Disentangling the *X*(3872) with *T*cc

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Based on arXiv: 2306.12406
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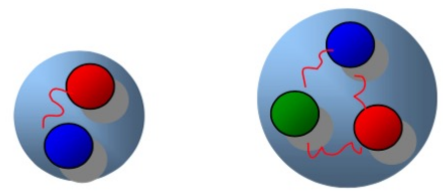
第六届强子谱和强子结构会议 2023/8/29

Hadron structures

- Mesons ($\bar{q}q$) and Baryons (qqq) in a simple picture

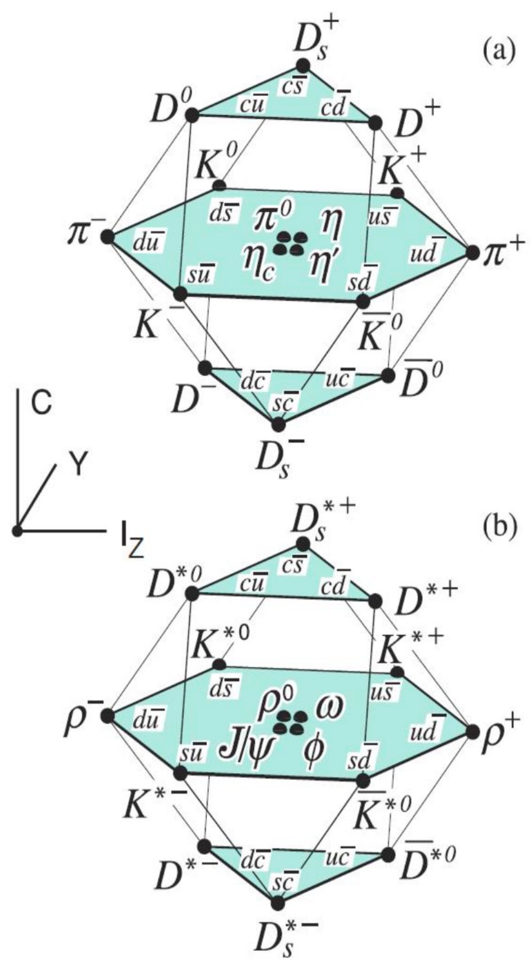
convential hadron

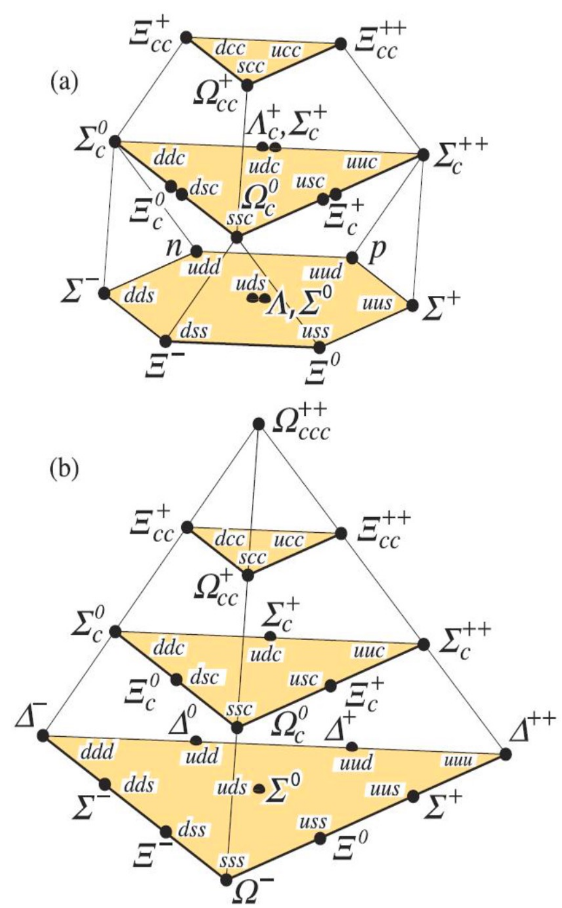


(q $\bar{\text{q}}$) (qqq)

J=0

J=1





J=1/2

J=3/2

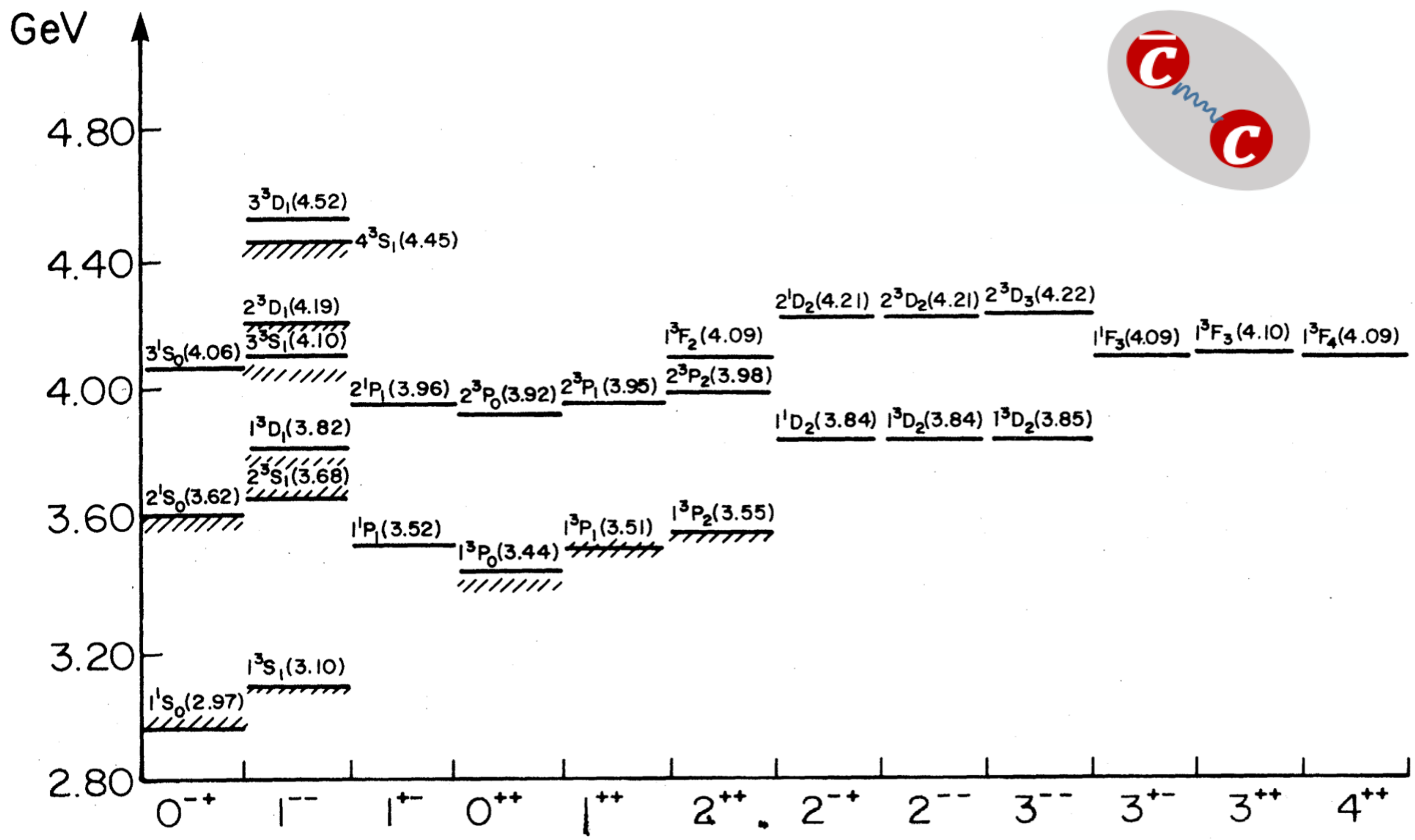
GI quark model

Mesons in a Relativized Quark Model with Chromodynamics #1

S. Godfrey (Toronto U.), Nathan Isgur (Toronto U.) (1985)

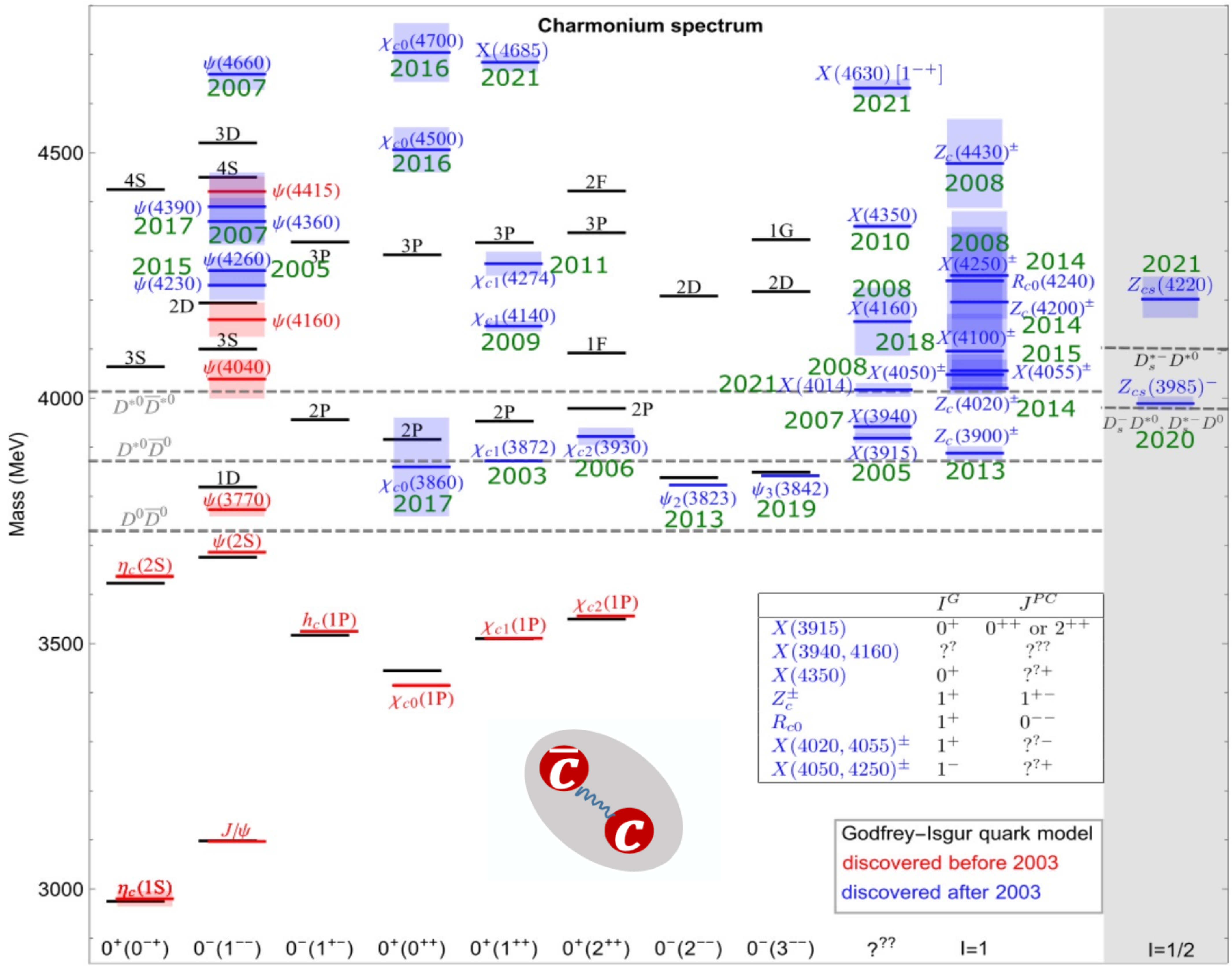
Published in: *Phys.Rev.D* 32 (1985) 189-231

