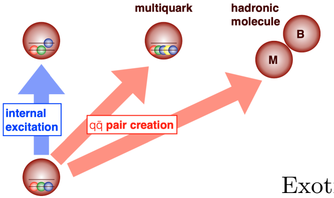
Understanding the nature of light scalar meson with ALICE



Junlee Kim
Jeonbuk National University, South Korea

Sep 30, 2022
Exotics and Exotic Phenomena in Heavy Ion Collisions

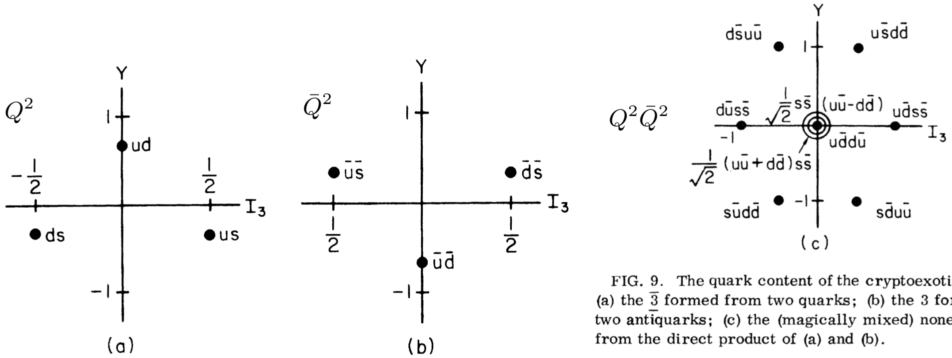
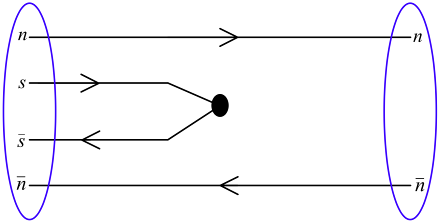


FIG. 9. The quark content of the cryptoexotic nonet. (a) the $\bar{3}$ formed from two quarks; (b) the 3 formed from two antiquarks; (c) the (magically mixed) nonet formed from the direct product of (a) and (b).

- Tetraquark picture was firstly suggested by: `Phys. Rev. D 15, 267 (1977)`
- Scalar mesons: zero spin + even parity
- Inverted masses ordering ($\sigma(500)$, $\kappa(800)$, $f_0(980)$ and so on)

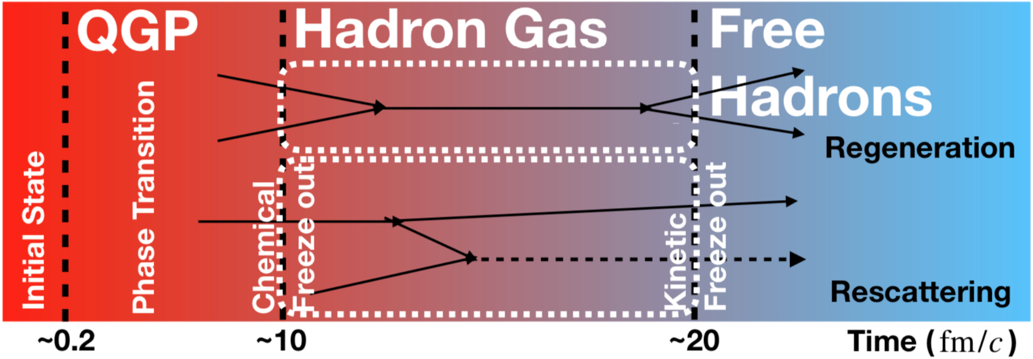
Conventional $q\bar{q}$ with angular momentum

- HADRON PROPERTIES FROM QCD SUM RULE, `PHYSICS REPORTS 127, No. 1(1985) 1-97`
- In quark model, scalar meson can be expressed as $q\bar{q}$ with $L = 1$ to make parity even.
- In equation (4.50) of the physics report cited above, $m_{n\bar{n}} = 1.00$ GeV$/c^2$ ($f_0(980)$ mass) and $m_{s\bar{s}} = 1.35$ GeV$/c^2$
- Difficult to separate the molecular and the tetraquark state
- Many suggestions for the $f_0(980)$ structure.
  - $q\bar{q}$ 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)



