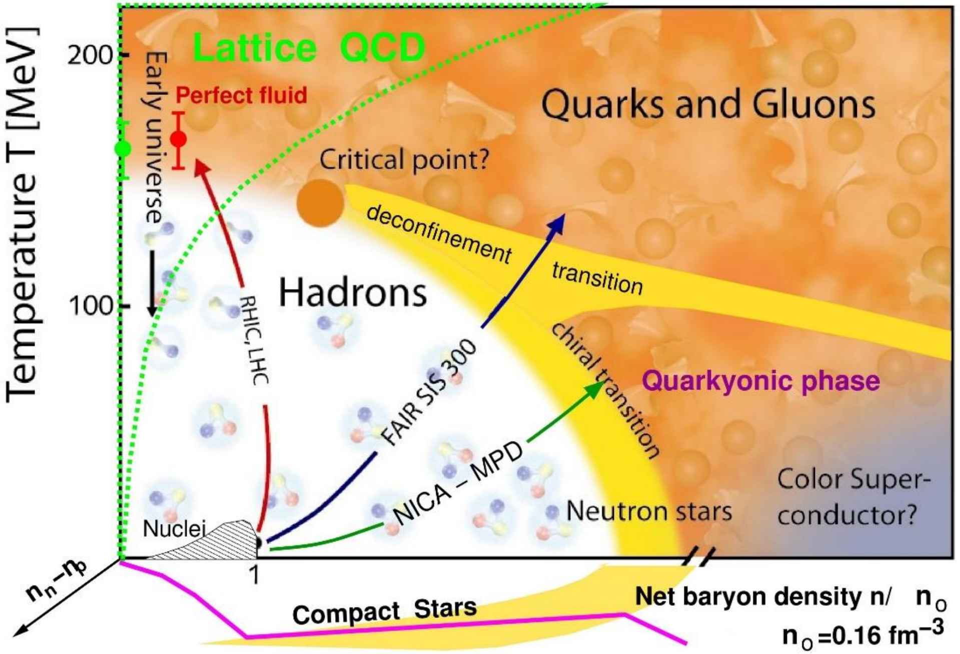
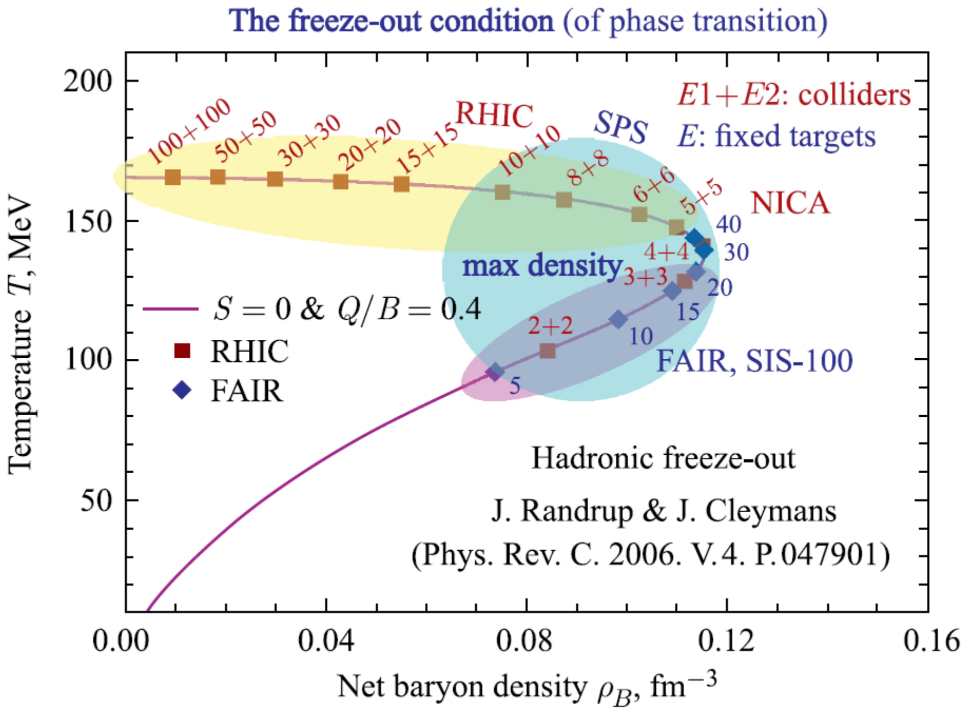
Recent developments in the MPD experiment at NICA complex

Alexey Aparin for the MPD collaboration
Joint Institute for Nuclear Research, Dubna

Theory of QGP

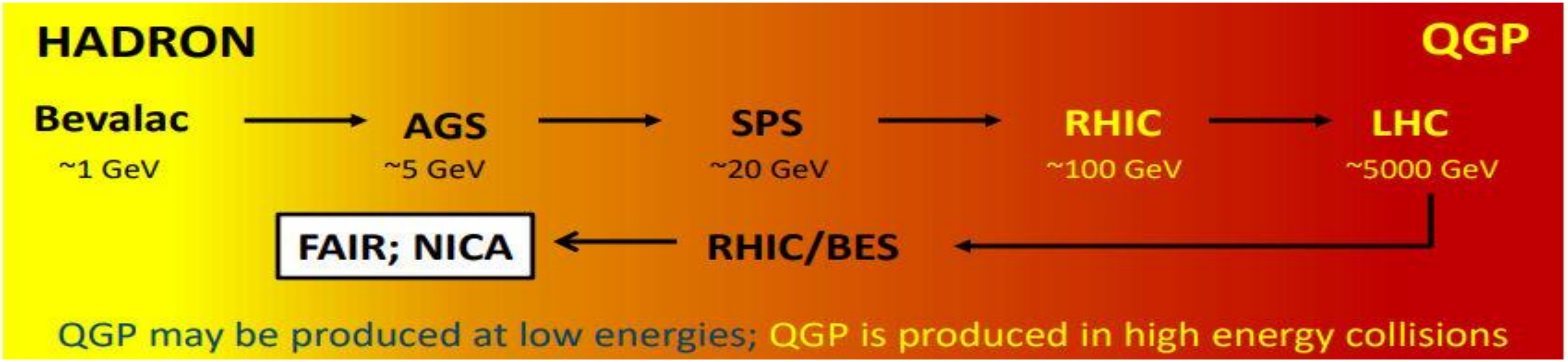




The energy scan covers the transition region from baryon to meson dominance in the chemical freeze-out regime. At the same time, this is the challenging domain of the transition from baryon stopping to nuclear transparency, where new experimental data would be very useful to progress in the theoretical understanding.

There is a minimum in the freeze-out volume related to the “softest point” in the EoS in the NICA energy window which is accessible to verification by femtoscopy measurements.

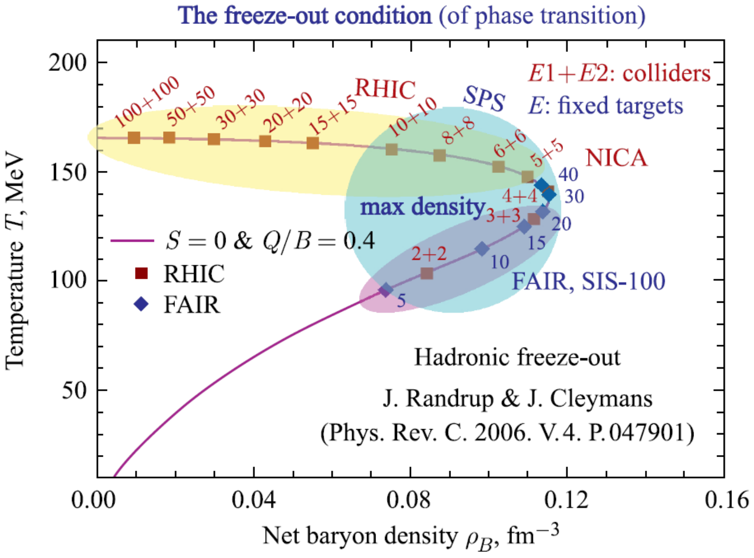
High baryon area



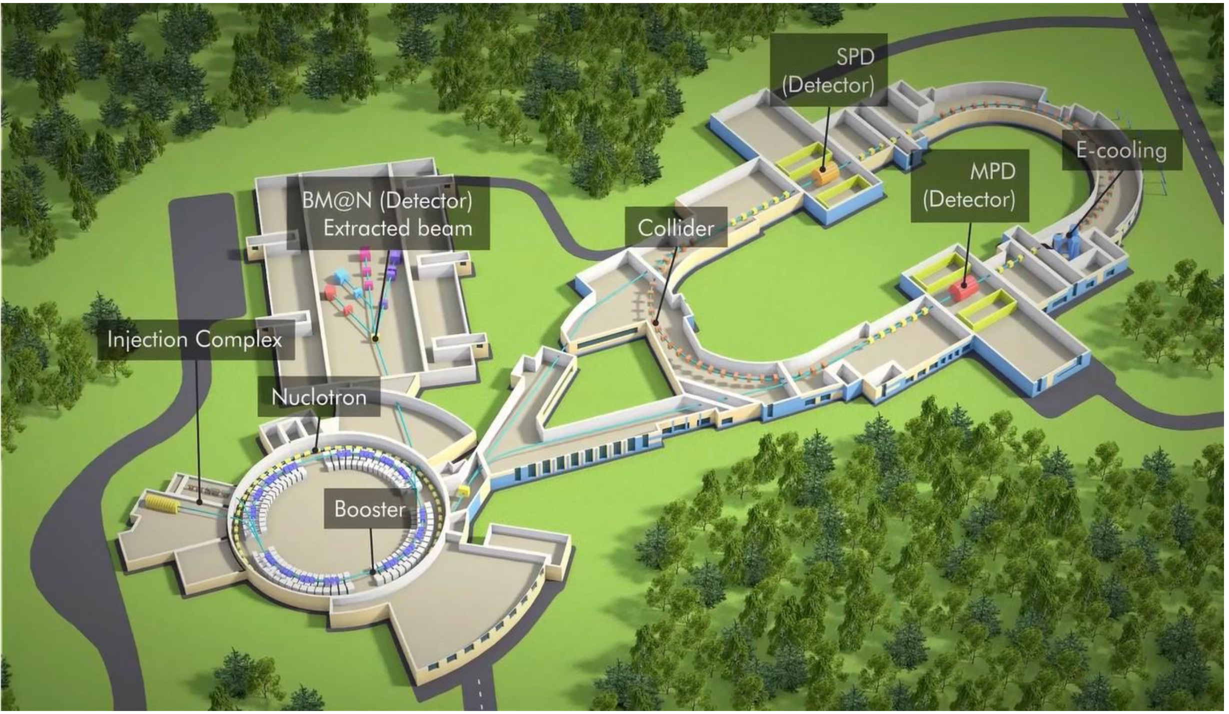
- ✓ Study of the QCD medium at extreme net baryon densities, phase transition at $\rho_c \sim 5\rho_0$
- ✓ Studied in several ongoing and future experiments:

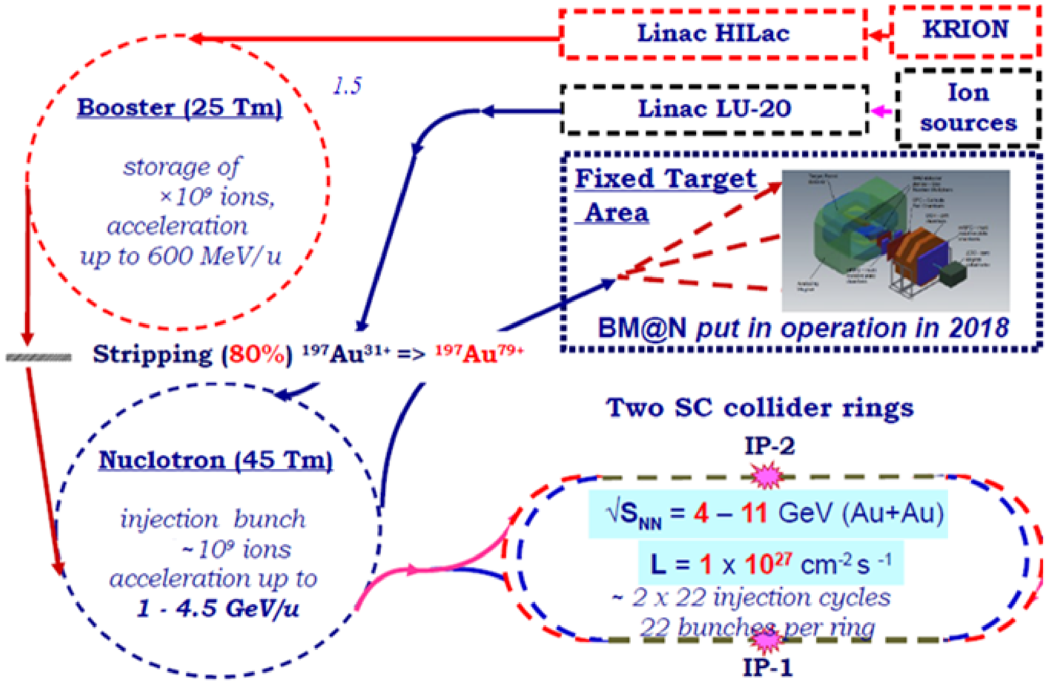
✓ collider experiments: maximum phase space, minimally biased acceptance, free of target parasitic effects

