Lattice QCD simulation of charged charmonium Z_c^+ channel

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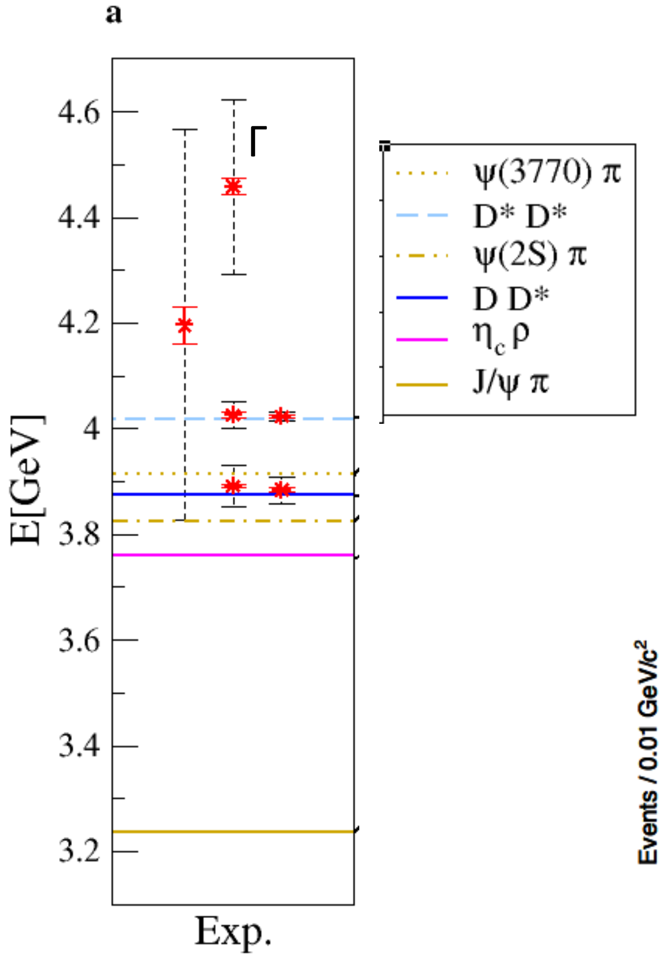
Charged charmonium Z_c^+ : experimental status

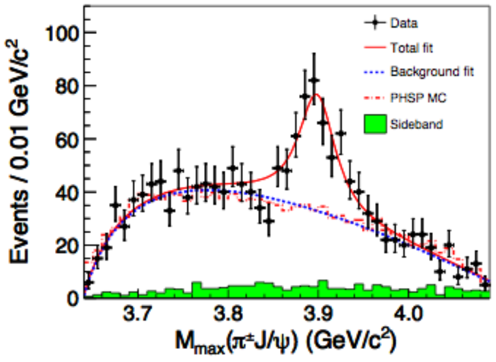
$\bar{c}\ u$
$c\ \bar{d}$

candidates with preferred
$I^G=1^+,\ J^{PC}=1^{+-}$



[review: Brambilla et al., 1404.3723]

particle	C	J^P	decay	year	coll
$Z^+(4430)$	-	1+	$\psi(2S)\ \pi^+$	2008	Belle, ~~BABAR~~, LHCb
$Z_c^+(3900)$	-	?	$J/\psi\ \ \pi^+$	2013	BESIII, Belle, CLEOc
$Z_c^+(3885)$	-	1+	$(DD^*)^+$	2013	BESIII
$Z_c^+(4020)$	-	?	$h_c(1P)\ \pi^+$	2013	BESIII
$Z_c^+(4025)$	-	?	$(D^*\ D^*)^+$	2013	BES III
$Z^+(4200)$	-	1+	$J/\psi\ \ \pi^+$	2014	Belle
$Z^+(4050)$	+	?	$\chi_{c1}\ \ \pi^+$	2008	Belle
$Z^+(4250)$	+	?	$\chi_{c1}\ \ \pi^+$	2008	Belle



[BESIII, 2013, 1303.5949, PRL]

$Z_c^+(3900)\ \rightarrow\ \ J/\Psi\ \ \pi^+$

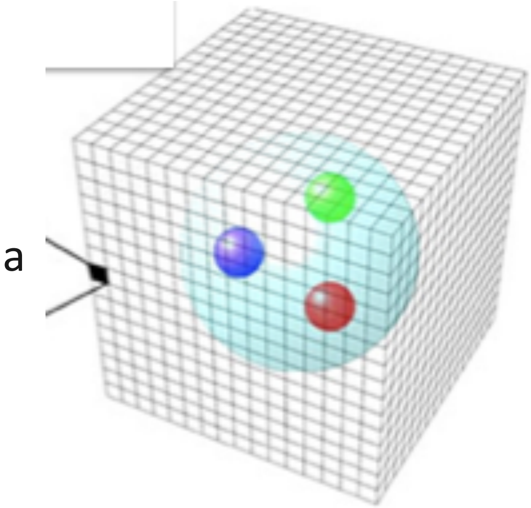
$\underline{c}c\ \ \underline{d}u$

$\bar{c}\ u$
$c\ \bar{d}$

QCD on lattice: ab initio non-perturbative metod

$$L_{QCD} = -\tfrac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q} i \gamma_\mu (\partial^\mu + i g_s G_a^\mu T^a) q - m_q \bar{q} q$$

input : g_s , m_q



Evaluation of Feynman path integrals in discretized space-time

$$S_{QCD} = \int d^4 x \, L_{QCD}[G(x), q(x), \bar{q}(x)]$$

$$\langle \mathrm{C} \rangle = \int DG \, Dq \, D\bar{q} \;\; C \, e^{-S_{QCD}}$$

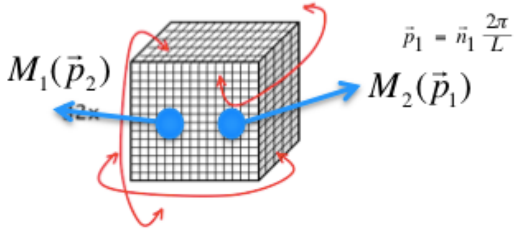
$$S = \int dt \, L[x(t)]$$

Discrete energy spectrum from correlators

$$\langle C\rangle \propto \int DG\,Dq\,D\bar{q}\;C(q,\bar{q},G)\,e^{i\,S_{QCD}/\hbar},\quad S_{QCD}=\int d^4x\,L_{QCD}$$

Example: meson channel with given J^{PC}

$$\mathcal{O}=\bar{q}\Gamma q,\quad \bar{q}\Gamma' q,\quad (\bar{q}\Gamma_1 q)(\bar{q}\Gamma_2 q),\ldots$$



$$C_{ij}(t)=\langle 0|\,\mathcal{O}_i(t)\;\mathcal{O}_j^{+}(0)\,|0\rangle$$

$$=\sum_n\;\langle 0|\mathcal{O}_i|n\rangle\;e^{-E_n t}\,\langle n|\mathcal{O}_j^{+}|0\rangle=\sum_n\;Z_i^n\,Z_j^{n*}\,e^{-E_n t}\qquad Z_i^n=\langle 0|\mathcal{O}_i|n\rangle$$

All physical states with given J^{PC} appear as energy levels E_n in principle : single particle, two-particle,...

