Exotic doubly charmed $D_{s0}^*(2317)D$ and $D_{s1}^*(2460)D^*$ molecules

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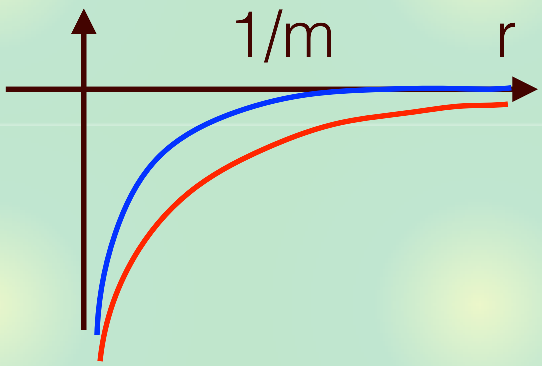
Long range force in QCD?

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.

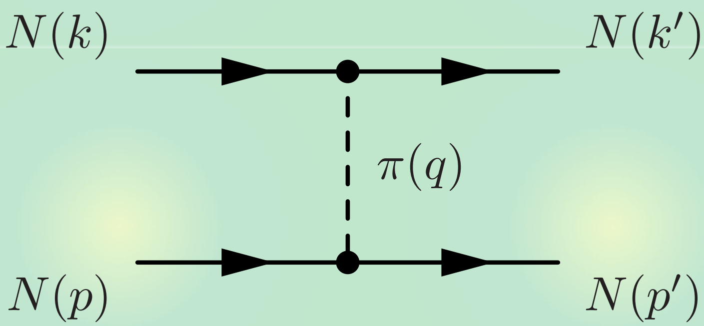
- **Longest interaction range : π exchange ~ 1 fm**
- **Absence of the long range force is the basis for the (standard) scattering theory, Lüscher/HAL method, etc.**

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]

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

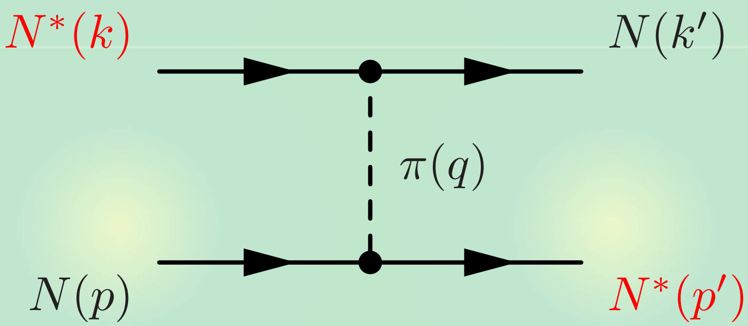
$$\frac{1}{(q^0)^2 - \boldsymbol{q}^2 - m_\pi^2}$$

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

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

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** $\tilde{g}\, \bar{N}^* \pi N + \mathrm{h.c.} \sim \tilde{g}\, \chi^\dagger \mathbf{1} \chi$

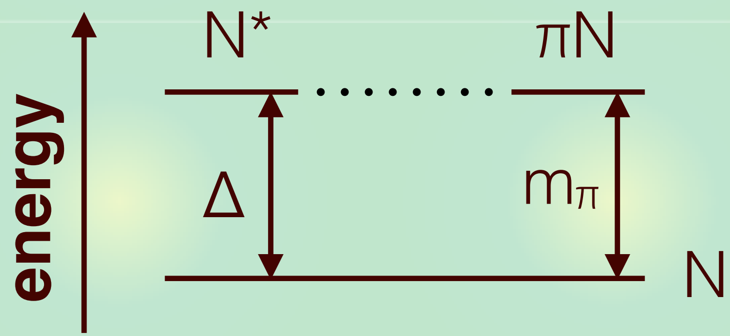
Potential (P_σ: spin exchange factor) $\mu = \sqrt{m_\pi^2 - \Delta^2}$

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

- **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 and zero-energy resonance

