NICA Nuclotron-based Ion Collider fAcility

Hadronic resonances in heavy-ion collisions at NICA energies and their reconstruction in the MPD setup

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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

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, $c\tau$, 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.

Resonance yields @ RHIC and LHC energies

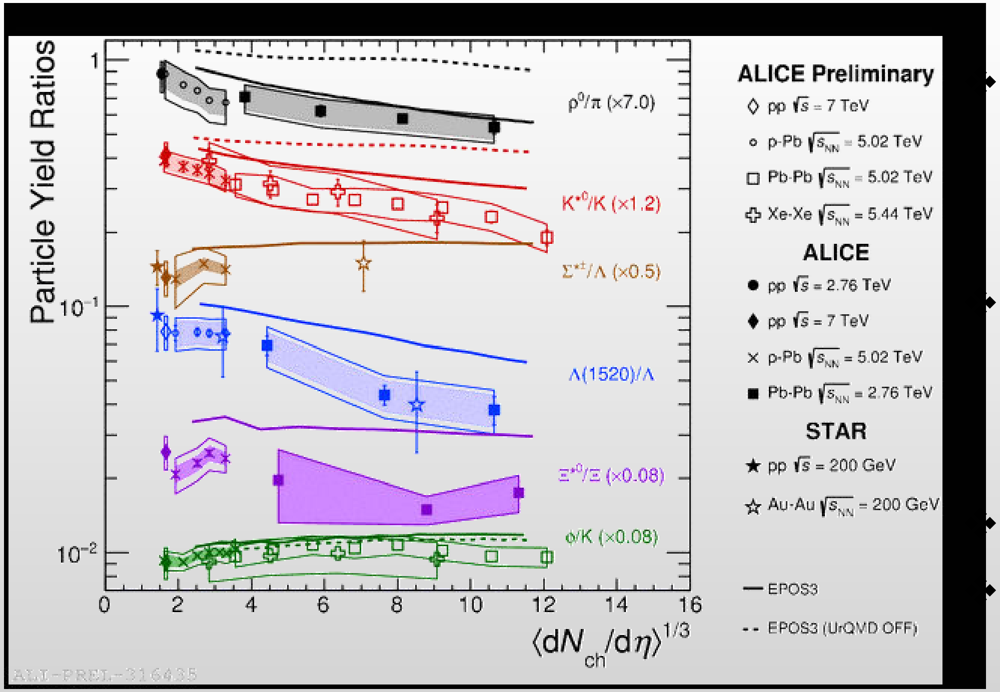
increasing lifetime →

	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



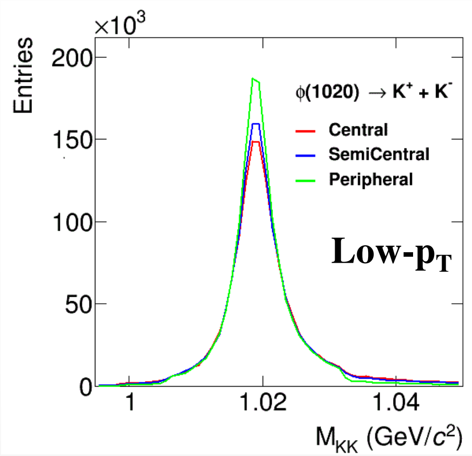
- SPS/RHIC/LHC observed multiplicity dependent suppression of ρ/π, K*/K, Λ*/Λ ratios, resonances with cτ ≤ 20 fm/c. Ratios of longer lived resonances are not affected
- Results support the existence of a hadronic phase that lives long enough to cause a significant reduction of the reconstructed yields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

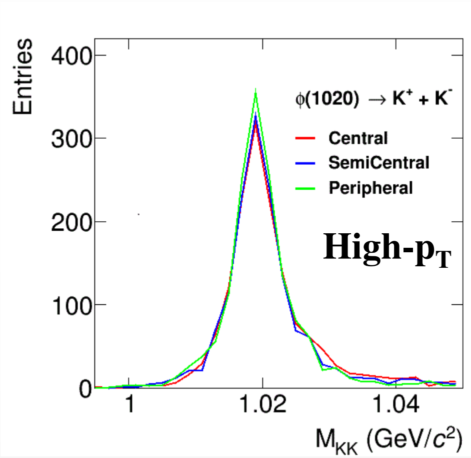
* ALICE, Phys.Lett.B 802 (2020) 135225, Phys.Rev.C 99 (2019) 024905

** PHENIX, Phys.Rev.C 93 (2016) 2, 024901

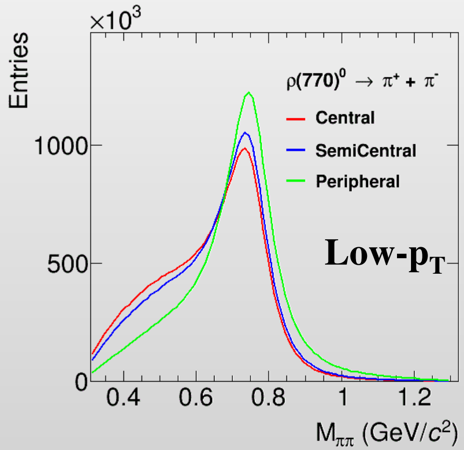
Resonances in AuAu@11, UrQMD

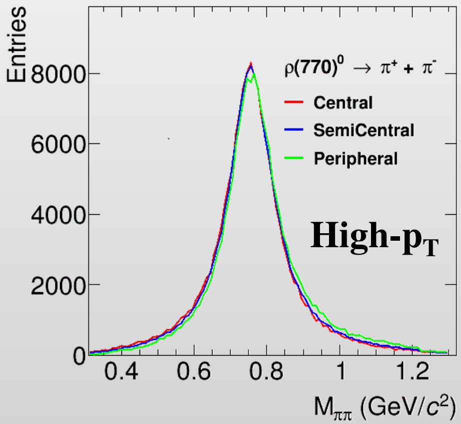
- Resonances are decayed by UrQMD, daughters participate in elastic and inelastic scattering
- Resonance are reconstructed by invariant mass method according to decay channels
- $\phi \rightarrow K^+K^-$ ($c\tau$ ~ 45 fm/c): modest line shape modifications in central AuAu@11 at low p_T





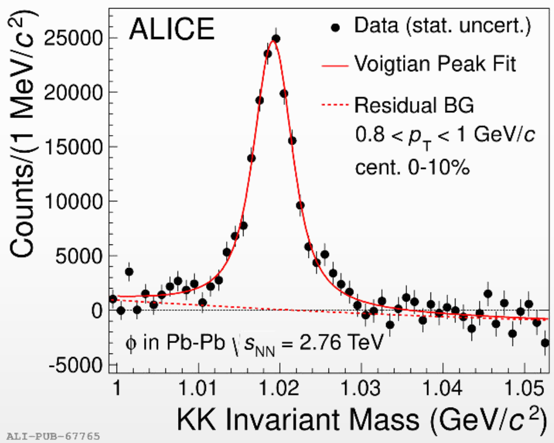
- $\rho(770)^0 \rightarrow \pi^+\pi^-$ ($c\tau$ ~ 1.3 fm/c): significant line shape modifications in central AuAu@11 at low p_T

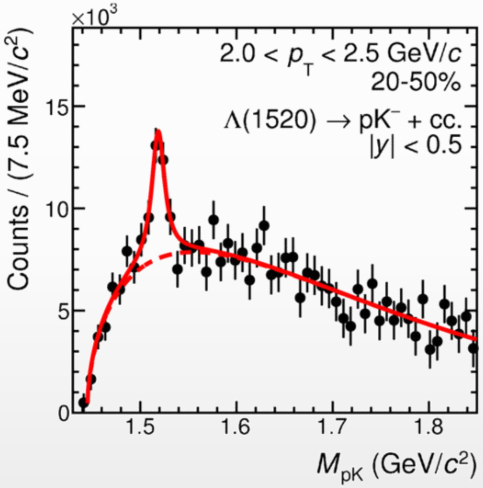


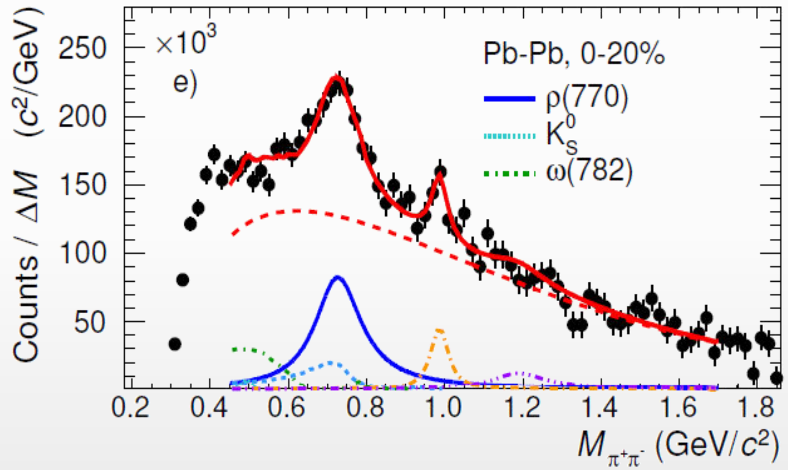


Resonance reconstruction in A-A collisions

- 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 $\rho(770)^0$:



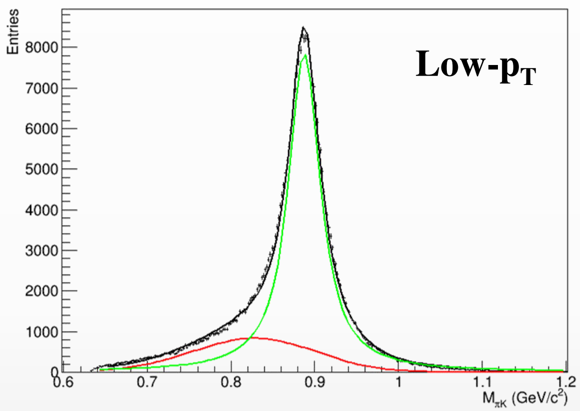


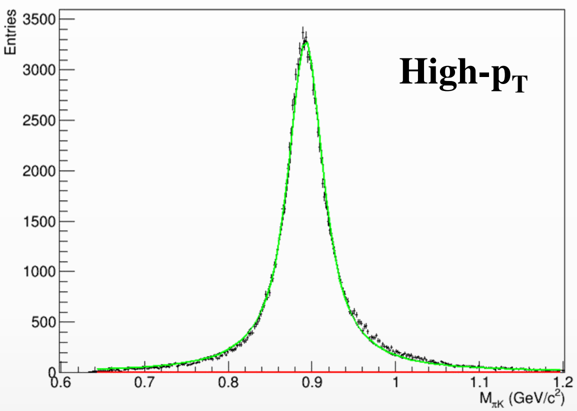


- For most of the cases, the peak models are inspired by theory and measurement in elementary e^+e^- and/or pp collisions where medium effects are not as important
- Line shape modifications will result in the change of the measured yield and masses/widths

