ISOSPIN VIOLATION

IN MESONIC MOLECULES

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OUTLINE

1. THE MOTIVATION

2. THE BINDING ENERGY OF THE DD* „MOLECULE“

3. THE WIDTH OF THE DD* „MOLECULE“

4. THE ISOSPIN VIOLATION IN THE DD* „MOLECULE“

5. THE ISOSPIN VIOLATION IN HIDDEN CHARM MOLECULES

1. THE MOTIVATION

Test of quark models.

Several constituent quark models agree more or less in the descripton of baryons and mesons.
They may, however, largely disagree in their predictions for dimesons (tetraquarks) and other exotics.
It is, anyway, one of the purposes of quark models to extra-polate our knowledge from known systems to new ones.

The most sensitive such system is the **Tcc+=ccud = DD* dimeson** since it is slightly below the 2-body thresholds and it is long-lived (it decays only electromagnetically, and strongly into DDπ with very small phase space).

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2. BINDING ENERGY OF THE DD* „MOLECULE“

In 2004 we predicted a weakly bound state Tcc+ of two heavy mesons.
Janc & Rosina : Tcc+ – (D + D*) = - 0.6 MeV (Bhaduri)
- 2.7 MeV (Grenoble AL1)
It is a great satisfaction that it has been finally detected and confirmed 17 years later in CERN in July 2021.

The nonrelativistic calculation of Janc & Rosina (2004) used the **one-gluon exchange** potential (including the chromomagnetic term) + the **linear confining** potential.

The model parameters fitted all relevant mesons and baryons.

A rich 4-body model space was used including gaussians of Jacobi coordinats of different optimized widths and positions.

THE CERN EXPERIMENT

The tetraquark (mesonic molecule) $\mathbf{T_{cc}^{+}}$ was produced in the proton-proton collision at the Large Hadron Collider and was detected as a narrow peak in the channel

$$T_{cc}^{+} \to D^0 D^{*+} \to D^0 D^0 \pi^+ \to (K^- \pi^+)\,(K^- \pi^+)\,\pi^+$$

The peak position is **273 keV below the D^0D^{*+} threshold** (1683 keV below the D^+D^{*0} threshold)

The deduced **Breit-Wigner width is 410 keV.**

A more advanced model using a unitarised Breit-Wigner profile gives the peak at 360 keV below the D^0D^{*+} threshold and a width ~48 keV

(Effective range of T^+cc and other parameters [LHCb, arXiv:2109.01056], Mikhail Mikhasenko).

Observation of T_{cc}^{+} state

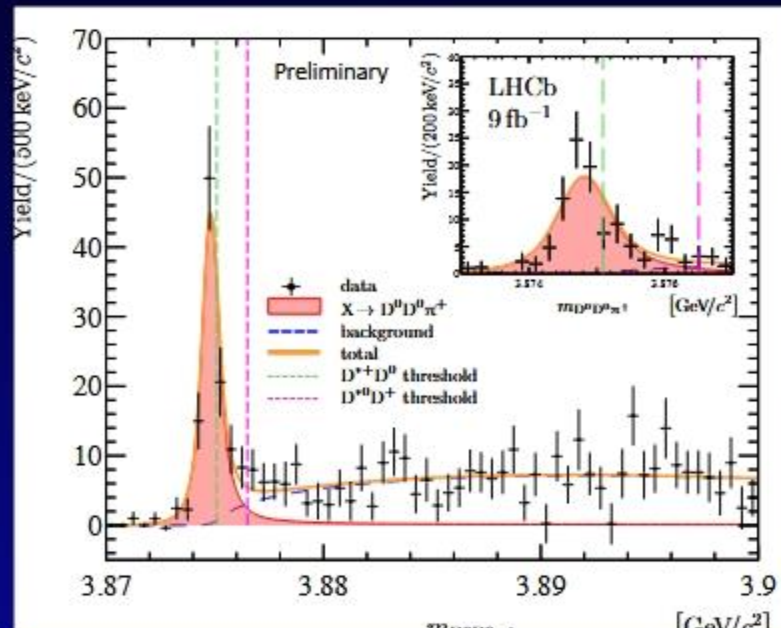
NEW

LHCb-PAPER-2021-031

- **First observation of a same-sign doubly charmed tetraquark T_{cc}^{+}**
  - Very narrow state in $D^0 D^0 \pi^+$ mass spectrum
  - Consistent with $cc\bar{u}\bar{d}$ tetraquark
  - Mass very close to $D^{*+}D^0$ mass thresholds
  - Manifestly exotic
- **Parameters of T_{cc}^{+}**
  - Fit structure with P-wave relativistic Breit-Wigner

$$\begin{aligned} \delta m_{\rm BW} &= -273 \pm 61 \pm 5\,^{+11}_{-14}\,{\rm keV}/c^2\,, \\ \Gamma_{\rm BW} &= 410 \pm 165 \pm 43\,^{+18}_{-38}\,{\rm keV}\,, \end{aligned}$$

