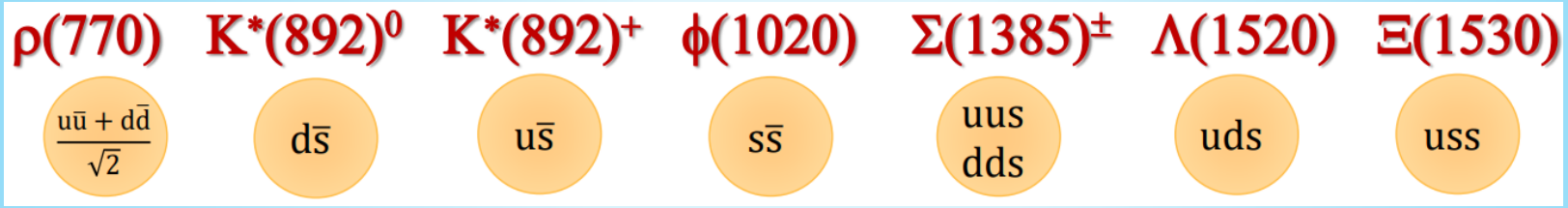
Resonance production at NICA energies

Mikhail Malaev

* We acknowledge support from Russian Ministry of Education and Science, state assignment for fundamental research (code FSEG-2025-0009)

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.

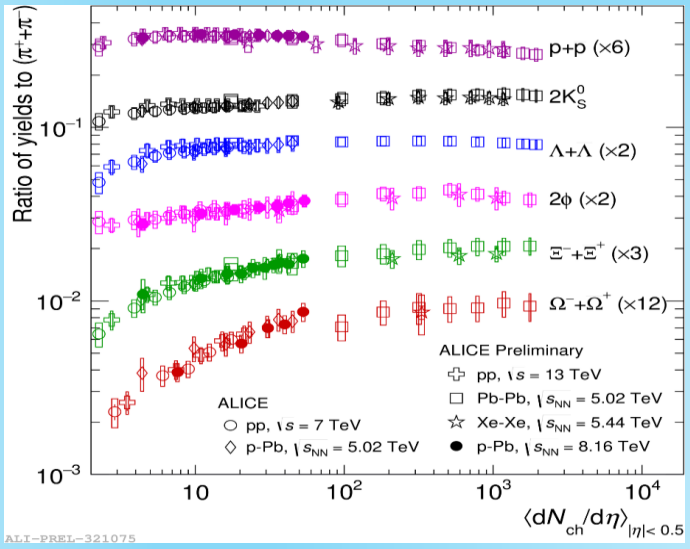


Particle	Mass (MeV/c^2)	Width (MeV/c^2)	Decay	BR (%)
ρ^0	770	150	$\pi^+\pi$	100
$K^{*\pm}$	892	50.3	$\pi^\pm K_s$	33.3
K^{*0}	896	47.3	πK^+	66.7
ϕ	1019	4.27	K^+K^-	48.9
Σ^{*+}	1383	36	$\pi^+\Lambda$	87
Σ^{*-}	1387	39.4	$\pi\Lambda$	87
A(1520)	1520	15.7	K^-p	22.5
Ξ^{*0}	1532	9.1	$\pi^+\Xi^-$	66.7

2

Motivation

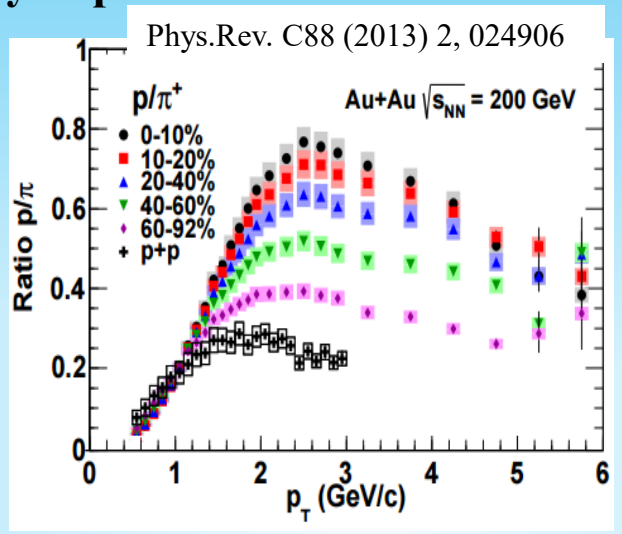
Strangeness enhancement



- 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
- 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

Baryon puzzle

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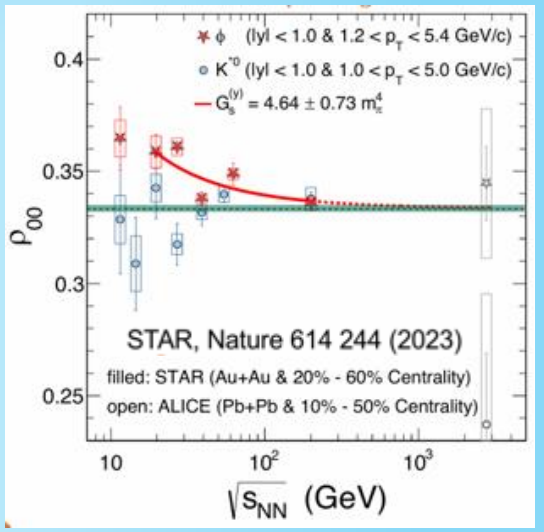


- Increased baryon-to-meson (p/π, Λ/K_s^0 , Λ_c^+/D) ratios in heavy-ion collisions at RHIC and the LHC
- Driving force of enhancement is not yet fully understood:
  - ✓ particle mass (hydrodynamic flow)?
  - ✓ quark count (baryons vs. mesons)?
- ϕ and K^{*0} are well suited for tests as mesons with 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

Spin Alignment

$$\frac{dN}{dcos\theta} = N_0\left[1 - \rho_{0,0} + cos^2\theta(3\rho_{0,0} - 1)\right]$$

$\rho_{0,0}$ is a probability for vector meson to be in spin state = 0

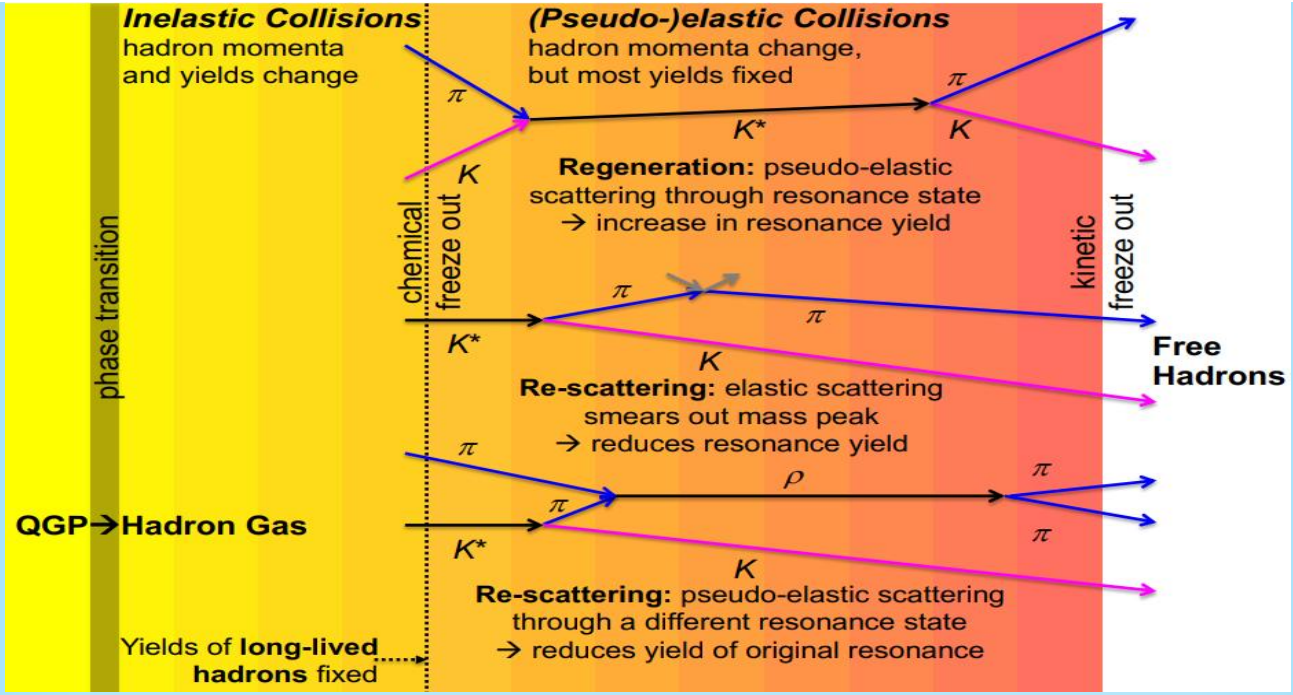


- Measurements at RHIC/LHC challenge theoretical understanding → $\rho_{0,0}$ can depend on multiple physics mechanisms (vorticity, magnetic field, hadronization scenarios, lifetimes and masses of the particles…)
- Measurements should be extended to lower collision energies

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



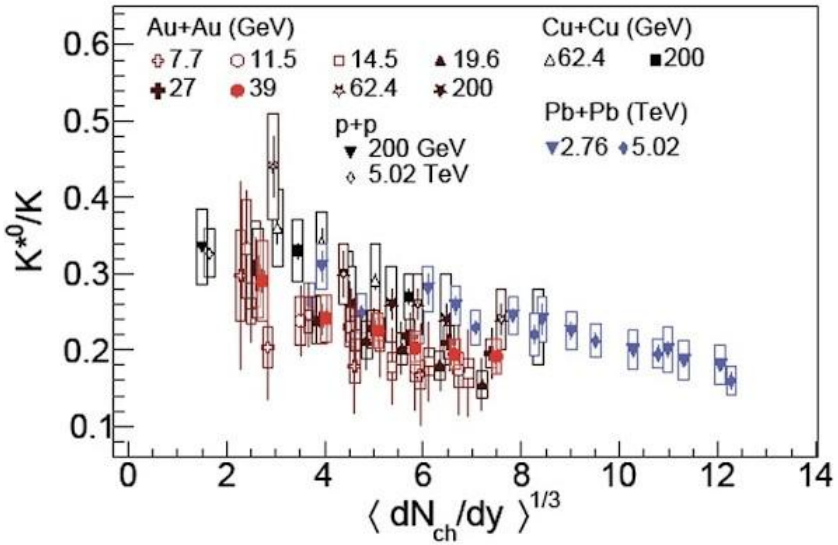
- Resonances have small lifetimes of cτ ~ 1 - 45 fm, part of them decays in the fireball
- Reconstructed resonance yields in heavy ion collisions are defined by:
  - ✓ resonance yields at chemical freeze-out
  - ✓ hadronic processes between chemical and kinetic freeze-outs:

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

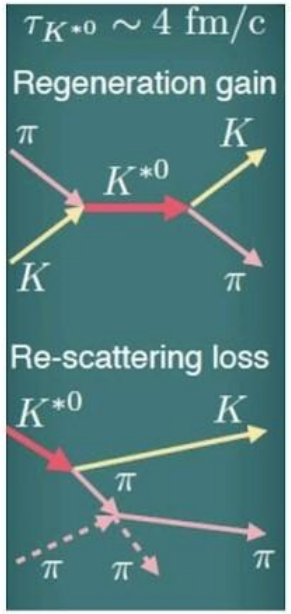
    regeneration: pseudo-elastic scattering of decay products ($\pi K \rightarrow K^{*0}$, $KK \rightarrow \phi$ etc.) → increased yields

Hadronic phase and medium modifications

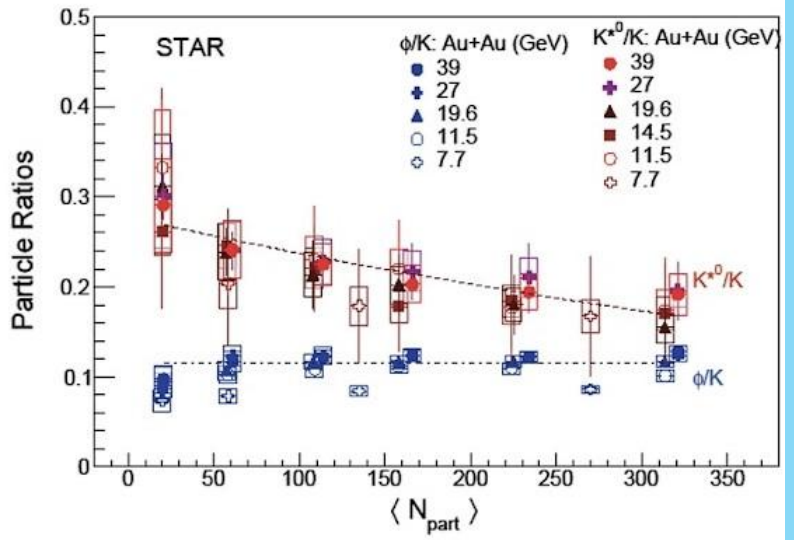
Ratio K^{*0} to K from BES data suggests re-scattering loss in medium due to shorter lifetime of K^{*0}



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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.



- 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:

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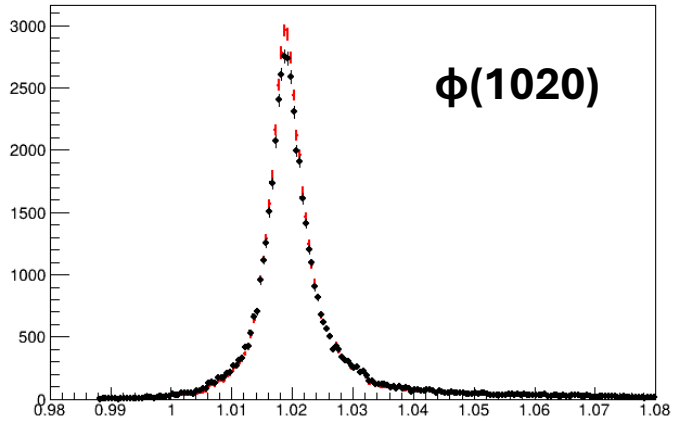
  regeneration: pseudo-elastic scattering of decay products ($\pi K \rightarrow K^{*0}$, $KK \rightarrow \phi$ etc.) → increased yields

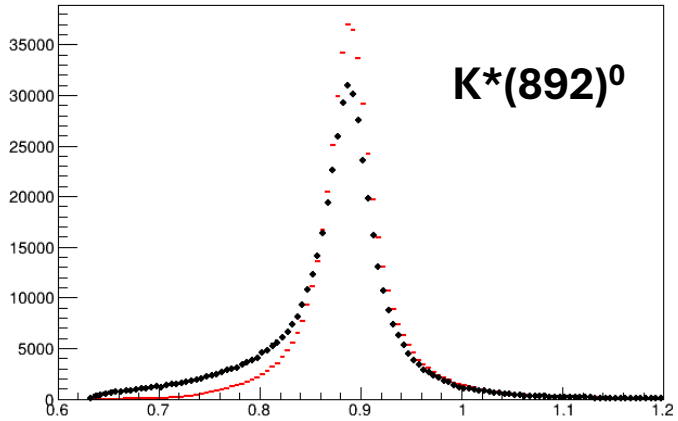
Yields modifications at NICA energies

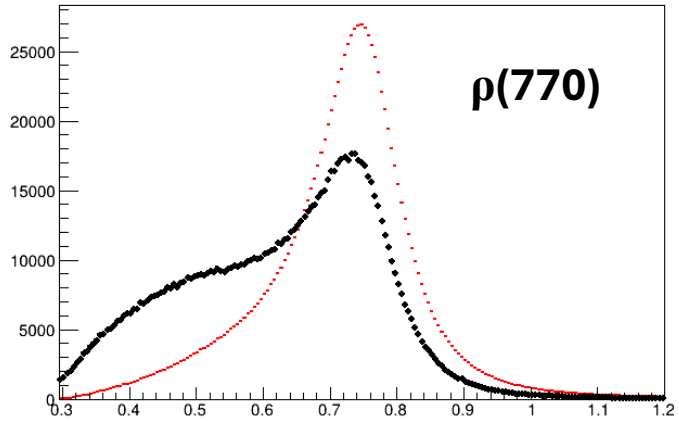
- **Yields modifications at NICA energies? Does UrQMD reproduces the measurements?**
- **(Possible)Peak shape modifications → reconstructed yields of resonances**
- Data: BiBi@9.2 GeV, UrQMD (v3.4) no specific configurations
- Output.f14 – all final state particles at 200 fm
- Output.f15 – all collisions in the event
- Resonances: $\phi \rightarrow K^{+}K^{-}$ ($c\tau \sim 45$ fm/c), $K^{*}(892)^{0} \rightarrow \pi^{\pm}K^{\pm}$ ($c\tau \sim 4.2$ fm/c), $\rho(770)^{0} \rightarrow \pi^{+}\pi^{-}$ ($c\tau \sim 1.3$ fm/c)
- Rapidity range: $-1.0 < Y_{cms} < 1.0$
- Number of charged pions in the event → centrality estimation
- Init distributions – Invariant mass of the resonance reconstructed via daughter particles at decay moment
- Rec distributions – Invariant mass of the resonance reconstructed via daughter particles from Output.f14 (if present) – after all possible interactions in hadron gas stage

Peak shape modifications (qualitatively) – BiBi@9.2 GeV

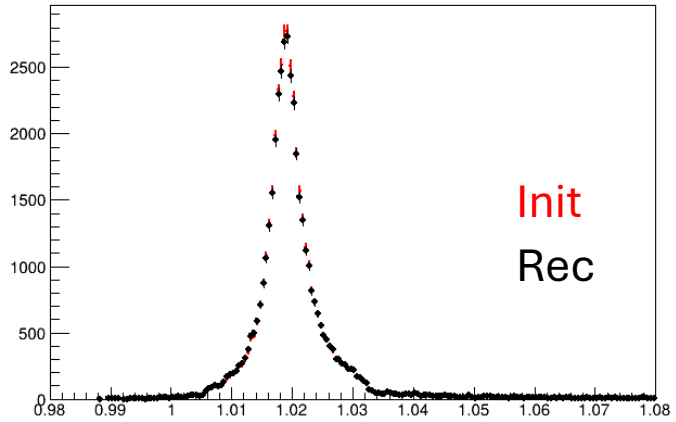
Central

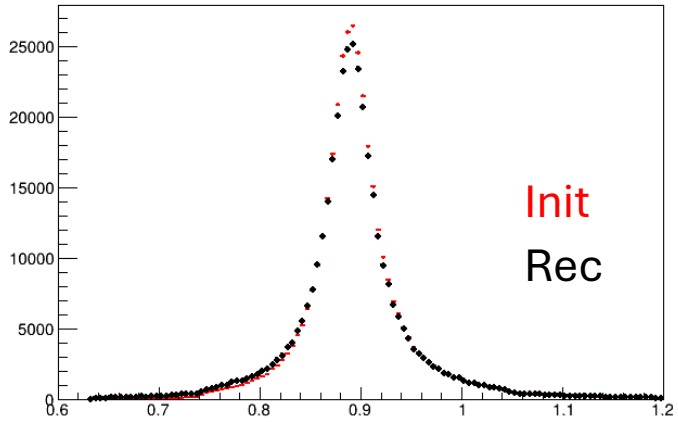


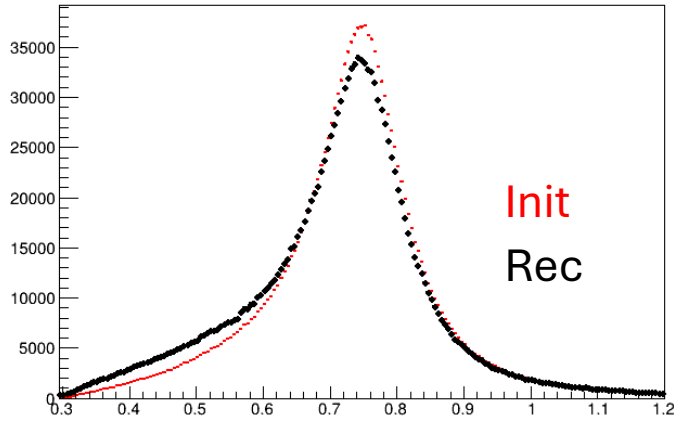




Peripheral







- Resonances are decayed by UrQMD, daughters participate in elastic and inelastic scattering
- Resonance are reconstructed by invariant mass method according to decay channels
- $\phi \rightarrow K^+K^-$ ($c\tau \sim 45$ fm/c): modest line shape modifications in central collisions
- $K^*(892)^0 \rightarrow \pi^{\pm}K^{\pm}$ ($c\tau \sim 4.2$ fm/c): line shape modifications in central collisions
- $\rho(770)^0 \rightarrow \pi^+\pi^-$ ($c\tau \sim 1.3$ fm/c): significant line shape modifications in central collisions

