The Ohio State University

Studying the $a_0(980)$ tetraquark candidate using $K^0_SK^{\pm}$ interactions in the LHC ALICE Collaboration

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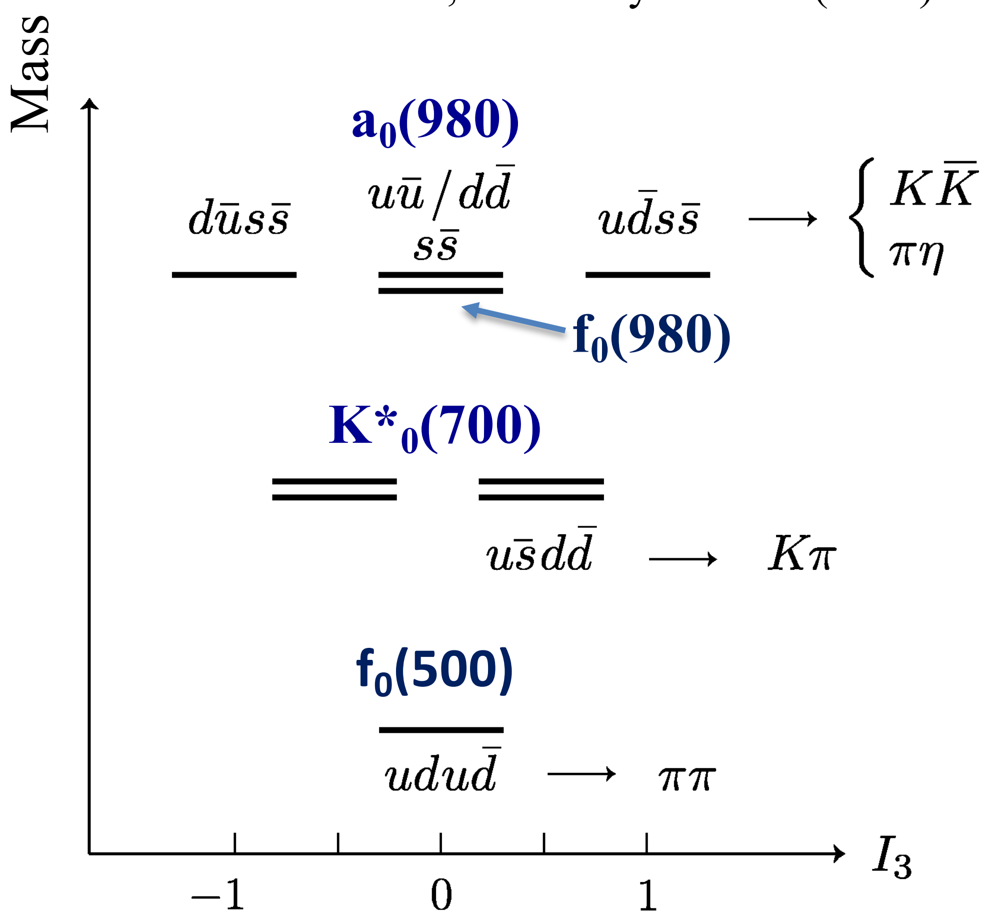
HADRON 2021

July 26 , 2021

Predicted low-lying tetraquark nonet with candidate mesons

Tetraquark nonet

Alford and Jaffe, Nucl. Phys. B 578 (2000)

