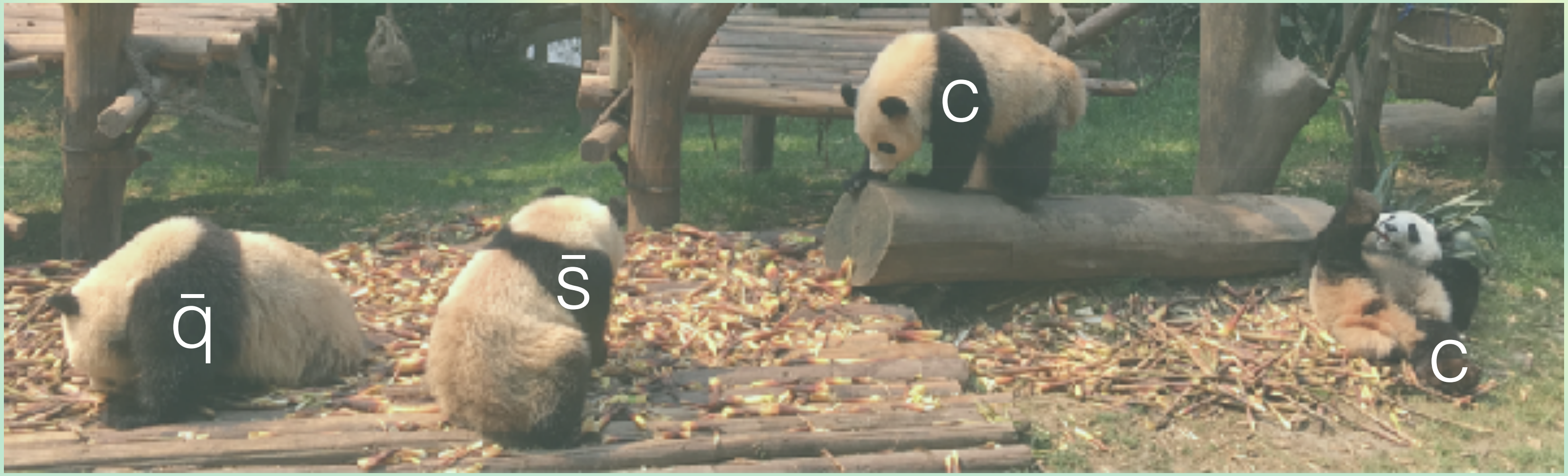
Exotic hadrons and emergent long range force in QCD



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Classification of hadrons

Observed hadrons

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

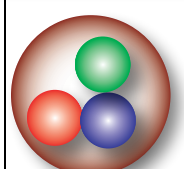
Only color singlet states are observed.

—> Color confinement problem

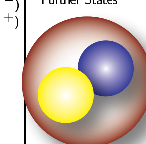
Flavor quantum numbers are described by $qqq/q\bar{q}$.

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

—> Exotic hadron problem, as notrivial as confinement!



~ 150 baryons



~ 210 mesons

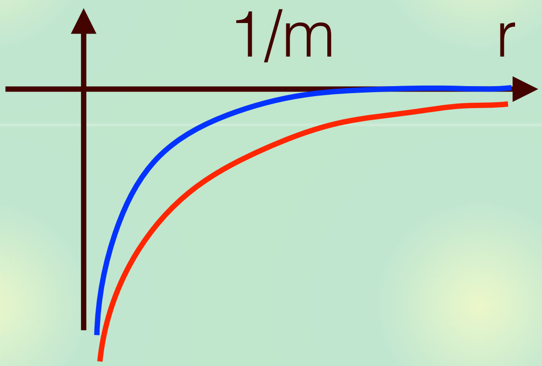
All ~ 360 hadrons emerge from single QCD Lagrangian.

