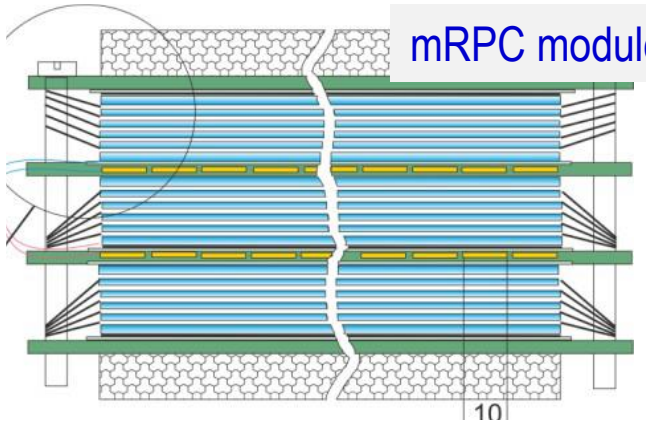


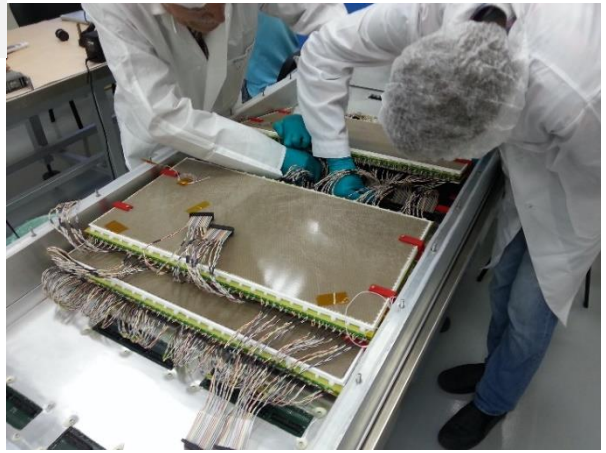
FEE tests

TPC manipulator

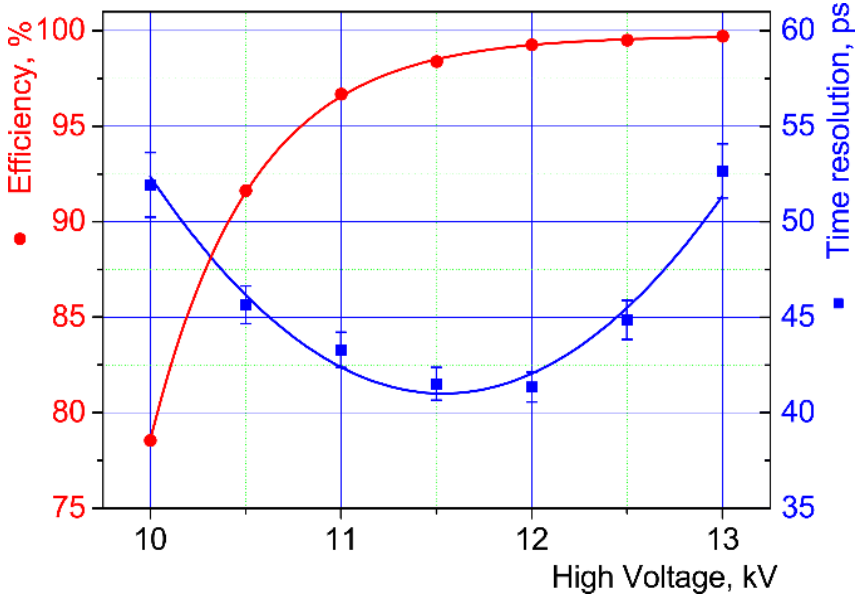
TPC fabrication - ongoing

Particle ID in MPD: mRPC TOF system

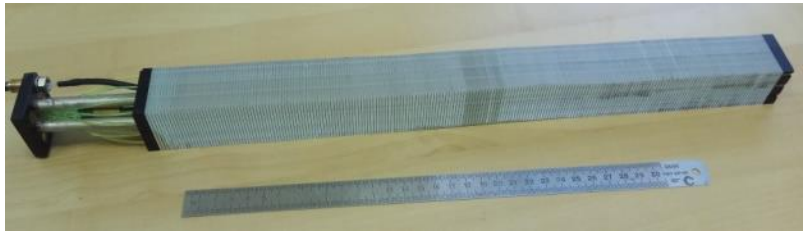




- σ_{TOF} ~ 80 ps



MPD Electromagnetic calorimeter - ECAL

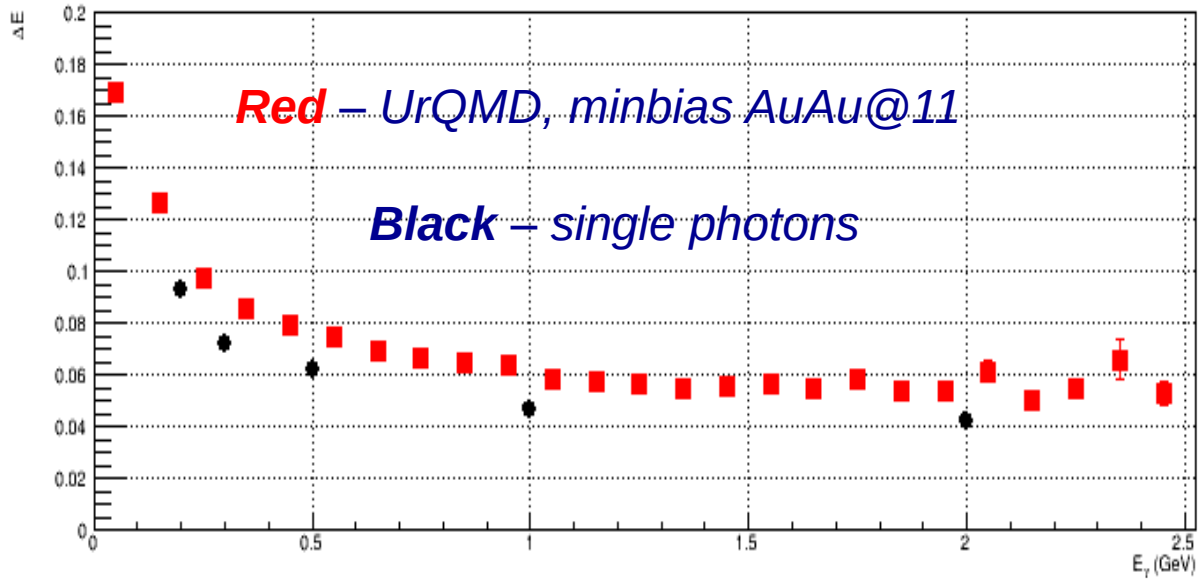


- Pb+Sc “Shashlyk”
- read-out: WLS fibers + MAPD
- L ~35 cm (~ 11.8 X0)
- Segmentation (4x4 cm2)
- σ(E) better than 5% @ 1 GeV
- time resolution ~500 ps