DOI cite claim reference search 3,134 citations



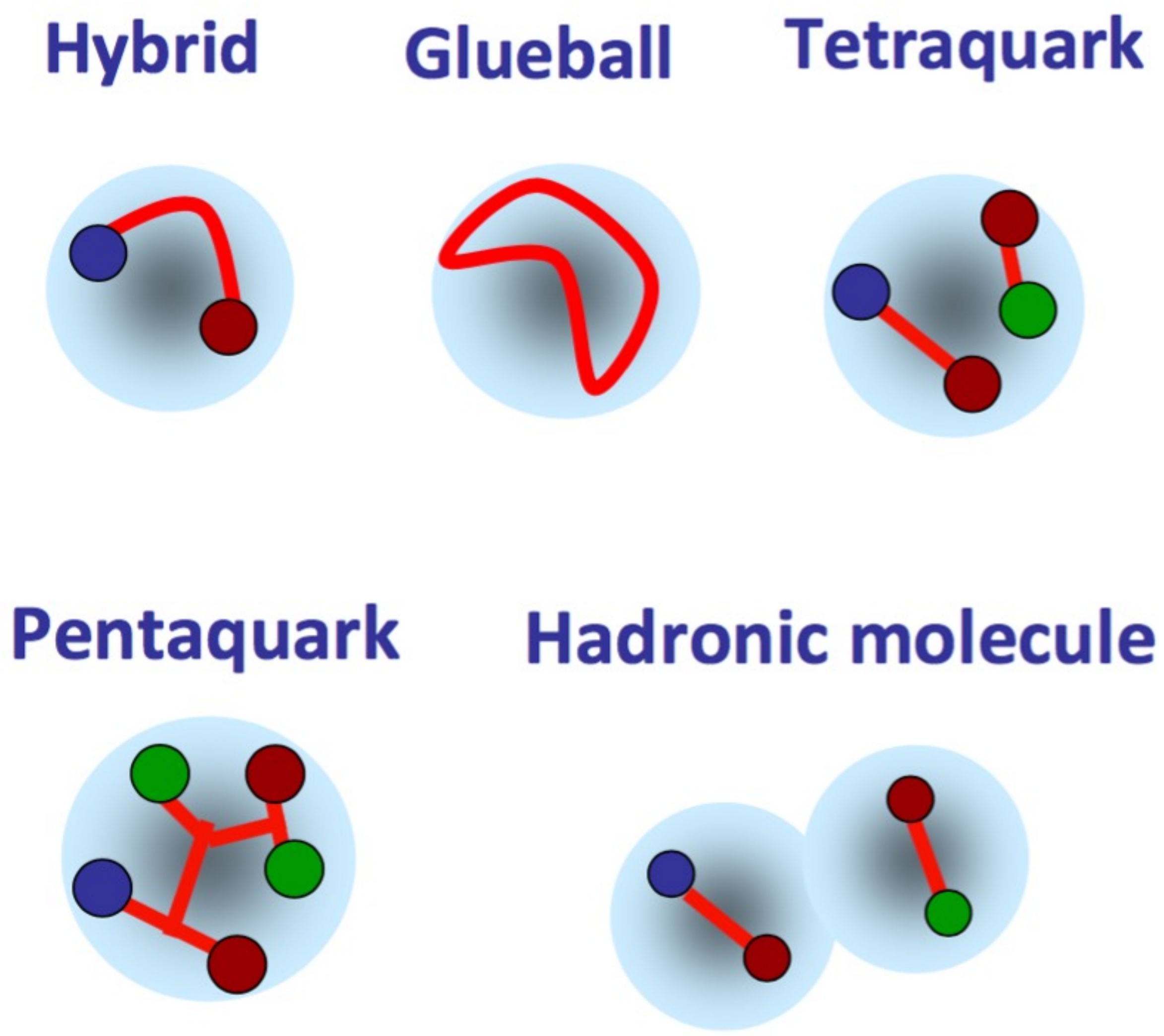
- Successfully explained properties of the ground states.
- Failed in some excited states.

Exotic hadrons in charmonium spectrum



From F.-K. Guo

Exotic structures



More complicated hadron structures.

X(3872)

Experiment	Mass [MeV]	Width [MeV]
Belle [63]	$3872 \pm 0.6 \pm 0.5$	< 2.3
Belle [75]	–	–
Belle [76]	$3875.4 \pm 0.7^{+0.4}_{-1.7} \pm 0.9$	–
Belle [77]	$3871.46 \pm 0.37 \pm 0.07$	–
Belle [78]	$3872.9^{+0.6+0.4}_{-0.4-0.5}$	$3.9^{+2.8+0.2}_{-1.4-1.1}$
Belle [79]	–	–
Belle [80]	$3871.84 \pm 0.27 \pm 0.19$	< 1.2
CDF [67]	$3871.3 \pm 0.7 \pm 0.4$	–
CDF [81]	–	–
CDF [82]	–	–
CDF [83]	$3871.61 \pm 0.16 \pm 0.19$	–
DØ [68]	$3871.8 \pm 3.1 \pm 3.0$	–
BaBar [84]	3873.4 ± 1.4	–
BaBar [85]	$3871.3 \pm 0.6 \pm 0.1$	< 4.1
	$3868.6 \pm 1.2 \pm 0.2$	–
BaBar [86]	–	–
BaBar [87]	$3875.1^{+0.7}_{-0.5} \pm 0.5$	$3.0^{+1.9}_{-1.4} \pm 0.9$
BaBar [88]	$3871.4 \pm 0.6 \pm 0.1$	< 3.3
	$3868.7 \pm 1.5 \pm 0.4$	–
BaBar [89]	–	–
BaBar [90]	$3873.0^{+1.8}_{-1.6} \pm 1.3$	–
LHCb [91]	$3871.95 \pm 0.48 \pm 0.12$	–
LHCb [70]	–	–
LHCb [92]	–	–
CMS [73]	–	–
BESIII [93]	$3871.9 \pm 0.7 \pm 0.2$	< 2.4

Phys. Rept. 639 (2016) 1-121

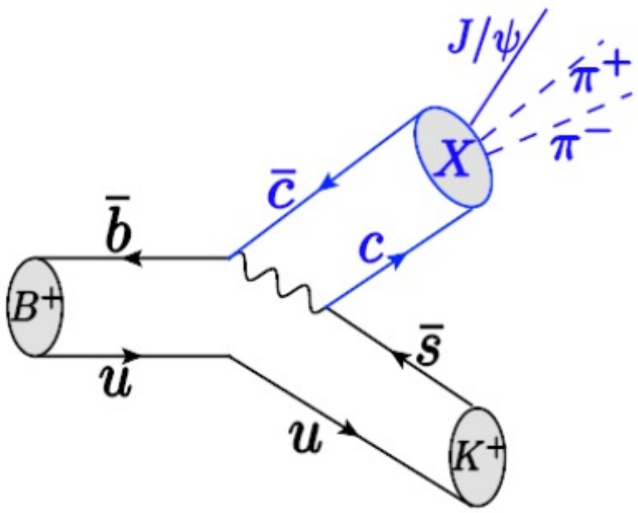
Observation of a narrow charmonium-like state in exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays

Belle Collaboration • S.K. Choi (Gyeongsang Natl. U.) et al. (Sep, 2003)

Published in: *Phys.Rev.Lett.* 91 (2003) 262001 • e-Print: hep-ex/0309032 [hep-ex]

pdf links DOI cite claim

2,295 citations



- Named as $\chi_{c1}(3872)$ in PDG.
- Observed in 2003 and confirmed. $J^{PC} = 1^{++}$.

Theoretical interpretation of X(3872)

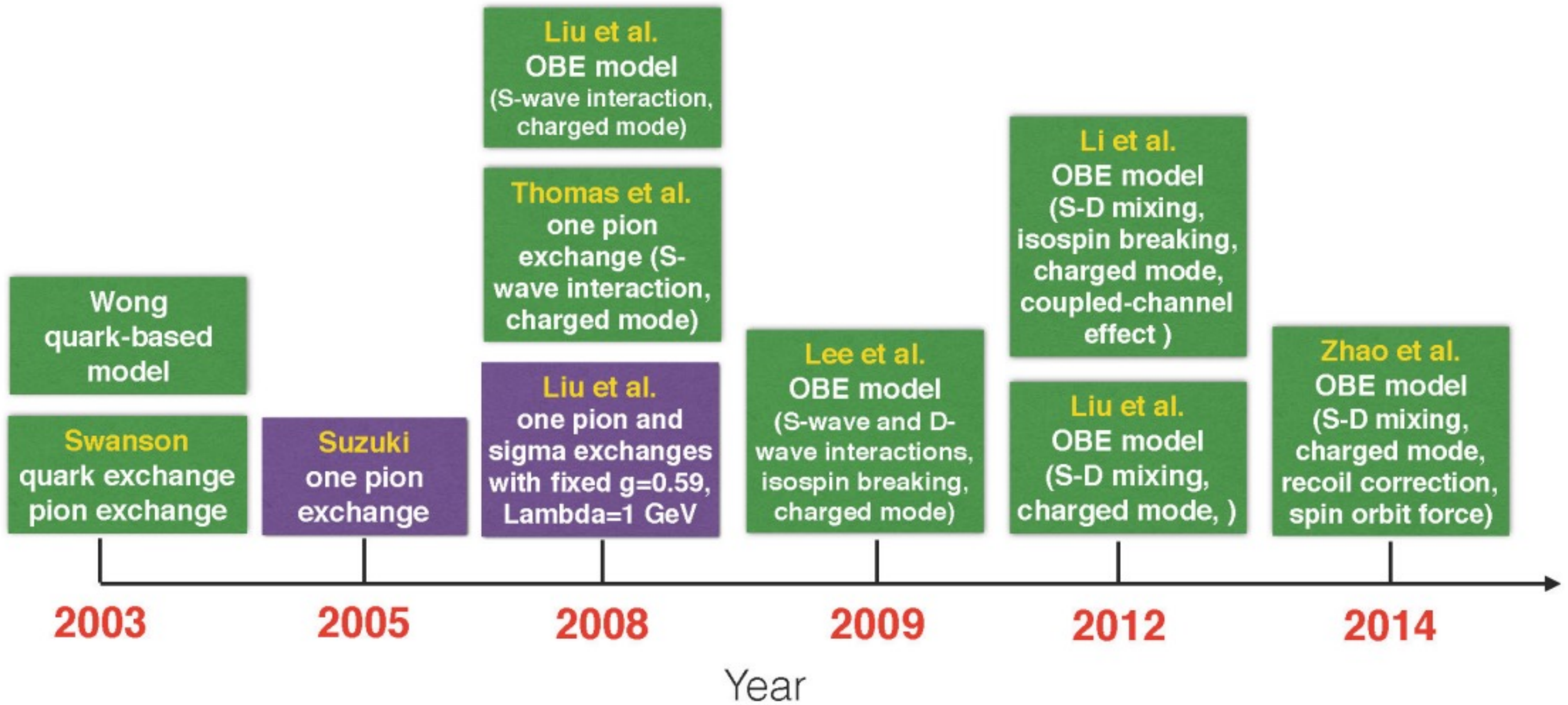


Figure 50: (Color online) A summary of the theoretical progresses on the dynamical studies of the $D\bar{D}^*$ molecular state of the $X(3872)$. Here, these studies are marked by green and purple backgrounds when the corresponding conclusion of whether the $X(3872)$ is a $D\bar{D}^*$ molecular state is positive and negative, respectively.

- Conventional $\bar{c}c$: $\chi_{c1}(2P)$.
  Eichten ,Lane, Quigg, Suzuki, Barnes, Godfrey,...

- Compact tetraquark state.
  Close, Maiani, Piccinini, Polosa, Riquer,...

Theoretical interpretation of X(3872)

- The $D\bar{D}^*/D^*\bar{D}$ molecular state.

  Swanson, Wong, Guo, liu,....

Close to $D^0\bar{D}^{*0}/D^{*0}\bar{D}^0$ thresholds

$$\delta m = m_{\overline{D^{*0}}D^0} - m_{X(3872)}$$

$$= 0.00 \pm 0.18 \text{ MeV}$$

PDG 22

Where is the corresponding state in quark model?

- The mixing of the $\bar{c}c$ core with $D\bar{D}^*/D^*\bar{D}$ component.

  Chao, H. Q. Zheng, Yu. S. Kalashnikova, P. G. Ortega...

