Tetraquarks: 50 Years of Quark Model

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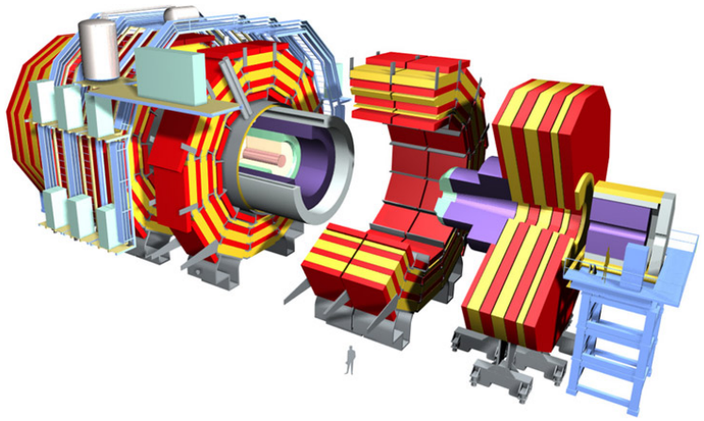


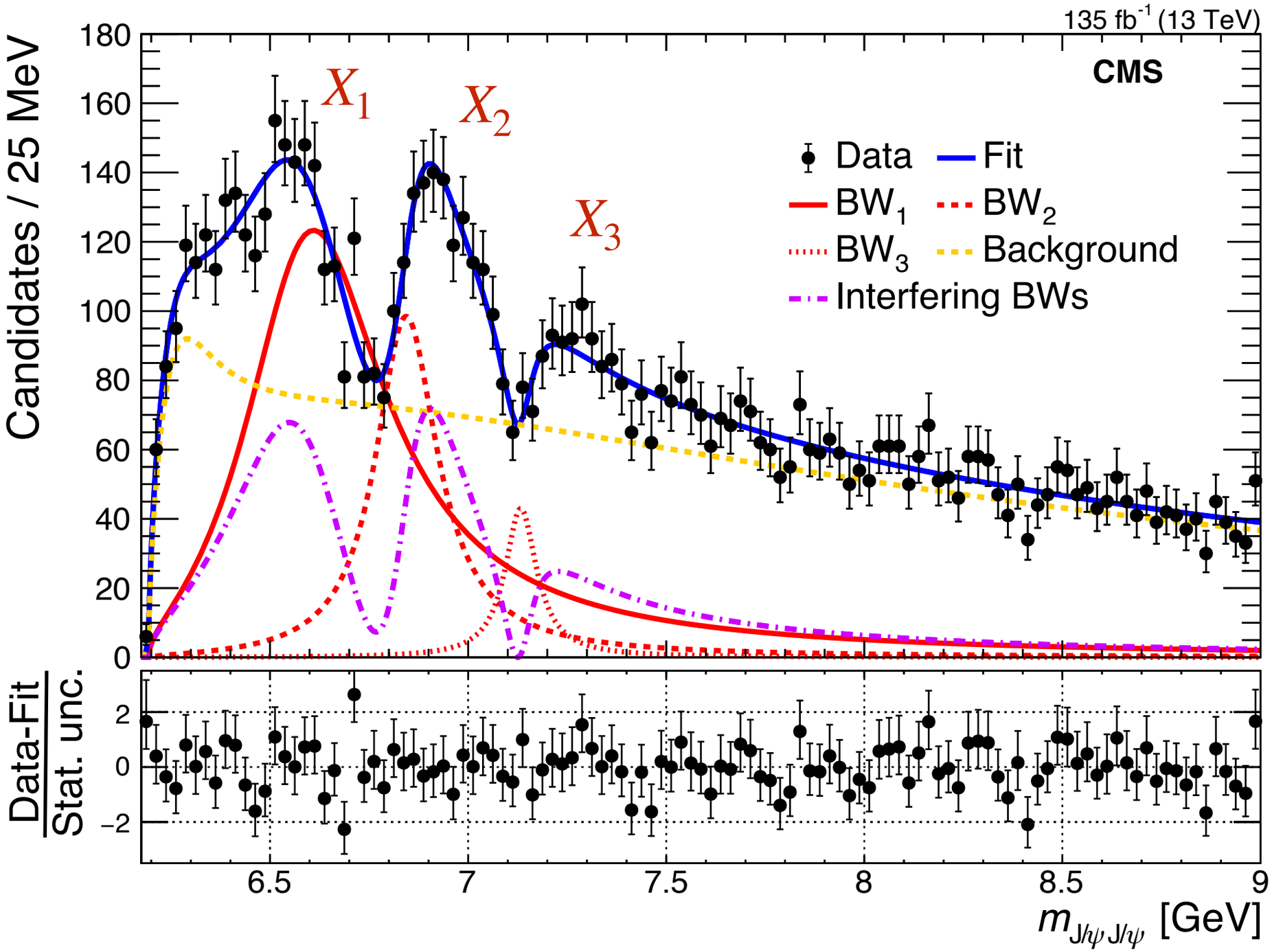
July 24, 2024

Johns Hopkins University

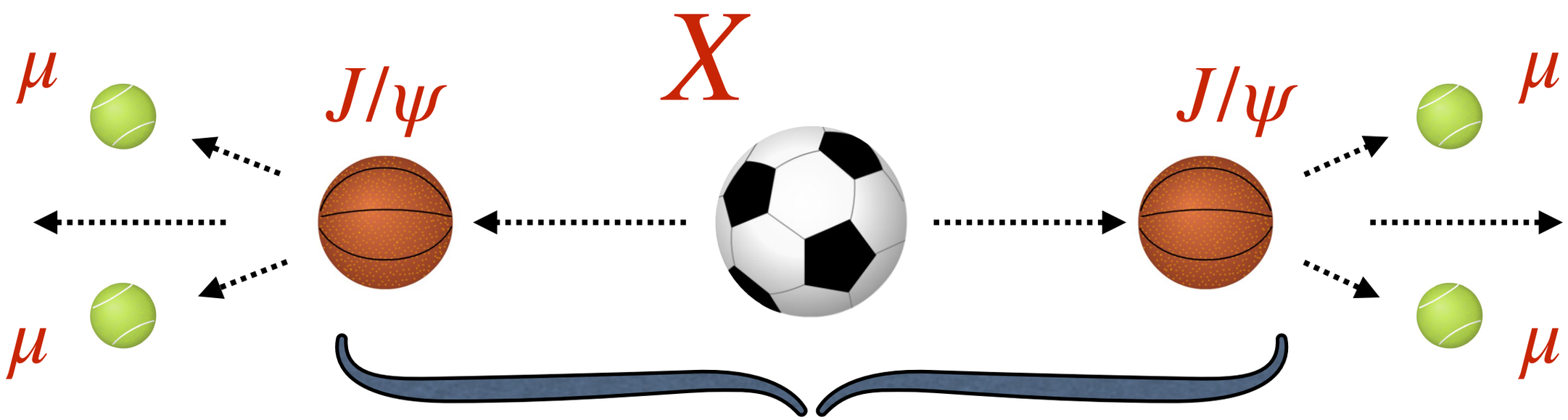
Johns Hopkins University QuarkNet Physics Workshop

Tetraquark candidates

- **arXiv:2306.07164**: Three states $X \to J/\psi J/\psi$



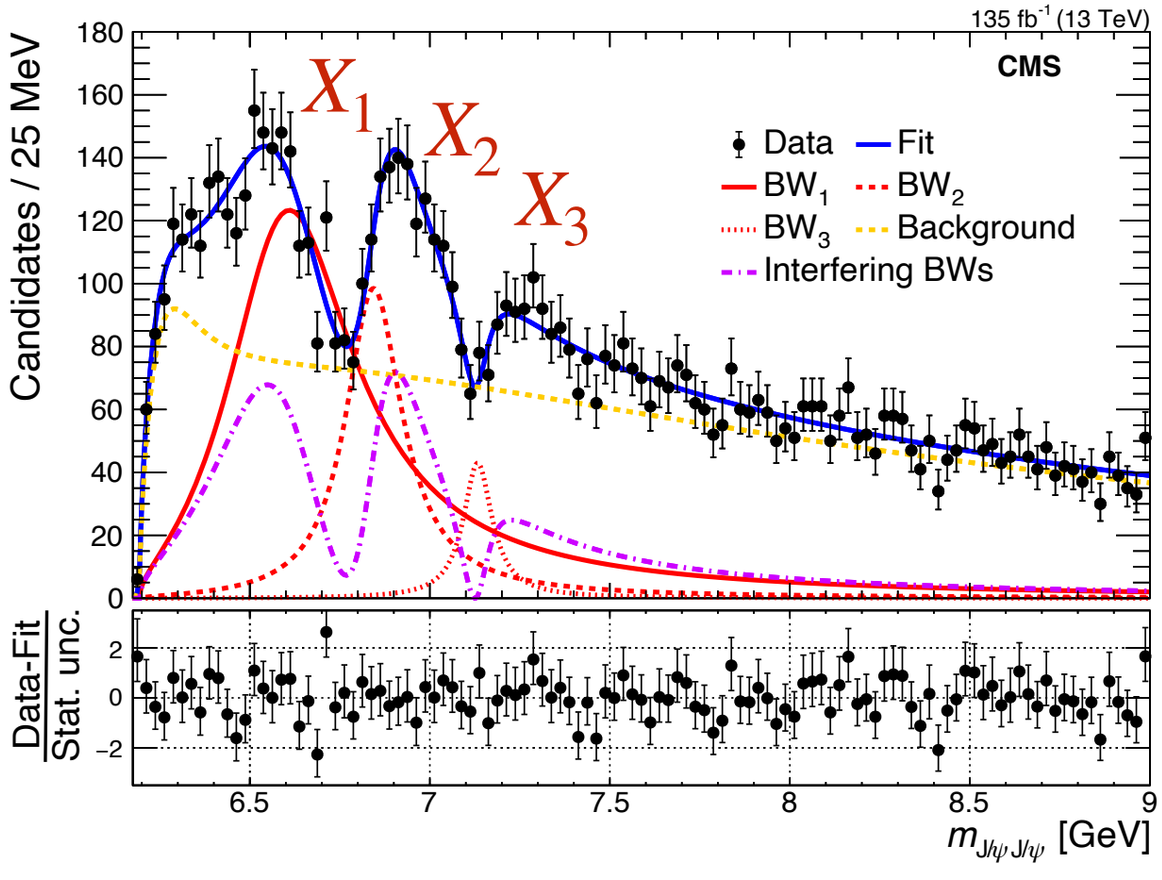
Tetraquark candidates



elementary particles

composite particles

elementary particles

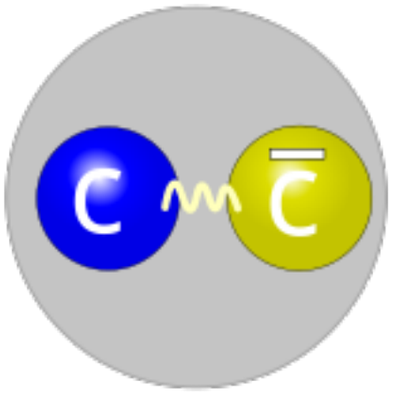


Elementary Particles

- Spin = 0 — H boson (discovered in 2012)
- Spin = $\frac{\hbar}{2}$ — $e^{\pm}, \mu^{\pm}, \tau^{\pm}, \nu_e, \nu_\mu, \nu_\tau, u, d, s, c, b, t$ — matter
- Spin = $\hbar$ — $\gamma, Z, W^{+}, W^{-}, g_1, g_2, g_3, g_4, g_5, g_6, g_7, g_8$ — interactions
- Spin = $\frac{3\hbar}{2}$ — Not known (may be supersymmetric particle, e.g. gravitino)
- Spin = $2\hbar$ — Not discovered, expect graviton G
- Arguments for higher Spin to be composite particles…