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
  <— exchange of lightest particle (π) ~ 1 fm

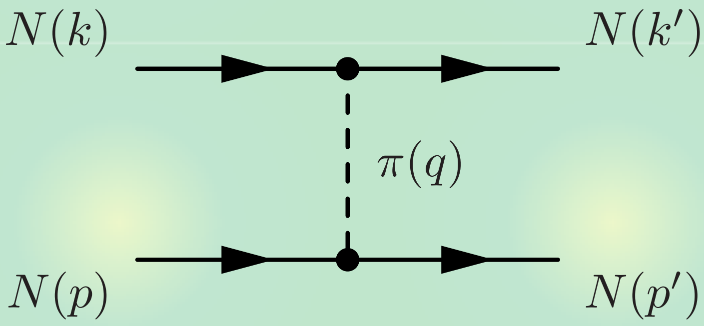
- Absence of the long range force is the basis for the (standard) scattering theory, Lüscher/HAL method, etc.

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]

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

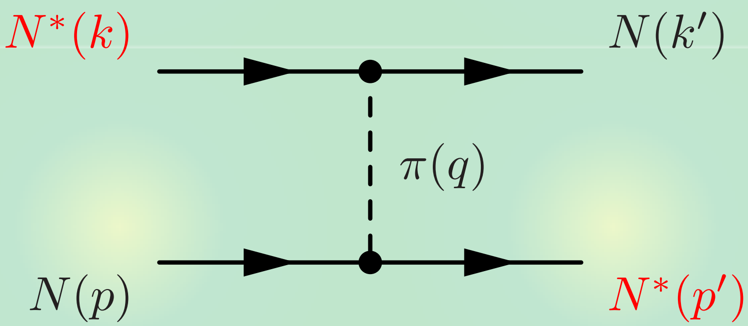
$$\frac{1}{(q^0)^2 - \boldsymbol{q}^2 - m_\pi^2}$$

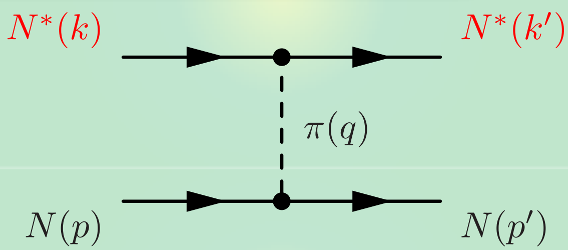
$$V(\boldsymbol{r}) \sim \text{F.T.}\left\{ g^2(\boldsymbol{\sigma}_1\cdot\boldsymbol{q})(\boldsymbol{\sigma}_2\cdot\boldsymbol{q})\frac{-1}{\boldsymbol{q}^2 + m_\pi^2} \right\}$$

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

NN* potential (exchange)

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)

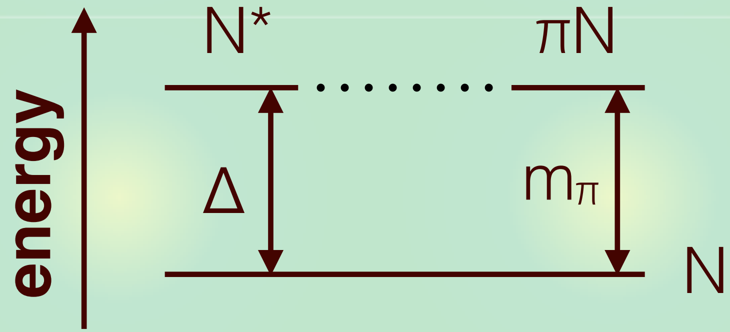
$$\mu = \sqrt{m_\pi^2 - \Delta^2}$$

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

- **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 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 —> universal physics**

