Understanding the nature of $f_0(980)$ with ALICE at the LHC

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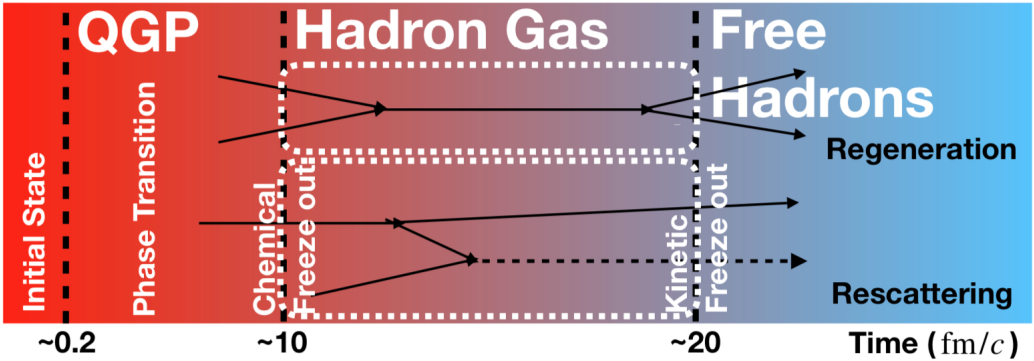
The 15th quark confinement and the hadron spectrum

Short-lived resonances

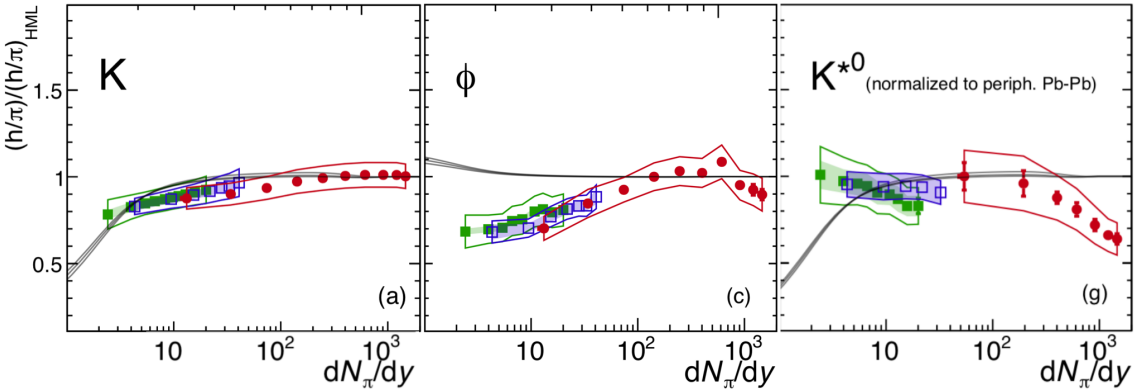


- Resonance yields can be modified in the hadronic gas via regeneration and rescattering.
- Short-lived resonances are powerful probes to study the properties of the hadronic gas.

Particle yield ratio

pp, p–Pb, Pb–Pb

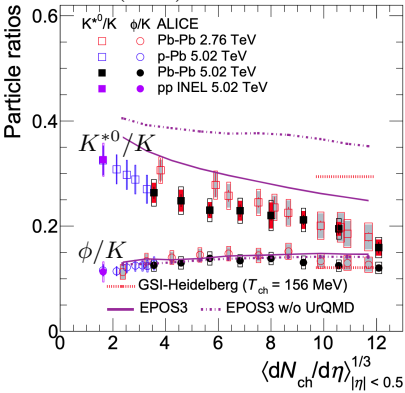
PRC 99, 024906 (2019)

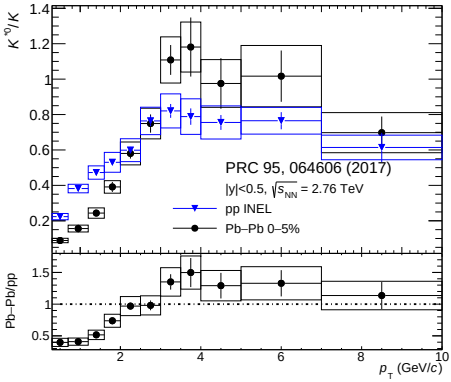


- Strangeness enhancement is seen in the (K/π) and (ϕ/π) ratios.
- Flat (K^{*0}/π) with increasing multiplicity in pp and p–Pb collisions, due to two competing effects.
  - Strangeness enhancement
  - Suppressions due to the short lifetime of K^{*0} ($\tau_{K^{*0}} \sim 4.2$ fm/c) → **evidence for rescattering effects**
- No strangeness enhancement + dominant rescattering effects in Pb–Pb: decreasing (K^{*0}/π)

