$X(3872)$ in the hybrid model of charmonium and hadronic molecule

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in collaboration with

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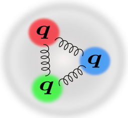
Atsushi Hosaka (RCNP, Osaka Univ.).

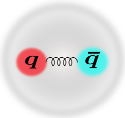
Experimental and theoretical status of and perspectives for XYZ states,
Online, 12-15 April 2021

Hadron structure: Constituent quark model

- Hadron = Quark composite system
- Ordinary Hadrons: Baryon (qqq) and Meson ($q\bar{q}$)



Baryon(proton,nucleon,...)



Meson (ρ,$K^{(*)}$,...)

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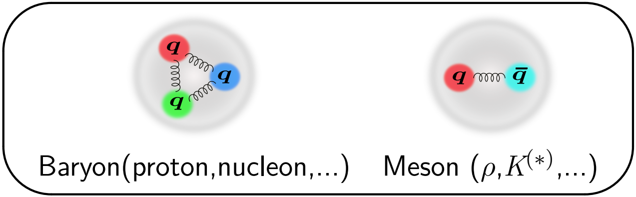
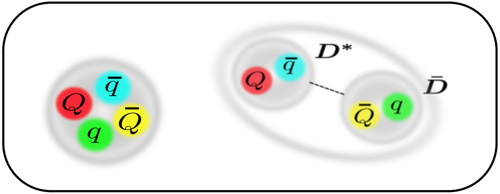
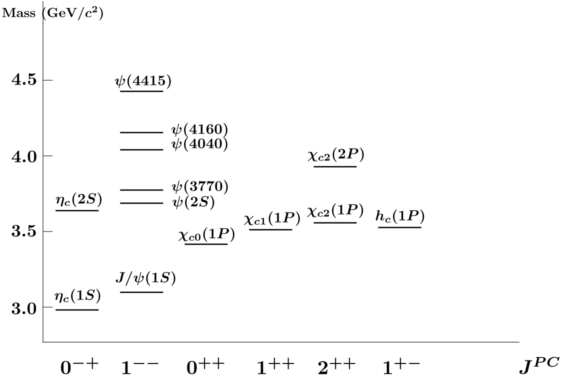


- Exotic Hadrons ($\neq qqq$, $q\bar{q}$): **Multiquark? Multihadron?**



Constituent quark picture and beyond

- e.g. $c\bar{c}$ mesons (Charmonium)



one-g exchange

$+$

Confinement

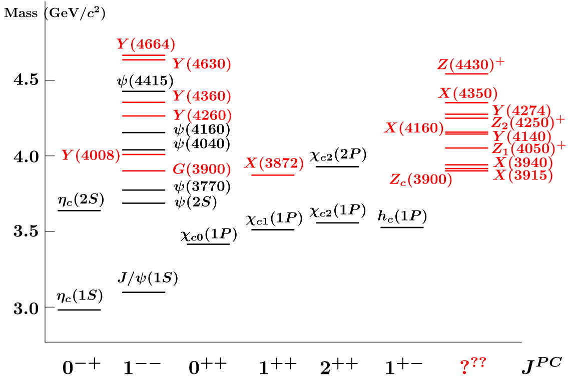
$\Downarrow$

$$V(r) = -\frac{\alpha_s}{r} + cr$$
$$+ \ldots$$

N. Brambilla,*et al.* Eur.Phys.J.C **71**(2011)1534, S. Godfrey and N. Isgur, PRD**32**(1985)189

Constituent quark picture and beyond

- e.g. $c\bar{c}$ mesons (Charmonium) and **Unexpected X, Y, Z**



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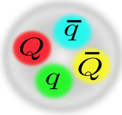
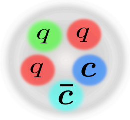
- Exotics $\neq c\bar{c}$ have been observed in the Experiments (BaBar, Belle, BESIII, LHCb,...) $\Rightarrow$ **Q. Structure? Physics?**

Exotic structures?

Compact multiquarks

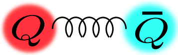


Tetraquark

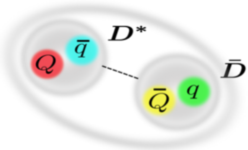


Pentaquark

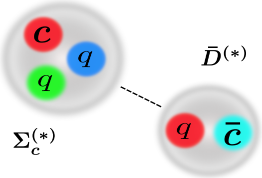
$Q\bar{Q}g$ Hybrid



Hadronic molecules

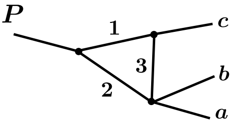


Meson-Meson



Meson-Baryon

Triangle Singularity

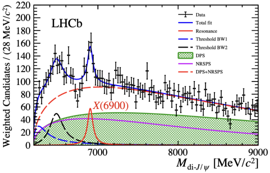


(w/o Resonance)

Recent reports of Exotic hadrons!