✓ fixed-target experiments: high rate of interactions, easily upgradeable, better vertex-finder for heavy flavor decays



NICA complex





Ring circumference, m	**503,04**
Number of bunches	**22**
r.m.s. bunch length, m	**0,6**
β, m	**0,35**
Energy in c.m., Gev/u	**4-11**
r.m.s. $\Delta p/p$, 10^{-3}	**1,6**
IBS growth time, s	**1800**
Luminosity, cm^{-2} s^{-1}	**$1x10^{27}$**

First runs in collider will be in

✓without electron cooling in collider, with stochastic cooling, reduced number of RFs → not-optimal beam optics

✓ reduced luminosity (~10^{25} is the goal for 2023) → collision rate ~ 50 Hz

✓ collision system available with the current sources: C (A=12), N (A=14), Ar (A=40), Fe (A=56), Kr (A=78-86),
Xe (A=124-134), Bi (A=209) → start with Bi+Bi 9.2 GeV in 2023, Au+Au 4-11 GeV to continue

Multi-**P**urpose **D**etector (MPD) Collaboration

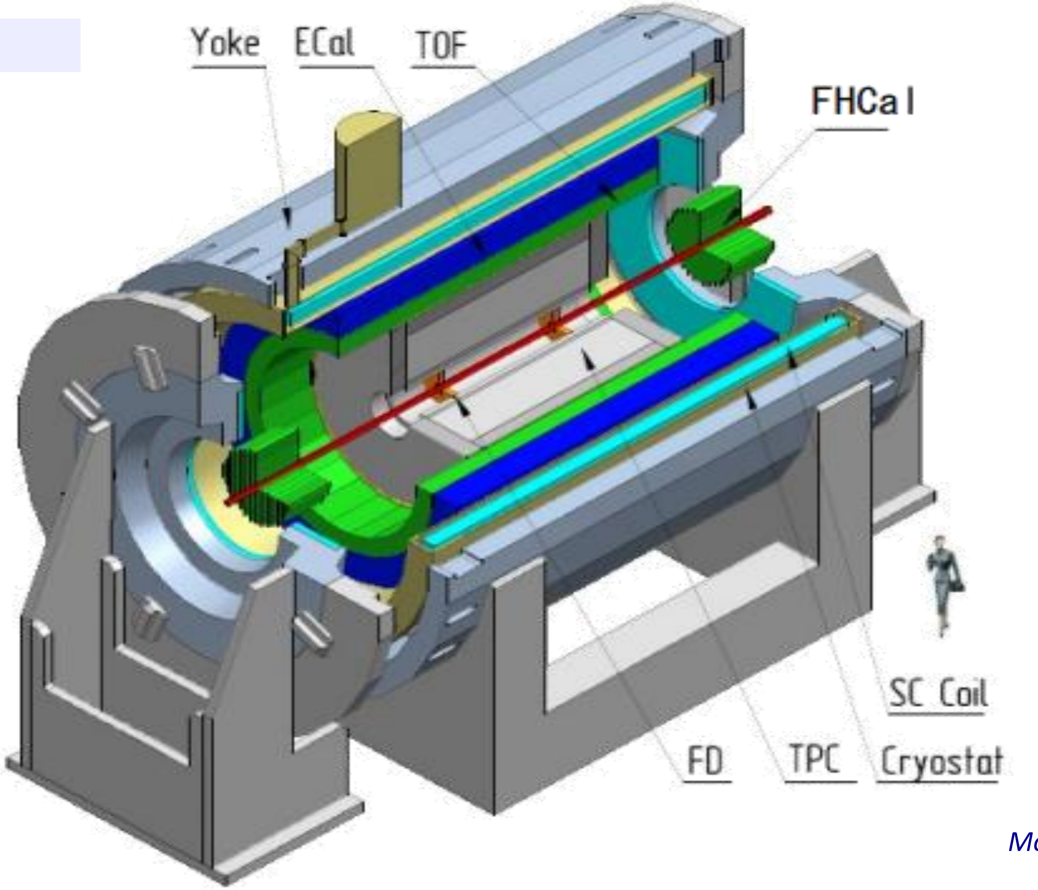
MPD** International Collaboration was established in **2018
to construct, commission and operate the detector

10** Countries, **>450** participants, **31** Institutes and **JINR

Organization

Acting Spokesperson:	***Victor Riabov***
Deputy Spokesperson:	***Zebo Tang***
Institutional Board Chair:	***Alejandro Ayala***
Project Manager:	***Slava Golovatyuk***

Joint Institute for Nuclear Research;
*AANL, Yerevan, **Armenia;***
*University of Plovdiv, **Bulgaria;***
*Tsinghua University, Beijing, **China**;*
*USTC, Hefei, **China**;*
*Huzhou University, Huizhou, **China**;*
*Institute of Nuclear and Applied Physics, CAS, Shanghai, **China**;*
*Central China Normal University, **China**;*
*Shandong University, Shandong, **China**;*
*IHEP, Beijing, **China**;*
*University of South China, **China**;*
*Three Gorges University, **China**;*
*Institute of Modern Physics of CAS, Lanzhou, **China**;*
*Tbilisi State University, Tbilisi, **Georgia**;*
*FCFM-BUAP (Heber Zepeda) Puebla, **Mexico**;*
*FC-UCOL (Maria Elena Tejeda), Colima, **Mexico**;*
*FCFM-UAS (Isabel Dominguez), Culiacán, **Mexico**;*
*ICN-UNAM (Alejandro Ayala), Mexico City, **Mexico**;*
*Institute of Applied Physics, Chisinev, **Moldova**;*
*Institute of Physics and Technology, **Mongolia**;*

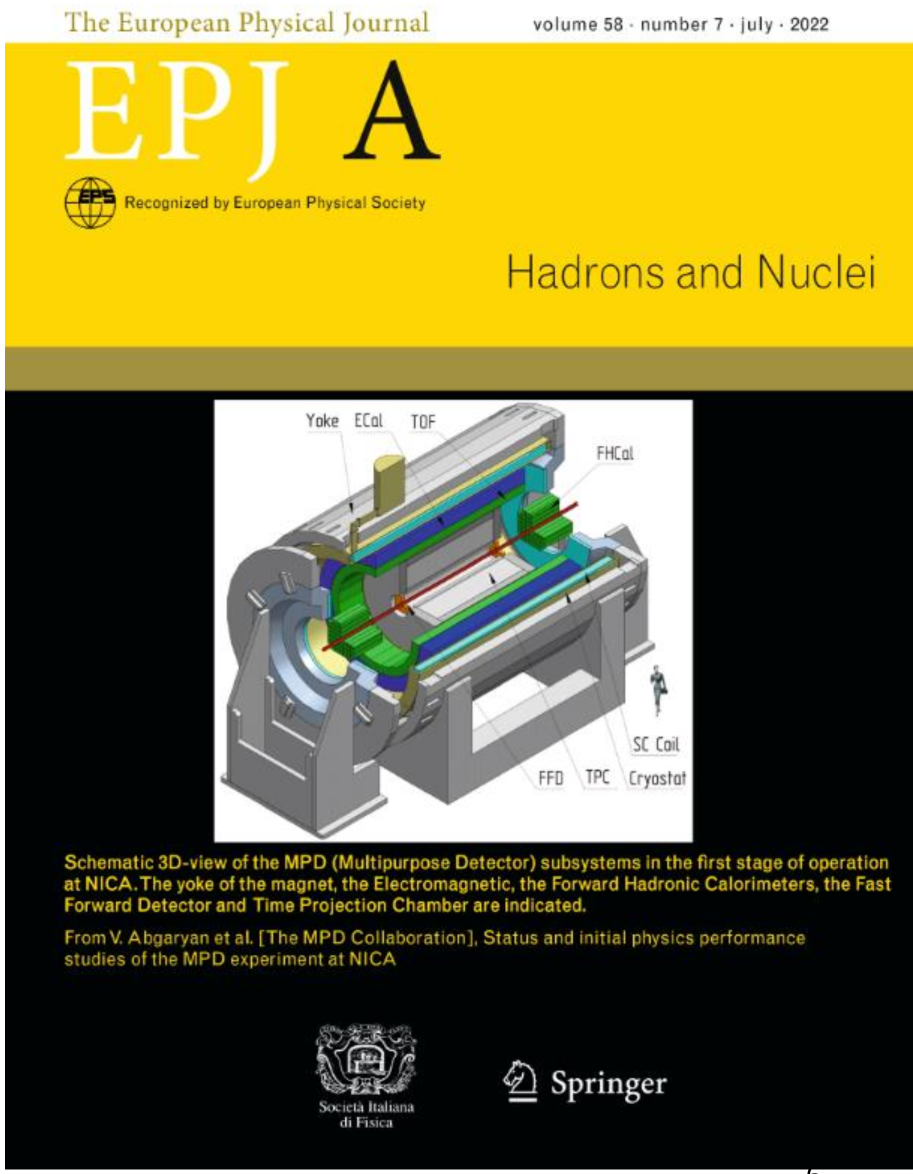


*Belgorod National Research University, **Russia**;*
*INR RAS, Moscow, **Russia**;*
*MEPhI, Moscow, **Russia**;*
*Moscow Institute of Science and Technology, **Russia**;*
*North Osetian State University, **Russia**;*
*NRC Kurchatov Institute, ITEP, **Russia**;*
*Kurchatov Institute, Moscow, **Russia**;*
*St. Petersburg State University, **Russia;***
*SINP, Moscow, **Russia**;*
*PNPI, Gatchina, **Russia**;*
*Vinča Institute of Nuclear Sciences, **Serbia**;*
*Pavol Jozef Šafárik University, Košice, **Slovakia***

MPD position in the physics landscape

Cover story for EPJ A

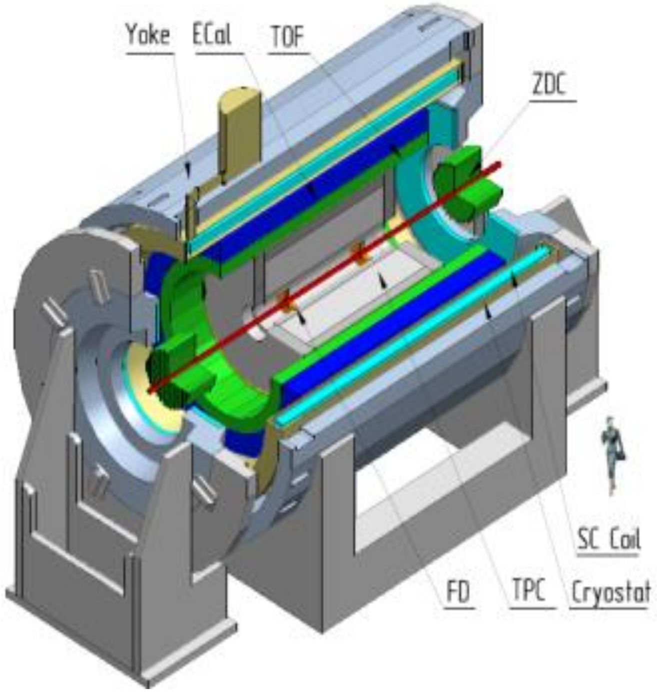
	NA61/SHINE at SPS	CBM at FAIR	STAR BES+FXT at RHIC	MPD + BM@N at NICA
Coverage of region of transition from baryon to meson dominance („horn”)	only higher $\sqrt{s_{NN}}$	only lower $\sqrt{s_{NN}}$	Yes (mixing collider and fixed target)	Yes (consistent acceptance)
expected luminosity (w.r.t. MPD)	lower	higher	lower	reference
possibility for system size scan	yes	yes	yes (?)	yes
full centrality range	no	yes (?)	yes	yes
acceptance type	Fixed target	Fixed target	Collider + fixed target	Collider + fixed target
running plan (heavy-ions)	approved for 2021 (per-year decision)	beyond 2025	running concluded in 2021	2023 and beyond
status at the facility (possible running time)	in competition with many projects (LHC)	CBM one of four main experiments	end of datataking (heavy-ion) in 2021	flagship experiments several months/year



