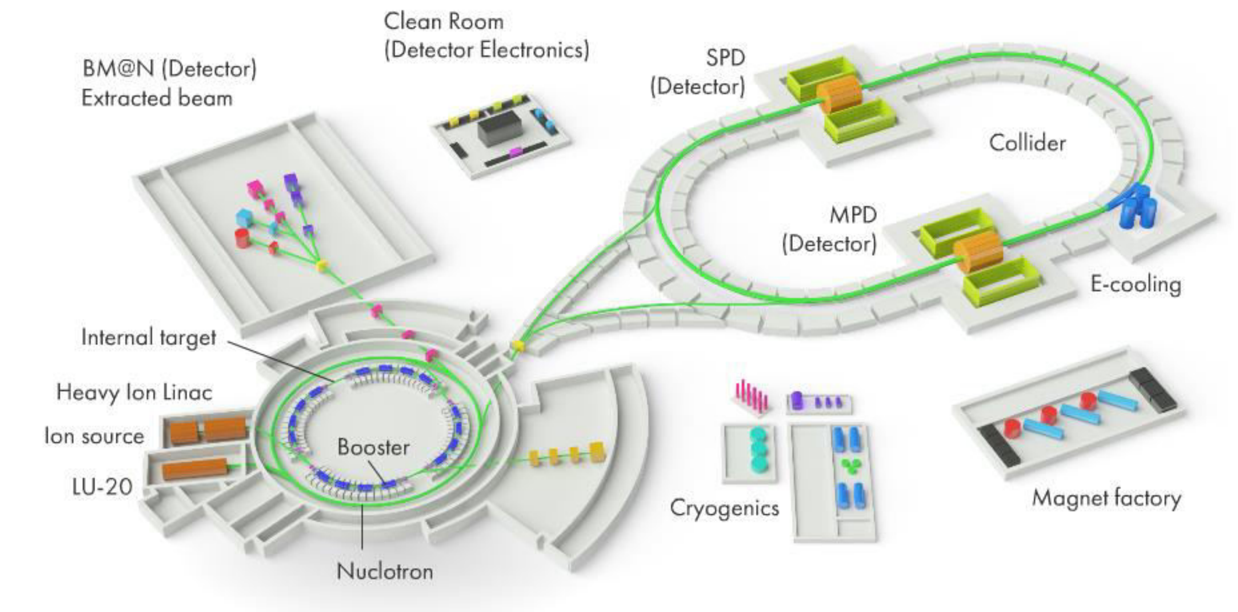
NICA Nuclotron-based Ion Collider fAcility

Study of the resonances in heavy-ion collisions at NICA energies using the MPD detector

V. Riabov* 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 particle reconstruction at NICA-MPD
- Summary

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	πK^+	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
  - ✓ flow, comparison with e^+e^- measurements, jet quenching, background for other probes etc.

Hadronic phase and medium modifications

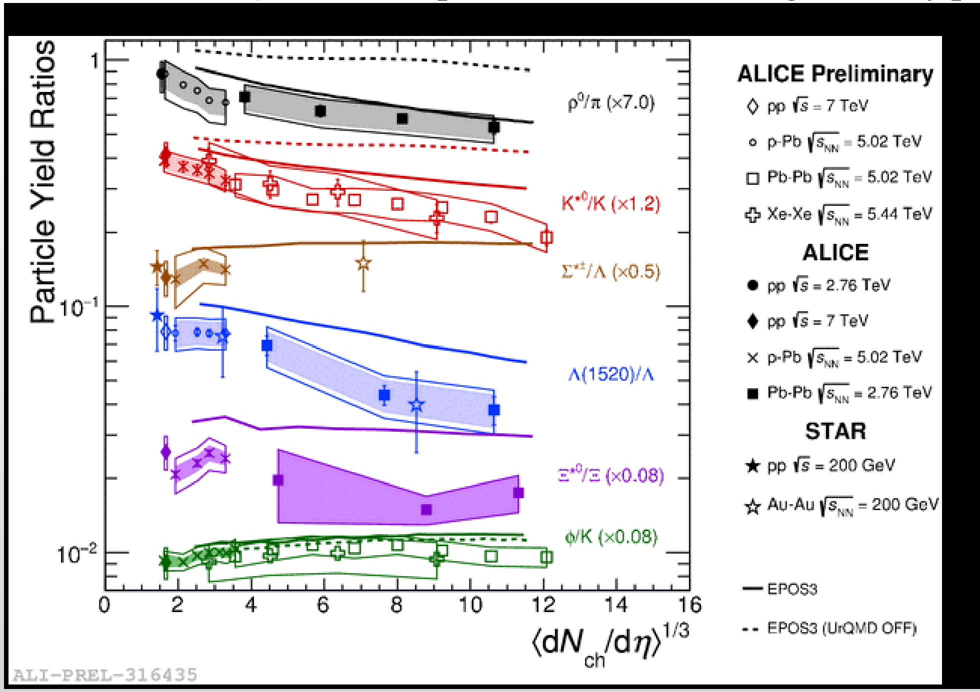
increasing lifetime →

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

- Resonances have small lifetimes of cτ ~ 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 (πK → K^{*0}, KK→ ϕ etc.) → increased yields

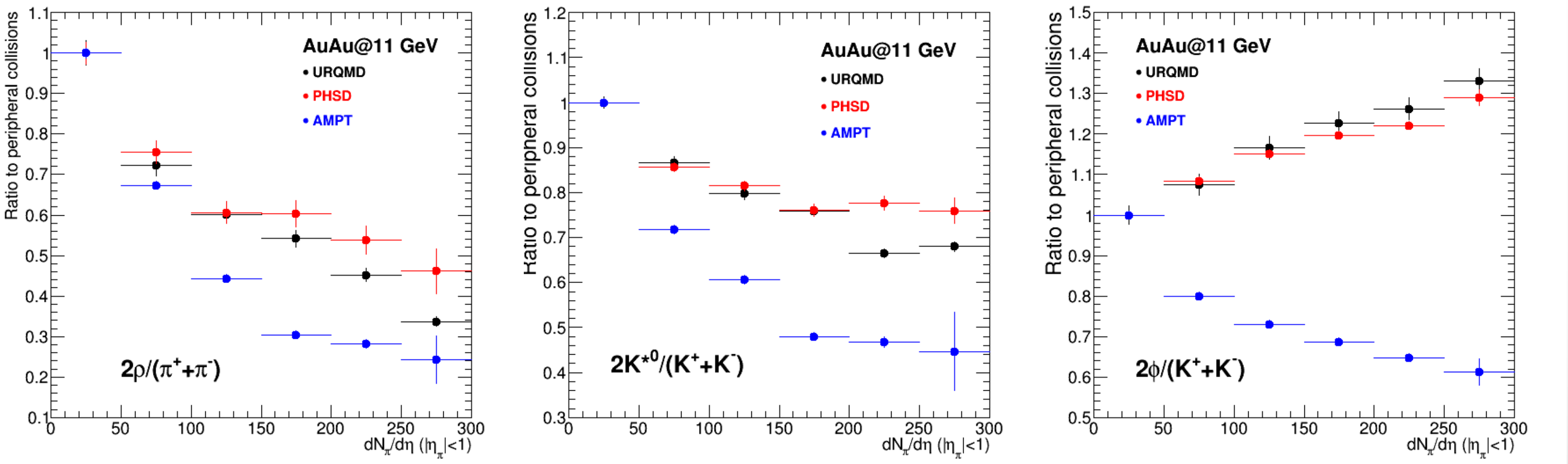


- SPS/RHIC/LHC observed multiplicity dependent suppression of ρ/π, K*/K, Λ*/Λ ratios, resonances with cτ ≤ 20 fm/c. Ratios of longer lived resonances are not affected
- Results support the existence of a hadronic phase that lives long enough to cause a significant reduction of the reconstructed yields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

