

近阈共振结构与强子分子态

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5th workshop on the XYZ particles, 郑州, 2018年10月19-23日

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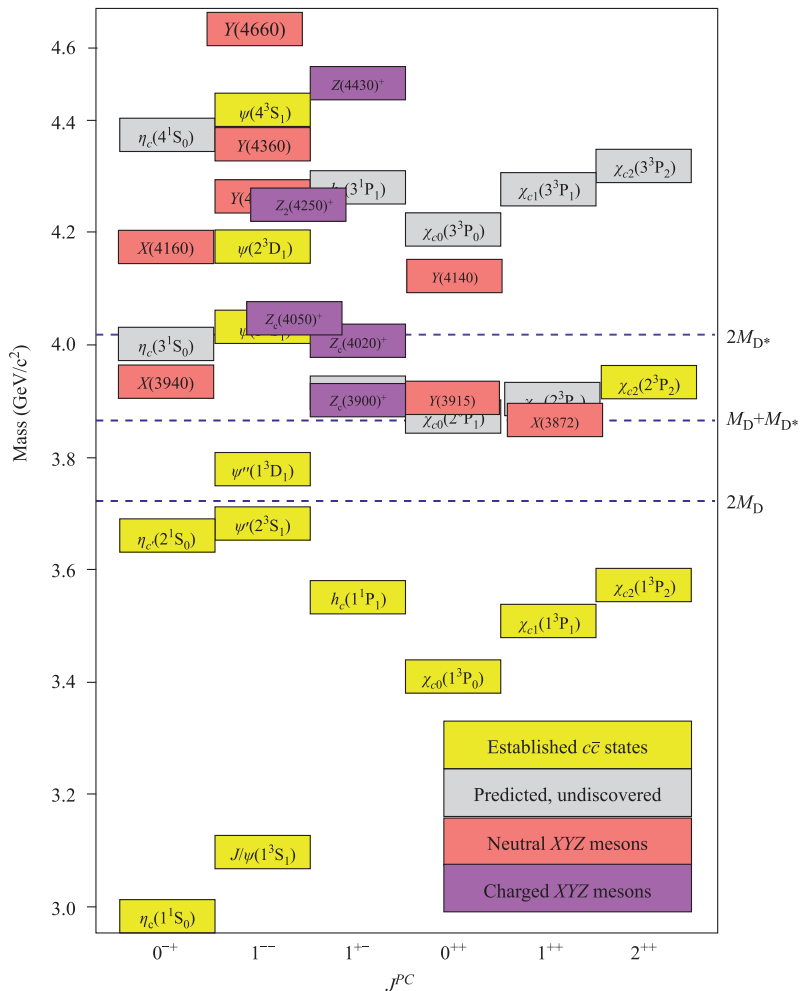
➤ 隐粲五夸克态及其隐奇异伴随态

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强子分子态

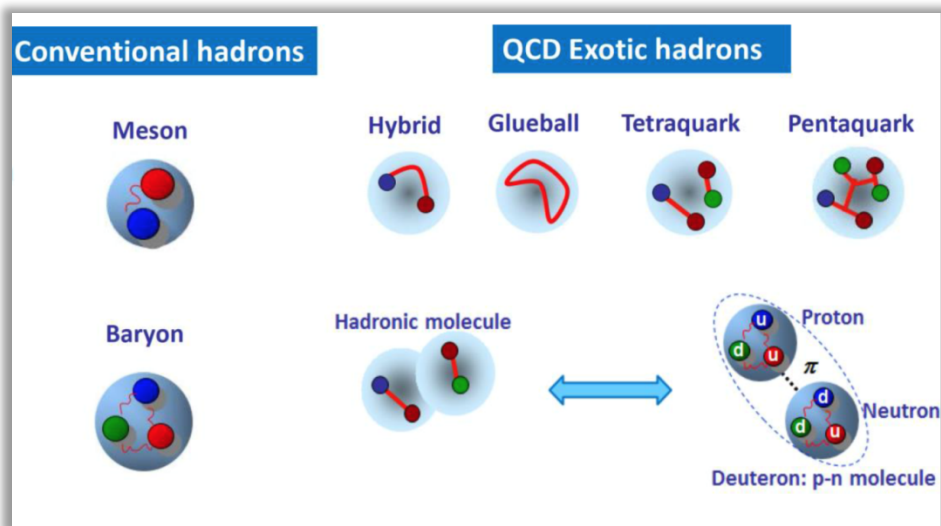
新强子态（奇特强子态）

粲夸克偶素

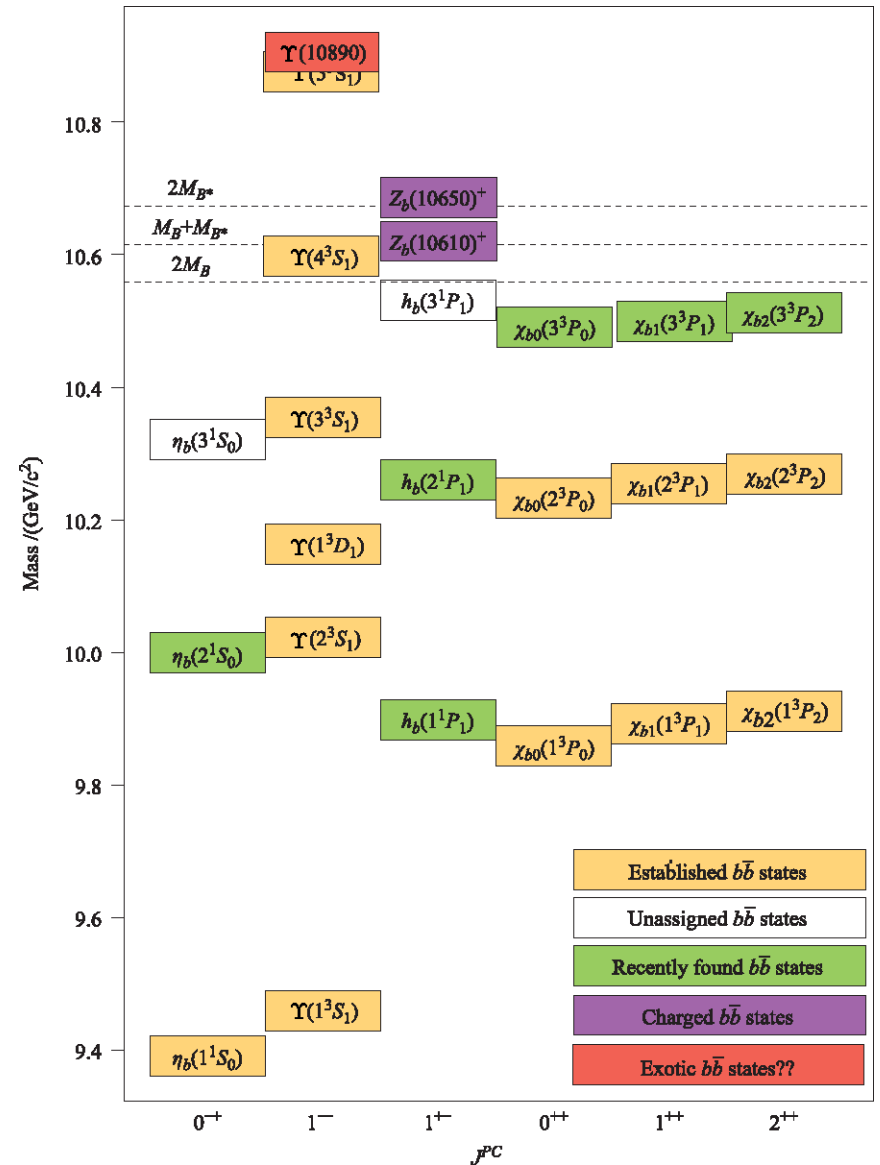
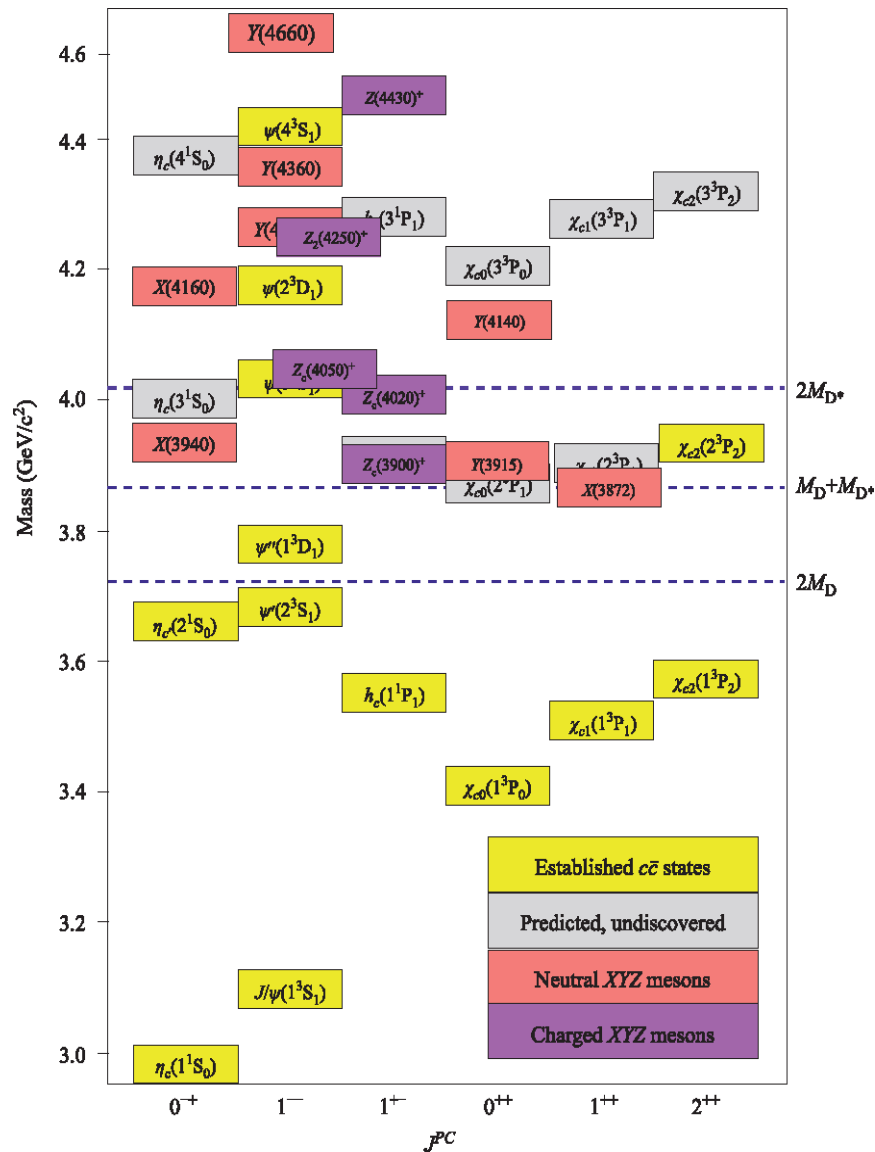


新强子态：不能由传统夸克模型解释的强子。

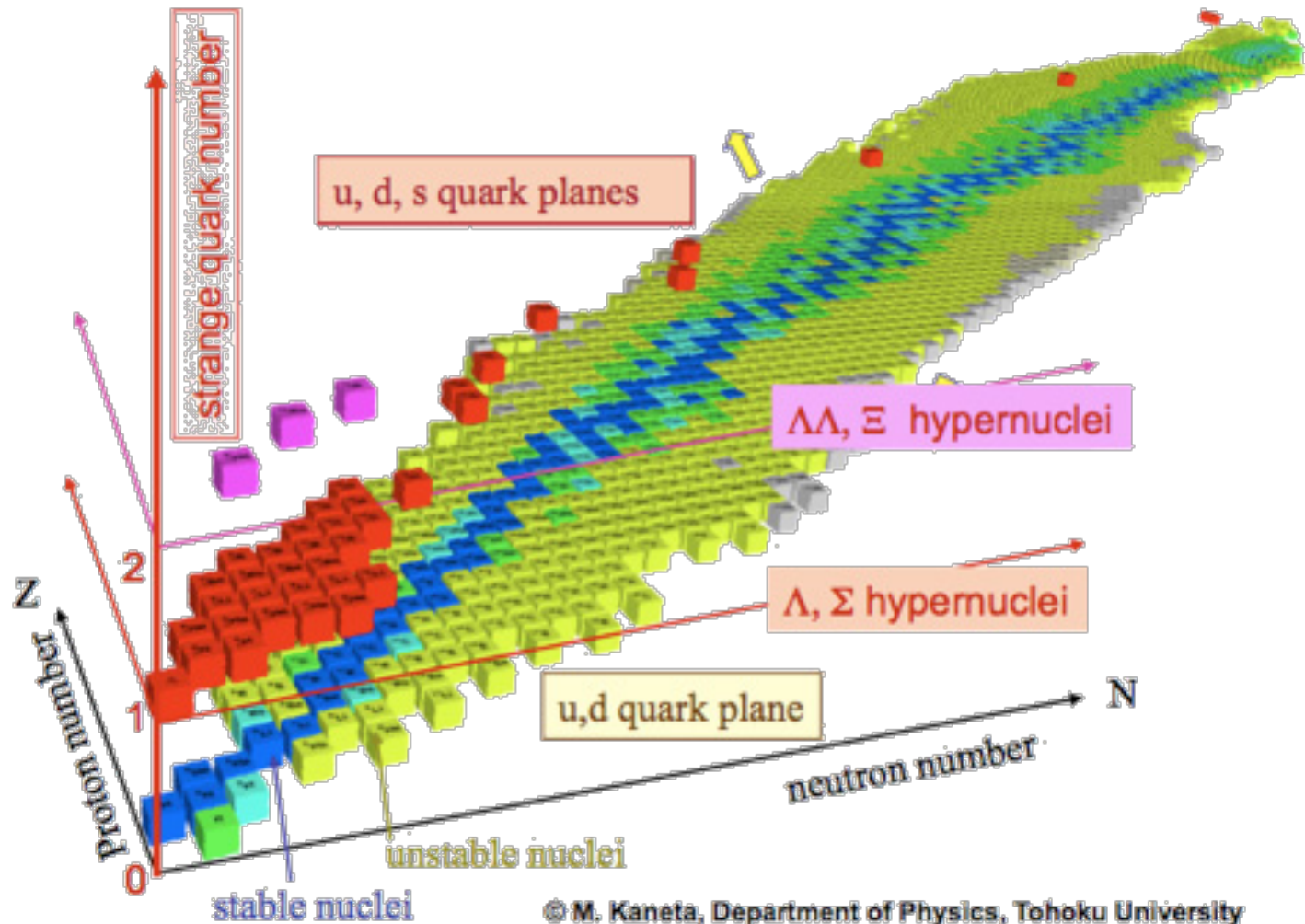
- 量子数在传统夸克模型中不存在
介子： 0^{-+} , 0^{+-} , 1^{-+} , 2^{+-} ,.....；带电粲介子
- 质量与传统夸克模型预言不符



强子分子态与强子强子相互作用



Multi-Favored Nuclear Chart



BB*/DD*/KK*相互作用
与相关的强子分子态

X(3872)

1. Observation of a narrow charmonium - like state in exclusive $B^+ \rightarrow K^+ \pi^+ \pi^- J/\psi$ decays

Belle Collaboration (S.K. Choi (Gyeongsang Natl. U.) *et al.*). Sep 2003. 10 pp.

Published in **Phys.Rev.Lett.** **91** (2003) 262001

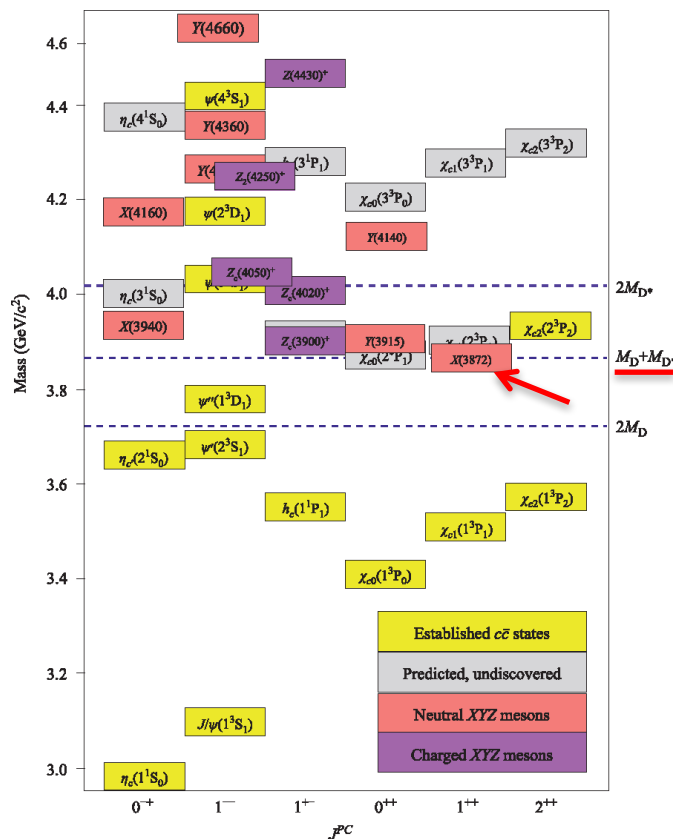
DOI: [10.1103/PhysRevLett.91.262001](https://doi.org/10.1103/PhysRevLett.91.262001)

e-Print: [hep-ex/0309032](https://arxiv.org/abs/hep-ex/0309032) | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[ADS Abstract Service](#); [ADS Abstract Service](#); [Link to PRESSRELEASE](#)