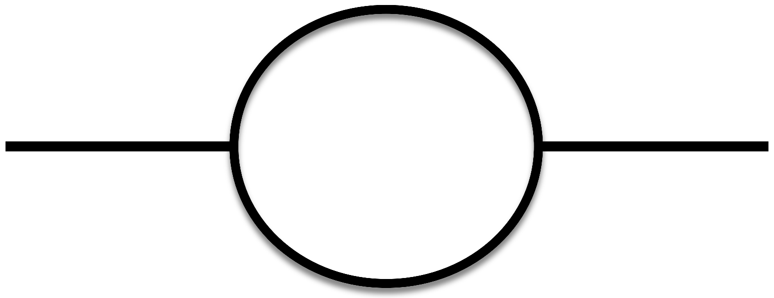
Close to charmonium $\chi_{c1}(2P)$: m=3953.5 MeV

$$\delta m = m_{\chi_{c1}(2P)} - m_{X(3872)} = 81.35 \text{ MeV}$$

$\rightarrow$ *Complicated coupled-channel effect:* $\bar{c}c$ & $D\bar{D}^*/D^*\bar{D}$

Phys. Rev. D 32, 189 (1985)

Coupled-channel effect



1. Yu. S. Kalashnikova, Phys.Rev.D 72, 034010 (2005)

   ☞ Charmonium

2. F.-K. Guo, S. Krewald, and U.-G. Meißner, Phys.Lett.B 665,157 (2008)
   Z.-Y. Zhou and Z. Xiao, Phys. Rev. D 84, 034023 (2011)

   ☞ Charmed and charmed-strange spectra

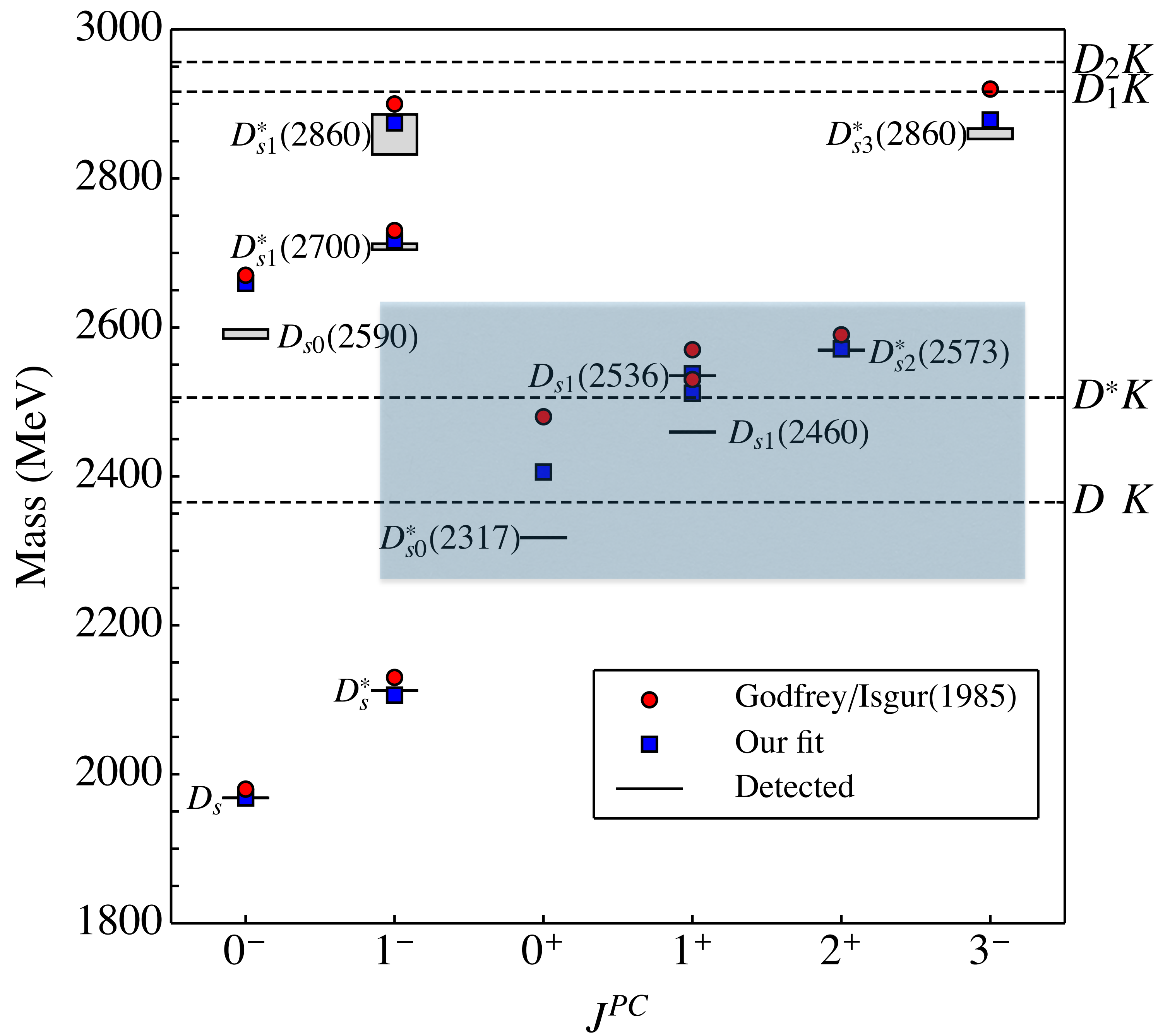
3. Y. Lu, M. N. Anwar, B. S. Zou, Phys.Rev.D 94, 034021 (2016)

   ☞ Bottomonium

……

- **Coupled-channel effect due to hadron loop could cause sizable mass shift on the state in quark model.**

Coupled-channel effect: the D_s case

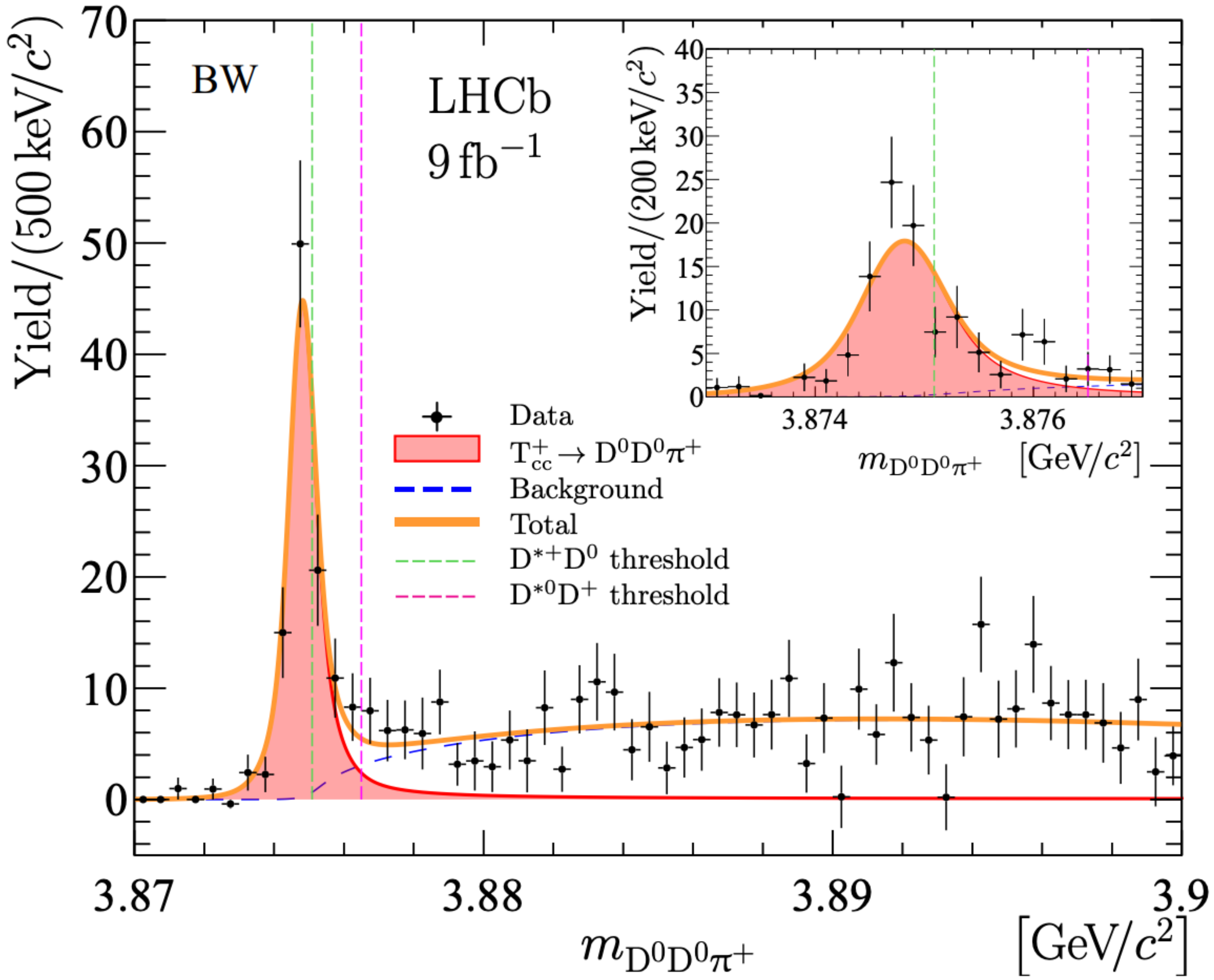


Phys.Rev.Lett. 128,112001(2022)

- **The coupling between bare state in quark model with channels could generate more complex structure than mesons.**

How to determine the component in the X(3872)?

Tcc



- $D^0D^0\pi^+$ channel
- Close to $D^{*+}D^0$ thresholds:

Conventional Breit-Wigner: assumed $J^P = 1^+$.

$$\delta m_{BW} = m_{T_{cc}} - m_{D^{*+}D^0}$$
$$= -273 \pm 61 \text{ keV}$$
$$\Gamma_{BW} = 410 \pm 165\text{keV}$$

EPS-HEP conference, Ivan Polyakov's talk,29/07/2021; Nature Physics,22'

Unitarized Breit-Wigner:

$$\delta m_U = m_{T_{cc}} - m_{D^{*+}D^0}$$
$$= -361 \pm 40 \text{ keV}$$
$$\Gamma_U = 47.8 \pm 1.9 \text{ keV}$$

LHCb, Nature Commun. 13 (2022) 1, 3351

- The second observed doubly charmed hadron after Ξ_{cc}^{++}.
- ***Only the D^*D coupled channel effect.***

C-parity

$\overline{D^*}D$ / $\overline{D}D^*$ interaction

One-boson-exchange model

$D^{(*)}D^{(*)}$

$$H_a^{(Q)} = \frac{1+ \not{v}}{2} \left[P_a^{*\mu}\gamma_\mu - P_a\gamma_5\right]$$

$$\bar{H}_a^{(Q)} \equiv \gamma_0 H^{(Q)\dagger}\gamma_0 = \left[P_a^{*\dagger\mu}\gamma_\mu + P_a^\dagger\gamma_5\right] \frac{1+ \not{v}}{2}$$

$$P = \left(D^0, D^+, D_s^+\right) \& P^* = \left(D^{*0}, D^{*+}, D_s^{*+}\right)$$

$$\mathcal{L}_{MH^{(Q)}H^{(Q)}} = ig \operatorname{Tr}\left[H_b^{(Q)}\gamma_\mu\gamma_5 A_{ba}^\mu \bar{H}_a^{(Q)}\right]$$

$$\mathcal{L}_{VH^{(Q)}H^{(Q)}} = i\beta \operatorname{Tr}\left[H_b^{(Q)} v_\mu \left(V_{ba}^\mu - \rho_{ba}^\mu\right) \bar{H}_a^{(Q)}\right] + i\lambda \operatorname{Tr}\left[H_b^{(Q)}\sigma_{\mu\nu}F^{\mu\nu}(\rho)_{ba}\bar{H}_a^{(Q)}\right]$$

$D^{(*)}\bar{D}^{(*)}$

$$H_a^{(\bar{Q})} \equiv C\left(\mathcal{C}H_a^{(Q)}\mathcal{C}^{-1}\right)^T C^{-1} = \left[P_{a\mu}^{(\bar{Q})*}\gamma^\mu - P_a^{(\bar{Q})}\gamma_5\right]\frac{1- \not{v}}{2}$$

$$\bar{H}_a^{(\bar{Q})} \equiv \gamma_0 H_a^{(\bar{Q})\dagger}\gamma_0 = \frac{1- \not{v}}{2}\left[P_{a\mu}^{(\bar{Q})*\dagger}\gamma^\mu + P_a^{(\bar{Q})\dagger}\gamma_5\right]$$

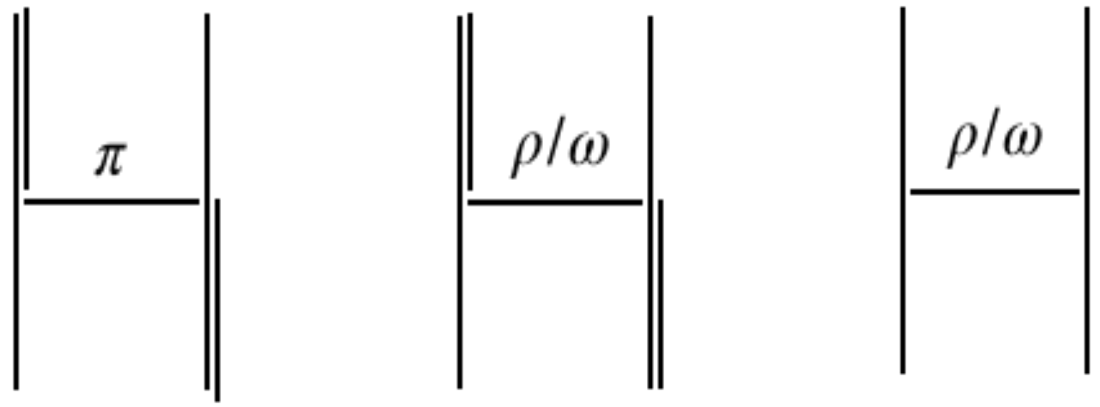
$$\tilde{P} = \left(\bar{D}^0, D^-, D_s^-\right) \& \ \tilde{P}^* = \left(\bar{D}^{*0}, D^{*-}, D_s^{*-}\right)$$

$$\mathcal{L}_{MH^{(\bar{Q})}H^{(\bar{Q})}} = ig \operatorname{Tr}\left[\bar{H}_a^{(\bar{Q})}\gamma_\mu\gamma_5 A_{ab}^\mu H_b^{(\bar{Q})}\right]$$

$$\mathcal{L}_{VH^{(\bar{Q})}H^{(\bar{Q})}} = -i\beta \operatorname{Tr}\left[\bar{H}_a^{(\bar{Q})} v_\mu \left(V_{ab}^\mu - \rho_{ab}^\mu\right) H_b^{(\bar{Q})}\right] + i\lambda \operatorname{Tr}\left[\bar{H}_a^{(\bar{Q})}\sigma_{\mu\nu}F_{ab}^{\prime\mu\nu}(\rho)H_b^{(\bar{Q})}\right]$$

- $g = 0.57$ is determined by the strong decays $D^* \to D\pi$.
- undetermined λ & β.