- ✓ The MPD strategy consists of performing a high-luminosity scan in energy and system size, looking for a wide variety of signals sensitive to the phase transition and presence of the critical point
- ✓ The scans are going to be performed using the same apparatus with all the advantages of collider experiments

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

Multi-Purpose Detector



Stage- I upgrade **Stage- II**

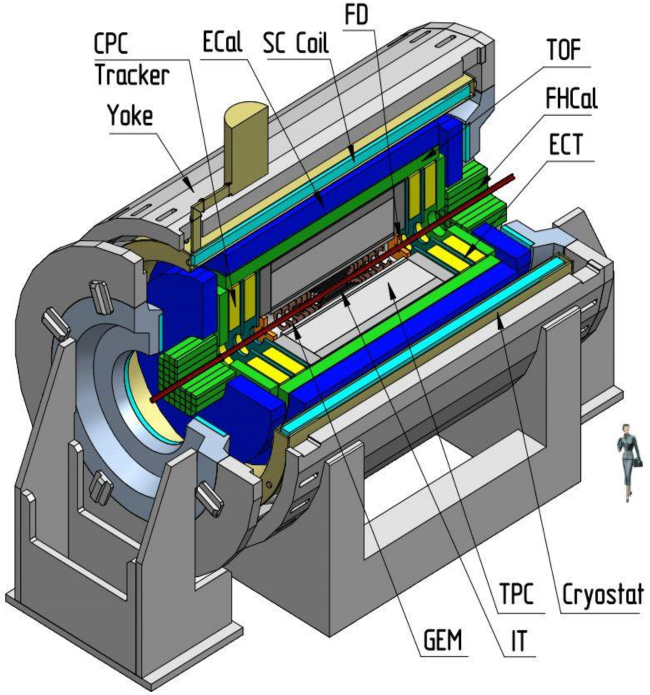
Length	340 cm
Vessel outer radius	140 cm
Vessel inner radius	27 cm
Default magnetic field	0.5 T
Drift gas mixture	90% Ar+10% CH_4
Maximum event rate	7 kHz ($L = 10^{27}$ $cm^{-2}s^{-1}$)

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

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

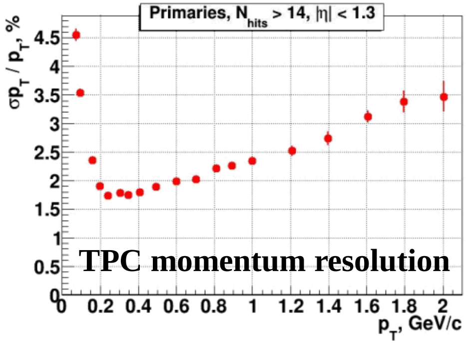
FFD: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$

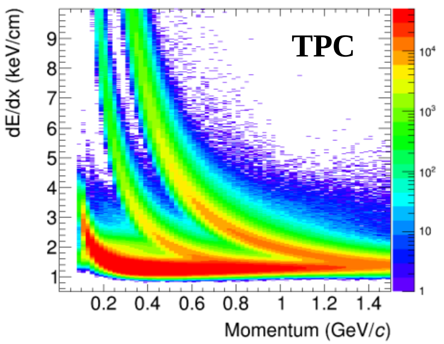
FHCAL: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

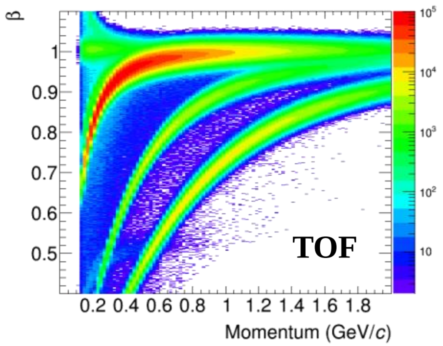


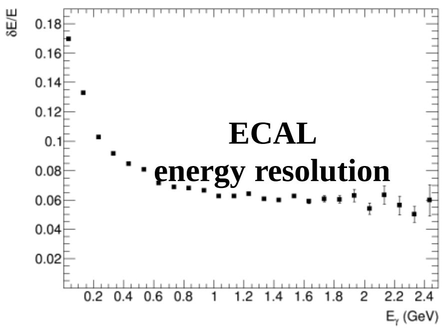
+ **ITS** (heavy-flavor measurements)
+ **forward spectrometers**

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







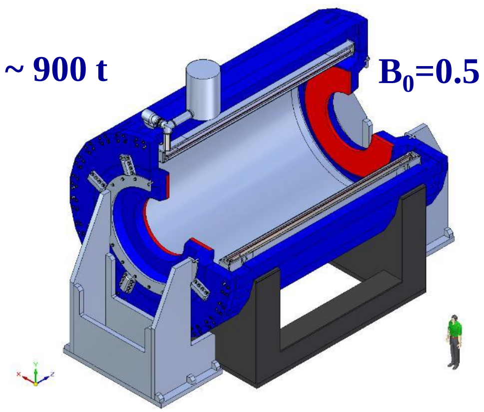


MPD subsystems in production

SC Solenoid + Iron Yoke

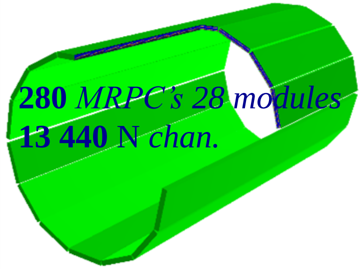
~ 900 t

B_0=0.5 T



Goal is to cool down and power the magnet + magnetic field measurements will start soon

TOF

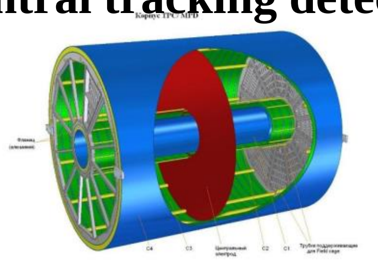


280 *MRPC's 28 modules*
13 440 N *chan.*

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

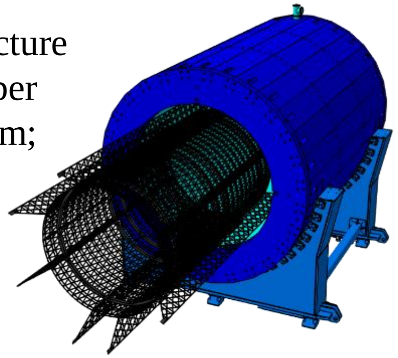
TPC – central tracking detector

ROCs done
Cyllinders done
Electronics in mass production



Support structure

support structure of carbon fiber sagite ~ **5** mm;
0,13 X_0



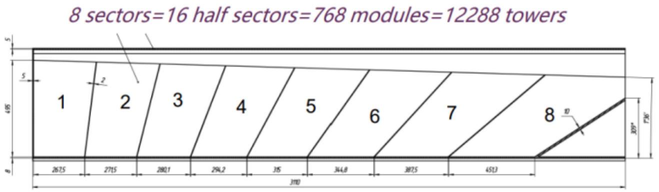
ECAL ~ 100 t

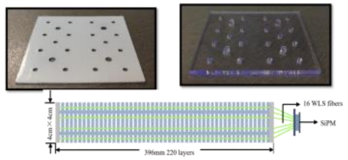
See http://mpd.jinr.ru/doc/mpd-tdr/ **for details**

ECAL (projective geometry)

38 400 towers

16/25 sectors will be produced for Stage-I, production of the remaining modules is possible by 2024





Pb+Sc "shashlyk"-type towers

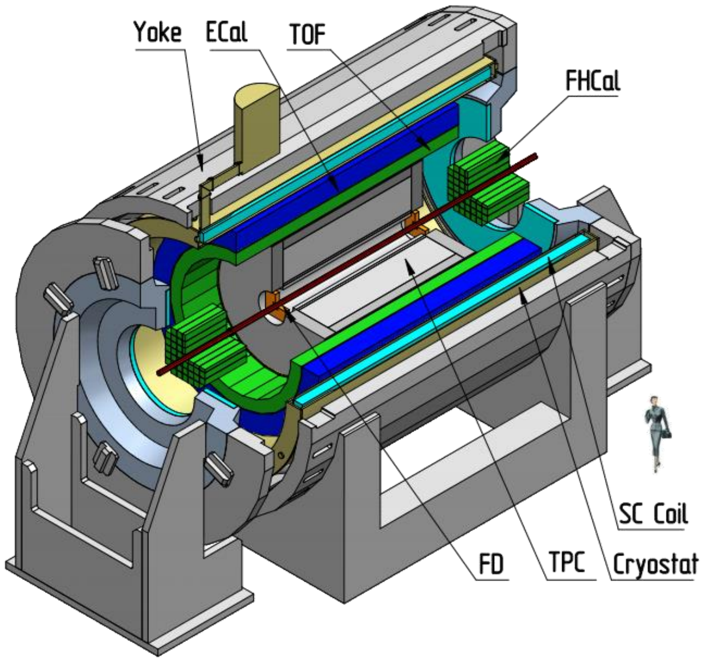
MPD assembly

- ✓ MPD hall is available for detector activities
- ✓ Installation of the MPD superconducting coil inside the magnet yoke - 29 July, 2021, followed by alignment of cold mass, pressure test of thermal shield and cryostat cold mass, replacement of flanges, vacuum test of solenoid vessel, leak test of cryostat
- ✓ Ongoing: temperature probes cables, assembling magnet yoke, alignment, installation of top platform, chimney installation, cryogenic system with control systems, magnetic field measurement

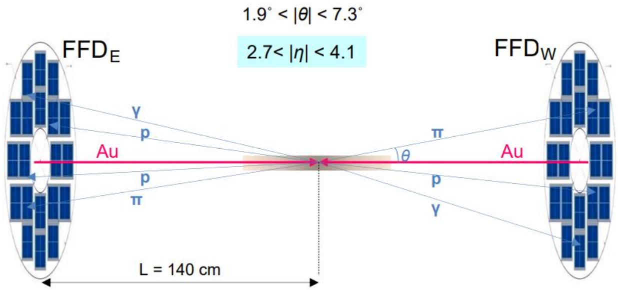
Cryogenic system assembly

- ✓ Barrel Magnet Yoke is completely assembled
- ✓ Cryogenic platform has been mounted, next step is mounting of the refrigerator, vacuum pumps, control electronics, etc.
- ✓ Assembling the refrigerator for installation on the platform
- ✓ Works on the magnet control system, cryogenics and power supplies
- ✓ Magnetic field mapper and magnetic field measurements

MPD trigger system

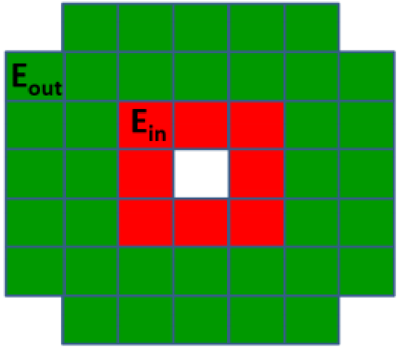


- FFD (Fast Forward Detector):
  - ✓ fast event triggering
  - ✓ T_0 for time measurements in the TOF and ECAL



- FHCAL (Forward Hadron Calorimeter) – detector for event centrality and reaction plane measurements with potential for event triggering

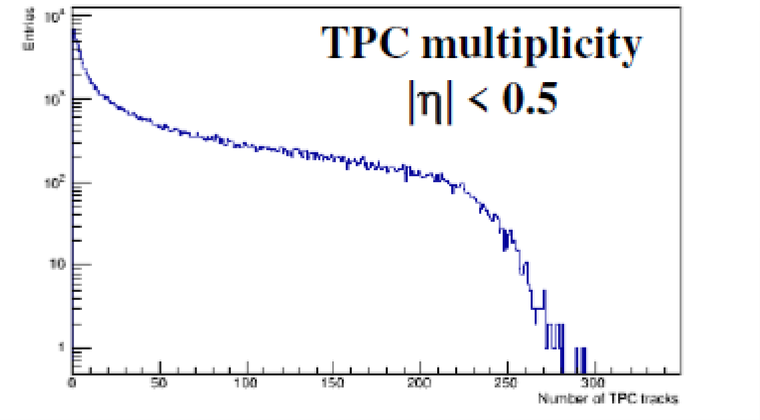
- MPD challenges at NICA energies:
  - ✓ low multiplicity of particles produced in heavy-ion collisions
  - ✓ particles are not ultra-relativistic (even the spectator protons)
- Forward detectors are in advanced state of production (electronics and integration)