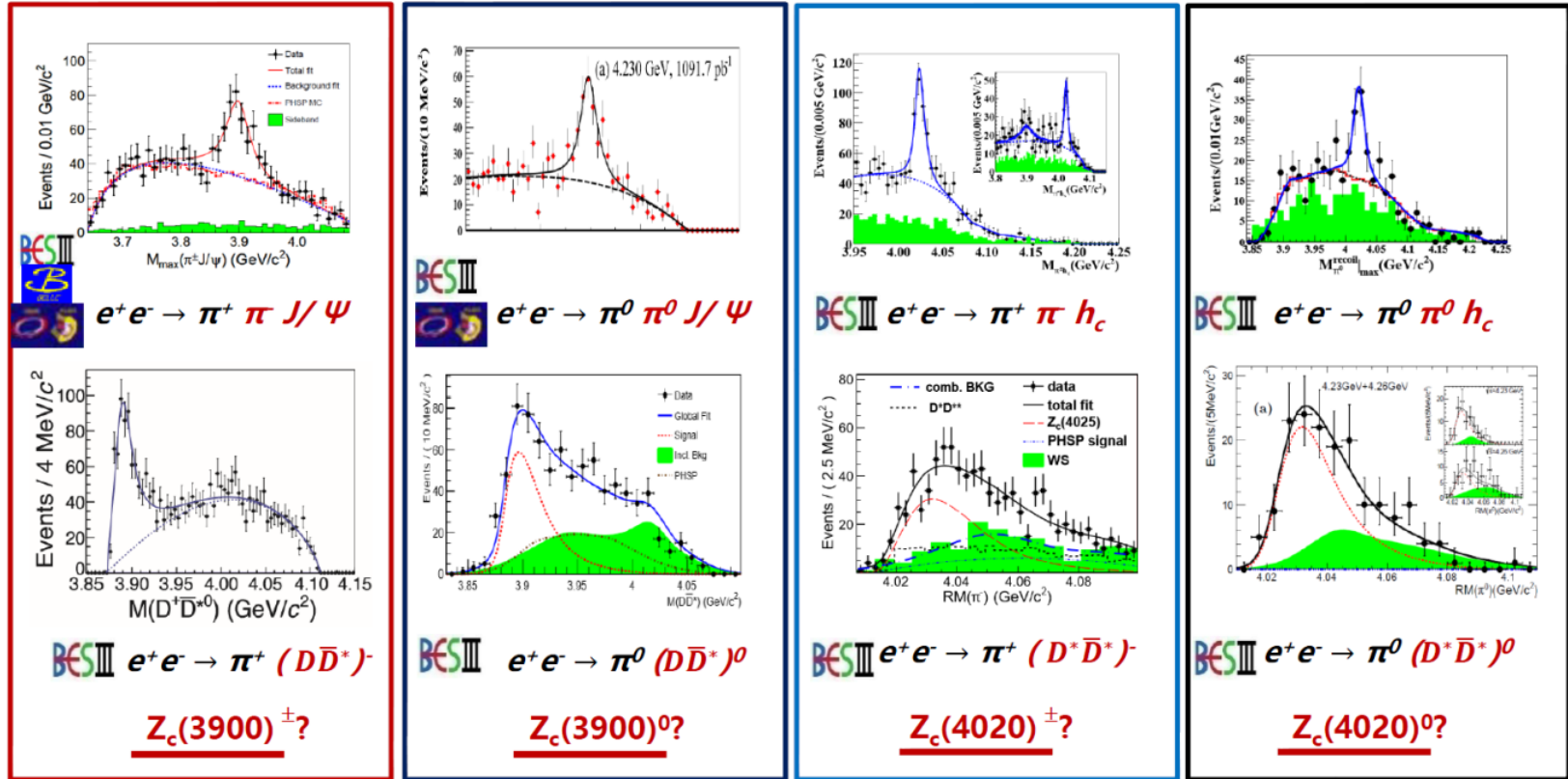
[Detailed record - Cited by 1328 records](#) 1000+



The resonance parameters of the X(3872) and its observed productions and decay channels. Here the X(3872) is abbreviated as X.

Experiment	Mass [MeV]	Width [MeV]	Productions and decay modes	J^{PC}
Belle [63]	$3872 \pm 0.6 \pm 0.5$	< 2.3	$B \rightarrow KX (\rightarrow \pi^+ \pi^- J/\psi)$	$C = +1$ $1^{++}/2^{++}$
Belle [75]	-	-	$B \rightarrow KX (\rightarrow \gamma J/\psi, \omega J/\psi \rightarrow \pi^+ \pi^- \pi^0 J/\psi)$	
Belle [76]	$3875.4 \pm 0.7^{+0.4}_{-1.7} \pm 0.9$	-	$B \rightarrow KX (\rightarrow D^0 \bar{D}^0 \pi^0)$	
Belle [77]	$3871.46 \pm 0.37 \pm 0.07$	-	$B \rightarrow KX (\rightarrow \pi^+ \pi^- J/\psi)$	
Belle [78]	$3872.9^{+0.6+0.4}_{-0.4-0.5}$	$3.9^{+2.8+0.2}_{-1.4-1.1}$	$B \rightarrow KX (\rightarrow D^{*0} \bar{D}^0)$	
Belle [79]	-	-	$B \rightarrow KX (\rightarrow \gamma J/\psi)$	$C = +1$ $1^{++}/2^{++}$
Belle [80]	$3871.84 \pm 0.27 \pm 0.19$	< 1.2	$B \rightarrow KX (\rightarrow \pi^+ \pi^- J/\psi)$	
CDF [67]	$3871.3 \pm 0.7 \pm 0.4$	-	$p\bar{p} \rightarrow \text{anything} + X (\rightarrow \pi^+ \pi^- J/\psi)$	
CDF [81]	-	-	$p\bar{p} \rightarrow \text{anything} + X (\rightarrow \pi^+ \pi^- J/\psi)$	
CDF [82]	-	-	$p\bar{p} \rightarrow \text{anything} + X (\rightarrow \pi^+ \pi^- J/\psi)$	
CDF [83]	$3871.61 \pm 0.16 \pm 0.19$	-	$p\bar{p} \rightarrow \text{anything} + X (\rightarrow \pi^+ \pi^- J/\psi)$	$C = +1$
DO [68]	$3871.8 \pm 3.1 \pm 3.0$	-	$p\bar{p} \rightarrow \text{anything} + X (\rightarrow \pi^+ \pi^- J/\psi)$	
BaBar [84]	3873.4 ± 1.4	-	$B^- \rightarrow K^- X (\rightarrow \pi^+ \pi^- J/\psi)$	
BaBar [85]	$3871.3 \pm 0.6 \pm 0.1$	< 4.1	$B^- \rightarrow K^- X (\rightarrow \pi^+ \pi^- J/\psi)$	
BaBar [86]	-	-	$B^0 \rightarrow K^0 X (\rightarrow \pi^+ \pi^- J/\psi)$	
BaBar [87]	$3875.1^{+0.7}_{-0.5} \pm 0.5$	$3.0^{+1.9}_{-1.4} \pm 0.9$	$B \rightarrow KX (\rightarrow \gamma J/\psi)$	$C = +1$
BaBar [88]	$3871.4 \pm 0.6 \pm 0.1$	< 3.3	$B^+ \rightarrow K^+ X (\rightarrow \pi^+ \pi^- J/\psi)$	
BaBar [89]	-	-	$B^0 \rightarrow K^0 X (\rightarrow \pi^+ \pi^- J/\psi)$	
BaBar [90]	$3873.0^{+1.8}_{-1.6} \pm 1.3$	-	$B \rightarrow KX (\rightarrow \gamma J/\psi, \rightarrow \gamma \psi(3686))$	
LHCb [91]	$3871.95 \pm 0.48 \pm 0.12$	-	$B \rightarrow KX (\rightarrow \omega J/\psi \rightarrow \pi^+ \pi^- \pi^0 J/\psi)$	
LHCb [70]	-	-	$pp \rightarrow \text{anything} + X (\rightarrow \pi^+ \pi^- J/\psi)$	2^- 1^{++}
LHCb [92]	-	-	$pp \rightarrow \text{anything} + X (\rightarrow \pi^+ \pi^- J/\psi)$	
CMS [73]	-	-	$pp \rightarrow \text{anything} + X (\rightarrow \gamma J/\psi, \rightarrow \gamma \psi(3686))$	
BESIII [93]	$3871.9 \pm 0.7 \pm 0.2$	< 2.4	$e^+ e^- \rightarrow Y(4260) \rightarrow \gamma X (\rightarrow \pi^+ \pi^- J/\psi)$	

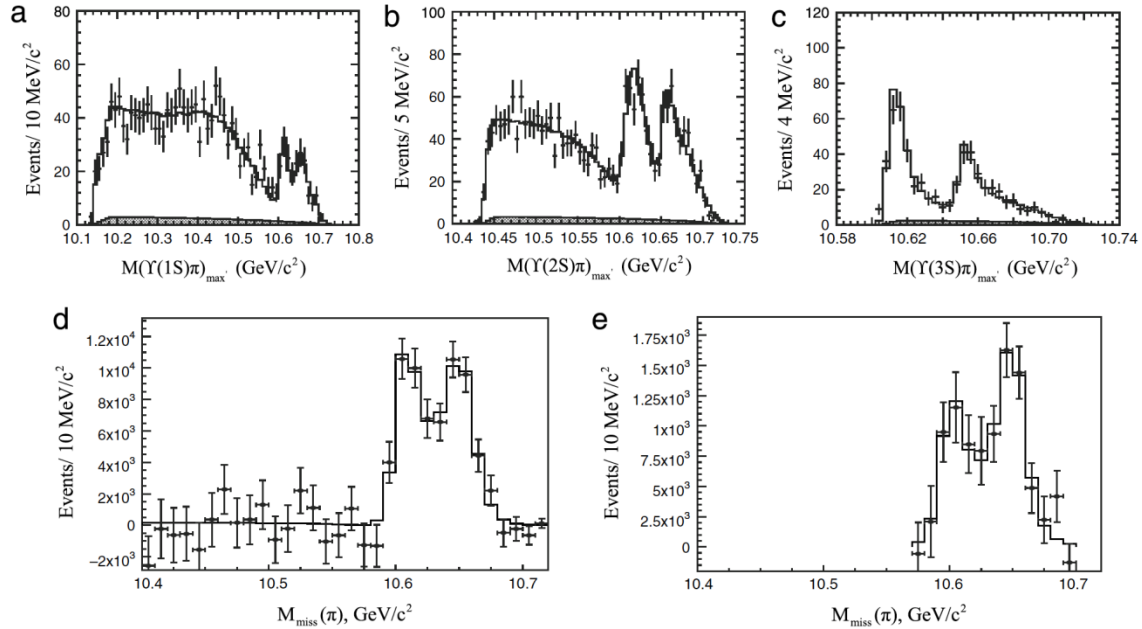
Z_c(3900)和Z_c(4020)



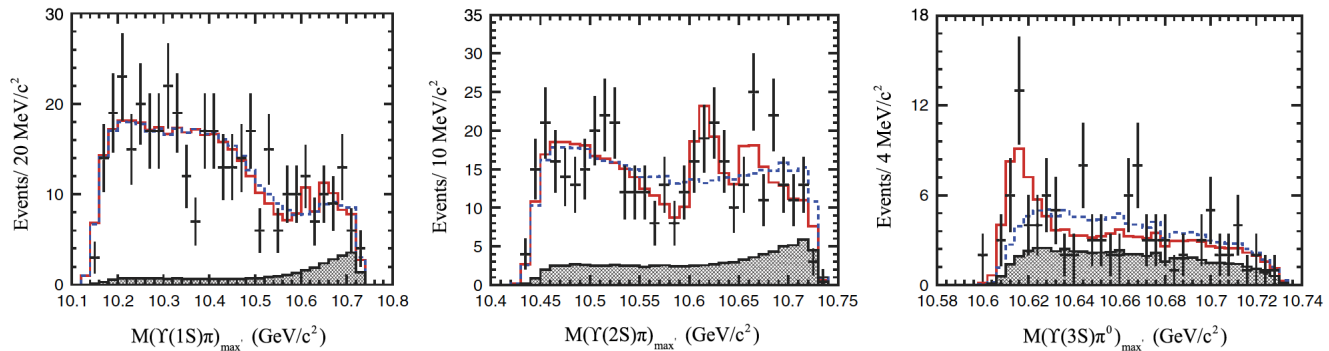
DD* 阈值附近

D^{*}D^{*} 阈值附近

Z_b(10610)和Z_b(10650)



Z_b(10610) and Z_b(10650) structures in (a) $\Upsilon(1S)\pi$, (b) $\Upsilon(2S)\pi$, (c) $\Upsilon(3S)\pi$, (d) $h_b(1P)\pi$, and (e) $h_b(2P)\pi$ from Belle



The neutral partner the Z_b(10610)⁰ in the $\Upsilon(nS)\pi^0$ (n = 1, 2, 3) final states from Belle

理论解释

6. $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$ as the $B^*\bar{B}$ and $B^*\bar{B}^*$ molecular states

(106) Zhi-Feng Sun, Jun He (Lanzhou U. & Lanzhou, Inst. Modern Phys.), Xiang Liu (Lanzhou, Inst. Modern Phys. & Lanzhou U.), Zhi-Gang Luo, Shi-Lin Zhu (Peking U. & Peking U., CAPT). Jun 2011. 11 pp.

Published in **Phys.Rev. D84 (2011) 054002**

DOI: [10.1103/PhysRevD.84.054002](https://doi.org/10.1103/PhysRevD.84.054002)

e-Print: [arXiv:1106.2968](https://arxiv.org/abs/1106.2968) [hep-ph] | [PDF](#)

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分子态

7. Bound state nature of the exotic Z_b states

(92) Martin Clevén (IAS, Jülich & Jülich, Forschungszentrum & JCHP, Jülich), Feng-Kun Guo (Bonn U., HISKP & Bonn U.), Christoph Hanhart (IAS, Jülich & Jülich, Forschungszentrum & JCHP, Jülich), Ulf-G. Meißner (IAS, Jülich & Jülich, Forschungszentrum & JCHP, Jülich & Bonn U., HISKP & Bonn U.). Jul 2011. 8 pp.

Published in **Eur.Phys.J. A47 (2011) 120**

DOI: [10.1140/epja/i2011-11120-6](https://doi.org/10.1140/epja/i2011-11120-6)

e-Print: [arXiv:1107.0254](https://arxiv.org/abs/1107.0254) [hep-ph] | [PDF](#)

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8. Radiative transitions from Upsilon(5S) to molecular bottomonium

(90) M.B. Voloshin (Minnesota U. & Moscow, ITEP). May 2011. 8 pp.

Published in **Phys.Rev. D84 (2011) 031502**

FTPI-MINN-11-13, UMN-TH-3003-11

DOI: [10.1103/PhysRevD.84.031502](https://doi.org/10.1103/PhysRevD.84.031502)

e-Print: [arXiv:1105.5829](https://arxiv.org/abs/1105.5829) [hep-ph] | [PDF](#)

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[Detailed record](#) - Cited by 90 records 50+

分子态

12. An Explanation of Belle states $Z_b(10610)$ and $Z_b(10650)$

(71) D.V. Bugg (Queen Mary, U. of London). May 2011. 4 pp.

Published in **Europhys.Lett. 96 (2011) 11002**

QMB-002

DOI: [10.1209/0295-5075/96/11002](https://doi.org/10.1209/0295-5075/96/11002)

e-Print: [arXiv:1105.5492](https://arxiv.org/abs/1105.5492) [hep-ph] | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [ADS Abstract Service](#)

[Detailed record](#) - Cited by 71 records 50+

非奇特态解释

13. Tetraquark Interpretation of the Charged Bottomonium-like states

(70) $Z_b^{+-}(10610)$ and $Z_b^{+-}(10650)$ and Implications

Ahmed Ali, Christian Hambrock, Wei Wang (DESY). Oct 2011. 4 pp.

Published in **Phys.Rev. D85 (2012) 054011**

DESY-11-164

DOI: [10.1103/PhysRevD.85.054011](https://doi.org/10.1103/PhysRevD.85.054011)

e-Print: [arXiv:1110.1333](https://arxiv.org/abs/1110.1333) [hep-ph] | [PDF](#)

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[Detailed record](#) - Cited by 70 records 50+

单色四夸克态

15. Z_b and Z_c Exotic States as Coupled Channel Cusps

(63) E. S. Swanson (Pittsburgh U.). Sep 10, 2014. 7 pp.

Published in **Phys.Rev. D91 (2015) no.3, 034009**

DOI: [10.1103/PhysRevD.91.034009](https://doi.org/10.1103/PhysRevD.91.034009)

e-Print: [arXiv:1409.3291](https://arxiv.org/abs/1409.3291) [hep-ph] | [PDF](#)

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[Detailed record](#) - Cited by 63 records 50+

非奇特态解释

16. Reproducing the $Z_c(3900)$ structure through the initial-single-pion-emission mechanism

(61) Dian-Yong Chen (Lanzhou, Inst. Modern Phys. & Lanzhou U.), Xiang Liu (Lanzhou U. & Lanzhou, Inst. Modern Phys.), Takayuki Matsuki (Tokyo Kasei U.). Apr 22, 2013. 5 pp.

Published in **Phys.Rev. D88 (2013) no.3, 036008**

DOI: [10.1103/PhysRevD.88.036008](https://doi.org/10.1103/PhysRevD.88.036008)

e-Print: [arXiv:1304.5845](https://arxiv.org/abs/1304.5845) [hep-ph] | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [ADS Abstract Service](#)

[Detailed record](#) - Cited by 61 records 50+

非奇特态解释

17. Heavy Quark Symmetry Predictions for Weakly Bound B-Meson Molecules

(61) Thomas Mehen, Joshua W. Powell (Duke U.). Sep 2011. 17 pp.

