NICA Nuclotron-based Ion Collider fAcility

Production and reconstruction of the short-lived resonances at NICA-MPD

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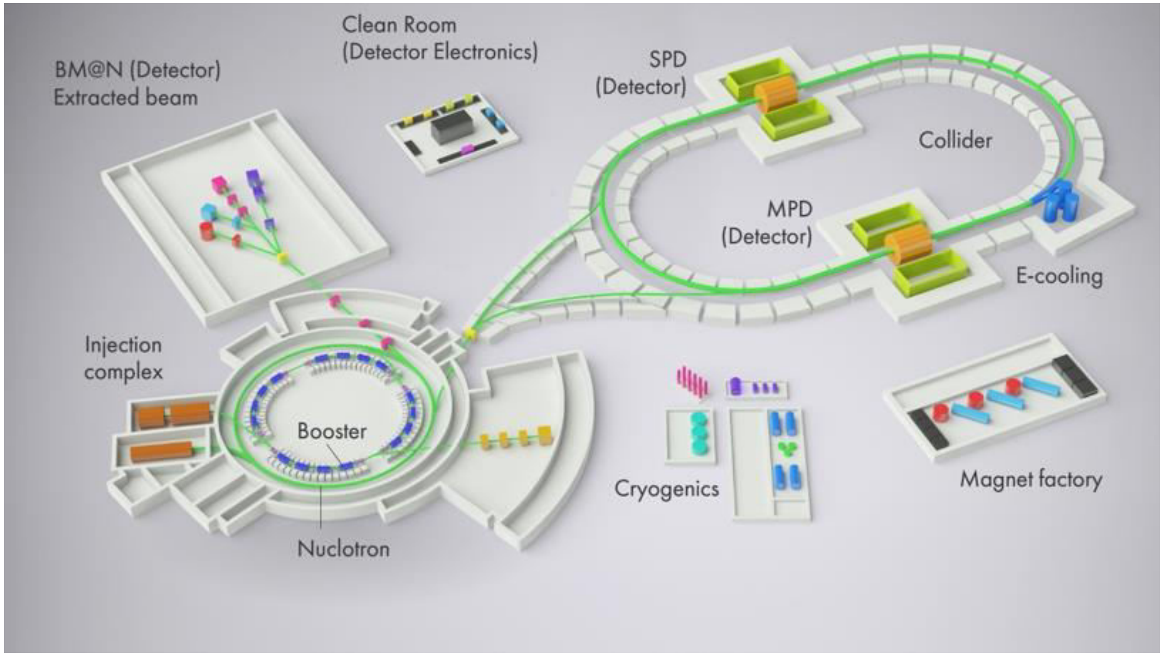


Outline

- Motivation for resonance studies in heavy-ion collisions
- Predictions for resonance properties in heavy-ion collisions at NICA energies
- Feasibility studies for resonance reconstruction at NICA-MPD
- Conclusions

Resonances in heavy-ion collisions

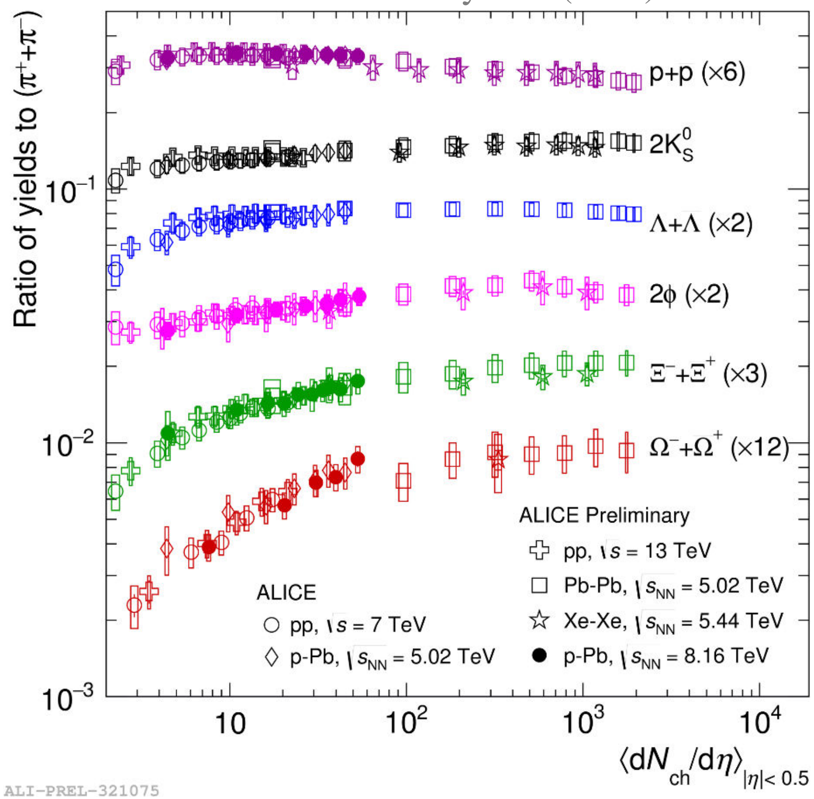
$\rho(770)$	$K^*(892)^0$	$K^*(892)^+$	$\phi(1020)$	$\Sigma(1385)^\pm$	$\Lambda(1520)$	$\Xi(1530)$
$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$d\bar{s}$	$u\bar{s}$	$s\bar{s}$	uus dds	uds	uss

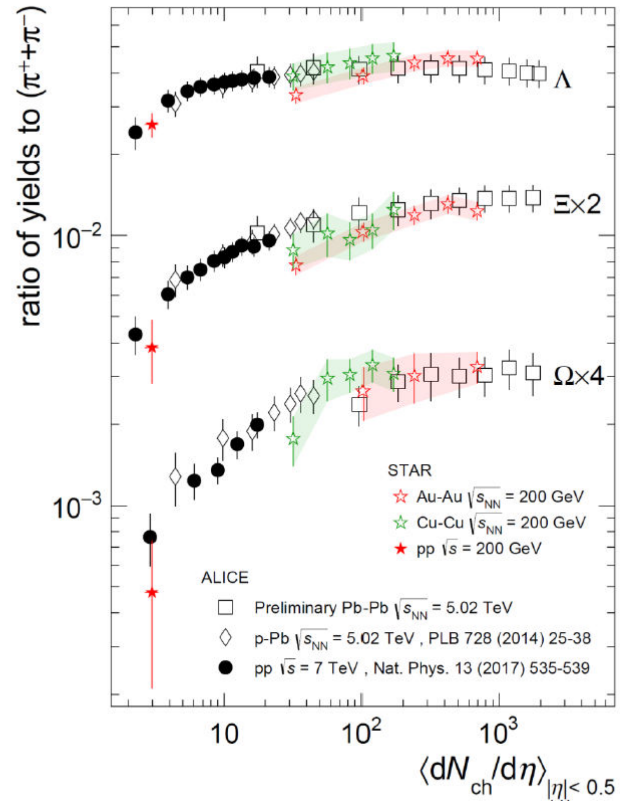
Particle	Mass (MeV/c^2)	Width (MeV/c^2)	Decay	BR (%)
ρ^0	770	150	$\pi^+\pi^-$	100
$K^{*\pm}$	892	50.3	$\pi^\pm K_s$	33.3
K^{*0}	896	47.3	$\pi^- K^+$	66.7
ϕ	1019	4.27	K^+K^-	48.9
Σ^{*+}	1383	36	$\pi^+\Lambda$	87
Σ^{*-}	1387	39.4	$\pi^-\Lambda$	87
$\Lambda(1520)$	1520	15.7	K^-p	22.5
Ξ^{*0}	1532	9.1	$\pi^+\Xi^-$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

- 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
  - ✓ reaction dynamics and particle p_T spectra
  - ✓ lifetime and properties of the hadronic phase
  - ✓ …
  - ✓ flow, comparison with e^+e^- measurements, jet quenching, background for other analyses, etc.

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 for ground-state hadrons and resonances (ϕ/π, Σ^*/π, Ξ^*/π)
- Origin of the strangeness enhancement in small/large systems is still debated
- 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

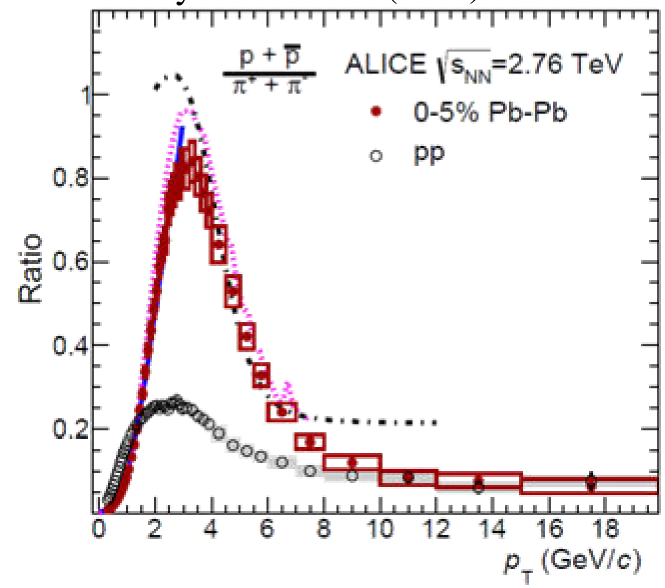
- Baryon puzzle - increased baryon-to-meson (p/π, Λ/K_s^0 , Λ_c^+/D) ratios in heavy-ion collisions at RHIC and the LHC

- Driving force of enhancement is not yet fully understood:
  - ✓ particle mass (hydrodynamic flow)?
  - ✓ quark count (baryons vs. mesons)?

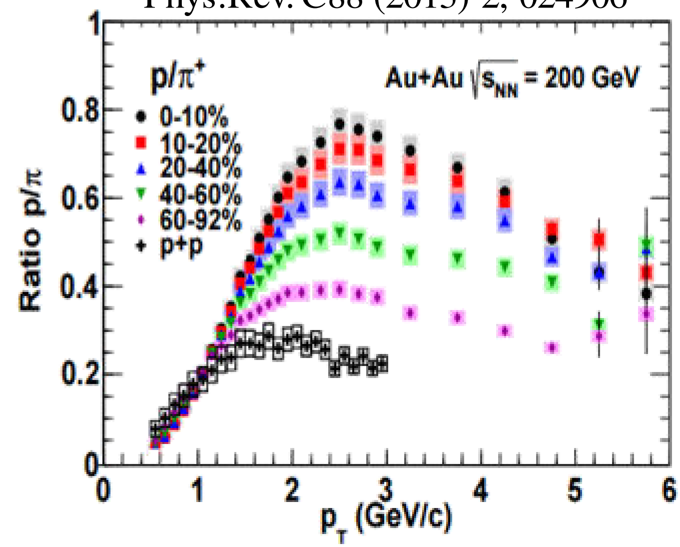
- ϕ and K^{*0} are well suited for tests as mesons with masses very close to that of a proton:

✓ Δm_ϕ~ 80 MeV/c^2, Δm_{K*0}~ -45 MeV/c^2

Phys.Lett. B736 (2014) 196-207



Phys.Rev. C88 (2013) 2, 024906



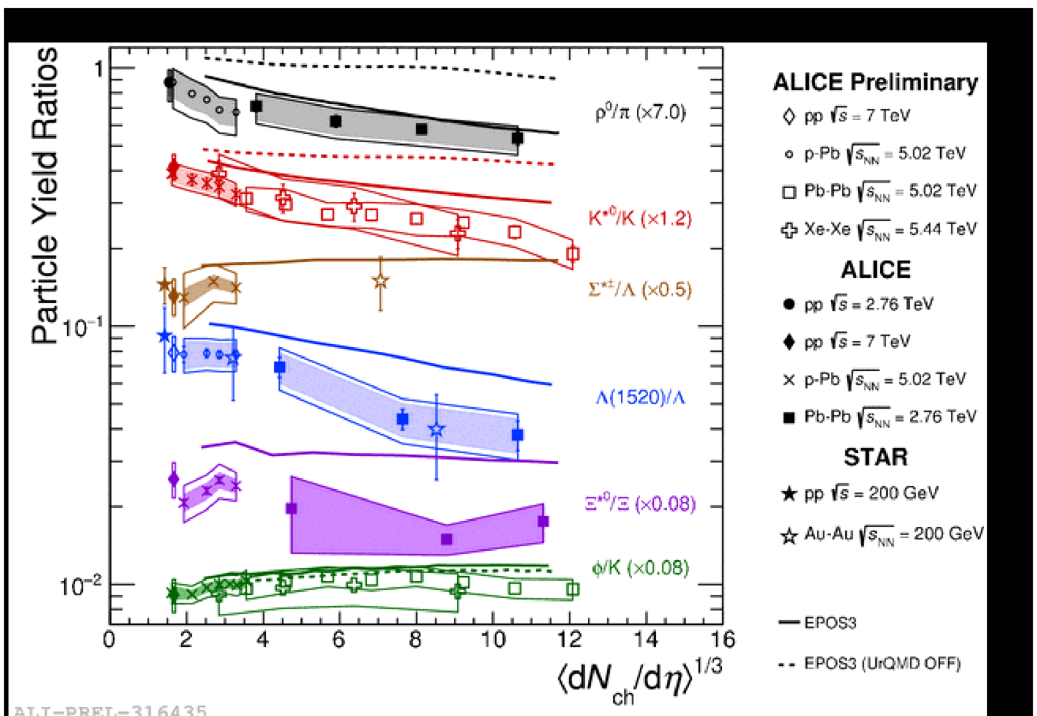
Hadronic phase and medium modifications

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
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

- 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

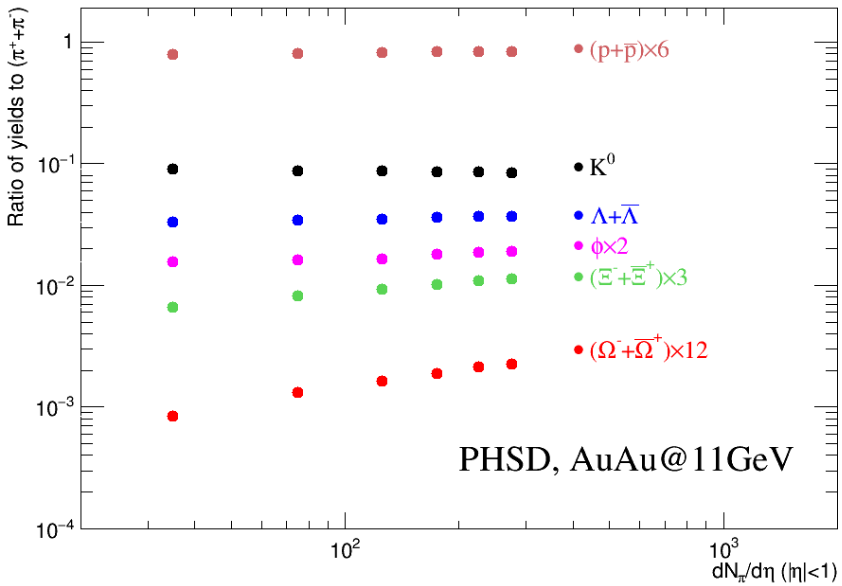


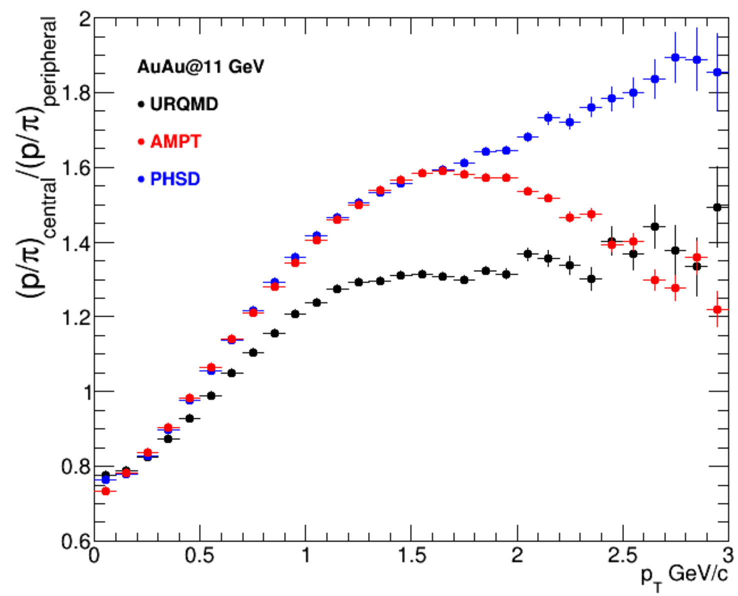
- SPS/RHIC/LHC results for resonance yields support the existence of a hadronic phase that lives long enough to cause a significant reduction of the reconstructed yields of short lived resonances
- Lower limit for the lifetime of the hadronic phase, τ > 2 fm/c*

* G. Torrieri and J. Rafelski, J. Phys. G 28, 1911 (2002); C. Markert et al., arXiv:hep-ph/0206260v2 (2002)

Model predictions for resonances at NICA

- UrQMD, PHSD, PLUTO, 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.

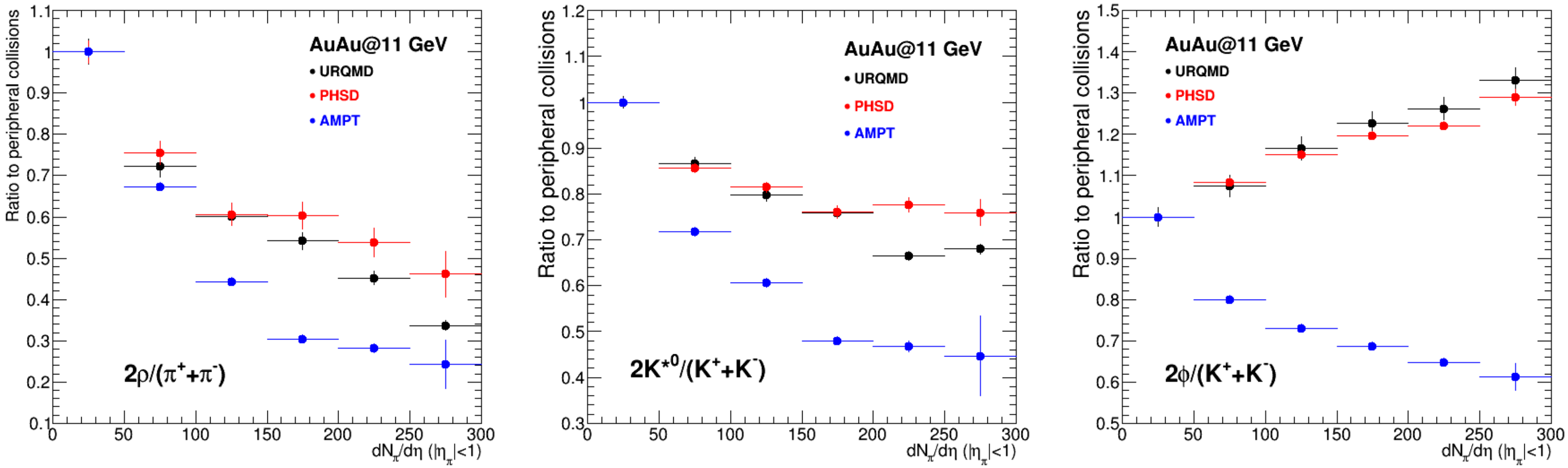




- Eventually, model predictions (integrated yields, <p_T>, particle ratios etc.) should be compared to data to differentiate different model assumptions

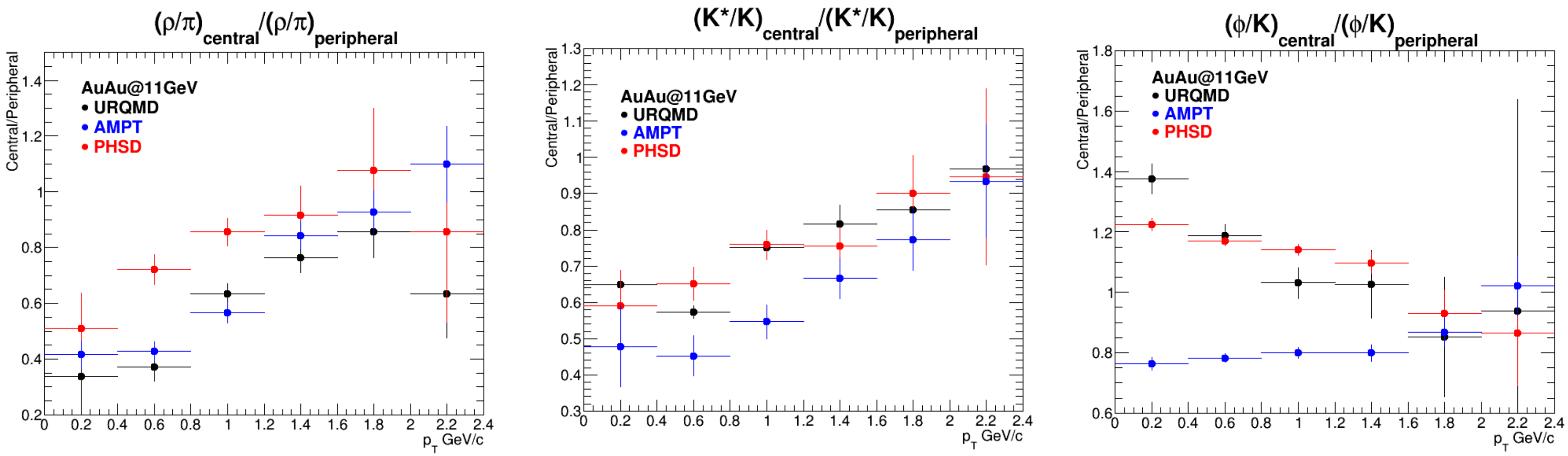
Hadronic phase and particle ratios

- Models with hadronic cascades (UrQMD, PHSD, AMPT) → properties of hadronic phase
- Models predict centrality dependent ρ/π, K^*/K, Λ*/Λ and ϕ/K ratios in AuAu@11
- Ratios are suppressed going from peripheral to central collisions for resonances with small cτ
- Results are qualitatively similar to those obtained at SPS/RHIC/LHC



Hadronic phase and particle ratios

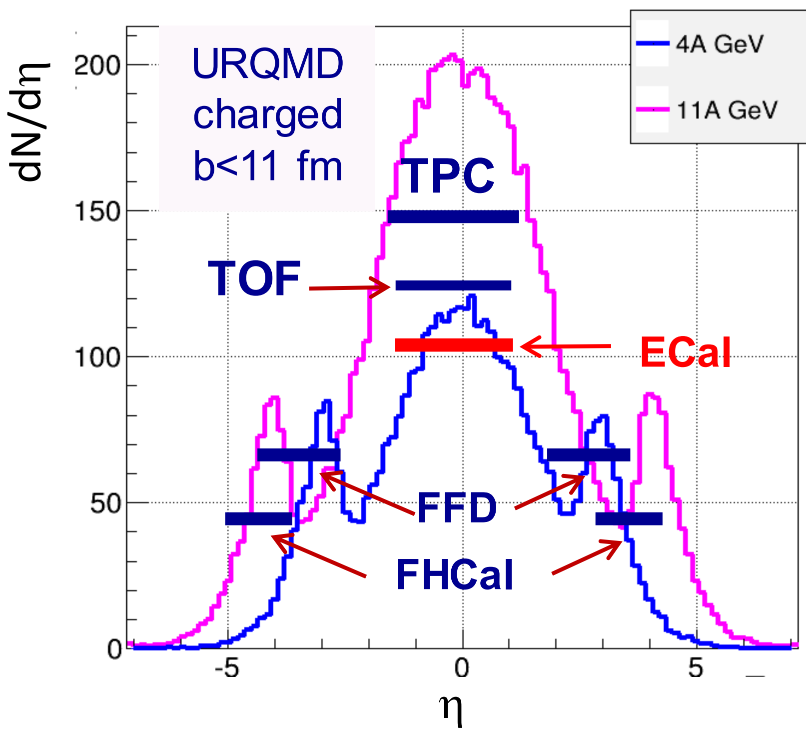
- Modifications occur at low momentum as expected for hadronic phase effects

