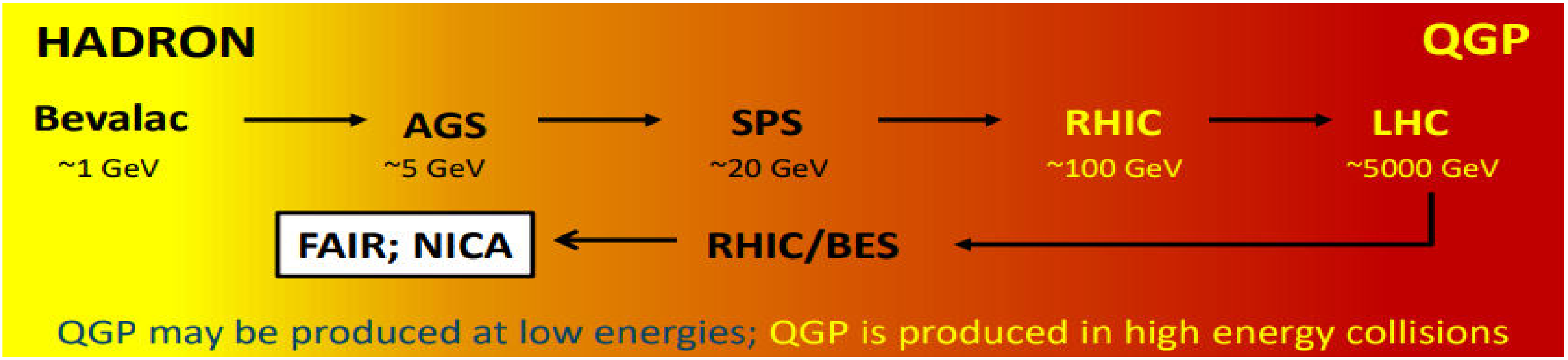
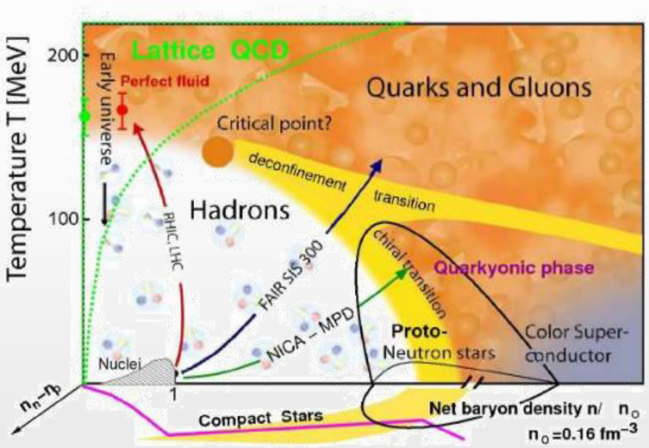
Nuclotron-based
Ion Collider fAcility

Статус и перспективы эксперимента MPD на коллайдере NICA

В.Г. Рябов

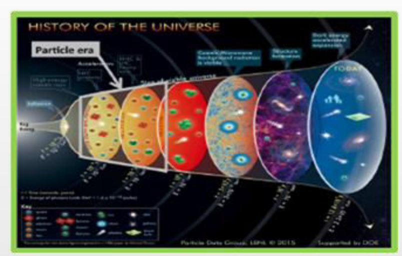
Heavy-ion collisions





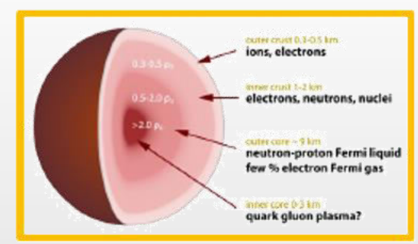
High beam energies ($\sqrt{s_{NN}} > 100$ GeV)

High temperature:
Early Universe evolution



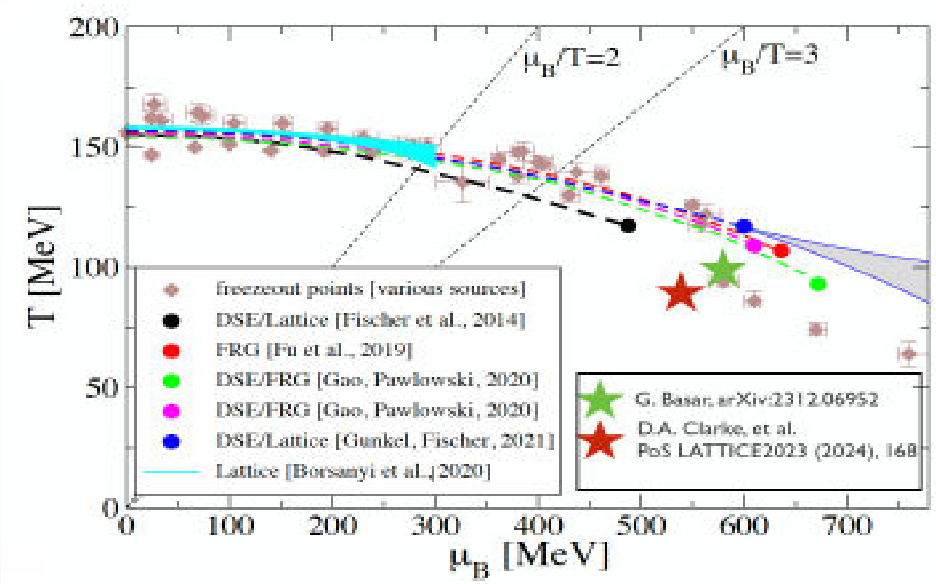
Low beam energies ($\sqrt{s_{NN}} \sim 10$ GeV)

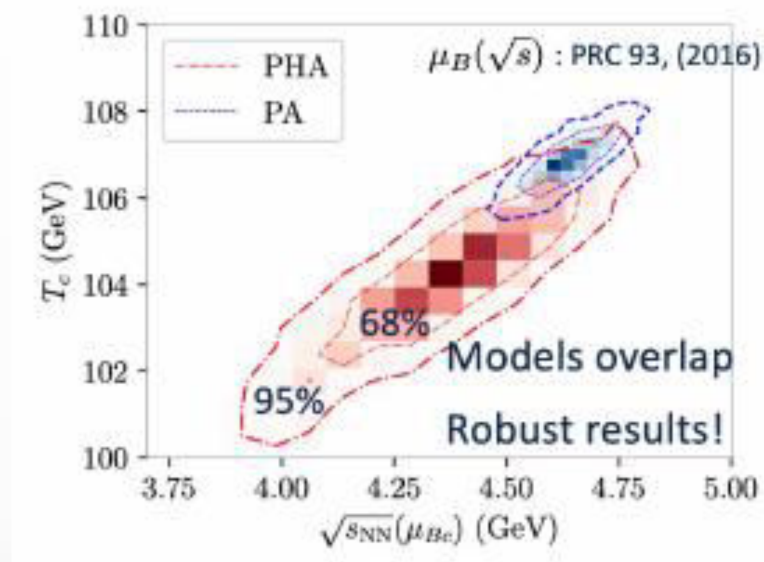
high baryon densities
→ inner structure of
compact stars



- 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

QCD critical point: predictions/estimations





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

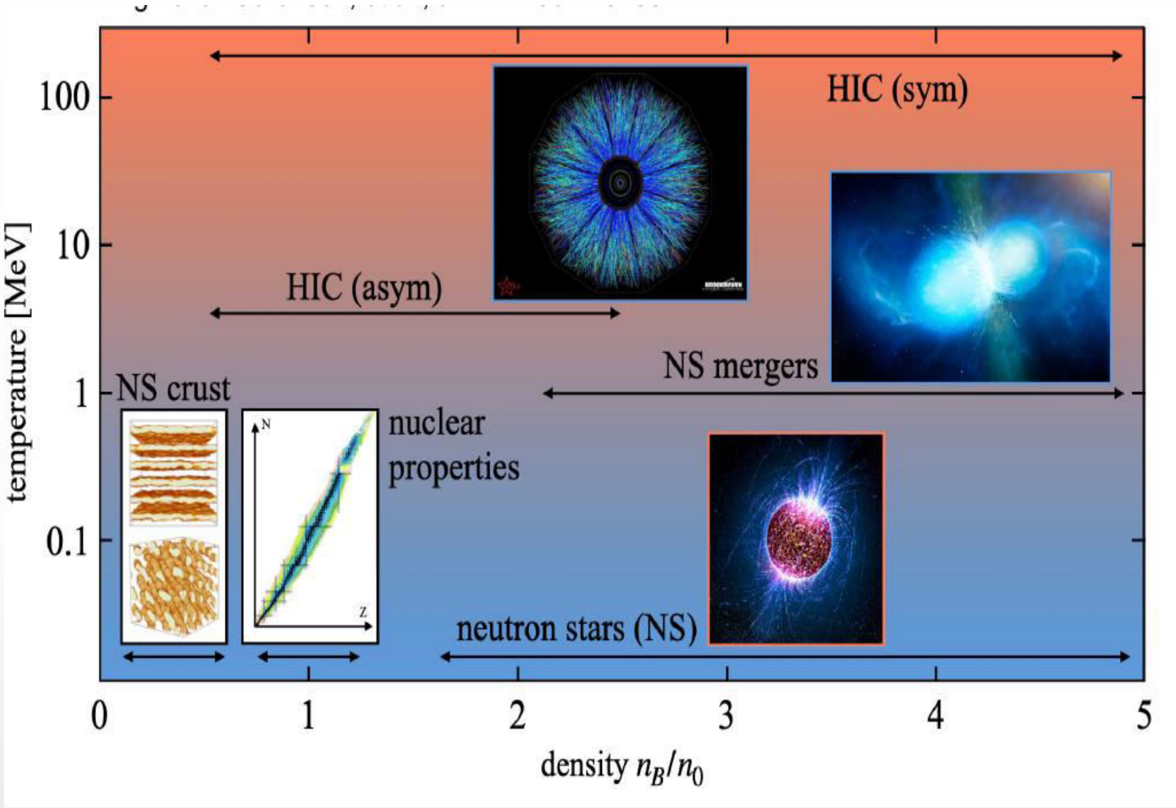
Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	F. Karsch et al.
Summary	**495 - 654**	**100 - 119**

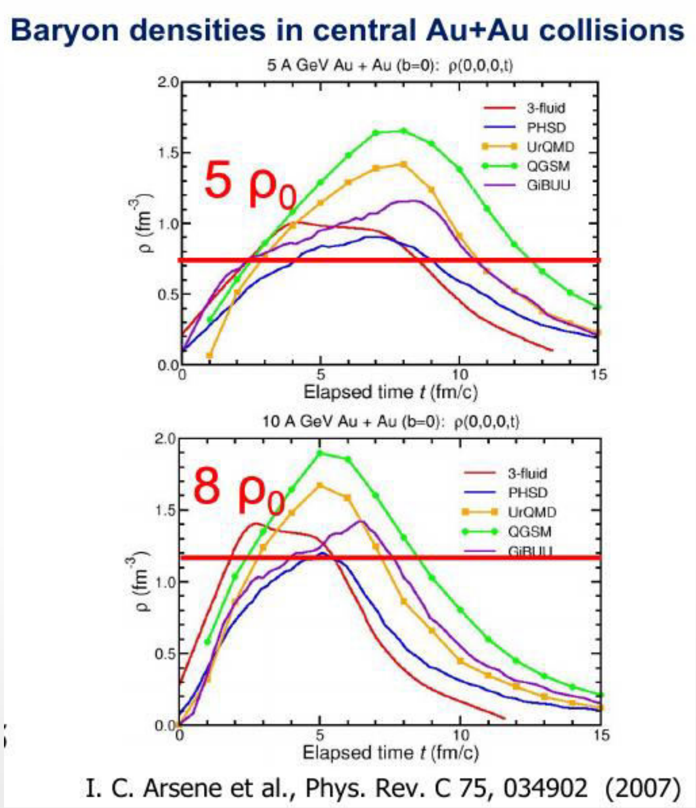
(μ_c, T_c) = (495 - 654, 100 - 119) MeV ➡ $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

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

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

Dense Nuclear Matter

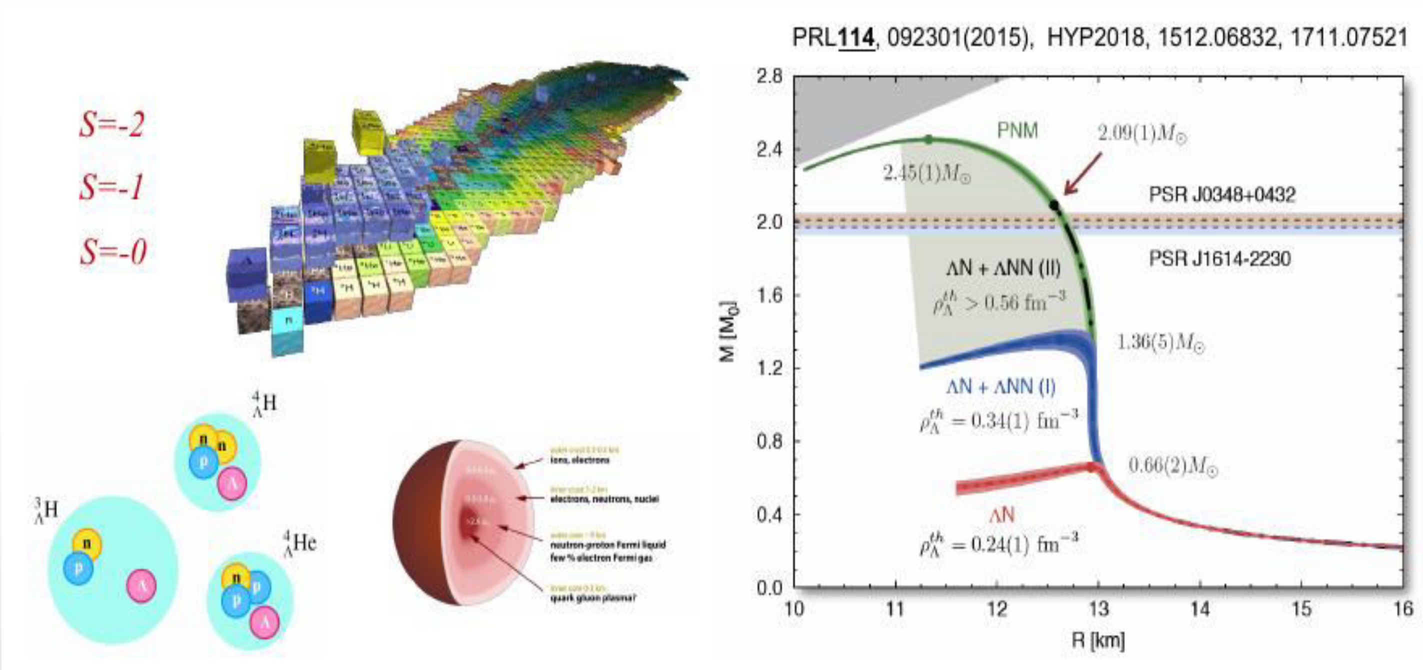




Relativistic heavy-ion collisions provide a unique and controlled experimental way to study the properties of nuclear matter at high baryon density.

Hyperon and Hyper-Nuclei Production in Heavy-Ion Collisions and Neutron Stars

❖ Nature of matter at extreme density (up to 5-10 ρ_0)

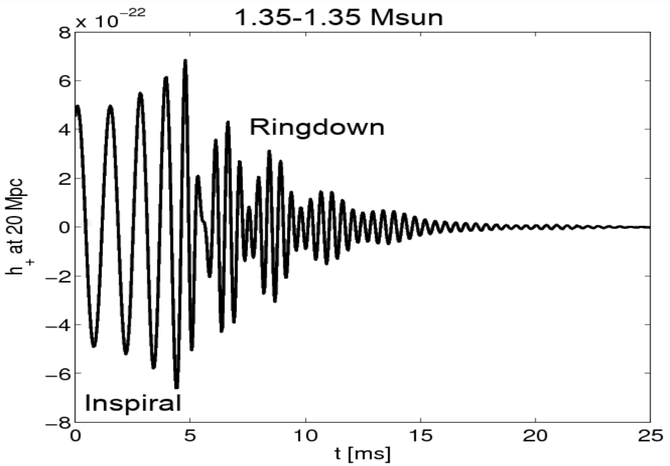


Hyperon and hyper-nuclei measurements in HIC → hyperon–nucleon interactions (NY, YNN) → key to understanding the EoS at high baryon density and inner structure of neutron stars

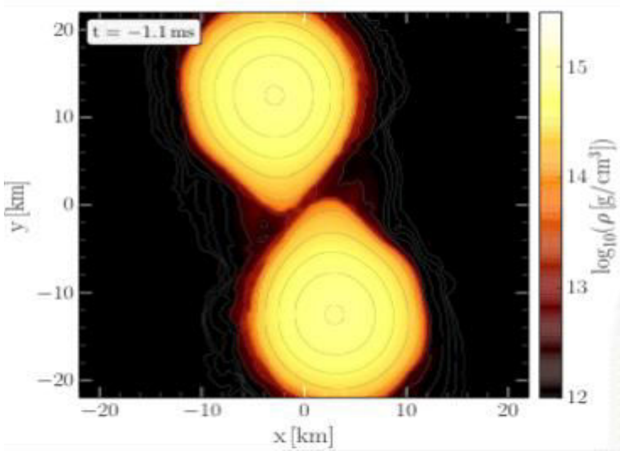
Neutron star mergers and heavy-ion collisions

LIGO and Virgo Collaborations, Phys. Rev. Lett. 119 (2017) 16, 161101; Nature Phys. 15 (2019) 10, 1040-1045

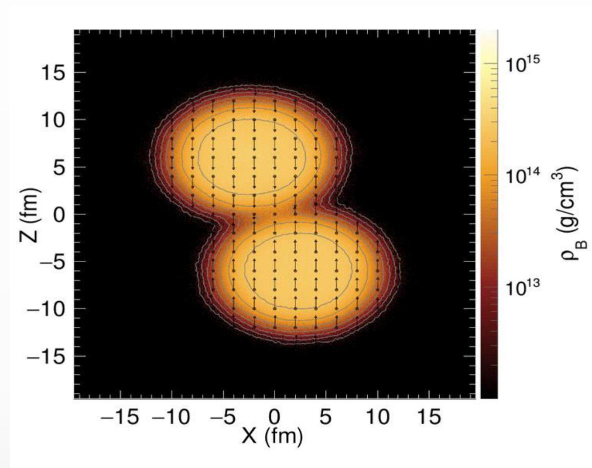
Gravitational wave signal



Neutron star mergers



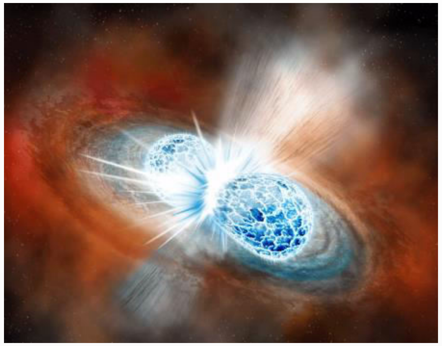
HIC: Au+Au 1.25 AGeV

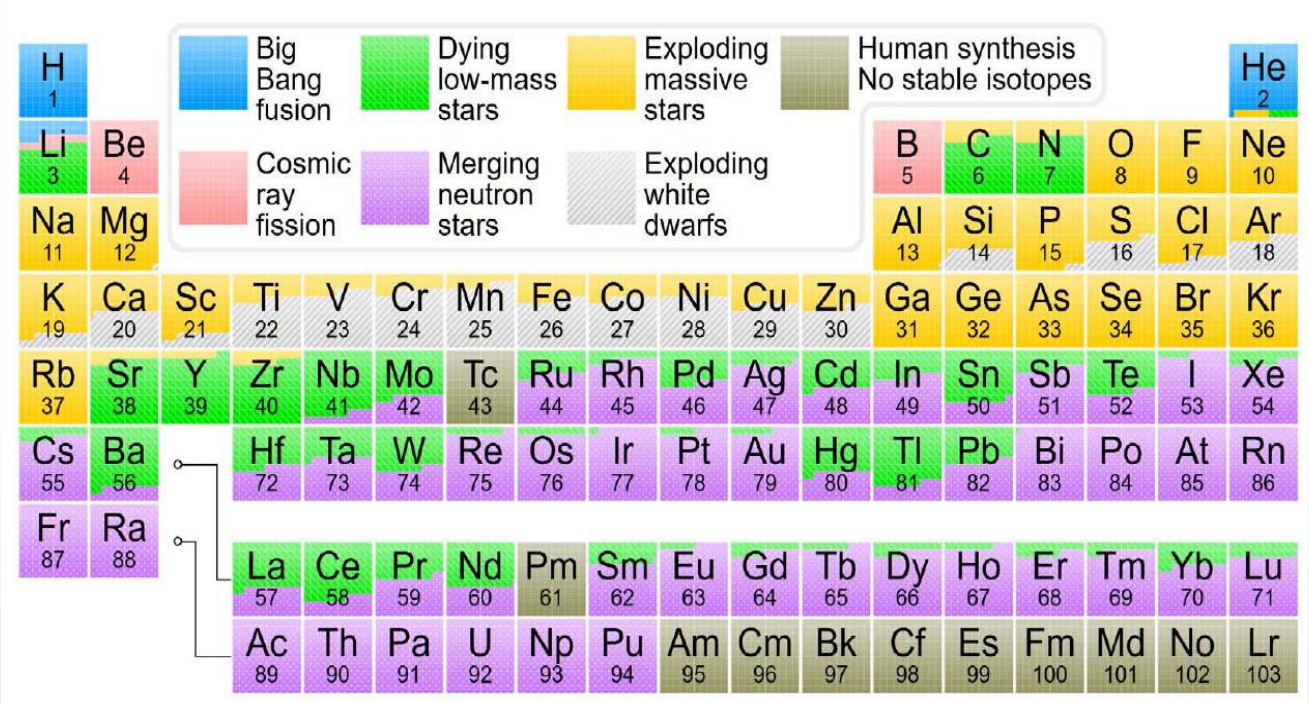


- ✓ Gravitational wave detection from GW170817, confirmation by astronomical observations
- ✓ T < 70 MeV, ρ ~ 3ρ0 → about the same conditions as achieved in HIC in the laboratory

