Short-lived resonances in the physical program of the MPD experiment at NICA.

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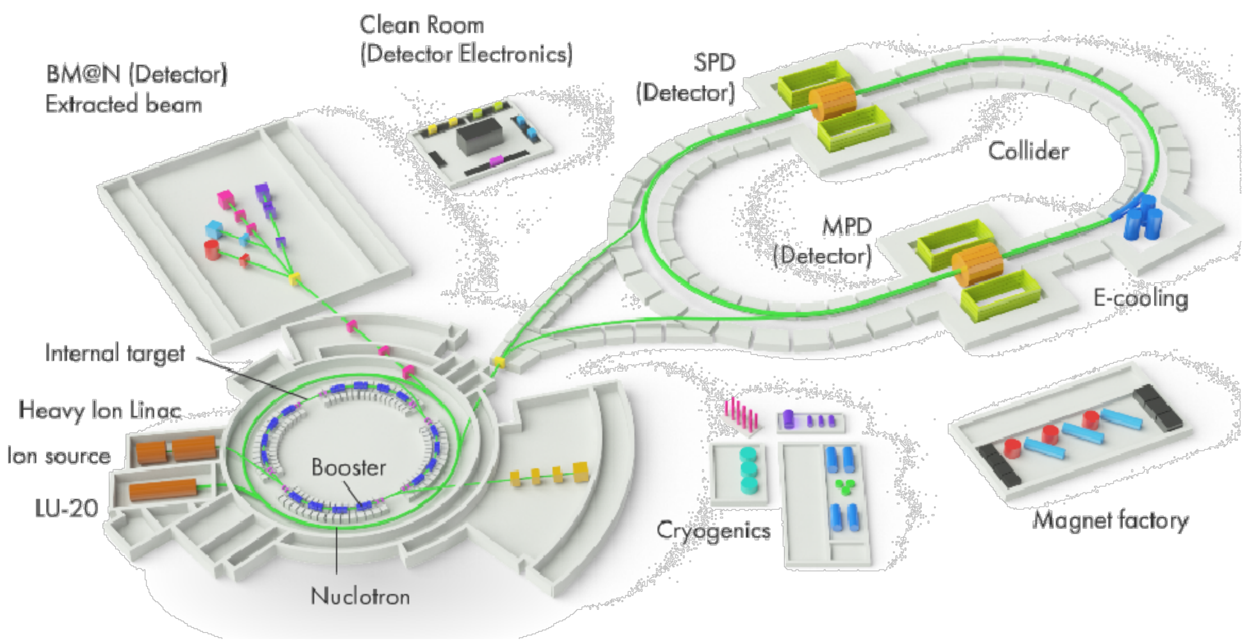
NICA, MPD



Construction of Collider to provide collisions of

- ***Ion species from p to Au at energy range $\sqrt{S_{NN}}$= 4 - 11 GeV***
- ***polarized p and d up to energy $\sqrt{s}$ =27 GeV (p)***
- ***Construction of 3 detectors: Baryonic Matter @ Nuclotron (BM@N), Multi Purpose Detector (MPD) and Spin Physics Detector (SPD)***

Outline

- **The motivation for resonance studies;**
- **Experimental background;**
- **Model expectations for resonance properties in heavy-ion collisions at NICA energies;**
- **Resonance reconstruction;**
- **Summary.**

Motivation

❖ Large number of resonances in the PDG (most often measured shown);

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

❖ These resonances have large cross sections of formation in HI collisions;
❖ Well defined properties in the PDG (mass, width, decay channels and BRs);
❖ Large branching ratios in hadronic decay channels → experimentally measurable even at top multiplicities;
❖ Probe reaction dynamics and particle production mechanisms vs. system size and $\sqrt{s_{NN}}$:

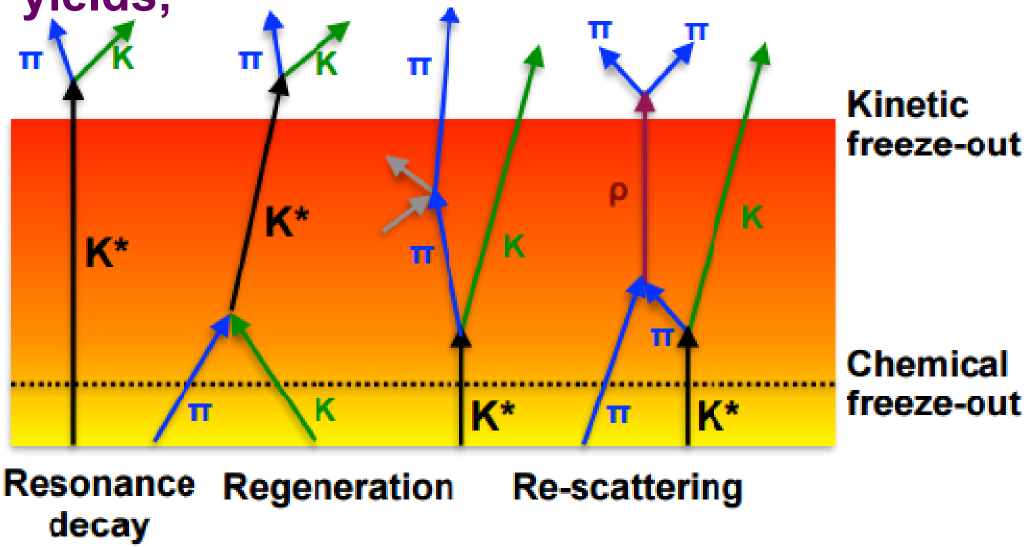
- ✓ hadron chemistry and strangeness production, ϕ with hidden strangeness is one of the key probes;
- ✓ reaction dynamics and shape of particle p_T spectra, p/K*, p/ϕ vs. p_T;
- ✓ lifetime and properties of the hadronic phase;
- ✓ flow, comparison with *e+e-* measurements, jet quenching, background for other probes etc.

Motivation, medium modification.

Short-lived resonances (hadronic decay channels) affected by hadronic phase: used for estimation of lifetime, density.

❖ ***Reconstructed resonance yields in heavy ion collisions are defined by:***

- ✓ ***Resonance yields at chemical freeze-out;***
- ✓ ***Hadronic processes between chemical and kinetic freeze-out:***
  - ***Rescattering: rescattering of daughter particles changes the decay kinematics → particle is not reconstructed → loss of signal ;***
  - ***Regeneration*: pseudo-elastic scattering of background hadrons may result in the production of resonances ($\pi K \rightarrow K^{*0}$, $KK \rightarrow \phi$ etc.) → increased yields;**



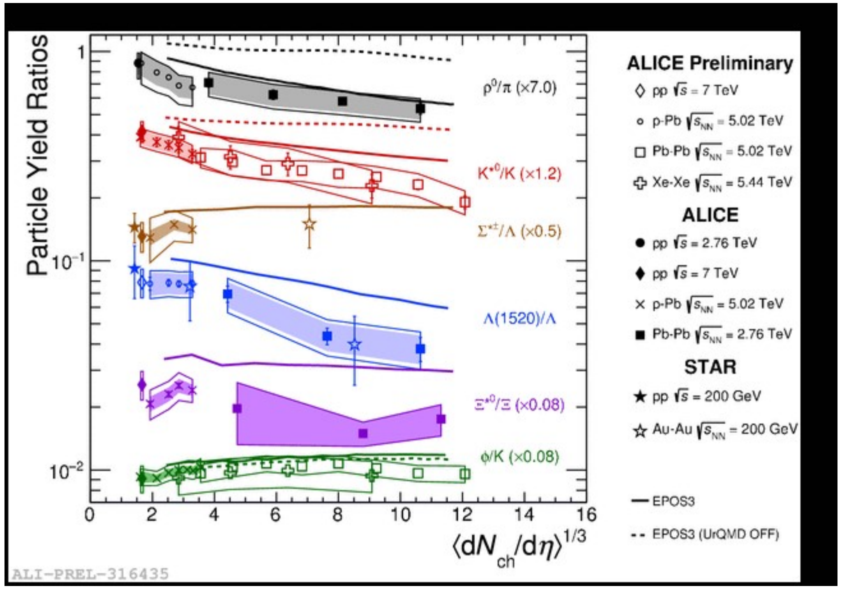
For most of the cases rescattering takes over regeneration and the total effect of the hadronic phase is a loss of signal.

Experimental summary.

