Heavy hadron spectroscopy "@ EicC "

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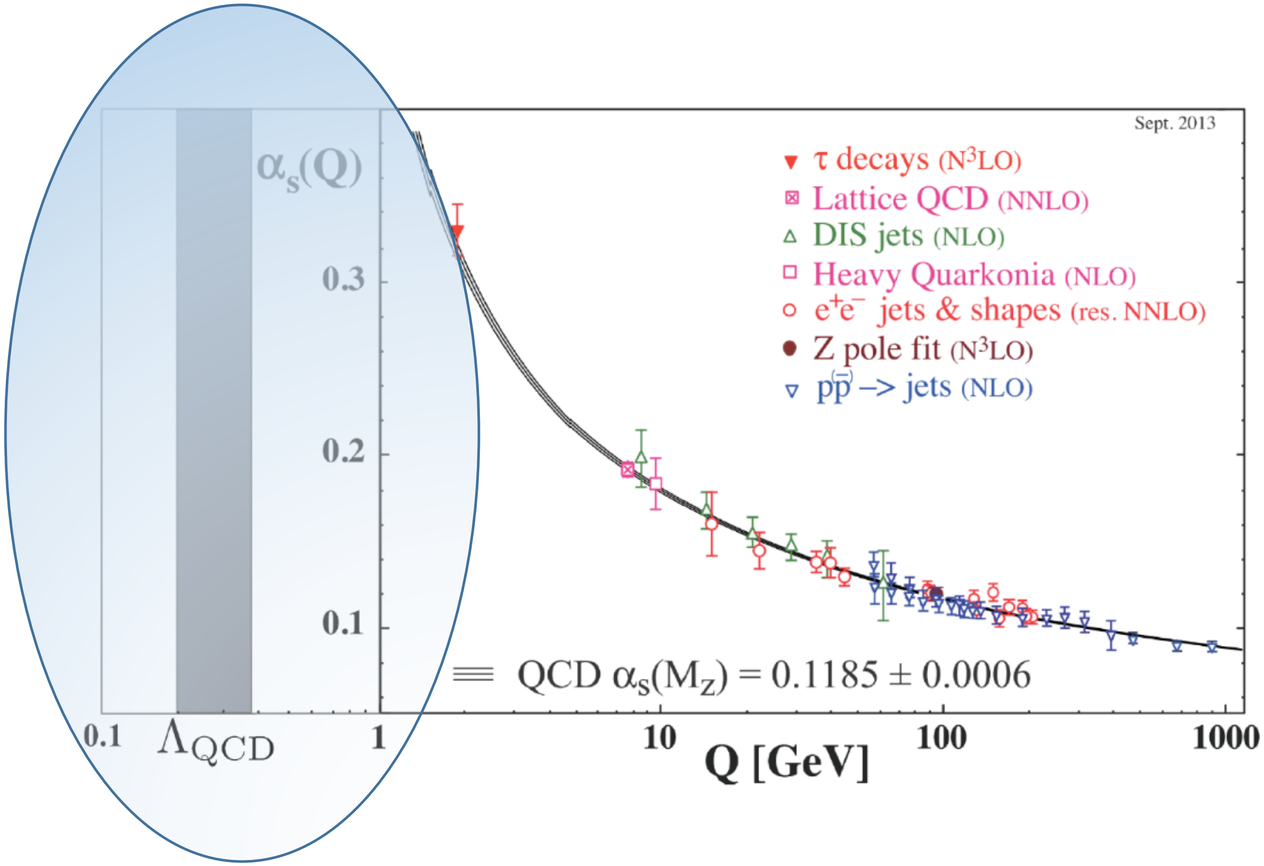
Prepared for the EicC discussion

