The Coupled-channel framework for the exotic structures near thresholds

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Based on Phys.Rev.Lett. 128,112001(2022); JHEP01(2023)058; Sci.Bull. 69,3036(2024)
In collaboration with Guang-Juan Wang, Jia-Jun Wu, Makoto Oka, Shi-Lin Zhu

East Asian Workshop on Exotic Hadrons 2024
Nanjing 2024/12/10

Content

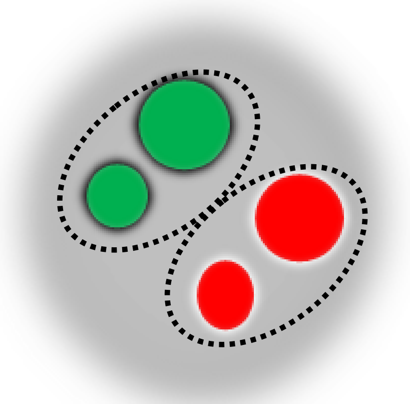
- Background
- Masses of exotic hadrons:

  $D_{s0}(2317)$ and $D_{s1}(2460)$

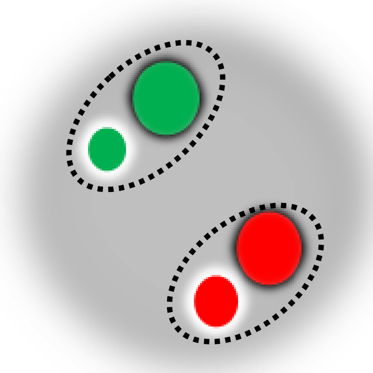
  $X(3872)$

- Decay width of $X(3872)$
- Summary

Exotic states



Compact multiquark



Hadronic molecule

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest

8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

G. Zweig
CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

...

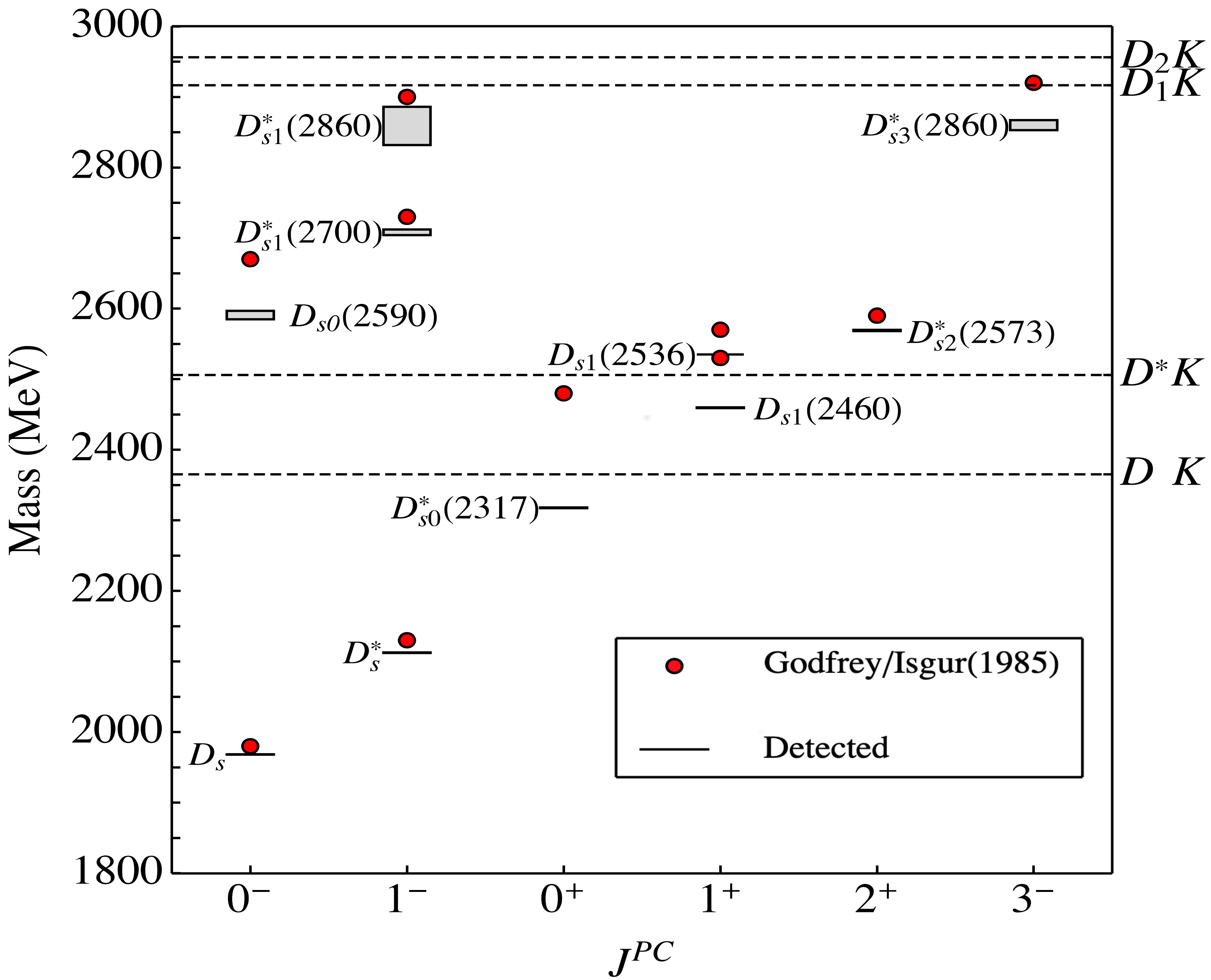
6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $AAAA\bar{A}$, $AAAAAA\bar{A}\bar{A}$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\bar{A}$, $AA\bar{A}\bar{A}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $A\bar{A}$ and AAA, that is, "deuces and treys".

GI quark model for for D_s meson

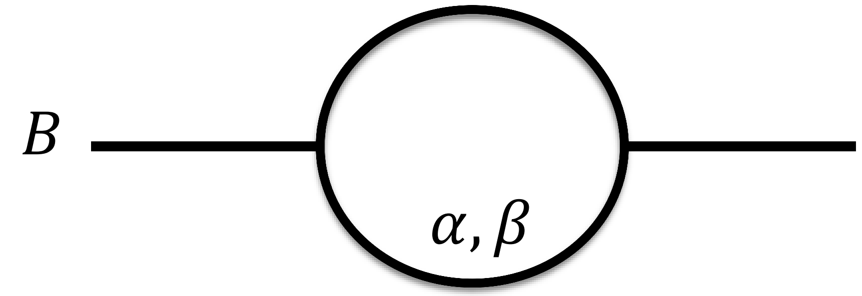
Mesons in a Relativized Quark Model with Chromodynamics #1

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

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



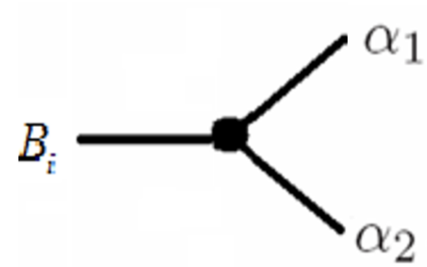
Coupled-channel framework



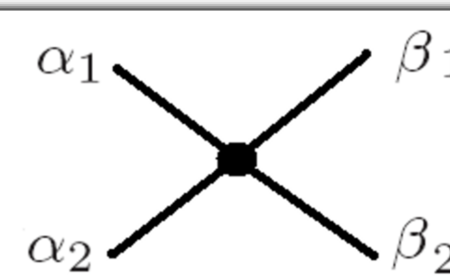
- Coupled-channel effect due to hadron loop could cause sizable mass shift on the state in quark model.

