PETERSBURG NUCLEAR PHYSICS INSTITUTE NAMED BY B.P. KONSTANTINOV
OF NATIONAL RESEARCH CENTRE «KURCHATOV INSTITUTE»

Study of φ(1020), ρ(770) and *K**(892) resonance production in Bi+Bi collisions at $\sqrt{s_{NN}} = 9.2$ GeV in the MPD detector at NICA collider

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(SPbPU and NRC «Kurchatov Institute» - PNPI) for the MPD collaboration

The 7th international conference on particle physics and astrophysics

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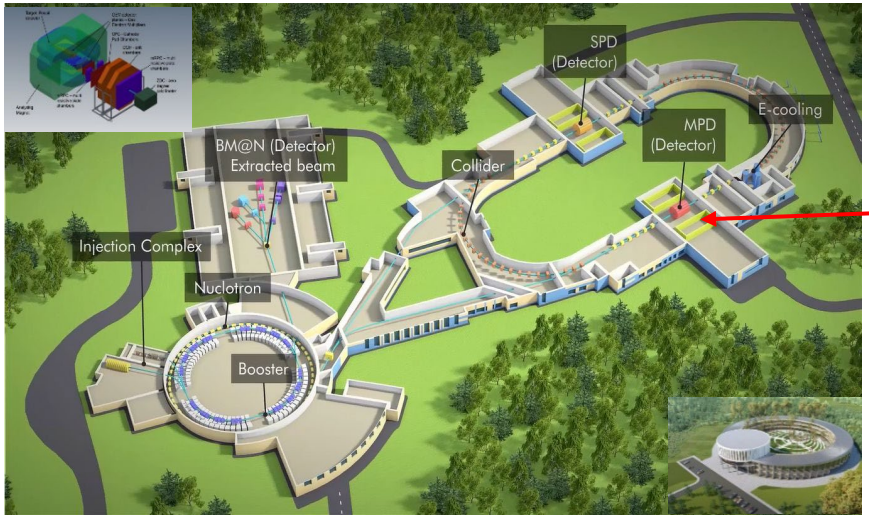
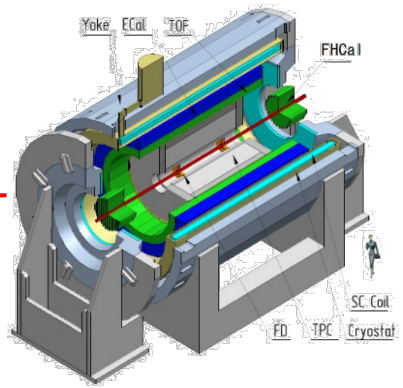
MPD at NICA

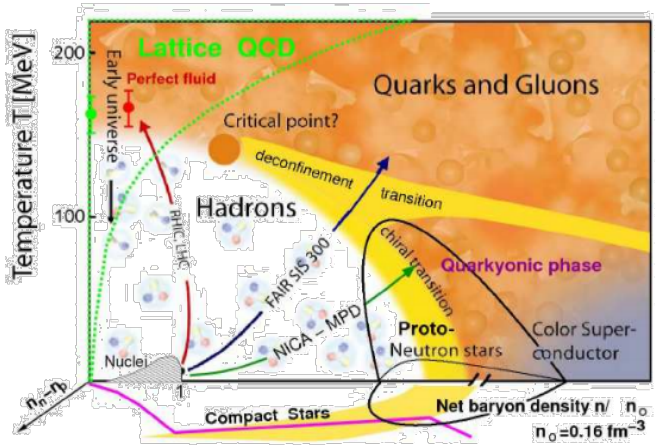
- One of two experiments at NICA collider to study heavy-ion collisions at $\sqrt{s_{NN}} = 4 - 11$ GeV



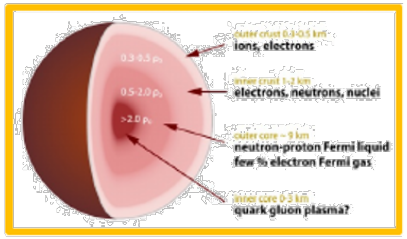


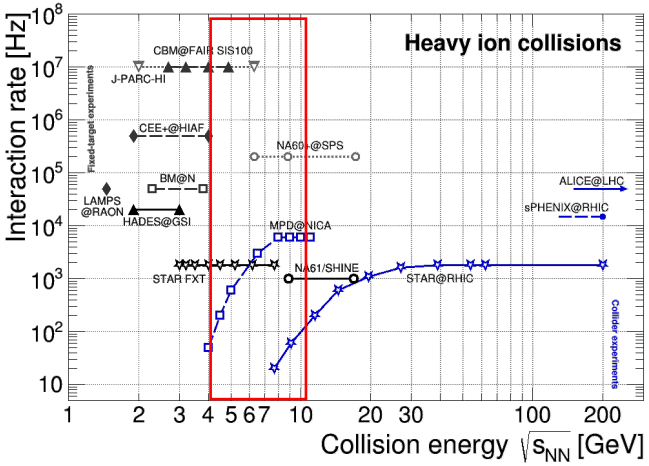
Stage- I

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



high baryon densities
→ inner structure of
compact stars



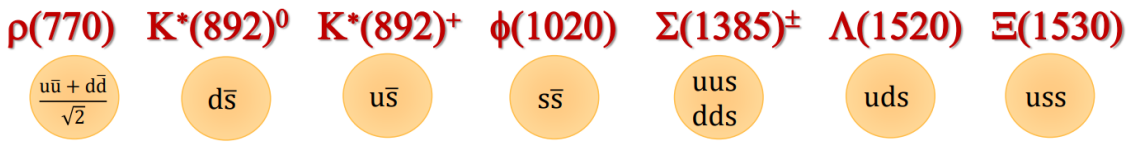


- NICA will study QCD medium at extreme net baryon densities → 1st order phase transition + QCD CEP
- Many ongoing (NA61/Shine, STAR-BES) and future experiments (CBM) in ~ same energy range

