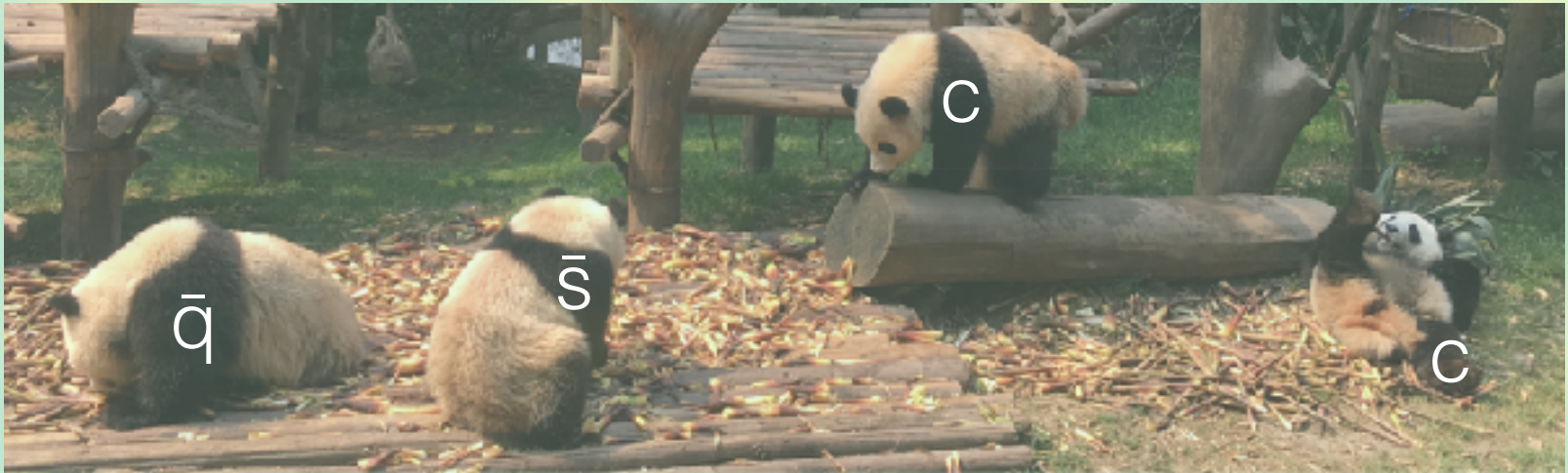


Exotic hadrons and emergent long range force in QCD



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Classification of hadrons

Observed hadrons

PDG2018 : <http://pdg.lbl.gov/>

| | | | | | | | | | | | | |
|-----------------------|---------|-----------------------|----|-----------------------|----------------|-----------------------|----|-----------------------|-------------------------------|----------------|----------------------------|----------------|
| 1/2 ⁺ **** | Λ(1220) | 3/2 ⁺ **** | Σ* | 1/2 ⁺ **** | Ξ ⁰ | 1/2 ⁺ **** | Λ* | 1/2 ⁺ **** | LIGHT UNFLAVORED (u, d, s) | STRANGE (s) | CHARMED, STRANGE (c, s) | cc̄ (c, c̄) |
|-----------------------|---------|-----------------------|----|-----------------------|----------------|-----------------------|----|-----------------------|-------------------------------|----------------|----------------------------|----------------|

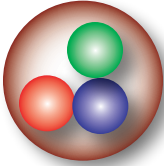
Only **color singlet** states are observed.

—> Color confinement problem

Flavor quantum numbers are described by $qqq/q\bar{q}$.

Why no $qqq\bar{q}$, $qqqq\bar{q}$, ... states (exotic hadrons)?

