Charmed & bottomed mesons

~ 重いクォークを含むマルチクォーク系 ~

- Heavy flavor exotic hadrons

  S. H. Lee and S. Y. arXiv:0901.2977 [hep-ph]

- Exotic nuclei with heavy flavor mesons

  S. Y. and K. Sudoh, in preparation

S. Yasui (KEK)

27-28 Feb. 2009
特定領域研究「ストレンジネスで探るクォーク多体系」理論班主催
「ストレンジネスを含むクォーク多体系分野の理論的将来を考える」研究会
KKRホテル熱海

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- Explicitly exotic heavy hadrons
  - Tetraquark with C=±2
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Introduction

QUESTIONS

What is exotic hadron?

tetra-, penta-, hexa-, ...

What is flavor world in nuclear physics?

up, down, strange, charm, bottom, top

Introduction

What is exotic hadron?

Tetraquark	$uu^{bar}dd^{bar}$	$f_0(980)$, $a_0(980)$, ...
(Hybrid)	$uu^{bar}sc^{bar}$	$D_s(2317)$, $D_s(2460)$, ...
	$uu^{bar}cc^{bar}$	X(3872), Y(4260), ...
Pentaquark	$uuds s^{bar}$	Λ*(1405), N(1535), ...
	$uudd s^{bar}$	Θ(1540)
H dibaryon	uuddss	H

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NOT explicitly exotic

NOT established yet

NOT seen yet

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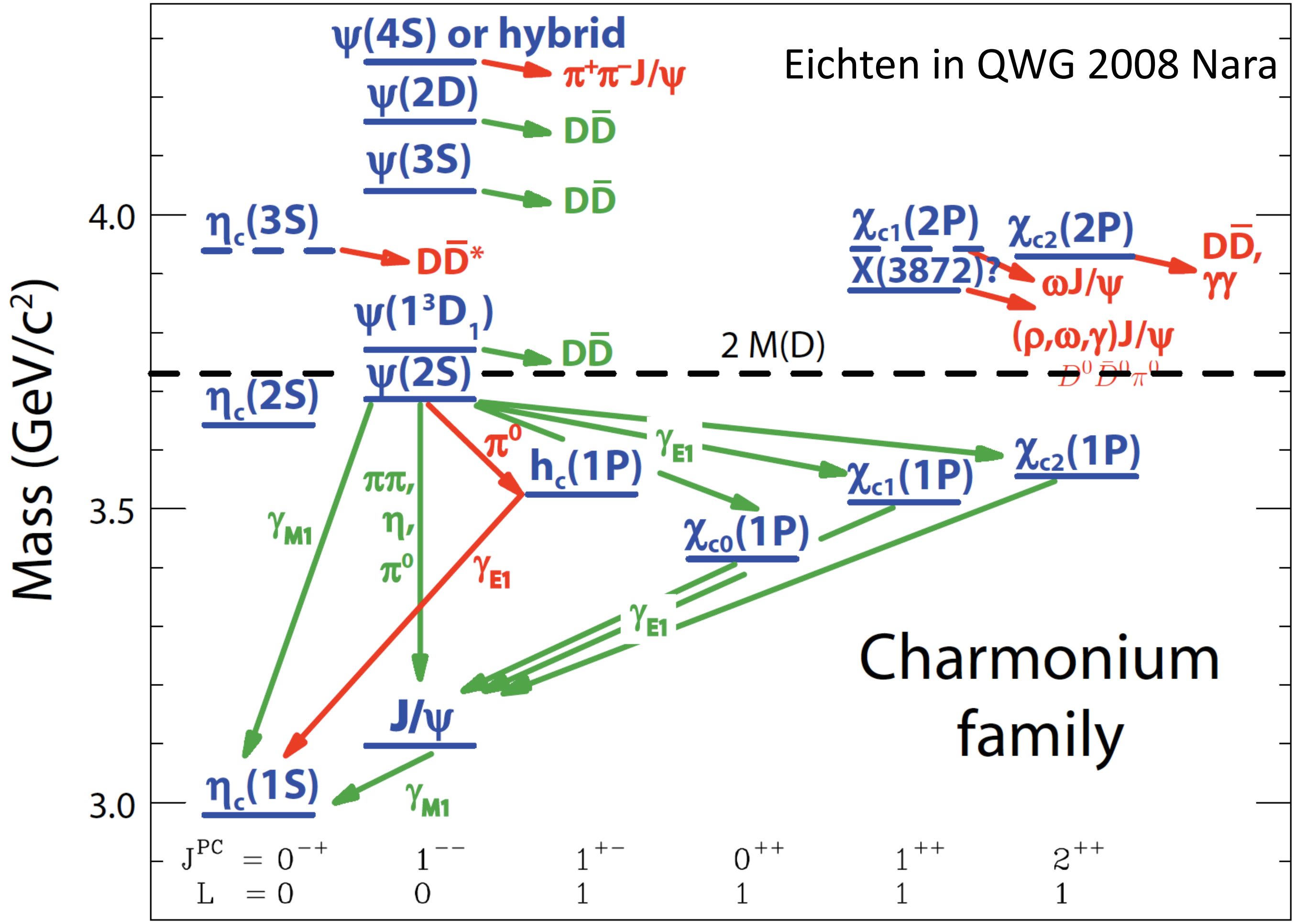
We want to know more about exotics.

Exotic charm mesons

Exotic charm mesons

exotics?



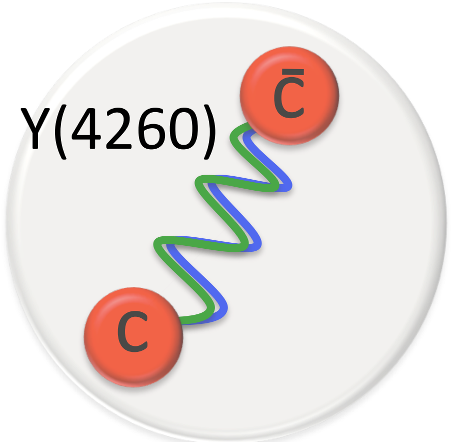
Exotic charm mesons

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

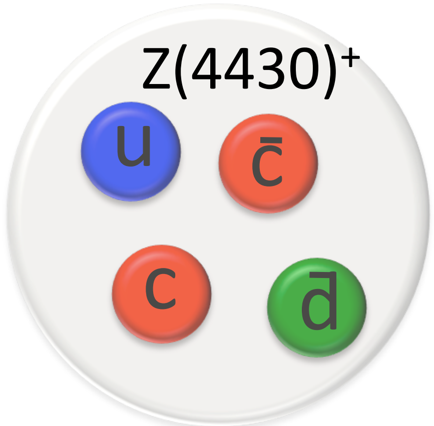
Why exotic?

- small decay width (< 50 MeV)
- mass different from cc^{bar} model (~100 MeV)

meson molecule
Tornqvist 1991



cc^{bar}G hybrid
S. L. Zhu 2005



really tetraquark

Exotic charm mesons

Let‘s explore exotic charm hadrons !!

↓

But WHAT shall we see?

Explicitly exotic heavy hadrons

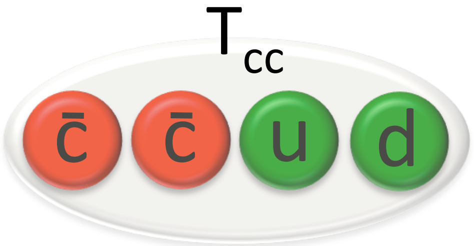
Explicitly exotic hadrons

- ✓ Tetraquark T_{cc}, T_{cb}, T_{bb}
- ✓ Pentaquark Θ_{cs}, Θ_{bs}
- ✓ H dibaryon H_c, H_b, H_{cb}, ...

What does „explicit" mean?

Explicitly exotic heavy hadrons

✓ Tetraquark T_{cc} ($c^{bar}c^{bar}ud$; C=+2)



T_{cc} cannot be regared as two quark state.
So, it is „explicitly“ exotic.

Carlson, Heller, Tjon (1988)
Silvestre-Brac and Semay (1993)
Manohar and Wise (1993)

Explicitly exotic heavy hadrons

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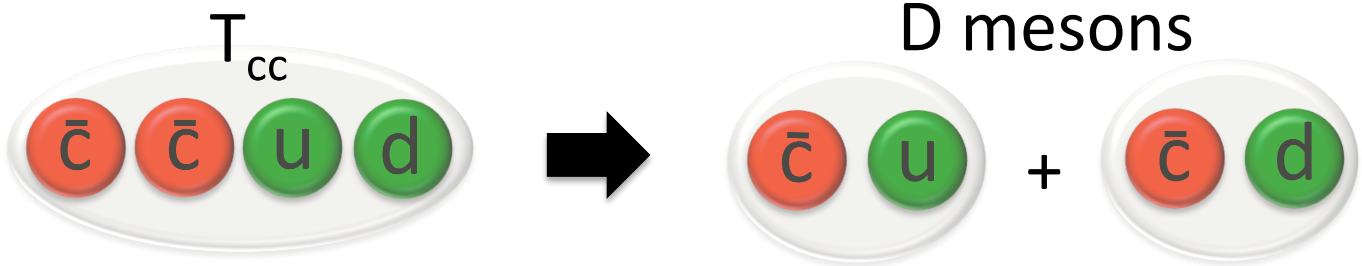

Stable against decay to two D meosns?

