The Ohio State University

ALICE

Investigating the nature of the $K_0^*(700)$ state with $\pi^{\pm}K_S^0$ correlations with ALICE at the LHC

ALICE Collaboration

Thomas Humanic (Ohio State University)

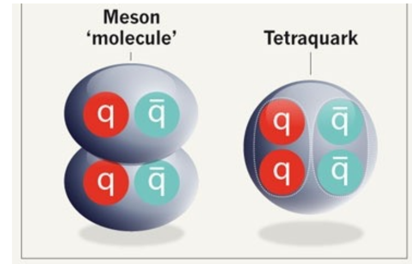
Outline of talk

- Introduction
- Previous ALICE study of $a_0(980)$
- New results from ALICE study of $K_0^*(700)$
- Summary

SQM2024

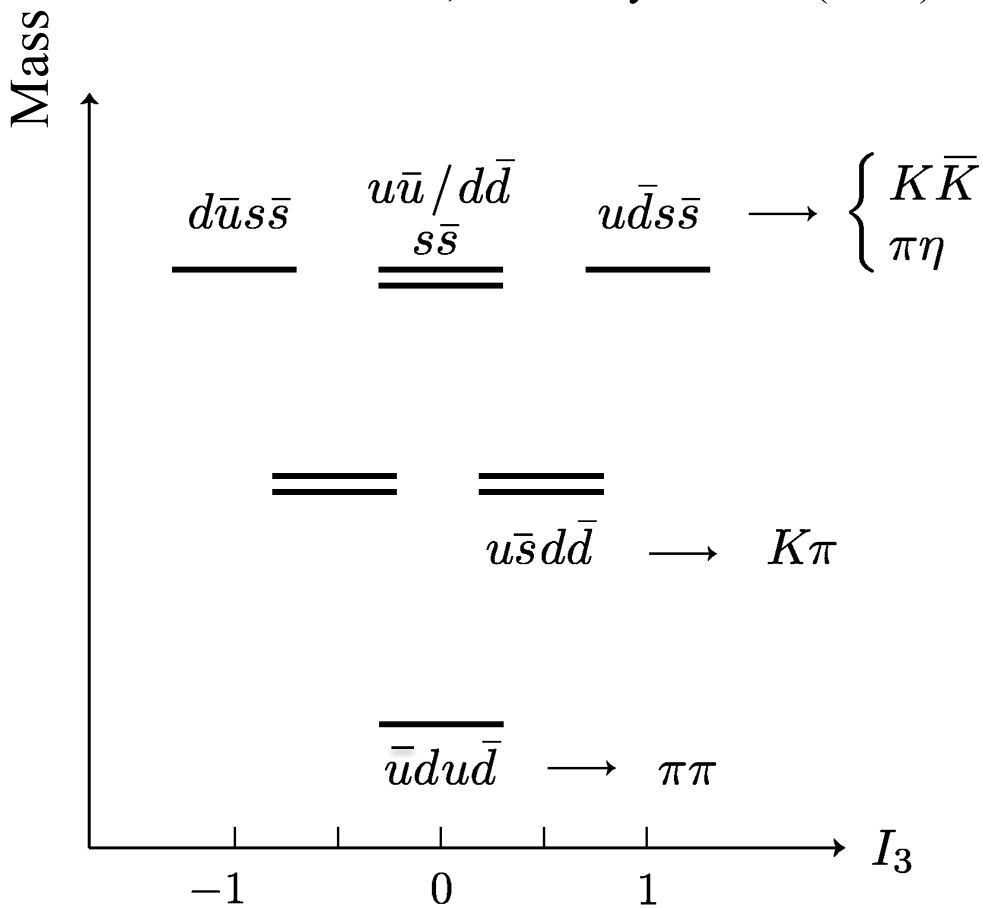
The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

Predicted low-lying tetraquark nonet



Tetraquark nonet

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

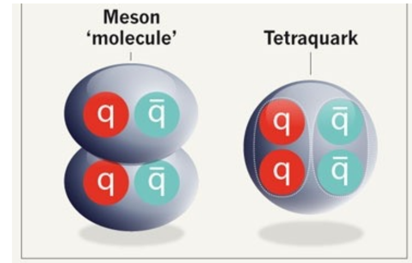


Low-lying tetraquark states have been predicted for > 40 years.

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).

Predicted low-lying tetraquark nonet with candidate mesons



Tetraquark nonet

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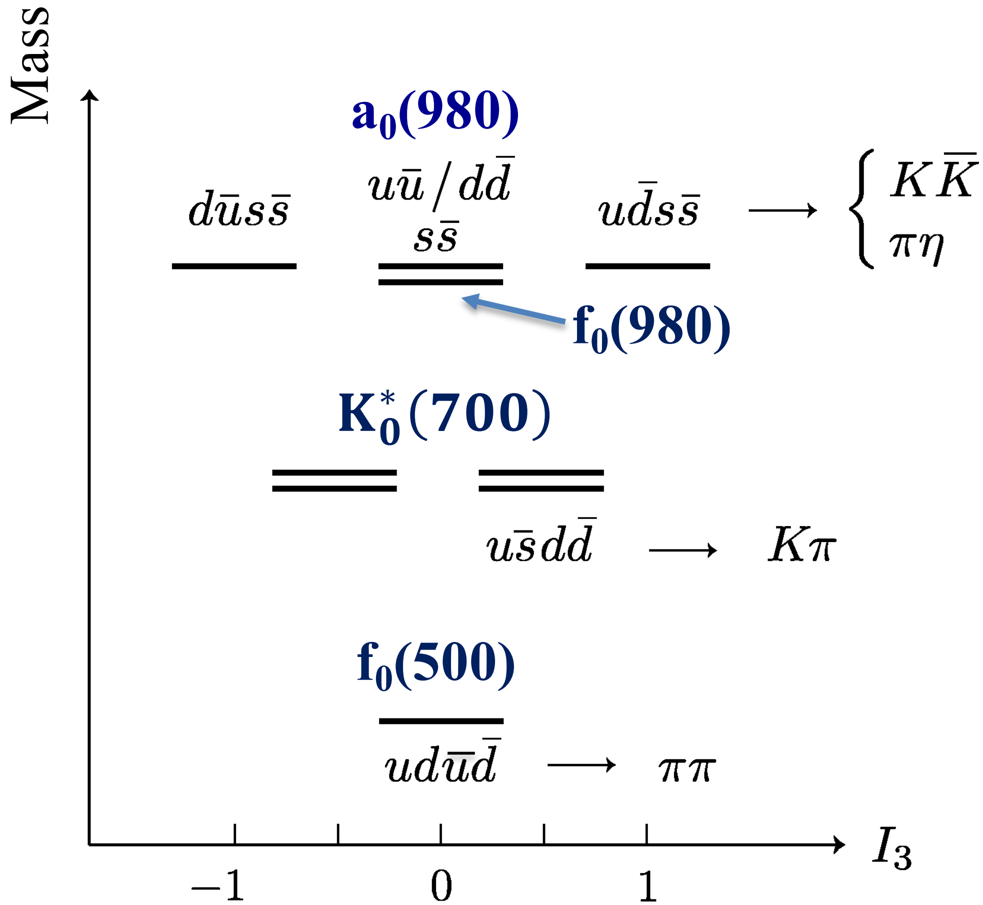

