The Multi-Purpose Detector: A window to study the dense and hot nuclear matter produced in relativistic heavy-ion collisions

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XIV LATIN-AMERICAN SYMPOSIUM ON NUCLEAR PHYSICS AND APPLICATIONS

Instituto de Ciencias Nucleares UNAM

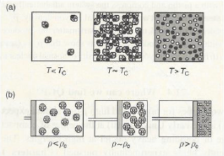
Heavy-ion collisions:
Nuclear matter under extreme conditions

- QCD is a fundamental theory of strong interactions
- Only colorless particles observed in the experiment (no free quarks or gluons) → confinement
- QGP is a state of matter in which quarks and gluons are free to move in space >> size of the nucleon
- QGP matter formation:

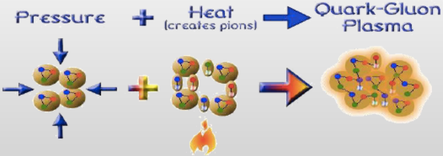
Two recipes:

(a) at high T - Early universe

(b) at high baryon density – Neutron stars

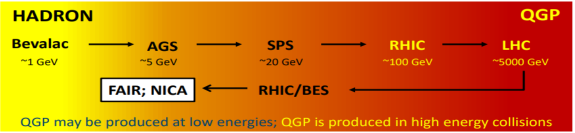


Relativistic heavy ion collisions - A combination of the two recipes



Nuclotron Ion Collider fAcility

NICA: Unique and complementary



Short heavy-ion physics history

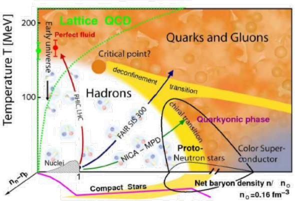
❖ **BEVALAC – LBNL** 1972-1984 max. $\sqrt{s_{NN}}$ = 2.2 GeV			Fixed target
❖ **SPS – CERN** 1986-2000	$\sqrt{s_{NN}}$ = 17.3 GeV	NA35/49, NA44, NA38/50/51, NA45, NA52, NA57, NA60, WA80/98, WA97 ...	Fixed target
❖ **AGS – BNL** 1988-1996	$\sqrt{s_{NN}}$ = 4.8 GeV	E864/941, E802/859/866/917, E814/877, E858/878, E810/891, E896, E910 ...	Fixed target
❖ **SIS18 – GSI** 1990 →	$\sqrt{s_{NN}}$ = 2.4 GeV		Fixed target
❖ **RHIC – BNL** 2000-2025	$\sqrt{s_{NN}}$ = 200 GeV	BRAHMS, PHENIX, PHOBOS, STAR	Collider
❖ **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

NICA is a quark-baryon bridge to neutron stars

- Heavy-ion collisions are used to:
  - ✓ study QCD under extreme conditions of high temperatures and densities
  - ✓ explore the QCD phase diagram, search for the QGP and study its properties



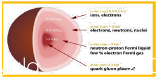
Why Quark-gluon plasma is of interest?

- ✓ primordial form of QCD matter at high temperatures and/or (net)baryon densities
- ✓ present during the first microseconds after Big Bang and in cores of the compact neutron stars / mergers
- ✓ provides important insights on the origin of mass for matter, and how quarks are confined into hadrons

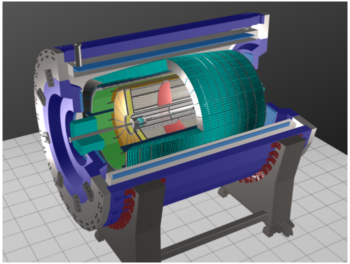
- Heavy-ion collisions at NICA create extremely dense matter at moderate temperatures:
  - ✓ net baryon density (n) up to 10 times that in normal nuclear matter (n_0)
  - ✓ baryonic chemical potential μ_B = (300 - 600) MeV, T_{ch} ~ (120-150) MeV

- Comparable baryon density may exist in cores of compact neutron stars and in neutron star mergers

