LIA meeting, ITA
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Hadron interactions studied with effective field theories

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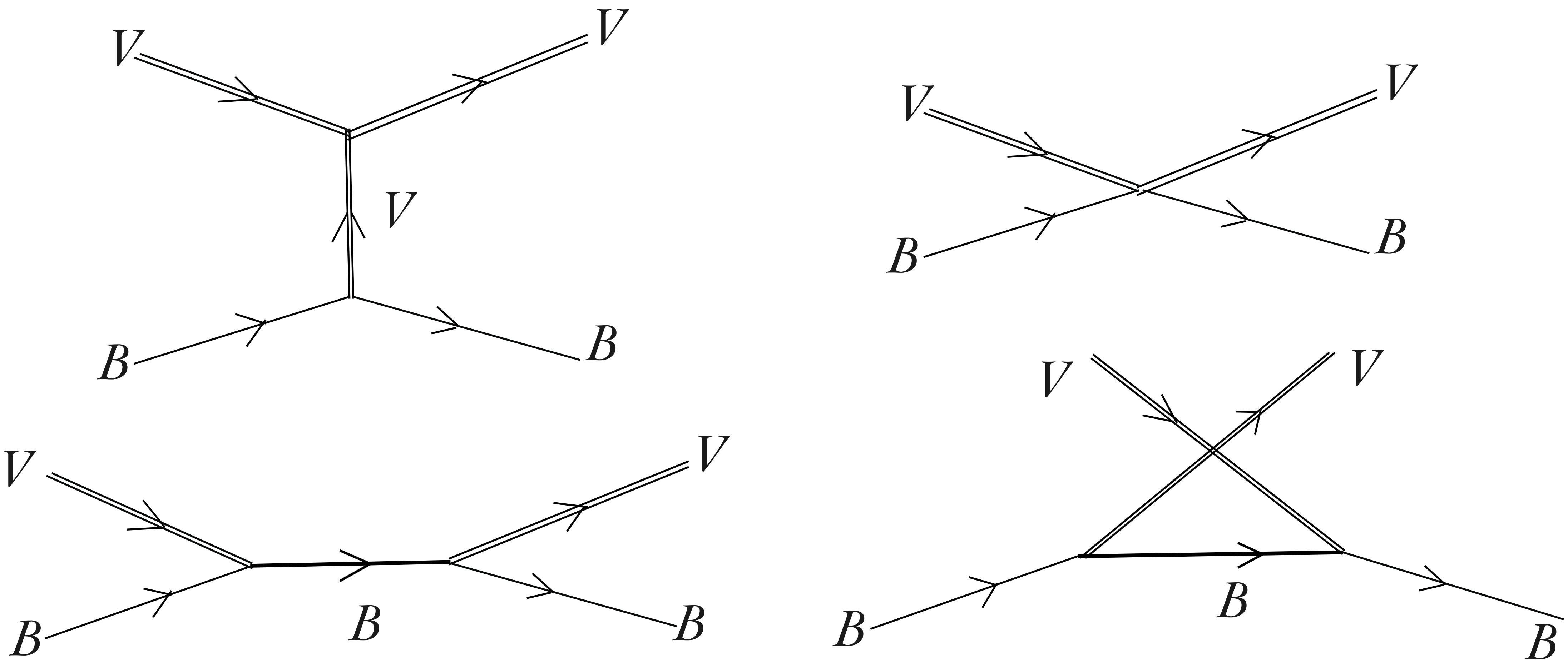
Dynamical generation of resonances in two, three (and more) hadron systems

- Weakly bound two, three and more hadron systems
- Coupled channel solution of Bethe-Salpeter equation for two hadron systems
- Faddeev equations for three-hadron system
- For more than 3-hadrons, we solve Faddeev equations for 3-body subsystem(s) and parameterize as a two-hadron amplitude—> solve Faddeev equations again.

Examples: Two light hadron system



Formalism:

SU(3):

$$\mathcal{L}_{VB} = -g\Big\{ \langle \bar{B}\gamma_\mu [V_8^\mu, B]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V_8^\mu\rangle + \frac{1}{4M}\left(F\langle \bar{B}\sigma_{\mu\nu}[V_8^{\mu\nu}, B]\rangle + D\langle \bar{B}\sigma_{\mu\nu}\{V_8^{\mu\nu}, B\}\rangle\right) + \langle \bar{B}\gamma_\mu B\rangle\langle V_0^\mu\rangle + \frac{C_0}{4M}\langle \bar{B}\sigma_{\mu\nu}V_0^{\mu\nu}B\rangle \Big\}$$

D = 2.4

F = 0.82

$\longrightarrow$ D + F = 3.22 $\approx \kappa_\rho$ $C_0 = 3F - D$ $g = \dfrac{m_v}{\sqrt{2}f_\pi}$

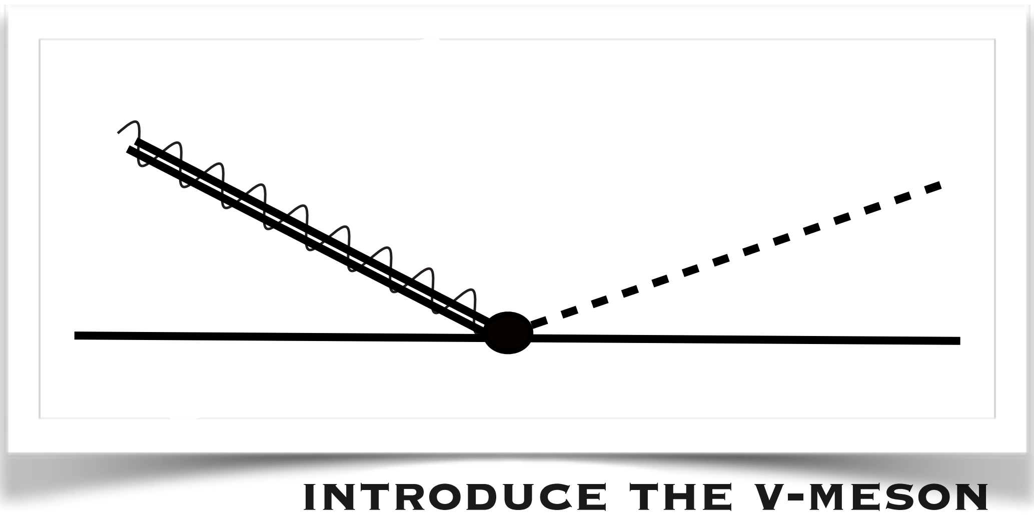
$$V^{\mu\nu} = \partial^\mu V^\nu - \partial^\nu V^\mu + ig[V^\mu, V^\nu]$$

$$V = \begin{pmatrix} \frac{\rho^0}{2} + \frac{\omega}{2} & \frac{\rho^+}{\sqrt{2}} & \frac{K^{*+}}{\sqrt{2}} \\ \frac{\rho^-}{\sqrt{2}} & -\frac{\rho^0}{2} + \frac{\omega}{2} & \frac{K^{*0}}{\sqrt{2}} \\ \frac{K^{*-}}{\sqrt{2}} & \frac{\bar{K}^{*0}}{\sqrt{2}} & \frac{\phi}{\sqrt{2}} \end{pmatrix} \quad B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & \frac{-2\Lambda}{\sqrt{6}} \end{pmatrix}$$