Resonances as a probe of heavy-ion collisions

Resonances in heavy-ion collisions

- Wide variety of resonances in the PDG, most often/easily measured are:



Particle	Mass (MeV/c^2)	Width (MeV/c^2)	Decay	BR (%)
ρ^0	770	150	$\pi^+\pi$	100
$K^{*\pm}$	892	50.3	$\pi^\pm K_s$	33.3
K^{*0}	896	47.3	πK^+	66.7
ϕ	1019	4.27	K^+K^-	48.9
Σ^{*+}	1383	36	$\pi^+\Lambda$	87
Σ^{*-}	1387	39.4	$\pi\Lambda$	87
Λ(1520)	1520	15.7	K^-p	22.5
Ξ^{*0}	1532	9.1	$\pi^+\Xi^-$	66.7

- Vacuum properties of the resonances are well defined (m, τ, BR etc.)
- Copiously produced in heavy-ion collisions at ~ GeV energies, large branching ratios in hadronic decay channels → possible to measure
- Probe reaction dynamics and particle production mechanisms vs system size and $\sqrt{s_{NN}}$:
  - ✓hadron chemistry and strangeness production, ϕ with hidden strangeness is one of the key probes
  - ✓ reaction dynamics and shape of particle p_T spectra, p/K^*, p/ϕ vs p_T
  - ✓ lifetime and properties of the hadronic phase
  - ✓ spin alignment of vector mesons in rotating QGP (polarization of quarks from spin-orbital interactions)
  - ✓ flow, comparison with e^+e^- measurements, jet quenching, background for other probes etc

Hadronic phase and medium modifications

- Resonances have small lifetime of $\tau \sim 1 - 45$ fm/c, part of them decays in the fireball

increasing lifetime →

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

Reconstructed resonance yields in heavy ion collisions are defined by:

✓resonance yields at chemical freeze-out

✓hadronic processes between chemical and kinetic freeze-outs:

rescattering: daughter particles undergo elastic scattering or pseudo-elastic scattering through a different resonance → parent particle is not reconstructed → loss of signal

regeneration: pseudo-elastic scattering of decay products ($\pi K \rightarrow K^{*0}$, $KK \rightarrow \phi$ etc.) → increased yields

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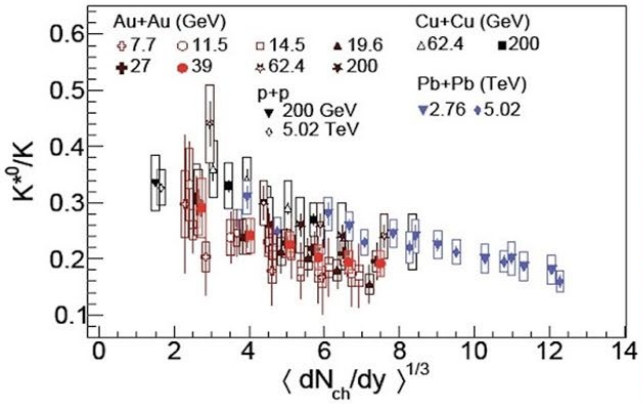
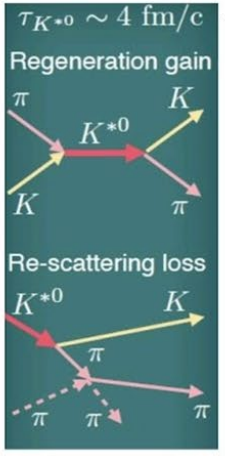
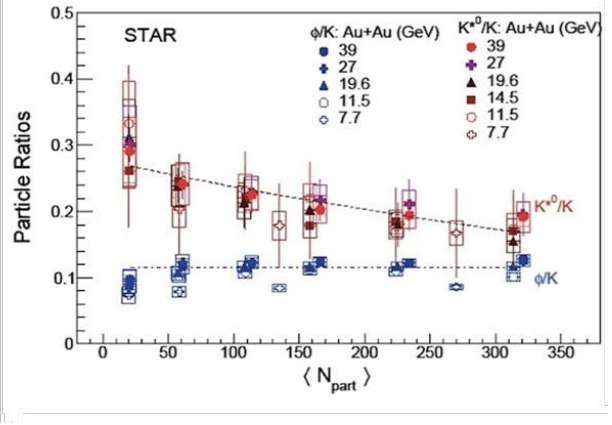




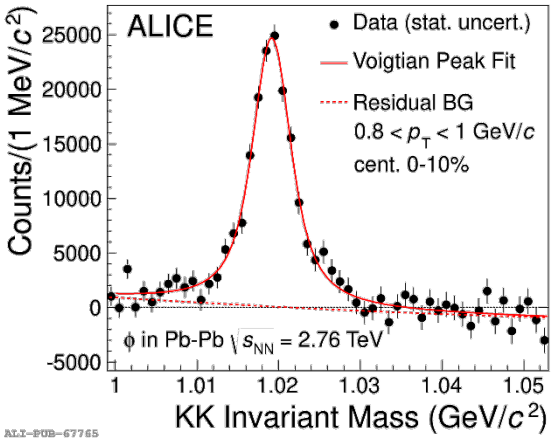


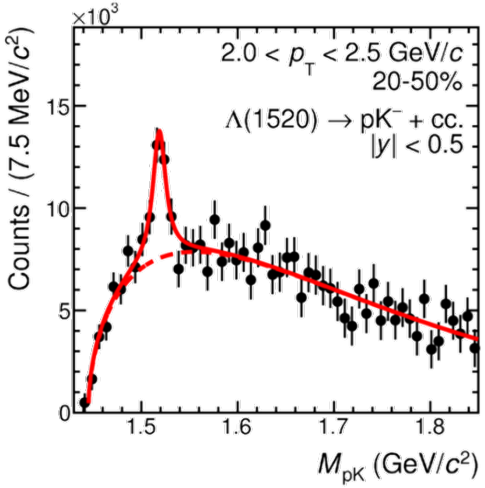
- Precise measurements at NICA are needed to validate description of the hadronic phase in models

