Reanalysis of uudc$\bar{c}$ pentaquark states

Hongxia Huang & Jialun Ping
Nanjing Normal University
Fan Wang
Nanjing University

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Outline

I. Introduction

II. Dynamic calculation in the limited space

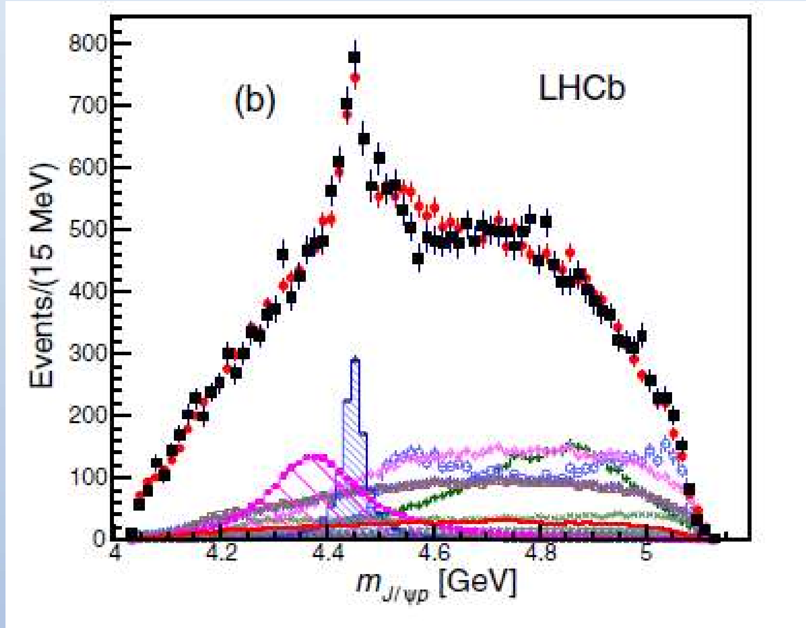
III. Resonance states in the scattering process

IV. Summary

I. Introduction

➢ Experimental results

- **2015** LHCb Collaboration, Phys. Rev. Lett. 115, 072001



- The two P_c^+ states are found to have **masses and widths** of
  $M_{P_c\,(4380)} = 4380 \pm 8 \pm 29$ MeV
  $\Gamma_{P_c\,(4380)} = 205 \pm 18 \pm 86$MeV
  $M_{P_c\,(4450)} = 4449.8 \pm 1.7 \pm 2.5$ MeV
  $\Gamma_{P_c\,(4450)} = 39 \pm 5 \pm 19$ MeV

- The preferred **spin-parity J^P** are of opposite values, with one state having spin 3/2 and the other 5/2.

- **2019** LHCb Collaboration, Phys. Rev. Lett. 122 222001

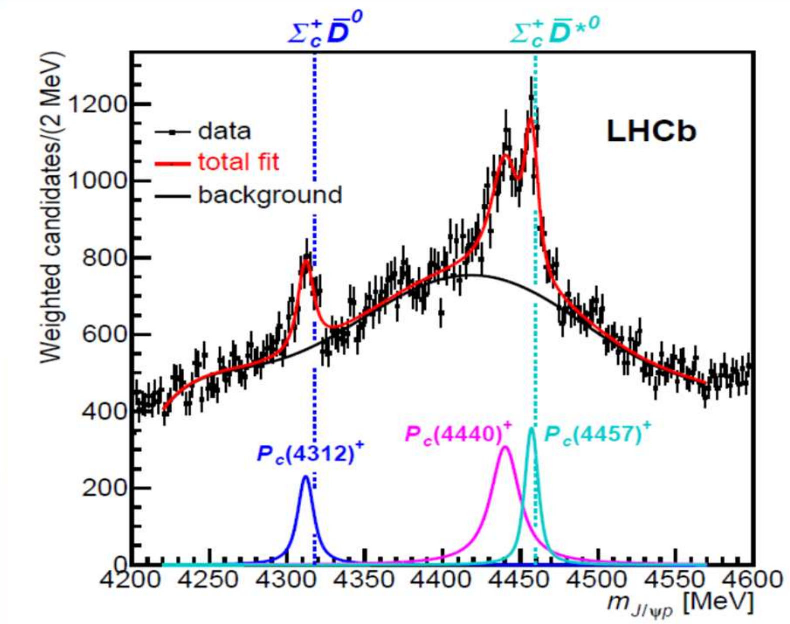


Figure 6: Fit to the $\cos\theta_{P_c}$-weighted $m_{J/\psi p}$ distribution with three BW amplitudes and a sixth-order polynomial background. This fit is used to determine the central values of the masses and widths of the P_c^+ states. The mass thresholds for the $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^+ \bar{D}^{*0}$ final states are superimposed.

- The *Pc*(4312) was discovered with 7.3*σ* significance by analyzing the *J/ψp* invariant mass spectrum.
- The previously reported *Pc*(4450) structure was resolved at 5.4*σ* significance into two narrow states: the *Pc*(4440) and *Pc*(4457).

Table 1: Summary of P_c^+ properties. The central values are based on the fit displayed in Fig. 6.

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

➢ Theoretical studies

- After LHCb's Pc results (2015)

1) Loosely bound molecular baryon-meson pentaquark states:

M. Karliner and J. L. Rosner, Phys. Rev. Lett. 115, 122001 (2015).

R. Chen, X. Liu, X.-Q. Li, S.-L. Zhu, Phys.Rev.Lett. 115, no.13, 132002 (2015).

H. X. Chen, W. Chen, X. Liu, T.G. Steele and S. L. Zhu, Phys.Rev.Lett. 115, no.17, 172001 (2015) .

L. Roca, J. Nieves and E. Oset, Phys. Rev. D 92, 094003 (2015).

J. He, Phys.Lett. B753, 547-551 (2016) .

H. X. Huang, C. R. Deng, J. L. Ping, and F. Wang, Eur. Phys. J. C 76, 624 (2016).

H. X. Huang and J. L. Ping, Phys. Rev. D 99, 014010 (2019).

G. Yang and J. L. Ping, Phys. Rev. D 95, 010014 (2017).

A. Feijoo, V. K. Magas, A. Ramos and E. Oset, Phys. Rev. D 95, no.3, 039905 (2017).

and others.