Explicitly exotic heavy hadrons

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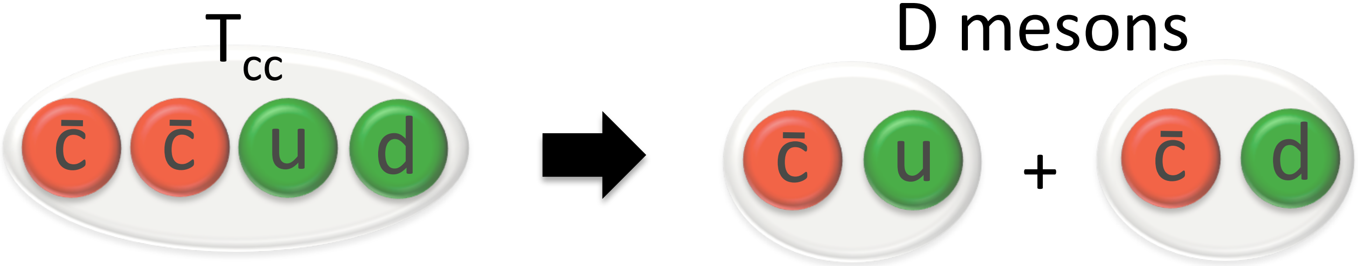

Stable against decay to two D meosns?

We consider color-spin interaction.

$$C_H \sum_{i>j} \vec{s}_i \cdot \vec{s}_j \frac{1}{m_i m_j} \qquad C_H = v_0 \lambda_i \cdot \lambda_j \langle \delta(r_{ij}) \rangle$$

$$\vec{s}_i \cdot \vec{s}_j = \begin{cases} -3/4 & \text{for spin sinlet} \\ 1/4 & \text{for spin triplet} \end{cases}$$

$$m_{u,d} = 300,\ m_s = 500,\ m_c = 1500,\ m_b = 4700\ [\text{MeV}]$$

Explicitly exotic heavy hadrons

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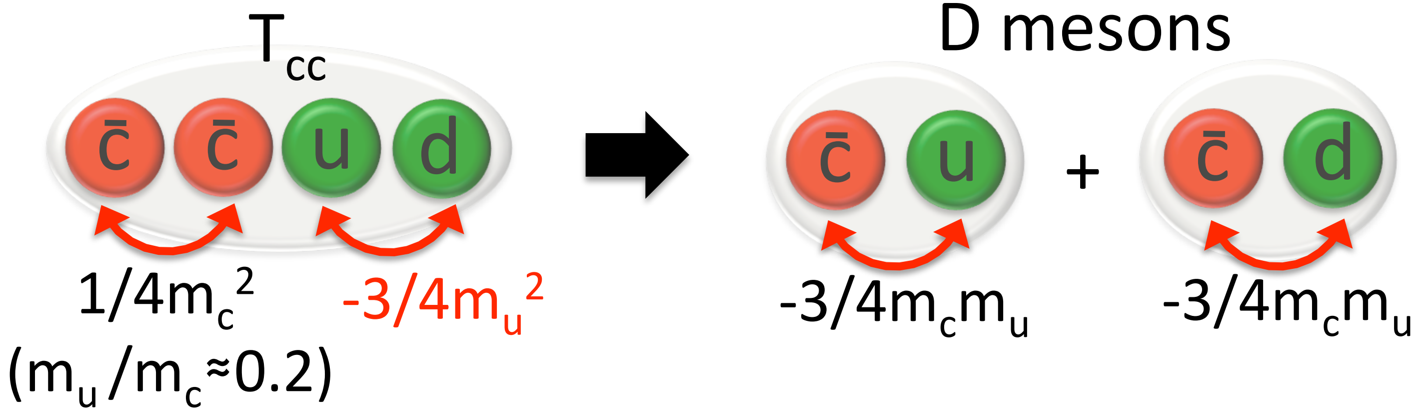

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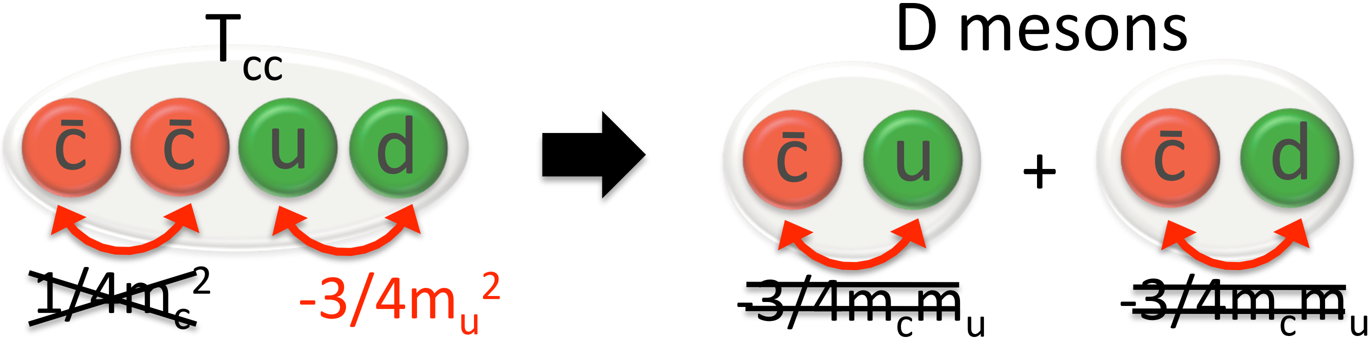

($m_u/m_c \approx 0.2$) *ud* pair (spin singlet) is dominantly attractive.

→ Tcc seems really stable state.

Explicitly exotic heavy hadrons

✓ Tetraquark T_{cc} ($c^{bar}c^{bar}ud$; C=+2)

1) How is color-spin interaction nice?

qq pair (C_B/m_u^2=193 MeV)

Mass Diff.	$M_\Delta - M_N$	$M_\Sigma - M_\Lambda$	$M_{\Sigma_c} - M_{\Lambda_c}$	$M_{\Sigma_b} - M_{\Lambda_b}$
Formula	$\frac{3C_B}{2m_u^2}$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_s})$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_c})$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_b})$
Fit	290 MeV	77 MeV	154 MeV	180 MeV
Experiment	290 MeV	75 MeV	170 MeV	192 MeV

qq^{bar} pair (C_M/m_u^2=635 MeV)

Mass Diff.	$M_\rho - M_\pi$	$M_{K^*} - M_K$	$M_{D^*} - M_D$	$M_{B^*} - M_B$
Formula	$\frac{C_M}{m_u^2}$	$\frac{C_M}{m_u m_s}$	$\frac{C_M}{m_u m_c}$	$\frac{C_M}{m_u m_b}$
Fit	635 MeV	381 MeV	127 MeV	41 MeV
Experiment	635 MeV	397 MeV	137 MeV	46 MeV

($C_M \approx 3C_B$ ← color factor $\lambda_i \lambda_j$)

Consistent fitting with experimental data.

Explicitly exotic heavy hadrons

✓ Tetraquark T_{cc} ($c^{bar}c^{bar}ud$; C=+2)

2) Binding energy of diquarks with flavor combination.

$$-\frac{3}{4}\frac{C_B}{m_{q_1} m_{q_2}}$$

(spin singlet and color anti-triplet)

(ud) -144.75			
(us) -86.85	(ds) -86.85		
(uc) -28.95	(dc) -28.95	(sc) -17.37	
(ub) -9.23	(db) - 9.23	(sb) -5.54	(cb) -1.84

MeV

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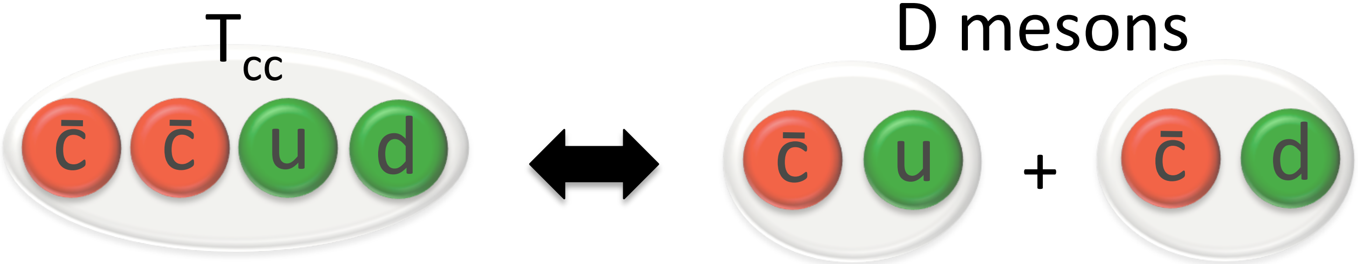
MeV

Explicitly exotic heavy hadrons

✓ Tetraquark T_{cc} ($c^{bar}c^{bar}ud$; C=+2)

3) How much is T_{cc} stable?



Binding energy of $T_{cc(bb)}$

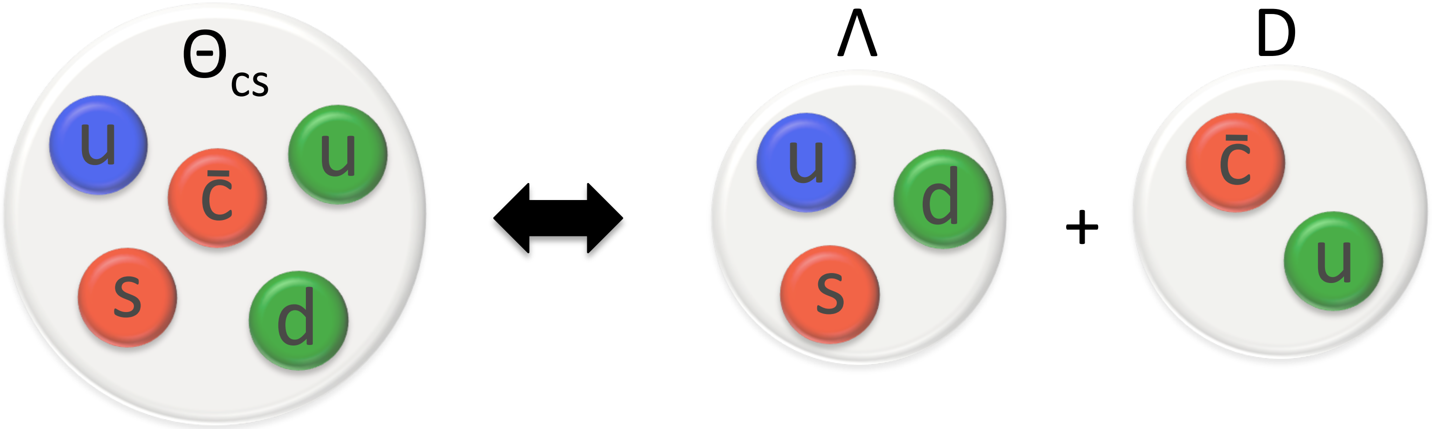
T^1_{cc}	$ud\bar{c}\bar{c}$	$us\bar{c}\bar{c}$	$ds\bar{c}\bar{c}$
	-74.9	-4.3	-4.3
	$\bar{D}^0 + D^{*-}$, $\bar{D}^{*0} + D^-$	$\bar{D}^0 + D_s^{*-}$	$D^- + D_s^{*-}$
T^1_{bb}	$ud\bar{b}\bar{b}$	$us\bar{b}\bar{b}$	$ds\bar{b}\bar{b}$
	-123.8	-61.4	-61.4
	$B^+ + B^{*0}$, $B^{*+} + B^0$	$B^+ + B_s^{*0}$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