Published in **Phys.Rev. D84 (2011) 114013**

DOI: [10.1103/PhysRevD.84.114013](https://doi.org/10.1103/PhysRevD.84.114013)

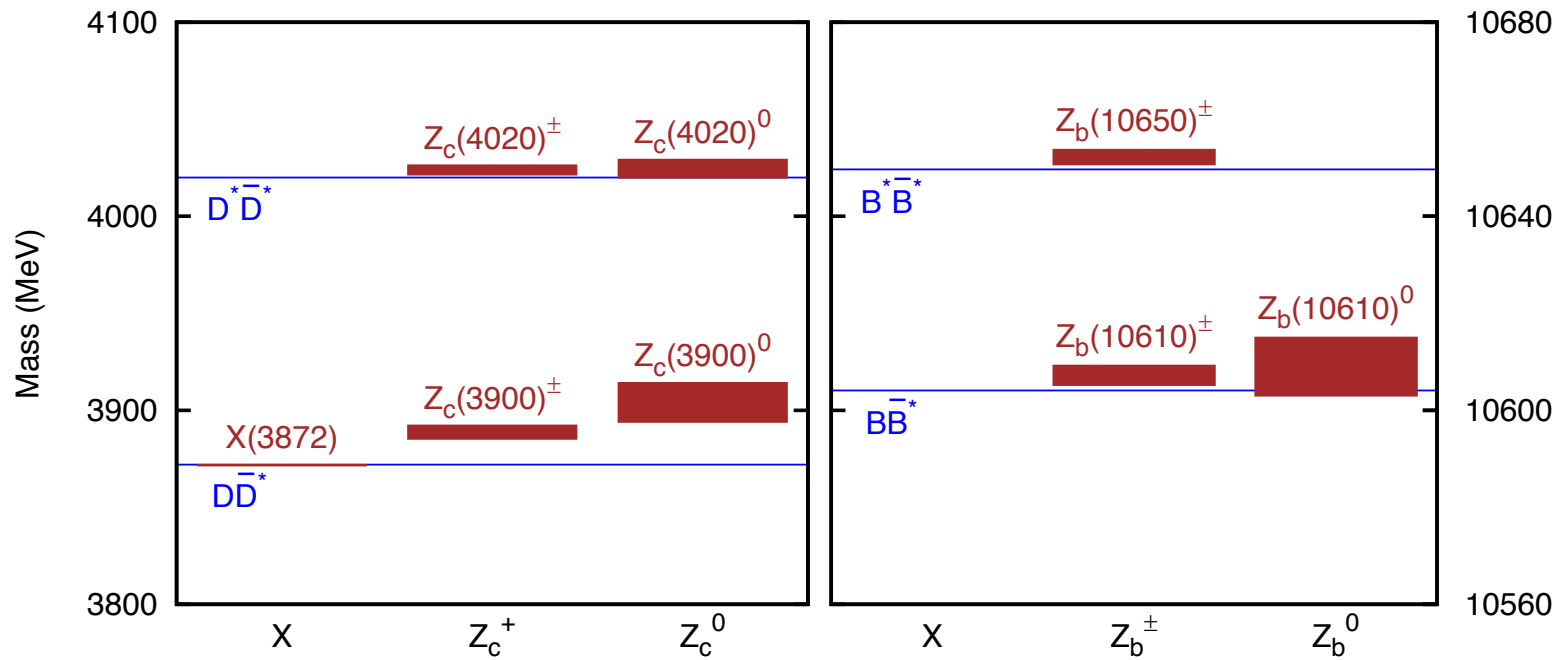
e-Print: [arXiv:1109.3479](https://arxiv.org/abs/1109.3479) [hep-ph] | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [ADS Abstract Service](#)

[Detailed record](#) - Cited by 61 records 50+

分子态

BB*/DD*/KK*阈值



$f_1(1285)$ 也被认为可能是KK*相互作用的束缚态

BB*相互作用与Z_b(10610)

$$\begin{cases} |Z_{\text{BB}^*}^{(\text{T})+}\rangle = \frac{1}{\sqrt{2}}(|B^{*+}\bar{B}^0\rangle + c|B^+\bar{B}^{*0}\rangle), \\ |Z_{\text{BB}^*}^{(\text{T})-}\rangle = \frac{1}{\sqrt{2}}(|B^{*-}\bar{B}^0\rangle + c|B^-\bar{B}^{*0}\rangle), \\ |Z_{\text{BB}^*}^{(\text{T})0}\rangle = \frac{1}{2}[(|B^{*+}B^-\rangle - |B^{*0}\bar{B}^0\rangle) \\ + c(|B^+B^{*-}\rangle - |B^0\bar{B}^{*0}\rangle)], \end{cases}$$

$$\begin{aligned} |Z_{\text{BB}^*}^{(\text{S})0}\rangle &= \frac{1}{2}[(|B^{*+}B^-\rangle + |B^{*0}\bar{B}^0\rangle) \\ &+ c(|B^+B^{*-}\rangle + |B^0\bar{B}^{*0}\rangle)], \end{aligned}$$

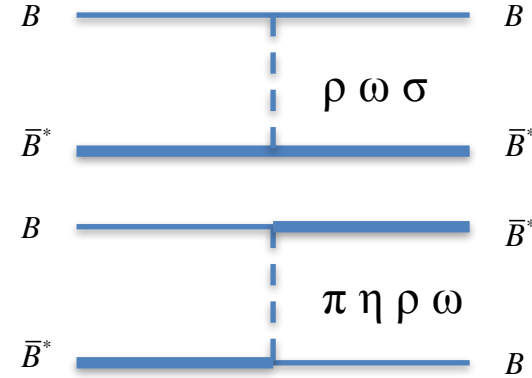


Table 2. The obtained bound state solutions (binding energy E and root-mean-square radius r_{RMS}) for the BB^* systems. Here, we discuss two situations, i.e., including all one meson exchange (OME) contribution and only considering one pion exchange (OPE) potential.

$I^G(J^{PC})$	state	OME			OPE		
		Λ	E/MeV	r_{RMS}/fm	Λ	E/MeV	r_{RMS}/fm
$1^+(1^+)$	$Z_{\text{BB}^*}^{(\text{T})}$	2.1	-0.22	3.05	2.2	-8.69	0.62
		2.3	-1.64	1.31	2.4	-20.29	0.56
		2.5	-4.74	0.84	2.6	-38.54	0.50
$1^-(1^+)$	$Z_{\text{BB}^*}^{(\text{T})'}$	4.9	-0.14	3.64	4.5	-17.79	0.56
		5.0	-0.41	2.45	4.6	-22.65	0.52
		5.1	-0.85	1.80	4.7	-28.29	0.48
$0^-(1^{+-})$	$Z_{\text{BB}^*}^{(\text{S})}$	1.0	-0.28	3.35	1.8	-10.09	0.96
		1.05	-1.81	1.71	1.9	-15.11	0.84
		1.1	-5.36	1.18	2.0	-21.53	0.76
$0^+(1^{++})$	$Z_{\text{BB}^*}^{(\text{S})'}$	0.8	-0.95	1.84	1.0	-7.68	0.82
		0.9	-6.81	0.91	1.1	-15.30	0.65
		1.0	-19.92	0.65	1.2	-26.53	0.53

dominant

Zb(10610)

DD*相互作用与Z_c(3900)和X(3827)

$$\begin{array}{c} k'_1 \\ \leftarrow \\ \text{---} \\ \leftarrow k_1 \\ k'_2 \\ \leftarrow \\ \text{---} \\ \leftarrow k_2 \end{array} \text{---} \mathcal{M} = \begin{array}{c} k'_1 \\ \leftarrow \\ \text{---} \\ \leftarrow k_1 \\ k'_2 \\ \leftarrow \\ \text{---} \\ \leftarrow k_2 \end{array} \text{---} \nu + \begin{array}{c} k'_1 \\ \leftarrow \\ \text{---} \\ \leftarrow k_1 \\ k'_2 \\ \leftarrow \\ \text{---} \\ \leftarrow k_2 \end{array} \text{---} \nu \text{---} \mathcal{M}$$

$$\begin{array}{c} k'_1 \\ \leftarrow \\ \text{---} \\ \leftarrow k_1 \\ k'_2 \\ \leftarrow \\ \text{---} \\ \leftarrow k_2 \end{array} \text{---} \nu = \sum_i I_i^d \begin{array}{c} k'_1 \\ \leftarrow \\ \text{---} \\ \leftarrow k_1 \\ \downarrow q \\ k'_2 \\ \leftarrow \\ \text{---} \\ \leftarrow k_2 \end{array} + \sum_j I_j^c \begin{array}{c} k'_1 \\ \leftarrow \\ \text{---} \\ \leftarrow k_1 \\ \downarrow q \\ k'_2 \\ \leftarrow \\ \text{---} \\ \leftarrow k_2 \end{array}$$

TABLE I. The isospin factors I_i^d and I_i^c for direct and cross diagrams and different exchange mesons.

	Direct diagram				Crossed diagram				
	ρ	ω	J/ψ	σ	π	η	ρ	ω	J/ψ
$[PP^*]^T$	$-\frac{1}{2}$	$\frac{1}{2}$	1	1	$-\frac{1}{2}c$	$\frac{1}{6}c$	$-\frac{1}{2}c$	$\frac{1}{2}c$	c
$[PP^*]^S$	$\frac{3}{2}$	$\frac{1}{2}$	1	1	$\frac{3}{2}c$	$\frac{1}{6}c$	$\frac{3}{2}c$	$\frac{1}{2}c$	c

TABLE II. The position of the bound state from the $D\bar{D}^*$ interaction at the real axis $\text{Re}(z) = W$ with a Λ scan. The second and third columns are for the full model. The results without the J/ψ exchange are listed in the fourth and fifth columns and compared with the results in Ref. [8]. The J/ψ (I) in the eighth and ninth columns and J/ψ (II) in the tenth and eleventh columns are for the results from only J/ψ exchange with and without form factor. The cutoff Λ and energy W are in units of GeV.

$I^G(J^{PC})$	Full model		No J/ψ		Ref. [8]		J/ψ (I)		J/ψ (II)	
	Λ	W	Λ	W	Λ	W	Λ	W	Λ	W
$0^-(0^{--})$	...	...	...	...	...	...	...	...	...	...
$0^+(0^{-+})$	...	...	...	...	...	...	...	...	...	...
$0^-(1^{--})$	...	...	...	...	...	...	...	...	...	...
$0^+(1^{-+})$	...	...	...	...	...	...	...	...	...	...
$0^-(1^{+-})$	1.0	3.864	1.0	3.868	1.3	3.876	...	...	2.5	3.867
	1.2	3.848	1.2	3.854	1.4	3.870	...	...	2.6	3.850
$0^+(1^{++})$	1.9	3.873	1.9	3.875	2.0	3.876	...	...	3.9	3.875
	2.4	3.871	2.4	3.874	2.4	3.872	...	...	4.0	3.836
$1^+(0^-)$	...	...	...	...	...	...	...	...	...	...
$1^-(0^-)$	...	...	...	...	...	...	...	...	...	...
$1^+(1^-)$	...	...	...	...	...	...	...	...	...	...
$1^-(1^-)$	...	...	...	...	...	...	...	...	...	...
$1^+(1^+)$	3.0	3.874	...	...	...	...	...	...	2.4	3.875
	3.3	3.858	...	...	...	...	...	...	2.5	3.867
$1^-(1^+)$	...	...	...	...	...	...	...	...	...	...

J/ψ 交换对于
产生Z_c(3900)
很重要

X(3872)

Z_c(3900)

KK* 相互作用与f₁(1285)

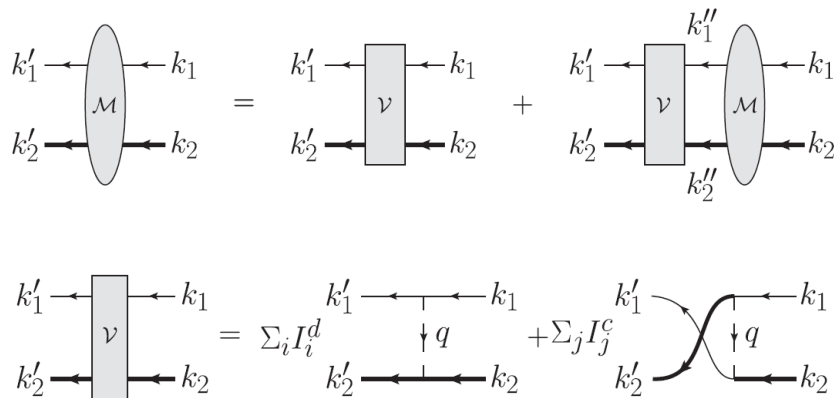


Table 1. The flavor factors I_d^i and I_c^i for direct and cross diagrams with different exchanged mesons. .

	Direct			Cross					
Exchanged	V			P			V		
meson	ρ	ω	ϕ	π	η	η'	ρ	ω	ϕ
$I = 1$	$-\frac{1}{2}$	$\frac{1}{2}$	1	$-\frac{1}{2}c$	$\frac{4}{3}c$	$\frac{1}{6}c$	$-\frac{1}{2}c$	$\frac{1}{2}c$	c
$I = 0$	$\frac{3}{2}$	$\frac{1}{2}$	1	$\frac{3}{2}c$	$\frac{4}{3}c$	$\frac{1}{6}c$	$\frac{3}{2}c$	$\frac{1}{2}c$	c

Table 2. The pole position W at different cutoffs Λ . The second and third columns are for the full model, the fourth and fifth columns for the cross pseudoscalar-meson exchanges, the sixth and seventh columns for the direct vector-meson exchanges, the eighth and ninth columns for the direct vector-meson exchanges after taking $q^2 \rightarrow 0$, and the last two columns for the WT term. The cutoff Λ and energy W are in units of GeV.

$I^G(J^{PC})$	Full		V_P^c		V^d		$V^d _{q^2 \rightarrow 0}$		V^{WT}	
	Λ	W	Λ	W	Λ	W	Λ	W	Λ	W
$0^+(1^{++})$	0.6	1.389	1.0	1.387	1.0	1.383	0.8	1.380	0.7	1.381
	0.8	1.369	1.1	1.377	1.1	1.376	0.9	1.366	0.8	1.365
	1.0	1.326	1.2	1.359	1.2	1.368	1.0	1.343	0.9	1.336
	1.2	1.247	1.4	1.293	1.4	1.343	1.1	1.311	1.0	1.301
$0^-(1^{+-})$	0.8	1.385	1.2	1.386	1.0	1.383	0.8	1.380	0.7	1.381
	1.0	1.354	1.3	1.375	1.1	1.376	0.9	1.366	0.8	1.365
	1.1	1.318	1.4	1.337	1.2	1.368	1.0	1.343	0.9	1.336
	1.2	1.258	1.5	1.207	1.4	1.343	1.1	1.311	1.0	1.301
$1^-(1^+)$	—	—	—	—	4.6	1.388	2.5	1.379	1.4	1.381
	—	—	—	—	4.7	1.383	2.6	1.359	1.5	1.358
	—	—	—	—	4.8	1.376	2.7	1.332	1.6	1.336
	—	—	—	—	4.9	1.366	2.8	1.302	1.7	1.310
$1^+(1^+)$	1.8	1.389	2.7	1.389	4.6	1.388	2.5	1.379	1.4	1.381
	1.9	1.384	2.8	1.380	4.7	1.383	2.6	1.359	1.5	1.358
	2.0	1.372	2.9	1.343	4.8	1.376	2.7	1.332	1.6	1.336
	2.1	1.334	3.0	1.254	4.9	1.366	2.8	1.302	1.7	1.310

矢量介子交换为主

f₁(1285)

h₁(1380)

b₁(1235)

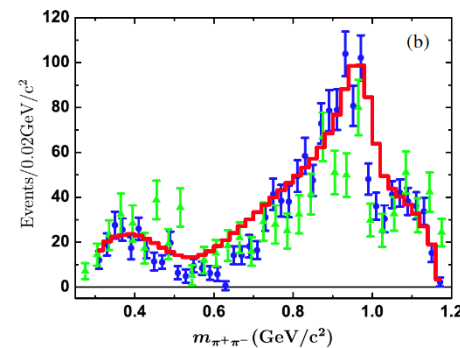
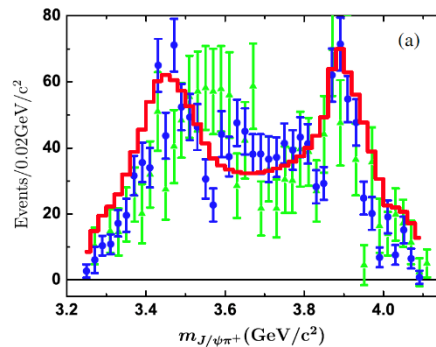
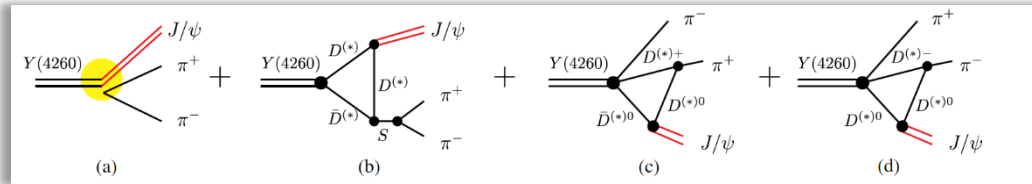
	$B\bar{B}^*(b\bar{b}q\bar{q})$		$D\bar{D}^*(c\bar{c}q\bar{q})$		$K\bar{K}^*(s\bar{s}q\bar{q})$	
$I^G(J^{PC})$	Theo.	Exp.	Theo.	Exp.	Theo.	Exp.
$0^-(0^{--})$						
$0^+(0^{-+})$						
$0^-(1^{--})$						
$0^+(1^{-+})$						
$0^-(1^{+-})$	✓	?	✓	?	✓	$h_1(1380)$
$0^+(1^{++})$	✓	?	✓	$X(3872)$	✓	$f_1(1285)$
$1^+(0^-)$						
$1^-(0^-)$						
$1^+(1^-)$						
$1^-(1^-)$						
$1^+(1^+)$	✓	$Z_b(10610)$	✓	$Z_c(3900)$	✓	$b_1(1235)$
$1^-(1^+)$						

