$\varphi(1020)$ and $K^*(892)^0$ resonance production in BiBi@9.2 GeV

Mikhail Malaev

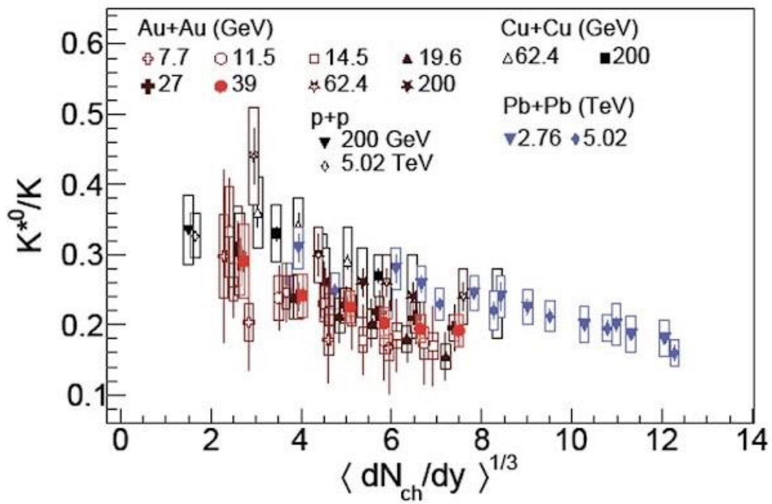
Resonances in heavy-ion collisions

- ✓ Vacuum properties of resosnances are well defined; 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.

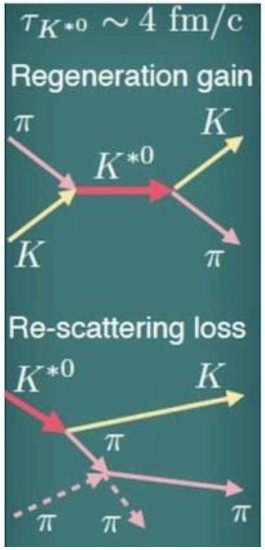
Hadronic phase and medium modifications

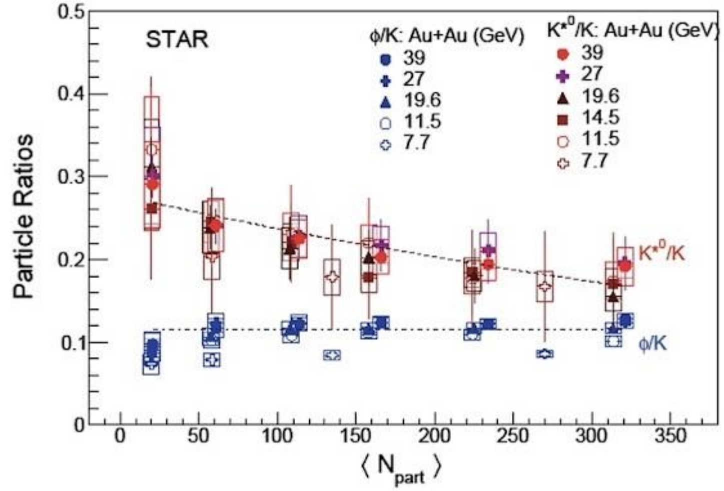
Ratio K^{*0} to K from BES data suggests re-scattering loss in medium due to shorter lifetime of K^{*0}

The K^{*0}/K ratio shows a centrality dependence and follows the same trend among different collision energies. On the contrary, the ϕ/K ratio is mostly independent of centrality.



DOI: [10.1103/PhysRevC.107.034907](https://doi.org/10.1103/PhysRevC.107.034907)





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

Reconstructed resonance yields in heavy ion collisions are defined by:

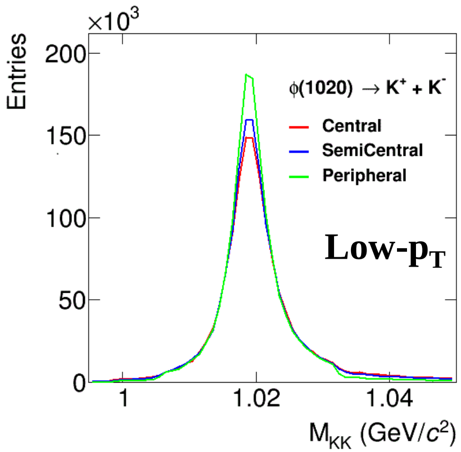
- ✓ resonance yields at chemical freeze-out
- ✓ hadronic processes between chemical and kinetic freeze-outs:

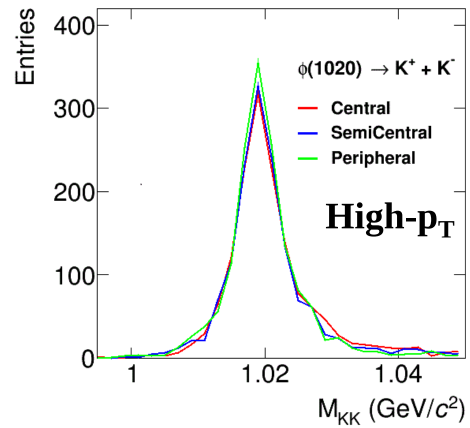
rescattering: daughter particles undergo elastic scattering or pseudo-elastic scattering through a different resonance → parent particle is not reconstructed → loss of signal

regeneration: pseudo-elastic scattering of decay products ($\pi K \to K^{*0}$, $KK \to \phi$ etc.) → increased yields

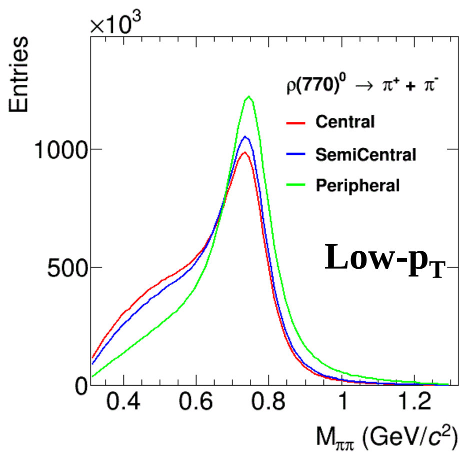
Resonances in AuAu@11 GeV, UrQMD

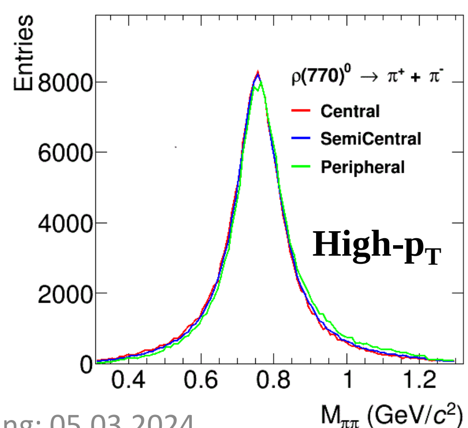
- ❖ Resonances are decayed by UrQMD, daughters participate in elastic and inelastic scattering
- ❖ Resonance are reconstructed by invariant mass method according to decay channels
- ❖ $\phi \to K^+K^-$ ($c\tau$ ~ 45 fm/c): modest line shape modifications in central AuAu@11 at low p_T