Projective geometry
Barrel ~ 37000 modules

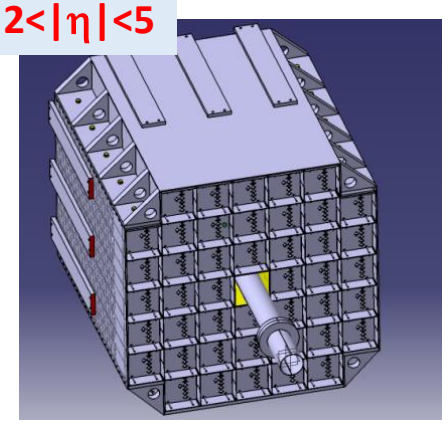
ECAL - high acceptance & purity e/γ identification:
- *good energy resolution*
- *projective geometry – uniform response*

Several production sites in China and Russia allow manufacturing all ECAL modules during 2020-2021



MPD Centrality & Event Plane Detector: FHCAL

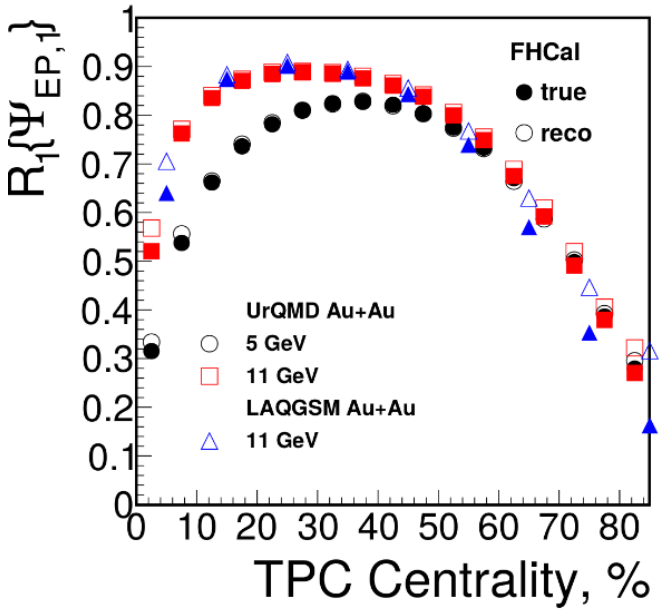
2<|η|<5



- Two-arms at ~3.2 m from the interaction point.
- Each arm consists of 45 individual modules.
- Module size 150x150x1100cm^3 (55 layers)
- Pb(16mm)+Scint.(4mm) sandwich
- 7 longitudinal sections
- 6 WLS-fiber/MAPD per section
- 7 MAPDs/module

Transverse granularity allowing:

- *the reaction plane with the accuracy* ~ 30^0



- **All FHCAL modules are ready**
- **FEE is ready**
- **Support platform is under construction**

MPD Civil Construction status

- MPD Hall close to ready for equipment installation

MPD Hall external covering

MPD Hall crane weight test

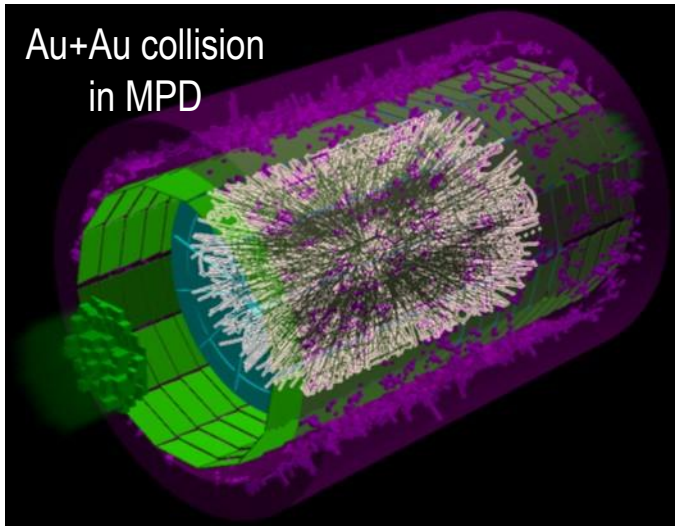
Transportation of MPD Magnet Yoke parts into the MPD pit (inside MPD Hall)

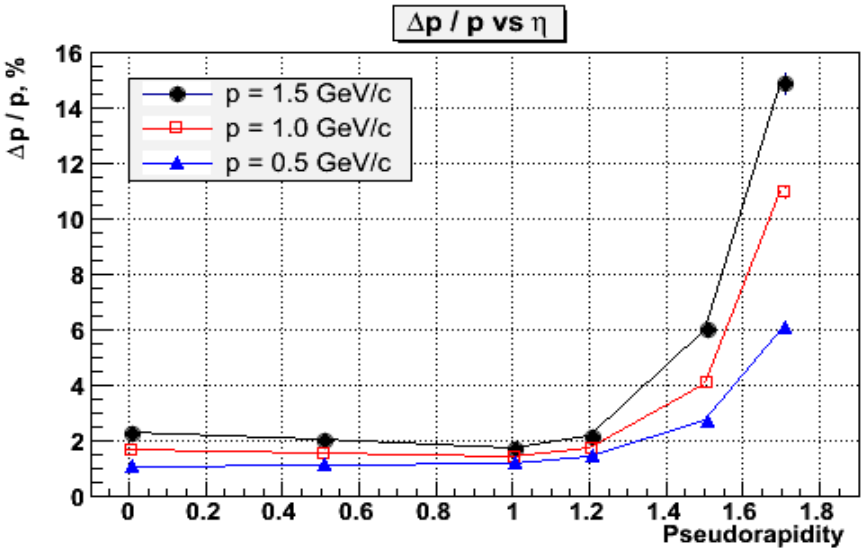
Результаты моделирования для MPD детектора.