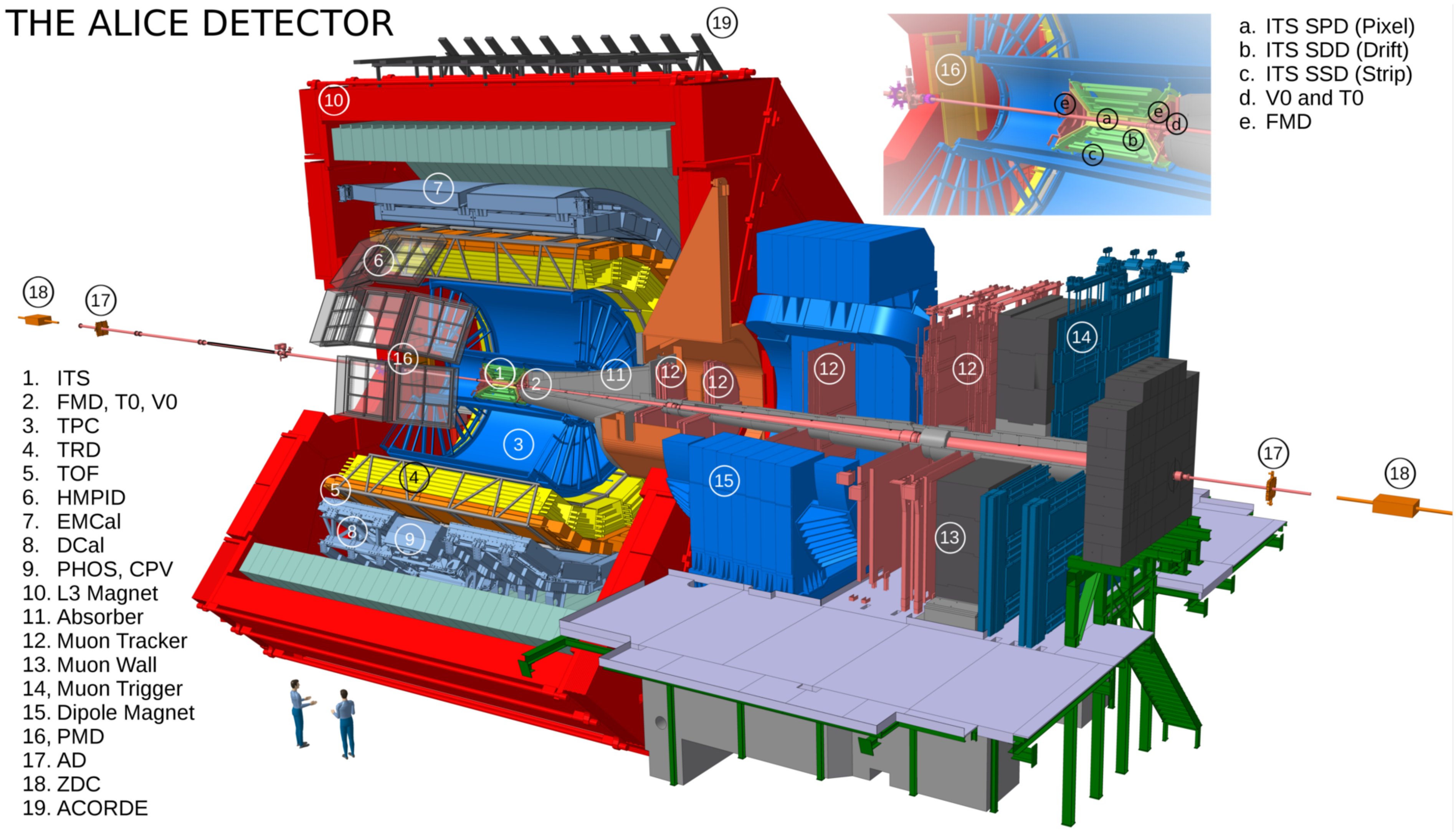


Low-lying tetraquark states have been predicted for > 40 years.

Candidate mesons with the expected masses, isospins and decay channels have been found:
e.g. $a_0(980)$, $f_0(980)$, $K^*_0(700)$, $f_0(500)$..

→ But, it is still controversial whether or not these mesons are four-quark states (e.g. see "Non-qq-bar Mesons" in 2021 Review of Particle Physics)

→ Study the $a_0(980)$ with $K^0_SK^\pm$ femtoscopy in pp and Pb-Pb collisions in the LHC ALICE Collaboration



Data sets used in this analysis: →

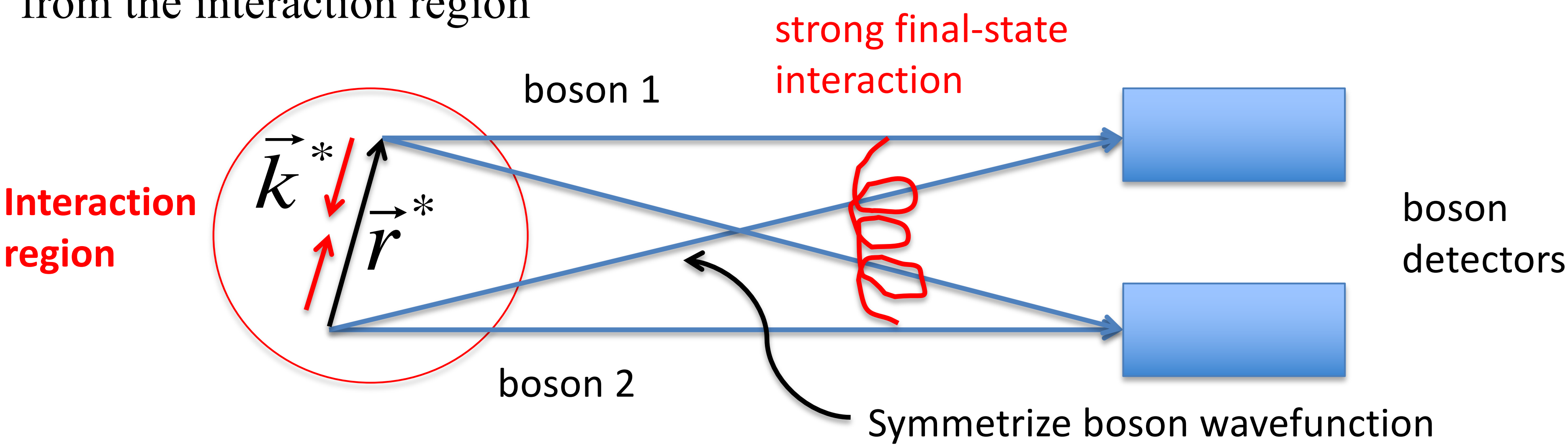
$\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV Pb − Pb collisions, 0-10% central

$\sqrt{s} = 7$ TeV pp collisions, minimum bias

Femtoscopy with quantum statistics and strong final-state interactions

R. Lednicky and V.L. Lyuboshits, (Sov. J. Nucl. Phys. 35 (1982))

Consider the correlations of two **identical bosons**, e.g. $K^0_S K^0_S$, emitted from the interaction region



If $\vec{r}^*$ and $\vec{k}^*$ are the relative distance between the bosons and the momentum of each boson in the pair reference frame, then the non-symmetrized wavefunction describing the elastic interaction between the bosons is

S-wave scattering amplitude

$$\Psi_{-\vec{k}^*}\left(\vec{r}^*\right) = e^{-i\vec{k}^* \bullet \vec{r}^*} + f\left(\vec{k}^*\right)\frac{e^{ik^* r^*}}{r^*}$$

plane wave

s-wave FSI term

Assume the boson source density in the pair reference frame is a Gaussian with radius parameter, R,

$$S\left(r^*\right) \sim \exp\left(-\frac{r^{*2}}{4R^2}\right)$$

The two-boson correlation function is calculated by integrating over the symmetrized wavefunction weighted by the boson source density,

$$C(k^*) = \int d^3\vec{r}^{\,*} S\left(r^*\right) \left|\Psi^S_{-\vec{k}^*}\left(\vec{r}^{\,*}\right)\right|^2$$

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

quantum statistics term

Final-state interaction term

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

The parameter λ is an empirical parameter that measures the correlation strength → λ = 1 in the ideal case, and α = 0.5 for $K^0_S K^0_S$ correlations.

