

チャームで見る エキゾチックハドロン・原子核

KEK

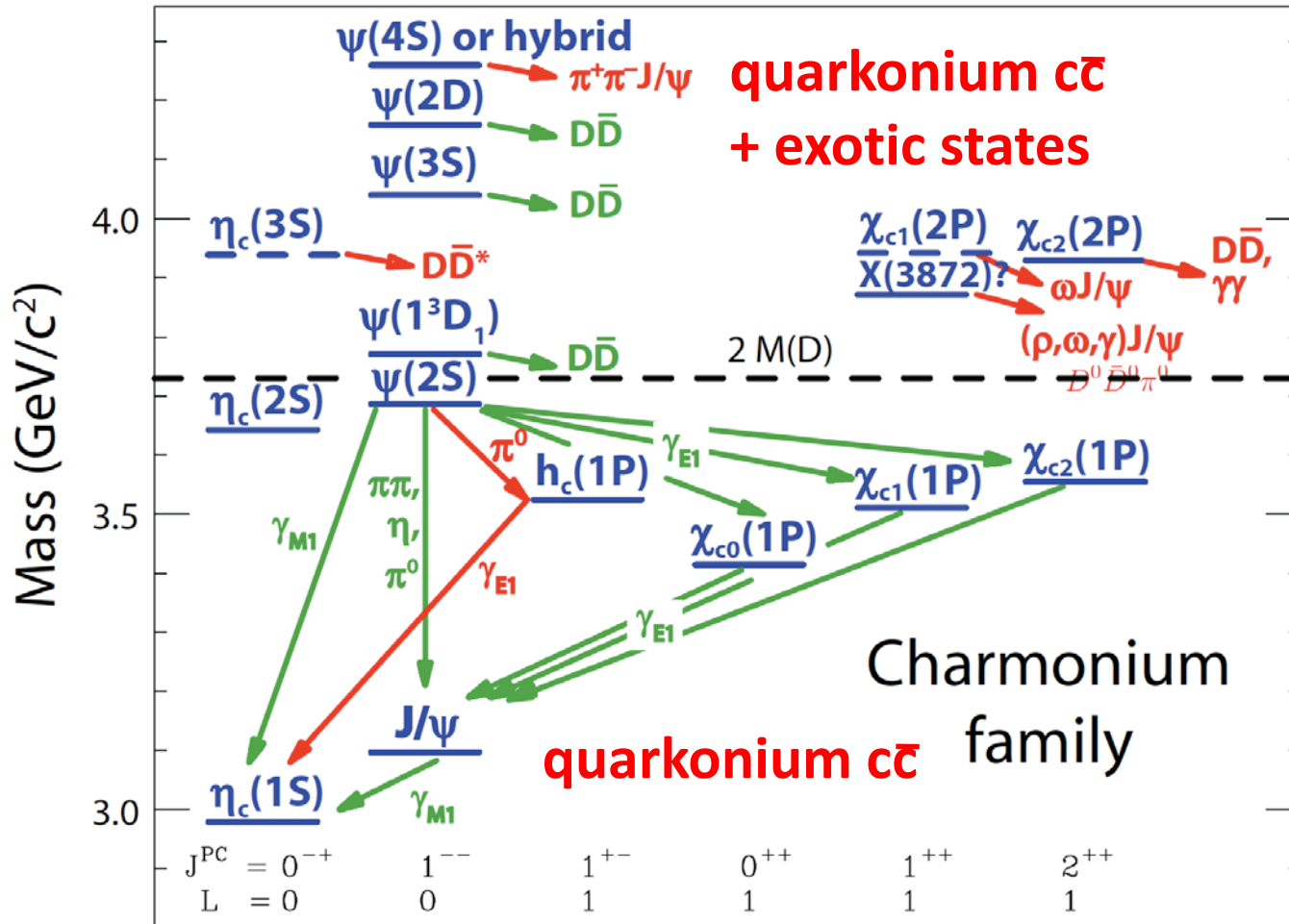
安井 繁宏

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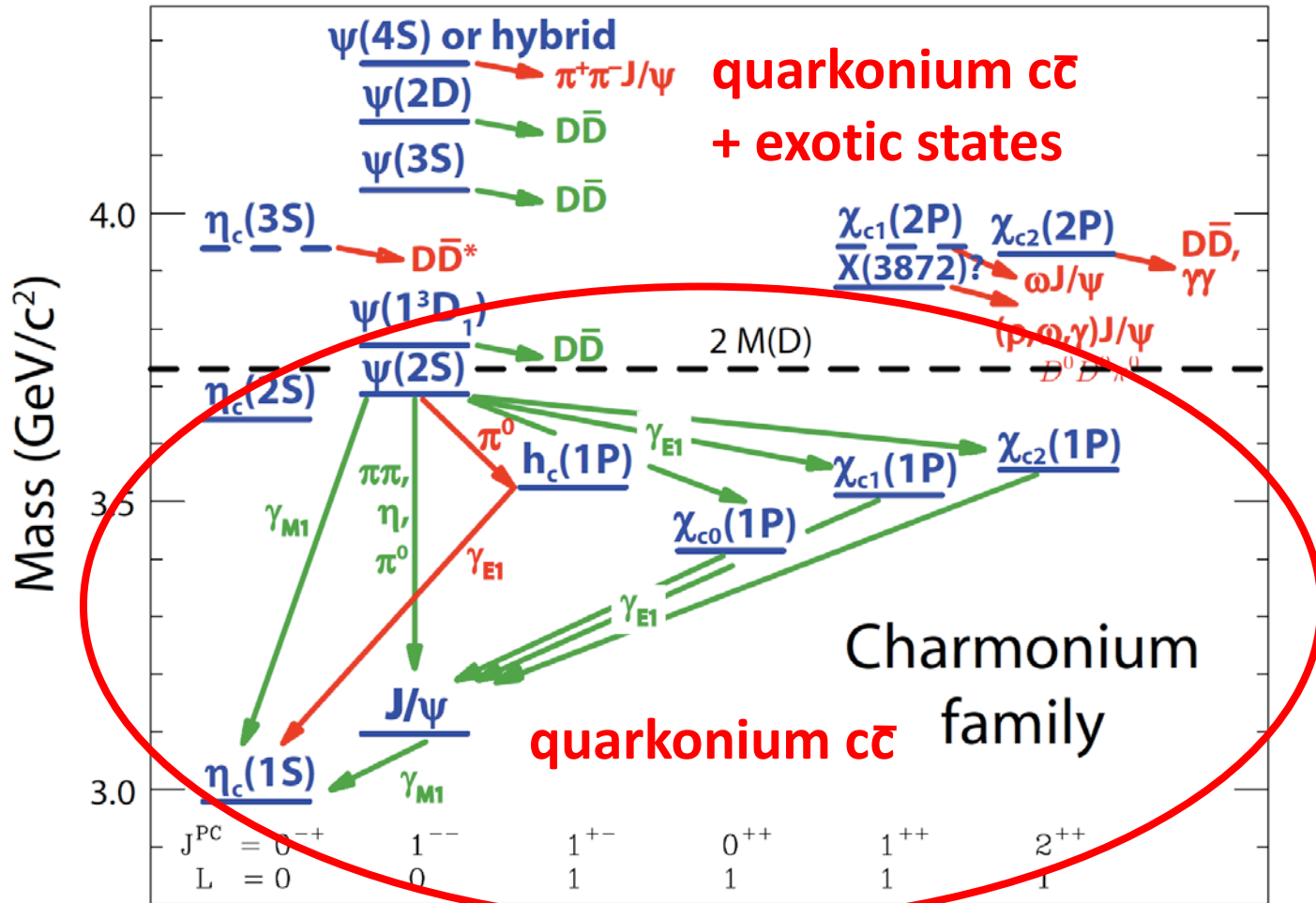
1. Introduction

Many new $c\bar{c}$ states above threshold



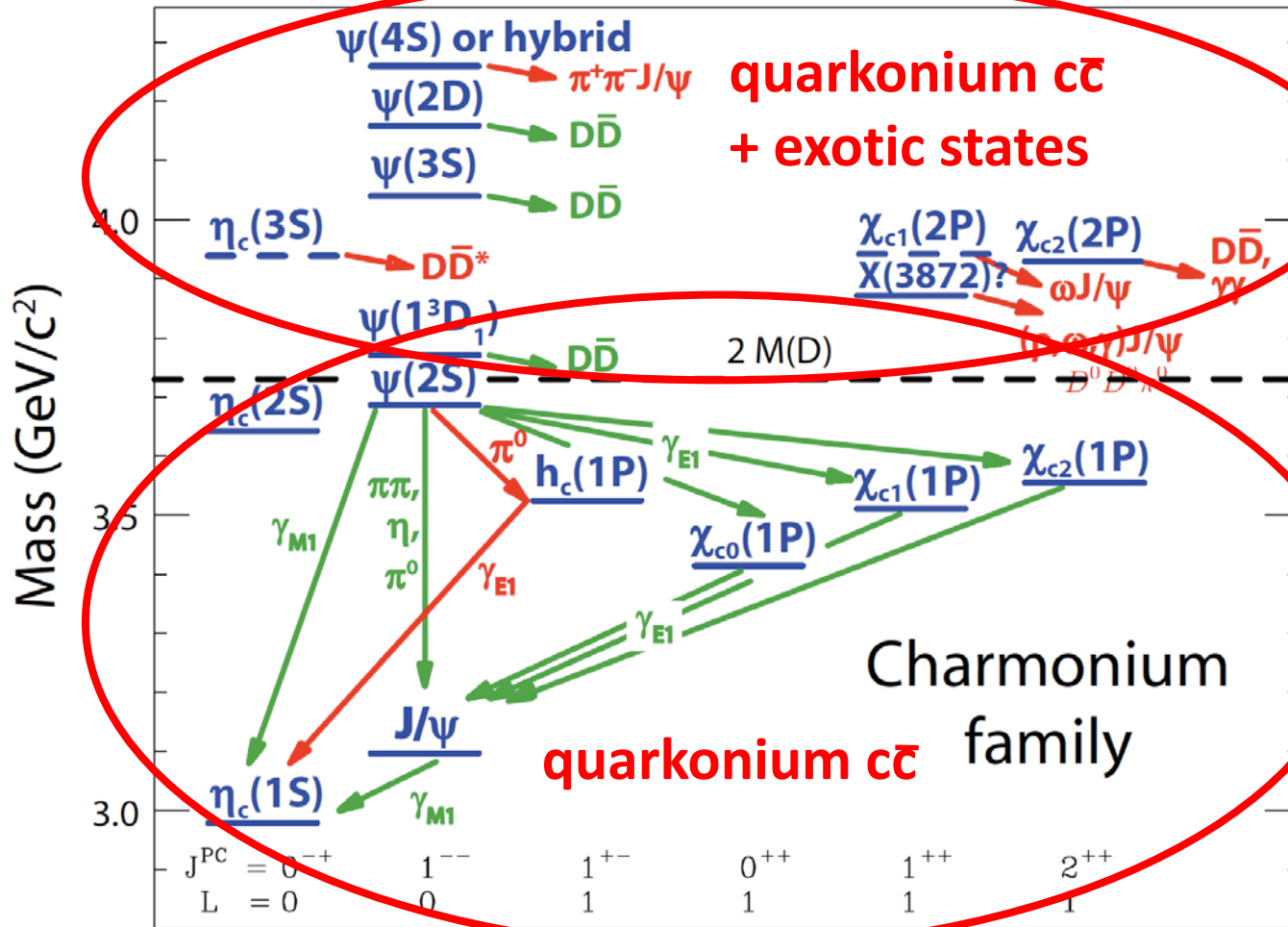
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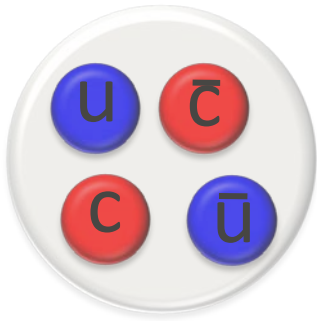
1. Introduction

$X(3872)$, $X(3940)$, $Y(4260)$, $Z(4430)^+$, ... Y_b , Z_b , ...

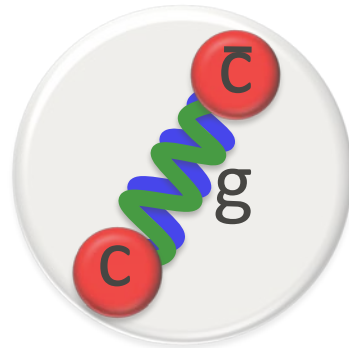
Why are they exotic?

- unusual decay widths and branching ratios
- mass difference from $c\bar{c}$ in quark model (~ 100 MeV)

$X(3872)$



$Y(4260)$



$Z(4430)^+$ (Z_b)



T_{cc}^1



$D\bar{D}^*$ ($c\bar{c}u\bar{u}$) molecule
Tornqvist (1991)



$D\bar{D}^*$ threshold ?

$c\bar{c}g$ hybrid
S. L. Zhu (2005)



gluon dynamics ?

$c\bar{c}u\bar{d}$ ($b\bar{b}u\bar{d}$)
really tetraquark



new correlation ?

$\bar{c}\bar{c}ud$
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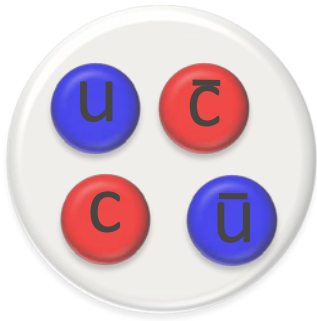
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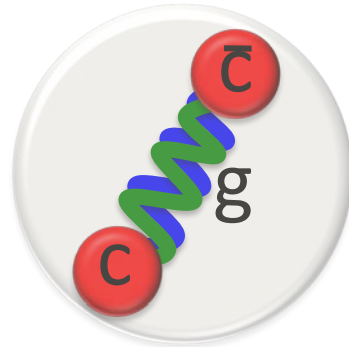
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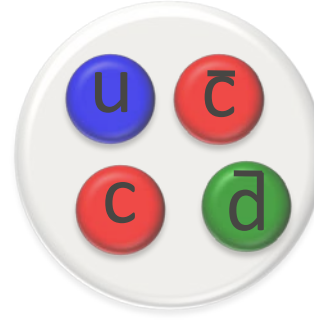
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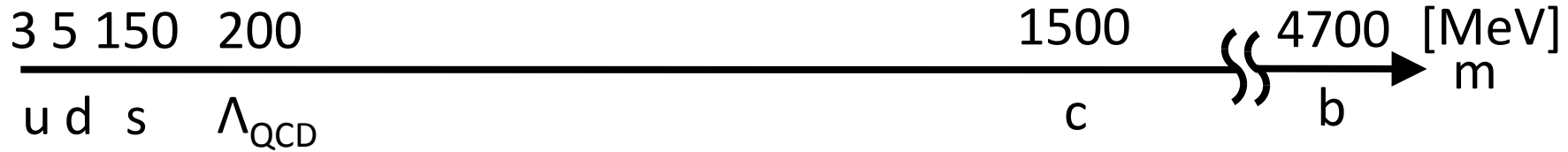
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**What states are allowed as solutions of QCD?
Can we construct effective theories from QCD?**

D

n ?

2. Symmetry and dynamics of heavy quark hadrons



Chiral Symmetry

$SU(3)_L \times SU(3)_R$

π , K as Nambu-Goldstone bosons

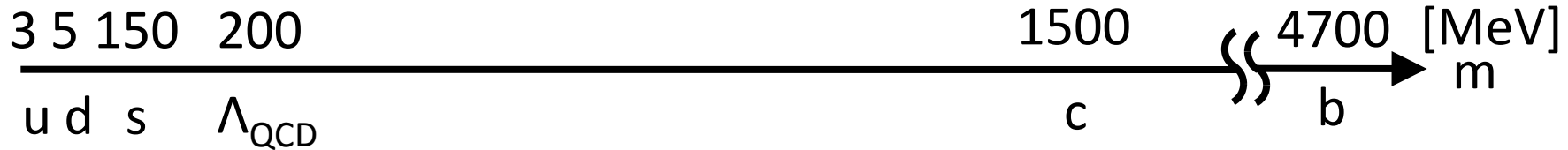
Chiral multiplets (ρ - a_1 , N - N^* , ...)

Nucleus formed by tensor force

Hypernuclei as g.s. of QCD matter

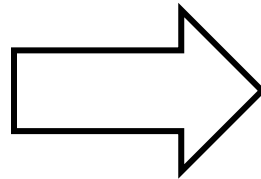
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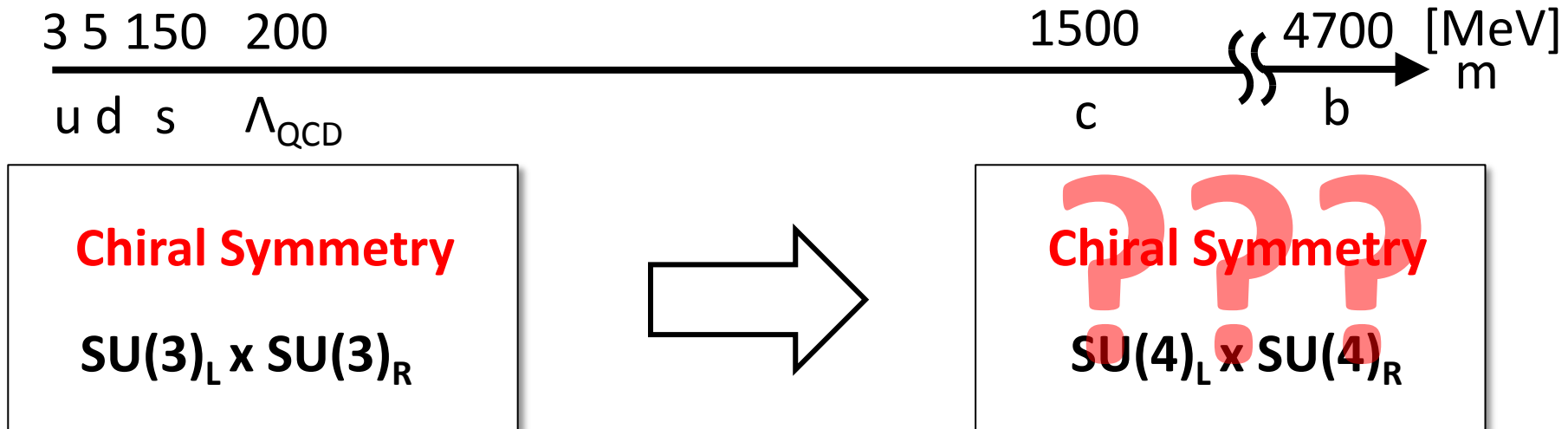
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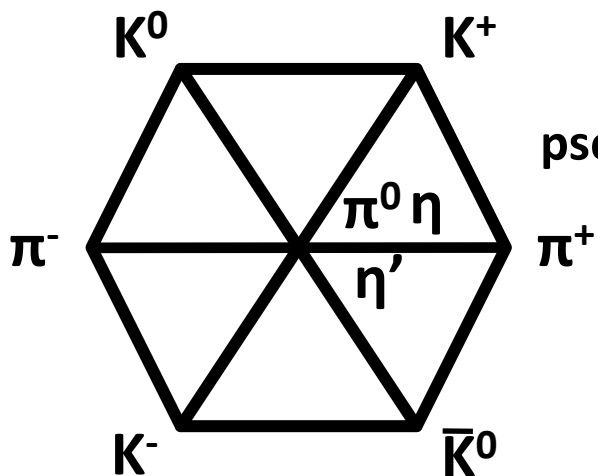
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$SU(3)_f$ symmetry

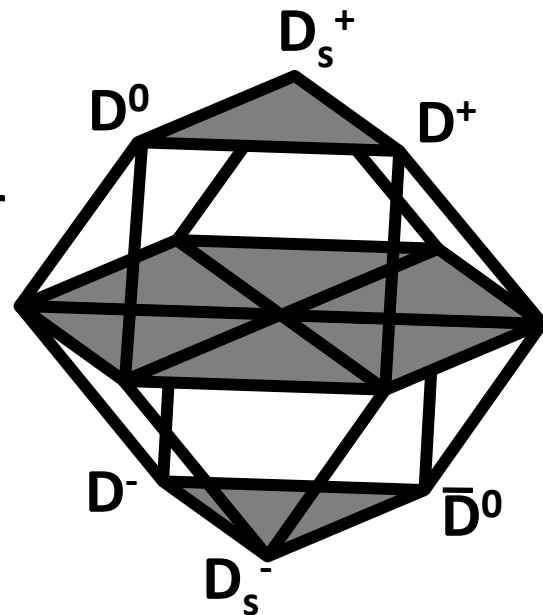


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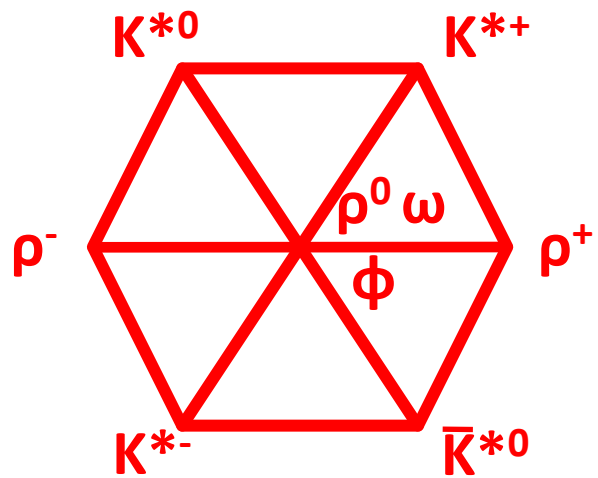
m_{ps}



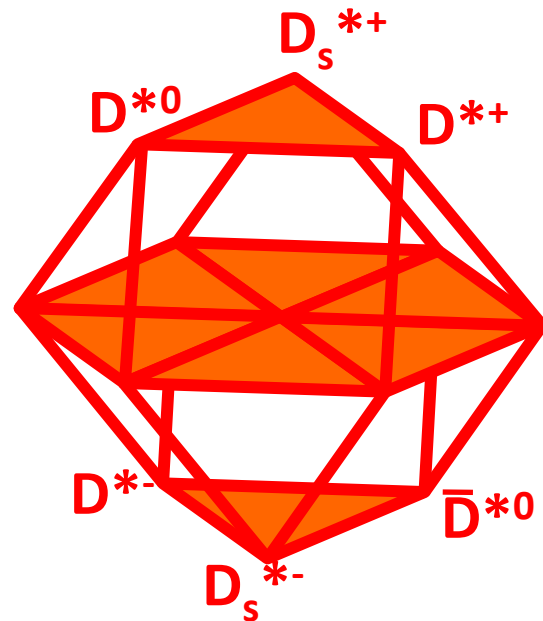
pseudo-scalar



m_v



vector

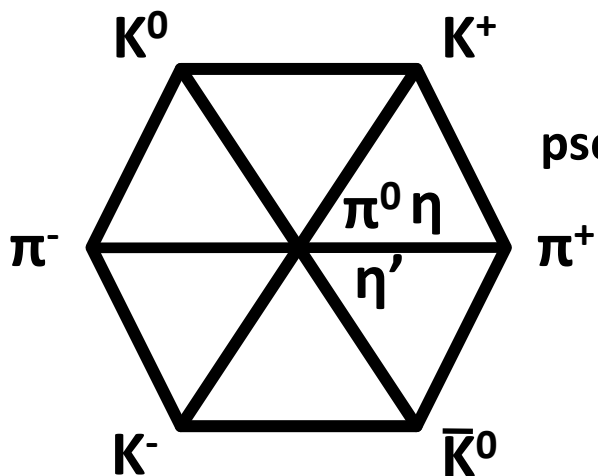


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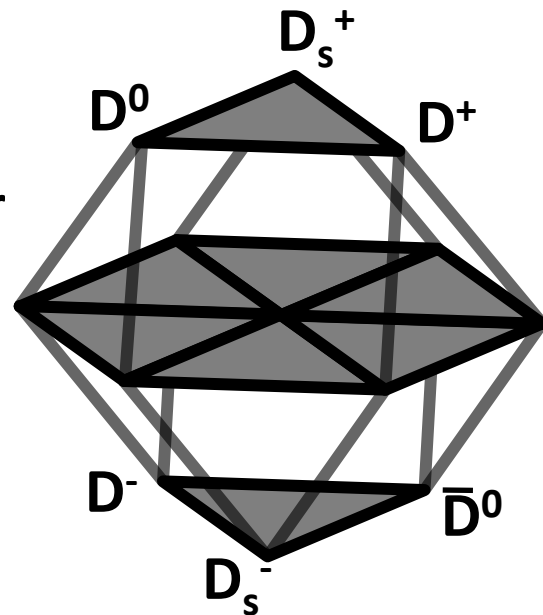