Hadronic phase and particle ratios

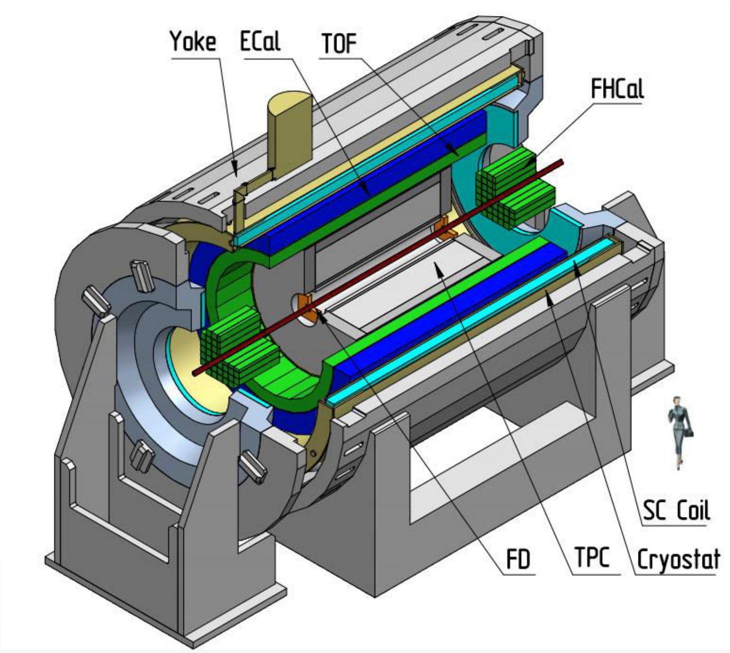
- ❖ Models with hadronic cascades (UrQMD, PHSD, AMPT) → properties of hadronic phase
- ❖ Models predict centrality dependent ρ/π, K^*/K, ϕ/K and Λ^*/Λ, Σ^*/Λ, Ξ^*/Ξ ratios in AuAu@11
- ❖ Ratios are suppressed going from peripheral to central collisions for resonances with small $c\tau$
- ❖ Modifications occur at low momentum as expected for the hadronic phase effects



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

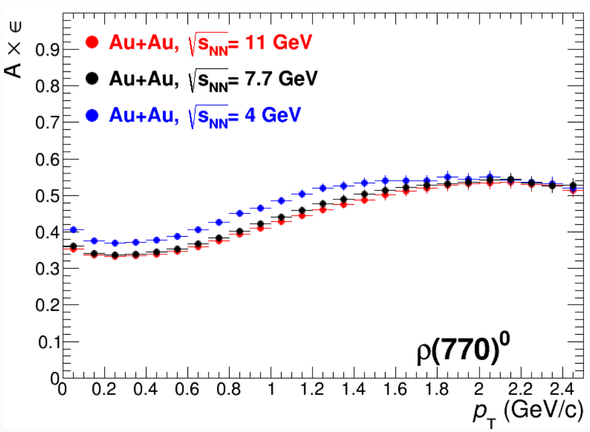
TOF, EMC: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.4$

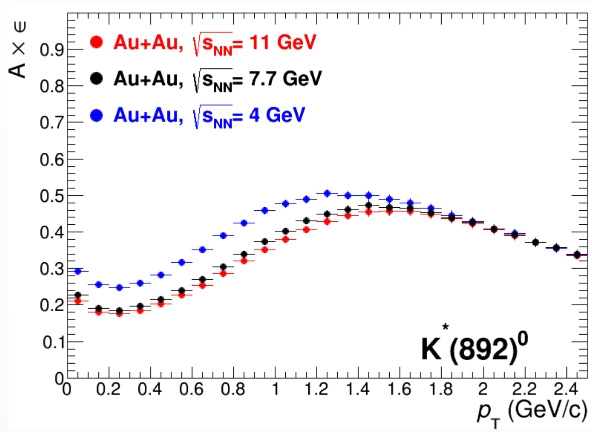
FFD: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$

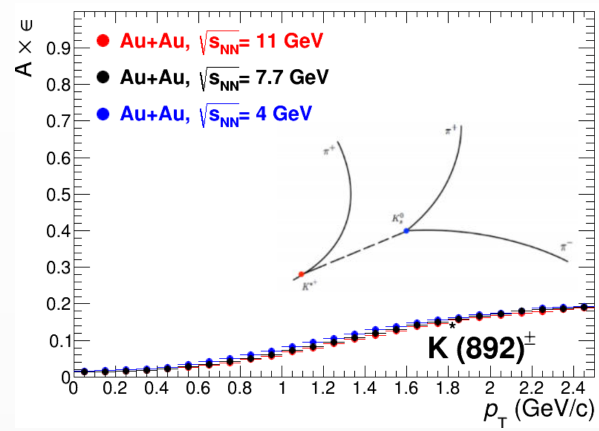
FHCAL: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

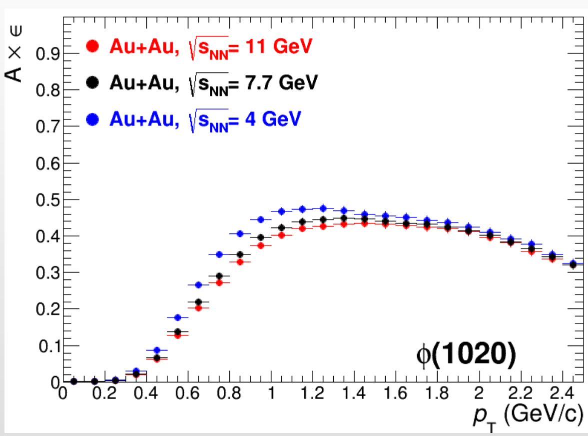
Reconstruction efficiency: ρ(770), K*(892), ϕ(1020), Λ(1520)

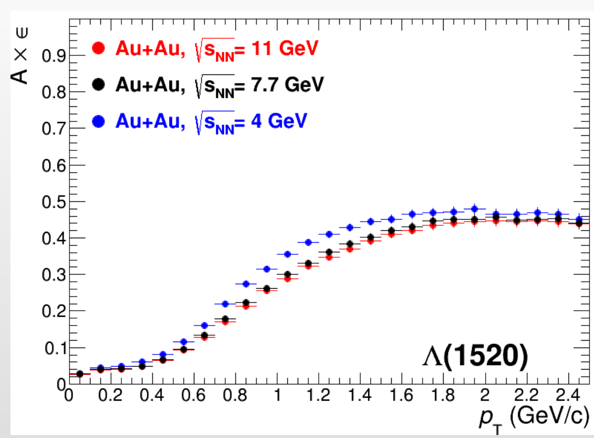
❖ Typical reconstruction efficiencies (A x ∈) in AuAu @ **4**, **7.7** and **11** GeV, |y| < 1









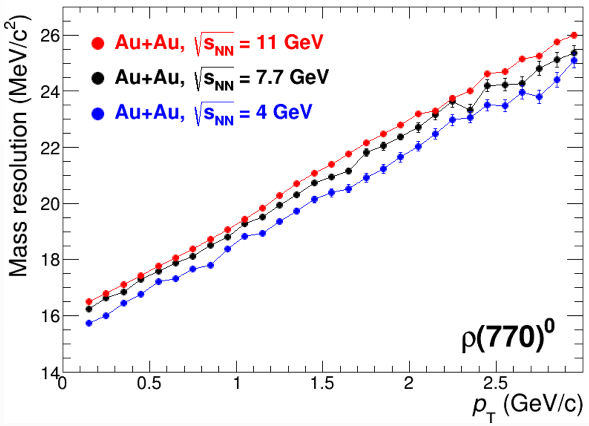


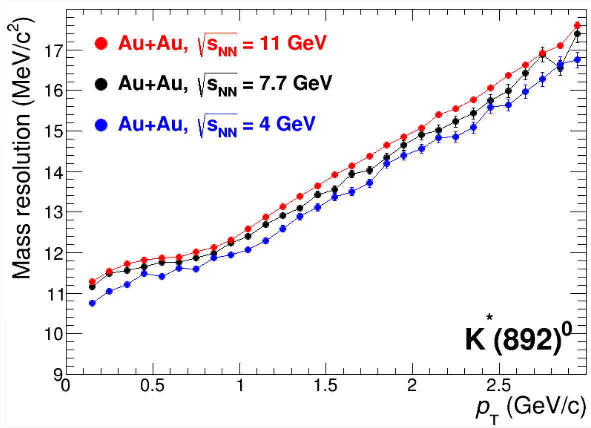
❖ Reasonable efficiencies in the wide p_T range, |y| < 1

