

Interaction of external particles with molecular states

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$p f_1(1285)$

$K f_1(1285)$

$\pi f_1(1285), \eta f_1(1285)$

$K D_{s0}^*(2317)$

πT_{cc}

Scattering observables and correlation function for $p f_1(1285)$ revisited

P.~Encarnacion, A.~Feijoo and E.~Oset,

"Correlation function for the $p f_1(1285)$ interaction,"
Phys. Rev. D **111**, no.11, 114023 (2025)

Phys.Rev.D 113 (2026) 11, L111502

$$f_1(1285) = \frac{1}{2} (K^{*+} K^- + K^{*0} \bar{K}^0 - K^{*-} K^+ - \bar{K}^{*0} K^0)$$

$$I^G(J^PC) = 0^+(1^{++})$$

$$f_1(1285) = -\frac{1}{\sqrt{2}} (K^* \bar{K})^{I=0} - \frac{1}{\sqrt{2}} (\bar{K}^* K)^{I=0}$$

For $p f_1$ interaction we follow the traditional method of **particle-nucleus interaction**:

Define optical potential and solve the Lippmann Schwinger Equation

The optical potential is provided by the Fixed Center Approach to Faddeev equations, which is particularly suited to this case, since we have a well defined “cluster” the f_1 molecule

The FCA

Partition
functions

$$T_{11} = t_1 + t_1 \tilde{G} T_{21},$$

$$T_{12} = t_1 \tilde{G} T_{22},$$

$$T_{21} = t_2 \tilde{G} T_{11},$$

$$T_{22} = t_2 + t_2 \tilde{G} T_{12},$$

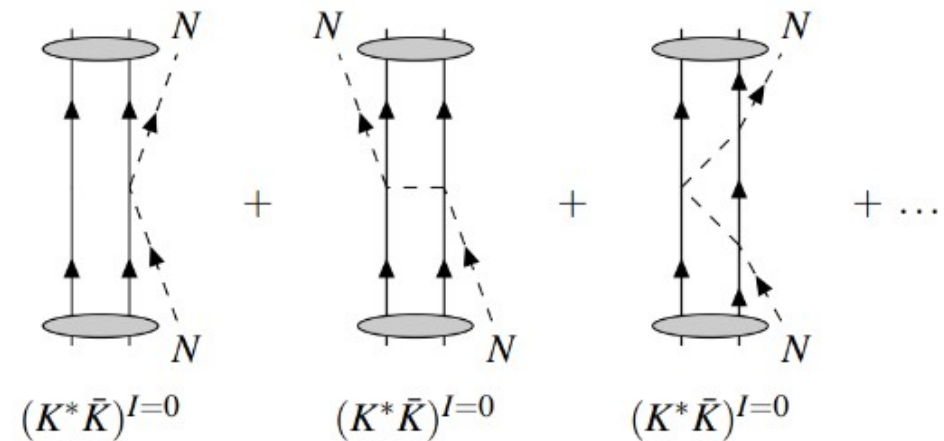
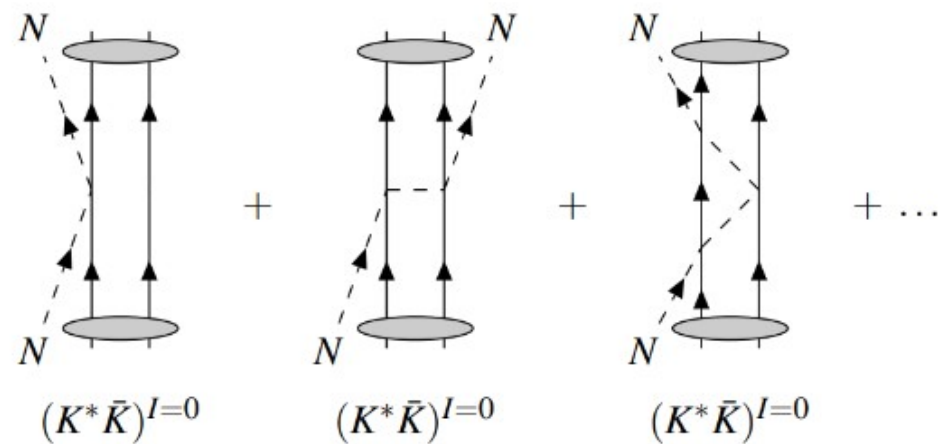
$$t_1 = \frac{3}{4} t_{pK^*}^{(1)} + \frac{1}{4} t_{pK^*}^{(0)}$$

$$t_2 = \frac{3}{4} t_{p\bar{K}}^{(1)} + \frac{1}{4} t_{p\bar{K}}^{(0)}$$

$$\tilde{t}_1 = \frac{M_C}{M_{K^*}} t_1 \quad ; \quad \tilde{t}_2 = \frac{M_C}{M_K} t_2$$

$$\tilde{T}_{11} = \frac{\tilde{t}_1}{1 - \tilde{t}_1 \tilde{t}_2 G_0^2} \quad ; \quad \tilde{T}_{22} = \frac{\tilde{t}_2}{1 - \tilde{t}_1 \tilde{t}_2 G_0^2}$$

$$\tilde{T}_{12} = \tilde{T}_{21} = \frac{\tilde{t}_1 \tilde{t}_2 G_0}{1 - \tilde{t}_1 \tilde{t}_2 G_0^2}$$



$$G_0(\sqrt{s}) = \int \frac{d^3 q}{(2\pi)^3} \frac{2M_N}{2E(q)2\omega_C(q)} \frac{F_C(q)}{\sqrt{s} - E(q) - \omega_C(q) + i\epsilon} \times \theta(q_{max}^{(1)} - q_1^*) \theta(q_{max}^{(2)} - q_2^*) \quad (8)$$

Version for students. Schroedinger Eqn. $(H_0 + V)|\psi\rangle = E|\psi\rangle$ $H_0|\phi\rangle = E|\phi\rangle$.

$$(E - H_0)|\psi - \phi\rangle = V|\psi\rangle,$$

$$|\psi - \phi\rangle = \frac{1}{E - H_0} V|\psi\rangle,$$

$$|\psi\rangle = |\phi\rangle + \frac{1}{E - H_0} V|\psi\rangle \quad \text{define } T \text{ such that } \bar{T}|\phi\rangle = V|\psi\rangle$$

$$T|\phi\rangle = V|\phi\rangle + V \frac{1}{E - H_0} V|\psi\rangle \quad T = V + V \frac{1}{E - H_0} T \quad \text{Lippmann Schwinger eqn.}$$

Assume $\langle p'|V|p\rangle = V(p', p) = v\theta(\Lambda - p')\theta(\Lambda - p),$

$$\langle p|T|p'\rangle = \langle p|V|p'\rangle + \int d^3 p'' \frac{\langle p|V|p''\rangle}{E - m_1 - m_2 - p''^2/2\mu} \langle p''|T|p'\rangle$$

$$\langle p|T|p'\rangle \equiv \theta(\Lambda - p')\theta(\Lambda - p)t,$$

which has the solution

$$t = v + vGt = \frac{v}{1 - vG} = \frac{1}{v^{-1} - G} \quad G = \int_{p < \Lambda} d^3 p \frac{1}{E - m_1 - m_2 - p^2/2\mu + i\epsilon}.$$

Wave functions

$$(H_0 + V)|\psi\rangle = E|\psi\rangle$$

$$|\psi\rangle = \frac{1}{E - H_0} V |\psi\rangle,$$

$$\langle \vec{p} | \psi \rangle = \int d^3 k \int d^3 k' \langle \vec{p} | \frac{1}{E - H_0} | \vec{k}' \rangle \langle \vec{k}' | V | \vec{k} \rangle \langle \vec{k} | \psi \rangle$$

$$= v \frac{\Theta(\Lambda - p)}{E - m_1 - m_2 - \frac{\vec{p}^2}{2\mu}} \int_{k < \Lambda} d^3 k \langle \vec{k} | \psi \rangle,$$

Generalization to coupled channels

$$\langle \vec{p} | \psi_i \rangle = \Theta(\Lambda - p) \frac{1}{E - M_i - \frac{\vec{p}^2}{2\mu_i}} \sum_j v_{ij} \int_{k < \Lambda} d^3 k \langle \vec{k} | \psi_j \rangle,$$

$$T = V + V \frac{1}{E - H} V.$$

$$T_{ij} = v_{ij} + \sum_{mn} v_{im} \int_{k < \Lambda} d^3 k \langle \vec{k} | \psi_m \rangle \frac{1}{E - E_\alpha} \\ \times \int_{k' < \Lambda} d^3 k' \langle \vec{k}' | \psi_n \rangle v_{nj},$$

$$g_i = \sum_j v_{ij} \int_{k < \Lambda} d^3 k \langle \vec{k} | \psi_j \rangle$$

$$\sum_i \langle \psi_i | \psi_i \rangle = \int d^3 p \sum_i |\langle \vec{p} | \psi_i \rangle|^2$$

$$\sum_i g_i^2 \frac{dG_{ii}}{dE} \Big|_{E=E_\alpha} = -1$$

$$T_{ij} \approx g_i g_j / (E - E_\alpha)$$

Around the pole

Each term with minus sign
gives the probability
of the corresponding channel

$$F_c(q) = \tilde{F}_c(q)/\tilde{F}_c(0)$$

with

$$\begin{aligned} \tilde{F}_c(q) = & \int \frac{d^3 p}{(2\pi)^3} \frac{1}{M_c - \omega_{K^*}(p) - \omega_{\bar{K}}(p)} \\ & \times \frac{1}{M_c - \omega_{K^*}(\vec{p} - \vec{q}) - \omega_{\bar{K}}(\vec{p} - \vec{q})} \\ & |\vec{p}| < q_{max} \\ & |\vec{p} - \vec{q}| < q_{max} \end{aligned}$$

