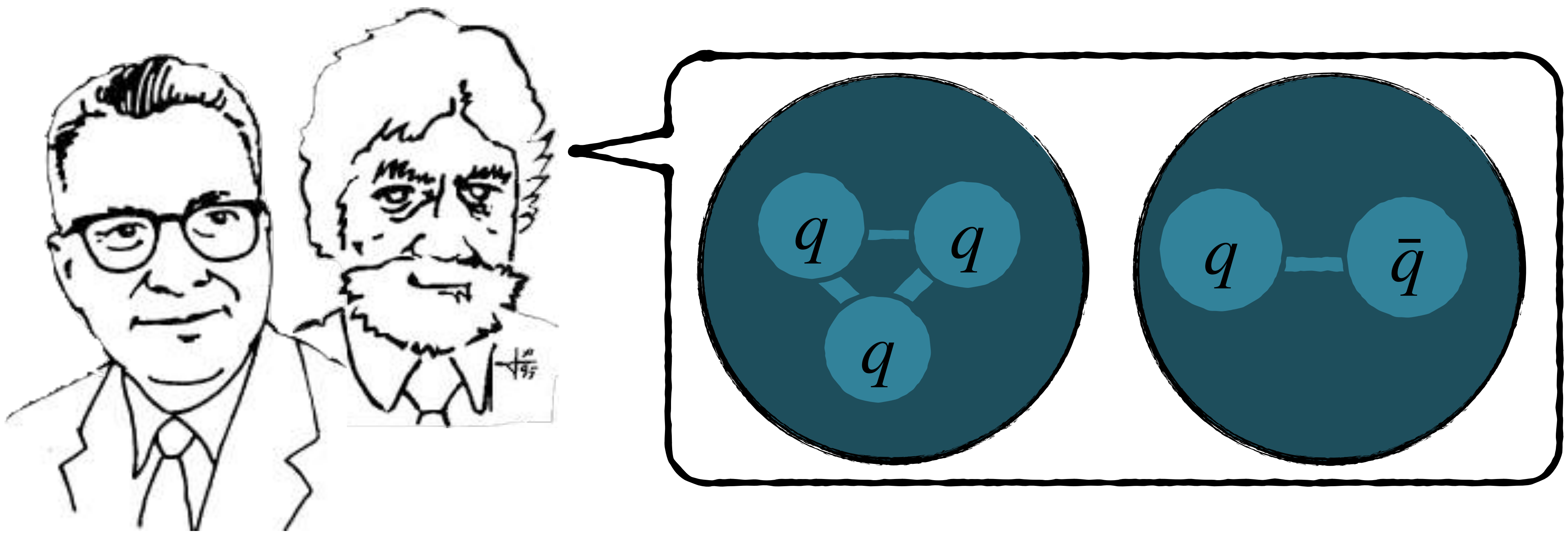
FORMATION OF EXOTIC HADRONS FROM TWO- AND THREE-BODY DYNAMICS

ALBERTO MARTÍNEZ TORRES (IFUSP)
KANCHAN KHEMCHANDANI (UNIFESP)
BRENDA BERTOTTO MALABARBA (IFUSP,PHD STUDENT)
NATHÁLIA MAYUME FUKASE (IFUSP,MASTER STUDENT)
BRENO AGATÃO GARCIA (IFUSP, PHD STUDENT)
ALONSO VERTEL NIETO (IFUSP, MASTER STUDENT)
RAFAELA COSTA TELES (IFUSP, IC STUDENT)
GUILHERME PERES DE ANDRADE (IFUSP, IC STUDENT)
AMANDA CRISTINA GAROFALO (UNIFESP-UFABC, IC STUDENT)
TAISA VELOSO (UNIFESP, MASTER STUDENT)

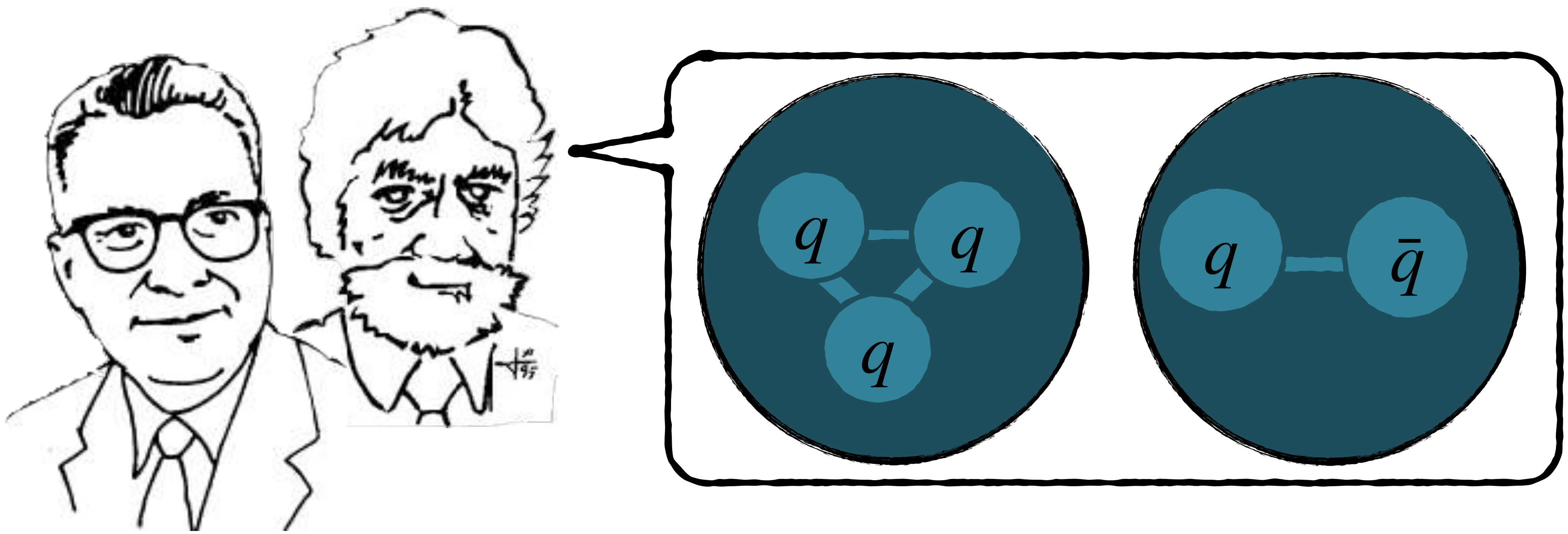
EXOTIC HADRONS

- Quark model of Gell-Mann and Zweig:



EXOTIC HADRONS

- Quark model of Gell-Mann and Zweig:



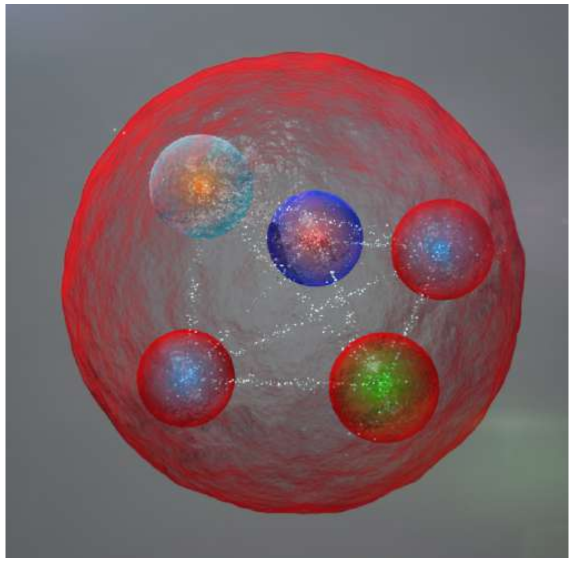
- Quantum Chromodynamics:

$$|M\rangle = \alpha|q\bar{q}\rangle + \beta|qq\bar{q}\bar{q}\rangle + \gamma|qqq\bar{q}\bar{q}\bar{q}\rangle + \eta|M_1M_2\rangle + \zeta|\mathbb{M}_1\mathbb{M}_2\mathbb{M}_3\rangle + \cdots$$

$$|B\rangle = \alpha|qqq\rangle + \beta|qqqq\bar{q}\rangle + \gamma|qqqqq\bar{q}\bar{q}\rangle + \eta|\mathrm{MB}\rangle + \zeta|\mathbb{M}_1\mathbb{M}_2\mathbb{B}\rangle + \cdots$$

