FYS3500 - spring 2019

Quark Model and Color*

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***Martin and Shaw, Particle Physics, 4th Ed., Chapter 6**

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- u and d quark masses are similar but not equal, electric charges are not the same and EM interaction is smaller than strong but not zero $\Rightarrow$ Isospin an approximate symmetry

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  - In practice there are small mass differences

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- Same sum-rule for third ("z") component! Constant in isospin-conserving strong interactions:

$$I_3 = \sum_i I_3^i, \text{ where } I_3(u, \bar{d}) = \frac{1}{2},\ I_3(\bar{u}, d) = -\frac{1}{2}$$

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- Can show that (in fact this came before quarks)

$$I_3 = Q - \frac{Y}{2}$$

Y, I Quantum numbers (quarks)

$$Y = B + S + C + \tilde{B} + T$$

Quark	B	Y	Q	I	I_3
u	1/3	1/3	2/3	1/2	1/2
d	1/3	1/3	-1/3	1/2	-1/2
c	1/3	4/3	2/3	0	0
s	1/3	-2/3	-1/3	0	0
t	1/3	4/3	2/3	0	0
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- For antiquarks I is same but the rest change sign

Hadrons with $C = \tilde{B} = T = 0$

Isospin states: $\frac{1}{2} + \frac{1}{2} = (0,1)$ $\quad \frac{1}{2} + \frac{1}{2} + \frac{1}{2} = (0,1) + \frac{1}{2} = \frac{1}{2}, \frac{1}{2}, \frac{3}{2}$

Hadrons	Quarks	S	I
Baryons	qqq	0	3/2, 1/2
	qqs	-1	1, 0
	qss	-2	1/2
	sss	-3	0
Mesons	$q\bar{s}$	1	1/2
	$s\bar{s}$	0	0
	$q\bar{q}$	0	1, 0
	$\bar{q}s$	-1	1/2

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  - Must be a strange baryon with zero hypercharge:

$$B = 1, S = -1 \ \Rightarrow Y = B + S = 0$$

$$I_3 = Q - Y/2 = 1 - 0 = 1$$

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$$B = 1, S = -1 \Rightarrow Y = B + S = 0$$

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  - Should belong to I=1 multiplet with 3 particles

$$I_3 = 1, 0, -1 = Q \Rightarrow \Sigma^+, \Sigma^0, \Sigma^-$$

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- No doubly charged states observed, as expected in the quark model

$$\Sigma^{++}, \Sigma^{--}$$ ❌

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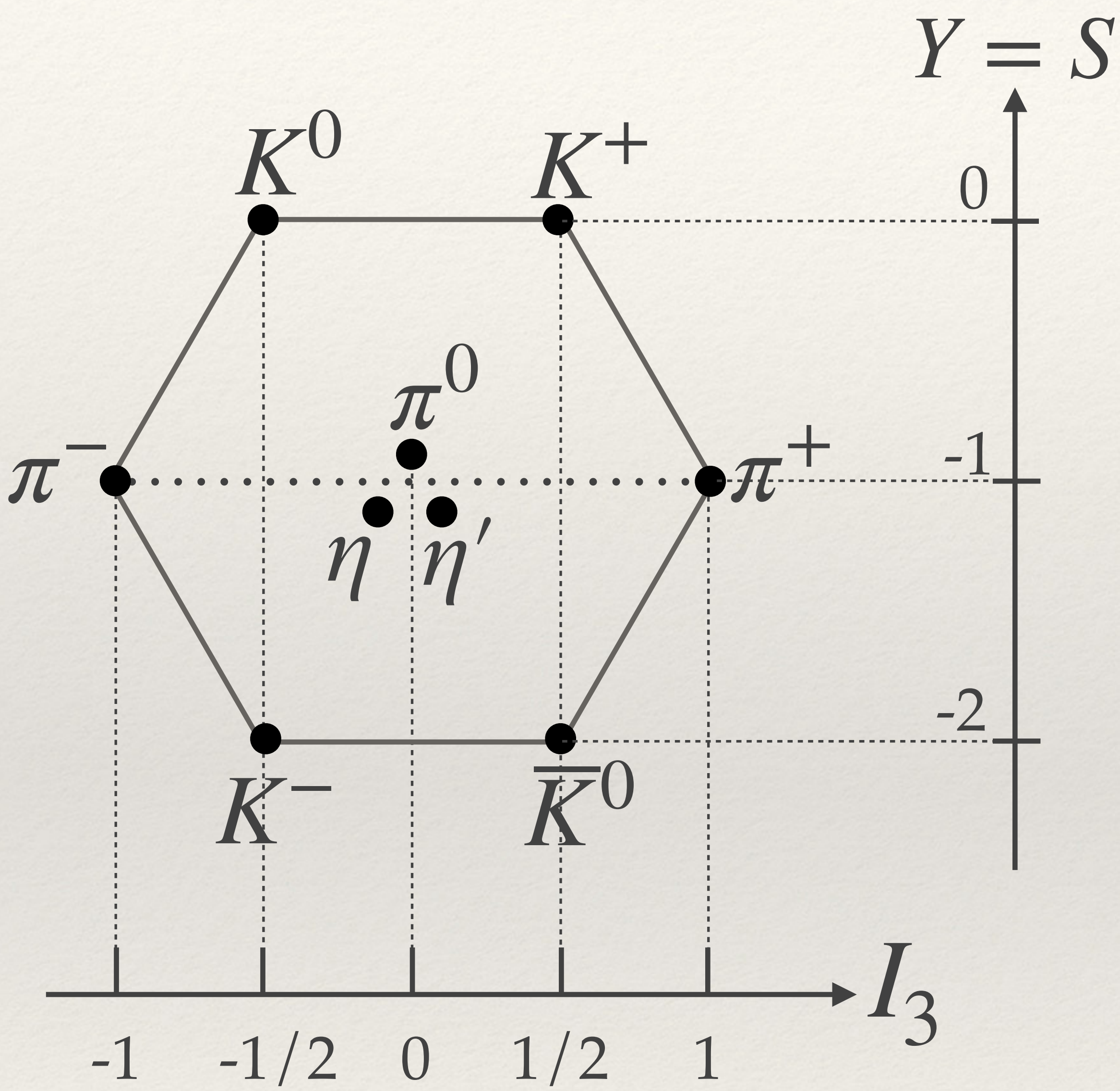

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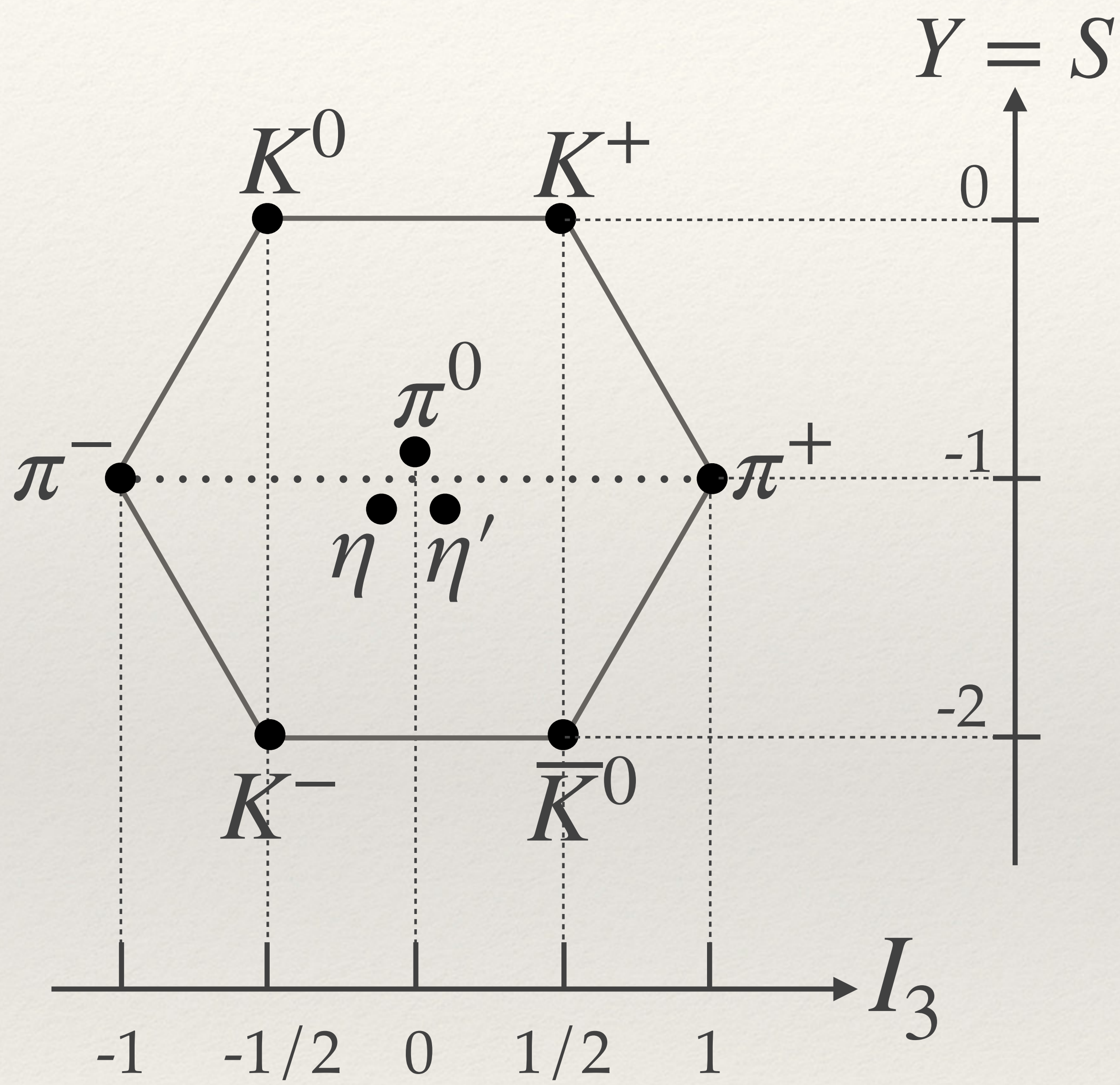

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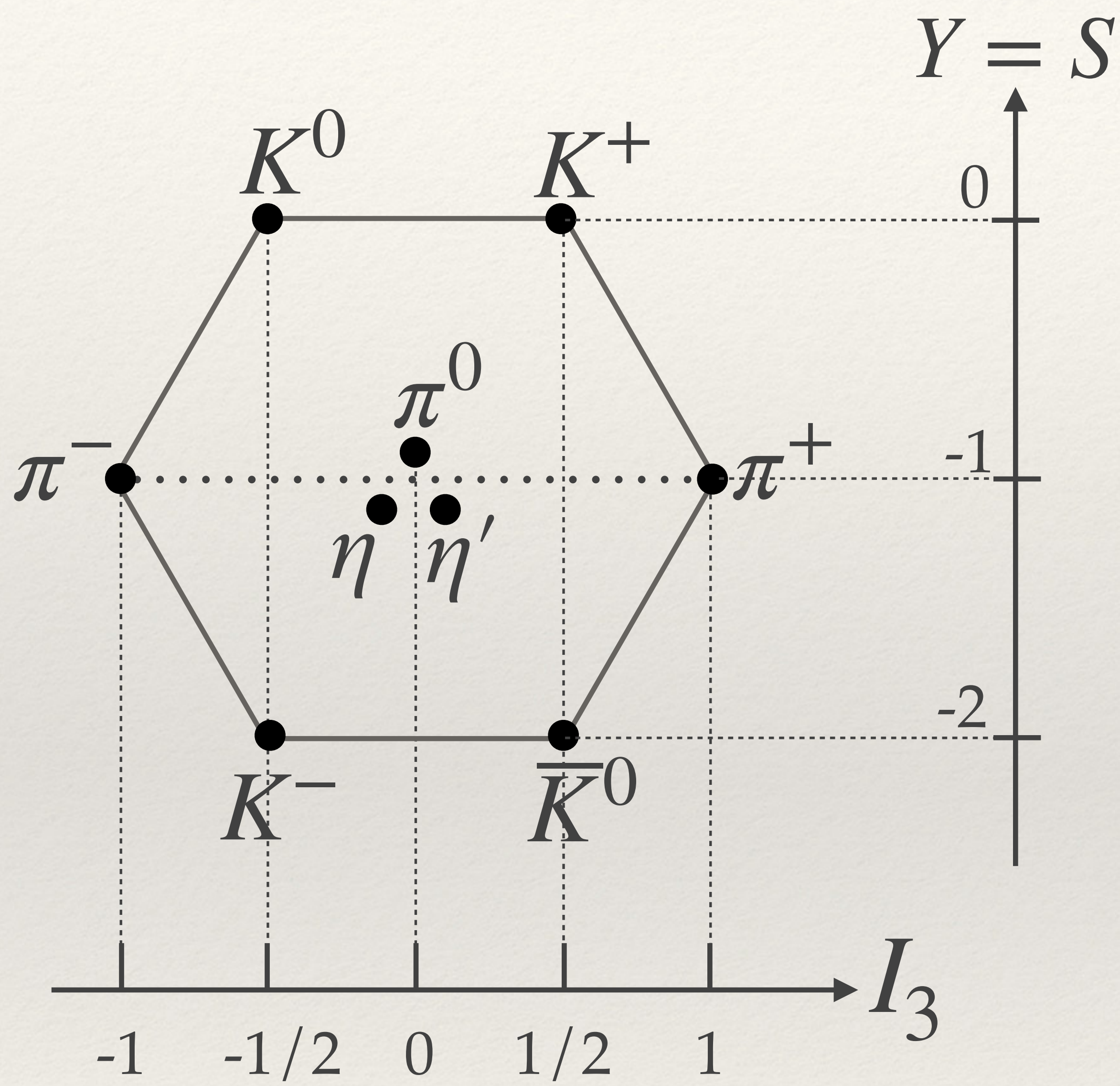

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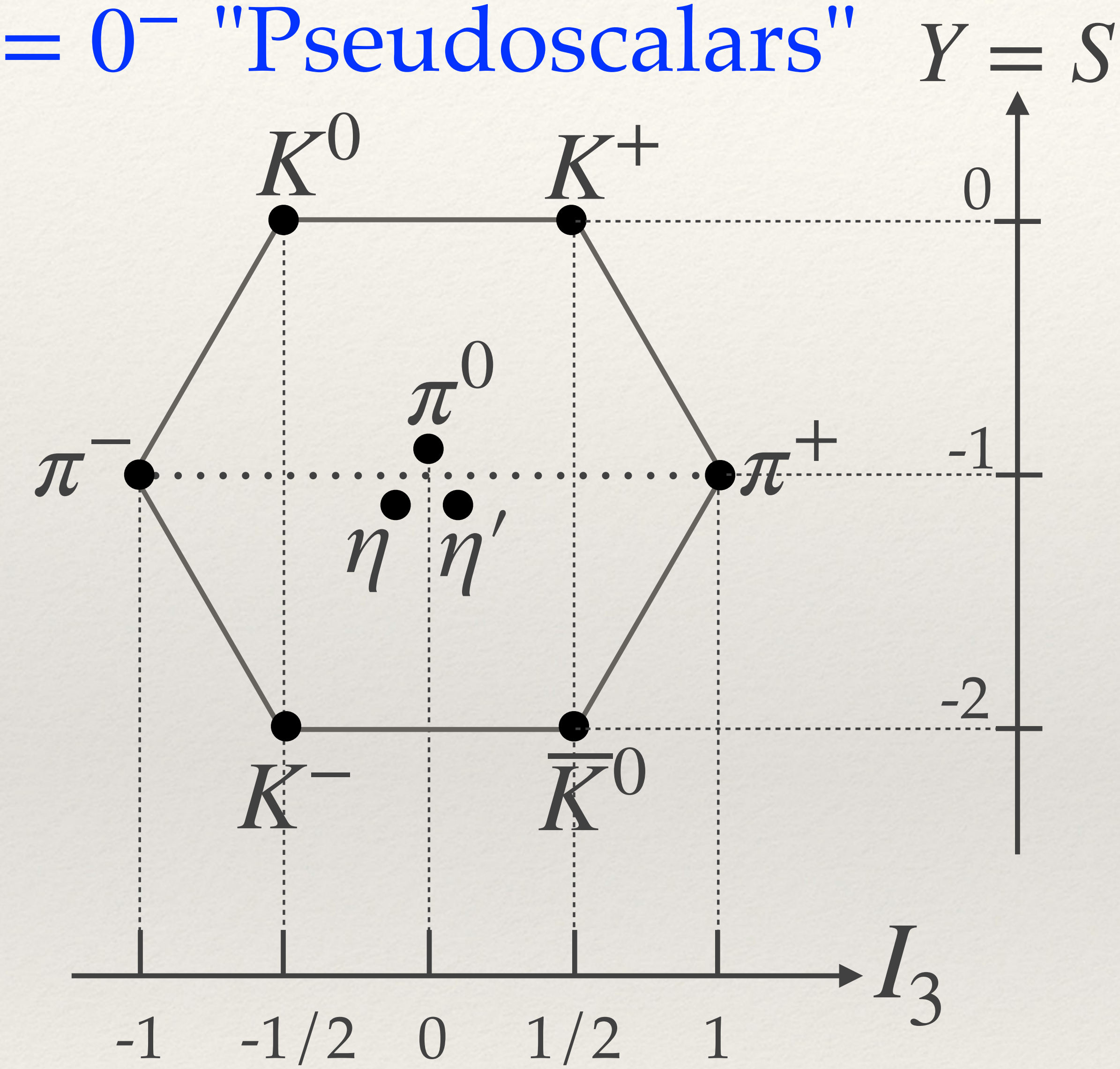
$J^P = 0^-$ "Pseudoscalars"