The 10th Workshop on Hadron Physics in China and Opportunities Worldwide

Weihai, 26-30 July 2018

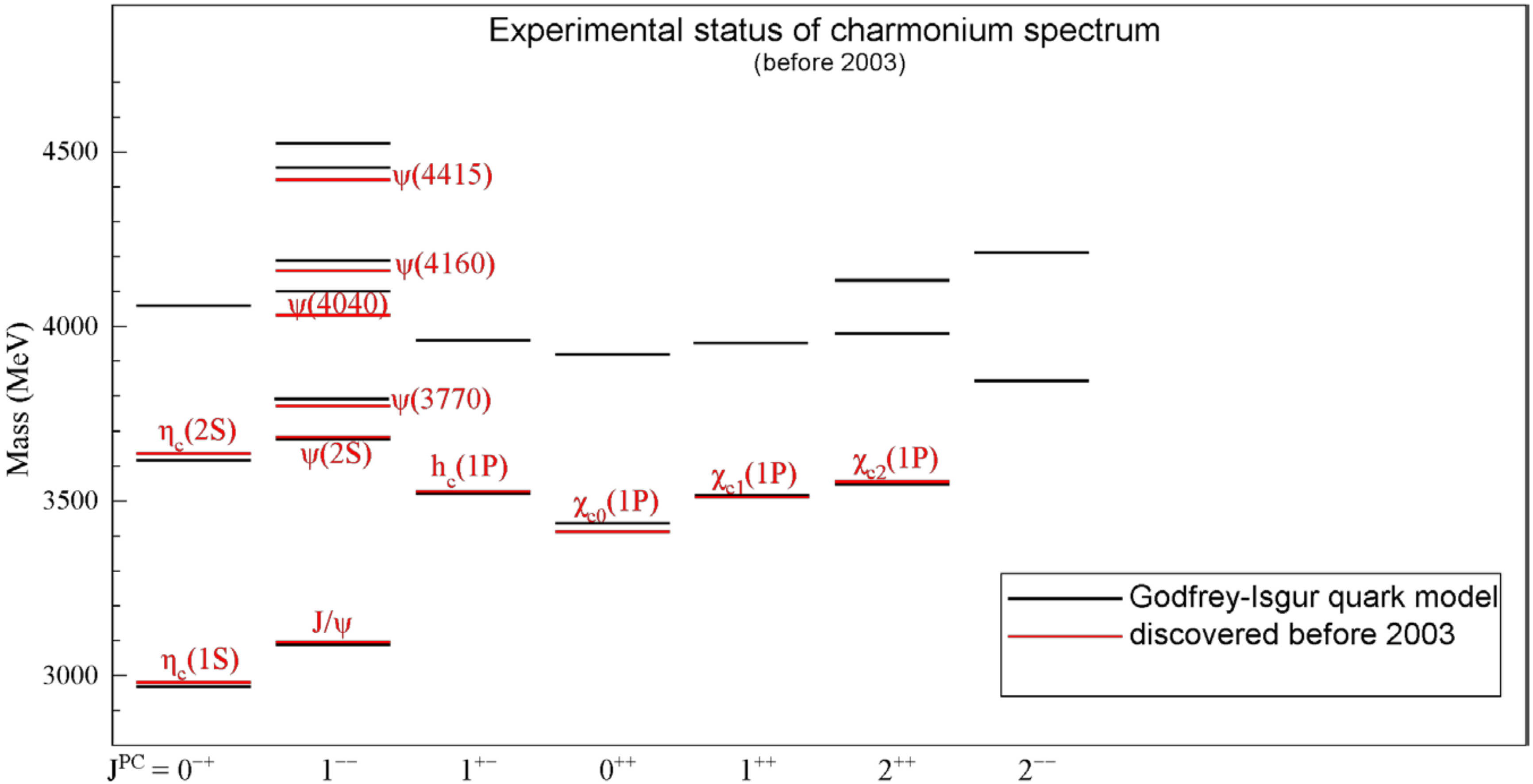
Low-energy QCD: big challenge



Nucleon structure

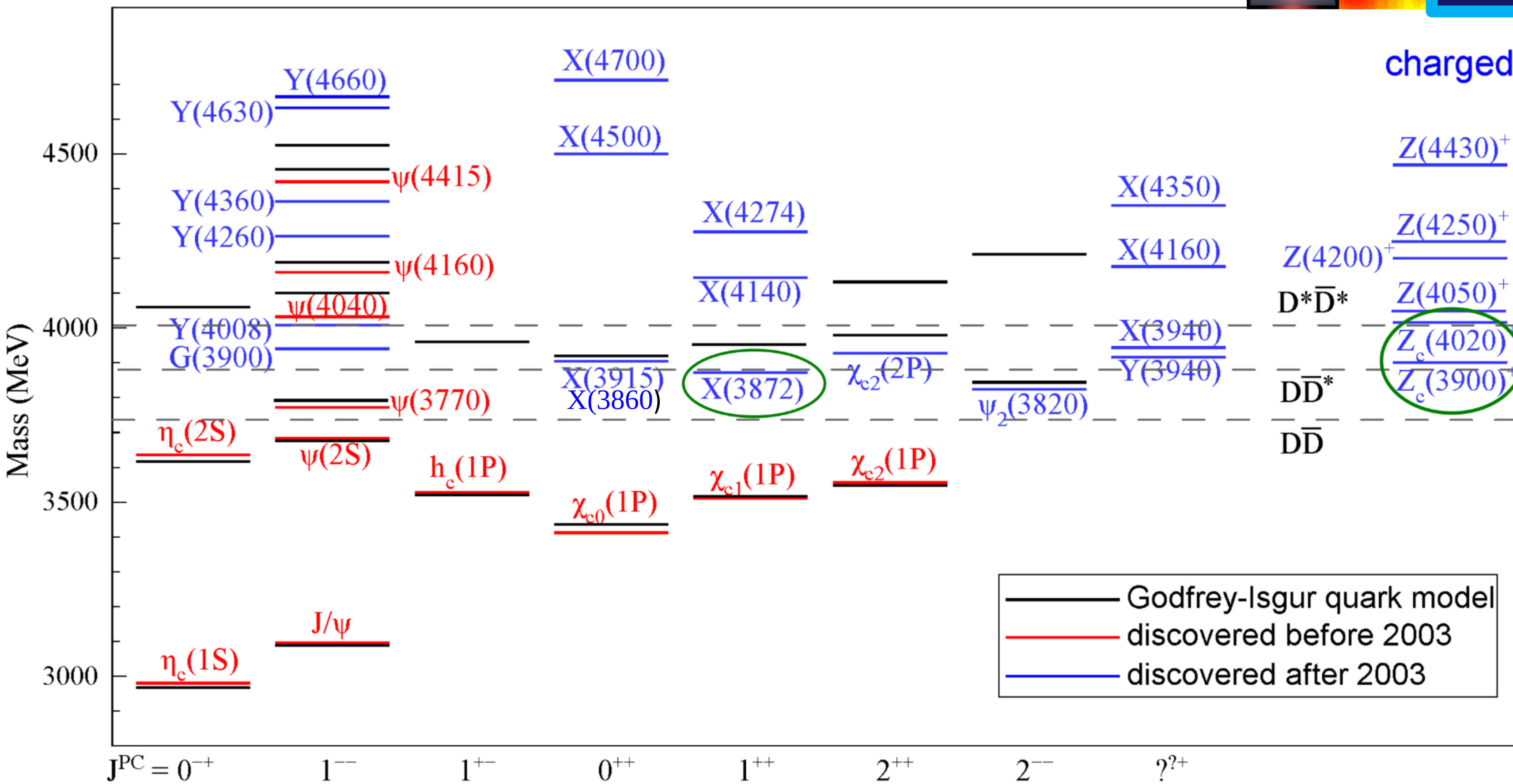
Mysteries in hadron spectroscopy

Hidden-charm XYZ states



- Quark model works very well for the low-lying states

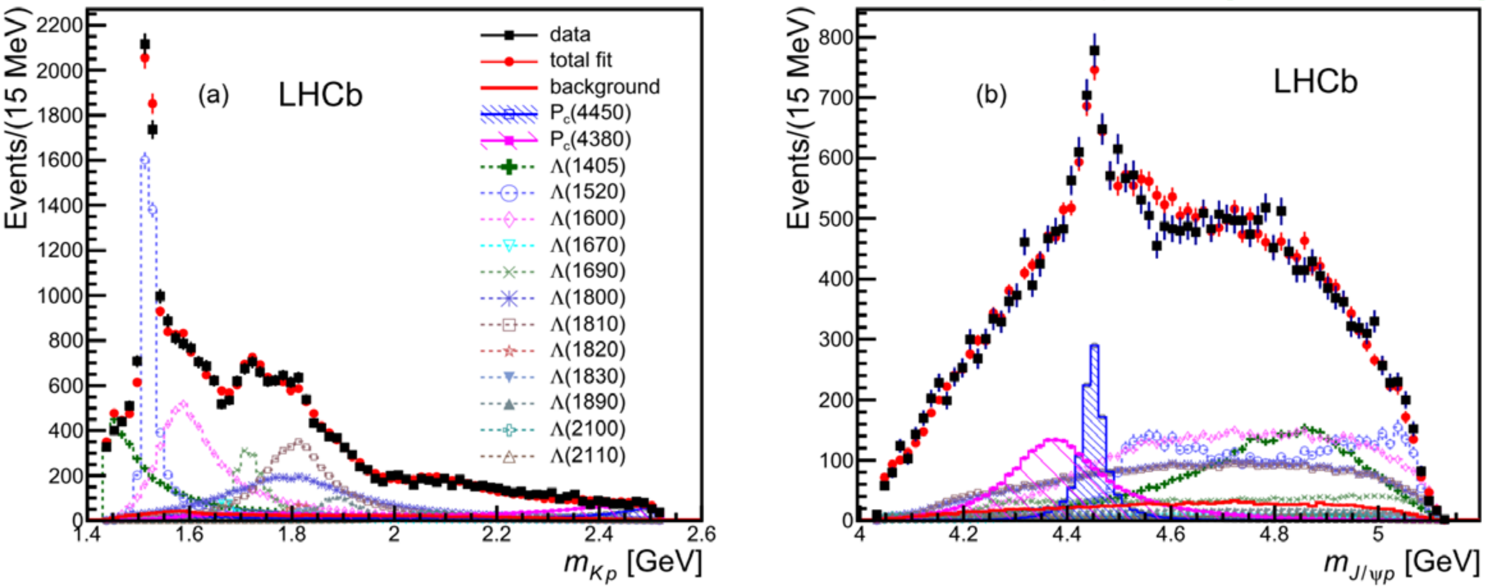
Hidden-charm XYZ states



- Some states are very close to two-body S-wave thresholds

Pentaquark candidates: P_c

PRL115(2015)072001 [arXiv:1507.03414]



$$M_1 = (4380 \pm 8 \pm 29)\ \text{MeV}, \qquad \Gamma_1 = (205 \pm 18 \pm 86)\ \text{MeV},$$