π 交换重要性降低，矢量介子交换重要性增大

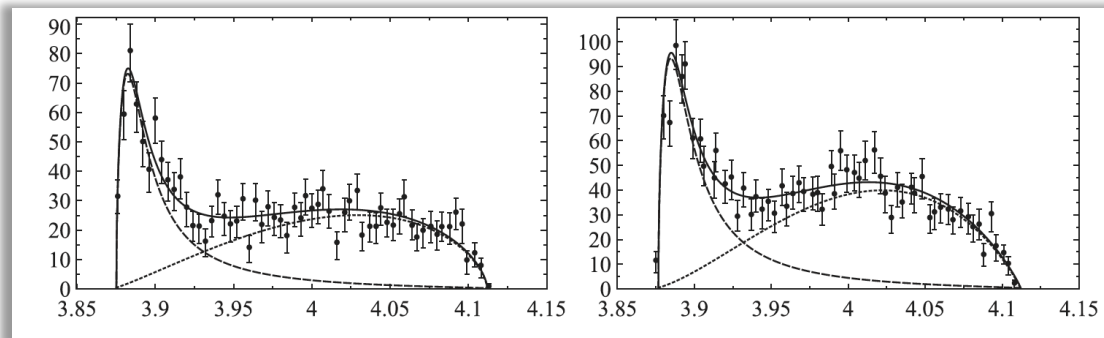
Reproduce the invariant mass spectrum

Chen, Liu and Matsuki, Phys. Rev. D88(2013)036008

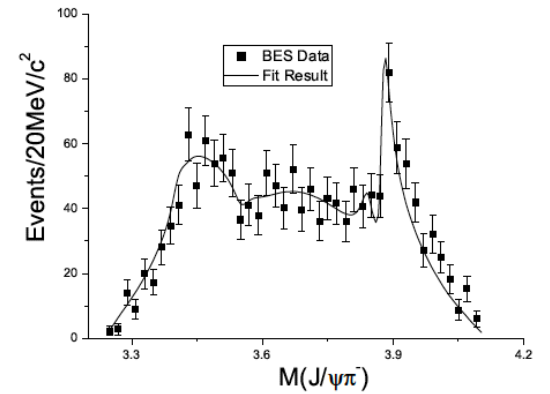
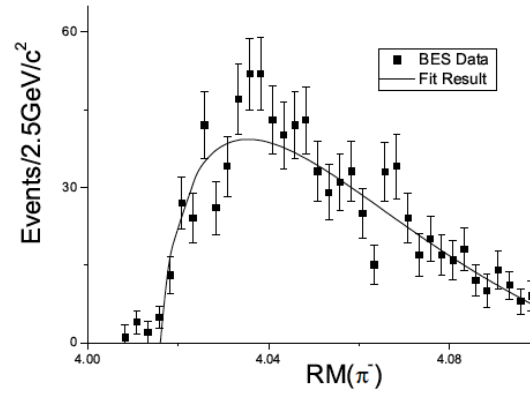
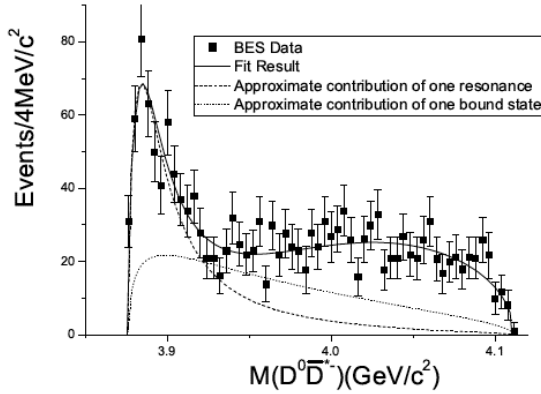
ISPE



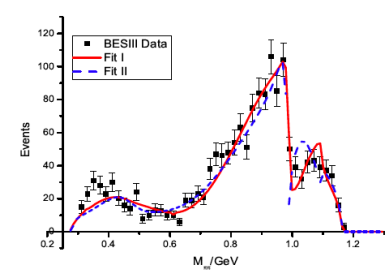
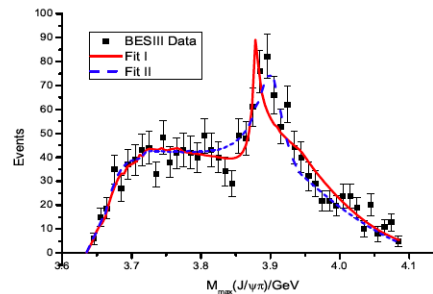
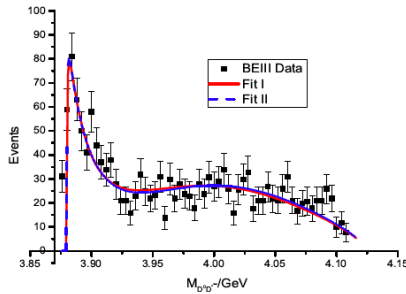
Aceti, Bayar, Oset, Phys. Rev. D90 (2014) 016003



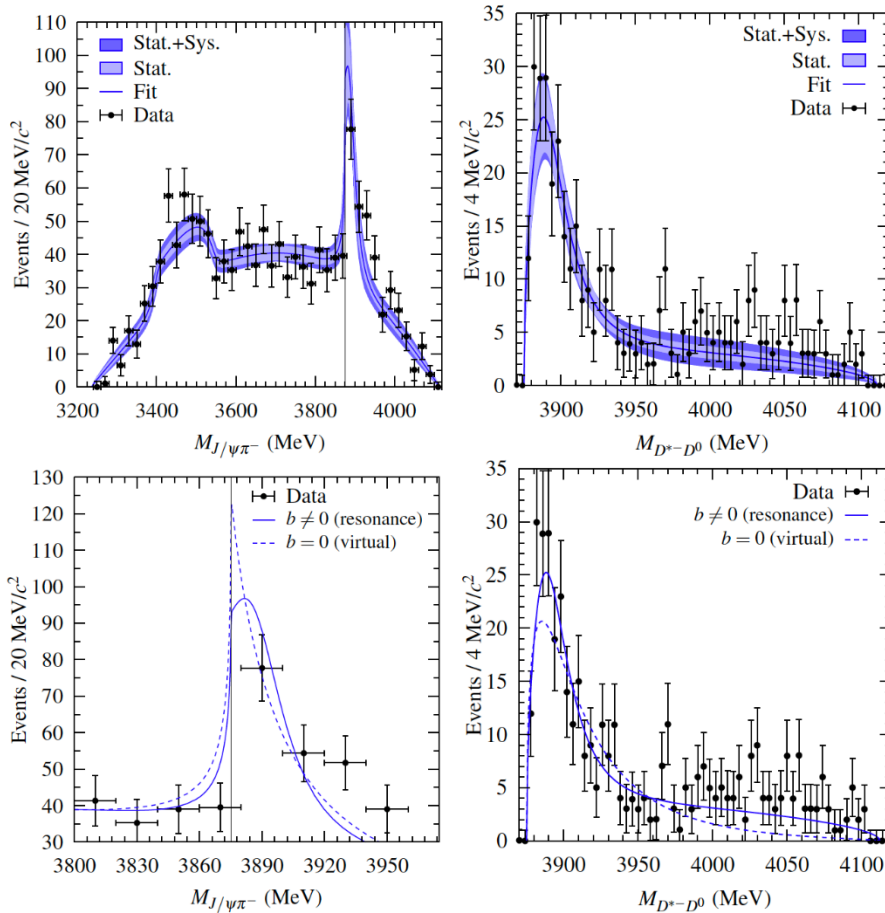
the invariant mass spectra were obtained with mass and width obtained from the interaction.



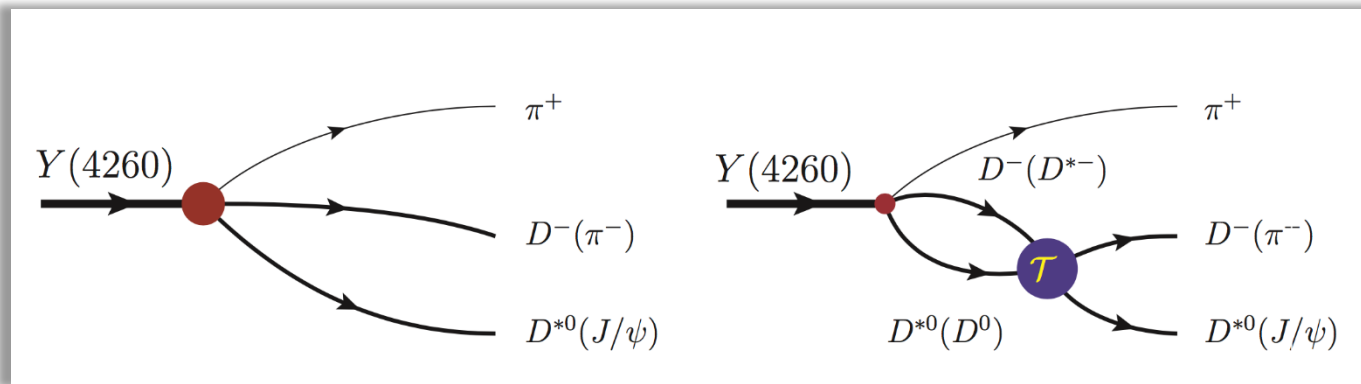
$$\sqrt{s^{III}} = 3.875 \pm 0.016i \text{ GeV}.$$



	sheet I	sheet II	sheet III	sheet IV
Fit I	—	$3.87988 \pm 0.00390i$	—	—
Fit II	—	—	—	$3.87909 \pm 0.00143i$



M_{Z_c} (MeV)	$\Gamma_{Z_c}/2$ (MeV)	Ref.	Final state
3899 ± 6	23 ± 11	[1] (BESIII)	$J/\psi \pi$
3895 ± 8	32 ± 18	[2] (Belle)	$J/\psi \pi$
3886 ± 5	19 ± 5	[3] (CLEO-c)	$J/\psi \pi$
3884 ± 5	12 ± 6	[4] (BESIII)	$\bar{D}^* D$
3882 ± 3	13 ± 5	[5] (BESIII)	$\bar{D}^* D$
$3894 \pm 6 \pm 1$	$30 \pm 12 \pm 6$	$\Lambda = 1.0 \text{ GeV}$	$J/\psi \pi, \bar{D}^* D$
$3886 \pm 4 \pm 1$	$22 \pm 6 \pm 4$	$\Lambda = 0.5 \text{ GeV}$	$J/\psi \pi, \bar{D}^* D$
$3831 \pm 26_{-28}^{+7}$	virtual state	$\Lambda = 1.0 \text{ GeV}$	$J/\psi \pi, \bar{D}^* D$
$3844 \pm 19_{-21}^{+12}$	virtual state	$\Lambda = 0.5 \text{ GeV}$	$J/\psi \pi, \bar{D}^* D$



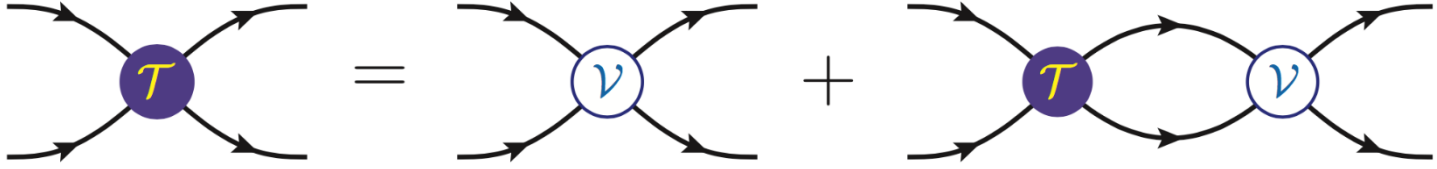
$$\frac{d\Gamma}{dM_{23}} = \frac{1}{6M} \frac{1}{(2\pi)^5} \frac{\check{p}_1 p_3^{cm}}{M} \sum_{i \geq 0; j \geq 0; J^P} \frac{1}{N_J^2} |\hat{\mathcal{M}}_{i;j}^{J^P}(M_{23})|^2$$

$$\hat{\mathcal{M}}_{i;i}^{J^P}(M_{23}) = \hat{\mathcal{A}}_{j;i}^{bk,J^P}(M_{23}) + \sum_k \int \frac{dp_3'^{cm} p_3'^{cm2}}{(2\pi)^3} i\hat{\mathcal{T}}_{j;k}^{J^P}(p_3'^{cm}, M_{23}) G_0(p_3'^{cm}) \hat{\mathcal{A}}_{k;i}^{J^P}(p_3'^{cm}, M_{23})$$

$$\hat{\mathcal{A}}_{j;i}^{bk,J^P}(M_{23}) = c(M_{23} - M_{min})^a (M_{max} - M_{23})^b \hat{\mathcal{A}}_{j;i}^{J^P}(M_{23})$$

$$\mathcal{L}_{Y \rightarrow \pi DD^*} = g_{Y \rightarrow \pi DD^*} Y^\mu (D \tau \cdot \pi \bar{D}_\mu^* + D_\mu^* \tau \cdot \pi \bar{D}),$$

$$\pi^- J/\psi - D^- D^{*0} - D^{*-} D^0$$



$$D^- D^{*0} \rightarrow D^- D^{*0}$$

$$\begin{aligned} \mathcal{V}_V &= \frac{i I_V \beta^2 g_V^2}{2 (q^2 - m_V^2)} (k_2 + k'_2) \cdot (k_1 + k'_1) \epsilon_2 \cdot \epsilon'_2, \\ \mathcal{V}_{J/\psi} &= \frac{-i g_{D^* D^* J/\psi} g_{D D J/\psi}}{q^2 - m_{J/\psi}^2} [\epsilon'_2 \cdot (k_1 + k'_1) \epsilon_2 \cdot (k_2 + k'_2) \\ &\quad + \epsilon'_2 \cdot (k_2 + k'_2) \epsilon_2 \cdot (k_1 + k'_1) \\ &\quad - (k_2 + k'_2) \cdot (k_1 + k'_1) \epsilon'_2 \cdot \epsilon_2], \\ \mathcal{V}_\sigma &= \frac{i 4 g_\sigma^2 m_P m_{P^*}}{q^2 - m_\sigma^2} \epsilon_2 \cdot \epsilon'_2. \end{aligned} \quad (\text{B.9})$$

$$D^- D^{*0} \rightarrow \pi^- J/\psi$$

$$\begin{aligned} \mathcal{V}_{D^*,t} &= \frac{-i 2 g \sqrt{m_D m_{D^*}} g_{D^* D^* J/\psi}}{f_\pi (q^2 - m_{D^*}^2)} k_1^\mu (-g^{\mu\nu} + q^\mu q^\nu / m_{D^*}^2) \\ &\quad \cdot [\epsilon'_2 \cdot \epsilon_2 (k_2 - q)^\nu - \epsilon'_2 \cdot (k_2 - q) \epsilon_2^\nu + \epsilon_2'^\nu \epsilon_2 \cdot (k_2 - q)], \\ \mathcal{V}_{D,u} &= \frac{-i 4 g \sqrt{m_D m_{D^*}} g_{D D J/\psi}}{f_\pi (q^2 - m_D^2)} k'_1 \cdot \epsilon_2 k_1 \cdot \epsilon'_2, \\ \mathcal{V}_{D^*,u} &= \frac{-4 i g g_{J/\psi D^* D}}{f (q^2 - m_{D^*}^2)} \epsilon_{\alpha\beta\rho\mu} \epsilon_2^\beta q^\alpha k'_1{}^\rho \epsilon^{\alpha\beta\nu\tau} k_2'^\alpha \epsilon_2'^\beta q^\tau. \end{aligned} \quad (\text{B.11})$$

$$D^{*-} D^0 \rightarrow D^- D^{*0}$$

$$\begin{aligned} \mathcal{V}_V &= \frac{-i 2 I_V \lambda^2 g_V^2}{q^2 - m_V^2} \epsilon_{\lambda\alpha\beta\mu} (k_2 + k'_2)^\lambda q^\alpha \epsilon_2'^\mu \epsilon_{\lambda'\alpha'\beta\nu} (k_1 + k'_1)^{\lambda'} q^{\alpha'} \epsilon_1^\nu, \\ \mathcal{V}_{J/\psi} &= \frac{i g_{D D^* J/\psi}^2}{q^2 - m_{J/\psi}^2} \epsilon^{\beta\mu\alpha\tau} q^\beta \epsilon_2'^\alpha (k'_2 + k_2)^\tau \epsilon^{\beta'\mu\alpha'\tau'} q^{\beta'} \epsilon_1'^\alpha (k'_1 + k_1)^{\tau'}, \\ \mathcal{V}_\mathbb{P} &= -i \frac{4 I_\mathbb{P} g^2 m_P m_{P^*}}{f_\pi^2 (q^2 - m_\mathbb{P}^2)} q \cdot \epsilon_1 q \cdot \epsilon'_2. \end{aligned} \quad (\text{B.10})$$

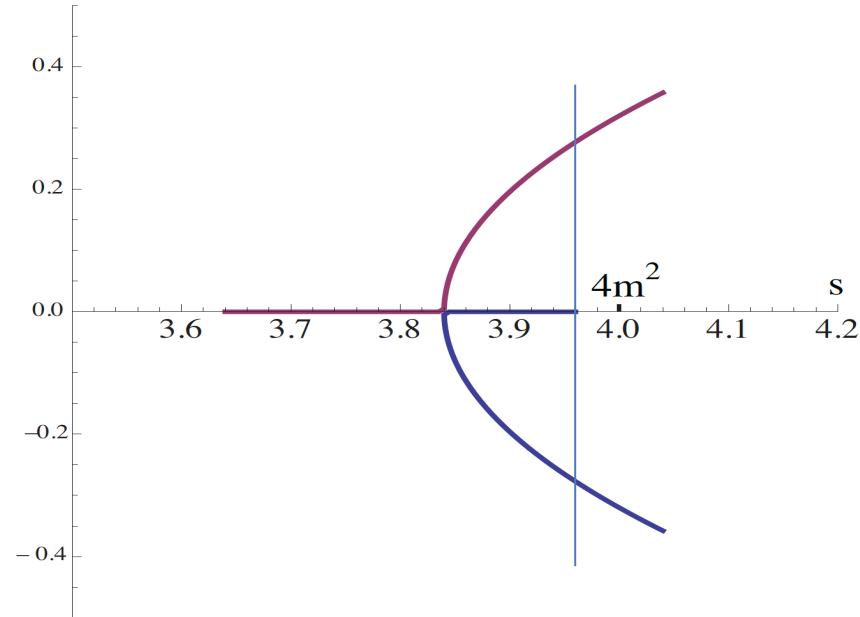
Form factor

$$f(q^2) = \frac{\Lambda^4 + (q_t^2 - m^2)^2 / 4}{\Lambda^4 + (q^2 - (q_t^2 + m^2) / 2)^2},$$

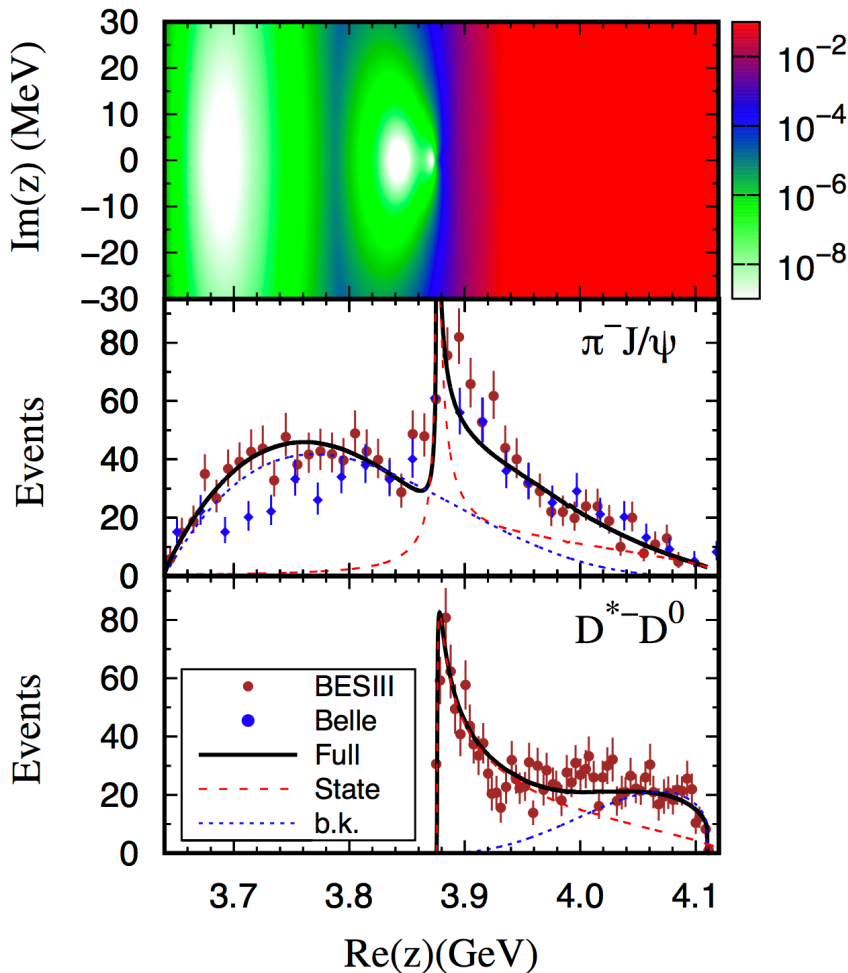
TABLE I. Classification of the properties of poles in the effective range expansion for $r_e < 0$.