Scattering amplitude for $K^0_S K^0_S$

$$f(k^*) = \frac{f_0(k^*) + f_1(k^*)}{2}$$

where,

$$f_I(k^*) = \frac{\gamma_I}{m_I^2 - s - i(\gamma_I k^* + \gamma_I' k_I')}.$$

$I = 0$ refers to the isospin-0 **f_0(980)** resonance and $I = 1$ refers to the isospin-1 **a_0(980)** resonance, and the γ_I are the couplings of the resonances to their decay channels.

$f_0(980)$ [j] $I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 990 \pm 20$ MeV

Full width $\Gamma = 10$ to 100 MeV

f_0(980) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	dominant	476
$K\overline{K}$	seen	36
$\gamma\gamma$	seen	495

$a_0(980)$ [j] $I^G(J^{PC}) = 1^-(0^{++})$

Mass $m = 980 \pm 20$ MeV

Full width $\Gamma = 50$ to 100 MeV

a_0(980) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\eta\pi$	dominant	319
$K\overline{K}$	seen	†
$\gamma\gamma$	seen	490

From Particle Data Book for light quark-antiquark mesons

$C(k^*)$ **is measured experimentally as**

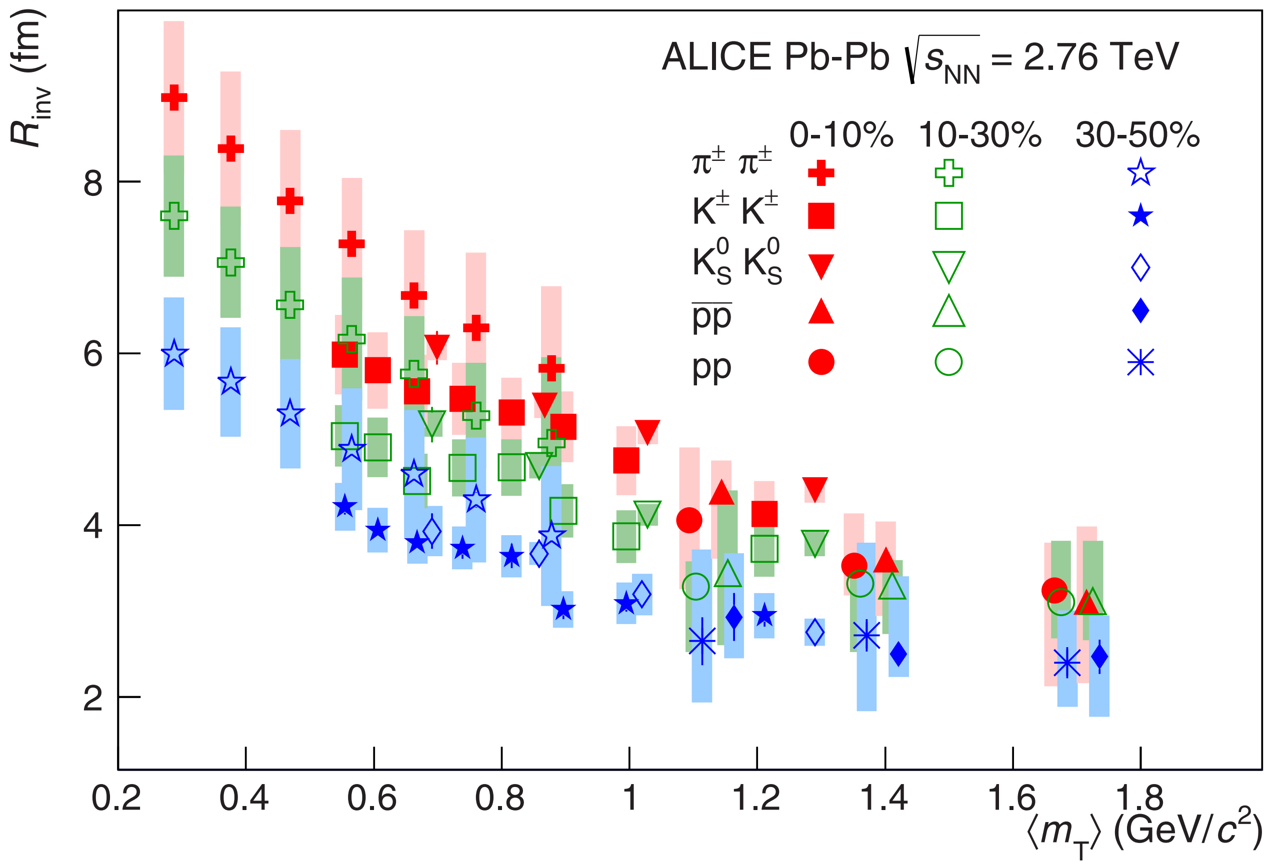
$$C\left(k^*\right) = \frac{A\left(k^*\right)}{B\left(k^*\right)}$$

Where $A(k^*)$ is the measured distribution of boson pairs from the same event, and $B(k^*)$ is the reference distribution of boson pairs from mixed events.

One extracts R and λ parameters from the data by fitting the Lednicky equation to this experimental ***$C(k^*)$***

The LHC ALICE Experiment has published three femtoscopy papers using $K^0_S K^0_S$ pairs to extract geometric information about the collision interaction region:

- 7 TeV pp → $K^0_S K^0_S$ — Phys.Lett.B717 (2012)
- 2.76 TeV Pb-Pb → $K^0_S K^0_S$, $K^\pm K^\pm$, ππ, pp — Phys.Rev.C92 (2015)
- 2.76 TeV Pb-Pb → 3D $K^0_S K^0_S$, $K^\pm K^\pm$ — Phys.Rev.C96 (2017)



Phys.Rev.C92 (2015)

Radial flow effects and m_T scaling seen.