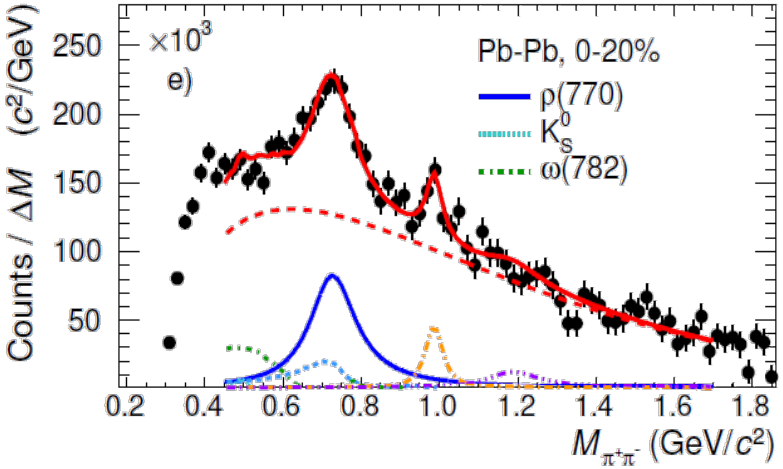
- suppressed production of short-lived resonances ($\tau < 20$ fm/c) in central A+A collisions → rescattering takes over the regeneration
- no modification for longer-lived resonances, ϕ-meson ($\tau \sim 40$ fm/c)
- yield modification depends on event multiplicity, not on collision system/energy

Resonance reconstruction

- Hadronic decays of resonances are studied with the invariant mass method in the experiments
- After subtraction of uncorrelated combinatorial background estimated with mixed-event pairs, like-sigh pairs, rotation pairs etc., the resonance peaks are approximated with a given peak-model (rBW + mass resolution + mass-dependent width + phase space correction + …) + background function
- Examples of invariant mass distributions and fits from ALICE for ϕ, $\Lambda(1520)$ and $\rho(770)^0$:





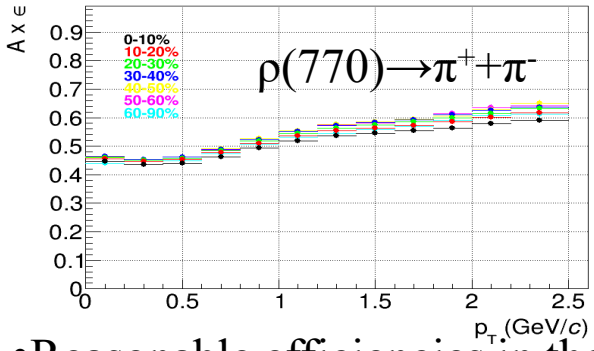


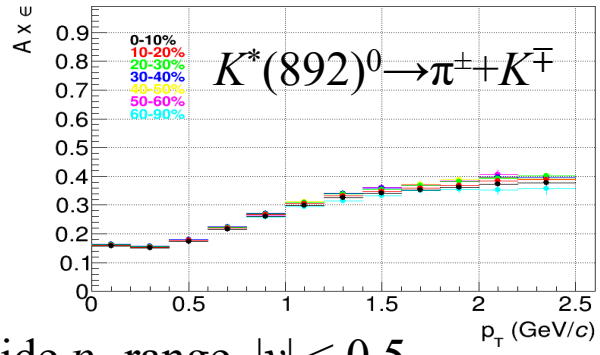
- For most of the cases, the peak models are inspired by theory and measurement in elementary e^+e^- and/or pp collisions where medium effects are not as important
- Line shape modifications will result in the change of the measured yield and masses/widths

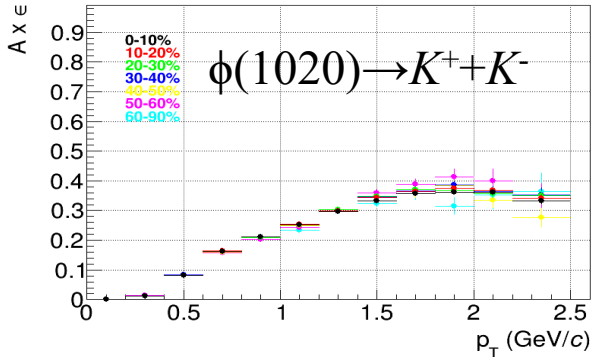
Studies for resonances reconstruction possibility at NICA-MPD in Bi+Bi collisions at $\sqrt{s_{NN}} = 9.2$ GeV

Reconstruction efficiencies and Mass resolutions

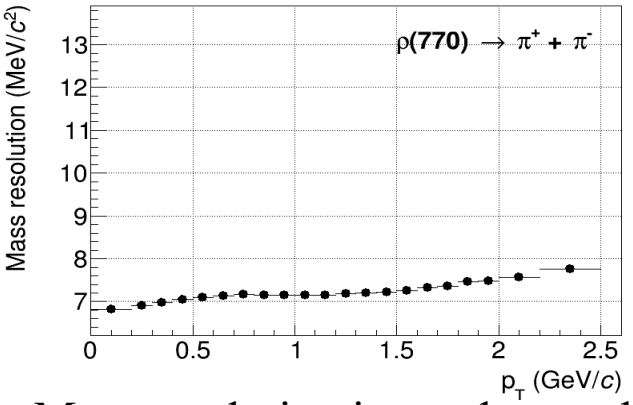
- Full chain simulation and reconstruction with UrQMD v.3.4 (BiBi@9.2 GeV, 50M events)
- Particles propagation through the MPD with 'mpdroot' (Geant v.4):
  - ✓realistic simulation of subsystem response (raw signals)
  - ✓track/signal reconstruction and pattern recognition
- Typical reconstruction efficiencies (A x $\in$) at different centralities, $|y| < 0.5$