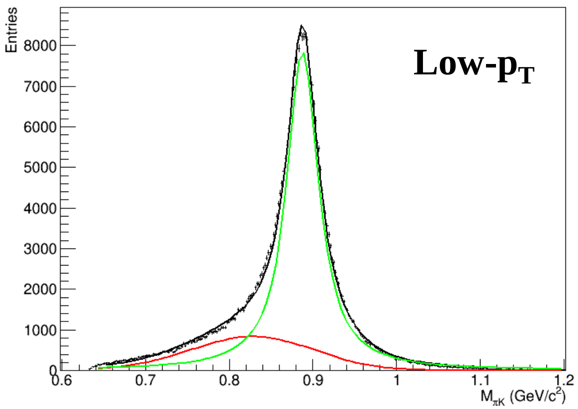
- ❖ $\rho(770)^0 \to \pi^+\pi^-$ ($c\tau$ ~ 1.3 fm/c): significant line shape modifications in central AuAu@11 at low p_T

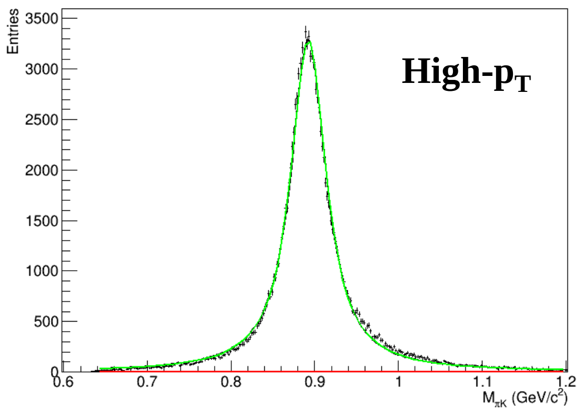




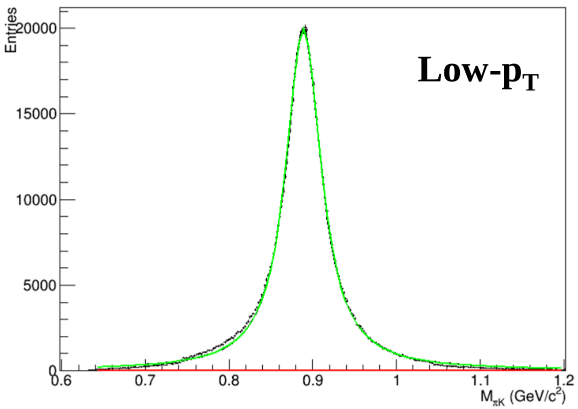
K*(892)^0 in AuAu@11 GeV, UrQMD

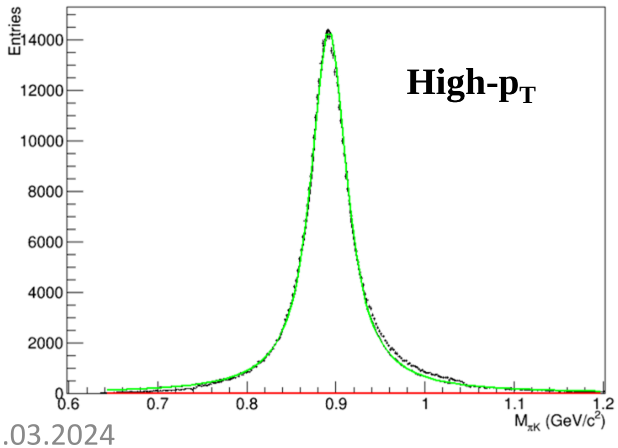
- $K^*(892)^0 \rightarrow \pi^\pm K^\pm$ ($c\tau$ ~ 4.2 fm/c); combine $\pi^\pm K^\pm$ pairs from true $K^*(892)^0$ decays
- Same fitting function for $K^*(892)^0$ and background as in ALICE
- Central collisions: small line shape modifications at low p_T; nothing at higher momentum





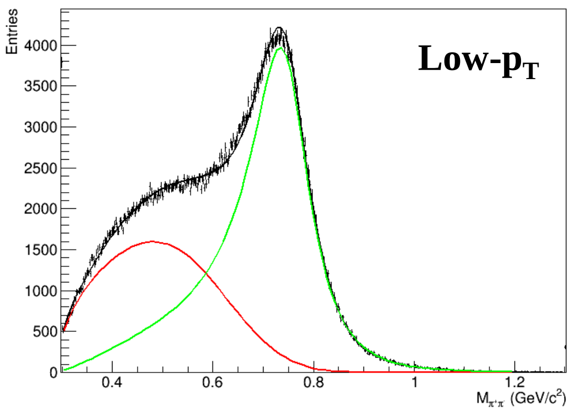
- Peripheral collisions: nothing

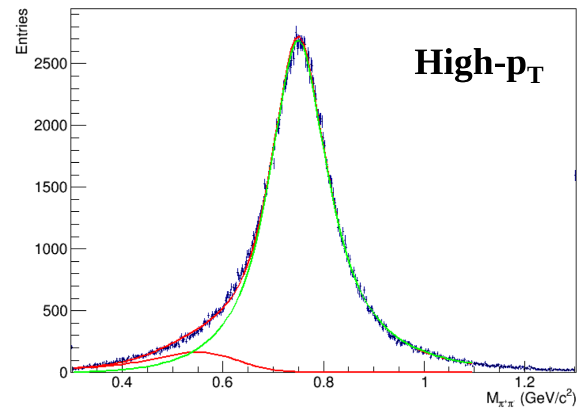




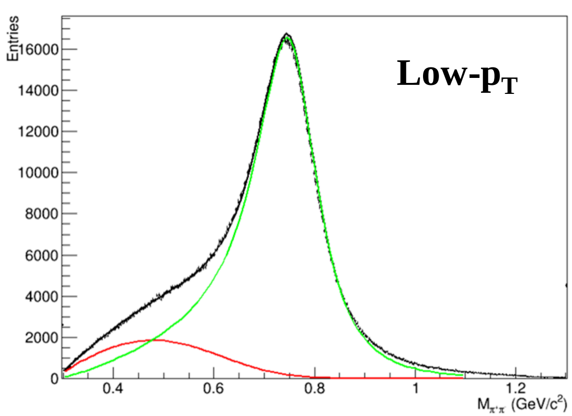
ρ(770) in AuAu@11 GeV, UrQMD

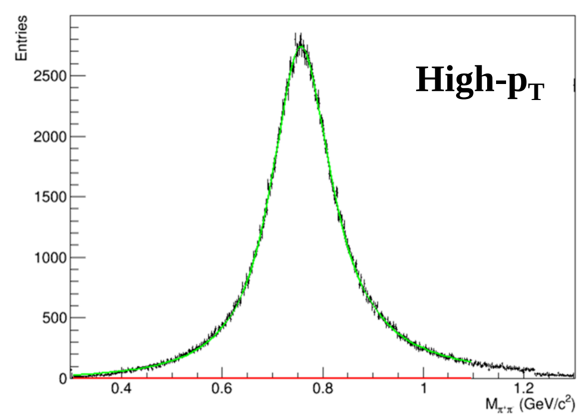
- $\rho(770)^0 \rightarrow \pi^+\pi^-$ ($c\tau \sim 1.3$ fm/c); combine $\pi^+\pi^-$ pairs from true $\rho(770)^0$ decays
- Same fitting function for $\rho(770)^0$ and background as in ALICE
- Central collisions: significant line shape modifications; excess with respect to the peak model is described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





