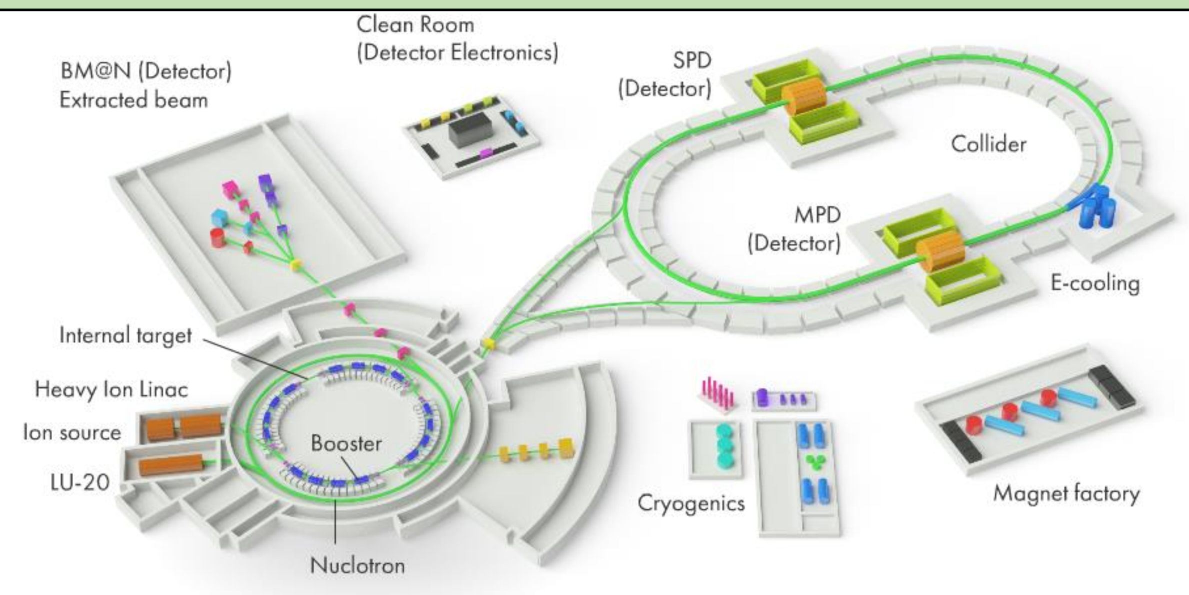
NICA

Nuclotron-based Ion Collider fAcility

PNPI

Study of the centrality and collision energy dependence of resonance production using the MPD detector at NICA

D. Ivanishchev, D. Kotov, M. Malaev, V. Riabov, Yu. Ryabov fot the MPD collaboration



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

Outline

- Motivations 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

Resonances in heavy-ion collisions

- ✓ Vacuum properties of resosnances are well defined; 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.

increasing lifetime →

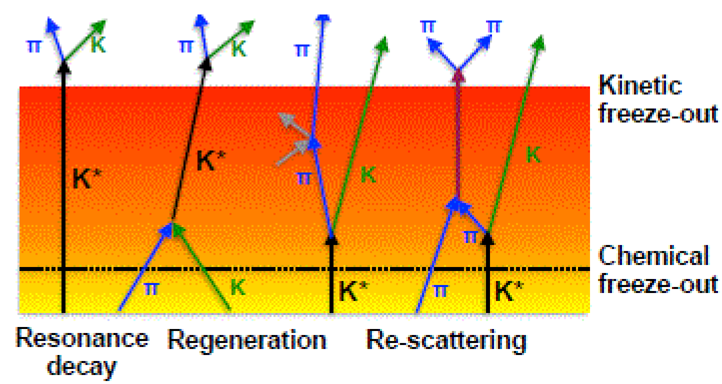
	ρ(770)	$K^*(892)$	Σ(1385)	Λ(1520)	Ξ(1530)	ϕ(1020)
cτ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

Reconstructed resonance yields in heavy ion collisions are defined by:

- ✓ resonance yields at chemical freeze-out
- ✓ hadronic processes between chemical and kinetic freeze-outs:

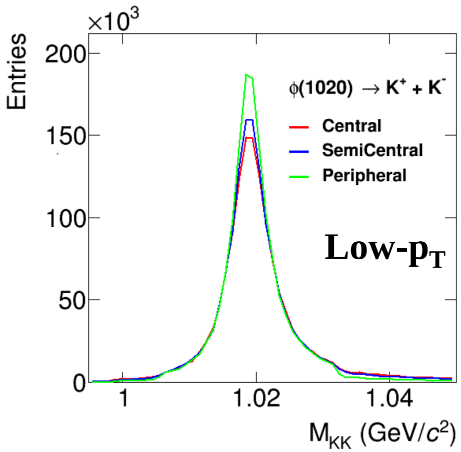
rescattering: daughter particles undergo elastic scattering or pseudo-elastic scattering through a different resonance → parent particle is not reconstructed → loss of signal

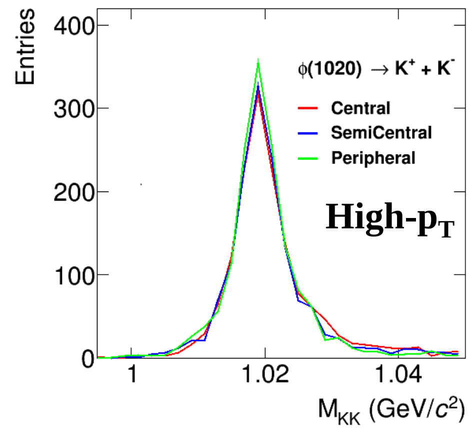
regeneration: pseudo-elastic scattering of decay products ($\pi K \rightarrow K^{*0}$, $KK \rightarrow \phi$ etc.) → increased yields



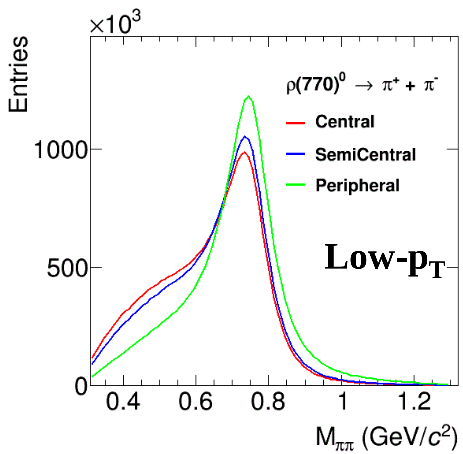
Resonances in AuAu@11, UrQMD

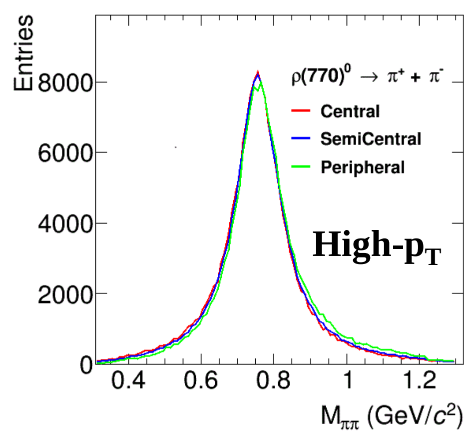
- Resonances are decayed by UrQMD, daughters participate in elastic and inelastic scattering
- Resonance are reconstructed by invariant mass method according to decay channels
- $\phi \rightarrow K^+K^-$ ($c\tau \sim 45$ fm/c): modest line shape modifications in central AuAu@11 at low p_T





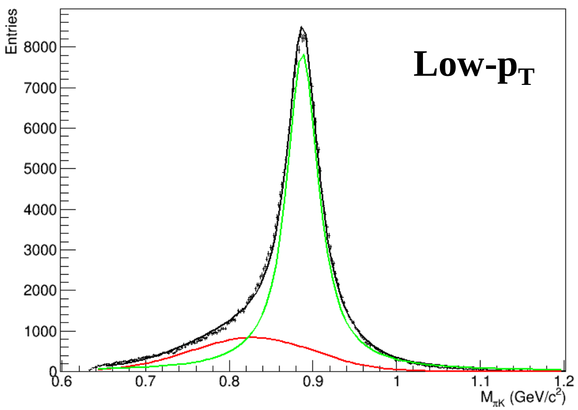
- $\rho(770)^0 \rightarrow \pi^+\pi^-$ ($c\tau \sim 1.3$ fm/c): significant line shape modifications in central AuAu@11 at low p_T

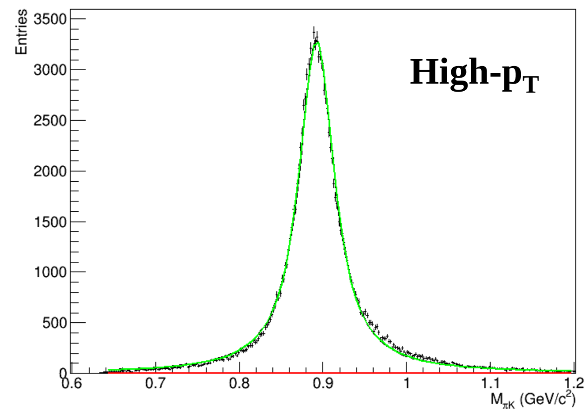




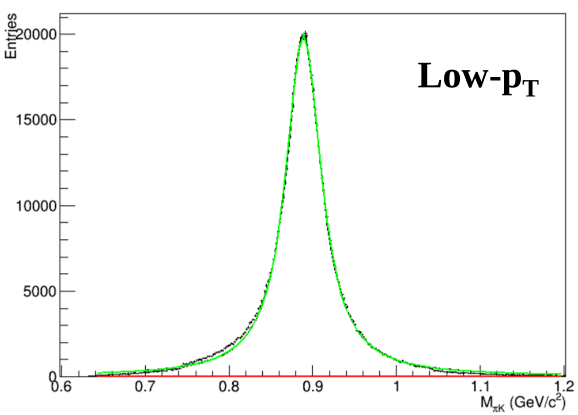
Yield and mass modifications in AuAu@11, UrQMD

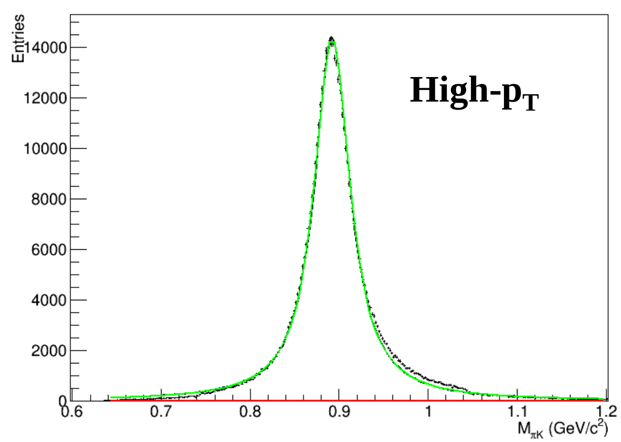
- $K^*(892)^0 \rightarrow \pi^{\pm}K^{\pm}$ ($c\tau$ ~ 4.2 fm/c); combine $\pi^{\pm}K^{\pm}$ pairs from true $K^*(892)^0$ decays
- Same fitting function for $K^*(892)^0$ and background as in ALICE
- Central collisions: small line shape modifications at low p_T; nothing at higher momentum