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



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

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

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

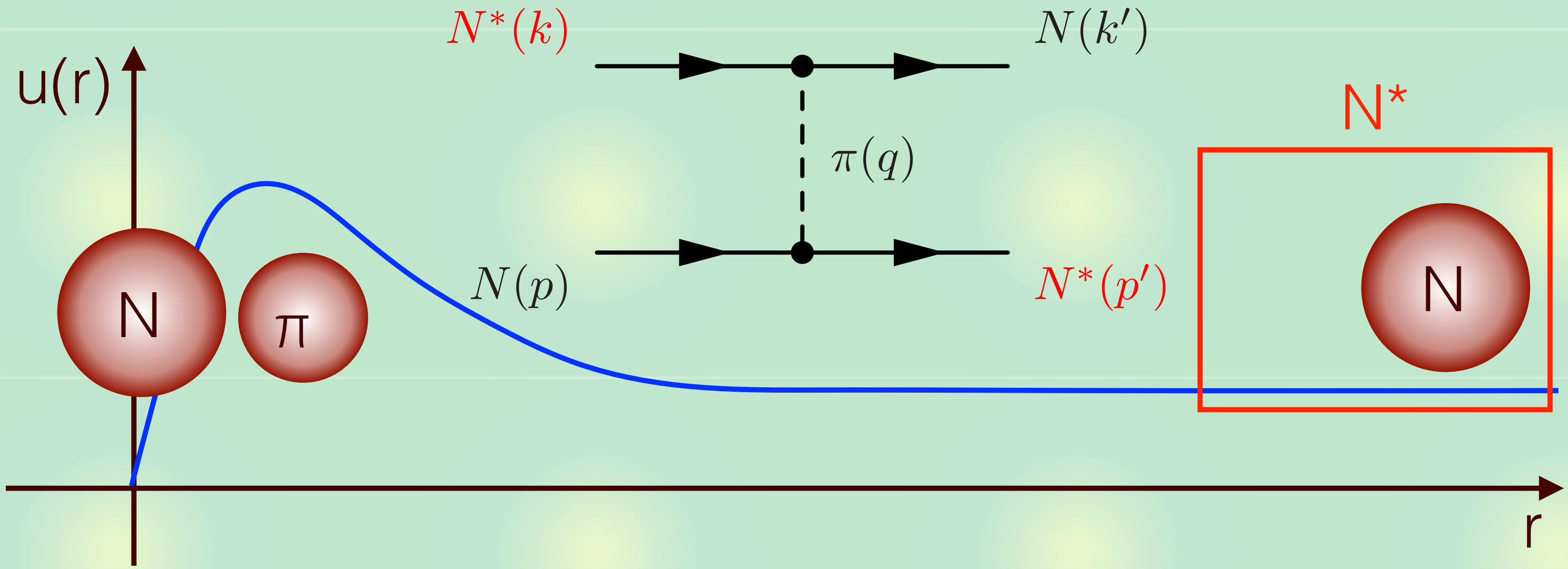
E. Braaten, H.-W. Hammer, Phys. Rept. 428, 259 (2006)

- **completely composite : w.f. of** N* **spreads to infinity.**

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

Origin of the long range force

Origin of the long range force



Realization in physical hadron systems

- **No system with exact** μ=0 (N***:** Δ~595 MeV / m_π~140 MeV)
- **Is there any system with small μ? (c.f.** $\bar{K}$NN **~** Λ*N**)**

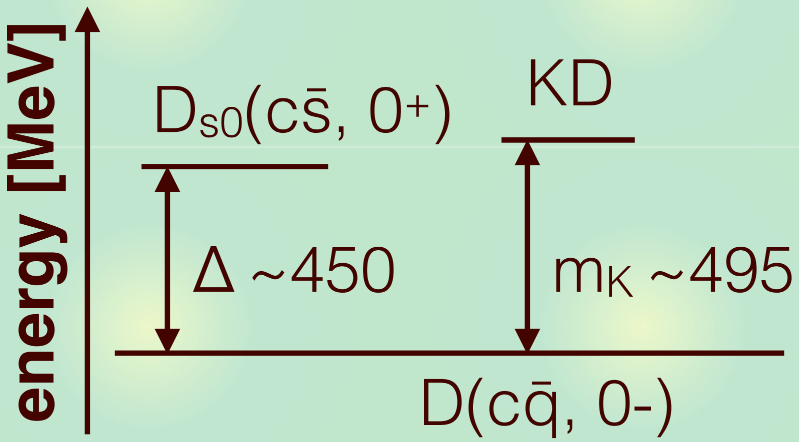
T. Uchino, T. Hyodo, M. Oka, Nucl. Phys. A, 868-869, 53 (2011)