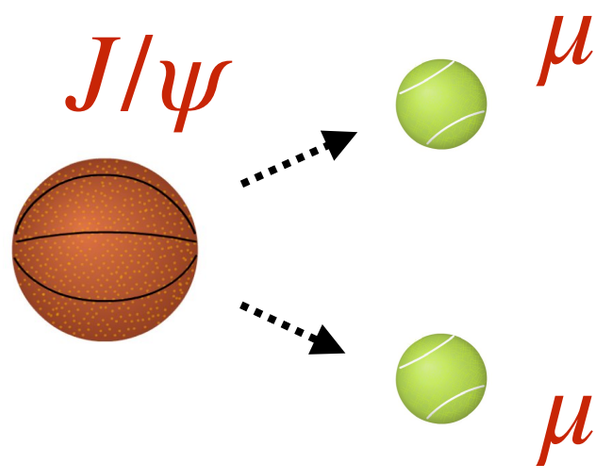
November 1974: 50 years ago

- Discovery of $J/\psi \to \mu^+\mu^-$ helped to establish the quark model



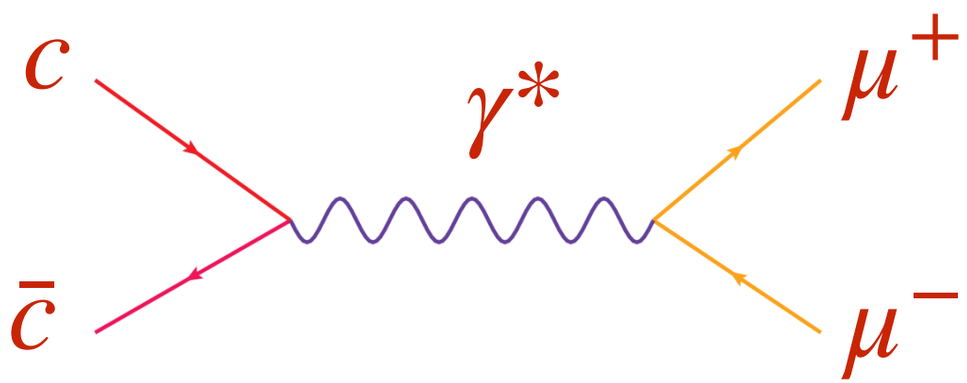
J/ψ composite particle

Spin = $\hbar$

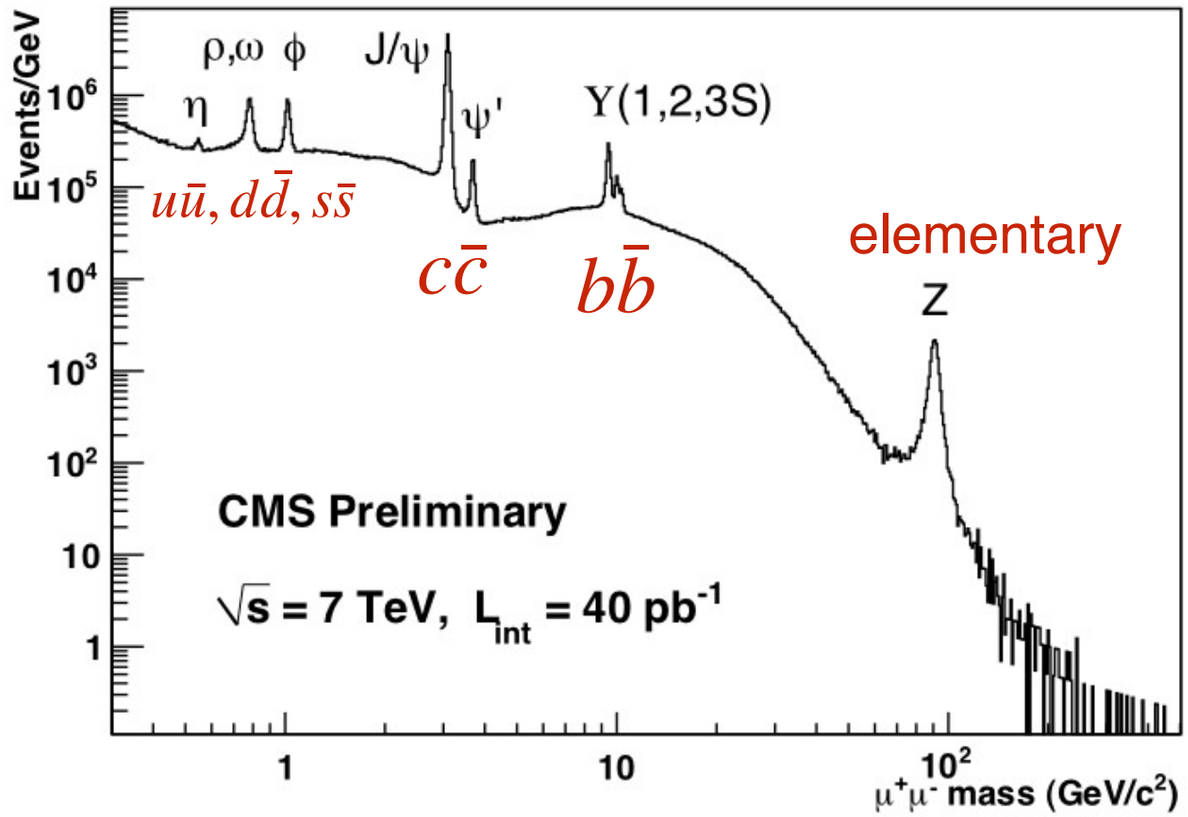


$\mu^{\pm}$ elementary particles

Spin = $\frac{\hbar}{2}$



$X \to \mu^+\mu^-$ at LHC

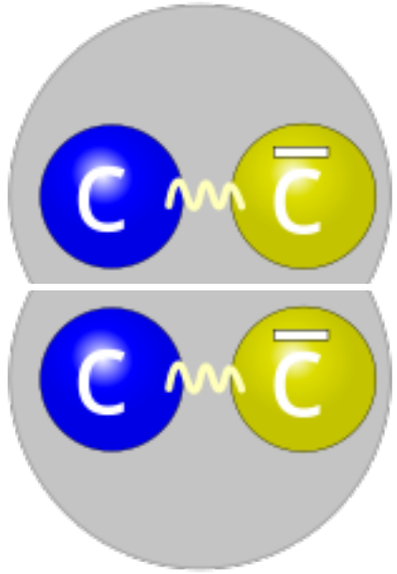


2024: What is $X \to J/\psi J/\psi$?

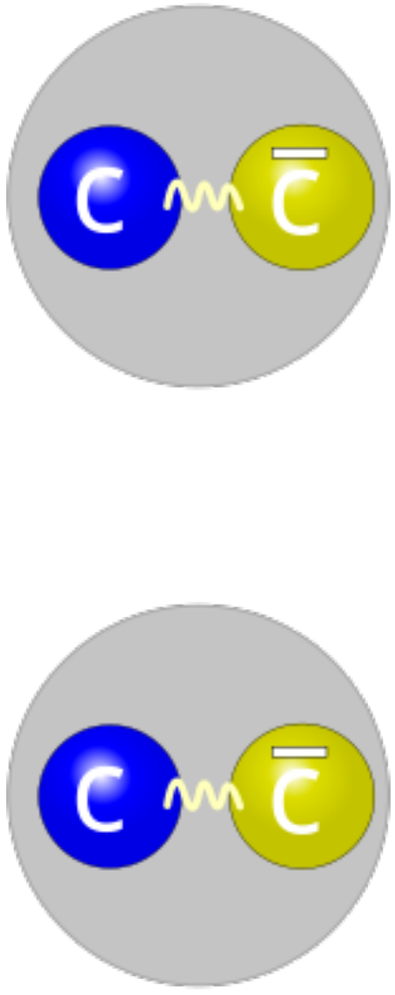
- Natural to expect to be composed of $c, c, \bar{c}, \bar{c}$

One popular model is a "molecule"
kind of a bound state of two mesons
connected by a strong nuclear force…

Is it correct ?



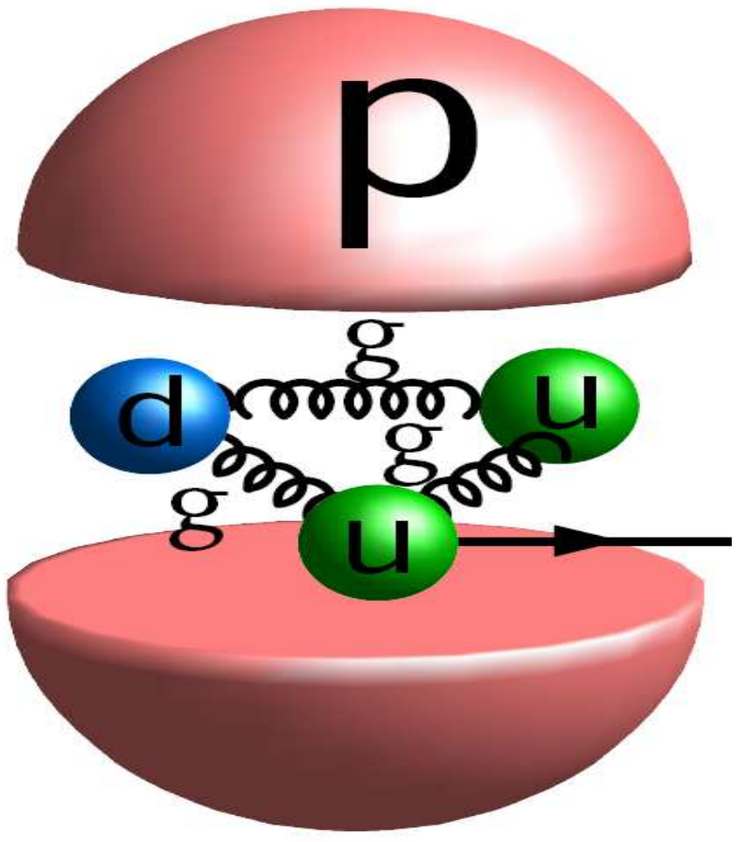
X composite particle

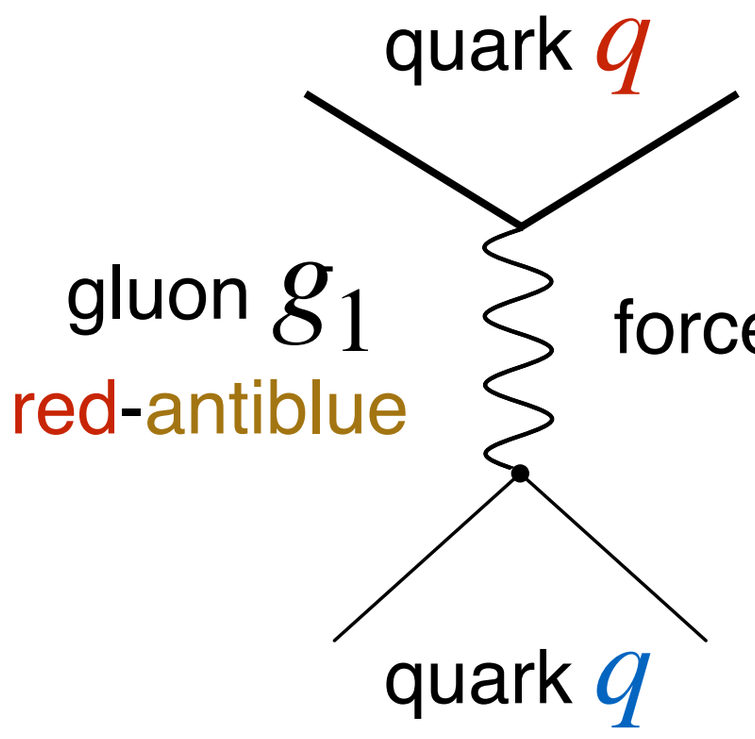


Strong Force

- Nucleon (proton or neutron) is held together by the strong force

  “color” (red, blue, green) is a charge in strong force





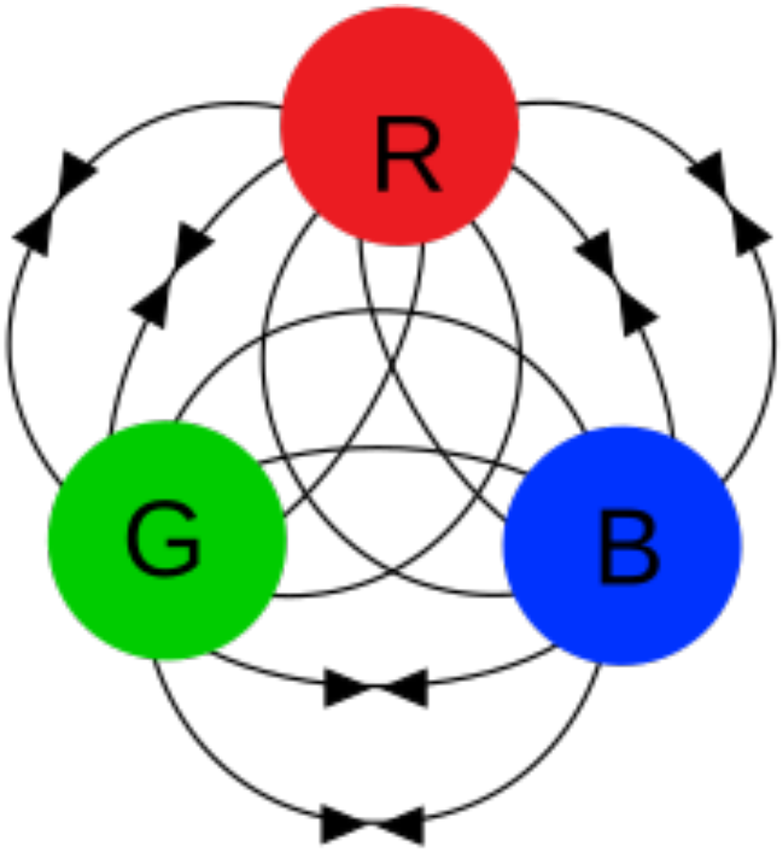
$$V_{\mathrm{QCD}}(r) = -\frac{4\alpha_S}{3r} + kr$$

Strong Force

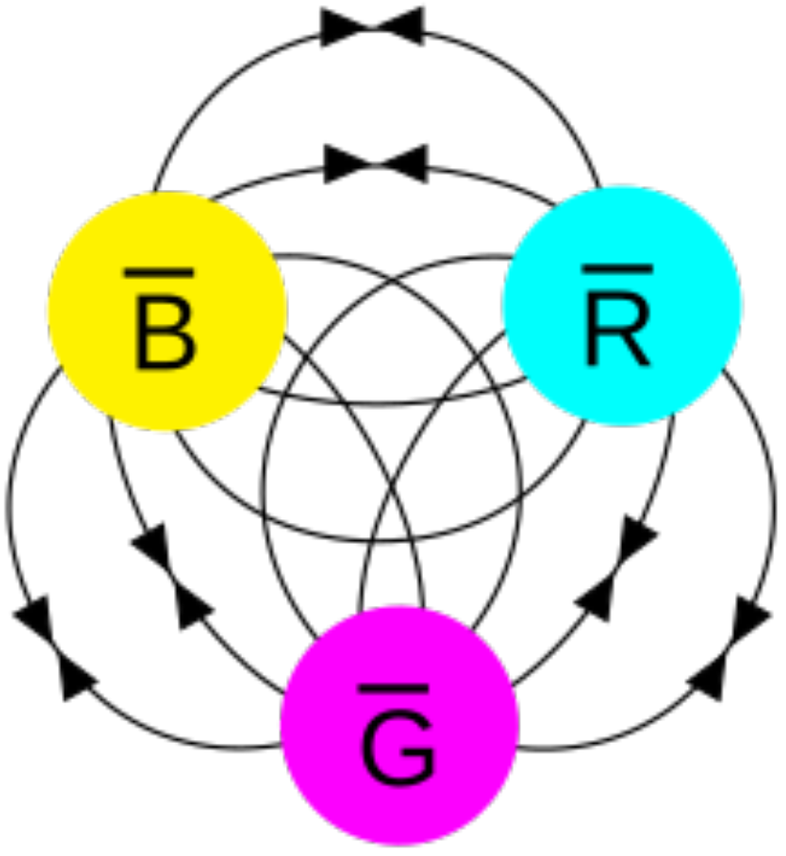
- Nucleon is held together by the strong force