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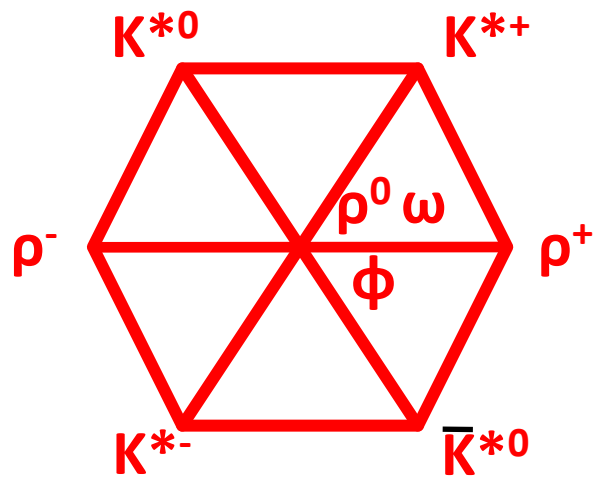
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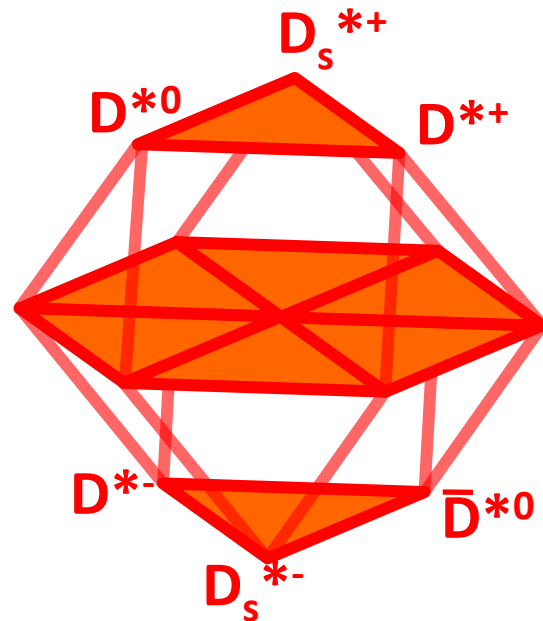
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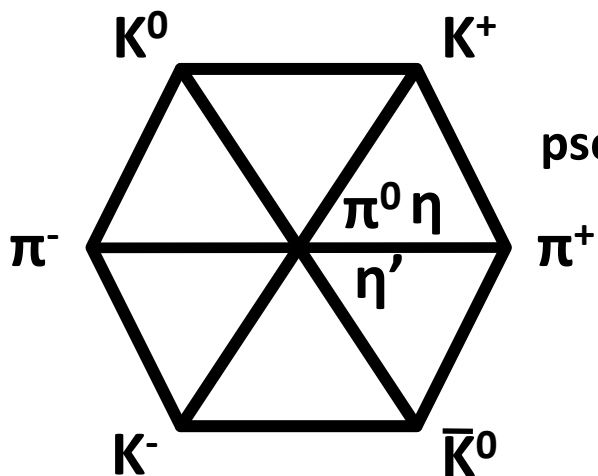


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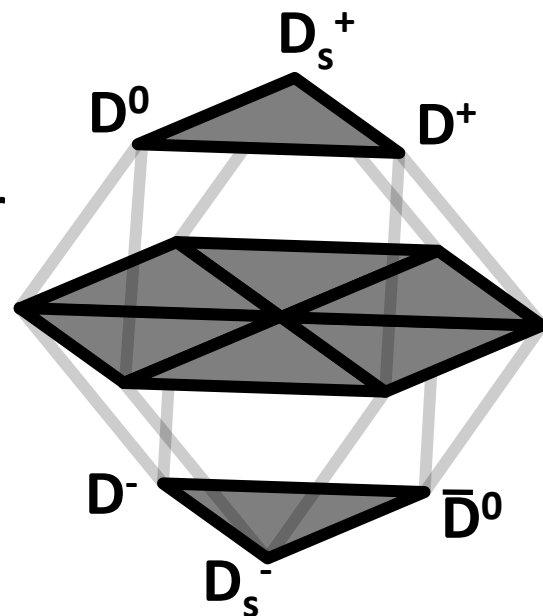


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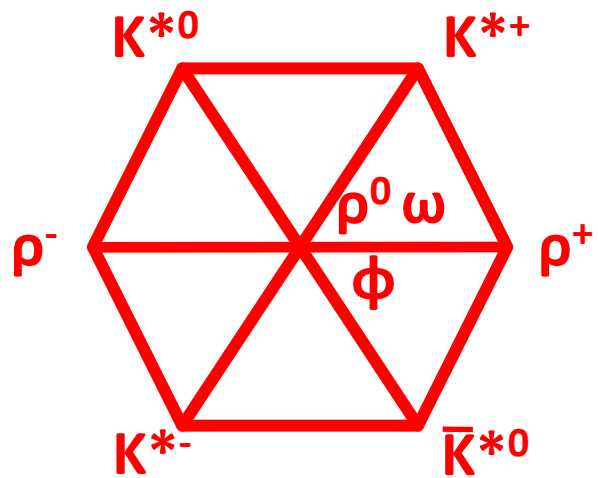
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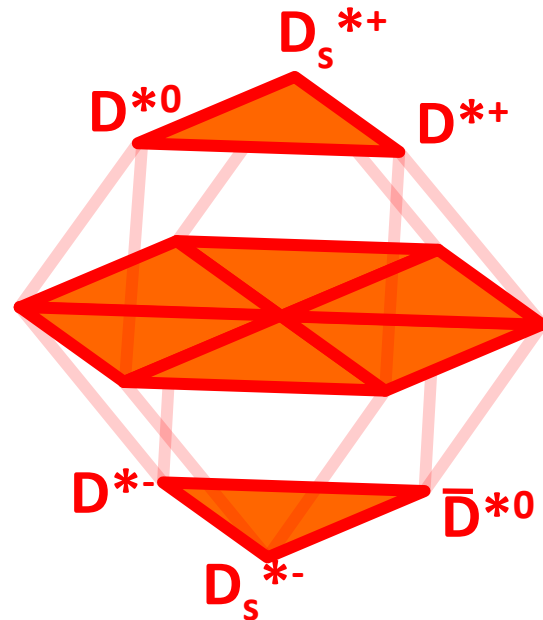
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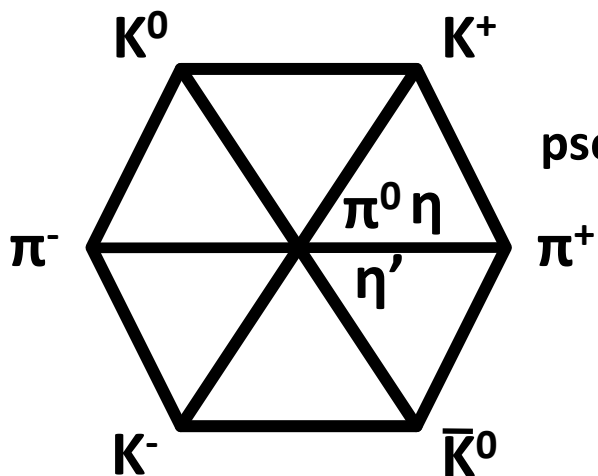


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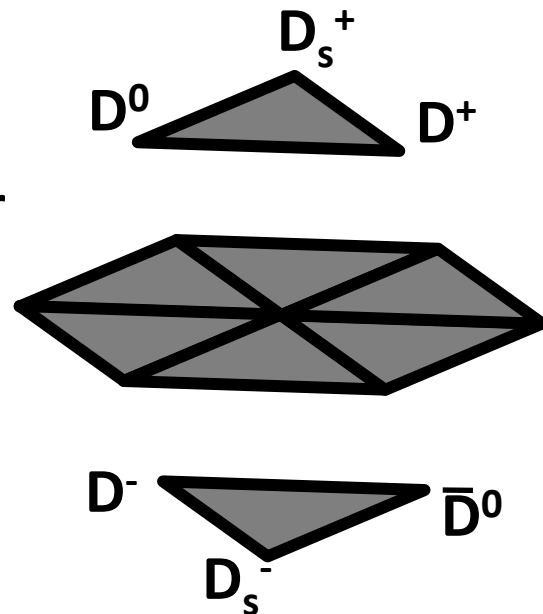


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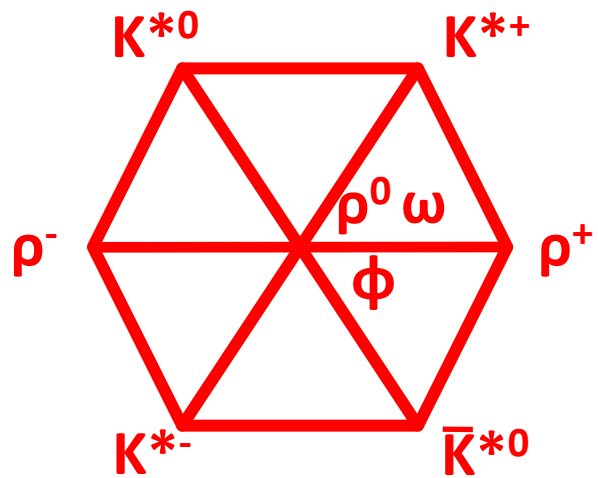
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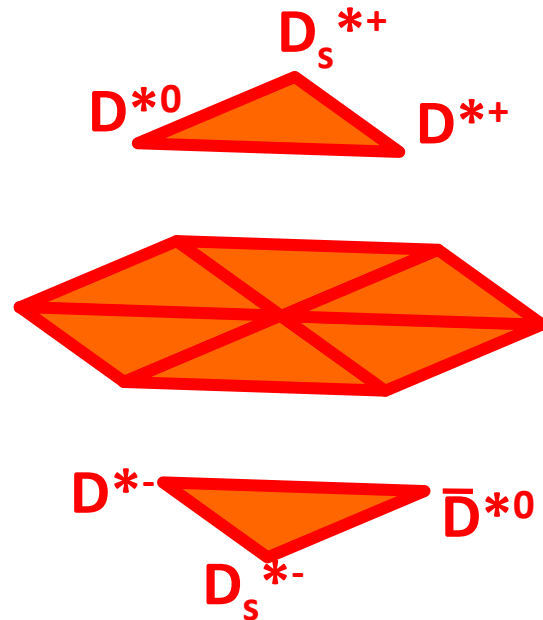
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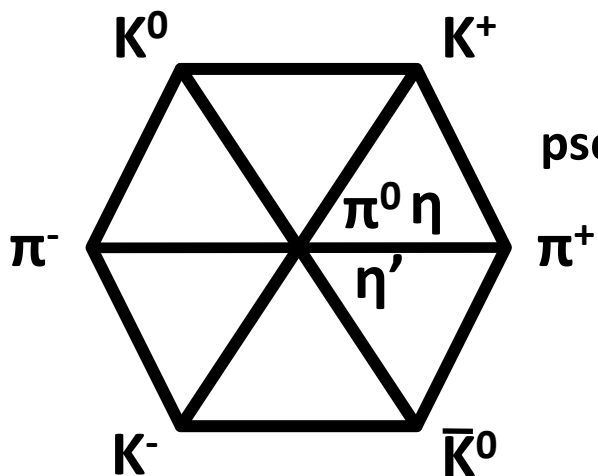


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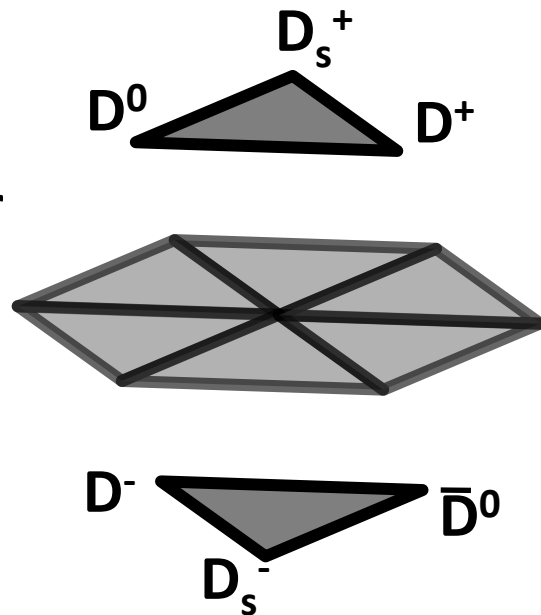


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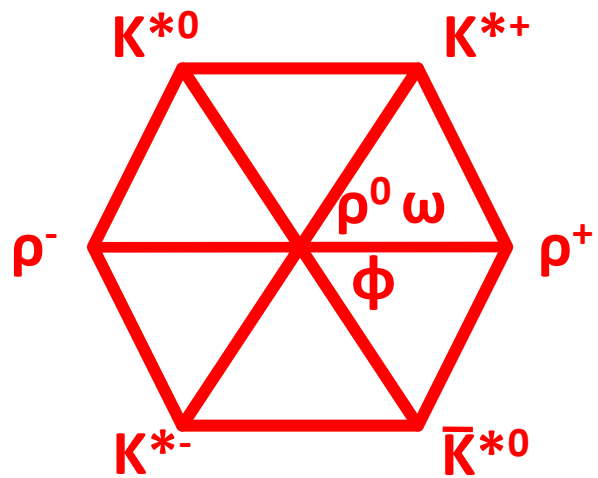
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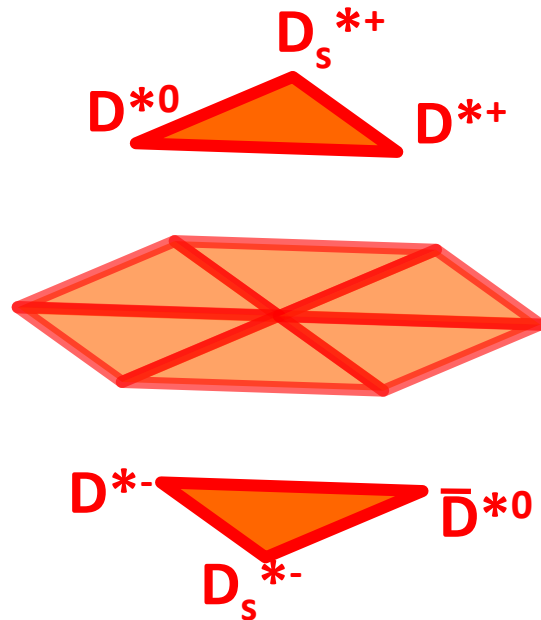
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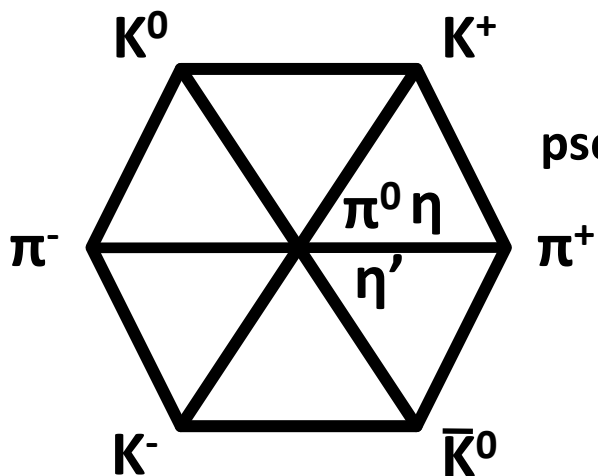


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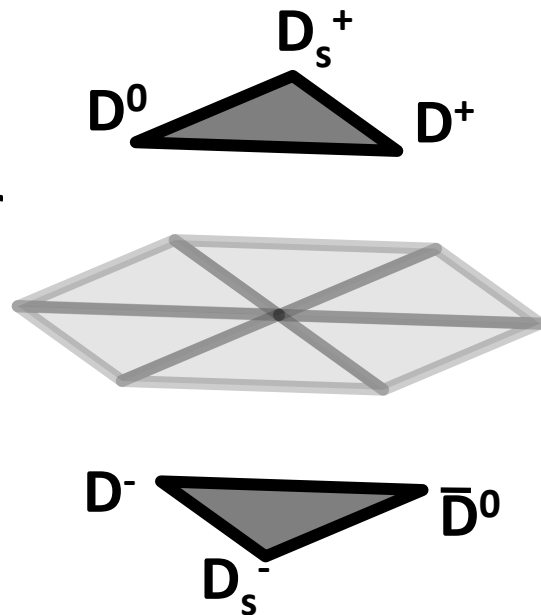


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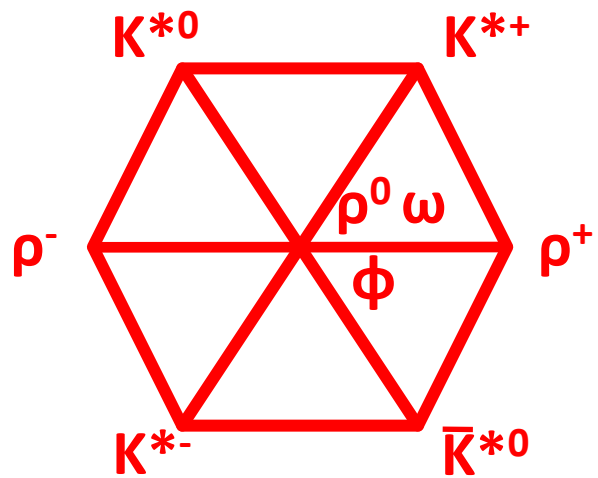
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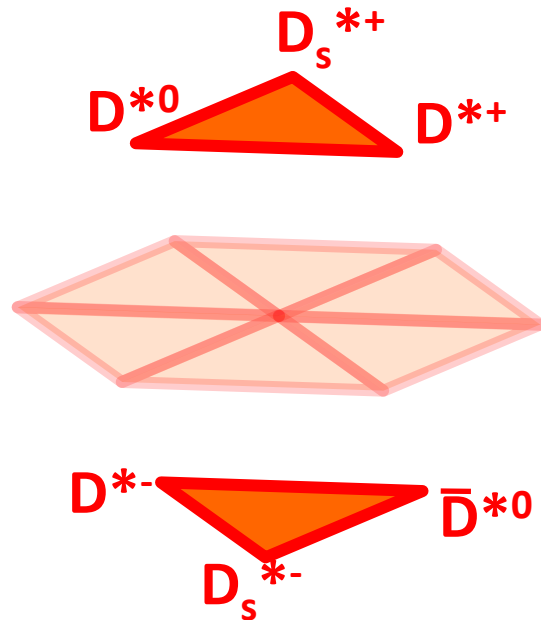
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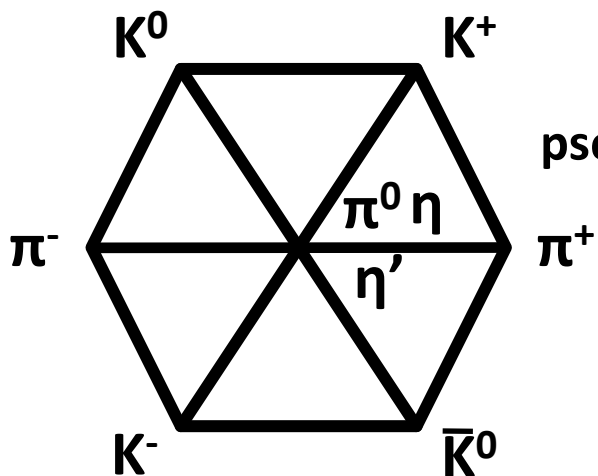


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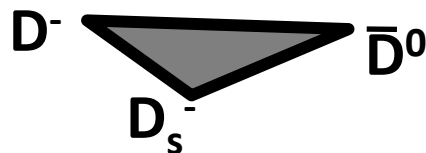
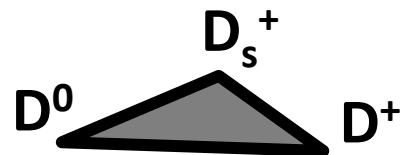


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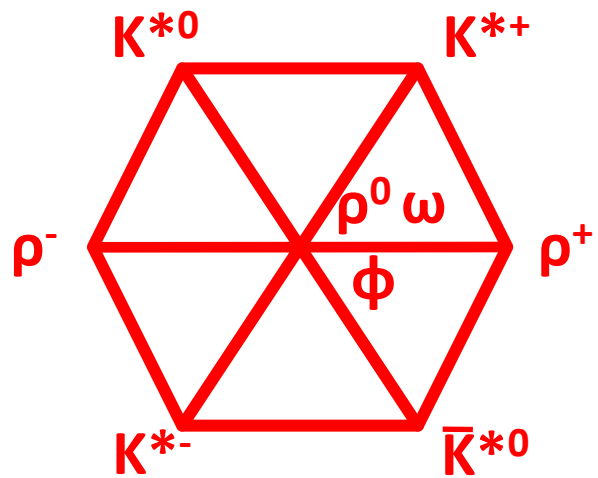
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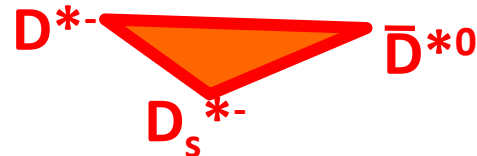
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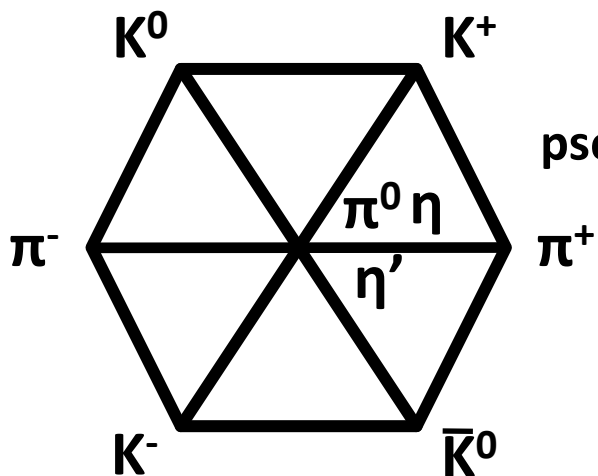


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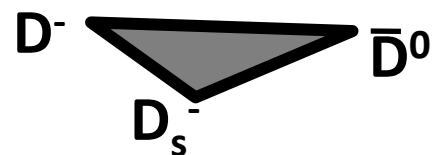
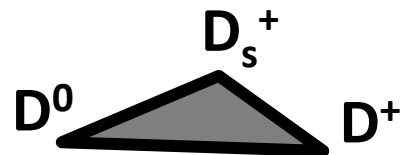