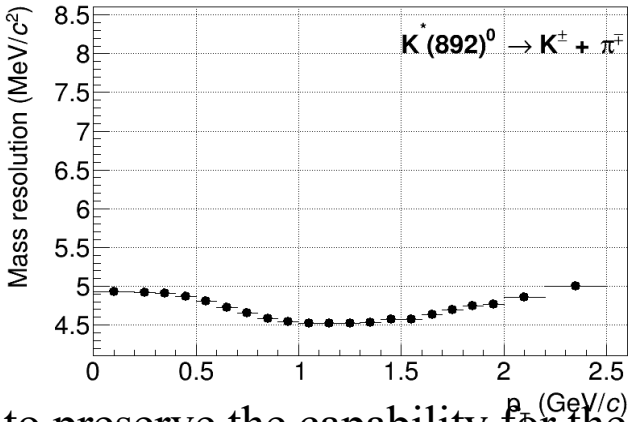


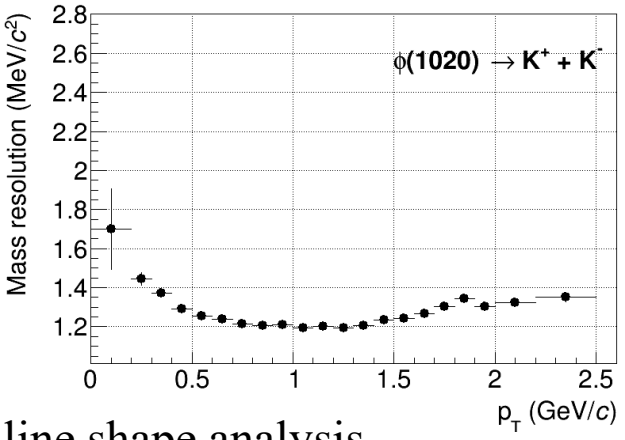




- Reasonable efficiencies in the wide p_T range, $|y| < 0.5$
- Measurements are possible from 0 momentum for $K^*(892)^0$, ρ(770) and from 0.2 – 0.4 GeV/c for ϕ(1020)
- Modest centrality dependence





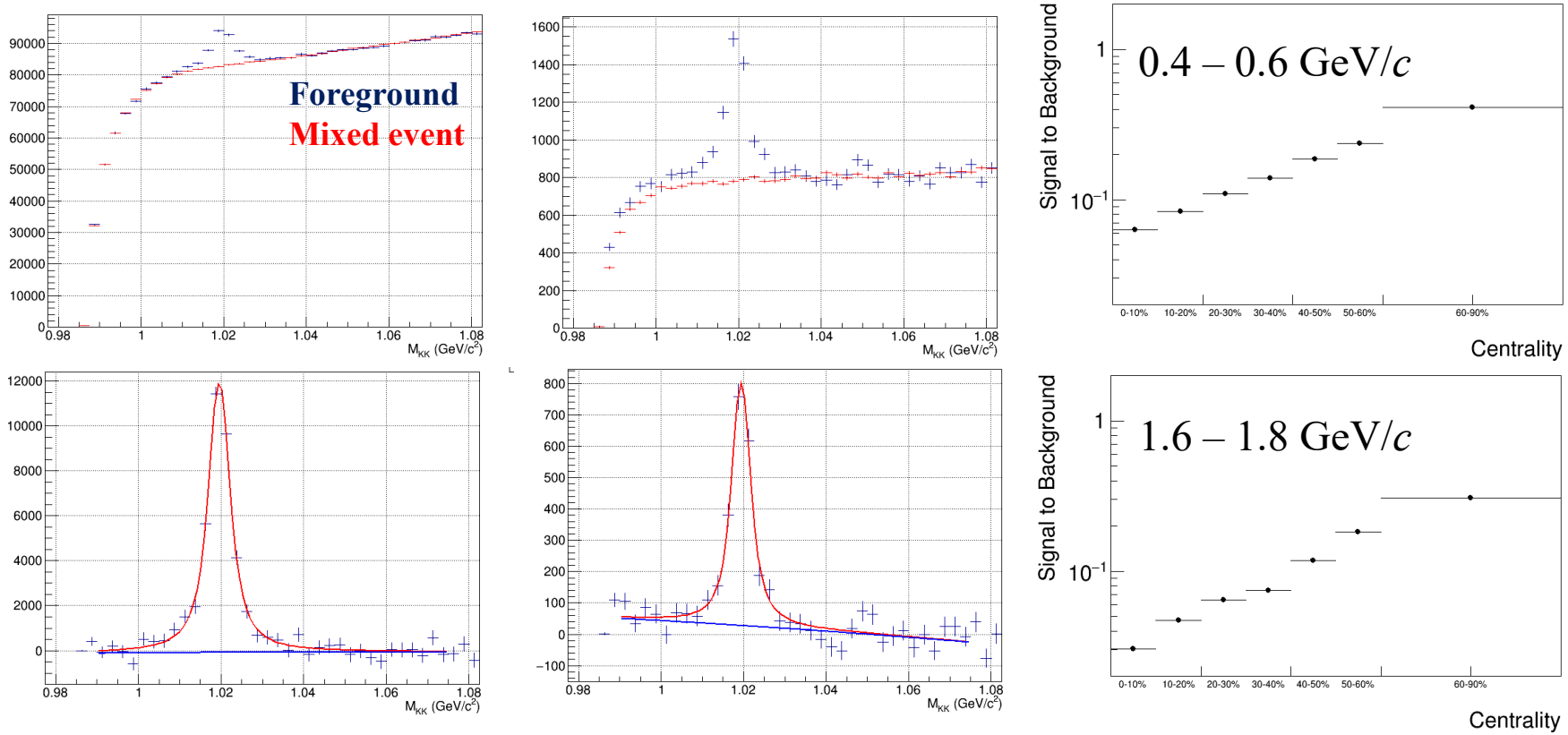


- Mass resolution is good enough to preserve the capability for the line shape analysis