Yu. S. Kalashnikova, Phys.Rev.D 72, 034010 (2005);
Z.-Y. Zhou and Z. Xiao, Phys. Rev. D 84, 034023 (2011)

bare state core -> channel：



channel -> channel：



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

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

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

Quark pair creation model (QPC):

$$g_{\alpha B}(|\vec{k}|) = \gamma I_{\alpha B}(|\vec{k}|) e^{-\frac{\vec{k}^2}{2\Lambda'^2}}$$

truncate the hard vertices given by usual QPC

P. G. Ortega, et al,
Phys. Rev. D 94, 074037 (2016)

Effective Lagrangian: (exchanging mesons, e.g. ρ/ω)

Form factor: $\left(\frac{\Lambda^2}{\Lambda^2 + p_f^2}\right)^2 \left(\frac{\Lambda^2}{\Lambda^2 + p_i^2}\right)^2$

Coupled-channel framework

- For the T-matrix,

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

$$\mathcal{V}(\vec{k}_{D^*}, \vec{k}'_{D^*}; E) = \frac{g(\vec{k}_{D^*}) g(\vec{k}'_{D^*})}{E - m_B} + v(\vec{k}_{D^*}, \vec{k}'_{D^*})$$

- For the Hamiltonian

$$H = H_0 + H_I,$$

where the non-interacting one is

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

And the interacting one includes two parts

$$H_I = g + v$$

Content

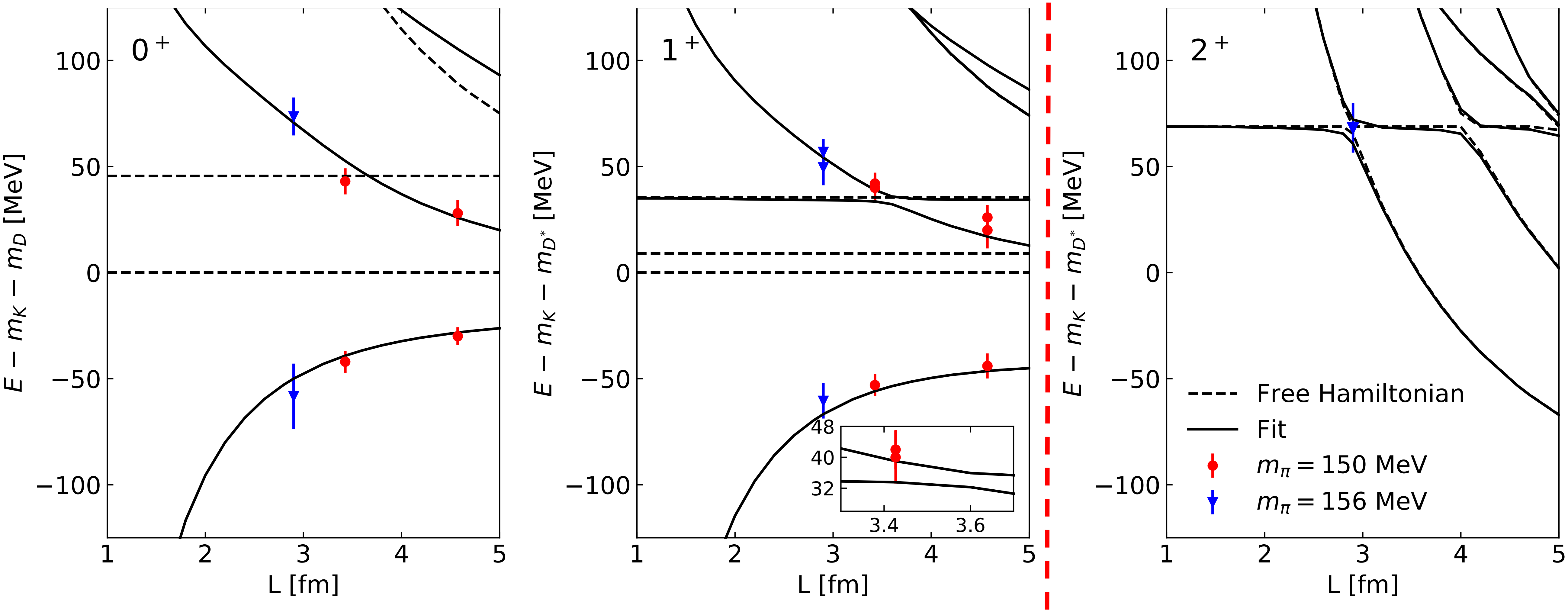
- ❖ $D_{s0}(2317)$ and $D_{s1}(2460)$
- ❖ $X(3872)$

Fit the lattice data： $D_s(2317,2460,2536)$

Lattice data from: C. B. Lang et al., **Phys. Rev. D 90, 034510 (2014);**
G. S. Bali et al., **Phys. Rev. D 96, 074501 (2017)**

Fit

Postpredict



Component and pole mass

	$P(c\bar{s})[\%]$	ours	exp
$D_{s0}^*(2317)$	$32.0^{+5.2}_{-3.9}$	$2338.9^{+2.1}_{-2.7}$	2317.8 ± 0.5
$D_{s1}^*(2460)$	$52.4^{+5.1}_{-3.8}$	$2459.4^{+2.9}_{-3.0}$	2459.5 ± 0.6
$D_{s1}^*(2536)$	$98.2^{+0.1}_{-0.2}$	$2536.6^{+0.3}_{-0.5}$	2535.11 ± 0.06
$D_{s2}^*(2573)$	$95.9^{+1.0}_{-1.5}$	$2570.2^{+0.4}_{-0.8}$	2569.1 ± 0.8

$D_{s0}(2317)$, $D_{s1}(2460)$

- Bare $c\bar{s}$ has strong coupling to S-wave $D^{(*)}K$ channels, and significant mass shift.
- Both the bare $c\bar{s}$ core and molecular components are significant and essential.

$D_{s1}(2536)$, $D_{s2}(2573)$

- Coupling to D-wave $D^{(*)}K$ channels can be neglected.
- Mainly pure $c\bar{s}$.