Inverse scattering length	$1/a < 0$	$0 < 1/a < -2/r_e$	$-2/r_e < 1/a < -1/r_e$	$-1/r_e < 1/a$
Primary pole	bound state	virtual state	virtual state with width	resonance
Conjugate pole	virtual state	virtual state	anti-virtual state with width	anti-resonance
Compositeness	$0 < X < 1$	$1 < X$	$1 < \bar{X}$	$0 < \bar{X} < 1$

Hyodo, *Phys. Rev. Lett.*, **2013**, 111, 132002



Hanhart, Pelaez, Rios, *Phys. Lett.*, **2014**, B739, 375-382

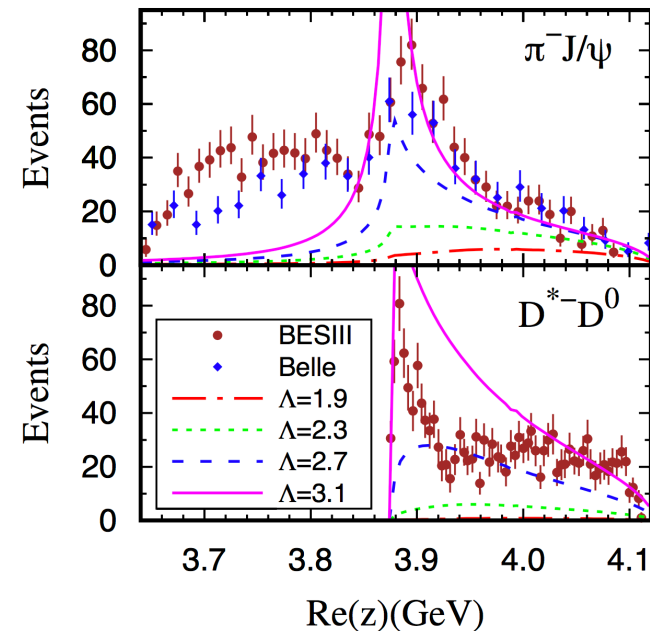


$$\Lambda = 1.85 \text{ GeV}$$

Table 1 The bound states from the $\pi^- J/\psi - D^{*-} D^0 - D^- D^{*0}$ interaction with typical cutoffs Λ . The cutoff Λ and energy W are in units of GeV, and MeV, respectively.

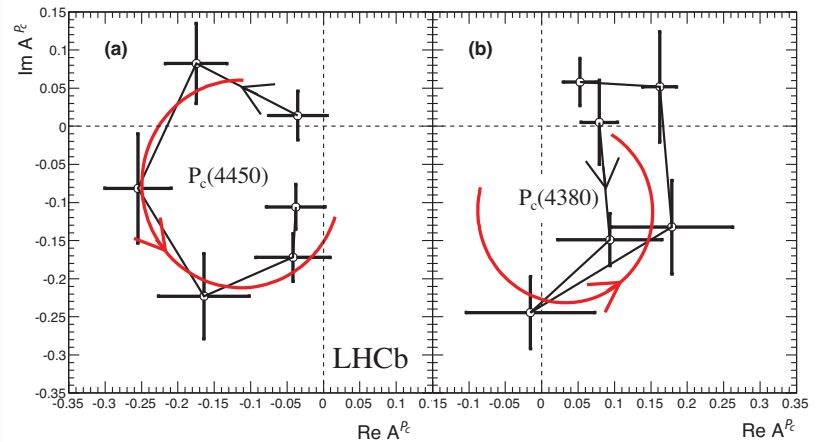
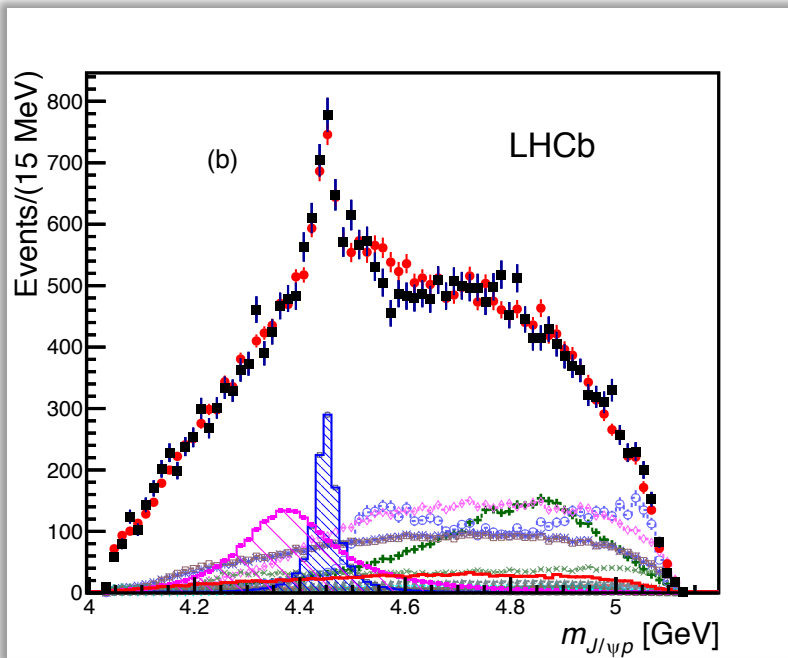
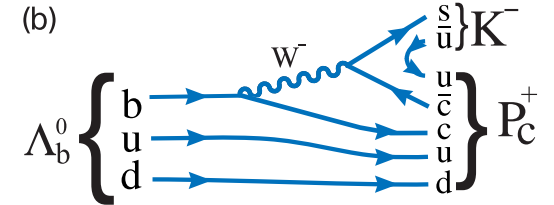
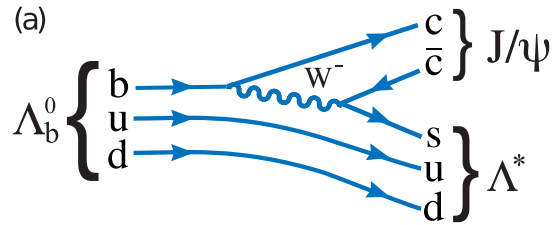
Full model				No $\pi^- J/\psi$			
Λ	W	Λ	W	Λ	W	Λ	W
1.5	3833	2.1	3875+0i	1.6	3837	2.4	3875
1.7	3862	2.3	3873+1i	1.8	3865	2.6	3873
1.9	3873	2.5	3863+3i	2.0	3873	2.8	3867
2.0	3875	2.7	3845+5i	2.2	3875	3.0	3856

No $D^- D^{*0} - D^{*-} D^0$



隱粲五夸克态及其隱奇异伴随态

LHCb pentaquarks



$J=3/2$ or $5/2$; opposite parities

Theoretical interpretation of the LHCb pentaquark

3. How to reveal the exotic nature of the $P_c(4450)$

⁽¹³⁸⁾ Feng-Kun Guo (Bonn U. & Bonn U., HISKP), Ulf-G. Meißner (Bonn U. & Bonn U., HISKP & IAS, Jülich & JCHP, Jülich & Jülich, Forschungszentrum), Wei Wang (Shanghai Jiaotong U., INPAC & Beijing, Inst. Theor. Phys.), Zhi Yang (Bonn U. & Bonn U., HISKP). Jul 17, 2015. 6 pp.
Published in *Phys.Rev. D92* (2015) no.7, 071502
DOI: [10.1103/PhysRevD.92.071502](https://doi.org/10.1103/PhysRevD.92.071502)
e-Print: [arXiv:1507.04950](https://arxiv.org/abs/1507.04950) [hep-ph] | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#)
[ADS Abstract Service](#)

Detailed record - Cited by 138 records 100+

kinematical effects

4. Identifying exotic hidden-charm pentaquarks

⁽¹¹⁶⁾ Rui Chen, Xiang Liu (Lanzhou U. & Lanzhou, Inst. Modern Phys.), Xue-Qian Li (Nankai U.), Shi-Lin Zhu (Peking U., SKLNPT & Peking U., CHEP). Jul 13, 2015. 5 pp.
Published in *Phys.Rev.Lett.* 115 (2015) no.13, 132002
DOI: [10.1103/PhysRevLett.115.132002](https://doi.org/10.1103/PhysRevLett.115.132002)
e-Print: [arXiv:1507.03704](https://arxiv.org/abs/1507.03704) [hep-ph] | [PDF](#)

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[ADS Abstract Service](#)

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Molecular state

5. LHCb pentaquark as a $\bar{D}^* \Sigma_c - \bar{D}^* \Sigma_c^*$ molecular state

⁽¹¹⁵⁾ L. Roca (Murcia U.), J. Nieves (Valencia U., IFIC), E. Oset (Valencia U. & Valencia U., IFIC). Jul 15, 2015. 5 pp.
Published in *Phys.Rev. D92* (2015) no.9, 094003
DOI: [10.1103/PhysRevD.92.094003](https://doi.org/10.1103/PhysRevD.92.094003)
e-Print: [arXiv:1507.04249](https://arxiv.org/abs/1507.04249) [hep-ph] | [PDF](#)

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[CERN Document Server](#); [ADS Abstract Service](#)

Detailed record - Cited by 115 records 100+

Molecular state

6. Understanding the newly observed heavy pentaquark candidates

⁽¹¹⁴⁾ Xiao-Hai Liu (Tokyo Inst. Tech.), Qian Wang (IAS, Jülich & JCHP, Jülich & Jülich, Forschungszentrum), Qiang Zhao (Beijing, Inst. High Energy Phys. & TPCSF, Beijing). Jul 19, 2015. 6 pp.
Published in *Phys.Lett. B757* (2016) 231-236
DOI: [10.1016/j.physletb.2016.03.089](https://doi.org/10.1016/j.physletb.2016.03.089)
e-Print: [arXiv:1507.05359](https://arxiv.org/abs/1507.05359) [hep-ph] | [PDF](#)

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[ADS Abstract Service](#); [Link to Article from](#)

Detailed record - Cited by 114 records 100+

Triangle Singularity

8. The New Pentaquarks in the Diquark Model

⁽¹⁰⁹⁾ L. Maiani, A.D. Polosa, V. Riquer (INFN, Rome & Rome U.). Jul 17, 2015. 4 pp.
Published in *Phys.Lett. B749* (2015) 289-291
DOI: [10.1016/j.physletb.2015.08.008](https://doi.org/10.1016/j.physletb.2015.08.008)
e-Print: [arXiv:1507.04980](https://arxiv.org/abs/1507.04980) [hep-ph] | [PDF](#)

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[ADS Abstract Service](#); [Link to Article from](#)

Detailed record - Cited by 109 records 100+

Compact pentaquark

9. Towards exotic hidden-charm pentaquarks in QCD

⁽¹⁰⁷⁾ Hua-Xing Chen (BeiHang U.), Wei Chen (Saskatchewan U.), Xiang Liu (Lanzhou U. & Lanzhou, Inst. Modern Phys.), T.G. Steele (Saskatchewan U.), Shi-Lin Zhu (Peking U., SKLNPT & Peking U., CHEP). Jul 14, 2015. 6 pp.
Published in *Phys.Rev.Lett.* 115 (2015) no.17, 172001
DOI: [10.1103/PhysRevLett.115.172001](https://doi.org/10.1103/PhysRevLett.115.172001)
e-Print: [arXiv:1507.03717](https://arxiv.org/abs/1507.03717) [hep-ph] | [PDF](#)

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[ADS Abstract Service](#)

Detailed record - Cited by 107 records 100+

Molecular state

10. The Pentaquark Candidates in the Dynamical Diquark Picture

⁽¹⁰⁵⁾ Richard F. Lebed (Arizona State U.). Jul 21, 2015. 5 pp.
Published in *Phys.Lett. B749* (2015) 454-457
DOI: [10.1016/j.physletb.2015.08.032](https://doi.org/10.1016/j.physletb.2015.08.032)
e-Print: [arXiv:1507.05867](https://arxiv.org/abs/1507.05867) [hep-ph] | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#)
[ADS Abstract Service](#); [Link to Article from](#)

Detailed record - Cited by 105 records 100+

Compact pentaquark

12. $\bar{D} \Sigma_c^*$ and $\bar{D}^* \Sigma_c$ interactions and the LHCb hidden-charmed pentaquarks

⁽¹⁰²⁾ Jun He (Lanzhou, Inst. Modern Phys. & Lanzhou U. & Beijing, Inst. Theor. Phys.). Jul 18, 2015. 5 pp.
Published in *Phys.Lett. B753* (2016) 547-551
DOI: [10.1016/j.physletb.2015.12.071](https://doi.org/10.1016/j.physletb.2015.12.071)
e-Print: [arXiv:1507.05200](https://arxiv.org/abs/1507.05200) [hep-ph] | [PDF](#)

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[ADS Abstract Service](#); [Link to Article from](#)

Detailed record - Cited by 102 records 100+

Molecular state

13. New Exotic Meson and Baryon Resonances from Doubly-Heavy Hadronic Molecules

⁽⁹⁰⁾ Marek Karliner (Tel Aviv U.), Jonathan L. Rosner (Chicago U. & Chicago U., EFI). Jun 21, 2015. 4 pp.
Published in *Phys.Rev.Lett.* 115 (2015) no.12, 122001
DOI: [10.1103/PhysRevLett.115.122001](https://doi.org/10.1103/PhysRevLett.115.122001)
e-Print: [arXiv:1506.06386](https://arxiv.org/abs/1506.06386) [hep-ph] | [PDF](#)

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Detailed record - Cited by 90 records 50+

Molecular state

14. Testing the $\chi_{c1} p$ composite nature of the $P_c(4450)$

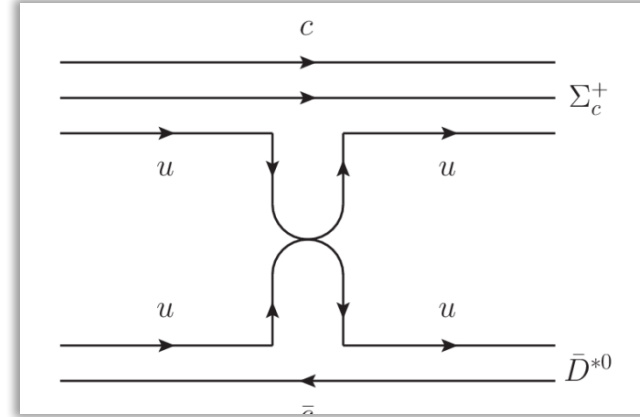
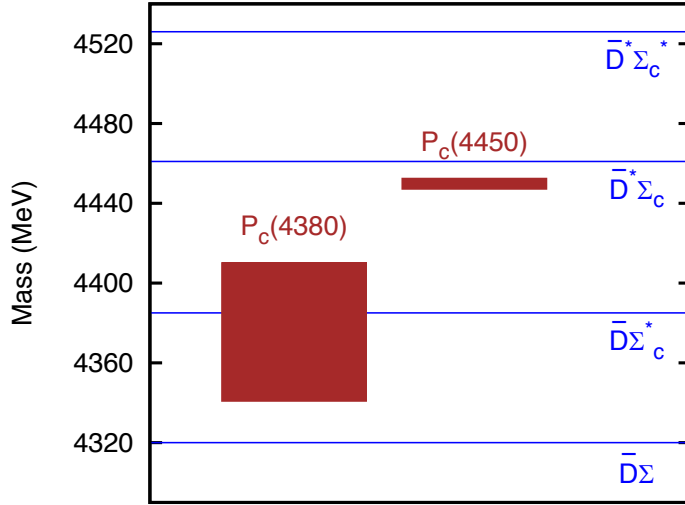
⁽⁸⁵⁾ Ulf-G. Meißner (Bonn U. & Bonn U., HISKP & IAS, Jülich & JCHP, Jülich & Jülich, Forschungszentrum), José A. Oller (Murcia U.). Jul 27, 2015. 4 pp.
Published in *Phys.Lett. B751* (2015) 59-62
DOI: [10.1016/j.physletb.2015.10.015](https://doi.org/10.1016/j.physletb.2015.10.015)
e-Print: [arXiv:1507.07478](https://arxiv.org/abs/1507.07478) [hep-ph] | [PDF](#)

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[ADS Abstract Service](#); [Link to Article from](#)