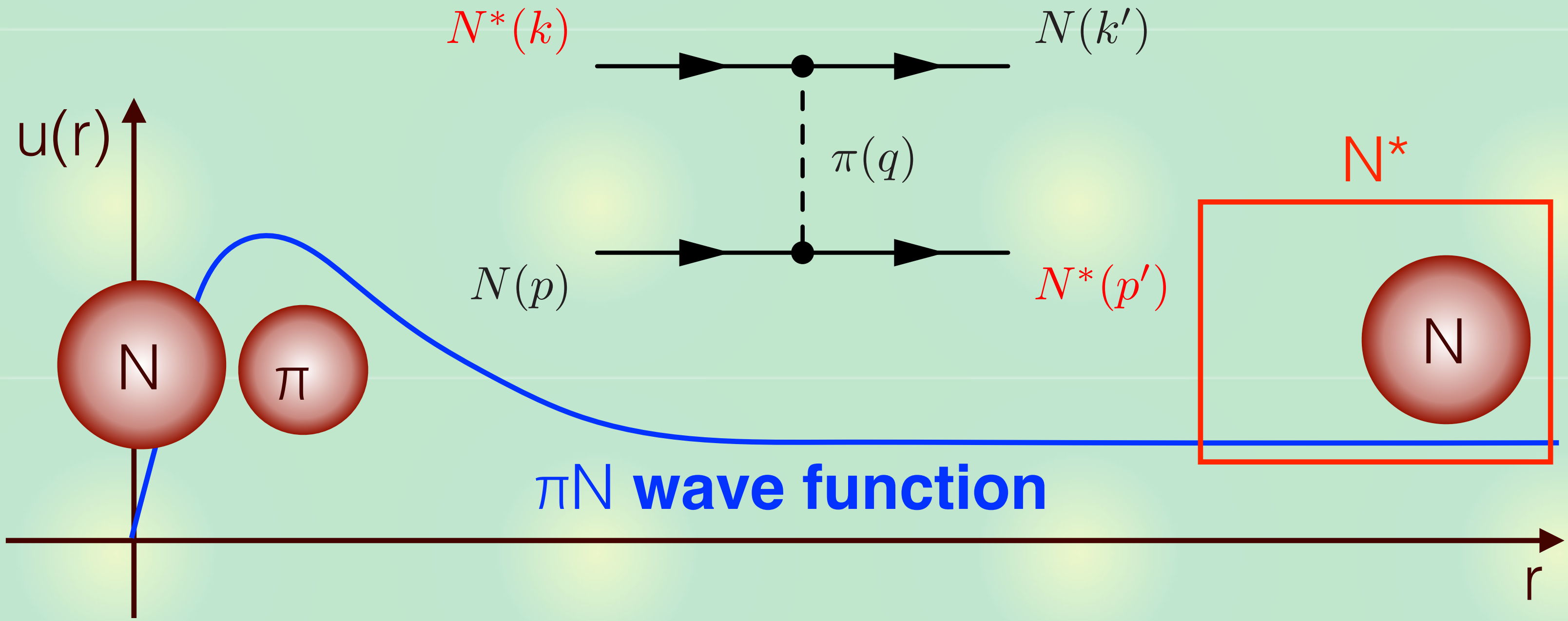
E. Braaten, H.-W. Hammer, Phys. Rept. 428, 259 (2006)

- **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**)**

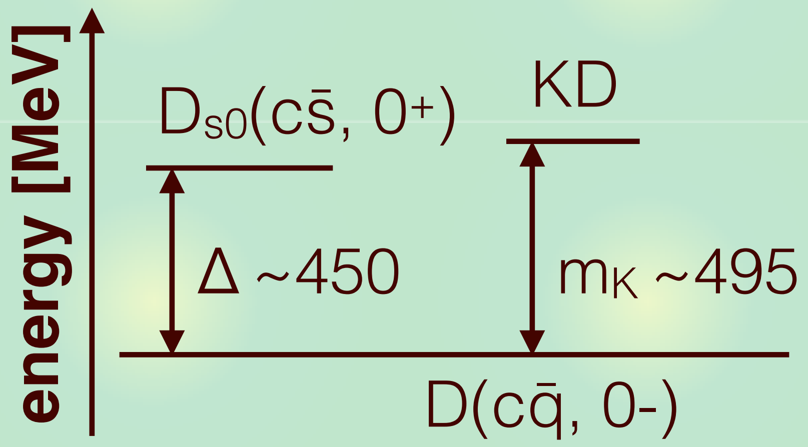
T. Uchino, T. Hyodo, M. Oka, Nucl. Phys. A, 868-869, 53 (2011)

