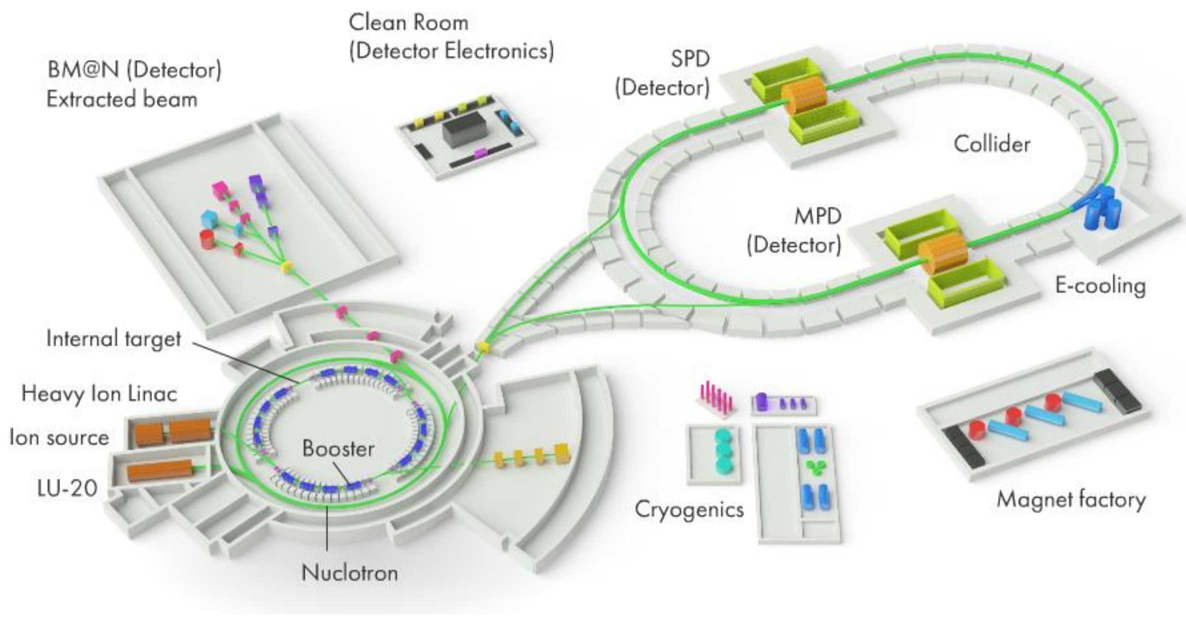
Production and reconstruction of short-lived resonances in heavy-ion collisions at NICA energies using the MPD detector

V. Riabov* for the MPD Collaboration



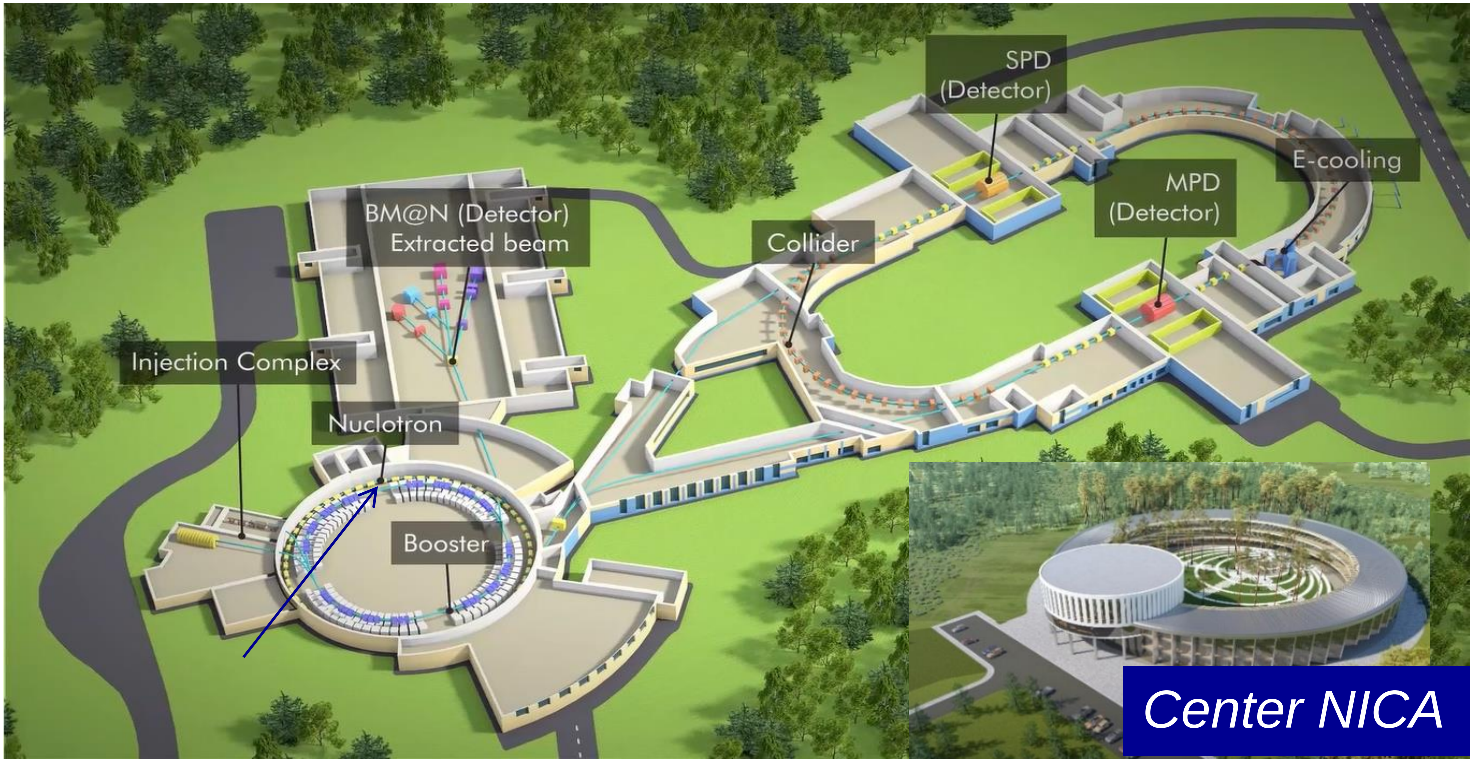
* This work was supported by RFBR according to the research project № 18-02-40038

Outline

- NICA complex
- Motivation for resonances studies in heavy-ion collisions
- Expectations for resonance properties in heavy-ion collisions at NICA energies
- Feasibility studies for particle reconstruction at NICA-MPD
- Conclusions