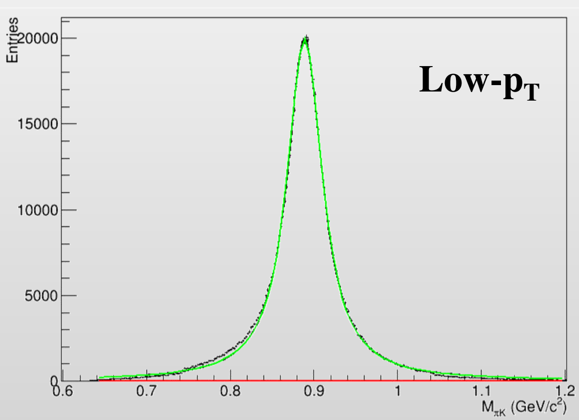
Yield and mass modifications in AuAu@11, UrQMD

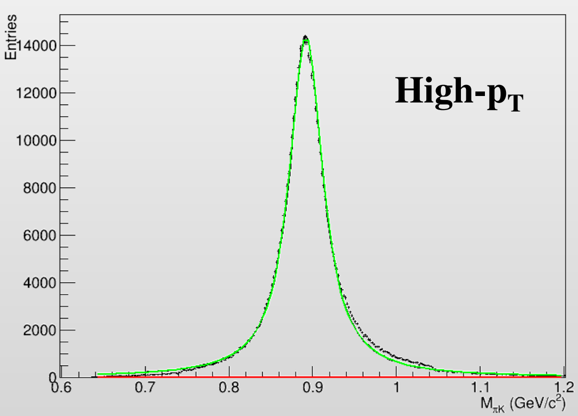
- $K^*(892)^0 \rightarrow \pi^\pm K^\pm$ ($c\tau$ ~ 4.2 fm/c); combine $\pi^\pm K^\pm$ pairs from true $K^*(892)^0$ decays
- Same fitting function for $K^*(892)^0$ and background as in ALICE
- Central collisions: small line shape modifications at low p_T; nothing at higher momentum





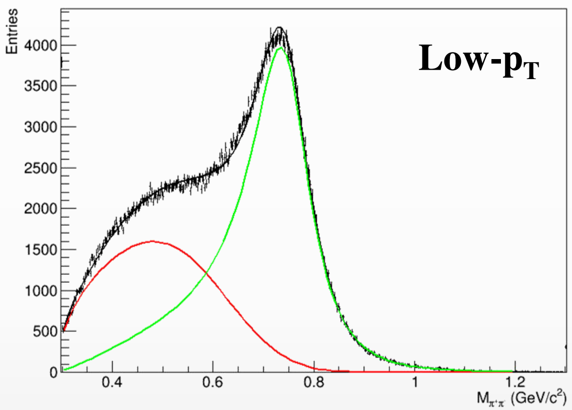
- Peripheral collisions: nothing

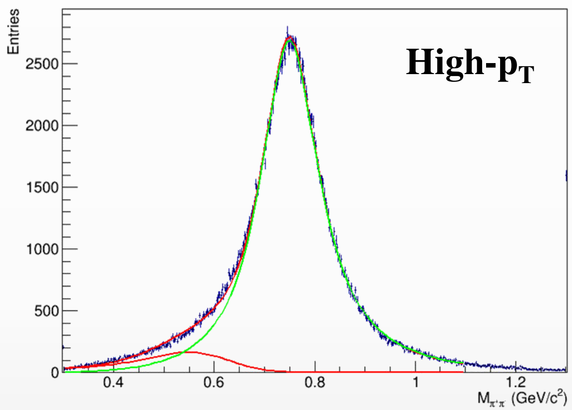




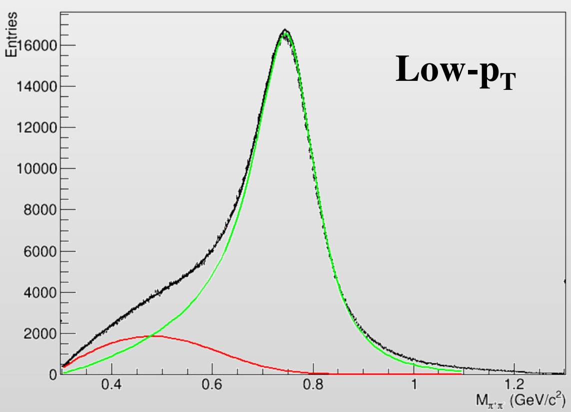
Yield and mass modifications in AuAu@11, UrQMD

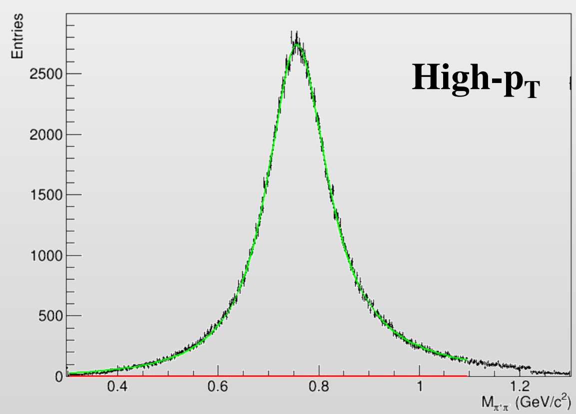
- $\rho(770)^0 \rightarrow \pi^+\pi^-$ ($c\tau \sim 1.3$ fm/c); combine $\pi^+\pi^-$ pairs from true $\rho(770)^0$ decays
- Same fitting function for $\rho(770)^0$ and background as in ALICE
- Central collisions: significant line shape modifications; excess with respect to the peak model is described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





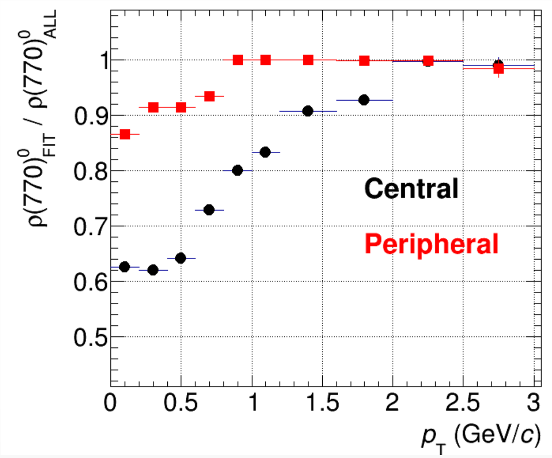
- Peripheral collisions: much smaller modifications are observed, only at low momentum



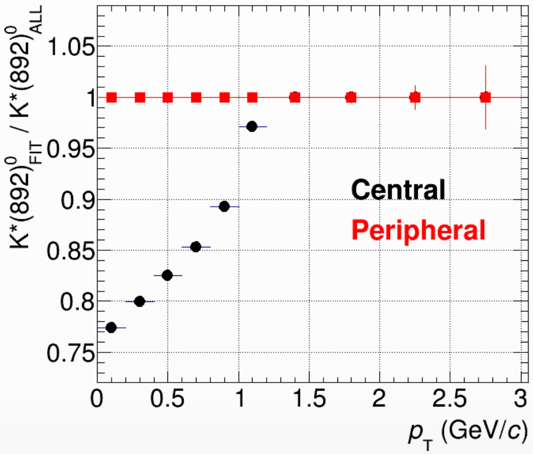


Yields of $K^*(892)^0$ and $\rho(770)^0$ in AuAu@11, UrQMD

- $\rho(770)^0 \to \pi^+\pi^-$ ($c\tau$ ~ 1.3 fm/c)
  - ✓ yield is undercounted because of pion rescattering;



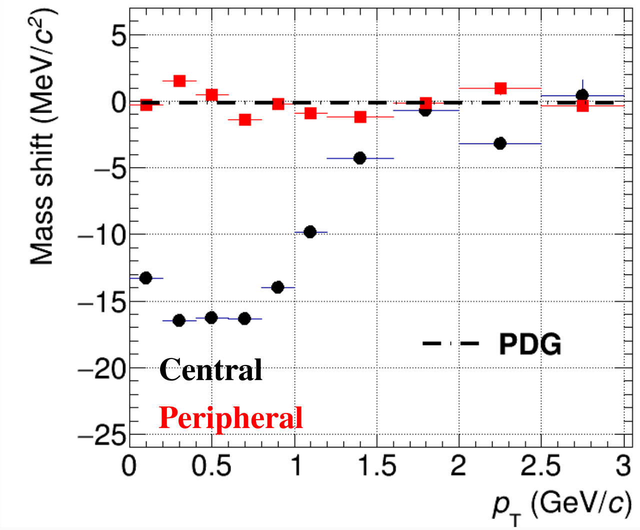
- $K^*(892)^0 \to \pi^\pm K^\pm$ ($c\tau$ ~ 4.3 fm/c)
  - ✓ yield is undercounted because of pion and kaon rescattering



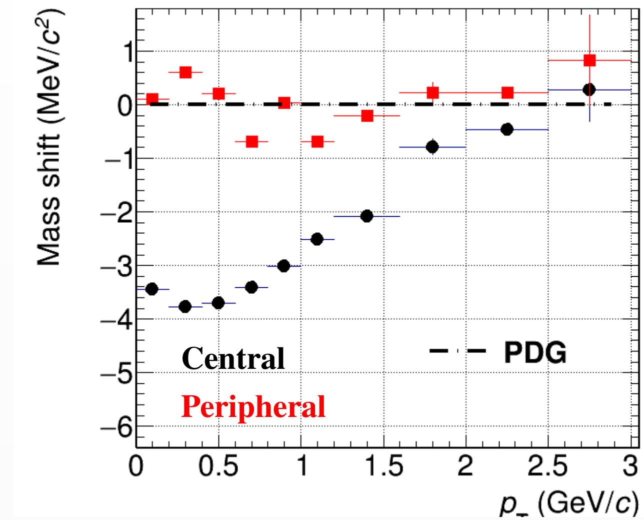
- Signal losses are larger for shorter-lived $\rho(770)^0$ → higher chance for $\rho(770)^0$ to decay and for daughters to rescatter in the medium
- Predicted signal losses are noticeable for the total (p_T-integrated) yields since bulk of the hadrons is produced at low p_T at NICA energies

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

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



❖ $K^*(892)^0 \rightarrow \pi^\pm K^\pm$ ($c\tau$ ~ 4.3 fm/c)