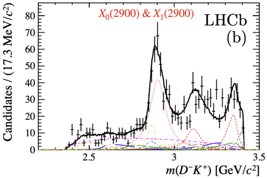
▷ $X(6900)$ **($cc\bar{c}\bar{c}$?)**

LHCb, Science Bulletin 65 (2020) 1983



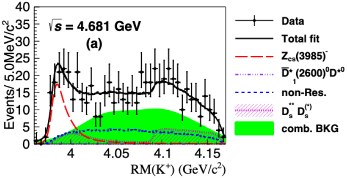
▷ $X_{0,1}(2900)$ **($\bar{c}\bar{s}ud$?)**

LHCb, PRL125, 242001 (2020), PRD102, 112003 (2020)



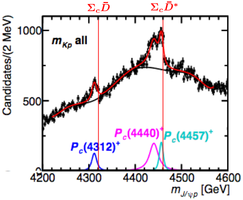
▷ Z_{cs} **($c\bar{c}s\bar{u}$?)**

BESIII PRL126, 102001 (2021)



▷ P_c **($uudc\bar{c}$?)**,

LHCb PRL**115**(2015)072001, PRL**122**(2019)222001



Recent reports of Exotic hadrons!

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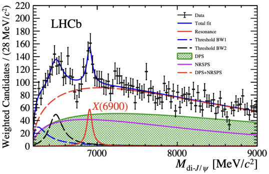

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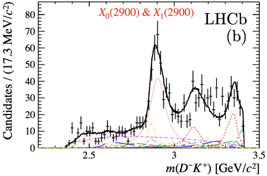
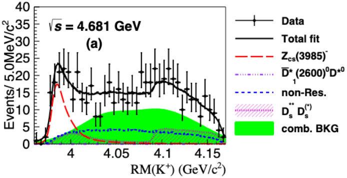


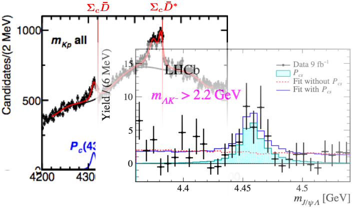
▷ Z_{cs} $\boldsymbol{(c\bar{c}s\bar{u}?)}$

BESIII PRL126, 102001 (2021)



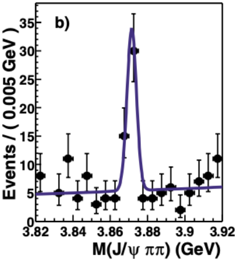
▷ P_c $\boldsymbol{(uudc\bar{c}?)}$, P_{cs} $\boldsymbol{(udsc\bar{c}?)}$

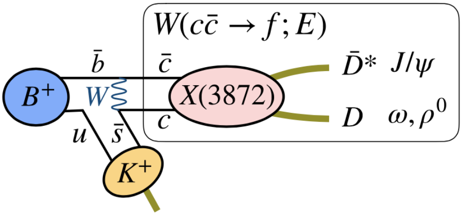
LHCb PRL**115**(2015)072001, PRL**122**(2019)222001 , 2012.10380



Observation of $X(3872)$!

- $X(3872)$ (or $\chi_{c1}(3872)$) was reported by Belle in $B \to K\pi^+\pi^- J/\psi$ decay
  S.-K. Choi *et al.*, PRL91(2003)262001





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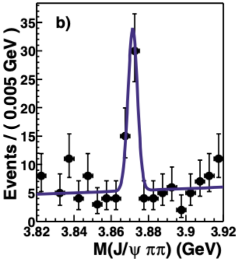

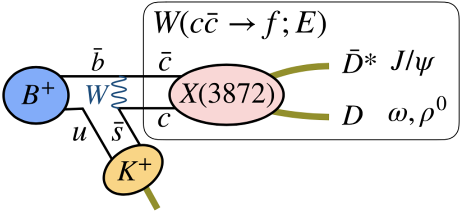

- Mass, width and $I^G(J^{PC})$ from PDG P.A. Zyla *et al.* (Particle Data Group), PTEP 2020, 083C01 (2020)
  Mass: 3871.69 ± 0.17 MeV $\mathbf{I^G(J^{PC})} = 0^+(1^{++})$
  Width: < 1.2 MeV