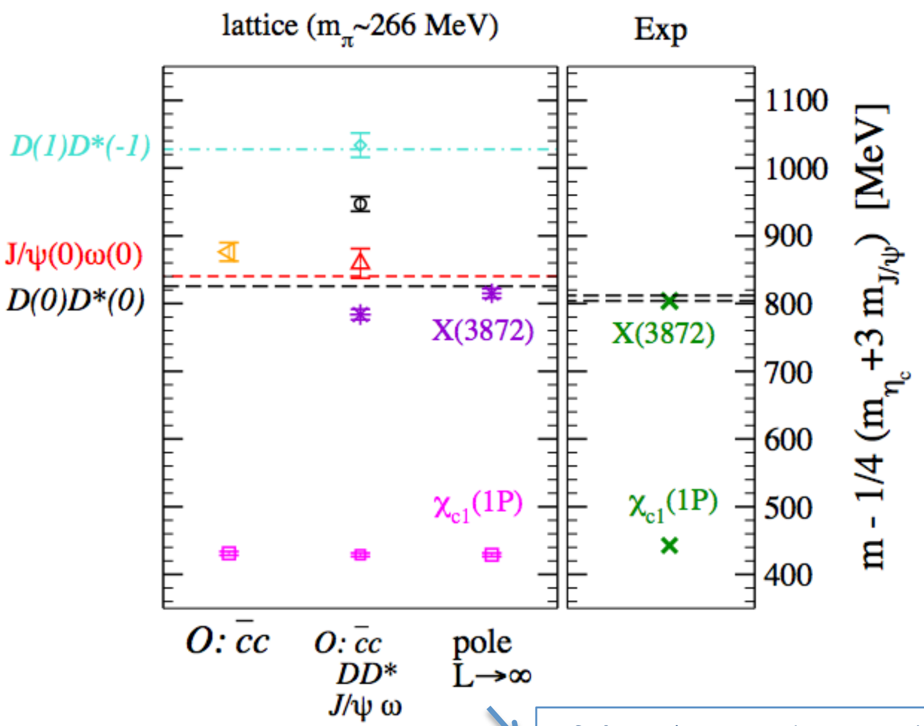
channel :	"eigenstates"
$J^{PC}=1^{--},\bar{s}u:$	$K^*(892),\quad K\pi$
$J^{PC}=1^{++},\bar{c}c:$	$\chi_{c1},X(3872),\;DD^*,$
$J^{PC}=1^{+-},\bar{c}c\bar{d}u:$	$Z_c^+,\quad J/\psi\;\pi^+,\ldots$

In experiment: these correspond to two-meson decay products with continous spectrum.

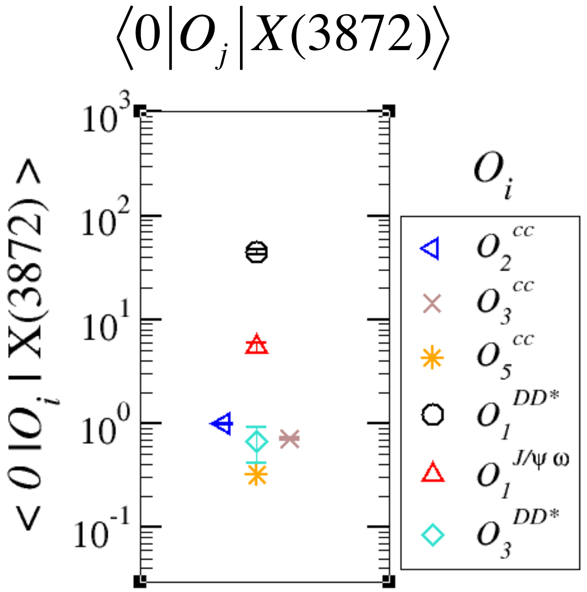
On lattice: these are discrete due to finite box and periodic BC.

Evidence for X(3872) from lattice : $J^{PC}=1^{++}$, $I=0$

$\mathcal{O}: \bar{c}\,c, \quad DD^*, \quad J/\psi\omega$



- δ_0 for DD* extracted using Luscher's rel. and interpolated near threshold
- pole in T-matrix $T \propto [\cot\delta - i]^{-1} = \infty$ found just below DD* threshold.



Overlaps normalized to <0|O_1^{cc} |X(3872)>

X(3872)	m - (m_{D0}+m_{D0*})
lat	- 11 ± 7 MeV
exp	- 0.14 ± 0.22 MeV

[S.P. and L. Leskovec : 1307.5172, Phys. Rev. Lett. 2013]

m_π≈266 MeV, L≈2 fm, Nf=2

Other searches for $Z_c^+(3900)$ from lattice

- Search in $J^{PC}=1^{+-}$ channel for m < 4 GeV:

  no Z_c^+ candidate found

  [S.P. & L. Leskovec, 1308.2097, PLB]

- Search for resonance in $D\underline{D}^*$ scattering with $J^{PC}=1^{+-}$ near threshold E ~ 3.9 GeV

  no Z_c^+ candidate found

  [Y. Chen et al, 1403.1318, PRD]

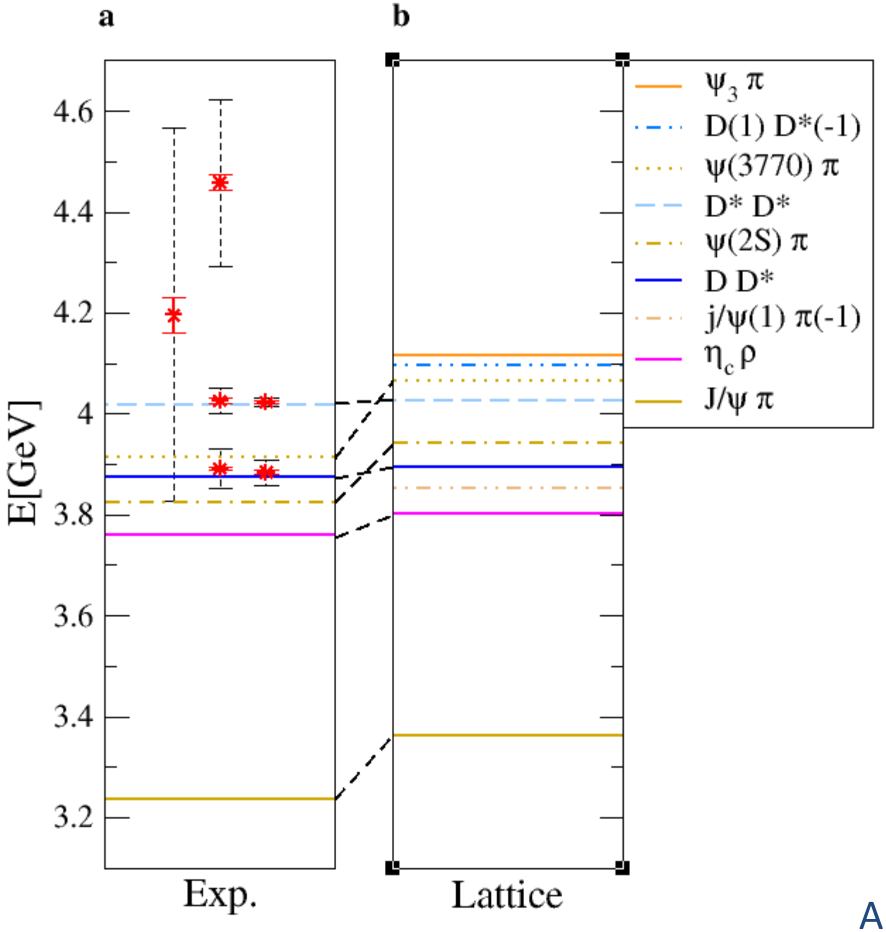
- Search with Ψ π and D $\underline{D}$* interpolators

  no Zc+ candidate found yet (ongoing project)

  [C. DeTar, Song-haeng Lee, poster session @ Lattice 2014]