—> Exotic hadron problem, as nontrivial as confinement!

| | | | | |
|-------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|---|
| Λ(2700) 13/2 ⁺ ** | Λ(1710) 1/2 ⁺ * | Σ(3000) * | Σ(3170) * |  <p>~ 150 baryons</p> |
| Λ(1800) 1/2 ⁻ *** | Σ _b 1/2 ⁺ *** | Σ _b 3/2 ⁺ *** | Σ _b 1/2 ⁺ *** | |
| Λ(1810) 1/2 ⁺ *** | Σ _b 3/2 ⁺ *** | Ξ _b 1/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | |
| Λ(1820) 5/2 ⁺ **** | Ξ _b 1/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | Ξ _b 1/2 ⁺ *** | |
| Λ(1830) 5/2 ⁻ **** | Ξ _b 3/2 ⁺ *** | Ξ _b 1/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | |
| Λ(1890) 3/2 ⁺ **** | Ξ _b 3/2 ⁺ *** | Ξ _b 1/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | |
| Λ(2000) * | Ξ _b 3/2 ⁺ *** | Ξ _b 1/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | |
| Λ(2020) 7/2 ⁺ * | Ξ _b 3/2 ⁺ *** | Ξ _b 1/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | |
| Λ(2050) 3/2 ⁻ * | Ξ _b 3/2 ⁺ *** | Ξ _b 1/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | |
| Λ(2100) 7/2 ⁻ **** | Ξ _b 3/2 ⁺ *** | Ξ _b 1/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | |
| Λ(2110) 5/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | Ξ _b 1/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | |
| Λ(2325) 3/2 ⁻ * | Ξ _b 3/2 ⁺ *** | Ξ _b 1/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | |
| Λ(2350) 9/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | Ξ _b 1/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | |
| Λ(2585) ** | Ξ _b 3/2 ⁺ *** | Ξ _b 1/2 ⁺ *** | Ξ _b 3/2 ⁺ *** | |

| | | | | |
|---|---|---|---|--|
| a ₁ (1640) 1 ⁻ (1 ⁺ -) | a ₀ (2450) 1 ⁺ (6 ⁺ -) | D _s (2400) ⁰ 1/2(0 ⁺) | BOTTOM, CHARMED (B = C = ±1) | χ _{b1} (1P) 0 ⁻ (1 ⁻ -) |
| f ₂ (1640) 0 ⁺ (2 ⁺ +) | f ₀ (2510) 0 ⁺ (6 ⁺ +) | D _s (2400) [±] 1/2(0 ⁺) | B _c (2S) [±] 0(0 ⁻) | χ _{b2} (1P) 0 ⁺ (2 ⁺ +) |
| ρ ₂ (1645) 0 ⁺ (2 ⁻ -) | | D _s (2420) ⁰ 1/2(1 ⁺) | | η _b (2S) 0 ⁺ (0 ⁻ -) |
| ω(1650) 0 ⁻ (1 ⁻ -) | | D _s (2420) [±] 1/2(?) | | γ(2S) 0 ⁻ (1 ⁻ -) |
| ω ₃ (1670) 0 ⁻ (3 ⁻ -) | | D _s (2430) ⁰ 1/2(1 ⁺) | | γ(1D) 0 ⁻ (2 ⁻ -) |
| π ₂ (1670) 1 ⁻ (2 ⁻ +) | | D _s (2460) ⁰ 1/2(2 ⁺) | | χ _{b0} (2P) 0 ⁺ (0 ⁺ +) |
| | | D _s (2460) [±] 1/2(2 ⁺) | | χ _{b1} (2P) 0 ⁺ (1 ⁺ +) |
| | | D(2550) ⁰ 1/2(0 ⁻) | | h _b (2P) ?(1 ⁺ -) |
| | | D(2600) 1/2(?) | | χ _{b2} (2P) 0 ⁺ (2 ⁺ +) |
| | | D [*] (2640) [±] 1/2(?) | | γ(3S) 0 ⁻ (1 ⁻ -) |
| | | D(2750) 1/2(?) | | χ _{b1} (3P) 0 ⁺ (1 ⁺ +) |
| | | | | γ(4S) 0 ⁻ (1 ⁻ -) |
| | | | | X(10610) [±] 1 ⁺ (1 ⁺) |
| | | | | X(10610) ⁰ 1 ⁺ (1 ⁺) |
| | | | | X(10650) [±] ?(1 ⁺) |
| | | | | γ(10860) 0 ⁻ (1 ⁻ -) |
| | | | | γ(11020) 0 ⁻ (1 ⁻ -) |