EXOTIC HADRONS

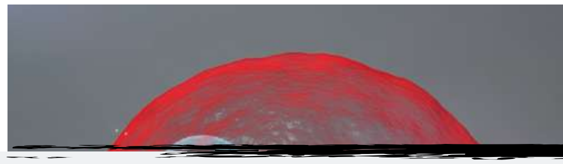
LHCb experiment discovers a new pentaquark



The analysis presented today at the Rencontres de Moriond quantum chromodynamics (QCD) conference (http://moriond.in2p3.fr/2019/QCD/) used nine times more data from the Large Hadron Collider (/science/accelerators/large-hadron-collider) than the 2015 analysis. The data set was first analysed in the same way as before and the parameters of the previously reported $P_c(4450)^+$ and $P_c(4380)^+$ structures were consistent with the original results. As well as revealing the new $P_c(4312)^+$ particle, the analysis also uncovered a more complex structure of $P_c(4450)^+$ consisting of two narrow overlapping peaks, $P_c(4440)^+$ and $P_c(4457)^+$, with the two-peak structure having a statistical significance of 5.4 sigma. More experimental and theoretical study is still needed to fully understand the internal structure of the observed states.

EXOTIC HADRONS

LHCb experiment discovers a new pentaquark



The analysis presented today at th
(http://moriond.in2p3.fr/2019/QCD
(/science/accelerators/large-hadro
way as before and the parameters
with the original results. As well as
complex structure of $P_c(4450)^+$ con
two-peak structure having a statist
needed to fully understand the inte

BES III- Highlight: Observation of the Zcs(3985) strange four-quark meson

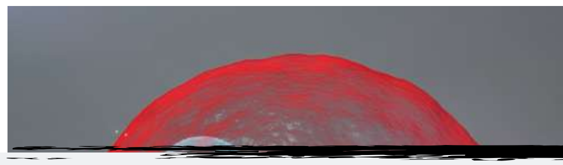
06/08/2021 | News | Created by BES III Experiment

The first hidden-charm tetraquark state with non-zero strangeness

In the March 12th, 2021 issue of Physical Review Letters, the BESIII collaboration reports the discovery of an exotic multi-quark structure, dubbed the Zcs(3985), that is produced in the process of $e^+e^- \to K^+ (D_s^- D^{*0} + D_s^{*-} D^0)$ at an e^+e^- center-of-mass energy of 4.68 GeV. The Zcs(3985) is observed to decay to a charged strange-charmed meson plus a neutral charmed meson, i.e., $D_s^- D^{*0} + D_s^{*-} D^0$, and has a mass of 3.98 GeV/c^2.
This is the first candidate for a tetra-quark meson containing hidden-charm with non-zero strangeness.

EXOTIC HADRONS

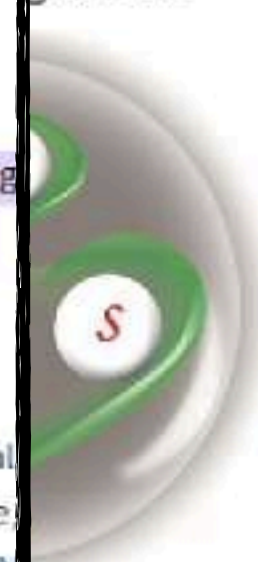
LHCb experiment discovers a new pentaquark



The analys
(http://mo
(/science/a
way as bef
with the or
complex st
two-peak s
needed to

...5) strange

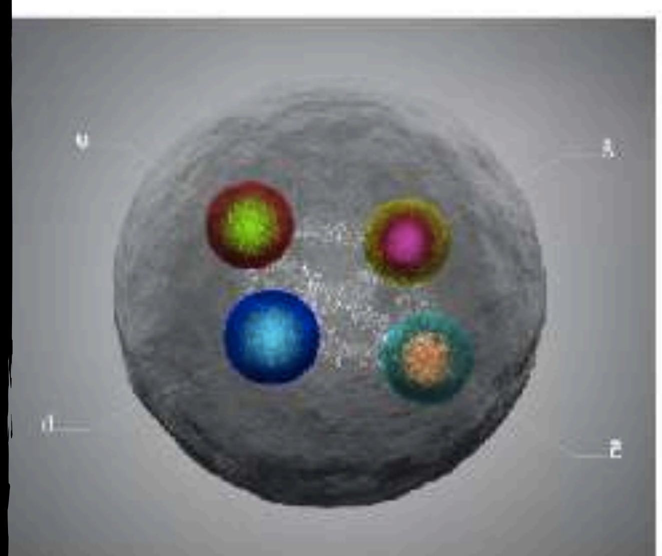
...geness



LHCb discovers first "open-charm" tetraquark

The particle, which has been called X(2900), was detected by analysing all the data LHCb has recorded so far from collisions at CERN's Large Hadron Collider

21 AUGUST, 2020 | By Achintya Rao



The LHCb experiment at CERN has developed a penchant for finding exotic combinations of quarks, the elementary particles that come together to give us composite particles such as the more familiar proton and neutron. In particular, LHCb has observed several tetraquarks, which, as the name suggests, are made of four quarks (or rather two quarks and two antiquarks). Observing these unusual particles helps scientists advance our knowledge of the strong force, one of the four known fundamental forces in the universe. At a CERN seminar held virtually on 11 August, LHCb announced the first signs of an entirely new kind of tetraquark with a mass of 2.9 GeV/c^2: the first such particle with only one charm quark.

EXOTIC HADRONS

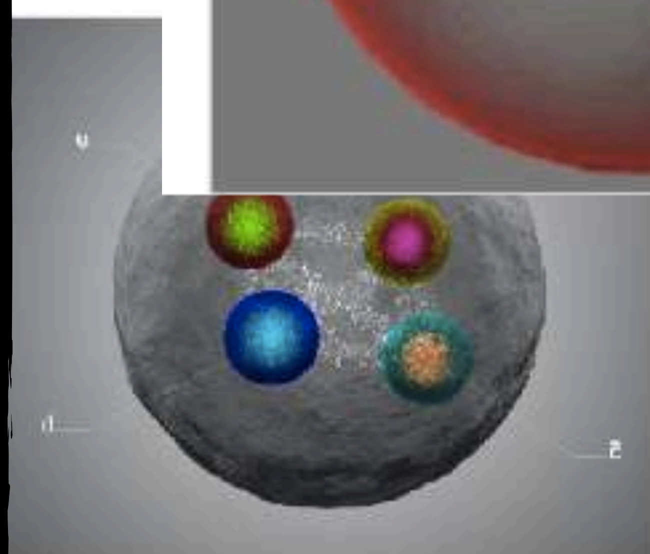
LHCb
penta

The analys
(http://mo
(/science/a
way as bef
with the o
complex st
two-peak s
needed to