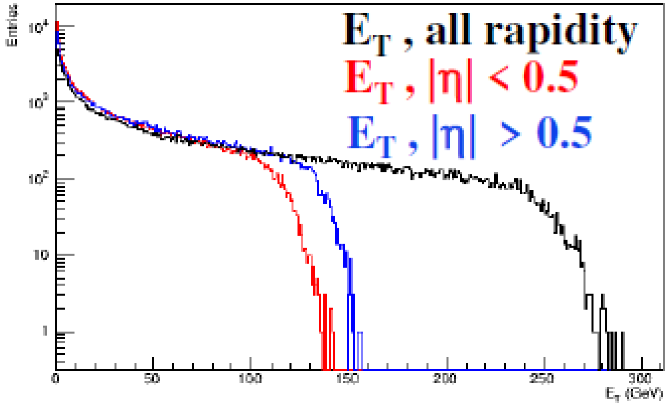


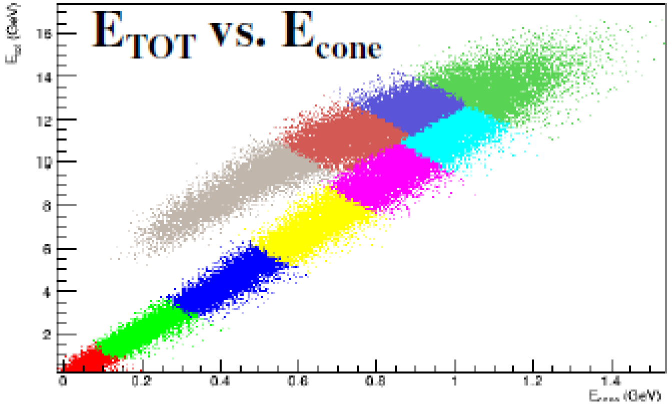
$2 < |\eta| < 5$

$\sim 1x1\ m^2$

Centrality determination

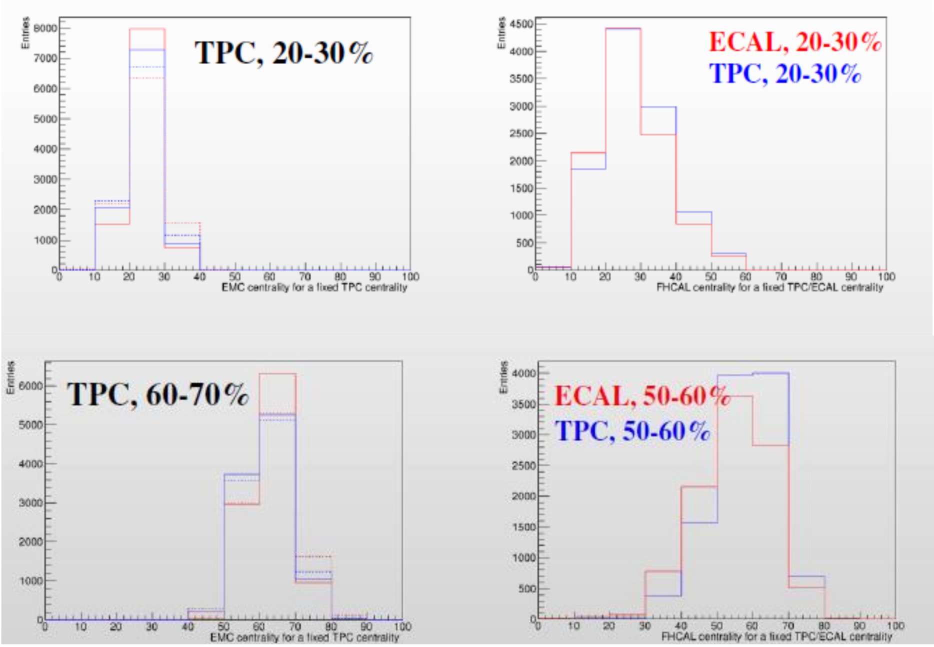




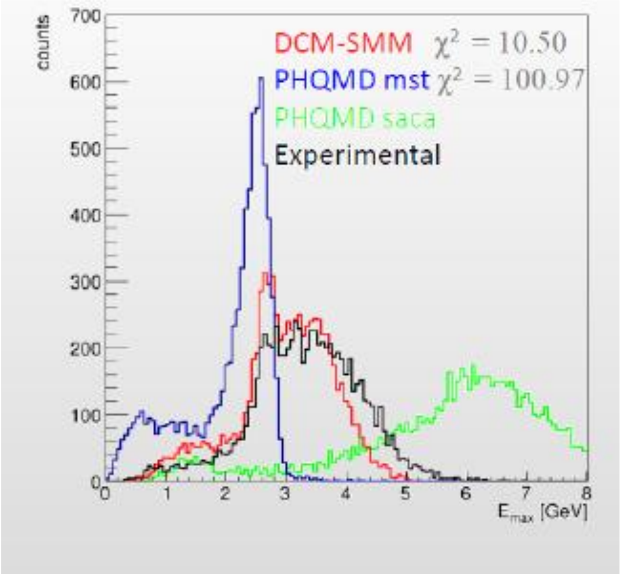


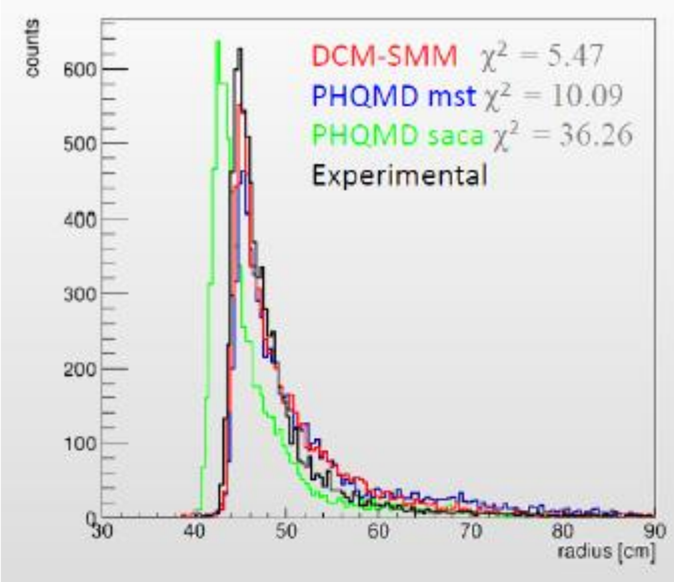
TPC and ECAL produce similar results for centrality

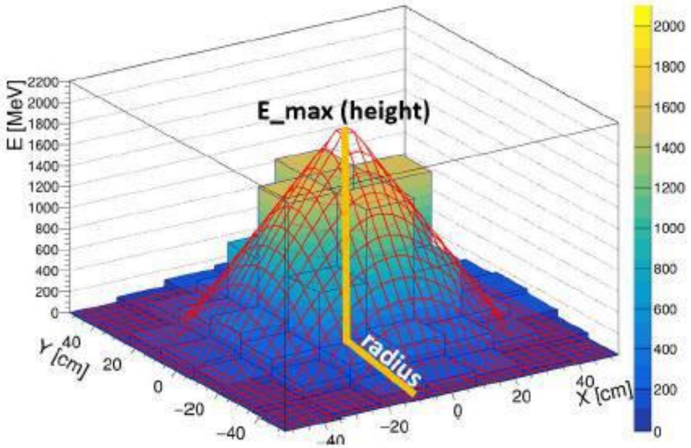
FHCAL centrality has a very wide correlation with the TPC/ECAL centrality; resolution by impact parameter is worse



Forward calorimeter





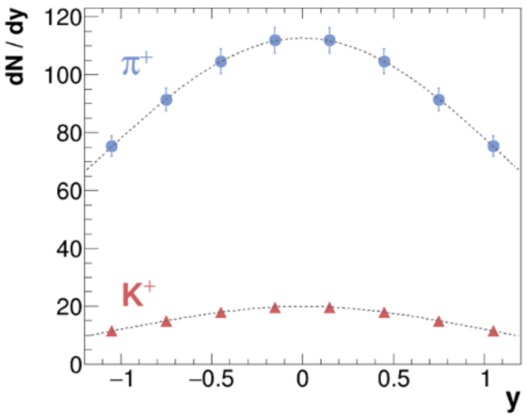


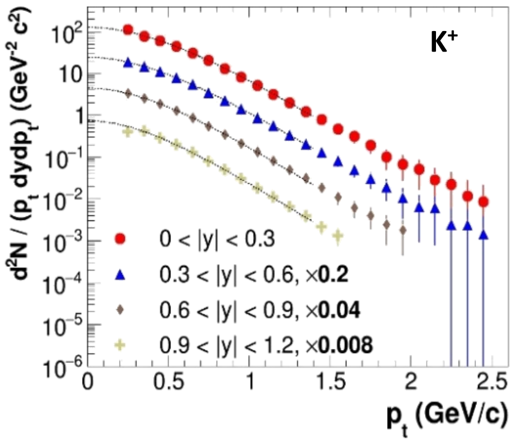
Comparison of MC results with data from NA61 FHCAL on the spectator energy Experimental data for hadronic calorimeter (PSD) in Pb-Pb at 30 GeV/n, fixed-target.
The DCM-SMM reproduces the measurement results, PHQMD not

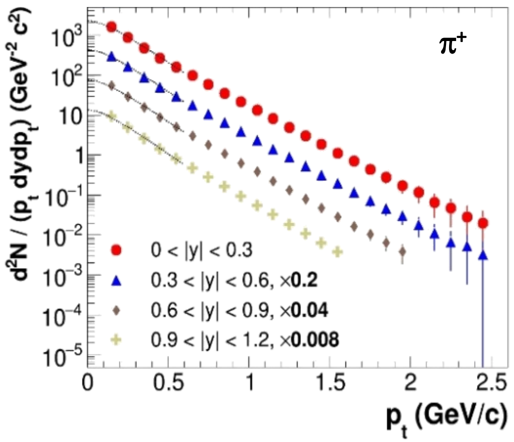
Identified hadron spectra

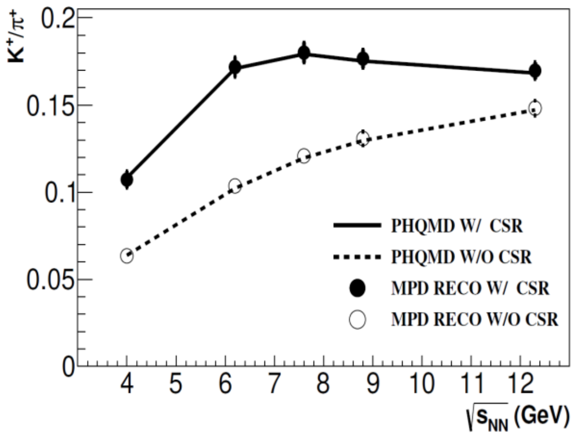
- Particle spectra, yields and ratios probe bulk properties of the firerball and flow
- Advantage of the MPD is in large and uniform acceptance, excellent PID capabilities using combined analysis of TPC (dE/dx) and TOF signals

0-5% central AuAu@9 GeV (PHSD, with partonic phase and chiral symmetry restoration effects):









✓ MPD samples ~ 70% of the π/K/p production in the full phase space

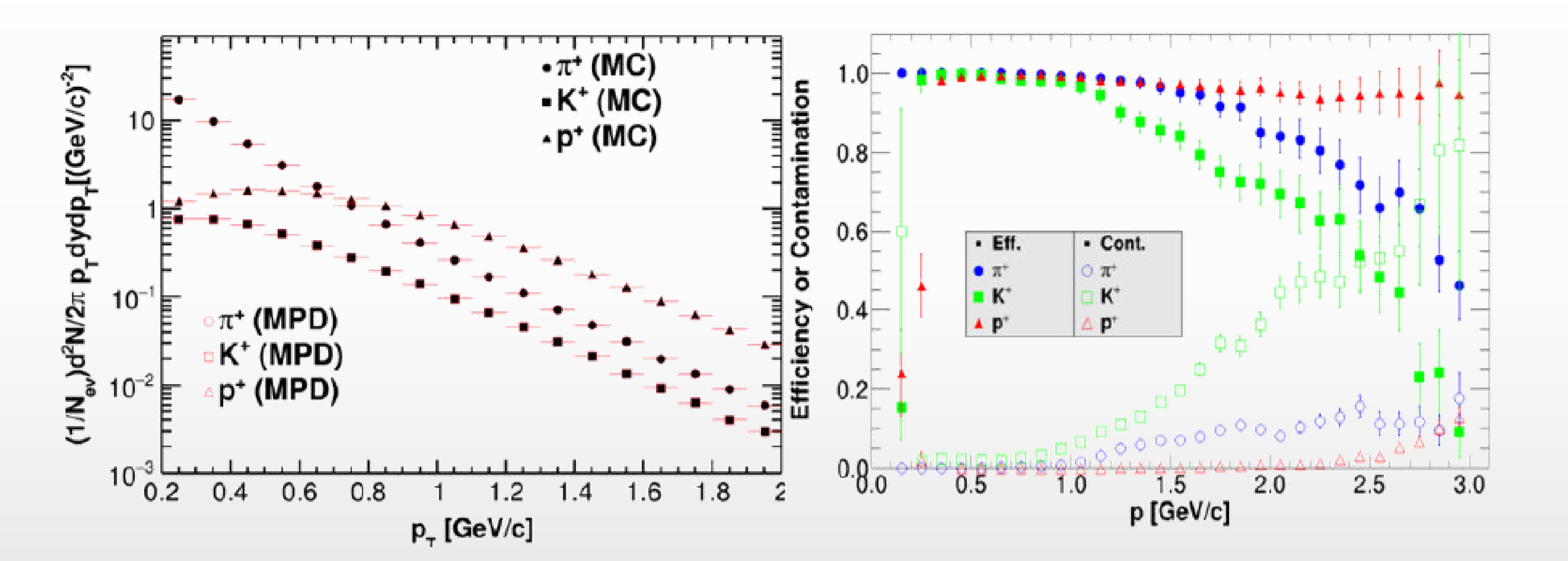
✓ hadron spectra are measured from 0.2 MeV/c to 2.5 GeV/c in transverse momentum with the TPC&TOF

