Study of production features, modeling and optimization of algorithms for reconstruction of short-lived hadronic resonances in the MPD experimental setup at the NICA collider

D. Ivanishchev, D. Kotov, M. Malaev, V. Riabov, Yu. Ryabov for the MPD Collaboration

This work was supported by RFBR according to the research project № 18-02-40038

Outline

- Motivation for resonance studies in heavy-ion collisions
- Expectations for resonance properties in heavy-ion collisions at NICA energies
- Feasibility studies for resonance reconstruction at NICA-MPD
- Summary

Study of production features, modeling and optimization of algorithms for reconstruction of short-lived hadronic resonances in the MPD experimental setup at the NICA collider

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- ✓ study of the resonance properties in heavy-ion collisions at NICA
- ✓ feasibility studies for reconstruction of resonances in the MPD detector

Resonances in heavy-ion collisions

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

$\rho(770)$	$K^*(892)^0$	$K^*(892)^+$	$\phi(1020)$	$\Sigma(1385)^\pm$	$\Lambda(1520)$	$\Xi(1530)$
$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$d\bar{s}$	$u\bar{s}$	$s\bar{s}$	uus dds	uds	uss

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	$\pi^- K^+$	66.7
ϕ	1019	4.27	K^+K^-	48.9
Σ^{*+}	1383	36	$\pi^+\Lambda$	87
Σ^{*-}	1387	39.4	$\pi^-\Lambda$	87
$\Lambda(1520)$	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, cτ, 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.

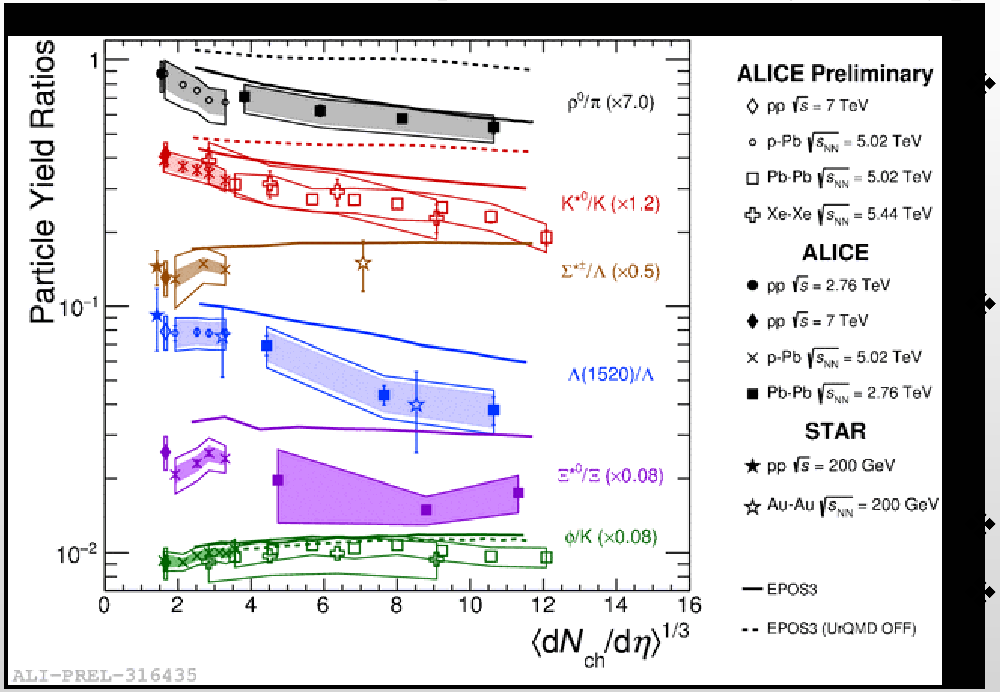
Hadronic phase and medium modifications

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
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

- Resonances have small lifetimes of $c\tau \sim 1$ - 45 fm, part of them decays in the fireball
- 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 ($\pi K \to K^{*0}$, $KK \to \phi$ etc.) → increased yields

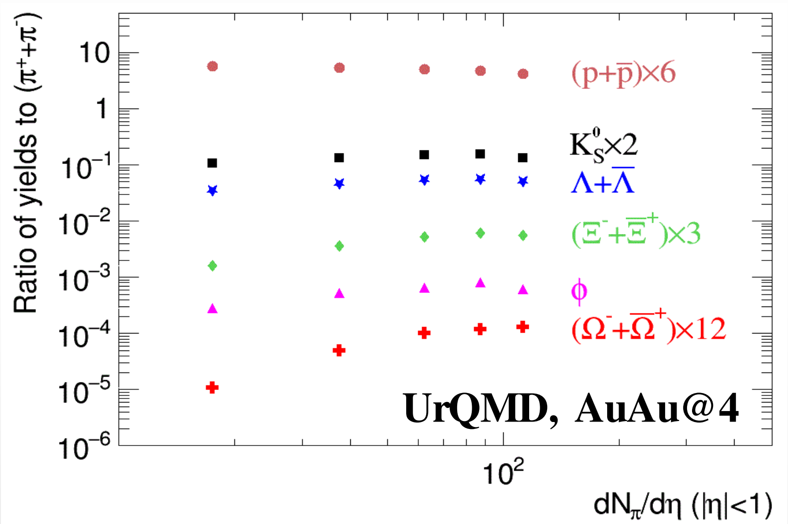


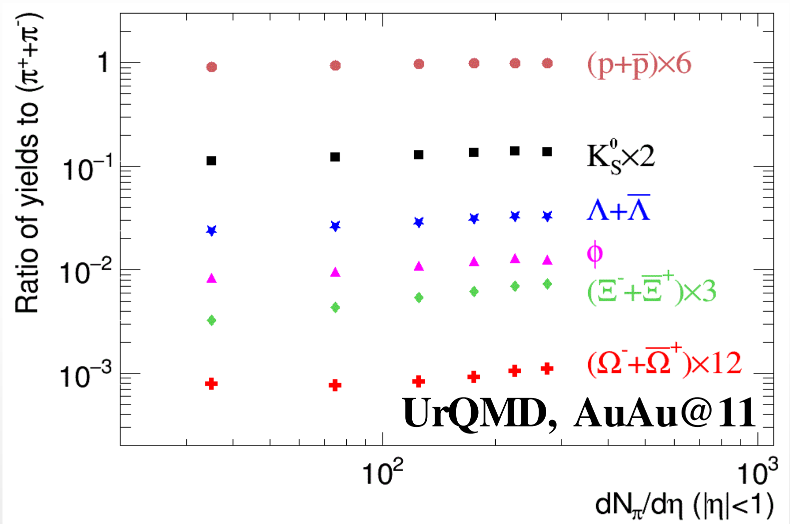
- SPS/RHIC/LHC observed multiplicity dependent suppression of ρ/π, K^*/K, Λ^*/Λ ratios, resonances with $c\tau \leq 20$ fm/c. Ratios of longer lived resonances are not affected
- Results support the existence of a hadronic phase that lives long enough to cause a significant reduction of the reconstructed yields of short lived resonances
- Hadronic phase lifetime, $\tau \sim 10$ fm/c*
- NICA: $<dN_{ch}/d\eta>^{1/3} \sim 6$** → RHIC/LHC report modifications at such multiplicities

* ALICE, Phys.Lett.B 802 (2020) 135225, Phys.Rev.C 99 (2019) 024905
** PHENIX, Phys.Rev.C 93 (2016) 2, 024901

Model predictions for resonances at NICA

- UrQMD, PHSD, AMPT, EPOS …
- General predictions:
  - ✓ resonances are copiously produced and can be used to study physics of heavy-ion collisions
  - ✓ models predict enhanced production of particles with strangeness, for example UrQMD:

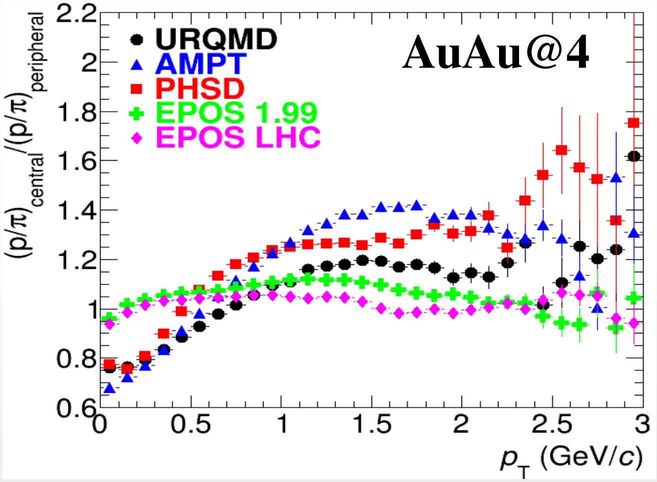


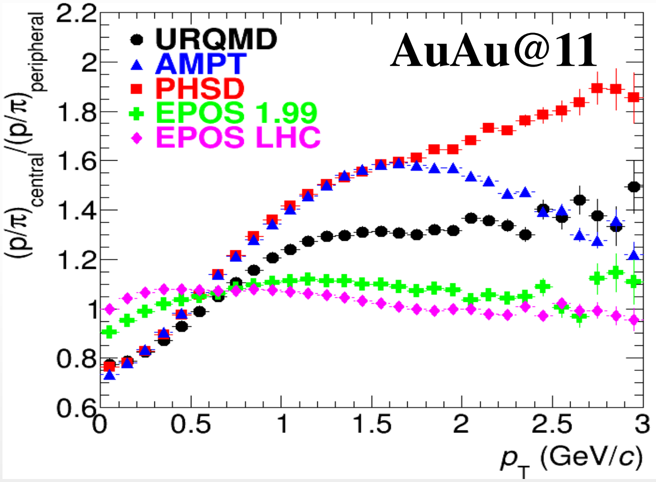


- ➢ predictions of event generators are qualitatively similar
- ➢ enhancement is more pronounced for particles containing a larger number of s-quarks
- ➢ relative enhancement is stronger at lower collision energies
- ➢ $\phi(1020)$ meson with hidden strangeness (a key observable) behaves like a hadron with open strangeness

Model predictions for resonances at NICA

- UrQMD, PHSD, AMPT, EPOS …
- General predictions:
  - ✓ resonances are still copiously produced and can be used to study physics of heavy-ion collisions
  - ✓ models predict enhanced production of particles with strangeness
  - ✓ baryon/meson (B/M) ratios evolve with centrality/multiplicity





