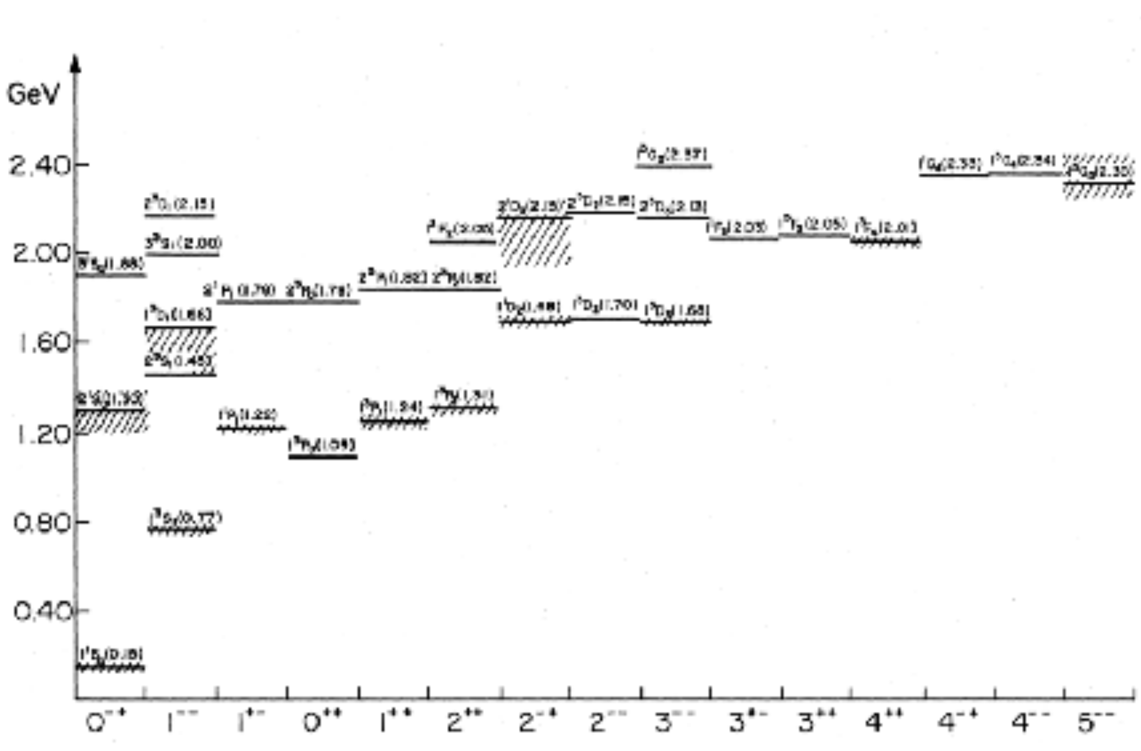
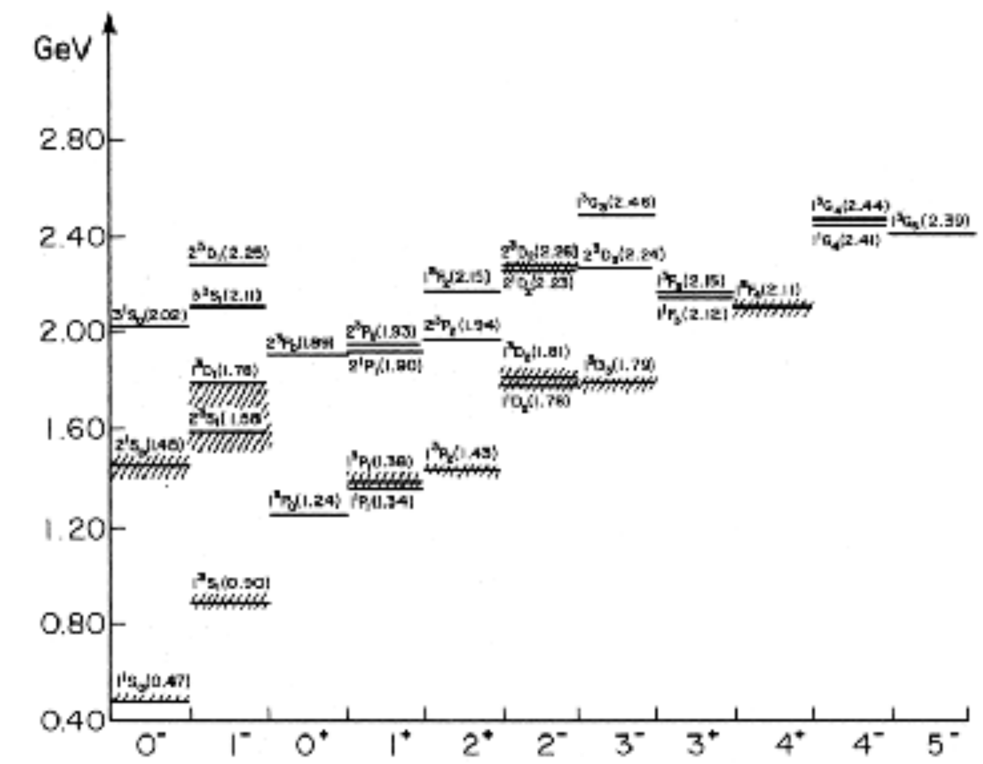
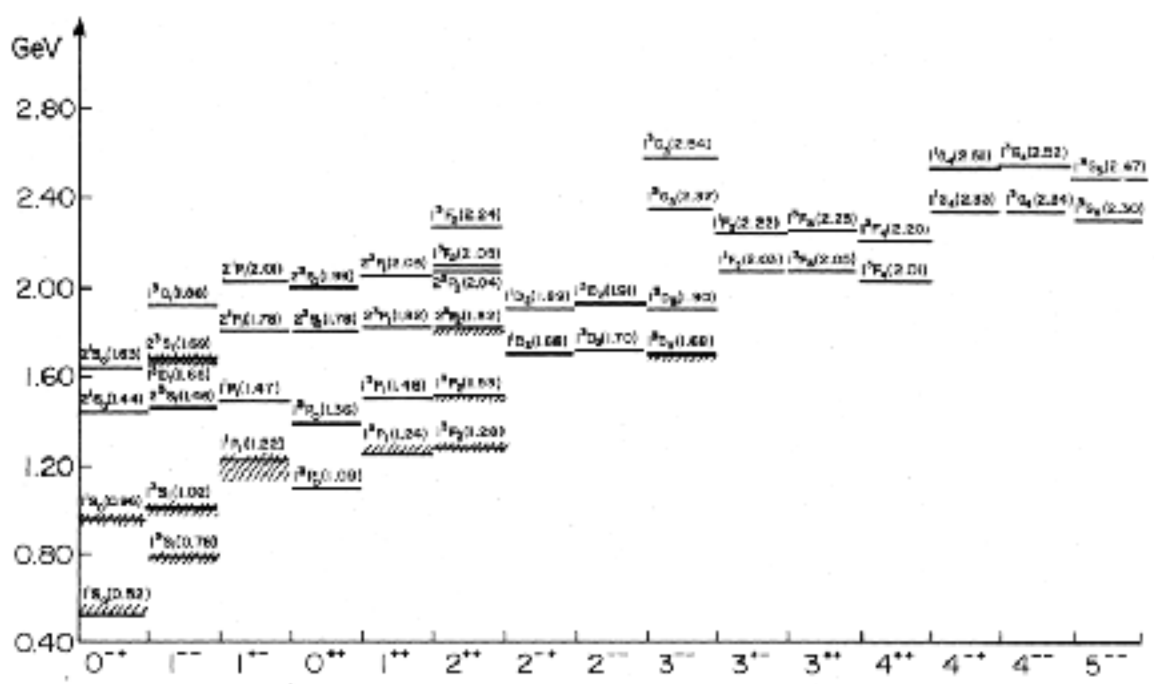
Sept, 2017

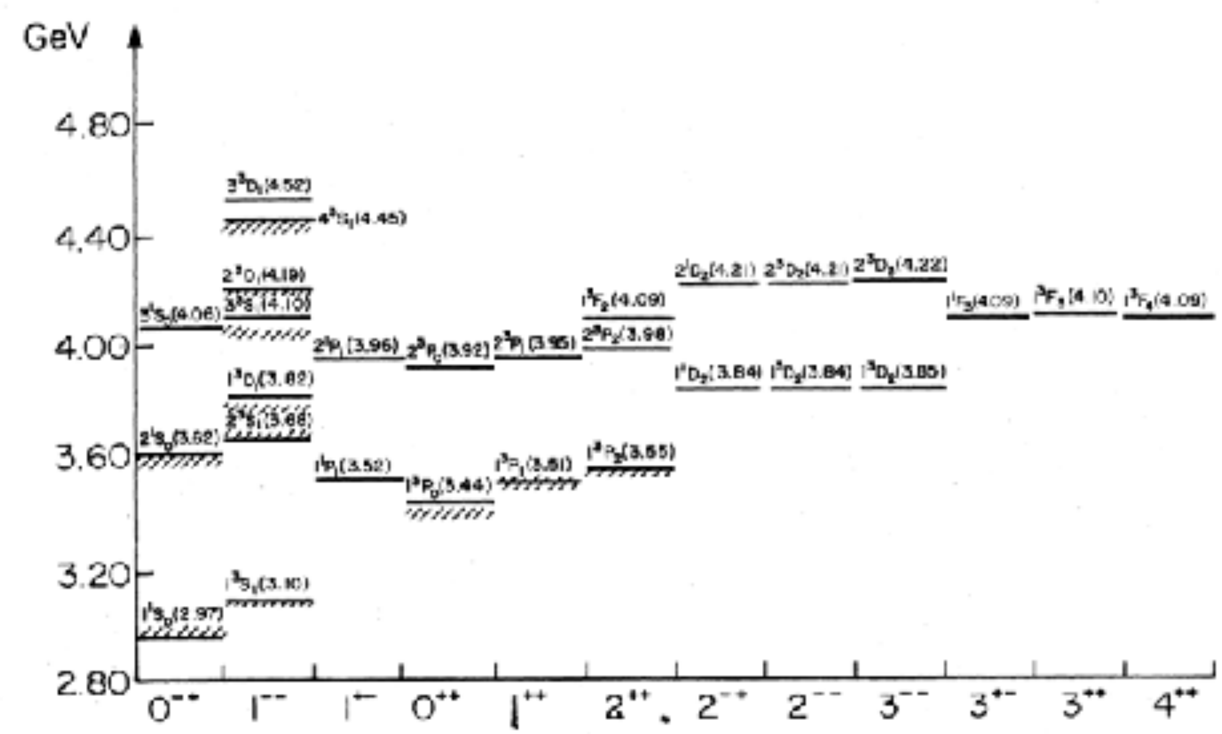
XYZ Theory

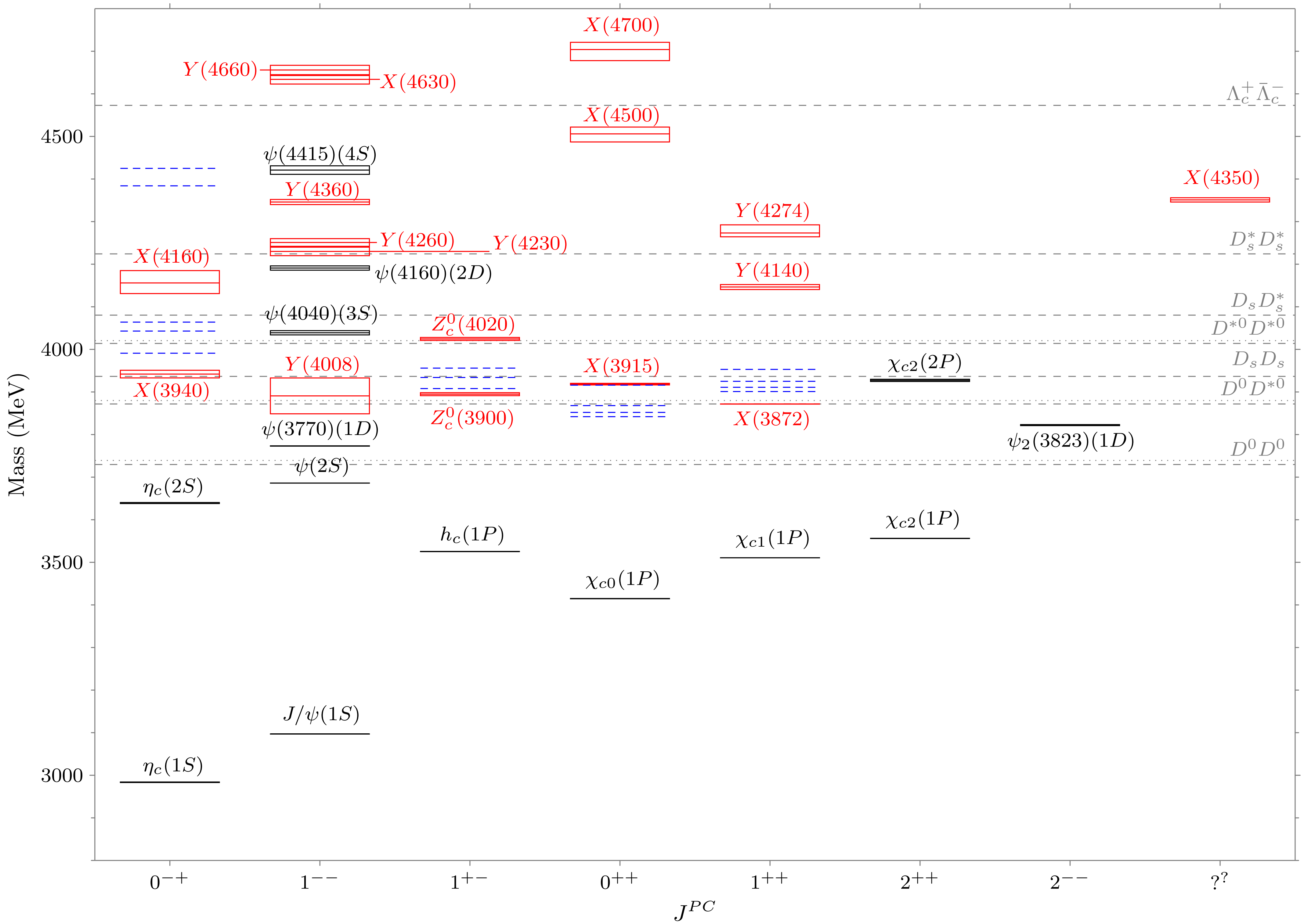
Eric Swanson


GeV
2.40
2.00
1.60
1.20
0.80
0.40
0⁻⁺ 1⁻⁻ 1⁺⁻ 0⁺⁺ 1⁺⁺ 2⁺⁺ 2⁻⁺ 2⁻⁻ 3⁻⁻ 3⁺⁻ 3⁺⁺ 4⁺⁺ 4⁻⁺ 4⁻⁻ 5⁻⁻