✓ unmeasured hadron yields at low p_T and large values of rapidity can be extracted from extrapolation of the measured spectra (B-W for p_T spectra and Gaussian for rapidity spectra in exampled above)

Ability to cover full energy range of the "horn" with consistent acceptance across different collision systems and collision energies

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

Machine learning in PID



Development of methods for identification of charged tracks using the TPC and TOF

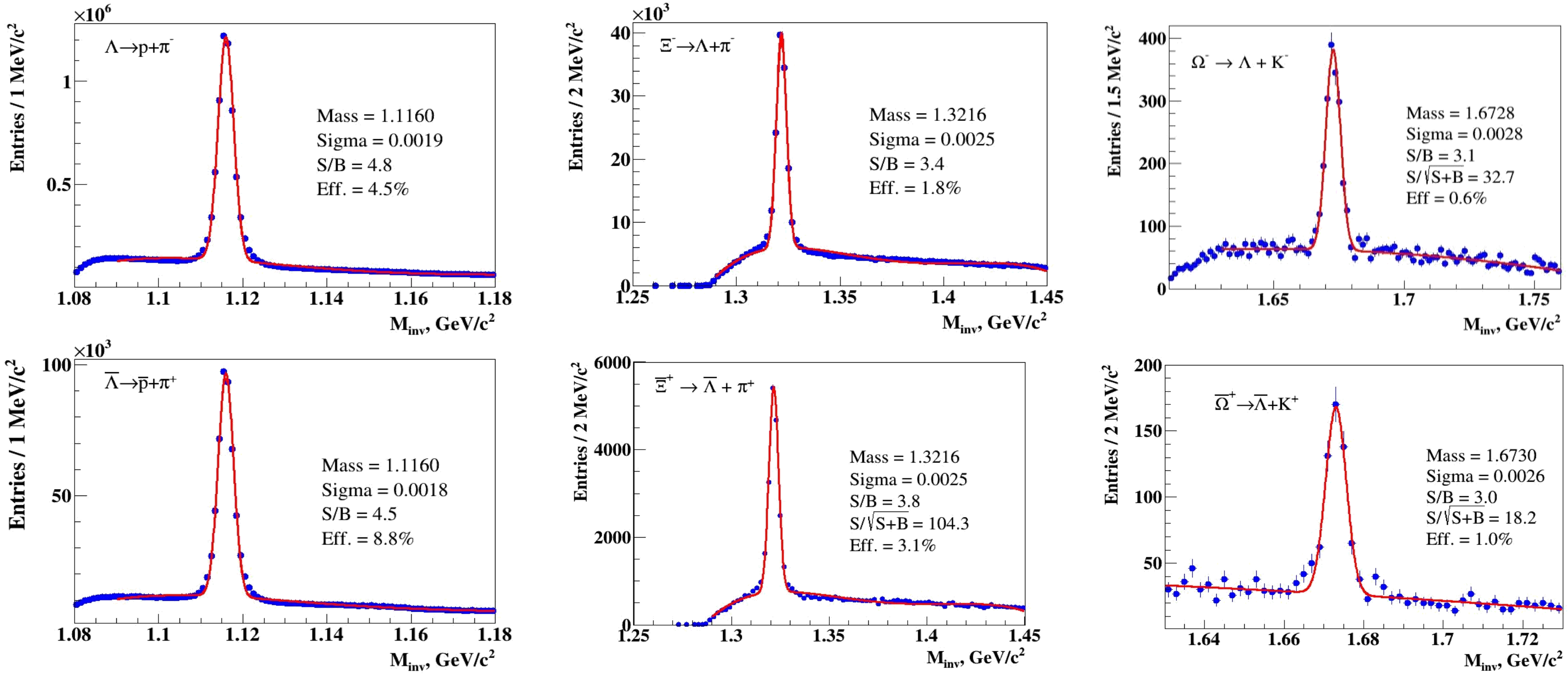
Purpose: higher efficiency and purity of the signals

Options: different field configurations, systems and energies, methods, including machine learning approaches (Decision Tree Approach)

Weak decays of strange baryons

- Strangeness production probes the EoS, phase boundaries and onset of deconfinement
- Antibaryon-to-baryon ratios at intermediate momenta are sensitive to CEP (a falling trend in contrast to a constant behavior in the scenario without CEP)
- AuAu@11 GeV (PHSD):

Λ	anti-Λ	Ξ^-	anti-Ξ^+	Ω^-	anti–Ω^+
$3 \cdot 10^8$	$3.5 \cdot 10^6$	$1.5 \cdot 10^6$	$8.0 \cdot 10^4$	$7 \cdot 10^4$	$1.5 \cdot 10^4$



✓ Strange baryons can be reconstructed with good S/B ratios using charged hadron identification in the TPC&TOF and different decay topology selections

✓ Relative yields of the baryons for ~ 500 M sampled events:

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

Short-lived resonances

Resonances probe reaction dynamics and particle production mechanisms vs. system size and $\sqrt{s_{NN}}$

- ✓ hadron chemistry and strangeness production, lifetime and properties of the hadronic phase, spin alignment of vector mesons, flow etc.

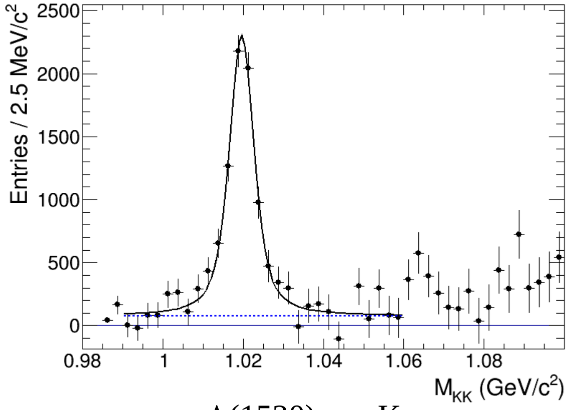
increasing lifetime ⟶

	ρ(770)	K*(892)	Σ(1385)	Λ(1520)	Ξ(1530)	ϕ(1020)
cτ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

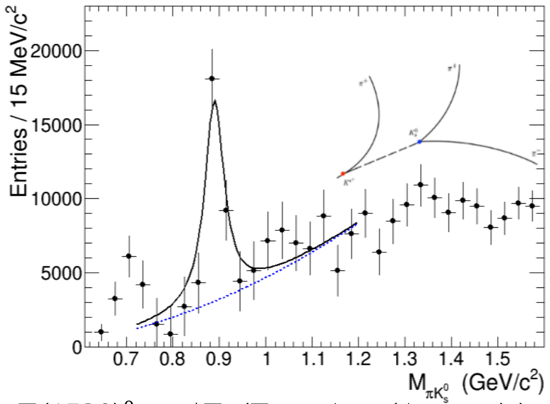
- ✓ MPD is capable of reconstruction the resonance peaks in the invariant mass distributions using combined charged hadron identification in the TPC and TOF
- ✓ decays with weakly decaying daughters require additional second vertex and topology cuts for reconstruction

BiBi@9.2 GeV (UrQMD) after mixed-event background subtraction:

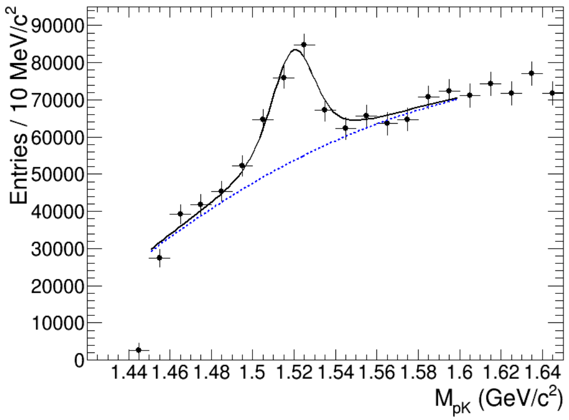
$\phi(1020) \to K^+K^-$



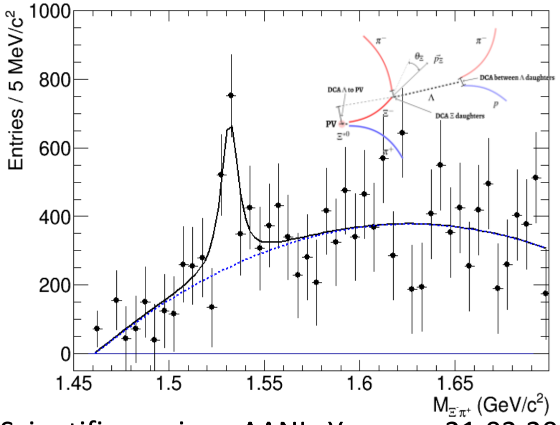
$K^*(892)^\pm \to \pi^\pm K_s$ ($K_s \to \pi^+\pi^+$)



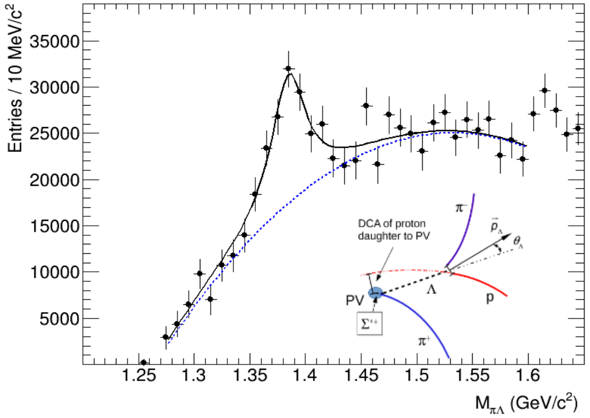
$\Lambda(1520) \to pK^-$



$\Xi(1530)^0 \to \pi^+\Xi^-$ ($\Xi^- \to \Lambda\pi^-$, ($\Lambda \to p\,\pi^-$))



$\Sigma(1385)^\pm \to \pi^\pm\Lambda$ ($\Lambda \to p\pi$)



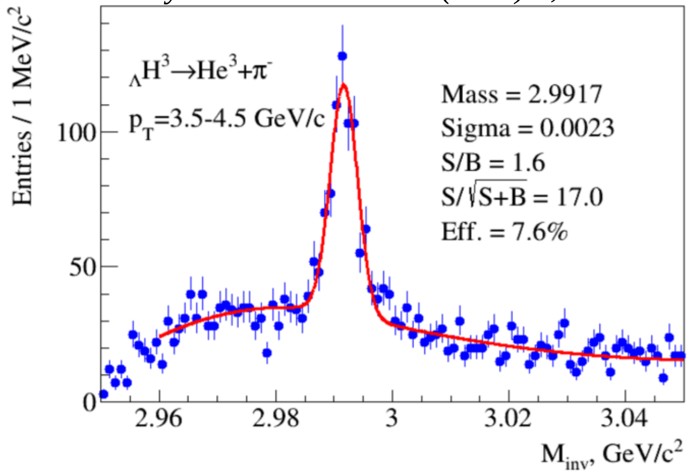
Phys.Scripta 96 (2021) 6, 064002

Reconstruction of hypertritons

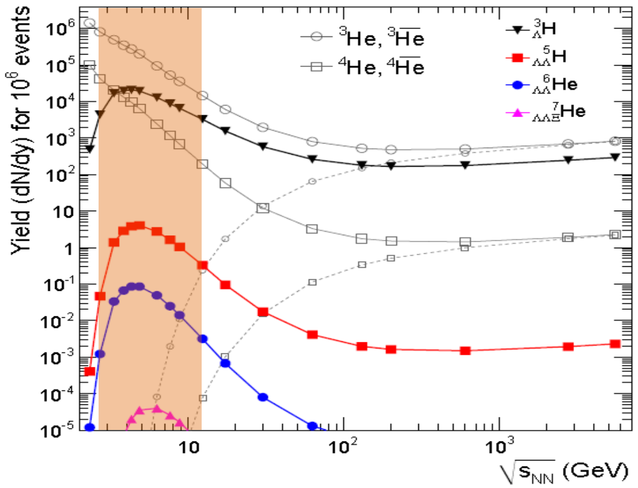
Information on YN interactions, strange sector of nuclear EoS, astrophysics

