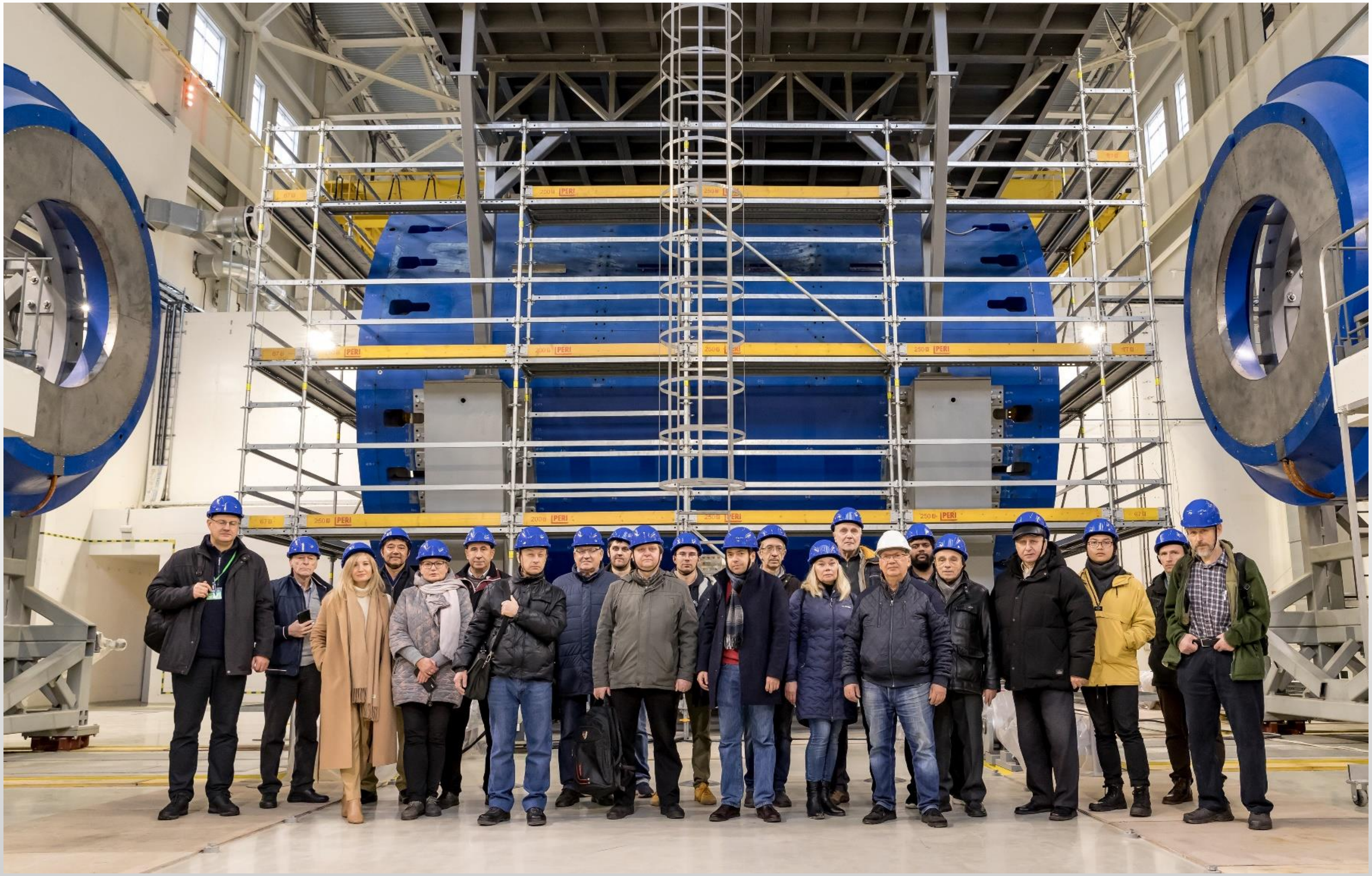
Nuclotron based Ion Colider fAcility

Участие ОФВЭ в эксперименте MPD-NICA

Михаил Малаев



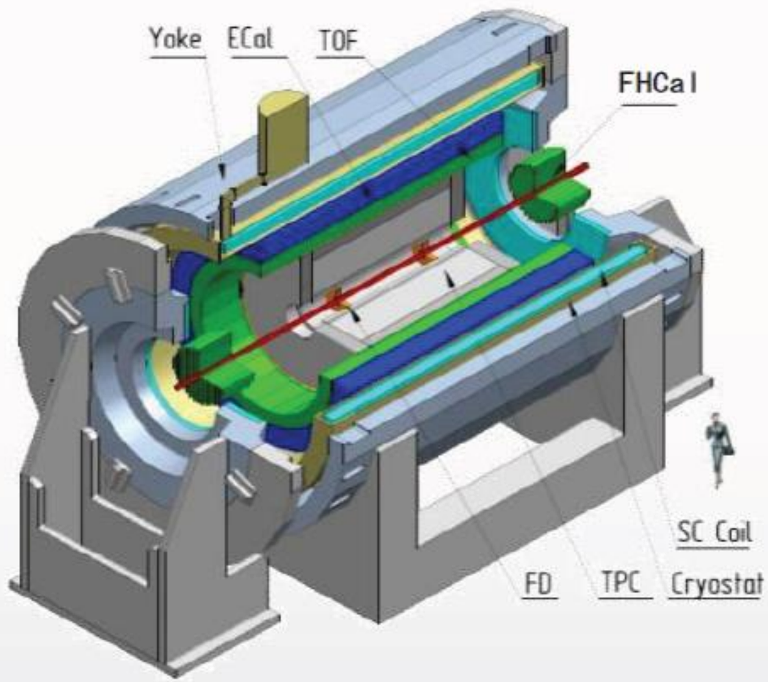
Multi-**P**urpose **D**etector (MPD) Collaboration

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

10** Countries, **>450** participants, **33** 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**;*
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*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**;*
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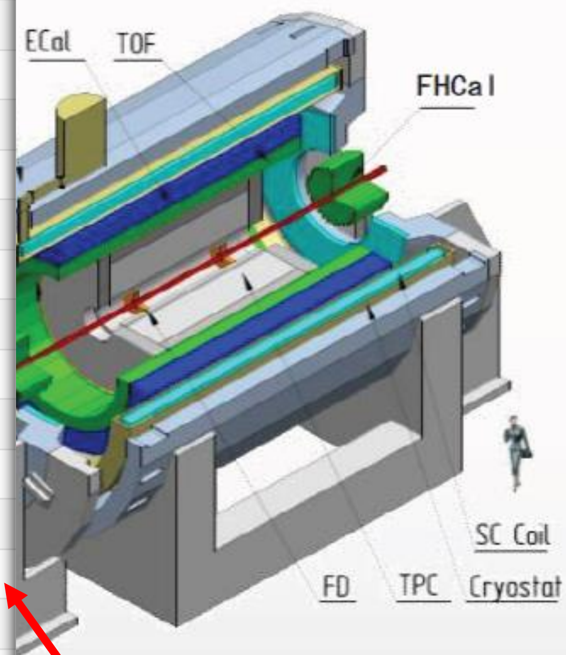
*...tion was established in **2018***
...and operate the detector



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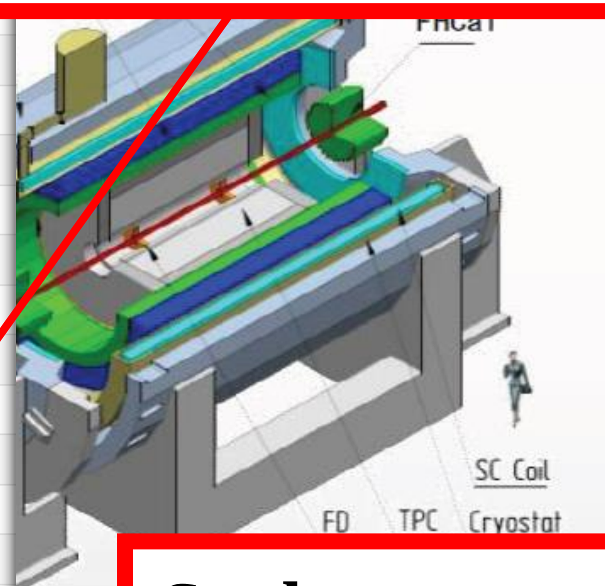
Institutional Board member



Spokesperson

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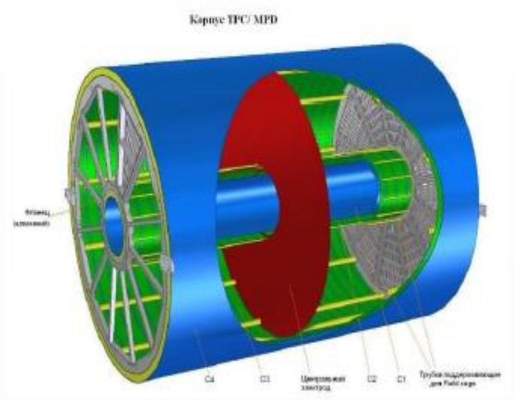
*Pavol Jozef Šafárik University, Košice, **Slovakia***

TPC gas system



length	*340 см*
outer Radii	*140 см*
inner Radii	*27 см*
gas	*90%Ar+10%CH_4*
drift velocity	*5.45 см / μs;*
drift time	*< 30 μs;*
# R-O chamb.	*12 + 12*
# pads/ chan.	***95 232***
max rate	*< 7kGz (L= 10^{27})*

TPC MPD gas system was designed in 2014 and assembled at PNPI in 2016. It provides (Ar + 10% Methane) gas mixture to the TPC detector at the correct differential pressure (2mbar). The system operates nominally as a closed circuit gas system with the majority of gas recirculation through the detector. The TPC MPD gas system is the first system designed in our laboratory with two recirculation circuits. The inner circuit provides fast gas mixture exchange in the detector at large flowrate. The outer one provides quality control of the mixture, fresh gas supply, pressure stabilization etc. The slow control for the gas system is based on single DAQ32 module.

https://lkst.pnpi.nw.ru/projects/nica/tpc/

MPD-ECAL, tasks and goals

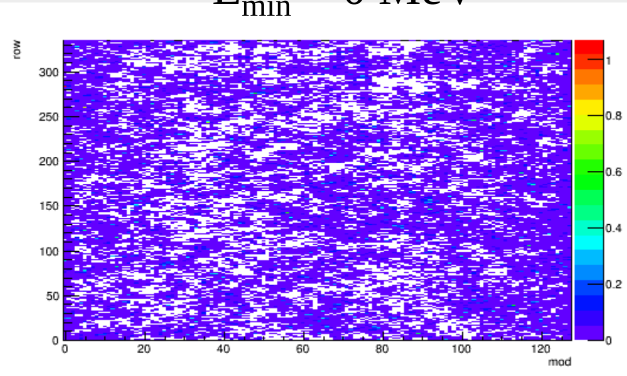
- Compared to calorimeters in other HI collider experiments at RHIC/LHC:
  - ✓ softer signals → bad for resolution, $\sigma(E) \sim 1/\sqrt{E}$
  - ✓ smaller radius, 2 m vs. ~ 5 m → higher signal density and higher importance of spatial resolution

TASKS

- Correct reconstruction of electromagnetic signals
- Algorithms of electromagnetic signals selection development
- Friendly interface for users
- Estimation of ECAL capabilities for physics studies

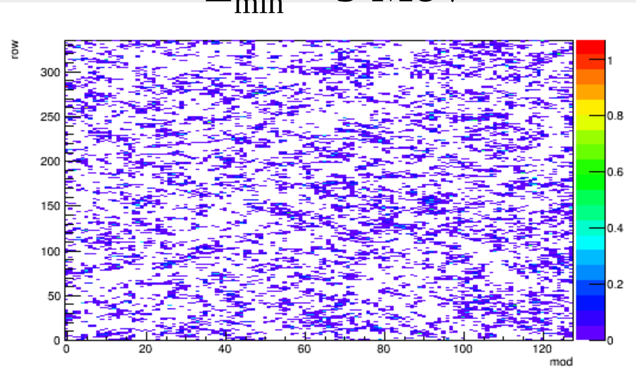
- Optimistic/realistic estimate of the minimum tower threshold is $E_{min} \sim 5$ MeV
- Occupancy is ~ 27% → comparable to that in higher energy experiments

$E_{min} = 0$ MeV



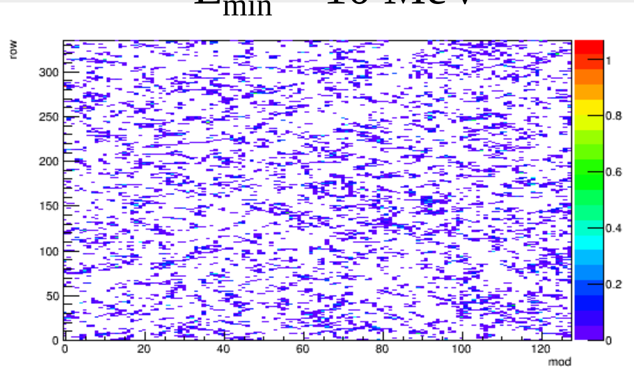
occupancy ~ 0.72

$E_{min} = 5$ MeV



occupancy ~ 0.27

$E_{min} = 10$ MeV



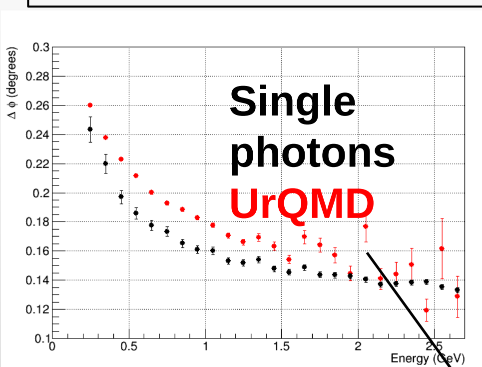
occupancy ~ 0.20

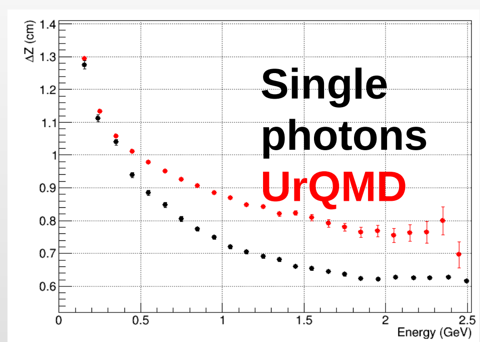
MPD-ECAL resolution for photons

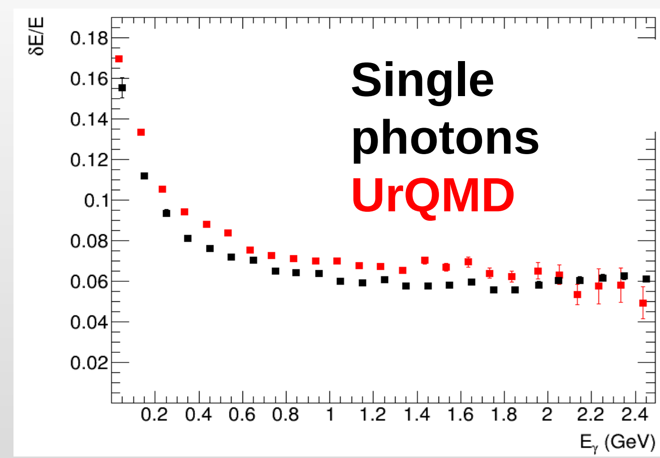
UrQMD, minbias AuAu@11, realistic vertex distribution, selected photons

- Spatial resolution is energy dependent
- Comparable for single photons and photons in high-multiplicity events
- Achieved resolution is good enough → does not significantly affect: (1) the mass resolution for neutral mesons in the expected p_T range of measurements; (2) width of track-to-cluster and cluster-to-track matching

- Energy resolution is energy dependent, $\delta E/E \sim 1/\sqrt{E}$
- Energy resolution defines width of the reconstructed π^0/η, E/p peaks
- There is still potential for improvement (with better tower-by-tower calibration)







~ 180 cm * tan(0.15 degrees) = 0.5 cm

MPD physics program

G. Feofilov, A. Aparin

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

V. Riabov, 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

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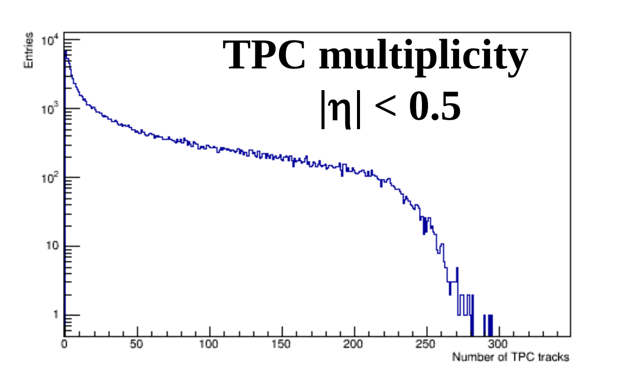
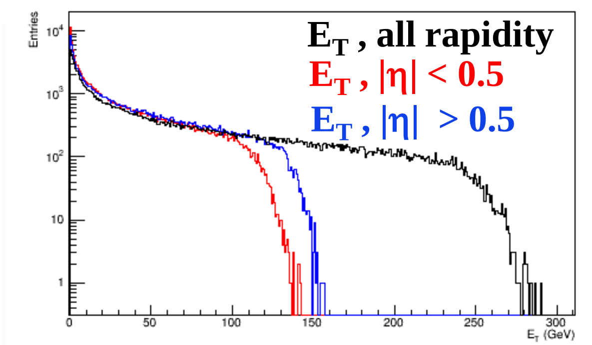
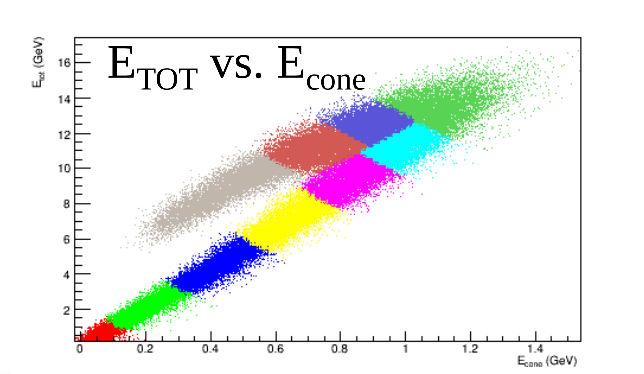
Centrality categorization (DCM-QGSM-SMM)

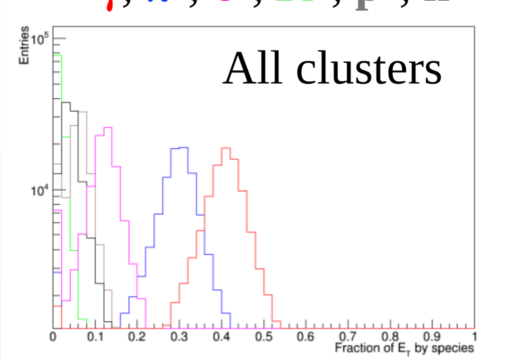
❖Use TPC multiplicity, transverse energy E_T and FHCAL energy to determine event centrality

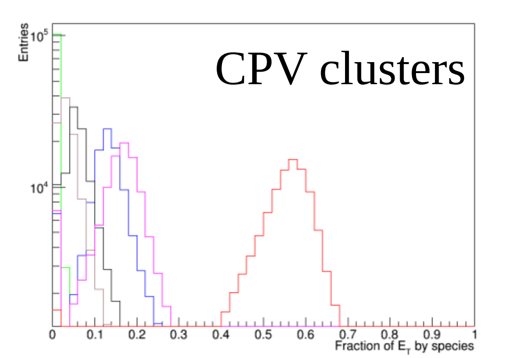




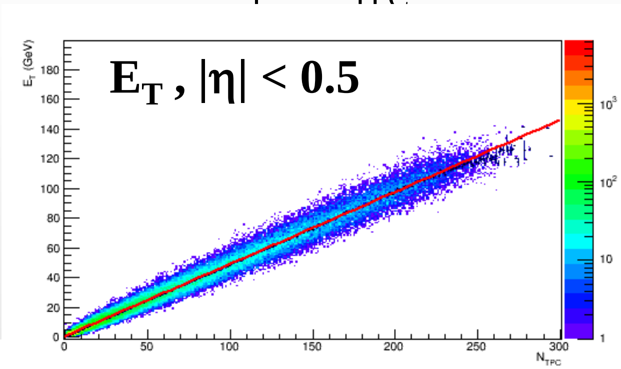


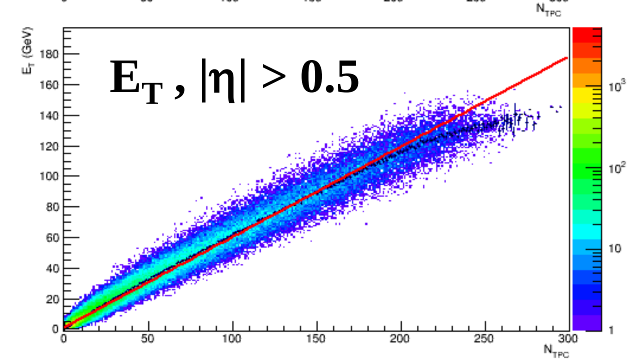
γ, $\pi^{\pm}$, $e^{\pm}$, $K^{\pm}$, $p^{\pm}$, n