MeV

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

Explicitly exotic heavy hadrons

✓ Pentaquark Θ_{cs} ($udus\bar{c}$)



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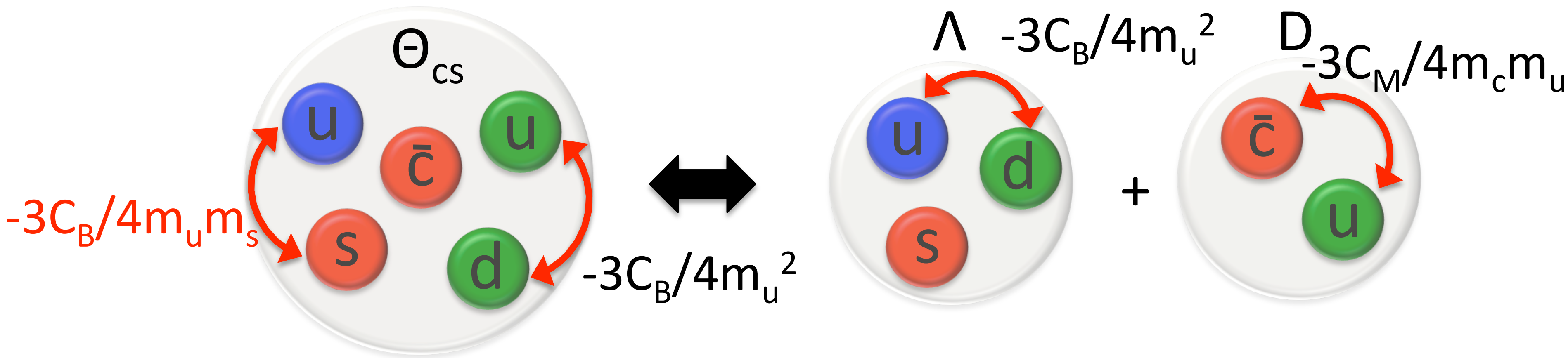

color-spin interaction.

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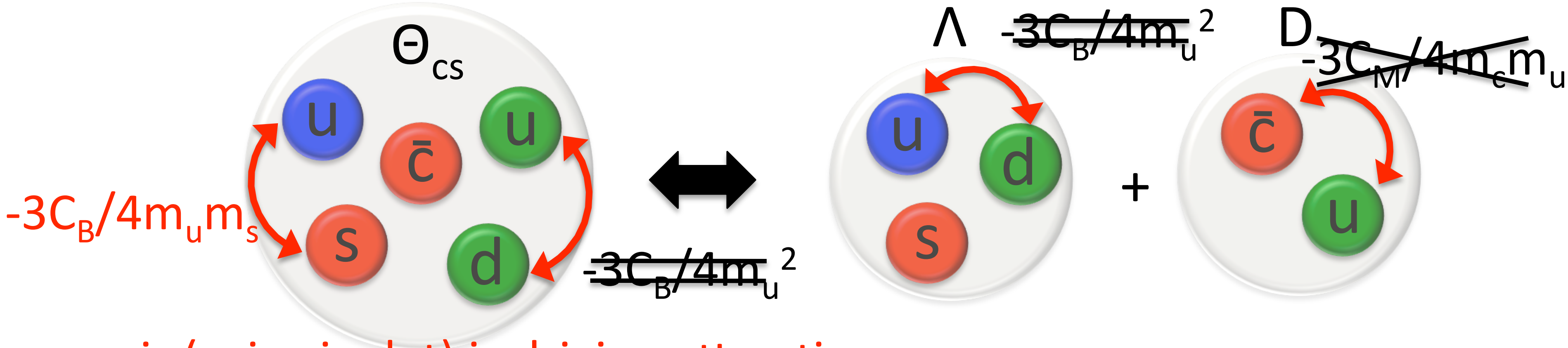

us pair (spin singlet) is driving attraction.

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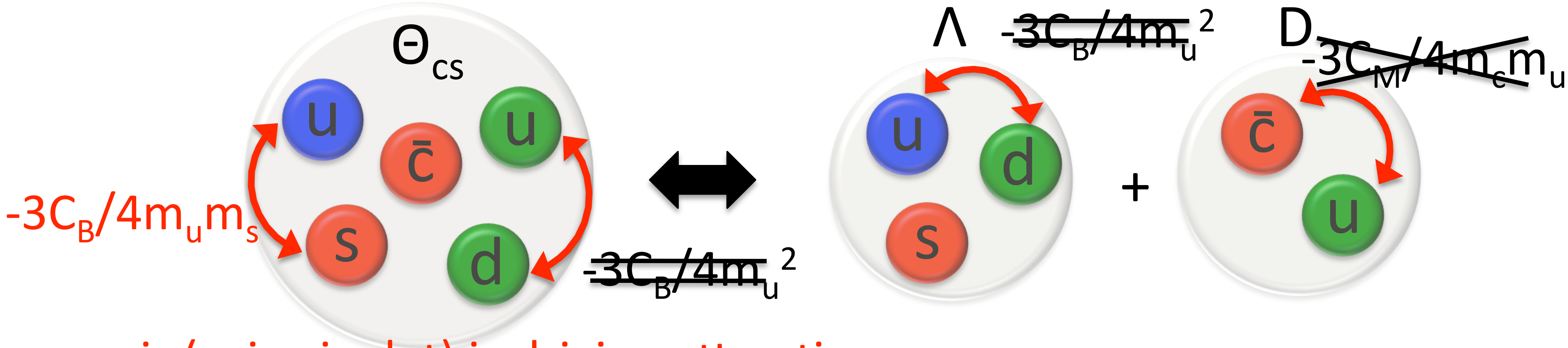

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Binding energy of $\Theta_{sc(b)}$

	config. of Θ	config. of $M+B$	$\bar{u}$	$\bar{s}$	$\bar{c}$	$\bar{b}$
Θ_{qs}	$ud\,us\,\bar{q}$	$ud\,s+u\bar{q}$	389.4	198.9	8.4	-56.4
Θ_{qss}	$us\,ds\,\bar{q}$	$ds\,s+u\bar{q}$	389.4	198.9	8.4	-56.4
		$ud\,s+s\bar{q}$	256.8	142.5	28.4	-10.7

MeV

Explicitly exotic heavy hadrons

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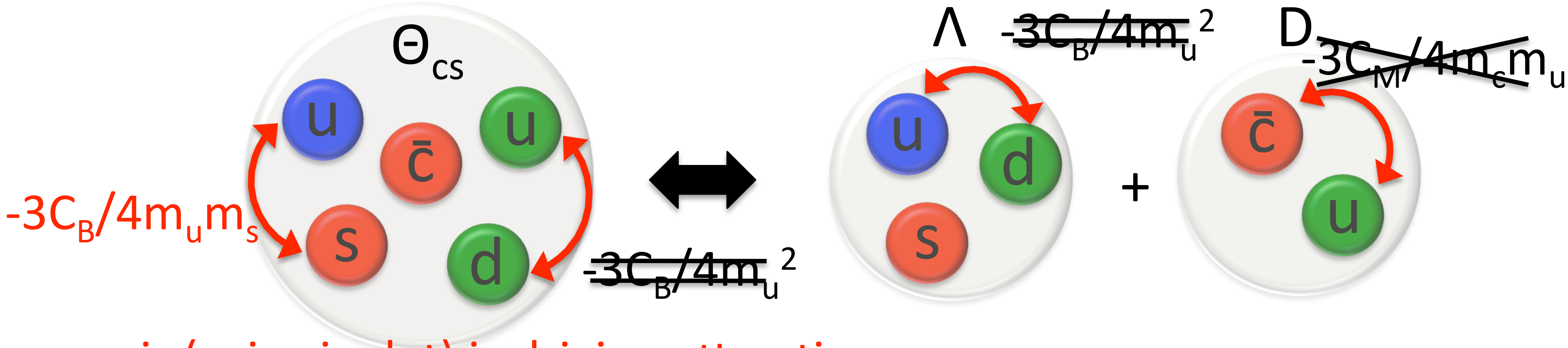