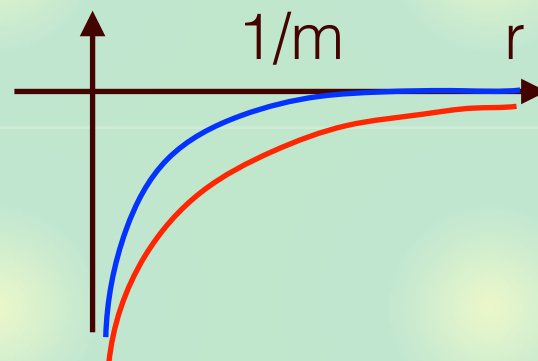
All ~ 360 hadrons emerge from single QCD Lagrangian.

Long range force in QCD?

Two-body potential

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

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



Hadron-hadron interaction is considered to be **finite range**.

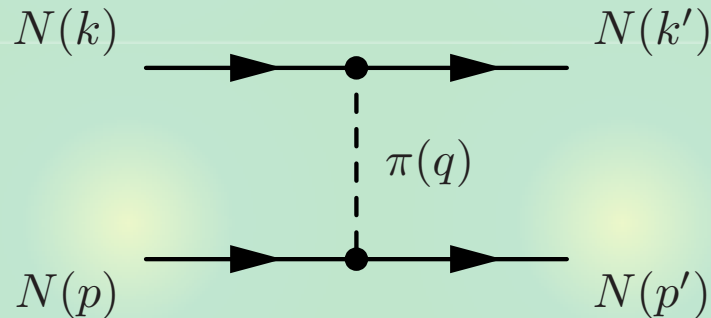
- Longest interaction range
← exchange of lightest particle (π) ~ 1 fm
- Absence of the long range force is the basis for the (standard) scattering theory, Lüscher/HAL method, etc.

There can be (quasi) **long range** force beyond 1 fm.

M. Sanchez Sanchez, L.S. Geng, J. Lu, T. Hyodo, M.P. Valderrama,
[arXiv:1707.038202 \[hep-ph\]](https://arxiv.org/abs/1707.038202)

NN potential

Low energy NN interaction : π exchange



- **Static approx.** $p^\mu = (M_N, \mathbf{p})$, $p'^\mu = (M_N, \mathbf{p}')$, $q^\mu = p'^\mu - p^\mu = (0, \mathbf{q})$

- **Coupling** $g\bar{N}i\gamma_5\pi N \sim g\chi^\dagger \boldsymbol{\sigma} \cdot \mathbf{q}\chi$ **(isospin ignored)**

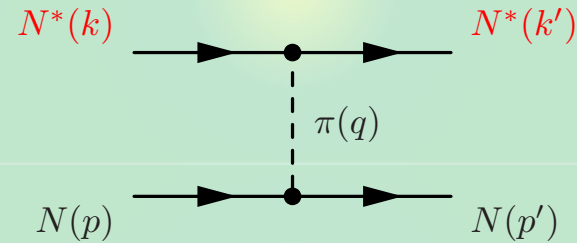
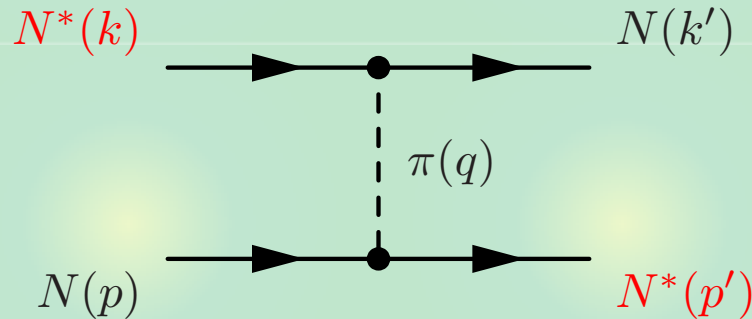
Potential