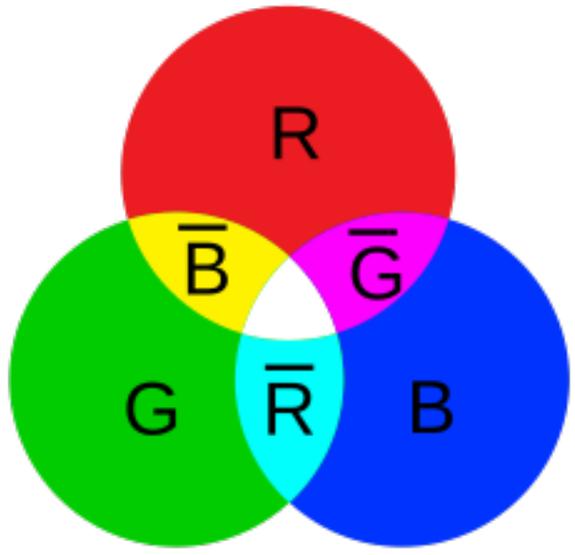
  "color" (red, blue, green) is a charge in strong force

proton (uud)



anti-proton ($\bar{u}\bar{u}\bar{d}$)



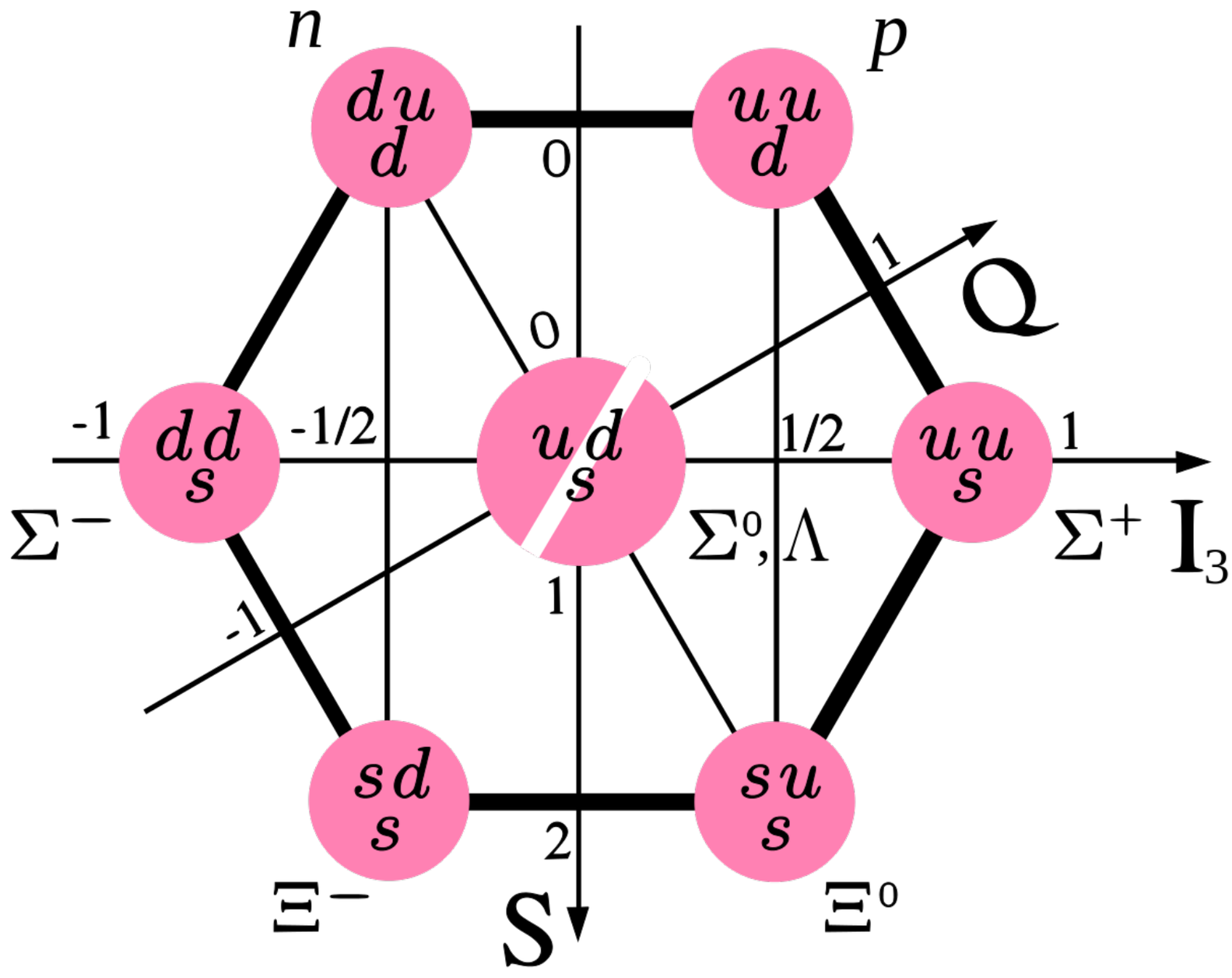


$$V_{\mathrm{QCD}}(r) = -\frac{4\alpha_S}{3r} + kr$$

- Any object should be color-neutral (e.g red-blue-green)

Strong Force: Baryons

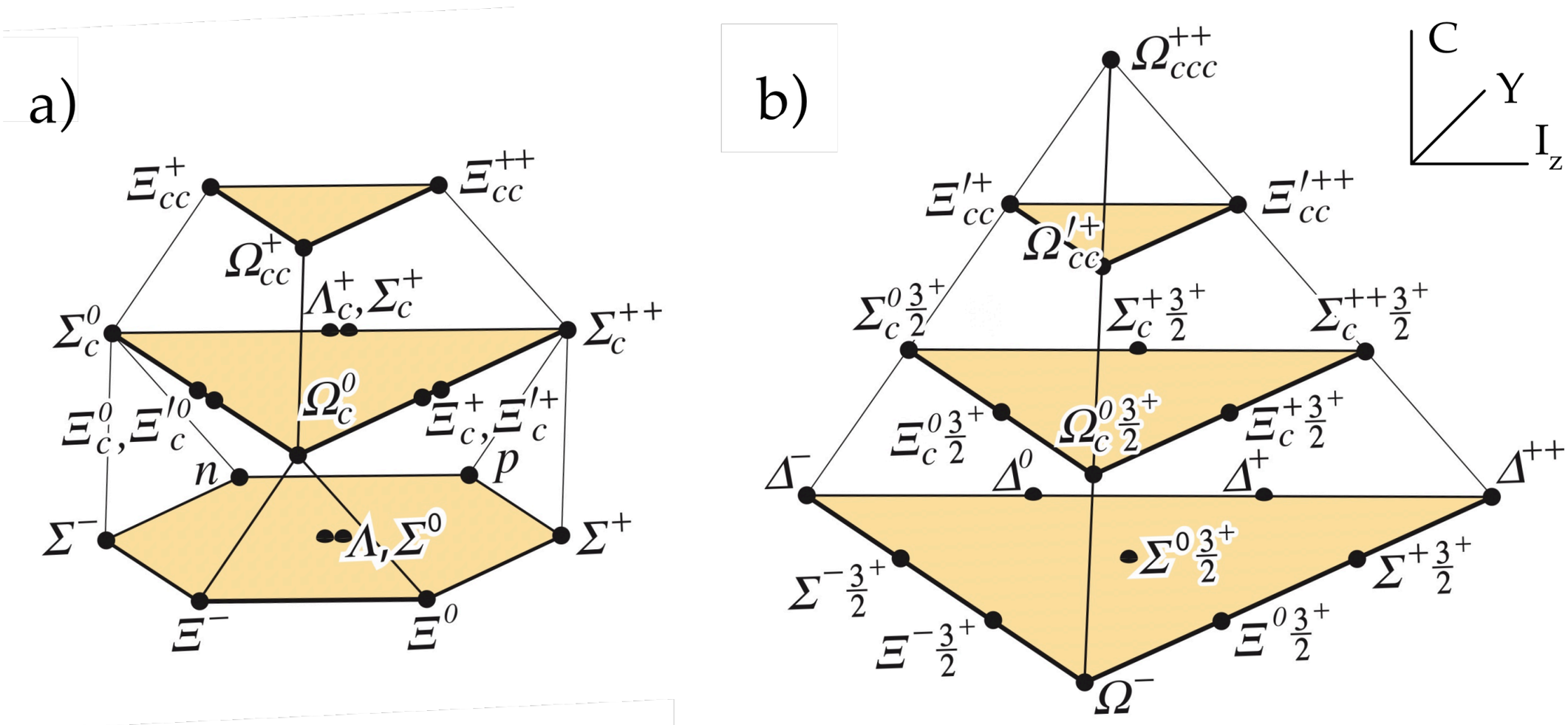
qqq Spin = $\frac{\hbar}{2}$



Strong Force: Baryons

qqq Spin = $\frac{\hbar}{2}$

qqq Spin = $\frac{3\hbar}{2}$



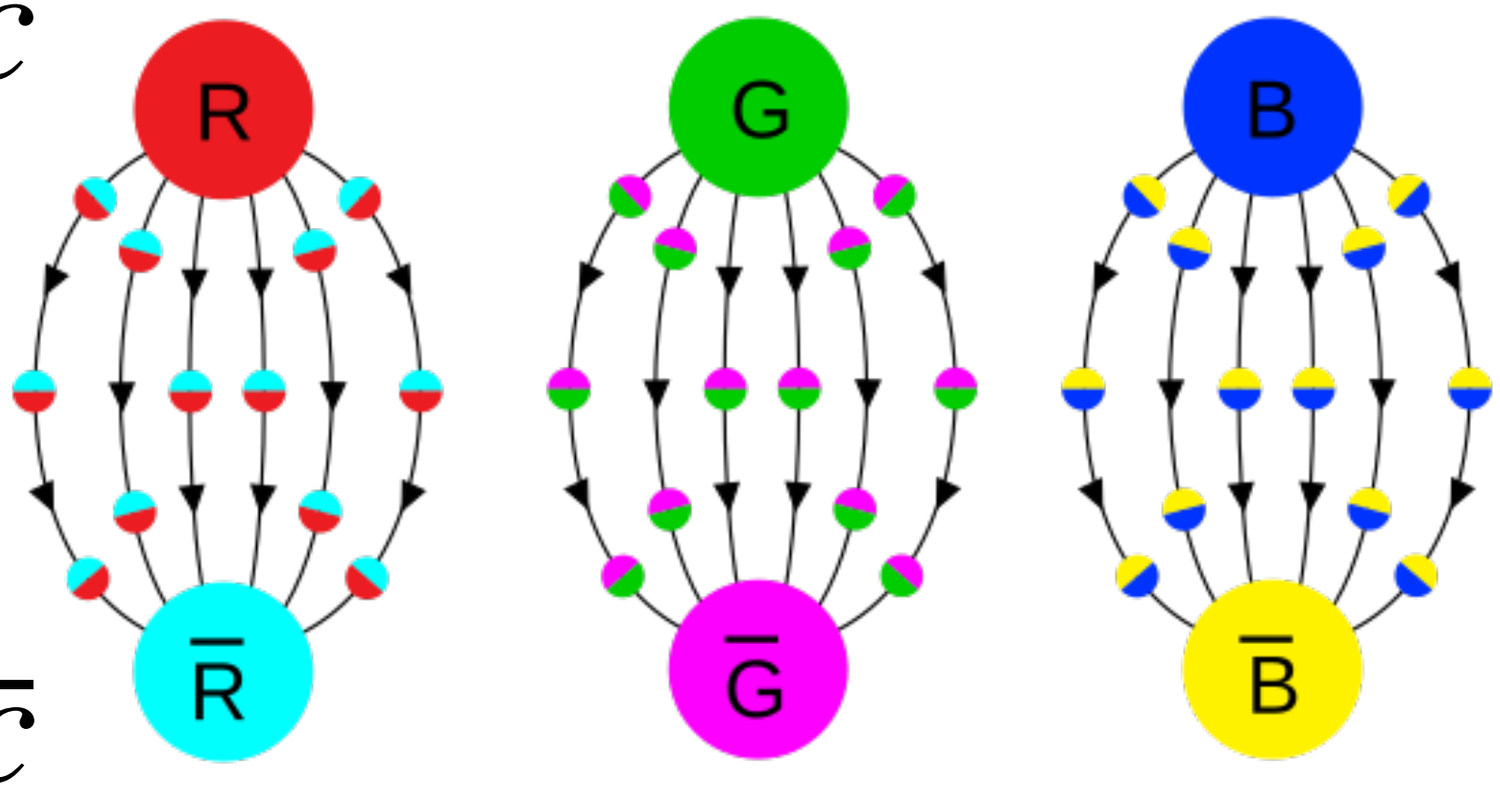
Strong Force: Mesons

- Meson is held together by the strong force

  "color" (red, blue, green) is a charge in strong force

Spin = $0, 1\hbar, ..$ neutral color = $(r\bar{r} + b\bar{b} + g\bar{g})/\sqrt{3}$