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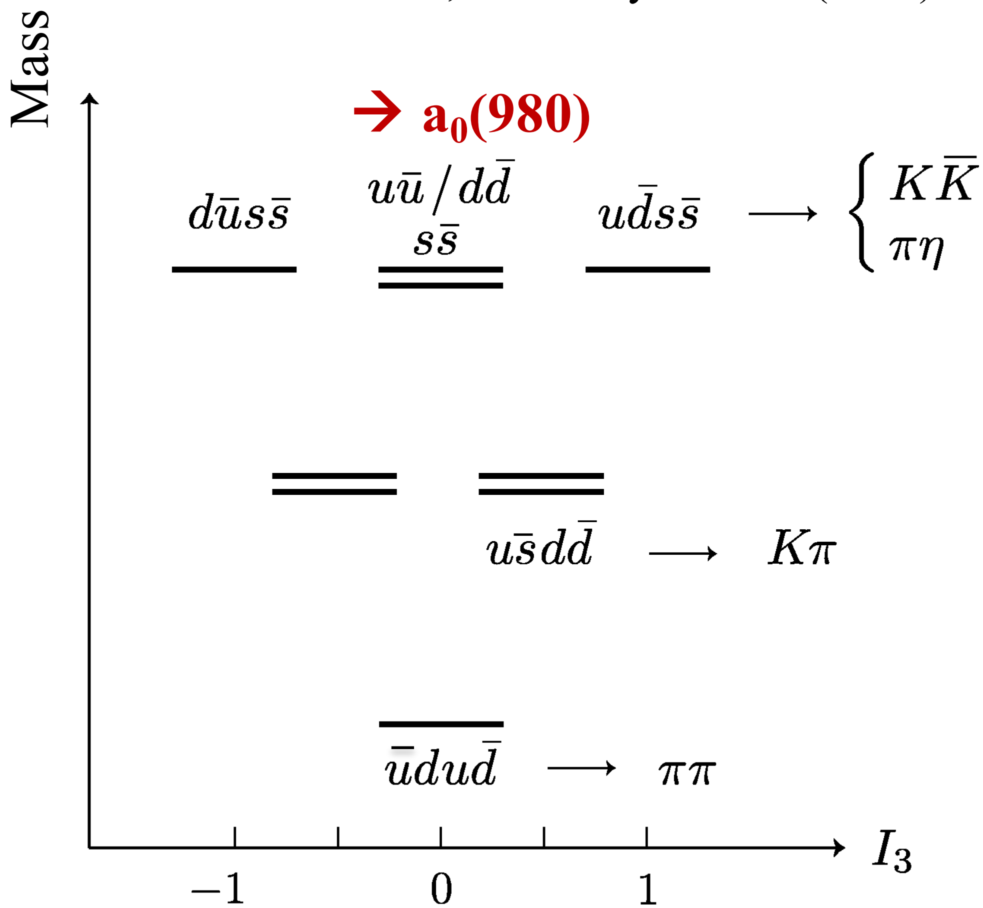
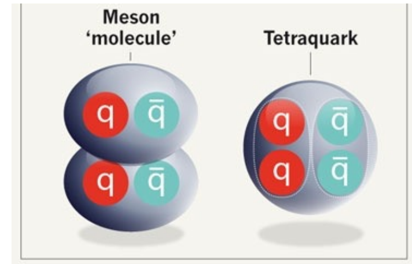
Predicted low-lying tetraquark nonet with $a_0(980)$ candidate meson

Tetraquark nonet

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





$f_0(980)$ [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
$K\bar{K}$	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
$K\bar{K}$	seen	†
$\gamma\gamma$	seen	490

From Review of Particle Physics for light quark-antiquark mesons

The $a_0(980)$ has been studied with $K^0_S K^\pm$ femtoscopy in pp and Pb–Pb collisions by ALICE → PLB 774 (2017), PLB 790 (2019), PLB 833 (2022).

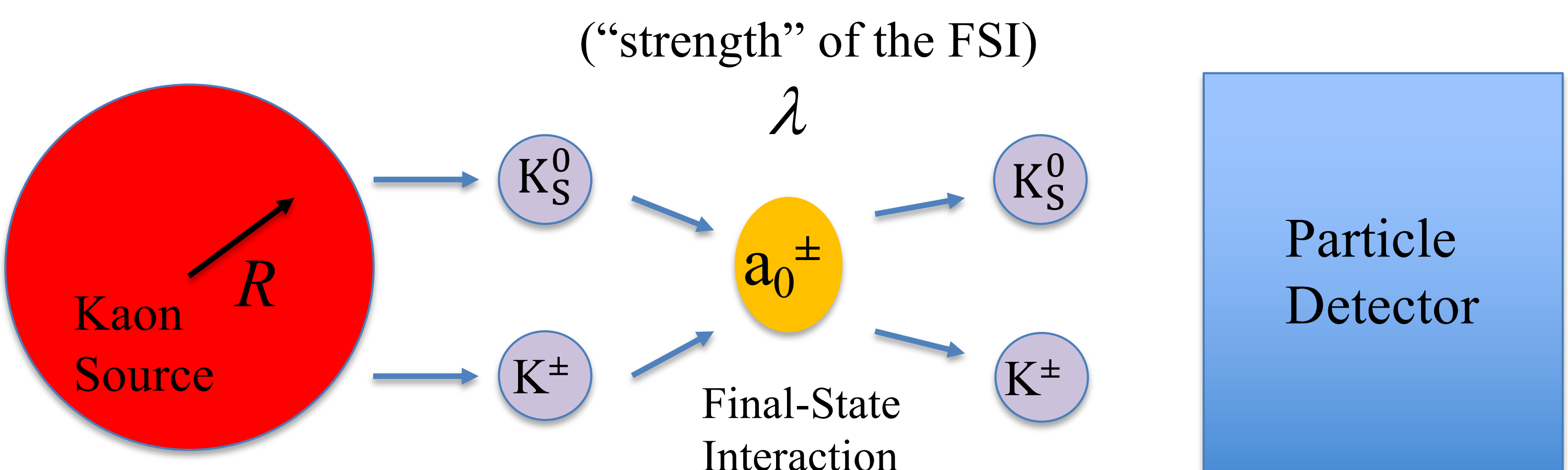
$K^0_S K^\pm$ femtoscopy
(ALICE first to study this!)

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

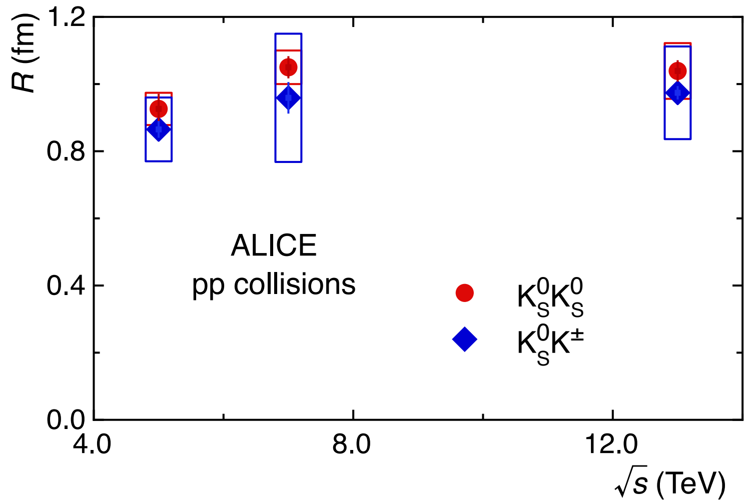
- Non-identical pairs → no quantum statistics.
- K^0_S is uncharged → no Coulomb interaction.
- $f_0(980)$ resonance is isospin = 0 → no $f_0(980)$ strong interaction.
- $a_0(980)$ resonance is isospin = 1 → $a_0(980)$ strong interaction.

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 Final-state Interaction (FSI).



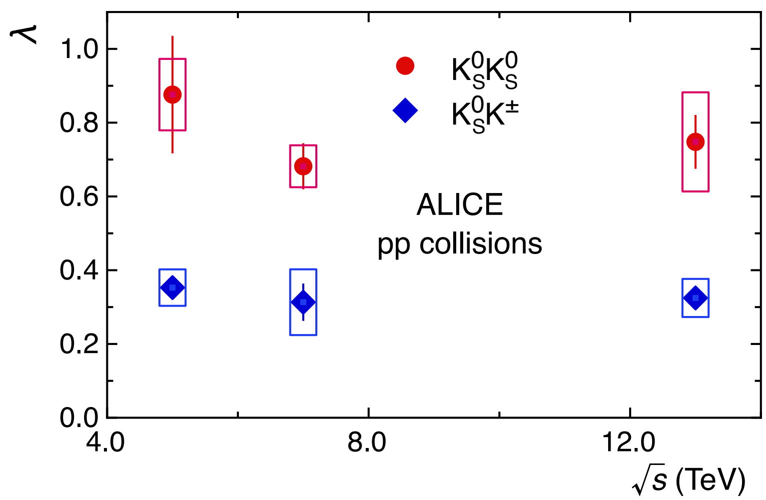
ALICE results for $\mathbf{K^0_S K^0_S}$ and $\mathbf{K^0_S K^\pm}$ femtoscopy in 5.02, 7 and 13 TeV pp collisions (*Phys. Lett. B833 (2022)*)



- $a_0(980)$ is the FSI for the $K^0_S K^\pm$ pair. The $K^0_S K^0_S$ correlation function is dominated by quantum statistics due to identical-boson pairs.