Nuclear synthesis in NS mergers

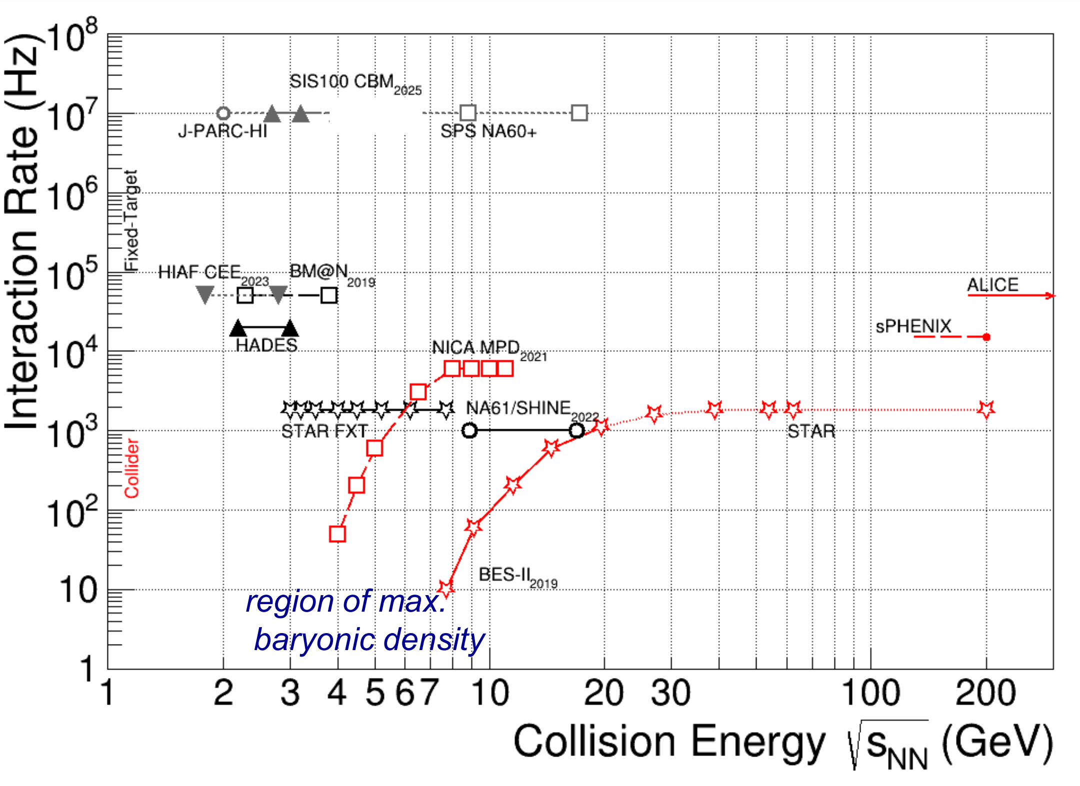
Nuclear EoS is important also for the r-process nuclear synthesis in neutron star merger





Neutron capture process (r-process) in NS mergers is responsible for the production of heavy elements such as Au, Pt, U

Relativistic Heavy Ion Experiments



Present:

HADES BES (SIS): Au+Au at $\sqrt{s_{NN}}$ = 2.42 GeV,
Ag+Ag at $\sqrt{s_{NN}}$ = 2.42 GeV, 2.55 GeV.
STAR BES (RHIC): Au+Au at $\sqrt{s_{NN}}$ = 3-200 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-?)

NICA collision energy

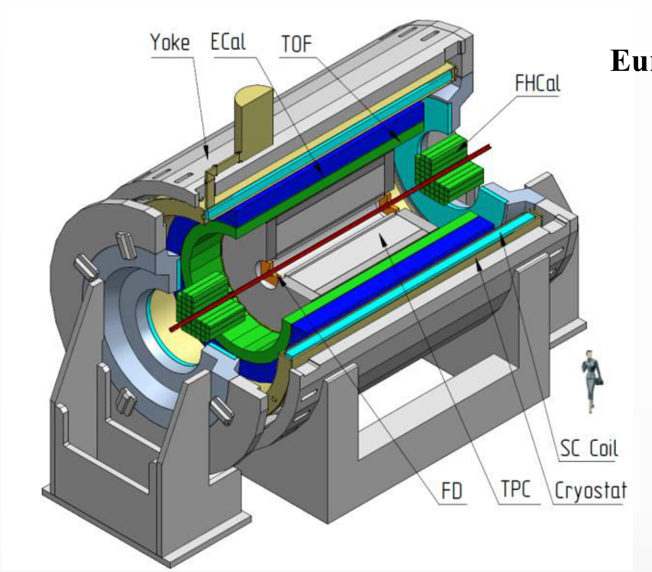
BM@N: 2.3 - 3.3 GeV
MPD: 4 - 11 GeV

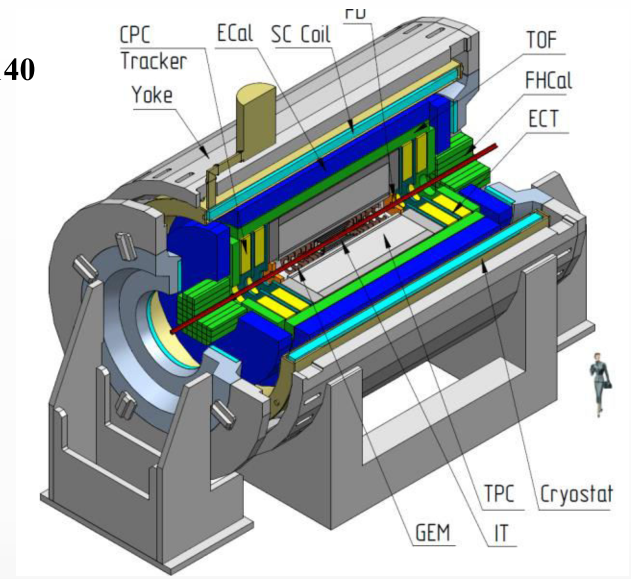
Multi-Purpose Detector

Stage-I → start of commissioning in 2025

Stage-II → 2030+

Eur.Phys.J.A 58 (2022) 7, 140

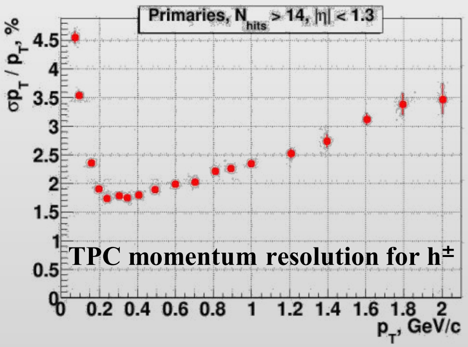


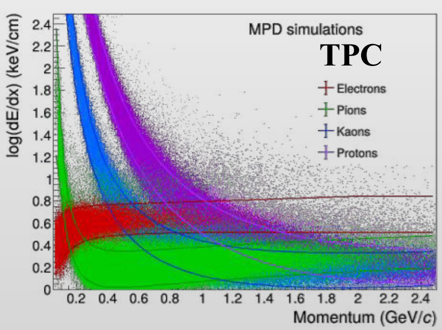


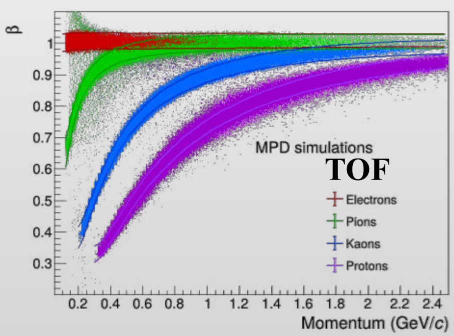
TPC: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.6$; **TOF, EMC**: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.4$
FFD: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$; **FHCAL**: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

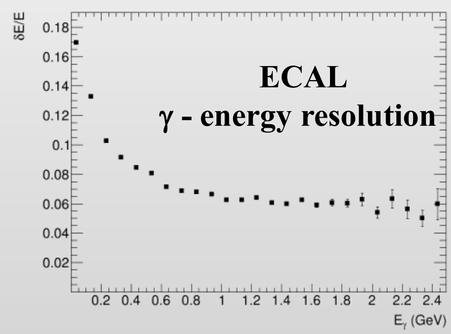
\+ **ITS** : $|\Delta\varphi| < 2\pi$, $|\eta| \leq 3$
\+ **Forward Spectrometers**: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 2.2$

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

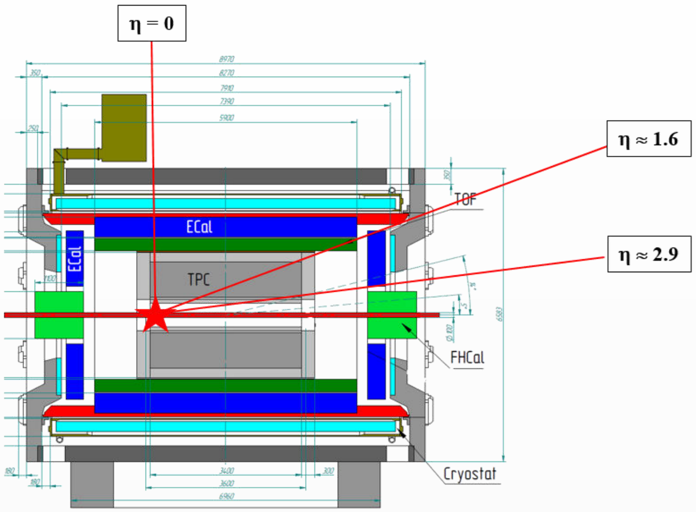


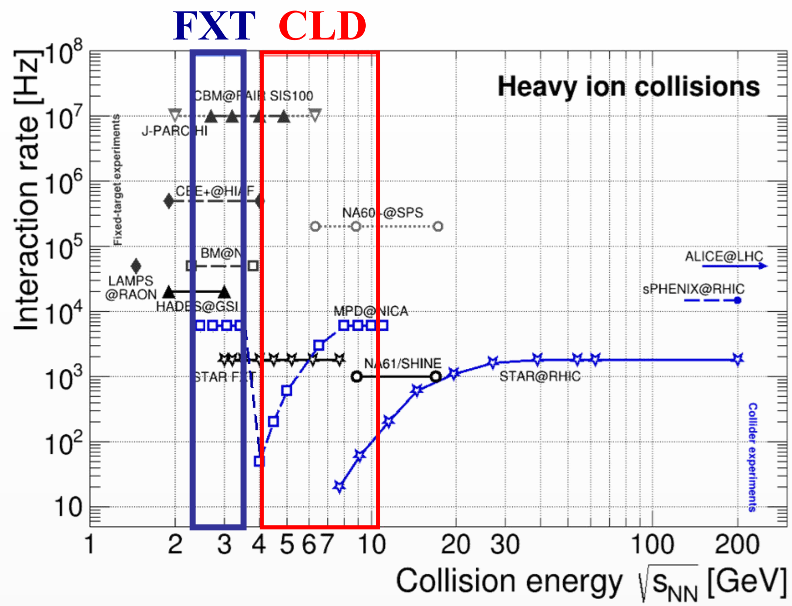






CLD and FXT operation at NICA

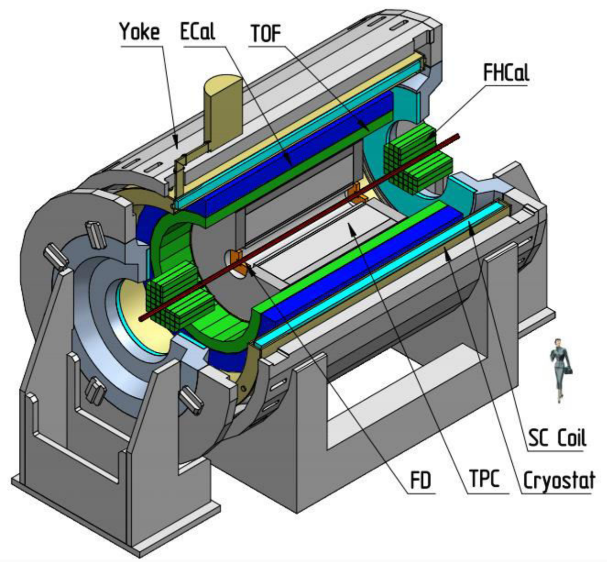




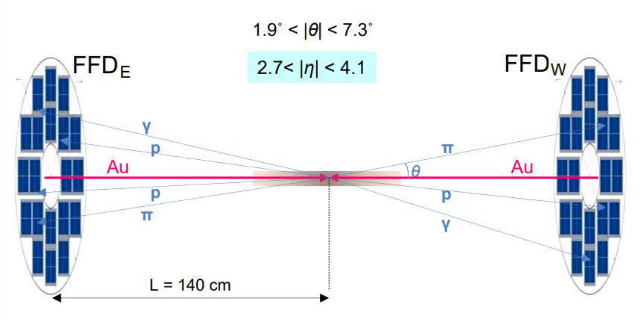
- ❖ MPD-CLD and MPD-FXT operation options
- ❖ Collider mode: two beams, $\sqrt{s_{NN}}$ = 4-11 GeV → Xe+Xe/Bi+Bi at $\sqrt{s_{NN}}$ ~ 7 GeV, ~ 50 Hz at start-up
- ❖ Fixed-target mode: one beam + thin wire (~ 50 μm) → Xe/Bi+W/Au at $\sqrt{s_{NN}}$ ~ 3 GeV, ~ kHz at start-up

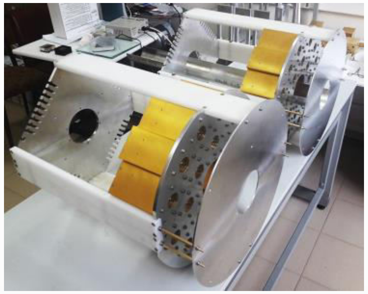
- ❖ MPD strategy – high-luminosity scans in **energy** and **system size** to measure a wide variety of signals:
  - ✓ order of the phase transition and search for the QCD critical point → structure of the QCD phase diagram
  - ✓ hypernuclei and equation of state at high baryon densities → inner structure of compact stars, star mergers
- ❖ Scans to be carried out using the **same apparatus** 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

Trigger detectors

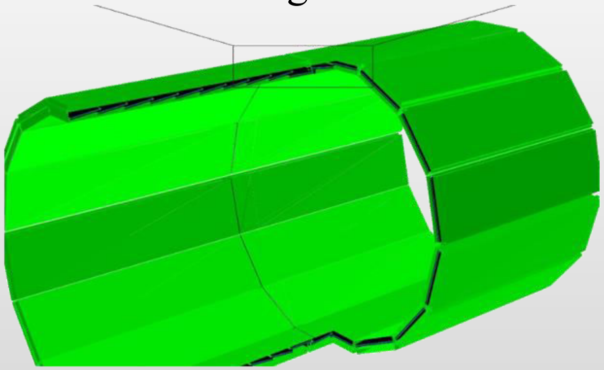


- FFD (Fast Forward Cherenkov Detector):
  - ✓ fast (~ 50 ps) event triggering → photons from π^0's
  - ✓ T_0 for time-of-flight measurements (TOF and ECAL)





- TOF ($|\eta| < 1.5$):
  - ✓ 280 fast signals for each MRPC chamber
  - ✓ no online timing information



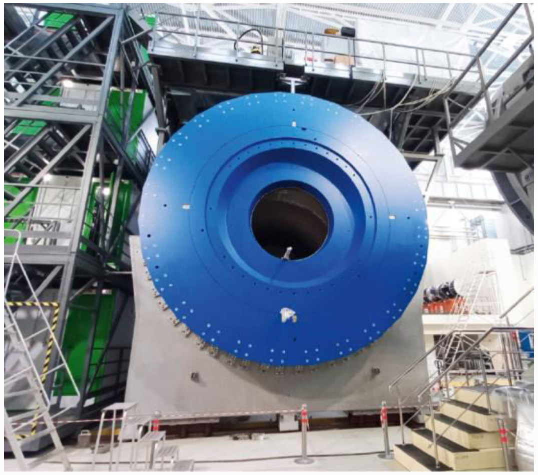
- FHCAL (Forward Hadron Calorimeter):
  - ✓ Fast signals for event triggering
  - ✓ poor T_0 (~ 1 ns) and event z-vertex resolution

two FHCAL detectors
at $2 < |\eta| < 5$,
~ 1x1 m^2 each

Trigger system of the MPD is effective for <u>different HI collision systems and energies</u> as well as for <u>different operation modes</u> (MPD-CLD vs. MPD-FXT)

MPD magnet

Magnet yoke

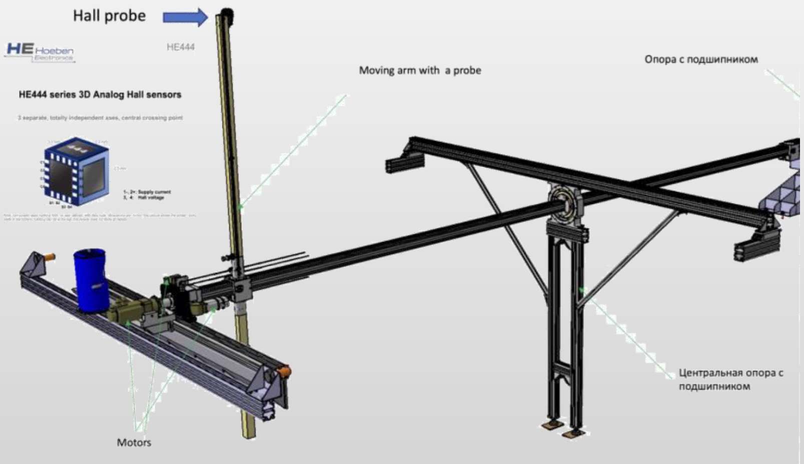


Cryogenic platform

Strings for cryogenic pipes and cables hold

- February: solenoid power cable thermal isolation inside of the Chimney
- Now: solenoid cooled down to the working temperature of 4.5 K, test current supply

Magnetic field mapper



Novosibirsk BINP magnetic field mapper

	Along radius (R)	Along azimuth angle (ϕ)	Along beam (z)
Step size, см	5	21	10
Total length, см	220	360° (1380 см at max. R)	700
Number of measurements	44	64	70

Single 3D Hall probe moves in 3 directions: z , R, ϕ
Accuracy: 0.1 – 0.3 Gs
Number of points: ~ $2\cdot10^5$ (90 hours)
Fields to measure: 0.3 – 0.57 T (5-6 points)
Number of tunes per field: 5
Total time of measurements: ~ 3-4 months

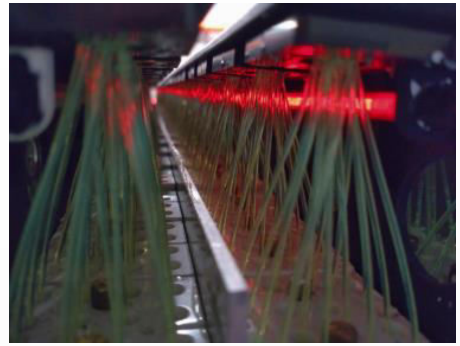
April: mapper delivery to JINR and installation of stationary Hall probes
Summer: MF measurements at 02-0.55 T

Central barrel subsystems

Frame - ready

Carbon fiber support frame delivered and unpacked, sagita ~ 5 mm at full load, rails for the TPC and TOF are installed

ECAL



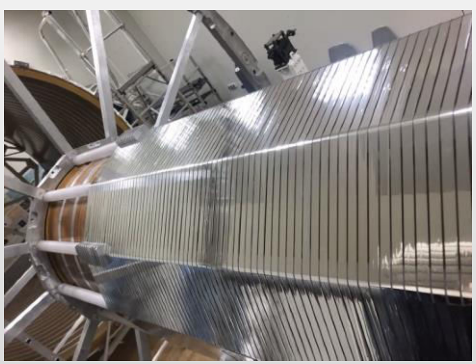
ECAL ~ 38400 towers (2400 modules)
produced by Tsinghua University, Shandong University, Fudan University, South China University, Huzhou University and JINR – production in IHEP (Protvino) and Tenzor (Dubna)

45 half-sectors to be ready by August, the rest depends on WLS fiber supply from Tver

TOF - ready

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

TPC – central tracking detector



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

TPC mechanical body assembly with ROCs, leak test and HV test	**June 2025**
TPC installation to MPD and test	**Nov –Dec 2025**