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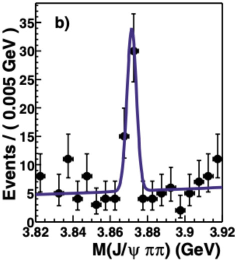

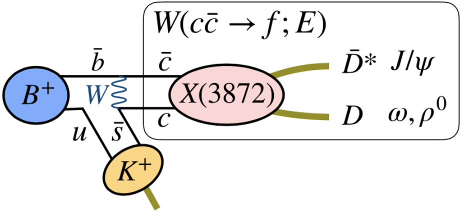

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  Mass: 3871.69 ± 0.17 MeV $\quad \mathbf{I^G(J^{PC})} = 0^+(1^{++})$
  Width: < 1.2 MeV
- Found in many types of experiments (summarized in Y.Y *et al.*, J.Phys.G 47 (2020)053001)
  ***B*-decay:** Belle, *BABAR*, LHCb,... , $\quad e^+e^-$ BESIII, ...
  ***pp*:** LHCb, CMS, ATLAS, ..., $\quad p\bar{p}$ CDF (II) D0,...
  PbPb: CMS 2102.13048 [hep-ex]

Exotic nature of $X(3872) \neq c\bar{c}$

- Isospin violation in the $X(3872)$ decay [Belle, *BABAR*,...]

$$\frac{Br(X \to \pi^+\pi^-\pi^0 J/\psi)_{I=0}}{Br(X \to \pi^+\pi^- J/\psi)_{I=1}} = \mathbf{1.0 \pm 0.4 \pm 0.3}$$

$\Rightarrow$ Isospin mixed state !? $\to$ **Exotic structure (e.g. $c\bar{c}q\bar{q}$)** is expected

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- $X(3872)$ **near the $D\bar{D}^*$ thresholds**

D^+D^{*-} **3879.84 MeV**

3871.69 MeV

$D^0\bar{D}^{*0}$ **3871.68 MeV**

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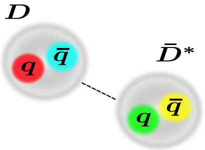
- $X(3872)$ **near the $D\bar{D}^*$ thresholds**

D^+D^{*-} — 3879.84 MeV

$D^0\bar{D}^{*0}$ — 3871.69 MeV / 3871.68 MeV



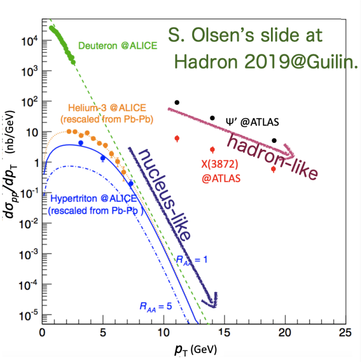
$X(3872) = D\bar{D}^*$ molecule?

$\Rightarrow$ Hadronic molecule is expected near thresholds

$\Rightarrow$ **$X(3872)$ as $D\bar{D}^*$ molecule?**

Possible existence of a $c\bar{c}$ core component in $X(3872)$

Production in the pp collisions



- $(d\sigma/dp)_{X(3872)}$ **is similar to that of ψ'** rather than that of nuclei (a hadron composite)

$\Rightarrow$ Existence of a $c\bar{c}$ core component ($\sim 5\%$)?

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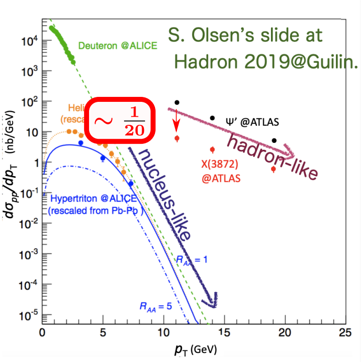

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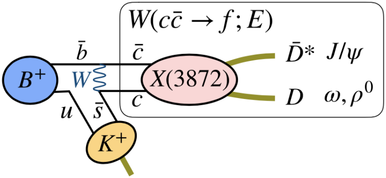
Inconsistency between $X \to J/\psi\pi\pi$ and $X \to D\bar{D}^*$ in the B-decay process?