❖Resonances differ by lifetime, mass and quark content → useful in studying the dynamics of the reaction and the mechanisms of particle formation in different collision systems;

increasing lifetime →

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



❖ 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;

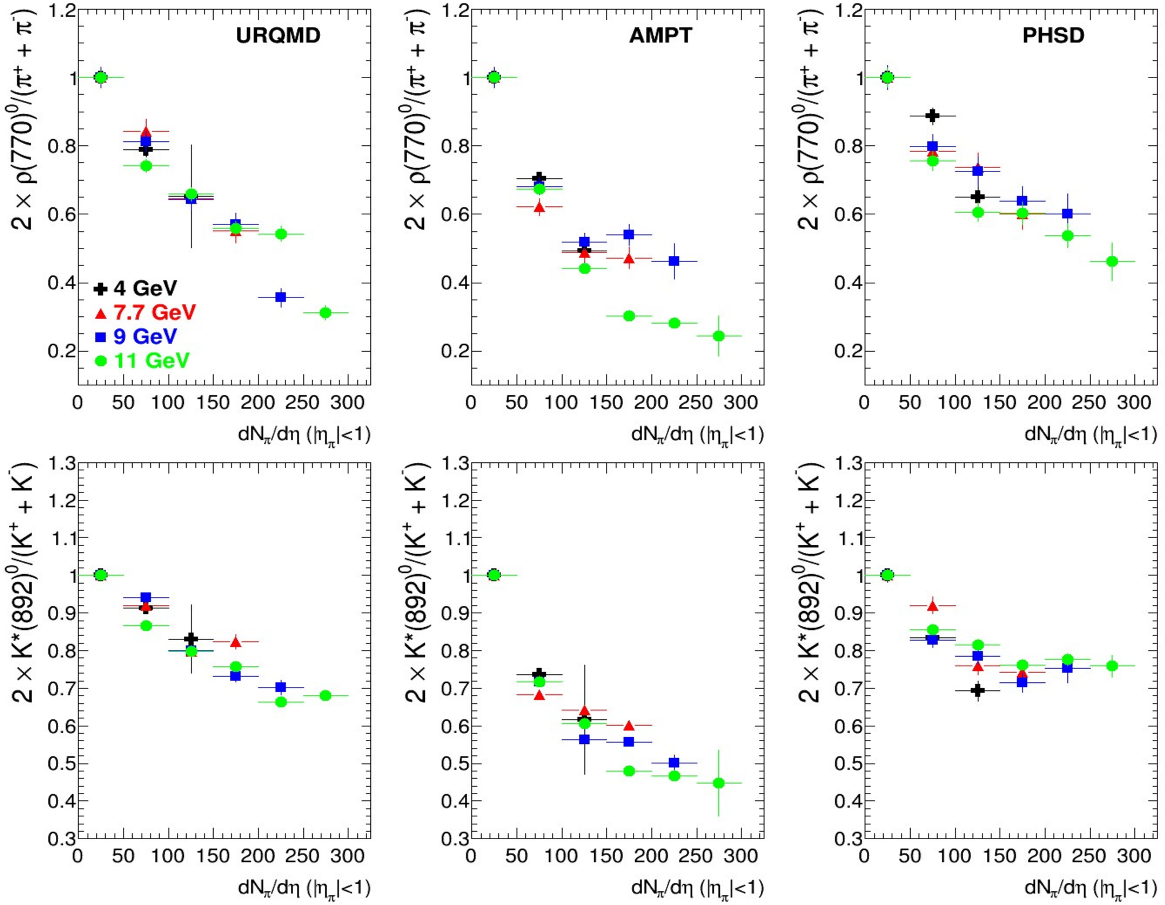
❖ Hadronic phase lifetime, τ ~ 10 fm/c*;

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

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



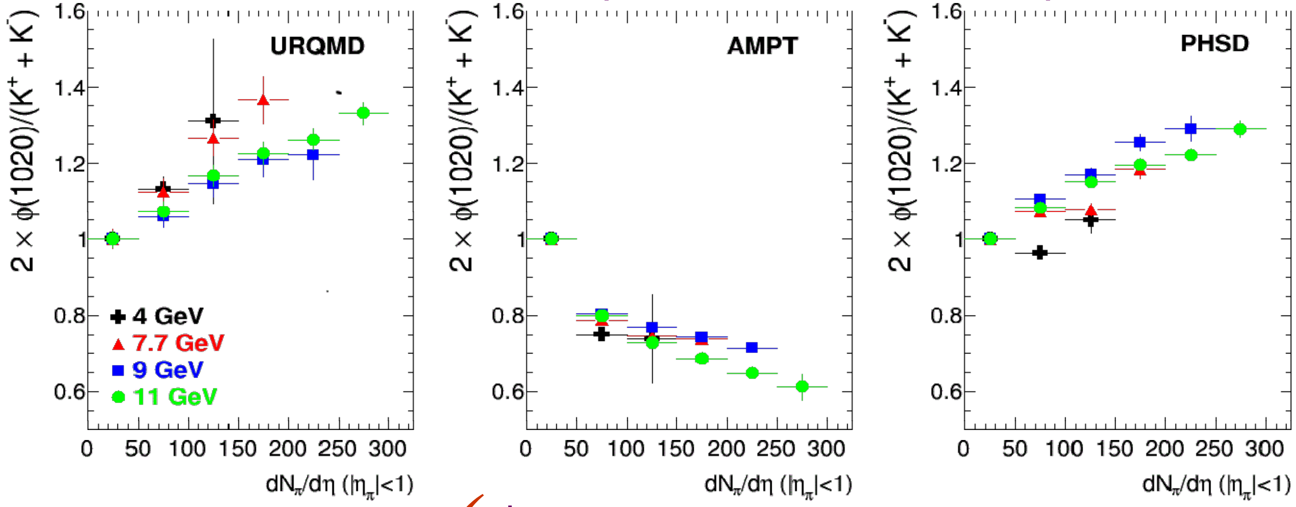
❖ Models predict centrality dependent ρ/π, K^*/K in AuAu@4-11;

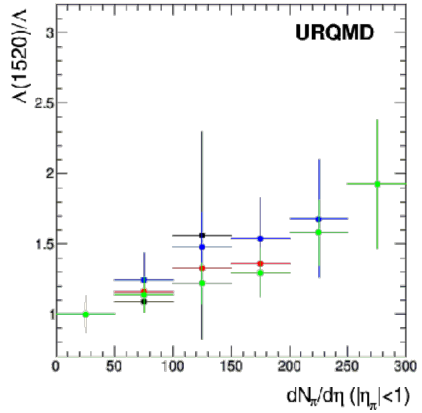
❖ Ratios are suppressed going from peripheral to central collisions for resonances with small $c\tau$;

❖ Modifications occur at low momentum as expected for the hadronic phase effects.

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

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





✓ **φ(1020)/K ratio is predicted to be enhanced by UrQMD and PHSD and suppressed by AMPT;**

✓ **Λ(1520) is available in UrQMD only, Λ(1520)/Λ ratio gradually increases with multiplicity at all energies;**

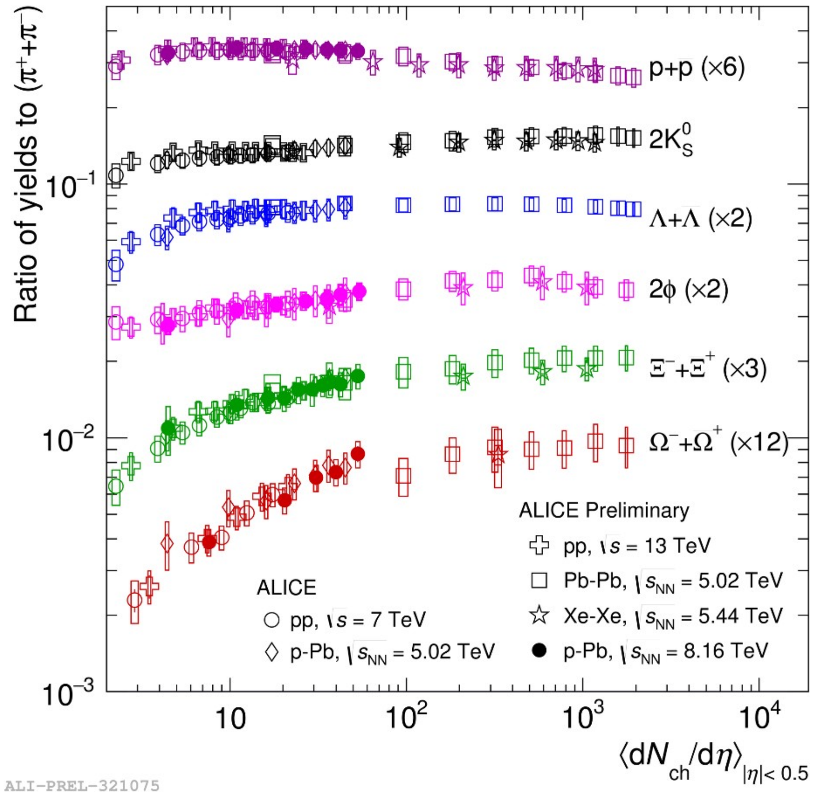
✓ **φ(1020)/K and Λ(1520)/Λ ratios are consistent for different collision energies at similar multiplicities.**