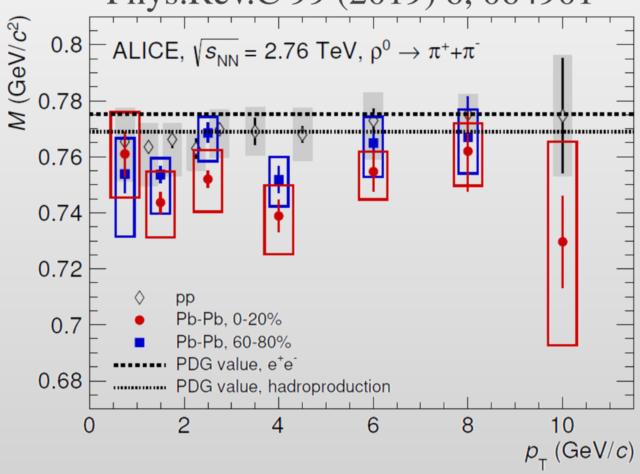


❖ In peripheral collisions, the peak models return masses and widths as measured in vacuum

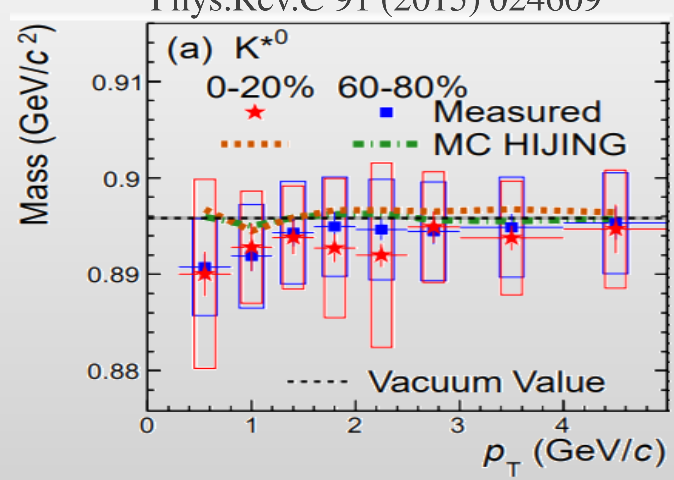
❖ In central collisions, the masses are measured smaller

❖ Similar mass “modifications” have been reported @ RHIC and the LHC, large uncertainties:

Phys.Rev.C 99 (2019) 6, 064901

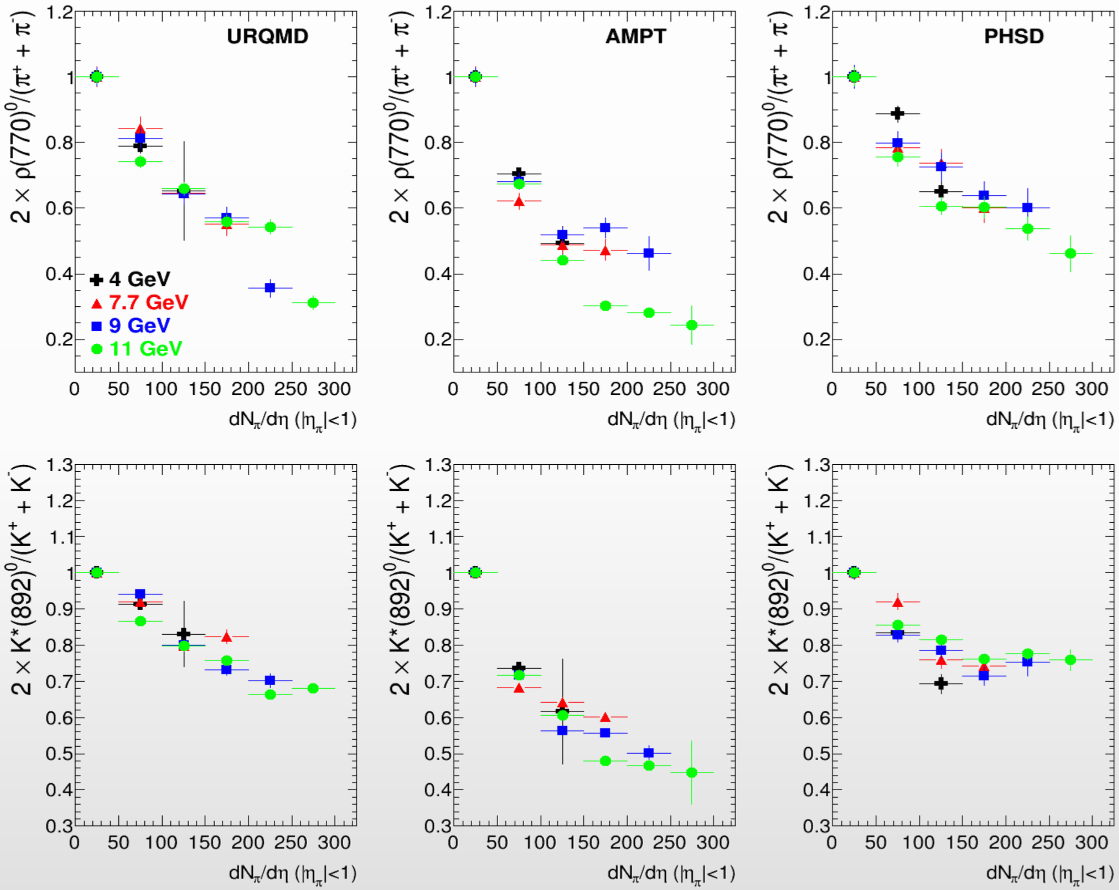


Phys.Rev.C 91 (2015) 024609



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

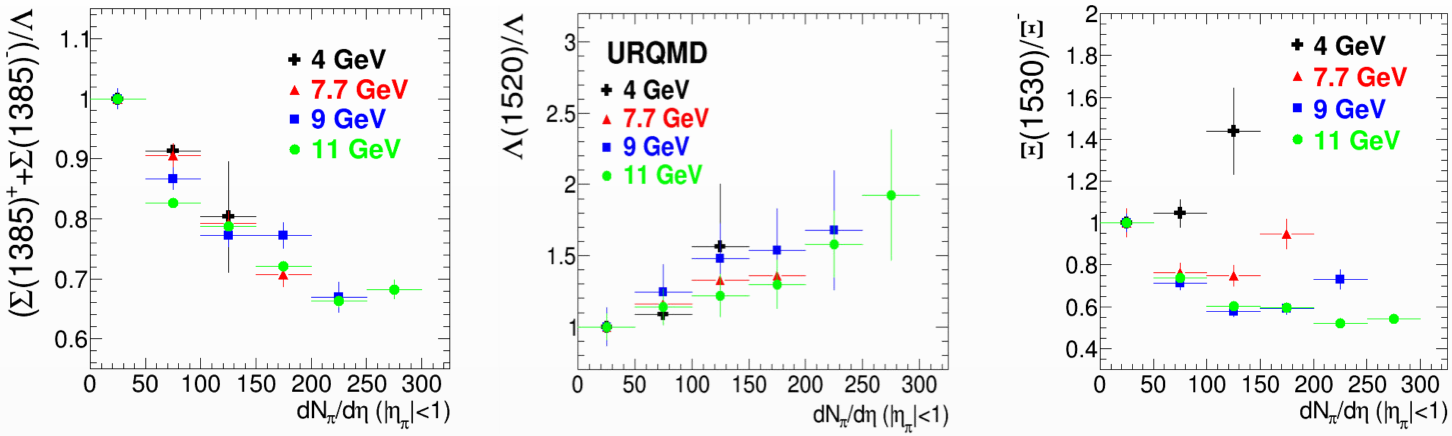
- ❖ Models with hadronic cascades (UrQMD, PHSD, AMPT)
- ❖ Ratios for two shortest-lived resonances (ϕ, $K^*(892)$) are shown normalized to most peripheral collisions

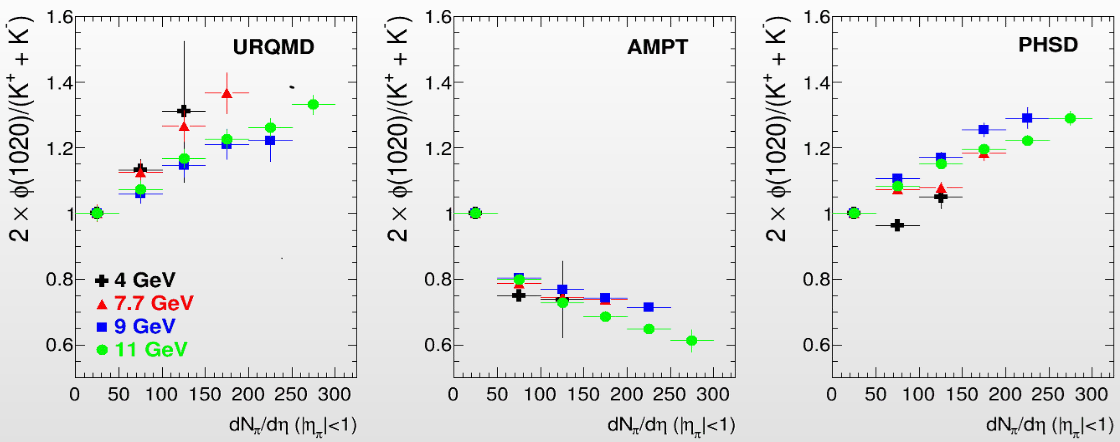


- ➢ Models predict suppression of ρ/π and K^*/K ratios in Au+Au@4-11, resonances with small cτ
- ➢ Suppression depends on the final state multiplicity rather than on collision energy
- ➢ Yield losses occur at low momentum as has been demonstrated before

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

- Models with hadronic cascades (UrQMD, PHSD, AMPT)
- Ratios for longer-lived resonances ($\Sigma(1385)$, $\Lambda(1520)$, $\Xi(1530)$ and ϕ)