$$m_T = \sqrt{k_T^2 + m^2}$$

where

$$k_T = \frac{1}{2}|\overrightarrow{p_{T1}} + \overrightarrow{p_{T2}}|$$

$K^0_S K^\pm$ femtoscopy

Pair-wise interactions present (or absent) for $K^0_s K^\pm$ pairs

- non-identical pairs → no quantum statistics
- K^0_S is uncharged → no Coulomb interaction
- $f_0(980)$ resonance is neutral → no $f_0(980)$ strong interaction
- $a_0(980)$ resonance is isospin = 1 → $a_0(980)$ strong interaction should be present for both $K^0_s K^+$ and $K^0_s K^-$ pairs

→ $K^0_S K^\pm$ femtoscopy selects for the $a_0(980)^\pm$ as the FSI

Version of R. Lednicky equation used to extract (R, λ) for $K^0_S K^\pm$

R. Lednicky and V.L. Lyuboshits, Sov. J. Nucl. Phys. 35 (1982)

$\bar{K}^0 K^+$ or $K^0 K^-$

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

No quantum statistics term or symmetrization

Since $|K^0_S\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K^0}\rangle\right)$ → α = ½ , assuming no asymmetry

$$f(k^*) = \frac{\gamma_{a0\to K\bar{K}}}{m_{a0}^2 - s - i\gamma_{a0\to K\bar{K}}k^* - i\gamma_{a0\to\pi\eta}k_{\pi\eta}}$$

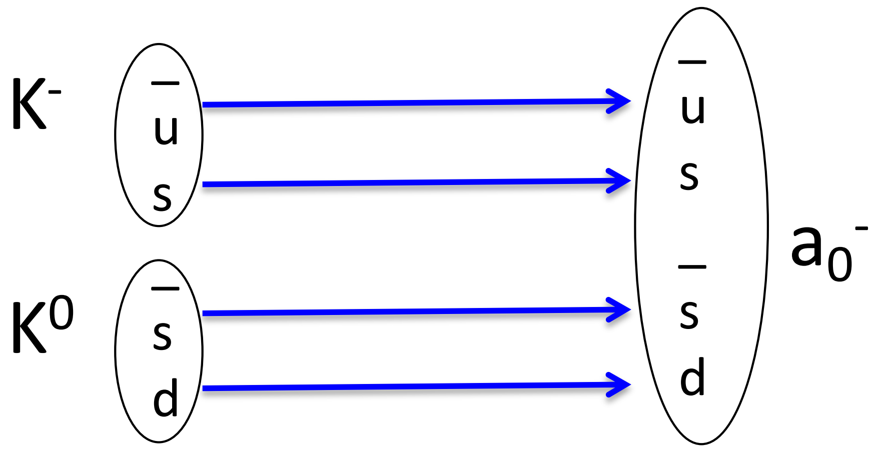
Ref	m_{f_0}	$\gamma_{f_0 K\bar{K}}$	$\gamma_{f_0\pi\pi}$	m_{a_0}	$\gamma_{a_0 K\bar{K}}$	$\gamma_{a_0\pi\eta}$
[15, 16]	0.967	0.34	0.089	1.003	0.8365	0.4580

The f_0 and a_0 masses and coupling parameters used in the present analysis, all in GeV.

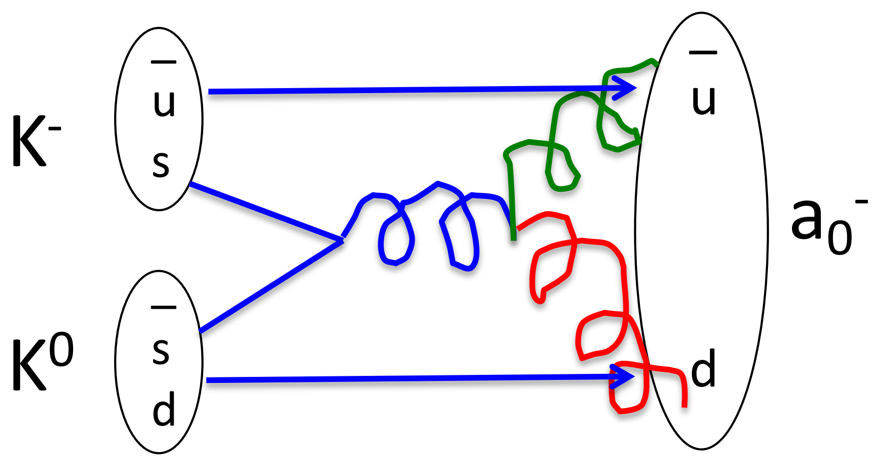
[15] N. N. Achasov and A. V. Kiselev, "The New analysis of the KLOE data on the phi → eta pi0 gamma decay," *Phys. Rev.* D68 (2003)
[16] ALICE Collaboration, K. Mikhaylov, "K+K− correlations in Pb-Pb collisions at √sNN = 2.76 TeV by ALICE at the LHC," *Phys. Part. Nucl. (WPCF 2019, Dubna)* (2020)

Two scenarios for FSI of $K^0K^- \rightarrow a_0(980)^- \rightarrow \{ K^0K^-, \eta\pi^- \}$

Tetraquark vs. Diquark



Tetraquark formation is a 1st-order process that proceeds through the direct transfer of existing quarks to the a_0^- from the collision of K^0K^-