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	config. of Θ	config. of $M+B$	$\bar{u}$	$\bar{s}$	$\bar{c}$	$\bar{b}$
Θ_{qs}	$ud\,us\,\bar{q}$	$ud\,s{+}u\bar{q}$	389.4	198.9	8.4	-56.4
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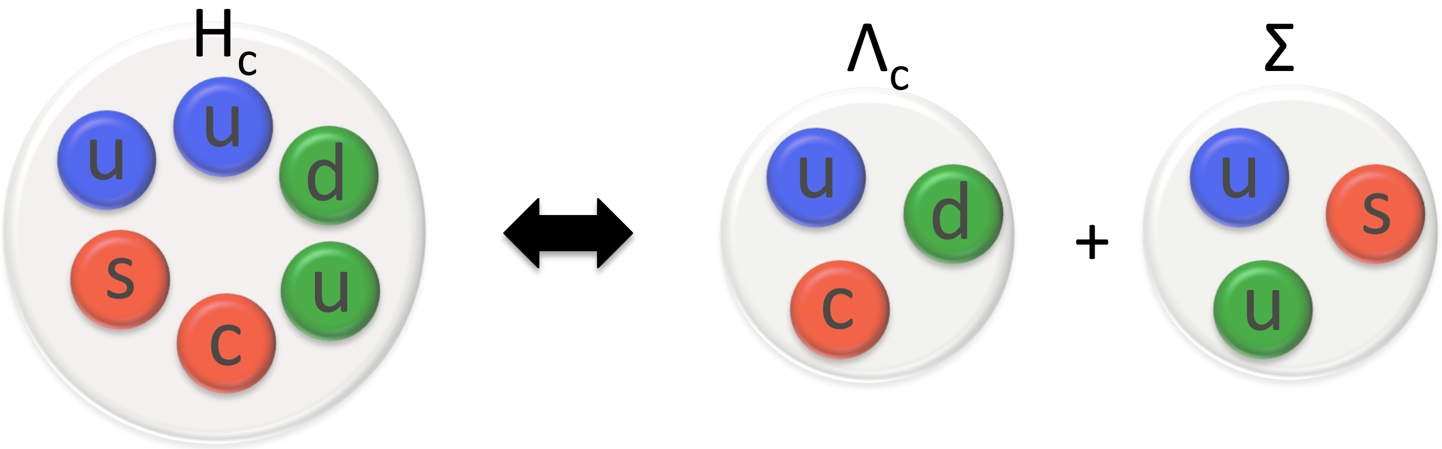
		$ud\,s{+}s\bar{q}$	256.8	142.5	28.4	-10.7

MeV

→ Θ_{bs} and Θ_{bss} are stable as 3_f multiplet of $SU(3)_f$.

Explicitly exotic heavy hadrons

✓ H dibaryon H_c (udusuc)



Explicitly exotic heavy hadrons

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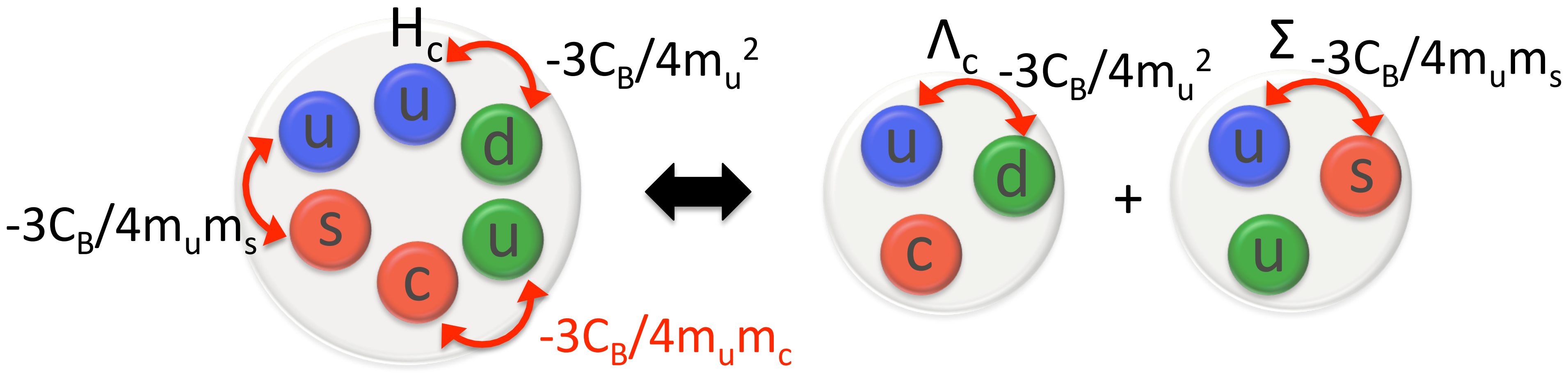

Explicitly exotic heavy hadrons

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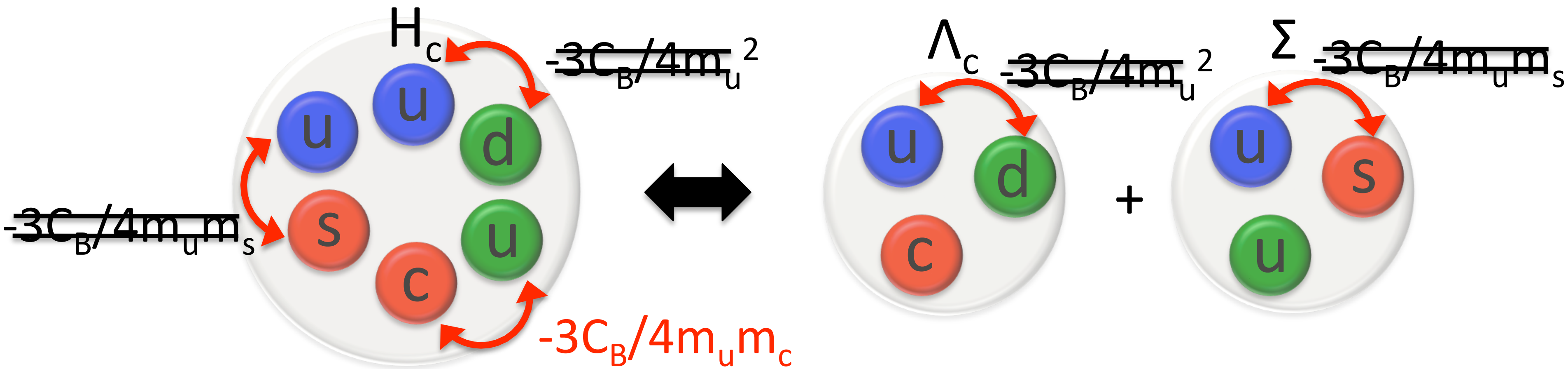

uc pair (spin singlet) is driving attraction.

		flavor	config. of H	I	I_z	S	config. of $B+B'$	B_H [MeV]
H	$qq\,qq\,qq$	22200	$ud\,us\,ds$	0	0	-2	$ud\,s+ud\,s$	-28.95
H_c	$qq\,qq\,qQ$ $(Q=c)$	31110	$ud\,us\,uc$	1	1	-1	$ud\,c+us\,u,\ ud\,u+us\,c$	
		22110	$ud\,\frac{1}{\sqrt{2}}(us\,dc+ds\,uc)$	1	0	-1	$ud\,s+ud\,c,\ ud\,s+ud\,c$	-28.95
		13110	$ud\,ds\,dc$	1	-1	-1	$ud\,c+ds\,d,\ ud\,d+ds\,c$	
		21210	$ud\,us\,sc$	1/2	1/2	-2	$ud\,c+us\,s,\ ud\,s+us\,c$	-17.37
		12210	$ud\,ds\,sc$	1/2	-1/2	-2	$ud\,c+ds\,s,\ ud\,s+ds\,c$	
		11310	$\frac{1}{\sqrt{2}}(us\,ds-ds\,us)\,sc$	0	0	-3	$us\,s+ds\,c,\ us\,c+ds\,s$	-17.37
H_b	$qq\,qq\,qQ$ $(Q=b)$	31101	$ud\,us\,ub$	1	1	-1	$ud\,u+us\,b,\ ud\,b+us\,u$	
		22101	$ud\,\frac{1}{\sqrt{2}}(us\,db+ds\,ub)$	1	0	-1	$ud\,s+ud\,b,\ ud\,s+ud\,b$	-9.23
		13101	$ud\,ds\,db$	1	-1	-1	$ud\,b+ds\,d,\ ud\,d+ds\,b$	
		21202	$ud\,us\,sb$	1/2	1/2	-2	$ud\,b+us\,s,\ ud\,s+us\,b$	-5.54
		12201	$ud\,ds\,sb$	1/2	-1/2	-2	$ud\,b+ds\,s,\ ud\,s+ds\,b$	
		11301	$\frac{1}{\sqrt{2}}(us\,ds-ds\,us)\,sb$	0	0	-3	$us\,b+ds\,s,\ us\,s+ds\,b$	-5.54
H_{cb}	$qq\,qQ\,qQ'$ $(Q,\ Q'=c,\ b)$	31011	$ud\,uc\,ub$	1	1	0	$ud\,b+uc\,u,\ ud\,u+uc\,b$	
		22011	$ud\,\frac{1}{\sqrt{2}}(uc\,db+dc\,ub)$	1	0	0	$ud\,b+uc\,u,\ ud\,u+uc\,b$	-9.23
		13011	$ud\,dc\,db$	1	-1	0	$ud\,b+dc\,d,\ ud\,d+dc\,b$	
		30111	$us\,uc\,ub$	3/2	3/2	-1	$us\,u+uc\,b,\ us\,b+uc\,u$	
		21111	$\frac{1}{\sqrt{3}}((us\,dc+ds\,uc)\,ub+us\,uc\,db)$	3/2	1/2	-1	$ud\,b+us\,c,\ ud\,c+us\,b$	-9.23
		12111	$\frac{1}{\sqrt{3}}((us\,dc+ds\,uc)\,db+ds\,dc\,ub)$	3/2	-1/2	-1	$ud\,b+ds\,c,\ ud\,c+ds\,b$	
		03111	$ds\,dc\,db$	3/2	-3/2	-1	$ds\,b+dc\,d,\ ds\,d+dc\,b$	
		10311	$us\,sc\,sb$	1/2	1/2	-3	$us\,b+sc\,s,\ us\,s+sc\,b$	-5.54
		01311	$ds\,sc\,sb$	1/2	-1/2	-3	$ds\,b+sc\,s,\ ds\,s+sc\,b$	
H'_{cb}	$qq\,qq\,QQ'$ $(Q,\ Q'=c,\ b)$	21111	$ud\,us\,cb$	1/2	1/2	-1	$ud\,b+us\,c,\ ud\,c+us\,b$	-1.84
		12111	$ud\,ds\,cb$	1/2	-1/2	-1	$ud\,b+ds\,c,\ ud\,c+ds\,b$	
		11211	$\frac{1}{\sqrt{2}}(us\,ds-ds\,us)\,cb$	0	0	-2	$us\,b+ds\,c,\ us\,c+ds\,b$	-1.84
H_{ccb}	$qq\,qQ\,QQ'$ $(Q,\ Q'=c,\ b)$	21021	$ud\,uc\,cb$	1/2	1/2	0	$ud\,b+uc\,c,\ ud\,c+uc\,b$	-1.84
		12021	$ud\,dc\,cb$	1/2	-1/2	0	$ud\,b+dc\,c,\ ud\,c+dc\,b$	
		20121	$us\,uc\,cb$	1	1	-1	$us\,b+uc\,c,\ us\,c+uc\,b$	
		11121	$\frac{1}{\sqrt{2}}(us\,dc+ds\,uc)\,cb$	1	0	-1	$us\,b+dc\,c,\ us\,c+dc\,b$	-1.84
		02121	$ds\,dc\,cb$	1	-1	-1	$ds\,b+dc\,c,\ ds\,c+dc\,b$	
		11121	$ud\,sc\,cb$	0	0	-1	$ud\,b+sc\,c,\ ud\,c+sc\,b$	-1.84