ϕ(1020), reconstructed peaks

- Full chain simulation and reconstruction, $p_T = 0.4 - 0.6$ GeV/c, $\phi(1020) \rightarrow K^+ + K^-$, $|y| < 0.5$

0 – 10% 60 – 90%

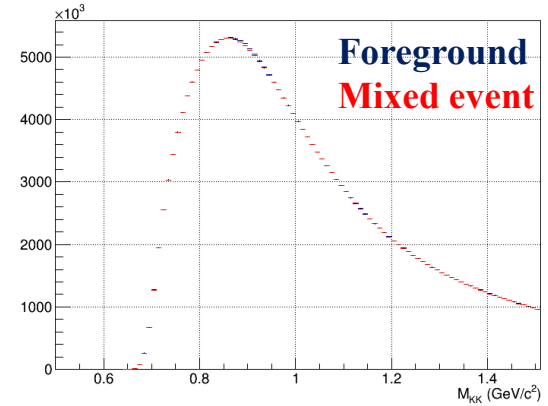


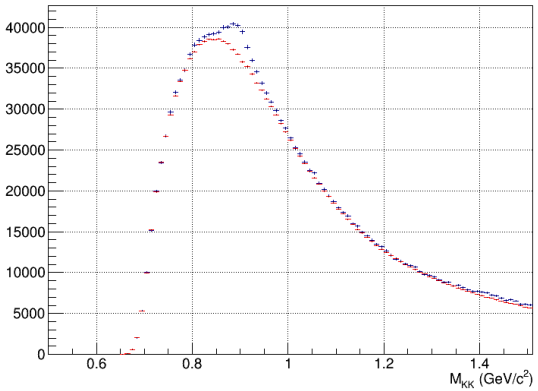
- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Distributions are fit to Voigtian function + polynomial (mass resolution fixed to estimated value, Γ – free parameter)
- Signal can be reconstructed at $p_T > 0.2$ GeV/c, high-p_T reach is limited by available statistics
- S/B ratios deteriorates with increasing centrality

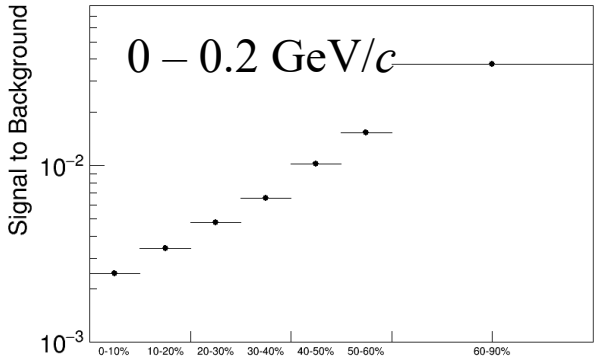
$K^*(892)^0$, reconstructed peaks

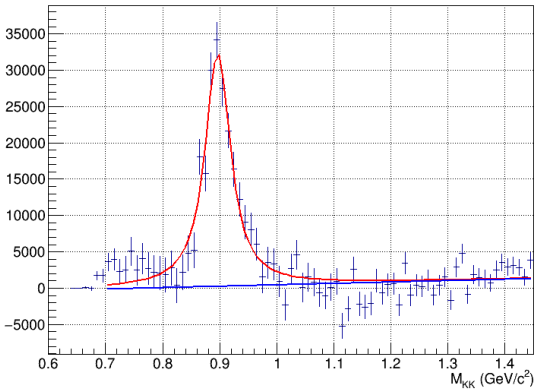
- Full chain simulation and reconstruction, $p_T = 0.0 - 0.2$ GeV/c, $K^*(892)^0 \rightarrow \pi^{\pm} + K^{\mp}$, $|y| < 0.5$