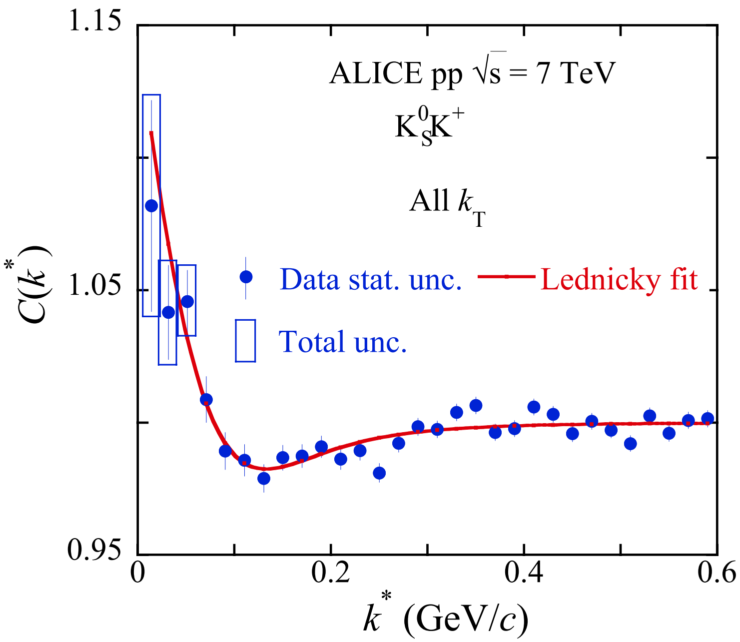


Diquark formation is a higher-order process requiring the annihilation of the strange quarks in the K^0K^- collision and transfer of energy via gluons to a_0^-

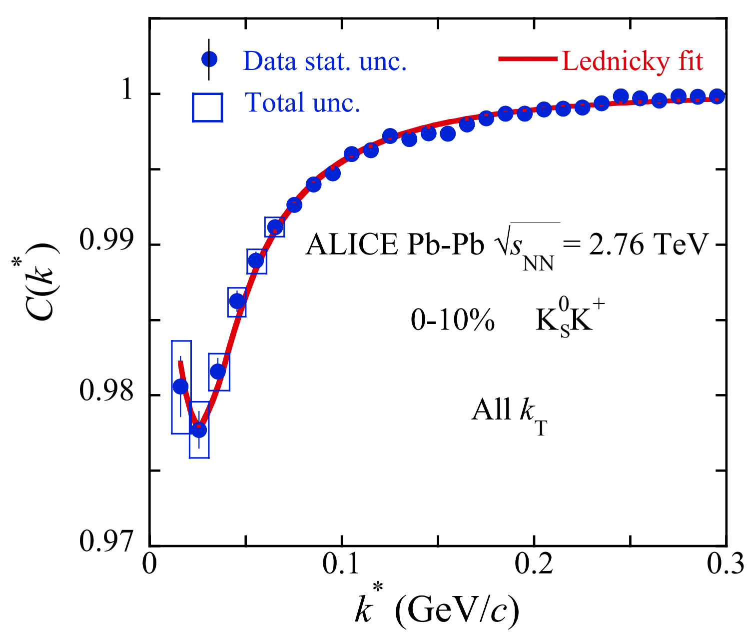
Can we see a signature of Tetraquark vs. Diquark in femtoscopy?

Examples of $K^0_S K^{\pm}$ correlation functions from ALICE with Lednicky fits

Phys. Lett. B 790 (2019)



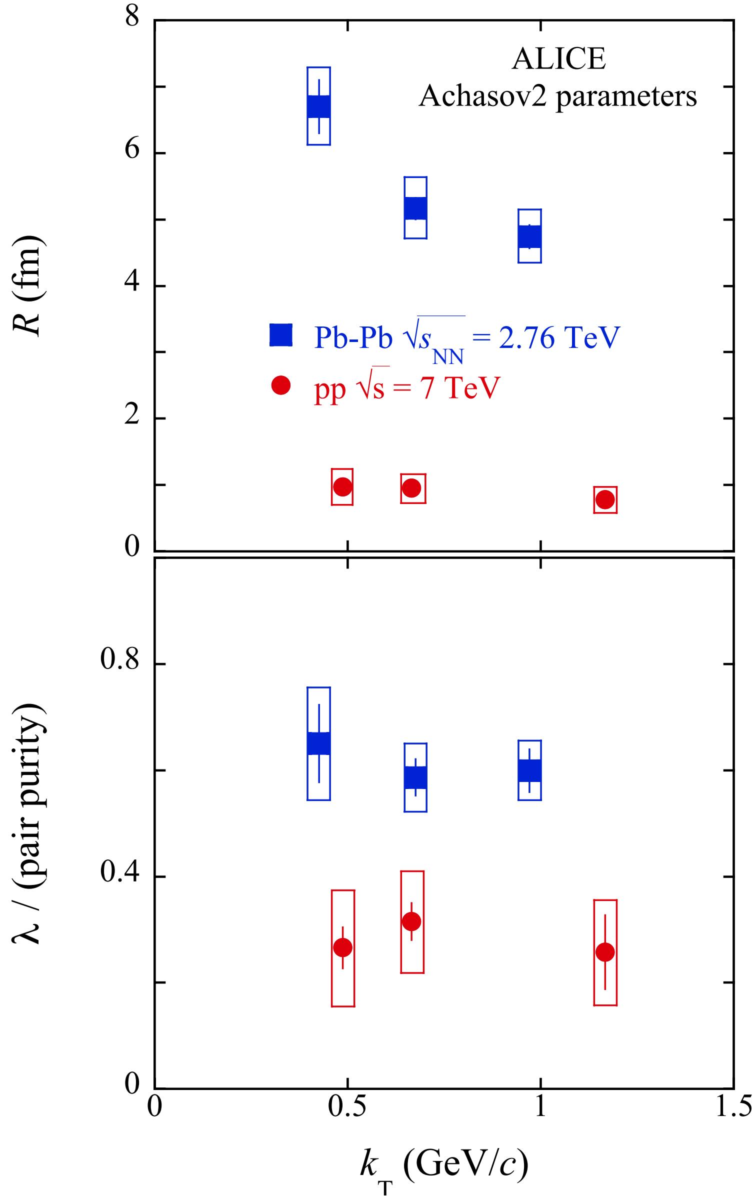
Phys. Lett. B 774 (2017)



The Lednicky equation with the assumption of an $a_0(980)$ FSI models the different shapes of the measured correlation functions well for both large and small systems for $K^0_S K^{\pm}$ correlations!

