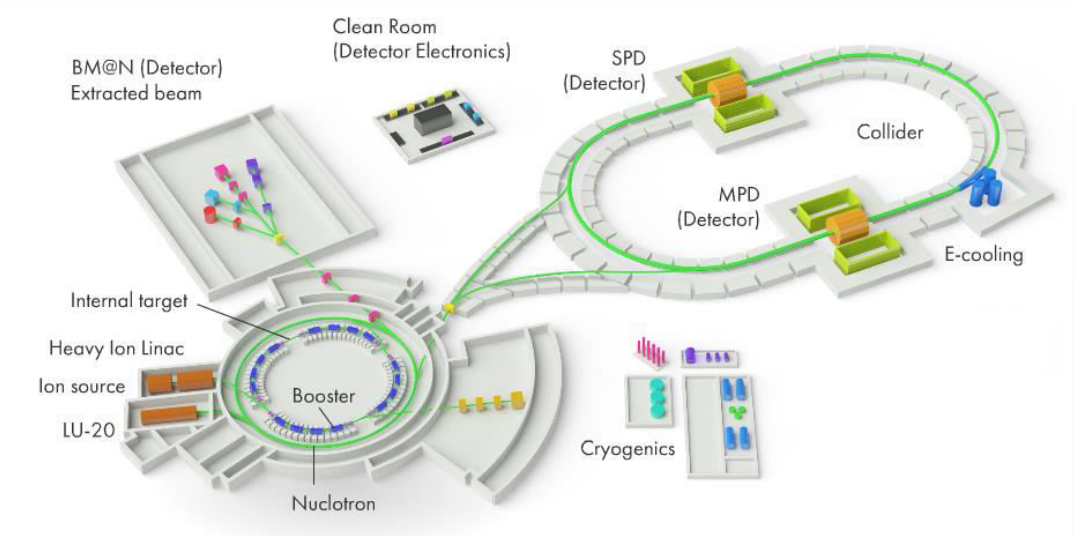
Nuclotron-based
Ion Collider fAcility

Experiments at NICA facility

V. Riabov for NICA Collaborations

Nuclotron-based **I**on **C**ollider f**A**cility **(NICA)**



- ❖ Heavy-ion beams, fixed-target and collider (up to Au, $\mathcal{L} = 10^{27}$ cm^{-2}s^{-1}, $\sqrt{s_{NN}}$= 2.4-11 GeV) → strongly-interacting matter at extreme conditions of maximum baryonic density

Ion sourse (KRION-6T)
Heavy Ion Linac (HILac)
Booster
BM@N (Detector)
MPD (Detector)

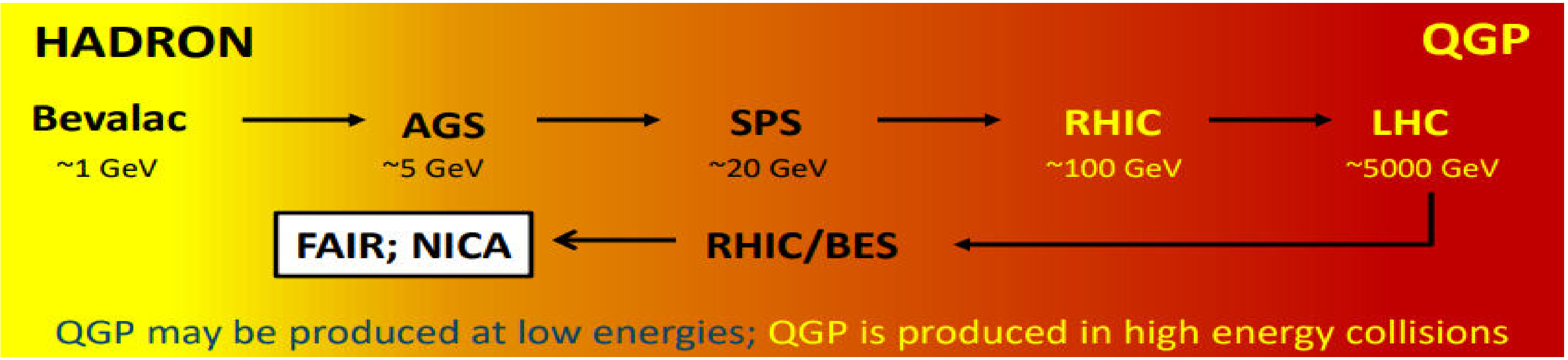
- ❖ Polarized beams of protons and deuterons in the collider (up to $\mathcal{L} = 10^{32}$ cm^{-2}s^{-1}, $\sqrt{s_{NN}}$= 12.6 (d) 27 (p) GeV) → nucleon spin structure research and clarification of the spin origin

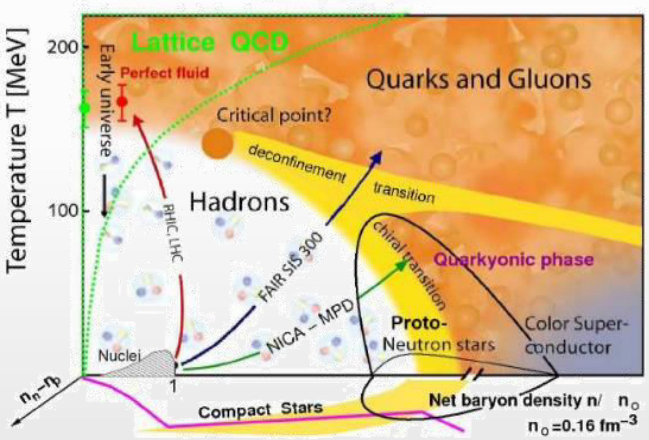
LU-20
Nuclotron
SPD (Detector)

- ❖ NICA project is approaching its full commissioning:
  - ✓ already running in the fixed-target mode – BM@N, ARIADNA
  - ✓ start of operation in collider mode in 2025 – MPD and later SPD

Heavy-ion program

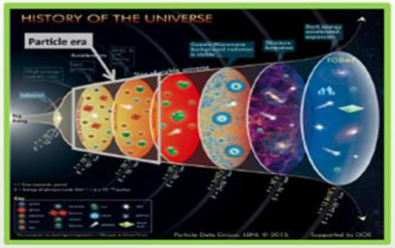
Heavy-ion collisions





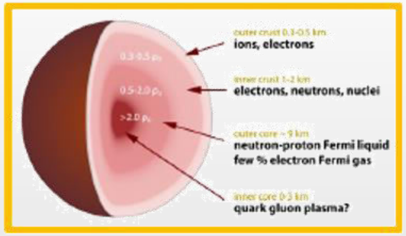
High beam energies ($\sqrt{s_{NN}} > 100$ GeV)

High temperature:
Early Universe evolution



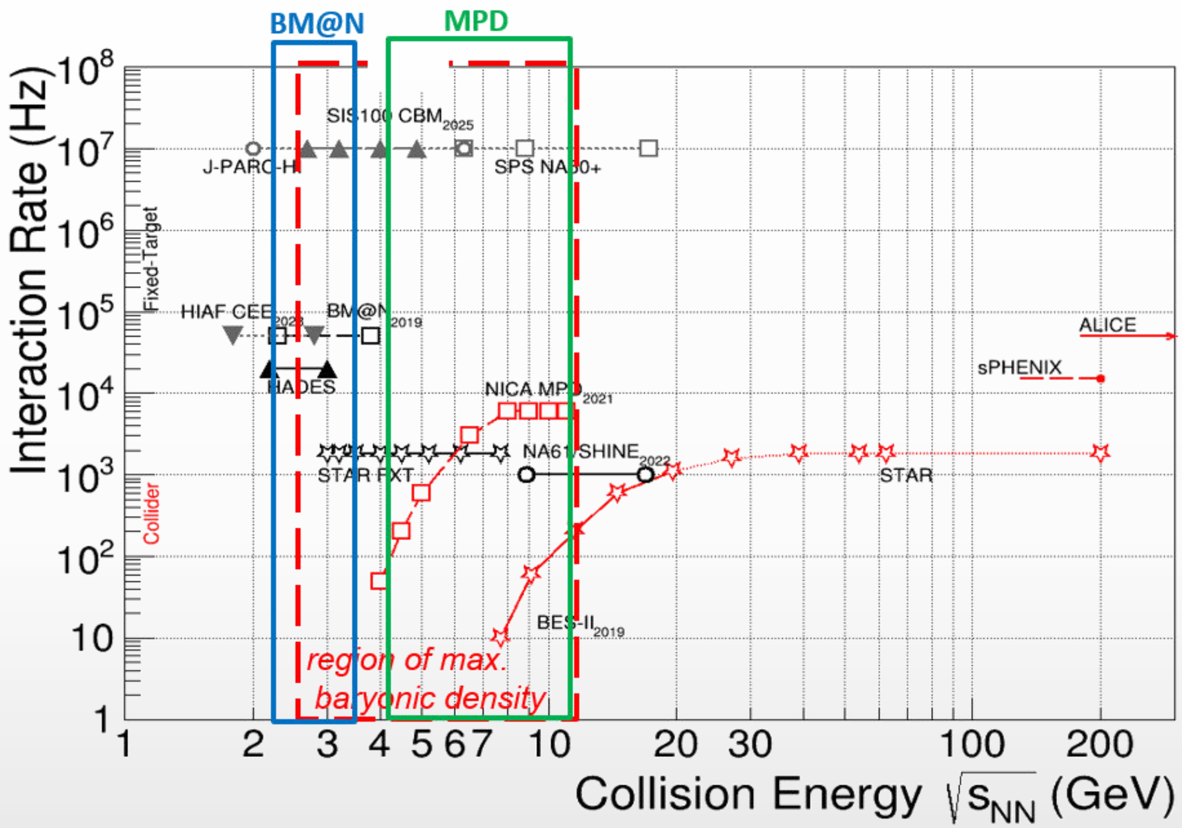
Low beam energies ($\sqrt{s_{NN}} \sim 10$ GeV)

high baryon densities
→ inner structure of
compact stars



- At $\mu_B \sim 0$, smooth crossover (lattice QCD calculations + data)
- At large μ_B, 1st order phase transition → QCD critical point
- MPD @NICA → study QCD medium at extreme net baryon densities

Heavy ion experiments



competitors:

Present:

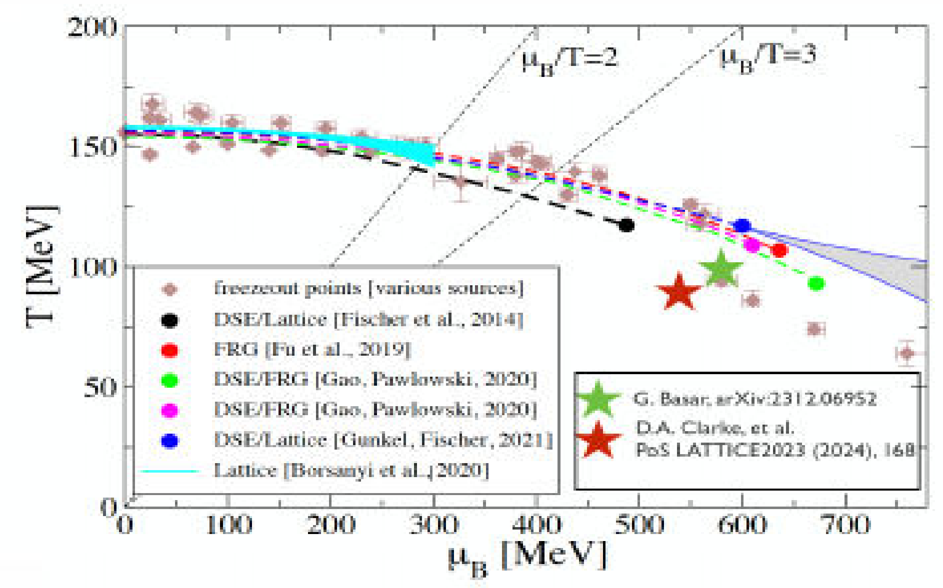
RHIC/STAR (USA)
3-200 GeV
SIS18/HADES (Germany)
2.4-2.55 GeV

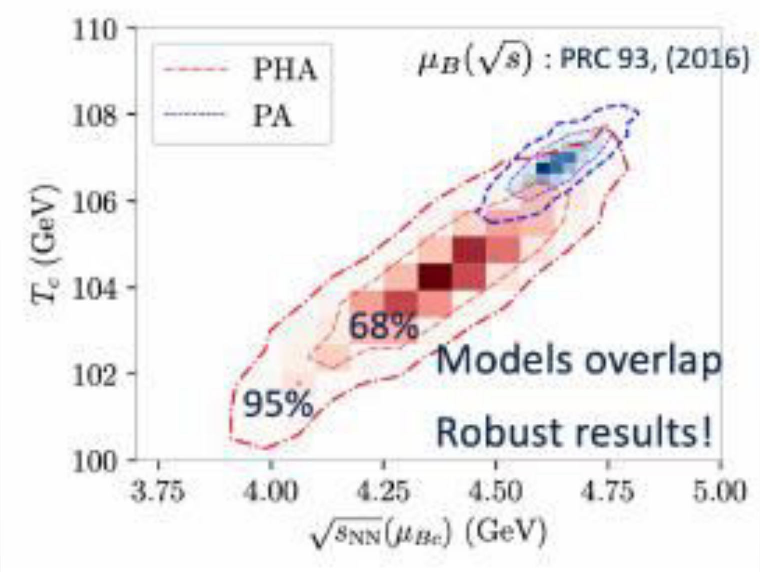
Future:

HIAF/CEE (China)
2.1-4.5 GeV (2026-?)
FAIR/CBM (Germany)
2.4-4.9 GeV (2029-?)
JPARC-HI (Japan)
2-5 GeV (2030-?)

