On the existence of a doubly charmed DDK bound state

Lisheng Geng @ Beihang U.

1309.4743

1704.06123

1705.00516

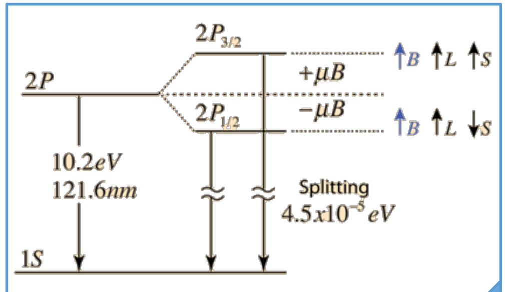
1707.03802

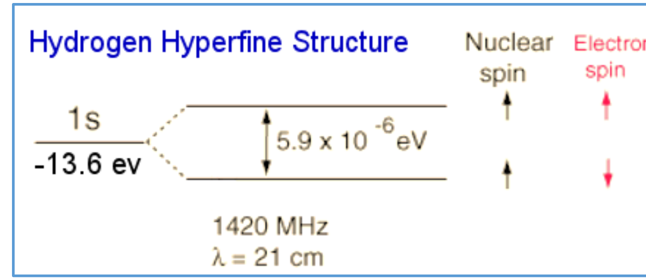
1805.08330

180-9.01059

+some preliminary results

Why spectroscopy—Atomic





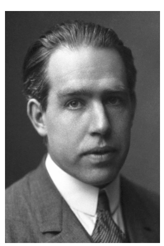
Hyperfine structure

Fine structure

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

Rydberg formula

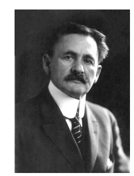
Johannes Rydberg



Niels Henrik David Bohr

Edward W. Morley

Arnold Sommerfeld

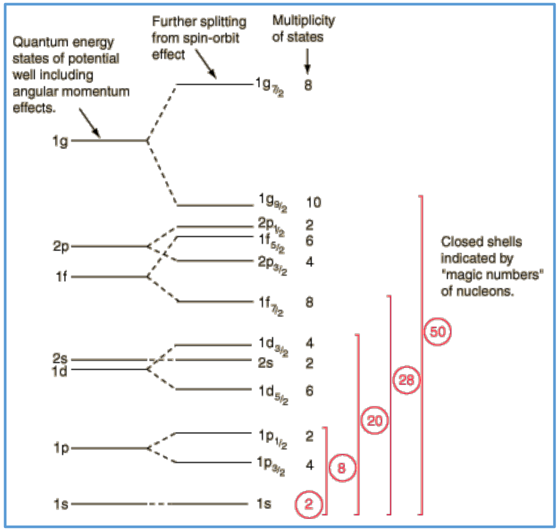


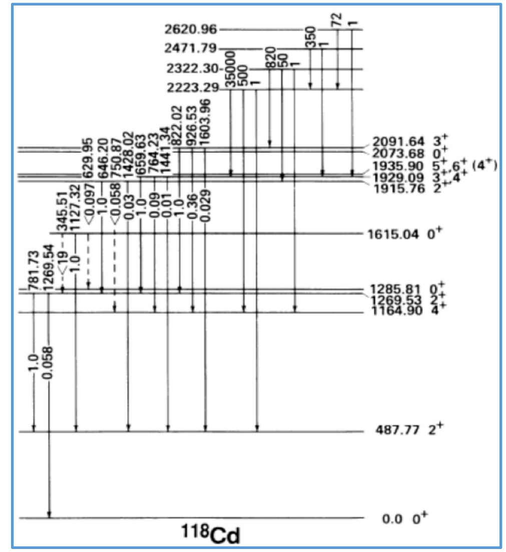
Albert Abraham Michelson

Wolfgang Pauli

Why spectroscopy—Nuclear

Single particle motion

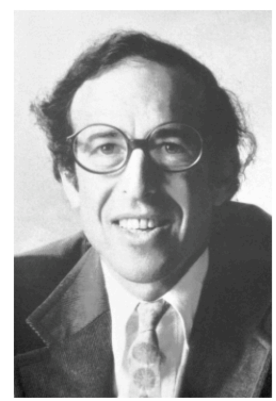




Collective motion



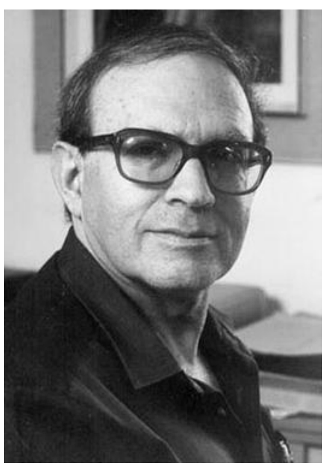




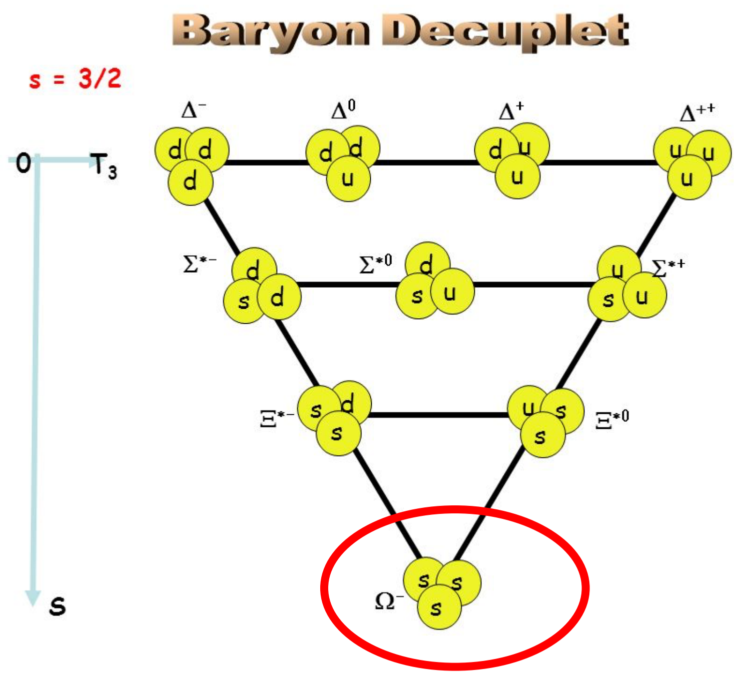

Eugene Paul Wigner Maria Goeppert Mayer J. Hans D. Jensen Aage Niels Bohr, Ben Roy Mottelson Leo James Rainwater

Why spectroscopy—Particle/Hadron

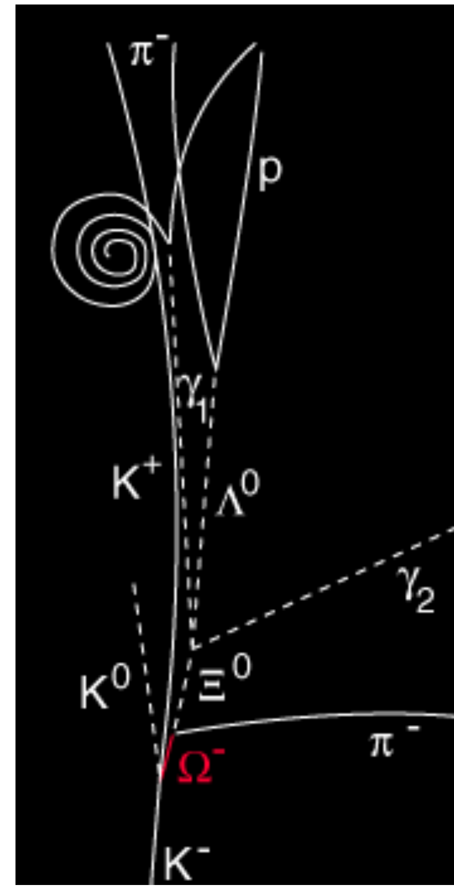
Murray Gell-Mann



Yuval Ne'eman.



Eightfold way → Quark model → QCD



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

Remain model independent in studies of exotic hadrons

- Today, one of the central topic in hadronic physics community is the study of **exotic hadrons,** which surely will lead to new understanding of the strong interaction
- **Exotic hadrons** refer to those hadrons that **do not fit** into the conventional qqq or qqbar picture
- **Theoretically**, one can study them from either **quark-gluon degrees of freedom** or **hadronic degrees of freedom** and one would like to remain **as model independent as possible**—**difficult to achieve**

Remain model independent in studies of exotic hadrons

- **In terms of hadronic degrees of freedom,** one possibility to remain **model independent** is to search for bound states or resonances **formed by long-range interactions, mediated by pion/kaon exchanges**, where unknown short physics does not matter (much).
- Another alternative is to use **experimental data to constrain two-body interaction and from them build multi hadron systems** (similar to ab initio nuclear physics)

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  - **Near-threshold Coulomb-like Baryonia: $\Lambda_c(2595)\Sigma_c(\overline{\Sigma_c})$**
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- **An explicit study of the DDK** system: **R^{++}(4140)**
  - **Preliminary result on its decay width and on the existence of a DDDK bound state**
- **A K*(4307) with hidden charm as KX(3872)/Zc(3900) molecule**
- **Summary and outlook**

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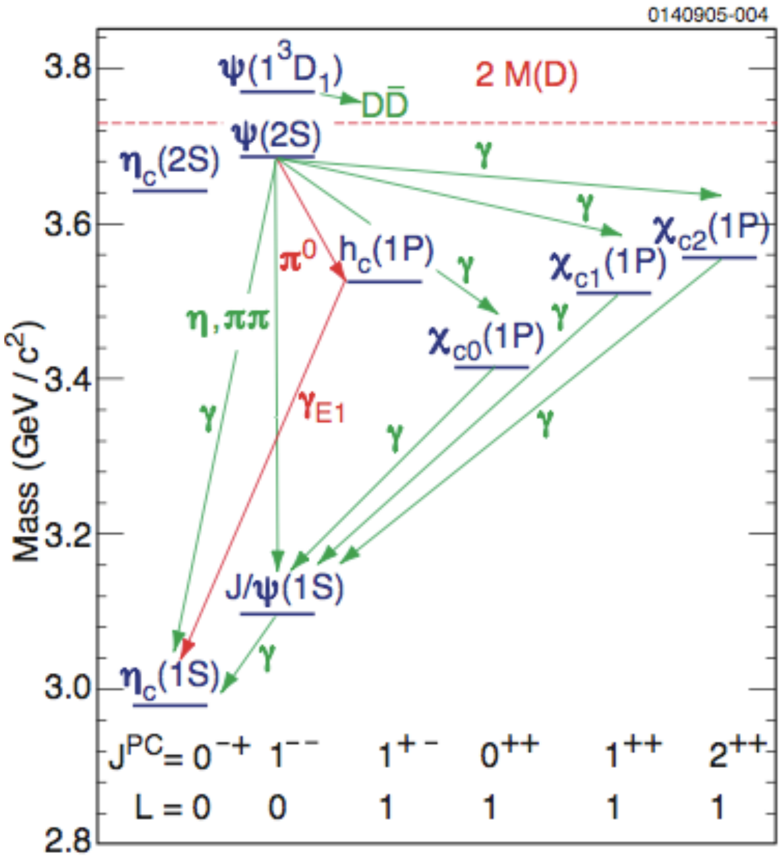
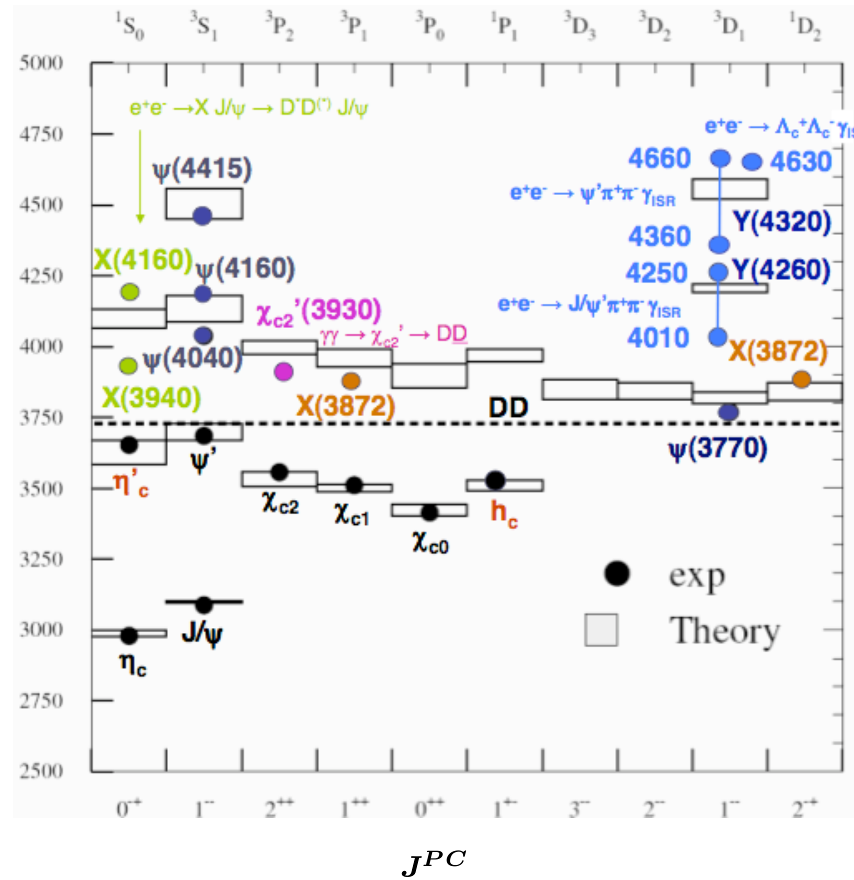
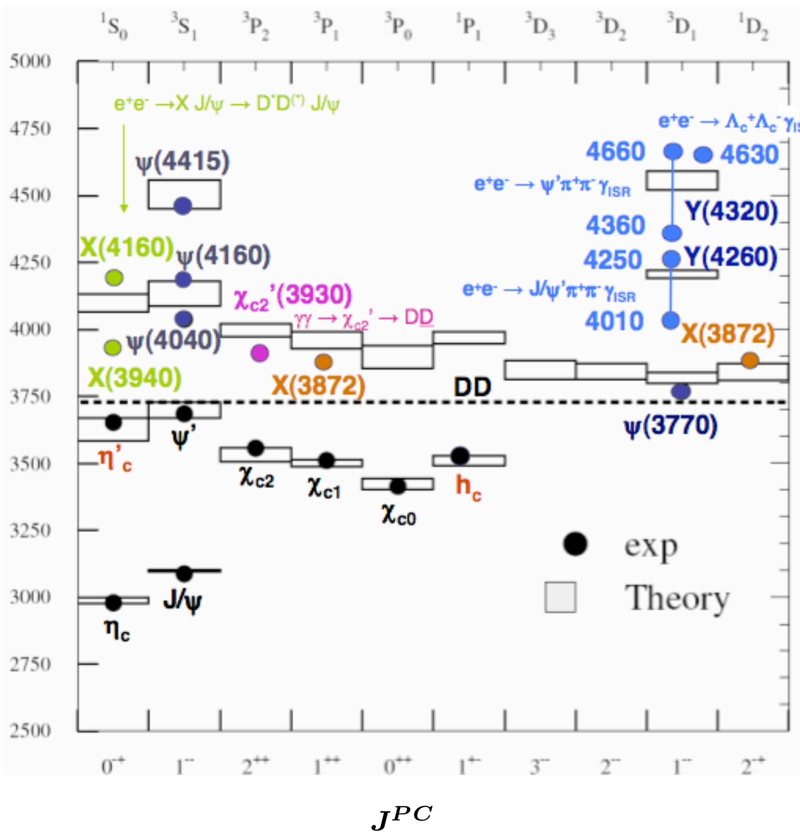
Charmonium spectroscopy before/after B factories





- A lot of new states, but the nature of some states are not well understood, e.g. Y(4260), X(3872), Zc(3900)
- In complete contrast to the before-B-factory period, when potential models worked quite well.