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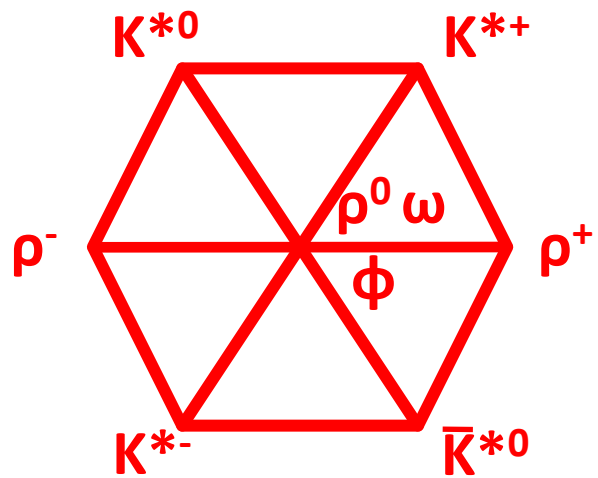
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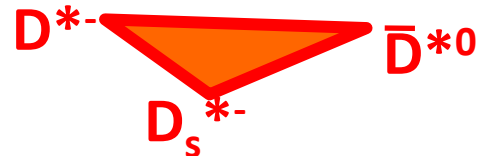
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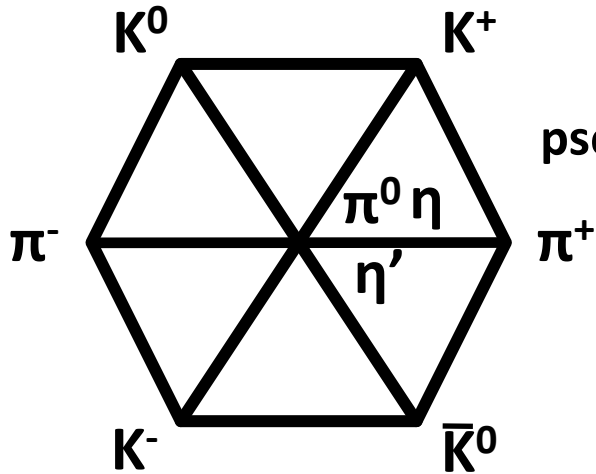


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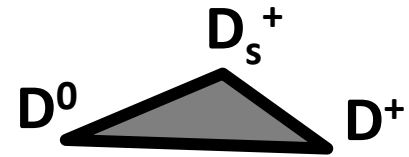


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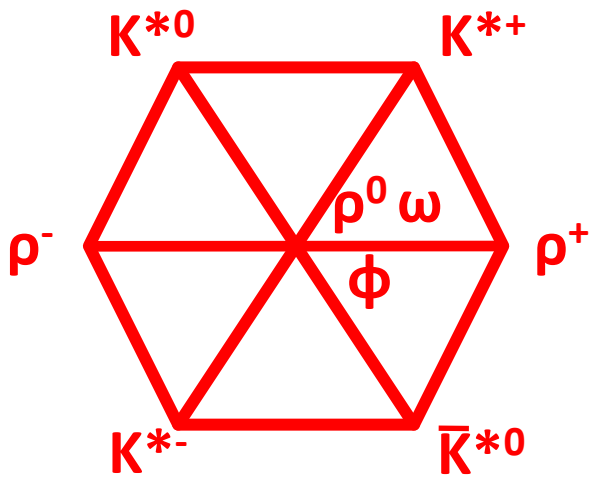
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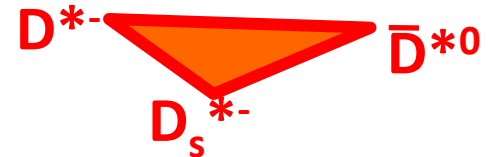
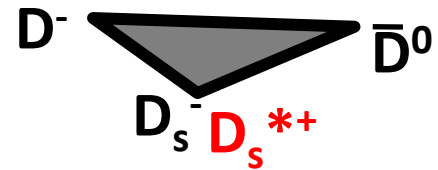
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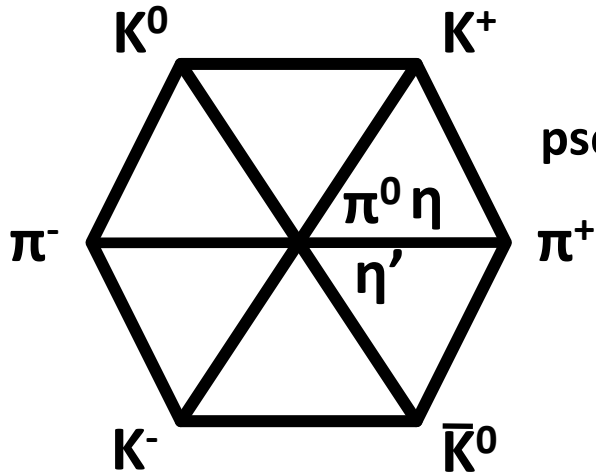


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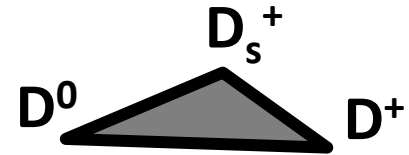


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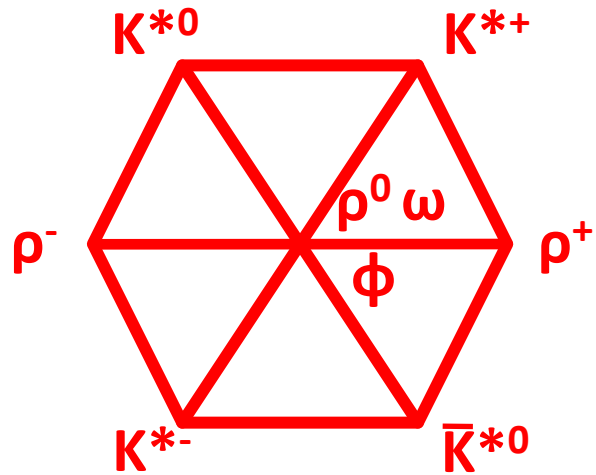
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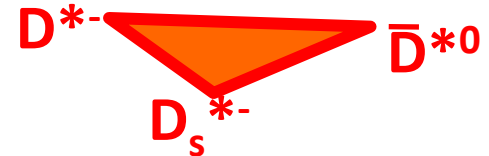
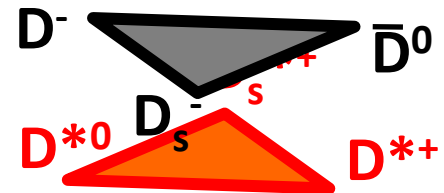
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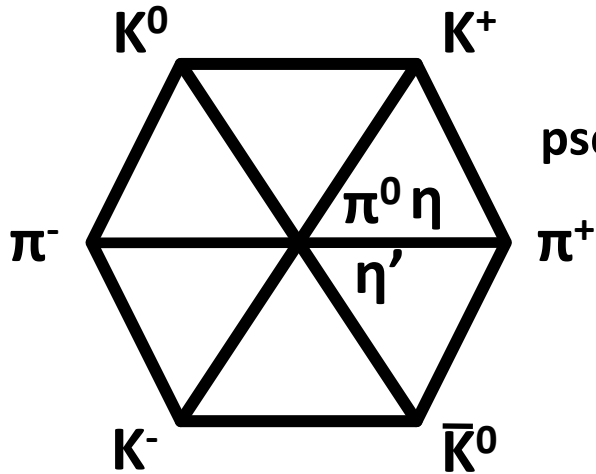


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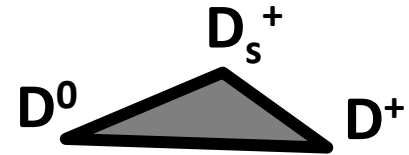


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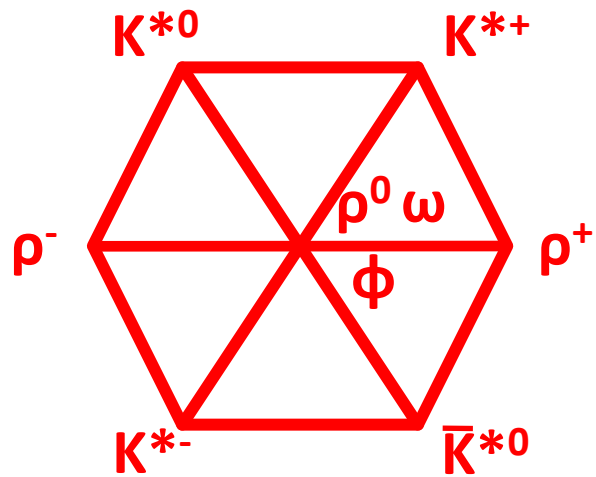
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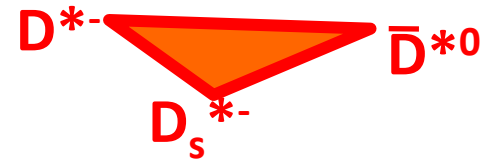
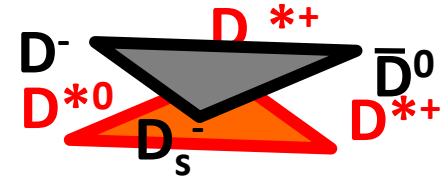
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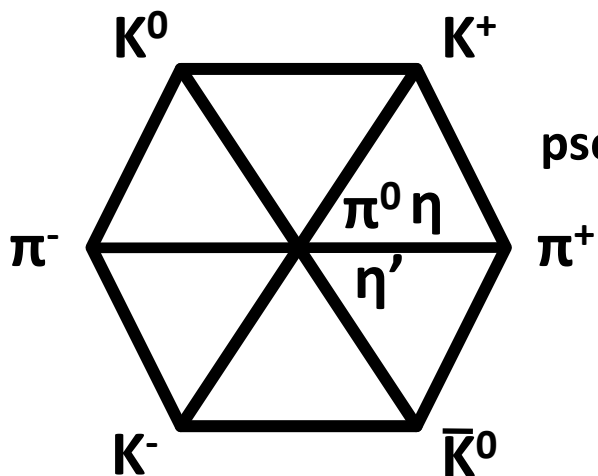


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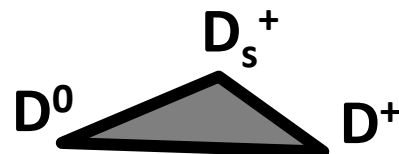


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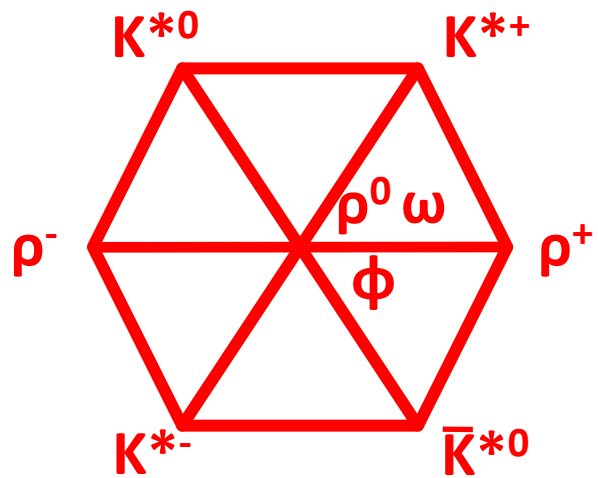
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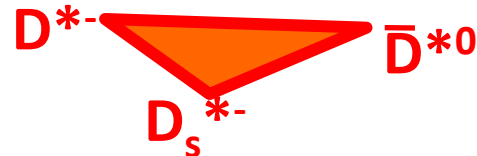
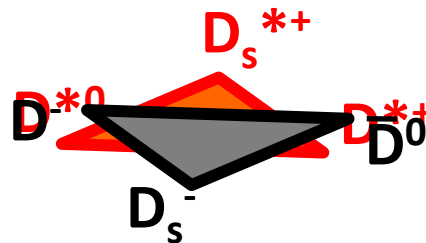
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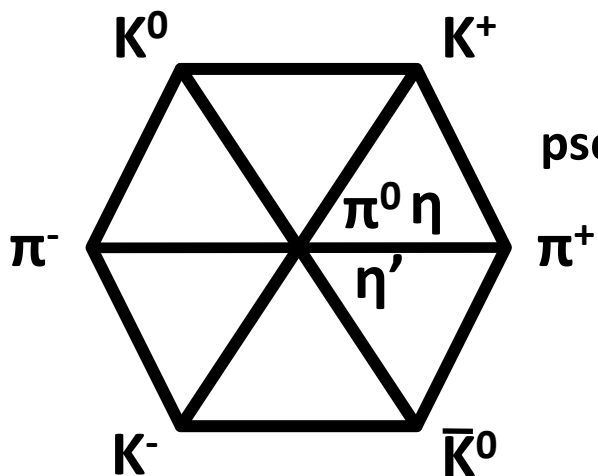


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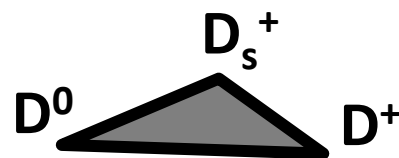


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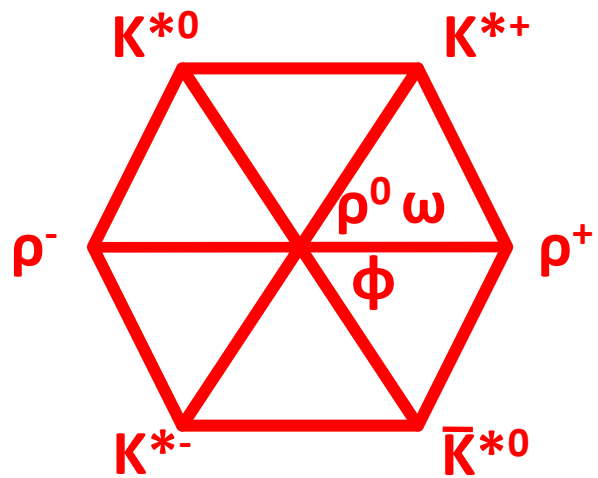
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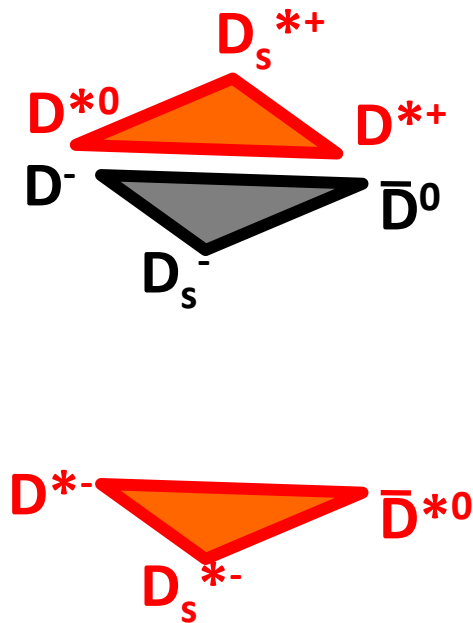
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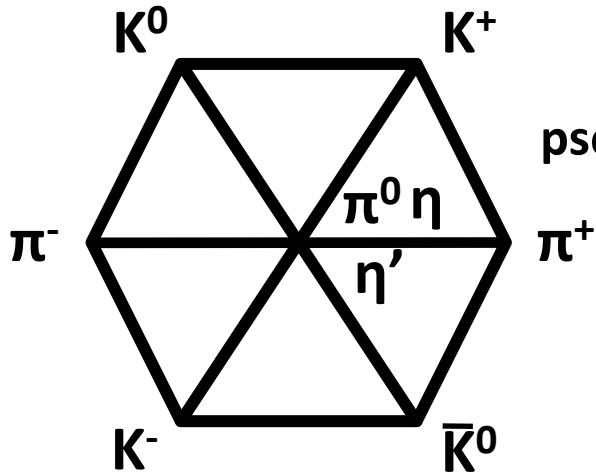


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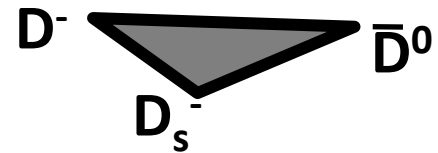
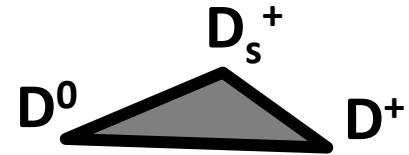


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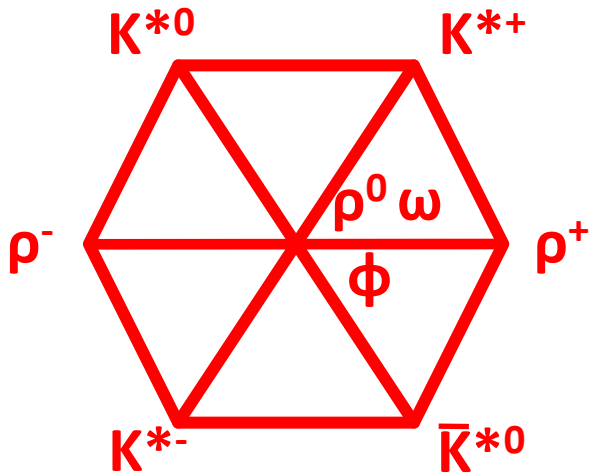
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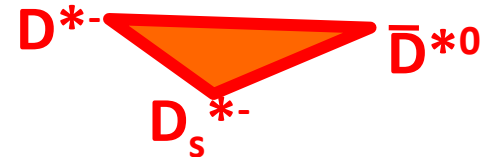
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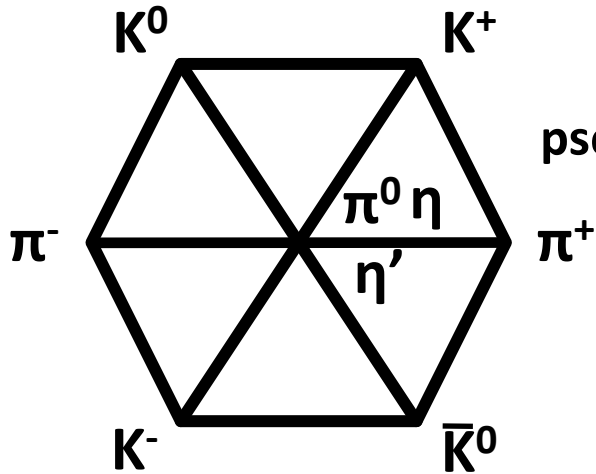


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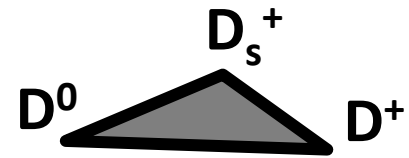


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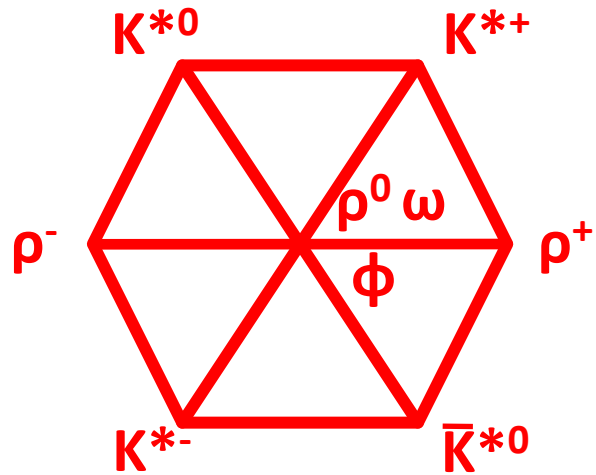
m_{ps}



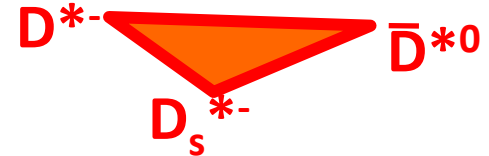
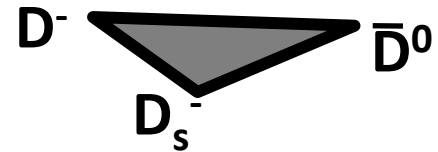
pseudo-scalar



m_v



vector

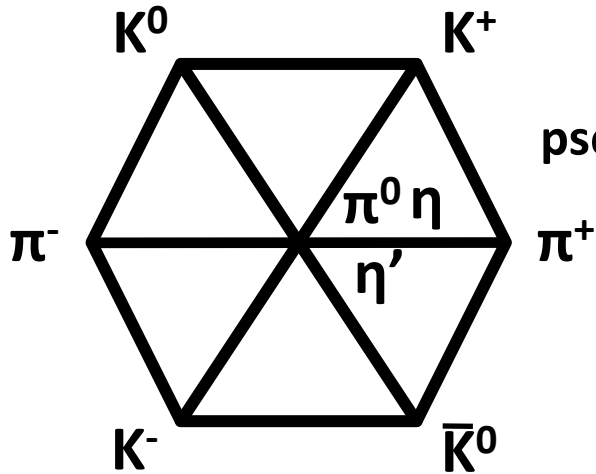


$SU(3)_f$ symmetry

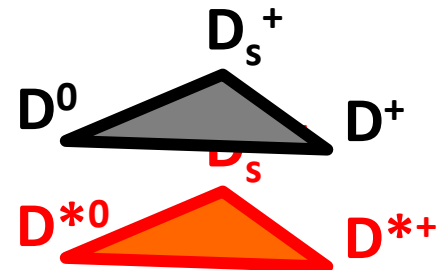


$SU(4)_f$ symmetry ?

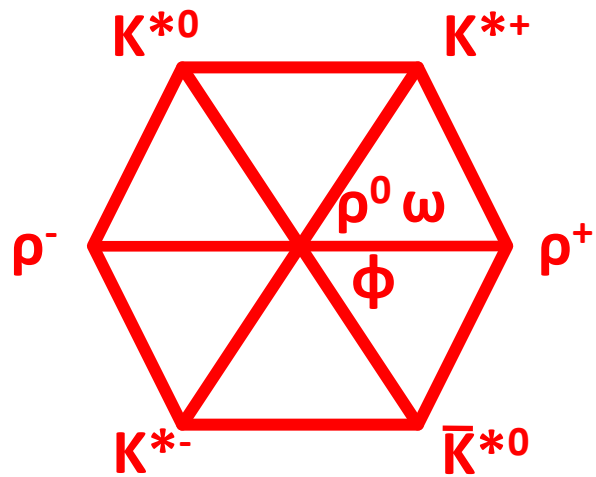
m_{ps}



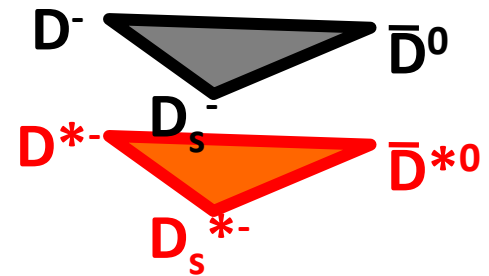
pseudo-scalar



m_v



vector

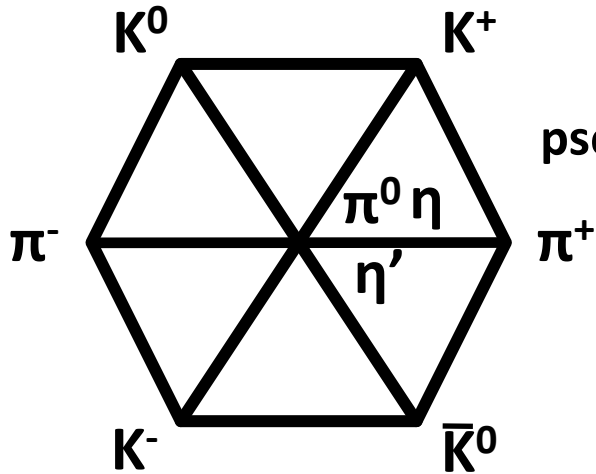


$SU(3)_f$ symmetry

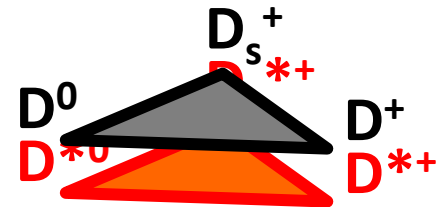


$SU(4)_f$ symmetry ?