Component and pole mass

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A. M. Torres, E. Oset, S. Prelovsek, and A. Ramos **JHEP 05, 153 (2015)**

$$P(KD) = 72 \pm 13 \pm 5\ \%\,,\ \text{for the } D_{s0}^*(2317)$$

$$P(KD^*) = 57 \pm 21 \pm 6\ \%\,,\ \text{for the } D_{s1}(2460)$$

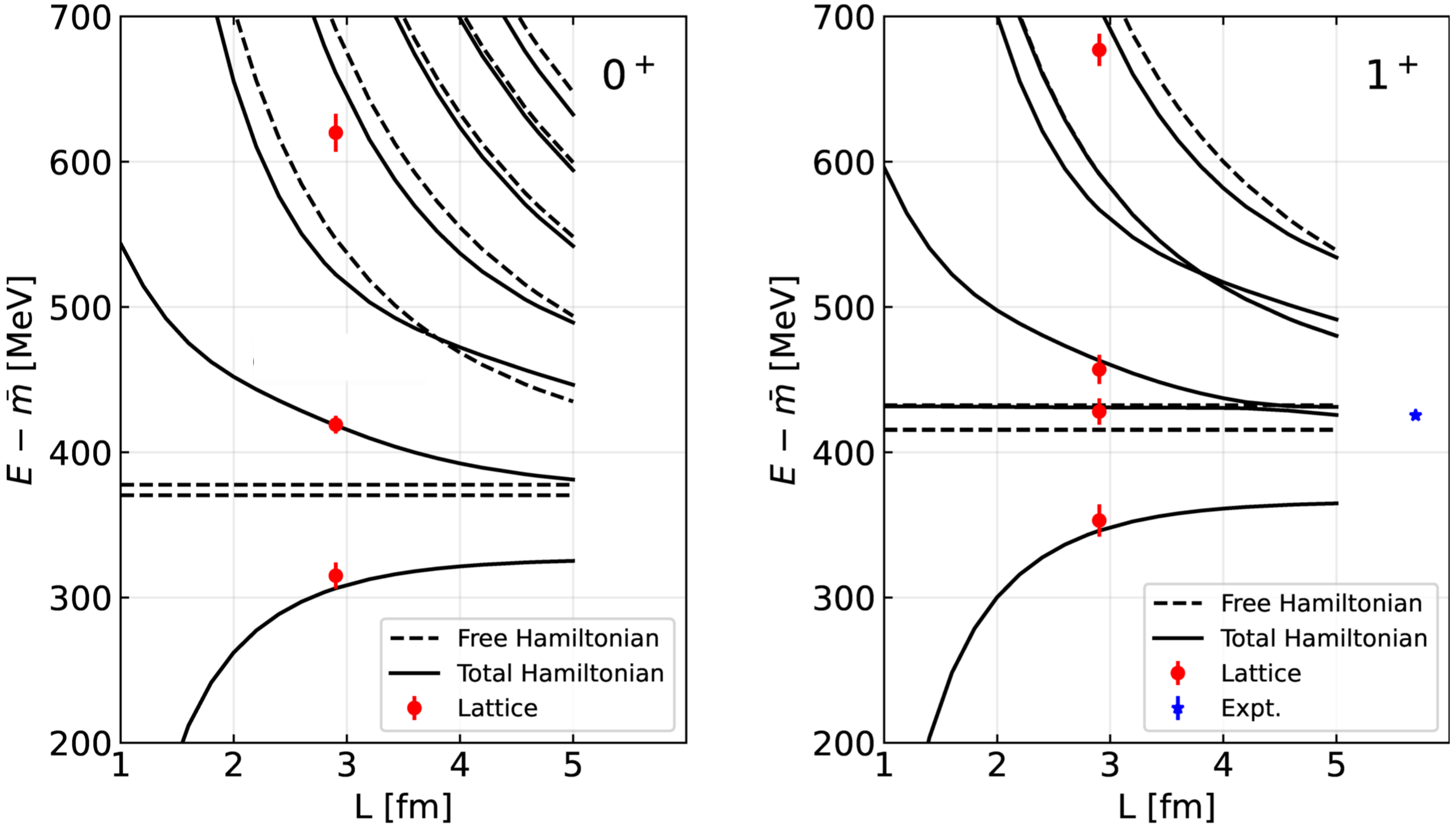
L.M. Liu, K. Orginos, F.-K. Guo, C. Hanhart, Ulf-G. Meissner **Phys.Rev.D 87 (2013) 1, 014508**

$$P(KD) = [0.68, 0.73],\ \text{for the } D_{s0}^*(2317)$$

B_s energy levels

- The heavy quark symmetry seems to be a good symmetry here.
- Use the same parameters as D_s .

Postprediction, not a fit !



$\bar{m} = \frac{1}{4}(m_{B_s} + 3m_{B_s^*})$

Lattice data from: C. B. Lang et al., **Phys. Lett. B 750, 17 (2015)**

Content

❖ $D_{s0}(2317)$ and $D_{s1}(2460)$

❖ $X(3872)$

GI quark model for charmonium

Mesons in a Relativized Quark Model with Chromodynamics #1

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

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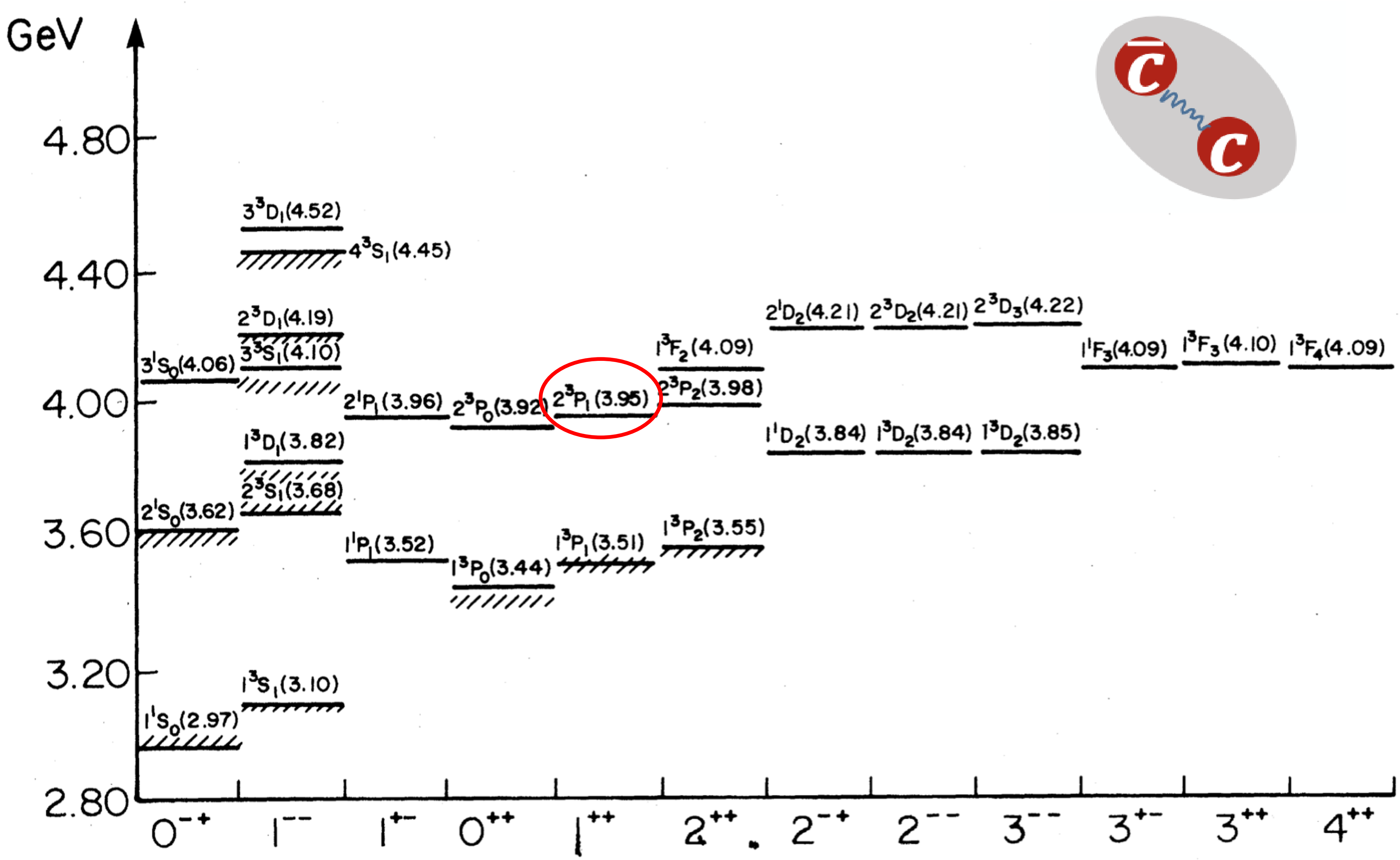
DOI cite claim reference search 3,134 citations