BM@N: $\sqrt{s_{NN}}$= 2.3 - 3.3 GeV
MPD: $\sqrt{s_{NN}}$= 2.4 - 11 GeV

QCD critical point: predictions/estimations





M. Hippert et al., Phys. Rev. D 110, 094006 (2024)

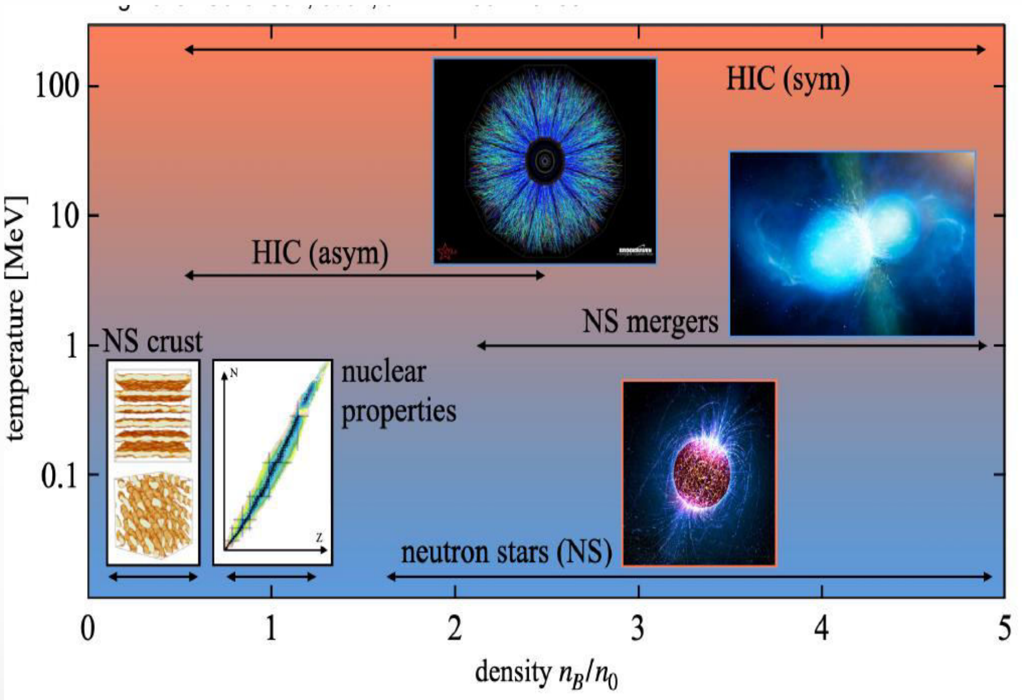
Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	F. Karsch et al.
Summary	**495 - 654**	**100 - 119**

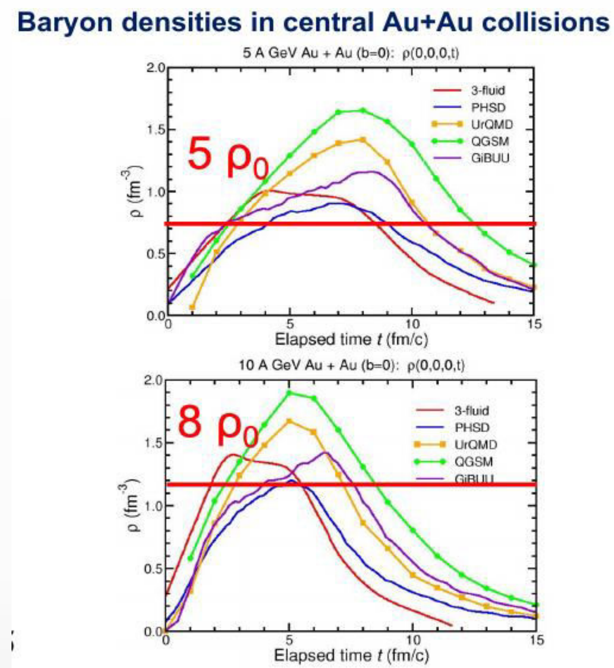
BM@N: $\sqrt{s_{NN}}$= 2.3 - 3.3 GeV
MPD: $\sqrt{s_{NN}}$= 2.4 - 11 GeV

(μ_c, T_c) = (495 - 654, 100 - 119) MeV → $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

BM@N and MPD in the collision energy range of the predicted CEP location

Dense Nuclear Matter





I. C. Arsene et al., Phys. Rev. C 75, 034902 (2007)

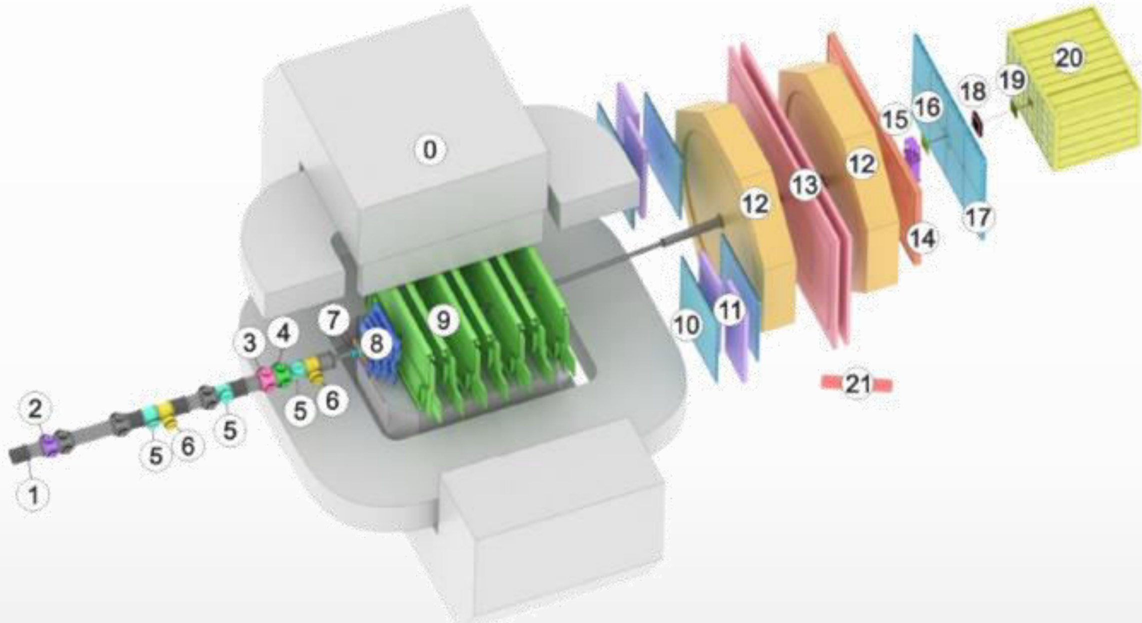
- Neutron star mergers LIGO and Virgo Collaborations, Phys. Rev. Lett. 119 (2017) 16, 161101; Nature Phys. 15 (2019) 10, 1040-1045
  - ✓ gravitational wave detection from GW170817, confirmation by astronomical observations
  - ✓ T < 70 MeV, ρ ~ 3ρ0 → about the same conditions as achieved in HIC in the laboratory

- Hyperon and hyper-nuclei measurements in HIC → hyperon–nucleon interactions (NY, YNN)
  - ✓ key to understanding the EoS at high baryon density and inner structure of neutron stars

Relativistic heavy-ion collisions provide a unique and controlled experimental way to study the properties of nuclear matter at high baryon density

Baryonic **M**atter @ **N**uclotron

Nucl.Instrum.Meth.A 1965 (2024) 169352



- Magnet SP-41 (0)
- Vacuum Beam Pipe (1)
- BC1, VC, BC2 (2-4)
- SiBT, SiProf (5, 6)
- Triggers: BD + SiMD (7)
- FSD, GEM (8, 9)
- CSC 1x1 m^2 (10)
- TOF 400 (11)
- DCH (12)
- TOF 700 (13)
- ScWall (14)
- FD (15)
- Small GEM (16)
- CSC 2x1.5 m^2 (17)
- Beam Profilometer (18)
- FQH (19)
- FHCal (20)
- HGN (21)

FSD, GEM, CSC, DCH: charged particle tracking + momentum measurements

TOF400, TOF700: charged particle identification by m^2/β

FQH, FHCAL: event geometry, event centrality

Several technical runs since 2015

First physics run in 2022/2023: ^{124}Xe + CsI at 3 and 3.8 AGeV, > $5.5 \cdot 10^8$ events

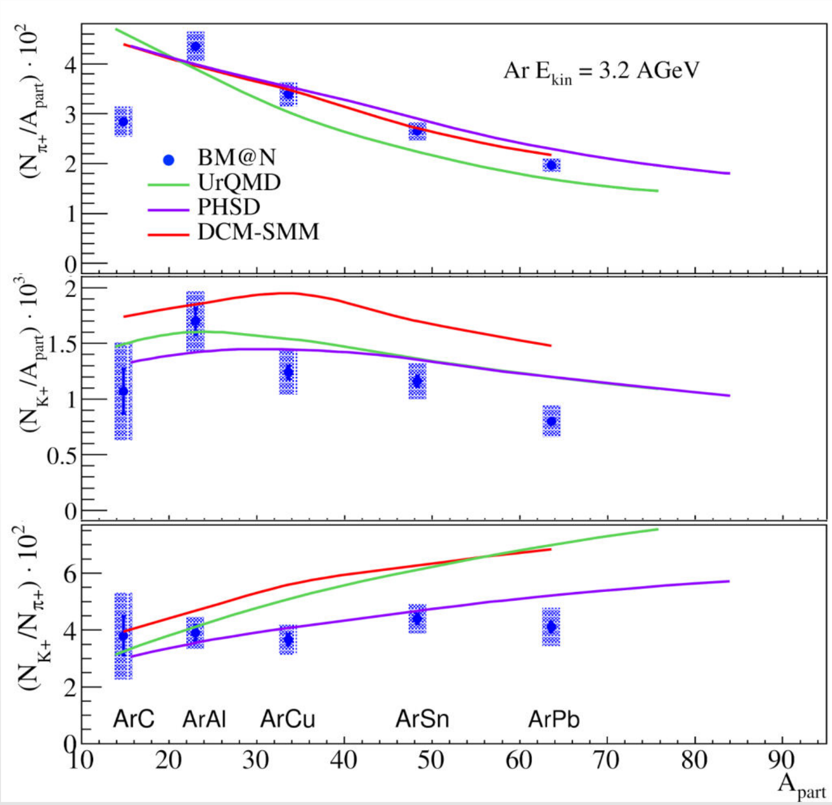
Physics run in 2025 with new silicon micro-strip detectors and extended ToF-400 acceptance