High baryon density:
Inner structure of
compact stars



Multi-Purpose Detector



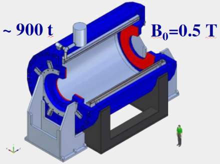
Length	340 cm
Vessel outer radius	140 cm
Vessel inner radius	27 cm
Default magnetic field	0.5 T
Drift gas mixture	90% Ar+10% CH_4
Maximum event rate	7 kHz ($L = 10^{27}$ $cm^{-2}s^{-1}$)

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

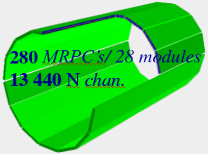
TPC: charged particle tracking + momentum measurements + identification by dE/dx
TOF: charged particle identification by m^2/β
EMC: energy and PID for $\gamma/e^{\pm}$ + charged particle identification (limited ability)
FFD/FHCAL: event triggering, event geometry, T_0
ITS: secondary vertex reconstruction for heavy-flavor decays (very small S/B ratio)

MPD subsystems in production

SC Solenoid + Iron Yoke



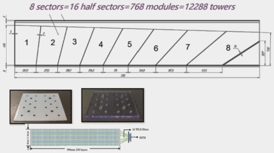
Goal is to cool down and power the magnet + magnetic field measurements are to be expected for the middle of 2023



TOF

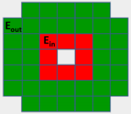
94(60)% of MRPCs(modules) are ready, mass production and tests ongoing.

ECAL (projective geometry)



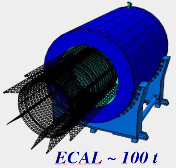
38400 towers
16/25 sectors will be produced for stage-I, production of remaining modules is possible by 2024

FHCal



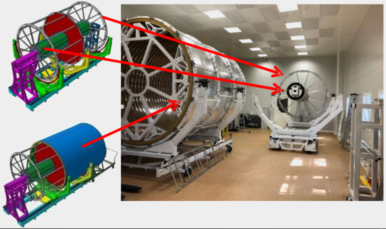
Forward detectors - are in advanced state of production(electronic and integration)

Support structure

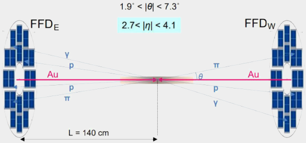


made of carbon fiber sagite ~ 5 mm, 0.13 X_0
Will be ready in Dec. 2022

TPC central tracking detector

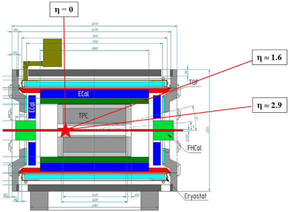


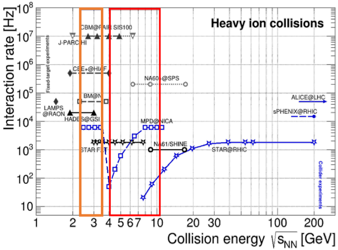
FFD



MPD operation modes: collider and fixed target

- With a wire-target at z ~ -100 cm

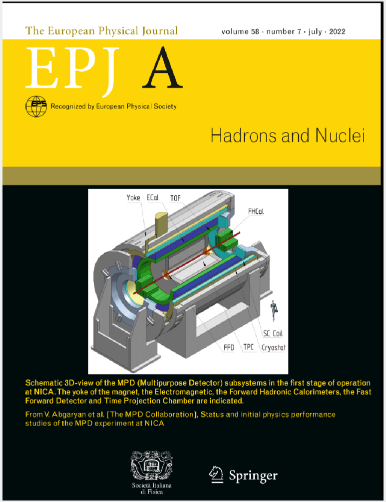




- ❖ Discussing the option of NICA operation in the collider and fixed-target modes in the same campaign
- ❖ Fixed-target mode: one beam + thin wire (~ 100 μm) close to the edge of the MPD central barrel:
  - ✓ extends energy range of MPD to $\sqrt{s_{NN}}$ = 2.4-3.5 GeV (overlap with HADES, BM@N and CBM)
  - ✓ solves problem of low event rate at lower collision energies (only ~ 50 Hz at $\sqrt{s_{NN}}$ = 4 GeV at design luminosity)
  - ✓ backup start-up solution (too low luminosity, only one beam, etc.)