One-boson-exchange model

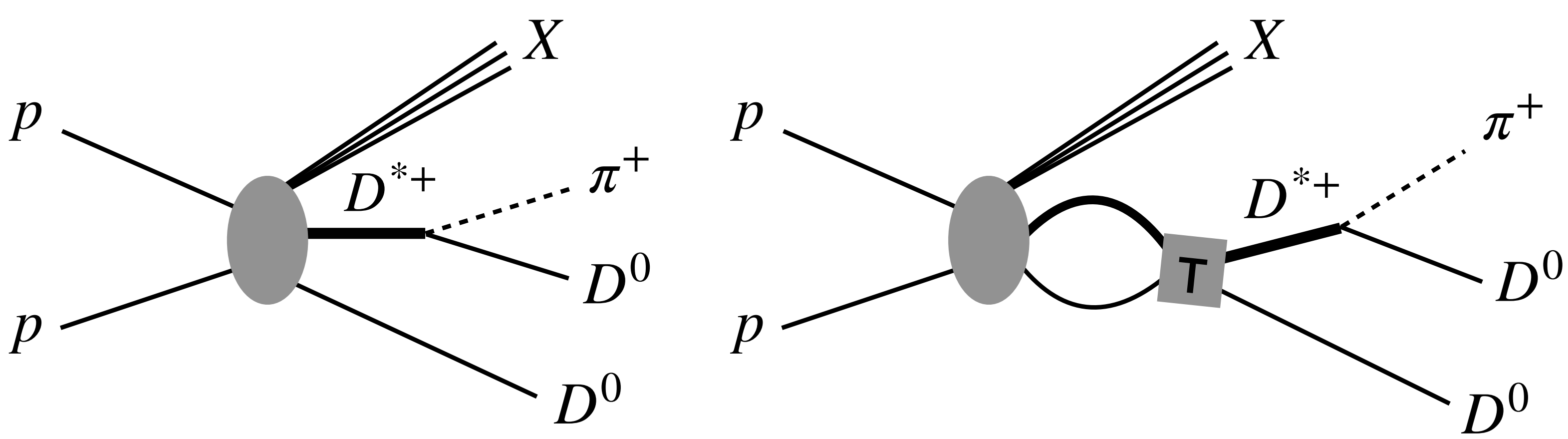


	π	$\rho/\omega,\ u$	$\rho/\omega,\ t$
$V_{DD*}^{I=0}$	$\frac{3}{2}V_\pi$	$\frac{3}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t + \frac{1}{2}V_\omega^t$
$V_{DD*}^{I=1}$	$\frac{1}{2}V_\pi$	$\frac{1}{2}V_\rho^u + \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t + \frac{1}{2}V_\omega^t$
$V_{X(3872)}^{I=0,C=+}$	$\frac{3}{2}V_\pi$	$-\frac{3}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t - \frac{1}{2}V_\omega^t$
$V_{X'}^{I=1,C=+}$	$-\frac{1}{2}V_\pi$	$\frac{1}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t - \frac{1}{2}V_\omega^t$

- The π interactions for $DD^*(I=0, T_{cc})$ are the same with those of $D\bar{D}^*(I=0, C=+)(X(3872))$
- The long-range meson-meson interactions for $T_{cc}, X(3872)$ are related to each other.

The inclusive production of the T_{cc}

$pp \to D^0(p_{D_1})D^0(p_{D_2})\pi^+(p_\pi)X$, X denotes all the other produced particles



The amplitude of the process

$$i\mathcal{M}_{pp\to DD\pi X} = \mathcal{A}^{\mu}_{pp\to DD^*X}\left\{g_{\mu\alpha} - \frac{i}{(2\pi)^4}\int d^4q_{D^*}G_{D^*\,\mu\nu}(q_{D^*})G_D(p_{D_1}+p_{D_2}+p_\pi-q_{D^*})T^{\nu}_{\alpha}(q_{D^*},p_{D_1}+p_\pi)\right\}$$
$$\times G^{\alpha\beta}_{D^*}(p_{D_2}+p_\pi)(g\,p_{\pi,\beta}) + (p_{D_1}\to p_{D_2}),$$

The iso-vector and iso-scalar assignment for the $\mathcal{A}$ with the production amplitudes satisfying

$$\mathcal{A}^{\mu}_{pp\to D^+D^{0*}X} = \pm\mathcal{A}^{\mu}_{pp\to D^0D^{*+}X}$$

- We can only find a satisfactory fit to the experimental data only in the iso-scalar case.

The inclusive production of the T_{cc}

The differential cross section for the $pp \to D(p_{D_1})D(p_{D_2})\pi(p_\pi)$ channel reads

$$d\sigma_{pp\to XDD\pi} = \frac{(2\pi)^4}{4\sqrt{(p_{p_1}\cdot p_{p_2} - m_p^2 m_p^2)}} |\mathcal{M}|^2 d\Phi_{XDD\pi}$$

$$\frac{d\sigma_{pp\to XDD\pi}}{dm_{DD\pi}} \approx 2m_{DD\pi} \int \; d\sigma_{pp\to X+DD\pi} B_2 d\Phi_{DD\pi}$$

$$\approx 2m_{DD\pi} \int \; dm_{12} dm_{23} B_2(E; m_{12}, m_{23})$$

B_2 is obtained with the $\mathcal{M}$,

$$|\mathcal{M}|^2 = \left|a_{pp\to DD^*X}\right|^2 B_2,$$

$$B_2 = \sum_{\lambda_X} \epsilon_\mu(p_X, \lambda_X)\epsilon^\dagger_{\mu'}(p_X, \lambda_X)\mathcal{B}\mu\mathcal{B}^{\dagger\mu'}.$$

We have approximated $\mathcal{A}^\mu_{pp\to DD^*X} = a_{pp\to DD^*X}\, \epsilon^\mu(p_X, \lambda_X)$.

T-matrix

The T-matrix can be solved from the Lippmann-Schwinger equation

$$T(\vec{k}_{D^*},\vec{k}'_{D^*};E)=\mathcal{V}(\vec{k}_{D^*},\vec{k}'_{D^*};E)+\int d\,\vec{q}\,\frac{\mathcal{V}(\vec{k}_{D^*},\vec{q};E)T(\vec{q},\vec{k}'_{D^*};E)}{E-\sqrt{m_D^2+q^2}-\sqrt{m_{D^*}^2+q^2}+i\epsilon}$$

The effective potential is obtained with light-meson exchange potentials

$$\mathcal{V}=\left(V_\pi+V_{\rho/\omega}^t+V_{\rho/\omega}^u\right)\left(\frac{\Lambda^2}{\Lambda^2+p_f^2}\right)^2\left(\frac{\Lambda^2}{\Lambda^2+p_i^2}\right)^2$$

with

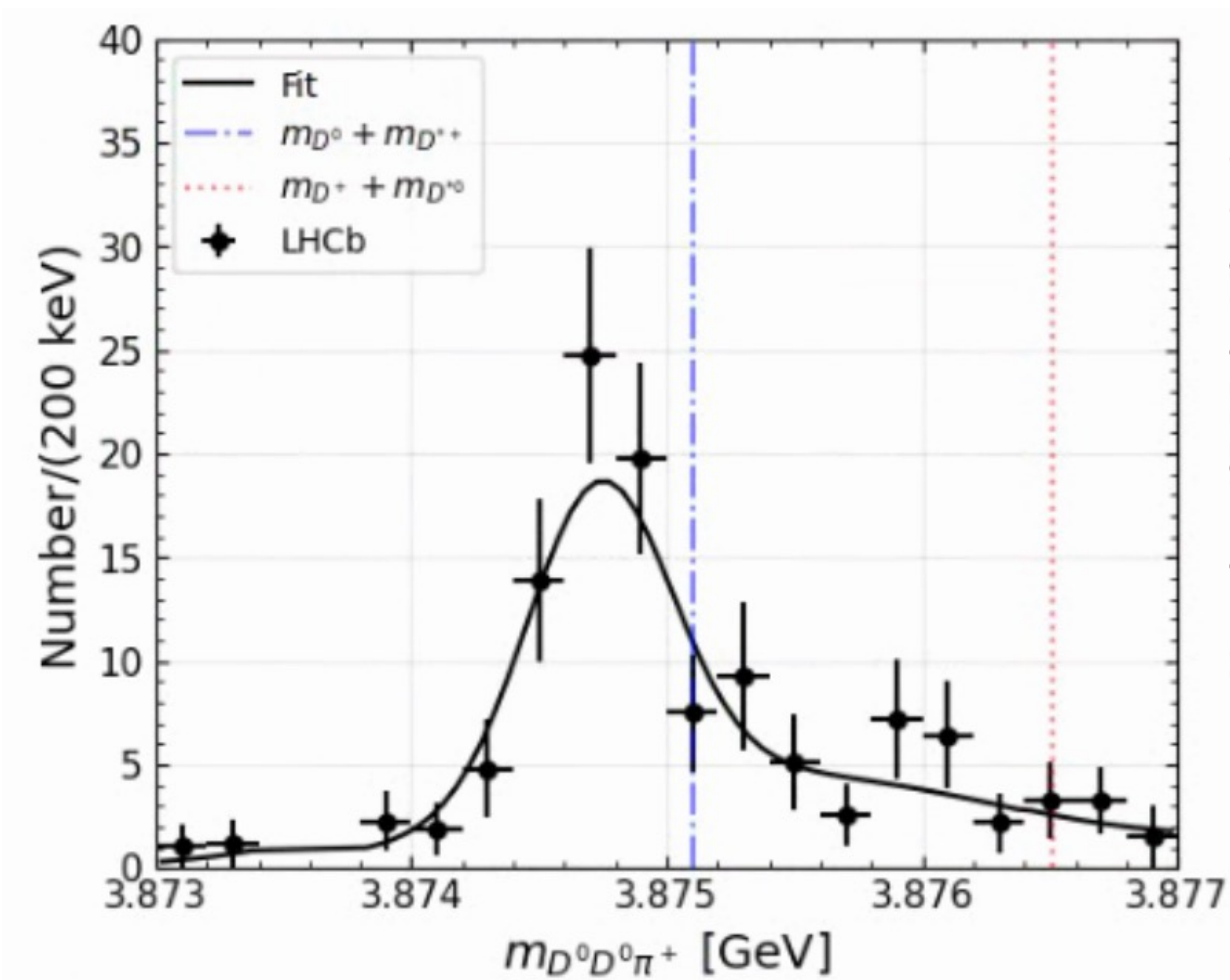
$$V_\pi=\frac{g^2}{f_\pi^2}\frac{(q\cdot\epsilon_\lambda)(q\cdot\epsilon_{\lambda'}^\dagger)}{q^2-m_\pi^2},$$

$$\mathcal{V}_{\rho/\omega}^u=-2\lambda^2g_V^2\,\frac{(\epsilon_{\lambda'}^\dagger\cdot q)(\epsilon_\lambda\cdot q)-q^2(\epsilon_\lambda\cdot\epsilon_{\lambda'}^\dagger)}{q^2-m_{\rho/\omega}^2},$$