NICA complex

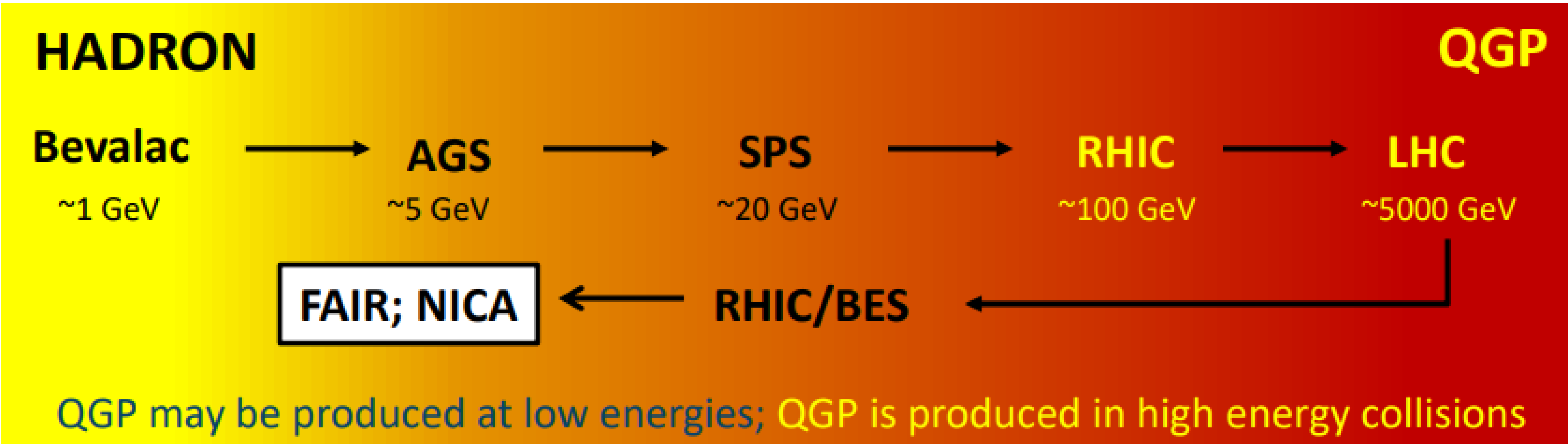
Nuclotron-based
Ion Collider fAcility

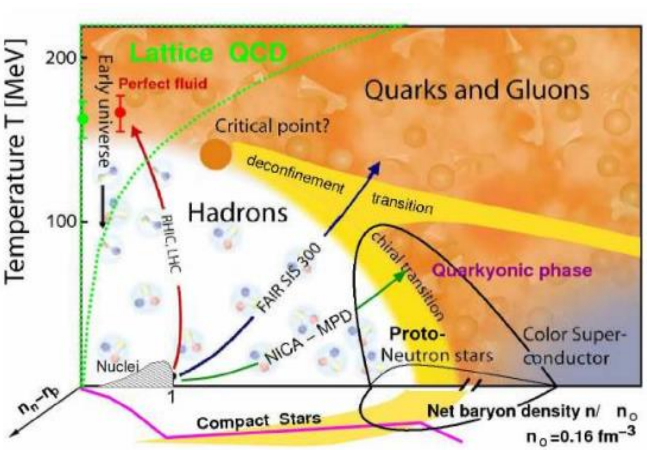


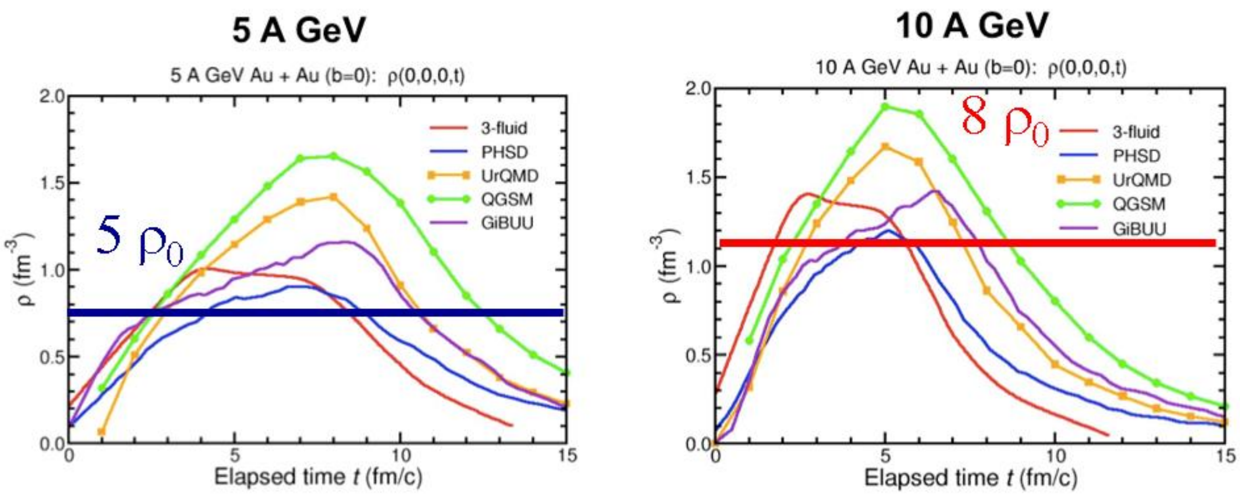
Ring circumference, m	**503,04**
Number of bunches	**22**
r.m.s. bunch length, m	**0,6**
max. int. Energy, Gev/u	**11,0**
r.m.s. Δp/p, 10-3	**1,6**
Luminosity, $cm^{-2}\ s^{-1}$	**$1x10^{27}$**

- Modernization of existing Nuclotron facility
- Construction of collider complex to collide:
  - ✓ relativistic ions up to Au, $\sqrt{s_{NN}}$ = 4-11 GeV
  - ✓ polarized p and d, $\sqrt{s_{NN}}$ = 27 GeV (for p)
- Two collider experiments: MPD, SPD
- One fixed target experiment: BM@N

Heavy-ion collisions at NICA







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

- ❖ Study of the properties of hot and dense QCD matter, phase transition to QGP
- ❖ 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

MPD experiment, construction progress

Resonances in heavy-ion collisions

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

$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$ $d\bar{s}$ $u\bar{s}$ $s\bar{s}$ 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

- Wide variety of resonances in the PDG, most popular are listed on the top
- Vacuum properties of these particles are well defined (m, cτ, BR etc.)
- Copiously produced in heavy-ion collisions at ~ GeV energies
  → relatively easy to measure in hadronic decay channels
- Probe reaction dynamics and particle production mechanisms vs. system size and $\sqrt{s_{NN}}$:
  - ✓ hadron chemistry and strangeness production, ϕ 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
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

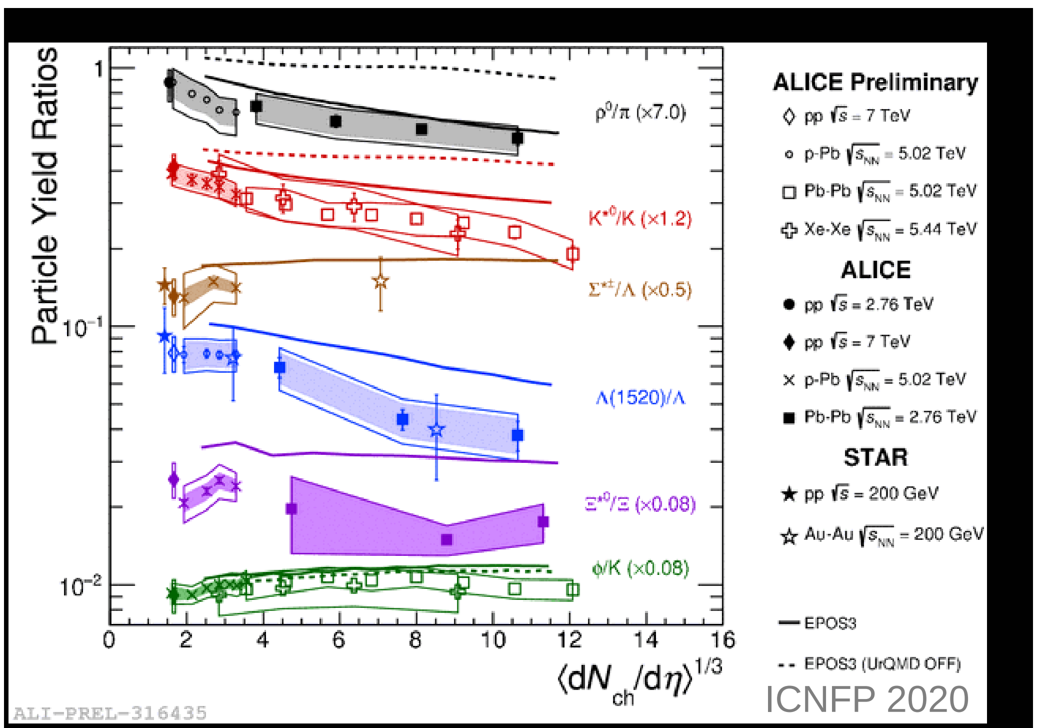
❖ Resonances have small lifetimes of cτ ~ 1 - 45 fm, part of them decays in the fireball

❖ 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

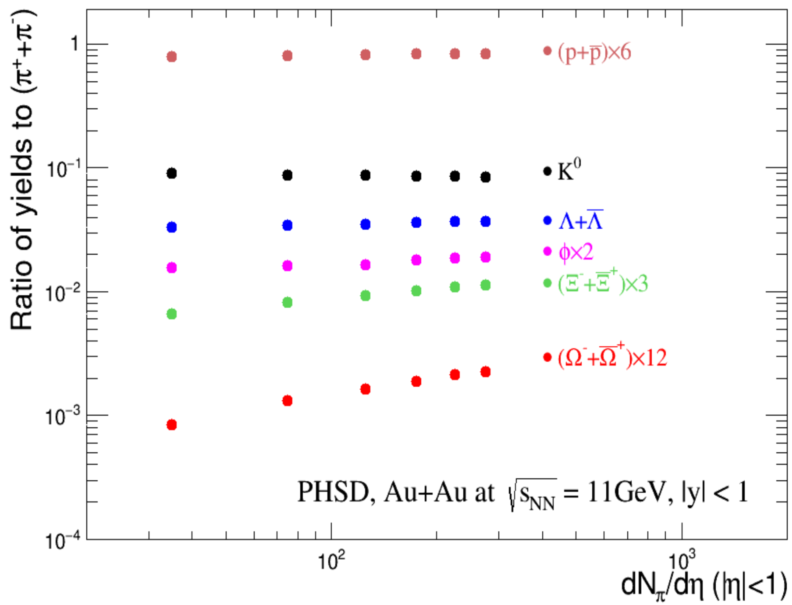


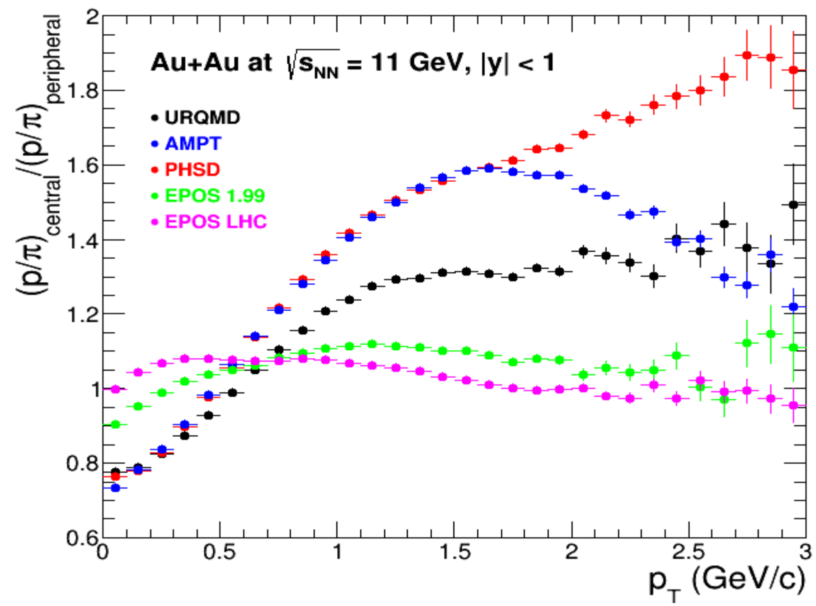
❖ SPS/RHIC/LHC results for resonance yields support the existence of a hadronic phase that lives long enough to cause a significant reduction of the reconstructed yields of short lived resonances

❖ Lower limit for the lifetime of the hadronic phase, τ ~ 10 fm/c

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.