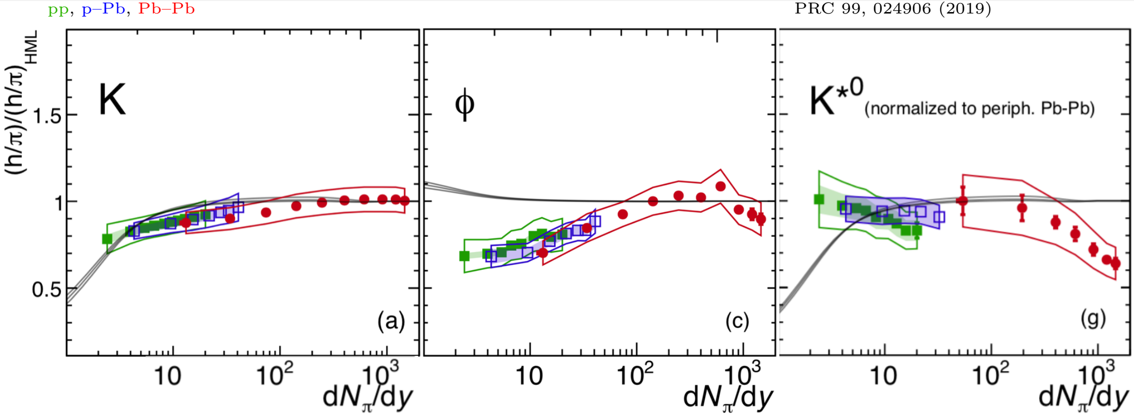
	ρ^0	K^*	$f_0(980)$	ϕ
Mass (MeV$/c^2$)	775	892	990	1020
J^P	1^-	1^-	0^+	1^-
Contents	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$d\bar{s}$	???	$s\bar{s}$
lifetime (fm$/c$)	1.3	4.2	$\sim$ 2–20	46.2

Measurement for short-lived resonances in HIC



- 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 hadron gas.
- Modification of the $f_0(980)$ yield: good tool to study the hadron gas

Particle yield ratio



- 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) $\rightarrow$ **evidence for rescattering effects**
- No strangeness enhancement + dominant rescattering effects in Pb–Pb: decreasing (K^{*0}/π)

K^{*0}/K

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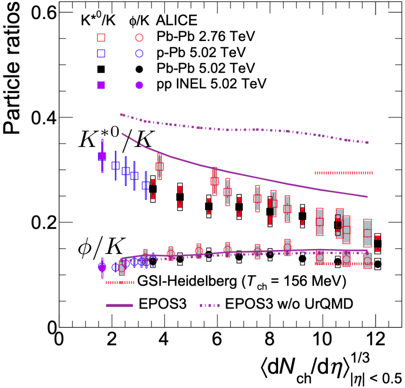
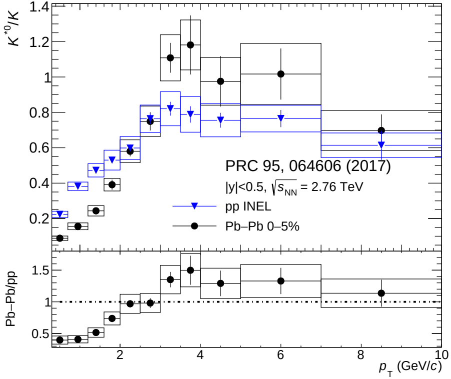
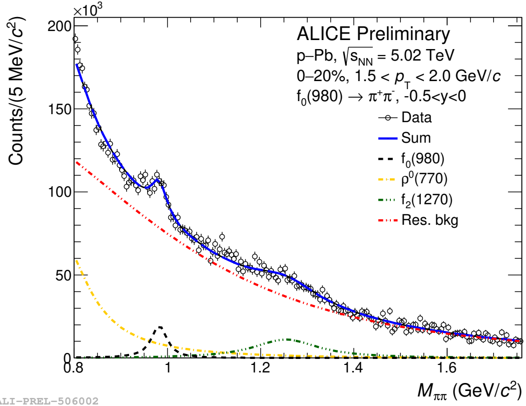




- Strangeness enhancement effect is not expected in (K^{*0}/K) ratio.
- Rescattering effects dominate the decreasing trend.
  - EPOS+UrQMD can qualitatively reproduce the (K^{*0}/K) ratio from small to large collision systems.
  - Strong suppression at low p_{T} + no suppression at high p_{T}
- Therefore,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