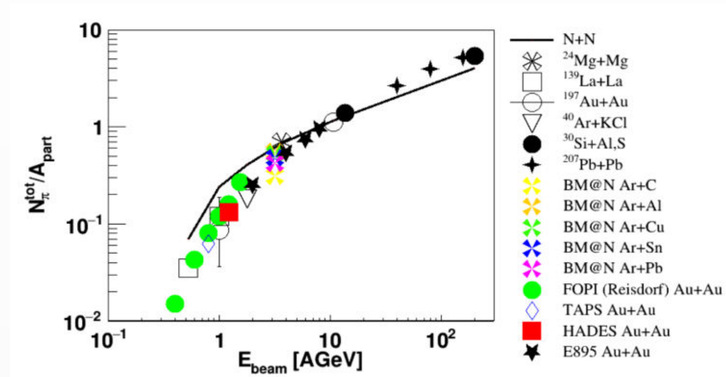
V. Zharova (INR RAS) Investigation of compensation properties of the forward hadron calorimeter at the BM@N experiment
V. Volkov (INR RAS) Performance study of the scintillation wall in the first BM@N physics run

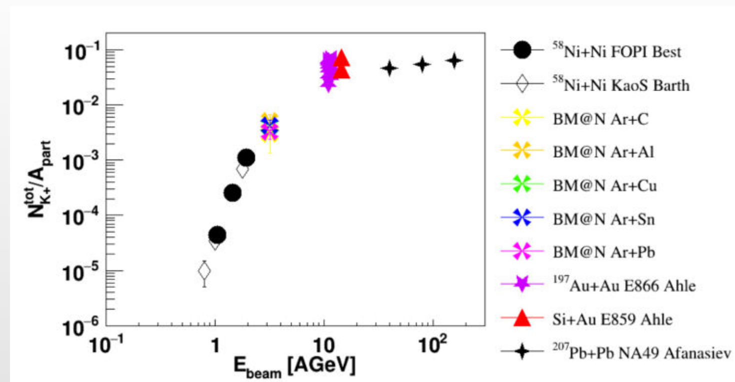
Production of π^+ and K^+ mesons in argon-nucleus interactions at 3.2 AGeV

❖ Technical run with Ar beam at 3.2 AGeV and C/Al/Cu/Sn/Pb targets

JHEP 07 (2023) 174





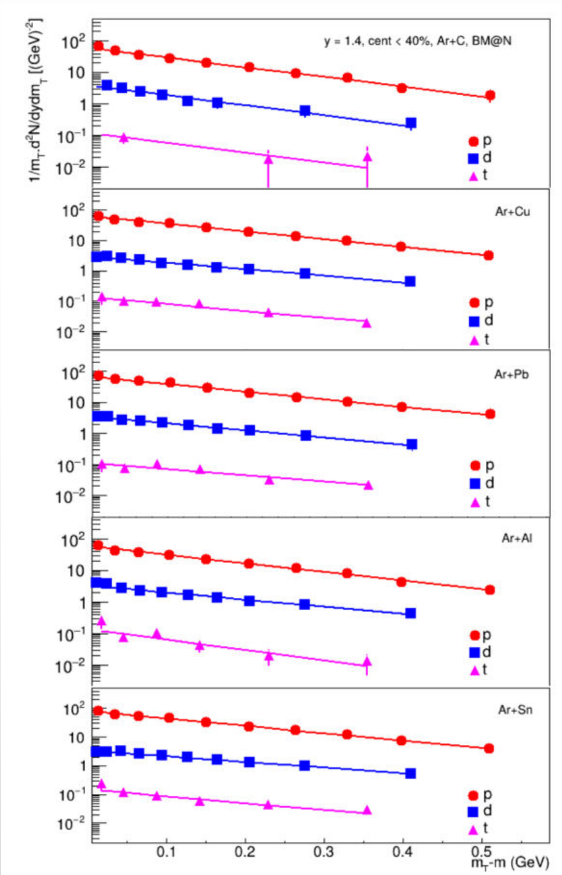


- The ratios of K^+ to π^+ multiplicities show no significant dependence on the mean number of participant nucleons A_{part}
- PHSD is compatible with this result, DCM-SMM and UrQMD predict a smooth rising of the ratio
- The BM@N results are in trend with the world measured data

Production of p, d, t in Ar-Nucleus interactions

❖ Technical run with Ar beam at 3.2 AGeV and C/Al/Cu/Sn/Pb targets

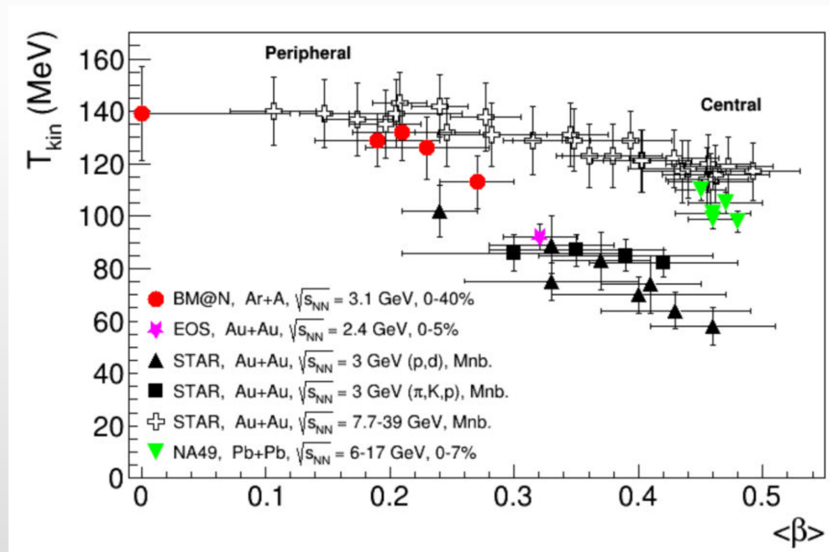
https://arxiv.org/abs/2504.02759, submitted to JHEP



Blast-Wave model parametrization:

$$\frac{1}{m_T}\frac{d^2N}{dm_T dy} = C(y)\int_0^R m_T K_1\left(\frac{m_T\cosh\rho(r)}{T}\right) I_0\left(\frac{p_T\sinh\rho(r)}{T}\right) r dr$$

The average radial flow velocity ⟨β⟩ and source temperature T_{kin} at the kinetic freeze-out extracted from fit:



❖ dN/dy spectra are softer for heavier targets

❖ Models describe the shapes of rapidity dependences, but underestimate yields by a factor of ~5

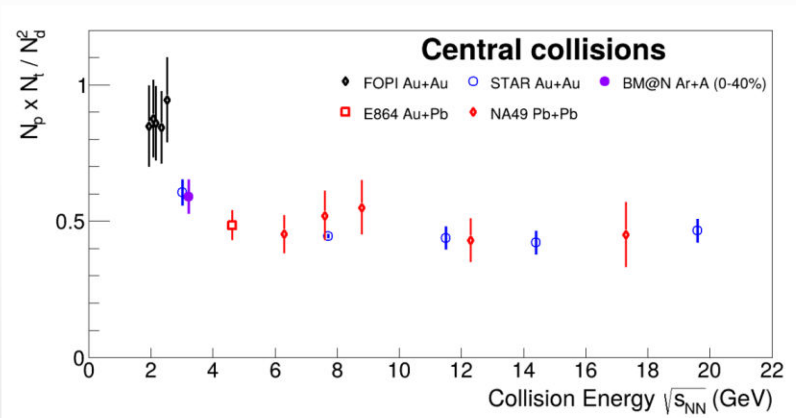
Production of p, d, t in Ar-Nucleus interactions

❖ Technical run with Ar beam at 3.2 AGeV and C/Al/Cu/Sn/Pb targets

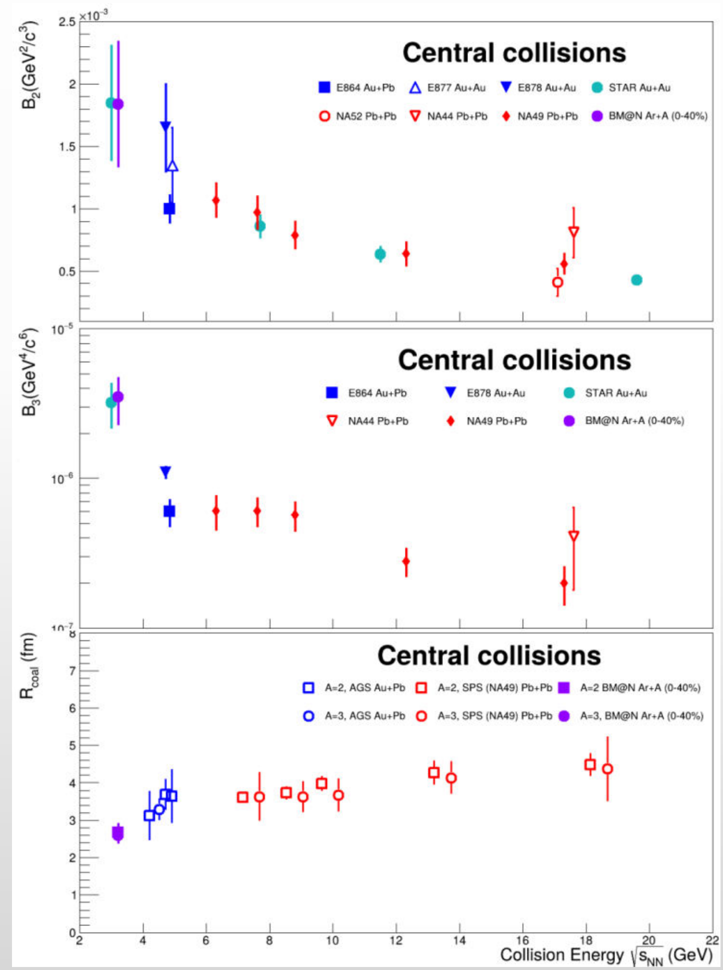
https://arxiv.org/abs/2504.02759, submitted to JHEP

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3}\right)^Z \left(E_n \frac{d^3N_n}{dp_n^3}\right)^{A-Z}$$

B_A is the coalescence parameter that characterizes the probability of nucleons to form nucleus A



- In the coalescence models, the ratio $N_pN_t/N^2_d \approx 0.3(1 + \Delta n)$ is related to the neutron density fluctuation Δn - irregular increase is expected near the CEP
- B_A at BM@N follow the increasing trend with the decreasing collision energy
- The estimated BM@N coalescence radius of $2.5 - 3$ fm at $p_T = 0$ is practically independent of the target mass.