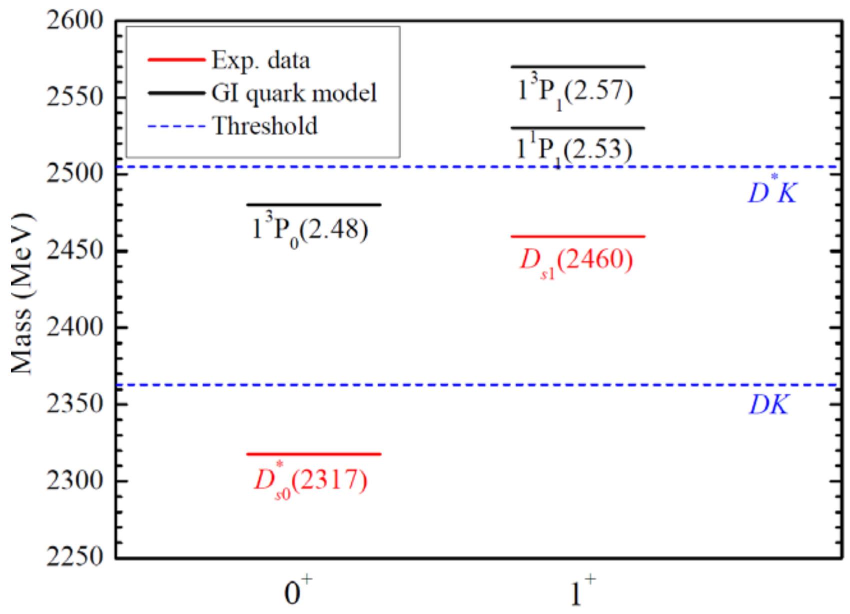
$$M_2 = (4449.8 \pm 1.7 \pm 2.5)\ \text{MeV}, \qquad \Gamma_2 = (39 \pm 5 \pm 19)\ \text{MeV}.$$

- observed in $J/\psi p$ invariant mass distribution: pentaquark $(c\bar{c}uud)$ candidates
- quantum numbers not determined
- Narrow pentaquark-like structures with hidden-charm had been predicted 5 years before (07.2010):

  Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV,

  J.-J. Wu, R. Molina, E. Oset, B.-S. Zou, PRL105(2010)232001

Charmed mesons



GI quark model: Godfrey, Isgur (1985)

Puzzles:

(1) Why $D^*_{s0}(2317), D_{s1}(2460)$ so light?

(2) Why $\underbrace{M_{D_{s1}(2460)^\pm} - M_{D^*_{s0}(2317)^\pm}}_{=(141.8\pm0.8)\text{ MeV}} \simeq \underbrace{M_{D^{*\pm}} - M_{D^\pm}}_{=(140.67\pm0.08)\text{ MeV}}$?

(3) Why $M_{D^*_0(2400)} \gtrsim M_{D^*_{s0}(2317)}$ and $M_{D_1(2430)} \sim M_{D_{s1}(2460)}$?

$D^*_0(2400)^0$ $I(J^P) = 1/2(0^+)$

$J^P = 0^+$ assignment favored (ABE 2004D).

$D^*_0(2400)^0$ MASS	2318 ± 29 MeV
$D^*_0(2400)^0$ WIDTH	267 ± 40 MeV

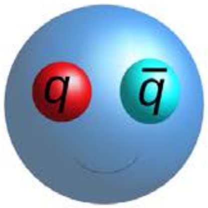
$D_1(2430)^0$ $I(J^P) = 1/2(1^+)$

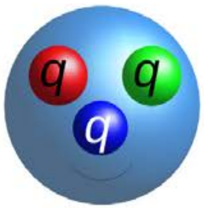
$J = 1^+$ assignment favored (ABE 2004D).

$D_1(2430)^0$ MASS	2427 ± 40 MeV
$D_1(2430)^0$ WIDTH	384^{+130}_{-110} MeV

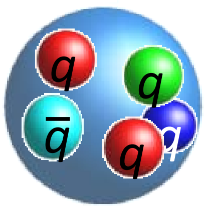
What are they?

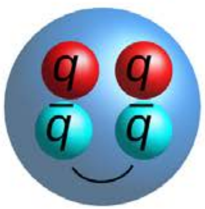
- Hadron resonances due to QCD dynamics, poles of the *S*-matrix
  - ☞ Ordinary mesons and baryons

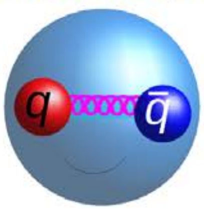


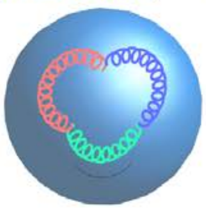


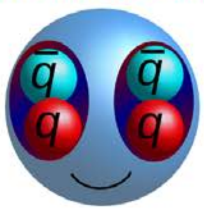
  - ☞ Exotic hadrons: multiquark states, hybrids, glueballs, and hadronic molecules









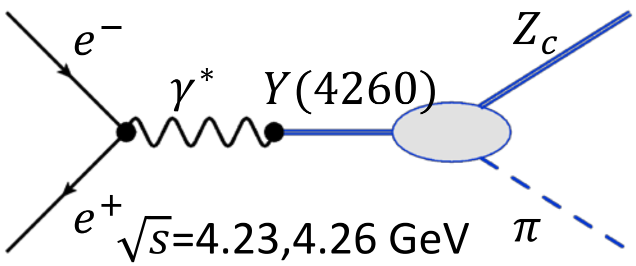


- Kinematic effects, (normally) branching point of the *S*-matrix
  - ☞ normal two-body threshold cusp
  - ☞ triangle singularity
  - ☞ . . .