LHC
tetr

The part
LHCb ha

21 AUGUS

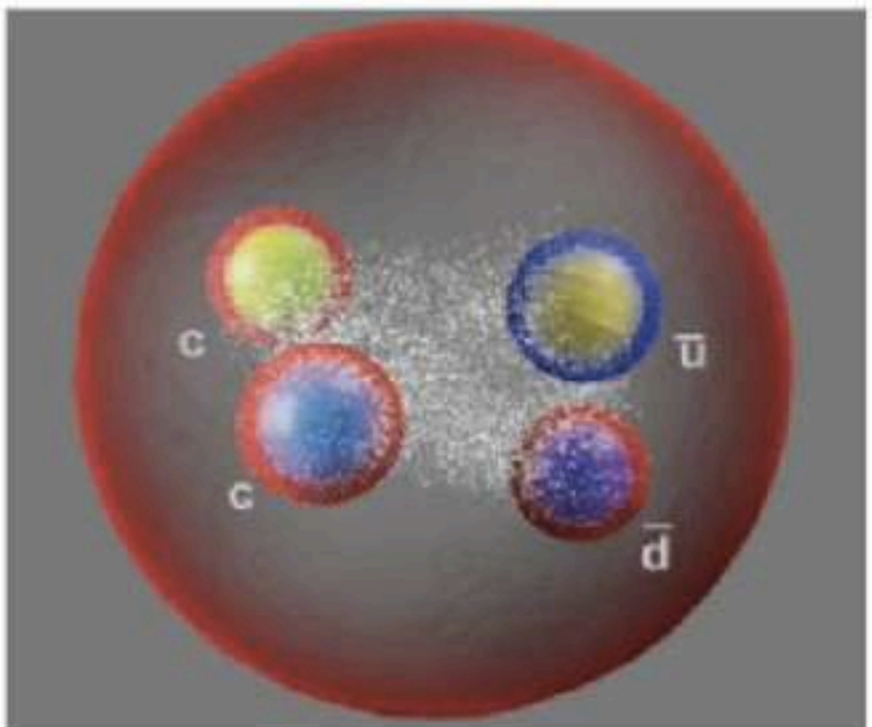


proton and neutron. In particular, LHCb has observed several tetraquarks, which, as the name suggests, are made of four quarks (or rather two quarks and two antiquarks). Observing these unusual particles helps scientists advance our knowledge of the strong force, one of the four known fundamental forces in the universe. At a CERN seminar held virtually on 11 August, LHCb announced the first signs of an entirely new kind of tetraquark with a mass of 2.9 GeV/c^2: the first such particle with only one charm quark.

CERNCOURIER | Reporting on international high-energy physics

New tetraquark a whisker away from stability

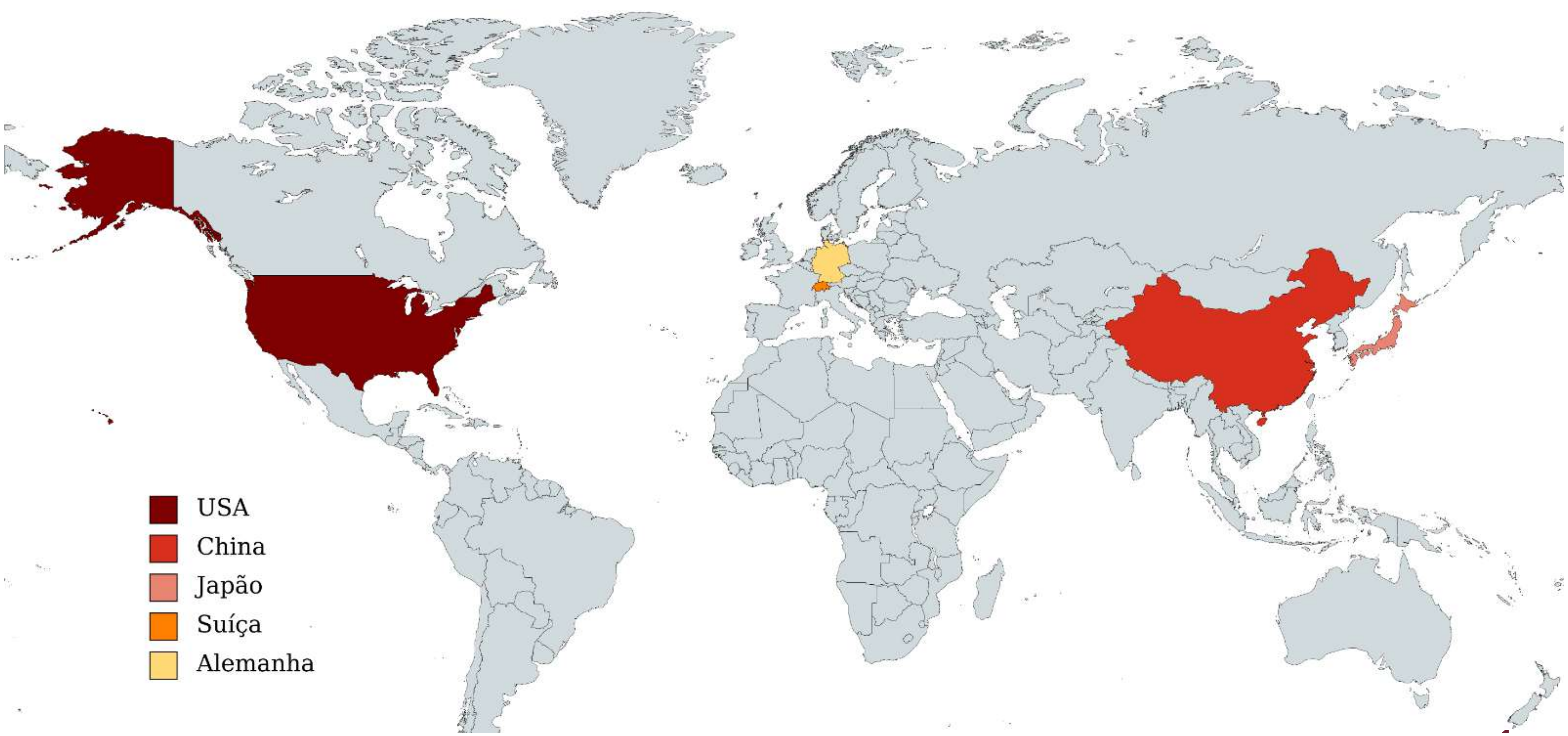
29 July 2021



All the exotic hadrons that have been observed so far decay rapidly via the strong interaction. The $cc\bar{u}\bar{d}$ tetraquark (T_{cc}^{+}) just discovered by the LHCb collaboration is no exception. However, it is the longest-lived state yet, and reinforces expectations that its beautiful cousin, $bb\bar{u}\bar{d}$, will be stable with respect to the strong interaction when its peak emerges in future data.

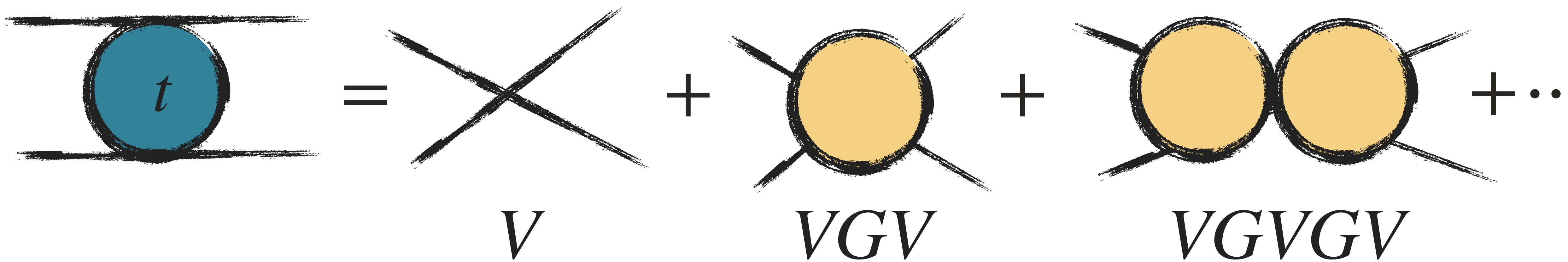
EXOTIC HADRONS

- Experimental facilities are bringing more information: LHCb ($p\bar{p}$, Switzerland), BES/BEPC (e^+e^-, China), JLAB (e^- accelerator, USA), JPARC (p accelerator, Japan), Belle (e^+e^-, Japan), LEP/Spring-8 ($e^-\gamma$, Japan), PANDA ($p\bar{p}$, Germany), new one in Novosibirsk (Russia).