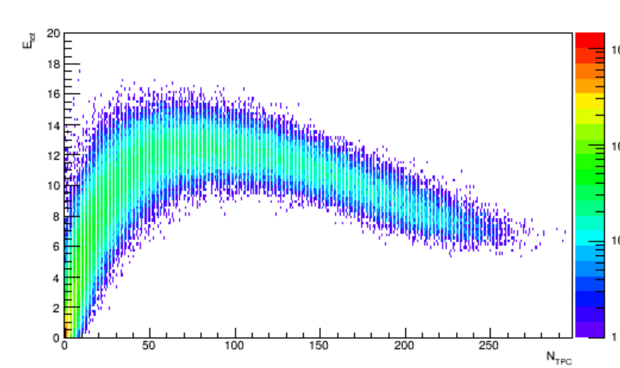


$E_T \sim N_{TPC}$





E_{FHCAL} vs. N_{TPC} → ambiguity



Short-lived resonances

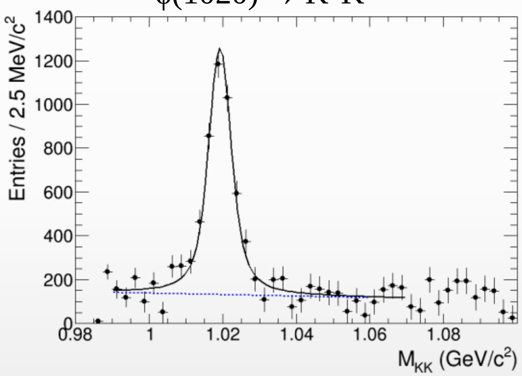
- Resonances probe reaction dynamics and particle production mechanisms vs. system size and $\sqrt{s_{NN}}$:
  - ✓ hadron chemistry and strangeness production, lifetime and properties of the hadronic phase, spin alignment of vector mesons, flow etc.

increasing lifetime ⟶

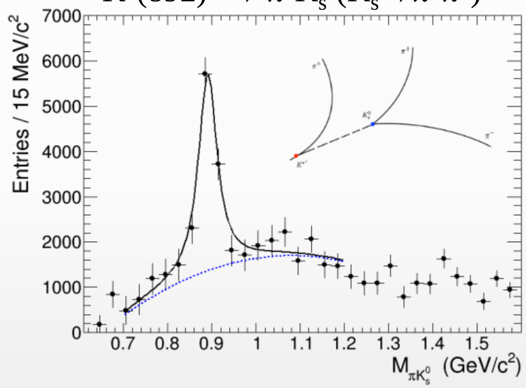
	$\rho(770)$	$K^*(892)$	$\Sigma(1385)$	$\Lambda(1520)$	$\Xi(1530)$	$\phi(1020)$
$c\tau$ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

- AuAu@11 GeV (UrQMD) after mixed-event background subtraction:

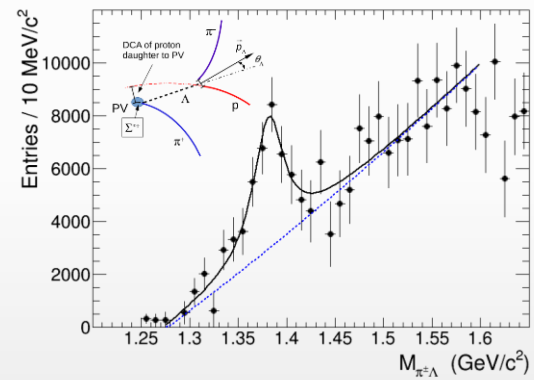
$\phi(1020) \to K^+K^-$



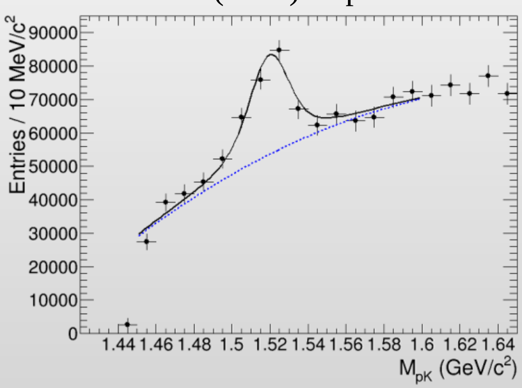
$K^*(892)^\pm \to \pi^\pm K_s$ ($K_s \to \pi^+\pi^+$)



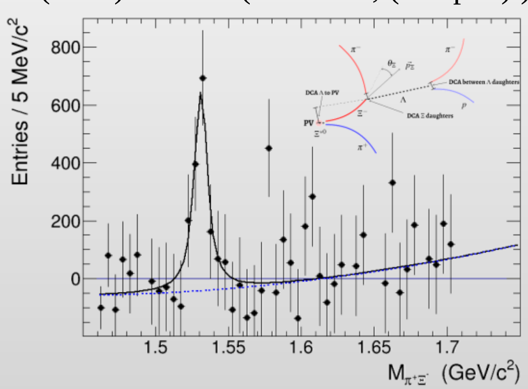
$\Sigma(1385)^\pm \to \pi^\pm\Lambda$ ($\Lambda \to p\pi$)



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



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

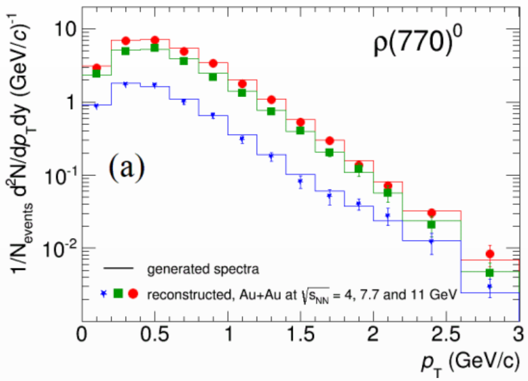


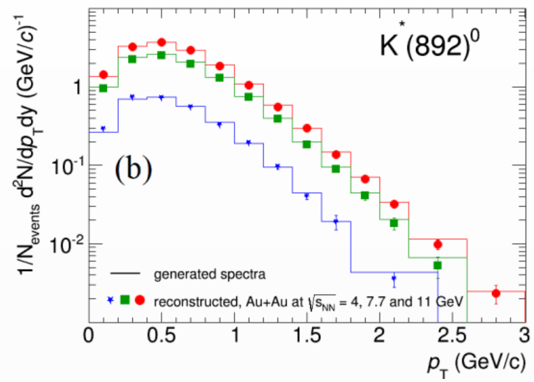
✓ MPD is capable of reconstruction the resonance peaks in the invariant mass distributions using combined charged hadron identification in the TPC and TOF

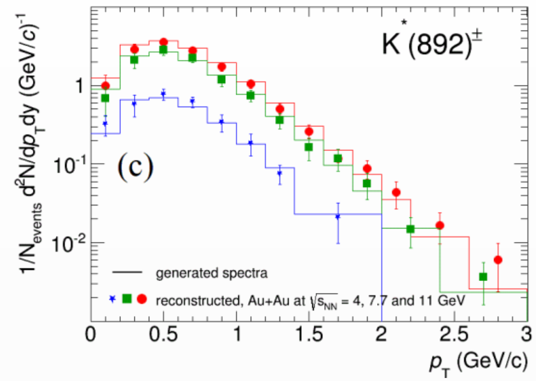
✓ decays with weakly decaying daughters require additional second vertex and topology cuts for reconstruction

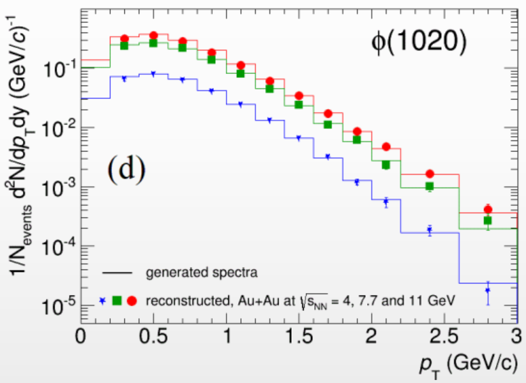
MC closure tests

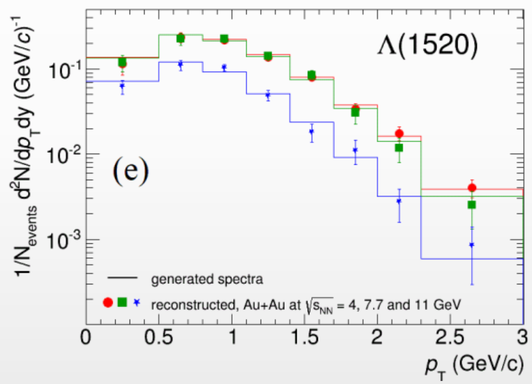
- Full chain simulation and reconstruction, p_T ranges are limited by the possibility to extract signals, $|y| < 1$

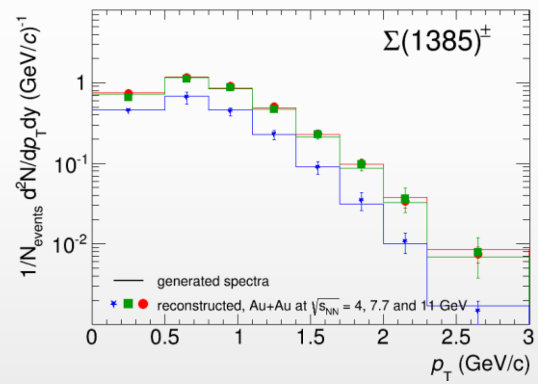


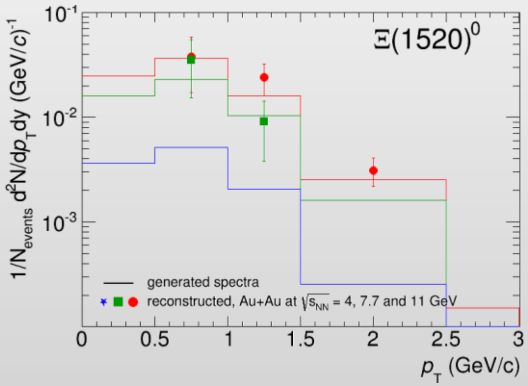








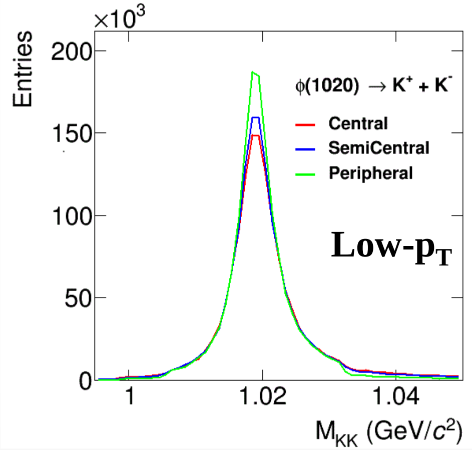


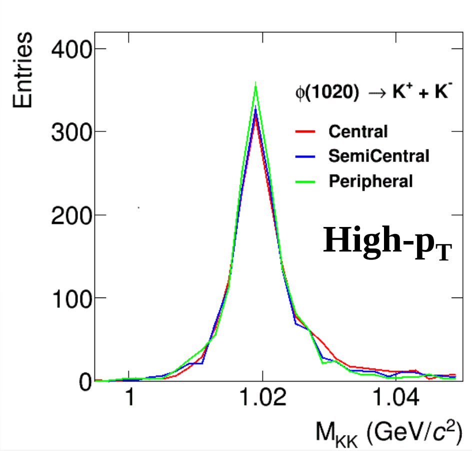


- Reconstructed spectra match the generated ones within uncertainties
- First measurements for resonances will be possible with accumulation of ~ 10^7 A+A events
- Measurements are possible starting from ~ zero momentum → sample most of the yield, sensitive to possible modifications
- Measurements of $\Xi(1530)^0$ are very statistics hungry

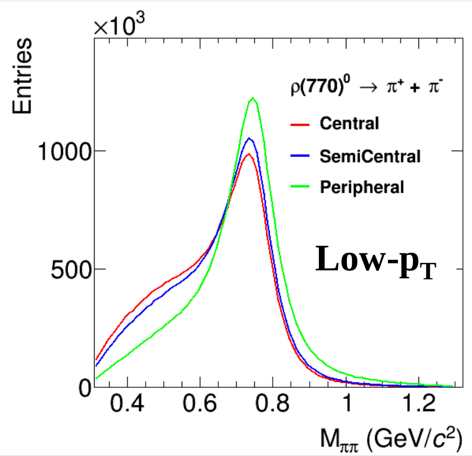
Resonances in AuAu@11GeV, UrQMD

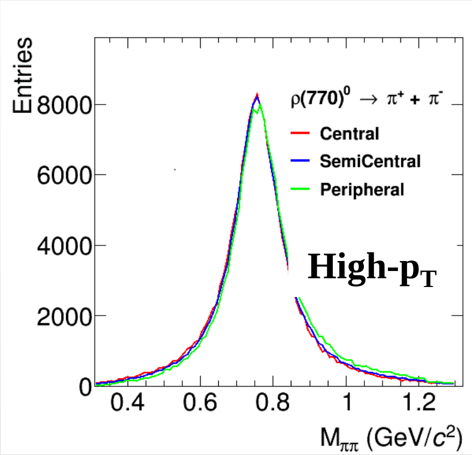
- Resonances are decayed by UrQMD, daughters participate in elastic and inelastic scattering
- Resonance are reconstructed by invariant mass method according to decay channels
- $\phi \to K^+K^-$ ($c\tau$ ~ 45 fm/c): modest line shape modifications in central AuAu@11 at low p_T

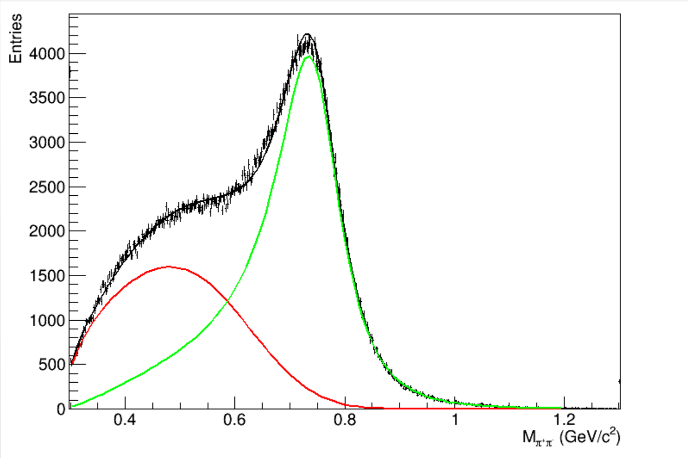




- $\rho(770)^0 \to \pi^+\pi^-$ ($c\tau$ ~ 1.3 fm/c): significant line shape modifications in central AuAu@11 at low p_T

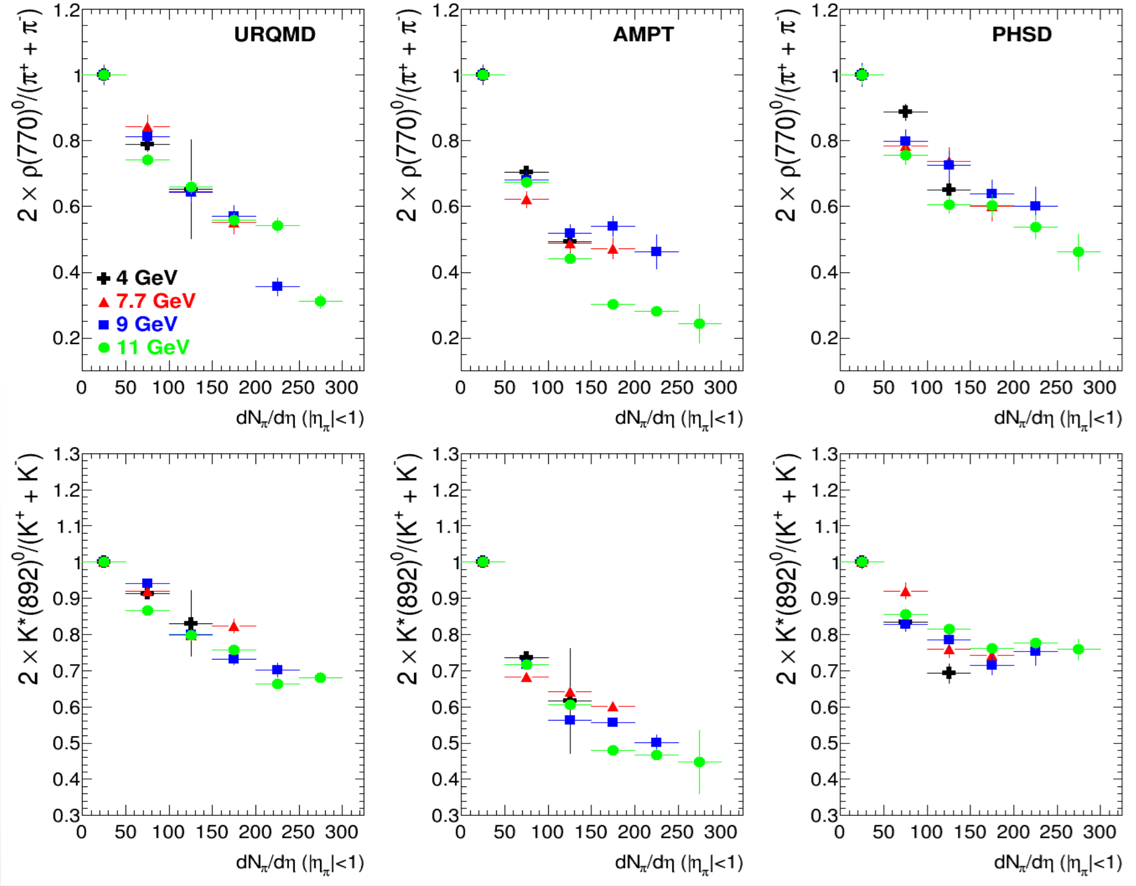


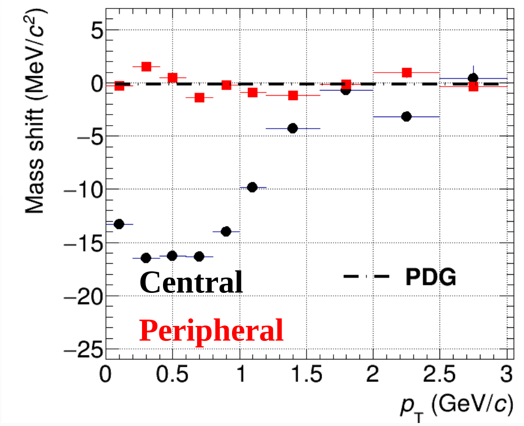


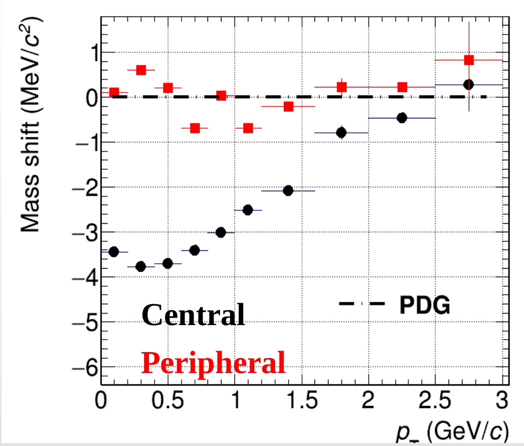


Modifications

- ❖ Models with hadronic cascades (UrQMD, PHSD, AMPT)
- ❖ Ratios for two shortest-lived resonances (ρ, $K^*(892)$) are shown normalized to most peripheral collisions





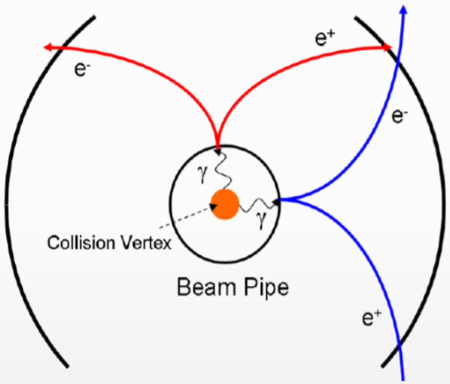


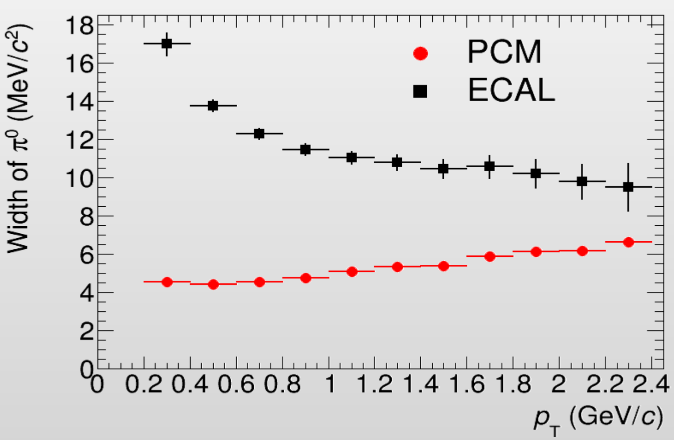
- ➢ Models predict suppression of ρ/π and K^*/K ratios in Au+Au@4-11, resonances with small cτ
- ➢ Suppression depends on the final state multiplicity rather than on collision energy
- ➢ Yield losses occur at low momentum as has been demonstrated before
- ➢ In peripheral collisions, the peak models return masses and widths as measured in vacuum
- ➢ In central collisions, the masses are measured smaller

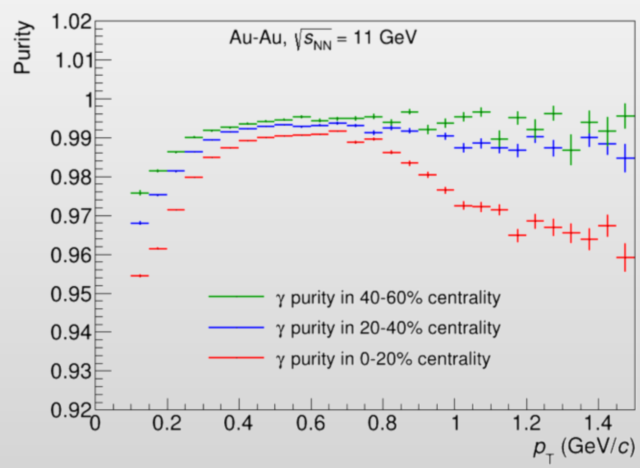
Reconstruction of photons

- Electromagnetic calorimeter ECAL:
  - ✓ dedicated detector to measure electromagnetic signals like $\gamma/e^{\pm}$ (energy, position, time of flight)
  - ✓ energy resolution ~ $1/\sqrt{E}$, better suited for high-E signals
  - ✓ suffer from large hadronic background at low energies
  - ✓ shower shape and time-of-flight selections for identification of photons

