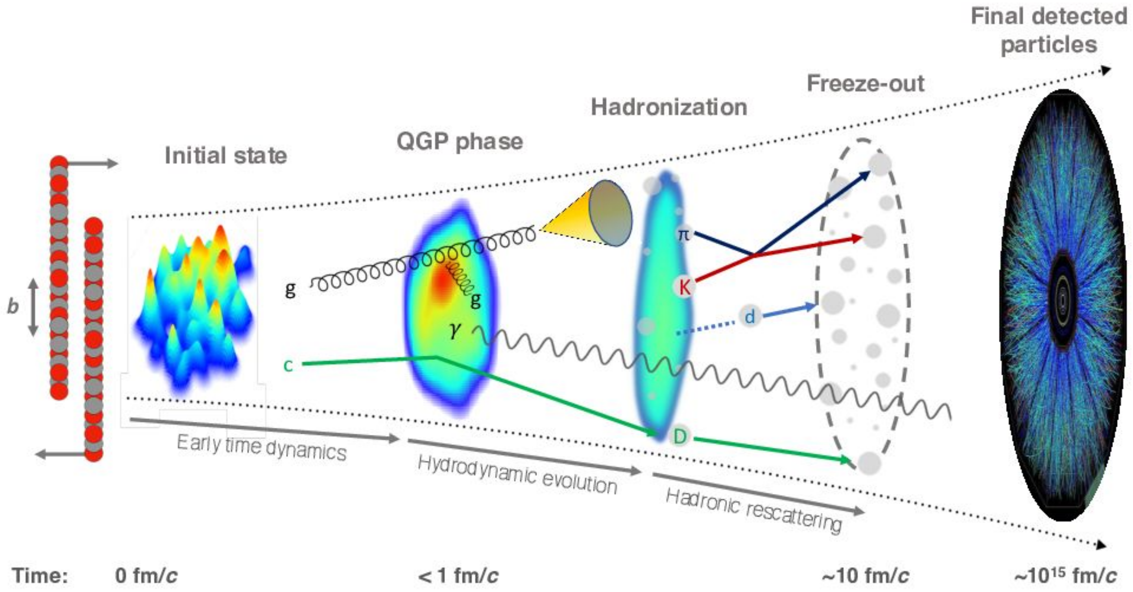
Studying chiral partner resonances K* and K_1 to investigate chiral symmetry restoration with ALICE

Marta Urioni on behalf of the ALICE collaboration

Introduction

- In high-energy heavy-ion collisions at the Large Hadron Collider (LHC) a **Quark-Gluon Plasma (QGP)** is formed and cools down to a hadron gas (hadronization)



- **Hadronic phase evolution**:
  - Chemical freeze-out
    T_{ch} ~ 156 MeV
    - Hadron yields are ~ fixed

  Resonance rescattering and regeneration in the hadronic phase

  - Kinetic freeze-out:
    - Momenta distributions are fixed

- **Resonances** → lifetime of few fm/*c* → sensitive to the very small timescales of the QGP system evolution → probe of the hadronic phase

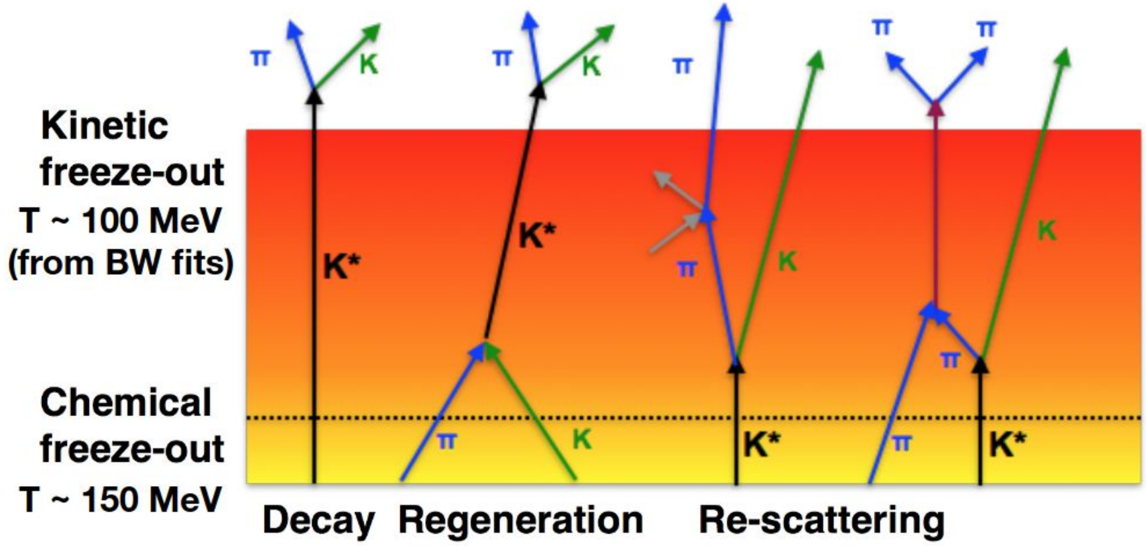
Resonances in the hadronic phase

- Resonances reconstructed via **invariant mass** technique

$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$

- Due to **rescattering** the information on $\mathbf{p_1}$, $\mathbf{p_2}$ is lost
  ⇒ Not possible to reconstruct M
  ⇒ Broadening of the measured resonance width

- Interactions between hadrons can **regenerate** resonances after the chemical freeze-out

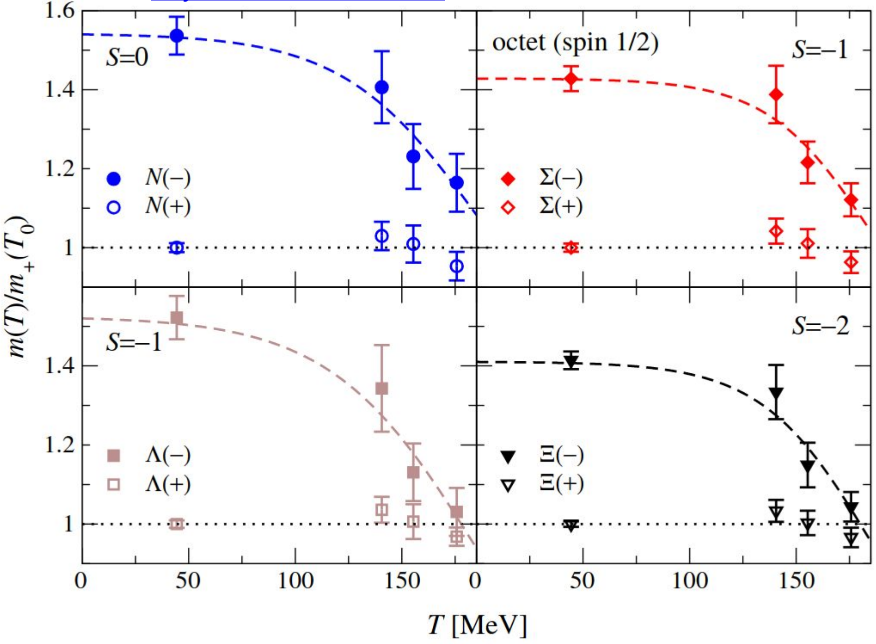


- Rescattering → **reducing** the resonance yield
- Regeneration → **enhancing** the resonance yield