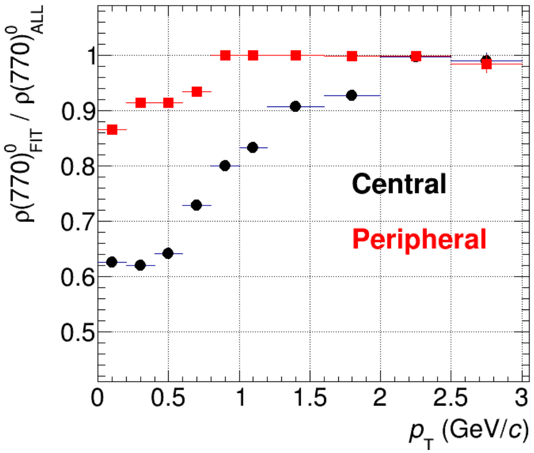
- Peripheral collisions: much smaller modifications are observed, only at low momentum



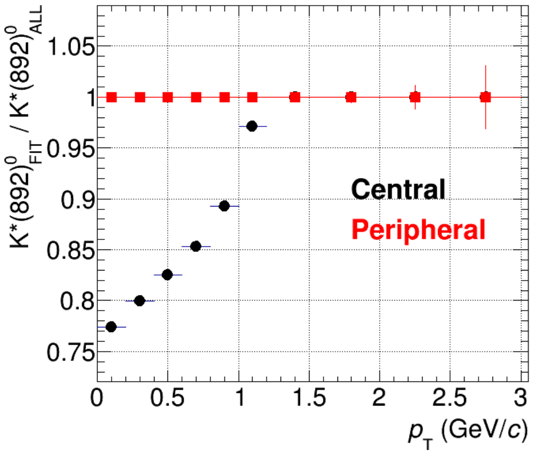


Yields of $K^*(892)^0$ and $\rho(770)^0$ in AuAu@11 GeV, UrQMD

❖ $\rho(770)^0 \to \pi^+\pi^-$ ($c\tau$ ~ 1.3 fm/c)
- ✓ yield is undercounted because of pion rescattering;
- ✓ this yield is preserved in e^+e^- measurements !!!



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

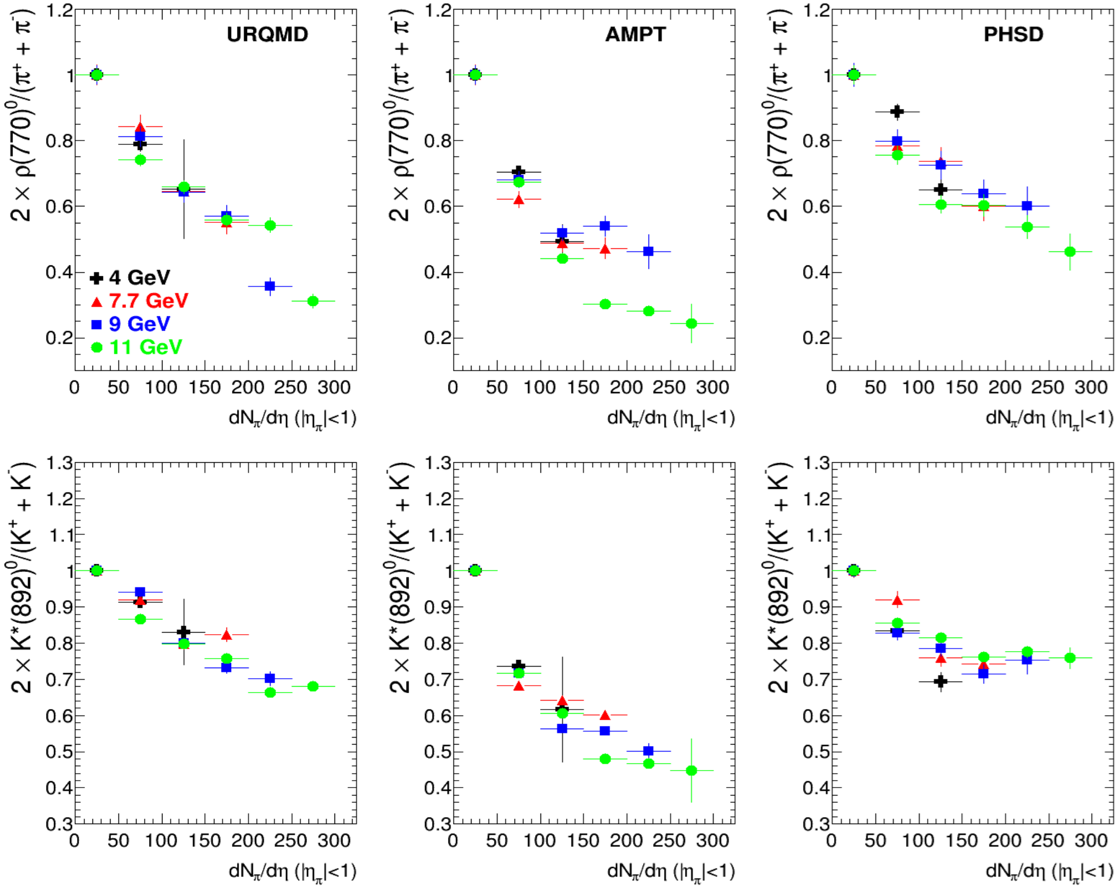


❖ Signal losses are larger for shorter-lived $\rho(770)^0$ → higher chance for $\rho(770)^0$ to decay and for daughters to rescatter in the medium

❖ 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

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

- ❖ Models with hadronic cascades (UrQMD, PHSD, AMPT)
- ❖ Ratios for two shortest-lived resonances (ρ, $K^{*}(892)$) 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

Analysis Details

- Data: Request 25, BiBi@9.2 GeV, UrQMD+Geant4
- Analysis train: Request 6 with resonance wagons
  - Event and track selection:

Event selection:

mZvtxCut 130 // cut on vertex z coordinate

event.getCentrTPC() // Centrality determination

PID cuts:

mPIDsigTPC 2 // dEdx PID parameters

mPIDsigTOF 2 // dEdx PID parameters

mNofHitsCut 10 // minimal number of hits for a track

mEtaCut 1.0 // maximal pseudorapidity for a track

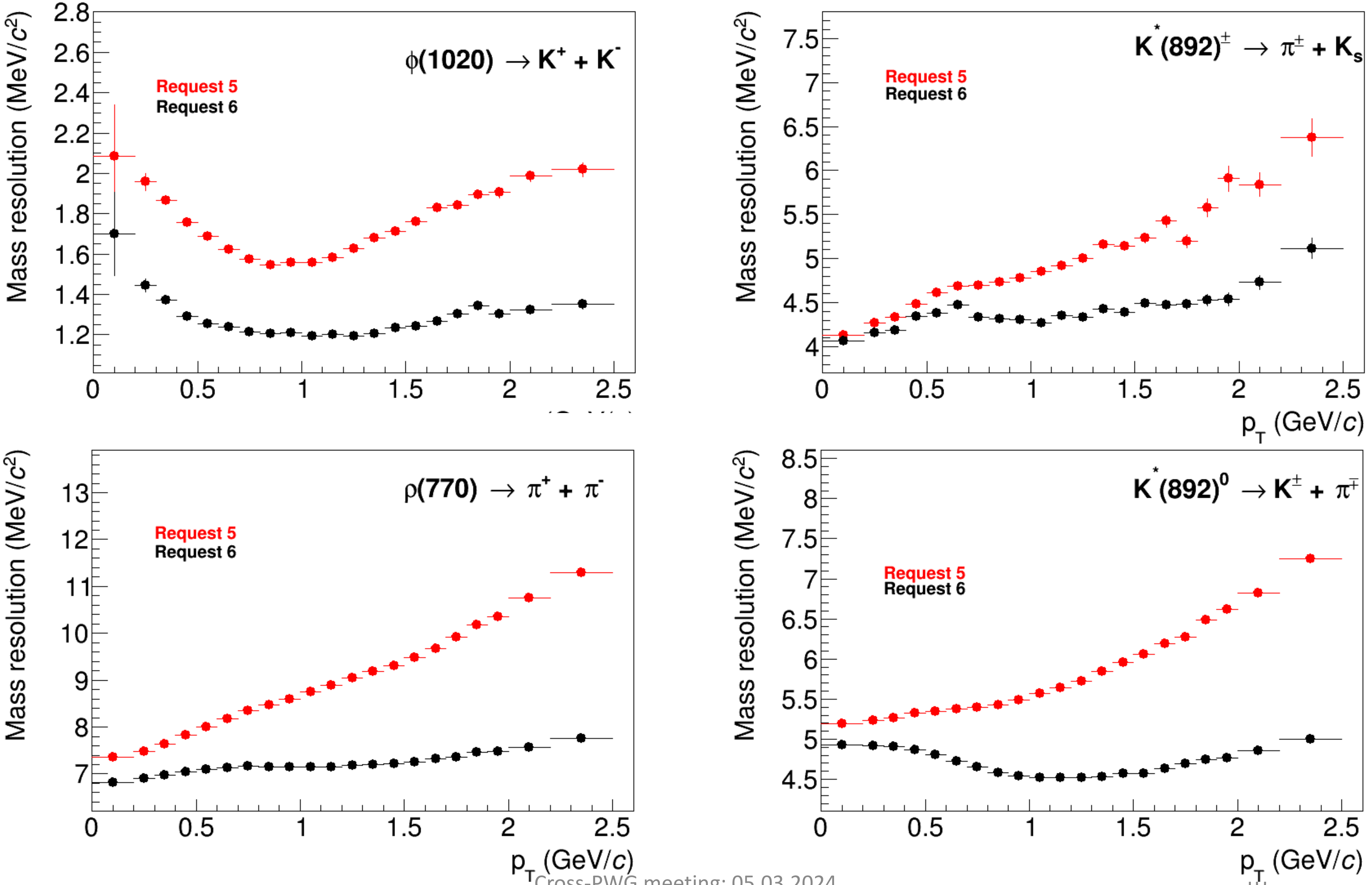
mPtminCut 0.1 // minimal pt for a track

mDCACut 2.0*σ // maximum DCA for a track ($\sigma = \sigma(p_T$, centrality))

Pair cuts:

mYCut 0.5 // pair rapidity cut

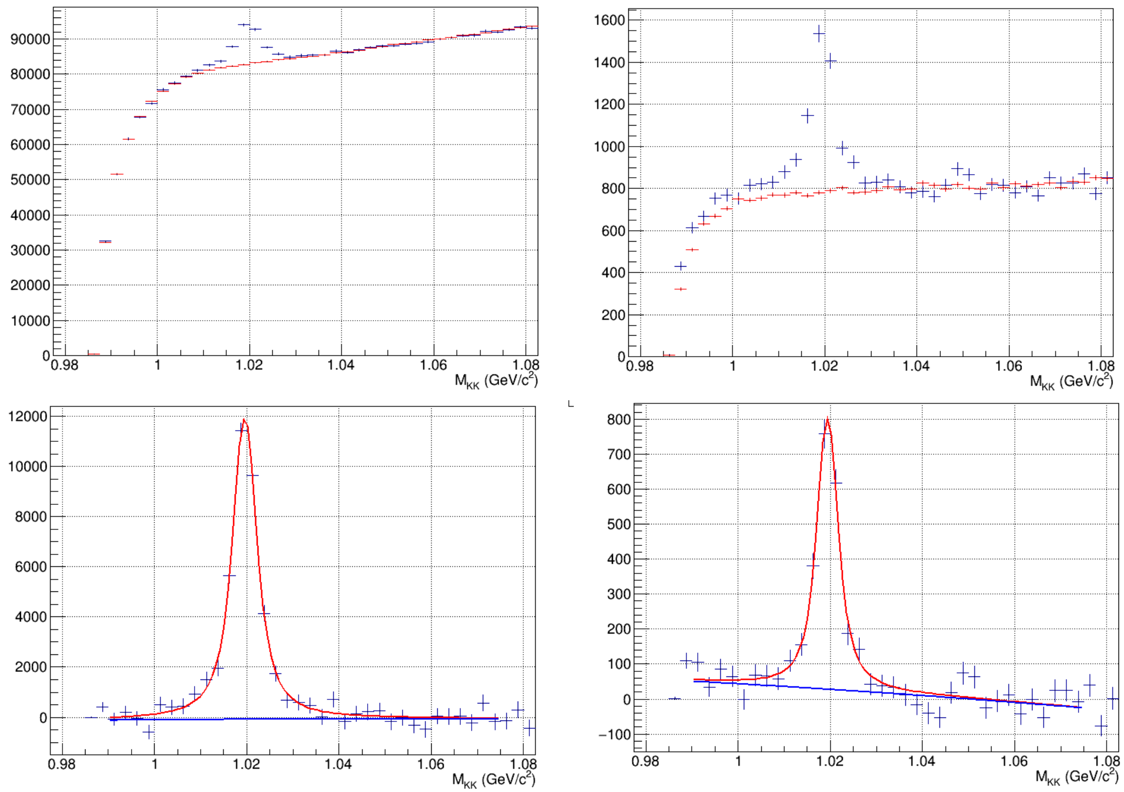
Mass Resolution for resonances

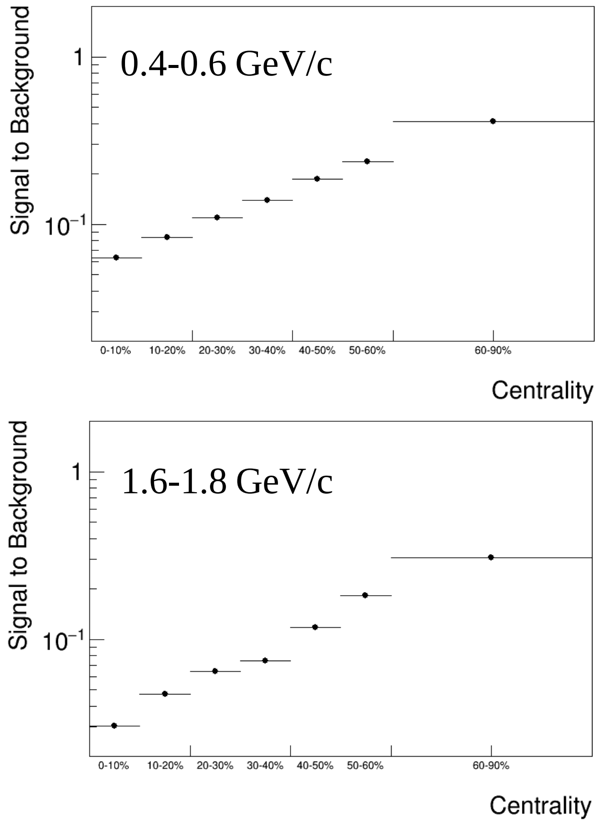


φ(1020), reconstructed peaks

❖ Full chain simulation and reconstruction, p_T = 0.4-0.6 GeV/c, φ(1020)→K^+ + K^-, |y| < 0.5

0-10% 60-90%





❖ Mixed-event combinatorial background is scaled to foreground at high mass and subtracted