- Photon conversion method (PCM) :
  - ✓ photons are identified as e^+e^- pairs with small invariant mass after some second vertex topology, single track and pair selection cuts optimized for better S/B ratio
  - ✓ energy resolution ~ E, better suited for low-E
  - ✓ typically provides very high photon purity
  - ✓ suffer from small γ conversion probability



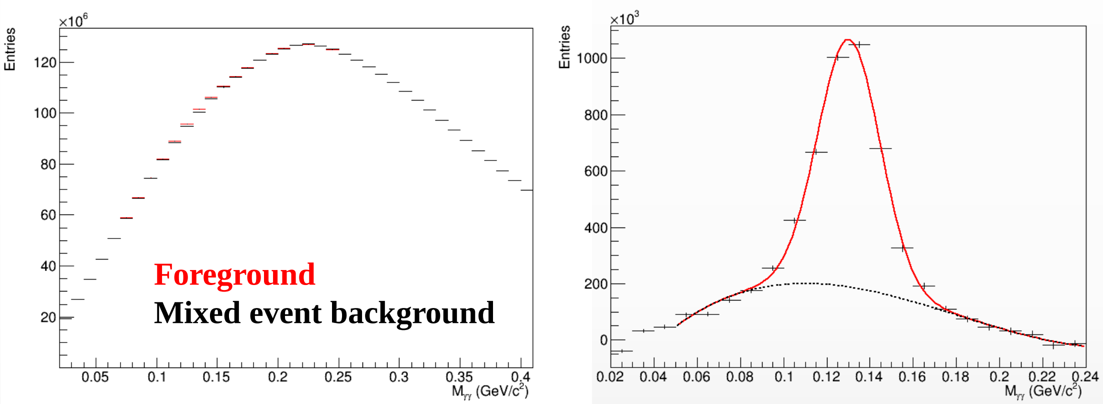




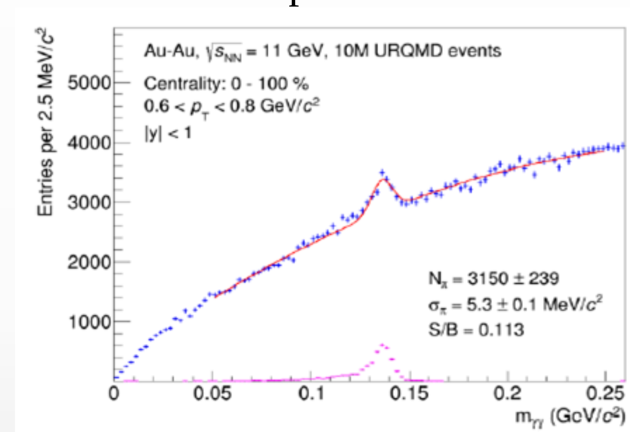
Neutral mesons

- Extend p_T range of charged particle measurements, various species (η, ω, η', etc.)
- Neutral mesons are the main source of background for direct photon and (di)electron measurements
- AuAu@11 GeV (UrQMD): realistic ECAL reconstruction and analysis in high multiplicity environment + photon conversion method

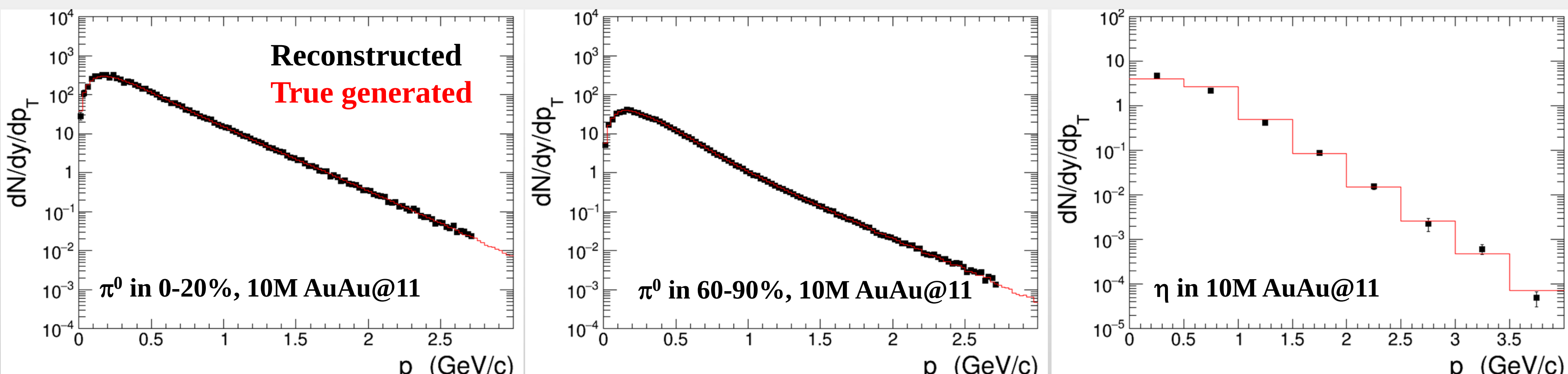
Photon pairs in the ECAL



Photon pairs with PCM

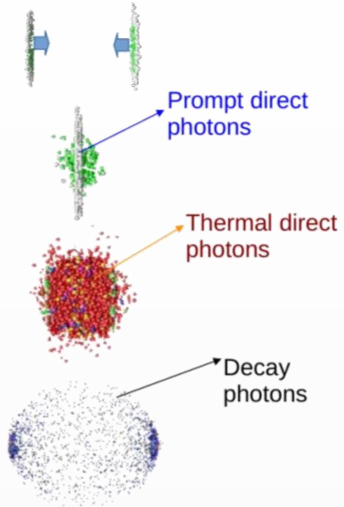


- π^0 and η MC closure tests: reconstructed spectra match the generated ones

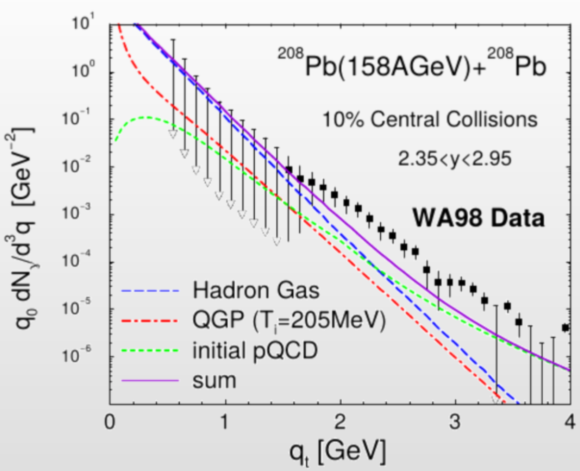


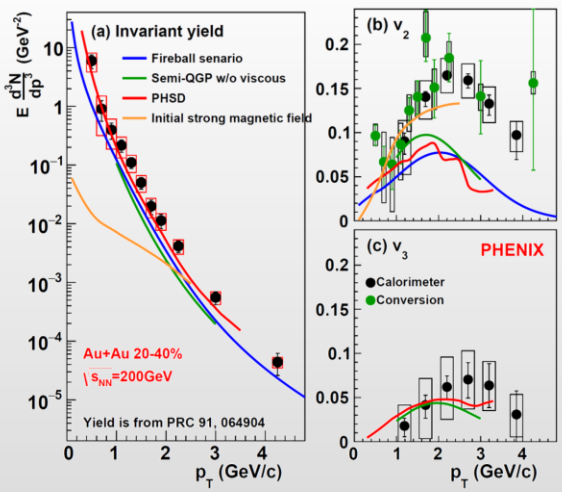
Direct photons

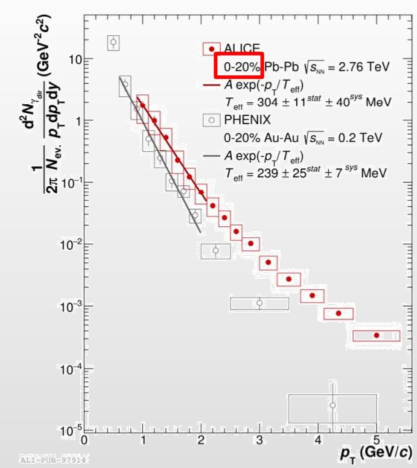
- Direct photons – photons not from hadronic decays.
- Produced throughout the system evolution (thermal + prompt) :
  - ✓ penetrating probe
  - ✓ low-E - most direct estimation of the effective system temperature
  - ✓ high-E - hard scattering probe
- Direct photons in A-A collisions:
  - ✓ LHC, PbPb @ 2.76 and 5 TeV
  - ✓ RHIC, Au-Au(CuCu) @ 62-200 GeV
  - ✓ SPS, PbPb @ 17.2 GeV
- No measurements at NICA energies: yields and flow vs. p_T and centrality



Phys.Rev. C94 (2016) no.6, 064901







Simultaneous description of the large photon yields and flow is a challenge for theoretical models at RHIC and the LHC → "direct photon puzzle"

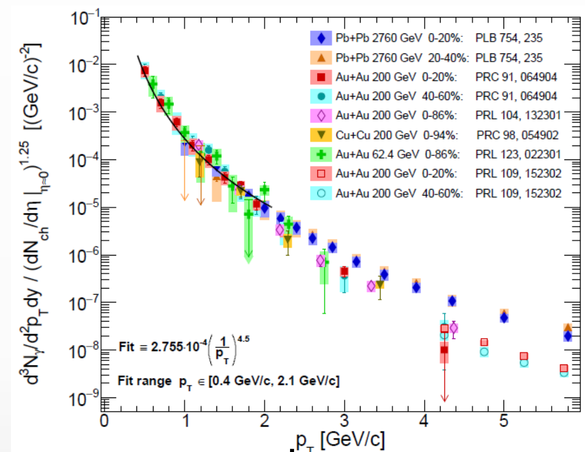
Direct photon yields at NICA

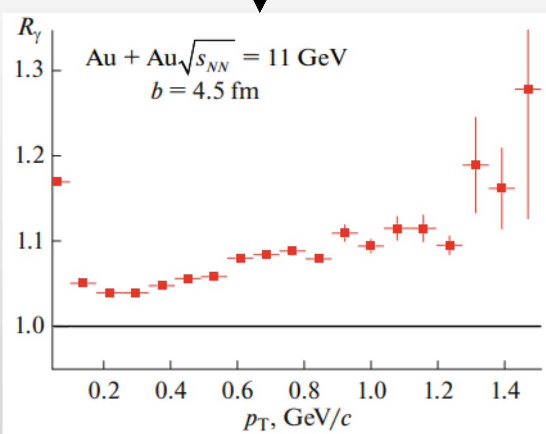
Estimation of the direct photon yields @NICA

model calculations

empirical scaling

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

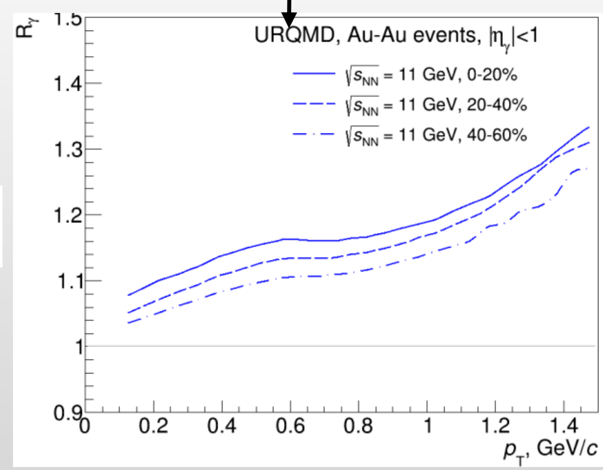




Physics of Particles and Nuclei, 2021, Vol. 52, No. 4, pp. 681–685

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

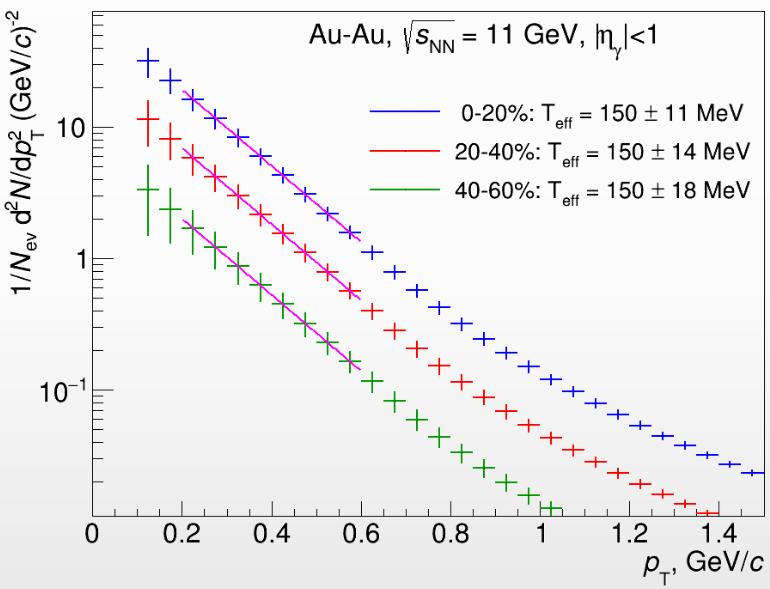
$$\gamma_{\rm direct} = \left(1 - \frac{1}{R_\gamma}\right) \cdot \gamma_{\rm inc}$$



- Non-zero direct photon yields are predicted, Rγ ~ 1.05 – 1.15

Prospects for the MPD

- Photons can be measured in the ECAL or in the tracking system as e^+e^- conversion pairs (PCM)
- Main sources of systematic uncertainties for direct photons:
  - ✓ detector material budget → conversion probability
  - ✓ π^0 reconstruction efficiency
  - ✓ p_T-shapes of π^0 and η production spectra



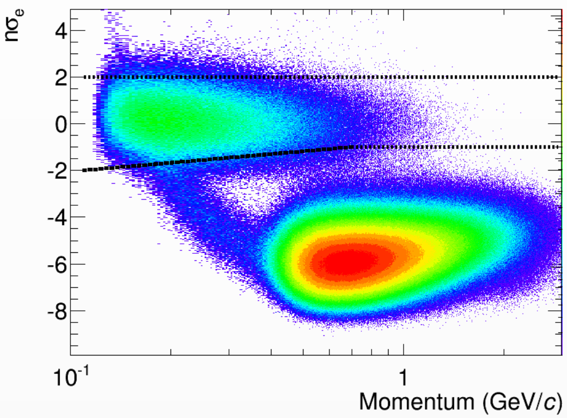
- ECAL and PCM for photon reconstruction and measurement of neutral mesons (background)
- With Rγ ~ 1.1 and δRγ/Rγ ~ 3% → uncertainty of T_{eff} ~ 10%
- Development of reconstruction techniques and estimation of needed statistics are in progress

→ MPD can provide unique measurements for direct photon production @ NICA energies

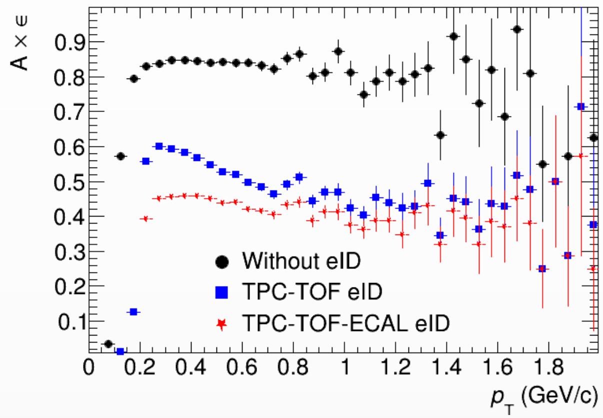
Dielectrons

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

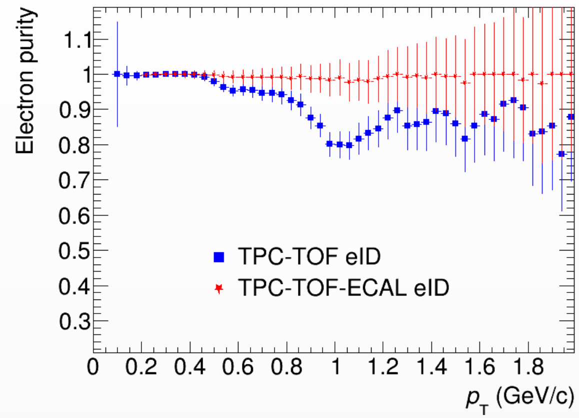
$n\cdot\sigma_e^{TPC}$ with $2\sigma_e$ PID in the TOF

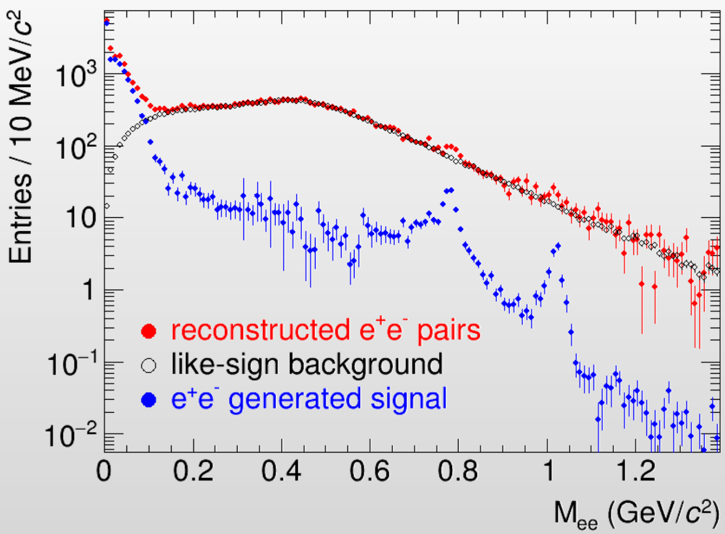


Efficiency of e-track reconstruction



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

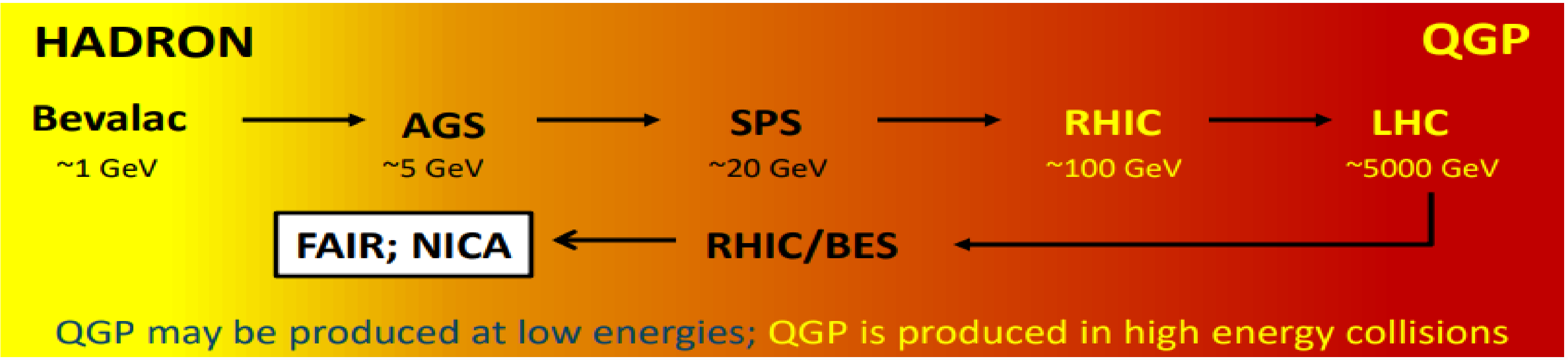
Summary

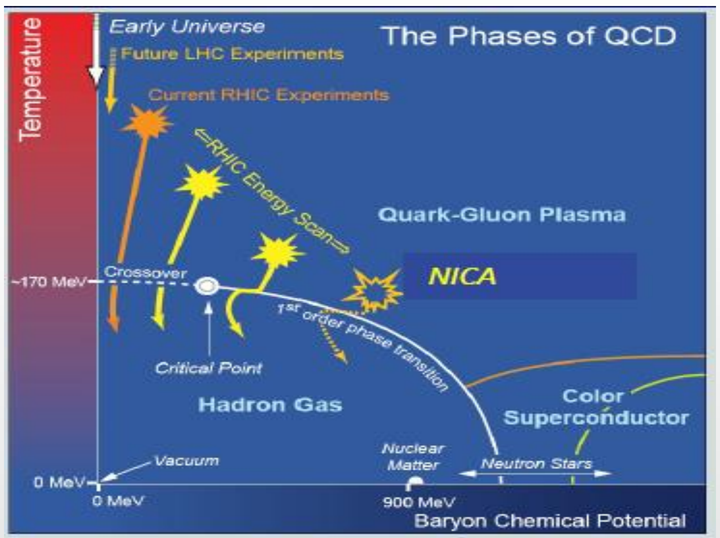
- ❖ Физическая программа эксперимента MPD не окончательная и каждый вклад важен
- ❖ ПИЯФ разработал и построил газовую систему детектора TPC, а также внес значительный вклад в создание программного обеспечения электромагнитного калориметра ECAL
- ❖ Сотрудники ПИЯФ участвуют в работе многих рабочих групп в коллаборации MPD и вносят свой вклад их полученные результаты
- ❖ Новые участники приветствуются!

С НОВЫМ ГОДОМ!