GeV
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0⁻ 1⁻ 0⁺ 1⁺ 2⁺ 2⁻ 3⁻ 3⁺ 4⁺ 4⁻ 5⁻


GeV
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0⁻⁺ 1⁻⁻ 1⁺⁻ 0⁺⁺ 1⁺⁺ 2⁺⁺ 2⁻⁺ 2⁻⁻ 3⁻⁻ 3⁺⁻ 3⁺⁺ 4⁺⁺ 4⁻⁺ 4⁻⁻ 5⁻⁻


GeV
4.80
4.40
4.00
3.60
3.20
2.80
0⁻⁺ 1⁻⁻ 1⁺⁻ 0⁺⁺ 1⁺⁺ 2⁺⁺ 2⁻⁺ 2⁻⁻ 3⁻⁻ 3⁺⁻ 3⁺⁺ 4⁺⁺

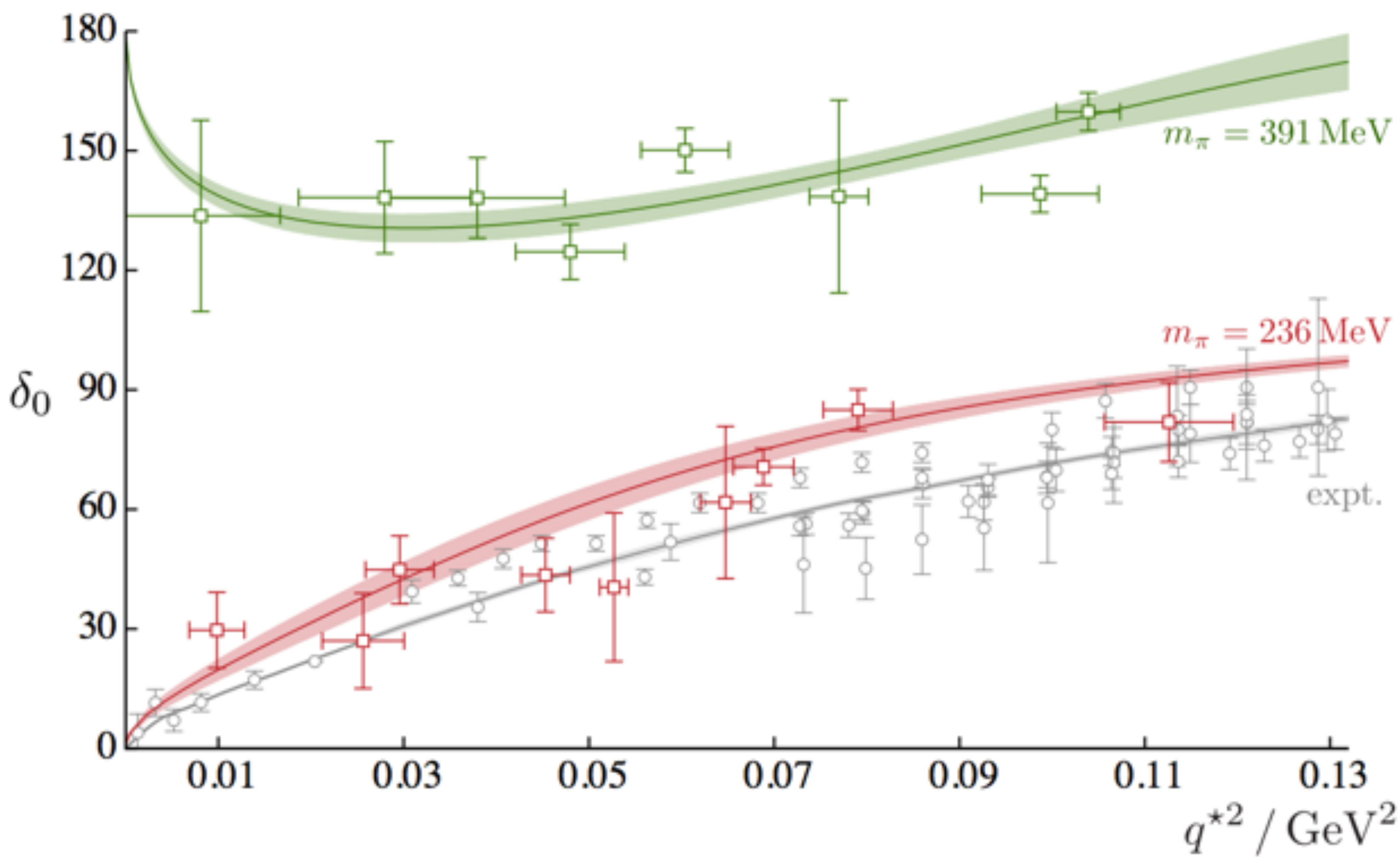


Mass (MeV)
4500
4000
3500
3000
J^{PC}
0^{-+}
1^{--}
1^{+-}
0^{++}
1^{++}
2^{++}
2^{--}
$?^?$
$X(4700)$
$Y(4660)$
$X(4630)$
$\Lambda_c^+\bar{\Lambda}_c^-$
$X(4500)$
$\psi(4415)(4S)$
$Y(4360)$
$X(4350)$
$Y(4274)$
$Y(4260)$
$Y(4230)$
$D_s^*D_s^*$
$X(4160)$
$\psi(4160)(2D)$
$Y(4140)$
$D_sD_s^*$
$\psi(4040)(3S)$
$Z_c^0(4020)$
$D^{*0}\bar{D}^{*0}$
$Y(4008)$
$X(3915)$
$\chi_{c2}(2P)$
D_sD_s
$X(3940)$
$D^0\bar{D}^{*0}$
$Z_c^0(3900)$
$X(3872)$
$\psi(3770)(1D)$
$\psi_2(3823)(1D)$
$D^0\bar{D}^0$
$\psi(2S)$
$\eta_c(2S)$
$h_c(1P)$
$\chi_{c1}(1P)$
$\chi_{c2}(1P)$
$\chi_{c0}(1P)$
$J/\psi(1S)$
$\eta_c(1S)$

Lattice Scattering

Briceno, R. A., J. J. Dudek, R. G. Edwards, and D. J. Wilson (2017a), Phys. Rev. Lett. 118 (2), 022002.

Raul A. Briceno, Jozef J. Dudek, and Ross D. Young, Scattering processes and resonances from lattice QCD, arXiv:1706.06223



I=0 pi pi S-wave. Green: pole on the real axis at 758 MeV — bound state just below 2 mpi=782.

Zc(3900)

$\pi\pi J/\psi$
$\pi D\bar{D}^*$

$Z_c(3900)$

$\pi\pi h_c$
$\pi D^*\bar{D}^*$

$Z_c(4025)$

$K\pi\chi_{cJ}$
$\pi\psi(2S)$

$Z_1(4050)$
$Z_2(4250)$

$K\pi J/\psi$

$Z_c(4200)$

$\pi K\psi'$

$Z_c(4240)$
$Z_c(4475)$

$\pi\pi\Upsilon(nS)$
$\pi\pi h_b(nP)$
$\pi B\bar{B}^*$

$Z_b(10610)$
$Z_b(10650)$

Zc(3900) & Loops

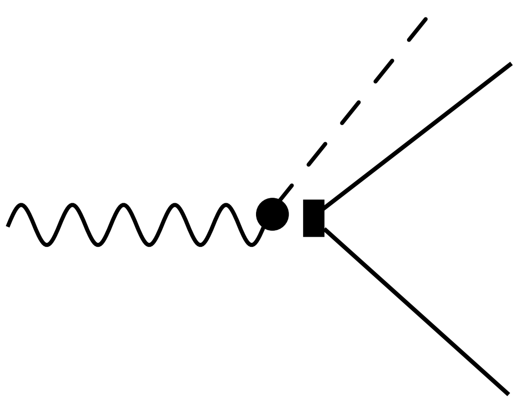
D. V. Bugg, Europhys. Lett. 96, 11002 (2011)

D. V. Bugg, Int. J. Mod. Phys. A 24, 394 (2009)

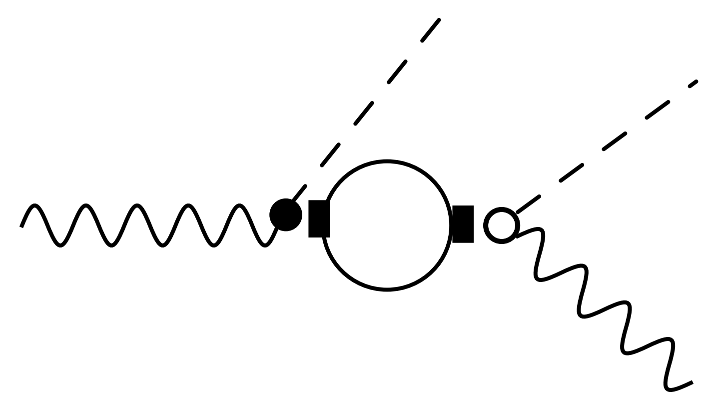
Attempt a "microscopic" cusp model.

[separable nonrelativistic model; solve exactly]

[iterate all bubbles]



$Y(4260) \to \pi D\bar{D}^*$



$Y(4260) \to \pi\pi J/\psi$

$$g_{DD^*} \cdot \exp(-\lambda(s_{\pi Y})/\beta^2_{\pi Y}) \exp(-\lambda(s_{DD^*})/\beta^2_{DD^*})$$

