第五届“强子谱和强子结构研讨会”(2021年1月23—25日，广州，中山大学)

北京航空航天大學
BEIHANG UNIVERSITY

Understanding the pentaquark states from an EFT perspective

Lisheng Geng（耿立升） @ Beihang U.

- **Emergence of a complete heavy-quark spin symmetry multiplet: seven molecular pentaquarks in light of the latest LHCb analysis [1903.11560]**
- **Model independent determination of the spins of the** Pc**(4440) and** Pc**(4457) from the spectroscopy of the triply charmed dibaryons [1907.11220]**
- **Can discovery of hidden charm strange pentaquark states help determine the spins of Pc(4440) and Pc(4457)** [2011.07935]

More on pentaquarks at this conf

- Sunday, 10:30-11:00, 陈华星
- Sunday, 11:00-11:30, 肖褚文
- Sunday, Session 3, 14:50-15:15, 杨智
- Sunday, Session 4, 16:00-16:20, 陈锐
- Sunday, Session 4, 16:20-16:40, 沈超玮
- Sunday, Session 4, 16:40-17:00, 旷仕卿
- Sunday, Session 4, 17:20-17:40, 谢亚平
- ……

Contents

- ☐ **Motivation: a new paradigm in studies of the strong interaction**
- ☐ **The new pentaquark states as $\bar{D}\Sigma_c$ molecules**
- ☐ **From $\Xi_{cc}\Sigma_c$ dibaryon mass splitting to the pentaquark spins**
- ☐ **From Pcs to the pentaquark spins**
- ☐ **Summary and outlook**

Contents

☐ Motivation: a new paradigm in studies of the strong interaction

☐ The new pentaquark states as $\bar{D}\Sigma_c$ molecules

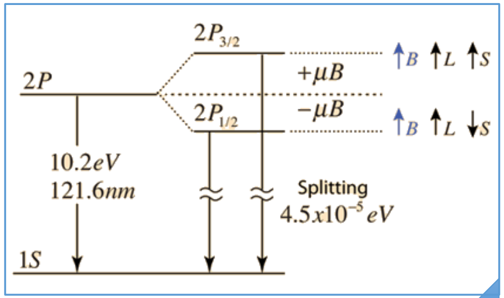
☐ From $\Xi_{cc}\Sigma_c$ dibaryon mass splitting to the pentaquark spins

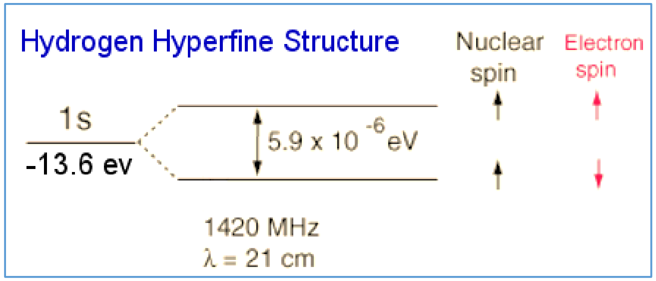
☐ From Pcs to the pentaquark spins

☐ Summary and outlook

Why spectroscopy—Atomic

We need high precision





$$\frac{1}{\lambda_{\text{vac}}} = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

Rydberg formula

Fine structure

Hyperfine structure

Johannes Rydberg

Niels Henrik David Bohr

Edward W. Morley

Arnold Sommerfeld

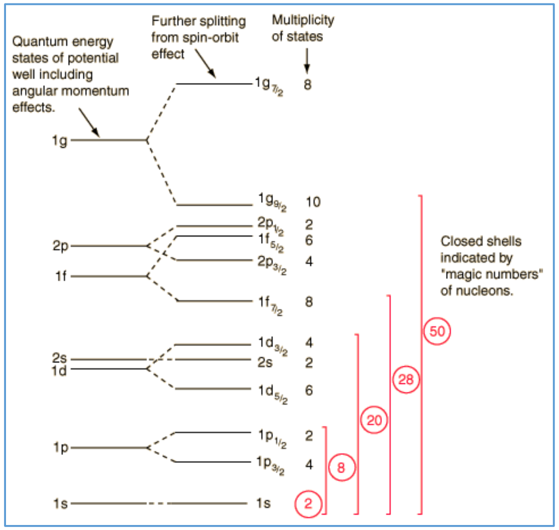
Albert Abraham Michelson

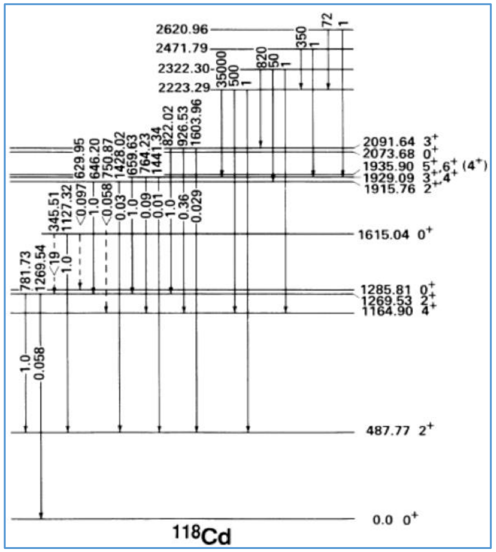
Wolfgang Pauli

Why spectroscopy—Nuclear

We need more systematics

Single particle motion





Collective motion

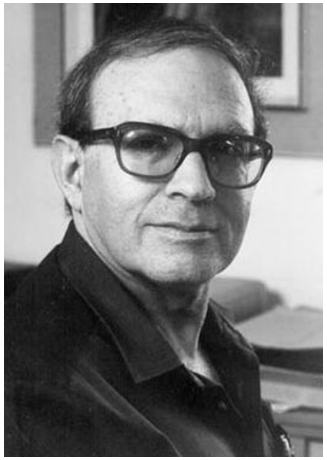
Maria Goeppert Mayer J. Hans D. Jensen

Aage Niels Bohr, Ben Roy Mottelson Leo James Rainwater

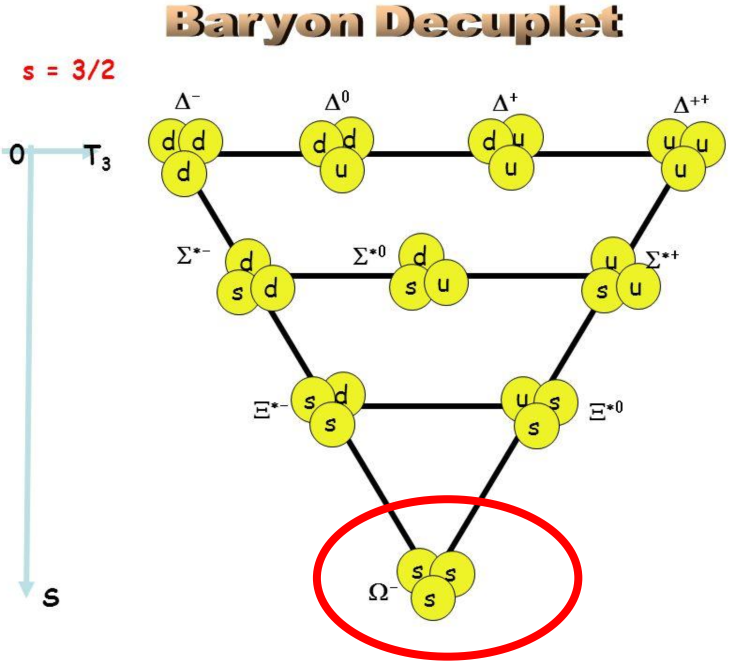
Why spectroscopy—particle/hadron

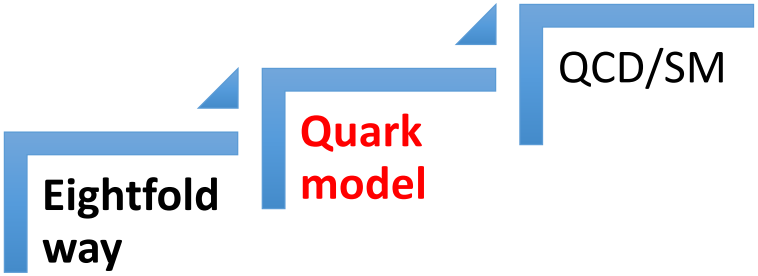
We need good theory/imagination

Murray Gell-Mann



Yuval Ne'eman.

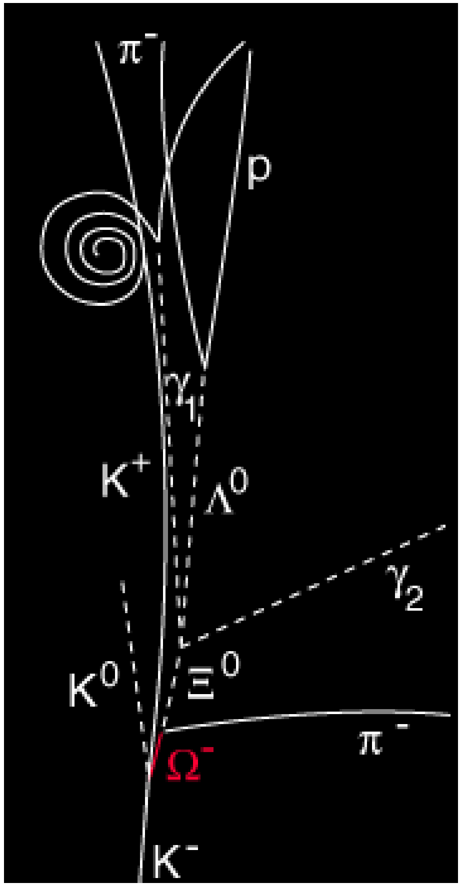




Eightfold way

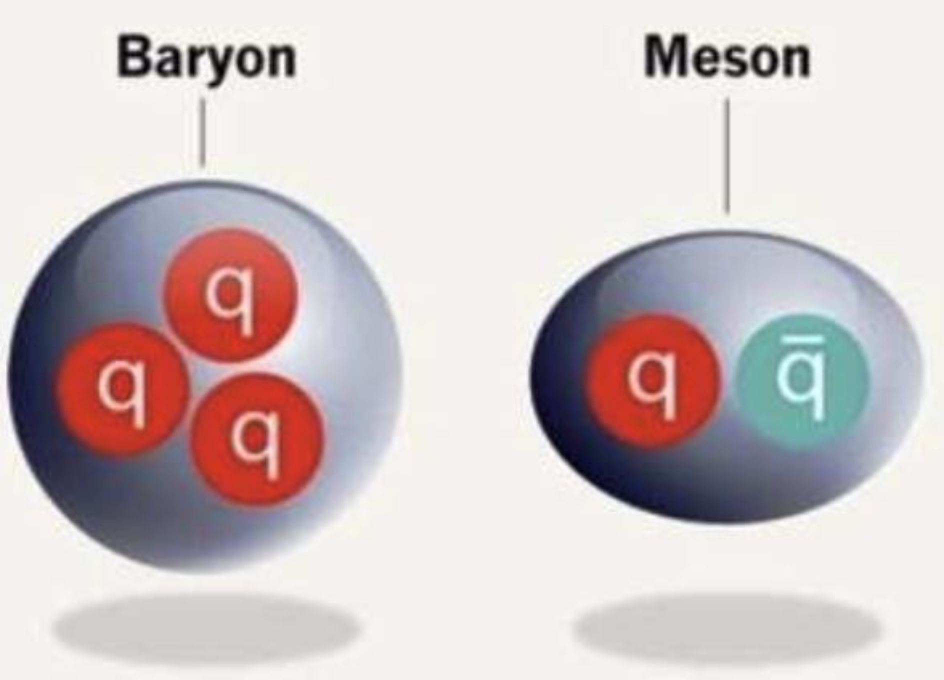
Quark model

QCD/SM



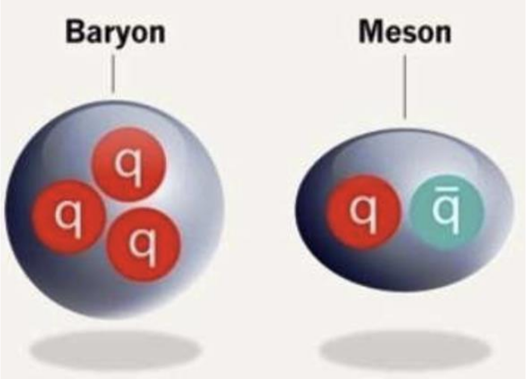
V. E. Barnes et al., Phys. Rev. Lett. 12, 204 (1964)

Naive QM: qqq & qqbar



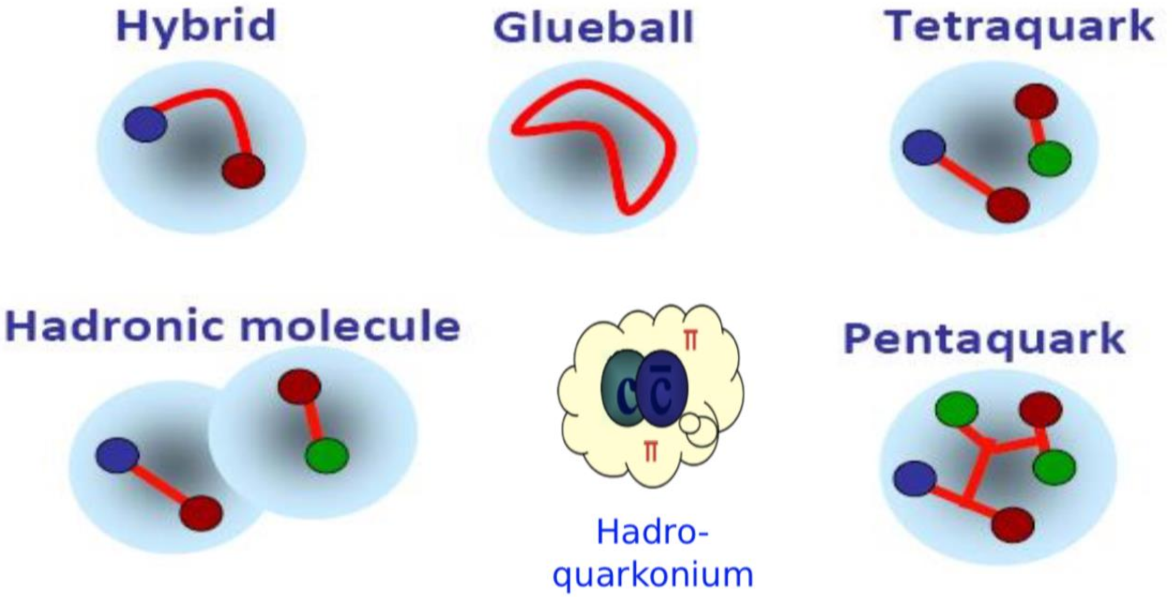
Huge Success not well understood

More complicated structure allowed



In the naïve quark model

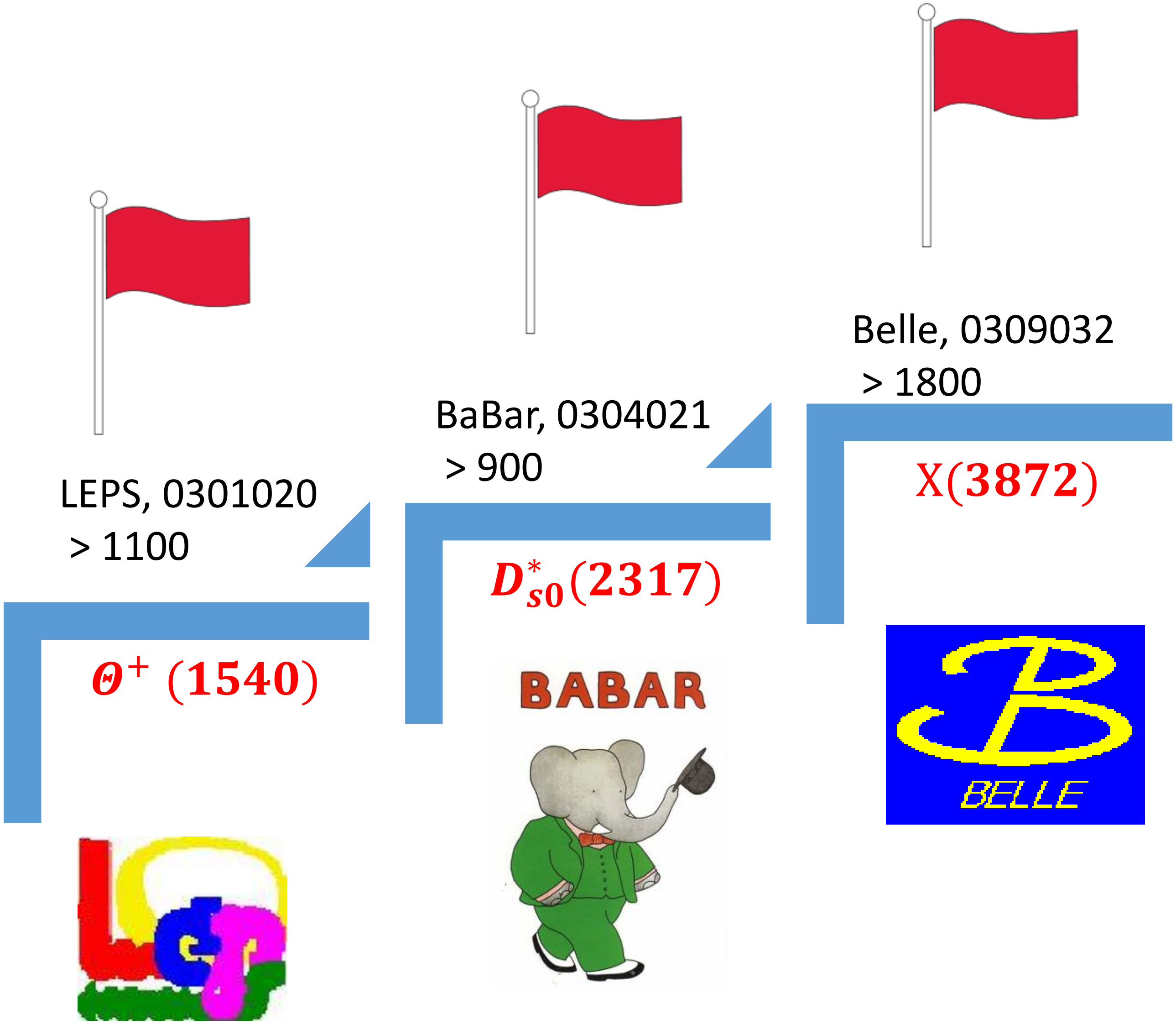
In principle,
QCD allows



Not much happened until 2003

$\Lambda(1405)$, $N^*(1535)$,...
$f_0(500)$, $f_0(980)$, $a_0(980)$, ...