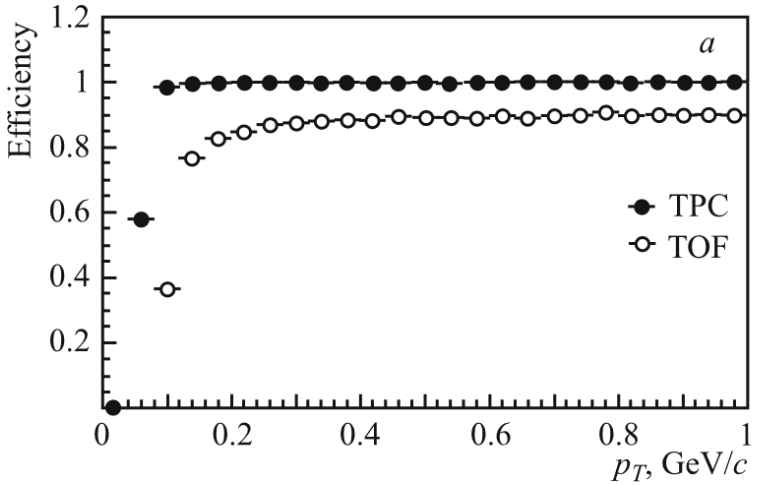
- Характеристики по трековосстановлению и идентификации
- Анализ выходов адронов и их отношений
- Перспективы по поиску критической точки
- Дилептоны
- Гипероны и гиперядра

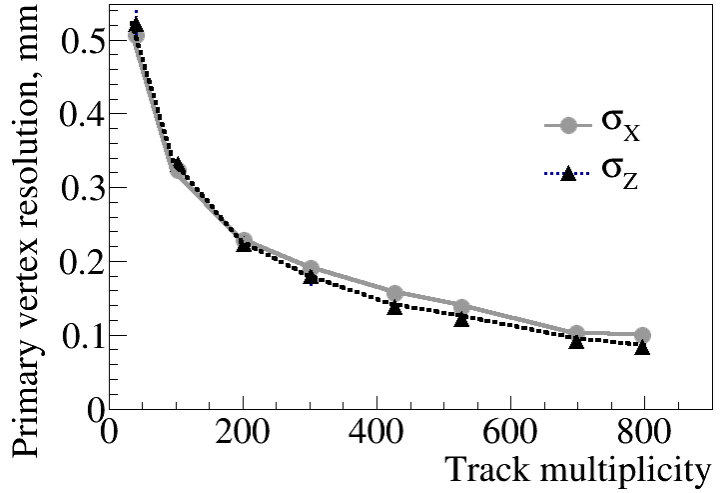
MPD tracking & PID performance

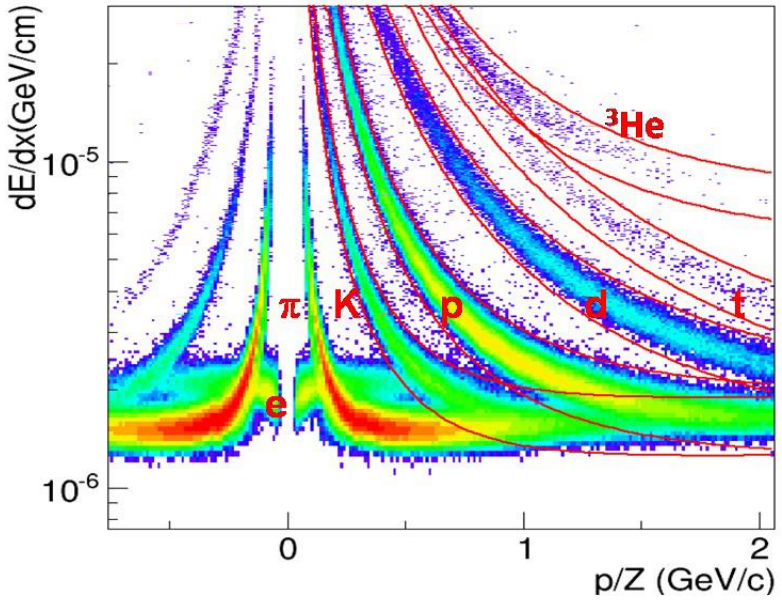
Based on realistic event simulation within the MPDRoot framework

