第二届“强子物理与重味物理理论与实验联合研讨会”
(2021 年 3月 25—29日，兰州，兰州大学)

北京航空航天大學
BEIHANG UNIVERSITY

Selected topics on pentaquark states: from Pc to Pcs.

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]
- **Test the nature of Pcs(4459) in the $\Xi_b \to J/\psi \Lambda K$ decay, in preparation**

Contents

- **Motivation: a new paradigm in studies of the strong interaction**
- **Selected topics**
  1. **The new pentaquark states as $\bar{D}\Sigma_c$ molecules**
  2. **From $\Xi_{cc}\Sigma_c$ dibaryon mass splitting to the pentaquark spins**
  3. **From P_c to P_{cs} and the pentaquark spins**
  4. **Decay of $\Xi_b \to J/\psi\Lambda K$ and the P_{cs} spin**
- **Summary and outlook**

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Beginning of a new era: 2003

LEPS, 0301020
> 1154

Θ^+ (1540)

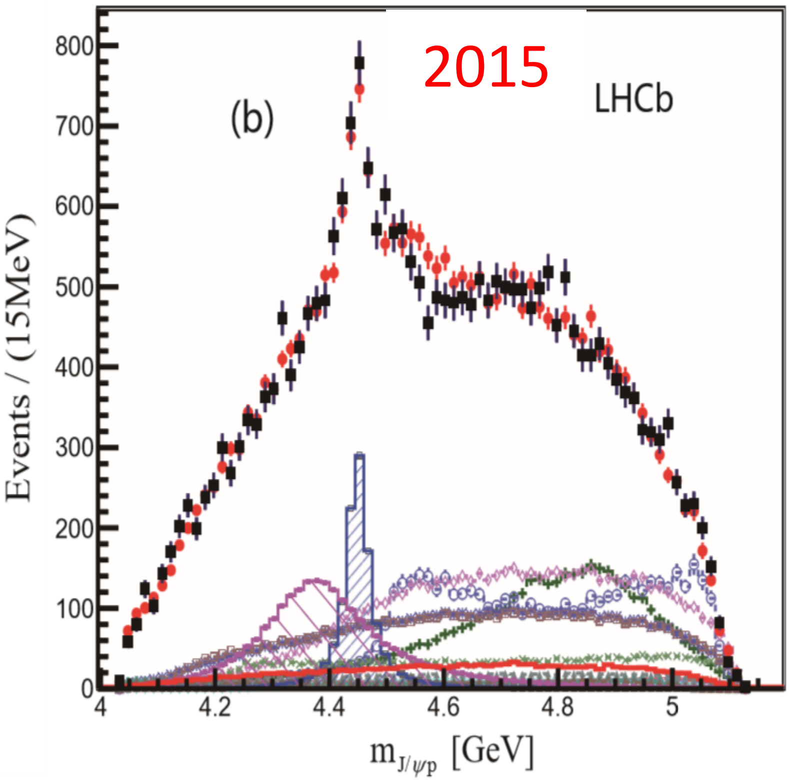
BaBar, 0304021
> 903

$D_{s0}^*(2317)$

Belle, 0309032
> 1916

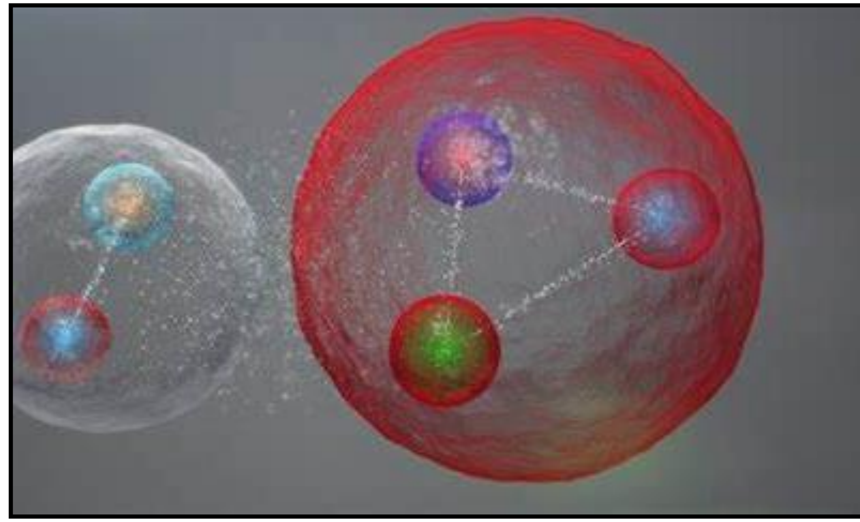
X(3872)

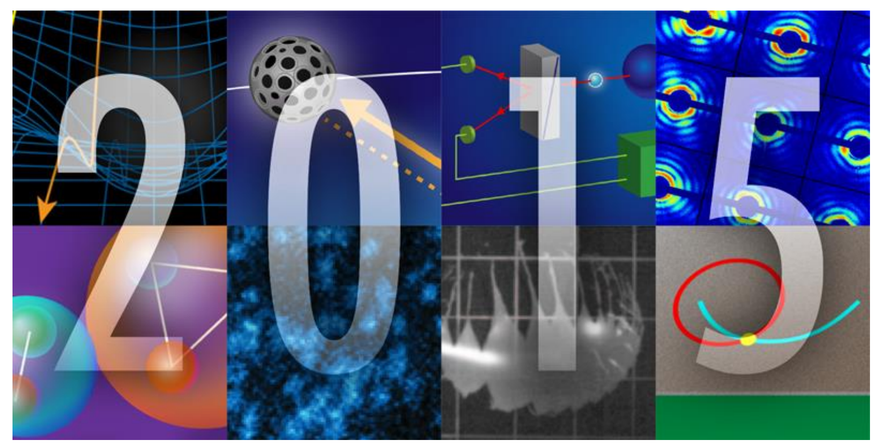
2015: pentaquarks from $\Lambda_b^0 \to J/\psi p K^-$



PRL 115 (2015) 072001

1173 citations

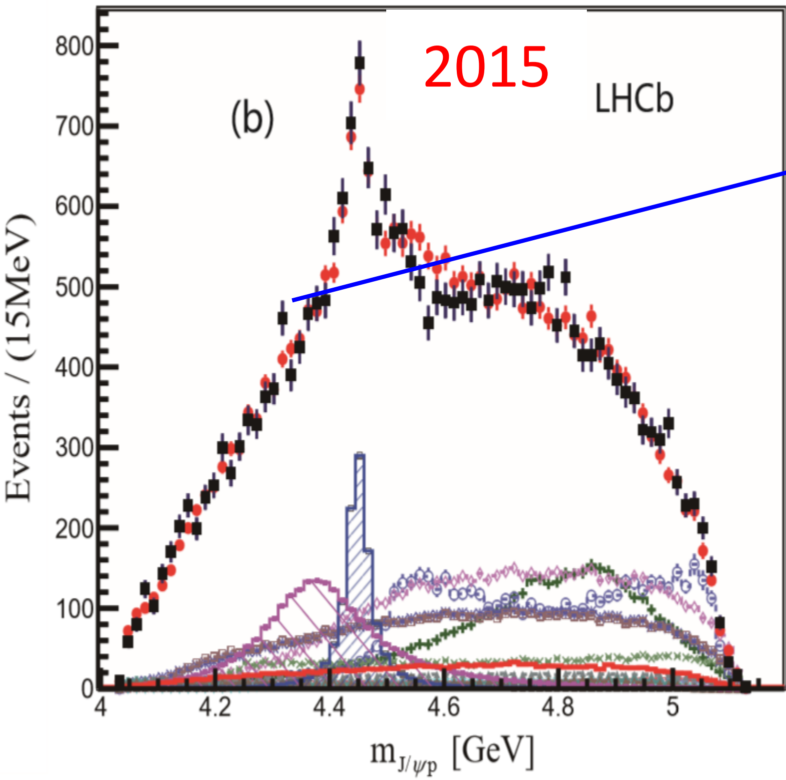




Highlights of the year, Particle High Five/LHCb

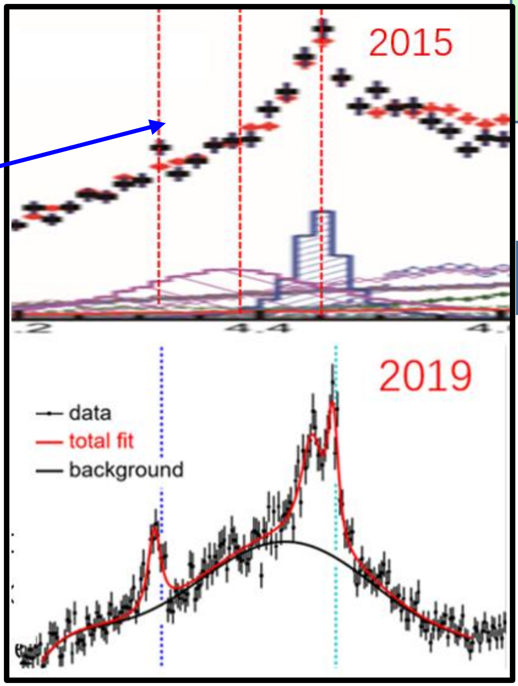
the research covered in Physics that **really made waves in and beyond the physics community**