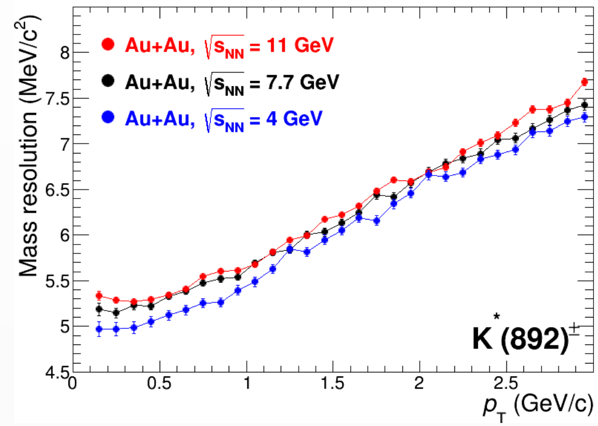
❖ Modest multiplicity (and/or $\sqrt{s_{NN}}$) dependence

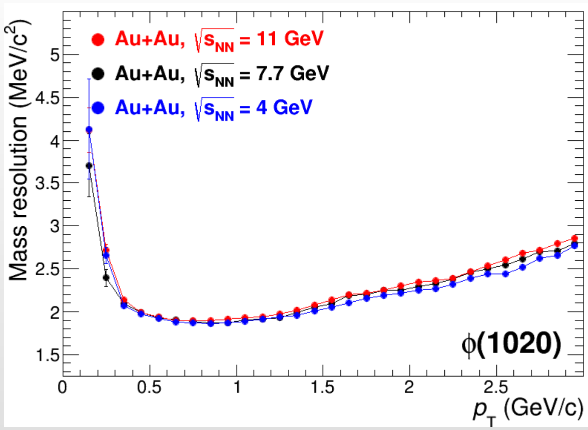
Mass resolution:
ρ(770), K*(892), ϕ(1020), Λ(1520)

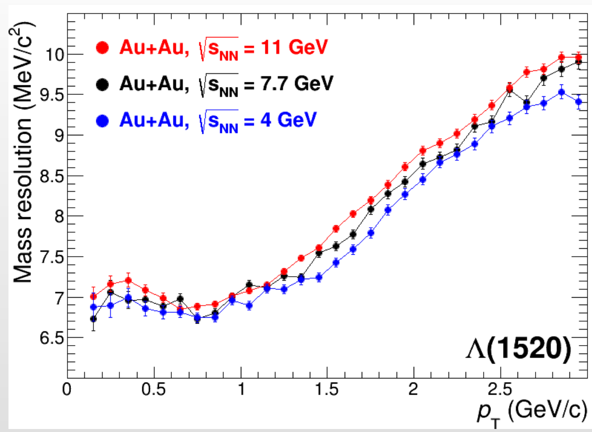
❖ Detector mass resolution ($m_{reconstructed} - m_{generated}$) in AuAu @ **4**, **7.7** and **11** GeV, |y| < 1









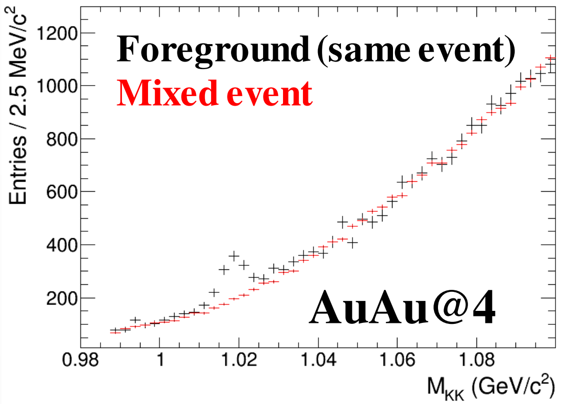


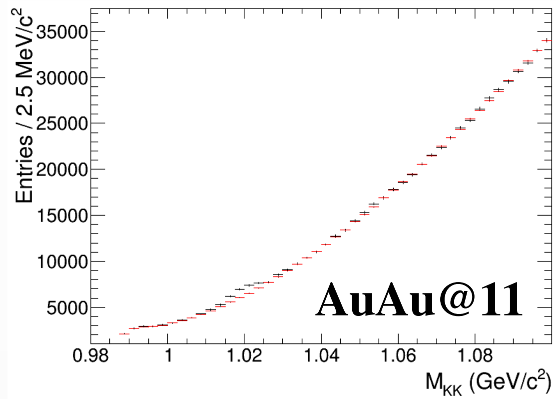
❖ Acceptable mass resolution

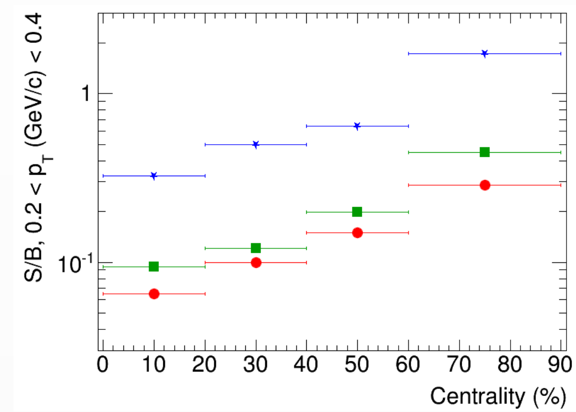
❖ Modest multiplicity (and/or $\sqrt{s_{NN}}$) dependence

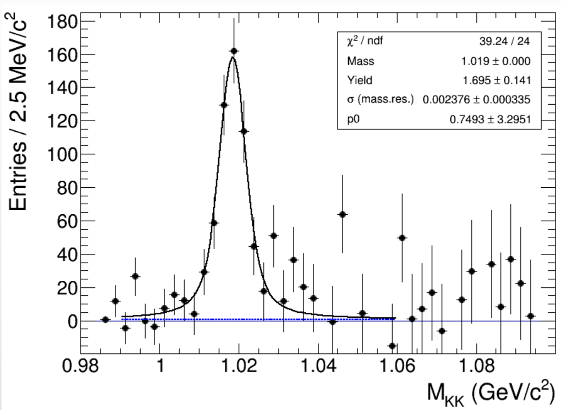
φ(1020), reconstructed peaks

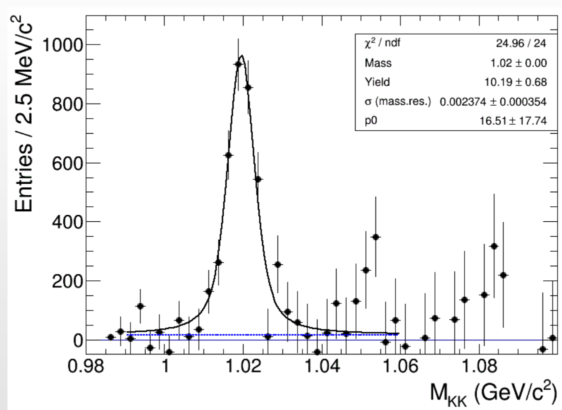
- UrQMD v.3.4: AuAu@11 (10M events), AuAu@7.7 (5M events), AuAu@4 (5M events)
- Full chain simulation and reconstruction, $p_T = 0.2\text{-}0.4$ GeV/c, $|y| < 1$