From PDG

$\chi_{c1}(3872)$ MASS FROM $J/\psi X$ MODE	$M_{X(3872)}$	3871.69 ± 0.17 MeV
$\chi_{c1}(3872)$ MASS FROM $\overline{D}^{*0} D^0$ MODE		
$m_{\chi_{c1}(3872)} - m_{J/\psi}$		
$m_{\chi_{c1}(3872)} - m_{J/\psi}$		775 ± 4 MeV
$m_{\chi_{c1}(3872)} - m_{\psi(2S)}$		
$\chi_{c1}(3872)$ WIDTH	$\Gamma_{X(3872)}$	< 1.2 MeV CL=90.0%
$\chi_{c1}(3872)$ WIDTH FROM $\overline{D}^{*0} D^0$ MODE		



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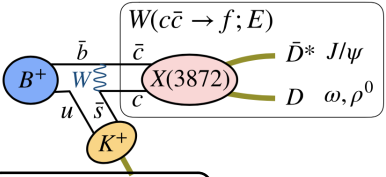

$B \to J/\psi\pi\pi K$

$B \to D\bar{D}^* K$

$M_X = 3871.69 \pm 0.17$ MeV
$\Gamma_X < 1.2$ MeV

$\Leftrightarrow$

[Belle]

$M_X = 3872.9^{+0.6\,+0.4}_{-0.4\,-0.5}$ MeV

$\Gamma_X = 3.9^{+2.8\,+0.2}_{-1.4\,-1.1}$ MeV

[*BABAR*]

$M_X = 3875.1^{+0.7}_{-0.5} \pm 0.5$ MeV

$\Gamma_X = 3.0^{+1.9}_{-1.4} \pm 0.9$ MeV

Inconsistency between $X \to J/\psi\pi\pi$ and $X \to D\bar{D}^*$ in the B-decay process?

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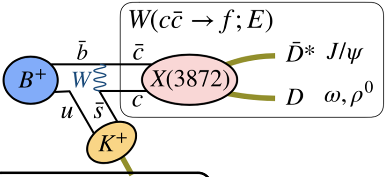
$$B \to J/\psi\pi\pi K$$



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$M_X = 3875.1^{+0.7}_{-0.5} \pm 0.5$ MeV

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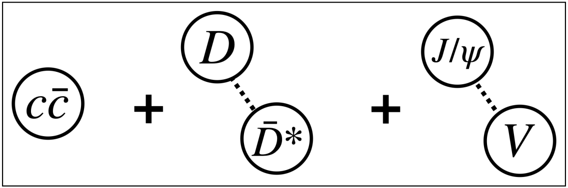
$$\Rightarrow \quad (M_X, \Gamma_X)_{X \to J/\psi\pi\pi} < (M_X, \Gamma_X)_{X \to D\bar{D}^*}$$

Our model: a hybrid state of $c\bar{c}$ and hadronic molecules



Core + Molecules

$c\bar{c}$

$D^0\bar{D}^{*0}(^3S_1, ^3D_1)$, $D^{*0}\bar{D}^{*0}(^5D_1)$,

$D^\pm\bar{D}^{*\mp}(^3S_1, ^3D_1)$, $D^{*\pm}\bar{D}^{*\mp}(^5D_1)$

$J/\psi\omega(^3S_1)$, $J/\psi\rho(^3S_1)$

- Core $c\bar{c}$ as $\chi_{c1}(2P)$ with $m_{c\bar{c}} = 3950$ MeV (quark model pred.)
- One pion exchange potential (OPEP) between $D^{(*)}\bar{D}^{(*)}$ (Central + Tensor)
- Couplings of $c\bar{c} - D\bar{D}^*$, $D\bar{D}^* - J/\psi V \Rightarrow$ determined empirically

Model Hamiltonian [J.Phys.G 47 (2020)053001]

- Potentials

$$D^{(*)}\bar{D}^{(*)} - D^{(*)}\bar{D}^{(*)}: \quad V_{OPEP}$$

$$c\bar{c} - D\bar{D}^{*}: \quad u(\vec{q}) = \frac{g_{c\bar{c}}}{\sqrt{\Lambda_q}} L_{\Lambda_q}(\vec{q})$$ with Form factor $L_{\Lambda_q}(\vec{q}) = \frac{\Lambda_q^2}{\Lambda_q^2 + \vec{q}^{\,2}}$

$$D\bar{D}^{*} - J/\psi V: \quad v(\vec{q}, \vec{q}\,') = \frac{v_0}{\Lambda_q^2} L_{\Lambda_q}(\vec{q}) L_{\Lambda_q}(\vec{q}\,')$$