Starting detector commissioning in late 2025 remains the main priority

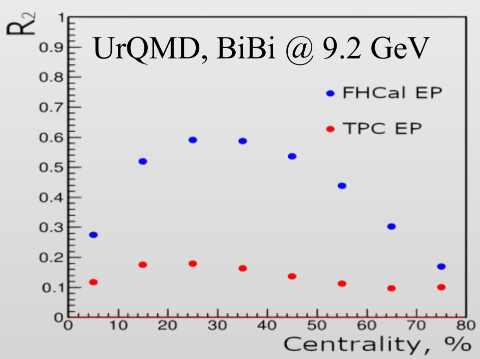
Forward subsystems

FHCAL - ready

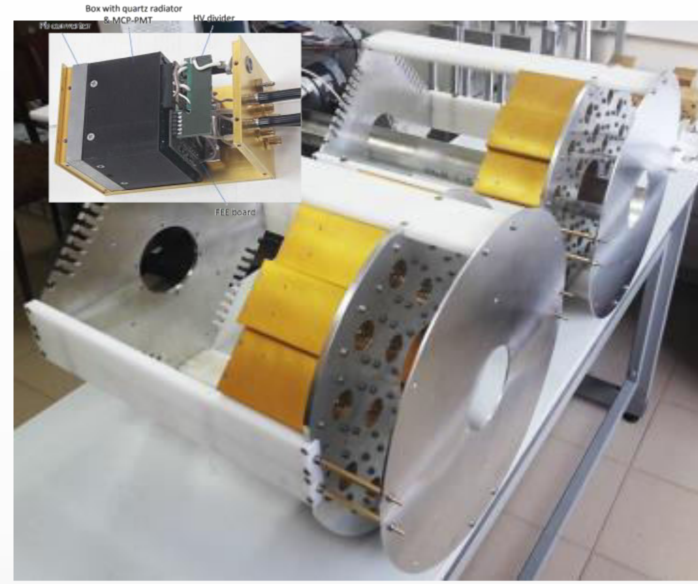
FHCal assembled on the platform, (modules are equipped with FEE)

Test installation of FHCAL → autumn 2024

FHCAL provides triggering information, centrality and event plane

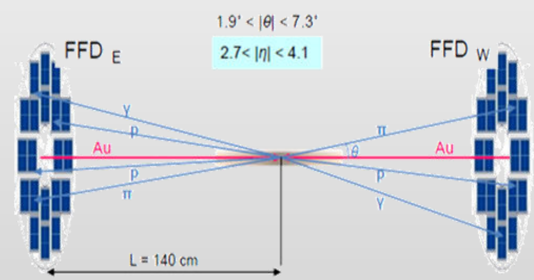


FFD - ready



Cherenkov modules of FFDE and FFDW, mechanics for installation in container with beam pipe are available, Long term tests with cosmic rays & laser ongoing

FFD provides triggering information, even z-vertex and T_0 for timing measurements



Extension of the MPD project, 2026-2030

Cost estimation

Proposed schedule and resource request for the MPD Project

Expenditures, resources, funding sources			**Cost (thousands of US dollars)/ Resource requirements**	**Cost/Resources, distribution by years** 1st year	2nd year	3rd year	4th year	5th year
		International cooperation	1000	200	200	200	200	200
		Materials	23350	3700	5250	6500	5350	2550
		Equipment, Third-party company services	6450	1100	1150	1850	1550	800
		Commissioning	300	0	50	100	100	50
		R&D contracts with other research organizations	450	100	100	100	100	50
		Software purchasing						
		Design/construction						
		Service costs *(planned in case of direct project affiliation)*	1000	200	200	200	200	200
Resources required	**Standard hours**	Resources						
		- the amount of FTE,	625	125	125	125	125	125
		- accelerator/installation,	13720	2200	2880	2880	2880	2880
		- reactor,…						
Sources of funding	**JINR Budget**	JINR budget *(budget items)*	**33000**	**5400**	**7050**	**9050**	**7600**	**3900**
	Extra fudning (supplementary)	Contributions by partners	500	100	100	100	100	100
		Funds under contracts with customers						

Project Leader Голованюк V.M.Golovatyuk

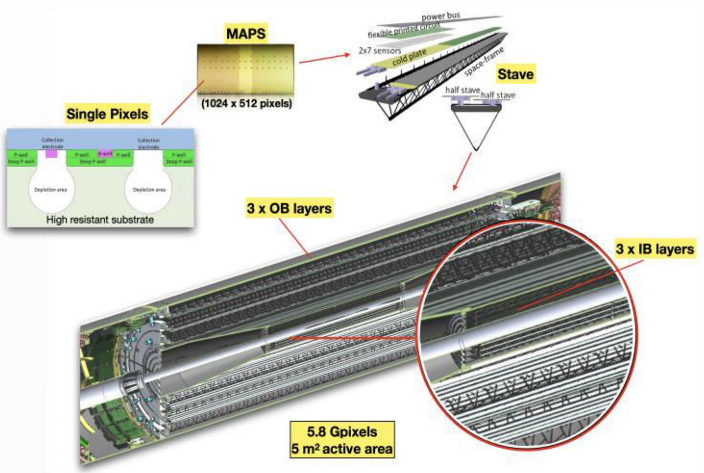
Laboratory Economist ________ V.V.Morozov

Resources distribution by years

The main systems, resources, funding souces			Cost of the main subsystems (k$)	Cost/Resources distributiom by years (k$) 1 y. (2026)	2 y. (2027)	3 y. (2028)	4 y. (2029)	5 y. (2030)
Resources required	The main systems	Time Projection Chamber upgrade (TPC)	5250	700	1200	1650	1000	700
		Upgrade of Ecal	700	200	200	100	100	100
		Upgrade of FHCal	350	100	100	50	50	50
		Upgrade of Forward FFD	250	50	50	50	50	50
		Cryogenic and Power Supply systems of Magnet	3500	1100	900	800	500	200
		Upgrade of DAQ	850	150	150	200	200	150
		Infrastructure of the MPD	900	250	250	200	100	100
		Second stage detectors						
		Forward TOF	3770	420	750	1100	1100	400
		Forward Ttracker	13140	1350	2850	3650	3450	1840
		Inner Tracker (ITS)	4290	1270	1050	1200	700	70
		Total:	**33000**	**5590**	**7500**	**9000**	**7250**	**3660**
		International Cooperation	825	165	165	165	165	165

Inner Tracking System – ITS

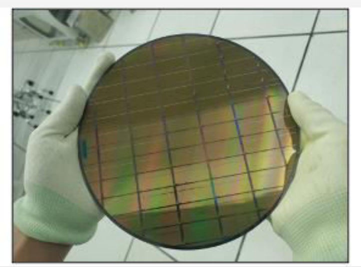
The ITS is the key to measuring the production of heavy-flavor hadrons



The complete structure of the 6-layer MPD-ITS detector, from a single pixel to the inner and outer cylindrical layers

1) The TDR was finalized to build an ITS consisting of six cylindrical layers of MAPS (Monolithic Active Pixel Sensors) around the interaction region: 3 layers of inner barrel (IB) surrounded by 3 layers of outer barrel (OB)

2) An agreement was reached with Chinese partners to jointly research, develop and manufacture in China the missing components needed to build the tracker and its readout system.



- first prototype of ALPIDE-like MAPS (MICA) sensor developed at CCNU and produced in China

- FPGA-based Readout System and the Power Unit developed at USTC for reading out the "staves" comprising of MICA sensors of IB and OB → tests at LHEP in 2025

- first porotypes of the GBT ASICs for the fast aggregation of data and transfer via optical lines designed and manufactured → lab tests ongoing in CCNU.

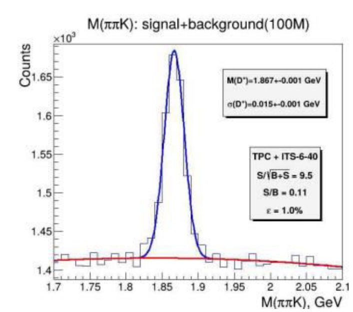
6 layers in 2 barrels final conceptional design and its optimization- by 2024

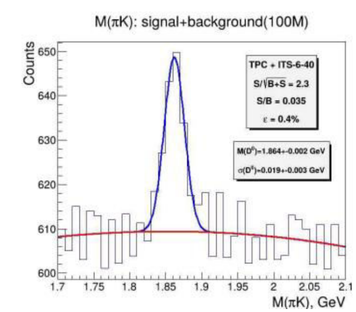
LHEP ЛФВЭ

MPD - ITS

D⁺ and D⁰ reconstruction using KF with TPC-TOF PID

$D^+ \to K^- + \pi^+ + \pi^+$ $D^0 \to K^- + \pi^+$





N_D = 19 000 mesons/month for D^+
N_D = 3 200 mesons/month for D^0

Using the optimal BDT cut allows to reconstruct D^+ and D^0 with an efficiency of **1.0%** and **0.4%** respectively.

Particle	D^+	D^0
Efficiency, %	1.0	0.4
Significance	9.5	2.3
S/B(2σ) ratio	0.11	0.035

Courtesy of Prof. V.Kondratiev (SPbSU)

D^0 and D^+ reconstruction using information from ITS+TPC+TOF subsystems

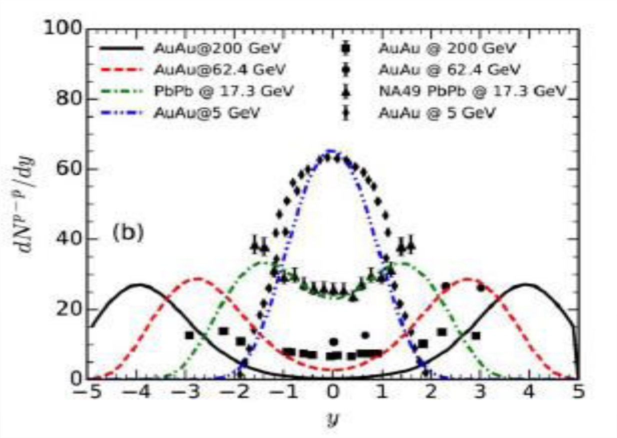
Rapidity scan with MPD at NICA

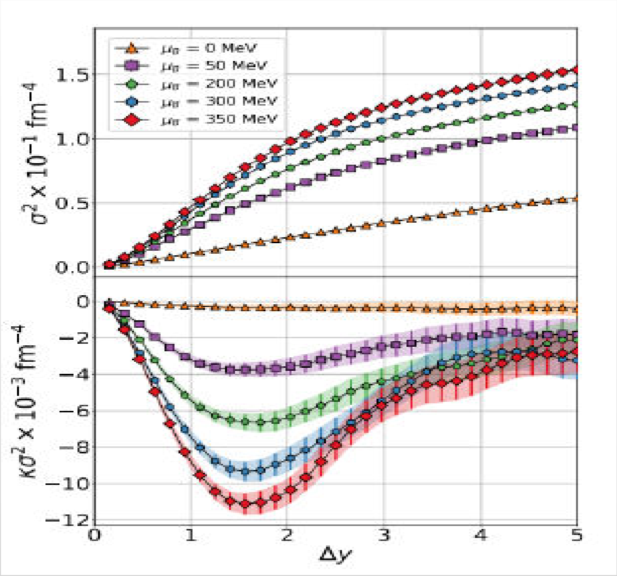
More detailed study of the QCD phase diagram by utilizing a three-dimensional scan in collision energy, interacting system size, and particle rapidity

<u>Motivation for Forward upgrade</u>:

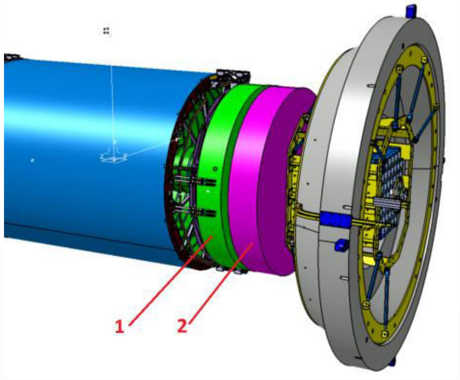
1. Full yields of (heavier) identified hadrons and light nuclei with non-trivial rapidity dependence due to baryon stopping, more detailed study of the “horn”, the “step” effects for lighter hadrons
2. Two-particle correlation and multiparticle cumulant studies with wider coverage in $\Delta\eta$
3. Directed and elliptic flow → tighter constraints on η/s
4. Search for CEP with event-by-event fluctuations of conserved charges → higher sensitivity with wider rapidity coverage
5. Hyperon global polarization vs rapidity → insights on the origin of the global polarization signal, tighter constraints for models
6. Extended forward rapidity coverage may be beneficial for diffractive studies in proton-proton collisions, such as instanton searches
7. Improved trigger efficiency, centrality and event plane determination

… and more

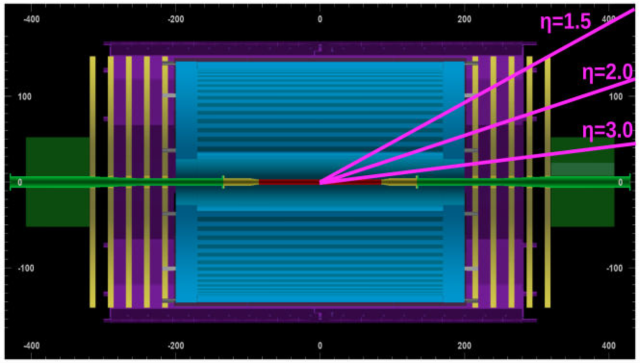




Forward spectrometers – tracking



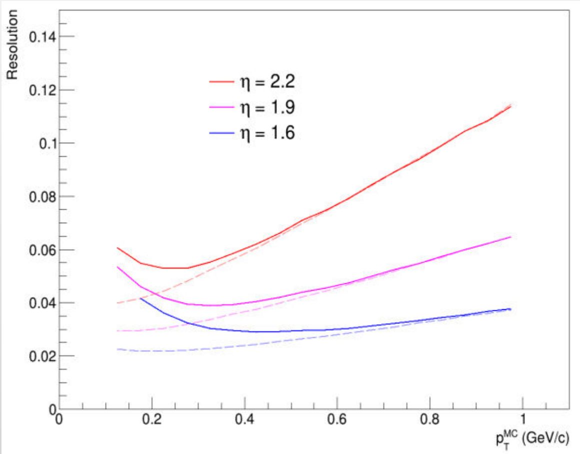
Two volumes (green and magenta) available for the installation of forward tracker stations

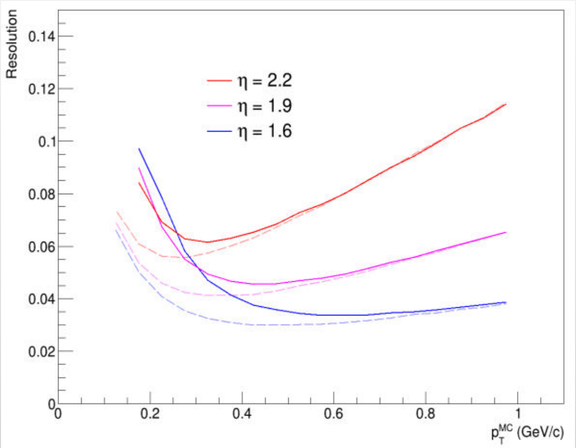


Pseudorapidity coverage of the forward spectrometer

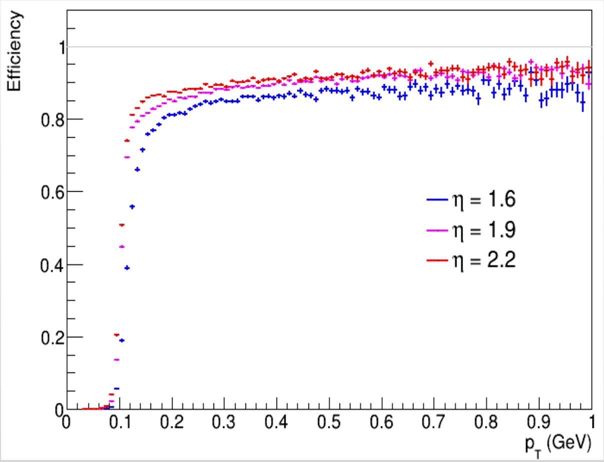
- Five tracking layers within z = 210–300 cm, 1% X_0, ~ 80 μm spatial resolution
- Tracking – ACTS package – experiment-independent high-level track reconstruction toolkit, including seeding tools and combinatorial Kalman Filter for track finding and vertex reconstruction

Momentum resolution for pions (left) and protons (right) at different η





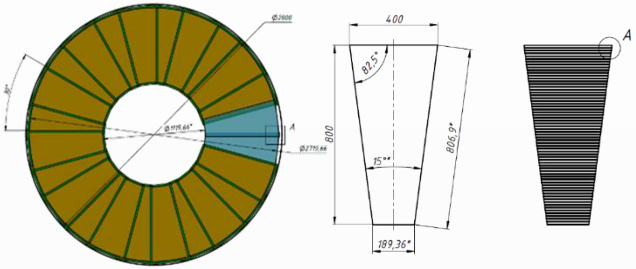
Tracking efficiency at different η



Forward spectrometers – PID

❖ Last layer is a TOF detector built of MRPC chambers

End-cap TOF detector(s)



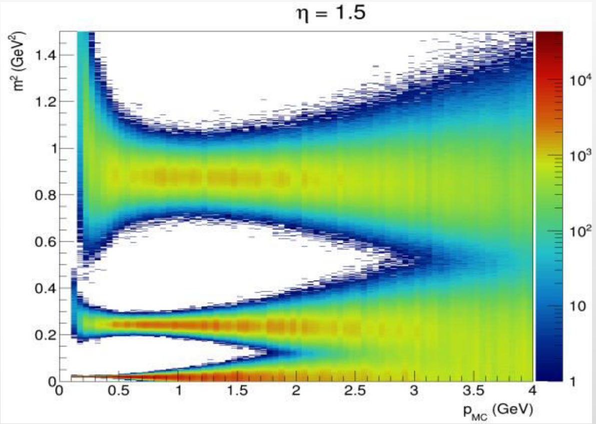
End-cap TOF ring design based on a trapezoidal MRPCs

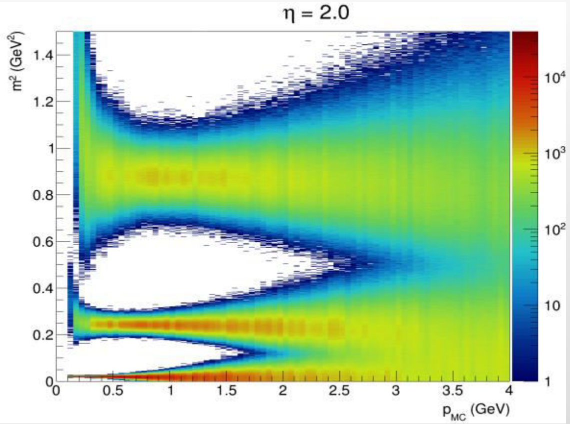
Each MRPC chamber contains 64 strips, which both-sides read-out

Each TOF ring contains 24 MRPCs → 6144 read-out channels in total

Same electronics based on NINO and HPTDC chips as in the basic TOF-MPD

❖ Reliable π/K/p separation vs. particle momentum for different rapidity ranges





Rather limited momentum resolution is compensated by a large path length (~3m) → reasonable PID for charged hadrons

Funding

- Support program from Russian Ministry of Education and Science for NICA:
  - ✓ Russian groups from subordinated organizations participating in NICA with signed MOUs
  - ✓ 200 MRUB (~2.2 M$) in 2024 for all NICA activities: MPD, BM@N, SPD, ARIADNA collaborations, accelerator
  - ✓ program has been extended to 2025-2026
  - ✓ new participating institution are possible

- ~ 40 MRUB for MPD per year:
  - ✓ supported organizations: MEPhI, St.Petersburg Polytechnic University, INR RAS, Belgorod National Research University, North Ossetia State University

- Problems:
  - ✓ KI, MSU, SPbSU, HSE University are excluded from the program (not subordinated organizations)
  - ✓ no funds for travel (shifts, etc.)