2) Tightly bound pentaquark states

L. Maiani, A.D. Polosa, and V. Riquer, Phys.Lett. B 749, 289-291 (2015).

R. F. Lebed, Phys.Lett. B 749, 454-457 (2015).

G.-N. Li, X.-G. He, M. He, JHEP 1512, 128 (2015).

Z.-G. Wang, Eur. Phys. J. C 76, no.2, 70 (2016).

R. Zhu and C. F. Qiao, Phys.Lett. B 756, 259 (2016).
V. V. Anisovich et al., arXiv:1507.07652.
R. Ghosh, A. Bhattacharya, and B. Chakrabarti, Phys. Part. Nucl. Lett. 14, 550 (2017).

and others.

3) Peaks due to triangle-diagram processes

F.-K. Guo, U.-G. Meißner, W. Wang, and Z. Yang, Phys. Rev. D 92, 071502(R) (2015).
U.-G. Meißner and J. A. Oller, Phys. Lett. B 751, 59 (2015).
X.-H. Liu, Q. Wang, and Q. Zhao, Phys. Lett. B 757, 231 (2016).
Q. Wang, X.-H. Liu, and Q. Zhao, Phys.Rev. D92, 034022 (2015).
M. Mikhasenko, arXiv:1507.06552.

and others.

- Immediately after LHCb's Pc results (2019)

R. Chen, X. Liu, Z.-F. Sun, and S.-L. Zhu, arXiv:1903.11013 [hep-ph].

F. K. Guo, H. J. Jing, U.-G. Meissner, and S. Sakai, arXiv:1903.11503 [hep-ph].

J. He, arXiv:1903.11872 [hep-ph].

Hua-Xing Chen , Wei Chen, Shi-Lin Zhu, arXiv: 1903.11001 [hep-ph].

H. X. Huang, J. He, and J. L. Ping, arXiv: 1904.00221 [hep-ph].

C. J. Xiao, Y. Huang, Y. B. Dong, L. S. Geng, and D. Y. Chen, arXiv:1904.00872 [hep-ph].

M. Z. Liu, Y. W. Pan, F. Z. Peng, M. S. Sanchez, L. S. Geng, A. Hosaka, and M. P. Valderrama, , Phys. Rev. Lett. **122**, 242001 (2019)

and others.

- Some early studies

J. J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. Lett. **105**, 232001 (2010) [arXiv:1007.0573 [nucl-th]].

J. J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. C **84**, 015202 (2011) [arXiv:1011.2399 [nucl-th]].

J. J. Wu, T.-S. H. Lee and B. S. Zou, Phys. Rev. C **85**, 044002 (2012) [arXiv:1202.1036 [nucl-th]].

Z. C. Yang, Z. F. Sun, J. He, X. Liu and S. L. Zhu, Chin. Phys. C **36**, 6 (2012) [arXiv:1105.2901 [hep-ph]].

and others.

➢ Our work

1) Dynamic calculation in the limited space

H. X. Huang, C. R. Deng, J. L. Ping, and F. Wang, Eur. Phys. J. C. 76, 624 (2016), arXiv: 1510.04648.

- One bound state: $J^P = 1/2^-$ Nηc
- Resonance states? (Strong attraction between Σc/Σc* and D/ D*)

$J^P = 1/2^-$ ΣcD, ΣcD*, Σc*D*

$J^P = 3/2^-$ Σc*D, ΣcD*, Σc*D*, NJ/ψ

$J^P = 5/2^-$ Σc*D*

These states should couple to open channels to check whether they are resonance states or not.

2) Resonance states in the scattering process

H. X. Huang and J. L. Ping, Phys. Rev. D. 99, 014010 (2019) , arXiv: 1811.04260.

Six resonance states were found:

$J^P = 1/2^-$ ΣcD, ΣcD*, Σc*D*

$J^P = 3/2^-$ Σc*D, ΣcD*, Σc*D*

II. Dynamic calculation in the limited space

Eur. Phys. J. C. 76, 624 (2016)

- **Quark model**

  Quark delocalization color screening model (QDCSM)

- QDCSM was developed by Nanjing-Los Alamos collaboration in 1990s aimed to multi-quark study.

  (Phys. Rev. Lett. 69, 2901, 1992)