ALICE results for $K^0_S K^\pm$ femtoscopy in pp and Pb-Pb collisions

Phys. Lett. B 790 (2019)



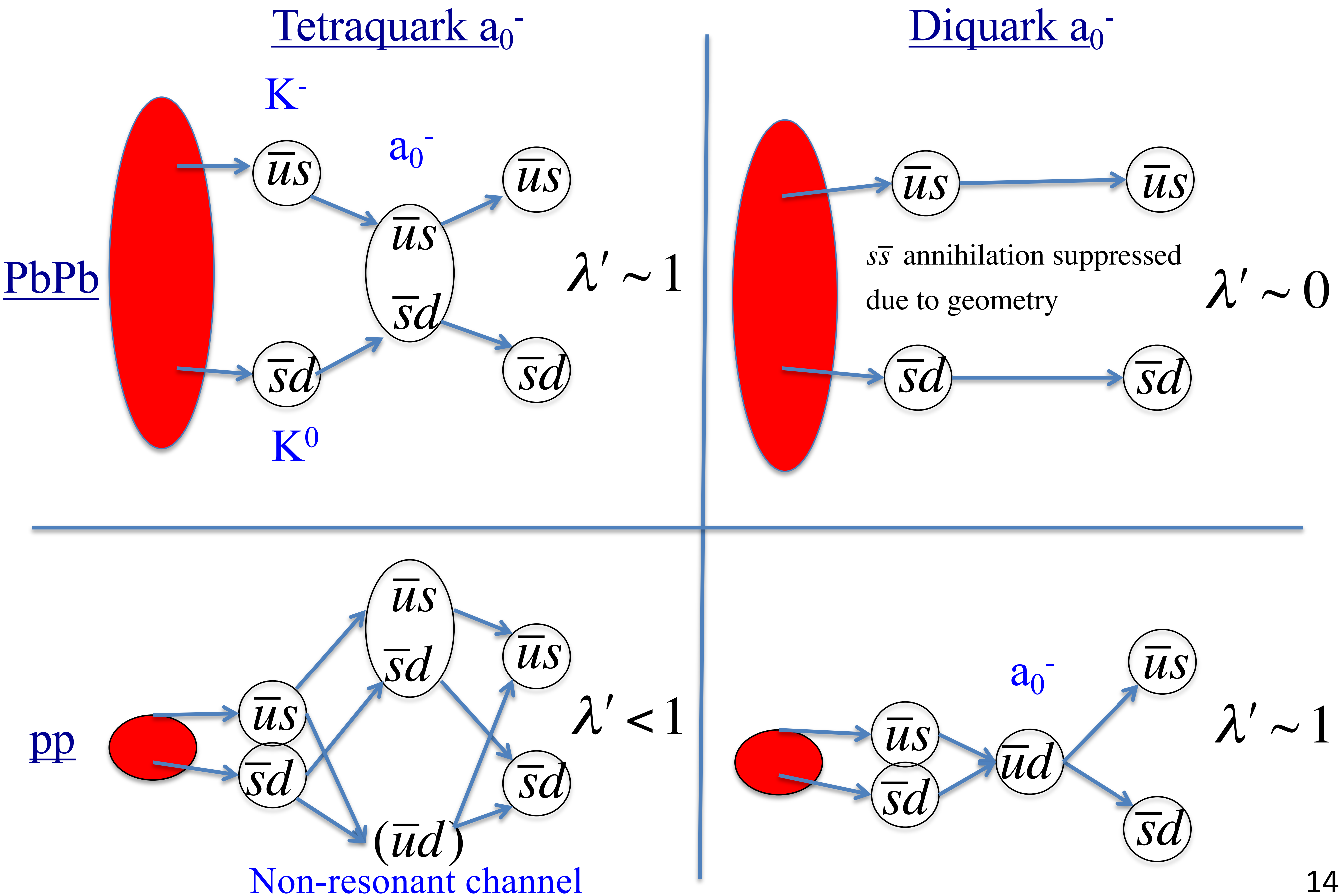
Observations for R:

- R(Pb-Pb) > R(pp)
- R(Pb-Pb) ~ 5-6 fm, R(pp) ~ 1 fm, both as expected from $r_0 A^{1/3}$
- For Pb-Pb, R decreases significantly for increasing k_T, as expected for hydrodynamic flow effects
- For pp, R is not sensitive to changes in k_T as expected since flow mostly not present for pp