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

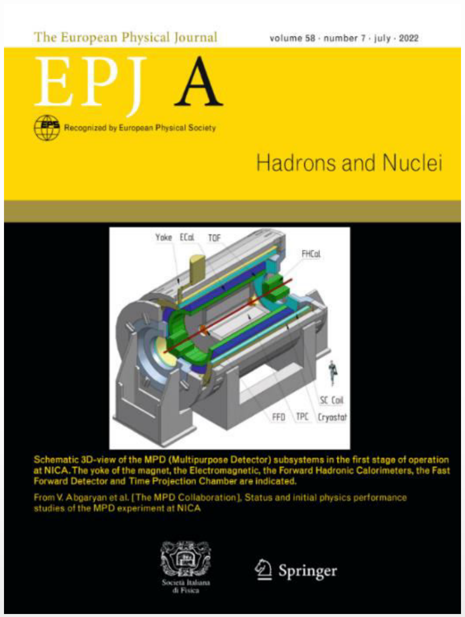
Heavy flavor

- 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

Collaboration papers

❖ 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)



Eur. Phys. J. A manuscript No.
(will be inserted by the editor)

Status and initial physics performance studies of the MPD experiment at NICA

The MPD Collaboration

Contents

1 Introduction

II. **MPD physics performance studies in Bi+Bi collisions at $\sqrt{s_{NN}}$ = 9.2 GeV**
consolidation and publication of physics feasibility studies for BiBi@9.2 GeV, 40+ pages

arXiv:2503.21117 [nucl-ex]

paper has been submitted to the journal, Revista Mexicana de Física

Initial state

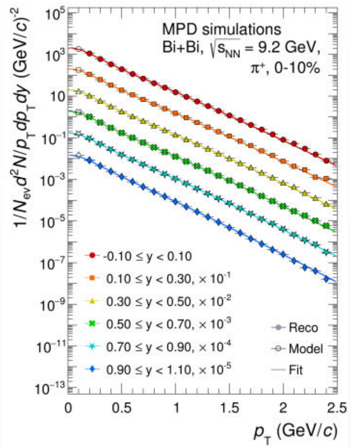
QGP as a perfect fluid

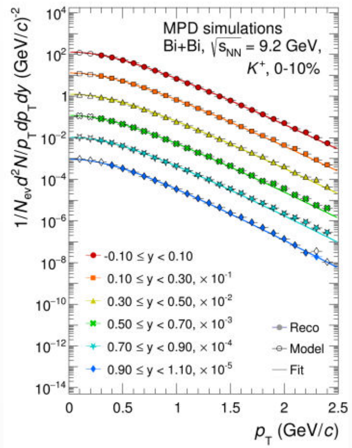
Light identified hadrons

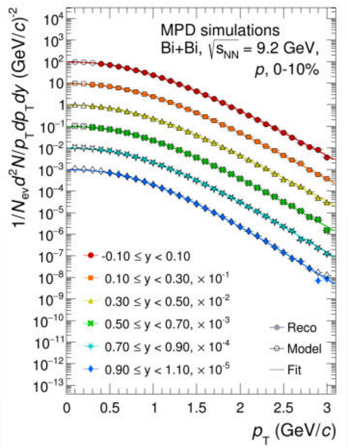
- ✓ probe freeze-out conditions
- ✓ radial flow and collective expansion
- ✓ hadronization mechanisms, thermal models vs. coalescence
- ✓ strangeness production, “horn” for K/π, hidden strangeness with $\phi(1020)$
- ✓ lifetime and properties of the late hadronic phase
- ✓ fluctuation of net-baryon (proton) and net-strangeness (kaon) numbers
- ✓ parton energy loss
- ✓ …

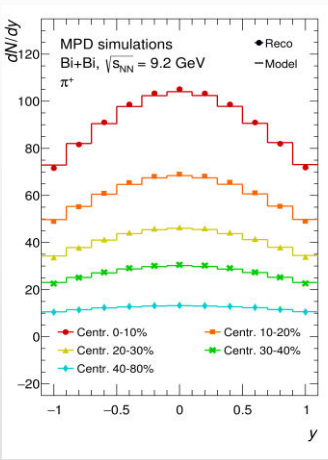
Charged hadrons, Bi + Bi @ 9.2 GeV

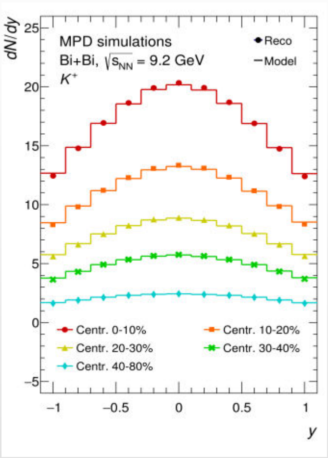
❖ Charged hadrons: large and uniform acceptance + excellent PID capabilities of TPC and TOF

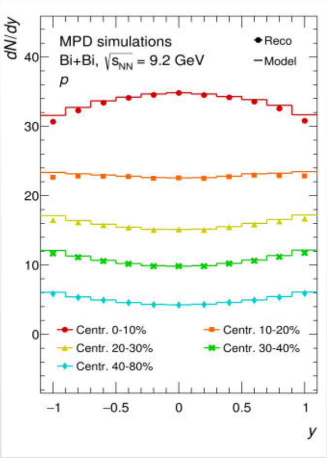












Cover (p_T - rapidity) phase space corresponding to ~ 70% of π/K/p total production

Cover p_T range that corresponds to > 90% of π/K/p total production at midrapidity → small unc. for dN/dy

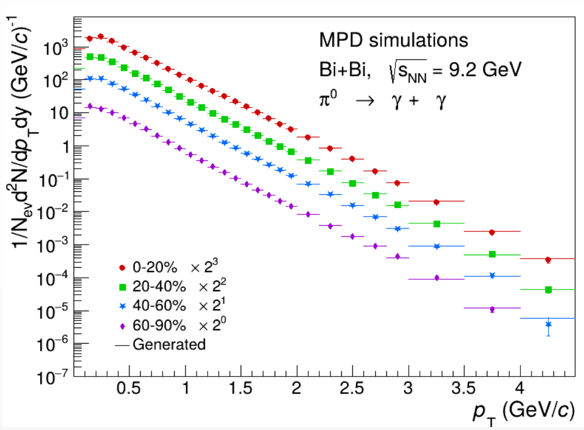
Wide p_T coverage for combined Blast-Wave fits → β, T_{kin}

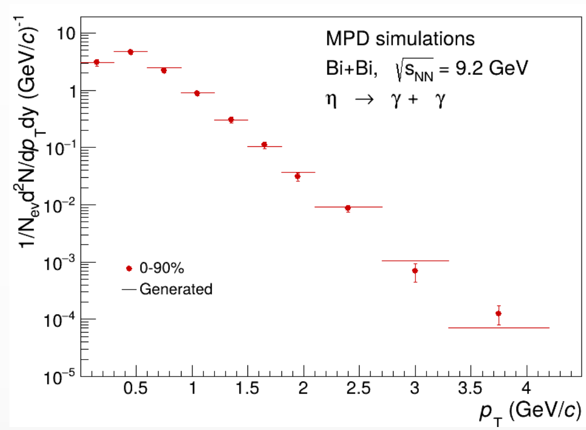
Neutral identified hadrons, Bi + Bi @ 9.2 GeV

❖ Neutral mesons:

✓ $\pi^0/\eta \rightarrow \gamma\gamma$, $\pi^0/\eta \rightarrow \gamma(e^+e^-)$, $\pi^0/\eta \rightarrow (e^+e^-)(e^+e^-)$; $K_s \rightarrow \pi^0\pi^0$; $\omega \rightarrow \pi^0\gamma$, $\omega/\eta \rightarrow \pi^0\pi^+\pi^-$; $\eta' \rightarrow \eta\pi^+\pi^-$

❖ Photons: ECAL reconstruction + photon conversion method (PCM)

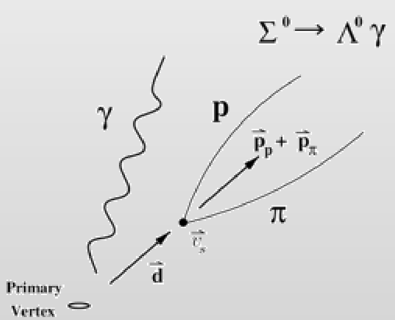


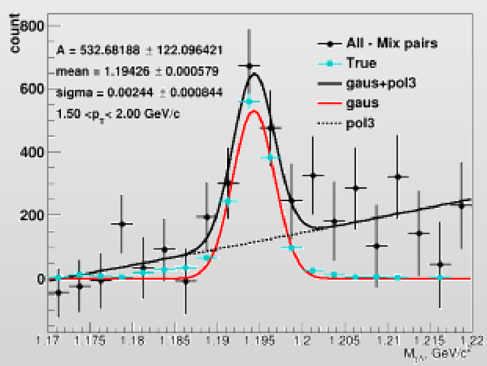


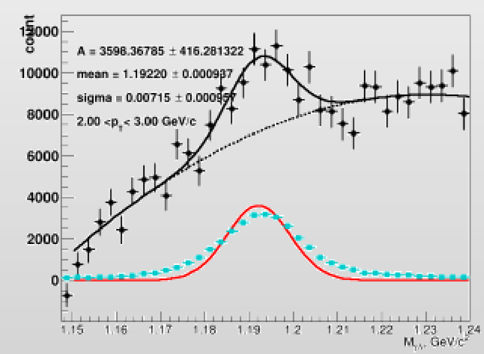
Extended p_T ranges compared to charged particle measurements

Different systematics and species (masses, quark contents)

❖ … and event baryons: $\Sigma^0 \rightarrow \Lambda\gamma$, $\Sigma^0 \rightarrow \Lambda(e^+e^-)$, $\Sigma^+ \rightarrow p\pi^0$







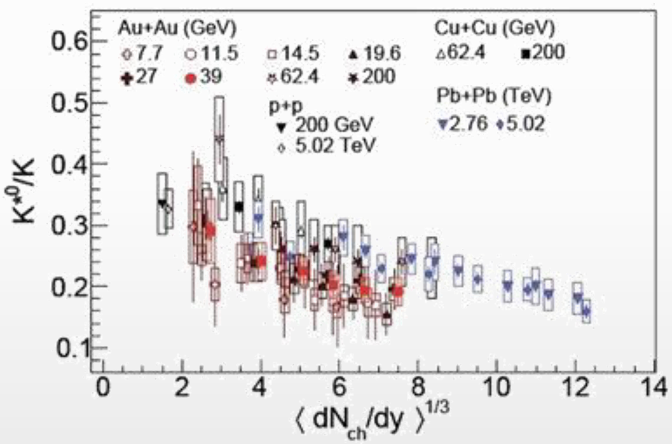
Hadronic resonances

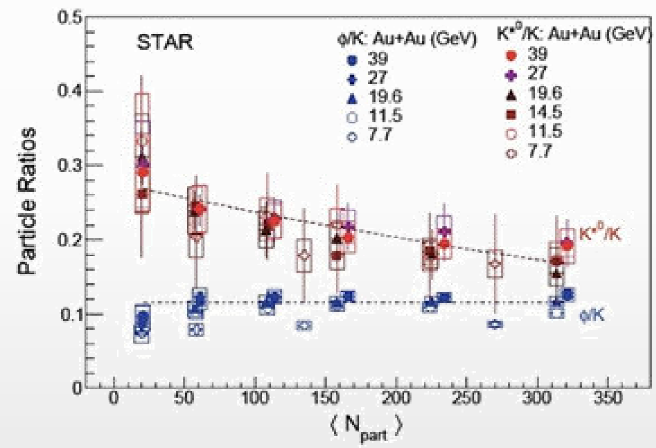
- Resonances probe reaction dynamics and particle production mechanisms vs. system size and $\sqrt{s_{NN}}$:
  - ✓ strangeness production, lifetime and properties of the hadronic phase, spin alignment of vector mesons, flow etc.

increasing lifetime →

	$\rho(770)$	$K^*(892)$	$\Sigma(1385)$	$\Lambda(1520)$	$\Xi(1530)$	$\phi(1020)$
$c\tau$ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

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



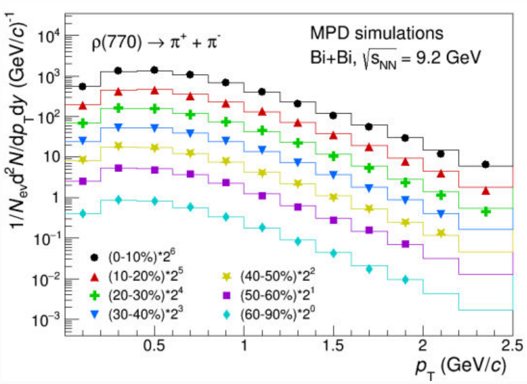


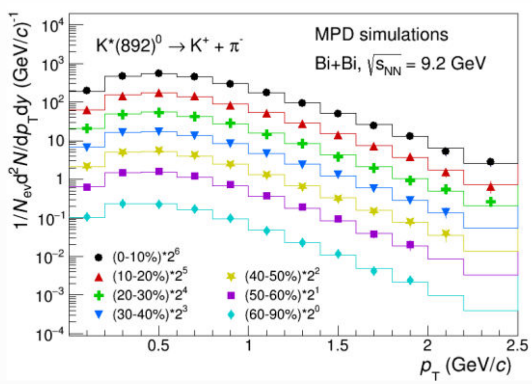
- Suppression of the ratios for shorter-lived resonances is explained by the existence of a hadronic phase that lives long enough (up to $\tau \sim 10$ fm/c) to cause a significant reduction of the reconstructed yields → present at NICA confirmed by measurements and transport model (UrQMD) calculations

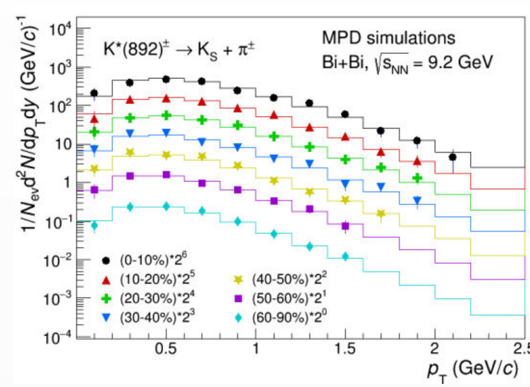
Precise measurements at NICA are needed to validate description of the hadronic phase in models

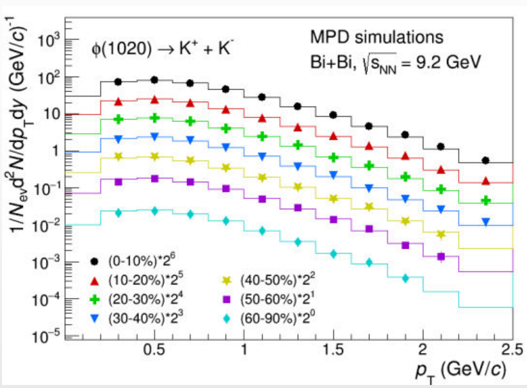
Hadronic resonances, Bi + Bi @ 9.2 GeV

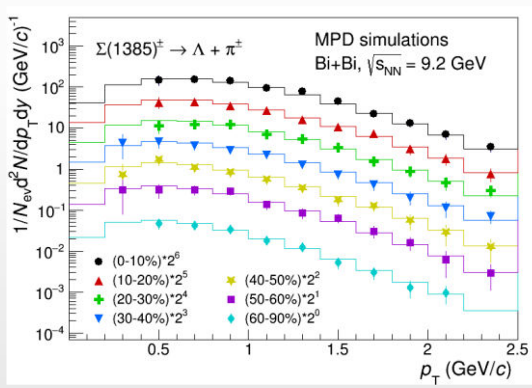
❖ PID capabilities of TPC and TOF + topology selections for weak decays of daughters (K_s, Λ)

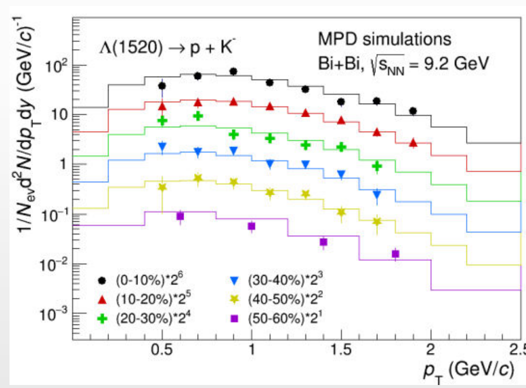












A wide variety of resonances is constructible, ρ(770), K*(892), ϕ(1020), Σ(1385), Λ(1520)

Measurements are possible starting from ~ zero momentum → sample most of the yields

Angular dependent measurements with larger statistics → spin alignment, collective flow

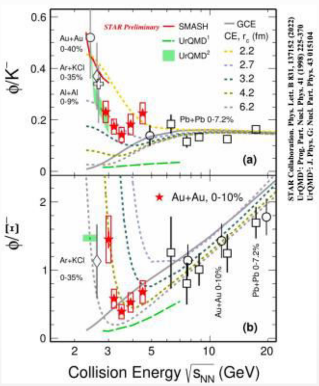
Initial state

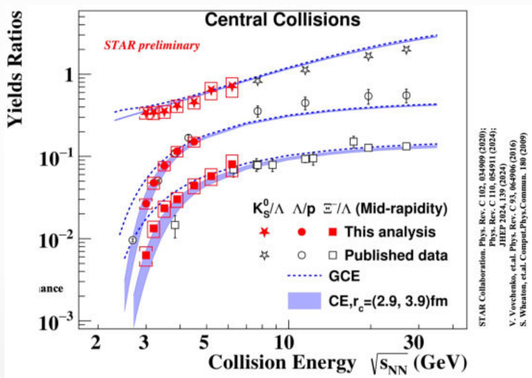
QGP as a relativistic fluid

(Multi)strange baryons

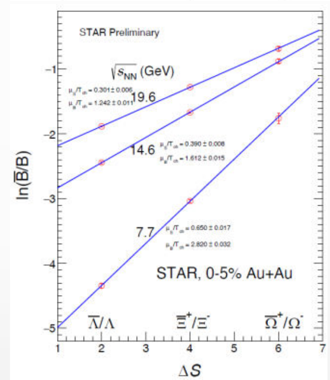
Strangeness production

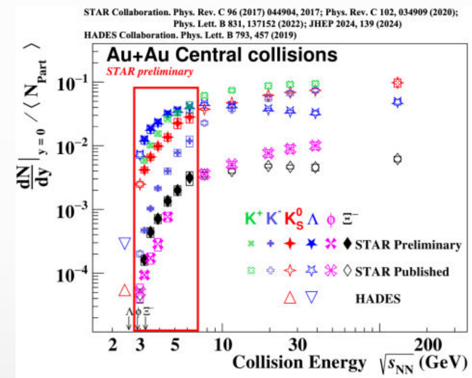
- Small hadronic cross-sections
  → sensitivity to early stages of medium dynamics
- Yields of strange hadrons (low p_T)
  → strangeness enhancement, proposed as a signature of QGP since 80's, now described by statistical/thermal models
  → information about chemical freeze-out parameters
  → near or sub-threshold production



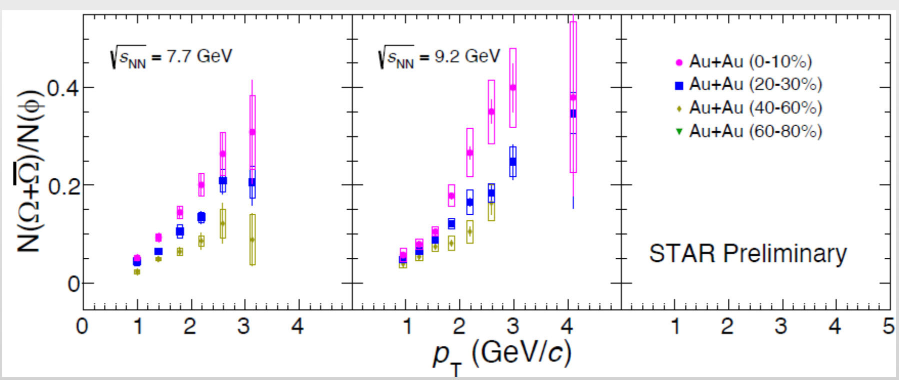


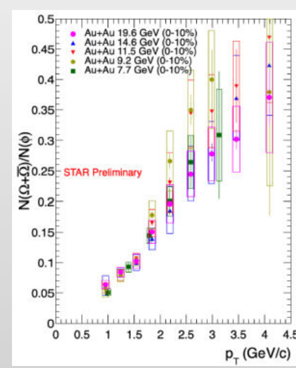
$\ln(\overline{B}/B) = -2\mu_B/T_{ch} + \mu_S/T_{ch}\Delta S$

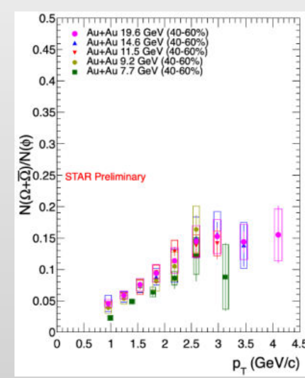




- Hyperon-to-meson ratios vs. p_T (intermediate p_T)
  → hadronization with parton coalescence, freeze-out conditions