- Apply to the study of baryon-baryon interaction and dibaryons

  deuteron, d,*

  NN, $N\Lambda$, $N\Omega$, …

- Apply to the study of baryon-meson interaction and pentaquarks

  Nphi (hidden-strange system),

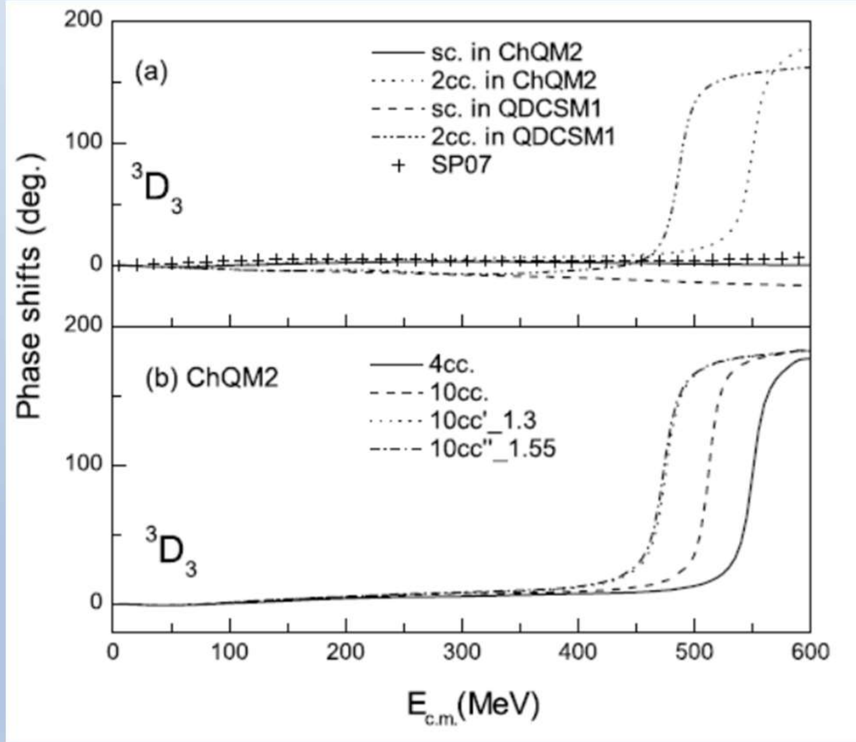
  NK, Npi, …

- Some examples

1). d* mass and width in NN scattering

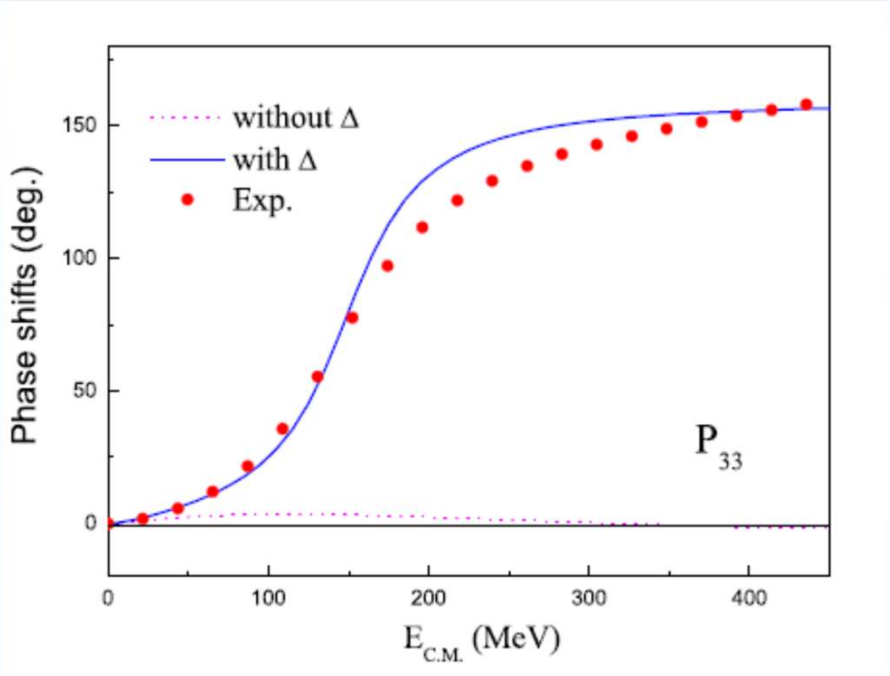
PRC 79 (2009) 024001

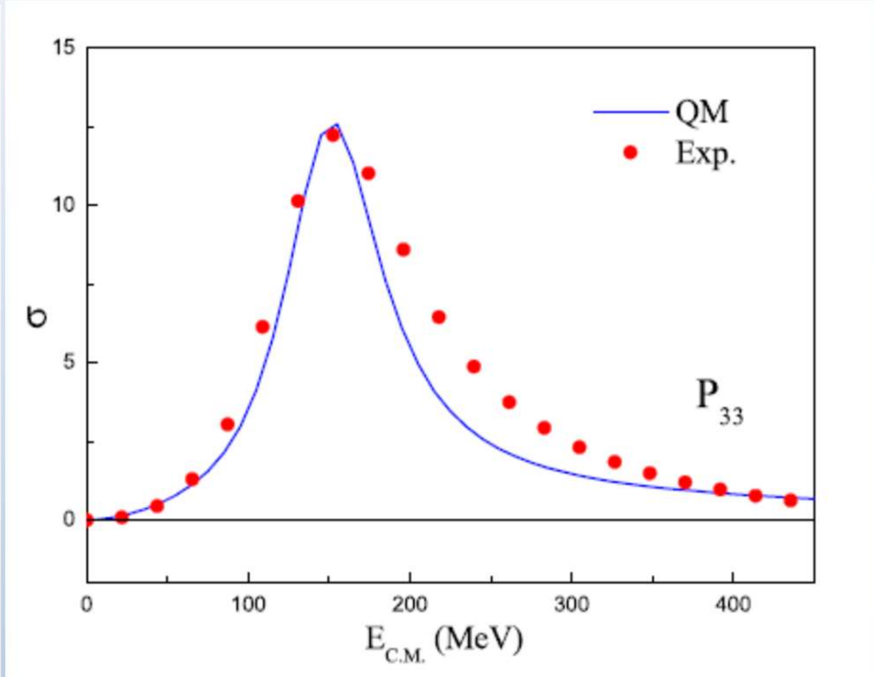
N_{ch}	ChQM2		ChQM2a		QDCSM0		QDCSM1		QDCSM3	
	M	Γ	M	Γ	M	Γ	M	Γ	M	Γ
1c	2425	–	2430	–	2413	–	2365	–	2276	–
2cc	2428	17	2433	10	2416	20	2368	20	2278	19
4cc	2413	14	2424	9	2400	14	2357	14	2273	17
10cc	2393	14			–	–	–	–	–	–
10cc′	2353	17			–	–	–	–	–	–
10cc″	2351	21			–	–	–	–	–	–



$$m = 2.37\ \text{GeV}, \Gamma \approx 70\ \text{MeV and}\ I(J^P) = 0(3^+)$$

2). Δ mass and width in Npi scattering





M0=1525 MeV ⟶ $M = 1232\ \text{MeV},\ \Gamma \sim 90\ \text{MeV}$

- ✓ The mass of the resonance state will shift by coupling to the open channel. It is better to study the resonances in the scattering process rather than in the limited space.
- ✓ Extending the work to the hidden-charm pentaquark system is feasible.

➢ Hidden-charm pentaquarks

Eur. Phys. J. C. 76, 624 (2016)

- The hidden charm pentaquark channels with I=1/2

Table 3 The channels involved in the calculation

$S=\frac{1}{2}$	$N\eta_c$	NJ/ψ	$\Lambda_c D$	$\Lambda_c D^*$	$\Sigma_c D$
	$\Sigma_c D^*$	$\Sigma_c^* D^*$			
$S=\frac{3}{2}$	NJ/ψ	$\Lambda_c D^*$	$\Sigma_c D^*$	$\Sigma_c^* D$	$\Sigma_c^* D^*$
$S=\frac{5}{2}$	$\Sigma_c^* D^*$				

✓ The state with the positive parity is unbound in present calculations.