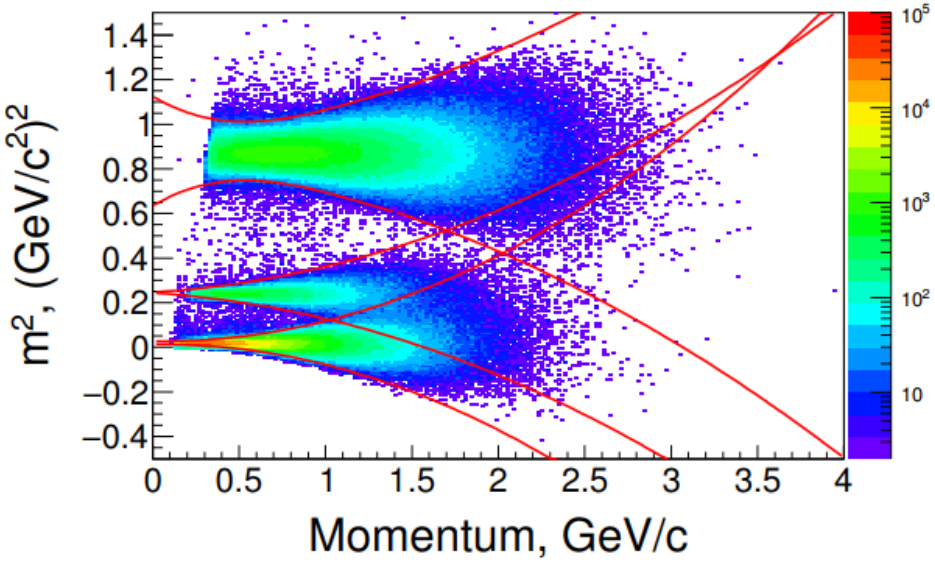








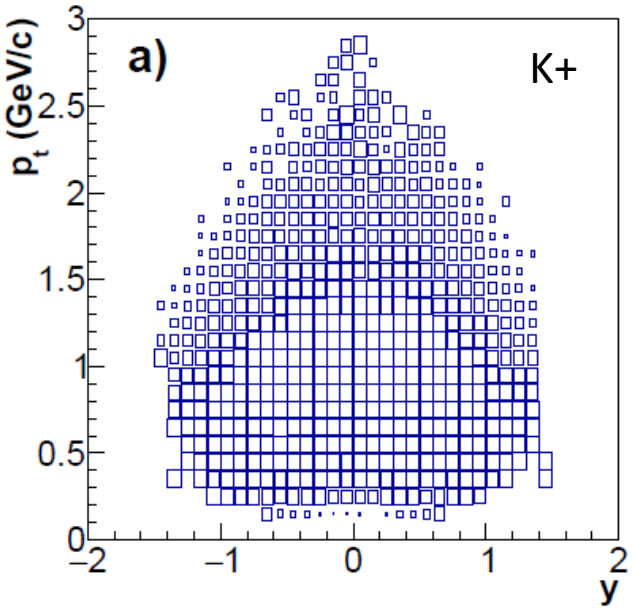


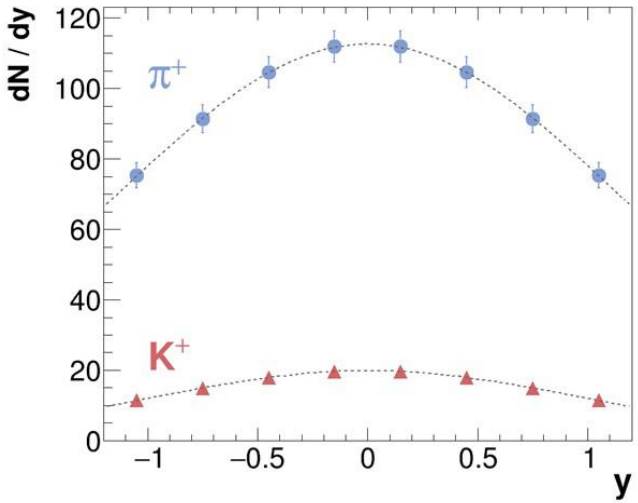


- **High tracking efficiency over the reaction phase-space**
- **Efficient vertexing**
- **Combined (dE/dx+TOF) PID for hadrons provides π/K up to 2 GeV/c and K/p up 3 GeV/c**

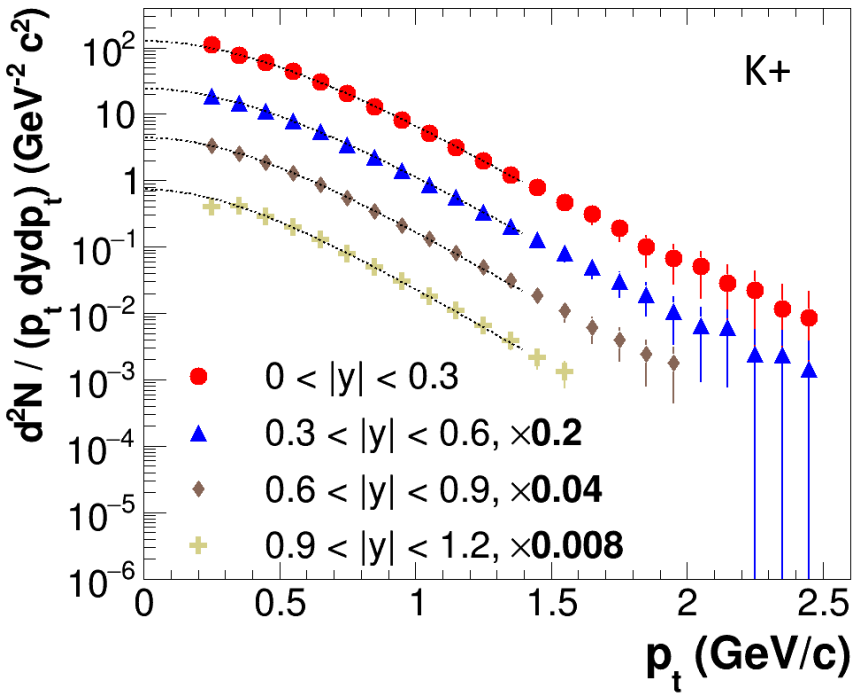
Hadroproduction with MPD

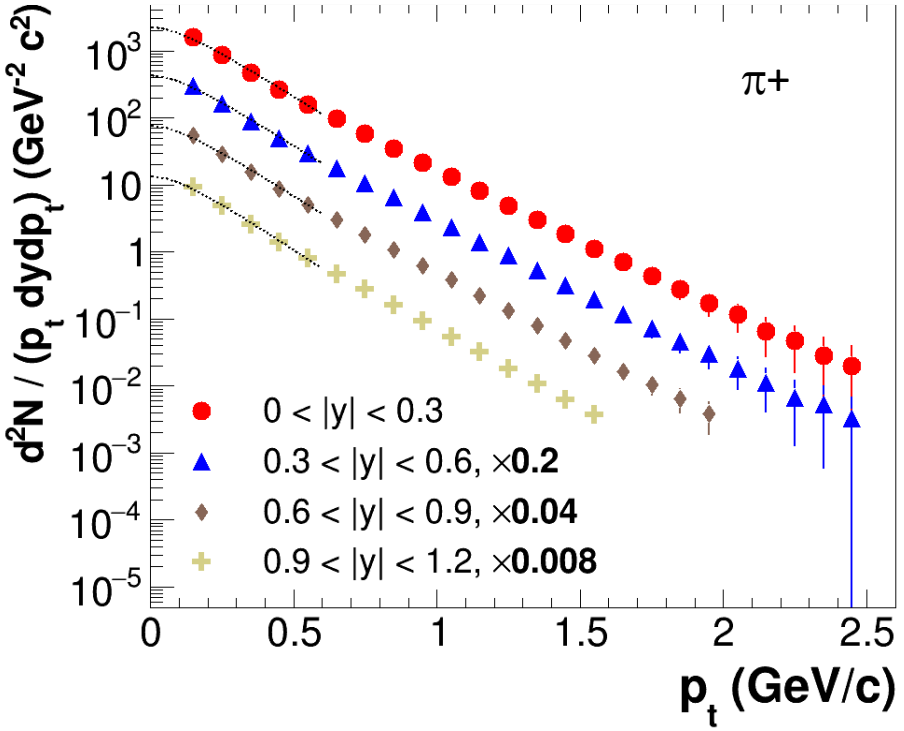
- Particle spectra, yields & ratios are sensitive to bulk fireball properties and phase transformations in the medium
- Uniform acceptance and large phase coverage are crucial for precise mapping of the QCD phase diagram