Formalism:

PB → VB

Extension of Kroll-Ruderman term $\gamma \Rightarrow$ V in $\gamma N \rightarrow \pi$ N and introducing it in the non-linear sigma model:



INTRODUCE THE V-MESON AS THE GAUGE BOSON OF THE HLS

$$\mathcal{L}_{\pi N} = \bar{\psi}\left[i\gamma^\mu \partial_\mu - g_{\pi NN}\left(\sigma + i\vec{\tau}.\vec{\pi}\gamma_5\right)\right]\psi \quad i\partial\!\!\!/ \longrightarrow i\partial\!\!\!/ - g\rho\!\!\!/ \quad \mathcal{L}_{\pi N\rho N} = -i\frac{g g_A}{2f_\pi}\bar{N}\left[\pi, \rho^\mu\right]\gamma_\mu\gamma_5 N$$

$$\text{SU(3)} \qquad \mathcal{L}_{PBVB} = \frac{-ig}{2f_\pi}\Big(F\langle\bar{B}\gamma_\mu\gamma_5\left[\left[P, V_\mu\right], B\right]\rangle + D\langle\bar{B}\gamma_\mu\gamma_5\left\{\left[P, V_\mu\right], B\right\}\rangle\Big)$$

$$\frac{-ig}{2f_\pi} \rightarrow \frac{m_\rho}{\sqrt{2}f_\pi}$$

F = 0.46, D = 0.8

Formalism:

For light pseudoscalar baryon interaction, we use standard chiral Lagrangian

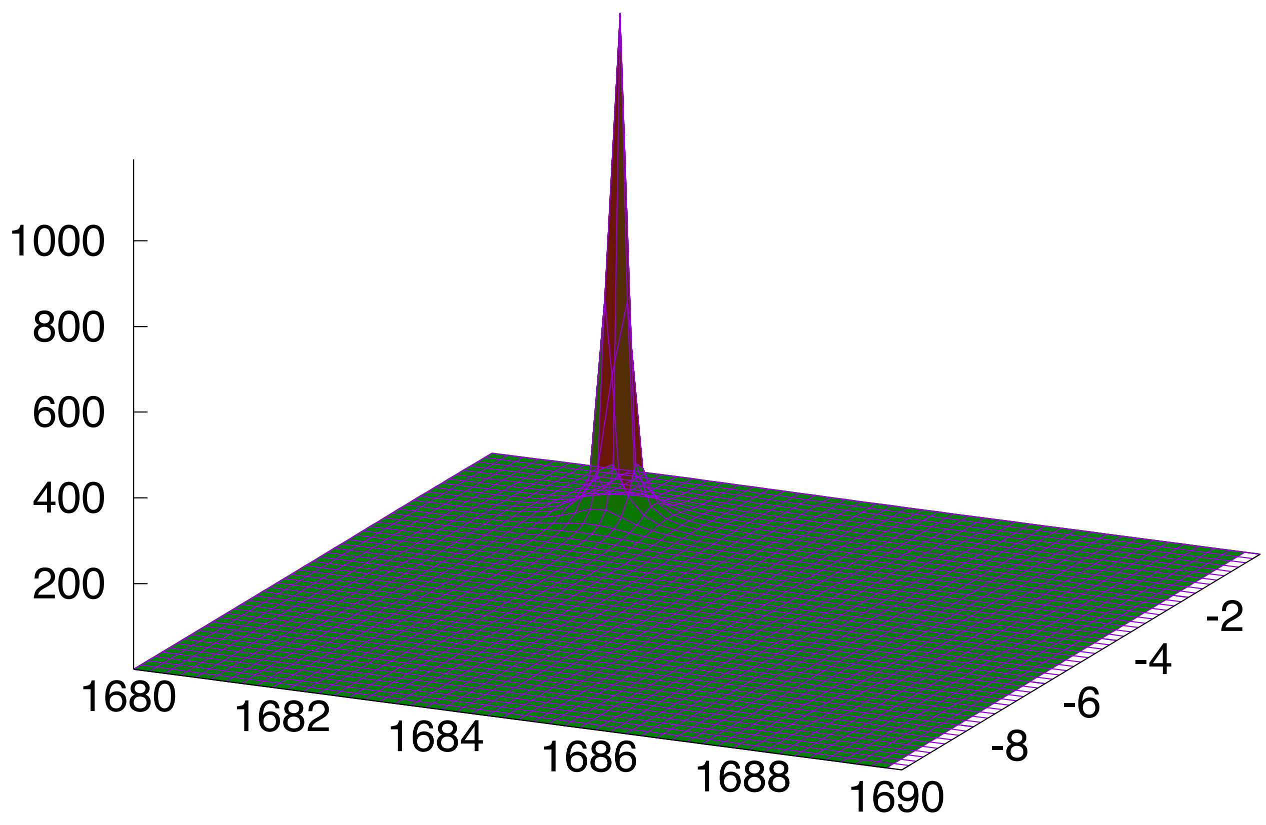
$$\mathcal{L}_{PB} = \langle \bar{B} i \gamma^\mu \partial_\mu B + \bar{B} i \gamma^\mu [\Gamma_\mu, B] \rangle - M_B \langle \bar{B} B \rangle$$
$$+ \frac{1}{2} D' \langle \bar{B} \gamma^\mu \gamma_5 \{u_\mu, B\} \rangle + \frac{1}{2} F' \langle \bar{B} \gamma^\mu \gamma_5 [u_\mu, B] \rangle$$

$$\Gamma_\mu = \frac{1}{2} \left(u^\dagger \partial_\mu u + u \partial_\mu u^\dagger \right), \; u_\mu = i u^\dagger \partial_\mu U u^\dagger,$$
$$U = u^2 = exp \left(i \frac{P}{f_P} \right).$$

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

Examples: Two light hadron system

Solving Bethe-Salpeter equation in coupled channel approach for S = -2 systems: $\pi\Xi,\ \eta\Xi,\ \bar{K}\Sigma,\ \bar{K}\Lambda,\ \rho\Xi,\ \omega\Xi,\ \phi\Xi, \bar{K}^*\Sigma$ and $\bar{K}^*\Lambda$



$J^\pi = 1/2^-$

$$M - i\Gamma/2 = 1682 - i3\ \text{MeV}$$

$$M = \left(1684.7 \pm 1.3^{+2.2}_{-1.6}\right)\ \Gamma = \left(8.1^{+3.9+1.0}_{-3.5-0.9}\right)\ \text{MeV}$$ BABAR

$$M = (1688 \pm 2)\ \text{MeV}, \quad \Gamma = (11 \pm 4)\ \text{MeV}$$ BELLE

Examples: Two light hadron systems

PHYSICAL REVIEW D **97,** 034005 (2018)