Unique capability of target and collision energy overlap between the experiments at NICA

Collaboration activity



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

Physics program

G. Feofilov, P. Parfenov
Global Observables
- Total event multiplicity
- Total event energy
- Centrality determination
- Total cross-section measurement
- Event plane measurement at all rapidities
- Spectator measurement

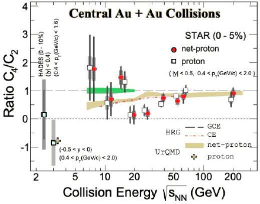
V. Kolesnikov, Xianglei Zhu
Spectra of light flavor and hypernuclei
- Light flavor spectra
- Hyperons and hypernuclei
- Total particle yields and yield ratios
- Kinematic and chemical properties of the event
- Mapping QCD Phase Diagram

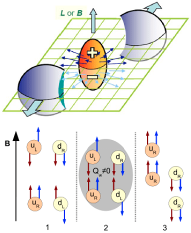
K. Mikhailov, A. Taranenko
Correlations and Fluctuations
- Collective flow for hadrons
- Vorticity, Λ polarization
- E-by-E fluctuation of multiplicity, momentum and conserved quantities
- Femtoscopy
- Forward-Backward correlations
- Jet-like correlations

D. Peresunko, Chi Yang
Electromagnetic probes
- Electromagnetic calorimeter measurement
- Photons in ECAL and central barrel
- Low mass dilepton spectra in-medium modification of resonances and intermediate mass region

Wangmei Zha, A. Zinchenko
Heavy flavor
- Study of open charm production
- Charmoinium with ECAL and central barrel
- Charmed meson through secondary vertices in ITS and HF electrons
- Explore production at charm threshold

Global observables at large μ_B





D.Kharzeev, arXiv:1312.3348

- **Hot topics :**

--- **Search for QCD critical point** and non-monotonic energy dependence of net-proton $k\sigma^2 = C_4/C_2$ for 5% most central events;

--- **Chiral magnetic effect search** in isobar collisions: charge separation due to anomaly induced chiral imbalance and large (10^{15} T) magnetic field. The Chiral Magnetic Effect can only operate in the deconfined, ch ar

$$\frac{dN_\alpha}{d\phi^*} \approx \frac{N_\alpha}{2\pi}\left[1 + 2v_{1,\alpha}\cos(\phi^*) + 2a_{1,\alpha}\sin(\phi^*) + 2v_{2,\alpha}\cos(2\phi^*) + \cdots\right],$$

$\Phi^* = \Phi - \Psi_{RP}$, with Φ and Φ_{RP} being the azimuthal angle of a particle and of the Reaction Plane (RP). The "γ correlator: $\gamma_{\alpha\beta} = \langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP})$. Here φ_α and φ_β are the azimuthal angles of particles of interest (POIs).

Mapping the phase diagram

- Measurements of particle differential and integrated yields are used to determine **freeze-out conditions**
- In Statistical Model of Hadron Production, abundancy (N_c) of particles, which are emitted from the interaction region in statistical equilibrium with mass m and charge q, baryon number B and spin factor $g = 2s+1$:

$$N_C = \frac{gV}{\pi^2} m^2 T K_2\left(m/T\right) \exp\left(\frac{B\mu_B + q\mu_q}{T}\right), \text{ where } \mu_q/T = \frac{1}{2} \ln \frac{\pi^+}{\pi^-}$$

Particle integrated yields → determine T, μ_B and V as fit parameters → **chemical freeze-out** conditions