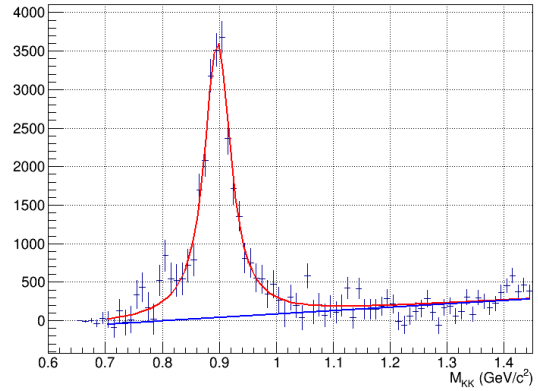
0 – 10% 60 – 90%

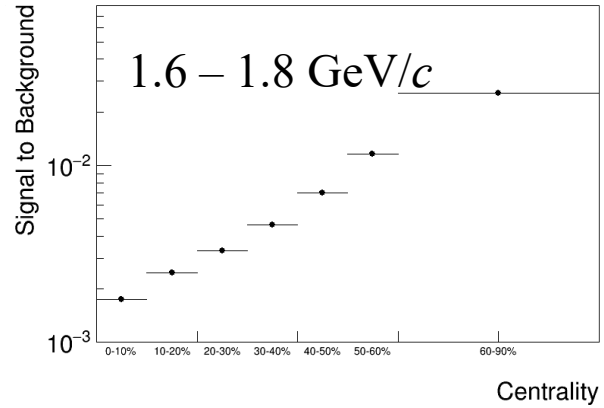








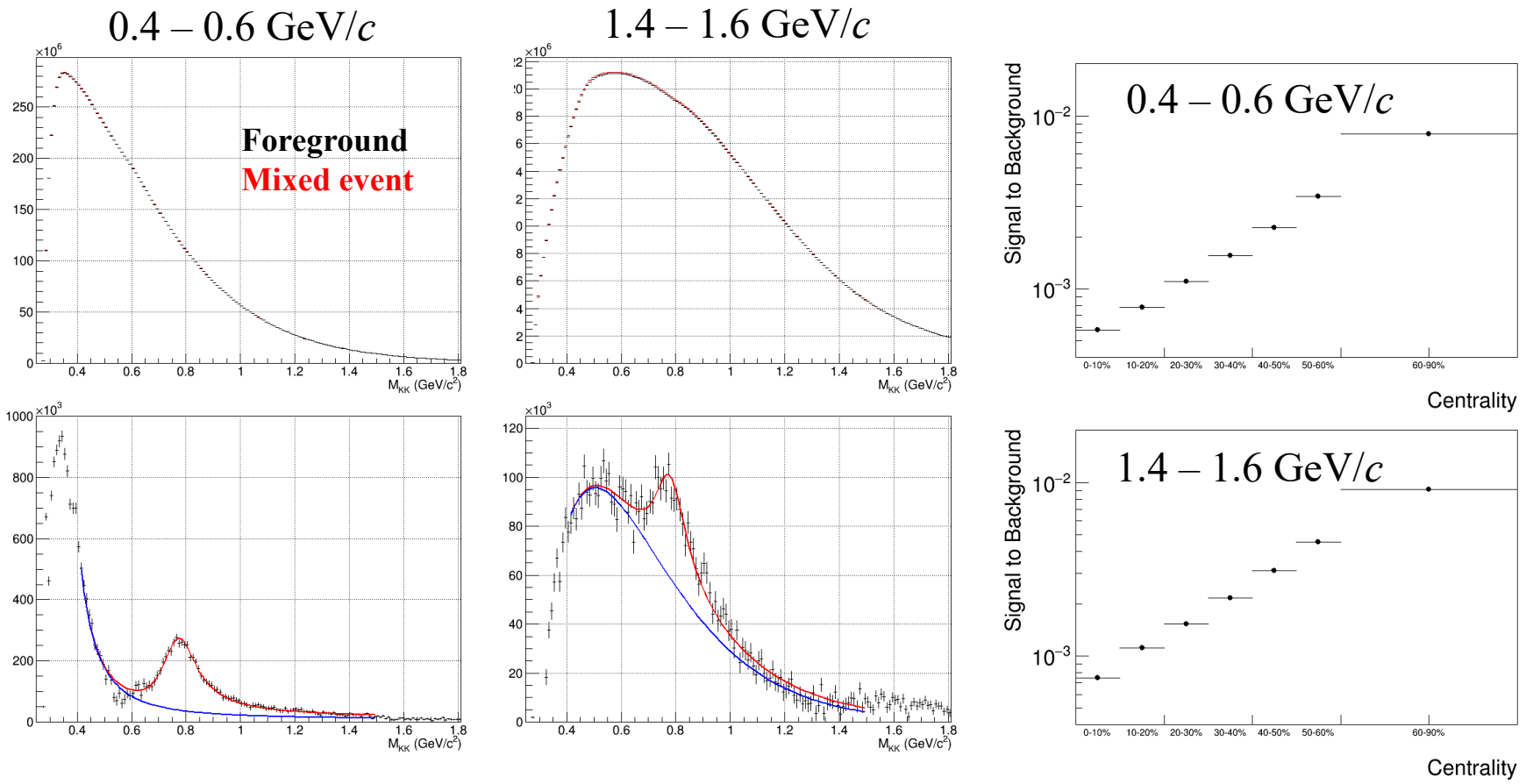




- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Distributions are fit to Voigtian function + polynomial (mass resolution fixed to estimated value, Γ – free parameter)
- Signal can be reconstructed at $p_T > 0$, high-p_T reach is limited by available statistics
- S/B ratios deteriorates with increasing centrality

ρ(770), reconstructed peaks

- Full chain simulation and reconstruction, centrality 0-10%, $\rho(770) \rightarrow \pi^+ + \pi^-$, $|y| < 0.5$



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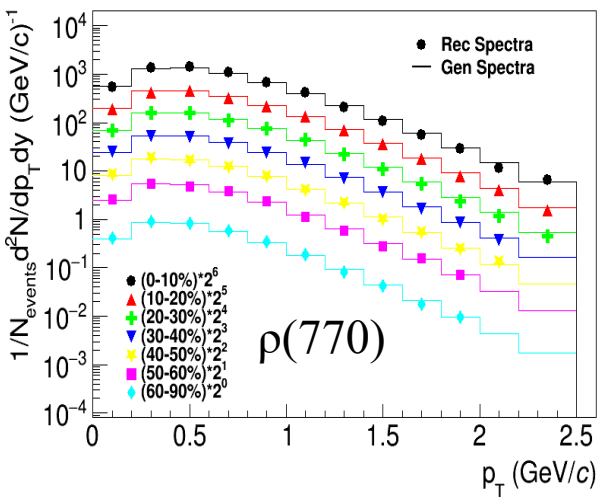
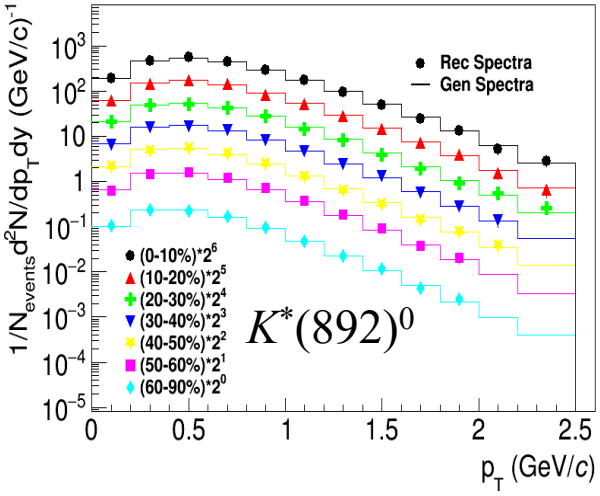
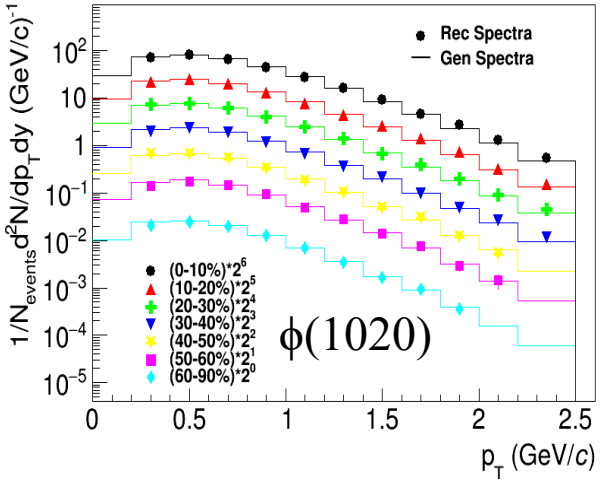
- S/B ratios deteriorates with increasing centrality