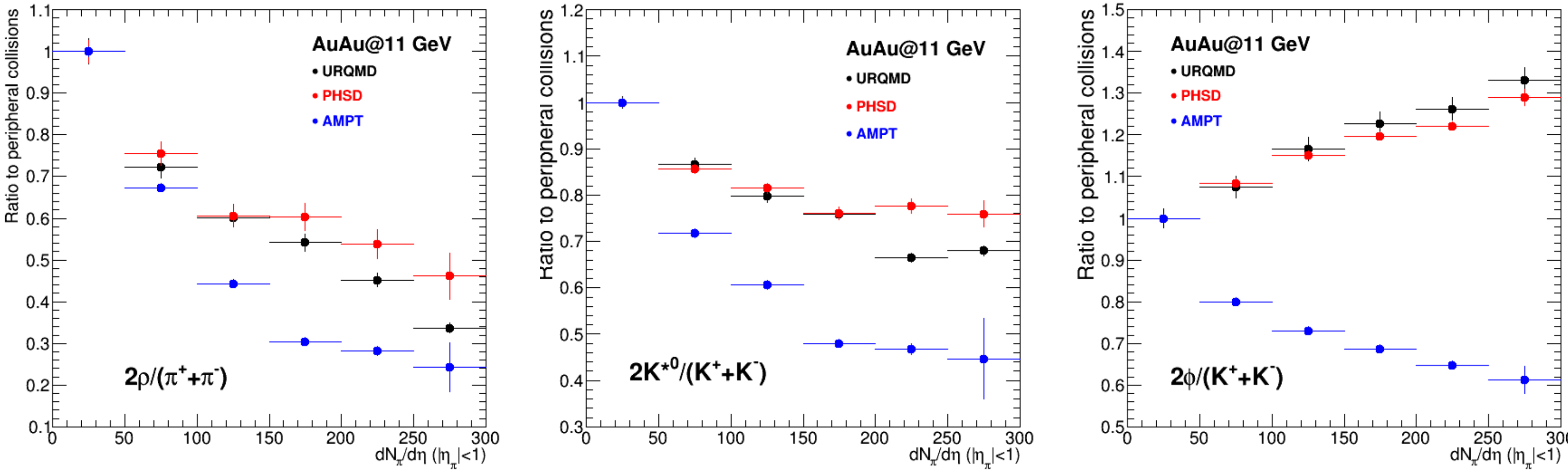




- Eventually, model predictions (integrated yields, <p_T>, particle ratios etc.) should be compared to data to differentiate different model assumptions

Hadronic phase and particle ratios

- 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 hadronic phase effects

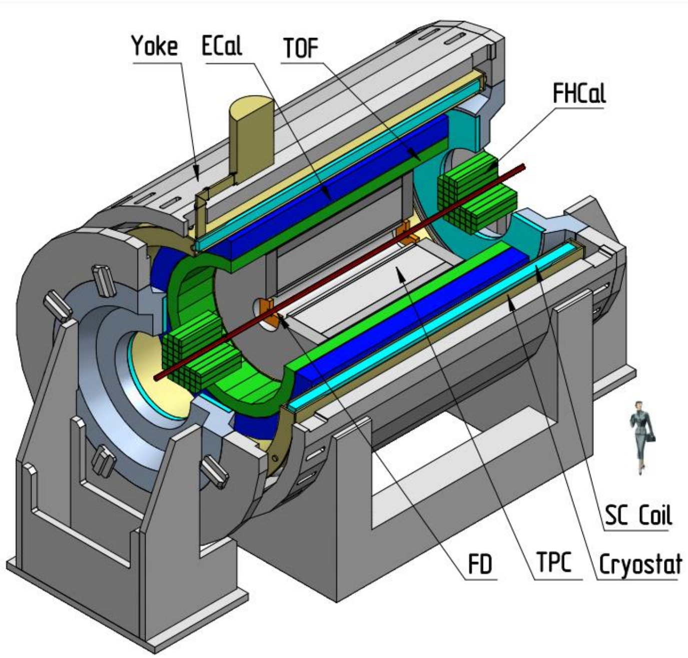


- Models predict yield modifications qualitatively similar to those obtained at SPS/RHIC/LHC:
  - ✓ lifetime and density of the hadronic phase are high enough
  - ✓ modification of particle properties in the hadronic phase should be taken into account when model predictions for different observables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

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
    - $p_T > 50\text{-}100$ MeV/c
    - TPC-TOF combined π/K/p PID
  - ✓ combinatorial background:
    - event mixing ($|\Delta_{Zvrtx}| < 2$ cm, $|\Delta_{Mult}| < 20$, $N_{ev} = 10$)

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

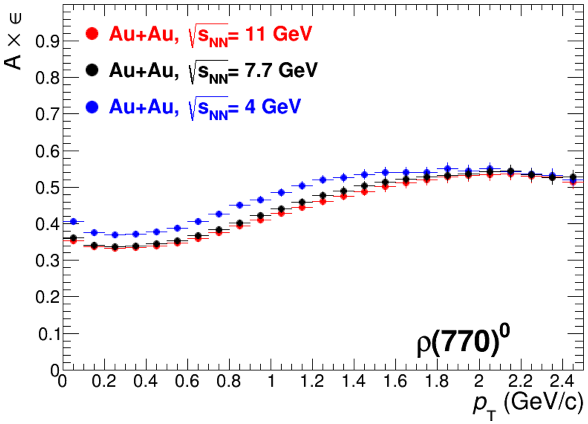
TOF, EMC: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.4$

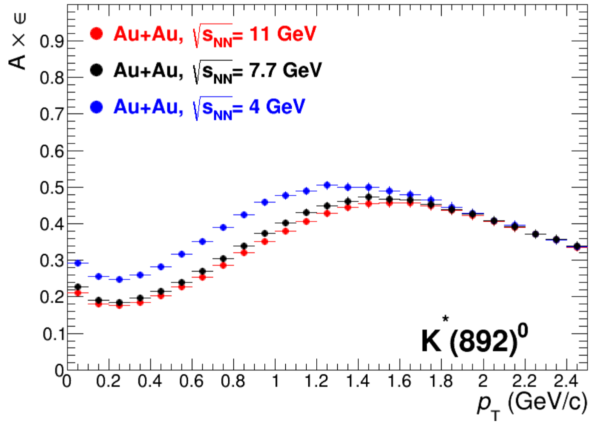
FFD: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$

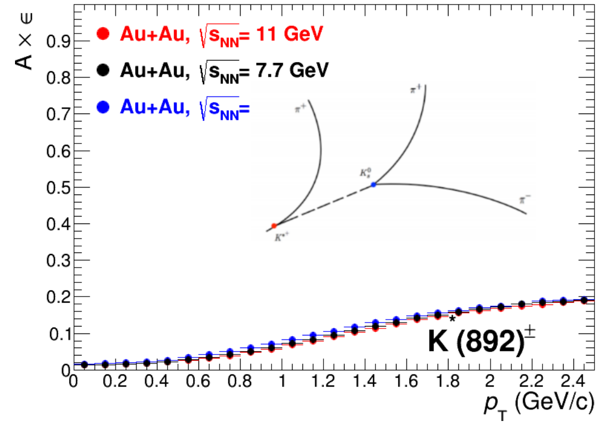
FHCAL: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

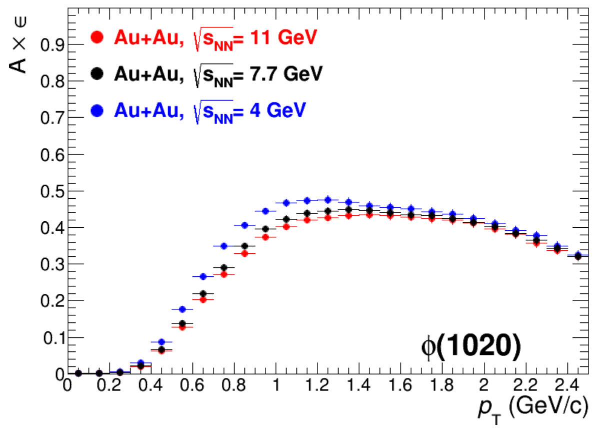
Reconstruction efficiency: ρ(770), K*(892), ϕ(1020), Λ(1520)