$$V(\mathbf{r}) \sim \text{F.T.} \left\{ \underbrace{g^2 (\boldsymbol{\sigma}_1 \cdot \mathbf{q})(\boldsymbol{\sigma}_2 \cdot \mathbf{q})}_{\text{Tensor op.}} \underbrace{\frac{-1}{q^2 + m_\pi^2}}_{\text{Yukawa}} \right\} \frac{1}{(q^0)^2 - \mathbf{q}^2 - m_\pi^2}$$

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

NN* potential (exchange)

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



**Mass difference
= energy transfer**

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

- **Static approx.** $p^\mu = (M_N, \mathbf{p})$, $p'^\mu = (M_{N^*}, \mathbf{p}')$, $q^\mu = (\Delta, \mathbf{q})$

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

Potential (P_σ: spin exchange factor)

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

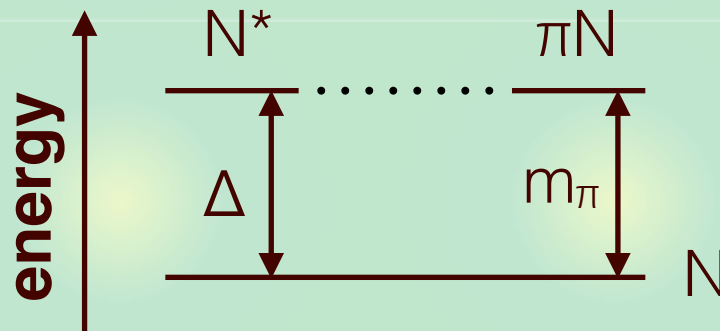
$$V(r) \sim \text{F.T.} \left\{ \tilde{g}^2 \frac{1}{\Delta^2 - \mathbf{q}^2 - m_\pi^2} \right\} P_\sigma = \text{F.T.} \left\{ \tilde{g}^2 \frac{-1}{\mathbf{q}^2 + \mu^2} \right\} P_\sigma \sim \tilde{g}^2 P_\sigma \frac{e^{-\mu r}}{r}$$

- **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 $\mu = (m_\pi^2 - \Delta^2)^{1/2} = 0 \Leftrightarrow \Delta = m_\pi$ 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 \rightarrow universal physics