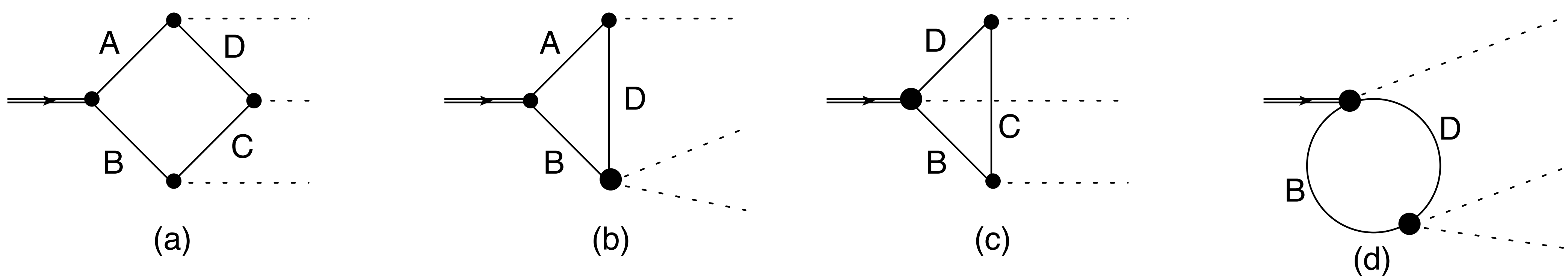
Zc(3900) & Loops

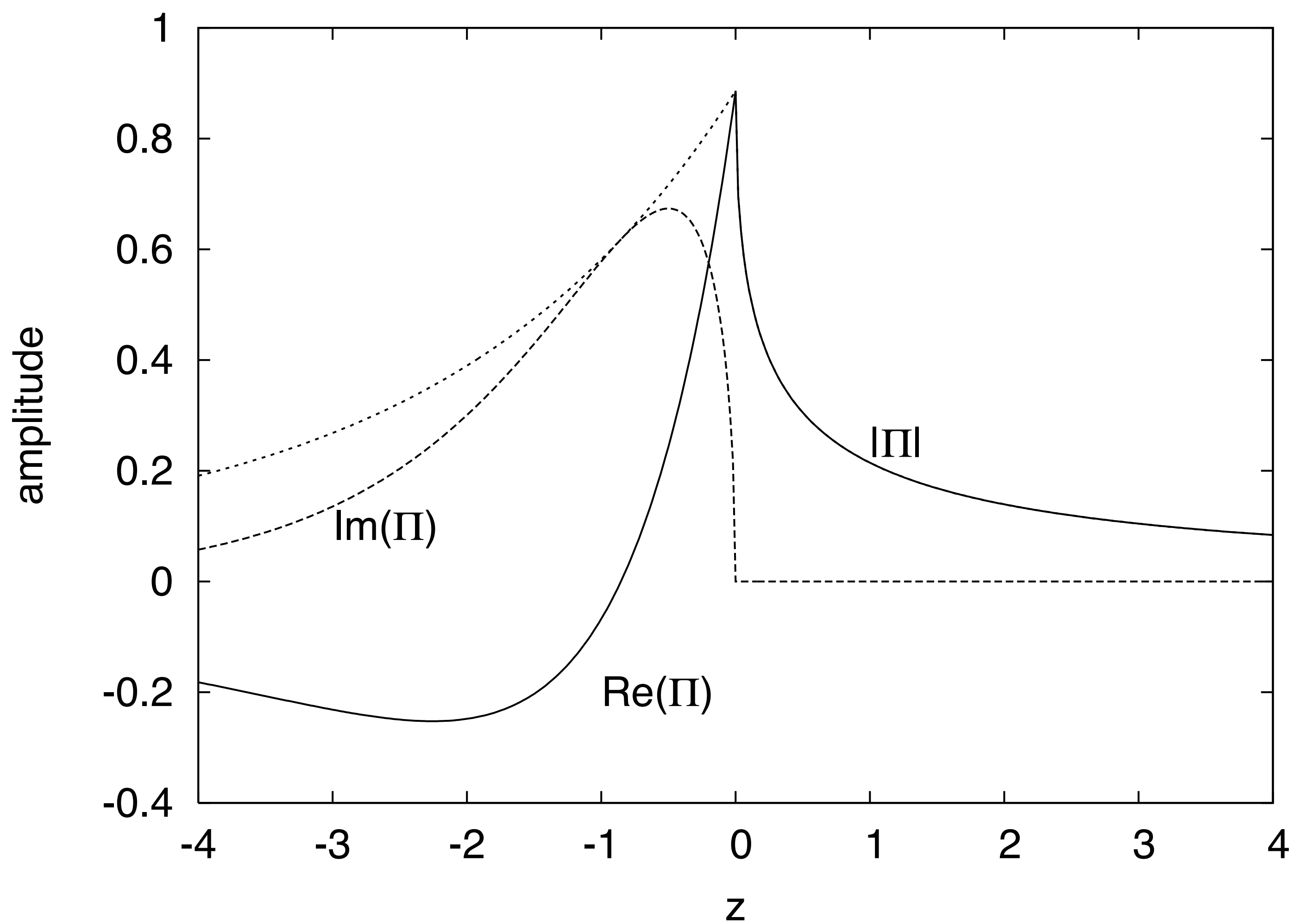
E.P. Wigner, Phys. Rev. 73 (1948) 1002

D. V. Bugg, Europhys. Lett. 96, 11002 (2011)

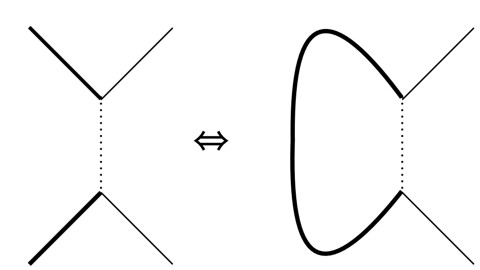
D. V. Bugg, Int. J. Mod. Phys. A 24, 394 (2009)

E.S. Swanson, arXiv:1409.3291

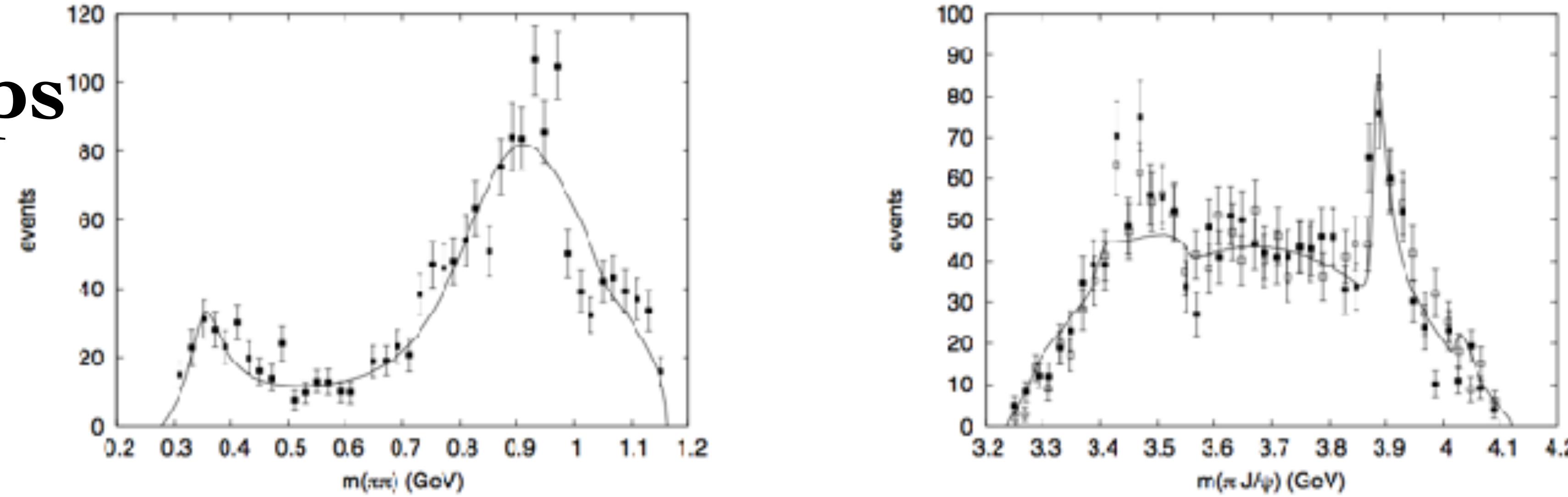




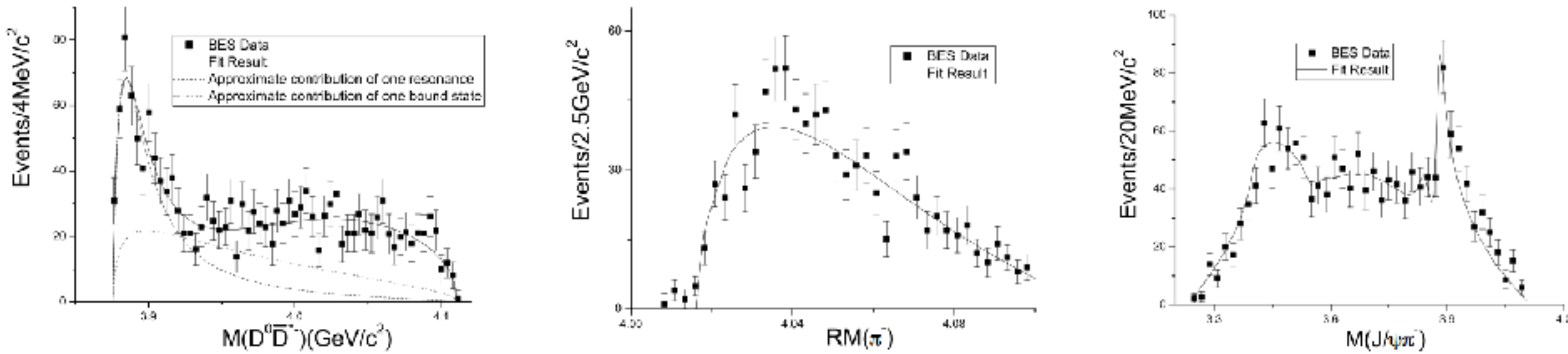
and are related to thresholds



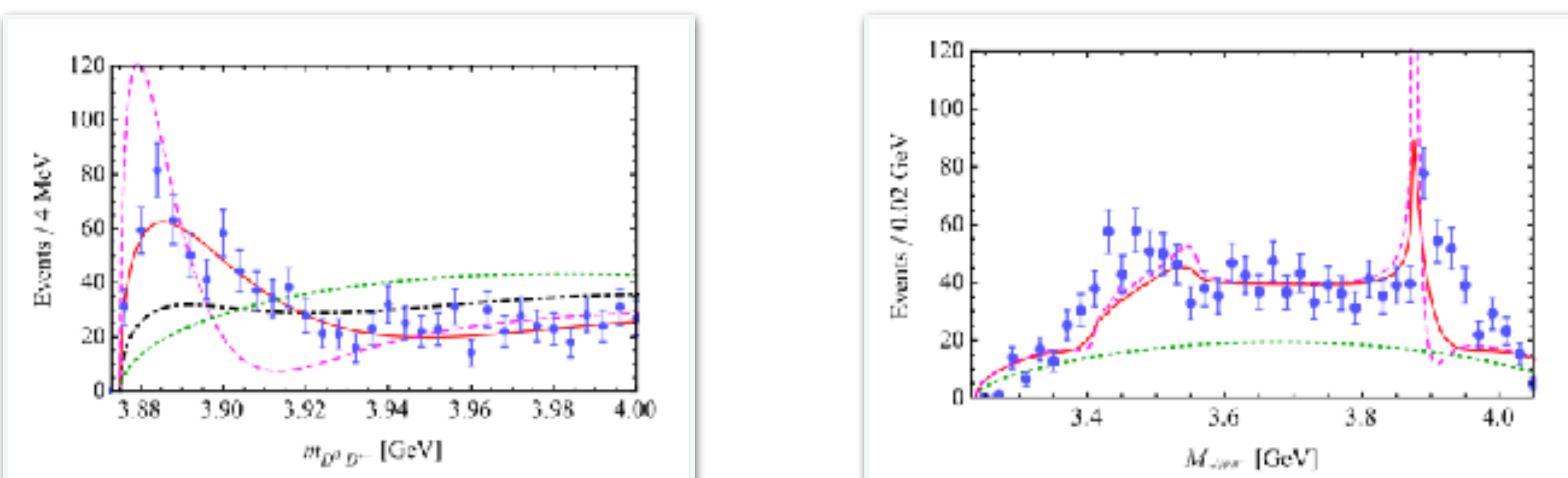
Zc(3900) & Loops



E.S. Swanson, ``Cusps and Exotic Charmonia,'' arXiv:1504.07952 [hep-ph].



Z.Y. Zhou and Z. Xiao, ``Distinguishing cusp effects and near-threshold-pole effects,'' arXiv:1505.05761 [hep-ph].



F.K. Guo, C. Hanhart, Q. Wang and Q. Zhao, `Could the near-threshold XYZ states be simply kinematic effects?,''
Phys. Rev. D {91}, no. 5, 051504 (2015)

Zc(3900) & Loops

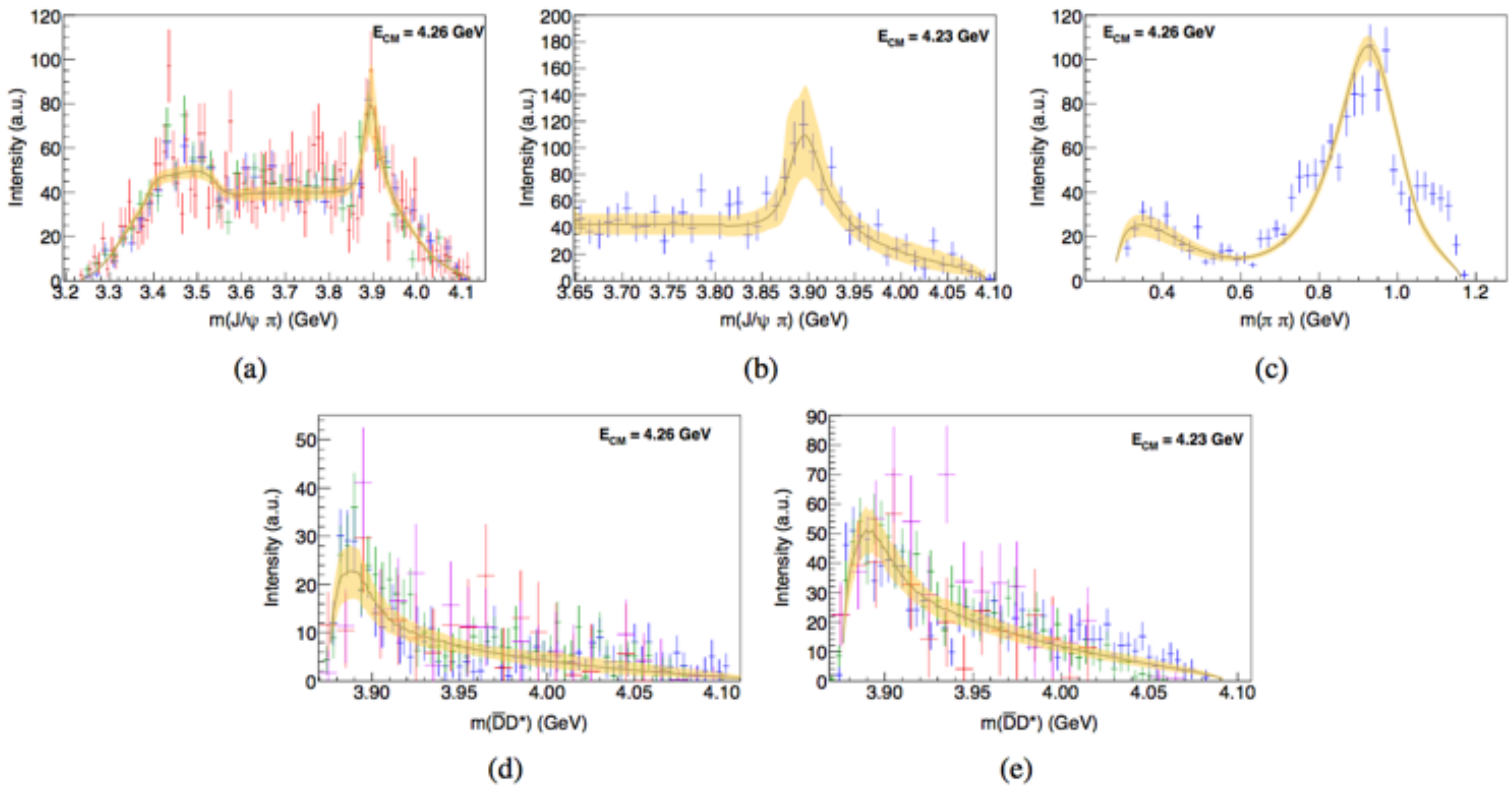
A. Pilloni et al [JPAC] Amplitude analysis and the nature of the $Z_c(3900)$ arXiv:1612.06490

$$f_i(s,t,u) = 16\pi \sum_{l=0}^{L_{\max}} (2l+1)\left(a_{l,i}^{(s)}(s)P_l(z_s) + a_{l,i}^{(t)}(t)P_l(z_t) + a_{l,i}^{(u)}(u)P_l(z_u)\right)$$