- λ from $K^0_S K^\pm$ is significantly smaller than λ from $K^0_S K^0_S$.

→ tetraquark signature for the $a_0(980)$?



$$\left\langle \frac{\lambda_{K^0_S K^\pm}}{\lambda_{K^0_S K^0_S}} \right\rangle \approx 0.44 \pm 0.07$$

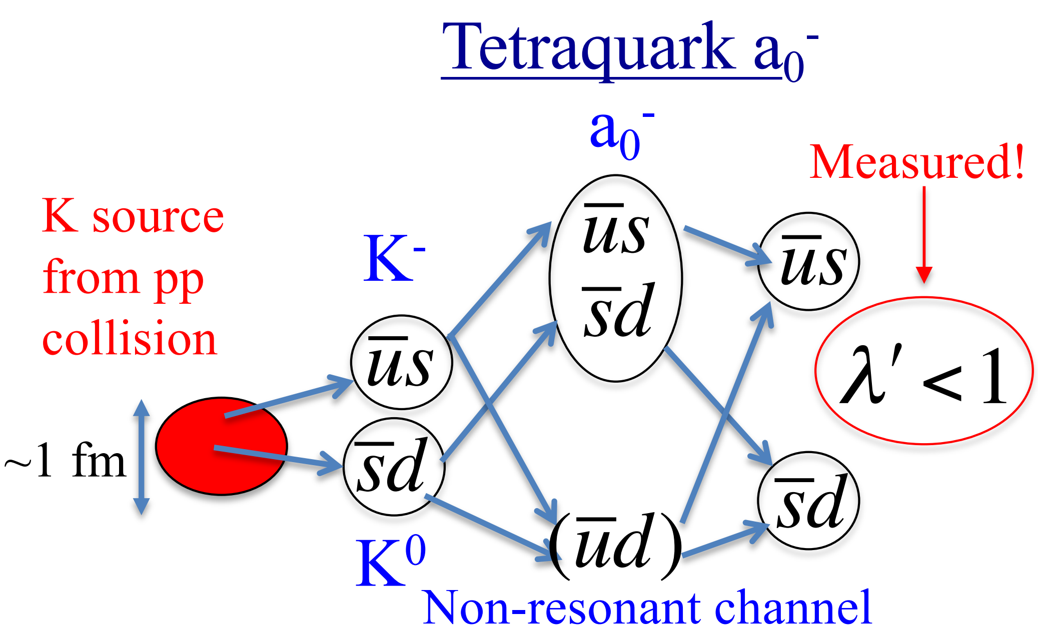
A simple geometric picture in pp collisions

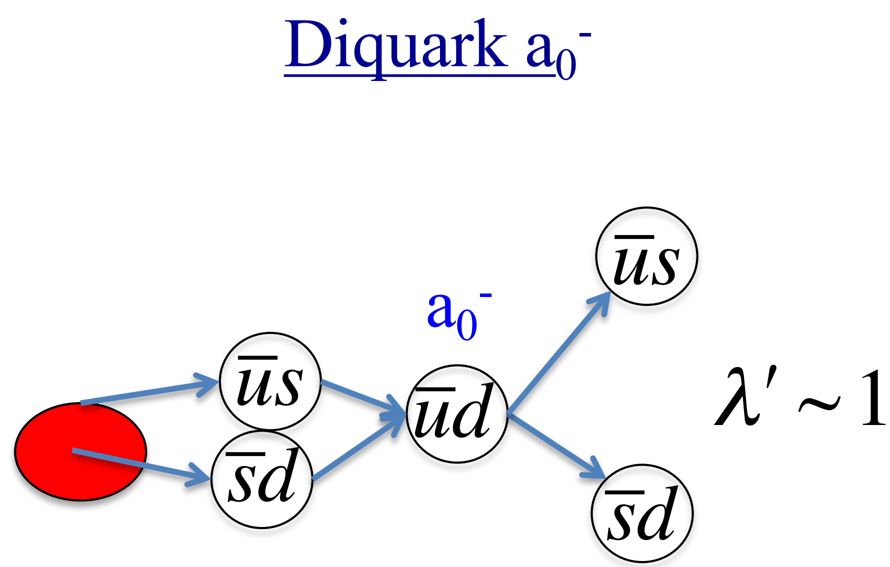
Tetraquark a_0 FSI -- suppressed due to strange quark annihilation opening up a non-resonant channel.

Diquark a_0 FSI -- favored from the annihilation process.

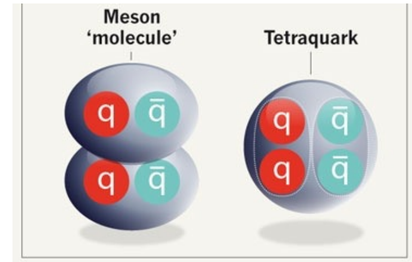
Identical kaon λ - parameter

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



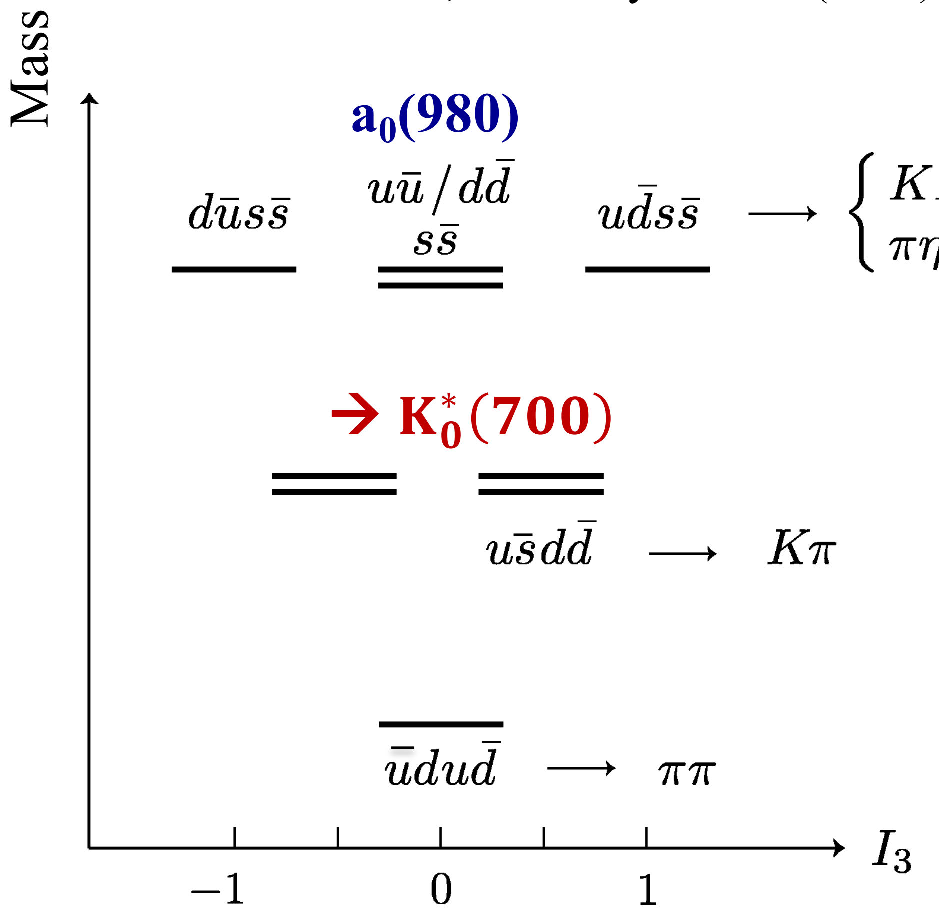


Predicted low-lying tetraquark nonet with $K_0^*(700)$ candidate meson



Tetraquark nonet

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



$K_0^*(700)$ $\quad I(J^P) = \frac{1}{2}(0^+)$

Mass (T-Matrix Pole $\sqrt{s}$) = (630–730) − i (260–340) MeV
Mass (Breit-Wigner) = 824 ± 30 MeV
Full width (Breit-Wigner) = 478 ± 50 MeV