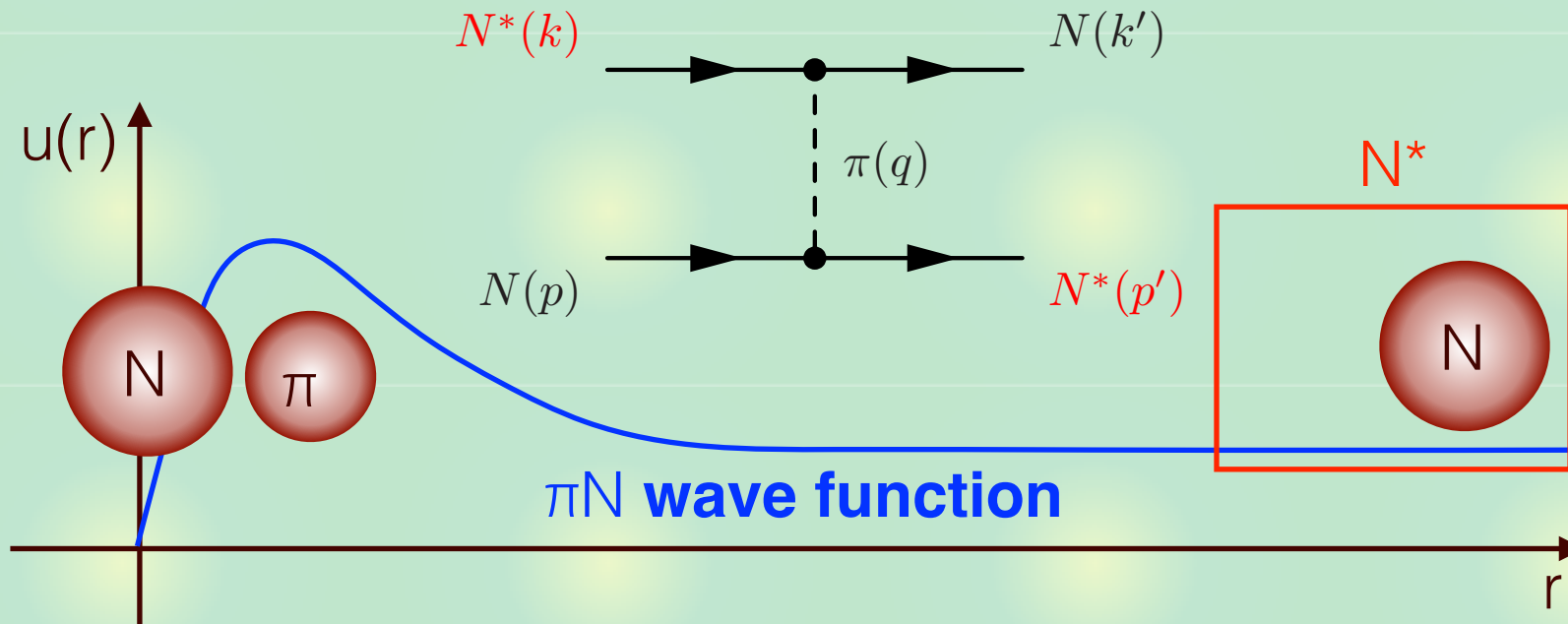
E. Braaten, H.-W. Hammer, Phys. Rept. 428, 259 (2006)

- 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 $\mu=0$ (N^* : $\Delta \sim 595$ MeV / $m_\pi \sim 140$ MeV)
- Is there any system with **small** μ ? (c.f. $\bar{K}NN \sim \Lambda^*N$)

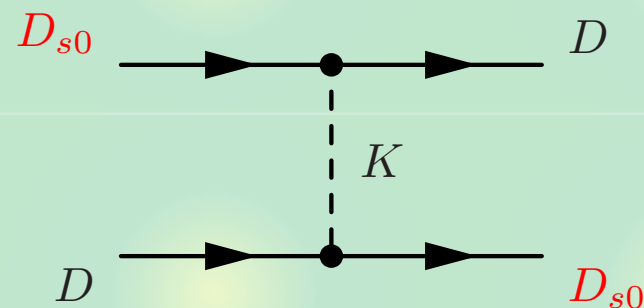
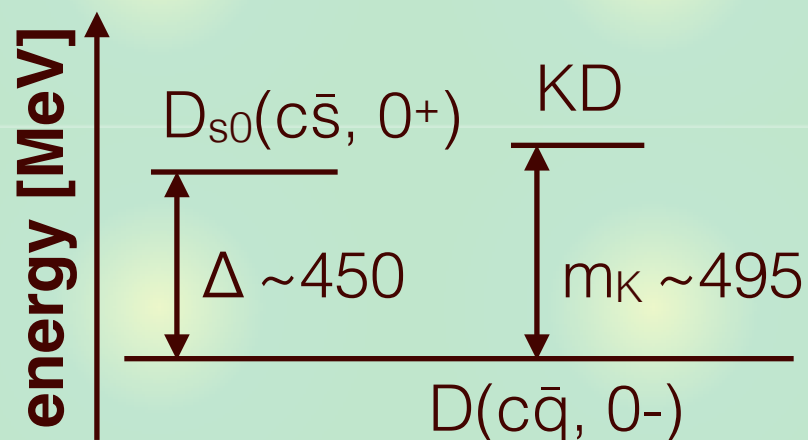
T. Uchino, T. Hyodo, M. Oka, Nucl. Phys. A, 868-869, 53 (2011)