$^{*}g_{c\bar{c}}$, v_0 determined empirically, $c\bar{c} - J/\psi V$ is not considered because of the OZI rule

Model Hamiltonian [J.Phys.G 47 (2020)053001]

- Potentials

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$$D\bar{D}^{*} - J/\psi\, V: \quad v(\vec{q}, \vec{q}\,') = \frac{v_0}{\Lambda_q^2} L_{\Lambda_q}(\vec{q}) L_{\Lambda_q}(\vec{q}\,')$$

$^{*}g_{c\bar{c}}$, v_0 determined empirically, $c\bar{c} - J/\psi\, V$ is not considered because of the OZI rule

- Hamiltonian of $c\bar{c}$ + two mesons (mm): $H = \begin{pmatrix} m_{c\bar{c}} & U^{(mc)} \\ U^{(mc)} & H^{(mm)} \end{pmatrix}$

  - Hamiltonian of two mesons:

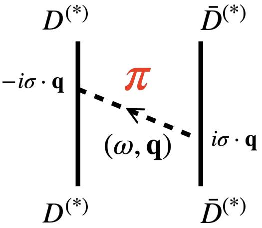
$$H^{(mm)} = H_0 + V^{D\bar{D}^{*} - J/\psi\, V} + V_{\text{OPEP}}$$

  - Matrices of the $c\bar{c} - (mm)$ potential and $D\bar{D} - J/\psi\, V$ potentials

$$U^{(mc)} = \begin{array}{cc} c\bar{c} & \\ \begin{pmatrix} -u \\ u \\ 0 \\ 0 \end{pmatrix} & \begin{array}{c} D^0\bar{D}^{*0} \\ D^+\bar{D}^{*-} \\ J/\psi\omega \\ J/\psi\rho \end{array} \end{array} \qquad V^{D\bar{D}^{*} - J/\psi\, V} = \begin{array}{c} D^0\bar{D}^{(*0)}, D^+D^{*-}, J/\psi\omega, J/\psi\rho \\ \begin{pmatrix} 0 & 0 & -v & -v \\ 0 & 0 & v & -v \\ -v & v & 0 & 0 \\ -v & -v & 0 & 0 \end{pmatrix} \end{array}$$

One pion exchange potential for $D^{(*)}\bar{D}^{(*)}$

Y.Y *et al.*, J.Phys.G 47 (2020)053001



- Effective $\pi D^{(*)} D^{(*)}$ Lagrangian

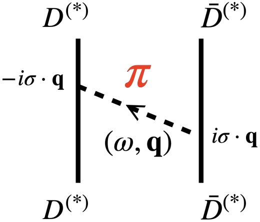
$$\mathcal{L}_{\pi HH} = i\frac{g_\pi}{2f_\pi}\mathrm{tr}\left[H_a\gamma_\mu\gamma_5\vec{\tau}\cdot i\partial^\mu\vec{\pi}\bar{H}_a\right]$$

$$H_a = \frac{1+\not{v}}{2}\left[-P^*_{a\mu}\gamma^\mu + P^a\gamma_5\right], \bar{H}_a = \gamma_0 H_a^\dagger\gamma_0$$

- Nonzero energy transfer $\omega^2 \sim (m_{D^*} - m_D)^2$
  $\rightarrow$ Effective π mass: $\mu^2 = m_\pi^2 - \omega^2 < 0$

One pion exchange potential for $D^{(*)}\bar{D}^{(*)}$

Y.Y *et al.*, J.Phys.G 47 (2020)053001



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- OPEP with the imaginary mass $m = i\mu$:

$$V_{OPEP}(r) = \left(\frac{g_\pi}{2f_\pi}\right)^2\frac{1}{3}\left[\vec{S}_1\cdot\vec{S}_2 C(r;\mu) + S_{12}(\hat{r})T(r;\mu)\right]\vec{\tau}_1\cdot\vec{\tau}_2$$

Central **Tensor**

* the real part is employed, while the imaginary one is ignored

** the contact term is not considered

- Form factor with Cutoff Λ (determined by the hadron size)

$$F(\vec{q}^{\,2}) = \frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 + \vec{q}^{\,2}}, \quad \Lambda_\pi \sim 1130 \text{ MeV}$$