Chiral symmetry restoration

- **Chiral** $SU(2)_L$ x $SU(2)_R$ **symmetry** in QCD **in the limit that** $m_u = m_d = 0$
- Due to spontaneous symmetry breaking → **Chiral symmetry is not exactly realized in QCD**
- Lattice QCD → **chiral symmetry restoration expected to happen at T_{ch}**
  HotQCD Collaboration, Physics Letters B 795 (2019) 15–21
- **Chiral partners**: two resonances with the same quantum numbers but opposite parity

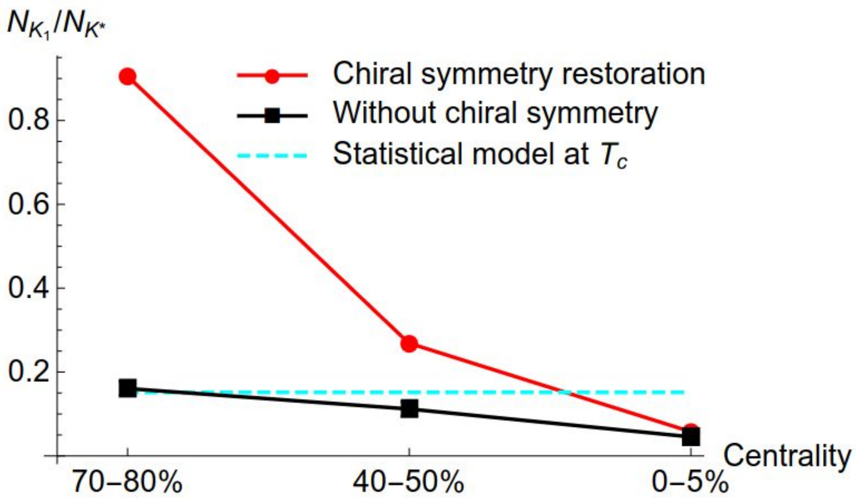
G. Aarts, C. Allton, D. De Boni, and B. Jäger Phys. Rev. D 99, 074503



K* and K_1 study – physics motivation

- **If the chiral symmetry is restored** the differences in masses and production yields between parity partners should disappear

- K* and K_1 are good candidates:
  - Small Γ < 100 MeV
  - Small hadronic dissociation cross section



H. Sung et. al,
Physics Letters B 819 (2021) 136388

- The **K_1/K* enhancement** should be observable in peripheral collisions:
  - Shorter lifetime of the hadronic phase
  - Small influence of rescattering effects

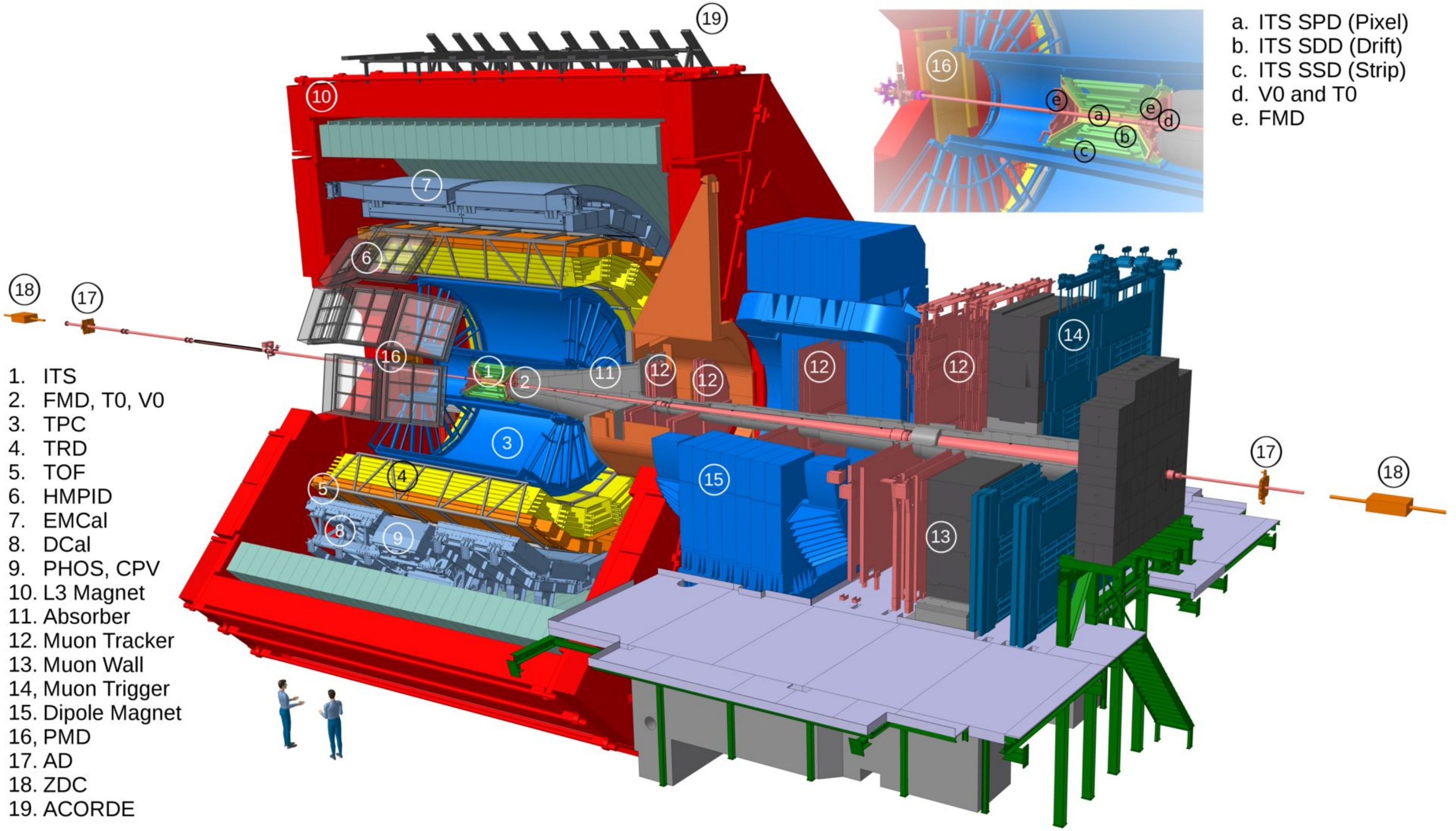
Recent results on $K^*(892)^0$ production