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



PRL 115 (2015) 072001
1173 citations

4320 4380 4450



PRL 122 (2019) 222001
280 citations

2015

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

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

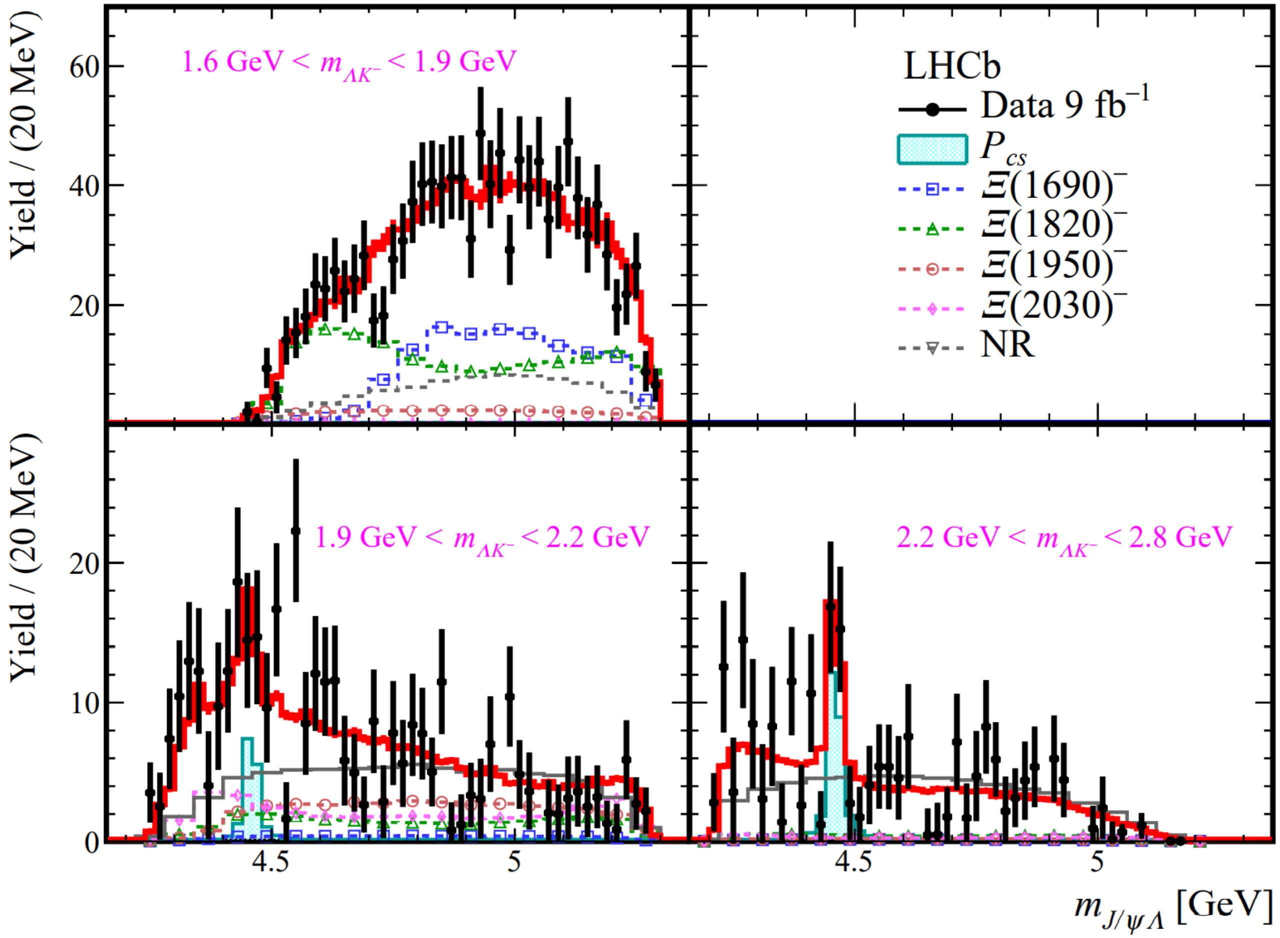
2019

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

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

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

Pentaquarks from $\Xi_b^- \to J/\psi \Lambda K^-$



2020 3.1σ

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

2012.10380

17 citations

Five pentaquark states—challenges for theoretical models

$P_c(4380)$
$P_c(4450)$

1173 citations

2015.07

2019.04

$P_c(4457)$
$P_c(4440)$
$P_c(4312)$

280 citations

2020.12

$P_{cs}(4459)$

17 citations,
most molecules

Before the 2015 LHCb discovery

INSPIRE HEP

As of 2021.03.22

- **Wu, Molina, Oset, Zou, PRL105, 232001(2001)-- 295**
- Wang, Huang, Zhang, Zou, PRC84, 015203(2011)--126
- Yang, Sun, He, Liu, Zhu, CPC36,6(2012)--171
- Wu, Lee, Zou, PRC85,044002(2012) --81
- Xiao, Nieves, Oset, PRD88,056012(2013)--147
- Karliner, Rosner, PRL115, 122001(2015)--199

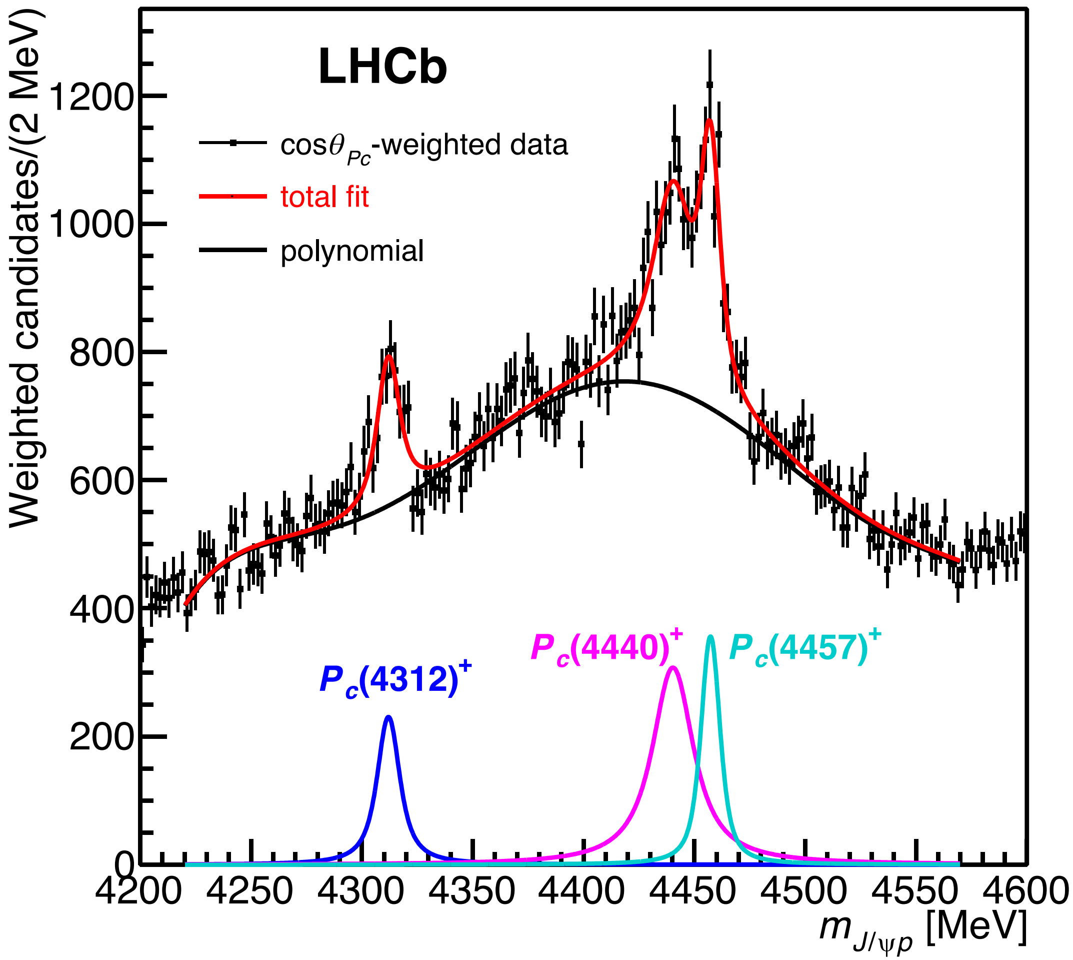
TABLE II. Pole positions z_R and coupling constants g_a for the states from $PB \to PB$.

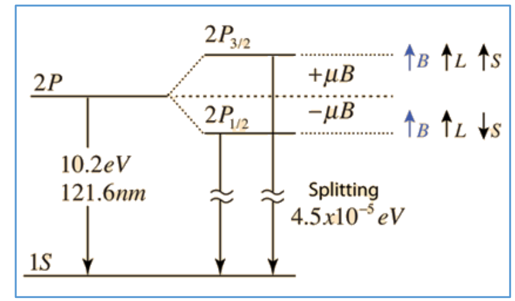
(I, S)	z_R (MeV)	g_a		
$(1/2, 0)$		$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$	
	4269	2.85	0	
$(0, -1)$		$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$
	4213	1.37	3.25	0
	4403	0	0	2.64

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

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

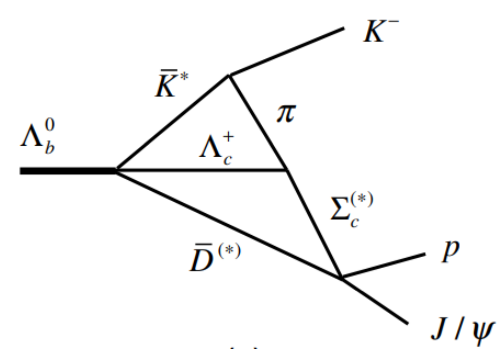
- ✓ Michael I. Eides et al., 1904.11616

☐ Virtual states -- Pc(4312)

- ✓ JPAC, 1904.10021

☐ Triangle singularities or cusp effects

- ✓ *Satoshi. X. Nakamura, 2103.06817,Pc(4312), Pc(4380), Pc(4457)*



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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

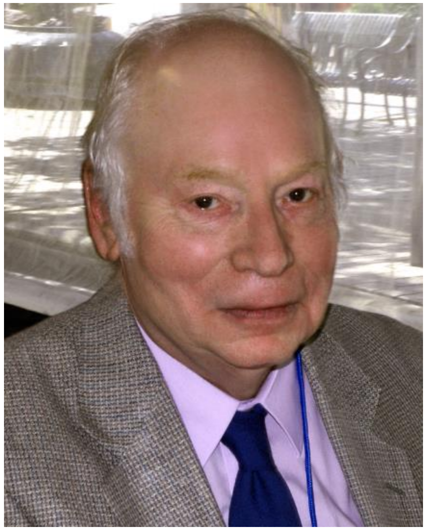
- ✓ Chiral perturbation theory ($\pi\pi, NN$)
- ✓ Heavy quark effective field theory
- ✓ Non-relativistic QCD
- ✓ Soft collinear effective field theory

☐ 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

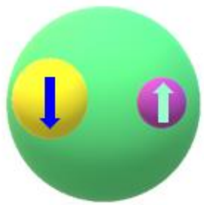


Steven Weinberg
Nobel prize 1979

Heavy quark spin symmetry

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

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

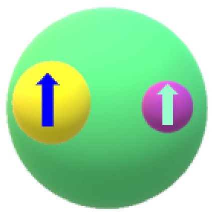


HQSS is broken in charm and bottom sector

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

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

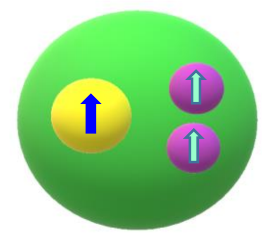
$J = J_l + \frac{1}{2}$



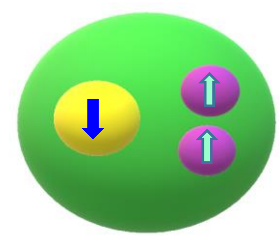
$$m_{\Sigma_c^*} - m_{\Sigma_c} = 64 MeV$$

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

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



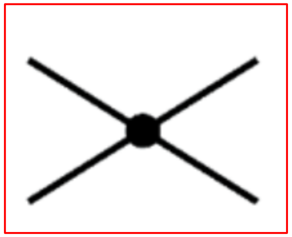
$J = J_l + \frac{1}{2}$



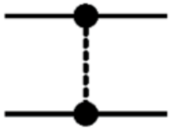
Effective field theory: $\bar{D}$ $(\overline{D^*})$ Σ_c (Σ_c^*)

Power counting: naïve dimensional analysis

- **Leading order**
  - **Contact**
  - **One pion exchange**

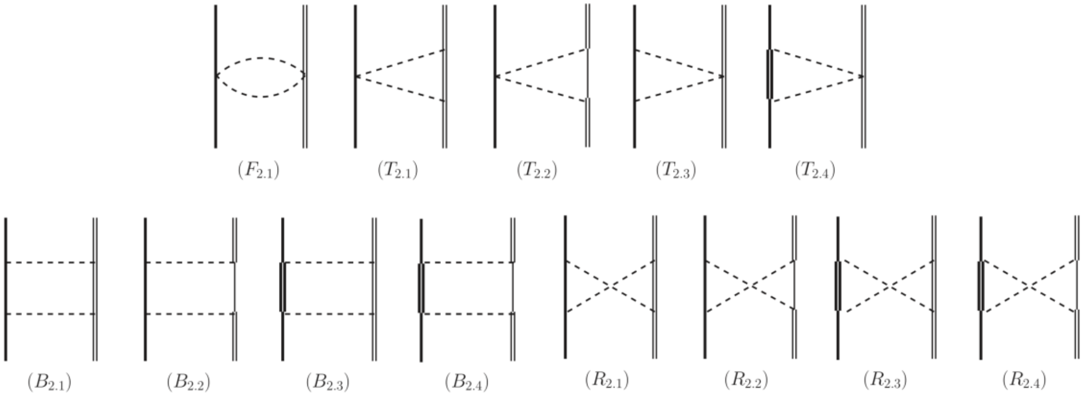


pionless



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

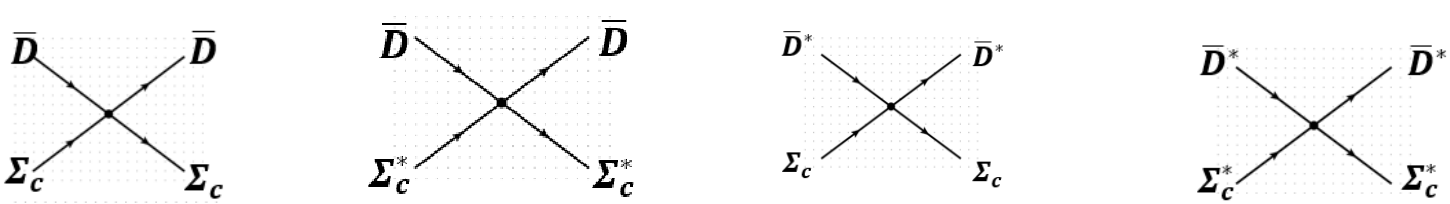
$$L = C_a Tr[H_c^\dagger H_c]\vec{S}_c \cdot \vec{S}_c{}^\dagger + C_b \sum_{i=1}^{3} Tr[H_c^\dagger \sigma_i H_c]\vec{S}_c \cdot (J_i \vec{S}_c{}^\dagger)$$