Based on

$$\Psi(p) \sim \frac{\Theta(q_{max} - |\vec{p}|)}{M_c - \omega_{K^*}(\vec{p}) - \omega_{\bar{K}}(\vec{p})}$$

$$\tilde{T} = \begin{pmatrix} \tilde{T}_{11} & \tilde{T}_{12} \\ \tilde{T}_{21} & \tilde{T}_{22} \end{pmatrix}$$

$$\tilde{T}' = [1 - \tilde{T} G_C]^{-1} \tilde{T}$$

$$G_C = \begin{pmatrix} G_C^{(1)} & 0 \\ 0 & G_C^{(2)} \end{pmatrix}$$

Formalism developed in N. Ikeno, E. Oset

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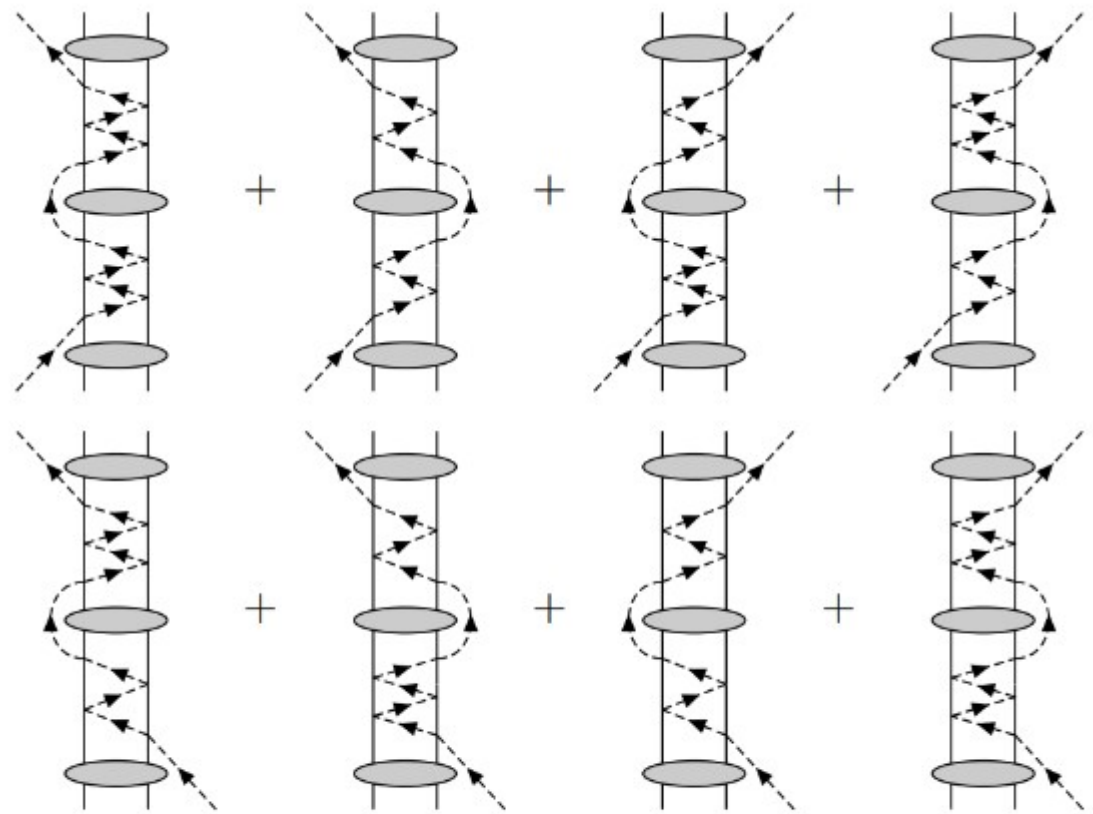


FIG. 2. Diagrams required for the unitarization of the $pf_1(1285)$

$$G_C^{(i)}(\sqrt{s}) = \int \frac{d^3 q}{(2\pi)^3} \frac{2M_N}{2E(q)2\omega_C(q)} \frac{[F_C^{(i)}(q)]^2}{\sqrt{s} - E(q) - \omega_C(q) + i\varepsilon} \times \theta(q_{\max}^{(i)} - q_i^*), \quad (15)$$

$$F_C^{(1)}(q) = F_C \left(\frac{m_{\bar{K}}}{m_{K^*} + m_{\bar{K}}} q \right)$$

$$F_C^{(2)}(q) = F_C \left(\frac{m_{K^*}}{m_{K^*} + m_{\bar{K}}} q \right)$$

Yamagata
Nieves
PRD 83

$$T_{K^*\bar{K}}^{\text{tot}}(\sqrt{s}) = \sum_{i,j} \tilde{T}'_{ij} = \frac{\tilde{t}_1 + \tilde{t}_2 + (2G_0 - G_C^{(1)} - G_C^{(2)})\tilde{t}_1\tilde{t}_2}{1 - G_C^{(1)}\tilde{t}_1 - G_C^{(2)}\tilde{t}_2 - (G_0^2 - G_C^{(1)}G_C^{(2)})\tilde{t}_1\tilde{t}_2} \quad (17)$$

$$-\frac{8\pi\sqrt{s}}{2M_N}(T_{K^*\bar{K}}^{\text{tot}})^{-1} = (f^{QM})^{-1} \simeq -\frac{1}{a_0} + \frac{1}{2}r_0q_{cm}^2 - iq_{cm}$$

unitarity

$$(T^{\text{tot}})^{-1} = \frac{1}{2} [(T_{K^*\bar{K}}^{\text{tot}})^{-1} + (T_{\bar{K}^*K}^{\text{tot}})^{-1}]$$

Exact unitarity proved in B. Agatao, P. Brandao, A. Martinez, K. Khemchandani, L. Abreu, E. Oset

(1) $\bar{K}N, I = 0$

We obtain this one using the chiral unitary approach of [92] with the coupled channels $\bar{K}N, \pi\Sigma, \eta\Lambda, K\Xi$. The T matrix is given by

$$T = [1 - VG]^{-1}V \quad (\text{A1})$$

with G the loop function regularized with a cutoff $q_{\text{max}} = 630$ MeV, and with

$$V_{ij} = -\frac{1}{4f^2}D_{ij}(k^0 + k'^0), \quad (\text{A2})$$

(2) $\bar{K}N, I = 1$

We follow the same work [92] with the coupled channels $\bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Sigma, K\Xi$. The potential is now given by

$$V_{ij} = -\frac{1}{4f^2}F_{ij}(k^0 + k'^0), \quad (\text{A3})$$

[92] E. Oset and A. Ramos, Nonperturbative chiral approach to S-wave KN interactions, Nucl. Phys. A635, 99 (1998).

$$\frac{1}{a_0} = \frac{8\pi\sqrt{s}}{2M_N} (T_{K^*\bar{K}}^{\text{tot}})^{-1}|_{\text{th}}$$

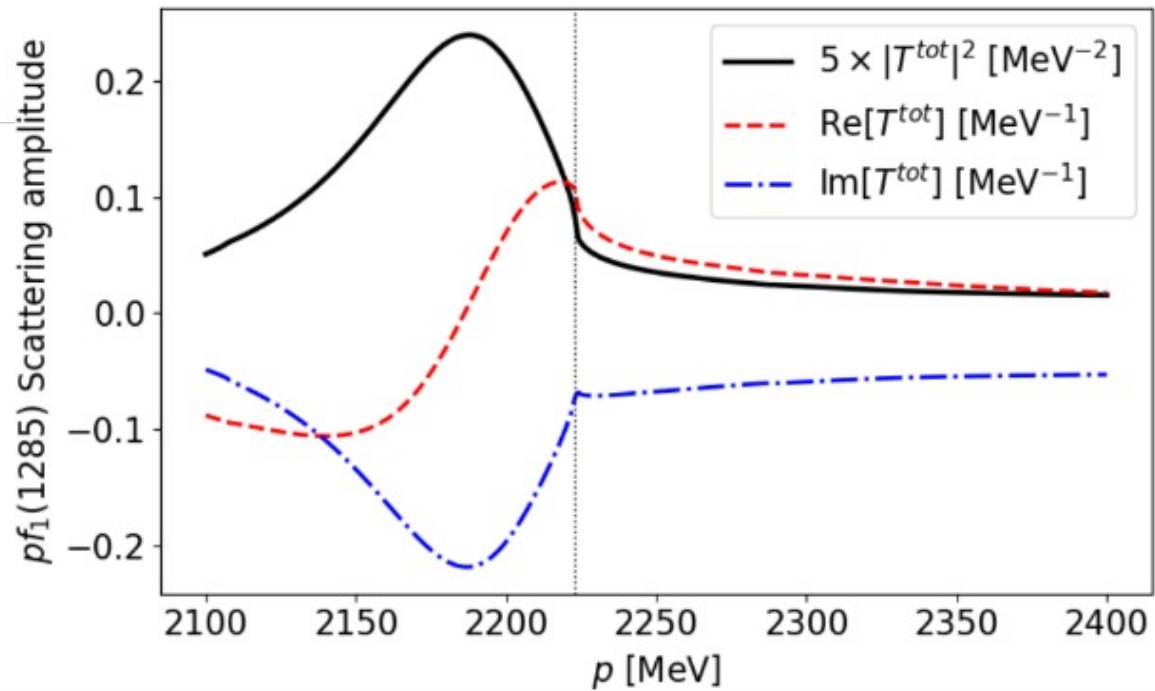
$$r_0 = \frac{1}{\mu} \left[\frac{\partial}{\partial \sqrt{s}} \left(-\frac{8\pi\sqrt{s}}{2M_N} (T_{K^*\bar{K}}^{\text{tot}})^{-1} + iq_{cm} \right) \right]_{\text{th}}$$