Signal extraction for $f_0(980)$

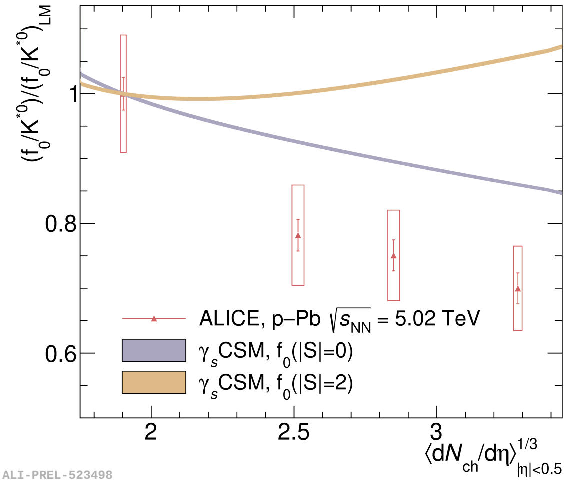
- Subtracting the combinatorial background using like-sign backgrounds
- The contributions from other resonances, $f_2(1270)$ and $\rho(770)$, are considered at the same time.
- The residual background is modeled using the function:
  $f_{\mathrm{BG}}(M_{\pi\pi}) = (M_{\pi\pi} - 2m_\pi)^n A\exp(BM_{\pi\pi}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



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

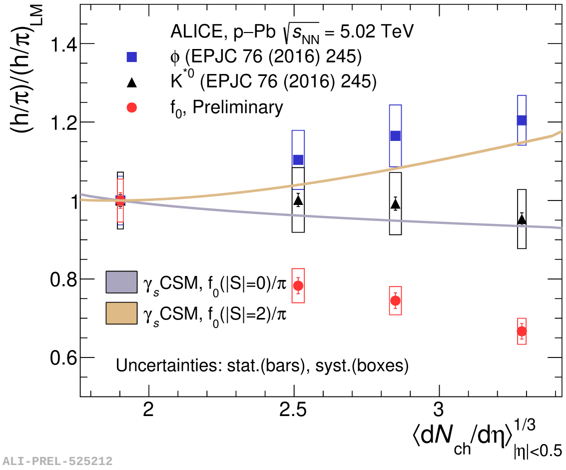
- Canonical statistical model (CSM) with multiplicity dependent $\gamma_s \leq 1$ [1] is used to predict (f_0/K^{*0}) ratio for different strangeness content hypotheses.
- Hidden strangeness $|S|$: $|S|^{\rho} = 0$ and $|S|^{\phi} = 2$
- CSM predicts an almost flat behavior for $|S| = \mathbf{2}$ while a decreasing trend (qualitatively similar to what seen in data) is expected for $|S| = \mathbf{0}$.
  - N.B.: No rescattering effects in CSM
  - Lifetimes of K^{*0} and $\mathrm{f}_0(980)$ are comparable to each other.
  - [1] V. Vovchenko et al, PRC 100 (2019) 5, 054906

	K^*	$\mathrm{f}_0(980)$	ϕ
lifetime (fm/c)	4.2	$\sim$4	46.2

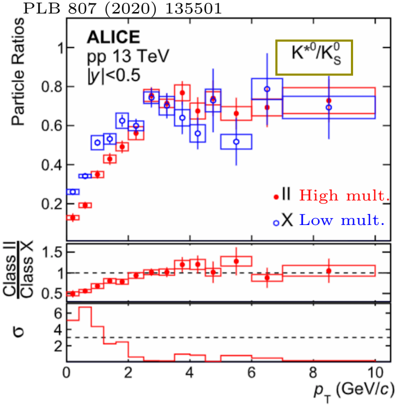


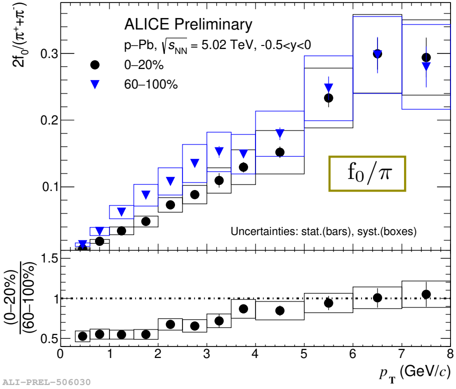
- (f_0/π) ratio decreases with increasing $\langle dN/d\eta \rangle$.
  - Similar trend as observed for (K^{*0}/K) but larger decrease with the multiplicity
  - Larger rescattering effects or smaller regeneration effects for $f_0(980)$?
- γ_sCSM predicts (f_0/π) increasing trend for $\boxed{|S| = 2}$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