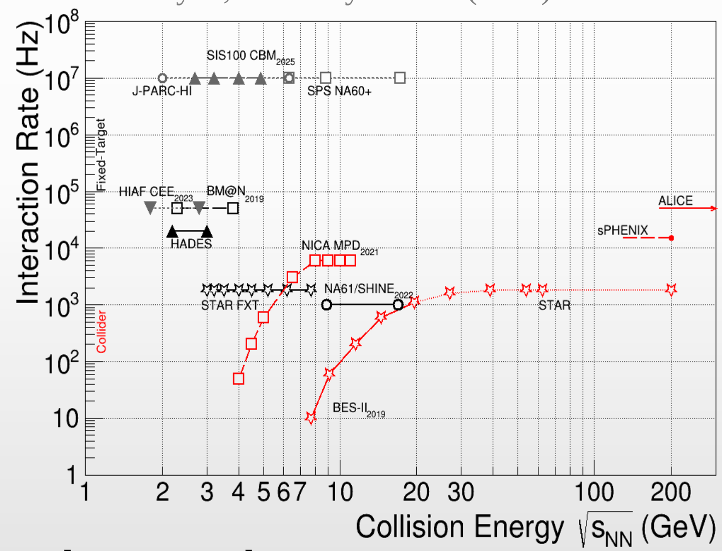
BACKUP

Introduction



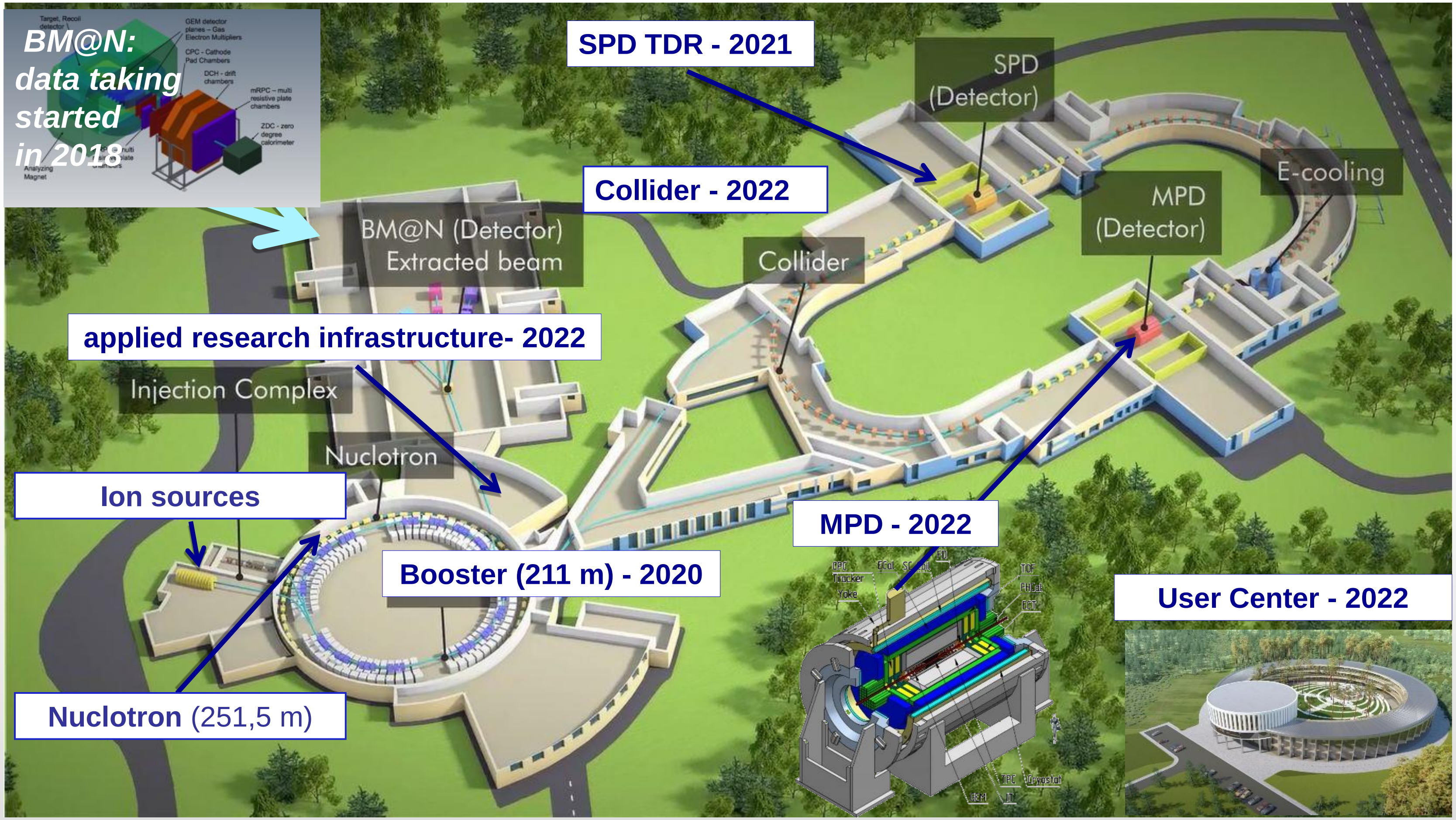


T. Galatyuk, Nucl.Phys. A982 (2019)



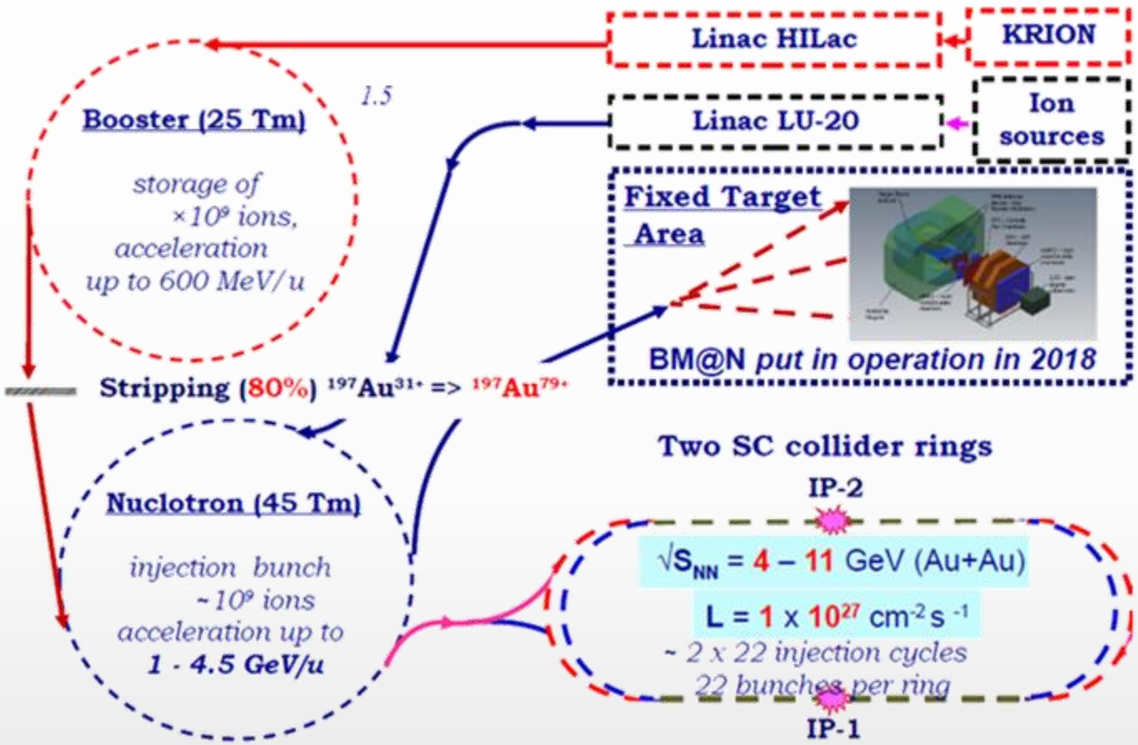
- ❖ Study of the QCD medium at extreme net baryon densities, phase transition at $\rho_c \sim 5\rho_0$
- ❖ Studied in several ongoing and future experiments:
  - ✓ collider experiments: maximum phase space, minimally biased acceptance, free of target parasitic effects
  - ✓ fixed-target experiments: high rate of interactions, easily upgradeable, better vertex-finder for heavy flavor decays

Accelerator Complex in Dubna



- ❖ Budget ~ 500 M$
- ❖ First collisions in MPD – end of 2023

Accelerator Complex in Dubna



❖ Expected limitations in Stage-I:

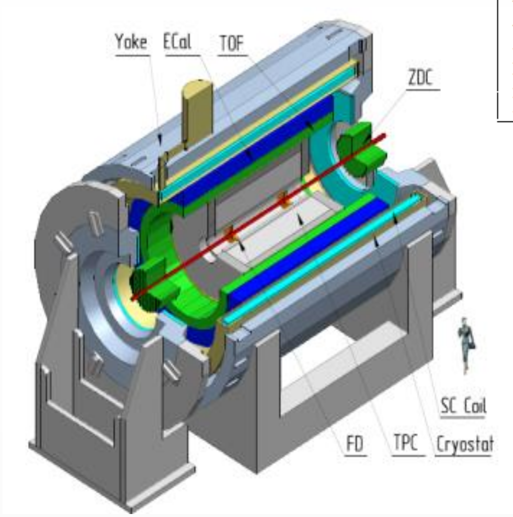
- ✓ without electron cooling in collider, with stochastic cooling, reduced number of RFs → not-optimal beam optics
- ✓ reduced luminosity (~10^{25} is the goal for 2023) → collision rate ~ 100 Hz
- ✓ collision system available with the current sources: C (A=12), N (A=14), Ar (A=40), Fe (A=56), Kr (A=78-86), Xe (A=124-134), Bi (A=209) → start with Bi+Bi @ 9.2 GeV in 2023, Au+Au @ 4-11 GeV to come later

NICA schedule

- Year 2021:
  - ✓ extensive commissioning of Booster
  - ✓ heavy-ion (Fe/Kr/Xe) run of full Booster + Nuclotron setup
- Year 2022:
  - ✓ completion of collider and Nuclotron-to-collider transfer lines
  - ✓ assembly of the MPD detector
- Year 2023:
  - ✓ technical run with Bi+Bi @ 9.2 GeV (7.7 GeV is the second priority) with luminosity ~ 10^{25} $cm^{-2}s^{-1}$
  - ✓ collect ~ 100 M minimum bias events with the MPD to be used for detector alignment, calibration and physics
- Year 2024:
  - ✓ Au+Au beams (source), beam acceleration in collider up to top energy (Au+Au @ 11 GeV)
- Year 2025 and beyond:
  - ✓ reaching design luminosity, system size and collision energy scan by request

Multi-Purpose Detector

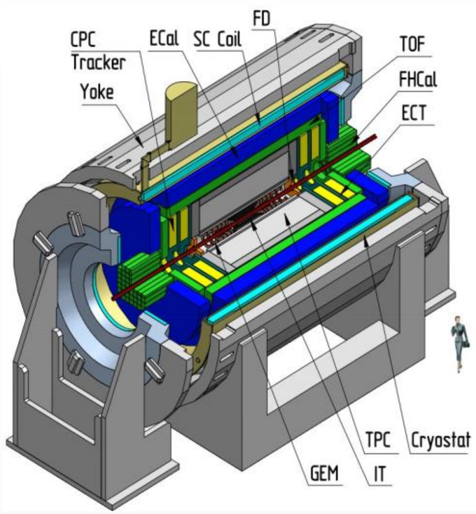
Stage- I



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 ($L = 10^{27}$ $cm^{-2}s^{-1}$)

upgrade

Stage- II



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

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

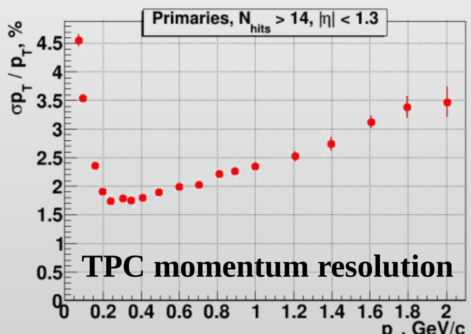
FFD: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$

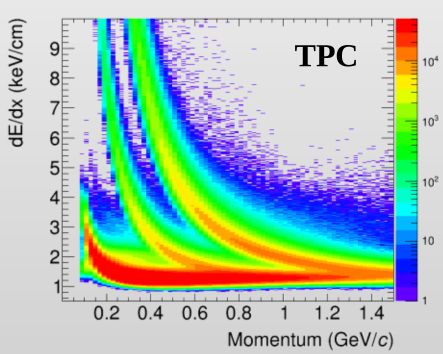
FHCAL: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

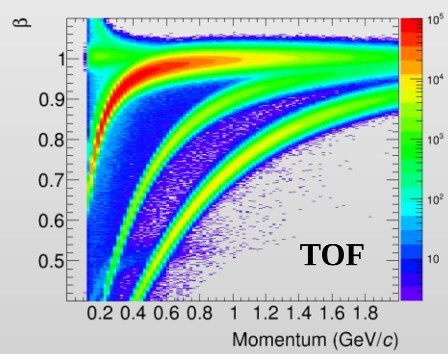
+ ITS (heavy-flavor measurements)

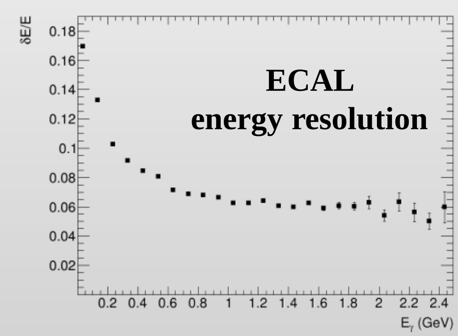
+ forward spectrometers

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

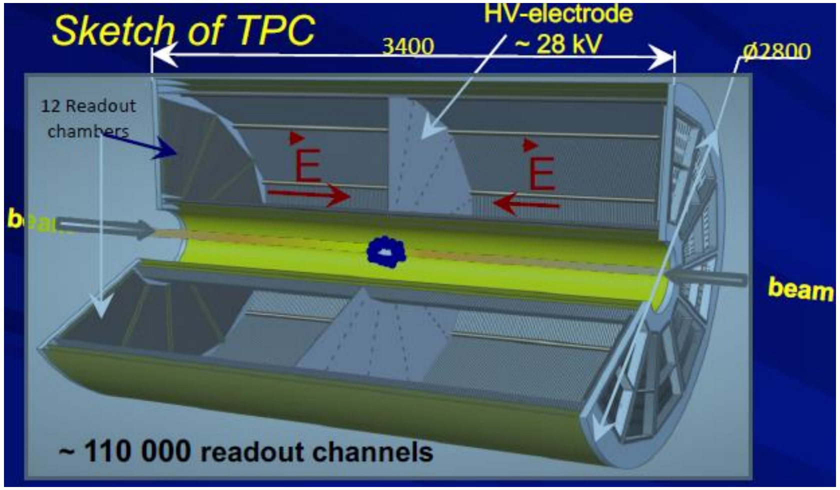




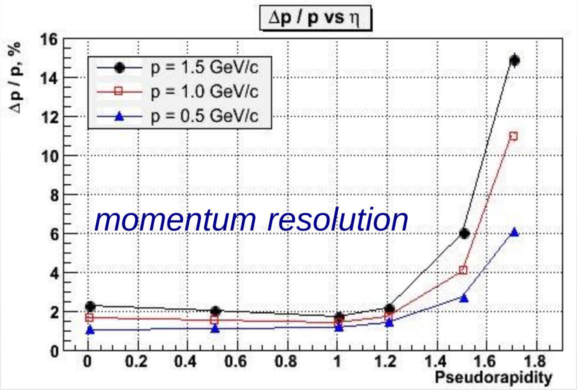


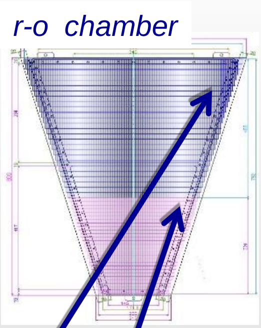


Time Projection Chamber (TPC): main tracker



length	*340 см*
outer Radii	*140 см*
inner Radii	*27 см*
gas	*90%Ar+10%CH_4*
drift velocity	*5.45 см / μs;*
drift time	*< 30 μs;*
# R-O chamb.	*12 + 12*
# pads/ chan.	***95 232***
max rate	*< 7kGz (L= 10^{27})*





FE electronics: **FEC64SAM** –
*dual **SAMPA** card (**ALICE** technology)*

pad structure:
- rows – 53
- large pads 5 × 18 mm^2

Read-Out Chambers (ROCs) are ready and tested (production at JINR)
113 Electronics sets (8%) produced
Two sites (Moscow, Minsk) tested for electronics production
C1-C2 and C3-C4 cylinders assembled
TPC flange under finalization

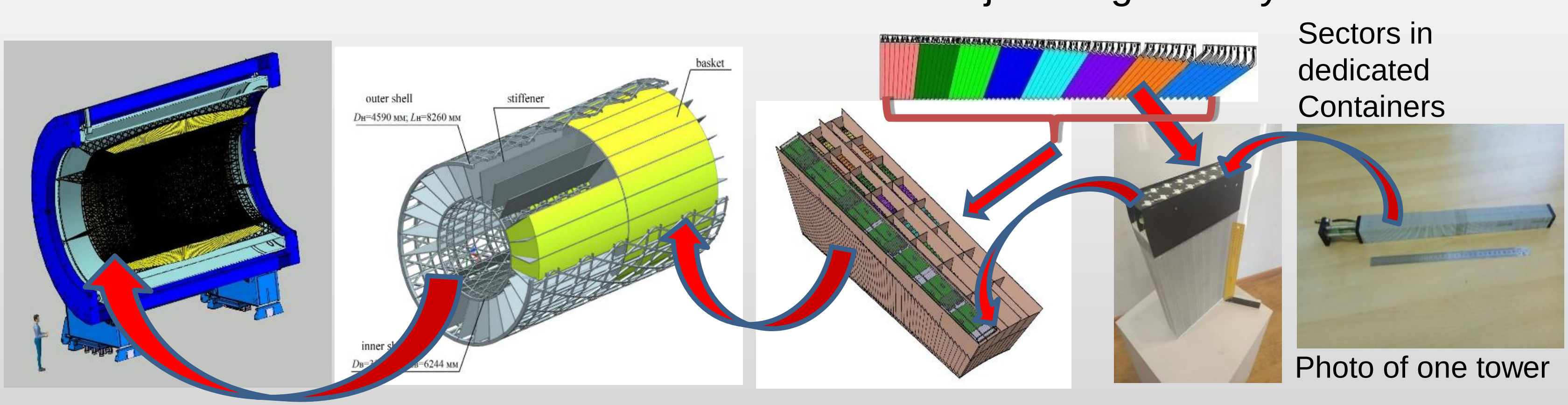
Electromagnetic Calorimeter (ECAL)

- *Pb+Sc "Shashlyk"* — *read-out: WLS fibers + MAPD* — *L ~35 cm (~ 14 X_0)*
- *Segmentation (4x4 cm^2)* — *σ(E) better than 5% @ 1 GeV* — *time resolution ~500 ps*

Barrel ECAL = 38400 ECAL towers (2x25 half-sectors x 6x8 modules/half-sector x 16 towers/module)

So far ~300 modules (16 towers each) = 3 sectors are produced
Another 3 sectors are planned to be completed by May 2022
Chinese collaborators will produce 8 sectors by the end of 2022
25% of all modules are produced by JINR (production area in Protvino) 75% produced in China, currently funding is secured for approx. 25%

Projective geometry



MPD-ECAL, tasks and goals

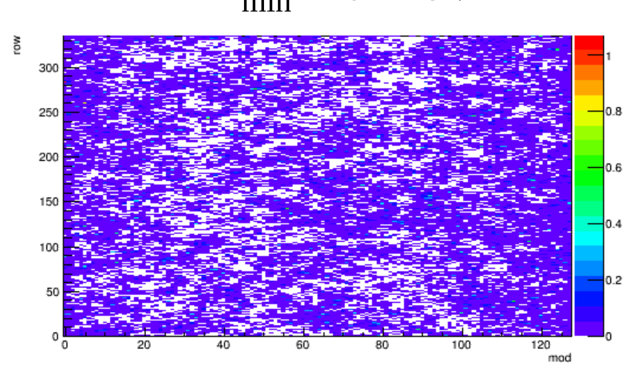
- Correct reconstruction of electromagnetic signals:
  - ✓ Unfolding of merged clusters
  - ✓ Cluster energy and coordinate correction (depth, hade)
  - ✓ Distance to the closest track (dphi, dz + track identifier)
  - ✓ MC contributors
  - ✓ Adequate performance (<20% of total event processing time)
- Algorithms of electromagnetic signals selection development:
  - ✓ Shower shape, comparison with expected shape
  - ✓ Cluster elliptic shape analysis
  - ✓ Matching parametrization vs. p_T, charge …
- Friendly interface for users:
  - ✓ Documentation and examples hot to use developed software
  - ✓ Recommendations on the methods for signal selection
- Estimation of ECAL capabilities for physics studies:
  - ✓ photons, mesons, (di)leptons and so on.