The ALICE detector in Run 2

Time Projection Chamber (TPC)
Tracking and PID via *dE/dx*

Time Of Flight (TOF)
PID via Time-of-flight

Inner Tracking System (ITS)
tracking and vertexing

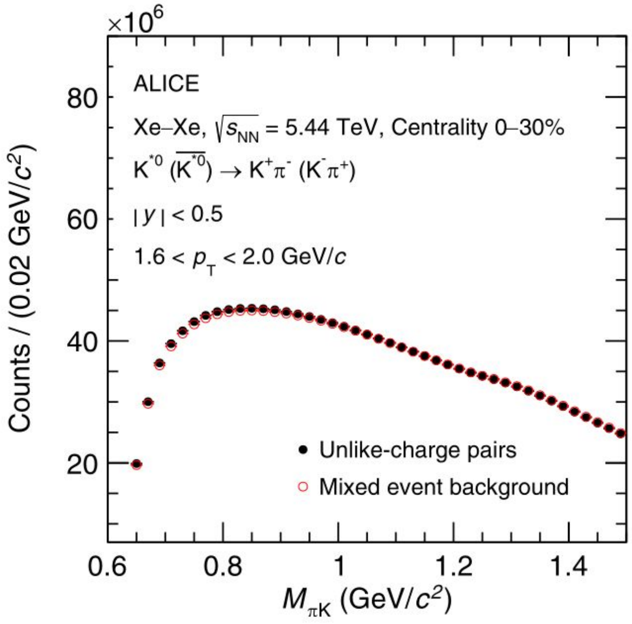


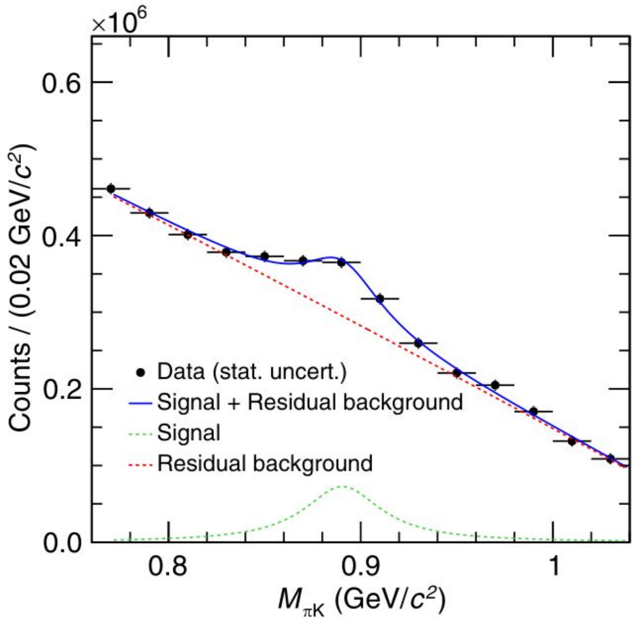
K*(892)^0 reconstruction

- K*(892)^0 → K$^+$ π^- (BR ~66.6%)
- $\overline{\text{K*}}$(892)^0 → K$^-$ π^+

ALICE Collaboration, Phys. Rev. C 109, 014911

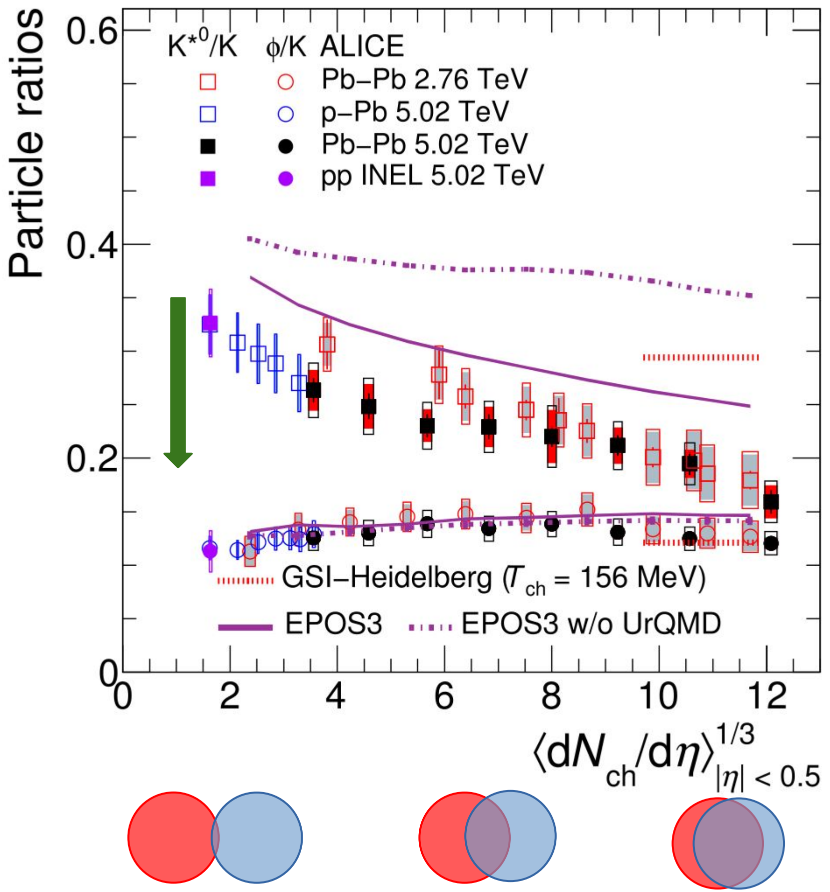
- Topological selection: tracks pointing to the **primary vertex**
- Daughter tracks are identified in the **TPC and TOF**





K*(892)^0 and ϕ(1020) ratios vs system size

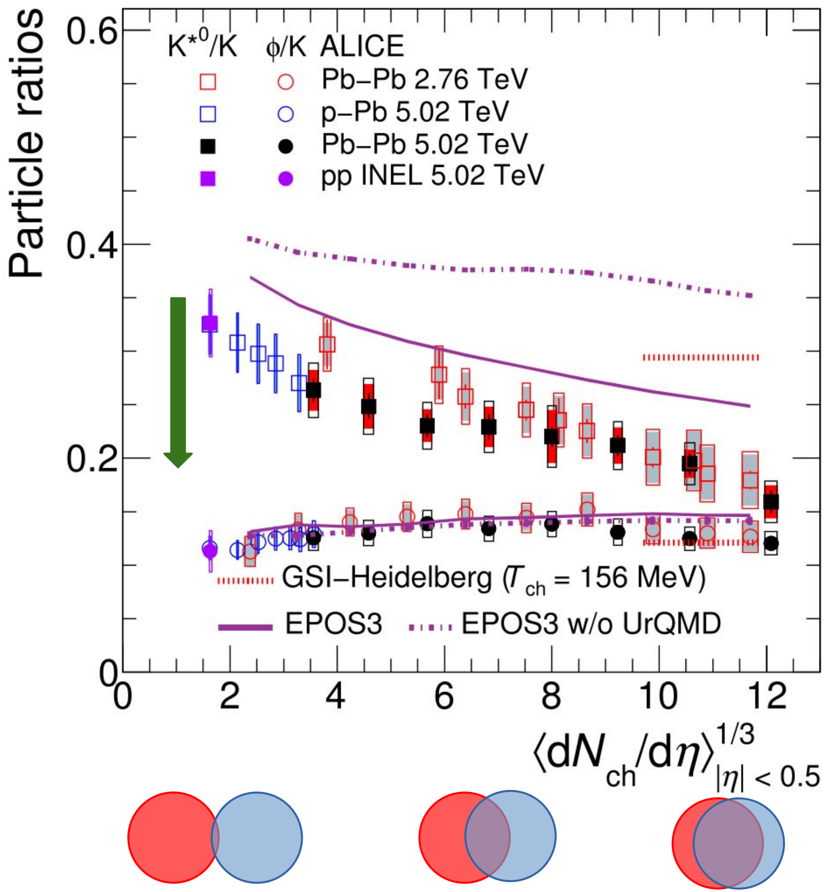
- K* decay products are **rescattered** in the hadronic phase:
  - $K^* \rightarrow K^+ \pi^-$
    $\rightarrow \pi^+ \pi^- \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$



