USING HADRONS AS EFFECTIVE FIELDS TO DECIPHER EXPERIMENTAL DATA

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DAVI MARQUES GONÇALVES (UNIFESP, IC STUDENT)

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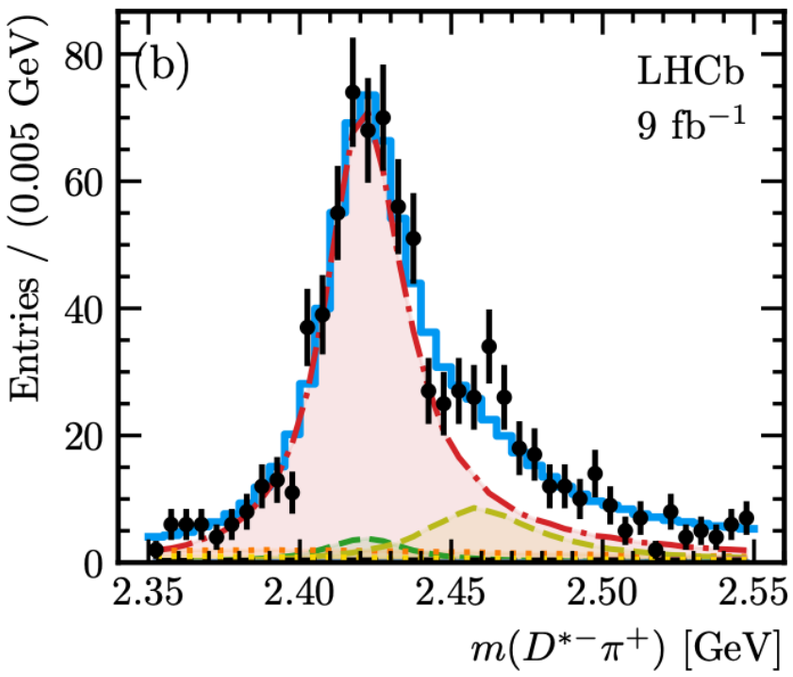
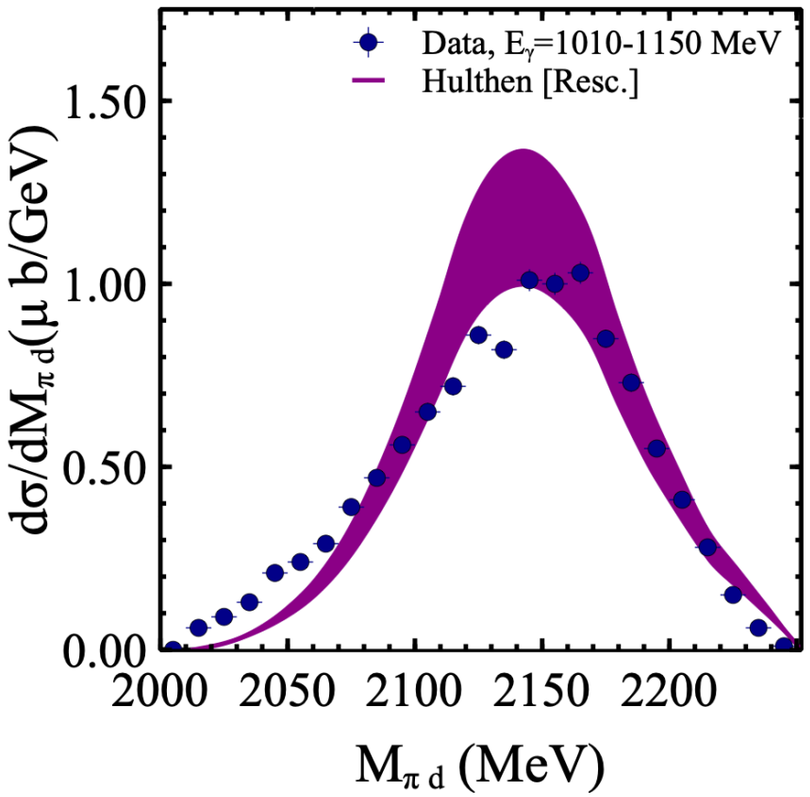
$B^+ \to D_s^+ D^{*+} \pi^-$ (R.Aaij et al. (LHCb), JHEP08,165 (2024)): $D_1(2420)$



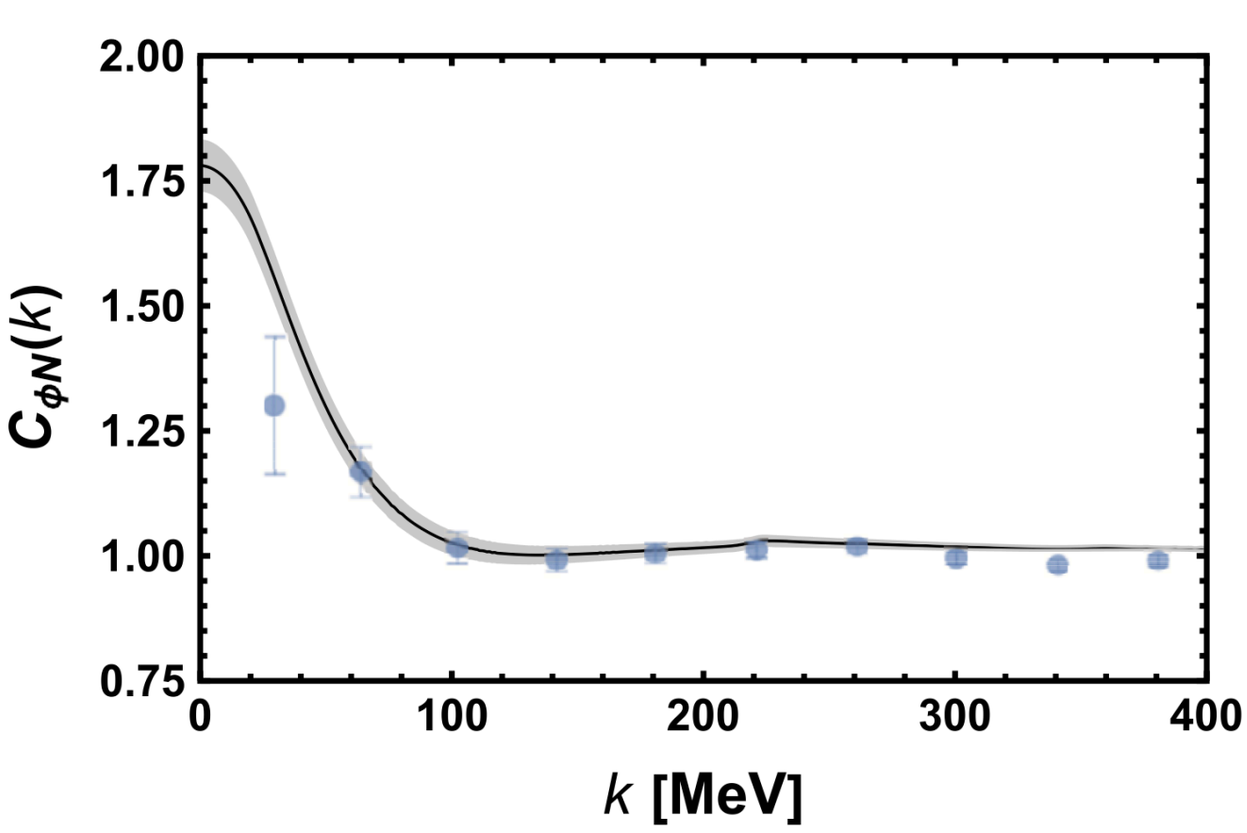
$\gamma d \to \pi^0 \eta d$

[Phys. Rev. C105, 045201 (2022)]: dibaryons



ϕN attraction from pp collisions at $\sqrt{s} = 13$ TeV.

[S. Acharya et al. (ALICE), Phys. Rev. Lett. 127, 172301 (2021)]



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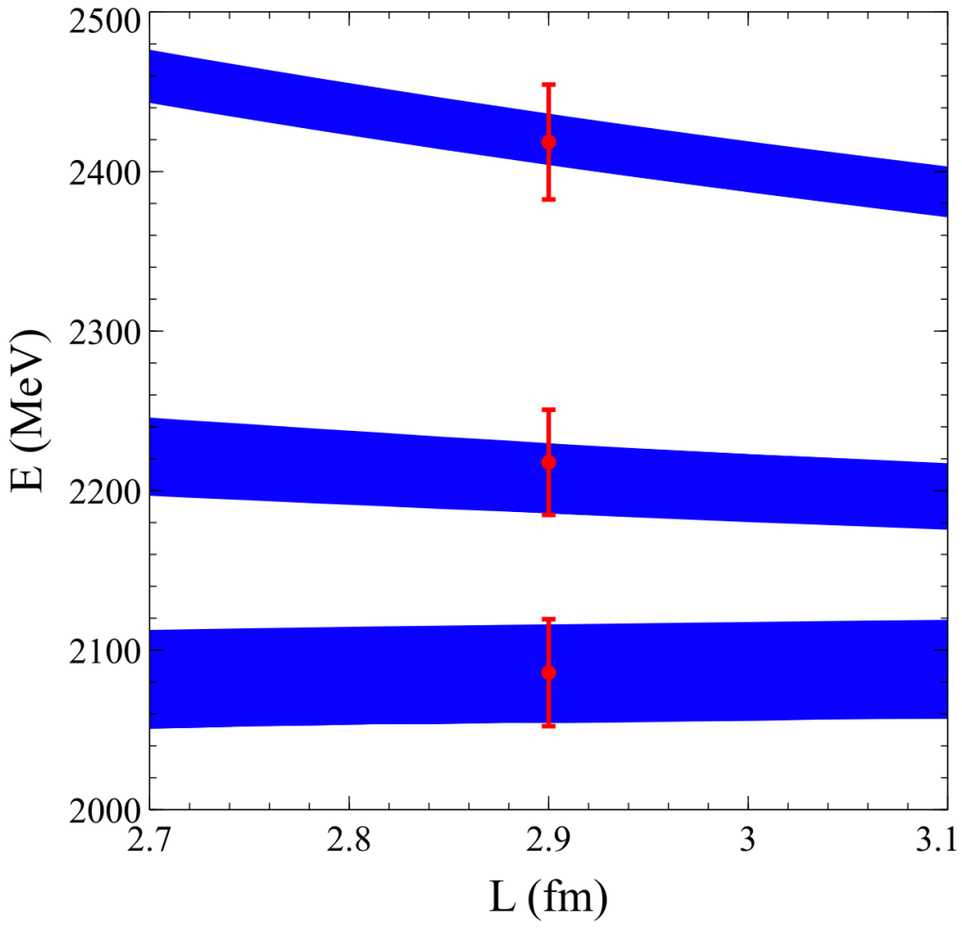

D-meson-Kaon scattering from Lattice QCD [Mohler, Lang, Leskober, Prelovsek, Phys. Rev. Lett. 111, 222001 (2013)]: $D_{s0}^{*}(2317)$