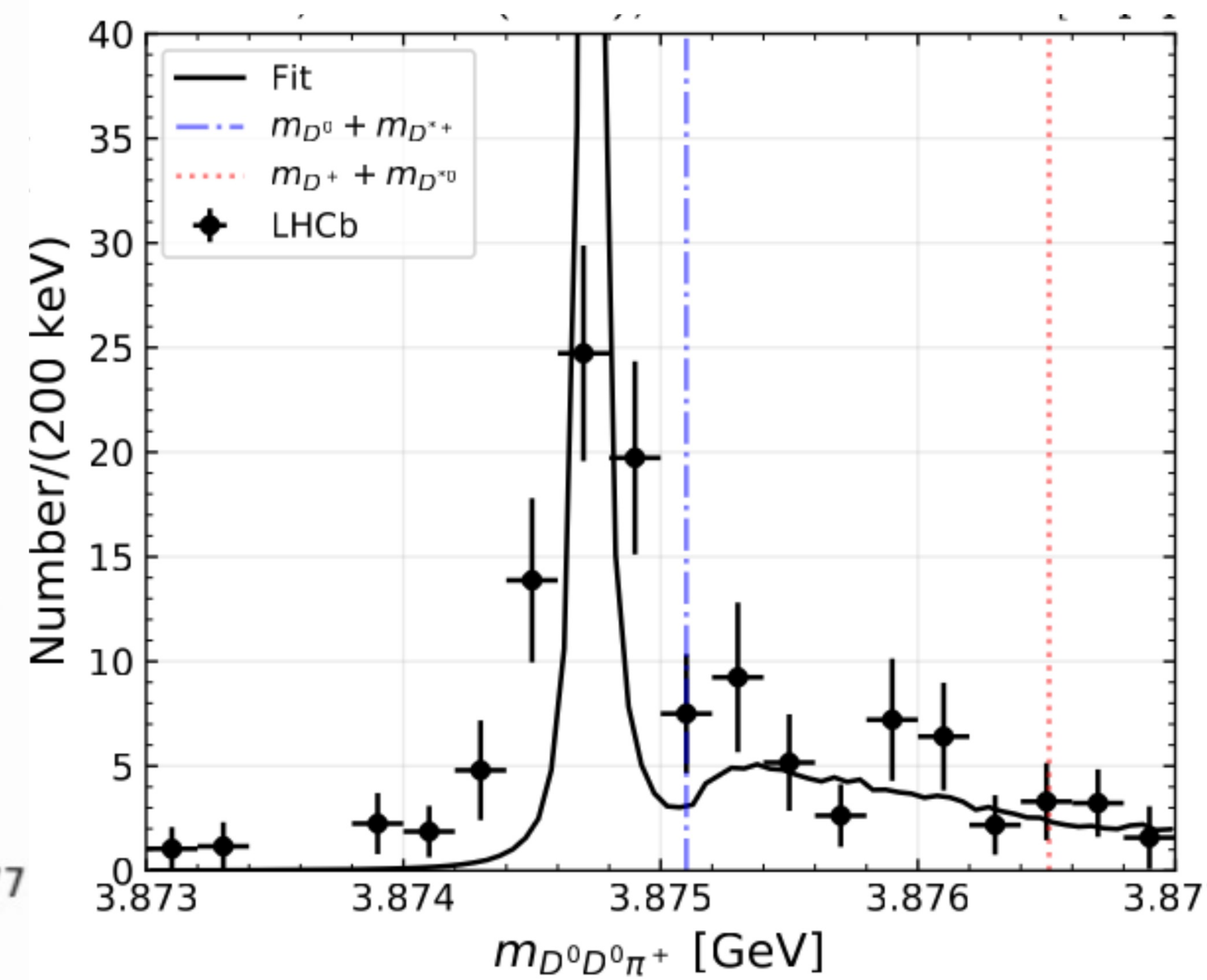
$$V_{\rho/\omega}^t=\frac{\beta^2g_V^2}{2}\frac{(\epsilon_\lambda\cdot\epsilon_{\lambda'}^\dagger)}{q^2-m_{\rho/\omega}^2}.$$

Fitting result

$\Lambda = 0.8$ GeV, χ^2/dof =0.76

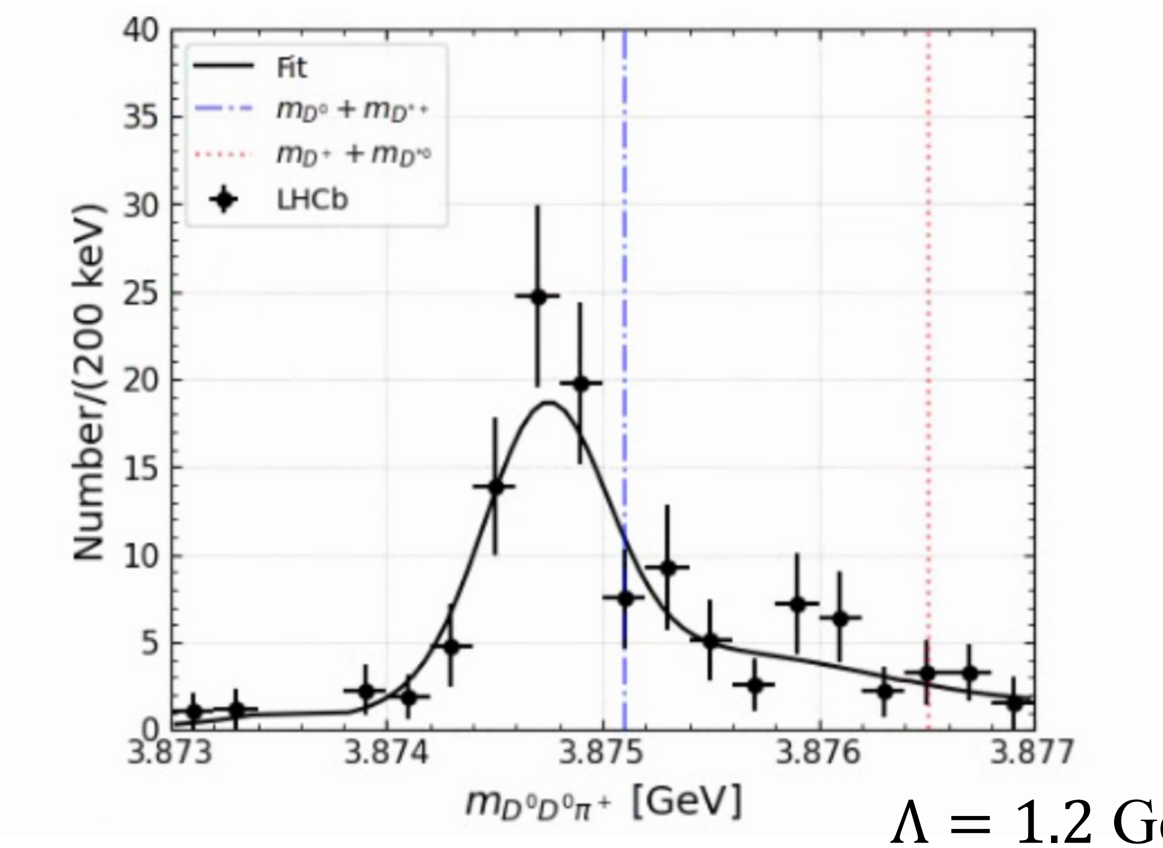


Without resolution function

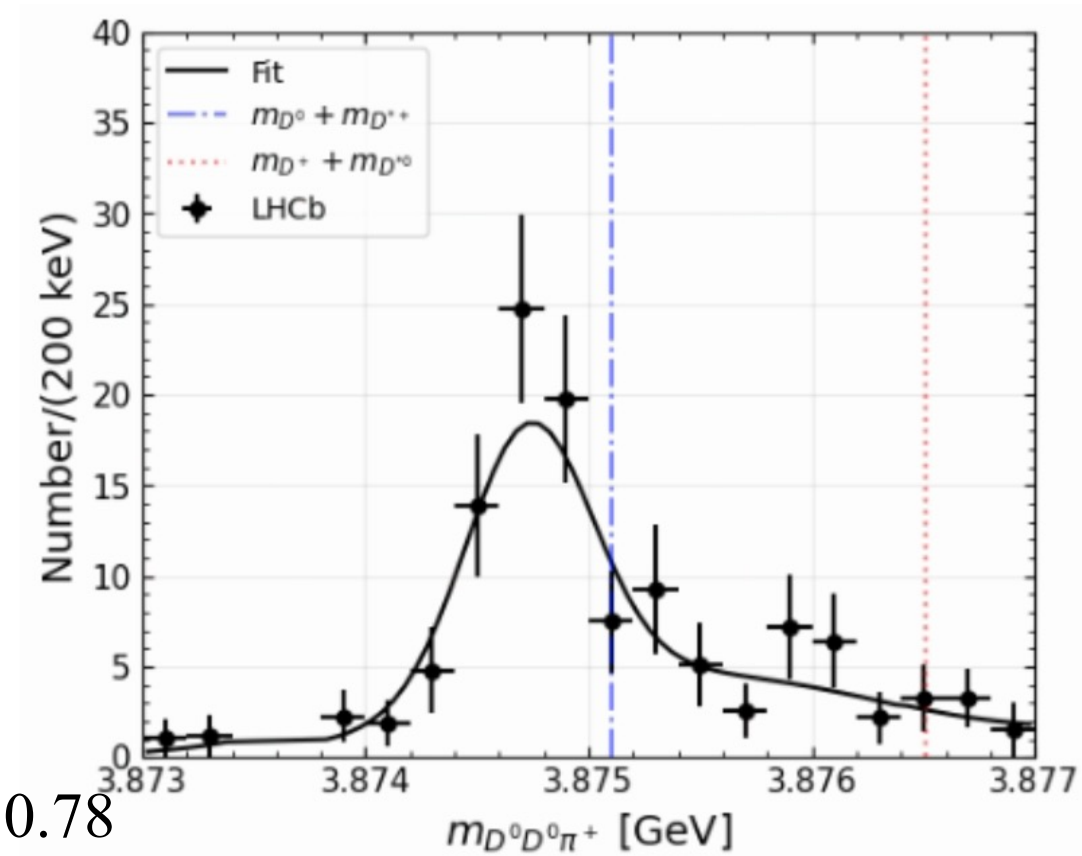


Fitting result

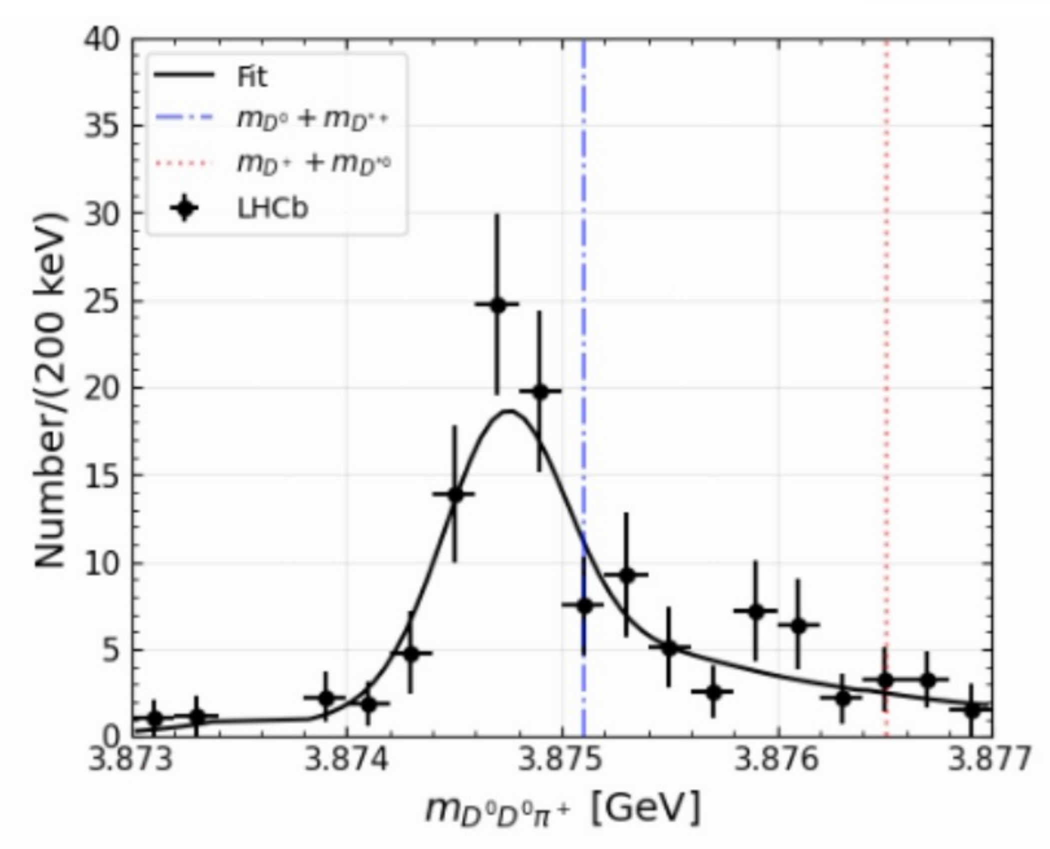
$\Lambda = 0.8$ GeV, χ^2/dof =0.76



$\Lambda = 1.0$ GeV, χ^2/dof =0.76



$\Lambda = 1.2$ GeV, χ^2/dof =0.78



Parameters

- Parameters consistent with those in one-boson-exchange model

Parameters	Λ(fixed)	λ	β
Best fit	0.8 GeV	0.890 ± 0.20	0.810 ± 0.11
Best fit	1 GeV	0.683 ± 0.025	0.687 ± 0.017
Best fit	1.2 GeV	0.587 ± 0.027	0.550 ± 0.027
Ref. [1]	1.17 GeV	0.56	0.9