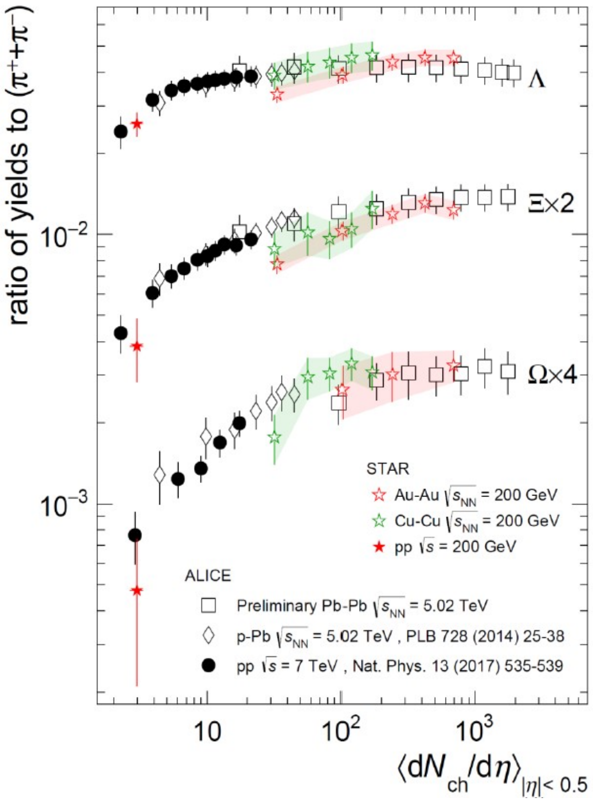
❖ **Models predict yield modifications qualitatively similar to those obtained at SPS/RHIC/LHC:**

- ✓ **lifetime and density of the hadronic phase are high enough;**
- ✓ **modification of particle properties in the hadronic phase should be taken into account when model predictions for different observables are compared to data;**
- ✓ **study of short-lived resonances is a unique tool to tune the hadronic phase simulations.**

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

Nature Phys. 13 (2017) 535

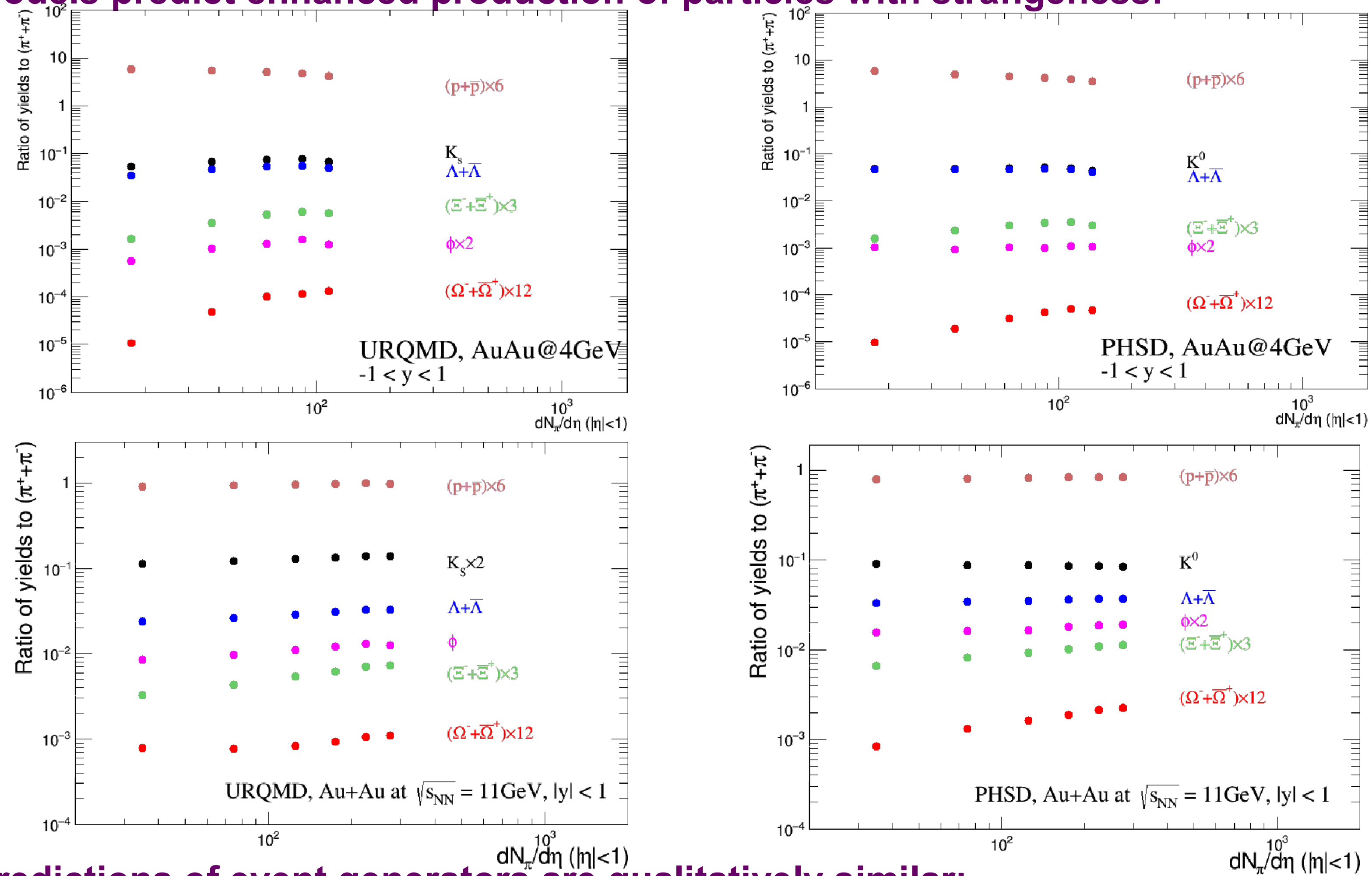




- **Observed in heavy-ion collisions at AGS, SPS, RHIC and LHC;**
- **For the first time observed in pp and p-A collisions by ALICE at the LHC**
- **Observed as for ground-state hadrons as for resonances (ϕ/π, Σ^*/π, Ξ^*/π)**
- **Strangeness production in A-A collisions is reproduced by statistical hadronization 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 !!!**

Predictions, strangeness production

- UrQMD, PHSD, AMPT, EPOS …
- Models predict enhanced production of particles with strangeness:

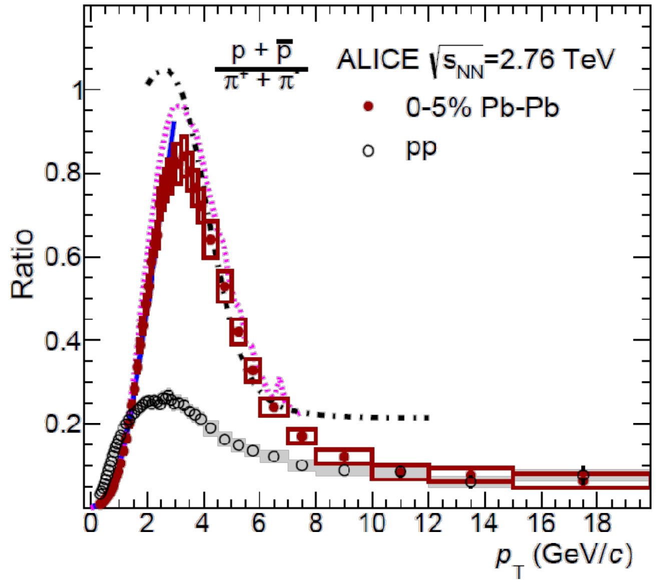


- Predictions of event generators are qualitatively similar;
- Enhancement is more pronounced for particles containing a larger number of s-quarks;
- Relative enhancement is stronger at lower collision energies
- ϕ(1020) meson with hidden strangeness behaves like a hadron with open strangeness