EXOTIC HADRONS

- Resolution of the Bethe-Salpeter equation for two-hadron system: V obtained from an effective Lagrangian.



$$t = V + VGt = [1 - VG]^{-1}V$$

- The procedure can be generalized to a finite volume and lattice data can be analyzed.

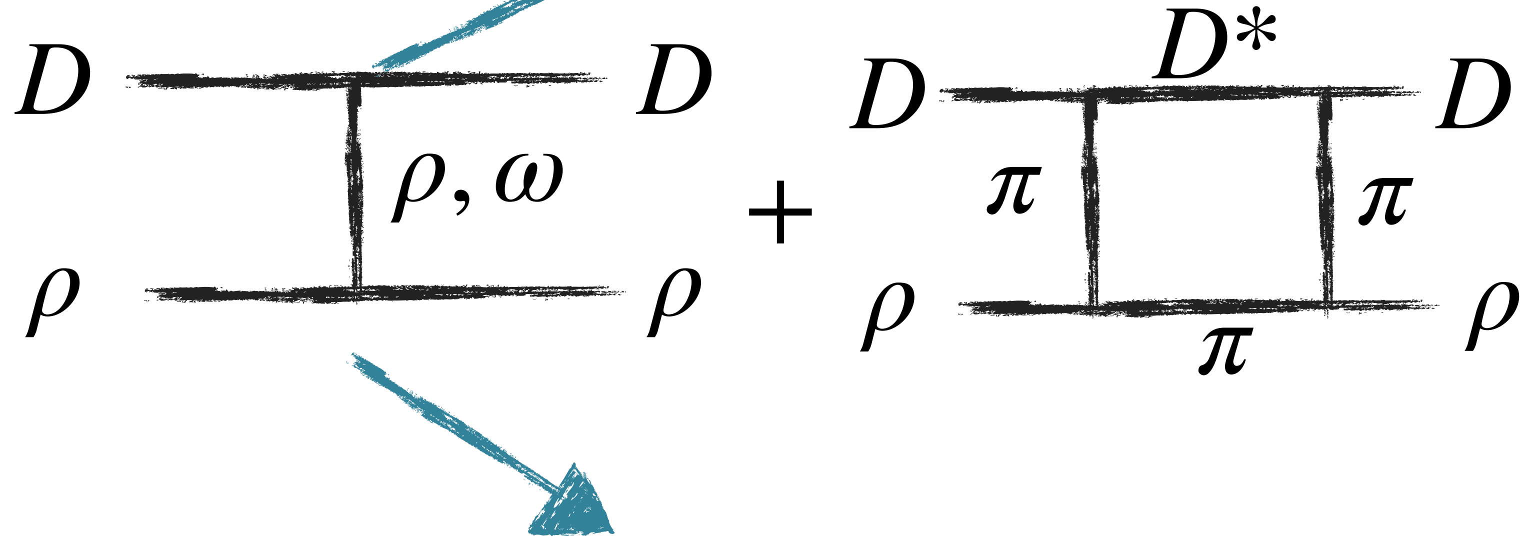
EXOTIC HADRONS

- Axial resonances with open charm

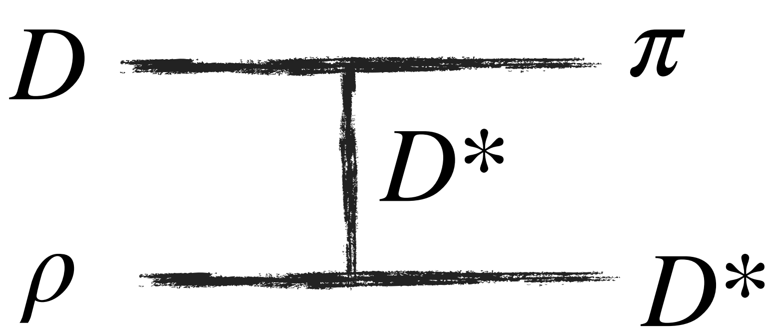
From $\mathscr{L}_{VPP} = -igV^{\mu}[\partial_{\mu}\Phi, \Phi]$,

V^{μ} $\equiv$ **Matrix vector meson octet fields**

Φ $\equiv$ **Matrix pseudoscalar meson octet fields**



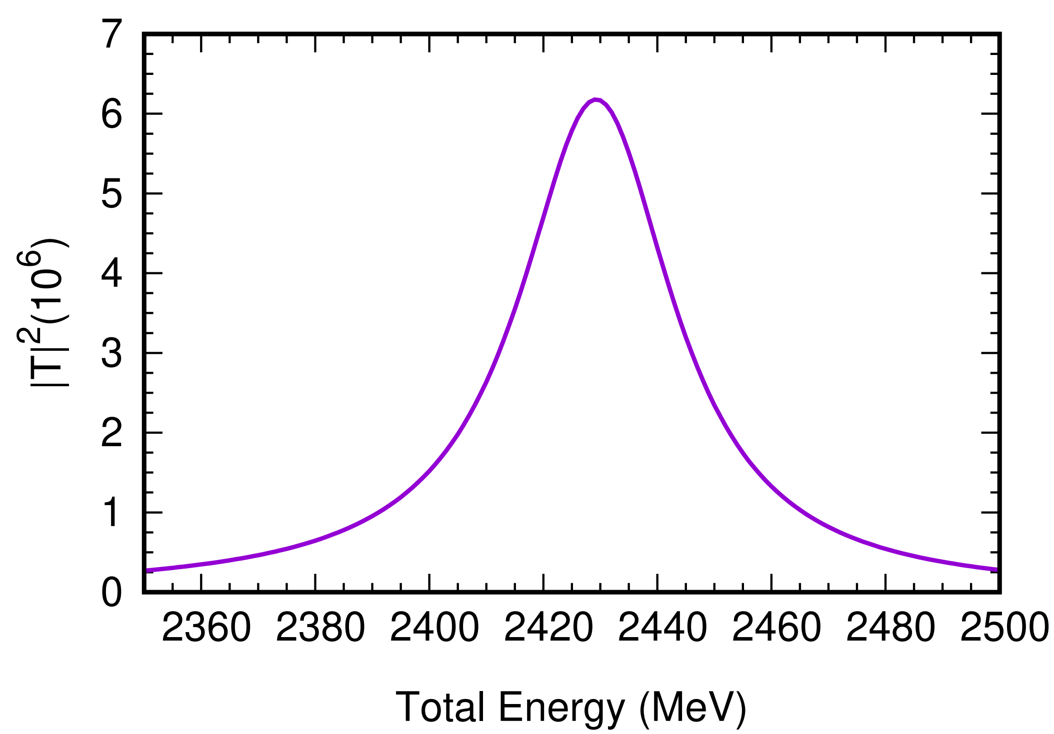
$$\mathscr{L}_{VVV} = ig\langle(\partial_{\mu}V_{\nu} - \partial_{\nu}V_{\mu})V^{\mu}V^{\nu}\rangle$$



$D_1(2420)$:

$M \simeq 2428$ MeV,

$\Gamma \simeq 33$ MeV

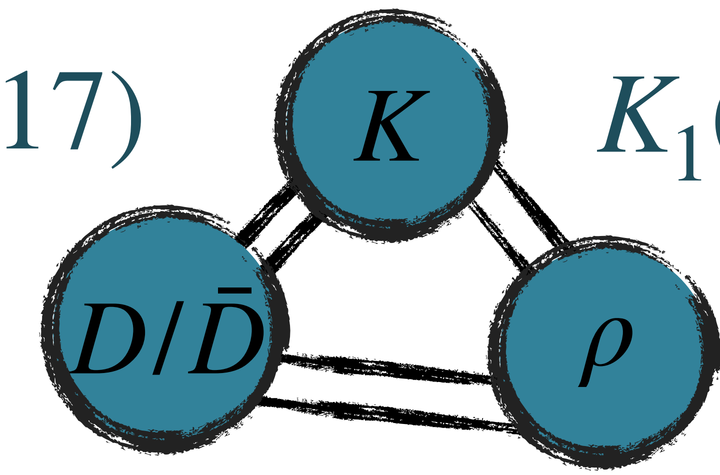


Brenda B. Malabarba, K. P. Khemchandani, A. Martínez Torres, E. Oset, Phys. Rev. D107, 036016 (2023).