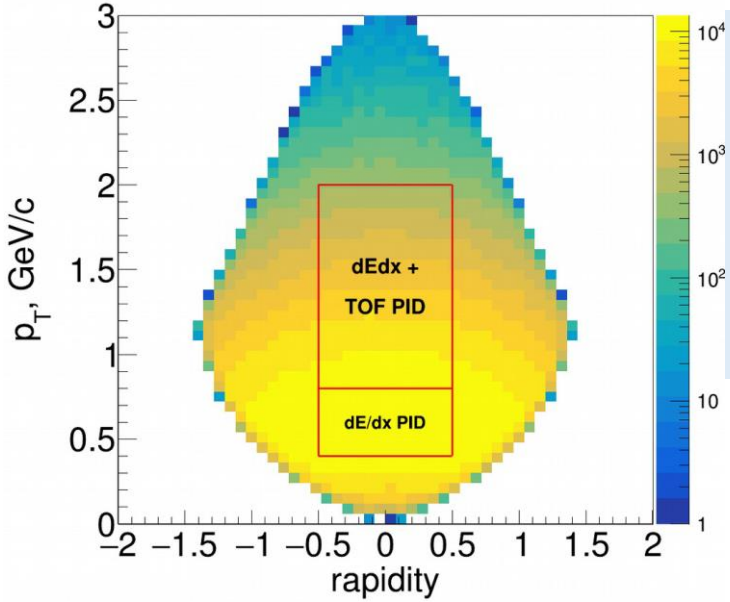
- MPD provides large phase-space coverage for identified pions and kaons (> 70% of the full phasespace at 9 GeV)
- Hadron spectra can be measured from pT=0.2 to 2.5 GeV/c
- Extrapolation to full pT-range and to the full phase space can be performed exploiting the spectra shapes (see BW fits for pT-spectra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





MPD prospects for the QCD critical end point (CEP) search: net-proton cumulants

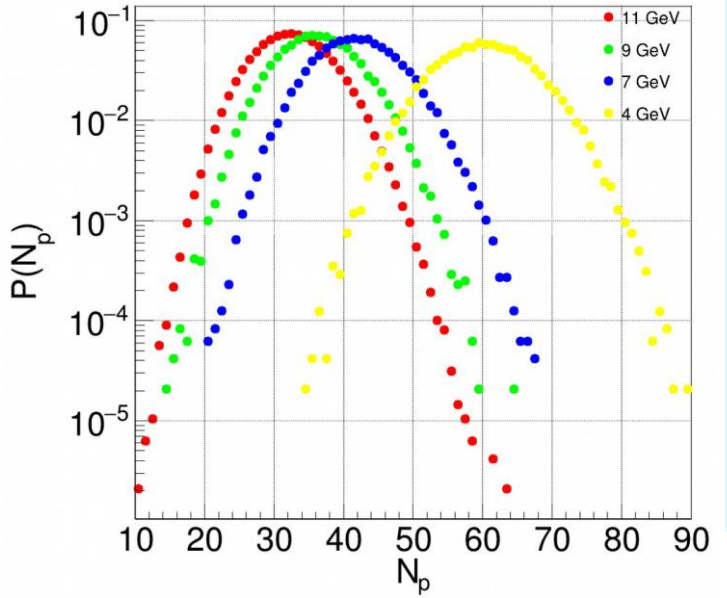
Cumulant ratios of net-proton multiplicity distribution are directly compared to susceptibilities, which diverge in the proximity of CEP in central A+A collisions



- Au+Au 5% central (PHSD model)
- Full MPD reconstruction
- Combined dE/dx+TOF particle ID