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



p_{T}-differential yield ratios of $\mathrm{f}_0(980)$ 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 for ($\mathrm{pp_{high}}/\mathrm{pp_{low}}$) and (Pb–Pb/pp) for (K^{*0}/K)
  - Similar p_{T} dependence for double ratios of (K^{*0}/K) and (f_0/π)

p_{T}-differential yield ratios of $\mathrm{f}_0(980)$ to K^{*0}

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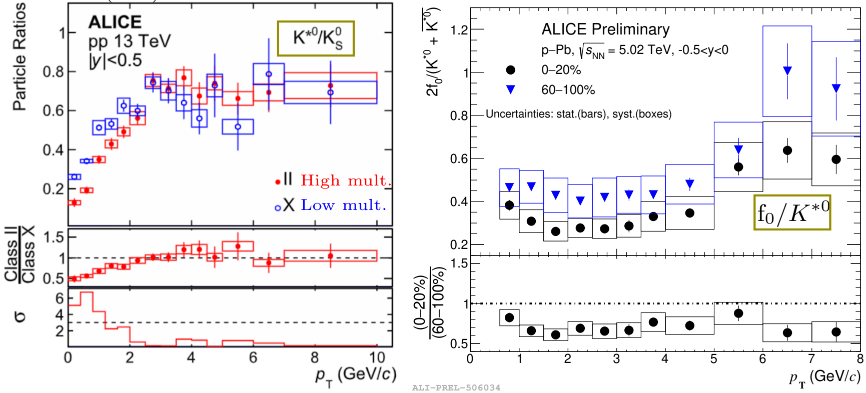
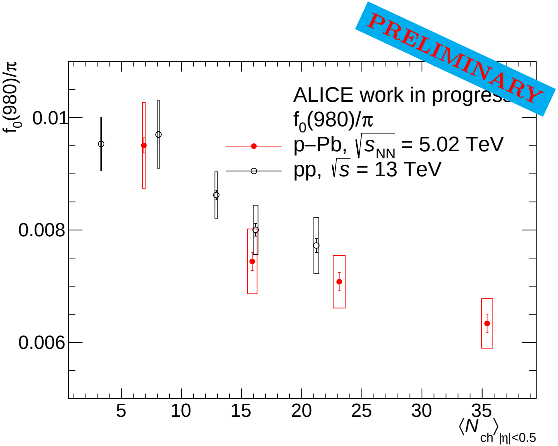
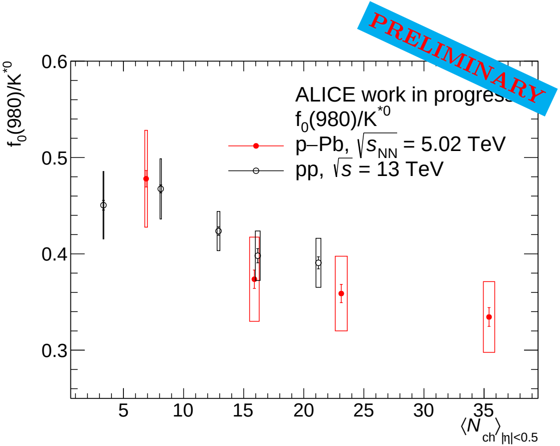


- Rescattering effects should be comparable between $\mathrm{f}_0(980)$ and K^{*0} as they have comparable lifetime.
- Different behavior between (K^{*0}/K) and (f_0/K^{*0}) in the full measured p_{T} interval
- (f_0/K^{*0}): Modification in the entire p_{T} range.
  $\rightarrow$ due to different quark content for the two particles?