- The effective potentials

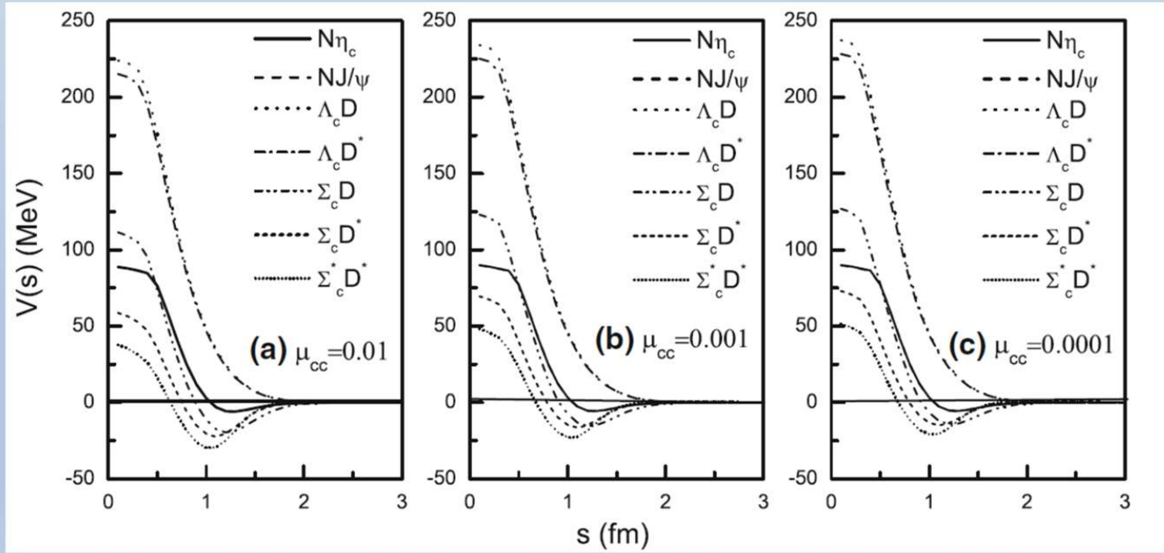


Fig. 1 The potentials of different channels for the $IJ^P = \frac{1}{2}\frac{1}{2}^-$ system

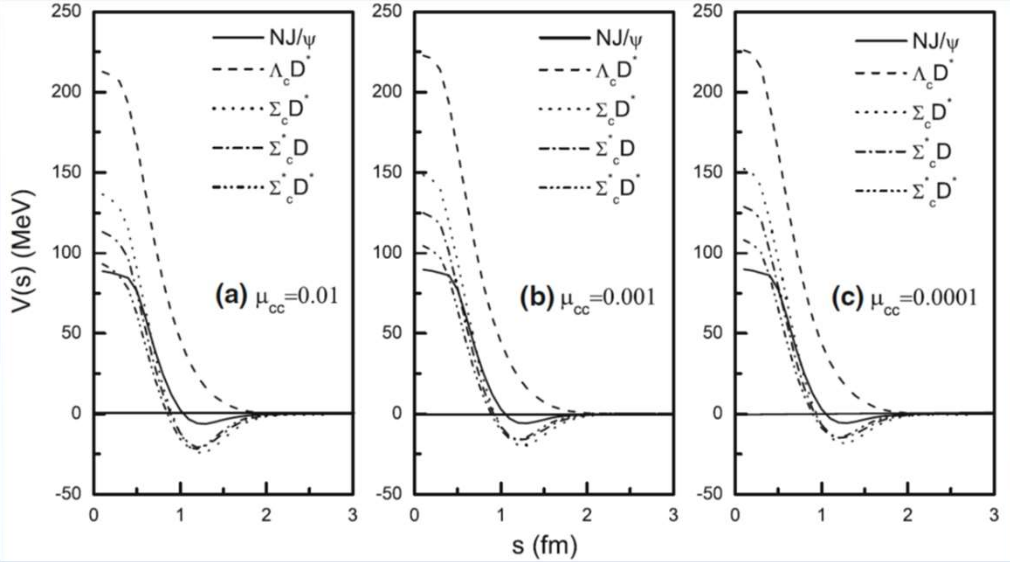


Fig. 2 The potentials of different channels for the $IJ^P = \frac{1}{2}\frac{3}{2}^-$ system

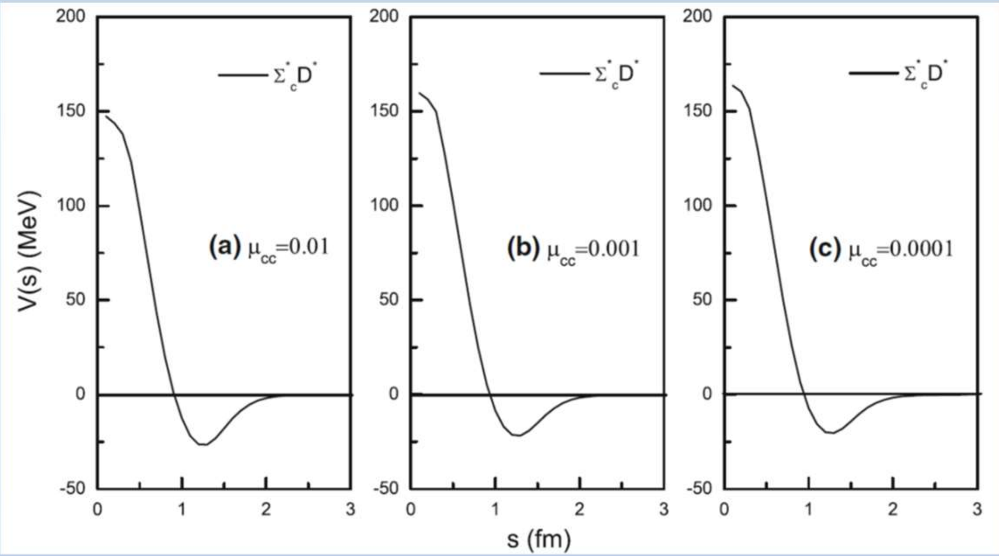


Fig. 3 The potential of a single channel for the $IJ^P = \frac{1}{2}\frac{5}{2}^-$ system

- ✓ The potentials are repulsive between *Λ*c and D/D*. So no bound states or resonances can be formed in these two channels *ΛcD and ΛcD*.*
- ✓ Strong attractions between Σc/Σc* and D/D*.
- ✓ It is possible for Σc/Σc* and D/ D* to form bound states or resonance states.