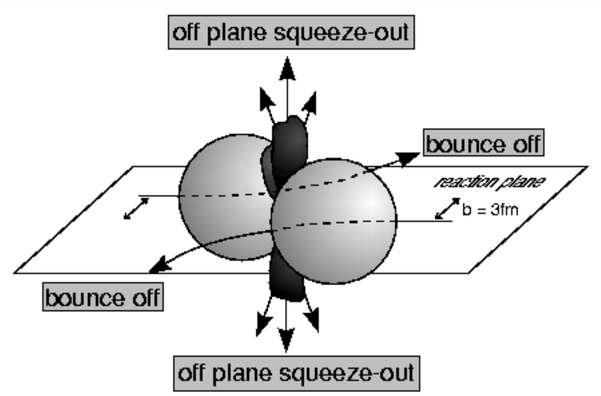


Collective flow of p and d in Xe + CsI collisions

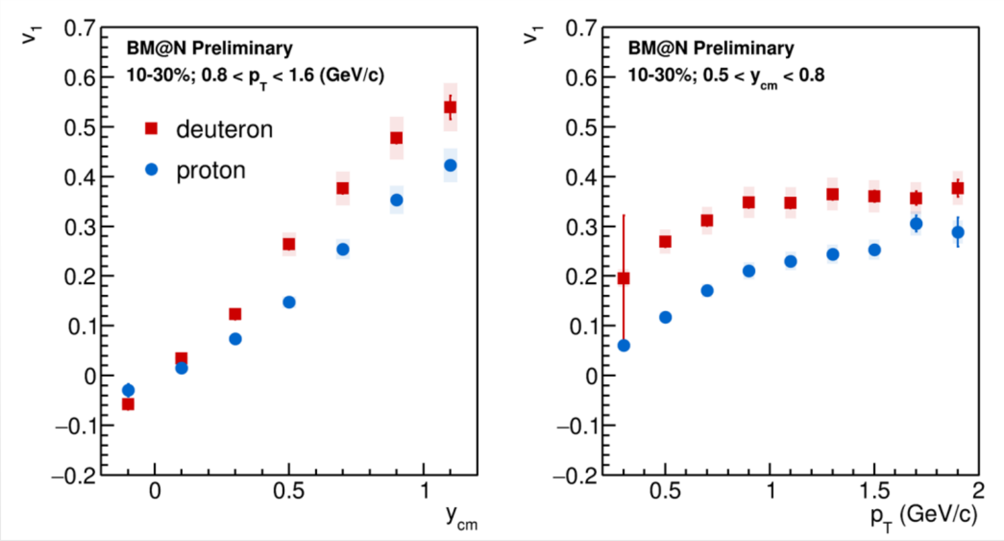
❖ Physics run with Xe beam at 3.8 AGeV and CsI target

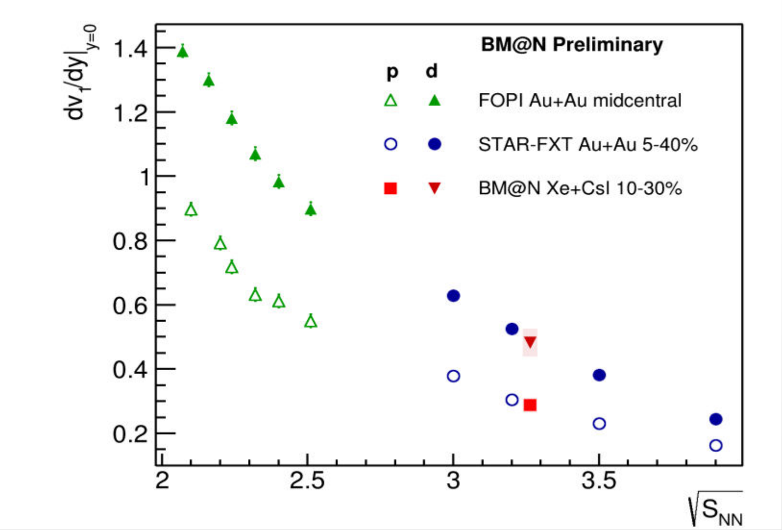
Azimuthal angle distribution of particles w/r to event plane:

$$dN/d\varphi \sim (1 + 2v_1 \cos\varphi + 2v_2 \cos 2\varphi)$$



Preliminary results



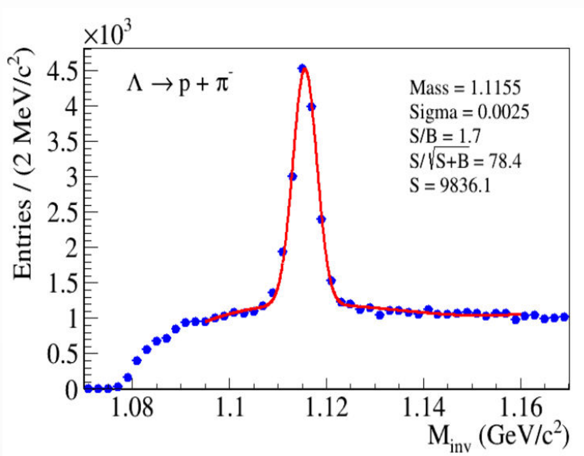


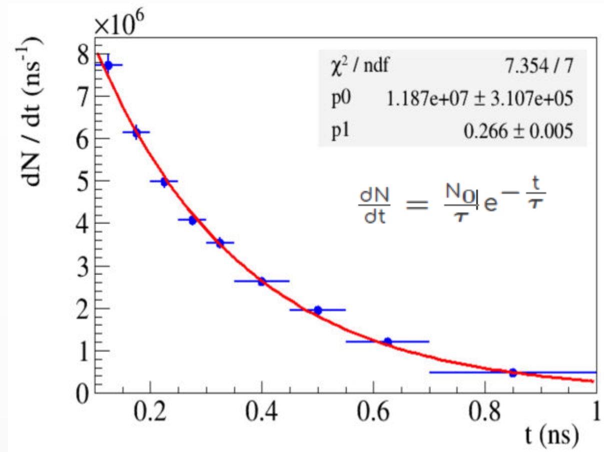
- Direct flow v_1 vs. rapidity and transverse momentum
- Slope of v_1 is in good agreement with the world data
- Direct flow of p vs d: scaling with mass (predicted by coalescence model)
- Both STAR and BM@N results for directed flow prefer stiff EoS
- Analysis of charged pions and Λ hyperon flow is in progress

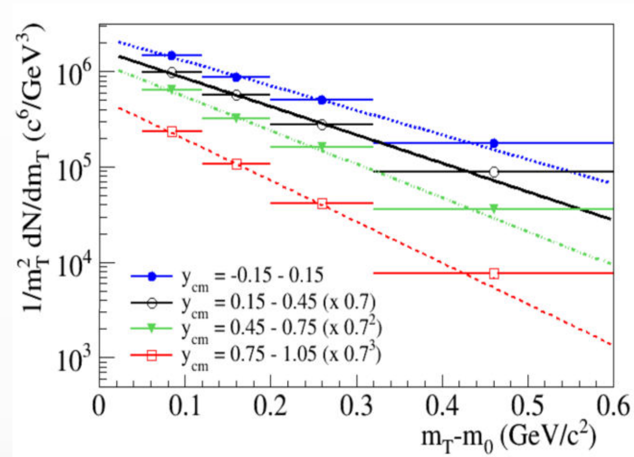
Reconstruction of Λ and K^0_s in Xe + CsI collisions

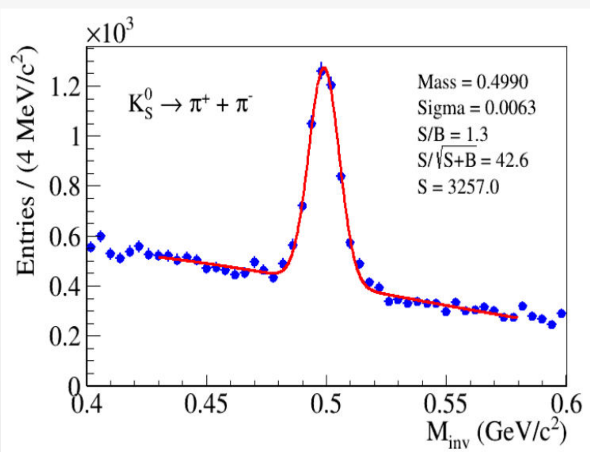
- Physics run with Xe beam at 3.8 AGeV and CsI target

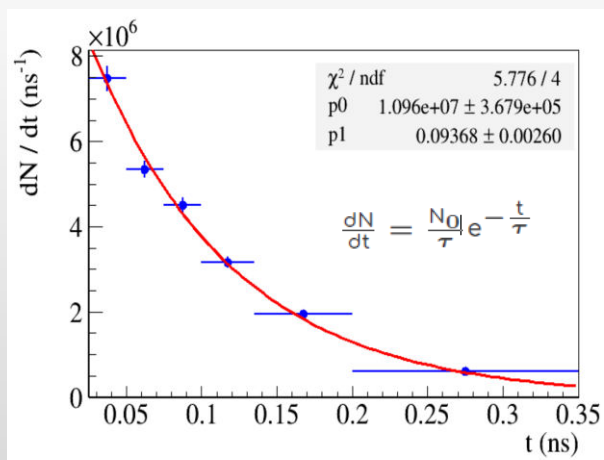
Work in progress

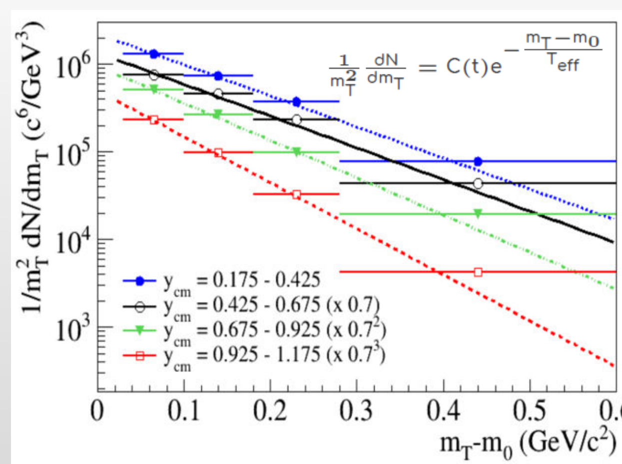










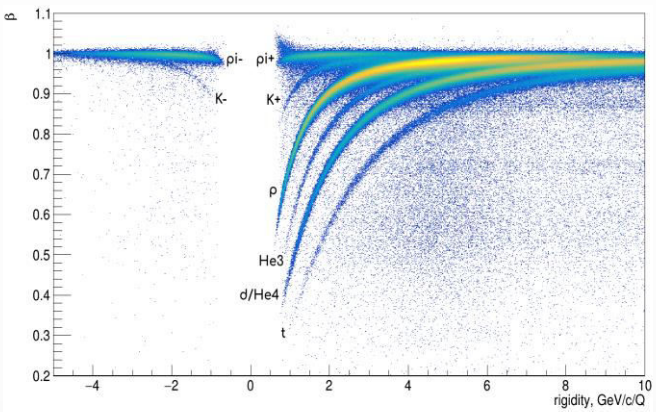


BM@N is capable of reconstruction of weak decays in high multiplicity environment

Observation of ϕ(1020) and hypernuclei signals in Xe + CsI collisions

❖ Physics run with Xe beam at 3.8 AGeV and CsI target

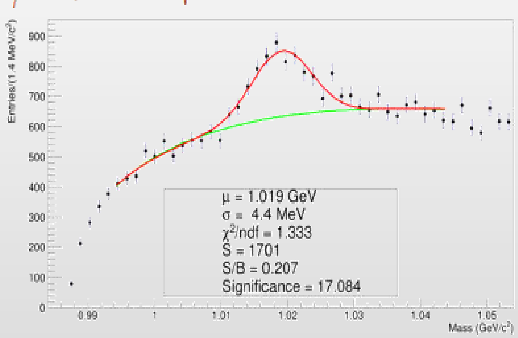
Work in progress



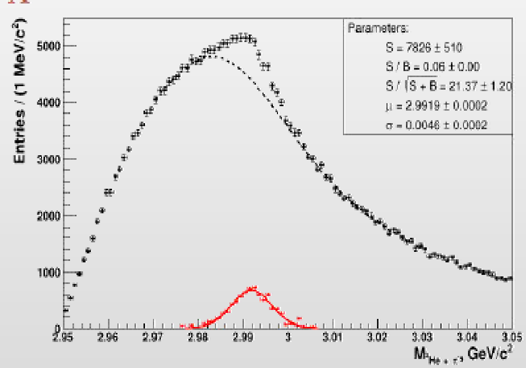
❖ Ongoing improvements:

- ✓ improve dE/dx in GEM detectors for ^{3}He, ^{4}He selection
- ✓ combined ToF-400 and ToF-700 data for K+ and K− identification
- ✓ TMVA to separate fake tracks (mostly $\pi-$)

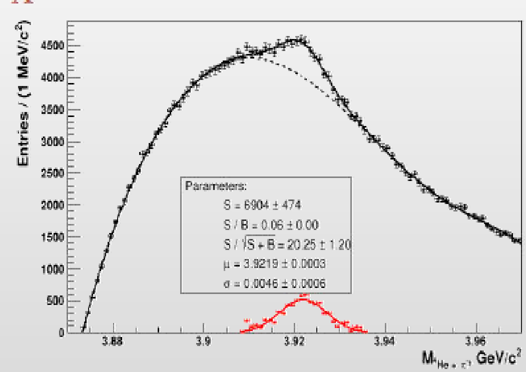
$\phi \rightarrow K^+ + K^-$



$^3_\Lambda H \rightarrow {}^3He + \pi^-$



$^4_\Lambda H \rightarrow {}^4He + \pi^-$

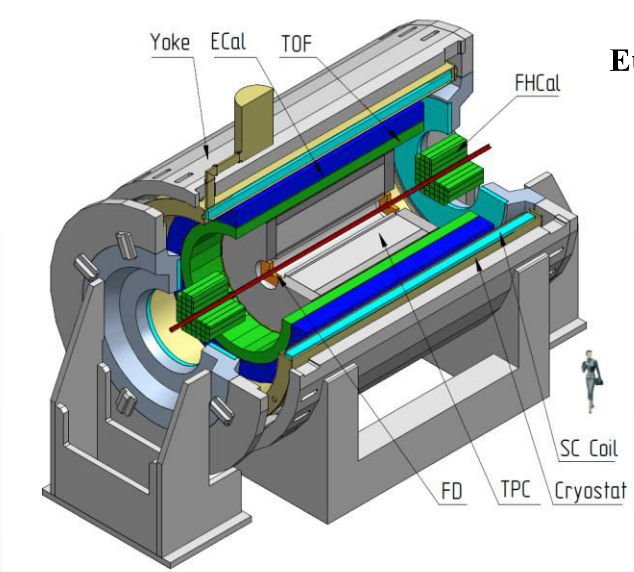


Stay tuned for new results !!!