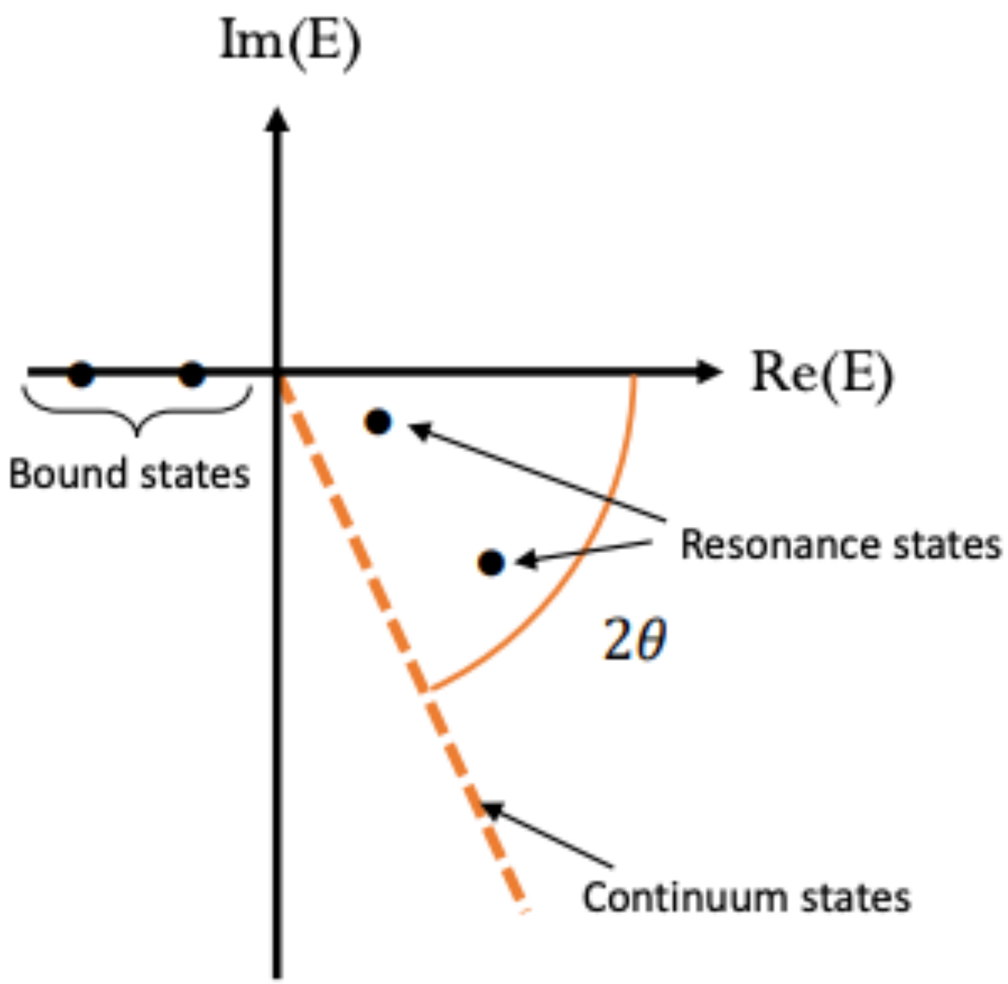
[1] Cheng, et al. Phys. Rev. D 106,016012 (2022).

Complex scaling method

The radius and momentum will rotate with an angle θ:

$$\boldsymbol{r} \to \boldsymbol{r}e^{i\theta}, \quad \boldsymbol{q} \to \boldsymbol{q}e^{-i\theta}$$

$$H_\theta \Phi_\theta = E_\theta \Phi_\theta, \qquad H_\theta = H(\mathbf{r}_\theta, \mathbf{q}_\theta) = \frac{q^2}{2u}e^{-2i\theta} + V(\mathbf{r}e^{i\theta}, \mathbf{q}e^{-i\theta})$$



S.Aoyama et al. PTP. 116, 1 (2006).
T. Myo et al. PPNP. 79, 1 (2014)
N. Moiseyev, Physics reports 302, 212 (1998)

With the varying θ:

- the scattering states will rotate with 2θ
- while the bound and resonant states will stay stable

Results with $\Lambda = 0.8$ GeV

- Only one pole appears—bound states

  $m_{T_{cc}}$=3874.7 MeV, $\Delta E = -387.7$ keV
  $\Gamma_{T_{cc}} = 67.3$ keV

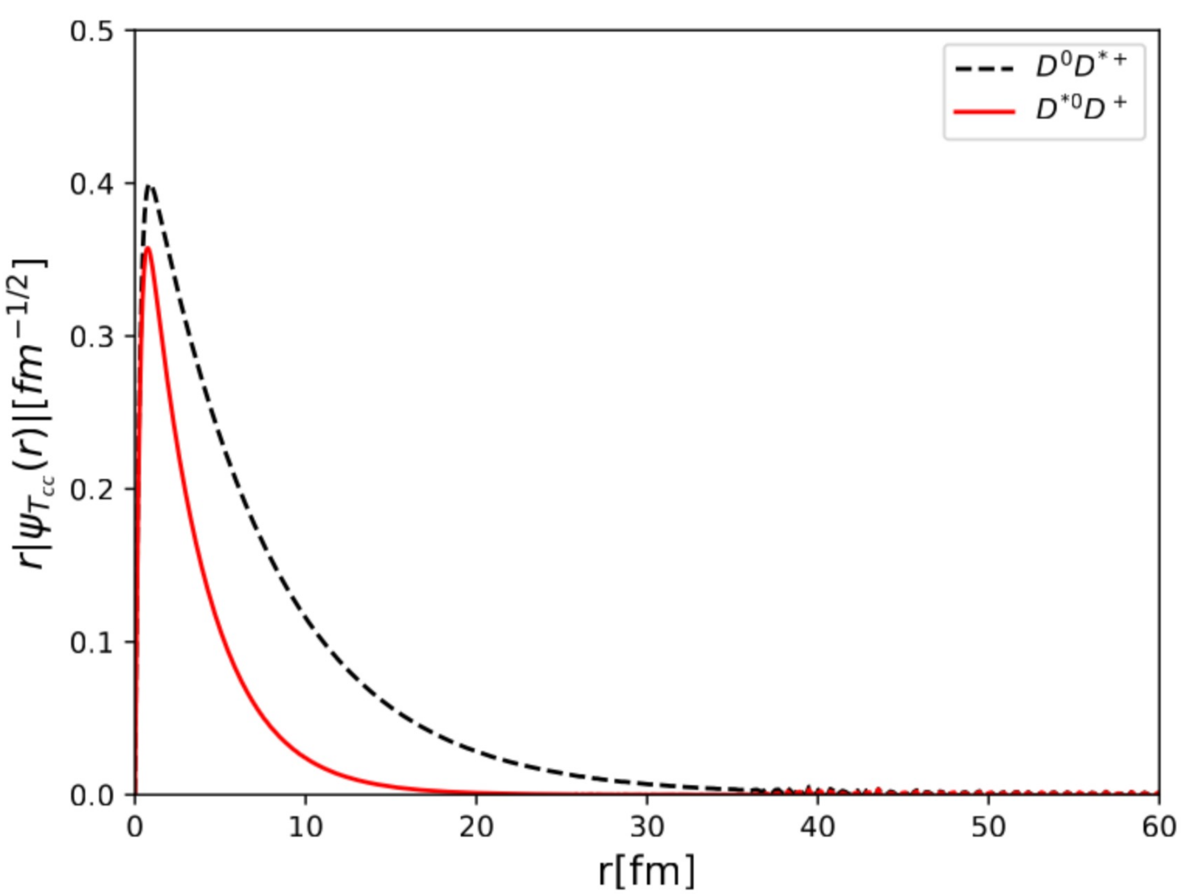
- $\sqrt{\langle r^2 \rangle} = 4.8\ fm$

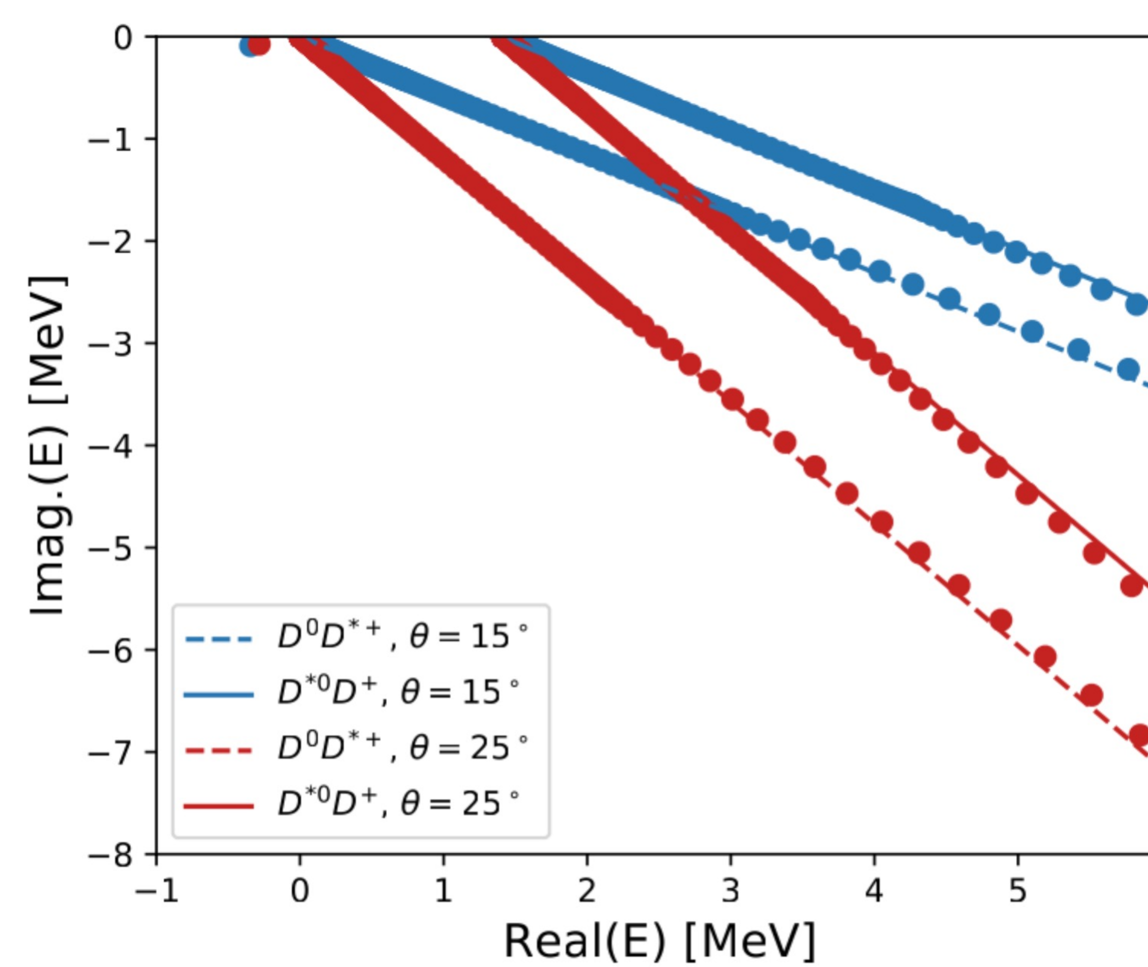
- 70.1% $D^{*+}D^0$, 30% D^+D^{*0} ⟺ 95.8%, $DD^*(I = 0)$ 4.2% $DD^*(I = 1)$

