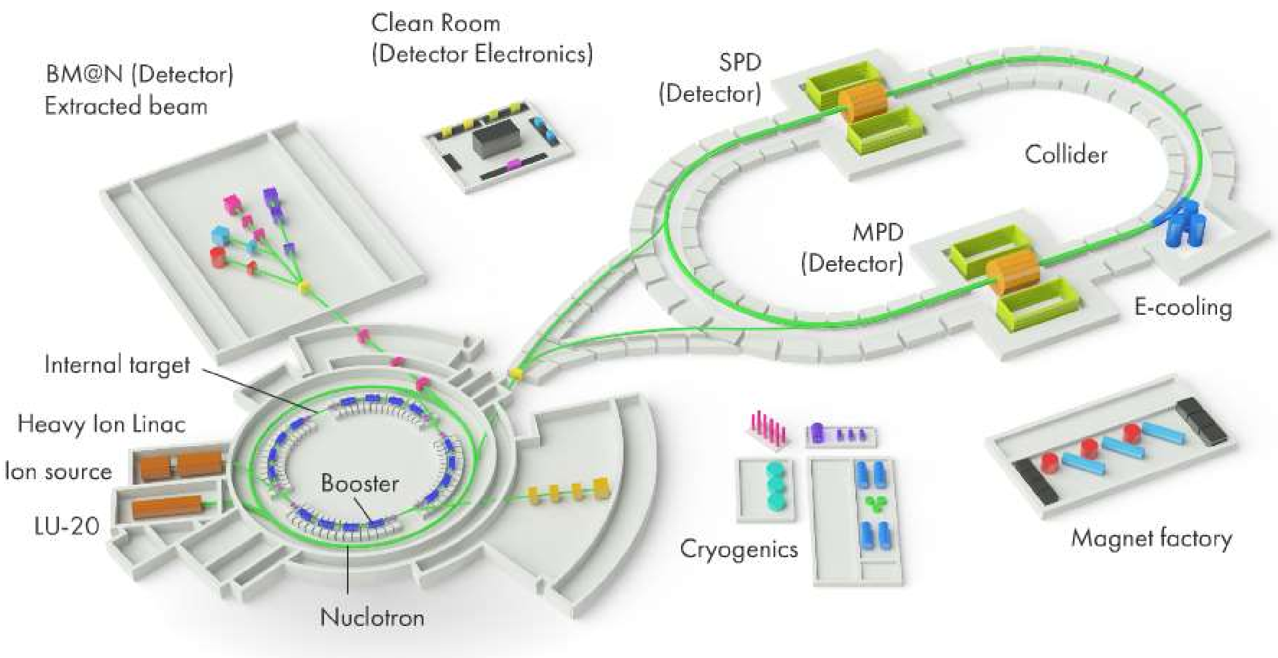
NICA
Nuclotron-based
Ion Collider fAcility

Short-lived resonances and neutral mesons in the physical program of the NICA-MPD

V. Riabov* for the MPD Collaboration



* This work was supported by RFBR according to the research project № 18-02-40038, 18-02-40045

Outline

- Motivation for studies of resonances and neutral mesons in heavy-ion collisions
- Predictions for resonance properties in heavy-ion collisions at NICA energies
- Feasibility studies for particle reconstruction at NICA-MPD
- Conclusions

Neutral mesons in heavy-ion collisions

- Wide variety of neutral mesons:
  - ✓ π^0 ($\pi^0 \rightarrow \gamma\gamma$)
  - ✓ η ($\eta \rightarrow \gamma\gamma$, $\eta \rightarrow \pi^0\, \pi^+\, \pi$)
  - ✓ K_s ($K_s \rightarrow \pi^0\, \pi^0$)
  - ✓ ω ($\omega \rightarrow \pi^0\, \gamma$, $\omega \rightarrow \pi^0\, \pi^+\, \pi$)
  - ✓ η' ($\eta' \rightarrow \eta\, \pi^+\, \pi$)
  - ✓ etc.

- Neutral mesons are of great interest from different points of view:
  - ✓ complementary measurements to $\pi^{\pm}$, $K^{\pm}$ etc. with different systematics
  - ✓ study of mass and quark content/count dependent effects such as collective flow, recombination, parton energy loss, strangeness production etc.
  - ✓ source of background for many other observables such as direct photons, e_{HF} and di-electrons
  - ✓ …

Resonances in heavy-ion collisions

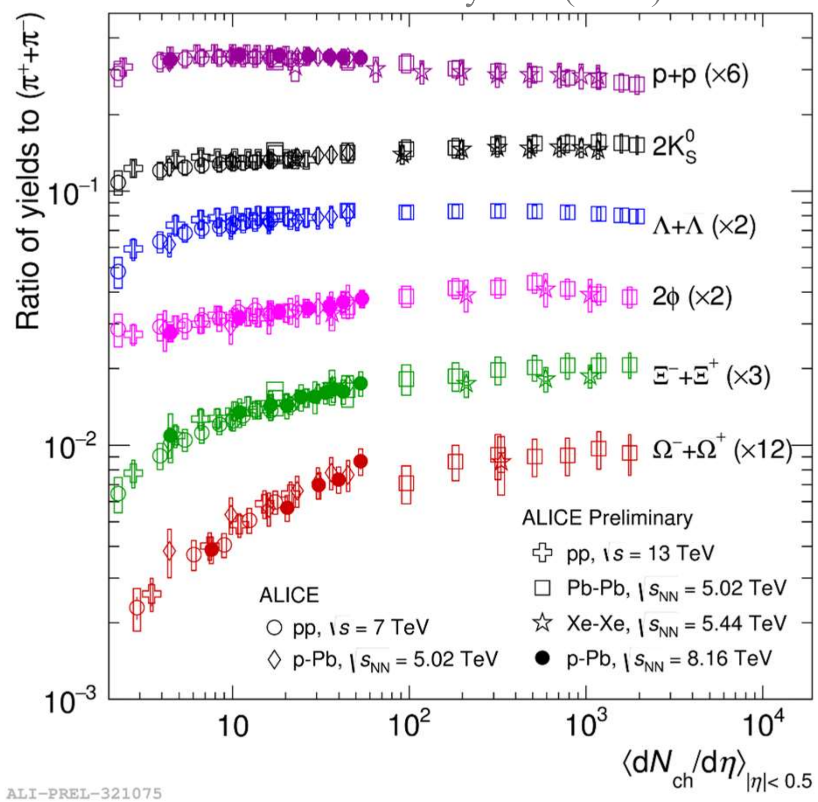
$\rho(770)$	$K^*(892)^0$	$K^*(892)^+$	$\phi(1020)$	$\Sigma(1385)^\pm$	$\Lambda(1520)$	$\Xi(1530)$
$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$d\bar{s}$	$u\bar{s}$	$s\bar{s}$	uus dds	uds	uss

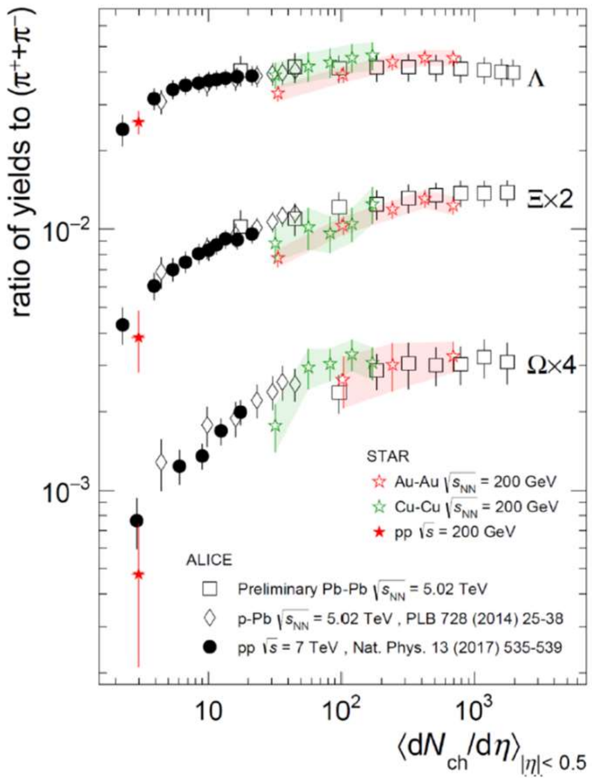
Particle	Mass (MeV/c^2)	Width (MeV/c^2)	Decay	BR (%)
ρ^0	770	150	$\pi^+\pi$	100
$K^{*\pm}$	892	50.3	$\pi^\pm K_s$	33.3
K^{*0}	896	47.3	πK^+	66.7
ϕ	1019	4.27	K^+K^-	48.9
Σ^{*+}	1383	36	$\pi^+\Lambda$	87
Σ^{*-}	1387	39.4	$\pi\Lambda$	87
$\Lambda(1520)$	1520	15.7	K^-p	22.5
Ξ^{*0}	1532	9.1	$\pi^+\Xi^-$	66.7

- Wide variety of resonances in the PDG, most popular are listed on the top
- 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
  - ✓ …

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

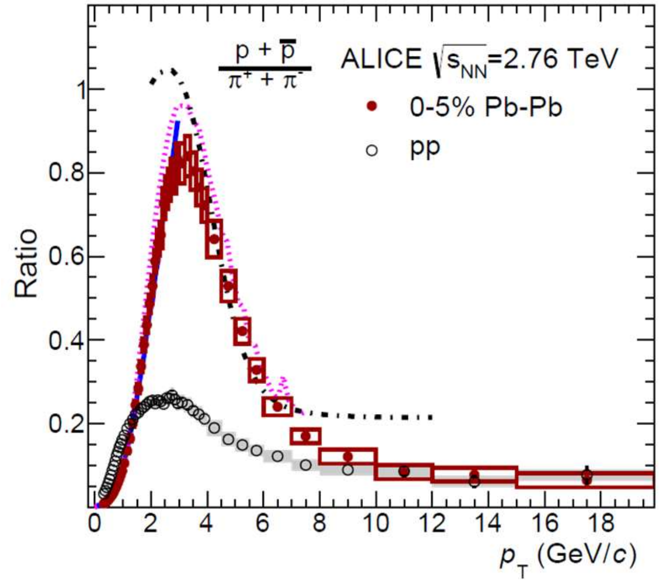
- Baryon puzzle - increased baryon-to-meson (p/π, Λ/K_s^0, Λ_c^+/D) ratios in heavy-ion collisions at RHIC and the LHC

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

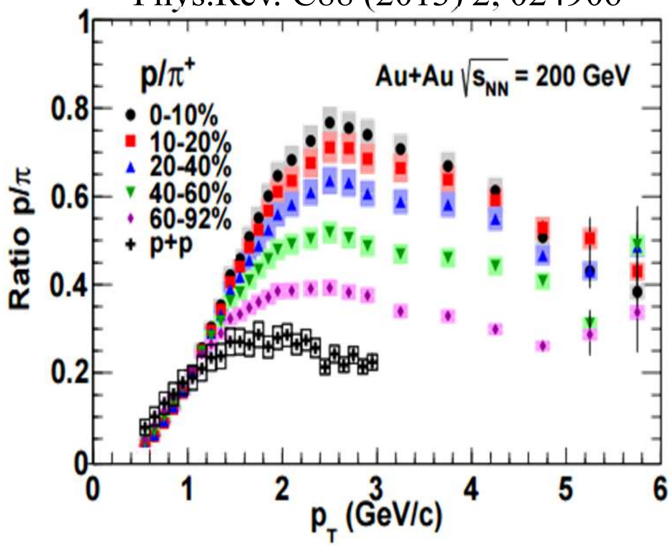
- ϕ and K^{*0} are well suited for tests as mesons with masses very close to that of a proton:

✓ $\Delta m_\phi \sim 80$ MeV/c^2, $\Delta m_{K^{*0}} \sim -45$ MeV/c^2

Phys.Lett. B736 (2014) 196-207



Phys.Rev. C88 (2013) 2, 024906



Hadronic phase and medium modifications

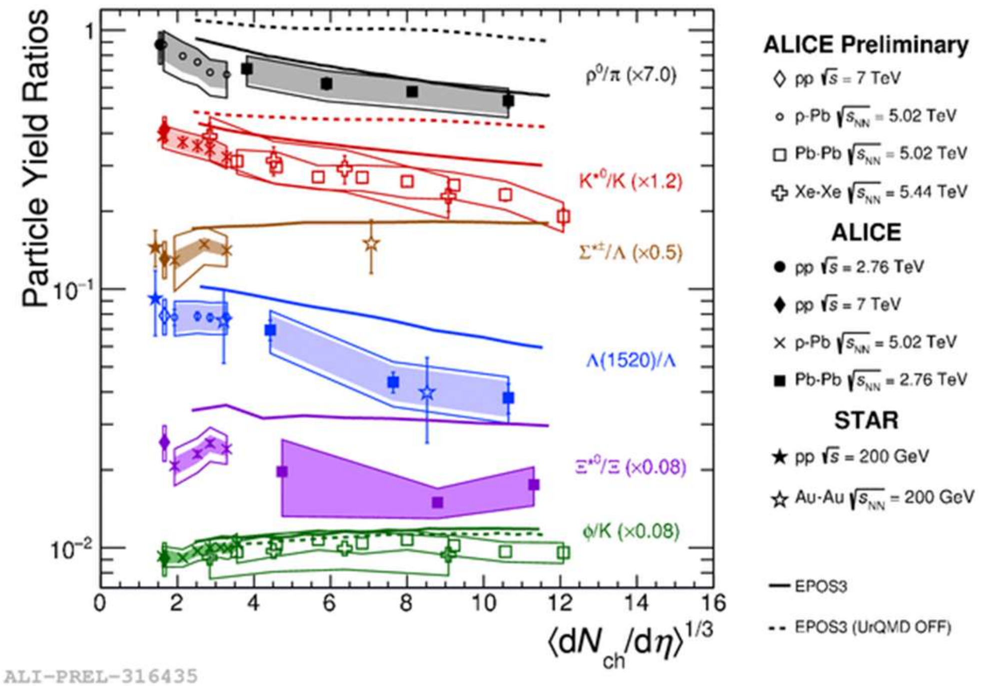
increasing lifetime →

	$\rho(770)$	$K^*(892)$	$\Sigma(1385)$	$\Lambda(1520)$	$\Xi(1530)$	$\phi(1020)$
$c\tau$ (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 $c\tau \sim 1 - 45$ 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 ($\pi K \rightarrow K^{*0}$, $KK \rightarrow \phi$ etc.) → increased yields