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

Spin 1 matrices

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

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



Threshold

0 | 64 MeV | 142 MeV | 208 MeV

Leading order potentials

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

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

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

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

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

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

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

- 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 $\overline{D^*}\,\Sigma_c$ bound states

Pc(4440)/Pc(4457)

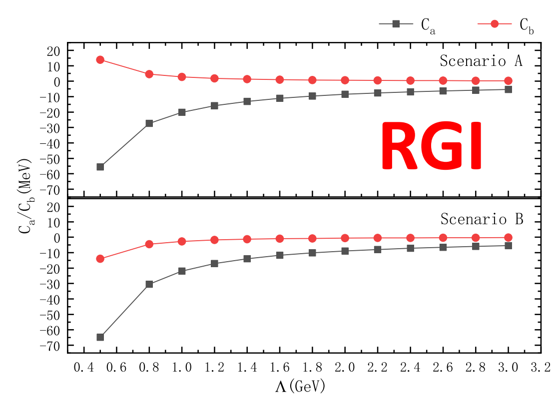
Search for bound states

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

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



Fit to the LHCb data: two scenarios

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

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

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

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

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

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

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

LHCb data

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

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

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

Three experimental data and two unknown coupling constants

⇓

C_a and C_b can be determined !

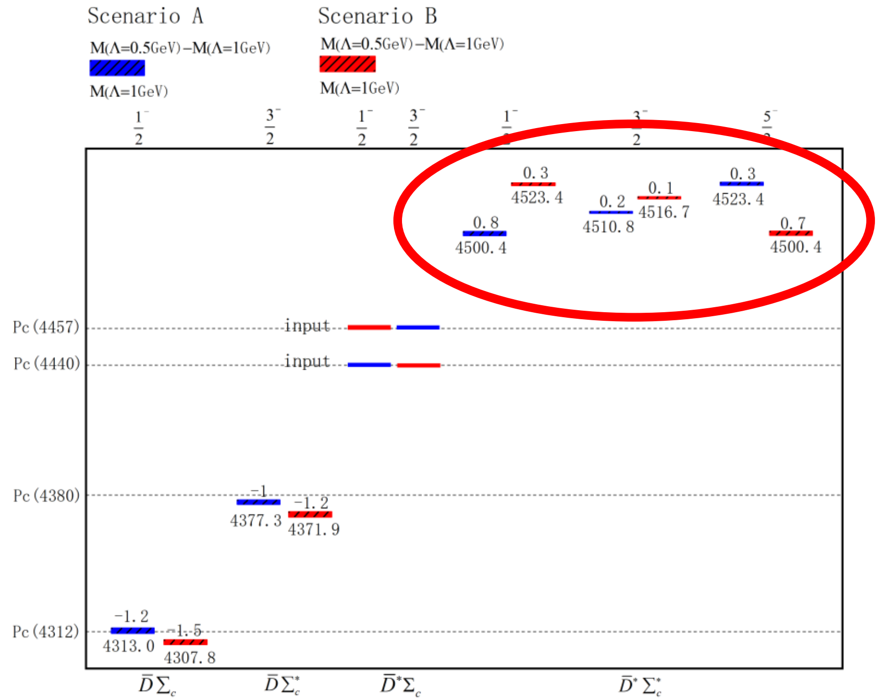
Input

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

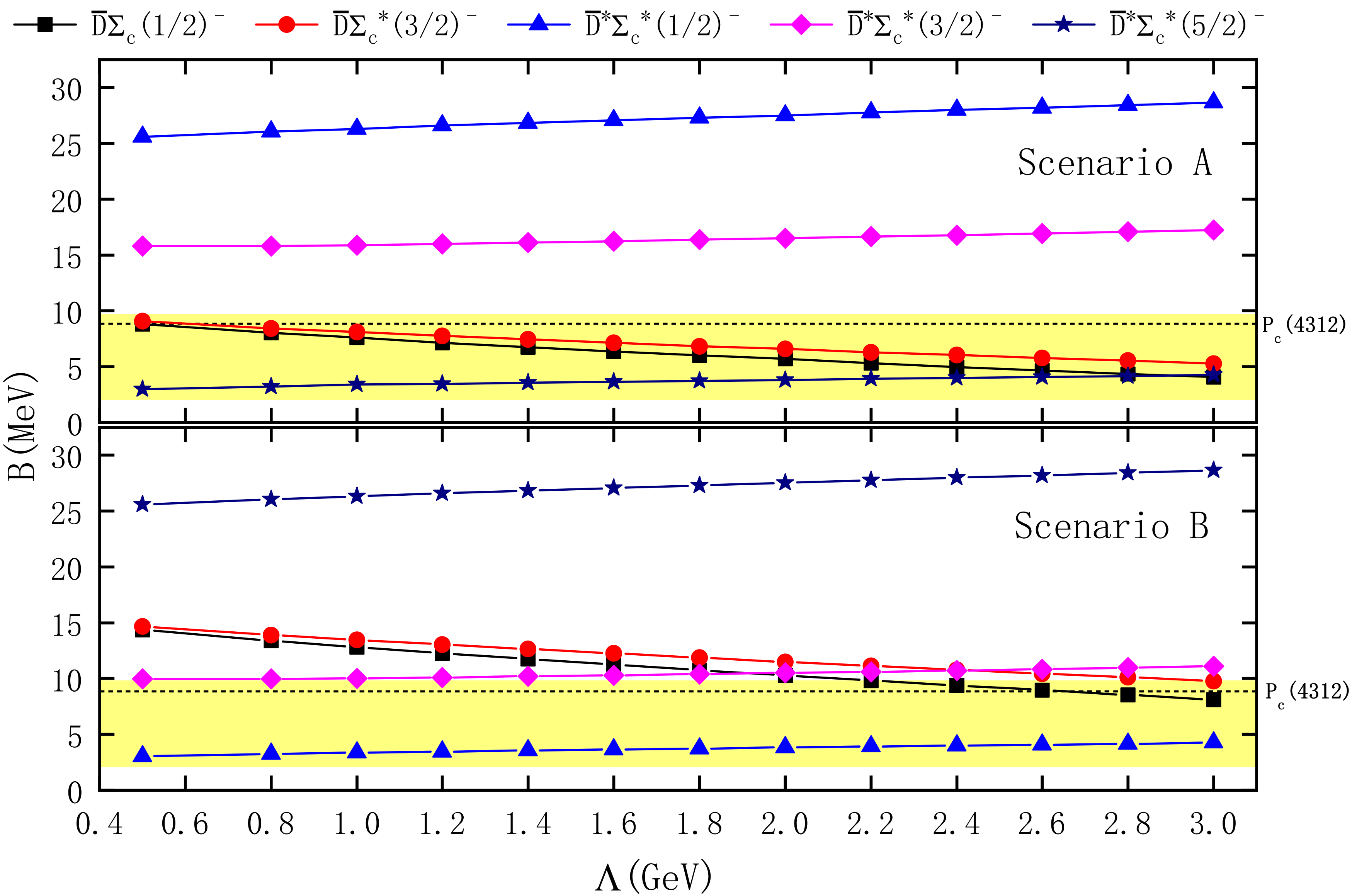
Emergence of a complete HQS multiplet (7)

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

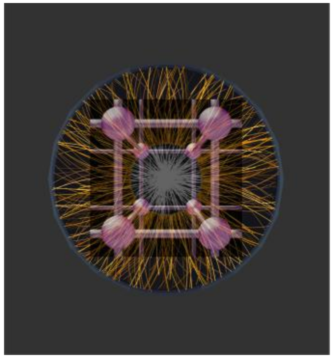
- Spins of the Pc(4457) and Pc(4440) undetermined
- Different molecular models show different preferences

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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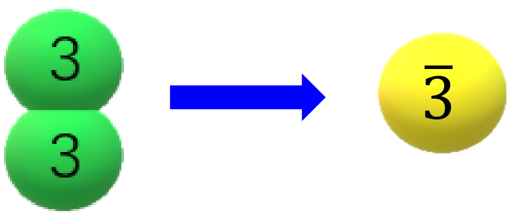
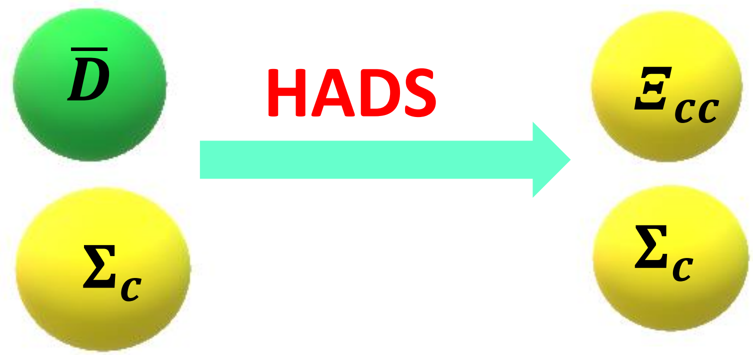
Heavy Antiquark Diquark symmetry(HADS)

- 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%)

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

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

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

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

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

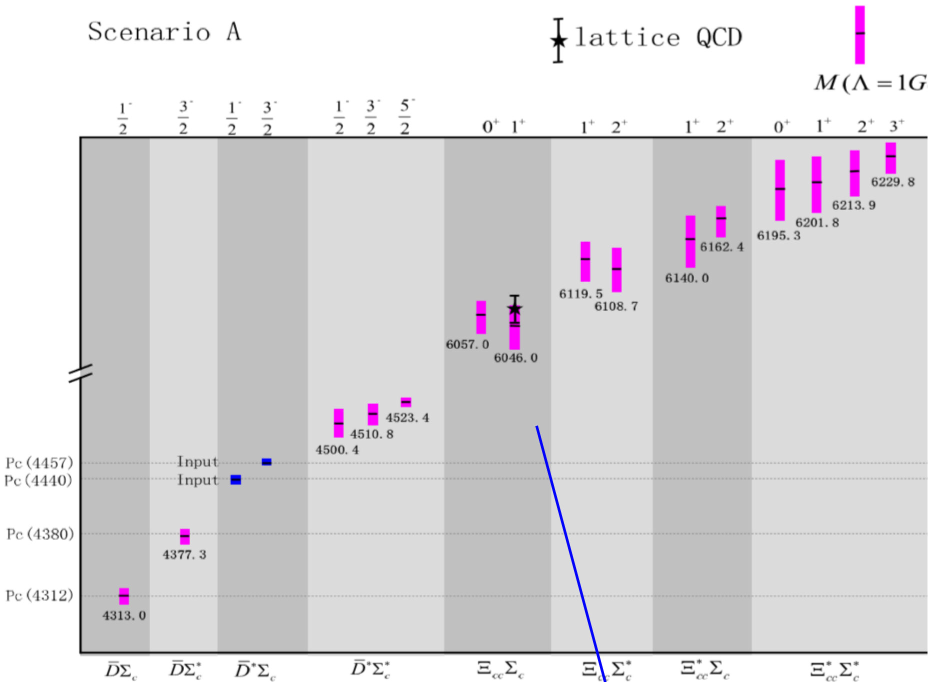
$$L_{\Xi_{cc}\Sigma_c} = C_a Tr[\vec{T}_{cc}^\dagger \vec{T}_{cc}]\vec{S}_c \cdot \vec{S}_c{}^\dagger + C_b \sum_{i=1}^{3} Tr[\vec{T}_{cc}^\dagger \sigma_i \vec{T}_{cc}]\vec{S}_c \cdot (J_i \vec{S}_c{}^\dagger)$$