Beginning of a new era： 2003



LEPS, 0301020
> 1100

$\Theta^+ (1540)$

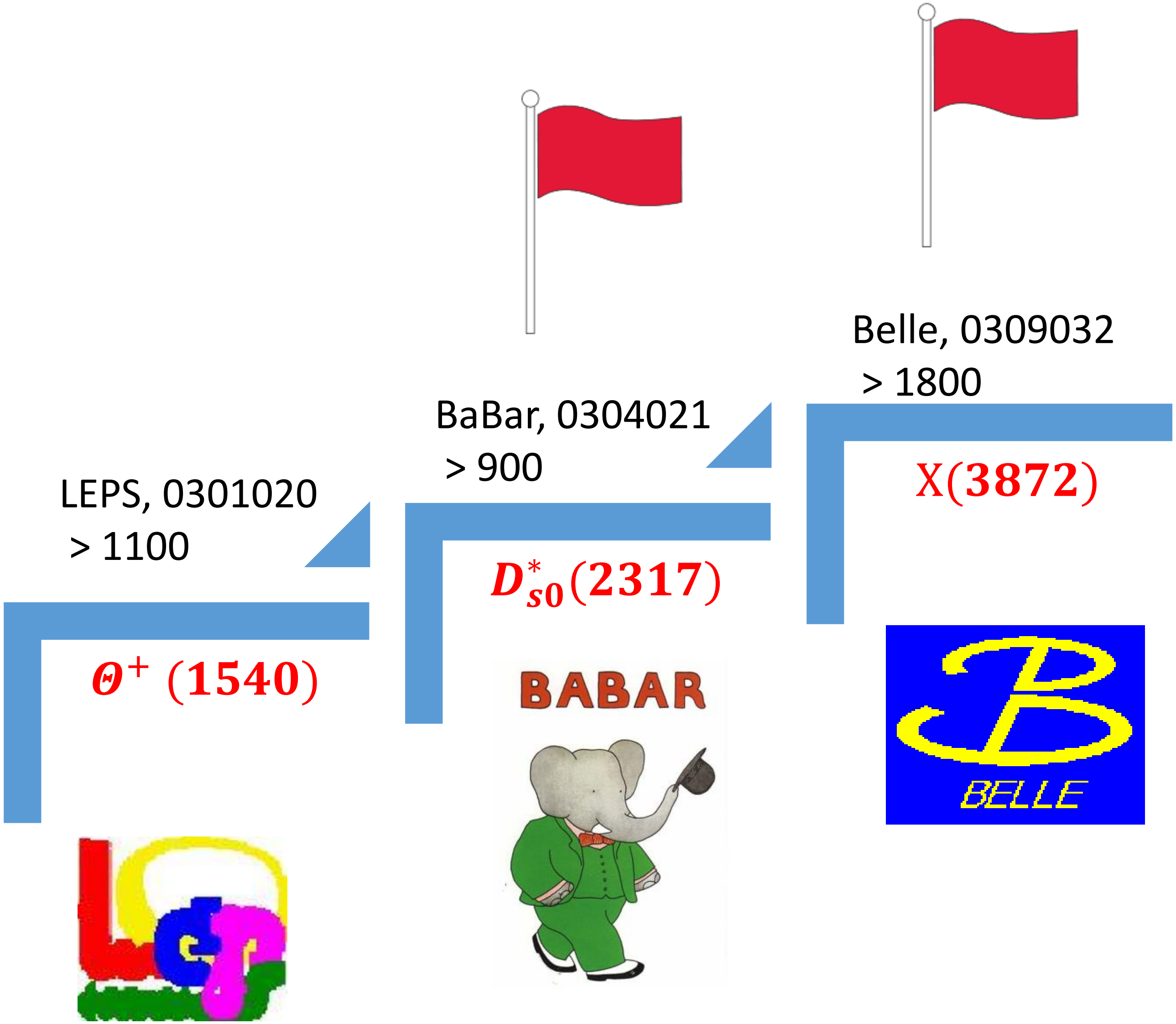
BaBar, 0304021
> 900

$D^*_{s0}(2317)$

Belle, 0309032
> 1800

$X(3872)$

Beginning of a new era: 2003



LEPS, 0301020
> 1100

Θ^+ (1540)

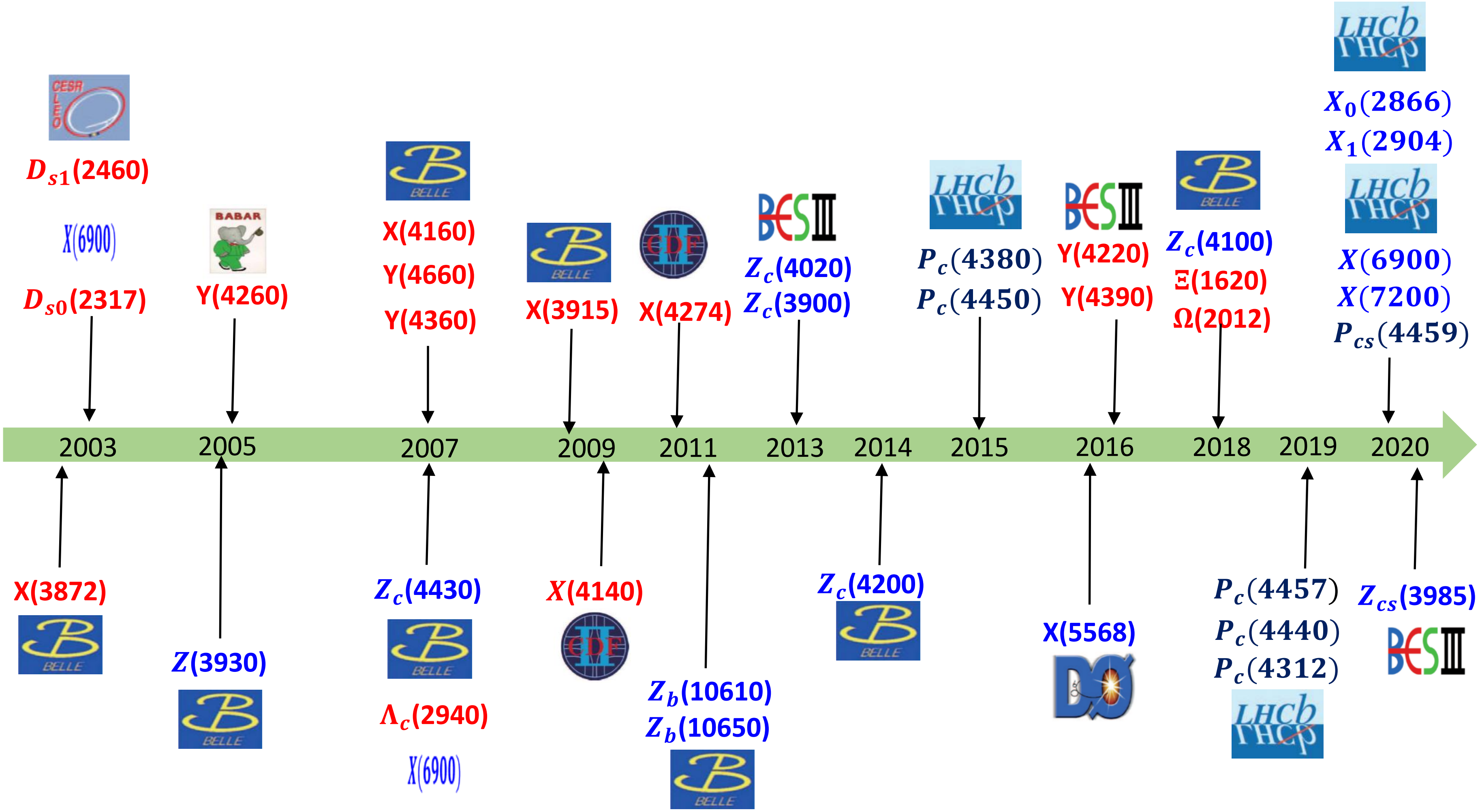
BaBar, 0304021
> 900

$D_{s0}^*(2317)$

Belle, 0309032
> 1800

X(3872)

Exotic mesons or baryons Tetraquark states Pentaquark states



2003

$D_{s1}(2460)$

X(6900)

$D_{s0}(2317)$

X(3872)

2005

Y(4260)

$Z(3930)$

2007

X(4160)

Y(4660)

Y(4360)

$Z_c(4430)$

$\Lambda_c(2940)$

X(6900)

2009

X(3915)

$X(4140)$

2011

X(4274)

$Z_b(10610)$

$Z_b(10650)$

2013

$Z_c(4020)$

$Z_c(3900)$

2014

$Z_c(4200)$

2015

$P_c(4380)$

$P_c(4450)$

2016

Y(4220)

Y(4390)

X(5568)