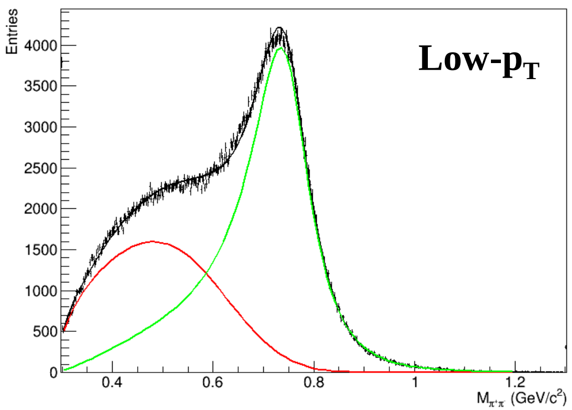
- Peripheral collisions: nothing

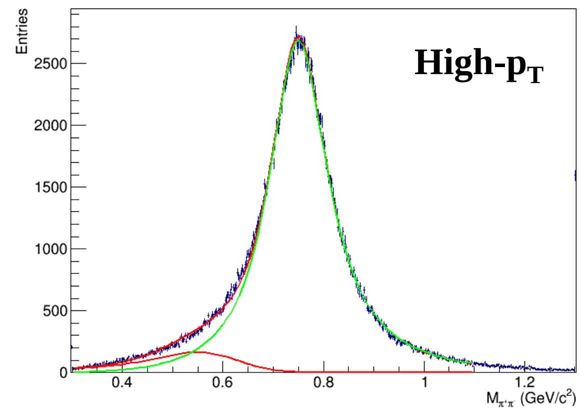




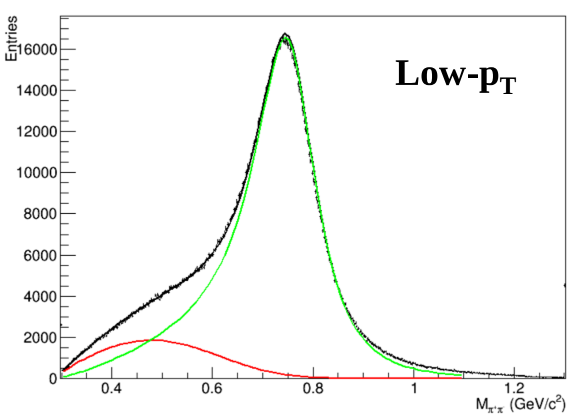
Yield and mass modifications in AuAu@11, UrQMD

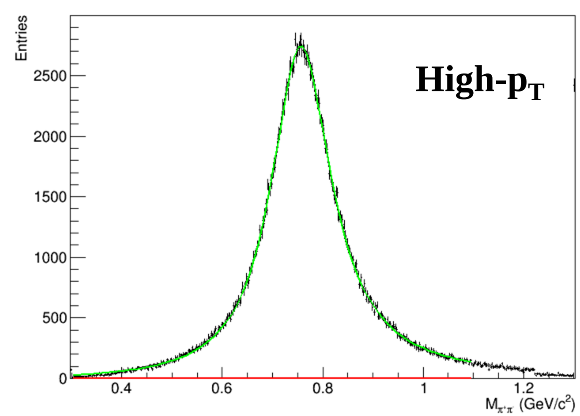
- $\rho(770)^0 \rightarrow \pi^+\pi^-$ ($c\tau \sim 1.3$ fm/c); combine $\pi^+\pi^-$ pairs from true $\rho(770)^0$ decays
- Same fitting function for $\rho(770)^0$ and background as in ALICE
- Central collisions: significant line shape modifications; excess with respect to the peak model is described with a background function





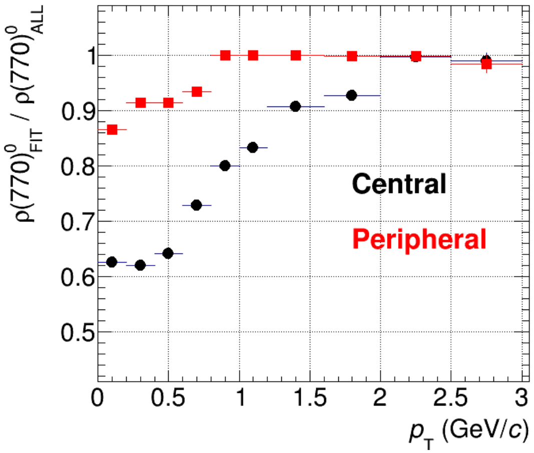
- Peripheral collisions: much smaller modifications are observed, only at low momentum



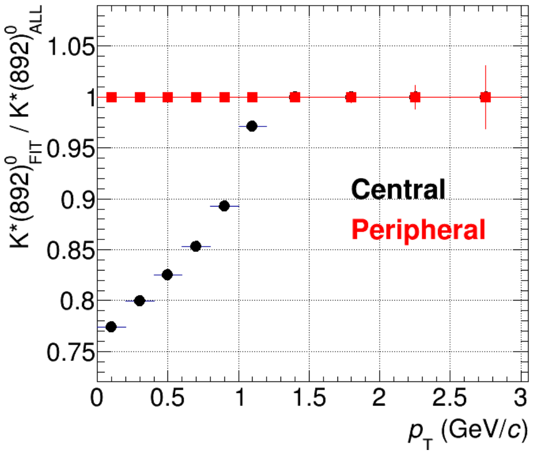


Yields of $K^*(892)^0$ and $\rho(770)^0$ in AuAu@11, UrQMD

❖ $\rho(770)^0 \rightarrow \pi^+\pi^-$ ($c\tau$ ~ 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

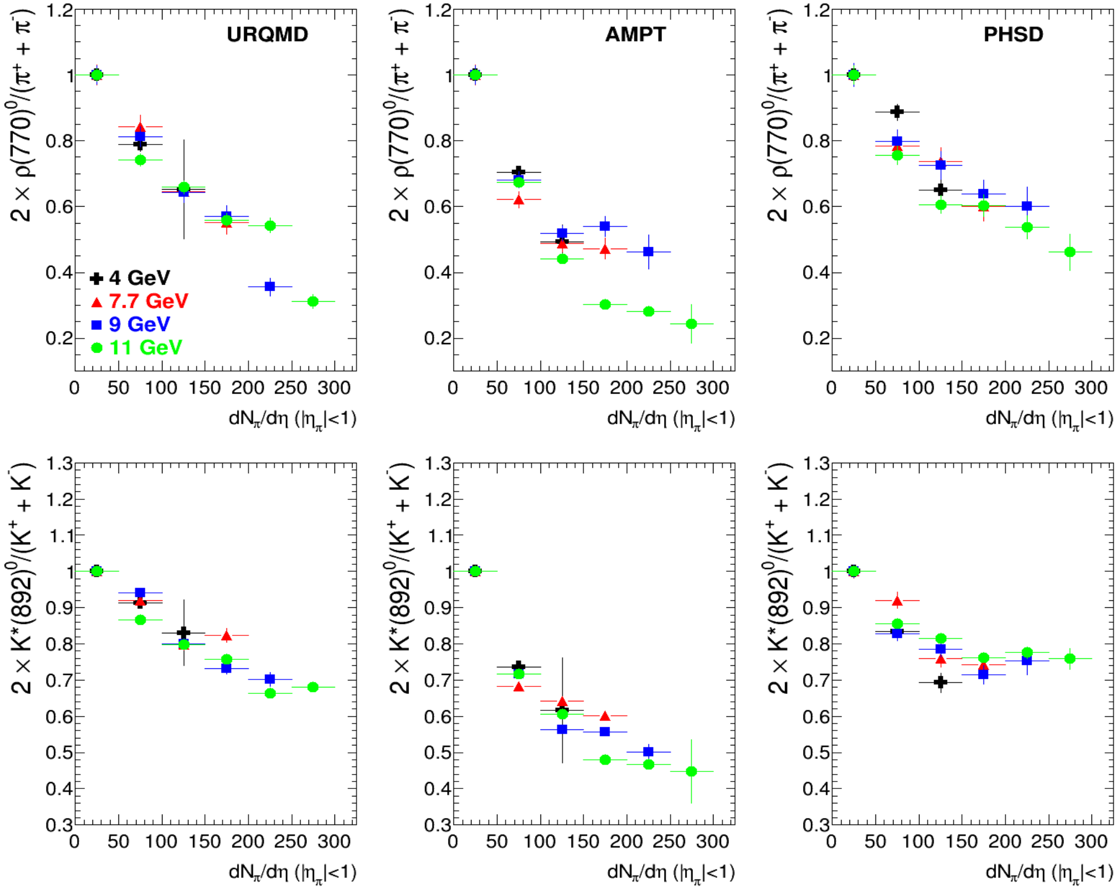


❖ Signal losses are larger for shorter-lived $\rho(770)^0 \rightarrow$ higher chance for $\rho(770)^0$ to decay and for daughters to rescatter in the medium

❖ 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

Particle ratios in AuAu@4-11, UrQMD, AMPT, PHSD

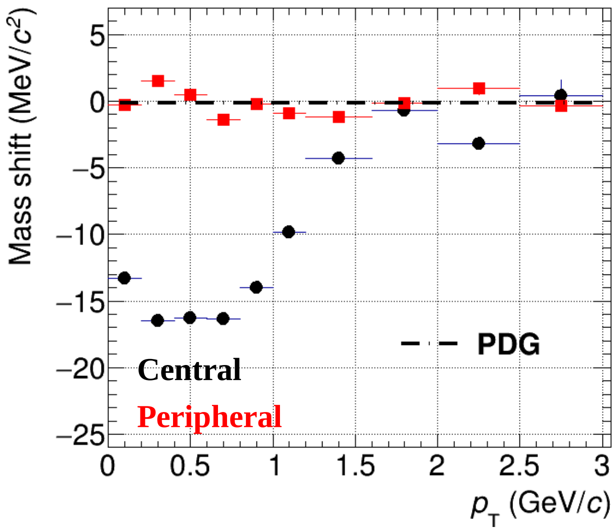
- ❖ Models with hadronic cascades (UrQMD, PHSD, AMPT)
- ❖ Ratios for two shortest-lived resonances (ϕ, $K^*(892)$) are shown normalized to most peripheral collisions

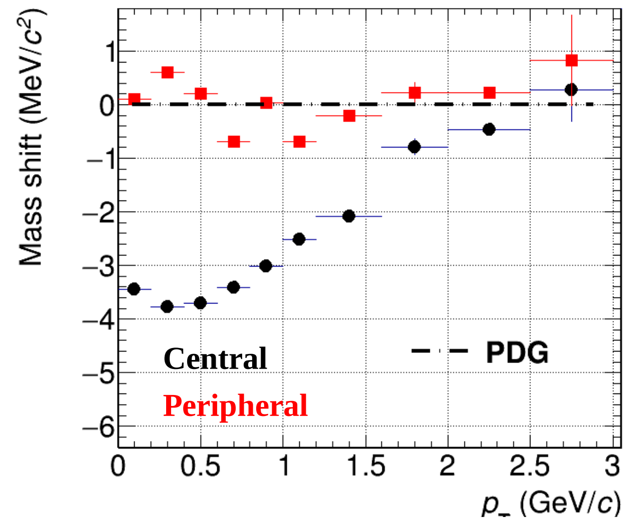


- ➢ Models predict suppression of ρ/π and K^*/K ratios in Au+Au@4-11, resonances with small $c\tau$
- ➢ Suppression depends on the final state multiplicity rather than on collision energy
- ➢ Yield losses occur at low momentum as has been demonstrated before