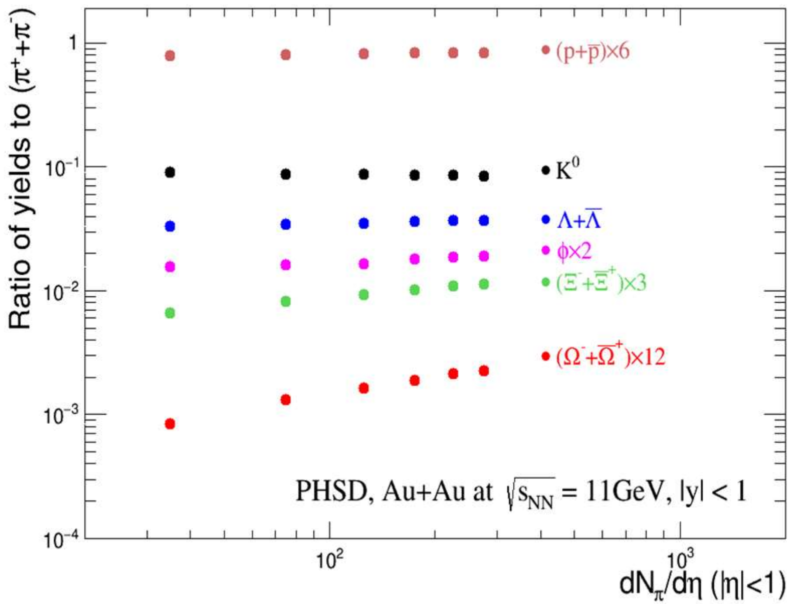


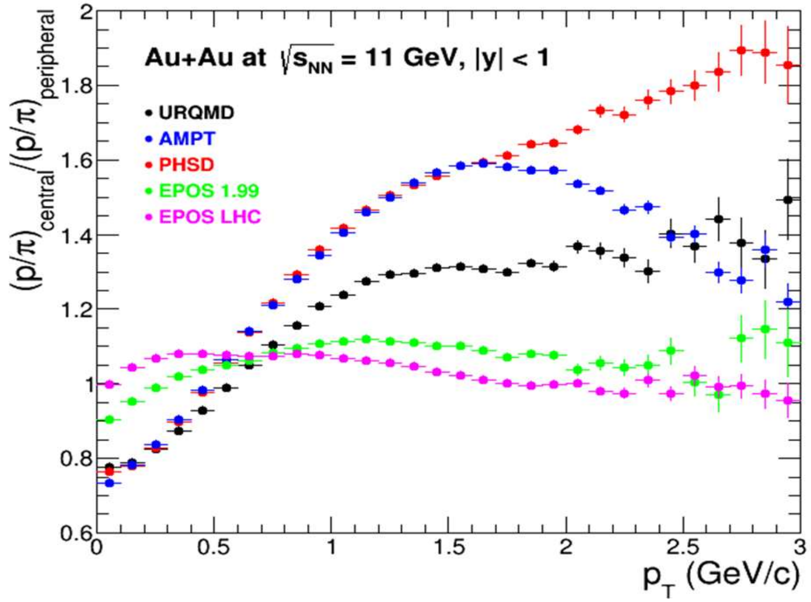
- SPS/RHIC/LHC results for resonance yields support the existence of a hadronic phase that lives long enough to cause a significant reduction of the reconstructed yields of short lived resonances
- Lower limit for the lifetime of the hadronic phase, $\tau > 2$ fm/c*

* 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, 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.

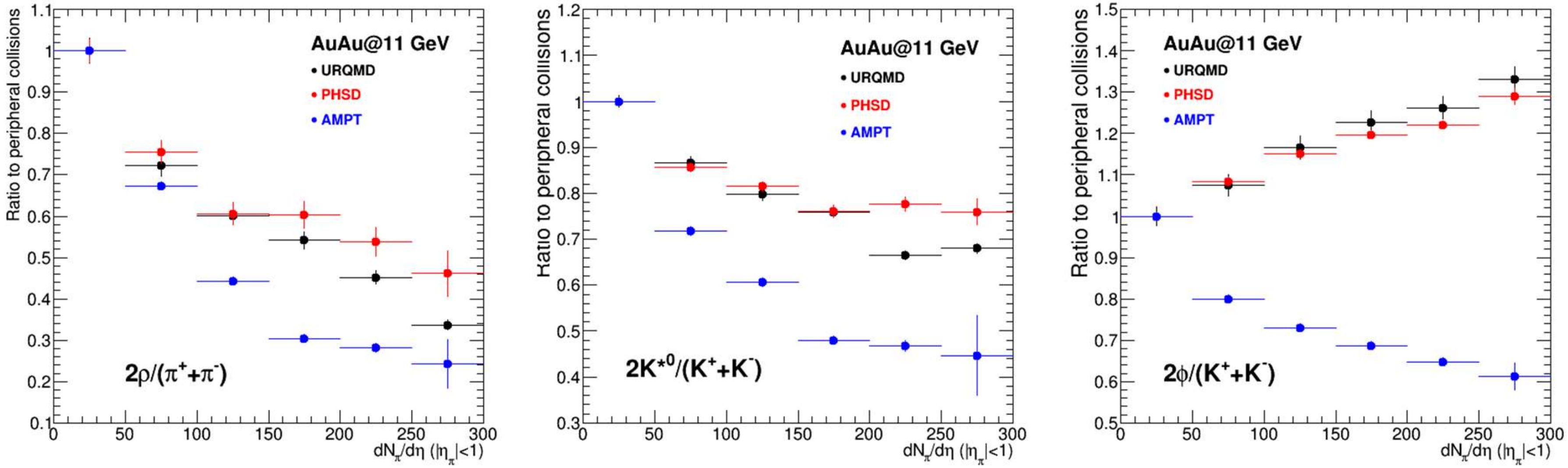




- Eventually, model predictions (integrated yields, <p_T>, particle ratios etc.) should be compared to data to differentiate different model assumptions

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 $c\tau$



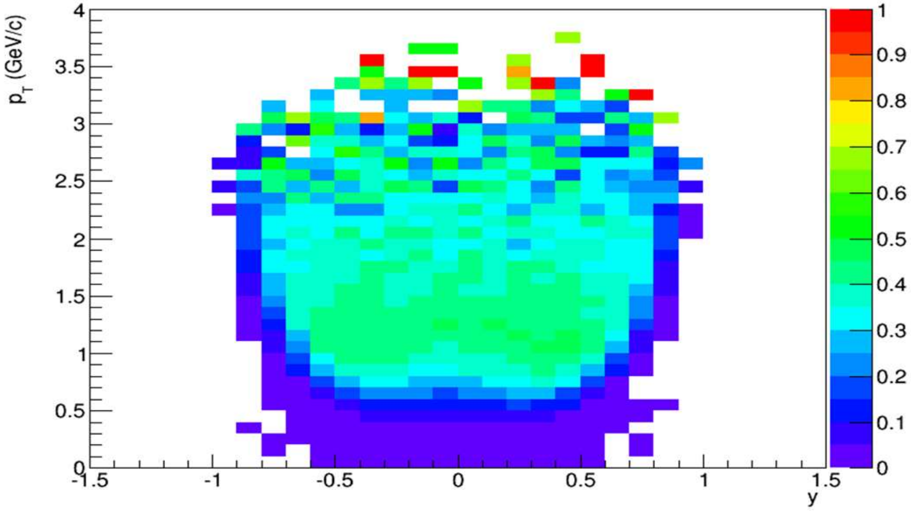
- Models predict yield modifications similar to those observed at higher collision energies:
  - ✓ lifetime and density of the hadronic phase are high enough
  - ✓ modification of particle properties in the hadronic phase should be taken into account when model predictions for different observables are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

Feasibility studies, framework

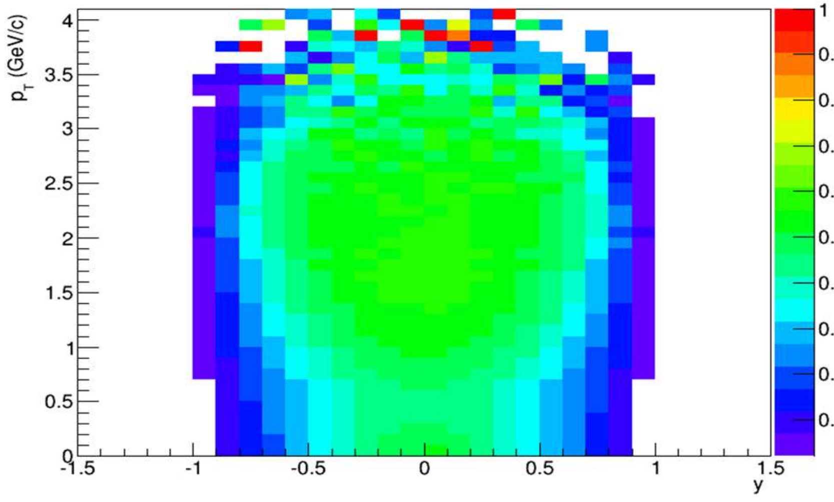
- Simulated minbias AuAu@11 GeV collisions using UrQMD 3.4 with default settings
- Tracked simulated particles through the MPD Phase-I detector using *mpdroot*
- Analysis cuts were optimized in each case for higher signal significance
  - Event selection:
    - ✓ $|Z_{vrtx}| < 50$ cm, realistic distribution
  - Basic track selections:
    - ✓ number of TPC hits > 20
    - ✓ $|\eta| < 1.0$
    - ✓ $p_T > 50$ 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:
    - ✓ $|DCA(x,y,z)| < 2\sigma$ (parametrization by P. Parfenov)
  - V0 & cascades:
    - ✓ topology cuts for weakly decaying secondary particles ($K_s \to \pi\pi$, $\Lambda \to p\pi$, $\Xi \to \Lambda\pi$)
  - Photon selection:
    - ✓ ECAL clusters after unfolding
    - ✓ e^+e^- conversion pairs, secondary vertex and pair selection cuts
- Combinatorial background:
  - ✓ event mixing ($|\Delta_{Zvrtx}| < 2$ cm, $|\Delta_{Mult}| < 20$, $N_{ev} = 10$)

Efficiencies: $A \cdot \in = N_{rec}(p_T, y) \,/\, N_{gen}(p_T, y)$

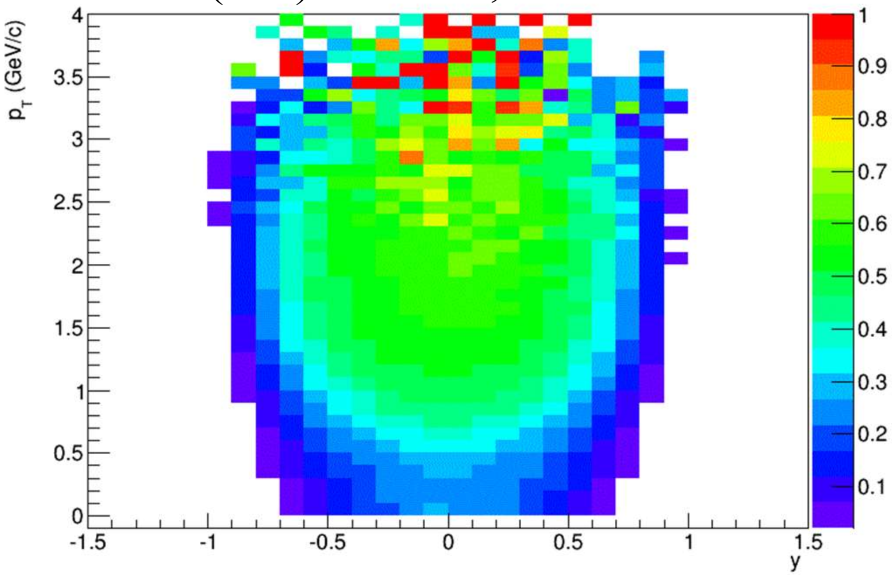
$\phi(1020) \to K^+K^-$, BR = 48.9 %



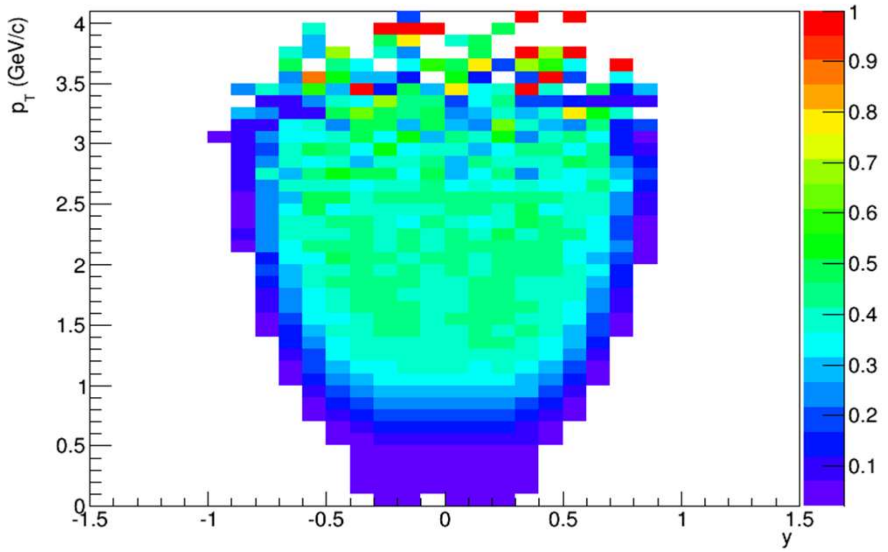
$\rho(770)^0 \to \pi^+ \pi^-$, BR ~ 100 %