2018

$Z_c(4100)$

$\Xi(1620)$

$\Omega(2012)$

2019

$P_c(4457)$

$P_c(4440)$

$P_c(4312)$

2020

$X_0(2866)$

$X_1(2904)$

$X(6900)$

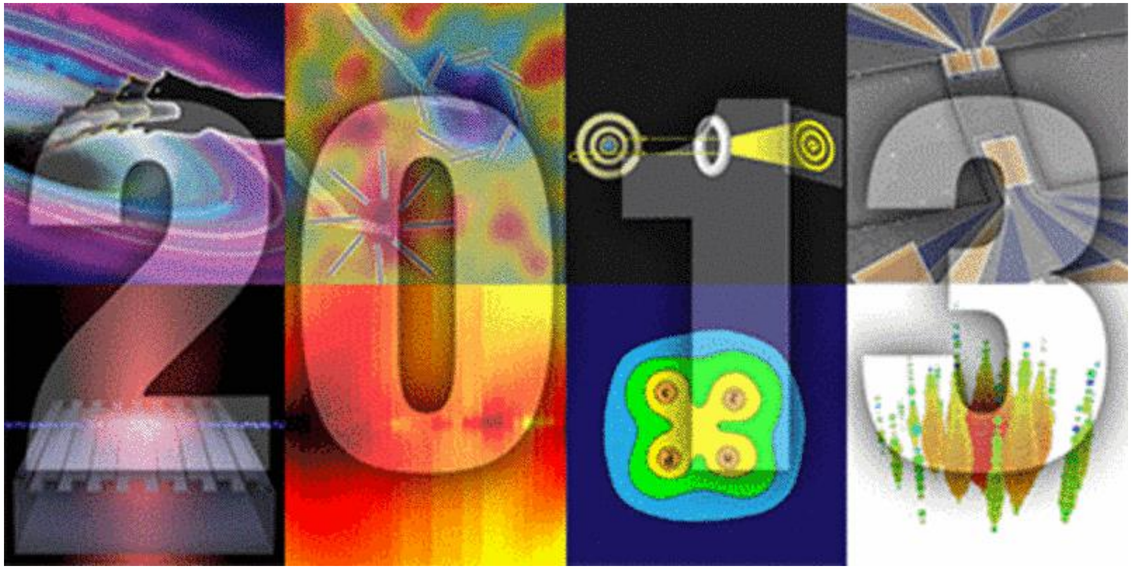
$X(7200)$

$P_{cs}(4459)$

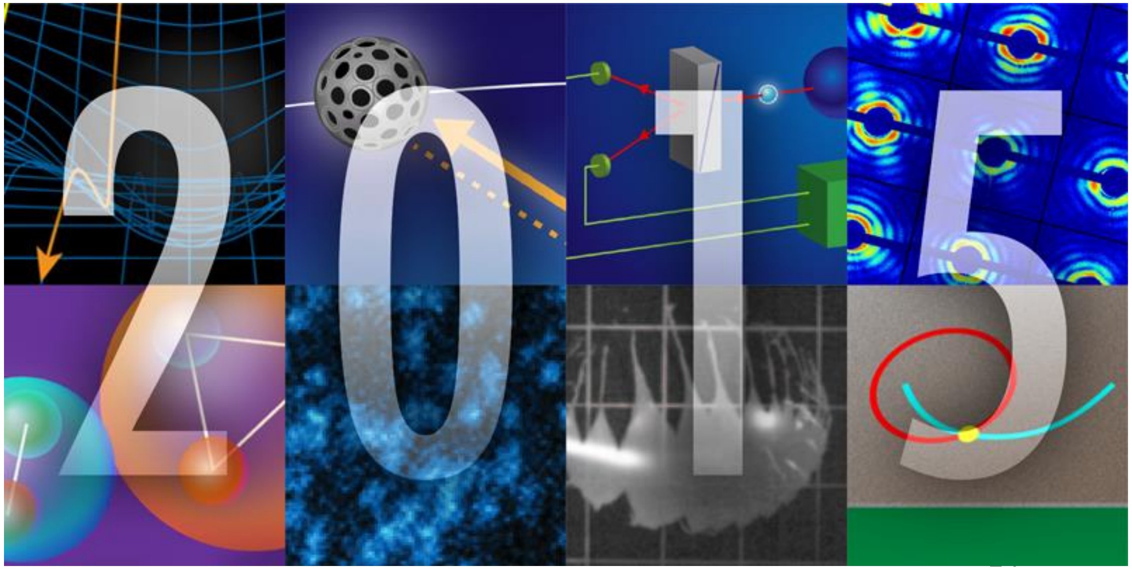
$Z_{cs}(3985)$

Highlights of the year

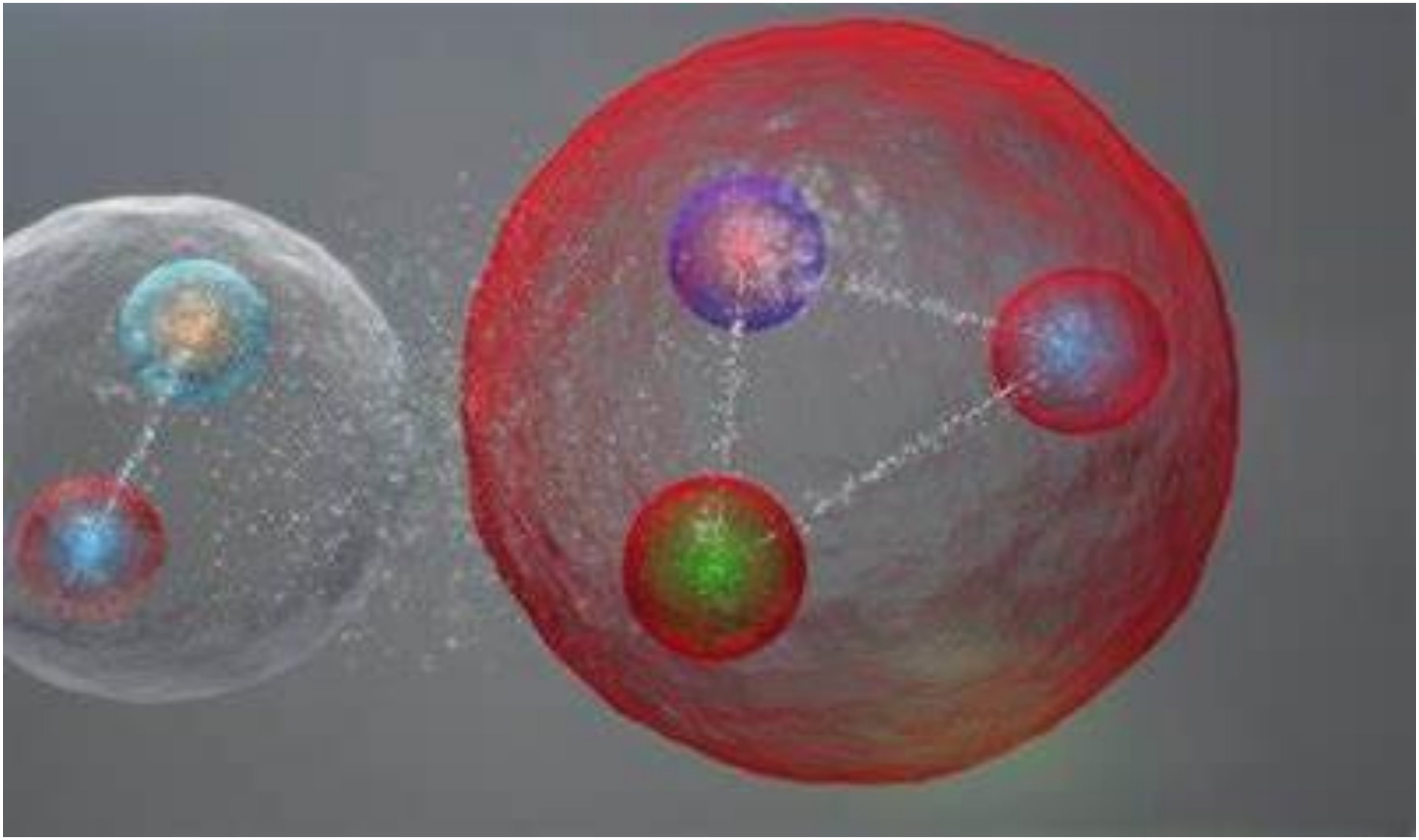
the research covered in Physics that **really made waves in and beyond the physics community.**



Four-Quark Matter/BESIII



Particle High Five/LHCb

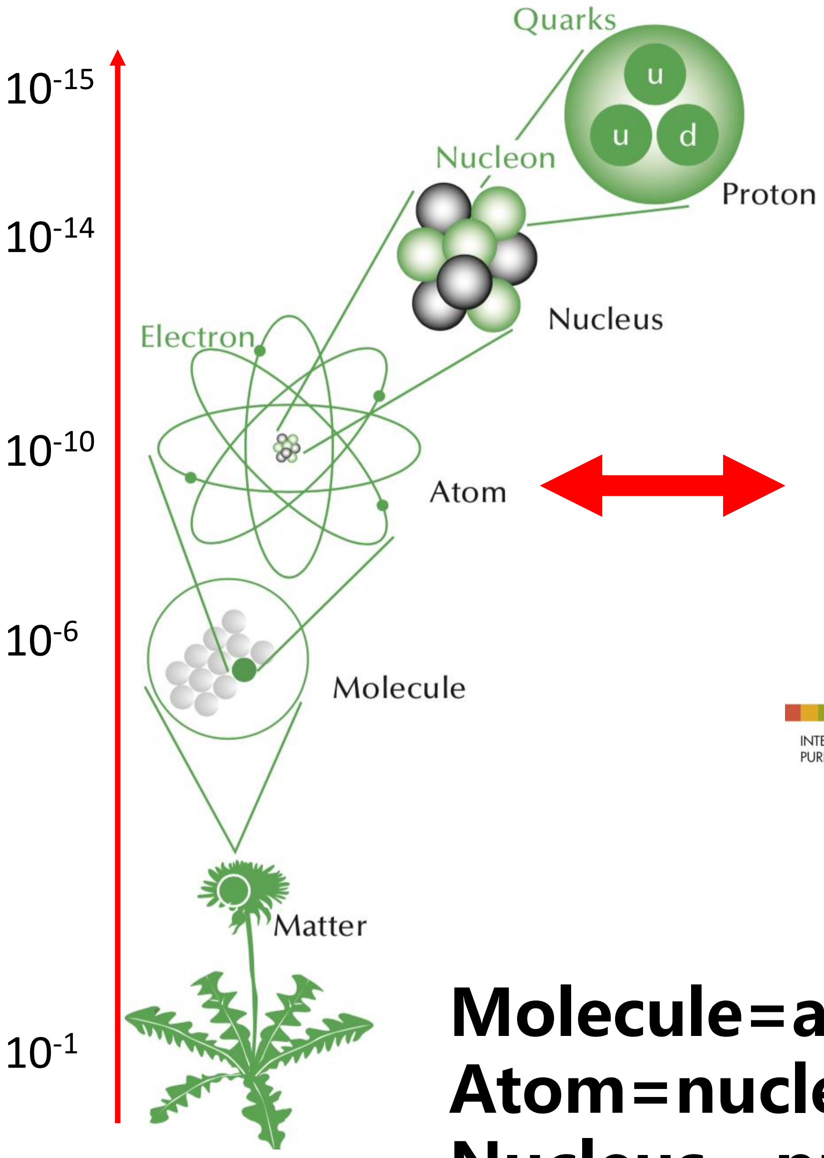


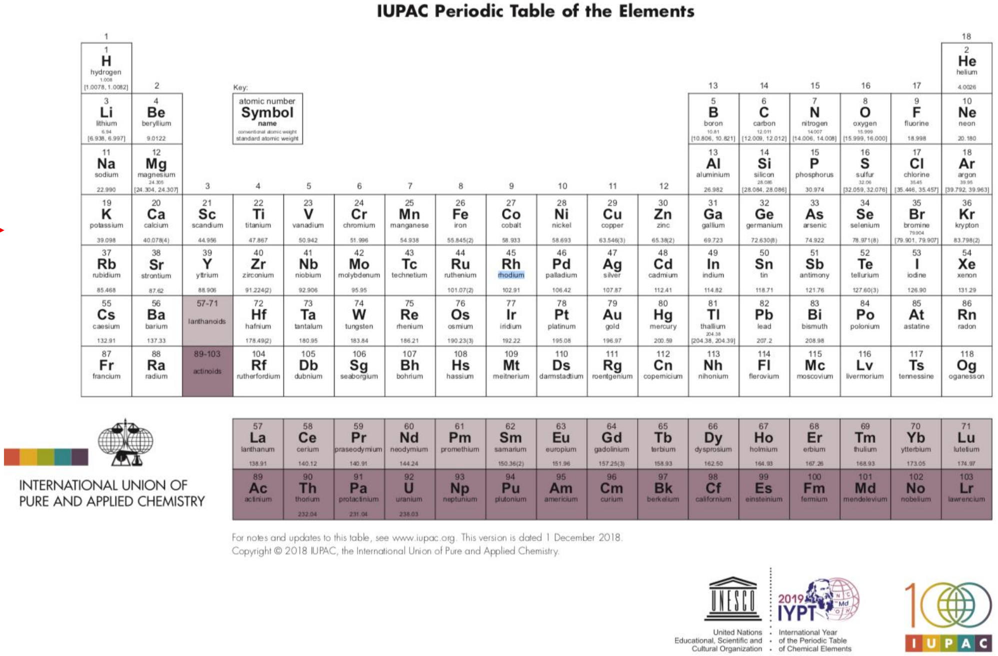
The molecular picture for the pentaquark states

Molecules are all around us, then why not

United Nations
Educational, Scientific and
Cultural Organization

International Year
of the Periodic Table
of Chemical Elements





IUPAC Periodic Table of the Elements

Key:
atomic number
Symbol
name
conventional atomic weight
standard atomic weight

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** hydrogen 1.008 [1.0078, 1.0082]																	2 **He** helium 4.0026
3 **Li** lithium 6.94 [6.938, 6.997]	4 **Be** beryllium 9.0122											5 **B** boron 10.81 [10.806, 10.821]	6 **C** carbon 12.011 [12.009, 12.012]	7 **N** nitrogen 14.007 [14.006, 14.008]	8 **O** oxygen 15.999 [15.999, 16.000]	9 **F** fluorine 18.998	10 **Ne** neon 20.180
11 **Na** sodium 22.990	12 **Mg** magnesium 24.305 [24.304, 24.307]											13 **Al** aluminium 26.982	14 **Si** silicon 28.085 [28.084, 28.086]	15 **P** phosphorus 30.974	16 **S** sulfur 32.06 [32.059, 32.076]	17 **Cl** chlorine 35.45 [35.446, 35.457]	18 **Ar** argon 39.95 [39.792, 39.963]
19 **K** potassium 39.098	20 **Ca** calcium 40.078(4)	21 **Sc** scandium 44.956	22 **Ti** titanium 47.867	23 **V** vanadium 50.942	24 **Cr** chromium 51.996	25 **Mn** manganese 54.938	26 **Fe** iron 55.845(2)	27 **Co** cobalt 58.933	28 **Ni** nickel 58.693	29 **Cu** copper 63.546(3)	30 **Zn** zinc 65.38(2)	31 **Ga** gallium 69.723	32 **Ge** germanium 72.630(8)	33 **As** arsenic 74.922	34 **Se** selenium 78.971(8)	35 **Br** bromine 79.904 [79.901, 79.907]	36 **Kr** krypton 83.798(2)
37 **Rb** rubidium 85.468	38 **Sr** strontium 87.62	39 **Y** yttrium 88.906	40 **Zr** zirconium 91.224(2)	41 **Nb** niobium 92.906	42 **Mo** molybdenum 95.95	43 **Tc** technetium	44 **Ru** ruthenium 101.07(2)	45 **Rh** rhodium 102.91	46 **Pd** palladium 106.42	47 **Ag** silver 107.87	48 **Cd** cadmium 112.41	49 **In** indium 114.82	50 **Sn** tin 118.71	51 **Sb** antimony 121.76	52 **Te** tellurium 127.60(3)	53 **I** iodine 126.90	54 **Xe** xenon 131.29
55 **Cs** caesium 132.91	56 **Ba** barium 137.33	57-71 lanthanoids	72 **Hf** hafnium 178.49(2)	73 **Ta** tantalum 180.95	74 **W** tungsten 183.84	75 **Re** rhenium 186.21	76 **Os** osmium 190.23(3)	77 **Ir** iridium 192.22	78 **Pt** platinum 195.08	79 **Au** gold 196.97	80 **Hg** mercury 200.59	81 **Tl** thallium 204.38 [204.38, 204.39]	82 **Pb** lead 207.2	83 **Bi** bismuth 208.98	84 **Po** polonium	85 **At** astatine	86 **Rn** radon
87 **Fr** francium	88 **Ra** radium	89-103 actinoids	104 **Rf** rutherfordium	105 **Db** dubnium	106 **Sg** seaborgium	107 **Bh** bohrium	108 **Hs** hassium	109 **Mt** meitnerium	110 **Ds** darmstadtium	111 **Rg** roentgenium	112 **Cn** copernicium	113 **Nh** nihonium	114 **Fl** flerovium	115 **Mc** moscovium	116 **Lv** livermorium	117 **Ts** tennessine	118 **Og** oganesson

57 **La** lanthanum 138.91	58 **Ce** cerium 140.12	59 **Pr** praseodymium 140.91	60 **Nd** neodymium 144.24	61 **Pm** promethium	62 **Sm** samarium 150.36(2)	63 **Eu** europium 151.96	64 **Gd** gadolinium 157.25(3)	65 **Tb** terbium 158.93	66 **Dy** dysprosium 162.50	67 **Ho** holmium 164.93	68 **Er** erbium 167.26	69 **Tm** thulium 168.93	70 **Yb** ytterbium 173.05	71 **Lu** lutetium 174.97
89 **Ac** actinium	90 **Th** thorium 232.04	91 **Pa** protactinium 231.04	92 **U** uranium 238.03	93 **Np** neptunium	94 **Pu** plutonium	95 **Am** americium	96 **Cm** curium	97 **Bk** berkelium	98 **Cf** californium	99 **Es** einsteinium	100 **Fm** fermium	101 **Md** mendelevium	102 **No** nobelium	103 **Lr** lawrencium

INTERNATIONAL UNION OF
PURE AND APPLIED CHEMISTRY

For notes and updates to this table, see www.iupac.org. This version is dated 1 December 2018.

United Nations
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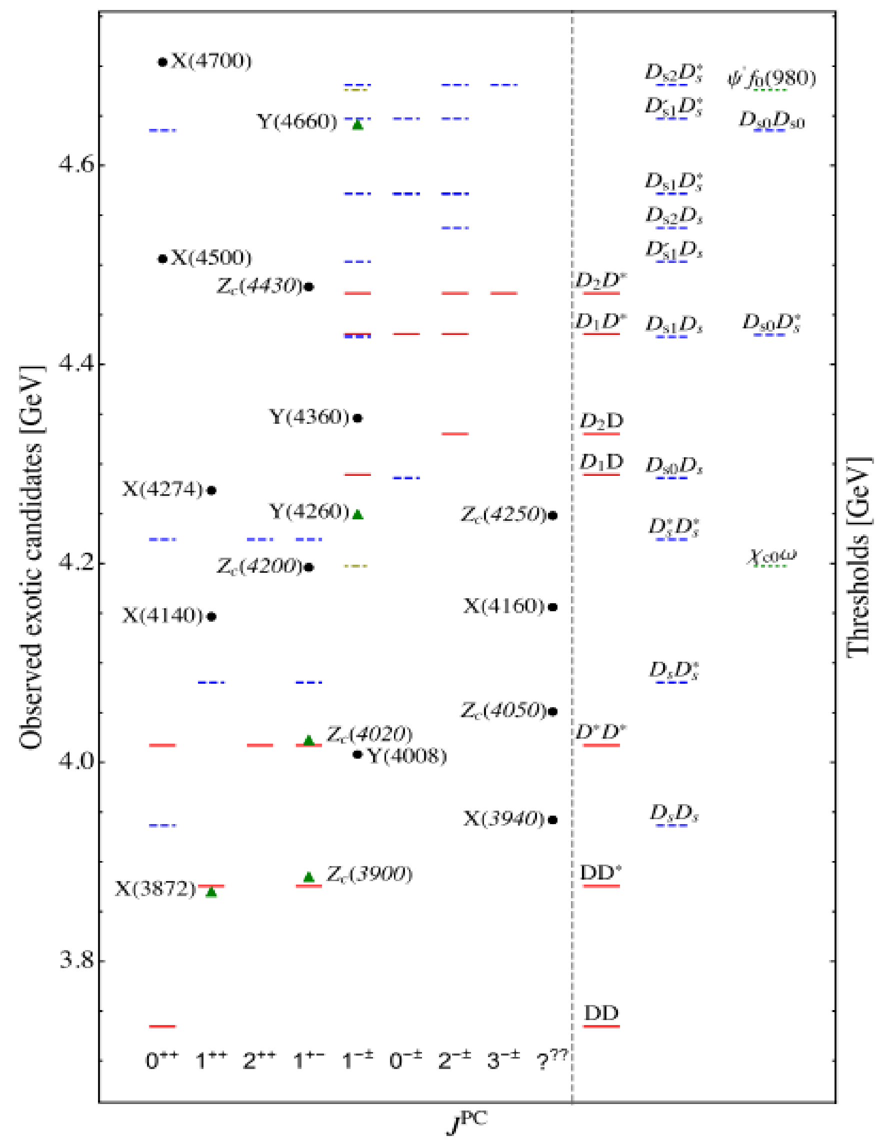
International Year
of the Periodic Table
of Chemical Elements

Molecule=atom + atom
Atom=nucleus + electron
Nucleus= proton(s) + neutron(s)