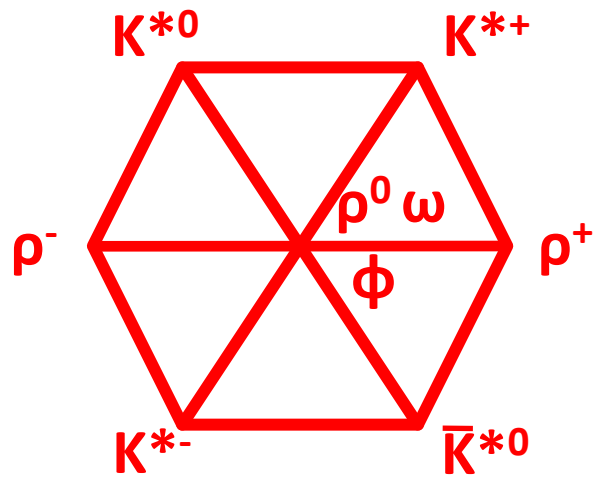
m_{ps}



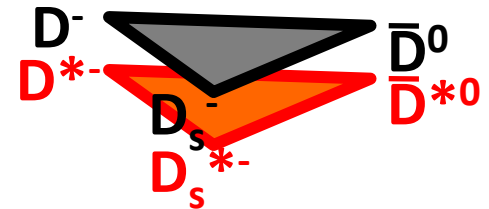
pseudo-scalar



m_v



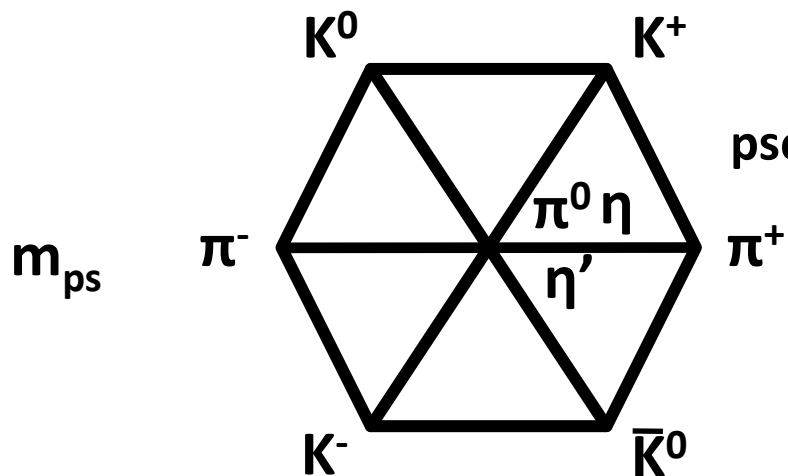
vector



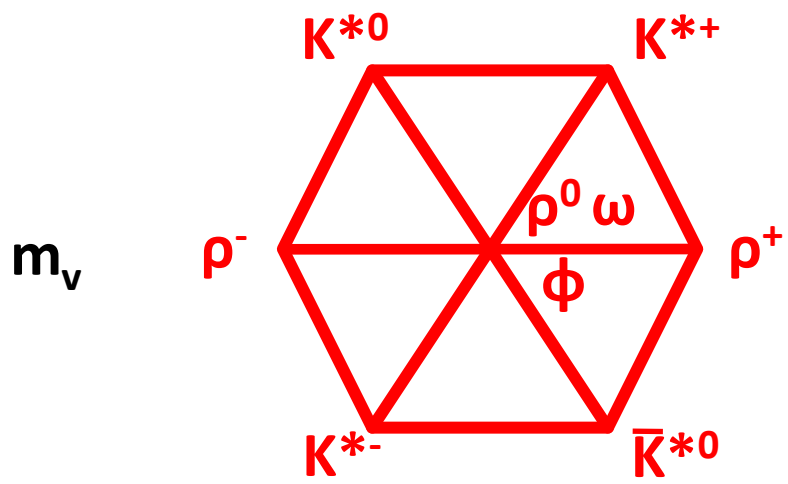
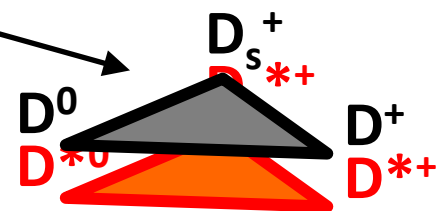
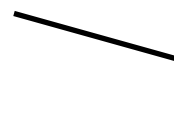
$SU(3)_f$ symmetry



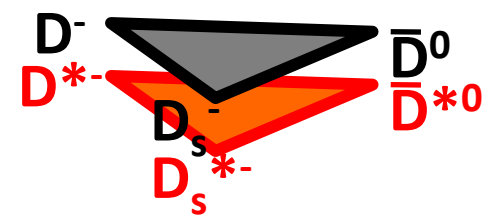
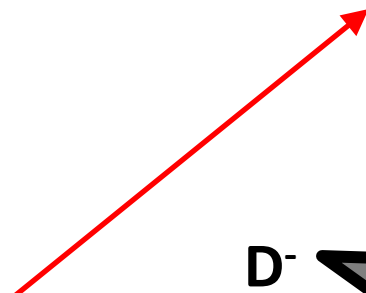
$SU(4)_f$ symmetry ?



pseudo-scalar



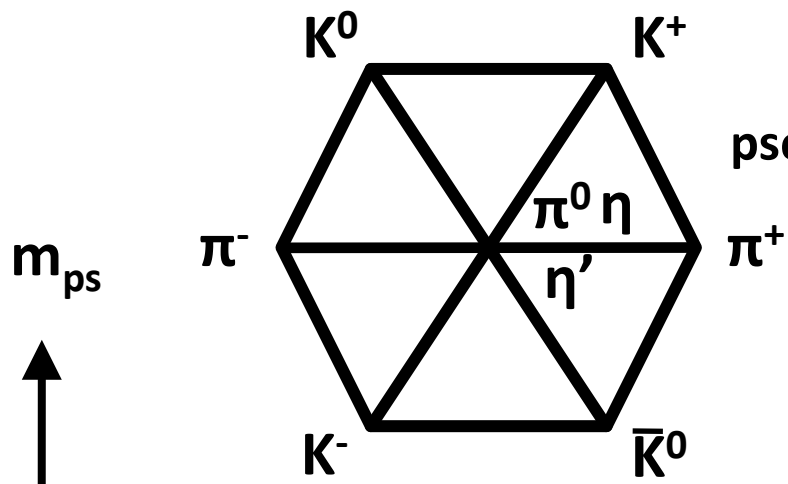
vector



$SU(3)_f$ symmetry



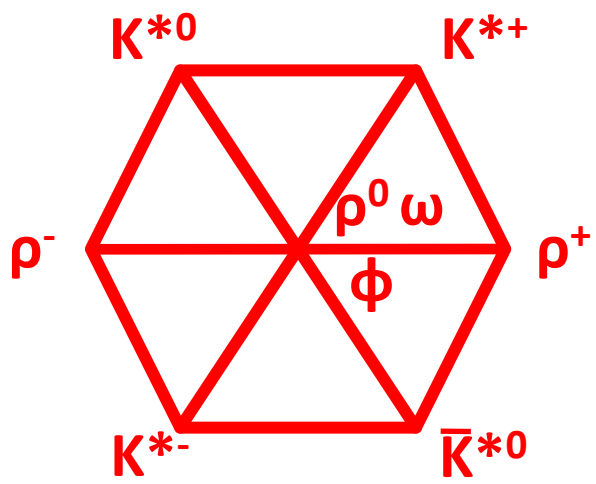
$SU(4)_f$ symmetry ?



m_{ps}

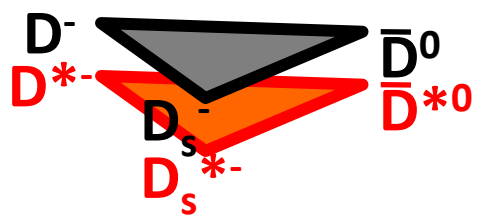
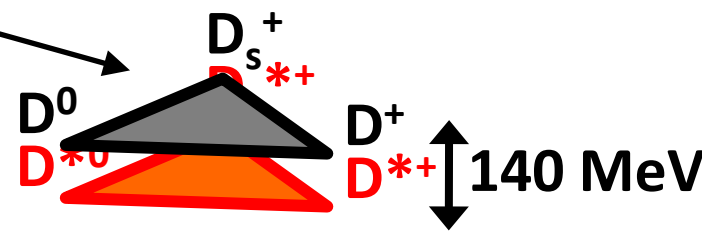
400-600 MeV

m_v



pseudo-scalar

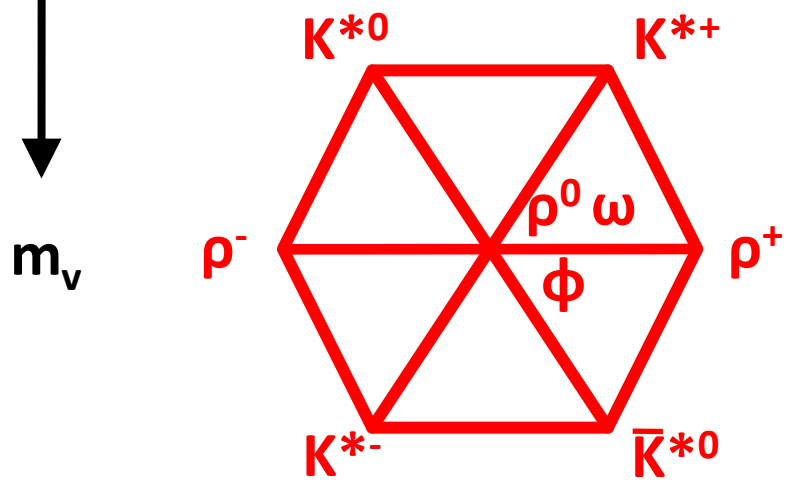
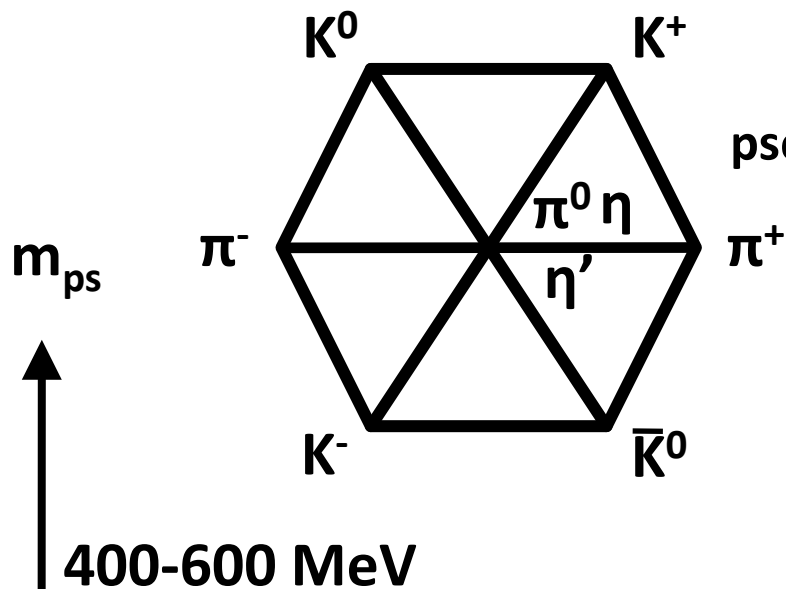
vector



$SU(3)_f$ symmetry



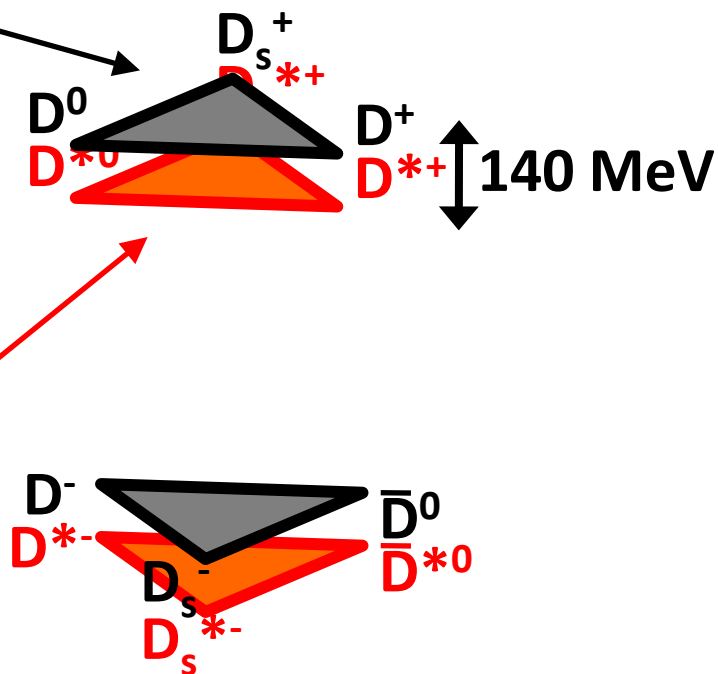
$SU(4)_f$ symmetry ?



pseudo-scalar

$$m_D \approx m_{D^*}$$

vector

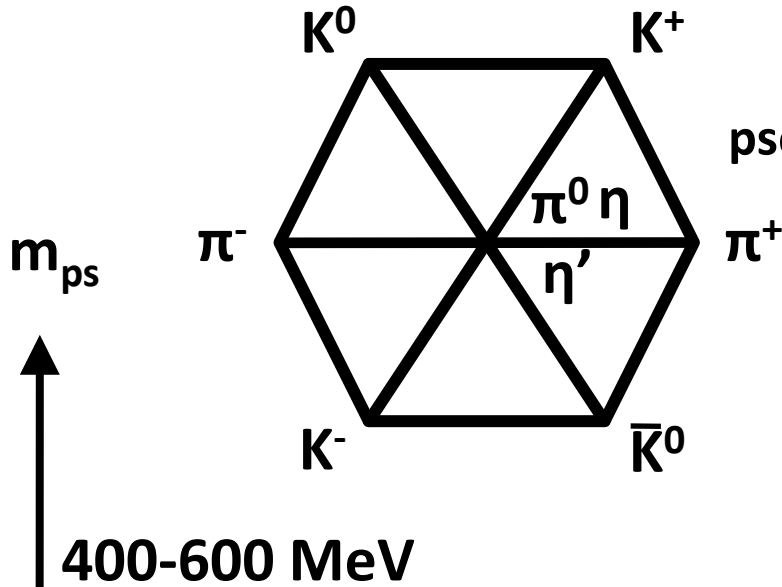


$SU(3)_f$ symmetry



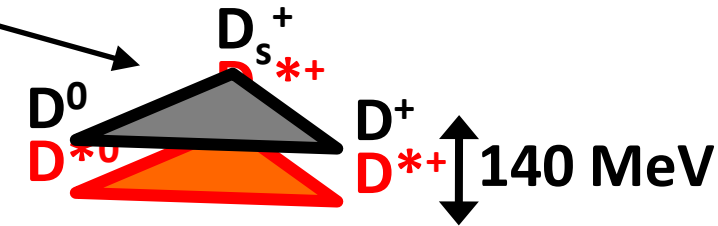
~~$SU(4)_f$ symmetry ?~~

Heavy Quark Symmetry

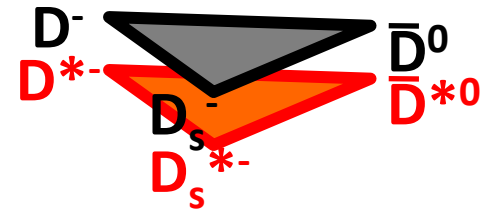
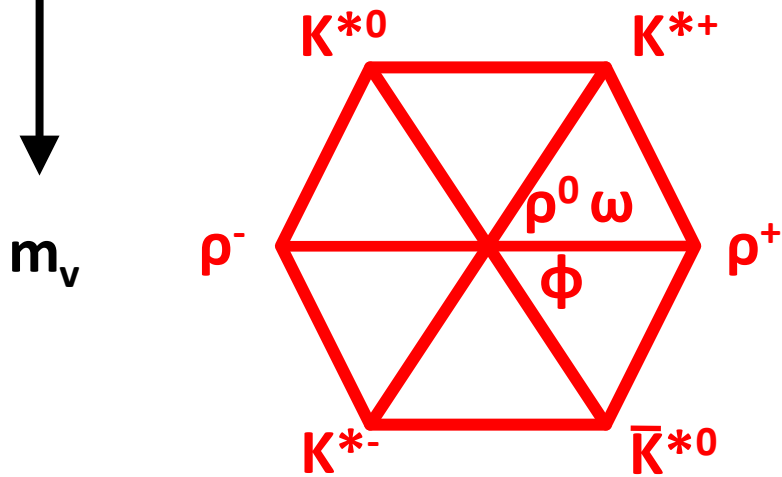