for (anti)protons: p-pbar=net-protons

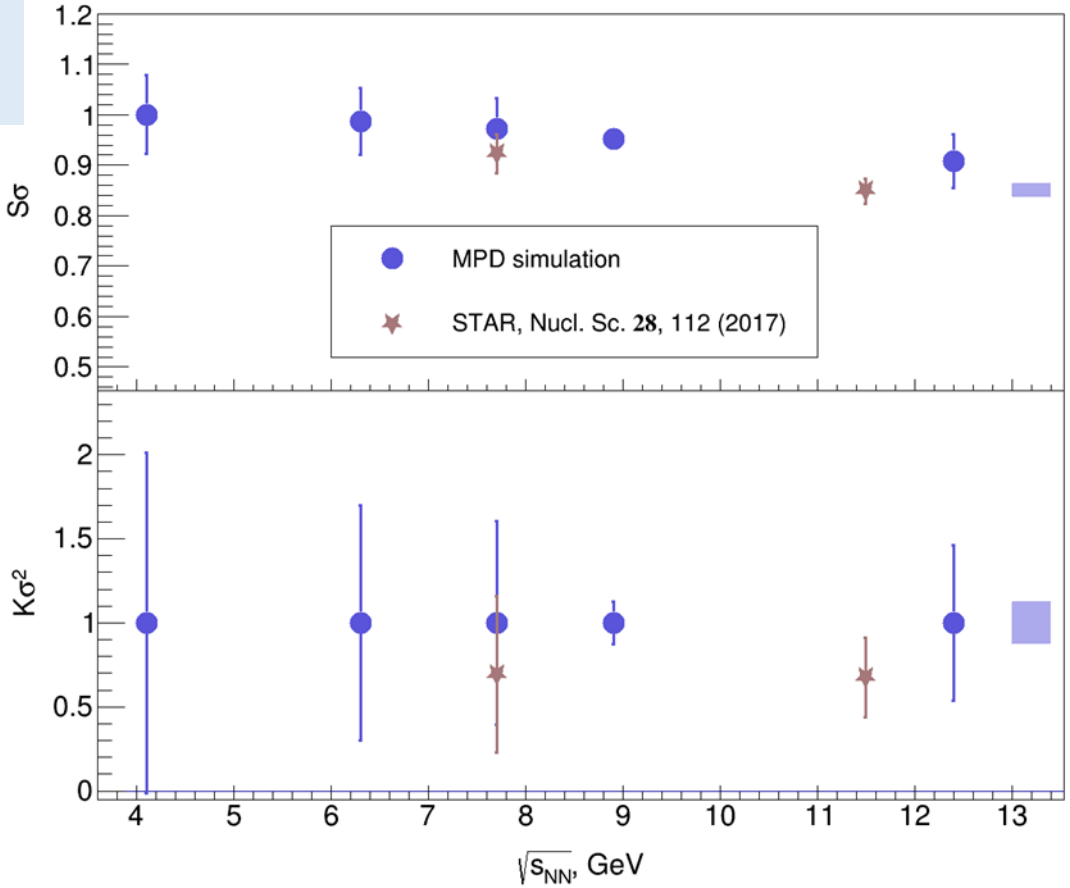
Corrections for the MPD inefficiency:
A..Bzdak and V. Koch,
Phys. Rev. C 86, 044904 (2012)



- **MPD detector provides a large midrapidity phase-space**
- **From 35 to 65 identified p-pbar (Au+Au, |y|<0.5, pT<1.8 GeV/c)**
- **Event statistics above 1Mevents provides sufficient precision of measurements**

$$\frac{k_3}{k_2} = S\sigma \qquad \frac{k_4}{k_2} = K\sigma^2$$

Cumulant ratio at MPD within
|y| < 0.5 and 0.2 < pT < 2.0 GeV/c



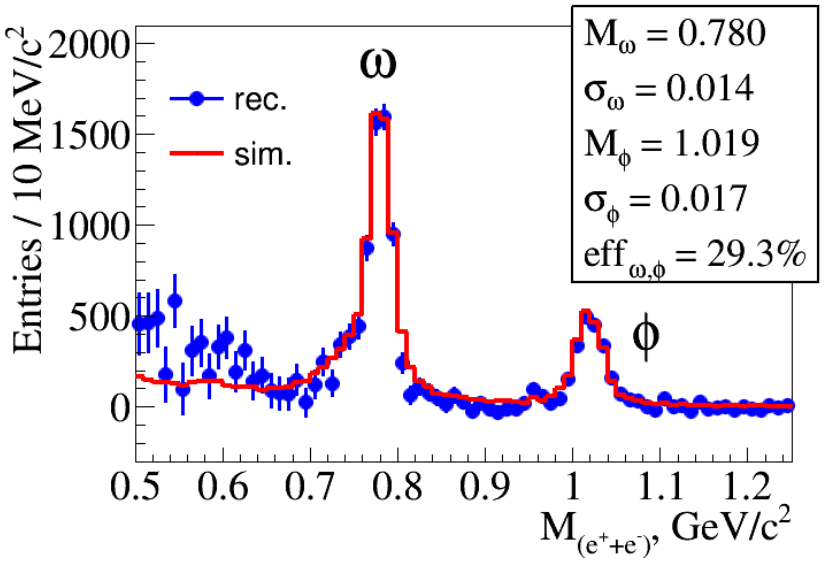
MPD prospects for dileptons

Electromagnetic probes ideally suited to probe the properties of dense QCD matter:

MPD SIMULATION RESULTS

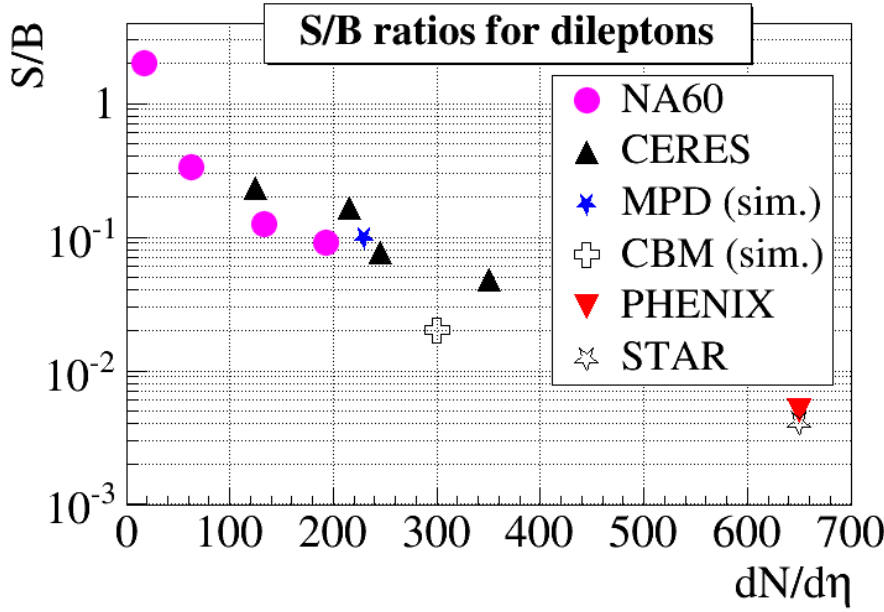
- **Data set:** central Au+Au @ 7 GeV (UrQMD+cocktail)
- **PID** : dE/dx (from TPC) + TOF + ECAL

Invariant mass of dileptons (background subtracted): red-MC, blue- reco.