Challenge: two-meson states $I^G=1^+$, $J^{PC}=1^{+-}$

$\bar{c}\ u$
$c\ \bar{d}$



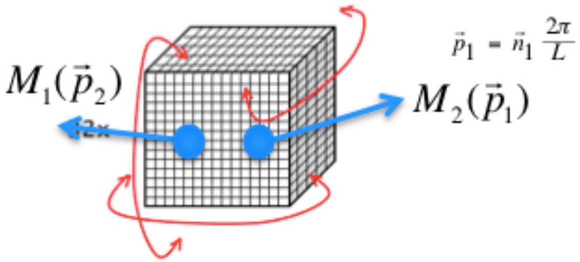
Lattice:

lines represent

energies of two-meson states

$E = E[\ M_1(p_1)\ ] + E[\ M_2(p_2)\ ]$

in non-interacting case



Aim:

- identify all those two-meson eigenstates
- establish whether there are extra states due to possible exotics

[S.P., Lang, Leskovec, Mohler]

$m_\pi \approx 266$ MeV, $L \approx 2$ fm, $N_f=2$

Interpolating fields

14 two-meson (MM)

Aiming at 9 two-meson states listed in previous slide

$$\mathcal{O}_1^{\psi(0)\pi(0)} = \bar{c}\gamma_i c(0)\ \bar{d}\gamma_5 u(0)\,,$$

$$\mathcal{O}^{\psi(1)\pi(-1)} = \sum_{e_k=\pm e_{x,y,z}} \bar{c}\gamma_i c(e_k)\ \bar{d}\gamma_5 u(-e_k)\,,$$

$$\mathcal{O}^{\eta_c(0)\rho(0)} = \bar{c}\gamma_5 c(0)\ \bar{d}\gamma_i u(0)\,,$$

$$\mathcal{O}_1^{D(0)D^*(0)} = \bar{c}\gamma_5 u(0)\ \bar{d}\gamma_i c(0) + \{\gamma_5 \leftrightarrow \gamma_i\}\,,$$

$$\mathcal{O}^{D^*(0)D^*(0)} = \epsilon_{ijk}\ \bar{c}\gamma_j u(0)\ \bar{d}\gamma_k c(0)\,,$$

and 9 others ..

4 diquark-antidiquark (4Q)

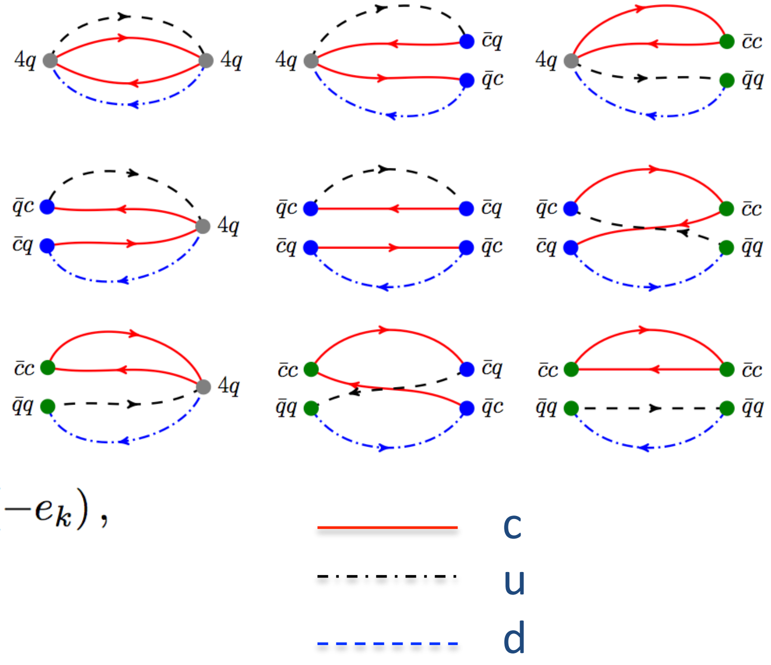
Aiming to find additional state related to exotic Z_c^+

$$O_1^{4q} \approx [\bar{c}\ C\gamma_5\ \bar{d}\,]_{3_c}\,[c\ \gamma_i C\ u]_{\bar{3}c}$$

$$O_2^{4q} \approx [\bar{c}\ C\ \bar{d}\,]_{3_c}\,[c\ \gamma_i\gamma_5 C\ u]_{\bar{3}c}$$

and 2 others ..

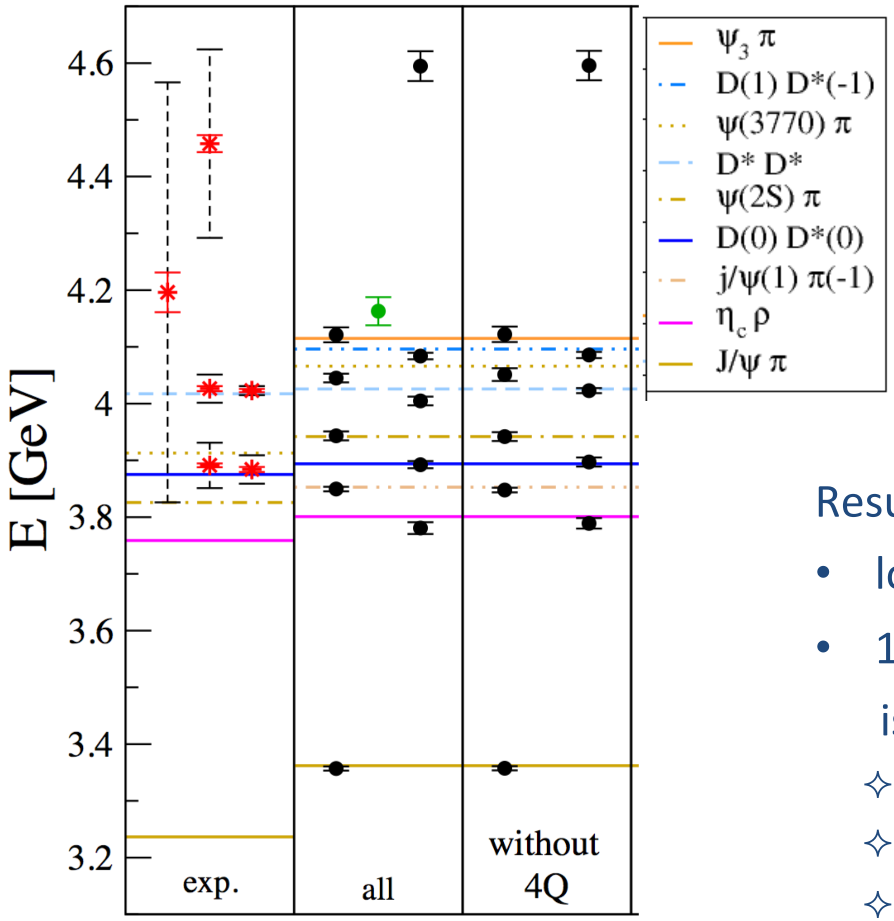
Wick contractions



$$C_{ij}(t) = \langle 0 |\, \mathcal{O}_i(t)\ \mathcal{O}_j^{+}(0)\, | 0 \rangle$$

Eigenstates in Z_c^+ channel: $I^G=1^+$, $J^{PC}=1^{+-}$

18 interp.



