Hadronic molecules and long range force in QCD

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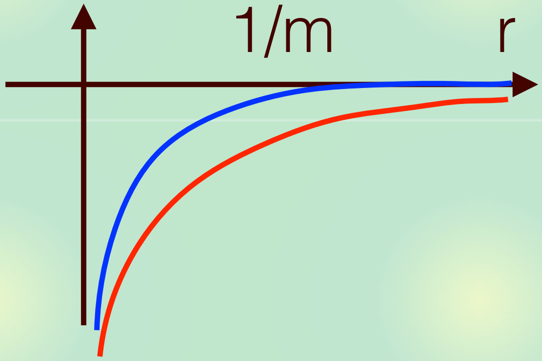
Long range force in QCD?

Two-body potential

$V(r) \propto \frac{1}{r}$: long (infinite) range

$V(r) \propto \frac{e^{-mr}}{r}$: finite (~1/m) range



Hadron-hadron interaction is considered to be finite range.

- Longest interaction range : π exchange ~ 1 fm
- Absence of the long range force is the basis for the (standard) scattering theory, Lüscher/HAL method, etc.

Emergence of (quasi) long range force

L.S. Geng, J. Lu, M.P. Valderrama, arXiv:1704.06123 [hep-ph]

M. Sanchez Sanchez, L.S. Geng, J. Lu, T. Hyodo, M.P. Valderrama, arXiv:1707.038202 [hep-ph]

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- **Emergence of long range force**
  - **- Yukawa potential**
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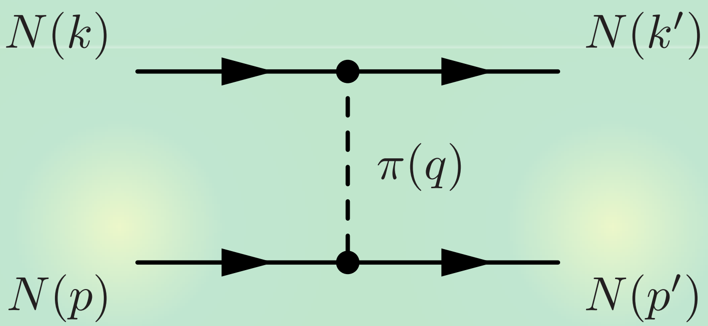
- **Hadronic molecules by (quasi)long range force**
  - **-** $D^*\bar{D}$ **molecules ~** X(3872), Z_c(3900)
  - **-** Λ^*N **molecule ~** $\bar{K}NN$

    T. Uchino, T. Hyodo, M. Oka, Nucl. Phys. A, 868-869, 53 (2011)
  - **- Doubly charmed** $D_{s0}D$ **molecules**

    M. Sanchez Sanchez, L.S. Geng, J. Lu, T. Hyodo, M.P. Valderrama, arXiv:1707.038202 [hep-ph]

NN potential

Low energy NN interaction : π exchange



- **Static approx.** $p^\mu = (M_N, \boldsymbol{p}), \quad p'^\mu = (M_N, \boldsymbol{p}'), \quad q^\mu = p'^\mu - p^\mu = (0, \boldsymbol{q})$
- **Coupling** $g\bar{N} i\gamma_5 \pi N \sim g\chi^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{q}\chi$ **(isospin ignored)**

Potential

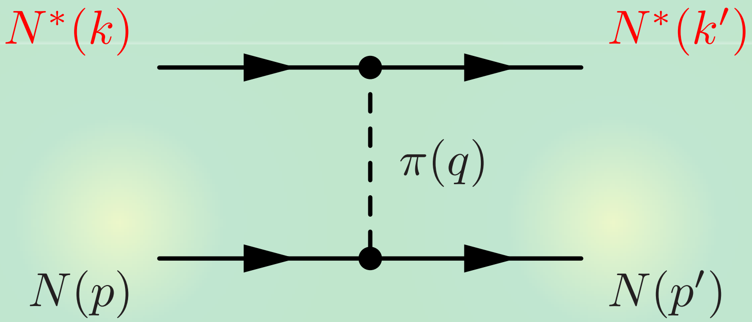
$$\frac{1}{(q^0)^2 - \boldsymbol{q}^2 - m_\pi^2}$$

$$V(\boldsymbol{r}) \sim \mathrm{F.T.}\left\{ g^2 (\boldsymbol{\sigma}_1\cdot\boldsymbol{q})(\boldsymbol{\sigma}_2\cdot\boldsymbol{q}) \frac{-1}{\boldsymbol{q}^2 + m_\pi^2} \right\}$$