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

- $\rho(770)^0 \rightarrow \pi^+\pi^-$ ($c\tau$ ~ 1.3 fm/c)
- $K^*(892)^0 \rightarrow \pi^\pm K^\pm$ ($c\tau$ ~ 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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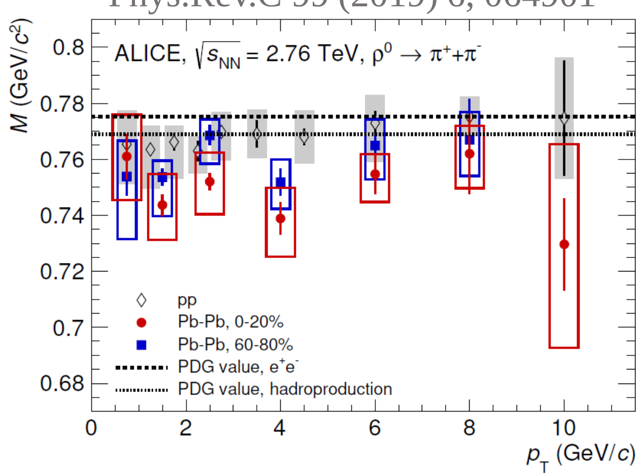

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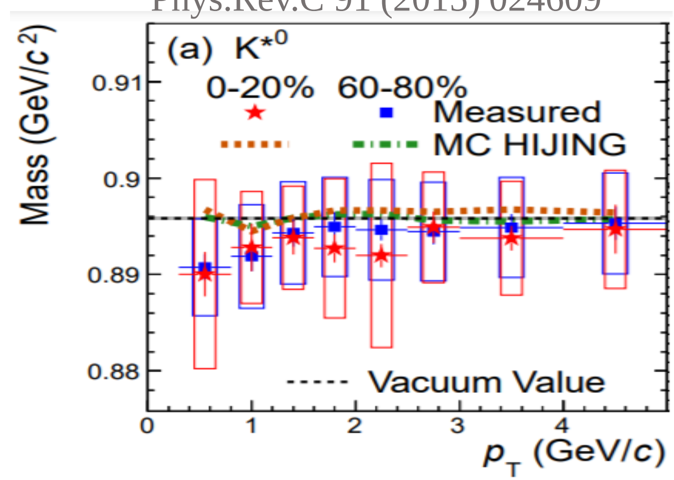
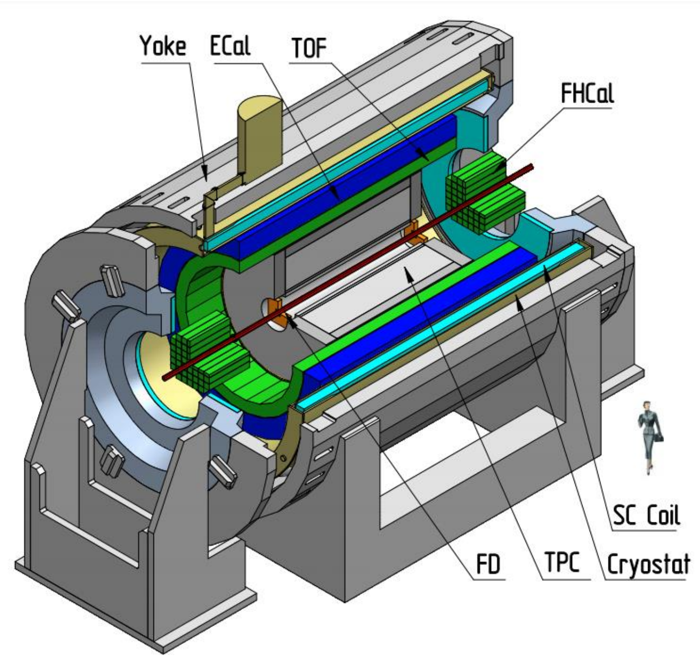


MPD experiment, Phase 1

- ✓ Phase 1: **TPC, TOF, FFD, FCAL и ECAL**
- ✓ Startup in 2021-2022
- ✓ Simulate AuAu@4-11 collisions using different event generators
- ✓ Propagate particles through the MPD, ‘mpdroot’:
  - ✓ Geant (v.3 or v.4) 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| < 2σ for primary tracks
    - V0 topology cuts for weakly decaying secondaries
    - $p_T > 50$-100 MeV/c
    - TPC-TOF combined π/K/p PID
  - ✓ combinatorial background:
    - event mixing ($|\Delta_{Zvrtx}| < 2$ cm, $|\Delta_{Mult}| < 20$, $N_{ev} = 10$)



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

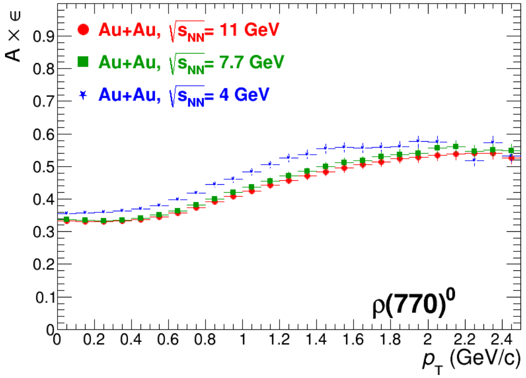
TOF, EMC: $|\Delta\varphi| < 2\pi$, $|\eta| \le 1.4$

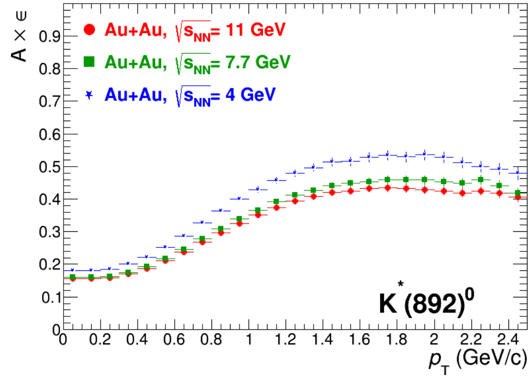
FFD: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$

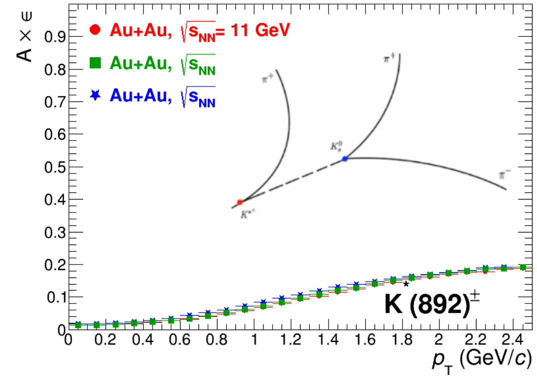
FHCAL: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

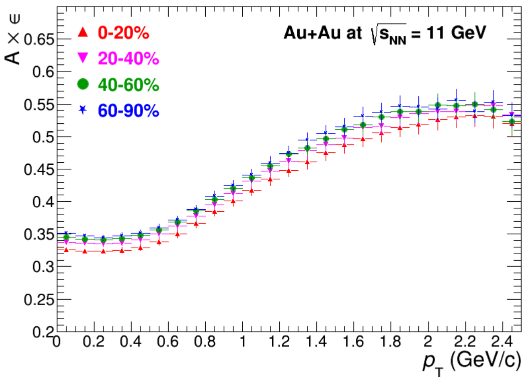
Reconstruction efficiencies

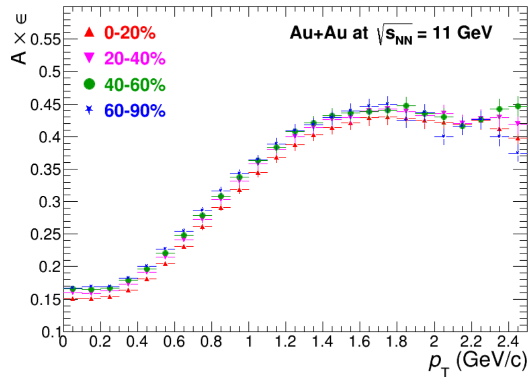
❖ Typical reconstruction efficiencies (A x ∈) in AuAu @ **4**, **7.7** and **11** GeV, |y| < 1

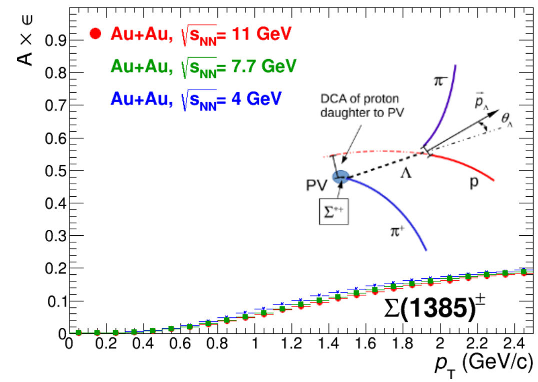


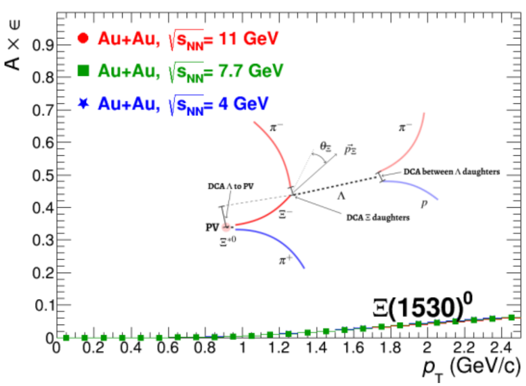












❖ Reasonable efficiencies in the wide p_T range, |y| < 1

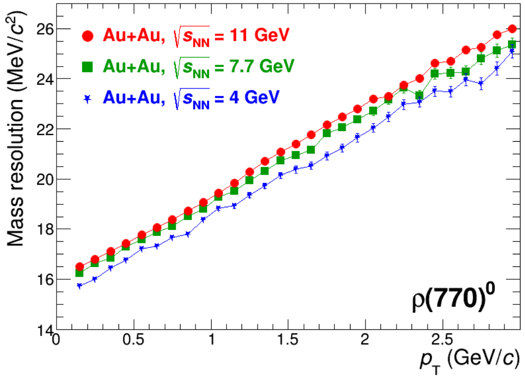
❖ Efficiencies are noticeably lower for multi-stage decays with weakly decaying daughters (Ξ, Λ, K_S^0)

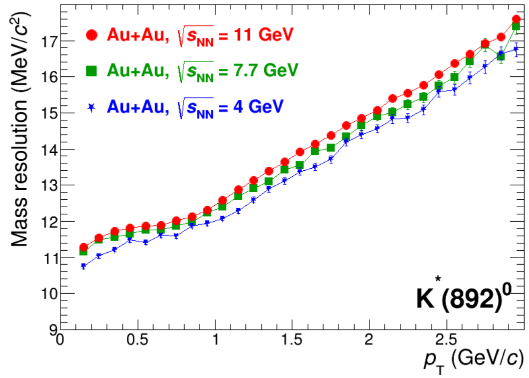
❖ Measurements are possible from zero momentum

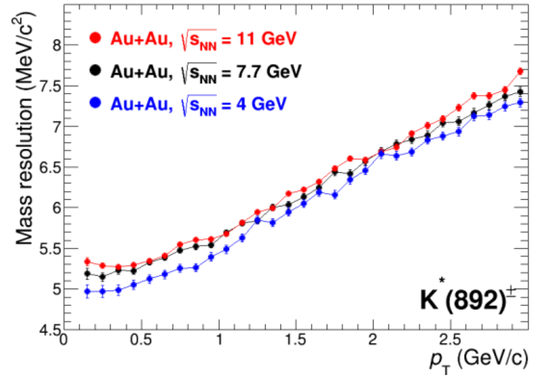
❖ Modest multiplicity (and/or $\sqrt{s_{NN}}$) dependence