Coupled channel effects?



Channel	Threshold Energy (MeV)	
$D^0\bar{D}^0$	3729.4	
D^+D^-	3738.8	
$D^0\bar{D}^{*0}$ or D^*	3871.5	X(3872)
$\rho^0 J/\psi$	3872.7	
$D^\pm D^{*\mp}$	3879.5	
$\omega^0 J/\psi$	3879.6	
$D_s^+D_s^-$	3936.2	
$D^{*0}\bar{D}^{*0}$	4013.6	
$D^{*+}D^{*-}$	4020.2	
$\eta' J/\psi$	4054.7	
$f^0 J/\psi$	$\approx$ 4077	
$D_s^+\bar{D}_s^{*-}$ or D_s^*	4080.0	
$a^0 J/\psi$	4081.6	
$\varphi^0 J/\psi$	4116.4	
$D_s^{*+}D_s^{*-}$	4223.8	

Coupled channel effects?

$^3P_0$ model

TABLE I: Mass shifts (in MeV) and $c\bar{c}$ probabilities for low-lying charmonium states due to couplings to two-meson continua. This one-loop estimate sets the unperturbed bare masses to the experimental values, and assumes $^3P_0$ model and SHO wave-function parameters $\gamma = 0.35$ and $\beta = 0.5$ GeV and quark mass ratios $r_n = m_n/m_c = 0.33/1.5$ and $r_s = m_s/m_c = 0.55/1.5$.

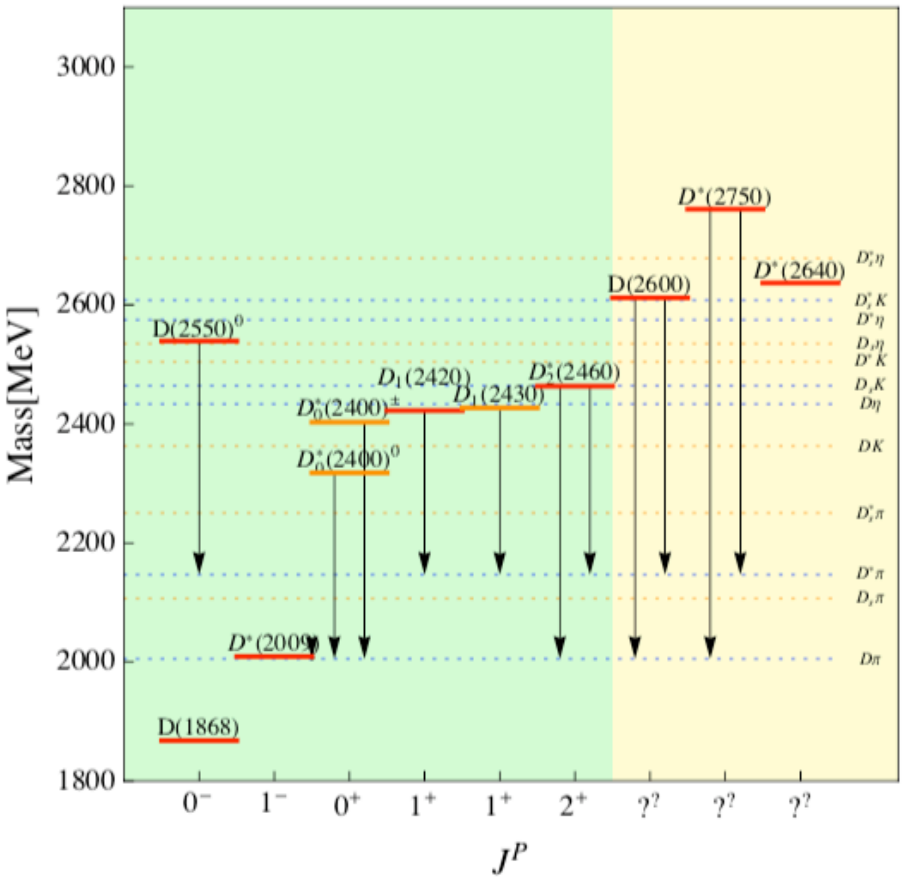
Bare $c\bar{c}$ State Multiplet	State	Mass Shifts by Channel, ΔM_i (MeV) DD	DD^*	D^*D^*	D_sD_s	$D_sD_s^*$	$D_s^*D_s^*$	Total	$P_{c\bar{c}}$
1S	$J/\psi(1^3S_1)$	−23	−83	−132	−21	−76	−123	−457	0.69
	$\eta_c(1^1S_0)$	0	−114	−105	0	−106	−98	−423	0.73
2S	$\psi'(2^3S_1)$	−27	−84	−126	−19	−70	−113	−440	0.51
	$\eta_c'(2^1S_0)$	0	−118	−103	0	−102	−94	−416	0.61
1P	$\chi_2(1^3P_2)$	−40	−105	−144	−33	−88	−111	−521	0.49
	$\chi_1(1^3P_1)$	0	−127	−148	0	−90	−130	−496	0.52
	$\chi_0(1^3P_0)$	−57	0	−196	−34	0	−172	−459	0.58
	$h_c(1^1P_1)$	0	−149	−130	0	−118	−107	−504	0.52

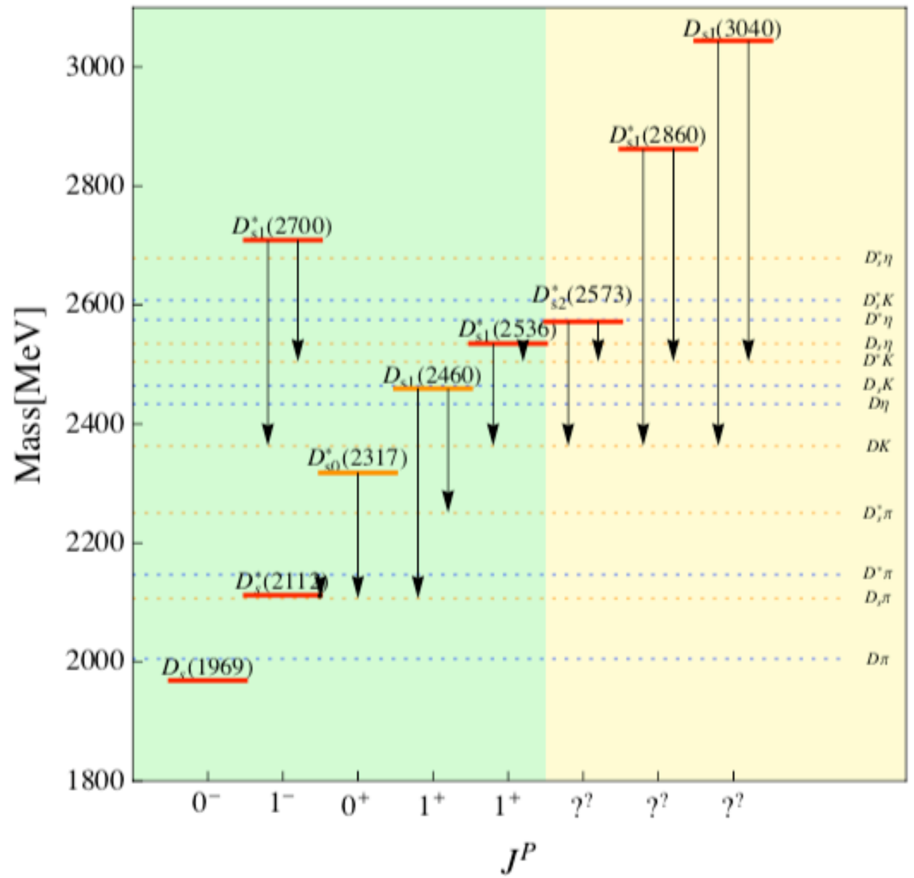
T. Barnes and E. S. Swanson, PRC77, 055206 (2008)

- Mass shift to J/psi: several hundred MeV?
- Studies using Cornell-coupled channels gave similar results
- A model-independent approach needed! EFT?

See the recent refined work of Bing-Song Zou et al.

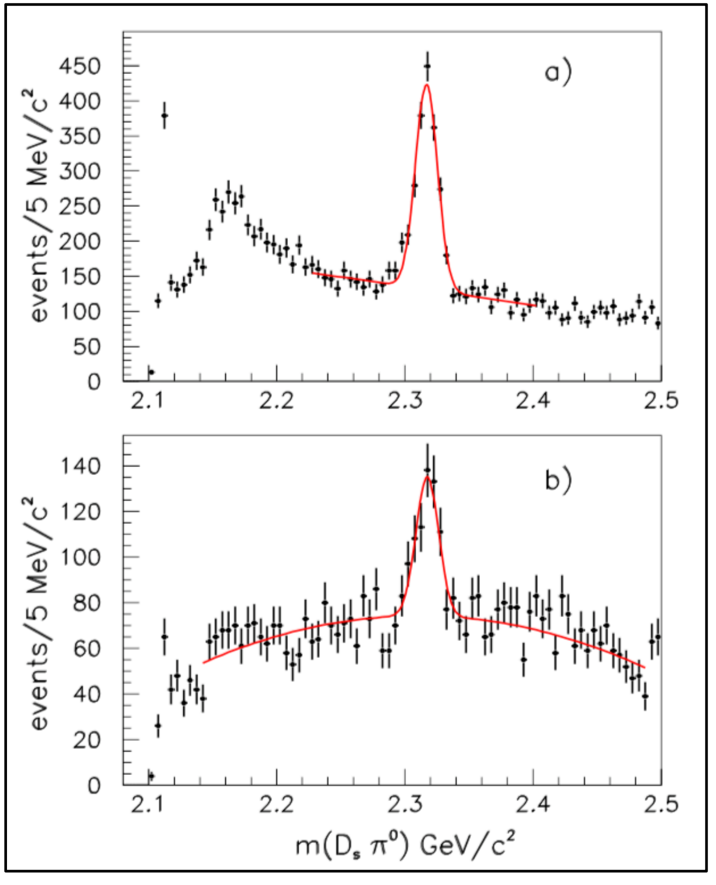
Coupled channel effects?





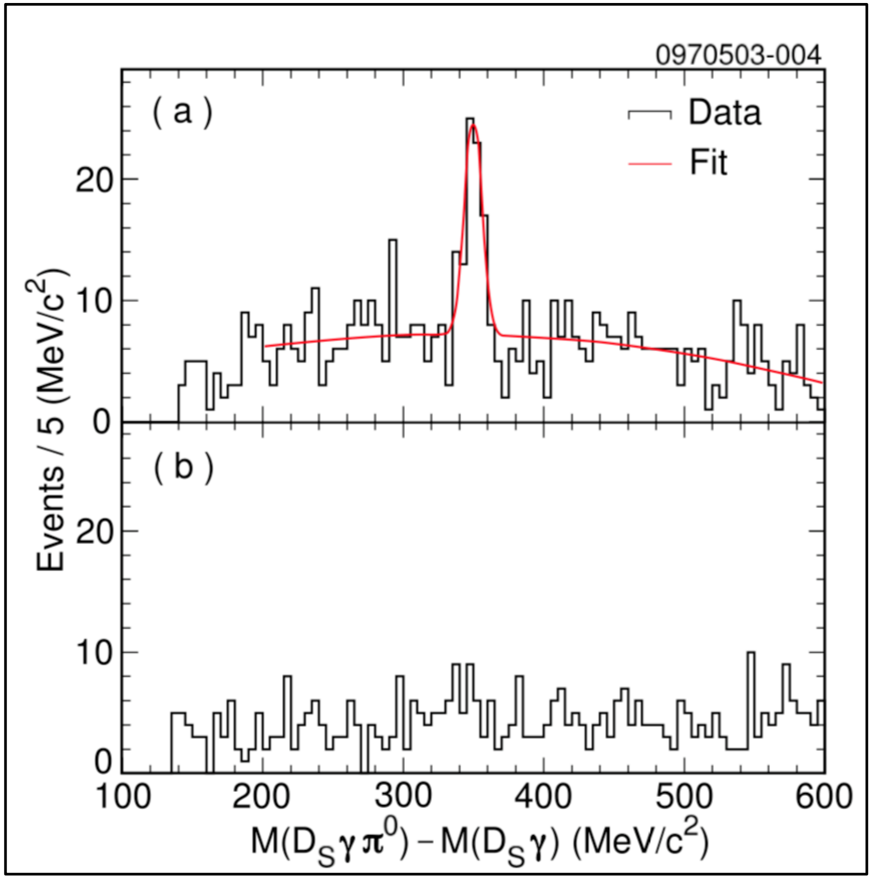
Coupled channel effects?

Ds0*(2317)



BaBar PRL90,242001(2003)

Ds1(2460)



CLEO PRD68,032002(2003)

Coupled channel effects?

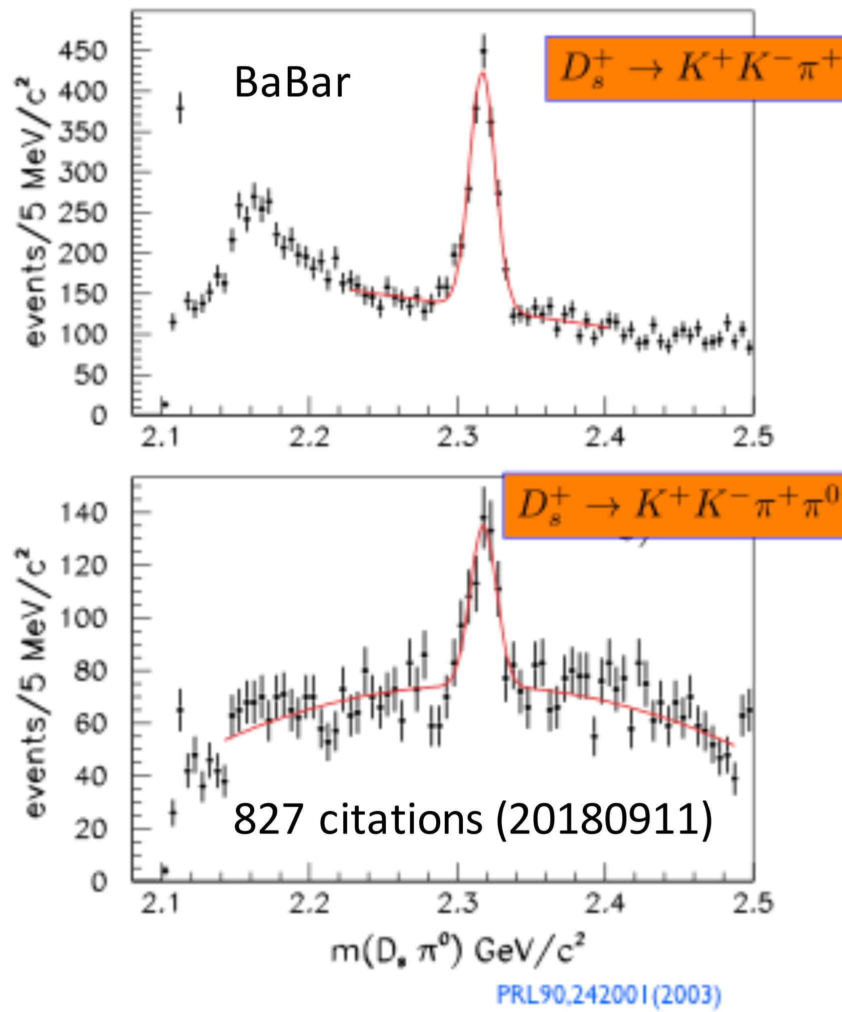
- $\mathbf{D^*_{s0}(2317)}$, $\mathbf{D_{s1}(2460)}$

- 160/70 MeV lower than quark model predictions--difficult to be understood as conventional csbar states.