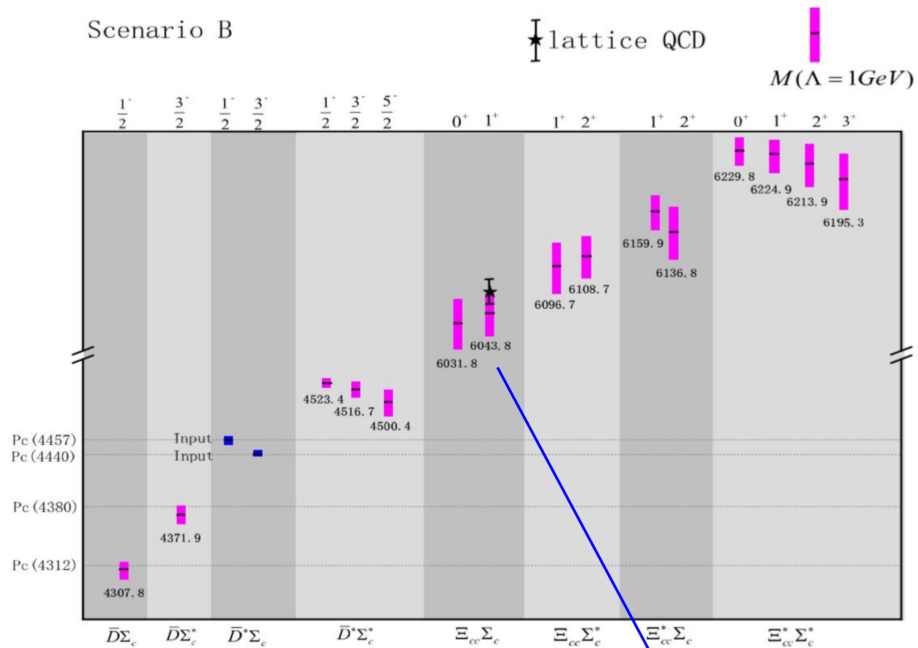
The same potentials in the HQS limit

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^+	$C_a-\frac{5}{3}C_b$
				1^+	$C_a-\frac{11}{9}C_b$
	$3/2^-$	$C_a-\frac{2}{3}C_b$		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



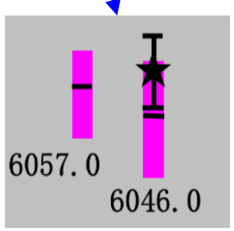


Mass splitting of $\Xi_{cc}\Sigma_c$ system ⟵ **Lattice QCD**

1906.06054

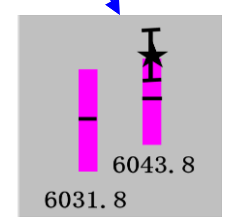
$$1^+ - 0^+ = -8.4\ MeV$$

$$\Delta_m < 0$$



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

$$\Delta_m > 0$$



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

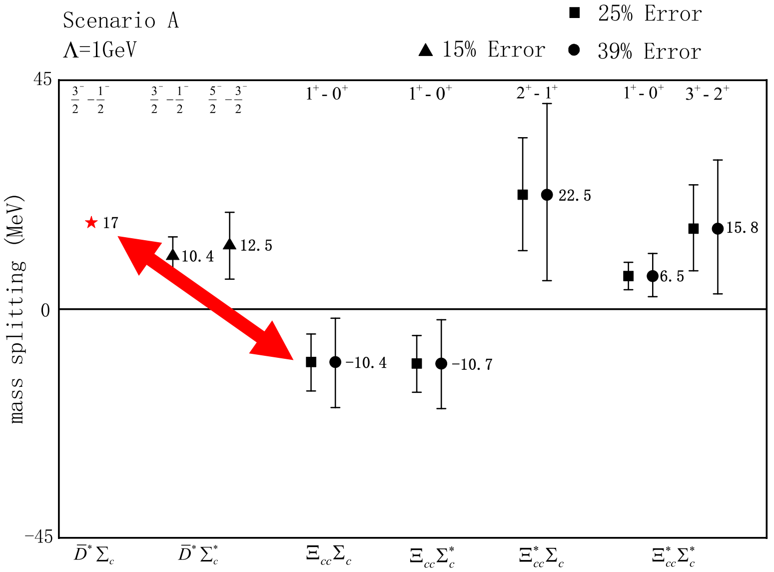
$$1^+ - 0^+ = 6.3 \sim 13.1\ MeV$$

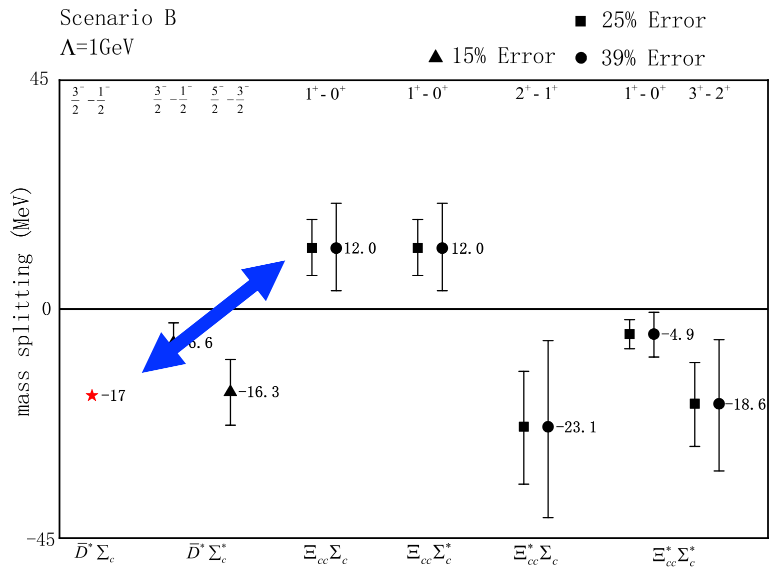
$$\Delta_m > 0$$

Scenario B

1/2 higher
3/2 lower

Breaking up to 39%

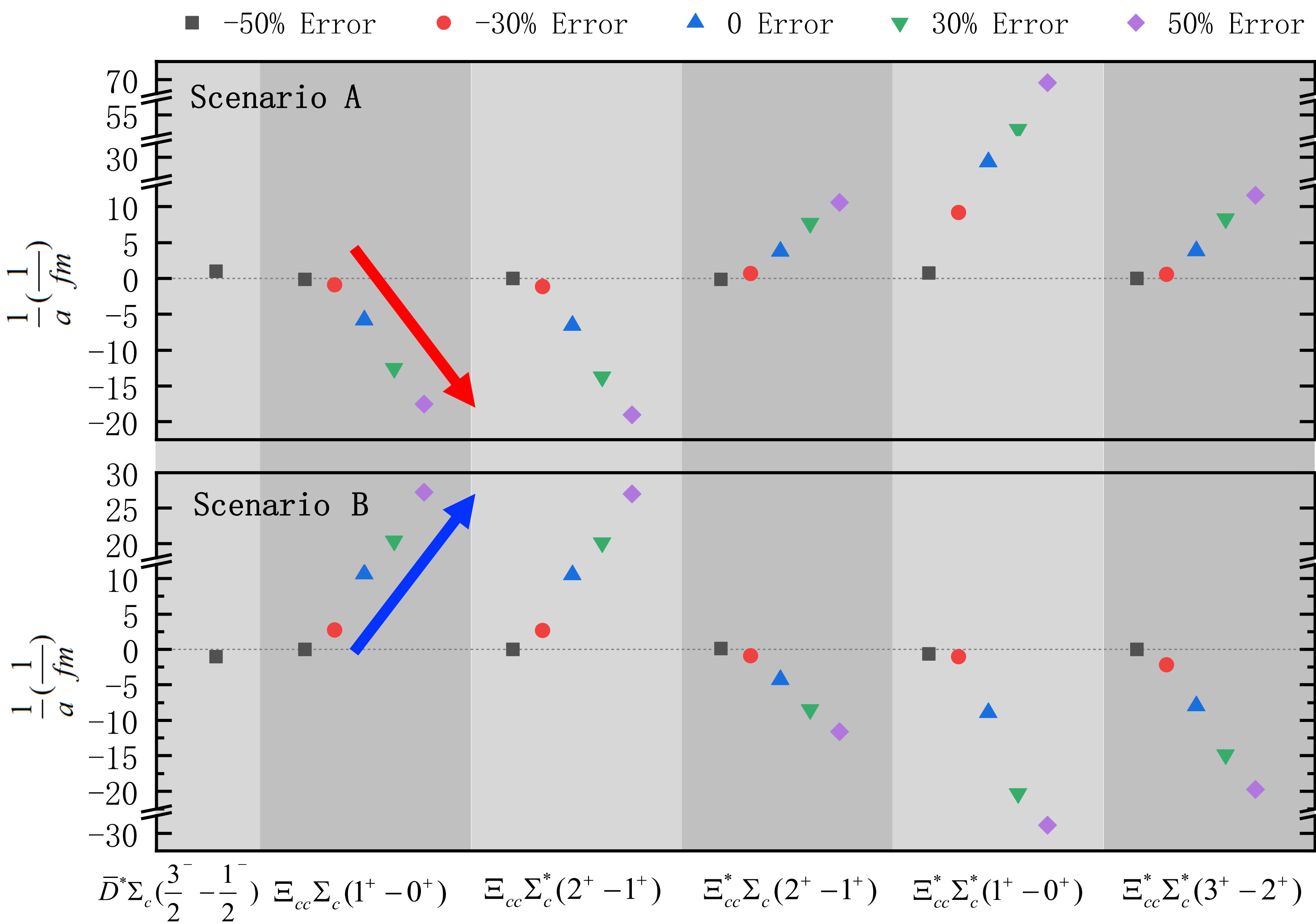




Pc(4457): 3/2
Pc(4440): 1/2

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

Correlation in case of even larger breaking



Scattering lengths

Contents

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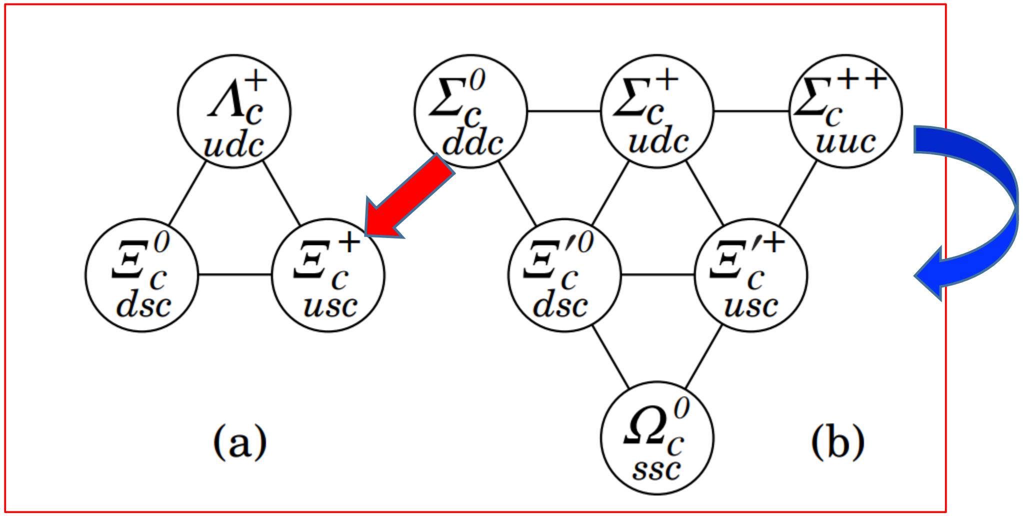
- Summary and outlook