Production spectra and MC closure test

- Full chain simulation and reconstruction, ranges are limited by the possibility to extract signals, $|y| < 0.5$







- Reconstructed spectra match the generated ones within uncertainties
- First measurements for resonances in centrality dependent analysis will be possible with accumulation of ~ 10^8 Bi+Bi@9.2 GeV events
- Measurements are possible starting from ~ zero momentum → sample most of the yield, sensitive to possible modifications

Conclusions and outlook

- Measurement of resonances contribute to the MPD physical program
  - ✓hadronic phase properties, strangeness production, hadronization mechanisms and collectivity, hadrochemistry, spin alignment etc …
- First measurements for ρ(770), $K^*(892)^0$, ϕ(1020) resonances in centrality dependent analysis will be possible with ~10^8 sampled Bi + Bi collisions at $\sqrt{s_{NN}}$ = 9.2 GeV
- Measurements are possible starting from very low momenta (for most of the cases from zero momenta) with decent mass resolution → high sensitivity to different physics phenomena most prominent at low p_T
- Feasibility study of the reconstruction of other resonances such as $K^*(892)^{\pm} \rightarrow \pi^{\pm} K_s$, $\Sigma(1385)^{\pm} \rightarrow \pi^{\pm} \Lambda$, $\Lambda(1520) \rightarrow pK^-$ in Bi + Bi collisions at $\sqrt{s_{NN}}$ = 9.2 GeV is required for systematic study of resonance production and is in progress

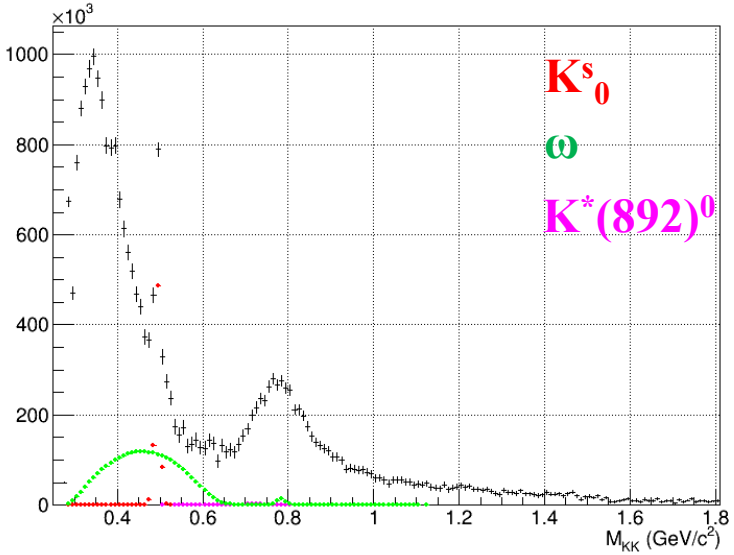
We acknowledge support from Russian Ministry of Education and Science, state assignment for fundamental research (code FSEG-2024-0033)

Backup

ρ(770), peak shape and correlated background

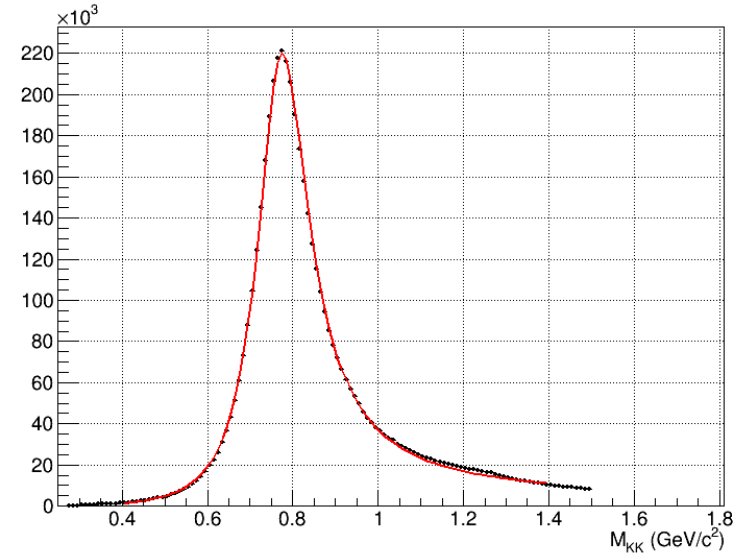
•Full chain simulation and reconstruction, centrality 0-10%, $\rho(770) \rightarrow \pi^+ + \pi^-$, $|y| < 0.5$

- Peak-like contribution from:
  - ✓$K_s^0 \rightarrow \pi^+\pi^-$
  - ✓$\omega \rightarrow \pi^+\pi^-$
  - ✓$\omega \rightarrow \pi^+\pi^-\pi^0$ (with missing π^0)
  - ✓$K^*(892)^0 \rightarrow \pi^{\pm}K^{\pm}$ (with misidentified kaon)
- Contributions must be measured in advance and subtracted (or accounted for)