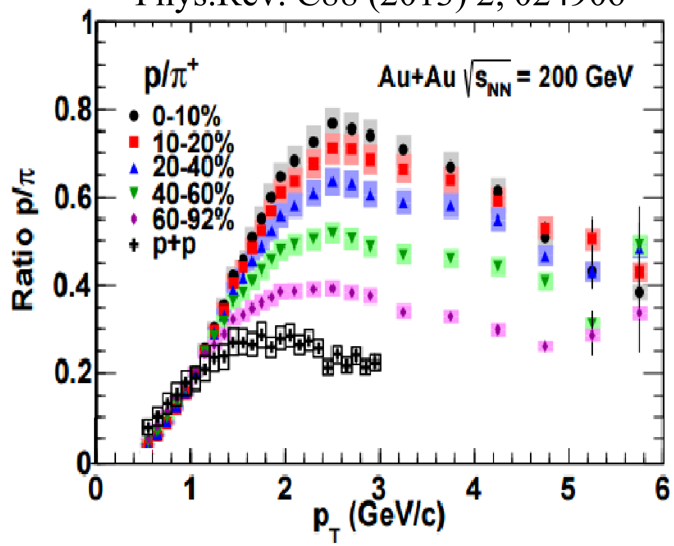
Hadronization at intermediate momenta.

- **Baryon puzzle - increased B/M (p/π, Λ/K_s^0 , Λ_c^+/D etc.) ratios at RHIC and the LHC**
- **Driving force of enhancement is not yet fully understood:**
  - ✓ **particle mass (hydro)?**
  - ✓ **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

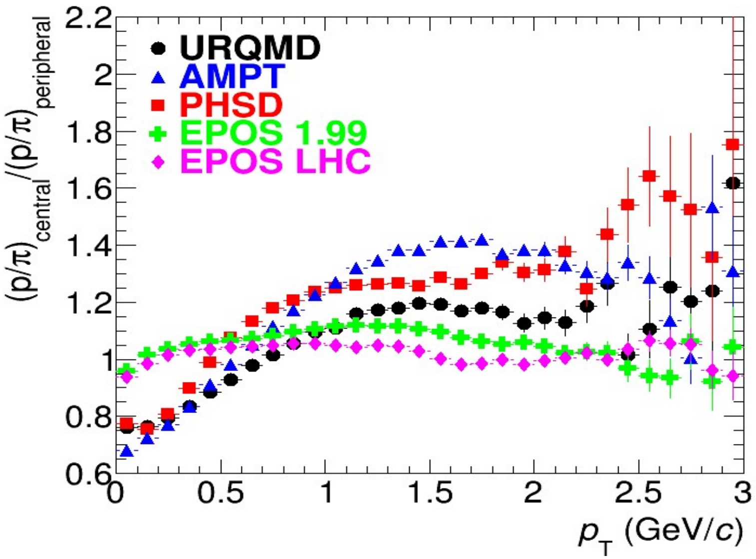


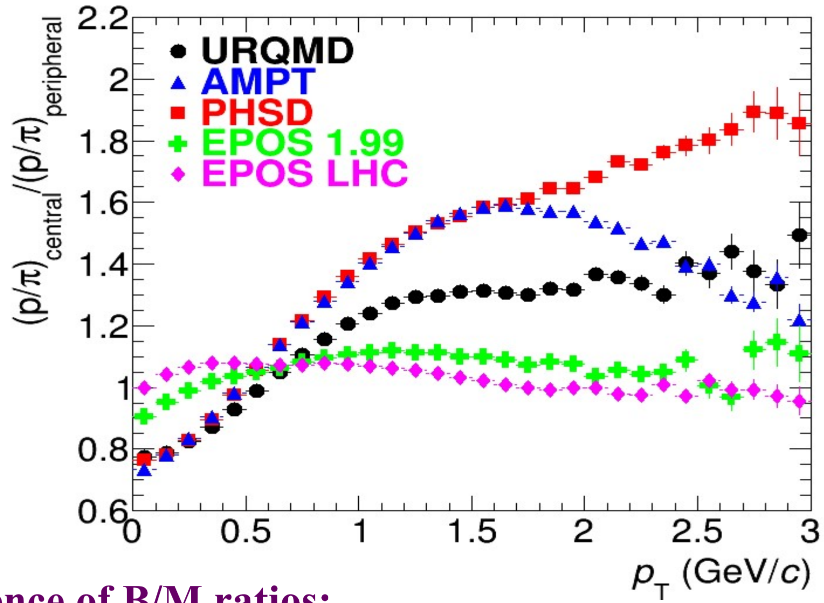
Phys.Rev. C88 (2013) 2, 024906



Model predictions, B/M ratios

- UrQMD, PHSD, AMPT, EPOS …
- Baryon/meson (B/M) ratios evolve with centrality/multiplicity.



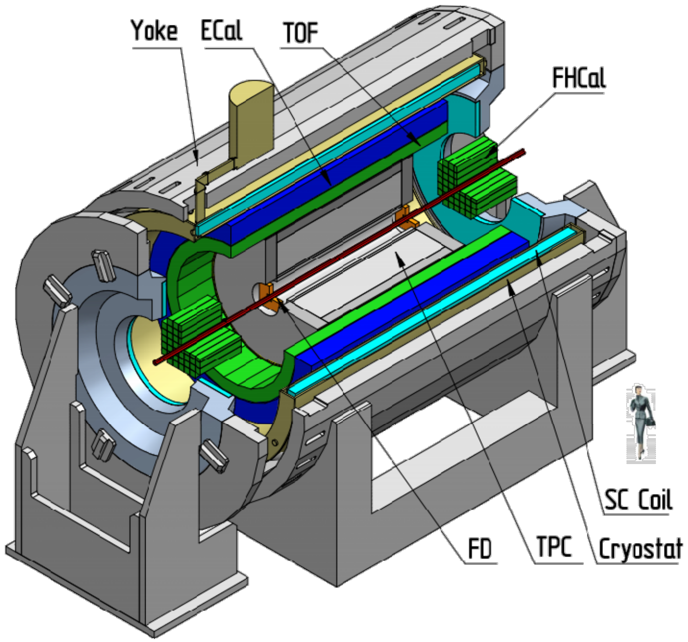


- ✓ strong model and collision energy dependence of B/M ratios;
- ✓ predictions are qualitatively similar to experimental observations at RHIC and the LHC;
- ✓ origin of the evolution of B/M ratios is not understood (radial flow, quark recombination, …);
- ✓ measurements of p/ϕ(1020) and p/K*(892) ratios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

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

Feasibility studies for resonances.

- MPD Stage-1: TPC, TOF, FFD, FHCAL and 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: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.6$

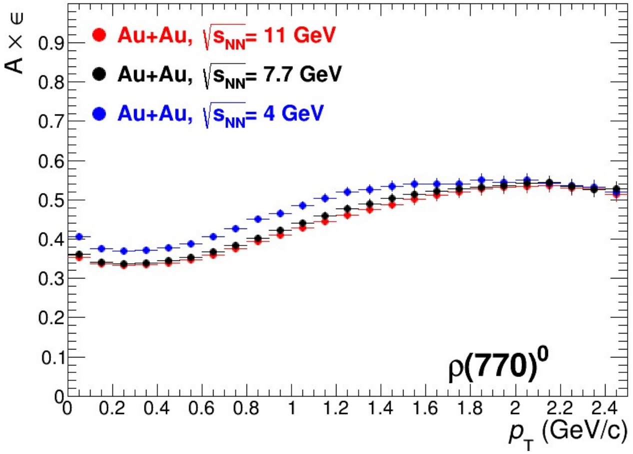
TOF, EMC: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.4$