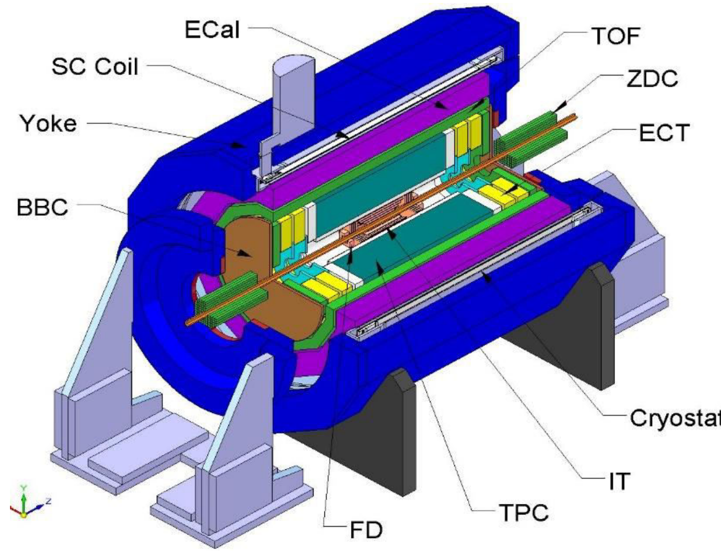


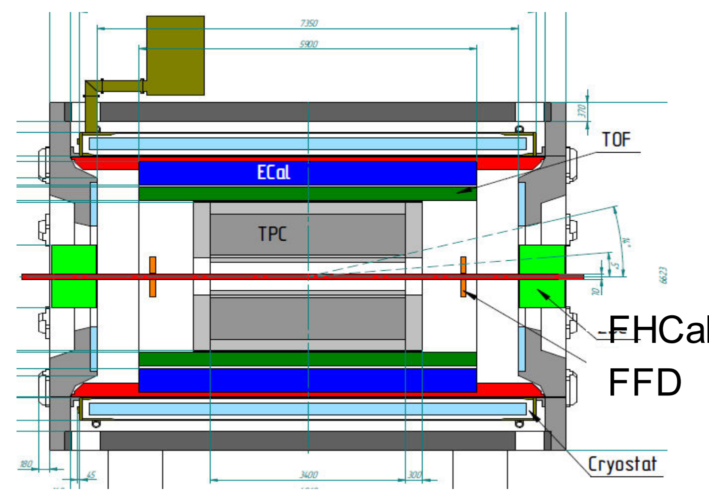
- Models predict yield modifications for resonances qualitatively similar to those observed at higher collision energies:
  - ✓ lifetime and density of the hadronic phase are high enough
  - ✓ modification of particle properties in the hadronic phase should be taken into account when model predictions for different observables are compared to data
  - ✓ resonances can be used as a tool to tune hadronic phase simulations

MPD experiment, Phase 1

- Phase 1: **TPC, TOF, FFD, FCAL и ECAL**
- Detector is ideologically and constructively close to STAR and ALICE
- Startup in 2021-2022







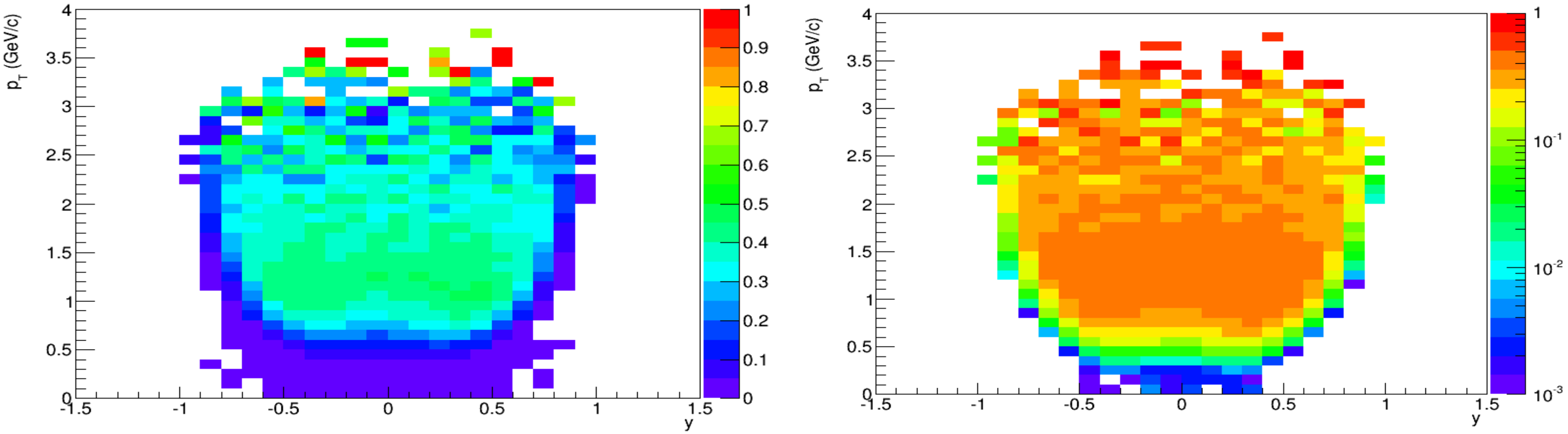
Feasibility studies, framework

- Simulated minbias AuAu@11 collisions using UrQMD 3.4 with default settings
- Tracked simulated particles through the MPD Phase-I detector using *mpdroot*
- Analysis cuts were optimized for higher signal significance (no p_T variation)

  - Event selection:
    - ✓ $|Z_{vrtx}| < 50$ cm, realistic distribution
  - Basic track selections:
    - ✓ number of TPC hits > 24
    - ✓ $|\eta| < 1.0$
    - ✓ $p_T > 50$ MeV/c
    - ✓ TPC-TOF combined PID, probability > 0.5 (*mpdpid* class by A. Mudrokh)
    - ✓ TPC-refit for kaons and protons based on track PID hypothesis
  - Primary tracks:
    - ✓ $|DCA(x,y,z)| < 2\sigma$
  - V0 & cascades:
    - ✓ topology cuts for weakly decaying secondary particles ($K_s \rightarrow \pi\pi$, $\Lambda \rightarrow p\pi$, $\Xi \rightarrow \Lambda\pi$)

- Combinatorial background:
  - ✓ event mixing ($|\Delta_{Zvrtx}| < 2$ cm, $|\Delta_{Mult}| < 20$, $N_{ev} = 10$)

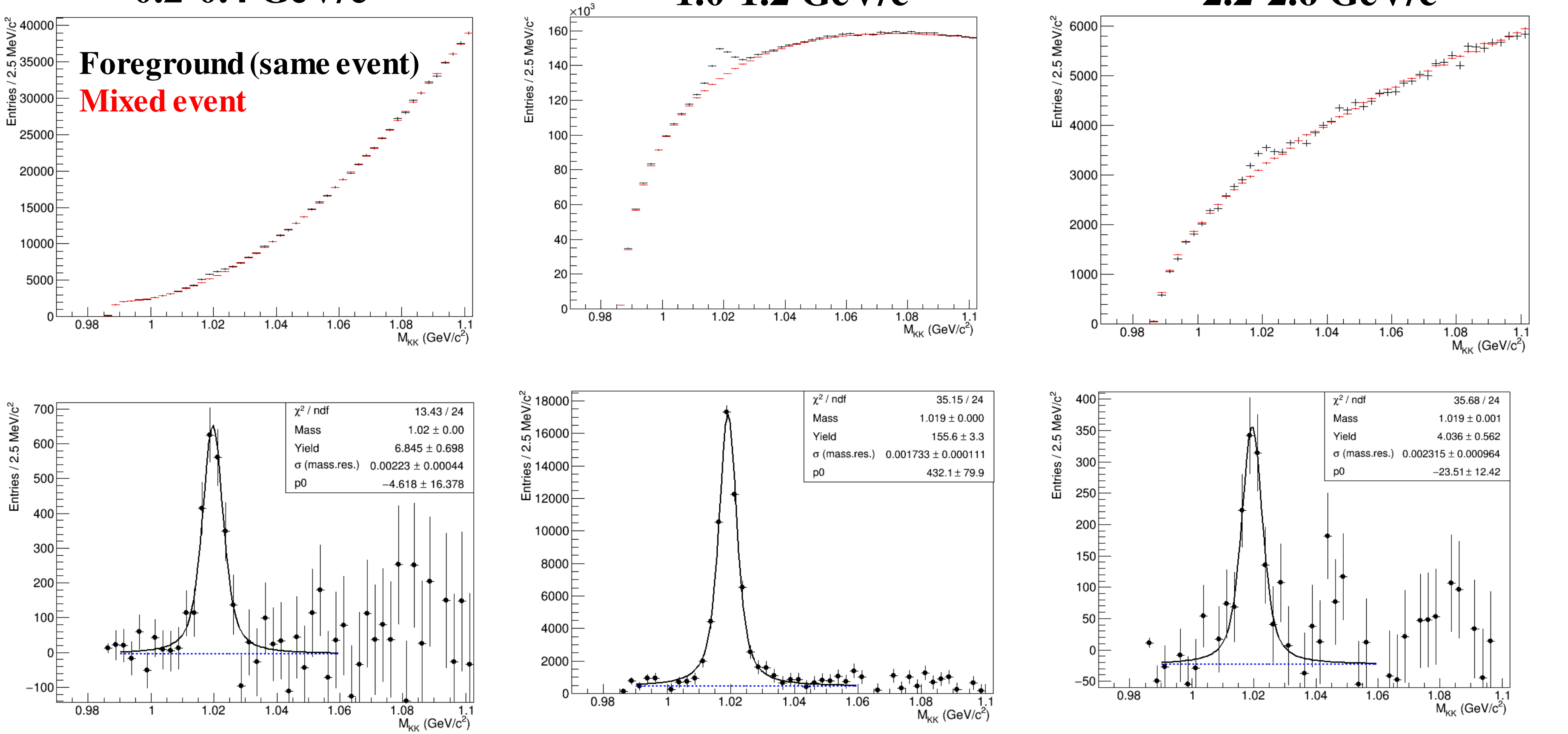
Feasibility study, $\phi(1020)$



- $\phi(1020) \rightarrow K^+K^-$, BR = 48.9 %
- Acceptance x reconstruction efficiency: $A \cdot \in = N_{rec}(\phi \rightarrow K^+K^-) / N_{gen}(\phi \rightarrow K^+K^-)$
- Efficiency grows with transverse momentum, nearly zero at p_T < 200 MeV/c
- Particles can be reconstructed in the rapidity range, $|y| < 1.0$

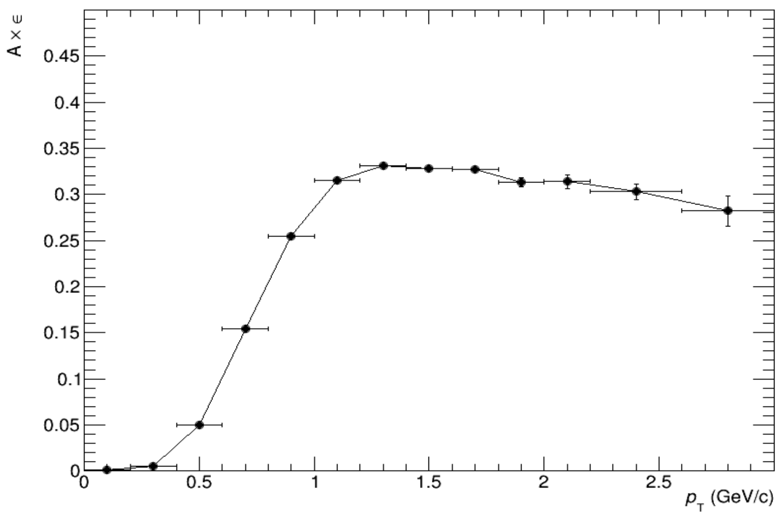
φ(1020), reconstructed peaks

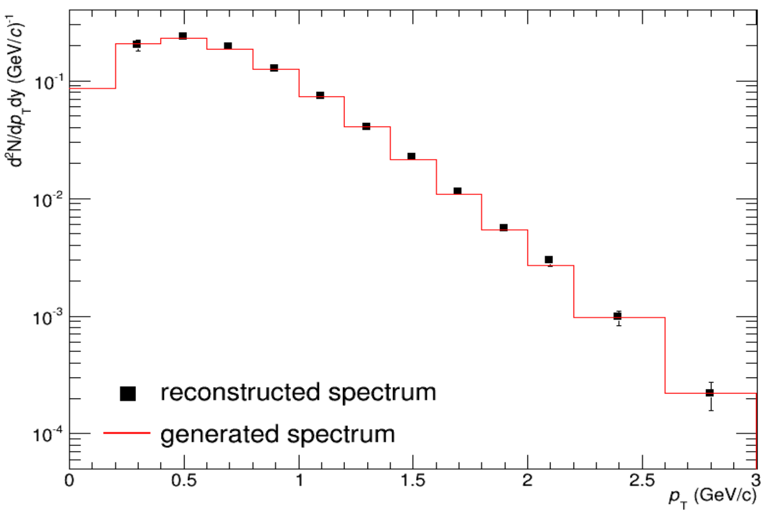
0.2-0.4 GeV/c | 1.0-1.2 GeV/c | 2.2-2.6 GeV/c