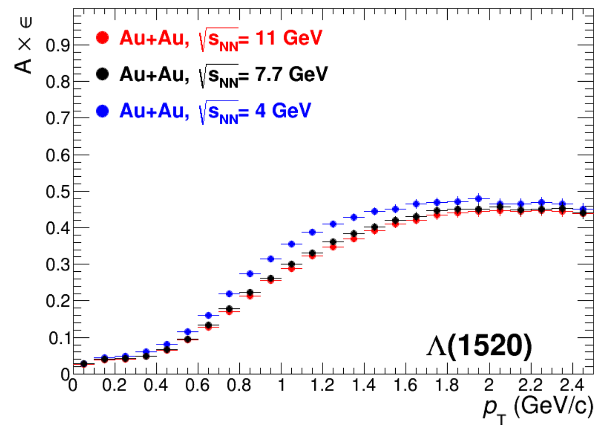
❖ Typical reconstruction efficiencies (A x ∈) in AuAu @ **4**, **7.7** and **11** GeV









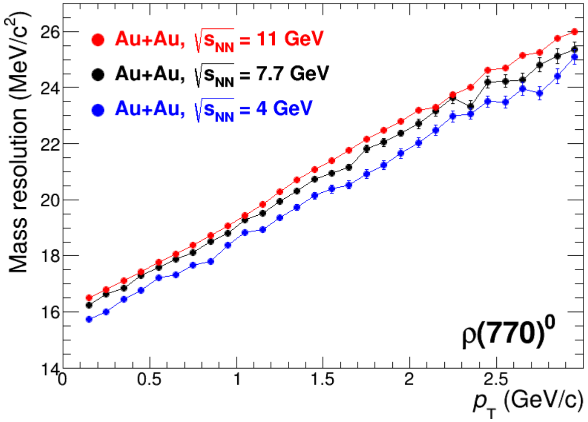


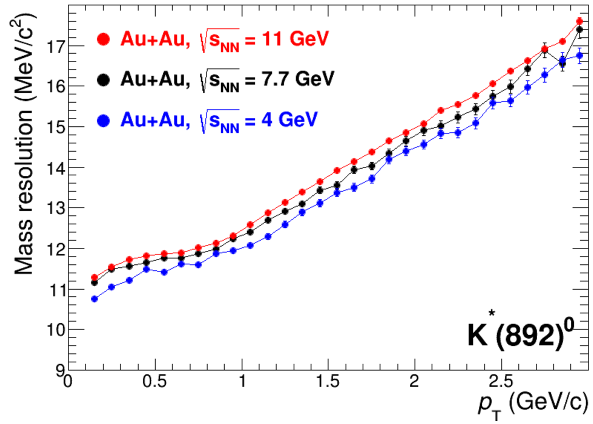
❖ Reasonable efficiencies in the wide p_T range, |y| < 1

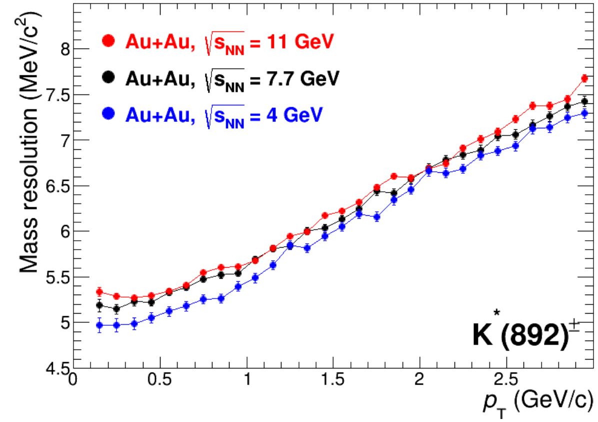
❖ Modest multiplicity (or $\sqrt{s_{NN}}$) dependence

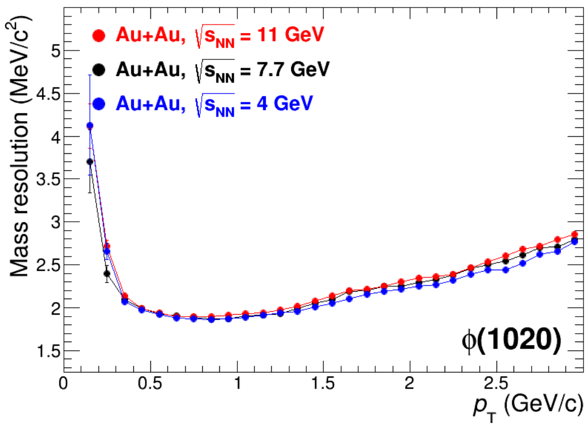
Mass resolution: ρ(770), K*(892), ϕ(1020), Λ(1520)

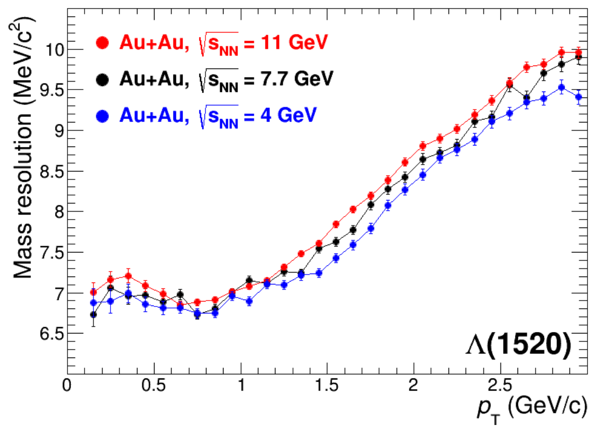
❖ Detector mass resolution ($m_{reconstructed} - m_{generated}$) in AuAu @ **4**, **7.7** and **11** GeV