ALICE Collaboration, Physics Letters B Volume 802, 135225

K*(892)^0 and ϕ(1020) ratios vs system size

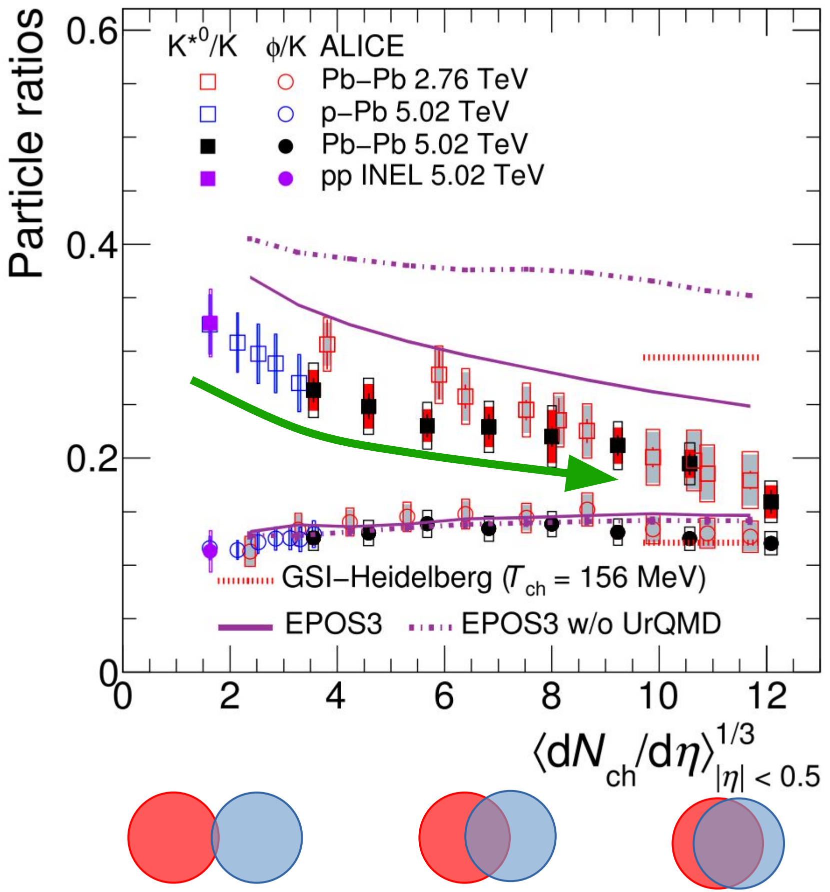
- K* decay products are **rescattered** in the hadronic phase:
  - $K^* \rightarrow K^+ \pi^-$
    $\rightarrow \pi^+ \pi^- \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$
- Suppression of K*/K → Rescattering is dominant over **regeneration**:
  - $\pi K \rightarrow K^*(892)^0 \rightarrow \pi K$



ALICE Collaboration, Physics Letters B Volume 802, 135225

$K^*(892)^0$ and ϕ(1020) ratios vs system size

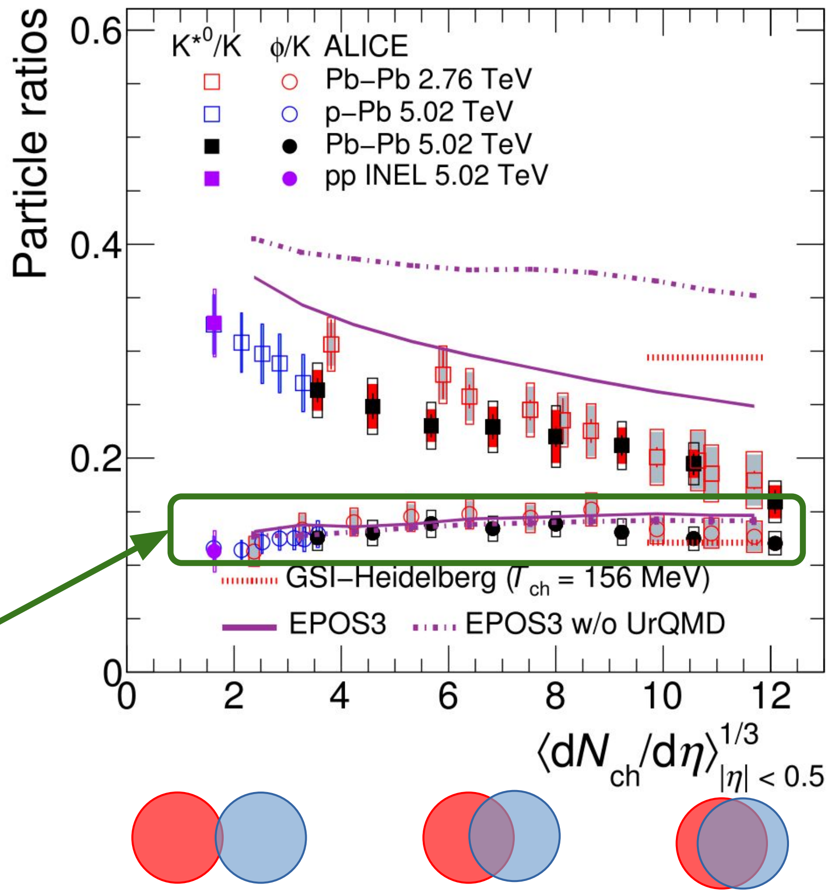
- K* decay products are **rescattered** in the hadronic phase:
  - $K^* \rightarrow K^+ \pi^-$
    $\rightarrow \pi^+ \pi^- \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$
- Suppression of K*/K → Rescattering is dominant over **regeneration**:
  - $\pi K \rightarrow K^*(892)^0 \rightarrow \pi K$
- The suppression of K*/K **increases with system size**



ALICE Collaboration, Physics Letters B Volume 802, 135225

K*(892)^0 and ϕ(1020) ratios vs system size

- K* decay products are **rescattered** in the hadronic phase:
  - $K^* \rightarrow K^+ \pi^-$
    $\rightarrow \pi^+ \pi^- \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$
- Suppression of K*/K → Rescattering is dominant over **regeneration**:
  - $\pi K \rightarrow K^*(892)^0 \rightarrow \pi K$
- The suppression of K*/K **increases with system size**
- ϕ decaying predominantly outside the hadronic medium thanks to its longer lifetime
  - $\tau_{K^*} \simeq 4.16$ fm/c, $\tau_\phi \simeq 46.3$ fm/c