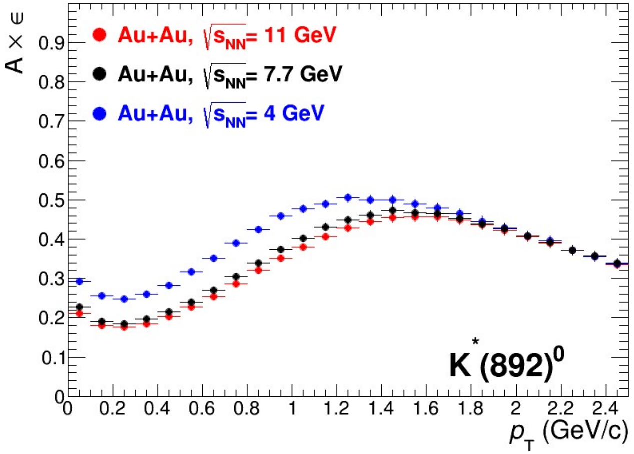
FFD: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$

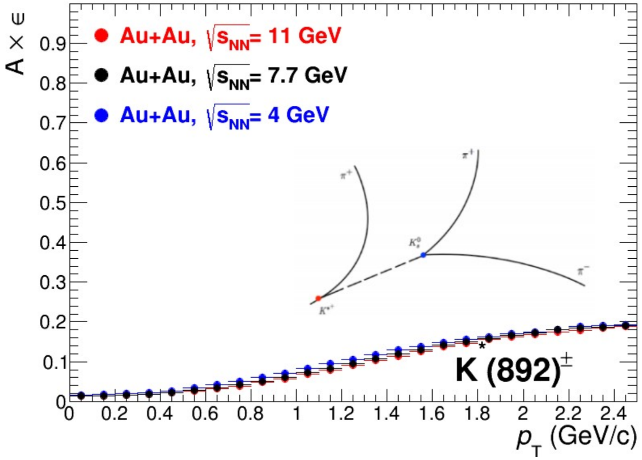
FHCAL: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

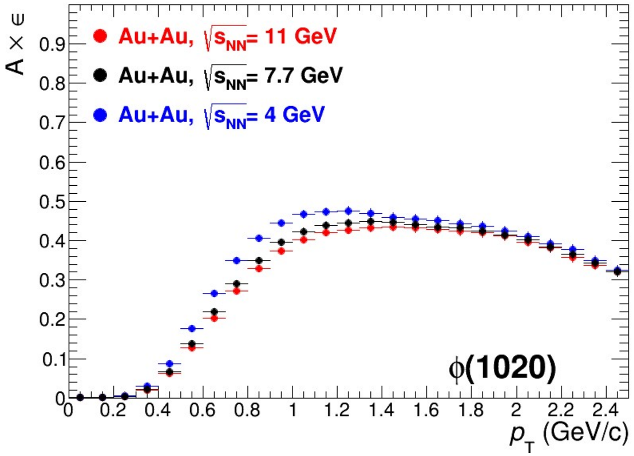
Reconstruction efficiency: $\rho(770)$, $K^*(892)$, $\phi(1020)$, $\Lambda(1520)$

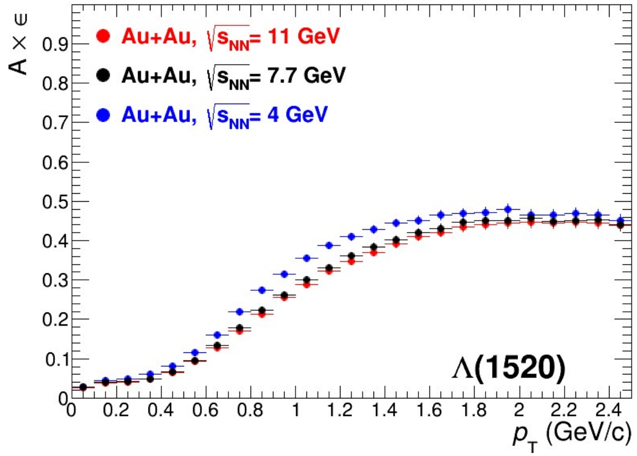
❖ Typical reconstruction efficiencies (A x ϵ) in AuAu @ 4, 7.7 and 11 GeV, |y| < 1;









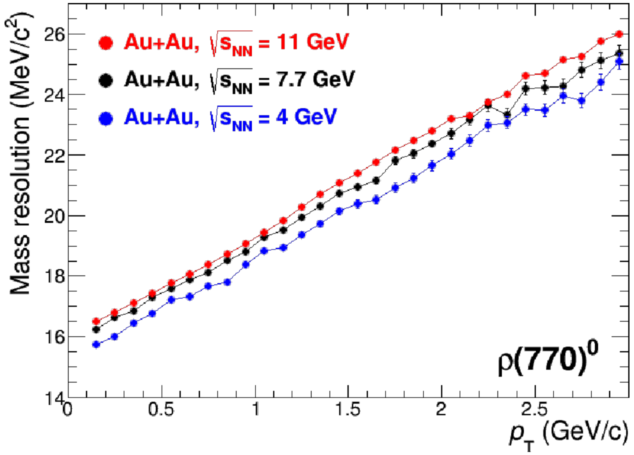


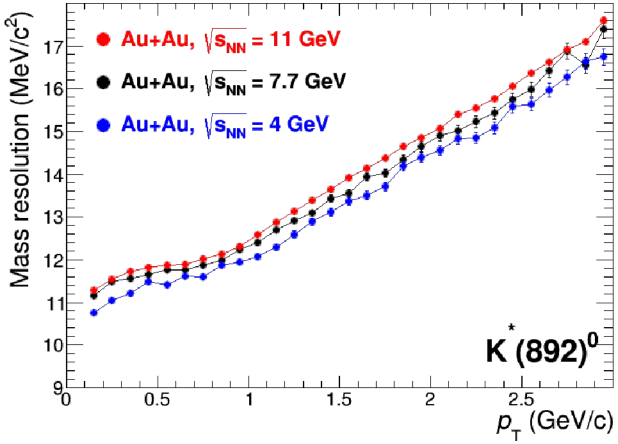
❖ Reasonable efficiencies in the wide p_T range, |y| < 1;

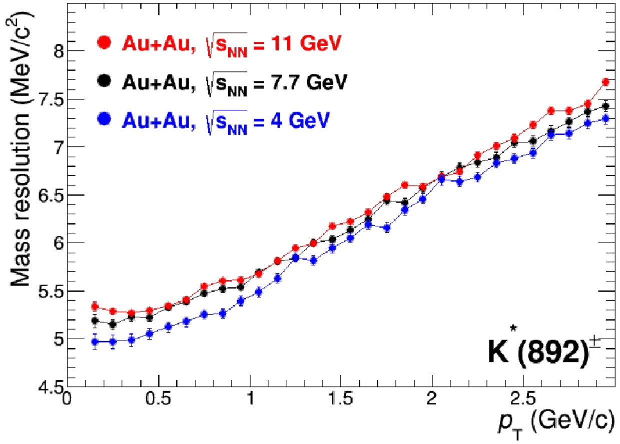
❖ Modest multiplicity (and/or $\sqrt{s_{NN}}$) dependence.

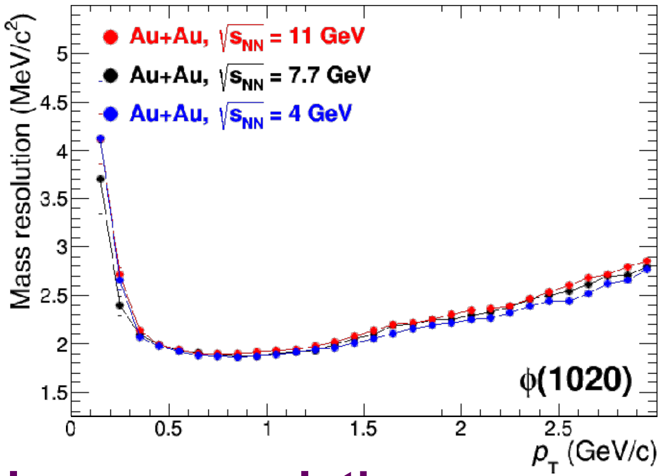
Mass resolution:
ρ (770), K*(892), ϕ (1020), Λ (1520)

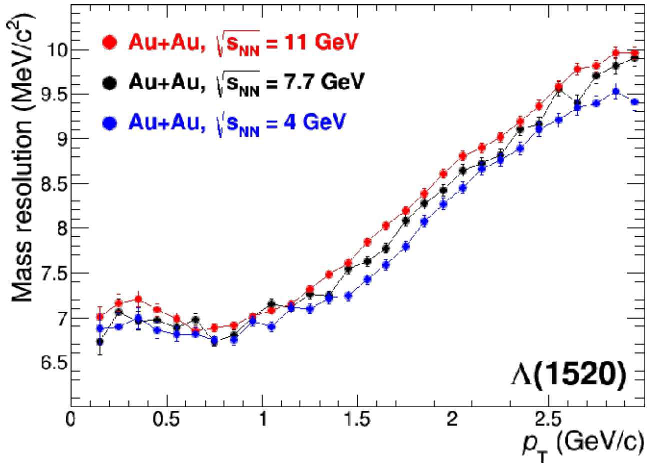
- Detector mass resolution ($m_{reconstr.} – m_{generated}$) in AuAu @ 4, 7.7 and 11 GeV, |y| < 1;