$e^+e^- \to K_R\bar{K}$ [BESIII, Phys. Rev. Lett. 104, 032007 (2021)]: $\phi(2170)$

$$B_1 = \frac{\Gamma_{\phi_R \to K^+(1460)K^-}}{\Gamma_{\phi_R \to K_1^+(1400)K^-}}$$

$$B_2 = \frac{\Gamma_{\phi_R \to K^+(1460)K^-}}{\Gamma_{\phi_R \to K_1^+(1270)K^-}}$$

$$B_3 = \frac{\Gamma_{\phi_R \to K^+(1270)K^-}}{\Gamma_{\phi_R \to K_1^+(1400)K^-}}$$

$$\left[B_1^{\rm exp} = \begin{cases} 0.64 \pm 0.92, \ \text{Solution 1}, \\ 0.03 \pm 0.04, \ \text{Solution 2}, \end{cases} \right.$$

$$B_2^{\rm exp} = \begin{cases} 0.40 \pm 0.54, \ \text{Solution 1}, \\ 0.02 \pm 0.03, \ \text{Solution 2}, \end{cases}$$

$$\left. B_3^{\rm exp} = \begin{cases} 1.62 \pm 1.38, \ \text{Solution 1}, \\ 1.55 \pm 0.19, \ \text{Solution 2}. \end{cases} \right]$$

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Quantum Chromodynamics:

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

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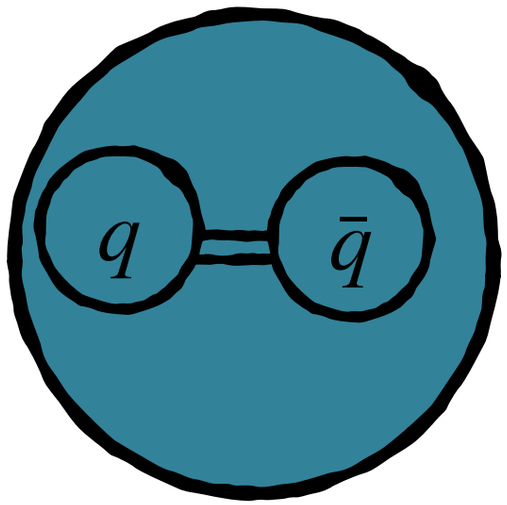
MESONS:



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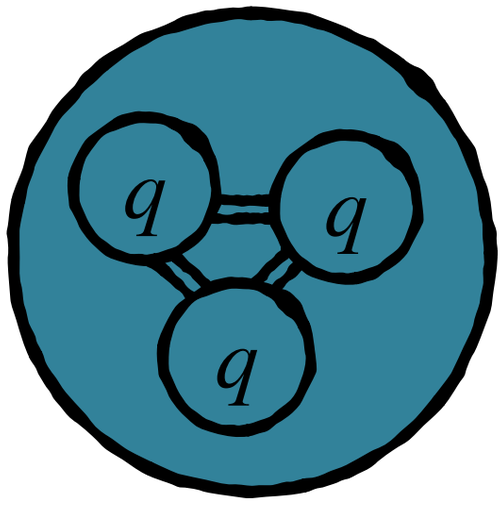

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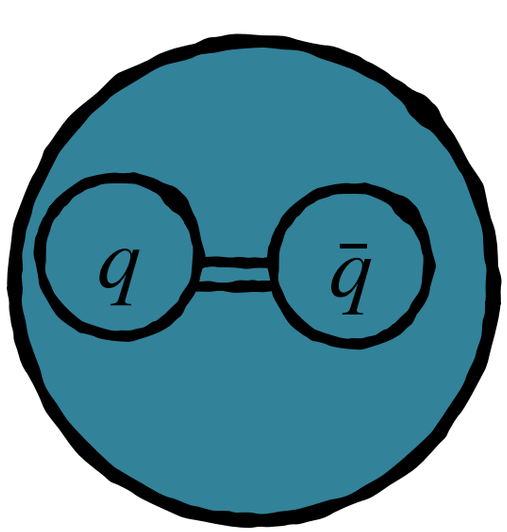

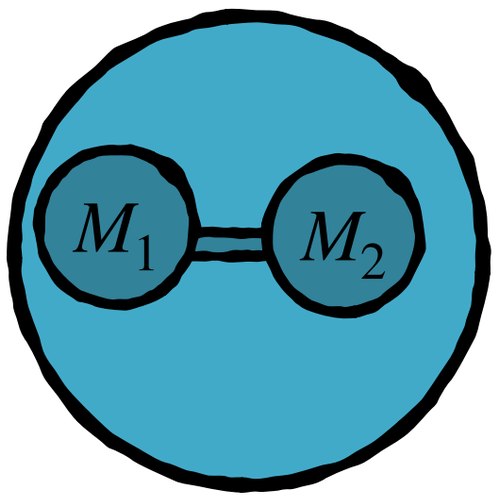

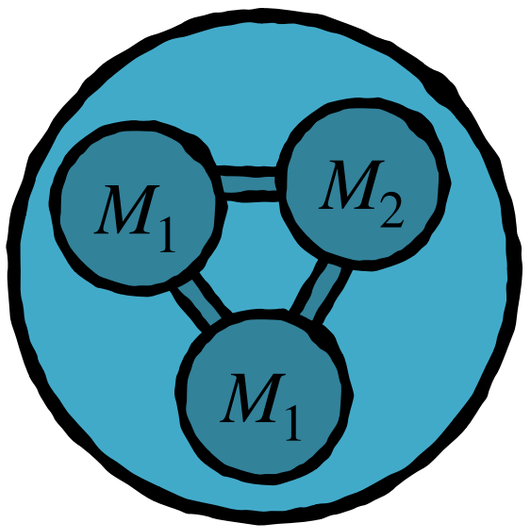

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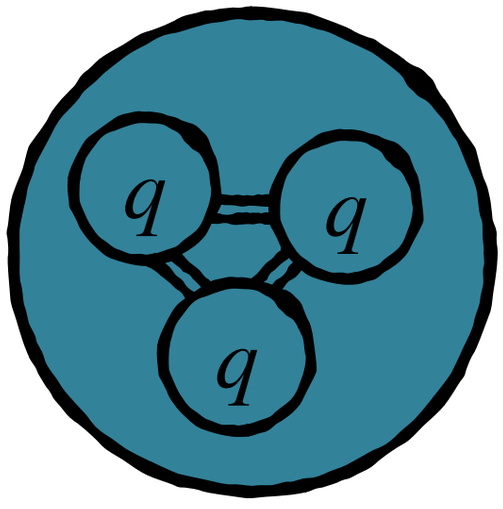

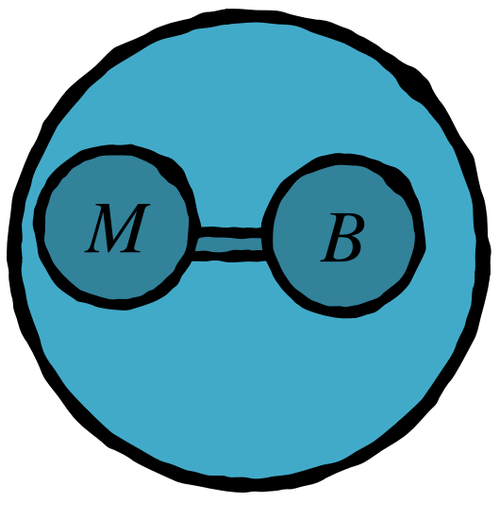

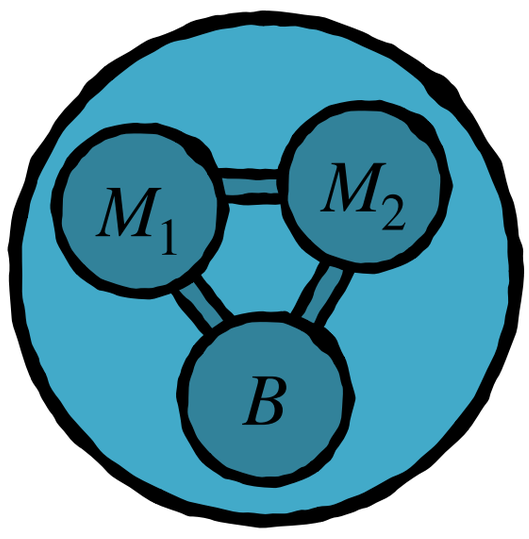

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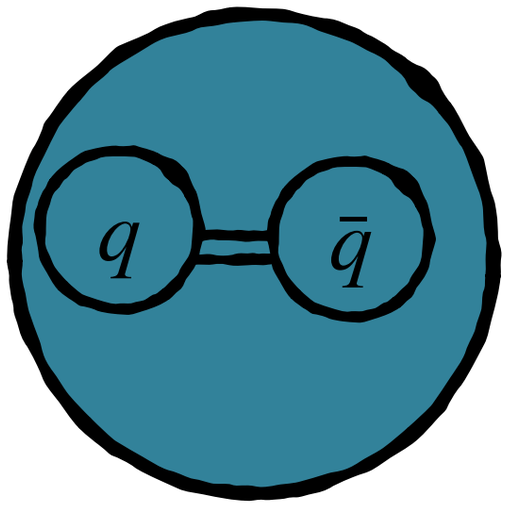

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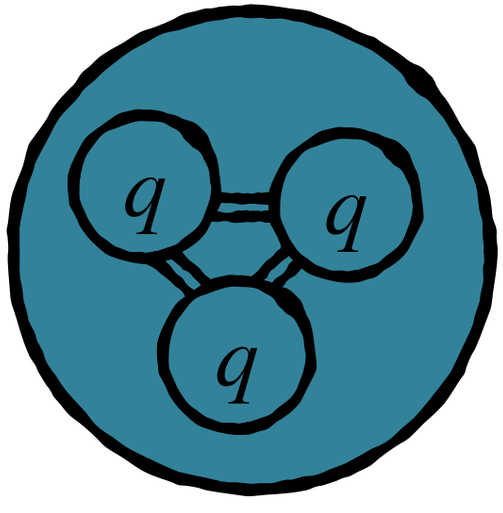