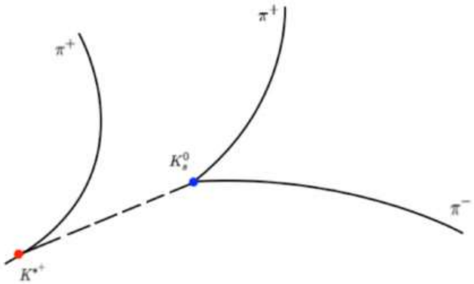
$K^*(892)^0 \to \pi^{\pm}K^{\pm}$, BR = 66.7 %

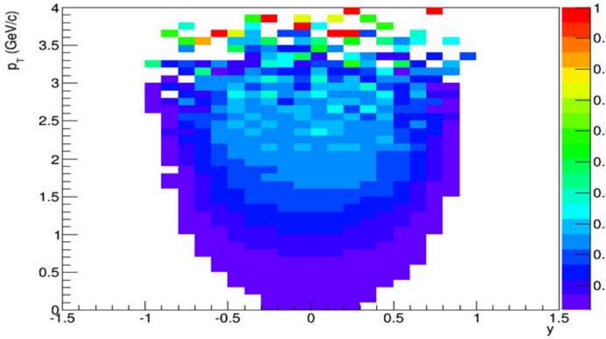


$\Lambda(1520) \to pK^-$

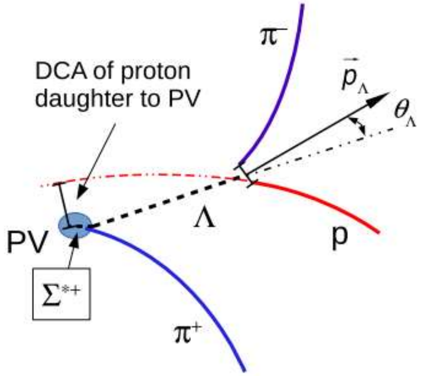


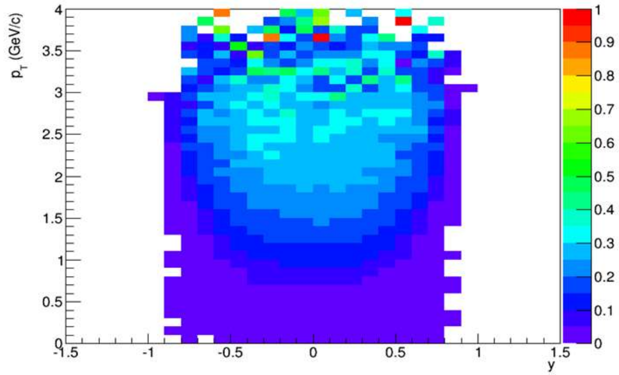
Efficiencies: $A\cdot\in = N_{rec}(p_T,y) \,/\, N_{gen}(p_T,y)$



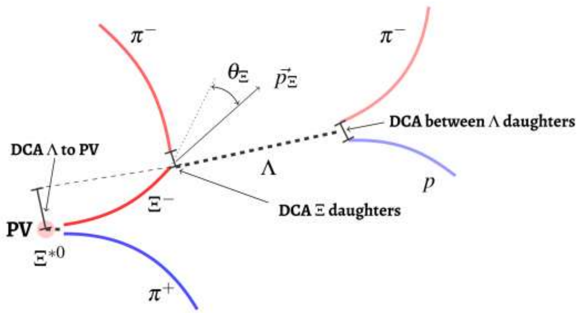


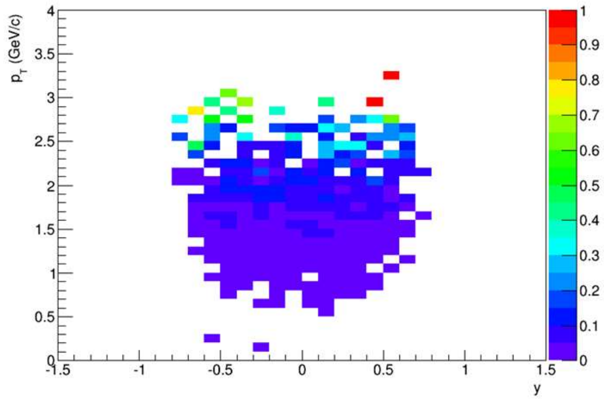
$K^*(892)^\pm \rightarrow \pi^\pm K_s \ (K_s \rightarrow \pi^+\pi^-)$





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



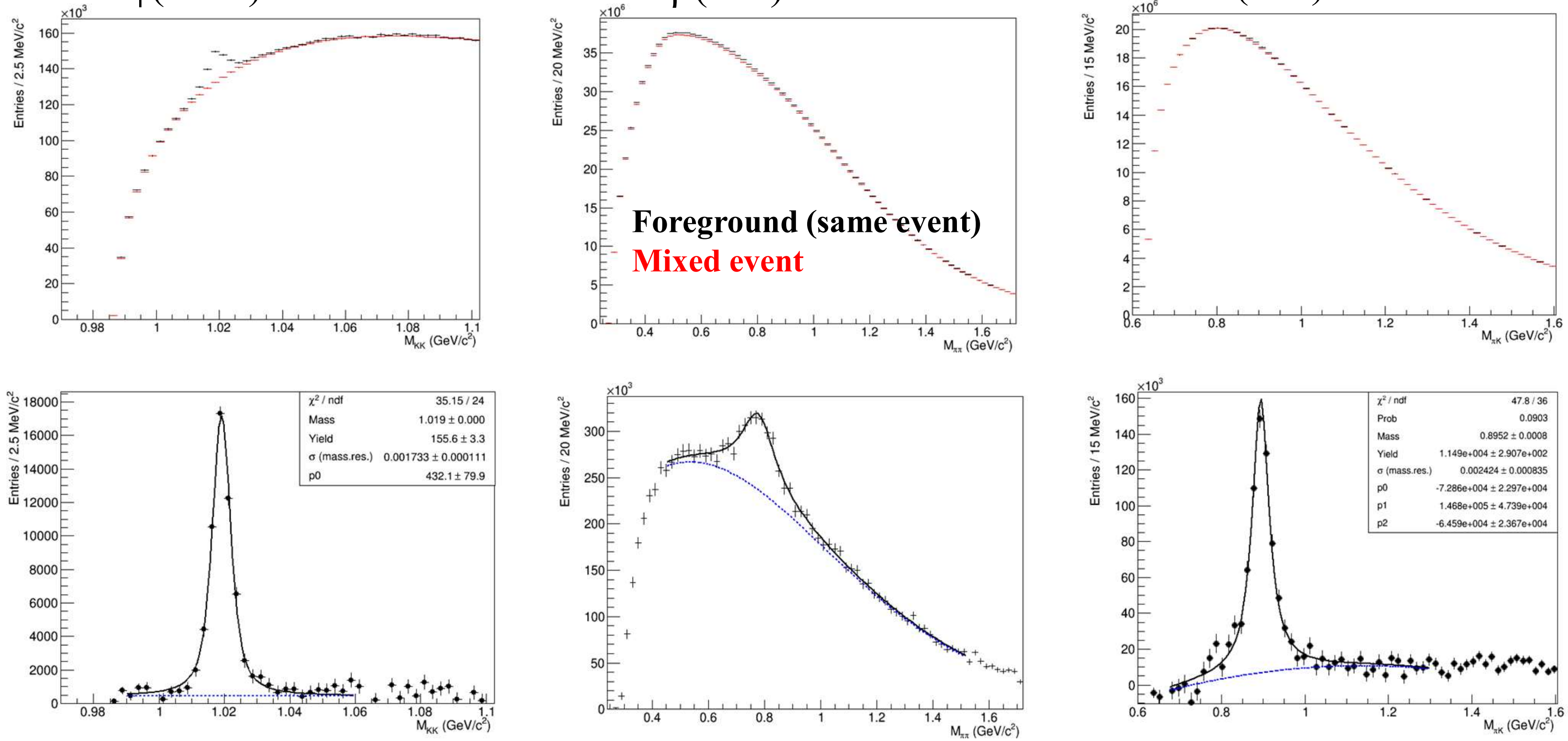


$\Xi(1530)^0 \rightarrow \pi^+\Xi^-$,

$\Xi^- \rightarrow \Lambda\pi^-$, $(\Lambda \rightarrow p\,\pi^-)$

Reconstructed peaks: ϕ, ρ^0, K^{*0}

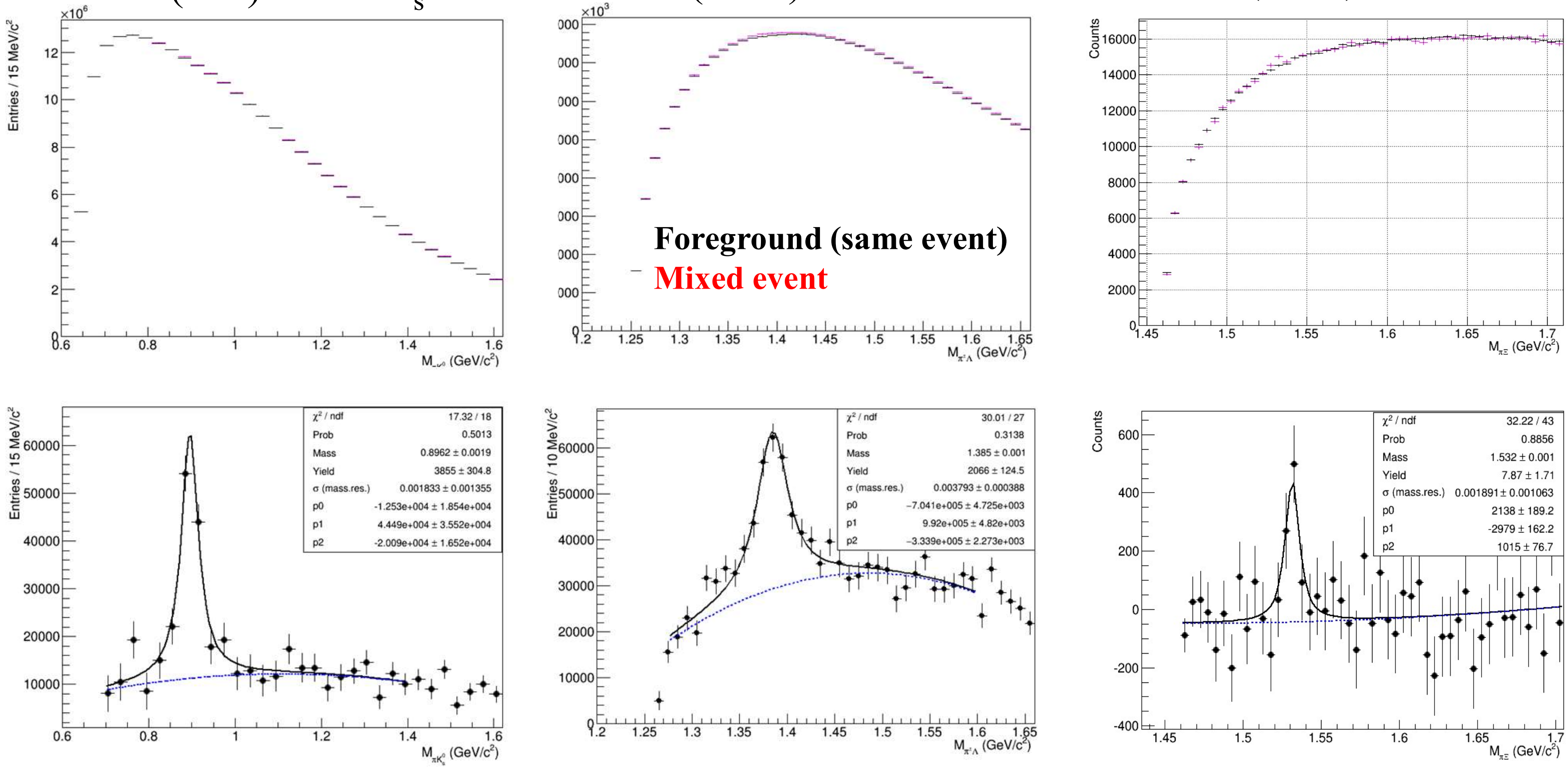
$\phi(1020) \rightarrow K^+K^-$ | $\rho(770)^0 \rightarrow \pi^+\pi^-$ | $K^*(892)^0 \rightarrow \pi^\pm K^\pm$



- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Distribution is fit to Voigtian function + pol0/pol2
- Signals can be reconstructed at $0 < p_T$ (GeV/c) < 3 GeV/c with 10^7 events
- High-p_T reach is limited by available statistics

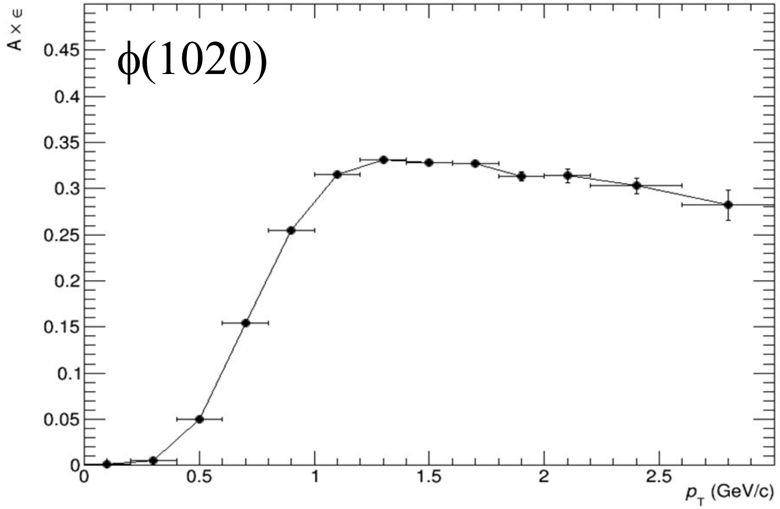
Reconstructed peaks: $K^{*\pm}$, $\Sigma(1385)^{\pm}$, $\Xi(1530)^0$

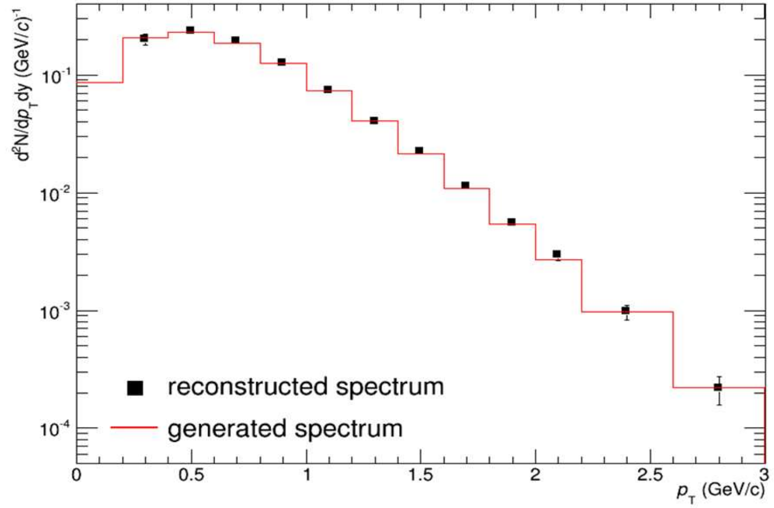
$K^*(892)^{\pm} \rightarrow \pi^{\pm}K_s$ | $\Sigma(1385)^{\pm} \rightarrow \pi^{\pm}\Lambda$ | $\Xi(1530)^0 \rightarrow \pi^{+}\Xi^{-}$

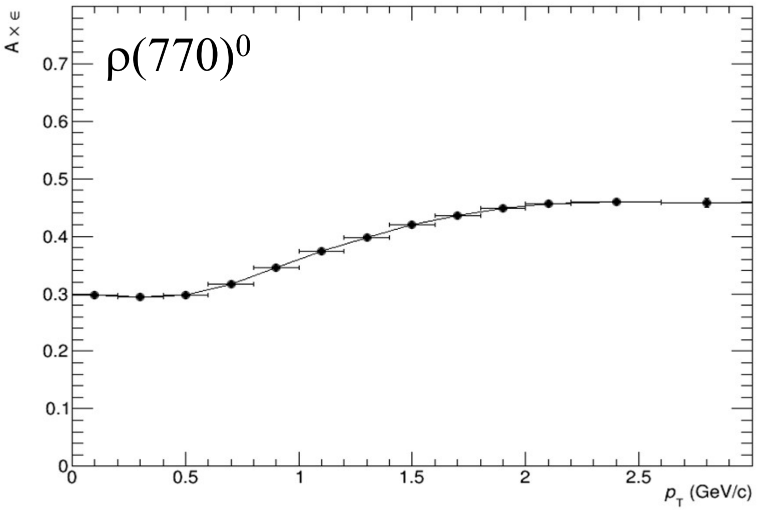


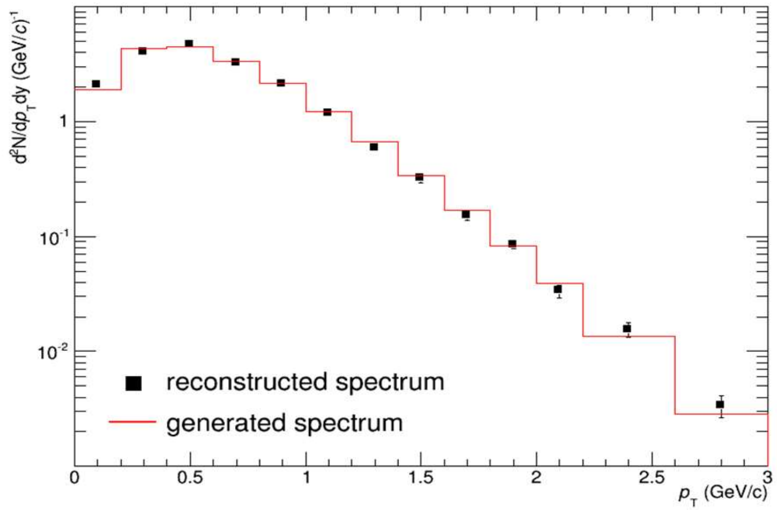
- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Distribution is fit to Voigtian function + pol2
- Signals can be reconstructed at $0 < p_T$ (GeV/c) < 3 GeV/c, except for $\Xi(1530)^0$
- $\Xi(1530)^0$ is observed

MC closure tests: ϕ, $\rho(770)^0$



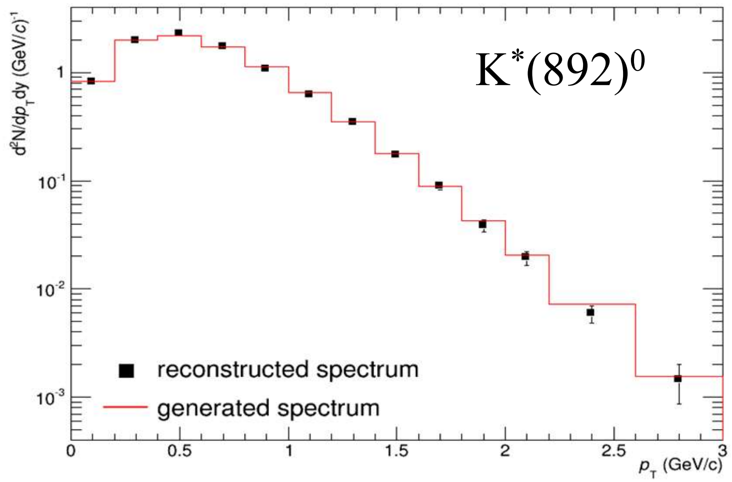


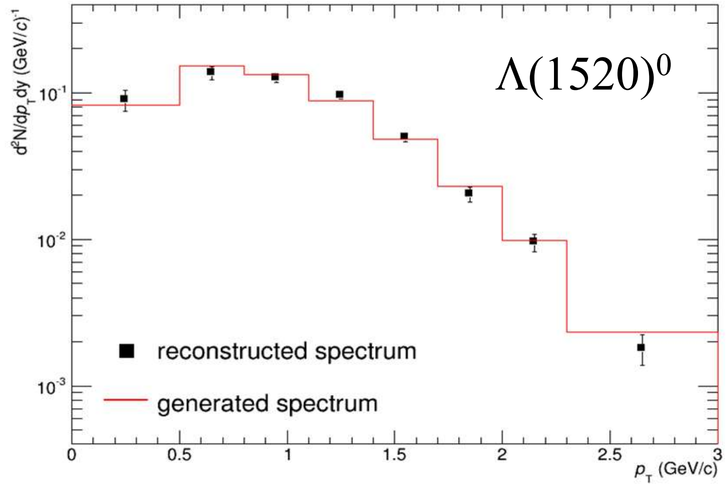


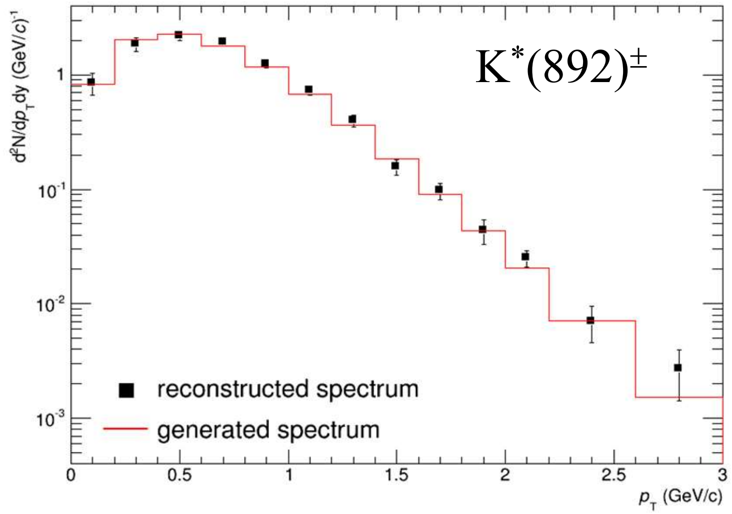


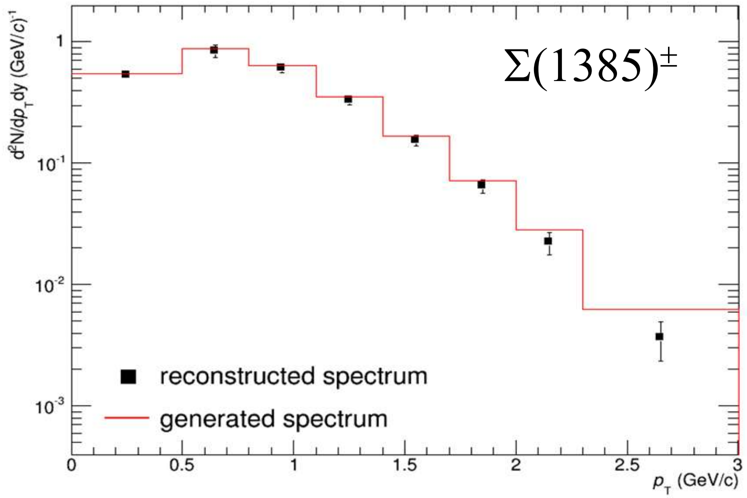
- Full chain reconstruction at $|y| < 1.0$
- Reconstructed spectrum matches the generated one within uncertainties

MC closure tests: $K^*(892)^0$, $K^*(892)^{\pm}$, $\Lambda(1520)$, $\Sigma(1385)^{\pm}$





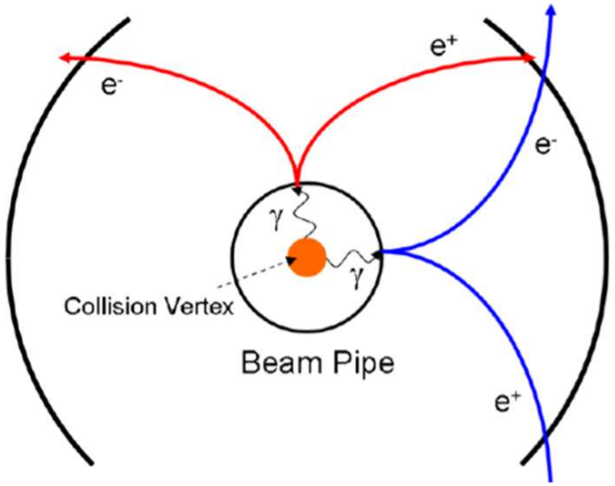


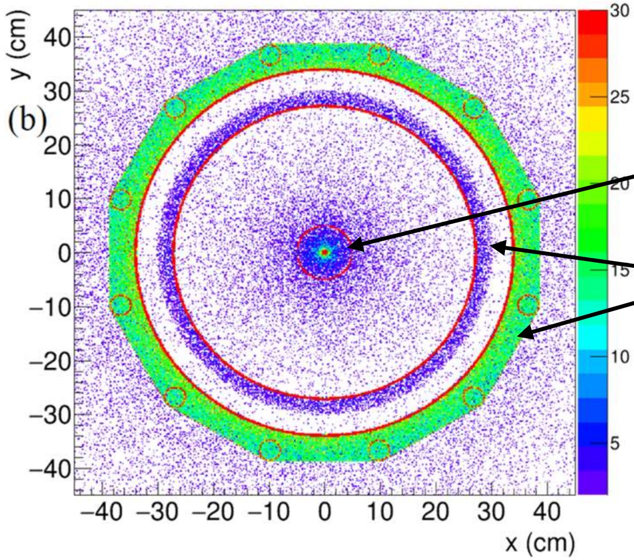


- Full chain reconstruction at $|y| < 1.0$
- Reconstructed spectrum matches the generated one within uncertainties