Tensor op. **Yukawa** $\dfrac{e^{-m_\pi r}}{r}$

NN* potential

Low energy NN*(J^P=1/2-) interaction



- **Static approx.** $p^\mu = (M_N, \boldsymbol{p}), \quad k^\mu = (M_{N^*}, \boldsymbol{k}), \quad q^\mu = p'^\mu - p^\mu = (0, \boldsymbol{q})$

- **Couplings** $g\bar{N}\gamma_5 \pi N \sim g\chi^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{q}\chi, \quad g^*\bar{N}^*\gamma_5\pi N^* \sim g^*\chi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{q}\chi$

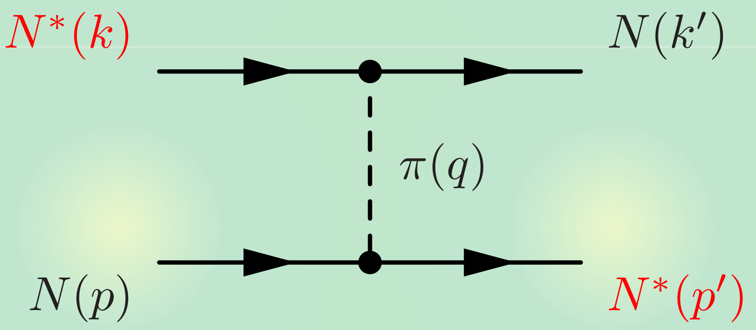
Potential

$$V(\boldsymbol{r}) \sim \text{F.T.}\left\{ g g^* (\boldsymbol{\sigma}_1\cdot\boldsymbol{q})(\boldsymbol{\sigma}_2\cdot\boldsymbol{q})\frac{-1}{\boldsymbol{q}^2 + m_\pi^2}\right\}$$

- **Sign of V(r) depends on the relative sign of g and g***

NN* potential (exchange)

Another diagram for NN*(J^P=1/2-) interaction



Mass difference = energy transfer

$$\Delta = M_{N^*} - M_N$$

- **Static approx.** $p^\mu = (M_N, \boldsymbol{p}), \quad p'^\mu = (M_{N^*}, \boldsymbol{p}'), \quad q^\mu = (\Delta, \boldsymbol{q})$
- **Coupling** $\tilde{g}\, \bar{N}^* \pi N + \text{h.c.} \sim \tilde{g}\, \chi^\dagger \mathbf{1} \chi$

Potential (P_σ: spin exchange factor)

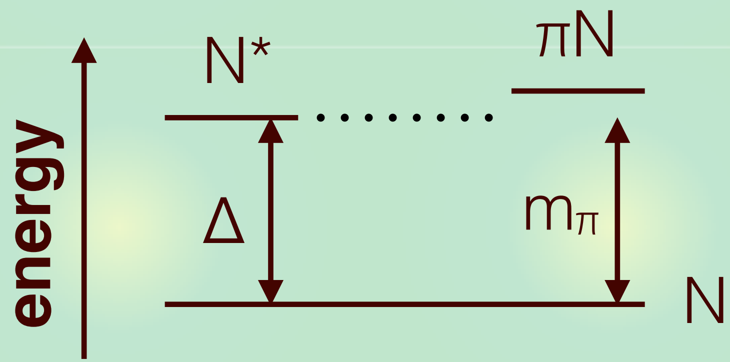
$$\mu = \sqrt{m_\pi^2 - \Delta^2}$$

$$V(r) \sim \text{F.T.} \left\{ \tilde{g}^2 \frac{1}{\Delta^2 - \boldsymbol{q}^2 - m_\pi^2} \right\} P_\sigma = \text{F.T.} \left\{ \tilde{g}^2 \frac{-1}{\boldsymbol{q}^2 + \mu^2} \right\} P_\sigma \sim \tilde{g}^2 P_\sigma \frac{e^{-\mu r}}{r}$$