Multi-Purpose Detector

Stage-I → start of commissioning in 2025

Stage-II → 2030+



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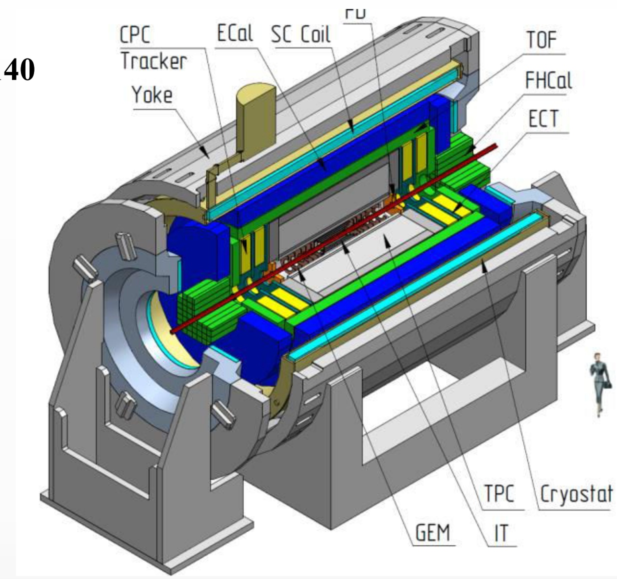
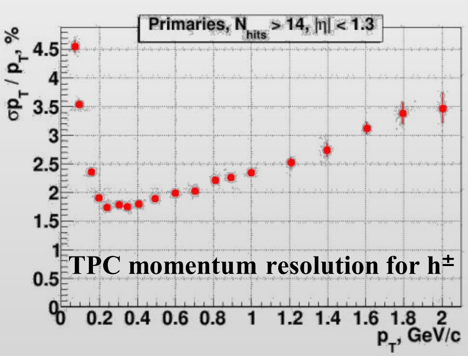
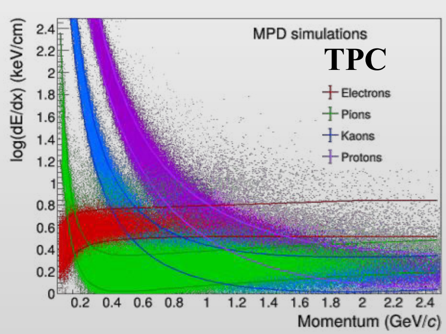


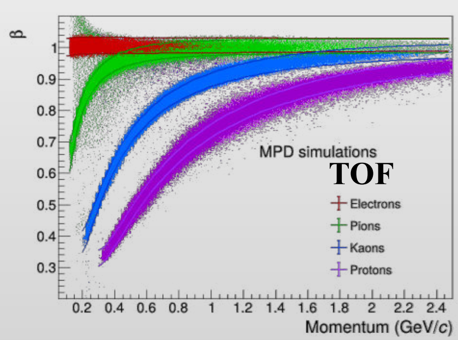
TPC: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.6$; **TOF, EMC**: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.4$
FFD: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$; **FHCAL**: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

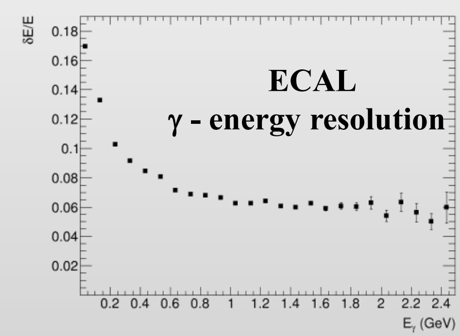
+ **ITS** : $|\Delta\varphi| < 2\pi$, $|\eta| \leq 3$
+ **Forward Spectrometers**: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 2.2$

Au+Au @ 11 GeV (full event simulation and reconstruction)







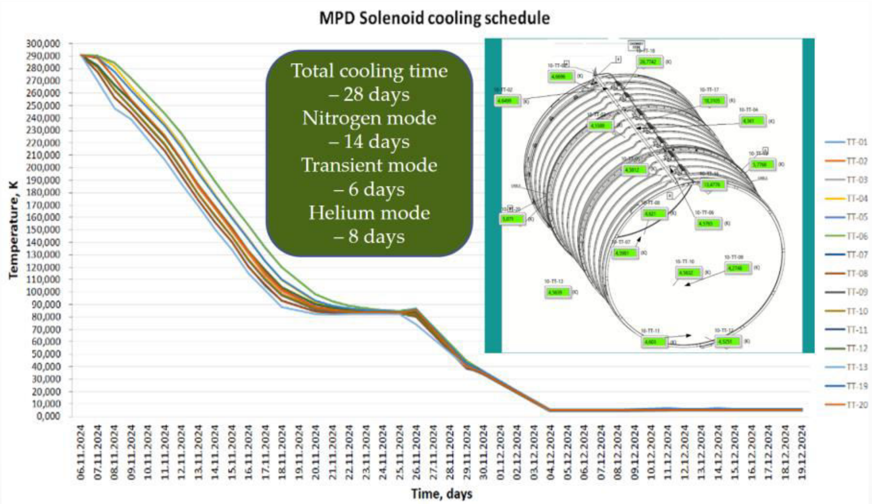


MPD superconducting magnet

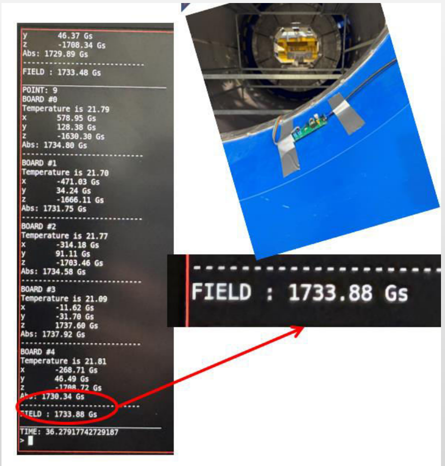
- Cooling of the magnet to LN2 and Lhe temperatures

Magnet yoke and cryogenic platform

Cooling procedure and rate

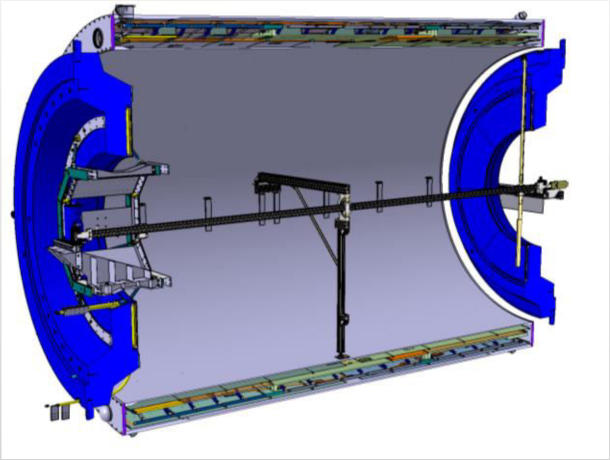


- SC coil training up to 0.15-0.2 T; full-scale magnetic field measurements starting in September



Calculation and experimental current for optimal field configuration

Current of nominal I_{SC},A	Current in to TRIM 2, A I_{trim2}	Current in to TRIM 1, A I_{trim1}	Calc. field, Gs	Measured data	
				I_{SC}, A	Gs
$0.2{\times}I_{SC}$=358	0	0	987	400	1067
	176	0	989	500	1350
	588	412	996	600	1600
$0.4{\times}I_{SC}$=716	588	412	1986	644	1730
	940	412	1989	700	1880
	1176	824	1995	750	2210
$0.6{\times}I_{SC}$=1074	1176	824	2982		
	1352	824	2984		
	1764	1236	2988		
$0.8{\times}I_{SC}$=1432	1764	1236	3971		
	1940	1236	3972		
	2352	1648	3983		
$1{\times}I_{SC}$=1790	2352	1648	4955		
	2528	1648	4957		
	2940	2060	4964		



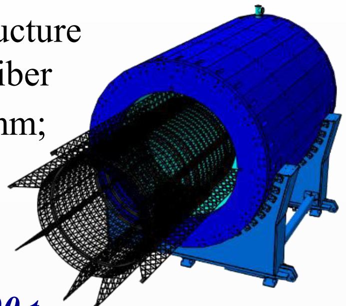
MPD subsystems

Support frame - READY

support structure of carbon fiber

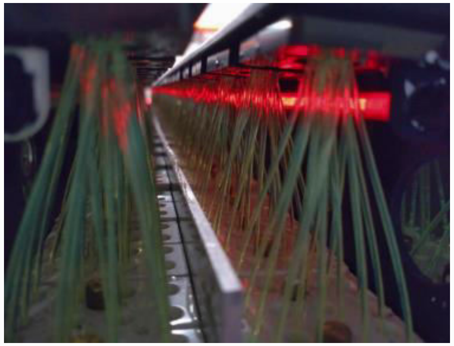
sagite ~ **5** mm;

0,13 X_0



ECAL ~ 100 t

ECAL – 83% READY



ECAL ~ 38400 towers (2400 modules)
produced by Chinese Universities (SDU, THU, FDU, SCUT, HZU) and JINR (IHEP (Protvino) and Tenzor (Dubna))

40(45) half-sectors to be ready by August (December),

TOF - READY

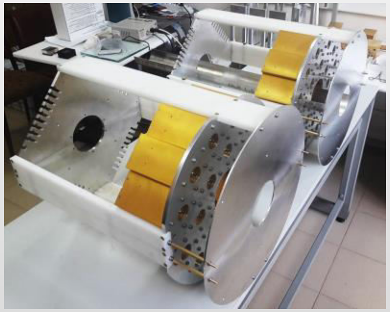
All 28 (100%) TOF modules are assembled, tested, stored and ready for installation. Spare modules in production

TPC - ASSEMBLY

24+ ROC ready; 100+ % FE cards manufactured
TPC gas volume assembly and HV/leakage tests – ongoing
TPC + ECAL cooling systems under commissioning

Forward subsystems - READY

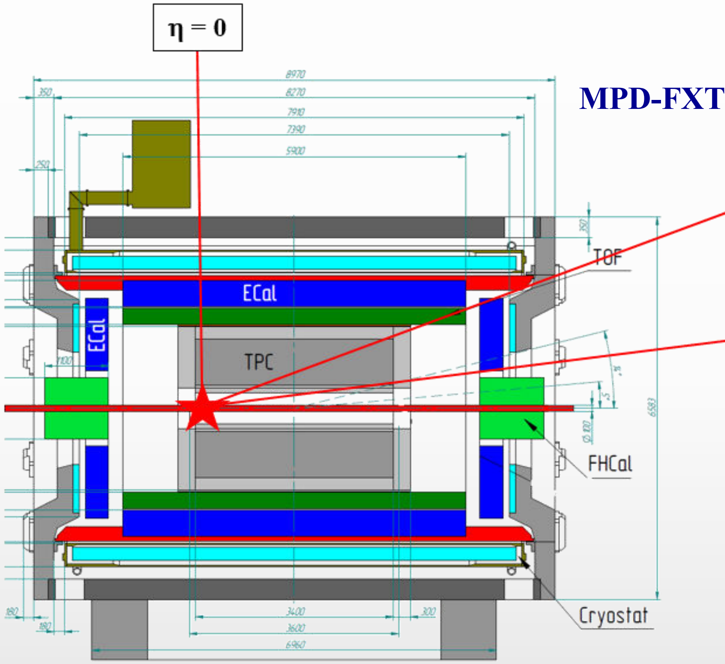
FHCAL in the Pole
(modules are equipped with FEE)