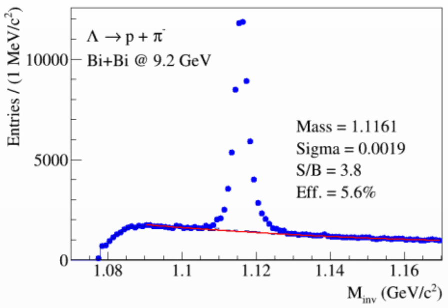


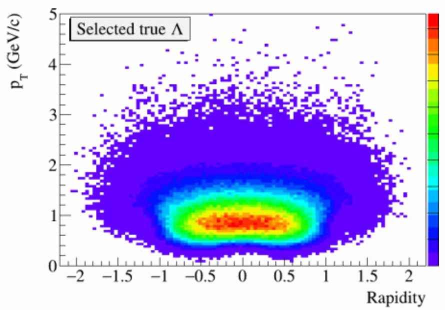


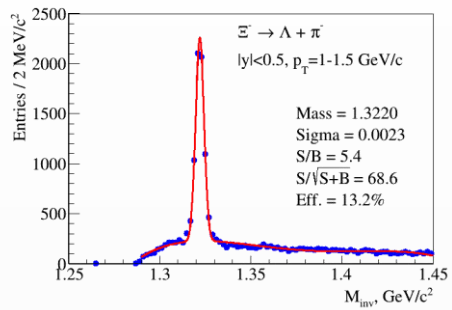


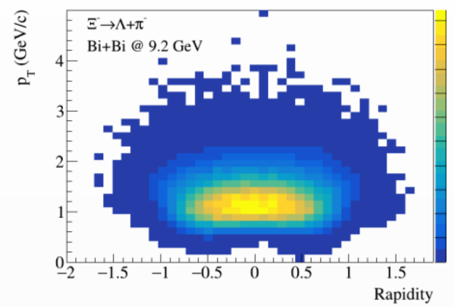
Hyperons, Bi + Bi @ 9.2 GeV

- PID capabilities of TPC and TOF + topology selections

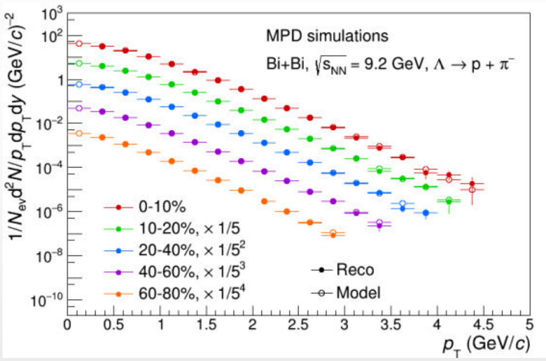


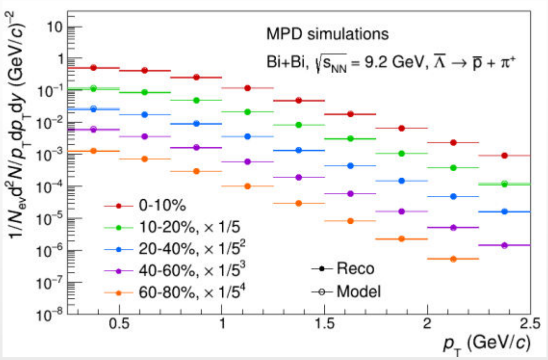


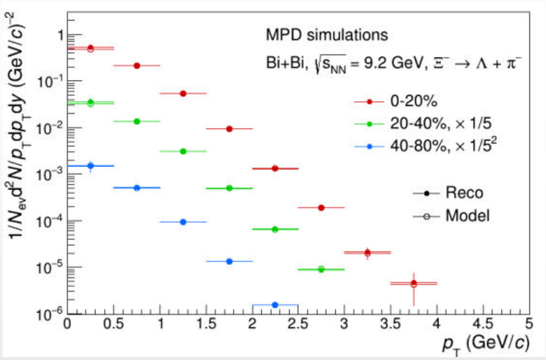


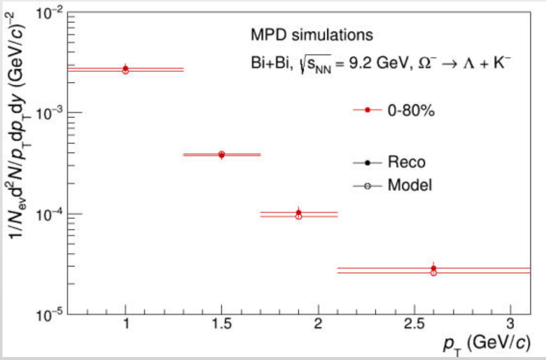


- different background estimates (fit function vs mixed-event), testing alternative Machine Learning techniques





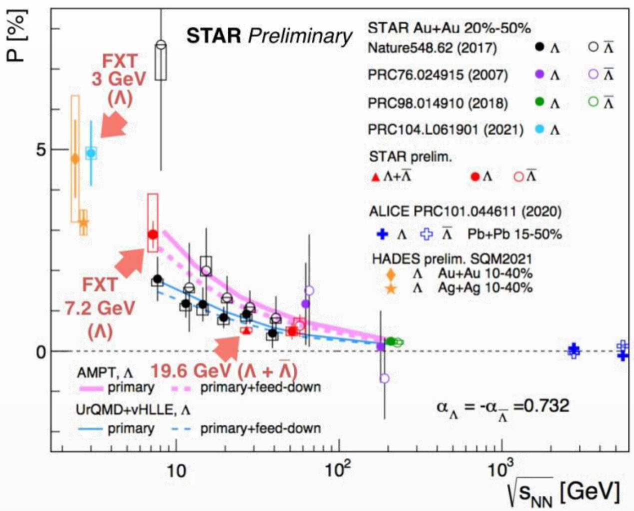




MPD has capabilities to measure production of strange charged/neutral kaons, (multi)strange baryons and resonances in pp, p-A and A-A collisions using h-ID in the TPC&TOF and different decay topology selections

Hyperon global polarization

- Global polarization of hyperons experimentally observed, decreases with $\sqrt{s_{NN}}$



✓ reproduced by AMPT, 3FD, UrQMD+vHLLE

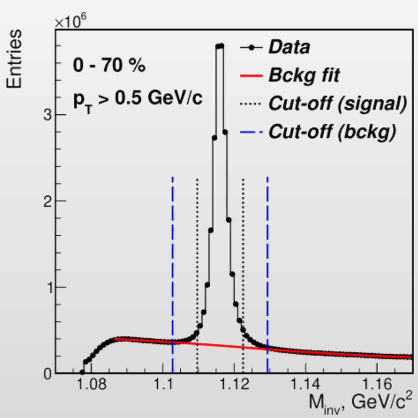
✓ hint for a Λ-$\bar{\Lambda}$ difference, magnetic field: ,

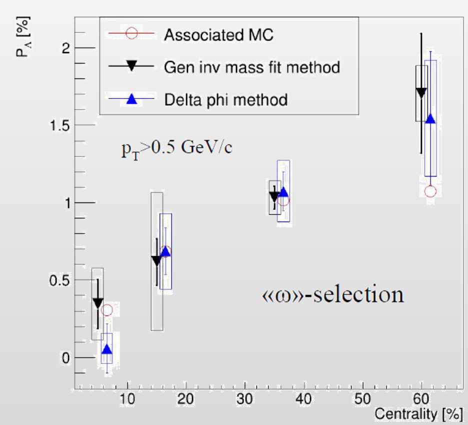
$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T} \qquad P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

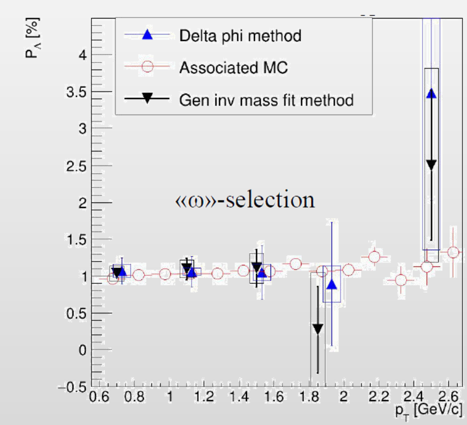
NICA: <u>extra points in the energy range 2-11 GeV</u>
centrality, p_T and rapidity dependence of polarization,
not only for Λ, but other (anti)hyperons (Λ, Σ, Ξ)

- MPD performance: BiBi@9.2 GeV (PHSD, 15 M events) → full reconstruction → Λ global polarization

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



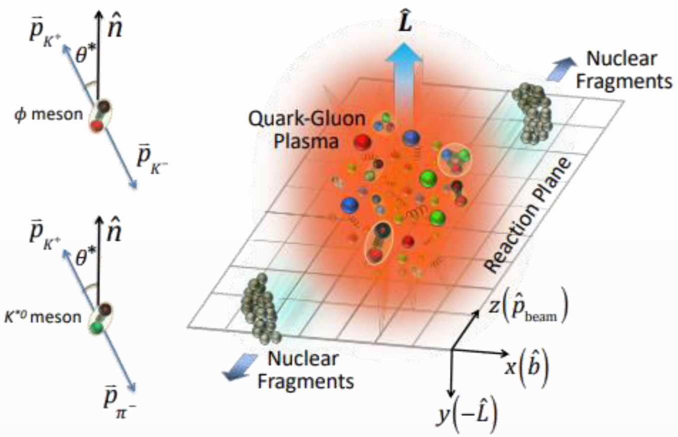




MPD: first global polarization measurements for $\Lambda/\bar{\Lambda}$ will be possible with ~ 20M data sampled events

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

Non-central heavy-ion collisions:



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

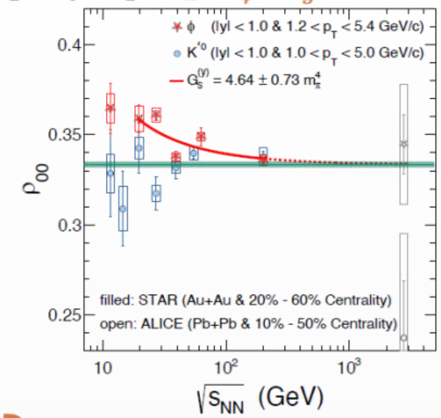
$\rho_{0,0}$ is a probability for vector meson to be in spin state = 0 → $\rho_{0,0}$ = 1/3 corresponds to no spin alignment

The large ρ_{00} puzzle

$$\rho_{00} \approx \frac{1}{3} + C_\Lambda + C_\varepsilon + C_E + C_F + C_L + C_A + C_\varphi + C_g$$

Physics Mechanisms	(ρ_{00})
c_Λ: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
c_ε: E-comp. of Vorticity tensor[1]	< 1/3 (Negative ~ 10^{-4})
c_E: Electric field[2]	> 1/3 (Positive ~ 10^{-5})
c_F: Fragmentation[3]	> or, < 1/3 (~ 10^{-5})
c_L: Local spin alignments[4]	< 1/3
c_A: Turbulent color field[5]	< 1/3
c_φ: Vector meson strong force field[6]	> 1/3 (Can accommodate large positive signal)
c_g: Glasma fields + effective potential	could be significant

strong force



STAR, Nature 614 244 (2023)

Nature 614 244 (2023)

ϕ exhibits surprisingly large global spin alignment while K* displays little.

Aihong Tang. QuarkMatter 2023, Houston, Sept 3-9 18

- 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 …)
- Measurements should be extended to lower collision energies

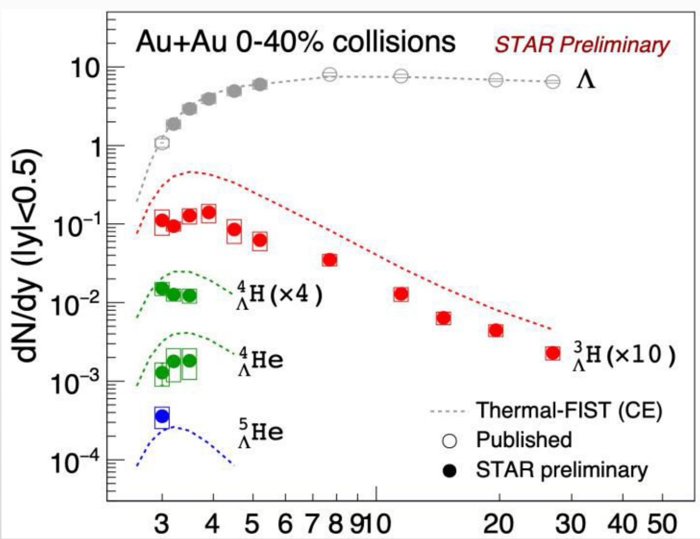
Initial state

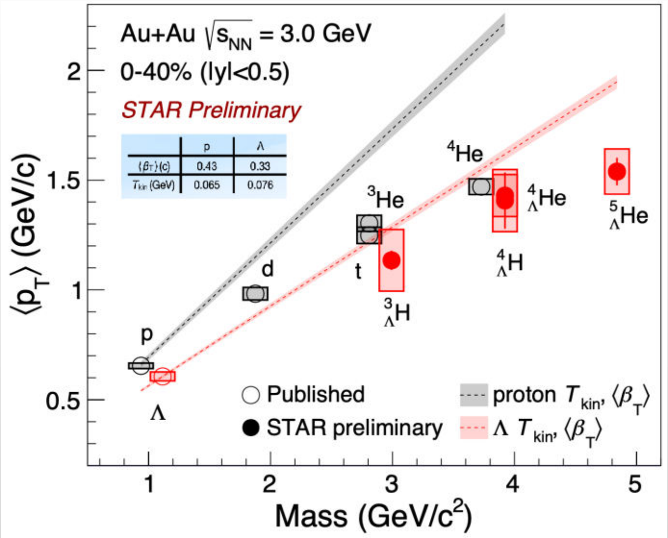
QGP as a relativistic fluid

Light (hyper)nuclei

(Hyper)nuclei

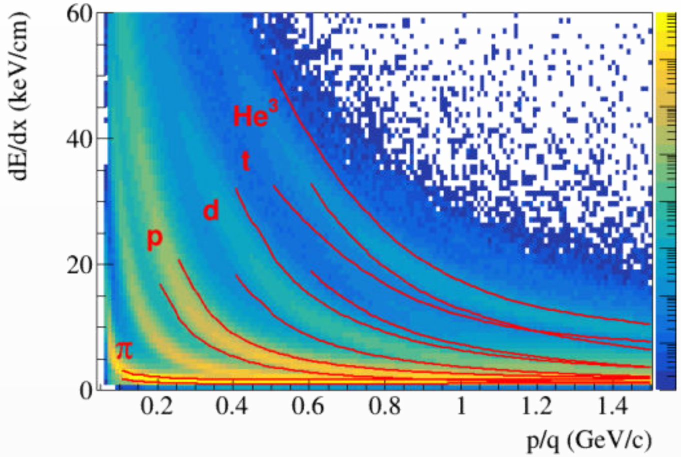
- Production mechanism usually described with two classes of phenomenological models :
  - ✓ statistical hadronization (SHM) → production during phase transition, dN/dy ∝ exp(-m/T_{chem}) [1]
  - ✓ coalescence → (anti)nucleons close in phase space ($\Delta p < p_0$) and matching the spin state form a nucleus [2]
- Hyper nuclei measurement studies are crucial:
  - ✓ microscopic production mechanism, Y-N potential, strange sector of nuclear EoS
  - ✓ strong implications for astronuclear physics → hyperons expected to exist in the inner core of neutron stars
- Models predict enhanced hypernuclear production at NICA energies→ offers great opportunity for hypernuclei measurements in MPD, double hypernuclei may be reachable
- Observables of interest: binding energies, lifetimes, branching ratios, $<p_T>$, dN/dy

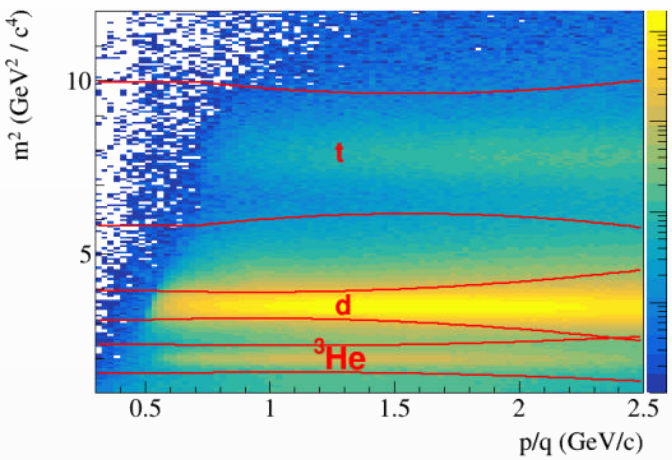




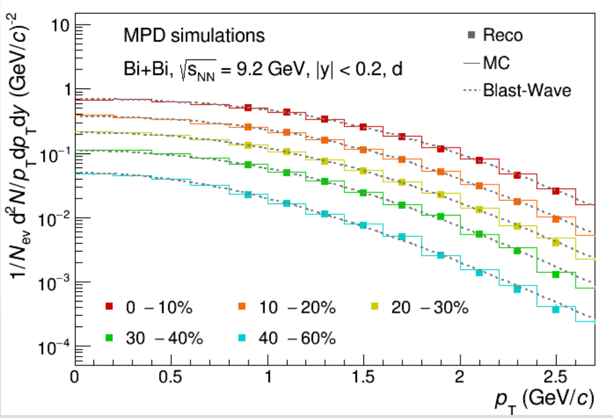
Light nuclei in the MPD

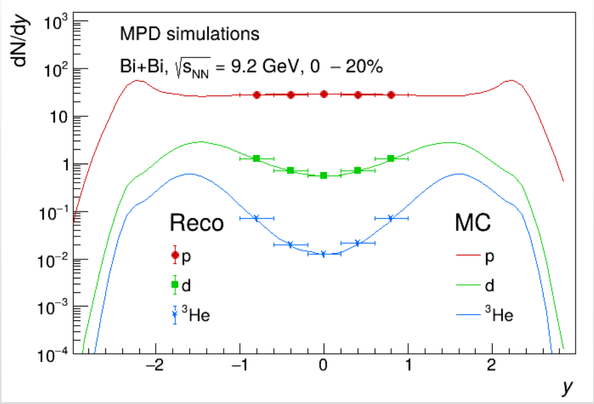
- MPD has excellent light fragment identification capabilities in a wide rapidity range





- Light nuclei reconstruction, Bi + Bi @ 9.2 GeV (PHQMD)

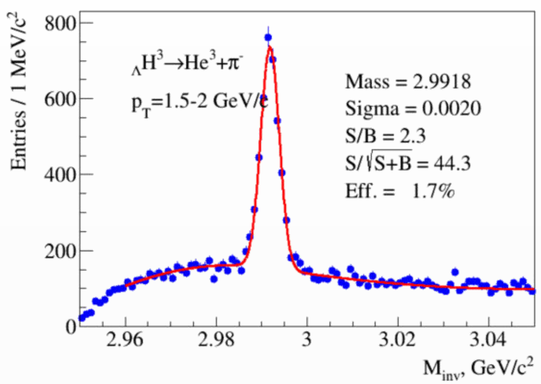


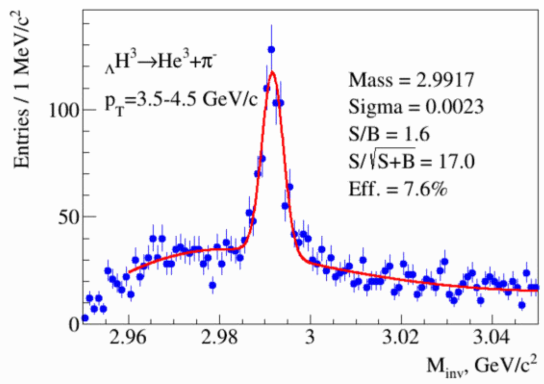


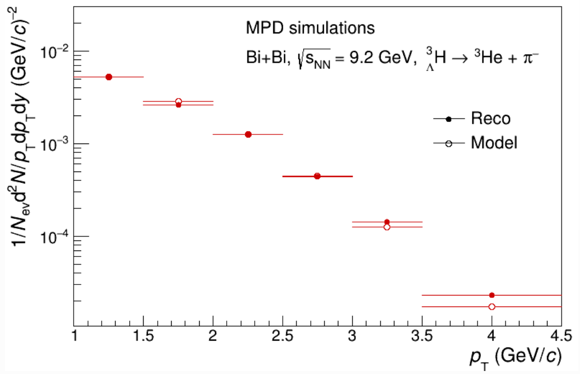
- NICA accelerator can deliver different ion beam species and energies → input to the heavy-ion data base for applied and space research to simulate damage from cosmic rays to astronauts, electronics, and spacecraft

MPD performance for hypenuclei

❖ Mass production 29 (PHQMD, BiBi@9.2 GeV, 40M events)



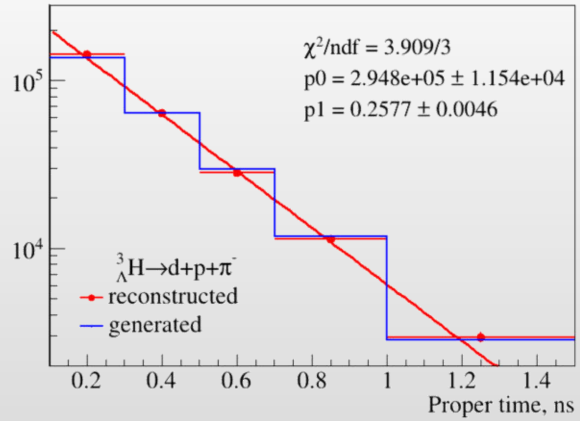


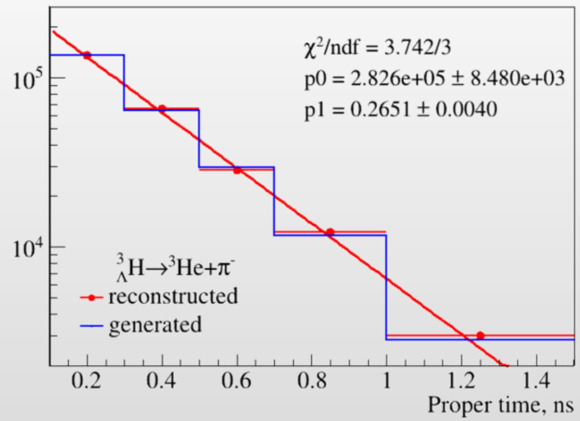


2- and 3-prong decay modes were studied separately to estimate systematics

$$N(\tau) = N(0)\exp\left(-\frac{\tau}{\tau_0}\right) = N(0)\exp\left(-\frac{ML}{cp\tau_0}\right),$$