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

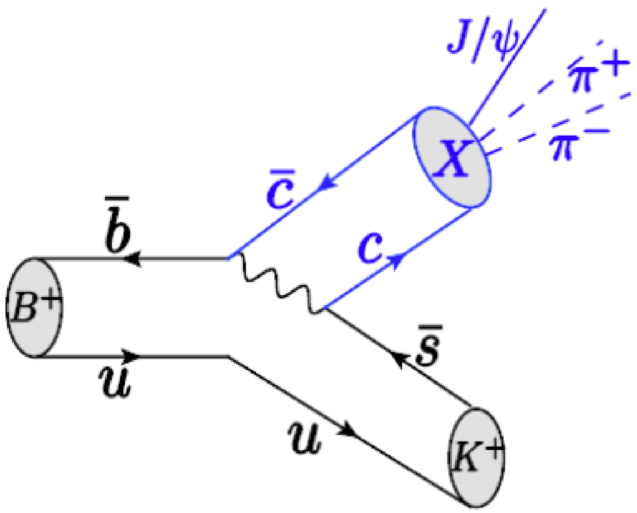
Phys. Rept. 639 (2016) 1-121

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



- 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

$$\delta m = m_{D^0\bar{D}^{*0}} - m_{X(3872)}$$
$$= 0.00 \pm 0.18 \text{ MeV}$$

PDG 22

Theoretical interpretation of X(3872)

Where is the $\chi_{c1}(2P)$ 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...

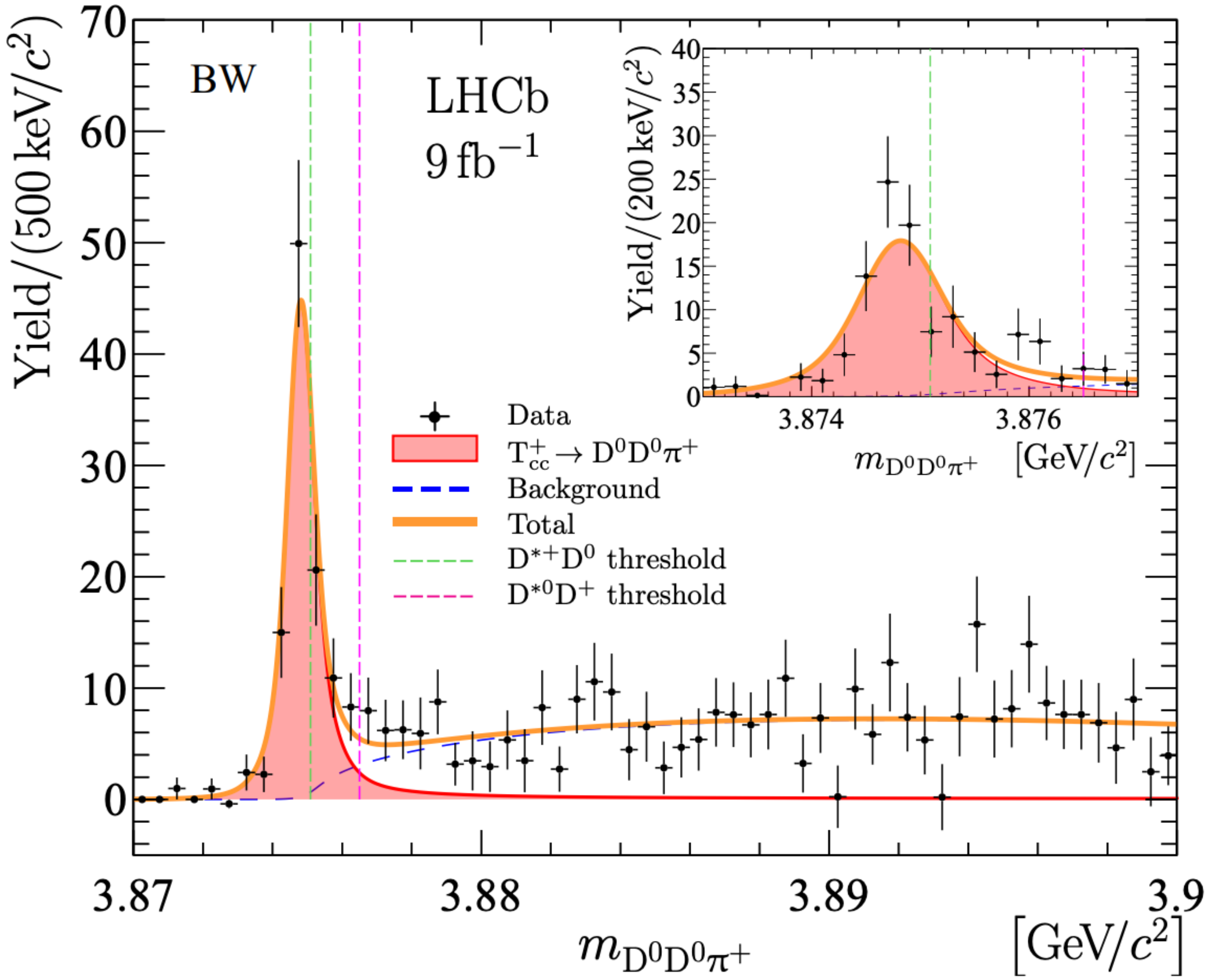
Close to charmonium $\chi_{c1}(2P)$: m=3953.5 MeV

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

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

Phys. Rev. D 32, 189 (1985)