		flavor	config. of H	I	I_z	S	config. of $B+B'$	B_H [MeV]
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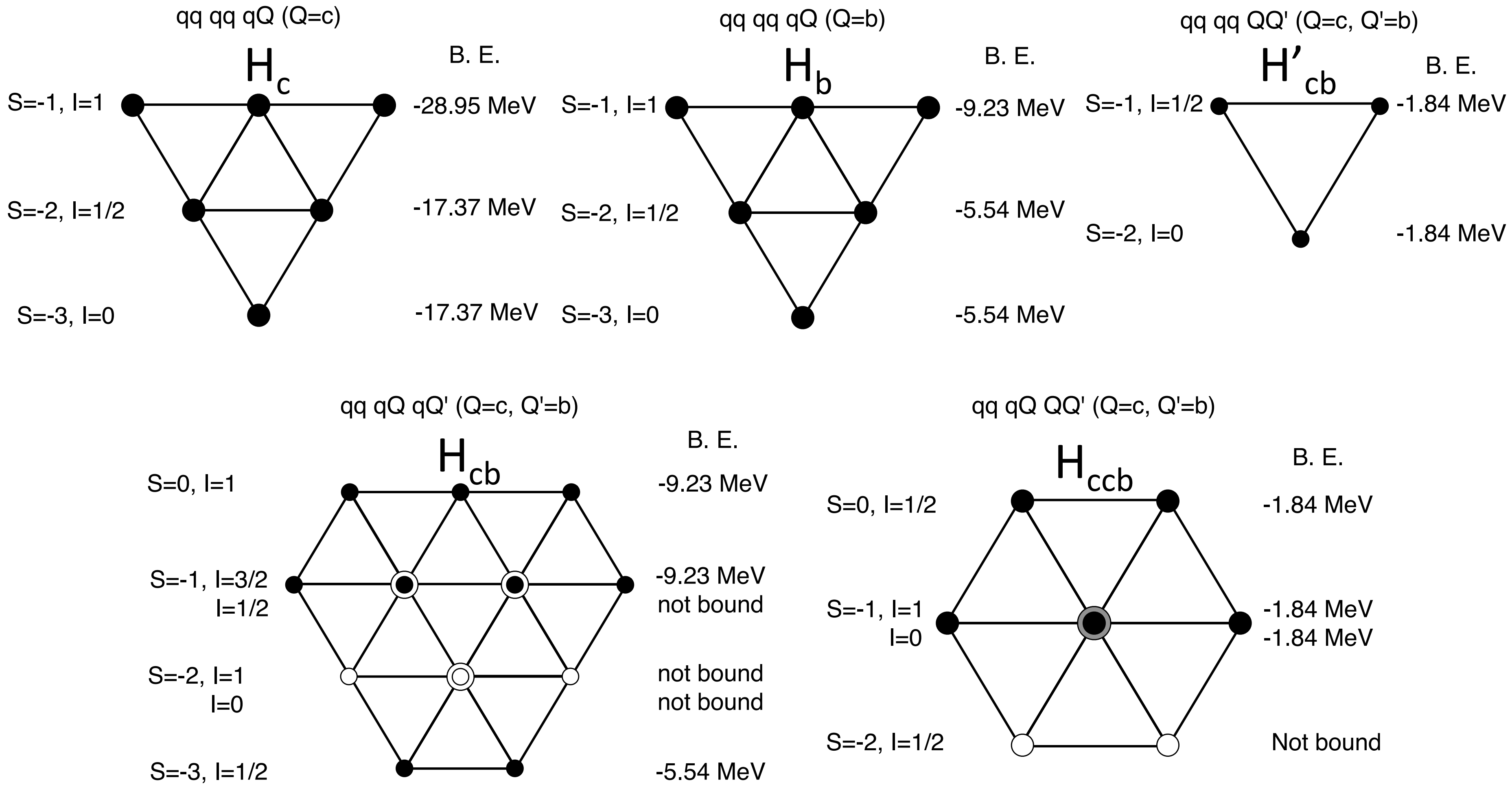
H_c	$qq\,qq\,qQ$ $(Q=c)$	31110	$ud\,us\,uc$	1	1	-1	$ud\,c+us\,u,\ ud\,u+us\,c$	
		22110	$ud\,\frac{1}{\sqrt{2}}(us\,dc+ds\,uc)$	1	0	-1	$ud\,s+ud\,c,\ ud\,s+ud\,c$	-28.95
		13110	$ud\,ds\,dc$	1	-1	-1	$ud\,c+ds\,d,\ ud\,d+ds\,c$	
		21210	$ud\,us\,sc$	1/2	1/2	-2	$ud\,c+us\,s,\ ud\,s+us\,c$	-17.37
		12210	$ud\,ds\,sc$	1/2	-1/2	-2	$ud\,c+ds\,s,\ ud\,s+ds\,c$	
		11310	$\frac{1}{\sqrt{2}}(us\,ds-ds\,us)\,sc$	0	0	-3	$us\,s+ds\,c,\ us\,c+ds\,s$	-17.37
H_b	$qq\,qq\,qQ$ $(Q=b)$	31101	$ud\,us\,ub$	1	1	-1	$ud\,u+us\,b,\ ud\,b+us\,u$	
		22101	$ud\,\frac{1}{\sqrt{2}}(us\,db+ds\,ub)$	1	0	-1	$ud\,s+ud\,b,\ ud\,s+ud\,b$	-9.23
		13101	$ud\,ds\,db$	1	-1	-1	$ud\,b+ds\,d,\ ud\,d+ds\,b$	
		21202	$ud\,us\,sb$	1/2	1/2	-2	$ud\,b+us\,s,\ ud\,s+us\,b$	-5.54
		12201	$ud\,ds\,sb$	1/2	-1/2	-2	$ud\,b+ds\,s,\ ud\,s+ds\,b$	
		11301	$\frac{1}{\sqrt{2}}(us\,ds-ds\,us)\,sb$	0	0	-3	$us\,b+ds\,s,\ us\,s+ds\,b$	-5.54
H_{cb}	$qq\,qQ\,qQ'$ $(Q,\ Q'=c,\ b)$	31011	$ud\,uc\,ub$	1	1	0	$ud\,b+uc\,u,\ ud\,u+uc\,b$	
		22011	$ud\,\frac{1}{\sqrt{2}}(uc\,db+dc\,ub)$	1	0	0	$ud\,b+uc\,u,\ ud\,u+uc\,b$	-9.23
		13011	$ud\,dc\,db$	1	-1	0	$ud\,b+dc\,d,\ ud\,d+dc\,b$	
		30111	$us\,uc\,ub$	3/2	3/2	-1	$us\,u+uc\,b,\ us\,b+uc\,u$	
		21111	$\frac{1}{\sqrt{3}}((us\,dc+ds\,uc)\,ub+us\,uc\,db)$	3/2	1/2	-1	$ud\,b+us\,c,\ ud\,c+us\,b$	-9.23
		12111	$\frac{1}{\sqrt{3}}((us\,dc+ds\,uc)\,db+ds\,dc\,ub)$	3/2	-1/2	-1	$ud\,b+ds\,c,\ ud\,c+ds\,b$	
		03111	$ds\,dc\,db$	3/2	-3/2	-1	$ds\,b+dc\,d,\ ds\,d+dc\,b$	
		10311	$us\,sc\,sb$	1/2	1/2	-3	$us\,b+sc\,s,\ us\,s+sc\,b$	-5.54
		01311	$ds\,sc\,sb$	1/2	-1/2	-3	$ds\,b+sc\,s,\ ds\,s+sc\,b$	
H'_{cb}	$qq\,qq\,QQ'$ $(Q,\ Q'=c,\ b)$	21111	$ud\,us\,cb$	1/2	1/2	-1	$ud\,b+us\,c,\ ud\,c+us\,b$	-1.84
		12111	$ud\,ds\,cb$	1/2	-1/2	-1	$ud\,b+ds\,c,\ ud\,c+ds\,b$	
		11211	$\frac{1}{\sqrt{2}}(us\,ds-ds\,us)\,cb$	0	0	-2	$us\,b+ds\,c,\ us\,c+ds\,b$	-1.84
H_{ccb}	$qq\,qQ\,QQ'$ $(Q,\ Q'=c,\ b)$	21021	$ud\,uc\,cb$	1/2	1/2	0	$ud\,b+uc\,c,\ ud\,c+uc\,b$	-1.84
		12021	$ud\,dc\,cb$	1/2	-1/2	0	$ud\,b+dc\,c,\ ud\,c+dc\,b$	
		20121	$us\,uc\,cb$	1	1	-1	$us\,b+uc\,c,\ us\,c+uc\,b$	
		11121	$\frac{1}{\sqrt{2}}(us\,dc+ds\,uc)\,cb$	1	0	-1	$us\,b+dc\,c,\ us\,c+dc\,b$	-1.84
		02121	$ds\,dc\,cb$	1	-1	-1	$ds\,b+dc\,c,\ ds\,c+dc\,b$	
		11121	$ud\,sc\,cb$	0	0	-1	$ud\,b+sc\,c,\ ud\,c+sc\,b$	-1.84