$$M_R = 2189 \pm 10 \text{ MeV},$$

$$\Gamma_R = 53 \pm 12 \text{ MeV},$$

$$a_0 = [0.689 \pm 0.040] - [0.413 \pm 0.084]i \text{ fm},$$

$$r_0 = [-0.025 \pm 0.077] + [0.146 \pm 0.084]i \text{ fm}.$$



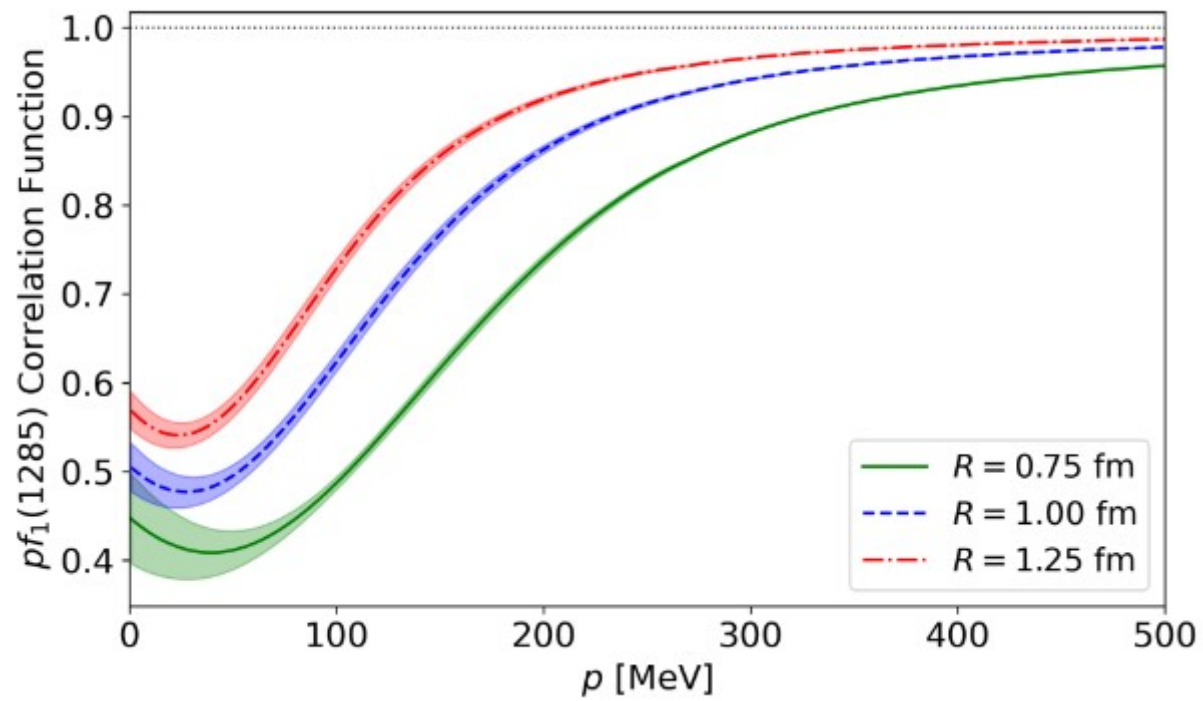
Correlation function

$$C_{pf_1}(p) = 1 + 4\pi \int_0^\infty dr r^2 S_{12}(r) \times \left\{ |j_0(pr) + TG|^2 - j_0^2(pr) \right\}$$

$$S_{12}(r) = \frac{1}{(4\pi R^2)^{3/2}} e^{-r^2/4R^2}$$

$$\begin{aligned} TG &\simeq \left(\tilde{T}'_{11} + \tilde{T}'_{21} + \tilde{T}'_{12} + \tilde{T}'_{22} \right) \frac{1}{2} \left(G_1(\sqrt{s}, r) + G_2(\sqrt{s}, r) \right) \\ &= T^{\text{tot}} \frac{1}{2} \left(G_1(\sqrt{s}, r) + G_2(\sqrt{s}, r) \right) \end{aligned} \quad (25)$$

$$\begin{aligned} G_i(\sqrt{s}, r) = \int \frac{d^3 q}{(2\pi)^3} \frac{2M_N}{2E(q)2\omega_C(q)} \frac{F_C^{(i)}(q) j_0(qr)}{\sqrt{s} - E(q) - \omega_C(q) + i\epsilon} \\ \times \theta(q_{\max}^{(i)} - q_i^*). \end{aligned} \quad (24)$$



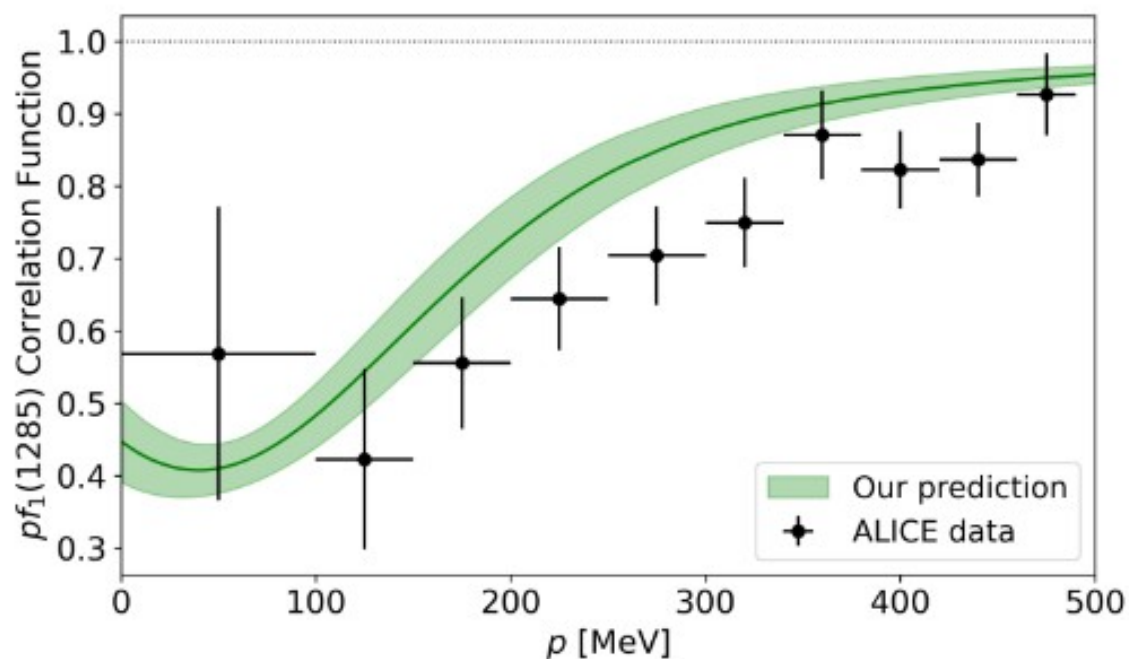


FIG. 5. $pf_1(1285)$ CF for $R = 0.75$ fm with the corresponding error band, compared with the ALICE experimental data taken from [54].

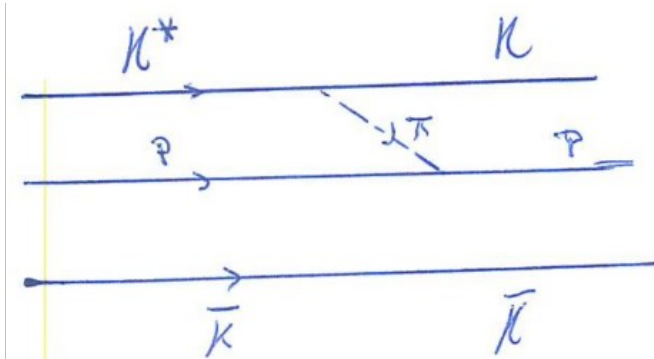
How to observe the state ?

$f_1(1285)$ DECAY MODES

Γ_9	$a_0(980)\pi$ $K\bar{K}$	[ignoring $a_0(980) \rightarrow$	$(38 \pm 4) \%$
Γ_{11}	$K\bar{K}\pi$		$(9.0 \pm 0.4) \%$

One must look at mass distribution of a proton + these other products

4 body



$$pK\bar{K} \quad I = 1/2, \quad J^P = 1/2^+, 3/2^+$$

3 body final state

The world of three body bound states involving mesons and baryons is a new frontier in Hadron Physics. ELSA could say something about.

K f1(1285) interaction

Wen Hao Jia, Jing Song, Wei Hong Liang, E. Oset

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We replace a proton by a kaon.

The formalism is identical, but we need now the amplitudes

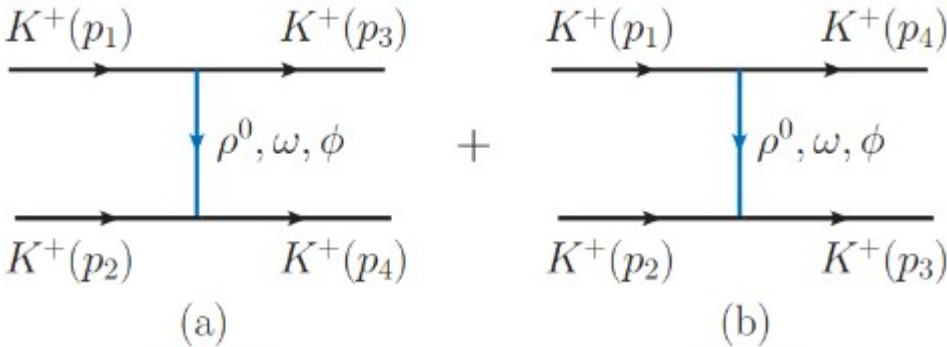
$K K^*$, $K K\text{bar}$, $K K^*\text{bar}$, $K K$

$$\mathcal{L}_{VPP} = -ig \langle [P, \partial_\mu P] V^\mu \rangle ,$$

$$\text{with } g = \frac{M_V}{2f}, \, M_V = 800 \text{ MeV and } f = 93 \text{ MeV.}$$

$$P = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{1}{\sqrt{3}}\eta, \end{pmatrix}$$

$$V = \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}$$



$$V_{KK}^{I=1} = \frac{4g^2}{M_V^2} \left(\frac{3}{2}s - 2M_K^2 \right)$$

$$T = \frac{V}{1 - \frac{1}{2}VG}.$$

$$V_{KK}^{I=0} = 0.$$

K K* interaction

$$\mathcal{L}_{VVV} = ig \langle (V^\mu \partial_\nu V_\mu - \partial_\nu V^\mu V_\mu) V^\nu \rangle$$

For $I=1$

$$V' = \frac{2g^2}{M_V^2} \left[\frac{3}{2}s - (M_K^2 + M_{K^*}^2) - \frac{1}{2s}(M_{K^*}^2 - M_K^2) \right],$$

(A10)

$$T = \frac{V'}{1 - V'G}$$

$$V_{KK^*}^{I=0} = 0,$$

The $K \bar{K}$ amplitudes we take from the chiral unitary approach , Oller, Oset

The $K \bar{K}^*$ also, One gets the axial vector meson states.