$K^*(892)$ $\quad I(J^P) = \frac{1}{2}(1^-)$

$K^*(892)^\pm$ hadroproduced mass m = 891.76 ± 0.25 MeV
$K^*(892)^\pm$ in τ decays mass m = 895.5 ± 0.8 MeV
$K^*(892)^0$ mass m = 895.55 ± 0.20 MeV (S = 1.7)
$K^*(892)^\pm$ hadroproduced full width Γ = 50.3 ± 0.8 MeV
$K^*(892)^\pm$ in τ decays full width Γ = 46.2 ± 1.3 MeV
$K^*(892)^0$ full width Γ = 47.3 ± 0.5 MeV (S = 1.9)

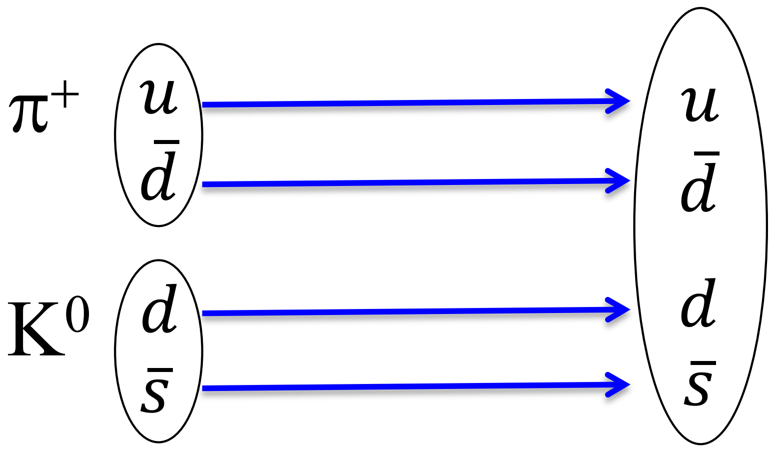
$K^*(892)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$K\pi$	~ 100 %		290
$K^0\gamma$	(2.46±0.21) × 10^{-3}		307
$K^\pm\gamma$	(1.00±0.09) × 10^{-3}		309
$K\pi\pi$	< 7 × 10^{-4}	95%	223

$K_0^*(700)$ decay channel listed in RPP as 100% πK ….. same as for $K^*(892)$

The $K_0^*(700)$ has been studied with $\pi^\pm K_S^0$ femtoscopy in 13 TeV pp collisions by the ALICE Collaboration → Paper is submitted to PLB (arXiv:2312.12830v2).

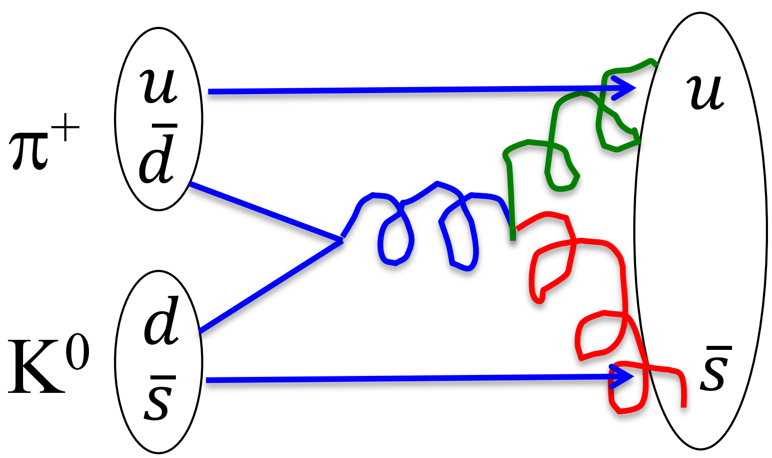
Two scenarios for FSI of $\pi^+K^0 \rightarrow K_0^*(700)^+ \rightarrow \pi^+K^0$

Tetraquark vs. Diquark



Tetraquark formation is a 1st-order process that proceeds through the direct transfer of existing quarks to the $\mathbf{K_0^*(700)}$ from the collision of π^+K^0.

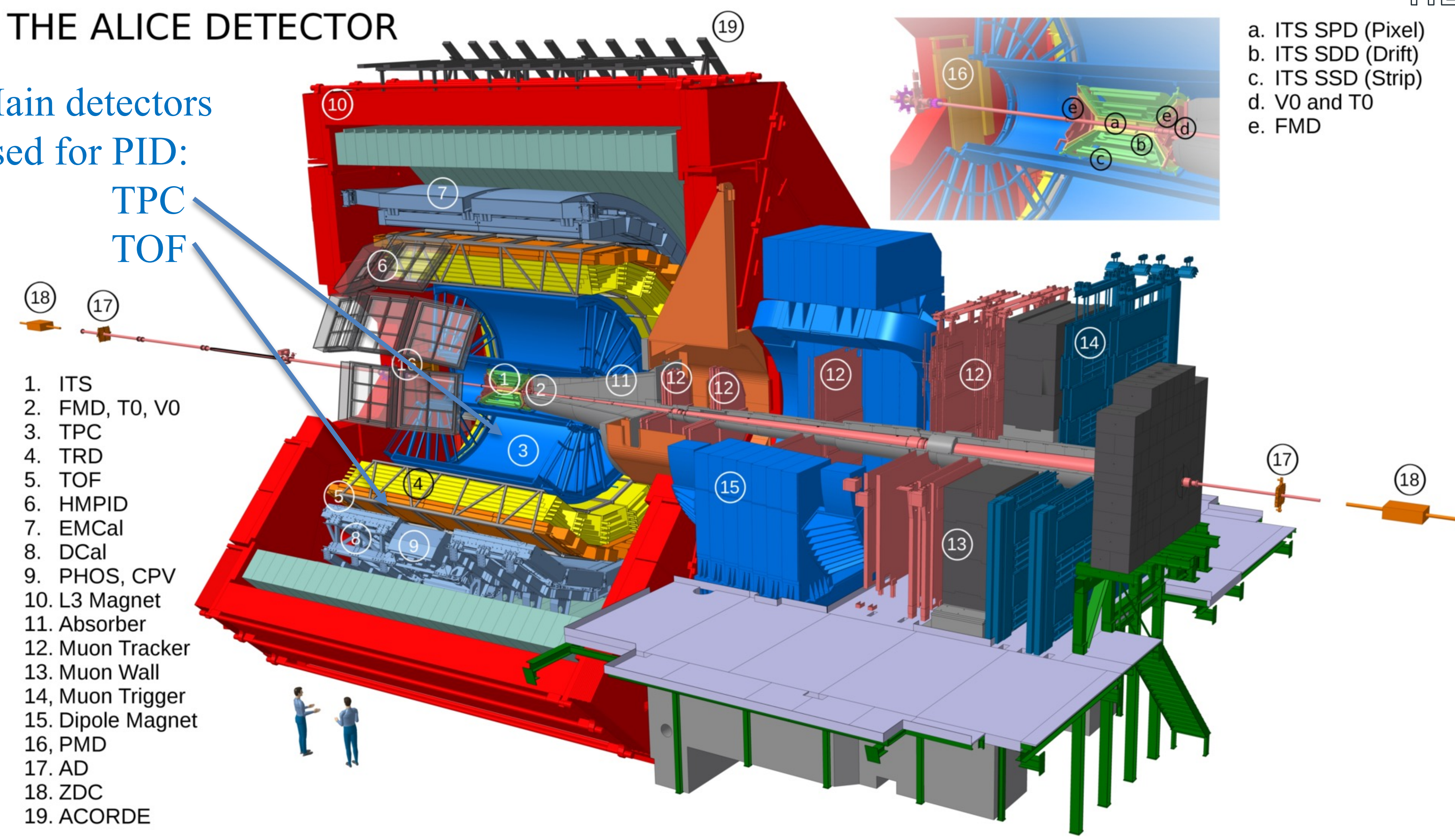
$K_0^*(700)^+$



Diquark formation is a higher-order process requiring the annihilation of the d quarks in the π^+K^0 collision and transfer of energy via gluons to $\mathbf{K_0^*(700)}$.

Can we see a signature of tetraquark vs. diquark in femtoscopy?