pseudo-scalar

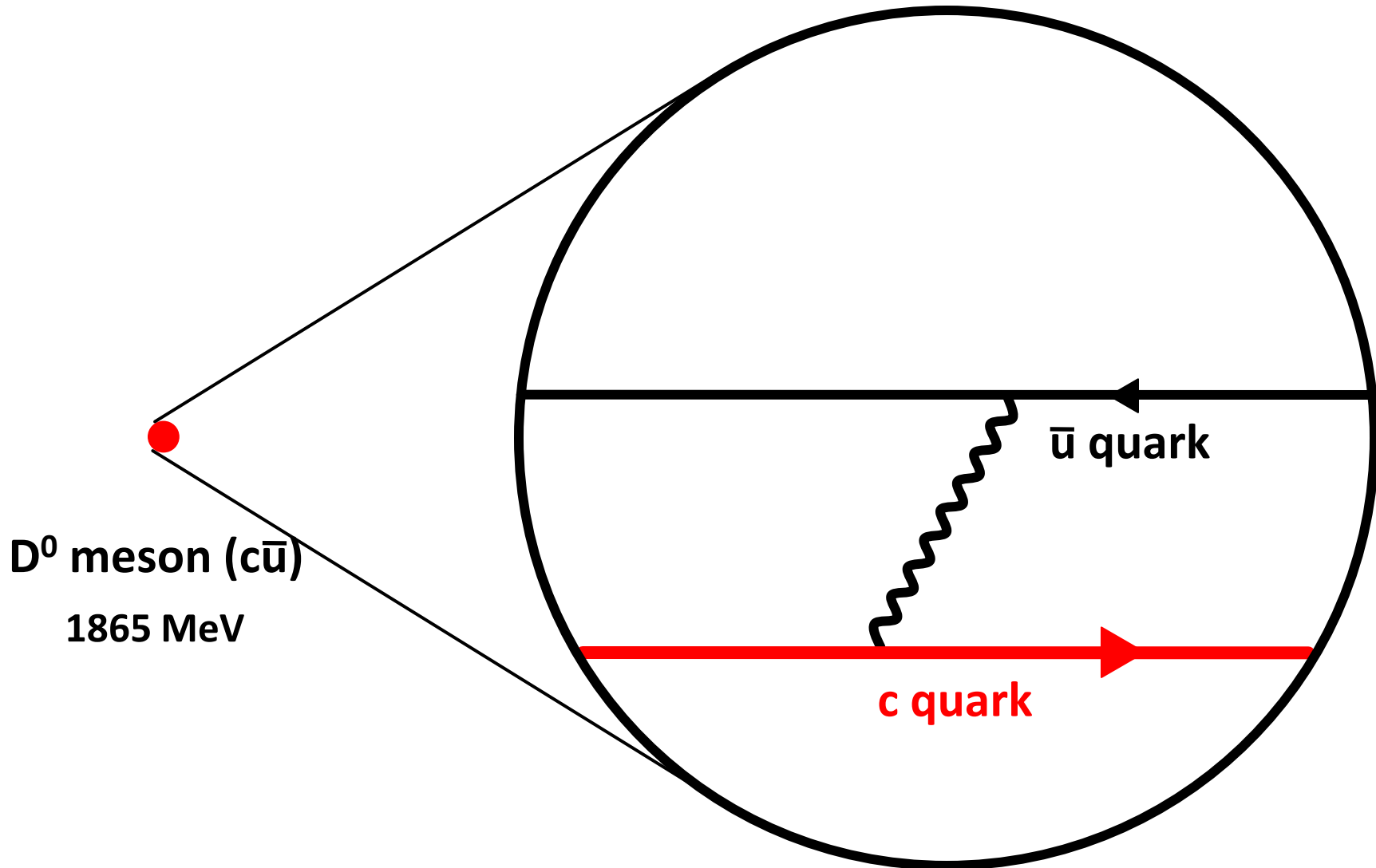
$$m_D \approx m_{D^*}$$



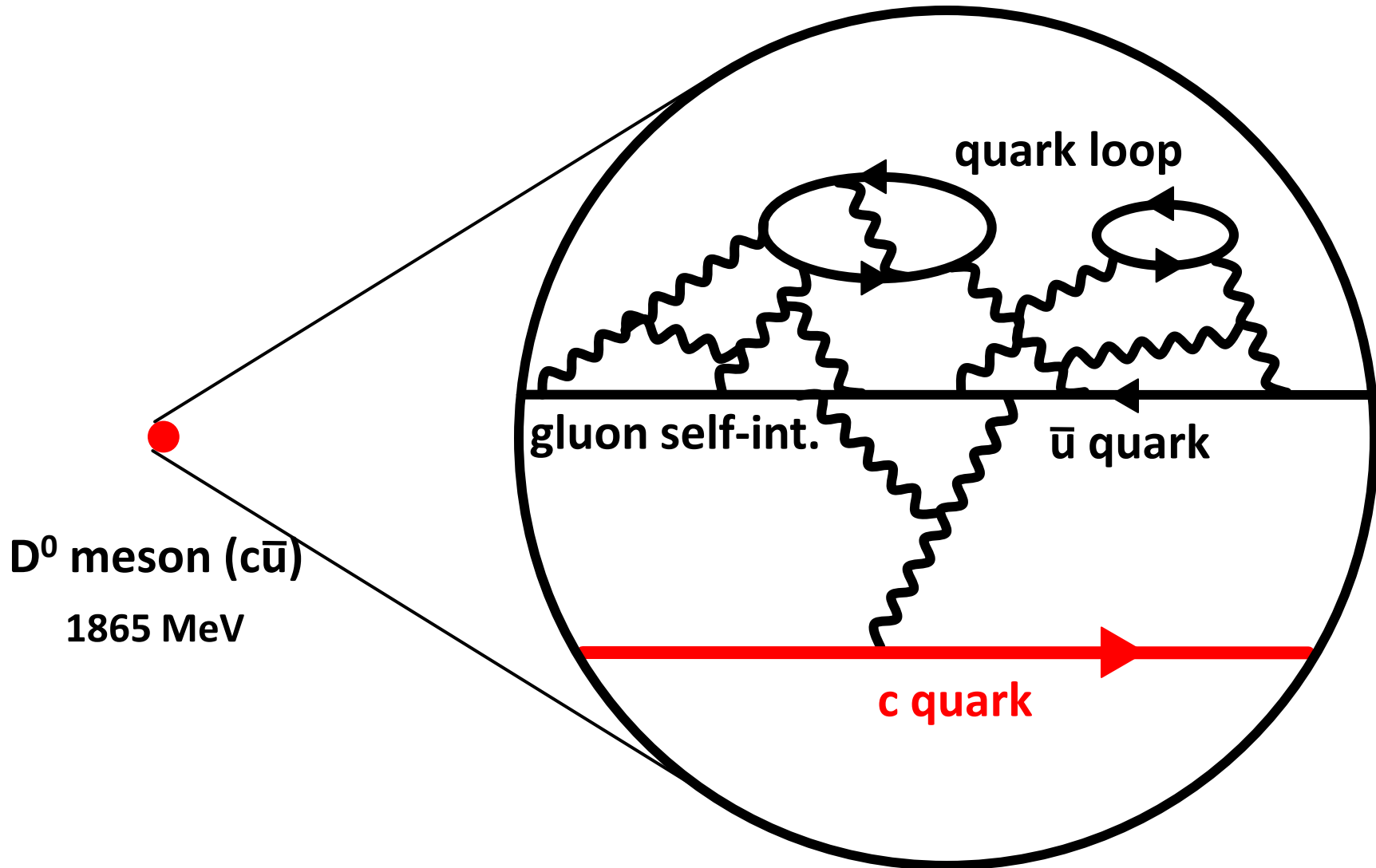
vector



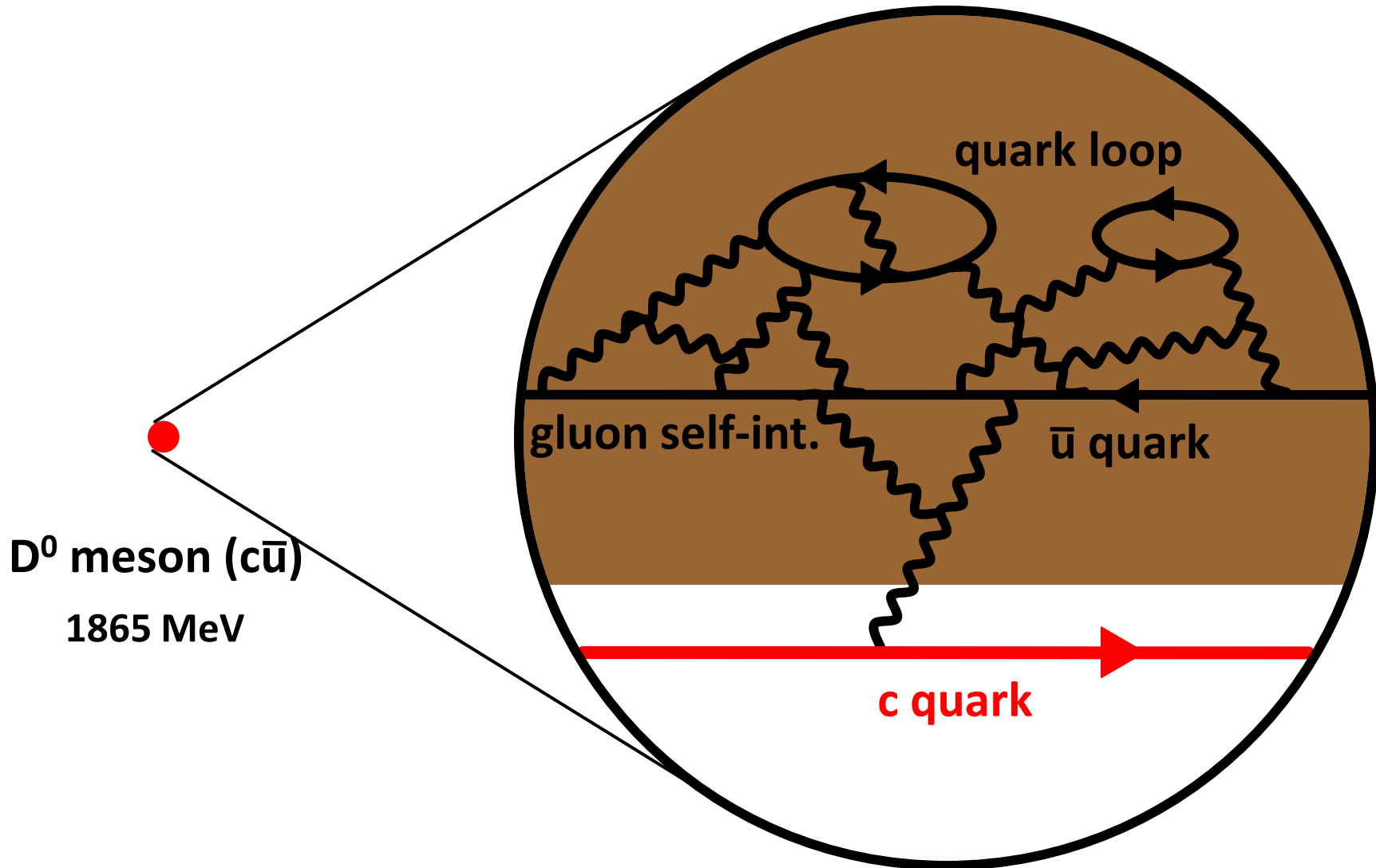
Heavy Quark Symmetry



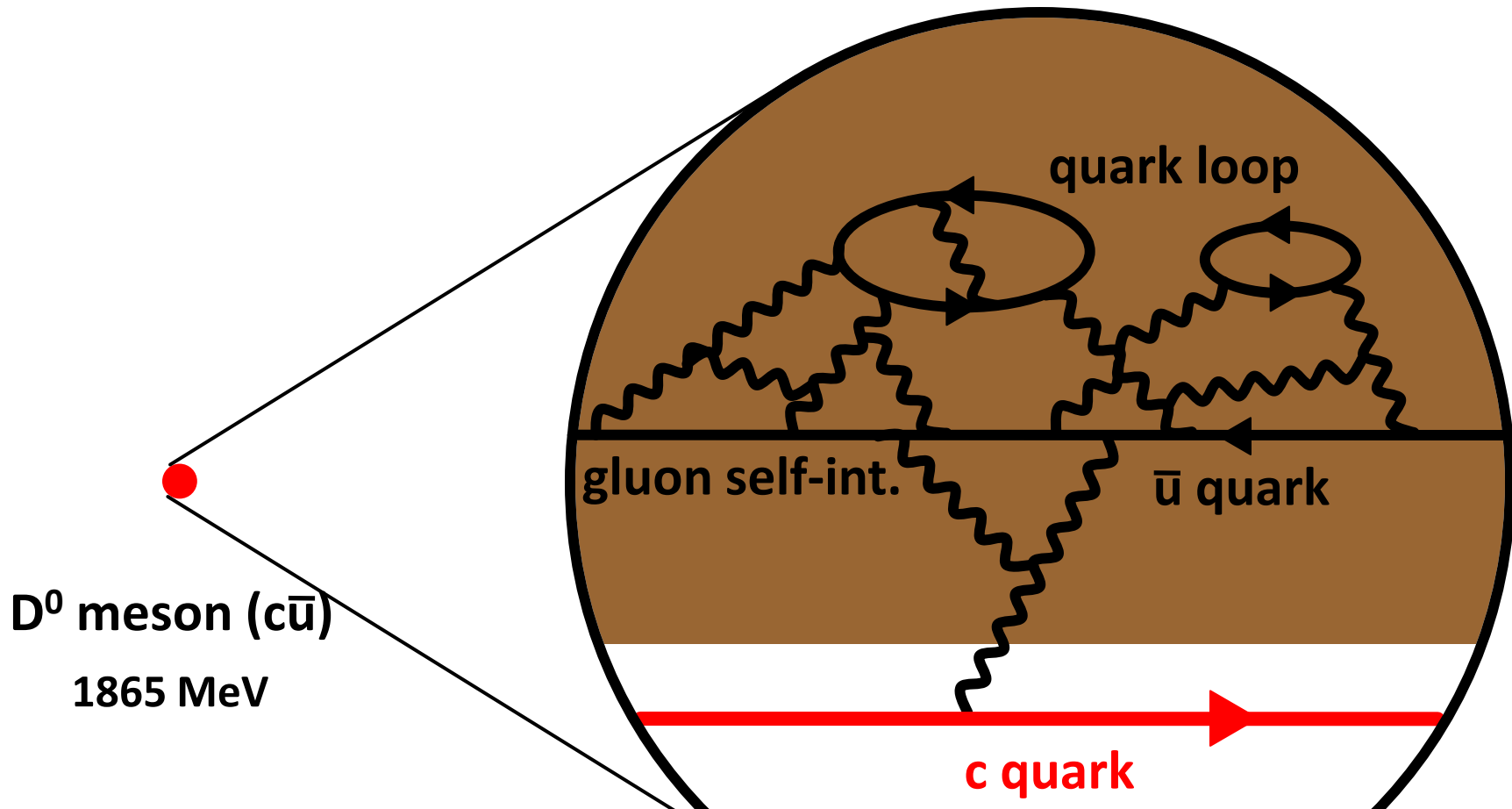
Heavy Quark Symmetry



Heavy Quark Symmetry

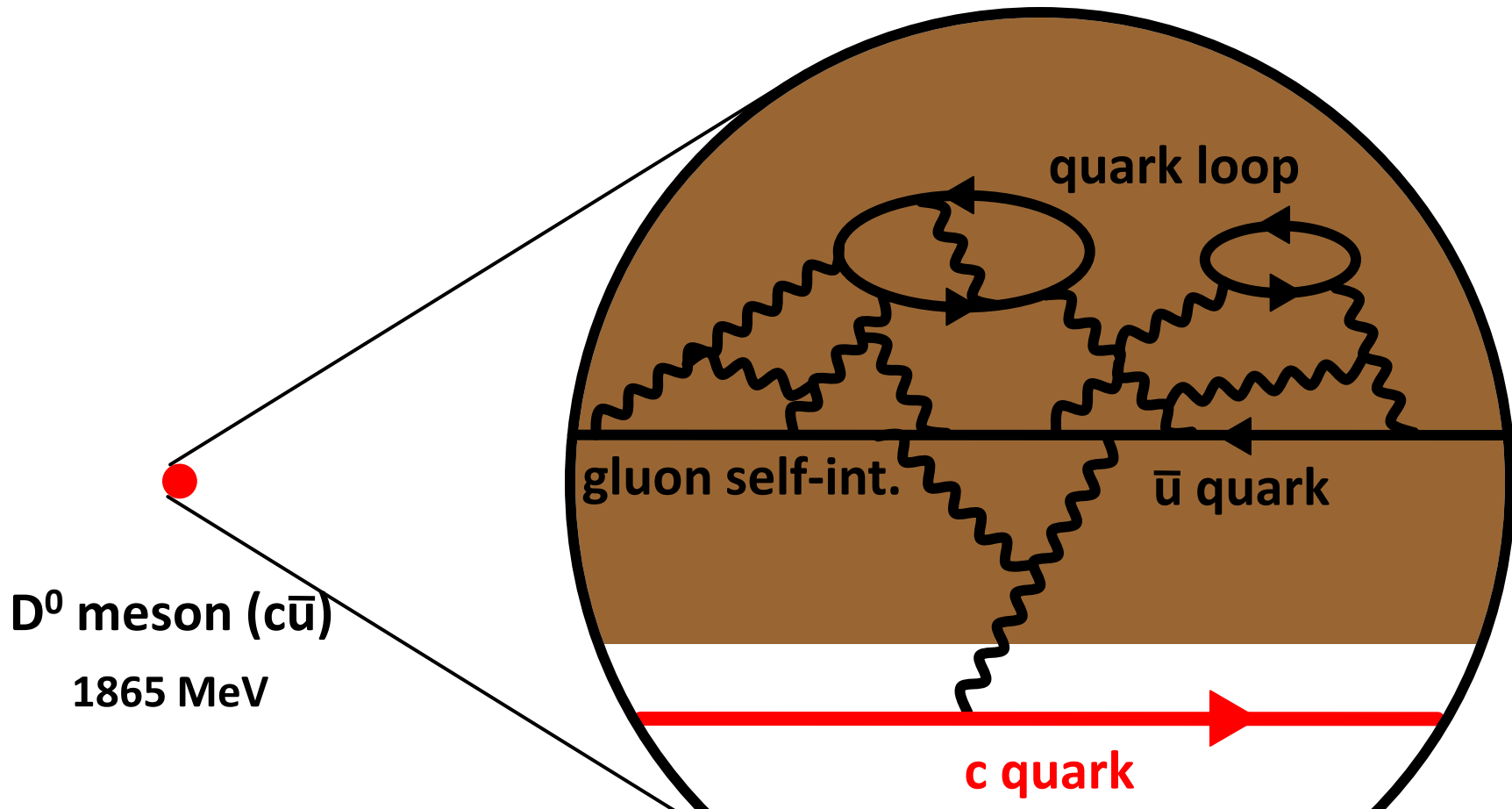


Heavy Quark Symmetry



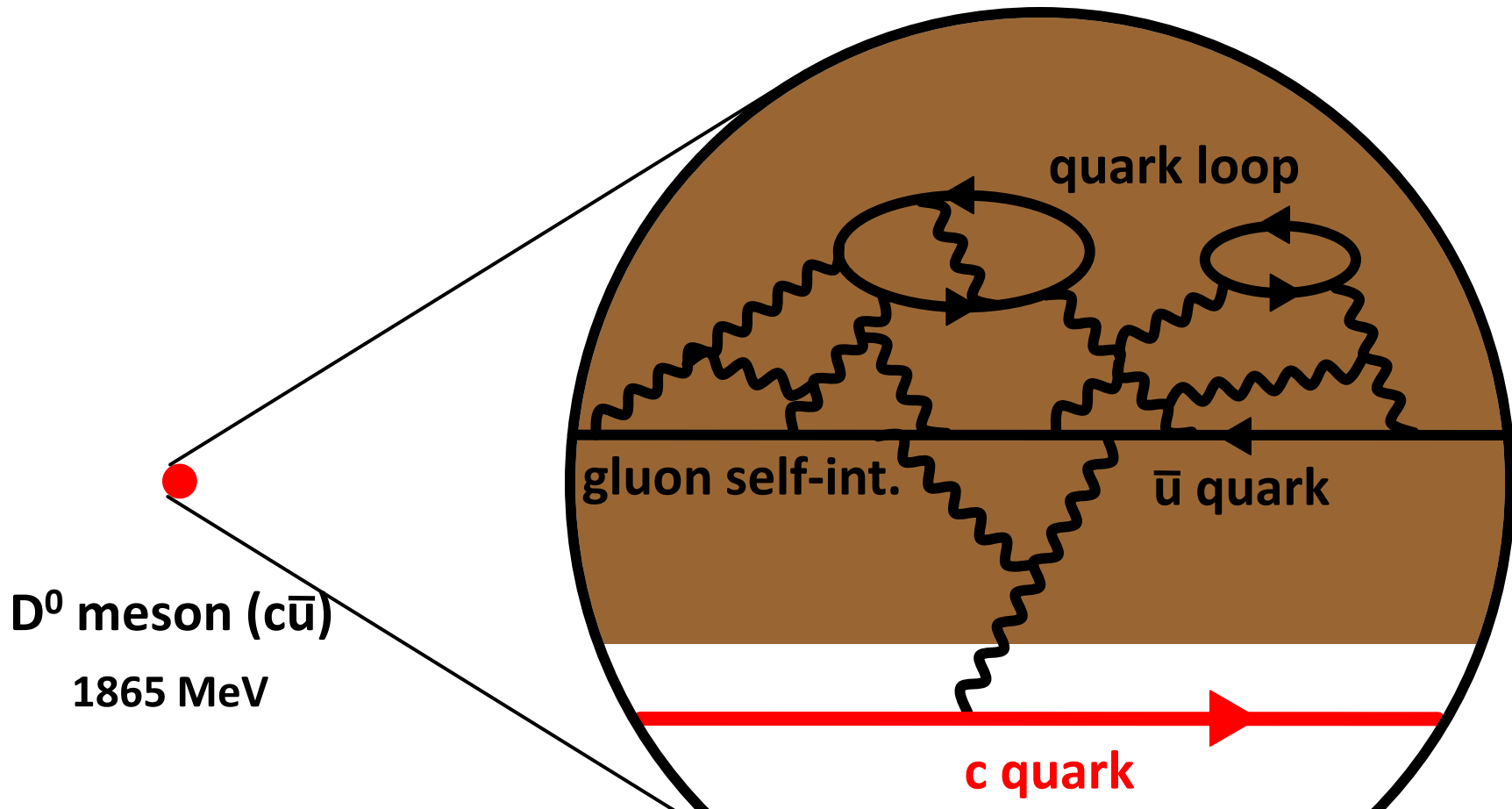
$$\mathcal{L}_{\text{HQET}} = \bar{Q}_v i v \cdot D Q_v - \bar{Q}_v \frac{D_\perp^2}{2m_Q} Q_v - \alpha(\mu) g \bar{Q}_v \frac{\sigma_{\mu\nu} G^{\mu\nu}}{4m_Q} Q_v + \dots$$

Heavy Quark Symmetry



$$\mathcal{L}_{\text{HQET}} = \bar{Q}_v i v \cdot D Q_v - \bar{Q}_v \frac{D_\perp^2}{2m_Q} Q_v - \alpha(\mu) g \bar{Q}_v \frac{\sigma_{\mu\nu} G^{\mu\nu}}{4m_Q} Q_v + \dots$$

Heavy Quark Symmetry

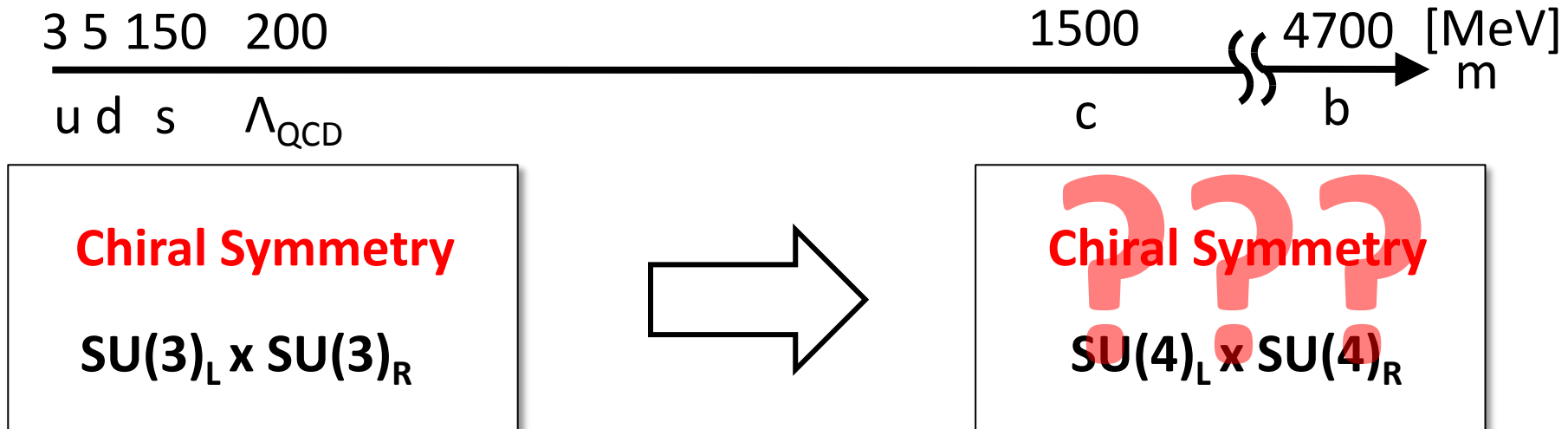


D^0 meson ($c\bar{u}$)
1865 MeV

$$\mathcal{L}_{\text{HQET}} = \bar{Q}_v iv \cdot D Q_v - \bar{Q}_v \frac{D_\perp^2}{2m_Q} Q_v - \alpha(\mu) g \bar{Q}_v \frac{\sigma_{\mu\nu} G^{\mu\nu}}{4m_Q} Q_v + \dots$$

$m_D \approx m_{D^*}$

2. Symmetry and dynamics of heavy quark hadrons



π , K as Nambu-Goldstone bosons

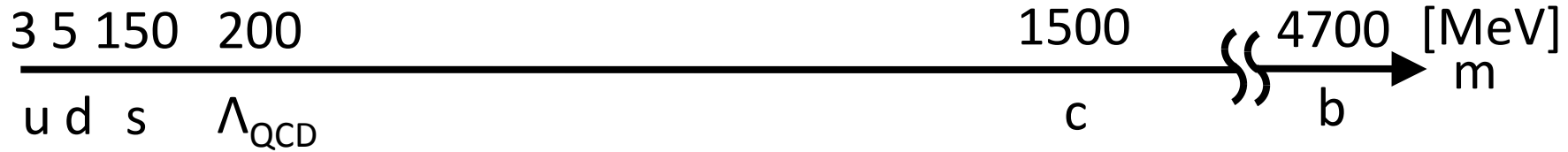
Chiral multiplets (ρ - a_1 , N - N^* , ...)

Nuclei formed by tensor force

Hypernuclei as g.s. of QCD matter

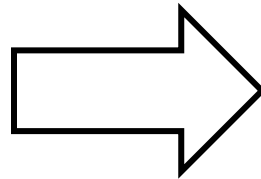
...

2. Symmetry and dynamics of heavy quark hadrons



Chiral Symmetry

$SU(3)_L \times SU(3)_R$



Heavy Quark Symmetry

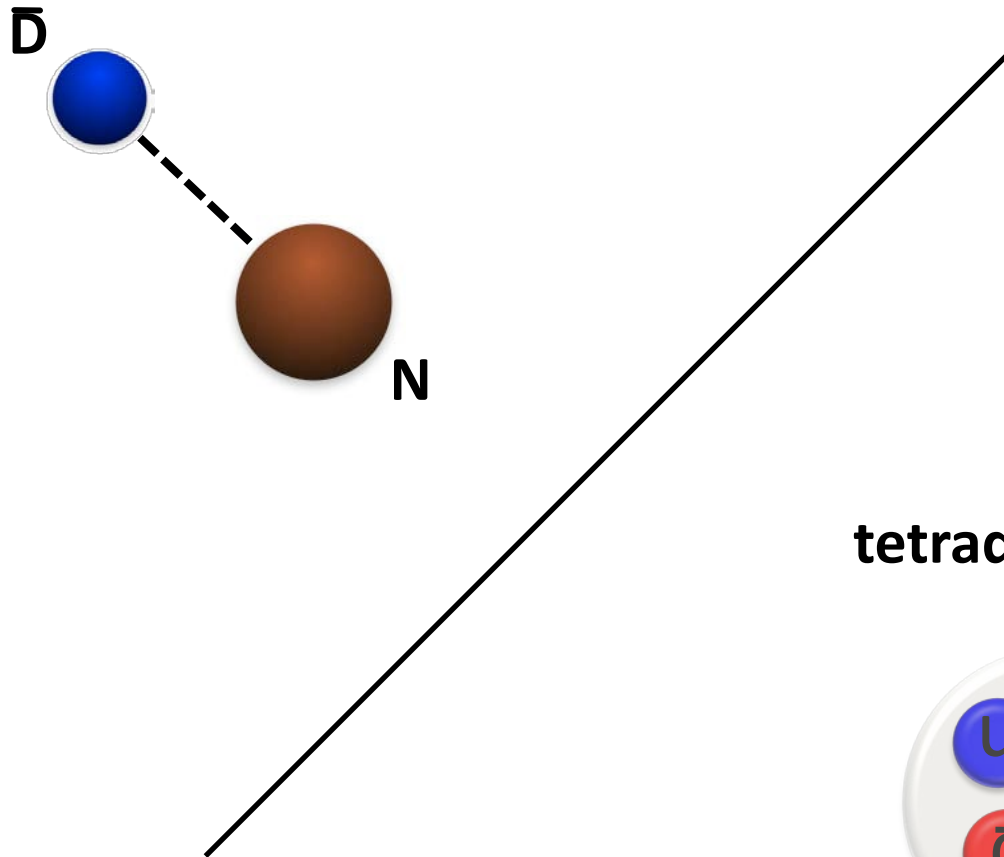
$SU(2)_{\text{spin}} \times SU(N_h)$

π , K as Nambu-Goldstone bosons
 Chiral multiplets (ρ - a_1 , N- N^* , ...)
 Nuclei formed by tensor force
 Hypernuclei as g.s. of QCD matter
 ...

D- D^* (Σ_c - Σ_c^* , Ξ_{cc} - Ξ_{cc}^*) mass degeneracy (heavy quark sym.)
 More exotics? (like Tcc with no pion decay)
 Charmed nuclei ?