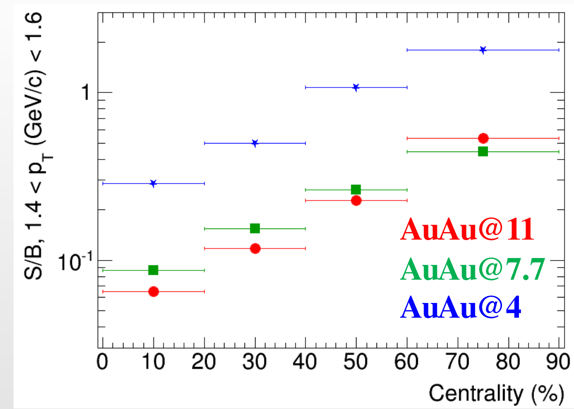










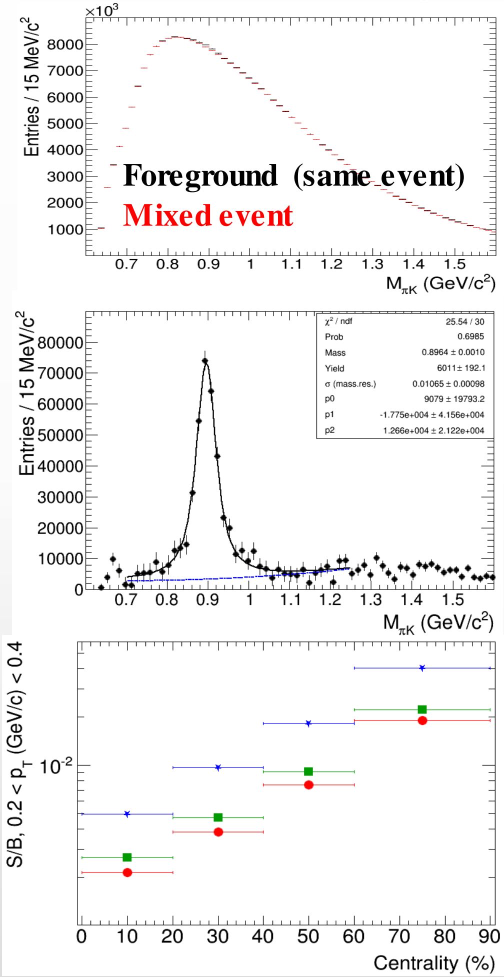


- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Distributions are fit to Voigtian function + polynomial
- Signal can be reconstructed at $p_T > 0.2$ GeV/c, high-p_T reach is limited by available statistics
- S/B ratios deteriorates with increasing centrality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

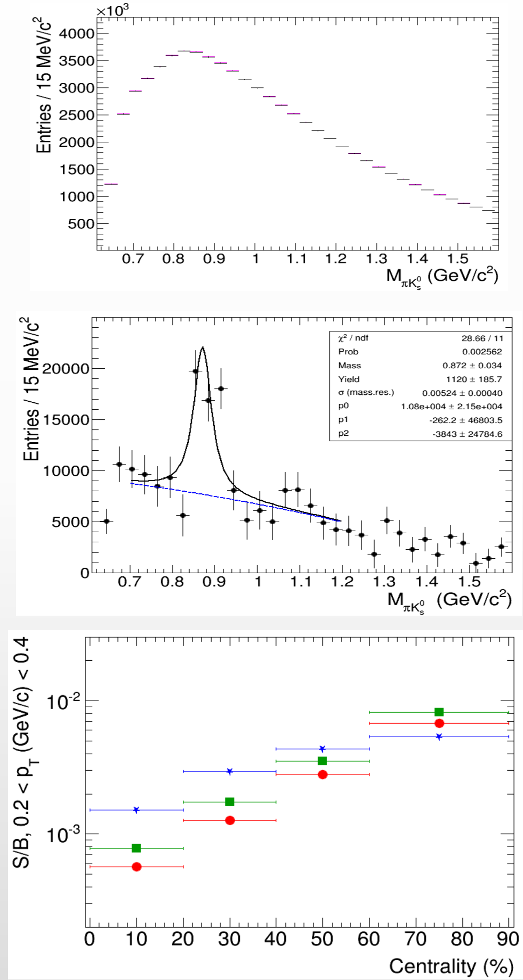
$K^*(892)$ and $\Lambda(1520)$, reconstructed peaks