How to determine the component in the X(3872): from Tcc



❖ Quark content: $cc\bar{u}\bar{d}$

❖ ***Only the D^*D coupled channel effect***

C-parity

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

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

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

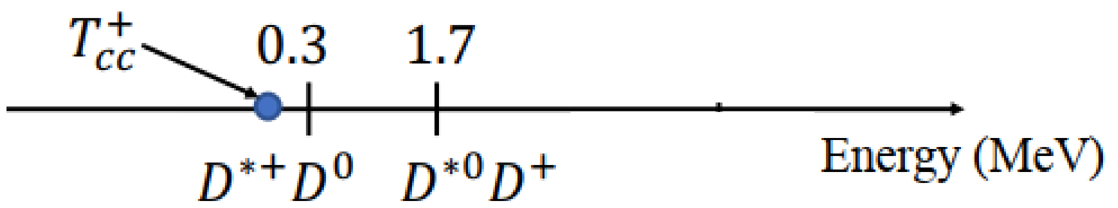
$$\delta m_{BW} = m_{T_{cc}} - m_{D^{*+}D^0}$$
$$= -273 \pm 61 \text{ keV}$$
$$\Gamma_{BW} = 410 \pm 165 \text{keV}$$

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



One-boson-exchange model

DD^*

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

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

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

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

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

$D\bar{D}^*$

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

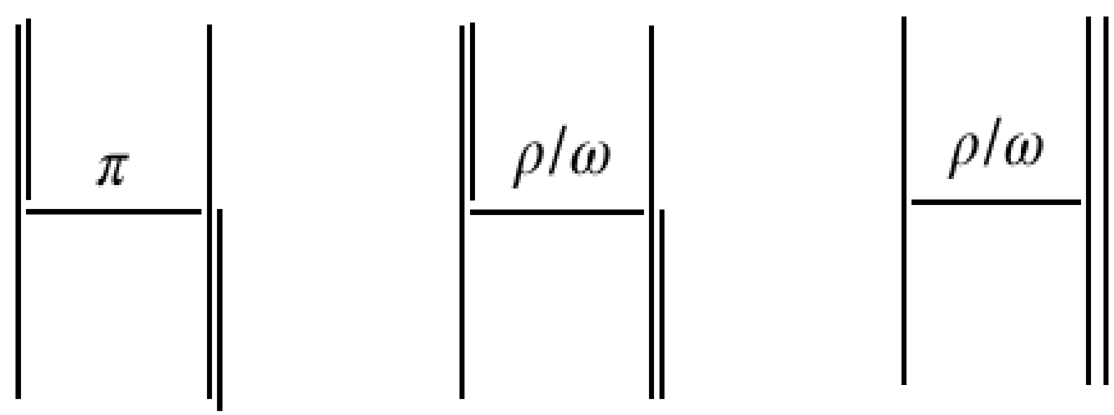
$$\bar{H}_a^{(\bar{Q})} \equiv \gamma_0 H_a^{(\bar{Q})\dagger}\gamma_0 = \frac{1-\not{v}}{2}\left[P_{a\mu}^{(\bar{Q})*\dagger}\gamma^\mu + P_a^{(\bar{Q})\dagger}\gamma_5\right]$$

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

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

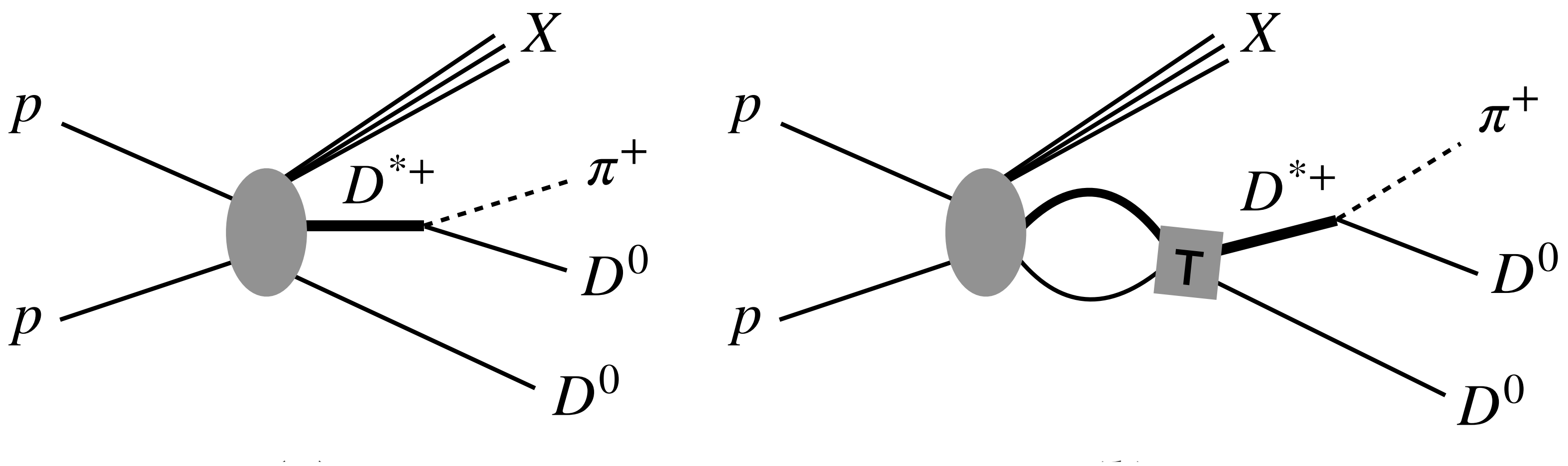
$$\mathcal{L}_{VH^{(\bar{Q})}H^{(\bar{Q})}} = -i\beta\,\mathrm{Tr}\left[\bar{H}_a^{(\bar{Q})} v_\mu \left(V_{ab}^\mu - \rho_{ab}^\mu\right) H_b^{(\bar{Q})}\right] + i\lambda\,\mathrm{Tr}\left[\bar{H}_a^{(\bar{Q})}\sigma_{\mu\nu}F_{ab}^{\prime\mu\nu}(\rho) H_b^{(\bar{Q})}\right]$$