Init – Invariant mass at decay moment

Rec – Invariant mass after all interactions

Peak shape modifications (fit) – BiBi@9.2 GeV

Use fitting function like in real data analysis (no mass resolution factor) for Rec distributions – Signal + BGR

$\phi \rightarrow K^+K^-$ ($c\tau \sim 45$ fm/c):

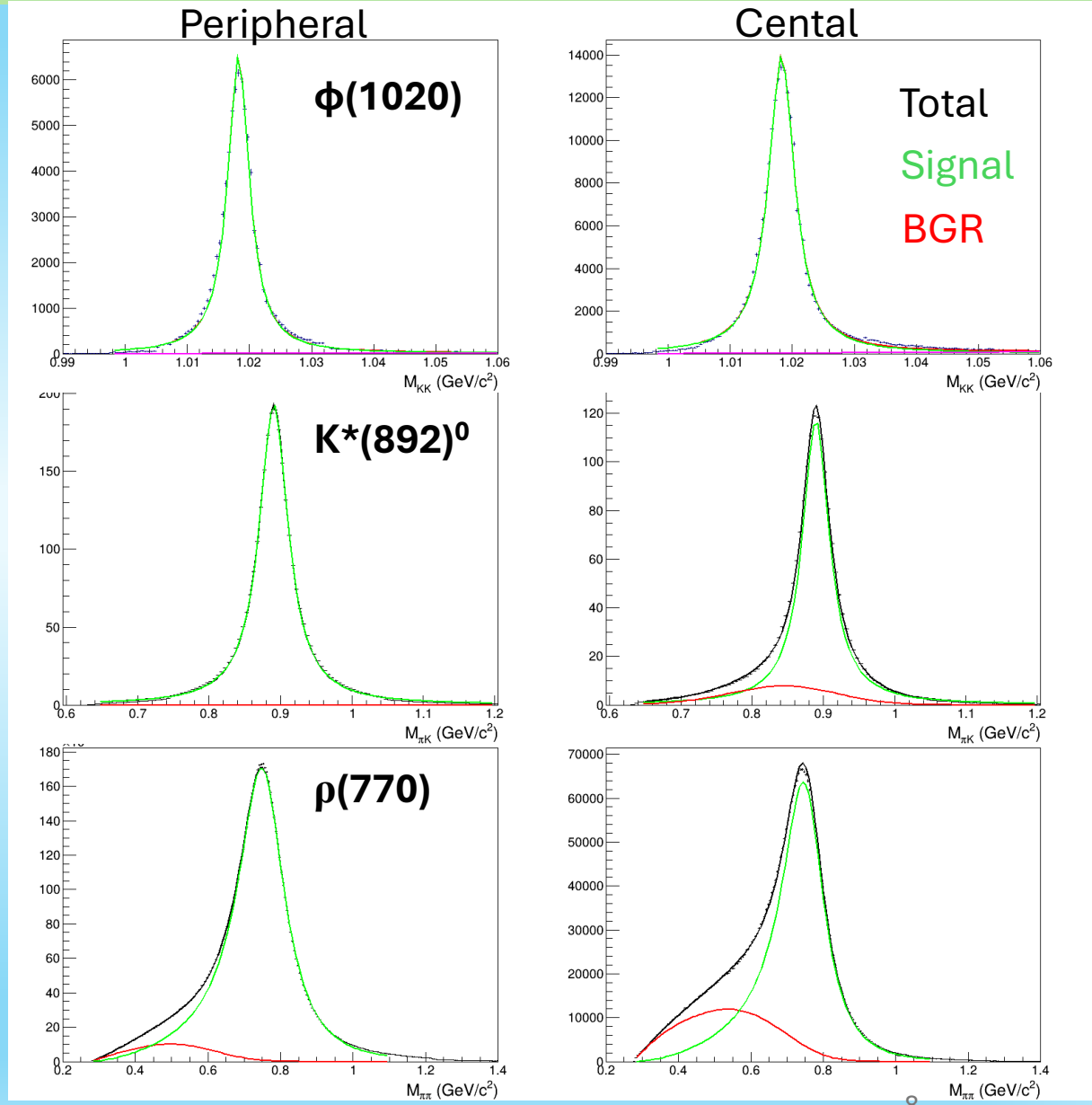
- Modest peak shape modifications only in high multiplicity events (central collisions)
- Rec peaks described by signal function, almost no contribution from BGR function

$K^*(892)^0 \rightarrow \pi^\pm K^\pm$ ($c\tau \sim 4.2$ fm/c):

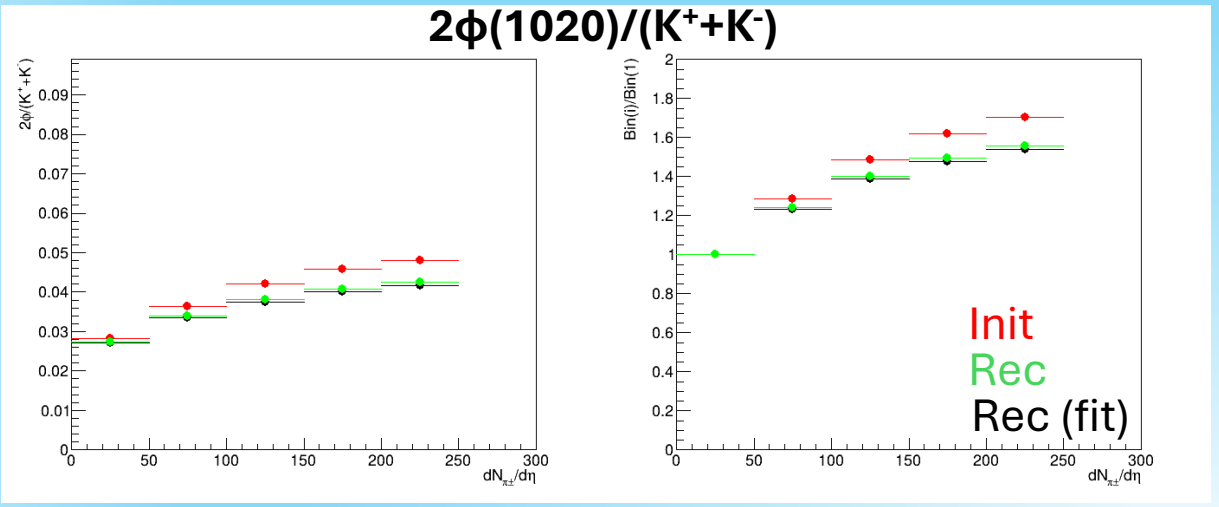
- Peak shape modifications in high multiplicity events (central collisions)
- Rec peaks described by signal function in peripheral events, contribution from BGR function in central events

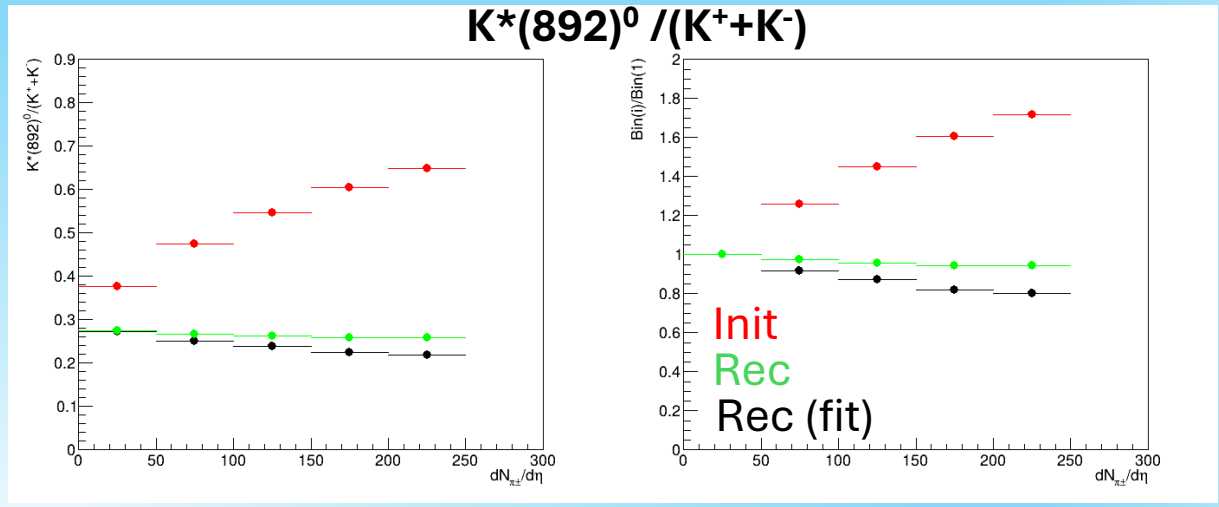
$\rho(770)^0 \rightarrow \pi^+\pi^-$ ($c\tau \sim 1.3$ fm/c):

- Peak shape modifications even in peripheral events
- Rec peaks described only by combination of signal and background, considerable contribution from BGR function in central events