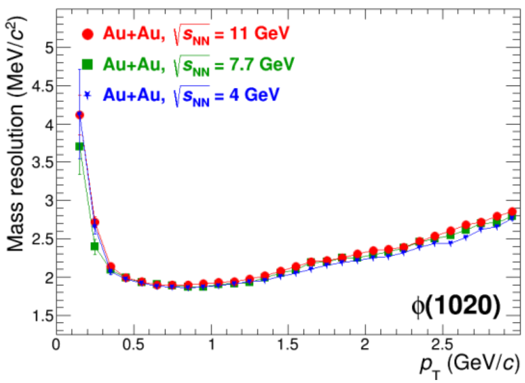
Mass resolution:

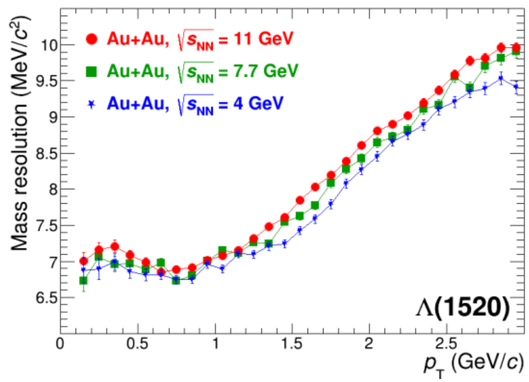
❖ Detector mass resolution ($m_{reconstructed} - m_{generated}$) in AuAu @ **4**, **7.7** and **11** GeV, $|y| < 1$

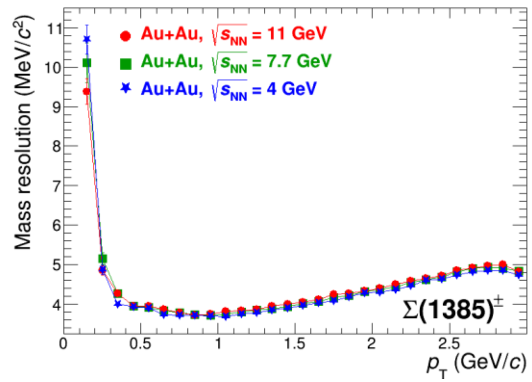


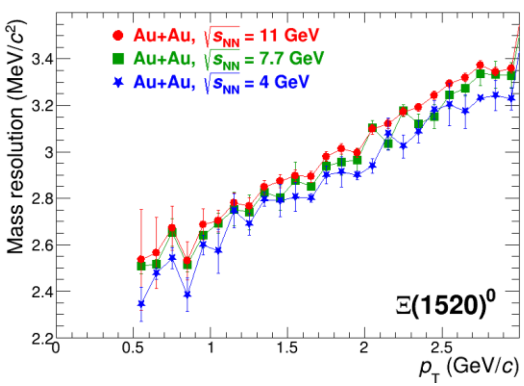










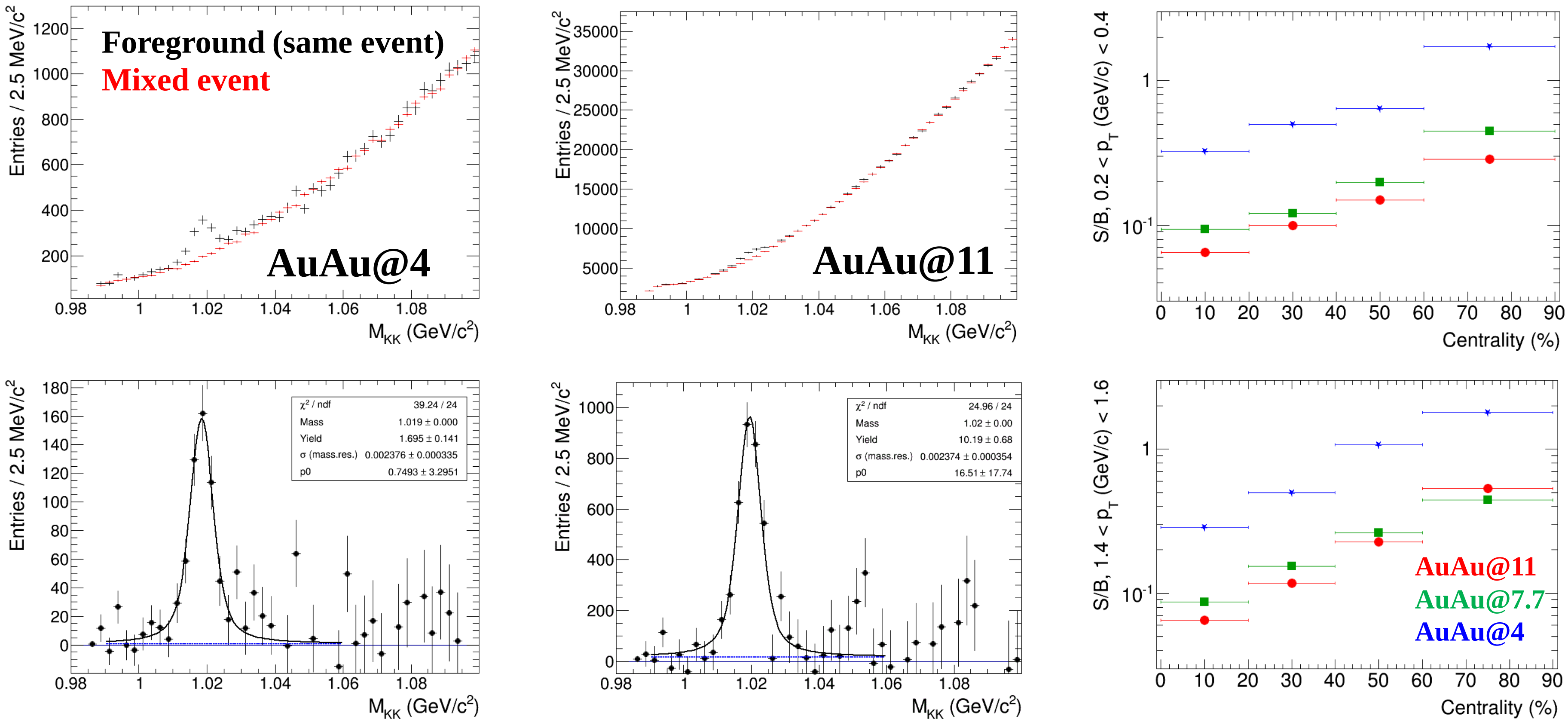


❖ Mass resolution is good enough to preserve the capability for the line shape analysis

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

ϕ(1020), reconstructed peaks

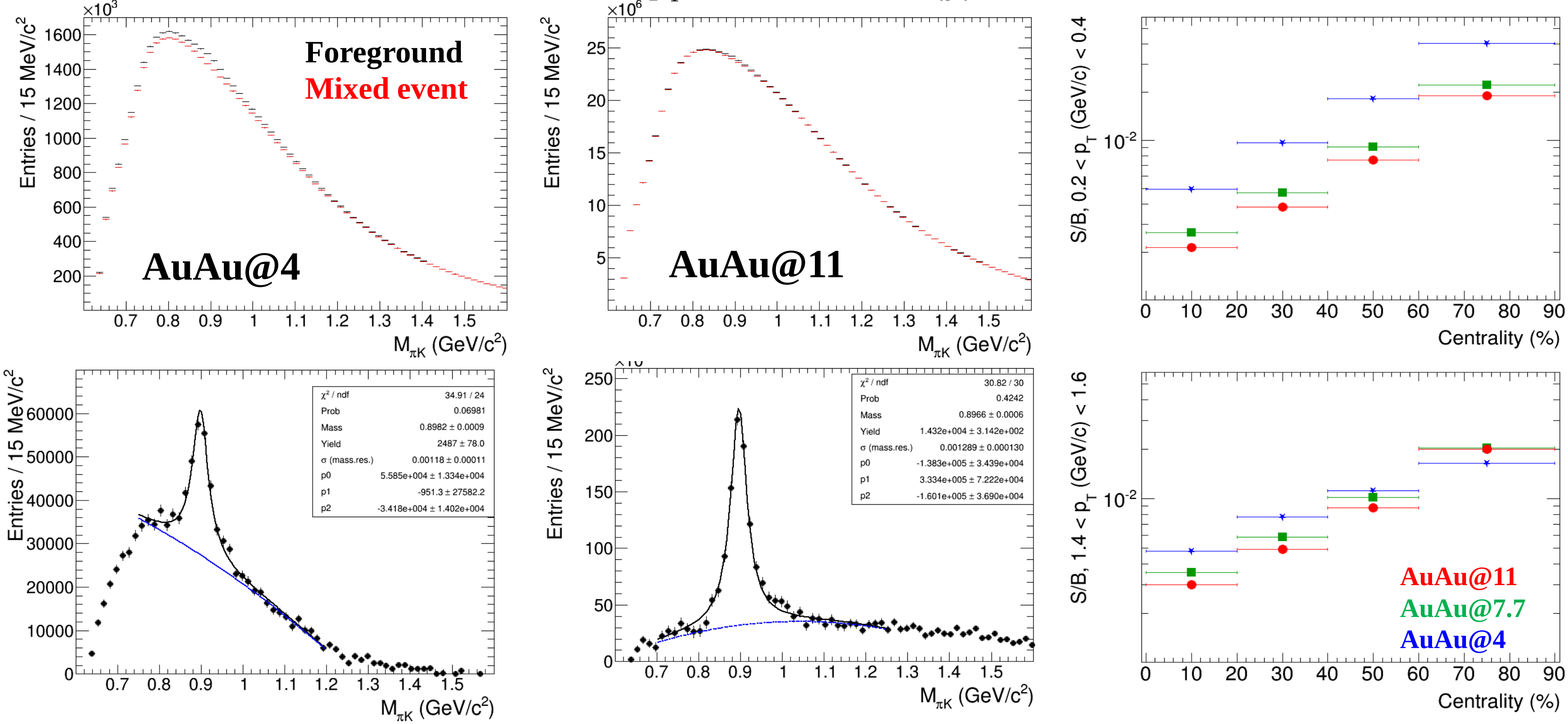
- UrQMD v.3.4: AuAu@11 (10M events), AuAu@7.7 (5M events), AuAu@4 (5M events)
- Full chain simulation and reconstruction, p_T = 0.2-0.4 GeV/c, |y| < 1