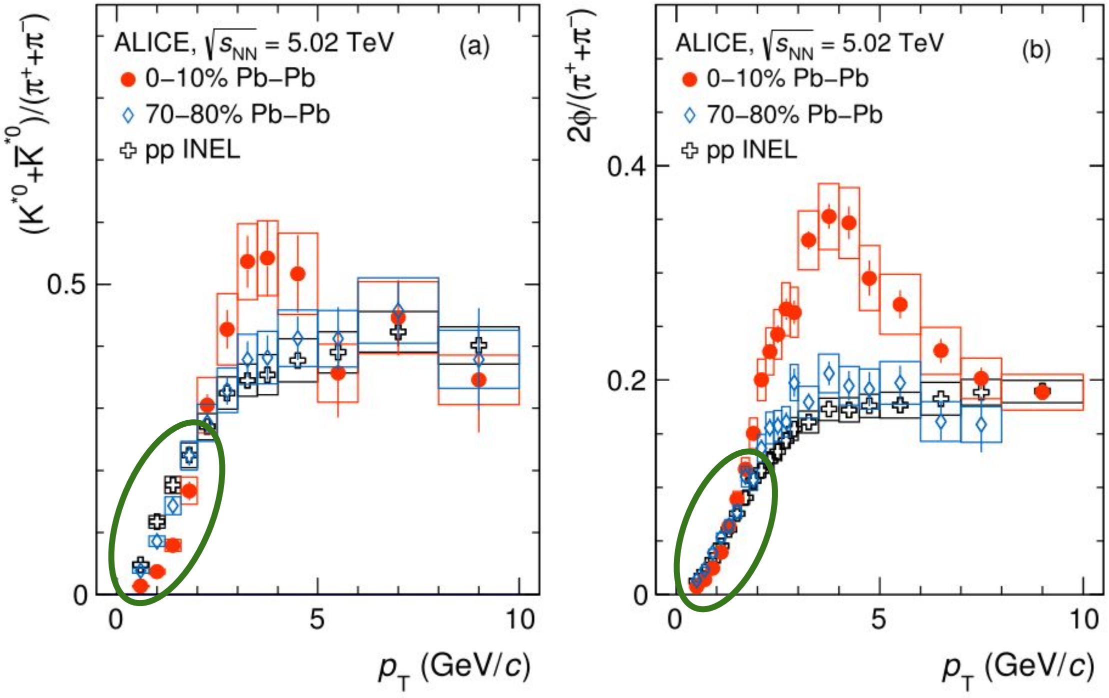


ALICE Collaboration, Physics Letters B Volume 802, 135225

K*(892)^0 and ϕ(1020) ratios vs p_T

- **Low p_T:**
  - **Rescattering effects** influence the K* resonance yields
  - ϕ is not affected by rescattering (central collisions ratio ≃ peripheral one)

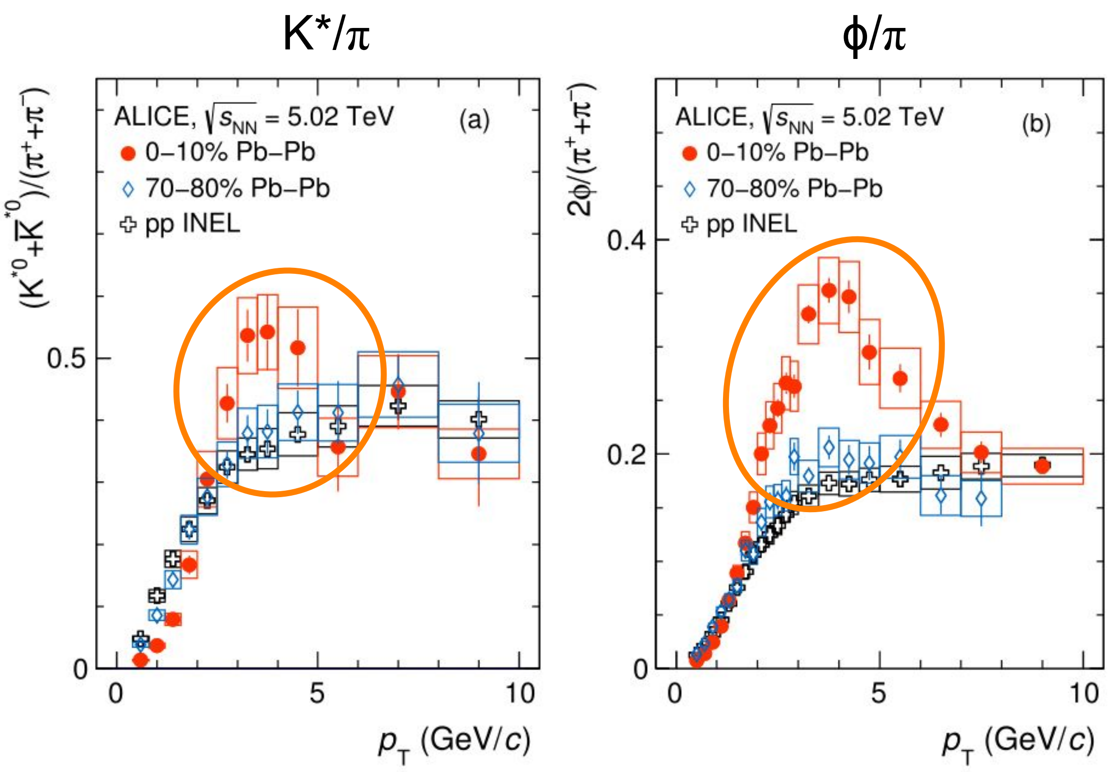
K*/π ϕ/π



ALICE Collaboration, Physics Letters B Volume 802, 135225

K*(892)^0 and ϕ(1020) ratios vs p_T

- **Low p_T:**
  - **Rescattering effects** influence the K* resonance yields
  - ϕ is not affected by rescattering (central collisions ratio ≃ peripheral one)
- **Intermediate p_T:**
  - Radial flow is influencing the K* and ϕ yield (ALICE Collaboration, Phys. Rev. C 101, 044907)
  - $M_{K^*} > M_{\pi\pm}$ → K* production is influenced more than $\pi^{\pm}$



ALICE Collaboration, Physics Letters B Volume 802, 135225

Lifetime of the hadronic phase

- **Time interval** between **Chemical** and **Kinetic** freeze-out (Lower bound):