- 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

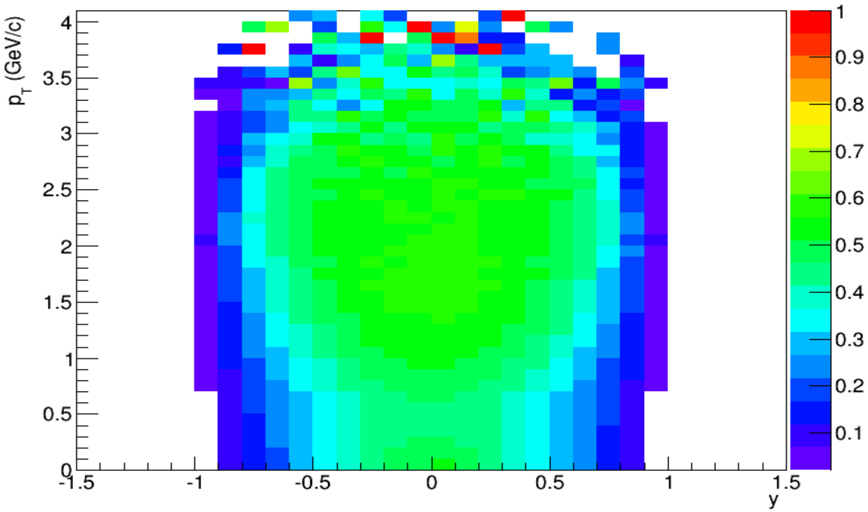
$\phi(1020)$, reconstruction

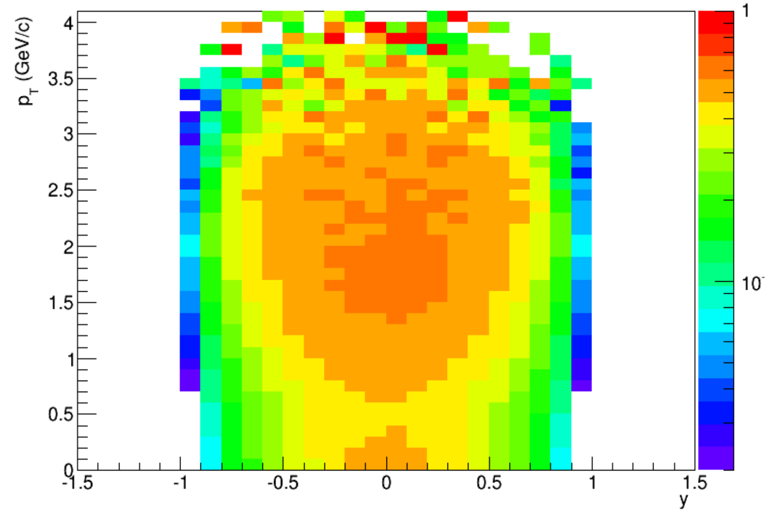




- Monte Carlo Closure Test
- Full chain reconstruction at $|y| < 1.0$
- Reconstructed spectrum matches the generated one within uncertainties
- Measurements are possible at $p_T > 0.2$ GeV/c, 90% of the total yield

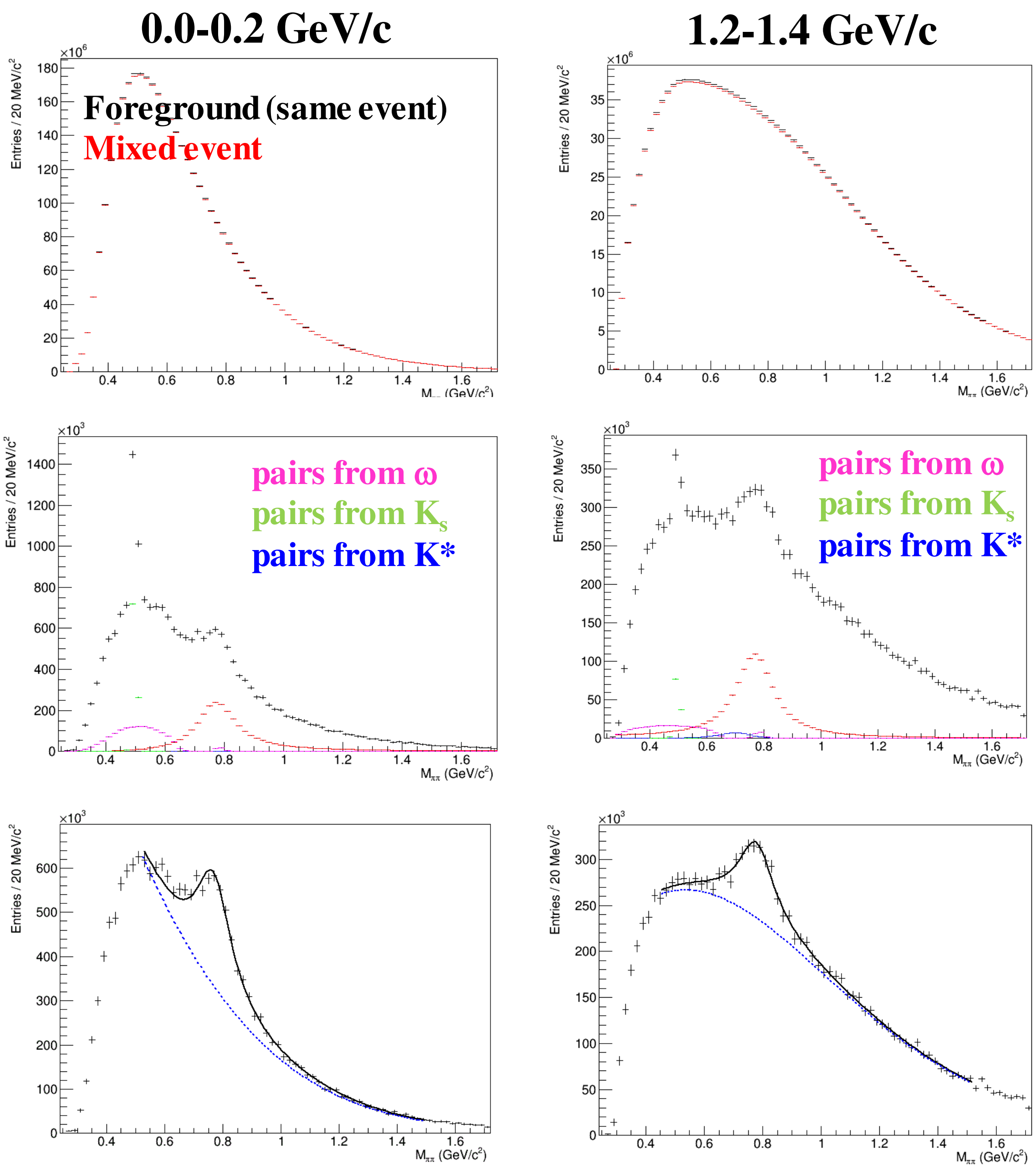
Feasibility study, $\rho(770)^0$





- $\rho(770)^0 \rightarrow \pi^+ \pi^-$, BR ~ 100 %
- Acceptance x reconstruction efficiency: $A\cdot\in = N_{rec}(\rho \rightarrow \pi^+ \pi^-) / N_{gen}(\rho \rightarrow \pi^+ \pi^-)$
- Efficiency grows with transverse momentum
- Particles can be reconstructed in the rapidity range, $|y| < 1.0$

ρ(770), reconstructed peaks



- 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
- Distribution is fit to BW function + pol2, mass resolution is of no importance
- Signal can be reconstructed from zero momentum
- High-p_T reach is limited by available statistics

ρ(770), signal extraction – practice tests

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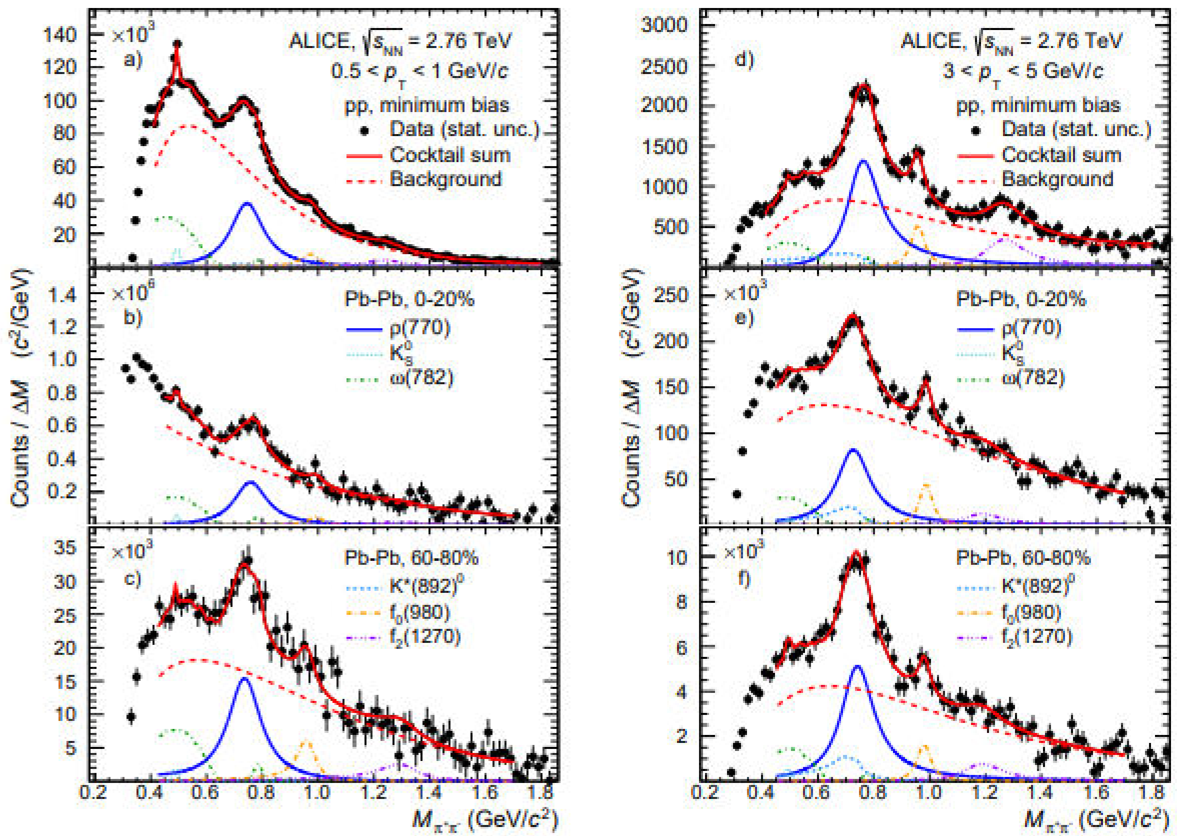
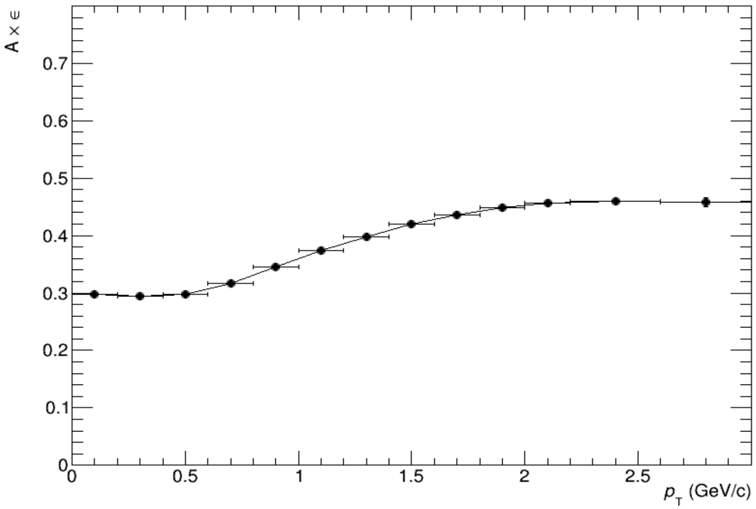
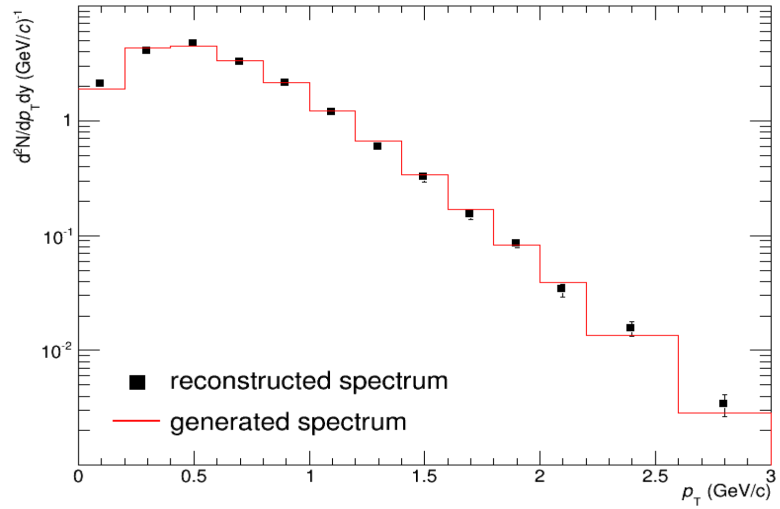