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

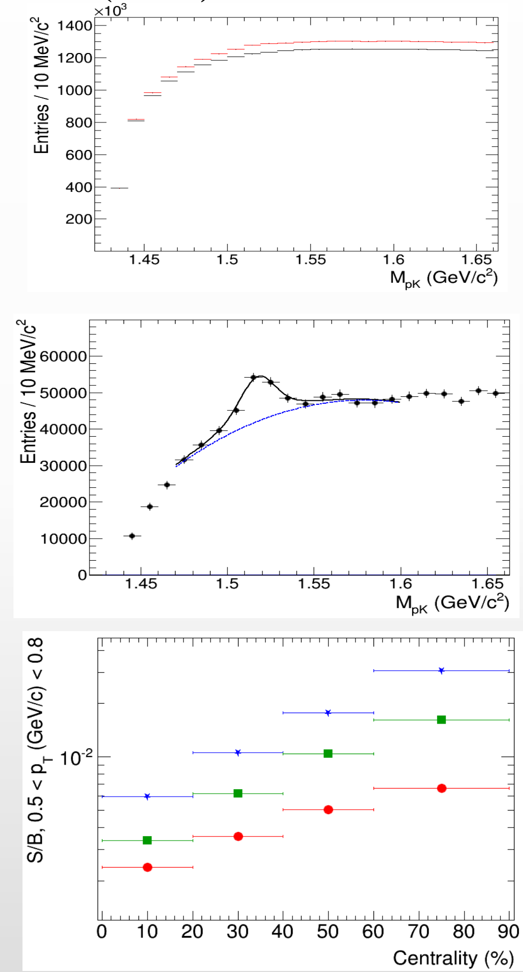
K^{*0}: 0.2-0.4 GeV/c



$K^{*\pm}$: 0.2-0.4 GeV/c



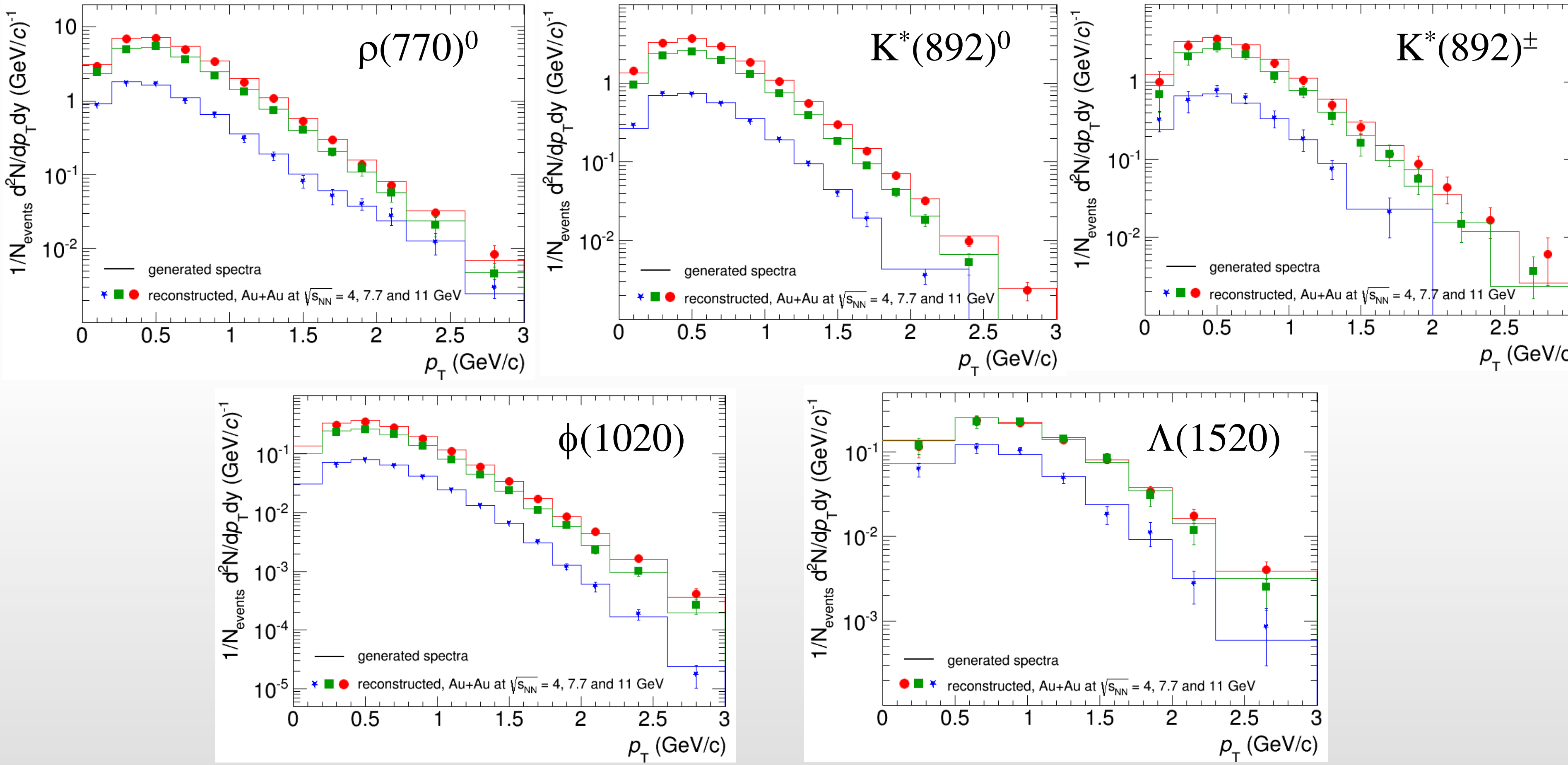
$\Lambda(1520)$: 0.5-0.8 GeV/c



- ❖ 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^*

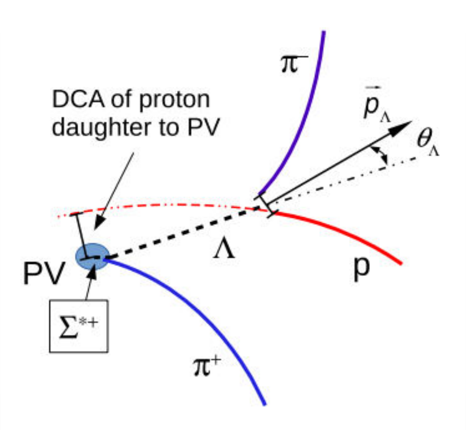
- UrQMD v.3.4: AuAu@11 (10M events), AuAu@7.7 (5M events), AuAu@4 (5M events)
- Full chain simulation and reconstruction, p_T ranges are limited by the possibility to extract signals, $|y| < 1$



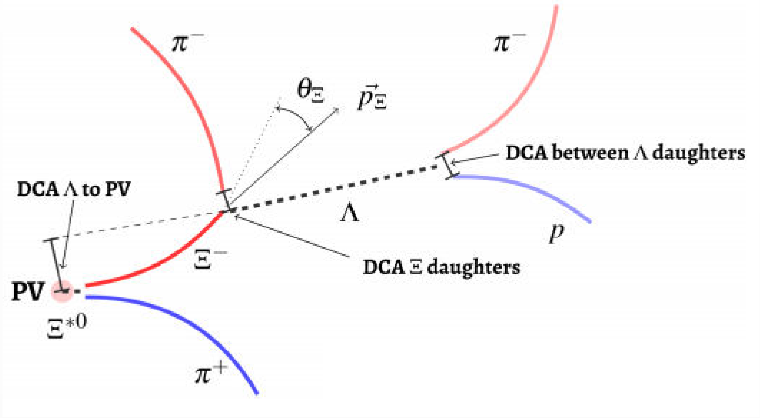
- Reconstructed spectra match the generated ones within uncertainties
- Measurements are possible starting from ~ zero momentum, sample p_T spectra in a wide range
- Maximum raw yields (smallest stat. uncertainties) are extracted at ~ 300 MeV/c

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

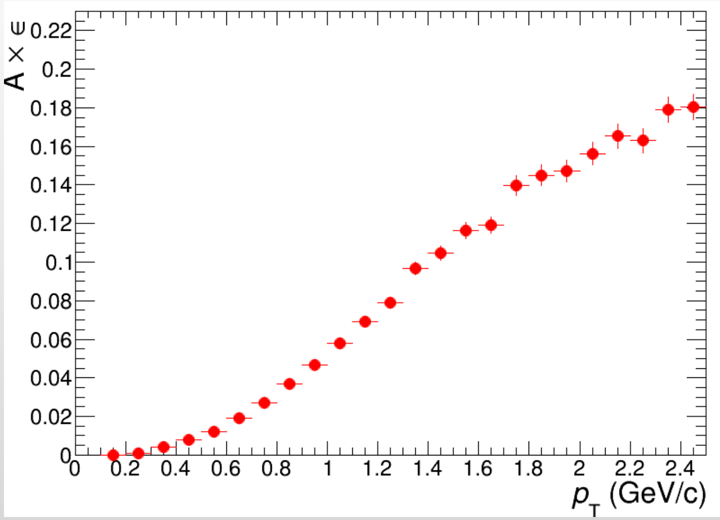
$\Sigma(1385)^{\pm} \to \pi^{\pm}\Lambda$ ($\Lambda \to p\pi$)

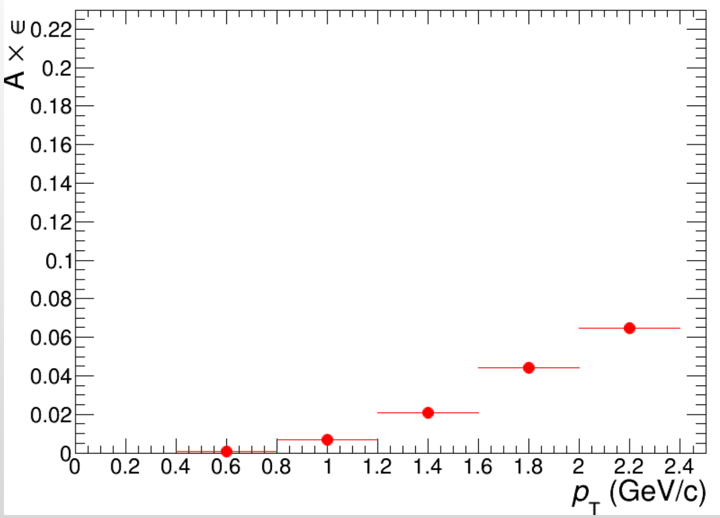


$\Xi(1530)^0 \to \pi^+\Xi^-$ ($\Xi^- \to \Lambda\pi^-$, ($\Lambda \to p\,\pi^-$))



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

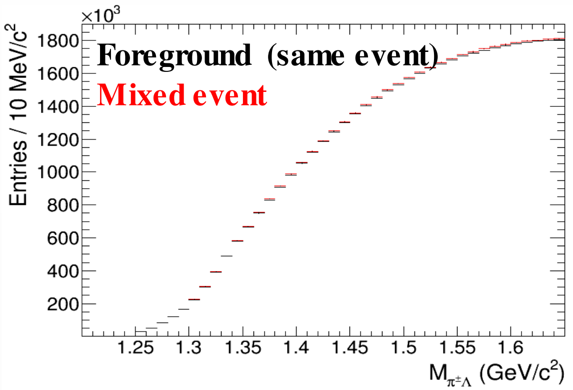


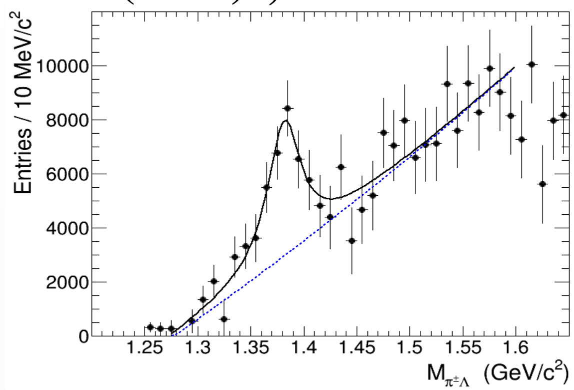


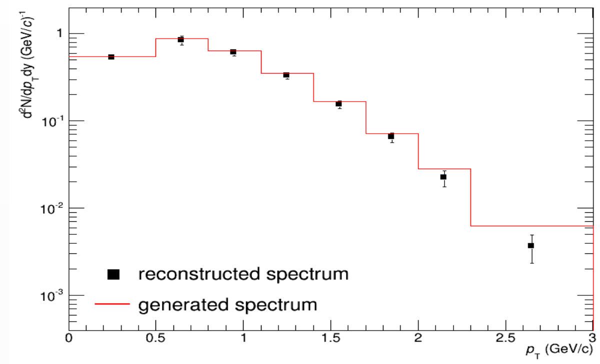
Reconstruction: Σ(1385)$^{\pm}$, Ξ(1530)^{0}