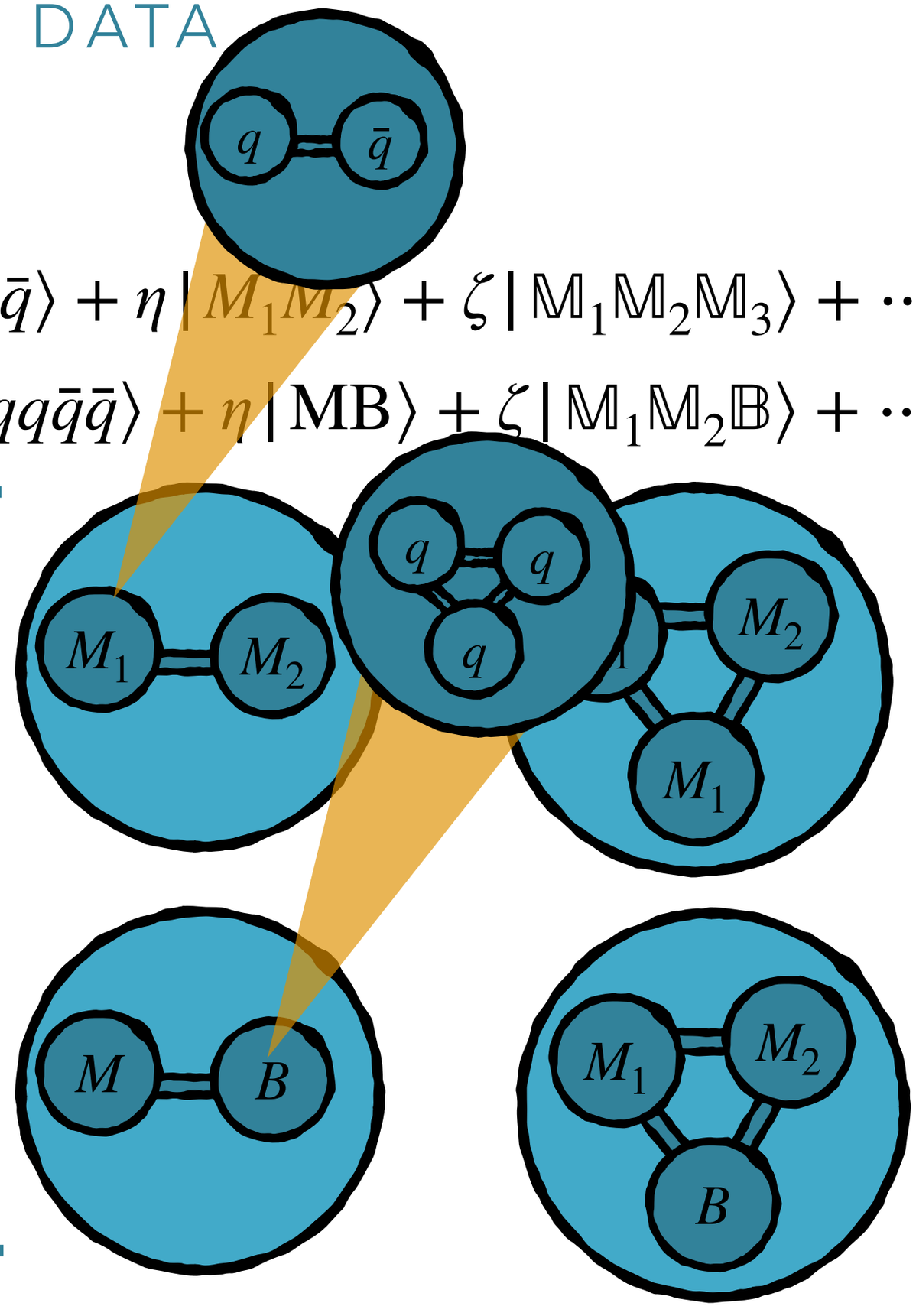

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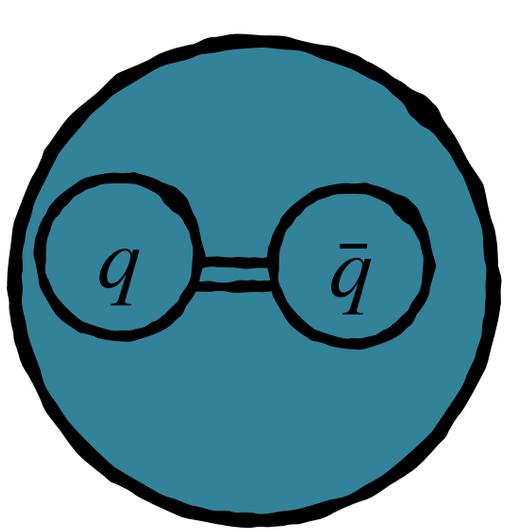

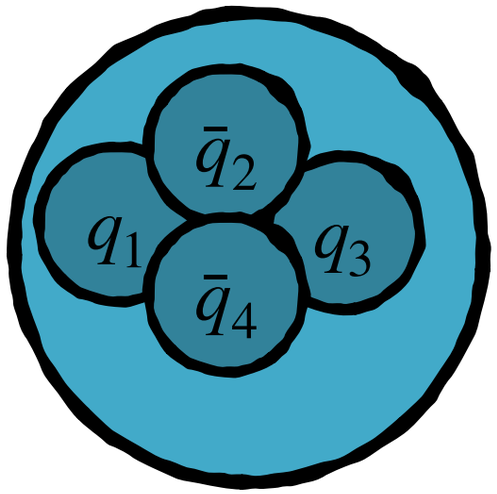

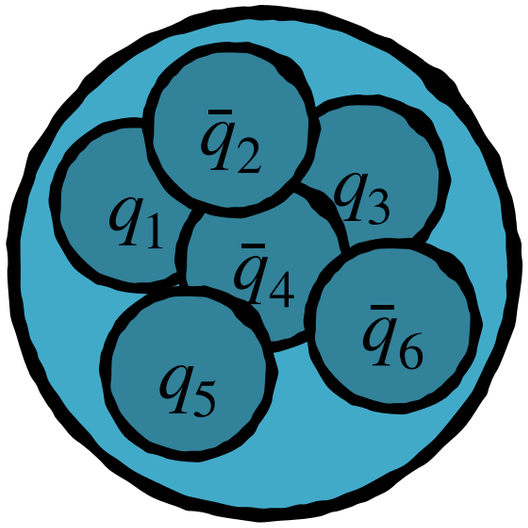

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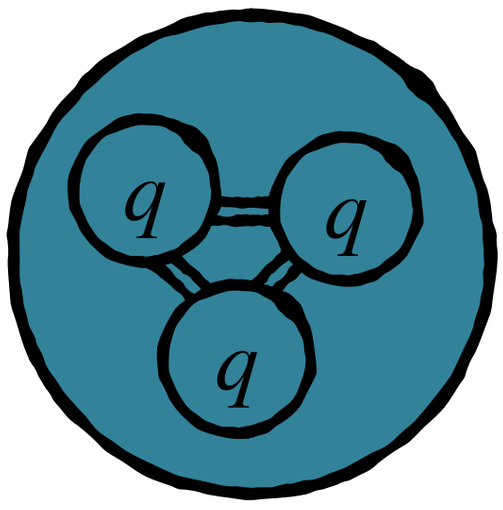

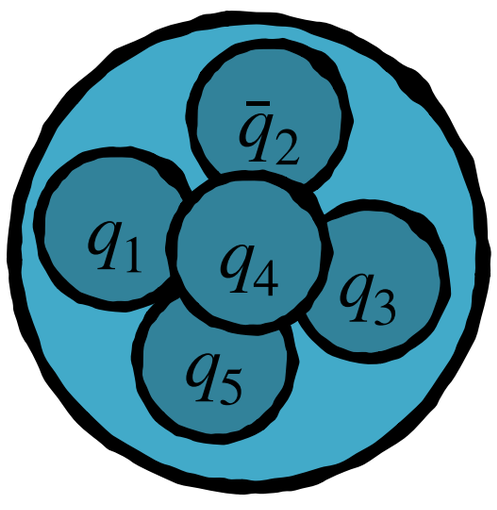

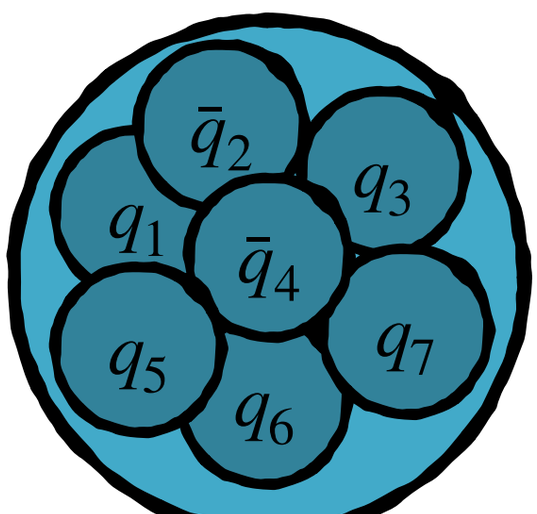

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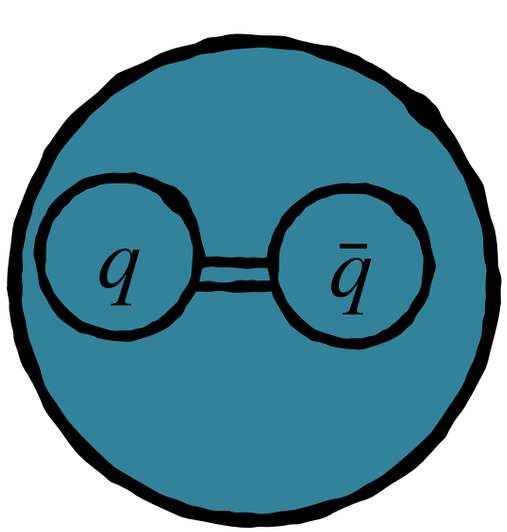

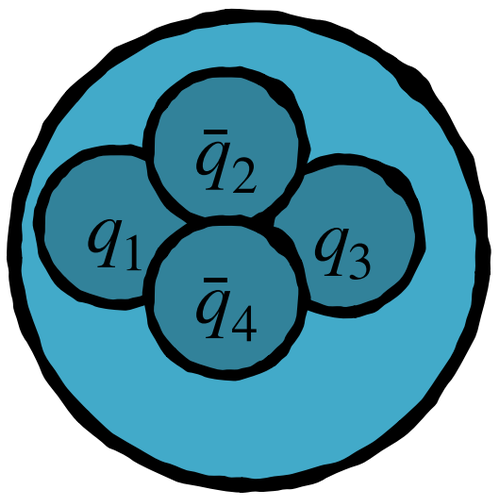

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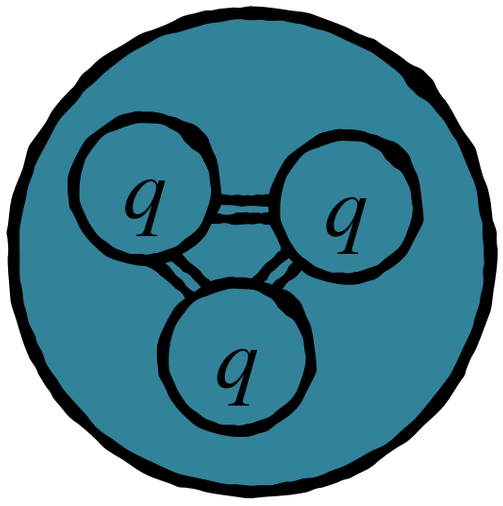

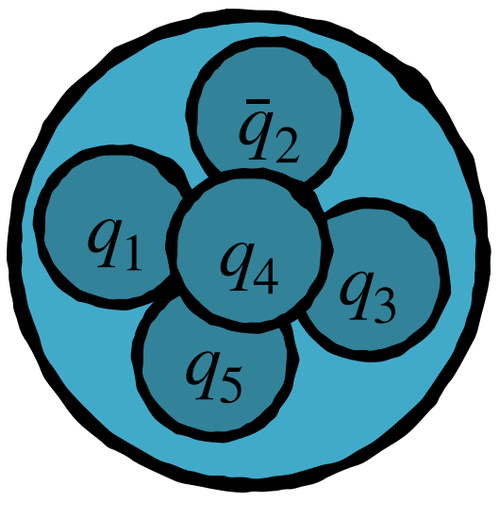

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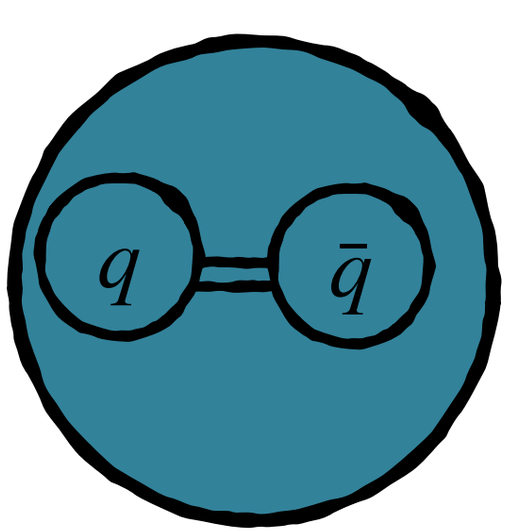