Example: Z_c

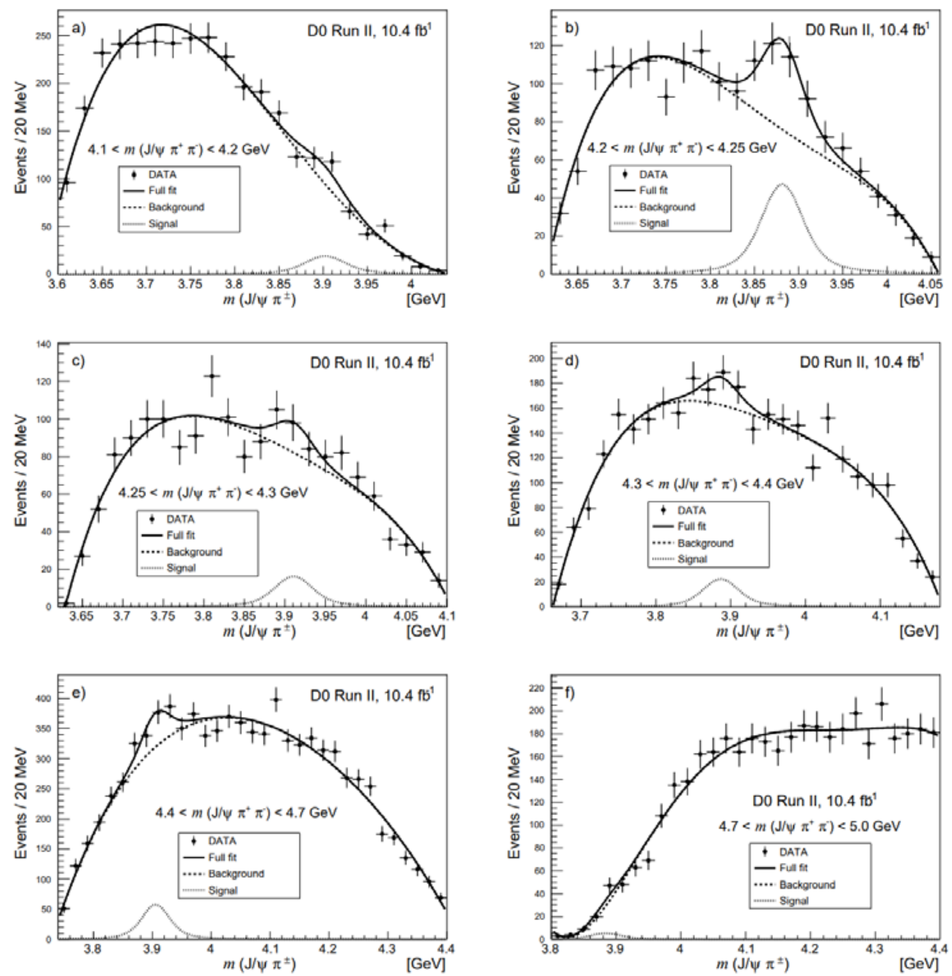
- BESIII and Belle observed in

BESIII, PRL110(2013)252001; Belle, PRL110(2013)252002

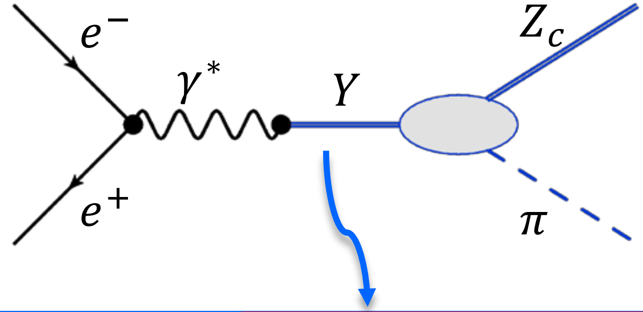


- D0 observed in inclusive decays of *b*-flavored hadrons, but still via $Y(4260) \to [J/\psi\pi]\pi$

D0, arXiv:1807.00183



Example: Z_c

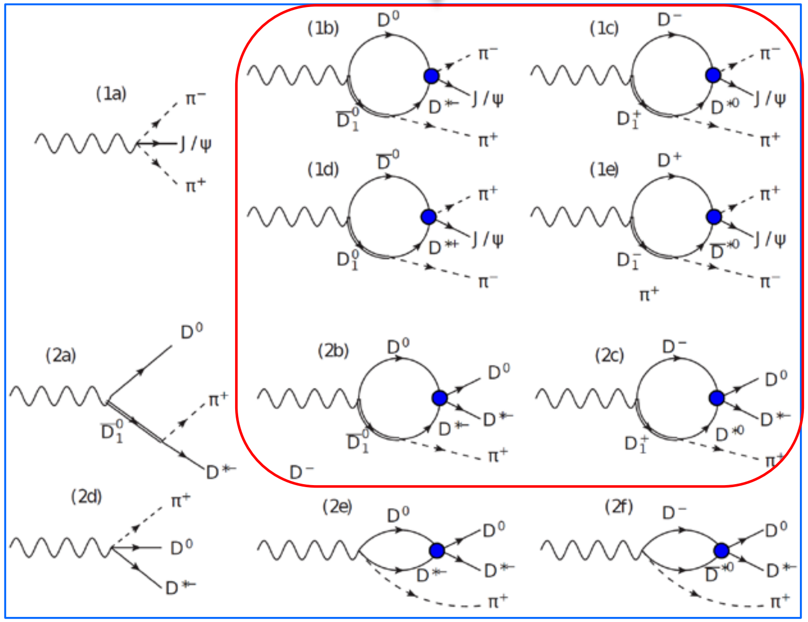


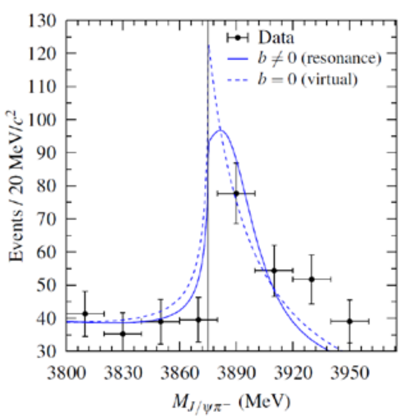
- Importance of a triangle singularity in $Y(4260) \to \pi Z_c(3900)$ noticed, but $Z_c(3900)$ still needed

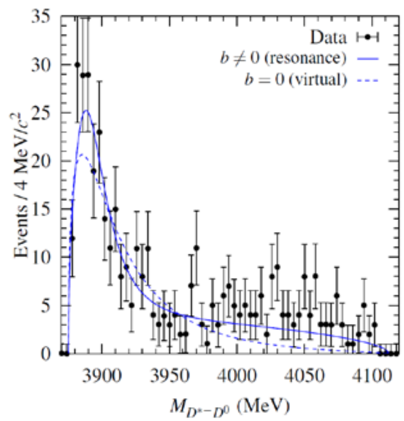
Q.Wang, Hanhart, Q.Zhao, PRL111(2013)132002; PLB725(2013)106

- Coupled-channel analysis with both triangle diagrams and FSI (Z_c generated)

Albaladejo, FKG, Hidalgo-Duque, Nieves, PLB755(2016)337







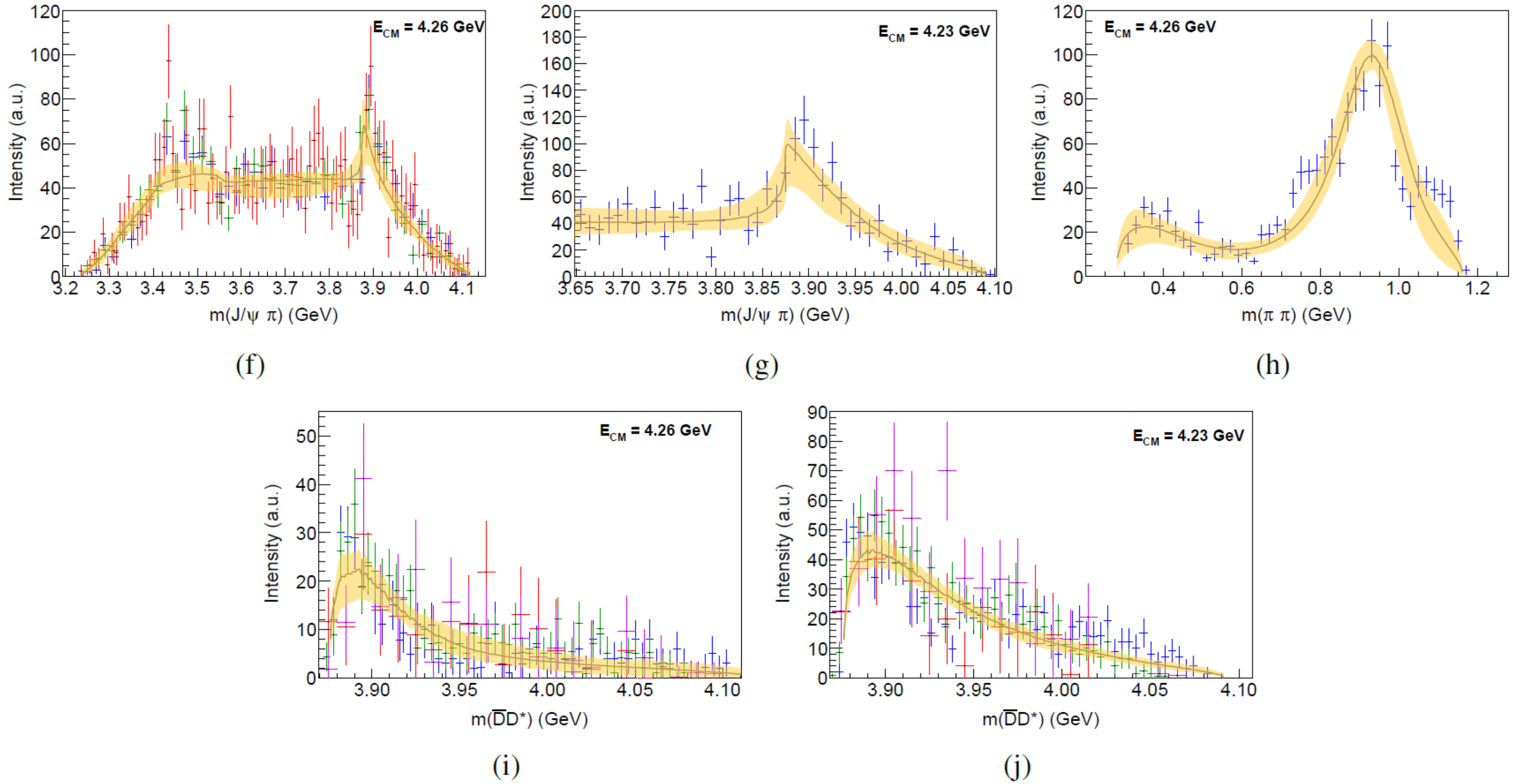
M_{Z_c} (MeV)	$\Gamma_{Z_c}/2$ (MeV)	Ref.	Final state
3899 ± 6	23 ± 11	[1] (BESIII)	$J/\psi\ \pi$
3895 ± 8	32 ± 18	[2] (Belle)	$J/\psi\ \pi$
3886 ± 5	19 ± 5	[3] (CLEO-c)	$J/\psi\ \pi$
3884 ± 5	12 ± 6	[4] (BESIII)	$\bar{D}^*D$
3882 ± 3	13 ± 5	[5] (BESIII)	$\bar{D}^*D$
$3894 \pm 6 \pm 1$	$30 \pm 12 \pm 6$	$\Lambda_2 = 1.0$ GeV	$J/\psi\ \pi$, $\bar{D}^*D$
$3886 \pm 4 \pm 1$	$22 \pm 6 \pm 4$	$\Lambda_2 = 0.5$ GeV	$J/\psi\ \pi$, $\bar{D}^*D$
$3831 \pm 26^{+7}_{-28}$	virtual state	$\Lambda_2 = 1.0$ GeV	$J/\psi\ \pi$, $\bar{D}^*D$
$3844 \pm 19^{+12}_{-21}$	virtual state	$\Lambda_2 = 0.5$ GeV	$J/\psi\ \pi$, $\bar{D}^*D$