3. New exotic hadrons and nuclei

D and nucleon



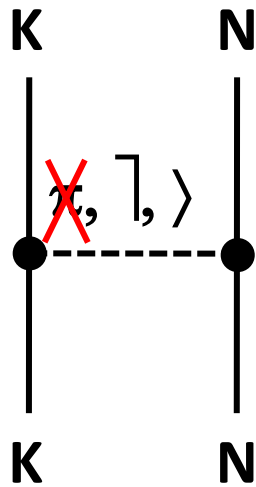
tetraquark T_{cc}^1



3. New exotic hadrons and nuclei

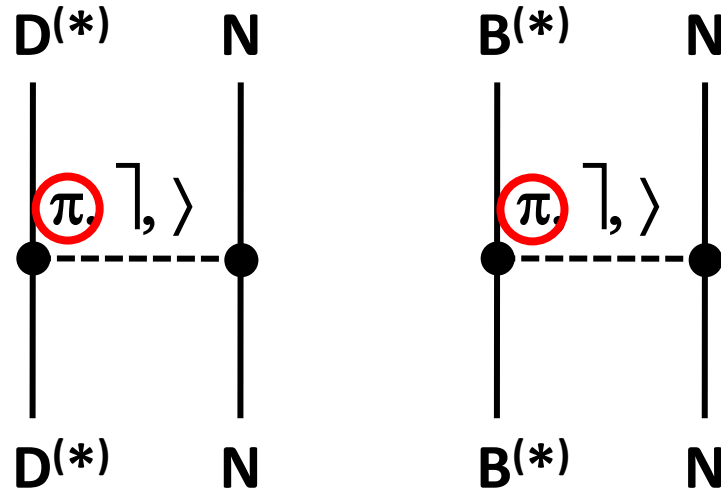
D and nucleon

KN interaction



One pion is absent.
(short range force)

D(B)N interaction



One pion is present.
(long range force)

Weinberg-Tomozawa

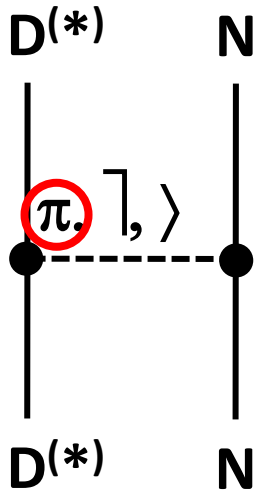
One pion exchange potential
(OPEP)

S. Y. and K. Sudoh, PRD80, 034008 (2009)

Y. Yamaguchi, S. Ohkoda, S. Y., A. Hosaka, arXiv:1105.0734

3. New exotic hadrons and nuclei

D and nucleon



Heavy Quark Symmetry

$$\mathcal{L}_{\pi HH} = g \text{tr} \bar{H}_a H_b \gamma_\nu \gamma_5 A_{ba}^\nu$$

$$H_a = \frac{1 + \not{\psi}}{2} [P_{a\mu}^* \gamma^\mu - P_a \gamma_5] \quad \text{with} \quad \bar{H}_a = \gamma_0 H_a^\dagger \gamma_0$$

vector + pseudoscalar P=D, B

G. Burdman and J.F. Donoghue (1992)
 M.B. Wise (1992)
 T.-M. Yan, H.-Y. Cheng, C.-Y. Cheung,
 G.-L. Lin, Y.C. Lin and H.-L. Yu (1997)

π-exchange pot.

S. Y. and K. Sudoh, PRD80, 034008 (2009)

$$V_{PN \rightarrow P^*N} = -\frac{gg_{\pi NN}}{\sqrt{2}m_N f} \frac{1}{4\pi} \frac{\mu^2}{3} \left[\vec{\varepsilon}^{(\lambda)\dagger} \cdot \vec{\sigma} C(r; \mu) + S_{\varepsilon^{(\lambda)}}^\dagger T(r; \mu) \right] \vec{\tau}_P \cdot \vec{\tau}_N$$

$$V_{P^*N \rightarrow P^*N} = \frac{gg_{\pi NN}}{\sqrt{2}m_N f} \frac{1}{4\pi} \frac{m_\pi^2}{3} \left[\vec{T} \cdot \vec{\sigma} C(r; m_\pi) + S_T T(r; m_\pi) \right] \vec{\tau}_P \cdot \vec{\tau}_N$$

ω and ρ-exchange pot.

Y. Yamaguchi, S. Ohkoda, S. Y., A. Hosaka,
 arXiv:1105.0734

3. New exotic hadrons and nuclei

\bar{D} and nucleon

$$I(J^P)=0(1/2^-) \quad \bar{D}N(^2S_{1/2}), \bar{D}^*N(^2S_{1/2}), \bar{D}^*N(^4D_{1/2})$$

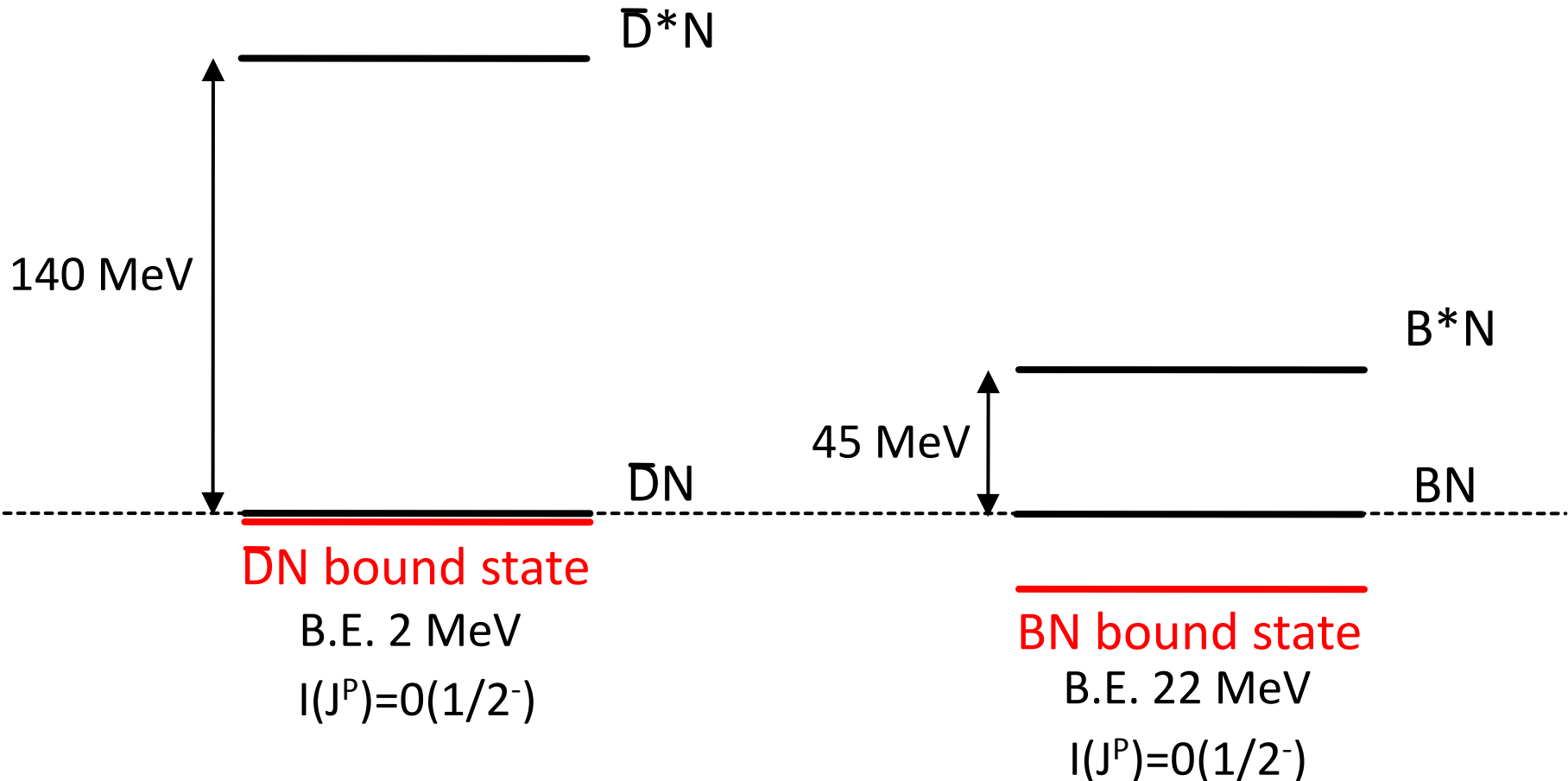
$$V_{1/2^-}^\pi = \frac{g_\pi g_{\pi NN}}{\sqrt{2}m_N f_\pi} \frac{1}{3} \begin{pmatrix} 0 & \sqrt{3}C_{m_\pi} & -\sqrt{6}T_{m_\pi} \\ \sqrt{3}C_{m_\pi} & -2C_{m_\pi} & -\sqrt{2}T_{m_\pi} \\ -\sqrt{6}T_{m_\pi} & -\sqrt{2}T_{m_\pi} & C_{m_\pi} - 2T_{m_\pi} \end{pmatrix} \vec{\tau}_P \cdot \vec{\tau}_N$$

$$I(J^P)=0(3/2^-) \quad \bar{D}N(^2D_{3/2}), \bar{D}^*N(^4S_{3/2}), \bar{D}^*N(^4D_{3/2}), \bar{D}^*N(^2D_{3/2})$$

$$V_{3/2^-}^\pi = \frac{g_\pi g_{\pi NN}}{\sqrt{2}m_N f_\pi} \frac{1}{3} \begin{pmatrix} 0 & \sqrt{3}T_{m_\pi} & -\sqrt{3}T_{m_\pi} & \sqrt{3}C_{m_\pi} \\ \sqrt{3}T_{m_\pi} & C_{m_\pi} & 2T_{m_\pi} & T_{m_\pi} \\ -\sqrt{3}T_{m_\pi} & 2T_{m_\pi} & C_{m_\pi} & -T_{m_\pi} \\ \sqrt{3}C_{m_\pi} & T_{m_\pi} & -T_{m_\pi} & -2C_{m_\pi} \end{pmatrix} \vec{\tau}_P \cdot \vec{\tau}_N$$

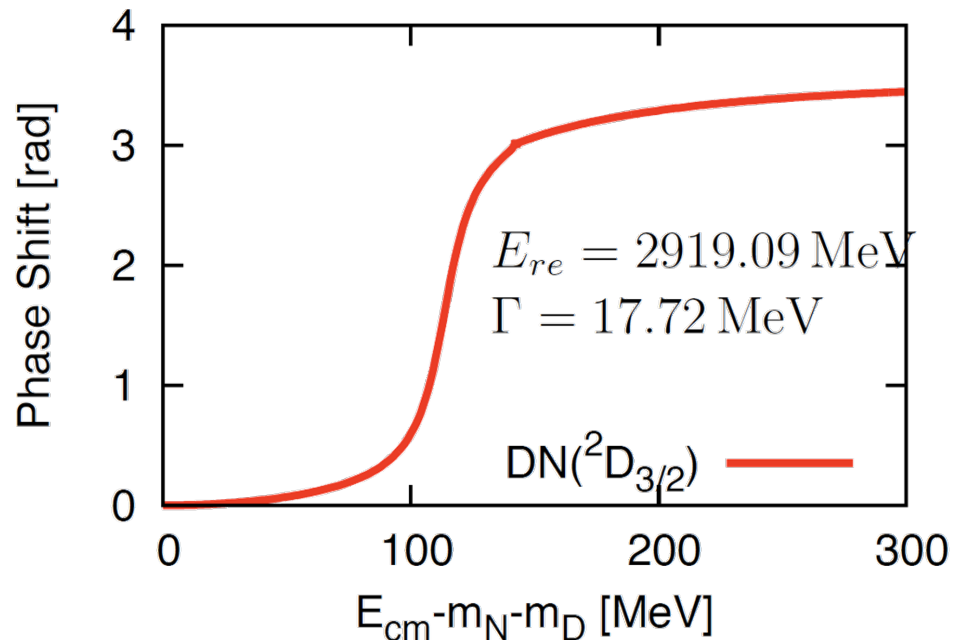
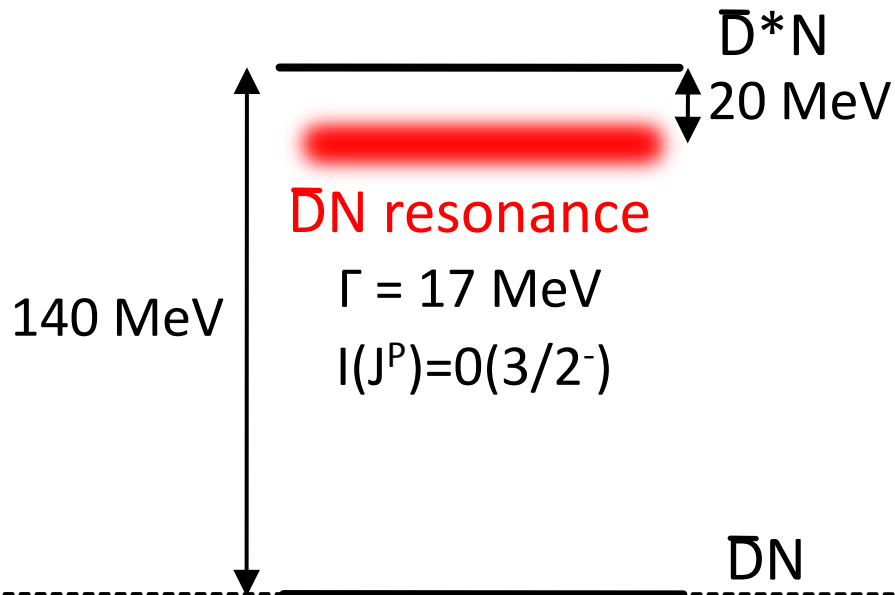
3. New exotic hadrons and nuclei