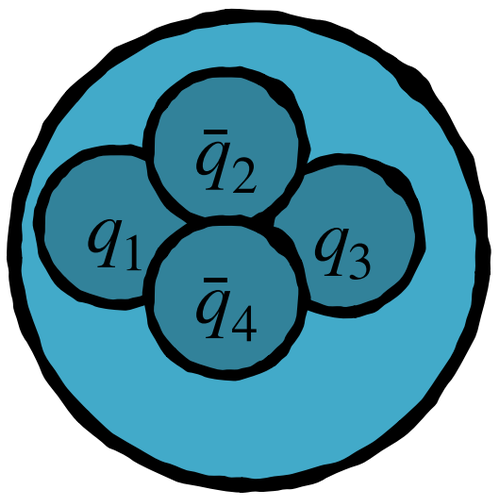

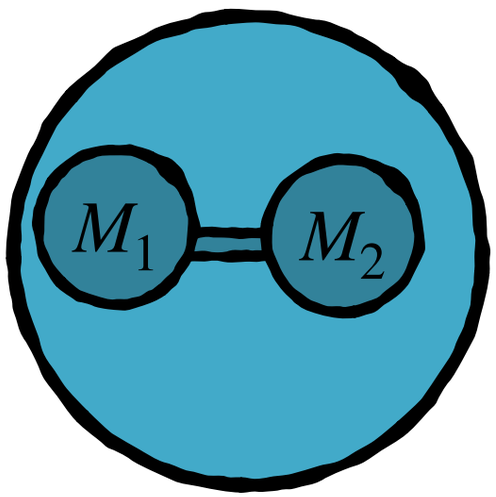

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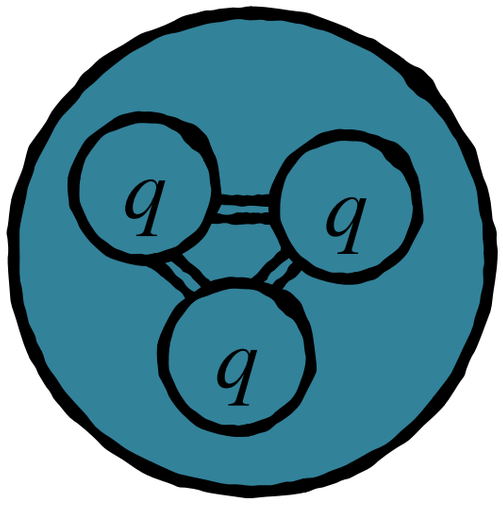

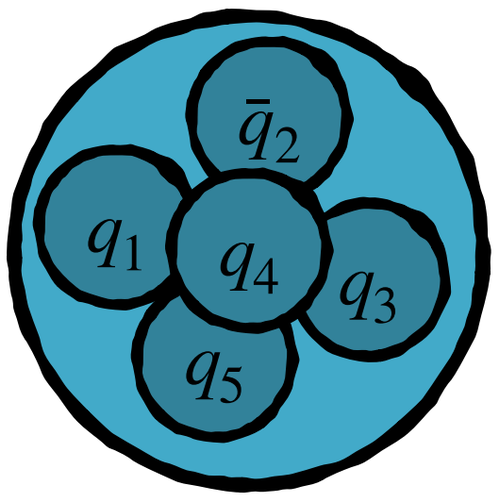

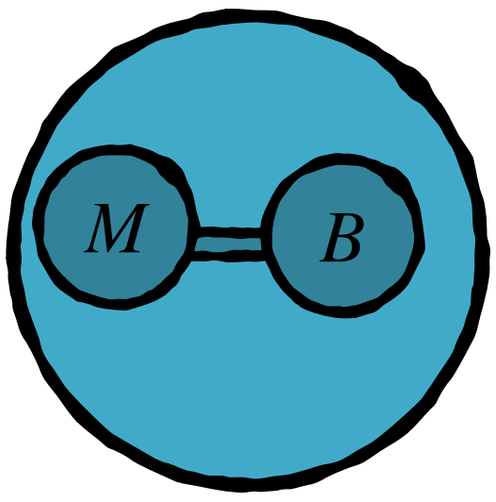

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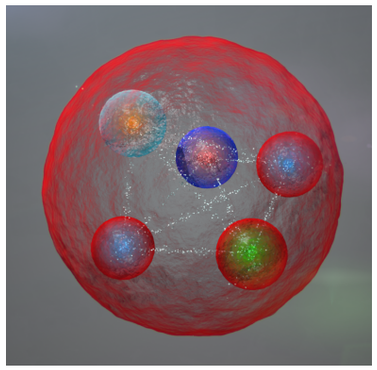
LHCb experiment discovers a new pentaquark



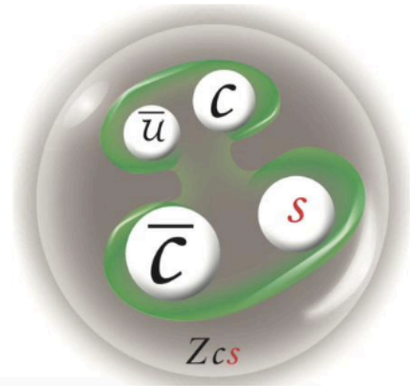
The analysis presented today at the Rencontres de Moriond quantum chromodynamics (QCD) conference (http://moriond.in2p3.fr/2019/QCD/) used nine times more data from the Large Hadron Collider (/science/accelerators/large-hadron-collider) than the 2015 analysis. The data set was first analysed in the same 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.

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

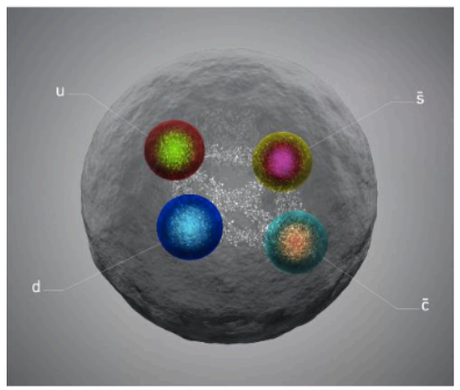
In the March 12th, 2021 issue of Physical Review Letters, the BESIII collaboration reports the discovery of an exotic multi-quark structure, dubbed the Zcs(3985), that is produced in the process of $e^+e^-\to K^+(D_s^-D^{*0}+D_s^{*-}D^0)$ at an e^+e^- center-of-mass energy of 4.68 GeV. The Zcs(3985) 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.



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

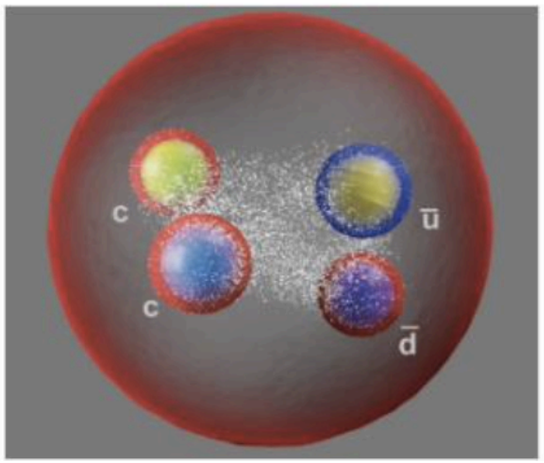


The LHCb experiment at CERN has developed a penchant for finding exotic combinations of quarks, the elementary particles that come together to give us composite particles such as the more familiar proton and neutron. In particular, LHCb has observed several tetraquarks, which, as the name suggests, are 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.

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.

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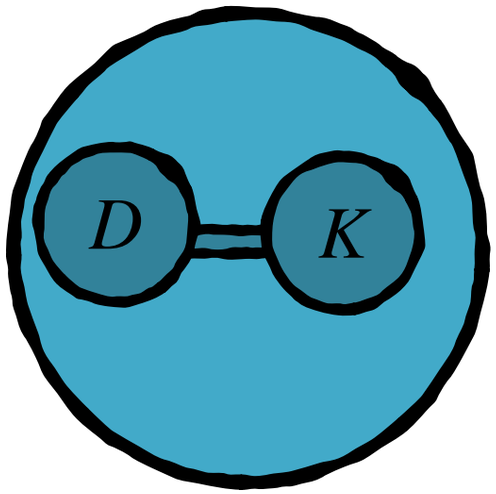
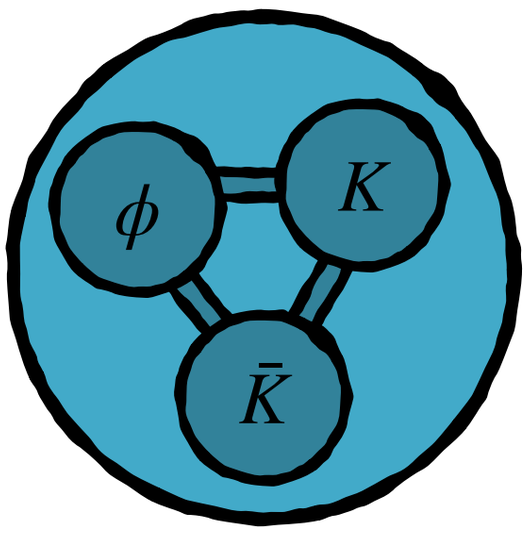
$D_{s0}^{*}(2317)$
[Discovered by BaBar at 2003, $\Gamma < 3.8$ MeV]



$m_D + m_K \sim 2363$ MeV
Quark model $c\bar{s}$:
$M \sim 2460$ MeV, $\Gamma \sim 100$ MeV
[Barnes, Close, Lipkin, Phys. Rev. D68, 054006 (2003)]

$\phi(2170)$
[Discovered by BaBar in 2006, $\Gamma = 125 \pm 65$ MeV]



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

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

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

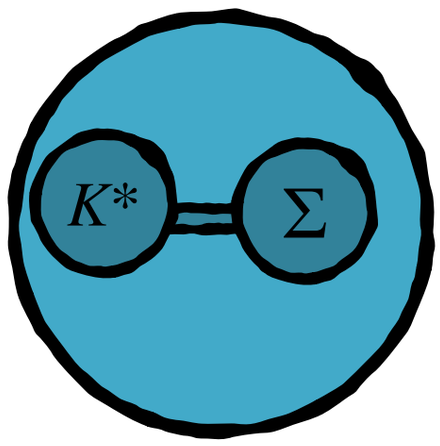
Tetraquark $\Longrightarrow$ Difficulties in obtaining a compatible mass.