Recent publication:

Why $\Xi(1690)$ and $\Xi(2120)$ are so narrow

K. P. Khemchandani,[1,2,*] A. Martínez Torres,[3] A. Hosaka,[4] H. Nagahiro,[4,5] F. S. Navarra,[3] and M. Nielsen[3]

Other systems:

K. P. Khemchandani, A. Martínez. Torres, H. Kaneko, H. Nagahiro, A. Hosaka, Phys. Rev. D 84, 094018 (2011)

K. P. Khemchandani, A. Martínez Torres,H. Nagahiro, A. Hosaka, Phys.Rev. D88 (2013) 114016.

K. P. Khemchandani, A. Martínez Torres,H. Nagahiro, A. Hosaka, Phys.Rev. D85 (2012) 114020.

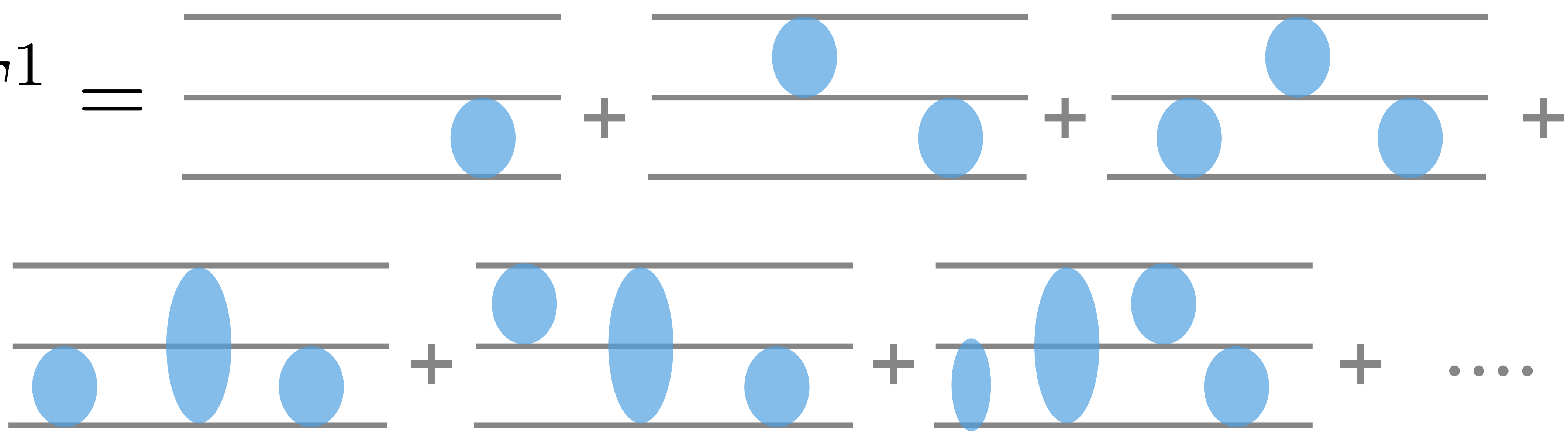
K. P. Khemchandani, A. Martínez Torres, F.S.Navarra, M.Nielsen, L.Tolos Phys.Rev. D91 (2015) 094008.

Examples: Three hadron systems

$$T = T^1 + T^2 + T^3$$

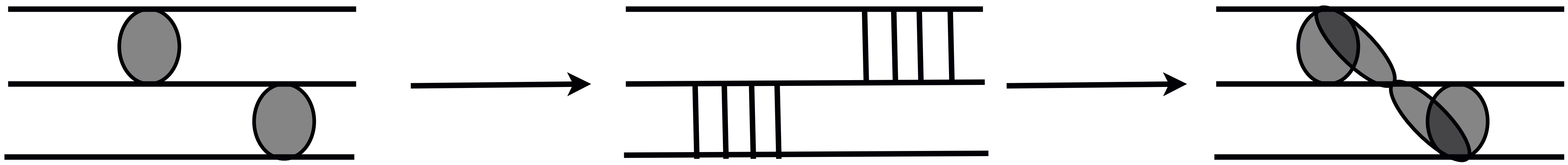
$$T^i = t^i \delta^3(\vec{k}_i' - \vec{k}_i) + t^i g(T^j + T^k)$$

$$T^1 = t^1 \delta^3(\vec{k}_1' - \vec{k}_1) + t^1 g(T^2 + T^3)$$

$T^1 =$ 

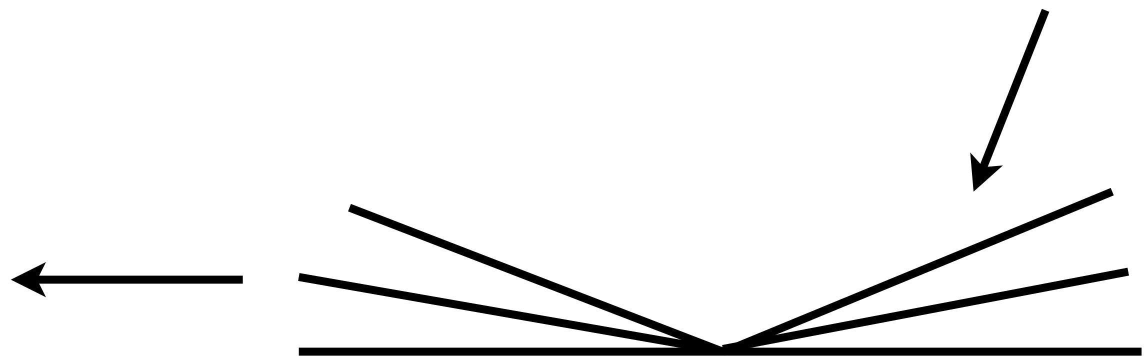
Examples: Three hadron systems

Very important finding of our work



kind of a 3 body force!