Detailed record - Cited by 85 records 50+

Molecular state

LHCb五夸克态的分子态解释



$$\begin{aligned} \mathcal{L}_{B_6 B_6 P} &= -\frac{g_1}{4f_\pi} \epsilon^{\alpha\beta\lambda\kappa} \langle \bar{B}_6 \overleftrightarrow{\partial}^\kappa \gamma_\alpha \gamma_\lambda \partial_\beta P B_6 \rangle, \\ \mathcal{L}_{B_6 B_6 V} &= -i \frac{\beta_S g_V}{2\sqrt{2}} \langle \bar{B}_6 \overleftrightarrow{\partial} \cdot \nabla B_6 \rangle \\ &\quad - \frac{im_{B_6} \lambda_S g_V}{3\sqrt{2}} \langle \bar{B}_6 \gamma_\mu \gamma_\nu (\partial^\mu \nabla^\nu - \partial^\nu \nabla^\mu) B_6 \rangle, \\ \mathcal{L}_{B_6 B_6 \sigma} &= -\ell_S m_{B_6} \langle \bar{B}_6 \sigma B_6 \rangle, \end{aligned}$$

$$\begin{aligned} \mathcal{L}_{\tilde{P} \tilde{P} V} &= \frac{\beta g_V}{\sqrt{2}} \tilde{P}_a^\dagger \overleftrightarrow{\partial}^\mu \tilde{P}_b \nabla_{ab}^\mu, \\ \mathcal{L}_{\tilde{P} \tilde{P} \sigma} &= -2g_S m_P \tilde{P}_b \tilde{P}_b^\dagger \sigma, \\ \mathcal{L}_{\tilde{P}^* \tilde{P}^* P} &= -\frac{g}{f_\pi} \epsilon_{\alpha\beta\lambda\kappa} \tilde{P}_a^{*\beta\lambda} \overleftrightarrow{\partial}^\alpha \tilde{P}_b^{*\kappa} \partial^\lambda P_{ab}, \\ \mathcal{L}_{\tilde{P}^* \tilde{P}^* V} &= -i \frac{\beta g_V}{\sqrt{2}} \tilde{P}_a^{*\dagger\mu} \overleftrightarrow{\partial}^\nu \tilde{P}_{b\mu}^* \nabla_{ab\nu} \\ &\quad - i2\sqrt{2} m_{P^*} \lambda_{g_V} \tilde{P}_a^{*\mu\dagger} \tilde{P}_b^{*\nu} (\partial_\mu \nabla_\nu - \partial_\nu \nabla_\mu)_{ab}, \\ \mathcal{L}_{\tilde{P}^* \tilde{P}^* \sigma} &= 2g_S m_{P^*} \tilde{P}_b^* \cdot \tilde{P}_b^{*\dagger} \sigma \end{aligned}$$

LHCb五夸克态的分子态解释

我们可以得到以下对应于LHCb五夸克态的束缚态

$$\begin{array}{lll} P_c(4380): & \bar{D}\Sigma_c^* [3/2^-, 0.7-1.4], & \bar{D}\Sigma_c^* [3/2^+, 2.8-5.0], & \bar{D}^*\Sigma_c [3/2^-, 3.0-3.7]; \\ P_c(4450): & \bar{D}^*\Sigma_c [5/2^+, 2.7-2.8], & \bar{D}^*\Sigma_c [5/2^-, 2.8-2.9], & \bar{D}^*\Sigma_c^* [5/2^+, 2-2.1]. \end{array}$$

与实验值比较

$$\begin{array}{ll} P_c(4380): & M = 4380 \pm 8 \pm 29 \text{ MeV}, & J^P = 3/2^-. \\ P_c(4450): & M = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}, & J^P = 5/2^+. \end{array}$$

LHCb五夸克态可以解释为

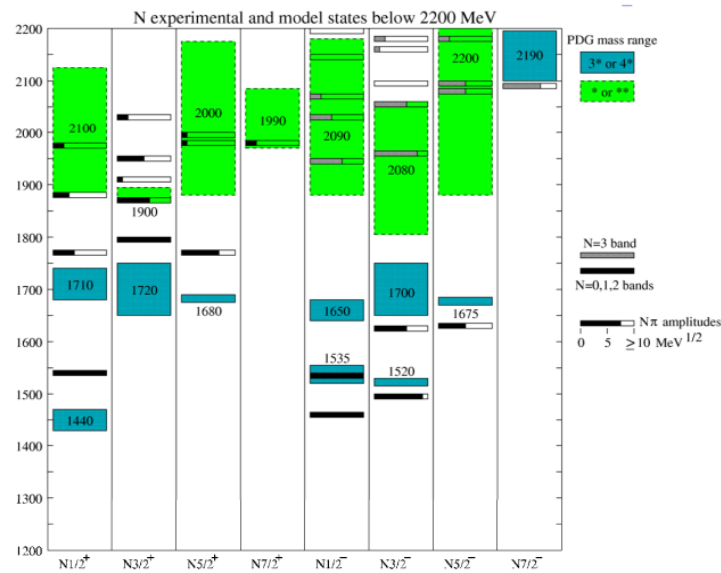
$$P_c(4380) : \bar{D}\Sigma_c^* [3/2^-]; \quad P_c(4450) : \bar{D}^*\Sigma_c [5/2^+].$$

S-wave state

P-wave state

核子共振态超重岛

质量在4 GeV附近的核子共振态(含正反粲夸克)



Prediction of Narrow N^* and Λ^* Resonances with Hidden Charm above 4 GeV

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(Received 5 July 2010; published 29 November 2010)

The interaction between various charmed mesons and charmed baryons is studied within the framework of the coupled-channel unitary approach with the local hidden gauge formalism. Several meson-baryon dynamically generated narrow N^* and Λ^* resonances with hidden charm are predicted with mass above 4 GeV and width smaller than 100 MeV. The predicted new resonances definitely cannot be accommodated by quark models with three constituent quarks and can be looked for in the forthcoming PANDA/FAIR experiments.



$s\bar{s}$ Component of the Proton and the Strangeness Magnetic Moment

B. S. Zou^{*}

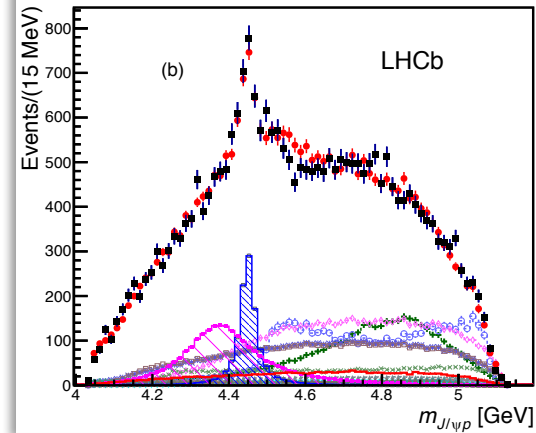
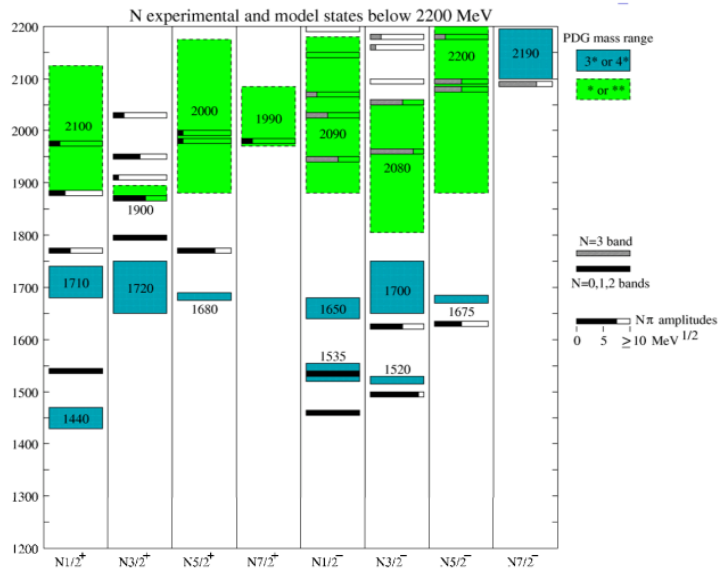
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(Received 25 February 2005; published 11 August 2005)

A complete analysis is given of the implications of the empirical indications for a positive strangeness magnetic moment μ_s of the proton on the possible configurations of the $uuds\bar{s}$ component of the proton. A positive value for μ_s is obtained in the $s\bar{s}$ configuration where the $uuds$ subsystem is in an orbitally excited state with $[4]_{FS}[22]_F[22]_S$ flavor-spin symmetry, which is likely to have the lowest energy. The configurations in which the $\bar{s}$ is orbitally excited, which include the conventional $K^+\Lambda^0$ configuration, with the exception of that in which the $uuds$ component has spin 2, yield negative values for μ_s . The hidden strangeness analogues of recently proposed quark cluster models for the θ^+ pentaquark give differing signs for μ_s .

N^* near 4 GeV with $c\bar{c}$



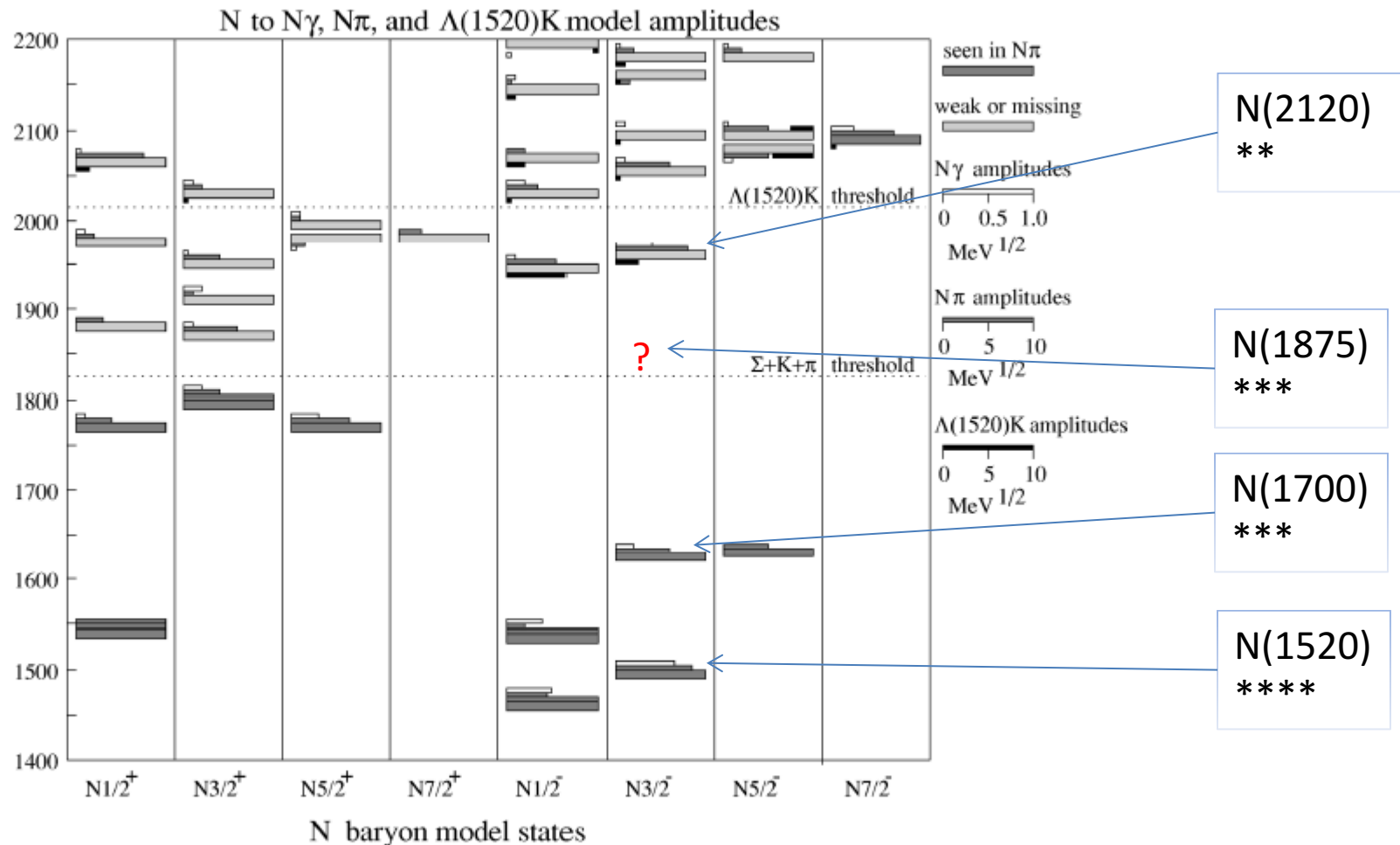
Hidden-Charm pentaquark



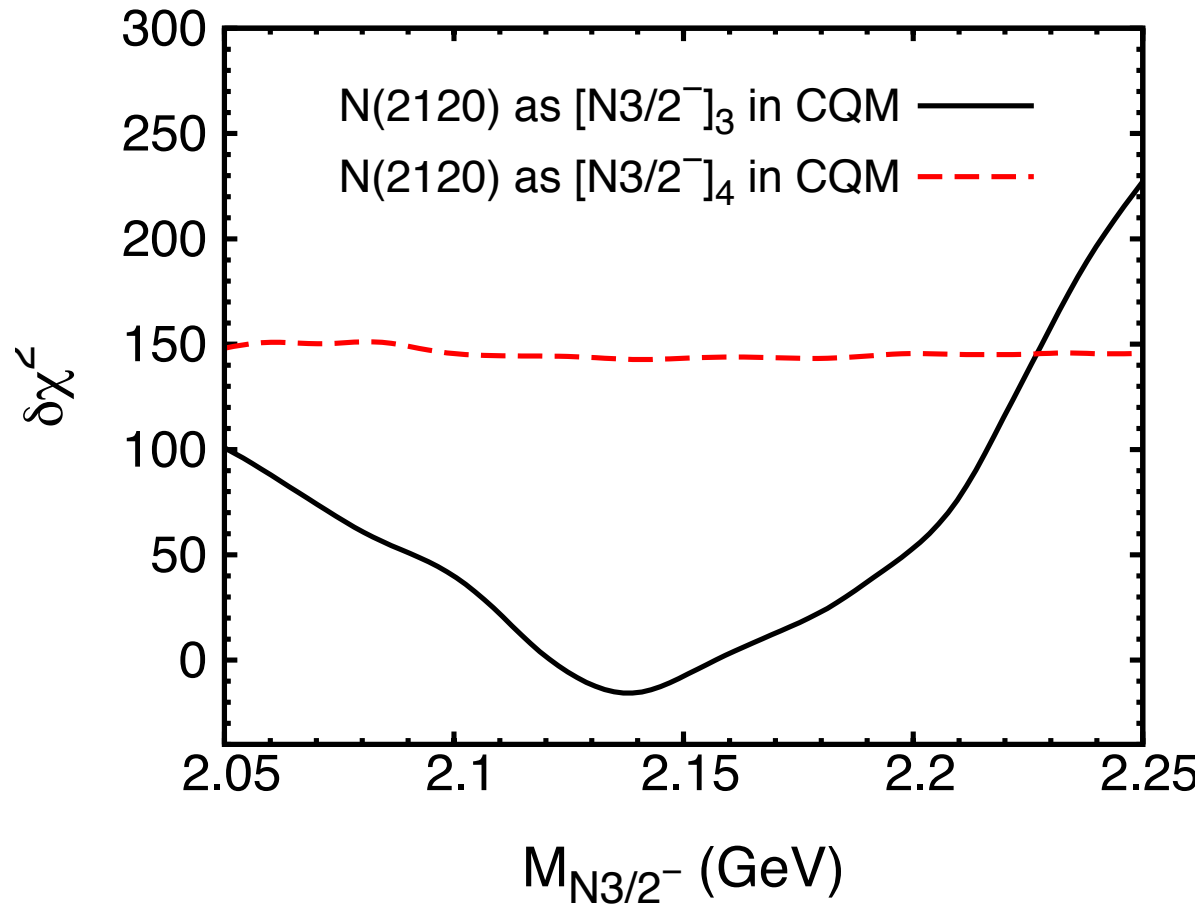
Hidden-strange
pentaquark?

3/2- 核子共振态

PDG



拟合 $\Lambda(1520)$ 光致产生数据



The N(2120) is essential to reproducing the experimental data with assumption it is the **third state with spin parity $3/2^-$** .



The results support molecular state assumption

Λ	E	Γ	$N\sigma$	$N\rho$	$N\omega$	$N\pi$	ΔK	ΣK
1.68	3	41	55.9	4.7	14.1	22.4	2.3	0.6
1.72	8	73	55.8	4.7	14.0	22.6	2.3	0.6
1.76	16	111	55.7	4.7	14.0	22.7	2.2	0.6
1.80	28	155	55.6	4.8	14.2	22.8	2.1	0.5
1.84	44	204	55.3	4.9	14.6	22.7	2.0	0.5
1.88	67	257	54.9	5.1	14.9	22.9	1.8	0.4
1.92	100	312	53.6	5.1	14.7	24.8	1.5	0.3
PDG [1]	30^{+25}_{-20}		24^{+24}_{-20}	6^{+6}_{-6}	20^{+4}_{-4}	7^{+6}_{-6}		$0.7^{+0.4}_{-0.4}$
BnGa [2]	20^{+20}_{-20}	200^{+20}_{-20}	60^{+12}_{-12}			3^{+2}_{-2}	4^{+2}_{-2}	15^{+8}_{-8}
$[N(\bar{\zeta})]_1$	-85	324		57.1	12.3	20.8	9.7	0

N(2100) in ϕ photoproduction

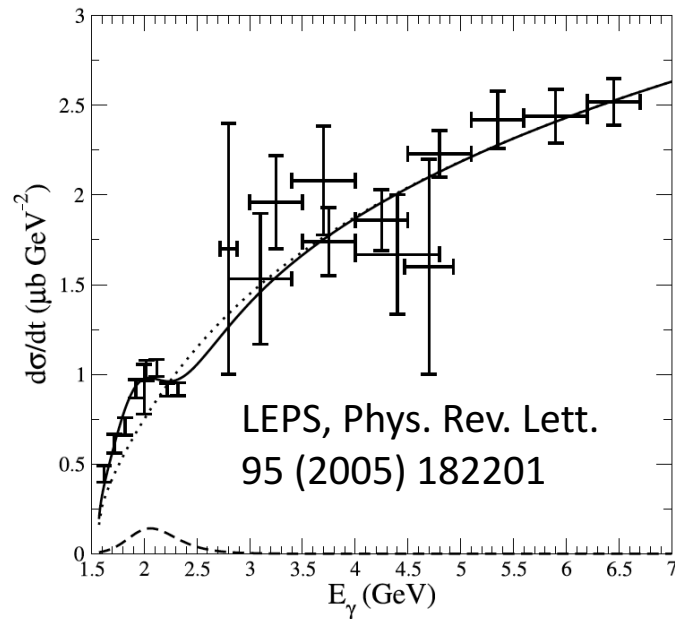


Fig. 2. Differential cross section of $\gamma p \rightarrow \phi p$ at forward direction as a function of photon energy E_γ . The dotted, dashed, and solid lines denote contributions from nonresonant, resonance with $J^P = 3/2^-$, and their sum, respectively. Data are from Refs. [10,17].