Peak shape modifications (quantitively) – BiBi@9.2 GeV



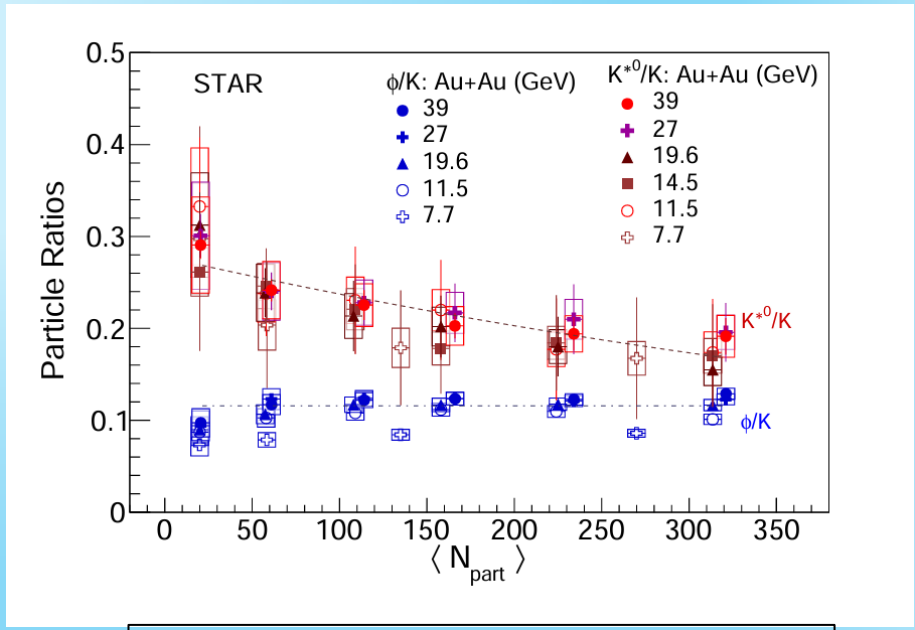


$\phi \rightarrow K^+K^-$ ($c\tau \sim 45$ fm/c):

- Almost no losses due to peak shape modification
- Losses due to daughter annihilation or inelastic rescattering
- Increasing trend with increasing centrality
- Urqmd underestimates phi production

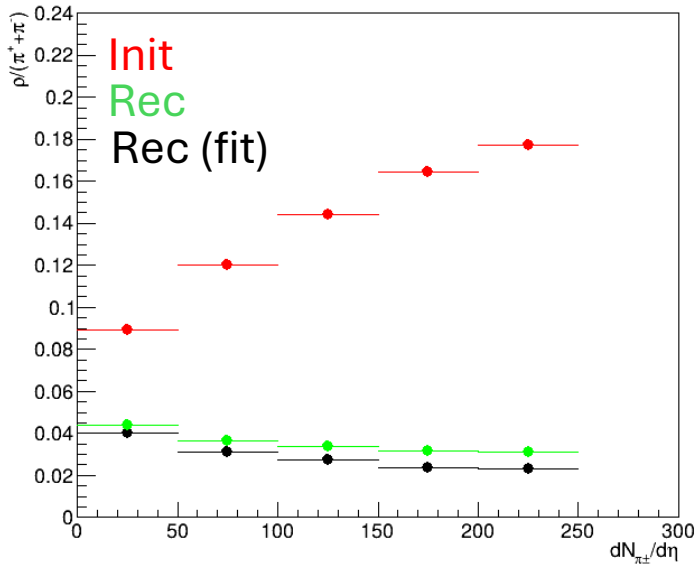
$K^*(892)^0 \rightarrow \pi^{\pm}K^{\pm}$ ($c\tau \sim 4.2$ fm/c):

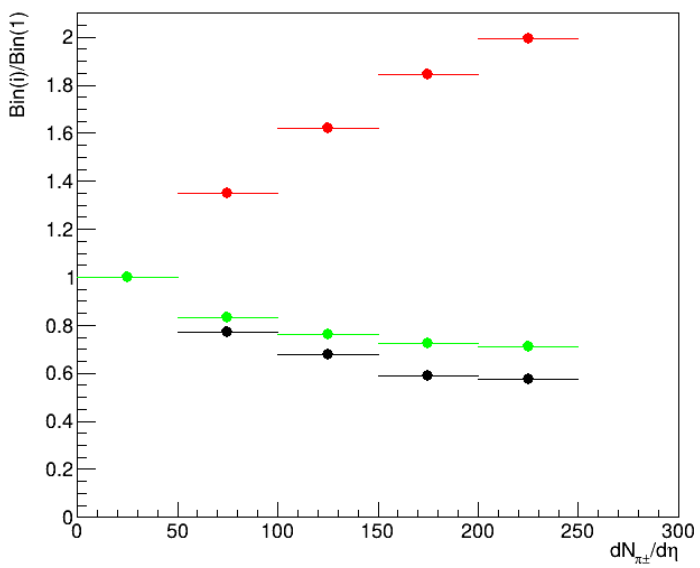
- Losses due to peak shape modification increase with increasing centrality
- Losses due to daughter annihilation or inelastic rescattering
- Decreasing trend with increasing centrality
- Comparable to STAR results

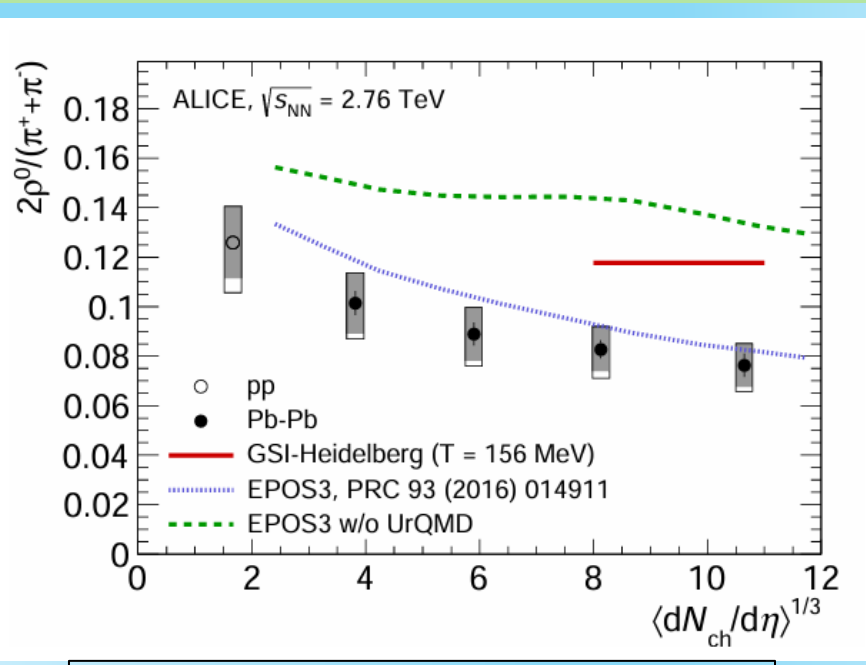


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Peak shape modifications (quantitively) – BiBi@9.2 GeV







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

- Losses due to peak shape modification increase with increasing centrality
- Losses due to daughter annihilation or inelastic rescattering
- Decreasing trend with increasing centrality
- No available results with close collision energy

Intermediate summary

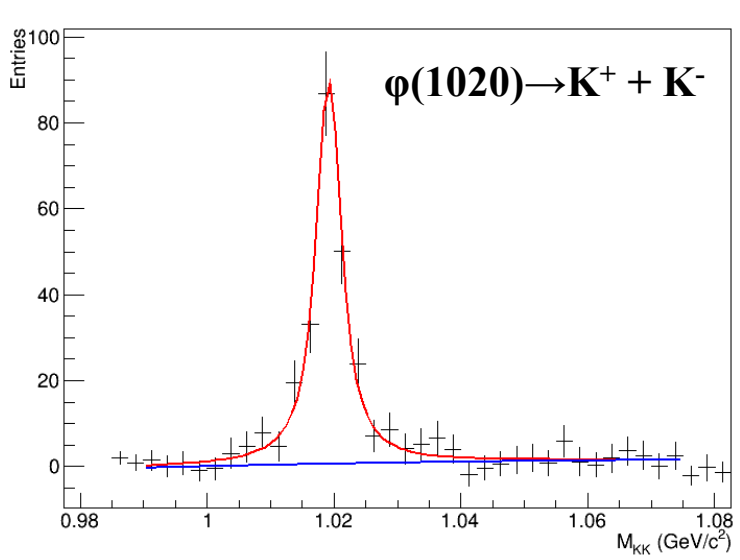
- Resonances are sensitive to properties of the hadronic medium produced in heavy-ion collisions at NICA energies
- Sensitivity depends on the resonance lifetime
- Peak shape modifications affect reconstructed yields of short-living resonances
- URQMD qualitatively (in some cases quantitively) consistent with STAR results at close NICA energies
- Plans: baryon resonances – Δ^{++}

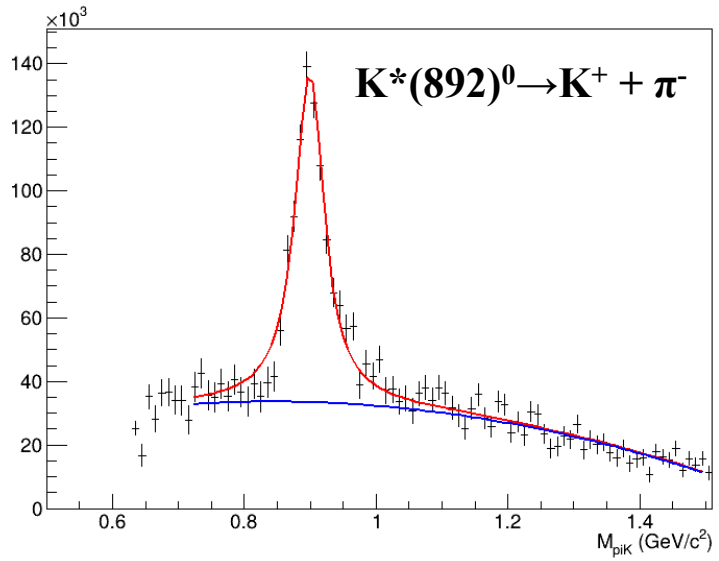
Feasibility Studies

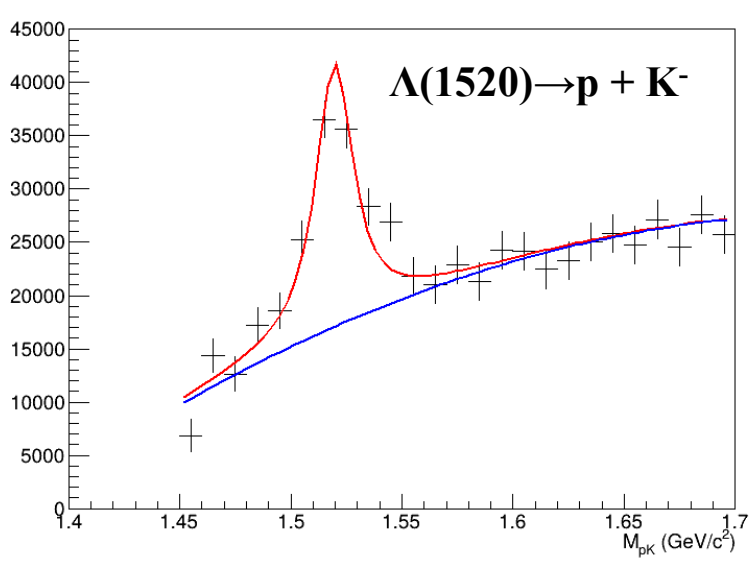
- **Estimate capabilities for resonances reconstruction with MPD experimental setup in collider and fixed target modes**
- Mostly interested in midrapidity region
- Centrality differentiated analysis
- Goal: reconstruct signal from resonance decays in as wide p_T region as possible (especially low p_T region)
- Collider mode:
  - ✓ Data: Request 25, BiBi@9.2 GeV, UrQMD+Geant4 (~50M events)
- Fixed target mode:
  - ✓ Data: Request 36, XeW@2.5 AGeV, UrQMD+Geant4 (~15M events)
  - ✓ Data: Request 40, XeW@2.5 AGeV, UrQMD+Geant4 (~100M events)