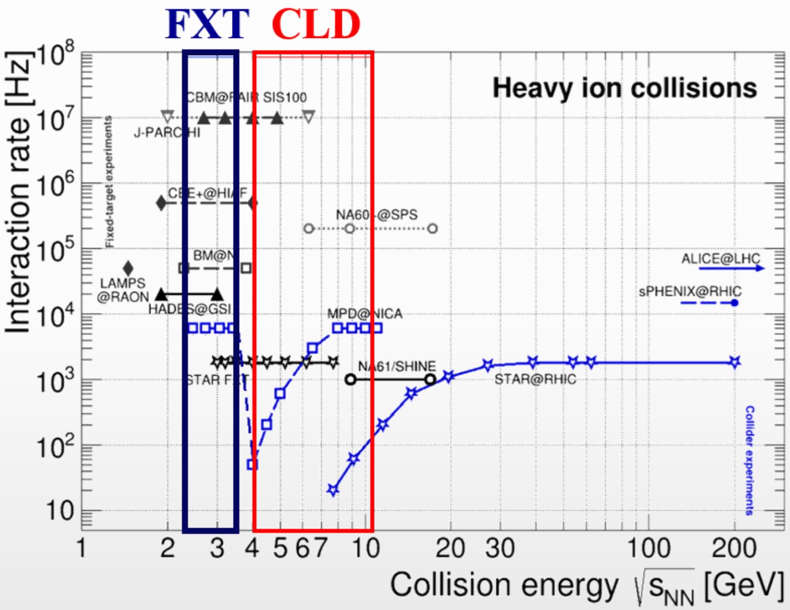


Cherenkov counters (FFD)
(tests with cosmics and lasers)

MPD strategy

- High-luminosity scans in **energy** and **system size** to measure a wide variety of signals
- Scans to be carried out using the **same apparatus** with all the advantages of collider experiments
- MPD-CLD and MPD-FXT operation modes approved from start-up:





- ✓ Collider mode: two heavy-ion beams, $\sqrt{s_{NN}}$ = 4-11 GeV
- ✓ Fixed-target mode: one beam + thin wire as a target (~ 50-100 μm) :
  - extends energy range to $\sqrt{s_{NN}}$ = 2.4-3.5 GeV (overlap with HADES, BM@N, CBM)
  - high event rate at lower collision energies

MPD physics program

❖ A comprehensive physics program: ions from **p** to **Au** and collision energies $\sqrt{s_{NN}}$= 2.4-11 GeV

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

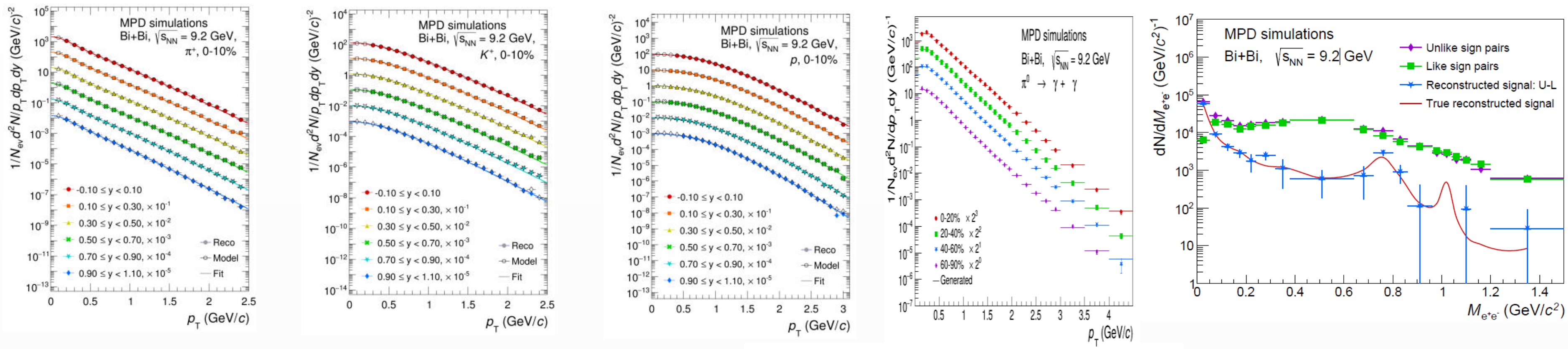
Heavy flavor

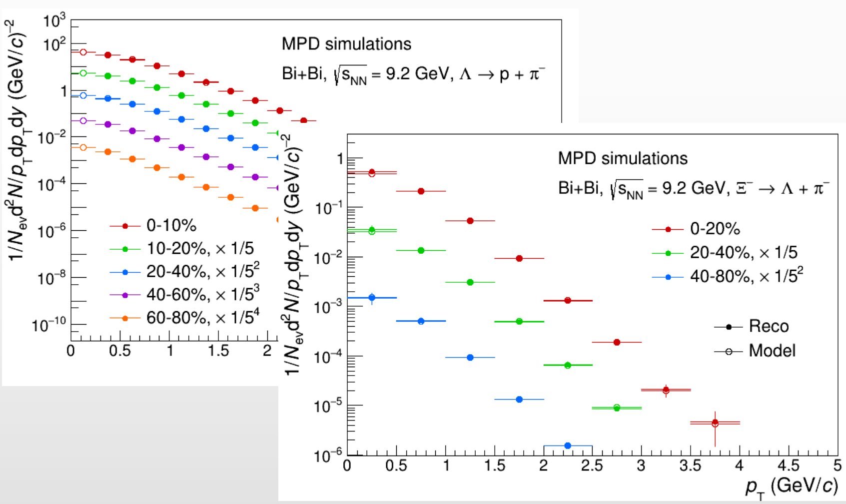
- Study of open charm production
- Charmonium with ECAL and central barrel
- Charmed meson through secondary vertices in ITS and HF electrons
- Explore production at charm threshold

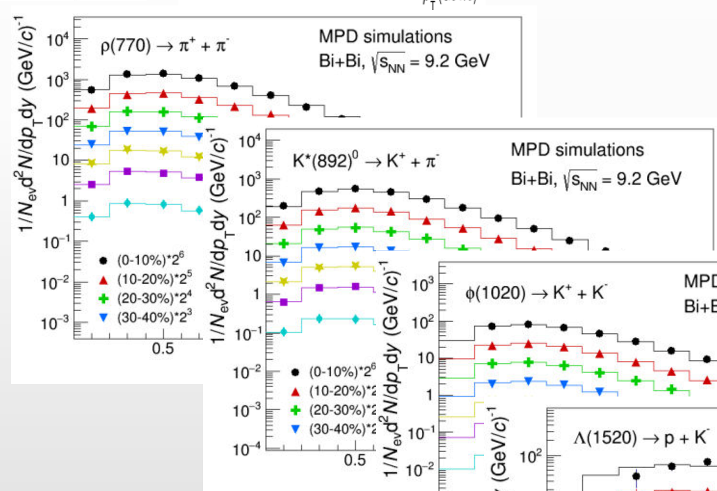
Y.Wang (Shandong Univ.) Reconstruction of sigma-zero hyperons using simulation data from the NICA-MPD experiment
D. Idrisov (INR RAS) Bayesian approach for centrality determination in nucleus-nucleus collisions at the NICA energy range

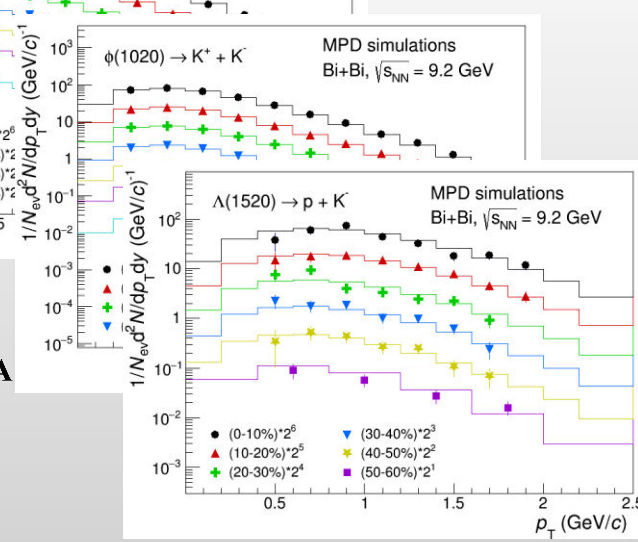
MPD feasibility studies

❖ Physics feasibility studies using large-scale Monte Carlo productions









❖ Collaboration papers:

I. **Status and initial physics performance studies of the MPD experiment at NICA**
Eur.Phys.J.A 58 (2022) 7, 140 (~ 50 pages)

II. **MPD physics performance studies in Bi+Bi collisions at $\sqrt{s_{NN}}$ = 9.2 GeV**
Rev.Mex.Fis. 71 (2025) 4, 041201, e-Print: 2503.21117 (~ 40 pages)

Summary

- Heavy-ion program at NICA → study of the QCD phase diagram in the region of maximum net-baryon density

- A comprehensive physics program to be studied for different ions (from p to Au) and collision energies ($\sqrt{s_{NN}}$ from 2.4 to 11A GeV):
  - ✓ event-by-event fluctuation of multiplicity, momentum and conserved quantities
  - ✓ femtoscopic correlation
  - ✓ multiparticle correlations
  - ✓ differential collective flow (v_n) for various hadrons
  - ✓ strange meson (including resonances) and (multi)strange hyperon production
  - ✓ light nuclei production including hypernuclei
  - ✓ (direct)photon and (di)electron probes
  - ✓ charge asymmetry
  - ✓ heavy flavor production

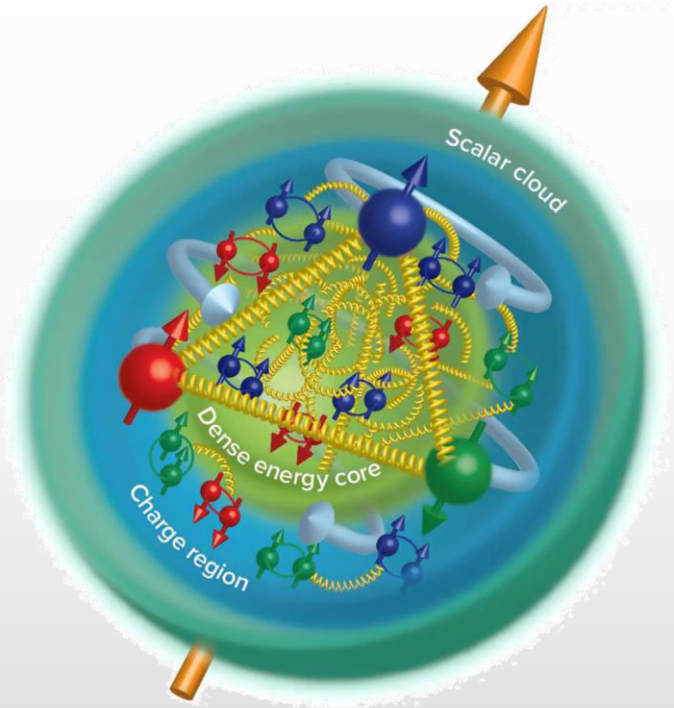
- Flagship project in the world on the study of heavy-ion collisions at intermediate energies

- More information can be found at http://bmn.jinr.ru and http://mpd.jinr.ru

Program with polarized p↑ and d ↑ beams

Spin Physics Detector

❖ The Spin Physics Detector (**SPD**) at the NICA collider is a universal facility for comprehensive study of polarized and unpolarized gluon content of proton and deuteron in polarized high-luminosity p-p and d-d collisions



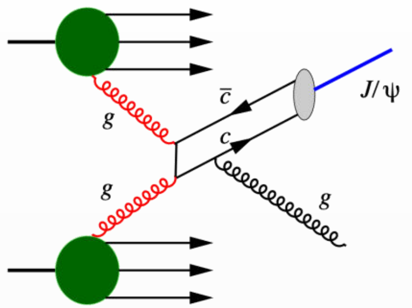
Study the contribution of partons to the nucleon and deuteron spins

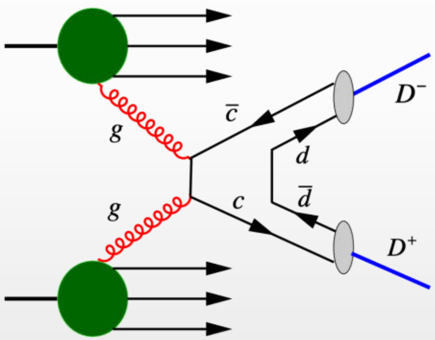
especially their gluon component!