e.g. J/ψ c



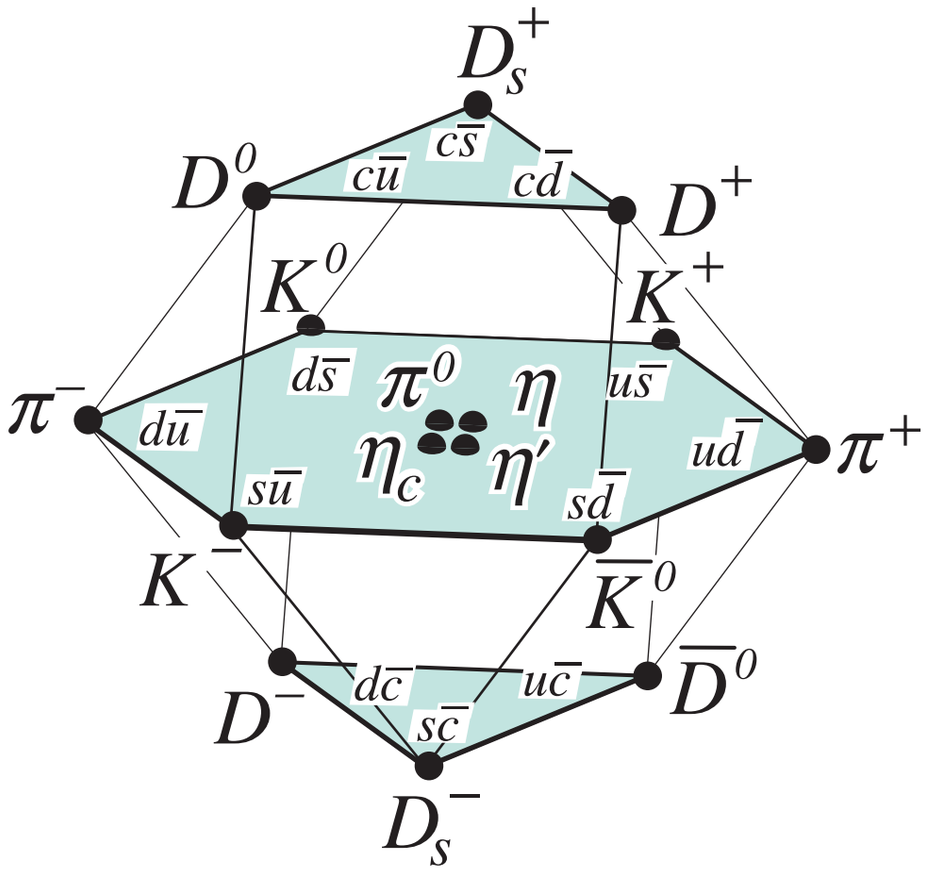
$\bar{c}$

$$V_{\mathrm{QCD}}(r) = -\frac{4\alpha_S}{3r} + kr$$

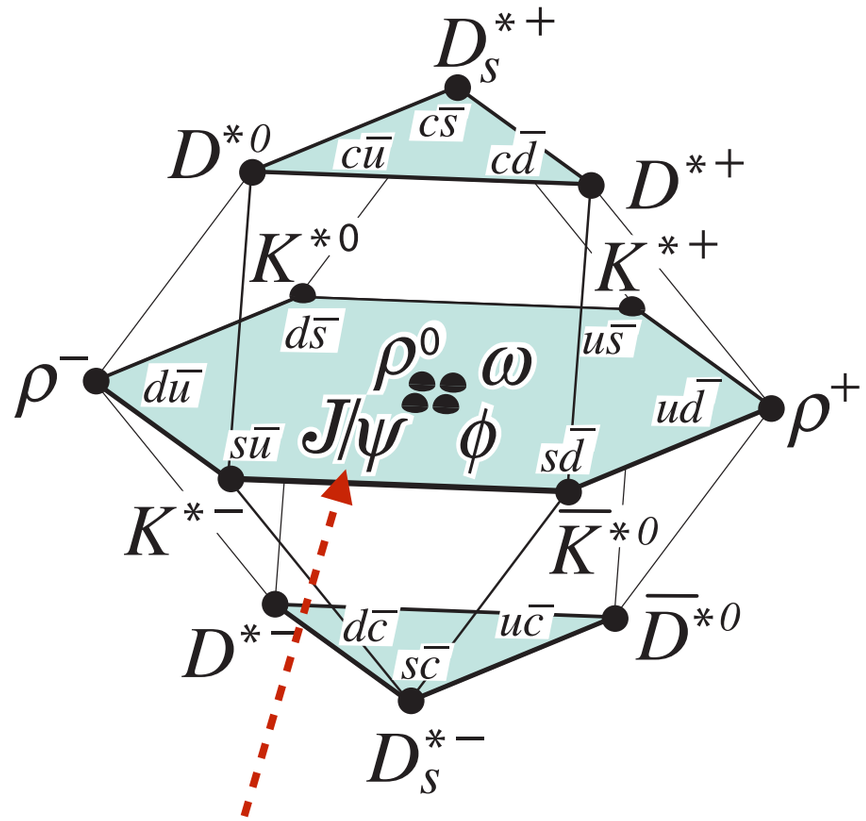
- Any object should be color-neutral (e.g $r\bar{r}+g\bar{g}+b\bar{b}$)

Strong Force: Mesons

$q\bar{q}$ Spin = 0



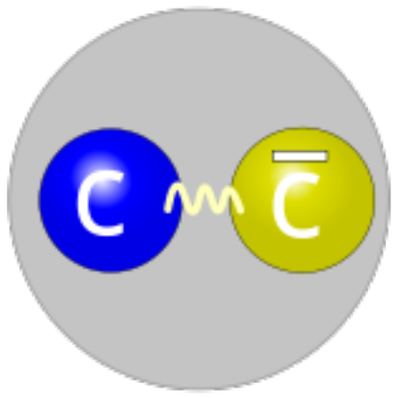
$q\bar{q}$ Spin = $1\hbar$



note J/ψ

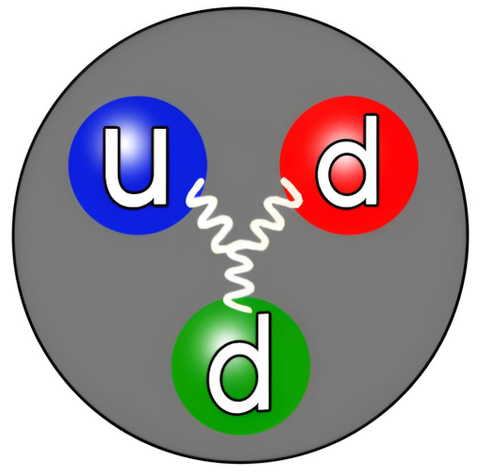
The Quark Model

$q\bar{q}$ Mesons



color-neutral!

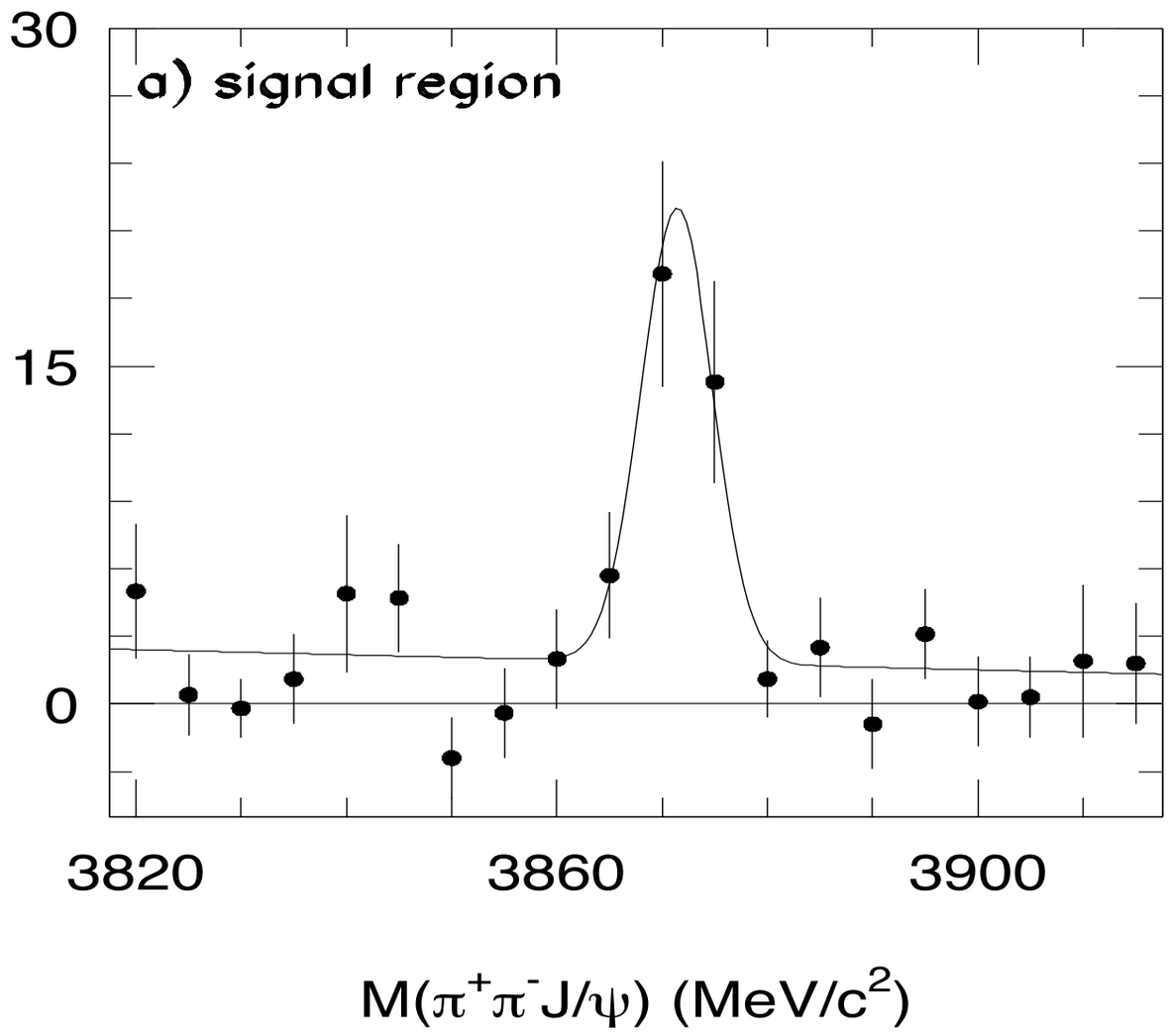
qqq Baryons

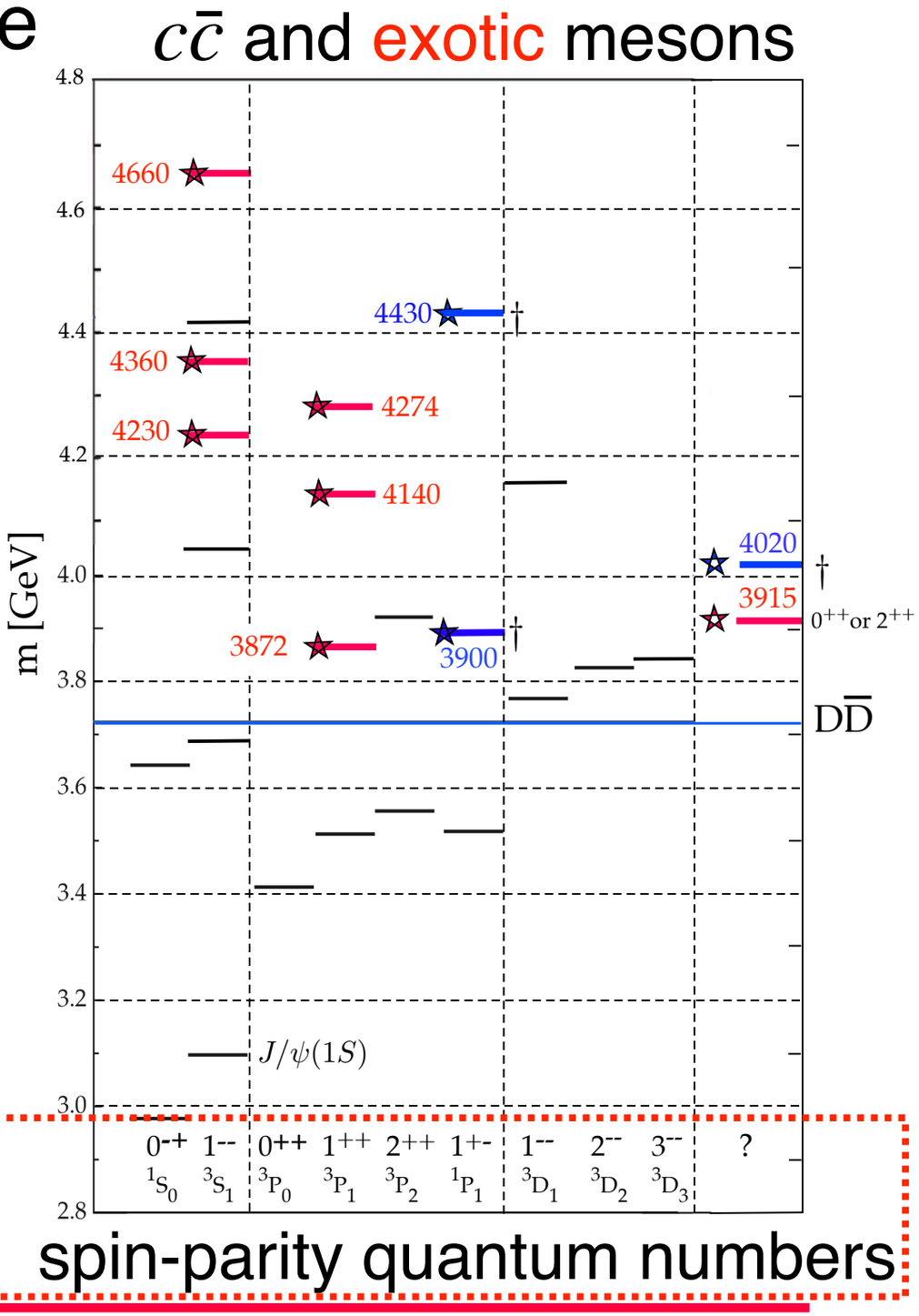


- In principle possible color-neutral composite particles:
  - Tetra-quarks: $q\bar{q}q\bar{q}$
  - Penta-quarks: $q\bar{q}qqq$ or $\bar{q}q\bar{q}\bar{q}\bar{q}$
  - Glueballs: $gg(g)$
  - Hybrids: linear combination of any of the above