✓ H dibaryon H_c (udusuc)

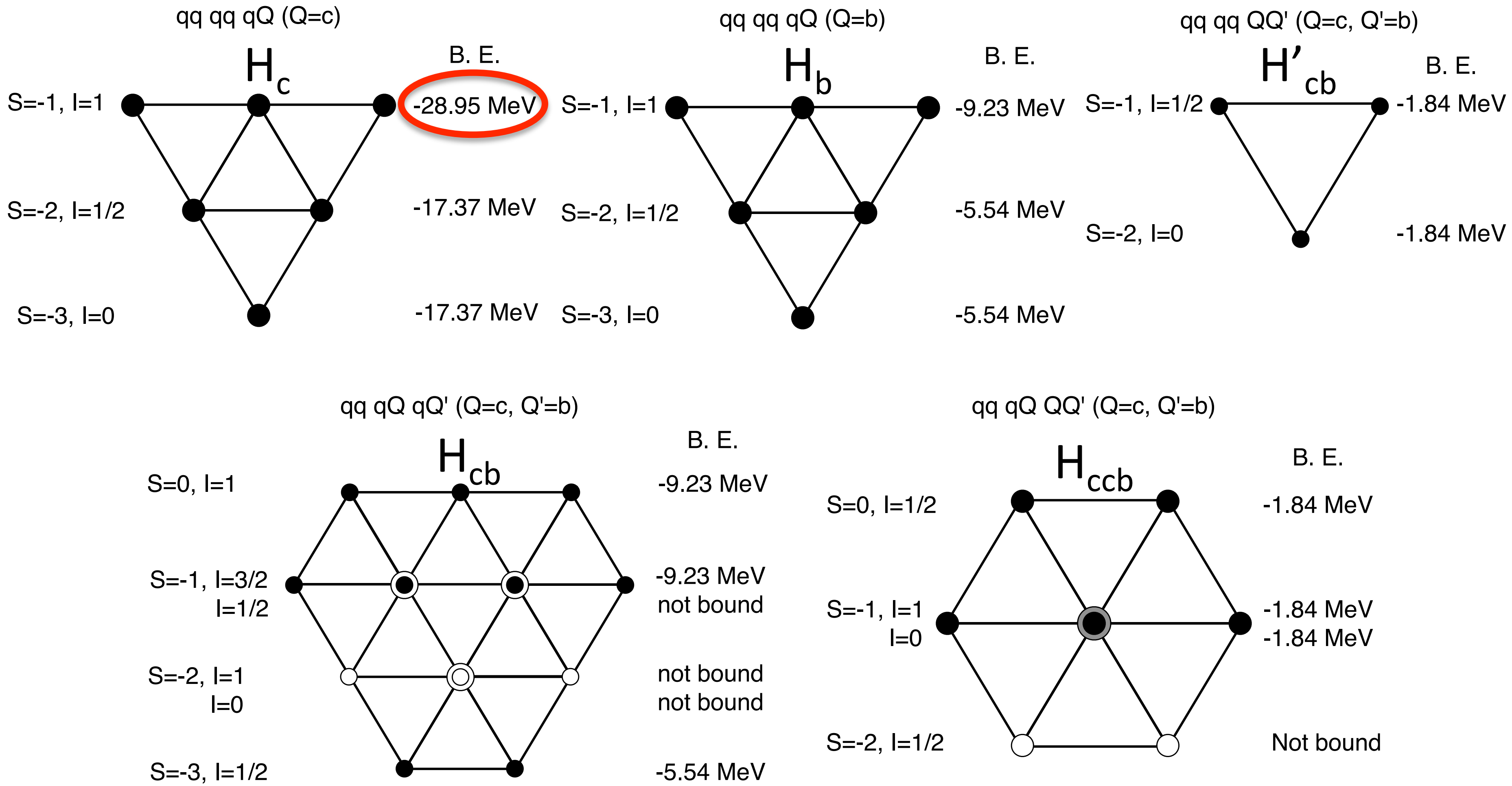
multiplets of $SU(3)_f$.



→ H dibaryons (H, H_c, H_b, ...) are stable as 3_f multiplet of $SU(3)_f$.

✓ H dibaryon H_c (udusuc)

multiplets of $SU(3)_f$.



→ H dibaryons (H, H_c, H_b, ...) are stable as 3_f multiplet of $SU(3)_f$.

Observation

✓ LHC (Large Hadron Collider)
from QGP (Quark Gluon Plasma)

✓Belle, BaBar, etc.
from e^+e^- (or pp) collisions

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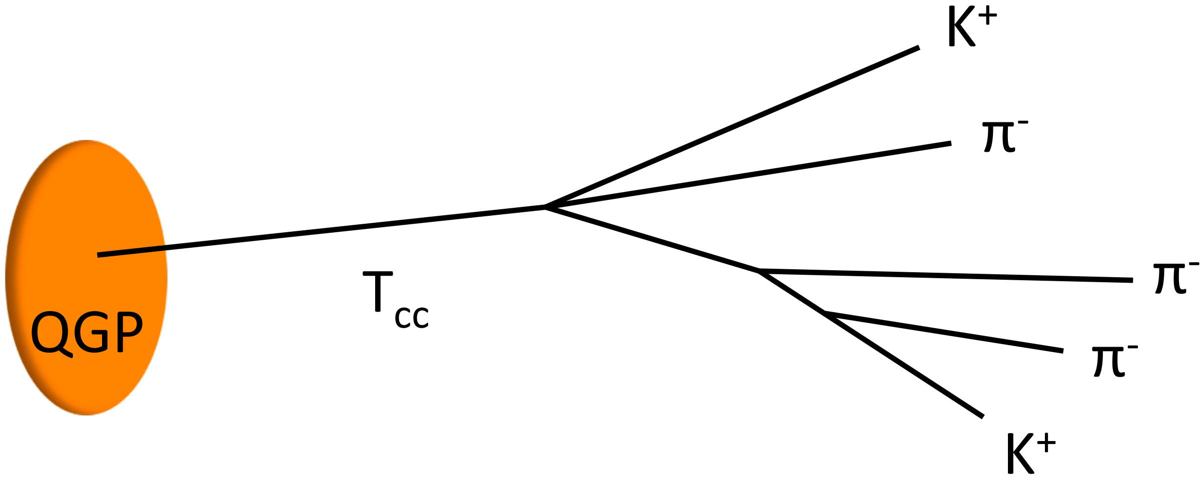


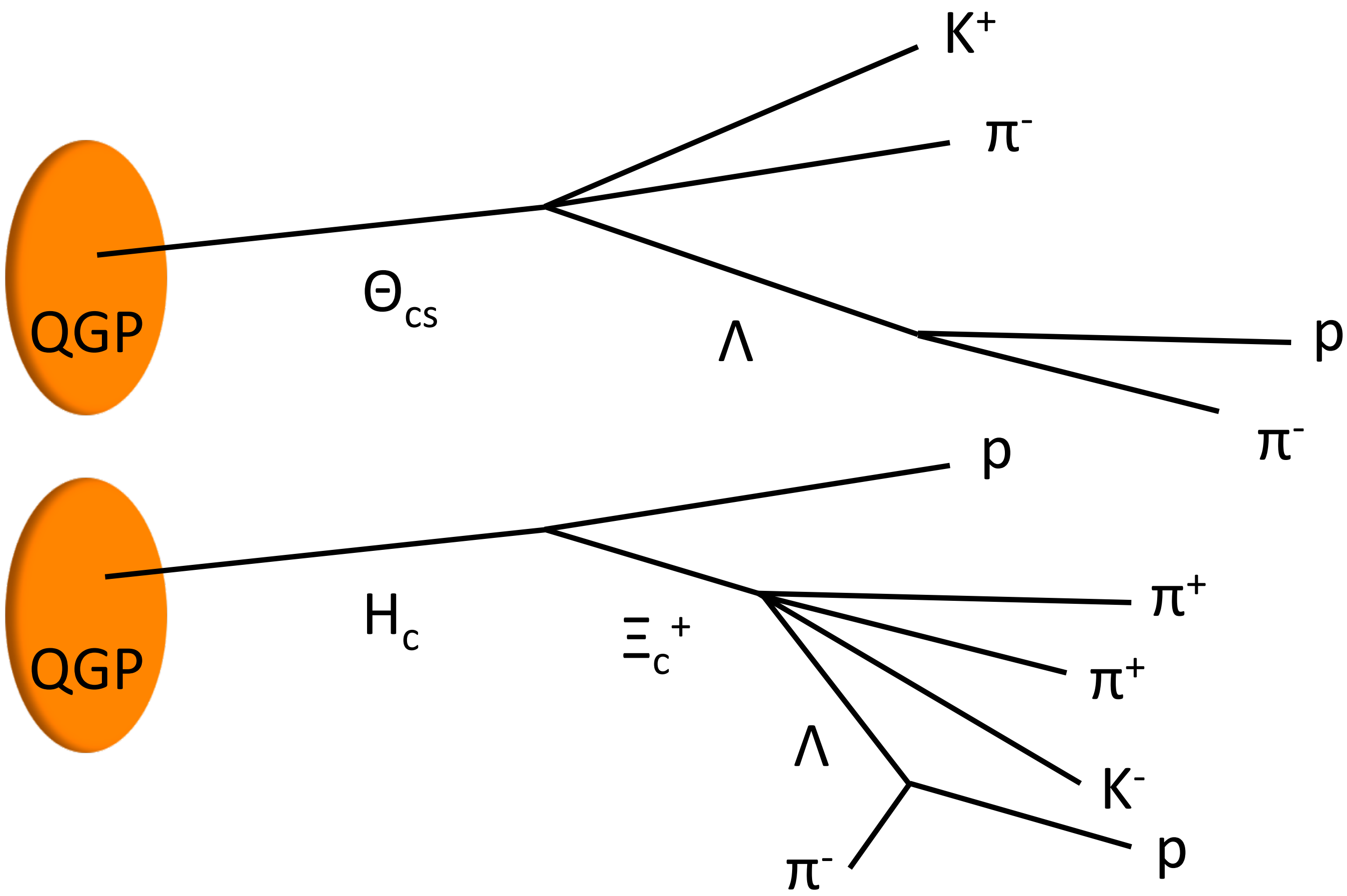
Yield per nucleus (by coalescence model)