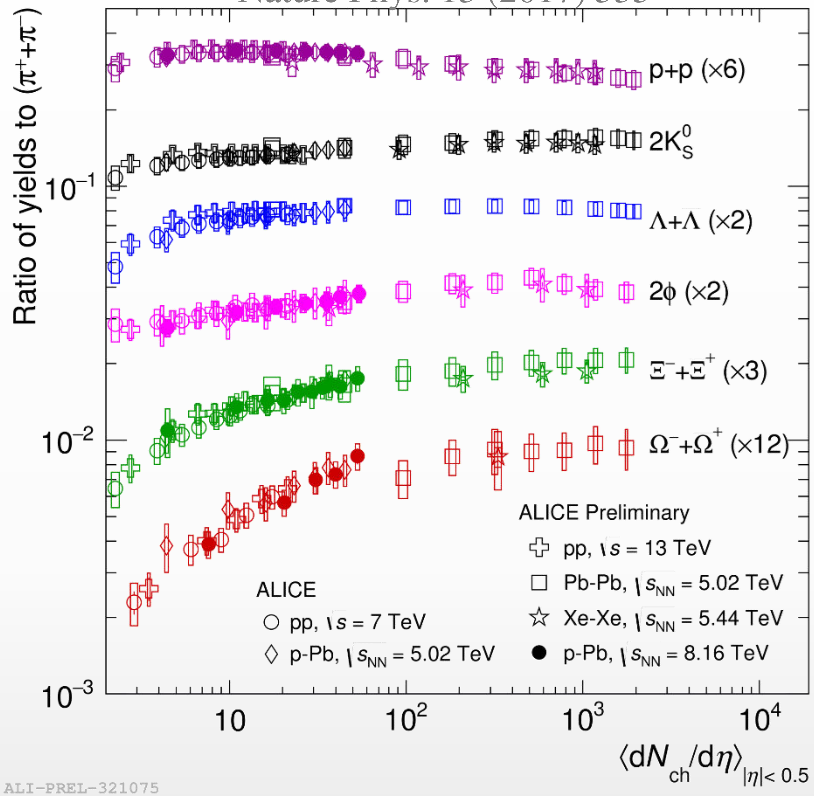


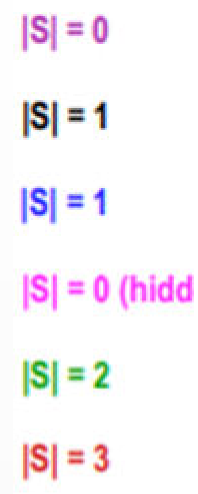


- Event generators predict yield modifications qualitatively similar to those obtained at RHIC/LHC:
  - → lifetime and density of the hadronic phase are high enough
  - → modification of particle properties in the hadronic phase should be taken into account when model predictions for different observables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

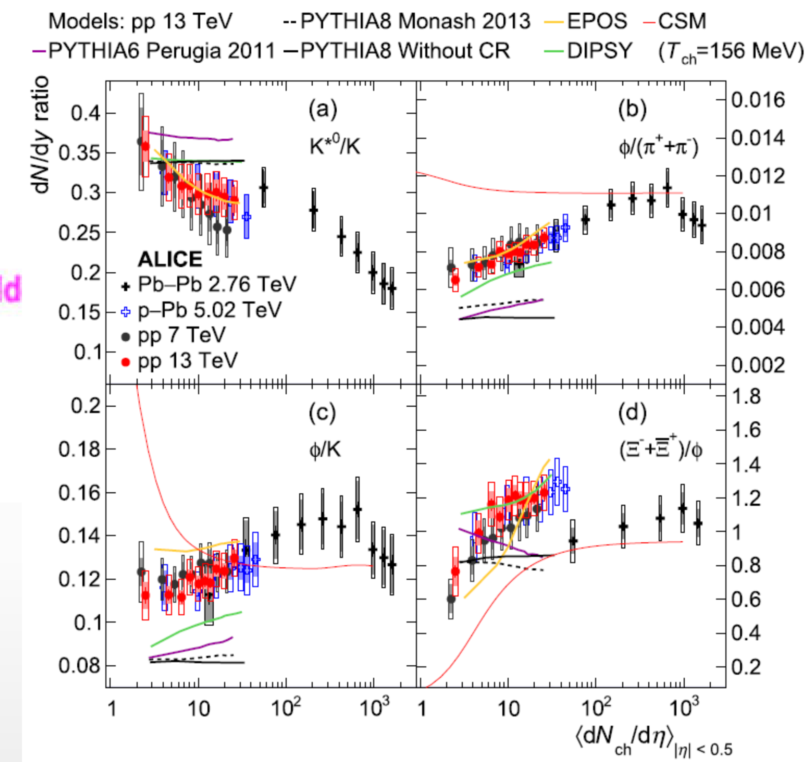
Strangeness production: pp, p-A and A-A

Nature Phys. 13 (2017) 535





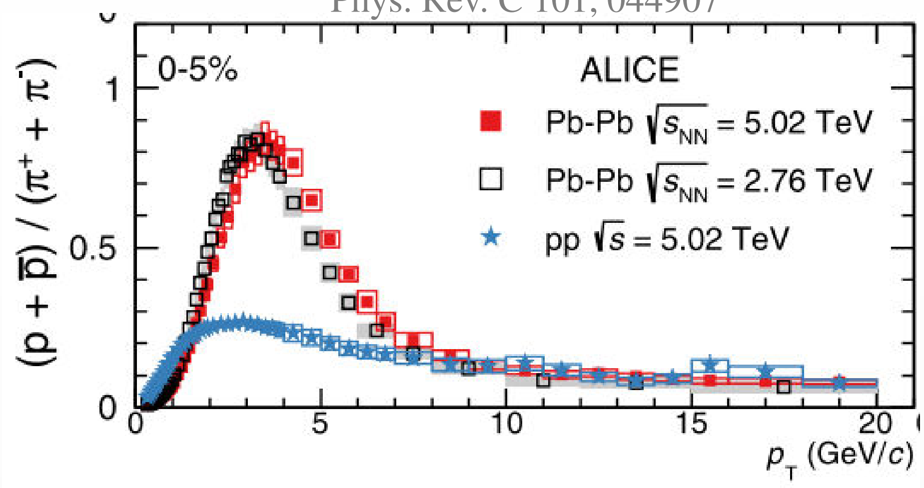
Phys. Lett. B807 135501(2020)



- Smooth evolution vs. multiplicity in pp, p-Pb, Xe-Xe, Pb-Pb collisions at $\sqrt{s_{NN}}$ = 0.2-13 TeV
- Strangeness enhancement increases with strangeness content and particle multiplicity
- Origin of the strangeness enhancement in small/large systems is still under debate
- ϕ with hidden strangeness is a key probe to study strangeness enhancement
  - ✓ ϕ/π increases with multiplicity in pp/p-Pb → not expected for canonical suppression
  - ✓ ϕ/π saturates in Pb-Pb and is consistent with thermal model predictions, effective strangeness ~ 1-2
- ϕ is not expected to be modified in the hadronic phase at NICA energies and will serve as one of the key observables in the strange sector → need resonance measurements !!!

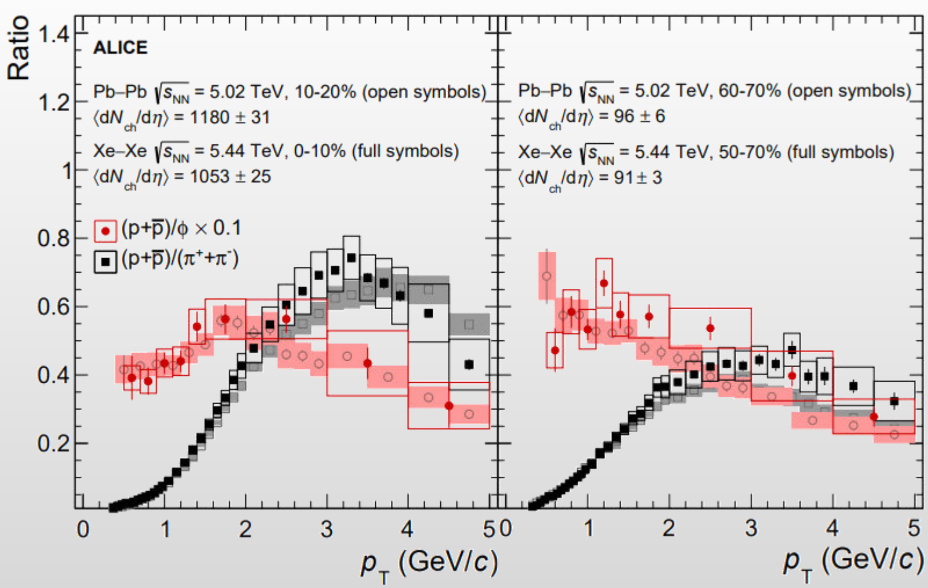
Enhanced baryon-to-meson ratios in A-A

Phys. Rev. C 101, 044907



- Enhanced baryon-to-meson ratios (p/π, Λ/K) in central heavy-ion collisions at intermediate p_T observed @ RHIC and the LHC → quark coalescence + flowing medium
- The bulk effect, not present in jets

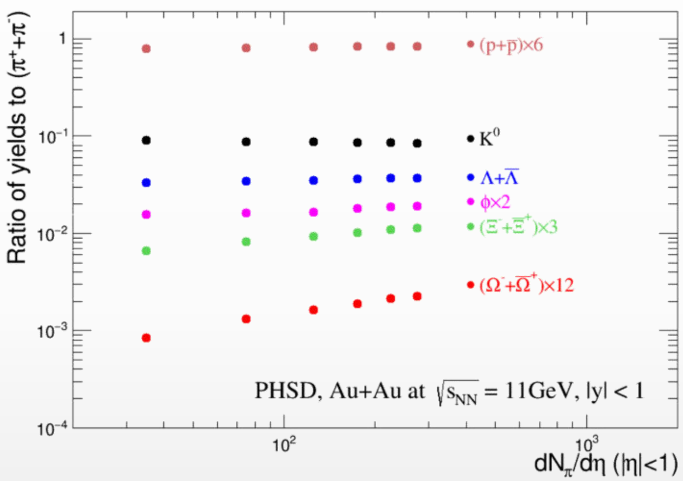
arXiv:2101.03100

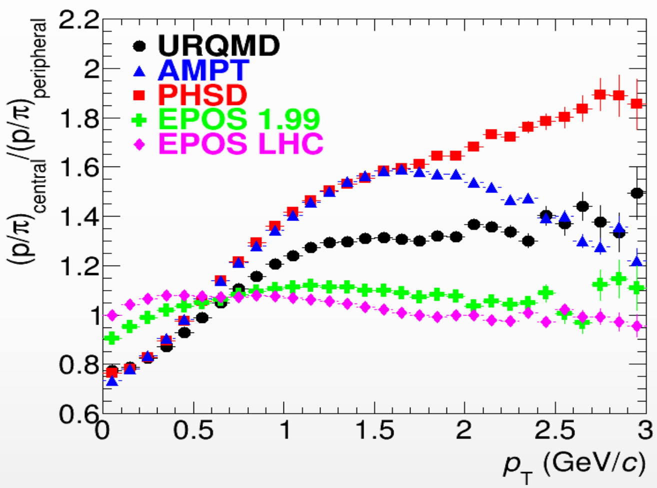


- p/ϕ ratio is almost constant vs. p_T at intermediate momenta in Pb-Pb and Xe-Xe collisions → spectral shapes are driven by particle masses:
  - ✓ consistent with hydrodynamics
  - ✓ recombination models are not ruled-out (V. Greco et al, PRC 92 054904 (2015))

Model predictions for resonances at NICA

- ❖ UrQMD, PHSD, AMPT, EPOS … AuAu@11
- ❖ General predictions:
  - ✓ models predict enhanced production of particles with strangeness
  - ✓ baryon/meson (B/M) ratios evolve with centrality/multiplicity and collision energy