  - Uncertainties stat, syst and due $J^P = 1^+$ assumption
  - Significance for signal > 10 σ
  - Significance for $\delta m_{BW} < 0$ 4.3 σ



Recent LHCb results on exotic meson candidates
Ivan Polyakov

Predicted mass spectrum

Mikhail Mikhasenko

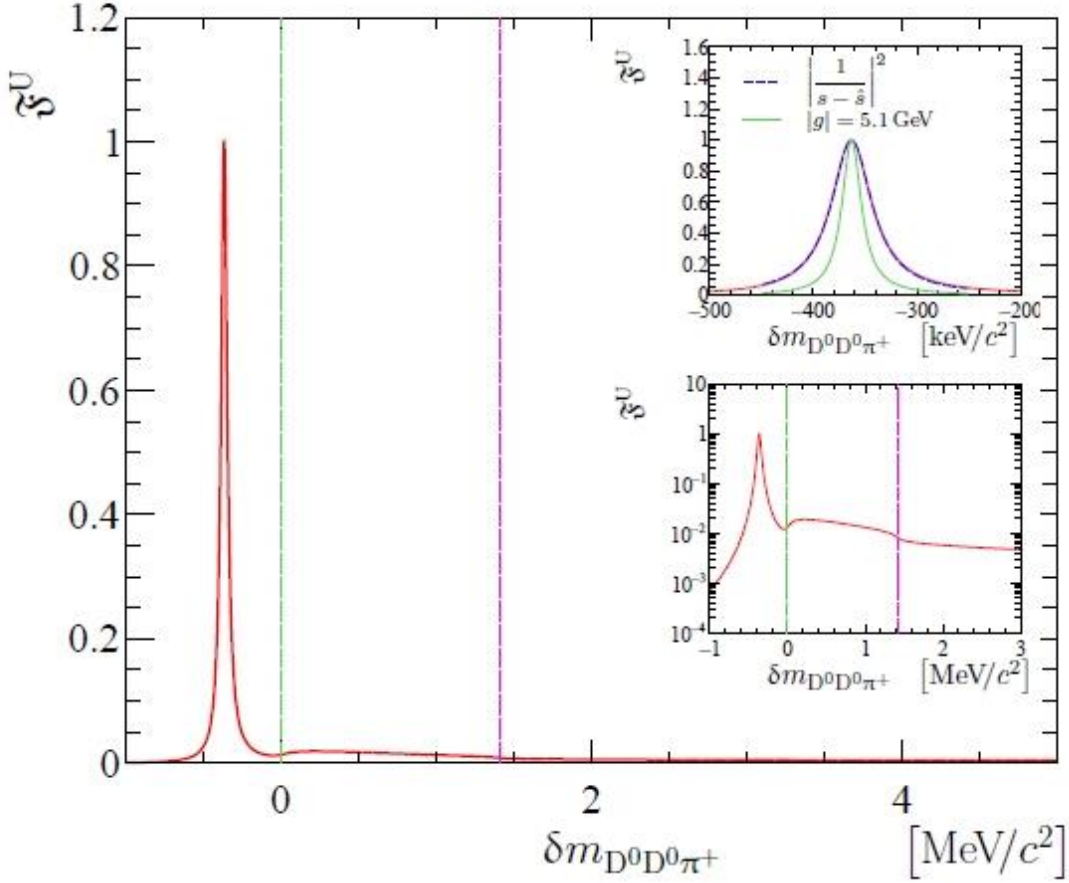
resolution removed

Visible characteristics:

- Peak position: $-359 \pm 40\,\mathrm{keV}$

  (The most precise ever wrt to the threshold)
- FWHM: $47.8 \pm 1.9\,\mathrm{keV}$,
- Lifetime: $\tau \approx 10^{-20}\,s$.