Three levels

Adapted from LHC the guide

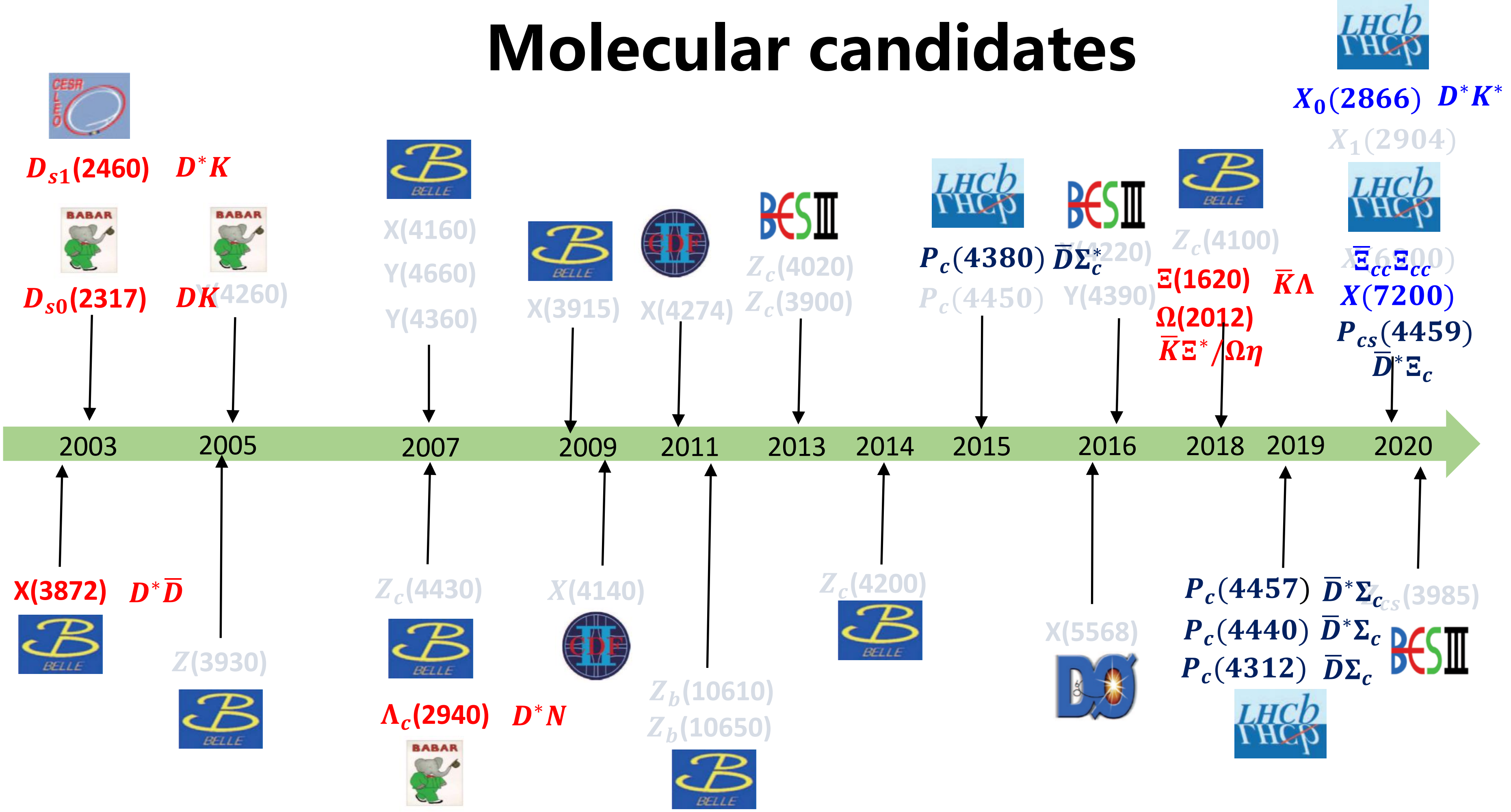
Many (if not all) of them close to thresholds



Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meißner, Qian Wang, Qiang Zhao, Bing-Song Zou. Rev.Mod.Phys. 90 (2018) 015004.

Exotic mesons or baryons **Tetraquark states** **Pentaquark states**

Molecular candidates



$D_{s1}(2460)$ D^*K

$D_{s0}(2317)$ DK

X(3872) $D^*\bar{D}$

Y(4260)

Z(3930)

X(4160)

Y(4660)

Y(4360)

$Z_c(4430)$

$\Lambda_c(2940)$ D^*N

X(3915)

$X(4140)$

X(4274)

$Z_b(10610)$

$Z_b(10650)$

$Z_c(4020)$

$Z_c(3900)$

$Z_c(4200)$

$P_c(4380)$ $\bar{D}\Sigma_c^*$

$P_c(4450)$

Y(4220)

Y(4390)

X(5568)

$Z_c(4100)$

$\Xi(1620)$ $\bar{K}\Lambda$

$\Omega(2012)$

$\bar{K}\Xi^*/\Omega\eta$

$P_c(4457)$ $\bar{D}^*\Sigma_c$

$P_c(4440)$ $\bar{D}^*\Sigma_c$

$P_c(4312)$ $\bar{D}\Sigma_c$

$X_0(2866)$ D^*K^*

$X_1(2904)$

X(6900) $\bar{\Xi}_{cc}\Xi_{cc}$

$X(7200)$

$P_{cs}(4459)$

$\bar{D}^*\Xi_c$

$Z_{cs}(3985)$

Before the 2015 LHCb discovery

As of 2021.01.20

- ☐ **Wu, Molina, Oset, Zou, PRL105, 232001(2001)-- 289**
- ☐ Wang, Huang, Zhang, Zou, PRC84, 015203(2011)--120
- ☐ Yang, Sun, He, Liu, Zhu, CPC36,6(2012)--166
- ☐ Wu, Lee, Zou, PRC85,044002(2012)—77
- ☐ Xiao, Nieves, Oset, PRD88,056012(2013)--143
- ☐ Karliner, Rosner, PRL115, 122001(2015)--193

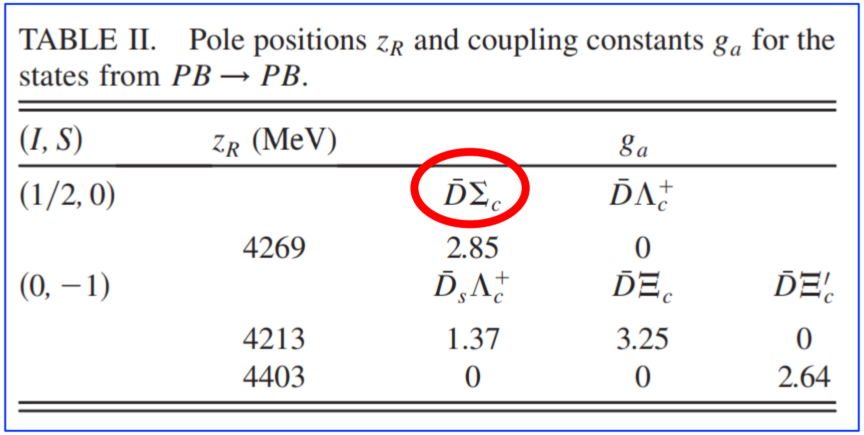


TABLE II. Pole positions z_R and coupling constants g_a for the states from $PB \to PB$.

(I, S)	z_R (MeV)	g_a		
$(1/2, 0)$		$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$	
	4269	2.85	0	
$(0, -1)$		$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi'_c$
	4213	1.37	3.25	0
	4403	0	0	2.64

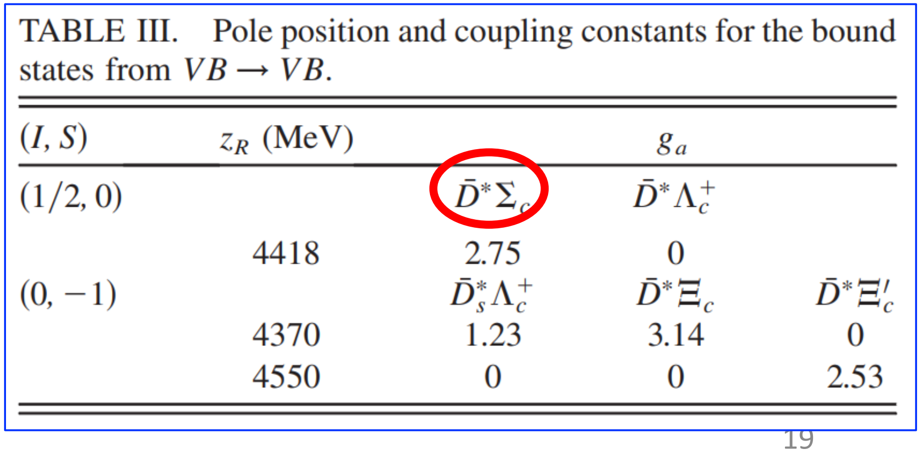
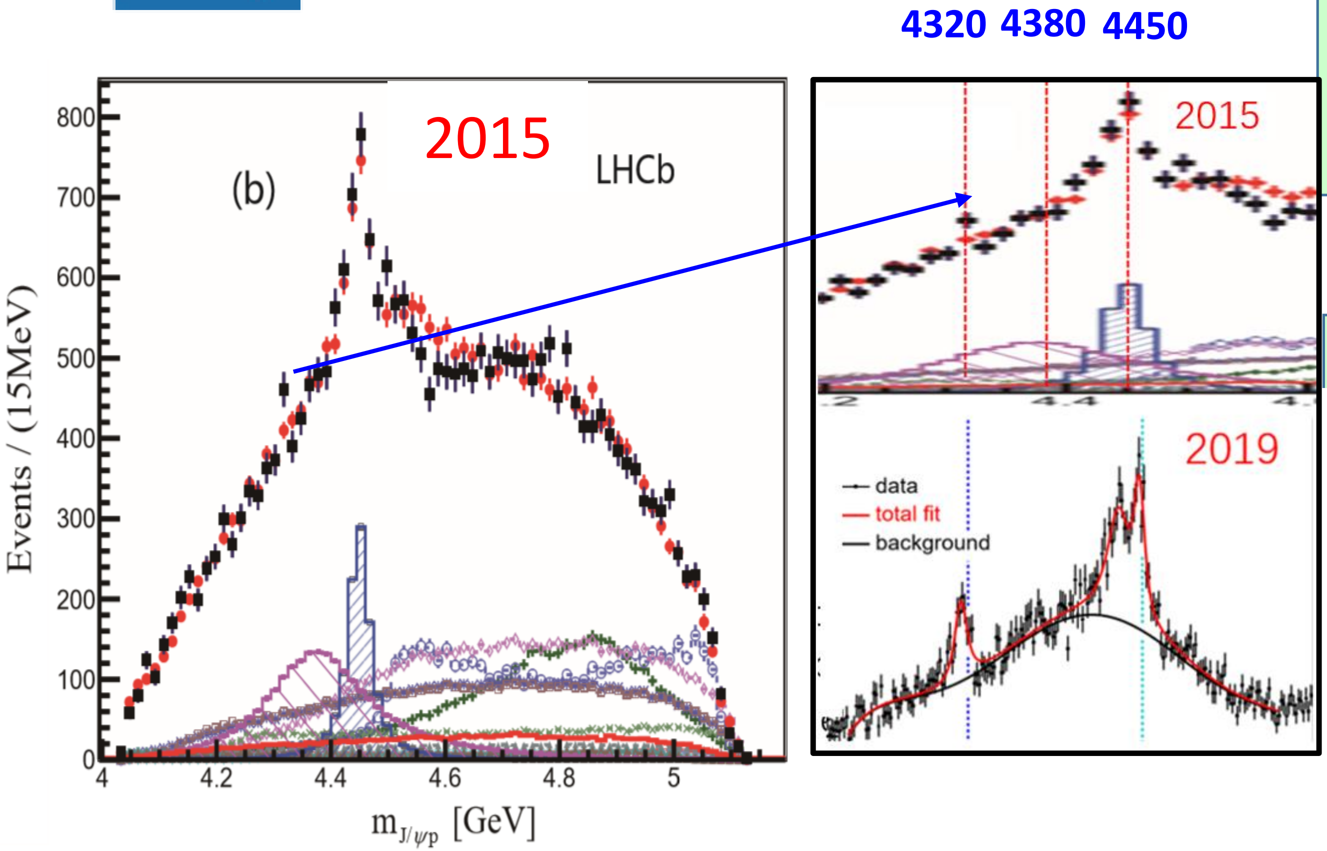


TABLE III. Pole position and coupling constants for the bound states from $VB \to VB$.

(I, S)	z_R (MeV)	g_a		
$(1/2, 0)$		$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$	
	4418	2.75	0	
$(0, -1)$		$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi'_c$
	4370	1.23	3.14	0
	4550	0	0	2.53

Pentaquarks from $\Lambda_b^0 \to J/\psi p K^-$



PRL 115 (2015) 072001
1140 citations

PRL 122 (2019) 222001
257 citations

as of 2021.01.21

2015

$$P_{c1} = 4380 \pm 8 \pm 29 + \frac{i}{2} 205 \pm 18 \pm 86$$

$$P_{c2} = 4449.8 \pm 1.7 \pm 2.5 + \frac{i}{2} 39 \pm 5 \pm 19$$

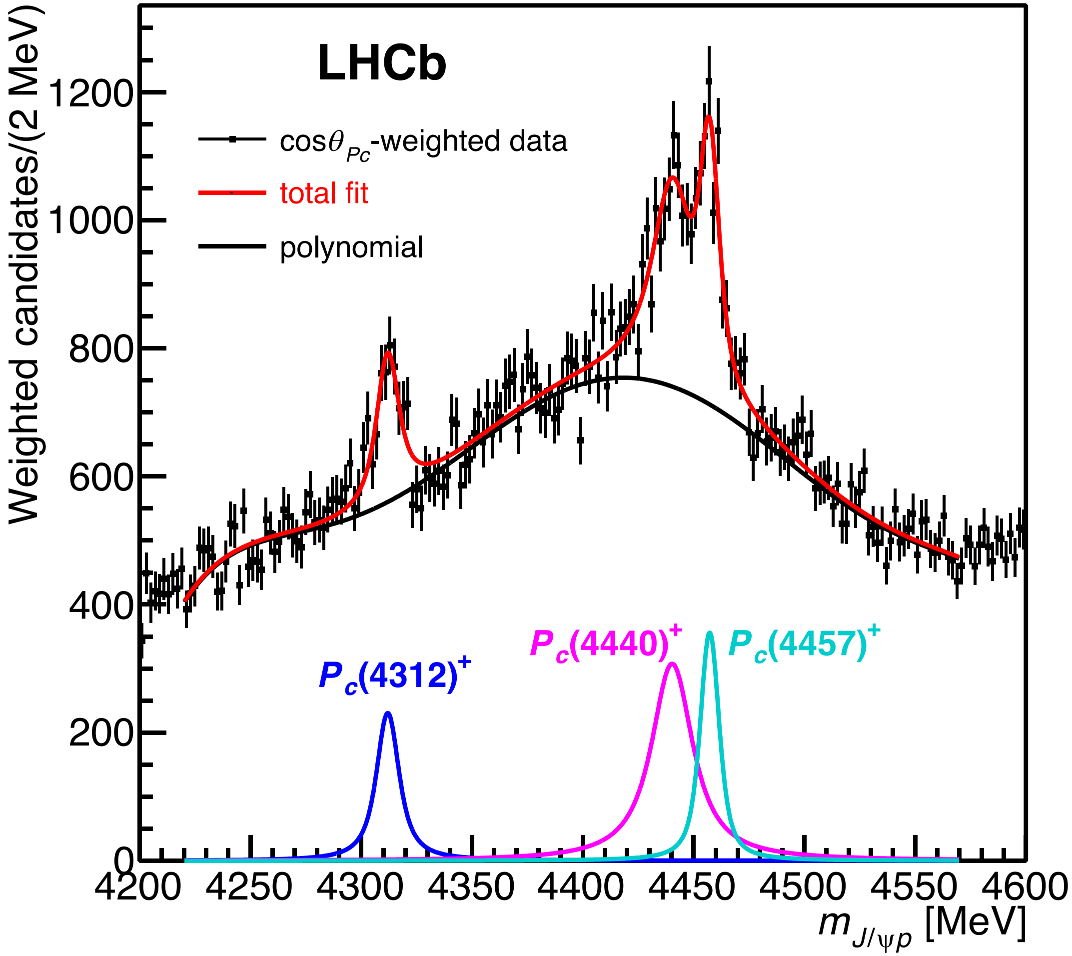
2019

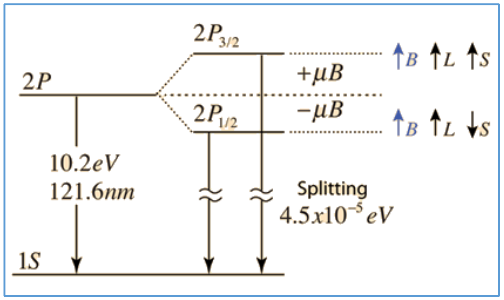
$$P_{c1} = 4311.9 \pm 0.7^{+6.8}_{-0.6} + \frac{i}{2} 9.8 \pm 2.7^{+3.7}_{-4.5}$$

$$P_{c2} = 4440.3 \pm 1.3^{+4.1}_{-4.7} + \frac{i}{2} 20.6 \pm 4.9^{+8.7}_{-10.1}$$

$$P_{c3} = 4457.3 \pm 0.6^{+4.1}_{-1.7} + \frac{i}{2} 6.4 \pm 2.0^{+5.7}_{-1.9}$$