Resonance reconstruction (BiBi@9.2GeV)

- Full chain simulation and reconstruction, BiBi 9.2 GeV (URQMD generator), |y| < 0.5



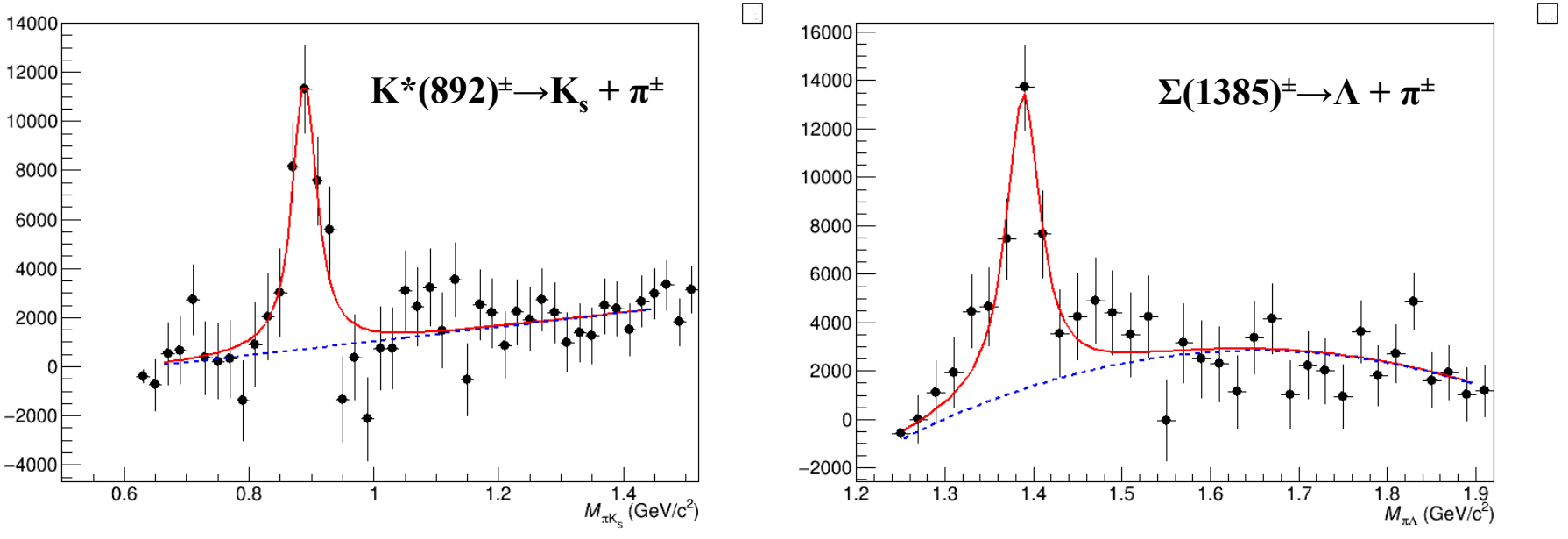


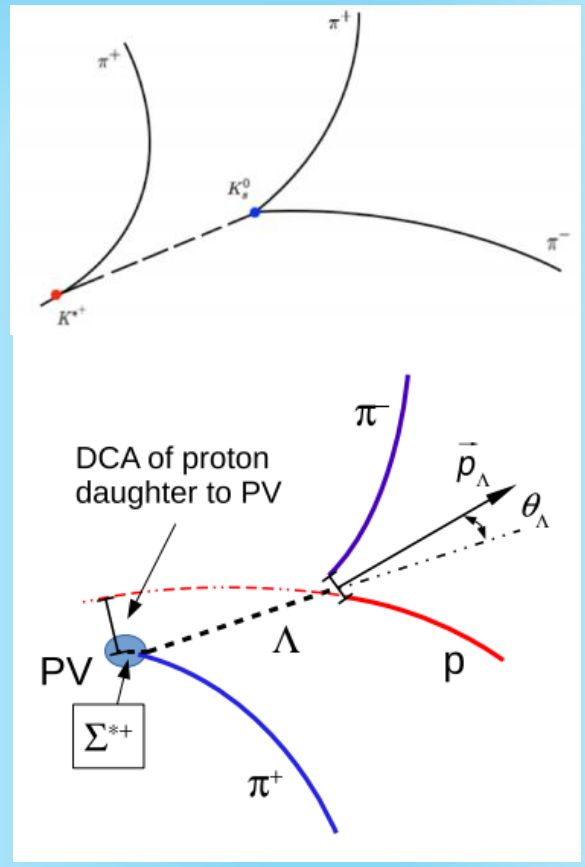


- Resonances can not be directly detected in the experimental setup
- Invariant Mass method: mass of the resonance reconstructed via its daughter particles
- Mixed-event combinatorial background is scaled to foreground at high mass and subtracted
- Distributions are fit to Voigtian function + polynomial (mass resolution fixed to estimated value, Γ - free parameter)

Multi-Stage decay channels (BiBi@9.2GeV)

- ✓ $K^*(892)^{\pm} \rightarrow \pi^{\pm}Ks$ ($Ks \rightarrow \pi^+\pi^-$)
- ✓ $\Sigma(1385)^{\pm} \rightarrow \pi^{\pm}\Lambda$ ($\Lambda \rightarrow p\pi$)
- ✓ $\Xi(1530)^0 \rightarrow \pi^+\Xi^-$ ($\Xi^- \rightarrow \Lambda\pi^-$, ($\Lambda \rightarrow p\,\pi^-$))