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 $\bar{D}^{(*)}\Xi_c'^{(*)}$**, 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: undetermined

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

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

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

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

- $F_{1/2} = LHG$

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

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

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

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 in** helping 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
- $\bar{D}^*\ \Xi_c$ states could correspond to Pcs(4459), but spin could be either 1/2 or 3/2

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- **Summary and outlook**

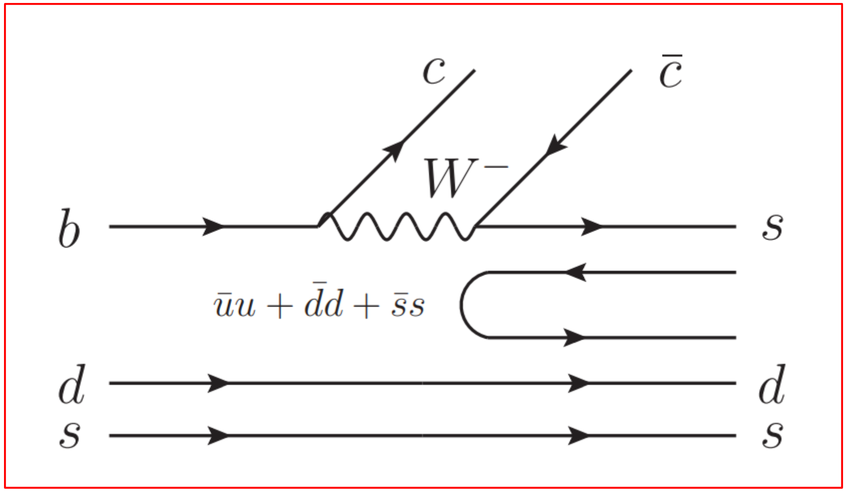
$\Xi_b \to J/\psi\Lambda K$—mechanism 1

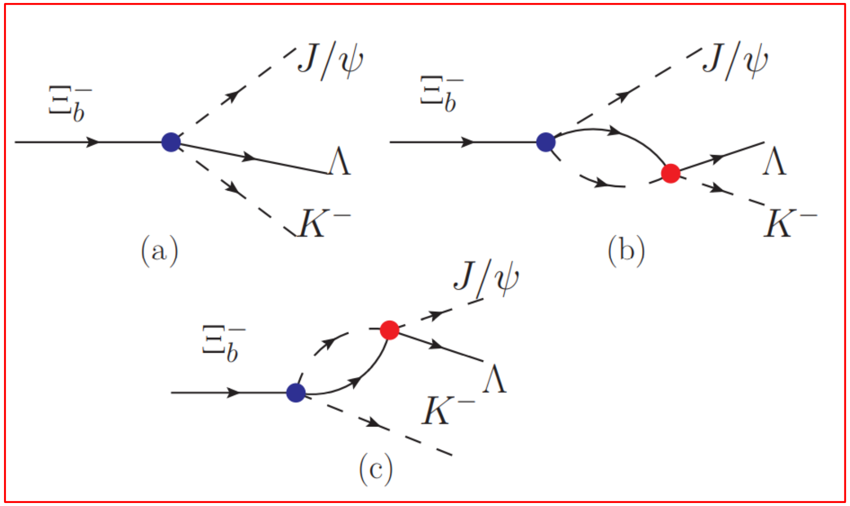
2015

Looking for a hidden-charm pentaquark state with strangeness S=−1 from Ξ_b^- decay into $J/\psi K^-\Lambda$

Hua-Xing Chen (BeiHang U.), Li-Sheng Geng (BeiHang U. and Beijing, Inst. Theor. Phys.), Wei-Hong Liang (Guangxi Normal U.), Eulogio Oset (Lanzhou, Inst. Modern Phys. and Valencia U. and Valencia U., IFIC), En Wang (Zhengzhou U.) et al. (Oct 6, 2015)

Published in: *Phys.Rev.C* 93 (2016) 6, 065203 • e-Print: 1510.01803 [hep-ph]





Weak decay

Hadronization

$\Xi_b \to J/\psi\Lambda K$—mechanism 1

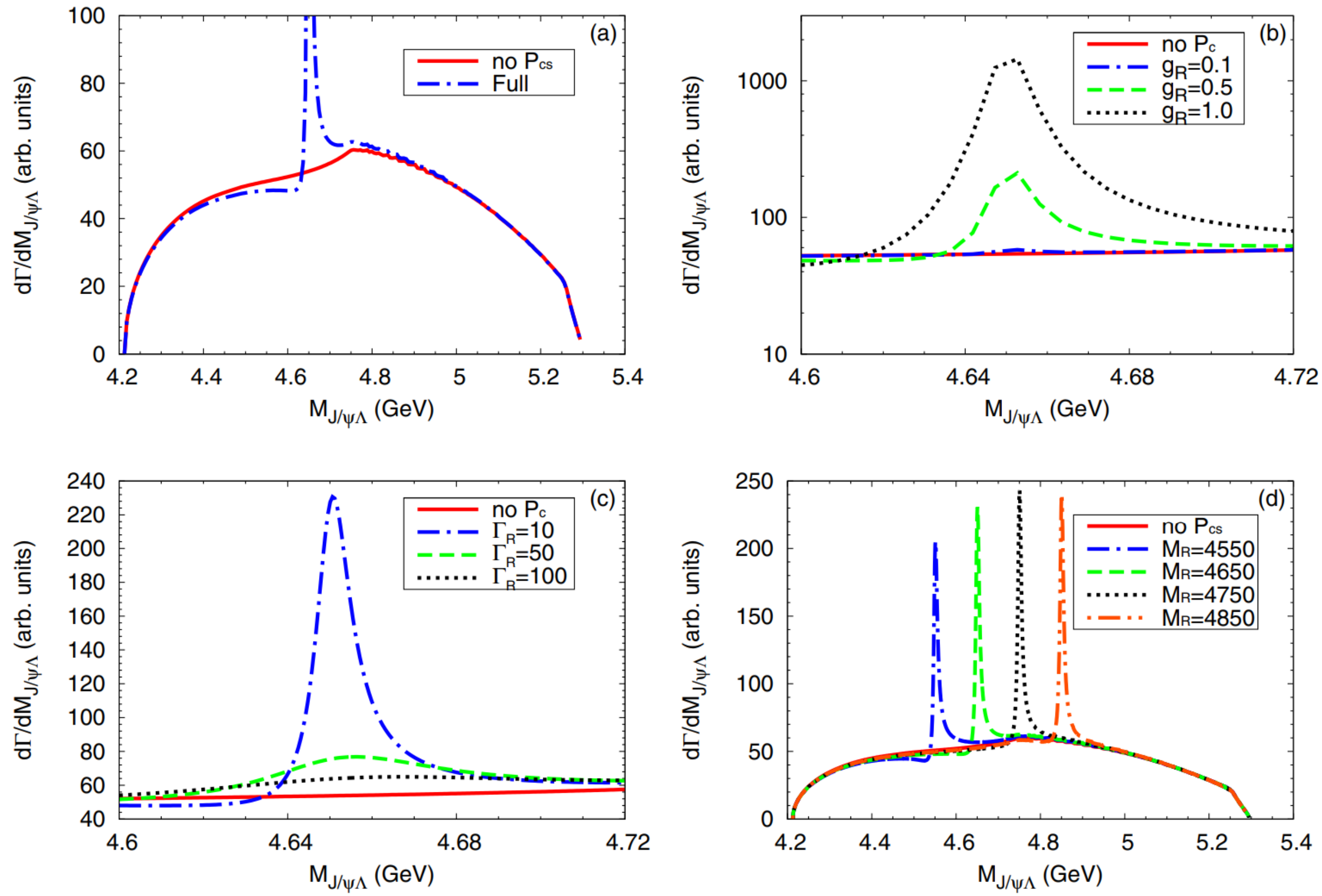
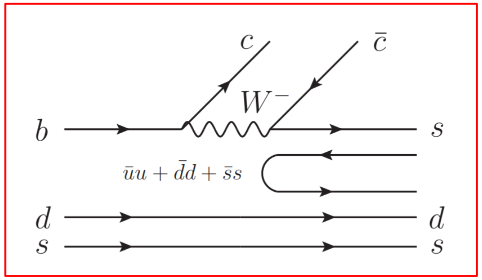
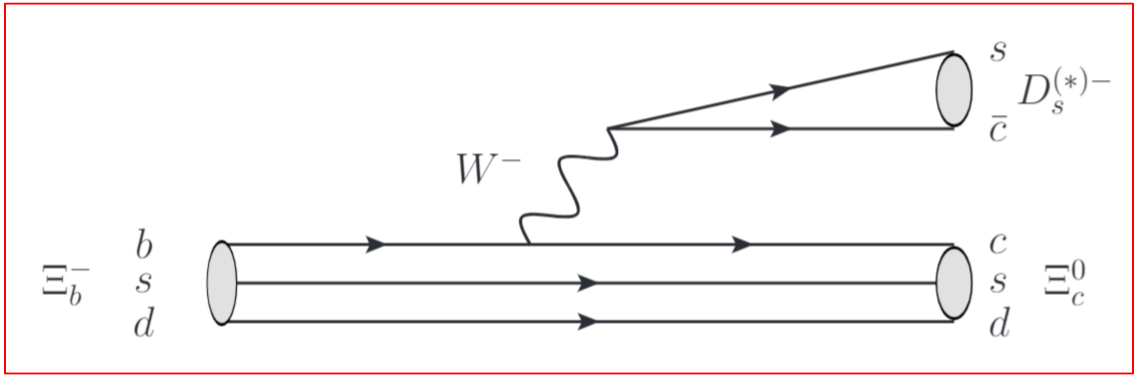
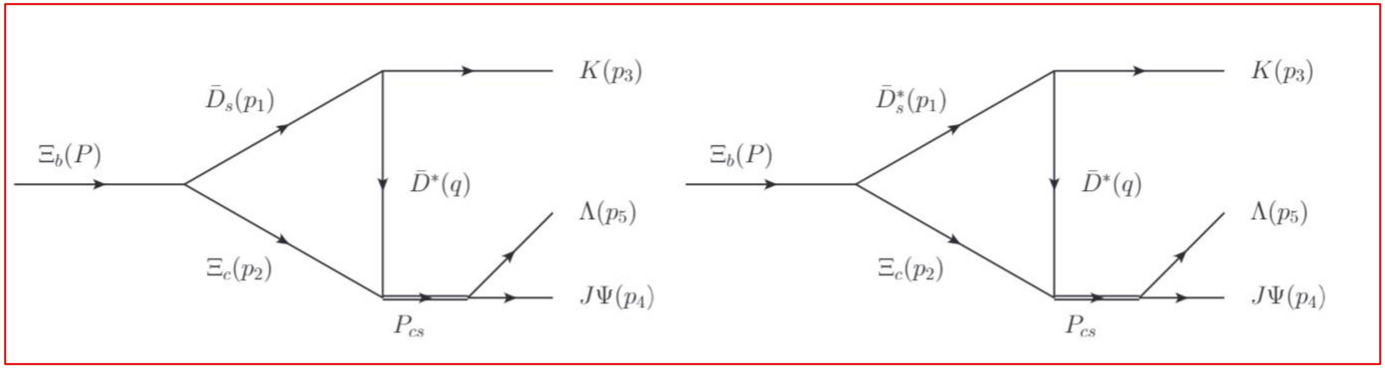


FIG. 6. $J/\psi\,\Lambda$ invariant mass distributions for $\Xi_b \to J/\psi\,\Lambda\,\bar{K}$ with $M_R = 4650$ MeV, $g_{J/\psi\Lambda} = 0.5$, and $\Gamma_R = 10$ Mev (a) and with two of the parameters fixed and the other varying as shown in the plots (b)–(d).