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

Σ(1385)$^{\pm}$, 0-0.5 GeV/c

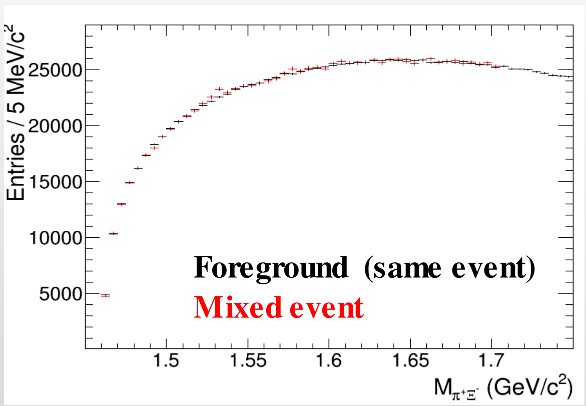


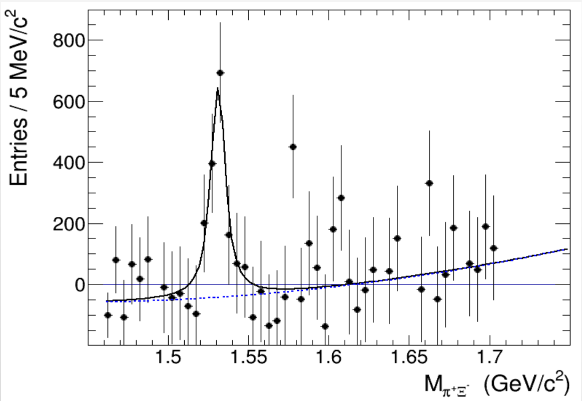




- Σ(1385)$^{\pm}$ signal can be reconstructed starting from zero momentum, high-p_T reach is limited by statistics
- Monte Carlo closure test is passed

Ξ(1530)^{0}, p_T > 0.4 GeV/c





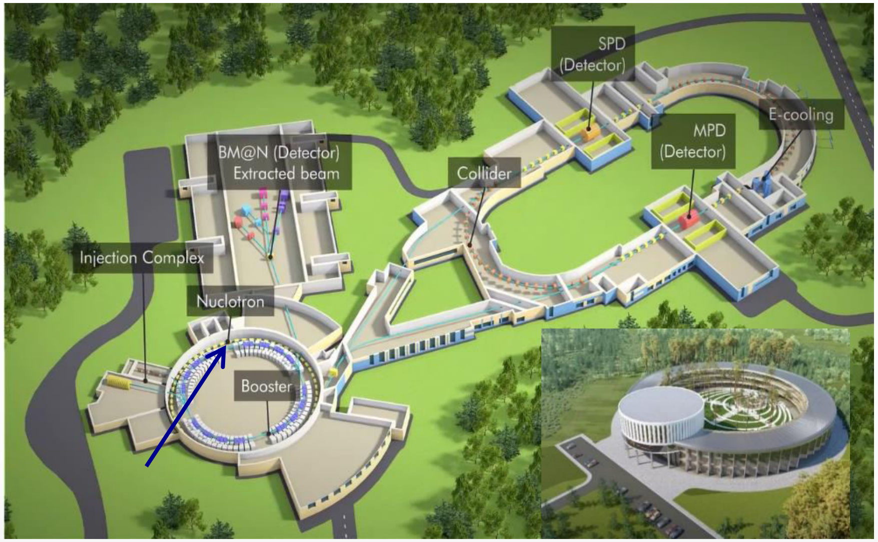
- For Ξ(1530)^{0} observe a hint of a signal at p_T > 0.4 GeV/c, statistics-hungry measurement
- Larger data sample and embedded simulations are required

Summary

- ✓ Measurement of resonances is important for the MPD physical program
- ✓ Models predict high sensitivity of resonances to the properties of the partonic/hadronic medium produced in heavy-ion collisions at NICA energies
- ✓ Resonances can be reconstructed/measured using the MPD detector from zero momentum to ~ 3 GeV/c with 10^7 minimum bias events sampled, x10 events is needed for multiplicity dependent studies
- ✓ Measurements of resonances is a plausible task for year-1 operation

BACKUP

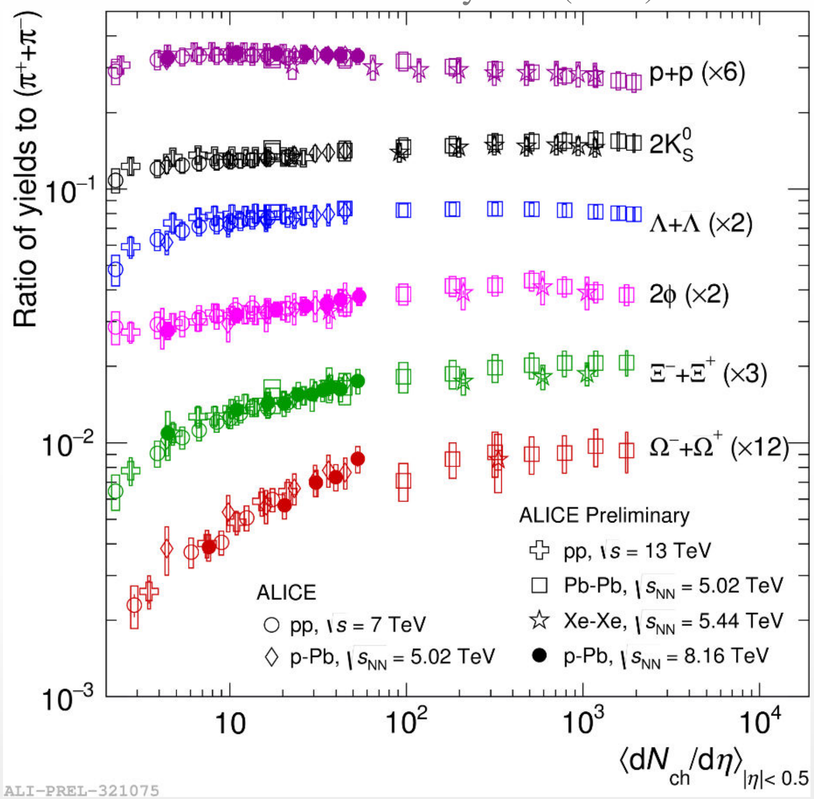
NICA complex

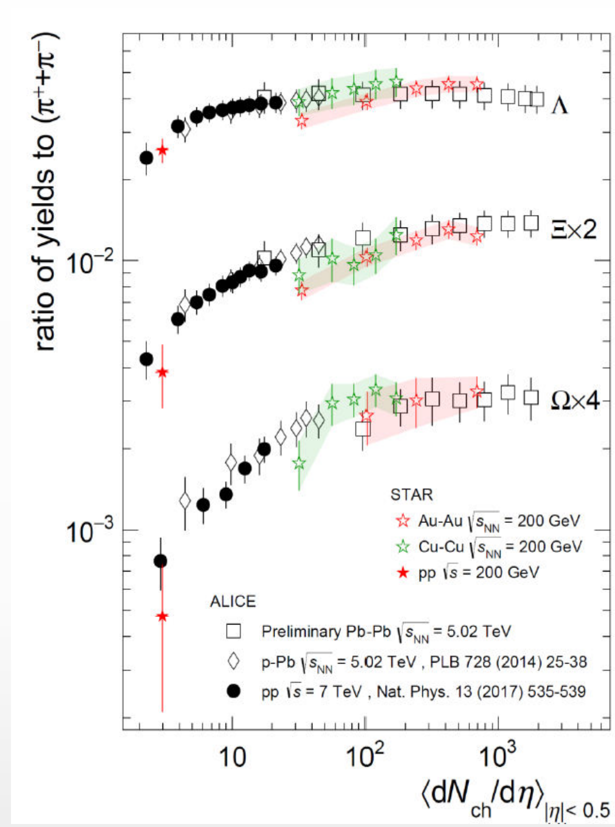


- ❖ Modernization of the existing Nuclotron facility
- ❖ Fixed target experiment: BM@N
- ❖ Construction of collider complex to collide:
  - ✓ heavy ions up to Au, $\sqrt{s_{NN}}$ = 4-11 GeV, $\mathcal{L} \sim 10^{27}$ cm^{-2}s^{-1}
  - ✓ polarized p and d, $\sqrt{s_{NN}}$ = 27 GeV, $\mathcal{L} \sim$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