  (Unprecedented for exotic hadrons)



- A bound state below $D^{*+}D^0$ threshold with a narrow width due to D^*
- Still, the NLL scan suggest the low limit to the width, $\Gamma > 10\,\mathrm{keV}$ at 95 CL.

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3. THE WIDTH OF THE T_{cc}^{+} DIMESON

The width of the T_{cc}^{+} dimeson is not expected to differ considerably from the widths of its constituent D^{*0} and D^{*+}.

The width of D^{*+} is well measured (Γ = 83.4 ± 1.8 keV).

Unfortunately, reliable values of the D^{*0} (< 2.1 MeV) and

T_{cc}^{+}(< 410 keV) widths are not yet known

and at least theoretical estimates would be welcome.

PIONIC DECAYS OF D*+ AND D*0

		MeV	keV	keV	
$D^{*+} \to D^+ \pi^0$,		ΔE=5.62,	Γ=83.4,	Γ0=25.6,	BR=0.307
$D^{*+} \to D^0 \pi^+$,		ΔE=5.86,	Γ=83.4,	Γ+=56.5,	BR=0.677,
$D^{*0} \to D^0 \pi^0$,		ΔE=7.03,	**Γ=55,**	**Γ0=35.6,**	BR=0.647,
$D^{*0} \to D^+ \pi^-$,		ΔE=-2.38,	**Γ=55,**	Γ+=0,	BR=0,

Theoretical values (from D^{*+} width; $D^{*+} \to D^+\gamma$ and $D^{*0} \to D^0\gamma$ branching & chiral and isospin symmetry):

Eric Braaten, Li-Ping He, Kevin Ingles and Jun Jiang,
Charm-meson Triangle Singularity in e^+e^- Annihilation
into $D^{*0}D^0 + \gamma$, arxiv.org/abs/2004.12841

PIONIC DECAYS OF D*+ AND D*0 --- MY ESTIMATE

		MeV	keV	keV	
$D^{*+} \to D^+ \pi^0$,		ΔE=5.62,	Γ=83.4,	Γ^0=25.6,	BR=1/3 → 0.323
$D^{*+} \to D^0 \pi^+$,		ΔE=5.86,	Γ=83.4,	Γ^+=56.5,	BR=2/3 → 0.661
$D^{*0} \to D^0 \pi^0$,		ΔE=7.03,	Γ=44,	Γ^0=28.6,	BR=1/3 → 0.647
$D^{*0} \to D^+ \pi^-$,		ΔE=-2.38,	Γ=44,	Γ^+=0,	BR=2/3 → 0

My estimate is based on isospin symmetry, phase space and gamma decay fraction: $D^{0*} \to D^0 + \gamma +$ 142 MeV (35 %)

$D^{+*} \to D^+ + \gamma +$ 141 MeV (2 %)

Predictions for isospin ½, BR_π= 0.984, and phase space $\propto \sqrt{\Delta E}$:

$BR_\pi \times (⅓\sqrt{5.62})/(⅓\sqrt{5.62} + ⅔\sqrt{5.86}) = 0.323$

$BR_\pi \times (⅔\sqrt{5.86})/(⅓\sqrt{5.62} + ⅔\sqrt{5.86}) = 0.661$

My estimate for $D^{*0} \to D^0 \pi^0$: $\Gamma^0 = 25.6 \times \sqrt{7.03}/\sqrt{5.62} = 28.6$, Γ=44 keV

PIONIC DECAYS OF D*+ AND D*0

	MeV	keV	keV	
D*+ → D+ π0,	ΔE=5.62,	Γ=83.4,	Γ0=25.6,	BR=0.307
D*+ → D0 π+,	ΔE=5.86,	Γ=83.4,	Γ+=56.5,	BR=0.677,
D*0 → D0 π0,	ΔE=7.03,	**Γ=55,**	**Γ0=35.6**,	BR=0.647,
D*0 → D+ π-,	ΔE= -2.38,	**Γ=55,**	Γ+=0,	BR=0,

	MeV	keV	keV	
D*+ → D+ π0,	ΔE=5.62,	Γ=83.4,	Γ0=25.6,	BR=1/3 → 0.323
D*+ → D0 π+,	ΔE=5.86,	Γ=83.4,	Γ+=56.5,	BR=2/3 → 0.661
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D*0 → D+ π-,	ΔE= -2.38,	Γ=44,	Γ+=0,	BR=2/3 → 0

TOY MODEL FOR THE Tcc+ WIDTH

$$\begin{pmatrix} (\boldsymbol{m_1} - \mathrm{i}\Gamma_1/2), & \boldsymbol{B} \\ \boldsymbol{B}, & (\boldsymbol{m_2} - \mathrm{i}\Gamma_2/2) \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = (E - \mathrm{i}\Gamma/2) \begin{pmatrix} x \\ y \end{pmatrix}$$

MOTIVATION:

To understand the relation between the widths of

D^{*+} (83.4 ± 1.8 keV), D^{*0} (< 2.1 MeV)

And Tcc+ (410 ± 165 ± 45 ± 38 keV OR SMALLER !?!)