Numerical results: $X(3872)$ as a hybrid state of $c\bar{c}$ and $D\bar{D}^*$

PTEP**2013**,093D01, PTEP**2014**,123D01, J.Phys.G 47 (2020)053001

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Parameter sets

Model	$g_{c\bar{c}}$	Λ_q [GeV]	g_π	Λ_π [GeV]	rms($D^0\bar{D}^{*0}$) [fm]	rms($D^\pm\bar{D}^{*\mp}$) [fm]	BE [MeV]
only $c\bar{c}-D\bar{D}^*$	0.05110	0.5	—	—	8.39	1.56	**0.16** **(input)**
only OPEP	—	—	0.55	1.791	8.25	1.44	**0.16** **(input)**
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Mixing ratios: Comparison of models

Model	$c\bar{c}$	$D^0\bar{D}^{*0}(^3S)$	$D^0\bar{D}^{*0}(^3D)$	$D^{*0}\bar{D}^{*0}(^5D)$	$D^\pm\bar{D}^{*\mp}(^3S)$	$D^\pm\bar{D}^{*\mp}(^3D)$	$D^{*\pm}\bar{D}^{*\mp}(^5D)$
only $c\bar{c}-D\bar{D}^*$	8.6%	84.8%	—	—	6.7%	—	—
only OPEP	—	91%	0.4%	0.4%	7.3%	0.5%	0.6%
Full	5.9%	86.9%	0.2%	0.1%	6.5%	0.2%	0.1%

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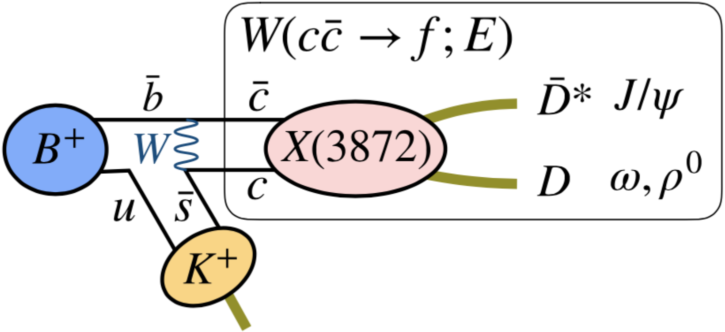
- **$c\bar{c}$ component $\sim 5.9\%$** $\rightarrow$ consistent with result of the production ratio in the pp collision
- Only OPEP $\Rightarrow$ **Large cutoff $\Lambda_\pi \sim 1.8$ GeV** is needed.

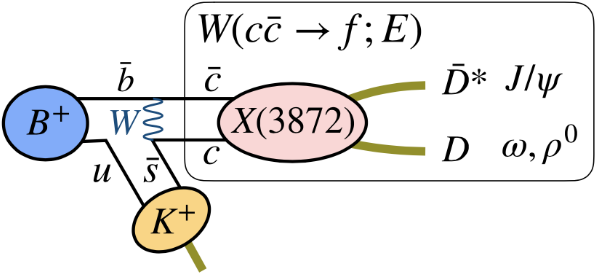
$\Rightarrow$ **$c\bar{c} - D\bar{D}^*$ coupling helps to generate a bound state**

Decay Spectrum



Decay spectrum

- Studying peak structures of $X(3872)$ in the B-decay process



M.Takizawa, S.Takeuchi PTEP2013,093D01, S.Takeuchi, K. Shimizu, M.Takizawa, PTEP2014,123D01

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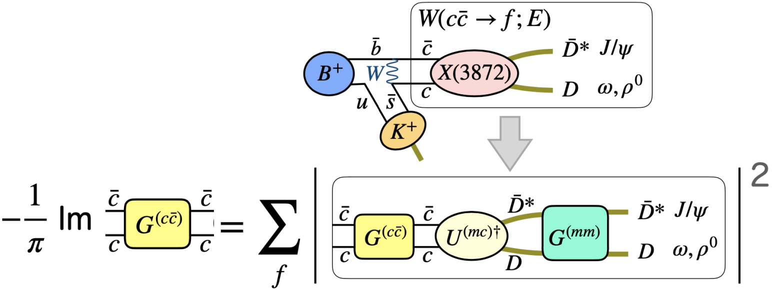

M.Takizawa, S.Takeuchi PTEP2013,093D01, S.Takeuchi, K. Shimizu, M.Takizawa, PTEP2014,123D01

$\Rightarrow$ computing the transfer from $c\bar{c}$ to two-meson final states $(D, \bar{D}^*)$, $(J/\psi, \rho)$,...