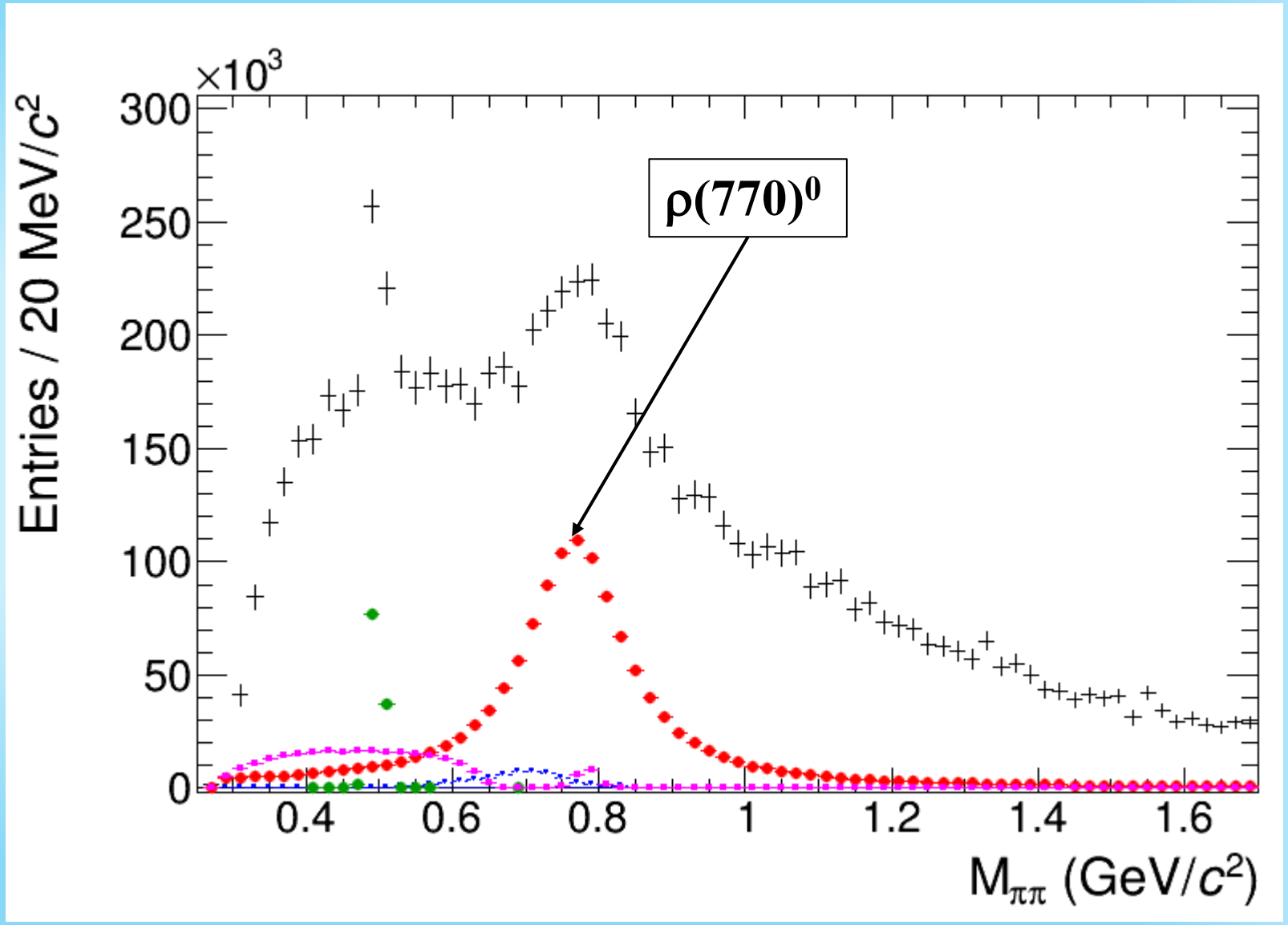




- ❖ Resonances can not be directly detected in the experimental setup
- ❖ Invariant Mass method: mass of the resonance reconstructed via its daughter particles
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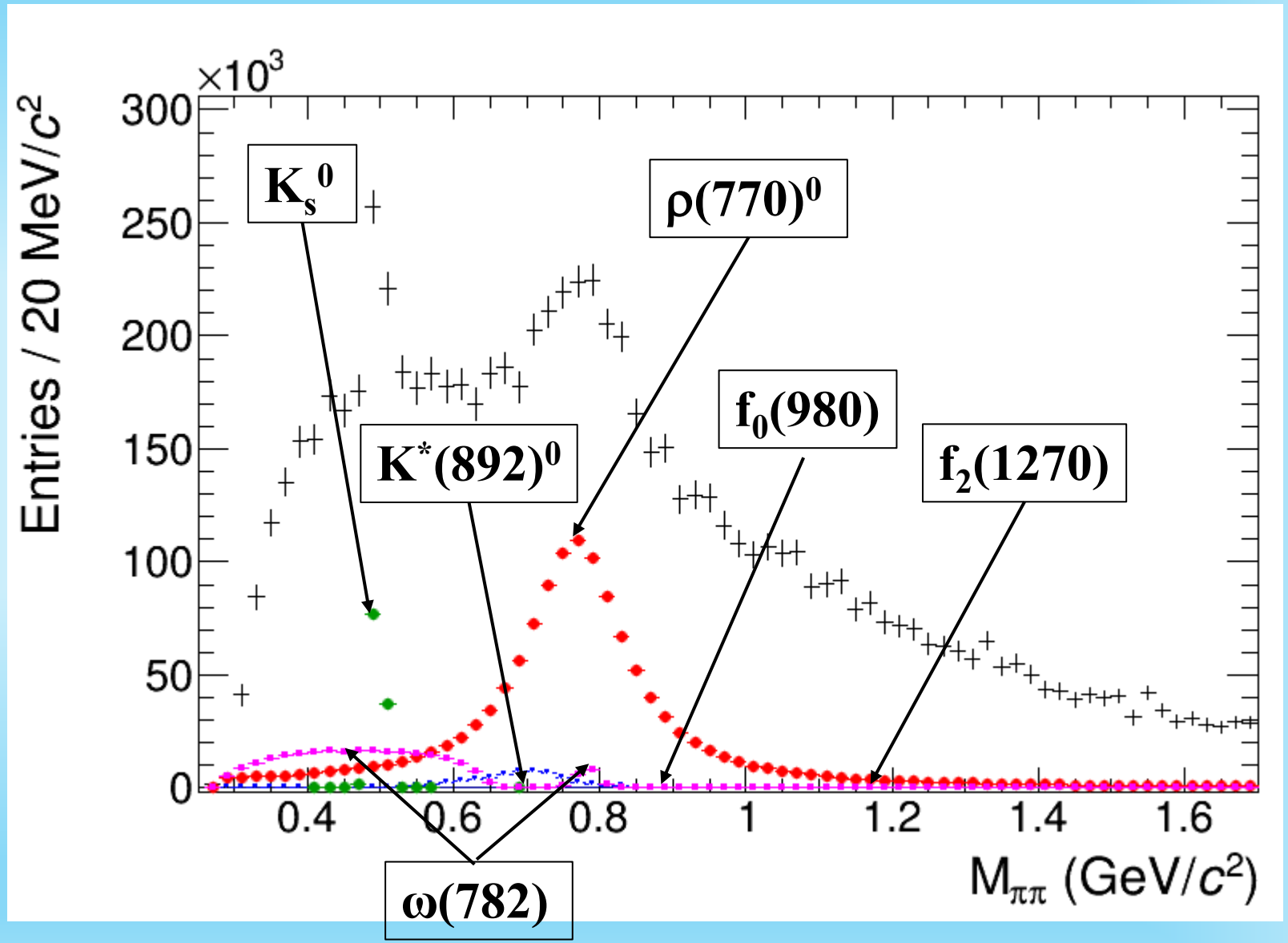
Specific case – $\rho(770)^0$ (BiBi@9.2GeV)

- ✓ Remaining background is shaped by correlated pairs from decays of other particle and angular correlations from (mini)jets
- ✓ Full Monter-Carlo simulation to study remaining background
- ✓ For most of the cases, remaining background is a smooth function of mass
- ✓ $\rho(770)^0$ is not the case…



Specific case – $\rho(770)^0$ (BiBi@9.2GeV)

- ✓ Remaining background is shaped by correlated pairs from decays of other particle and angular correlations from (mini)jets
- ✓ Full Monter-Carlo simulation to study remaining background
- ✓ For most of the cases, remaining background is a smooth function of mass
- ✓ $\rho(770)^0$ is not the case…
- ✓ Peak-like contribution from:
  - **$K^s_0 \rightarrow \pi^+\pi^-$**
  - **$\omega \rightarrow \pi^+\pi^-$**
  - **$\omega \rightarrow \pi^+\pi^-\ \pi^0$ (with missing π^0)**
  - **$K^*(892)^0 \rightarrow \pi^\pm K^\pm$ (with misidentified kaon)**
  - **$f_0(980) \rightarrow \pi^+\pi^-$**
  - **$f_2(1270) \rightarrow \pi^+\pi^-$**
- ✓ Contributions must be measured in advance and subtracted (or accounted for)



Peak shape model

- ✓ Resonances peak shape → (r) Breit-Wigner (BW)
- ✓ Peak shape modifications:
  - Detector mass resolution
  - Dependence of resonance width on mass (for wide resonances)
  - Phase space correction
  - Bose-Einstein correlations
  - Mass dependence of reconstruction efficiency (for wide resonances)

$$BW(M) = A\frac{MM_0\Gamma(M)}{(M_0^2 - M^2)^2 + M_0^2\Gamma(M)}$$

$$\Gamma(M) = \left[\frac{(M^2 - 4m_\pi^2)}{(M_0^2 - 4m_\pi^2)}\right]^{3/2} * \Gamma_0 * \left({}^{M_0}/_{M}\right)$$

$$PS(M) = \frac{M}{\sqrt{M^2 + p_T^2}} * \exp\left(-\frac{\sqrt{M^2 + p_T^2}}{T}\right)$$

$$f_i(M) = C\left(\frac{M_0^2 - M^2}{M\Gamma(M)}\right)$$

$$Fitting\ function = BW(M) * \Gamma(M) * \mathrm{PS(M)} * BE(M) * RecEff(M)$$

Specific case – $\rho(770)^0$ (BiBi@9.2GeV)