- “Dynamically generated” from strong DK interaction
  - ✓ E. E. Kolomeitsev 2004,
  - ✓ F. K. Guo 2006,
  - ✓ D. Gamermann 2007

$$m_{D_{s1}(2460)} - m_{D^*_{s0}(2317)} \approx m_{D^*} - m_D$$

$$\mathbf{M = 2317.8 \pm 0.6} \text{ and } \mathbf{\Gamma < 3.8} \text{ MeV}$$



Coupled channel effects?

$\mathbf{D_{s0}^*(2317)}$

- DK bound state
- **Dynamically generated**-- Unitary heavy hadron chiral perturbation theory
- Coupled channels

$\boldsymbol{\Lambda(1405)}$

- N-Kbar bound state
- **Dynamically generated**-- Unitary baryon chiral perturbation theory
- Coupled channels

The interaction between **a kaon and a heavy particle** seems to play an important role

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Unitarized Chiral Perturbation Theory

- **Kernel:** from chiral perturbation theory (ChPT)
- **Unitarization** procedure:
  - ✓ Bethe-Salpeter equation (Lippmann Schwinger equation)
  - ✓ N/D Method
  - ✓ Inverse Amplitude Method

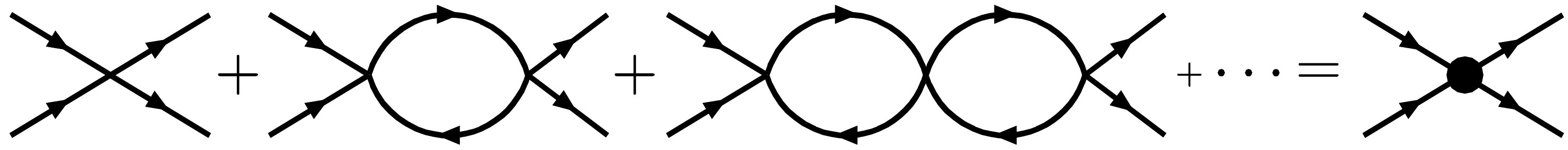
M. Altenbuchinger, LSG, W. Weise, PRD89 (2014) 014026

UChPT in Bethe-Salpeter equation

Unitarity implies

$$TT^\dagger = T^\dagger T = 1$$

which an be achieved via the Bethe-Salpeter equation



Schematically, one has

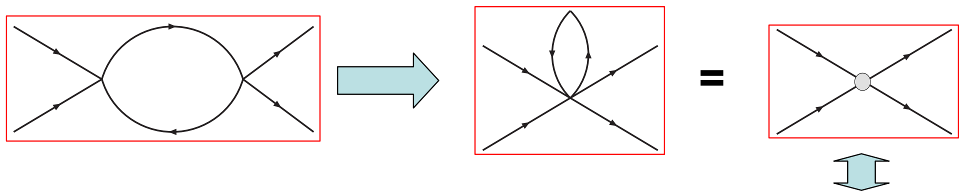
V + VGV + VGVGV + … = T

M. Altenbuchinger, **LSG** PRD89 (2014)054008

On-shell approximation

- **V in V, VGV, VGVGV, can be evaluated on-shell**

$$V(q^2) = V(m^2) + \frac{\partial V}{q^2}|_{q^2=m^2}(q^2 - m^2)$$



justification

renormalized V

- **Integral equation simplified to algebraic equation: Bethe-Salpeter equation**

$$VGV = i\int d^4q V(q^2)\frac{1}{q^2 - m_1^2 + i\epsilon}\frac{1}{(P-q)^2 - m_2^2 + i\epsilon}V(q^2)$$

$$= V(m^2)GV(m^2)$$

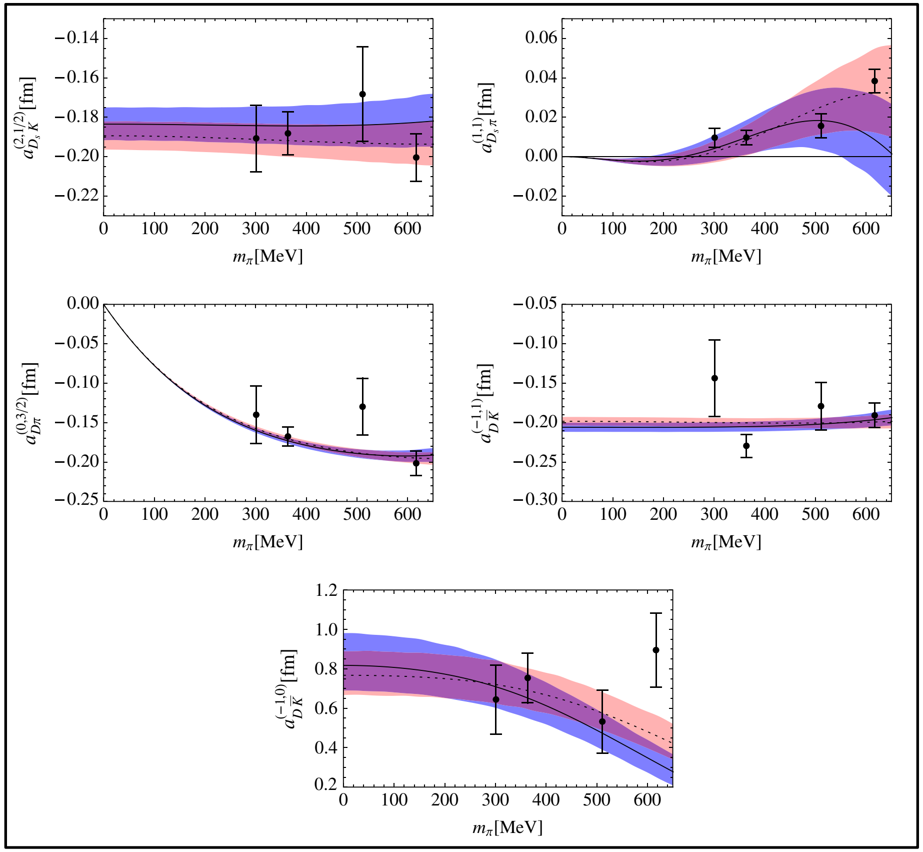
$$G = i\int d^4q \frac{1}{q^2 - m_1^2 + i\epsilon}\frac{1}{(P-q)^2 - m_2^2 + i\epsilon}$$

- **Bethe-Salpeter equation**

$$T = V + VGT$$

Fixing the LECs using latest LQCD* data

Liuming Liu et al., PRD87 (2013) 014508



- NLO ChPT kernel: 5 LECs
- A quite good description of the 20 Lattice **scattering lengths of pseudoscalar mesons and D mesons** can be achieved.
- Covariant UChPT seem to describe the data better

	a	c_{24}	c_{35}	c_4	c_5	χ^2/d.o.f.
HQS UChPT	−4.13(40)	−0.068(21)	−0.011(31)	0.052(83)	−0.96(30)	1.23
χ-SU(3) UChPT	···	−0.096(19)	−0.0037(340)	0.22(8)	−0.53(21)	1.57
HM UChPT	2.52 (11)	4.86(30)	−9.45(60)	···	···	2.69

Ds0 and Ds1 dynamically generated

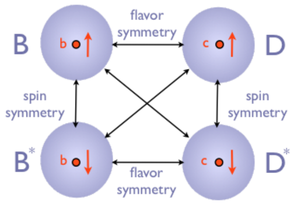
- **Charm sector**

"Post-diction"

$\mathbf{D^*_{s0}(2317),\ D_{s1}(2460)}$

TABLE V. Pole positions $\sqrt{s} = M - i\frac{\Gamma}{2}$ (in units of MeV) of charm mesons dynamically generated in the HQS UChPT.

(S, I)	$J^P = 0^+$	$J^P = 1^+$
(1, 0)	2317 ± 10	2457 ± 17
(0, 1/2)	$(2105 \pm 4) - i(103 \pm 7)$	$(2248 \pm 6) - i(106 \pm 13)$



- **Bottom Sector**

TABLE VI. Pole positions $\sqrt{s} = M - i\frac{\Gamma}{2}$ (in units of MeV) of bottom mesons dynamically generated in the HQS UChPT.

(S, I)	$J^P = 0^+$	$J^P = 1^+$
(1, 0)	5726 ± 28	5778 ± 26
(0, 1/2)	$(5537 \pm 14) - i(118 \pm 22)$	$(5586 \pm 16) - i(124 \pm 25)$

Predicted Bs0 and Bs1 states

Physics Letters B 750 (2015) 17–21

Contents lists available at ScienceDirect

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Predicting positive parity B_s mesons from lattice QCD

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[e] TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada

Table 5
Comparison of masses from this work to results from various model based calculations; all masses in MeV.

J^P	0^+	1^+
Covariant (U)ChPT [24]	5726(28)	5778(26)
NLO UHMChPT [19]	5696(20)(30)	5742(20)(30)
LO UChPT [17,18]	5725(39)	5778(7)
LO χ-SU(3) [16]	5643	5690
HQET + ChPT [20]	5706.6(1.2)	5765.6(1.2)
Bardeen, Eichten, Hill [15]	5718(35)	5765(35)
rel. quark model [5]	5804	5842
rel. quark model [22]	5833	5865
rel. quark model [23]	5830	5858
HPQCD [30]	5752(16)(5)(25)	5806(15)(5)(25)
this work	5713(11)(19)	5750(17)(19)

In agreement with lQCD

Further tests of the DK interaction

- DK or D^*K interaction is strong enough to form the Ds0*(2317) or Ds1(2460)
- A natural question is: if we add one more $D(\bar{D})$ or $D^*(\overline{D^*})$, can they form molecules of three hadrons?
- This seems to be a rather straightforward and naive question, but remains unexplored until we did so just one year ago
- But we did that from a very different perspective

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A two-channel study of the Pc(4450)

PHYSICAL REVIEW D **97,** 094036 (2018)

Scale invariance in heavy hadron molecules

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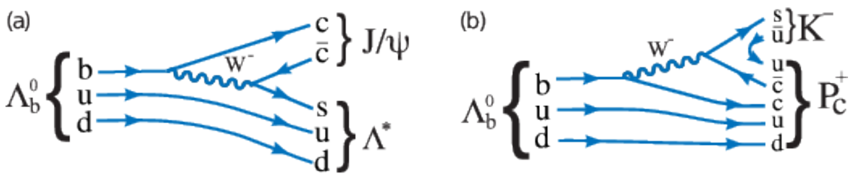
(Received 22 April 2017; published 31 May 2018)

First exotic heavy flavor baryons/N* with $c\bar{c}$



Two Breit-Wigner states

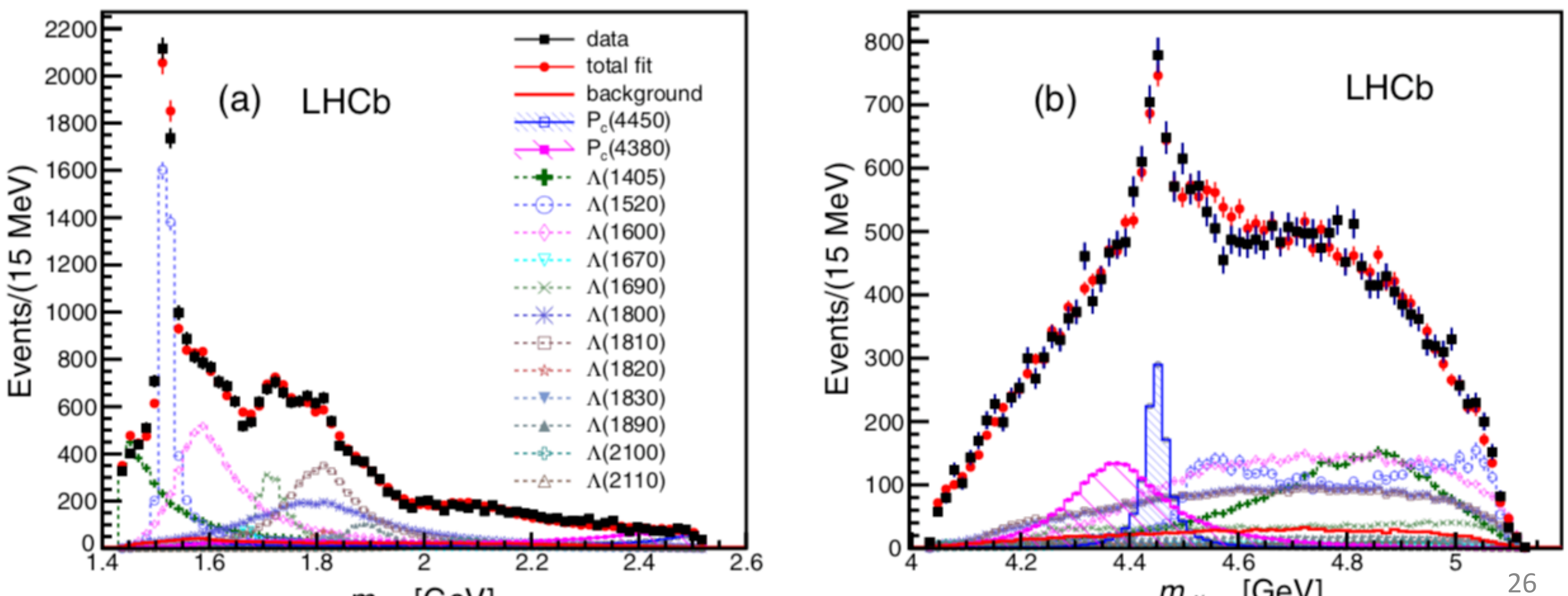
Pc(4380): $M = 4380 \pm 8 \pm 29$ MeV ;

$\Gamma = 205 \pm 18 \pm 86$ MeV

Pc(4450): $M = 4449.8 \pm 1.7 \pm 2.5$ MeV ;

$\Gamma = 39 \pm 5 \pm 19$ MeV

The preferred JP assignments are of opposite parity, with one state having spin 3/2 and the other 5/2: $(3/2^-,\ 5/2^+),\ (3/2^+,\ 5/2^-),\ (5/2^+,\ 3/2^-)$



Phys.Rev.Lett. 115 (2015) 072001

The pentaquark states

Even before the experimental discovery

- **Heavy-light diquarks.**
  - L. Maiani et al., Phys. Rev. D 71, 014028 (2005).
- **Diquark-diquark-antiquark**
  - R. Jaffe and F. Wilczek, Phys. Rev. Lett. 91, 232003 (2003).
  - A. Chandra et al., Mod. Phys. Lett. A 27, 1250006 (2012).
- **Diquark- triquark**
  - M. Karliner and H. J. Lipkin, Phys. Lett. B 575, 249 (2003).
- **Coupled channel**
  - **J.-J. Wu et al., Phys. Rev. Lett. 105, 232001 (2010).**
- **Weakly bound "molecules" of a baryon plus a meson**
  - M. B. Voloshin and L. B. Okun, JETP Lett. 23, 333 (1976)
  - A. De Rujula et al., Phys. Rev. Lett. 38, 317 (1977)
  - N. A. Törnqvist, Phys. Rev. Lett. 67, 556 (1991); N.A. Törnqvist, Z. Phys. C 61, 525 (1994)
  - Z.-C. Yang et al., Chin. Phys. C 36, 6 (2012)
  - W. L. Wang et al., Phys. Rev. C 84, 015203 (2011)
  - M. Karliner and J. L. Rosner, Phys.Rev.Lett. 115, 122001 (2015)