K^{*0}/K

PLB 802 (2020) 135225





- Strangeness enhancement effect is not expected in (K^{*0}/K) ratio.
- Rescattering effects dominate the decreasing trend.
  - EPOS+UrQMD can qualitatively reproduce the (K^{*0}/K) ratio from small to large collision systems.
  - Strong suppression at low p_{T} + no suppression at high p_{T}
- Therefore, **rescattering is dominant at low** p_{T}.

$f_0(980)$ resonance

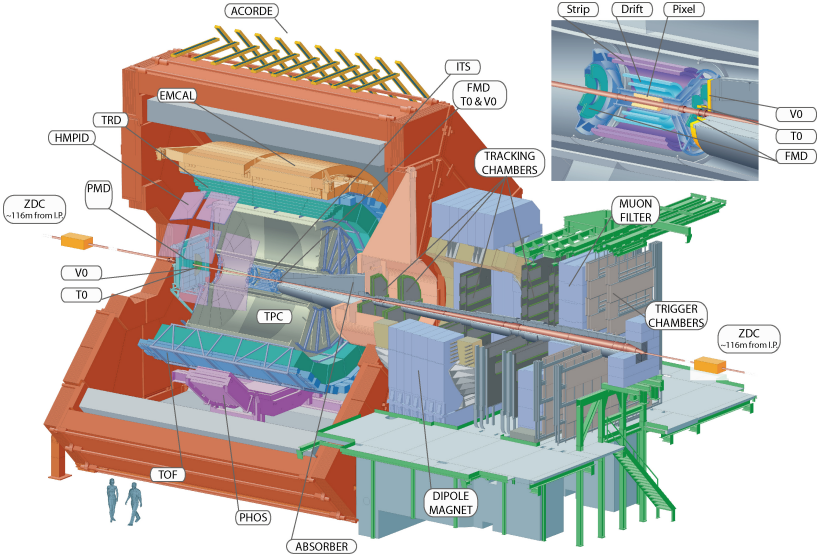
- Scalar meson whose quark content and structure are still unresolved.
  - $q\bar{q}$ state: PRD 67, 094011 (2003)
  - Tetraquark ($q\bar{q}s\bar{s}$) state: PRD 103, 014010 (2021)
  - $K\overline{K}$ molecule state: PRD 101 094034 (2020)
- Measured $f_0(980)$ yield in hadron-hadron collisions can be largely modified because of its short lifetime ($\tau_{f_0} \sim$ 2–20 fm/c).
- Particle yield ratios and nuclear modification factor (Q_{pPb}) of $f_0(980)$ allow to
  - Study the hadronic gas
  - Explore internal structure of $f_0(980)$

	ρ^0	K^*	$f_0(980)$	ϕ
Mass (MeV/c^2)	775	892	990	1020
J^P	1^-	1^-	0^+	1^-
Contents	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$d\bar{s}$	???	$s\bar{s}$
lifetime (fm/c)	1.3	4.2	$\sim$ 2–20	46.2

$$Q_{\mathrm{pPb}}(p_{\mathrm{T}}, \mathrm{cent}) = \frac{\mathrm{d}^2 N_{\mathrm{pPb}}^{\mathrm{cent}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{pPb}}^{\mathrm{cent}} > \mathrm{d}^2\sigma_{\mathrm{pp}}^{\mathrm{INEL}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}},$$

where $< T_{\mathrm{pPb}}^{\mathrm{cent}} >= N_{\mathrm{coll}}^{\mathrm{cent}}/\sigma_{\mathrm{NN}}$

ALICE detector

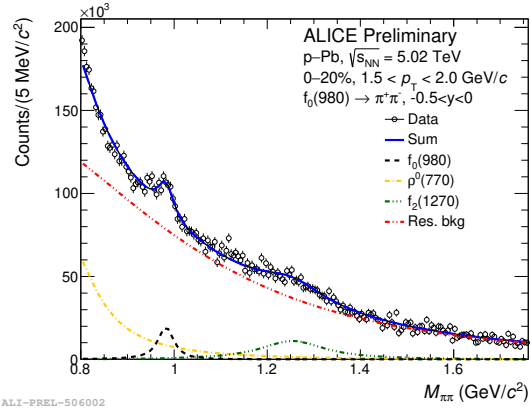


Great performance for tracking and PID down to very low p_{T}

- Tracking with TPC + ITS
- PID with TPC + TOF
- Multiplicity estimation with V0 + ZDC