Fig. 1: (Color online) Invariant mass distributions for $\pi^+\pi^-$ pairs after subtraction of the like-sign background. Plots on the left and right are for the low and high transverse momentum intervals, respectively. Examples are shown for minimum bias pp, 0–20% and 60–80% central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. Solid red curves represent fits to the function described in the text. Colored dashed curves represent different components of the fit function, which includes a smooth remaining background as well as contributions from K^0_S, ρ^0, $\omega(782)$, $K^*(892)^0$, $f_0(980)$ and $f_2(1270)$. See text for details.

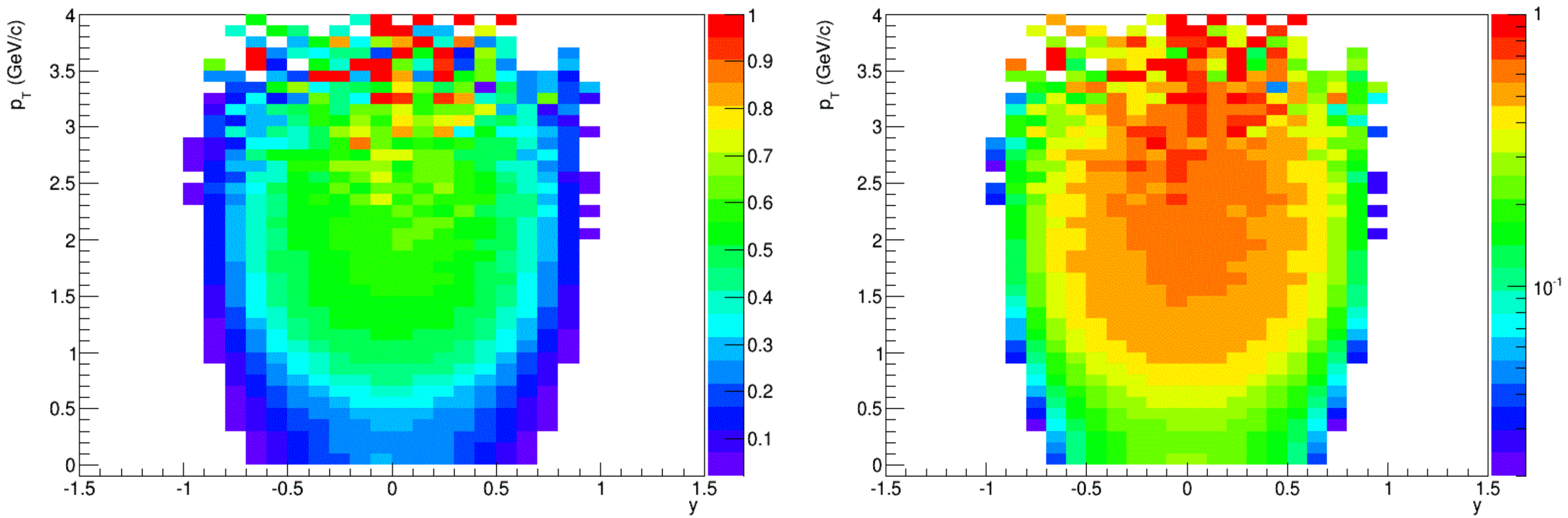
ρ(770), reconstruction





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

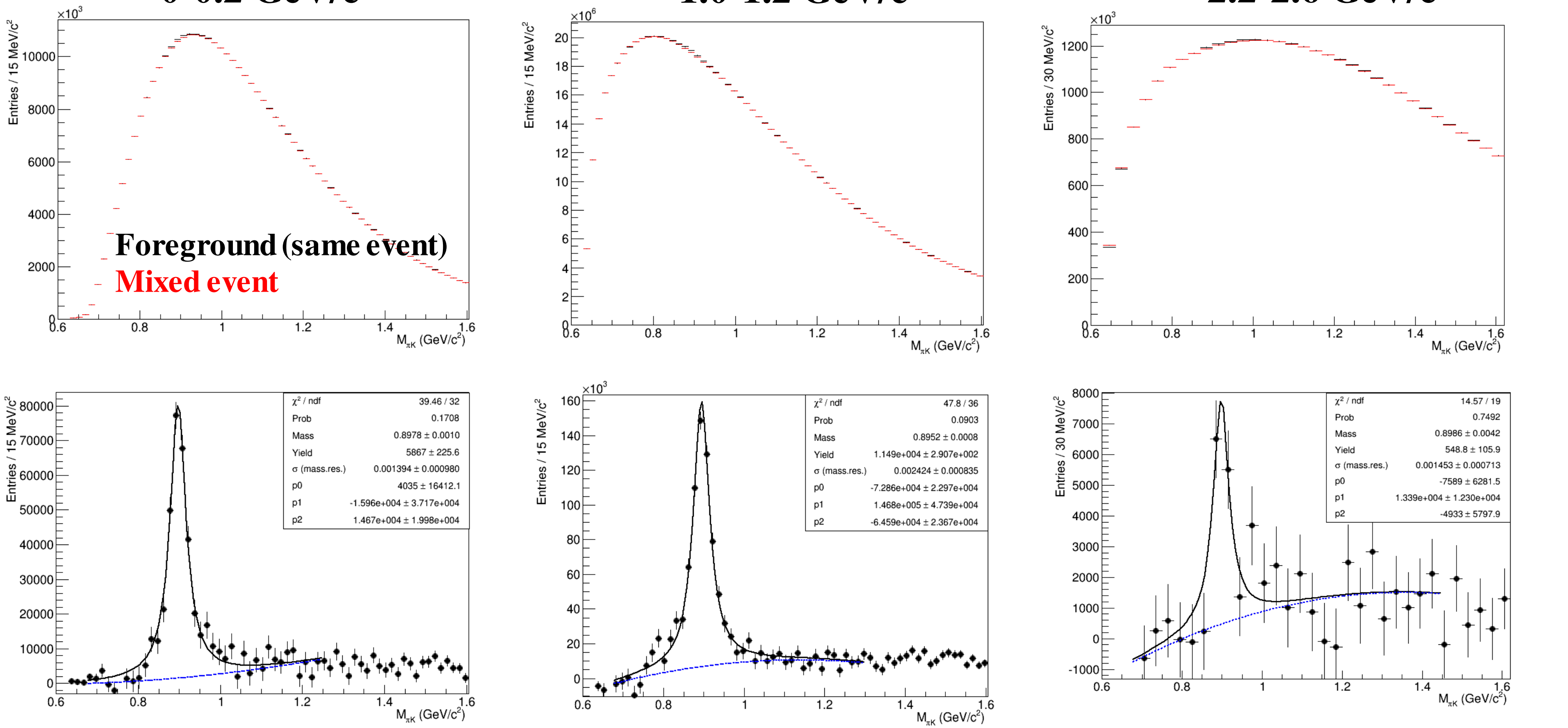
Feasibility study, $K^{*}(892)^{0}$



- $K^{*}(892)^{0} \rightarrow \pi^{\pm}K^{\pm}$, BR = 66.7 %
- Acceptance x reconstruction efficiency: $A\cdot\epsilon = N_{rec}(K^{*}\rightarrow\pi K) / N_{gen}(K^{*}\rightarrow\pi K)$
- Efficiency grows with transverse momentum
- Particles can be reconstructed in the rapidity range, $|y| < 1.0$

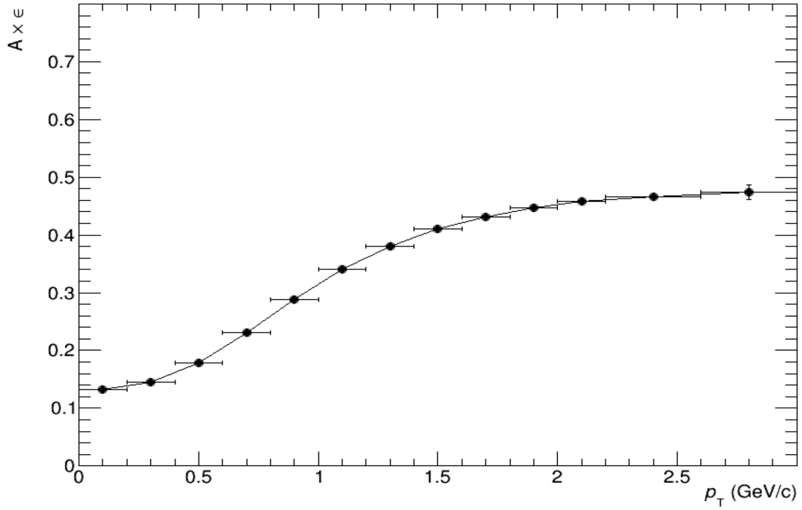
$K^{*}(892)^{0}$, reconstructed peaks

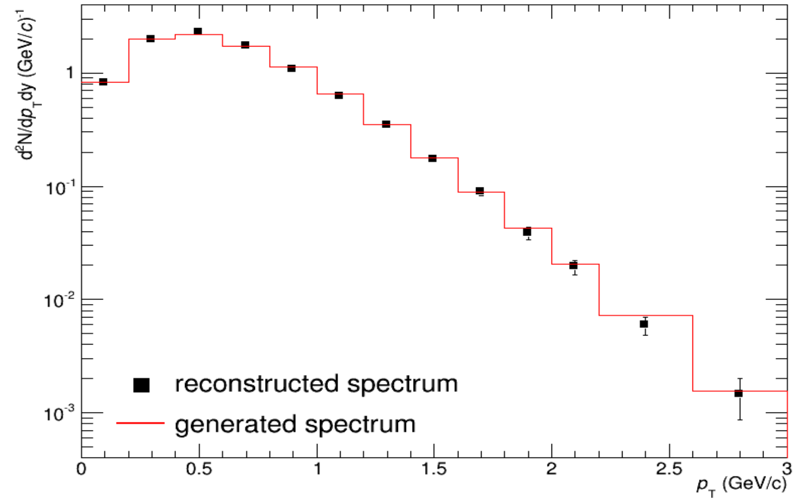
0-0.2 GeV/c | **1.0-1.2 GeV/c** | **2.2-2.6 GeV/c**



- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Fit to Voigtian + pol2 (p0-p2)
- Signal can be reconstructed from zero momentum
- High-p_T reach is limited by available statistics

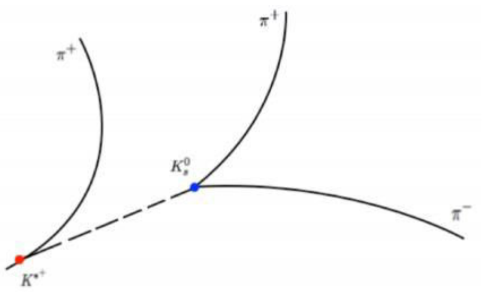
$K^{*}(892)^{0}$, reconstruction

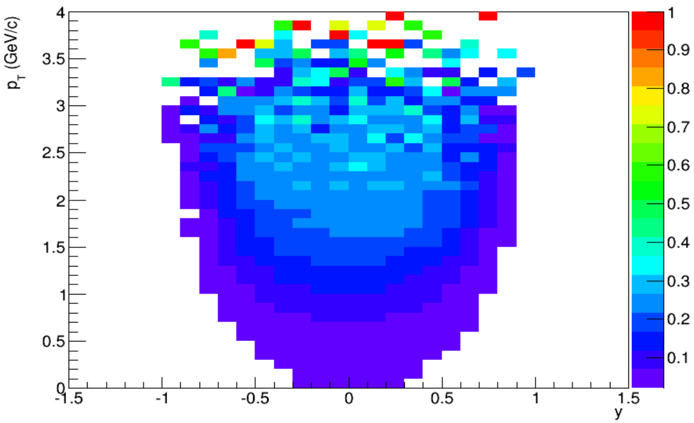


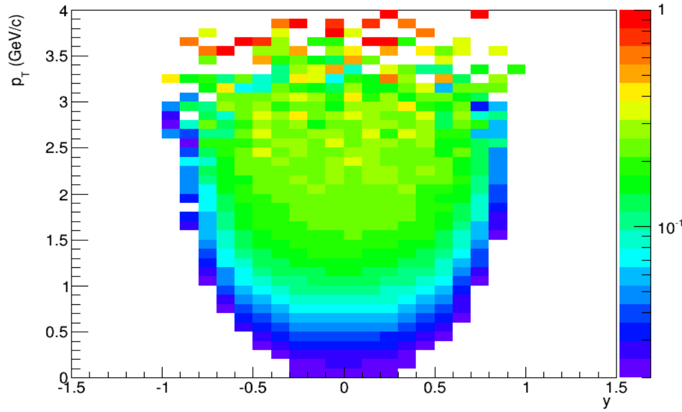


- Monte Carlo Closure Test
- Full chain reconstruction at $|y| < 1.0$
- Reconstructed spectrum matches the generated one within uncertainties
- Measurements are possible at $p_T > 0$ GeV/c

Feasibility study, $K^{*}(892)^{\pm}$

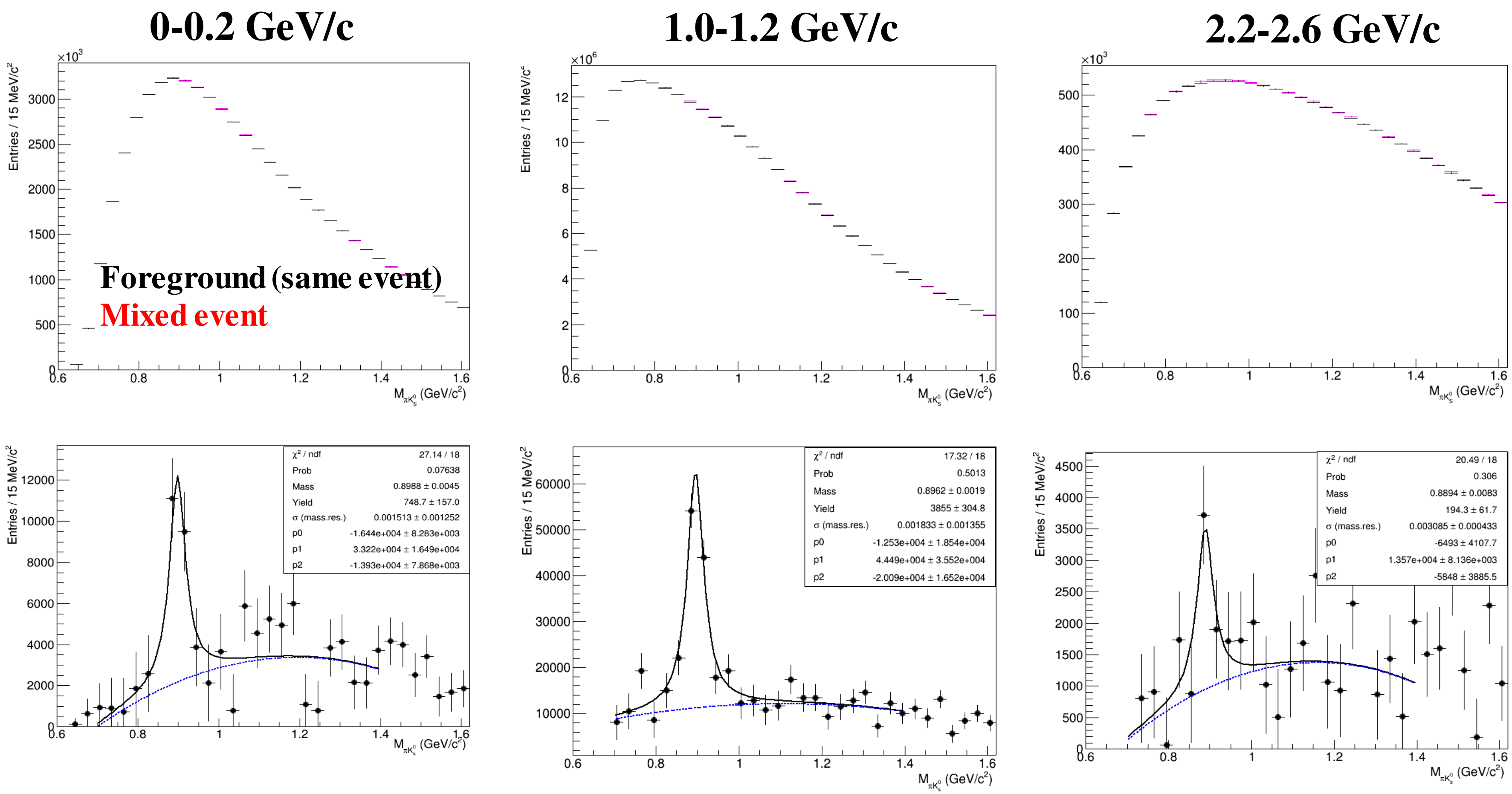






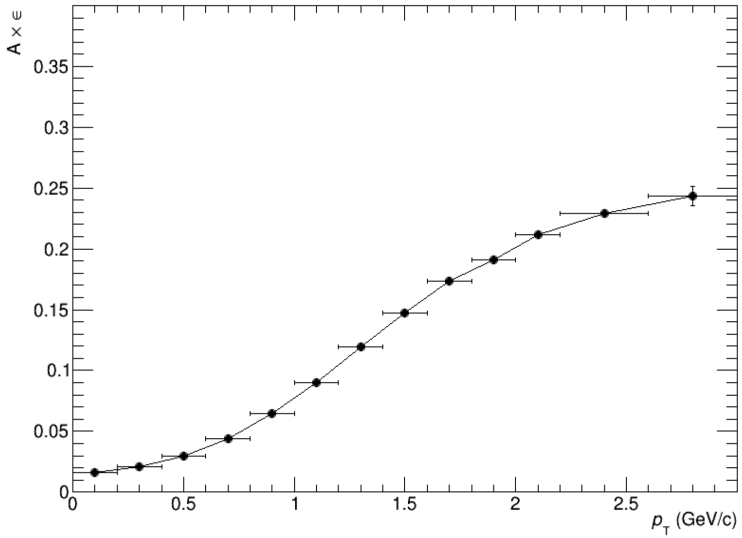
- $K^{*}(892)^{\pm} \rightarrow \pi^{\pm}K_s$ ($K_s \rightarrow \pi^{+}\pi^{-}$)
- Decay chain includes weak decay of K_s → V0 vertex
- Acceptance x reconstruction efficiency: $A \cdot \in = N_{rec}(K^{*} \rightarrow \pi K_s) / N_{gen}(K^{*} \rightarrow \pi K_s)$
- Efficiency is lower, increases with transverse momentum
- Particles can be reconstructed in the rapidity range, $|y| < 1.0$

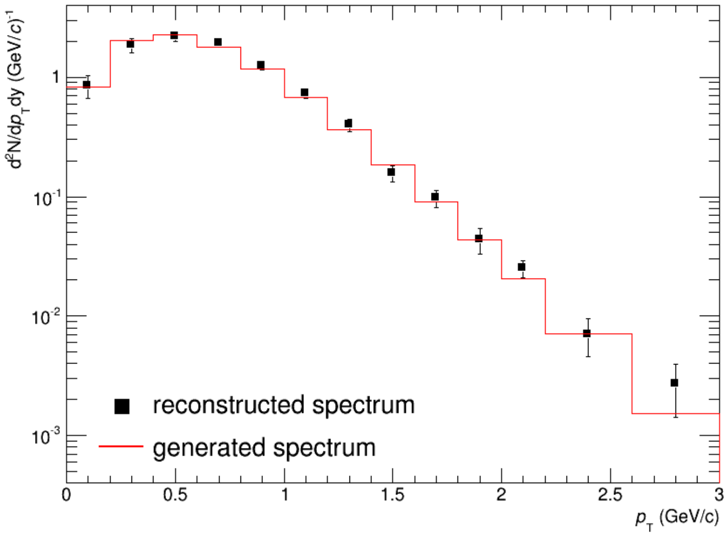
$K^{*}(892)^{\pm}$, reconstructed peaks



- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- K^{*} peak is fit to Voigtian + pol2 (p0-p2)
- Signal can be reconstructed starting from zero momentum
- High-p_T reach is limited by available statistics