- K-matrix with poles on the sheet closest to the real axis
- as above + logarithmic branch cut from a triangle singularity
- constant K-matrix + triangle
- as above, but force any poles in t to be far removed (tests the triangle)

Zc(3900) & Loops

A. Pilloni et al [JPAC] Amplitude analysis and the nature of the $Z_c(3900)$ arXiv:1612.06490



Unable to distinguish scenarios with only mass projections

Zc(3900) & Lattice

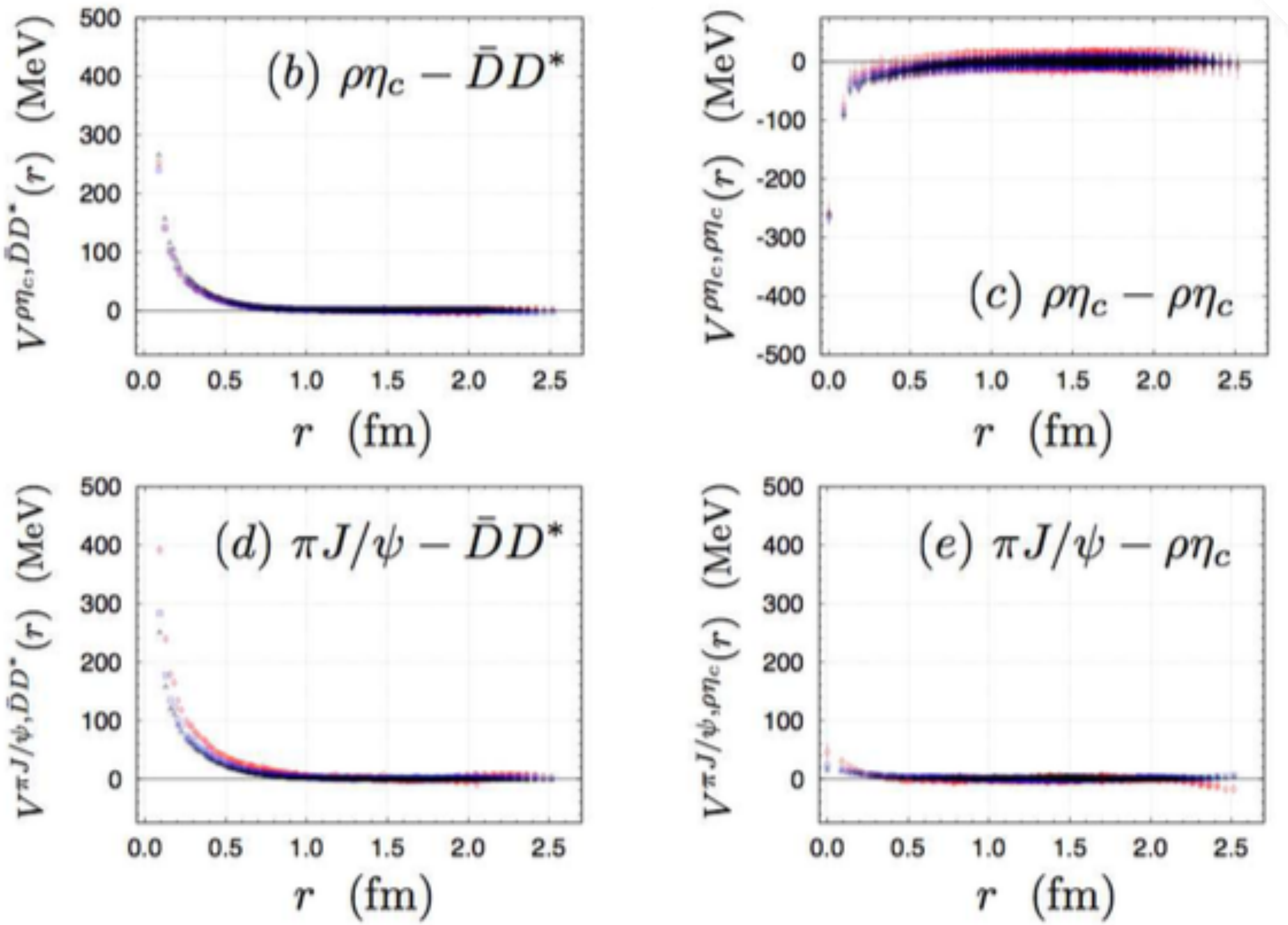
S. Prelovsek and L. Leskovec, Phys. Lett. B 727, 172 (2013);
S. Prelovsek et al., Phys. Rev. D 91, no. 1, 014504 (2015).

Unable to find *Zc* with local operators.

Y. Ikeda et al. [HAL QCD] Fate of the Tetraquark Candidate Z_c(3900) from Lattice QCD
arXiv:1602.03465v2 Phys. Rev. Lett. 117, 242001 (2016)

- Examine $\pi J/\psi,\, \rho\eta_c,\, \bar{D}D^*$ channels and extract "interactions" from the Bethe-Salpeter equation.
- "HAL-QCD method" [not yet tested on conventional resonances!]
- Relate a correlator to a "Schroedinger-type equation" w/ velocity expansion.

Zc(3900) & Lattice

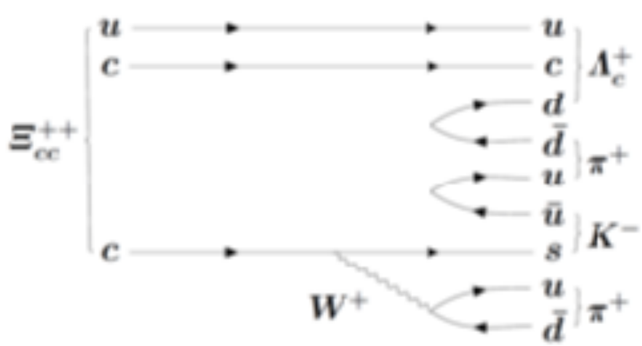


Plug into a T-matrix equation, determine that Zc is a threshold cusp effect.

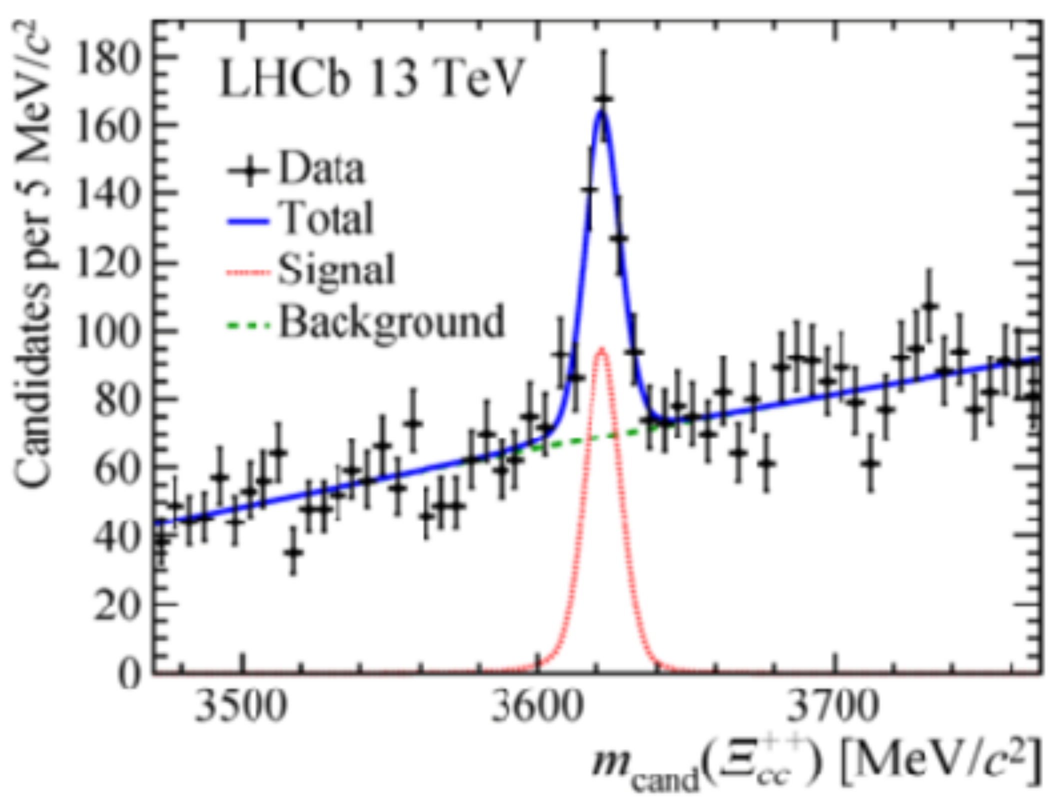
Xi_{cc}

6 July 2017: Observation of an exceptionally charming particle.

[$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14$ MeV/c^2]



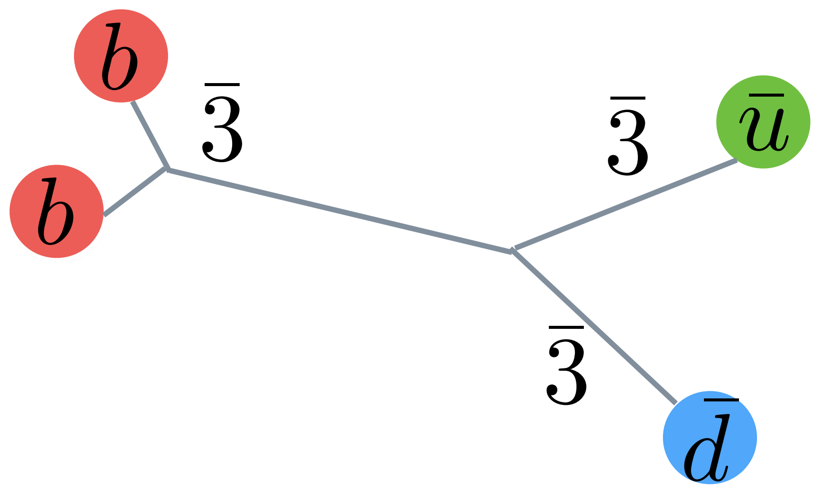
Today, at the EPS Conference on High Energy Physics, EPS-HEP 2017, in Venice, Italy, the LHCb collaboration presented the first observation of a doubly charmed particle. This particle, called the Ξ_{cc}^{++}, is a baryon (particle composed of three quarks) containing two charm quarks and one up quark, resulting in an overall doubly positive charge. It is a doubly charm counterpart of the well-known lower mass Ξ^0 baryon, which is composed of two strange quarks and an up quark.



The Ξ_{cc}^{++} baryon is identified via its decay into a Λ_c^+ baryon and three lighter mesons K^-, π^+ and π^+. The image above shows an example of a Feynman diagram contributing to this decay. The Λ_c^+ baryon decays in turn into a proton p, a K^- and a π^+ meson. The image shows the $\Lambda_c^+ K^- \pi^+ \pi^+$ invariant mass spectrum obtained with 1.7 fb^{-1} of data collected by LHCb in 2016 at the LHC centre-of-mass energy of 13 TeV. The mass is measured to be about 3621 MeV/c^2 which is almost four times heavier than the most familiar baryon, the proton, a property that arises from its doubly charmed-quark content. The signal candidates are consistent with particles that traveled a significant distance before decaying: even selecting only those Ξ_{cc}^{++} particles that survived more than approximately five times the expected decay time resolution, the signal remains highly significant. This state is therefore incompatible with a strongly decaying particle, but is consistent with a longer-lived decay involving weak interactions as would be expected for this particle.