resonance pole

or virtual state

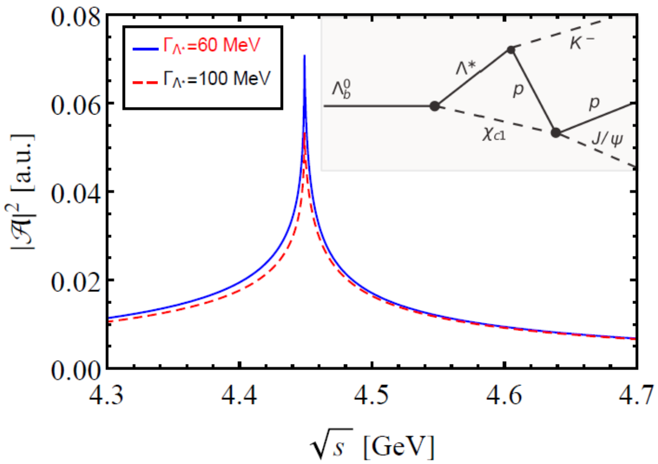
Example: $Z_c(3900)$

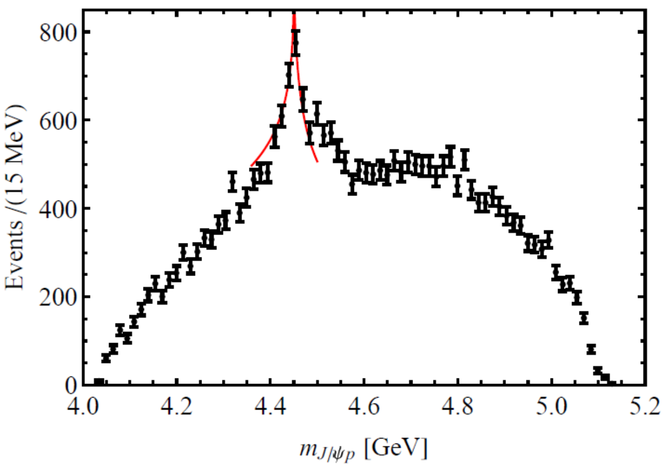
- JPAC analysis with triangle diagrams but w/o a nearby pole for Z_c Pilloni et al., PLB772(2017)200



Example: P_c

- Excellent candidates for hidden-charm pentaquarks
- For $P_c(4450)$, ambiguities due to nearby triangle singularities if $J^P = \frac{1}{2}^+$ or $\frac{3}{2}^+$

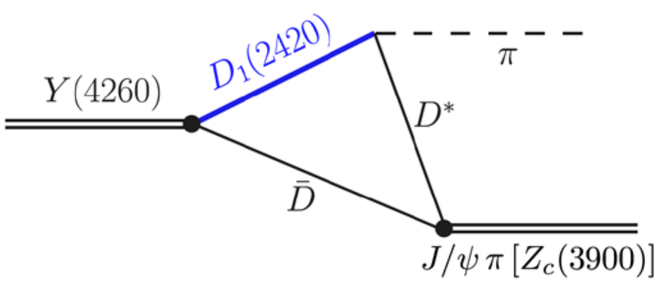


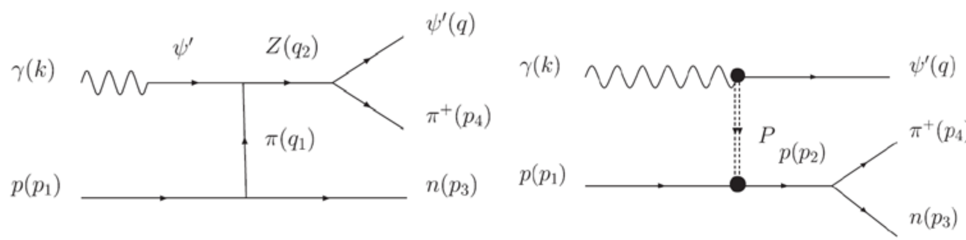


FKG, Meißner, W. Wang, Z. Yang, PRD92(2015)071502(R);
X.-H. Liu, Q. Wang, Q. Zhao, PLB757(2015)231;
Bayar, Aceti, FKG, Oset, PRD94(2016)074039

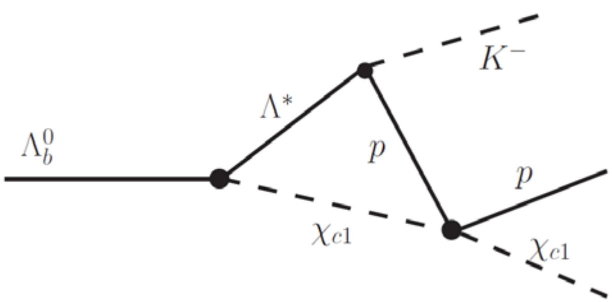
Need completely different production processes

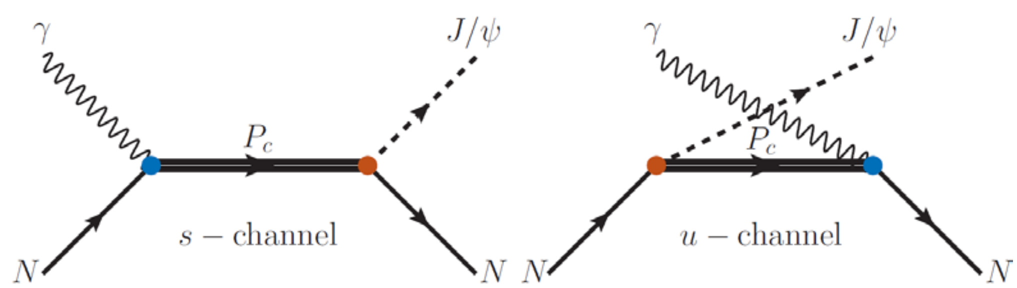
- To establish exotic multiquarks, distinguish from triangle singularities
- Triangle singularities depend strongly on the kinematics, thus different production processes needed! ⇒ photoproduction