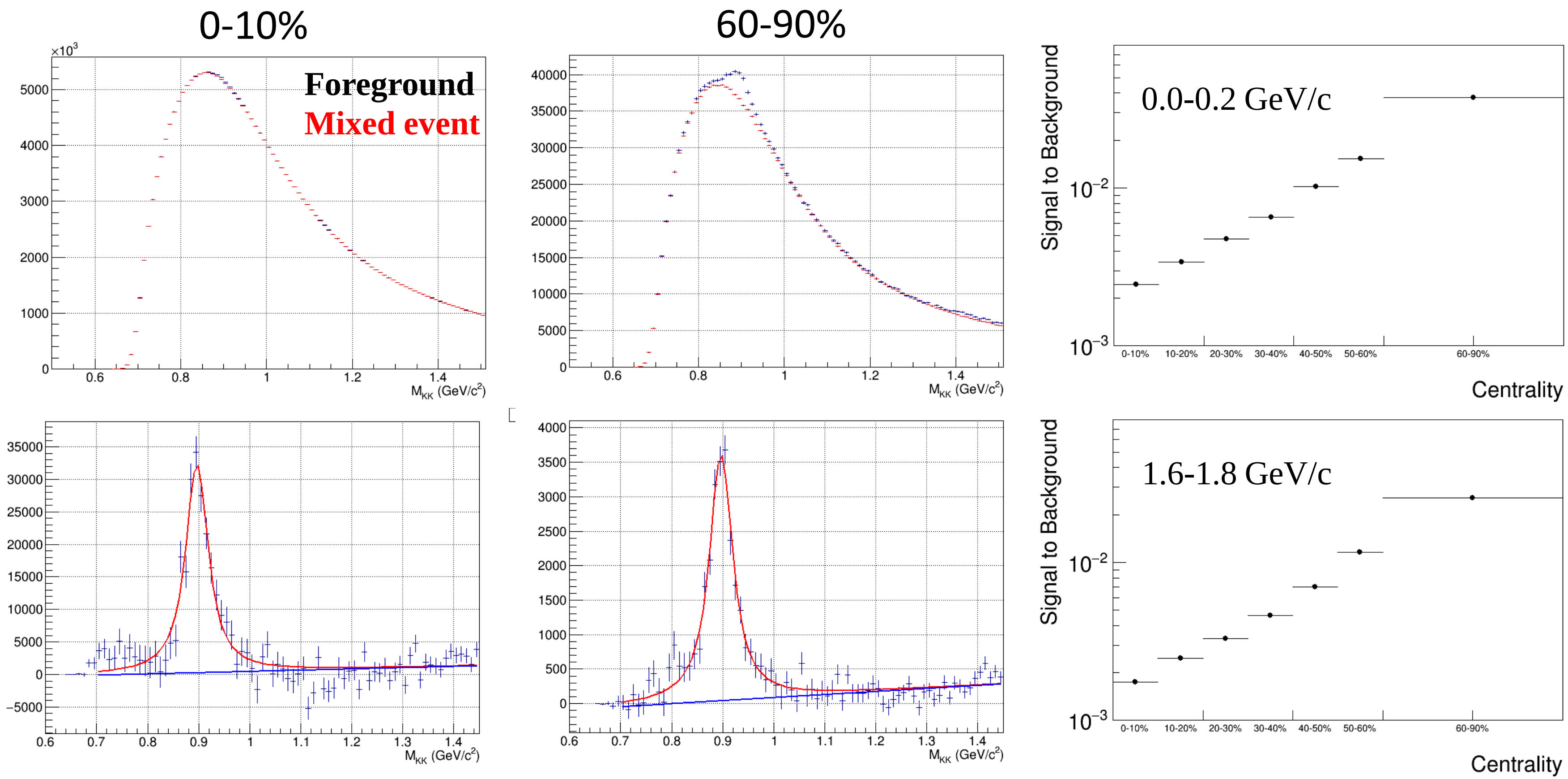
❖ Distributions are fit to Voigtian function + polynomial (mass resolution fixed to estimated value, Γ - free parameter)

❖ 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

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

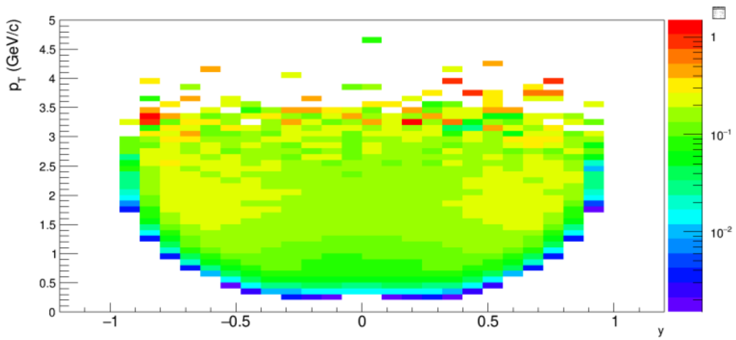
- Full chain simulation and reconstruction, p_T = 0.0-0.2 GeV/c, $K^*(892)^0 \rightarrow K^+ + \pi^-$, $|y| < 0.5$

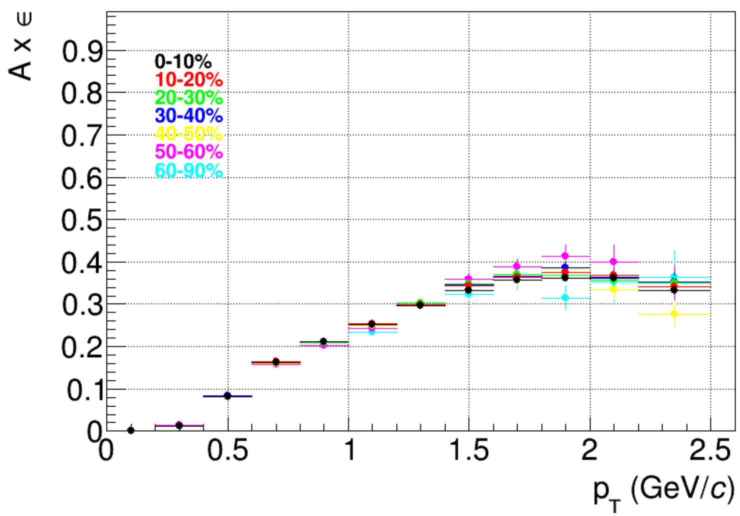


- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Distributions are fit to Voigtian function + polynomial (mass resolution fixed to estimated value, Γ - free parameter)
- Signal can be reconstructed at $p_T > 0$ for $K^*(892)^0$, high-p_T reach is limited by available statistics
- S/B ratios deteriorates with increasing centrality

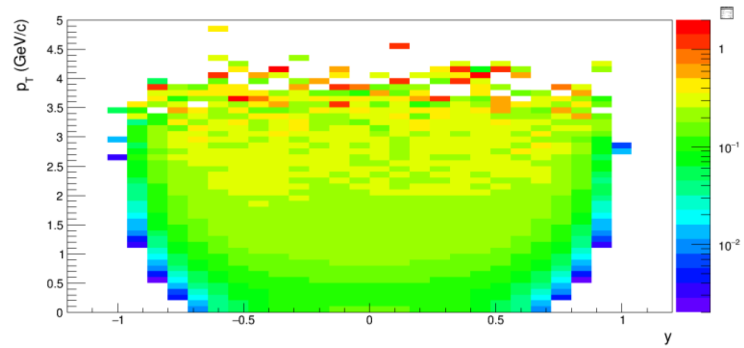
Reconstruction efficiencies

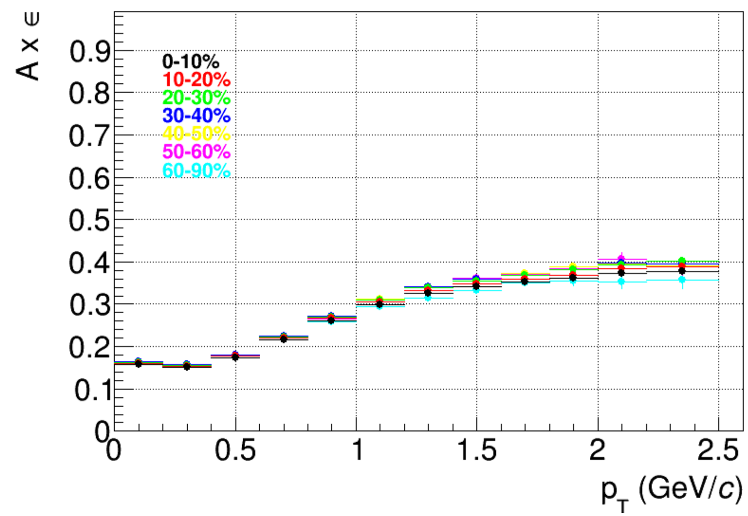
ϕ(1020)