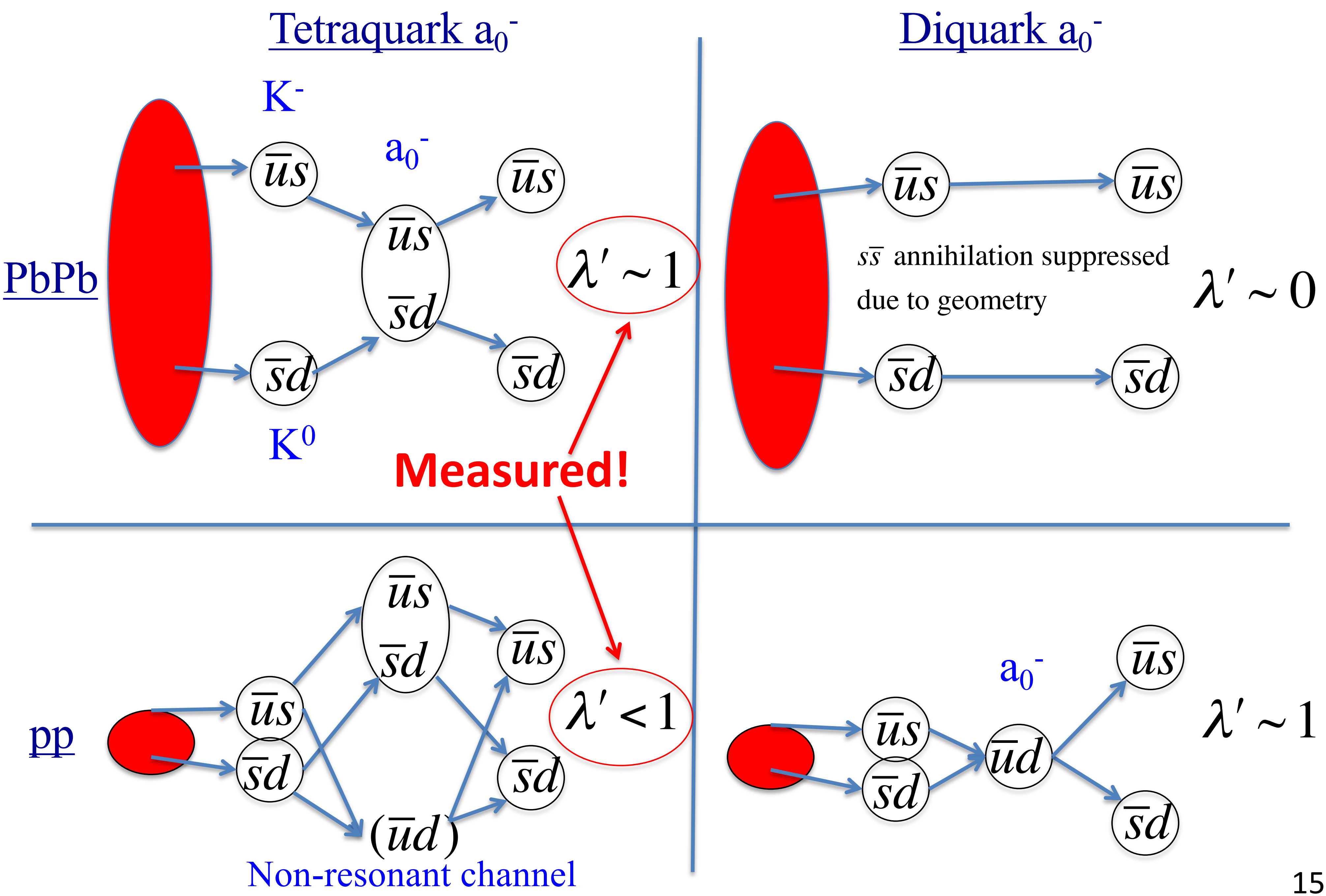
Observations for λ:

- λ(Pb-Pb) > λ(pp)
- λ(Pb-Pb) ~ 0.6, λ(pp) ~ 0.3
- For Pb-Pb, λ is about the same as is measured for $K^0_S K^0_S$
- For pp, λ is also significantly less than what is measured in pp for $K^0_S K^0_S$

$\lambda' \equiv \lambda_{K^0K^-}/\lambda_{KK}$ for $\bar{u}s\bar{s}d$ vs. $\bar{u}d$ a_0^- expected from geometry



$\lambda' \equiv \lambda_{K^0K^-}/\lambda_{KK}$ for $\bar{u}s\bar{s}d$ vs. $\bar{u}d$ a_0^- expected from geometry



Summary

➢ $K^0_S K^{\pm}$ femtoscopic analyses in $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb and $\sqrt{s} = 7$ TeV pp collisions from ALICE were shown

➢ Main physics take-aways from the $K^0_S K^{\pm}$ analyses:

1) The extracted R parameters are as expected in Pb-Pb and pp collisions

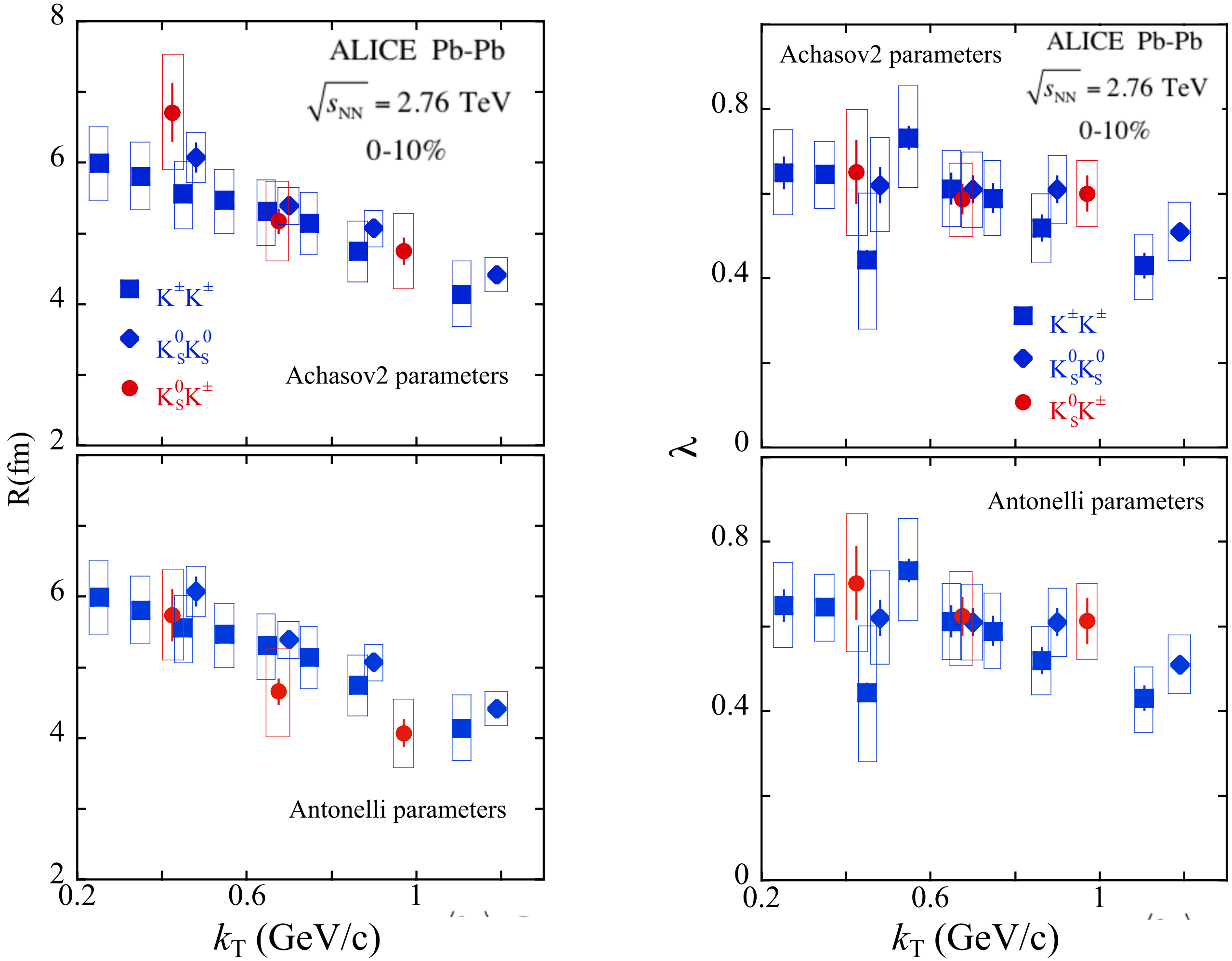
2) $\lambda(pp) < \lambda(\text{Pb-Pb})$, whereas $\lambda(\text{Pb-Pb})$ agrees with the values extracted in $K^0_S K^0_S$ measurements