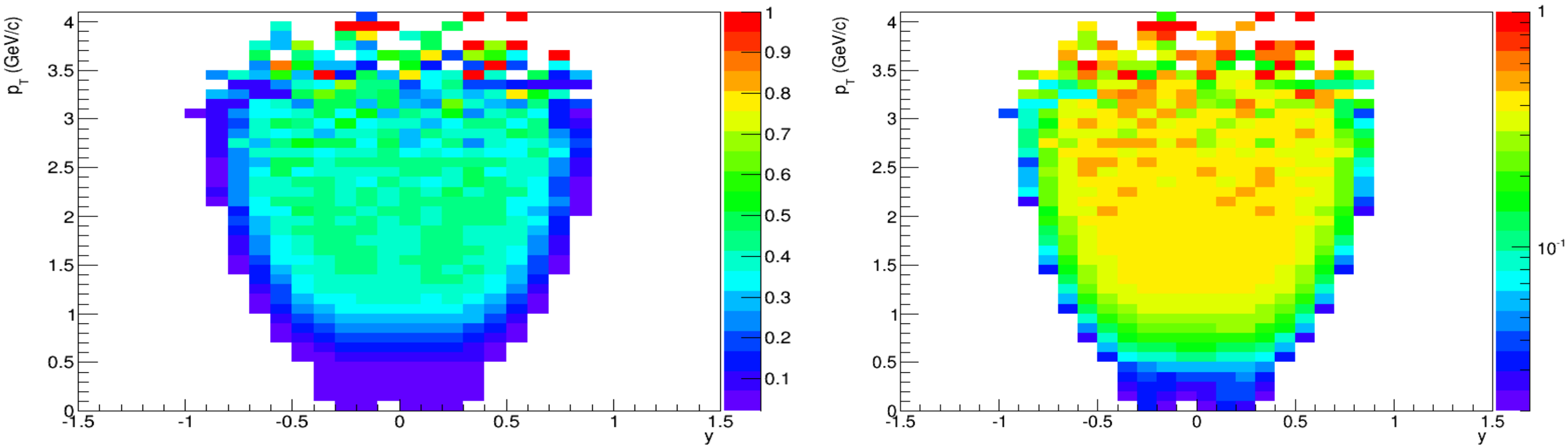
$K^*(892)^{\pm}$, reconstruction





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

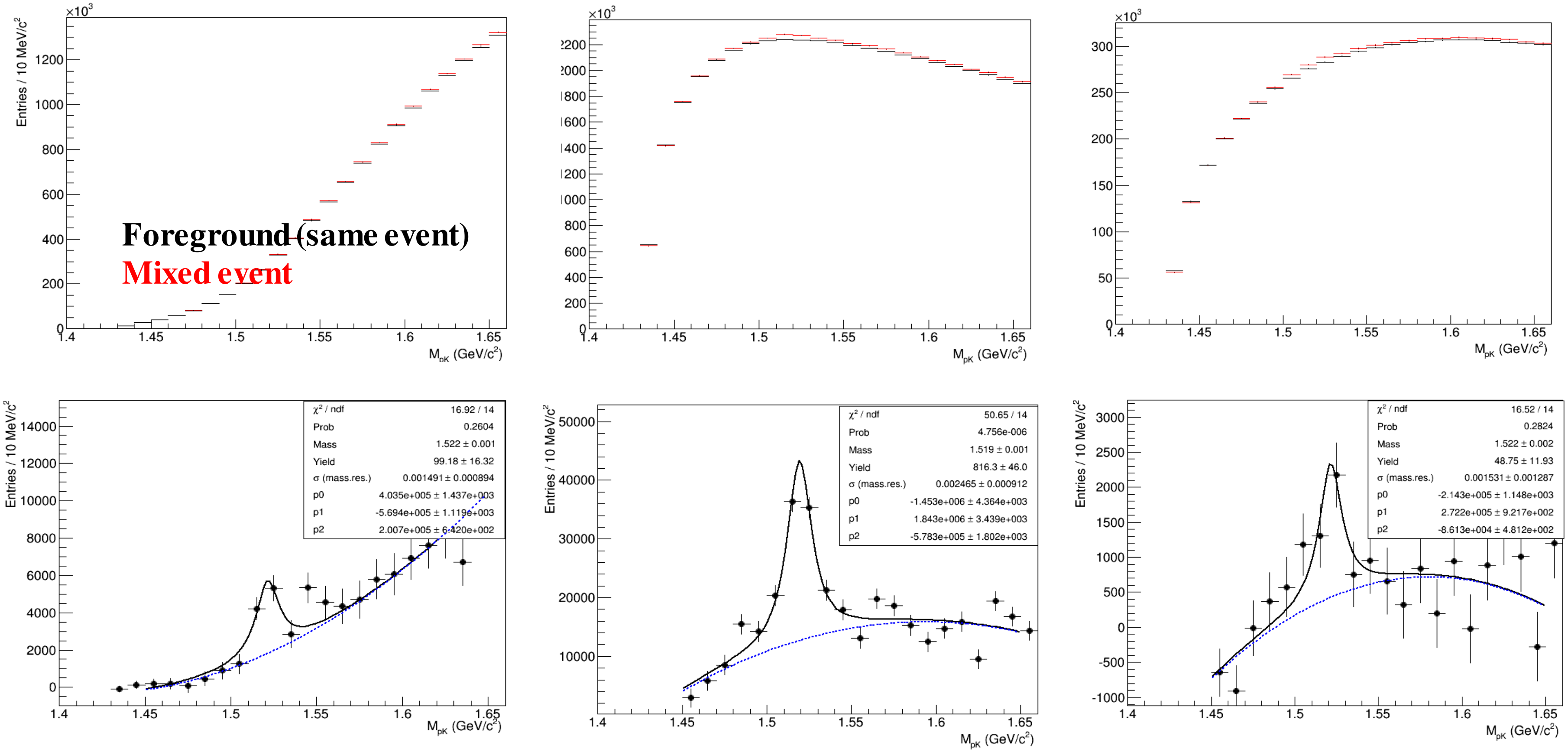
Feasibility study, Λ(1520)



- $\Lambda(1520) \rightarrow pK^-$
- Acceptance x reconstruction efficiency: $A \cdot \in \, = N_{rec}(\Lambda^* \rightarrow pK^-) \, / \, N_{gen}(\Lambda^* \rightarrow pK^-)$
- Efficiency increases with transverse momentum
- Particles can be reconstructed in the rapidity range, $|y| < 1.0$

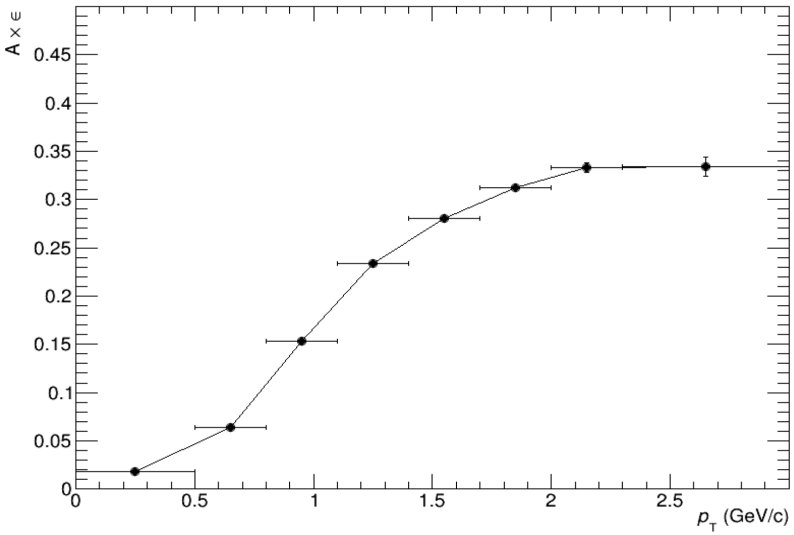
Λ(1520), reconstructed peaks

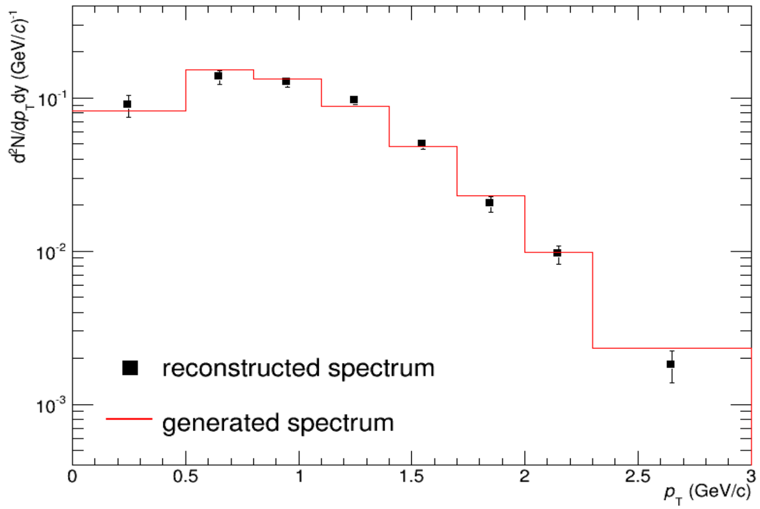
0-0.5 GeV/c | 1.1-1.4 GeV/c | 2.0-2.3 GeV/c



- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Λ^* peak is fit to Voigtian + pol2 (p0-p2)
- Signal can be reconstructed starting from zero momentum
- High-p_T reach is limited by available statistics

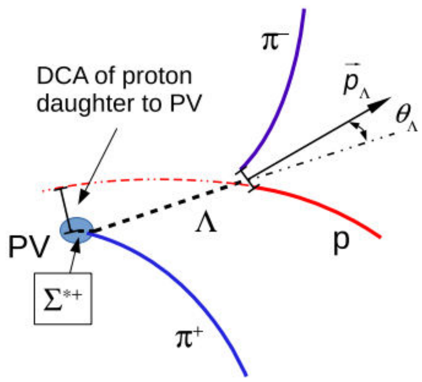
Λ(1520), reconstruction

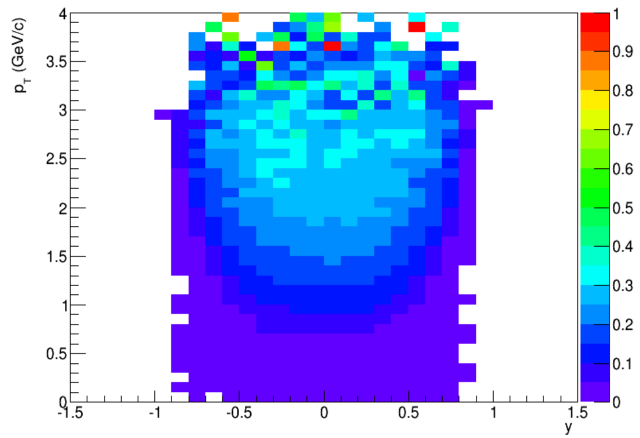


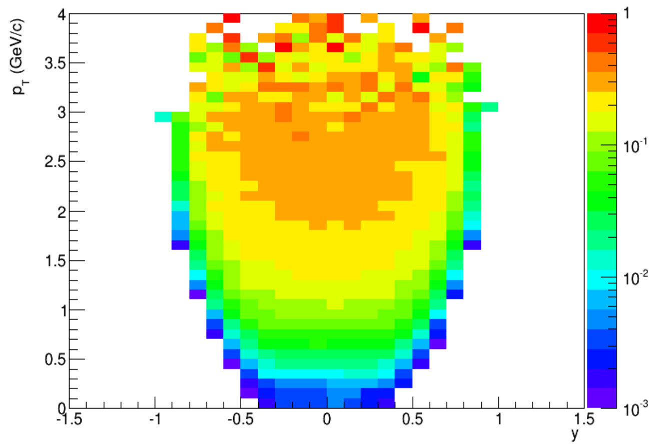


- Monte Carlo Closure Test
- Full chain reconstruction at |y| < 1.0
- Reconstructed spectrum matches the generated one within uncertainties
- Measurements are possible at p_T > 0 GeV/c