$$[K^{*0}/K]_{kin} = [K^{*0}/K]_{chem} \times \exp(-\tau/\tau_{K^*})$$

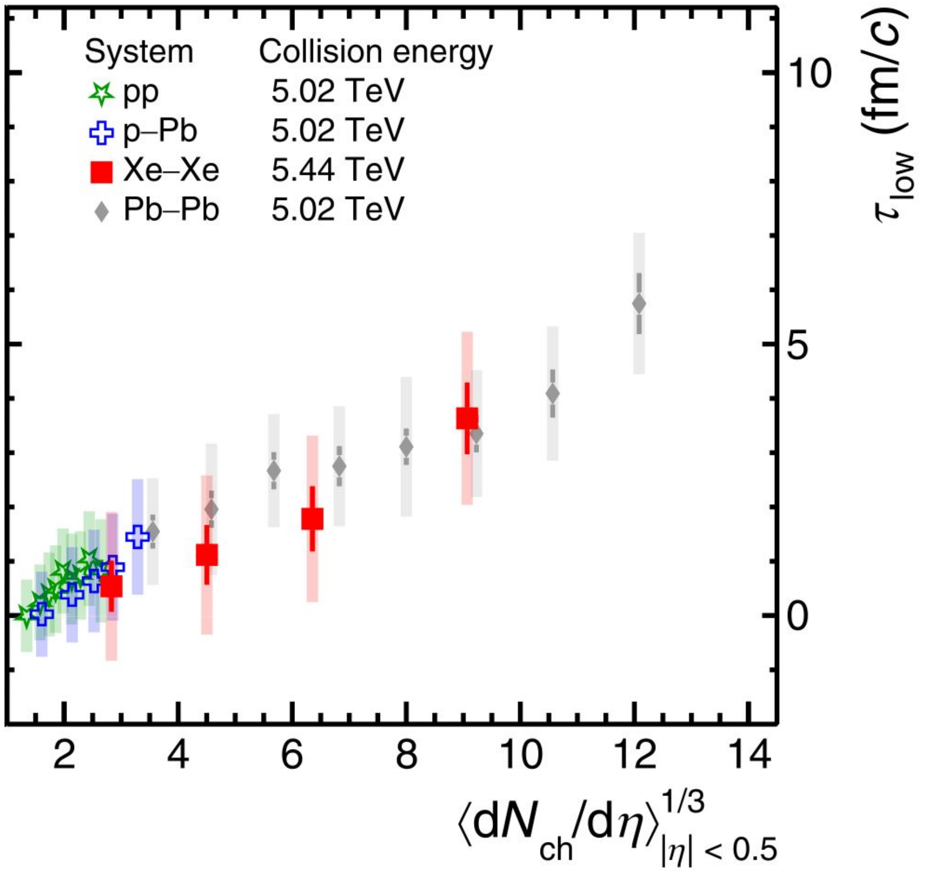
other systems — pp - low multiplicity

  - Assuming all the K* are lost due to rescattering

- For central Pb-Pb collisions:
  - $\tau \simeq 4 - 7$ fm/c
  - **Close to the K* lifetime**

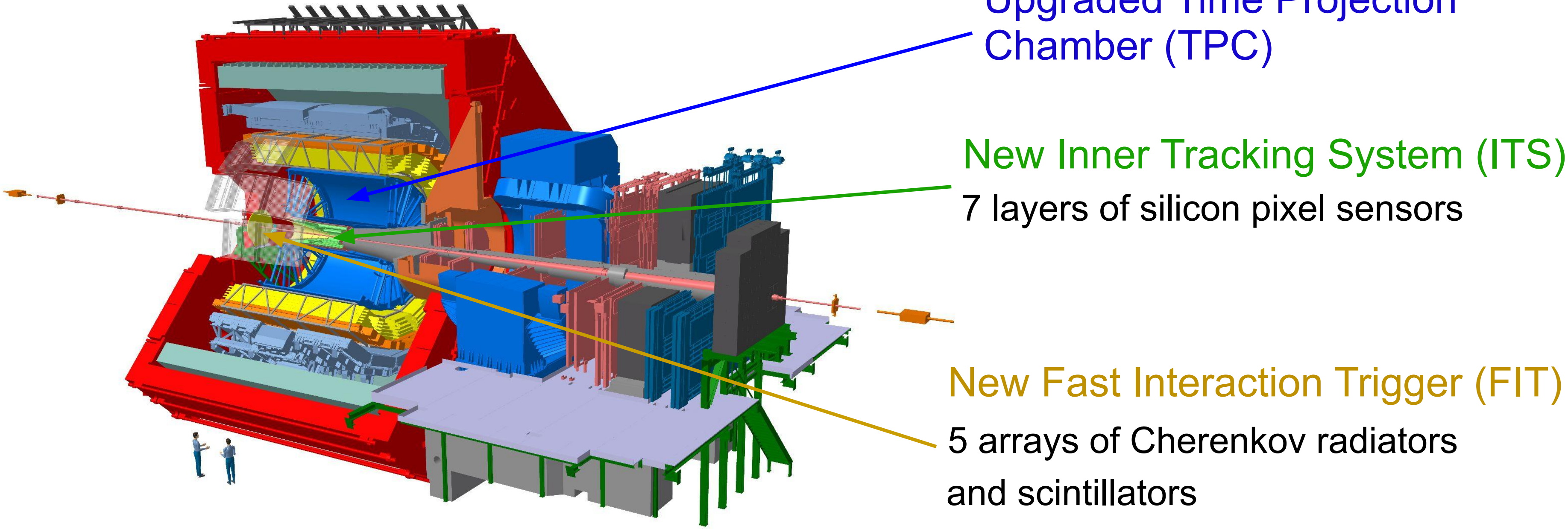
The hadronic phase lifetime can be probed through resonance measurements

ALICE Collaboration, Phys. Rev. C 109, 014911



Feasibility studies of K* and K_1 reconstruction on LHC Run 3 with ALICE

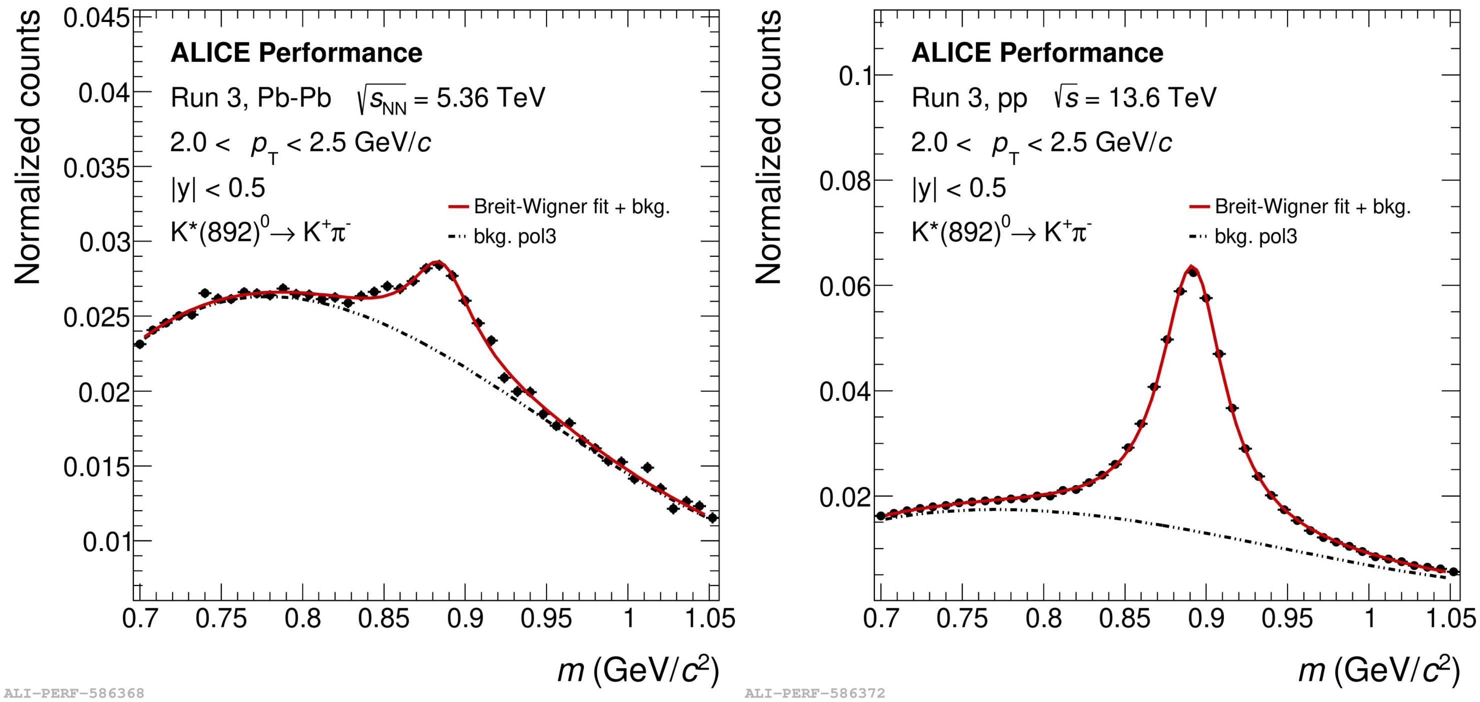
The ALICE Run 3 detector



- Run 3: much larger statistics (Pb-Pb: ~10 x Run 2 events) (pp: ~40 x Run 2 events)
- TPC, TOF: identify particles in a momentum range of [100 MeV, 3.5 GeV]
- ITS: high resolution on the impact parameter (improved by a factor ~ 5 with respect to Run 2)