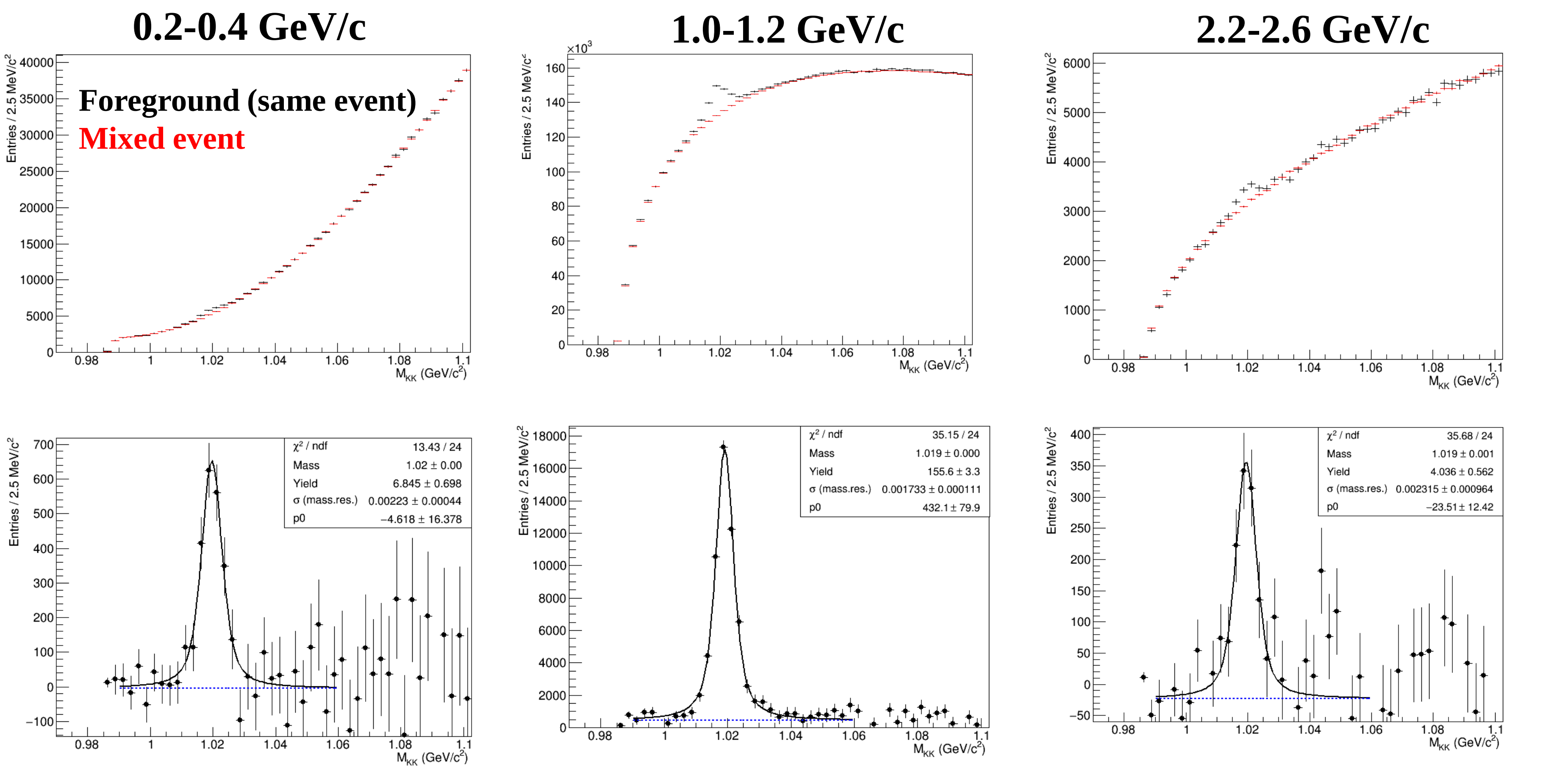


❖ Not outstanding but acceptable mass resolution

❖ Reasonable efficiencies in the wide p_T range

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

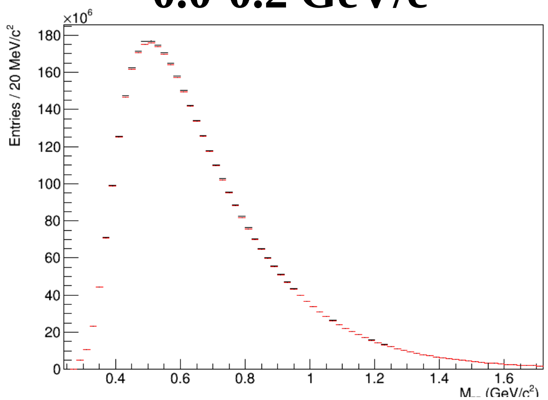
ϕ(1020), reconstructed peaks

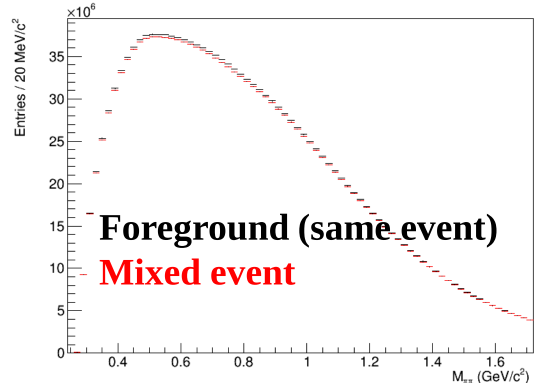


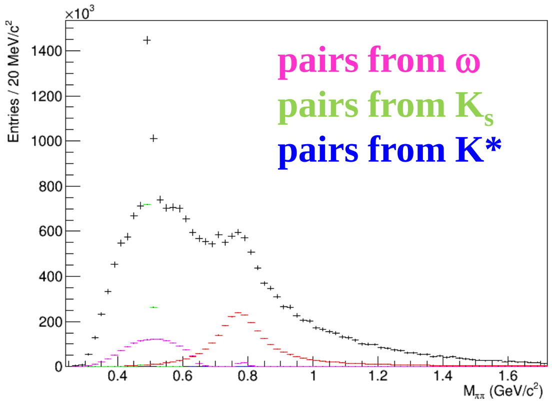
- 10M simulated AuAu@11(UrQMD v.3.4)
- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Distribution is fit to Voigtian function + constant (p0)
- Signal can be reconstructed at $p_T > 0.2$ GeV/c, ~ 90% of the total yield in this range for ϕ
- High-p_T reach is limited by available statistics

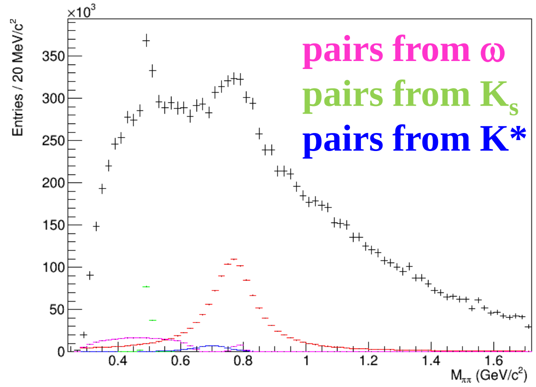
ρ(770), reconstructed peaks

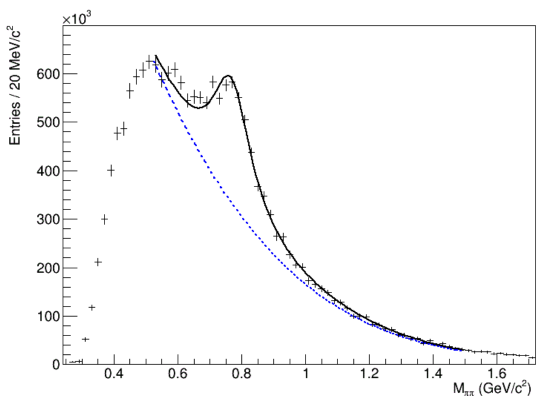
0.0-0.2 GeV/c | **1.2-1.4 GeV/c**

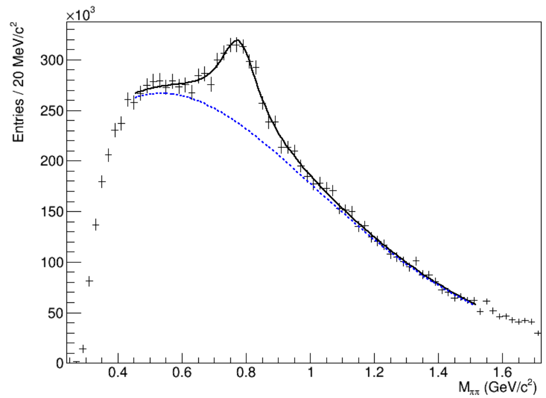








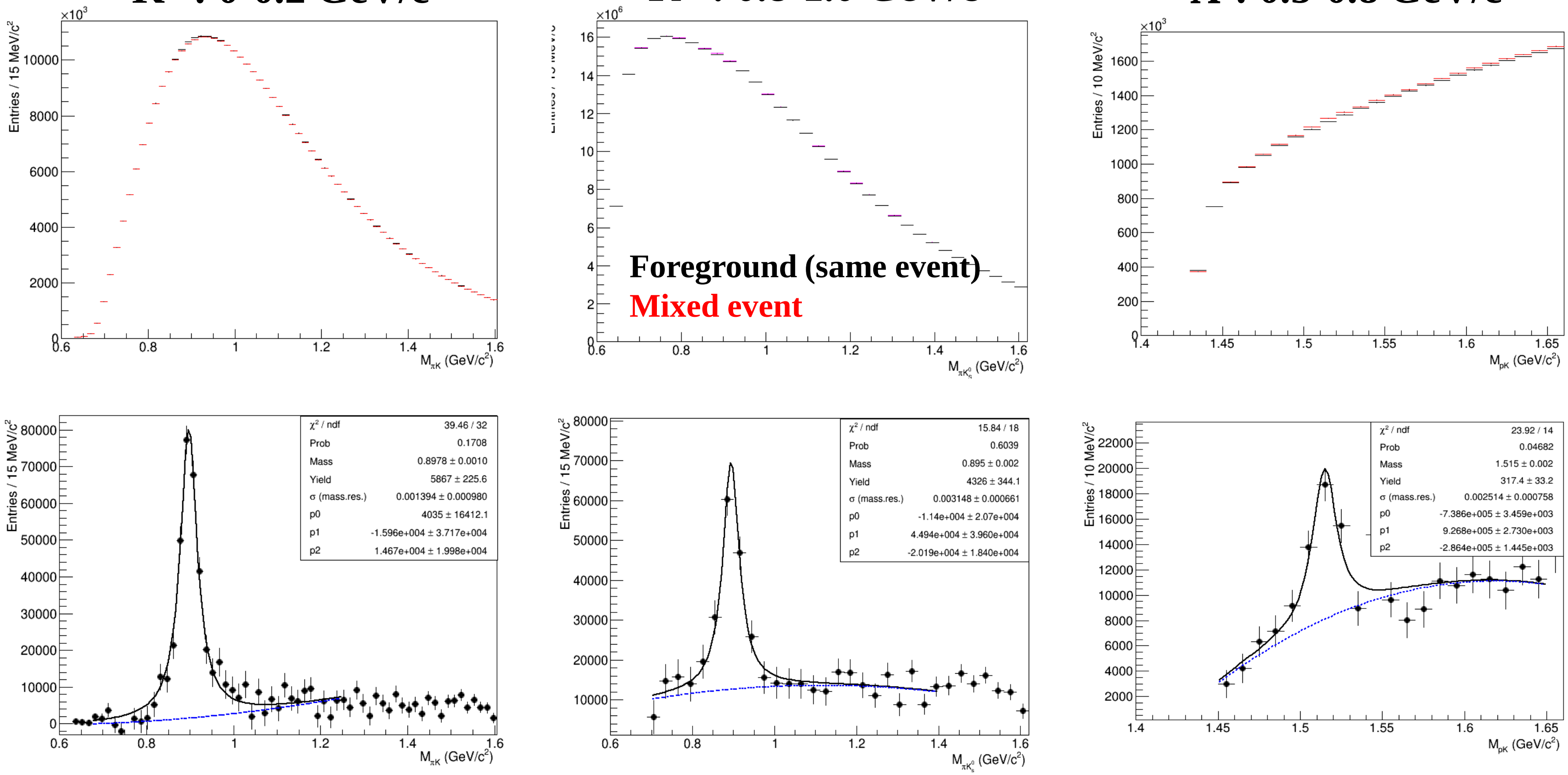




- 10M simulated AuAu@11 (UrQMD v.3.4)
- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- "Known" contributions from K_s, ω, K^* are subtracted (need to be measured in advance); f0, f2 are missing in simulation; similar to ALICE analysis, Phys.Rev. C99 (2019) no.6, 064901
- Distribution is fit to BW function + pol2, mass resolution is not important
- Signal can be reconstructed from zero momentum
- High-p_T reach is limited by available statistics