	RHIC	LHC
T_{cc}	5.5×10^{-6}	9.0×10^{-5}
Θ_{cs}	1.2×10^{-4}	7.9×10^{-4}

S.H.Lee, S.Y., W.Liu, C.M.Ko (2007)

Observation

✓ LHC (Large Hadron Collider)
QGP (Quark Gluon Plasma)



Observation

✓ Belle, BABAR, etc.

e^+e^- (or pp) collisions

double charm production

Belle

$e^+e^- \to J/\psi\ \eta_c$ PRL89, 142001 (2002)

$J/\psi\ \chi_c$, $J/\psi\ \eta_c(2S)$ PRD70, 071102 (2004)

BABAR

$e^+e^- \to J/\psi\ \eta_c$, $J/\psi\ \chi_{c0}$, $J/\psi\ \eta_c(2S)$ PRD72, 031101 (2005)

→ Possible to search T_{cc}+c+c ?

Conclusion

- Explicityly exotic hadrons with charm and bottom would be stable.
  - Tetraquark T_{cc} ($udc^{bar}c^{bar}$), T_{bb} ($udb^{bar}b^{bar}$)
  - Pentaquark Θ_{bs} ($udusb^{bar}$), Θ_{bss} ($usdsb^{bar}$)
  - H dibaryon H_c (udusuc), H_b (udusub), ...
- Heavy ion collisions and e^+e^- collisions would be available to search exotic mesons.
- More sophisticated calculation (ex. by quark model, QCDSR, HQET, Lattice QCD) is required.

Perspective

What is flavor world in nuclear physics?

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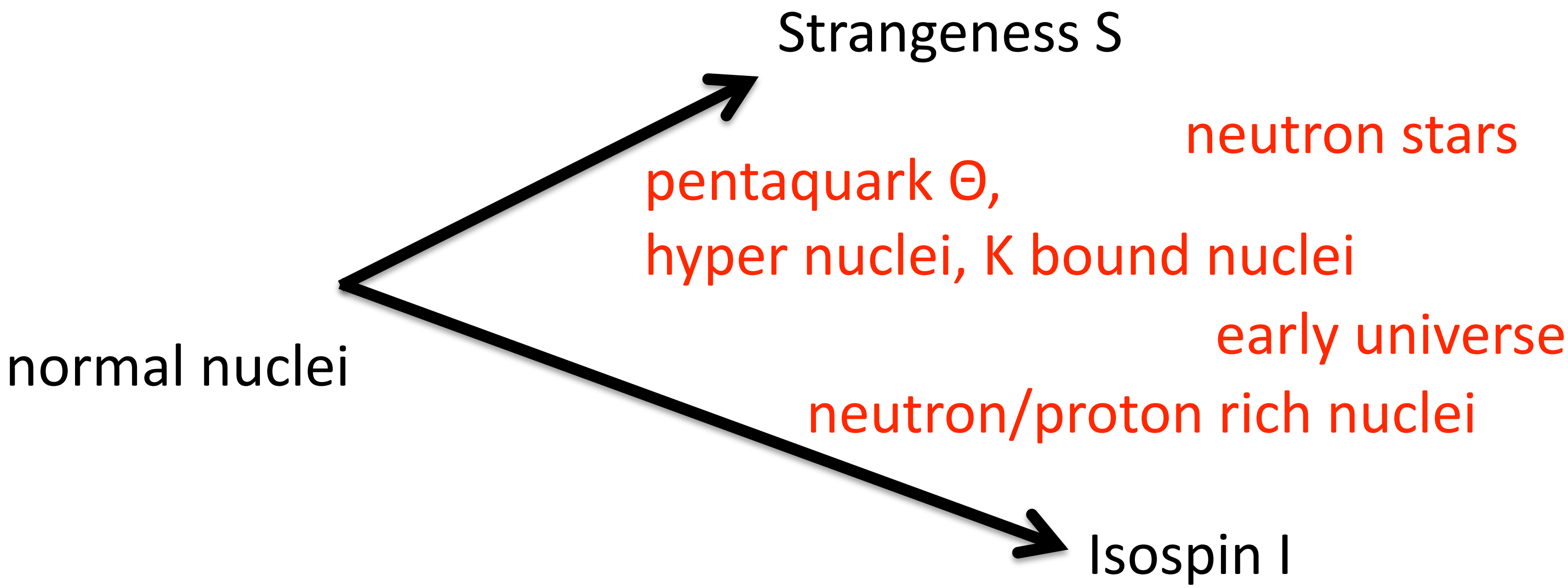
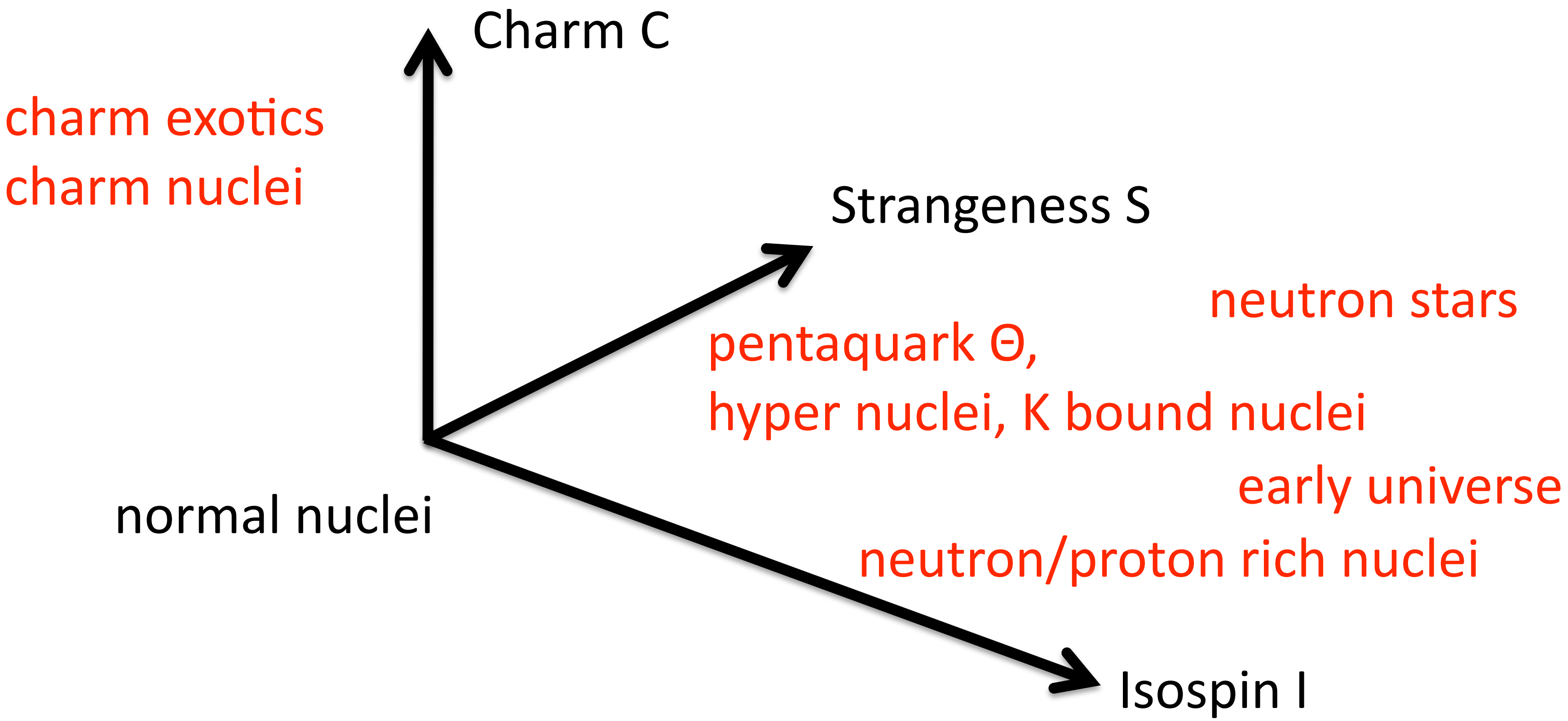