- The single channel calculation

$J^P = \frac{1}{2}^-$				$J^P = \frac{3}{2}^-$			
μ_{cc}	0.01	0.001	0.0001	μ_{cc}	0.01	0.001	0.0001
$N\eta_c$	ub	ub	ub	NJ/ψ	ub	ub	ub
NJ/ψ	ub	ub	ub	$\Lambda_c D^*$	ub	ub	ub
$\Lambda_c D$	ub	ub	ub	$\Sigma_c D^*$	-16/4446	-11/4451	-10/4452
$\Lambda_c D^*$	ub	ub	ub	$\Sigma_c^* D$	-17/4367	-14/4370	-12/4372
$\Sigma_c D$	−19/4300	−15/4304	−13/4306	$\Sigma_c^* D^*$	−17/4510	−15/4512	−13/4514
$\Sigma_c D^*$	−21/4441	−19/4443	−18/4444	$J^P = \frac{5}{2}^-$			
$\Sigma_c^* D^*$	−24/4503	−23/4504	−21/4506	$\Sigma_c^* D^*$	−15/4512	−10/4517	−10/4517

$\Sigma_c D^*$ ($J^P = \frac{3}{2}^-$) $\neq$ **Pc(4450)**

$\Sigma_c^* D$ ($J^P = \frac{3}{2}^-$) $\Rightarrow$ **Pc(4380)**

Comparing with the LHCb's result in 2015

- ✓ The main component of the Pc(4380) maybe Σc*D with $J^P = 3/2^-$.
- ✓ The mass of the ΣcD* with $J^P = 3/2^-$ is close to the reported Pc(4450), but the opposite parity of this state to Pc(4380) may prevent one from making this assignment at that time.

- The channel-coupling calculation

Table 6 The masses (in MeV) of the hidden-charm molecular pentaquarks with all channels coupling and the percentages of each channel in the eigen-states

$J^P = \frac{1}{2}^-$				$J^P = \frac{3}{2}^-$				$J^P = \frac{5}{2}^-$			
μ_{cc}	0.01	0.001	0.0001	μ_{cc}	0.01	0.001	0.0001	μ_{cc}	0.01	0.001	0.0001
M_{cc}	3881	3883	3884	M_{cc}	3997	3998	3998	M_{cc}	4512	4517	4517
$N\eta_c$	41.7	49.7	35.2	NJ/ψ	80.8	71.0	62.1	$\Sigma_c^* D^*$	100.0	100.0	100.0
NJ/ψ	23.1	24.4	29.3	$\Lambda_c D^*$	8.7	11.9	15.9				
$\Lambda_c D$	14.6	11.7	14.5	$\Sigma_c D^*$	1.2	1.9	2.6				
$\Lambda_c D^*$	0.9	0.4	2.0	$\Sigma_c^* D$	3.5	5.8	7.3				
$\Sigma_c D$	0.1	4.8	6.0	$\Sigma_c^* D^*$	5.8	9.4	12.1				
$\Sigma_c D^*$	4.5	6.4	12.4								
$\Sigma_c^* D^*$	15.1	2.6	0.6								

✓ A bound state: $J^P = 1/2^-$ Nηc

✓ $J^P = 3/2^-$ NJ/ψ (*decay to open channels: D−wave Nηc*)

✓ $J^P = 5/2^-$ Σc*D* (*decay to open channels: some D−wave channels*)

✓ Where are these states?

$J^P = 1/2^-$ ΣcD, ΣcD*, Σc*D* *(decay to open channels: S-wave Nηc, NJ/ψ, ΛcD, ΛcD* and some D-wave channels)*

$J^P = 3/2^-$ Σc*D, ΣcD*, Σc*D* *(decay to open channels: S−wave NJ/ψ, ΛcD* and some D−wave channels)*

They maybe the resonance states.

To check whether they are resonance states or not, the study of scattering process of the corresponding open channels are needed !

III. Resonance states in the scattering process

➢ **Hidden-charm pentaquarks**

arXiv: 1811.04260, Phys. Rev. D. 99, 014010 (2019)

1. $J^P = 1/2^-$

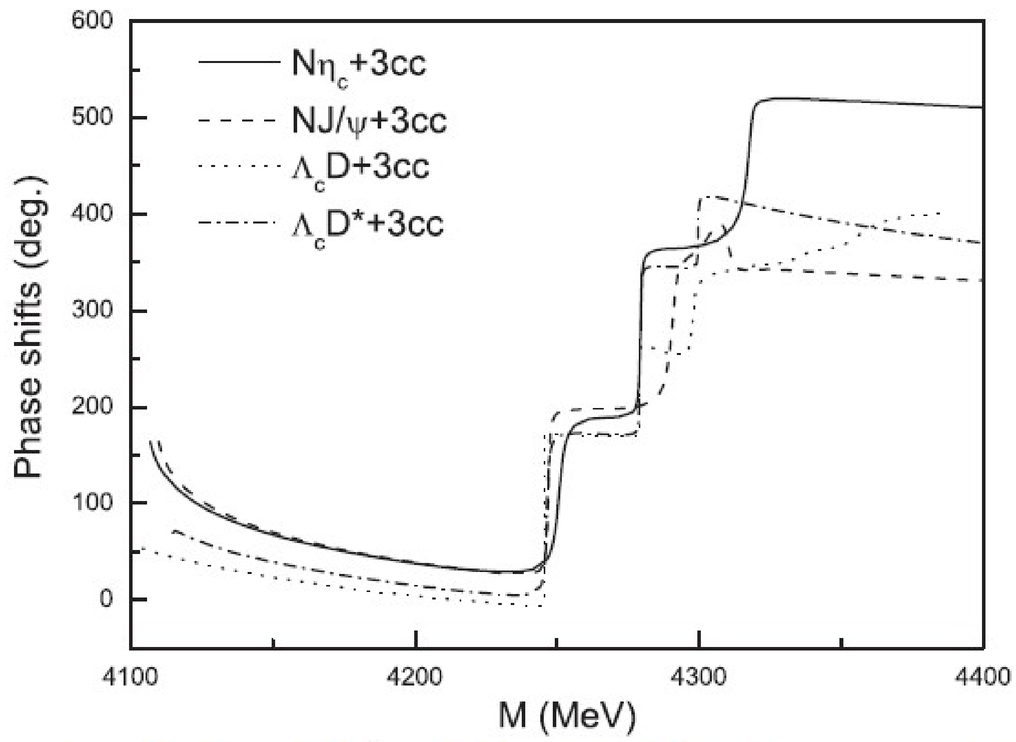


FIG. 2. The $N\eta_c$, NJ/ψ, $\Lambda_c D$, and $\Lambda_c D^*$ S-wave phase shifts with four-channel coupling for the $IJ^P = \frac{1}{2}\frac{1}{2}^-$ system.