First Tetra-quark Candidates

- Found in $B \to XK,\ X \to \pi^+\pi^- J/\psi$ by Belle in 2003
  - — possible $c\bar{q}q\bar{c}$, but not conclusive
  - — may be molecule 2 D mesons or may be tetra-quark

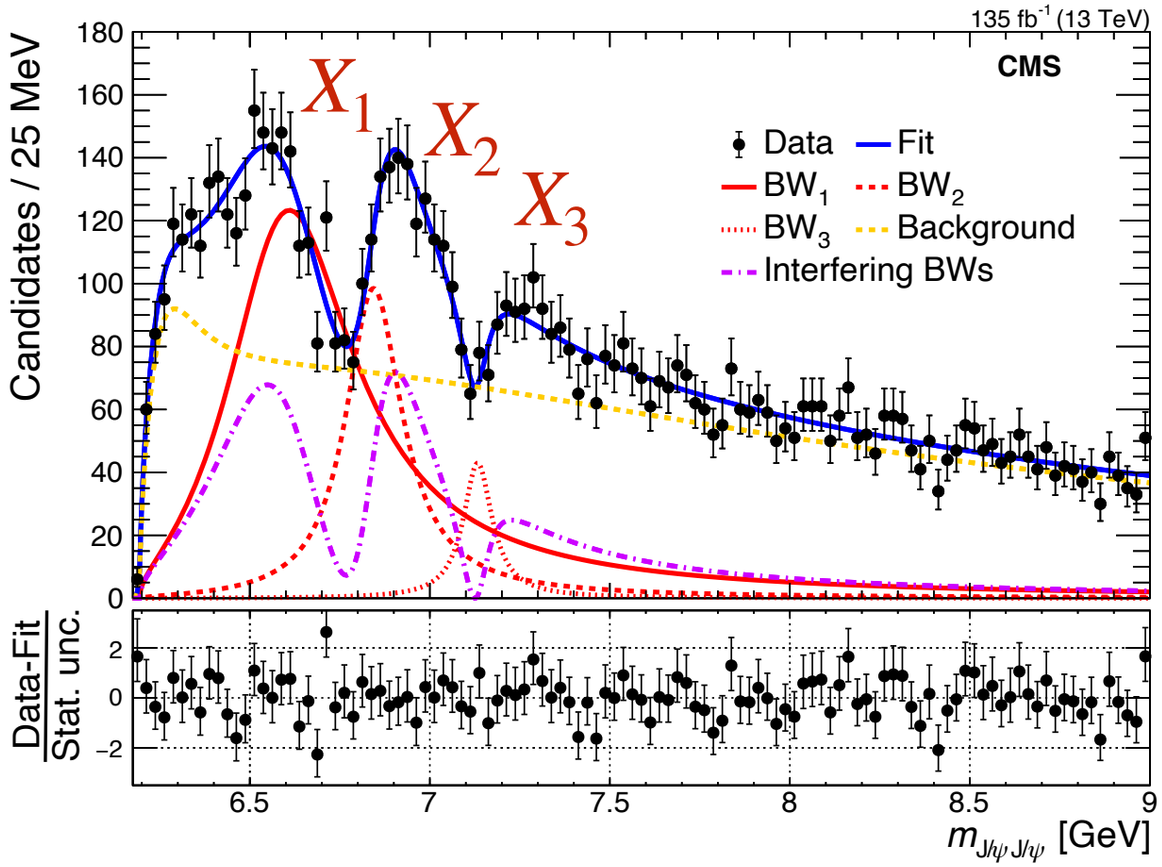




spin-parity quantum numbers

Recent Tetra-quark Candidates

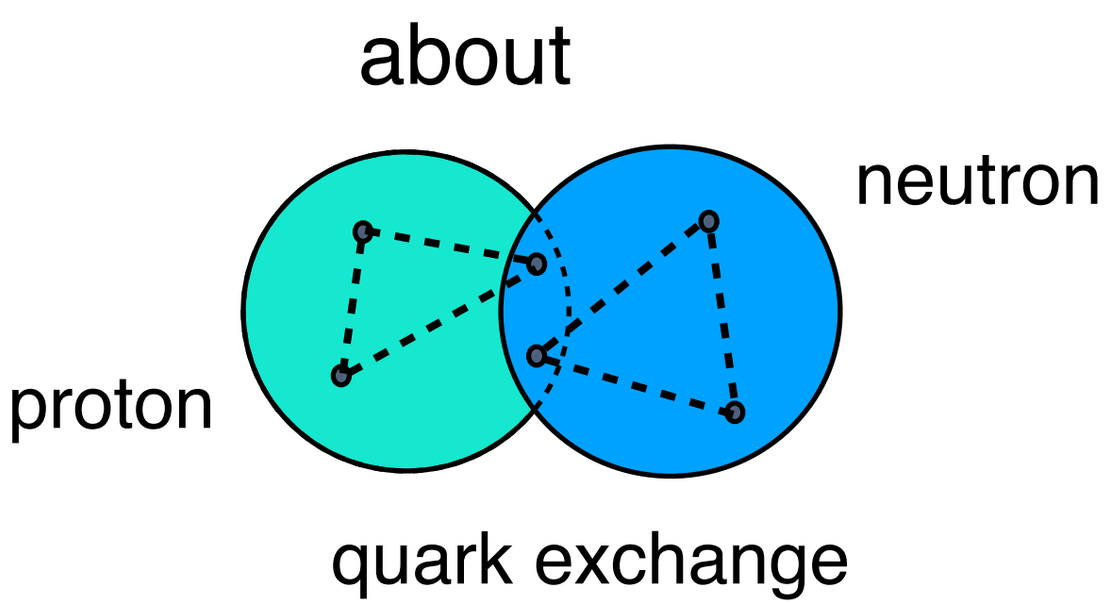
- What is special about the recent Tetra-quark candidates?
  - for the first time composed of 4 heavy $c, c, \bar{c}, \bar{c}$
  - may allow us to understand the structure!
  - now need to measure its properties!

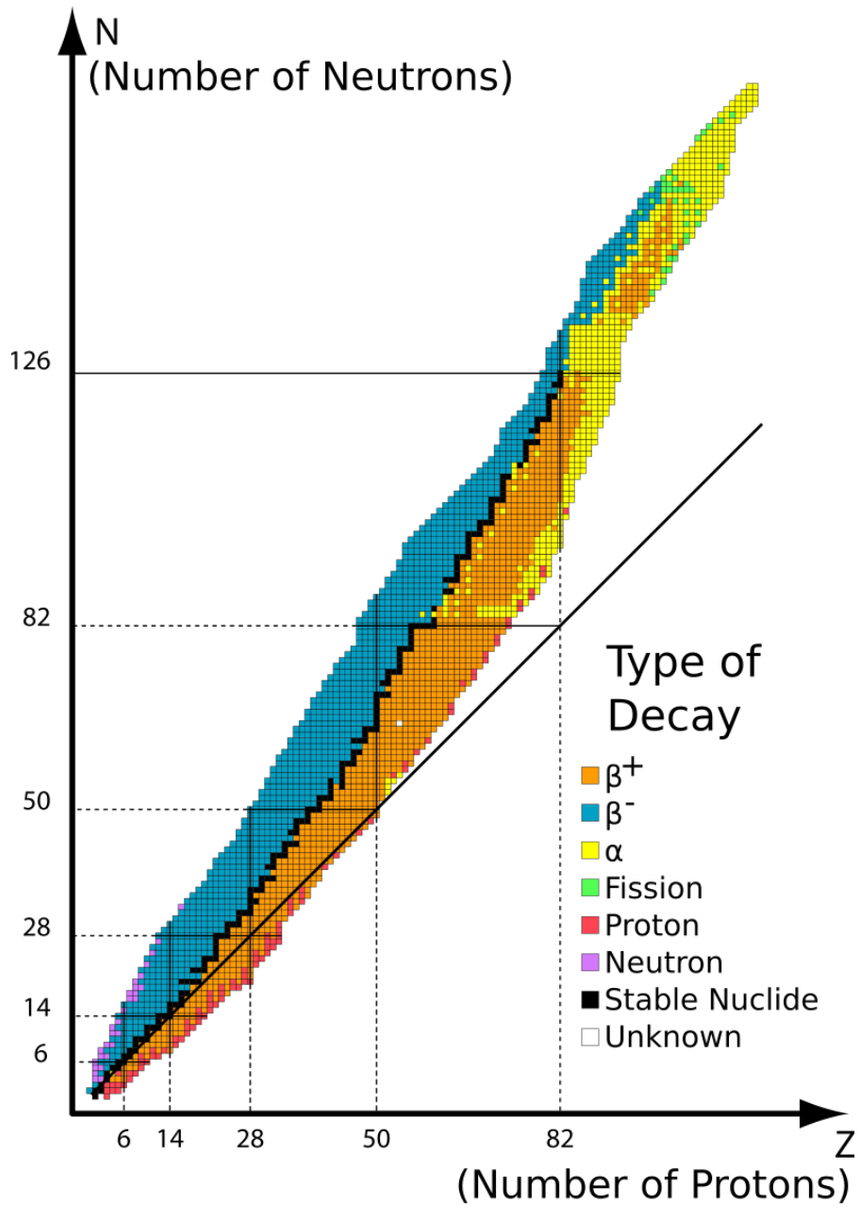


Back to the Strong Nuclear Force

- What holds nucleus together?

  — it is still strong force, but more complicated:





Nature of the Nuclear Force

- What holds nucleus together?

Nuclear force - based on strong force, but works differently than binding force of mesons and baryons

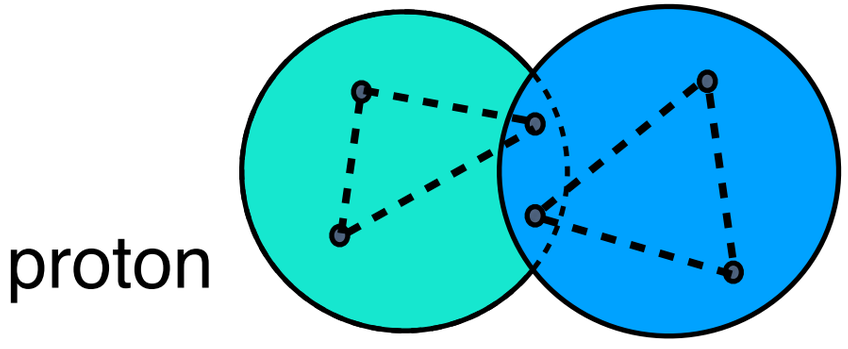
no strong or EM force at large distance

neutron
color-neutral
charge-neutral

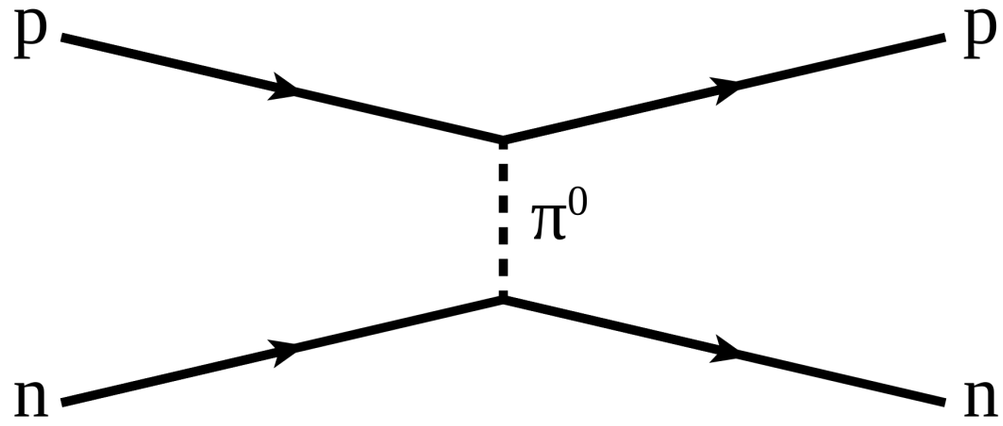
proton
color-neutral
(electric charge)