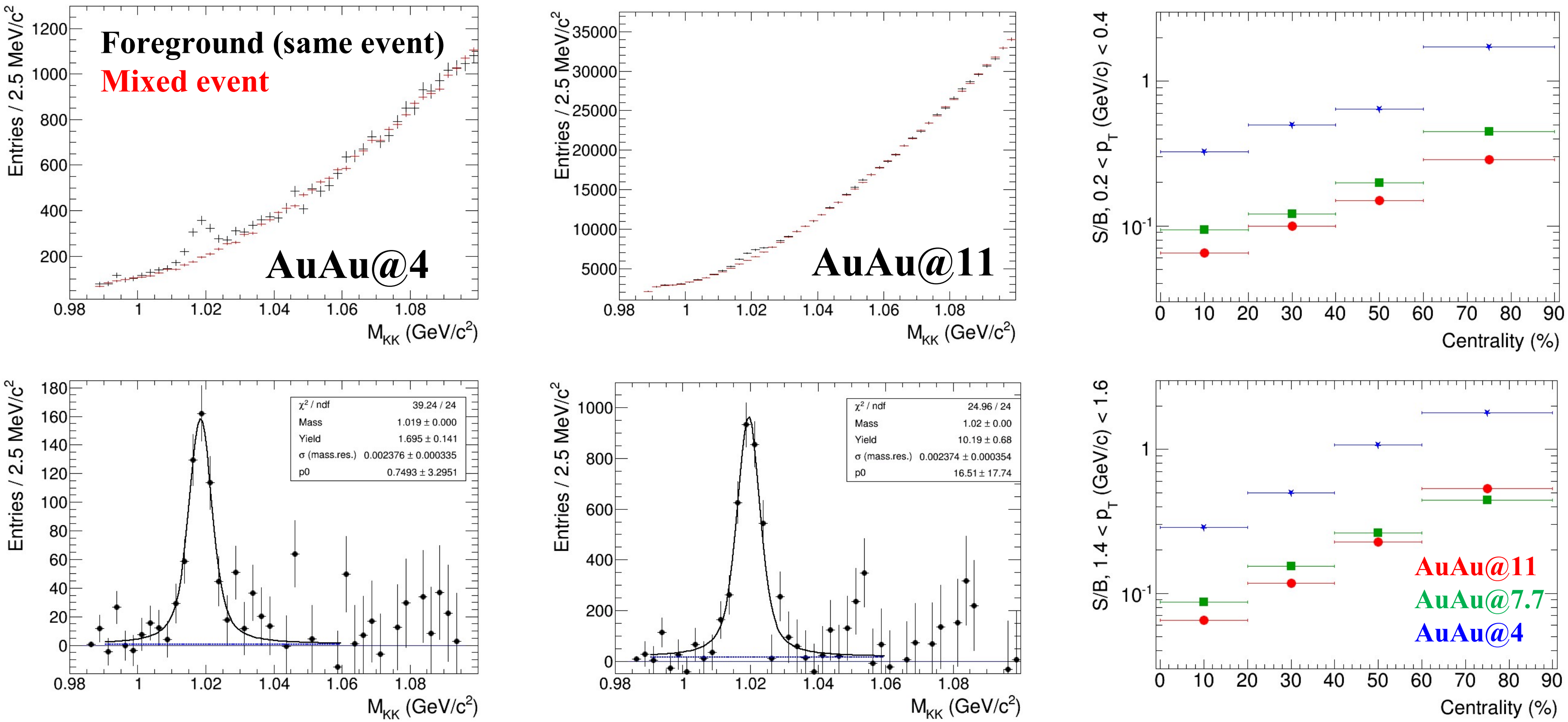




- **Acceptable mass resolution;**
- **Modest multiplicity (and/or $\sqrt{s_{NN}}$) dependence.**

ϕ (1020), reconstructed peaks

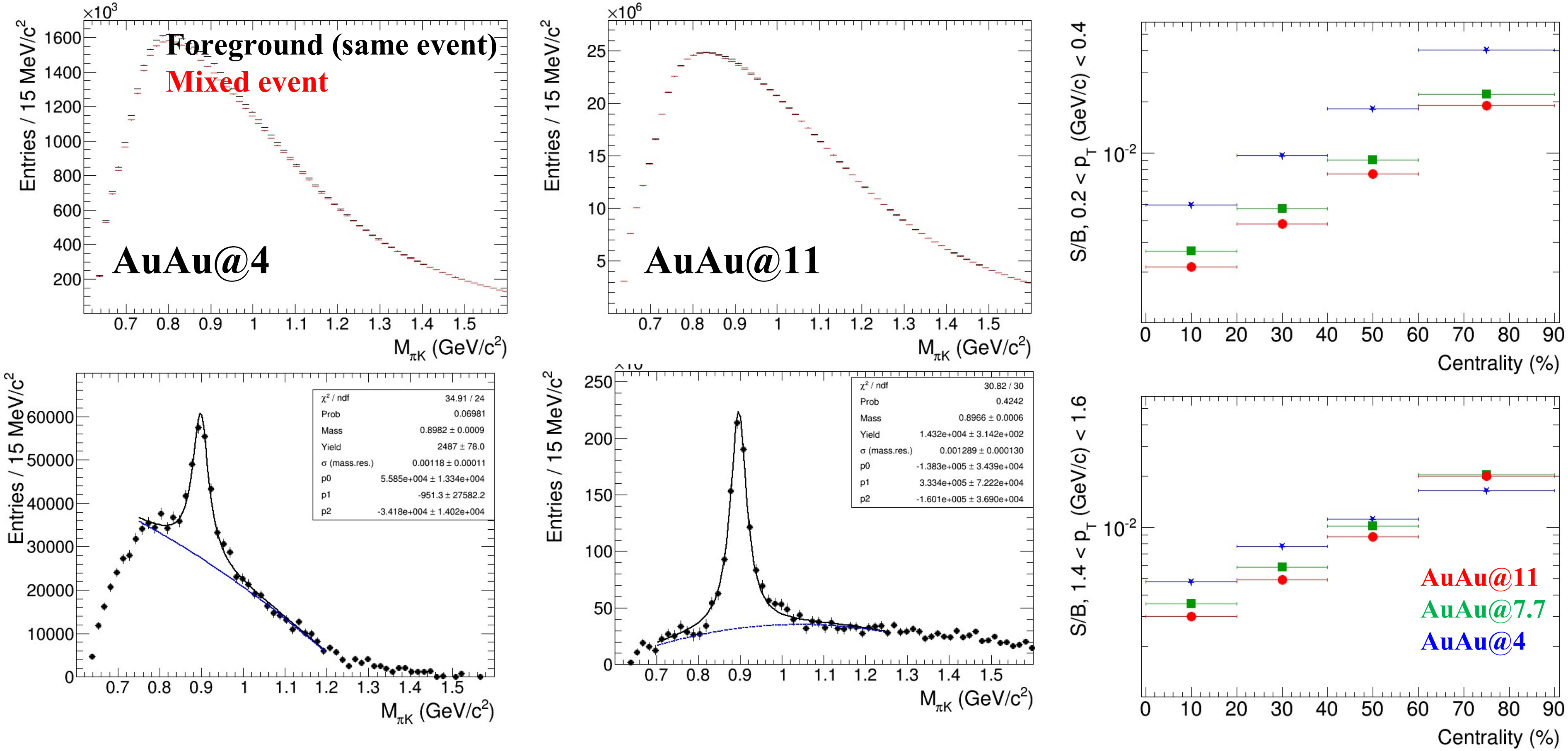
- UrQMD v.3.4: AuAu@11 (10M events), AuAu@7.7 (5M events), AuAu@4 (5M events);
- Full chain simulation and reconstruction, example for p_T = 0.2-0.4 GeV/c bin, |y| < 1;



- 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, example for p_T = 0.2-0.4 GeV/c bin, |y| < 1;