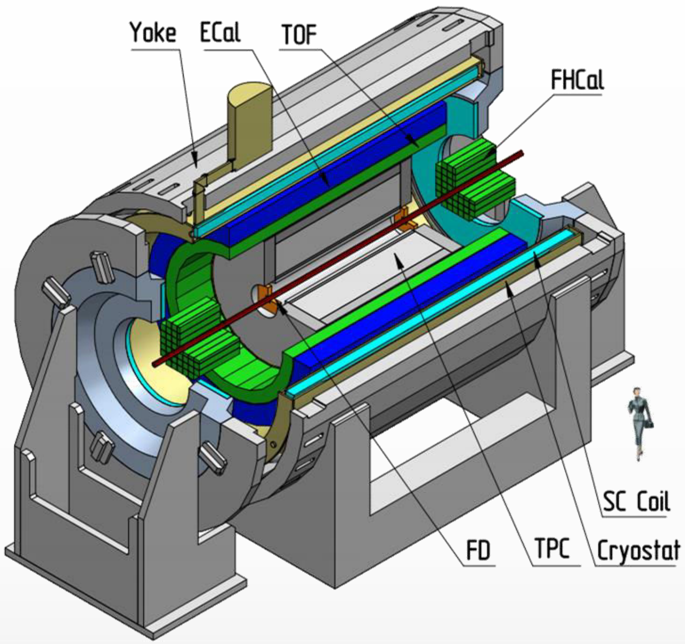


- ❖ Eventually, model predictions (integrated yields, <p_T>, particle ratios etc.) should be compared to data to differentiate different model assumptions

MPD experiment, Stage-1

- Stage-1: **TPC, TOF, FFD, FHCAL и ECAL**
- Startup in 2023

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

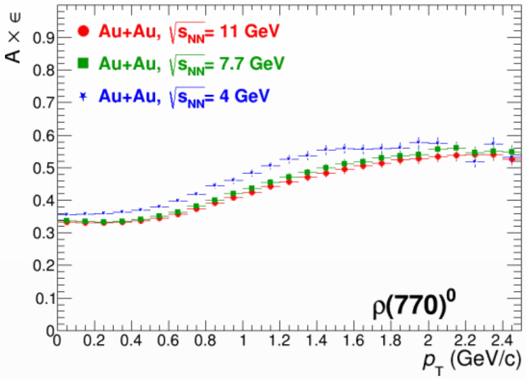
TOF, EMC: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.4$

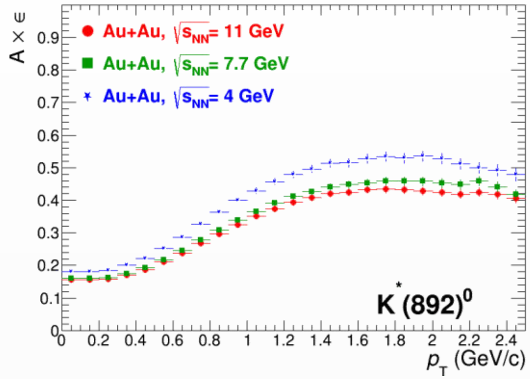
FFD: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$

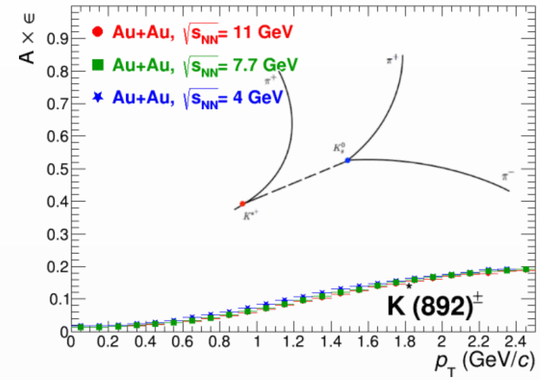
FHCAL: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

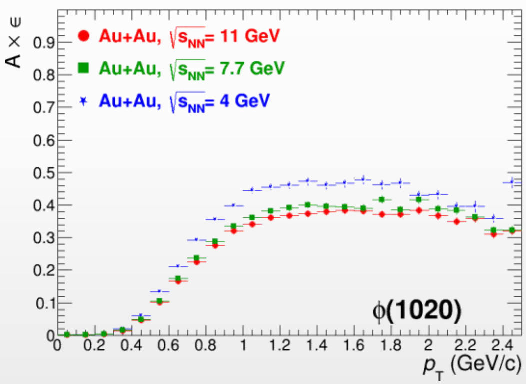
Reconstruction efficiencies

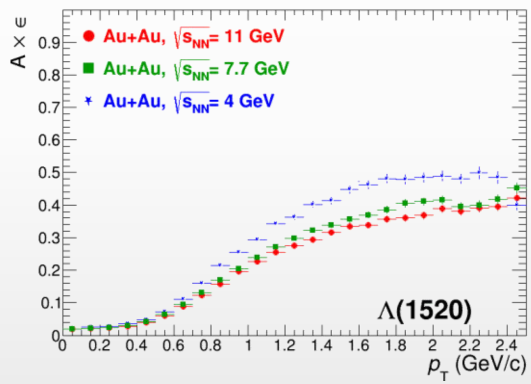
❖ Typical reconstruction efficiencies (A x ∈) in AuAu @ 4, 7.7 and 11 GeV, |y| < 1

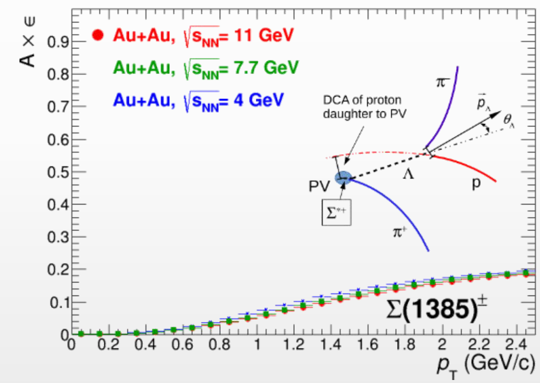


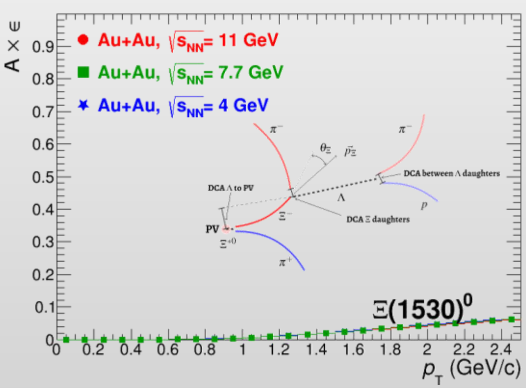












❖ Reasonable efficiencies in the wide p_T range, |y| < 1

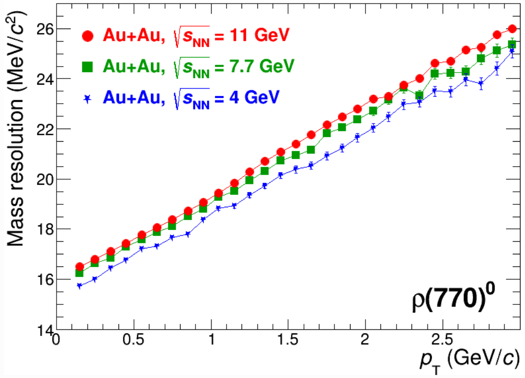
❖ Efficiencies are noticeably lower for multi-stage decays with weakly decaying daughters (Ξ, Λ, K_s^0)

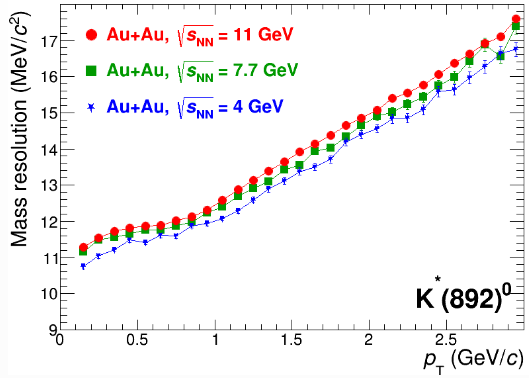
❖ Measurements are possible from zero momentum

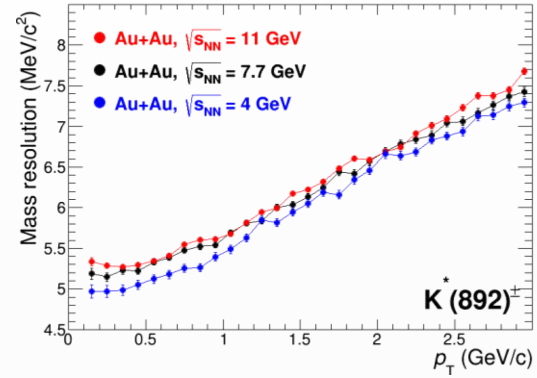
❖ Modest multiplicity (and/or $\sqrt{s_{NN}}$) dependence

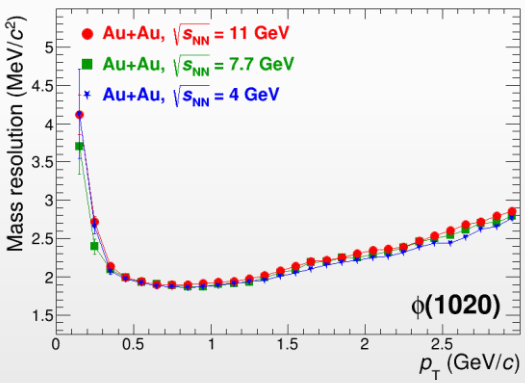
Mass resolution:

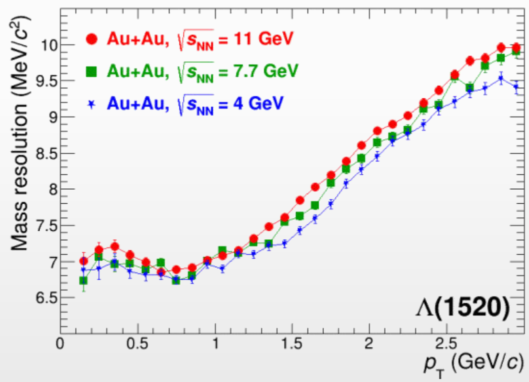
❖ Detector mass resolution ($m_{reconstructed} - m_{generated}$) in AuAu @ **4**, **7.7** and **11** GeV, |y| < 1