- **Sign of V(r) is fixed and attractive (c.f. σ exchange in NN)**
- **Effective mass μ=0 —> long range force (Coulomb like)**

Unitary limit

What does $\mu = (m_\pi^2 - \Delta^2)^{1/2} = 0$ $(\Delta = m_\pi)$ **mean?**



- $\Delta < m_\pi$: N* **cannot decay to** πN **—> virtual** π **exchange**

- $\Delta > m_\pi$: N* **decays to** πN **—> real** π **exchange**
  (N* **acquires a width, potential picture is not adequate)**

- $\Delta = m_\pi$: N* **lies on top of the** πN **threshold**

s-wave resonance at threshold : unitary limit of πN **system**

E. Braaten, H.-W. Hammer, Phys. Rept. 428, 259 (2006)

- **Scattering length diverges —> universal physics**

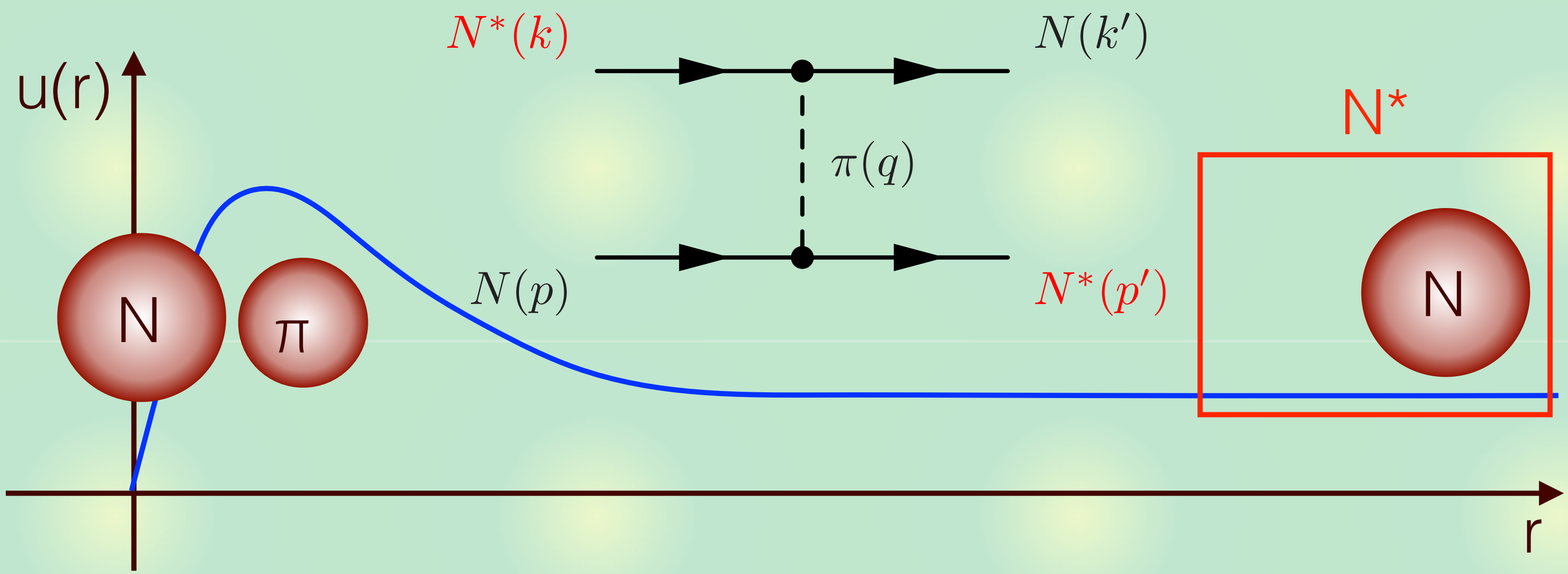
Zero-energy resonance

Resonance at threshold, "zero-energy resonance"

- **Decay width vanishes, potential picture still valid.**
- **Completely composite and coupling g is fixed**

T. Hyodo, Phys. Rev. C 90, 055208 (2014)

- **Wavefunction of N*(πN) spreads to infinity.**



Origin of the long range force?