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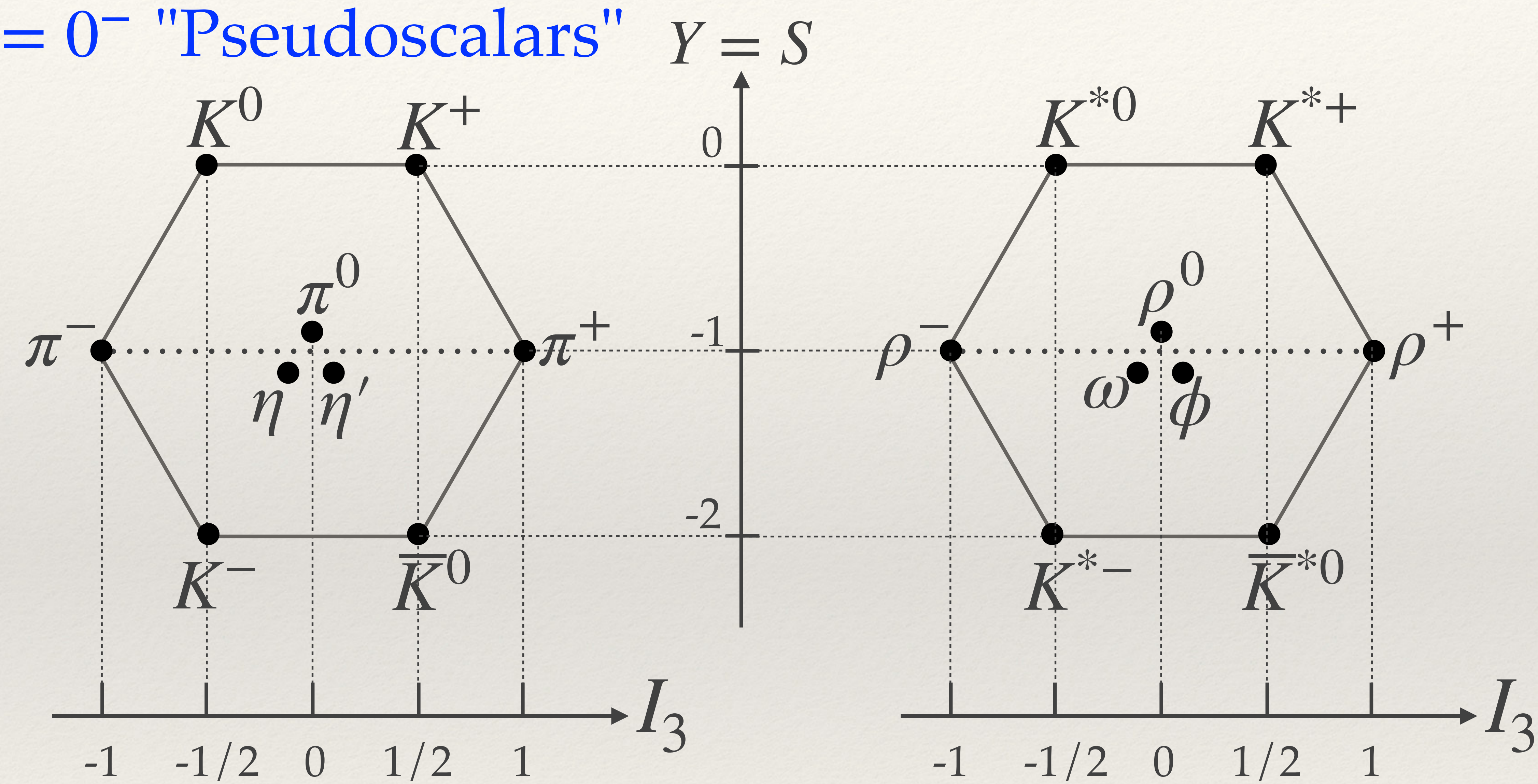

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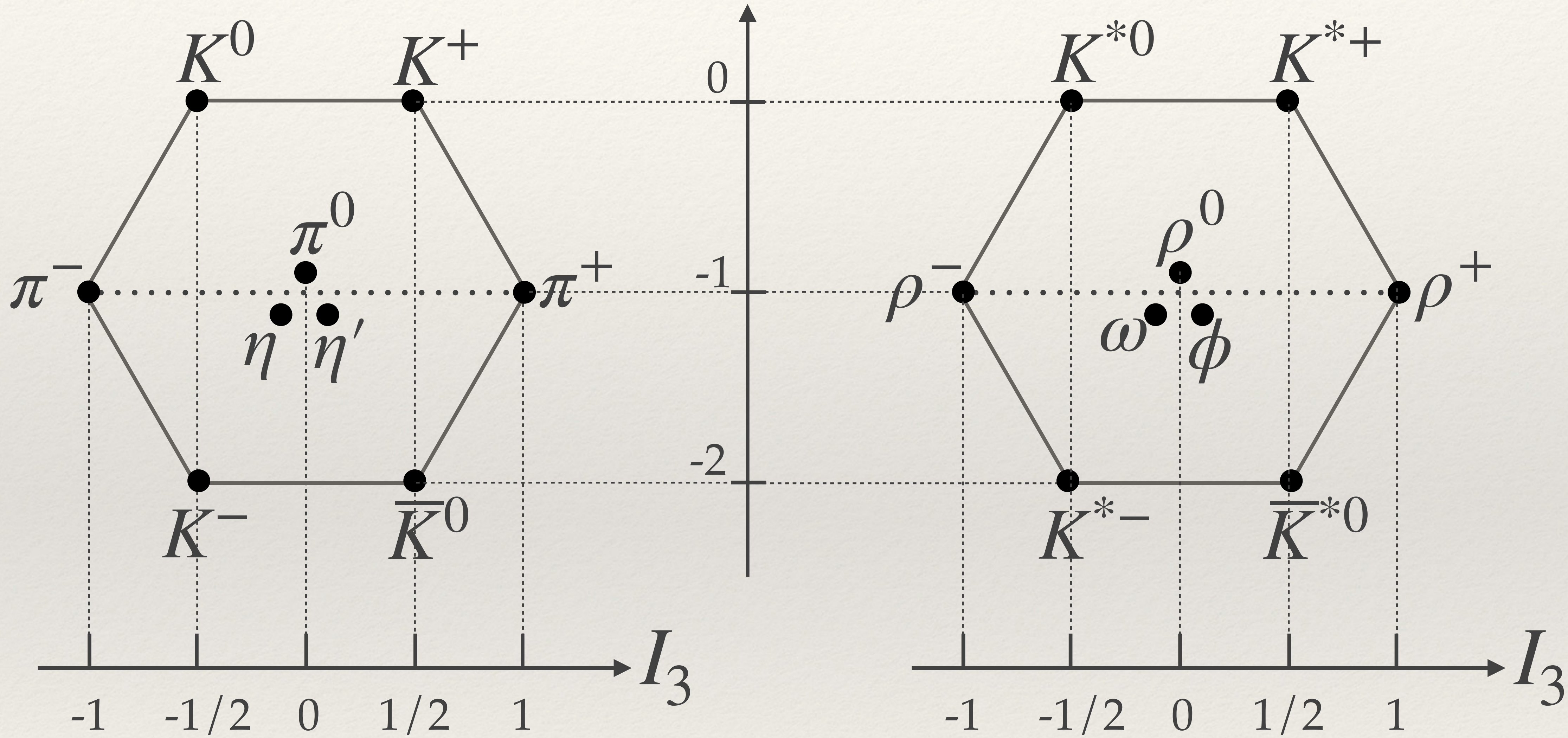
$J^P = 0^-$ "Pseudoscalars" $Y = S$ $J^P = 1^-$ "Vectors"



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Quark content	J^P=0$^-$	Mass	J^P=1$^-$	Mass
$u\bar{d}$	π^+	140	ρ^+	768
$(u\bar{u} - d\bar{d})/\sqrt{2}$	π^0	135	ρ^0	768
$d\bar{u}$	π^-	140	ρ^-	768
$u\bar{s}$	K^+	494	K^{*+}	892
$d\bar{s}$	K^0	498	K^{*0}	896
$s\bar{d}$	$\overline{K}^0$	498	$\overline{K}^{*0}$	896
$s\bar{u}$	K^-	494	K^{*-}	892

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- The quark contents of the K's, π's and ρ's are unambiguous

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$s\bar{u}$	K^-	494	K^{*-}	892

- The quark contents of the K's, π's and ρ's are unambiguous
- $\phi(1020) = s\bar{s}$, $\omega(782) = (u\bar{u} + d\bar{d})/\sqrt{2}$

Light meson nonets (9)

Quark content	$J^P=0^-$	Mass	$J^P=1^-$	Mass
$u\bar{d}$	π^+	140	ρ^+	768
$(u\bar{u}-d\bar{d})/\sqrt{2}$	π^0	135	ρ^0	768
$d\bar{u}$	π^-	140	ρ^-	768
$u\bar{s}$	K^+	494	K^{*+}	892
$d\bar{s}$	K^0	498	K^{*0}	896
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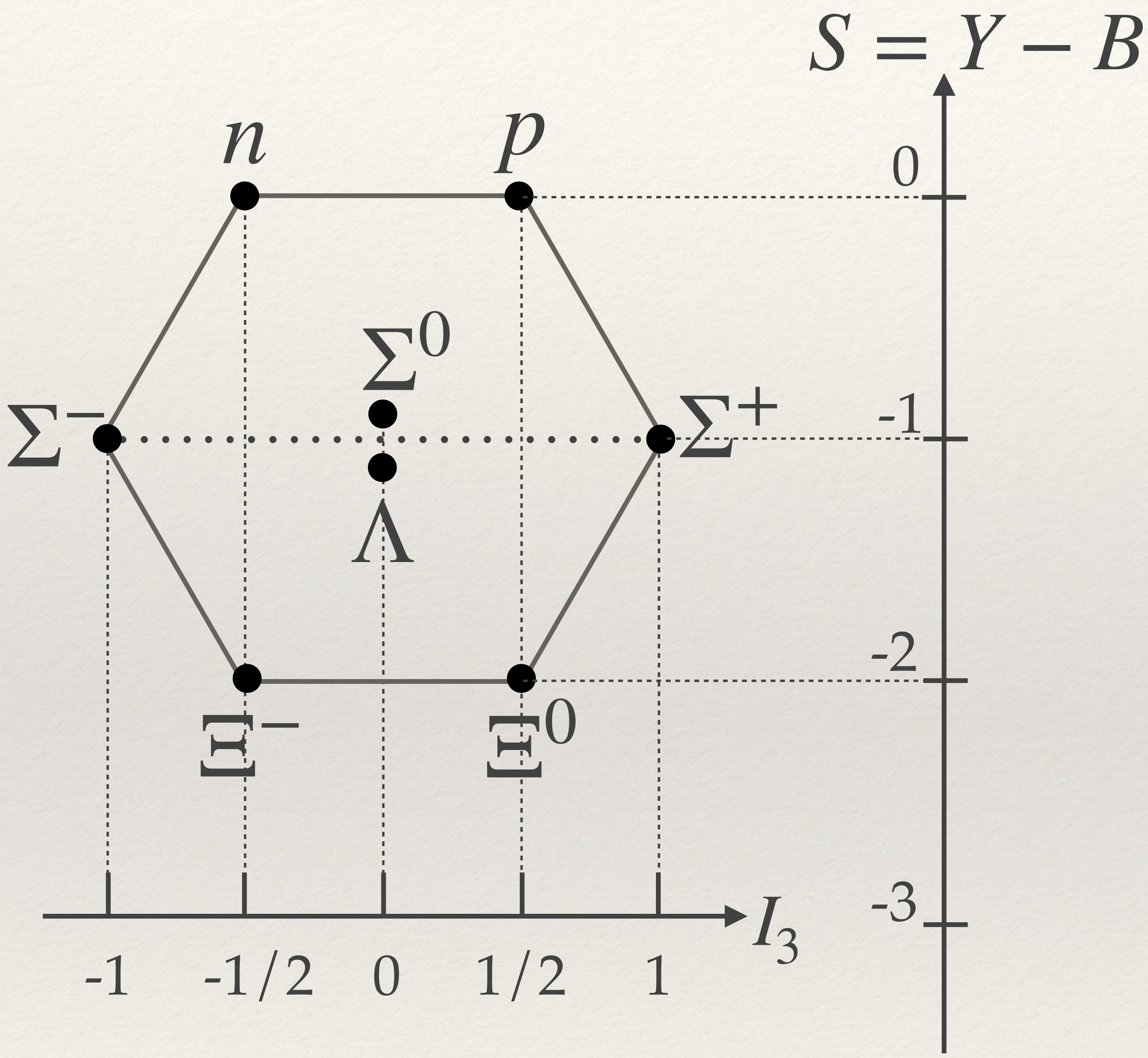
- The quark contents of the K's, π's and ρ's are unambiguous
- $\phi(1020) = s\bar{s}$, $\omega(782) = (u\bar{u} + d\bar{d})/\sqrt{2}$ but η, η' linear combinations

Light baryon multiplets (L_{12}=L_3=0)

|

Light baryon multiplets ($L_{12}=L_3=0$)



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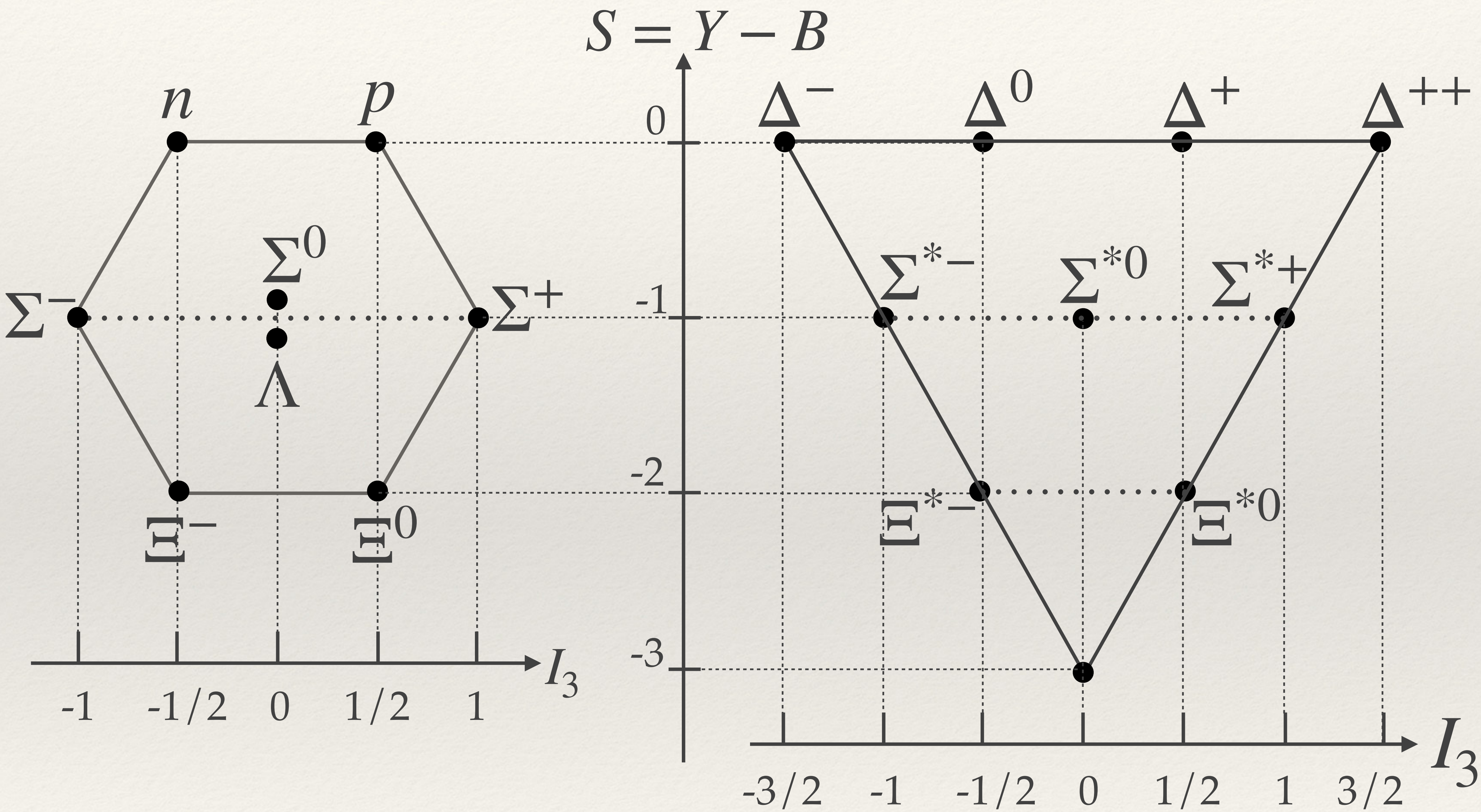