Nature of the Nuclear Force

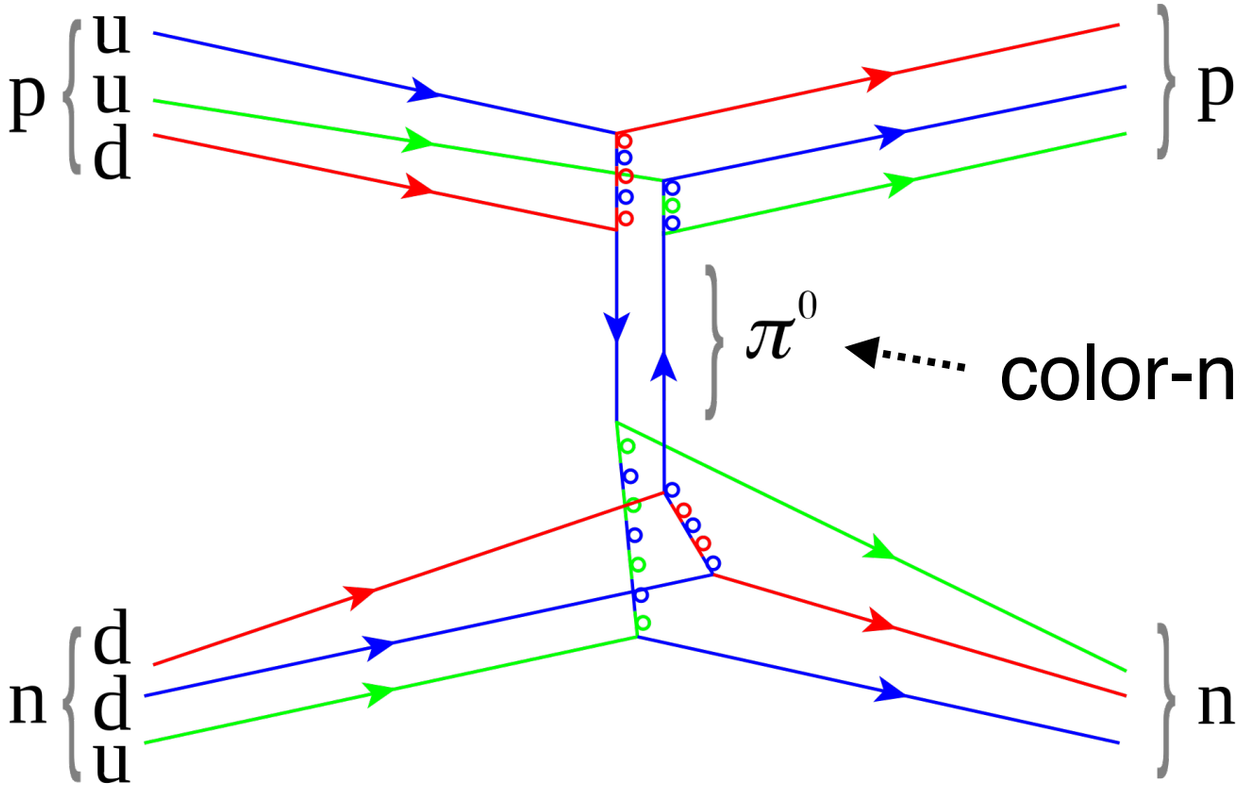
It gets more complicated, but gluons still connect it all:



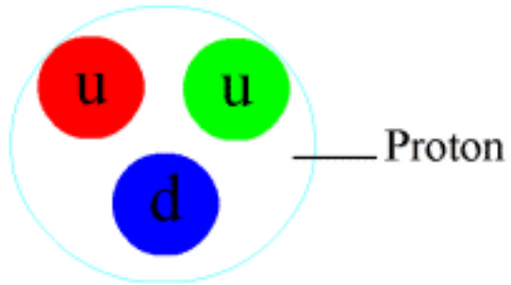
quark exchange

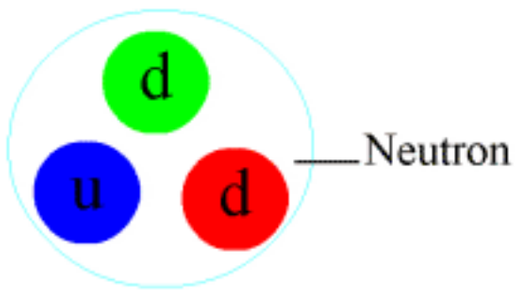


meson exchange

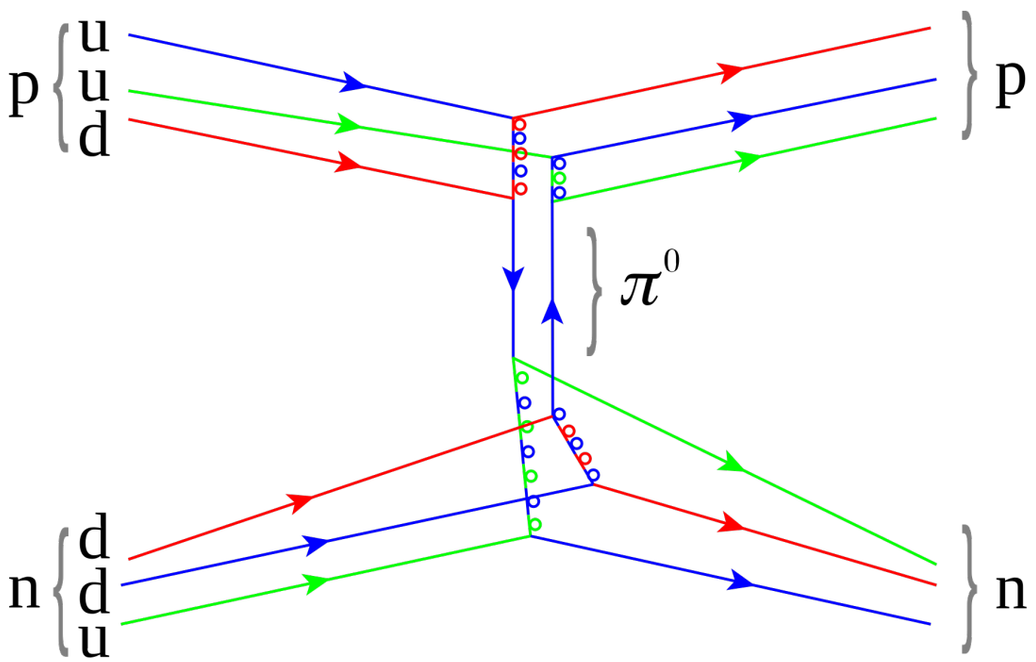


color-neutral





Nature of the Nuclear Force



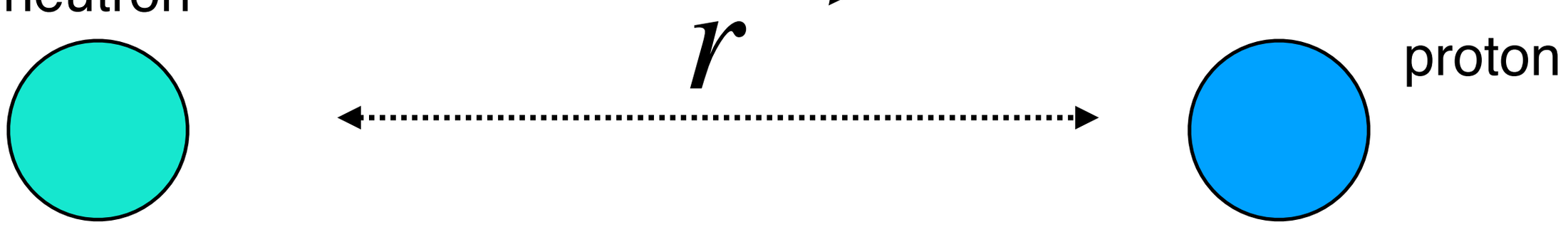
Yukawa potential at larger distances:

$$V(r) = g \cdot \frac{e^{-\frac{m_\pi c}{\hbar} r}}{r}$$

note pion mass

$$\text{range } d \sim \frac{\hbar}{m_\pi c} \sim 1.4 \text{ fm}$$

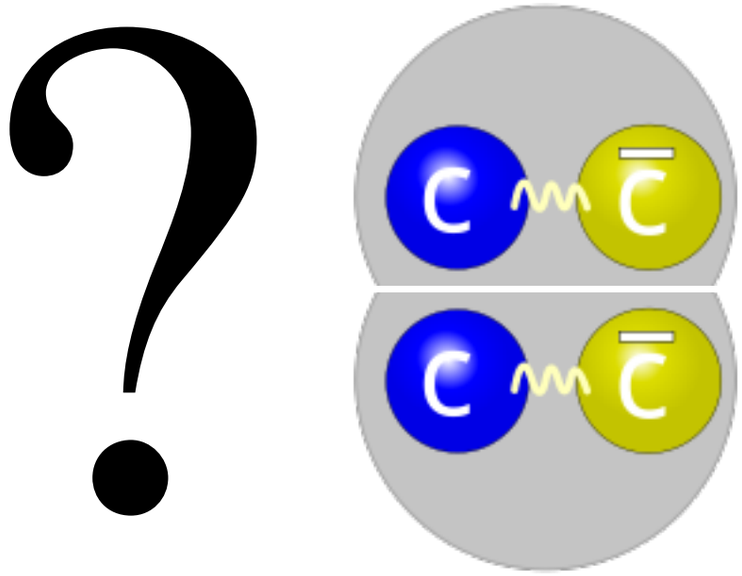
$$\sim 1.4 \times 10^{-15} \text{ m}$$



Compare for $q\bar{q}$ (colored): $V_{\text{QCD}}(r) = -\frac{4\alpha_S}{3r} + kr$

2024: What is $X \to J/\psi J/\psi$?

One popular model is a "molecule"
kind of a bound state of two mesons
connected by a strong nuclear force
like proton and neutron in a nucleus…



X composite particle

$$V(r) = g \cdot \frac{e^{-\frac{m_{\eta_c} c}{\hbar} r}}{r}$$

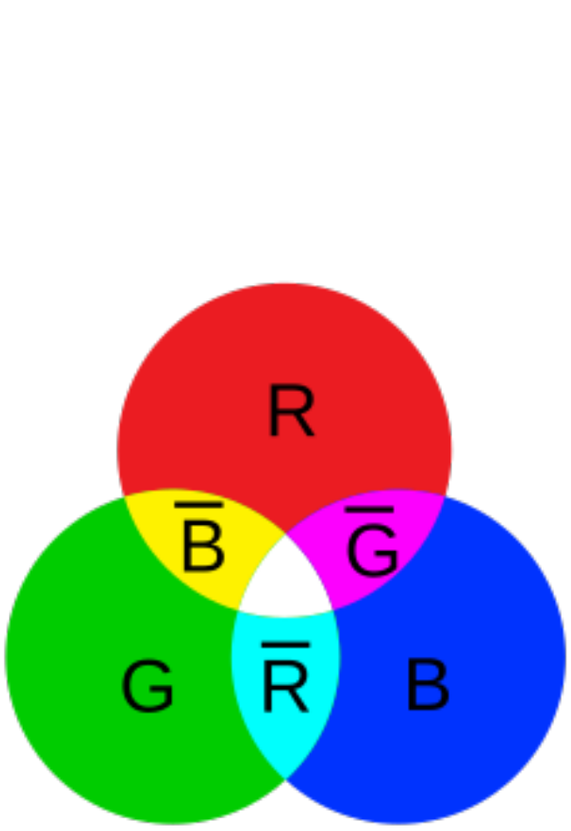
note $(c\bar{c})$ mass × 22 heavier

binding would be
much weaker than
in a nucleus or
light "tetra-quarks"

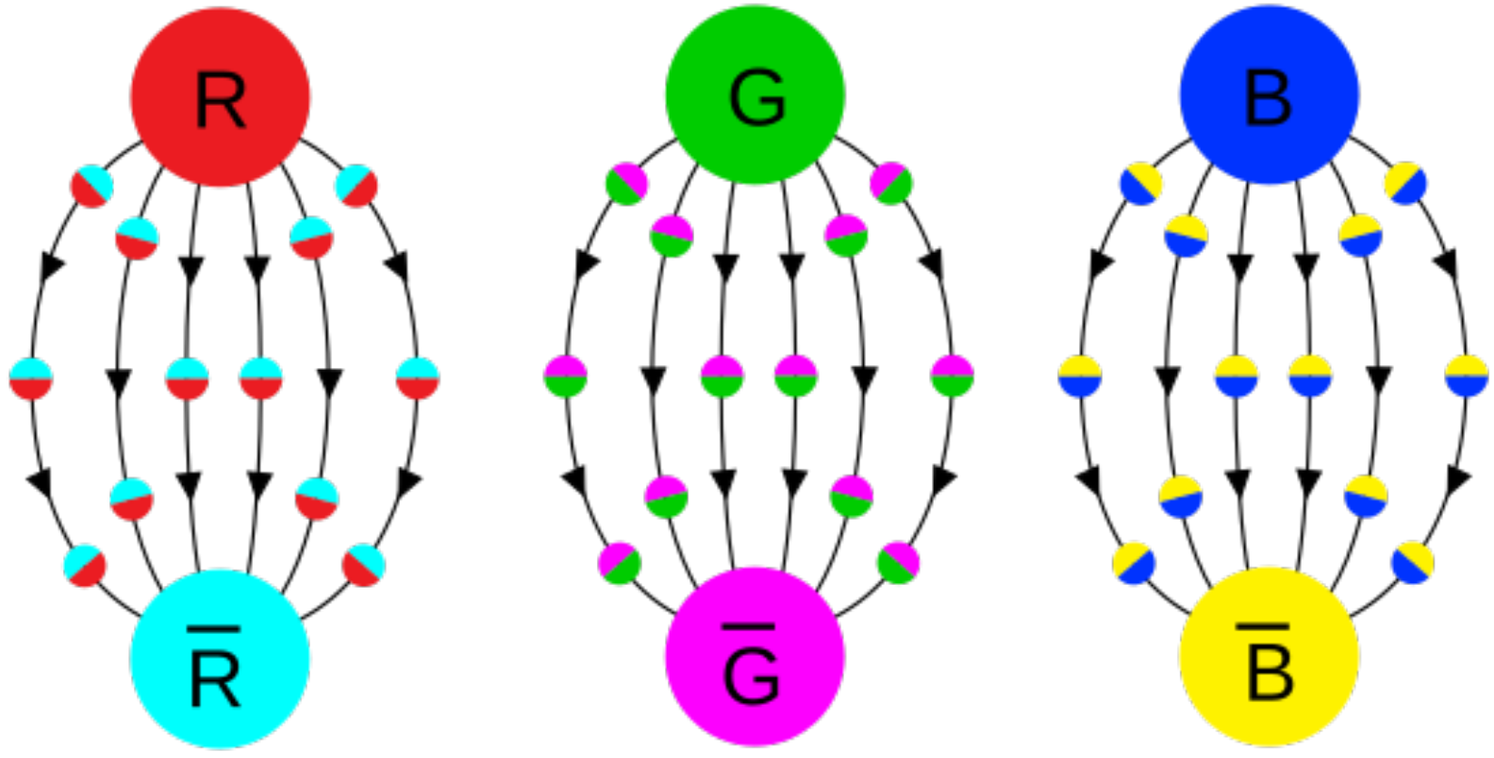
- Strong argument against "molecular" nature!