Reconstruction of neutral mesons

- All neutral mesons require reconstruction of photons in the final state:
- Photons can be measured with ECAL or in the tracking system as e^+e^- conversion pair (PCM)





beam pipe (0.3% X_0)

inner TPC vessels (2.4% X_0)

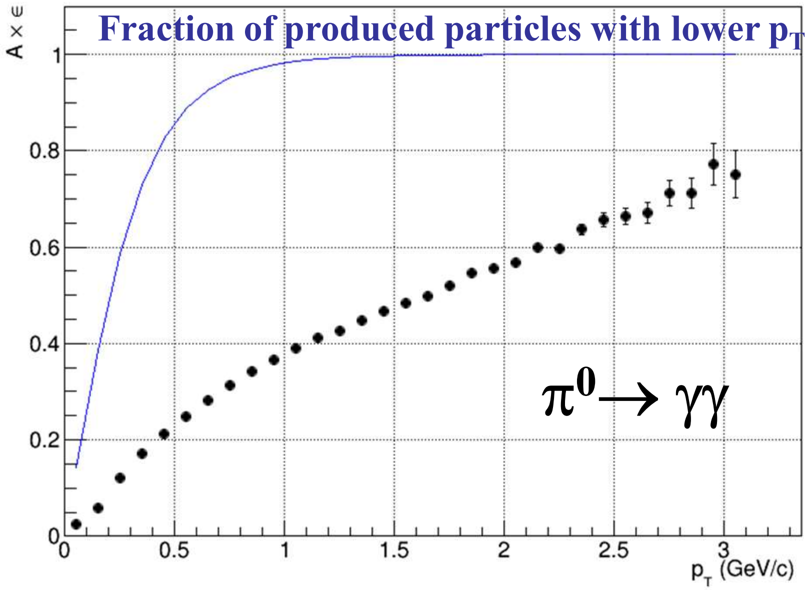
- ECAL:

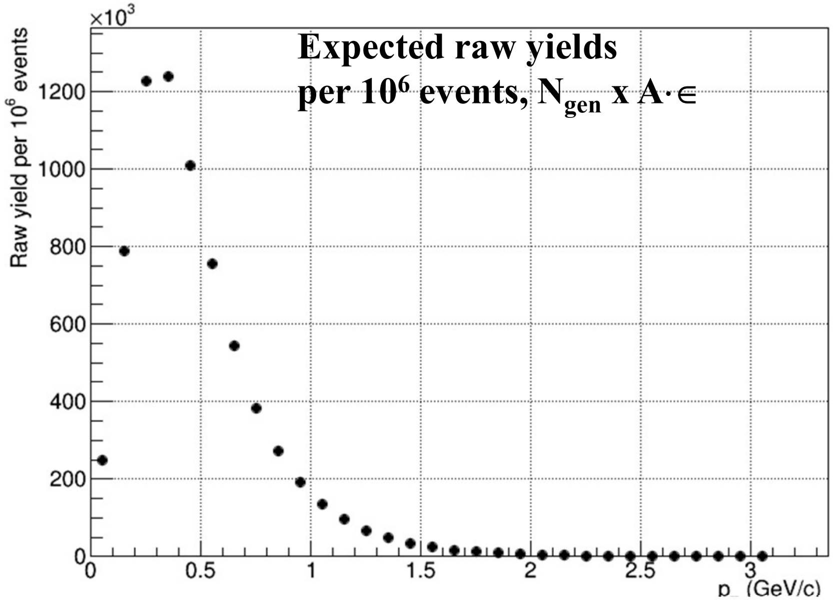
✓ large acceptance 👍
✓ high efficiency 👍
✓ good resolution at E >> 1 👍
✓ bad resolution at E ~ 1 👎

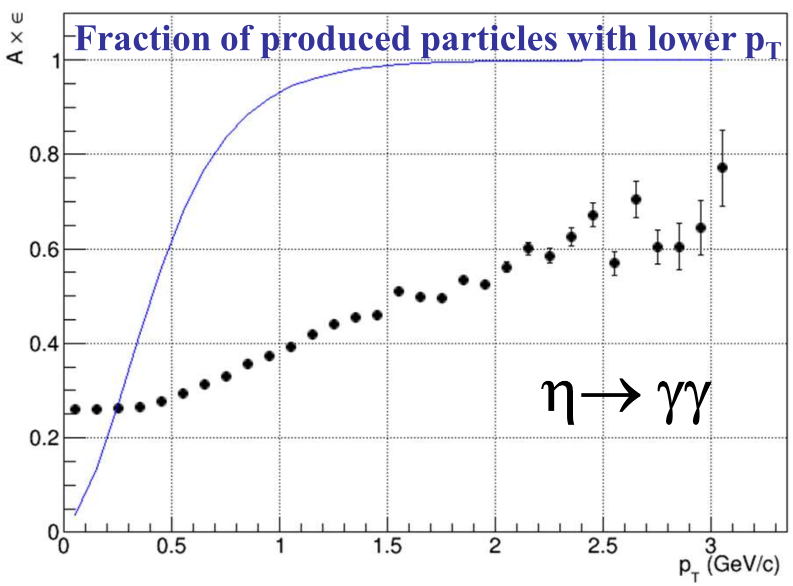
- PCM:

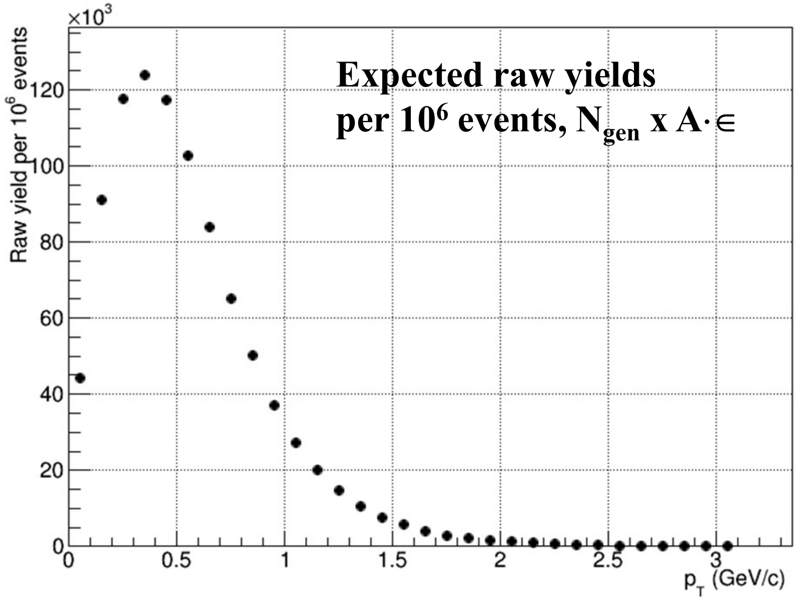
✓ large acceptance 👍
✓ low efficiency 👎
✓ modest resolution at E >> 1 👍
✓ good resolution at E ~ 1 👍