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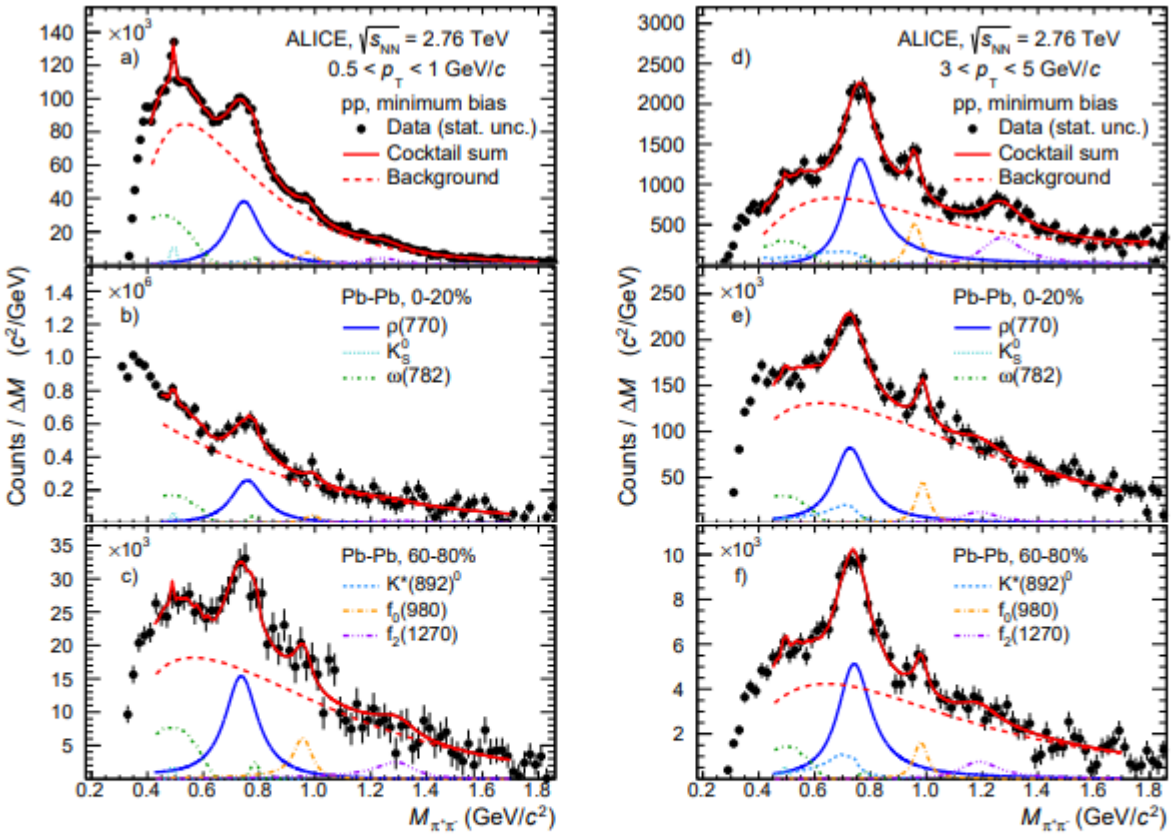
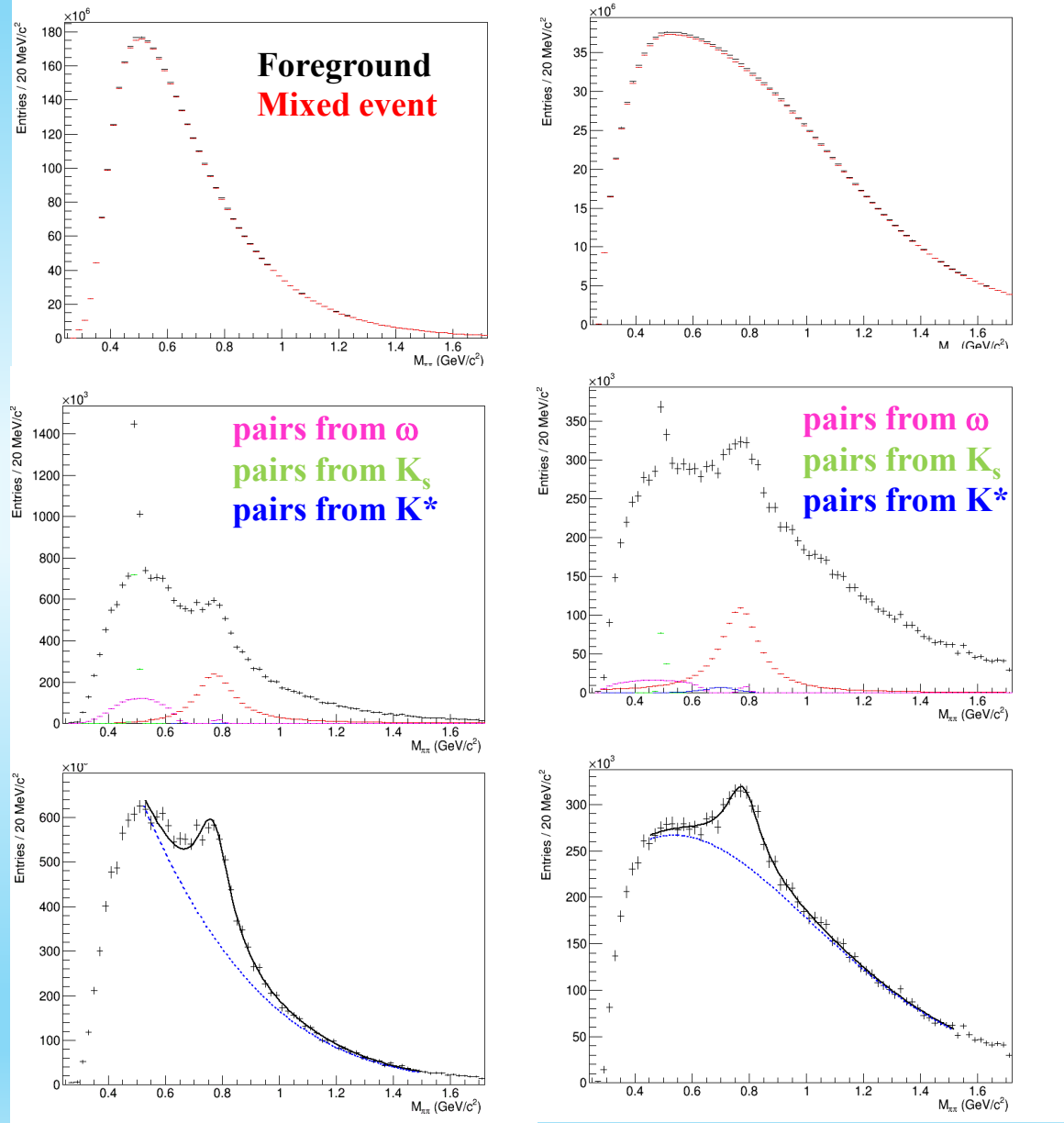
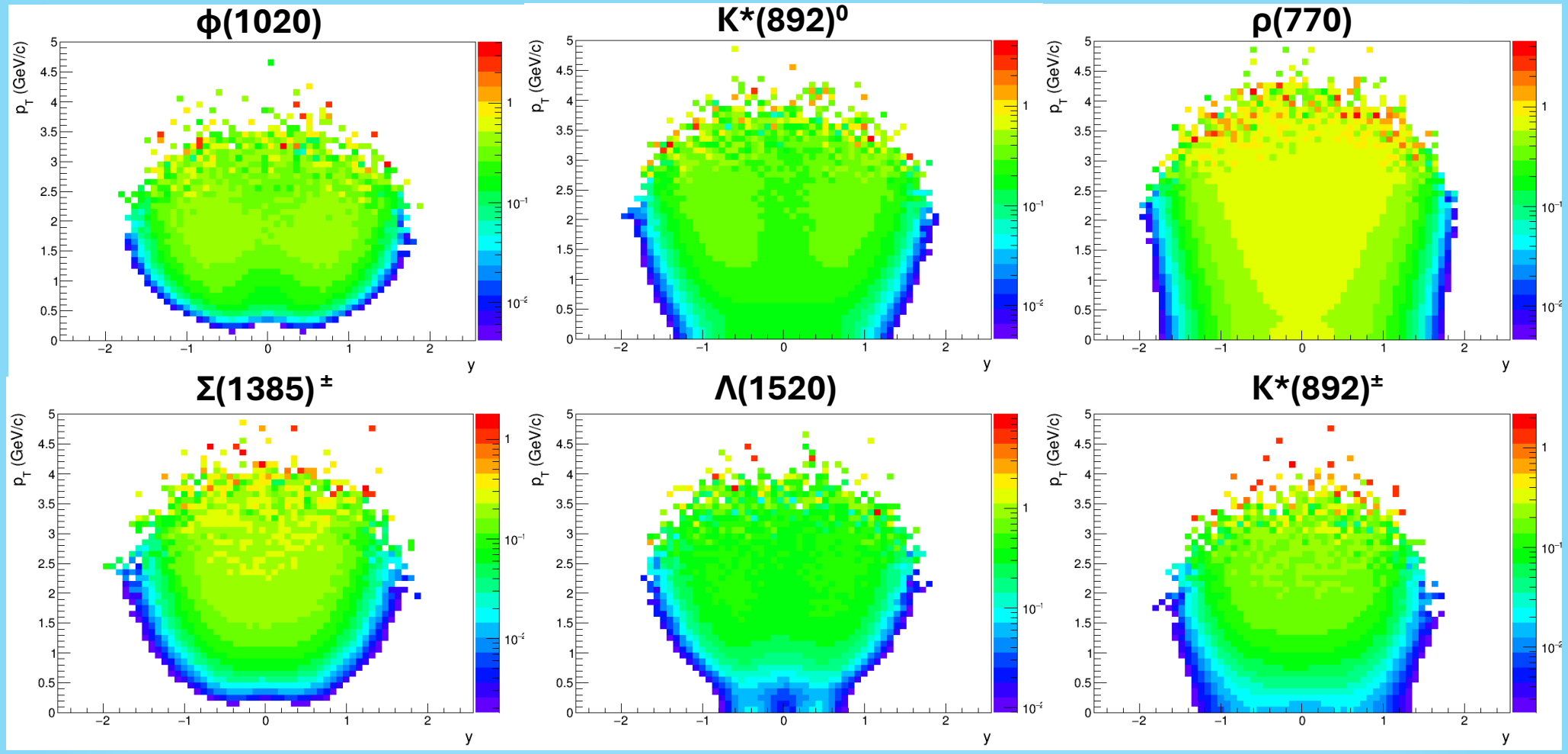


Fig. 1: (Color online) Invariant mass distributions for $\pi^+\pi^-$ pairs after subtraction of the like-sign background. Plots on the left and right are for the low and high transverse momentum intervals, respectively. Examples are shown for minimum bias pp, 0–20% and 60–80% central Pb–Pb collisions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

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



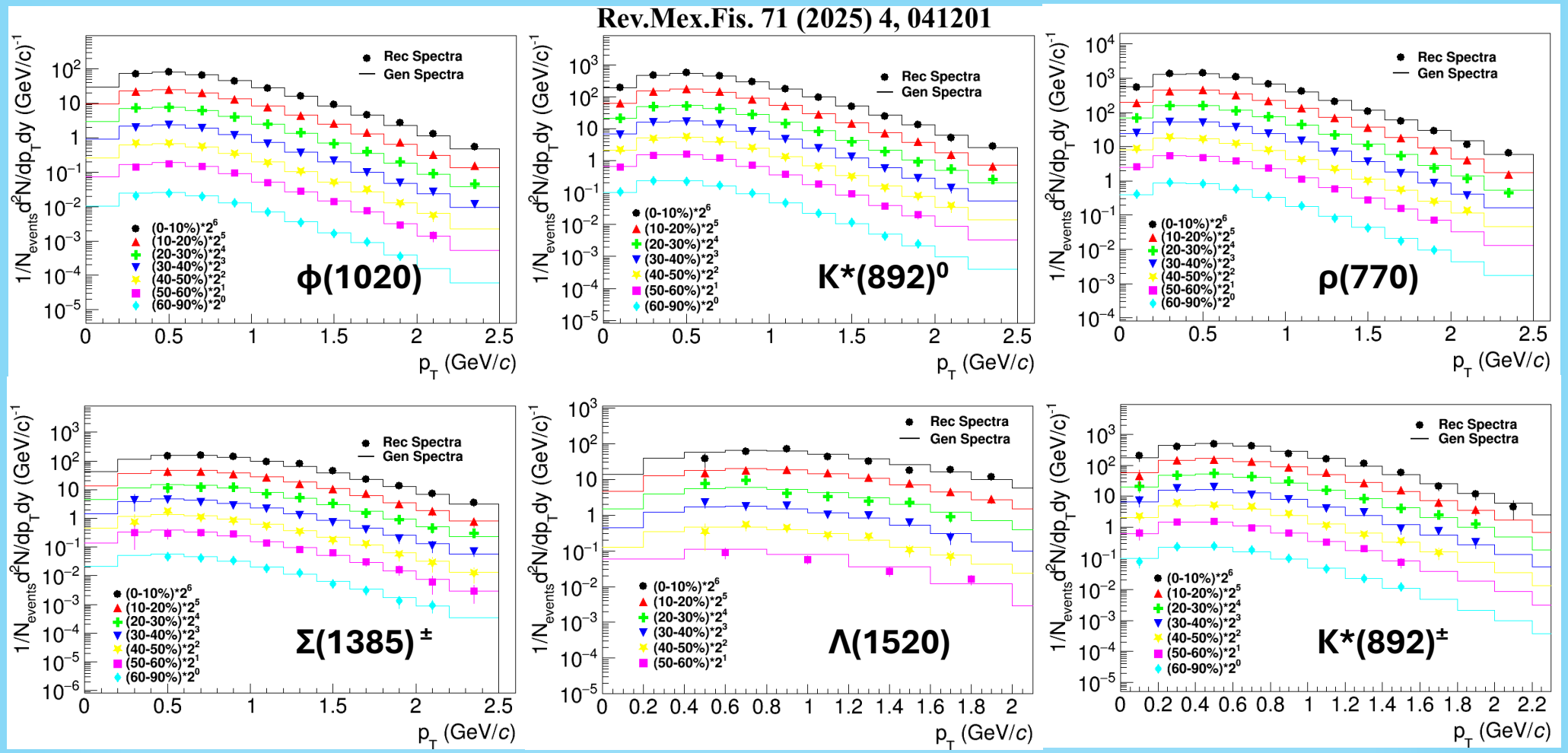
Phase space available (BiBi@9.2GeV)