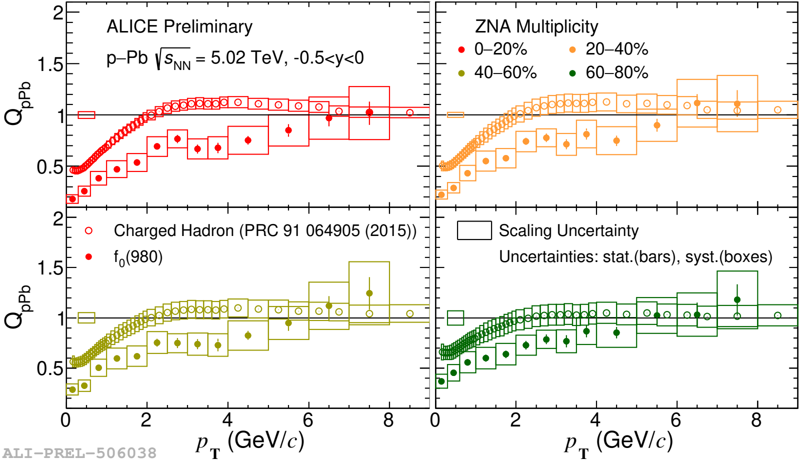
Comparison with pp collisions





- Sequential suppressions with the increasing multiplicity.

Nuclear modification factor, Q_{pPb}

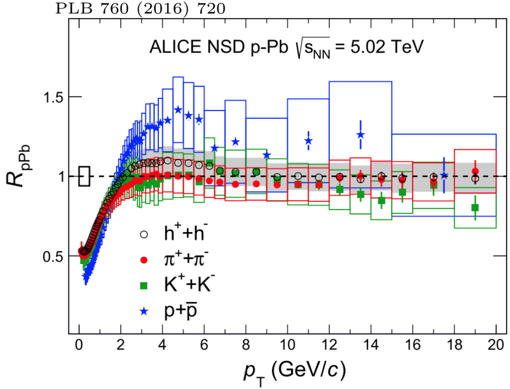


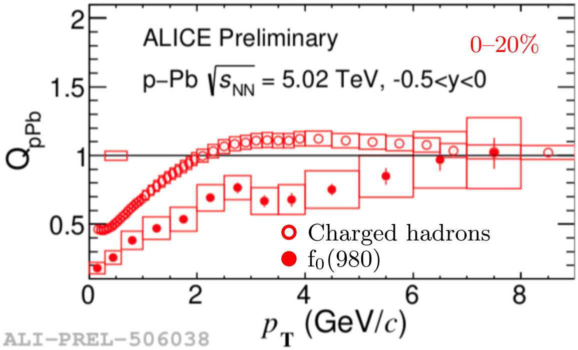
$$Q_{\mathrm{pPb}}(p_{\mathrm{T}}, \mathrm{cent}) = \frac{\mathrm{d}^2 N^{\mathrm{cent}}_{\mathrm{pPb}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}{< T^{\mathrm{cent}}_{\mathrm{pPb}} > \mathrm{d}^2\sigma^{\mathrm{INEL}}_{\mathrm{pp}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}},$$

where $< T^{\mathrm{cent}}_{\mathrm{pPb}} >= N^{\mathrm{cent}}_{\mathrm{coll}}/\sigma_{\mathrm{NN}}$

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

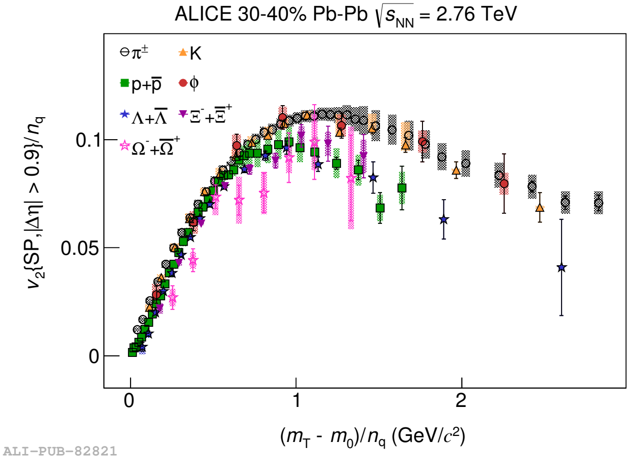
Cronin peak



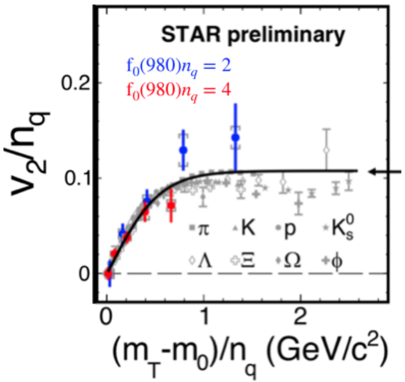


- Cronin enhancement at intermediate p_T: J. W. Cronin et al, PRD 11 3105 (1975)
- No Cronin peak is observed for $f_0(980)$ in contrast to what is observed for baryons.