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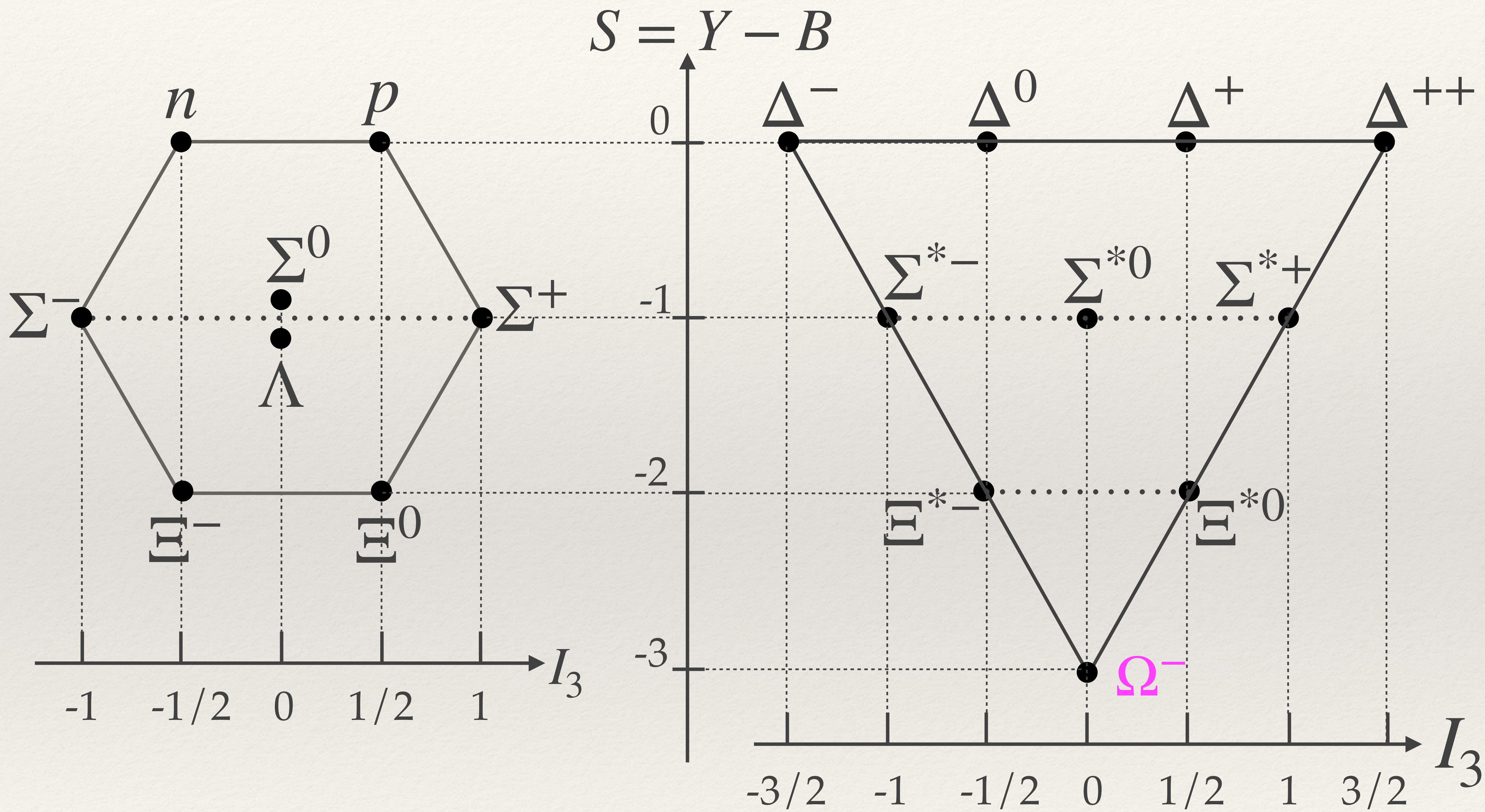

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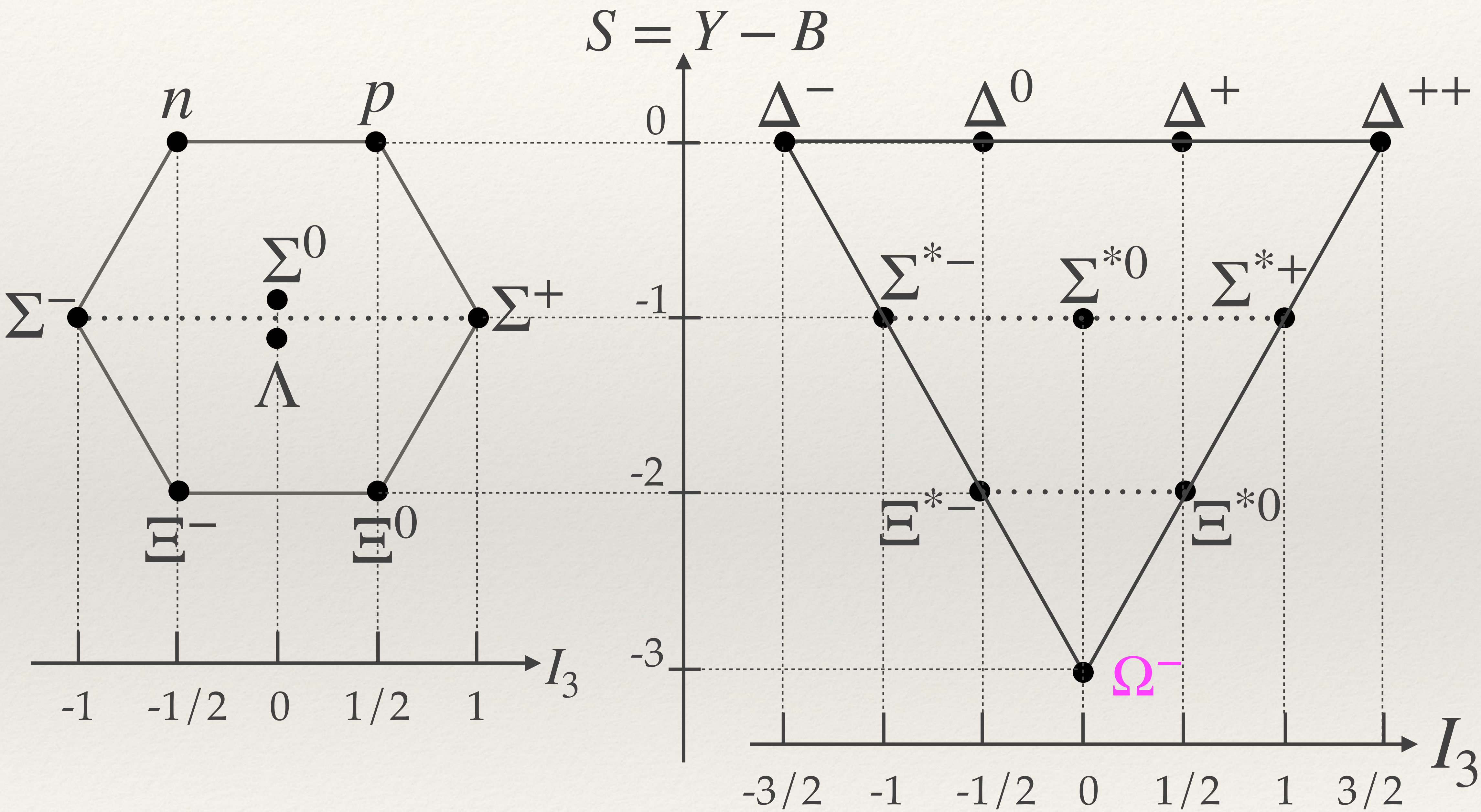

$$J = L + S = 0 + S = \frac{1}{2} + \frac{1}{2} + \frac{1}{2} = \frac{1}{2}, \frac{1}{2}, \frac{3}{2}$$

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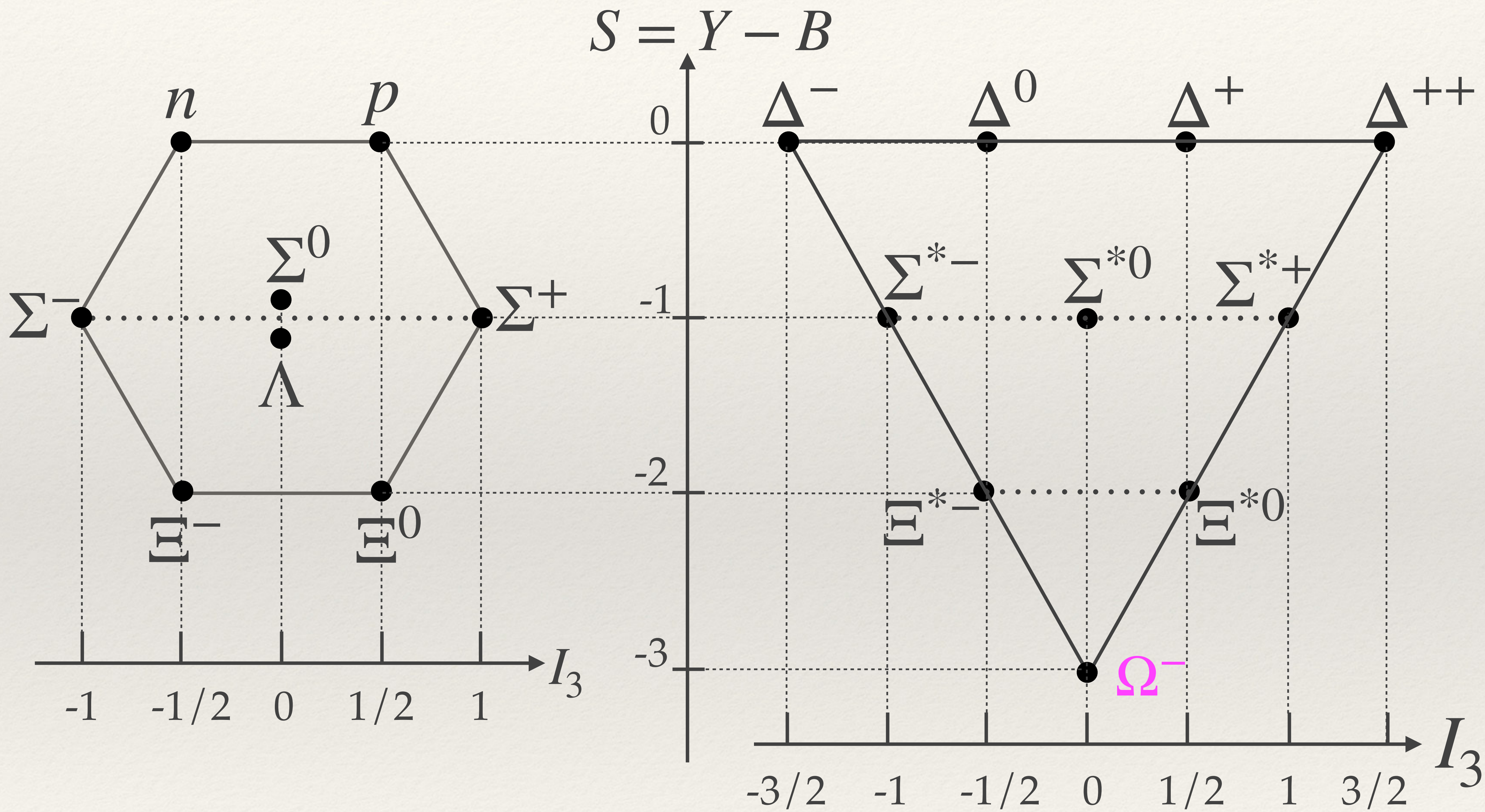

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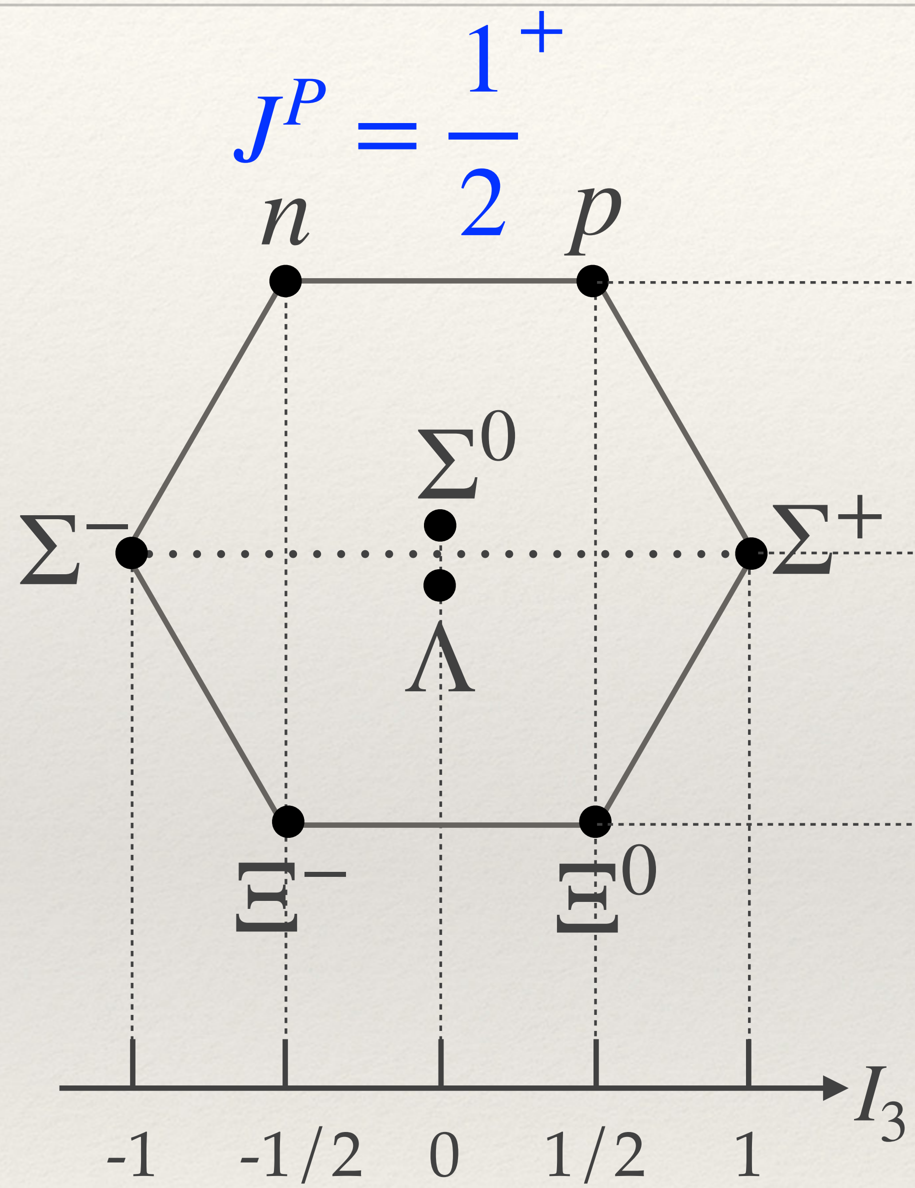

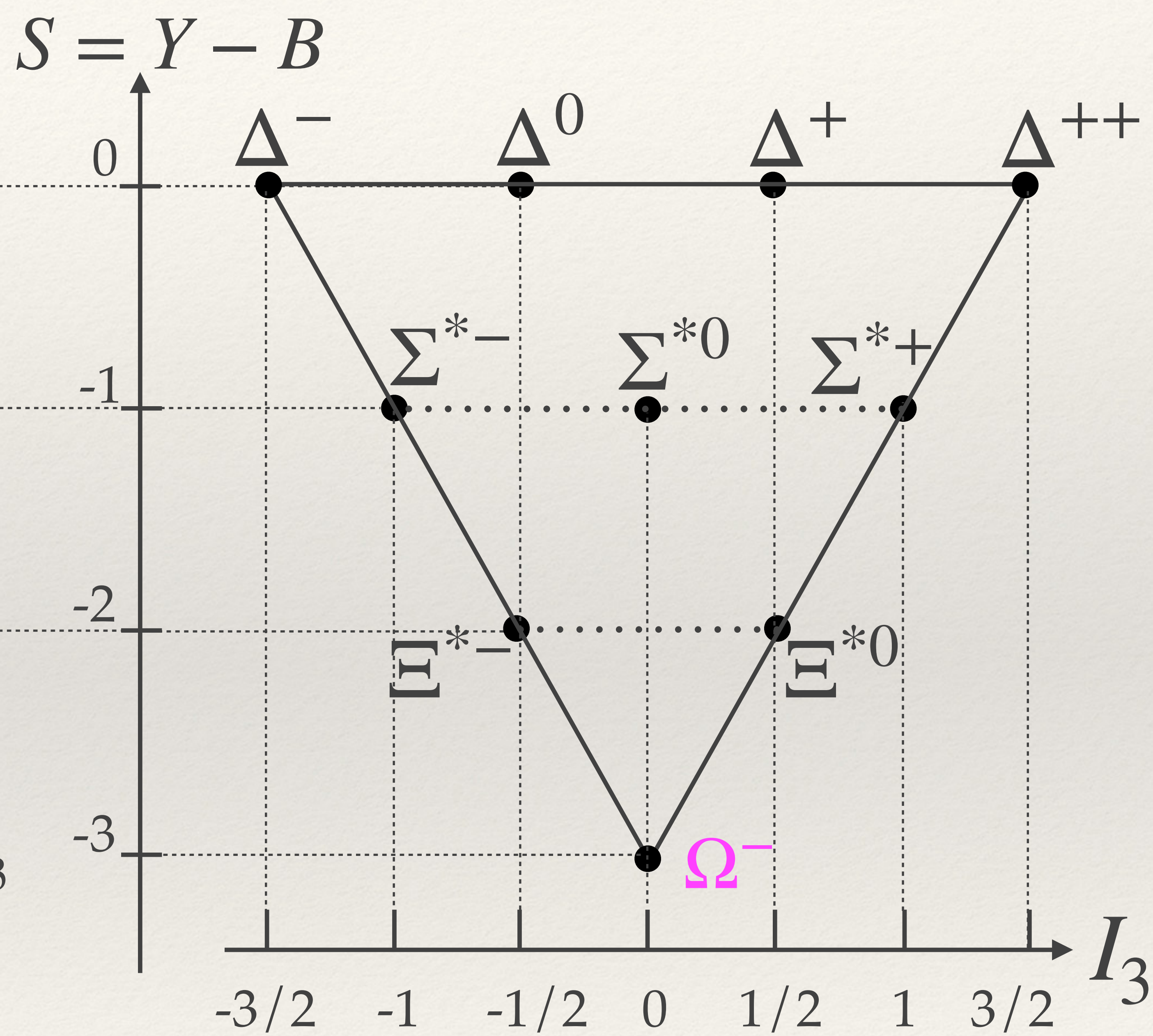

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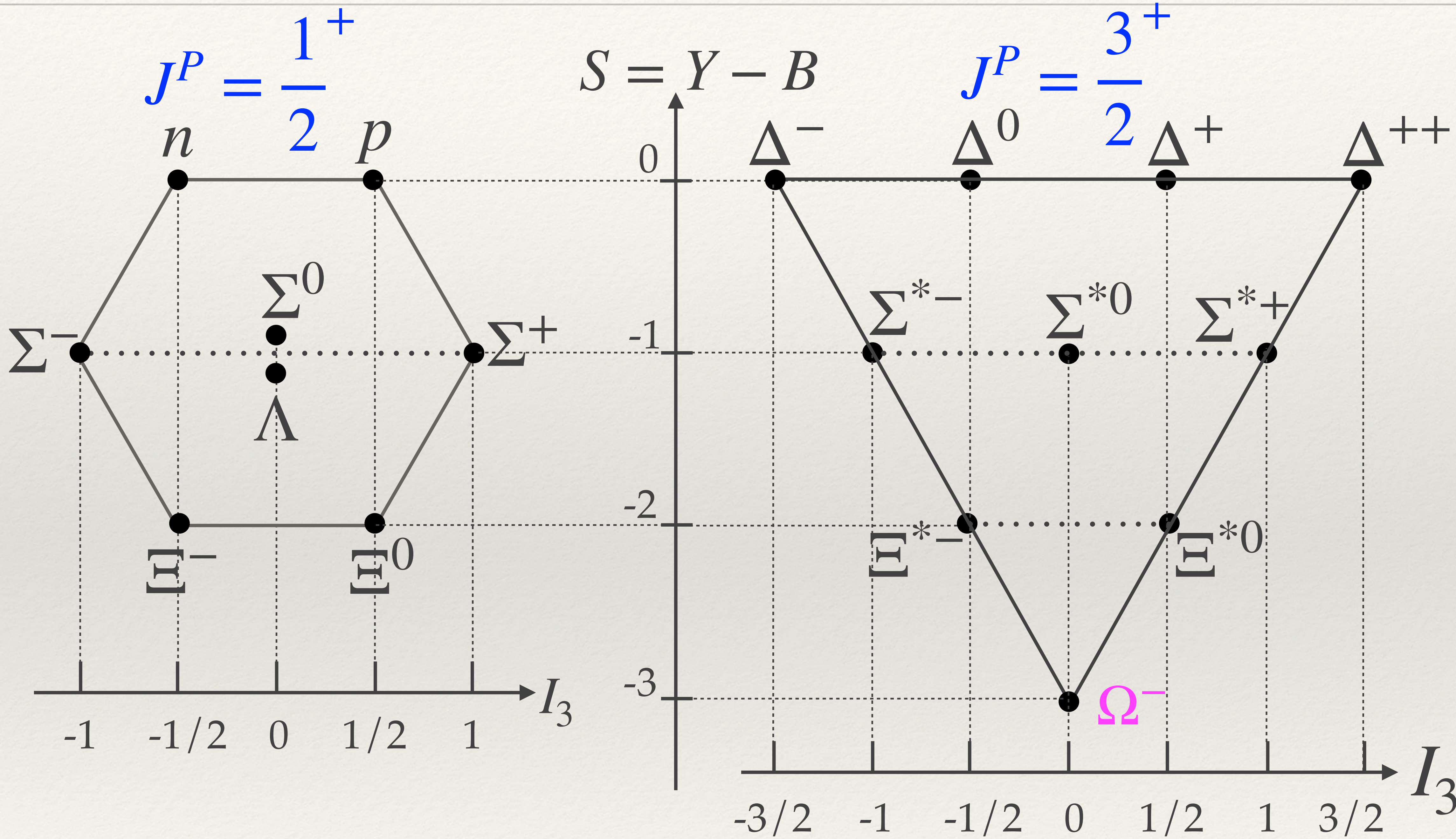