$K^*(892)^0$



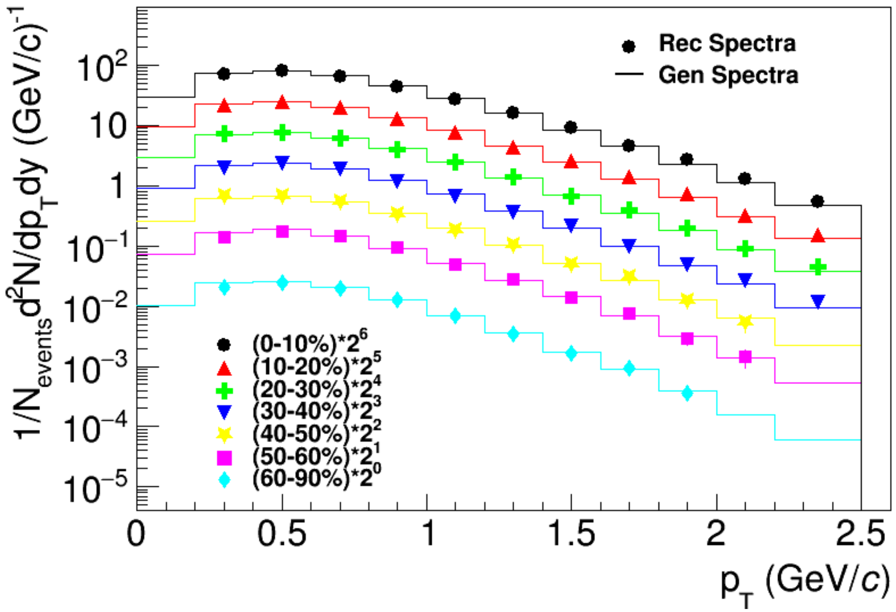


- Reasonable efficiencies in the wide p_T range, $|y| < 0.5$
- Measurements are possible from 0 momentum for $K^*(892)^0$ and from 0.2 GeV/c for φ(1020)
- Modest centrality dependence

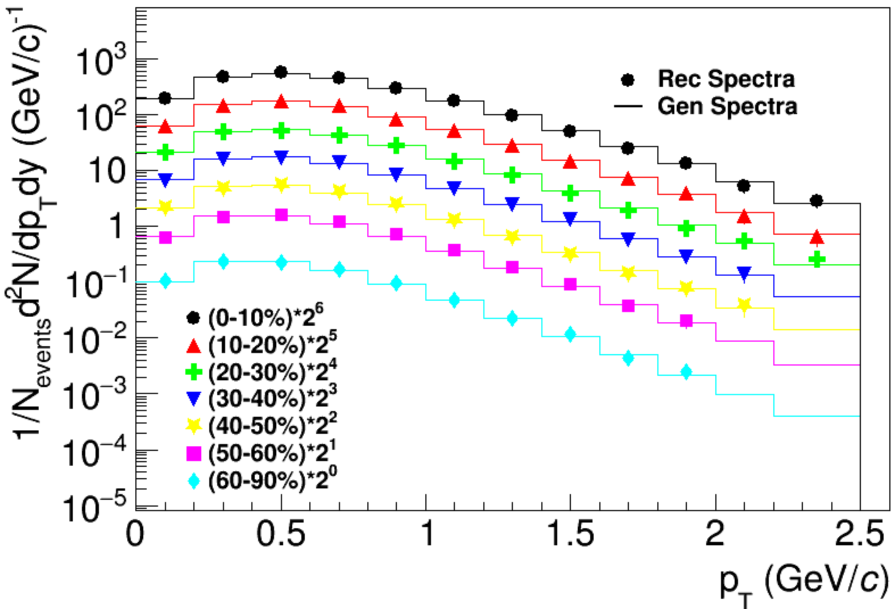
MC closure tests

❖ Full chain simulation and reconstruction, p_T ranges are limited by the possibility to extract signals, $|y| < 0.5$

ϕ(1020)



K*(892)⁰



❖ Reconstructed spectra match the generated ones within uncertainties

❖ First measurements for resonances in centrality dependent analysis will be possible with accumulation of ~ 10^8 A+A events

❖ Measurements are possible starting from ~ zero momentum → sample most of the yield, sensitive to possible modifications

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 in centrality dependent analysis will be possible with accumulation of ~ 10^8 A+A events

- ✓ Measurements are possible starting from very low momenta with decent mass resolution → high sensitivity to different physics phenomena most prominent at low p_T

- ✓ Other resonances including multi-stage decays of $K^*(892)^{\pm}$, $\Sigma(1385)^{\pm}$ and $\Xi(1520)^0$ → work in progress

Backup slides

Feasibility studies, framework

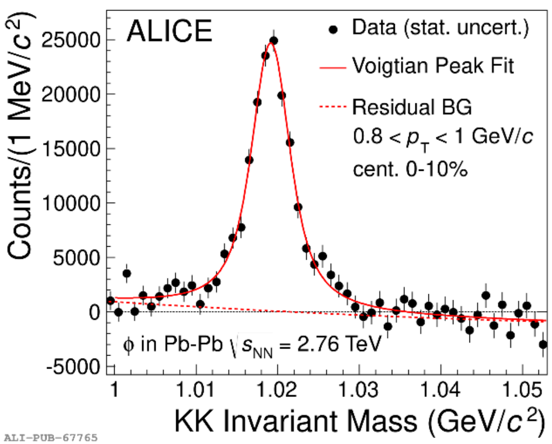
- Simulated minbias AuAu@11 collisions using UrQMD 3.4 with default settings
- Tracked simulated particles through the MPD Phase-I detector using *mpdroot*
- Analysis cuts were optimized for higher signal significance (no p_T variation)

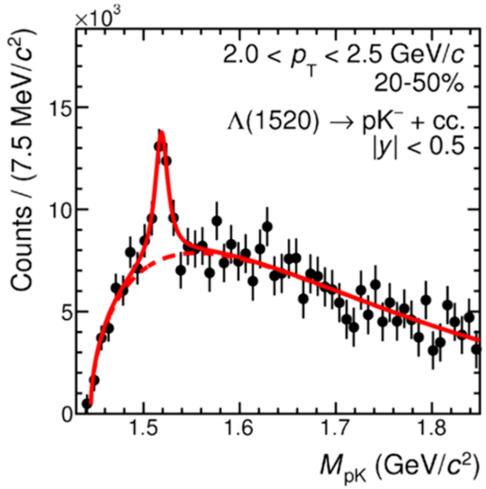
  - Event selection:
    - ✓ $|Z_{vrtx}| < 50$ cm, realistic distribution
  - Basic track selections:
    - ✓ number of TPC hits > 24
    - ✓ $|\eta| < 1.0$
    - ✓ $p_T > 50$ MeV/c
    - ✓ TPC-TOF combined PID, probability > 0.5
    - ✓ TPC-refit for kaons and protons based on track PID hypothesis
  -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