S.P., Lang, Leskovec, Mohler

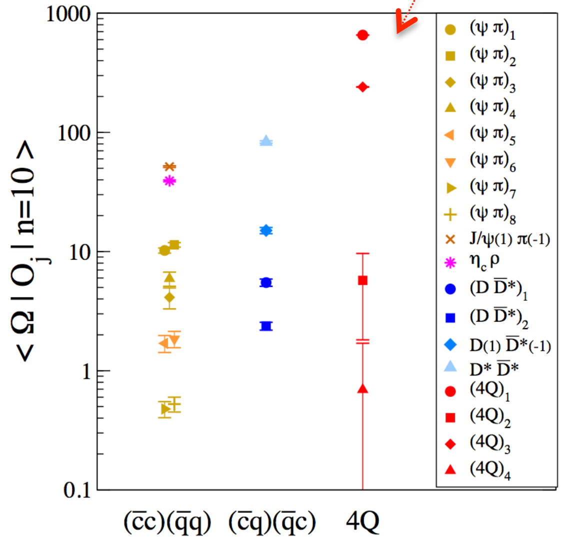
1405.7623v1

$m_\pi \approx 266$ MeV, L≈2 fm, Nf=2

green level

$[\bar{c}\, C\gamma_5\, \bar{d}]_{3_c} [c\, \gamma_i C\, u]_{\bar{3}c}$

$$\langle 0 | O_j | n=10 \rangle$$



Results:

- lowest 9 states (black): two-meson states
- 10th state (green):

  is it Z_c^+ candidate with m≈4.16 GeV ?

  ✧ arises in addition to 9 expected two-meson states

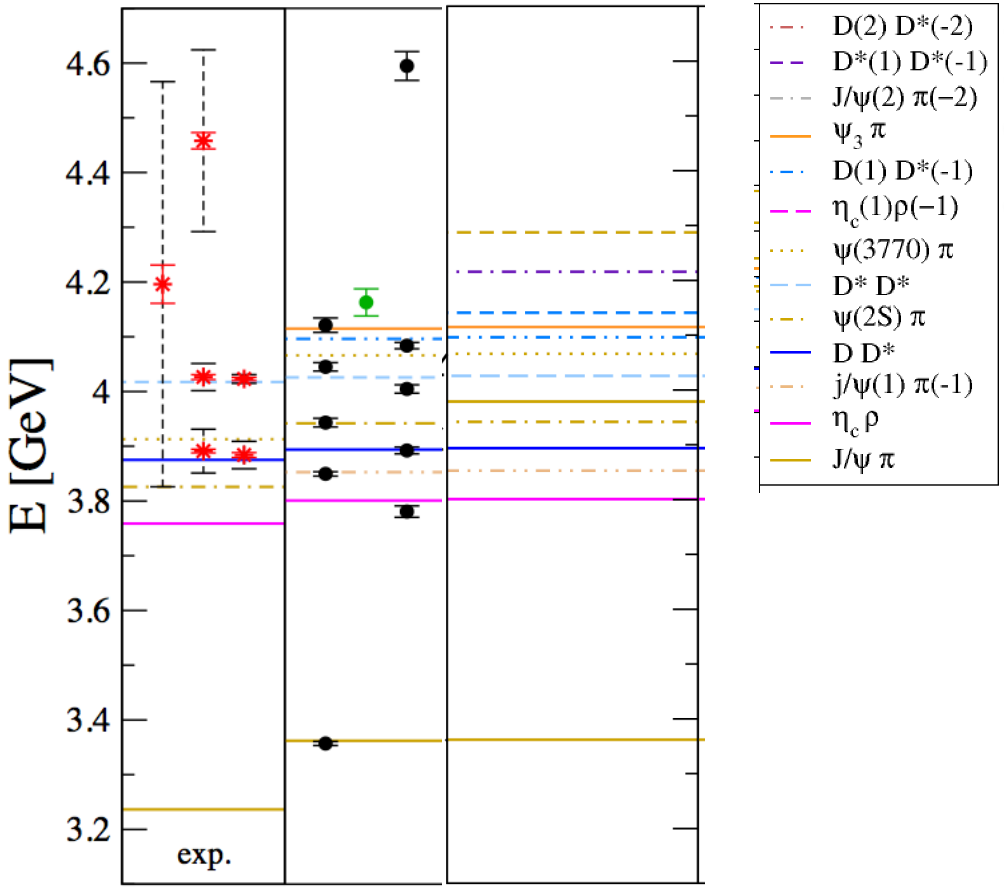
  ✧ diquark-antidiquark interpolators crucial for its existence

  ✧ couples best to diquark-antidiquark interpolators

  ✧ however: there are few other two-meson near 4.2 GeV

  Will Z_c^+ candidate survive also after those are established ?

Aiming at additional two-mesons states around 4.2 GeV



spectrum
from 18
interp.

two-meson
states below
4.3 GeV

we implement 4 additional two-meson interpolators

$$O^{D(2)D^*(-2)}=\sum_{|u_k|^2=2}\bar{c}\gamma_5 u(u_k)\ \bar{d}\gamma_i c(-u_k)+\{\gamma_5\leftrightarrow\gamma_i\}$$

$$O^{D^*(1)D^*(-1)}=\sum_{e_k=\pm e_{x,y,z}}\epsilon_{ijl}\ \bar{c}\gamma_j u(e_k)\ \bar{d}\gamma_l c(-e_k)$$

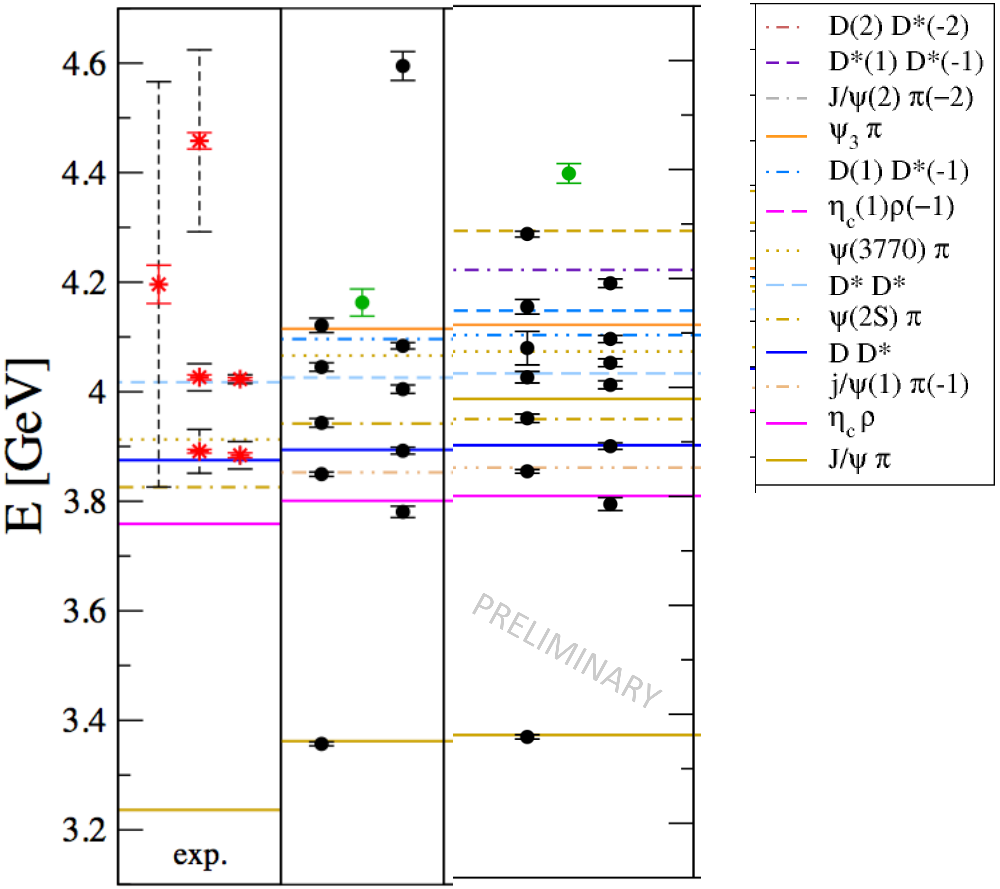
$$O^{\psi(2)\pi(-2)}=\sum_{|u_k|^2=2}\bar{c}\gamma_i c(u_k)\ \bar{d}\gamma_5 u(-u_k)$$

$$O^{\eta_c(1)\rho(-1)}=\sum_{e_k=\pm e_{x,y,z}}\bar{c}\gamma_5 c(e_k)\ \bar{d}\gamma_i u(-e_k)$$

Eigenstates in Z_c^+ channel with extended interpolator basis

spectrum from 18 interp.

spectrum from 22 interp.