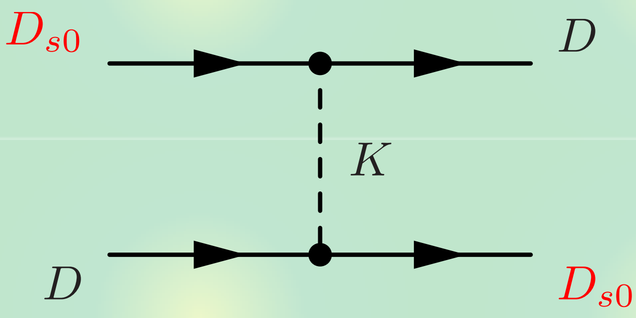
Doubly charmed exotic meson

We consider $D_{s0}(0^+)D(0-)$ **molecule via** K **exchange**

- Charm C=2**: manifestly exotic (at least four quarks)**

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





- K **exchange gives quasi-long range (**μ~200 **MeV) attraction**

- Repulsive ω **exchange is forbidden by OZI rule.**

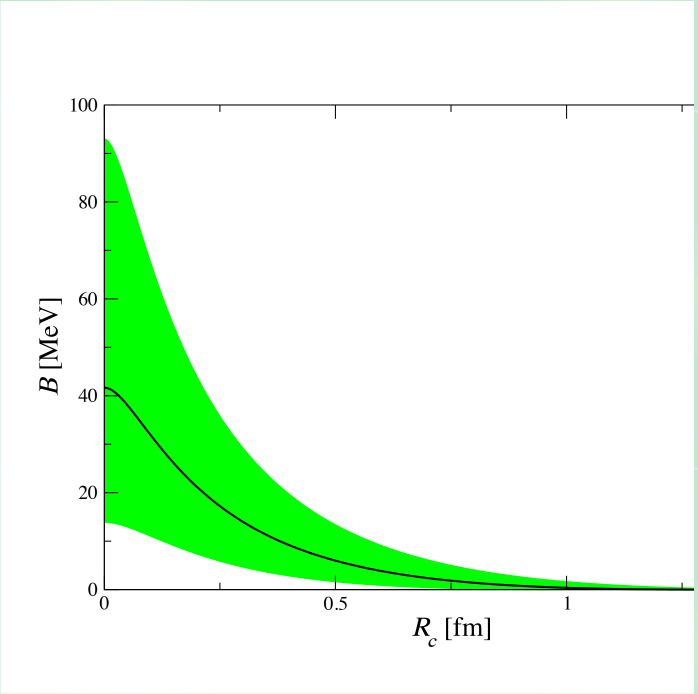
- Same mechanism in $D_{s1}(1^+)D^*(1-)$ **(HQ symmetry)**

Prediction of binding energy

Effective Lagrangian for $D_{s0}DK$ (and HQ partner) coupling

$$\mathcal{L} = \frac{h}{2}\mathrm{Tr}[\bar{H}_a S_b \not{A}_{ab} \gamma_5] + \mathrm{C.C.}$$

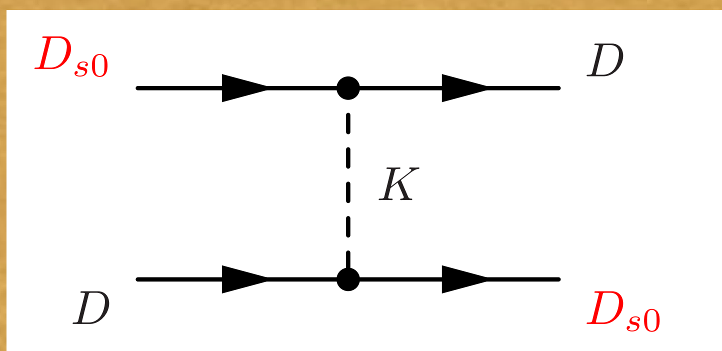
- **coupling constant** h **:** D_0 —>$D\pi$ **decay + SU(3) symmetry**
- **Short range cutoff** R_c **<— hadron size**



- R_c ~ 0.5 **fm —>** ~ 6 **MeV binding**

Summary

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



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

- K **exchange in** $D_{s0}(0^+)D(0-)$ **system:** μ~200 **MeV**

  —> exotic doubly charmed hadronic molecule

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