Promising results for studying dileptons at MPD/NICA

Signal-to-Background ratio ($0.2<Mi_{e+e-}<1.1$) in A+A collisions

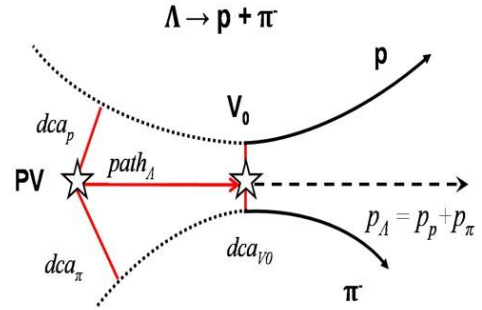


Particle	Yields		Decay mode	BR	Effic. %	Yield/1 w
	4π	y=0				
ρ	31	17	e+e-	$4.7 \cdot 10^{-5}$	35	$7.3 \cdot 10^{4}$
ω	20	11	e+e-	$7.1 \cdot 10^{-5}$	35	$7.2 \cdot 10^{4}$
φ	2.6	1.2	e+e-	$3 \cdot 10^{-4}$	35	$1.7 \cdot 10^{4}$

Hyperon reconstruction in MPD

- Excitation function of hadrons (yields, spectra, and ratios) → EOS and chemical equilibrium be probed
- Hyperons sensitive to early stage and phase transformations in QCD medium → lack of data at NICA energies

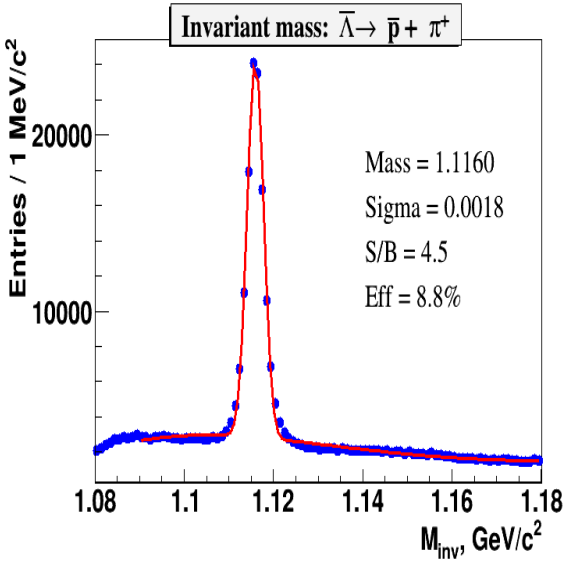
- ***8****M Au+Au @ 11 GeV (PHSD)*
- *TPC & TOF, $|\eta| < 1.3$*
- *track reconstruction and PID (dE/dx+TOF)*
- *secondary vertex finding technique*

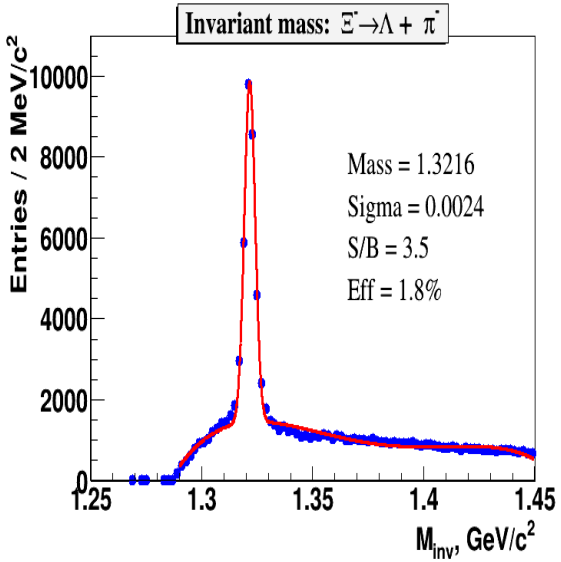


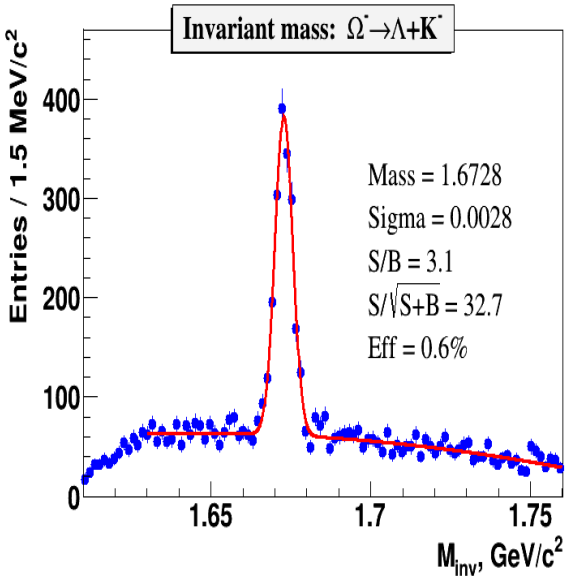
PV *- primary vertex*
V0 *- vertex of decay*
dca- *distance of closest approach*
path *– decay length*

Yields for 1 week of running (Stage'1)

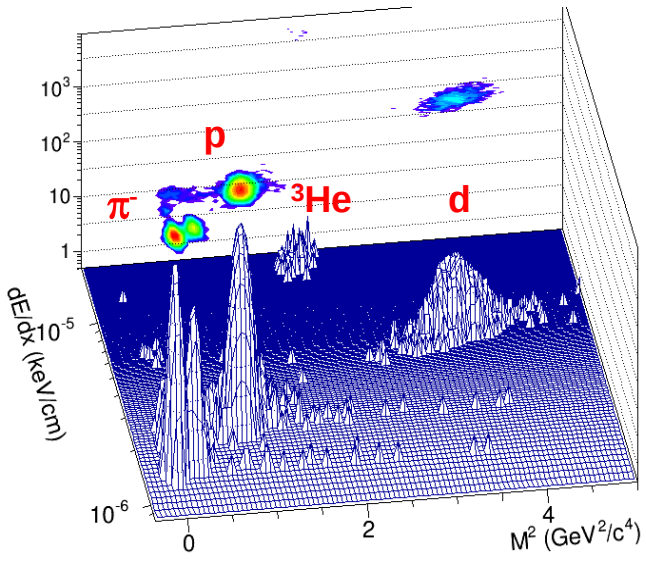
Λ	anti-Λ	Ξ⁻	anti-Ξ⁺	Ω⁻	anti–Ω⁺
$2 \cdot 10^7$	$3.5 \cdot 10^5$	$1.5 \cdot 10^5$	$8.0 \cdot 10^3$	$7 \cdot 10^3$	$1.5 \cdot 10^3$