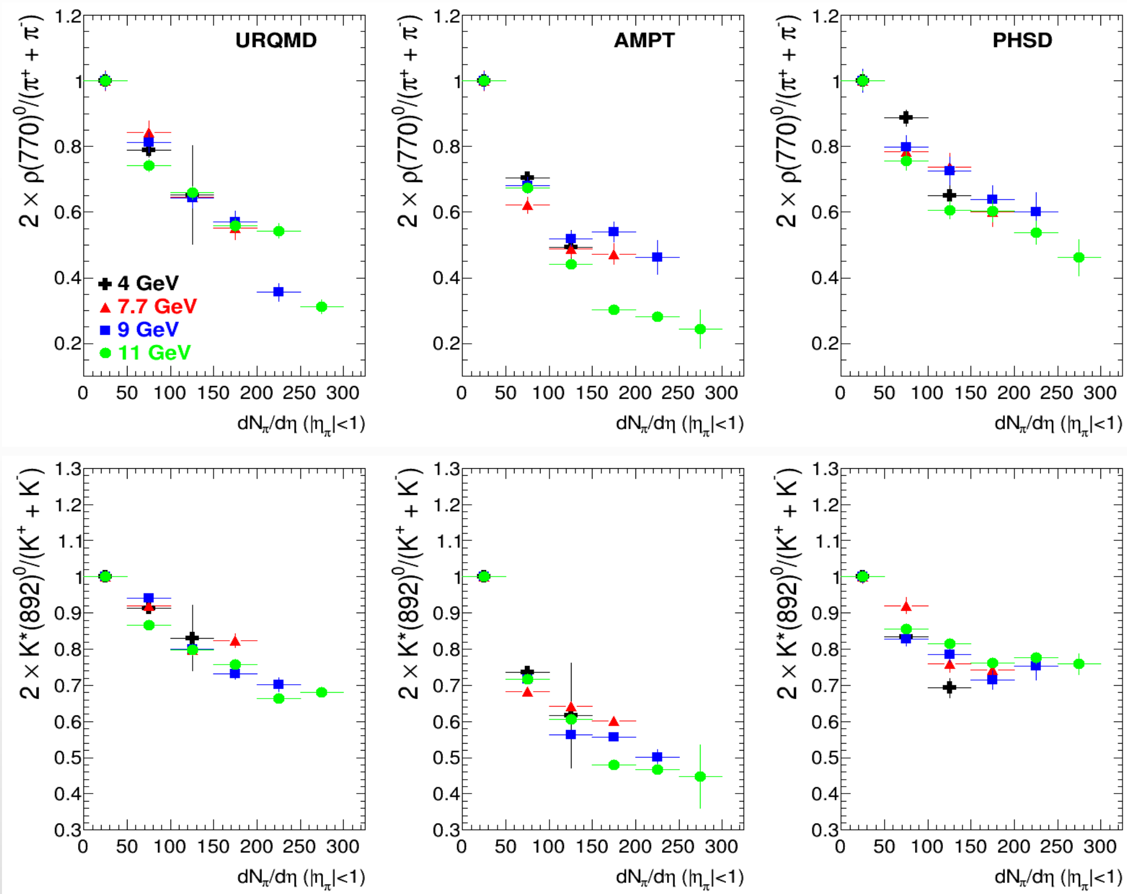
- ➢ strong model and collision energy dependence of B/M ratios
- ➢ predictions are qualitatively similar to experimental observations at RHIC and the LHC
- ➢ origin of the evolution of B/M ratios is not understood (radial flow, quark recombination, …)
- ➢ measurements of p/ϕ(1020) and p/K*(892) ratios will help to disentangle the mechanisms that shape the particle p_T spectra at low and intermediate momenta

- Eventually, model predictions (integrated yields, <p_T>, particle ratios etc.) should be compared to data to differentiate different model assumptions

Hadronic phase, Au+Au collisions at $\sqrt{s_{NN}}$ = 4-11 GeV

❖ Models with hadronic cascades (UrQMD, PHSD, AMPT) → properties of hadronic phase

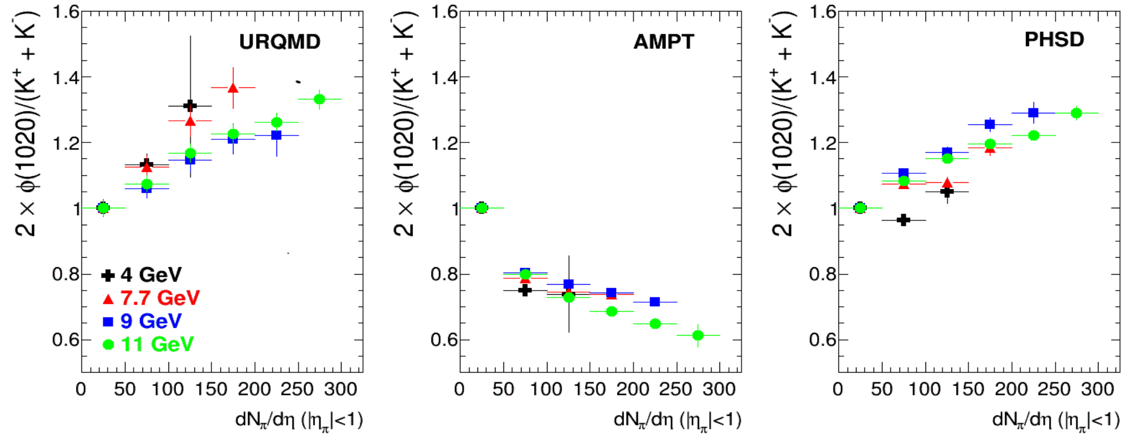
❖ Ratios are shown normalized to most peripheral collisions → start at unity in peripheral collisions

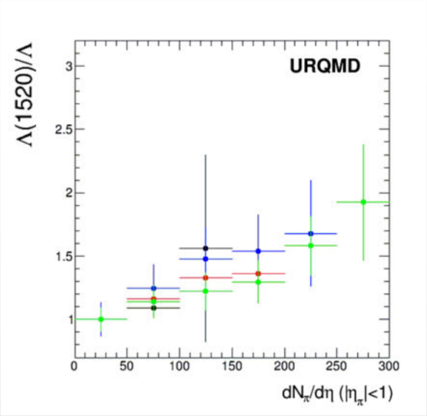


- models predict suppression of ρ/π and K^*/K ratios in Au+Au@4-11, resonances with small cτ
- suppression depends on the final state multiplicity rather than on collision energy
- modifications occur at low momentum as expected for the hadronic phase effects, ratios converge to unity at high momentum

Hadronic phase, Au+Au collisions at $\sqrt{s_{NN}}$ = 4-11 GeV

- ❖ Models with hadronic cascades (UrQMD, PHSD, AMPT) → properties of hadronic phase
- ❖ Ratios are shown normalized to most peripheral collisions → start at unity in peripheral collisions





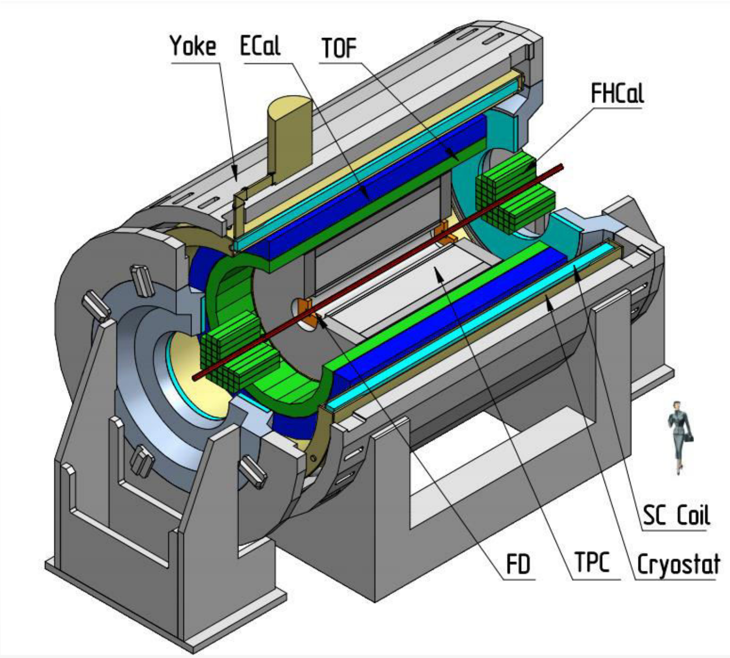
- ➢ φ(1020)/K ratio is predicted to be enhanced by UrQMD and PHSD and suppressed by AMPT
- ➢ Λ(1520) is available in UrQMD only, Λ(1520)/Λ ratio gradually increases with multiplicity at all energies
- ➢ φ(1020)/K and Λ(1520)/Λ ratios are consistent for different collision energies at similar multiplicities

- ❖ Models predict yield modifications qualitatively similar to those obtained at SPS/RHIC/LHC:
  - ✓ lifetime and density of the hadronic phase are high enough
  - ✓ modification of particle properties in the hadronic phase should be taken into account when model predictions for different observables are compared to data
  - ✓ study of short-lived resonances is a unique tool to tune the hadronic phase simulations

MPD experiment, Stage-1

- Stage-1: **TPC, TOF, FFD, FHCAL и ECAL**
- Startup in 2022

- Simulate AuAu@4-11 collisions using different event generators
- Propagate particles through the MPD, 'mpdroot':
  - ✓ Geant (v.3 or v.4) for particle transport
  - ✓ realistic simulation of subsystem response (raw signals)
  - ✓ track/signal reconstruction and pattern recognition



- Basic event and track selections:
  - ✓ event selection: $|Z_{vrtx}| < 50$ cm
  - ✓ track selection:
    - number of TPC hits > 24
    - $|\eta| < 1.0$
    - |DCA to PV| < 3σ for primary tracks
    - V0 topology cuts for weakly decaying secondaries
    - $p_T > 50$ MeV/c
    - TPC-TOF combined π/K/p PID
  - ✓ combinatorial background:
    - event mixing ($|\Delta_{Zvrtx}| < 2$ cm, $|\Delta_{Mult}| < 20$, $N_{ev} = 10$)

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

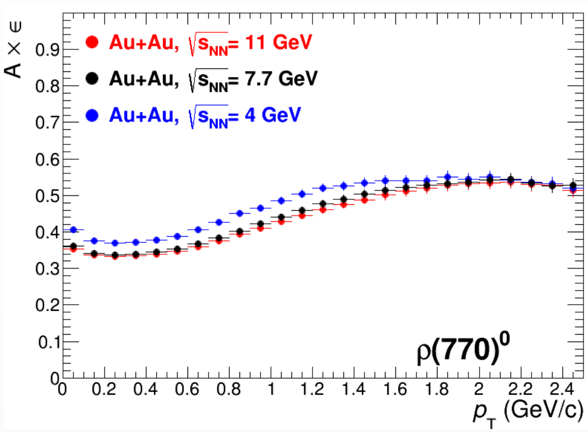
TOF, EMC: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.4$