TOY MODEL FOR THE Tcc+ WIDTH

$$\begin{pmatrix} (m_1 - i\Gamma_1/2), & B \\ B, & (m_2 - i\Gamma_2/2) \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = (E - i\Gamma/2) \begin{pmatrix} x \\ y \end{pmatrix}$$

We count the energies from the lower threshold

$D^{*+} D^0$: $m_1 = 0$, $\Gamma_1 = 83.4$ keV

$D^{*o} D^+$: $m_2 = 1.41$ MeV, $\Gamma_2 = 55$ keV or other trials

B = to fit E(Tcc+) = -- 273 keV **or -360 keV**

$$2E - i\Gamma = (m_1 - i\Gamma_1/2 + m_2 - i\Gamma_2/2)$$

$$\pm \sqrt{[m_1 - i\Gamma_1/2 - (m_2 - i\Gamma_2/2)]^2 + 4B^2}$$

We fix m_1, m_2, Γ_1, and make different choices for Γ_2.

The coupling B is fitted to get E(Tcc+) = -273 keV or -360 keV

keV			lower	upper	configuration	
Γ_2	E	**Γ**	x^2	y^2	iso0	iso1
40.8	-273	47	0.86	0.14	0.85	0.15
55	-273	59	0.86	0.14	0.85	0.15
100	-273	86	0.86	0.14	0.85	0.15
1000	-273	211	0.85	0.15	0.83	0.17
2420	**-273**	**410**	**0.84**	**0.16**	**0.79**	**0.21**
40.8	**-360**	**48**	**0.83**	**0.17**	**0.87**	**0.13**
55	-360	60	0.83	0.17	0.87	0.13
100	-360	86	0.83	0.17	0.87	0.13
1000	-360	238	0.82	0.18	0.86	0.14
2420	-360	478	0.82	0.18	0.82	0.18

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4. THE LARGE ISOSPIN VIOLATION.

The salient feature of this peak is its ISOSPIN VIOLATION which is due to the fact that this state is 273 keV below the $D^0 D^{*+}$ threshold and 1683 keV below the $D^+ D^{*0}$ threshold.

The $D^{*+} D^0$ and $D^{*0} D^+$ thresholds differ by 1.4 MeV, much more than the binding energy -0.27 MeV, therefore Tcc+ will not have a pure isospin coupling,

Tcc+ $\neq (D^{*+} D^0 - D^{*0} D^+)/\sqrt{2}$

and the actual composition may be seen in branching ratios.

SUGGESTIONS HOW TO MEASURE THE ISOSPIN BREAKING

(i) First one should better measure (very difficult!!)

or theoretically estimate the widths of D^{*0} and Tcc+.

(ii) One should compare the branching ratios of decays

$D^0 D^{*+} \to DD\pi \to (K\,\pi)\,(K\,\pi)\,\pi$, BR= 83 %

and

$D^+ D^{*0} \to DD\pi \to (K\,\pi)\,(K\,\pi)\,\pi$, BR= 17 %

(iii) One should compare the branching ratios of separate decays and take into account interferences between equal final states:

$D^0 D^{*+} \longrightarrow D^0 D^0 \pi^+ \longrightarrow (K^- \pi^+)(K^- \pi^+)\pi^+$

$D^0 D^{*+} \longrightarrow D^0 D^0 \pi^+ \longrightarrow (K^- \pi^+)(K^0 \pi^0)\pi^+$

$D^0 D^{*+} \longrightarrow D^0 D^0 \pi^+ \longrightarrow (K^0 \pi^0)(K^0 \pi^0)\pi^+$