BiBi@9.2 GeV (PHQMD), 40 M sampled events:

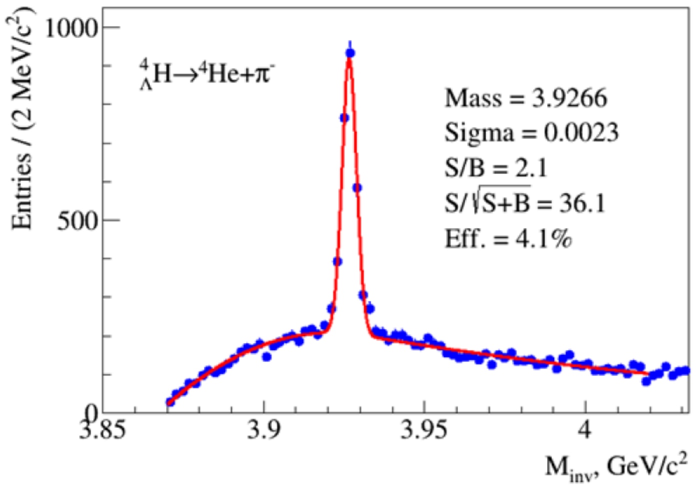
Phys.Part.Nucl.Lett. 19 (2022) 1, 46-53

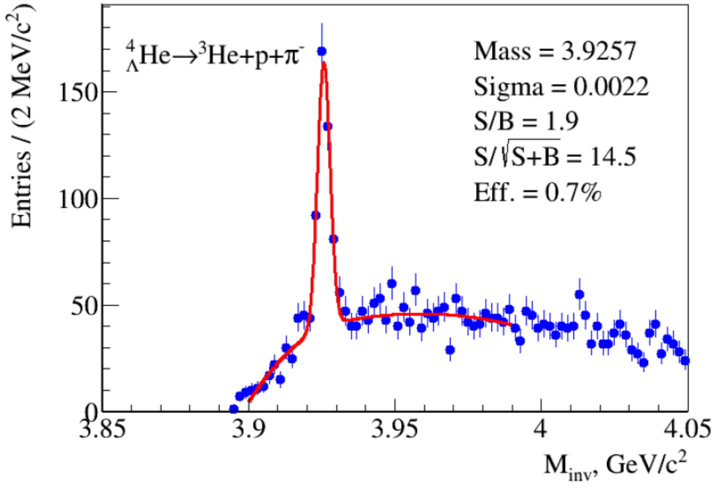


Phys. Lett. B697 (2011) 203



Thermal model predicts an enhanced hypernuclear production in the NICA energy range

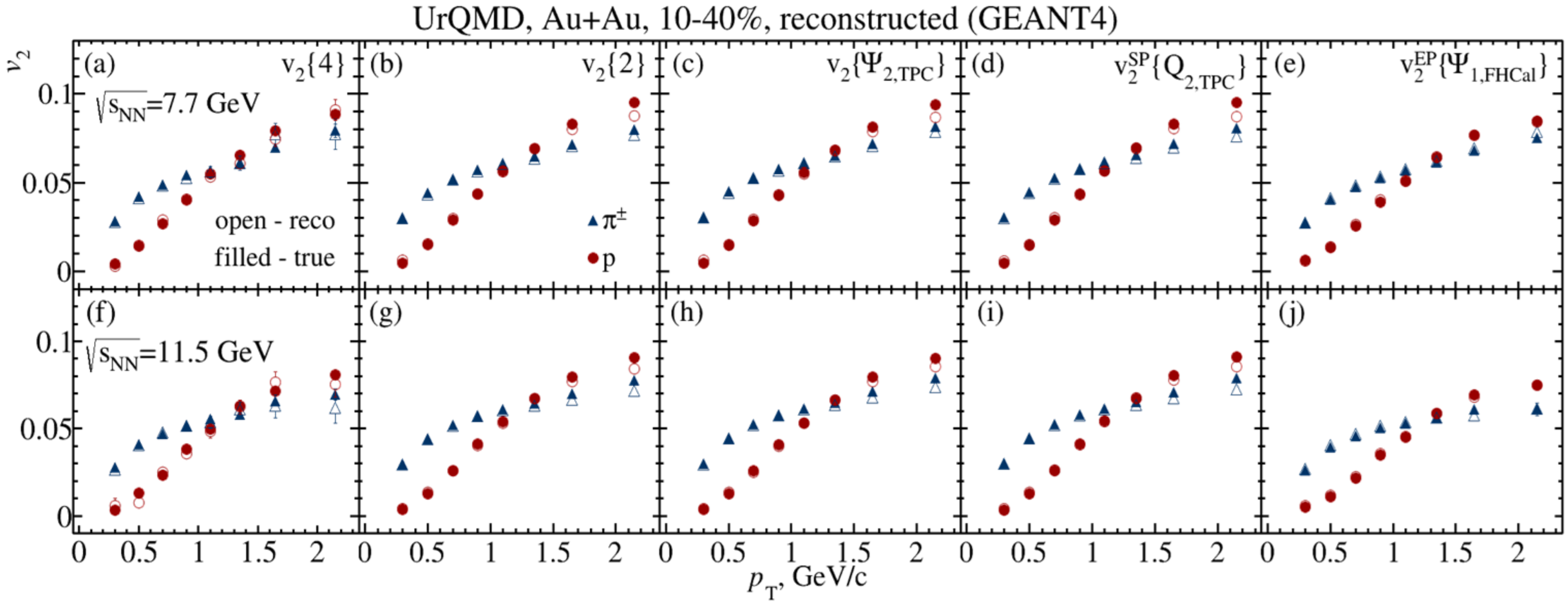




MC data sample was enriched with additional hypernuclei

v_2 for pions and protons

Flow has high sensitivity to the transport properties of the QCD matter: EoS, speed of sound (c_s), specific viscosity (η/s), etc.
Lack of existing differential measurements of v_n vs. p_T, centrality, species, etc.)
15 M of reconstructed UrQMD events for AuAu@7.7 GeV



Reconstructed and generated v_2 of pions and protons are in good agreement for all methods

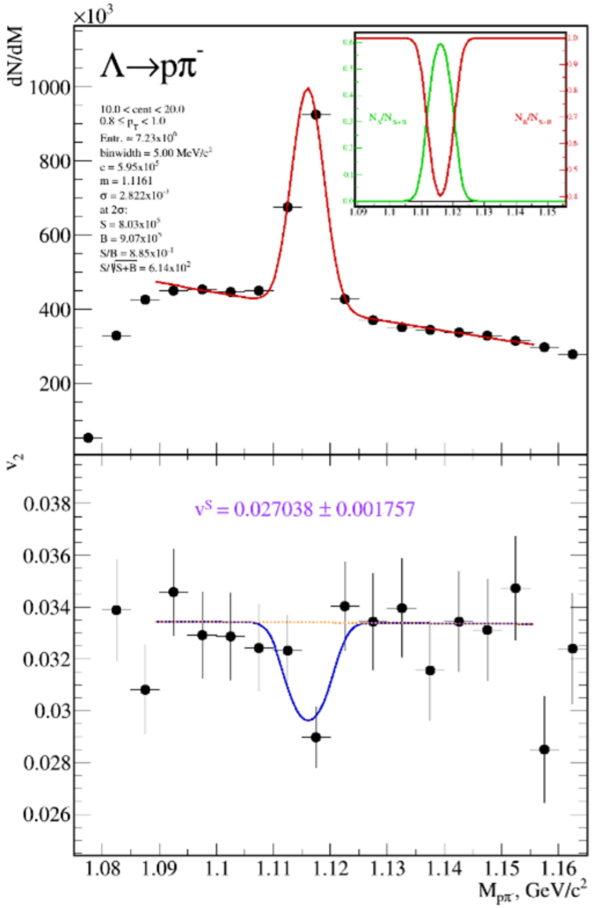
Collective flow for V0 (K_s^0 and Λ)

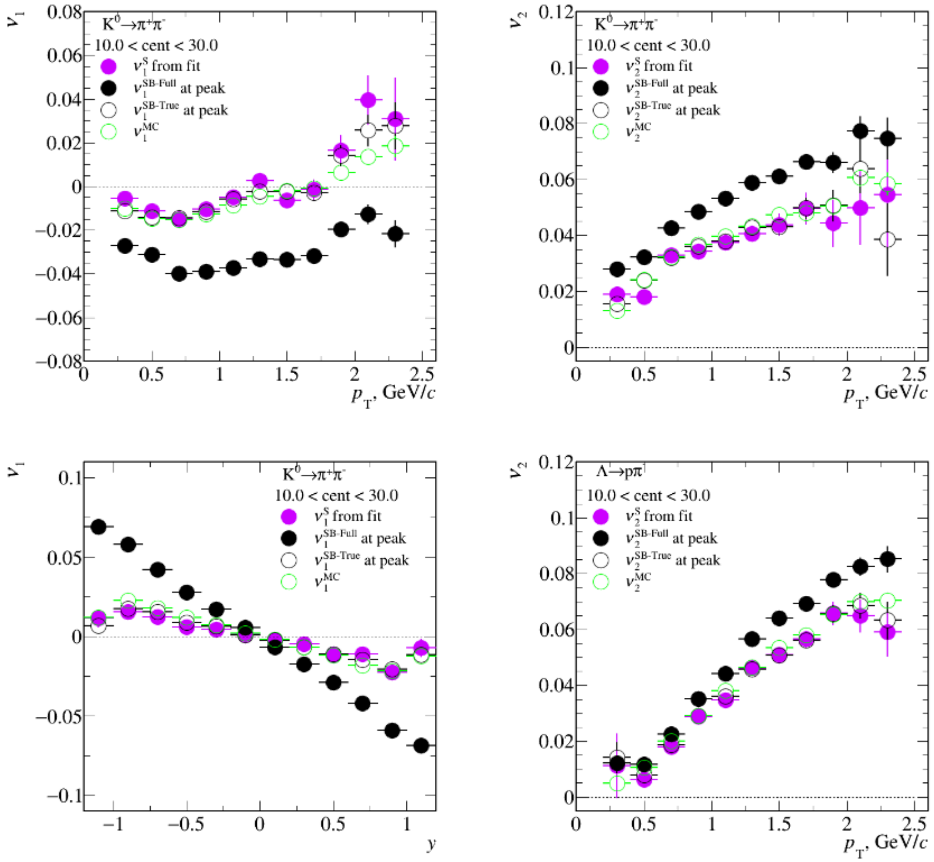
25 M AuAu@11 GeV (UrQMD)

Differential flow signal extraction using invariant mass fit method

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

Reasonable agreement between reconstructed and generated v_n signals for K_s^0 and Λ





v_1/v_2 **flow after fit**

Measured flow for (S+BG)