ECAL efficiency: A·∈, |y| < 0.5

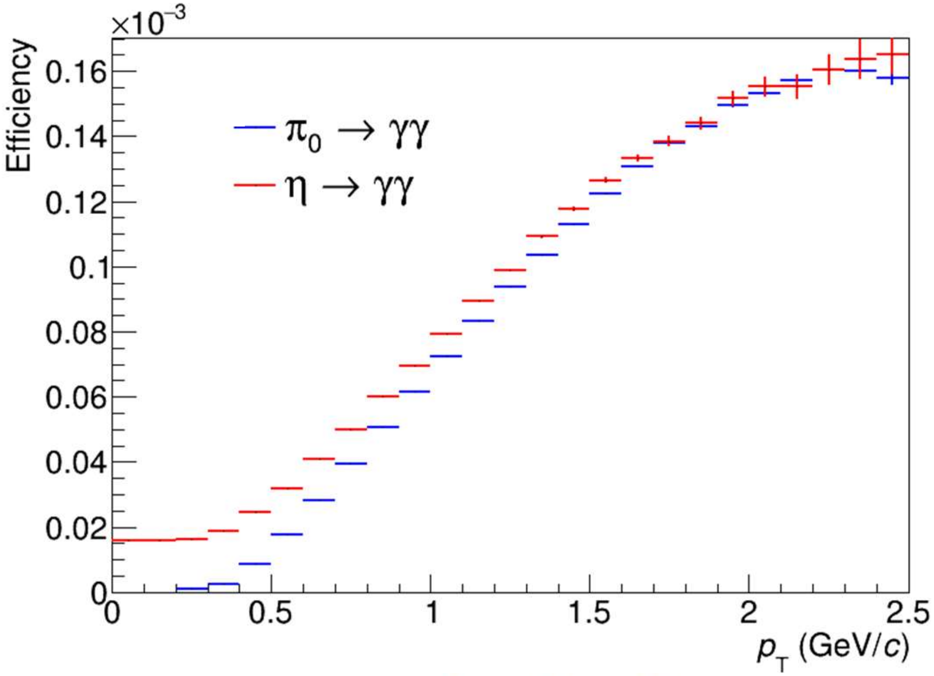




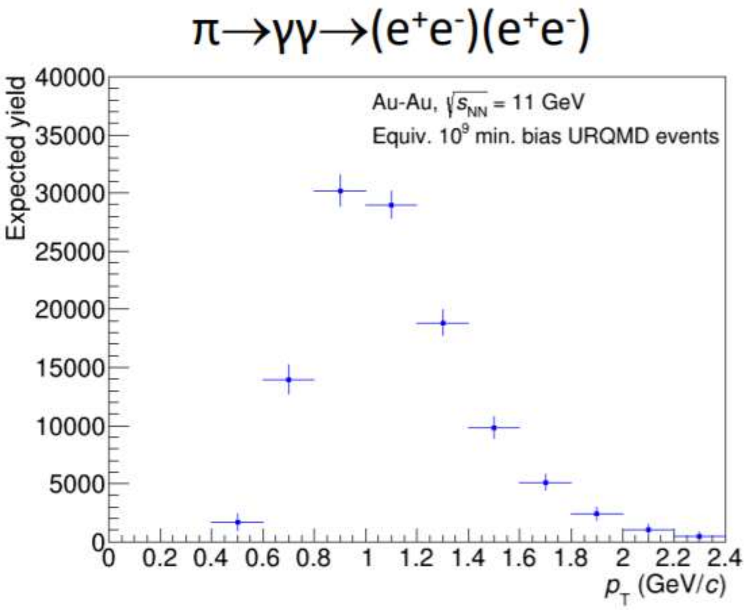


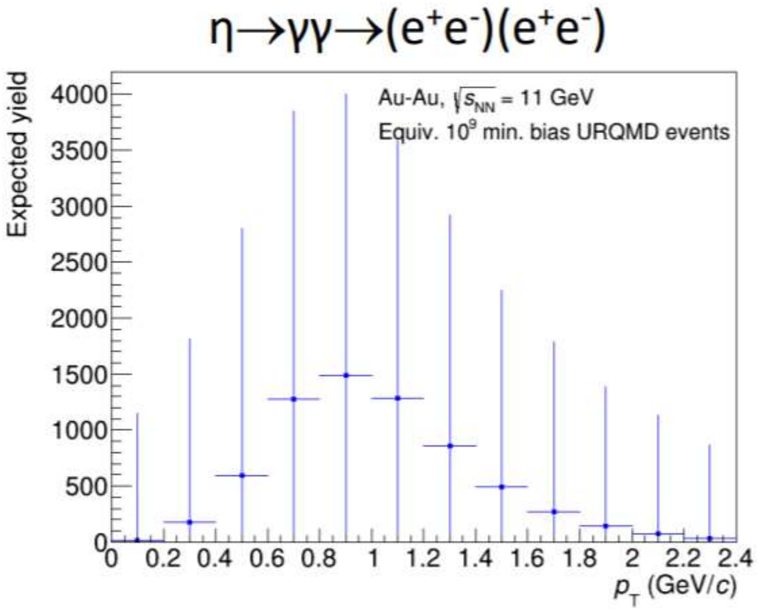


PCM efficiency: A·∈, |y| < 0.5

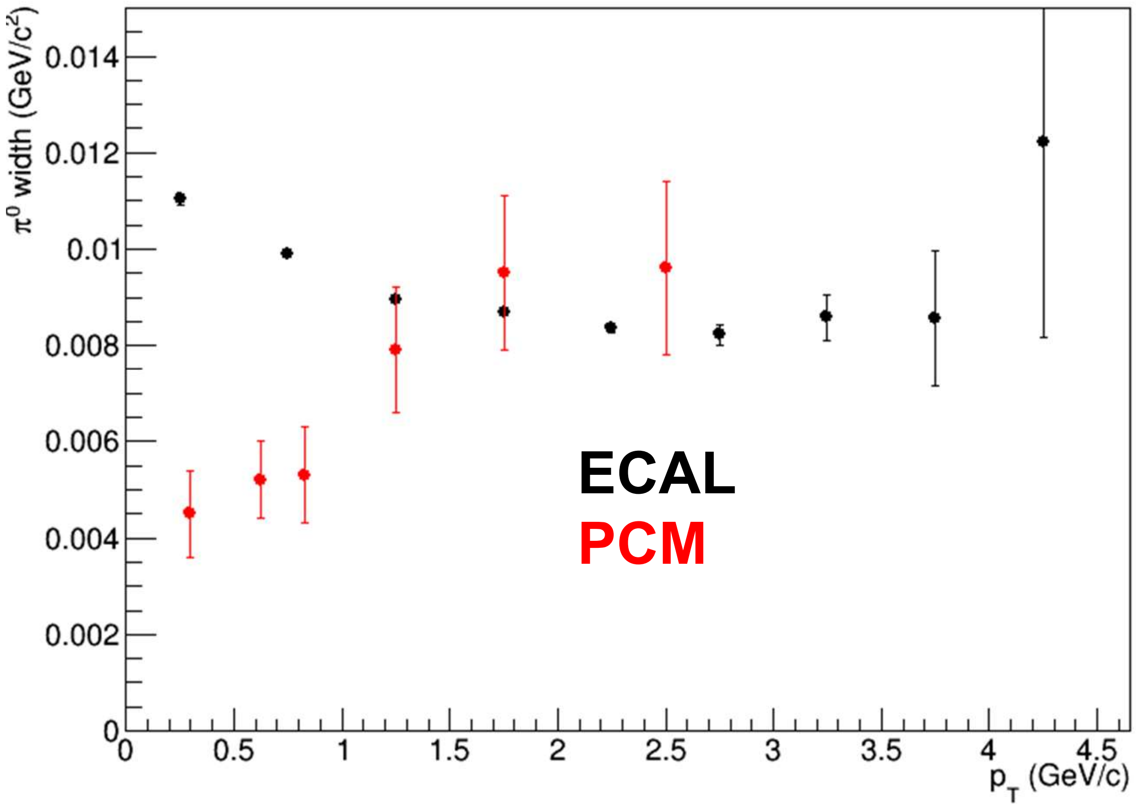


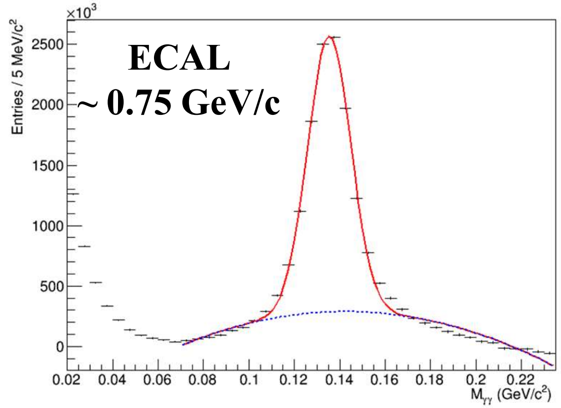
- Probability to reconstruct π_0/η is a factor of 1000 lower for PCM method
- Expected raw yields for 10^9 sampled minimum bias events are shown on the bottom, error bars estimated as $\sqrt{S+B}$
- BUT (!!!) PCM method is the most promising method for measurement of low-E photons, including thermal photons. Reconstruction of neutral mesons is a powerful cross check for the analysis chain

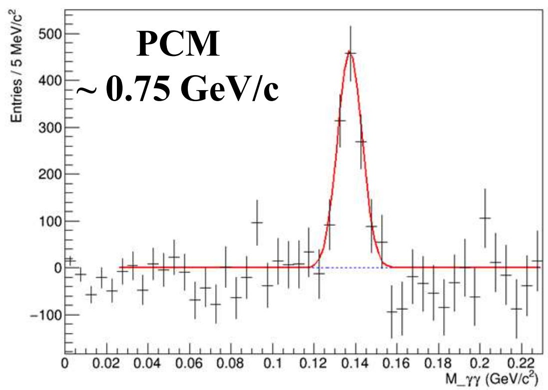




Reconstructed π^0, width vs. p_T



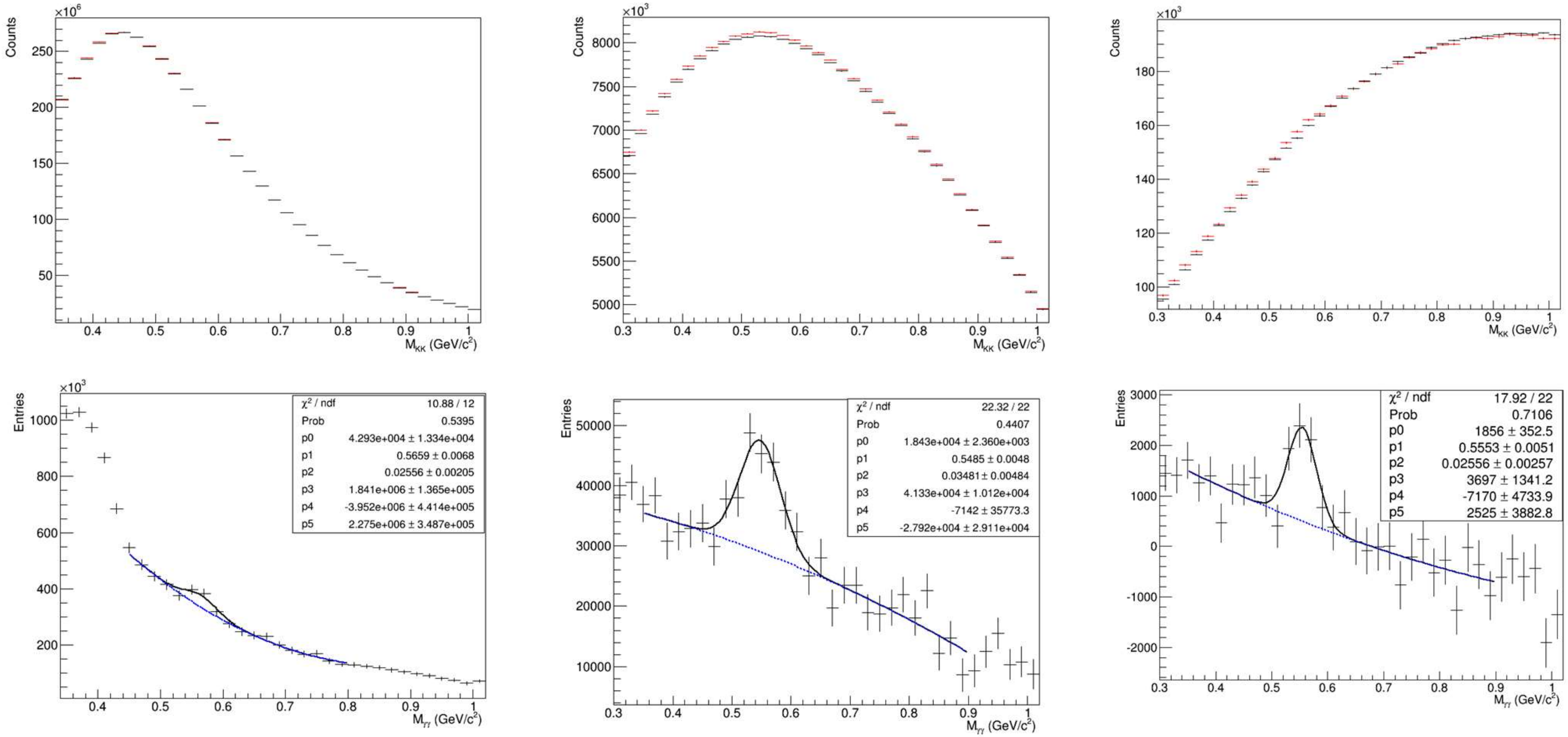




- PCM has three times better resolution at low momentum and much better S/B
- Resolution becomes comparable at $p_T \sim 2$ GeV/c
- ECAL has better resolution at $p_T > 3$ GeV/c

Reconstructed η

0-0.5 GeV/c **1.0-1.5 GeV/c** **2.5-3 GeV/c**



- ECAL:
  - ✓ combinatorial background is estimated using event mixing
  - ✓ signal can be reconstructed from low momentum
  - ✓ ~ 10 M events is enough to measure η

- PCM:
  - ✓ observe signal at 2-3σ
  - ✓ > 1 B events is required for signal reconstruction

Summary

- Resonance and neutral meson studies are important parts 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 centrality dependent study → within expectations for year-1 running
- π^0 and η will be reconstructed in the ECAL with 10^7 minimum bias events sampled, 10^8 events is needed for multiplicity dependent study → within expectations for year-1 running
- π^0 will be reconstructed with PCM method with 10^8 minimum bias events sampled → within expectations for year-1 running;
- η and centrality dependent studies with PCM method would require >= 10^9 events → probably not an year-1 task

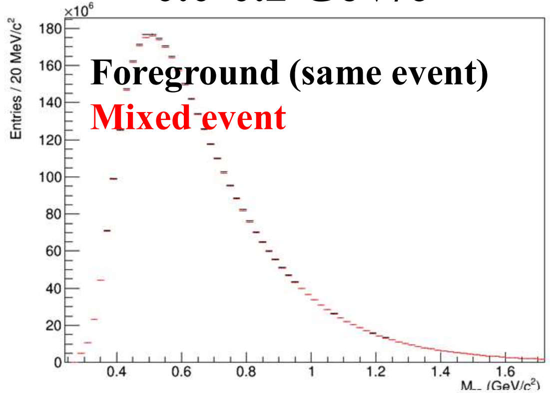
Join us !!!

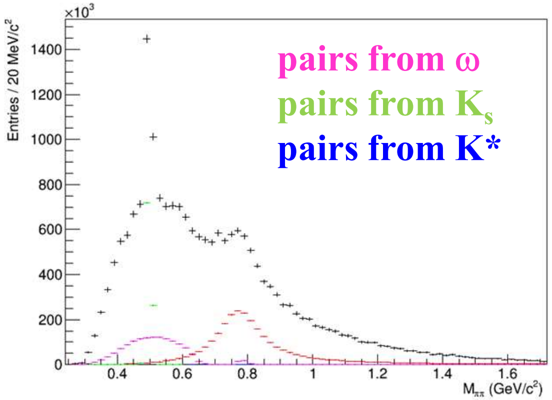
- Resonances belong to **PWG2**
- ECAL detector performance and basic physics performance studies are carried out in the **MPD-ECAL Software group**:
  - ✓ regular meetings with the possibility of remote access
  - ✓ many ongoing studies and vacant tasks related to detector and performance
  - ✓ contact me if you wish to join (riabovvg@gmail.com)
- Advanced neutral meson and electromagnetic signal studies belong to **PWG4**:
  - ✓ PWG4 is in the state of being formed, still develop tools for the advanced studies
  - ✓ please join and participate in formulation of agenda and active tasks
  - ✓ contact conveners if you wish to join
    - Victor Riabov – riabovvg@gmail.com
    - Chi Yang - chiyang@rcf.rhic.bnl.gov