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

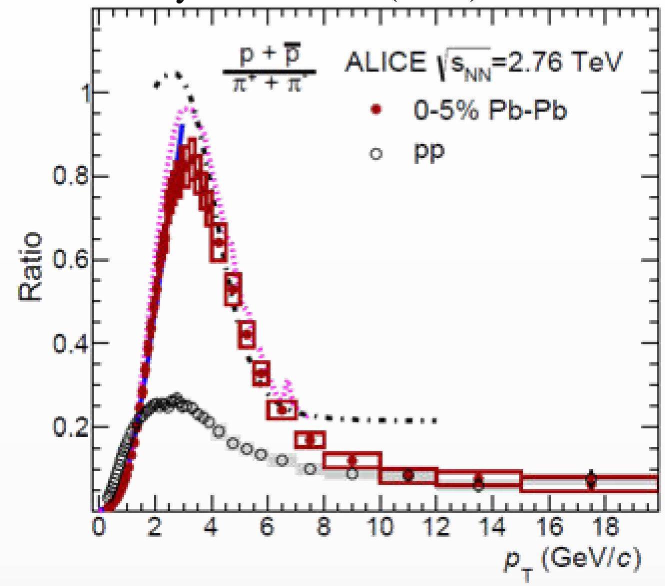
❖ Driving force of enhancement is not yet fully understood:

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

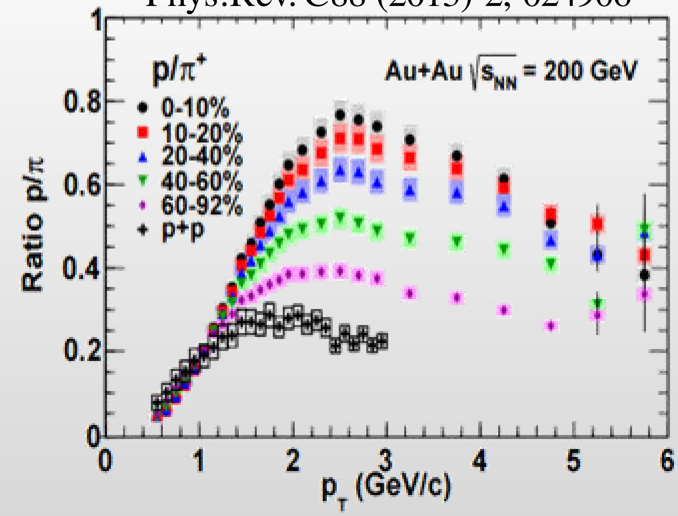
❖ ϕ and K^{*0} are well suited for tests as mesons with masses very close to that of a proton:

- ✓ $\Delta m_{\phi} \sim$ 80 MeV/c^2, $\Delta m_{K^{*0}} \sim$ -45 MeV/c^2

Phys.Lett. B736 (2014) 196-207

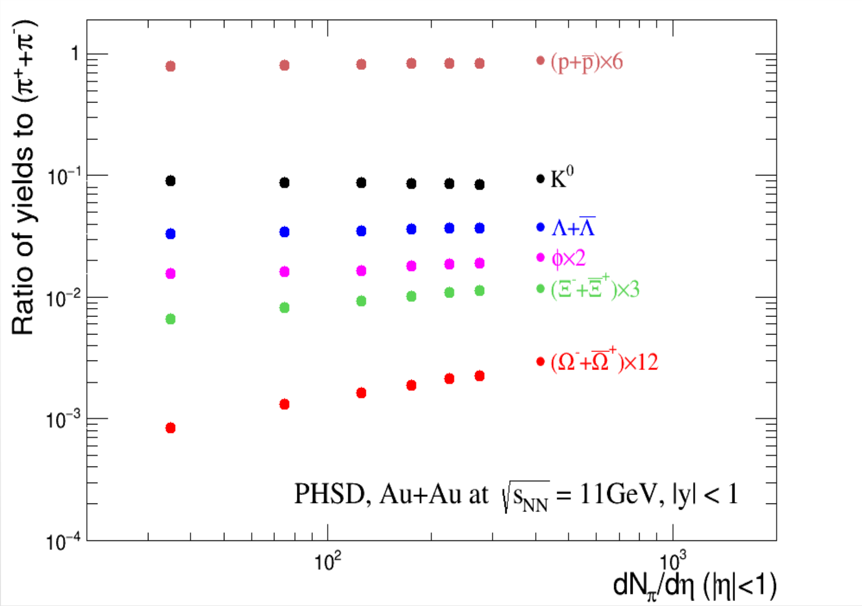


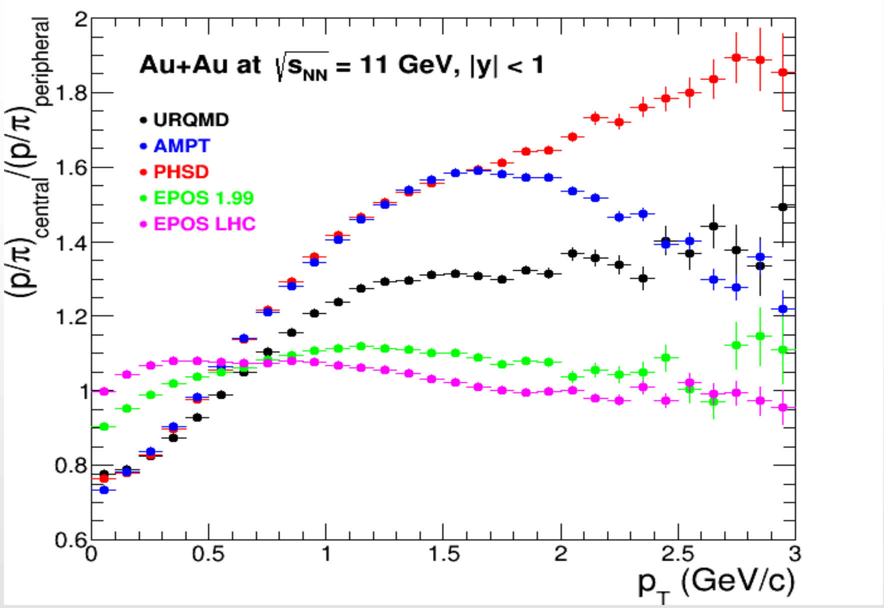
Phys.Rev. C88 (2013) 2, 024906



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.

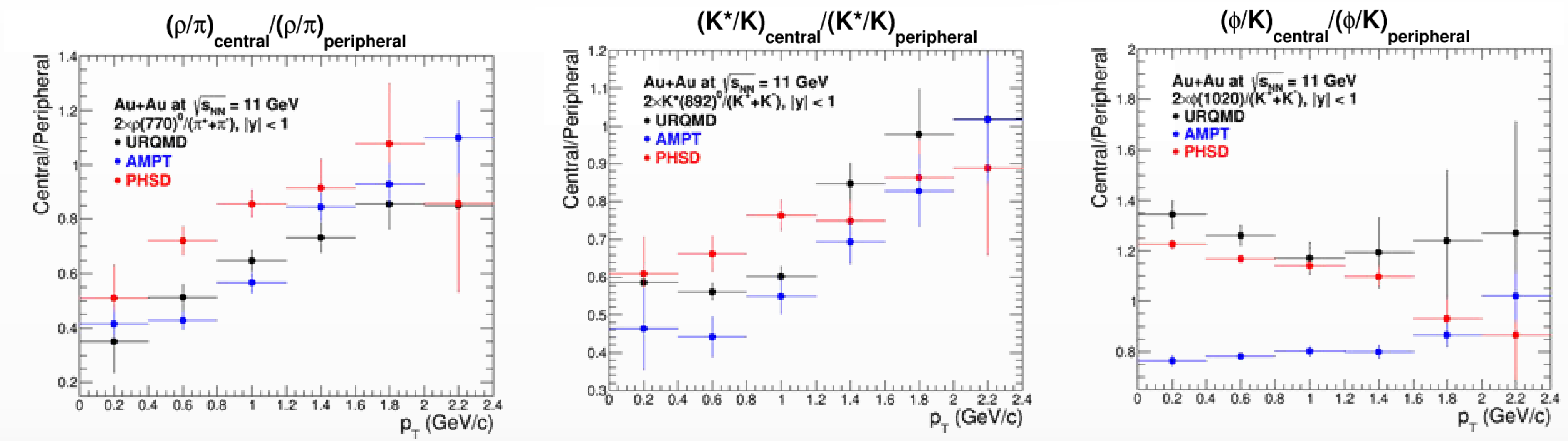




- Eventually, model predictions (integrated yields, <p_T>, particle ratios etc.) should be compared to data to differentiate different model assumptions