Phys.Rev.Lett. 115 (2015) 072001

Nature of the pentaquark states

- ☐ Tightly bound multiquark states
- ☐ Loosely bound multiquark sates—molecules
- ☐ Kinematical effects—triangle singularities

- ☐ One pion exchange or one boson exchange
- ☐ Unitary chiral coupled channels and their extensions
- ☐ Contact interactions formulated in an EFT language

Not easy to discriminate different scenarios, see, e.g., the debate on X(3872)

The pentaquark states

T.J. Burns
Eur. Phys. J. A (2015) 51: 152

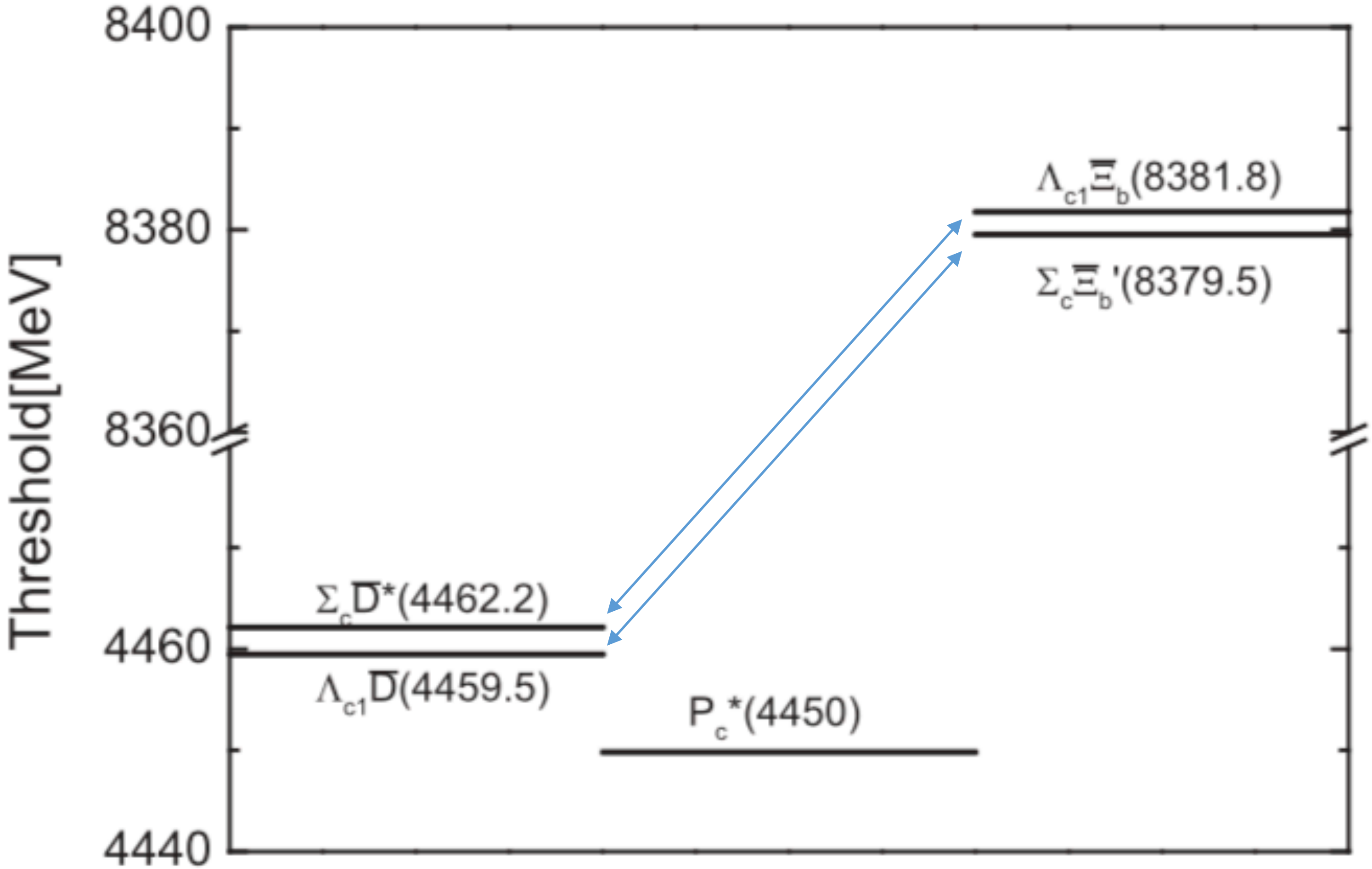
	$P_c(4380)^+$	$P_c(4450)^+$
Mass	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width	$205 \pm 18 \pm 86$	$35 \pm 5 \pm 19$
Assignment 1	$3/2^-$	$5/2^+$
Assignment 2	$3/2^+$	$5/2^-$
Assignment 3	$5/2^+$	$3/2^-$
$\Sigma_c^{*+}\bar{D}^0$	4382.3 ± 2.4	
$\chi_{c1}p$		4448.93 ± 0.07
$\Lambda_c^{*+}\bar{D}^0$		4457.09 ± 0.35
$\Sigma_c^+\bar{D}^{*0}$		4459.9 ± 0.5
$\Sigma_c^+\bar{D}^0\pi^0$		4452.7 ± 0.5

Analogy

X(3872) ⟷ Pc(4450)

$D\bar{D}^* + D^*\bar{D}$ ⟷ $\Sigma_c\bar{D}^* - \Lambda_{c1}\bar{D}$

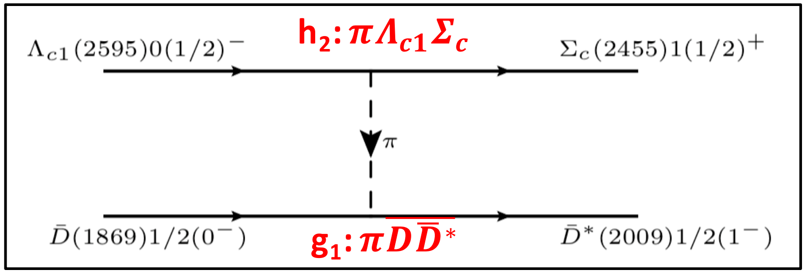
A two channel study of the $P_c(4450)$



A two channel study of the $P_c(4450)$

- There is standard one-pion exchange in the $\Sigma_c \bar{D}^*$ channel but no one-pion exchange in the $\Lambda_{c1} D$ channel—not our concern here

- In the off diagonal channel



$$\langle \Lambda_{c1}\bar{D}|V_{\text{OPE}}(\vec{r})|\Sigma_c\bar{D}^*\rangle = \omega_\pi \tau \vec{\epsilon}\cdot\hat{r} W_E(r)$$

$\tau = \sqrt{3}$ for I =1/2; $\tau = 0$ for I =3/2

$$W_E(r) = \frac{g_1 h_2 \mu_\pi^2}{4\pi\sqrt{2} f_\pi^2} \frac{e^{-\mu_\pi r}}{\mu_\pi r}\left(1 + \frac{1}{\mu_\pi r}\right)$$

$$\omega_\pi = m(\Lambda_{c1}) - m(\Sigma_c)$$

$$\mu_\pi = \sqrt{|m_\pi^2 - \omega_\pi^2|}$$

A two channel study of the $P_c(4450)$

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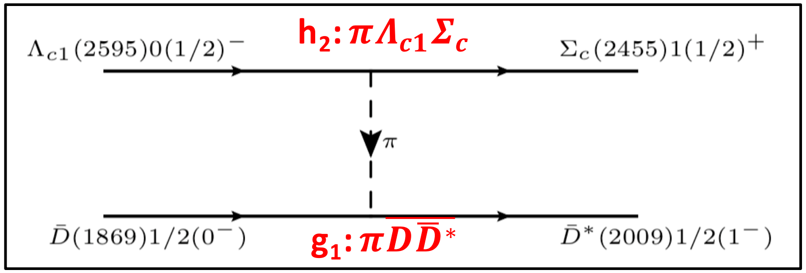


$$|\mu_\pi| = \sqrt{|\omega_\pi^2 - m_\pi^2|} = 5\sim35\ MeV \ll m_\pi$$

- In the $\mu_\pi = 0$ limit, for I=1/2, one has the following potential

$$\langle \Lambda_{c1} \bar{D} | V_{\rm OPE}(\vec{r}) | \Sigma_c \bar{D}^* \rangle = \frac{g_1 h_2 \omega_\pi}{4\pi f_\pi^2} \sqrt{\frac{3}{2}} \frac{\vec{\epsilon} \cdot \hat{r}}{r^2} + \mathcal{O}(\mu_\pi^2 r^2)$$

A 1/r^2 potential!!!

A $1/r^2$ potential and Efimov effect

- **At zero energy** the reduced Schroedinger equation **for the s-wave**

$$-u''(r) + \frac{g}{r^2} u(r) = 0$$

For a finite energy analysis, see M. Bawin and S. A. Coon, Phys. Rev. A 67, 042712 (2003).

  - **The above equation is scale invariant under the transformation $r \longrightarrow \lambda_0 r$,**
  - **The consequence is if E_n is the binding energy, so is $E_{n+1} = E_n/\lambda_0^2$**

- For $g > -1/4$, the above equation has a power law solution

$$u(r) = c_+ r^{\frac{1}{2}+\nu} + c_- r^{\frac{1}{2}-\nu} \qquad \nu = \sqrt{1/4 + g},$$

- **For $g < -1/4$, the solution enjoys discrete scale invariance**

$$u(r) = c r^{1/2} \sin\left(\nu \log \Lambda_2 r\right) \quad \nu = \sqrt{-1/4 - g} \qquad \lambda_0 = e^{\pi/\nu}$$

Λ_2 encodes short-distance physics and breaks the exact scale invariance

A surprising but accidental finding

The $\Sigma_c\bar{D}^* - \Lambda_{c1}D$ interaction behaves like a $\boldsymbol{1/r^2}$ potential, which may lead to **discrete scale invariance in a two-body hadronic system—an** Efimov like effect

$J^p = 3/2^-$ one of the possible assignment for the Pc(4450)

- Four coupled-channels

$$\Sigma_c\bar{D}^*(^2D_{3/2})\quad \Sigma_c\bar{D}^*(^4S_{3/2}),\ \Sigma_c\bar{D}^*(^4D_{3/2})\text{ and }\Lambda_{c1}\bar{D}(^2P_{3/2})$$

- The Schroedinger equation reads

$$-\mathbf{u}'' + \left[2\mu_{P_c^*}\mathbf{V}_{\text{OPE}} + \frac{\mathbf{L}^2}{r^2}\right]\mathbf{u} = 0$$

$$2\mu_{P_c^*}\mathbf{V}_{\text{OPE}} + \frac{\mathbf{L}^2}{r^2} = \frac{\mathbf{g}(\frac{3}{2}-)}{r^2} = \frac{1}{r^2}\begin{pmatrix} 6 & 0 & 0 & g \\ 0 & 0 & 0 & g \\ 0 & 0 & 6 & -g \\ g & g & -g & 2 \end{pmatrix}$$

diagonalization

$$-u_i'' + \frac{g_i}{r^2}u_i = 0$$

$$g_i = \{6, 2, 3+\sqrt{9+3g^2}, 3-\sqrt{9+3g^2}\}$$

$J^p = 3/2^-$: no discrete scale invariance

- Four coupled-channels

  $\Sigma_c \bar{D}^* (^2D_{3/2})$ $\Sigma_c \bar{D}^* (^4S_{3/2})$, $\Sigma_c \bar{D}^* (^4D_{3/2})$ and $\Lambda_{c1} \bar{D} (^2P_{3/2})$

- The Schroedinger equation reads

$$-u_i'' + \frac{g_i}{r^2} u_i = 0$$

$$g_i = \{6, 2, 3 + \sqrt{9 + 3g^2}, 3 - \sqrt{9 + 3g^2}\}$$

- Negative $\boldsymbol{g_i}(< -\frac{1}{4})$ can trigger discrete scale invariance, which means $|g| > \frac{5}{4\sqrt{3}} \sim 0.7217$.

- With $g_1 = 0.59 \pm 0.01 \pm 0.07$ from $D^* \to D\pi/\gamma$, this requires $|h_2| > 1.21^{+0.25}_{-0.19}$, **well above** $h_2 = 0.60 \pm 0.07$ from **the CDF value** extracted from $\Lambda_{c1} \to \Sigma_c \pi$

- For $\boldsymbol{J^p = 1/2^-, 3/2^+, 5/2^+, 5/2^-}$ the same conclusion

$J^p = 1/2^+$: discrete scale invariance likely

- Three coupled-channels

$$\Sigma_c \bar{D}^* ({}^2P_{1/2}) \quad \Sigma_c \bar{D}^* ({}^4P_{1/2}) \text{ and } \Lambda_{c1} \bar{\tilde{D}} ({}^2S_{1/2})$$

- The Schroedinger equation reads

$$\mathbf{g}\left(\frac{1^+}{2}\right) = \begin{pmatrix} 2 & 0 & g \\ 0 & 2 & -\sqrt{2}g \\ g & -\sqrt{2}g & 0 \end{pmatrix}.$$

- The attractive eigenvalue is $1-\sqrt{1+3g^2}$, which requires $|g| > \frac{\sqrt{3}}{4} \sim 0.4330$ and $h_2 = 0.73^{+0.11}_{-0.06}$, marginally overlapping with that of CDF $h_2 = 0.60 \pm 0.07$

Long and short range consequences

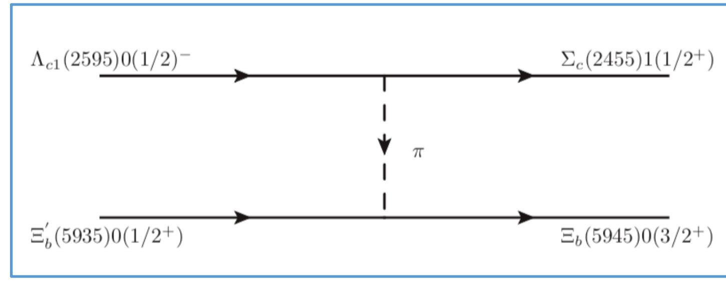
- The observation of geometric states in hadron and atomic physics shares a similar difficulty: **the fine-tuning of the pion mass (hadrons)** **or** **the scattering length (atoms)**.

- In atomic physics, one can turn to a magnetic field

- In hadron physics, one can fine-tune the pion mass in the lattice or increase $|g_-|$, by **having a larger reduced mass** (two bottom hadrons) or **exchanging a kaon**.
  - For the first way out, we strongly encourage our lattice QCD colleagues to pursue such a study
  - We will explore the 2nd and 3rd options in the following.