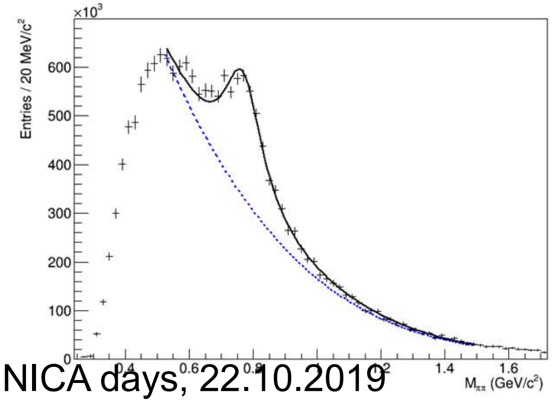
BACKUP

ρ(770), reconstructed peaks

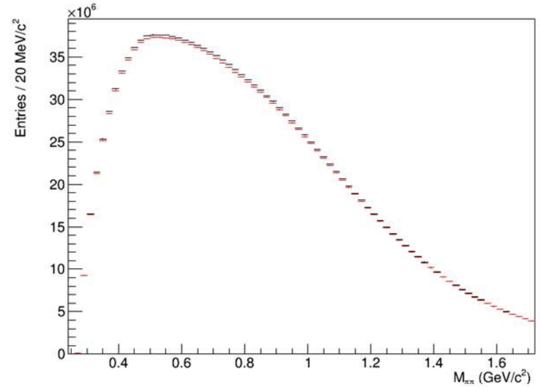
0.0-0.2 GeV/c

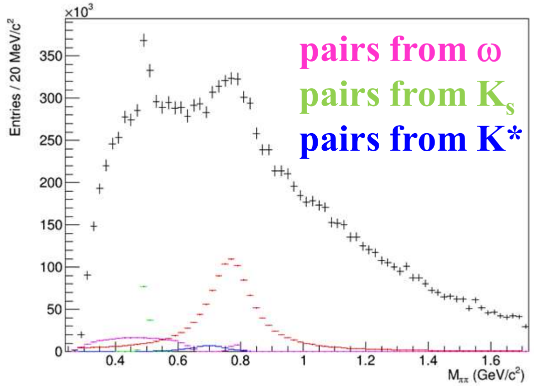


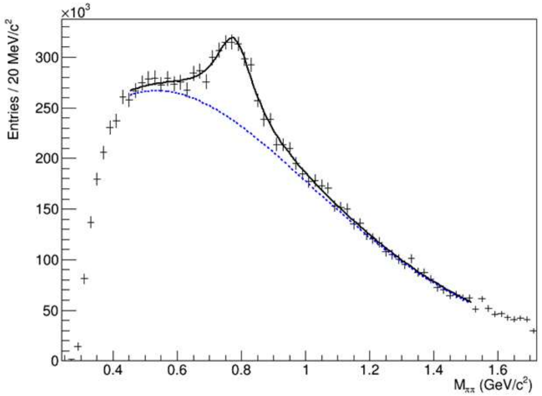




1.2-1.4 GeV/c







- 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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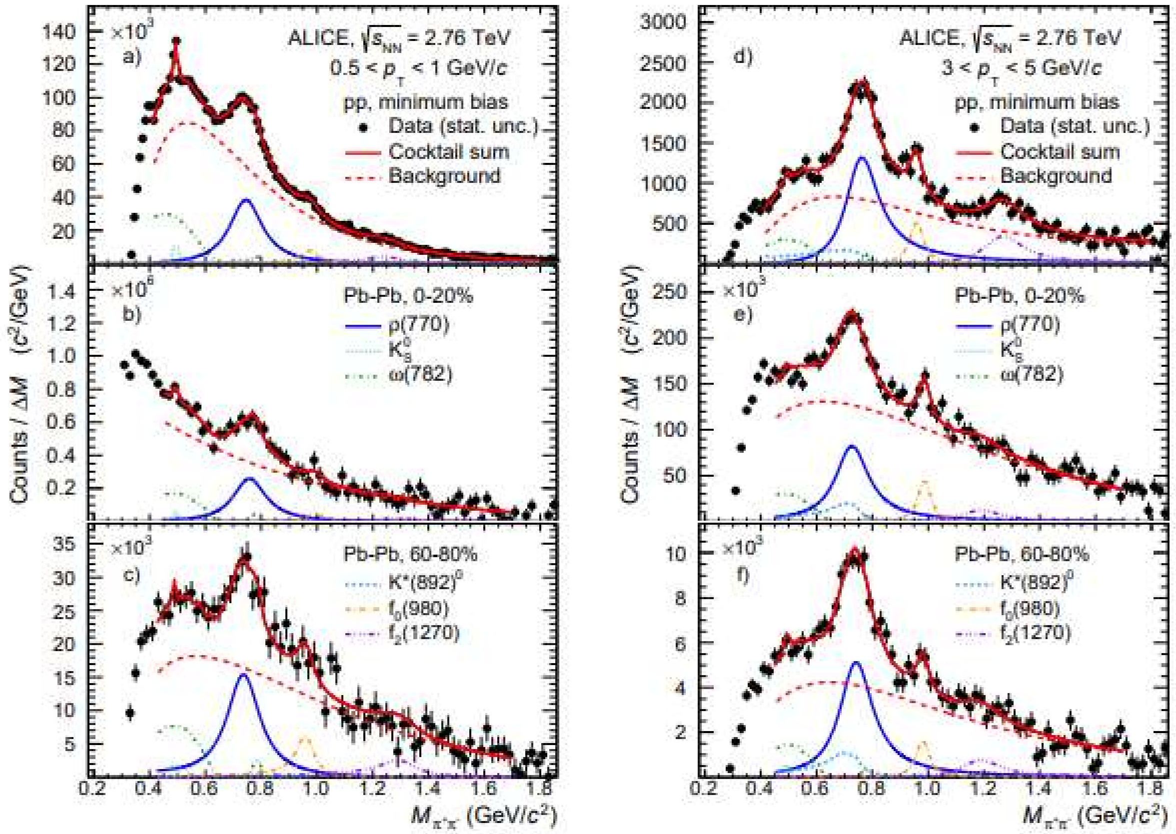
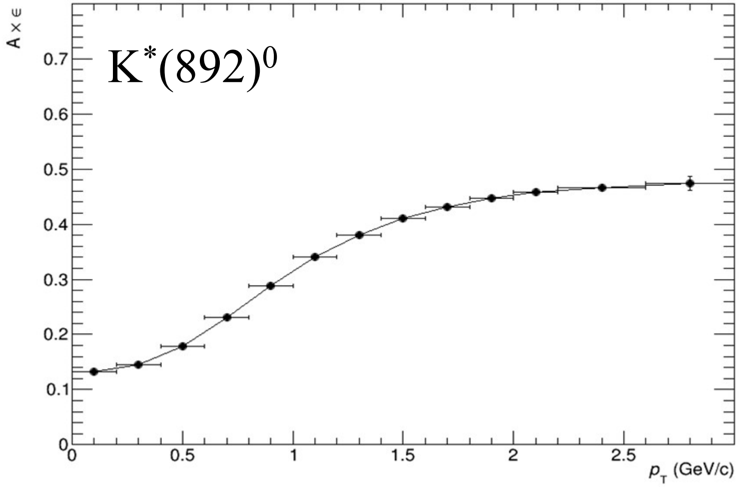
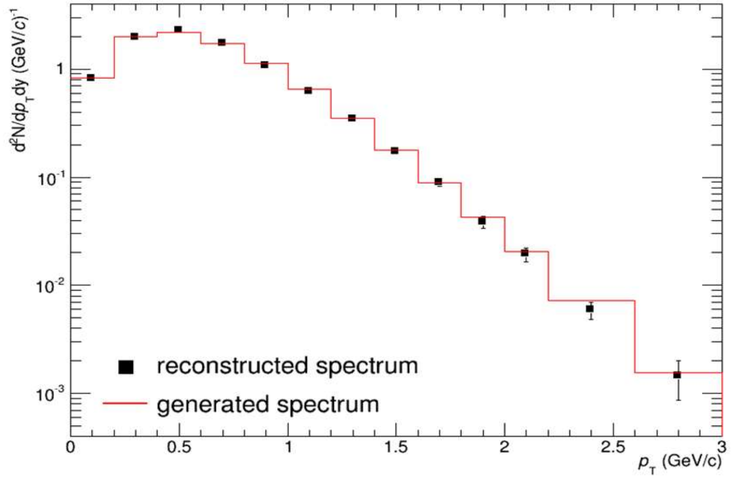
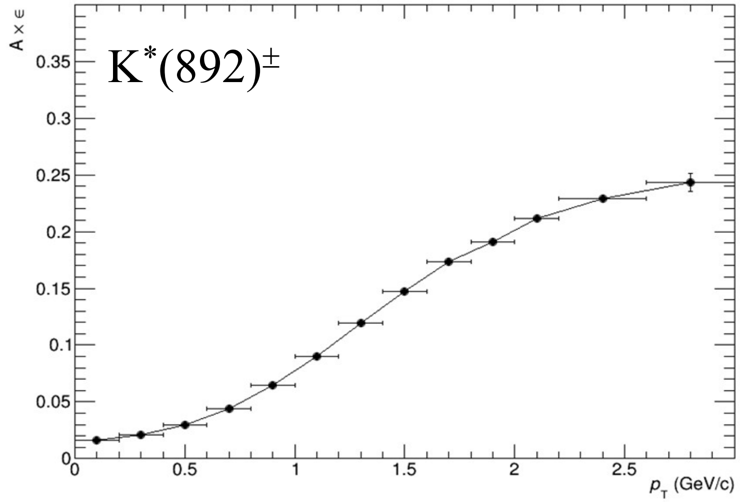


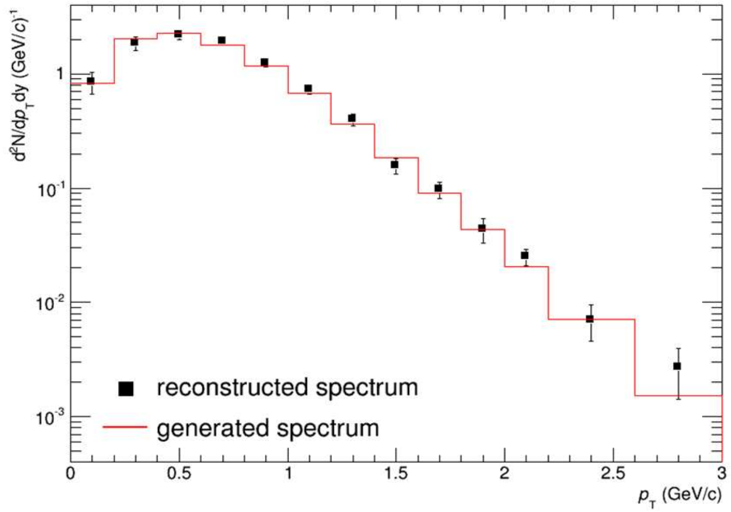
Fig. 1: (Color online) Invariant mass distributions for $\pi^+\pi^-$ pairs after subtraction of the like-sign background. Plots on the left and right are for the low and high transverse momentum intervals, respectively. Examples are shown for minimum bias pp, 0–20% and 60–80% central Pb–Pb collisions 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, ω(782), K*(892)^0, f_0(980) and f_2(1270). See text for details.

MC closure tests: $K^*(892)^0$, $K^*(892)^\pm$



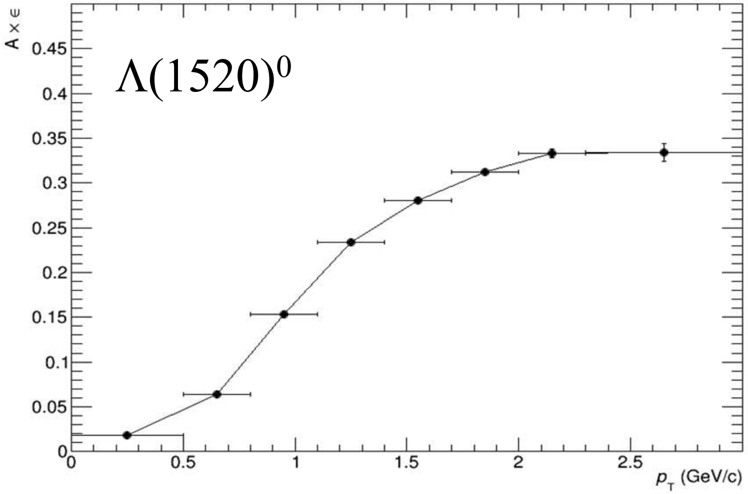


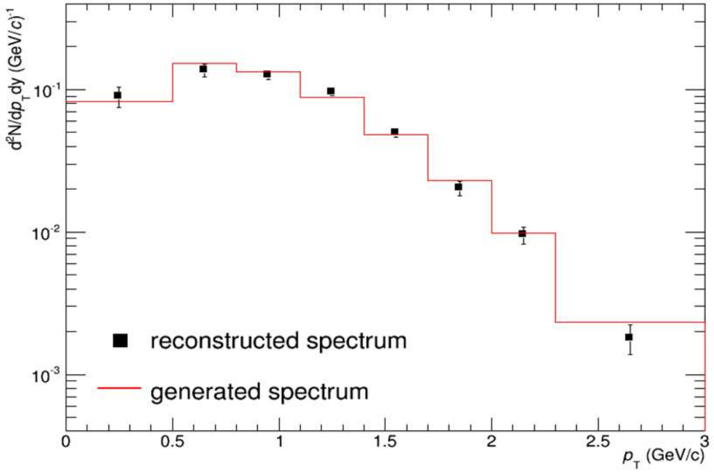


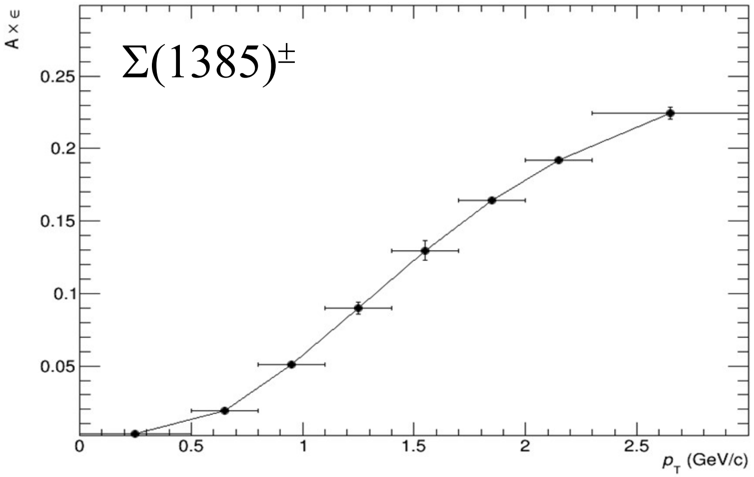


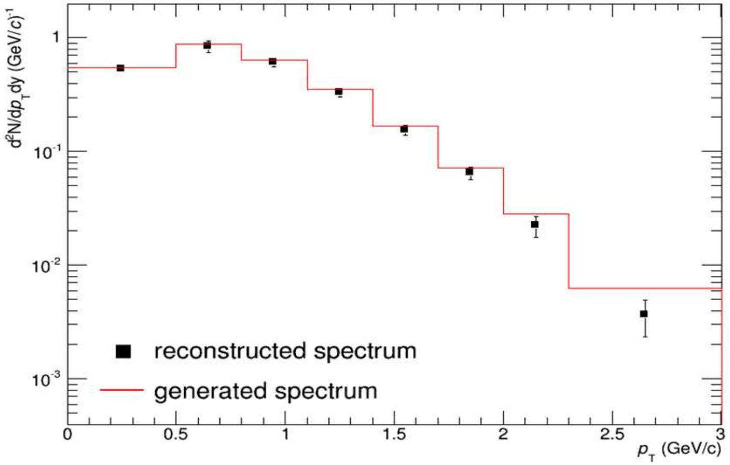
- Full chain reconstruction at $|y| < 1.0$
- Reconstructed spectrum matches the generated one within uncertainties