- $c\bar{c} - D\bar{D}^*$ coupling is allowed, while no direct $c\bar{c} - J/\psi V$ by the OZI rule
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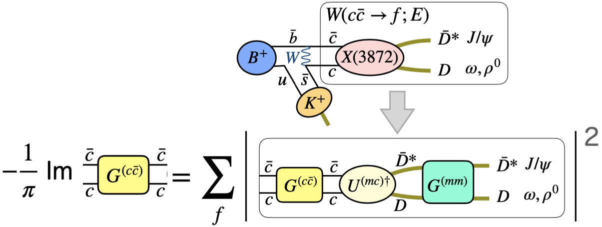

$$\Rightarrow -\frac{1}{\pi}\mathrm{Im}\langle c\bar{c}|G(E)|c\bar{c}\rangle = -\frac{1}{\pi}\sum_{\alpha}\langle c\bar{c}|\chi_\alpha^\theta\rangle\frac{1}{E-E_\alpha}\langle\tilde{\chi}_\alpha^\theta|c\bar{c}\rangle$$

M.Takizawa, S.Takeuchi PTEP2013,093D01, S.Takeuchi, K. Shimizu, M.Takizawa, PTEP2014,123D01

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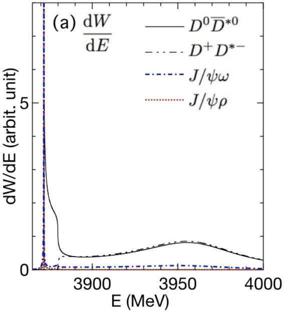
  $\leftrightarrow$ $D\bar{D}^* - J/\psi V$ coupling is allowed
- Complex scaling method (CSM) is employed T. Myo, *et al.*, PPNP 79 (2014) 1-56
  χ_α^θ: eigenfunction with the eigenvalue E_α obtained by CSM

Numerical results: Decay spectrum by CSM

- Contribution from each final states, $D\bar{D}^*$, $J/\psi\rho$, $J/\psi\omega$

dW/dE S. Takeuchi, K. Shimizu, M. Takizawa PTEP2014, 123D01



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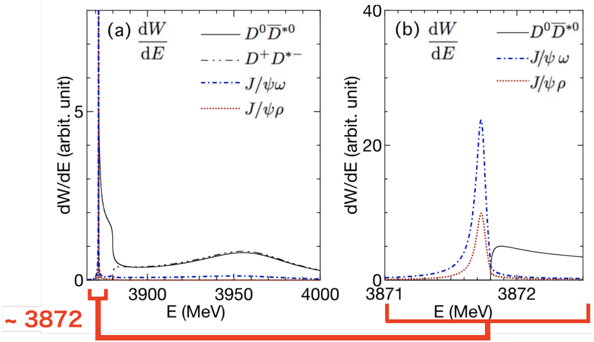

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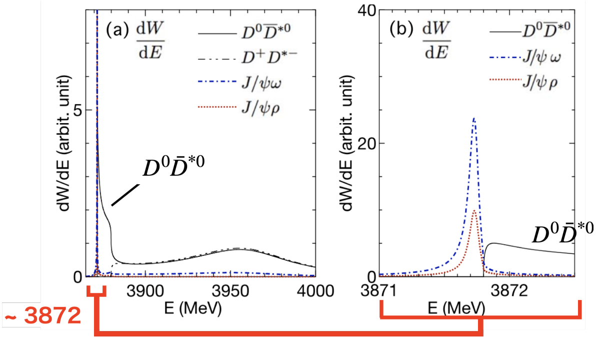

- $D^0\bar{D}^{*0}$ peak is wide,

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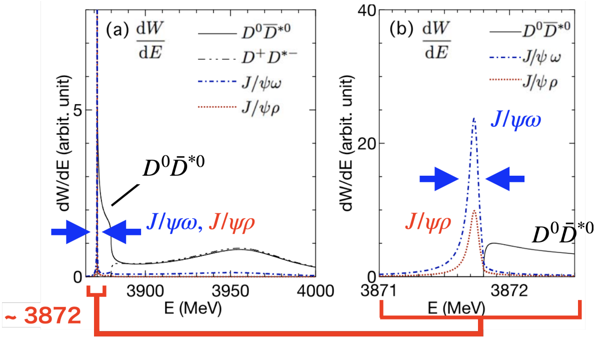
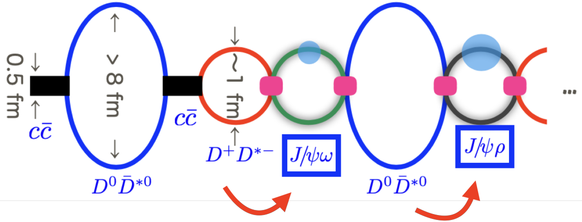