3) A simple geometric model used to explain the results presented in 2) is suggestive of the $a_0(980)$ being a tetraquark state.

Backup slides

Results for R and λ from 2.76 TeV Pb-Pb for $K^0_S K^\pm$ vs. $K^0_S K^0_S$ and $K^\pm K^\pm$

ALICE Collaboration, S. Acharya *et al.*, *Phys. Lett. B* 774 (2017)



* $K^0_S K^\pm$ R and λ agree with identical kaon results best for Achasov parameters

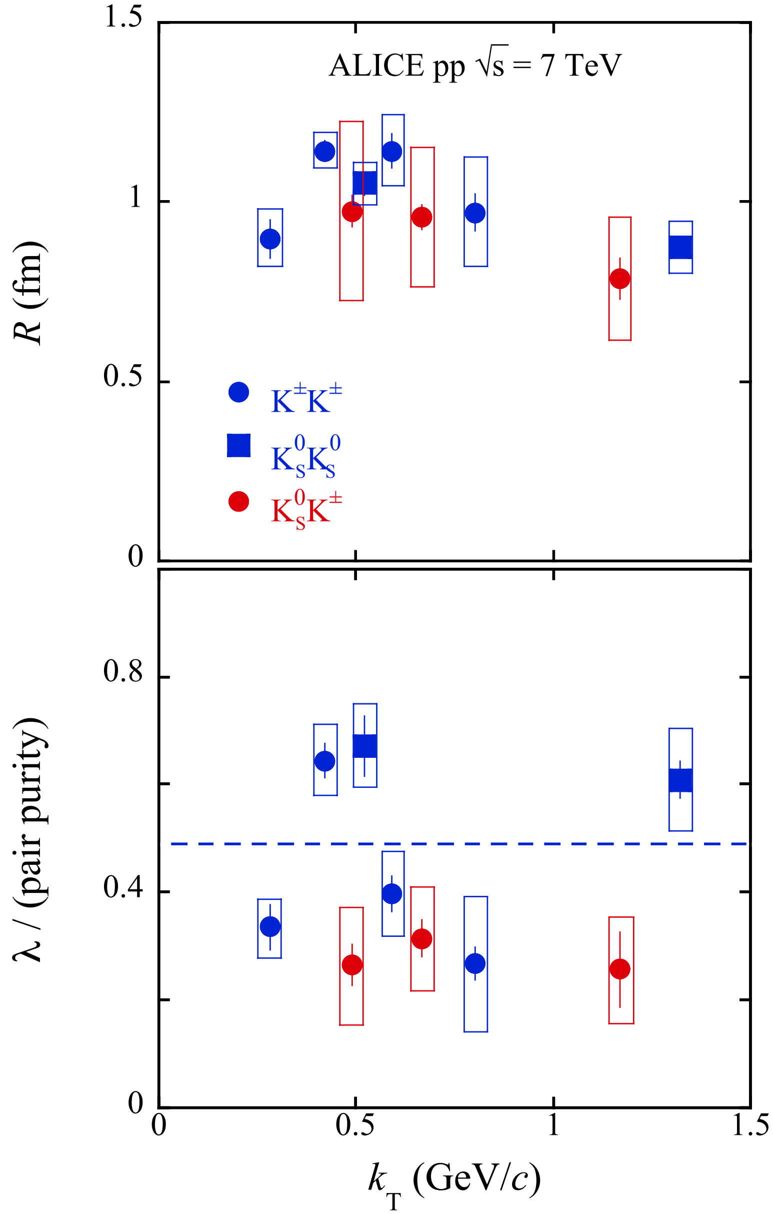
* $\lambda < 1$ due to long-lived resonance decay (e.g. $K^* \rightarrow K\pi$, estimate $\lambda \sim 0.55$ from K^*)

Agreement of $K^0_S K^\pm$ λ with identical kaons → FSI goes solely through a_0 channel

→ no non-resonant channel present

Results for R and λ from 7 TeV pp for $K^0_S K^\pm$ vs. $K^0_S K^0_S$ and $K^\pm K^\pm$

ALICE Collaboration, S. Acharya *et al.*,*Phys. Lett.* B790 (2019)



* **The R values all agree within uncertainties**

* **$\lambda(K^0_S K^\pm) < \lambda(K^0_S K^0_S)$**

The dashed line is the average of the identical-kaon λ parameters.