$\mathrm{Xi_{cc}}$ & bb Tetraquarks

Marek Karliner and Jonathan L. Rosner arXiv:1707.07666



Discovery of doubly-charmed Ξ_{cc} baryon implies a stable $bb\bar{u}\bar{d}$ tetraquark $J^P = 1^+$

Assume colour/space factorize (as in weak coupling) so QQ interaction strength is 1/2 QQ~ . Take (ud) w/ I=0 S=0

Xi_{cc} & bb Tetraquarks

Marek Karliner and Jonathan L. Rosner arXiv:1707.07666

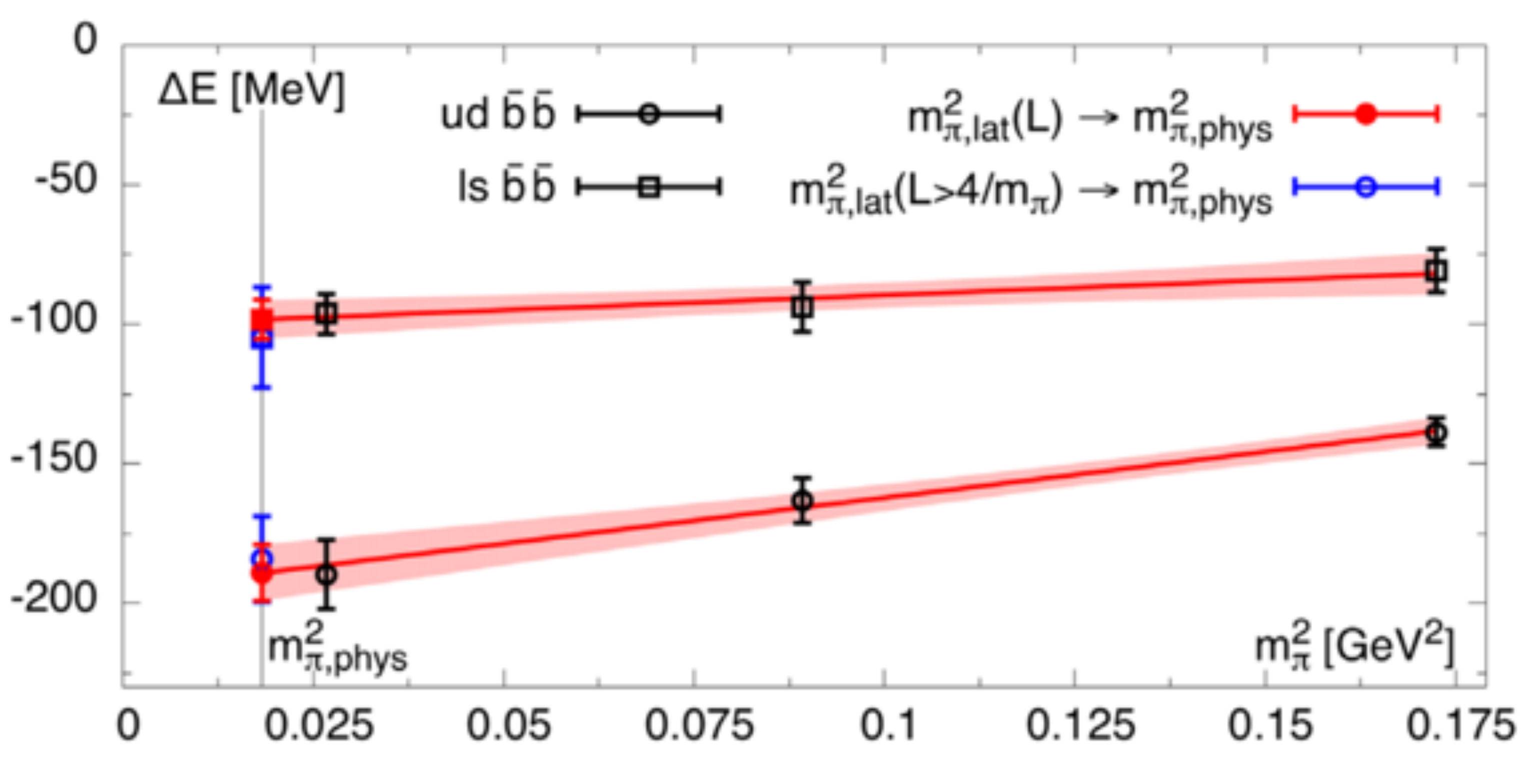
State (mass in MeV)	Spin	Expression for mass [24]	Predicted mass (MeV)
$N(939)$	$1/2$	$3m_q^b - 3a/(m_q^b)^2$	939
$\Delta(1232)$	$3/2$	$3m_q^b + 3a/(m_q^b)^2$	1239
$\Lambda(1116)$	$1/2$	$2m_q^b + m_s^b - 3a/(m_q^b)^2$	1114
$\Sigma(1193)$	$1/2$	$2m_q^b + m_s^b + a/(m_q^b)^2 - 4a/m_q^b m_s^b$	1179
$\Sigma(1385)$	$3/2$	$2m_q^b + m_s^b + a/(m_q^b)^2 + 2a/m_q^b m_s^b$	1381
$\Xi(1318)$	$1/2$	$2m_s^b + m_q^b + a/(m_s^b)^2 - 4a/m_q^b m_s^b$	1327
$\Xi(1530)$	$3/2$	$2m_s^b + m_q^b + a/(m_s^b)^2 + 2a/m_q^b m_s^b$	1529
$\Omega(1672)$	$3/2$	$3m_s^b + 3a/(m_s^b)^2$	1682

- Predict a stable $bb\bar{u}\bar{d}$ 1+ state at 10389, 215 MeV below BB* and 170 MeV below BBγ
- $bc\bar{u}\bar{d}$ might be below threshold too
- Electroweak decay modes, eg $(bb\bar{u}\bar{d})\rightarrow\bar{B}D\pi^+$

Xi_{cc} & bb Tetraquarks

A. Francis et al., PRL 118, 142001 (2017)

- NRQCD for the b quarks
- employ dq-DQ and BB* operators
- pions at 415, 299, 164 MeV

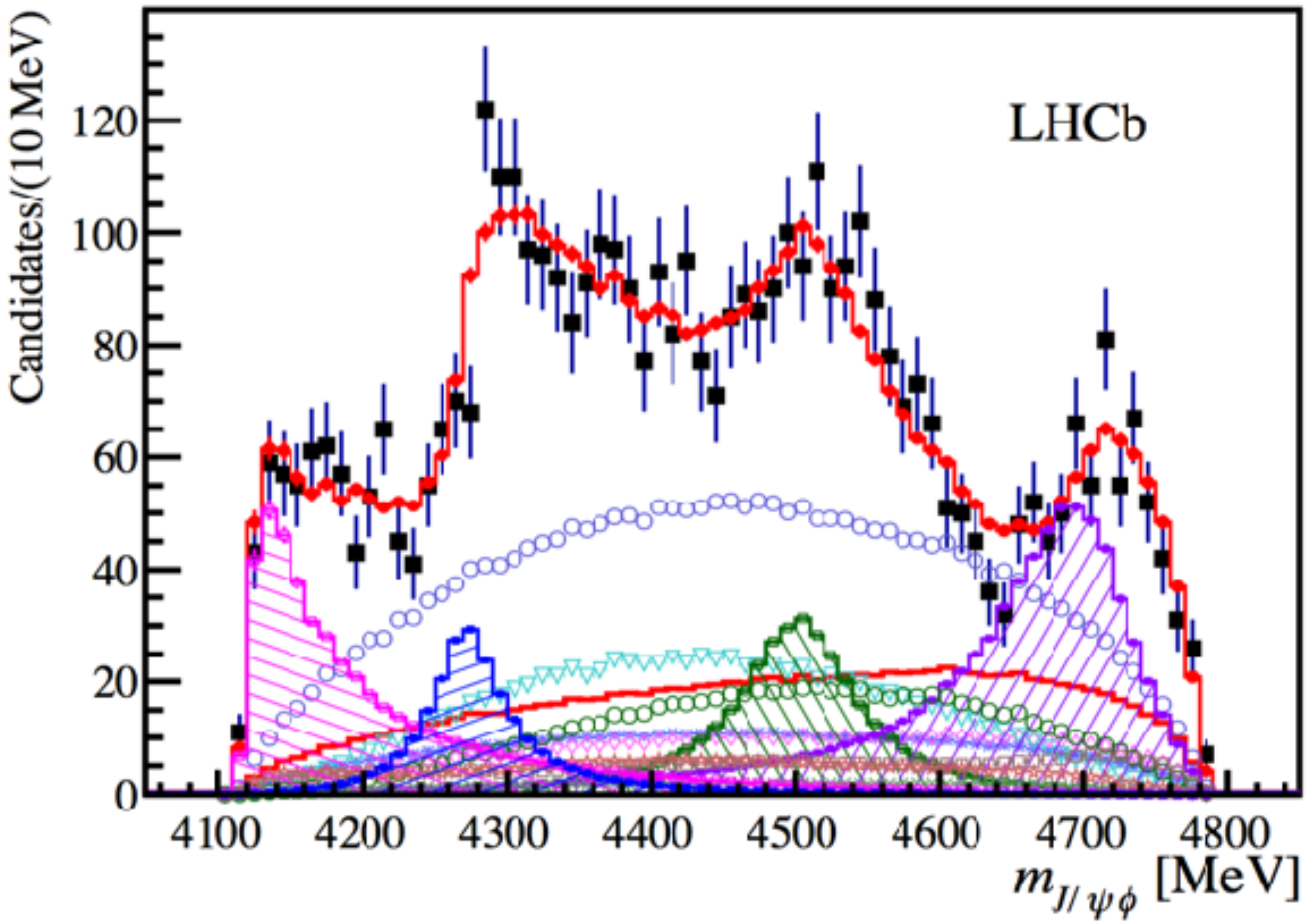


$$J^P = 1^+,\ I = 0$$

LHCb Tetraquarks

arXiv:1606.07895v1

$B \to KJ/\psi\phi$



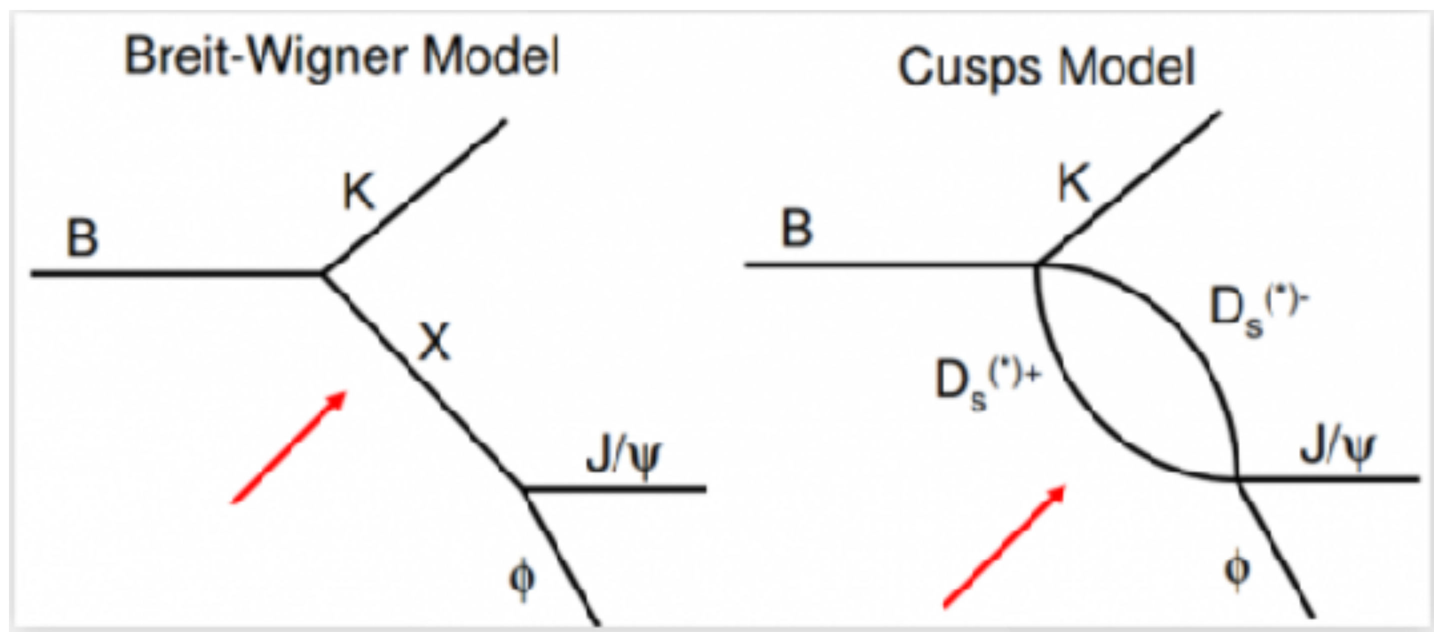
State	Mass (unct.) [MeV]	Width (unct.) [MeV]	J^{PC}
$Y(4140)$	4165.5(5,3)	83(21,16)	1^{++}
$Y(4274)$	4273.3(8,11)	56(11,10)	1^{++}
$X(4500)$	4506(11,13)	92(21,21)	0^{++}
$X(4700)$	4704(10,19)	120(31,35)	0^{++}

LHCb Tetraquarks

arXiv:1606.07895v1

PHYSICAL REVIEW D 91, 034009 (2015)