- Wide p_T range acceptable, $|y| < 0.5$
- Measurements are possible from 0 momentum for $K^*(892)^{\pm}$, $K^*(892)^0$, $\rho(770)$ and from 0.2-0.4 GeV/c for $\varphi(1020)$, $\Lambda(1520)$ and $\Sigma(1385)^{\pm}$

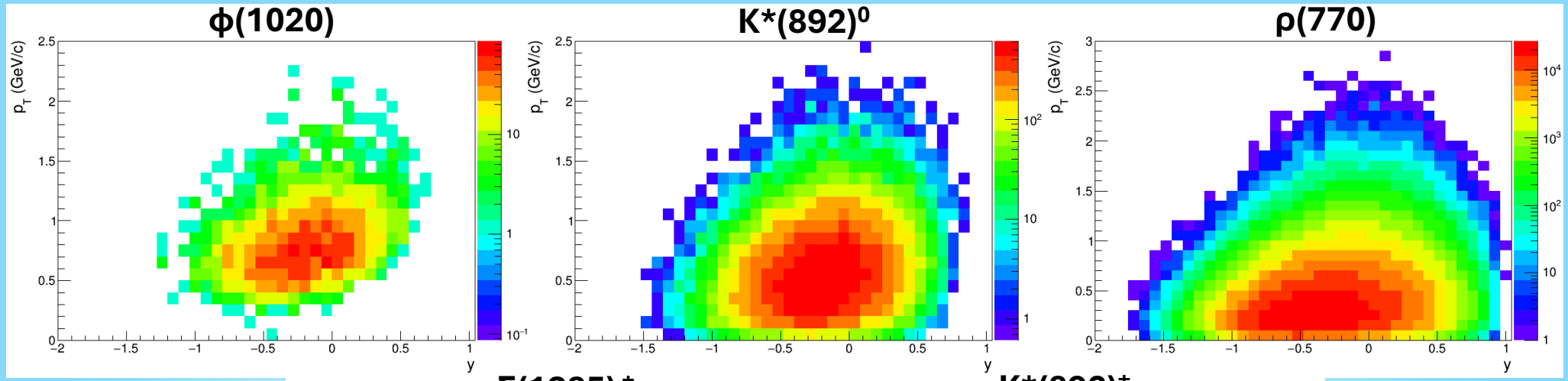
Closure test (BiBi@9.2GeV)

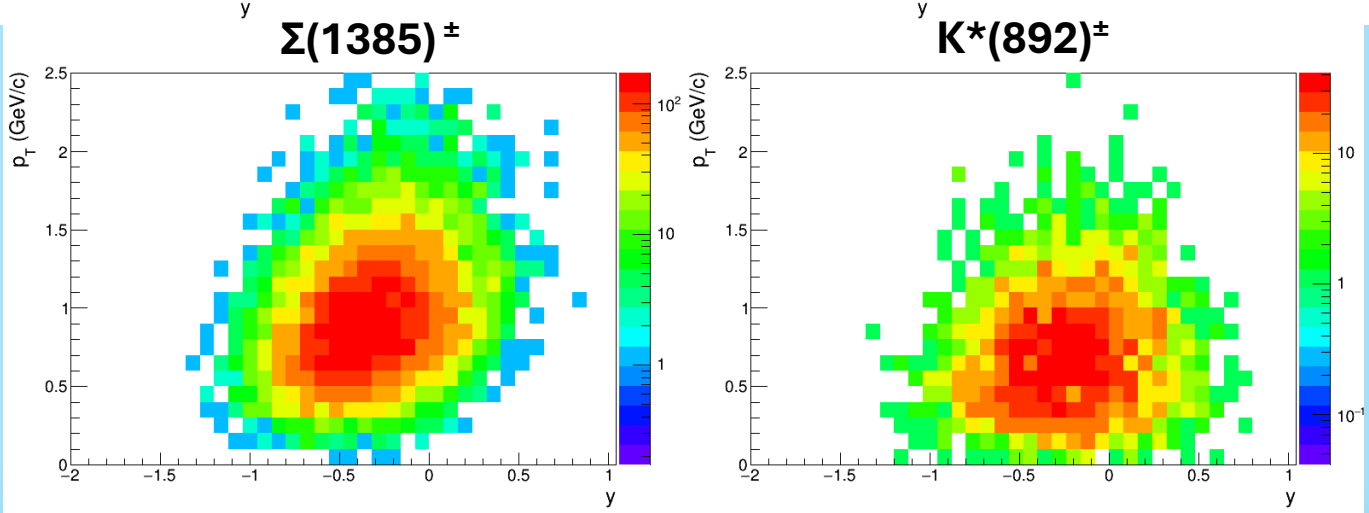
- Full chain simulation and reconstruction, p_T ranges are limited by the possibility to extract signals, $|y| < 0.5$



- 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

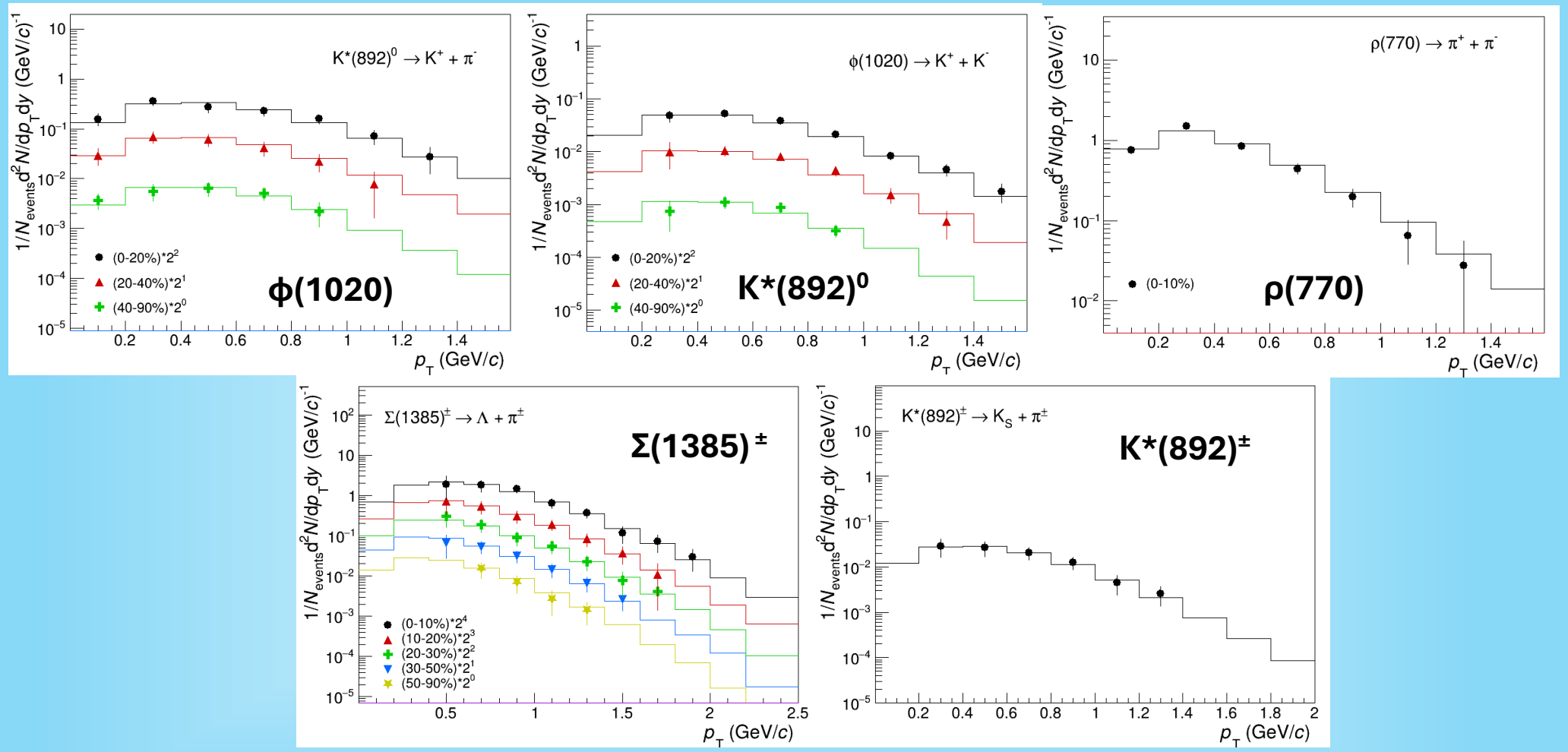
Phase space available (XeW@T_{kin} = 2.5AGeV, FT)





- Wide p_T range acceptable, $-1.0 < y_{cms} < 0$.
- Measurements are possible from 0 momentum for $K^*(892)^{\pm}$, $K^*(892)^0$, ρ(770) and from ~0.2 GeV/c for φ(1020) and $\Sigma(1385)^{\pm}$, no Λ(1520)

Closure test (XeW@T_{kin} = 2.5AGeV, FT)



- 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 low momentum → sample most of the yield, sensitive to possible modifications

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