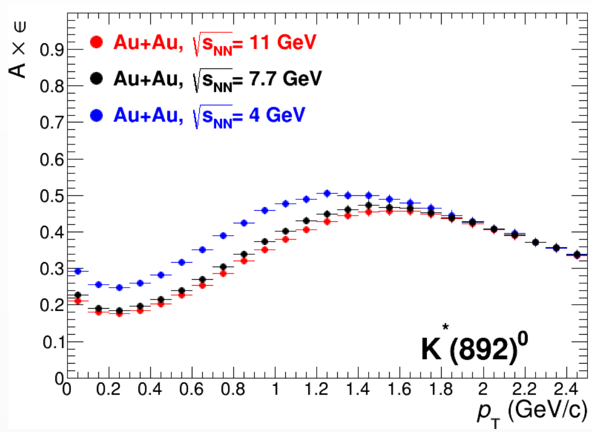
FFD: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$

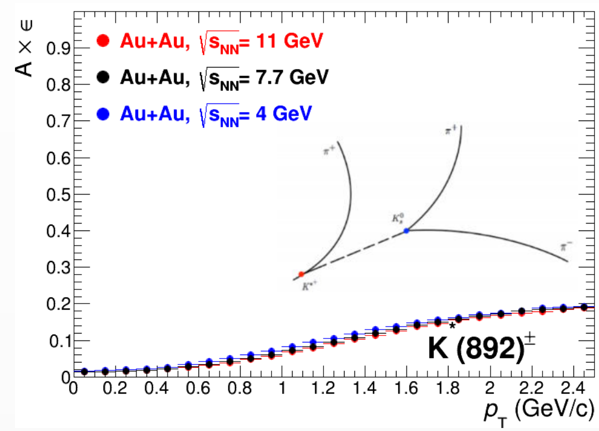
FHCAL: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

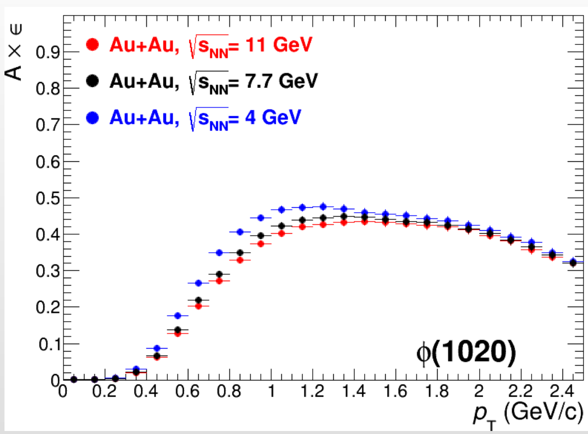
Reconstruction efficiency: ρ(770), K*(892), ϕ(1020), Λ(1520)

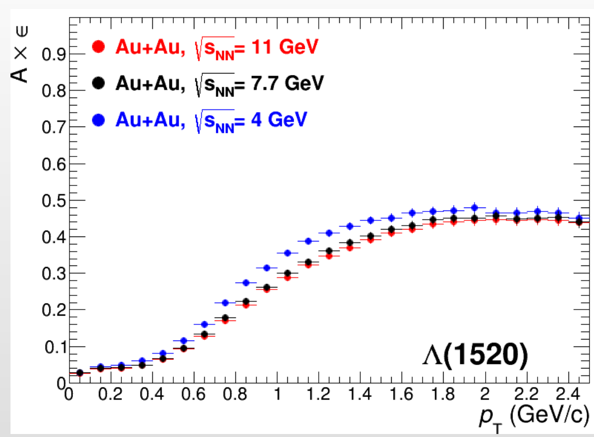
❖ Typical reconstruction efficiencies (A x ∈) in AuAu @ **4**, **7.7** and **11** GeV, |y| < 1









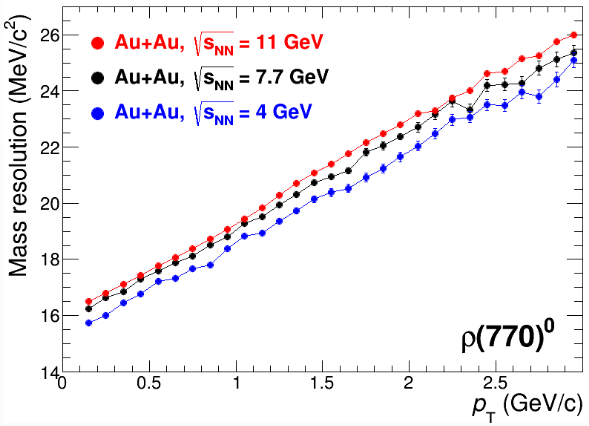


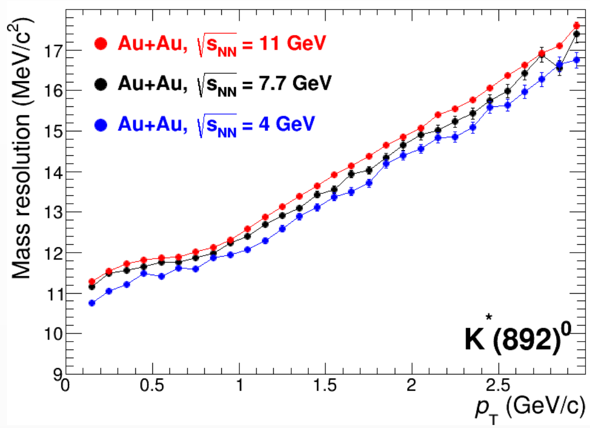
❖ Reasonable efficiencies in the wide p_T range, |y| < 1

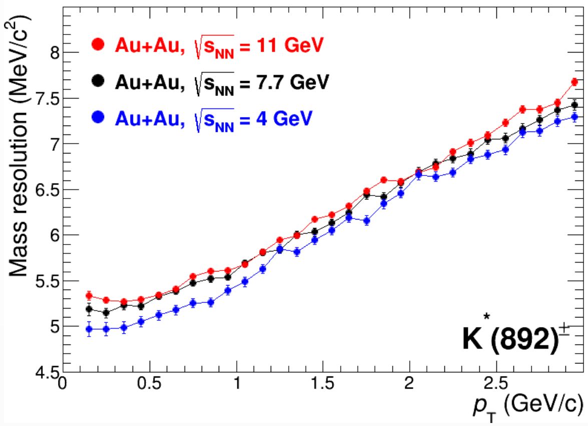
❖ Modest multiplicity (and/or $\sqrt{s_{NN}}$) dependence

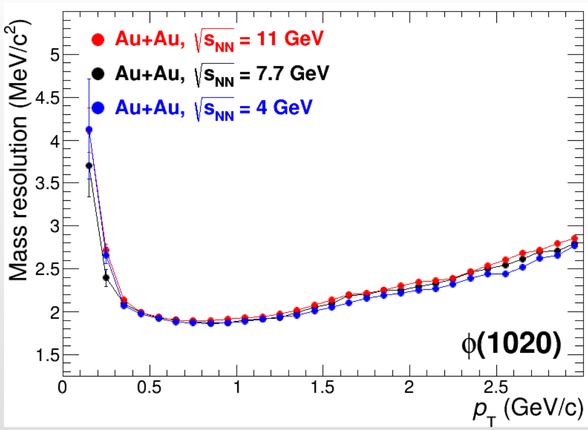
Mass resolution: $\rho(770)$, $K^*(892)$, $\phi(1020)$, $\Lambda(1520)$

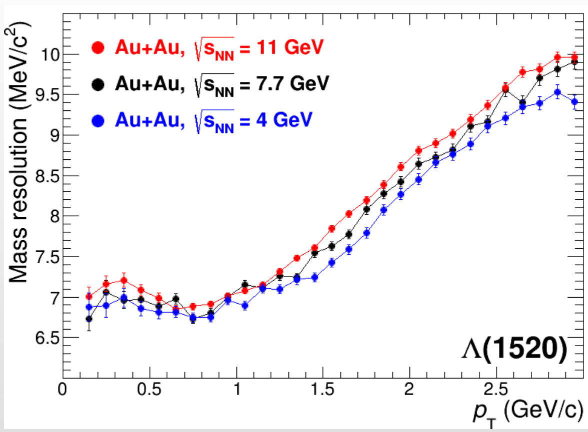
❖ Detector mass resolution ($m_{reconstructed} - m_{generated}$) in AuAu @ **4**, **7.7** and **11** GeV, $|y| < 1$