We use the results of Luis Roca and Singh PRD 72, Geng et al. PRD 90

1) $I = 0, C = +, f_1(1285)$

$$\begin{aligned} f_1(1285) &\equiv \frac{1}{\sqrt{2}} \left[-\frac{1}{\sqrt{2}} (K^+ K^{*-} + K^0 \bar{K}^{*0}) \right. \\ &\quad \left. + \frac{1}{\sqrt{2}} (K^- K^{*+} + \bar{K}^0 K^{*0}) \right] \\ &= \frac{1}{\sqrt{2}} [K \bar{K}^*(I=0) + \bar{K} K^*(I=0)] . \end{aligned}$$

2) $I = 1, C = +, a_1(1260)$

$$\begin{aligned} a_1(1260) &\equiv \frac{1}{\sqrt{2}} \left[-\frac{1}{\sqrt{2}} (K^+ K^{*-} - K^0 \bar{K}^{*0}) \right. \\ &\quad \left. + \frac{1}{\sqrt{2}} (K^- K^{*+} - \bar{K}^0 K^{*0}) \right] \\ &= \frac{1}{\sqrt{2}} [K \bar{K}^*(I=1) - \bar{K} K^*(I=1)] . \end{aligned}$$

3) $I = 0, C = -, h_1(1170), h_1(1415)$

$$h_1 \equiv \frac{1}{\sqrt{2}} [K \bar{K}^*(I=0) - \bar{K} K^*(I=0)]$$

4) $I = 1, C = -, b_1(1235)$

Here we have analogy to in Eq. (A15)

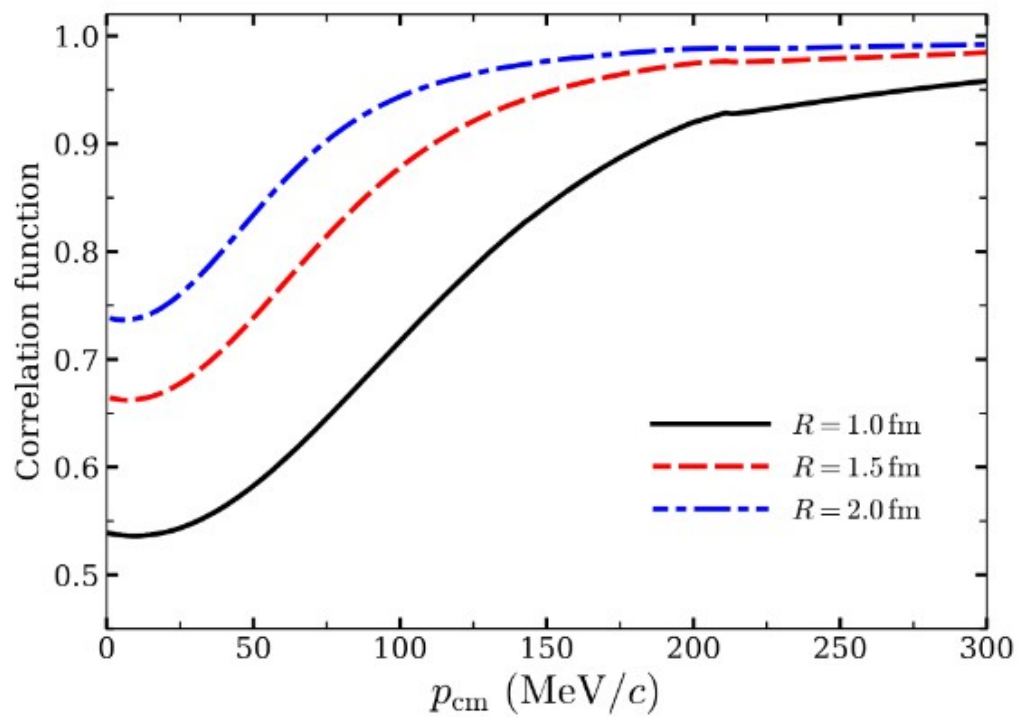
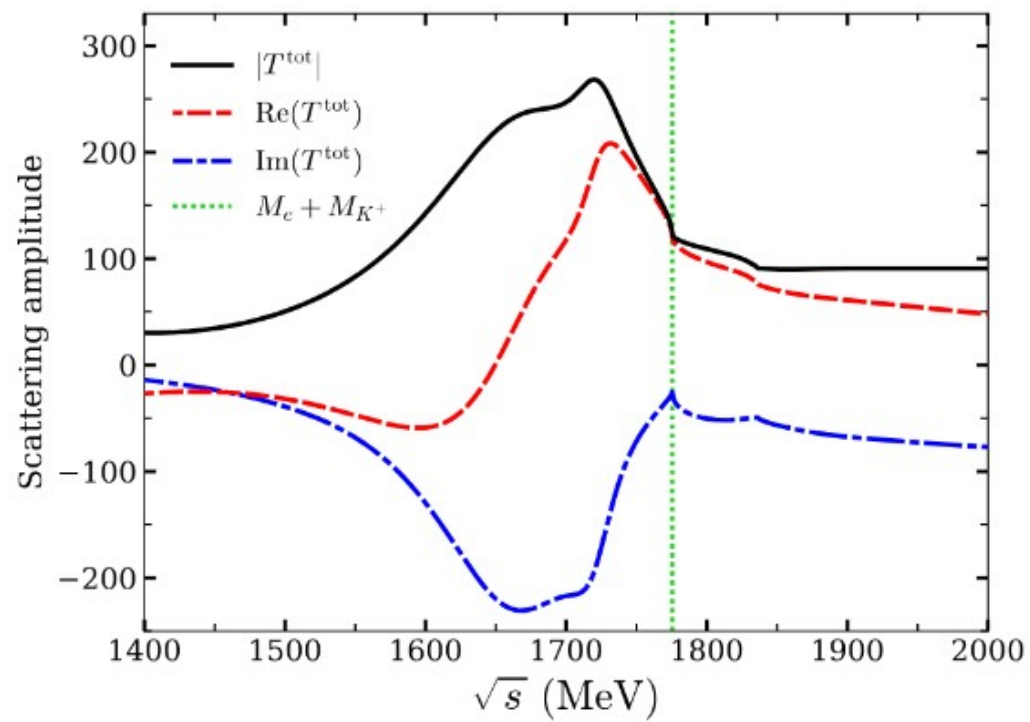
$$b_1(1235) = \frac{1}{\sqrt{2}} [K \bar{K}^*(I=1) + \bar{K} K^*(I=1)]$$

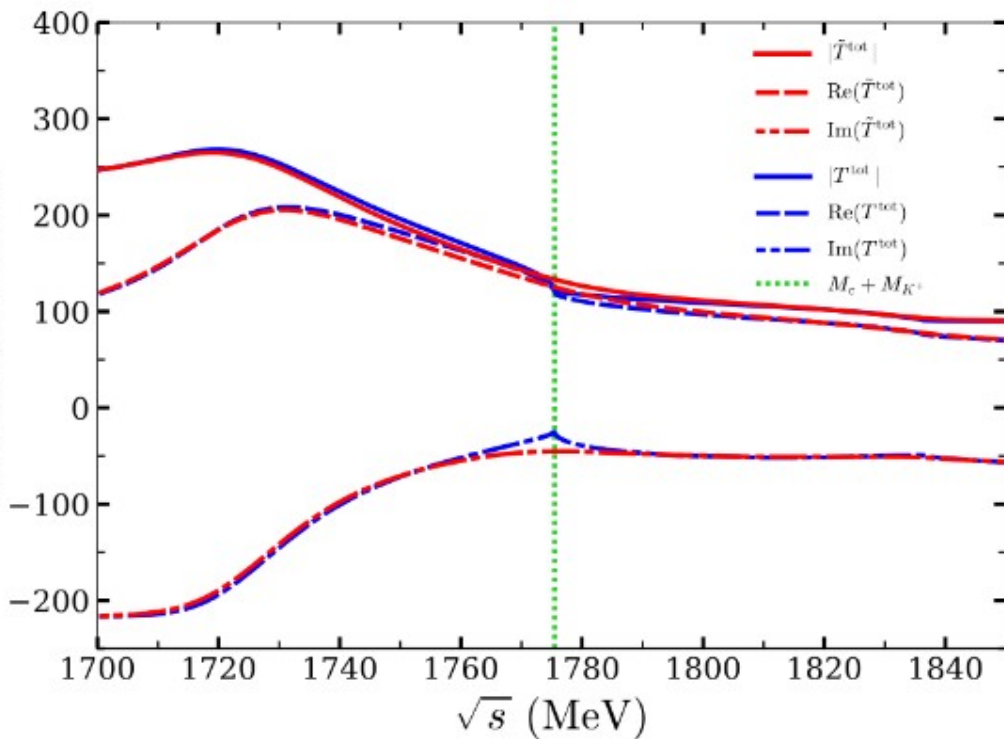
$$\begin{aligned}
& \langle f_1 | t | f_1 \rangle + \langle h_1 | t | h_1 \rangle \\
&= \langle K \bar{K}^*, I = 0 | t | K \bar{K}^*, I = 0 \rangle \\
&\quad + \langle \bar{K} K^*, I = 0 | t | \bar{K} K^*, I = 0 \rangle \\
&= 2 \langle K \bar{K}^*, I = 0 | t | K \bar{K}^*, I = 0 \rangle,
\end{aligned}$$

$$\left| \langle a_1 | t | a_1 \rangle + \langle b_1 | t | b_1 \rangle = 2 \langle K \bar{K}^*, I = 1 | t | K \bar{K}^*, I = 1 \rangle \right.$$

$$\langle R_i | t | R_i \rangle = \frac{g_i^2}{s - M_{R_i}^2 + i M_{R_i} \Gamma_{R_i}},$$