USING HADRONS AS EFFECTIVE FIELDS TO DECIPHER EXPERIMENTAL DATA

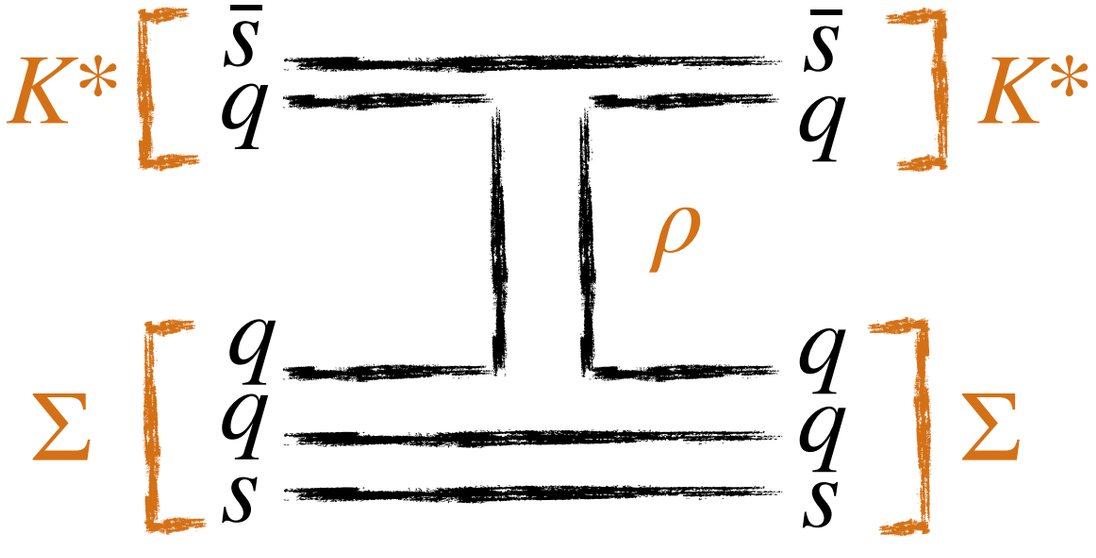
$P_s(2080)$

$[J^P = 3/2^-,\ M = 2079 \pm 30$ MeV]

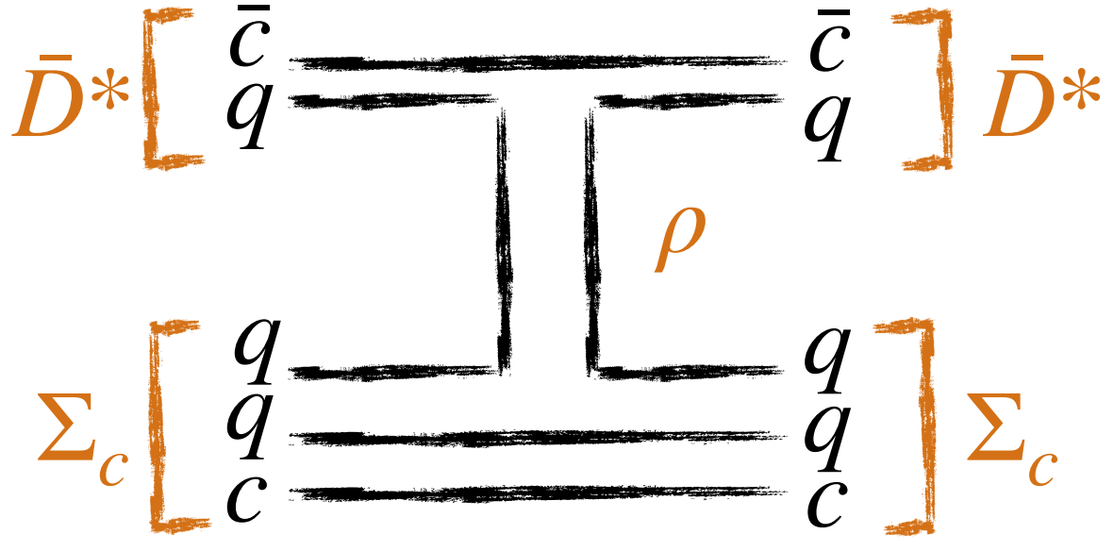
Vector-Baryon coupled channels (hidden local symmetry): $K^*\Sigma, K^*\Lambda, \rho N, \omega N$



$P_s(2080)$



$P_c(4457)\ [J^P = 3/2^-]$



USING HADRONS AS EFFECTIVE FIELDS TO DECIPHER EXPERIMENTAL DATA

PDG Live particle data group

$N(1900)$	$3/2^+$	****
$N(1990)$	$7/2^+$	**
$N(2000)$ was $N(1900)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$ was $N(2200)$	$5/2^-$	***
$N(2100)$	$1/2^+$	***
$N(2120)$	$3/2^-$	***
$N(2190)$	$7/2^-$	****

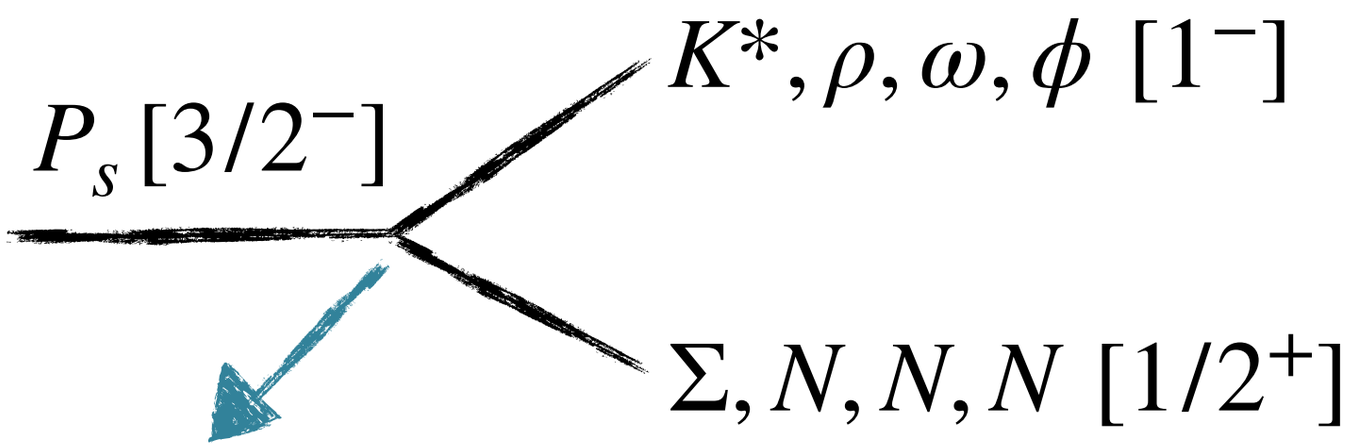
$N(2120)$ $I(J^P) = 1/2(3/2^-)$

$N(2120)$ **POLE POSITION**	
REAL PART	2050 to 2150 ($\approx$ 2100) MeV
$-2\times$IMAGINARY PART	200 to 360 ($\approx$ 280) MeV

- Partial Wave Analysis.
- Large Uncertainty in the masses.
- Broad states: 200-300 MeV
- πN, ηN final states

USING HADRONS AS EFFECTIVE FIELDS TO DECIPHER EXPERIMENTAL DATA

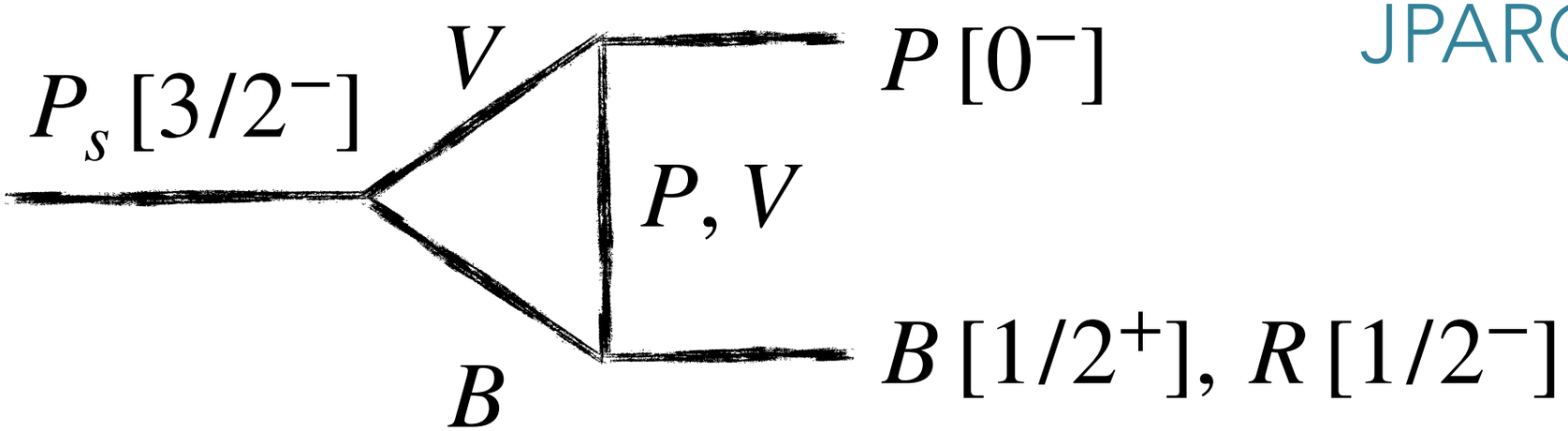
Where to observe $P_s(2080)$?



Breno Agatão et al., Phys. Rev. D111, 116013 (2025).

An ongoing proposal is being conducted at JPARC (Japan).

Coupling: $t = V + VGt$



$$R \equiv \Lambda(1405), N^*(1535), N^*(1650)[1/2^-]$$

USING HADRONS AS EFFECTIVE FIELDS TO DECIPHER EXPERIMENTAL DATA

$D_1(2420)$

$[J^P = 1^+]$

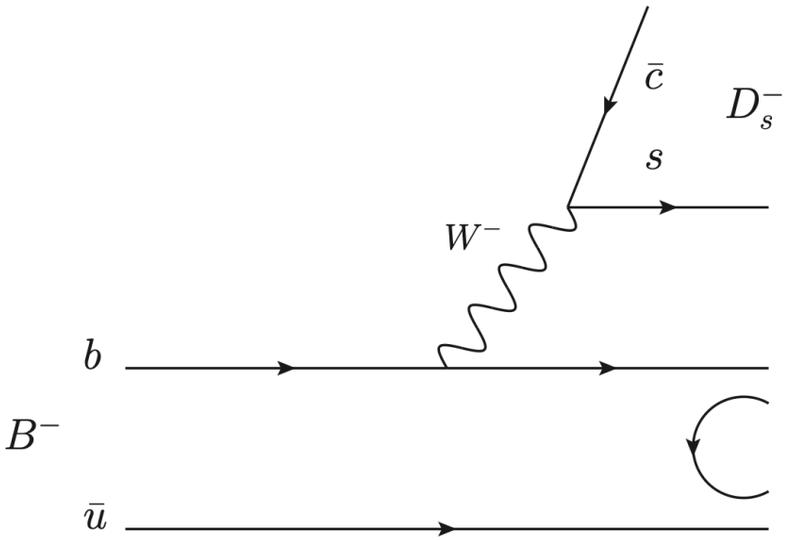
$D_1(2420)$ [narrow, $D^*\pi$ in d-wave],
$D_1(2430)$ [broad; $D^*\pi$ in s-wave].

Quark models have difficulties in explaining these properties.