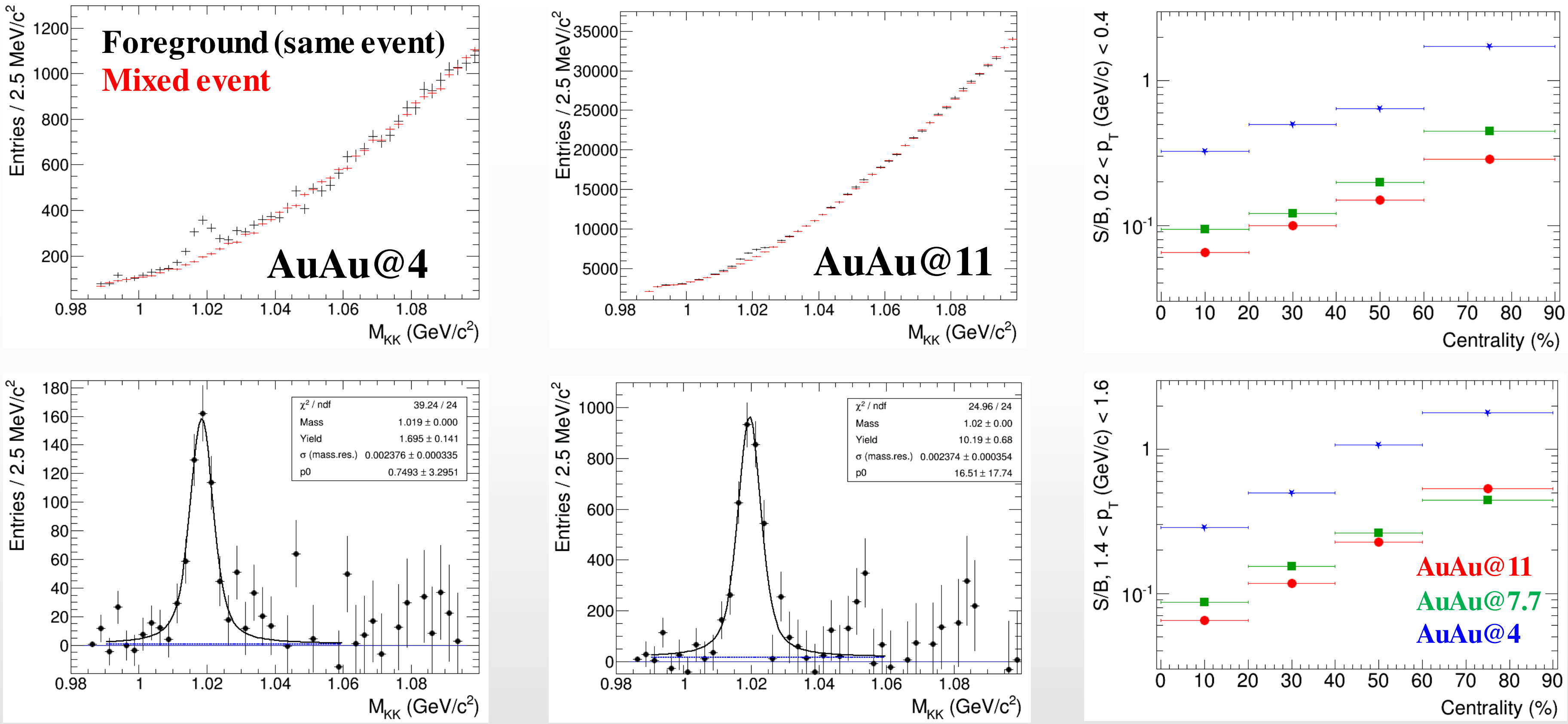


❖ Acceptable mass resolution

❖ Modest multiplicity (and/or $\sqrt{s_{NN}}$) dependence

ϕ(1020), reconstructed peaks

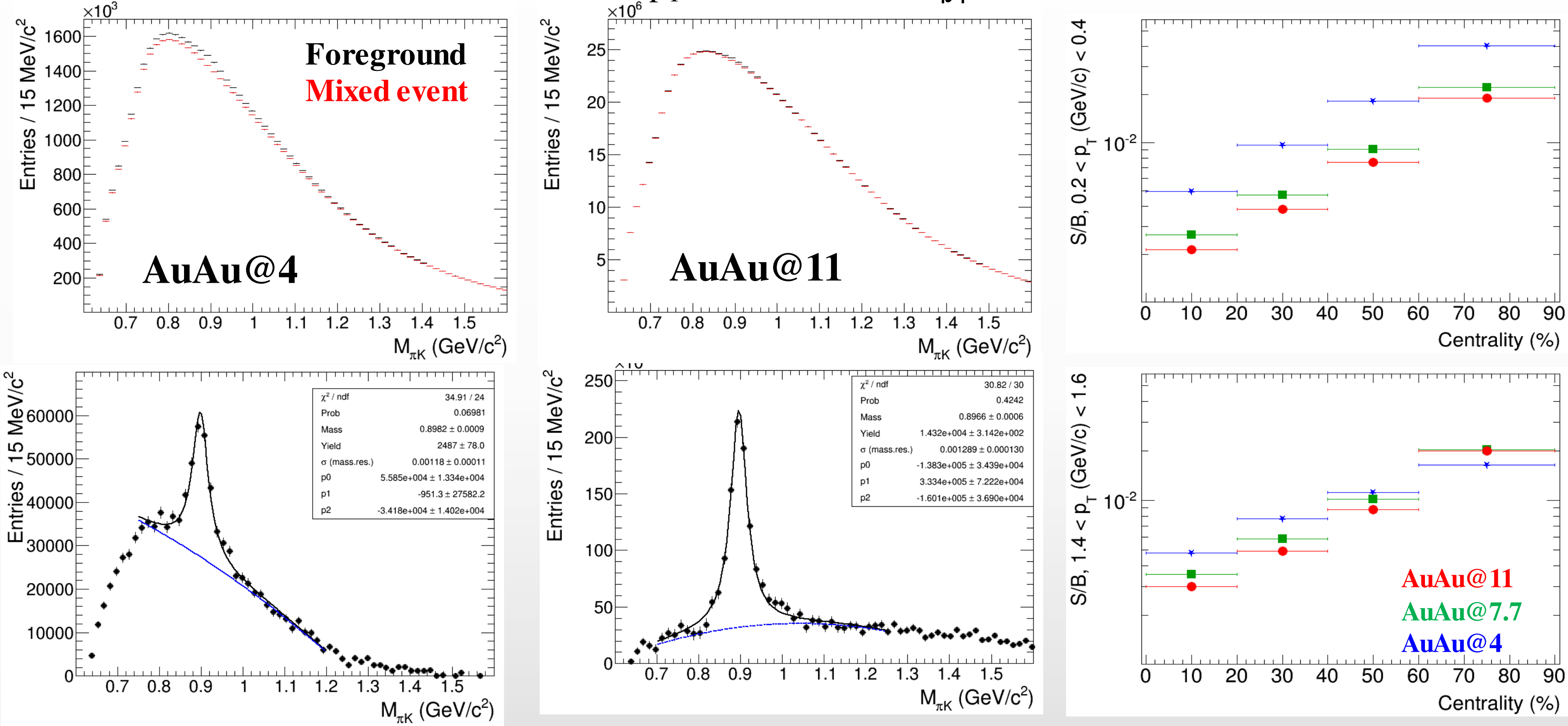
- UrQMD v.3.4: AuAu@11 (10M events), AuAu@7.7 (5M events), AuAu@4 (5M events)
- Full chain simulation and reconstruction, p_T = 0.2-0.4 GeV/c, |y| < 1



- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Distributions are fit to Voigtian function + polynomial
- 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 and collision energy

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

- ❖ UrQMD v.3.4: AuAu@11 (10M events), AuAu@7.7 (5M events), AuAu@4 (5M events)
- ❖ Full chain simulation and reconstruction, p_T = 0.2-0.4 GeV/c, |y| < 1

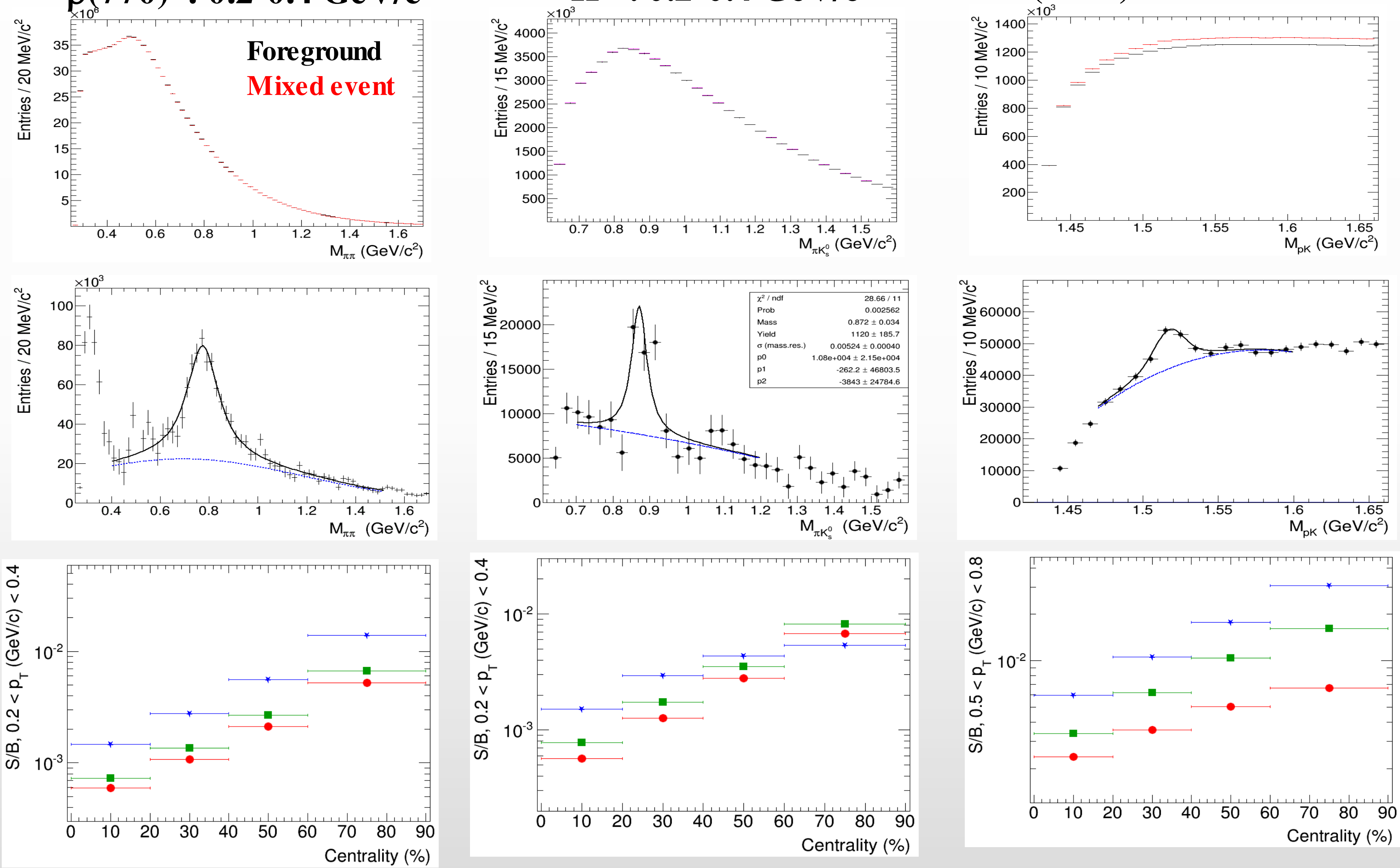


- ❖ Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- ❖ Distributions are fit to Voigtian function + polynomial
- ❖ Signal can be reconstructed at p_T > 0.2 GeV/c, high-p_T reach is limited by available statistics
- ❖ S/B ratios deteriorates with increasing centrality and collision energy

$K^*(892)$ and $\Lambda(1520)$, reconstructed peaks

❖ UrQMD v.3.4: AuAu@11 (10M events), **AuAu@7.7** (5M events), AuAu@4 (5M events), $|y| < 1$

$\rho(770)^0$: 0.2-0.4 GeV/c **$K^{*\pm}$: 0.2-0.4 GeV/c** **$\Lambda(1520)$: 0.5-0.8 GeV/c**