Doubly charmed exotic meson

We consider $D_{s0}(c\bar{s}, 0^+)D(c\bar{q}, 0^-)$ system via K exchange

- Charm $C=2$: manifestly **exotic** ($cc\bar{q}\bar{s}$)

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



- K exchange gives **quasi-long range** ($\mu \sim 200$ MeV) attraction

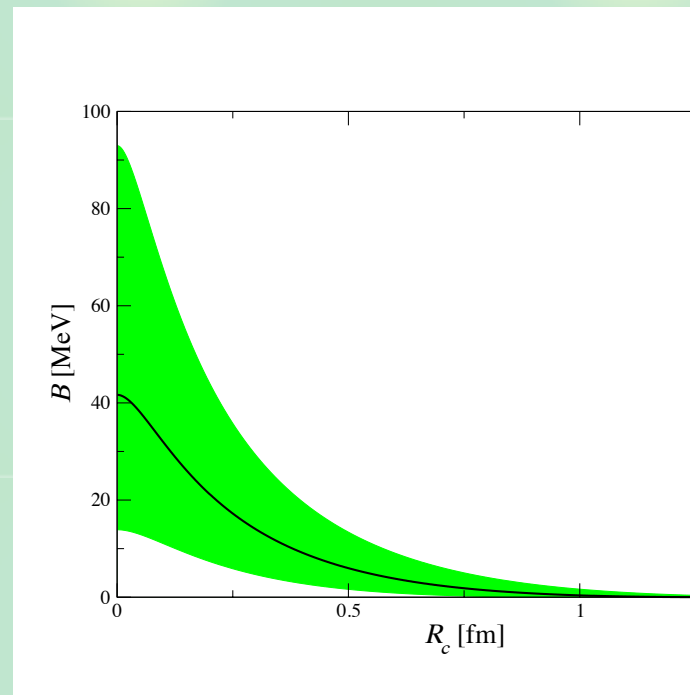
Can the attraction generate a bound state?

Prediction of binding energy

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

$$\mathcal{L} = \frac{h}{2} \text{Tr}[\bar{H}_a S_b A_{ab} \gamma_5] + \text{C.C.}$$

- coupling constant h : $D_0 \rightarrow D\pi$ decay + SU(3) symmetry
- Short range cutoff $R_c \leftarrow$ hadron size

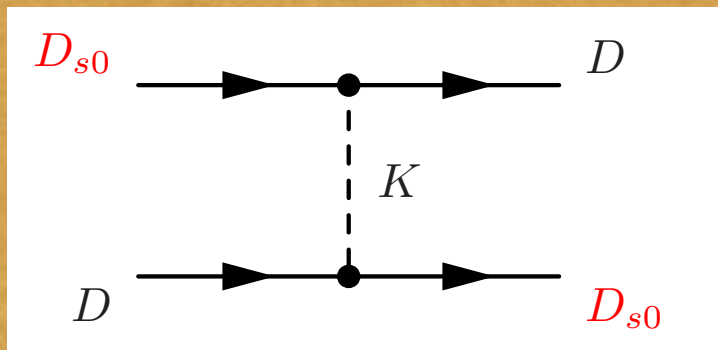


- $R_c \sim 0.5$ fm \rightarrow ~ 6 MeV binding

Summary



Long range force among hadrons emerges when the mass difference Δ matches with the mass of the exchange particle m .



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



K exchange in $D_{s0}(0^+)D(0^-)$ system: $\mu \sim 200$ MeV
—> prediction of exotic charmed tetraquark

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