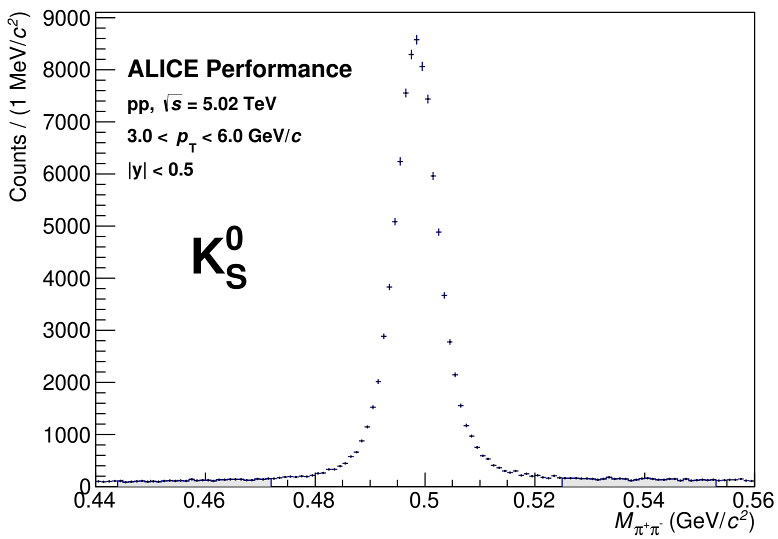
Main detectors used for PID:
TPC
TOF



Run 2 data set used in this analysis → $\sqrt{s}$ = 13 TeV pp collisions, minimum bias trigger

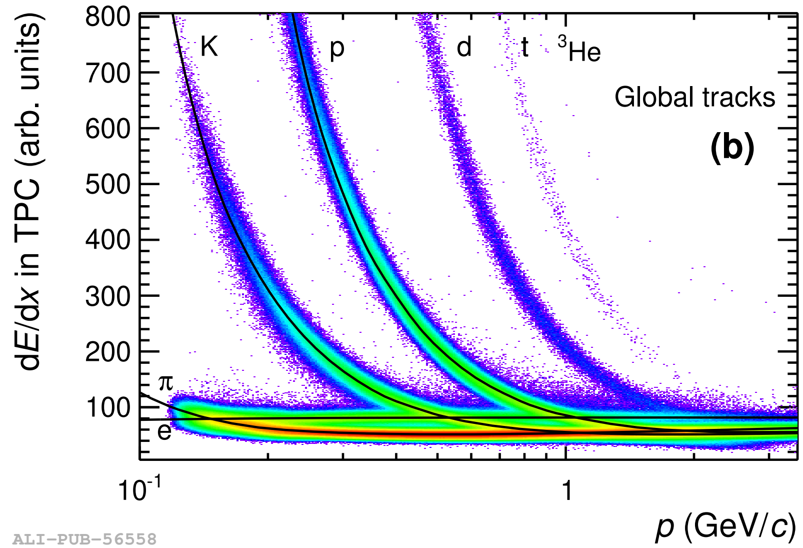
Excellent PID purity for K^0_S and $\pi^\pm$

Particle ID using $K^0_S \rightarrow \pi^+\pi^-$

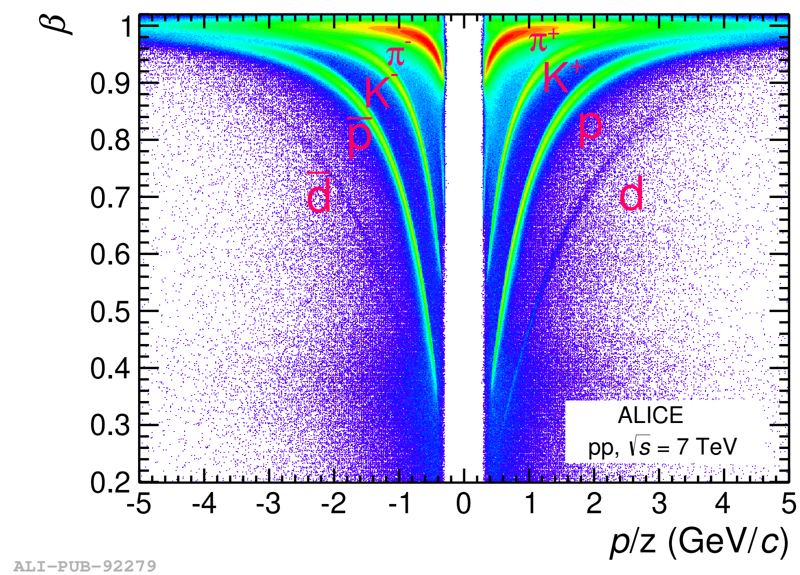


K^0_S purity ~98%

dE/dx



TOF

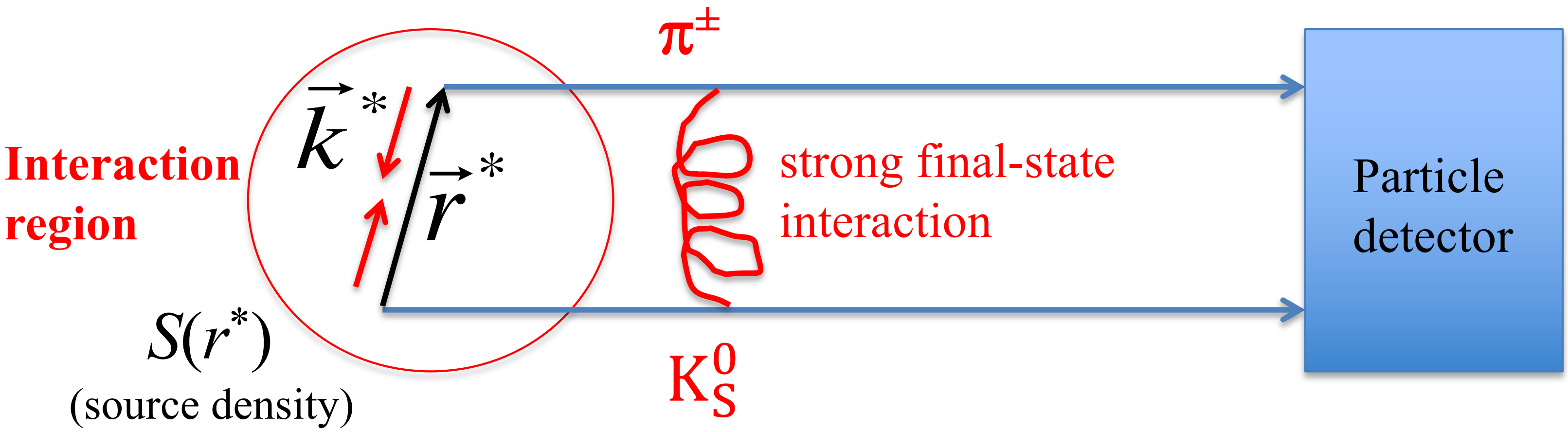


$\pi^\pm$ purity ~98%

Femtoscopy using strong final-state interactions

R. Lednický and V.L. Lyuboshits, (Sov. J. Nucl. Phys. 35 (1982) 770)

Consider the correlations of two **non-identical particles**, e.g. $\pi^{\pm}K_S^0$, emitted from the interaction region



$\vec{r}^*$ → relative distance between the particle emission points in the pair reference frame.
$\vec{k}^*$ → momentum of the particles in the pair reference frame.

The wave function describing the elastic interaction between the particles is:

S-wave scattering amplitude

$$\Psi_{-\vec{k}^*} = e^{-\vec{k}^* \cdot \vec{r}^*} + f(\vec{k}^*)\frac{e^{ik^*r^*}}{r^*}$$

plane wave   S-wave final-state interaction (FSI) term

Two-particle correlation function:

ALICE

$$C(k^*) = \int d^3\vec{r}^{\,*} S(r^*) \left|\Psi_{-\vec{k}^*}(\vec{r}^{\,*})\right|^2 \text{, where } S(r^*) \sim e^{-\frac{r^{*2}}{4R^2}}$$

Radius parameter

Correction to spherical outgoing wave assumption

Lambda parameter

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

Integral functions

Assume the FSI of the $\pi^{\pm}K^0_S$ is due to a **Resonance** $\Rightarrow$ $f(k^*) = \frac{\gamma}{M_R{}^2 - s - i\gamma k^*}$

γ is the coupling parameter for the decay of the resonance into $\pi^{\pm}K^0_S$ $\Rightarrow$ $\Gamma_R = \frac{\langle k^* \rangle}{M_R}\gamma$

where $\boldsymbol{M_R}$ and $\boldsymbol{\Gamma_R}$ are the mass and width of the FSI resonance, and $\langle k^* \rangle$ is the average k^* over the fit range.