- There are three resonance states: ΣcD, ΣcD*, and Σc*D* in the Nηc scattering phase shifts.
- In other scattering channels there are only two resonance states: ΣcD and ΣcD*.
- There is only a cusp around the threshold of the third state Σc*D*, because the channel coupling pushes the higher state above the threshold.

TABLE II. The masses and decay widths (in MeV) of the $IJ^P = \frac{1}{2}\frac{1}{2}^-$ resonance states in the $N\eta_c$, NJ/ψ, $\Lambda_c D$, and $\Lambda_c D^*$ S-wave scattering process.

	Two-channel coupling						Four-channel coupling					
	$\Sigma_c D$		$\Sigma_c D^*$		$\Sigma_c^* D^*$		$\Sigma_c D$		$\Sigma_c D^*$		$\Sigma_c^* D^*$	
	M'	Γ_i	M'	Γ_i	M'	Γ_i	M'	Γ_i	M'	Γ_i	M'	Γ_i
$N\eta_c$	4312.9	6.0	4451.7	1.1	4523.1	3.5	4311.3	4.5	4448.8	1.0	4525.8	4.0
NJ/ψ	4309.9	2.0	4461.6	4.0	4514.7	1.2	4307.9	1.2	4459.7	3.9	nr	$\cdots$
$\Lambda_c D$	4308.4	0.003	4452.6	1.0	4512.6	0.004	4306.7	0.02	4461.6	1.0	nr	$\cdots$
$\Lambda_c D^*$	4311.6	3.5	4452.5	1.0	4510.8	0.005	4307.7	1.4	4449.0	0.3	nr	$\cdots$
Γ_{total}		11.5		7.1		4.7		7.1		6.2		4.0

Pc(4312) **Pc(4457)**

2. $J^P = 3/2^-$

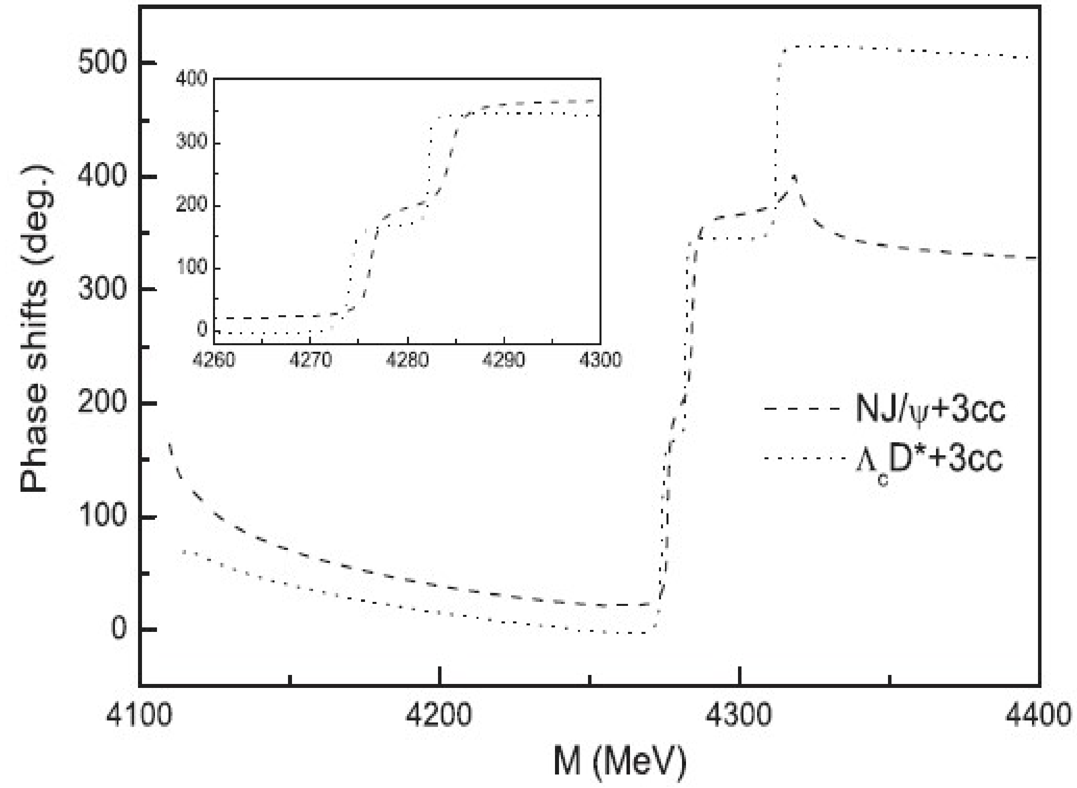


FIG. 4. The NJ/ψ and $\Lambda_c D^*$ S-wave phase shifts with four-channel coupling for the $IJ^P = \frac{1}{2}\frac{3}{2}^-$ system.

- There are two resonance states: ΣcD* and Σc*D in the NJ/ψ scattering phase shifts.
- There are three resonance states: ΣcD*, Σc*D and Σc*D* in the ΛcD* scattering phase shifts.

TABLE III. The masses and decay widths (in MeV) of the $IJ^P = \frac{1}{2}\frac{3}{2}^-$ resonance states in the NJ/ψ and $\Lambda_c D^*$ S-wave scattering process.