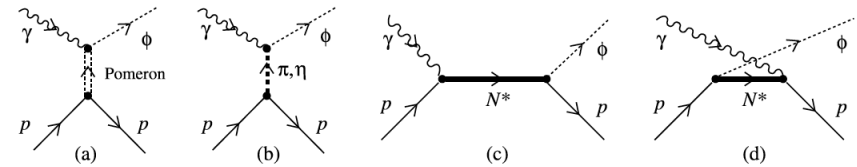


Fig. 1. (a) Pomeron-exchange, (b) (π, η) -exchange, and (c,d) s - and u -channel N^* -exchange diagrams for $\gamma p \rightarrow \phi p$ reaction.

Kiswandhi, Xie, Yang, Phys. Lett. B 691 (2010) 214

Kiswandhi, Yang, Phys. Rev. C 86(2012) 015203

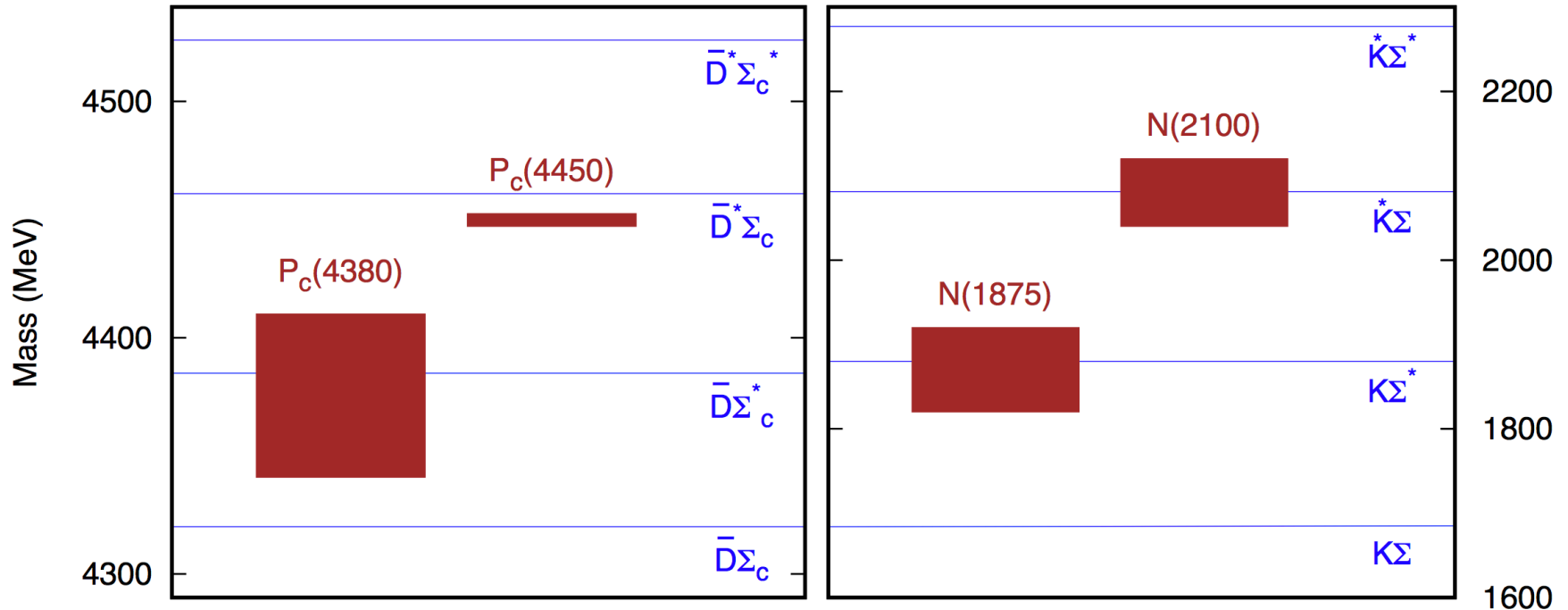
Kiswandhi, Yang, Dong, Phys. Rev. C94(2016) 015202

A nucleon resonance with a mass about 2.10 GeV in ϕp channel with $3/2^-$

OZI rule $\Rightarrow$ N^* decay to ϕp should be suppressed in three quark picture

If we recall that the $P_c(4450)$ was observed in $J/\psi p$ channel, $N(2100)$ may be its partner in the strange sector observed ϕp channel.

Threshold and mass



$P_c(4380)$ is close to $\Sigma_c^* D$ threshold
 $P_c(4450)$ is close to $\Sigma_c D^*$ threshold



$N(1875)$ is close to $\Sigma^* K$ threshold
 $N(2100)$ is close to ΣK^* threshold

Lagrangians for Σ^*K and ΣK^* interactions

$$\begin{aligned}\mathcal{L}_{\Sigma^*\Sigma^*\rho} &= -g_{\Sigma^*\Sigma^*\rho} \bar{\Sigma}^{*\mu} [\gamma^\nu - \frac{K_{\Sigma^*\Sigma^*\rho}}{2m_{\Sigma^*}} \sigma^{\nu\rho} \partial_\rho] \rho_\nu \cdot T\Sigma_\mu^*, \\ \mathcal{L}_{\Sigma^*\Sigma^*\omega} &= -g_{\Sigma^*\Sigma^*\omega} \bar{\Sigma}^{*\mu} [\gamma^\nu - \frac{K_{\Sigma^*\Sigma^*\omega}}{2m_{\Sigma^*}} \sigma^{\nu\rho} \partial_\rho] \omega_\nu \Sigma_\mu^*, \\ \mathcal{L}_{\Sigma^*\Sigma^*\phi} &= -g_{\Sigma^*\Sigma^*\phi} \bar{\Sigma}^{*\mu} [\gamma^\nu - \frac{K_{\Sigma^*\Sigma^*\phi}}{2m_{\Sigma^*}} \sigma^{\nu\rho} \partial_\rho] \phi_\nu \Sigma_\mu^*,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{KK\rho} &= -ig_{KK\rho} K\rho^\mu \cdot \tau \partial_\mu K, \\ \mathcal{L}_{KK\omega} &= -ig_{KK\omega} K\omega^\mu \partial_\mu K, \\ \mathcal{L}_{KK\phi} &= -ig_{KK\phi} K\phi^\mu \partial_\mu K,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\Sigma\Sigma\pi} &= -\frac{f_{\Sigma\Sigma\pi}}{m_\pi} \bar{\Sigma} \gamma^5 \gamma^\mu \partial_\mu \pi \cdot T\Sigma, \\ \mathcal{L}_{\Sigma\Sigma\eta} &= -\frac{f_{\Sigma\Sigma\eta}}{m_\pi} \bar{\Sigma} \gamma^5 \gamma^\mu \partial_\mu \eta \Sigma,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{K^*K^*\pi} &= g_{K^*K^*\pi} \epsilon^{\mu\nu\alpha\beta} \partial_\mu K_\nu^* \partial_\alpha \pi \cdot \tau K_\beta^*, \\ \mathcal{L}_{K^*K^*\eta} &= g_{K^*K^*\eta} \epsilon^{\mu\nu\sigma\tau} \partial_\mu K_\nu^* \partial_\sigma \eta K_\tau^*,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\Sigma\Sigma\rho} &= -g_{\Sigma\Sigma\rho} \bar{\Sigma} [\gamma^\nu - \frac{K_{\Sigma\Sigma\rho}}{2m_\Sigma} \sigma^{\nu\rho} \partial_\rho] \rho_\nu \cdot T\Sigma, \\ \mathcal{L}_{\Sigma\Sigma\omega} &= -g_{\Sigma\Sigma\omega} \bar{\Sigma} [\gamma^\nu - \frac{K_{\Sigma\Sigma\omega}}{2m_\Sigma} \sigma^{\nu\rho} \partial_\rho] \omega_\nu \Sigma, \\ \mathcal{L}_{\Sigma\Sigma\phi} &= -g_{\Sigma\Sigma\phi} \bar{\Sigma} [\gamma^\nu - \frac{K_{\Sigma\Sigma\phi}}{2m_\Sigma} \sigma^{\nu\rho} \partial_\rho] \phi_\nu \Sigma,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{K^*K^*\rho} &= i\frac{g_{K^*K^*\rho}}{2} (K^{*\mu} \rho_{\mu\nu} K^{*\nu} + K^{*\mu\nu} \rho_\mu K^{*\nu} + K^{*\mu} \rho_\nu K^{*\nu\mu}) \cdot \tau, \\ \mathcal{L}_{K^*K^*\omega} &= i\frac{g_{K^*K^*\omega}}{2} (K^{*\mu} \omega_{\mu\nu} K^{*\nu} + K^{*\mu\nu} \omega_\mu K^{*\nu} + K^{*\mu} \omega_\nu K^{*\nu\mu}), \\ \mathcal{L}_{K^*K^*\phi} &= i\frac{g_{K^*K^*\phi}}{2} (K^{*\mu} \phi_{\mu\nu} K^{*\nu} + K^{*\mu\nu} \phi_\mu K^{*\nu} + K^{*\mu} \phi_\nu K^{*\nu\mu}),\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\Sigma^*\Sigma\pi} &= \frac{f_{\Sigma^*\Sigma\pi}}{m_\pi} \bar{\Sigma}^\mu \partial_\mu \pi \cdot T\Sigma, \\ \mathcal{L}_{\Sigma^*\Sigma\eta} &= \frac{f_{\Sigma^*\Sigma\eta}}{m_\pi} \bar{\Sigma}^\mu \partial_\mu \eta \Sigma,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{K^*K\pi} &= -ig_{K^*K\pi} K^{*\mu} (\pi \partial_\mu - \partial_\mu \pi) \cdot \tau K, \\ \mathcal{L}_{K^*K\eta} &= -ig_{K^*K\eta} K^{*\mu} (\eta \partial_\mu - \partial_\mu \eta) K,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\Sigma^*\Sigma\rho} &= -i\frac{f_{\Sigma^*\Sigma\rho}}{m_\rho} \bar{\Sigma}^{*\mu} \gamma^5 \gamma^\nu [\partial_\mu \rho_\nu - \partial_\nu \rho_\mu] \cdot T\Sigma, \\ \mathcal{L}_{\Sigma^*\Sigma\omega} &= -i\frac{f_{\Sigma^*\Sigma\omega}}{m_\rho} \bar{\Sigma}^{*\mu} \gamma^5 \gamma^\nu [\partial_\mu \omega_\nu - \partial_\nu \omega_\mu] \Sigma, \\ \mathcal{L}_{\Sigma^*\Sigma\phi} &= -i\frac{f_{\Sigma^*\Sigma\phi}}{m_\rho} \bar{\Sigma}^{*\mu} \gamma^5 \gamma^\nu [\partial_\mu \phi_\nu - \partial_\nu \phi_\mu] \Sigma,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{K^*K\rho} &= g_{K^*K\rho} \epsilon^{\mu\nu\sigma\tau} \partial_\mu K_\nu^* \rho \cdot \tau \partial_\sigma K, \\ \mathcal{L}_{K^*K\omega} &= g_{K^*K\omega} \epsilon^{\mu\nu\sigma\tau} \partial_\mu K_\nu^* \omega \partial_\sigma K, \\ \mathcal{L}_{K^*K\phi} &= g_{K^*K\phi} \epsilon^{\mu\nu\sigma\tau} \partial_\mu K_\nu^* \phi \partial_\sigma K,\end{aligned}$$

The coupling constants are obtained with SU(3) symmetry.

The bound states from the Σ^*K interaction

with vector meson (ρ , ω , ϕ) exchanges

$$i\mathcal{V}_V = f_I \frac{g_{KKV}g_{\Sigma^*\Sigma^*V}}{q^2 - m_V^2} \bar{u}^\mu \left\{ -\not{k}_1 + \frac{q \cdot k_1 \not{q}}{m_V^2} - \frac{\kappa_{\Sigma^*\Sigma^*V}}{4m_{\Sigma^*}} [\not{k}_1, \not{q}] \right\} u_\mu$$

TABLE I: The bound states from the Σ^*K interaction with the variation of the cutoffs Λ or p^{max} . The cutoff Λ , cutoff p^{max} , and energy W are in units of GeV, GeV, and MeV, respectively.

$I(J^P)$	Λ	p^{max}	W	$I(J^P)$	Λ	p^{max}	W
$\frac{1}{2}(\frac{3}{2}^-)$ N(1875)	1.5	1.10	1880	$\frac{3}{2}(\frac{1}{2}^+)$	1.60	1.238	1878
	1.6	1.15	1879		1.61	1.249	1870
	1.7	1.25	1874		1.62	1.259	1862
	1.8	1.34	1862		1.63	1.269	1854
	1.9	1.56	1832		1.64	1.280	1844

The bound states from the ΣK^* interaction

with vector (ρ, ω, ϕ) meson
and pseudoscalar (η, π) meson
exchanges.

$$\begin{aligned}
 i\mathcal{V}_V &= f_I \frac{g_{K^*K^*\mathbb{V}} g_{\Sigma\Sigma\mathbb{V}}}{2} [\epsilon^\dagger \cdot q \epsilon^\nu + (k_1 + k'_1)^\nu \epsilon^\dagger \cdot \epsilon \\
 &\quad - \epsilon^{\dagger\nu} \epsilon \cdot q - k_1 \cdot \epsilon \epsilon^{\dagger\nu} - k'_1 \cdot \epsilon^\dagger \epsilon^\nu] \\
 &\quad \cdot \frac{g_{\nu\nu'} - q_\nu q_{\nu'} / m_V^2}{q^2 - m_V^2} \bar{u}(\gamma^{\nu'} - i \frac{\kappa_{\Sigma\Sigma\mathbb{V}}}{2m_\Sigma} \sigma^{\nu'\rho} q_\rho) u \\
 i\mathcal{V}_P &= f_I \frac{g_{K^*K^*\mathbb{P}} f_{\Sigma\Sigma\mathbb{P}}}{m_\pi(q^2 - m_\pi^2)} \epsilon^{\mu\nu\alpha\beta} k'_{1\mu} \epsilon_v^\dagger k_{1\alpha} \epsilon_\beta \bar{u} \gamma_5 \not{q} u,
 \end{aligned}$$

TABLE III: The bound states from the ΣK^* interaction at different cutoffs Λ or p^{max} . The cutoff Λ , cutoff p^{max} , and energy W are in units of GeV, GeV, and MeV, respectively.

$I(J^P)$	Λ	p^{max}	W	$I(J^P)$	Λ	p^{max}	W
$\frac{1}{2}(\frac{3}{2}^-)$	0.8	0.46	2086	$\frac{1}{2}(\frac{5}{2}^+)$	1.17	0.755	2086
	0.9	0.50	2085		1.19	0.765	2082
	1.0	0.57	2081		1.21	0.781	2076
	1.1	0.62	2076		1.23	0.796	2069
	1.2	0.69	2068		1.25	0.808	2060
N(2100)	1.25	0.831	2086	$\frac{3}{2}(\frac{5}{2}^+)$	1.31	0.910	2087
	1.26	0.839	2084		1.32	0.917	2084
	1.27	0.845	2080		1.33	0.935	2071
	1.28	0.849	2076		1.34	0.945	2061
	1.29	0.854	2072		1.29	0.953	2048
$\frac{1}{2}(\frac{5}{2}^-)$	1.43	0.999	2086	$\frac{3}{2}(\frac{1}{2}^+)$	0.93	0.603	2085
	1.44	1.007	2080		0.94	0.612	2084
	1.45	1.015	2071		0.95	0.620	2081
	1.46	1.022	2059		0.96	0.625	2078
	1.47	1.031	2044		0.97	0.631	2074

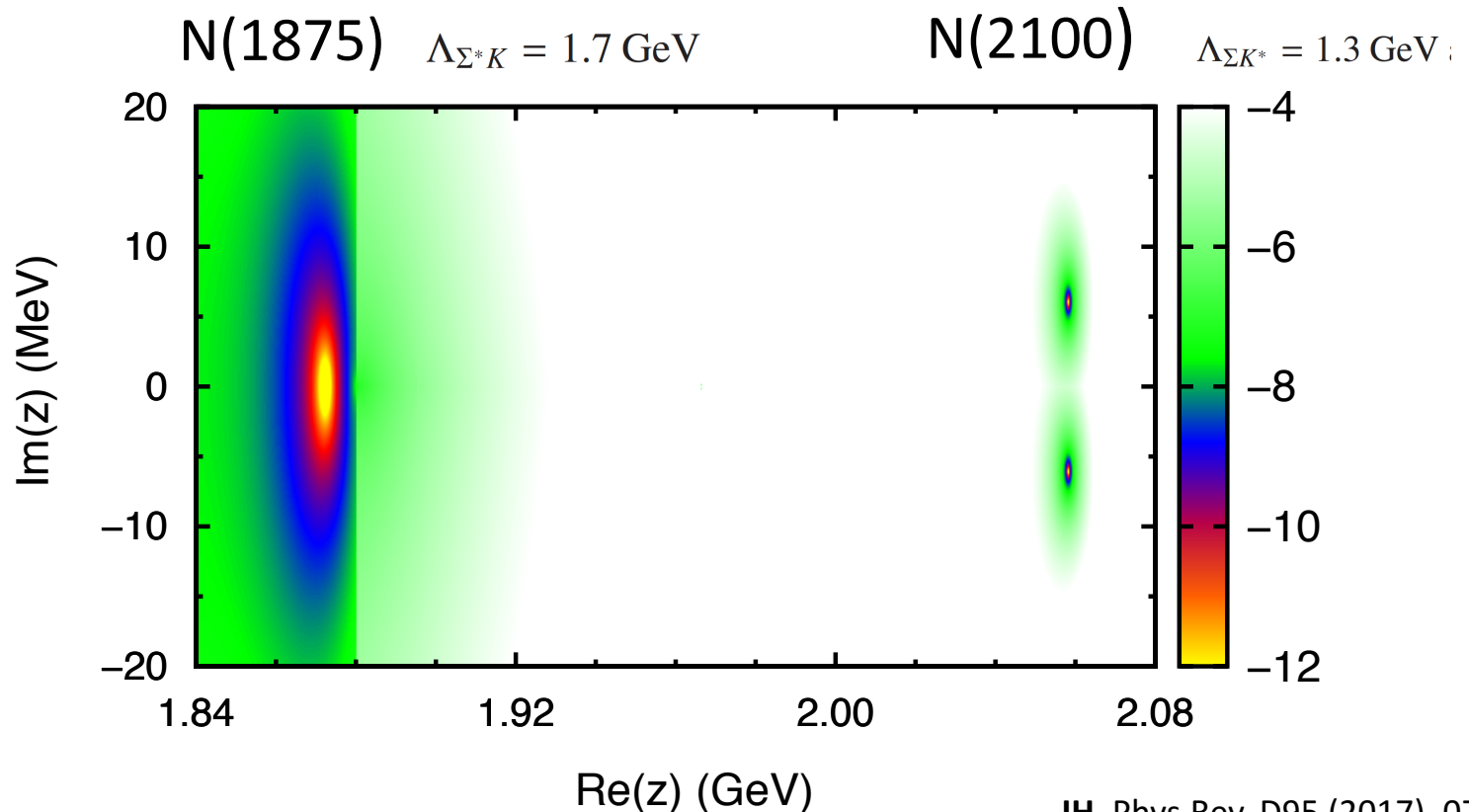
3/2⁻ state in the Σ^*K - ΣK^* interaction

with vector (ρ, ω, ϕ) meson
and pseudoscalar (η, π)
meson exchanges.