Toward physical realization

We show that

- **long range force emerges if the effective mass** $\mu=0$,
- **induced by the zero-energy resonance, and**
- **the interaction is Coulomb like attraction (in some channel).**

$$V(r) \sim \frac{e^{-\mu r}}{r}, \quad \mu = \sqrt{m^2 - \Delta^2}$$

Attraction at long distance in hadron-hadron interaction

- **can generate a hadronic molecule (loosely bound two-hadron system)?**

Realization in physical hadron systems

- **No system with exact** $\mu=0$ (N*: $\Delta\sim595$ MeV / $m_\pi\sim140$ MeV)
- **Is there any system with small** μ**?**

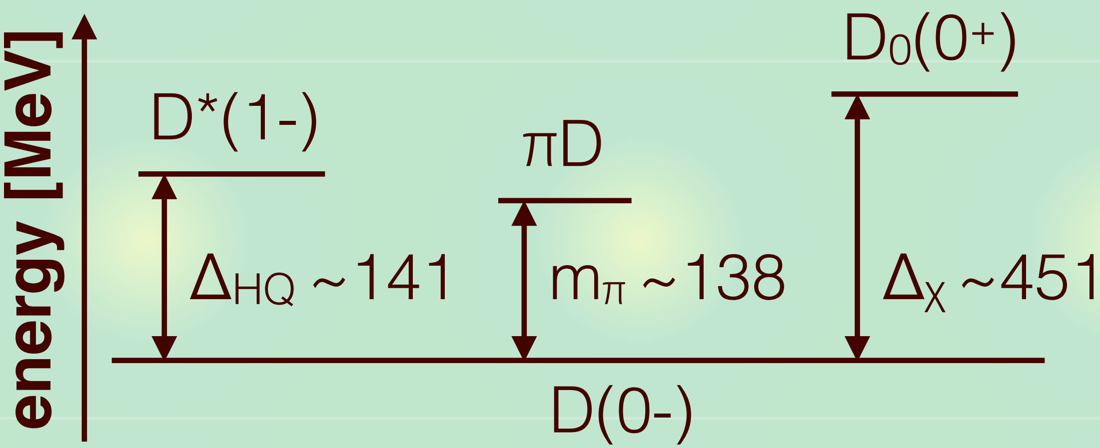
Charmonium-like XYZ exotics

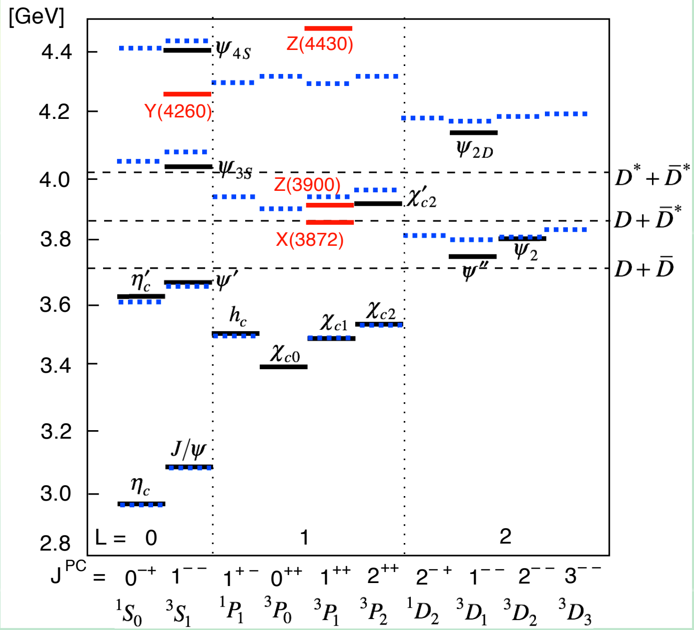
XYZ **states: exotic candidates above** $D\bar{D}$ **threshold**