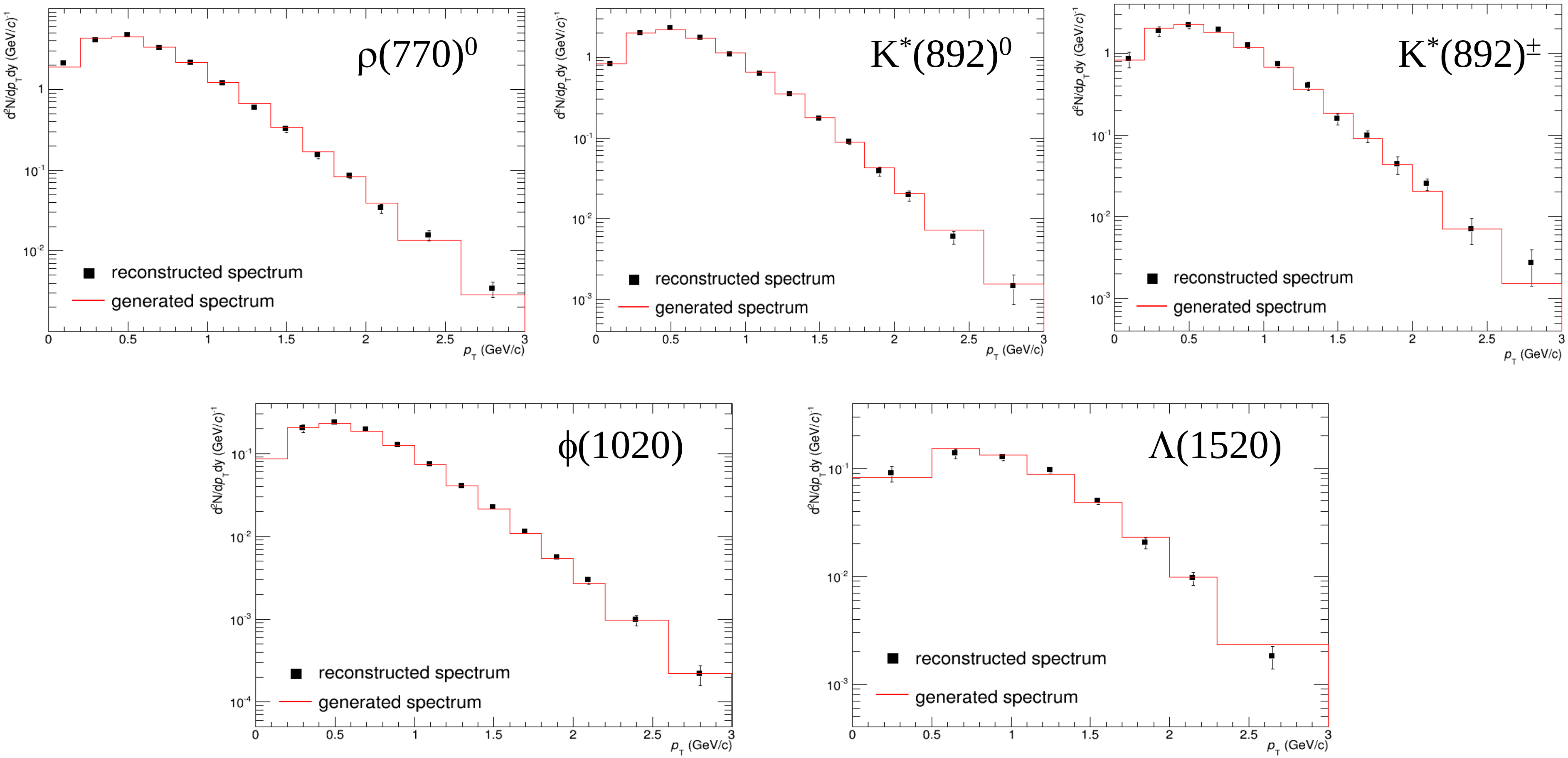
$K^*(892)$ and $\Lambda(1520)$, reconstructed peaks

K^{*0}: 0-0.2 GeV/c | **$K^{*\pm}$: 0.8-1.0 GeV/c** | **Λ^*: 0.5-0.8 GeV/c**



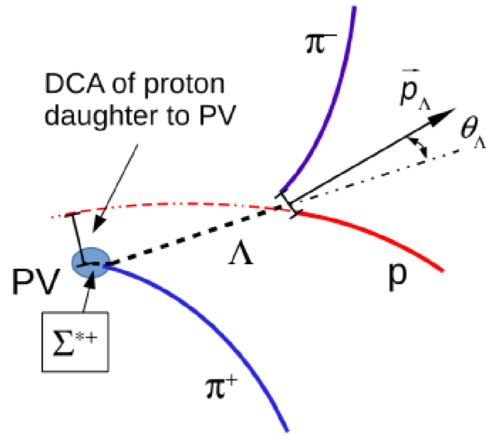
- 10M simulated AuAu@11(UrQMD v.3.4)
- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Fit to Voigtian + pol2
- Signal can be reconstructed from zero momentum
- High-p_T reach is limited by available statistics

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



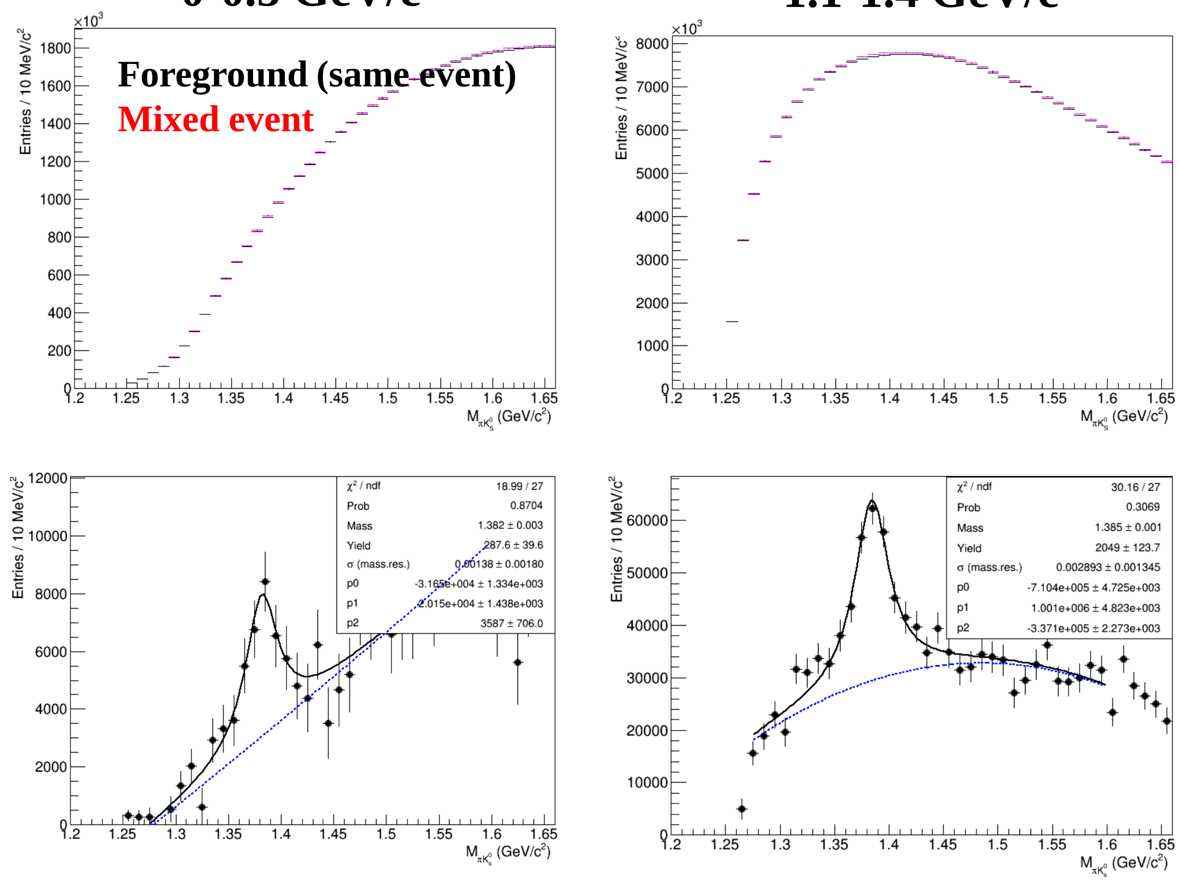
- 10M simulated AuAu@11(UrQMD v.3.4)
- Full chain reconstruction at |y| < 1.0
- Reconstructed spectra matches the generated ones within uncertainties
- Expected p_T range of measurements: 0-3GeV/c