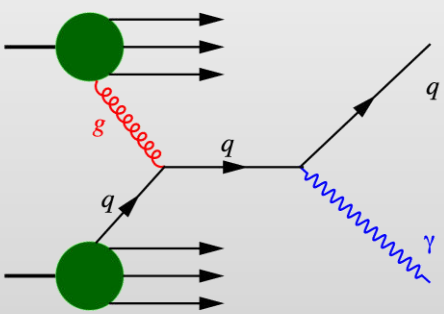
Gluon TMD PDFs via asymmetries and angular modulations in the cross sections

SPD and gluon structure of nucleon

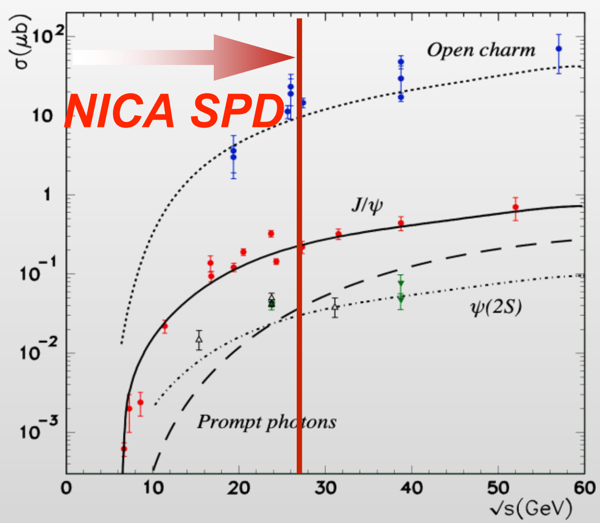
Not only J/ψ!

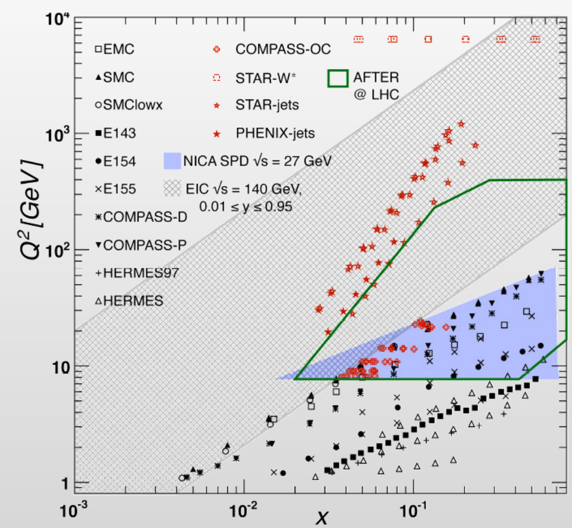




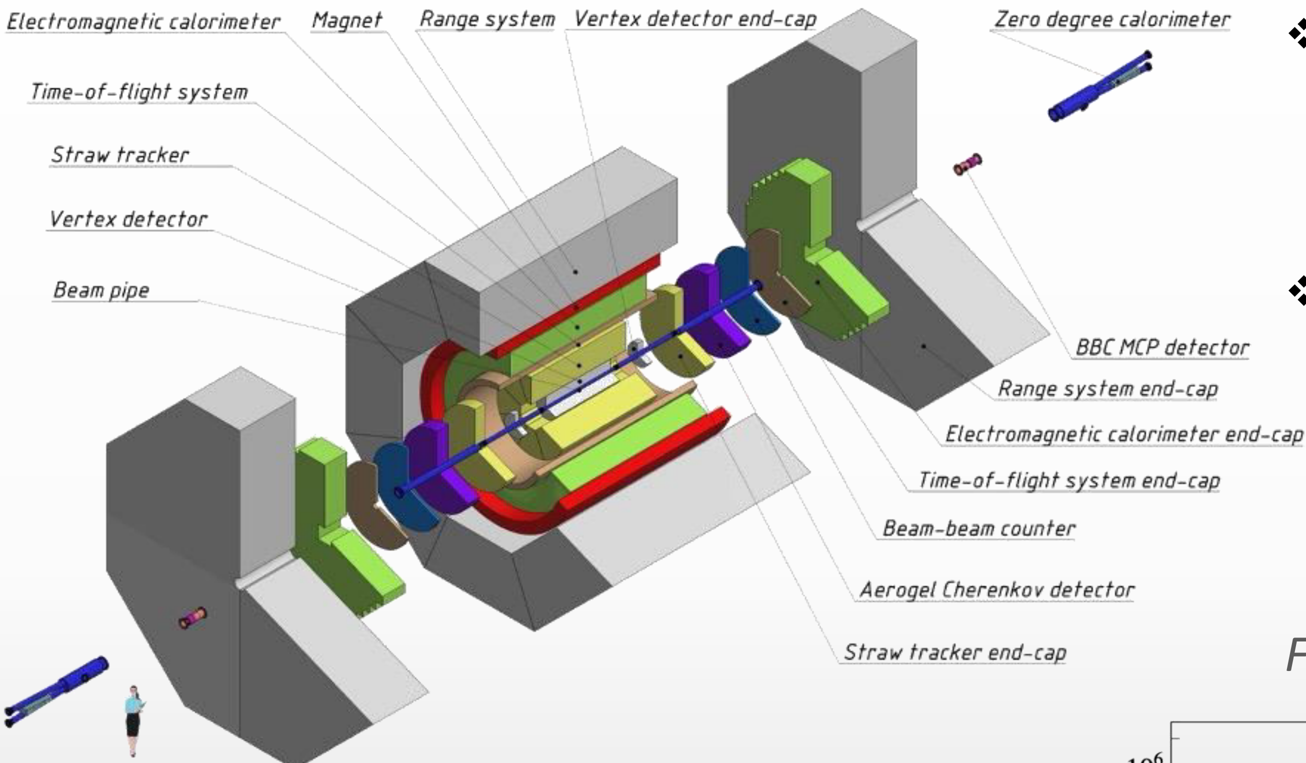


Physics goal	Observable	Experimental conditions
Gluon helicity $\Delta g(x)$	A_{LL} asymmetries	p_L-p_L, $\sqrt{s}=27$ GeV
Gluon Sivers PDF $f_{1T}^{\perp g}(x,k_T^2)$, Gluon Boer-Mulders PDF $h_1^{\perp g}(x,k_T^2)$ TMD-factorization test	A_N asymmetries, Azimuthal asymmetries Diff. cross-sections, A_N asymmetries	p_T-p, $\sqrt{s}=27$ GeV p-p, $\sqrt{s}=27$ GeV p_T-p, energy scan
Unpolarized gluon density $g(x)$ in deuteron Unpolarized gluon density $g(x)$ in proton	Differential cross-sections	d-d, p-p, p-d $\sqrt{s_{NN}}=13.5$ GeV p-p, $\sqrt{s}\leq 27$ GeV
Gluon transversity $h_1^g(x)$ "Tensor porlarized" PDF $C_G^T(x)$	Double vector/tensor asymmetries Single vector/tensor asymmetries	d_{tensor}-d_{tensor}, $\sqrt{s_{NN}}=13.5$ GeV d_{tensor}-d, p-d_{tensor}



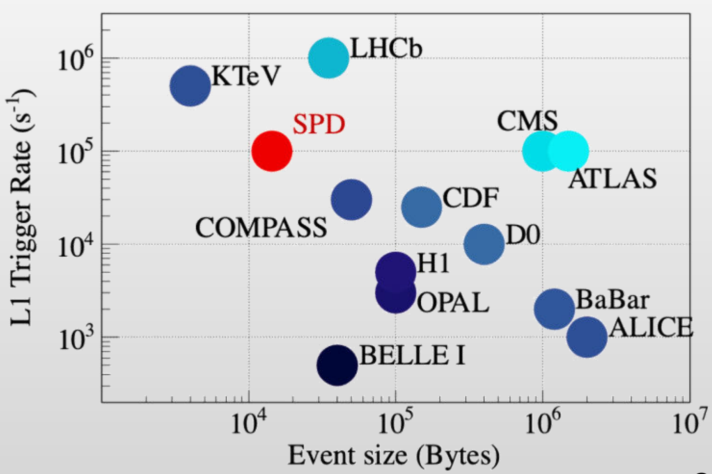


SPD setup



- Beams of protons and deuterons in the collider (up to $\mathcal{L} = 10^{32}$ cm^{-2}s^{-1}, $\sqrt{s_{NN}}$= 13 (dd), 19 (pd), 27 (pp) GeV)
- Beam polarization up to 70%

Free-running DAQ



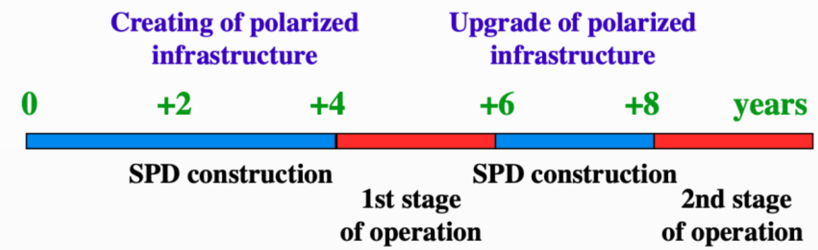
Physics of the first stage

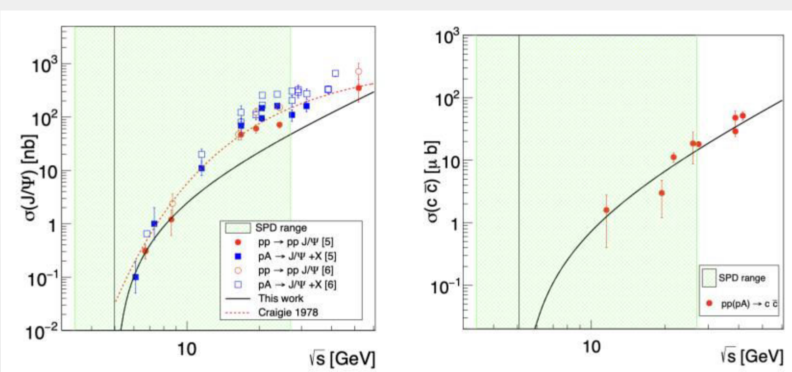
Transition scan

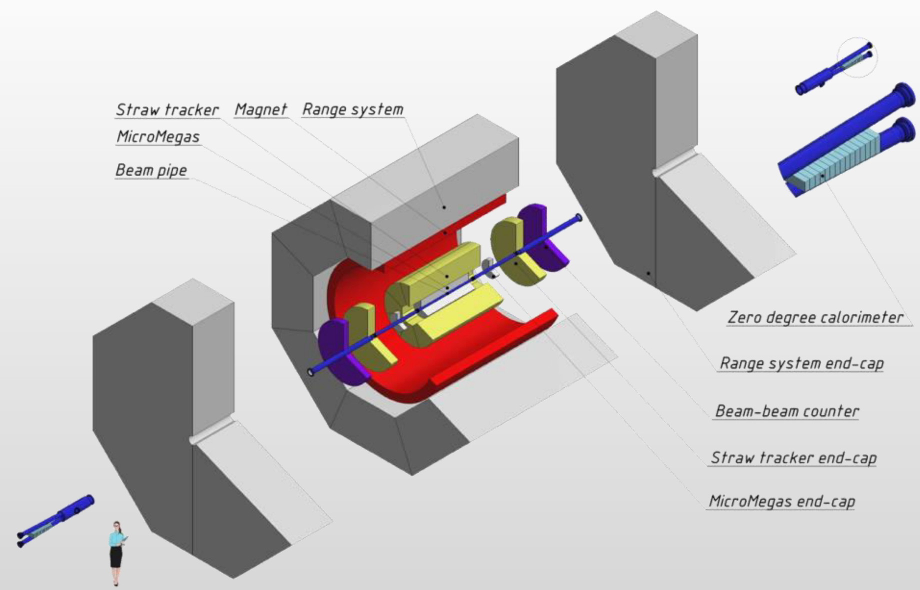
Non-perturbative QCD ***Perturbative QCD***