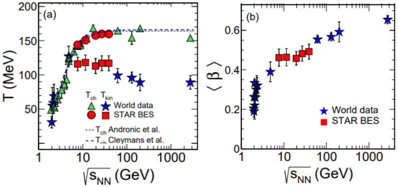
- In a simplified hydrodynamic model, three parameters define shape of particle production spectra from a thermalized source + radial flow boost (Blast-Wave model):
  - ✓ T_{Kin}: kinetic freeze out temperature
  - ✓ $\langle\beta_T\rangle$: transverse radial flow velocity
  - ✓ n: velocity profile exponent

$$E\frac{d^3N}{dp^3} \propto \int_0^R m_T I_0\left(\frac{p_T \sinh(\rho)}{T_{Kin}}\right) K_1\left(\frac{m_T \cosh(\rho)}{T_{Kin}}\right) r\,dr$$

$$m_T = \sqrt{m^2 + p_T^2} \qquad \rho = \tanh^{-1}(\beta_T) \qquad \beta_T = \beta_s\left(\frac{r}{R}\right)^n$$

Particle p_T-differential spectra → determine T_{kin} and $\langle\beta_T\rangle$ as fit parameters → **kinetic freeze-out** conditions

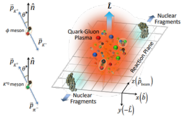
Phys. Rev. C 96, 044904 (2017)

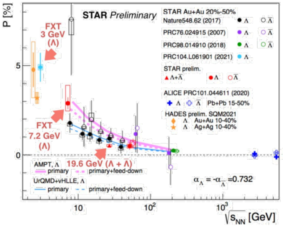


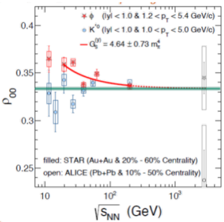
- ✓ T_{ch} increases up to 19.6 GeV and then remains constant and similar for all centralities
- ✓ T_{Kin} increases from central to peripheral collisions suggesting longer lived fireball in central collisions
- ✓ $\langle\beta_T\rangle$ descreases from central to peripheral collisions suggesting stronger expansion in central collisions

Transferring of vorticity to spin

- Global hyperon polarization in mid-central A+A collisions (Λ, Ξ, Ω and antiparticles)
- Spin alignment of vector mesons, $K^*(892)$ and $\phi(1020)$







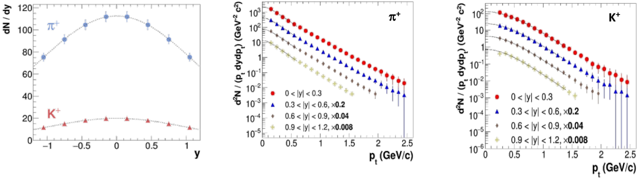
Task for the MPD: extra points in the energy range 4-11 GeV with small

MPD capabilities: identified light hadrons

- Charged hadrons: large and homogeneous acceptance + excellent PID capabilities of the TPC and TOF:
  - ✓ samples phase space corresponding to ~ 70% of the π/K/p production
  - ✓ hadron spectra are measured from $p_T \sim 0.1$ GeV/c

0-5% central AuAu@9 GeV (PHSD) → full event/detector simulation and reconstruction

Phys.Part.Nucl. 53 (2022) 2, 203-206

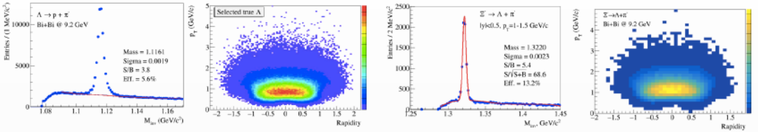


- Neutral mesons (π^0, η, K_s, ω, η'): ECAL reconstruction + photon conversion method (PCM) :
  - ✓ extend p_T ranges of charged particle measurements
  - ✓ different systematics