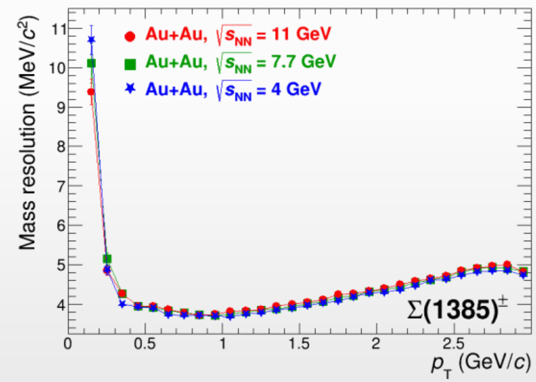


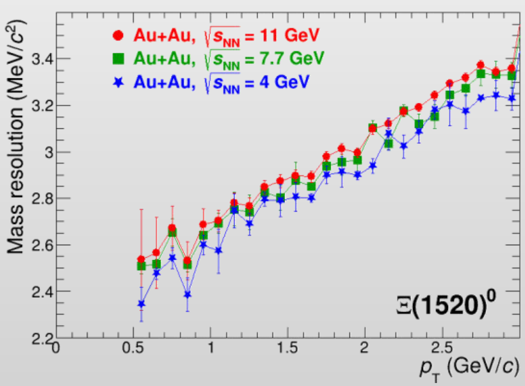










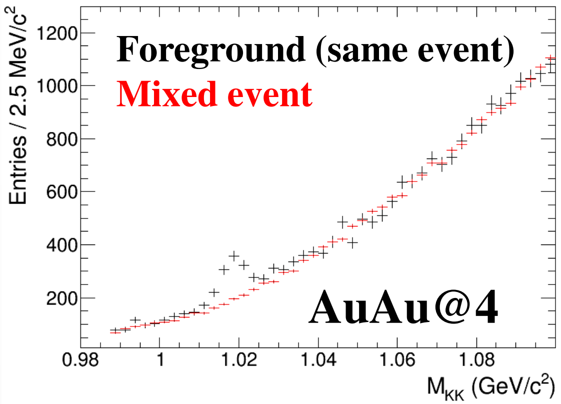


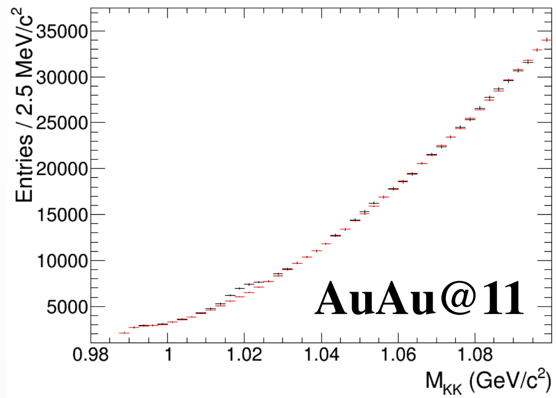
❖ Mass resolution is good enough to preserve the capability for the line shape analysis

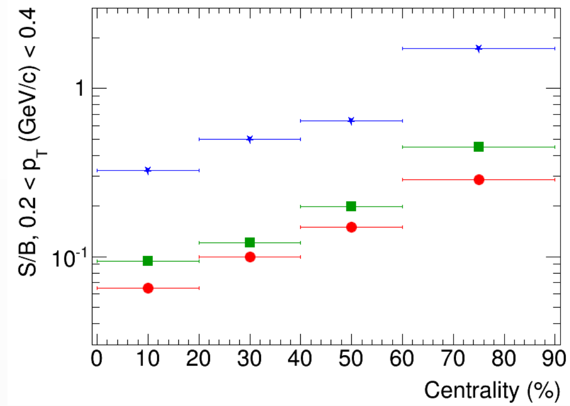
❖ Modest multiplicity (and/or $\sqrt{s_{NN}}$) dependence

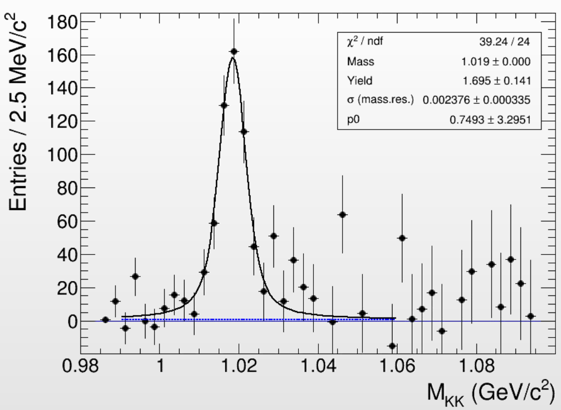
φ(1020), reconstructed peaks

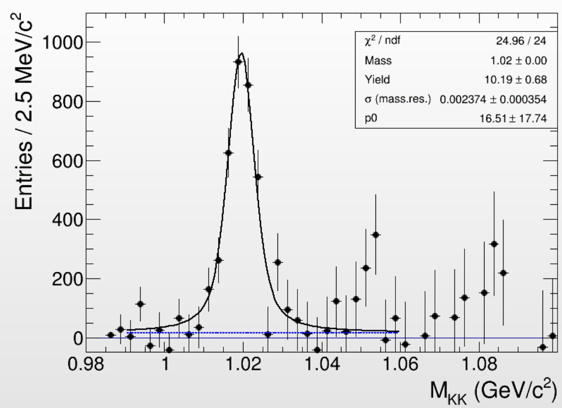
- UrQMD v.3.4: AuAu@11 (10M events), AuAu@7.7 (5M events), AuAu@4 (5M events)
- Full chain simulation and reconstruction, p_T = 0.2-0.4 GeV/c, |y| < 1

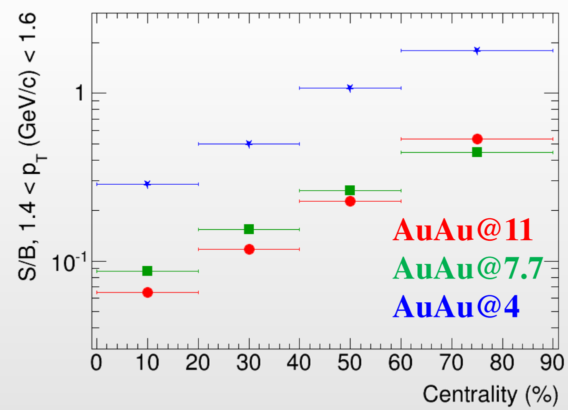










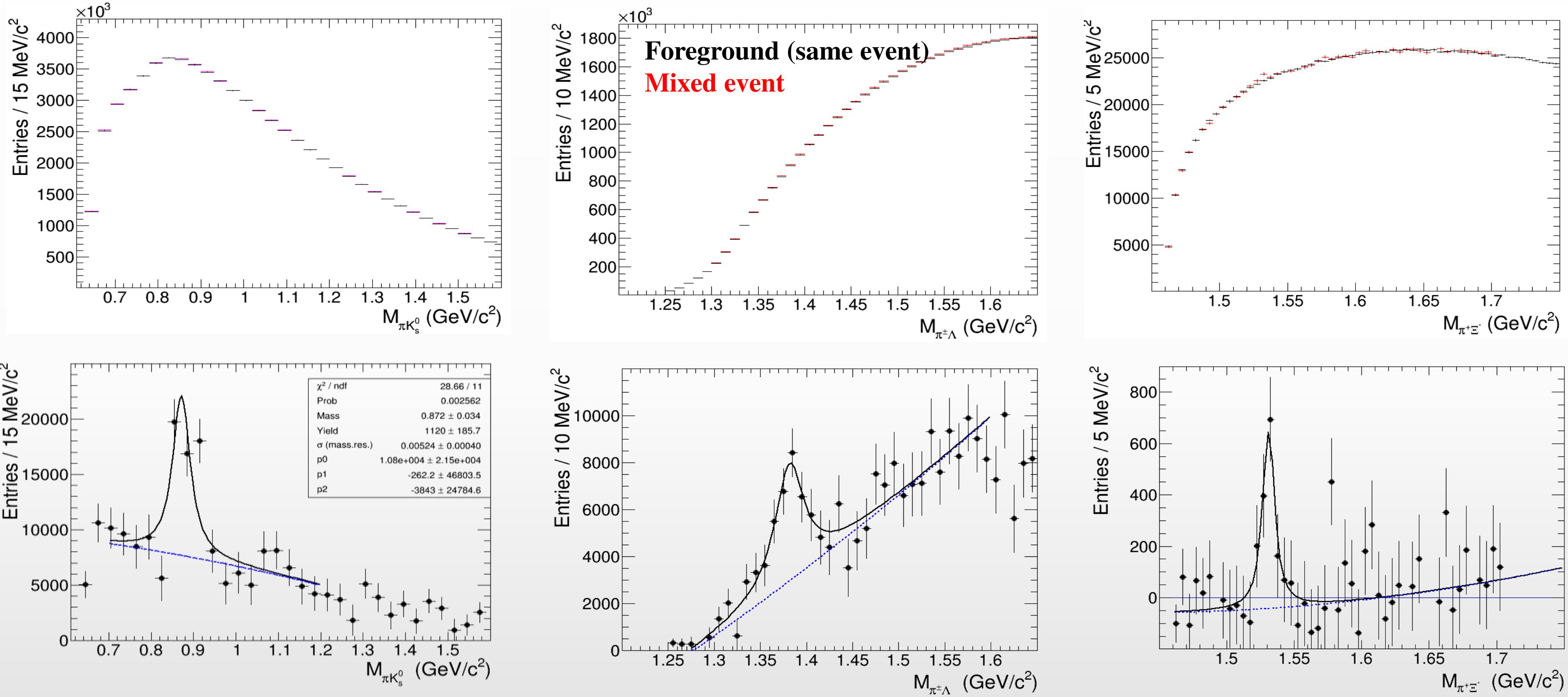


- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Distributions are fit to Voigtian function + polynomial
- Signal can be reconstructed at p_T > 0.2 GeV/c, high-p_T reach is limited by available statistics
- S/B ratios deteriorates with increasing centrality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