+ 3 body forces from the chiral Lagrangian

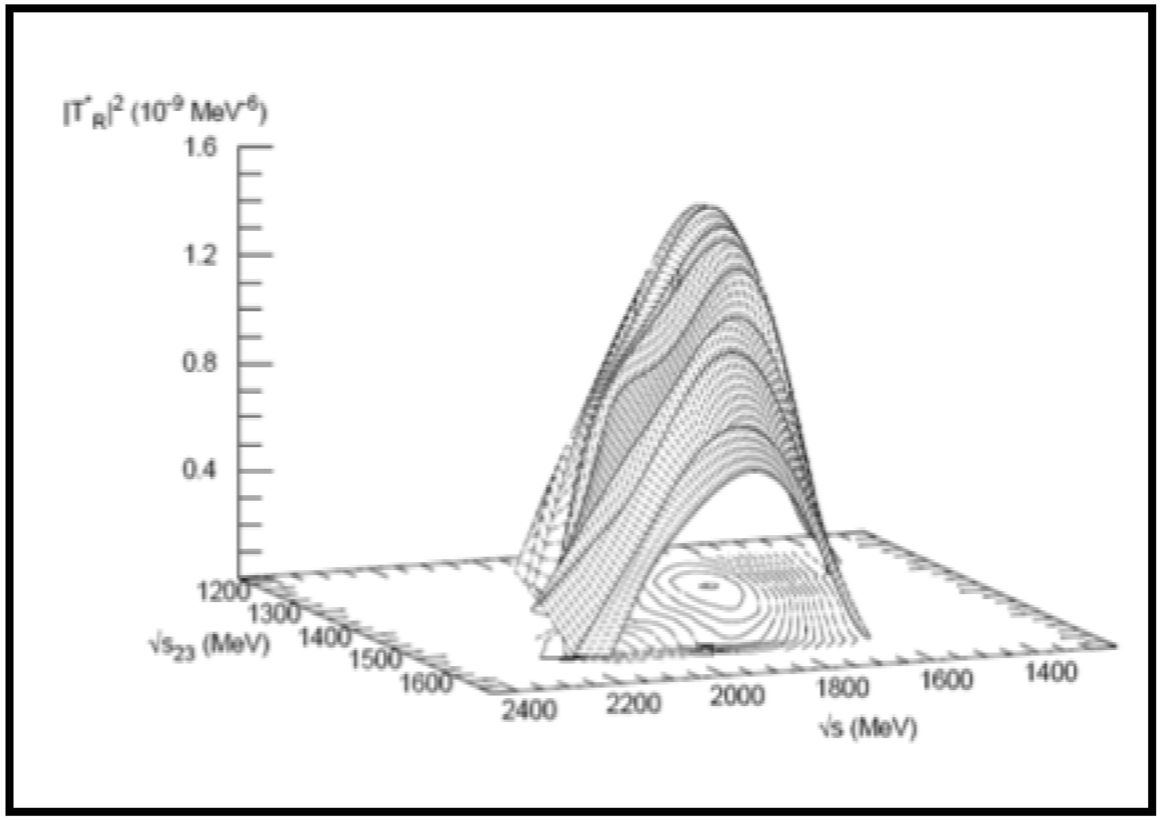


The sum of these three-body forces cancels (exactly, analytically) in SU(3)/Chiral limit ⇒ study of multichannel three (and more) hadron systems possible.

Examples: Three hadron systems

$\pi\pi$N and coupled channel system

Coupled channels: $\pi^0\pi^0 n, \pi^0\pi^- p, \pi^0 K^+\Sigma^-, \pi^0 K^0\Sigma^0, \pi^0 K^0\Lambda, \pi^0\eta n, \pi^+\pi^- n, \pi^+ K^0\Sigma^-, \pi^-\pi^+ n, \pi^-\pi^0 p, \pi^- K^+\Sigma^0, \pi^- K^0\Sigma^+, \pi^- K^+\Lambda, \pi^-\eta p$