EXOTIC HADRONS

- What happens if we add one more hadron

$D^*_{s0}(2317)$ $K_1(1270)$



$D_1(2420)$

$K\rho\bar{D}, K\pi\bar{D}^*, \cdots$

LHCb: D^-K^+ invariant mass

$X_0(2900)\ (J^P = 0^+) : \bar{D}^*K,$

$X_1(2900)\ (J^P = 1^-) :?$

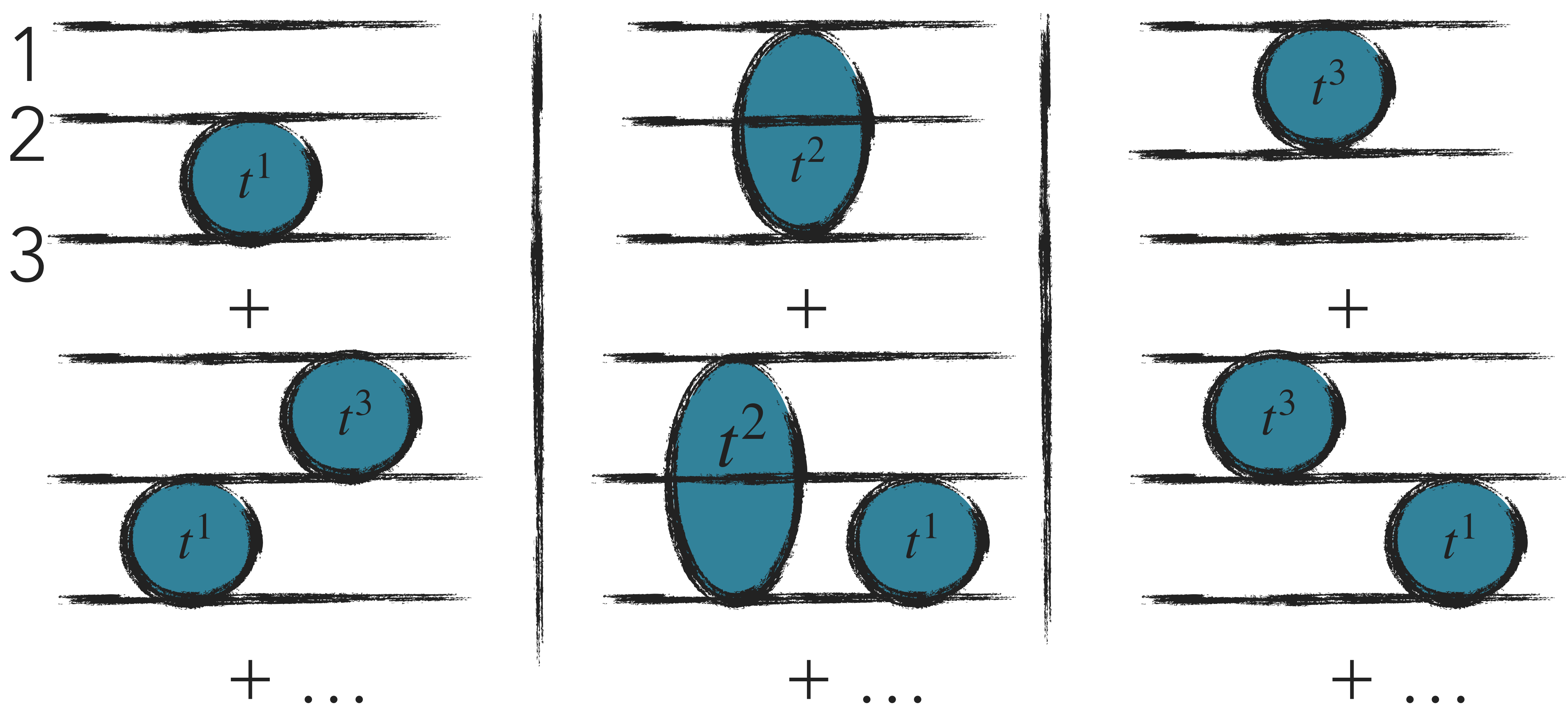
We can form three-hadron resonances/bound state $\Longrightarrow$ Faddeev equations

A. Martínez Torres, E. Oset, S. Prelovsek, A. Ramos, JHEP 05, 153 (2015); L. S. Geng, E. Oset, L. Roca, J. A. Oller, Phys. Rev. D75, 014017 (2007); Brenda B. Malabarba, K. P. Khemchandani, A. Martínez Torres, E. Oset, Phys. Rev. D107, 036016 (2023).

EXOTIC HADRONS

- Resolution of the Faddeev equations for a three-hadron system:

$$T^1 = t^1 + t^1 G[T^2 + T^3]$$
$$T^2 = t^2 + t^2 G[T^1 + T^3]$$
$$T^3 = t^3 + t^3 G[T^1 + T^2]$$

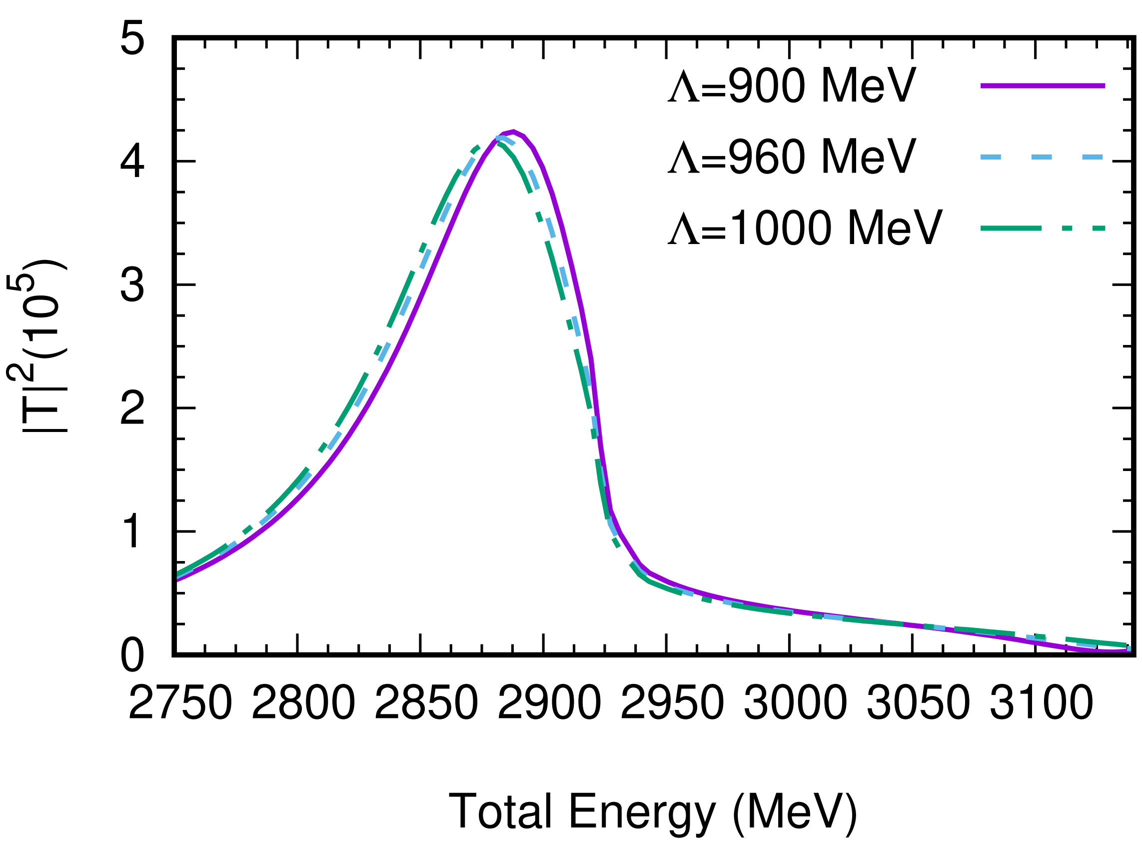


EXOTIC HADRONS

- Open charm states with strangeness:

$K\rho\bar{D} \Longrightarrow X_1$ states with masses $\simeq 3100$ MeV

$K\rho D$: It should be more attractive



BABAR [PRL97, 222001 (2006)]
LHCb [PRL113,162001(2014)] :

$D^*_{s1}(2860)$: $B^0_s \to \bar{D}^0 K^- \pi^+$

$I(J^P) = 0\,(1^-)$

$M = 2859 \pm 27$ MeV

$\Gamma = 159 \pm 80$ MeV

$M \simeq 2872$ MeV $\quad \Gamma \simeq 100$ MeV

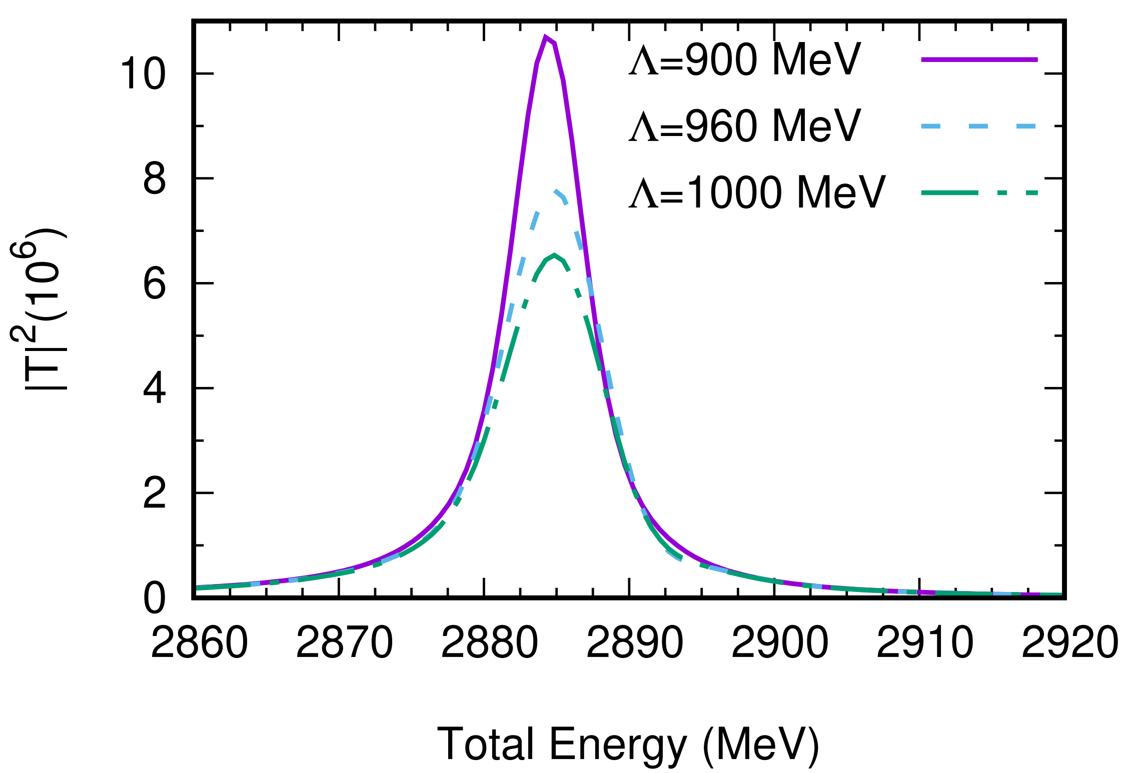
Brenda B. Malabarba, K. P. Khemchandani, A. Martínez Torres, E. Oset, Phys. Rev. D107, 036016 (2023).

EXOTIC HADRONS

- Open charm states with strangeness:

  $K\rho\bar{D} \Longrightarrow X_1$ states with masses $\simeq 3100$ MeV

  $K\rho D$: It should be more attractive



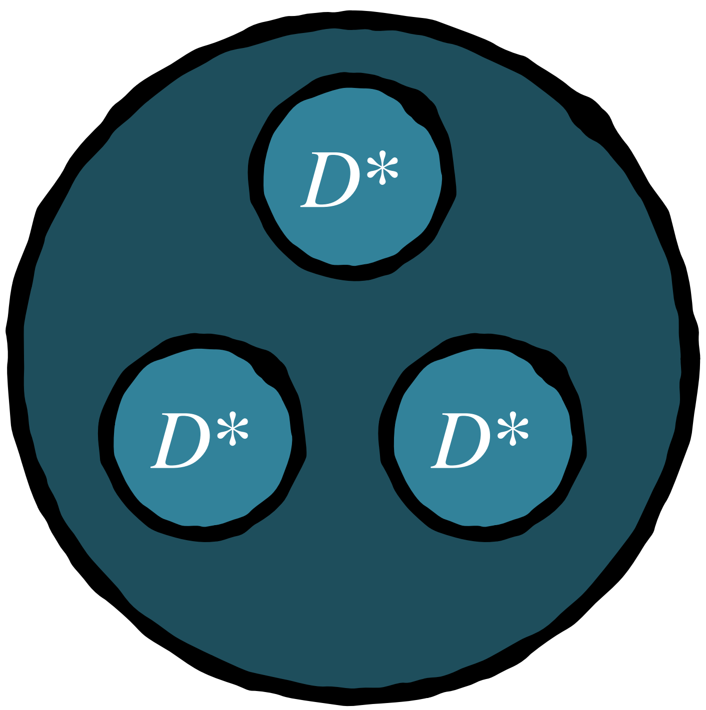
$$I(J^P) = 1\,(1^-)$$

$M \simeq 2883$ MeV $\quad \Gamma \simeq 8$ MeV

Brenda B. Malabarba, K. P. Khemchandani, A. Martínez Torres, E. Oset, Phys. Rev. D107, 036016 (2023).

EXOTIC HADRONS

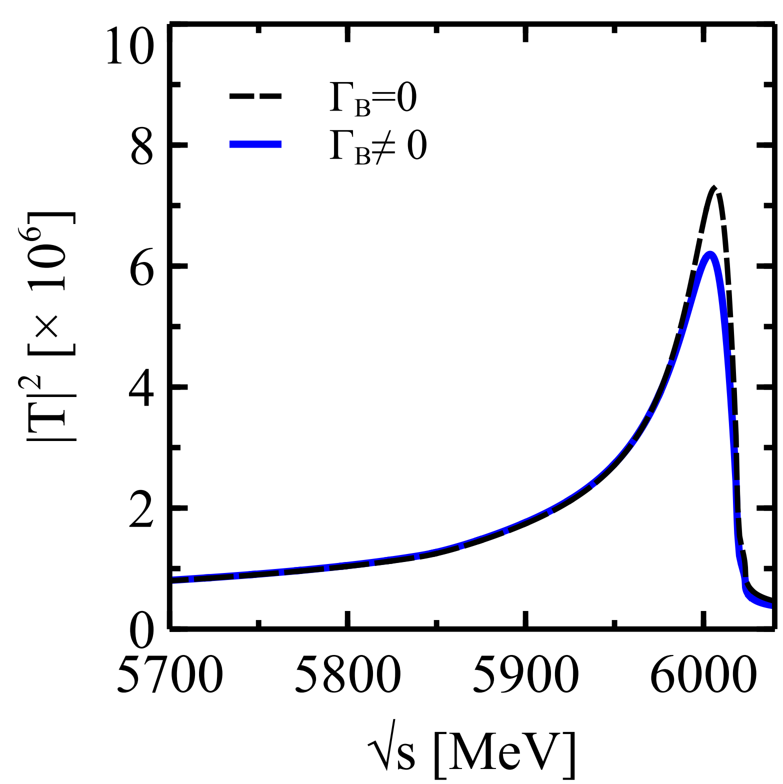
- What about states with triple charm?