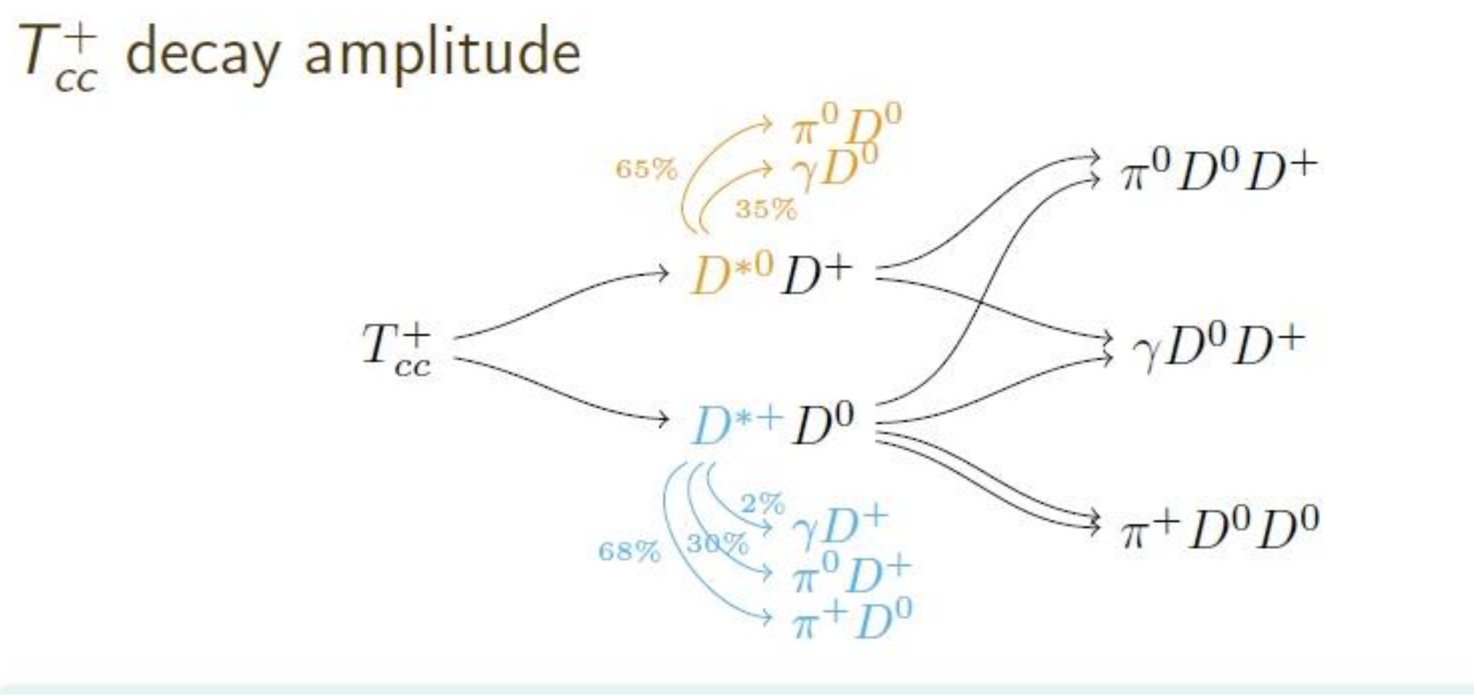
$D^0 D^{*+} \longrightarrow D^0 D^+ \pi^0 \longrightarrow (K^- \pi^+)(K^0 \pi^+)\pi^0$

$D^0 D^{*+} \longrightarrow D^0 D^+ \pi^0 \longrightarrow (K^0 \pi^0)(K^0 \pi^+)\pi^0$

$D^+ D^{*0} \longrightarrow D^+ D^0 \pi^0 \longrightarrow (K^0 \pi^+)(K^- \pi^+)\pi^0$

$D^+ D^{*0} \longrightarrow D^+ D^0 \pi^0 \longrightarrow (K^0 \pi^+)(K^0 \pi^0)\pi^0$

(iv) One should recognize intermediate states using the decay structure of the off-shell D^{*+} mesons in the $D_0\,\pi_+$ mass distribution.



From: Mikhail Mikhasenko, [LHCb, arXiv:2109.01056]

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The isospin violation in hidden charm molecules is not easy to see because their widths are several MeV, sometimes larger than the level spacing. Therefore, a careful determination of branching ratioes is necessary.

Work is in progress to „fish out“ some interesting example for which experiments are feasible and a theoretical model for decays is promissing.