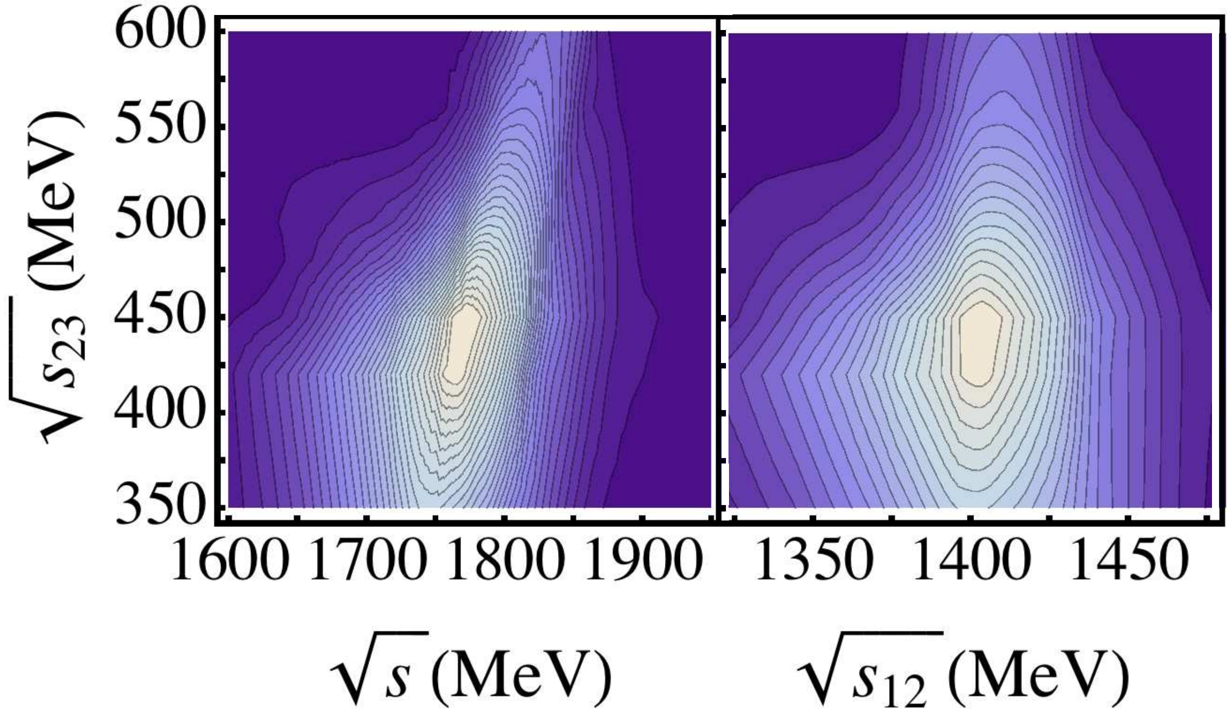
RESULTS: I=1/2, $I_{\pi\pi}$ =0

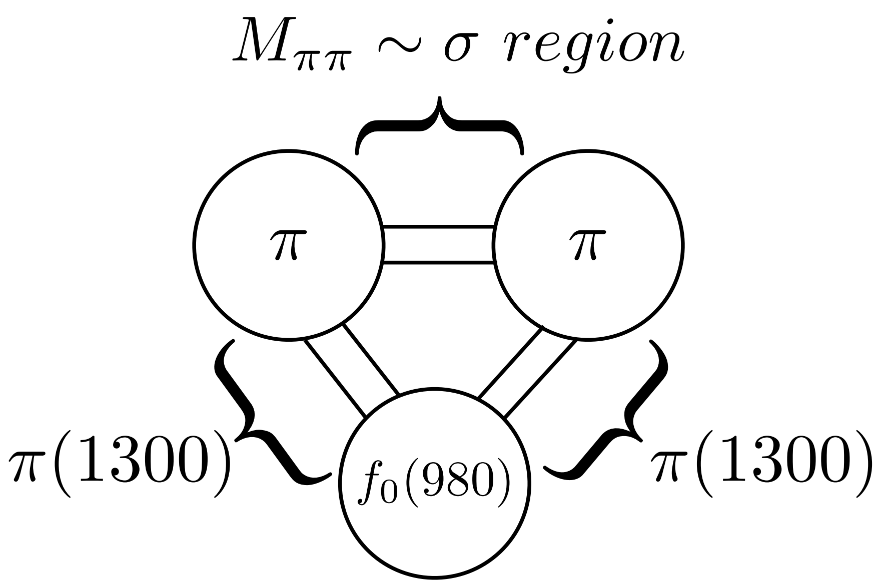
$1704 - i375/2\ MeV$

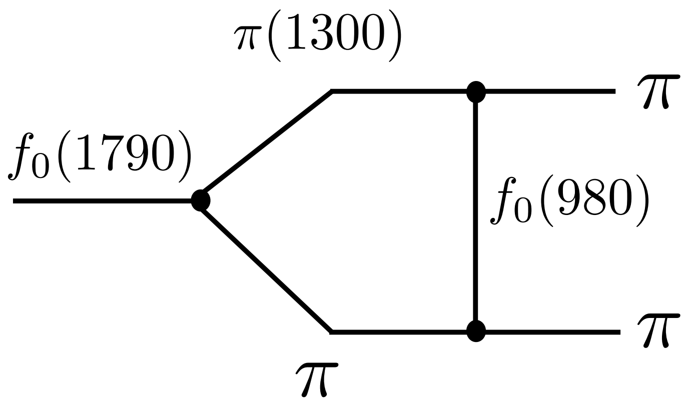
$N^*(1710)\ P_{11}[I(J^p) = 1/2(1/2)^+]^{***}$

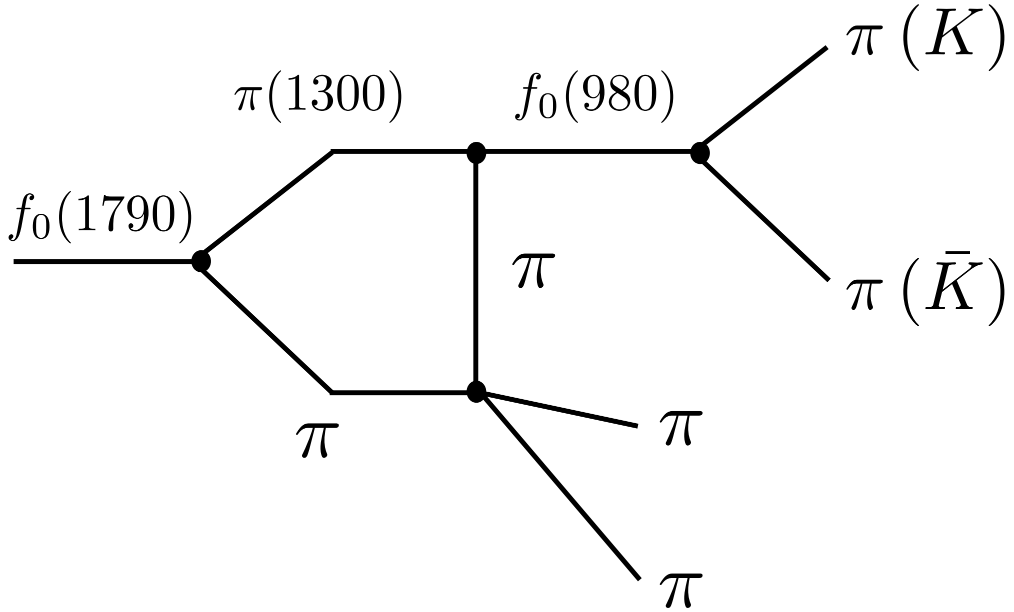
Examples: More hadron systems

We found a scalar resonance in the study of $\pi\pi K\bar{K}$







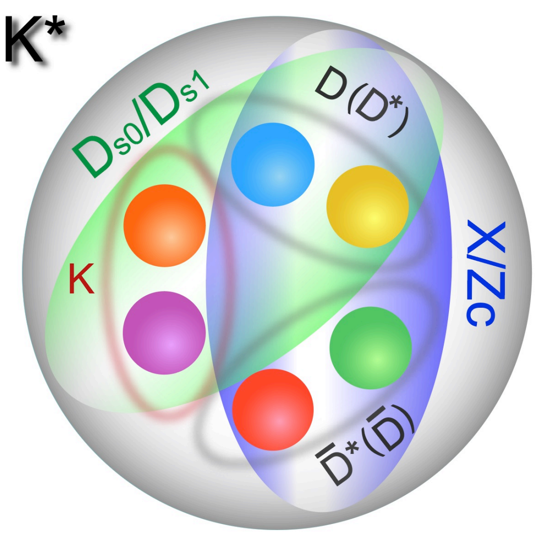


Examples: Three hadron systems

arXiv:1805.08330v1 [hep-ph] 22 May 2018

K^* mesons with hidden charm arising from $KX(3872)$ and $KZ_c(3900)$ dynamics

Xiu-Lei Ren,[1] Brenda B. Malabarba,[2] Li-Sheng Geng,[3,4,*] K. P. Khemchandani,[5,3,†] and A. Martínez Torres[2,3]