Feasibility study, $\Sigma(1385)^{\pm}$



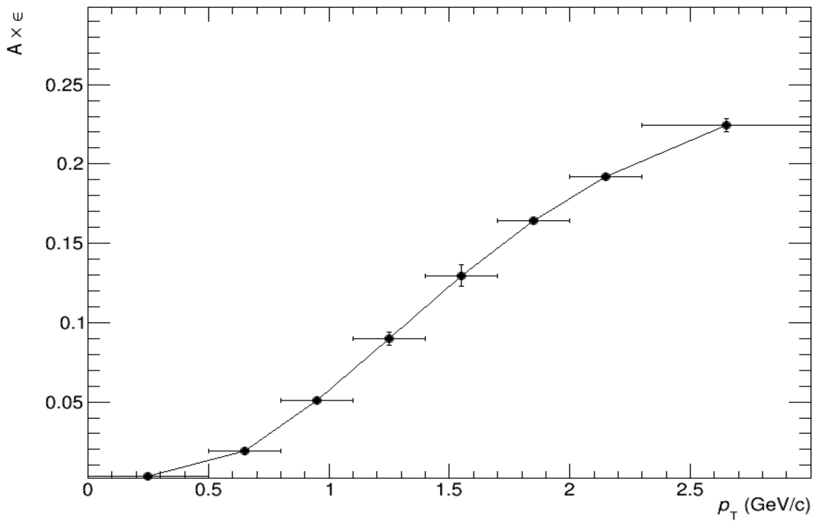
- ❖ $\Sigma(1385)^{\pm} \rightarrow \pi^{\pm}\Lambda$ ($\Lambda \rightarrow p\pi$)
- ❖ Decay chain includes weak decay of Λ → V0 vertex

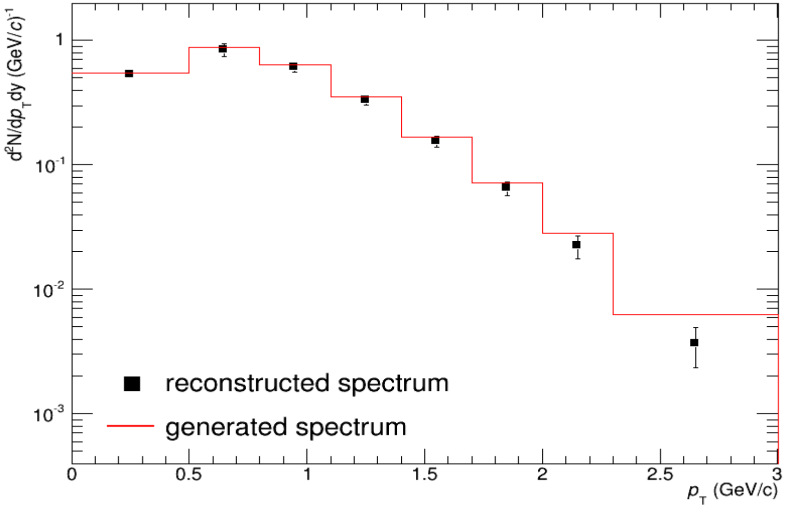
0-0.5 GeV/c **1.1-1.4 GeV/c**



- ❖ 10M simulated AuAu@11(UrQMD v.3.4)
- ❖ Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- ❖ Σ^{*} peak is fit to Voigtian + pol2
- ❖ Signal can be reconstructed starting from zero momentum
- ❖ High-p_T reach is limited by available statistics

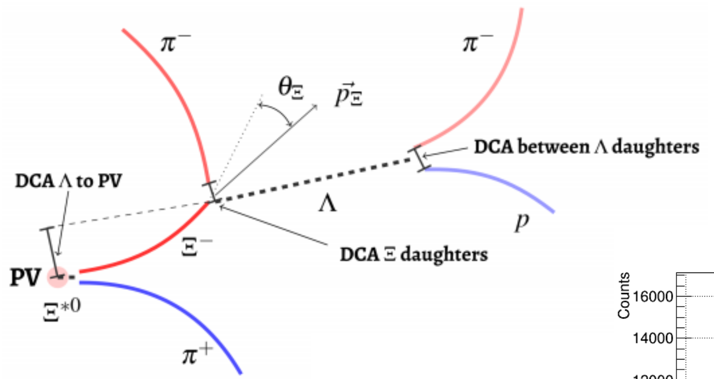
MC closure test: $\Sigma(1385)^{\pm}$





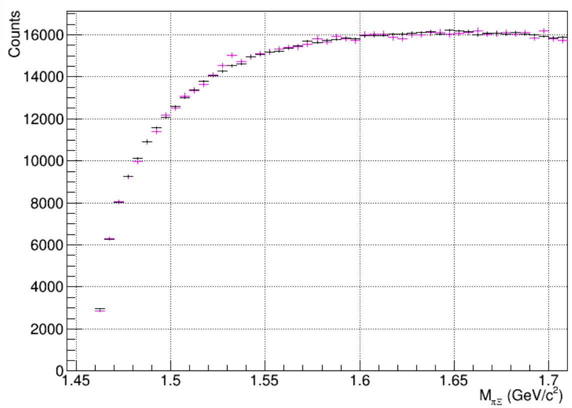
- Full chain reconstruction at $|y| < 1.0$
- Reconstructed spectrum matches the generated one within uncertainties
- Measurements are possible at $p_T > 0$ GeV/c

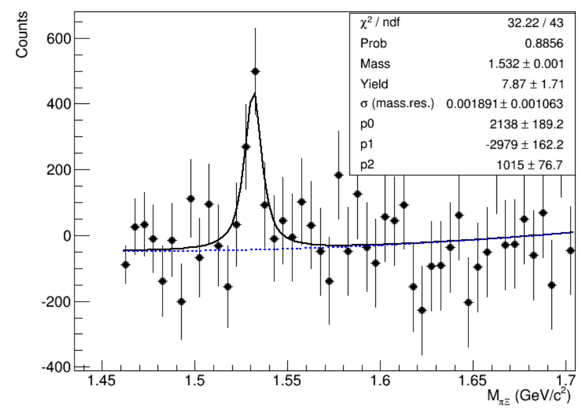
Feasibility study, $\Xi(1530)^0$



- $\Xi(1530)^0 \to \pi^+\Xi^-$ ($\Xi^- \to \Lambda\pi^-$, ($\Lambda \to p\,\pi^-$))
- Decay chain includes weak decay of Λ and cascade

$p_T > 1.0$ GeV/c





- Hint of a signal at $p_T > 1$ GeV/c
- Statistics hungry analysis → embedded simulations and large data samples …

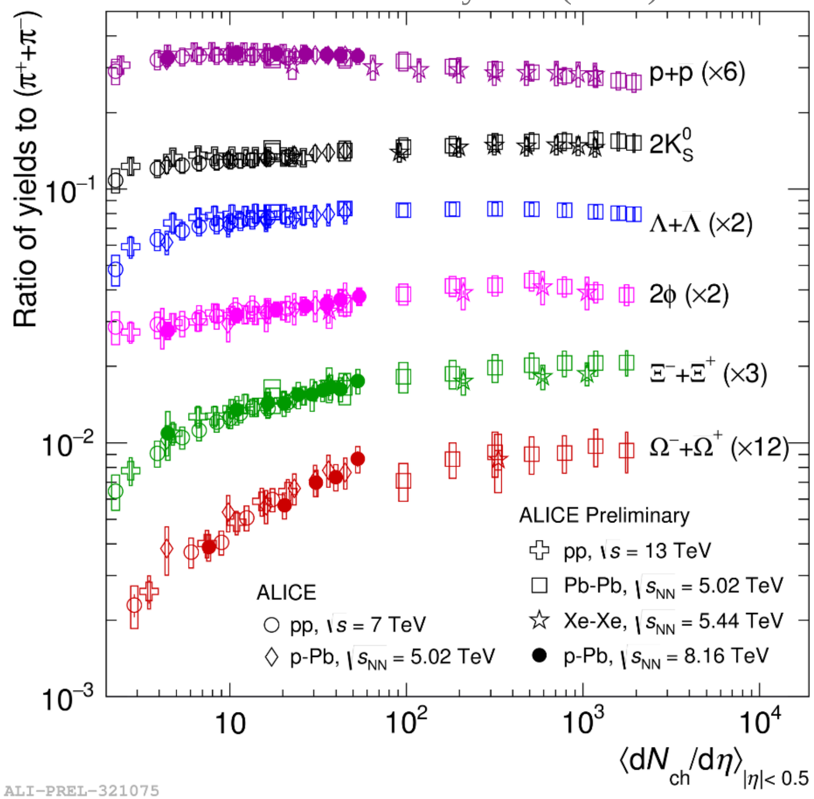
Summary

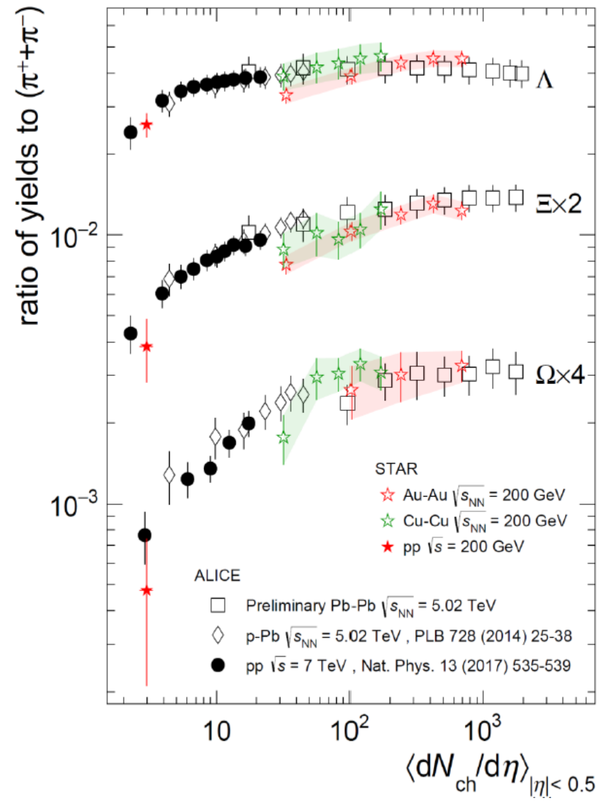
- ✓ Resonance study is an important part of the MPD physical program
- ✓ Resonances are expected to be sensitive to properties of the partonic/hadronic medium produced in heavy-ion collisions at NICA energies
- ✓ Resonances can be reconstructed/measured using the MPD detector from zero momentum to ~ 3 GeV/c with 10^7 minimum bias events sampled
- ✓ About 10^8 events is needed for multiplicity dependent study → within expectations for year-1 running