$\Xi_b \to J/\psi\Lambda K$—mechanism 2

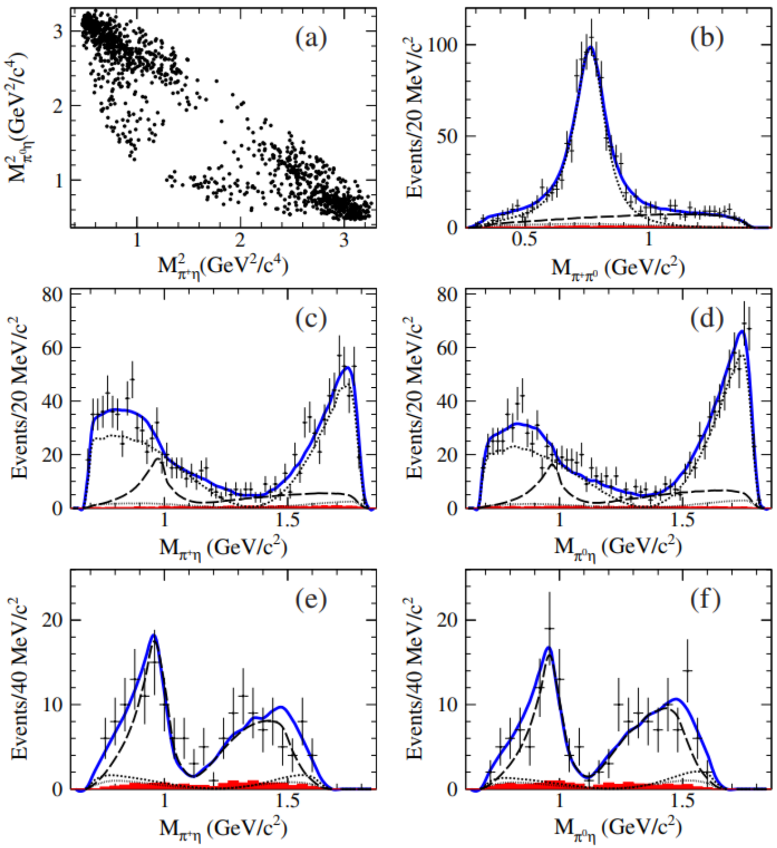






$\Xi_b \to J/\psi \Lambda K$—mechanism 2

Lesson from the study of $D_s^+ \to \pi^+\pi^0\eta$



PHYSICAL REVIEW LETTERS **123,** 112001 (2019)

Amplitude Analysis of $D_s^+ \to \pi^+\pi^0\eta$ and First Observation of the W-Annihilation Dominant Decays $D_s^+ \to a_0(980)^+\pi^0$ and $D_s^+ \to a_0(980)^0\pi^+$

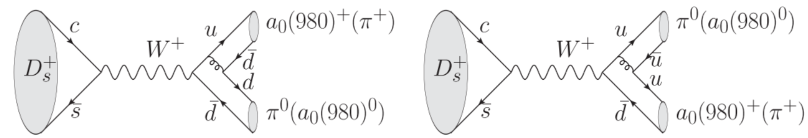


FIG. 1. $D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)}$ WA-topology diagrams, where the gluon lines can be connected with the quark lines in all possible cases and the contributions from FSI are included.

which is larger than the branching fractions of other measured pure W-annihilation decays by at least one order of magnitude.

$\Xi_b \to J/\psi \Lambda K$—mechanism 2

Can the nature of $a_0(980)$ be tested in the $D_s^+ \to \pi^+\pi^0\eta$ decay?

Xi-Zhe Ling (Beihang U.), Ming-Zhu Liu (Beihang U.), Jun-Xu Lu (Beihang U.), Li-Sheng Geng (Beihang U. and Zhengzhou U.), Ju-Jun Xie (Lanzhou, Inst. Modern Phys. and Beijing, GUCAS and Zhengzhou U.) (Feb 10, 2021)

e-Print: 2102.05349 [hep-ph]

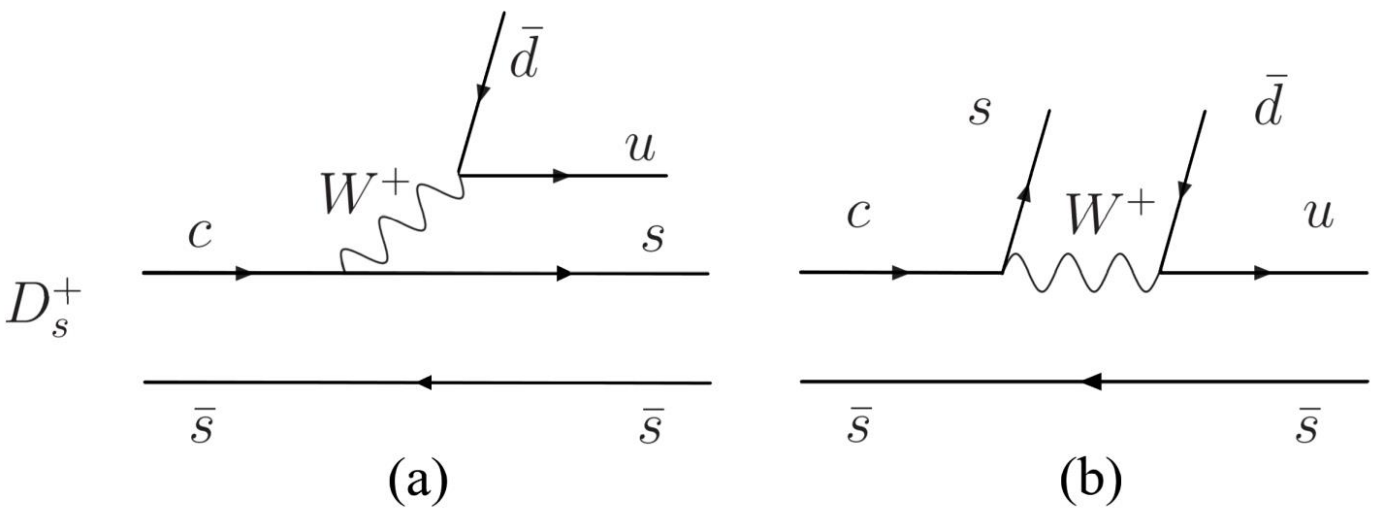
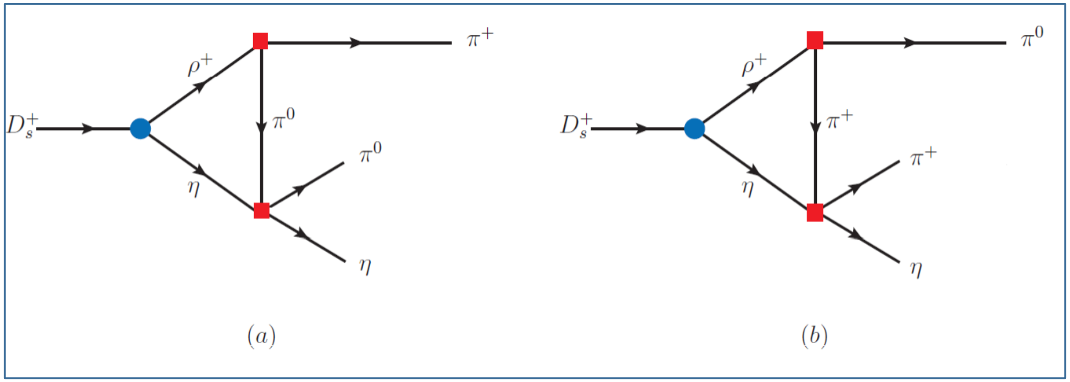


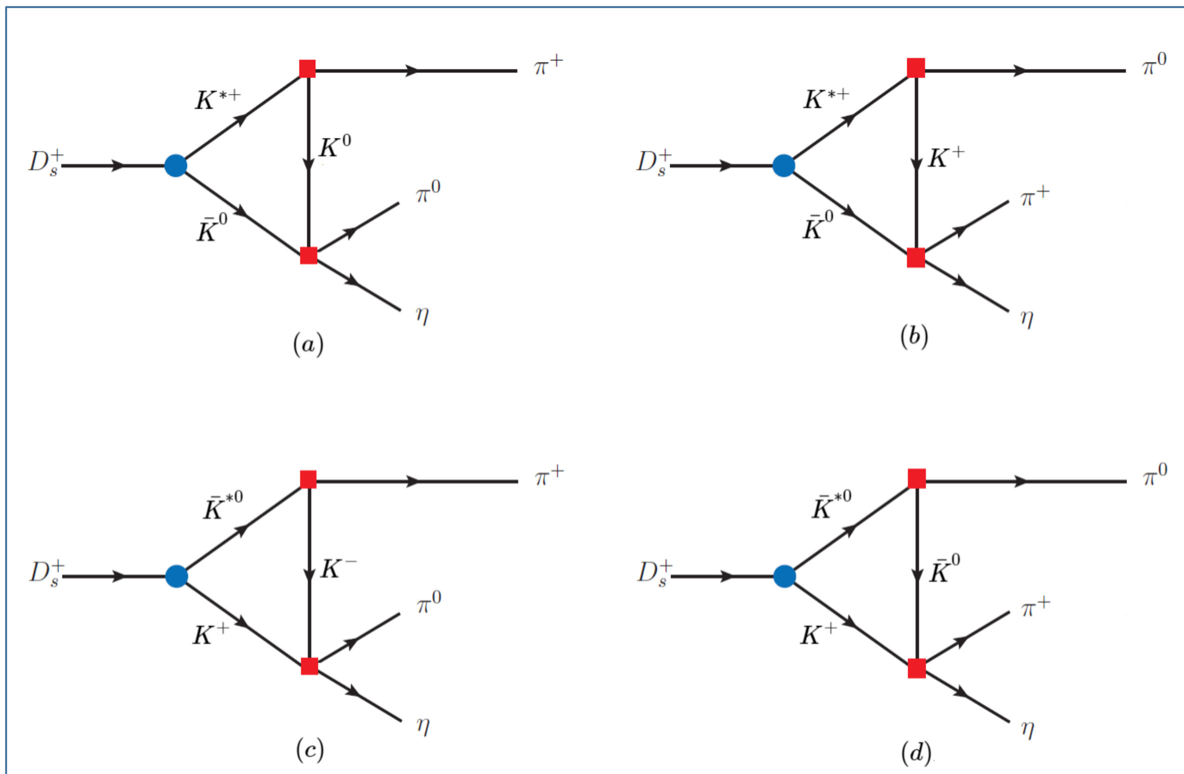
FIG. 1. (a) External W-emission mechanism for $D_s^+ \to \rho^+\eta$ and (b) internal W-conversion mechanisms for $D_s^+ \to K^+\bar{K}^{*0}/K^{*+}\bar{K}^0$.