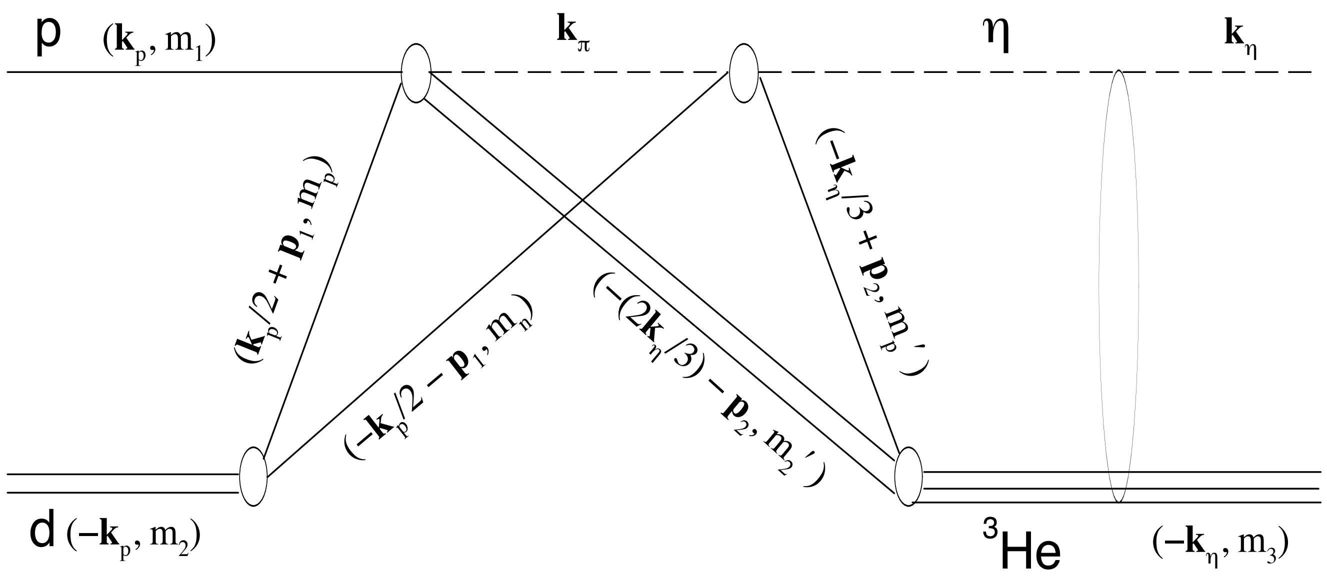


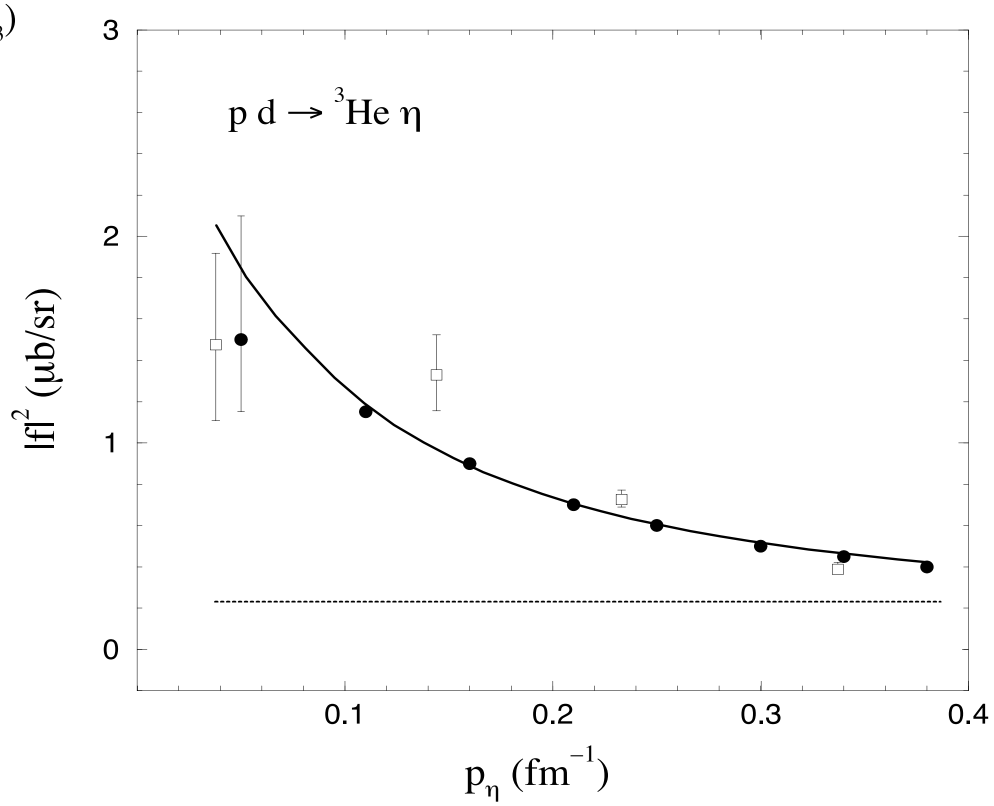
Examples: Three hadron systems

Many other systems have been studied:

- Searching for exotic states in the N(pi)K system: K.P. Khemchandani, A. Martınez Torres, E. Oset, Phys. Lett. B 675 (2009) 407; arXiv:0902.4425 [nucl-th].
- S=-1 Meson-meson-baryon systems : A. Martınez, K. P. Khemchandani and E. Oset, Phys. Rev. C (**Rapid Communication**) 77 (2008) 042203; arXiv:0706.2330 [nucl-th]
- The X(2175) as a resonant state of the phi K anti-K system: A. Martınez Torres, K.P. Khemchandani, L.S. Geng, M. Napsuciale, E. Oset, Phys. Rev. D 78 (2008) 074031; arXiv:0801.3635 [nucl-th].
- Testing the three-hadron nature of the N*(1920) resonance A. Martınez Torres, K.P. Khemchandani, Ulf-G. Meissner, E. Oset, Eur. Phys. J. A 41,361-368 (2009); arXiv:0902.3633 [nucl-th].
- Solution to Faddeev equations with two-body experimental amplitudes as input and application to J**P = 1/2+, S = 0 baryon resonances A. Martınez Torres, K.P. Khemchandani, E. Oset, Phys. Rev. C 79 (2009) 065207; arXiv:0812.2235 [nucl-th].
- The Y(4260) as a J/psi K anti-K system A. Martınez Torres, K.P. Khemchandani, D. Gamermann, E. Oset, submitted to Phys. Rev. D 80 (2009) 094012, arXiv:0906.5333 [nuclth].
- Theoretical support for the (1300) and the recently claimed f0(1790) as molecular resonances, A. Martınez Torres, K. P. Khemchandani, D. Jido, A. Hosaka, Phys. Rev. D 84 (2011) 074027, arXiv:1106.6101 [nucl-th].