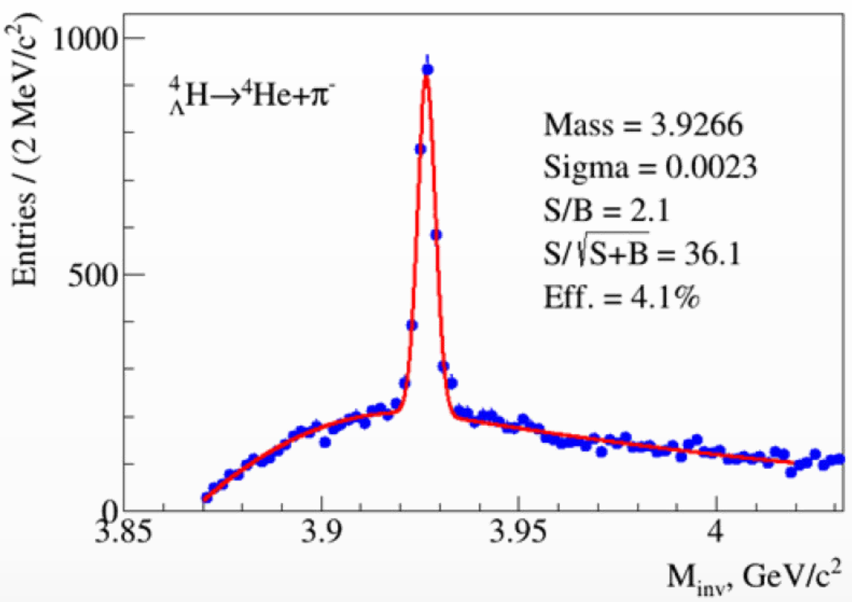
Decay channel	Branching ratio	Decay channel	Branching ratio
$\pi^- + {}^3He$	24.7%	$\pi^- + p + p + n$	1.5%
$\pi^0 + {}^3H$	12.4%	$\pi^0 + n + n + p$	0.8%
$\pi^- + p + d$	36.7%	$d + n$	0.2%
$\pi^0 + n + d$	18.4%	$p + n + n$	1.5%

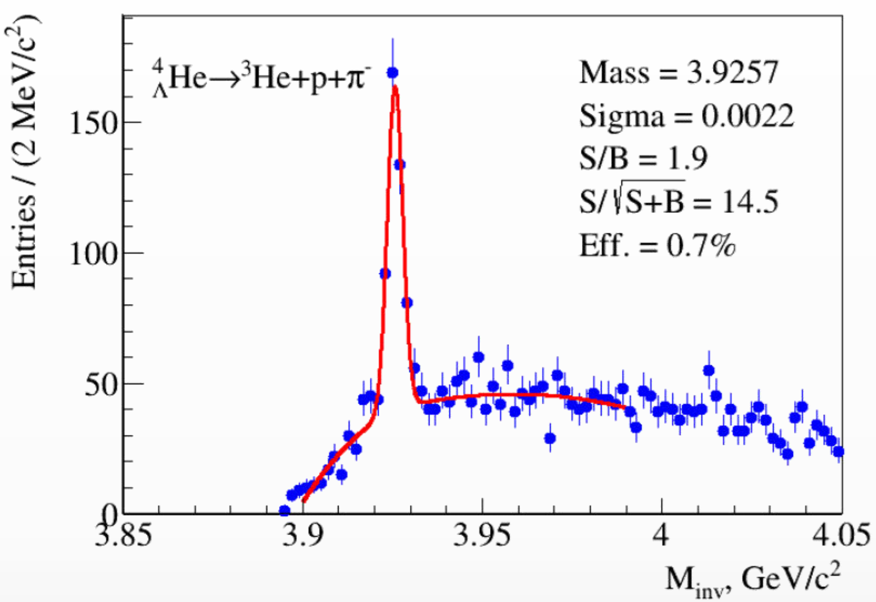




$_\Lambda H^3$ reconstruction with ~ 50M samples events

Heavier hypernuclei





- PHQMD events enhanced with hypernuclei signals with the correct (η-p_T) phase space distribution

$_{\Lambda}H^4$, $_{\Lambda}He^4$ reconstruction with ~ 150M samples events

Initial state

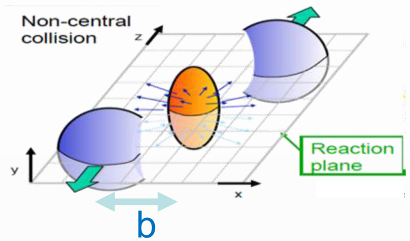
QGP as a relativistic fluid

Collective flow

Anisotropic flow at RHIC/LHC

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

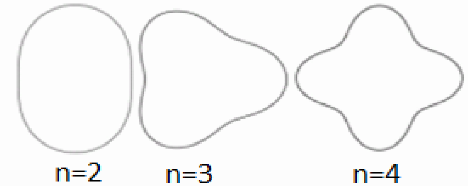
Spatial anisotropy of the nuclear overlap region



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

$\epsilon_n \propto v_n$

Azimuthal distribution of produced particles wrt to reaction plane (Ψ_n)

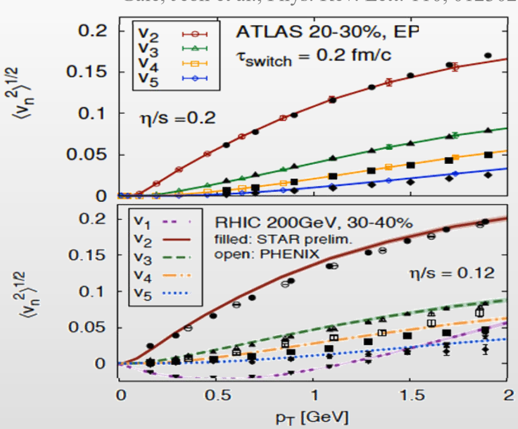


$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

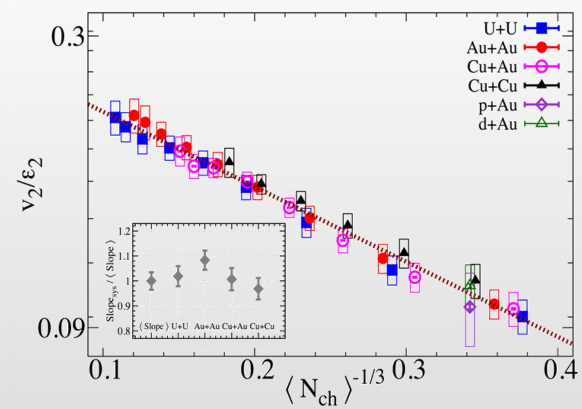
Anisotropic flow: $v_n = \langle \cos[n(\varphi - \Psi_n)]\rangle$

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

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



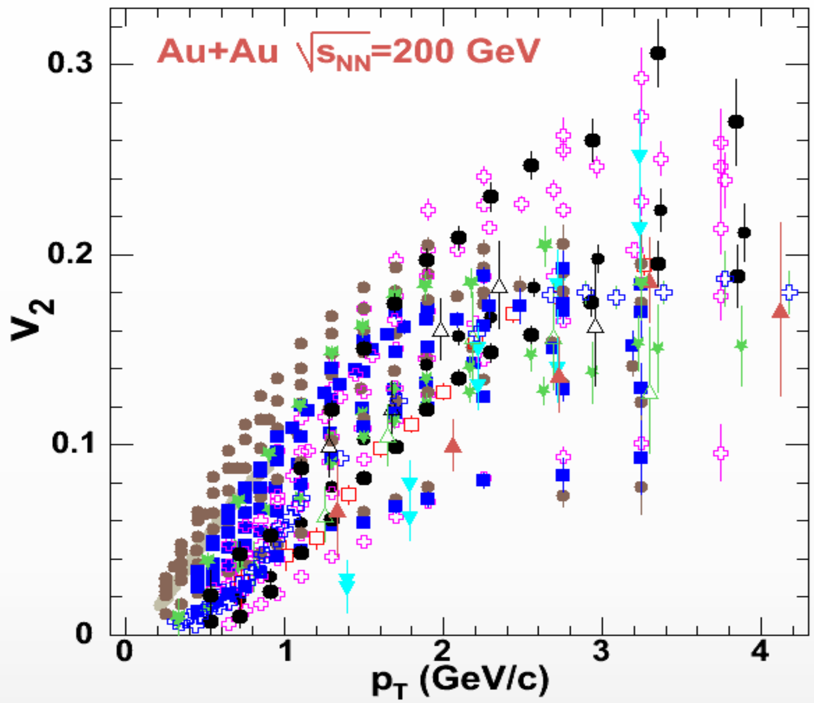
Phys. Rev. Lett. 122 (2019) 172301



System size scan (p-A, A-A) is an important ingredient:

initial geometry → flow harmonics → $\boldsymbol{\frac{\eta}{s}(T,\mu), \frac{\zeta}{s}(T,\mu), c_s(T), \alpha_s(T), etc.}$

Anisotropic flow at RHIC – partonic?

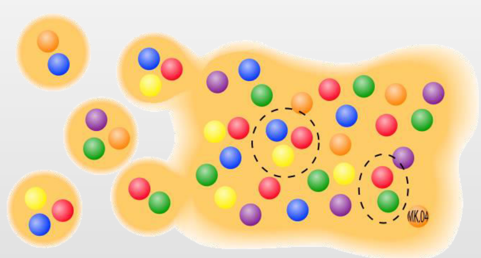


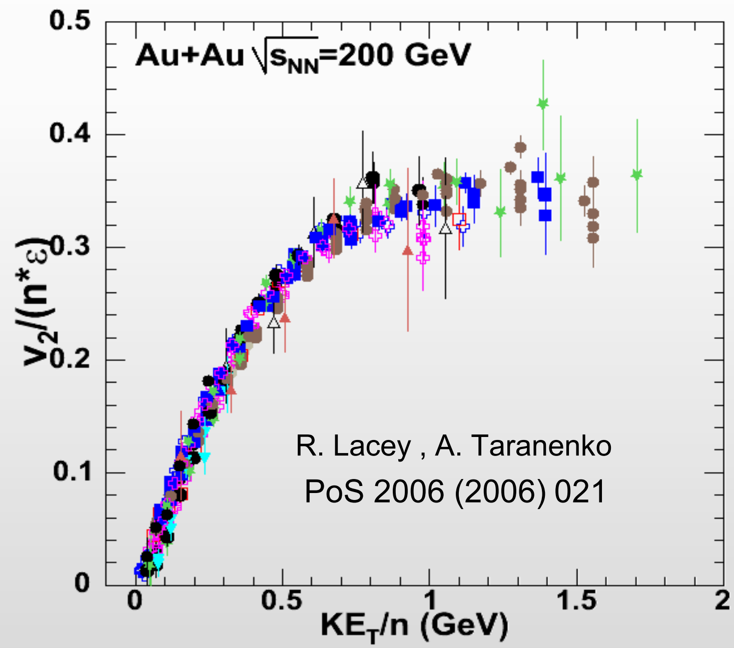
PHENIX (Phys.Rev.Lett.91, Preliminary: QM05, GRC 06)

- $\pi^+ + \pi^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $K^+ + K^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $p + \bar{p}$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- d : min.bias, 10-50%
- ϕ : 20-60%

STAR (Phys. Rev. Lett. 92,Phys. Rev. C 72 (2005), Preliminary QM05, SQM06)

- $\pi^+ + \pi^-$: min.bias
- K_S^0 : min.bias, 5-30%,30-70%
- $p + \bar{p}$: min.bias
- $\Lambda + \bar{\Lambda}$: min.bias, 5-30%,30-70%
- $\Xi + \bar{\Xi}$: min.bias
- $\Omega + \bar{\Omega}$: min.bias
- ϕ : min.bias



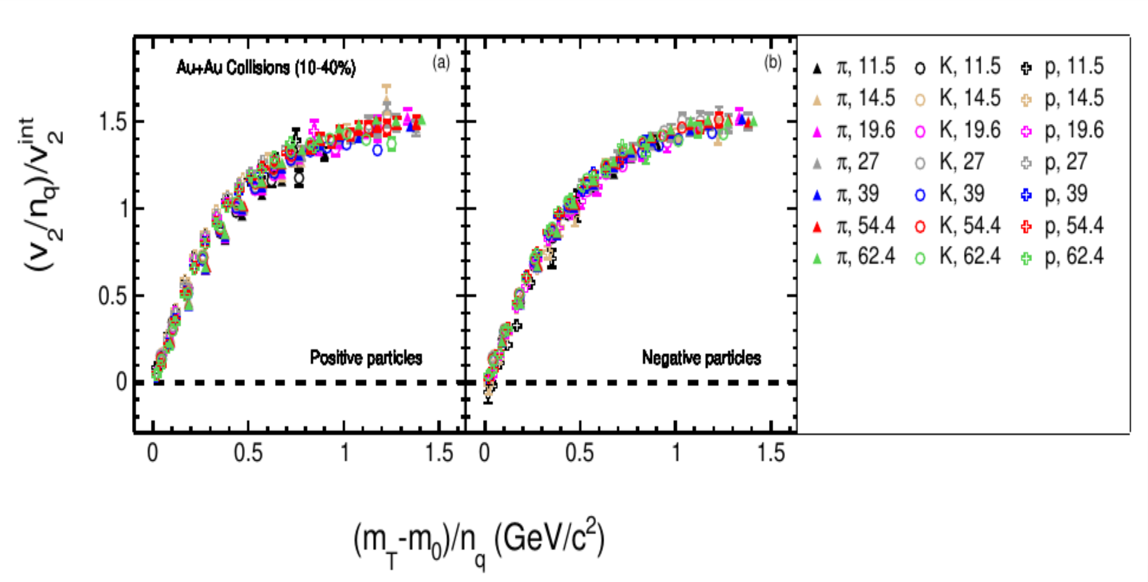


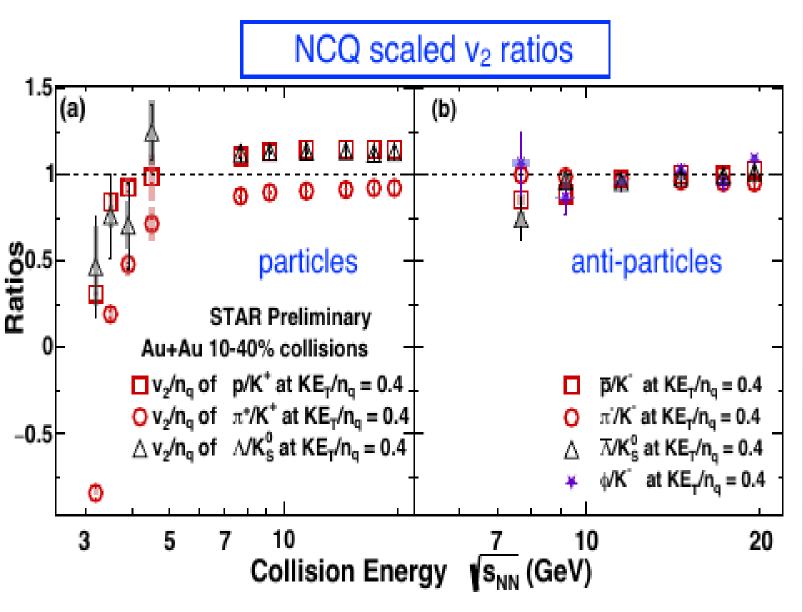
n=2 for mesons
n=3 for baryons

$$kE_T = m(\gamma_T - 1) = m_T - m_0$$

Elliptic flow from STAR BES program - I

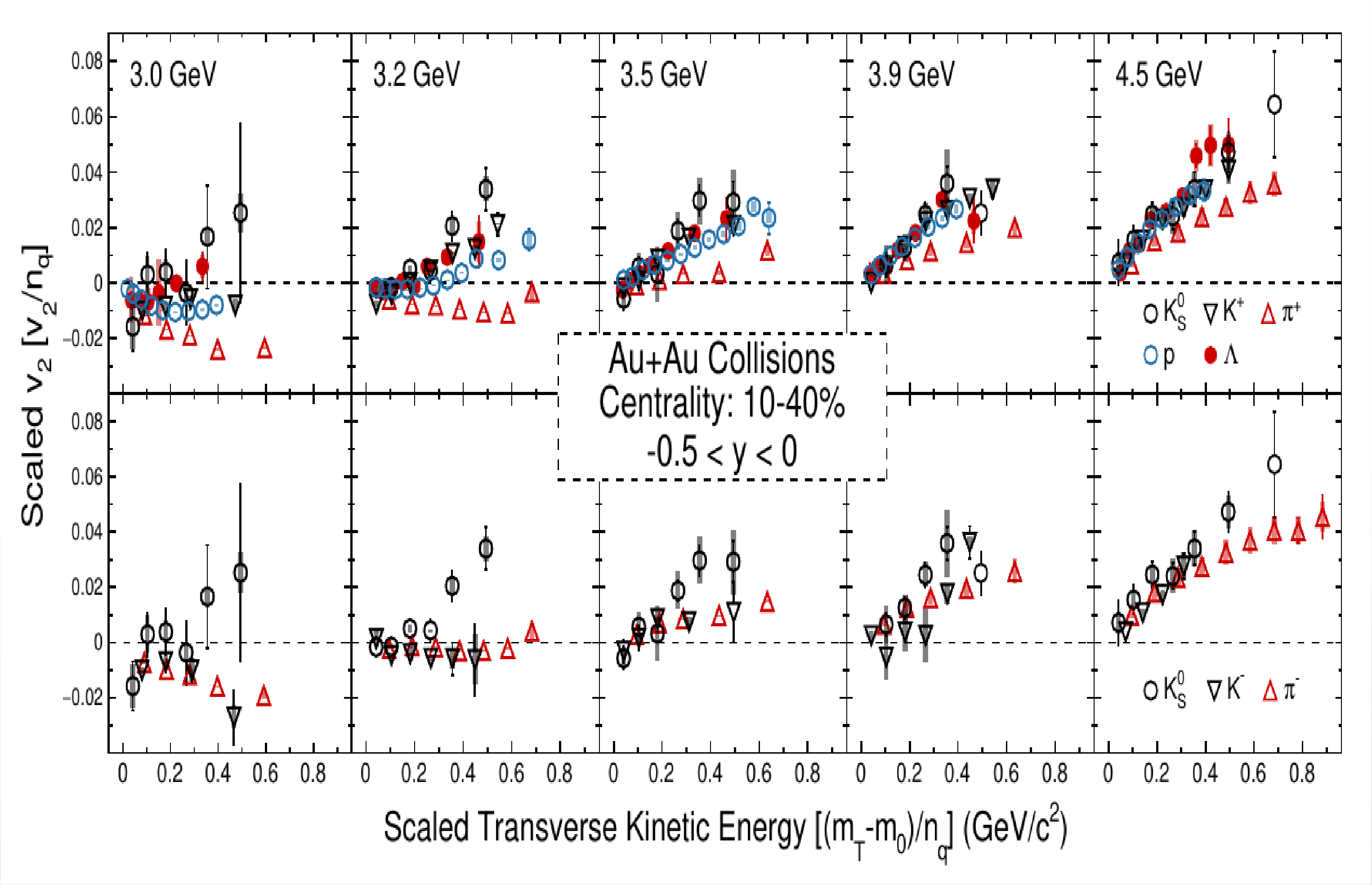
STAR , Phys Rev C93, 14907 (2016)





Elliptic flow from STAR BES program - II

Li-Ke Liu (CCNU), STAR Collaboration, CPOD 2024

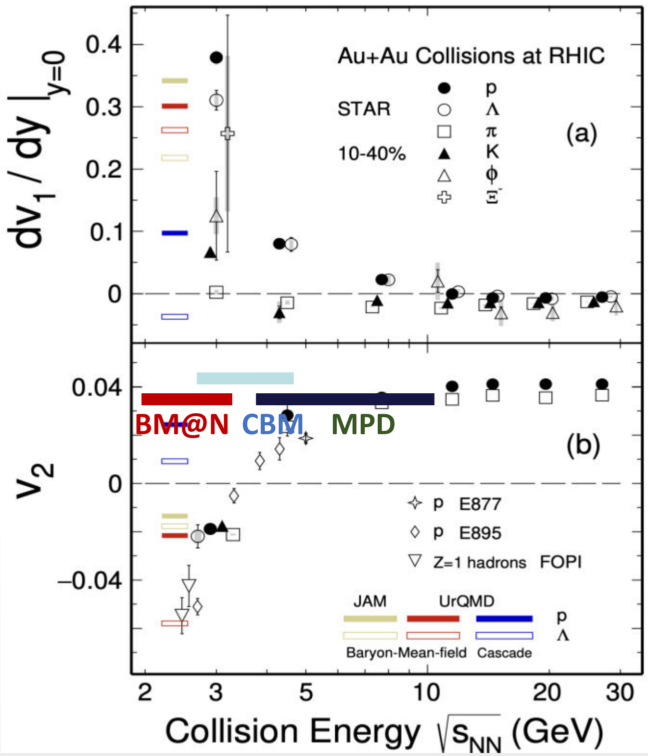


At $\sqrt{s_{NN}}$ energies > 5-7 GeV, data follows NCQ scaling, indicating partonic collectivity (?)