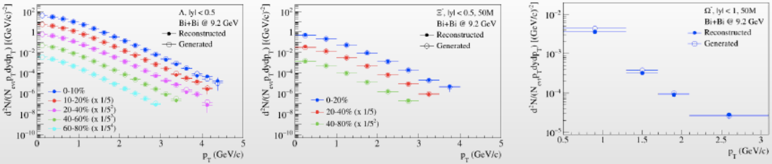
MPD will be able to measure differential production spectra, integrated yields and $\langle p_T \rangle$, particle ratios for a wide variety of identified hadrons (π, K, η, ω, p, η')

MPD capabilities: Hyperon reconstruction

- BiBi@9.2 GeV (UrQMD, 50M events), full event reconstruction



- different background estimates (fit function vs mixed-event)
- different PID selections for high-p_T daughter particles
- testing alternative Machine Learning techniques

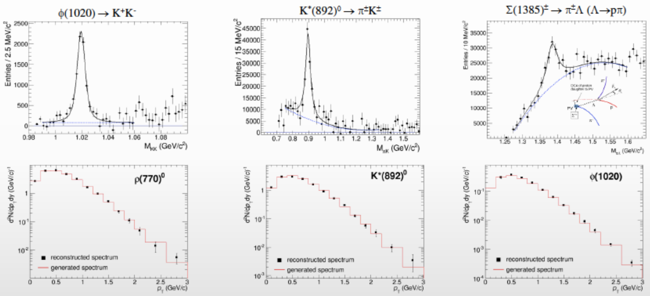


MPD has capabilities to measure production of strange kaons, (multi)strange baryons and resonances in pp, p-A and A-A collisions using h-ID in the TPC&TOF and different decay topology selections

MPD capabilities: Hadron resonances

- BiBi@9.2 GeV (UrQMD) after mixed-event background subtraction, 10M events
- Examples of the low-p_T bins

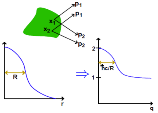
Phys.Scripta 96 (2021) 6, 064002



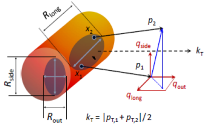
MPD is capable of resonance reconstruction using h-ID in the TPC and TOF + topology selections for weak decays

First measurements are possible with 10M sampled events

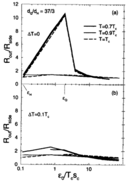
MPD capabilities: femtoscopy



Bertch-Pratt LCMS PRC 37 (1988) 1896, PRD 33 (1986) 1314



D.H. Rischke et al. NPA 608 (1996) 479



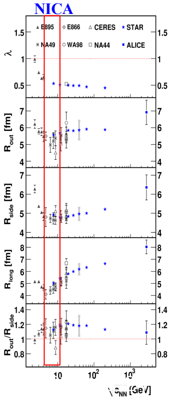
Correlation femtoscopy:
Measurement of space-time characteristics of particle production using particle correlations due to the effects of quantum statistics and final state interactions.
Correlation function: $C(p_1, p_2) = \int d^4 r S(r,q) |\Psi(r,q)|^2,\ q = p_1 - p_2,\ r = x_1 - x_2$

NICA energy range: $\sqrt{s_{NN}}$ = 4 – 11 GeV:

- first collider measurement bellow 7.7 GeV
- precise measurements in a broad energy range
- need for more precise measurements at low energies
- precise measurements exist only with pions
- need heavier particles (K, p, Λ, ...)

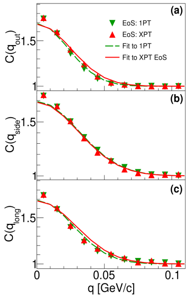
- R_{side} → geometrical size
- R_{out} → emission duration
- R_{long} → system lifetime

- Study source radii(out,side,long) vs m_T → constraint to the theoretical models (and/or EoS)
- R_{out}/R_{side} → search for the 1st-order phase transition



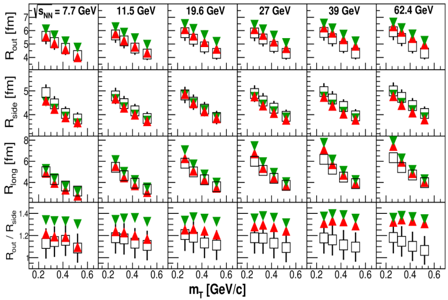
Example:3D pion radii versus m_T with vHLLE+UrQMD