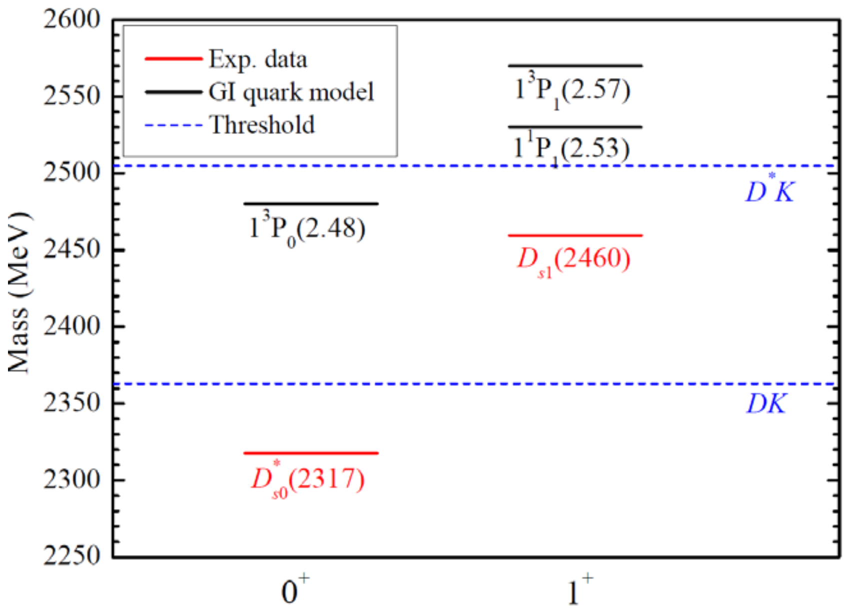
X.-H. Liu, Q. Zhao, F. E. Close, PRD77(2008)094005





Q. Wang, X.-H. Liu, Q. Zhao, PRD92(2015)034022

From charm to bottom



GI quark model: Godfrey, Isgur (1985)

Puzzles and possible solutions:

(1) Why $D^*_{s0}(2317), D_{s1}(2460)$ so light?

Hadronic molecules (DK, D^*K)

(2) Why $\underbrace{M_{D_{s1}(2460)^\pm} - M_{D^*_{s0}(2317)^\pm}}_{=(141.8\pm0.8)\text{ MeV}} \simeq \underbrace{M_{D^{*\pm}} - M_{D^\pm}}_{=(140.67\pm0.08)\text{ MeV}}$?

Heavy quark spin symmetry

(3) Why $M_{D^*_0(2400)} \gtrsim M_{D^*_{s0}(2317)}$

and $M_{D_1(2430)} \sim M_{D_{s1}(2460)}$?

Lowest: $M_{D^*_0} \approx 2.10$ GeV, $M_{D_1} \approx 2.25$ GeV

Du et al., arXiv:1712.07957

- One important theory idea: heavy quark symmetry (HQS)
- HQS is better for bottom than charm $\frac{\Lambda_{\text{QCD}}}{m_b} \ll \frac{\Lambda_{\text{QCD}}}{m_c}$

From charm to bottom

- Heavy-strange

Du et al., arXiv:1712.07957

meson	J^P	prediction (MeV)	PDG2017 (MeV)	lattice (MeV)
D_{s0}^*	0^+	2315^{+18}_{-28}	2317.7 ± 0.6	2348^{+7}_{-4}[1]
D_{s1}	1^+	2456^{+15}_{-21}	2459.5 ± 0.6	2451 ± 4[1]
B_{s0}^*	0^+	5720^{+16}_{-23}	–	5711 ± 23[2]
B_{s1}	1^+	5772^{+15}_{-21}	–	5750 ± 25[2]

[1] Bali et al., PRD96(2017)074501

[2] Lang et al., PLB750(2015)17

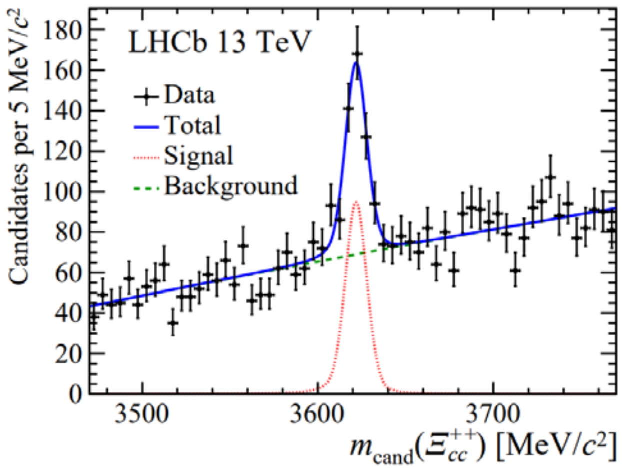
- Heavy-nonstrange, two $I = 1/2$ states $(M, \Gamma/2)$:

	Lower (MeV)	Higher (MeV)	PDG2017 (MeV)
D_0^*	$(2105^{+6}_{-8}, 102^{+10}_{-11})$	$(2451^{+36}_{-26}, 134^{+7}_{-8})$	$(2318 \pm 29, 134 \pm 20)$
D_1	$(2247^{+5}_{-6}, 107^{+11}_{-10})$	$(2555^{+47}_{-30}, 203^{+8}_{-9})$	$(2427 \pm 40, 192^{+65}_{-55})$
B_0^*	$(5535^{+9}_{-11}, 113^{+15}_{-17})$	$(5852^{+16}_{-19}, 36 \pm 5)$	–
B_1	$(5584^{+9}_{-11}, 119^{+14}_{-17})$	$(5912^{+15}_{-18}, 42^{+5}_{-4})$	–

- Predictions for bottom partners distinguish different scenarios
- $X, Y, Z \Rightarrow X_b, Y_b, Z_b$
- $P_c \Rightarrow P_b$

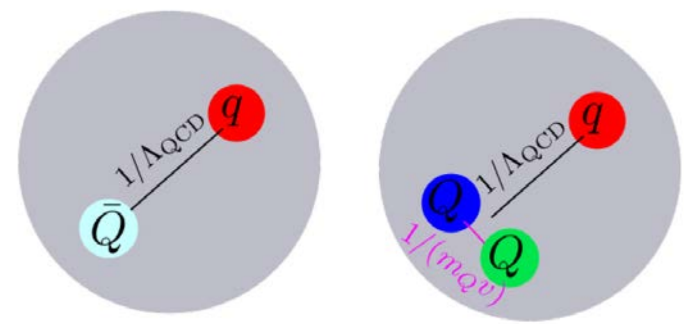
see the talk by B.-S. Zou on 30 July

From doubly-charm baryons to doubly-bottom tetraquarks

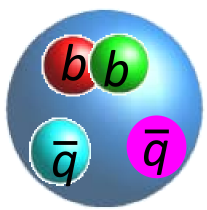


LHCb, PRL119(2017)112001

Savage, Wise (1990)



Heavy antiquark-diquark symmetry



$$M(Q_iQ_j\bar{q}_k\bar{q}_l) - M(Q_iQ_jq_m)$$
$$= M(\bar{Q}_x\bar{q}_k\bar{q}_l) - M(\bar{Q}_xq_m)$$