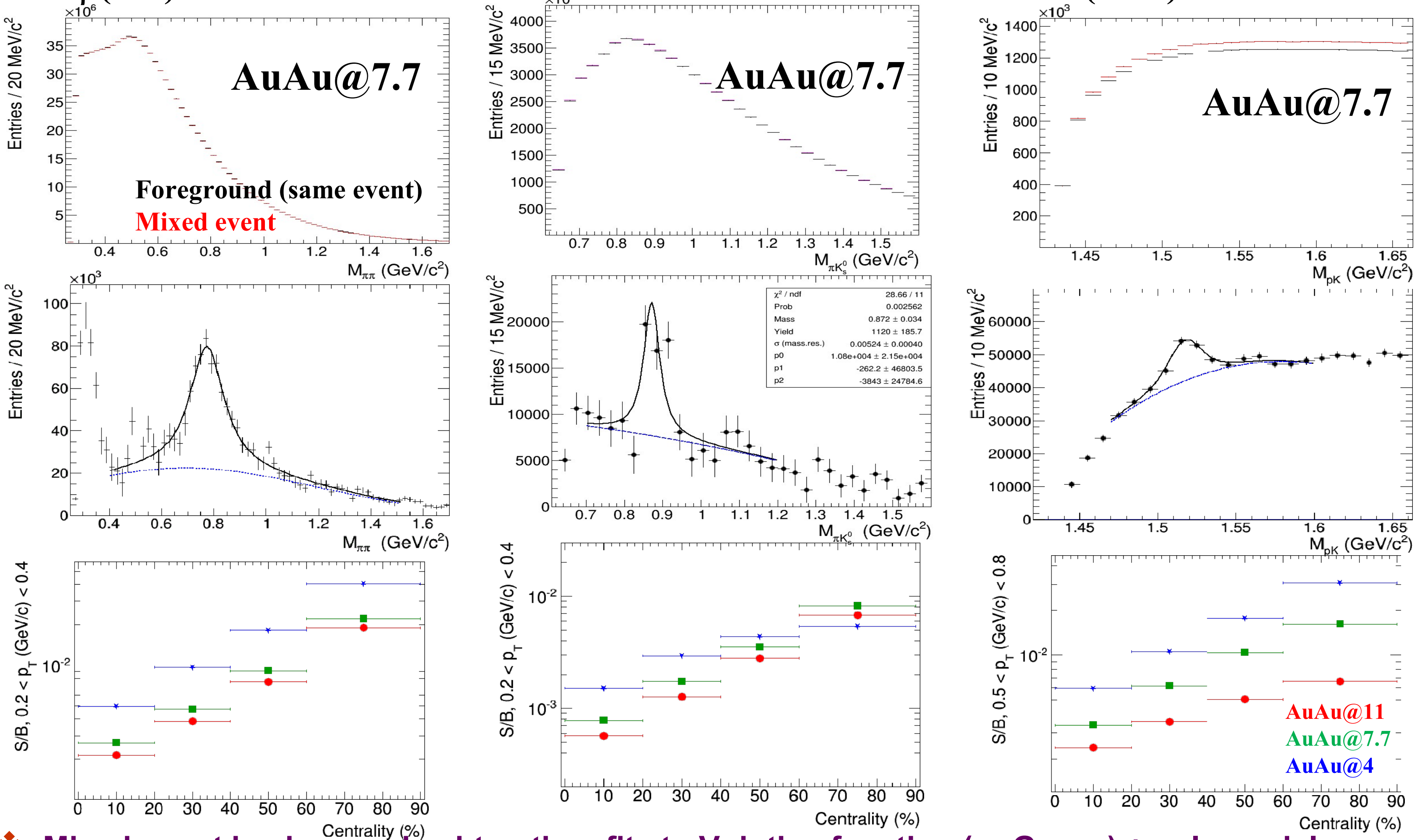
- Signal can be reconstructed from zero momentum, high-p_T reach is limited by statistics;
- S/B ratios deteriorates with increasing centrality and collision energy.

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

$\rho(770)^0$, $K^*(892)^\pm$ and $\Lambda(1520)$, reconstructed peaks

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

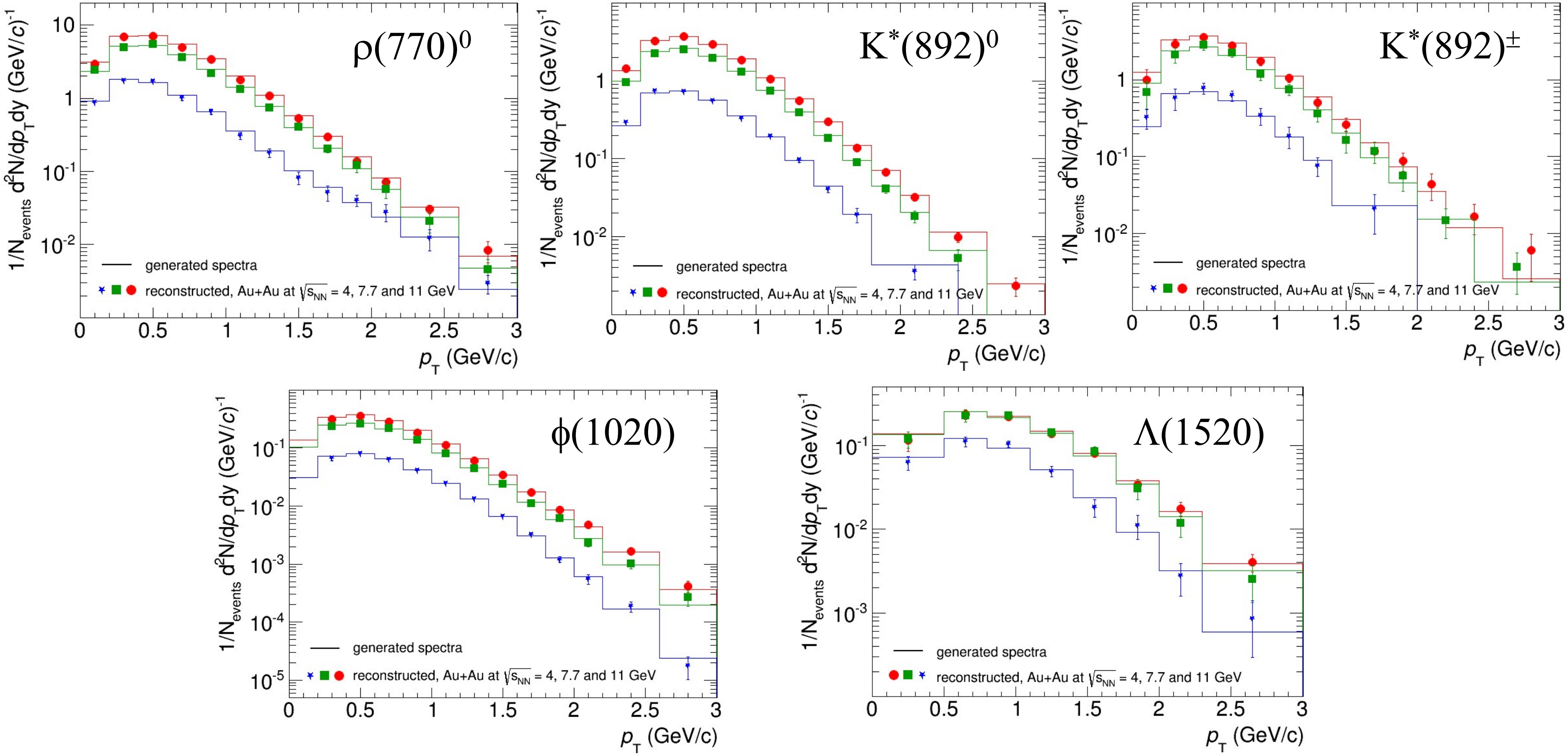
$\rho(770)^0$: 0.2-0.4 GeV/c $\quad$ $K^{*\pm}$: 0.2-0.4 GeV/c $\quad$ $\Lambda(1520)$: 0.5-0.8 GeV/c



- Mixed-event background subtraction, fits to Voigtian function (or Gauss) + polynomial;
- Contributions from K_s, ω, K^{*0}, f_0, f_2(for ρ) 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.