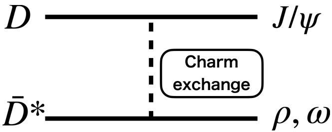
- $D^0\bar{D}^{*0}$ peak is wide, while **$J/\psi\rho$, $J/\psi\omega$ peaks are very narrow!**
- Contribution from $J/\psi\rho$ is smaller than that from $J/\psi\omega$

Narrow width of $J/\psi\rho$, $J/\psi\omega$ peaks

- Suppression of the $c\bar{c} \to J/\psi V$ transition ($V = \rho, \omega$)
  1. No direct $c\bar{c} \to J/\psi V$ coupling $\leftrightarrow$ OZI rule
  2. Rearrangement is necessary



- Quark rearrangement $\Rightarrow$ color factor $1/9$
- Charm exchange is needed in $D\bar{D} - J/\psi V$



- $X(3872)$ is isosinglet-like in the short range
  $\Rightarrow$ suppression of the $(J/\psi\rho)_{I=1}$ decay

$X(3872)$ pole above the threshold

Previous works: PTEP**2013**,093D01
PTEP**2014**,123D01

BE= 0.16 MeV below $D^0\bar{D}^{*0}$ threshold was assumed **[PDG2012]**

$\Updownarrow$

[PDG2020] $M_{X(3872)}$ **above the $D^0\bar{D}^{*0}$ threshold**

D^+D^{*-} **3879.84 MeV**

3871.69 MeV

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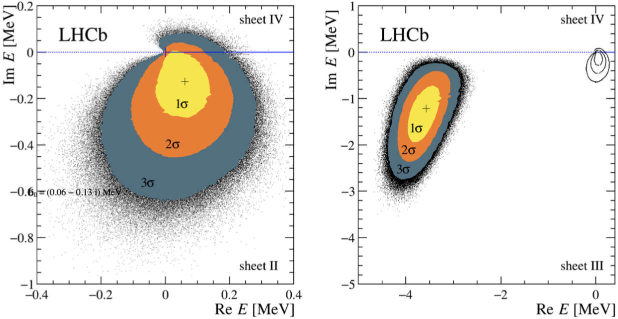
$\rightarrow$ **Q. Can we obtain a pole above $D^0\bar{D}^{*0}$ in the hybrid model?**

$X(3872)$ pole in the LHCb analysis

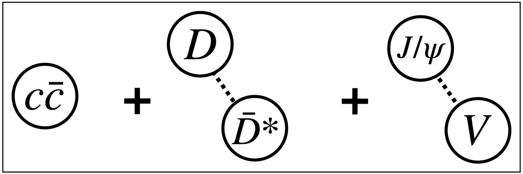
- Poles by the Flatté approach (Only the $D^0\bar{D}^{*0}$ channel is considered)

R. Aaij *et al.*, (LHCb collaboration) PRD**102**(2020)092005



- Two poles are found
  1. $E_{II} = 0.06 - 0.13i$ MeV on the physical sheet $\rightarrow$ **above $D^0\bar{D}^{*0}$ threshold**
  2. $E_{III} = -3.58 - 1.22i$ MeV on the unphysical sheet

Summary



- $X(3872)$ as a hybrid state of $c\bar{c}$ and hadronic molecules
- The $X(3872)$ spectrum is reproduced reasonably.
  $\Rightarrow$ About 6% $c\bar{c}$ component $\Leftrightarrow$ agreement with the production measurement
- The difference between $X \to J/\psi\pi\pi$ and $X \to D\bar{D}^*$ in the B decay spectrum.
  $\Rightarrow$ $D\bar{D}^*$ peak is wide, while the peaks of $J/\psi\rho$, $J/\psi\omega$ peak are narrow.
- The pole can be above the $\bar{D}^0\bar{D}^{*0}$ threshold thanks to the finite width of ρ and ω

M.Takizawa, S.Takeuchi PTEP**2013**,093D01, S.Takeuchi, K. Shimizu, M.Takizawa, PTEP**2014**,123D01,
Y.Y, A. Hosaka, S. Takeuchi, M. Takizawa J. Phys. G:Nucl. Part. Physx. **47** (2020) 053001
S. Takeuchi, M. Takizawa, Y.Y, and A. Hosaka in preparation

Thank you for your kind attention.