MC closure tests: $\Lambda(1520)$, $\Sigma(1385)^{\pm}$



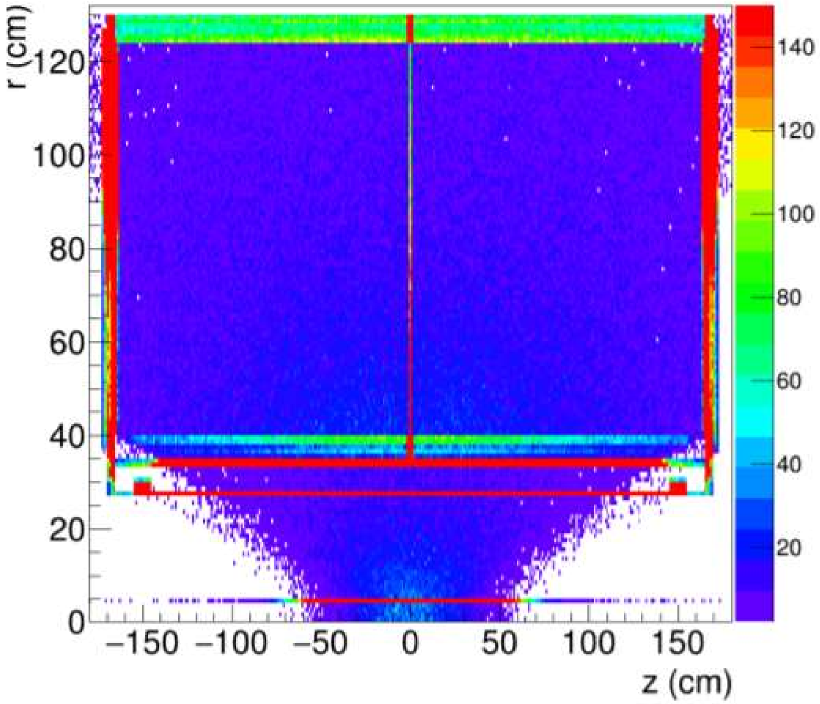


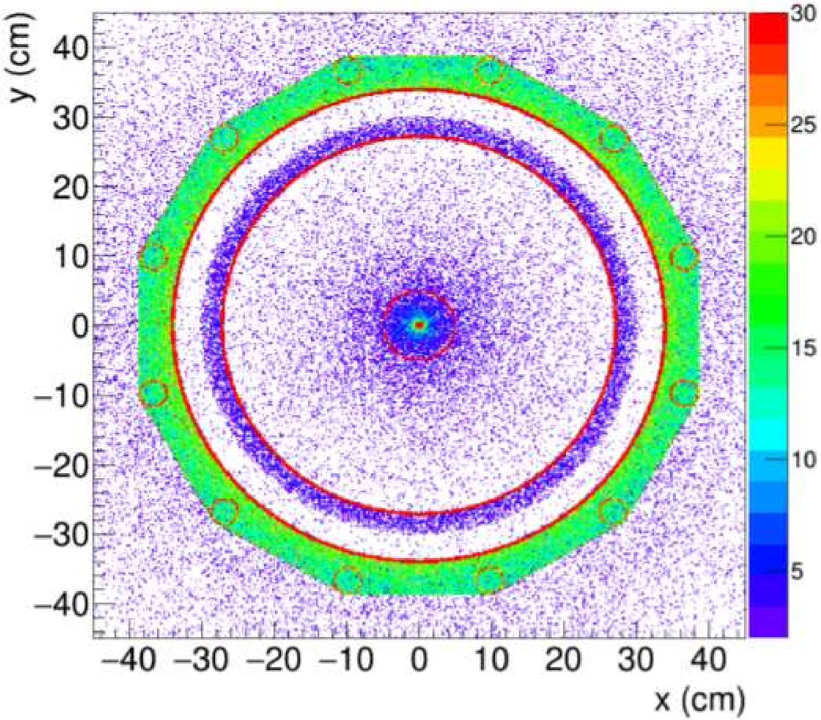




- Full chain reconstruction at $|y| < 1.0$
- Reconstructed spectrum matches the generated one within uncertainties

Photon conversion centers





Main conversion structures in Stage 1:

- Beam pipe: 0.3% X_0
- Inner TPC barrel structures: 2.4% X_0

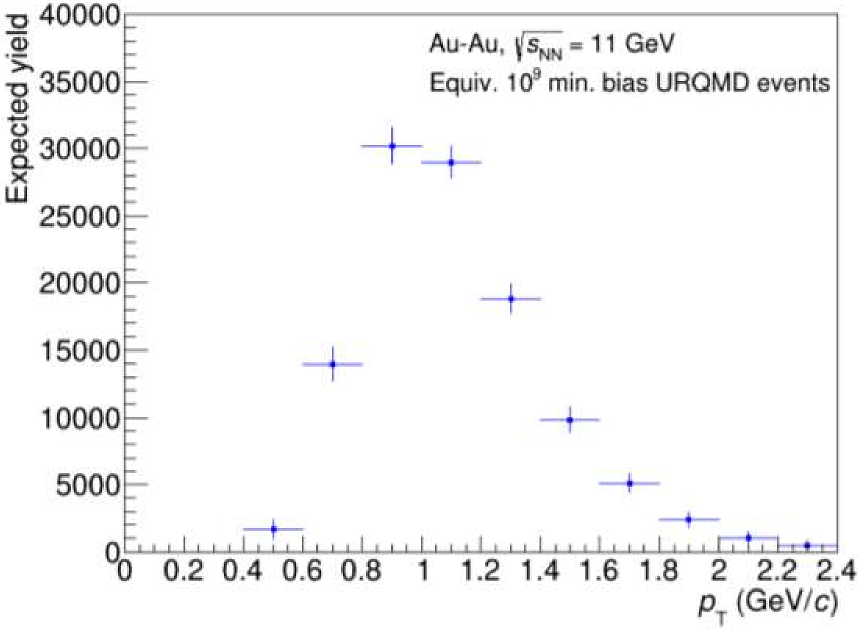
Future:

- Inner tracking system
- Dedicated photon convertor (cylindrical metal pipe) under investigation

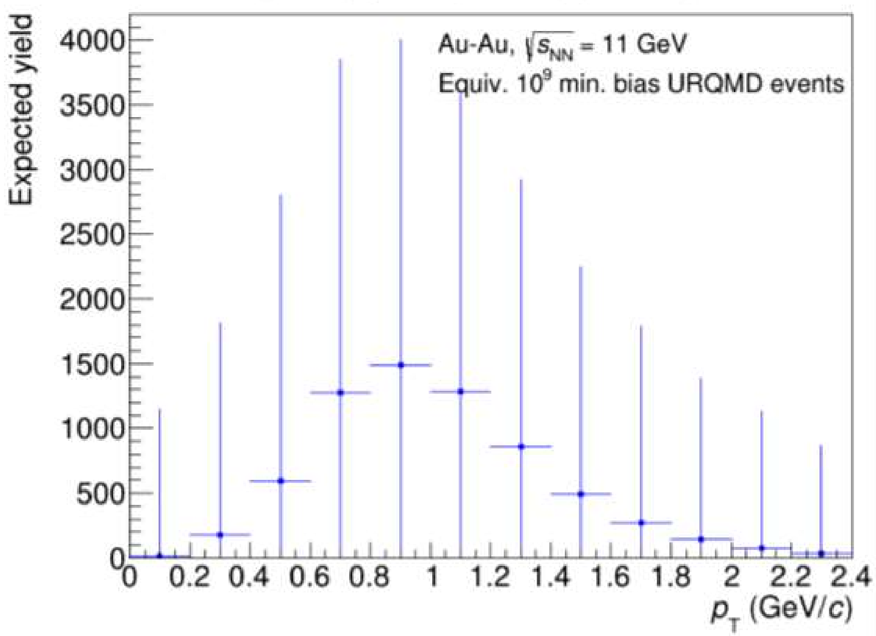
First-year projections

- L ~5 x 10^{25} cm^{-1} s^{-1}
- 10 weeks
- 50% duty factor
- => 10^9 minimum bias events
- Background and signal distributions scaled to 10^9 min. bias events
- Statistical uncertainties estimated as sqrt(S+B)

$\pi \rightarrow \gamma\gamma \rightarrow (e^+e^-)(e^+e^-)$



$\eta \rightarrow \gamma\gamma \rightarrow (e^+e^-)(e^+e^-)$



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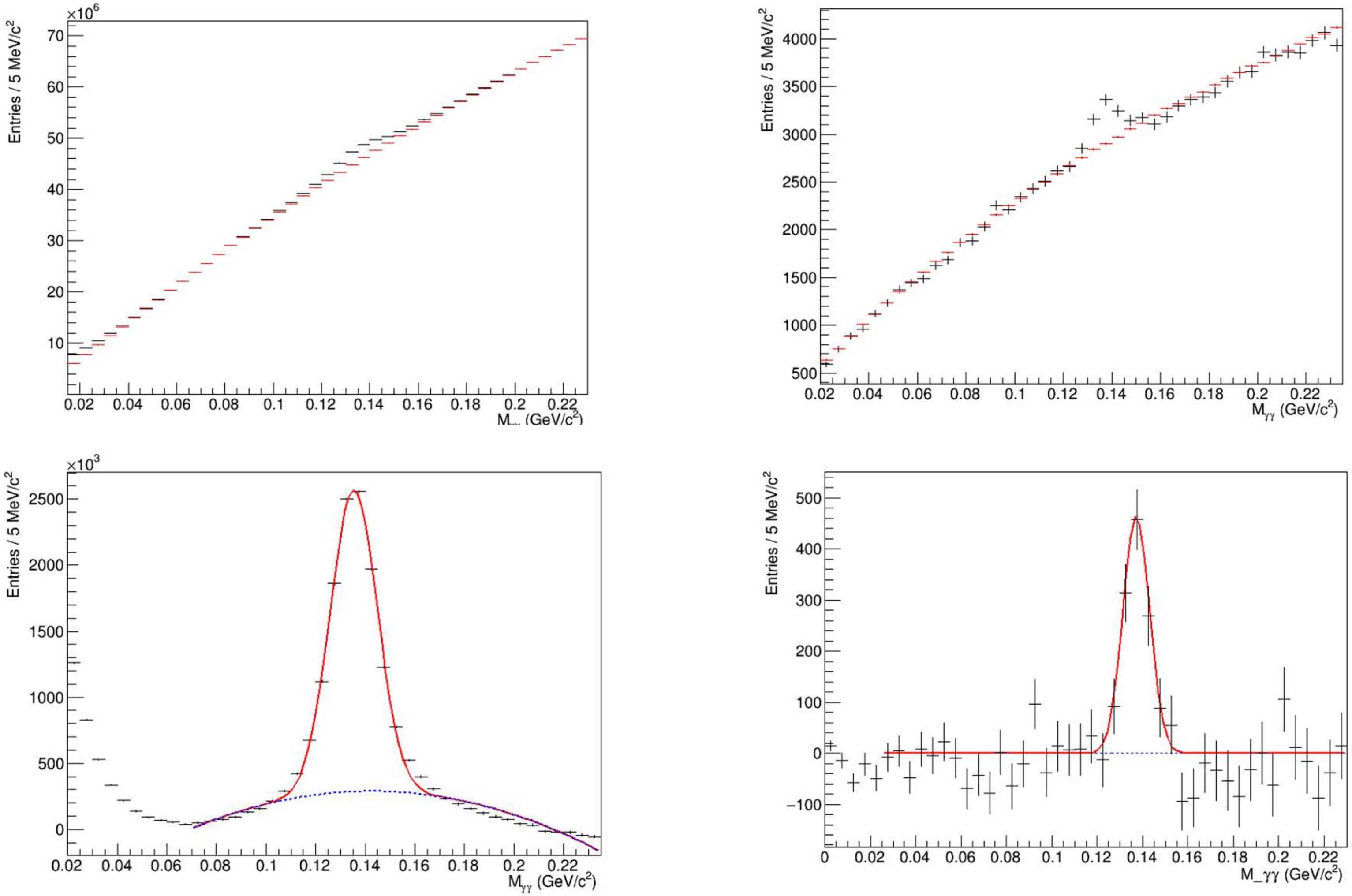
Reconstructed π^0, $p_T \sim 0.75$ GeV/c



- Advantage of ECAL – high efficiency and huge statistics
- Advantage of PCM – better S/B ratio and higher resolution