- 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
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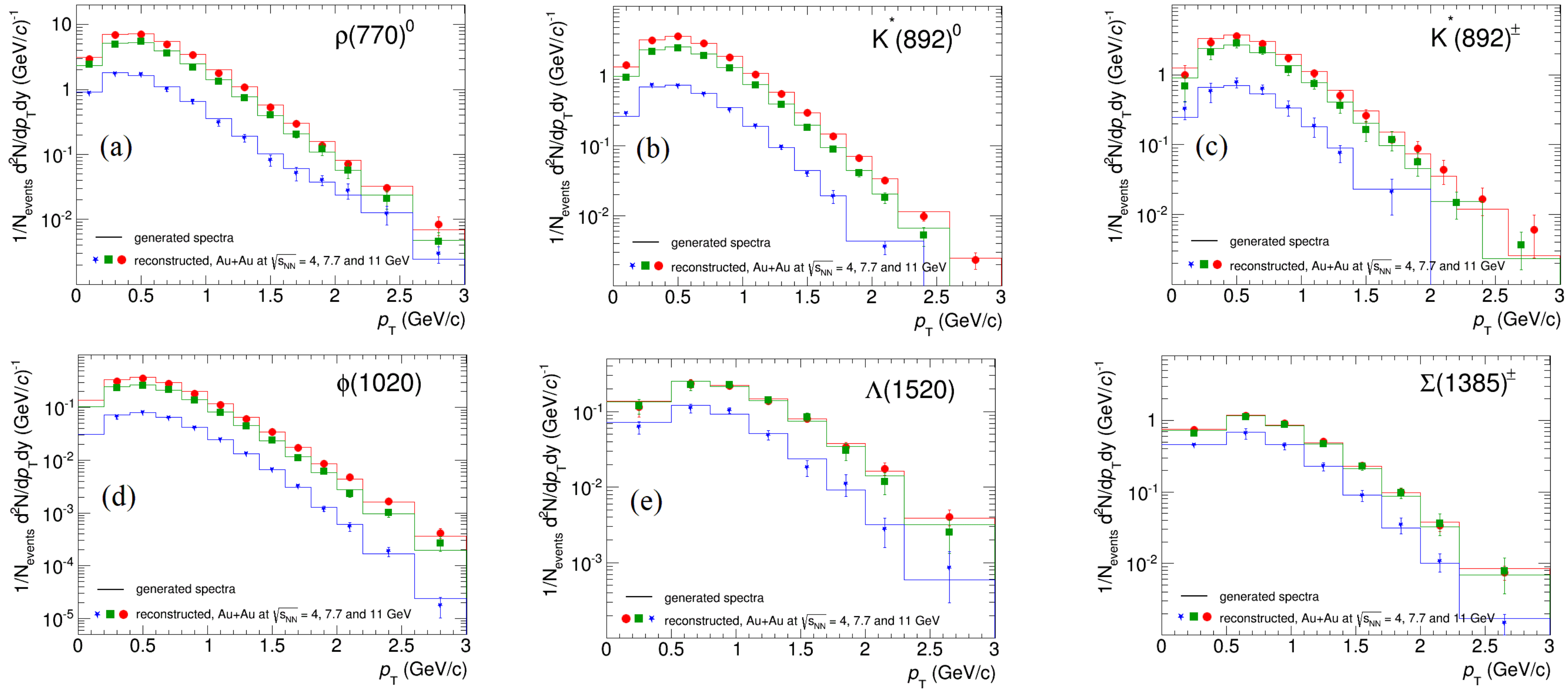
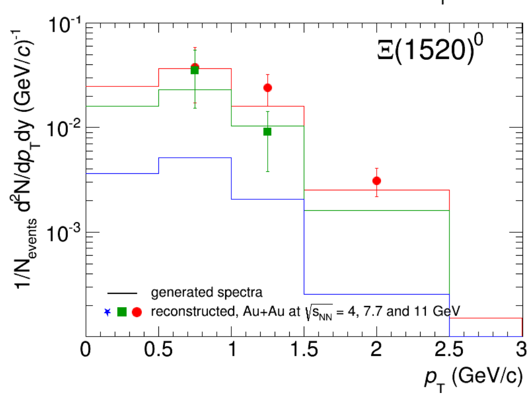
- Signal can be reconstructed at p_T > 0.2 GeV/c, high-p_T reach is limited by available statistics
- S/B ratios deteriorates with increasing centrality and collision energy

MC closure tests

- 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
- 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

Summary

❖ 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 resonances will be possible with ~10^7 sampled Au+Au collisions at $\sqrt{s_{NN}}$ = 4-11 GeV → year-1 measurements

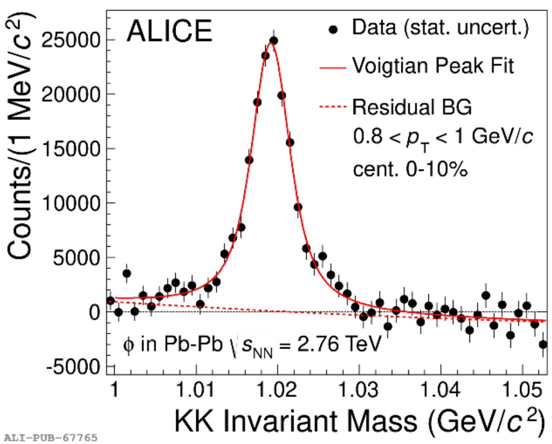
✓ Measurements are possible starting from very low momenta (for most of the cases from zero momenta) with decent mass resolution → high sensitivity to different physics phenomena most prominent at low p_T

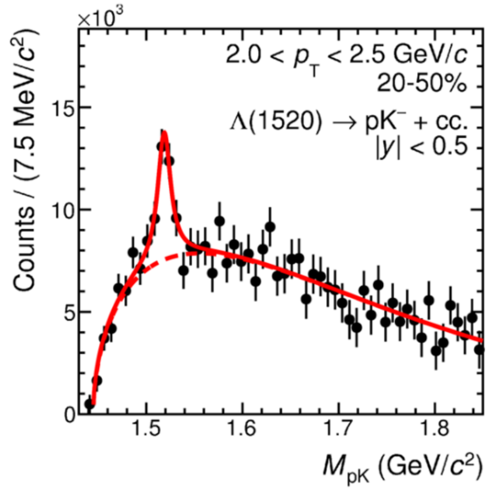
✓ More detailed and multiplicity-dependent studies would require x10-50 larger statistics, especially for multi-stage decays of $K^*(892)^{\pm}$, $\Sigma(1385)^{\pm}$ and $\Xi(1520)^0$

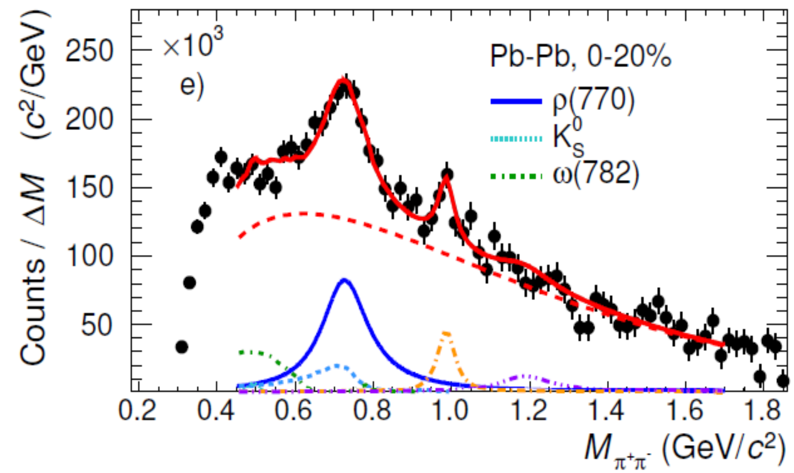
Backup slides

Resonance reconstruction in A-A collisions

- 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 $\rho(770)^0$:



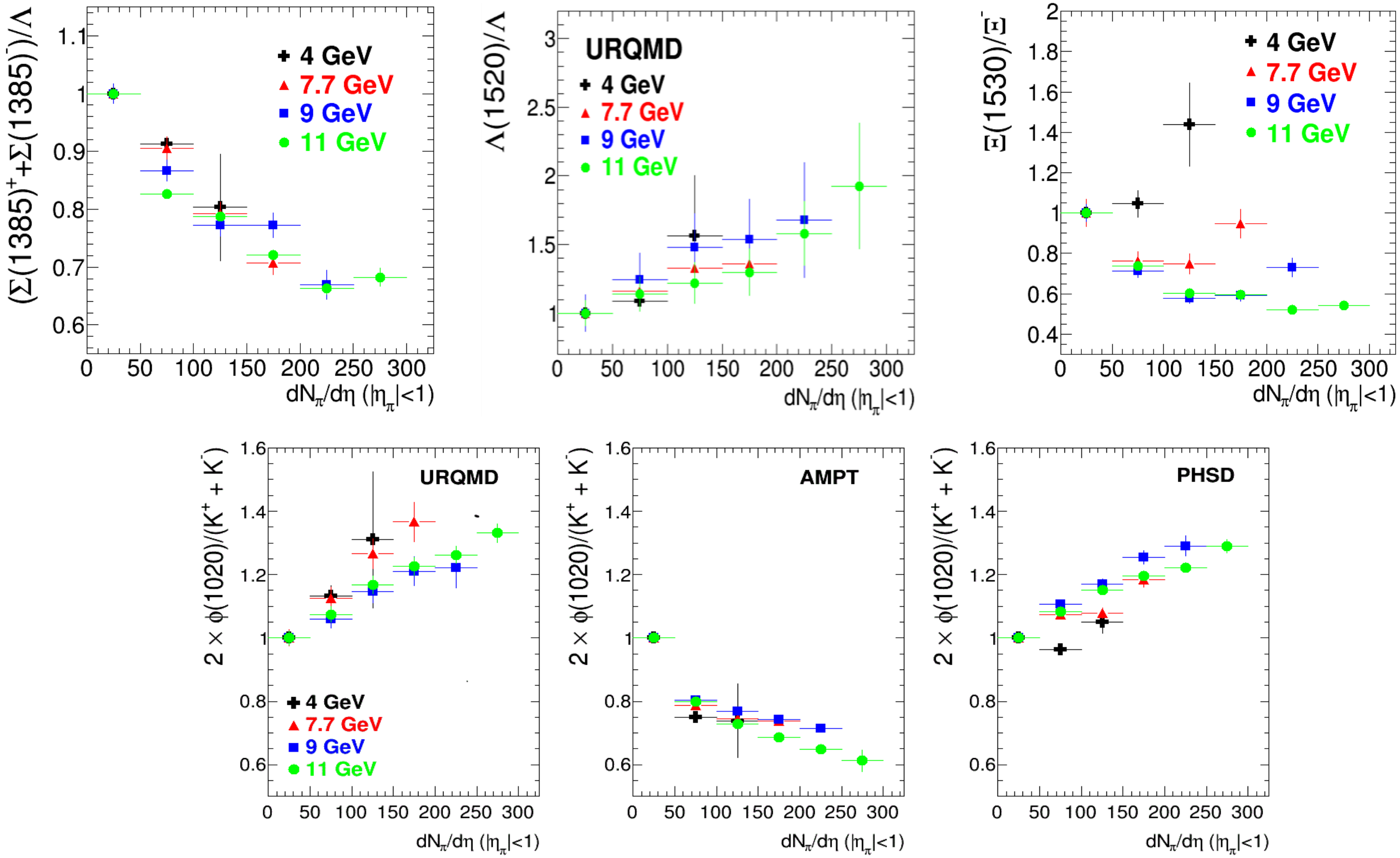




- For most of the cases, the peak models are inspired by theory and measurement in elementary e^+e^- and/or pp collisions where medium effects are not as important
- Line shape modifications will result in the change of the measured yield and masses/widths

Particle ratios in AuAu@4-11, UrQMD, AMPT, PHSD

- Models with hadronic cascades (UrQMD, PHSD, AMPT)
- Ratios for longer-lived resonances (Σ(1385), Λ(1520), Ξ(1530) and ϕ)