LHCb: T_{cc}, Nature Phys. 18, 751-754 (2022); Nature Commun. 13, 3351 (2022).

T_{cc} : DD^* state decaying into $DD\pi$
$\Longrightarrow D^*DD^*, D^*D^*D^*$.

D^*D^*: attractive in $I=0, J^P=1^+$ [L. R. Dai, R. Molina, E. Oset, Phys. Rev. D105,016029 (2022)]



$I(J^P) = 1/2\,(0^-)$

$M \simeq 6007$ MeV

$\Gamma \simeq 47$ MeV

M. Bayar, A. Martínez Torres, K. P. Khemchandani, R. Molina, E. Oset, Our. Phys. J. C83, 46 (2023).

EXOTIC HADRONS

- $\phi(2170)$: observed by different collaborations (2006-2020) in processes like $e^+e^- \to K^+K^-\pi^{+(0)}\pi^{-(0)}, J/\psi \to \eta K^+K^-\pi^+\pi^-, e^+e^- \to \phi\eta'$ (PDG: $M = 2160 \pm 80$ MeV, $\Gamma = 125 \pm 65$ MeV)

- Different theoretical models trying to explain its nature and properties:

$s\bar{s}\,(n^{2S+1}L_J = 3^3S_1) \implies \Gamma \sim 300$ MeV;

$s\bar{s}\,(2^3D_1) \implies \Gamma_{K^*(892)\bar{K}^*(892)}, \Gamma_{K^*(1410)\bar{K}} > \Gamma_{K(1460)\bar{K}}, \Gamma_{K_1(1400)\bar{K}}, \Gamma_{K_1(1270)\bar{K}}.$

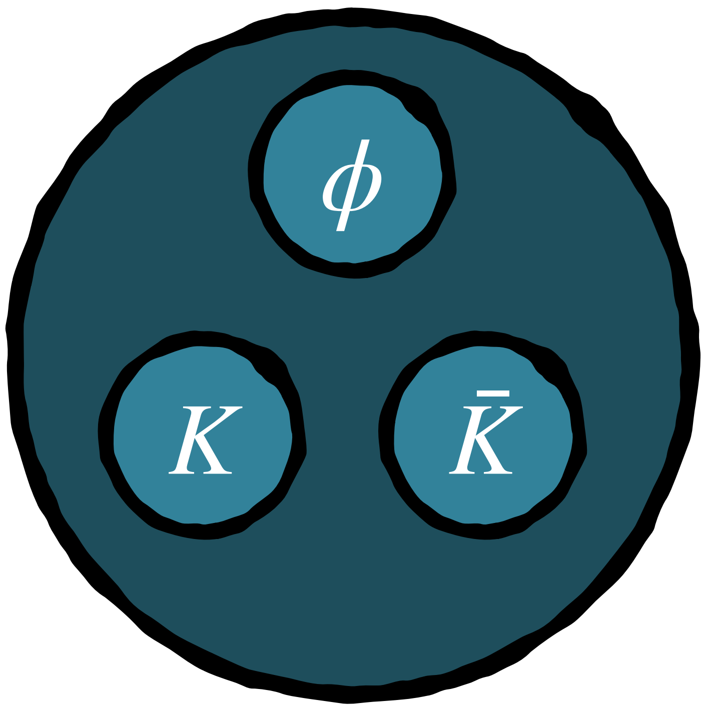
$s\bar{s}g \implies \Gamma_{K^*(1410)\bar{K}} \gtrsim \Gamma_{K_1(1270)\bar{K}}$, Mode $K(1460)\bar{K}$ forbidden.
Not supported by Lattice QCD and QCD Gaussian sum rules.

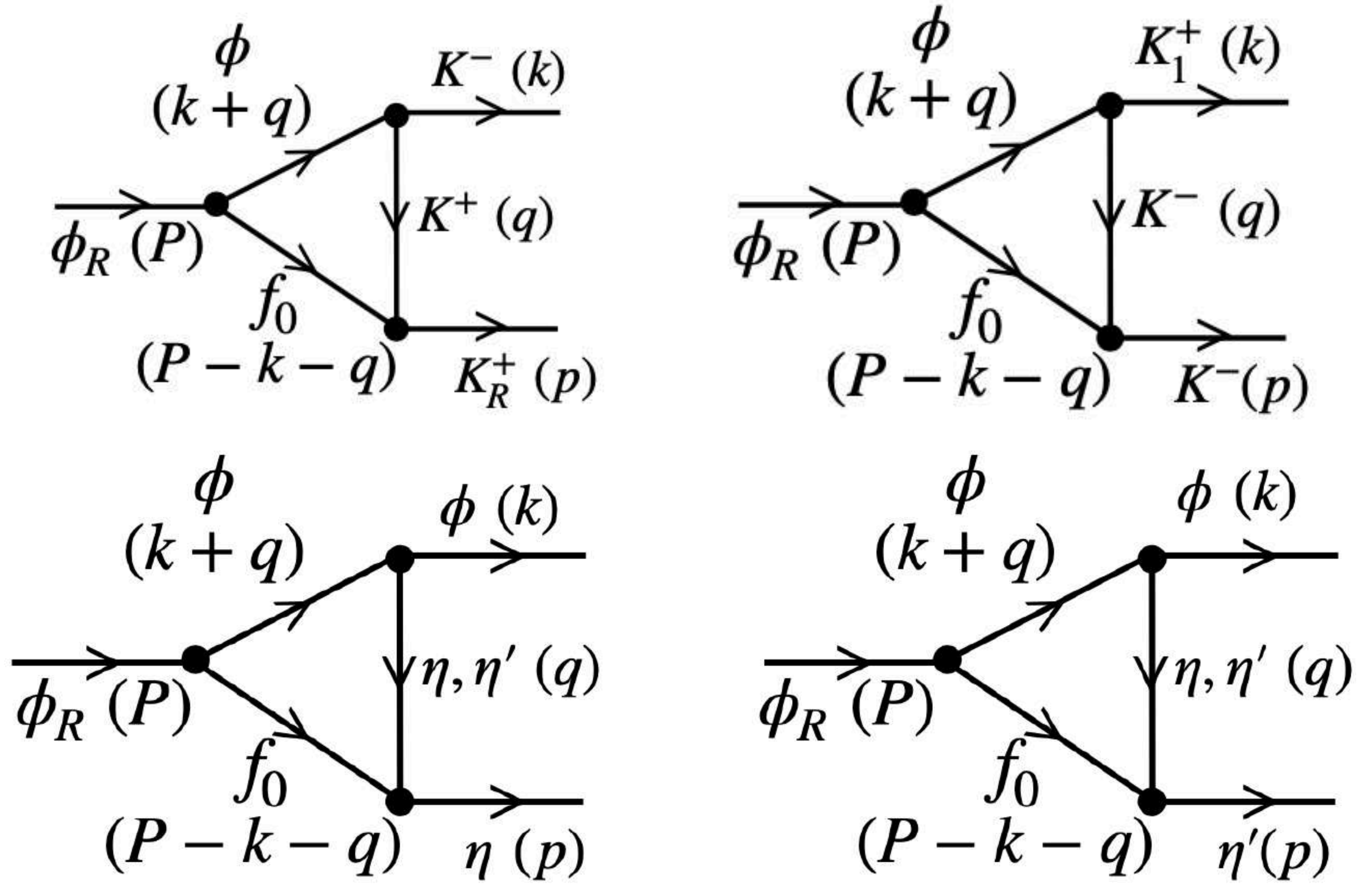
Tetraquark $\implies$ Difficulties in obtaining a compatible mass.

BESIII collaboration (Phys. Rev. Lett. 124, 112001 (2020); Phys. Rev. D104, 032007 (2021): $K^+(1460)K^-$, $K_1^+(1400)K^-$, $K^{*+}(1410)K^-$, $K_1^+(1270)K^-$, $K^{*+}(892)K^{*-}(892)$, $\phi\eta, \phi\eta'$

Brenda B. Malabarba, K. P. Khemchandani, A. Martínez Torres, Phys. Rev. D108, 036010 (2023).