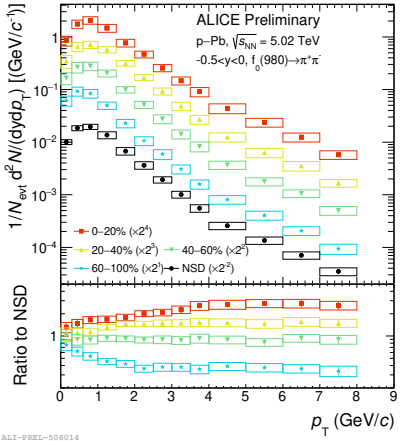
Signal extraction for $f_0(980)$

- Subtracting the combinatorial background using like-sign backgrounds
- The contributions from other resonances, $f_2(1270)$ and $\rho(770)$, are considered at the same time.
- The residual background is modeled using the function:
  $f_{\mathrm{BG}}(M_{\pi\pi}) = (M_{\pi\pi} - 2m_\pi)^n A\exp(BM_{\pi\pi} + CM_{\pi\pi}^2)$

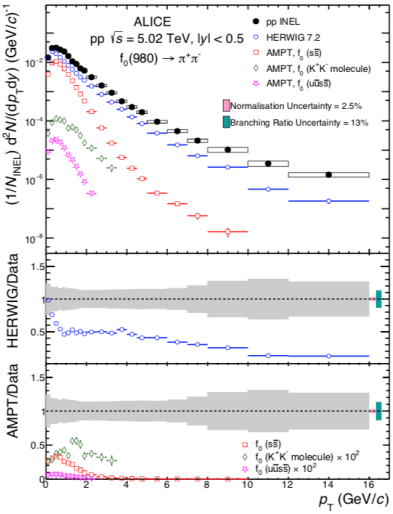


p_T spectra for $f_0(980)$

- Fully corrected p_T spectra for $f_0(980)$ down to $p_T = 0$ in different multiplicity classes
- $f_0(980)$ p_T spectra cannot be reproduced by HERWIG 7.2 model and AMPT+coalescence model in three configurations ($s\bar{s}$, $u\bar{u}s\bar{s}$, and $K\overline{K}$ molecule).
  - Some configurations for the $f_0(980)$ structure can be excluded in the context of AMPT and Herwig models



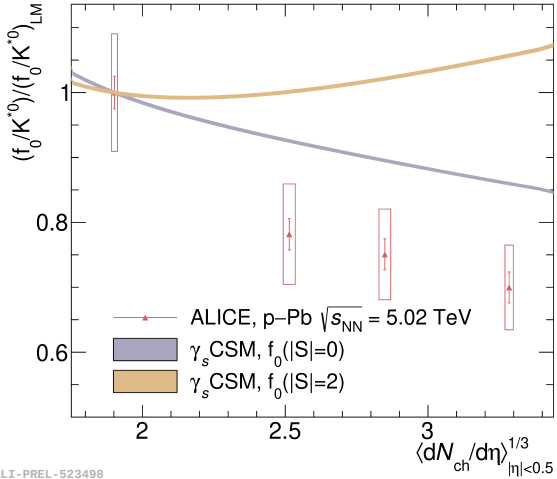
arXiv:2206.06216



Particle yield ratios: (f_0/K^{*0})

- Canonical statistical model (CSM) with multiplicity dependent $\gamma_s \leq 1$ [1] is used to predict (f_0/K^{*0}) ratio for different strangeness content hypotheses.
- Hidden strangeness $|S|$: $|S|^{\rho} = 0$ and $|S|^{\phi} = 2$
- CSM predicts an almost flat behavior for $|S| = 2$ while a decreasing trend (qualitatively similar to what seen in data) is expected for $|S| = 0$.
  - N.B.: No rescattering effects in CSM
  - Lifetimes of K^{*0} and $f_0(980)$ are comparable to each other.
  - [1] V. Vovchenko et al, PRC 100 (2019) 5, 054906