MPD-ECAL, operation conditions

- Compared to calorimeters in other HI collider experiments at RHIC/LHC:
  - ✓ softer signals → bad for resolution, $\sigma(E) \sim 1/\sqrt{E}$
  - ✓ smaller radius, 2 m vs. ~ 5 m → higher signal density and higher importance of spatial resolution

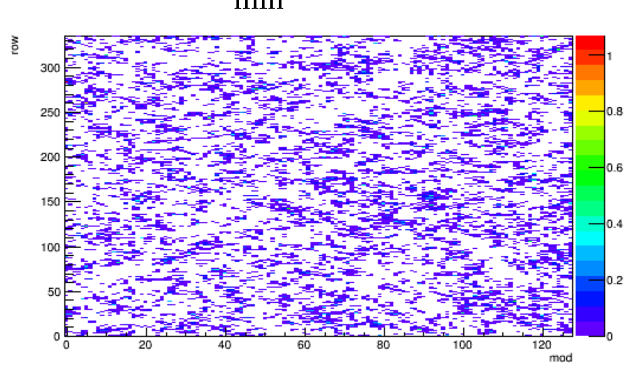
- UrQMD, AuAu@11, b ~ 1 fm → most central collisions
- Optimistic/realistic estimate of the minimum tower threshold is E_{min} ~ 5 MeV
- Occupancy is ~ 27% → comparable to that in higher energy experiments

E_{min} = 0 MeV



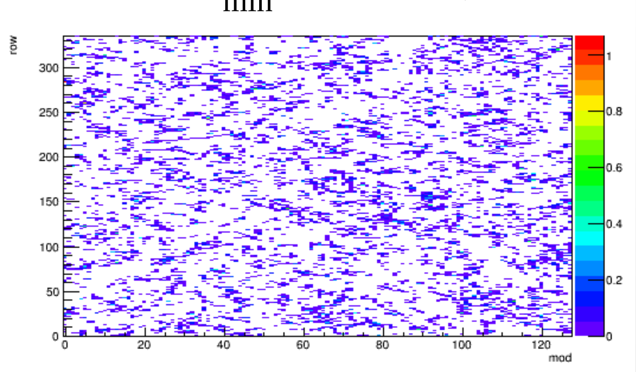
occupancy ~ 0.72

E_{min} = 5 MeV



occupancy ~ 0.27

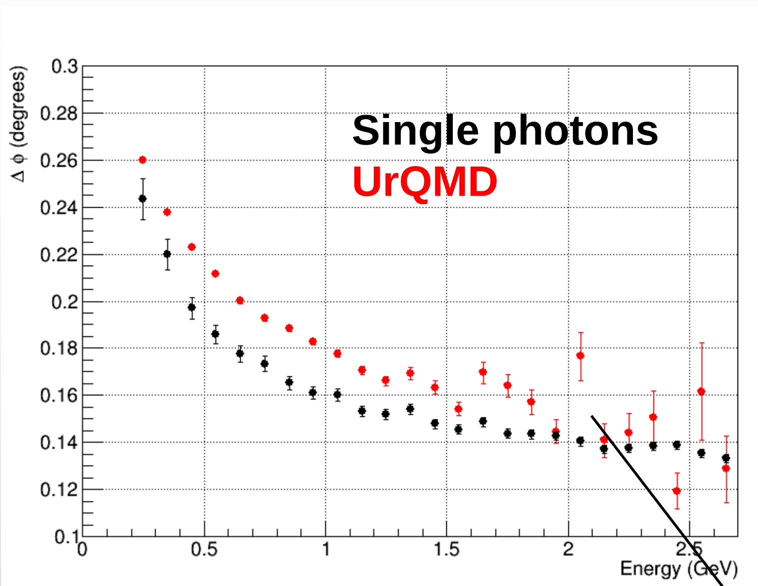
E_{min} = 10 MeV

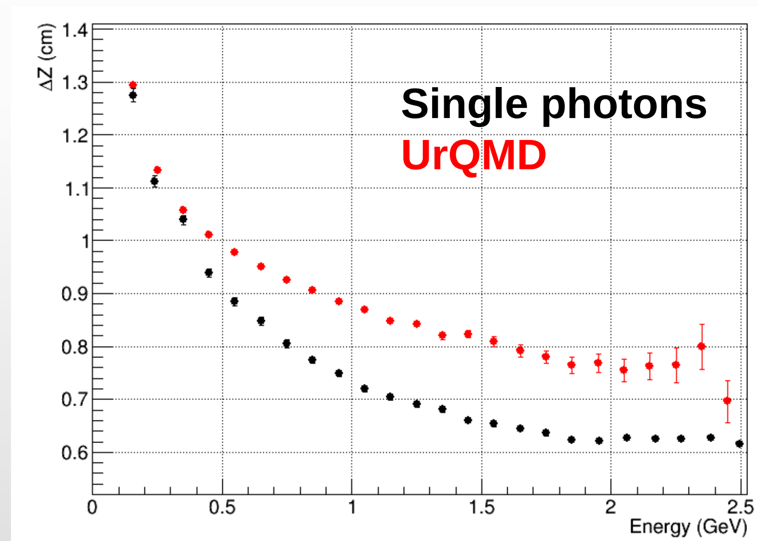


occupancy ~ 0.20

MPD-ECAL spatial resolution for photons

- UrQMD, minbias AuAu@11, realistic vertex distribution, selected photons
- Spatial resolution is energy dependent
- Comparable for single photons and photons in high-multiplicity events
- Achieved resolution is good enough → does not significantly affect: (1) the mass resolution for neutral mesons in the expected p_T range of measurements; (2) width of track-to-cluster and cluster-to-track matching

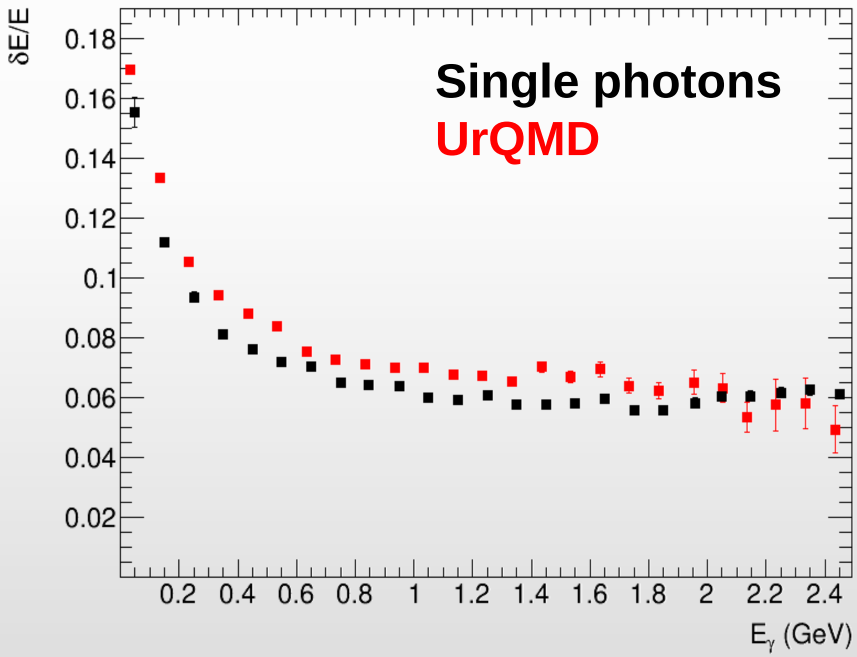




~ 180 cm * tan(0.15 degrees) = 0.5 cm

MPD-ECAL energy resolution for γ/e

- UrQMD, minbias AuAu@11, realistic vertex distribution, selected photons
- Energy resolution is energy dependent, $\delta E/E \sim 1/\sqrt{E}$
- Energy resolution defines width of the reconstructed π^0/η, E/p peaks
- There is still potential for improvement (with better tower-by-tower calibration)



Forward Hadron Calorimeter (FHCal)

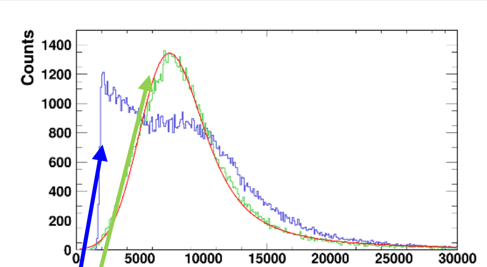
- Two-arms at ~3.2 m from the interaction point.
- Each arm consists of 44 individual modules.
- Module size 15x15x110cm^3 (42 layers)
- Pb(16mm)+Scint.(4mm) sandwich
- 7 longitudinal sections
- 6 WLS-fiber/MAPD per section
- 7 MAPDs/module

The activities with modules:

- Tests with cosmic muons;
- Tests of Front-End-Electronics (FEE);
- Study of FEE electronic noises;
- Development of FHCal trigger;
- Development of Slow Control.

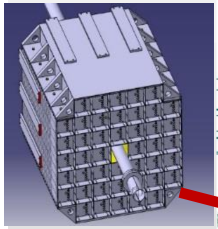
- All (90+spare) FHCal modules are assembled and are used for the tests.
- 100 Front-End-Electronics (FEE) boards are produced and tested.

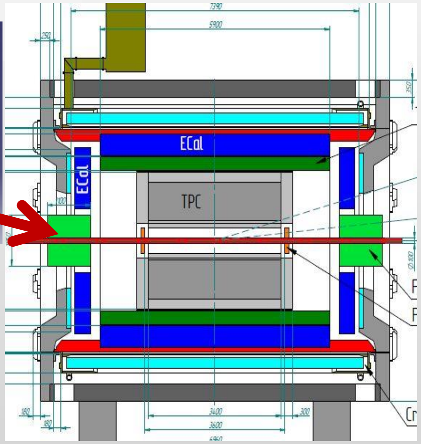
FHCal energy calibration with cosmic



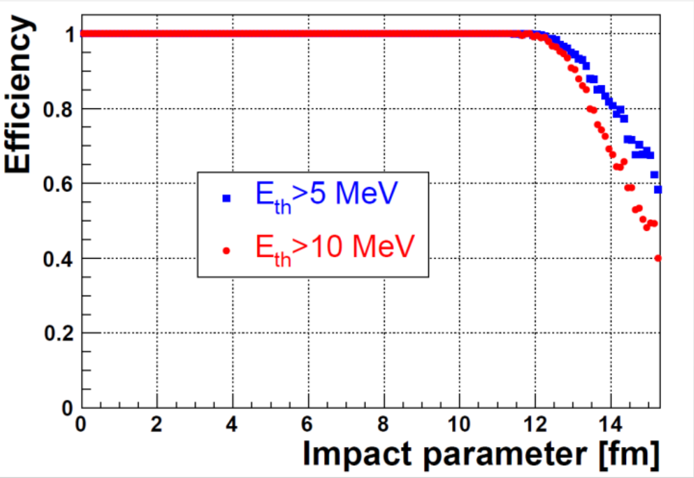
Raw spectrum in a single section

Corrected to the pass length in scintillators



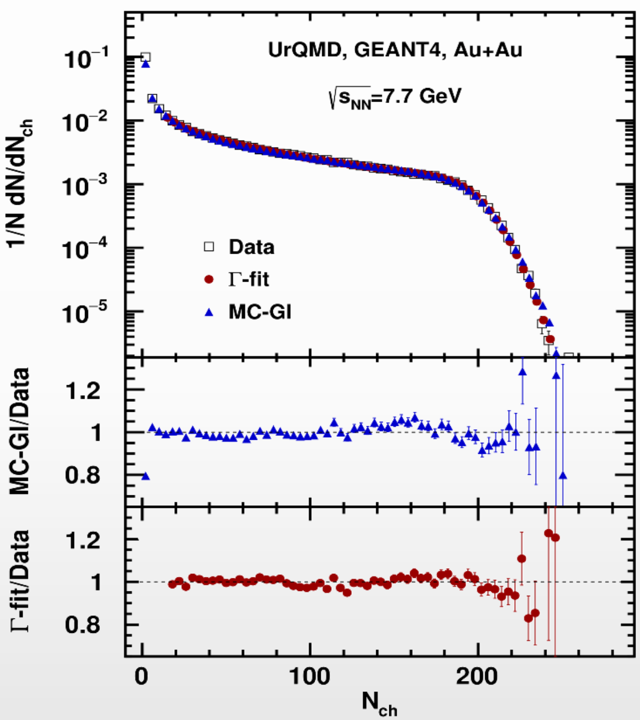


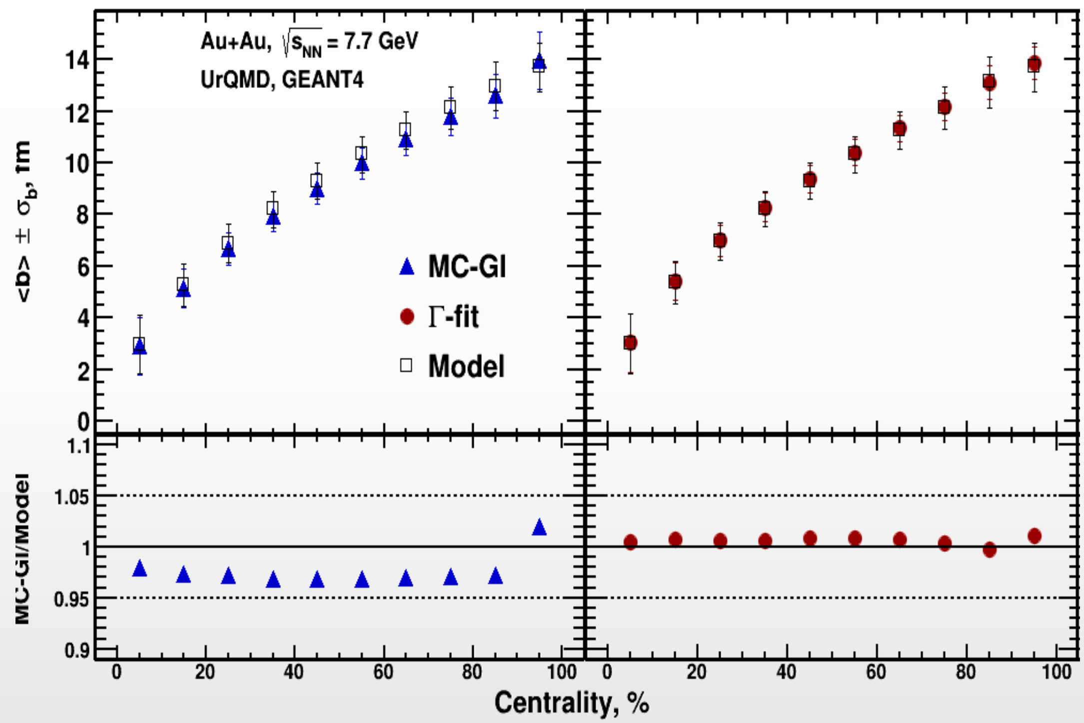
FHCal Trigger efficiency



Centrality by TPC multiplicity

- AuAu@7.7 GeV (UrQMD)
- Reconstruction of the impact parameter by **MC Glauber (MC-Gl)** and by **Bayesian inversion method (Γ-fit)**

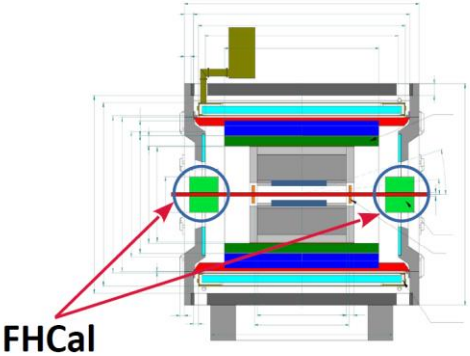




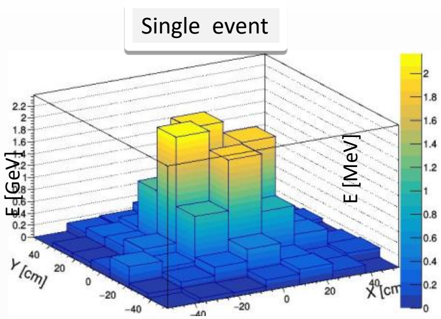
- Comparable results with PHSD and SMASH event generators at different energies

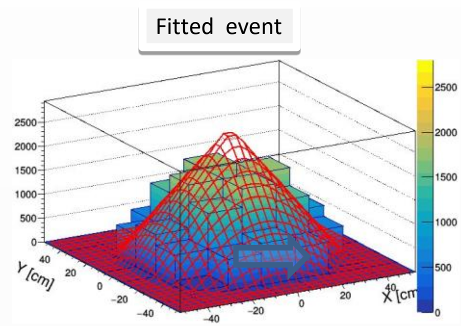
Centrality and reaction plane by FHCAL

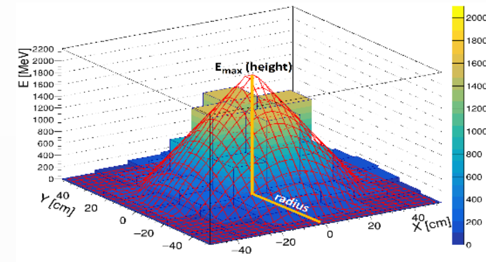
- FHCAL is a hadronic calorimeter, ~ 1 m^2, segmentation 15x15 cm^2, 2 < |η| < 5

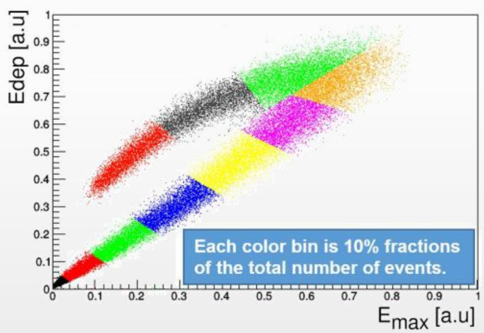


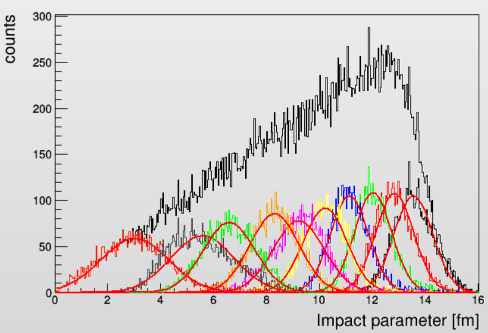
Two-dimensional fit of the energy depositions in FHCAL

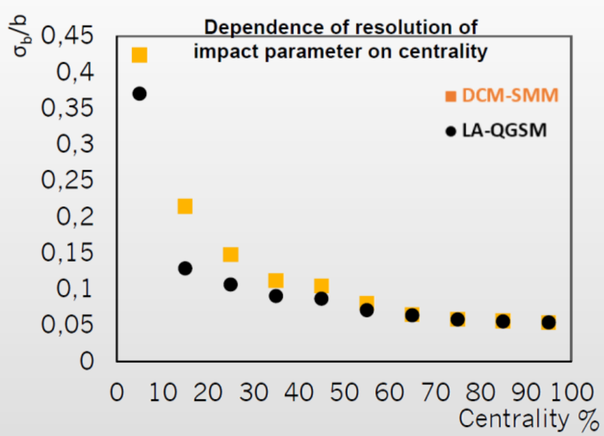


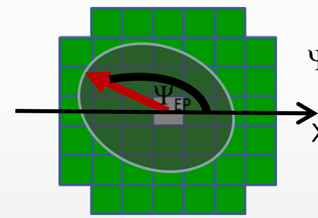






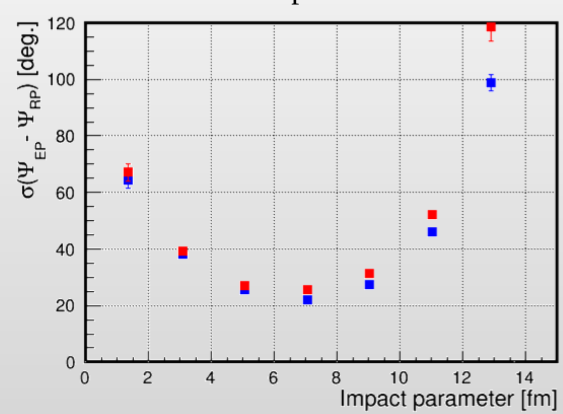






$$\Psi_{EP} = acrtg \frac{\sum E_i \sin(\varphi_i)}{\sum E_i \cos(\varphi_i)}$$

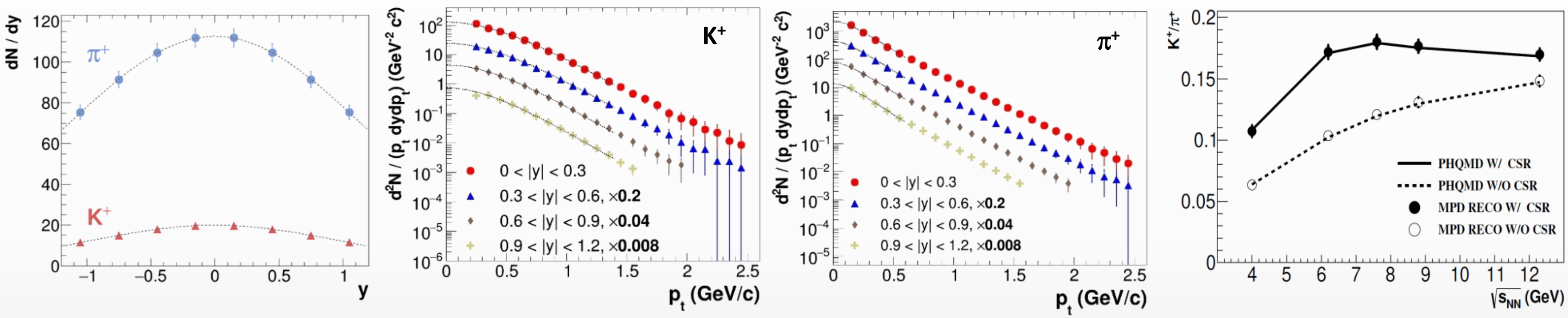
Reaction plane resolution



Identified hadron spectra

- ❖ Particle spectra, yields and ratios probe bulk properties of the fireball 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):