(1) To have a larger reduced mass

$\Lambda_{c1}\overline{\Xi}_b - \Sigma_c\overline{\Xi}_b'$ baryonia system



- The potential

$$\langle \Sigma_c\bar{\Xi}_b{}'|V_{\rm OPE}(\vec{r})|\Lambda_{c1}\bar{\Xi}_b\rangle = \frac{g_3 h_2 \omega_\pi}{8\pi f_\pi^2}\frac{\sigma_2\cdot\hat{r}}{r^2} + \mathcal{O}(\mu_\pi^2 r^2)$$

g_3: $\overline{\Xi}_b\ \overline{\Xi}_b'\ \pi$

- Considering the following partial wave channels

$$0^+ = \Sigma_c\bar{\Xi}_b{}'(^3P_0) - \Lambda_{c1}\bar{\Xi}_b(^1S_0),$$

$$0^- = \Sigma_c\bar{\Xi}_b{}'(^1S_0) - \Lambda_{c1}\bar{\Xi}_b(^3P_0),$$

$$1^- = \Sigma_c\bar{\Xi}_b{}'(^3S_1 - {}^3D_1) - \Lambda_{c1}\bar{\Xi}_b(^1P_1 - {}^3P_1).$$

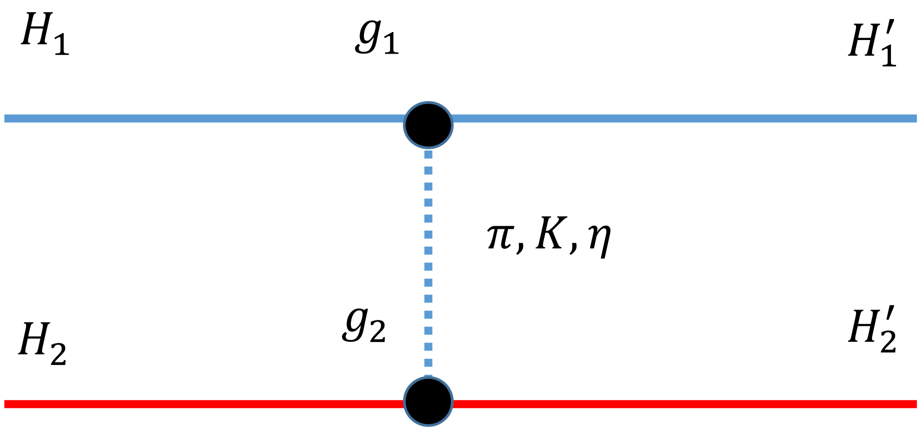
$$\mathbf{g}(0^+) = \begin{pmatrix} 2 & g \\ g & 0 \end{pmatrix},$$

$$\mathbf{g}(0^-) = \begin{pmatrix} 0 & g \\ g & 2 \end{pmatrix},$$

$$\mathbf{g}(1^-) = \begin{pmatrix} 0 & 0 & \frac{1}{\sqrt{3}}g & -\sqrt{\frac{2}{3}}g \\ 0 & 6 & -\sqrt{\frac{2}{3}}g & -\frac{1}{\sqrt{3}}g \\ \frac{1}{\sqrt{3}}g & -\sqrt{\frac{2}{3}}g & 2 & 0 \\ -\sqrt{\frac{2}{3}}g & -\frac{1}{\sqrt{3}}g & 0 & 2 \end{pmatrix}$$

For $|g| > 3/4$, the attractive eigenvalues will trigger discrete scale invariance, which with $g_3 = 0.973^{+0.019}_{-0.042}$ **requires $|h_2| > 0.67^{+0.03}_{-0.02}$, overlapping with the CDF value**

For the $1/r^2$ force to work



- H_1 and H_1' are of opposite parity but with the same spin
- H_2 and H_2' are of the same parity and their spin differs by one
- $m(H_{1/2}) - m(H'_{1/2}) \approx m(\phi)$, **implying long range interaction**
- **The larger $g_1, g_2, m(\phi)$, the smaller $m(H_{1/2}) - m(H'_{1/2})$-m(ϕ), the stronger the attraction**

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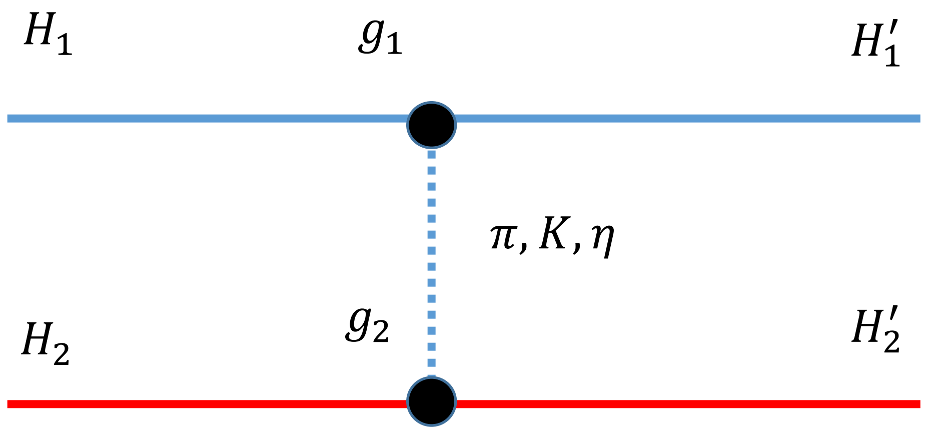
- **Summary and outlook**

A coulomb like force: a modification of the 1/r² case



- H_1 and H_1' are of opposite parity but with the same spin
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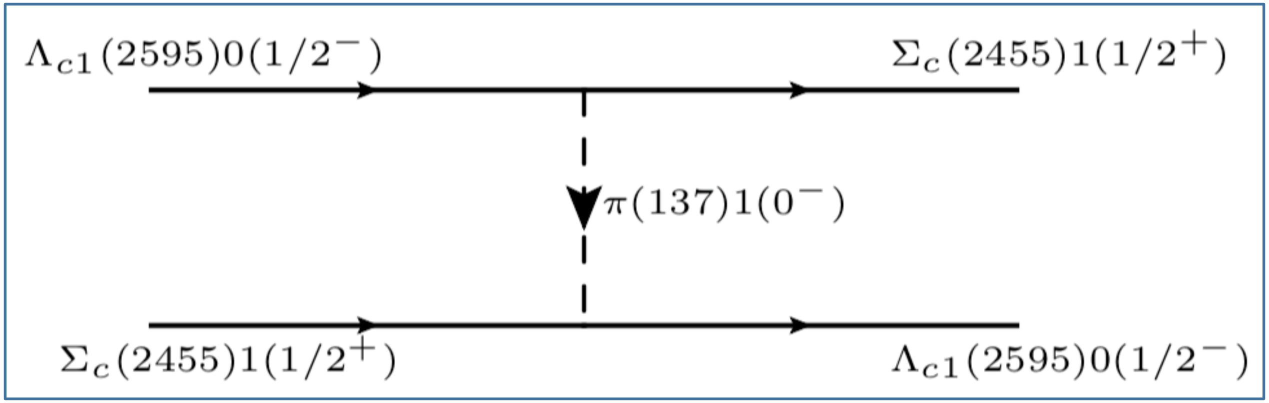
A doubly charmed baryon $Y_{cc}(5050)$



$$V_{\rm OPE}(r) = -\frac{h_2^2\omega_\pi^2}{4\pi f_\pi^2}\frac{e^{-\mu_\pi r}}{r}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

where $\mu_\pi^2 = m_\pi^2 - \omega_\pi^2$ with $\omega_\pi = m_{\Lambda_{c1}} - m_{\Sigma_c}$

Attraction appears in spin 0 channel:

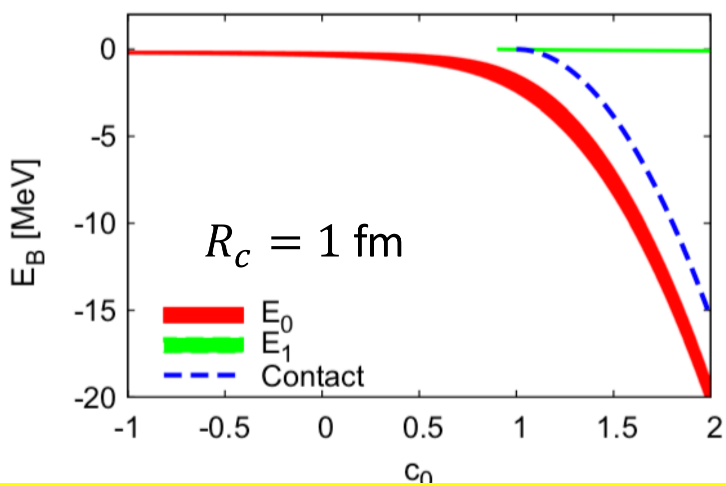
$$|Y_{cc}\rangle = \frac{1}{\sqrt{2}}\{|\Lambda_{c1}\Sigma_c\rangle + |\Sigma_c\Lambda_{c1}\rangle\}$$

A doubly charmed baryon $Y_{cc}(5050)$

Assuming that the one-baryon exchange is only valid above a certain cutoff radius

$$V(r) = V_{\mathrm{OPE}}(r)\theta(r - R_c) + \frac{C_0}{4\pi R_c^2}\delta(r - R_c).$$

Introducing a reduced coupling $c_0 = -\frac{2\mu_Y C_0}{4\pi R_c}$ and $c_0 \geq 1$ generates a bound state with binding momentum $\gamma = (c_0 - 1)/R_c$



- $c_0 \to -\infty$, $E_B = -0.09^{+0.06}_{-0.08}$ MeV
- $c_0 \to 1$, $E_B = -1.9^{+0.5}_{-0.6}$ MeV
- $c_0 > 0.9^{+0.2}_{-0.4}1$, a shallow excited state appears

$R_c = 1$ fm probably lies in an intermediate zone dominated by two-pion exchange and other contributions which might be attractive. Hence we expect the fundamental state of the doubly charmed Ycc to be deeper than the predictions from OPE alone

A hidden charmed baryon $Y_{c\bar{c}}$ (5050)

Replacing Σ_c with $\overline{\Sigma_c}$ will lead to a formation of **hidden charmed baryon $Y_{c\bar{c}}$(5050)** in both **spin 0 and 1**. The discussion is more involved because it involves annihilation.

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Rapid Communications

Are there near-threshold Coulomb-like Baryonia?

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[2]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*

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The $\Lambda_c(2590)\Sigma_c$ system ... mass-shell. Owing to the opposite intrinsic parity of the $\Lambda_c(2590)$ and Σ_c, the pion is exchanged in S-wave. This gives rise to a Coulomb-like force that might be able to bind the system. If one takes into account that the pion is not exactly on the mass shell, there is a shallow S-wave state, which we generically call the $Y_{cc}(5045)$ and $Y_{c\bar{c}}(5045)$ for the $\Lambda_c(2590)\Sigma_c$ and $\Lambda_c(2590)\bar{\Sigma}_c$ systems respectively. For the baryon-antibaryon case this Coulomb-like force is independent of spin: the $Y_{c\bar{c}}(5045)$ baryonia will appear either in the spin $S = 0$ or $S = 1$ configurations with G-parities $G = (-1)^{L+S+1}$. For the baryon-baryon case the Coulomb-like force is attractive in the spin $S = 0$ configuration, for which a doubly charmed molecule is expected to form near the threshold. This type of spectrum might be very well realized in other molecular states composed of two opposite parity hadrons with the same spin and a mass difference close to that of a pseudo-Goldstone boson, of which a few examples include the $\Lambda(1405)N$, $\Lambda(1520)\Sigma^*$, $\Xi(1690)\Sigma$, $D^*_{s0}(2317)D$ and $D^*_{s1}(2460)D^*$ molecules.

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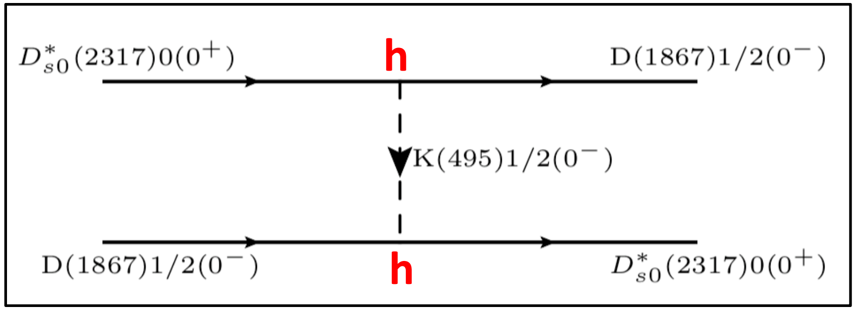
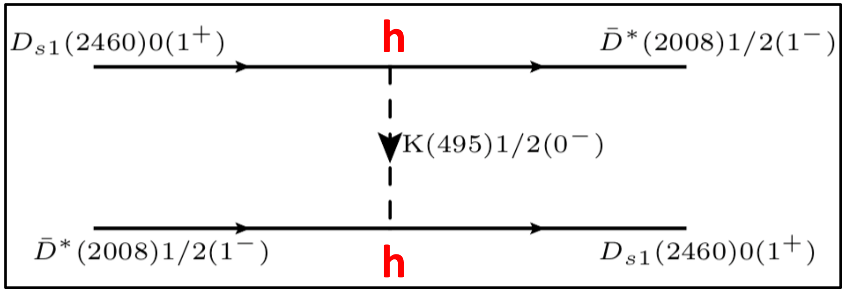
Exotic **doubly charmed** mesons

PRD98, 054001 (2018)

- A straightforward extension of the above idea is investigating **the exchange of the kaon—larger attraction**

- In such a case, $D_{s0}^{*}(2317)D$ and $D_{s1}(2460)D^{*}$ are two interesting systems





Exotic doubly charmed mesons

- In the following basis: $\{DD^*_{s0}, D^*_{s0}D\}\ \{D^*D^*_{s1}, D^*_{s1}D^*\}$

$$V(\vec{q}) = -h^2 \frac{\omega_K^2}{f_\pi^2} \frac{1}{m_K^2 - \omega_K^2 + \vec{q}^2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

off-diagonal

$$\omega_K = m_{D^*_{s0}} - m_D \text{ or } m_{D^*_{s1}} - m_{D^*}$$

- The effective range is set by $\mu_K^2 = m_K^2 - \omega_K^2$, about 200 MeV
- For the following linear combinations, the interaction is attractive

$$\frac{1}{\sqrt{2}}\left[|DD^*_{s0}\rangle + |D^*_{s0}D\rangle\right],$$
$$\frac{1}{\sqrt{2}}\left[|D^*D^*_{s1}\rangle + |D^*_{s1}D^*\rangle\right]$$

$$V(r) = -h^2 \frac{\omega_K^2}{f_\pi^2} \frac{e^{-\mu_K r}}{4\pi r}$$

Exotic doubly charmed mesons

h is the coupling of DDs0*K

- **The system will bind for** $$\lambda_B = \frac{2\mu_H}{\mu_K}\frac{\omega_K^2}{4\pi f_\pi^2}h^2 \geq 1.68$$

which means for DD_{s0}^* and DD_{s1}, $|\boldsymbol{h}| > \mathbf{0.43}$ **and 0.40**, respectively

- **The requirement is satisfied, because $h \approx 0.5 \sim 0.9$ regardless whether assuming they are csbar states or molecules**

$$\Gamma(D_0 \to D\pi) = \Gamma(D_0 \to D\pi^0) + \Gamma(D_0 \to D\pi^\pm) = \frac{3}{2}\Gamma(D_0 \to D\pi^\pm) = \frac{3}{2}\frac{m_D}{m_{D_0}}\frac{q_\pi}{2\pi}\frac{h^2}{f_\pi^2}(m_{D_0} - m_D)^2,$$

Residues from pole position

$$g = \sqrt{2m_{D_{s0}^*}2m_D}\,\omega_K\frac{h}{f_\pi}$$

- **Concretely, one has** $E_B = -40^{+30}_{-50}\ MeV \quad E_B = -50^{+30}_{-50}\ MeV$

Understanding the results in EFT

- The kaon exchange can be rewritten

$$V_{\rm OKE}(\vec{q}) = -\frac{2\pi}{\mu_H\,\Lambda_{\rm OKE}}\,\frac{\mu_K^2}{\mu_K^2+\vec{q}^2} \qquad \Lambda_{\rm OKE} = \frac{2\pi}{\mu_H}\,\frac{f_\pi^2\mu_K^2}{h^2\omega_K^2} \simeq 50^{+40}_{-20}\,{\rm MeV}$$

- We count $V_{\rm OKE}(\vec{q}) \sim \frac{2\pi}{MQ}$, which is enhanced

- Heavy quark symmetry implies

$$V_C(\vec{q}, DD_{s0}^*) = C_{0a}\,,$$
$$V_C(\vec{q}, D^*D_{s1}^*) = C_{0a} + \vec{S}_1\cdot\vec{S}_2\,C_{0b}$$