Model correlation functions



Comparison of extracted radii with the STAR data

(PRC 96, 024911(2017))



- Femtoscopic radii are sensitive to the type of the phase transition
- Crossover EoS does a better job at lowest collision energies
- R_{out} (XPT) at high energies and R_{out} (1PT) at all energies are slightly overestimated
- $R_{out,long}$ (1PT) > $R_{out,long}$ (XPT) by value of ~1-2 fm
- The difference in 1-2 fm in radii value should be measurable in the MPD

Direct photons and system temperature

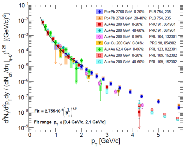
- Experimental measurements in A+A collisions are available from the LHC (2.76-5 TeV), RHIC (62-200 GeV) and WA98 (17.2 GeV)
- No measurements at NICA energies (direct photon yields and flow vs. p_T and centrality)

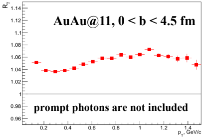
Estimation of the direct photon yields @NICA

model calculations

empirical scaling

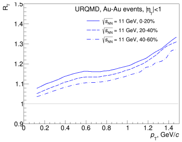
- UrQMD v3.4 with hybrid model (3+1D hydro, bag model EoS, hadronic rescattering and resonances within UrQMD)
- Each cell have Ti, Ei, μbi:
  - T is high – QGP phase (Peter Arnold, Guy D. Moore, Laurence G. Yaffe, JHEP 0112:009 2001)
  - T is low – HG phase (Simon Turbide, Ralf Rapp, Charles Gale, Phys.Rev.C69:014903,2004)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





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

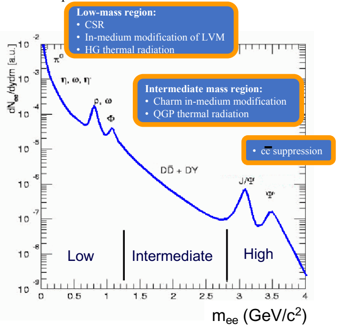
$$\gamma_{direct} = \left(1 - \frac{1}{R_\gamma}\right) \cdot \gamma_{inc}$$



- Non-zero direct photon yields are predicted, $R_\gamma \sim 1.05 - 1.15$ → experimentally reachable by MPD!!!

Dielectrons and light vector mesons

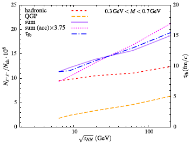
- The QCD matter produced in A-A interactions is transparent for leptons, once produced they leave the interaction region largely unaffected
- Dielectron continuum at low and intermediate mass/p_T carries a wealth of information about reaction dynamics and medium properties:
  - ✓ Mass (Lorentz-invariant): not sensitive to collective expansion
  - ✓ Low-mass part sensitive to late (hadronic) stage, intermediate mass — to hot stage
  - ✓ ρ-meson peak: modification of ρ-meson properties in hot matter (chiral phase transition)
  - ✓ charm production and correlations etc.

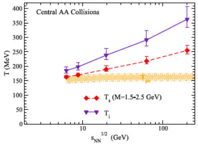


i	Dilepton channels	
1	Dalitz decay of π^0:	$\pi^0 \to \gamma e^+ e^-$
2	Dalitz decay of η:	$\eta \to \gamma l^+ l^-$
3	Dalitz decay of ω:	$\omega \to \pi^0 l^+ l^-$
4	Dalitz decay of Δ:	$\Delta \to N l^+ l^-$
5	Direct decay of ω:	$\omega \to l^+ l^-$
6	Direct decay of ρ:	$\rho \to l^+ l^-$
7	Direct decay of ϕ:	$\phi \to l^+ l^-$
8	Direct decay of J/Ψ:	$J/\Psi \to l^+ l^-$
9	Direct decay of Ψ':	$\Psi' \to l^+ l^-$
10	Dalitz decay of η':	$\eta' \to \gamma l^+ l^-$
11	pn bremsstrahlung:	$pn \to pn l^+ l^-$
12	$\pi^\pm N$ bremsstrahlung:	$\pi^\pm N \to \pi N l^+ l^-$