$B^+ \to D_s^+ D^{*+} \pi^-$ [LHCb collaboration]: $D_1(2420)$ mainly decays to $D^*\pi$ in d-wave (~70 %)

USING HADRONS AS EFFECTIVE FIELDS TO DECIPHER EXPERIMENTAL DATA

$$B^- \to D_s^- D^{*+} \pi^- :$$



$$P = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} & K^0 & D^- \\ K^- & \bar{K}^0 & -\frac{\eta}{\sqrt{3}} + \sqrt{\frac{2}{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix}$$

$$(q\bar{q}) = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} & u\bar{c} \\ d\bar{u} & d\bar{d} & d\bar{s} & d\bar{c} \\ s\bar{u} & s\bar{d} & s\bar{s} & s\bar{c} \\ c\bar{u} & c\bar{d} & c\bar{s} & c\bar{c} \end{pmatrix} \equiv M$$

Pedro Brandão, Breno Agatão, K. P. Khemchandani, A. Martínez Torres, L. M. Abreu, Phys. Lett. B878, 140527 (2026)

$$M \cdot M = M(\bar{u}u + \bar{d}d + \bar{c}c + \cdots)$$

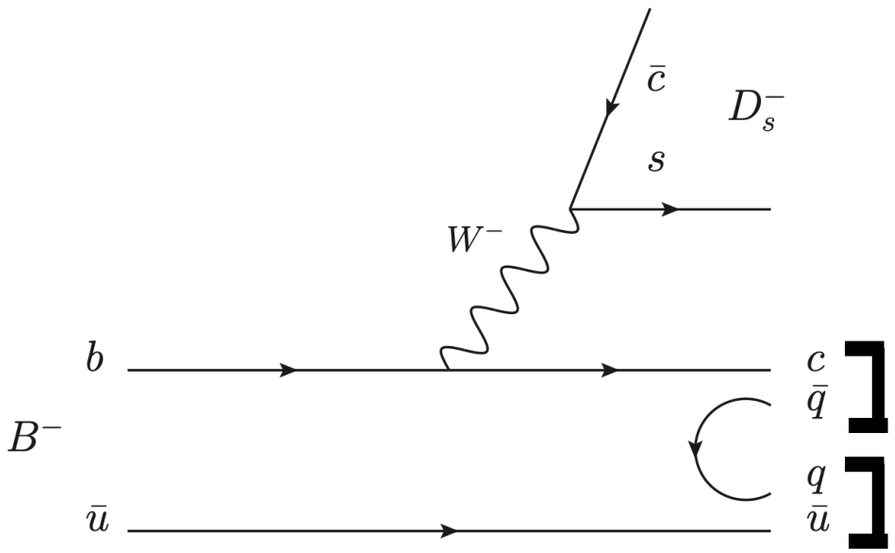
$$V_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & \frac{-\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu$$

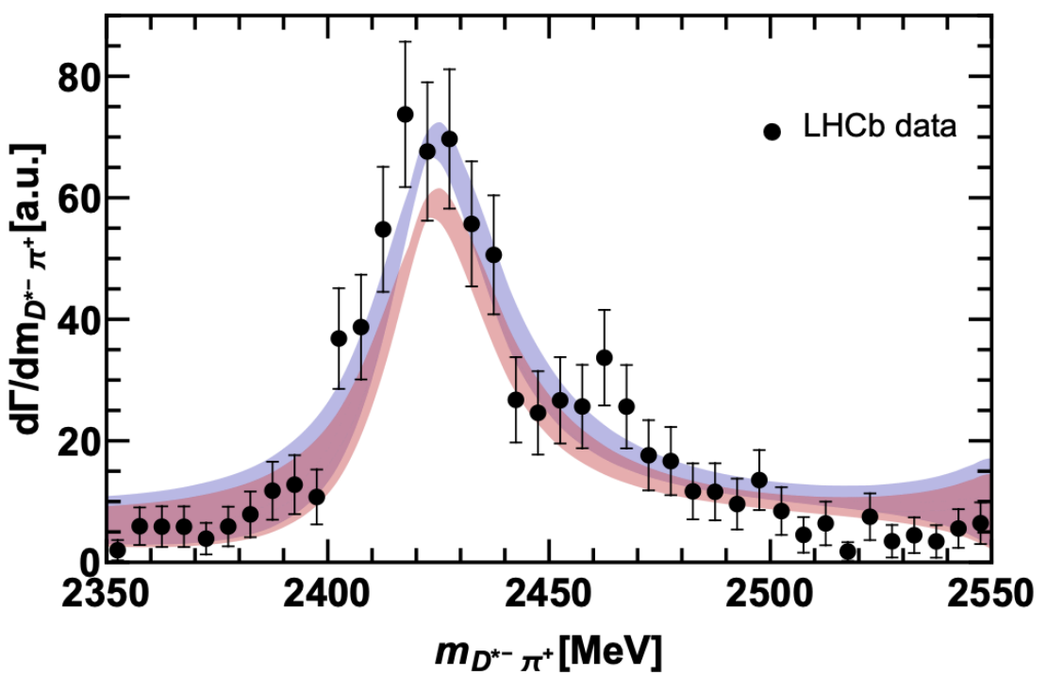
$$c\bar{u} \to \sum_{i=\{u,d,s,c\}} c\bar{q}_i q_i \bar{u} \left[\begin{array}{l} (VP)_{41} : \dfrac{D^{*0}\pi^0}{\sqrt{2}} + \dfrac{D^{*0}\eta}{\sqrt{3}} + D^{*+}\pi^- + D_s^{*+}K^- + \cdots \\ \\ (PV)_{41} : \dfrac{D^0\rho^0}{\sqrt{2}} + \dfrac{D^0\omega}{\sqrt{2}} + D^+\rho^- + D_s^+K^{*-} + \cdots \end{array} \right.$$

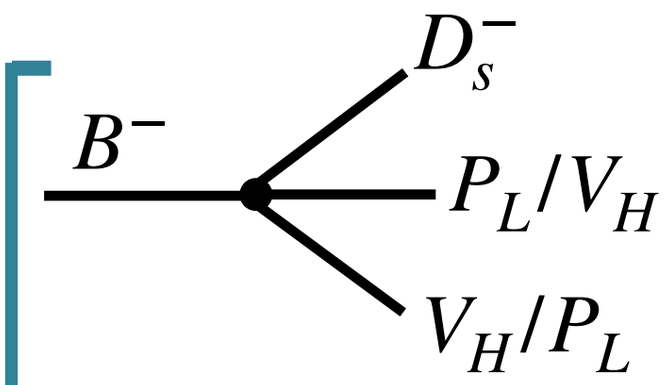
$D_1(2420)$: $D\rho, D^*\pi, \ldots$ interacting in s-wave [Brenda Malabarba, K. P. Khemchandani, A. Martínez Torres, E. Oset, Phys. Rev. D107,036016 (2023)]

USING HADRONS AS EFFECTIVE FIELDS TO DECIPHER EXPERIMENTAL DATA

$B^- \to D_s^- D^{*+} \pi^- :$

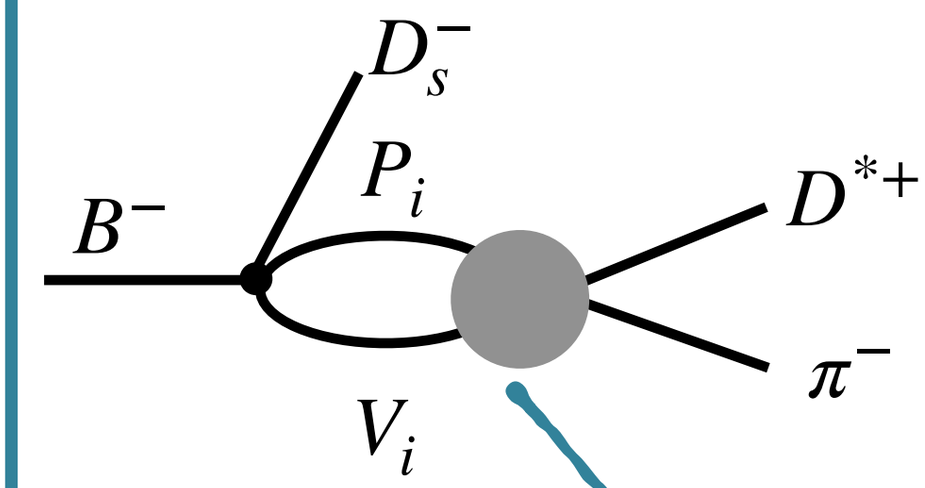






$0^- \to 0^- + 1^+(\text{p-wave})$

$t_{B^- \to D_s^- P_i V_i} = C \omega_i p_B \cdot \epsilon_{D^*}$



Generation of $D_1(2420)$

$t_{P_i V_i \to \pi^- D^{*+}}$

Pedro Brandão, Breno Agatão, K. P. Khemchandani, A. Martínez Torres, Luciano M. Abreu, Phys. Lett. B878,140527 (2026)

USING HADRONS AS EFFECTIVE FIELDS TO DECIPHER EXPERIMENTAL DATA

Correlation functions of two hadrons: femtoscopy

Prob. two particle state/Π_iProb. indiv.part

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

More details in the talk of Hao-nan Liu

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

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

Scattering length; Effective range

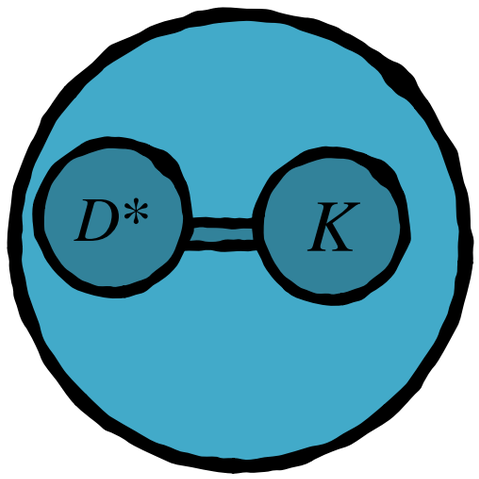
$\vec{k}, \vec{r}$: Relative linear momentum/position;

S_{12} : Normalized source function (It describes the distribution of relative positions of particles with identical velocities) $\Longrightarrow$ Typically a Gaussian.

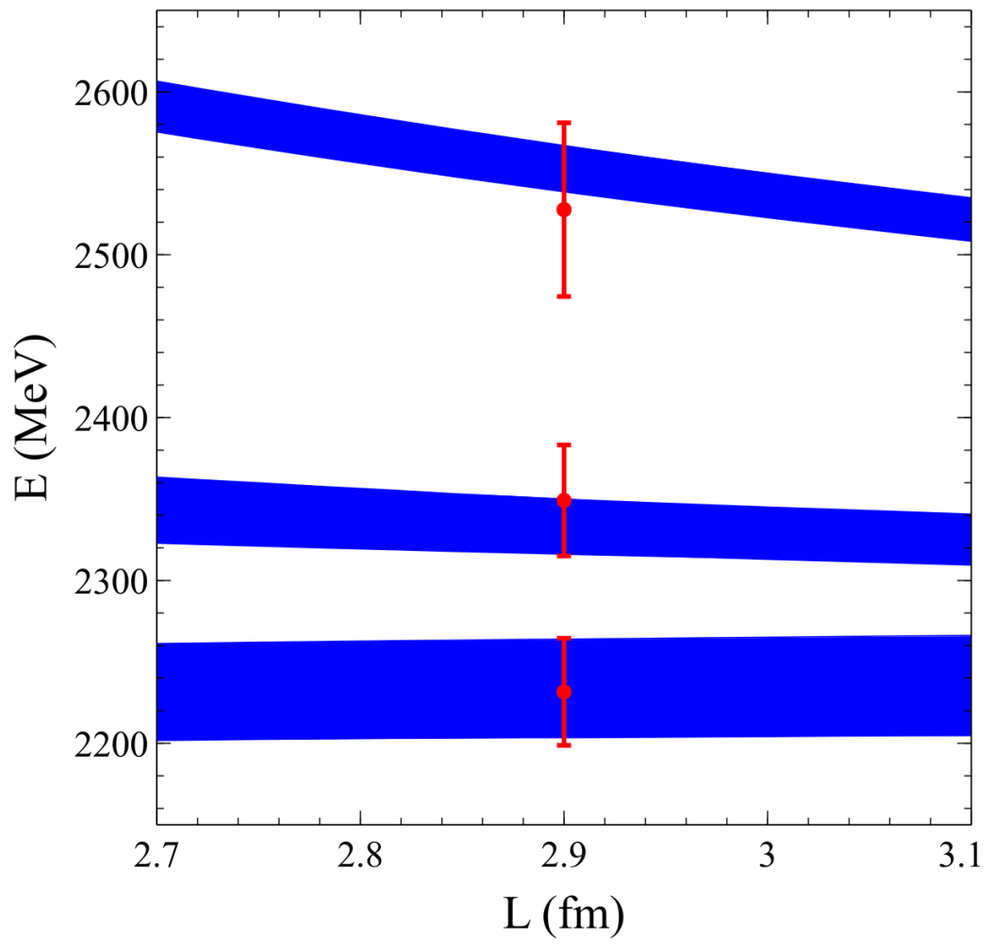
Ψ : Wave function of the two-particle system