A. Hosaka, *et al.*, PTEP 062C01 (2016)

- $D\bar{D}^*$ **molecule is proposed for** X(3872), Z(3900), **etc.**

D **meson and excited states**





- $\Delta_{HQ} \sim m_\pi$ **: origin of** $D\bar{D}^*$ **molecule?**

- $\Delta_{HQ}\sim 1/m_c$, $m_\pi^2 \sim m_q$, $\Delta_\chi \sim \langle\bar{q}q\rangle$ **are related to QCD symmetries**

<u>T. Sugiura, T. Hyodo, in progress</u>

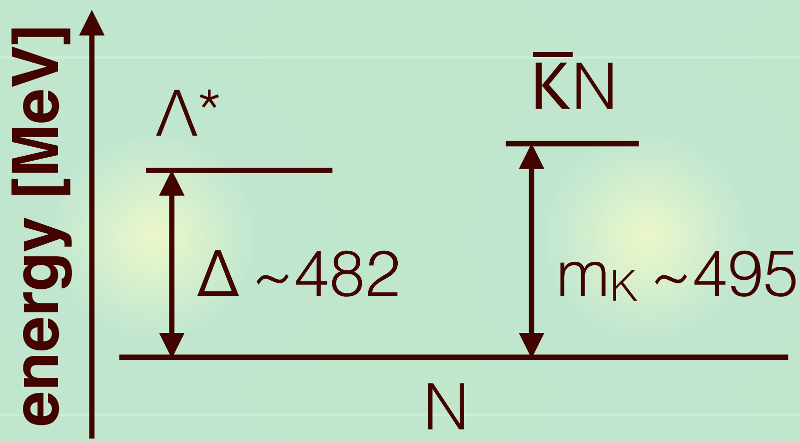
Strange dibaryon

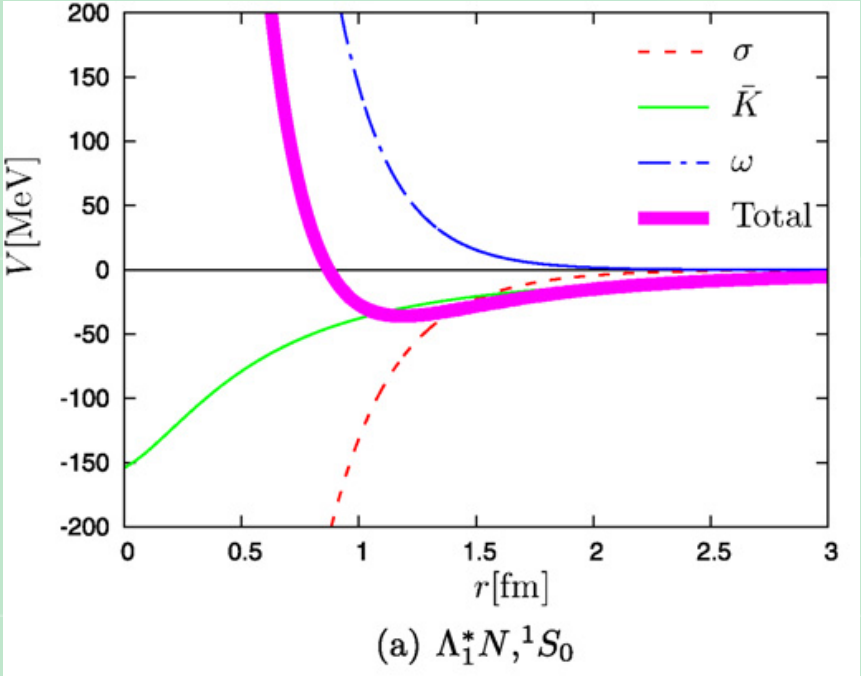
$\Lambda(1405)=\Lambda^*$: $\bar{K}N$ quasibound state near the threshold