***C(k*)* is measured experimentally as** $\Rightarrow$ $C(k^*) = \frac{A(k^*)}{B(k^*)}$

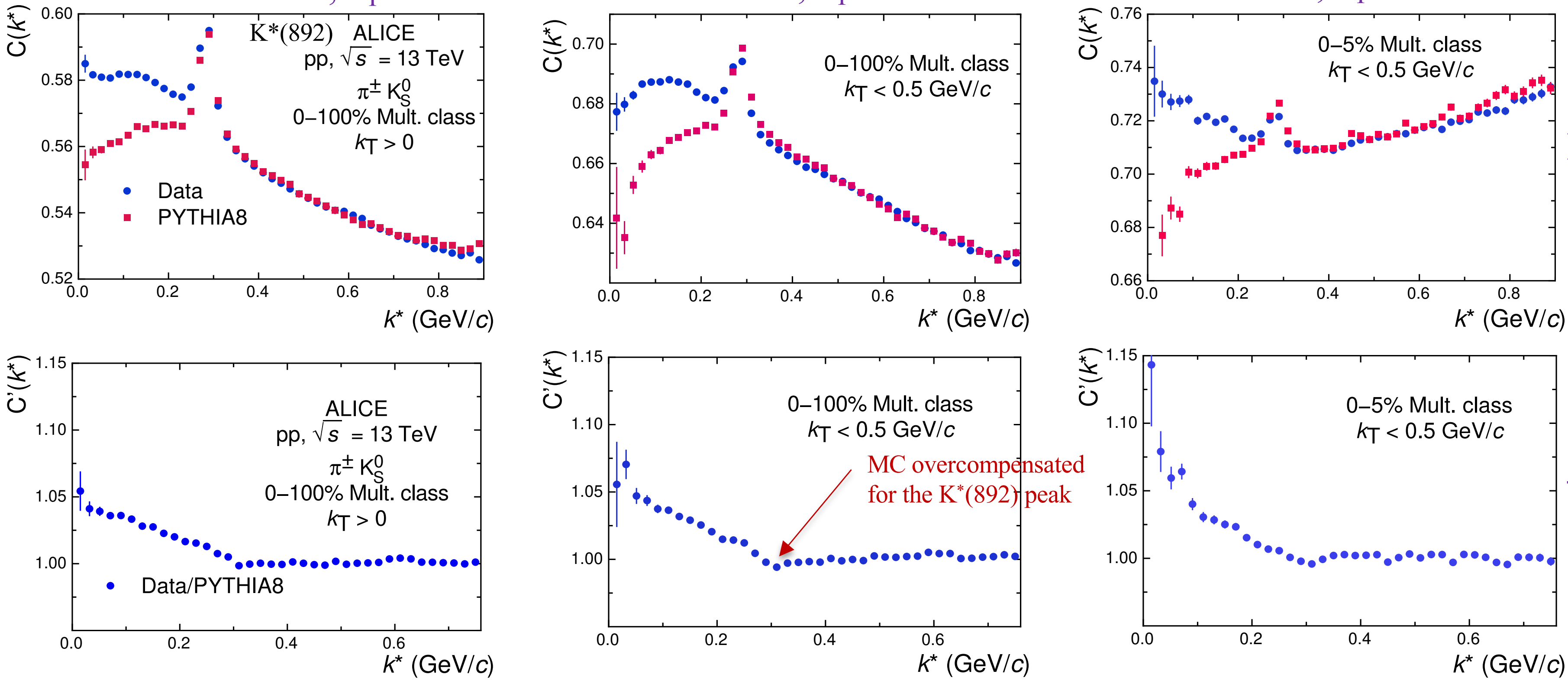
where $\boldsymbol{A(k^*)}$ is the measured distribution of particle pairs from the same event in a k^* bin, and $\boldsymbol{B(k^*)}$ is the reference distribution of particle pairs from mixed events in a k^* bin.

Raw $C(k^*)$ from 13 TeV pp → $\pi^\pm K^0_S$ data compared with PYTHIA8

(PYTHIA8 run through GEANT to simulate ALICE data)

NEW

0–100% Mult, $k_T > 0$ | 0–100% Mult, $k_T < 0.5$ GeV/c | 0–5% Mult, $k_T < 0.5$ GeV/c



Raw $C(k^*)$

$\frac{C_{\mathrm{Data}}}{C_{\mathrm{PYTHIA8}}}$

arXiv:2312.12830v2

Analyze these three sets of $C(k^*)$ with different kinematic cuts in order to extract the multiplicity and k_T dependences of λ and R.

PYTHIA8 does a good job describing the baseline of the data.

Data show large enhancement at $k^* \sim 0$ compared with PYTHIA8.

→ Is the extra enhancement in the data due to $\mathbf{K_0^*(700)}$ FSI ??

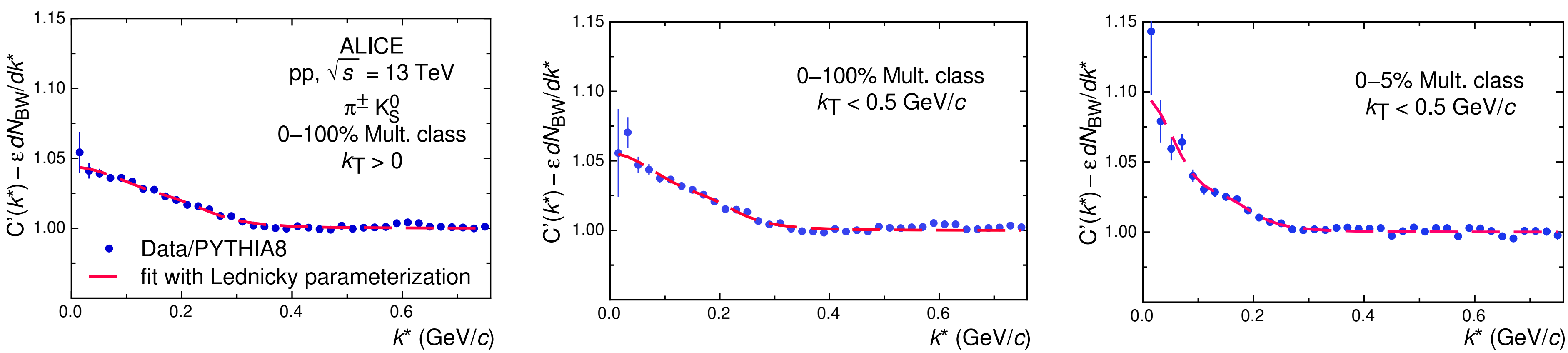
Add a Breit-Wigner resonance term to the Lednický equation to fit out the small K*(892) overcompensation in the MC:

$$C'(k^*) = C(k^*) + \varepsilon \frac{dN_{BW}}{dm}\frac{dm}{dk^*} \quad \text{where,} \quad \frac{dN_{BW}}{dm} \propto \frac{\Gamma_{892}}{(m - m_{892})^2 + \Gamma_{892}^2/4}$$

→ Fit $C'(k^*)$ to $C_{\text{data}}(k^*)/C_{\text{MC}}(k^*)$, with fit parameters R, λ, M_R , γ and ε