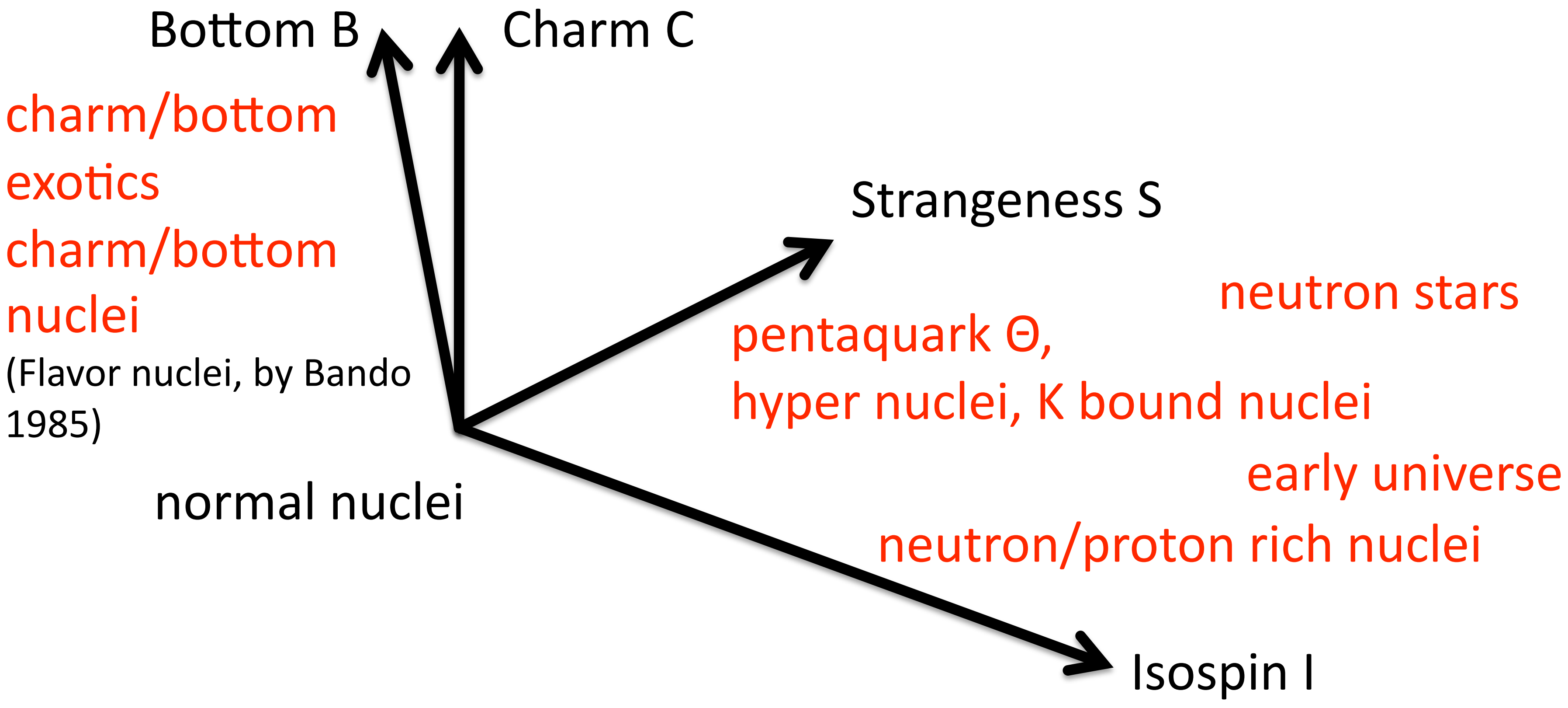
Perspective

What is flavor world in nuclear physics?



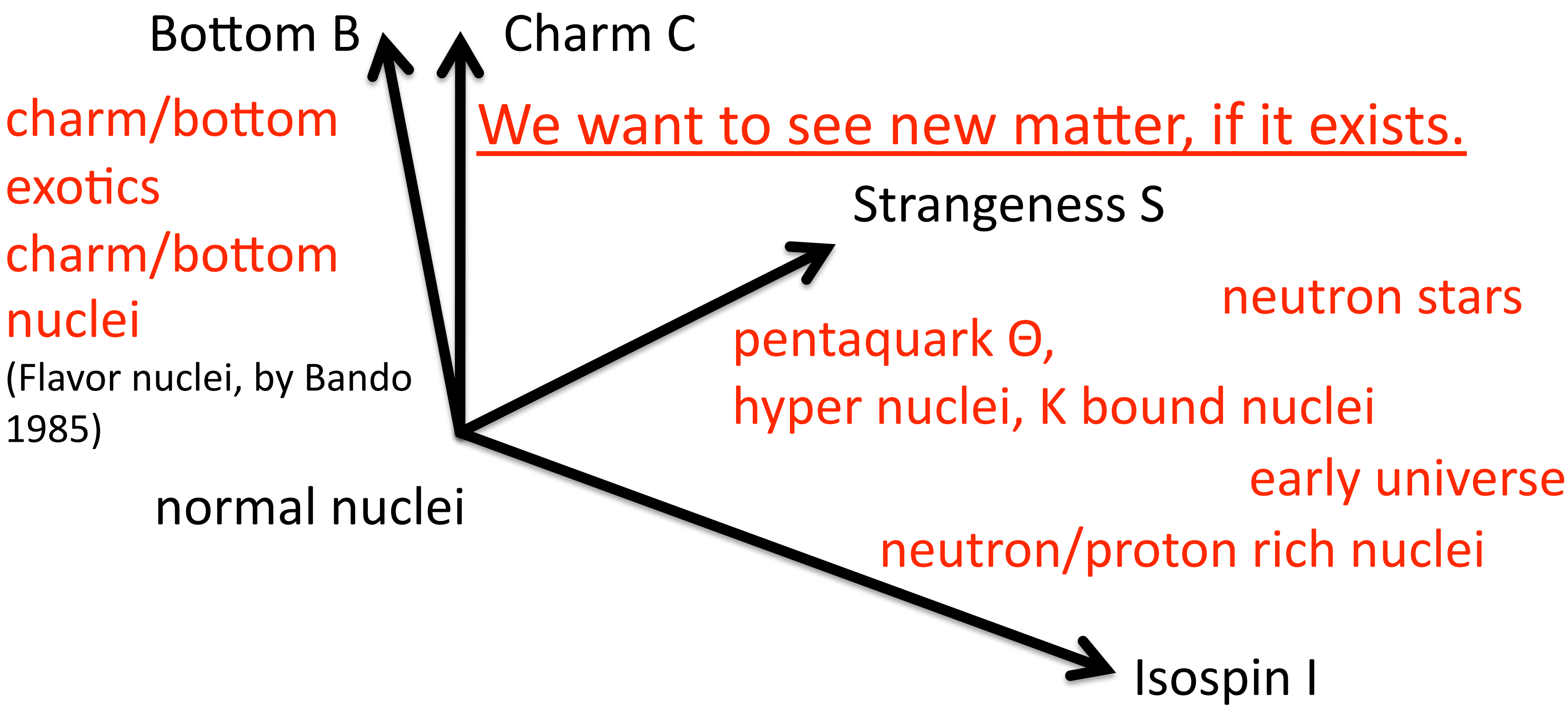
Perspective

What is flavor world in nuclear physics?



Perspective

What is flavor world in nuclear physics?



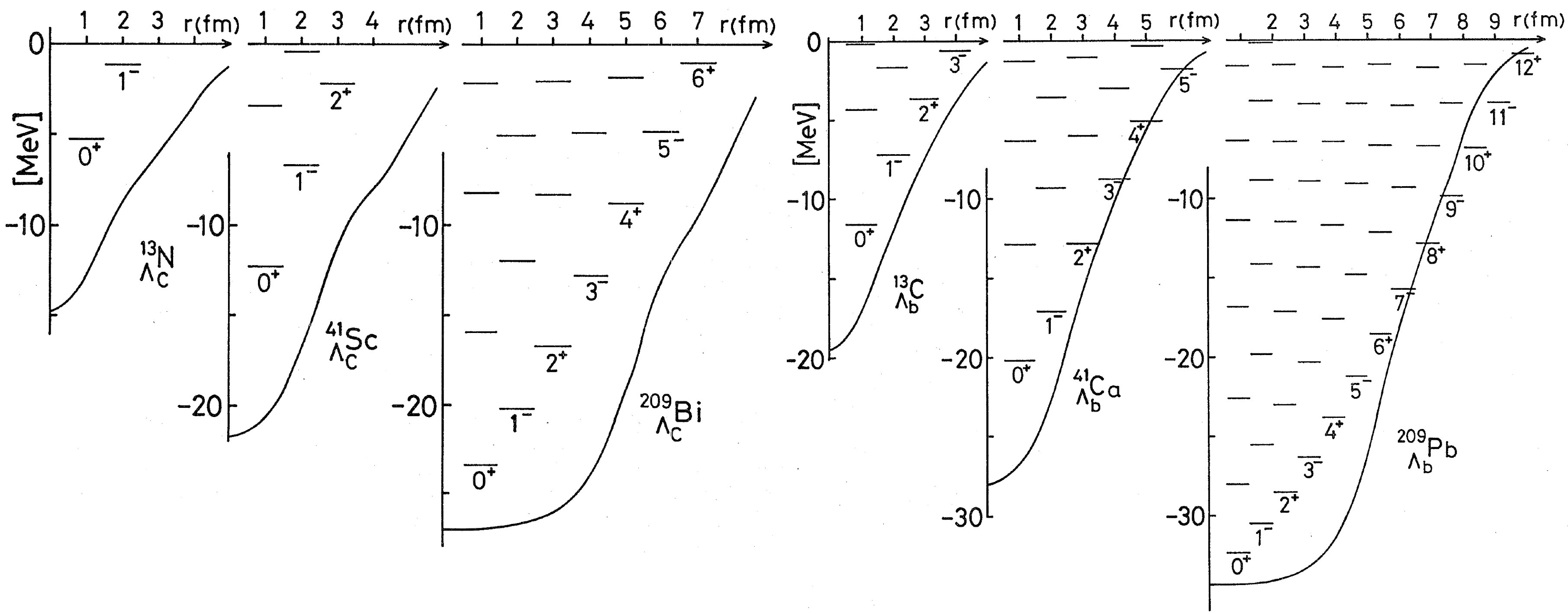
Perspective

Heavy flavor (charm&bottom) nuclei.

Strange nuclei	Charm nuclei	Bottom nuclei
K bound nuclei	D bound nuclei	B bound nuclei
Hyper nuclei	Charm baryon nuclei	Bottom baryon nuclei
	Bando (1985)	Bando (1985)

Perspective

Heavy flavor (charm&bottom) nuclei.



Bando, PTP Suppl. 81, 197 (1985)