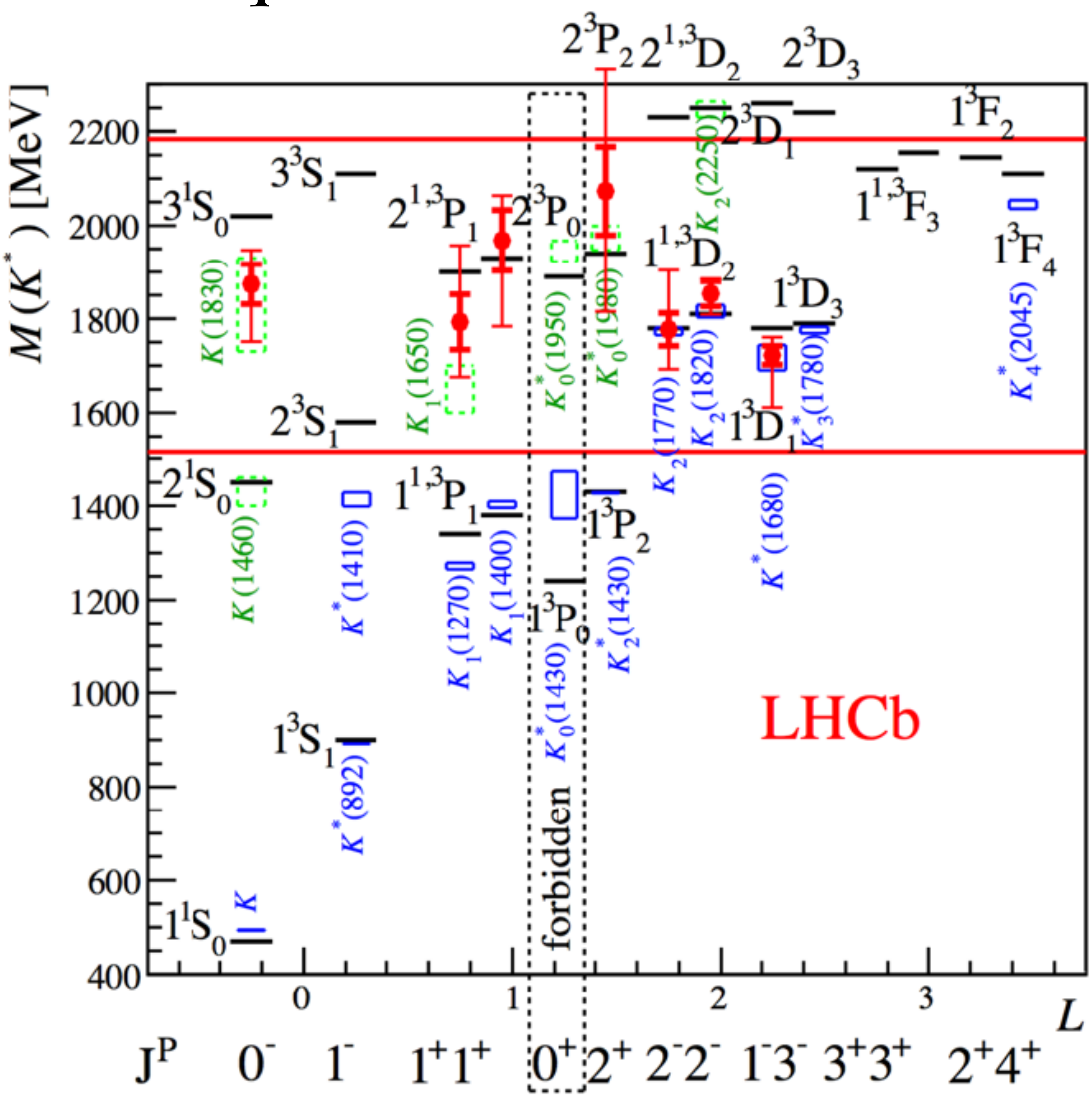
(v) similarly, $\bar{B}_s \to J/\psi\varphi\varphi$ and $\bar{B}_0 \to J/\psi\varphi K$ should exhibit cusp effects at $D_s\bar{D}_s^*$ and $D_s^*\bar{D}_s^*$ thresholds, while $\bar{B}_0 \to J/\psi\eta K$ will display $D\bar{D}^*$, $D^*\bar{D}^*$, $D_s\bar{D}_s^*$, and $D_s^*\bar{D}_s^*$ cusp enhancements;



Sobre todo desde que se publicó el modelo tipo cusp Ds⁺Ds⁻ para estos tetraquarks (E.S. Swanson, "Cusps and Exotic Charmonia," arXiv:1504.07952 [hep-ph]). Estos modelos

LHCb Tetraquarks

arXiv:1606.07895v1



red: LHCb fit
black GI
blue: PDG
green: unconfirmed

Pentaquarks

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

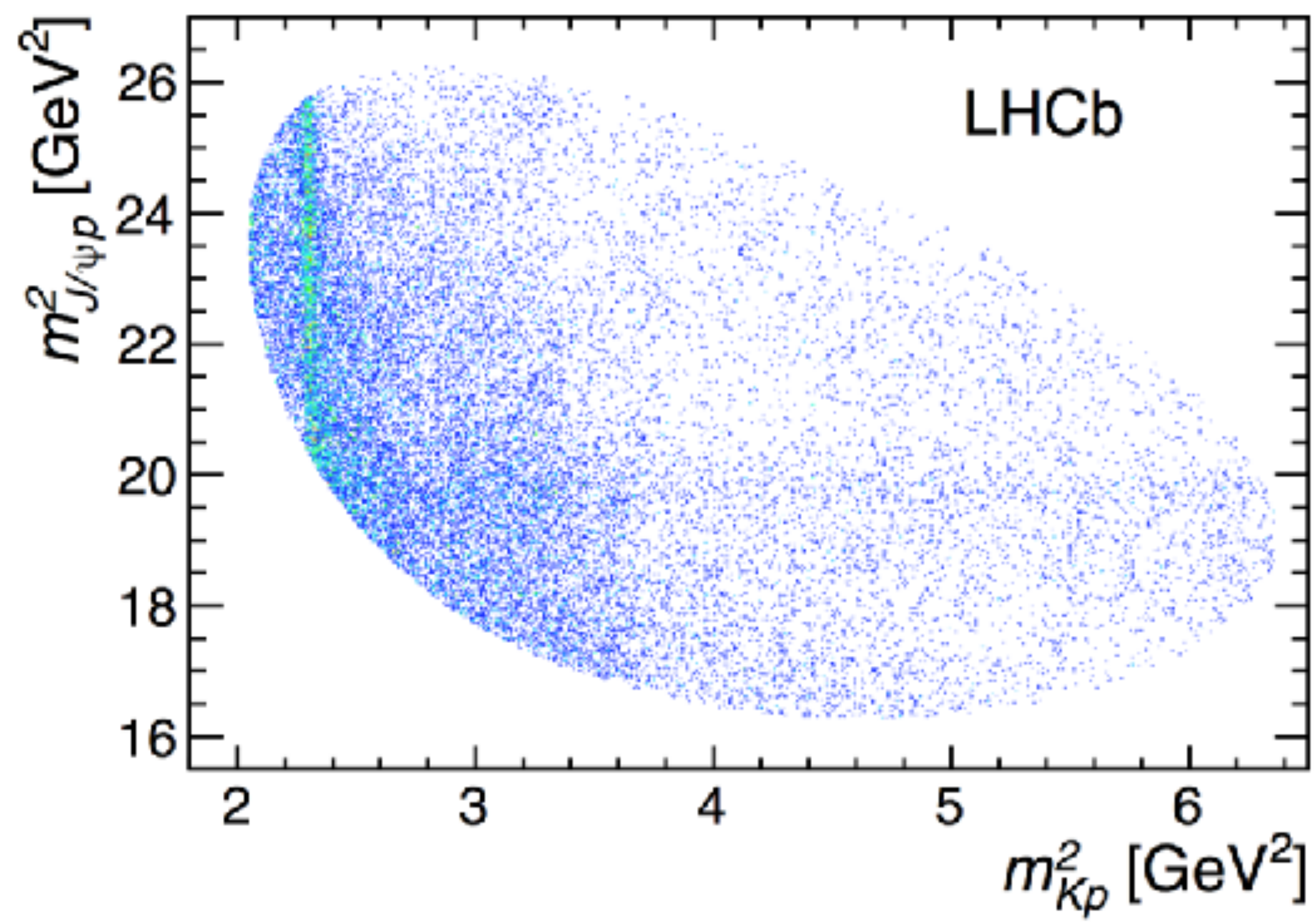
$P_c(4450)$ $\quad \Gamma = 39 \pm 5 \pm 19 \text{ MeV}$