- *M. P. Valderrama, Phys. Rev. D85, 114037 (2012), arXiv:1204.2400 [hep-ph].*
- *J.-X. Lu, L.-S. Geng, and M. Pavon Valderrama, (2017), arXiv:1706.02588 [hep-ph].*

Understanding the results in EFT

- In an natural scaling, the contact terms count as of subleading

$$C_{0a} \sim \frac{2\pi}{M^2} \quad , \quad C_{0b} \sim \frac{2\pi}{M^2}$$

- In an unnatural scaling, they also appear at LO (fine tuning)
  - Even in a worst case scenario, there exists a repulsive core at the cutoff radius

$$V_{\rm EFT} = V_{\rm OKE}(r)\,\theta(r - R_c) + C_0(R_c)\,\frac{\delta(r - R_c)}{4\pi R_c^2}$$

The system will still bind for $R_c \leq 1.3^{+0.3}_{-0.3}\,fm$

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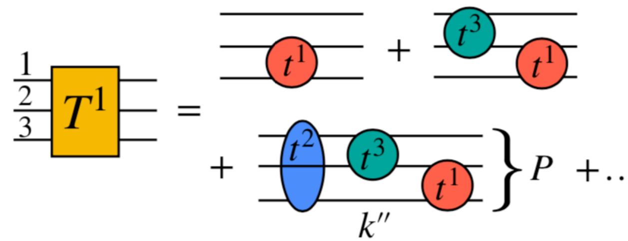
An explicit three-body study of DDK

A. Martínez Torres, K. P. Khemchandani, and ***LSG*** *1809.01059*

- **Coupled-three-channel problem:** $\mathrm{D}(\mathrm{DK} - D_s\pi - D_s\eta)$
- **Three-body scattering matrix**

$$T = \sum_{i=1}^{3} T^i$$



$$T^i = t^i\delta^3(\vec{k}_i' - \vec{k}_i) + \sum_{j\neq i=1}^{3} T_R^{ij}, \quad i = 1, 2, 3,$$

$$T_R^{ij} = t^i g^{ij} t^j + t^i \left[G^{iji} T_R^{ji} + G^{ijk} T_R^{jk} \right],$$

A. Martínez Torres, K. P. Khemchandani, and E. Oset PRC 77, 042203(R)

A. Martinez Torres, K.P. Khemchandani, ***LSG****, M. Napsuciale, E. Oset, PRD78 (2008) 074031*

An explicit three-body study of DDK

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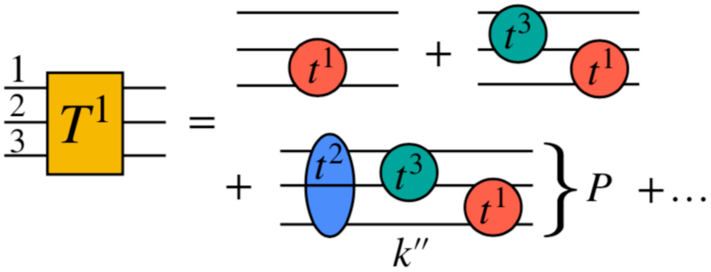
$$T_R^{ij} = t^i g^{ij} t^j + t^i \left[G^{iji} T_R^{ji} + G^{ijk} T_R^{jk}\right],$$



$$G^{ijk} = \int \frac{d^3k''}{(2\pi)^3} \tilde{g}^{ij} \cdot F^{ijk}.$$

$$g^{ij}(\vec{k}_i', \vec{k}_j) = \left(\frac{N_k}{2E_k(\vec{k}_i' + \vec{k}_j)}\right) \times \frac{1}{\sqrt{s} - E_i(\vec{k}_i') - E_j(\vec{k}_j) - E_k(\vec{k}_i' + \vec{k}_j) + i\epsilon},$$

$$\tilde{g}^{ij}(\vec{k}'', s_{lm}) = \frac{N_l}{2E_l(\vec{k}'')} \frac{N_m}{2E_m(\vec{k}'')} \times \frac{1}{\sqrt{s_{lm}} - E_l(\vec{k}'') - E_m(\vec{k}'') + i\epsilon}, \quad i \neq l \neq m,$$

$$F^{ijk}(\vec{k}'', \vec{k}_j', \vec{k}_k, s_{ru}^{k''}) = t^j(s_{ru}^{k''}) g^{jk}(\vec{k}'', \vec{k}_k) \times \left[g^{jk}(\vec{k}_j', \vec{k}_k)\right]^{-1} \left[t^j(s_{ru})\right]^{-1}, \quad j \neq r \neq u = 1, 2, 3.$$

An explicit three-body study of DDK

- **Six particle channels:** $D^+D^0K^+$, $D^+D^+K^0$,

  $D^+D_s^+\pi^0$, $D^+D_s^+\eta$, $D^0D^+K^+$, $D^0D_s^+\pi^+$

- **Three-body amplitude**

$$T_R \equiv \sum_{i=1}^{3} \sum_{j\neq i=1}^{3} T_R^{(ij)}$$

- **Isospin projection:** $\langle I, I_{23}|T_R|I, I_{23}\rangle$

Two-body subsystems

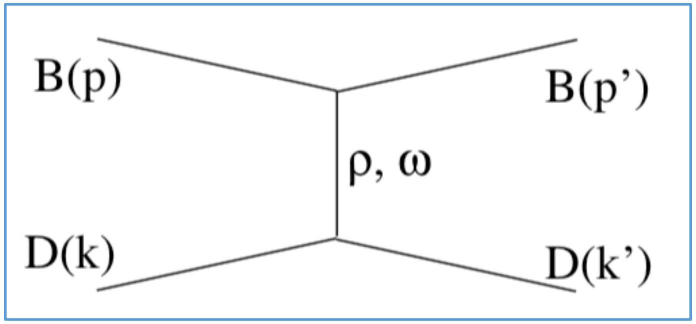
- **DK: leading order UChPT** DK, $D_s\eta$ and $D_s\pi$

$$V_{ij} = -\frac{C_{ij}}{4f^2}(s-u)$$

$a(\mu) = -1.846, \mu = 1000\ MeV \Rightarrow$
Pole=2318 MeV

F.-K. Guo, P.-N. Shen, H.-C. Chiang, R.-G. Ping, and B.-S. Zou, PL B641, 278 (2006).

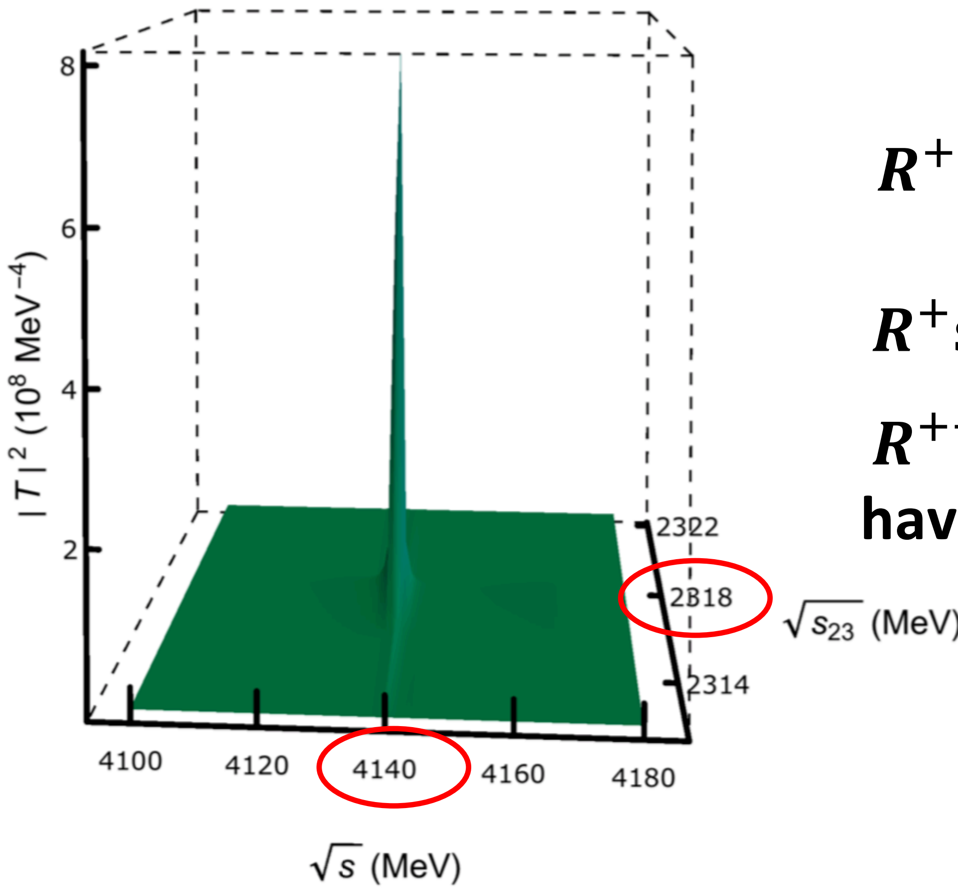
- **DD(Ds): local hidden gauge theory**



$a(\mu) = -1.3 \sim -1.5, \mu = 1500\ MeV$
$\Leftarrow$ fixed from $D\bar{D}/D\overline{D^*}$

S. Sakai, L. Roca, and E. Oset, PRD96, 054023 (2017).

Three-body amplitudes



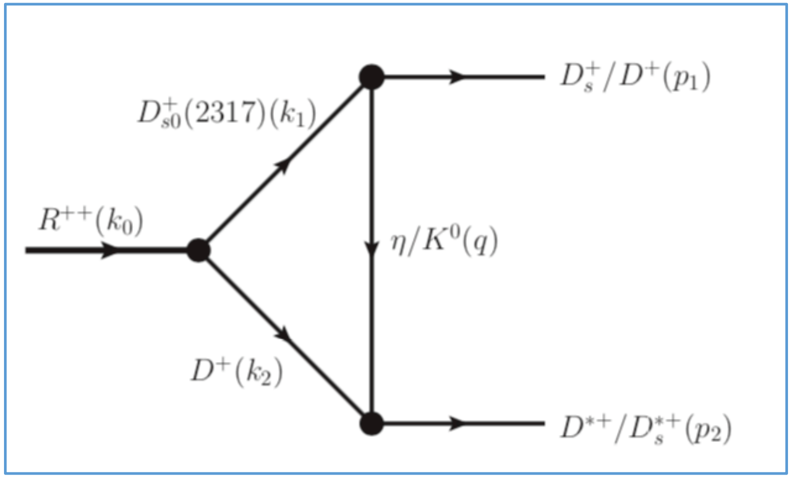
$$R^{++} = (I, I_{23}) = (\frac{1}{2}, 0)$$

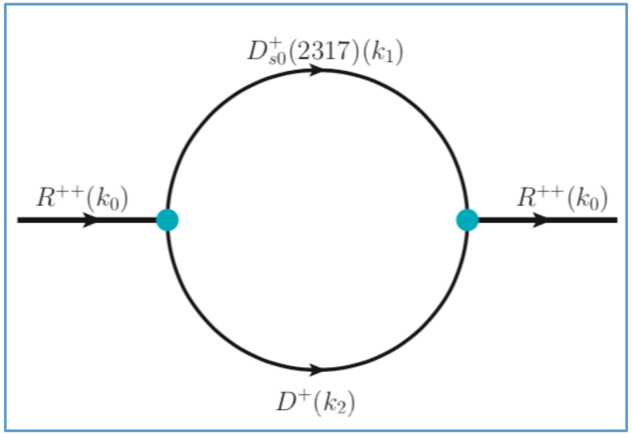
R^{+} should also exist

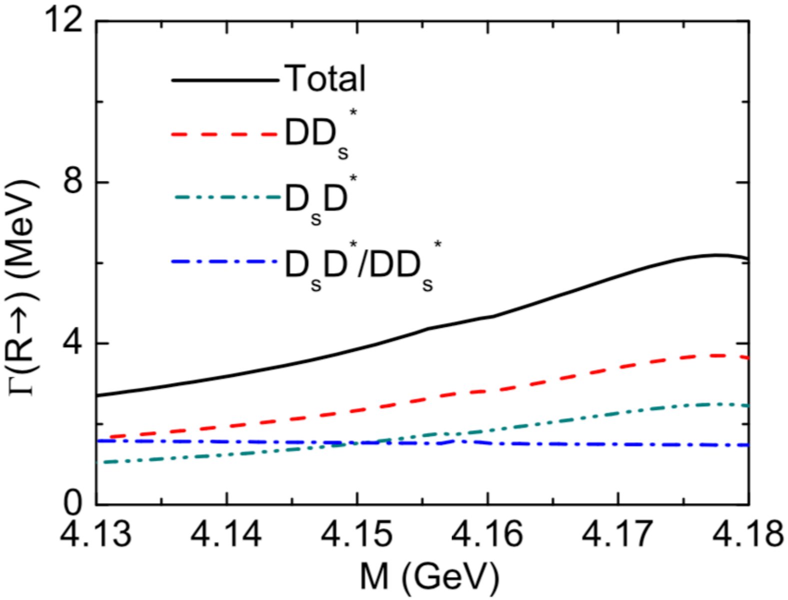
R^{++} is a bound state, but can have a width

Two-body decay width

*Yin Huang, **LSG**, et al., in preparation*







Very preliminary result:
$\Gamma \sim 4$ MeV

Different from the Tcc state

R^{++}(4140)

- DDK molecule
- ½(0-)
- $cc\bar{d}\bar{s}$
- Decay strongly—10 MeV
- Production mechanism to be studied

Tcc

- Compact tetraquark
- $0(1^+)$
- $cc\bar{q}\bar{q}$
- Decay weakly
- Production in PP/e+e- collisions studied extensively

Ds0*(2317) (DK bound state) plays a key as a doorway for the formation of the R^{++}

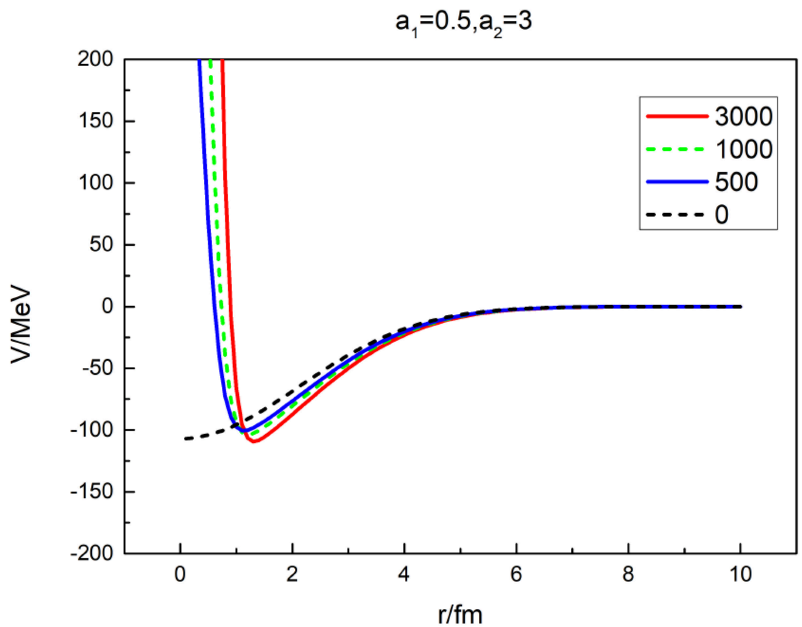
*Tian-Wei Wu, **LSG**, et al., in preparation*