$K^*(892)^\pm$, $\Sigma(1385)^\pm$, $\Xi(1530)^0$, reconstructed peaks

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

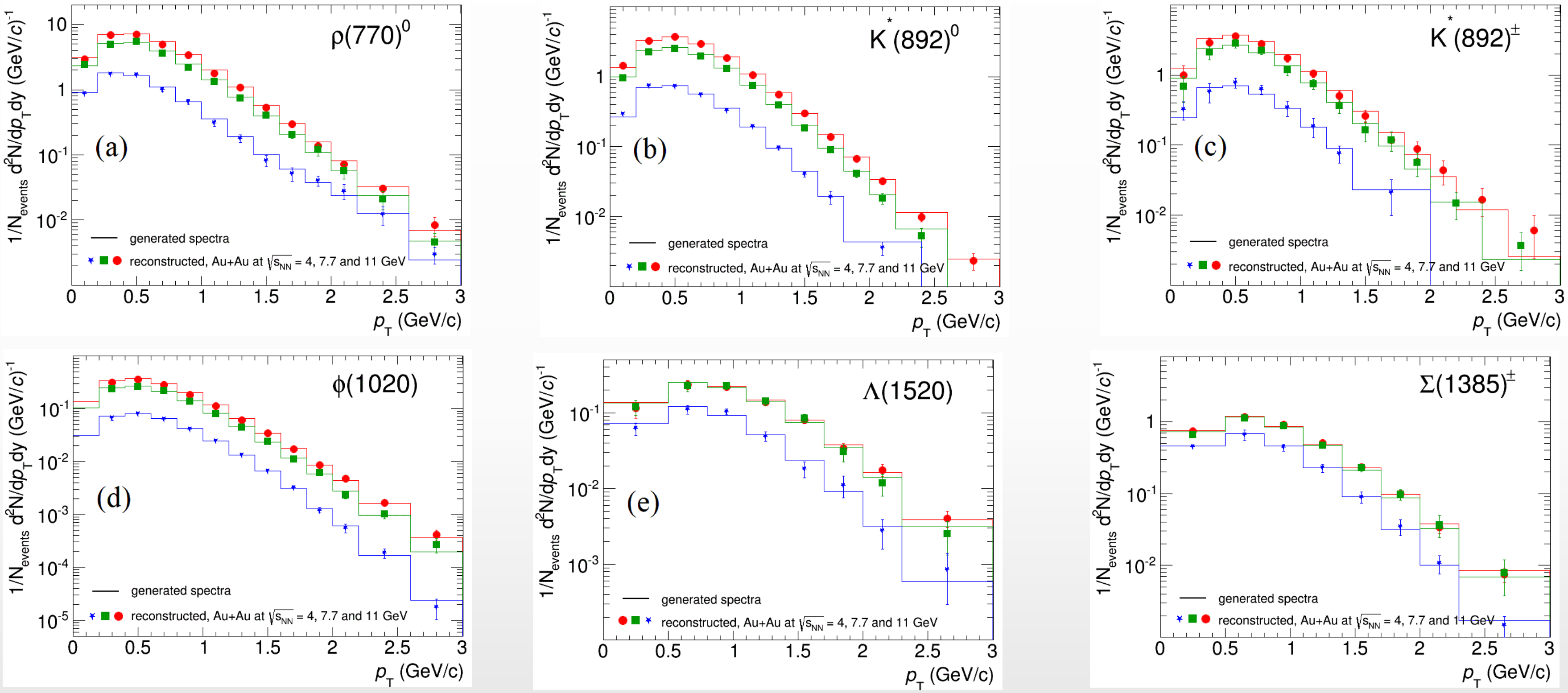
$K^{*\pm}$, 0.2-0.4 GeV/c | **$\Sigma(1385)^\pm$, 0-0.5 GeV/c** | **$\Xi(1530)^0$, 0.5-1 GeV/c**

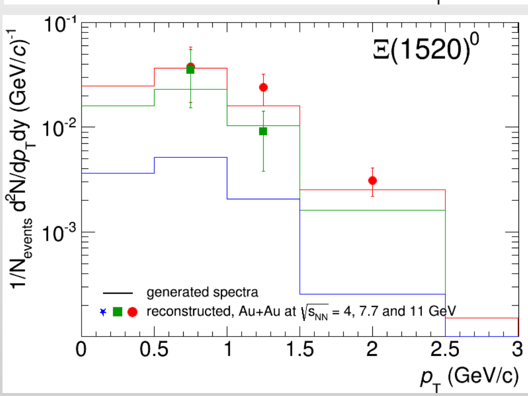


- Can reconstruct signals for multistage decays of $K^*(892)^\pm \rightarrow K_S^0\pi^\pm$ ($K_S^0 \rightarrow \pi^+\pi^-$), $\Sigma(1385)^\pm \rightarrow \pi^\pm\Lambda$ ($\Lambda\rightarrow p\pi$) and $\Xi(1530)^0 \rightarrow \pi^+\Xi^-$ ($\Xi^- \rightarrow \Lambda\pi^-$, ($\Lambda\rightarrow p\,\pi^-$))

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

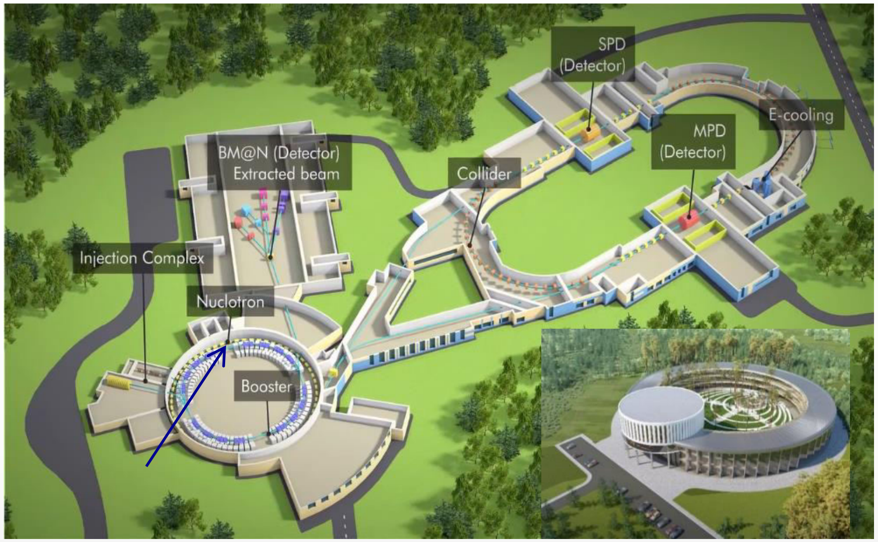
✓ Measurements are possible starting from very low momenta (for most of the cases from zero momenta) with decent mass resolution → high sensitivity to different physics phenomena most prominent at low p_T

✓ 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

Nuclotron-based
Ion Collider fAcility

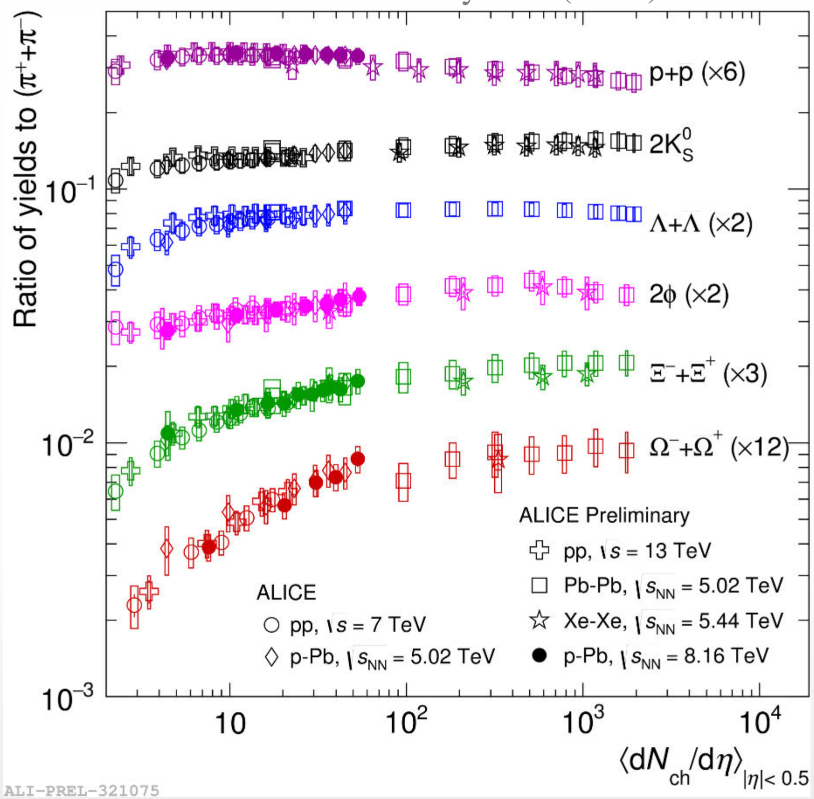
NICA complex

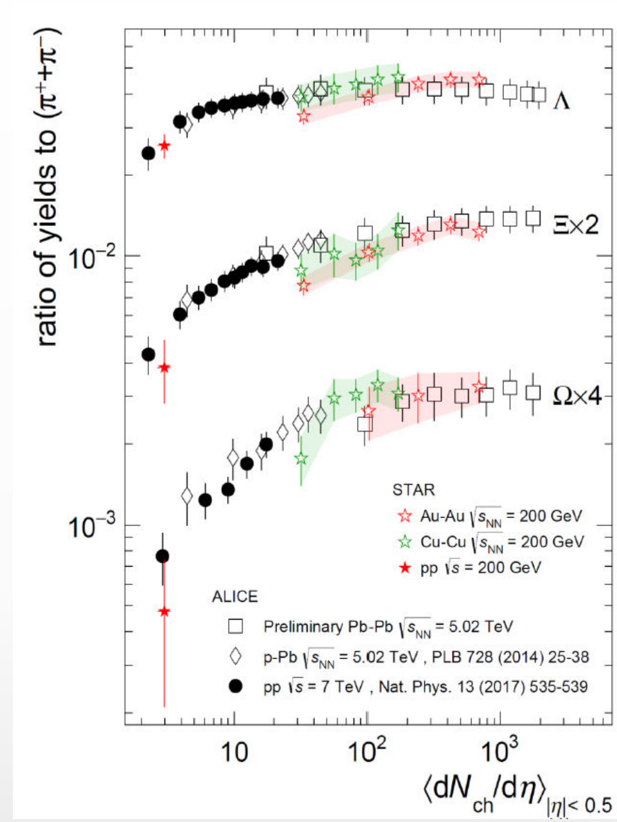


- ❖ Modernization of the existing Nuclotron facility
- ❖ Fixed target experiment: BM@N
- ❖ Construction of collider complex to collide:
  - ✓ heavy ions up to Au, $\sqrt{s_{NN}} = 4\text{-}11$ GeV, $\mathcal{L} \sim 10^{27}$ cm^{-2}s^{-1}
  - ✓ polarized p and d, $\sqrt{s_{NN}} = 27$ GeV, $\mathcal{L}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

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

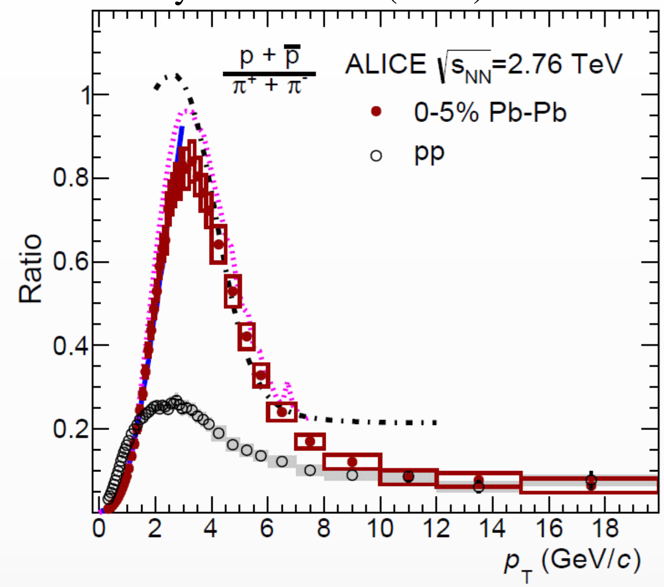
❖ Driving force of enhancement is not yet fully understood:

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

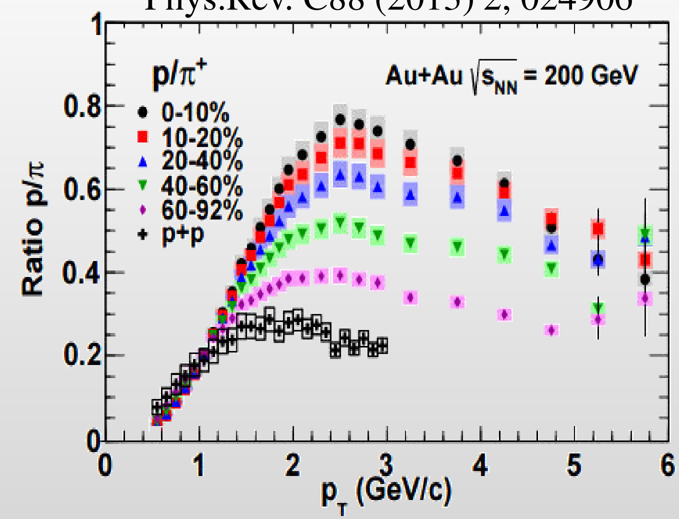
❖ ϕ and K^{*0} are well suited for tests as mesons with masses very close to that of a proton:

- ✓ 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



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

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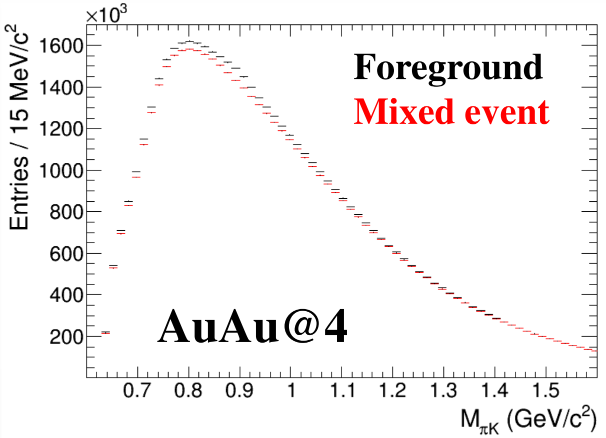

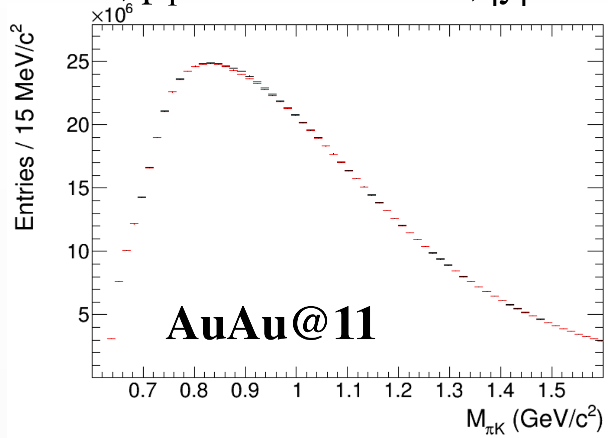

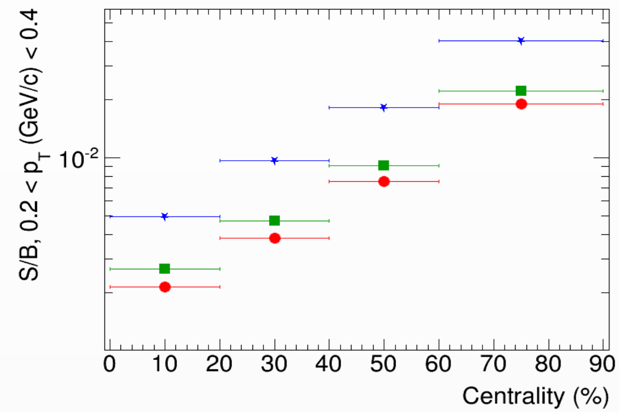

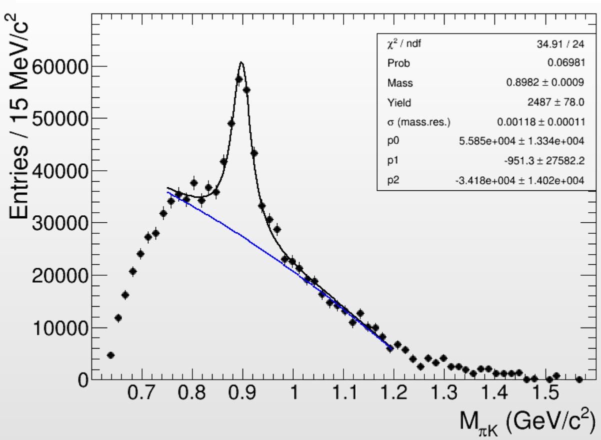

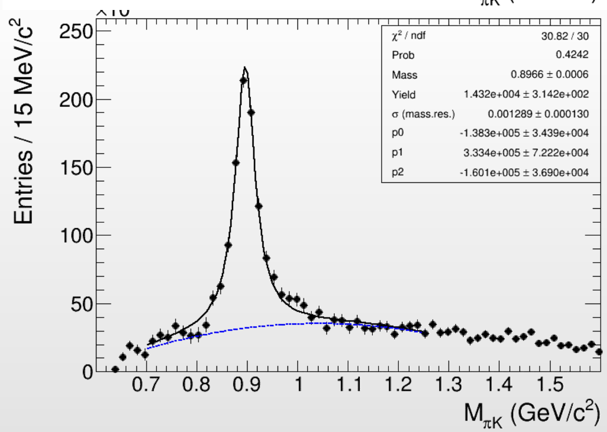

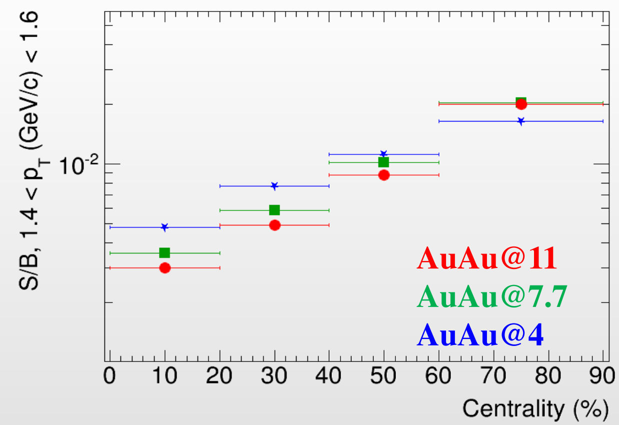

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- Signal can be reconstructed at p_T > 0.0 GeV/c, high-p_T reach is limited by available statistics
- S/B ratios deteriorates with increasing centrality and collision energy

ρ(770), signal extraction – practice tests

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

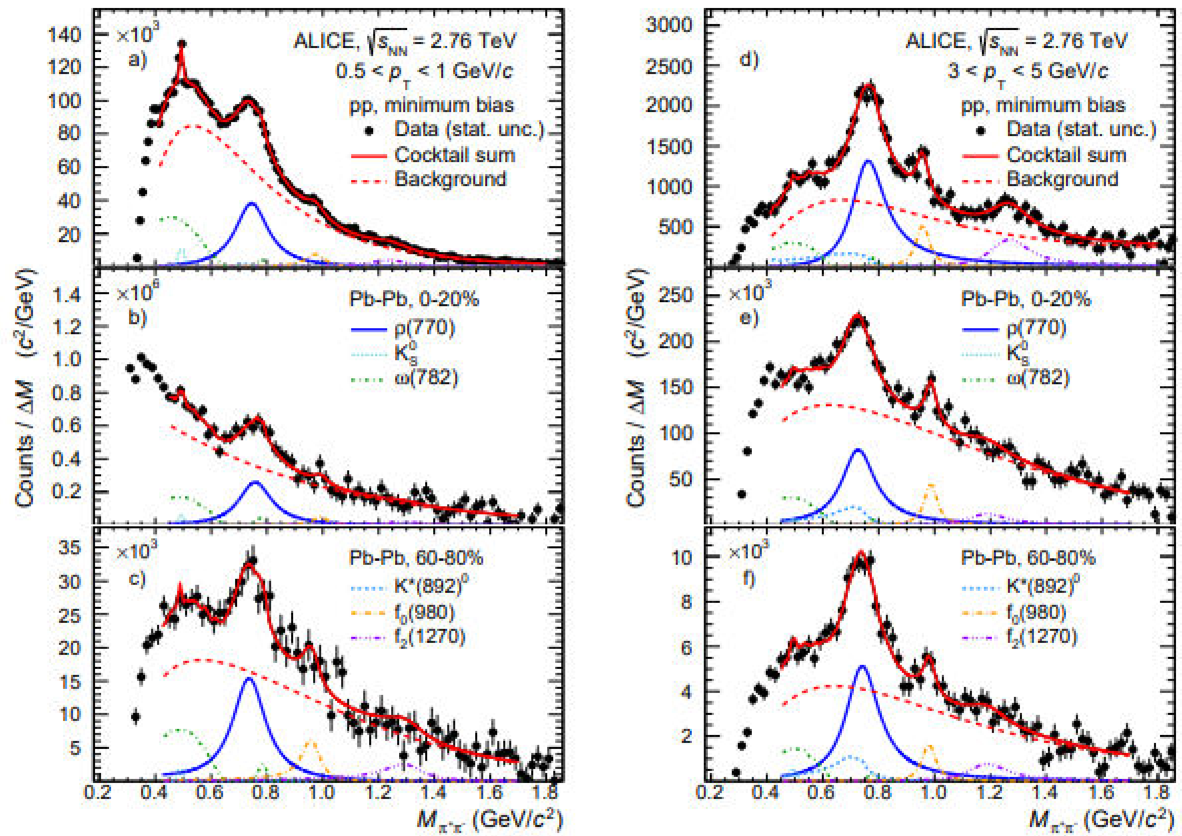

Fig. 1: (Color online) Invariant mass distributions for $\pi^+\pi^-$ pairs after subtraction of the like-sign background. Plots on the left and right are for the low and high transverse momentum intervals, respectively. Examples are shown for minimum bias pp, 0–20% and 60–80% central Pb–Pb collisions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