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



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

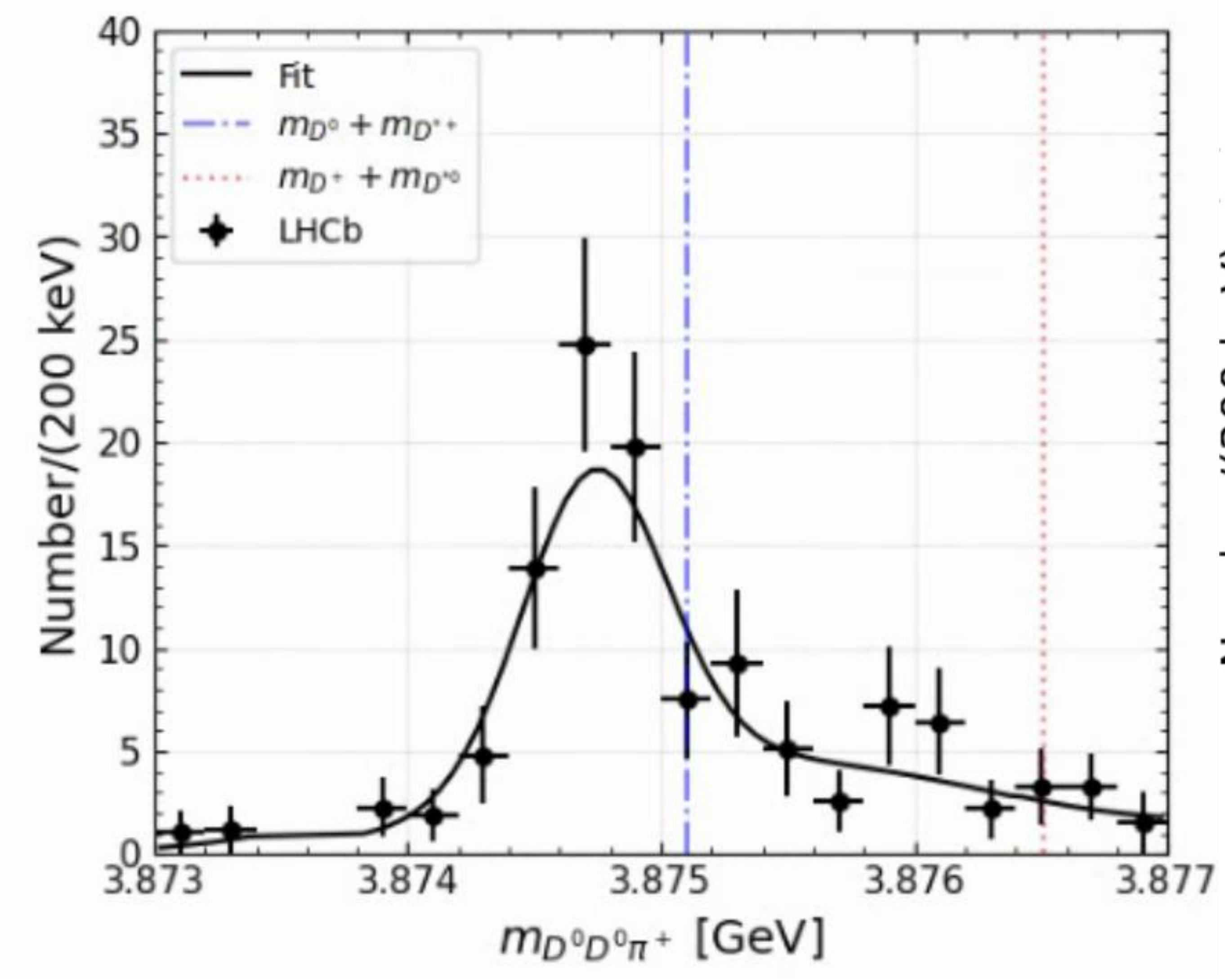
$$T(\vec{k}_{D^*},\vec{k}'_{D^*};E) = \mathcal{V}(\vec{k}_{D^*},\vec{k}'_{D^*};E) + \int d\,\vec{q}\,\frac{\mathcal{V}(\vec{k}_{D^*},\vec{q};E)T(\vec{q},\vec{k}'_{D^*};E)}{E-\sqrt{m_D^2+q^2}-\sqrt{m_{D^*}^2+q^2}+i\epsilon}$$

The effective potential is obtained with light-meson exchange potentials

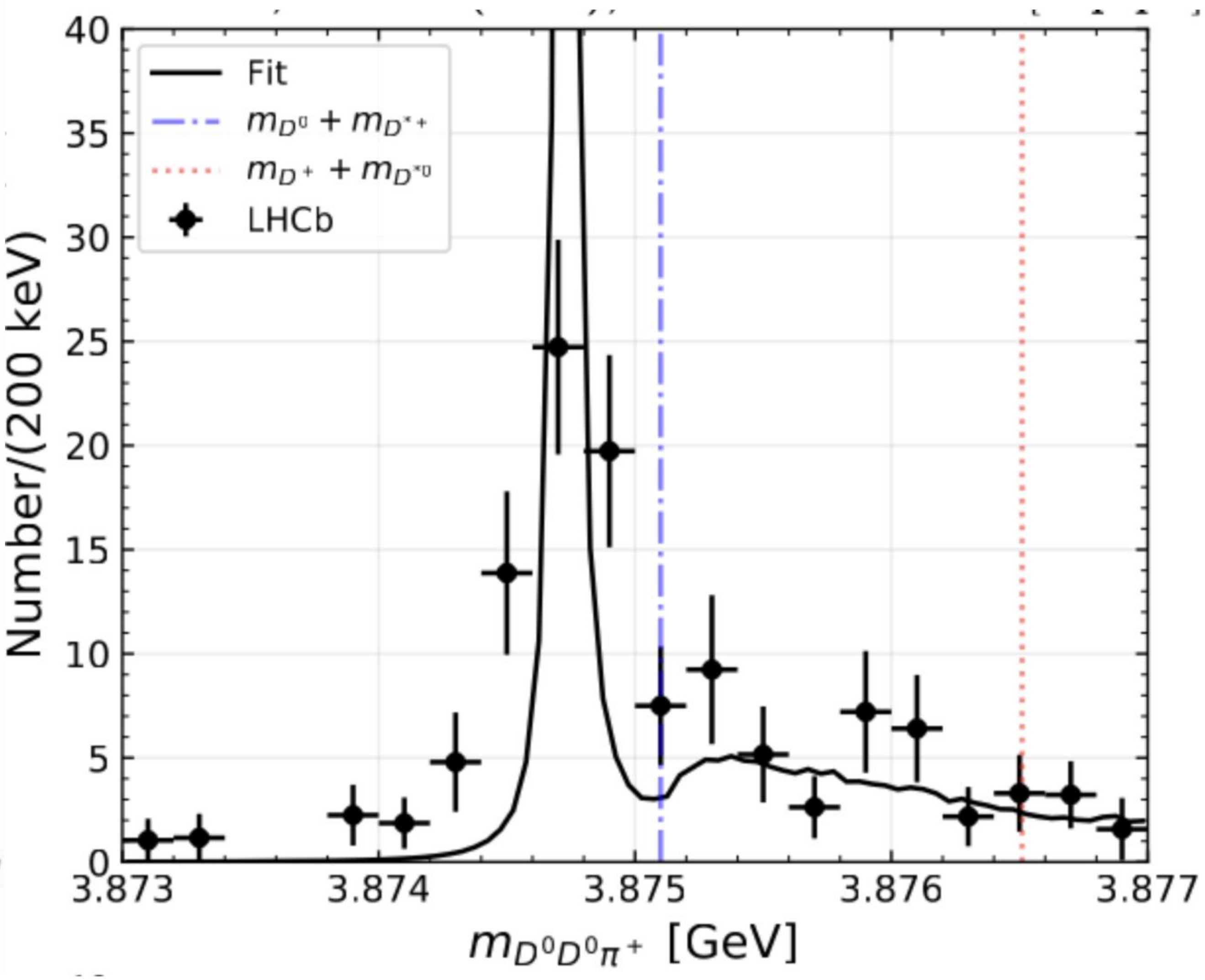
$$\mathcal{V} = (V_\pi + V^t_{\rho/\omega} + V^u_{\rho/\omega})\left(\frac{\Lambda^2}{\Lambda^2+p_f^2}\right)^2\left(\frac{\Lambda^2}{\Lambda^2+p_i^2}\right)^2$$