$P_c(4380)$ $\quad \Gamma = 205 \pm 18 \pm 86 \text{ MeV}$

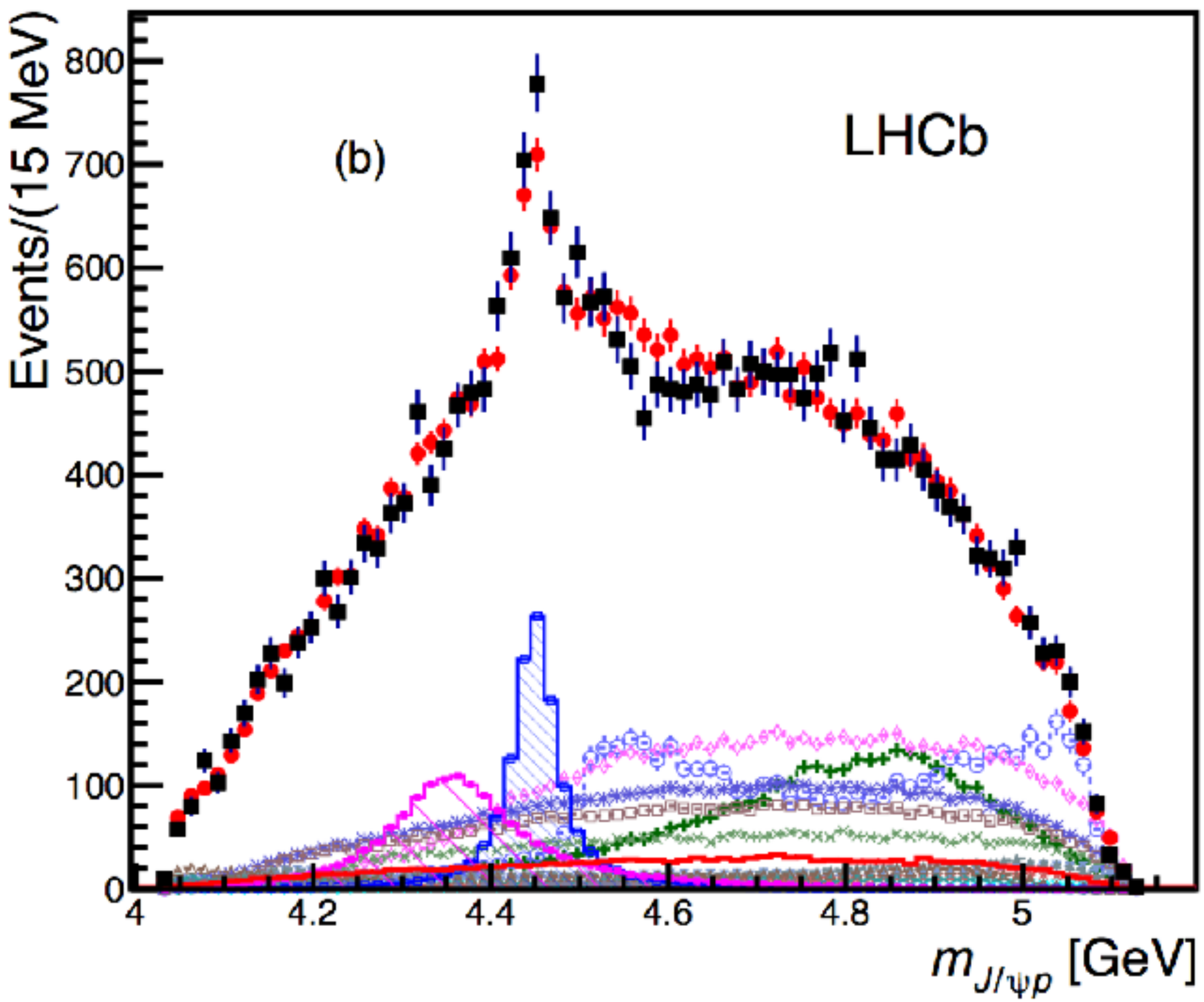
LHCb 1507.03414v2

$$J^P = \frac{3}{2}^{\pm}$$

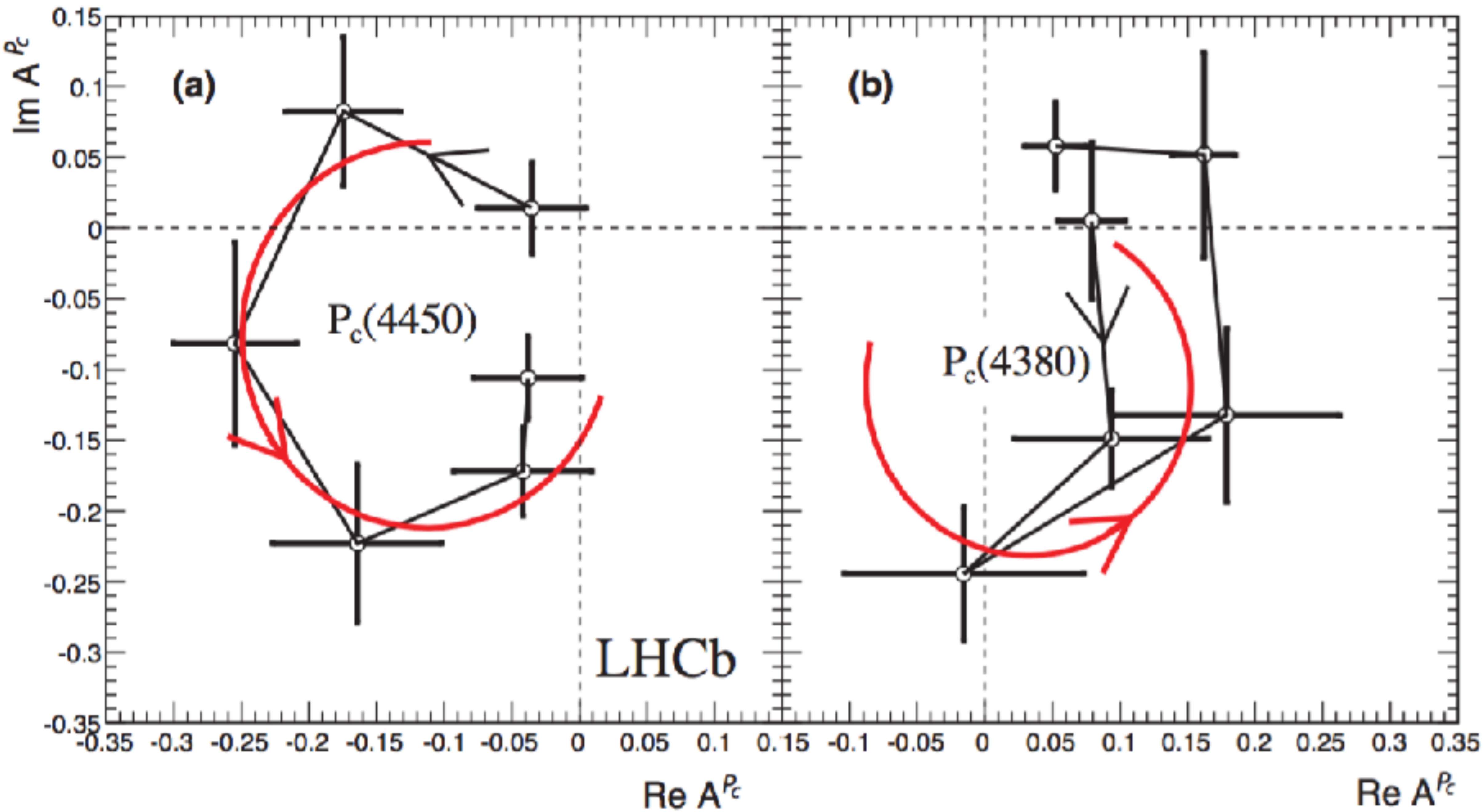
$$J^P = \frac{5}{2}^{\mp}$$



Pentaquarks

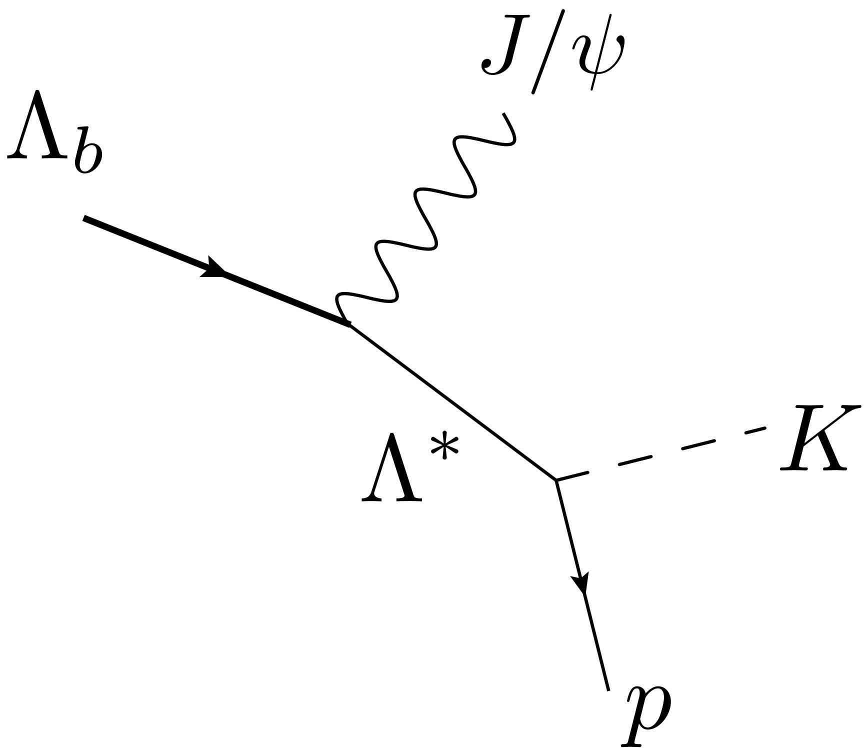


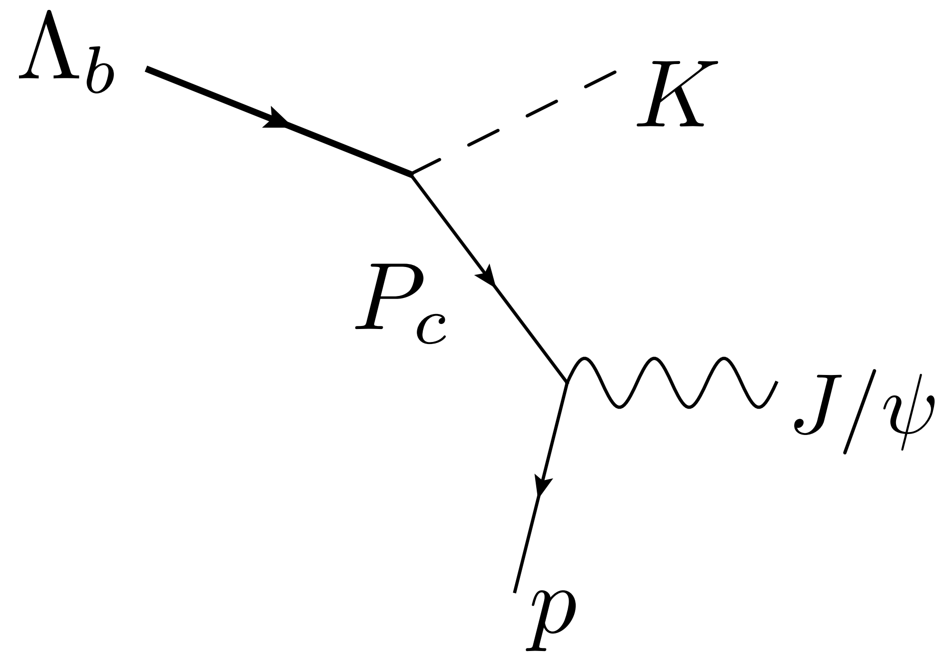
Pentaquarks

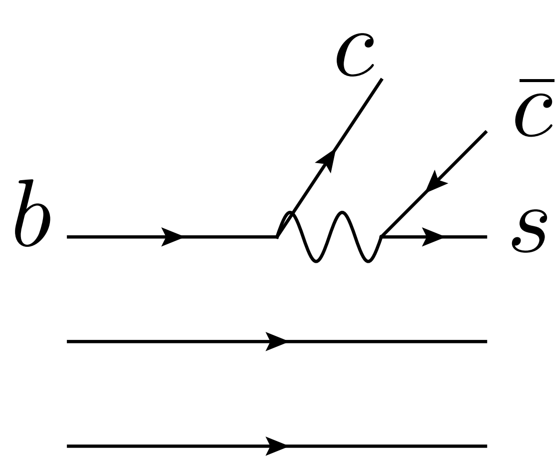


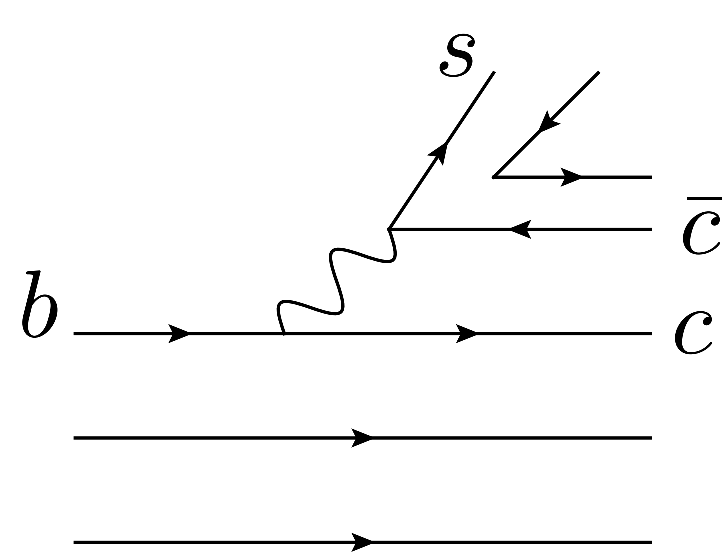
Pentaquarks

Production Mechanisms (tree)



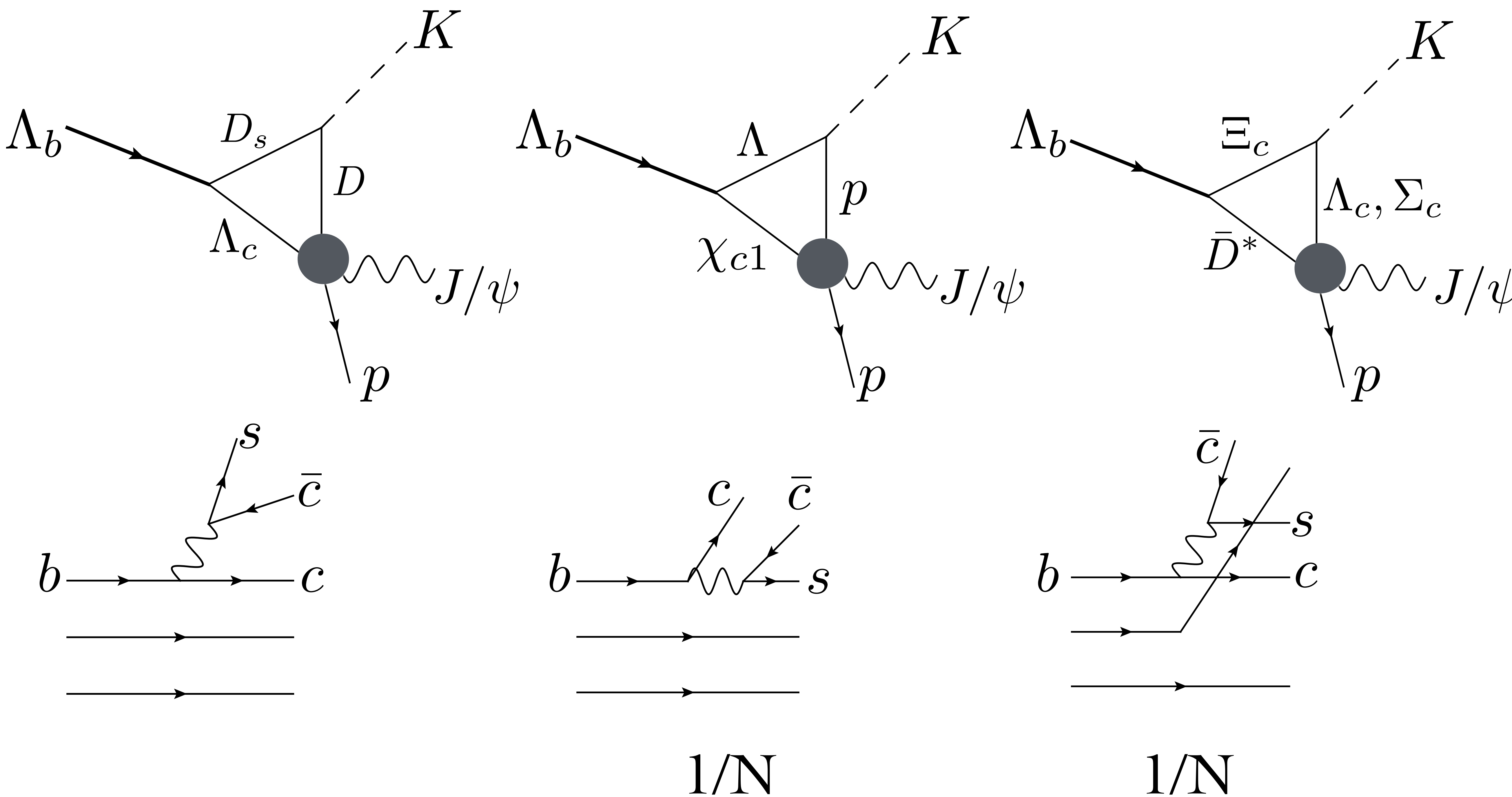






Pentaquarks

Production Mechanisms (loop)