Results from the extended basis:

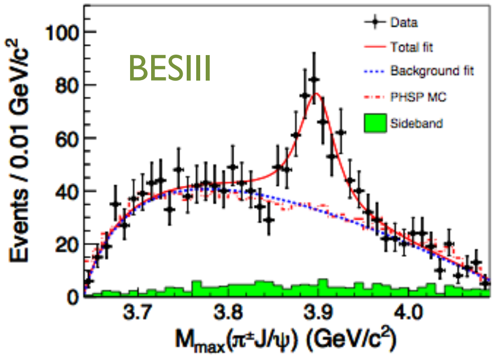
based on E_n and $Z_i^n = \langle 0|\mathcal{O}_i|n\rangle$

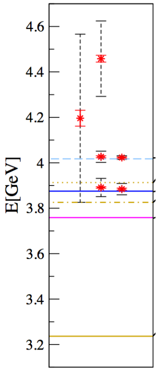
- lowest 13 states (black): two-meson states
- no extra state below 4.2 GeV
- no extra state at 4.16 GeV (extended basis gives an extra state at 4.4 GeV)
- attributing a state at 4.16 GeV to Z_c^+ (green) was a premature conclusion
- we can not exclude that state at 4.16 GeV was a linear combination of omitted two-meson states, induced via O^{4q}

Conclusion: we do not find Z_c^+ candidate below 4.2 GeV

Results based on extended basis will soon appear as S.P., Lang, Leskovec, Mohler, 1405.7623v2

Puzzle





Why does such large basis of creation operators not excite observed Z_c^+ (in addition to all expected two-meson states) ?

- ✧ Experimental candidates with $J^{PC}=1^{+-}$ and mass bellow 4.2 GeV are most likely not dominated by diquark antidiquark Fock component
- ✧ Two-meson inter. basis might not be rich enough to render Z_c in addition to all two-meson states
- ✧ Implementation of further structures will be valuable.
- ✧ Ideas for further interpolator structures from phenomenological community welcome

$J^{PC}=1^{+-}$

$$\begin{matrix} \bar{c} & u \\ c & \bar{d} \end{matrix}$$

$$\mathcal{O}_1^{\psi(0)\pi(0)} = \bar{c}\gamma_i c(0)\ \bar{d}\gamma_5 u(0)\,,$$

$$\mathcal{O}_2^{\psi(0)\pi(0)} = \bar{c}\gamma_i\gamma_t c(0)\ \bar{d}\gamma_5 u(0)\,,$$

$$\mathcal{O}_3^{\psi(0)\pi(0)} = \bar{c}\overleftarrow{\nabla}_j\gamma_i\overrightarrow{\nabla}_j c(0)\ \bar{d}\gamma_5 u(0)\,,$$

$$\mathcal{O}_4^{\psi(0)\pi(0)} = \bar{c}\overleftarrow{\nabla}_j\gamma_i\gamma_t\overrightarrow{\nabla}_j c(0)\ \bar{d}\gamma_5 u(0)\,,$$

$$\mathcal{O}_5^{\psi(0)\pi(0)} = |\epsilon_{ijk}||\epsilon_{klm}|\ \bar{c}\gamma_j\overleftarrow{\nabla}_l\overrightarrow{\nabla}_m c(0)\ \bar{d}\gamma_5 u(0)\,,$$

$$\mathcal{O}_6^{\psi(0)\pi(0)} = |\epsilon_{ijk}||\epsilon_{klm}|\ \bar{c}\gamma_t\gamma_j\overleftarrow{\nabla}_l\overrightarrow{\nabla}_m c(0)\ \bar{d}\gamma_5 u(0)\,,$$

$$\mathcal{O}_7^{\psi(0)\pi(0)} = R_{ijk}Q_{klm}\ \bar{c}\gamma_j\overleftarrow{\nabla}_l\overrightarrow{\nabla}_m c\ \bar{d}\gamma_5 u(0)\,,$$

$$\mathcal{O}_8^{\psi(0)\pi(0)} = R_{ijk}Q_{klm}\ \bar{c}\gamma_t\gamma_j\overleftarrow{\nabla}_l\overrightarrow{\nabla}_m c\ \bar{d}\gamma_5 u(0)\,,$$

$$\mathcal{O}^{\psi(1)\pi(-1)} = \sum_{e_k=\pm e_{x,y,z}} \bar{c}\gamma_i c(e_k)\ \bar{d}\gamma_5 u(-e_k)\,,$$

$$O^{\psi(2)\pi(-2)} = \sum_{|u_k|^2=2} \bar{c}\gamma_i c(u_k)\ \bar{d}\gamma_5 u(-u_k)\,,$$

$$\mathcal{O}^{\eta_c(0)\rho(0)} = \bar{c}\gamma_5 c(0)\ \bar{d}\gamma_i u(0)\,,$$

$$O^{\eta_c(1)\rho(-1)} = \sum_{e_k=\pm e_{x,y,z}} \bar{c}\gamma_5 c(e_k)\ \bar{d}\gamma_i u(-e_k)\,,$$

$$\mathcal{O}_1^{D(0)D^*(0)} = \bar{c}\gamma_5 u(0)\ \bar{d}\gamma_i c(0) + \{\gamma_5 \leftrightarrow \gamma_i\}\,,$$

$$\mathcal{O}_2^{D(0)D^*(0)} = \bar{c}\gamma_5\gamma_t u(0)\ \bar{d}\gamma_i\gamma_t c(0) + \{\gamma_5 \leftrightarrow \gamma_i\}\,,$$

$$\mathcal{O}^{D(1)D^*(-1)} = \sum_{e_k=\pm e_{x,y,z}} \bar{c}\gamma_5 u(e_k)\ \bar{d}\gamma_i c(-e_k) + \{\gamma_5 \leftrightarrow \gamma_i\}\,,$$

$$O^{D(2)D^*(-2)} = \sum_{|u_k|^2=2} \bar{c}\gamma_5 u(u_k)\ \bar{d}\gamma_i c(-u_k) + \{\gamma_5 \leftrightarrow \gamma_i\}$$

$$\mathcal{O}^{D^*(0)D^*(0)} = \epsilon_{ijl}\ \bar{c}\gamma_j u(0)\ \bar{d}\gamma_l c(0)\,,$$

$$O^{D^*(1)D^*(-1)} = \sum_{e_k=\pm e_{x,y,z}} \epsilon_{ijl}\ \bar{c}\gamma_j u(e_k)\ \bar{d}\gamma_l c(-e_k)$$

$$O_1^{4q} \approx [\bar{c}\ C\gamma_5\,\bar{d}\,]_{3_c}[c\ \gamma_i C\ u]_{\bar{3}c}$$

$$O_2^{4q} \approx [\bar{c}\ C\ \bar{d}\,]_{3_c}[c\ \gamma_i\gamma_5 C\ u]_{\bar{3}c}$$

Two-meson states represent challenge for all QCD approaches !