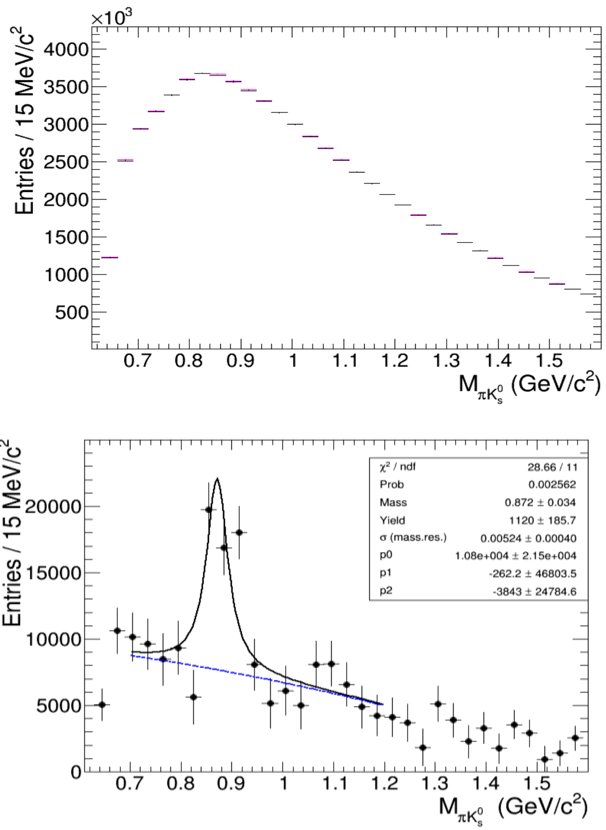


- Event generators predict yield modifications qualitatively similar to those obtained at RHIC/LHC:
  - → lifetime and density of the hadronic phase are high enough
  - → modification of particle properties in the hadronic phase should be taken into account when model predictions for different observables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

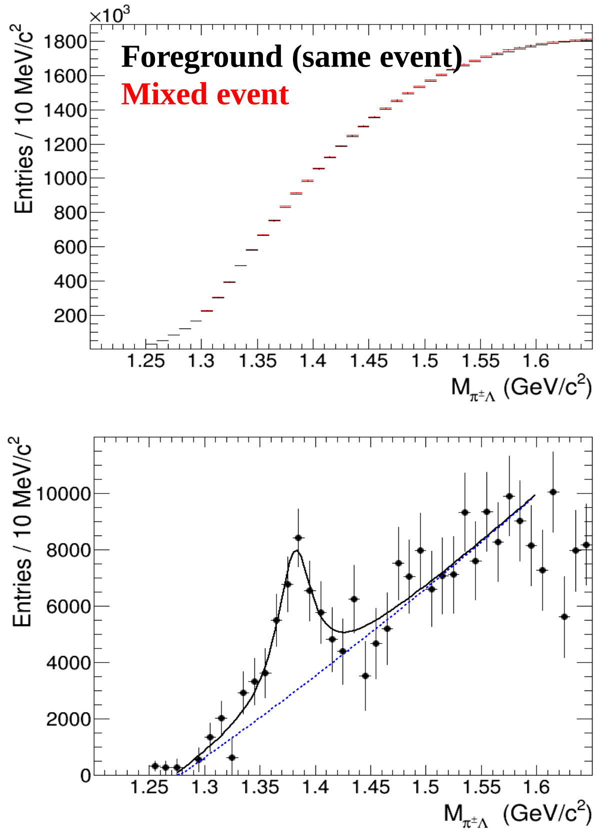
K*(892)±, Σ(1385)±, Ξ(1530)⁰, reconstructed peaks

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

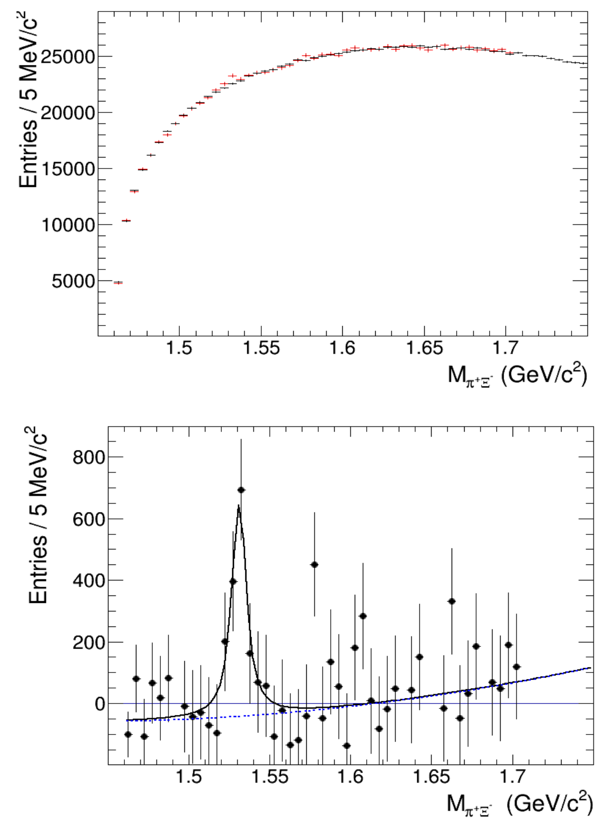
K*±, 0.2-0.4 GeV/c



Σ(1385)±, 0-0.5 GeV/c



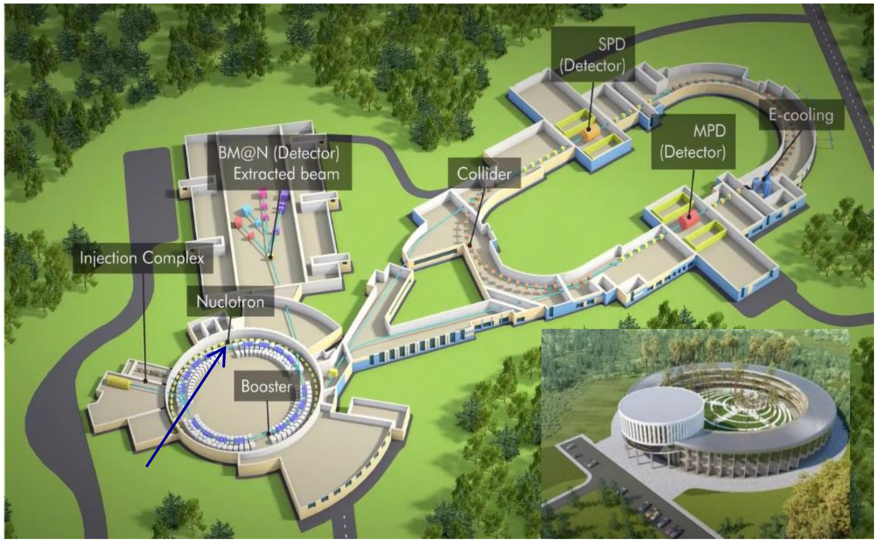
Ξ(1530)⁰, 0.5-1 GeV/c



- Can reconstruct signals for multistage decays of K*(892)± → $K_S^0\pi^{\pm}$ ($K_S^0 \to \pi^+\pi^-$), Σ(1385)± → $\pi^{\pm}\Lambda$ ($\Lambda \to p\pi$) and Ξ(1530)⁰ → $\pi^+\Xi^-$ ($\Xi^- \to \Lambda\pi^-$, ($\Lambda \to p\,\pi^-$))

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, $\sqrt{s_{NN}}$ = 4-11 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

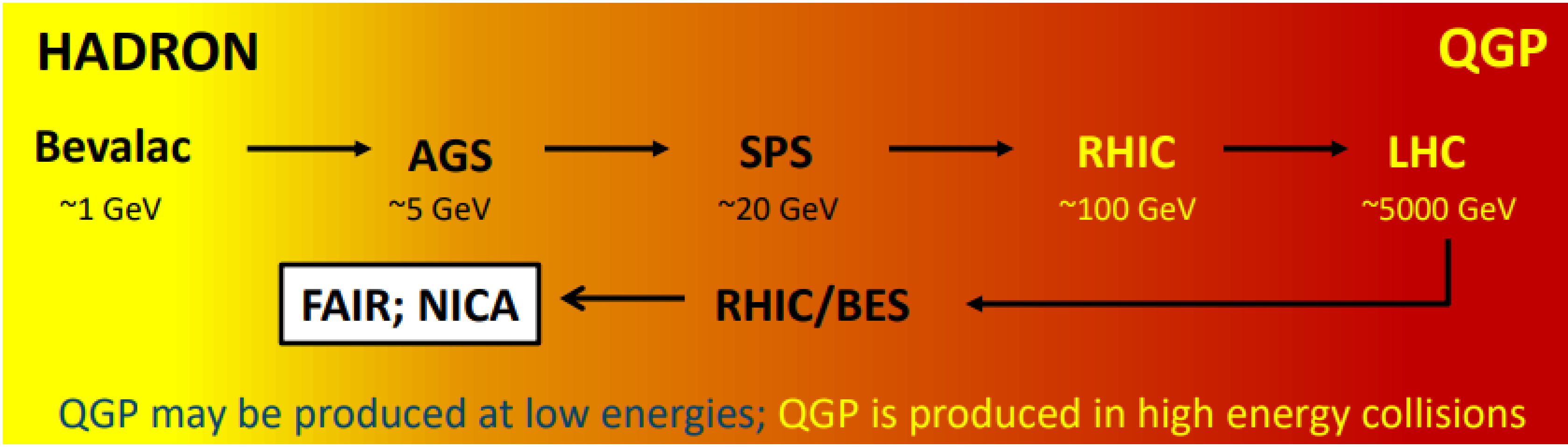
Resonances

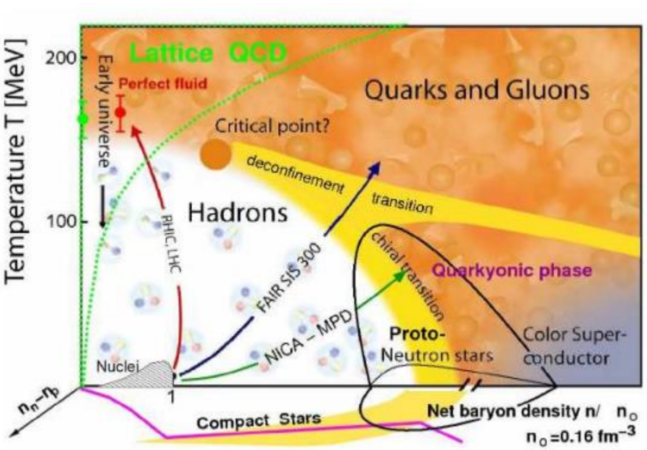
$\rho(770)$ $K^*(892)^0$ $K^*(892)^+$ $\phi(1020)$ $\Sigma(1385)^\pm$ $\Lambda(1520)$ $\Xi(1530)$

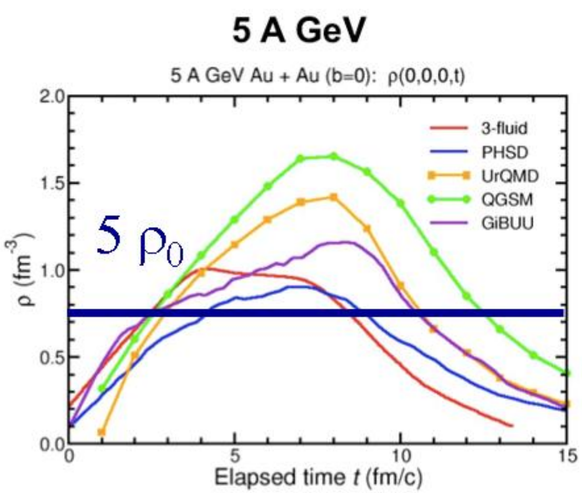
$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$ $d\bar{s}$ $u\bar{s}$ $s\bar{s}$ uus dds uds uss