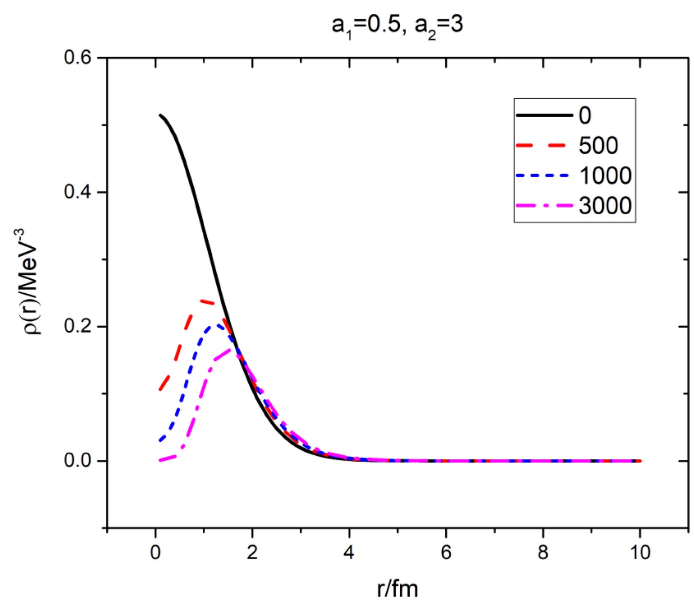
A DDDK/DDD$_{s0}$*(2317)state

1(0$^+$)

Gaussian Expansion Method

What if we add one more D? Very preliminary study show that such a state exists as well





Uncertainties are at **the order of 20 MeV**

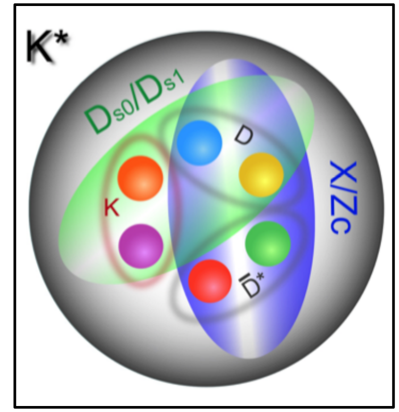
$$V_{DK}(r) = C_1 e^{-r^2/a_1^2} + C_2 e^{-r^2/a_2^2}$$

	DK*	DDK	DDDK
Binding	-45 MeV	-66 MeV	-88 MeV

Contents

- **Motivation: coupled channel effects in understanding new exotic hadrons**
- **Ds0*(2317) and Ds1(2460) as DK/D*K molecules**
- **A two-channel study of the $P_c(4450)$--a new (long range) binding mechanism**
  - **Near-threshold Coulomb-like Baryonia: $\Lambda_c(2595)\Sigma_c(\overline{\Sigma_c})$**
  - **Exotic doubly charmed $D_{s0}^*(2317)D$ and $D_{s1}(2460)D^*$ molecules**
- **An explicit study of the DDK** system: **$R^{++}(4140)$**
  - **Preliminary result on its decay width and on the existence of a DDDK bound state**
- **A K*(4307) with hidden charm as KX(3872)/Zc(3900) molecule**
- **Summary and outlook**

K*(4307)



Instead of a D, what happens if we add a $\overline{D}^*$ to the DK pair

Physics Letters B 785 (2018) 112–117

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K^* mesons with hidden charm arising from $KX(3872)$ and $KZ_c(3900)$ dynamics

Check for updates

Xiu-Lei Ren [a], Brenda B. Malabarba [b], Li-Sheng Geng [c,d], K.P. Khemchandani [e,c], A. Martínez Torres [b,c,*]

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[b] Instituto de Física, Universidade de São Paulo, C.P. 66318, 05389-970 São Paulo, São Paulo, Brazil
[c] School of Physics and Nuclear Energy Engineering & Beijing Key Laboratory of Advanced Nuclear Materials and Physics, Beihang University, Beijing 100191, China
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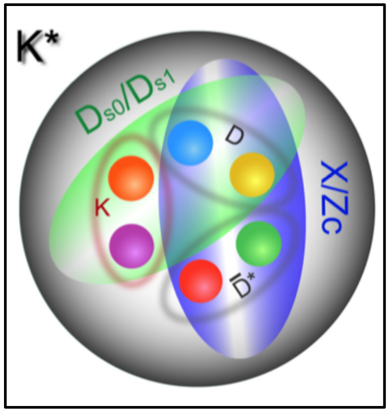
[e] Universidade Federal de São Paulo, C.P. 01302-907, São Paulo, Brazil

K*(4307)



- **Fixed center approximation:**

$$K(D\overline{D^*} + \overline{D}D^*) \sim KX(3872)/Zc(3900)$$

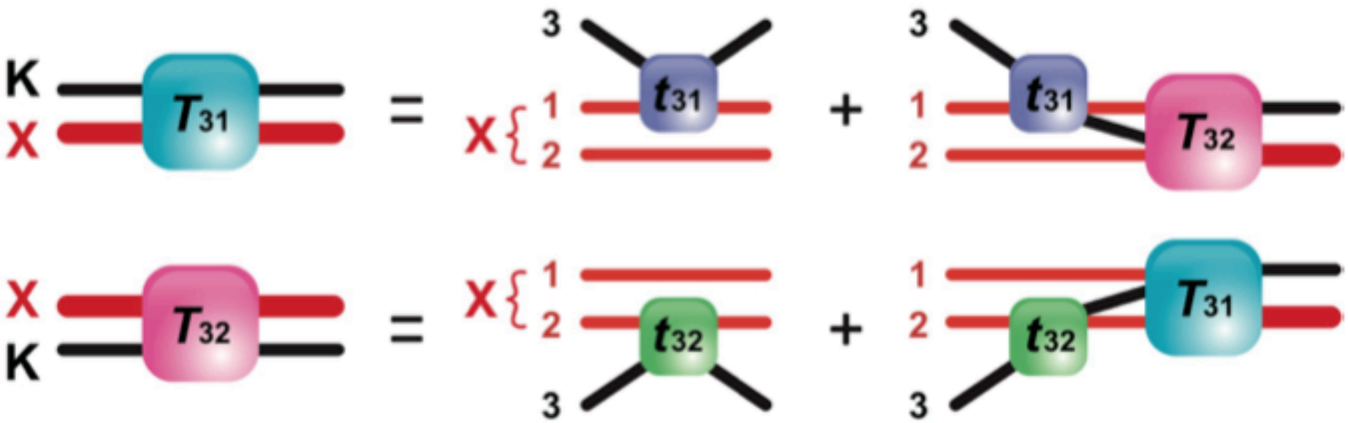
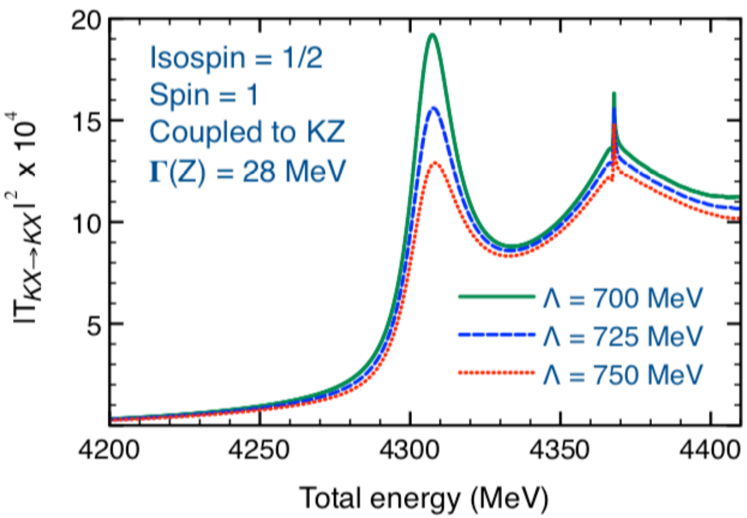
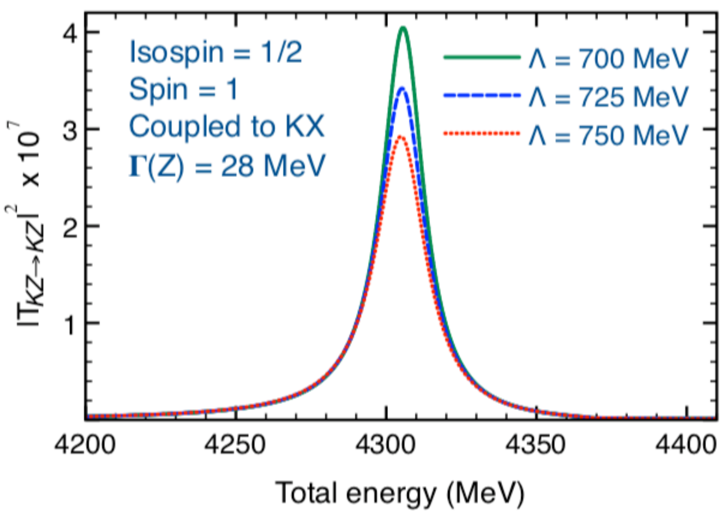
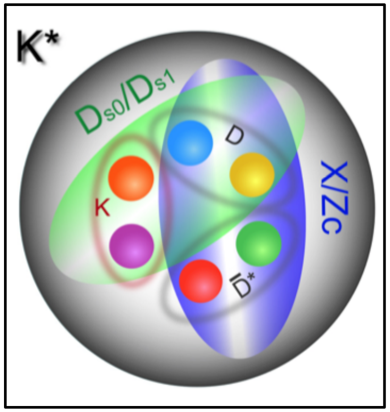


Figure 2: Diagrams showing the scattering of the particle labeled "3" (K) on a cluster (X) made of particles 1 (D) and 2 ($\bar{D}^*$).

K*(4307)—bosonic counterpart of Pc







- **Treating KX and KZ as coupled channel systems**
- **A resonance with M=(4307 ± 2) – i(9 ± 2) MeV with $I(J^P) = 1/2(1^-)$**

In agreement with Li Ma, Qian Wang, Ulf-G. Meißner, 1711.06143, but with completely different dynamics

Summary and outlook

- **DK interaction is strong enough** to form Ds0*(2317) and Ds1(2460)
- We show that it is possible to **have three-body bound states or resonances of DDK (DDD)K or $DD^{*}K$ systems**—molecules—three-body/two-body duality?

- We explored **a few new mechanisms** to form hadronic molecules—three-body/two-body duality?
- Some of the predictions are rather model independent

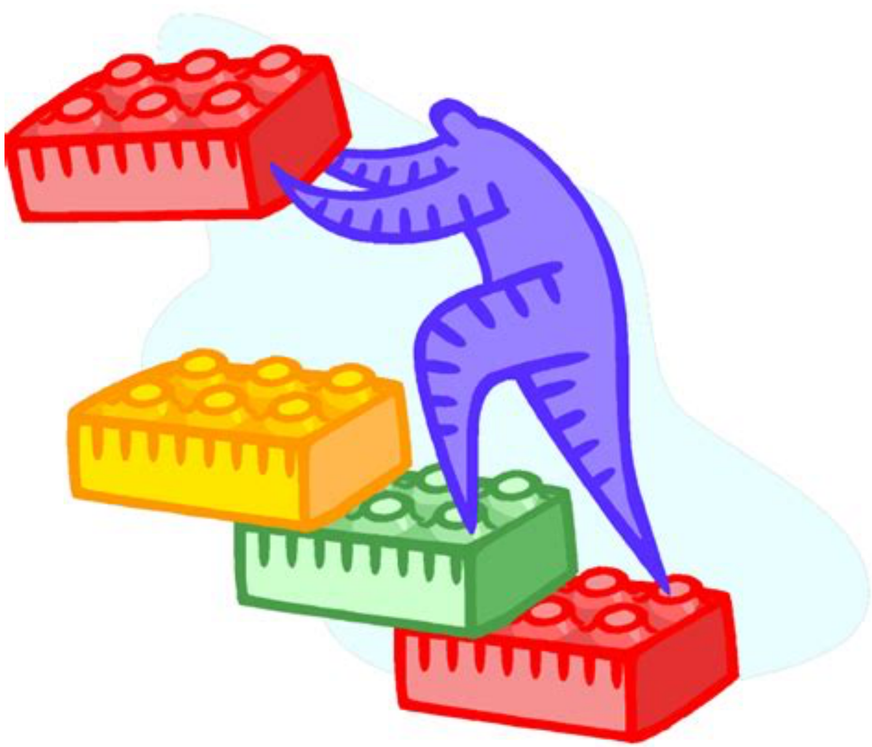
- The next step is to look for reactions where, particularly, the **R^{++}(4140),** they can be searched for—*close collaboration with experimentalists and theoreticians*

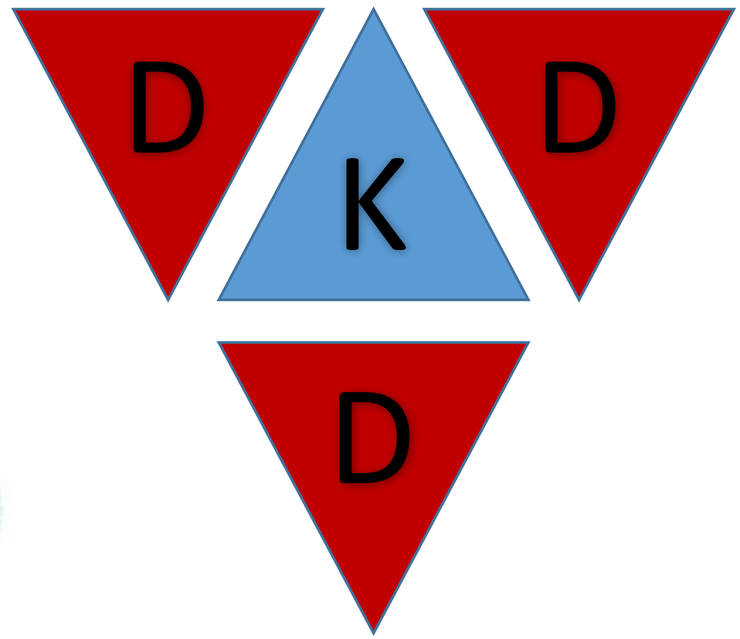
北京航空航天大學
BEIHANG UNIVERSITY

Thanks for your attention！

October 21th, 2018

Building blocks—DK/DDK/DDDK





Purely wild speculation

DK—Ds0*(2317)--observed

DDK—R^{++}(4140)--to be discovered

DDDK– calculated/to be discovered

DDDDK—to be calculated/discovered

……

Why 0(1⁺) Tcc preferred

Why 0(1+) 1608.03982

In the case of $(\bar{q}\bar{q}QQ)$ with spin-parity $J^P = 1^+$ and isospin $I = 0$, where Q stands for c or b and q for a light quark, there is the fortunate cooperation of two effects. First, the chromoelectric interaction (CE), even if alone, gives stability below the $(\bar{q}Q) + (\bar{q}Q)$ threshold if the quark-to-antiquark mass ratio is large enough, as it takes advantage of the deeper binding of the QQ pair [11–14]. Second, the chromomagnetic interaction (CM) between the light quarks is also favorable [15, 16]. Janc and Rosina predicted the stability of $(\bar{u}\bar{d}cc)$ using a quark model fitting ordinary hadrons [17]. Their calculation was confirmed and improved by Vijande *et al.* [18]. This configuration is also pointed out as a good candidate for a stable exotic in other approaches such as a DD^* molecule [19–23], lattice QCD [24–26] or QCD sum rules [27].