EXOTIC HADRONS





$$f_0(980) : \pi\pi, K\bar{K}, \eta\eta, \eta\eta', \eta'\eta'$$
$$K_1(1270) : K\rho, K^*\pi, \ldots$$
$$K(1460) : KK\bar{K}, K\pi\pi$$

J. A. Oller, E. Oset, Nucl. Phys. A 620, 438-456 (1997); L. S. Geng, E. Oset, L. Roca, Phys. Rev. D75, 014017 (2007); A. Martínez Torres, D. Jido, Y. Kanada-En'yo, Phys. Rev. C83, 065205 (2011); X. Zhang, C. Hanhart, U. G. Meissner, Ju-Jun Xie, Eur. Phys. J. A58,20 (2022); I. Filikhin et al, Phys. Rev. D, 094027 (2020).

Brenda B. Malabarba, K. P. Khemchandani, A. Martínez Torres, Phys. Rev. D108, 036010 (2023).

EXOTIC HADRONS

- Correlation functions of two hadrons: femtoscopy

Prob. two particle state/Π_iProb. indiv.part

$$C(k) = \int d^3r S_{12}(\vec{r}) |\Psi(\vec{k};\vec{r})|^2$$

It can be written in terms of the two-body t-matrix

$\vec{k}, \vec{r}$: Relative linear momentum/position;

S_{12} : Normalized emission source function (probability distribution of the relative distance of the two particles)

$\Longrightarrow$ Typically a Gaussian.

Ψ : Wave function of the two-particle system

Brenda B. Malabarba, K. P. Khemchandani, A. Martínez Torres, Phys. Rev. D108, 036010 (2023).

EXOTIC HADRONS

- Correlation functions of two hadrons: femtoscopy

Prob. two particle state/Π_iProb. indiv.part

$$C_i(k) \ = \ 1 + 4\pi\theta(q_{max} - k) \int_0^\infty drr^2 S_{12}(\vec{r}) \left(\sum_j w_j |j_0(kr)\delta_{ji} + T_{ji}(\sqrt{s})\widetilde{G}_j(r;s)|^2 - j_0^2(kr) \right)$$

$$\widetilde{G}_j(r;s) \ = \ \int_{|\vec{q}|<q_{max}} \frac{d^3q}{(2\pi)^3} \frac{\omega_1^{(j)} + \omega_2^{(j)}}{2\omega_1^{(j)}\omega_2^{(j)}} \frac{j_0(qr)}{s - \left(\omega_1^{(j)} + \omega_2^{(j)}\right)^2 + i\varepsilon}$$

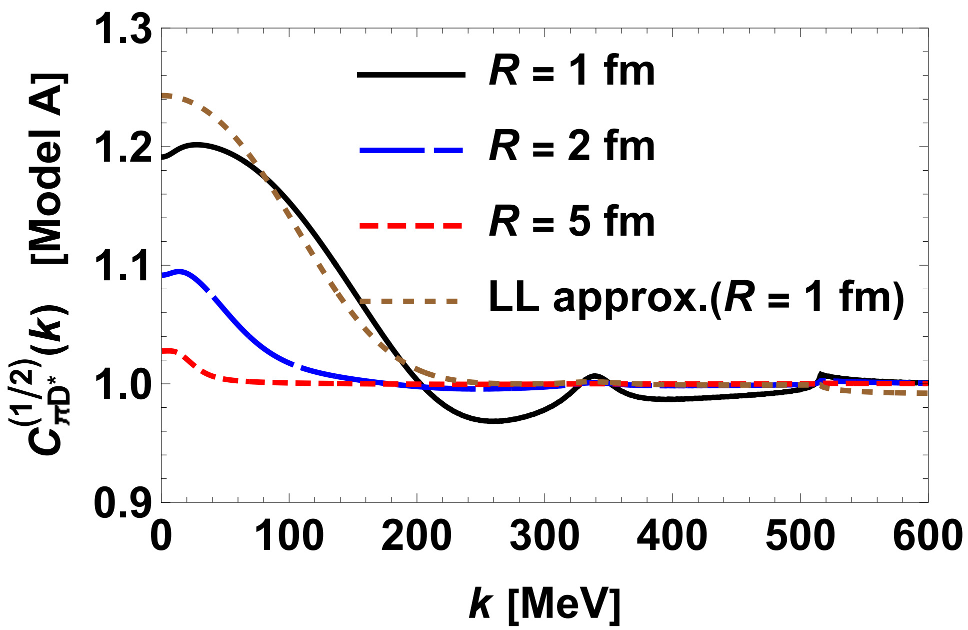
- Lednicky-Lyuboshits approximation: wave function is replaced by its non-relativistic, asymptotic behavior

The correlation function depends on a and R

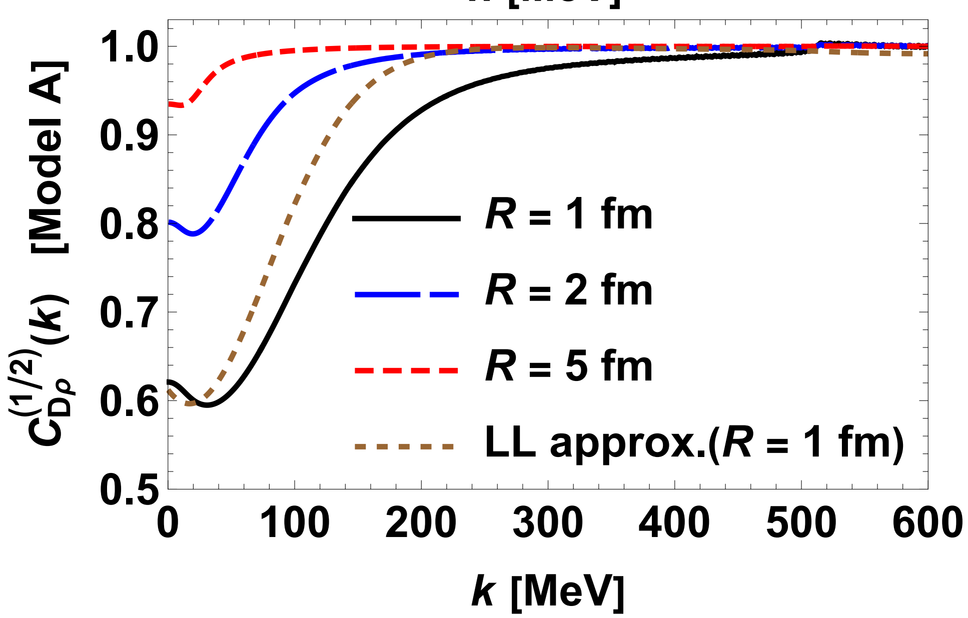
Brenda B. Malabarba, K. P. Khemchandani, A. Martínez Torres, Phys. Rev. D108, 036010 (2023).

EXOTIC HADRONS

- Correlation functions of two hadrons: femtoscopy



Enhancement at threshold: attractive character of this channel; Minimum at $k \simeq 250$ MeV due to a broad D_1



Dip close to threshold: presence of $D_1(2420)$

The ALICE collaboration has measured $D^{*+}\pi^{\mp}$ correlation functions less than 1 month ago: 2401.13541 [nucl-ex]!

K. P. Khemchandani, Luciano M. Abreu, A. Martínez Torres, F. S. Navarra, arXiv 2312.11811 (accepted in Phys. Rev. D)

EXOTIC HADRONS

- Leading Λ production in ep collisions: information about the proton structure (meson cloud)

$$|p\rangle \sim |\pi^+ n\rangle, |K^+\Lambda\rangle$$

$\Longrightarrow$ Virtual photon can be used to probe the meson structure

F. Carvalho, K. P. Khemchandani, V. P. Gonçalves, F. S. Navarra, D. S. Spiering, A. Martínez Torres, Phys. Rev. D 108, 094034 (2023).