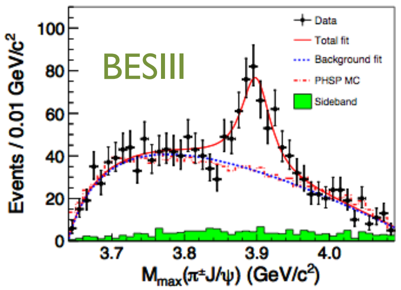
Two meson states are present since exotic states are found near or above thresholds.

based on correlators: $C_{ij} = \langle 0 | \mathcal{O}_i \mathcal{O}_j^+ | 0 \rangle$

Experiment:

continuous spectrum

two-meson states allow to observe exotics

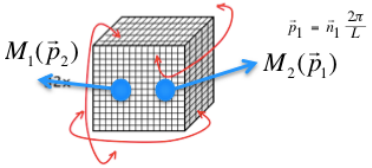


QCD Sum Rules:

continuous spectrum

Lattice QCD:

discrete spectrum



Exotics arising from theory can not be claimed until two-meson states are not rigorously treated as well.

No rigorous QCD-based theoretical evidence for exotics yet.

Conclusions

Near-threshold or resonant meson states
from lattice QCD simulations that take into account two-particle states:

Evidence/indication found only states that are not manifestly exotic: (examples in meson sector)

- ρ [results from many lattice collaborations]
- K*(892) [S.P., Lang, Leskovec, Mohler, PRD 2013; Dudek, Edwards, Thomas, Wilson, PRL 2014]
- $D_0^*(2400)$, $D_1(2430)$ [Mohler, S. P., Woloshyn, PRD 2012]
- $D_{s0}^*(2317)$ [Mohler, Lang, Leskovec, S.P., Woloshyn, PRL 2013, PRD 2014]
- X(3872) [S.P., Leskovec, PRL 2014]

Unfortunately, no reliable evidence found for manifestly exotic states (yet):

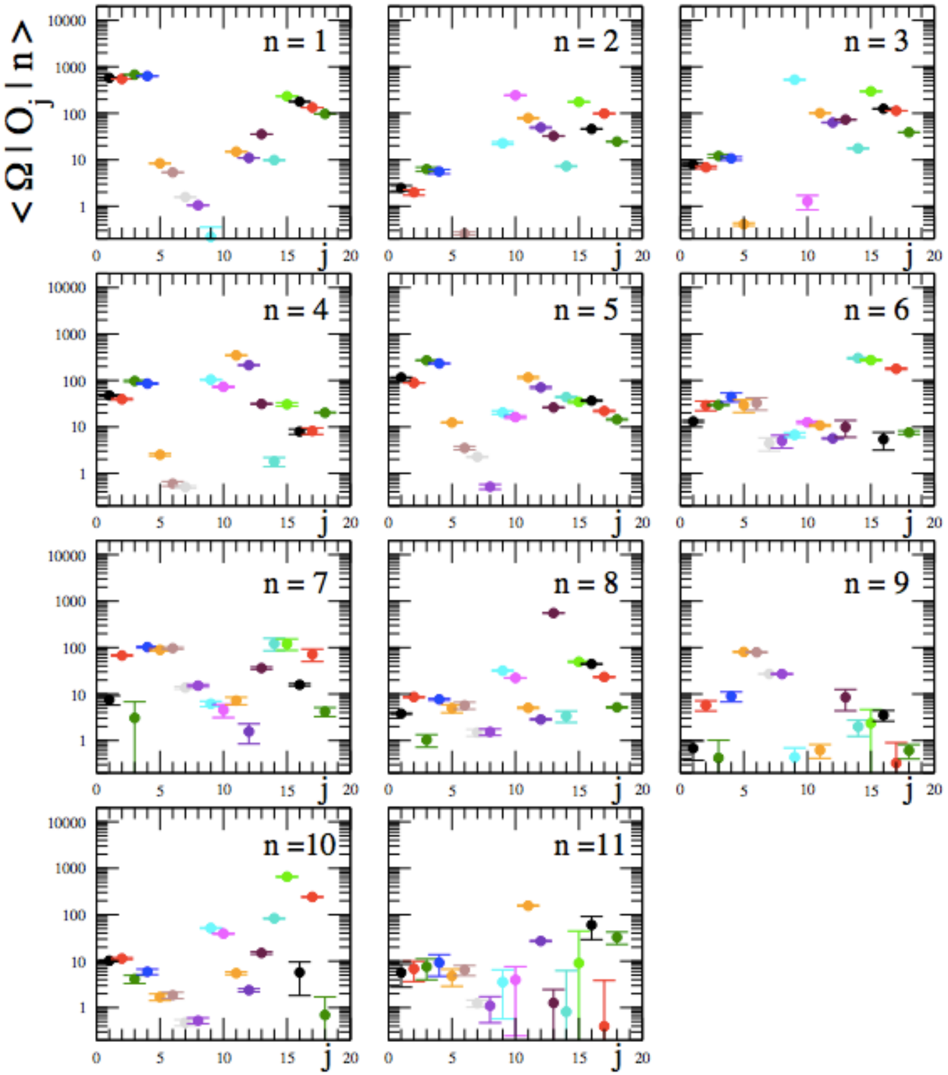
- $Z_c^+ = c\underline{c}u\underline{d}$ [references listed in this talk]
- $cc\underline{u}\underline{d}$ [Y. Ikeda, HALQCD coll, , 1311.6214, Phys. Lett. B 2014]

Theory is facing a serious challenge to establish whether exotic states arise from QCD or not.

Only after this is settled, theory can claim the structure (mesonic molecules, diquark antidiquark,...)