NEW

Lednický + BW fits to data/PYTHIA8 for 13 TeV pp → $\pi^{\pm}K^0_S$

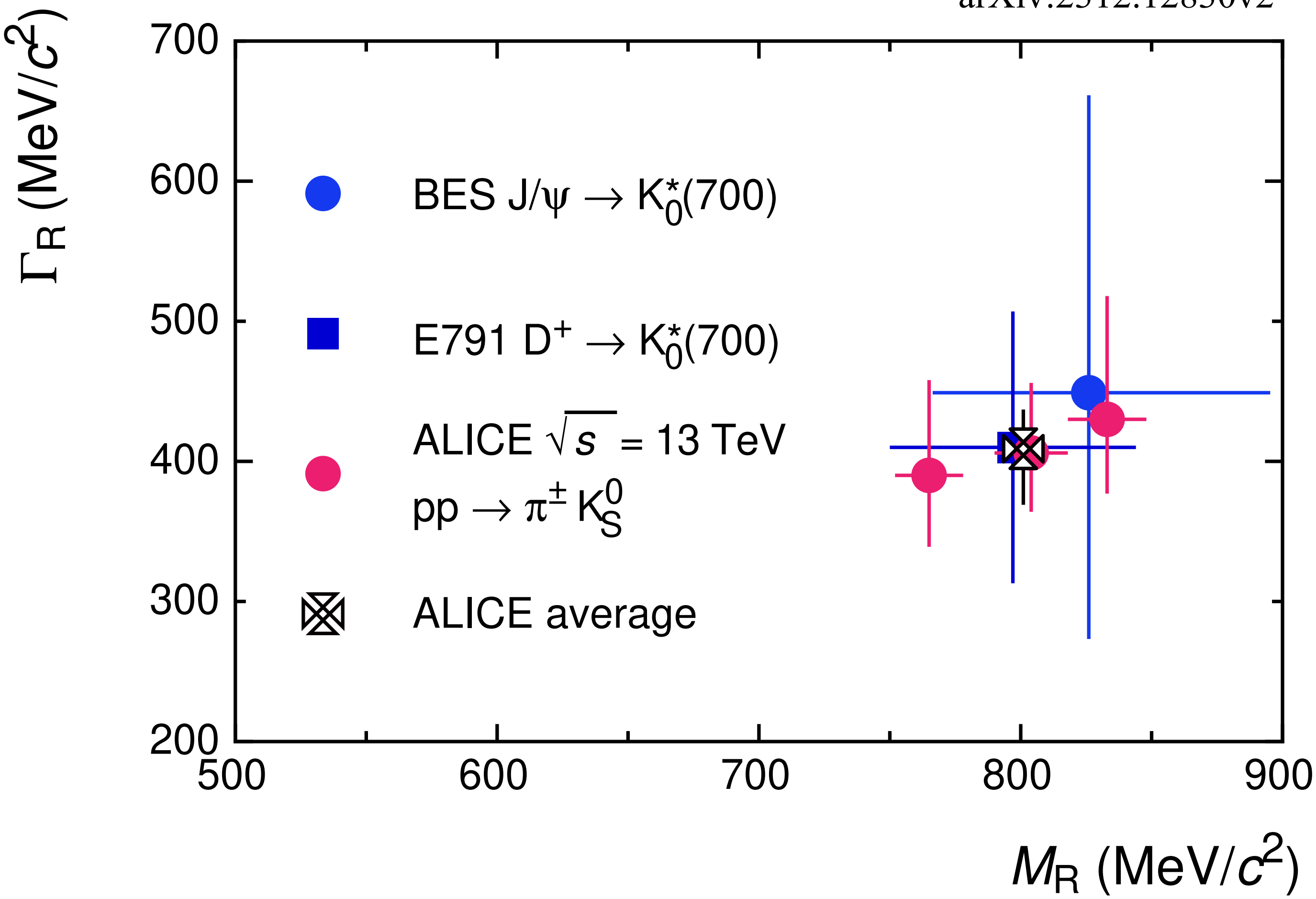


arXiv:2312.12830v2

The Lednický equation, assuming a resonance FSI, does a good job fitting the correlation function for each case.

Results of Lednický fits to 13 TeV pp → $\pi^{\pm}K^0_S$ for (M_R, Γ_R) and comparisons with other measurements

arXiv:2312.12830v2



NEW

BES Collab.
PLB 698 (2011)

E791 Collab.
PRL 89 (2002)

The $\pi^{\pm}K^0_S$ Γ_R and M_R agree with BES and E791 measurements of $\mathbf{K^*_0(700)}$.

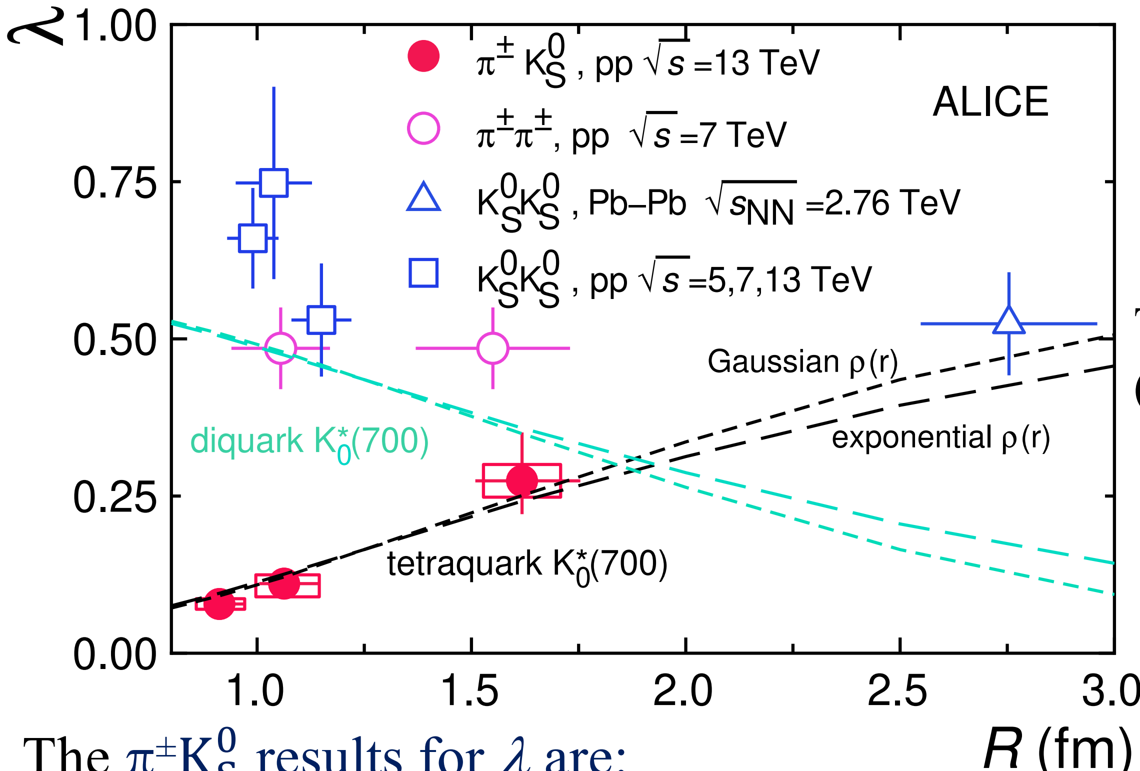
→ Shows that the $\pi^{\pm}K^0_S$ FSI is due to the $K^*_0(700)$.

Results of Lednický fits to 13 TeV pp → $\pi^{\pm}K^0_S$ for (R, λ) and comparisons with other measurements and a toy model

λ **vs** R from published ALICE pp, Pb–Pb → $K^0_S K^0_S$, ππ (PLB 833 (2022), PRC92 (2015), PRD84 (2011)) and the new 13 TeV pp → $\pi^{\pm}K^0_S$ results.

arXiv:2312.12830v2

NEW



Tetraquark model (black lines)

Diquark model (green lines)

The $\pi^{\pm}K^0_S$ results for λ are:

- ➢ smaller than for $K^0_S K^0_S$ and ππ.
- ➢ increase with R, unlike $K^0_S K^0_S$, ππ.
- ➢ consistent with the Tetraquark toy model R dependence.

→ **Behavior expected for a tetraquark $K^*_0(700)$.**

Summary

➢ $\mathbf{K^0_S K^\pm}$ femtoscopic analyses in $\sqrt{s_{NN}} = 2.76$ TeV Pb–Pb, and $\mathbf{K^0_S K^\pm}$ and $\mathbf{K^0_S K^0_S}$ analyses in $\sqrt{s} = 5.02$, 7 and 13 TeV pp collisions from ALICE are published in PLB

Main physics take-away:

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

➢ $\pi^\pm \mathbf{K^0_S}$ femtoscopic analysis in $\sqrt{s} = 13$ TeV pp collisions from ALICE was shown.

Main physics take-aways:

1) The FSI is shown to be due to the formation of the $\mathbf{K_0^*(700)}$.

2) The extracted R parameters are comparable to those from published $\pi\pi$ and $K^0_S K^0_S$ measurements in pp collisions.