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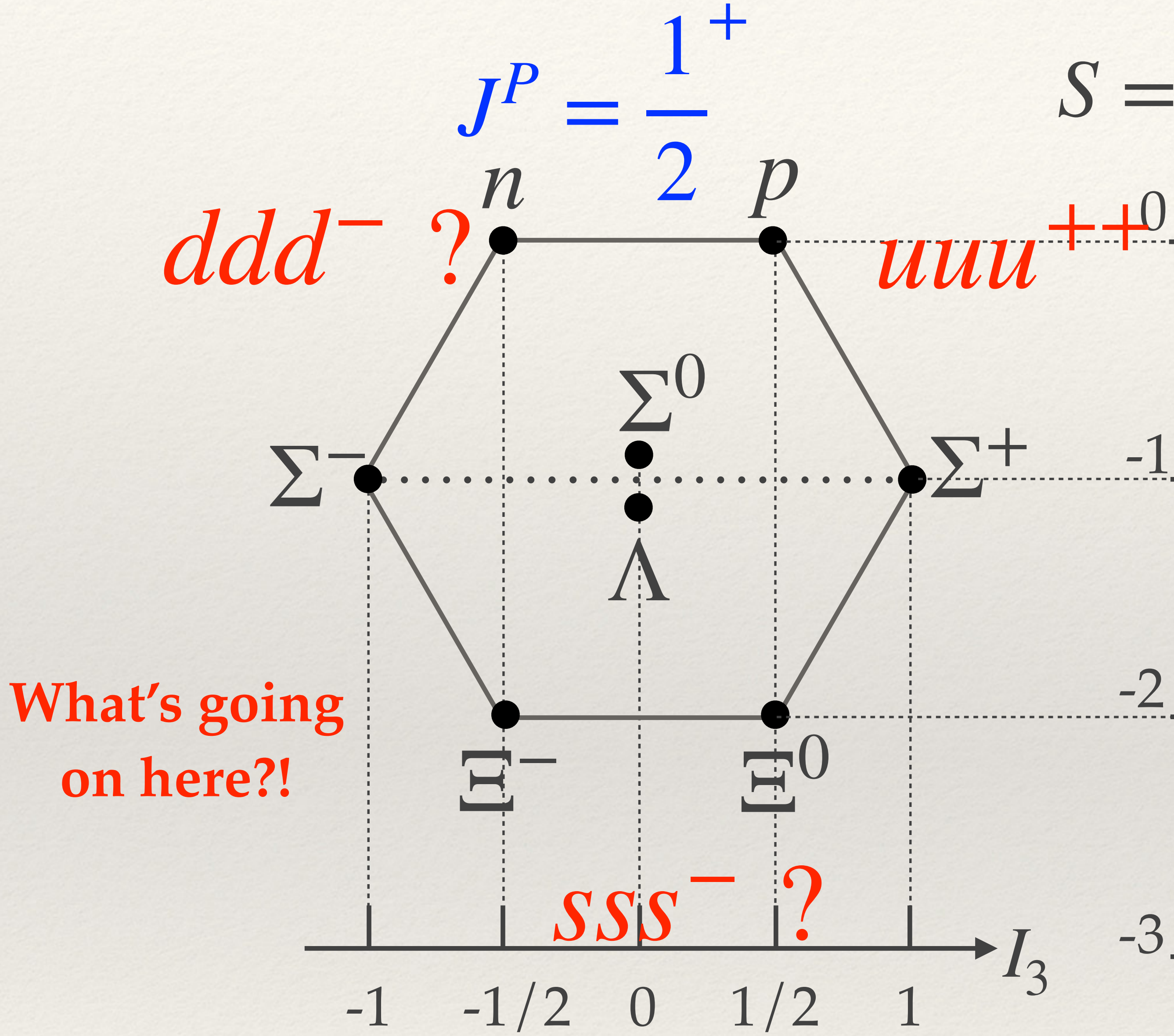

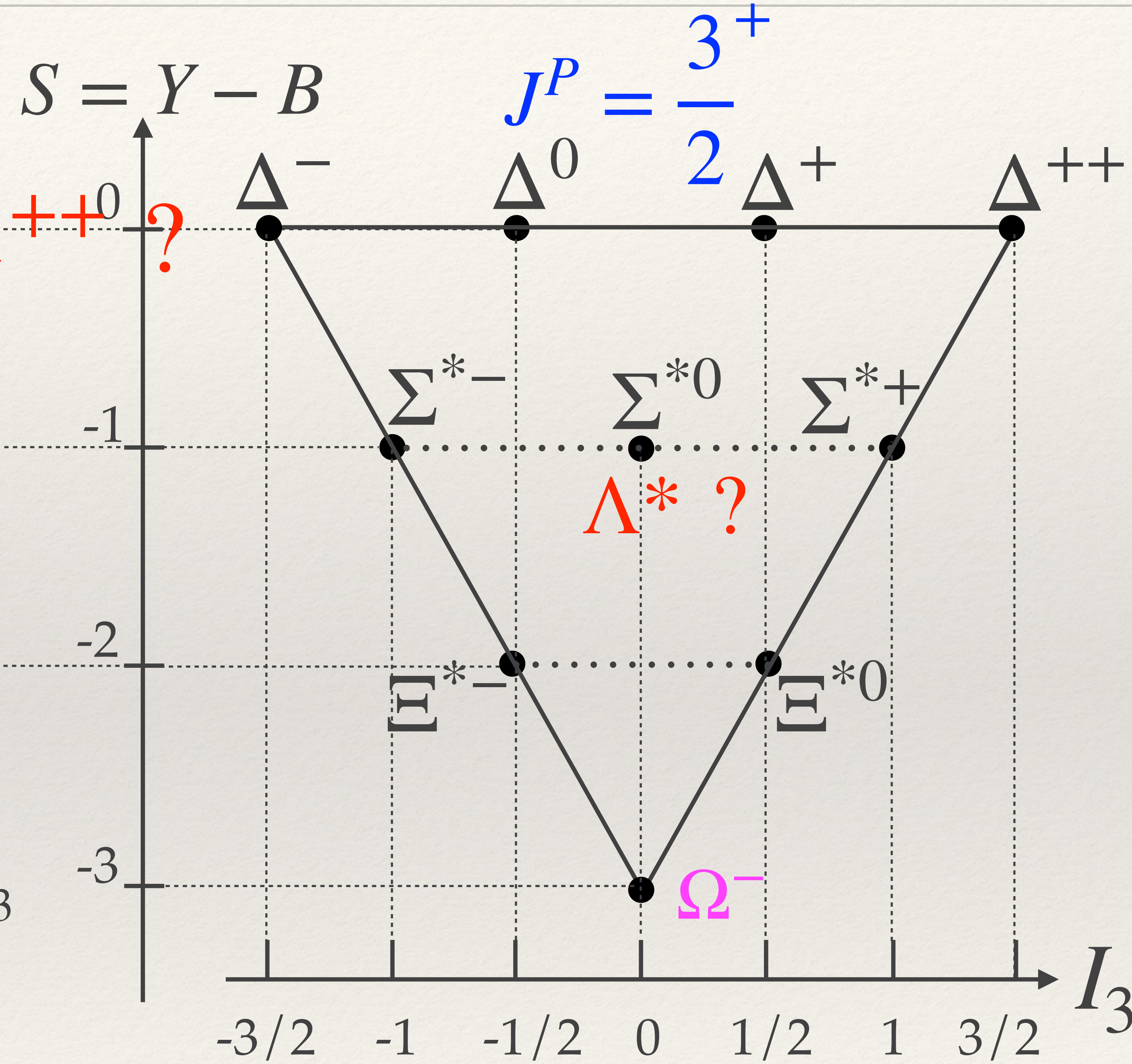

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Baryon quark-spin wave functions

- One elegant way to explain this pattern is to assume that the wavefunction for identical quarks (fermions) is symmetric - exactly the opposite of what we expect for identical fermions (The Pauli Principle)!
- Since $L_{12}=L_3=0$ makes the space part of the wavefunction symmetric, the spin part must also be symmetric (under this curious assumption).

$$\Psi = \psi_{space}(\vec{r})\chi_{spin}$$

Spin 1/2+1/2 wavefunctions

$$S_{total} = \frac{1}{2} + \frac{1}{2} = 0,1$$

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S=0 anti-symmetric under 1⟷2

S=1 symmetric under 1⟷2

All pairs of identical quarks in the baryon must be in S=1!

Baryon quark-spin wavefunctions

- For $\Delta^{++}(uuu), \Delta^{-}(ddd), \Omega^{-}(sss)$ the only way to make all pairs spin-symmetric is with all 3 spins parallel, i.e. J=3/2, i.e. no J=1/2 states.

$$\Uparrow_a \Uparrow_a \Uparrow_a$$

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- For *udd, uud* the two like quarks must be in *S=1*. Adding the third quark:

$$S = 1 + \frac{1}{2} = \frac{1}{2}, \frac{3}{2}$$

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- which gives us: $n, p \ (J = \frac{1}{2})$ and $\Delta^0, \Delta^+ \ (J = \frac{3}{2})$

Baryon quark-spin wavefunctions

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- For *uss, dss,* the *ss* must be in $S=1$. Adding the third quark:

Baryon quark-spin wavefunctions

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Baryon quark-spin wavefunctions

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$$\Xi^-, \Xi^0 \; (J = \frac{1}{2}) \text{ and } \Xi^{*-}, \Xi^{*0} \; (J = \frac{3}{2})$$

Baryon quark-spin wavefunctions

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Baryon quark-spin wavefunctions

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- which gives us:

$$\Sigma^-, \Sigma^+ \ (J = \frac{1}{2}) \text{ and } \Sigma^{*-}, \Sigma^{*+} \ (J = \frac{3}{2})$$

- The *uds* state has the *ud* in *S=1* by isospin symmetry. Adding the s quark gives us

$$\Sigma^0 \ (J = \frac{1}{2}) \text{ and } \Sigma^{*0} \ (J = \frac{3}{2})$$

Baryon quark-spin wavefunctions

- An orthognal *uds* state has the *ud* in S=0. Adding the *s* quark:

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Baryon quark-spin wavefunctions

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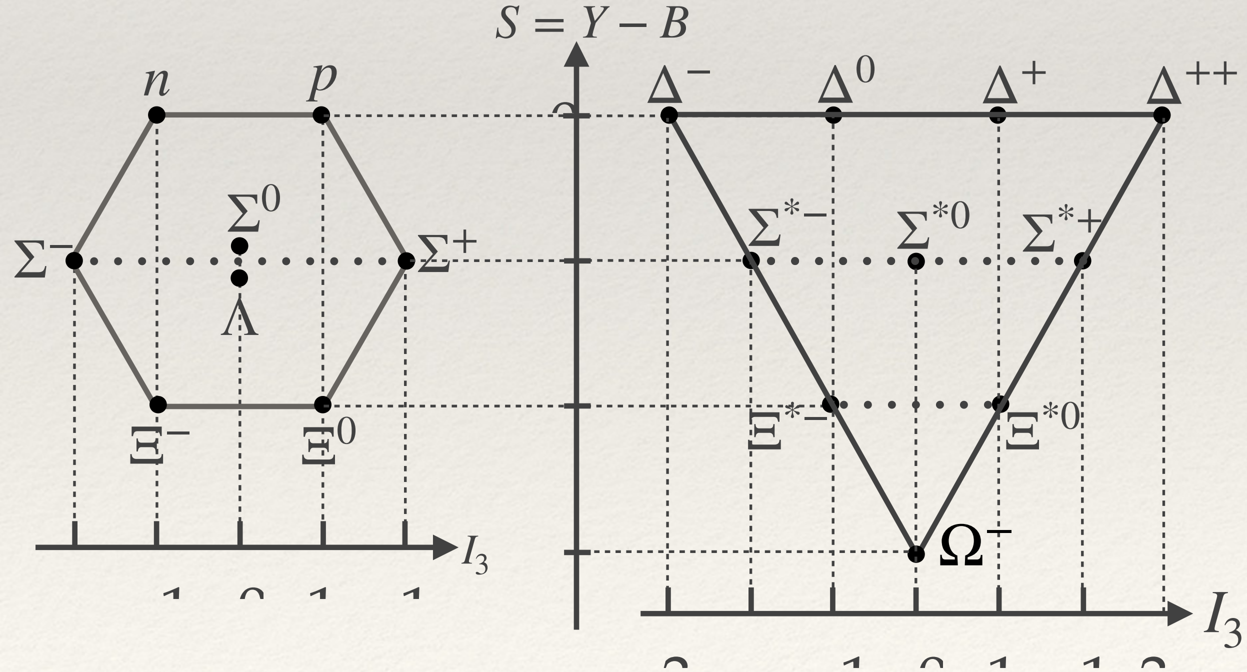
$$S = 0 + \frac{1}{2} = \frac{1}{2}$$

- which gives us only:

$$\Lambda(J = \frac{1}{2})$$

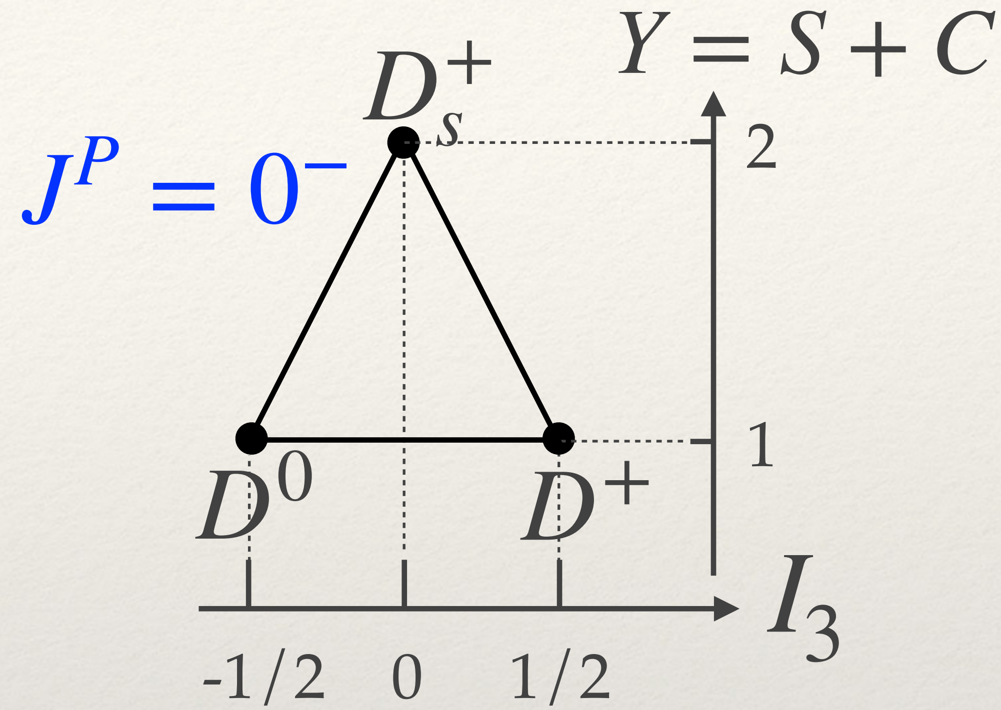
- We have now explained the pattern

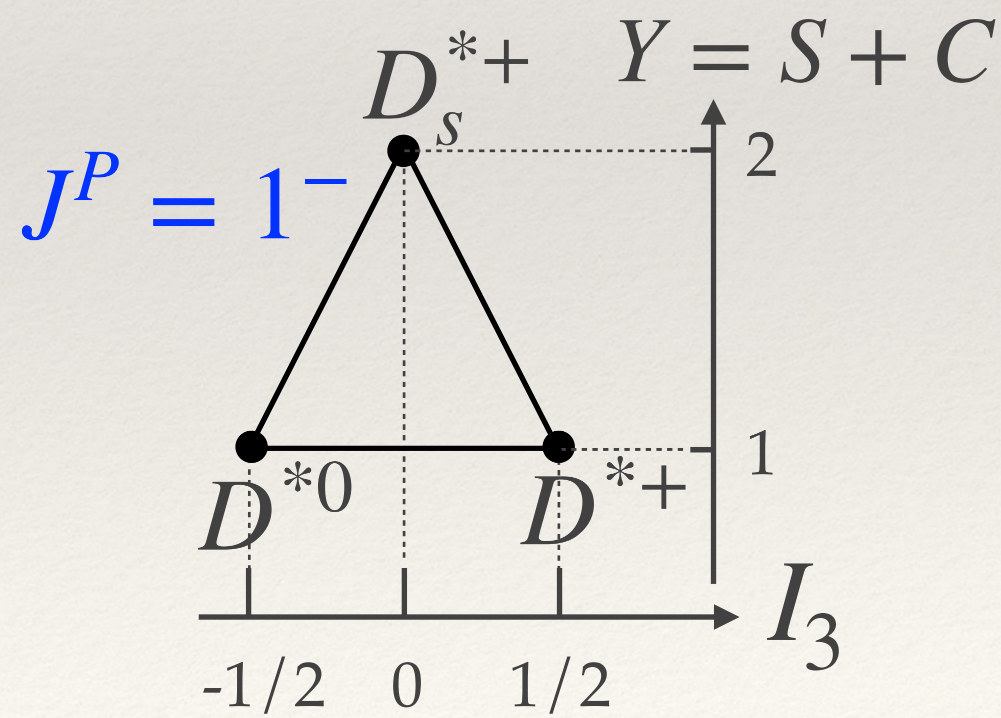


Heavy quark states (b,c)

- Similar patterns of allowed states for *J=0,1* mesons, *J=1/2, 3/2* baryons with 1,2,3 heavy quarks. Not yet all are seen but LHCb and other experiments are slowly but steadily finding them.