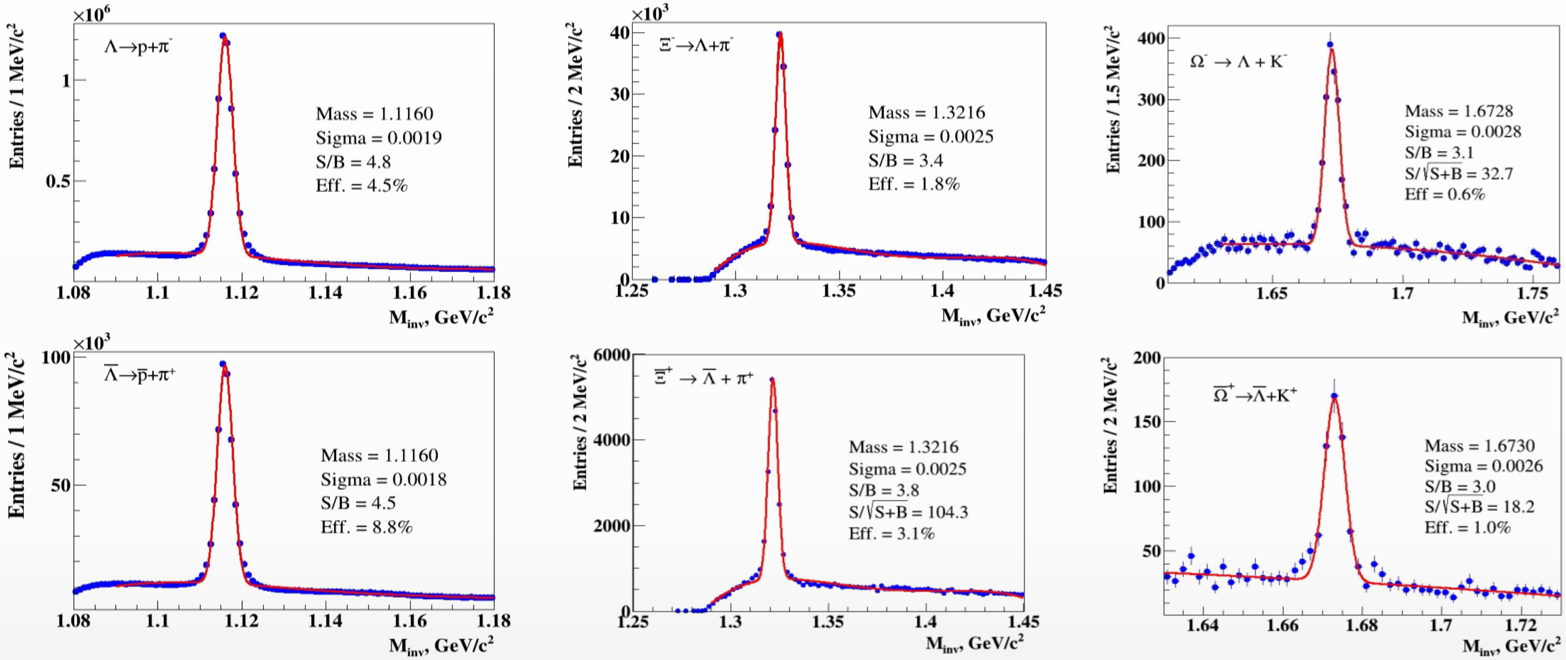


- ✓ MPD samples ~ 70% of the π/K/p production in the full phase space
- ✓ hadron spectra are measured from 0.2 MeV/c to 2.5 GeV/c in transverse momentum with the TPC&TOF
- ✓ unmeasured hadron yields at low p_T and large values of rapidity can be extracted from extrapolation of the measured spectra (B-W 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

Weak decays of strange baryons

❖ AuAu@11 GeV (PHSD):

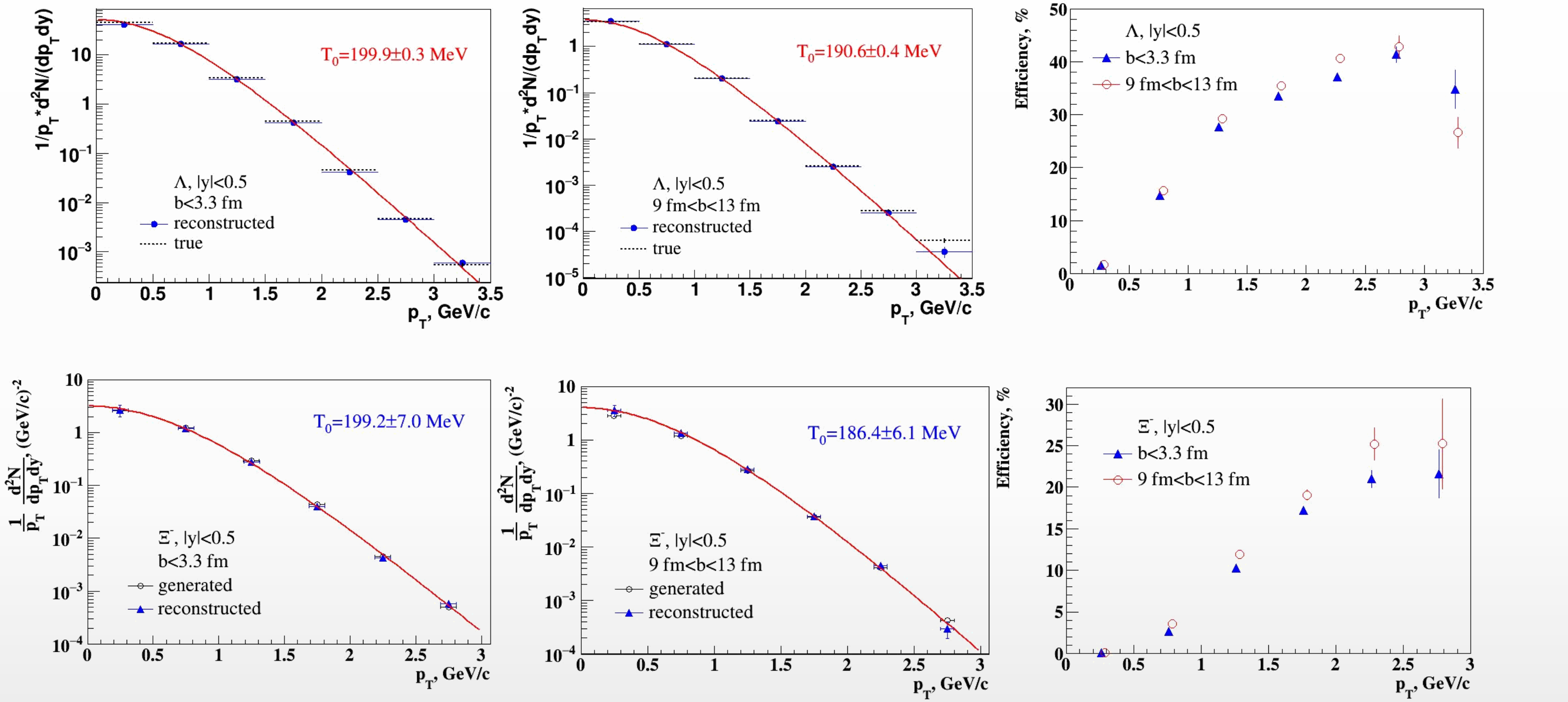


✓ Strange baryons can be reconstructed with good S/B ratios using charged hadron identification in the TPC&TOF and different decay topology selections

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

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

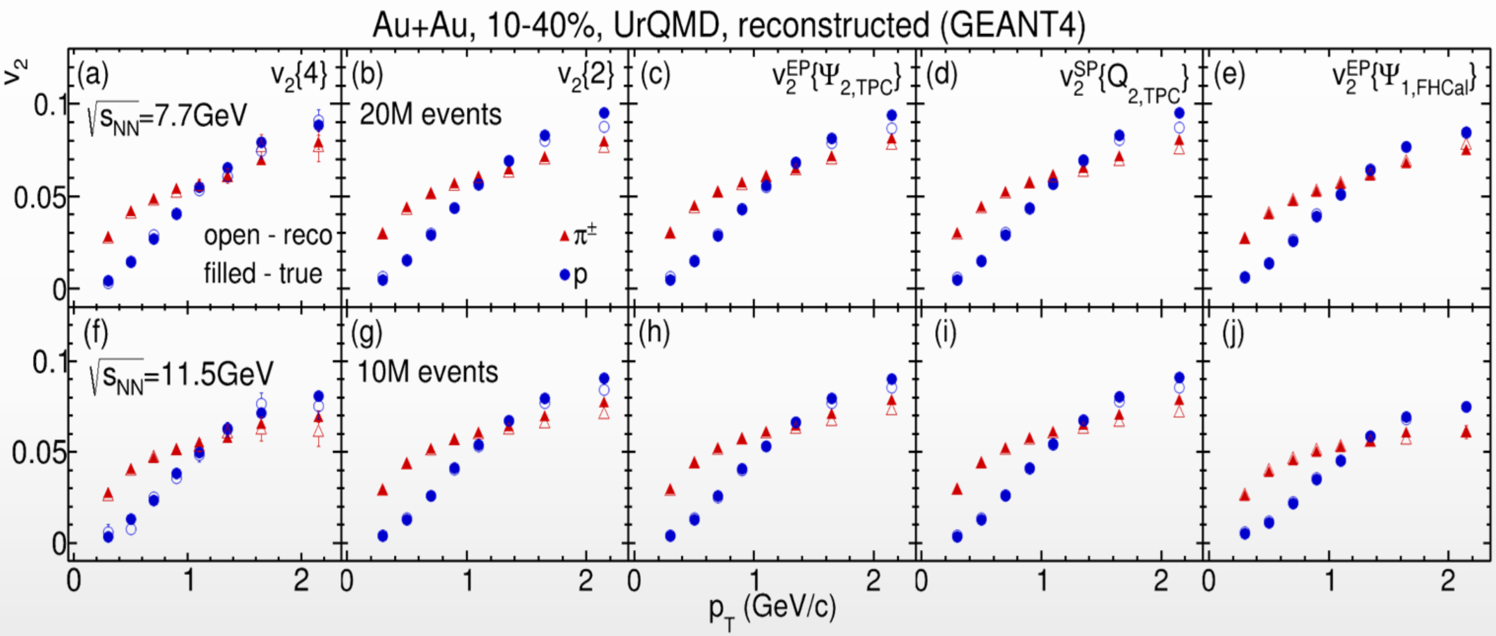
Efficiencies and p_T spectra



- ✓ Capability to reconstruct baryon yields down to low momenta with reasonable efficiencies
- ✓ High-p_T reach is limited by statistics
- ✓ Reconstructed spectra are consistent with the generated ones → MC closure test

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.)

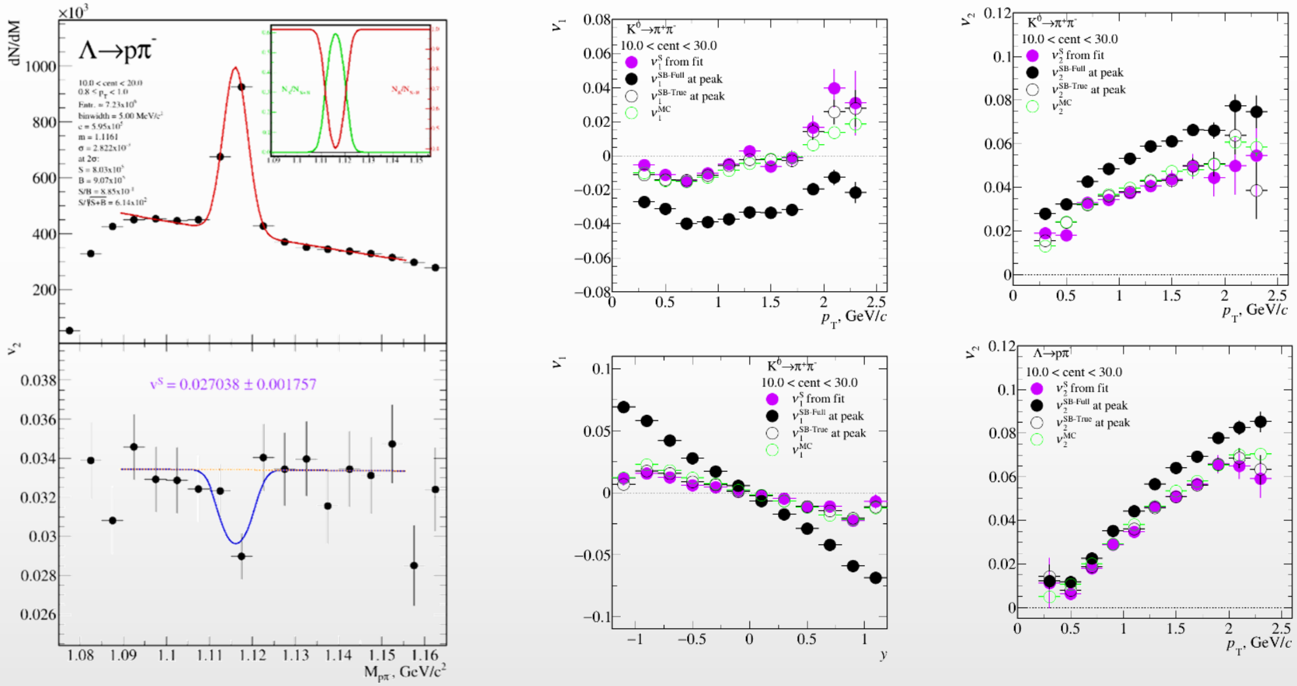


- Reconstructed and generated v_2 of pions and protons are in good agreement for all methods

Collective flow for V0 (K_s^0 and Λ)

- 25 M AuAu@11 GeV (UrQMD)
- Differential flow signal extraction using invariant mass fit method

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



v_1/v_2 flow after fit

Measured flow for (S+BG)

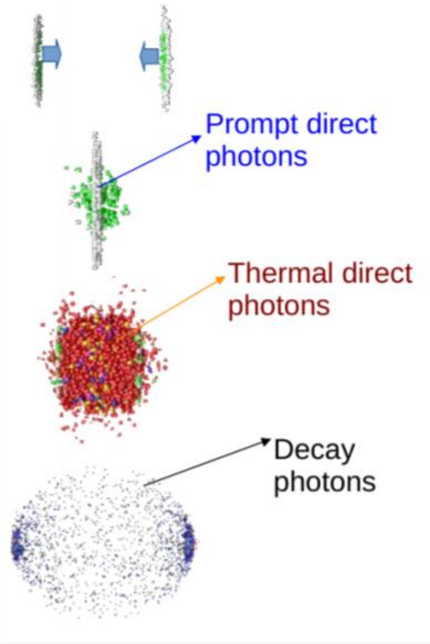
Measured flow for true pairs

Flow from event generator

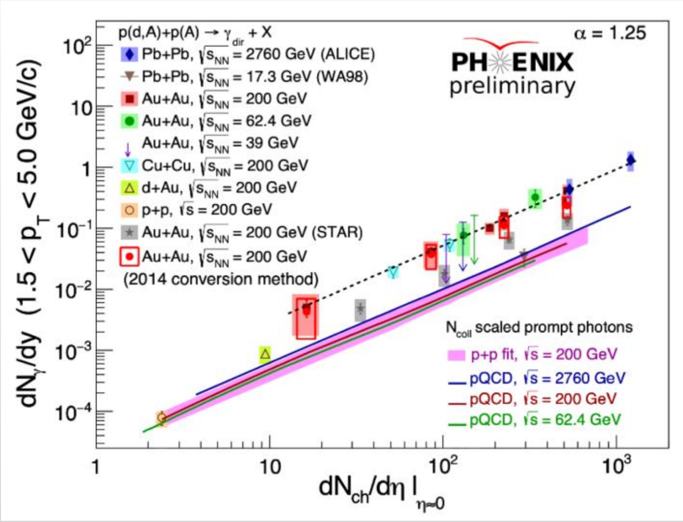
- Reasonable agreement between reconstructed and generated v_n signals for K_s^0 and Λ

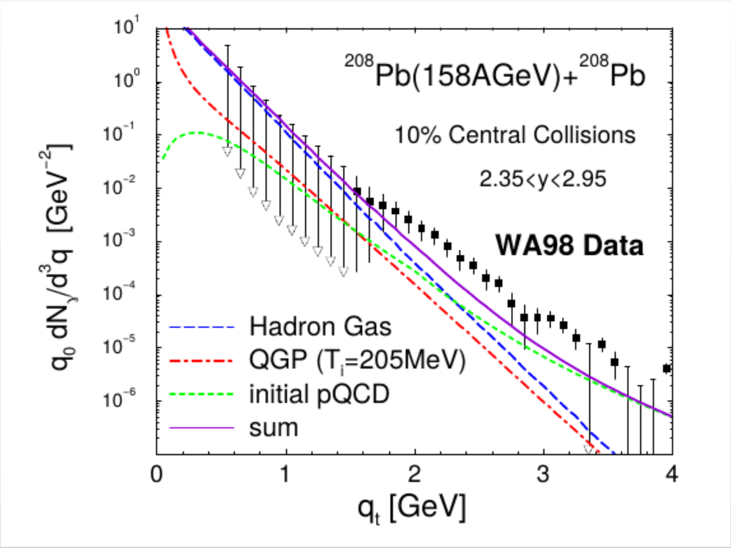
Photons: Motivation

- Direct photons – photons not from hadronic decays.
- Produced throughout the system evolution:
  - ✓ QCD matter is transparent for photons, once produced they leave the interaction region unaffected preserving their properties
  - ✓ estimation of the effective system temperature at low energy
  - ✓ hard scattering probe at high energy



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

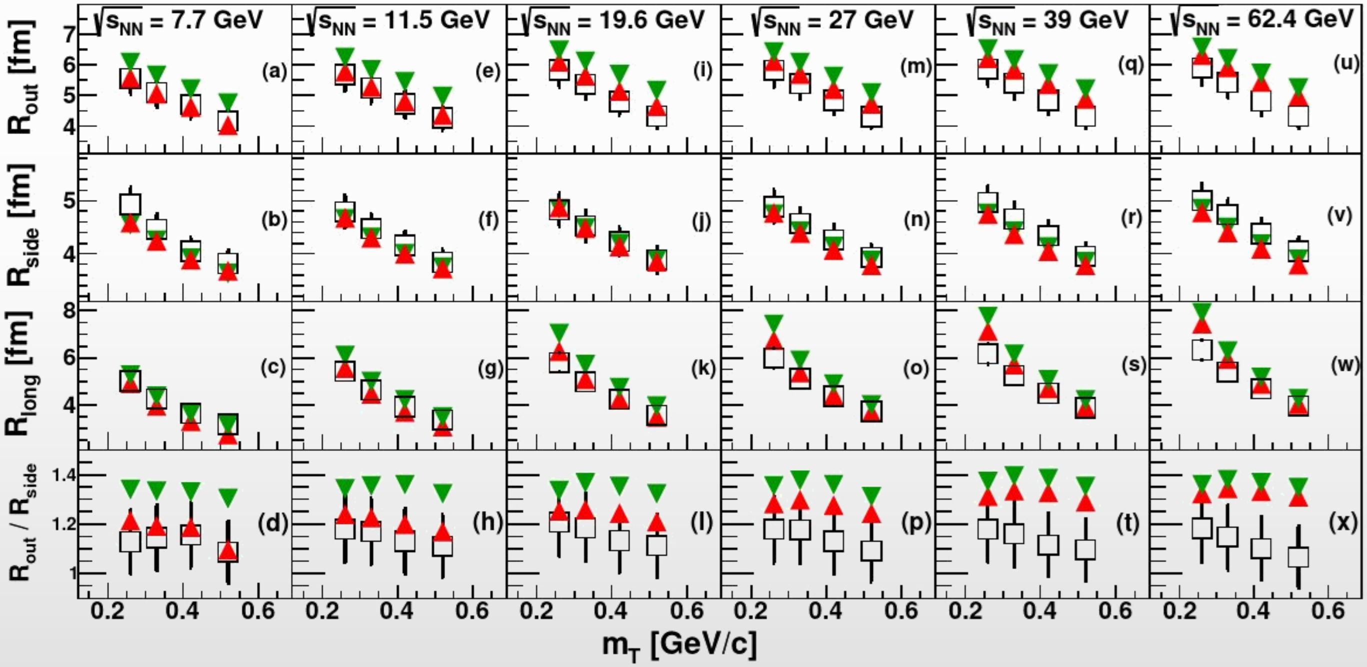




Two particle correlations

- Femtoscopy is used in heavy-ion collision to determine the size of the particle-emitting region and space-time evolution of the produced system.
- Measurement for pions are straightforward and robust, large discovery potential in correlations for kaons and protons, as well as correlations including hyperons

AuAu@7.7 GeV (vHLLE), extracted 3D pion radii versus m_T vs. STAR data (PRC 96, 024911(2017))

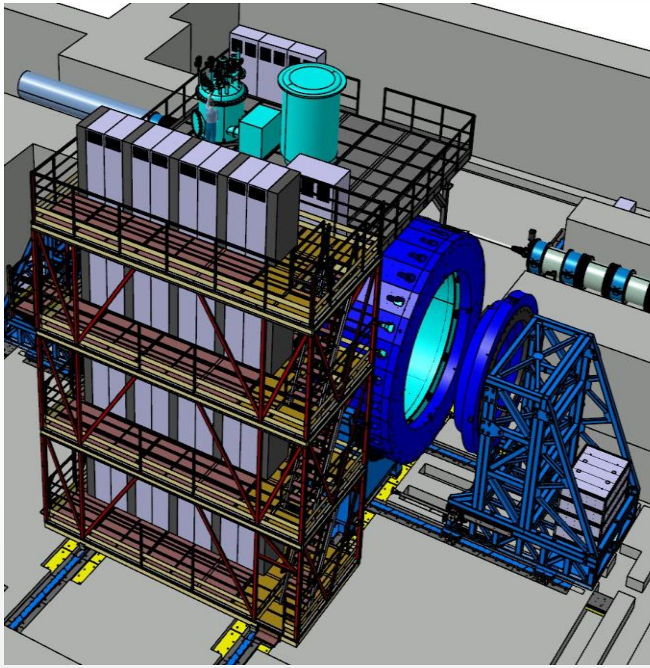


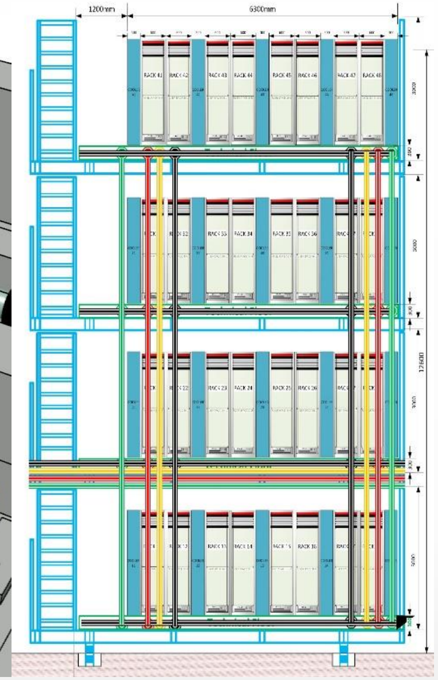
1st order phase transition

cross-over transition

- Simulations predict sensitivity of pion source size to the nature of the phase transition