	$\Sigma_c D^*$		$\Sigma_c^* D$		$\Sigma_c^* D^*$	
Two-channel coupling						
	M'	Γ_i	M'	Γ_i	M'	Γ_i
NJ/ψ	4453.8	1.7	4379.7	4.5	4526.4	2.5
$\Lambda_c D^*$	4452.7	0.8	4377.6	3.2	4522.7	1.8
Γ_{total}		2.5		7.7		4.3
Four-channel coupling						
	$\Sigma_c D^*$		$\Sigma_c^* D$		$\Sigma_c^* D^*$	
	M'	Γ_i	M'	Γ_i	M'	Γ_i
NJ/ψ	4445.7	1.5	4376.4	1.5	nr	$\cdots$
$\Lambda_c D^*$	4444.0	0.3	4374.4	0.9	4523.0	1.0
Γ_{total}		1.8		2.4		1.0

?

Pc(4440)　　**Pc(4380)**

➢ Compare with the experiment

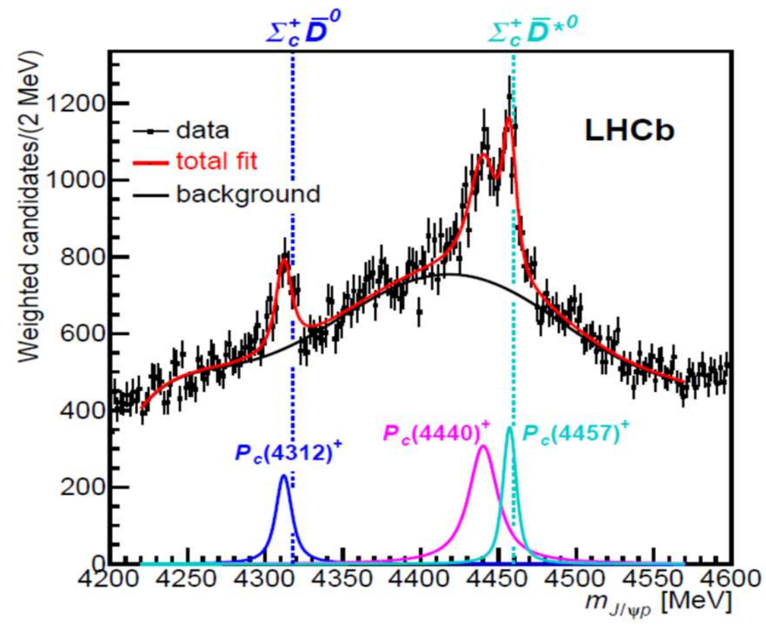
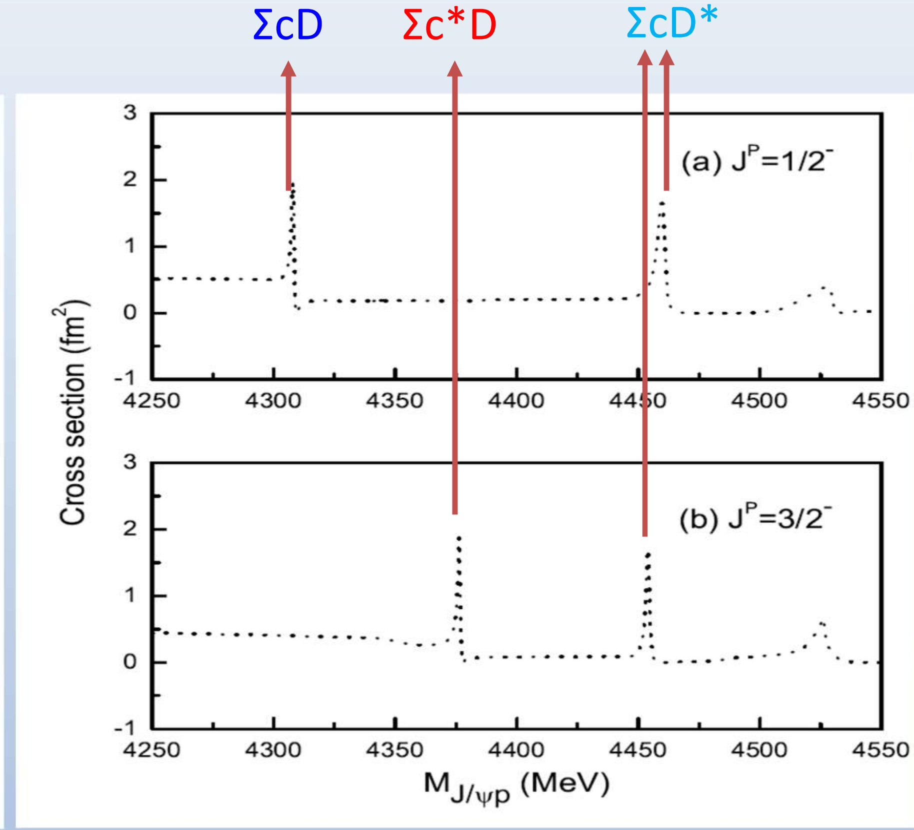


Figure 6: Fit to the $\cos\theta_{P_c}$-weighted $m_{J/\psi p}$ distribution with three BW amplitudes and a sixth-order polynomial background. This fit is used to determine the central values of the masses and widths of the P_c^+ states. The mass thresholds for the $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^+ \bar{D}^{*0}$ final states are superimposed.



LHCb Collaboration,
Phys. Rev. Lett. 122 222001 (2019)

Phys. Rev. D. 99, 014010 (2019),
arXiv: 1904.00221

➢ Hidden-bottom pentaquarks

1. $J^P = 1/2^-$

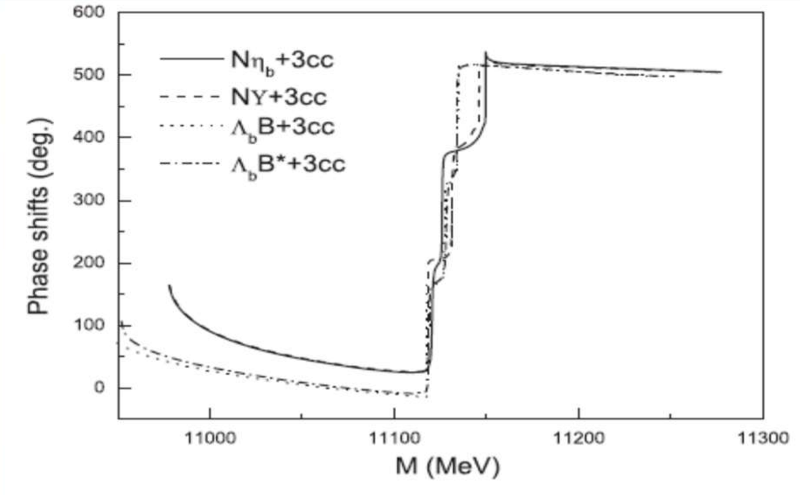


FIG. 6. The $N\eta_b$, $N\Upsilon$, $\Lambda_b B$ and $\Lambda_b B^*$ S-wave phase shifts with four-channel coupling for the $IJ^P = \frac{1}{2}\frac{1}{2}^-$ system.