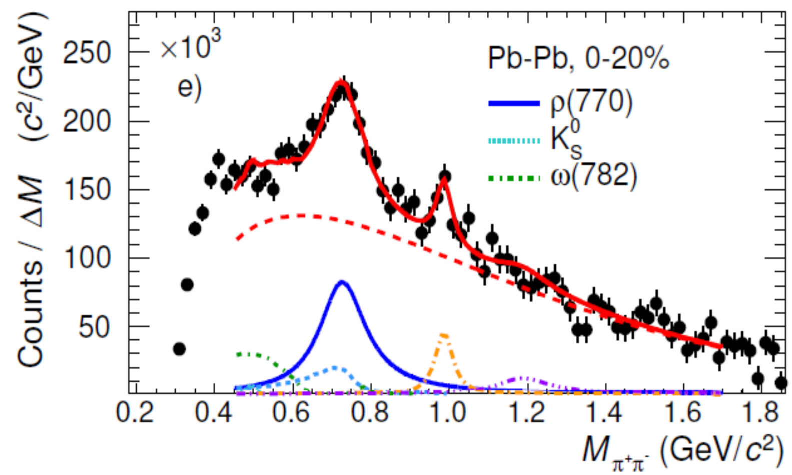
- Combinatorial background:
  - ✓ event mixing ($|\Delta_{Zvrtx}| < 2$ cm, $|\Delta_{Mult}| < 20$, $N_{ev} = 10$)

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

ρ(770), signal extraction – practice tests

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

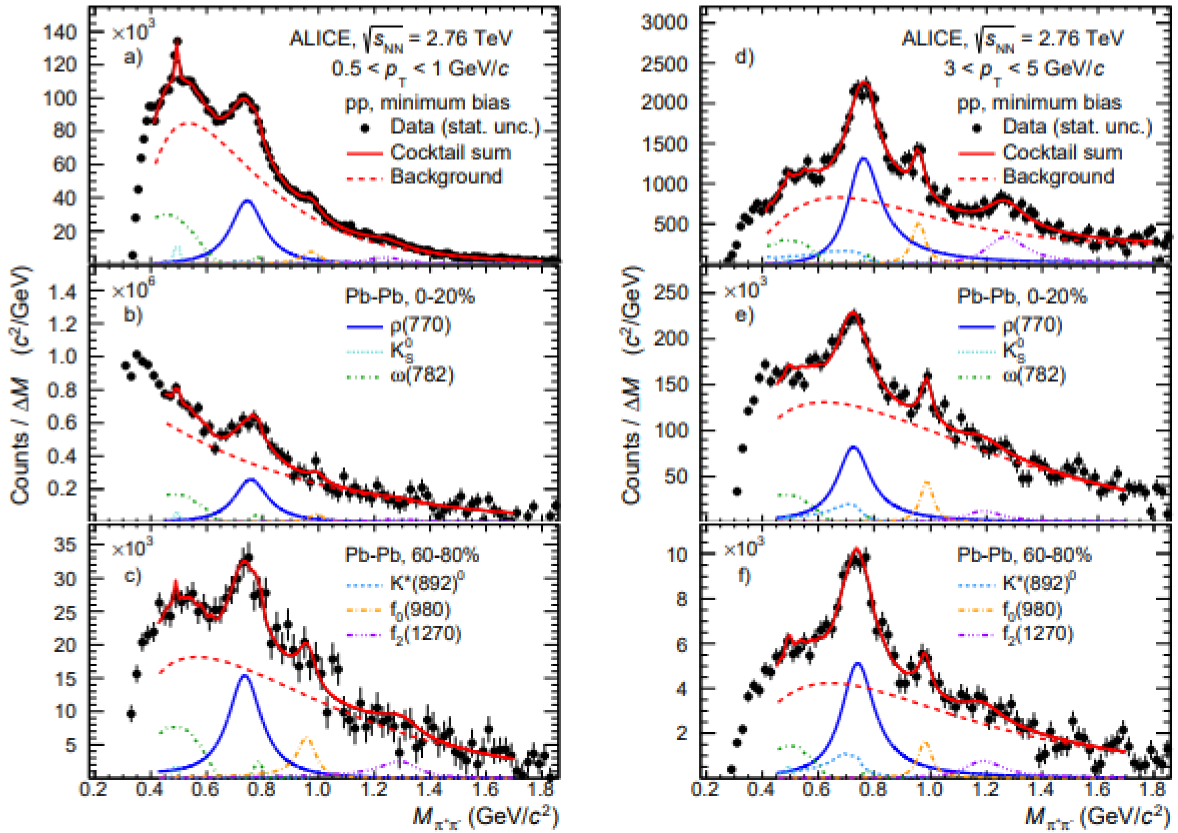
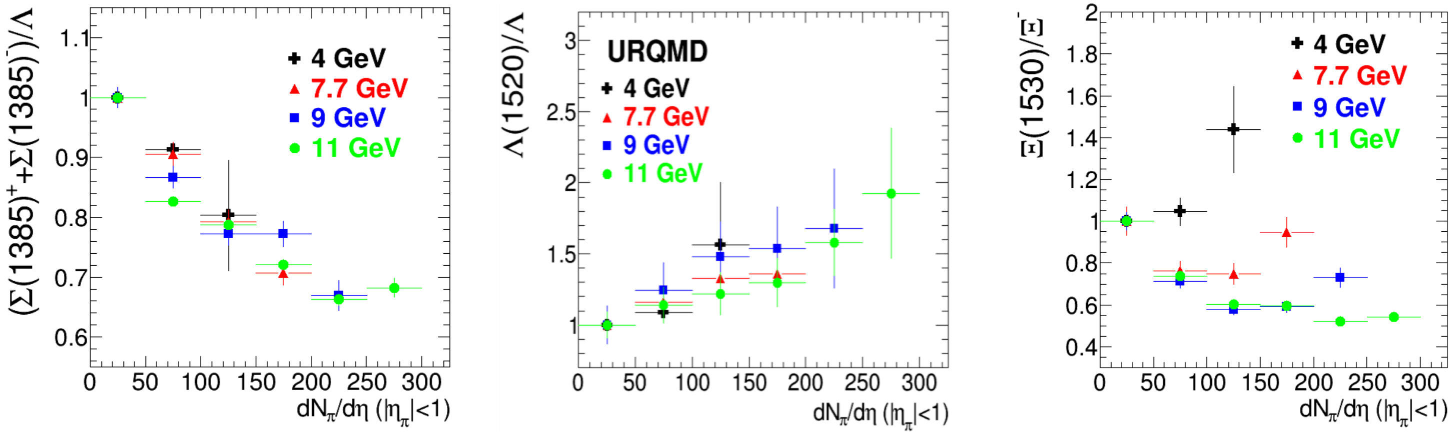
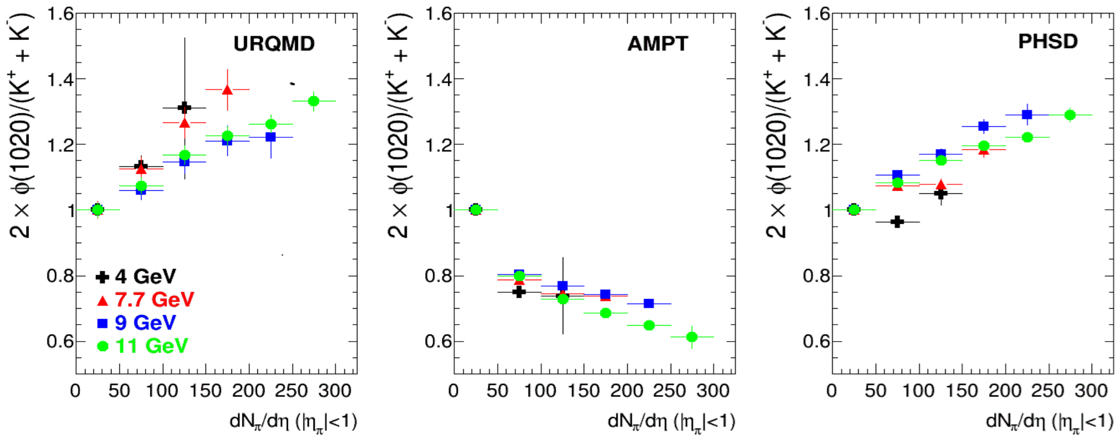