USING HADRONS AS EFFECTIVE FIELDS TO DECIPHER EXPERIMENTAL DATA

$$D_{s1}^{*}(2460)\,[J^P = 1^+]$$



E. Kolomeitsev, M. F. M. Lutz, Phys. Lett. B582, 39 (2004); D. Gamermann, E. Oset, D. Strottman, M. J. Vacas, Phys. Rev. D76, 074016 (2007);



$$P(KD^*) \simeq 60\,\%$$

A. Martínez Torres, E. Oset, S. Prelovsek, A. Ramos, JHEP05, 153 (2015).

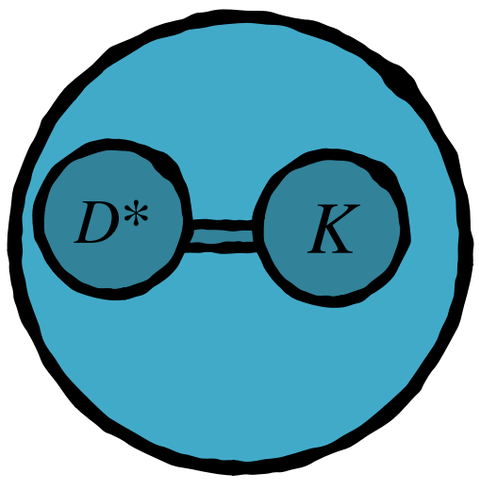
$$T = \frac{1}{V^{-1} - G} = \frac{1}{\tilde{G} - G} = \frac{1}{\lim\limits_{q_{\max}\to\infty}\left[\frac{1}{L^3}\sum\limits_{q_i}^{q_{\max}} I(\vec{q}_i) - \int\limits_{q<q_{\max}} \frac{d^3q}{(2\pi)^3} I(\vec{q})\right]},$$

$$I(\vec{q}) = \frac{\omega_1(\vec{q}) + \omega_2(\vec{q})}{2\omega_1(\vec{q})\omega_2(\vec{q})\left[P^2 - (\omega_1(\vec{q}) + \omega_2(\vec{q}))^2 + i\epsilon\right]} \qquad \vec{q}_i = \frac{2\pi}{L}\vec{n}_i, \quad \vec{n}_i \in \mathbb{Z}^3$$

$$g_i g_j = \lim_{s\to s_0}(s - s_0)T_{ij}, \quad \sum_i \left(-g_i^2 \frac{\partial G_i}{\partial s}\right) = 1$$

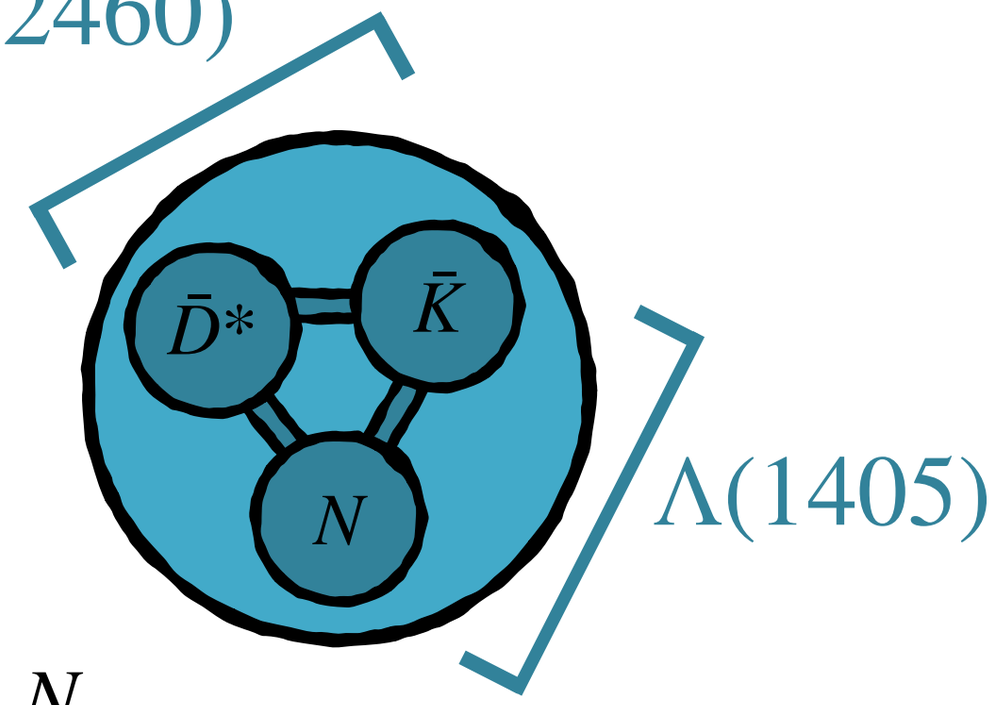
USING HADRONS AS EFFECTIVE FIELDS TO DECIPHER EXPERIMENTAL DATA

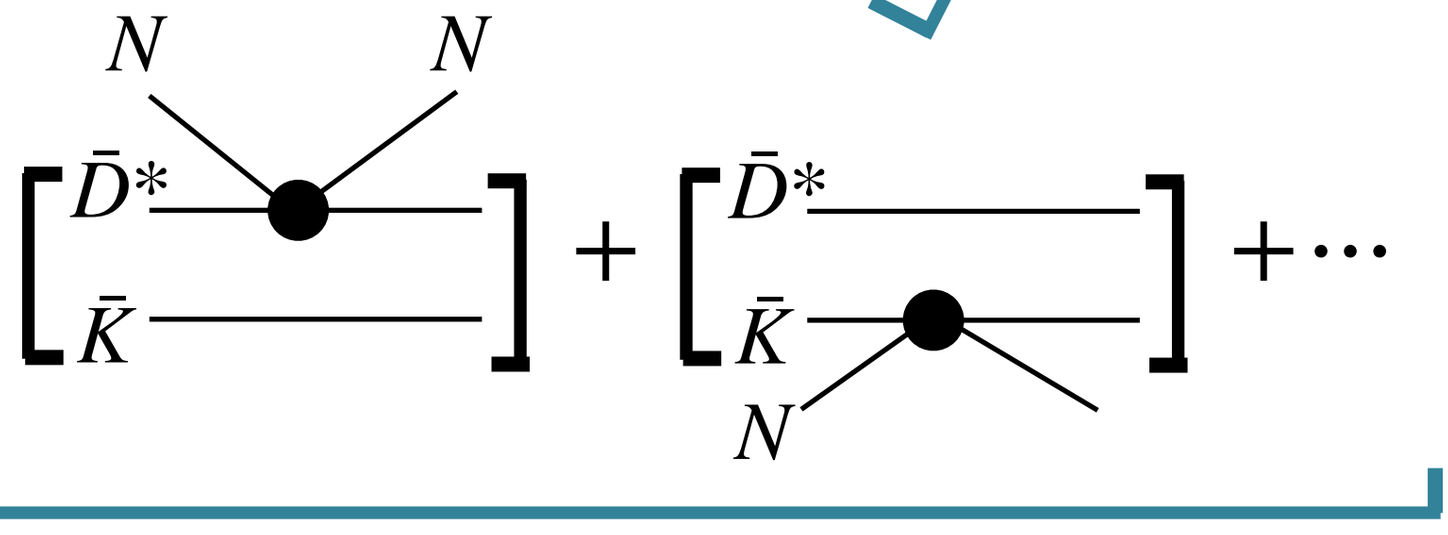
$D^*_{s1}(2460)\,[J^P = 1^+]$



E. Kolomeitsev, M. F. M. Lutz, Phys. Lett. B582, 39 (2004); D. Gamermann, E. Oset, D. Strottman, M. J. Vacas, Phys. Rev. D76, 074016 (2007);

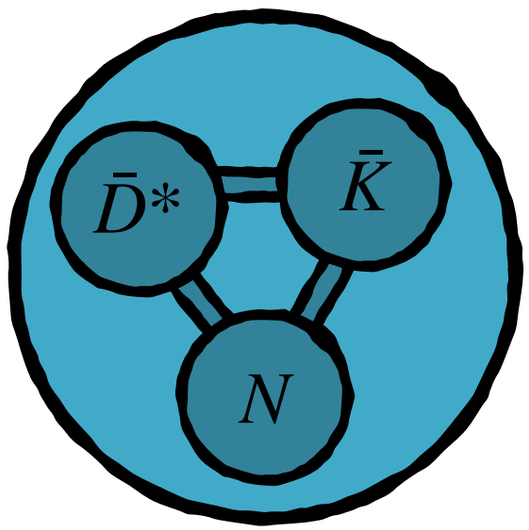
$\bar{D}^*_{s1}(2460)$





$t_{N\bar{D}^*_{s1}(2460)}$

USING HADRONS AS EFFECTIVE FIELDS TO DECIPHER EXPERIMENTAL DATA



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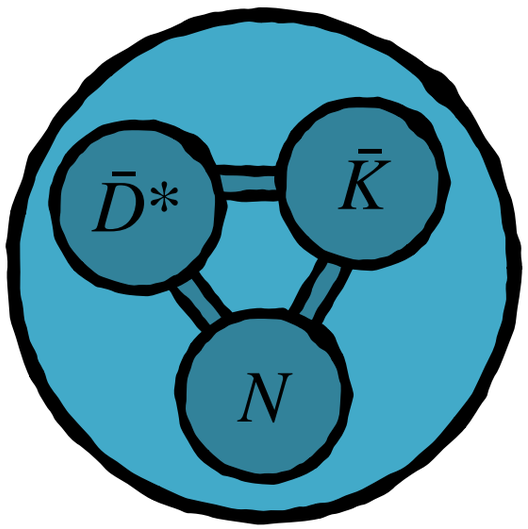