Fine structure–new era of exotic hadrons





The existence of 7 molecules
—likely existence of
a (first) complete multiplet

After the 2019 LHCb discovery

☐ Molecular states

- ✓ *Rui Chen et al., 1903.11013*
- ✓ *Mingzhu Liu et al., 1903.11560*
- ✓ *Jun He et al., 1903.11872*
- ✓ *Chuwen Xiao et al., 1904.01296*
- ✓ *Jun He et al., 1909.05681*
- ✓ *T.J. Burns et al., 1908.03528*
- ✓ *Yasuhiro Yamaguchi et al.,1907.04684*
- ✓ *Mingzhu Liu et al., 1907.06093*
- ✓ *Menglin Du et al., 1910.11846*
- ✓ …

☐ Compact pentaquark states

- ✓ *Ahmed Ali, 1904.00446*
- ✓ *Zhi-Gang Wang et al., 1905.0892*
- ✓ *Jian-Bo Chen et al., 1905.08605*
- ✓ *X. –Z. Weng et al., 1904.09891*
- ✓ *R. Zhu et al., 1904.10285*
- ✓ …

☐ hadrocharmonium states

- ✓ Michael I. Eides et al., 1904.11616

☐ Virtual states -- Pc(4312)

- ✓ JPAC, 1904.10021

☐ Triangle singularities or cusp effects

Contents

☐ **Motivation: a new paradigm in studies of the strong interaction**

☐ **The new pentaquark states as $\bar{D}\Sigma_c$ molecules**

☐ **From $\Xi_{cc}\Sigma_c$ dibaryon mass splitting to the pentaquark spins**

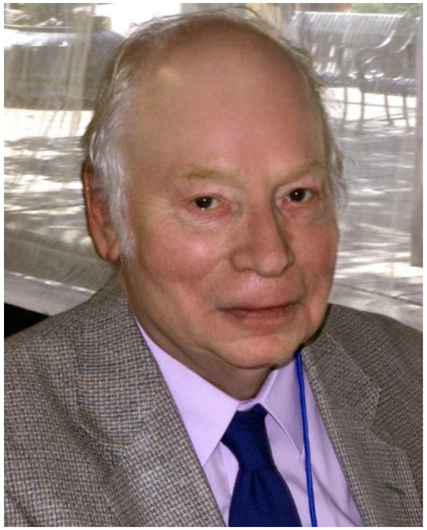
☐ **From Pcs to the pentaquark spins**

☐ **Summary and outlook**

Effective field theory

Phenomenological Lagrangians
Steven Weinberg (Harvard U. & Harvard-Smithsonian Ctr. Astrophys.). Oct 1978. 14 pp.
Published in **Physica A96 (1979) no.1-2, 327-340**
HUTP-78-A051A
DOI: 10.1016/0378-4371(79)90223-1
Conference: C78-02-18 Proceedings
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 3282 records 1000+

- ☐ **Some prominent examples**
  - ✓ Chiral perturbation theory ($\pi\pi, NN$)
  - ✓ Heavy quark effective field theory
  - ✓ Non-relativistic QCD
  - ✓ Soft collinear effective field theory
- ☐ **Three essential ingredients**
  - ✓ Effective degrees of freedom
  - ✓ Relevant symmetries
  - ✓ Power counting rules
- ☐ **Advantages**
  - ☐ Close relation with the underlying ‘full’ theory
  - ☐ Systematically improvable/uncertainties quantifiable
  - ☐ Self-consistent treatment of many-body interactions

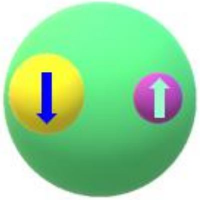


Steven Weinberg
Nobel prize 1979

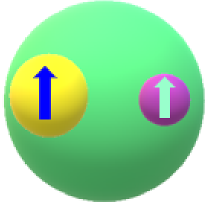
Heavy quark spin symmetry

$m_Q \to \infty$ **the strong interaction independent of the spin of heavy quark**

$$J = J_l - \frac{1}{2}$$



$$J = J_l + \frac{1}{2}$$



HQSS is broken in charm and bottom sector

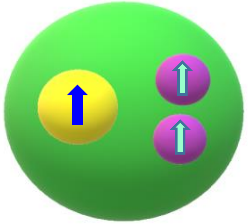
$$m_{D^*} - m_D = 142\ MeV$$

$$m_{B^*} - m_B = 46\ MeV$$

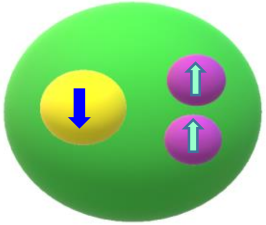
$$m_{\Sigma_c^*} - m_{\Sigma_c} = 64MeV$$

$$m_{\Sigma_b^*} - m_{\Sigma_b} = 21MeV$$

$$J = J_l - \frac{1}{2}$$



$$J = J_l + \frac{1}{2}$$

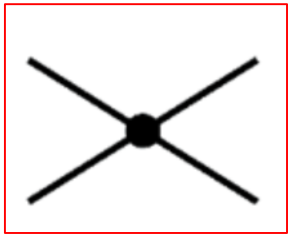


Effective field theory: $\bar{D}$ $(\overline{D^*})$ Σ_c (Σ_c^*)

Power counting: naïve dimensional analysis

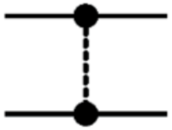
☐ **Leading order**

- **Contact**



pionless

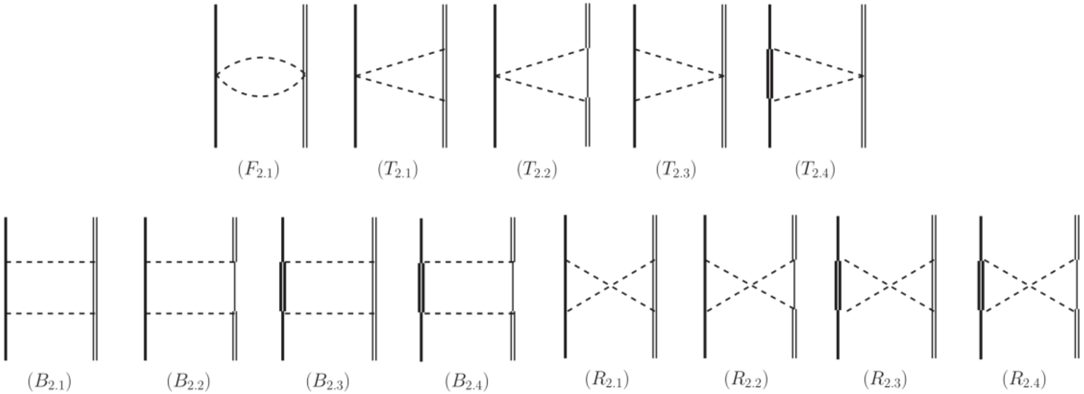
- **One pion exchange**



OPE is perturbative in charm hadronic interactions—*Jun-Xu Lu et al., PRD99 (2019) 074026*

M. Valderrama, 1907.05294

☐ **Next to leading order—pion full**



Lu Meng et al., PRD100 (2019) 014031; Bo Wang et al., 1909.13054

Leading order Lagrangian satisfying HQS

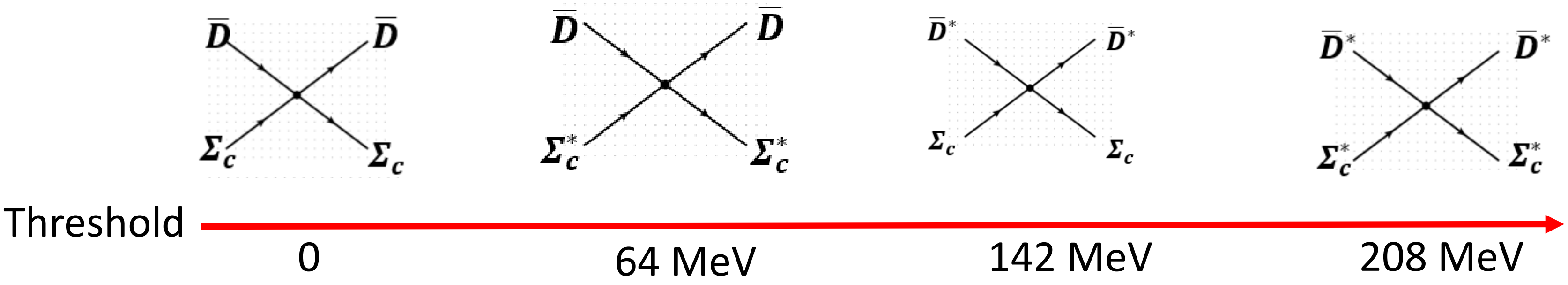
$$L = C_a Tr[H_c^\dagger H_c]\vec{S}_c \cdot \vec{S}_c^{\ \dagger} + C_b \sum_{i=1}^{3} Tr[H_c^\dagger \sigma_i H_c]\vec{S}_c \cdot (J_i \vec{S}_c^{\ \dagger})$$

$$H_c = \frac{1}{\sqrt{2}}(D + \vec{D}^* \vec{\sigma}) \qquad \vec{S}_c = \frac{1}{\sqrt{3}}(\Sigma_c \vec{\sigma} + \vec{\Sigma}^*{}_c)$$

Spin 1 matrices

$$J_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \qquad J_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{pmatrix}$$

$$J_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix},$$



Leading order potentials

$$V(\tfrac{1}{2}^-, \Sigma_c \bar{D}) = C_a$$

$$V(\tfrac{3}{2}^-, \Sigma_c^* \bar{D}) = C_a$$

$$V(1/2^-, \Sigma_c \bar{D}^*) = C_a - \frac{4}{3}\, C_b$$

$$V(3/2^-, \Sigma_c \bar{D}^*) = C_a + \frac{2}{3}\, C_b$$

$$V(1/2^-, \Sigma_c^* \bar{D}^*) = C_a - \frac{5}{3}\, C_b$$

$$V(3/2^-, \Sigma_c^* \bar{D}^*) = C_a - \frac{2}{3}\, C_b$$

$$V(5/2^-, \Sigma_c^* \bar{D}^*) = C_a + C_b$$

☐ C_a:responsible for overall interaction
C_b: responsible for spin splitting

☐ **Without experimental inputs, there is no (not much) predictive power**

☐ Two inputs are needed to fix the two LECs, LHCb provides three

☐ Ambiguity: two $\overline{D^*}\,\boldsymbol{\Sigma}_c$ bound states

Pc(4440)/Pc(4457)

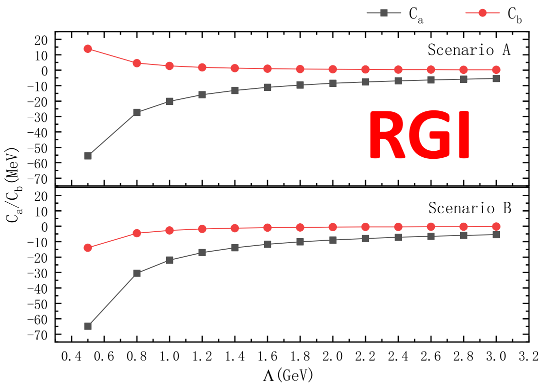
Search for bound states

☐ Lippmann-Schwinger Equation

$$\left\langle \vec{k}' \left| T \right| \vec{k} \right\rangle = \left\langle \vec{k}' \left| T \right| \vec{k} \right\rangle + \int \frac{d^3\vec{q}}{(2\pi)^3} \left\langle \vec{k}' \left| V \right| \vec{q} \right\rangle \frac{1}{E - \frac{\vec{q}^2}{2\mu}} \left\langle \vec{q} \left| T \right| \vec{k} \right\rangle$$

☐ Separable potential $\left\langle \vec{k} \left| V \right| \vec{q} \right\rangle = C(\Lambda) f\left(\Lambda, \left|\vec{k}\right|\right) f(\Lambda, |\vec{q}|)$

$$1 + \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{C(\Lambda) f^2(\Lambda, |\vec{q}|)}{B + \frac{\vec{q}^2}{2\mu}} = 0$$



RGI

Fit to the LHCb data: two scenarios

$$V(1/2^-,\Sigma_c\bar{D}\,) = C_a$$

$$V(3/2^-,\Sigma_c^*\bar{D}) = C_a$$

$$\boldsymbol{V(1/2^-,\Sigma_c\bar{D}^*) = C_a - \frac{4}{3}\,C_b}$$

$$\boldsymbol{V(3/2^-,\Sigma_c\bar{D}^*) = C_a + \frac{2}{3}\,C_b}$$

$$V(1/2^-,\Sigma_c^*\bar{D}^*) = C_a - \frac{5}{3}\,C_b$$

$$V(3/2^-,\Sigma_c^*\bar{D}^*) = C_a - \frac{2}{3}\,C_b$$

$$V(5/2^-,\Sigma_c^*\bar{D}^*) = C_a +\,C_b$$

LHCb data

$$P_{c1} = 4311.9 \pm 0.7^{+6.8}_{-0.6} + \frac{i}{2}9.8 \pm 2.7^{+3.7}_{-4.5}$$

$$\boldsymbol{P_{c2} = 4440.3 \pm 1.3^{+4.1}_{-4.7} + \frac{i}{2}20.6 \pm 4.9^{+8.7}_{-10.1}}$$

$$\boldsymbol{P_{c3} = 4457.3 \pm 0.6^{+4.1}_{-1.7} + \frac{i}{2}6.4 \pm 2.0^{+5.7}_{-1.9}}$$

Three experimental data and two unknown coupling constants

C_a and C_b can be determined !