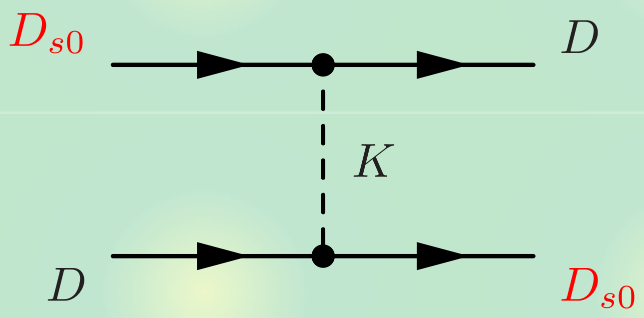
Doubly charmed exotic meson

We consider $D_{s0}(c\bar{s}, 0^{+})D(c\bar{q}, 0^{-})$ **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 (**μ~200 **MeV) attraction**

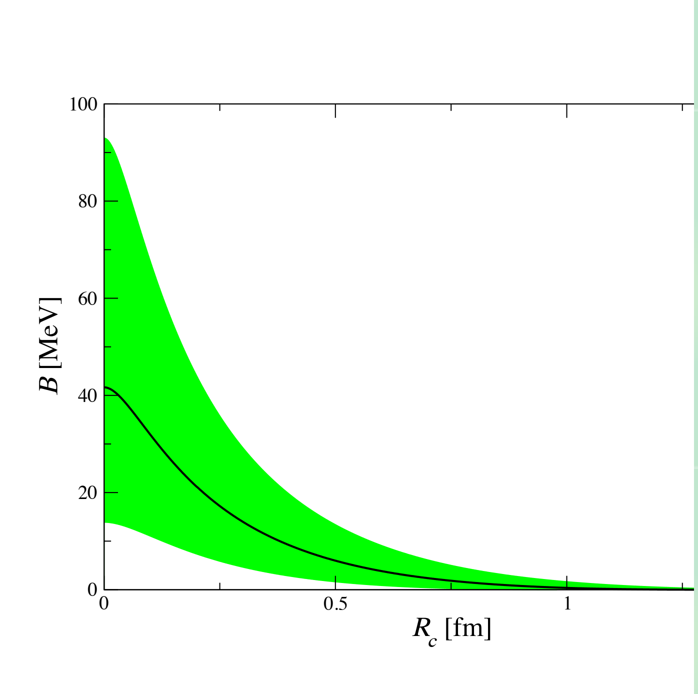
Can the attraction generate a bound state?

Prediction of binding energy

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

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

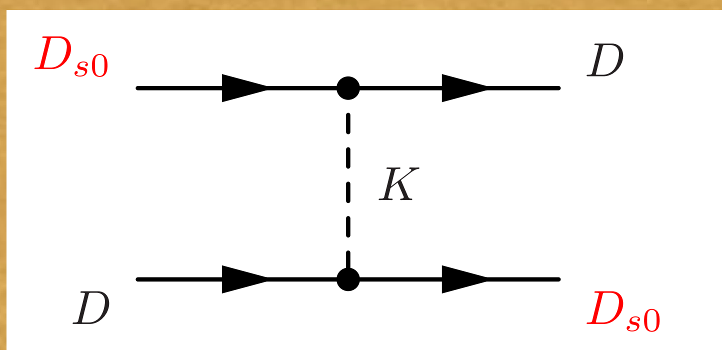
- **coupling constant** h **:** $D_0 \longrightarrow D\pi$ **decay + SU(3) symmetry**
- **Short range cutoff** R_c **<— hadron size**



- $R_c \sim 0.5$ **fm —>** ~ 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:** μ~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]