$$[I=0] = \frac{1}{\sqrt{2}}(D^{*+}D^0 - D^{*0}D^+)$$

$$[I=1] = \frac{1}{\sqrt{2}}(D^{*+}D^0 + D^{*0}D^+)$$

Mass differences of $D^{*+}D^0$ and D^+D^{*0}





Results with three Λ

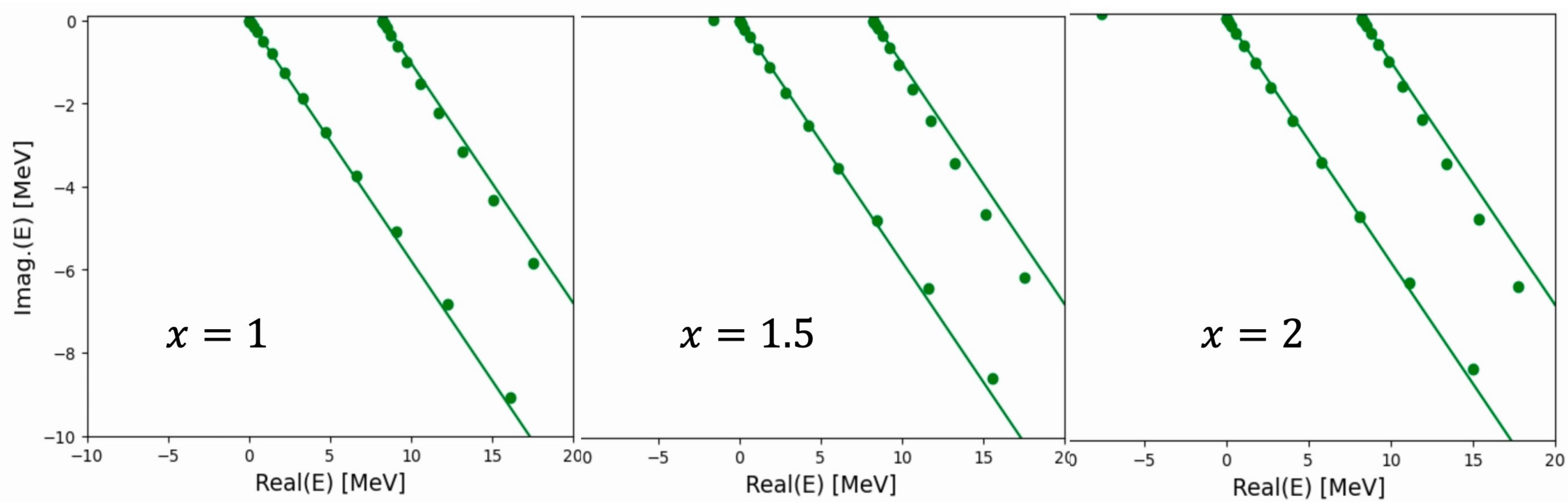
Λ (GeV)	BE (keV)	Γ (keV)	$\sqrt{\langle r^2\rangle}$	$I=0$	$I=1$	$P(D^0D^{*+})$	$P(D^+D^{*0})$	$\frac{\mathrm{Res}(D^0D^{*+})}{\mathrm{Res}(D^+D^{*0})}$
0.8	-387.7	67.3	4.8 fm	95.8%	4.2%	70.0%	30.0%	$-1.063+0.001I$
1.0	-393.0	70.4	4.7 fm	95.8%	4.2%	70.0%	30.0%	$-1.055+0.001I$
1.2	-391.6	72.7	4.7 fm	95.7%	4.3%	70.3%	29.7%	$-1.052+0.001I$

- The conclusion remains the same using the three different cutoff values.
- The binding energy of the bound state is around $\Delta E \sim -390\mathrm{keV}$, which is consistent with that of the measurement $\left(\Delta E_{\mathrm{exp}} = -360(40)\mathrm{keV}\right)$. LHCb, Nature Commun. 13 (2022) 1, 3351

How about the X(3872)?

Direct application to $D\bar{D}^*$: $X(3872)$

- Without the $c\bar{c}$ core, there are no bound states.
- $V'_{D\bar{D}^*} = x * V_{D\bar{D}^*}$



$D\bar{D}^*$ interaction is attractive but not strong enough to form a bound state. → ***Inclusion of $c\bar{c}$ core***

Coupled-channel framework

- The Hamiltonian reads

Ds(2317,2460): Phys.Rev.Lett. 128,112001(2022)

Bs partners: JHEP01(2023)058

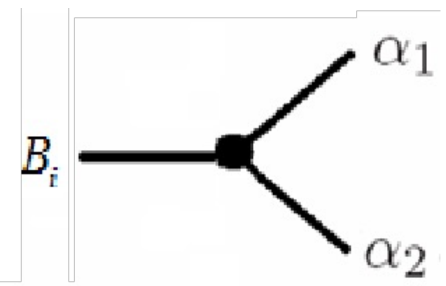
$$H = H_0 + H_I,$$

- Non-interacting Hamiltonian

$$H_0 = \sum_B \underbrace{|B\rangle}_{\text{Bare } \bar{c}c \text{ meson}} m_B \langle B| + \sum_\alpha \int d^3\vec{k} \underbrace{|\alpha(\vec{k})\rangle}_{\text{two-meson state}} E_\alpha(\vec{k}) \langle \alpha(\vec{k})|.$$

- Interacting Hamiltonian $H_I = g + v$

bare state core -> channel：



$$g = \sum_{\alpha, B} \int d^3\vec{k} \left\{ |\alpha(\vec{k})\rangle g_{\alpha B}(|\vec{k}|) \langle B| + h.c. \right\}$$

P.G. Ortega, et al. Phys. Rev. D 94, 074037.

Coupled-channel framework

- The Hamiltonian reads

Ds(2317,2460): Phys.Rev.Lett. 128,112001(2022)

Bs partners: JHEP01(2023)058

$$H = H_0 + H_I,$$

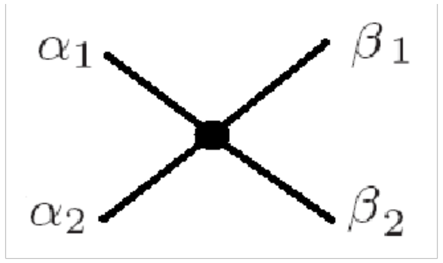
- Non-interacting Hamiltonian

$$H_0 = \sum_B \underline{|B\rangle} m_B \langle B| + \sum_\alpha \int d^3\vec{k} \underline{|\alpha(\vec{k})\rangle} E_\alpha(\vec{k}) \langle \alpha(\vec{k})|.$$

Bare $\bar{c}c$ meson   two-meson state

- Interacting Hamiltonian $H_I = g + v$

channel -> channel：



$$v = \sum_{\alpha,\beta} \int d^3\vec{k} d^3\vec{k}' |\alpha(\vec{k})\rangle V^L_{\alpha,\beta}(|\vec{k}|, |\vec{k}'|) \langle \beta(\vec{k}')|$$

$X(3872): D\bar{D}^* + c\bar{c}$

- The $D\bar{D}^*$ system with quantum number $I(J^{PC}) = 0(1^{++})$ can couple with the $\chi_{c1}(2P)$.
- The coupled channel effect between them can be described by the quark-pair-creation model:

$$g_{D\bar{D}^*,c\bar{c}}(|\vec{k}_{D\bar{D}^*}|) = \gamma I_{D\bar{D}^*,c\bar{c}}(|\vec{k}_{D\bar{D}^*}|)$$

where $\vec{k}_{D\bar{D}^*}$ is the relative momentum in the $D\bar{D}^*$ channel.

$I_{D\bar{D}^*,cc}(|\vec{k}_{D\bar{D}^*}|)$ is the overlap of the meson wave functions $\leftarrow$ GI quark model

- γ is determined to reproduce the $\psi(3770)$ with $M = 3772.8$ MeV and $\Gamma = 15.2$MeV:

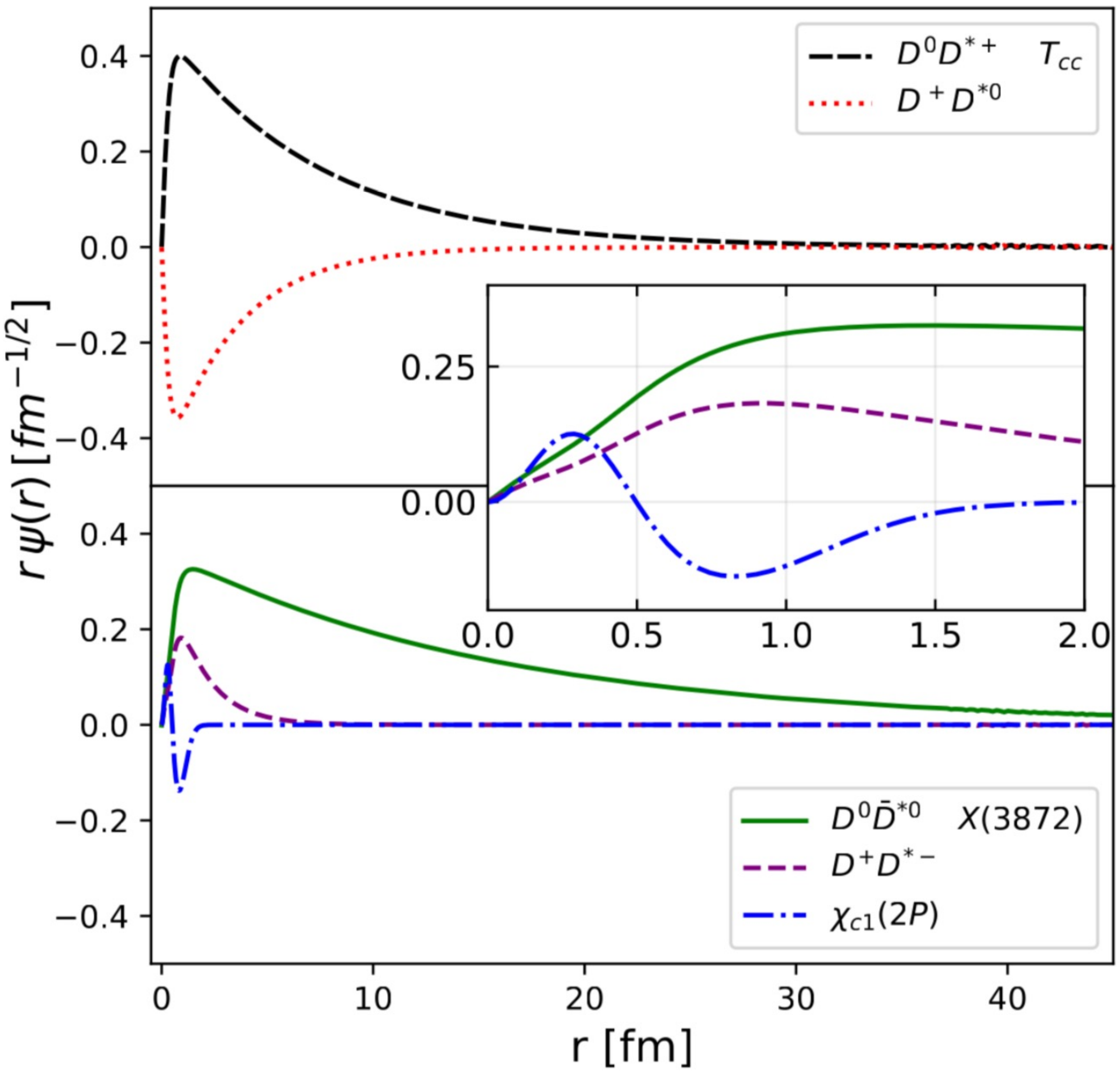
$$\gamma = 4.69$$

- The the X(3872) can be obtained:

$X(3872)$	BE (keV)	Γ (keV)	$\sqrt{\langle r^2\rangle}$	$I=0$	$I=1$	$P(D^0\bar{D}^{*0})$	$P(D^+D^{*-})$	$P(c\bar{c})$
	-80.4	32.5	11.2 fm	71.9%	28.1%	94.0%	4.8%	1.2%

Direct application to $D\bar{D}^*$: X(3872)

Wave functions of Tcc and X(3872)



- Long tails for the radius distribution.
- $X(3872)$ has a even longer tails than T_{cc}

✓ $r < 2$ fm, $c\bar{c} + \bar{D}D^*$ are important.

✓ $r < 0.5$ fm, $c\bar{c}$ core dominates.