Pentaquarks

diagonal only

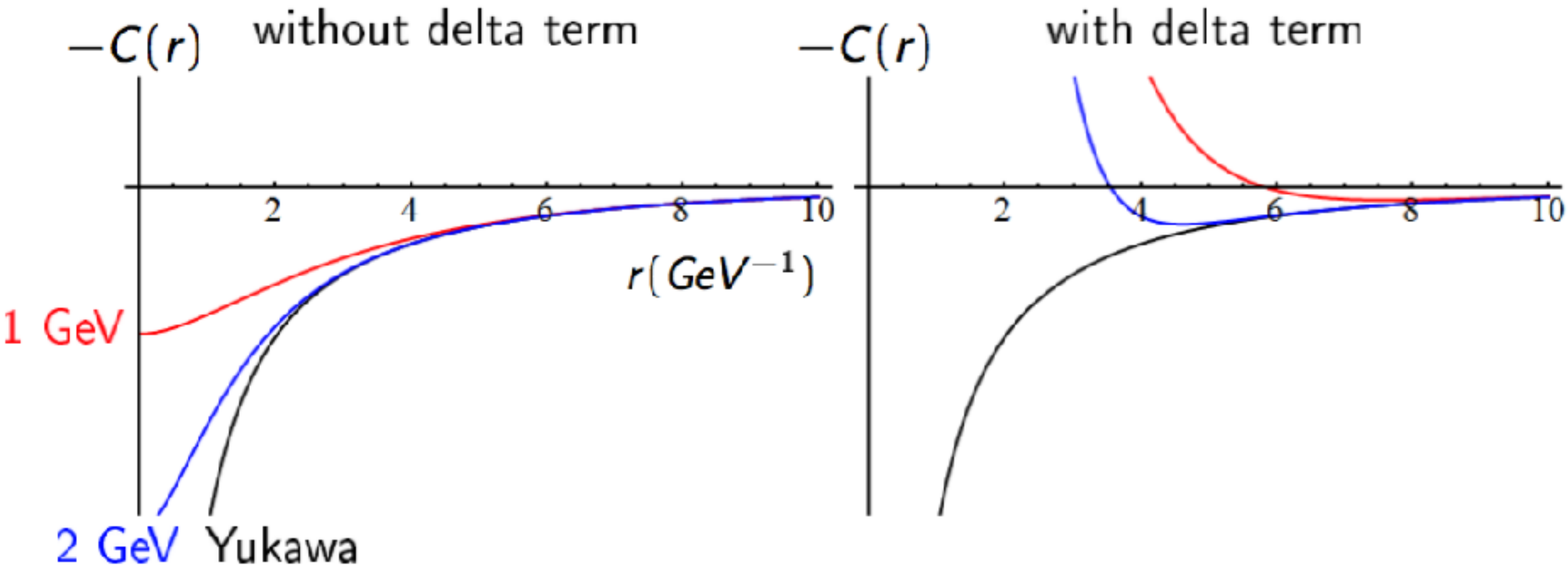
Potential without the delta term.
(Deuteron binding requires $\Lambda = 0.8$ GeV.)

	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		$+16/3$	$+20/3$
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	$-8/3$	$+8/3$
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						-4
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		$-8/3$	$-10/3$
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	$+4/3$	$-4/3$
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						$+2$

For point-like constituents:

$$C(r) = \frac{g^2 m^3}{12\pi f_\pi^2}\left(\frac{e^{-mr}}{mr} - \frac{4\pi}{m^3}\delta^3(\vec{r})\right)$$

For extended hadrons, use dipole form factors with cutoff Λ. The limit $\Lambda \to \infty$ recovers the point-like case.



Pentaquarks

J.M. Richard, A. Valcarce, J. Vijande, Stable heavy pentaquark in constituent models, July, 2017

Quark model calculation of $c\bar{c}qqq$

(J, I)	$(\bar{c}cqqq)$	Lowest threshold
$(1/2, 1/2)$	4.077	4.001 (S) / 4.408 (D)
$(3/2, 1/2)$	4.161	4.001 (D) / 4.097 (S)
$(5/2, 1/2)$	4.429	4.001 (D) / 4.562 (S)
$(1/2, 3/2)$	4.077	4.312 (D) / 4.329 (S)
$(3/2, 3/2)$	4.161	4.312 (S) / 4.329 (D)
$(5/2, 3/2)$	4.429	4.312 (D) / 4.408 (S)

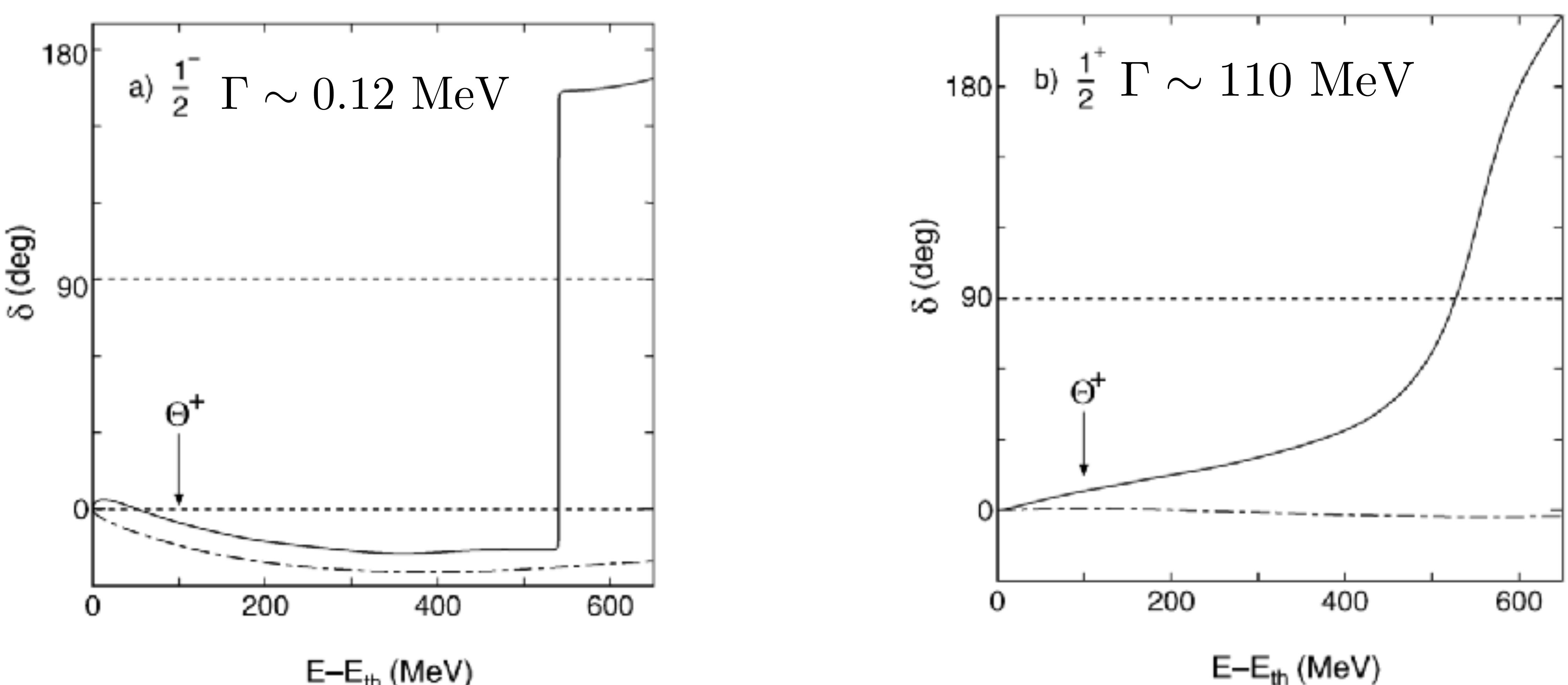
Binding energy decreases going to bbqqq because threshold degeneracy is lost.

Pentaquarks

E. Hiyama, M. Kamimura, A. Hosaka, H. Toki, M. Yahiro, Five-body calculation of resonance and scattering states of pentaquark system , Physics Letters B 633 (2006) 237-244

Quark model (IK) KN scattering computation.

$$H=\sum_i\left(m_i+\frac{\mathbf{p}_i^2}{2m_i}\right)-T_G+V_{\rm Conf}+V_{\rm CM},\qquad V_{\rm Conf}=-\sum_{i<j}\sum_{\alpha=1}^{8}\frac{\lambda_i^\alpha}{2}\frac{\lambda_j^\alpha}{2}\left[\frac{k}{2}(\mathbf{x}_i-\mathbf{x}_j)^2+v_0\right],\qquad V_{\rm CM}=\sum_{i<j}\sum_{\alpha=1}^{8}\frac{\lambda_i^\alpha}{2}\frac{\lambda_j^\alpha}{2}\frac{\xi_\sigma}{m_im_j}e^{-(\mathbf{x}_i-\mathbf{x}_j)^2/\beta^2}\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j.$$



Pentaquarks

PHYSICAL REVIEW D 84, 014032 (2011) Exotic baryons from a heavy meson and a nucleon: Negative parity states
Y Yamaguchi, S Ohkoda, S Yasui, and A Hosaka

- one pion+ one vector exchange interactions

TABLE IV. Binding energies, root mean square radii and cut-off parameters of heavy mesons. Results for the π and $\pi\rho\omega$ potentials are compared.

	$\bar{D}N(\pi)$	$\bar{D}N(\pi\rho\omega)$	$BN(\pi)$	$BN(\pi\rho\omega)$
E_B [MeV]	1.60	2.14	19.50	23.04
$\langle r^2\rangle^{1/2}$ [fm]	3.5	3.2	1.3	1.2
Λ_P [MeV]	1121	1142	1070	1091

$$(I, J^P) = (0, 1/2^-)$$

TABLE VI. The resonance energy and decay width for $(I, J^P) = (0, 3/2^-)$.

	$\bar{D}N(\pi)$	$\bar{D}N(\pi\rho\omega)$	$BN(\pi)$	$BN(\pi\rho\omega)$
E_{re} [MeV]	113.51	113.19	8.41	6.93
Γ [MeV]	19.43	17.72	0.16	0.0946

$$(I, J^P) = (0, 3/2^-)$$

Ultrafine Splittings

Quarkonium h States As Arbiters of Exoticity
arXiv:1705.03140
R.F. Lebed and E.S. Swanson

$$\begin{aligned}\Delta_{n,L} \equiv\ & M(n^1L_{J=L}) \\ & - \frac{2L-1}{3(2L+1)} M(n^3L_{J=L-1}) \\ & - \frac{2L+1}{3(2L+1)} M(n^3L_{J=L}) \\ & - \frac{2L+3}{3(2L+1)} M(n^3L_{J=L+1})\end{aligned}$$

use "ultrafine splitting" to test for valence light quark degrees of freedom.

$$\Delta_{n,1} = \frac{m_Q C_F^4 \alpha_s^5}{432\pi(n+1)^3} (8T_F n_\ell - C_A)$$

System	$h(^1P_1)$	$\chi_0(^3P_0)$	$\chi_1(^3P_1)$	$\chi_2(^3P_2)$	Δ
$c\bar{c}(1P)$	3525.38(11)	3414.75(31)	3510.66(7)	3556.20(9)	+0.08(13)
$c\bar{c}(2P)$	–	3862^{+26+40}_{-32-13}	–	3927.2(2.6)	–
$b\bar{b}(1P)$	9899.3(8)	9859.44(42)(31)	9892.78(26)(31)	9912.21(26)(31)	−0.57(88)
$b\bar{b}(2P)$	10259.8(1.2)	10232.5(4)(5)	10255.46(22)(50)	10268.65(22)(50)	−0.44(1.31)
Ps	11180(5)(4)	18499.65(1.20)(4.00)	13012.42(67)(1.54)	8624.38(54)(1.40)	+4.31(6.50)

Ultrafine Splittings

Heavy-Quark Hybrid Mass Splittings: Hyperfine and "Ultrafine"

arXiv:1708.02679

R.F. Lebed and E.S. Swanson

$$V_\Gamma^{\rm cLS}(\mathbf{r}=\mathbf{r}_Q-\mathbf{r}_{\bar{Q}}) = \left(\frac{\boldsymbol{\sigma}_Q\cdot\mathbf{L}_Q}{4m_Q^2}-\frac{\boldsymbol{\sigma}_{\bar{Q}}\cdot\mathbf{L}_{\bar{Q}}}{4m_{\bar{Q}}^2}\right)\frac{1}{r}\frac{dV_\Gamma}{dr}$$

Multiplet	J^{PC}	m (MeV)	D (MeV)	Δ (MeV)
H_1 $[\Sigma_u^-(1P),\Pi_u^+(1P)]$	1^{--}	4285(14)	139(21)	5.4(17.8)
	0^{-+}	4195(13)		
	1^{-+}	4217(16)		
	2^{-+}	4334(17)		
H_2 $[\Pi_u^-(1P)]$	1^{++}	4399(14)	55(40)	22(29)
	0^{+-}	4386(09)		
	1^{+-}	4344(38)		
	2^{+-}	4395(40)		
H_3 $[\Sigma_u^-(1S)]$	0^{++}	4472(30)	5(36)	−5(36)
	1^{+-}	4477(19)		
H_4 $[\Sigma_u^-(1D),\Pi_u^+(1D)]$	2^{++}	4492(21)	56(30)	−33(25)
	1^{+-}	4497(39)		
	2^{+-}	4509(18)		
	3^{+-}	4548(22)		

Questions:

- "Simple" quark models may be able to describe compact multiquark states (to be confirmed). The main issue is modelling the colour degrees of freedom. What about diquarks etc?

- How should long range dynamics (molecules) be modelled? One pion exchange has issues with on-shell pions and the contact portion.

- "Kinematical" effects are likely to be important in some cases. How can these be modelled and identified?

- Gluonic degrees of freedom are required. How can these be modelled and identified?