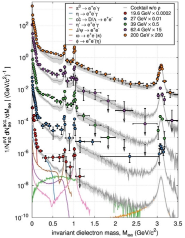
Available measurements and expectations

- Expectations (PLB 753, 586 (2016)):
  - ✓Integrated yield in the LMR → fireball lifetime
  - ✓ Inverse slope of the mass spectrum in the IMR → measurement of T





- Beam energy scan program by STAR at RHIC (PRL 113, 22301 (2014); PRC 92, 24912 (2015)):



LMR:
- ✓ clear enhancement wrt to hadronic cocktail of known sources
- ✓ small centrality dependence
- ✓ observed at all energies down to 19.6 GeV

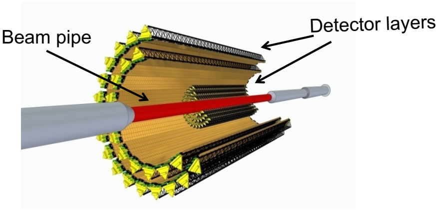
IMR:
- ✓ no clear picture

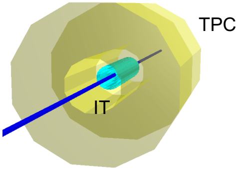
- MPD → extensive program of dielectron measurements in the NICA energy range, $\sqrt{s_{NN}}$= 4-11 GeV

Heavy-flavor studies

MPD is being constructed to study the properties of extremely dense nuclear matter formed in relativistic nucleus-nucleus collisions at NICA energies. The yields and spectra of charmed particles are the important observables sensitive to critical phenomena in phase transitions of the QCD-matter. So, a vertex detector (Inner Tracker IT) is required for efficient detection of such short-lived products of nuclear interactions. The detector based on MAPS (Monolitic Active Pixel Sensors) technology is under consideration.

Particle	Mass [MeV/c^2]	Mean path cτ [mm]	Decay channel	BR
D^+	1869.62±0.20	0.312	$\pi^+ + \pi^+ + K^-$	9.1%
D^0	1864.84±0.17	0.123	$\pi^+ + K^-$	3.9%
D_S^+	1968.47±0.33	0.150	$\pi^+ + K^+ + K^-$	5.2%
Λ_C^+	2286.46±0.14	0.060	$\pi^+ + p + K^-$	5.0%





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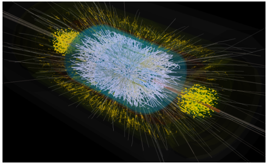
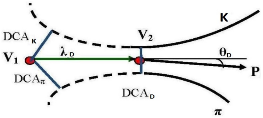
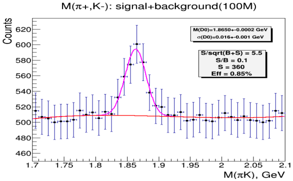
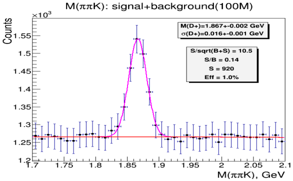
Open charm reconstruction





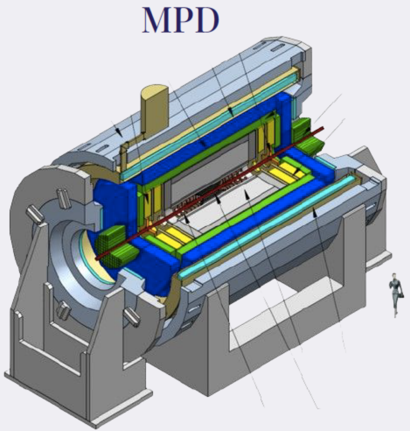
- To suppress the large combinatorial background in Au+Au collisions it is necessary to use strong criteria for signal selection. Two methods are used for signal selection:
  1)Method of topological cuts (TC)
  2)Method of multivariate data analysis (MVA)