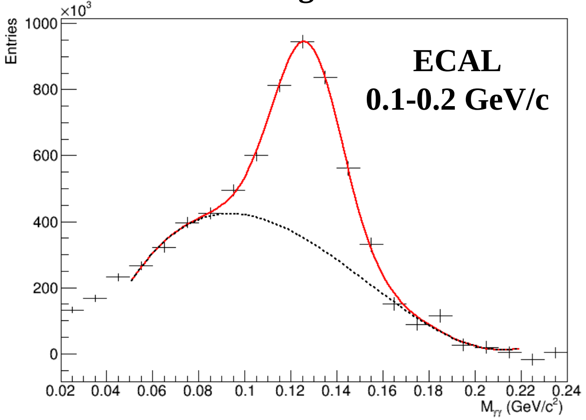
Measured flow for true pairs

Flow from event generator

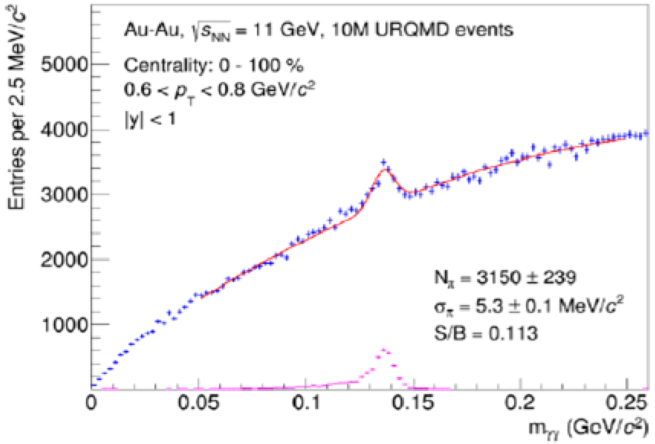
Neutral mesons

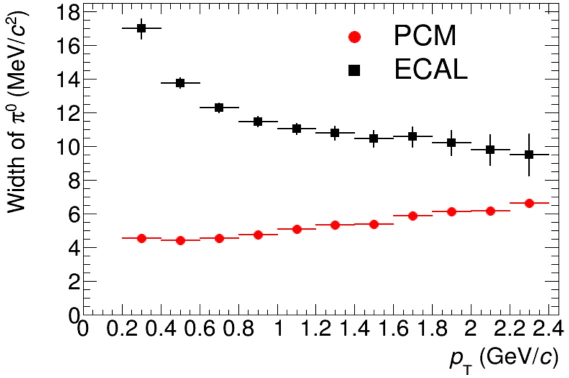
- Extend p_T range of charged particle measurements, various species (η, ω, η’, etc.)
- AuAu@11 GeV (UrQMD): realistic ECAL reconstruction and analysis in high multiplicity environment + photon conversion method

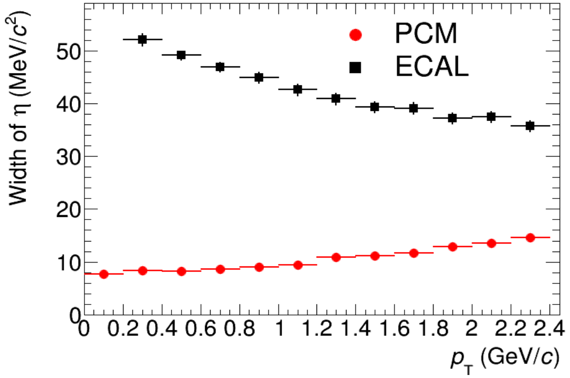
mixed-event background subtracted



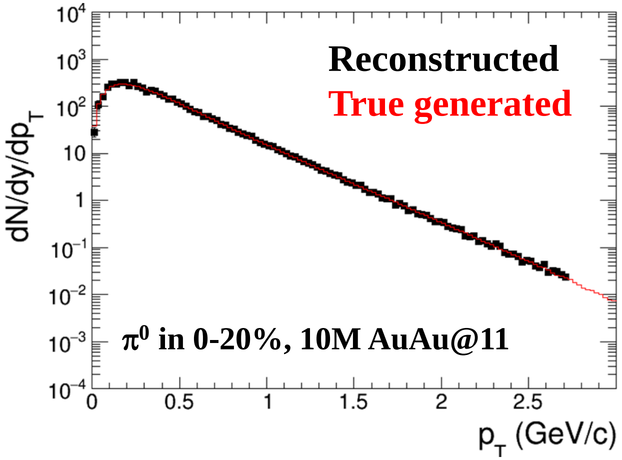
$\pi^0 \to \gamma\ (\gamma \to e^+e^-) + \gamma\ (\gamma \to e^+e^-)$

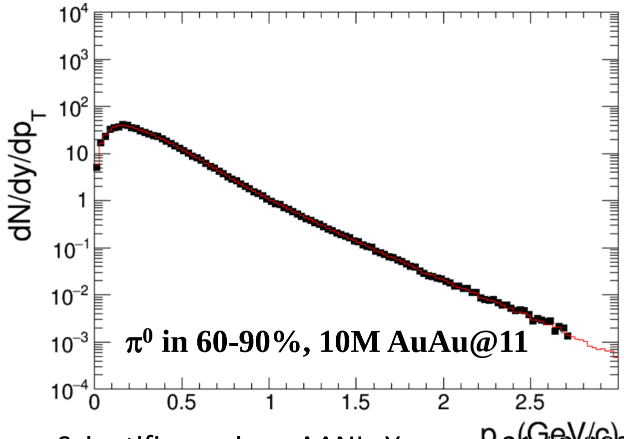


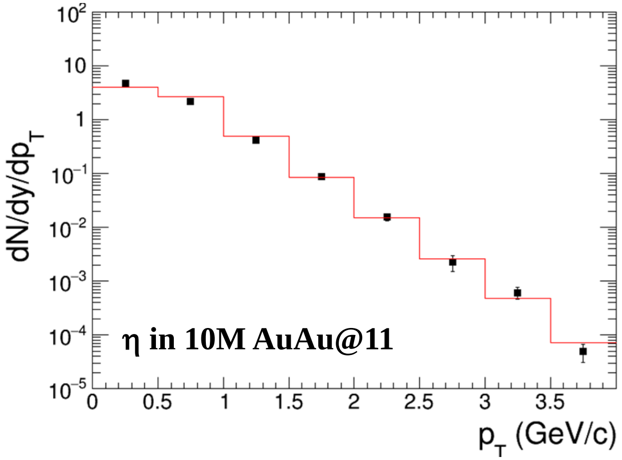




- π^0 and η MC closure tests: reconstructed spectra match the generated ones



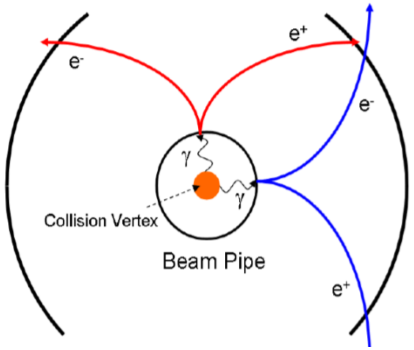


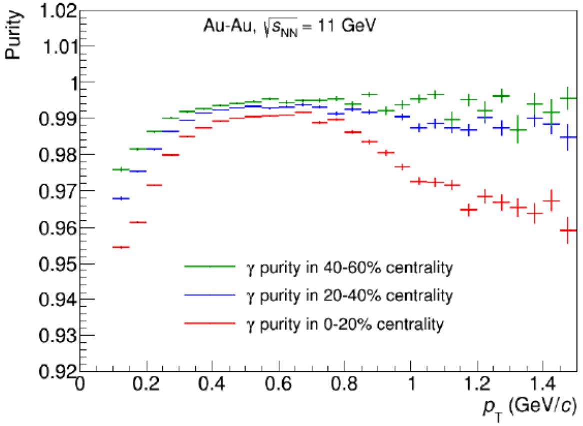


Photon measurements

AuAu@11 GeV (UrQMD)

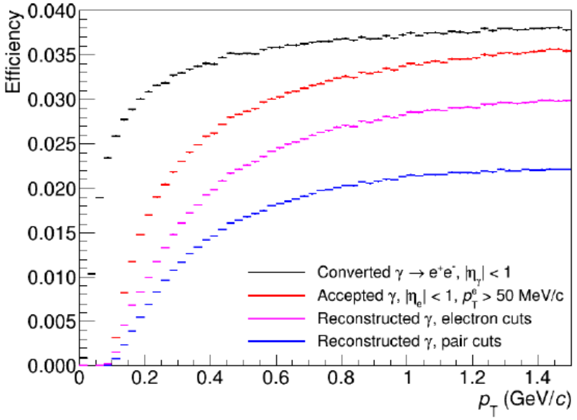
- ✓ EMCAL: large acceptance but modest resolution and small S/B at low momentum
- ✓ Conversion method: low efficiency (~ 1.5%) but high purity (> 95%) and good energy resolution



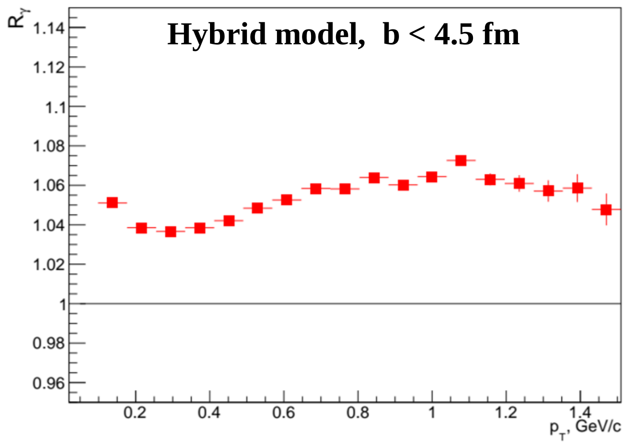


$$R_\gamma = \frac{\gamma^{incl}}{\gamma^{hadron}}$$ Rγ estimations

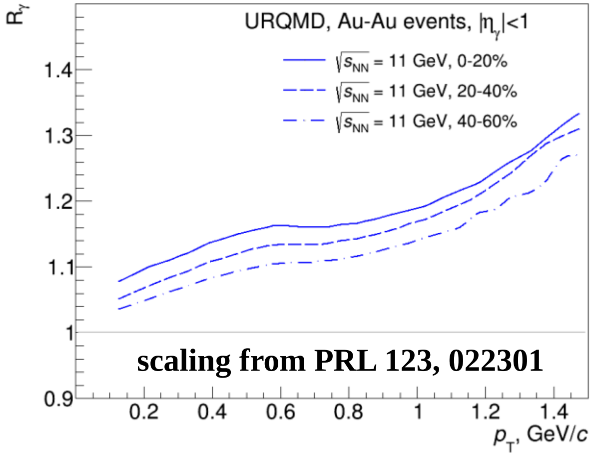
from 5% to 10% at p_T > 0.5 GeV/c at top NICA energies



Phys.Part.Nucl. 52 (2021) 4, 681-685

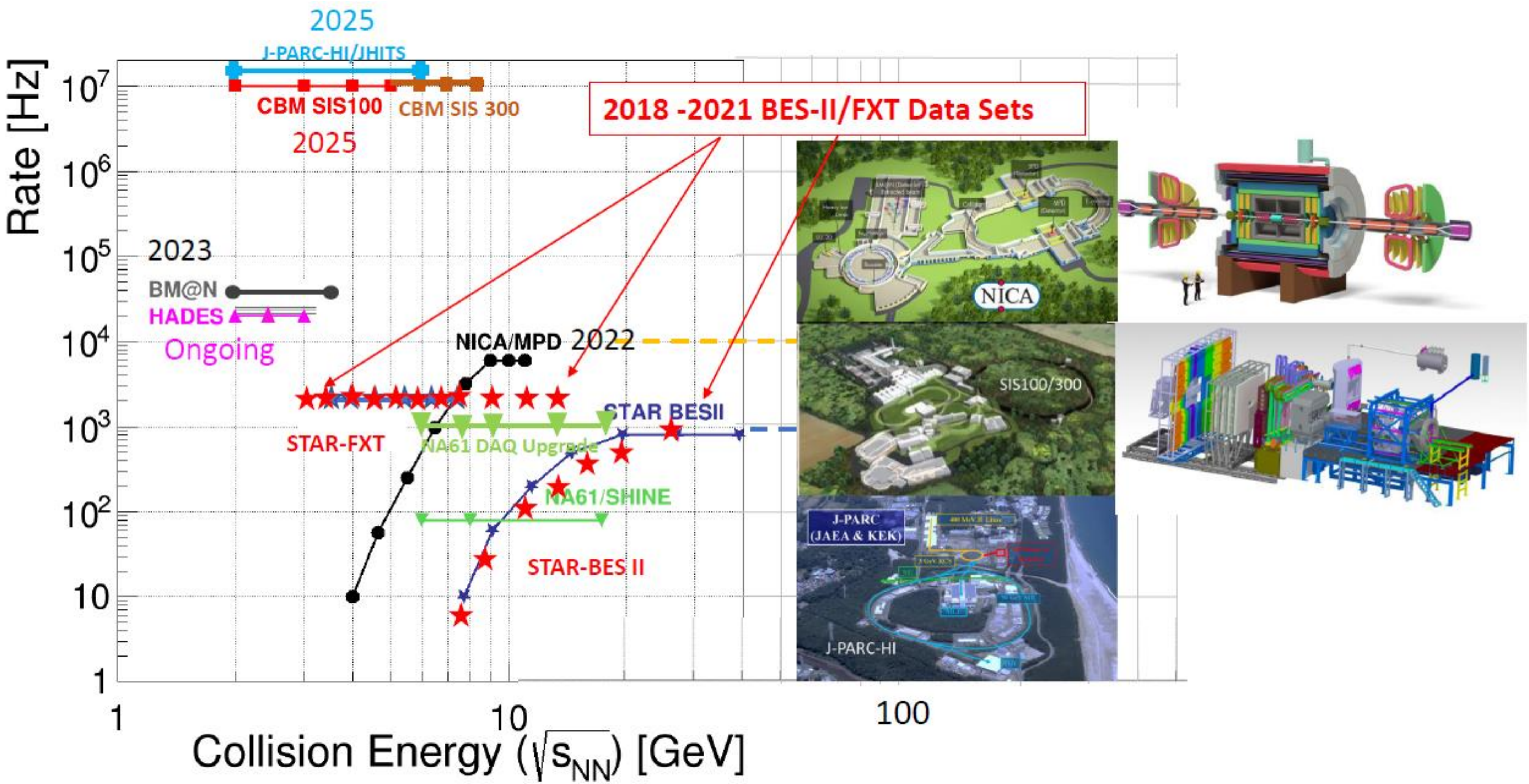


Phys.Part.Nucl. 52 (2021) 4, 669-674



❖ Rγ values ~5% have been measured by PHENIX → potential for direct photon measurements @MPD