We take mass and with from experiment and the couplings from the paper of Roca Singh

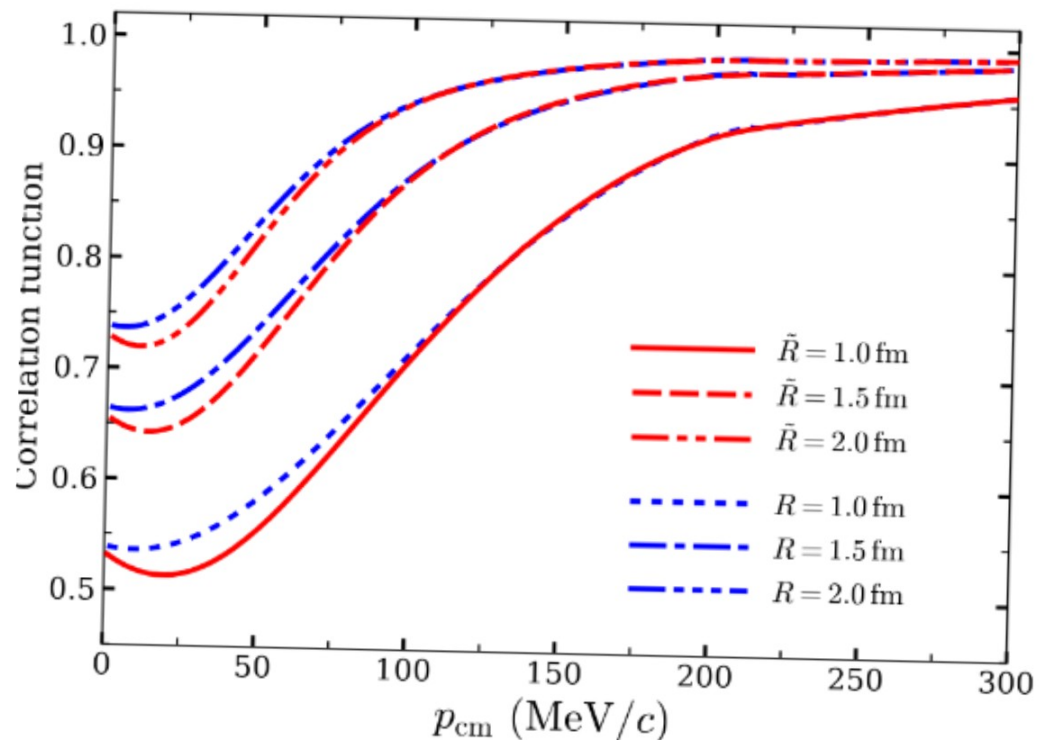




$$a = (0.55 - i 0.20) \text{ fm},$$

$$r_0 = (-1.85 + i 0.26) \text{ fm}.$$

With convolution for the f1 width



π^0 f1(1285), η f1(1285) scattering

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π^0 scattering

$$t_1 = \frac{2}{3} t_{\pi K^*}^{I=3/2} + \frac{1}{3} t_{\pi K^*}^{I=1/2}$$

$$t_2 = \frac{2}{3} t_{\pi K}^{I=3/2} + \frac{1}{3} t_{\pi K}^{I=1/2}$$

η scattering

$$t_1 = t_{\eta K^*}^{I=1/2},$$

$$t_2 = t_{\eta \bar{K}}^{I=1/2} = t_{\eta K}^{I=1/2}$$

Related to work

M.-J. Yan, J. M. Dias, A. Guevara, F.-K. Guo, and B.-

S. Zou, On the $\eta_1(1855)$, $\pi_1(1400)$ and $\pi_1(1600)$ as Dynamically Generated States and Their SU(3) Partners,

Universe 9, 109 (2023), arXiv:2301.04432 [hep-ph].

axial-vector mesons are assumed as matter fields, which provides the Weinberg-Tomozawa interaction of order $O(1/f^2)$, and these interaction give zero.

TABLE I. Transition potentials V_{ij} for the $\pi^- K^+$, $\pi^0 K^0$, and ηK^0 channels.

	$\pi^- K^+$	$\pi^0 K^0$	ηK^0
$\pi^- K^+$	$\frac{-1}{6f^2} \left[\frac{3}{2}s - \frac{3}{2s} (m_\pi^2 - m_K^2)^2 \right]$	$\frac{1}{2\sqrt{2}f^2} \left[\frac{3}{2}s - m_\pi^2 - m_K^2 - \frac{(m_\pi^2 - m_K^2)^2}{2s} \right]$	$\frac{1}{2\sqrt{6}f^2} \left[\frac{3}{2}s - \frac{7}{6}m_\pi^2 - \frac{1}{2}m_\eta^2 - \frac{1}{3}m_K^2 + \frac{3}{2s} (m_\pi^2 - m_K^2) (m_\eta^2 - m_K^2) \right]$
$\pi^0 K^0$		$\frac{-1}{4f^2} \left[-\frac{s}{2} + m_\pi^2 + m_K^2 - \frac{(m_\pi^2 - m_K^2)^2}{2s} \right]$	$-\frac{1}{4\sqrt{3}f^2} \left[\frac{3}{2}s - \frac{7}{6}m_\pi^2 - \frac{1}{2}m_\eta^2 - \frac{1}{3}m_K^2 + \frac{3}{2s} (m_\pi^2 - m_K^2) (m_\eta^2 - m_K^2) \right]$
ηK^0			$-\frac{1}{4f^2} \left[-\frac{3}{2}s - \frac{2}{3}m_\pi^2 + m_\eta^2 + 3m_K^2 - \frac{3}{2s} (m_\eta^2 - m_K^2)^2 \right]$

$$T = [1 - VG]^{-1} V,$$

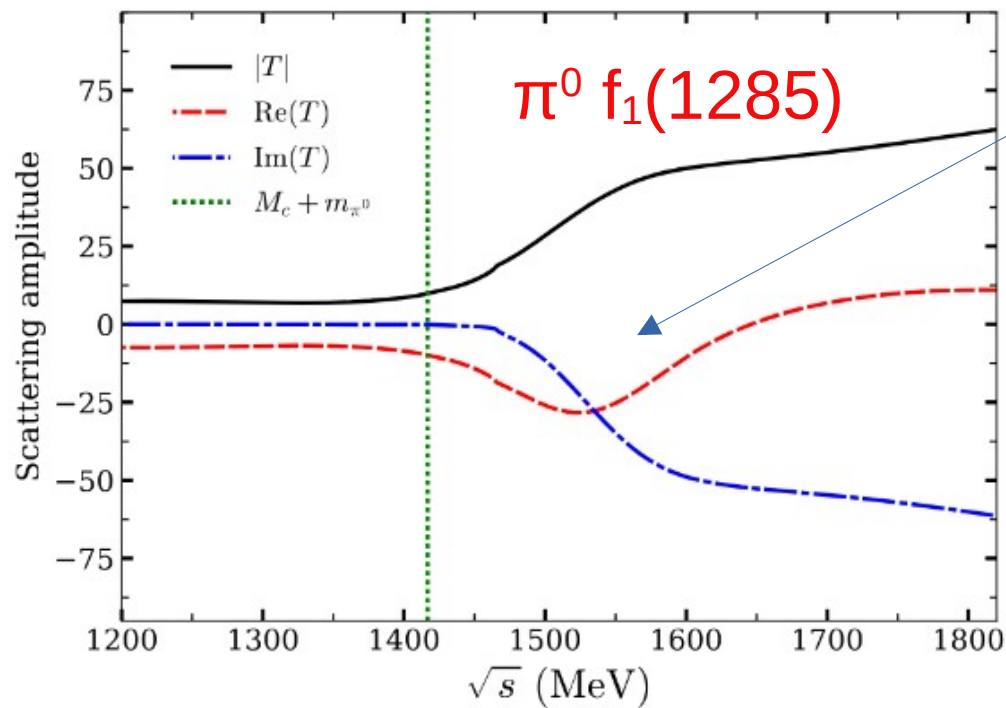


FIG. 3. $\pi^0 f_1(1285)$ scattering amplitude $T_{\pi^0 f_1}^{\text{tot}}$ as a function of $\sqrt{s}$.