TABLE IV. The masses and decay widths (in MeV) of the $IJ^P = \frac{1}{2}\frac{1}{2}^-$ resonance states in the $N\eta_b$, $N\Upsilon$, $\Lambda_b B$, and $\Lambda_b B^*$ S-wave scattering process.

	Two-channel coupling						Four-channel coupling					
	$\Sigma_b B$		$\Sigma_b B^*$		$\Sigma_b^* B^*$		$\Sigma_b B$		$\Sigma_b B^*$		$\Sigma_b^* B^*$	
	M'	Γ_i	M'	Γ_i	M'	Γ_i	M'	Γ_i	M'	Γ_i	M'	Γ_i
$N\eta_b$	11 083.3	4.0	11 123.9	1.4	11 154.5	4.7	11 079.8	1.2	11 120.6	0.4	11 156.9	2.0
$N\Upsilon$	11 080.4	1.4	11 135.4	6.6	11 146.2	2.0	11 077.5	0.1	11 125.8	0.8	11 153.5	3.0
$\Lambda_b B$	11 079.0	0.000 3	11 125.4	2.0	11 145.1	0.49	11 077.2	0.001	11 122.0	0.6	11 141.8	0.1
$\Lambda_b B^*$	11 082.2	2.6	11 126.2	2.3	11 142.7	0.22	11 078.3	0.3	11 123.0	1.2	11 141.5	0.4
Γ_{total}		7.0		12.3		7.4		1.6		3.0		5.5

2. $J^P = 3/2^-$

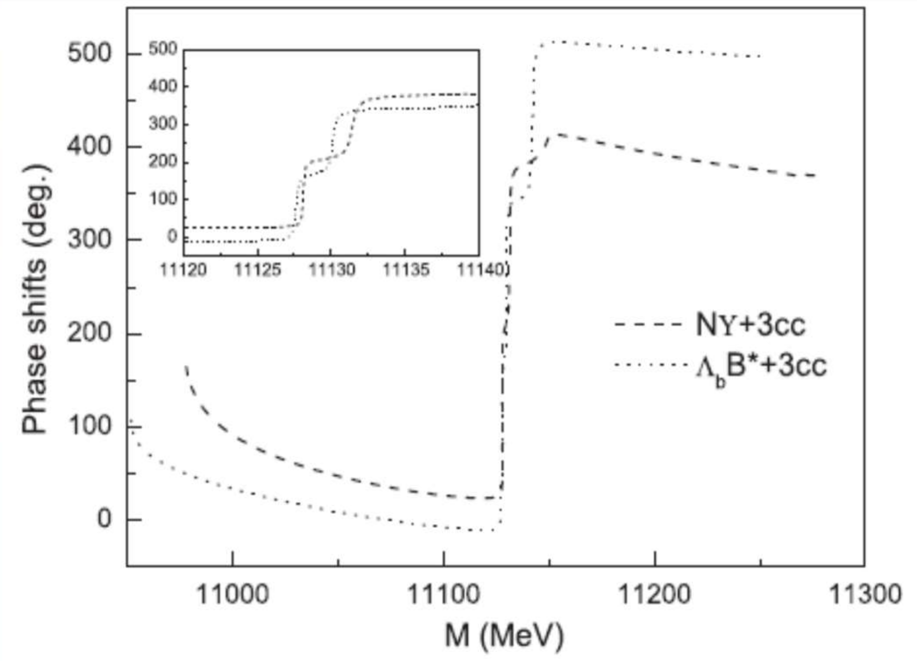


FIG. 8. The $N\Upsilon$ and $\Lambda_b B^*$ S-wave phase shifts with four-channel coupling for the $IJ^P = \frac{1}{2}\frac{3}{2}^-$ system.

TABLE V. The masses and decay widths (in MeV) of the $IJ^P = \frac{1}{2}\frac{3}{2}^-$ resonance states in the $N\Upsilon$ and $\Lambda_b B^*$ S-wave scattering process.

	$\Sigma_b B^*$		$\Sigma_b^* B$		$\Sigma_b^* B^*$	
Two-channel coupling						
	M'	Γ_i	M'	Γ_i	M'	Γ_i
$N\Upsilon$	11 126.3	1.7	11 105.8	4.4	11 155.7	3.8
$\Lambda_b B^*$	11 125.5	0.9	11 103.5	2.6	11 152.0	2.7
Γ_{total}		2.6		7.0		6.5
Four-channel coupling						
	M'	Γ_i	M'	Γ_i	M'	Γ_i
$N\Upsilon$	11 122.7	0.2	11 103.6	0.8	nr	...
$\Lambda_b B^*$	11 122.2	0.2	11 102.4	0.3	11 150.0	1.8
Γ_{total}		0.4		1.1		1.8

- The results are similar to the hidden-charm pentaquarks.
- Some narrow hidden-bottom pentaquark resonances above 11 GeV are found from corresponding scattering process.

IV. Summary

1. The measured states are resonances, it is better to do channel-coupling scattering calculation rather than as bound state calculations.

2. The state with the positive parity is unbound in present calculations.

3. Several bound states and resonance states with negative parity are obtained:

-- A bound state: Nηc $J^P = 1/2^-$

-- Four reported resonance states:

Pc(4312): ΣcD $J^P = 1/2^-$ Pc(4380): Σc*D $J^P = 3/2^-$?

Pc(4440) and Pc(4457): ΣcD* $J^P = 3/2^-, 1/2^-$

-- Four more resonance states:

Σc*D* $J^P = 1/2^-, 3/2^-$ Σc*D* $5/2^-$, NJ/ψ $J^P = 3/2^-$

4. For the hidden-bottom system, the results are similar. Several resonance states are found from corresponding scattering process. The masses of these states are all above 11 GeV while their widths are only a few MeV.

Thanks for your attention!