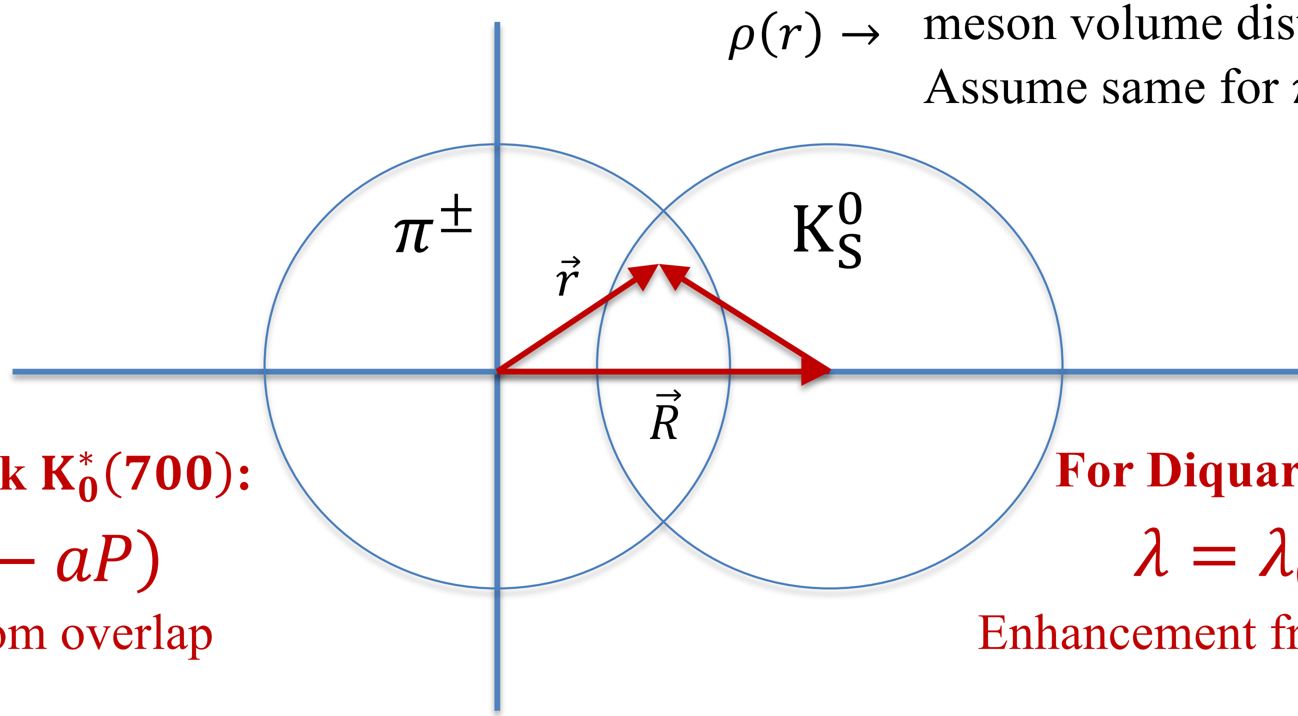
3) The λ parameter is much smaller than in the identical boson measurements.

4) The dependence of λ on R is as expected by a geometric toy model assuming a tetraquark $\mathbf{K_0^*(700)}$.

Backup slides

Toy model based on geometry to describe R dependence of λ for 13 TeV pp → $\pi^{\pm}K^0_S$

$\rho(r) \rightarrow$ meson volume distribution
Assume same for $\pi^{\pm}$ and K^0_S



For Tetraquark $K^*_0(700)$:

$$\lambda = \lambda_0(1 - aP)$$

Suppression from overlap

For Diquark $K^*_0(700)$:

$$\lambda = \lambda_0(aP)$$

Enhancement from overlap

$$P \equiv \frac{\int \rho(r)\rho(|\vec{r} - \vec{R}|)dV}{\int [\rho(r)]^2\, dV}$$ → "Overlap Probability"

$a \rightarrow$ "$d - \bar{d}$ annihilation efficiency"

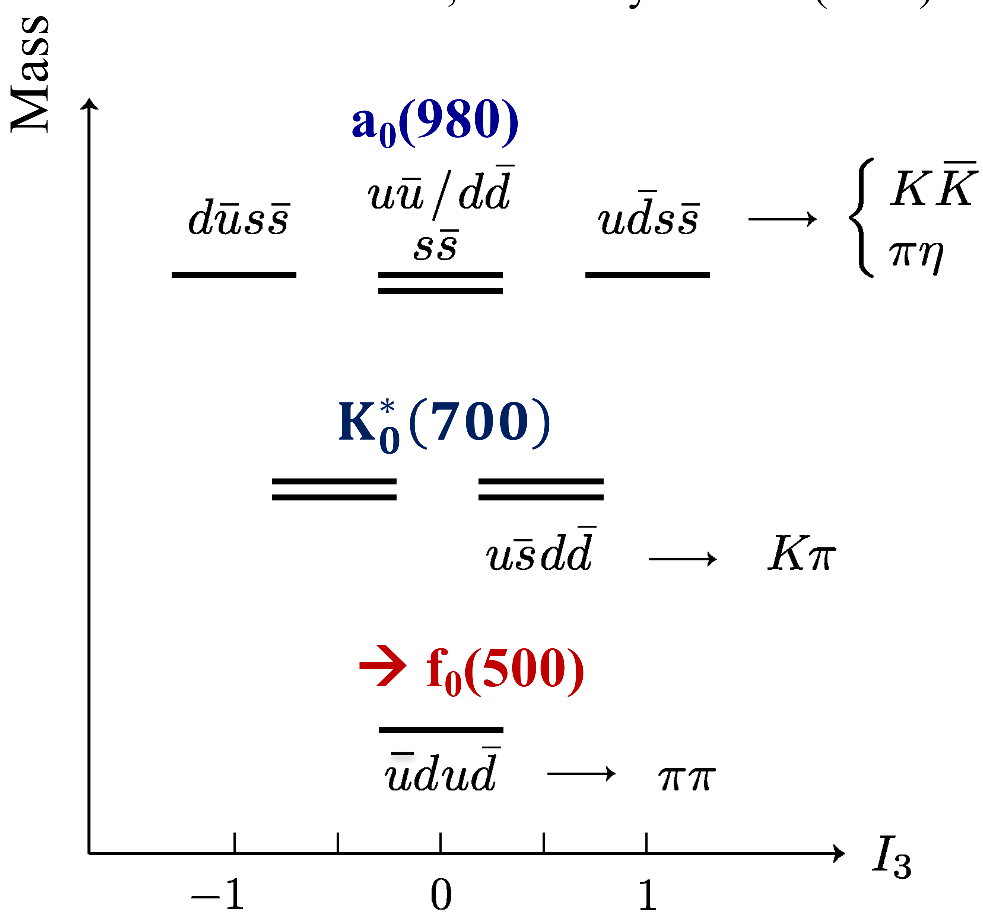
Try two cases:

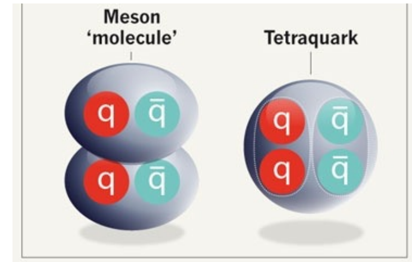
$$\begin{cases} \rho(r) \propto e^{-r^2/2\sigma^2} & \lambda_0 = 0.6, \quad \sigma = 1.1 \text{ fm}, \quad a = 1 \\ \rho(r) \propto e^{-r/r_0} & \lambda_0 = 0.6, \quad r_0 = 0.85 \text{ fm}, \quad a = 1 \end{cases}$$

Predicted low-lying tetraquark nonet with $f_0(500)$ candidate meson

Tetraquark nonet

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





$f_0(500)$ $I^G(J^{PC}) = 0^+(0^{++})$

also known as σ; was $f_0(600)$

See the review on "Scalar Mesons below 1 GeV."

Mass (T-Matrix Pole $\sqrt{s}$) = (400–550)−i(200–350) MeV

Mass (Breit-Wigner) = 400 to 800 MeV

Full width (Breit-Wigner) = 100 to 800 MeV

$f_0(500)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	seen	–
$\gamma\gamma$	seen	–

$\rho(770)$ $I^G(J^{PC}) = 1^+(1^{--})$

See the review on "Spectroscopy of Light Meson Resonances."

Mass m = 775.26 ± 0.23 MeV

Full width Γ = 149.1 ± 0.8 MeV

$\rho(770)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi\pi$	~ 100 %		363

→ Recently initiated the study of the $f_0(500)$ with $\pi^+\pi^-$ femtoscopy in 13 TeV pp collisions by ALICE → Work in progress!