- Work out the quark content of the mesons to the right.





Color wavefunction

- Greenberg (1964) proposed to extend the wavefunction with a color wavefunction

$$\Psi = \psi_{space}(\vec{r})\chi_{spin}\chi_{color}$$

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P.S. Typo in M&S Table 6.13

Color confinement 18.03.2019

- Hypothesis that hadrons have no net color charge

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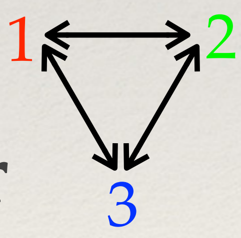

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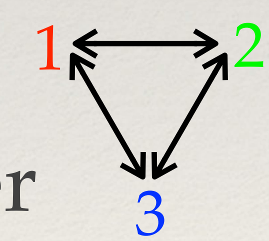

$$\chi_B^C = \frac{1}{\sqrt{6}}(r_1 g_2 b_3 - g_1 r_2 b_3 + b_1 r_2 g_3 - b_1 g_2 r_3 + g_1 b_2 r_3 - r_1 b_2 g_3)$$

Quark combinations allowed by color

- Color wave function for arbitrary collection of quarks and antiquarks

$$\chi_C = r^{\alpha} g^{\beta} b^{\gamma} \bar{r}^{\bar{\alpha}} \bar{g}^{\bar{\beta}} \bar{b}^{\bar{\gamma}}$$

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$$I_3^C = \frac{(\alpha - \bar{\alpha})}{2} - \frac{(\beta - \bar{\beta})}{2} \qquad Y^C = \frac{(\alpha - \bar{\alpha})}{2} + \frac{(\beta - \bar{\beta})}{2} - \frac{2(\gamma - \bar{\gamma})}{3}$$

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- Allowed numbers of quarks and antiquarks

$$(\alpha - \bar{\alpha}) = (\beta - \bar{\beta}) = (\gamma - \bar{\gamma}) \equiv p \implies m_q - n_{\bar{q}} = 3p$$

$$\implies (3q)^p (q\bar{q})^n \ (p, n \geq 0)$$

Hadrons allowed by color

- Anti-baryons also allowed

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$$(3q)^p(q\bar{q})^n \ (p, n \geq 0) \longrightarrow (3\bar{q})^l(3q)^p(q\bar{q})^n \ (l, p, n \geq 0)$$

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$$MM, MB, M\bar{B}$$

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Hadrons allowed by color

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*** Can you find the mistake on M&S p. 181?**

Exotic hadrons

- Growing evidence for exotic hadrons with heavy quarks

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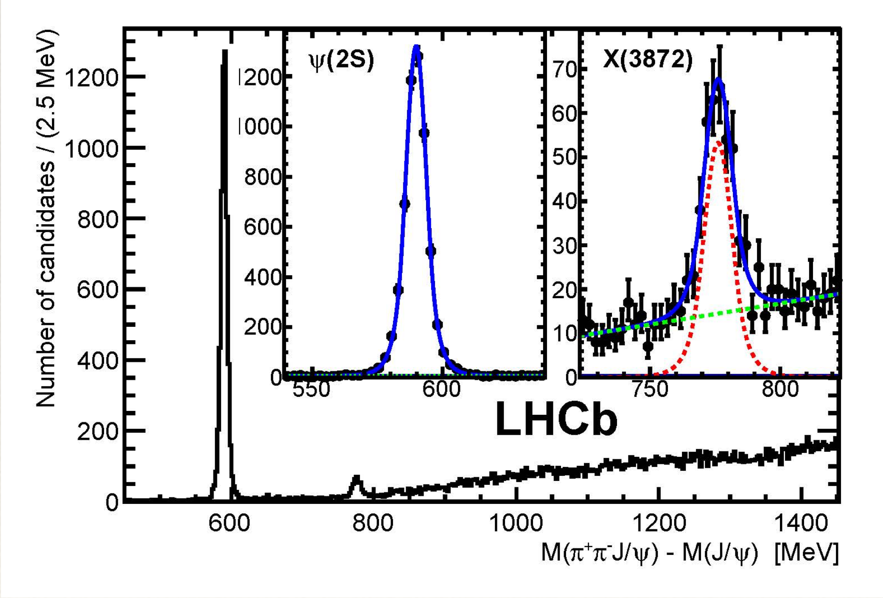

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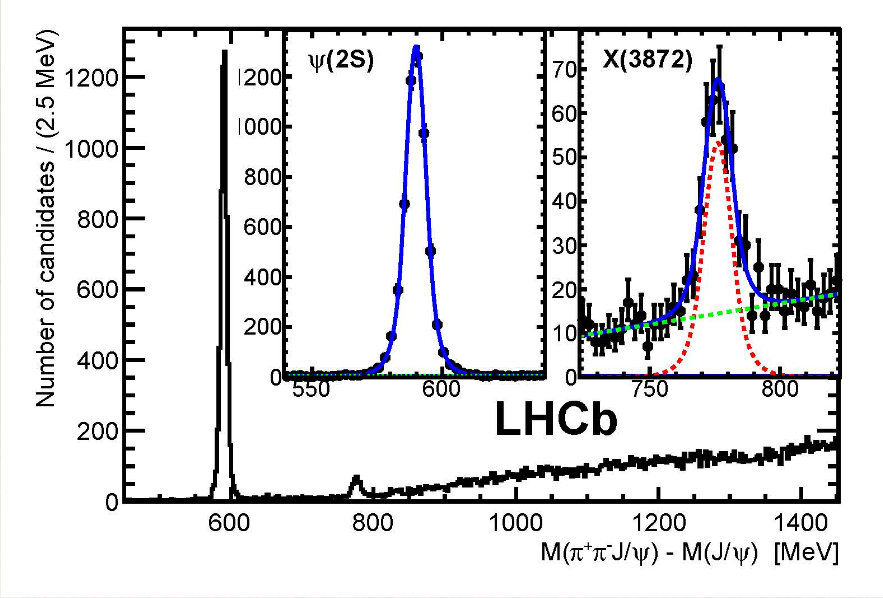

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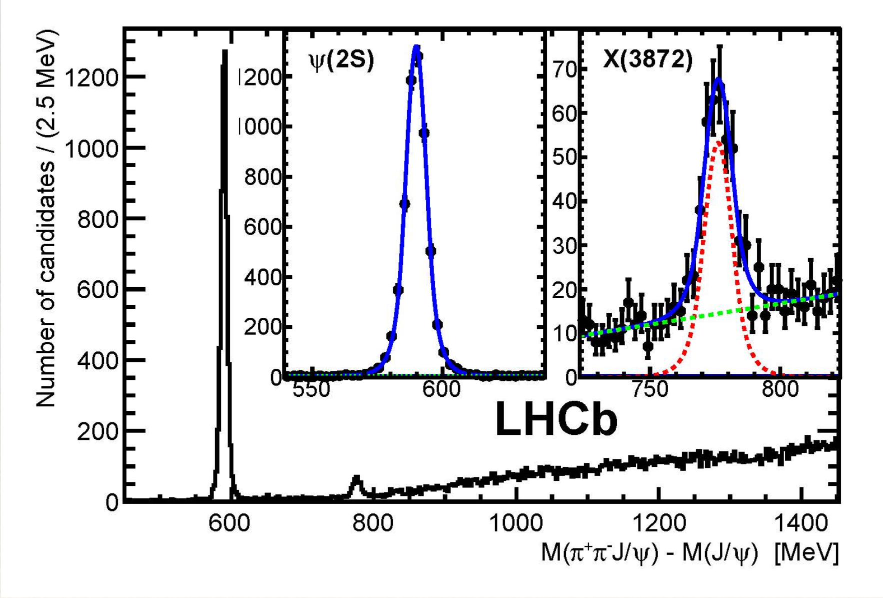

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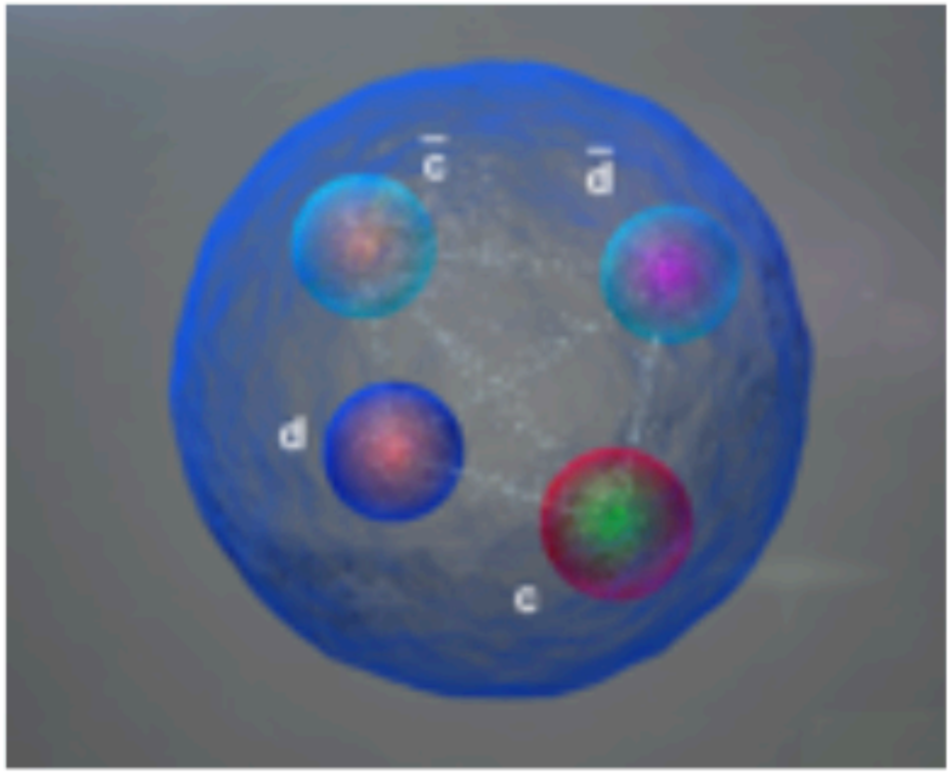
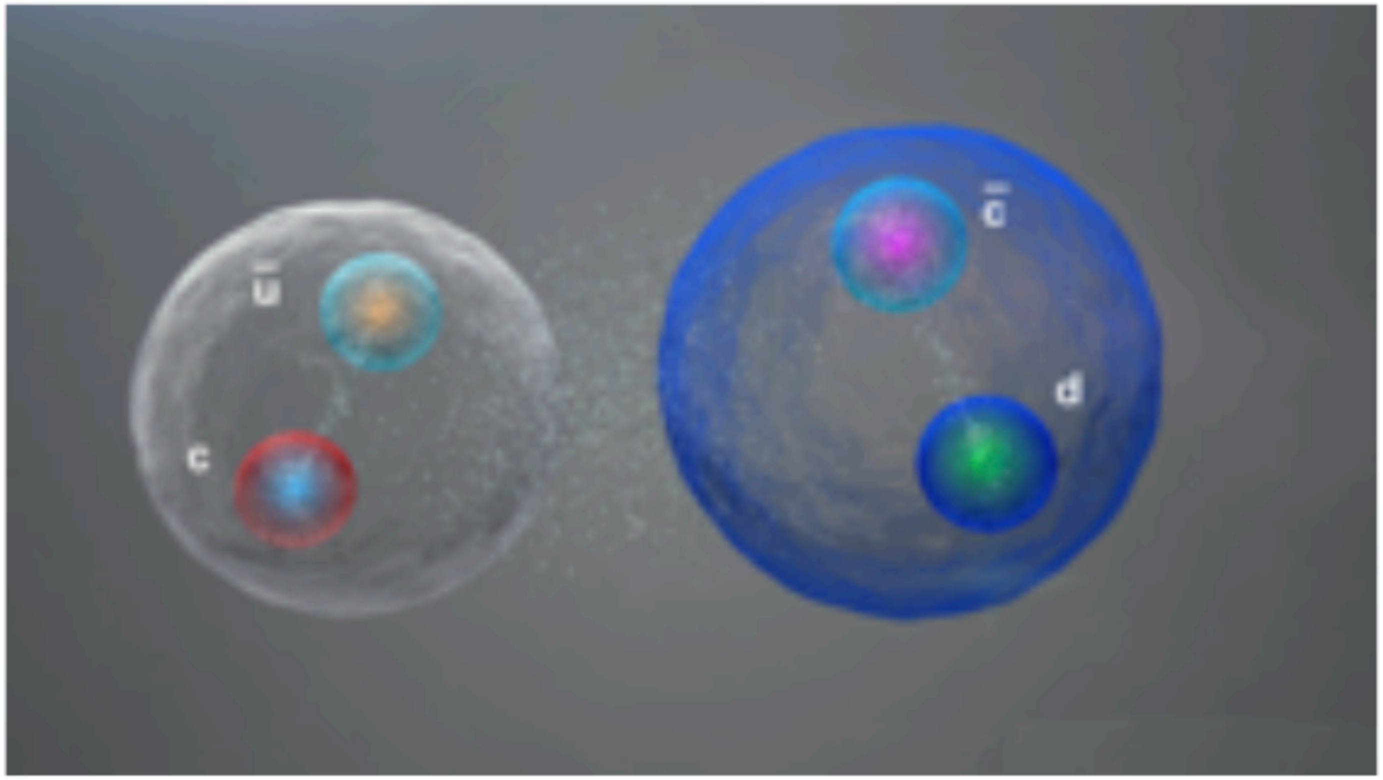
Could be tetraquark or $D\overline{D}*$

Exotic Z⁻(4430) confirmed by LHCb

"A model-independent confirmation of the Z(4430)⁻ state" was submitted for publication in October 2015. A possibility of explaning the Z(4430) enhancement by the so called reflection of Kπ resonances, proposed by the BaBar collaboration, is excluded with a significance exceeding 8σ. Experts are invited to see the Fig. 9 and 12a and read the details in the paper.