T. Hyodo, D. Jido, Prog. Part. Nucl. Phys. 67, 55 (2012)

- $\bar{K}$ exchange between Λ^* and N

Λ^* (at 1420 MeV), $\bar{K}N$ threshold





- μ~91 MeV: $\bar{K}$ exchange has longer tail than expected

- attractive in spin singlet channel —> $\bar{K}NN$ as Λ^*N system

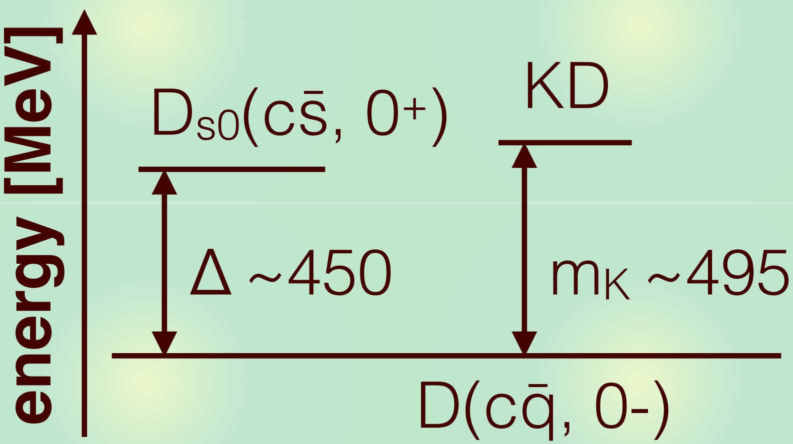
T. Uchino, T. Hyodo, M. Oka, Nucl. Phys. A, 868-869, 53 (2011)

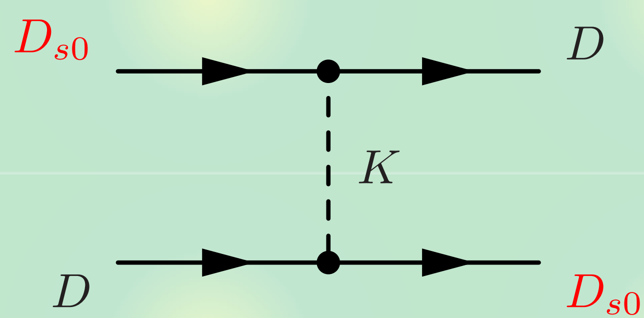
Doubly charmed exotic meson

Charm C=2 **meson: manifestly exotic (needs four quarks)**

- No state has been established.

D_{s0}(2317), KD **threshold**





- Vector exchange is forbidden by OZI rule.

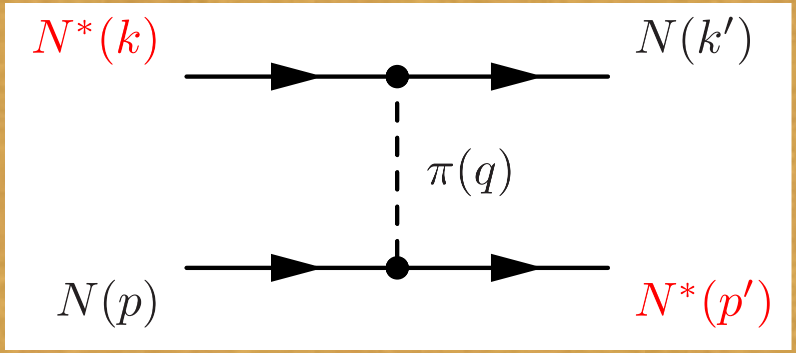
- Attraction —> $D_{s0}D$ **molecule with 6 MeV binding**

- Same mechanism in $D_{s1}(1^+)D^*(1^-)$ **—> 7 MeV binding**

M. Sanchez Sanchez, L.S. Geng, J. Lu, T. Hyodo, M.P. Valderrama, arXiv:1707.038202 [hep-ph]

Summary

- We show that the **long range force** emerges among hadrons when the mass difference Δ matches the mass of exchange particle m.



$$V(r) \sim \frac{e^{-\mu r}}{r}, \quad \mu = \sqrt{m^2 - \Delta^2}$$

- There are some physical systems with **small μ** so that the interaction range is enhanced. This can be an origin of some **hadronic molecules**.