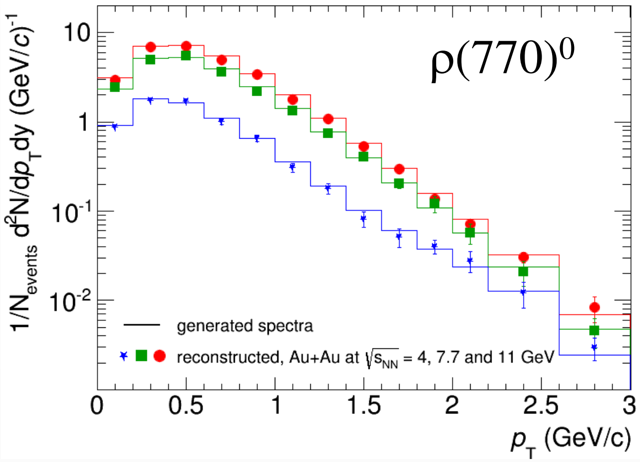


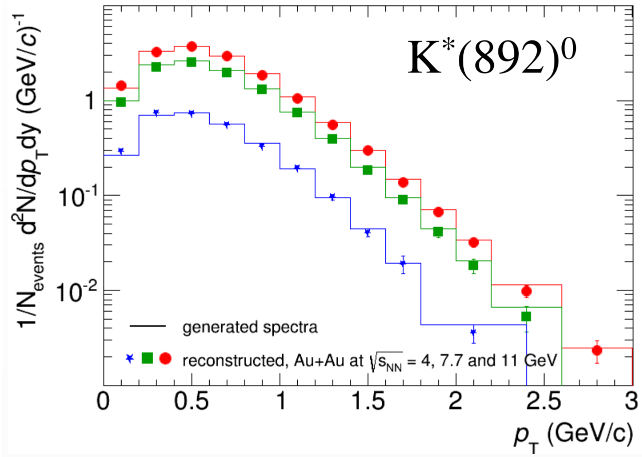
❖ Signal can be reconstructed from zero momentum, high-p_T reach is limited by statistics

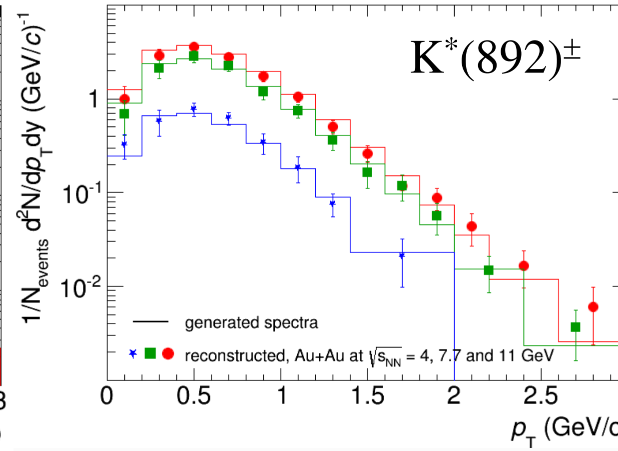
❖ S/B ratios deteriorates with increasing centrality and collision energy

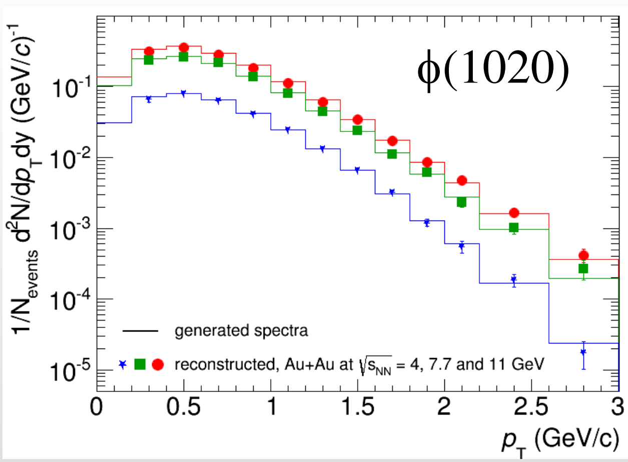
MC closure tests: ρ, $K^{*0,\pm}$, ϕ, Λ^{*}

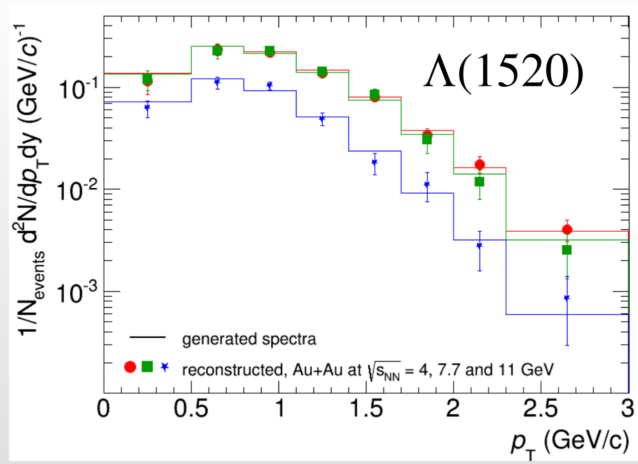
- UrQMD v.3.4: AuAu@11 (10M events), AuAu@7.7 (5M events), AuAu@4 (5M events)
- Full chain simulation and reconstruction, p_T ranges are limited by the possibility to extract signals, $|y| < 1$







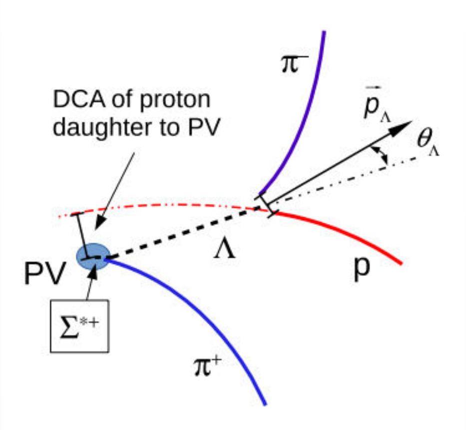




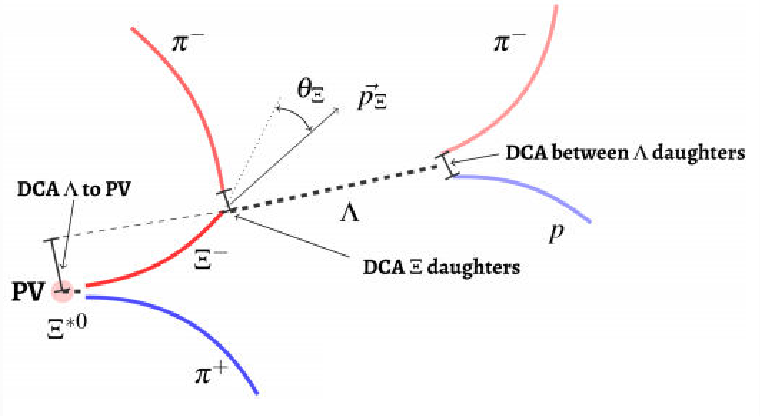
- Reconstructed spectra match the generated ones within uncertainties
- Measurements are possible starting from ~ zero momentum, sample p_T spectra in a wide range
- Maximum raw yields (smallest stat. uncertainties) are extracted at ~ 300 MeV/c

More complex decays: $\Sigma(1385)^{\pm}$, $\Xi(1530)^0$

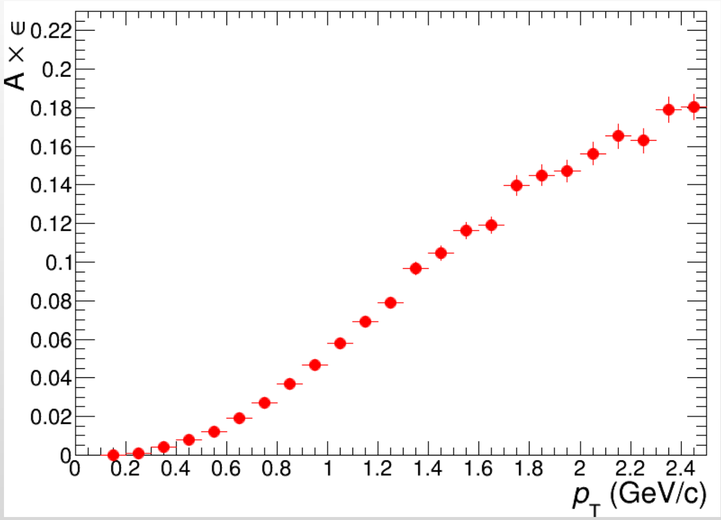
$\Sigma(1385)^{\pm} \rightarrow \pi^{\pm}\Lambda$ ($\Lambda \rightarrow p\pi$)

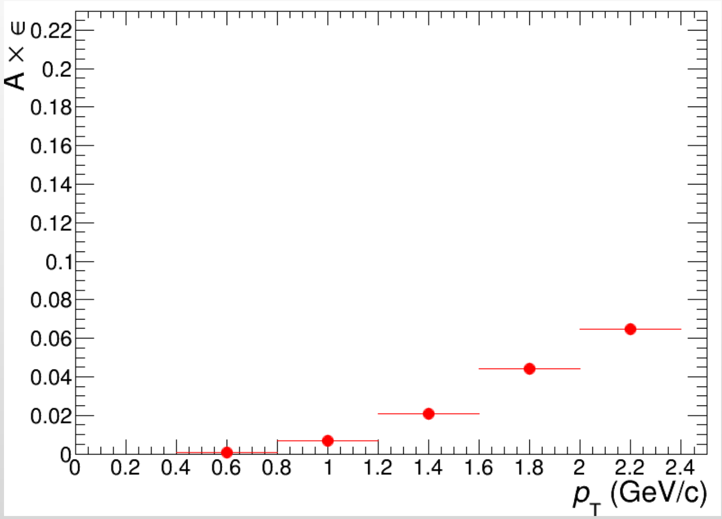


$\Xi(1530)^0 \rightarrow \pi^+\Xi^-$ ($\Xi^- \rightarrow \Lambda\pi^-$, ($\Lambda \rightarrow p\ \pi^-$))