Editors' Suggestion

Discovery of the Doubly Charmed Ξ_{cc} Baryon Implies a Stable $bb\bar{u}\bar{d}$ Tetraquark

Marek Karliner and Jonathan L. Rosner
Phys. Rev. Lett. **119**, 202001 – Published 15 November 2017

Editors' Suggestion

Heavy-Quark Symmetry Implies Stable Heavy Tetraquark Mesons $Q_iQ_j\bar{q}_k\bar{q}_l$

Estia J. Eichten and Chris Quigg
Phys. Rev. Lett. **119**, 202002 – Published 15 November 2017

Lattice Prediction for Deeply Bound Doubly Heavy Tetraquarks

A. Francis, R. J. Hudspith, R. Lewis, and K. Maltman
Phys. Rev. Lett. **118**, 142001 – Published 5 April 2017

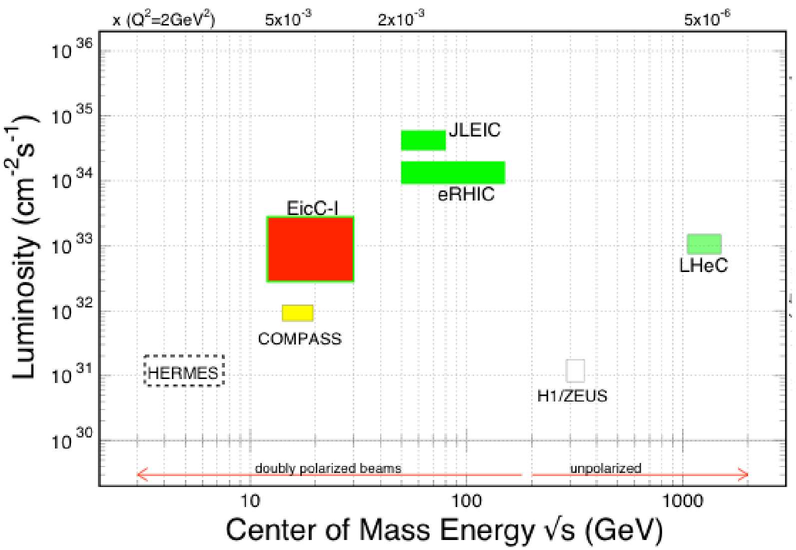
lattice

EicC

- Different production mechanisms ⇒ free of triangle singularities
- Polarization ⇒ quantum numbers
- Bottom: connected to charm, ideal to reveal the mystery of exotic hadrons (better HQS); both charm and bottom @ EicC
  - ✓ Bottom mesons and baryons: so far very few
  - ✓ $\Xi_{cc}, \Xi_{bc}, \Xi_{bb}, \ldots$
  - ✓ $X, Z_c, X_b, Z_b, \ldots$
  - ✓ $P_c, P_b, \ldots$ talk by B.-S. Zou on July 30
  - ✓ Doubly-heavy tetraq.: T_{cc}, T_{bc}, T_{bb}
  - ✓ Small-x, hybrids

Reliable cross section estimates/simulations need to be done

Complementary to



From N. Xu's talk

Refs. of photoproduction of XYZ and Pc

- XYZ

X.-H. Liu, Q. Zhao, F. E. Close, *Search for tetraquark candidate Z(4430) in meson photoproduction*, PRD77(2008)094005

J. He, X. Liu, *Discovery potential for charmonium-like state Y(3940) by the meson photoproduction*, PRD80(2009)114007

G. Galata, *Photoproduction of Z(4430) through mesonic Regge trajectories exchange*, PRC83(2011)0065203

Q.-Y. Lin, X. Liu, H.-S. Xu, *Charged charmoniumlike state $Z_c(3900)^{\pm}$ via meson photoproduction*, PRD88(2013)114009

Q.-Y. Lin, X. Liu, H.-S. Xu, *Probing charmoniumlike state X(3915) through meson photoproduction*, PRD89(2014)034016

X.-Y. Wang, X.-R. Chen, A. Guskov, *Photoproduction of the charged charmoniumlike $Z_c^+(4200)$*, PRD92(2015)094017

COMPASS, *Search for exclusive photoproduction of $Z_c^{\pm}(3900)$ at COMPASS*, PLB742(2015)330

COMPASS, *Observation of X(3872) muoproduction at COMPASS*, arXiv:1707.01796 [hep-ex]

J. Stevens, *Opportunities in Photoproduction and Spectroscopy at an EIC*, https://wiki.ge.infn.it/eic/images/d/d3/Eic_aps-1.pdf, APS meeting 2015

… …

- Pc

Y. Huang, J. He, H. F. Zhang, and X. R. Chen, *Discovery potential of hidden charm baryon resonances via photoproduction*, JPG41(2014)115004

Q. Wang, X.-H. Liu, Q. Zhao, *Photoproduction of hidden charm pentaquark states $P_c^+(4380)$ and $P_c^+(4450)$*, PRD92(2015)034022

V. Kubarovsky, M. B. Voloshin, *Formation of hidden-charm pentaquarks in photon-nucleon collisions*, PRD92(2015)031502

M. Karliner, J. Rosner, *Photoproduction of exotic baryon resonances*, PLB752(2016)329

A. N. Hiller Blin et al. (JPAC), *Studying the $P_c(4450)$ resonance in J/ψ photoproduction off protons*, PRD94(2016)034002; arXiv:1801.10211 [hep-ph]

M.-E. Meziani et al., *A Search for the LHCb Charmed 'Pentaquark' using Photo-Production of J/ψ at Threshold in Hall C at Jefferson Lab*, arXiv:1609.00676 [hep-ex]， E12-16-007 Experiment

S. Joosten, M.-E. Meziani, *Heavy Quarkonium Production at Threshold: from JLab to EIC*, arXiv:1802.02616 [hep-ex]

… …

http://www.ectstar.eu/node/4230

The spectroscopy program at EIC and future accelerators

From Wednesday, 19 December, 2018 - 08:30 to Friday, 21 December, 2018 - 14:00

Location: ECT* Conference room

Abstract:
Last decade witnessed the discovery of many states who challenged the quark model paradigm of hadrons. The workshop aims at reviewing the current status of light and heavy quark spectroscopy, with particular emphasis on exotic states, and focus on the opportunity for a comprehensive hadron spectroscopy program at the Electron-Ion collider (EIC), which is the highest priority project for the QCD community, expected to be built in the USA during the next years.

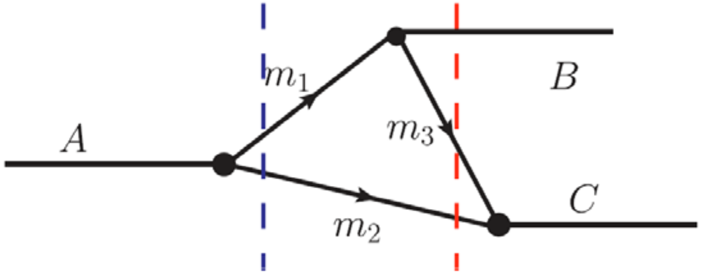
Registration period: 01 Oct 2018 to 27 Nov 2018

Organizers

Marco Battaglieri	INFN Genova	battaglieri@ge.infn.it
Alessandro Pilloni	Jefferson Lab	pillaus@jlab.org
Adam Szczepaniak	Indiana University & Jefferson Lab	aszczepa@indiana.edu

Thank you for your attention!