- Spin effects in p-p, p-d and d-d elastic scattering
- Spin effects in hyperons production
- Multiquark correlations
- Dibaryon resonances
- Physics of light and intermediate nuclei collision
- Exclusive reactions
- Hypernucei
- Open charm and charmonia near threshold
- Auxiliary measurements for astrophysics
- …

$\sqrt{s}$







Status summary

- SPD **physics program** is available at:
  - ✓ https://arxiv.org/abs/2011.15005
  - ✓ https://arxiv.org/abs/2102.08477

- SPD **Technical Design Report** was presented firstly in Jan 2023, then was updated in 2024 and passed international expertise this year: https://arxiv.org/abs/2404.08317

- The **first phase** of the SPD project is included into the JINR's 7-year plan (2024-2030)

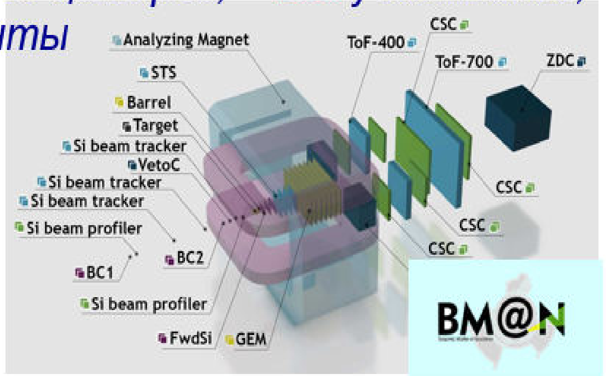
- More information can be found at http://spd.jinr.ru

NICA Collaboration

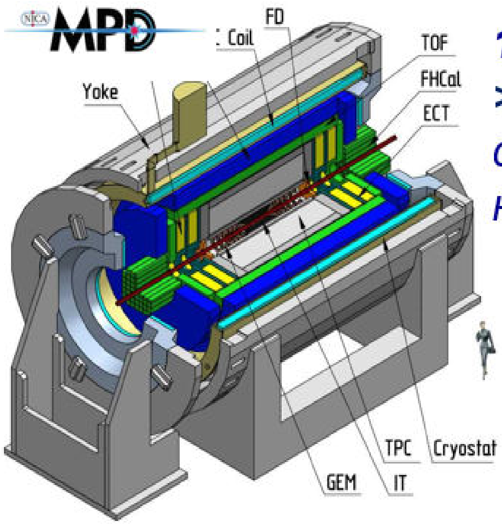
Коллаборации

Baryonic Matter at Nuclotron (BM@N):

*5 стран +**ОИЯИ**, 13 центров, > 200 участников; начаты эксперименты*



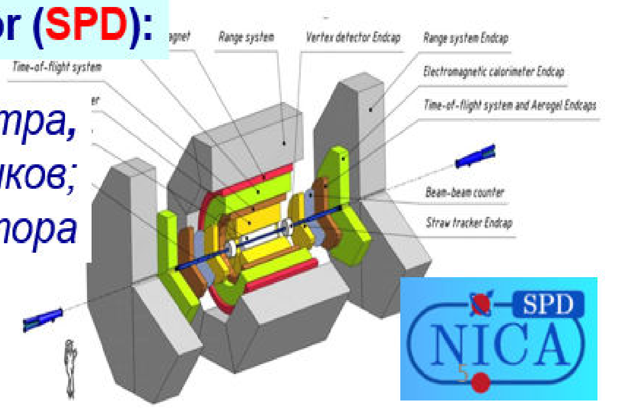
Multi Purpose Detector (MPD):



*13 стран + **ОИЯИ, 39** центров; > 500 участников; завершается создание детектора, подготовка к набору данных*

Spin Physics Detector (SPD):

*15 стран +**ОИЯИ, 34** центра, ~ 400 участников; начато создание детектора*



ARIADNA:

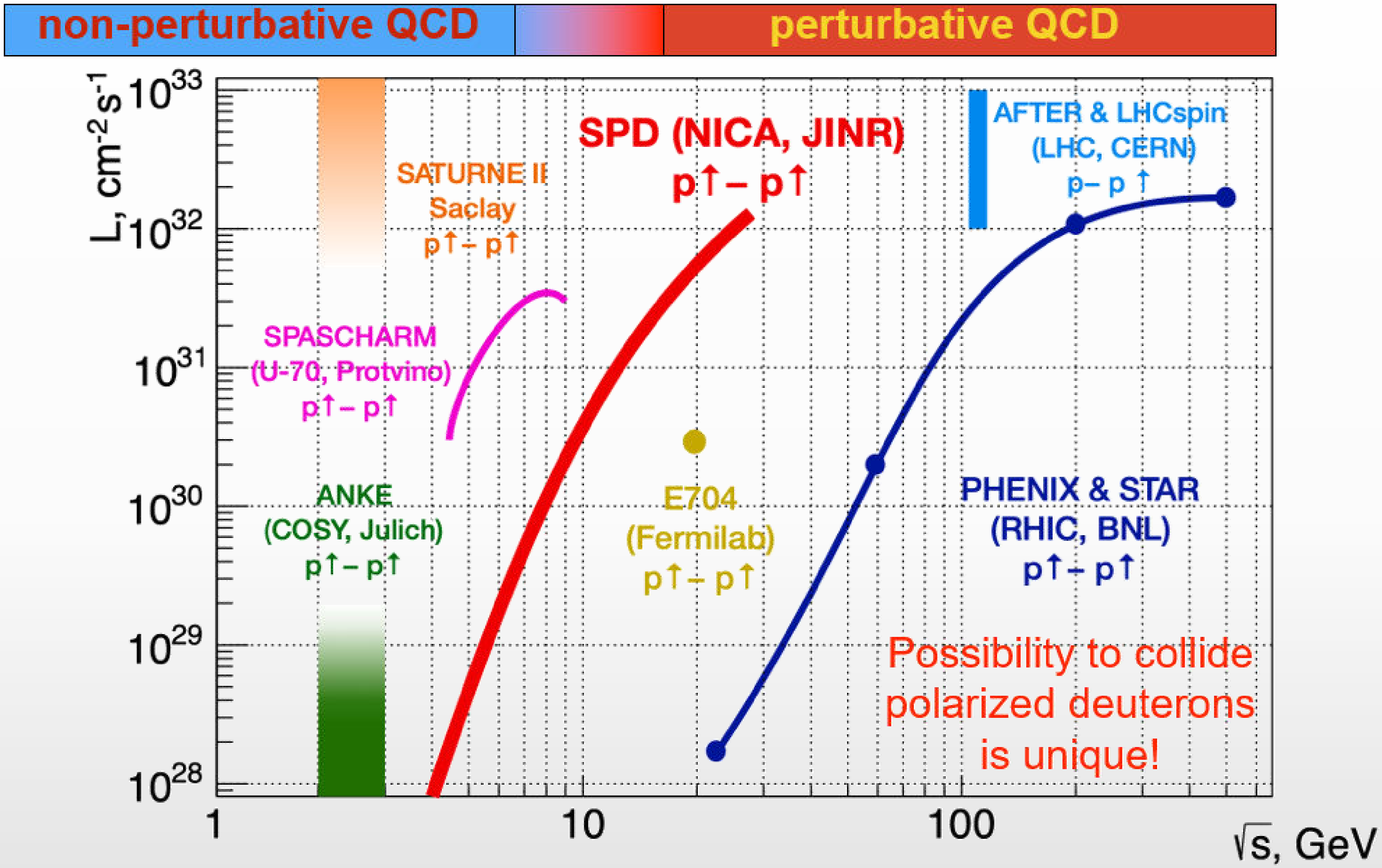
для прикладных и инновационных работ: **22** *центра, > 160 участников;* стартовала научная программа

Conclusions

- **NICA** is a mega-science project, which approaches its full commissioning
- **BM@N** and **MPD**: heavy-ion program has been started in the fixed-target mode, startup of the collider operation is expected in late 2025
- **SPD**: spin physics program with polarized beams is advancing to start in late 20-th
- Experiments at NICA are driven by **international collaborations** → new members are needed and welcome to fulfill the comprehensive research programs

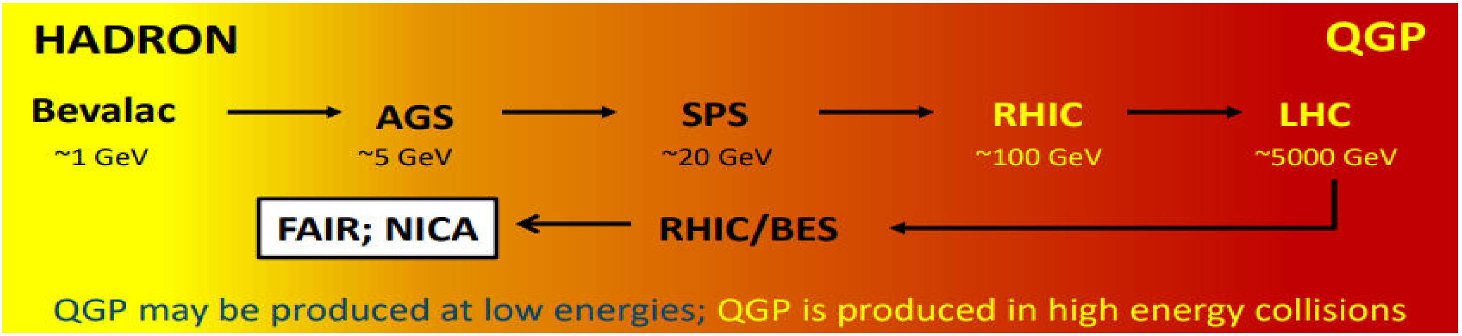
BACKUP

SPD and others



❖ The SPD gluon physics program is complementary to the other intentions to study the gluon content of nuclei (RHIC, AFTER, LHC-Spin, EIC, JLab experiments, EICc, …)

Heavy-ion collisions with accelerators



Short heavy-ion physics history

- **BEVALAC – LBNL** 1972-1984 max. $\sqrt{s_{NN}}$ = 2.2 GeV
- **SPS – CERN** 1986-2000 $\sqrt{s_{NN}}$ = 17.3 GeV — NA35/49, NA44, NA38/50/51, NA45, NA52, NA57, NA60, WA80/98, WA97 …
- **AGS – BNL** 1988-1996 $\sqrt{s_{NN}}$ = 4.8 GeV — E864/941, E802/859/866/917, E814/877, E858/878, E810/891, E896, E910 …
- **SIS18 – GSI** 1990 → $\sqrt{s_{NN}}$ = 2.4 GeV

Fixed target

- **RHIC – BNL** 2000-2025 $\sqrt{s_{NN}}$ = 200 GeV — BRAHMS, PHENIX, PHOBOS, STAR
- **LHC – CERN** 2010 → $\sqrt{s_{NN}}$ = 5.02 TeV — ALICE, ATLAS, CMS, LHCb

Collider

Near future

- NICA – JINR 2024 $\sqrt{s_{NN}}$ = 11 GeV — MPD, BM@N — Collider & Fixed target
- SIS100 – FAIR 2028? $\sqrt{s_{NN}}$ = 5 GeV — CBM, HADES — Fixed target