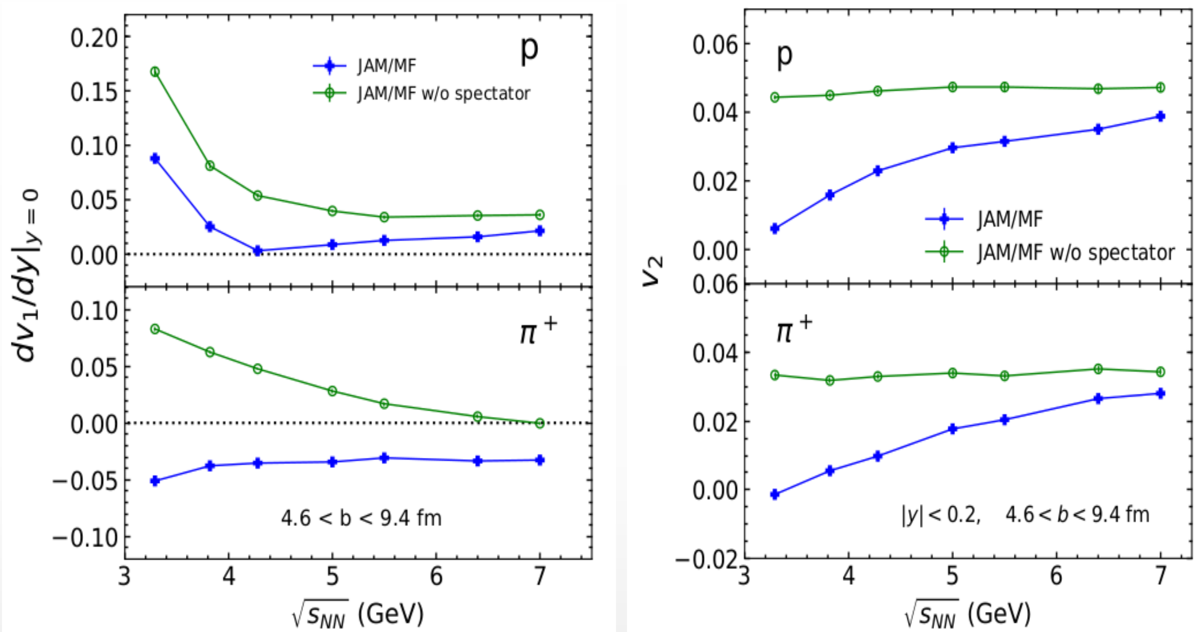
NCQ scaling for v_2 breaks completely at $\sqrt{s_{NN}}$ < 3.5 GeV

Anisotropic flow in HICs at high baryon density

M. Abdallah et al. STAR, Phys. Lett. B 827, 137003 (2022)



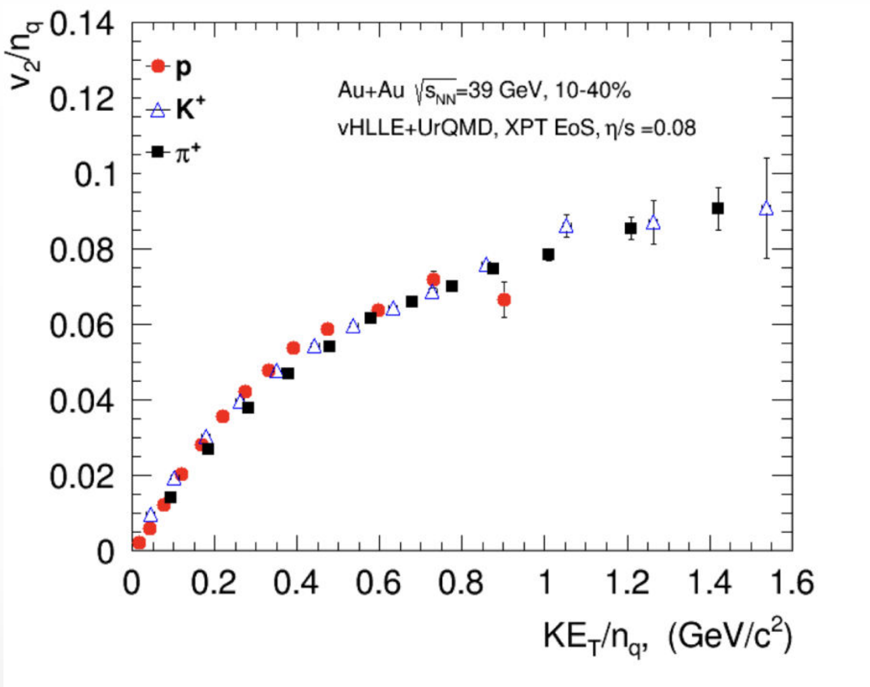
Phys. Rev. C 97, 064913 (2018)

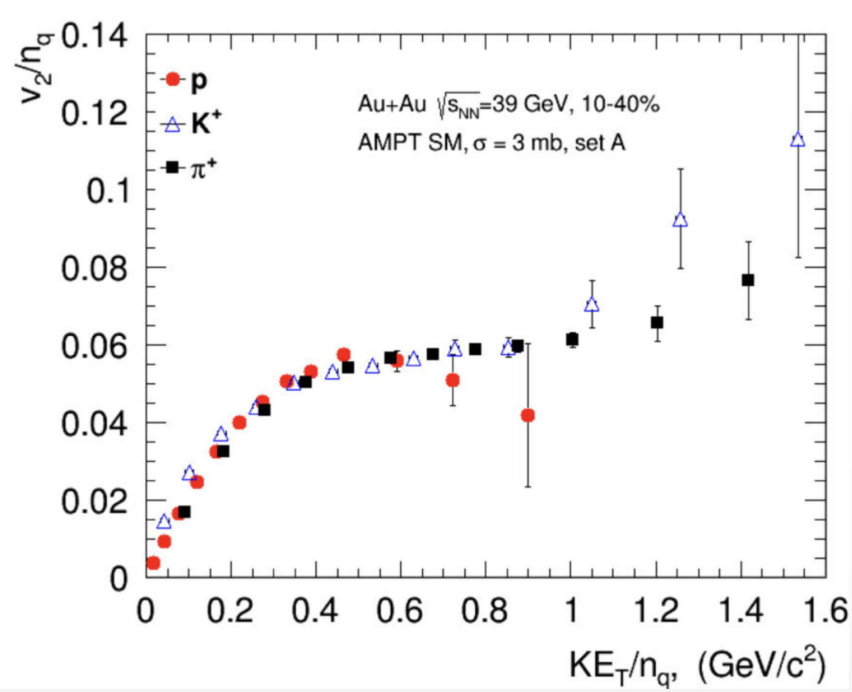


Anisotropic flow at NICA energies is a delicate balance between:

- reaction to pressure gradients developed early in the reaction zone ($t_{exp} = R/c_s\,, c_s = c\sqrt{dp/d\varepsilon}$)
- passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

NCQ scaling: hybrid models



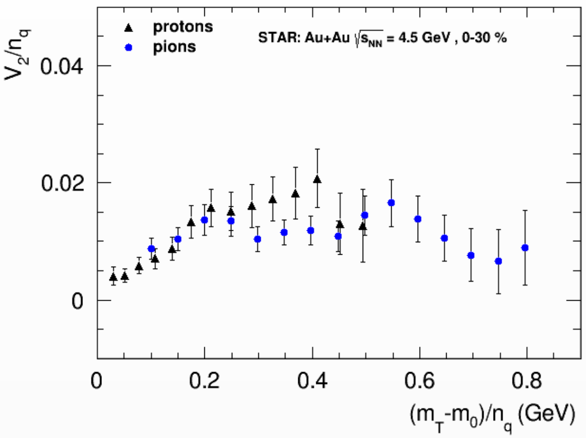


- Hybrid models with QGP phase are used for BES energy range ($\sqrt{s_{NN}} = 7.7 - 200$ GeV), such as vHLLE+UrQMD and AMPT SM

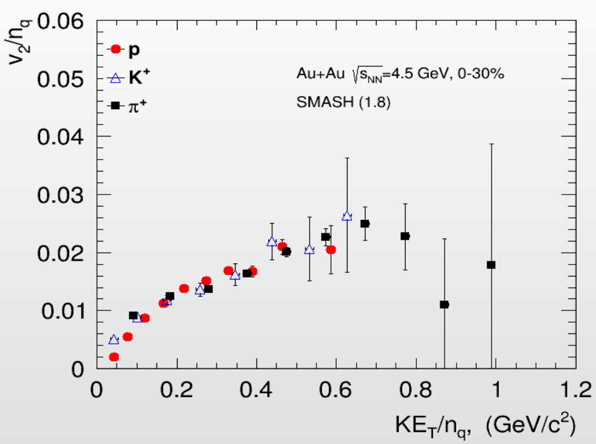
- NCQ scaling holds for hybrid models well

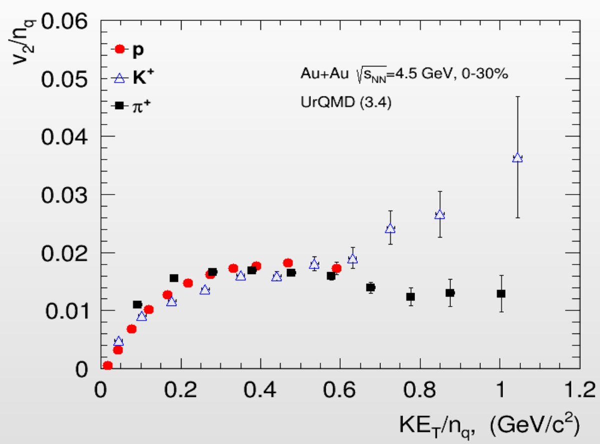
NCQ scaling: cascade models

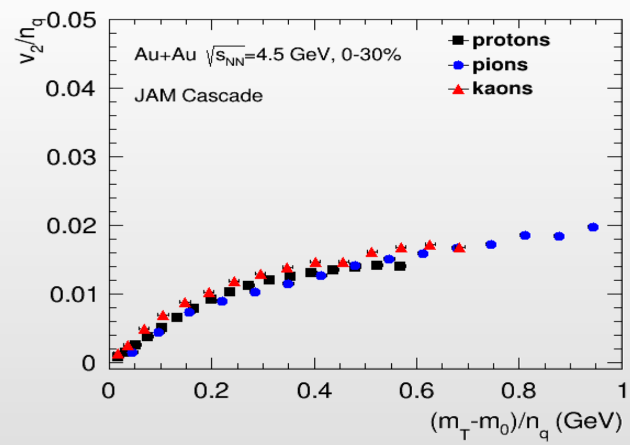
STAR Collaboration, arxiv.org/abs/2007.14005



❖ Scaling holds up at 4.5 GeV in STAR data and pure string/hadronic cascade models (without partonic d.o.f.)



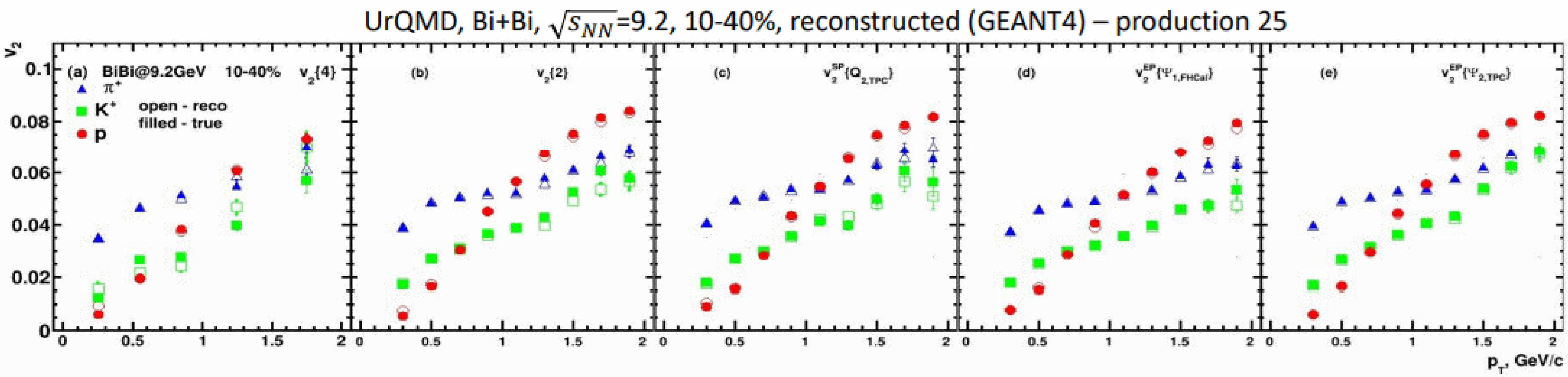


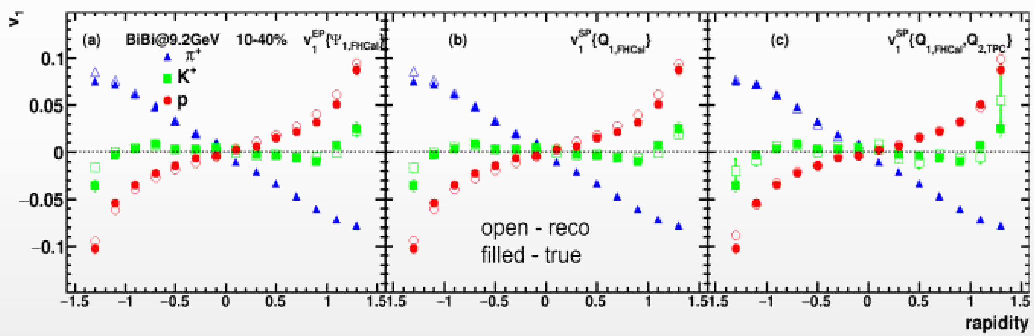


KE_T/n_q scaling at 4.5 GeV might be accidental – more detailed studies needed

MPD performance for v_1, v_2 of π/K/p

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





❖ Reconstructed and generated v_1 and v_2 for identified hadrons are in good agreement for all methods

MPD has capabilities to measure different flow harmonics for a wide variety of identified hadrons

System size scan for flow measurements is vital for understanding of the medium transport properties and onset of the phase transition

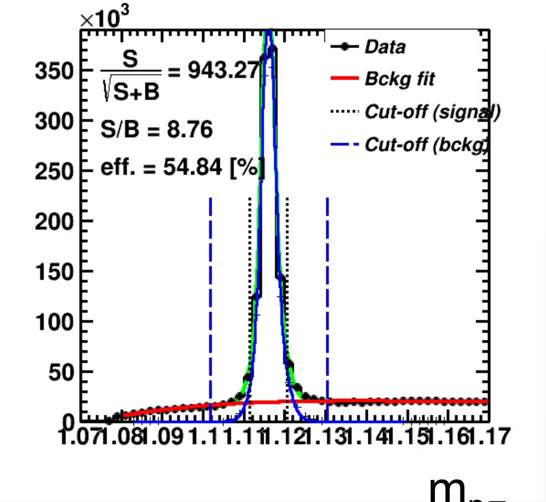
MPD performance for v_1, v_2 of V0 particles

- BiBi@9.2 GeV (PHSD, 15M), full event reconstruction

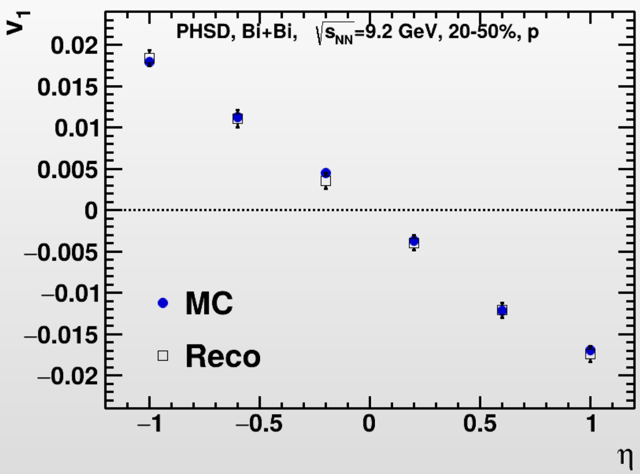
Differential flow can be defined using the following fit:

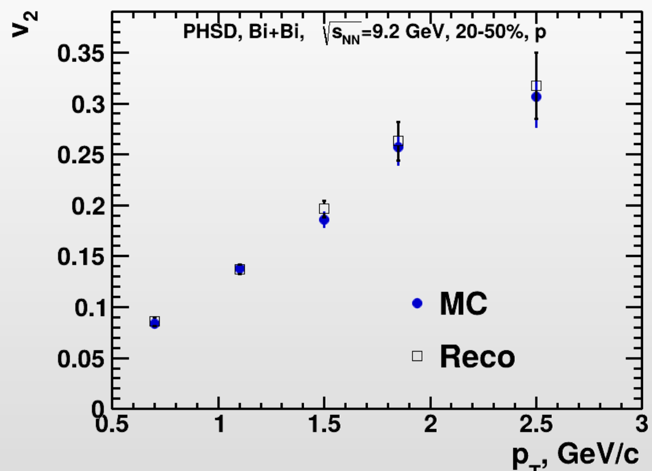
$$v_n^{SB}(m_{inv}) = v_n^S \frac{N^S(m_{inv})}{N^{SB}(m_{inv})} + v_n^B(m_{inv}) \frac{N^B(m_{inv})}{N^{SB}(m_{inv})}$$

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



- Performance of v_1 and v_2 of Λ hyperons:





- Good performance for v_1, v_2 using invariant mass fit and event plane methods
- Similar measurements for Ks, other hyperons and short-lived resonances

Electromagnetic radiation

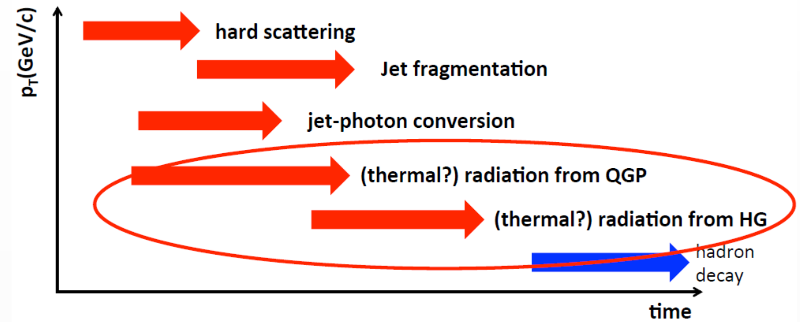
Direct photons and system temperature

- All photons not from the hadron decays:
  - ✓ produced during all stages of the collision → penetrating probe
- Thermal low-E photons → effective temperature of the system:

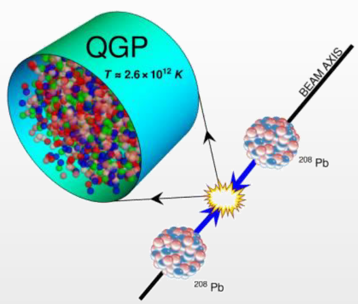
$$E_\gamma \frac{d^3 N_\gamma}{d^3 p_\gamma} \propto e^{-E_\gamma / T_{\text{eff}}}$$

- Prompt higher-p_T photons:

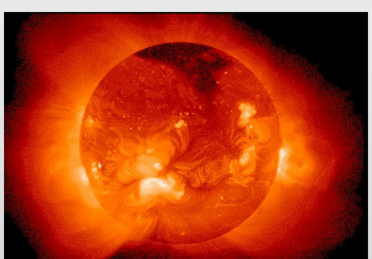
$$E\frac{d^3\sigma}{dp^3} = \sum_{i,j,k} f_i(x_i,Q^2)\otimes f_j(x_j,Q^2)\otimes D_k(z_k,Q^2) \quad \propto {}^{1}/_{p_T^n}$$



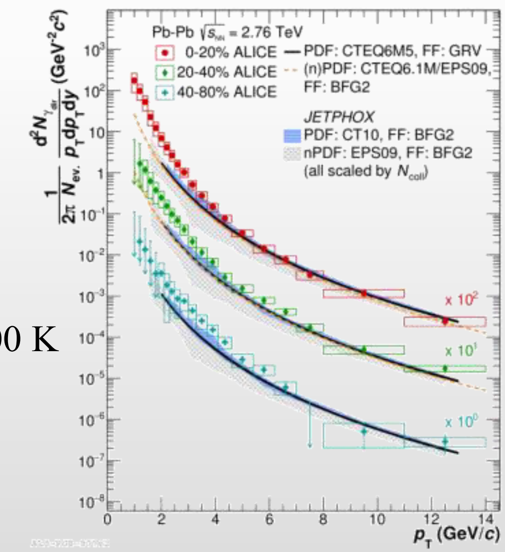
- Relativistic A+A collisions → the highest temperature created in laboratory ~ 10^{12} K

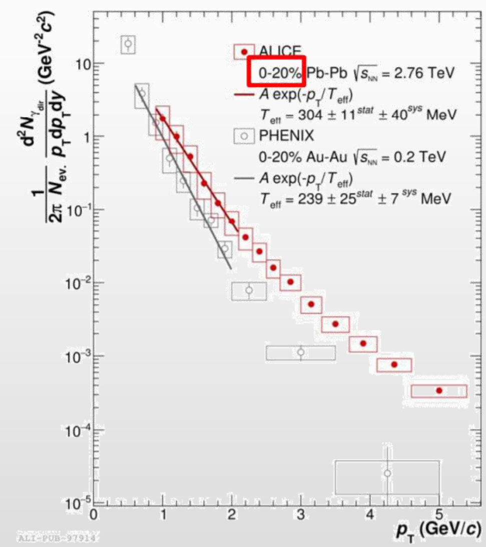


Temperature at the center of the Sun ~ 15 000 000 K



A medium of ~ 200 MeV is 100 000 times hotter !!!