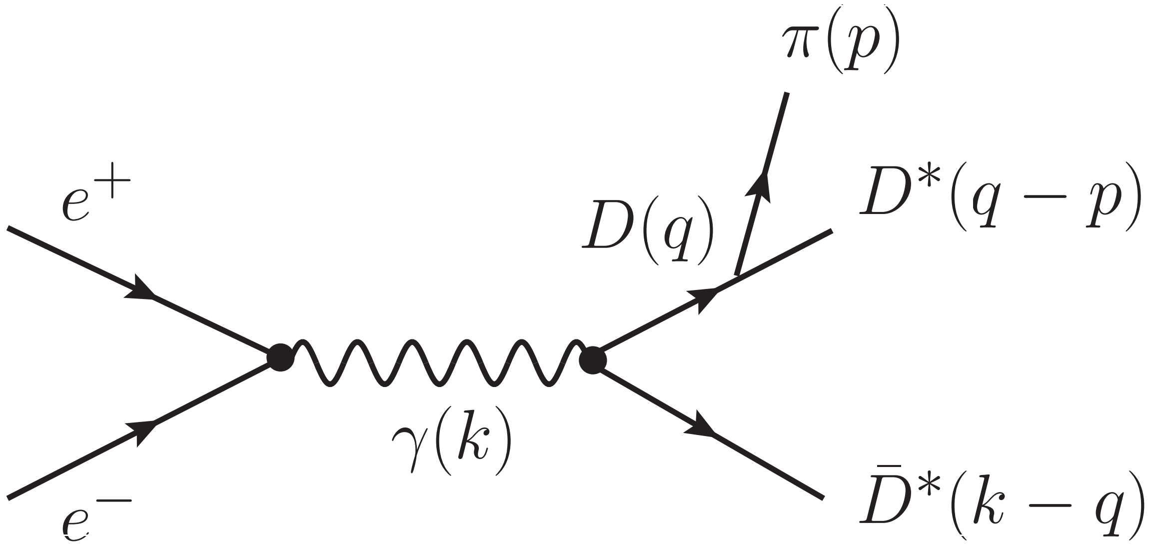
Reactions with hadron in final state

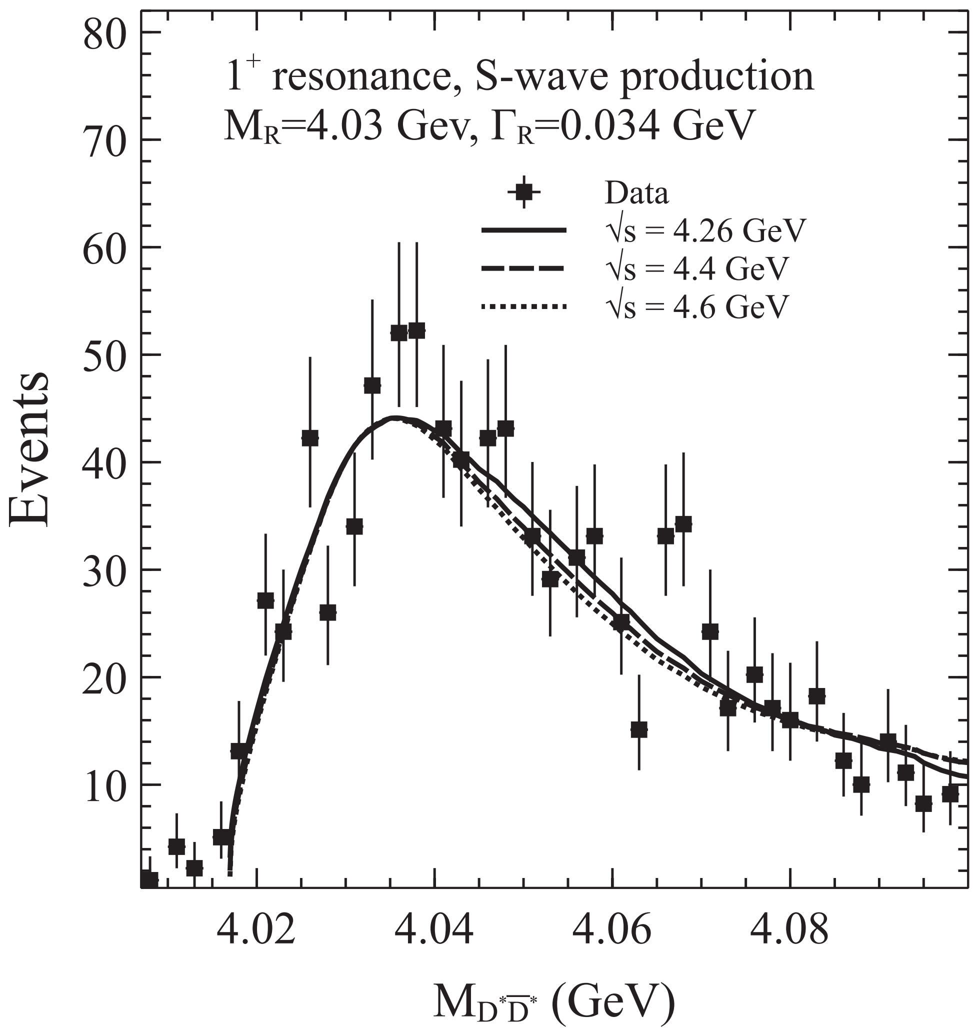




Mesic-nuclei production

Reactions with hadron in final state





Applications to heavy ion collisions

PHYSICAL REVIEW D **97,** 056001 (2018)