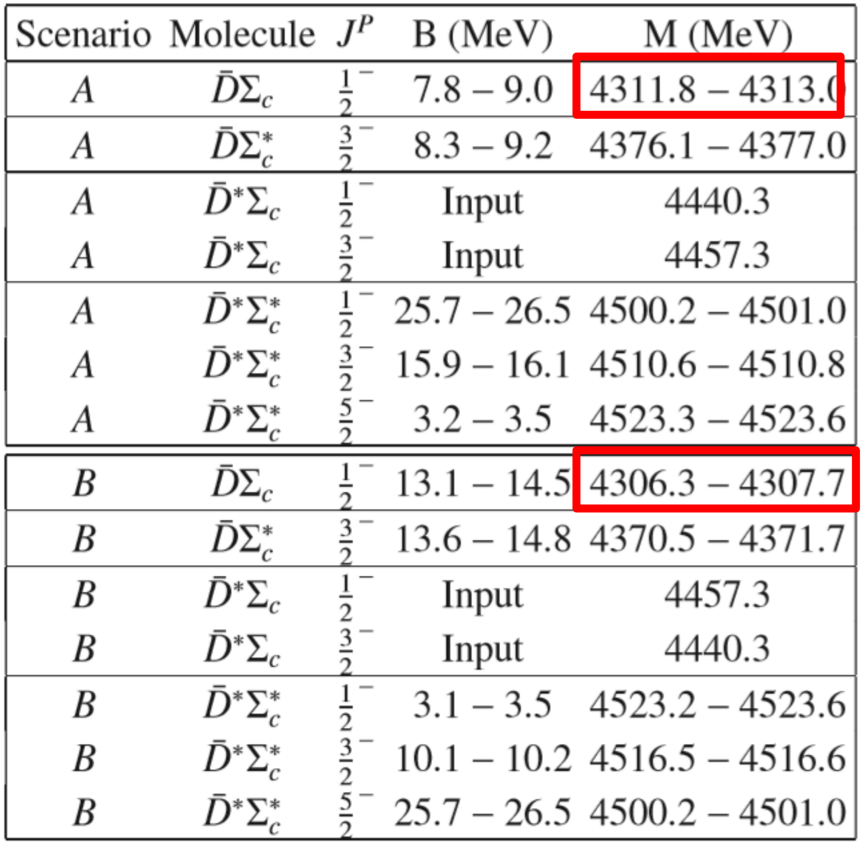
Input

A $\bar{D}^*\Sigma_c\,(3/2^-)\,Pc(4457)$ $\bar{D}^*\Sigma_c\,(1/2^-)\,Pc(4440)$

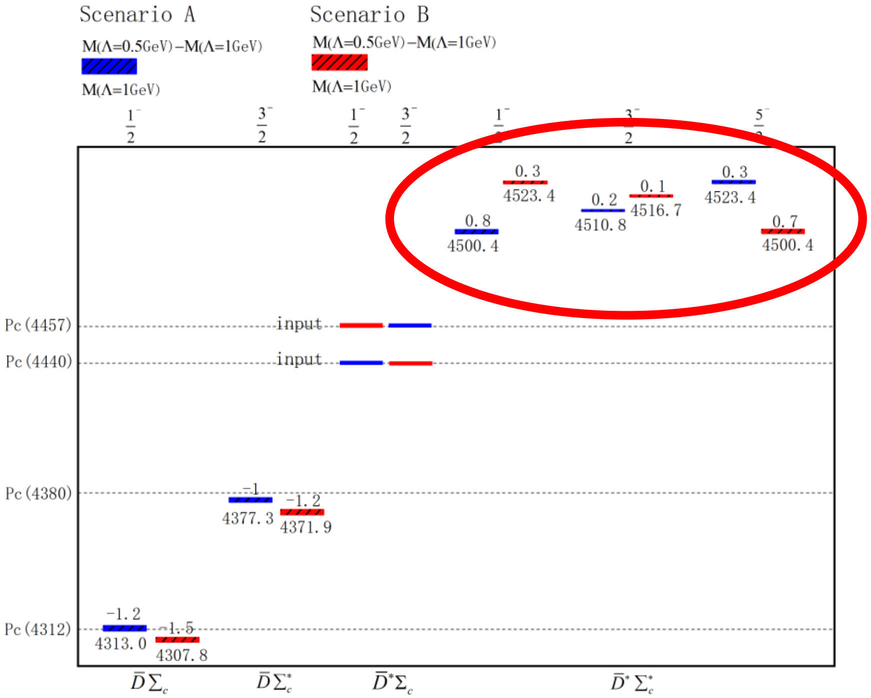
B $\bar{D}^*\Sigma_c\,(1/2^-)\,Pc(4457)$ $\bar{D}^*\Sigma_c\,(3/2^-)\,Pc(4440)$

Emergence of a complete HQS multiplet (7)

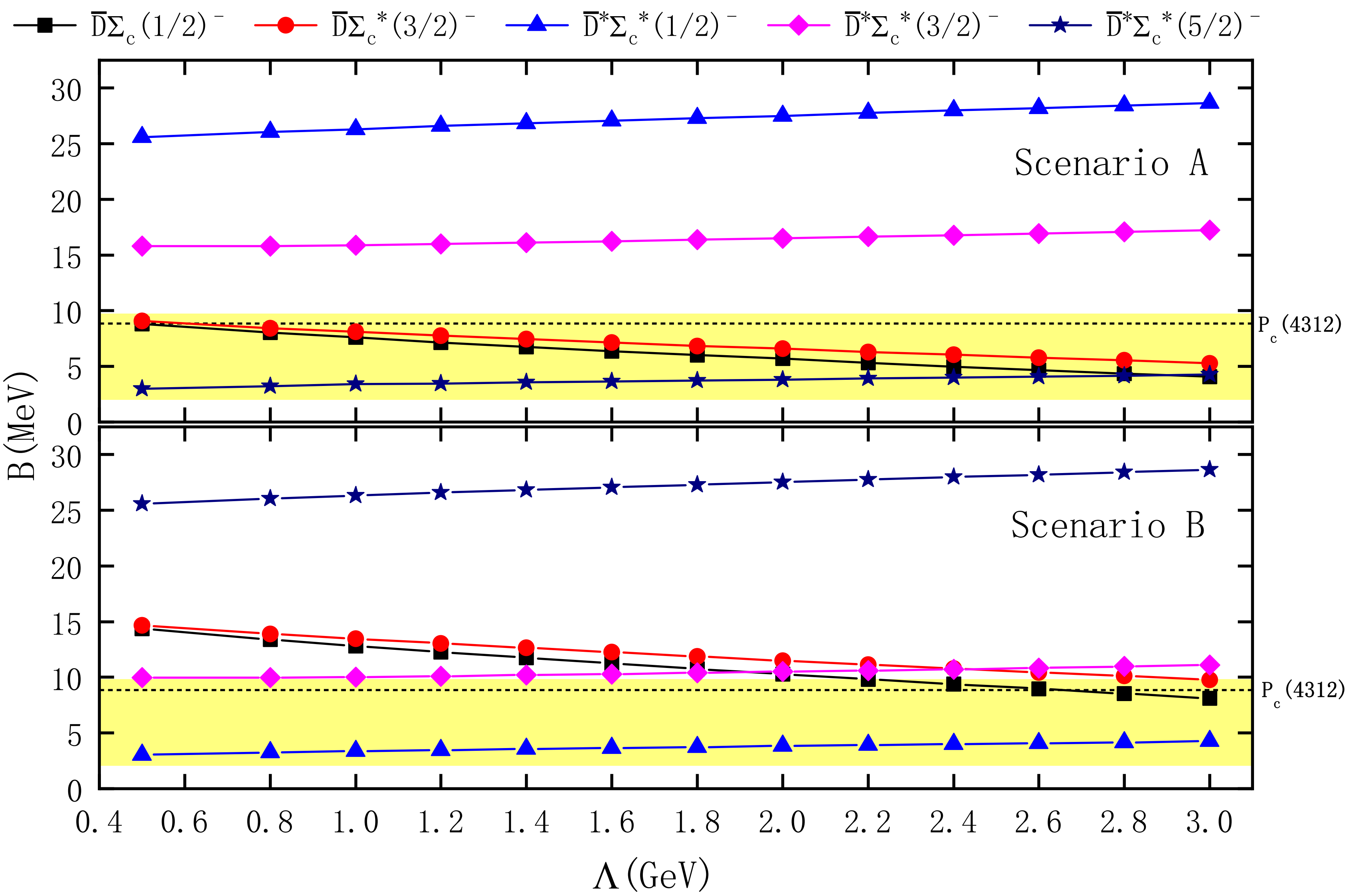
3 new states



Scenario	Molecule	J^P	B (MeV)	M (MeV)
A	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	$7.8-9.0$	$4311.8-4313.0$
A	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	$8.3-9.2$	$4376.1-4377.0$
A	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4440.3
A	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4457.3
A	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	$25.7-26.5$	$4500.2-4501.0$
A	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	$15.9-16.1$	$4510.6-4510.8$
A	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	$3.2-3.5$	$4523.3-4523.6$
B	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	$13.1-14.5$	$4306.3-4307.7$
B	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	$13.6-14.8$	$4370.5-4371.7$
B	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4457.3
B	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4440.3
B	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	$3.1-3.5$	$4523.2-4523.6$
B	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	$10.1-10.2$	$4516.5-4516.6$
B	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	$25.7-26.5$	$4500.2-4501.0$



RGI of binding energy of the pentaquarks



Spin-parities important to understand the Pcs

- ☐ Spins of the Pc(4457) and Pc(4440) undetermined
- ☐ Different molecular models show different preferences

Pc(4457): $3/2^-$
Pc(4440): $1/2^-$

Rui Chen et al., 1903.11013
Jun He et al., 1903.11872
Chuwen Xiao et al., 1904.01296
Jun He et al., 1909.05681

Vs.

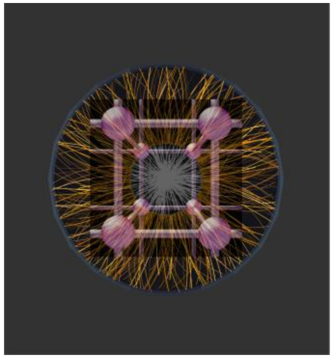
Pc(4457): $1/2^-$
Pc(4440): $3/2^-$

Y. Yamaguchi et al.,1907.04684
Mingzhu Liu et al., 1907.06093

- ☐ Other model predictions are even more distinct

Compact diquark model	QCD sum rule (M)	NR Quark model	QCD sum rule (C)
Ahmed Ali et al., 1904.00446	H. X. Chen et al., 1904.00446	Ruilin Zhu et al., 1904.00446	Zhi-Gang Wang et al., 1905.0892
Pc(4457): $5/2^+$	Pc(4457): $3/2^-$ ($5/2^-$)	Pc(4457): $1/2^-$	Pc(4457): 1,$3/2^-$
Pc(4440): $3/2^+$	Pc(4440): $3/2^-$($1/2^-$)	Pc(4440): $1/2^-$	Pc(4440): 1,3,$5/2^-$
Pc(4312): $3/2^-$	Pc(4312): $1/2^-$	Pc(4312): $3/2^-$ ($1/2^-$)	Pc(4312): $1/2^-$

Turn to lattice QCD?



☐ **Coupled channel study difficult**

☐ **Up to now, only two groups studied $J/\psi N$ interactions, and no pentaquark states found**

- ✓ *T. Sugiura, Y. Ikeda, and N. Ishii, 1905.02336.*
- ✓ *U. Skerbis and S. Prelovsek, 1811.02285.*

☐ **Recently, a study of 1+ $\Xi_{cc}\Sigma_c$ baryons was successfully performed, and some bound states were found**

B=8(17)MeV, Parikshit Junnarkar et al., 1906.06054

☐ **In a recent paper, we show that it is possible to determine the spins of the pentaquark states by studying the spectroscopy of the dibaryon systems via heavy antidquark diquark symmetry.**

Ya-Wen Pan et al., 1907.11220

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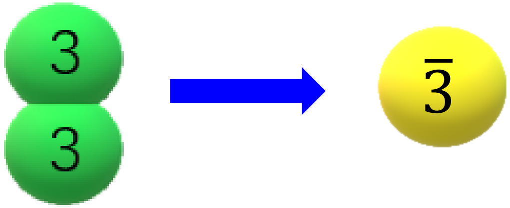
- ☐ **From Pcs to the pentaquark spins**
- ☐ **Summary and outlook**

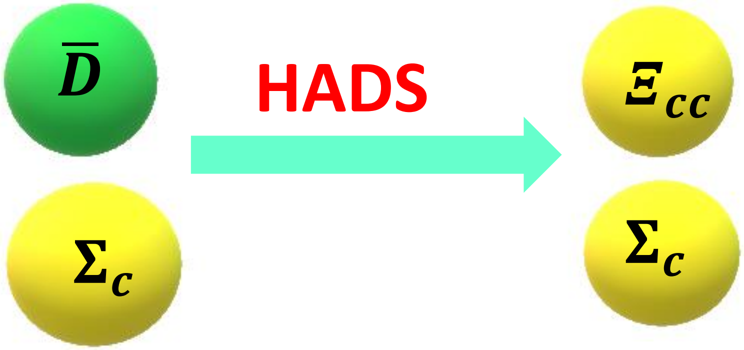
Heavy Antiquark Diquark symmetry(HADS)

- Heavy diquark behaves as a heavy anti-quark from color freedom

Savage et al., PLB248 (1990) 177; Hu et al., PRD73 (2006) 054003

$$3 \otimes 3 = 6 \oplus \bar{3}$$





- Predictions tested in lattice QCD (satisfied at the level of 25%)

$$m_{\Xi_{cc\,3/2}} - m_{\Xi_{cc\,1/2}} = \frac{3}{4}(m_{D*} - m_D) \approx 106.5 MeV$$

$$m_{\Omega_{cc\,3/2}} - m_{\Omega_{cc\,1/2}} = \frac{3}{4}(m_{Ds*} - m_{Ds}) \approx 107.9 MeV$$

M. Padmanath et al., Phys. Rev. D91, 094502 (2015), 1502.01845; Y.-C. Chen et al., Phys. Lett. B767, 193 (2017), 1701.02581; C. Alexandrou et al., Phys. Rev. D96, 034511 (2017), 1704.02647; N. Mathur et al., Phys. Rev. D99, 031501 (2019), 1807.00174.

Dibaryon systems

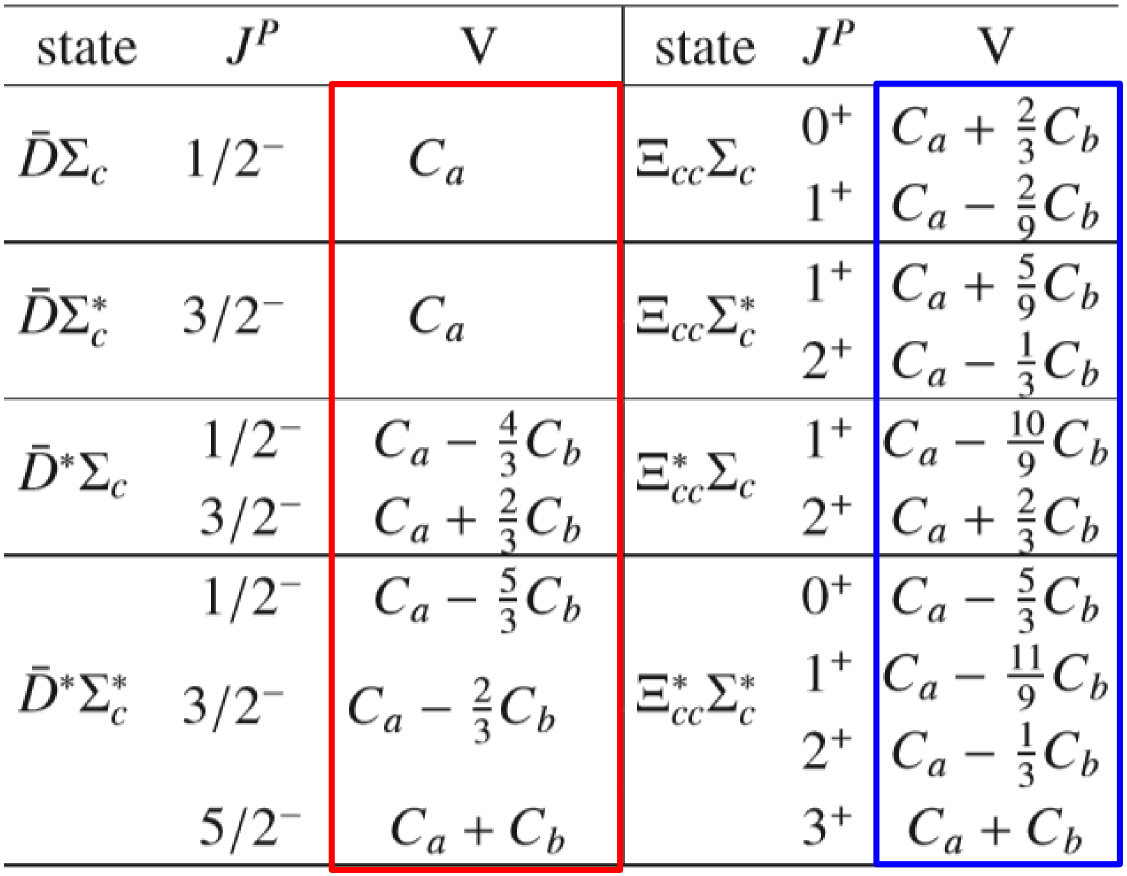
$$L_{D\Sigma_c} = C_a Tr[H_c^{\dagger} H_c]\vec{S}_c \cdot \vec{S}_c{}^{\dagger} + C_b \sum_{i=1}^{3} Tr[H_c^{\dagger}\sigma_i H_c]\vec{S}_c \cdot (J_i \vec{S}_c{}^{\dagger})$$

$$\Big\downarrow$$

$$H_c = \frac{1}{\sqrt{2}}(D + \vec{D}^{*}\vec{\sigma}) \Longrightarrow \vec{T}_{cc} = \frac{1}{\sqrt{3}}(\Xi_{cc}\vec{\sigma} + \vec{\Xi}^{*}{}_{cc})$$

$$L_{\Xi_{cc}\Sigma_c} = C_a Tr[\vec{T}_{cc}^{\dagger}\vec{T}_{cc}]\vec{S}_c \cdot \vec{S}_c{}^{\dagger} + C_b \sum_{i=1}^{3} Tr[\vec{T}_{cc}^{\dagger}\sigma_i \vec{T}_{cc}]\vec{S}_c \cdot (J_i \vec{S}_c{}^{\dagger})$$