Fig. 1: (Color online) Invariant mass distributions for $\pi^+\pi^-$ pairs after subtraction of the like-sign background. Plots on the left and right are for the low and high transverse momentum intervals, respectively. Examples are shown for minimum bias pp, 0–20% and 60–80% central Pb–Pb collisions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

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

- Models with hadronic cascades (UrQMD, PHSD, AMPT)
- Ratios for longer-lived resonances (Σ(1385), Λ(1520), Ξ(1530) and ϕ)

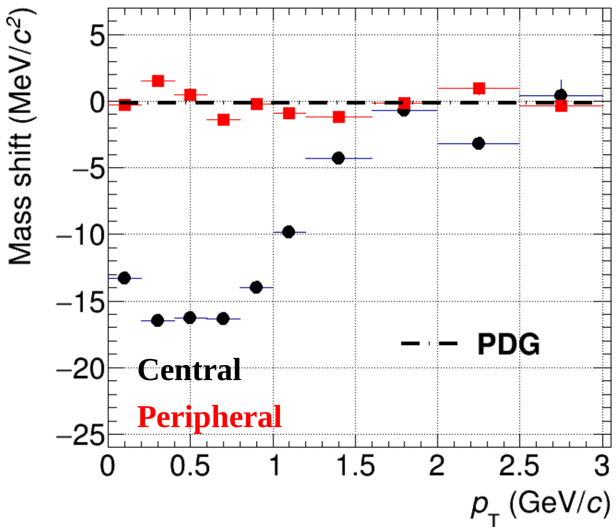




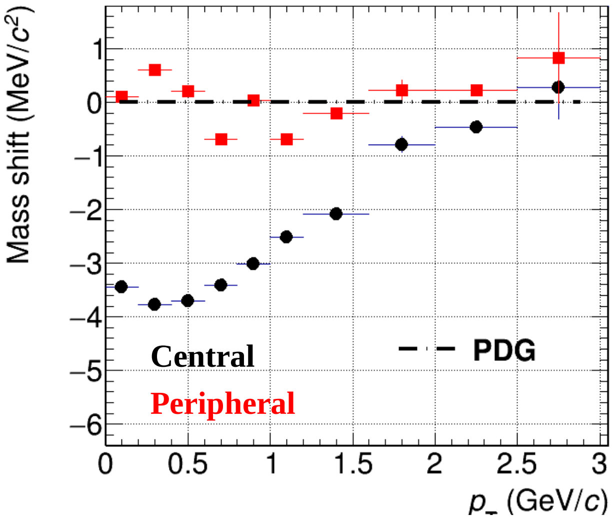
- Event generators predict yield modifications qualitatively similar to those obtained at RHIC/LHC:
  - → lifetime and density of the hadronic phase are high enough
  - → modification of particle properties in the hadronic phase should be taken into account when model predictions for different observables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

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

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

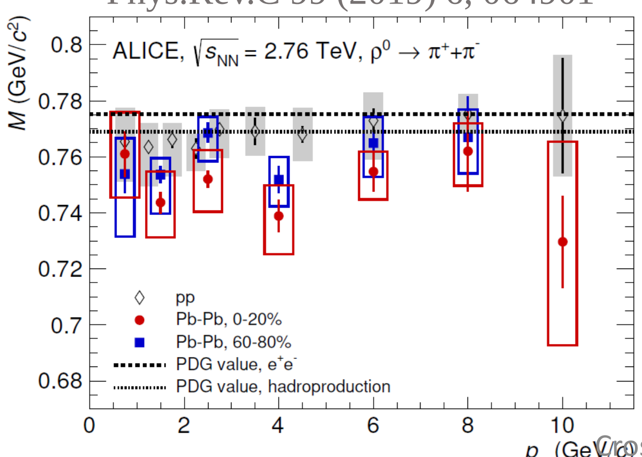


- ❖ $K^*(892)^0 \to \pi^\pm K^\pm$ ($c\tau \sim 4.3$ fm/c)

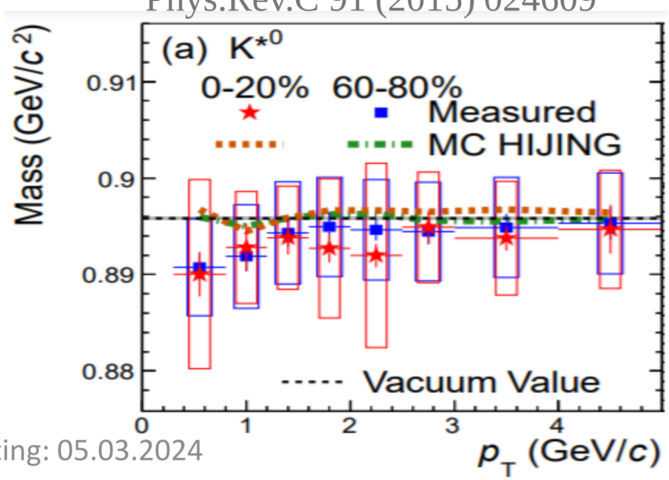


- ❖ In peripheral collisions, the peak models return masses and widths as measured in vacuum
- ❖ In central collisions, the masses are measured smaller
- ❖ Similar mass “modifications” have been reported @ RHIC and the LHC, large uncertainties:

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



Phys.Rev.C 91 (2015) 024609



Resonances

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

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

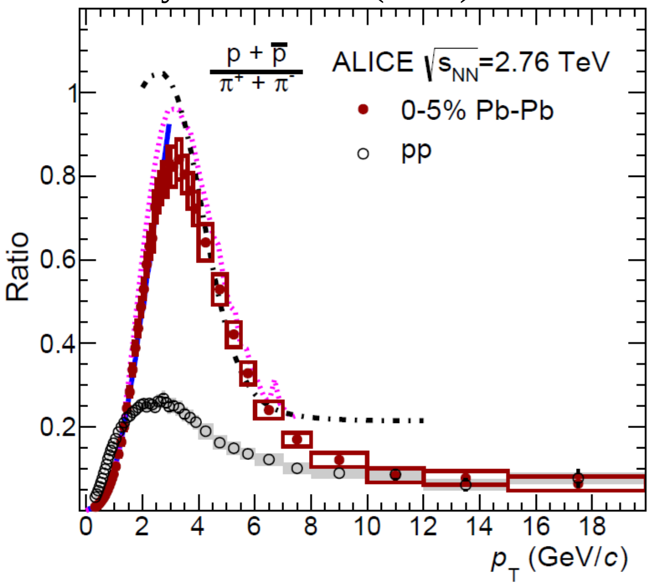
❖ Driving force of enhancement is not yet fully understood:

- ✓ 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