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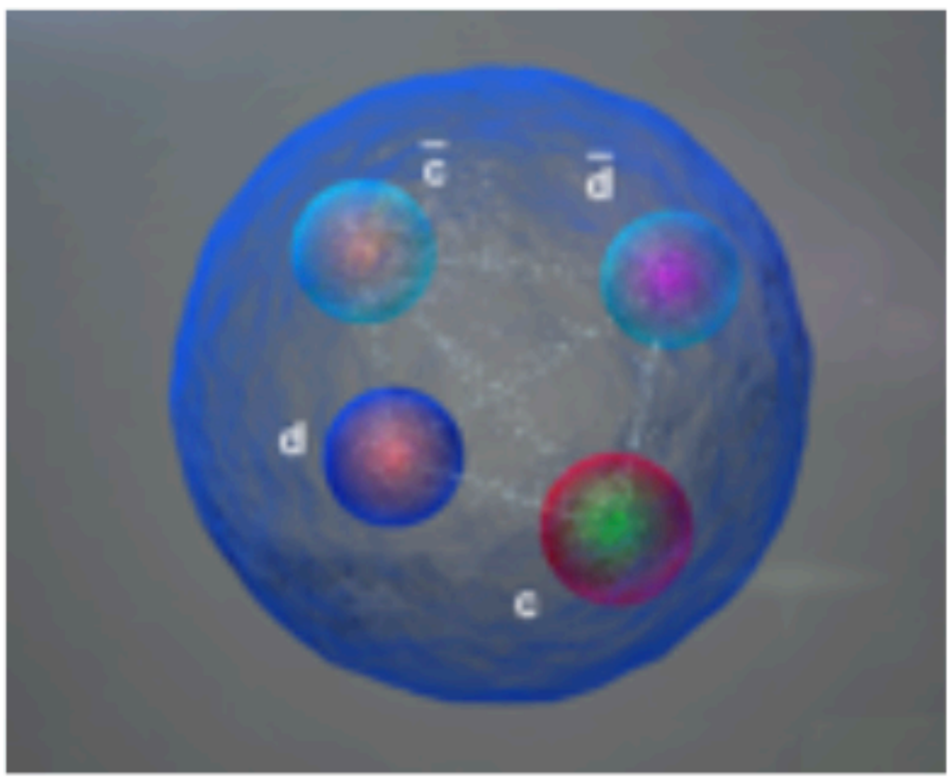

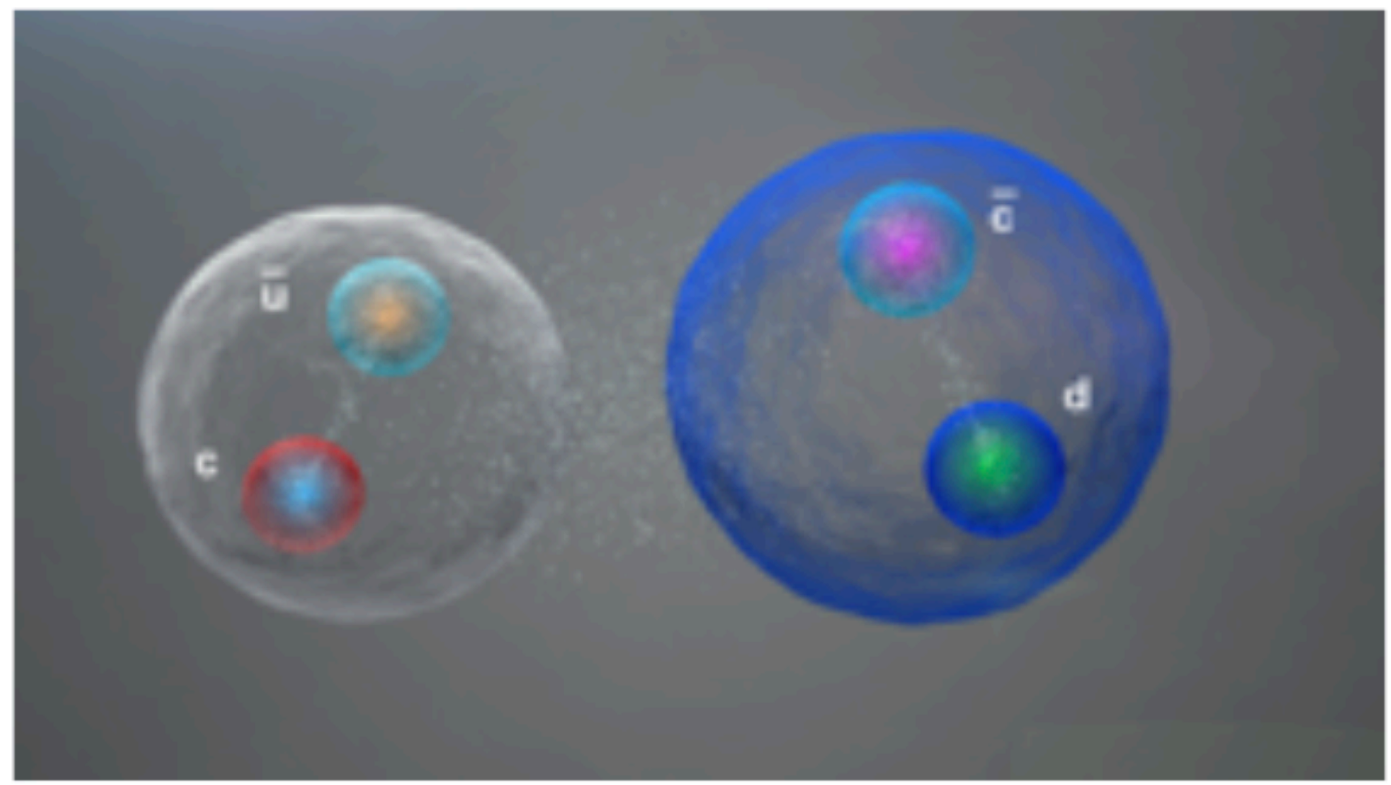

- More studies needed to distinguish tetraquark from hadronic molecule

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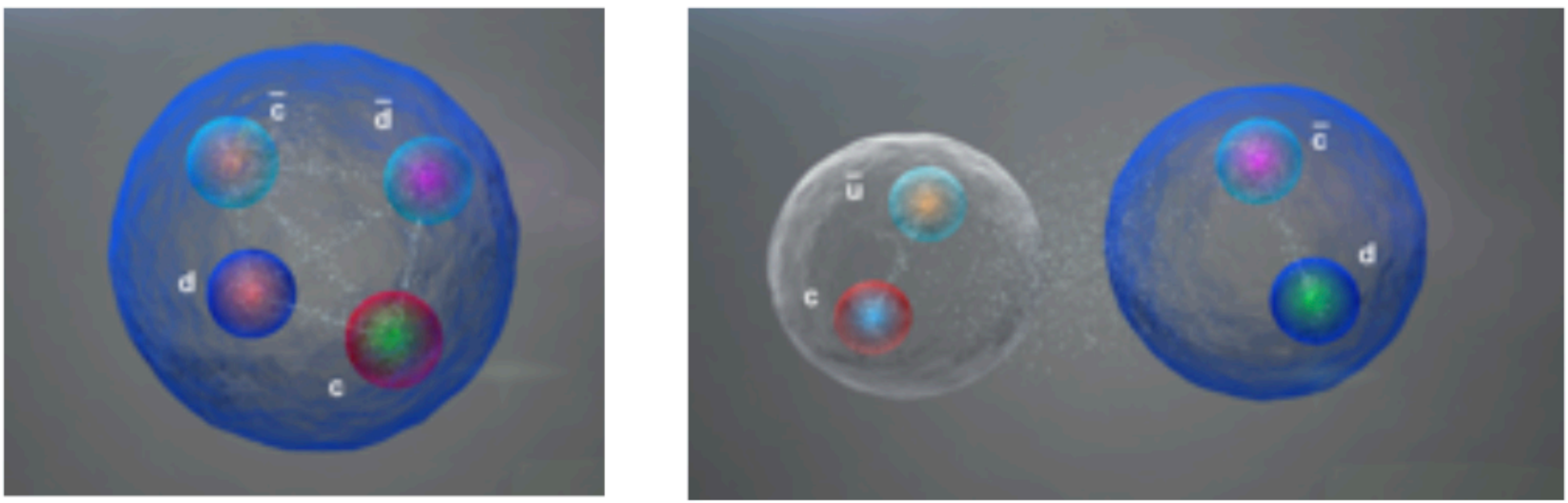

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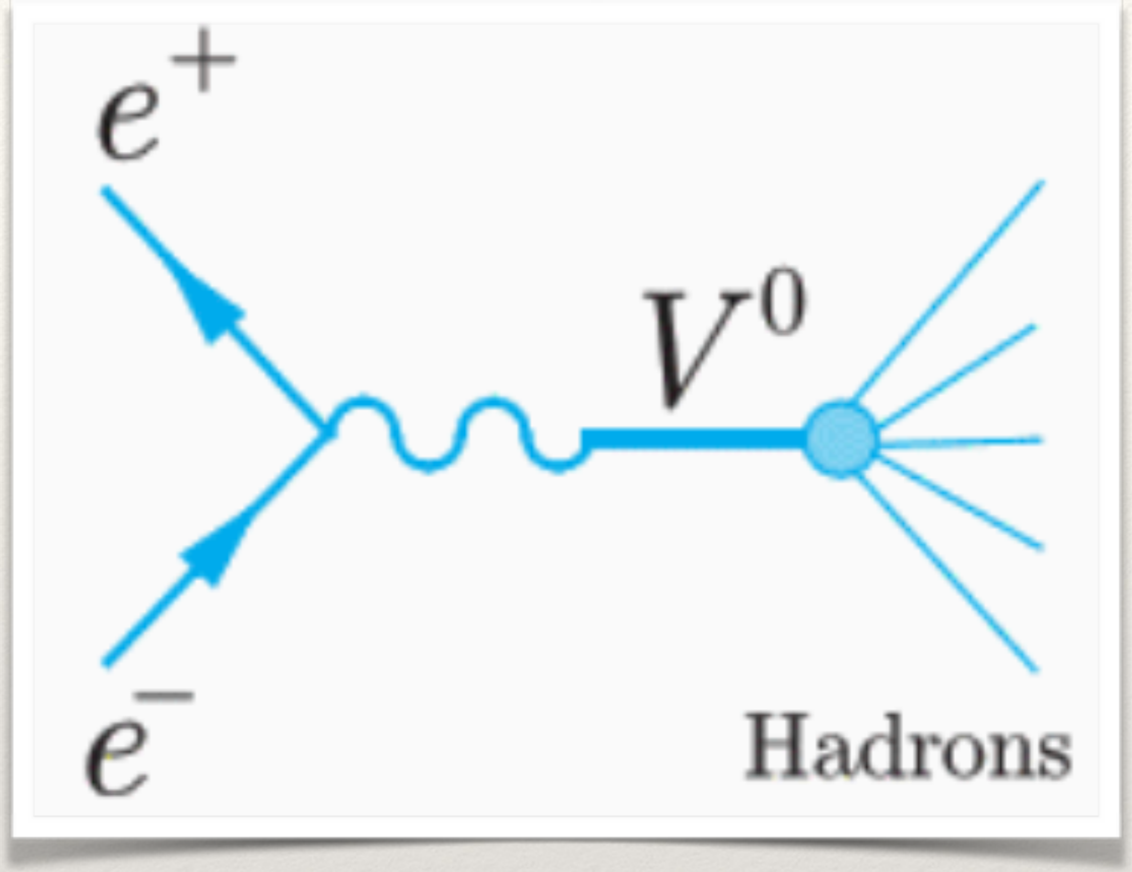
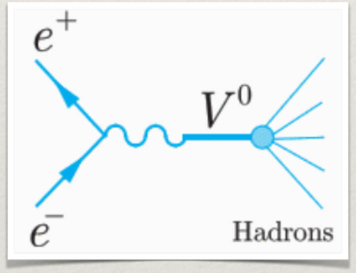
Charmonium and bottomonium



- Approximately non-relativistic bound states $c\bar{c},\ b\bar{b}$

Charmonium and bottomonium



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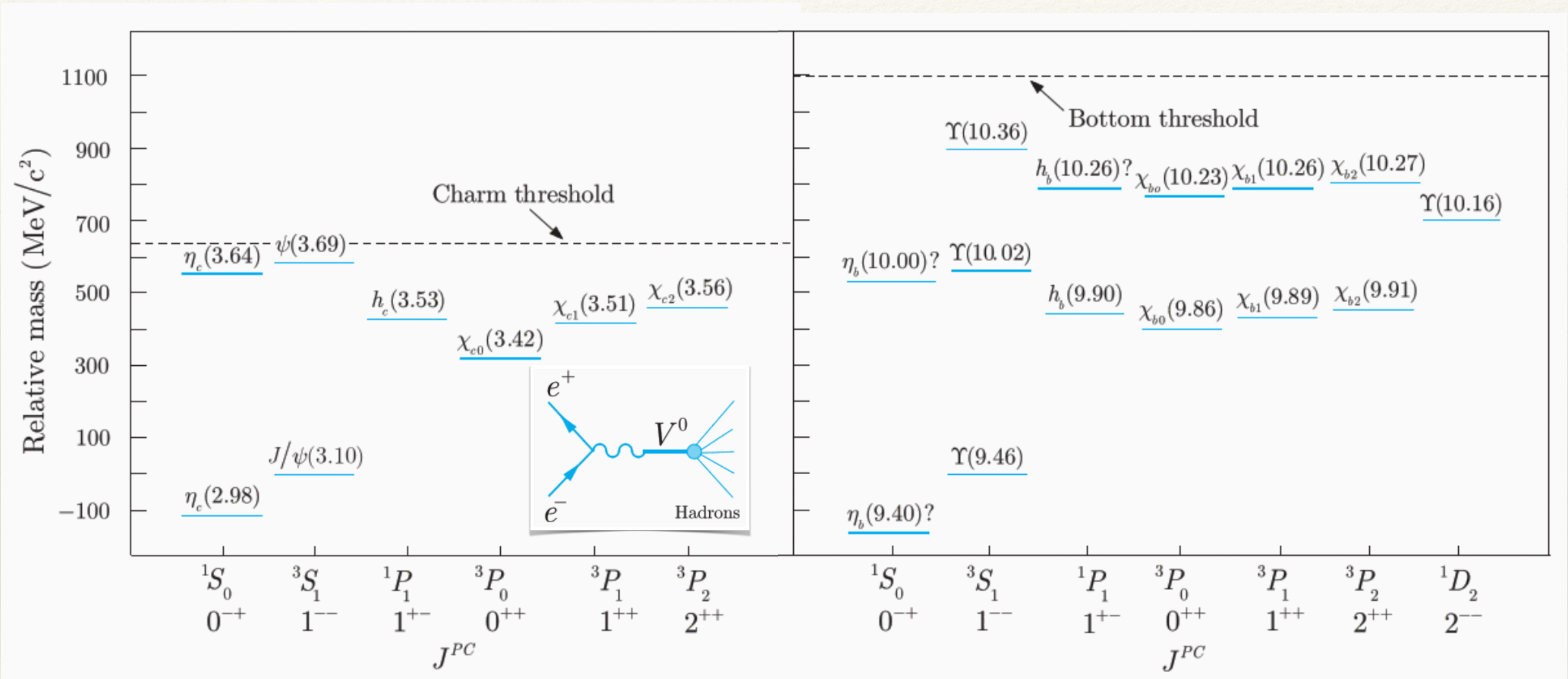

Martin and Shaw, Particle Physics, 4th ed., Figures 6.7,9,10

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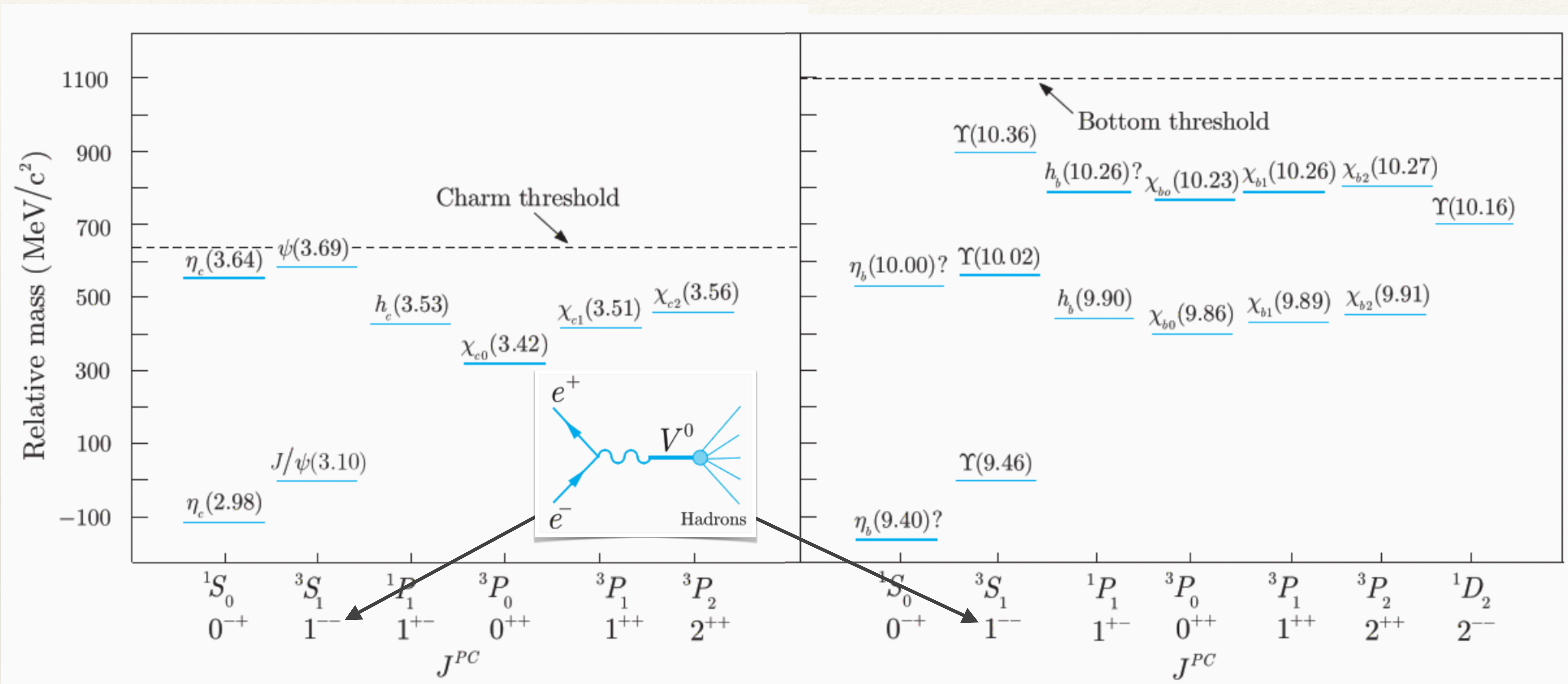