K*(892)^0 signal extraction

- Data samples: **Pb-Pb** at $\sqrt{s_{NN}}$ = 5.36 TeV, **pp** at $\sqrt{s}$ = 13.6 TeV
- Same event – Mixed event subtraction
- **Fit** of the resulting invariant mass distribution

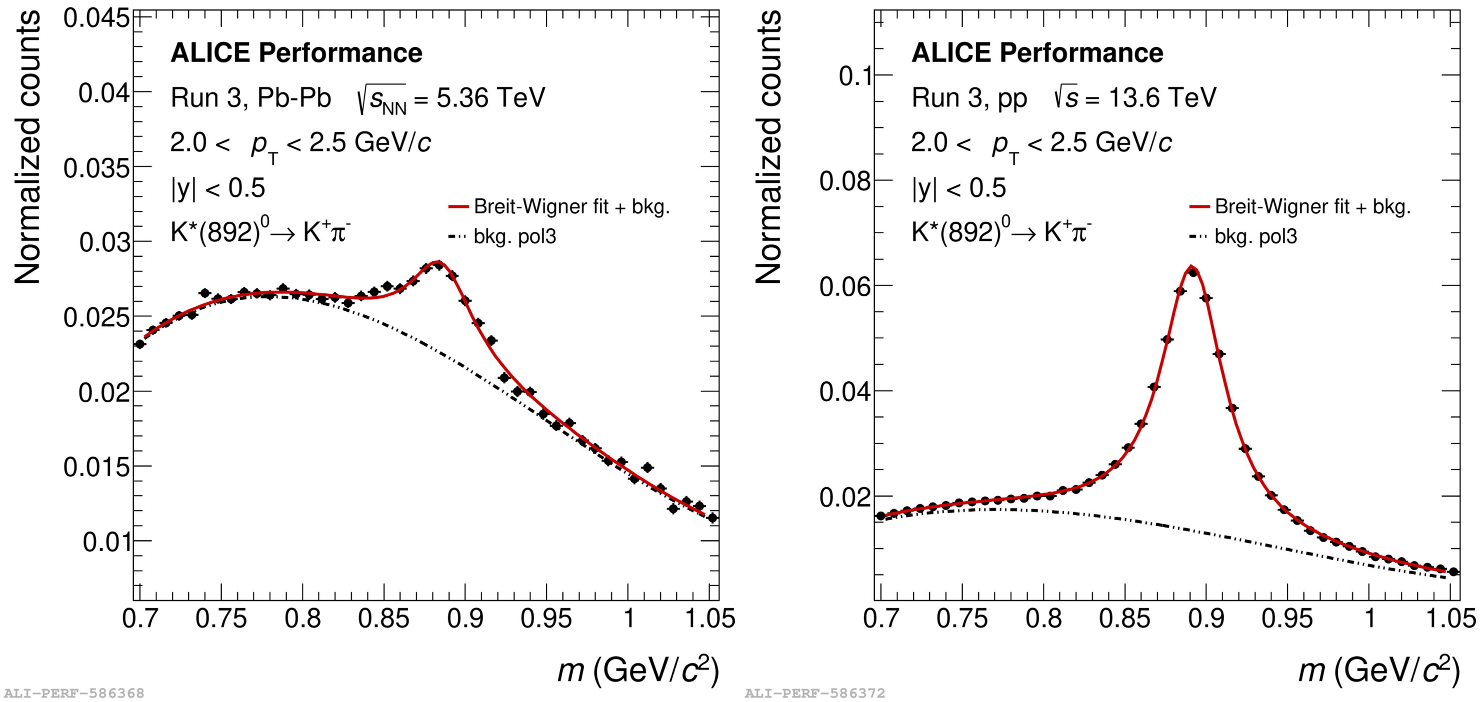


signal: $$f(m) \propto \frac{1}{(m-M_0)^2+\Gamma^2/4}$$

residual bkg: third degree polynomial

Spectra calculation

- Raw yield extraction (N^{raw})
- Efficiencies correction
- Extraction of spectra vs p_T



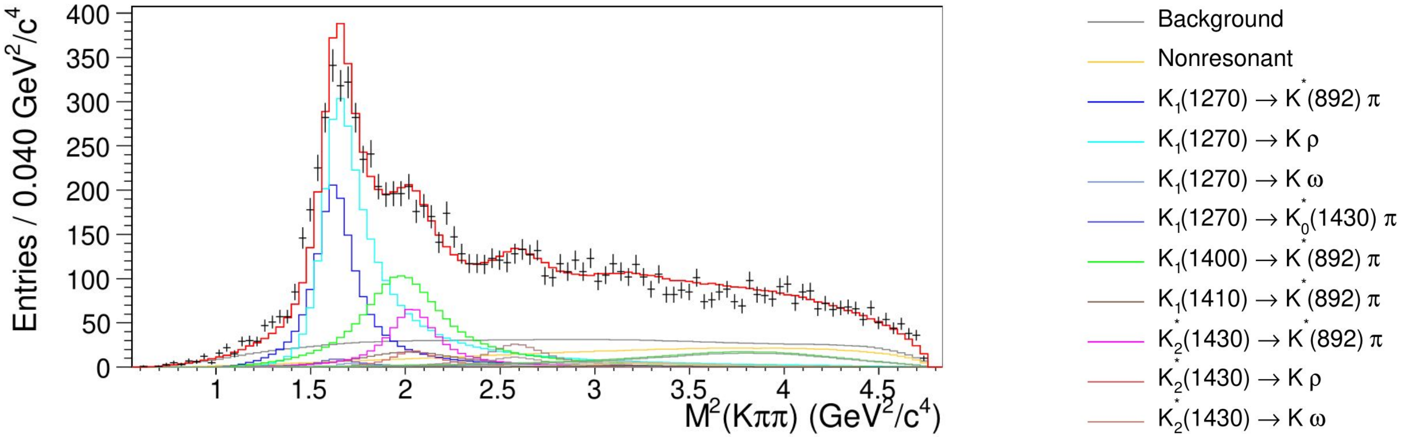
$$\frac{1}{N_{\mathrm{event}}}\frac{\mathrm{d}^2N}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}} = \frac{1}{N_{\mathrm{event}}^{\mathrm{acc}}}\frac{\mathrm{d}^2N^{\mathrm{raw}}}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}\frac{\varepsilon_{\mathrm{trig}}\cdot\varepsilon_{\mathrm{vert}}\cdot\varepsilon_{\mathrm{sig}}}{(A\times\varepsilon_{\mathrm{rec}})\cdot\mathrm{BR}}.$$