❖ Typical reconstruction efficiencies (A x ∈) in AuAu @ 11 GeV, |y| < 1

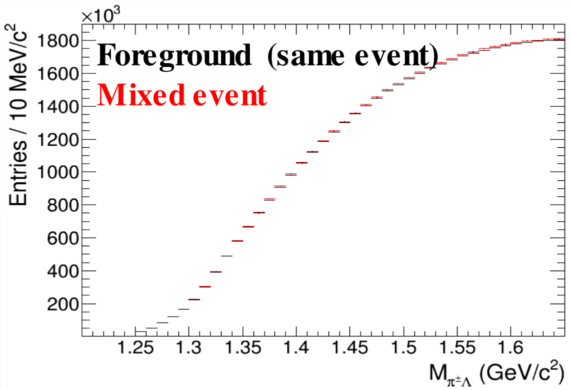


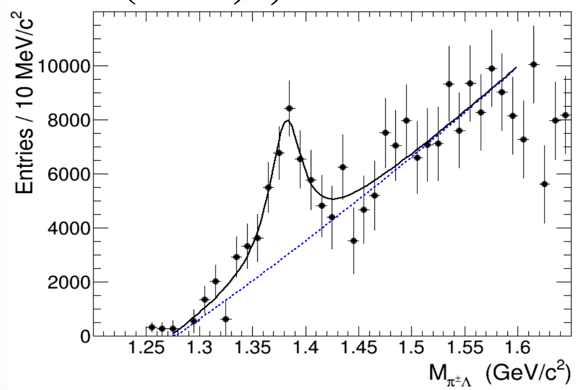


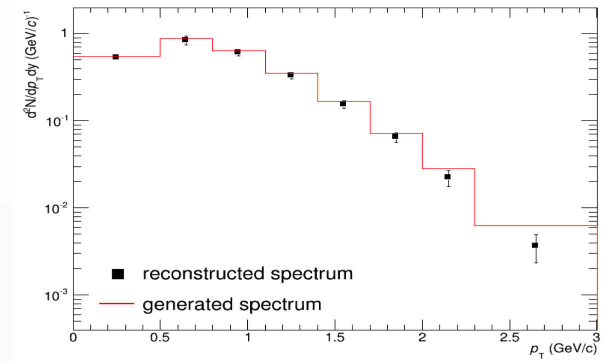
Reconstruction: $\Sigma(1385)^{\pm}$, $\Xi(1530)^{0}$

- UrQMD v.3.4: AuAu@11 (10M events), full chain simulation and reconstruction, $|y| < 1$

$\Sigma(1385)^{\pm}$, 0-0.5 GeV/c

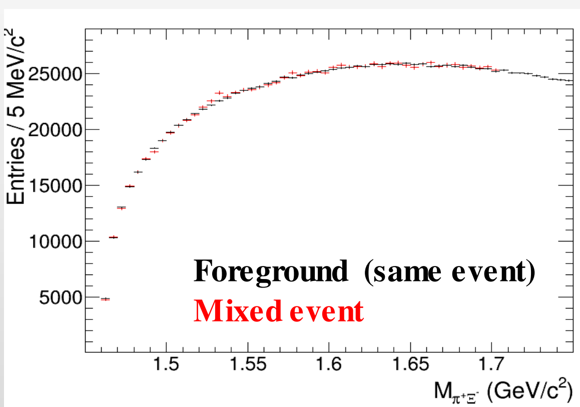


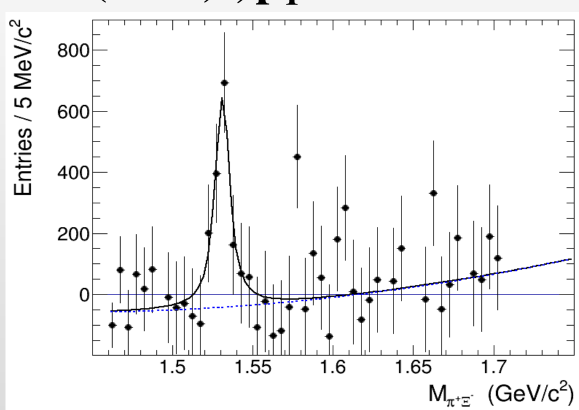




- $\Sigma(1385)^{\pm}$ signal can be reconstructed starting from zero momentum, high-p_T reach is limited by statistics
- Monte Carlo closure test is passed

$\Xi(1530)^{0}$, $p_T > 0.4$ GeV/c





- For $\Xi(1530)^{0}$ observe a hint of a signal at $p_T > 0.4$ GeV/c, statistics-hungry measurement
- Larger data sample and embedded simulations are required

Summary

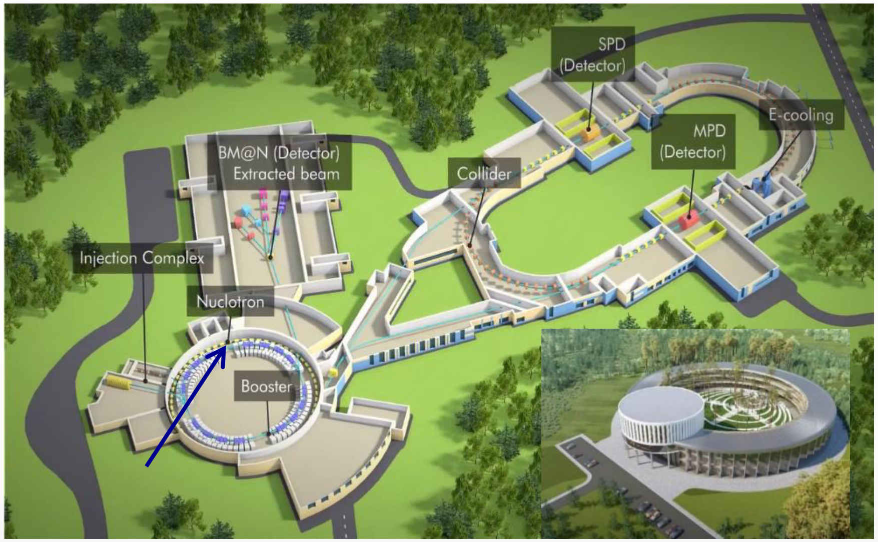
- ✓ Measurement of resonances contribute to the MPD physical program
- ✓ Resonances are expected to be very sensitive to the properties of the partonic/hadronic medium produced in heavy-ion collisions at NICA energies
- ✓ First-look measurements for resonances with the MPD detector are possible in a wide pT range from zero momentum up to ~ 3 GeV/c with ~10^7 sampled Au+Au collisions at $\sqrt{s_{NN}}$ = 4-11 GeV → plausible for year-1 operation
- ✓ More detailed and multiplicity-dependent studies would require x10-50 larger statistics, especially for multi-stage decays of $K^*(892)^{\pm}$, $\Sigma(1385)^{\pm}$ and $\Xi(1520)^0$

BACKUP

NICA

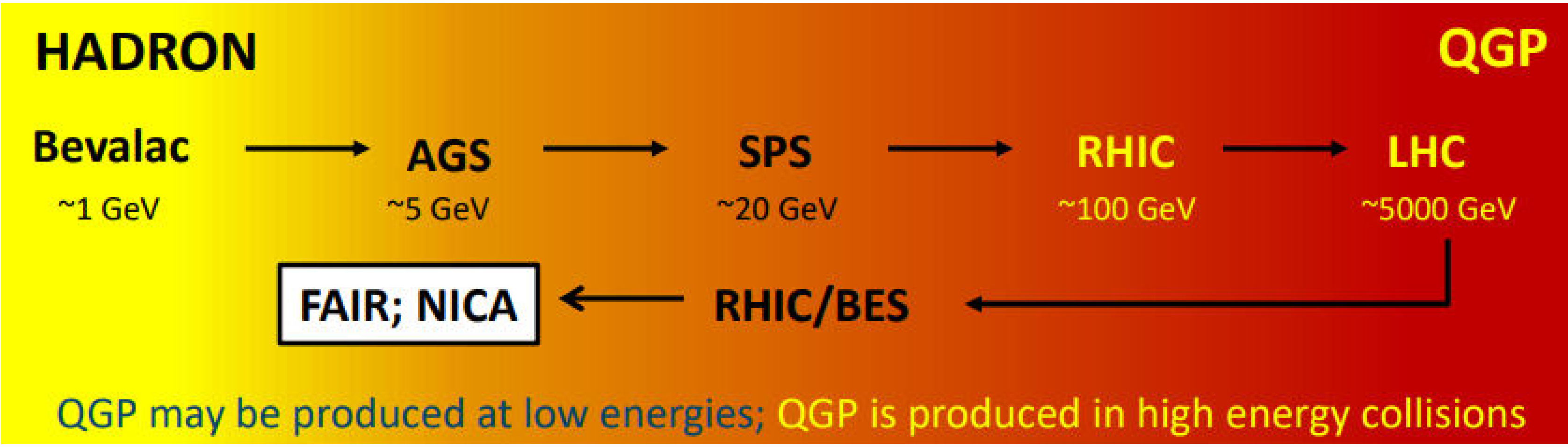
Nuclotron-based
Ion Collider fAcility

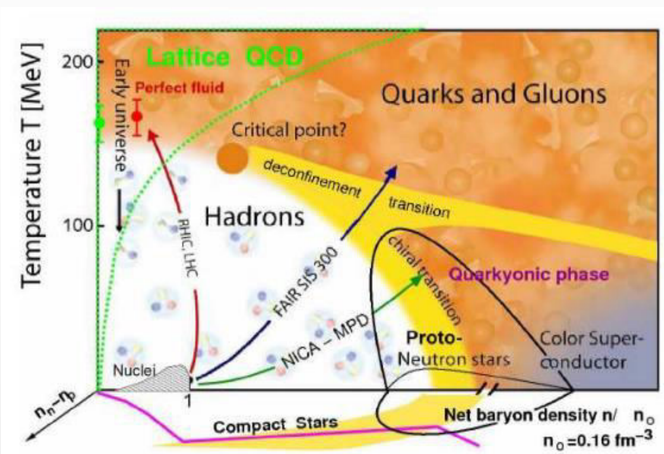
NICA complex

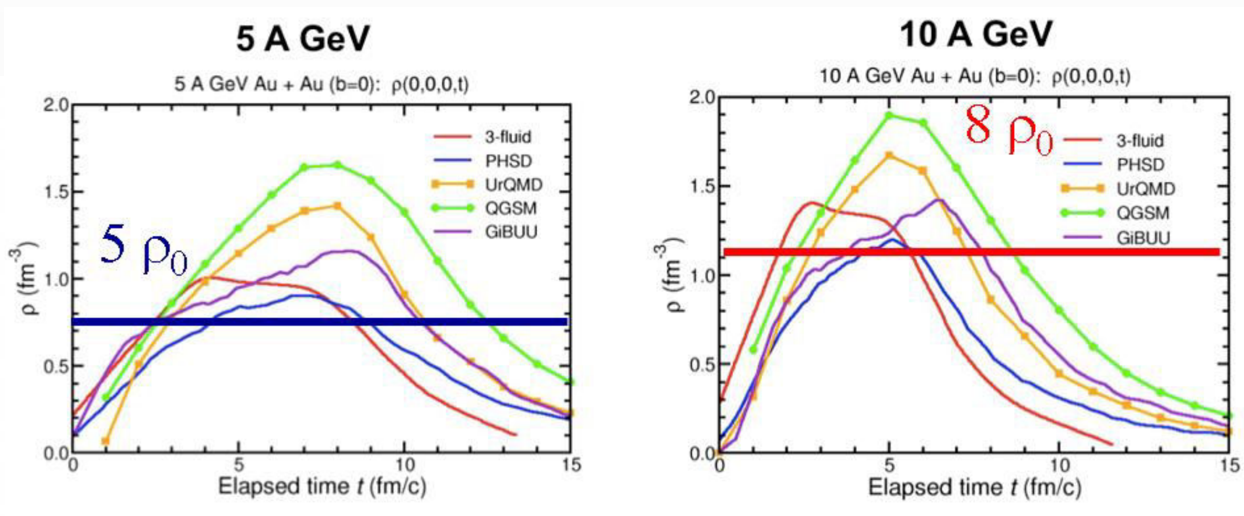


- ❖ Modernization of the existing Nuclotron facility
- ❖ Fixed target experiment: BM@N
- ❖ Construction of collider complex to collide:
  - ✓ heavy ions up to Au, $\sqrt{s_{NN}} = 4\text{-}11$ GeV, $\mathcal{L} \sim 10^{27}\,cm^{-2}s^{-1}$
  - ✓ polarized p and d, $\sqrt{s_{NN}} = 27$ GeV, $\mathcal{L} \sim 1032\,cm^{-2}s^{-1}$ (pp)
- ❖ Collider experiments: MPD, SPD
- ❖ NICA, MPD – start of operation in 2021-2022