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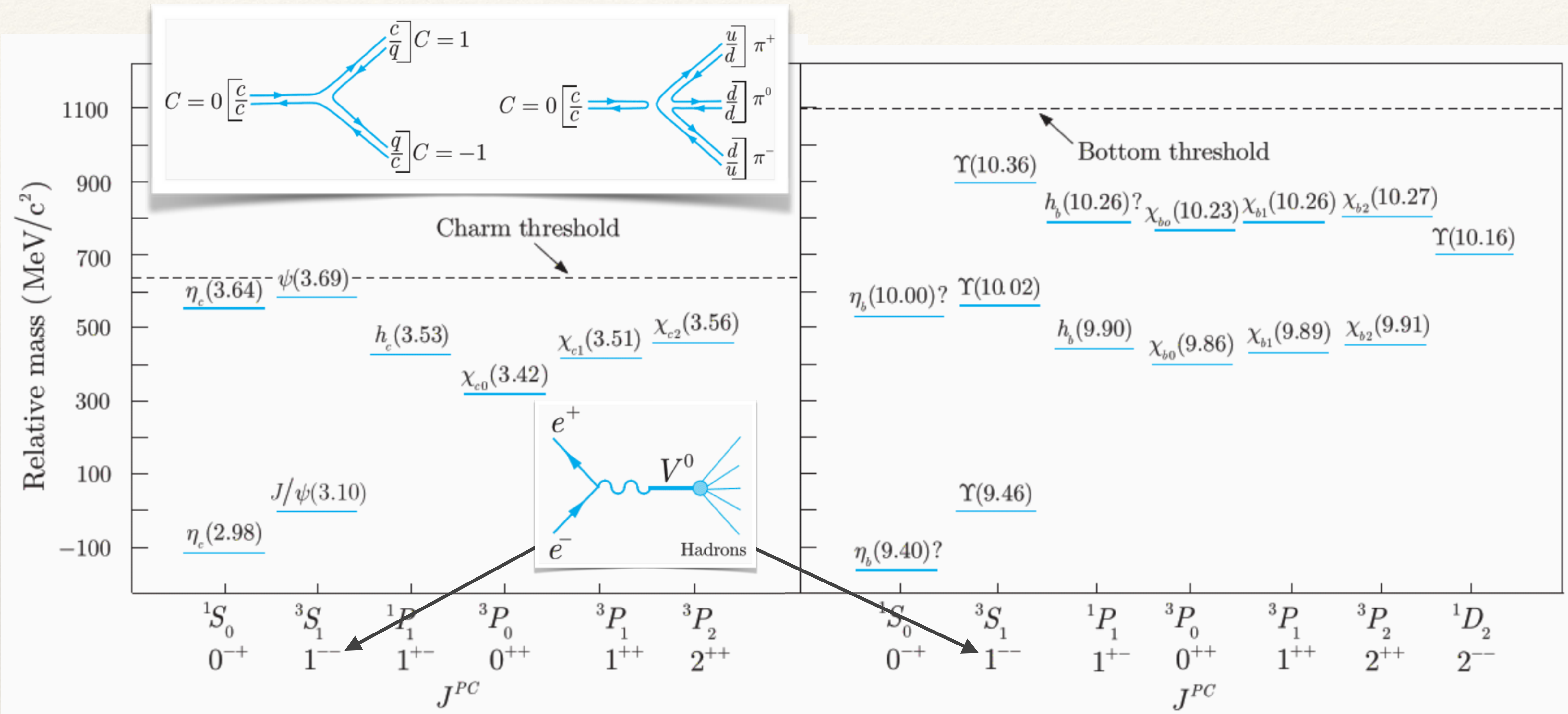

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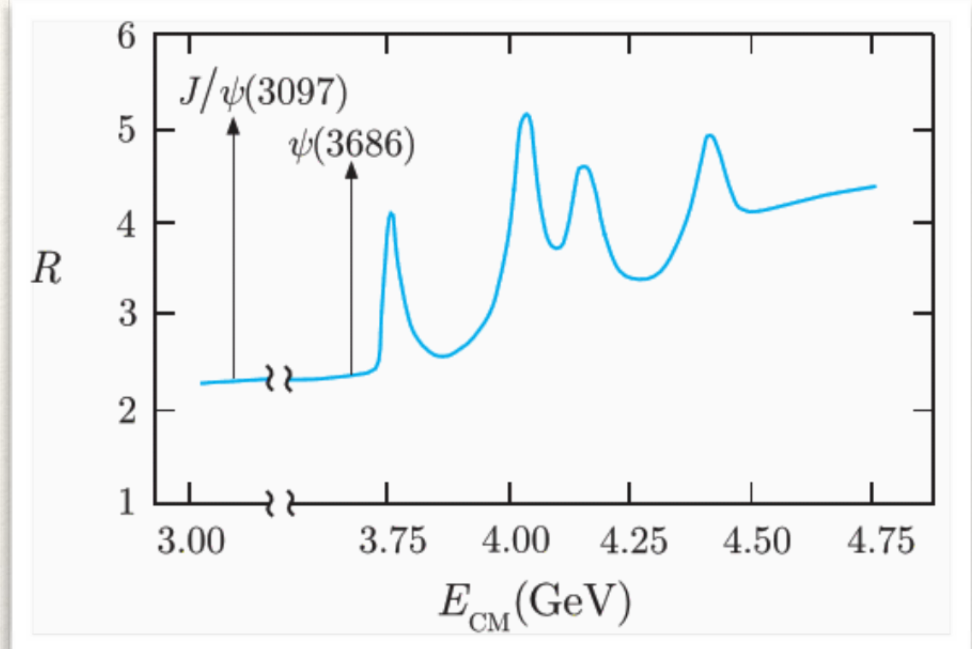

Martin and Shaw, Particle Physics, 4th ed., Figure 6.8

- Supressed annihilation of heavy quarks, long lifetime, narrow states
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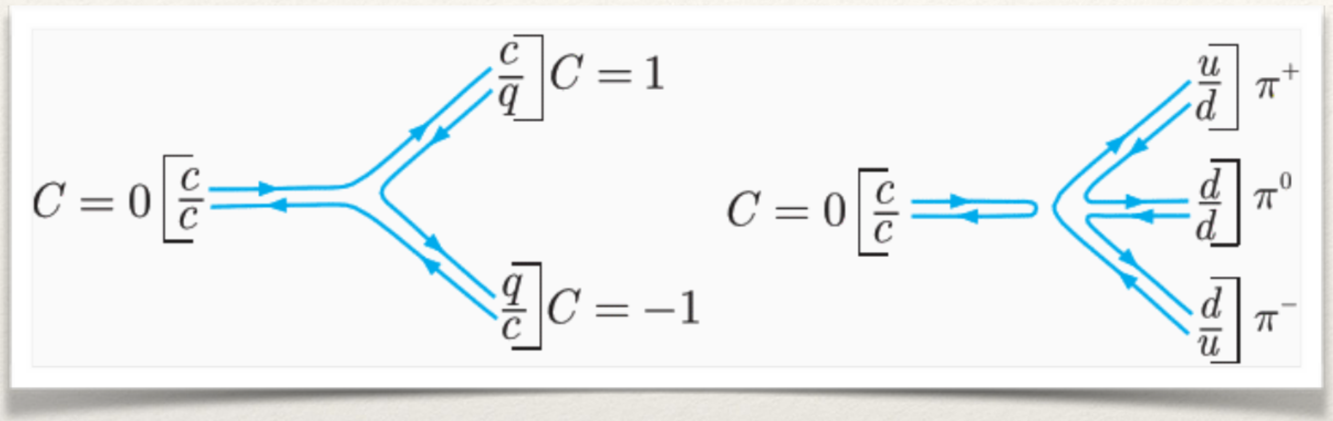
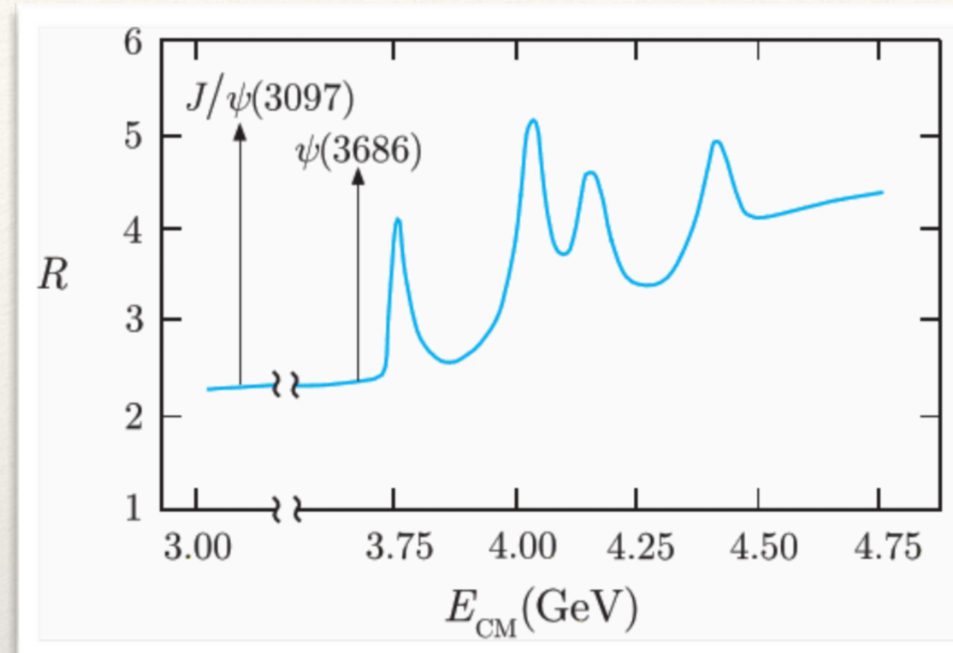
Charmonium and bottomonium





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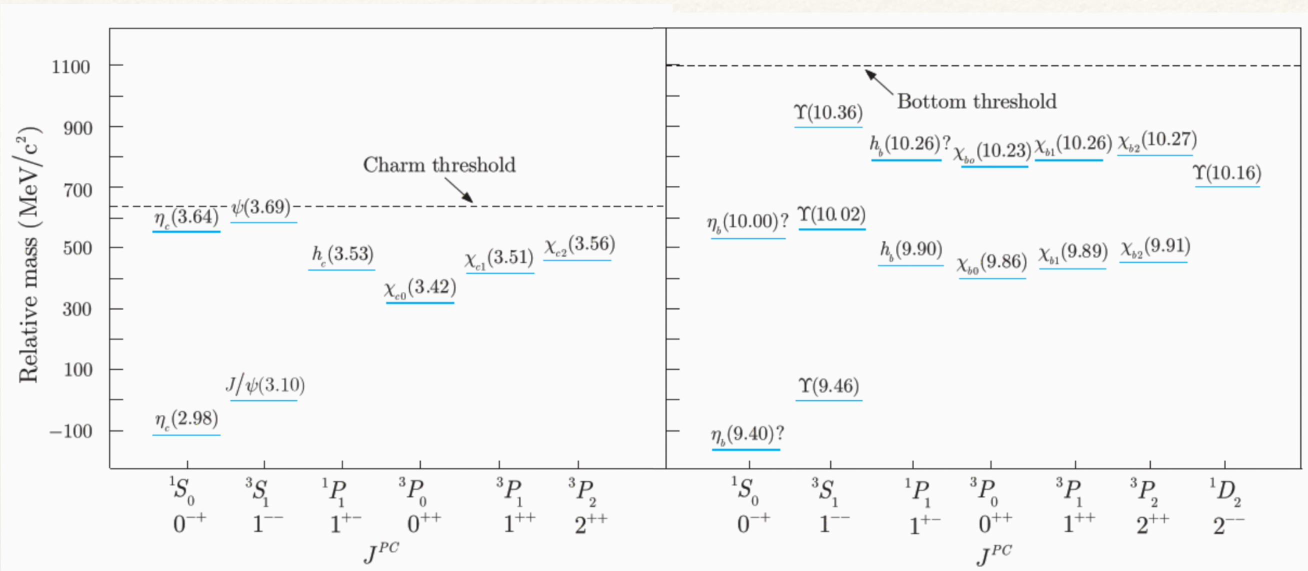

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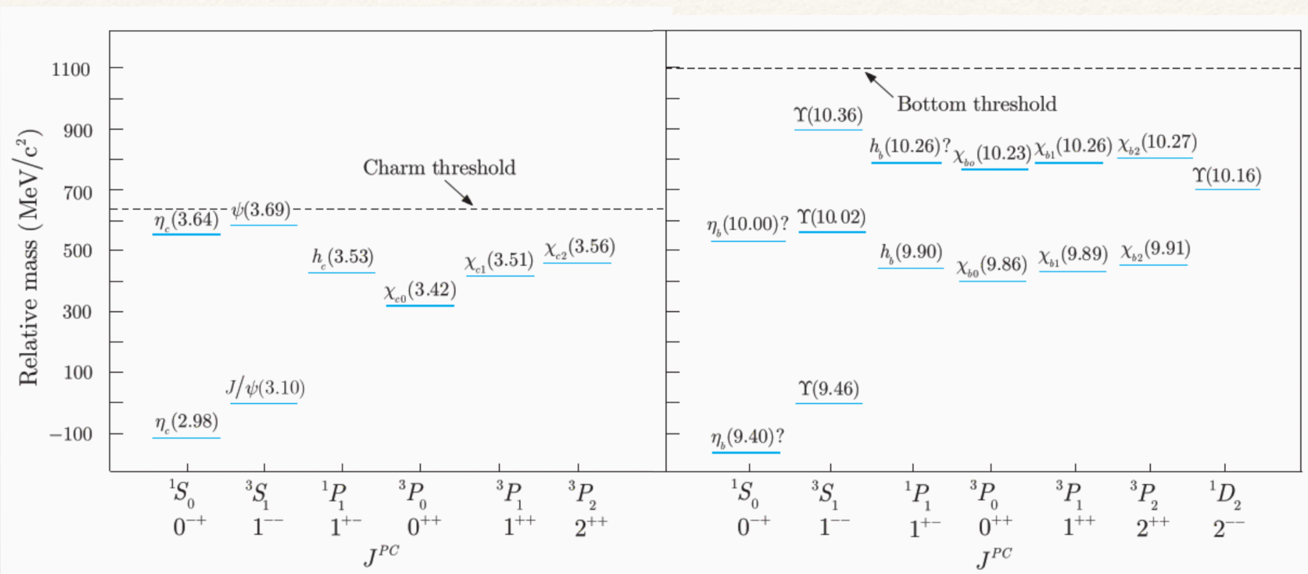
Charmonium and bottomonium



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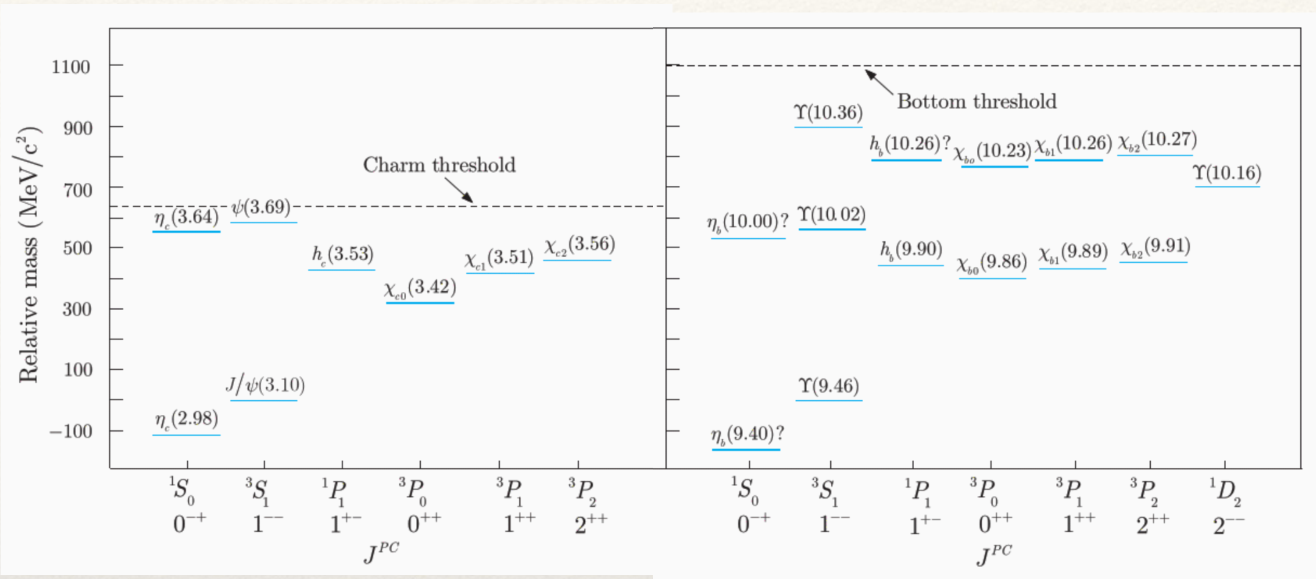

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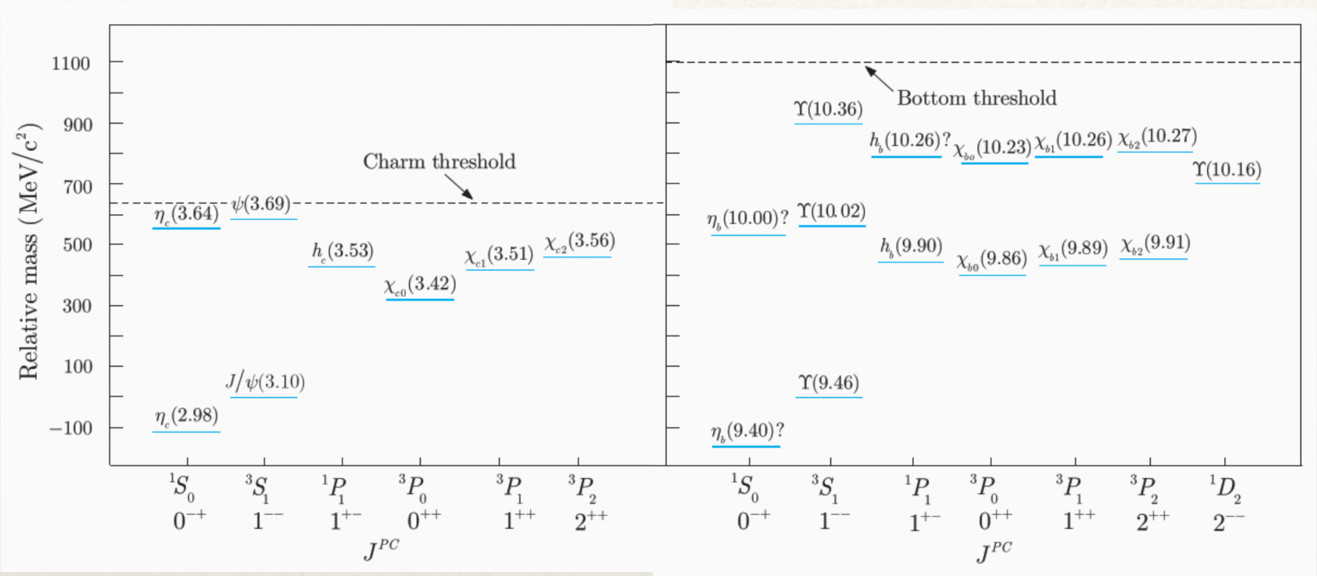