Backup slides

Overlaps of all states in Zc+ channel



for the case of basis with 18 interpolators in

S.P., Lang, Leskovec, Mohler

1405.7623v1

Challenges for the lattice community: quarkonium-*like* states

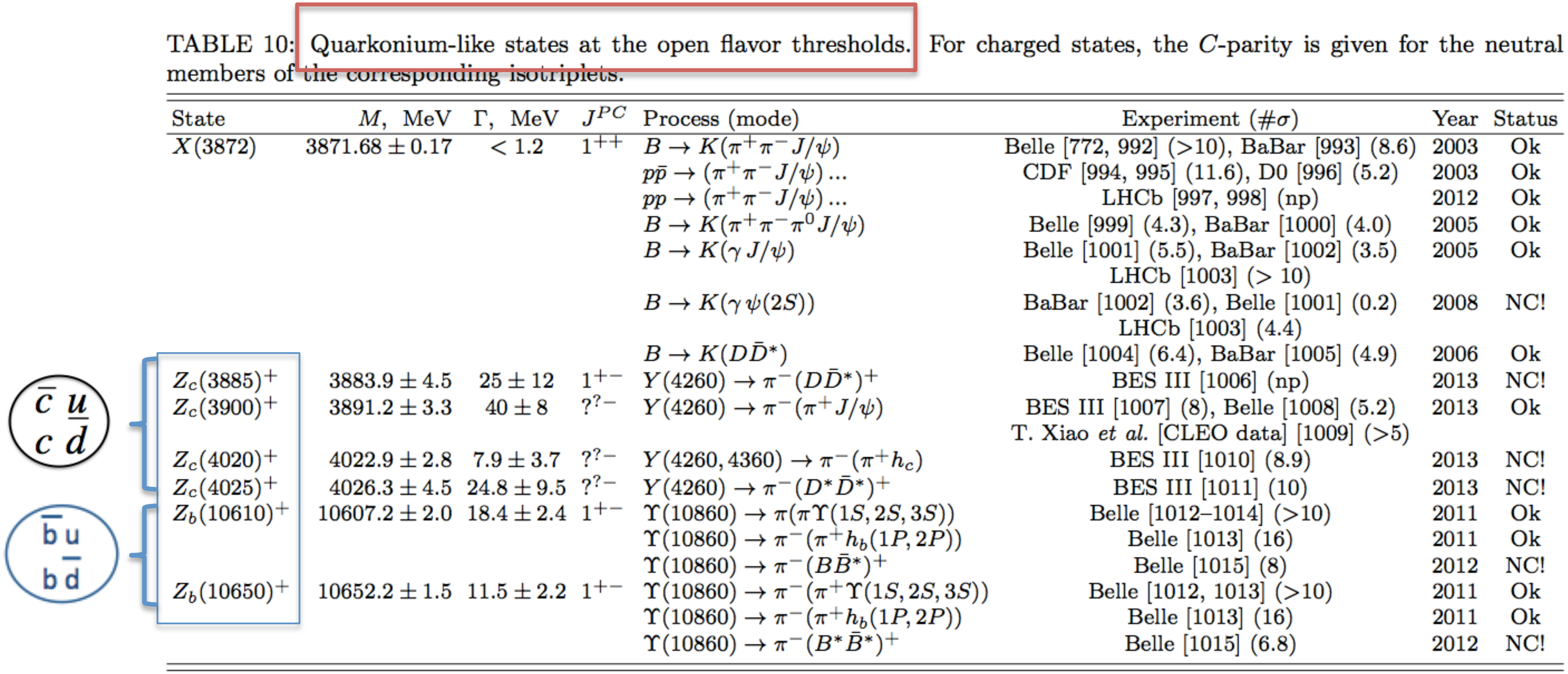
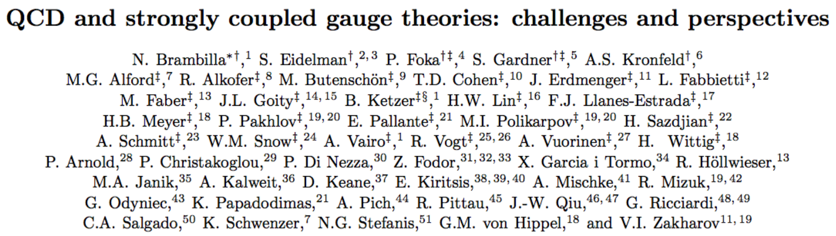


TABLE 10: Quarkonium-like states at the open flavor thresholds. For charged states, the C-parity is given for the neutral members of the corresponding isotriplets.

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [772, 992] (>10), BaBar [993] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF [994, 995] (11.6), D0 [996] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi)\ldots$	LHCb [997, 998] (np)	2012	Ok
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle [999] (4.3), BaBar [1000] (4.0)	2005	Ok
				$B \to K(\gamma\, J/\psi)$	Belle [1001] (5.5), BaBar [1002] (3.5) LHCb [1003] (> 10)	2005	Ok
				$B \to K(\gamma\, \psi(2S))$	BaBar [1002] (3.6), Belle [1001] (0.2) LHCb [1003] (4.4)	2008	NC!
				$B \to K(D\bar{D}^*)$	Belle [1004] (6.4), BaBar [1005] (4.9)	2006	Ok
$Z_c(3885)^+$	3883.9 ± 4.5	25 ± 12	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III [1006] (np)	2013	NC!
$Z_c(3900)^+$	3891.2 ± 3.3	40 ± 8	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III [1007] (8), Belle [1008] (5.2) T. Xiao *et al.* [CLEO data] [1009] (>5)	2013	Ok
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260, 4360) \to \pi^-(\pi^+ h_c)$	BES III [1010] (8.9)	2013	NC!
$Z_c(4025)^+$	4026.3 ± 4.5	24.8 ± 9.5	$?^{?-}$	$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III [1011] (10)	2013	NC!
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(10860) \to \pi(\pi\Upsilon(1S, 2S, 3S))$	Belle [1012–1014] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1013] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B\bar{B}^*)^+$	Belle [1015] (8)	2012	NC!
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(10860) \to \pi^-(\pi^+\Upsilon(1S, 2S, 3S))$	Belle [1012, 1013] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1013] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle [1015] (6.8)	2012	NC!

[review: Brambilla et al., 1404.3723]



QCD and strongly coupled gauge theories: challenges and perspectives

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More challenges: quarkonium-*like* states above threshold