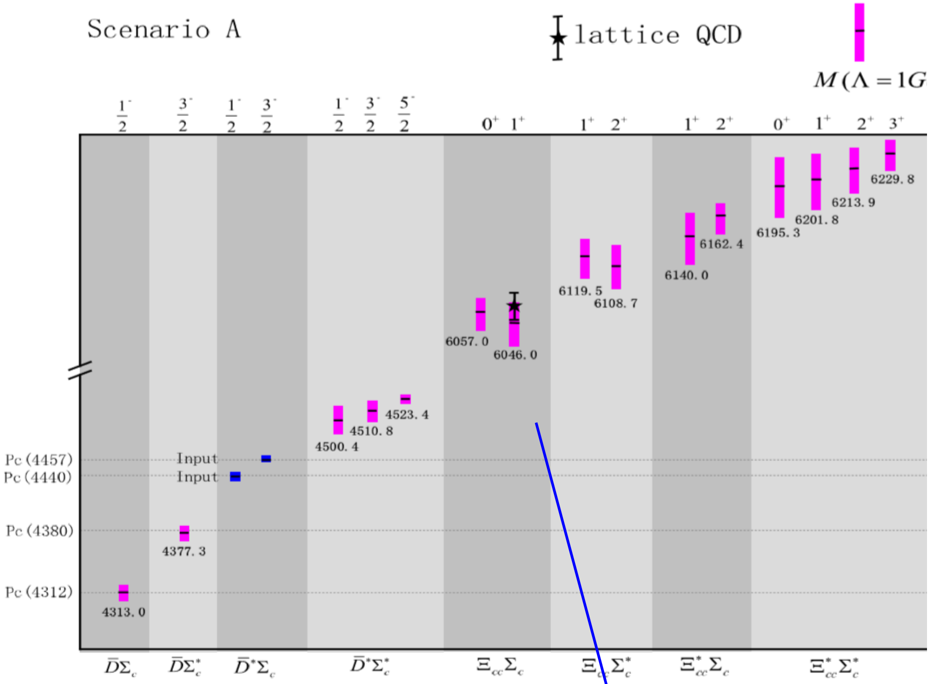
The same potentials in the HQS limit

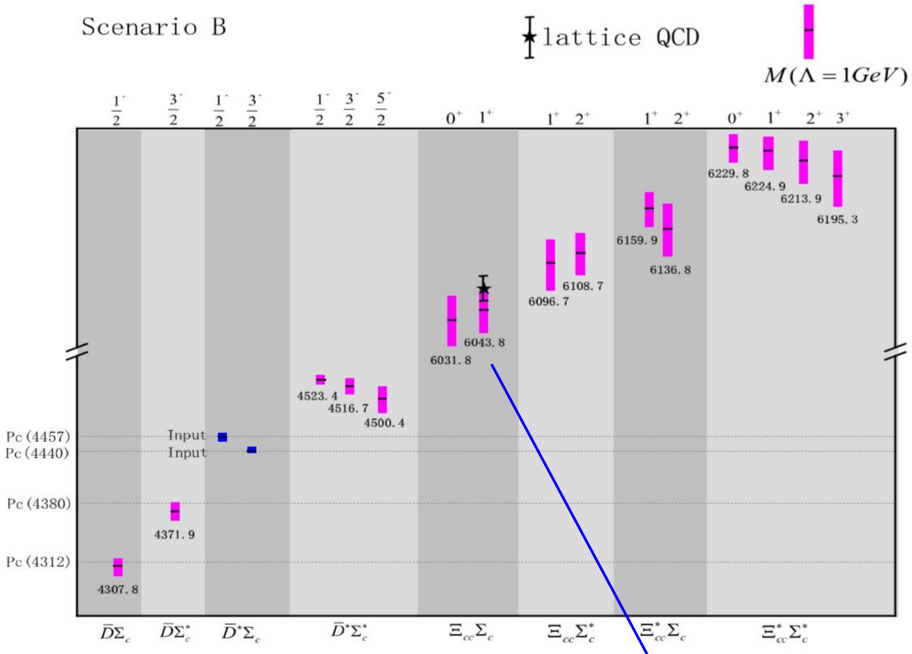


state	J^P	V	state	J^P	V
$\bar{D}\Sigma_c$	$1/2^-$	C_a	$\Xi_{cc}\Sigma_c$	0^+	$C_a+\frac{2}{3}C_b$
				1^+	$C_a-\frac{2}{9}C_b$
$\bar{D}\Sigma_c^*$	$3/2^-$	C_a	$\Xi_{cc}\Sigma_c^*$	1^+	$C_a+\frac{5}{9}C_b$
				2^+	$C_a-\frac{1}{3}C_b$
$\bar{D}^*\Sigma_c$	$1/2^-$	$C_a-\frac{4}{3}C_b$	$\Xi_{cc}^*\Sigma_c$	1^+	$C_a-\frac{10}{9}C_b$
	$3/2^-$	$C_a+\frac{2}{3}C_b$		2^+	$C_a+\frac{2}{3}C_b$
$\bar{D}^*\Sigma_c^*$	$1/2^-$	$C_a-\frac{5}{3}C_b$	$\Xi_{cc}^*\Sigma_c^*$	0^+	$C_a-\frac{5}{3}C_b$
	$3/2^-$	$C_a-\frac{2}{3}C_b$		1^+	$C_a-\frac{11}{9}C_b$
				2^+	$C_a-\frac{1}{3}C_b$
	$5/2^-$	C_a+C_b		3^+	C_a+C_b

LHCb data lead to **10 molecular dibaryon states**

From (10) dibaryons to (7) pentquarks





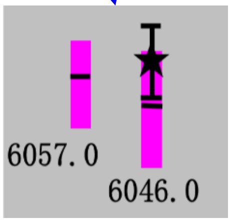
Mass splitting of $\Xi_{cc}\Sigma_c$ system

Lattice QCD

1906.06054

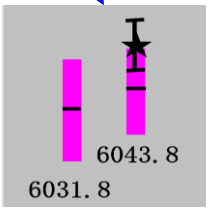
$$1^+ - 0^+ = -8.4\ MeV$$

$$\Delta_m < 0$$



$$1^+ - 0^+ = 9.7\ MeV$$

$$\Delta_m > 0$$



Correlations seem to be robust

- ☐ **Heavy quark spin symmetry breaking** $\frac{\Lambda_{QCD}}{m_c} \approx 15\%$
- ☐ **Heavy antiquark diquark symmetry breaking** $\frac{\Lambda_{QCD}}{m_c\, v} \approx 25\%$

$1^+ - 0^+ = -(4.9\sim 11.8) MeV$

$\Delta_m < 0$

Scenario A

3/2 higher
1/2 lower

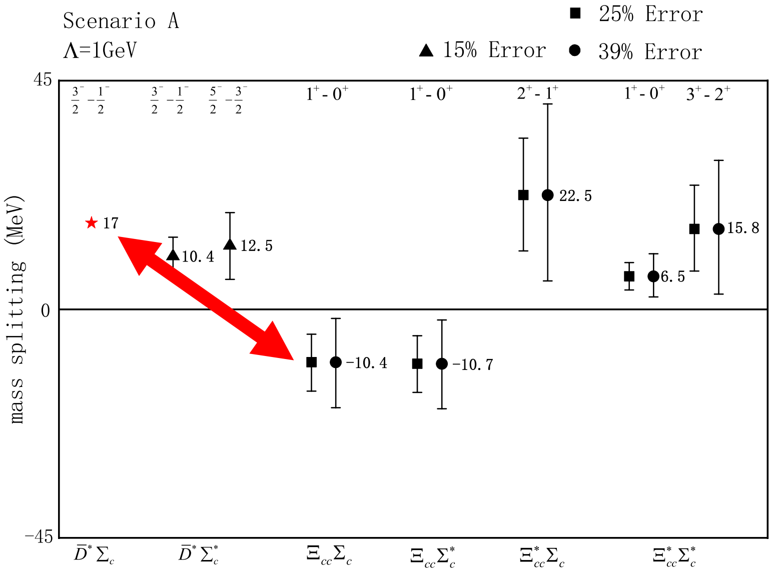
$1^+ - 0^+ = 6.3\sim 13.1\ MeV$

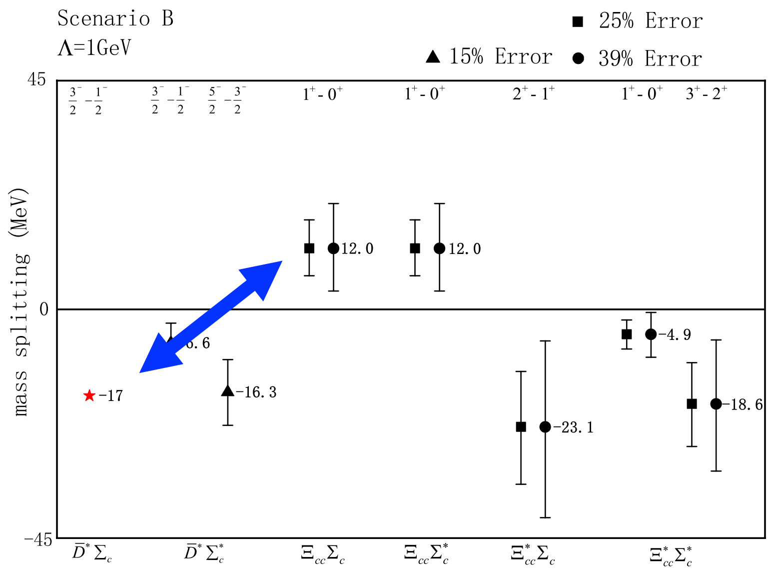
$\Delta_m > 0$

Scenario B

1/2 higher
3/2 lower

Breaking up to 39%

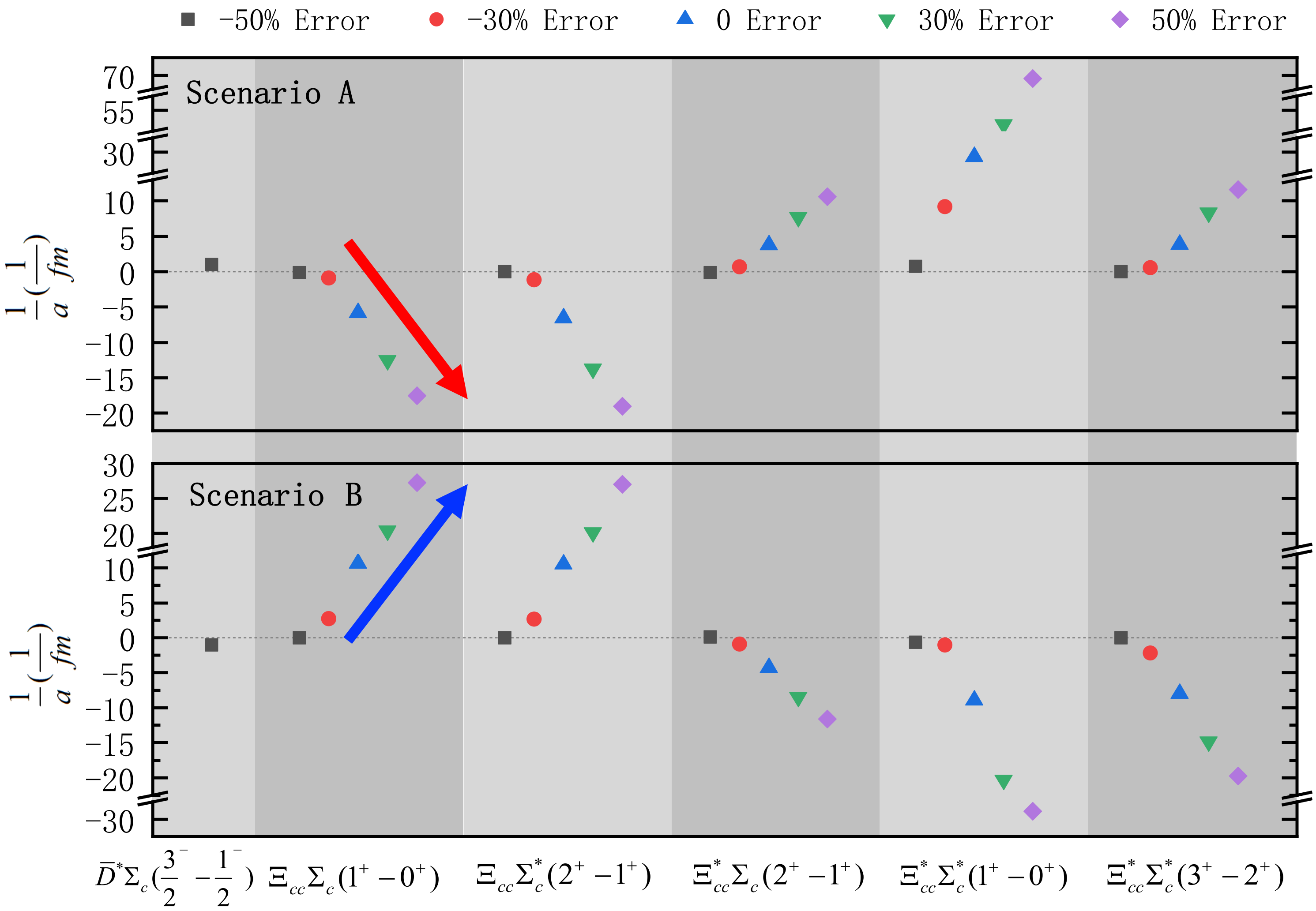




Pc(4457): 3/2
Pc(4440): 1/2

Pc(4457): 1/2
Pc(4440): 3/2

Correlation in case of **even larger** breaking



Scattering lengths

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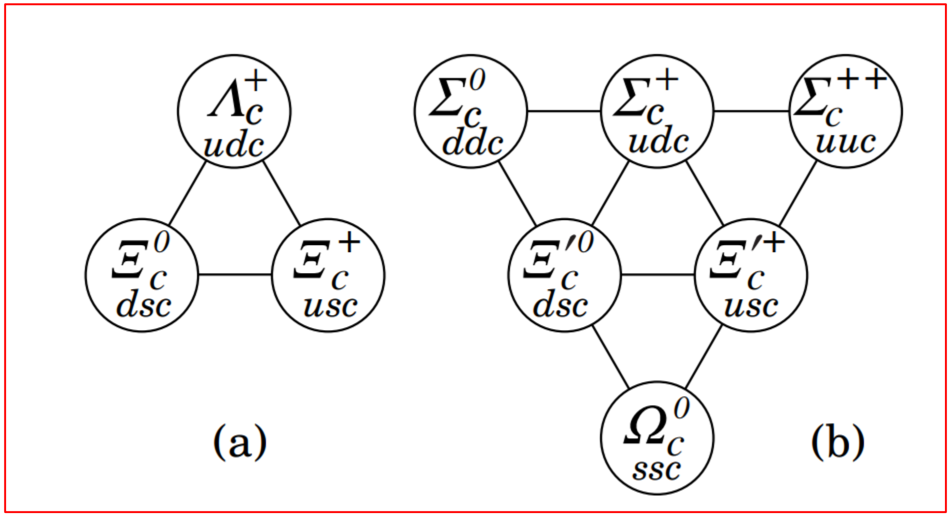
SU(3)symmetry

$$\bar{D}^{(*)}\Sigma_c^{(*)} \longrightarrow \bar{D}^{(*)}\Xi_c^{(\prime *)}$$

From Σ_c to Ξ_c', straightforward, the same light quark spin



$$V(\bar{D}\Xi_c', J=\tfrac{1}{2}) = C_a\,,$$

$$V(\bar{D}\Xi_c^*, J=\tfrac{3}{2}) = C_a\,,$$

$$V(\bar{D}^*\Xi_c', J=\tfrac{1}{2}) = C_a - \tfrac{4}{3}\,C_b\,,$$
$$V(\bar{D}^*\Xi_c', J=\tfrac{3}{2}) = C_a + \tfrac{2}{3}\,C_b\,,$$

$$V(\bar{D}^*\Xi_c^*, J=\tfrac{1}{2}) = C_a - \tfrac{5}{3}\,C_b\,,$$
$$V(\bar{D}^*\Xi_c^*, J=\tfrac{3}{2}) = C_a - \tfrac{2}{3}\,C_b\,,$$
$$V(\bar{D}^*\Xi_c^*, J=\tfrac{5}{2}) = C_a + C_b\,.$$