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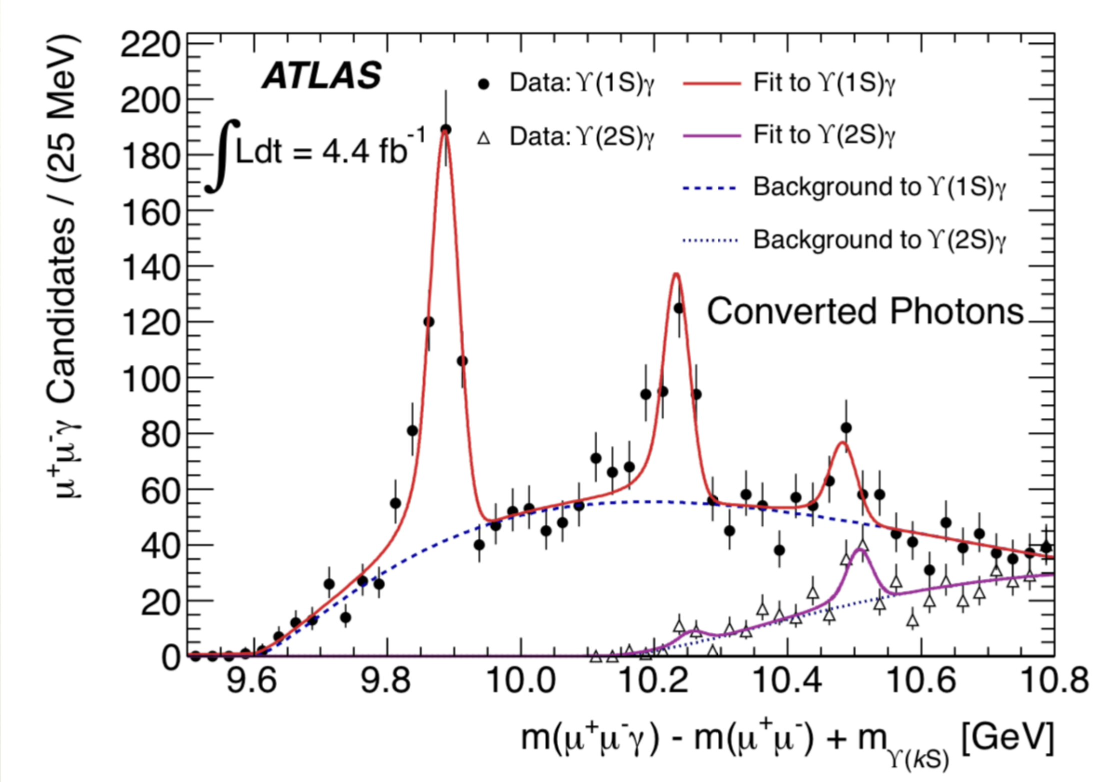

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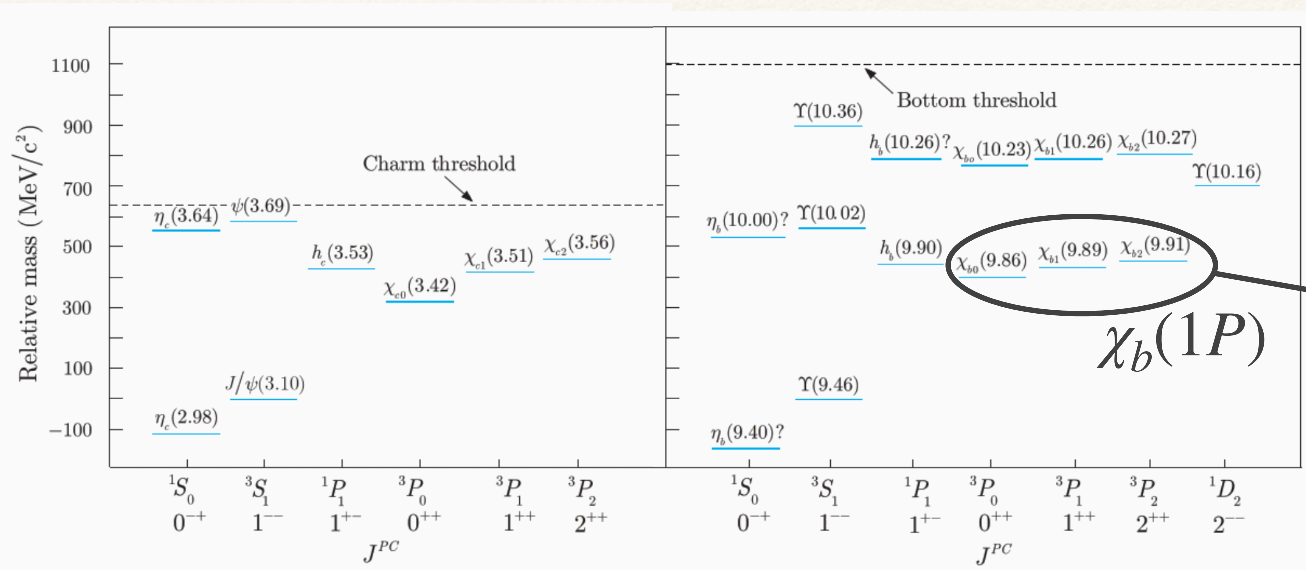

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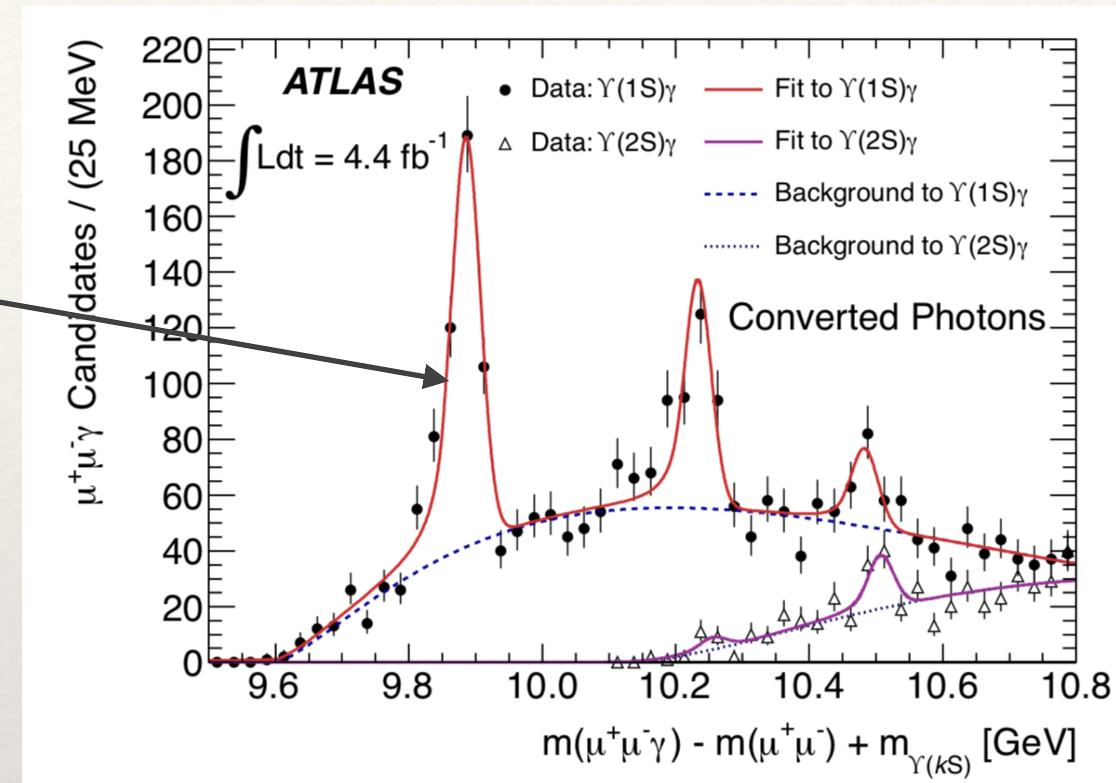

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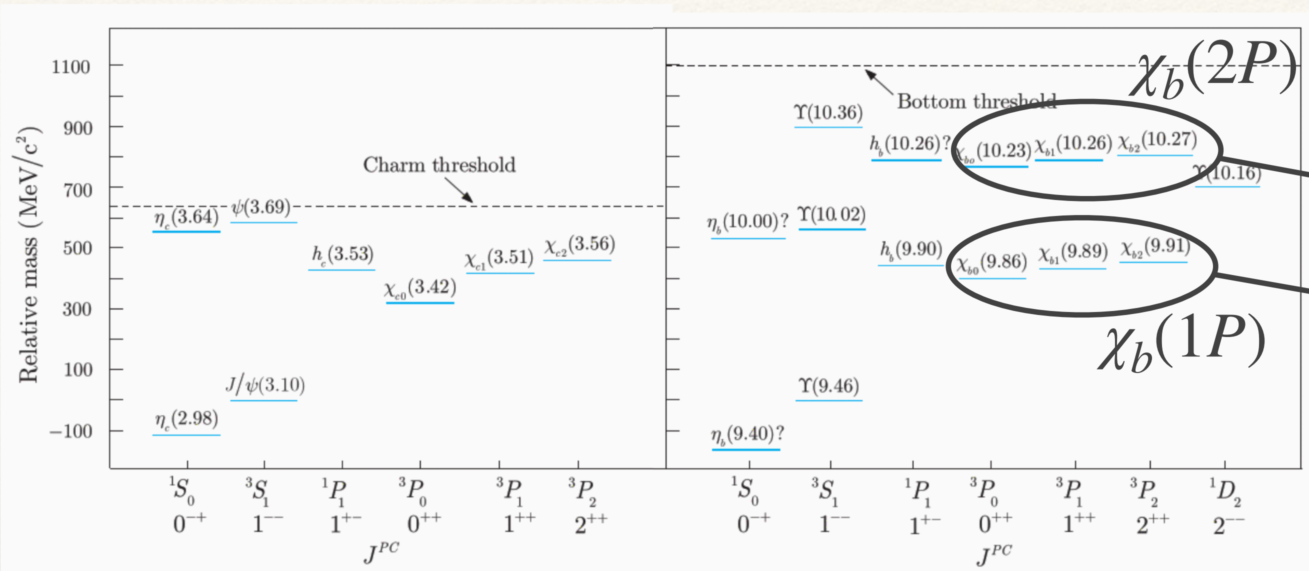

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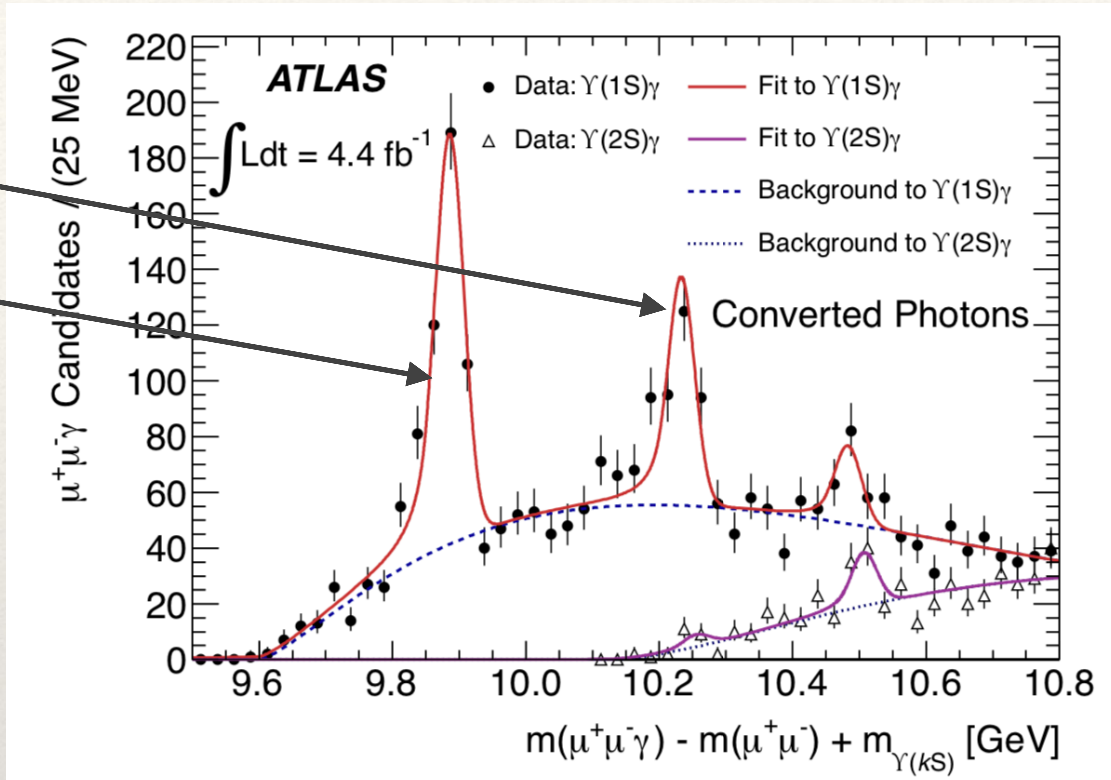

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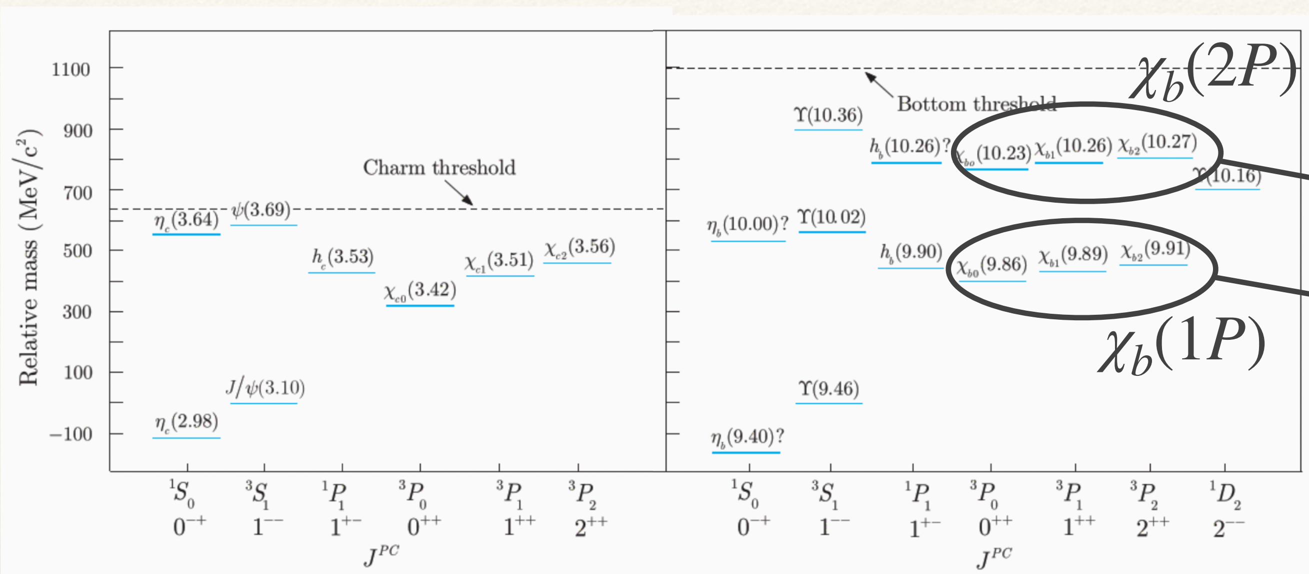

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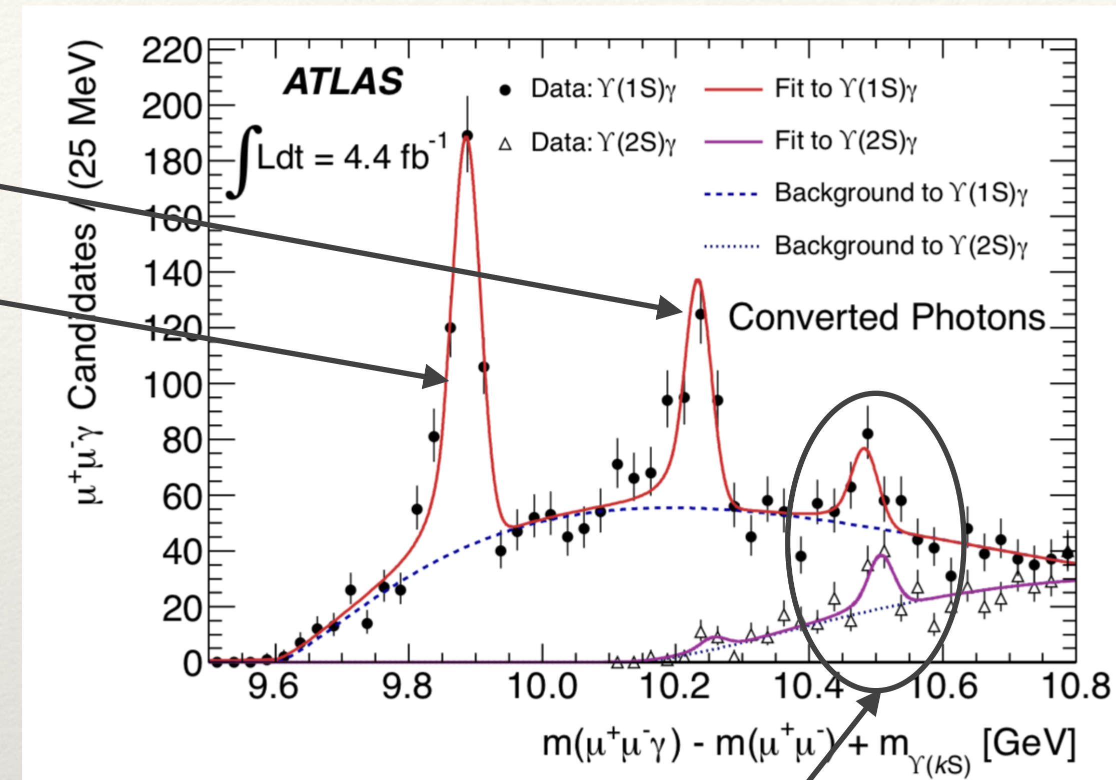

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Evidence for $\chi_b(3P)$!