\bar{D} and nucleon

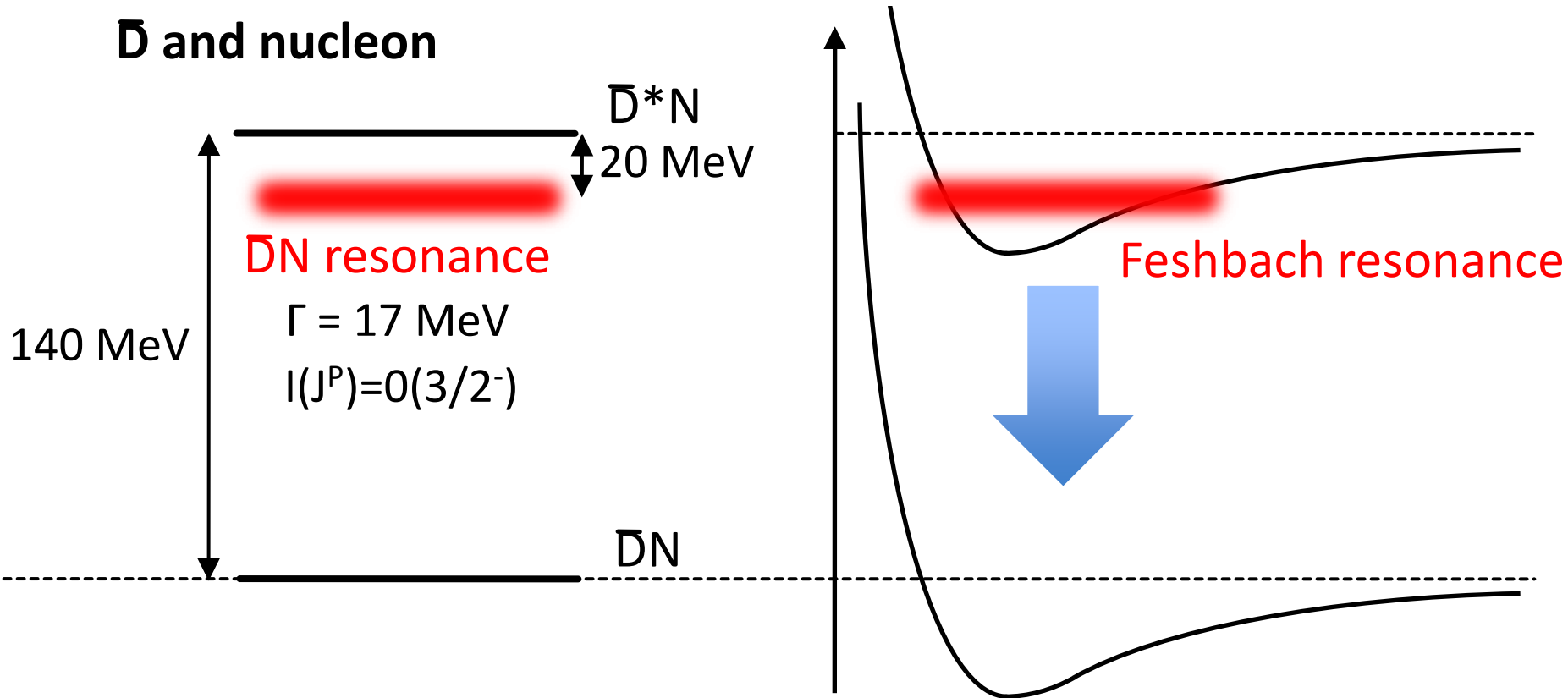


3. New exotic hadrons and nuclei

\bar{D} and nucleon

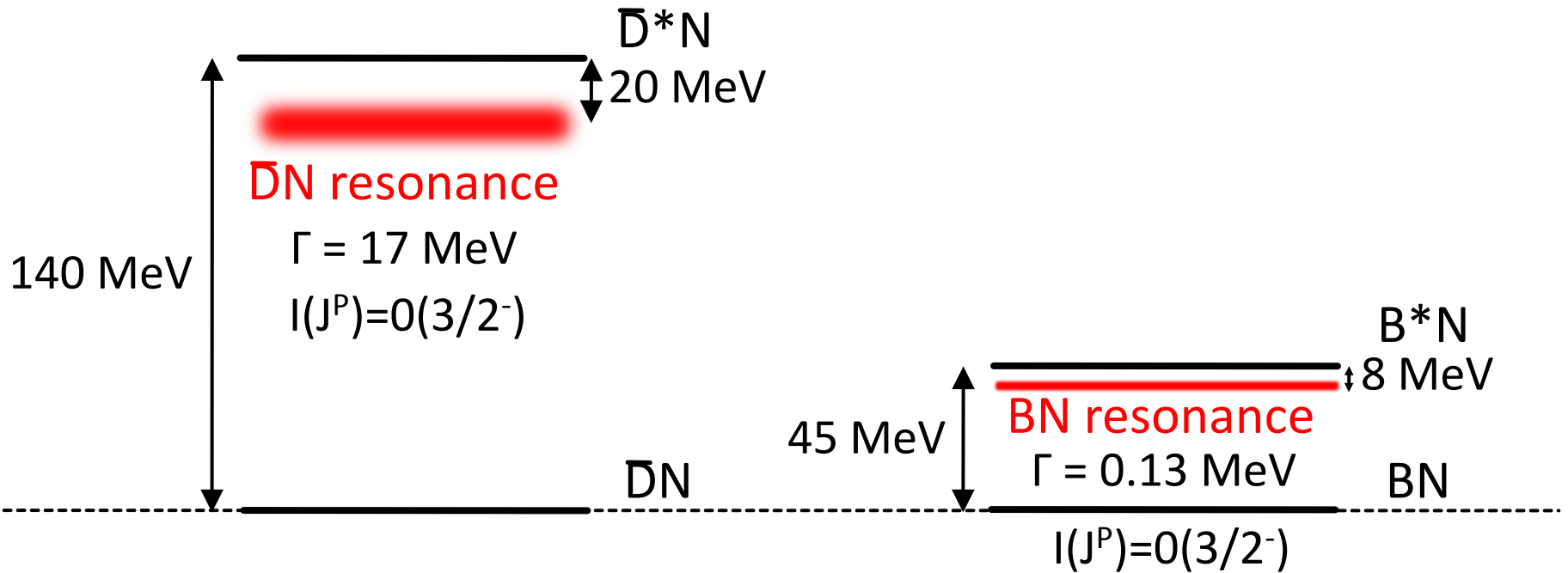


3. New exotic hadrons and nuclei



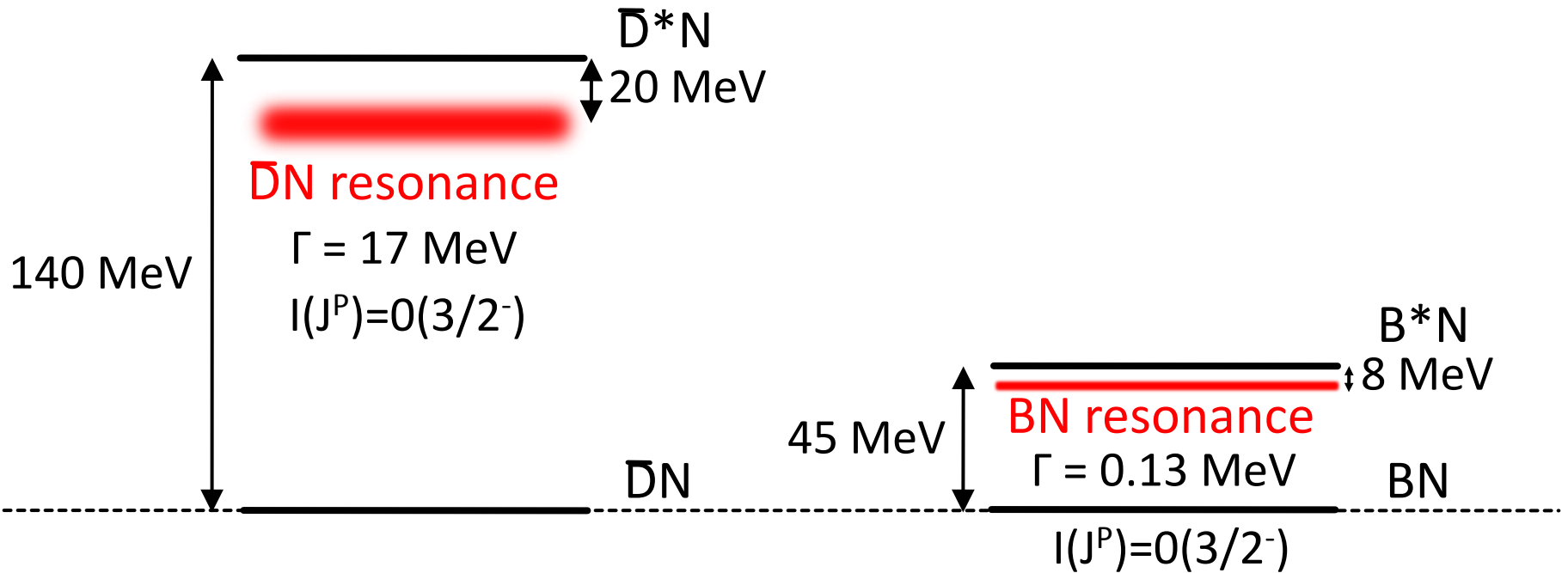
3. New exotic hadrons and nuclei

\bar{D} and nucleon



3. New exotic hadrons and nuclei

\bar{D} and nucleon

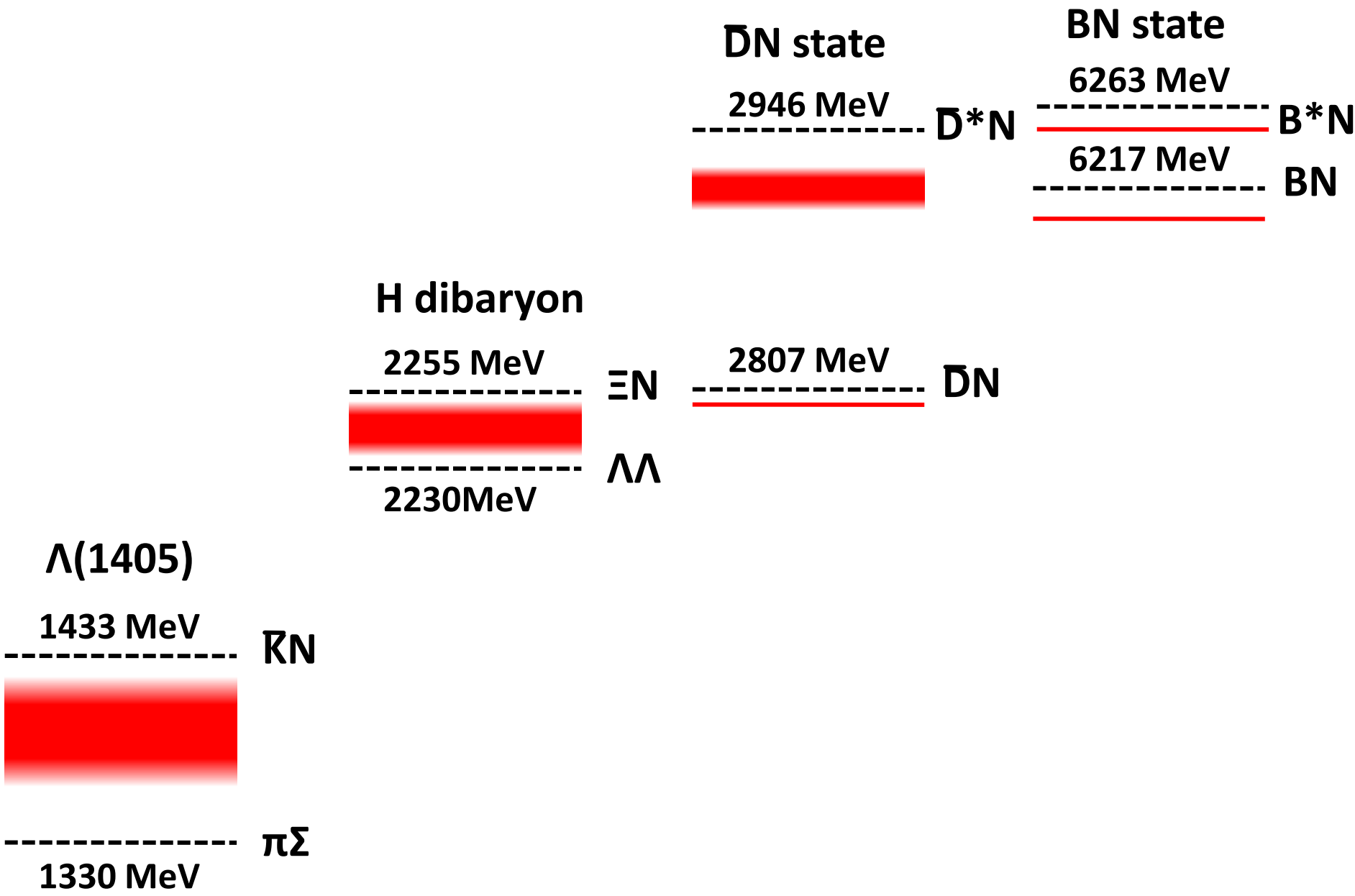


$I(J^P)=0(1/2^-)$ bound state

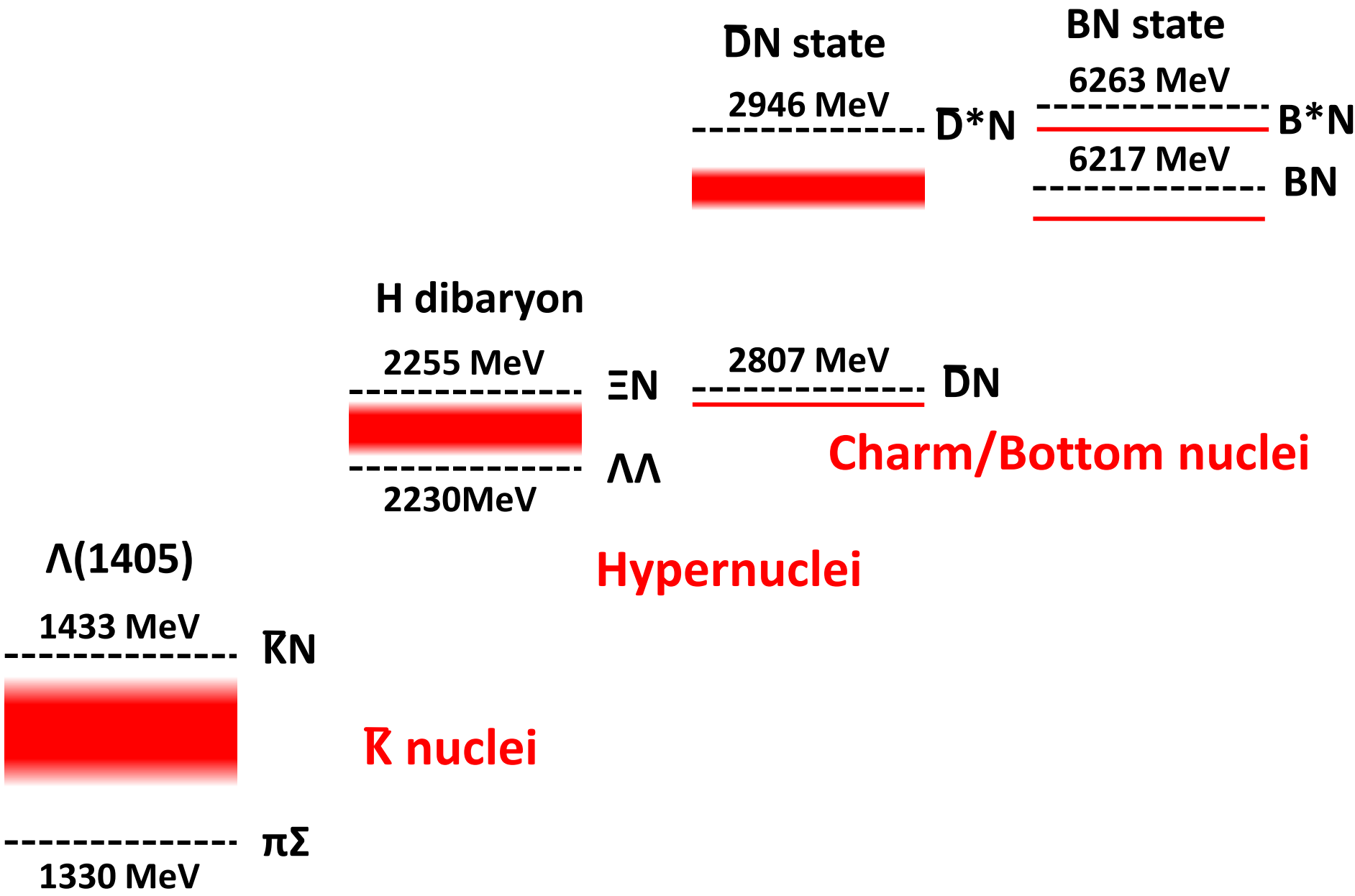
$I(J^P)=0(3/2^-)$ narrow resonance state

heavy quark mass dependence is very interesting!

3. New exotic hadrons and nuclei

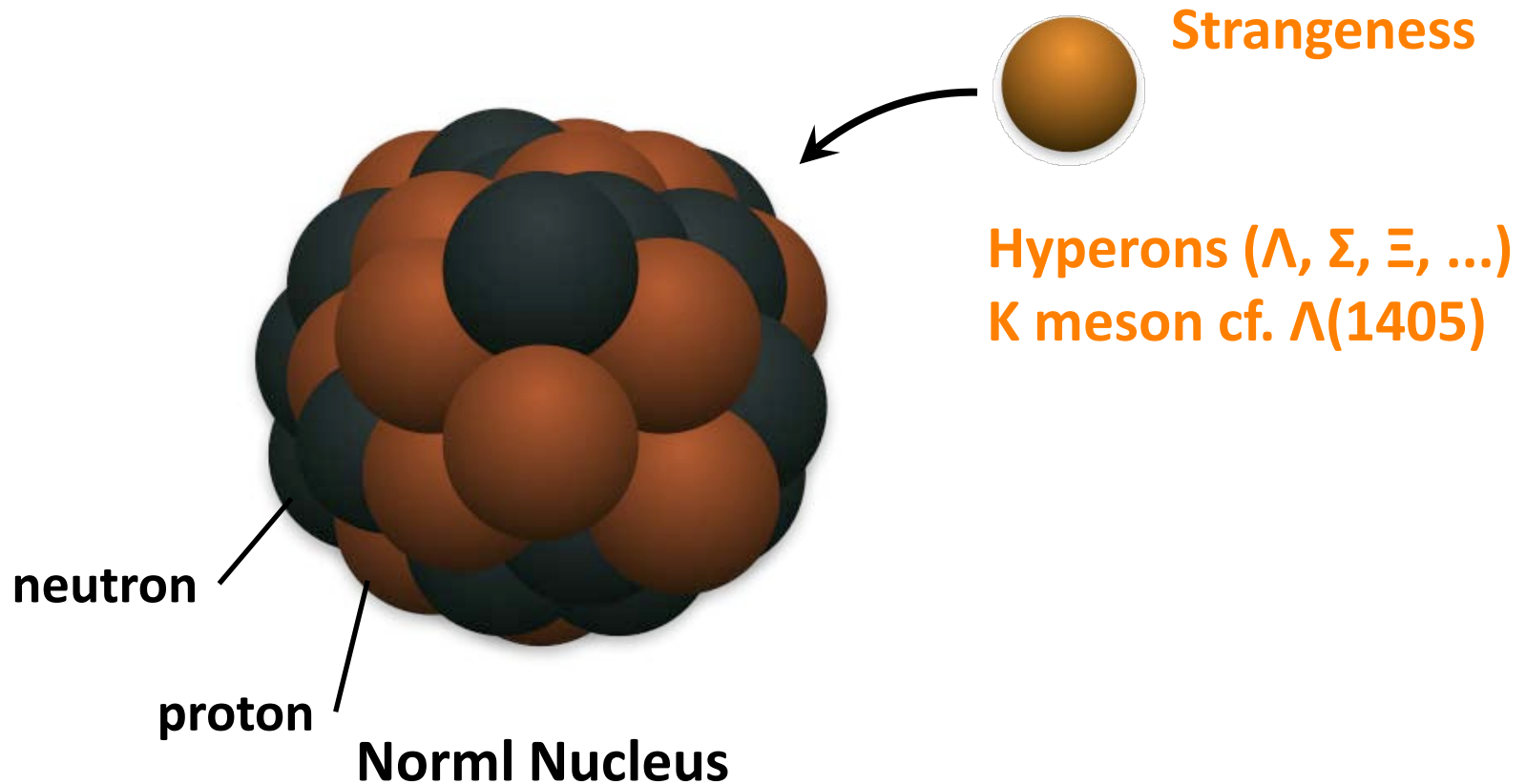


3. New exotic hadrons and nuclei



3. New exotic hadrons and nuclei

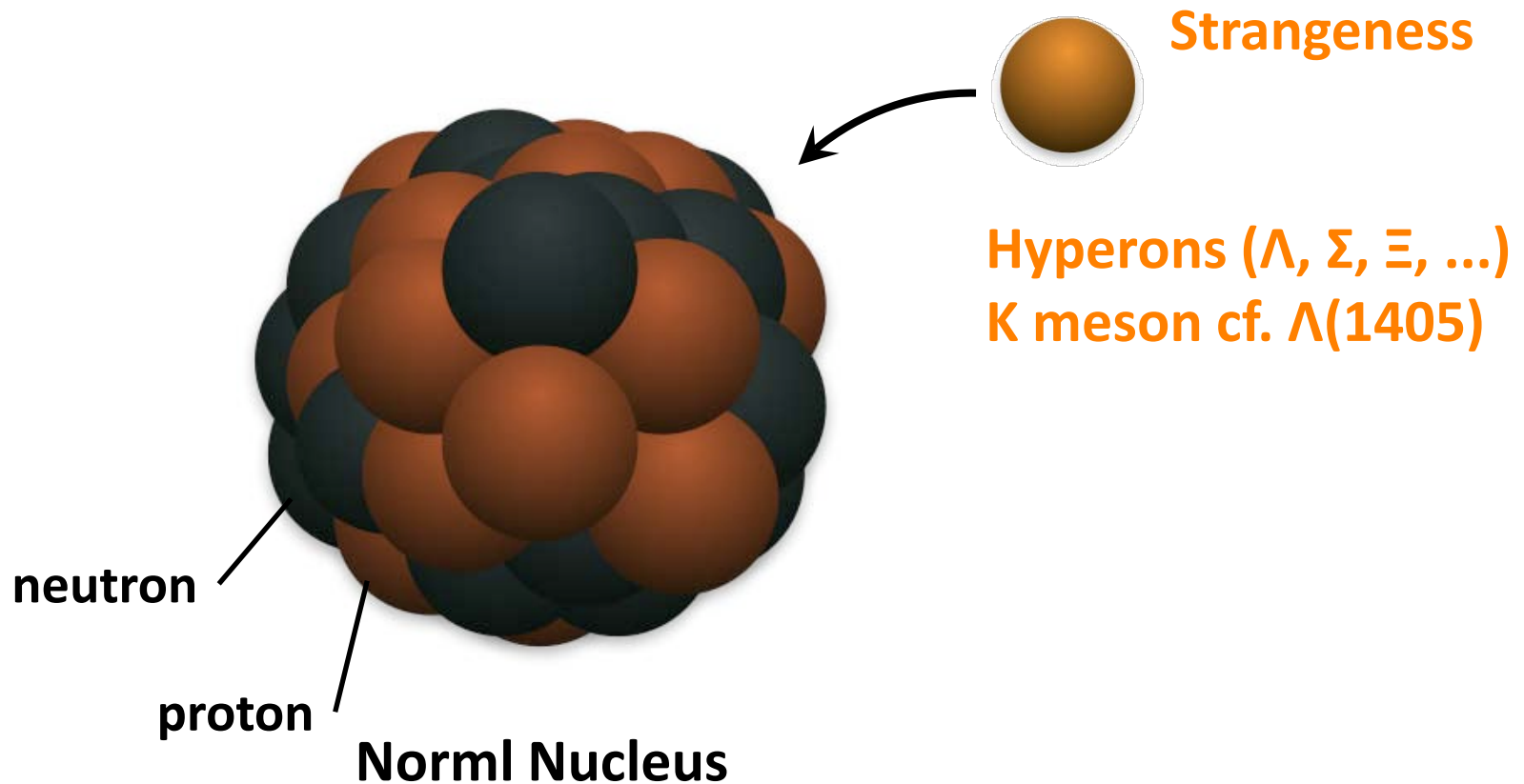
$$| \text{Strange Nuclei} \rangle = U | \text{Normal Nuclei} \rangle$$



$\exists U$: unitary transformation $SU(3)_f$ for some rep.

3. New exotic hadrons and nuclei

$$| \text{Strange Nuclei} \rangle = U | \text{Normal Nuclei} \rangle$$



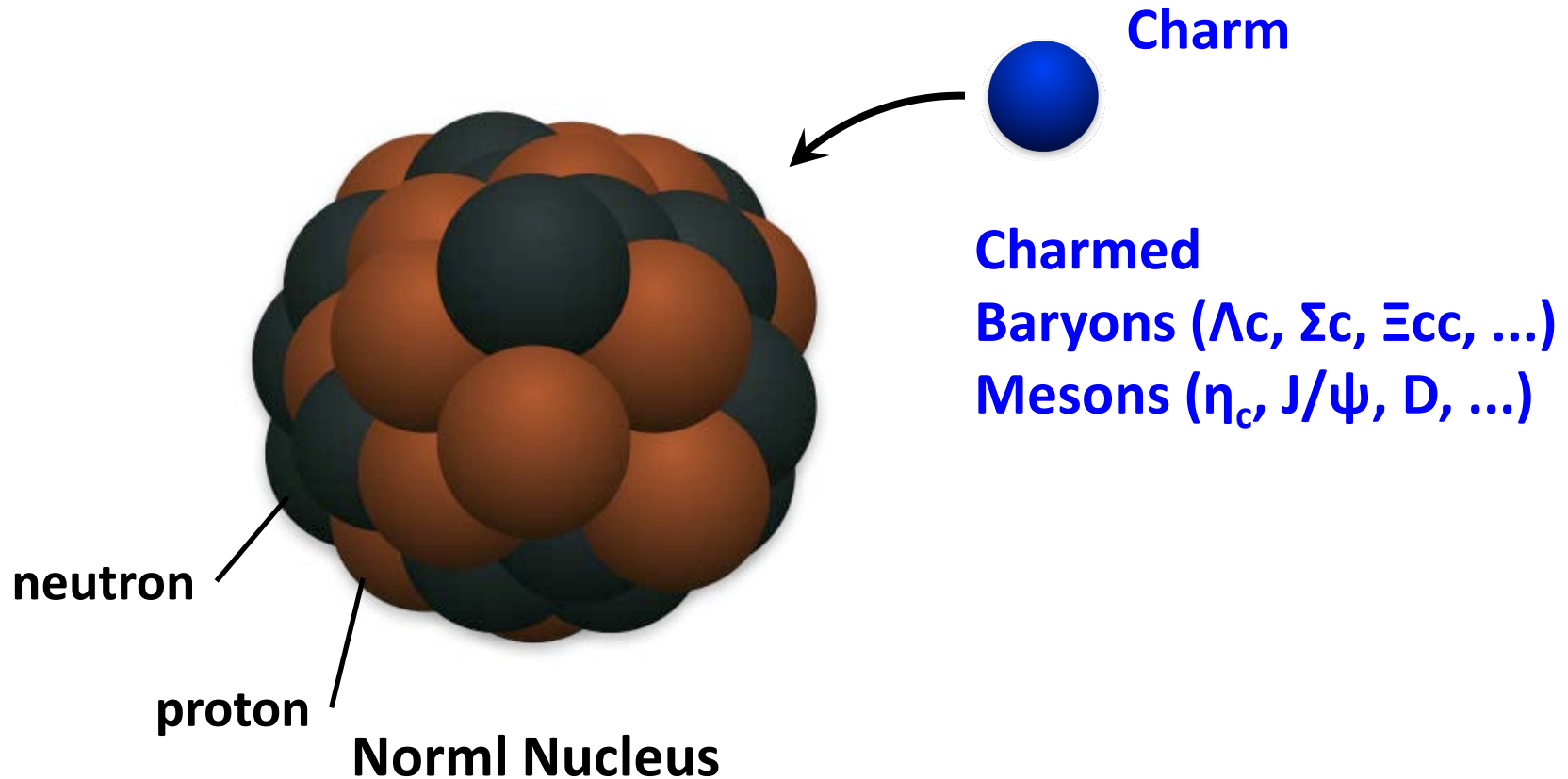
$\exists U$: unitary transformation $SU(3)_f$ for some representation

$$\text{BB system } 8 \times 8 = 1 + 8_s + 8_a + 10 + 10^* + 27$$

Inoue et al.
PTP124, 591 (2010)

3. New exotic hadrons and nuclei

| **Charmed Nuclei** $\rangle \neq U$ | Normal Nuclei \rangle

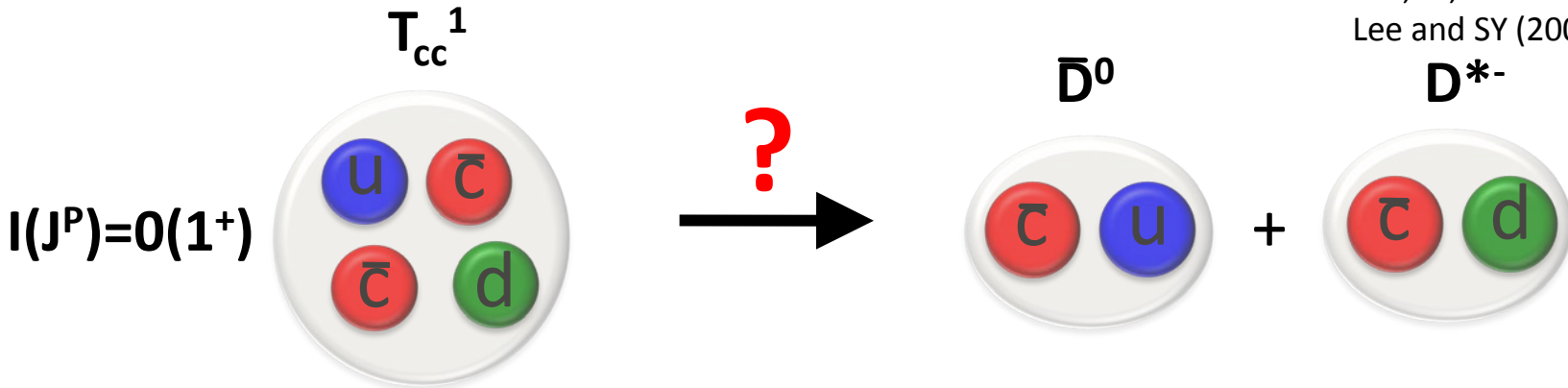


No unitary transformation

3. New exotic hadrons and nuclei

tetraquark T_{cc}^1 „explicitly“ exotic

Carlson, Heller, Tjon (1988)
 Silvestre-Brac and Semay (1993)
 Manohar and Wise (1993)
 Lee, SY, Liu and Ko (2008)
 Lee and SY (2009)



Spin-color int. $\vec{s} \cdot \vec{B}^a$ ($a=1, \dots, 8$) induces

$$H_{int} = \sum_{i>j} \frac{C_H}{m_i m_j} \vec{s}_i \cdot \vec{s}_j \quad C_H = v_0 \vec{\lambda}_i \cdot \vec{\lambda}_j \langle \delta(r_{ij}) \rangle$$

- | | | | |
|-----------------------|-----------------------------|---|---------------------------------------------------------------------------------------|
| $\tau\bar{\tau}$ pair | $1/m_Q^2$ | ← | further suppressed |
| τu pair | $1/m_Q^1$ | ← | suppressed |
| ud pair | $1/m_Q^0$ | ← | dominant attraction ($\bar{\mathbf{3}}_c, \bar{\mathbf{3}}_f, s=0$) |

3. New exotic hadrons and nuclei

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- | | | | |
|-----------------------------|-----------------------------|---|---------------------------------------------------------------------------------------|
| $\bar{c}\bar{c}$ pair | $1/m_Q^2$ | ← | further suppressed |
| $\bar{c}u$ pair | $1/m_Q^1$ | ← | suppressed |
| ud pair | $1/m_Q^0$ | ← | dominant attraction ($\bar{\mathbf{3}}_c, \bar{\mathbf{3}}_f, s=0$) |

3. New exotic hadrons and nuclei

Carlson, Heller, Tjon (1988)
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tetraquark T_{cc}^1 „explicitly“ exotic



Binding energy of $T_{cc(bb)}^1$ [MeV]

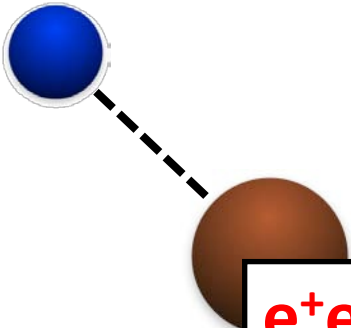
	$ud\bar{c}\bar{c}$	$us\bar{c}\bar{c}$	$ds\bar{c}\bar{c}$
T_{cc}^1	-74.9	-4.3	-4.3
	$\bar{D}^0 + D^{*-}, \bar{D}^{*0} + D^-$	$\bar{D}^0 + D_s^{*-}$	$D^- + D_s^{*-}$
	$ud\bar{b}\bar{b}$	$us\bar{b}\bar{b}$	$ds\bar{b}\bar{b}$
T_{bb}^1	-123.8	-61.4	-61.4
	$B^+ + B^{*0}, B^{*+} + B^0$	$B^+ + B_s^{*0}$	$B^0 + B_s^{*0}$

$\rightarrow T_{cc(bb)}^1$ are stable as $\bar{3}_f$ multiplet of $SU(3)_f$.