$$a = -0.06 \text{ fm},$$

$$r_0 = (-46.00 - i 0.43) \text{ fm}$$

r_0 is stable, large value tied to resonance above threshold

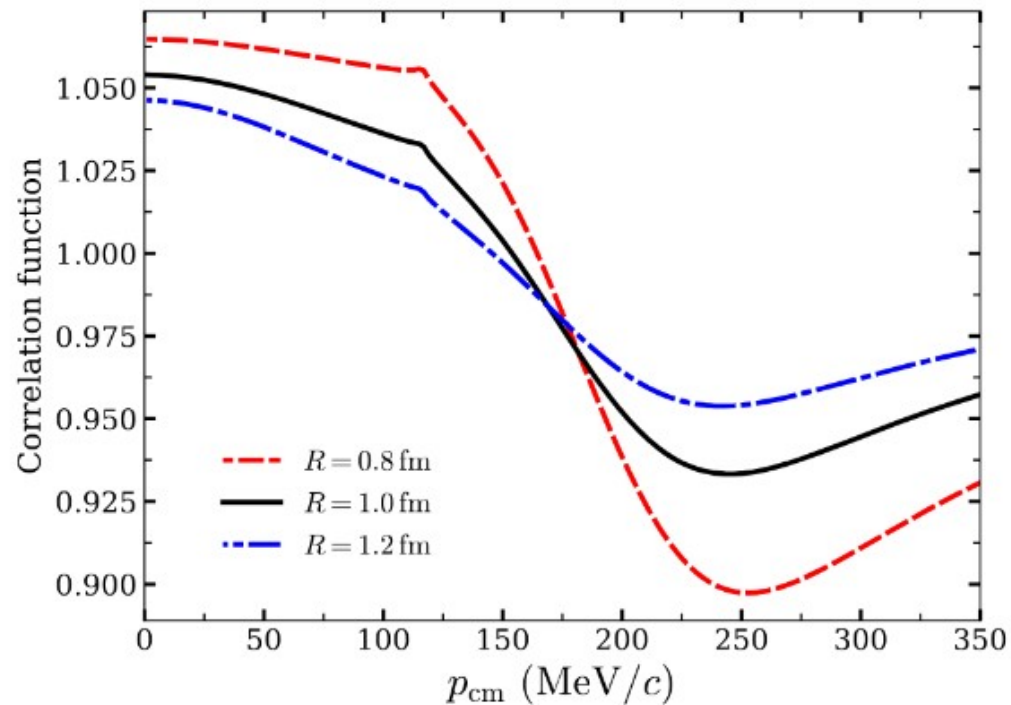
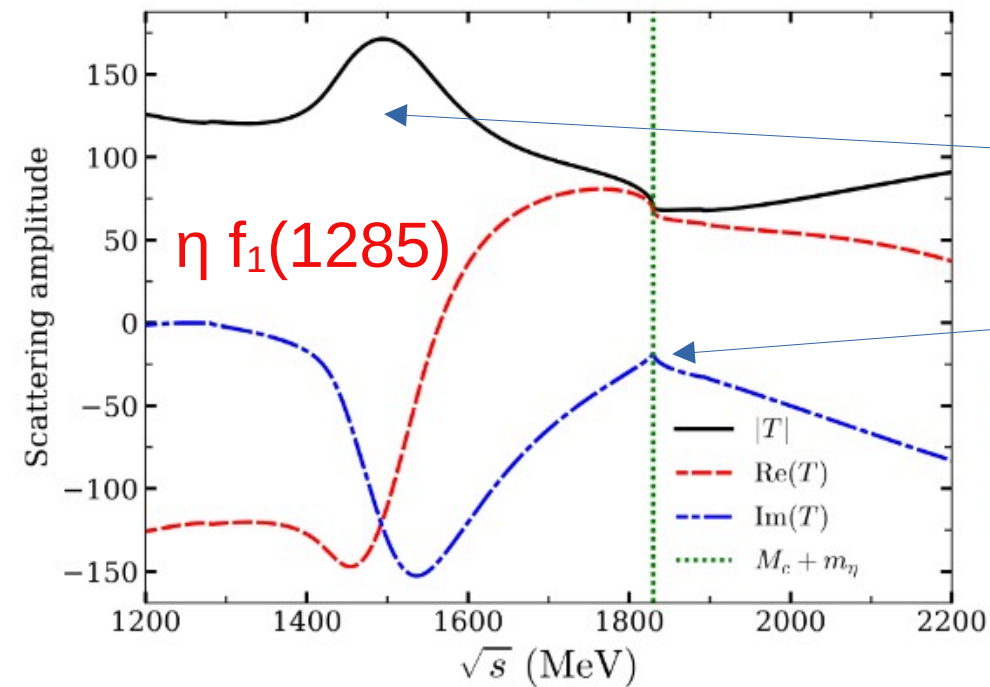


FIG. 5. Correlation functions for the $\pi^0 f_1(1285)$ system as a function of momentum p_{cm} , with different values of the source radius R .



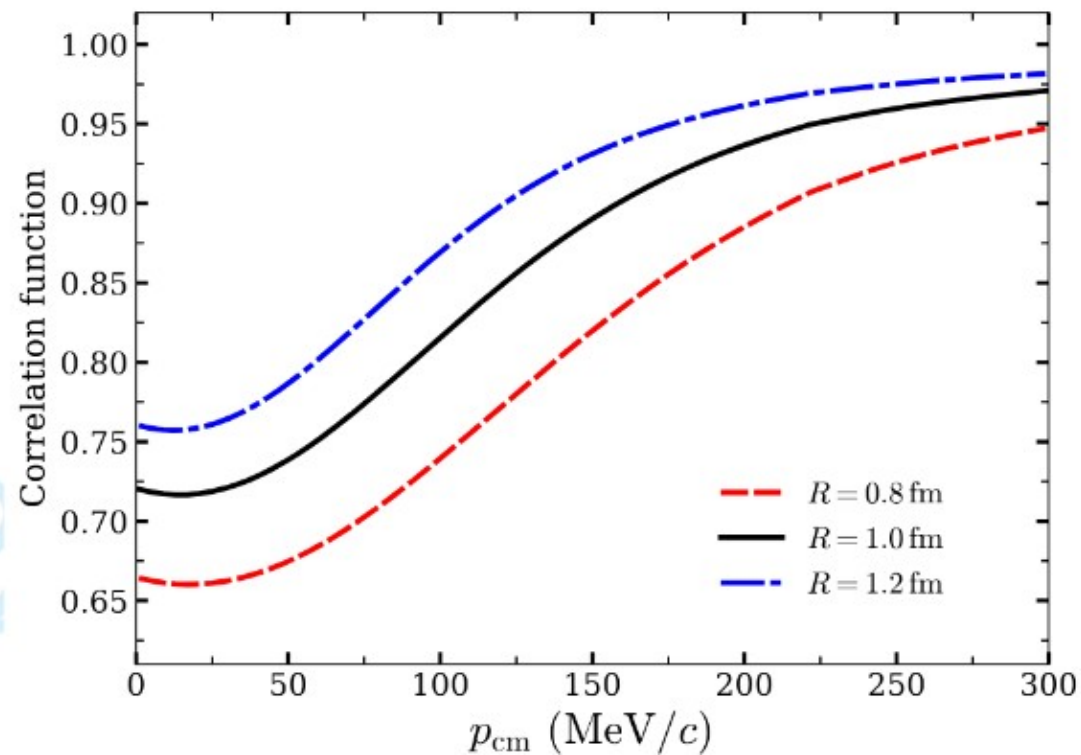
Too far away to be realistic

Anything to do with the eta1(1855) ?

FIG. 4. $\eta f_1(1285)$ scattering amplitude $T_{\eta f_1}^{\text{tot}}$ as a function of $\sqrt{s}$.

$$a = (0.29 - i 0.07) \text{ fm},$$

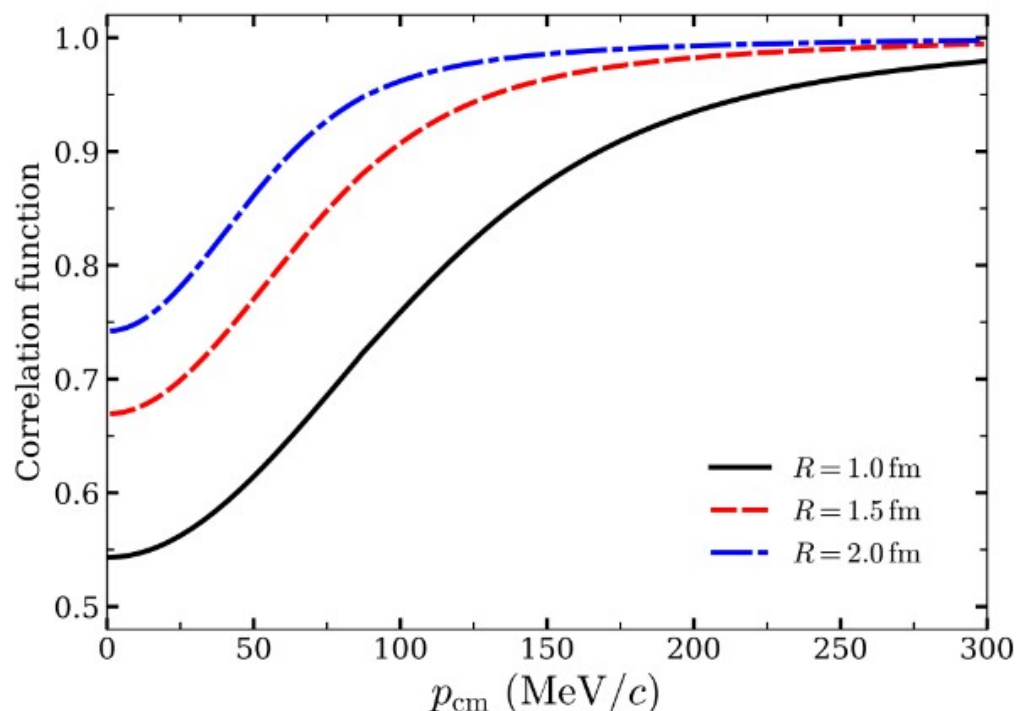
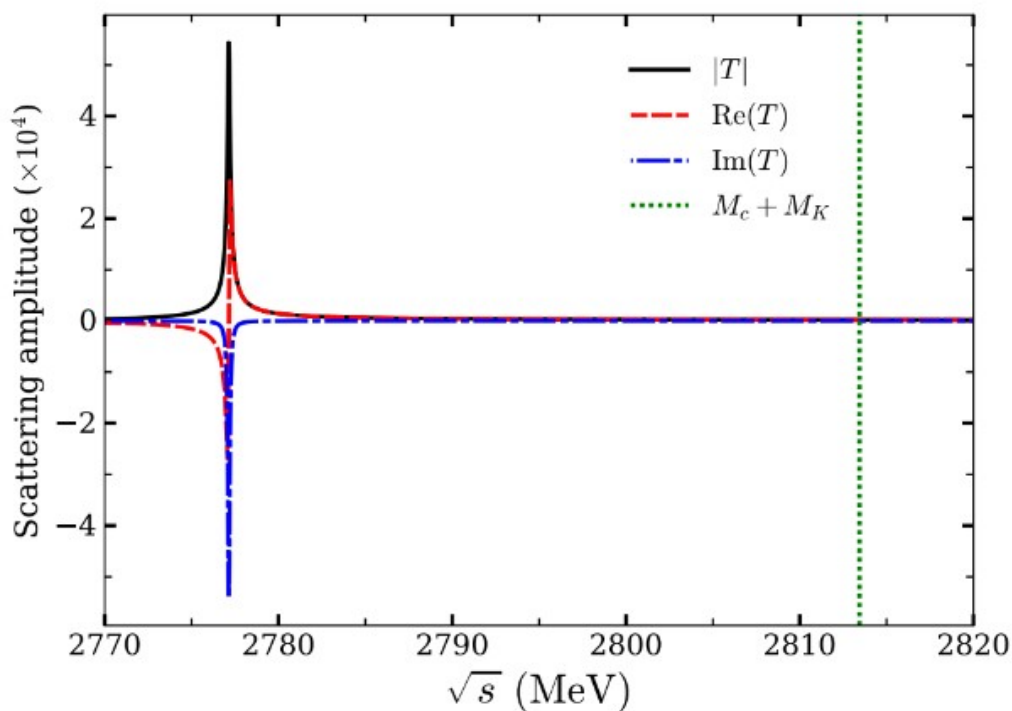
$$r_0 = (0.42 + i 0.45) \text{ fm}.$$