NCQ scaling for $f_0(980)$



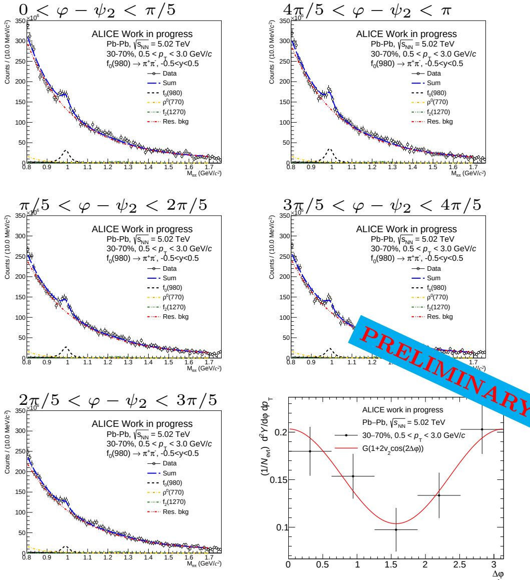
STAR preliminary at SQM 2021



- The NCQ scaling results in the same flow coefficients between baryons and mesons.
- The NCQ scaling test for $f_0(980)$

Preliminary results on NCQ scaling for $f_0(980)$

- Event plane method was applied to reconstruct the reaction plane, ψ_2.
- $dY/d\varphi \sim G(1 + 2v_2\cos(2\Delta\varphi))$
- Decreasing $dY/d\varphi$ observed at $\Delta\varphi = 0.5\pi$.
- $v_2(0.5 < p_T < 3.0) = 0.162 \pm 0.050_{\mathrm{stat}}$
  - $m_T - m_0 = 1.03$ GeV/c.
  - Comparable with other particles
  - NCQ scaling rarely provides a hint for the $f_0(980)$ structure at low p_T.
- Important to measure v_2 at high $p_T > 4$ GeV/c ($(m_T - m_0)/n_2 > 1.5$ GeV/c).



$K^0 K^{\pm}$ femtoscopy for $a_0(980)$

Lednicky eqution: Correlation function for two bosons
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$$C(k^*) = \int d^3\vec{r}^{\,*} S(r^*) \left|\Psi^S_{-\vec{k}^*}(\vec{r}^{\,*})\right|^2$$

$$= 1 + \lambda e^{-4k^{*2}R^2} + \lambda\alpha\left[\left|\frac{f(k^*)}{R}\right|^2 + \frac{4\Re f(k^*)}{\sqrt{\pi}R}F_1(2Rk^*) - \frac{2\Im f(k^*)}{R}F_2(2Rk^*) + \Delta C\right]$$

quantum statistics term

Final-state interaction term

$$\text{where } F_1(z) = \int_0^z dx \frac{e^{x^2-z^2}}{z} \qquad F_2(z) = \frac{1-e^{-z^2}}{z}$$

- Pairwise interactions present for $K_0 K^{\pm}$.
  - Non-identical pairs: no quantum statistics
  - No Coulomb interaction
  - $a_0(980)$ strong interaction
- Studying the geometry of kaon source, R: radius of source
- Exploring the Internal structure of $a_0(980)$, λ: correlations strength

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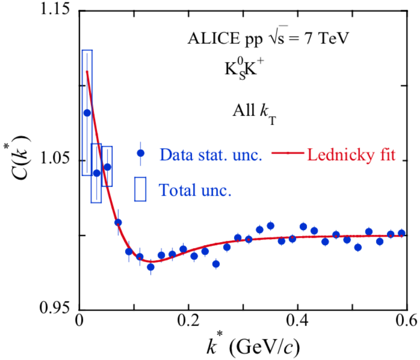
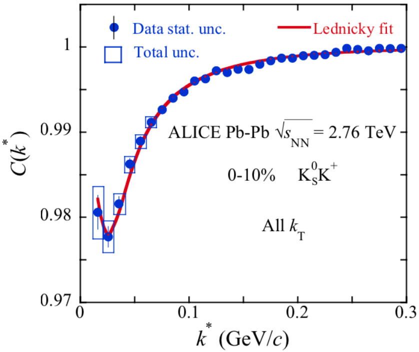