Fitting result

$\Lambda = 0.8$ GeV, χ^2/dof =0.76



Without resolution function

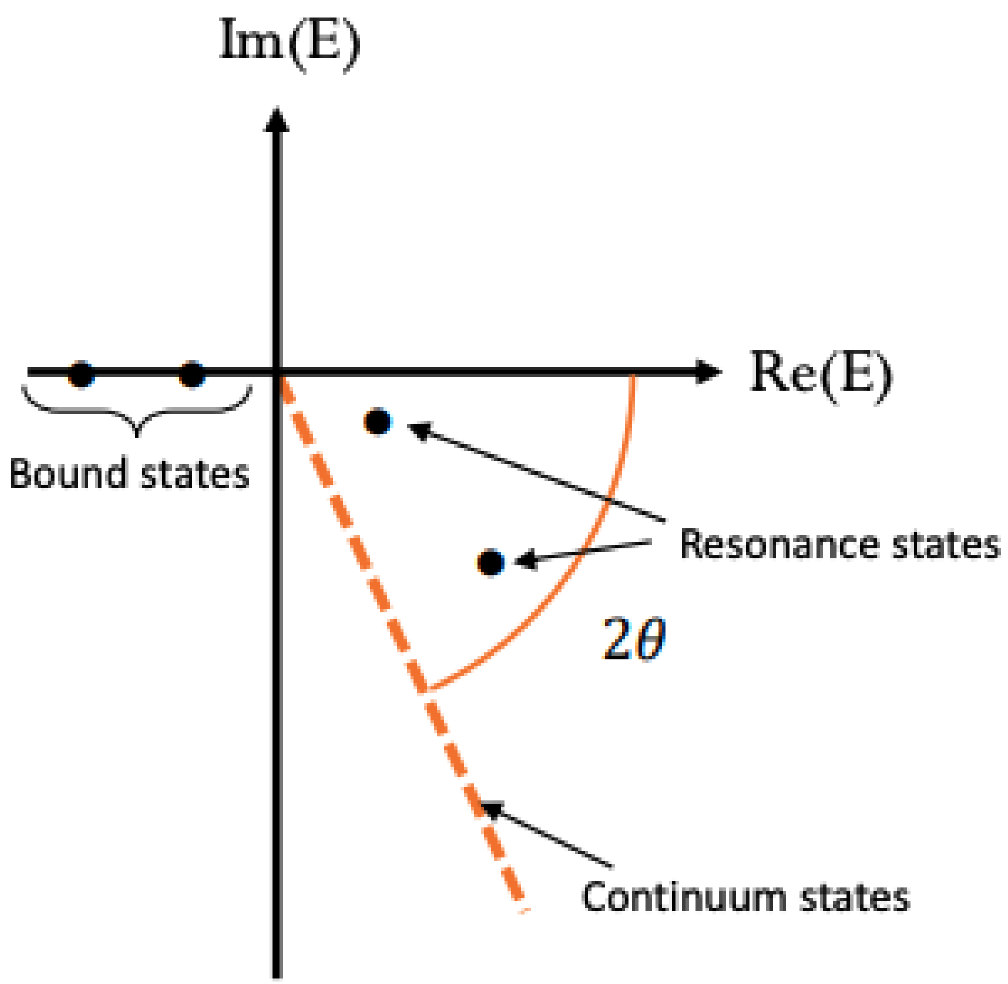


Complex scaling method

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

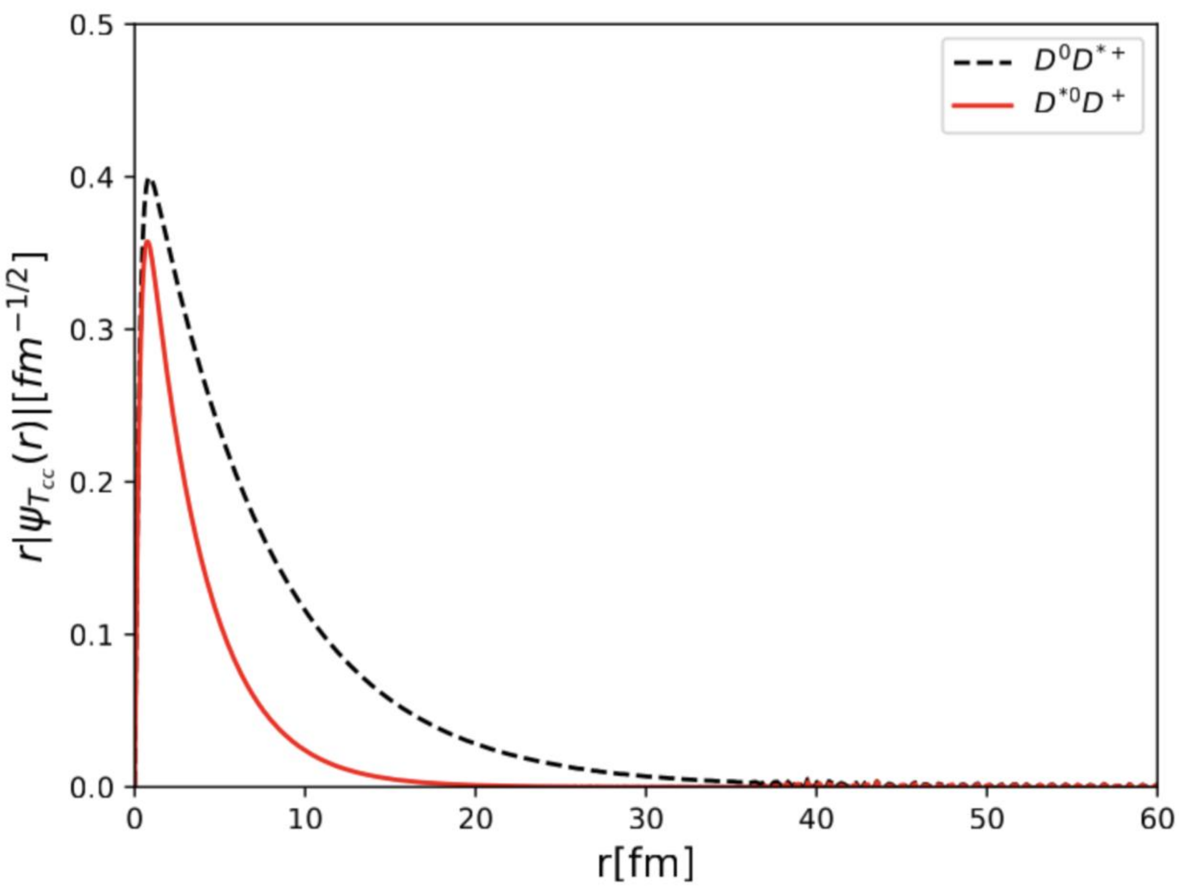
- $\sqrt{\langle r^2 \rangle} = 4.8\, fm$