MPD Electronics Platform





- Electronics platform has 4 levels with 8 racks on each level
- Each Rack provides cooling, fire safety and radiation control system
- Cable ducts connect detectors inside of MPD and Electronics Platform
- The mechanical part of the Platform is ready

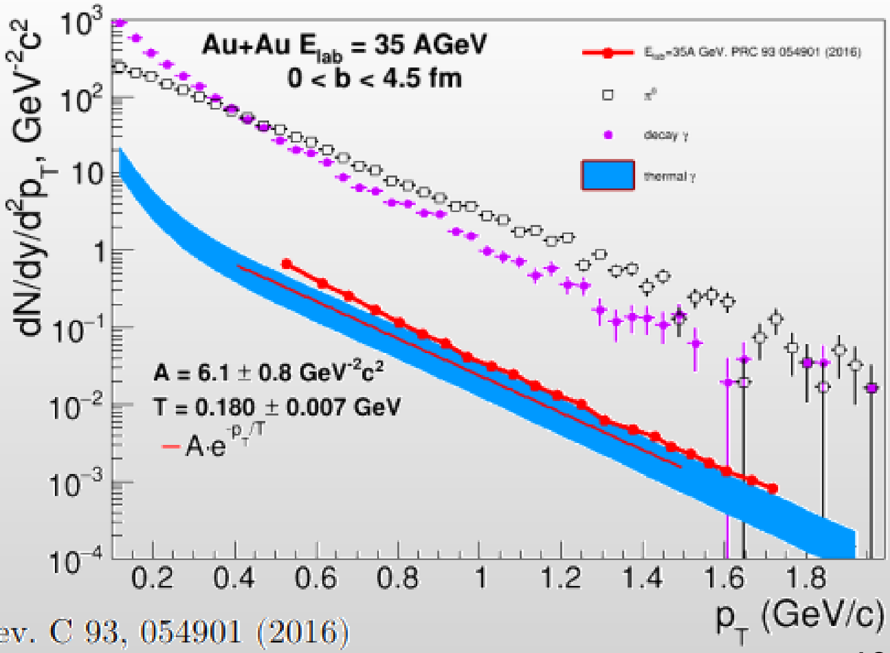
The design of the MPD Electronics Platform is a major contribution of the Polish groups to MPD
M. Peryt (WUT) – leader of the „Engineering Support" Sector of VBLHEP

Simulation setup

- ✓ UrQMD v3.4 with hybrid model (3+1d hydro, **bag model** EoS, hadronic rescattering and resonances within UrQMD)
- ✓ π^0 and decay photon spectrum are calculated **within the same simulation**
- ✓ impact parameter range 0<b<9 fm
- ✓ In hydrodynamical evolution, for each volume we calculate thermal gamma yield based on T, energy density (e), QGP fraction, baryonic chemical potential. We integrate these yields over time (until freeze-out time) and space.
- ✓ Two extreme cases: calculate thermal gamma emission from the volume above freeze-out criterion ($e > e_{freezeout}$), or calculate for all volumes. Reality somewhere in between (all volumes interact during hydro evolution). Comparing these options one can estimate theoretical uncertainties

$$\frac{d^3 N^{\gamma,therm}}{dy\, d^2 k_T} = \int_{\Omega} dV\, dt\, R_\gamma\left(k, T(x), \mu(x), u(x)\right)$$

Why simulations in PRC 93 054901 (2016) and PRC 81 044904 (2010) have almost the same yield despite ~5 times difference in energy (35 vs 158 AGeV)?

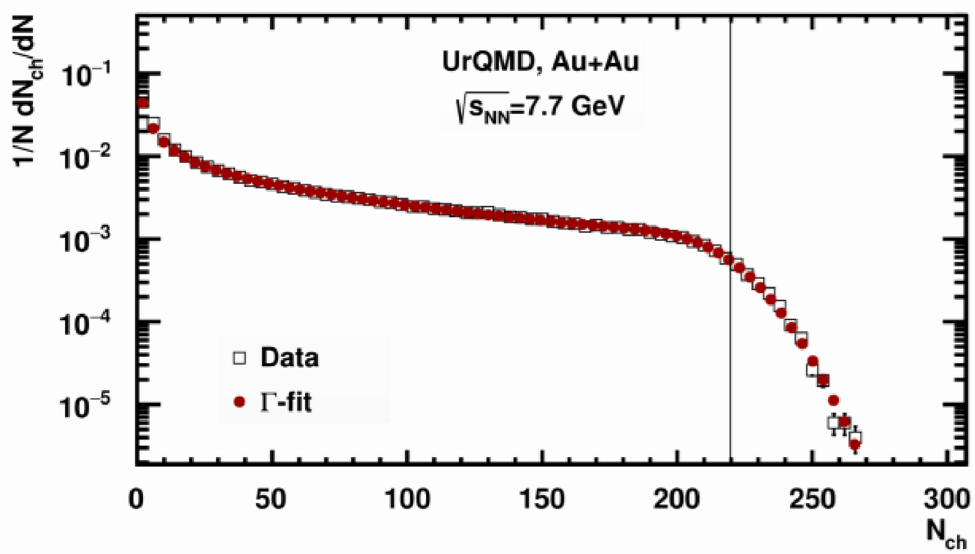


Comparison with S. Endres, H. van Hees, M. Bleicher, Phys. Rev. C 93, 054901 (2016)

The Bayesian inversion method (Γ-fit): main assumptions

- Relation between multiplicity N_{ch} and impact parameter b is defined by the fluctuation kernel:

$$P(N_{ch}|c_b) = \frac{1}{\Gamma(k(c_b))\theta^k} N_{ch}^{k(c_b)-1} e^{-n/\theta}$$



c_b – impact parameter based centrality

$$c_b = \frac{1}{\sigma_{inel}} \int_0^b P_{inel}(b')2\pi b' db' \simeq \frac{\pi b^2}{\sigma_{inel}}$$

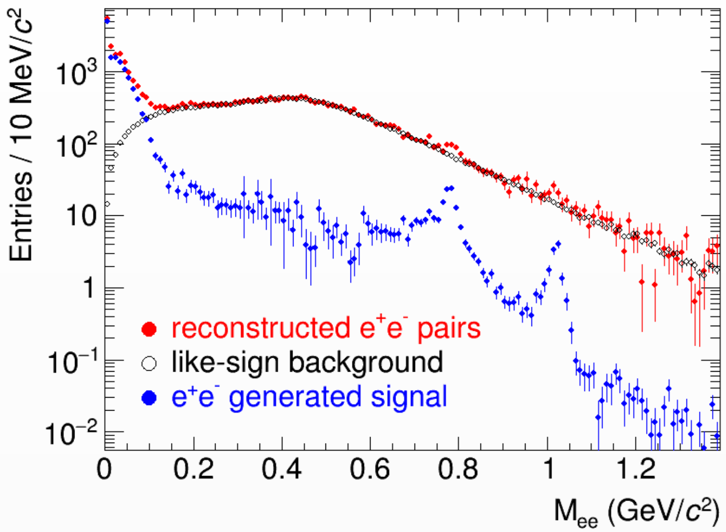
σ_{inel} – geometrical inelastic NN cross section

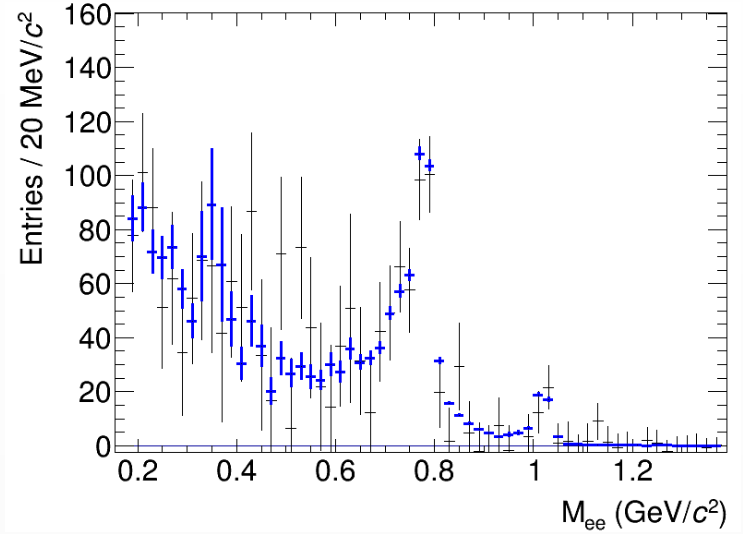
$P_{inel}(b)$ – probability of inelastic NN collision ($P_{inel}(b) \approx 1$)

R. Rogly, G. Giacalone and J. Y. Ollitrault, Phys.Rev. C98 (2018) no.2, 024902

Implementation in MPD: https://github.com/Dim23/GammaFit

Summary for dielectrons





- S/B (integrated in 0.2-1.5 GeV/c2) ~ 5-10%
- Methods to improve S/B ratio with a minimal penalty for pair reconstruction are being developed and matured
- Meaningful measurements for e^+e^- continuum and LVMs would require ~ 10^8 AuAu/BiBi sampled events, first observations will be possible with ~50 M events

NICA and Nuclotron beams

NICA collider beams:

- Heavy ion collisions up to $^{197}Au^{79+}$ + $^{197}Au^{79+}$ at:

  $\sqrt{s_{NN}}$ = 4 - 11 GeV , $L_{average}$= 10^{27} $cm^{-2}s^{-1}$

  same or higher $L_{average}$ for lighter ions

- Polarized proton and deuteron collisions:

  p↑p↑ $\sqrt{s_{pp}}$ = 12 - 26 GeV L_{max} ≈ 10^{32} $cm^{-2}s^{-1}$

  d↑d↑ $\sqrt{s_{NN}}$ = 4 - 13.8 GeV

Nuclotron extracted beams (for fixed target experiments):

- Light ions and polarized beams of p and d:

  Li - Au = 1 - 4.5 GeV /u

  p↑ = 5 - 12.6 GeV

  d↑ = 2 - 5.9 GeV/u

Main parameters of accelerator complex

Nuclotron

Parameter	SC synchrotron
particles	↑p, ↑d, nuclei (Au, Bi, ...)
max. kinetic energy, GeV/u	10.71 (↑p); 5.35 (↑d) **3.8** (Au)
max. mag. rigidity, Tm	38.5
circumference, m	251.52
vacuum, Torr	10^{-9}
intensity, **Au** /pulse	$1\ 10^{9}$

Booster

	value
ion species	A/Z ≤ 3
max. energy, MeV/u	**600**
magnetic rigidity, T m	1.6 – 25.0
circumference, m	210.96
vacuum, Torr	10^{-11}
intensity, **Au** /pulse	$1.5\ 10^{9}$

The Collider

Design parameters, Stage II

45 T*m, 11 GeV/u for Au^{79+}

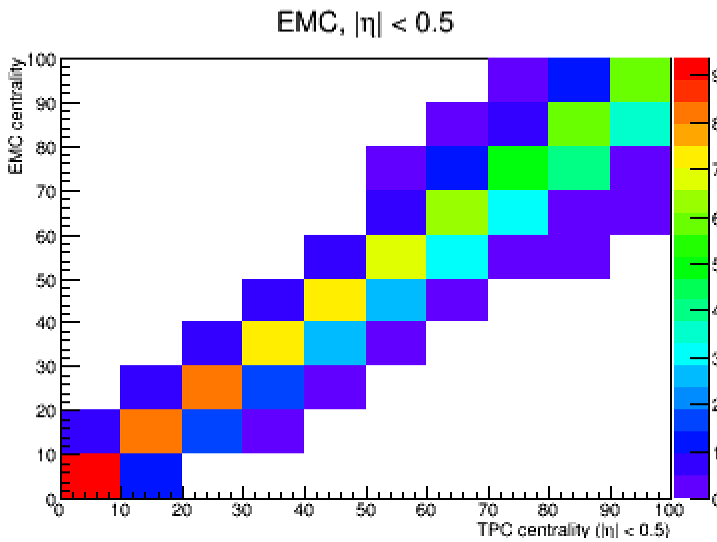
Ring circumference, m	**503,04**
Number of bunches	**22**
r.m.s. bunch length, m	**0,6**
β, m	**0,35**
Energy in c.m., GeV/u	**4-11**
r.m.s. Δp/p, 10^{-3}	**1,6**
IBS growth time, s	**1800**
Luminosity, $cm^{-2}\ s^{-1}$	**1×10^{27}**

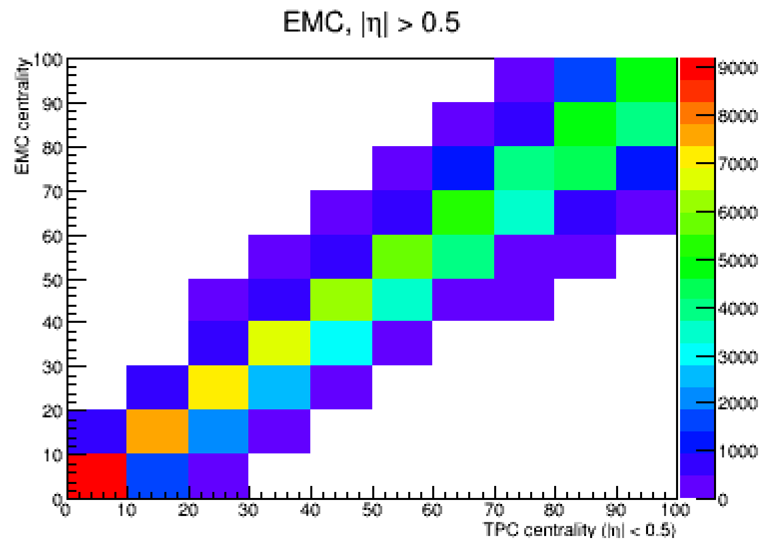
Stage I:

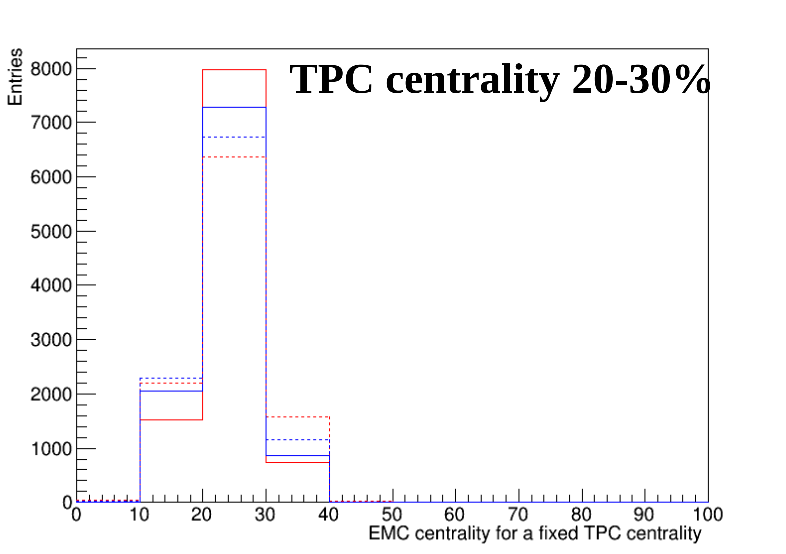
- *without ECS in Collider, with stochastic cooling*
- *reduced number of RF*
- *reduced luminosity (10^{25} is the goal for 2023)*

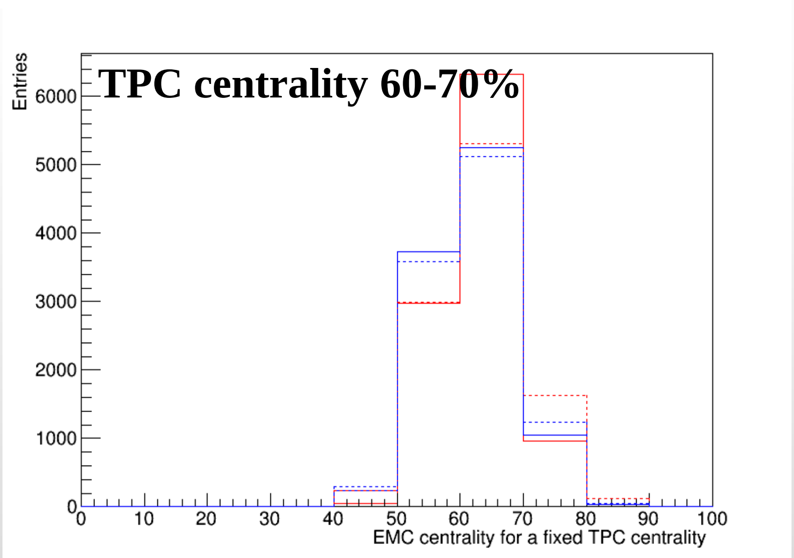
Collision system limited by source. *Now Available: C(A=12), N(A=14), Ne(A=20), Ar(A=40), Fe(A=56), Kr(A=78-86), Xe(A=124-134), Bi(A=209)*

Centrality by E_T vs. centrality by TPC





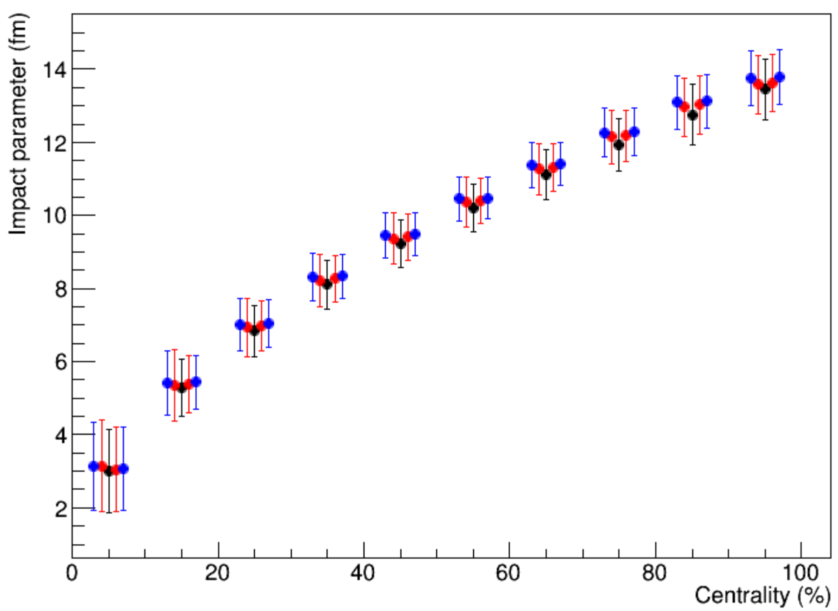


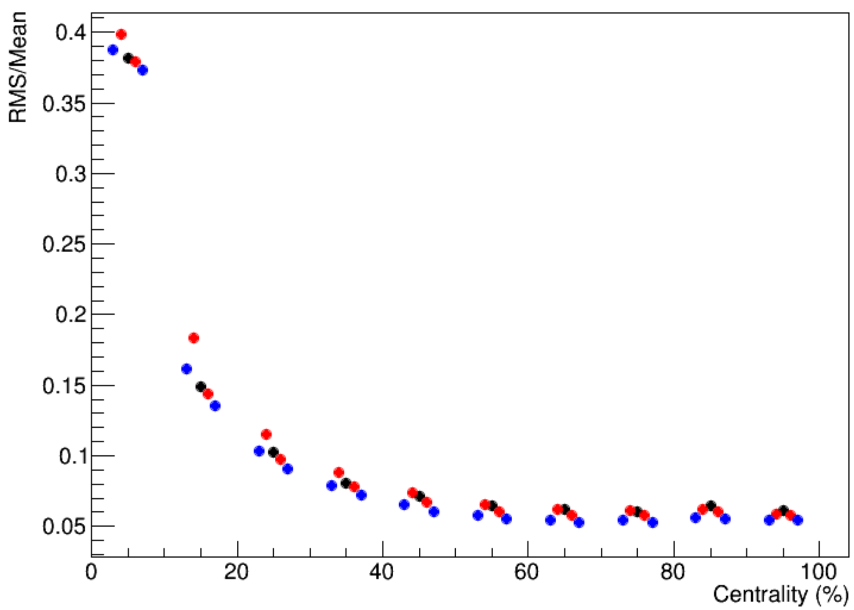


E_T , |η| < 0.5, all clusters
E_T , |η| > 0.5, all clusters
E_T , |η| < 0.5, CPV clusters
E_T , |η| > 0.5, CPV clusters

Sampled impact parameter distributions

E_T-CPV, $|\eta|> 0.5$, E_T-CPV, $|\eta|< 0.5$, TPC centrality, E_T, $|\eta|< 0.5$, E_T $|\eta|> 0.5$