PLB 774 (2017) 64-77



- The Lednicky eqution models experimental data well for different collision systems.
  - Extraction of R and λ

Comparison with $K^0_s K^0_s$

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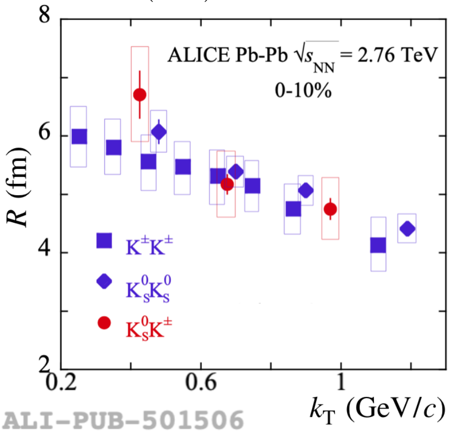
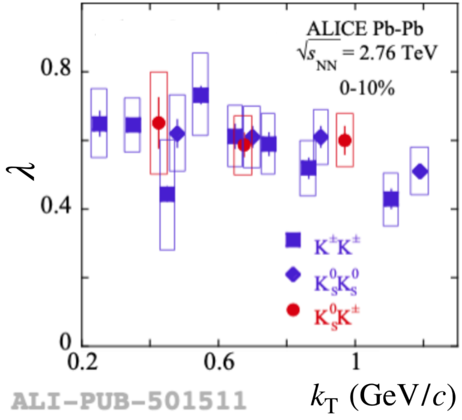
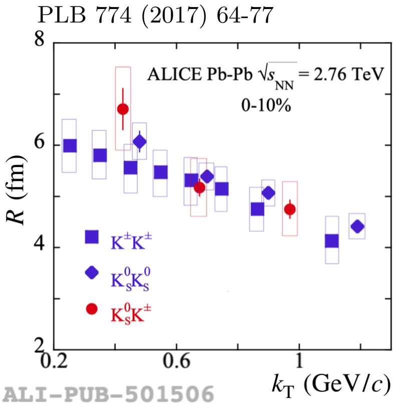
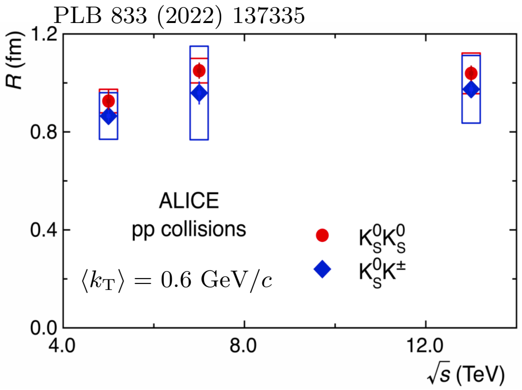




- Decreasing R: radial flow effects (PLB 356, 525 (1995))
- Comparable λ between $K^0_s K^0_s$ and $K^0 K^{\pm}$

Comparison with the system size





- Small source size for pp collisions ($R \sim A^{1/3}$)
- Small flow effects in small systems.

Comparison with the system size

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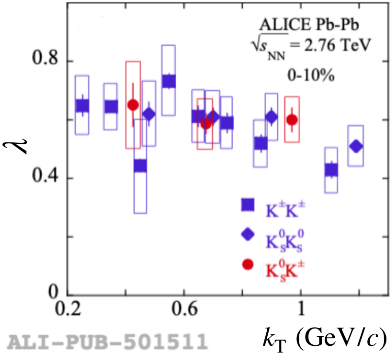

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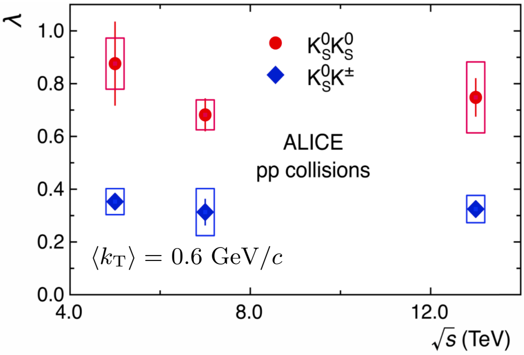