$\Xi_b \to J/\psi \Lambda K$—mechanism 2

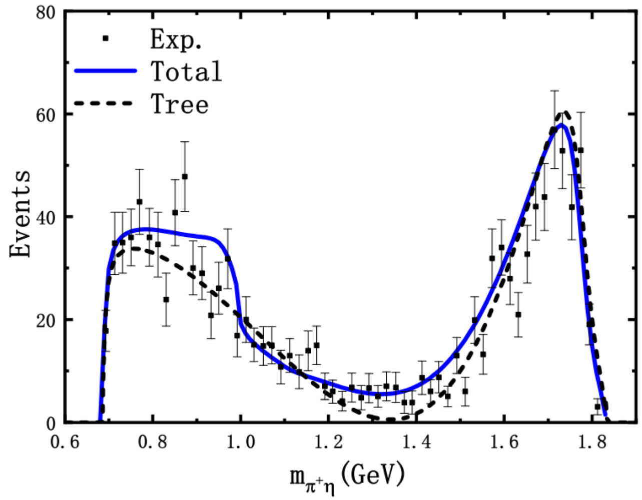


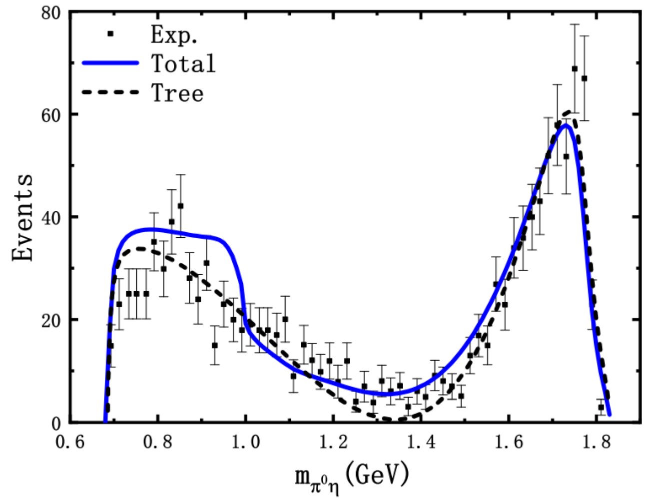
$D_s^+ \to \rho^+ \eta \to \pi a_0$

$D_s^+ \to K^* \overline{K} / \overline{K^*} K \to \pi a_0$

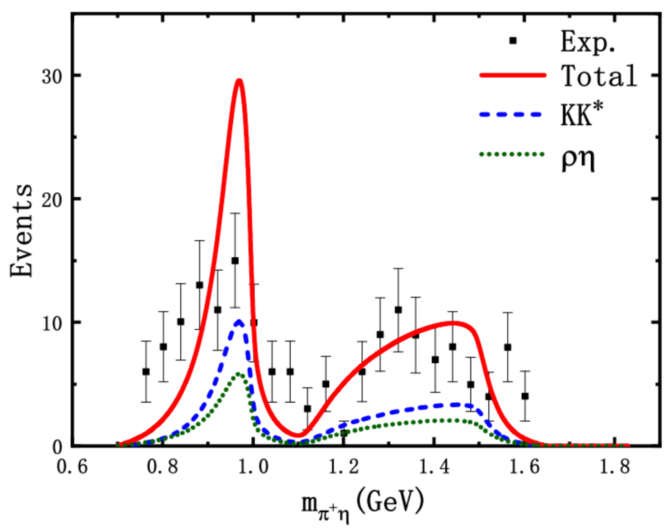


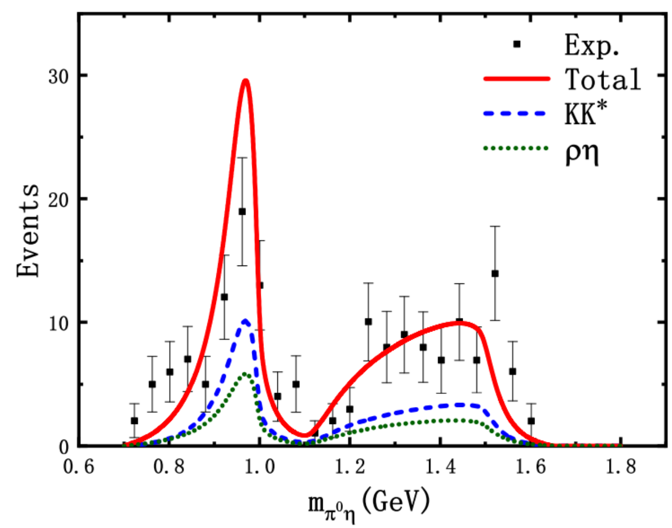
$\Xi_b \to J/\psi\Lambda K$—mechanism 2



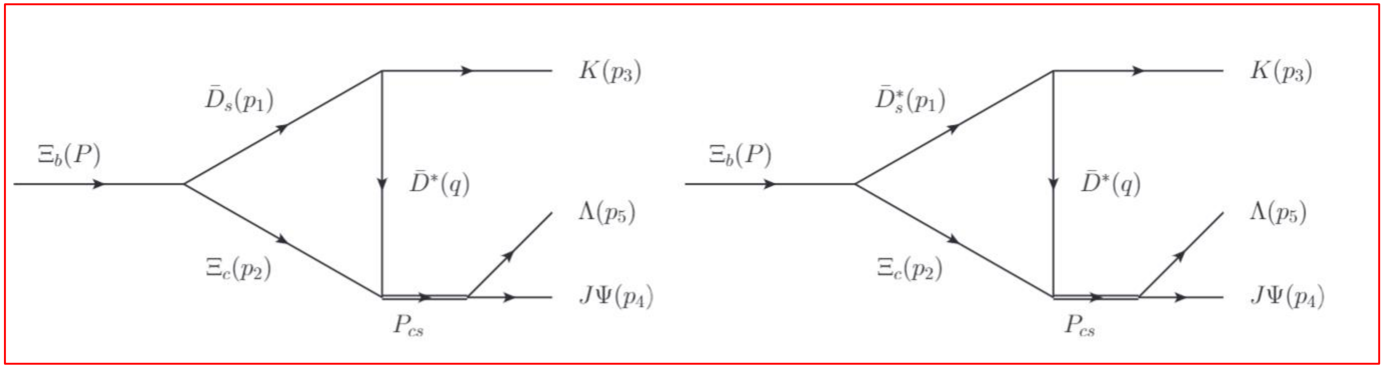


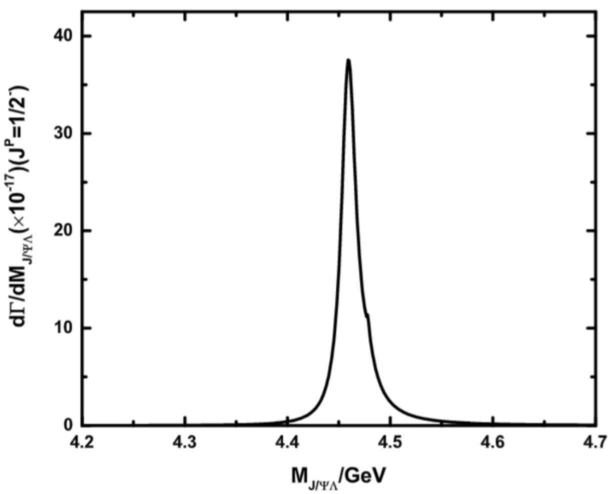
$m_{\pi\eta} > 1GeV$

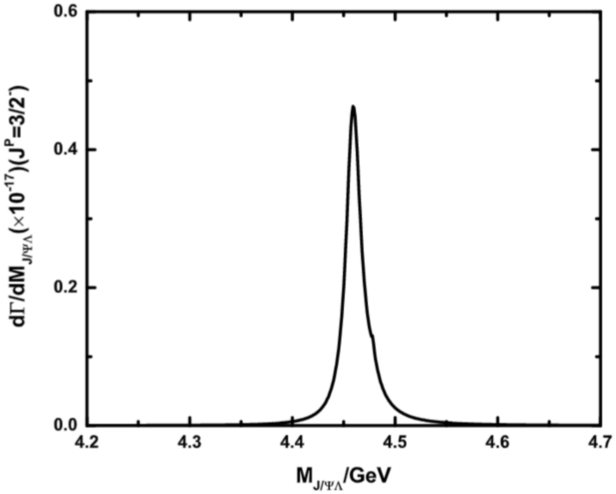




$\Xi_b \to J/\psi\Lambda K$—mechanism 2







To be compared with the LHCb data

Stay tuned, more to come

State	Mass (MeV)	Width (MeV)	R(%)	R(%)	Ref.
$P_c(4312)$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$0.30 \pm 0.07^{+0.34}_{-0.09}$		[22]
$P_c(4380)$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$		$8.4 \pm 0.7 \pm 4.2$	[1].
$P_c(4440)$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$1.11 \pm 0.33^{+0.22}_{-0.10}$	$4.1 \pm 0.5 \pm 1.1$	[22]
$P_c(4457)$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$0.53 \pm 0.16^{+0.15}_{-0.13}$		[22]
$P_{cs}(4459)$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$	$2.7^{+1.9+0.7}_{-0.6-1.3}$		[32]

We hope to provide a unified description of all the discovered and to-be-discovered pentaquark states

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)
- The nature of Pcs can be tested in the $\Xi_b \to J/\psi \Lambda K$ decay, which may also help to understand the production of Pc's in the $\Lambda_b \to J/\psi \mathrm{p} K$ decay

谢谢！ 敬请批评指正！

Outlook 1: How to understand production yields

Facts:

1. LHCb first observed Pc(4380) and Pc(4450)
2. With almost ten times more data, they observed Pc(4312), and Pc(4450) splits into Pc(4440) and Pc(4457)
3. No $\overline{\mathrm{D}}^{*}\Sigma_c^{*}$ states have been observed

Implications:

1. In terms of production yields,

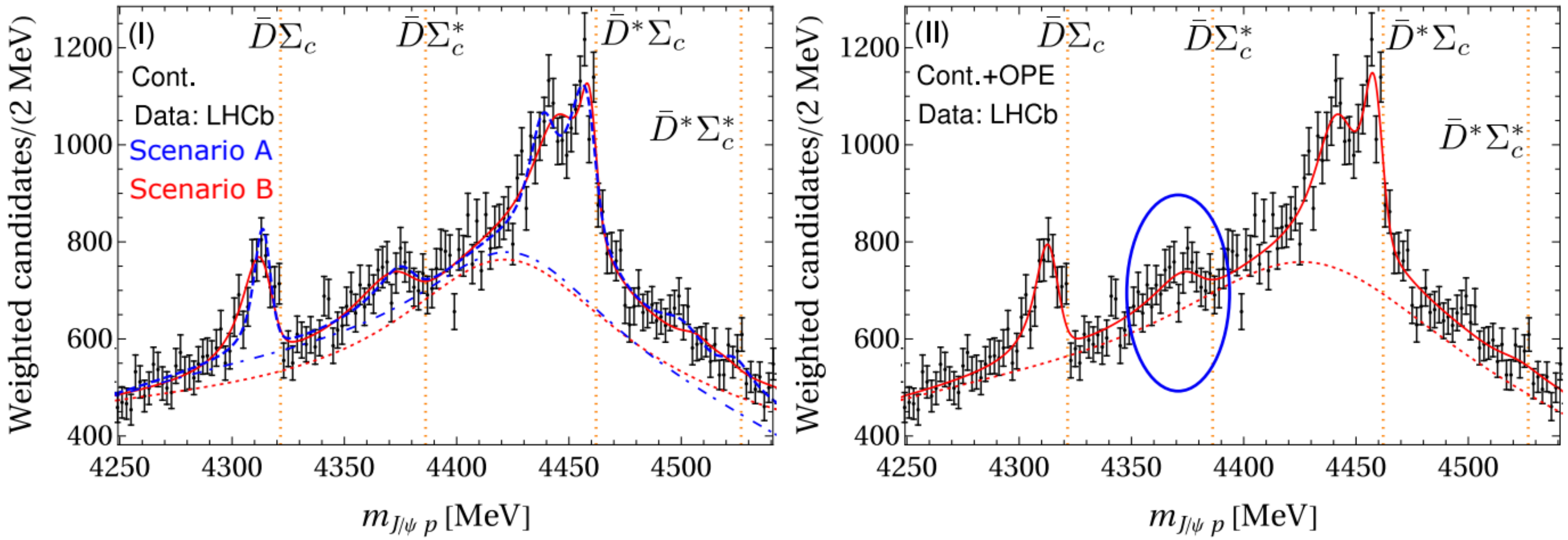
$$Pc(4440) + Pc(4457) \approx 10Pc(4312) \approx 100\overline{\mathrm{D}}^{*}\Sigma_c^{*} \text{ states}$$

2. And/or $\overline{\mathrm{D}}^{*}\Sigma_c^{*}$ states are very broad

Outlook 2: Pc(4380) also seen in 2019?