Production of Tcc at LHC

$$\sigma(pp \to T^{\{bb\}}_{[\bar{u}\bar{d}]} + X) = (2.8^{+1.0}_{-0.7})\ \text{nb} \qquad \sqrt{s} = 13\ \text{TeV}$$

$T^{\{bb\}}_{[\bar{u}\bar{s}]}$ and $T^{\{bb\}}_{[\bar{d}\bar{s}]}$ ~1/4

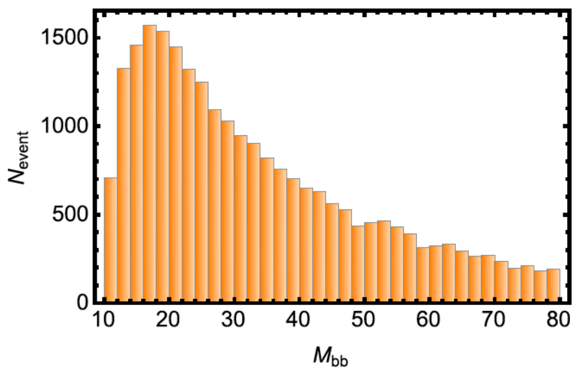


FIG. 1: The bb-quark-pair invariant-mass distribution for the process $pp \to (bb)_{\text{jet}} + \bar{b} + \bar{b} + X$ at $\sqrt{s} = 13$ TeV, obtained by generating 10^5 events using MadGraph and Pythia6 at the NLO accuracy.

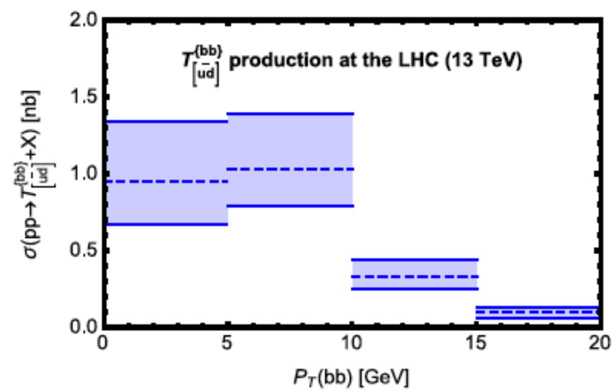
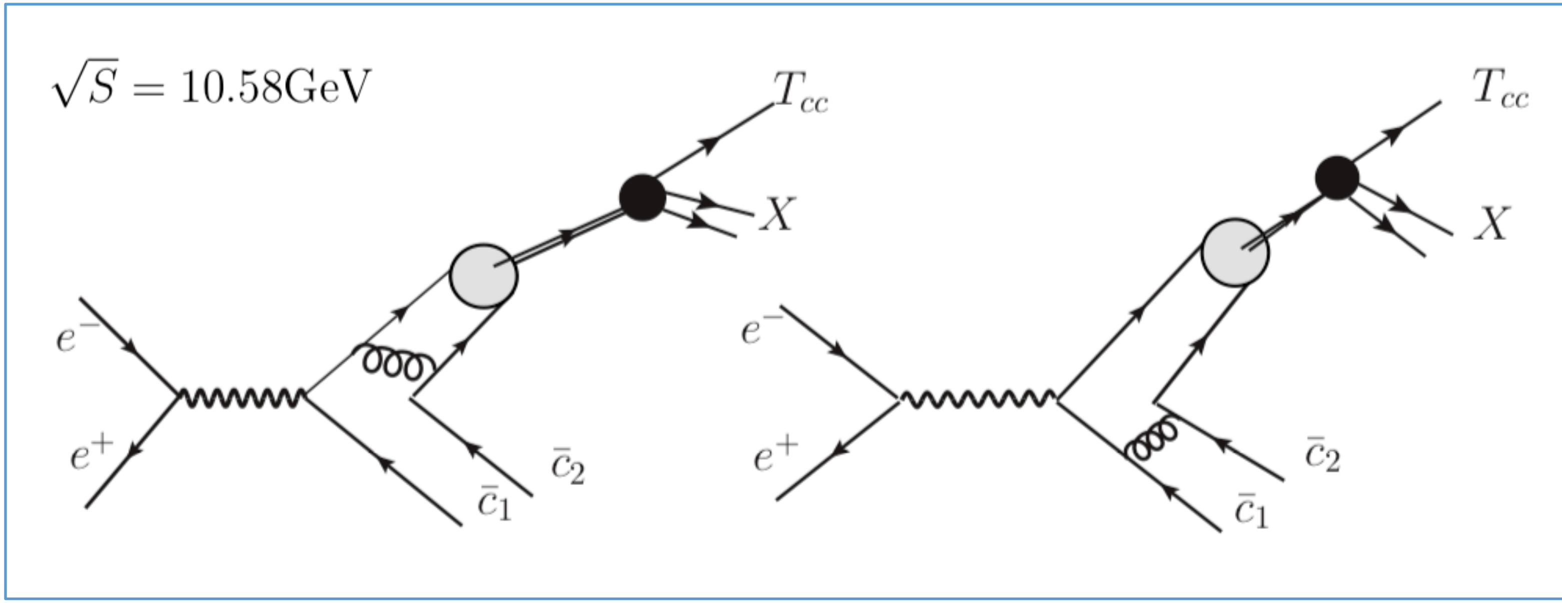


FIG. 4: Projected p_T-dependence of tetraquark production cross section in $pp \to T^{\{bb\}}_{[\bar{u}\bar{d}]} + X$ at the LHC for $\sqrt{s} = 13$ TeV.

Discovery potential of stable and near-threshold doubly heavy tetraquarks at the LHC
Ahmed Ali, Qin Qin, and Wei Wang
1806.09288

Production of Tcc at KEKb



Production of the tetraquark state T_{cc} at the B-factories, 1305.5711
Reyima Rashidin

$cc\bar{q}\bar{q}$ All angular momentum zero

$$\sigma_{total} = 2.669 \pm 0.0295\text{fb}$$

Ξ_b' and Ξ_b

$\Xi_b'(5935)^-$

$J^P = \frac{1}{2}^+$ Status: ∗∗∗

$\Xi_b'(5935)^-$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
5935.02±0.02±0.05	[1] AAIJ	15H	LHCB	pp at 7, 8 TeV

[1] Not independent of the mass difference measurement below. Observed in $\Xi_b^0 \pi^-$ channel with $\Xi_b^0 \to \Xi_c^+ \pi^-$ and $\Xi_c^+ \to p K^- \pi^+$.

$\Xi_b(5945)^0$

$J^P = \frac{3}{2}^+$ Status: ∗∗∗

Quantum numbers are based on quark model expectations.

$\Xi_b(5945)^0$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
5949.8±1.4 OUR AVERAGE				
5949.8±0.1±1.4	[1] AAIJ	16AE	LHCB	pp at 7, 8 TeV
5948.9±0.8±1.4	[2] CHATRCHYAN	12S	CMS	pp at 7 TeV, 5.3 fb^{-1}

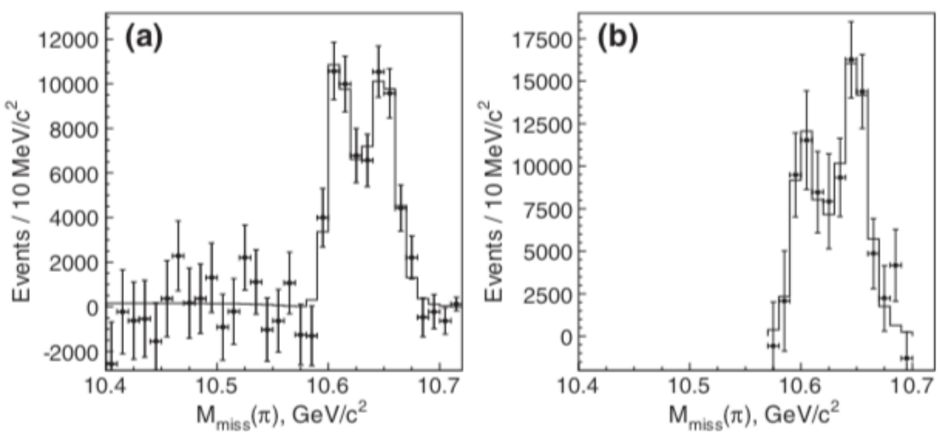
Hidden doubly heavy mesons

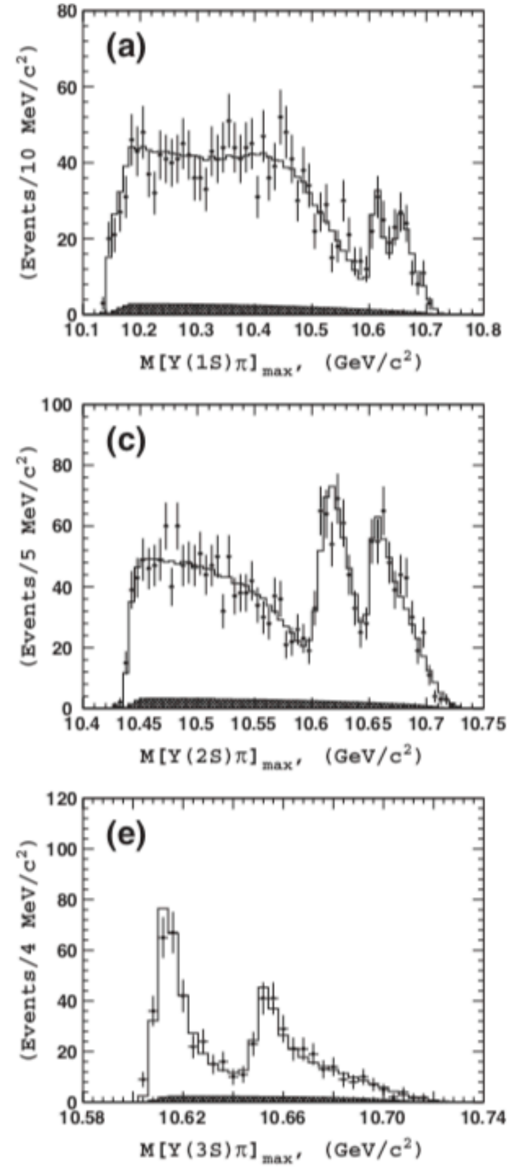
Zb(10610)/Zb(10650)

[Observation of two charged bottomonium-like resonances in Y(5S) decays]

$M = 10607.2 \pm 2.0$ MeV $\Gamma = 18.4 \pm 2.4$ MeV

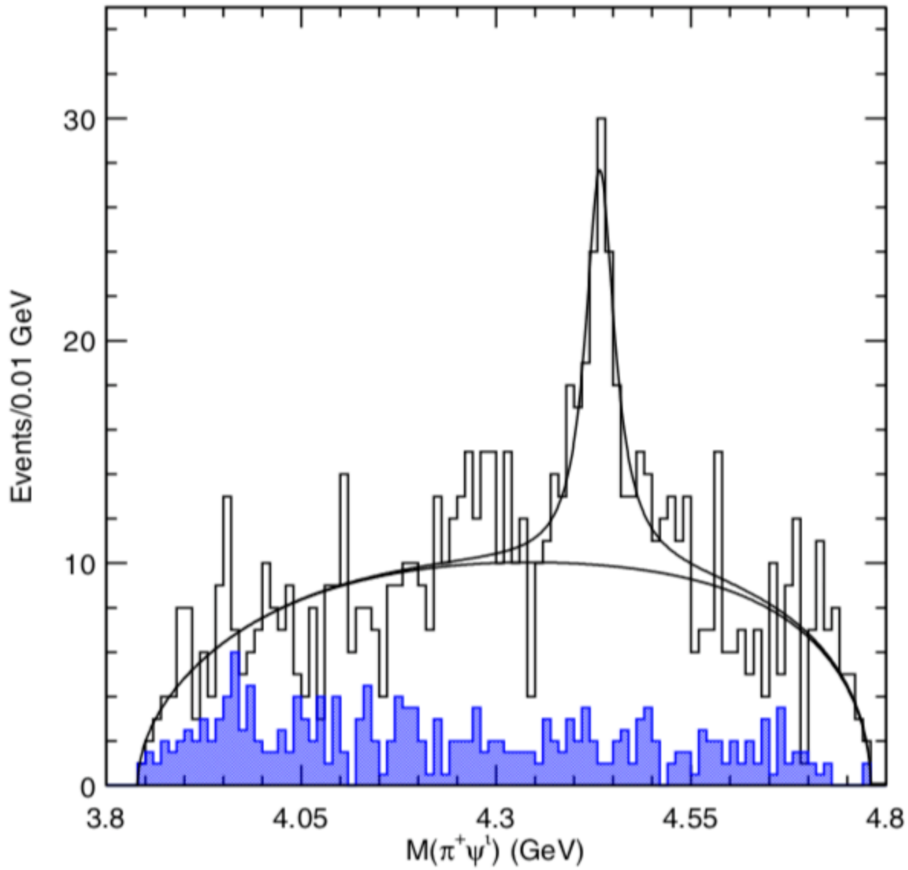
$M = 10652.2 \pm 1.5$ MeV $\Gamma = 11.5 \pm 2.2$ MeV





Belle Collaboration, 1110.2251, 439@2018.10.06

Zc(4430)



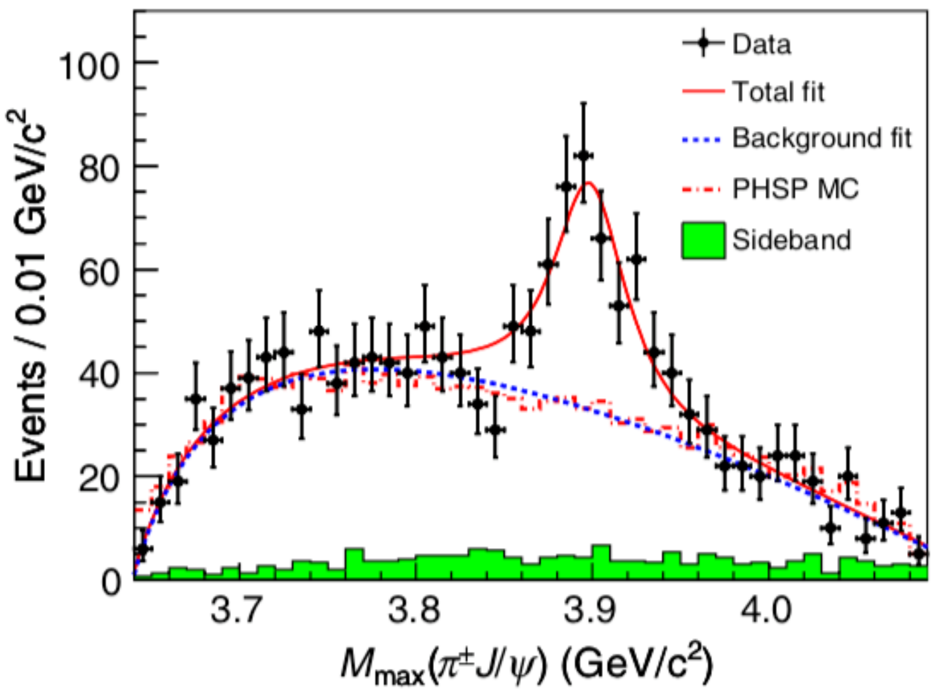
Observation of a resonance-like structure in the pi+- psi-prime mass distribution in exclusive B ---> K pi+- psi-prime decays

$$M = 4433 \pm 4 \pm 2 \text{ MeV}$$
$$\Gamma = 45^{+18}_{-13}\ {}^{+30}_{-13} \text{ MeV}$$

Belle Collaboration, 0708.1790, 569@2018.10.06

Zc(3900)

[Observation of a Charged Charmoniumlike Structure in e+e−e+e− → π+π−π+π− J/ψ at s√s =4.26 GeV]



$$M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV}$$
$$\Gamma = 46 \pm 10 \pm 20 \text{ MeV}$$

BESIII Collaboration, 1303.5949, 596@2018.10.06