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

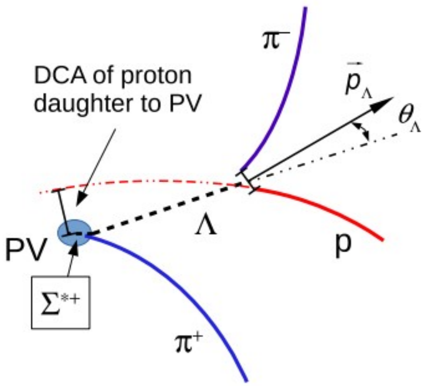
- UrQMD v.3.4: AuAu@11 (10M events), AuAu@7.7 (5M events), AuAu@4 (5M events);
- Full chain simul. and reconstr., p_T ranges are limited by the possibility to extract signals, |y| < 1.



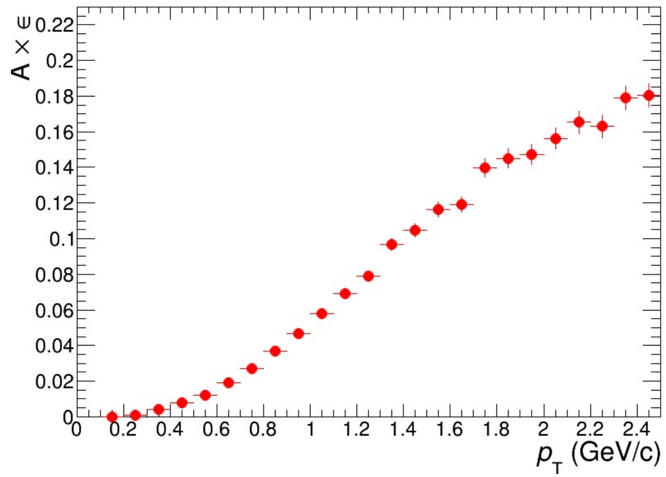
- Reconstructed spectra match the generated ones within uncertainties;
- Measurements are possible from ~ zero momentum, sample p_T spectra in a wide range;
- Maximum raw yields (smallest stat. uncertainties) are extracted at ~ 300 MeV/c.

More complex decays: $\Sigma(1385)^{\pm}$

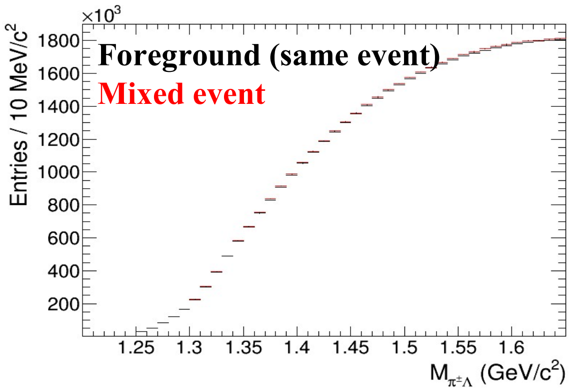
$\Sigma(1385)^{\pm} \rightarrow \pi^{\pm}\Lambda \ (\Lambda \rightarrow p\pi)$

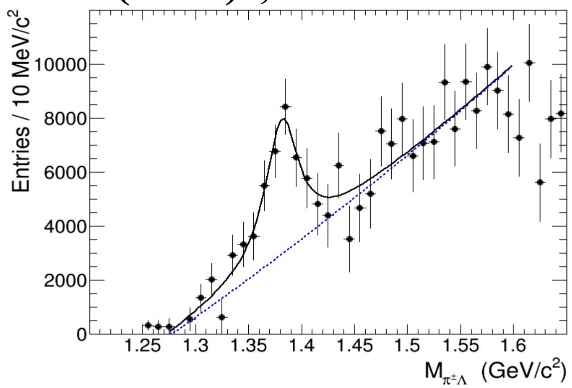


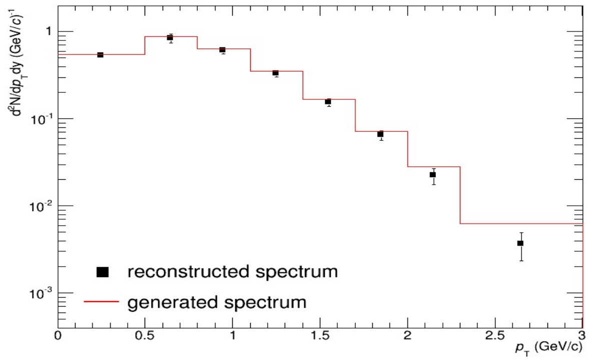
❖ **Reconstruction efficiencies, AuAu @ 11 GeV, |y| < 1**



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





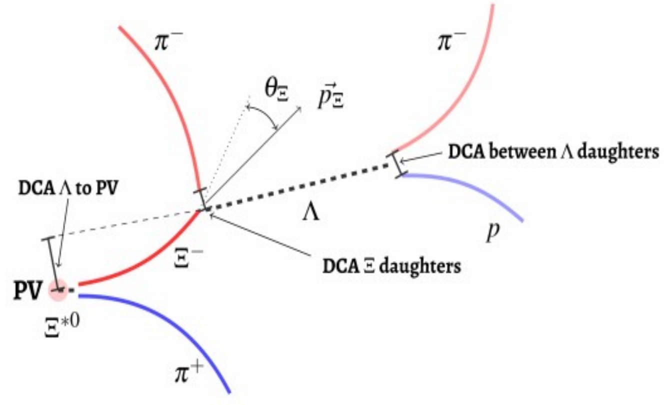


❖ **$\Sigma(1385)^{\pm}$ signal can be reconstructed starting from zero momentum, high-p_T reach is limited by statistics;**

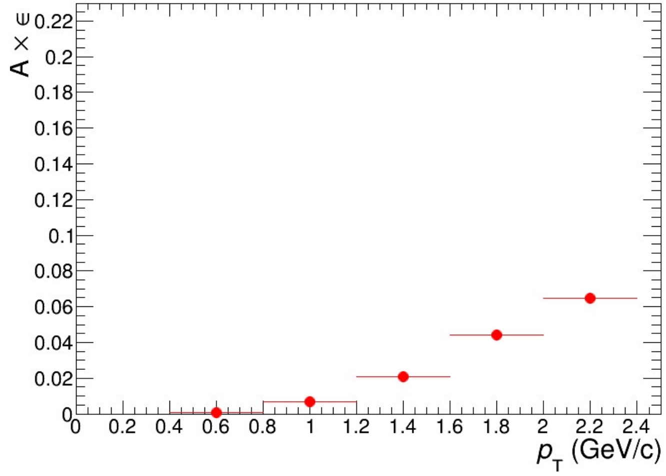
❖ **Monte Carlo closure test is passed;**

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

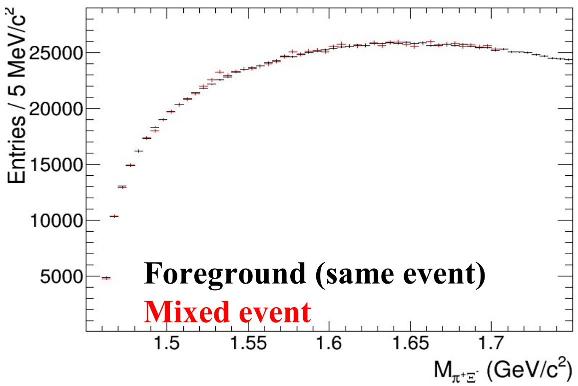
$\Xi(1530)^0 \to \pi^+\Xi^-$ ($\Xi^- \to \Lambda\pi^-$, ($\Lambda \to p\,\pi^-$))

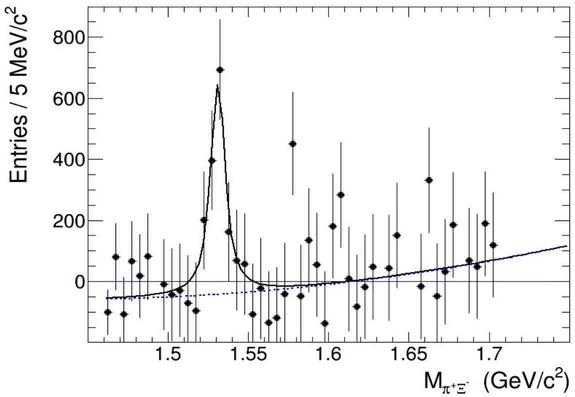


❖ **Reconstruction efficiencies, AuAu @ 11 GeV, |y| < 1**



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





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

Summary

- ✓ Measurement of resonances 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;
- ✓ 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 $\Xi(1520)^0$.
- ✓ Measurements of resonances is a plausible task for year-1 operation.

Backups