Fit to the LHCb $J/\psi p$ data using hadronic molecular model with HQSS:
coupled channels ($\bar{D}^{(*)}\Sigma_c^{(*)}$, $J/\psi p$), complex (modeling $\Lambda_c\bar{D}^{(*)}$) contact terms + OPE

M.-L. Du, V. Baru, FKG, C. Hanhart, U.-G. Meißner, J. A. Oller, Q. Wang, PRL124(2020)072001



- Scenario B is favored after considering the OPE (χ^2/dof $= 1.0$ (B) v.s. 1.3 (A)).
- Existence of a narrow $P_c(4380)$ with a significance of about 1.7σ

26 vs. 205 ± 18 ±86 (LHCb)?????

Outlook 3: couplings to $\bar{D}^{(*)}\Lambda_c$ are small

Alessio Piucci(Heidelberg U)

The above results are in contrast with the expectations from the majority of the $\Sigma^{(*)}\overline{\mathrm{D}}^{(*)}$ molecular models of the pentaquark candidates observed by LHCb. Visible pentaquark signals decaying to the $\overline{\mathrm{D}}^0\mathrm{K}^-$ system have been predicted by such models, in a quantitative way for the $P_c(4380)^+$ and $P_c(4450)^+$ states ([39], Section 8.1), and more qualitatively for the $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ pentaquarks [55, 56, 133].

On the other hand, the results support the predictions of the $\Sigma^{(*)}\overline{\mathrm{D}}^{(*)}$ molecular model from [59], in which the couplings of the P_C states to the $\Lambda_c^+\overline{\mathrm{D}}^0$ system are predicted to be small. As introduced in Section 1.5, this work makes use of the most recent LHCb data to tune the constants involved in the loop predictions.

[39] YH Lin et al., Phys.Rev.D 95 (2017) 11, 114017, e-Print: 1703.01045

[55] ZH Guo et al., Phys.Lett.B 793 (2019) 144-149, e-Print: 1904.00851

[56] XZ Weng et al., Phys.Rev.D 100 (2019) 1, 016014, e-Print: 1904.09891

[58] ME Eides et al., Mod.Phys.Lett.A 35 (2020) 18, 2050151, e-Print: 1904.11616

***[59] CW Xiao et al., Phys.Rev.D* 100 (2019) 1, 014021, e-Print: 1904.01296**

[133] JB Cheng et al., *Phys.Rev.D* 100 (2019) 5, 054002, e-Print: 1905.08605

Outlook 4: Pc(4457) consists of two states

1. Further structure due to the nearby $\Lambda_c(2595)\bar{D}$ threshold

- Lisheng Geng, Junxu Lu, Manuel Pavon Valderrama, *PRD* 97 (2018) 094036
- Fang-Zheng Peng, Junxu Lu, Mario Sánchez Sánchez, Mao-Jun Yan, Manuel Pavon Valderrama, e-Print: 2007.01198 [hep-ph] (1/2+, 1/2-)
- T.J. Burns, E.S. Swanson, *PRD*100 (2019) 114033 (1/2+)
- Hao Xu, Qiang Li, Chao-His Chang, Guo-Li Wang, *PRD* 101 (2020) 054037 (3/2-,1/2-)

2. Experimental hint, the production yields do not add up

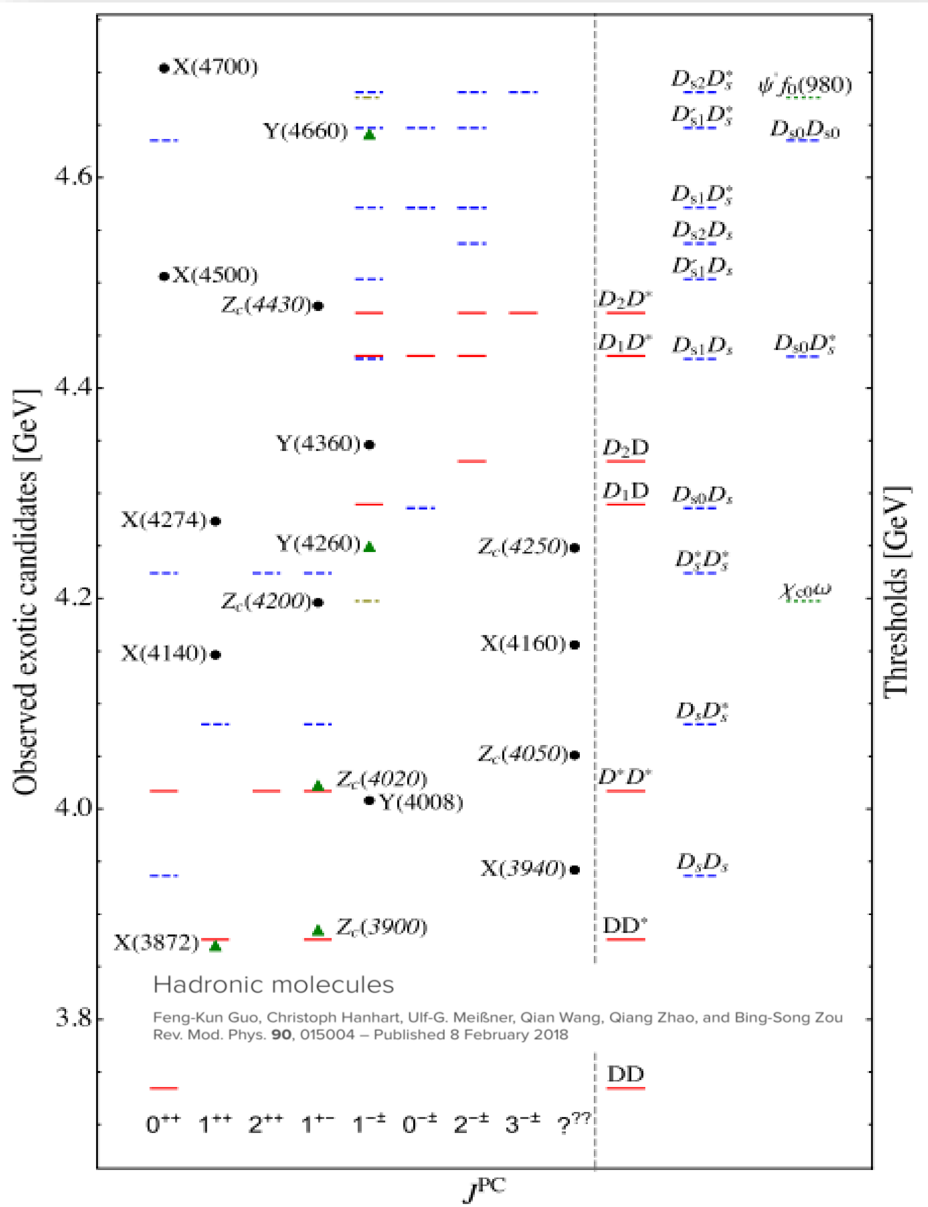
State	Mass (MeV)	Width (MeV)	R(%)	R(%)
$P_c(4312)$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$0.30 \pm 0.07^{+0.34}_{-0.09}$	
$P_c(4380)$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$		$8.4 \pm 0.7 \pm 4.2$
$P_c(4440)$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$1.11 \pm 0.33^{+0.22}_{-0.10}$	$4.1 \pm 0.5 \pm 1.1$
$P_c(4457)$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$0.53 \pm 0.16^{+0.15}_{-0.13}$	

LHCb 2015&2019

Outlook 5: where are the Pcs(4459) partners

1. **There exist 7 $\bar{D}^{(*)}\Xi_c'^{(*)}$ and 3 $\bar{D}^{(*)}\Xi_c$ states, why not seen**

- Qi Wu, Dian-Yong Chen, and Ran Ji, 2103.05257
- Jun-Xu Lu, Ming-Zhu Liu and Li-Sheng Geng, in preparation


Observed exotic candidates [GeV]
Thresholds [GeV]
J^{PC}
4.6
4.4
4.2
4.0
3.8
X(4700)
Y(4660)
X(4500)
Zc(4430)
Y(4360)
X(4274)
Y(4260)
Zc(4250)
Zc(4200)
X(4140)
X(4160)
Zc(4050)
Zc(4020)
Y(4008)
X(3940)
X(3872)
Zc(3900)
Hadronic molecules
Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meißner, Qian Wang, Qiang Zhao, and Bing-Song Zou
Rev. Mod. Phys. 90, 015004 – Published 8 February 2018
0++ 1++ 2++ 1+- 1-± 0-± 2-± 3-± ???
D2D*
D1D*
D2D
D1D
D*D*
DD*
DD
ψ′f0(980)
Ds0Ds0
Ds0D*s
χc0ω

CW Xiao et al., *Phys.Rev.D* 100 (2019) 1, 014021, e-Print: 1904.01296

TABLE I. Dimensionless coupling constants of the $(I = 1/2, J^P = 1/2^-)$ poles found in this work to the different channels. The imaginary part of the energies corresponds to $\Gamma/2$.

	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
$(4306.38 + i7.62)$ MeV							
g_i	$0.67 + i0.01$	$0.46 - i0.03$	$0.01 - i0.01$	$\mathbf{2.07 - i0.28}$	$0.03 + i0.25$	$0.06 - i0.31$	$0.04 - i0.15$
$\lvert g_i \rvert$	0.67	0.46	0.01	2.09	0.25	0.31	0.16
$(4452.96 + i11.72)$ MeV							
g_i	$0.24 + i0.03$	$0.88 - 0.11$	$0.09 - i0.06$	$0.12 - i0.02$	$0.11 - i0.09$	$\mathbf{1.97 - i0.52}$	$0.02 + i0.19$
$\lvert g_i \rvert$	0.25	0.89	0.11	0.13	0.14	2.03	0.19
$(4520.45 + i11.12)$ MeV							
g_i	$0.72 - i0.10$	$0.45 - i0.04$	$0.11 - i0.06$	$0.06 - i0.02$	$0.06 - i0.05$	$0.07 - i0.02$	$\mathbf{1.84 - i0.56}$
$\lvert g_i \rvert$	0.73	0.45	0.13	0.06	0.08	0.08	1.92

TABLE II. Same as Table I for $J^P = 3/2^-$.

$(4374.33 + i6.87)$ MeV	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.73 - i0.06$	$0.11 - i0.13$	$0.02 - i0.19$	$\mathbf{1.91 - i0.31}$	$0.03 - i0.30$
$\lvert g_i \rvert$	0.73	0.18	0.19	1.94	0.30
$(4452.48 + i1.49)$ MeV	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.30 - i0.01$	$0.05 - i0.04$	$\mathbf{1.82 - i0.08}$	$0.08 - i0.02$	$0.01 - i0.19$
$\lvert g_i \rvert$	0.30	0.07	1.82	0.08	0.19
$(4519.01 + i6.86)$ MeV	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.66 - i0.01$	$0.11 - i0.07$	$0.10 - i0.3$	$0.13 - i0.02$	$\mathbf{1.79 - i0.36}$
$\lvert g_i \rvert$	0.66	0.13	0.10	0.13	1.82