Hadronic phase and particle ratios

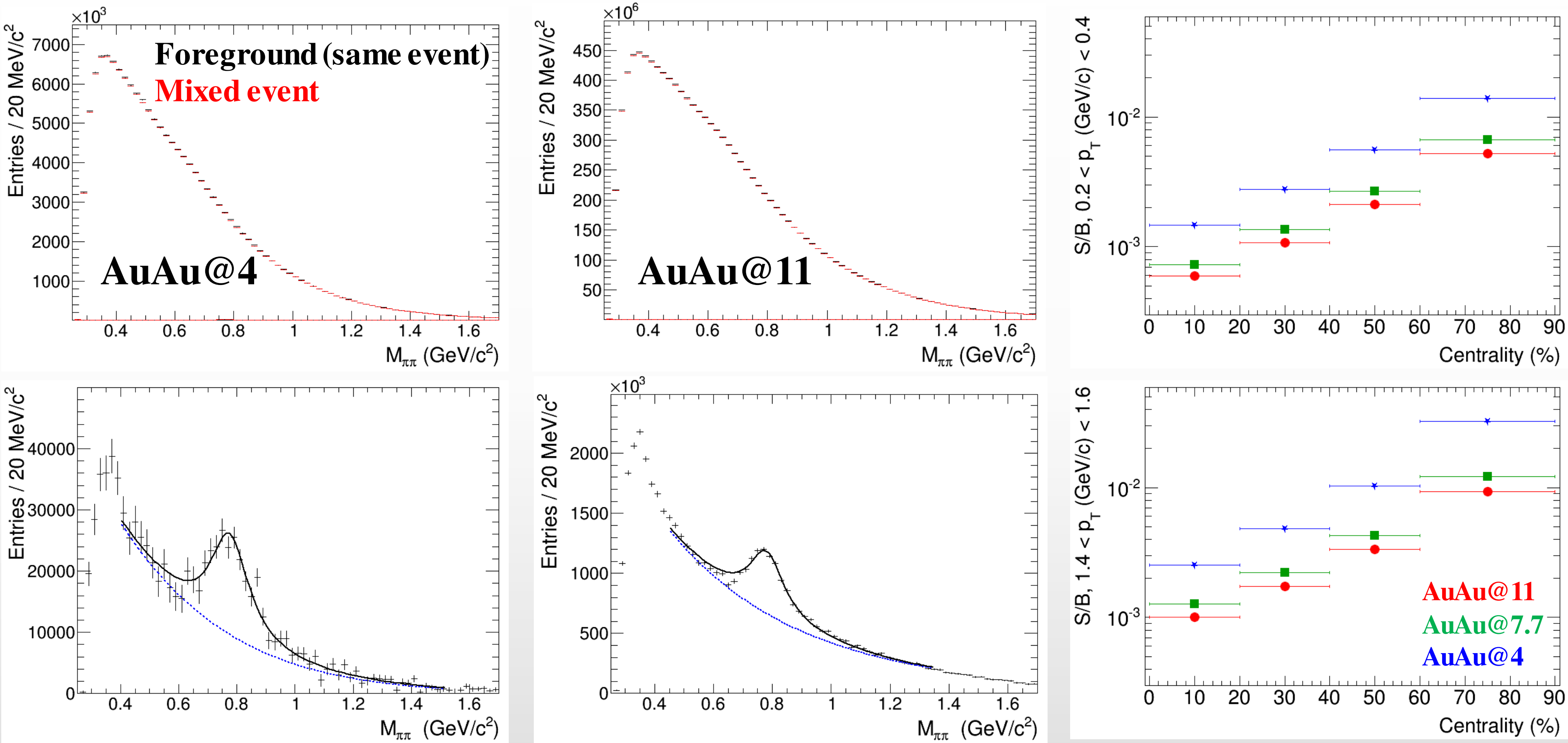
- Modifications occur at low momentum as expected for hadronic phase effects



- Models predict yield modifications for resonances qualitatively similar to those observed at higher collision energies:
  - ✓ 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 hadronic phase simulations

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, $p_T = 0.2\text{-}0.4$ 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

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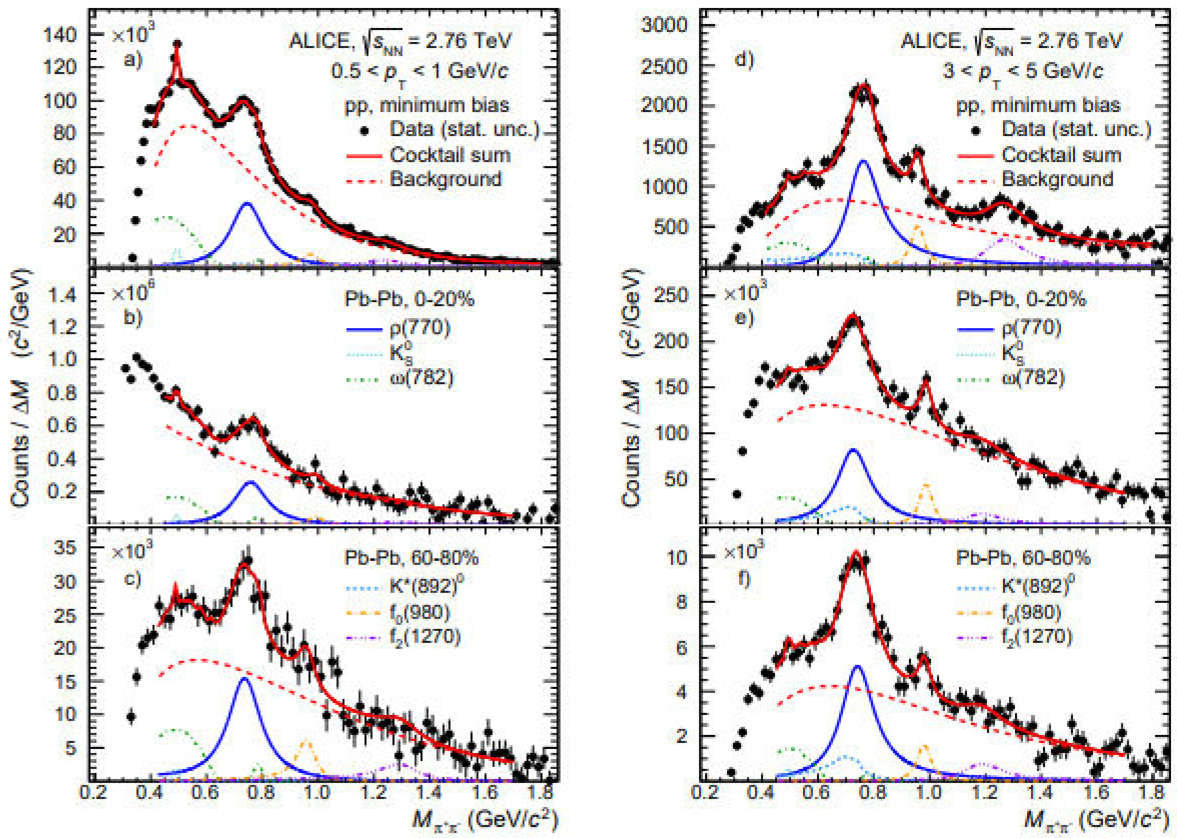

Fig. 1: (Color online) Invariant mass distributions for $\pi^+\pi^-$ pairs after subtraction of the like-sign background. Plots on the left and right are for the low and high transverse momentum intervals, respectively. Examples are shown for minimum bias pp, 0–20% and 60–80% central Pb–Pb collisions 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.