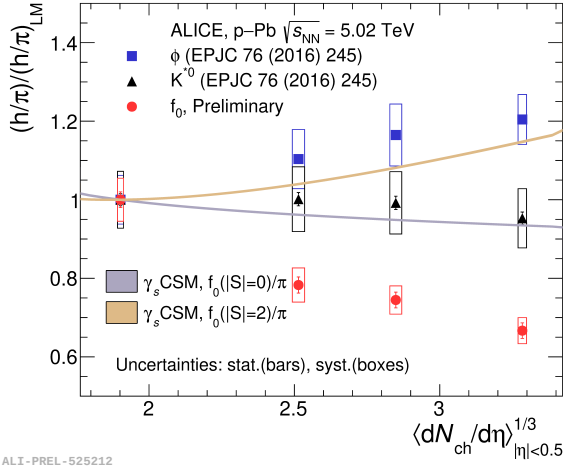
	K^*	$f_0(980)$	ϕ
lifetime (fm/c)	4.2	~4	46.2



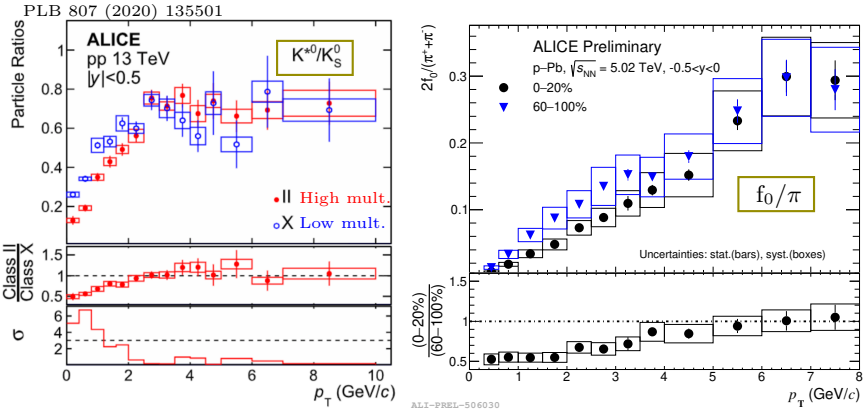
Particle yield ratios: (f_0/π)

- (f_0/π) ratio decreases with increasing $\langle dN/d\eta \rangle$.
  - Similar trend as observed for (K^{*0}/K) but larger decrease with the multiplicity
  - Larger rescattering effects or smaller regeneration effects for $f_0(980)$?
- γ_sCSM predicts (f_0/π) increasing trend for $|S| = 2$ while a flat behavior is expected for $|S| = 0$.
  - (f_0/π) is overestimated by CSM.
  - Rescattering effects for $f_0(980)$ is not considered.