2024: What is $X \to J/\psi J/\psi$?

- True tetra-quark connects
  two colored objects (cc) and $(\bar{c}\bar{c})$ — it is an exotic meson



$\bar{c}_{\bar{B}}\bar{c}_{\bar{G}}$ $\bar{c}_{\bar{R}}\bar{c}_{\bar{B}}$ $\bar{c}_{\bar{G}}\bar{c}_{\bar{R}}$



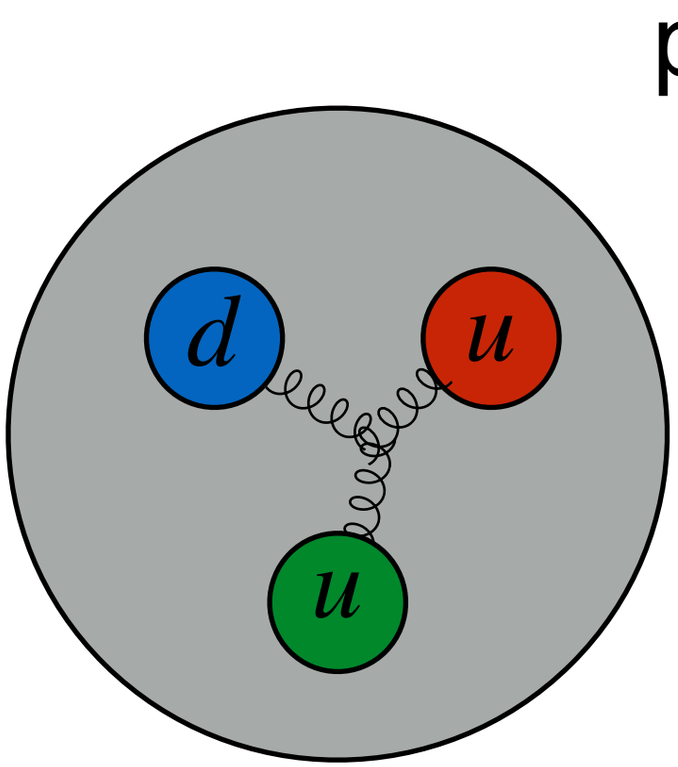
$c_G c_B$ $c_B c_R$ $c_R c_G$

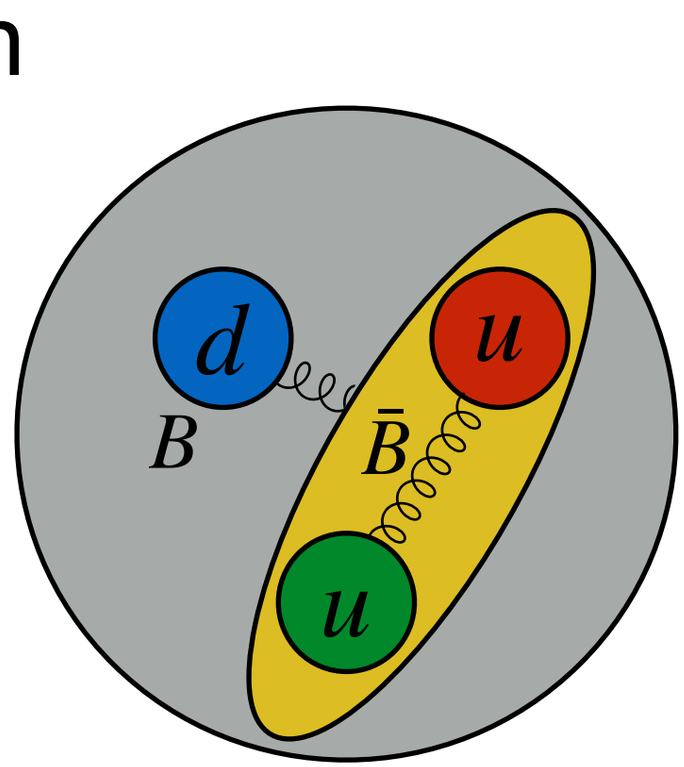
- We still need to learn a lot more about X …

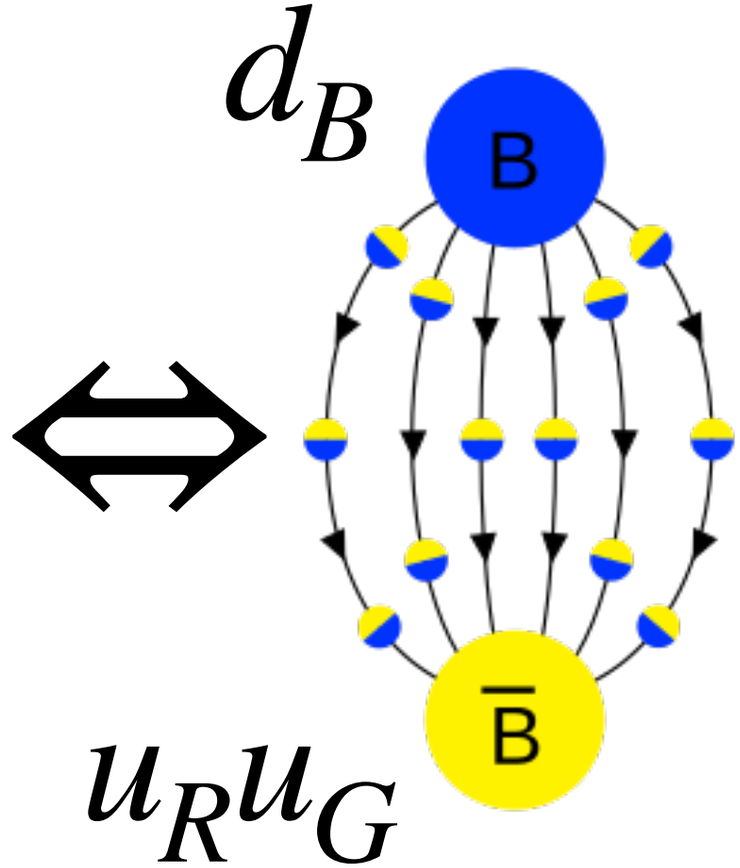
The same mechanism in nucleons?

- If this happens in tetra-quarks, why not in protons?
  - there is evidence of $(qq)_{\text{anticolor}}$ binding in proton
  - final structure is superposition of all combinations