T_{eff} ~ 240 MeV at RHIC; T_{eff} ~ 300 MeV at the LHC

T_{eff} >> T_c ~ 160 MeV predicted by LQCD

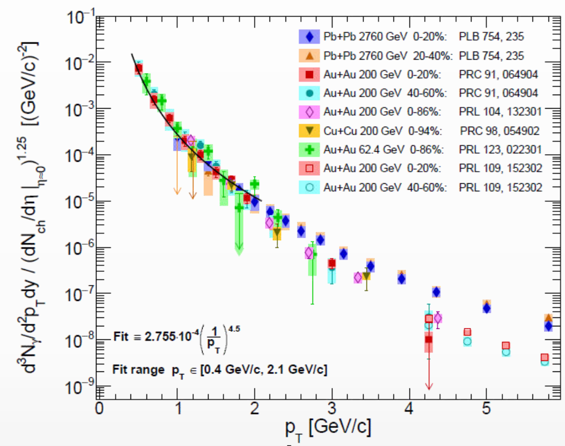
Direct photon yields at NICA

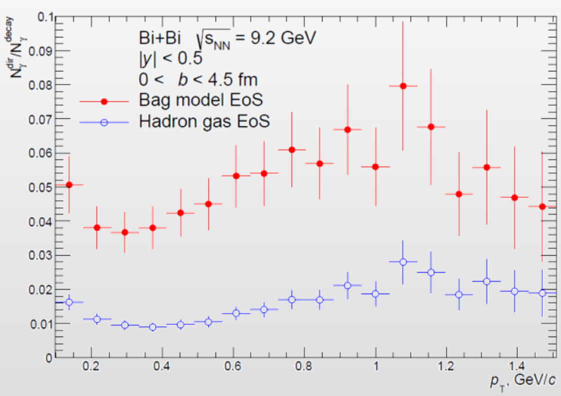
Estimation of the direct photon yields @NICA

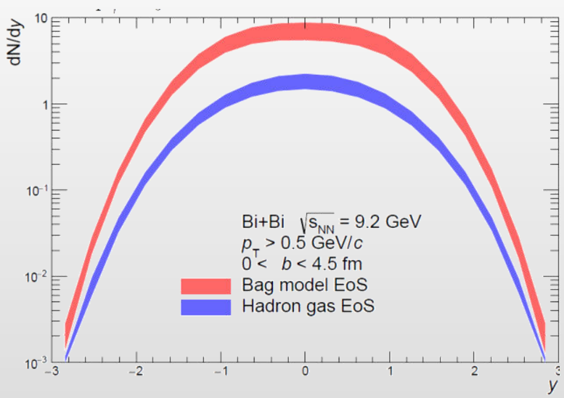
model calculations

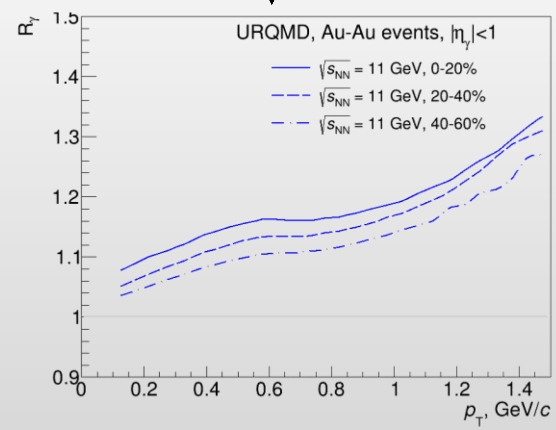
empirical scaling by PHENIX

- ✓ 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









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

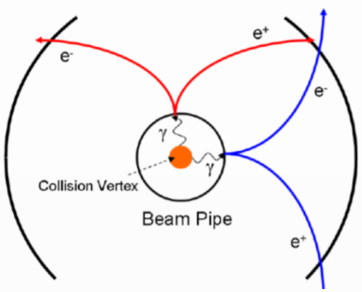
$$\gamma_{\text{direct}} = \left(1 - \frac{1}{R_\gamma}\right) \cdot \gamma_{\text{inc}}$$

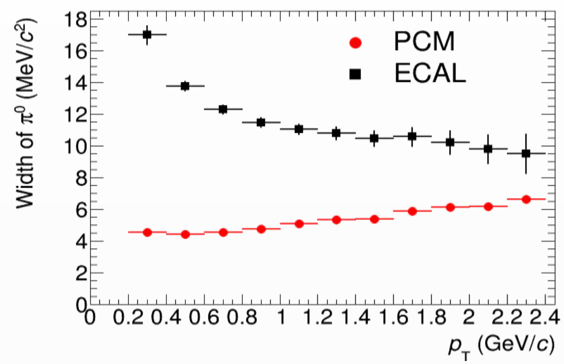
❖ Non-zero direct photon yields are predicted with Rγ ~ 1.05 – 1.15 and v2 ~ 0.5% at top NICA energy

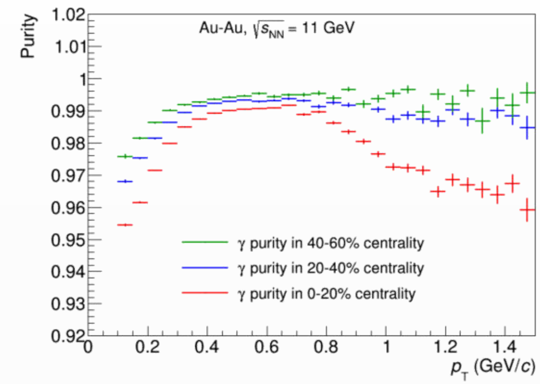
Prospects for the MPD

- 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)

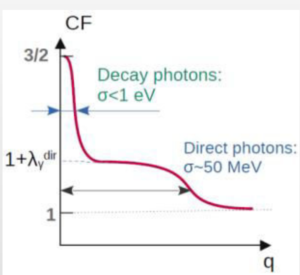






- Main sources of systematic uncertainties for direct photons → **potential yield measurements**:
  - ✓ detector material budget → conversion probability; p_T-shapes and reconstruction efficiencies of π^0 and η
  - ✓ with $R\gamma \sim 1.1$ and $\delta R\gamma/R\gamma \sim 3\%$ → uncertainty of $T_{eff} \sim 10\%$

- **Measurement of Bose-Einstein correlations** for direct photons:

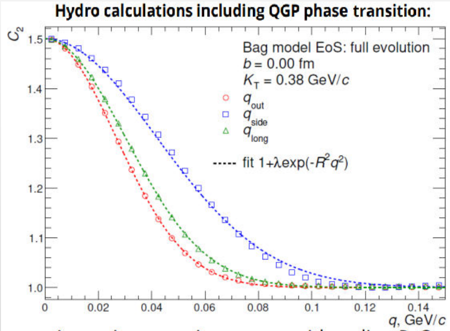


$$C_2(\boldsymbol{q},\boldsymbol{K}) \approx 1 + \left|\frac{\int d^4x S(x,K)\, e^{iq\cdot x}}{\int d^4x S(x,K)}\right|^2$$

Kinematics variables:

- Relative momentum of the pair: $\boldsymbol{q} = \boldsymbol{p}_1 - \boldsymbol{p}_2$
- Mean pair momentum: $\boldsymbol{K} = \frac{1}{2}(\boldsymbol{p}_1 + \boldsymbol{p}_2)$

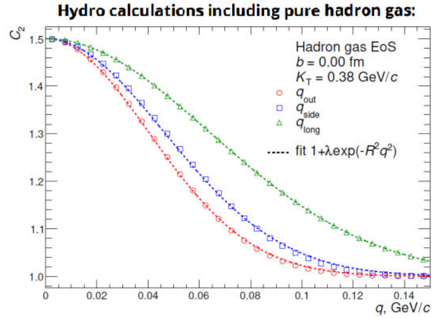
Hydro calculations including QGP phase transition:



- Assuming gaussian source with radius R, C_2 might be described as

$$C_2(q) = \lambda \exp(-q^2R^2)$$

Hydro calculations including pure hadron gas:



- C_2 are taken at a given mean transverse momentum of a pair

$$K_T = \frac{1}{2}(p_{1_T} + p_{2_T})$$

- ✓ Correlation function are different for QGP and HG scenario, the presence of the mixed phase causes increasing of the lifetime
- ✓ Possibility to extract yields of direct photons at low p_T:

$$\lambda = \frac{1}{2}\left(\frac{N_\gamma^{\mathrm{dir}}}{N_\gamma^{\mathrm{inc}}}\right)^2 \rightarrow R_\gamma = \frac{N_\gamma^{\mathrm{inc}}}{N_\gamma^{\mathrm{decay}}} = \frac{1}{1-\sqrt{2\lambda}}$$

MPD can potentially provide measurements for direct photon production in the NICA energy range

Summary

MPD Collaboration meeting in JINR (Dubna): April 23-25

- NICA energy range → QCD phase diagram at modest temperatures and maximum (net)baryon densities
- Preparation of the MPD detector and experimental program is ongoing, develop realistic analysis methods and techniques → MPD commissioning with beams in 2025
- 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), MPD@NICA provides capabilities for important/unique contributions in HIC physics

BACKUP

Hydrodynamic model

- Calculations were done using **UrQMD hydro model**
- We consider two scenarios of hydrodynamic evolution:
  - Thermalized hot dense nuclear matter with a first-order phase transition from QGP to hadronic phase **Bag model EoS**
  - Hadron gas including the same degrees of freedom as UrQMD (hadrons with masses up to 2.2 GeV) **HG EoS**
- We used **out-side-long parametrization** of relative momentum (and corresponding observables):
  - out – direction along the transverse momentum
  - long – along the longitudinal momentum
  - side – perpendicular to previous directions

$$K^\mu = (K^0, K_\perp, 0, K^z), \quad q^\mu = (q^0, q_o, q_s, q_l),$$

$$\Rightarrow \quad q_\mu K^\mu = 0 \quad \Rightarrow$$

both photons are on mass shell

$$q_o = (\boldsymbol{q}_\perp \cdot \boldsymbol{K}_\perp)/K_\perp, \quad q^0 = \frac{\boldsymbol{q} \cdot \boldsymbol{K}}{K^0}$$

$$q_s = |\boldsymbol{q}_\perp - (\boldsymbol{q}_\perp \cdot \boldsymbol{K}_\perp)\boldsymbol{K}_\perp/K_\perp^2|,$$

$$q_l = q_z.$$

$$\Rightarrow$$

$$R_s^2 = < x_s^2 >$$

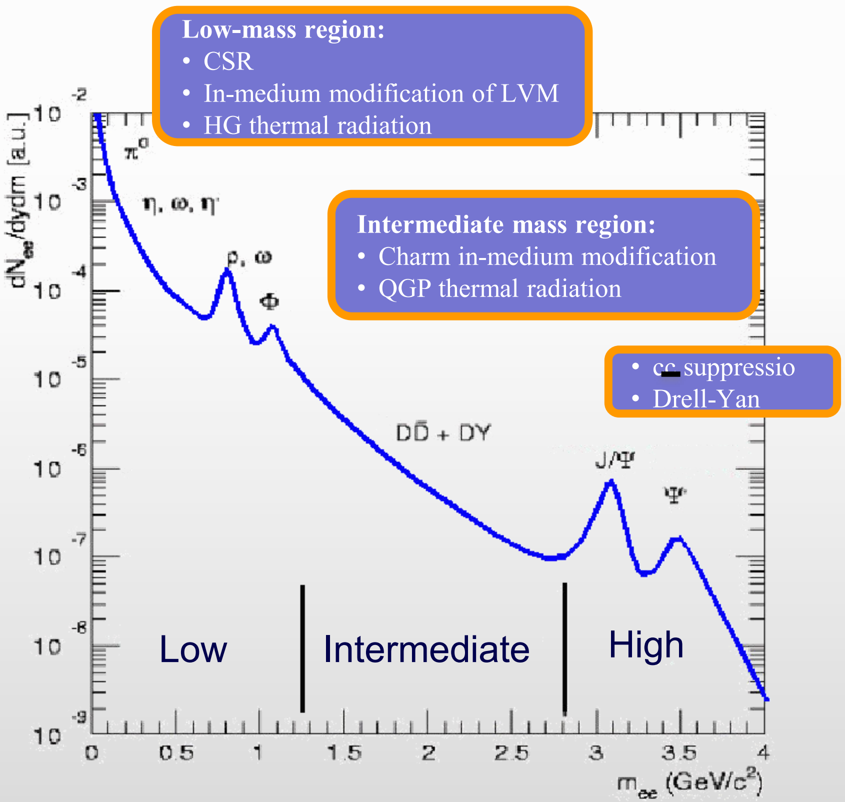
$$R_o^2 = <(x_o - \beta_T t)^2>$$

$$R_L^2 = <(x_l - \beta_L t)^2>$$

- For each cell in hydro calculations emission rates of thermal photons are calculate according to functions from previous slide:
  - estimation of thermal photon yields for given p_T (K_T) and φ in lab system
  integration over all cells and evolution time

Dielectron continuum and LVMs

- The QCD matter produced in A-A interactions is transparent for leptons, once produced they leave the interaction region largely unaffected + not sensitive to collective expansion
- Dielectron continuum carries a wealth of information about reaction dynamics and medium properties



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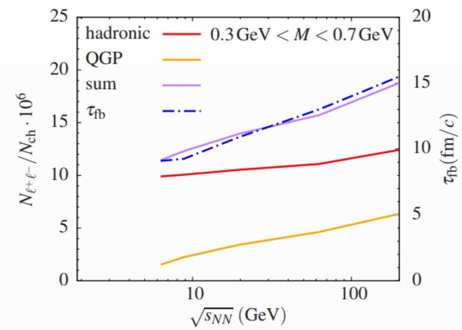
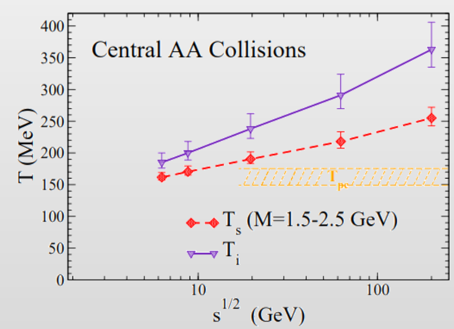
LMR as chronometer



Integrated thermal excess radiation
tracks the total fireball lifetime within ~ 10% →
non-monotonous lifetime variations trace critical phenomena

IMR as thermometer

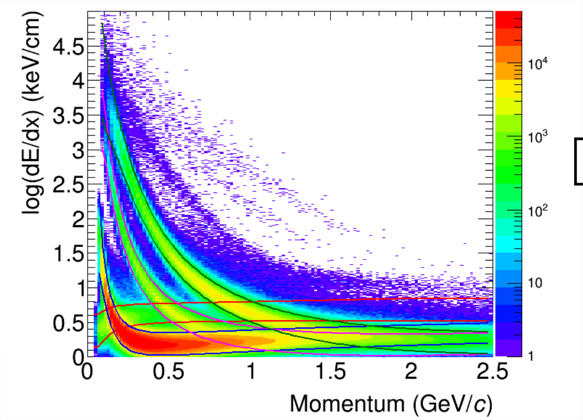


$dR_{ll}/dM \propto (MT)^{3/2} \exp(-M/T_s)$,
T_s smoothly evolves T = 160 MeV to 260 MeV

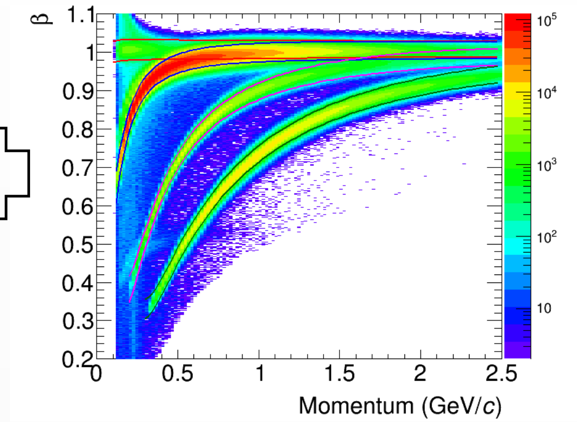
e-ID with MPD

❖ eID with TPC + TOF

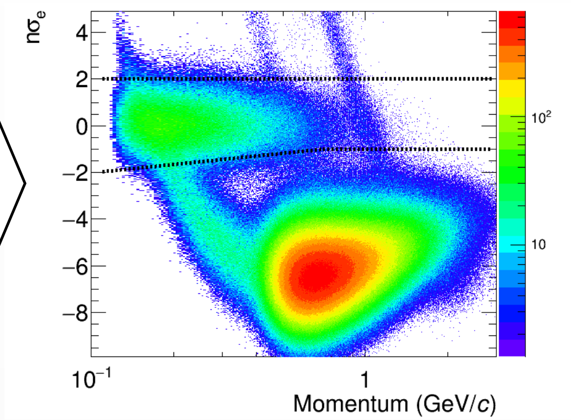
n-sigma dE/dx parameterization



n-sigma β-TOF parameterization

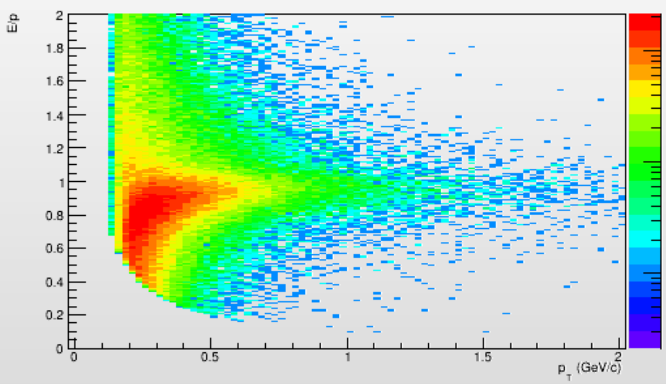


n-σ dE/dx distribution for tracks matched to TOF and identified as electrons



❖ eID with ECAL: steps in at higher energies where TPC/TOF become less effective

E/p for electron tracks

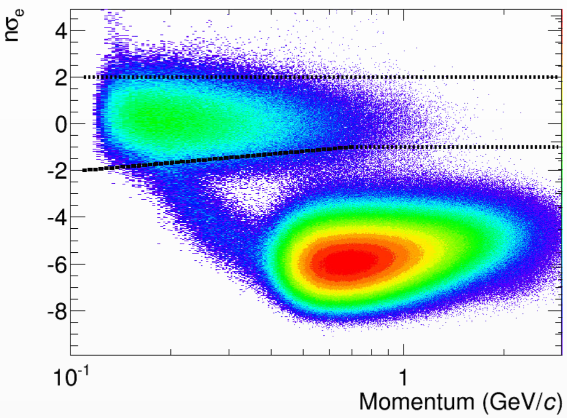


- ECAL e-ID for 2σ-matched tracks:
  - ✓ **TOF** < 2 ns (δ ~ 500 ps)
  - ✓ E/p ~ 1
- Turns on at p_T > 200 MeV/c

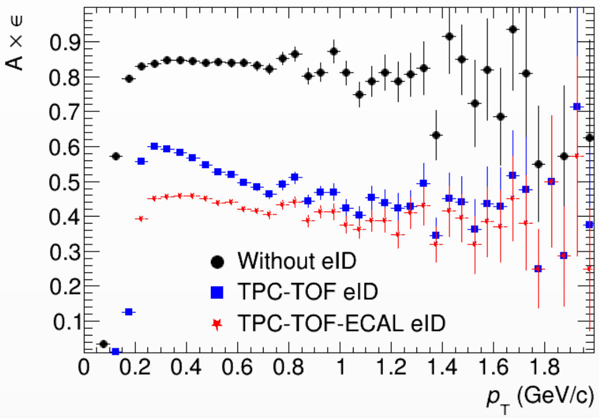
(Di)electrons

- Dielectron spectra are sensitive probes of the deconfinement and the chiral symmetry restoration
- AuAu@11 GeV (UrQMD for background & PHQMD for signal)

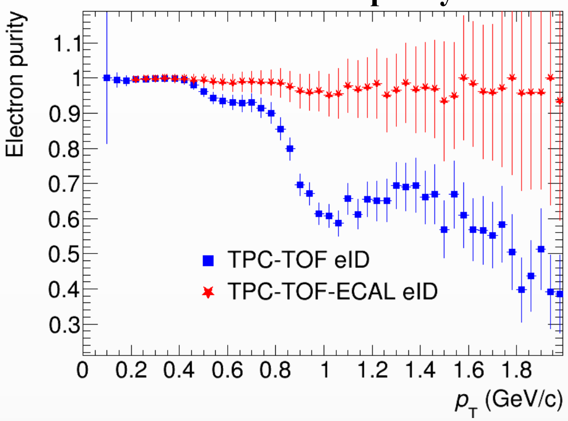
$\mathbf{n \cdot \sigma_e^{TPC}}$ **with 2σ_e PID in the TOF**

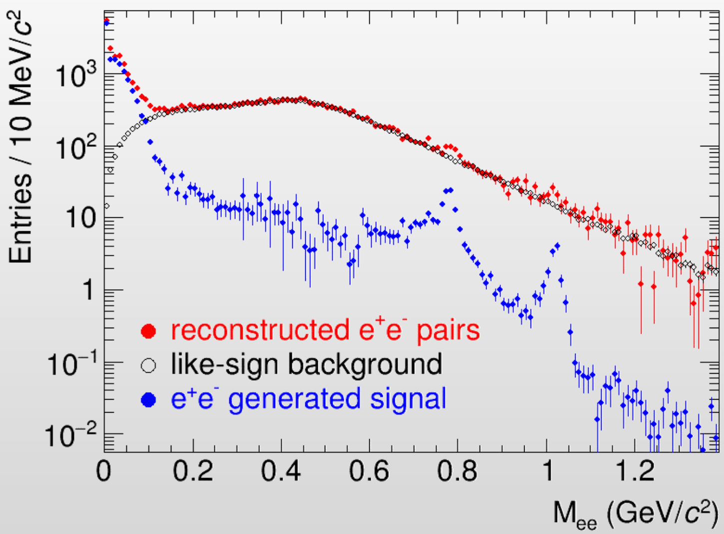


Efficiency of e-track reconstruction



Electron purity





- S/B (integrated in 0.2-1.5 GeV/c^2) ~ 5-10%
- Methods to improve S/B ratio while preserving reasonable efficiency for the pairs are being developed and matured