$$i\mathcal{V}_V = f_I g_{K^*K V} \frac{f_{\Sigma^*\Sigma V}}{m_V} \epsilon^{\mu\nu\sigma\tau} k_{1\mu} \epsilon_\nu q_\sigma$$

$$\cdot [\bar{u}^\rho \gamma^\tau q_\rho - \bar{\Sigma}^\tau \gamma^\rho q_\rho] \gamma_5 u \frac{1}{q^2 - m_V^2},$$

$$i\mathcal{V}_P = i f_I g_{K^*K\pi} \frac{f_{\Sigma^*\Sigma\pi}}{m_\pi} \epsilon^\mu (k'_1 + q)_\mu \bar{u}^\nu q_\nu u \frac{1}{q^2 - m_\pi^2}.$$



The quark delocalization color screening model

$$\begin{aligned}
 H &= \sum_{i=1}^5 \left(m_i + \frac{p_i^2}{2m_i} \right) - T_{CM} + \sum_{j>i=1}^5 (V_{ij}^C + V_{ij}^G + V_{ij}^X), \\
 V_{ij}^C &= -a_c \lambda_i^c \cdot \lambda_j^c (r_{ij}^2 + v_0), \\
 V_{ij}^G &= \frac{1}{4} \alpha_s \lambda_i^c \cdot \lambda_j^c \left[\frac{1}{r_{ij}} - \frac{\pi}{2} \delta(r_{ij}) \left(\frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{4\sigma_i \cdot \sigma_j}{3m_i m_j} \right) - \frac{3}{4m_i m_j r_{ij}^3} S_{ij} \right] \\
 V_{ij}^X &= V_\pi(r_{ij}) \sum_{a=1}^3 \lambda_i^a \cdot \lambda_j^a + V_K(r_{ij}) \sum_{a=4}^7 \lambda_i^a \cdot \lambda_j^a + V_\eta(r_{ij}) [(\lambda_i^8 \cdot \lambda_j^8) \cos \theta_P - (\lambda_i^0 \cdot \lambda_j^0) \sin \theta_P] \\
 V_\chi(r_{ij}) &= \frac{g_{ch}^2}{4\pi} \frac{m_\chi^2}{12m_i m_j} \frac{\Lambda_\chi^2}{\Lambda_\chi^2 - m_\chi^2} m_\chi \left\{ (\sigma_i \cdot \sigma_j) \left[Y(m_\chi r_{ij}) - \frac{\Lambda_\chi^3}{m_\chi^3} Y(\Lambda_\chi r_{ij}) \right] \right. \\
 &\quad \left. + \left[H(m_\chi r_{ij}) - \frac{\Lambda_\chi^3}{m_\chi^3} H(\Lambda_\chi r_{ij}) \right] S_{ij} \right\}, \quad \chi = \pi, K, \eta, \\
 S_{ij} &= \left\{ 3 \frac{(\sigma_i \cdot r_{ij})(\sigma_j \cdot r_{ij})}{r_{ij}^2} - \sigma_i \cdot \sigma_j \right\}, \\
 H(x) &= (1 + 3/x + 3/x^2)Y(x), \quad Y(x) = e^{-x}/x.
 \end{aligned}$$

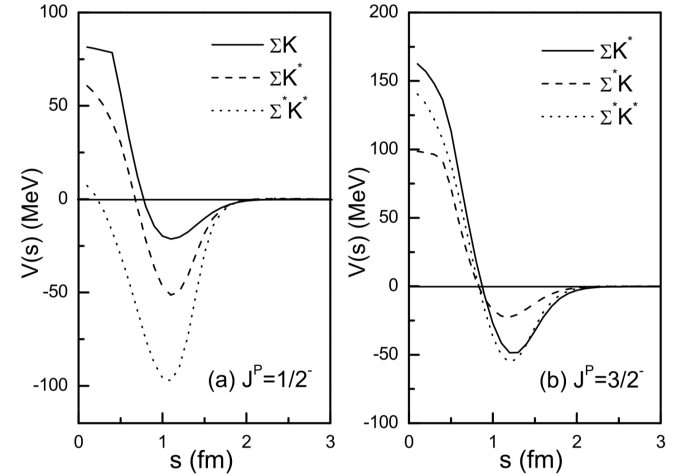
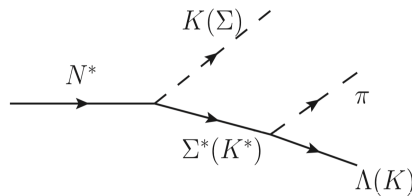
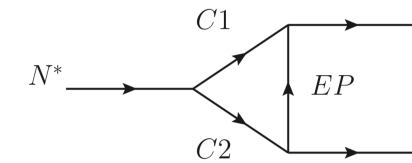


FIG. 1: The potentials of different channels for the $J^P = \frac{1}{2}^-$ and $J^P = \frac{3}{2}^-$ systems.

TABLE III: The binding energy and masses (in MeV) of the molecular pentaquarks.

$J^P = \frac{1}{2}^-$		$J^P = \frac{3}{2}^-$	
Channel	B/M	Channel	B/M
ΣK	-18.8/1669.2	ΣK^*	-22.7/2062.3
ΣK^*	-7.2/2077.8	$\Sigma^* K$	-7.4/1872.6
$\Sigma^* K^*$	-21.9/2255.1	$\Sigma^* K^*$	-6.8/2270.2

Decay behaviors in the effective Lagrangian approach



Mode	Widths (MeV)			
	$J^P = 3/2^-$		$J^P = 1/2^-$	
	$N(1875)$	$K\Sigma^*$	$N(2080)$	$K^*\Sigma$
$N\sigma(500)$	2.6		0.05	0.3
πN	3.8		0.2	22.7
ρN	2.3		3.8	6.1
ωp	6.6		11.3	18.2
$K\Sigma$	0.03		1.4	9.1
$K\Lambda$	0.7		3.7	19.3
ηp	0.6		0.4	1.8
$\pi\Delta$	201.4		82.6	46.9
$K^*\Lambda$	-		2.4	7.9
ϕp	-		19.2	27.0
$K\Sigma^*$	-		7.3	1.3
$K\Lambda(1520)$	-		0.1	1.3
$K\Lambda(1405)$	-		8.0	8.8
$K\pi\Lambda$	10.1		-	-
$K\pi\Sigma$	-		41.3	46.1
Total	228.2		181.7	216.8

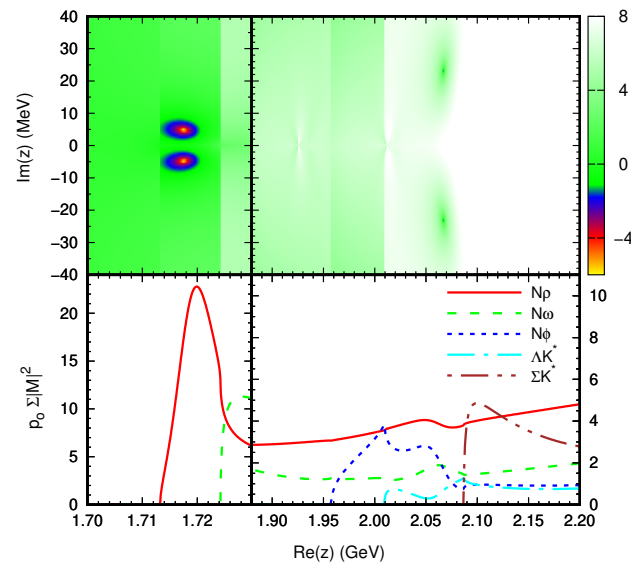
$N\rho - N\omega - N\phi - \Lambda K^* - \Sigma K^*$ interaction

$$i\mathcal{V}_V = \frac{C_{ij}^V G_V}{q^2 - m_V^2} \bar{B}_i [A_{ij} - \frac{A_{ij} \cdot q \not{q}}{m_V^2} + \frac{\tilde{\kappa}_{ij} \kappa_\rho (A_{ij} \not{q} - \not{q} A_{ij})}{2(m_i + m_j)}] B_j,$$

$$i\mathcal{V}_P = \frac{C_{ij}^P G_P}{q^2 - m_P^2} i\epsilon^{\mu\nu\sigma\tau} (k'_1 + k_1)^\mu \epsilon_i^{\nu\dagger} q^\sigma \epsilon_j^\tau \bar{B}_i \gamma_5 \not{q} B_j, \quad (3)$$

TABLE I: The coefficient C_{ij} and $\tilde{\kappa}_{ij}$. The $\{C_{ij}^V, \tilde{\kappa}_{ij}\}_V$ and $\{C_{ij}^P\}_P$ are for vector and pseudoscalar exchanges, respectively.

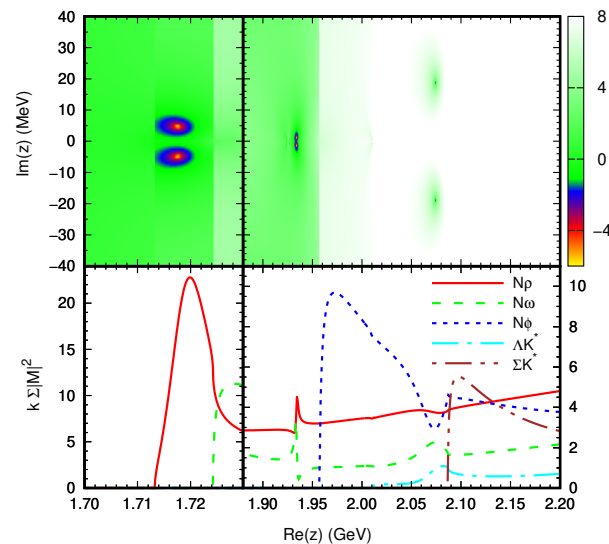
	$N\rho$	$N\omega$	$N\phi$	$K^*\Lambda$		$K^*\Sigma$	
$N\rho$	$\{-2, 1\}_\rho$	$\{-\sqrt{3}\}_\pi$	0	$\{\frac{3}{2}, -\frac{1}{2}\}_{K^*}$	$\{\frac{1}{2}(1+2\alpha)\}_K$	$\{\frac{1}{2}, -\frac{1}{2}\}_{K^*}$	$\{\frac{1}{2}(2\alpha-1)\}_K$
$N\omega$		0	0	$\{-\frac{\sqrt{3}}{2}, -\frac{1}{2}\}_{K^*}$	$\{-\frac{1}{2\sqrt{3}}(1+2\alpha)\}_K$	$\{-\frac{\sqrt{3}}{2}, -\frac{1}{2}\}_{K^*}$	$\{-\frac{\sqrt{3}}{2}(2\alpha-1)\}_K$
$N\phi$			0	$\{-\sqrt{\frac{3}{2}}, -\frac{1}{2}\}_{K^*}$	$\{-\frac{1}{\sqrt{6}}(1+2\alpha)\}_K$	$\{\sqrt{\frac{3}{2}}, -\frac{1}{2}\}_{K^*}$	$\{\sqrt{\frac{3}{2}}(2\alpha-1)\}_K$
$K^*\Lambda$				$\{1, -\frac{1}{4}\}_\omega$	$\{-1+\alpha\}_\eta$	$\{0, 0\}_{K^*}$	$\{(-1+\alpha)\}_K$
				$\{-1, \frac{1}{2}\}_\phi$			
$K^*\Sigma$						$\{-2, \frac{1}{4}\}_\rho$	$\{-2\alpha\}_\pi$
						$\{1, \frac{1}{4}\}_\omega$	$\{1-\alpha\}_\eta$
						$\{-1, -\frac{1}{2}\}_\phi$	



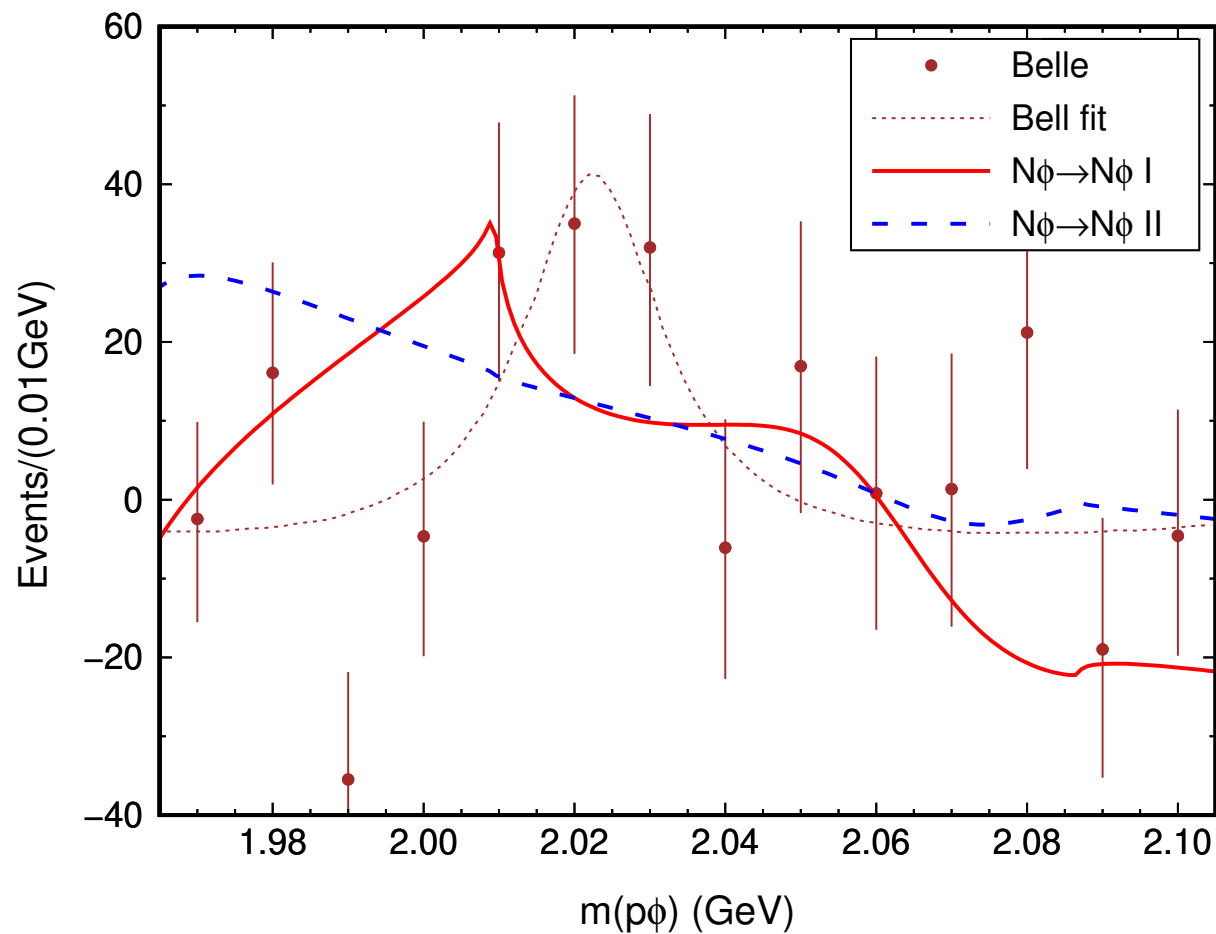
QCD van der Waals force

$$i\mathcal{V}_{N\phi} = (4\pi) \frac{\alpha}{q^2 - \mu^2} 2m_N \bar{N} N \phi \cdot \phi,$$

A narrow $N\phi$ bound state was found in the constituent quark model [Gao, Huang, Liu, Ping, Wang and Zhao, Phys. Rev. C 95, 055202 (2017)].



Compared with Belle data



Two hidden-charm pentaquarks were observed at LHCb.
It can be interpreted as $\Sigma_c^* D$ and $\Sigma_c D^*$ molecular states.

Three $3/2^-$ nucleon resonances:

- N (1875):
 $\Sigma^* K$ molecular state, partner of Pc(4380)
- N (2100) in ϕ photoproduction:
 ΣK^* molecular state, partner of Pc(4450)
- N (2120) in $K\Lambda(1520)$ photoproduction
 $[N(3/2^-)]_3$ in constituent quark model

总结

自2003年起，实验上发现了许多不能在夸克模型框架下解释的奇特共振结构，是新强子态的有力候选者。

很多奇特共振结构在两个强子的阈值附近，因此很可能是强子通交换介子形成的强子分子态

- LHCb隐粲五夸克态及其隐奇异伴随态；
- $BB^*/DD^*/KK^*$ 相互作用与 $Z_b(10610)$ 、 $Z_c(3900)$ 和 $f_1(1285)$ 。

强子分子态图像可以理解一系列的近阈奇特共振结构。

谢谢！