Table 78.3: As in Table 78.1, but for new states near the first open-flavor thresholds in the $c\bar{c}$ and $b\bar{b}$ regions, ordered by mass. Updated from Ref. [77] with kind permission, copyright (2011), Springer, and from Ref. [9] with kind permission from the authors.

PDG Name	Former Name(s)	m (MeV)	Γ (MeV)	$I^G(J^{PC})$	Production	Decay	Discovery Year	Summary Table
$\chi_{c1}(3872)$	$X(3872)$	3871.65±0.06	1.19 ± 0.21	$0^+(1^{++})$	$B \to KX$ $p\bar{p} \to X...$ $pp \to X...$ $e^+e^- \to \gamma X$	$\pi^+\pi^- J/\psi(1S)$ $3\pi J/\psi(1S)$ $D^{*0}\bar{D}^0$ $\gamma J/\psi(1S)$ $\gamma\psi(2S)$ $\pi^0\chi_{c1}(1P)$	2003	YES
$Z_c(3900)$		3887.1 ± 2.6	28.4 ± 2.6	$1^+(1^{+-})$	$\psi(4230) \to \pi^- X$ $\psi(4230) \to \pi^0 X$	$\pi^+ J/\psi(1S)$ $\pi^0 J/\psi(1S)$ $(D\bar{D}^*)^+$ $(D\bar{D}^*)^0$	2013	YES
$X(4020)$	$Z_c(4020)$	4024.1 ± 1.9	13 ± 5	$1^+(?^{?-})$	$\psi(4230, 4360) \to \pi^- X$ $\psi(4230, 4360) \to \pi^0 X$	$\pi^+ h_c$ $\pi^0 h_c$ $(D^*\bar{D}^*)^+$ $(D^*\bar{D}^*)^0$	2013	YES
$Z_b(10610)$		10607.2 ± 2.0	18.4 ± 2.4	$1^+(1^{+-})$	$\Upsilon(10860) \to \pi^- X$ $\Upsilon(10860) \to \pi^0 X$	$\pi^+\Upsilon(1S, 2S, 3S)$ $\pi^0\Upsilon(1S, 2S, 3S)$ $\pi^+ h_b(1P, 2P)$ $(B\bar{B}^*)^+$	2011	YES
$Z_b(10650)$		10652.2 ± 1.5	11.5 ± 2.2	$1^+(1^{+-})$	$\Upsilon(10860) \to \pi^- X$	$\pi^+\Upsilon(1S, 2S, 3S)$ $\pi^+ h_b(1P, 2P)$ $(B^*\bar{B}^*)^+$	2011	YES