3. New exotic hadrons and nuclei

D and nucleon ✓

D



e^+e^- collisions
 pp (pp^{bar}) collisions
heavy ion collisions

charm quark T_{cc}^1 ✓

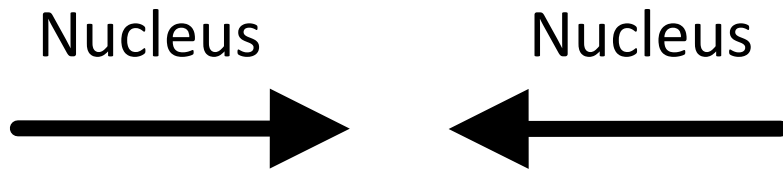


4. Experimental researches

Exotic hadrons from heavy ion collisions at RHIC and LHC

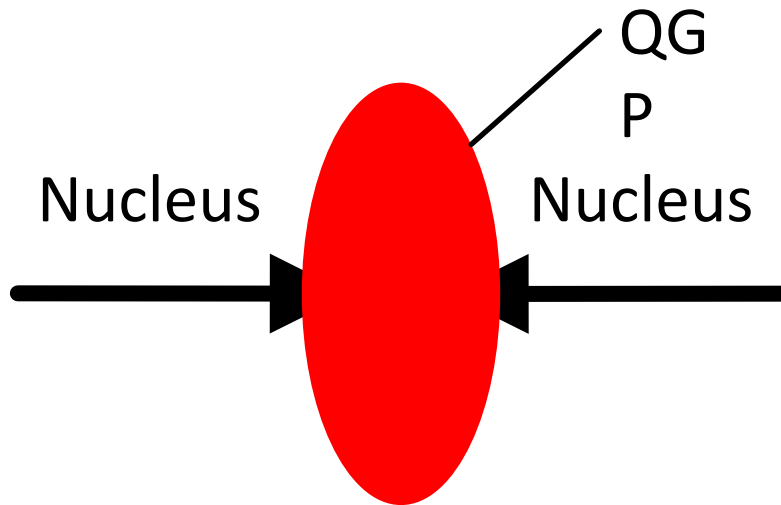
4. Experimental researches

Exotic hadrons from heavy ion collisions at RHIC and LHC



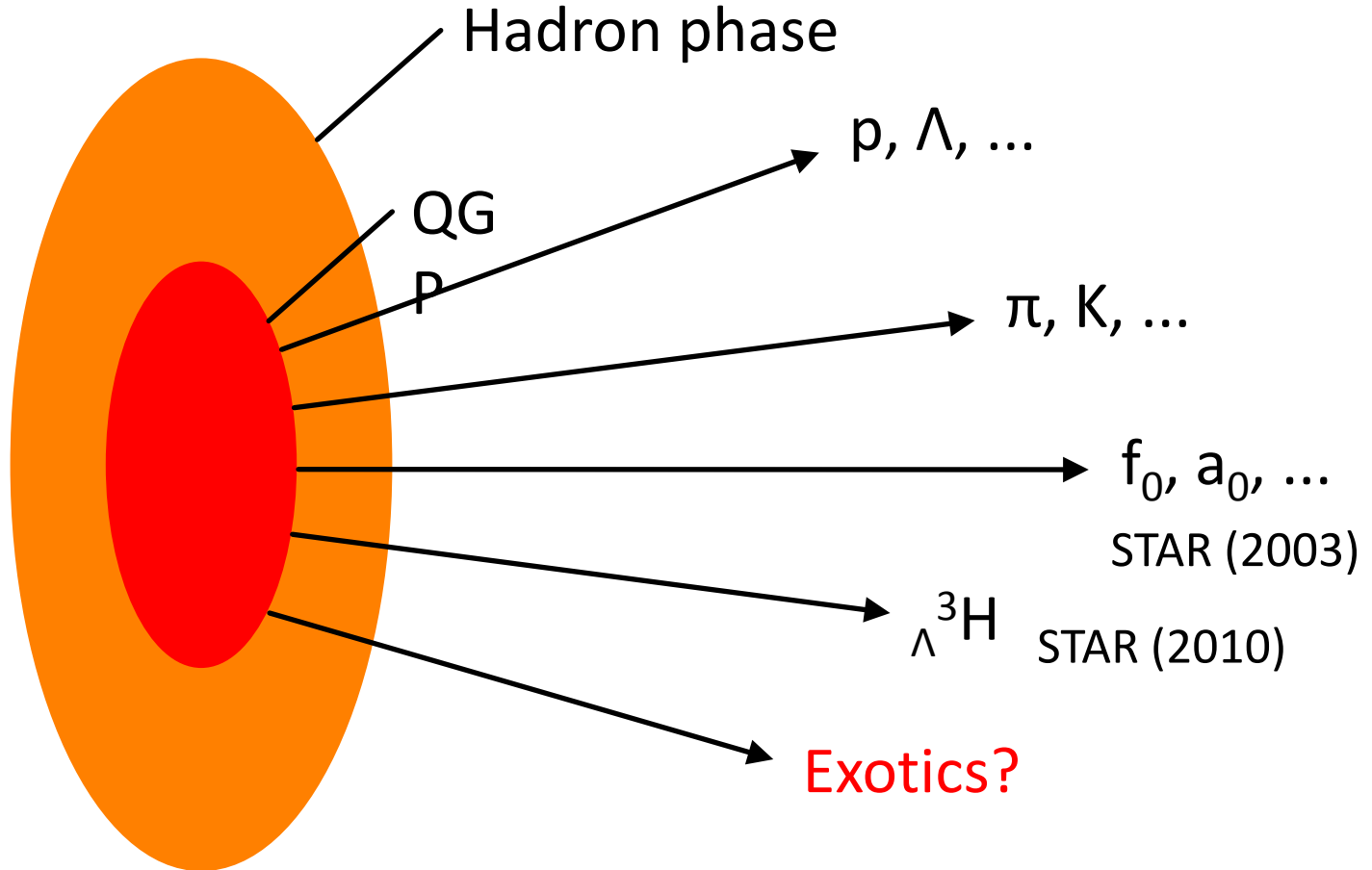
4. Experimental researches

Exotic hadrons from heavy ion collisions at RHIC and LHC



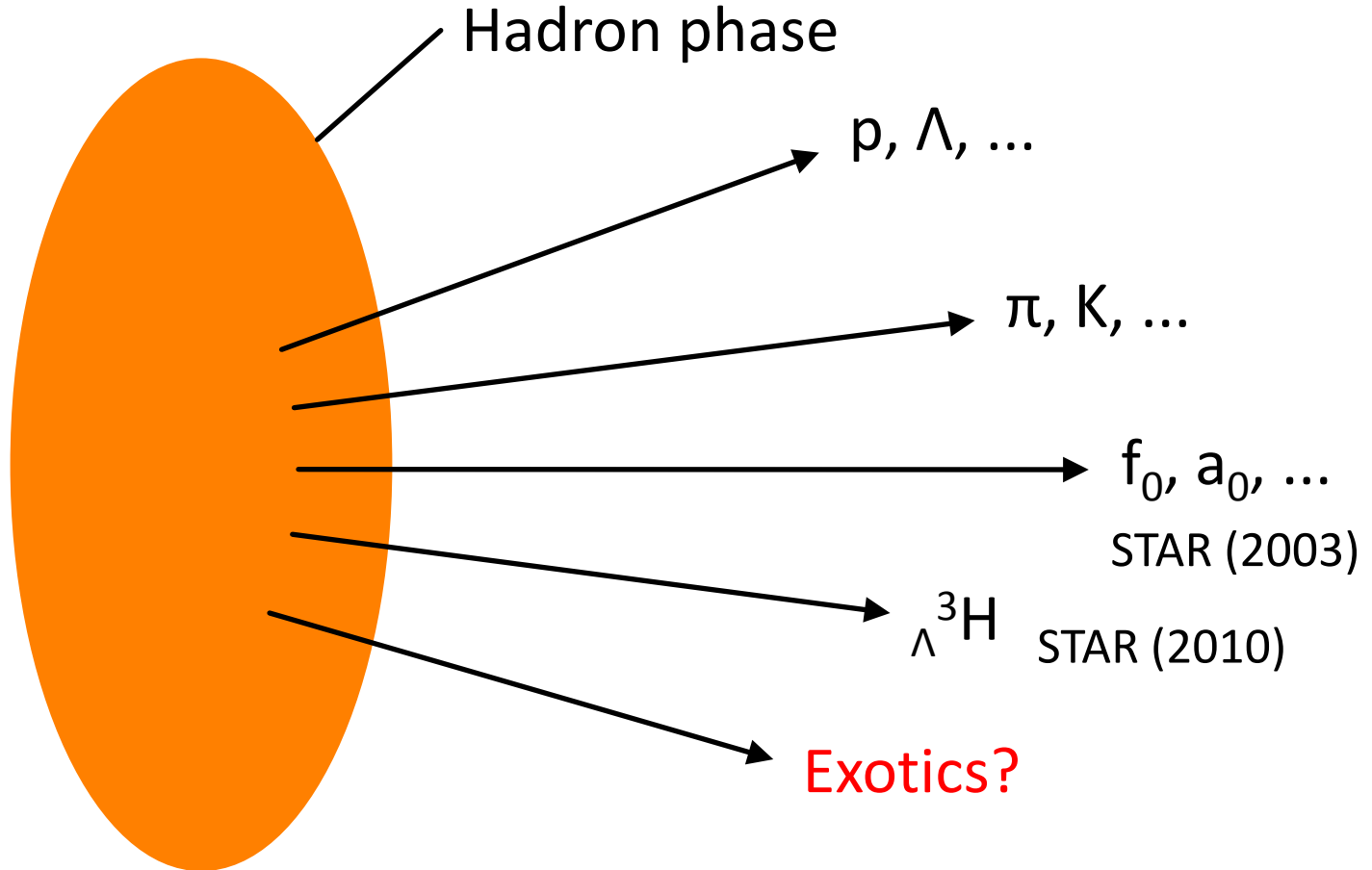
4. Experimental researches

Exotic hadrons from heavy ion collisions at RHIC and LHC



4. Experimental researches

Exotic hadrons from heavy ion collisions at RHIC and LHC



4. Experimental researches

Yields of exotic hadrons at RHIC and LHC

S. Cho *et al.* (the ExHIC collaboration), PRL106, 212001 (2011)

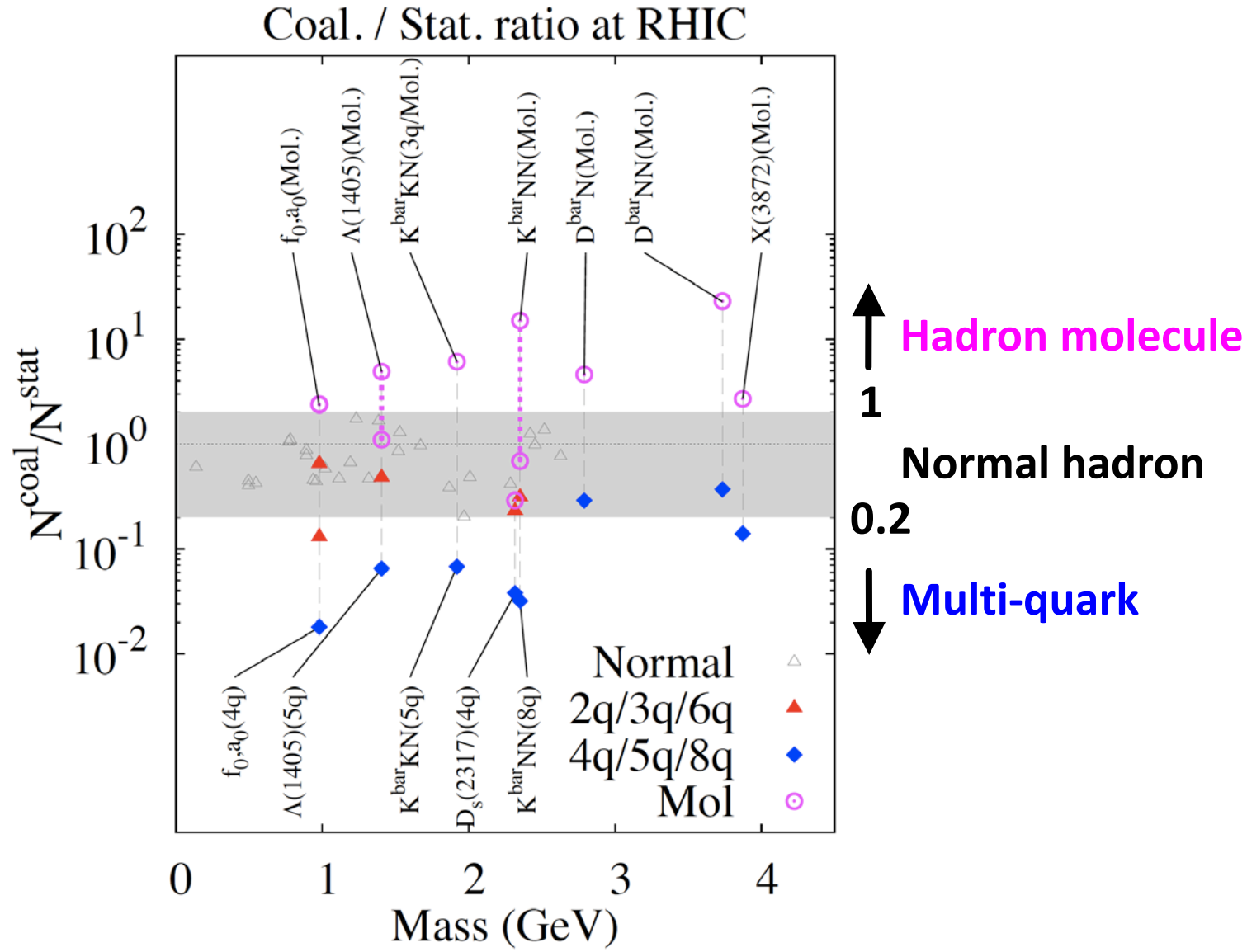
	RHIC				LHC			
	2q/3q/6q	4q/5q/8q	Mol.	Stat.	2q/3q/6q	4q/5q/8q	Mol.	Stat.
$f_0(980)$	3.8, 0.73($s\bar{s}$)	0.10	13	5.6	10, 2.0 ($s\bar{s}$)	0.28	36	15
$a_0(980)$	11	0.31	40	17	31	0.83	1.1×10^2	46
$D_s(2317)$	1.3×10^{-2}	2.1×10^{-3}	1.6×10^{-2}	5.6×10^{-2}	8.7×10^{-2}	1.4×10^{-2}	0.10	0.35
$X(3872)$	—	4.0×10^{-5}	7.8×10^{-4}	2.9×10^{-4}	—	6.6×10^{-4}	1.3×10^{-2}	4.7×10^{-3}
$\Lambda(1405)$	0.81	0.11	1.8–8.3	1.7	2.2	0.29	4.7–21	4.2
$\bar{K}KN$	—	0.019	1.7	0.28	—	5.2×10^{-2}	4.2	0.67
$\bar{D}N$	—	2.9×10^{-3}	4.6×10^{-2}	1.0×10^{-2}	—	2.0×10^{-2}	0.28	6.1×10^{-2}
$\bar{K}NN$	5.0×10^{-3}	5.1×10^{-4}	0.011–0.24	1.6×10^{-2}	1.3×10^{-2}	1.4×10^{-3}	0.026 – 0.54	3.7×10^{-2}
$\bar{D}NN$	—	2.9×10^{-5}	1.8×10^{-3}	7.9×10^{-5}	—	2.0×10^{-4}	9.8×10^{-3}	4.2×10^{-4}

ExHIC (Exotics from Heavy Ion Collisions) collaboration

S. Cho (Yonsei U.), T. Furumoto (YITP and RIKEN), T. Hyodo (Tokyo Inst. Technology), D. Jido (YITP), C.-M. Ko (Texas A&M U.), S. H. Lee (Yonsei U. and YITP), M. Nielsen (U. de Paulo), A. Ohnishi (YITP), T. Sekihara (YITP and Kyoto U.), K. Yazaki (YITP and RIKEN), S. Y. (KEK)

4. Experimental researches

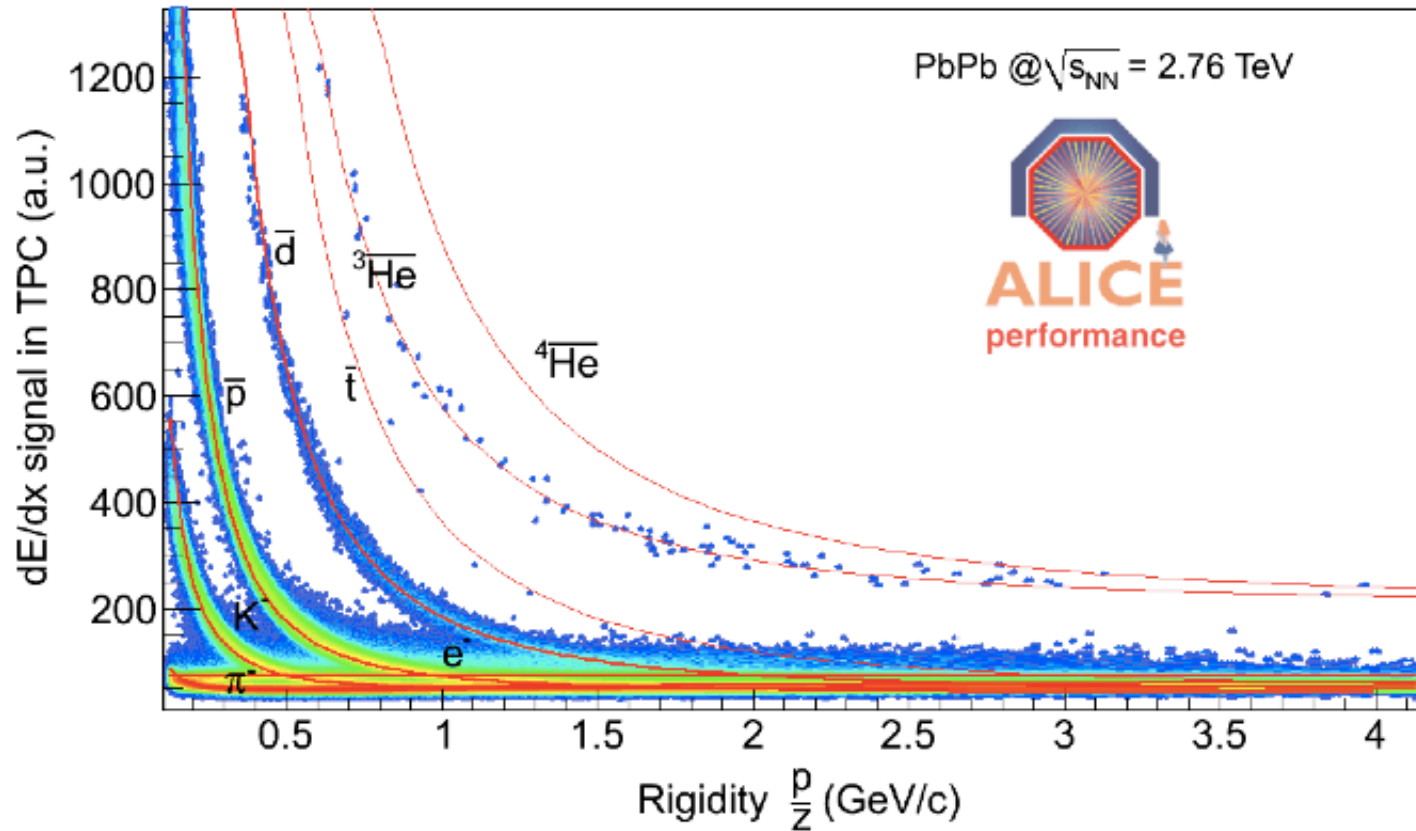
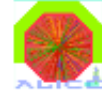
Hadron molecule vs. multi-quark



4. Experimental researches



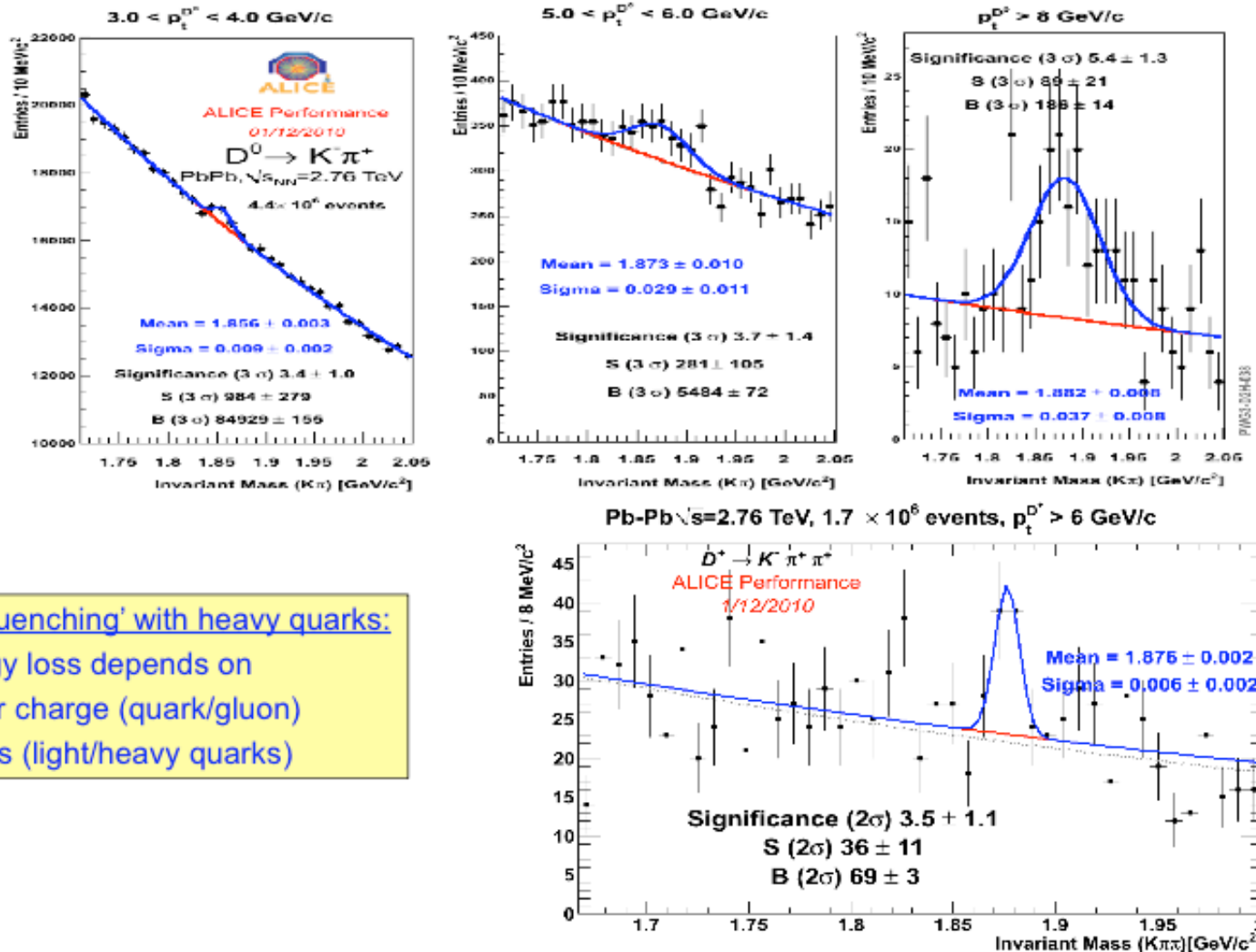
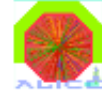
Anti-Nuclei



4. Experimental researches



Charm in Pb-Pb



'Jet quenching' with heavy quarks:
Energy loss depends on

- color charge (quark/gluon)
- mass (light/heavy quarks)

5. Summary

Heavy quarks have new symmetry and dynamics.

Heavy quark symmetry

D-D* mixing

...

Many exotic heavy hadrons and nuclei.

T_{cc}^1

$Z_b (I=1)$

$D^{\text{bar}}N$ bound and resonance states

...

Searches in e^+e^- , pp (pp^{bar}) and heavy ion collisions.