BACKUP

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

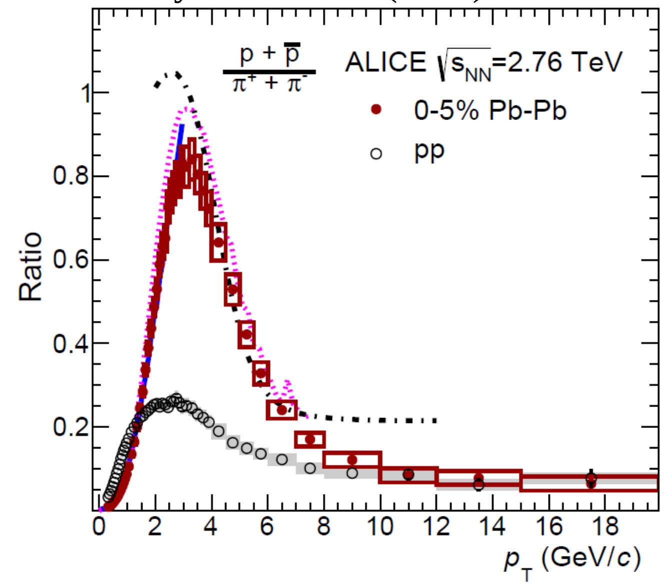
❖ Driving force of enhancement is not yet fully understood:

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

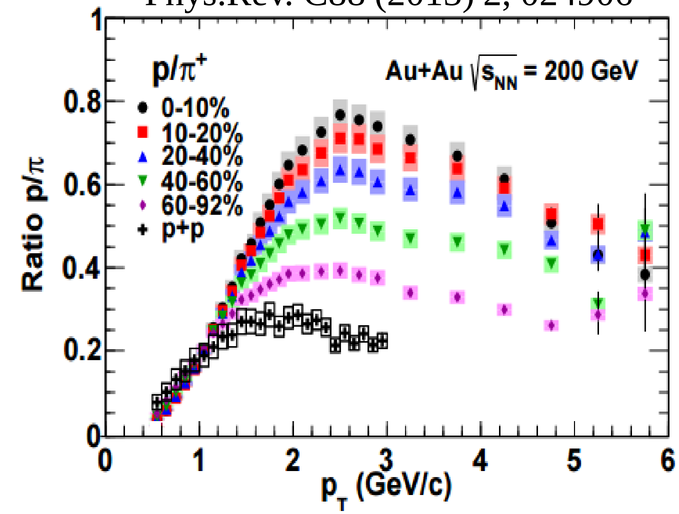
❖ ϕ and K^{*0} are well suited for tests as mesons with masses very close to that of a proton:

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

Phys.Lett. B736 (2014) 196-207

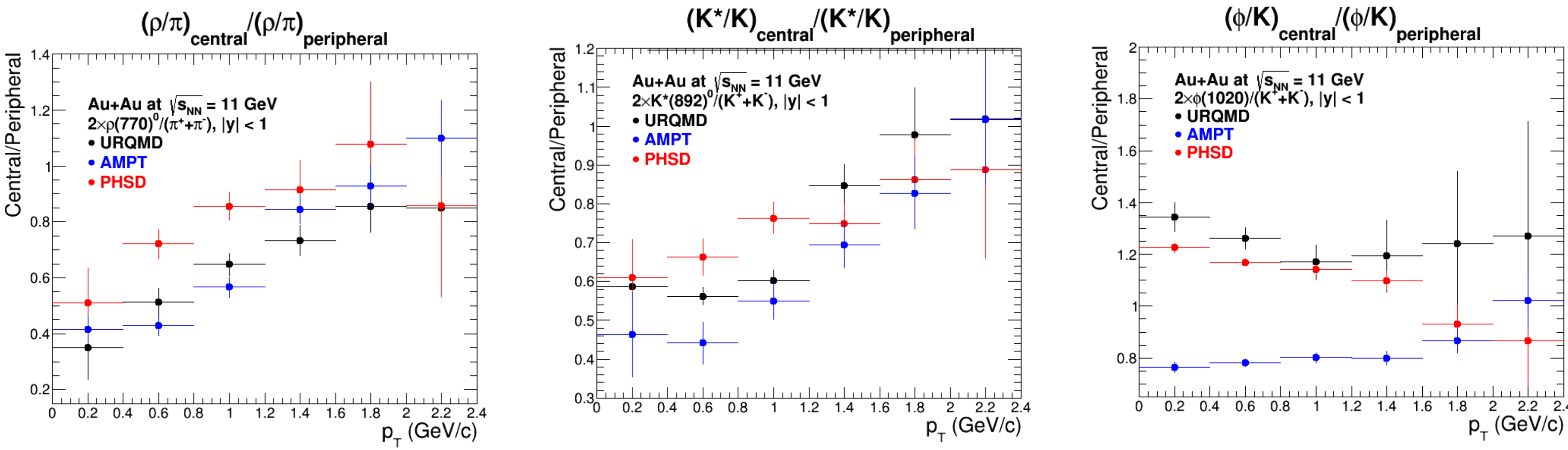


Phys.Rev. C88 (2013) 2, 024906



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), signal extraction – practice tests

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

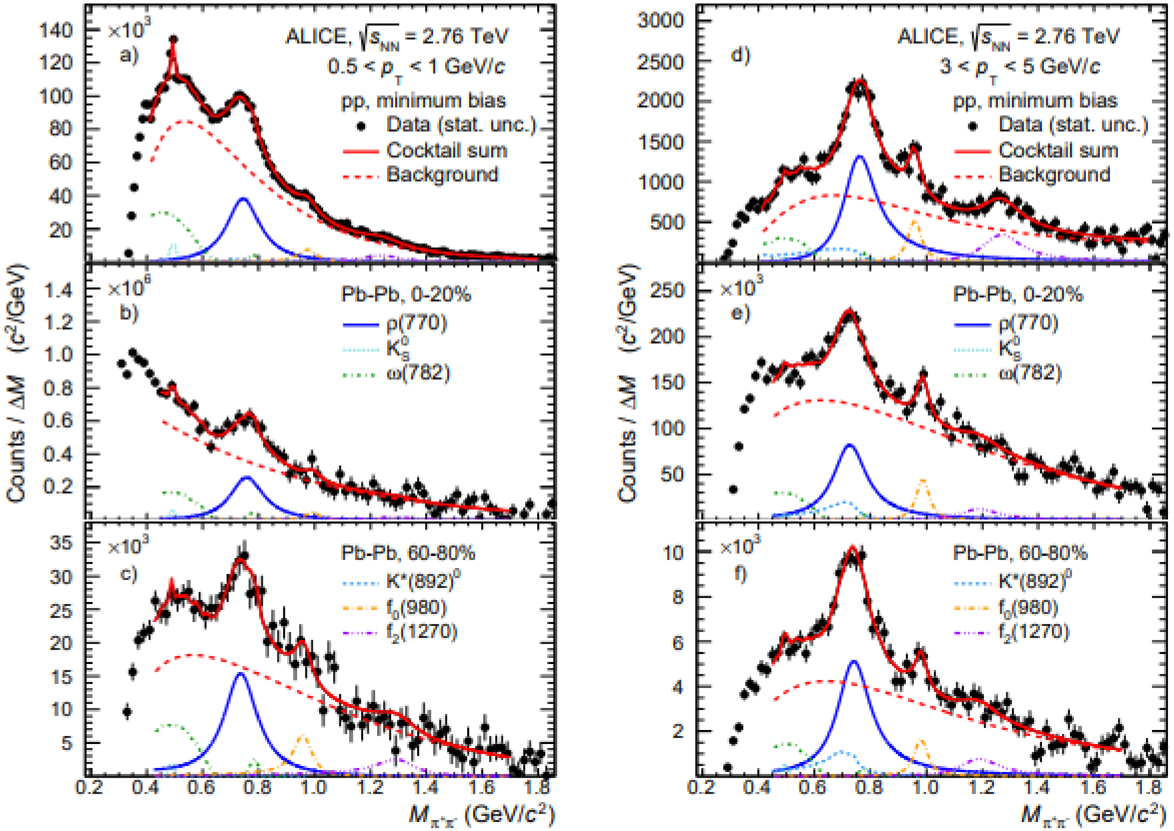


Fig. 1: (Color online) Invariant mass distributions for $\pi^+\pi^-$ pairs after subtraction of the like-sign background. Plots on the left and right are for the low and high transverse momentum intervals, respectively. Examples are shown for minimum bias pp, 0–20% and 60–80% central Pb–Pb collisions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