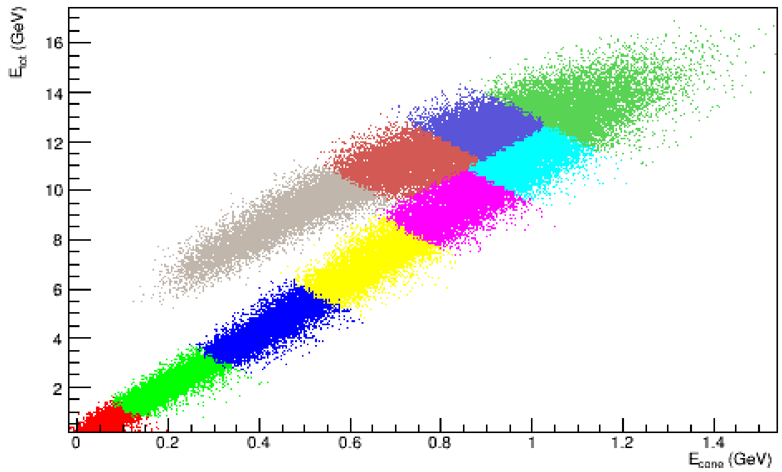


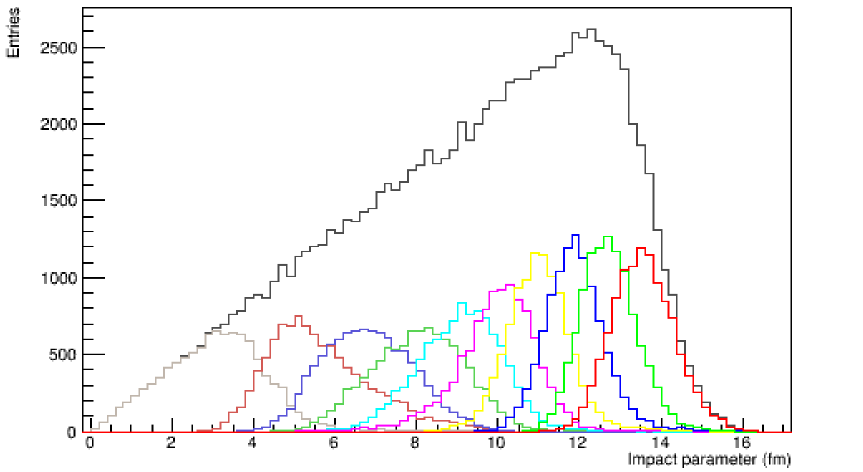


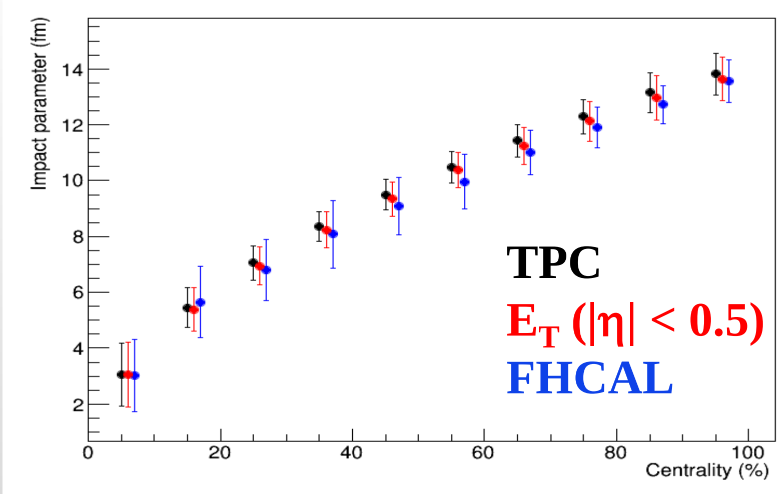
- Sampled impact parameter distributions are similar but event samples are different
- TPC and E_T can be used for centrality measurements, produce similar results

Centrality with FHCAL

E_{TOT} vs. E_{cone}

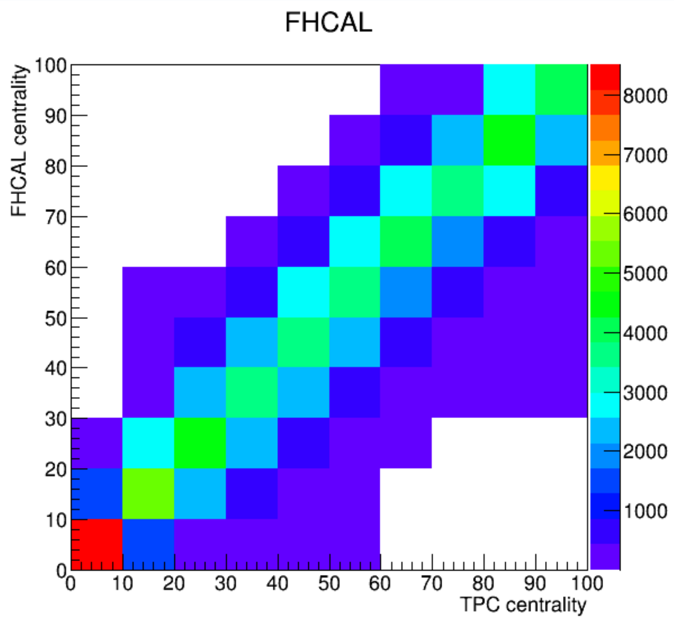


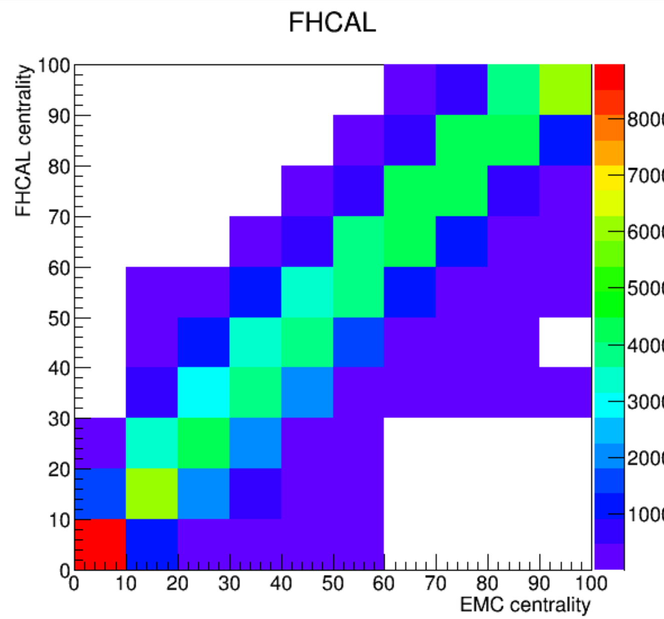


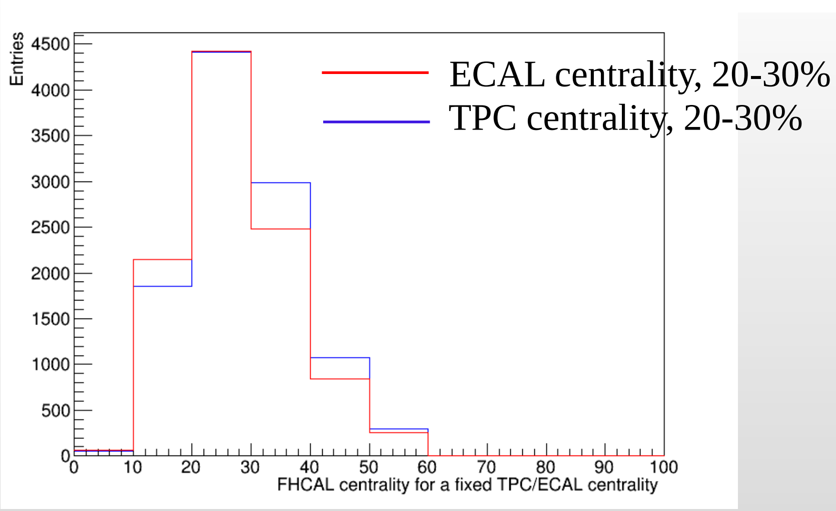


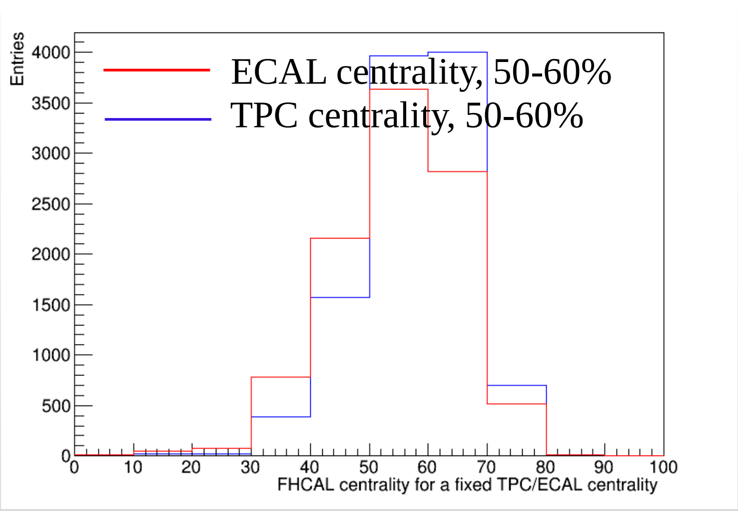
- TPC and ECAL are consistent
- FHCAL returns similar mean impact parameter values with wider spread (RMS) except for peripheral collisions

Centrality by FHCAL vs. centrality by TPC/ECAL





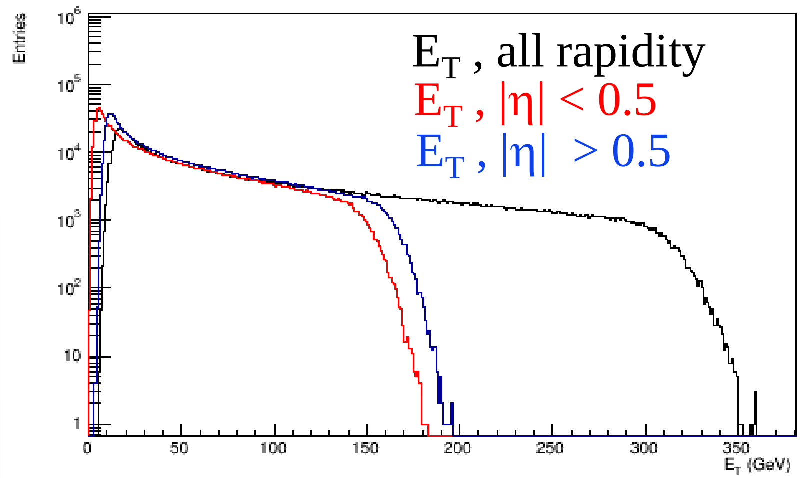




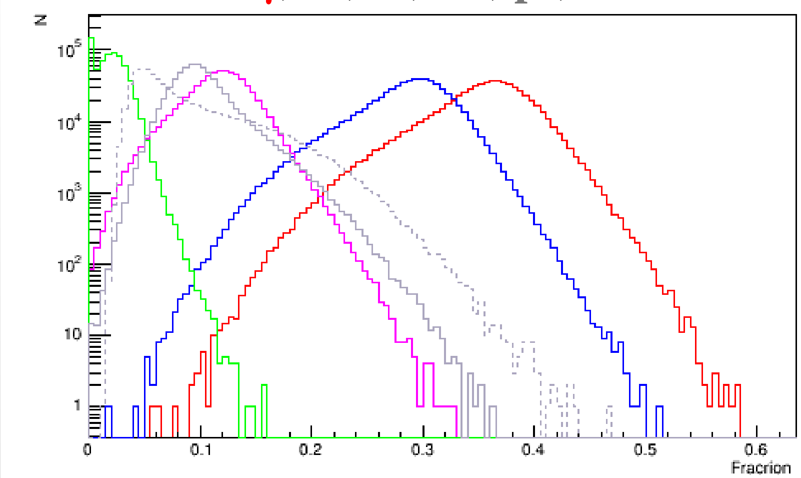
- FHCAL centrality has a very wide correlation with the TPC/E_T centrality
- Resolution by impact parameter is worse

E_T distributions

- Transverse energy E_T



- Contributors:



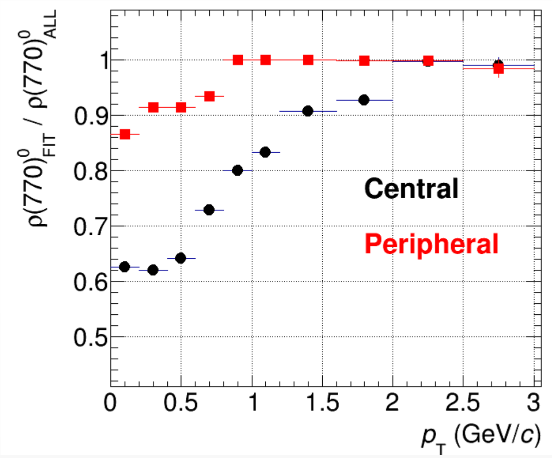
- Main contributors:
  - ✓ pions (**photons**, $\pi^{\pm}$)

MPD-ECAL, tasks and goals

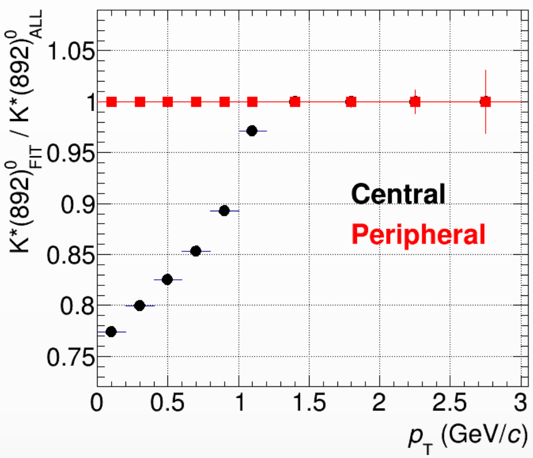
- Максимально корректное восстановление э/м сигналов:
  - ✓ разделение слипшихся кластеров (unfolding)
  - ✓ коррекция координат и энергий кластеров (глубина, угол падения)
  - ✓ расстояние до ближайшего трека (dphi, dz + идентификатор трека)
  - ✓ MC контрибуторы
  - ✓ разумное быстродействие (<20% общего времени обработки события)
- Разработка алгоритмов отбора э/м сигналов:
  - ✓ форма ливня, сравнение с ожидаемой
  - ✓ анализ эллипсоидности кластера
  - ✓ параметризация мэтчингов vs. p_T, charge …
- Дружественный интерфейс для пользователей:
  - ✓ документация и примеры по использованию разработанного п.о.
  - ✓ рекомендации по методам отбора сигналов
- Определение возможностей ECAL для решения физических задач:
  - ✓ фотоны, мезоны, (ди)лептоны и т.д.

Yields of $K^*(892)^0$ and $\rho(770)^0$ in AuAu@11, UrQMD

- $\rho(770)^0 \rightarrow \pi^+\pi^-$ ($c\tau$ ~ 1.3 fm/c)
  - ✓ yield is undercounted because of pion rescattering;
  - ✓ this yield is preserved in e^+e^- measurements !!!



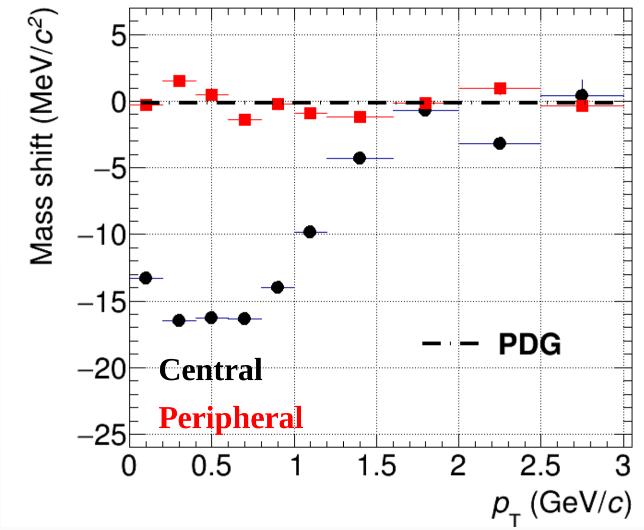
- $K^*(892)^0 \rightarrow \pi^\pm K^\pm$ ($c\tau$ ~ 4.3 fm/c)
  - ✓ yield is undercounted because of pion and kaon rescattering



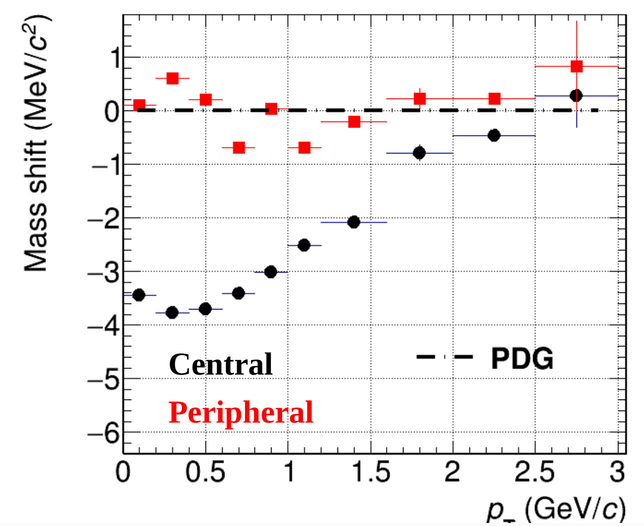
- Signal losses are larger for shorter-lived $\rho(770)^0 \rightarrow$ higher chance for $\rho(770)^0$ to decay and for daughters to rescatter in the medium
- Predicted signal losses are noticeable for the total (p_T-integrated) yields since bulk of the hadrons is produced at low p_T at NICA energies

Masses of $K^*(892)^0$ and $\rho(770)^0$ in AuAu@11, UrQMD

- $\rho(770)^0 \rightarrow \pi^+\pi^-$ ($c\tau \sim 1.3$ fm/c)



- $K^*(892)^0 \rightarrow \pi^{\pm}K^{\pm}$ ($c\tau \sim 4.3$ fm/c)



- In peripheral collisions, the peak models return masses and widths as measured in vacuum
- In central collisions, the masses are measured smaller
- Similar mass "modifications" have been reported @ RHIC and the LHC, large uncertainties:

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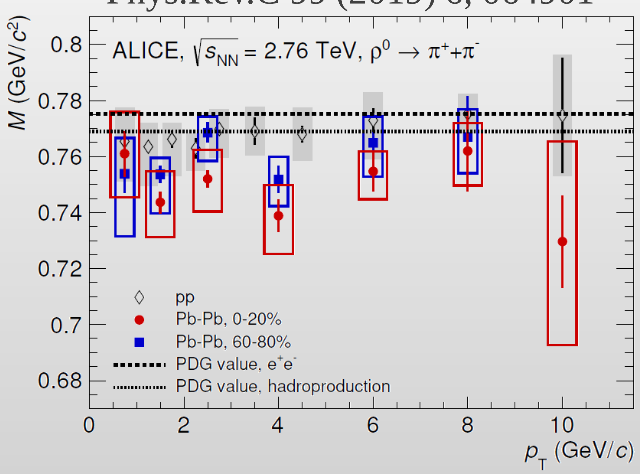

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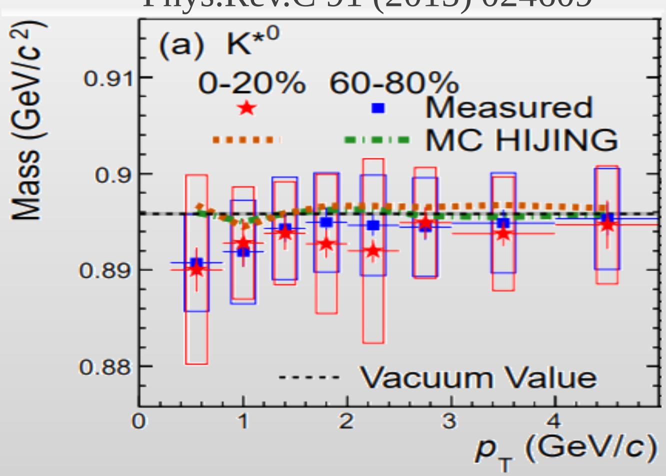
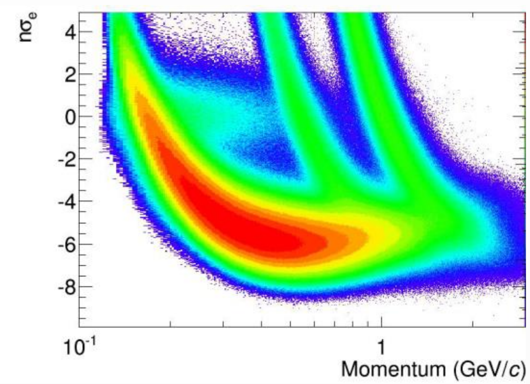
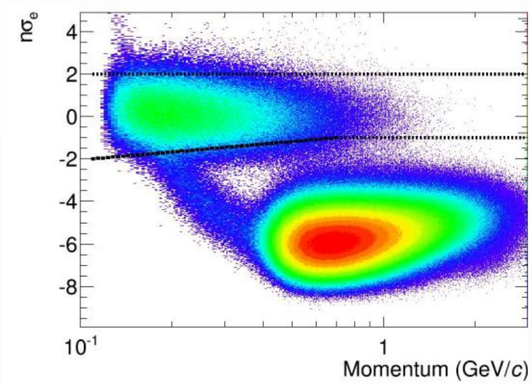
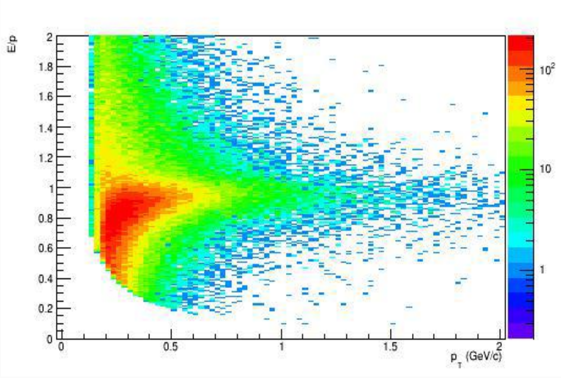


Reconstruction of electrons

- Charged particle tracks are reconstructed in the TPC
- Particles are identified in the TPC (<dE/dx>), TOF (v/*c* ~ 1) and ECAL (E/p ~ 1)







- Reasonable electron track reconstruction efficiency and electron purity after multiparametric optimization of selections