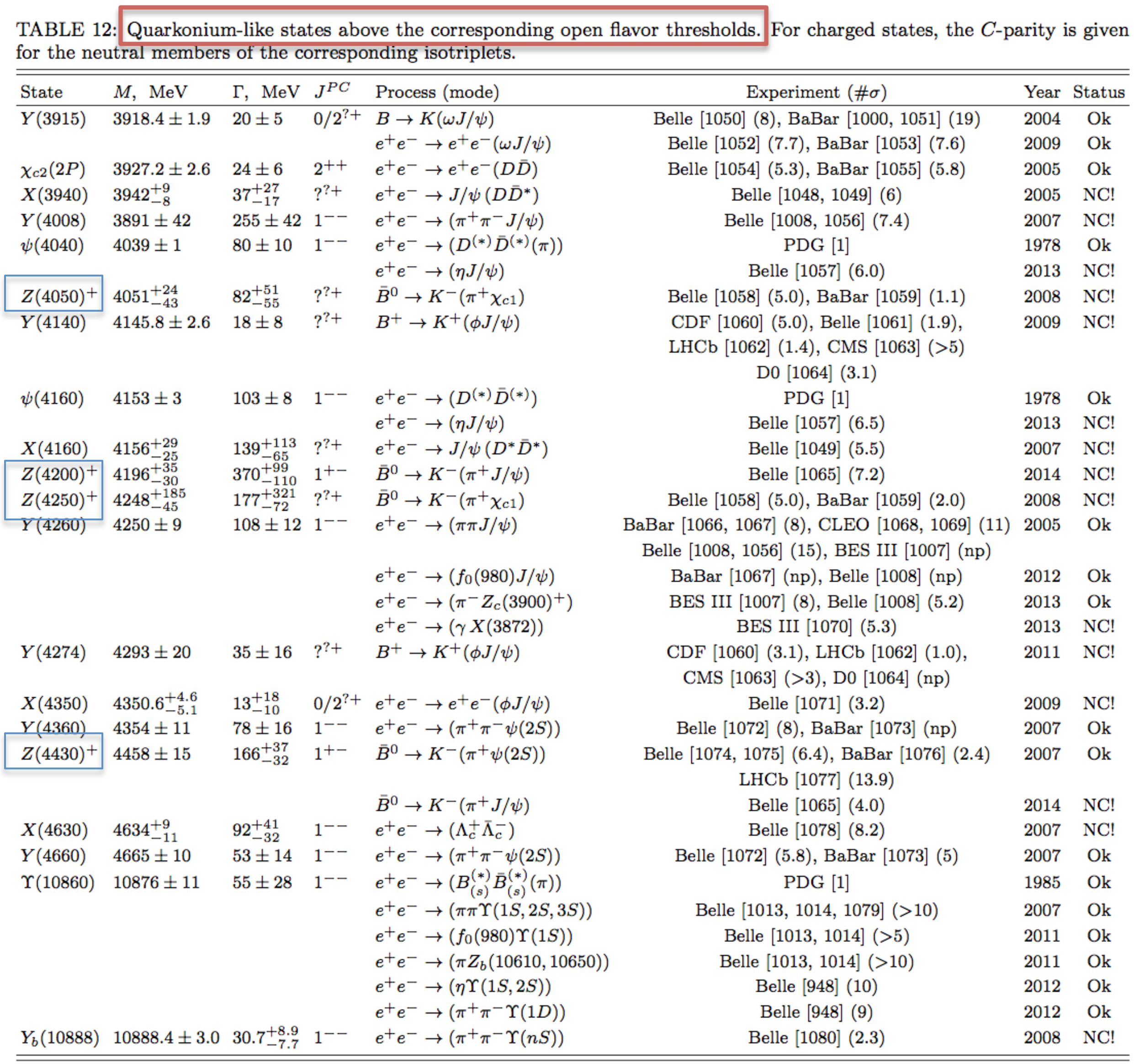


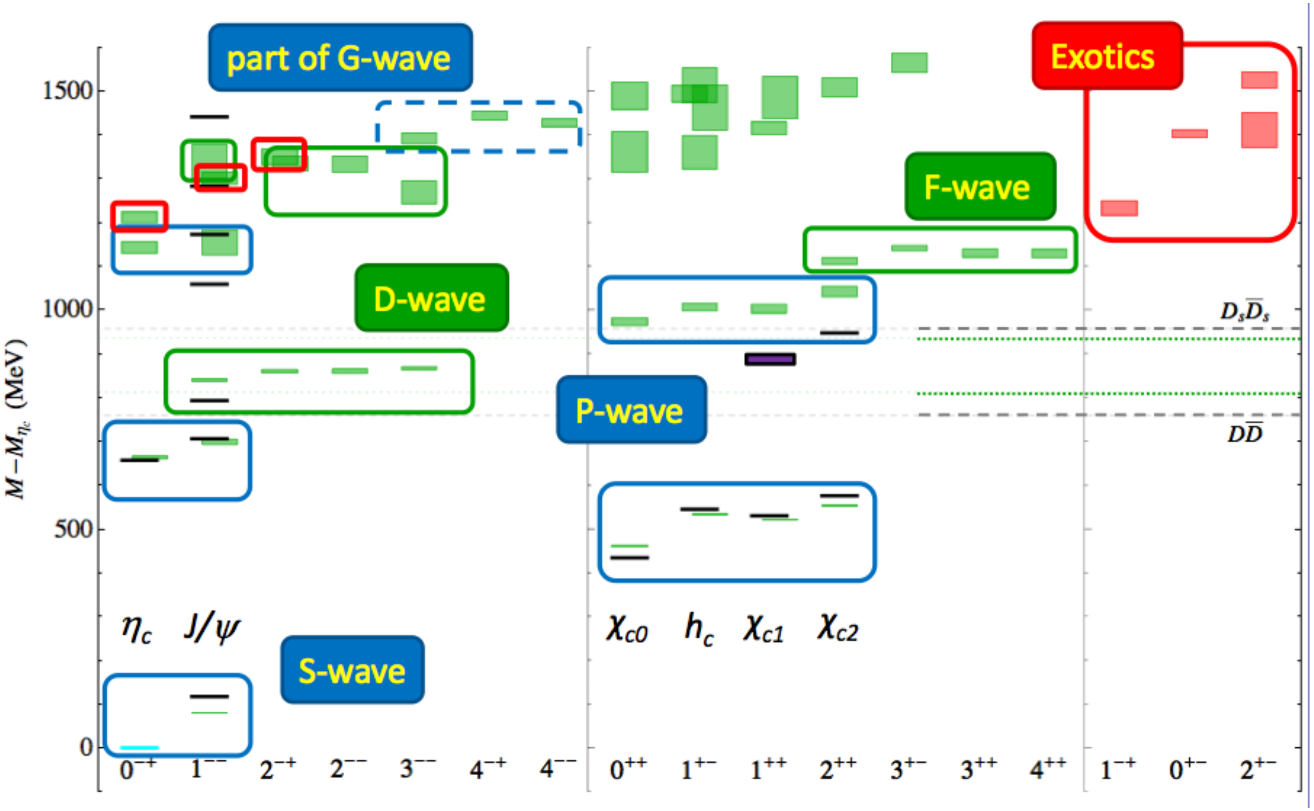
TABLE 12: Quarkonium-like states above the corresponding open flavor thresholds. For charged states, the C-parity is given for the neutral members of the corresponding isotriplets.

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$Y(3915)$	3918.4 ± 1.9	20 ± 5	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [1050] (8), BaBar [1000, 1051] (19)	2004	Ok
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [1052] (7.7), BaBar [1053] (7.6)	2009	Ok
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [1054] (5.3), BaBar [1055] (5.8)	2005	Ok
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [1048, 1049] (6)	2005	NC!
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle [1008, 1056] (7.4)	2007	NC!
$\psi(4040)$	4039 ± 1	80 ± 10	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)}(\pi))$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1057] (6.0)	2013	NC!
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1058] (5.0), BaBar [1059] (1.1)	2008	NC!
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1060] (5.0), Belle [1061] (1.9), LHCb [1062] (1.4), CMS [1063] (>5) D0 [1064] (3.1)	2009	NC!
$\psi(4160)$	4153 ± 3	103 ± 8	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)})$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1057] (6.5)	2013	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [1049] (5.5)	2007	NC!
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1065] (7.2)	2014	NC!
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1058] (5.0), BaBar [1059] (2.0)	2008	NC!
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	BaBar [1066, 1067] (8), CLEO [1068, 1069] (11) Belle [1008, 1056] (15), BES III [1007] (np)	2005	Ok
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [1067] (np), Belle [1008] (np)	2012	Ok
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III [1007] (8), Belle [1008] (5.2)	2013	Ok
				$e^+e^- \to (\gamma\, X(3872))$	BES III [1070] (5.3)	2013	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1060] (3.1), LHCb [1062] (1.0), CMS [1063] (>3), D0 [1064] (np)	2011	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [1071] (3.2)	2009	NC!
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1072] (8), BaBar [1073] (np)	2007	Ok
$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [1074, 1075] (6.4), BaBar [1076] (2.4) LHCb [1077] (13.9)	2007	Ok
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1065] (4.0)	2014	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle [1078] (8.2)	2007	NC!
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1072] (5.8), BaBar [1073] (5)	2007	Ok
$\Upsilon(10860)$	10876 ± 11	55 ± 28	1^{--}	$e^+e^- \to (B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)}(\pi))$	PDG [1]	1985	Ok
				$e^+e^- \to (\pi\pi\Upsilon(1S, 2S, 3S))$	Belle [1013, 1014, 1079] (>10)	2007	Ok
				$e^+e^- \to (f_0(980)\Upsilon(1S))$	Belle [1013, 1014] (>5)	2011	Ok
				$e^+e^- \to (\pi Z_b(10610, 10650))$	Belle [1013, 1014] (>10)	2011	Ok
				$e^+e^- \to (\eta\Upsilon(1S, 2S))$	Belle [948] (10)	2012	Ok
				$e^+e^- \to (\pi^+\pi^-\Upsilon(1D))$	Belle [948] (9)	2012	Ok
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [1080] (2.3)	2008	NC!

All these believed NOT to be $Q\bar{Q}$!

[review: Brambilla et al., 1404.3723]

$\underline{c}c$ spectrum: single hadron approximation



[HSC , L. Liu et al: 1204.5425, JHEP]

- $m_\pi \approx 400$ MeV, $L \approx 2.9$ fm, $N_f=2+1$
- reliable J^{PC} determination
- identification with $n\ ^{2S+1}L_J$ multiplets using $\langle O|n\rangle$
- green: lat, black: exp

Hybrids:

some of them have exotic J^{PC}

large overlap with $O = \underline{q}\, F_{ij}\, q$