Correlation function and bound state from the $KD_{s0}^*(2317)$ interaction

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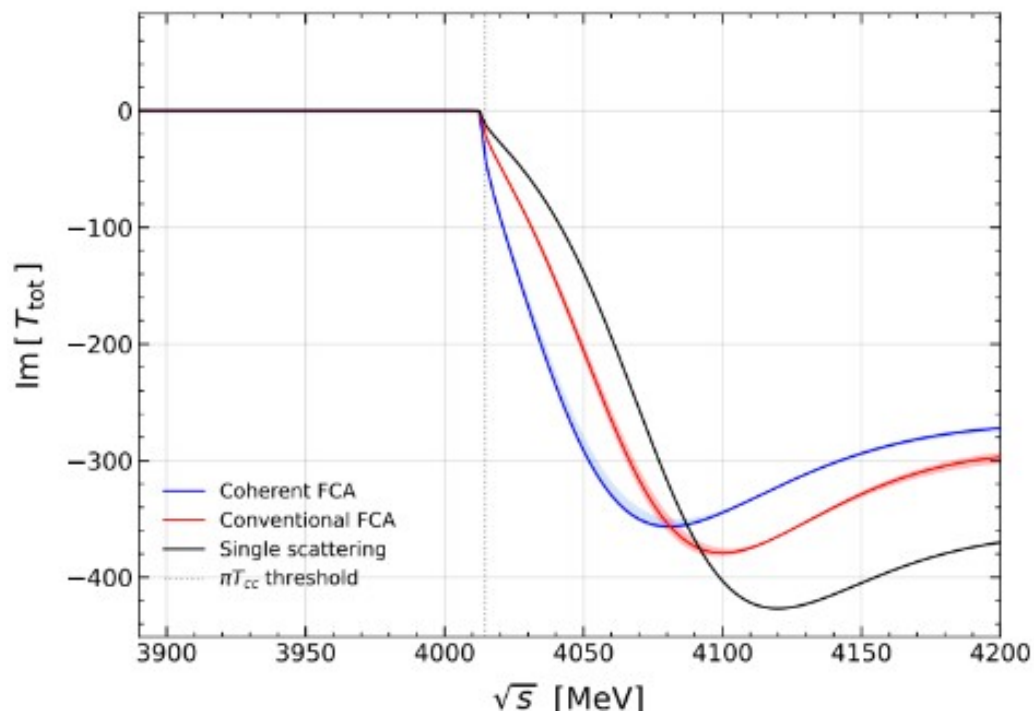
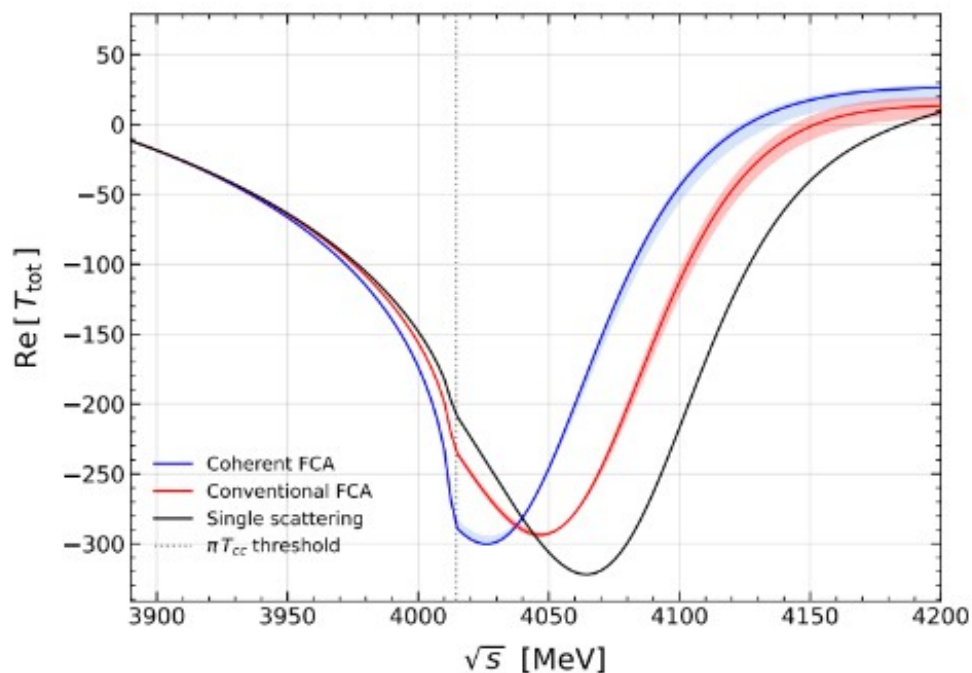


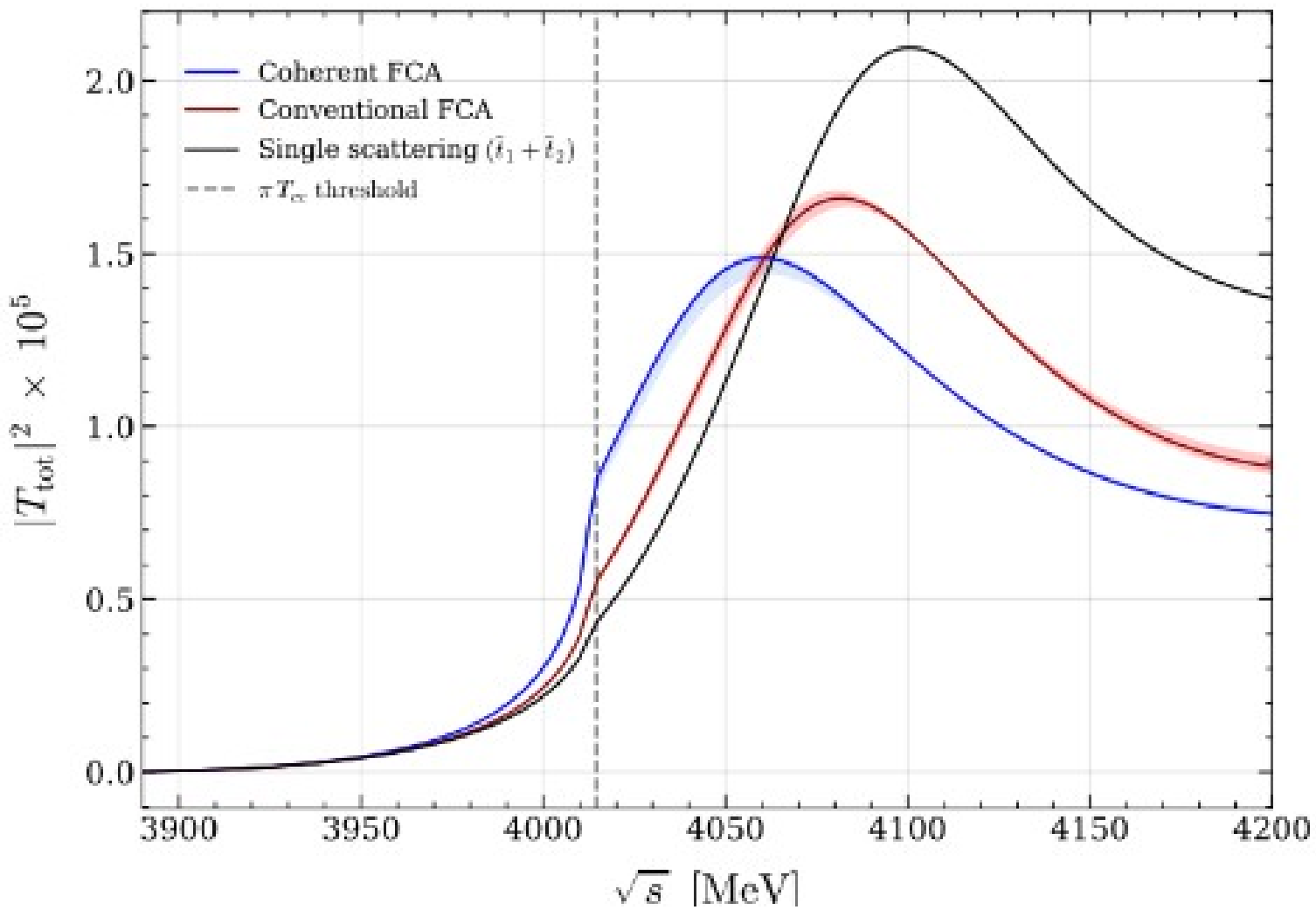
A pion-driven near-threshold enhancement in the πT_{cc} system