HIC landscape



SUMMARY

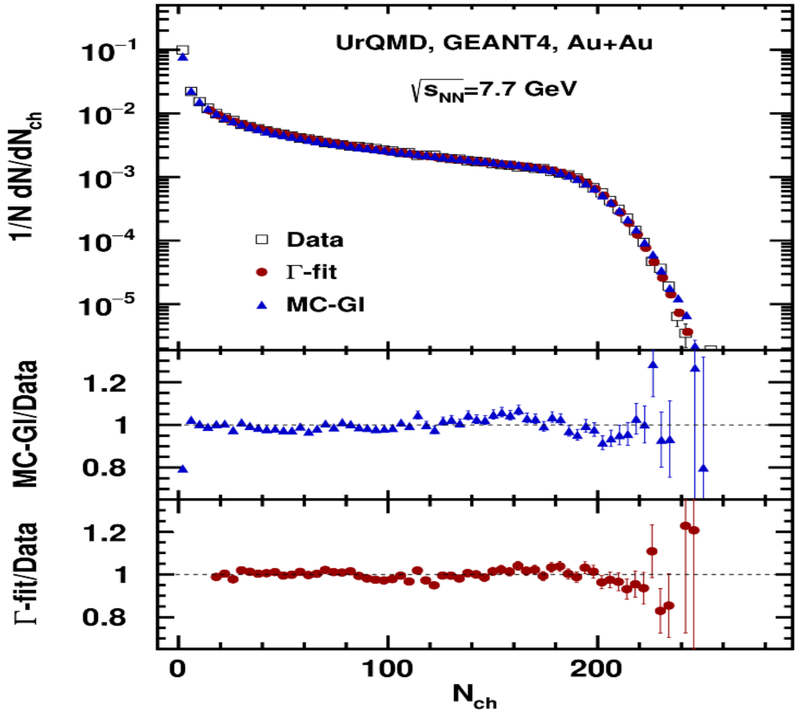
- ✓ MPD collaboration is steadily coming to final integration of the detector and first data taking on the beams from NICA
- ✓ Physics program for the first years of MPD data taking is formulated and the first physics paper was recently published
- ✓ MPD will provide unique opportunity for investigating properties of nuclear matter at maximal densities to search for phase transition and the Critical Point
- ✓ First operations of the MPD detector are expected at the end of 2023 with cosmic studies
- ✓ First BiBi beam at the NICA complex is expected at 2024

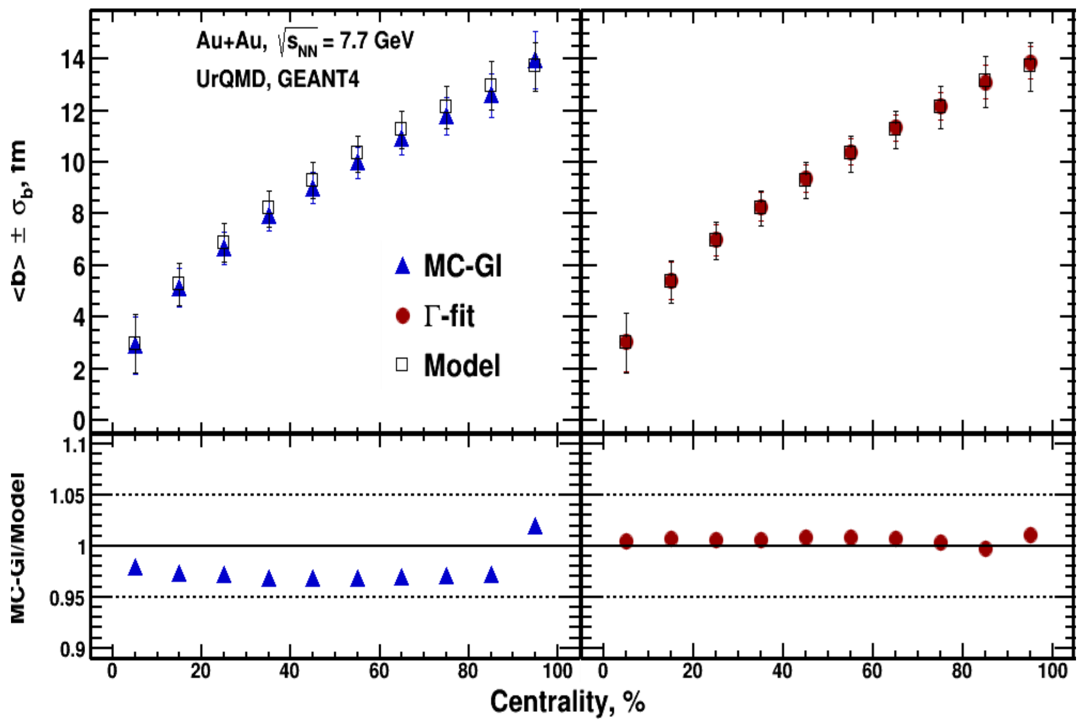
Backup slides

Centrality studies by TPC

AuAu@7.7 GeV (UrQMD), reconstructed data

MC Glauber (MC-Gl) and **Bayesian inversion method (Γ-fit)** methods for extraction of b



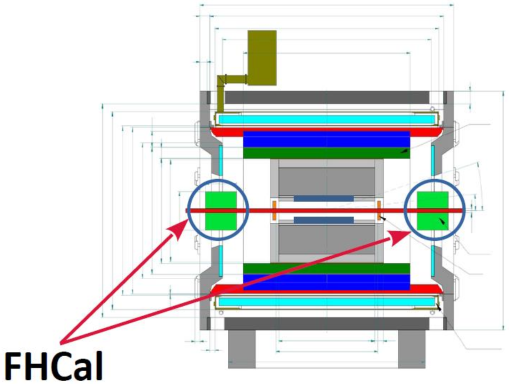


- ➢ Comparable results with PHSD and SMASH event generators at different energies → robust method
- ➢ Centrality estimation consistent with STAR → good for cross-checks between the experiments
- ➢ Centrality measurements are possible in a wide |z-vertex| < 120 cm range

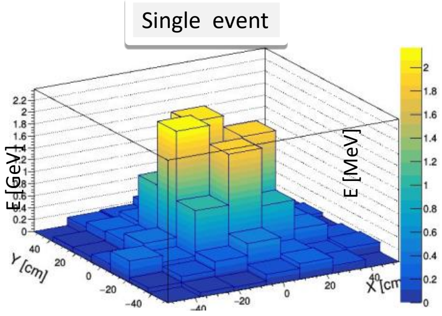
[1] Centrality Determination in Heavy-ion Collisions with MPD Detector at NICA, Acta Physica Polonica B 14 (2021) 3, 503-506
[2] Relating Charged Particle Multiplicity to Impact Parameter in Heavy-Ion Collisions at NICA Energies, Particles 4 (2021) 2, 275-287

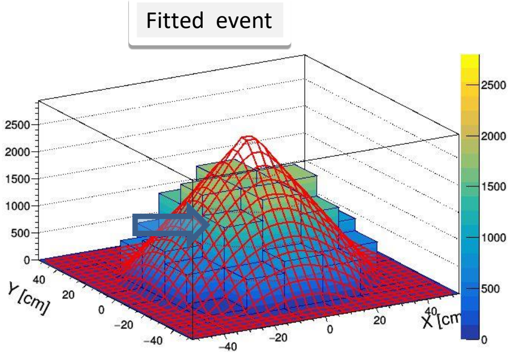
Centrality and reaction plane by FHCAL

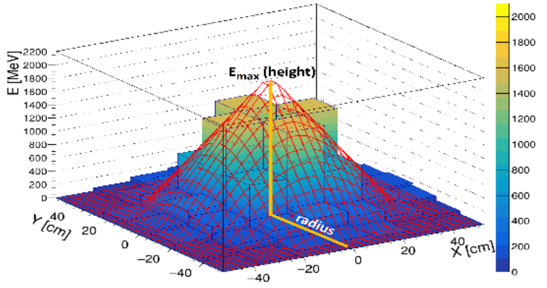
- FHCAL is a hadronic calorimeter, ~ 1 m^2, 45 segments 15x15 cm^2, $2 < |\eta| < 5$

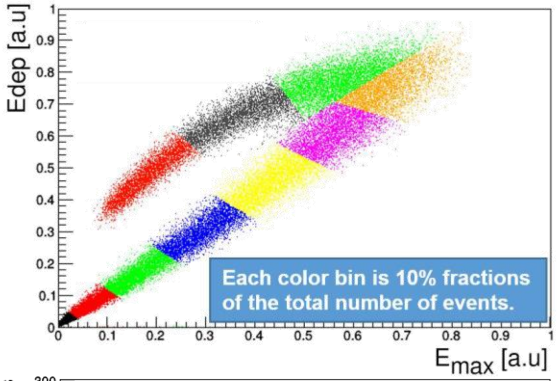


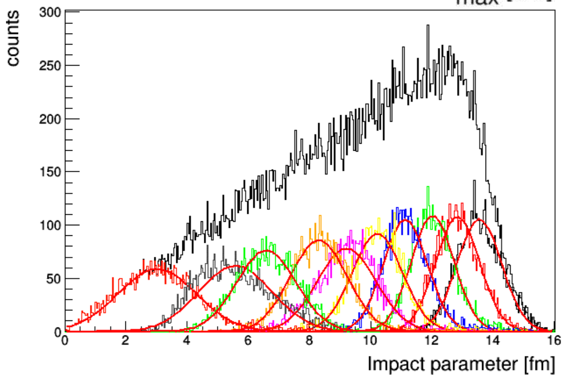
Two-dimensional fit of the energy depositions in FHCAL

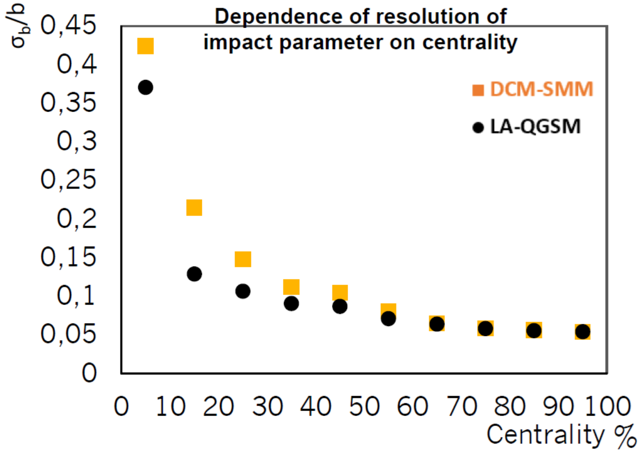


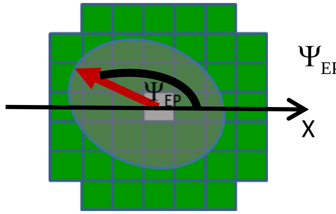






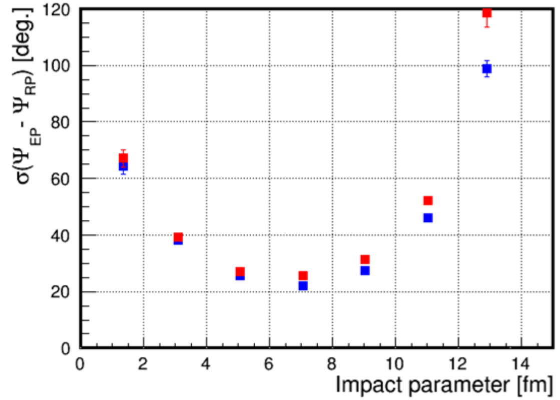






$$\Psi_{EP} = acrtg \frac{\sum E_i \sin(\varphi_i)}{\sum E_i \cos(\varphi_i)}$$

Reaction plane resolution



Phys.Part.Nucl. 52 (2021) 4, 578-583
AIP Conf.Proc. 2377 (2021) 1, 030015