$K_1(1270)$ reconstruction

- $K_1(1270)^{\pm} \rightarrow K^*(892)^0\,\pi^{\pm}$ (BR ~ 16 %)
- $M \simeq 1270$ MeV, $\Gamma \simeq 90$ MeV → challenging measurement

Never measured in heavy-ion collisions, but characterized by the Belle2 collaboration at the KEKB e^+e^- collider

Belle Collaboration,
Phys. Rev. D 83, 032005



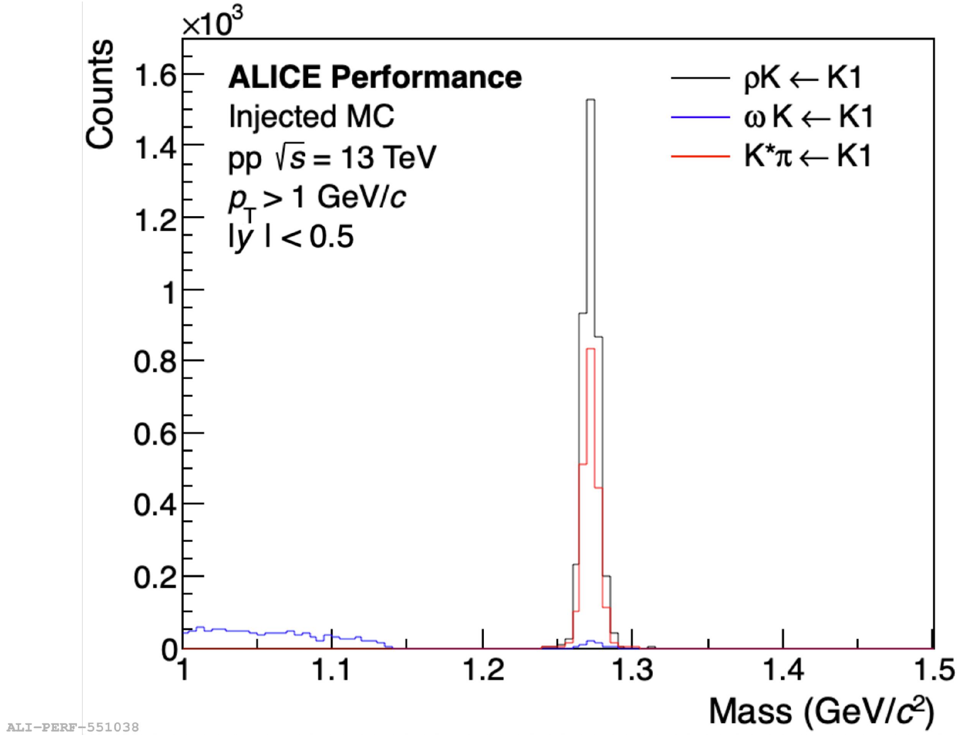
Several resonances are decaying into $K\pi\pi$ which makes the **extraction of the K_1 signal challenging**

$K_1(1270)$ reconstruction

- Now feasible also in ALICE with Run 3 data

- Very high **background** is expected:
  - Combinatorial
  - Correlated:
    - resonances decaying into $K\pi\pi$

- **Plans to reduce the background**:
  - Boosted Decision Tree classifier (combinatorial background reduction)
  - Deep Neural Networks



Conclusions

- **Resonances** are a useful probe to study the evolution of heavy-ion collisions
- $K^*(892)^0$ and $K_1(1270)$ **parity partner** resonances are good candidates for probing **chiral symmetry restoration** in heavy-ion collisions at T_{ch} (chemical freeze-out)
- **K* rescattering and regeneration** processes have been characterized by the ALICE collaboration using Run 2 data
- The **reconstruction of the K_1** resonance is **planned for Run 3**, exploiting the significantly larger data set and upgraded detectors

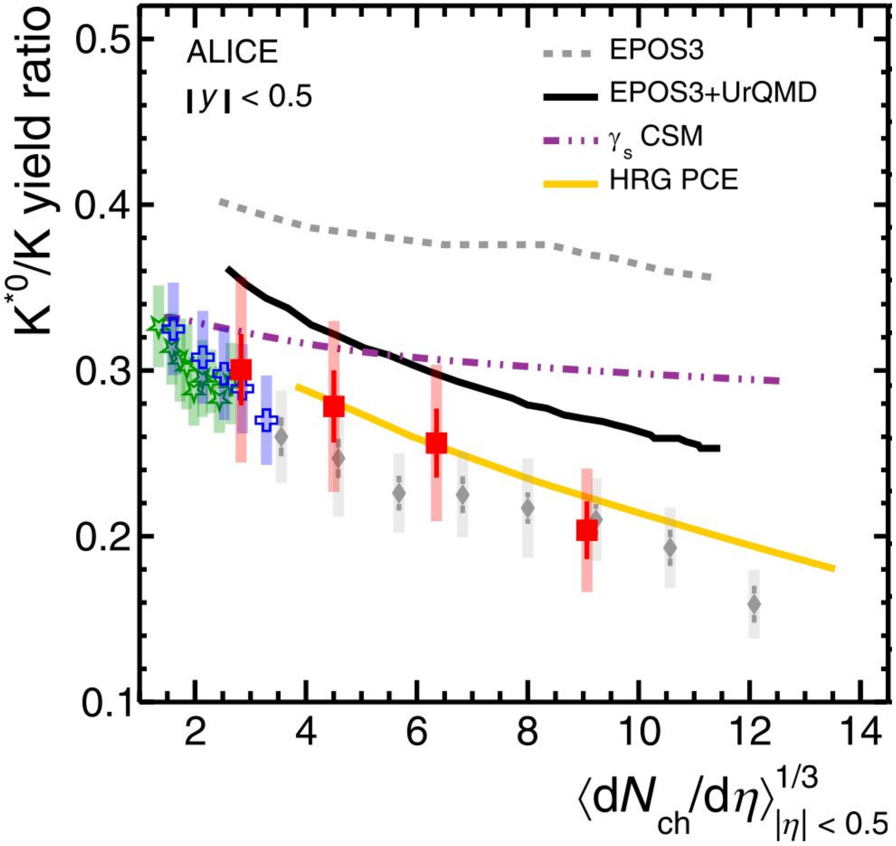
Backup

K*(892)^0 ratios – comparison to models

- Similar results obtained in all the collision systems at the LHC

System	Collision energy
pp	5.02 TeV
p–Pb	5.02 TeV
Xe–Xe	5.44 TeV
Pb–Pb	5.02 TeV

- Models:
  - EPOS3 with/wo UrQMD
    A. G. Knospe, C. Markert, K. Werner, J. Steinheimer, and M. Bleicher
    Phys. Rev. C 93, 014911
    core-corona model w/wo hadronic interactions
  - γ_s Canonical Statistical Model
    V. Vovchenko, B. Dönigus, and H. Stoecker
    Phys. Rev. C 100, 054906
    ideal hadron resonance gas in equilibrium at the chem. freezeout
  - Hadron Resonance Gas Partial Chemical Equilibrium model
    A. Motornenko, V. Vovchenko, C. Greiner, and H. Stoecker
    Phys. Rev. C 102, 024909



ALICE Collaboration, Phys. Rev. C 109, 014911