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



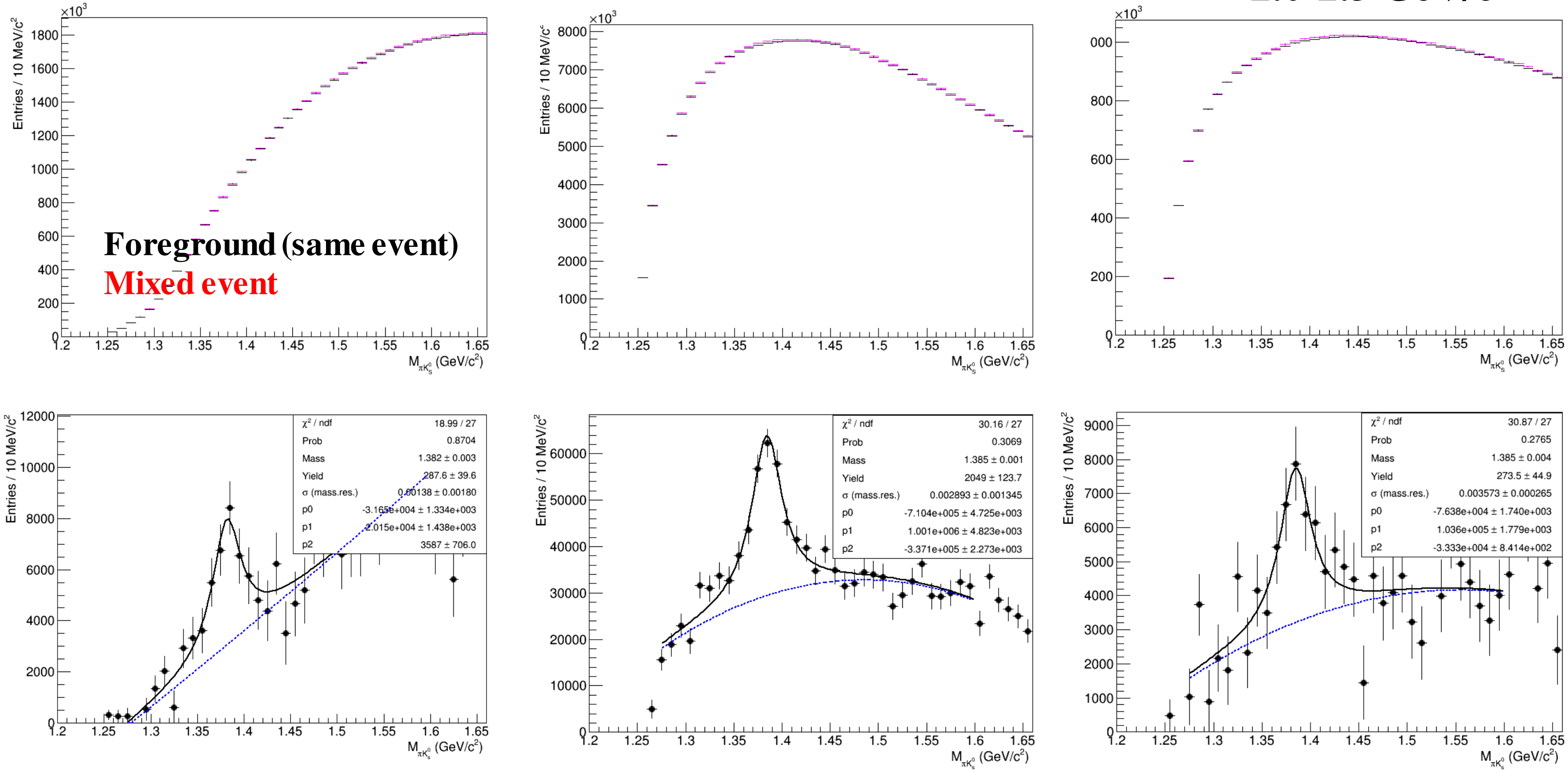




- $\Sigma(1385)^{\pm} \rightarrow \pi^{\pm}\Lambda$ ($\Lambda \rightarrow p\pi$)
- Decay chain includes weak decay of Λ → V0 vertex
- Acceptance x reconstruction efficiency: $A \cdot \in = N_{rec}(\Sigma^* \rightarrow \pi^{\pm}\Lambda) / N_{gen}(\Sigma^* \rightarrow \pi^{\pm}\Lambda)$
- Efficiency is lower, increases with transverse momentum
- Particles can be reconstructed in the rapidity range, $|y| < 1.0$

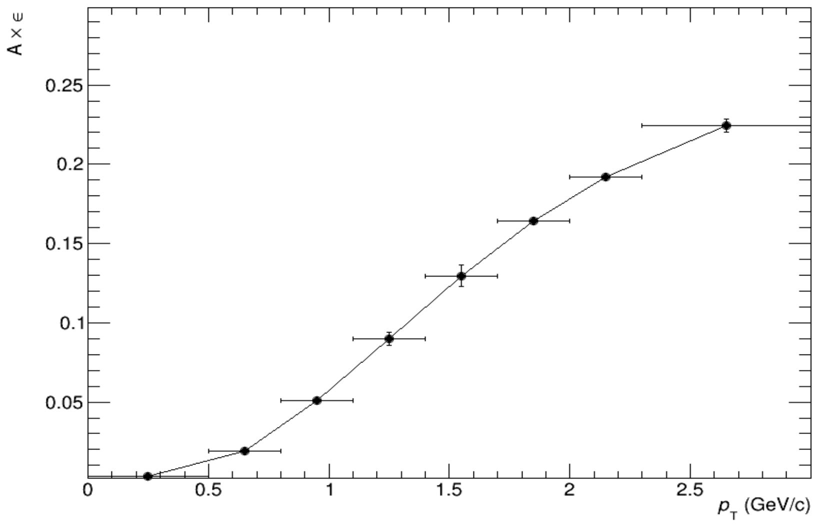
Σ(1385)±, reconstructed peaks

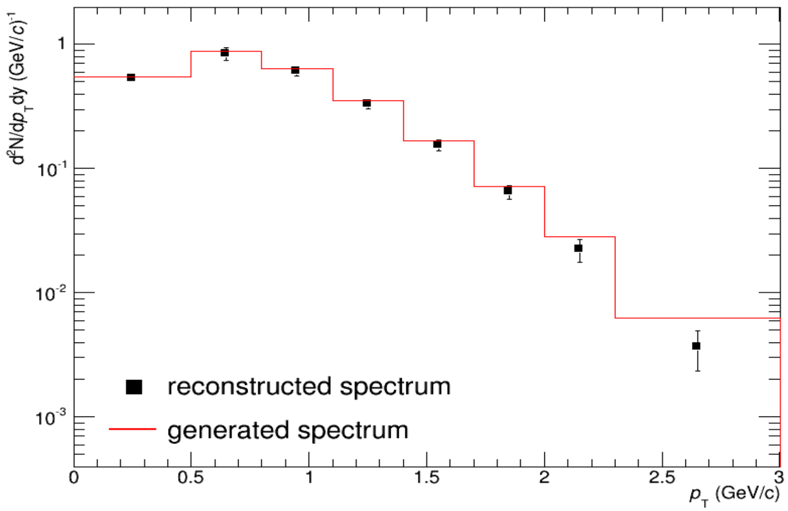
0-0.5 GeV/c | **1.1-1.4 GeV/c** | **2.0-2.3 GeV/c**



- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Σ^* peak is fit to Voigtian + pol2 (p0-p2)
- Signal can be reconstructed starting from zero momentum
- High-p_T reach is limited by available statistics

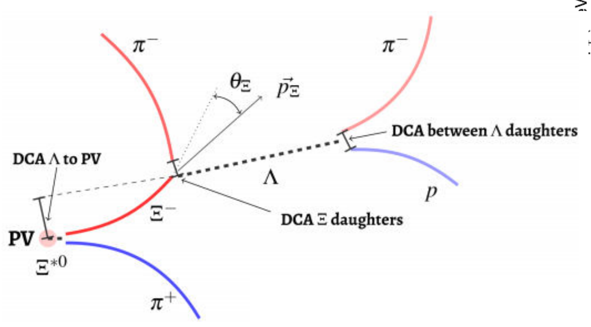
Σ(1385)±, reconstruction

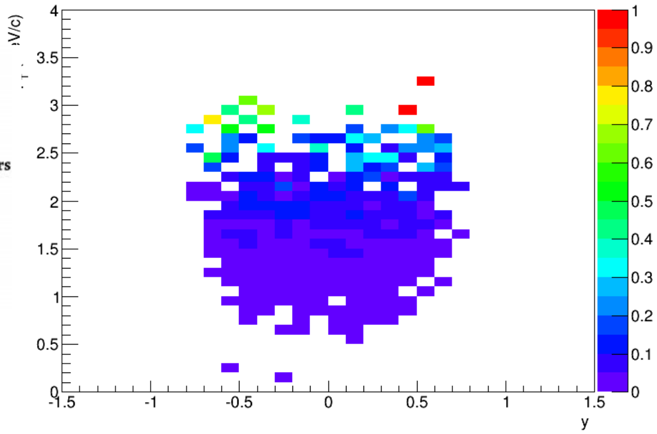


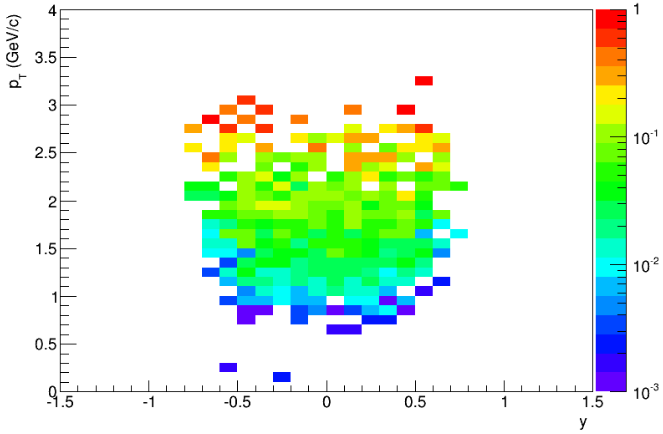


- Monte Carlo Closure Test
- Full chain reconstruction at $|y| < 1.0$
- Reconstructed spectrum matches the generated one within uncertainties
- Measurements are possible at $p_T > 0$ GeV/c

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



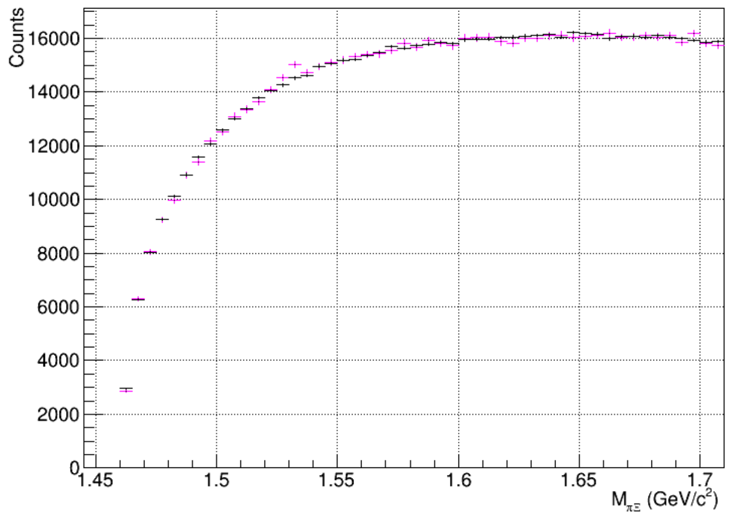


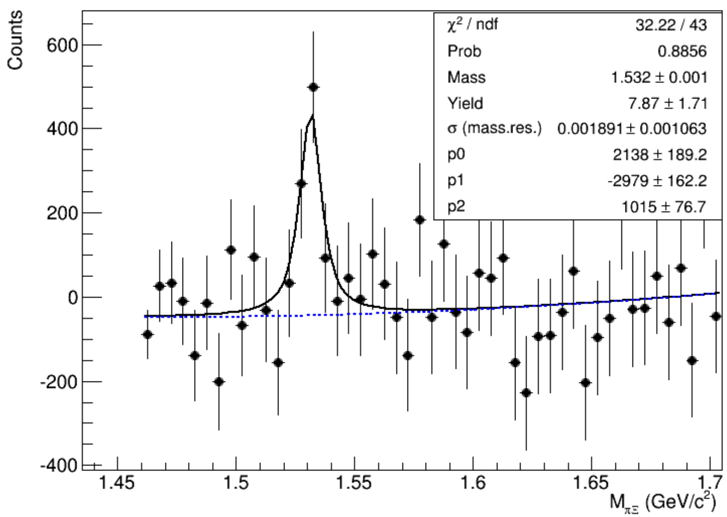


- $\Xi(1530)^0 \rightarrow \pi^+\Xi^-$ ($\Xi^- \rightarrow \Lambda\pi^-$, ($\Lambda \rightarrow p\,\pi^-$))
- Acceptance x reconstruction efficiency: $A \cdot \in\ = N_{rec}(\Xi^* \rightarrow \pi^+\Xi^-) / N_{gen}(\Xi^* \rightarrow \pi^+\Xi^-)$
- Low efficiency, increases with transverse momentum
- Particles can potentially be reconstructed in the rapidity range, $|y| < 1.0$

$\Xi(1530)^0$, reconstructed peak

p_T > 1.0 GeV/c





- Signal is observed at p_T > 1 GeV/c
- Statistics hungry analysis

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, 10^8 events is needed for multiplicity dependent study → within expectations for year-1 running

BACKUP