- Optimized selection cuts allow reconstructing D^0 and D^+ with an efficiency of 0.85% and 1.0%

miniBeBe (mini Beam-Beam counter detector)

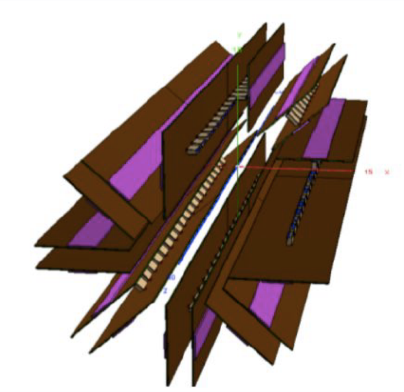


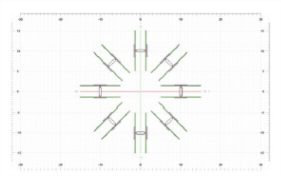
- Originally proposed as a wake up trigger for TOF
- Demanded efficient detection capabilities for low multiplicities p+p, p+A and A+A events
- Several adjustments in its design
- Adapted to the mechanical support of ITS
- Designed to be used only in Phase 0

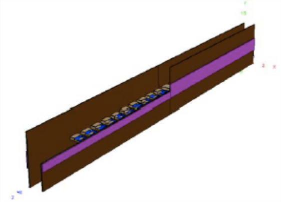
miniBeBe (mini Beam-Beam counter detector)

- 8 **H-shaped** rails
- Each module is formed by
  - A cuboid of **20 plastic scintillators** (EJ232, 20x20x5mm^3)
  - Each plastic surrounded by **two SiPM** (J Series, area 3.07x3.07mm^2) and electronics at each side
  - Fixed between the PCB and the cold plates
  - Electronic boards of 80x100mm^2
  - Cold Plates are the same of ITS
- Same space as ITS

miniBeBe (mini Beam-Beam counter detector)



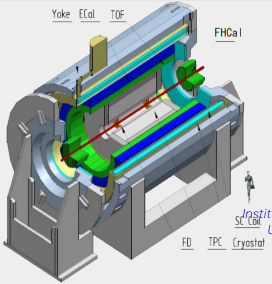




Multi-**P**urpose **D**etector Collaboration

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

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



Organization

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

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Institute of Physics and Technology, ***Kazakhstan***

MPD Status and plan

- 2024:
  PAC results include the schedule of a large campaign of NICA commissioning to start on December.
- 2025:
  Cool down of the west and east arcs of the collider and cooling of the Booster to start at the beginning of the year. First beams expected right after. Subsequent cooling of the Nuclotron **with beams during spring.** First attempts to inject beams in the collider and beam acceleration in the collider during summer. The first stage of the collider commissioning will target beam collisions with the fixed target installed in the beam pipe in the MPD interaction points (W-wire with diameter of 50-100 μm). Such collisions planned to take place at the end of summer. Stage two includes circulation of bunches (up to 2×10^8) in the collider rings by Fall. At this stage we may observe collisions in the collider mode, but the rate of collisions will be very low (L $< 5 \times 10^{24}$). Stage three will include multi-bunch injection of the rings with a noticeable event rate by the end of 2025.
- Beyond:
  Further plans will depend on the achieved level of progress.

Summary

- MPD collaboration is steadily coming to final integration of the detector and first data taking on the beams from NICA
- Physics program for the first years of MPD data taking is formulated and the first physics paper was recently published. Second paper under preparation to be submitted to the Mexican Journal of Physics
- MPD will provide a unique opportunity for investigating properties of nuclear matter at maximal densities to map the QCD phase diagram, to search for phase transition and the Critical End Point
- First operations of the MPD detector are expected at the end of 2025
- Start of data taking at fixed target mode

GRACIAS