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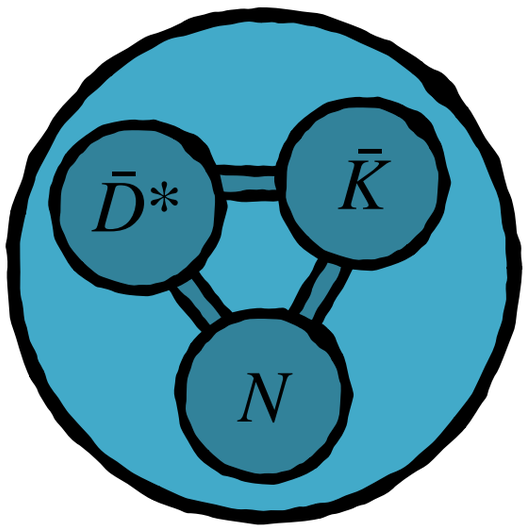
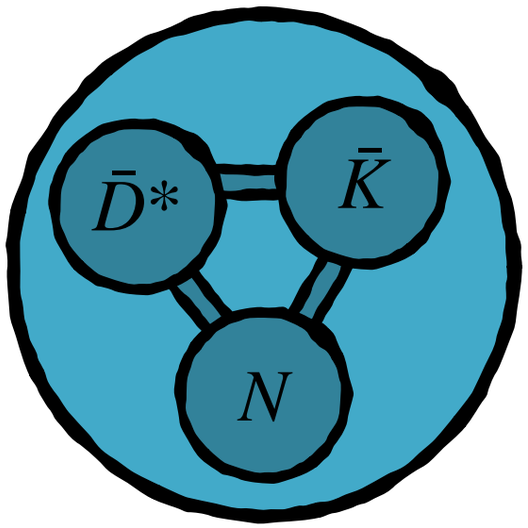
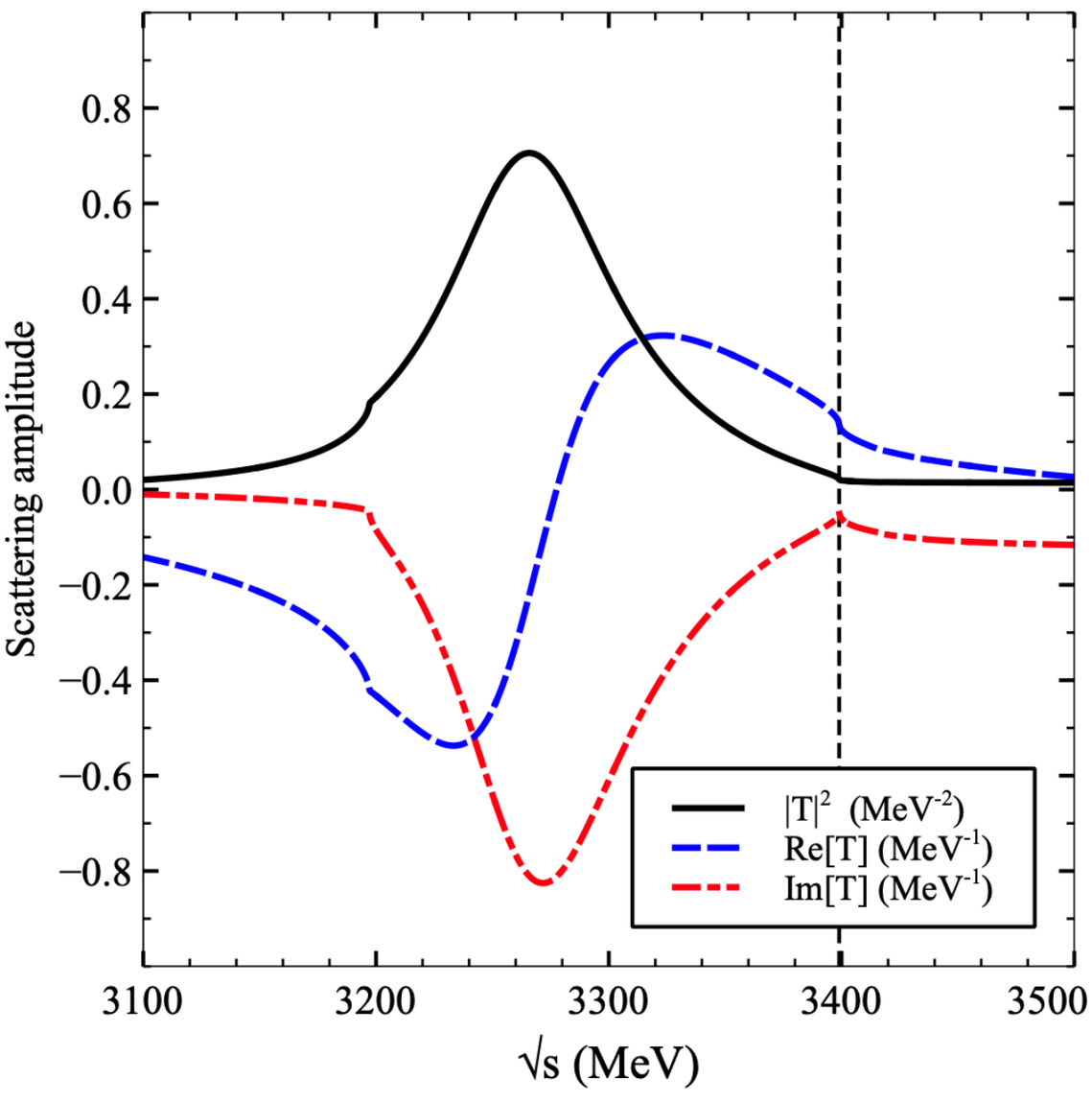


Breno Agatão, P. Brandão, A. Martínez Torres, K. P. Khemchandani, L. M. Abreu, E. Oset, Eur. Phys. J. C85, 1136 (2025)

USING HADRONS AS EFFECTIVE FIELDS TO DECIPHER EXPERIMENTAL DATA





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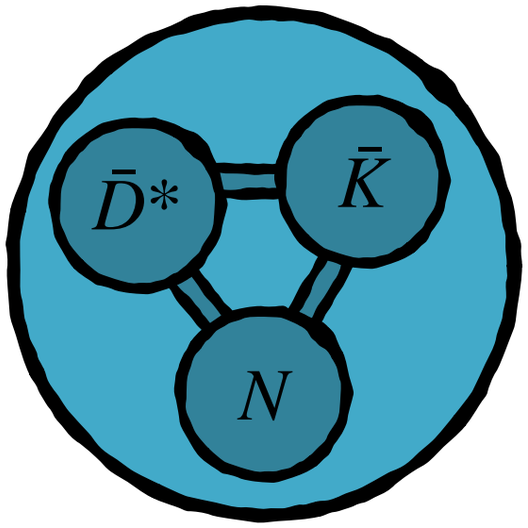

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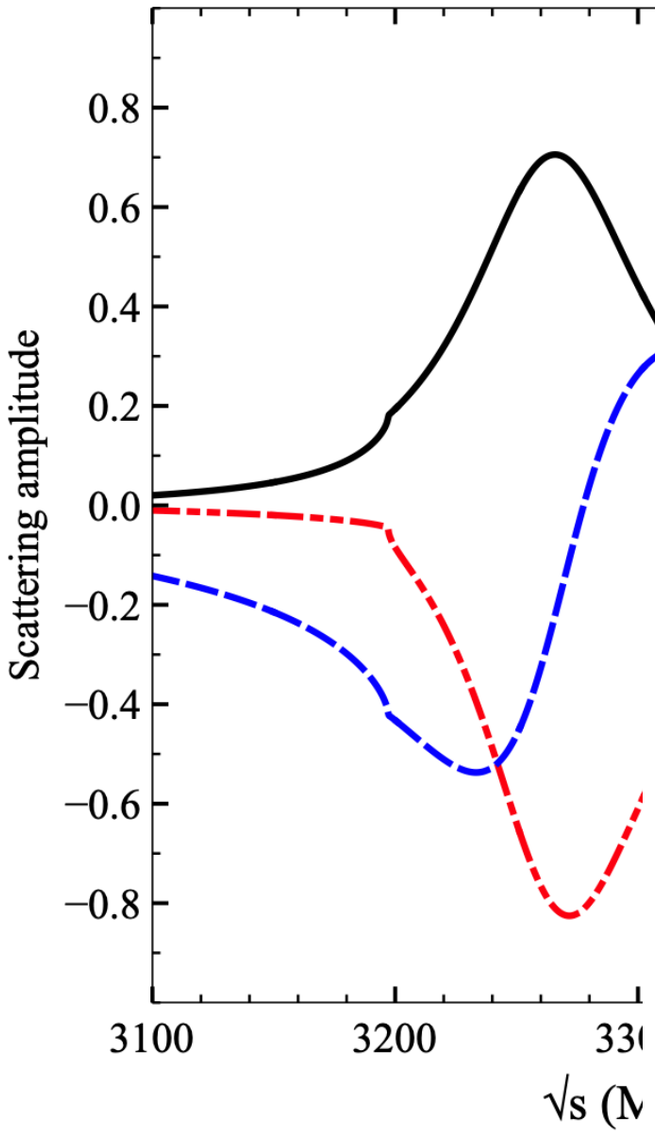

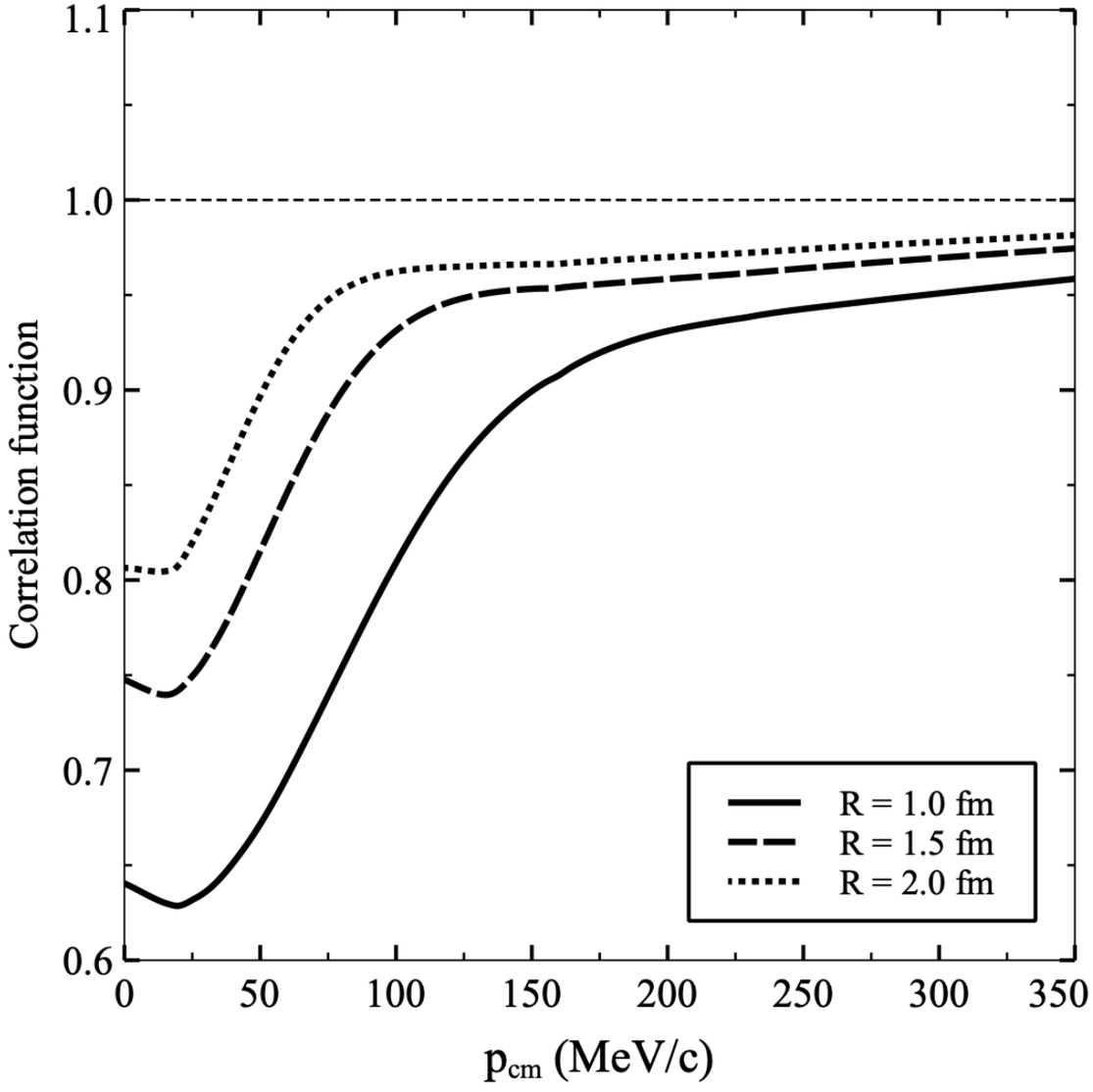

USING HADRONS AS EFFECTIVE FIELDS TO DECIPHER EXPERIMENTAL DATA

- Experimental and theoretical interest in understanding the nature of hadron states that do not fit the quark model.

- Cross sections, Invariant mass distributions, partial decay widths, correlation functions, Lattice data.

- We have been investigating these observables theoretically and have shown their compatibility with the existence of hadron molecules.