- Resonances peak shape Breit-Wigner (BW) with peak shape modifications:

✓detector mass resolution
✓dependence of resonance width on mass (for wide resonances)
✓phase space correction
✓Bose-Einstein correlations
✓mass dependence of reconstruction efficiency (for wide resonances)
✓(Partial) restoration of chiral symmetry
✓Hadronic phase modifications (rescatteringof daughter particles, regeneration)



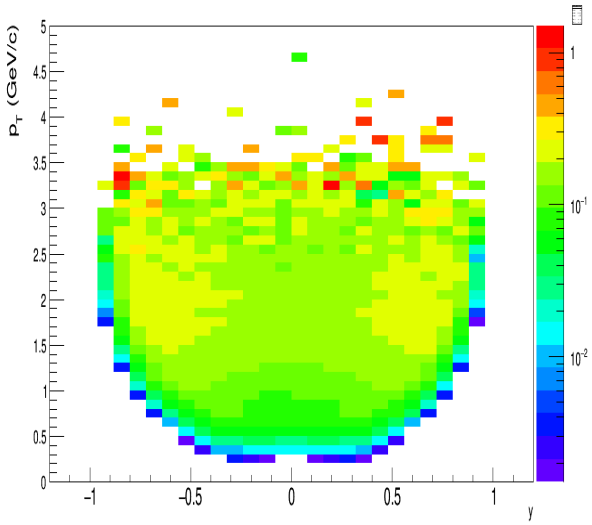
$$BW(M) = A\frac{MM_0\Gamma(M)}{(M_0^2 - M^2)^2 + M_0^2\Gamma(M)}$$

$$\Gamma(M) = \left[\frac{(M^2 - 4m_\pi^2)}{(M_0^2 - 4m_\pi^2)}\right]^{3/2} * \Gamma_0 * \left({}^{M_0}/_{M}\right)$$

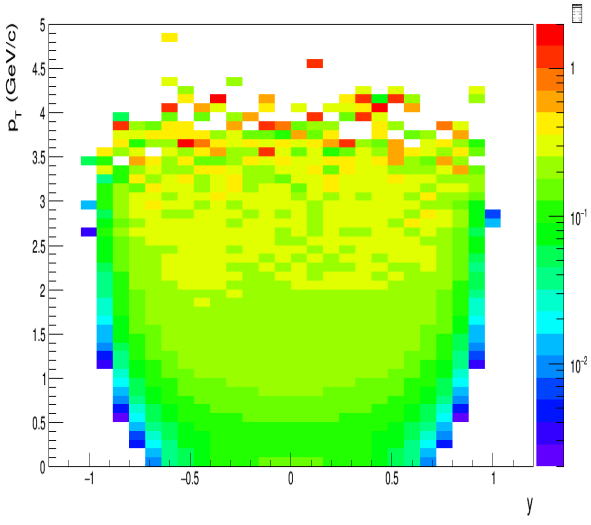
Feasibility studies, framework

- 50M simulated minimum bias Bi+Bi collisions at $\sqrt{s_{NN}}$ = 9.2 GeV using UrQMD 3.4 with default settings
- Tracked simulated particles through the MPD detector using *mpdroot*
- Decays of $\rho(770) \rightarrow \pi^+\pi^-$ ($\tau \sim 1.3$ fm/c); $K^*(892)^0 \rightarrow \pi^{\pm}K^{\mp}$ (~4); $\phi(1020) \rightarrow K^+K^-$ (~46) were reconstructed by combining all daughter particles within an event
- Analysis cuts were optimized for higher signal significance (no p_T variation)
- Event selection:
  - ✓$|z_{vrtx}| < 130$ cm, realistic distribution with $\sigma_z \sim 50$ см
- Basic track selections:
  - ✓number of TPC hits > 10
  - ✓$|\eta| < 1.0$
  - ✓$p_T > 100$ MeV/c
  - ✓TPC-TOF combined PID within 2σ
  - ✓TPC-refit for kaons and protons based on track PID hypothesis
- Primary tracks:
  - ✓$|\mathrm{DCA}(x,y,z)| < 2\sigma$
- Pairs:
  - ✓$|y| < 0.5$
- Combinatorial background:
  - ✓event mixing ($|\Delta_{\mathrm{Zvrtx}}| < 2$ cm, $|\Delta_{\mathrm{Mult}}| < 20$, $N_{\mathrm{ev}} = 10$)

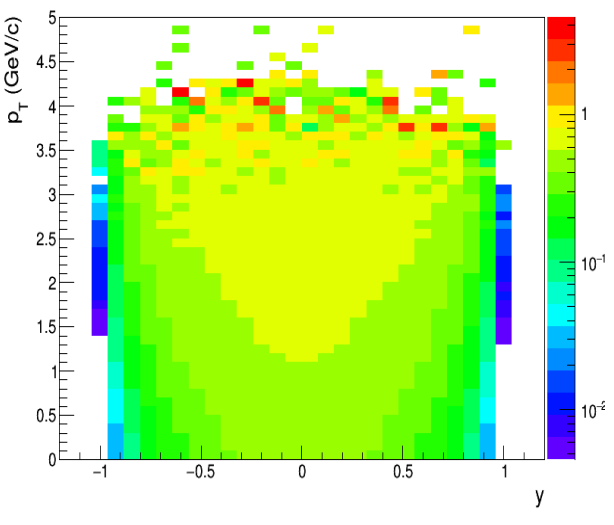
Reconstruction efficiencies 2D



$\phi(1020)$



$K^*(892)^0$



$\rho(770)$

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- Measurements are possible from 0 momentum for $K^*(892)^0$, $\rho(770)$ and from 0.2 – 0.4 GeV/c for $\phi(1020)$