Heavy-ion collisions at NICA





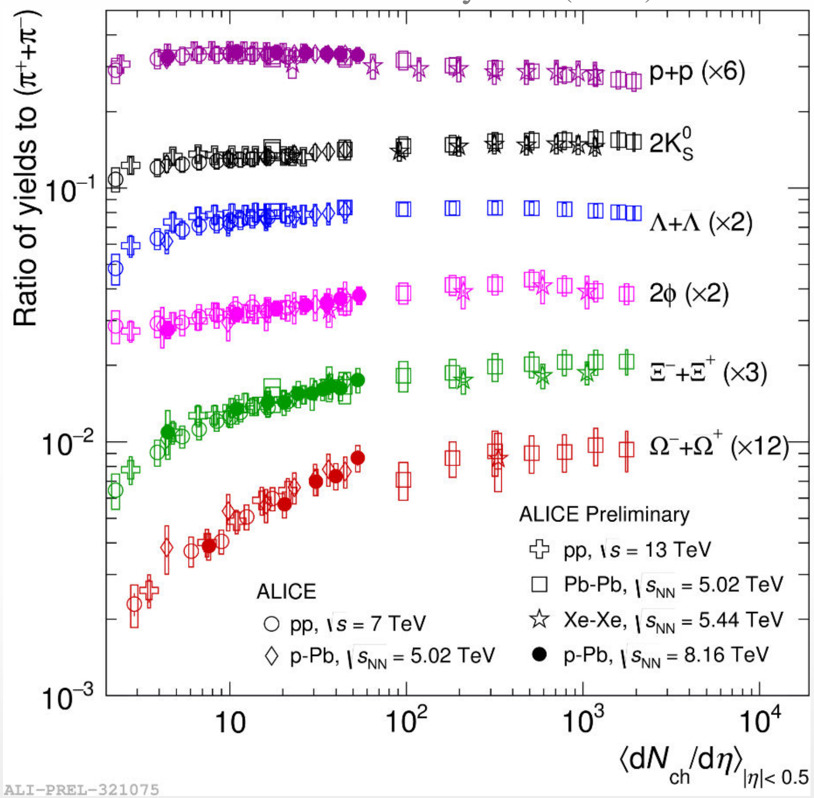


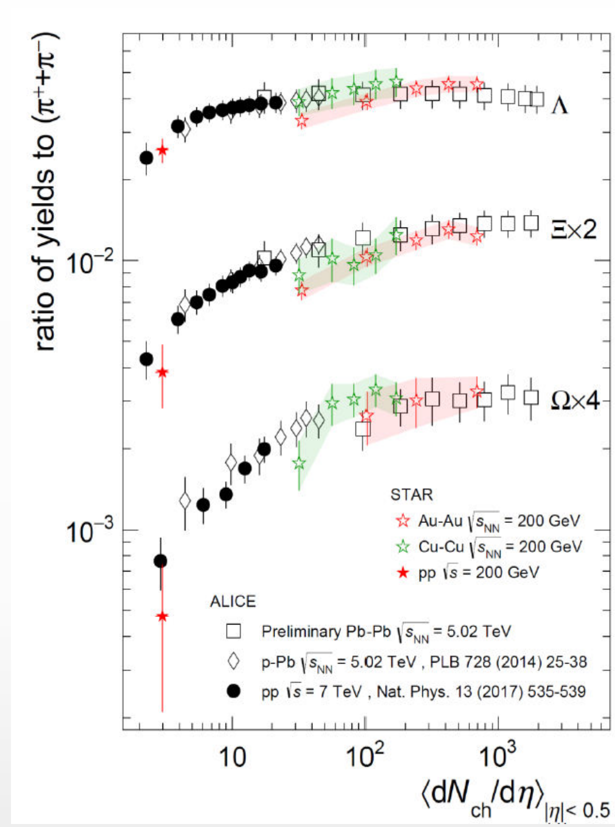
I.C. Arsene at al., Phys. Rev. C75 (2007) 24902.

- ❖ Properties of the hot and dense QCD matter, phase transition to the QGP, critical point
- ❖ Regime of the maximum baryon density (phase transition at $\rho_c \sim 5\rho_0$) at NICA
- ❖ Extension of modern heavy-ion programs at RHIC and the LHC to lower energies

Strangeness enhancement in pp, p-A and A-A

Nature Phys. 13 (2017) 535





- Observed in heavy-ion collisions at AGS, SPS, RHIC and LHC;
- For the first time observed in pp and p-A collisions by ALICE at the LHC
- Observed as for ground-state hadrons as for resonances (ϕ/π, Σ^*/π, Ξ^*/π)
- Strangeness production in A-A collisions is reproduced by statistical hadronization models. Canonical suppression models reproduce results in pp and p-A except for ϕ
- ϕ with hidden strangeness is not subject to canonical suppression → ϕ is a key observable !!!

Hadronization at intermediate momenta

❖ Baryon puzzle - increased baryon-to-meson (p/π, Λ/K_s^0 , Λ_c^+/D) ratios in heavy-ion collisions at RHIC and the LHC

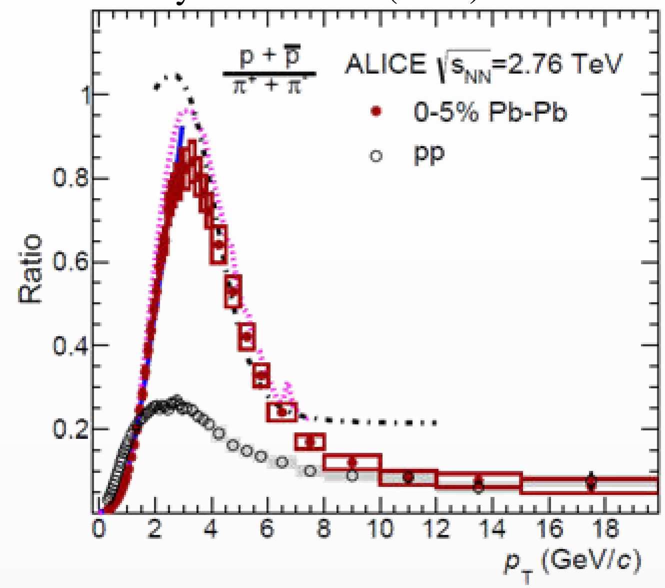
❖ Driving force of enhancement is not yet fully understood:

- ✓ particle mass (hydrodynamic flow)?
- ✓ quark count (baryons vs. mesons)?

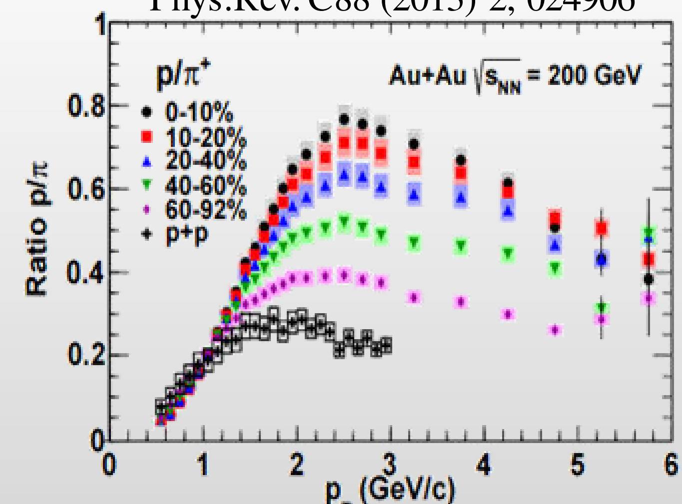
❖ ϕ and K^{*0} are well suited for tests as mesons with masses very close to that of a proton:

- ✓ Δm_{ϕ}~ 80 MeV/c^2, $\Delta m_{K^{*0}}$~ -45 MeV/c^2

Phys.Lett. B736 (2014) 196-207

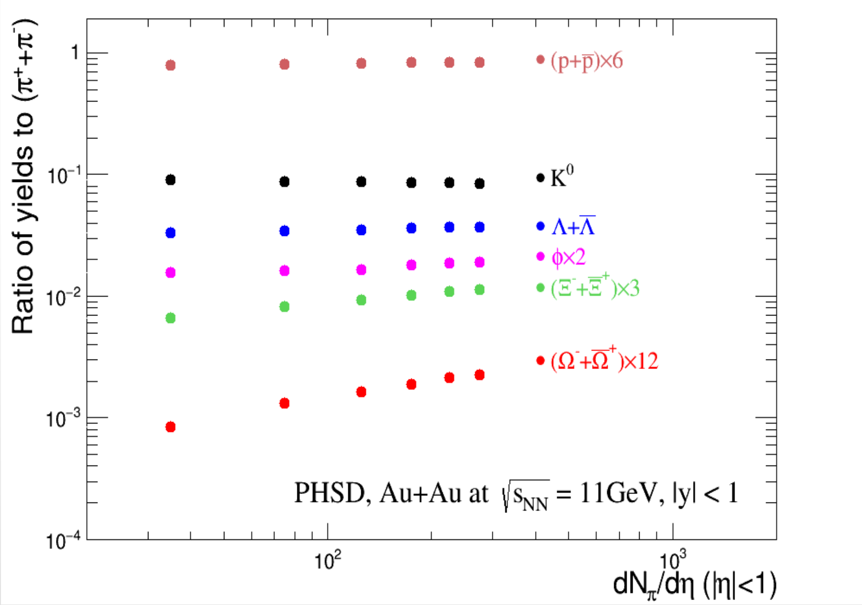


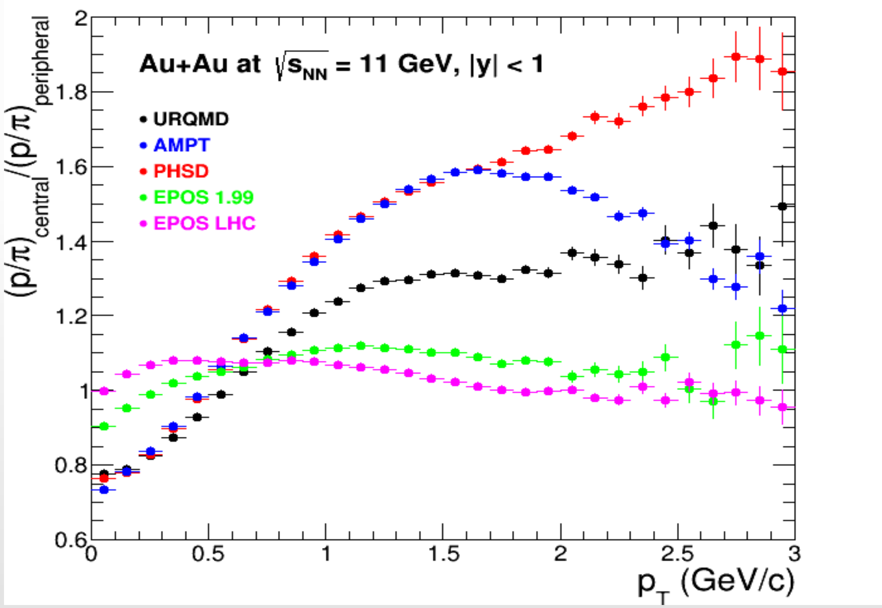
Phys.Rev. C88 (2013) 2, 024906



Model predictions for resonances at NICA

- ❖ UrQMD, PHSD, AMPT, EPOS …
- ❖ General predictions:
  - ✓ resonances are still copiously produced and can be used to study physics of heavy-ion collisions
  - ✓ models predict enhanced production of particles with strangeness and different interplay of mechanisms responsible for shaping of the particle p_T spectra.



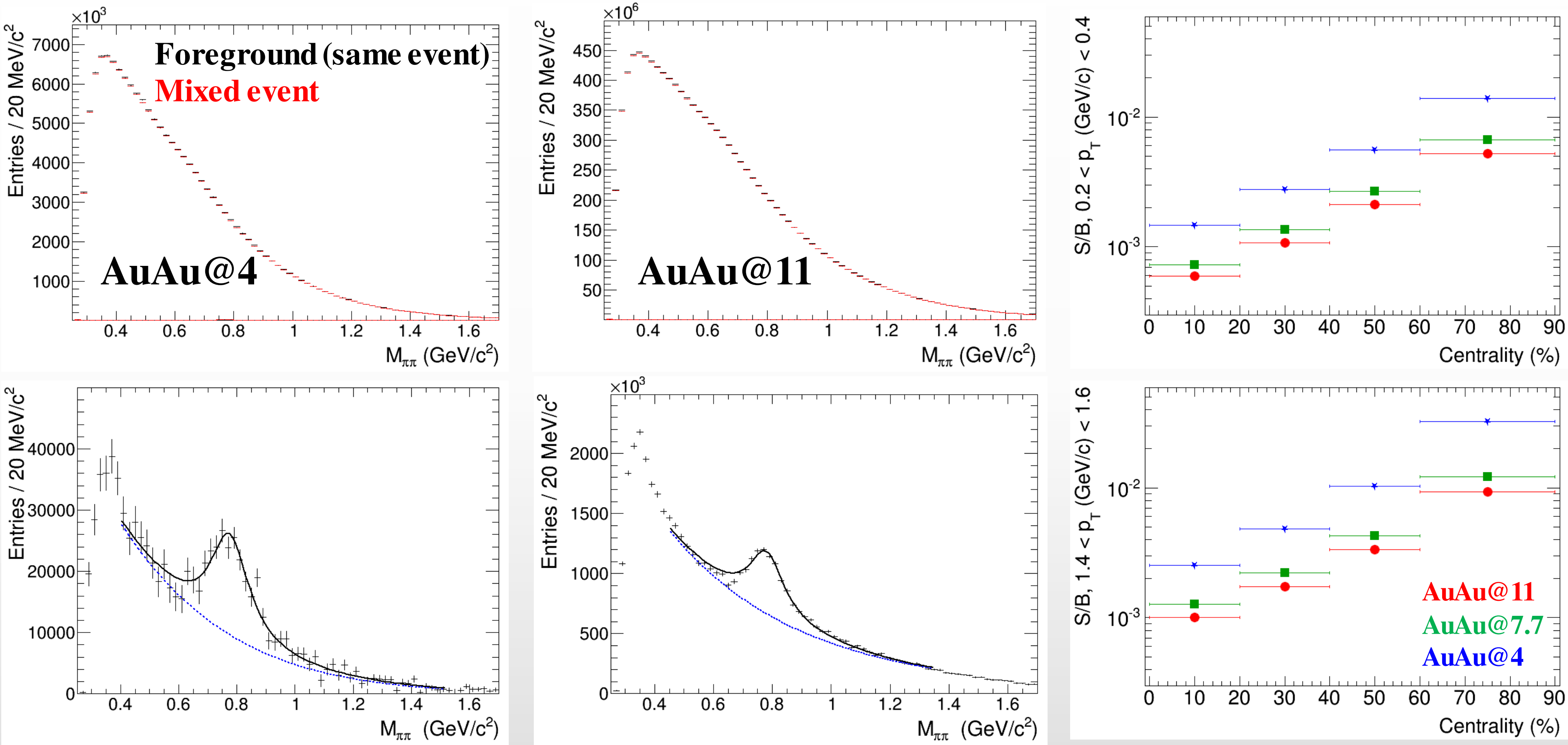


- ❖ Eventually, model predictions (integrated yields, <p_T>, particle ratios etc.) should be compared to data to differentiate different model assumptions

ρ(770), reconstructed peaks

❖ UrQMD v.3.4: AuAu@11 (10M events), AuAu@7.7 (5M events), AuAu@4 (5M events)

❖ Full chain simulation and reconstruction, p_T = 0.2-0.4 GeV/c, |y| < 1



❖ Mixed-event background subtraction, fits to Voigtian function + polynomial

❖ Contributions from K_s, ω, K^{*0}, f_0 and f_2 are subtracted (need to be measured in advance)*

❖ Signal can be reconstructed at p_T > 0 GeV/c, high-p_T reach is limited by available statistics

❖ S/B ratios deteriorates with increasing centrality and collision energy

*ALICE, Phys.Rev. C99 (2019) no.6, 064901

ρ(770), signal extraction – practice tests

Phys.Rev. C99 (2019) no.6, 064901

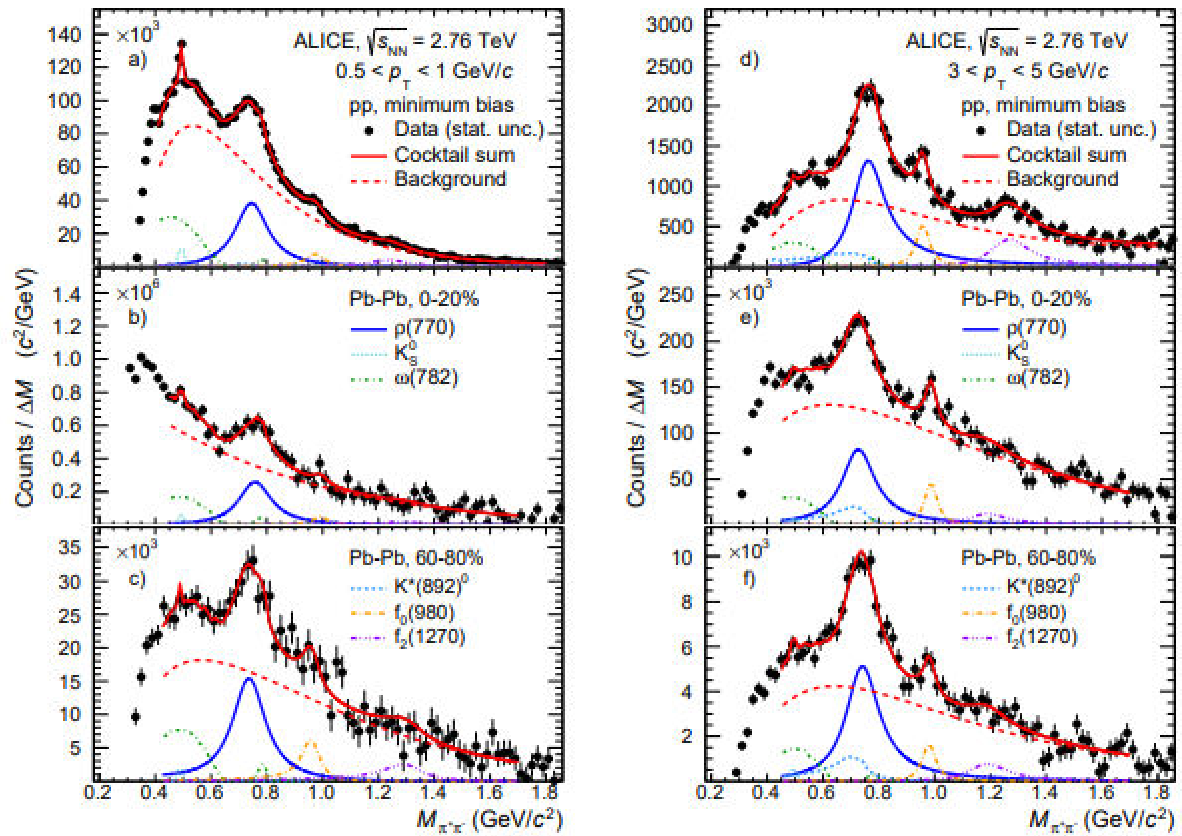


Fig. 1: (Color online) Invariant mass distributions for $\pi^+\pi^-$ pairs after subtraction of the like-sign background. Plots on the left and right are for the low and high transverse momentum intervals, respectively. Examples are shown for minimum bias pp, 0–20% and 60–80% central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. Solid red curves represent fits to the function described in the text. Colored dashed curves represent different components of the fit function, which includes a smooth remaining background as well as contributions from K^0_S, ρ^0, $\omega(782)$, $K^*(892)^0$, $f_0(980)$ and $f_2(1270)$. See text for details.