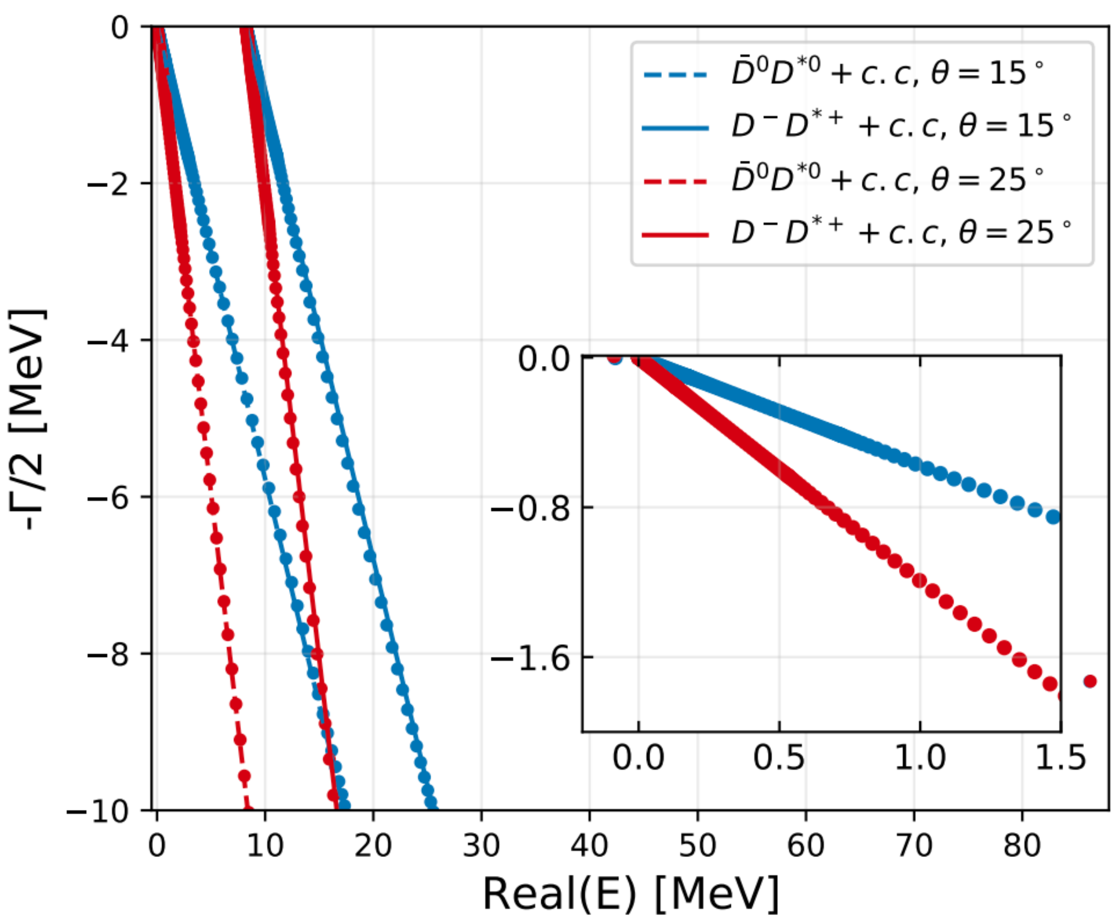
✓ $D\bar{D}^*$ plays the dominant role in the long-distance region, which contributes to $\sqrt{\langle r^2\rangle}$.

Direct application to $D\bar{D}^*$: Candidate for X(3940)?

- Besides the $X(3872)$, we also find a signal of the resonant state $\chi_{c1}(2P)$ with

$$M = 3957.9\text{MeV},\ \Gamma = 16.7\text{MeV},$$

which might be related to the $X(3940)$ observed in the $D\bar{D}^*$ channel.



$X(3940)$ MASS	3942 ± 9 MeV
$X(3940)$ WIDTH	37^{+27}_{-17} MeV

$X(3940)$ **Decay Modes**

	Mode	Fraction (Γ_i / Γ)
Γ_1	$D\overline{D}^*$ + c.c.	seen

Direct application to $D\bar{D}^*$: Other explanations for X(3940)

Rosner, AIP Conf. Proc., 815 (2006), pp. 218-232[218 (2005)].
V.V. Braguta, et.al, Phys. Rev. D, 74 (2006), 094004.
L.-P. He, et,al, Eur. Phys. J. C, 74 (12) (2014), p. 3208

Disfavors ηc (3S) : the X (3940) is that its mass is a bit lower than theoretical prediction

B.-Q. Li and K.-T. Chao, Phys. Rev. D, 79 (2009), Article 094004 ηc (3S) : **3991 GeV**
T. Barnes, S. Godfrey and E.S. Swanson, Phys. Rev. D, 72 (2005), 054026 **4043(NR) 4064(GI)**

Disfavors $\boldsymbol{\chi_{c1}(2P)}$

- No evidence of the $\boldsymbol{\chi_{c1}}$.
- There was no reason to expect the $\boldsymbol{\chi_{c1}}$ $\boldsymbol{(2P)}$ to be a stronger signal than the $\boldsymbol{\chi_{c1}}$.

E.S. Swanson, Phys. Rep., 429 (2006), 243-305

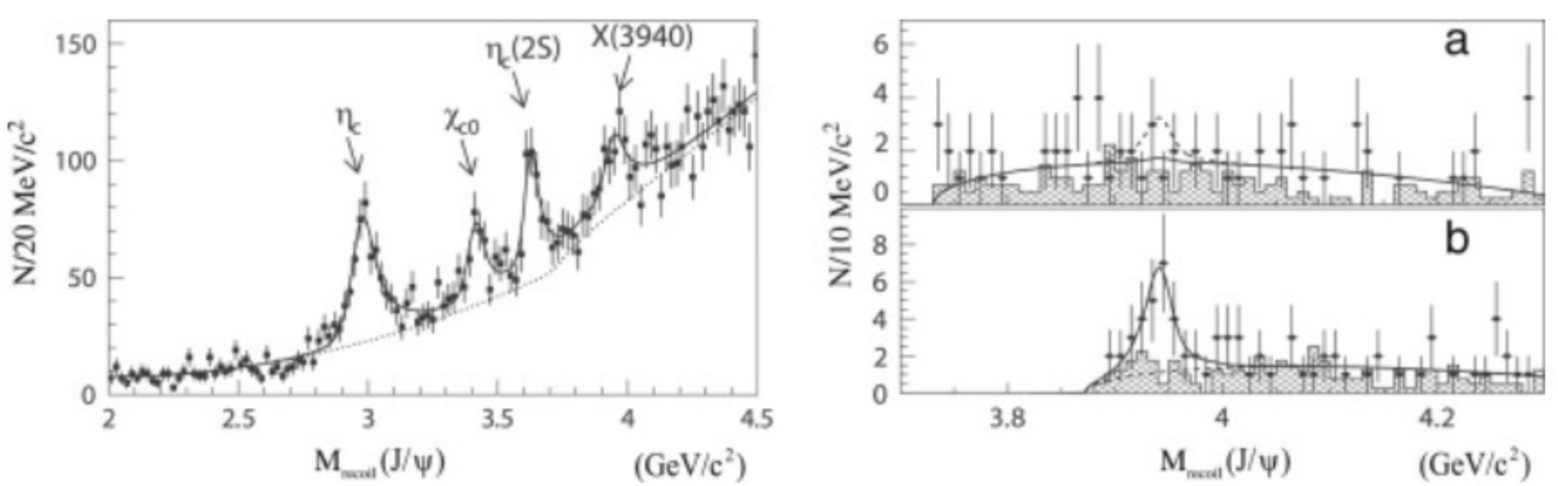


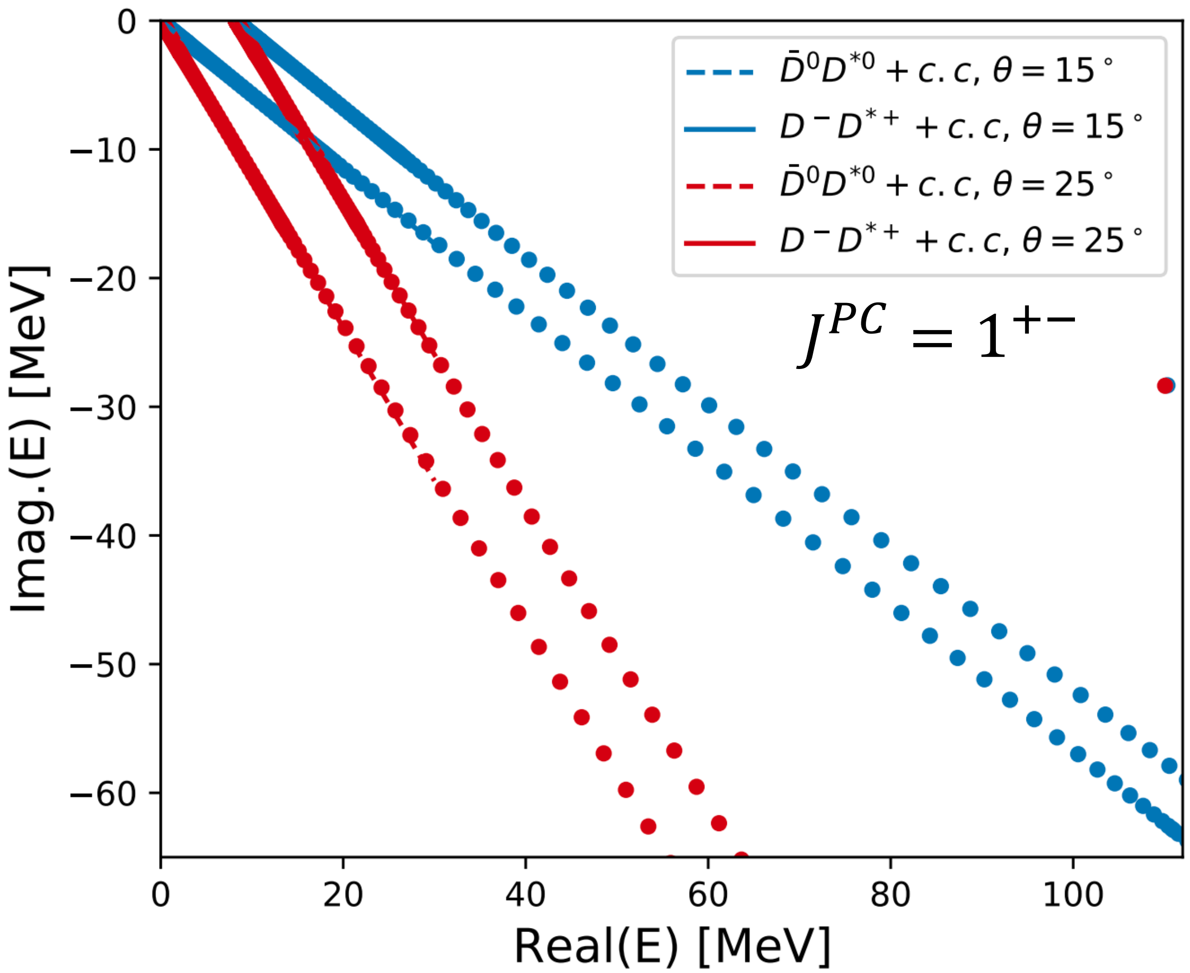
Fig. 24 The distribution of masses recoiling against the reconstructed J/ψ in inclusive $e^+e^- \rightarrow J/\psi X$ events (left). (a) and (b) are $M_{\text{recoil}}(J/\psi)$ distributions for events tagged and constrained as $e^+e^- \rightarrow J/\psi D\bar{D}$ and $e^+e^- \rightarrow J/\psi D^*\bar{D}$, respectively.

Direct application to $D\bar{D}^*$: Z_c and h_c

❖ $\mathrm{I}(J^{PC}) = 1(1^{+-})$ sector: only $D\bar{D}^*$ contributes

✓ a resonance pole around $3883 - i26$MeV

✓ a virtual state far away from the physical region.



❖ $\mathrm{I}(J^{PC}) = 0(1^{+-})$ sector: $D\bar{D}^*$ and $c\bar{c}$ both contribute.

✓ h_c : $M = 3963.4$ MeV and $\Gamma = 3.1$ MeV

Summary

- The T_{cc} can be explained as the bound molecule.

  Only one pole appears.

  The pole masses and decay widths coincided with unitarized analysis

- T_{cc} and $X(3872)$: long-range dynamics related by OBE

- Short-range interactions and structures of $X(3872)$ should be studied by considered the $c\bar{c}$ core.

Thank you !