PDG Name	Former Name(s)	m (MeV)	Γ (MeV)	$I^G(J^{PC})$	Production	Decay	Discovery Year	Summary Table
$\psi_3(3842)$		3842.71 ± 0.20	2.79 ± 0.62	$0^-(3^{--})^*$	$pp \to X...$	$D\bar{D}$	2019	YES
$\chi_{c0}(3860)$		3862^{+48}_{-35}	201^{+177}_{-106}	$0^+(0^{++})$	$e^+e^- \to J/\psi(1S)X$	$D\bar{D}$	2017	NO
$\chi_{c0}(3915)$	$X(3915)$, $Y(3940)$	3921.7 ± 1.8	18.8 ± 3.5	$0^+(0/2^{++})$	$B \to KX$ $e^+e^- \to e^+e^-X$	$\omega J/\psi(1S)$ $D\bar{D}$	2004	YES
$\chi_{c2}(3930)$	$\chi_{c2}(2P)$, $Z(3930)$	3922.5 ± 1.0	35.2 ± 2.2	$0^+(2^{++})$	$e^+e^- \to e^+e^-X$	$D\bar{D}$	2005	YES
$X(3940)$		3942^{+9}_{-8}	37^{+27}_{-17}	$?^?(?^{??})$	$e^+e^- \to J/\psi(1S)X$	$D\bar{D}^*$	2007	NO
$X(4050)^\pm$	$Z_1(4050)$	4051^{+24}_{-43}	82^{+51}_{-28}	$1^-(?^{?+})$	$\bar{B}^0 \to K^-X$	$\pi^+\chi_{c1}(1P)$	2008	NO
$X(4055)^\pm$	$Z_c(4055)$	4054 ± 3	45 ± 13	$1^+(?^{?-})$	$e^+e^- \to \pi^-X$	$\pi^+\psi(2S)$	2015	NO
$X(4100)^\pm$		4096^{+27}_{-30}	152^{+83}_{-68}	$1^-(?^{??})$	$\bar{B}^0 \to K^-X$	$\pi^+\eta_c(1S)$	2018	NO
$\chi_{c1}(4140)$	$Y(4140)$	4146.5 ± 3.0	19^{+7}_{-5}	$0^+(1^{++})$	$B^+ \to K^+X$	$\phi J/\psi(1S)$	2009	YES
$X(4160)$		4156^{+29}_{-25}	139^{+113}_{-65}	$?^?(?^{??})$	$e^+e^- \to J/\psi(1S)X$	$D^*\bar{D}^*$	2007	NO
$Z_c(4200)$		4196^{+35}_{-32}	370^{+99}_{-149}	$1^+(1^{+-})$	$\bar{B}^0 \to K^-X$	$J/\psi(1S)\pi^+$	2014	NO
$\psi(4230)$	$Y(4230)$ $Y(4260)$	4222.7 ± 2.6	49 ± 8	$0^-(1^{--})$	$e^+e^- \to X$	$\pi^+\pi^-J/\psi(1S)$ $\omega\chi_{c0}(1P)$ $\pi^+\pi^-h_c(1P)$ (see listings)	2015	YES
$R_{c0}(4240)$	$Z_c(4240)$	4239^{+48}_{-21}	220^{+118}_{-88}	$1^+(0^{--})$	$\bar{B}^0 \to K^-X$	$\pi^+\psi(2S)$	2014	NO
$X(4250)^\pm$	$Z_2(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$1^-(?^{?+})$	$\bar{B}^0 \to K^-X$	$\pi^+\chi_{c1}(1P)$	2008	NO
$\chi_{c1}(4274)$	$Y(4274)$	4286^{+8}_{-9}	51 ± 7	$0^+(1^{++})$	$B^+ \to K^+X$	$\phi J/\psi(1S)$	2011	YES
$X(4350)$		$4350.6^{+4.7}_{-5.1}$	13^{+18}_{-10}	$0^+(?^{?+})$	$e^+e^- \to e^+e^-X$	$\phi J/\psi(1S)$	2009	NO
$\psi(4360)$	$Y(4360)$	4372 ± 9	115 ± 13	$0^-(1^{--})$	$e^+e^- \to X$	$\pi^+\pi^-\psi(2S)$ $\pi^+\pi^-J/\psi(1S)$	2007	YES
$Z_c(4430)$		4478^{+15}_{-18}	181 ± 31	$1^+(1^{+-})$	$\bar{B}^0 \to K^-X$	$\pi^+\psi(2S)$ $\pi^+J/\psi(1S)$	2007	YES
$\chi_{c0}(4500)$	$X(4500)$	4474 ± 4	77^{+12}_{-10}	$0^+(0^{++})$	$B^+ \to K^+X$	$\phi J/\psi(1S)$	2017	NO
$X(4630)$		4626^{+24}_{-111}	174^{+137}_{-78}	$0^+(?^{?+})$	$B^+ \to K^+X$	$\phi J/\psi(1S)$	2021	NO
$\psi(4660)$	$Y(4660)$, $X(4630)$	4630 ± 6	72^{+14}_{-12}	$0^-(1^{--})$	$e^+e^- \to X$	$\pi^+\pi^-\psi(2S)$ $\Lambda_c^+\bar{\Lambda}_c^-$ $D_s^+D_{s1}(2536)$	2007	YES
$\chi_{c1}(4685)$		4684^{+15}_{-17}	126^{+40}_{-44}	$0^+(1^{++})$	$B^+ \to K^+X$	$\phi J/\psi(1S)$	2021	NO
$\chi_{c0}(4700)$	$X(4700)$	4694^{+16}_{-5}	87^{+18}_{-10}	$0^+(0^{++})$	$B^+ \to K^+X$	$\phi J/\psi(1S)$	2017	NO
$\Upsilon(10753)$		$10752.7^{+5.9}_{-6.0}$	36^{+18}_{-12}	$?^?(1^{--})$	$e^+e^- \to X$	$\pi\pi\Upsilon(1S,2S,3S)$	2019	NO
$\Upsilon(10860)$	$\Upsilon(5S)$	$10885.2^{+2.6}_{-1.6}$	37 ± 4	$0^-(1^{--})$	$e^+e^- \to X$	$B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi)$ $\pi\pi\Upsilon(1S,2S,3S)$	1985	YES

Thank you

for your attention!