Absorption and production cross sections of K and K^*

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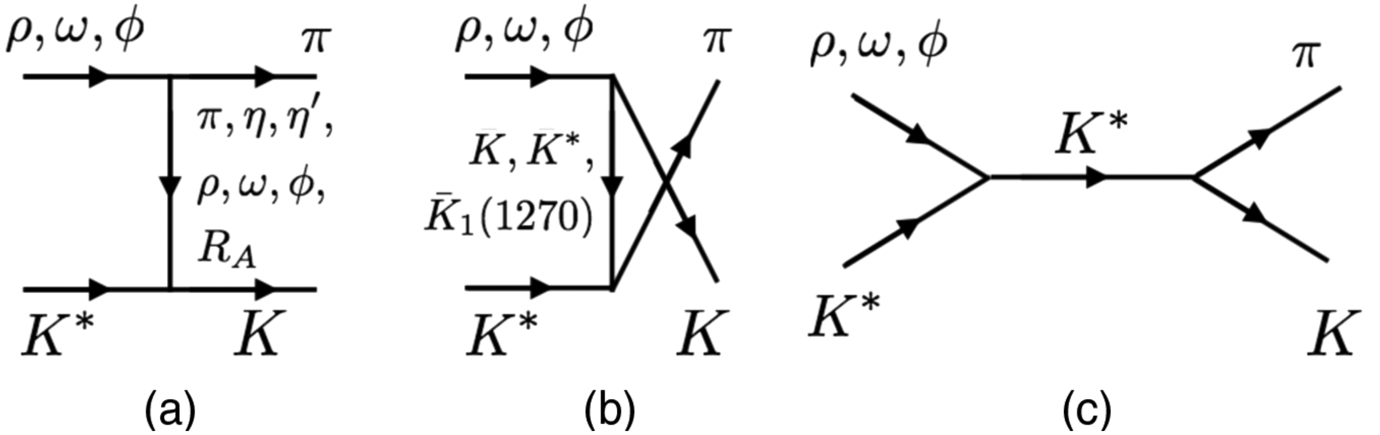
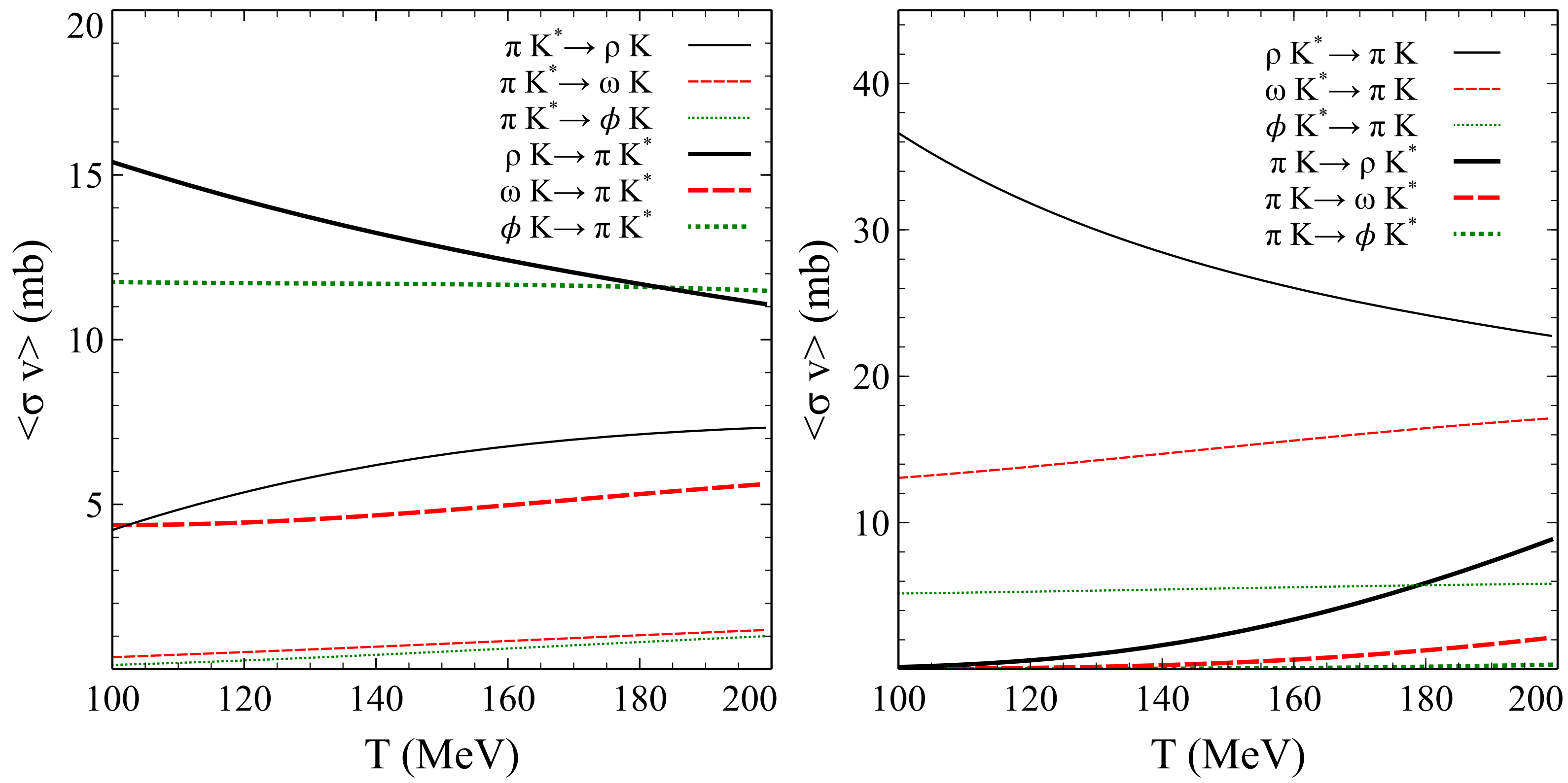
Applications to heavy ion collisions

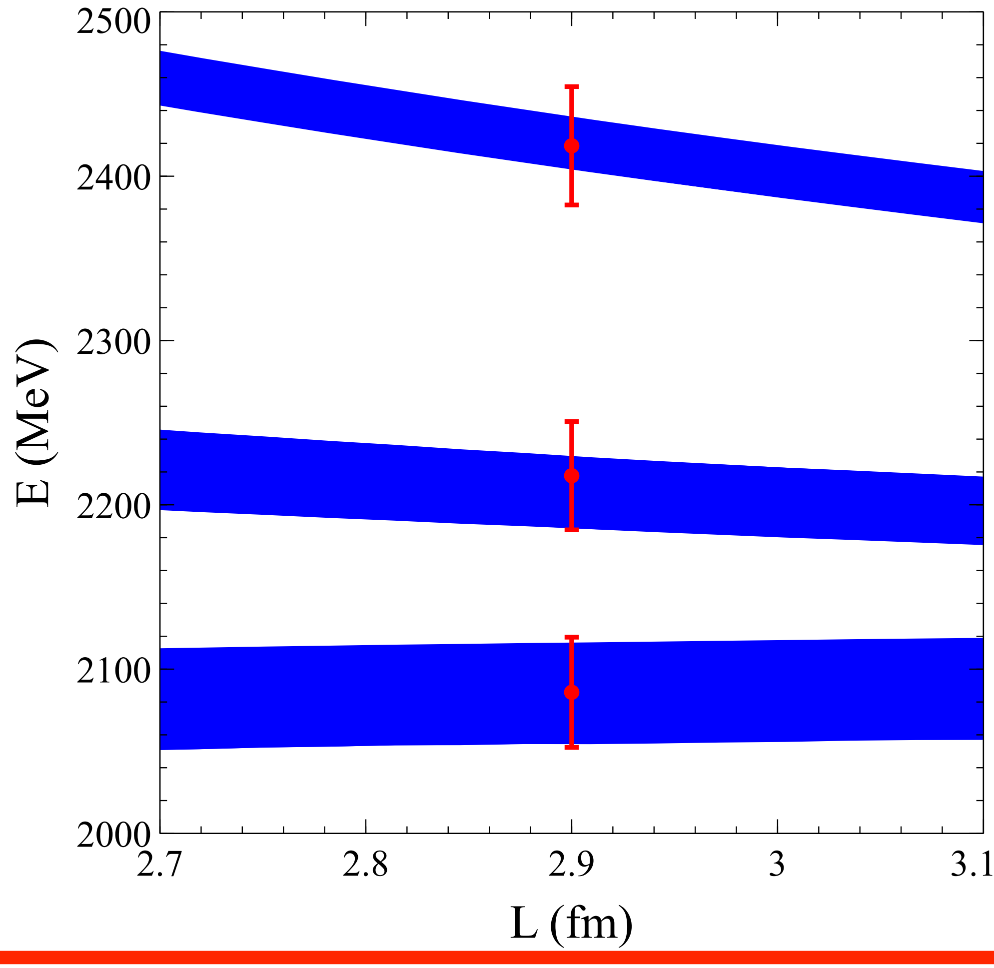




Unstable hadrons in finite volume: ASK Alberto

An analysis of the Lattice QCD spectra for $D^*_{s0}(2317)$ and $D^*_{s1}(2460)$

A. Martínez Torres[*a], E. Oset[b], S. Prelovsek[c,d,e], A. Ramos[f]



Unstable hadrons in finite volume: ASK Alberto

PHYSICAL REVIEW C **86**, 055201 (2012)

Strategy to find the two Λ(1405) states from lattice QCD simulations

A. Martínez Torres,[1] M. Bayar,[2,3] D. Jido,[1,4] and E. Oset[2]