proton

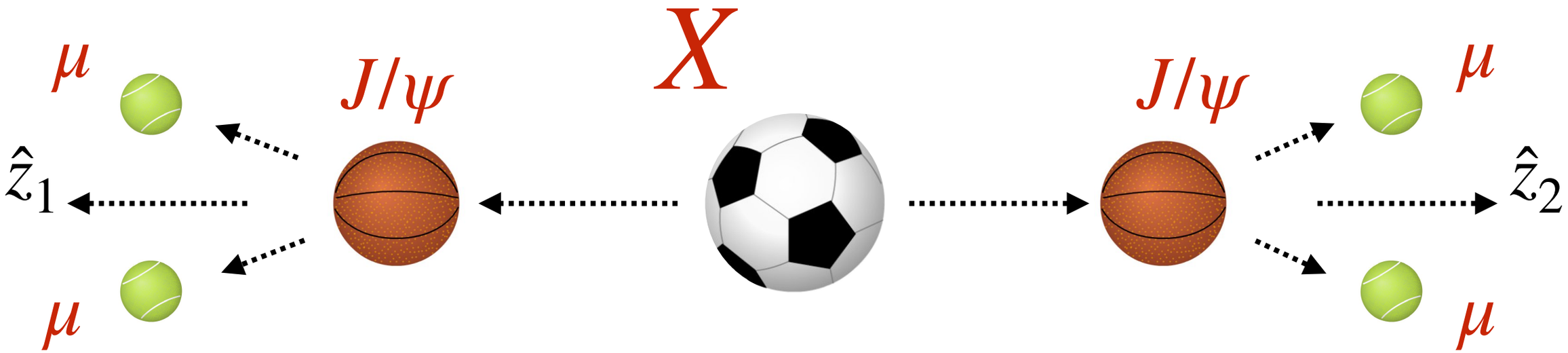




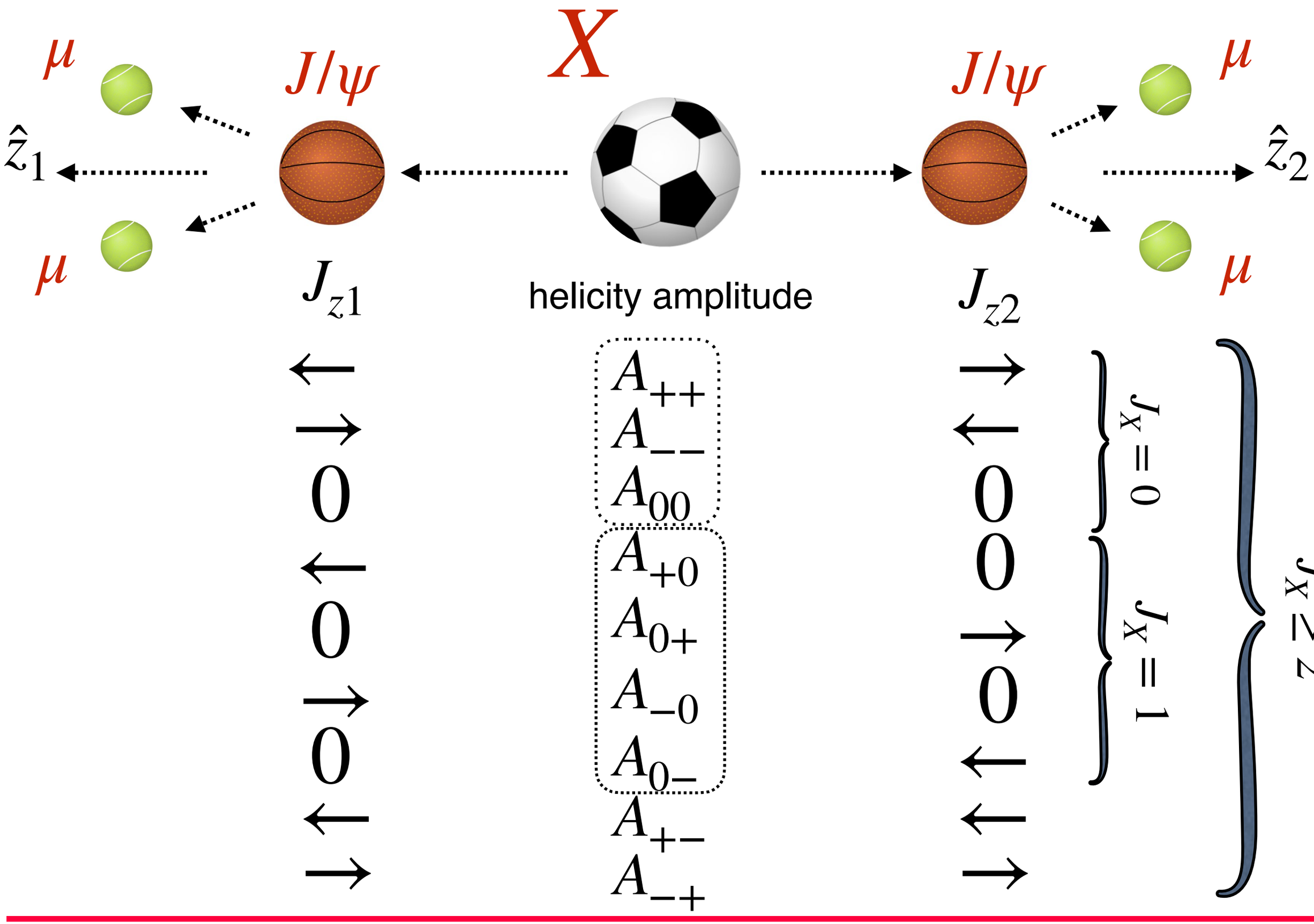


How to study the nature of X

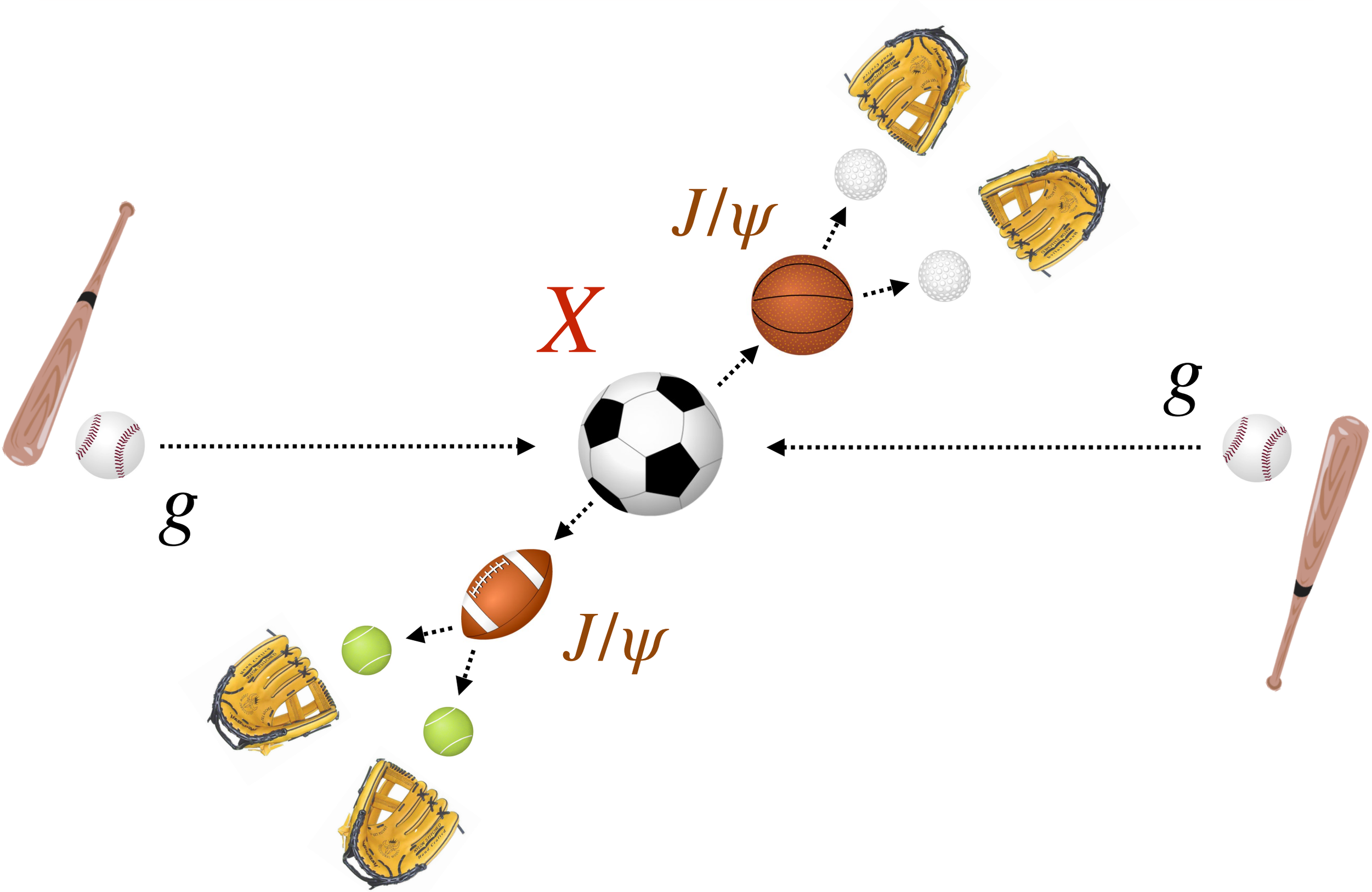
- If this happens in tetra-quarks, why not in protons?
  - follow spin correlations in decay chain
  - determine spin-parity quantum numbers



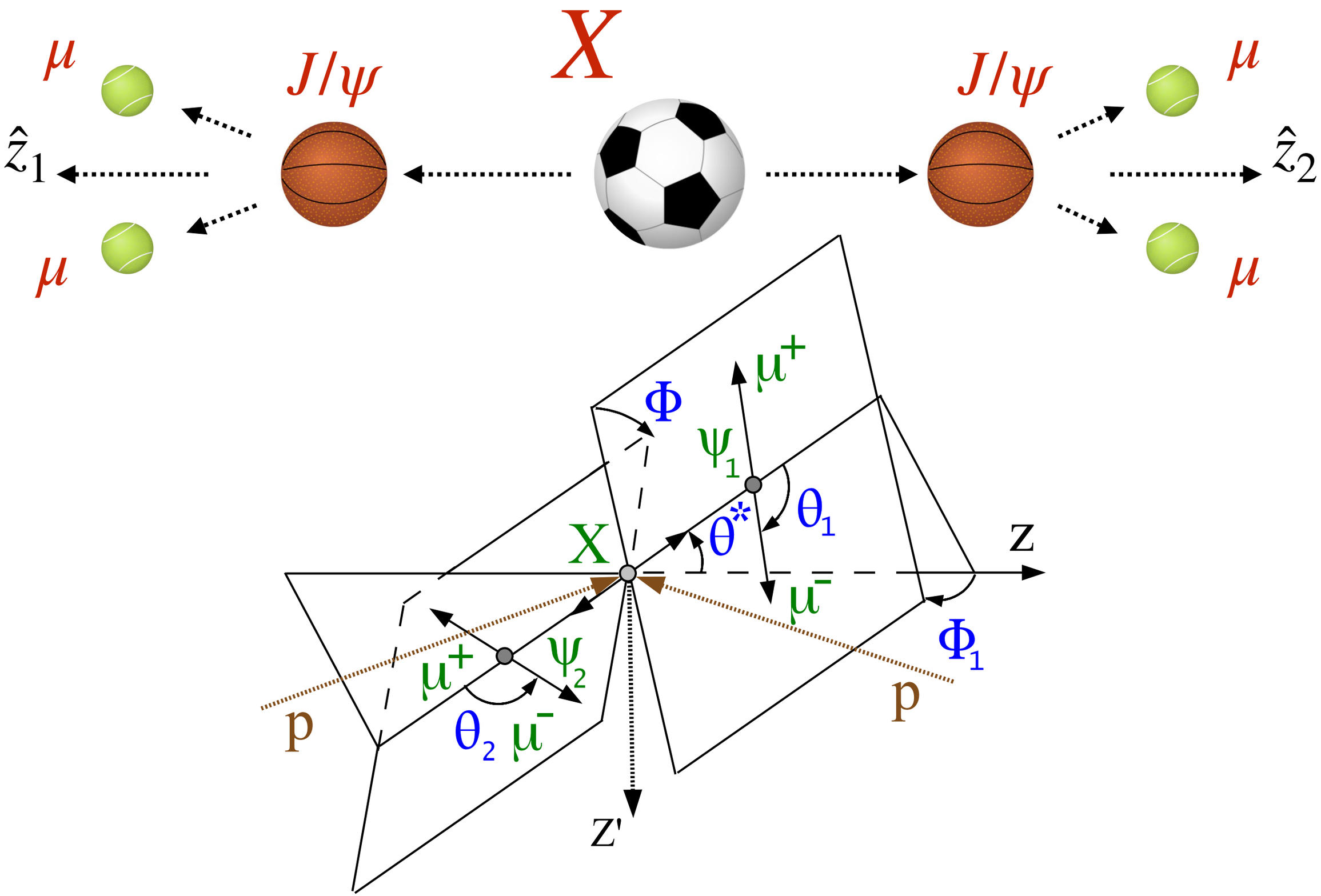
Determine the nature of X



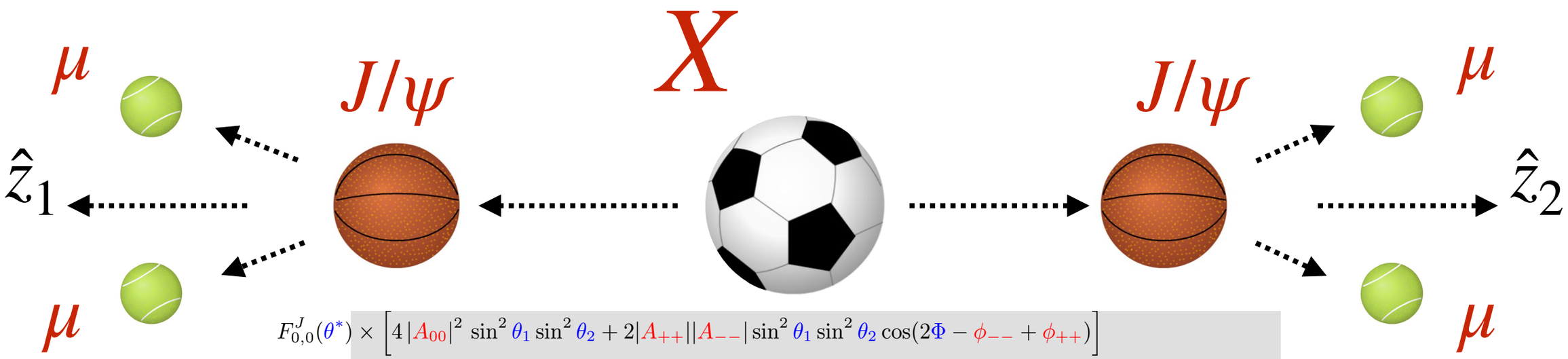
Determine the nature of X



Determine the nature of X



Decay: Angular Distributions



$$F^J_{0,0}(\theta^*) \times \Big[4\,|A_{00}|^2\,\sin^2\theta_1 \sin^2\theta_2 + 2|A_{++}||A_{--}|\sin^2\theta_1 \sin^2\theta_2 \cos(2\Phi - \phi_{--} + \phi_{++})\Big]$$
$$+ |A_{++}|^2 \left(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1\right)\left(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right)$$
$$+ |A_{--}|^2 \left(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1\right)\left(1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right) \qquad \text{spin} = 0\ \&\ \geq 1$$
$$+ 4|A_{00}||A_{++}|(A_{f_1} + \cos\theta_1)\sin\theta_1(A_{f_2} + \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{++})$$
$$+ 4|A_{00}||A_{--}|(A_{f_1} - \cos\theta_1)\sin\theta_1(A_{f_2} - \cos\theta_2)\sin\theta_2\cos(\Phi - \phi_{--})$$

A_{++}
A_{--}
A_{00}
A_{+0}
A_{0+}
A_{-0}
A_{0-}
A_{+-}
A_{-+}

$$+F^J_{1,1}(\theta^*) \times \Big[2|A_{+0}|^2(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)\sin^2\theta_2 + 2|A_{0-}|^2\sin^2\theta_1(1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2)$$
$$+ 2|A_{-0}|^2(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)\sin^2\theta_2 + 2|A_{0+}|^2\sin^2\theta_1(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2)$$
$$+ 4|A_{+0}||A_{0-}|(A_{f_1} + \cos\theta_1)\sin\theta_1(A_{f_2} - \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{+0} - \phi_{0-})$$
$$+ 4|A_{0+}||A_{-0}|(A_{f_1} - \cos\theta_1)\sin\theta_1(A_{f_2} + \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{0+} - \phi_{-0})\Big] \qquad \text{spin} \geq 1$$

$$+F^J_{1,-1}(\theta^*) \times \Big[4|A_{+0}||A_{0+}|(A_{f_1} + \cos\theta_1)\sin\theta_1(A_{f_2} + \cos\theta_2)\sin\theta_2\cos(2\Psi - \phi_{+0} + \phi_{0+})$$
$$+ 4|A_{0-}||A_{-0}|(A_{f_1} - \cos\theta_1)\sin\theta_1(A_{f_2} - \cos\theta_2)\sin\theta_2\cos(2\Psi - \phi_{0-} + \phi_{-0})$$
$$+4|A_{+0}||A_{-0}|\sin^2\theta_1\sin^2\theta_2\cos(2\Psi - \Phi - \phi_{+0} + \phi_{-0}) + 4|A_{0-}||A_{0+}|\sin^2\theta_1\sin^2\theta_2\cos(2\Psi + \Phi - \phi_{0-} + \phi_{0+})\Big]$$

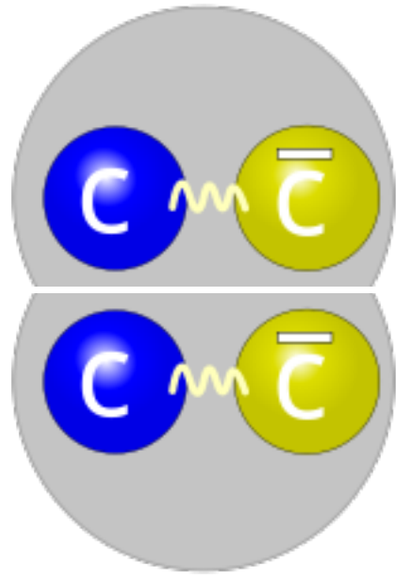
$$+F^J_{2,2}(\theta^*) \times \Big[|A_{+-}|^2(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)(1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2)$$
$$+ |A_{-+}|^2(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2)\Big] \qquad \text{spin} \geq 2$$
$$+F^J_{2,-2}(\theta^*) \times \Big[2|A_{+-}||A_{-+}|\sin^2\theta_1\sin^2\theta_2\cos(4\Psi - \phi_{+-} + \phi_{-+})\Big] + \text{other 26 interference terms for spin}$$

where $\Psi = \Phi_1 + \Phi/2$ and $F^J_{ij}(\theta^*) = \sum_{m=0,\pm1,\pm2} f_m\, d^J_{im}(\theta^*) d^J_{jm}(\theta^*)$

Summary

- Quark model has been successful for ~50 years
  — explains our existence
- Recent exotic states from quarks (?)

One popular model is a "molecule"
kind of a bound state of two mesons
connected by a strong nuclear force,
like proton and neutron in a nucleus



X composite particle

Another — true tetra-quark connects
two colored objects (cc) and $(\bar{c}\bar{c})$
through direct strong interactions
like quarks in a proton or neutron

- Fundamental study of matter at quark level…