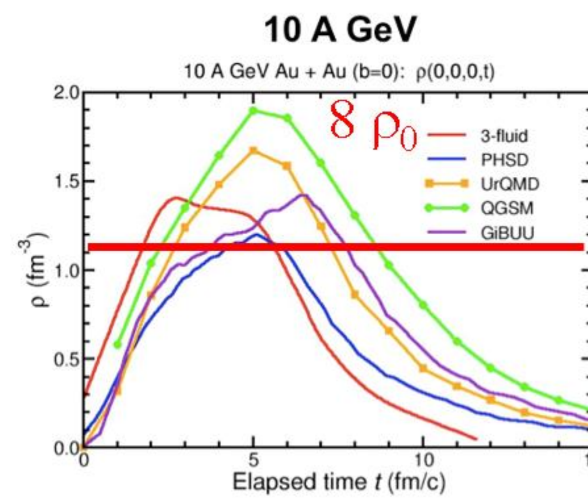
Particle	Mass (MeV/c^2)	Width (MeV/c^2)	Decay	BR (%)
ρ^0	770	150	$\pi^+\pi^-$	100
$K^{*\pm}$	892	50.3	$\pi^\pm K_s$	33.3
K^{*0}	896	47.3	$\pi^- K^+$	66.7
ϕ	1019	4.27	K^+K^-	48.9
Σ^{*+}	1383	36	$\pi^+\Lambda$	87
Σ^{*-}	1387	39.4	$\pi^-\Lambda$	87
$\Lambda(1520)$	1520	15.7	K^-p	22.5
Ξ^{*0}	1532	9.1	$\pi^+\Xi^-$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

Heavy-ion collisions at NICA







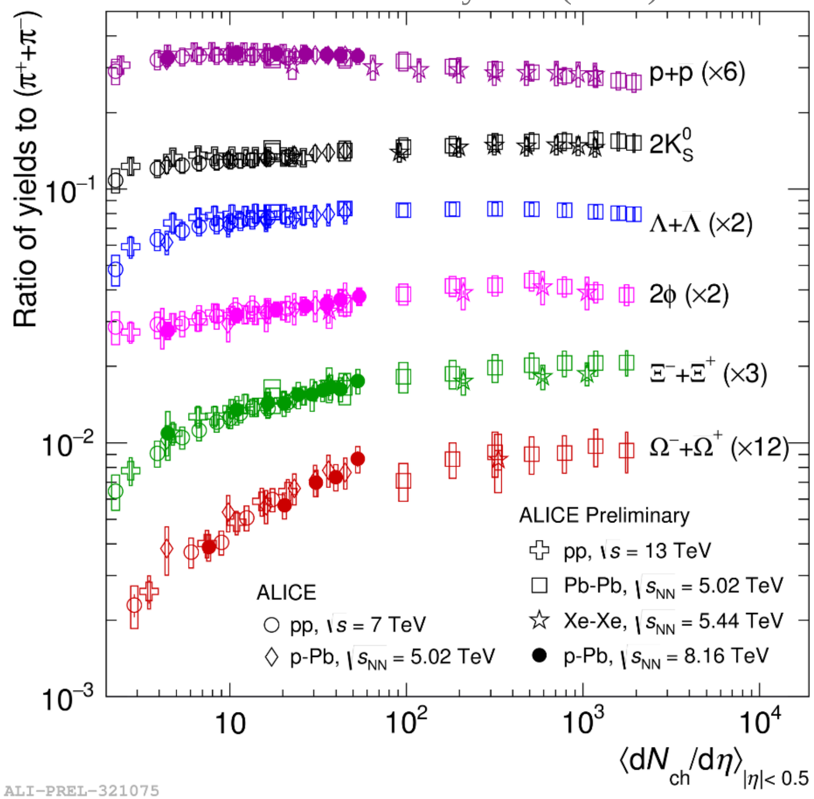


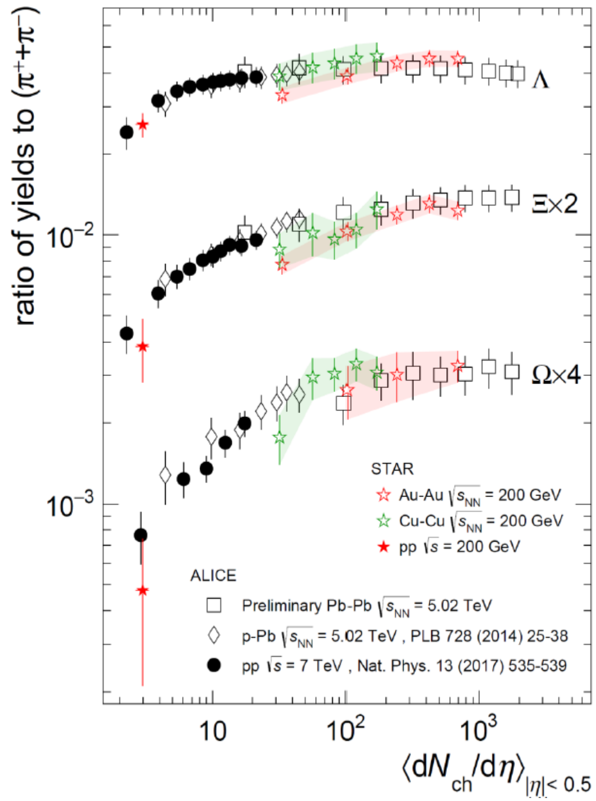
I.C. Arsene at al., Phys. Rev. C75 (2007) 24902.

- ❖ 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

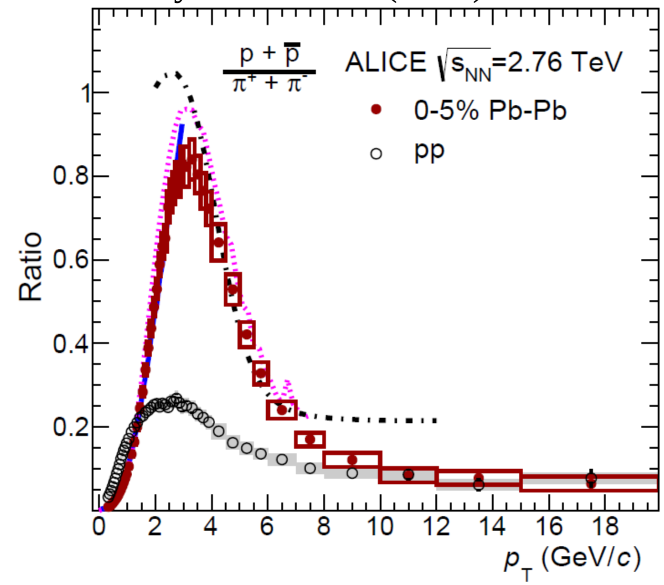
❖ Driving force of enhancement is not yet fully understood:

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

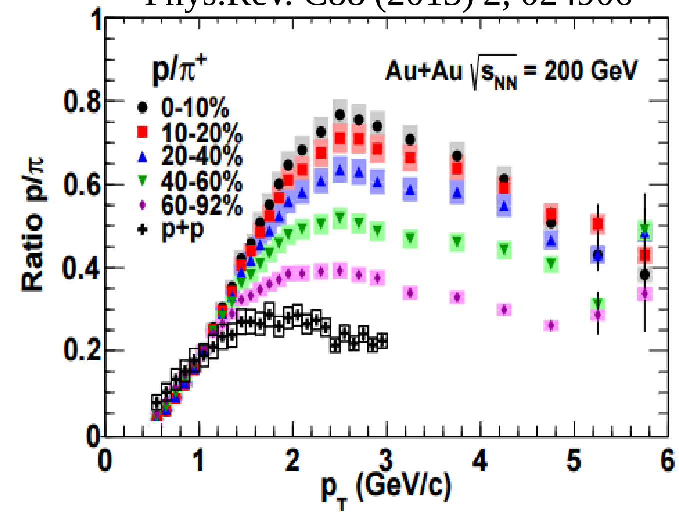
❖ ϕ and K^{*0} are well suited for tests as mesons with masses very close to that of a proton:

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

Phys.Lett. B736 (2014) 196-207

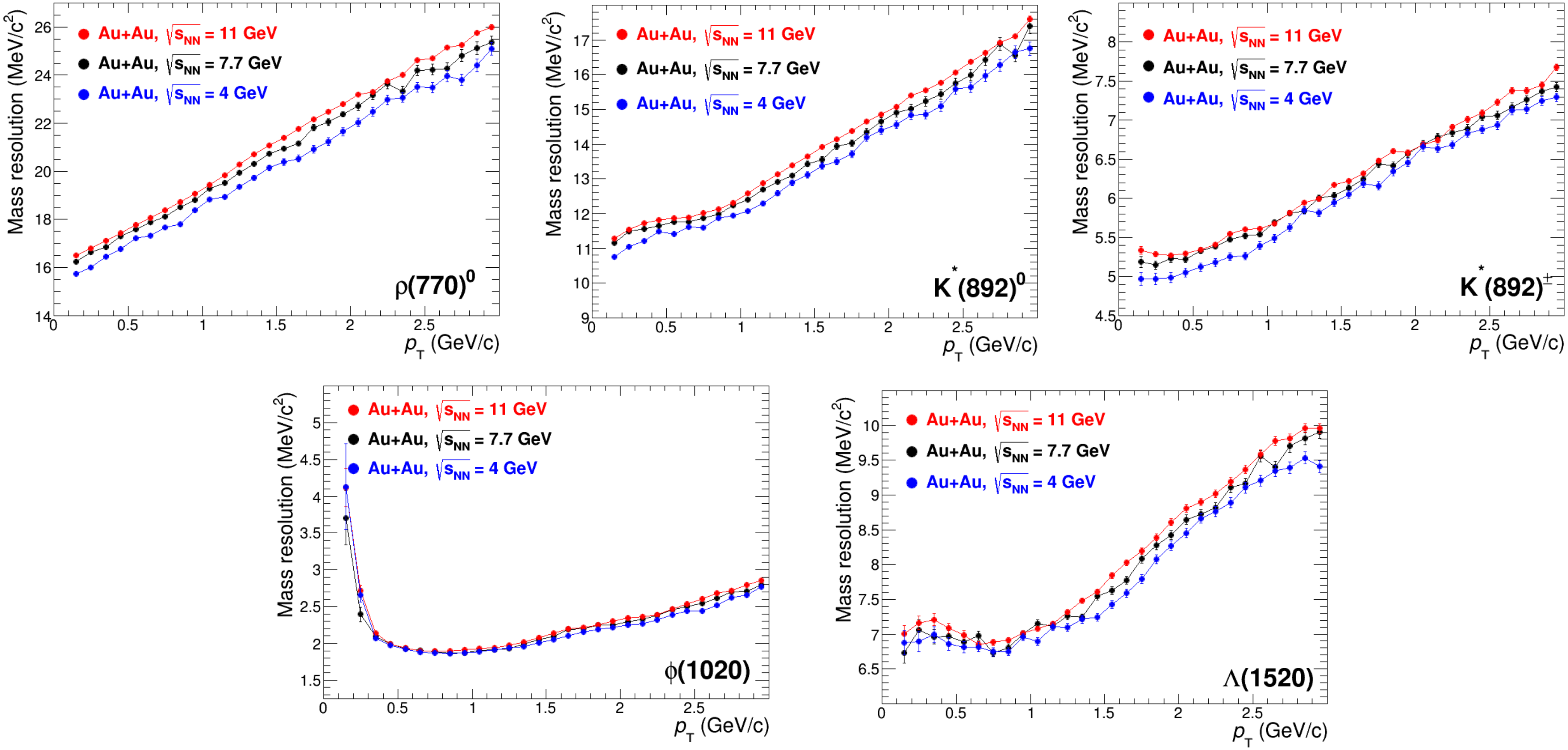


Phys.Rev. C88 (2013) 2, 024906



Mass resolution

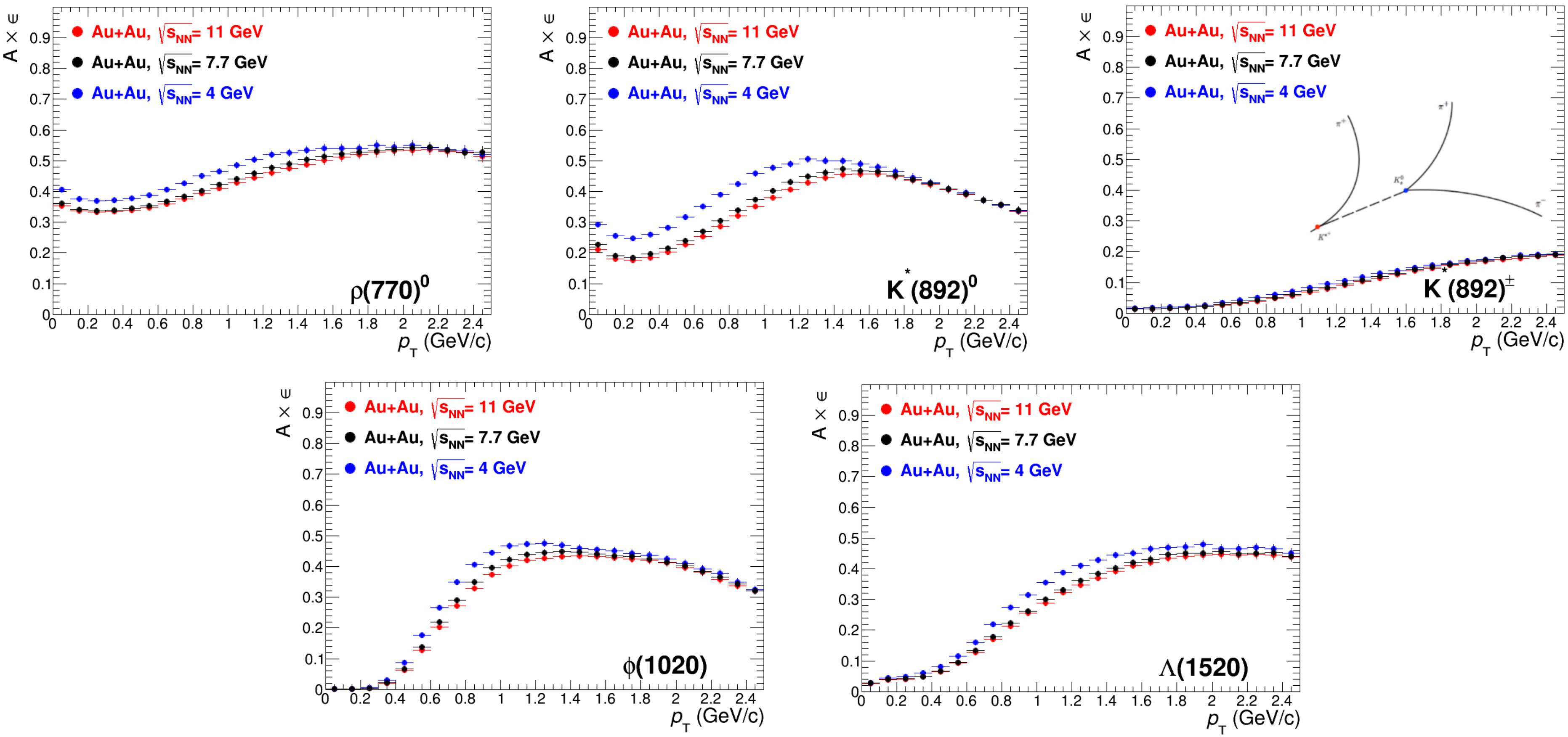
- ✓ Detector mass resolution ($m_{reconstructed} - m_{generated}$) in AuAu @ **4**, **7.7** and **11** GeV, $|y| < 1$



- ✓ Acceptable mass resolution
- ✓ Modest multiplicity (and/or $\sqrt{s_{NN}}$) dependence

Reconstruction efficiency

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

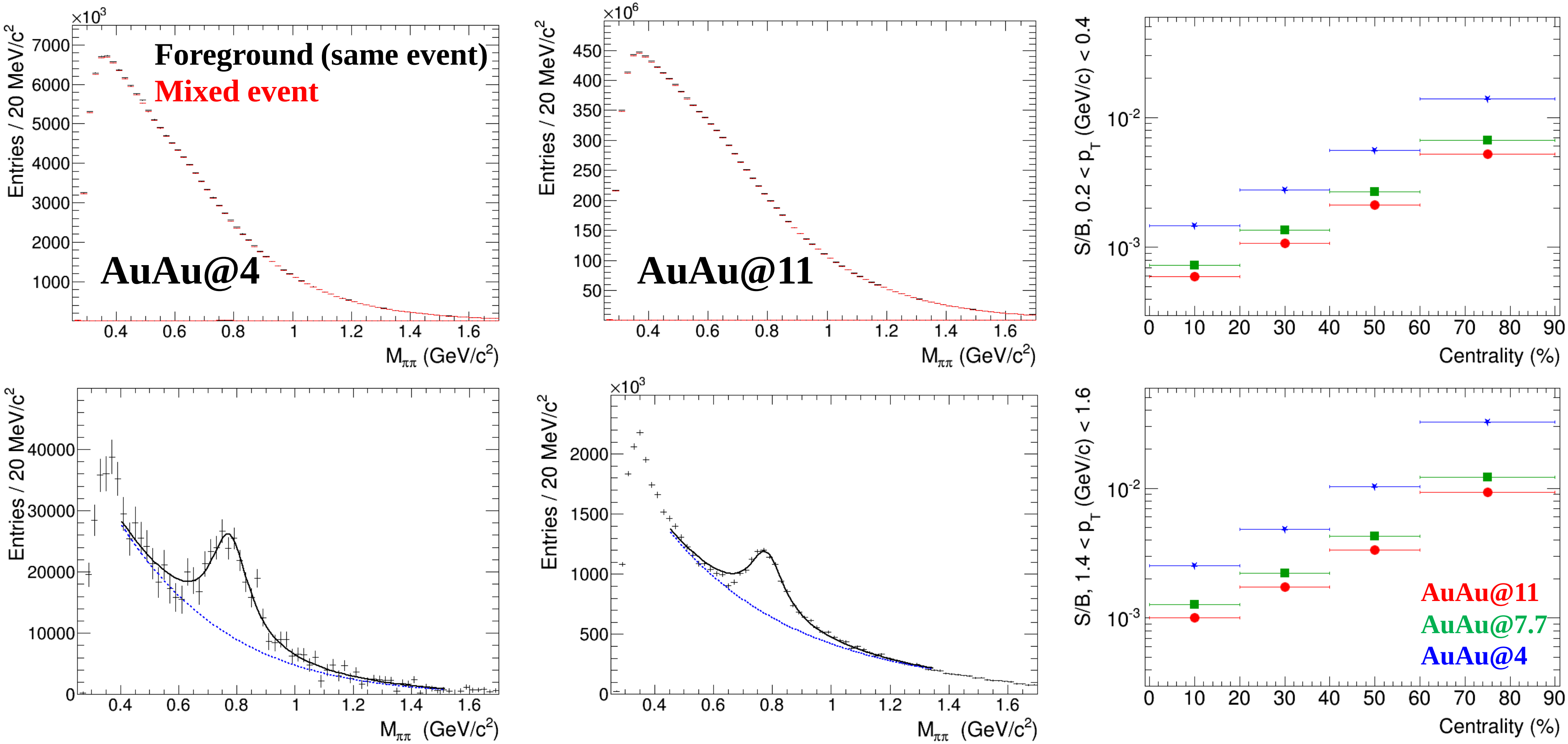


✓ Reasonable efficiencies in the wide p_T range, |y| < 1

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

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

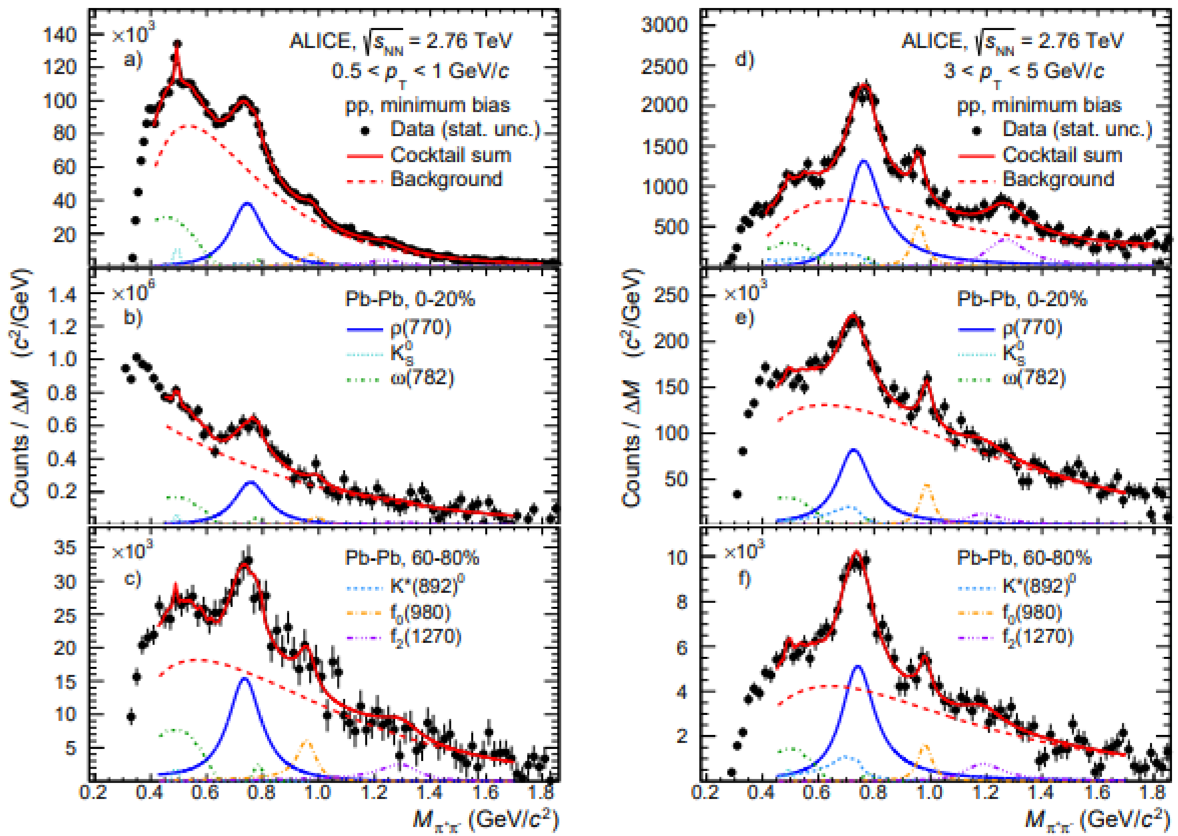


Fig. 1: (Color online) Invariant mass distributions for $\pi^+\pi^-$ pairs after subtraction of the like-sign background. Plots on the left and right are for the low and high transverse momentum intervals, respectively. Examples are shown for minimum bias pp, 0–20% and 60–80% central Pb–Pb collisions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