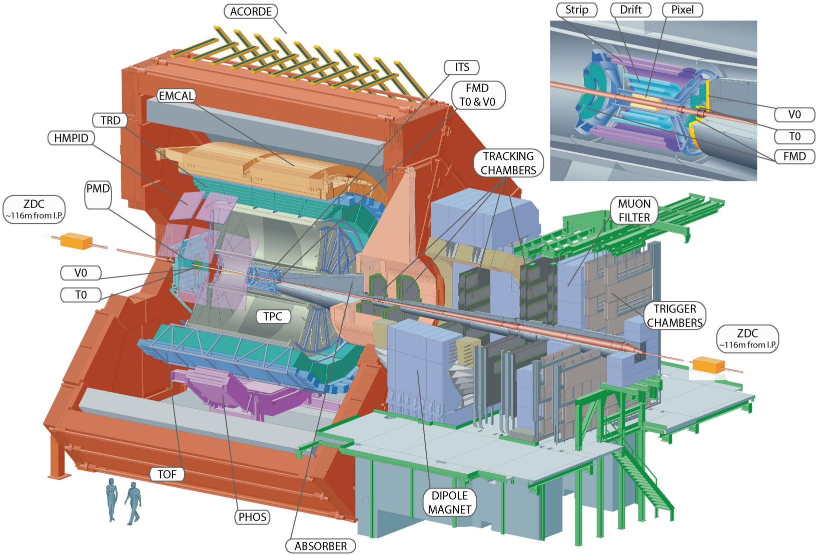
- Comparable λ for $K_s^0 K_s^0 \rightarrow$ Quantum statistics effects dominate the correlations
- $\lambda_{\mathrm{PbPb}} > \lambda_{\mathrm{pp}}$ for $K^0 K^{\pm}$
  - Enhanced s-$\bar{s}$ annihilation due to the small source size inside a_0?

Summary

- Decreasing (f_0/π) at low p_{T} in pp and p–Pb collisions
  - **Evidence of rescattering-like effects for the $\mathrm{f}_0(980)$**
- Decreasing (f_0/K^{*0}) in the full measured p_{T} range in pp and p–Pb collisions
  - **due to different quark content for $\mathrm{f}_0(980)$ and K^{*0}?**
- Multiplicity dependence of Q_{pPb} of $\mathrm{f}_0(980)$
  - **Stronger suppression of $\mathrm{f}_0(980)$ at low p_{T}: rescattering effects**
  - **No Cronin peak for Q_{pPb} of $\mathrm{f}_0(980)$ in high-multiplicity events.**
- Measurement of $\mathrm{f}_0(980)$ elliptic flow at high p_{T} to test the NCQ scaling with Run3 data in Pb–Pb collisions
- Femtoscopy measurement of $K^0_{\mathrm{s}}K^0_{\mathrm{s}}$ and $K^0K^{\pm}$
  - Source (system) size determination of pp and Pb–Pb collisions
  - System-size-dependent correlations strength $\rightarrow a_0$ to have $s\bar{s}$?

BACKUP

ALICE detector

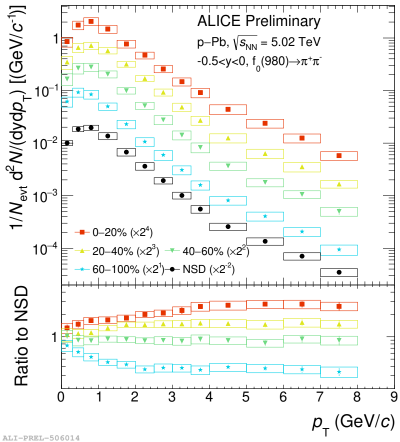


Great performance for tracking and PID down to very low p_{T}

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

p_{T} spectra for $\mathrm{f}_0(980)$

- Fully corrected p_{T} spectra for $\mathrm{f}_0(980)$ down to $p_{\mathrm{T}} = 0$ in different multiplicity classes
- $\mathrm{f}_0(980)$ 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 $\mathrm{f}_0(980)$ structure can be excluded in the context of AMPT and Herwig models



ALI-PREL-506014

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