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πT_{cc}





πT_{cc}

Conclusions

We have developed a framework to study the interaction of an external particle with a molecular state, and applied it to study $p f_1(1285)$, $K f_1$, $\pi^0 f_1$, ηf_1 , $K D s_0(2317)$

We calculate the scattering amplitude and the correlation function

For $p f_1$ and $K f_1$, $K D s_0(2317)$ we find a bound state of the three body system

For $\pi^0 f_1$, we find a structure above threshold, reminiscent of the $\pi_1(1400-1600)$

For ηf_1 the only structure that could be associated to the $\eta_1(1855)$ is a threshold effect at that the ηf_1 threshold.

The experimental results from ALICE for the correlation function of $p f_1$ give a particular credibility to the results that we obtain.

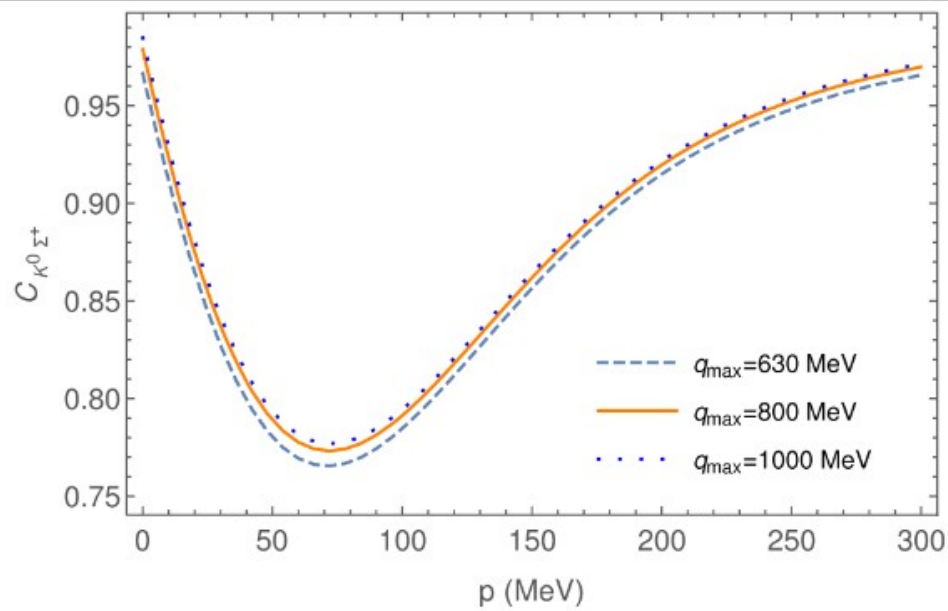


FIG. 1. Correlation function of the $K^0 \Sigma^+$ channel for different cutoffs and $R = 1$ fm.

R.~Molina and E.~Oset,
 "Determination of off-shell ambiguities in
 correlation functions: Strategies to
 minimize them,"
 Phys. Rev. D **112**, no.9, 096006
 (2025)

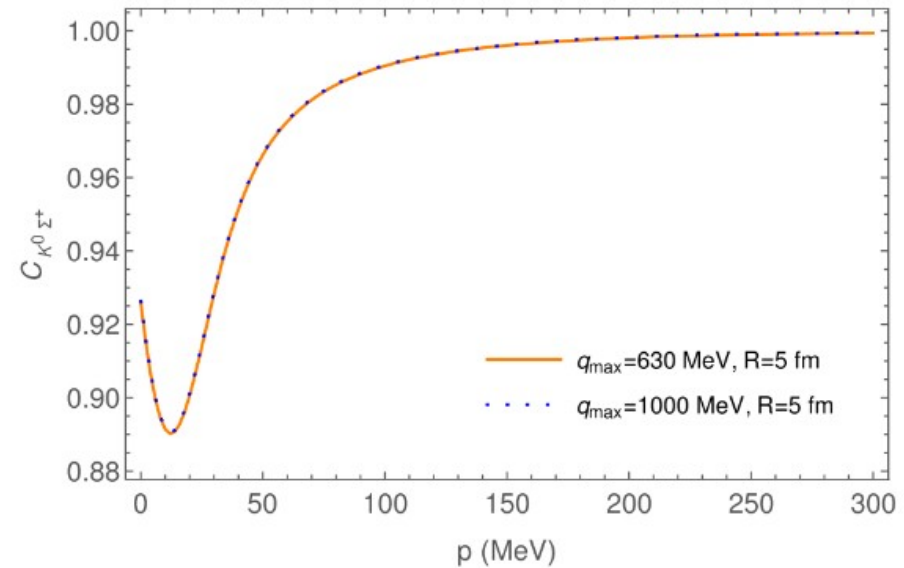


FIG. 5. Correlation function of the $k^0 \Sigma^+$ channel for $R = 5$ fm and different cutoffs.

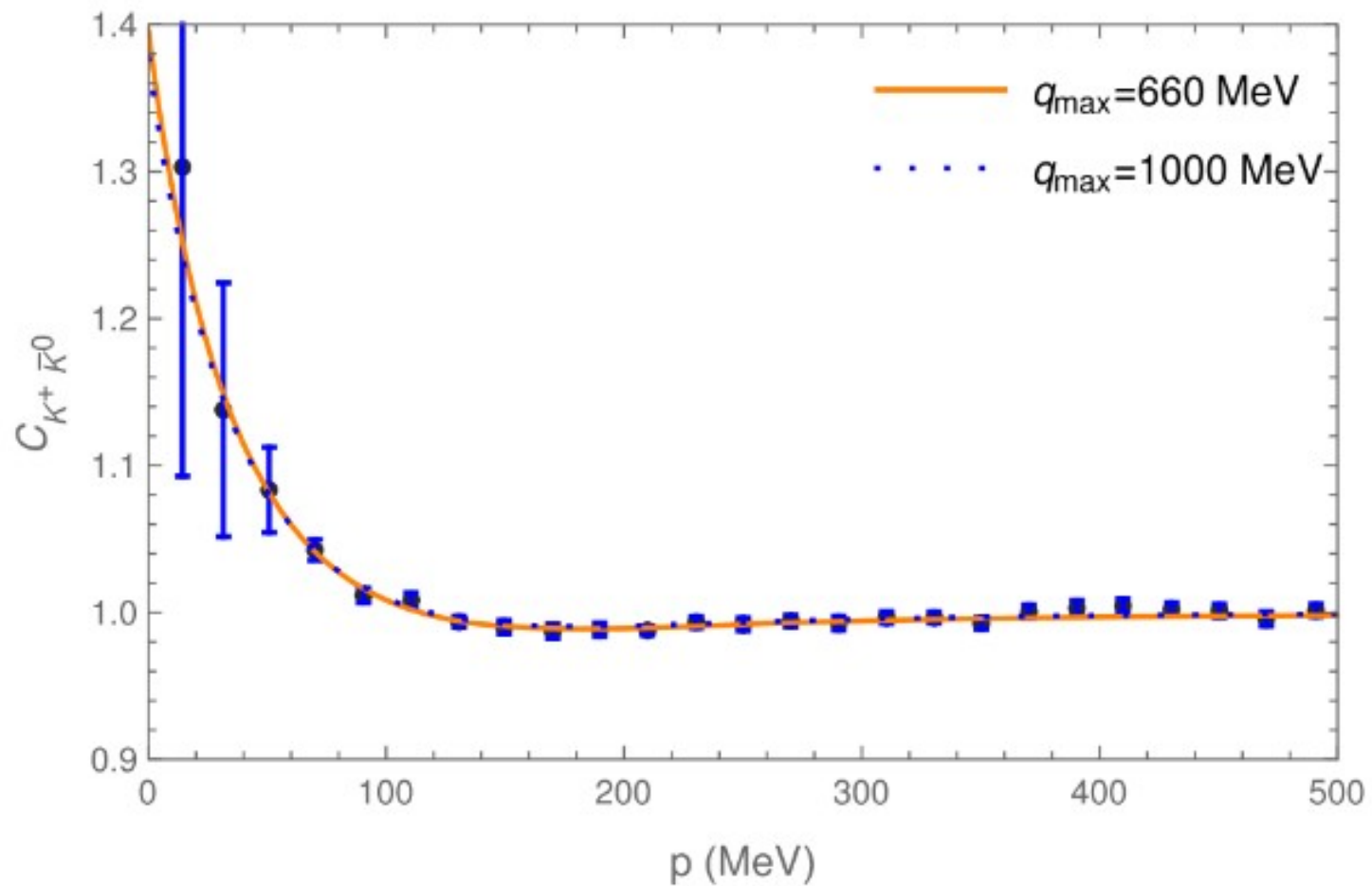


FIG. 6. Correlation function for Fit II in [23] for two different values of the cutoff in $\tilde{G}$.