Triangle singularity



$$\frac{1}{2m_A}\sqrt{\lambda(m_A^2, m_1^2, m_2^2)} \equiv \boxed{p_{2,\text{left}} = p_{2,\text{right}}} \equiv \gamma\left(\beta\, E_2^* - p_2^*\right)$$

on-shell momentum of m_2 at the left and right cuts in the A rest frame

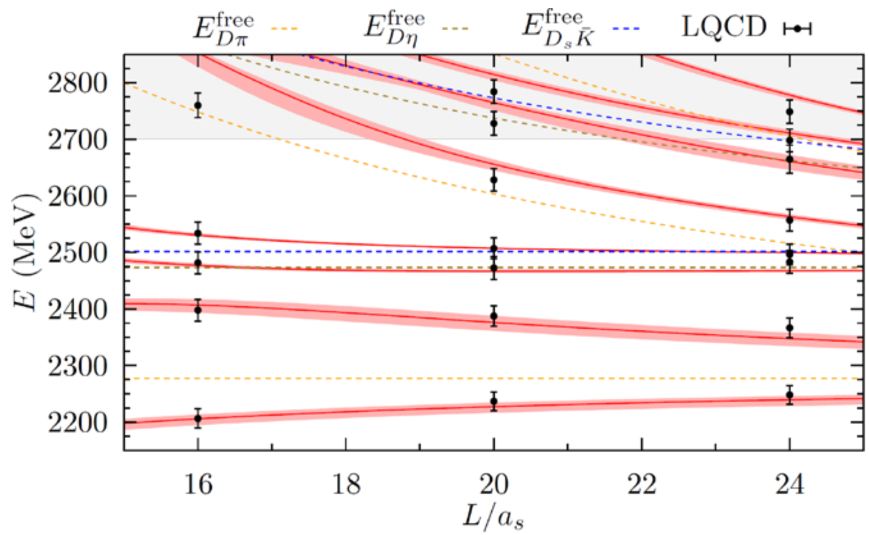
$\beta = |\vec{p}_{23}|/E_{23}, \gamma = 1/\sqrt{1-\beta^2}$ Bayar et al., PRD94(2016)074039

- $p_2 > 0, p_3 = \gamma\left(\beta\, E_3^* + p_2^*\right) > 0 \Rightarrow$ m_2 and m_3 move in the same direction
- velocities in the A rest frame: $v_3 > \beta > v_2$

$$v_2 = \beta\,\frac{E_2^* - p_2^*/\beta}{E_2^* - \beta\, p_2^*} < \beta\,, \qquad v_3 = \beta\,\frac{E_3^* + p_2^*/\beta}{E_3^* + \beta\, p_2^*} > \beta$$

- Conditions (Coleman–Norton theorem): Coleman, Norton (1965); Bronzan (1964)
  - ☞ all three intermediate particles can go on shell simultaneously
  - ☞ $\vec{p}_2 \parallel \vec{p}_3$, particle-3 can catch up with particle-2 (as a classical process)
- needs very special kinematics $\Rightarrow$ process dependent! (contrary to pole position)

Charmed mesons



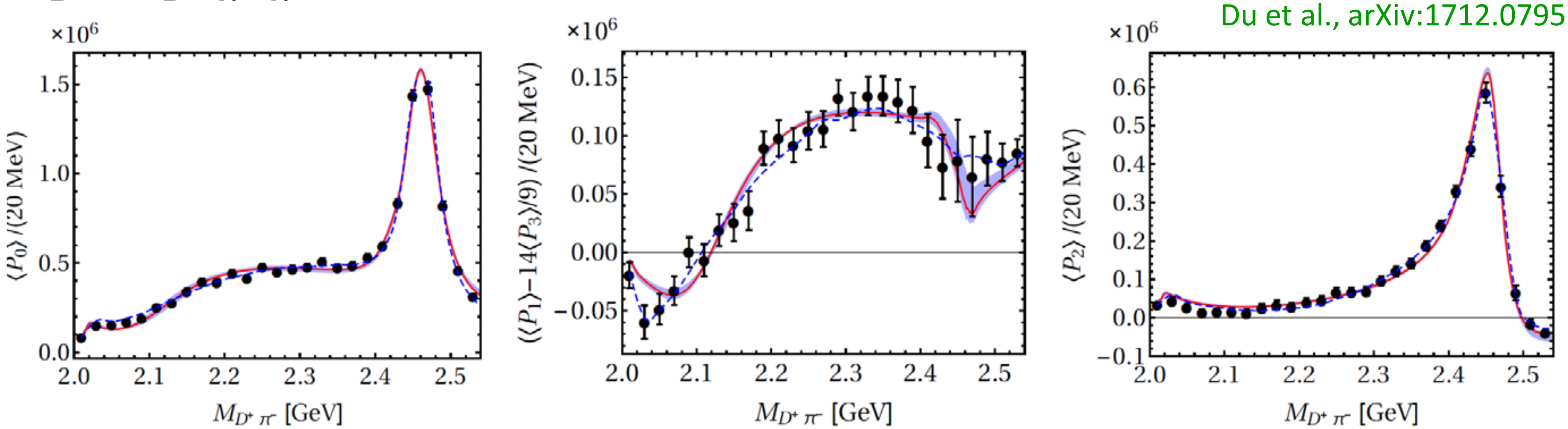
I=1/2 energy levels in finite volume

Albaladejo, Fernandez-Soler, FKG, Nieves, PLB767(2017)465

Lattice data: Moir et al., JHEP1610(2016)011

$B^- \to D^+\pi^-\pi^-$

Du et al., arXiv:1712.07957



Data: LHCb, PRD94(2016)072001

XYZ with bottom quarks

- Only two Z_b in bottomonium region (from $e^+e^- \to \Upsilon(10860,11020) \to \pi Z_b$)
- Any theory explaining XYZ states would predict similar states with bottom quarks. E.g., hadronic molecular model:

V_C	$I(J^{PC})$	States	Thresholds	Masses ($\Lambda = 0.5$ GeV)	Measurements
C_X	$0(1^{++})$	$\frac{1}{\sqrt{2}}(D\bar{D}^* - D^*\bar{D})$	3875.87	**3871.68 (input)**	3871.68 ± 0.17 PDG [$X(3872)$]
	$0(2^{++})$	$D^*\bar{D}^*$	4017.3	4012^{+4}_{-5}	?
	$0(1^{++})$	$\frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})$	10604.4	10580^{+9}_{-8}	?
	$0(2^{++})$	$B^*\bar{B}^*$	10650.2	10626^{+8}_{-9}	?
	$0(2^{+})$	D^*B^*	7333.7	7322^{+6}_{-7}	?
C_Z	$1(1^{+-})$	$\frac{1}{\sqrt{2}}(B\bar{B}^* + B^*\bar{B})$	10604.4	10602.4 ± 2.0 **(input)**	10607.2 ± 2.0 Belle [$Z_b(10610)$]
	$1(1^{+-})$	$B^*\bar{B}^*$	10650.2	10648.1 ± 2.1	10652.2 ± 1.5 Belle [$Z_b(10650)$]
	$1(1^{+-})$	$\frac{1}{\sqrt{2}}(D\bar{D}^* + D^*\bar{D})$	3875.87	3871^{+4}_{-12} (V)	$3899.0 \pm 3.6 \pm 4.9$ BESIII [$Z_c(3900)$]
					$3894.5 \pm 6.6 \pm 4.5$ Belle
					$3886 \pm 4 \pm 2$ CLEO-c
	$1(1^{+-})$	$D^*\bar{D}^*$	4017.3	4013^{+4}_{-11} (V)	$4026.3 \pm 2.6 \pm 3.7$ BESIII [$Z_c(4020)$]
	$1(1^{+})$	D^*B^*	7333.7	$7333.6^{\dagger}_{-4.2}$ (V)	?