SU(3)symmetry

$\bar{D}^{(*)}\Sigma_c^{(*)} \longrightarrow \bar{D}^{(*)}\Xi_c^{(*)}$

From Σ_c and Ξ_c , more assumptions are needed

- ☐ **For $\bar{D}^{(*)}\Xi_c^{(\prime *)}$**, one can denote the contact range interaction by $F'_{1/2}$ **and** $F'_{3/2}$

$$\frac{1}{2} \otimes 1 = \frac{1}{2} \oplus \frac{3}{2}$$

- ☐ ***For $\bar{D}^{(*)}\Xi_c^{(*)}$**, one can denote the contact range interaction by* $F_{1/2}$

$$\frac{1}{2} \otimes 0 = \frac{1}{2}$$

Two scenarios

- $F_{1/2} = F'_{1/2} = C_a - 2C_b$

$$V(\bar{D}\Xi_c, J=\tfrac{1}{2}) = C_a - 2\,C_b\,,$$

$$V(\bar{D}^*\Xi_c, J=\tfrac{1}{2}) = C_a - 2\,C_b\,,$$

$$V(\bar{D}^*\Xi_c, J=\tfrac{3}{2}) = C_a - 2\,C_b\,.$$

- $F_{1/2} = LHG$

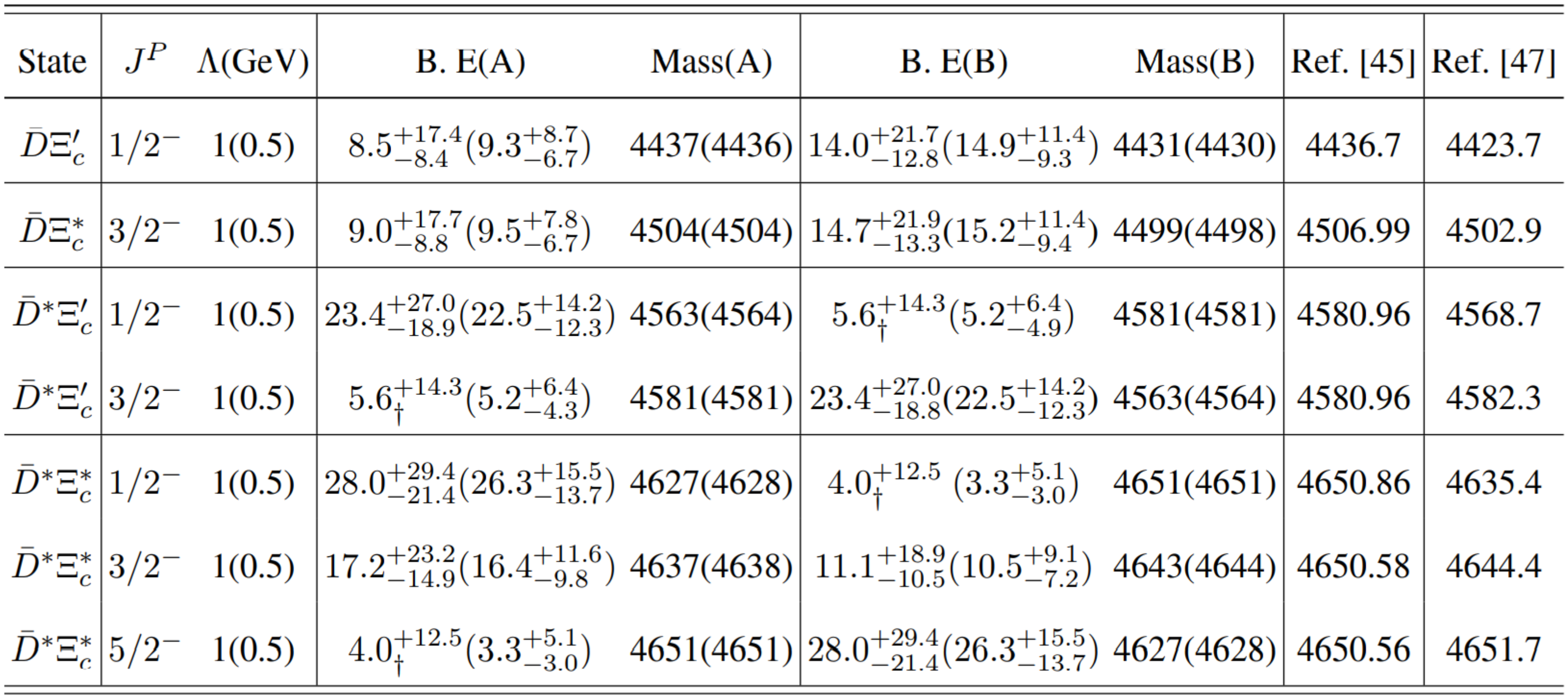
$$V(\bar{D}\Xi_c, J=\tfrac{1}{2}) = C_a,$$

$$V(\bar{D}^*\Xi_c, J=\tfrac{1}{2}) = C_a,$$

$$V(\bar{D}^*\Xi_c, J=\tfrac{3}{2}) = C_a.$$

C_a and C_b can be determined from reproducing Pc(4440) and Pc(4457)

Seven $\bar{D}^{(*)}\Xi_c^{(\prime *)}$ molecules (I=1/2)

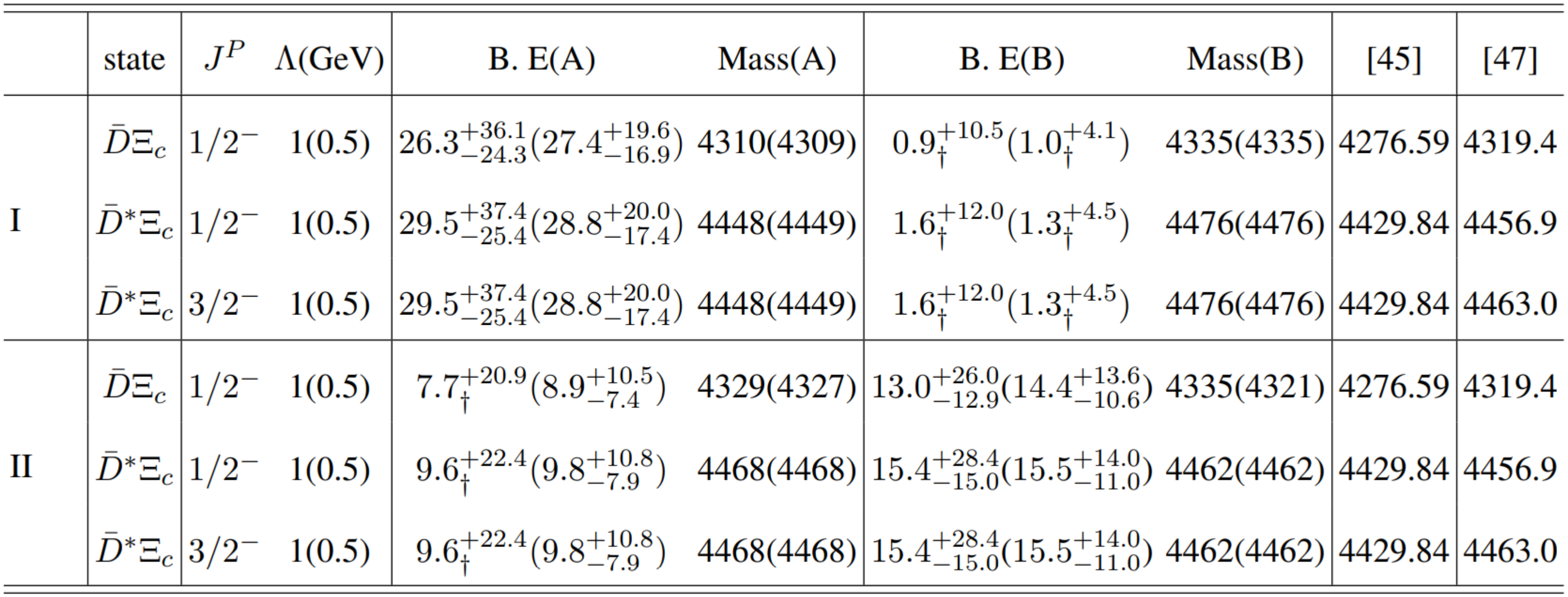


State	J^P	Λ(GeV)	B. E(A)	Mass(A)	B. E(B)	Mass(B)	Ref. [45]	Ref. [47]
$\bar{D}\Xi_c'$	$1/2^-$	1(0.5)	$8.5^{+17.4}_{-8.4}(9.3^{+8.7}_{-6.7})$	4437(4436)	$14.0^{+21.7}_{-12.8}(14.9^{+11.4}_{-9.3})$	4431(4430)	4436.7	4423.7
$\bar{D}\Xi_c^*$	$3/2^-$	1(0.5)	$9.0^{+17.7}_{-8.8}(9.5^{+7.8}_{-6.7})$	4504(4504)	$14.7^{+21.9}_{-13.3}(15.2^{+11.4}_{-9.4})$	4499(4498)	4506.99	4502.9
$\bar{D}^*\Xi_c'$	$1/2^-$	1(0.5)	$23.4^{+27.0}_{-18.9}(22.5^{+14.2}_{-12.3})$	4563(4564)	$5.6^{+14.3}_{\dagger}(5.2^{+6.4}_{-4.9})$	4581(4581)	4580.96	4568.7
$\bar{D}^*\Xi_c'$	$3/2^-$	1(0.5)	$5.6^{+14.3}_{\dagger}(5.2^{+6.4}_{-4.3})$	4581(4581)	$23.4^{+27.0}_{-18.8}(22.5^{+14.2}_{-12.3})$	4563(4564)	4580.96	4582.3
$\bar{D}^*\Xi_c^*$	$1/2^-$	1(0.5)	$28.0^{+29.4}_{-21.4}(26.3^{+15.5}_{-13.7})$	4627(4628)	$4.0^{+12.5}_{\dagger}(3.3^{+5.1}_{-3.0})$	4651(4651)	4650.86	4635.4
$\bar{D}^*\Xi_c^*$	$3/2^-$	1(0.5)	$17.2^{+23.2}_{-14.9}(16.4^{+11.6}_{-9.8})$	4637(4638)	$11.1^{+18.9}_{-10.5}(10.5^{+9.1}_{-7.2})$	4643(4644)	4650.58	4644.4
$\bar{D}^*\Xi_c^*$	$5/2^-$	1(0.5)	$4.0^{+12.5}_{\dagger}(3.3^{+5.1}_{-3.0})$	4651(4651)	$28.0^{+29.4}_{-21.4}(26.3^{+15.5}_{-13.7})$	4627(4628)	4650.56	4651.7

☐ **Consistent** with Chu-Wen Xiao et al [1906.0901], Bo Wang et al. [1912.12592], which favor that Pc(4440) ½ and Pc(4457) 3/2

☐ **Not very useful** to help distinguish the spins of Pc(4440) and Pc(4457)

Three $\bar{D}^{(*)}\Xi_c$ molecules (I=1/2)



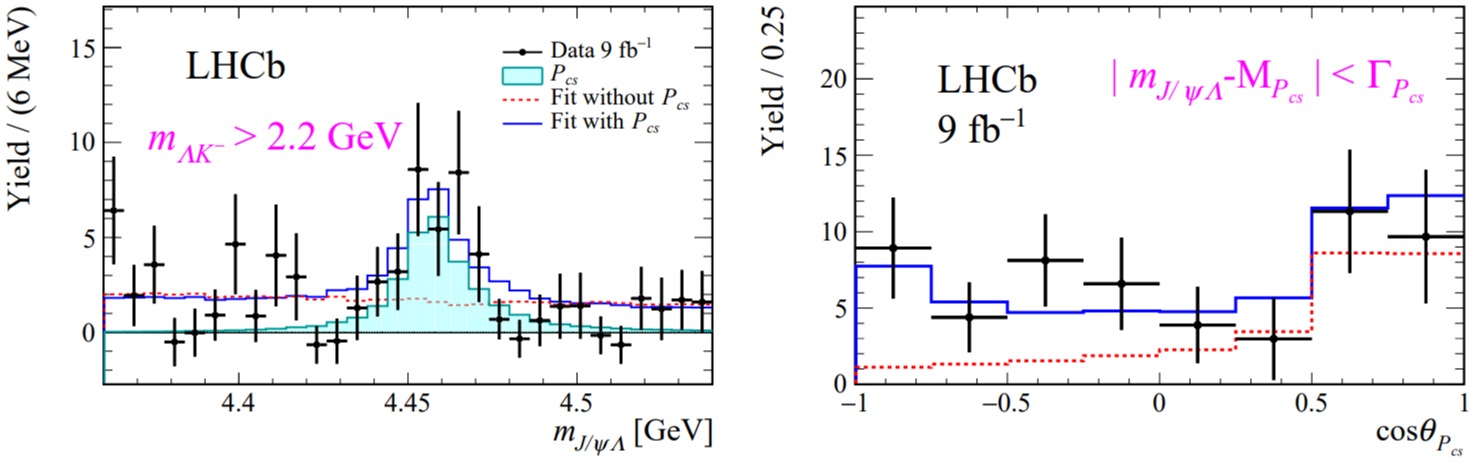
	state	J^P	Λ(GeV)	B. E(A)	Mass(A)	B. E(B)	Mass(B)	[45]	[47]
I	$\bar{D}\Xi_c$	$1/2^-$	1(0.5)	$26.3^{+36.1}_{-24.3}(27.4^{+19.6}_{-16.9})$	4310(4309)	$0.9^{+10.5}_{\dagger}(1.0^{+4.1}_{\dagger})$	4335(4335)	4276.59	4319.4
	$\bar{D}^*\Xi_c$	$1/2^-$	1(0.5)	$29.5^{+37.4}_{-25.4}(28.8^{+20.0}_{-17.4})$	4448(4449)	$1.6^{+12.0}_{\dagger}(1.3^{+4.5}_{\dagger})$	4476(4476)	4429.84	4456.9
	$\bar{D}^*\Xi_c$	$3/2^-$	1(0.5)	$29.5^{+37.4}_{-25.4}(28.8^{+20.0}_{-17.4})$	4448(4449)	$1.6^{+12.0}_{\dagger}(1.3^{+4.5}_{\dagger})$	4476(4476)	4429.84	4463.0
II	$\bar{D}\Xi_c$	$1/2^-$	1(0.5)	$7.7^{+20.9}_{\dagger}(8.9^{+10.5}_{-7.4})$	4329(4327)	$13.0^{+26.0}_{-12.9}(14.4^{+13.6}_{-10.6})$	4335(4321)	4276.59	4319.4
	$\bar{D}^*\Xi_c$	$1/2^-$	1(0.5)	$9.6^{+22.4}_{\dagger}(9.8^{+10.8}_{-7.9})$	4468(4468)	$15.4^{+28.4}_{-15.0}(15.5^{+14.0}_{-11.0})$	4462(4462)	4429.84	4456.9
	$\bar{D}^*\Xi_c$	$3/2^-$	1(0.5)	$9.6^{+22.4}_{\dagger}(9.8^{+10.8}_{-7.9})$	4468(4468)	$15.4^{+28.4}_{-15.0}(15.5^{+14.0}_{-11.0})$	4462(4462)	4429.84	4463.0

☐ **Case I can** help to infer the spins of Pc(4440) and Pc(4457), but **Case II can not**

☐ Binding energies from the LHG theory are much larger

Pcs from LHCb discovered

2012.10380 3.1 σ



- $M = 4458.8 \pm 2.9^{+4.71}_{-1.1}$ MeV
- $\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV

a $\overline{D}^{(*)}\Xi_c$ molecule

$$J^P = \frac{1^-}{2} / \frac{3^-}{2}$$

Summary

- ☐ We studied the latest LHCb pentaquark states using a contact-range effective field theory.
- ☐ We showed that they can be accommodated rather nicely as $\bar{D}\Sigma_c$ bound states and predicted the existence of three more states.
- ☐ We pointed out that it is possible to determine the spins of these states by studying the dibaryon systems, which seem to be feasible in lattice QCD already.
- ☐ Their SU(3) partners, i.e., Pcs, are very likely to exist, but may not offer much help to determine the spins of Pc(4457) and Pc(4440)

谢谢！ 敬请批评指正！