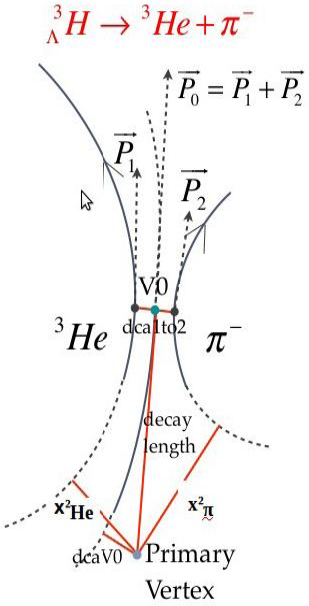


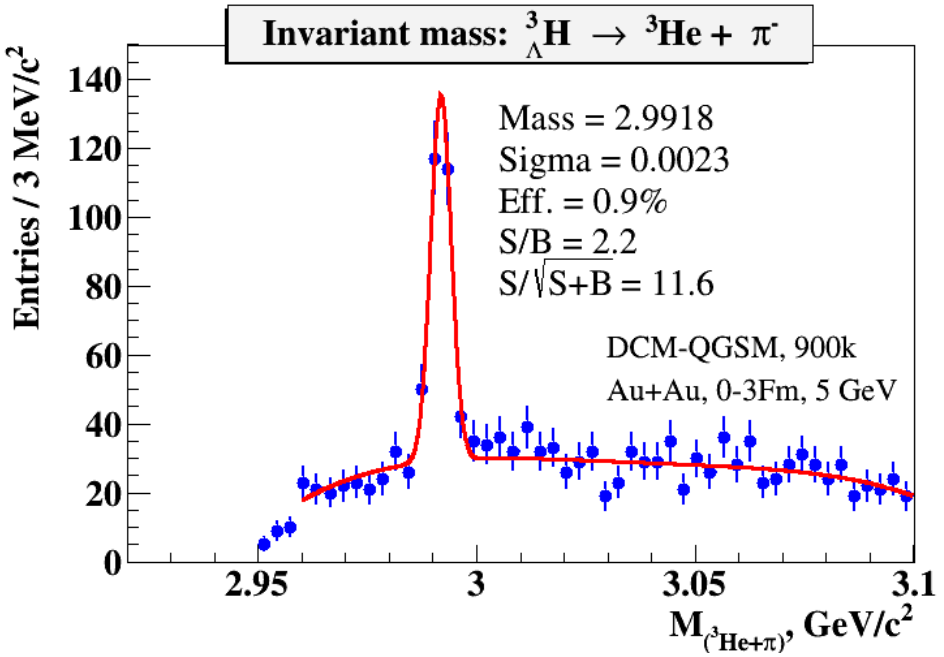
Hypertriton reconstruction with MPD

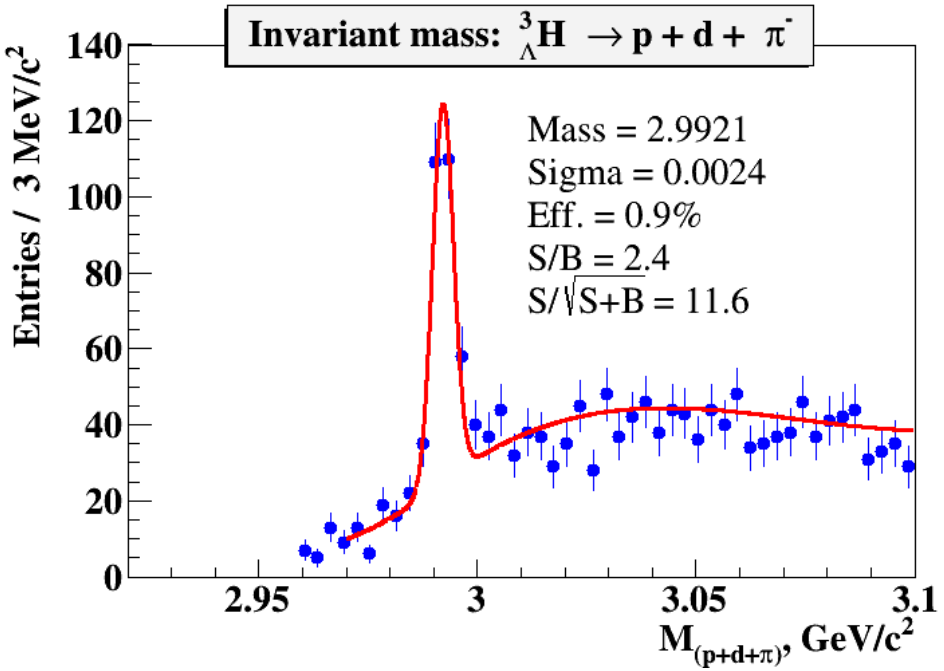


- **Generator: 900k** central Au+Au @ 5 GeV (DCM-QGSM[1])
- **Detectors:** MPD Satge'1 configuration (barrel)
- **Track acceptance criterion:** $|\eta| < 1.3$, $N_{hits} \geq 10$
- Realistic track reconstruction and PID (TPC + TOF)

[1] J. Steinheimer, K. Gudima, et al, Phys. Lett. B 714 (2012) pp 85-91







A signal of 400 $_\Lambda{}^3$H is seen (~2 days of data taking)

MPD Collaboration

33 institutions from 10 countries + JINR, 475 Collaboration members

Conclusions

- **NICA complex has a potential for competitive research in the fields of dense baryonic matter, spin physics, applied research and medicine**
- **The construction of accelerator complex and research infrastructure is progressing close to the schedule**
- **The international collaboration around the NICA is growing. New partners are invited to join NICA**

Thank you for the attention!