	K^*	$f_0(980)$	ϕ
lifetime (fm/c)	4.2	~4	46.2

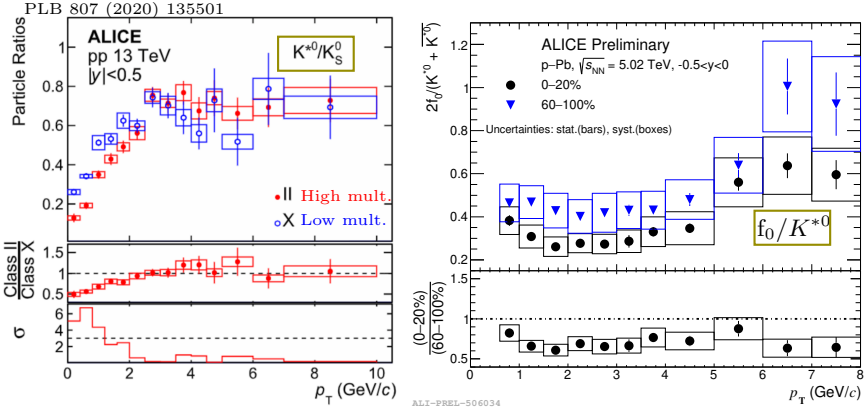


p_T-differential yield ratios of $f_0(980)$ to π



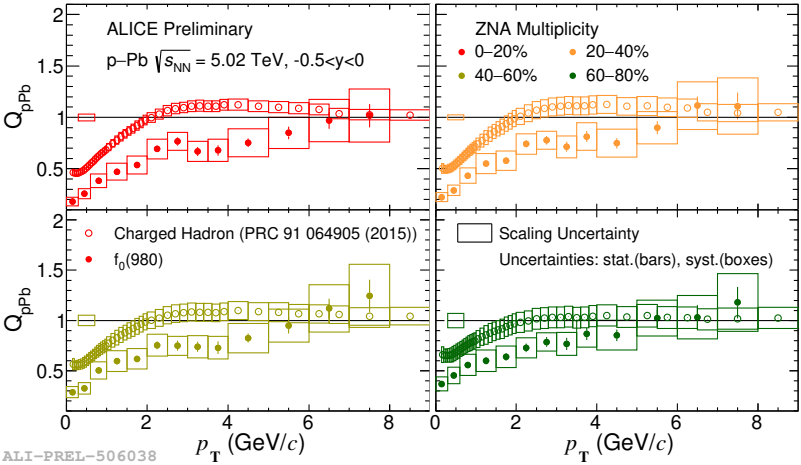
- (f_0/π): Significant modification at low p_T (< 3 GeV/c) and no modification at high p_T (> 4 GeV/c)
  - Similar p_T dependence between (pp_{high}/pp_{low}) and (Pb–Pb/pp) for (K^{*0}/K)
  - Similar p_T dependence between double ratio of (K^{*0}/K) and (f_0/π)

p_T-differential yield ratios of $f_0(980)$ to K^{*0}



- Rescattering effects should be comparable between $f_0(980)$ and K^{*0} as they have comparable lifetime.
- Different behavior between (K^{*0}/K) and (f_0/K^{*0}) in the full measured p_T interval
- (f_0/K^{*0}): Modification in the entire p_T range.
  $\rightarrow$ due to different quark content for the two particles?

Nuclear modification factor, Q_{pPb}

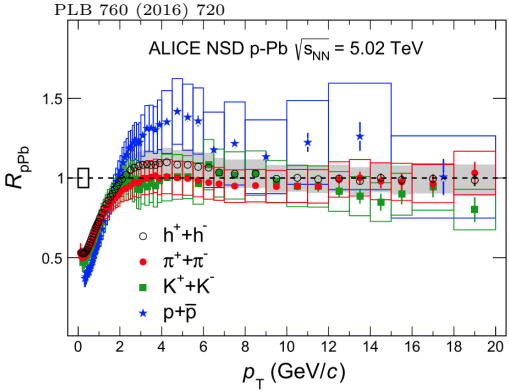


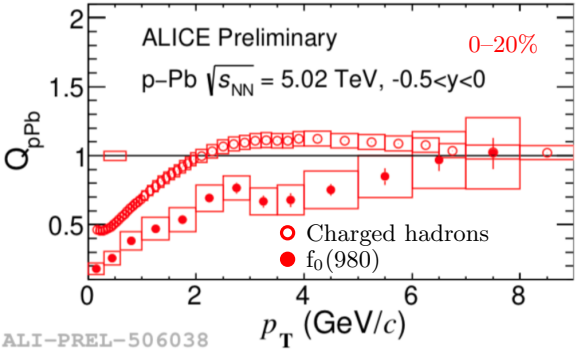
$$Q_{\mathrm{pPb}}(p_{\mathrm{T}}, \mathrm{cent}) = \frac{\mathrm{d}^2 N_{\mathrm{pPb}}^{\mathrm{cent}}/\mathrm{dy}\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{pPb}}^{\mathrm{cent}} > \mathrm{d}^2\sigma_{\mathrm{pp}}^{\mathrm{INEL}}/\mathrm{dy}\mathrm{d}p_{\mathrm{T}}},$$

where $< T_{\mathrm{pPb}}^{\mathrm{cent}} >= N_{\mathrm{coll}}^{\mathrm{cent}}/\sigma_{\mathrm{NN}}$

- Multiplicity dependent suppression for $f_0(980)$ at the low $p_{\mathrm{T}}(< 4$ GeV/$c)$
- Rescattering effects observed in all the centrality intervals

Cronin peak





- Cronin enhancement at intermediate p_T: J. W. Cronin et al, PRD 11 3105 (1975)
- No Cronin peak is observed for $f_0(980)$ in contrast to what is observed for baryons.

Summary

- Decreasing (f_0/π) at low p_T
  - **Evidence of rescattering-like effects for the f_0(980)**
- Decreasing (f_0/K^{*0}) in the full measured p_T range
  - **due to different quark content for f_0(980) and K^{*0}?**
- Multiplicity dependence of Q_{pPb} of f_0(980)
  - **Stronger suppression of f_0(980) at low p_T: rescattering effects**
  - **No Cronin peak for Q_{pPb} of f_0(980) in high-multiplicity events.**
- Models with different quark contents or structures are needed to shed light on f_0(980) structure.

BACKUP