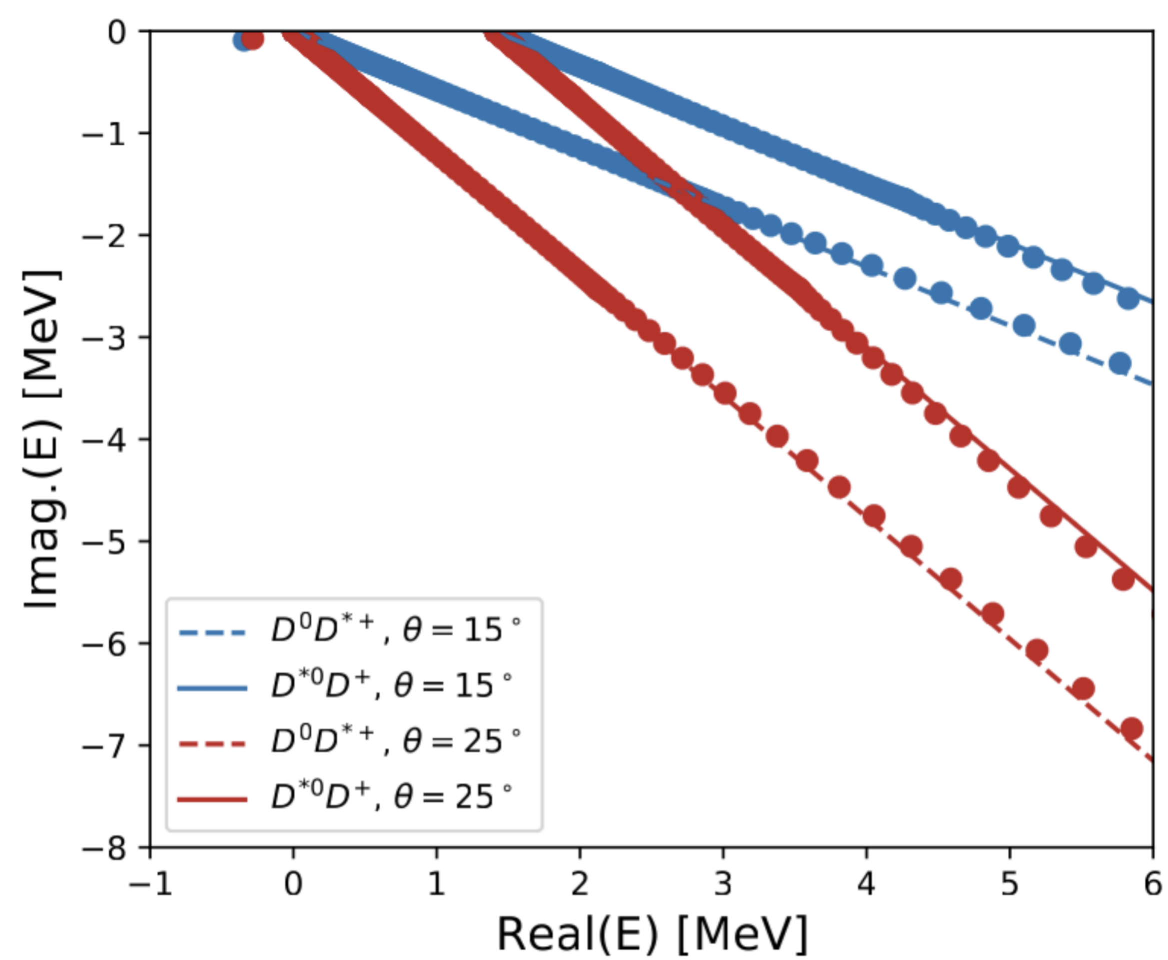
- 70.1% $D^{*+}D^0$, 30% D^+D^{*0} ⟺ 95.8%, $\mathrm{DD}^*(I = 0)$ 4.2% $\mathrm{DD}^*(I = 1)$

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

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

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





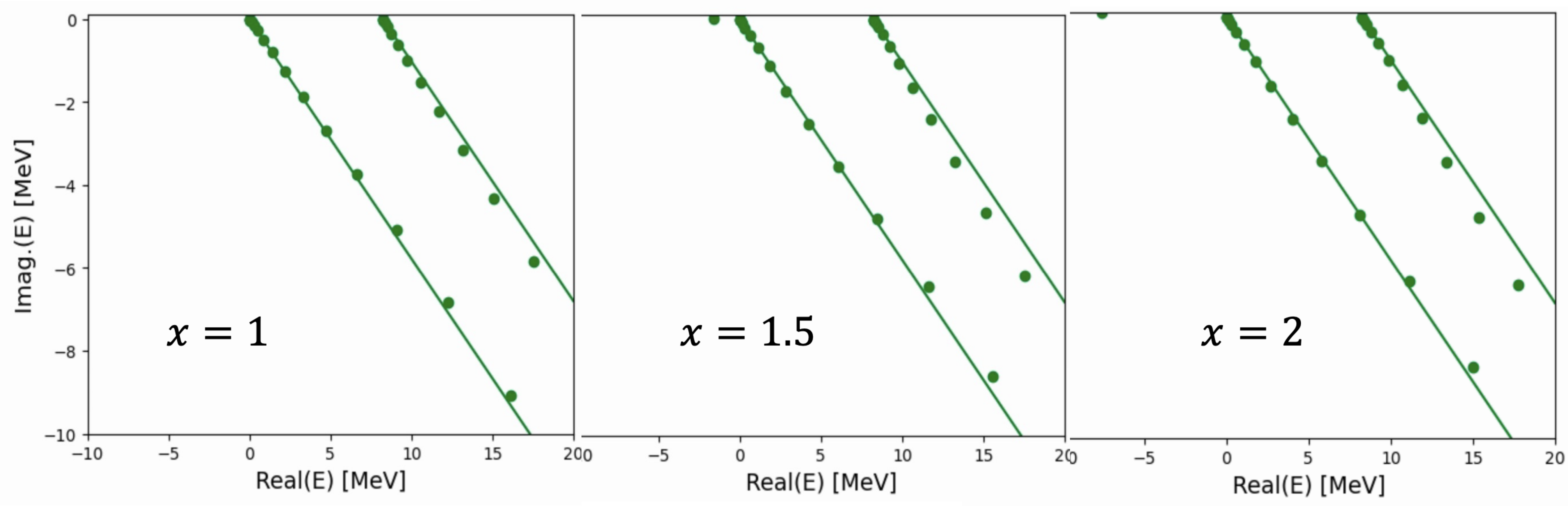
Results with three Λ

Λ (GeV)	BE (keV)	Γ (keV)	$\sqrt{\langle r^2 \rangle}$	$I=0$	$I=1$	$P(D^0 D^{*+})$	$P(D^+ D^{*0})$	$\frac{\mathrm{Res}(D^0 D^{*+})}{\mathrm{Res}(D^+ D^{*0})}$
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 $\Delta E \sim -390$keV, which is consistent with that of the measurement $(\Delta E_{\mathrm{exp}} = -360(40)\mathrm{keV})$. LHCb, Nature Commun. 13 (2022) 1, 3351

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***

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

- 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 $\psi(3770)$:

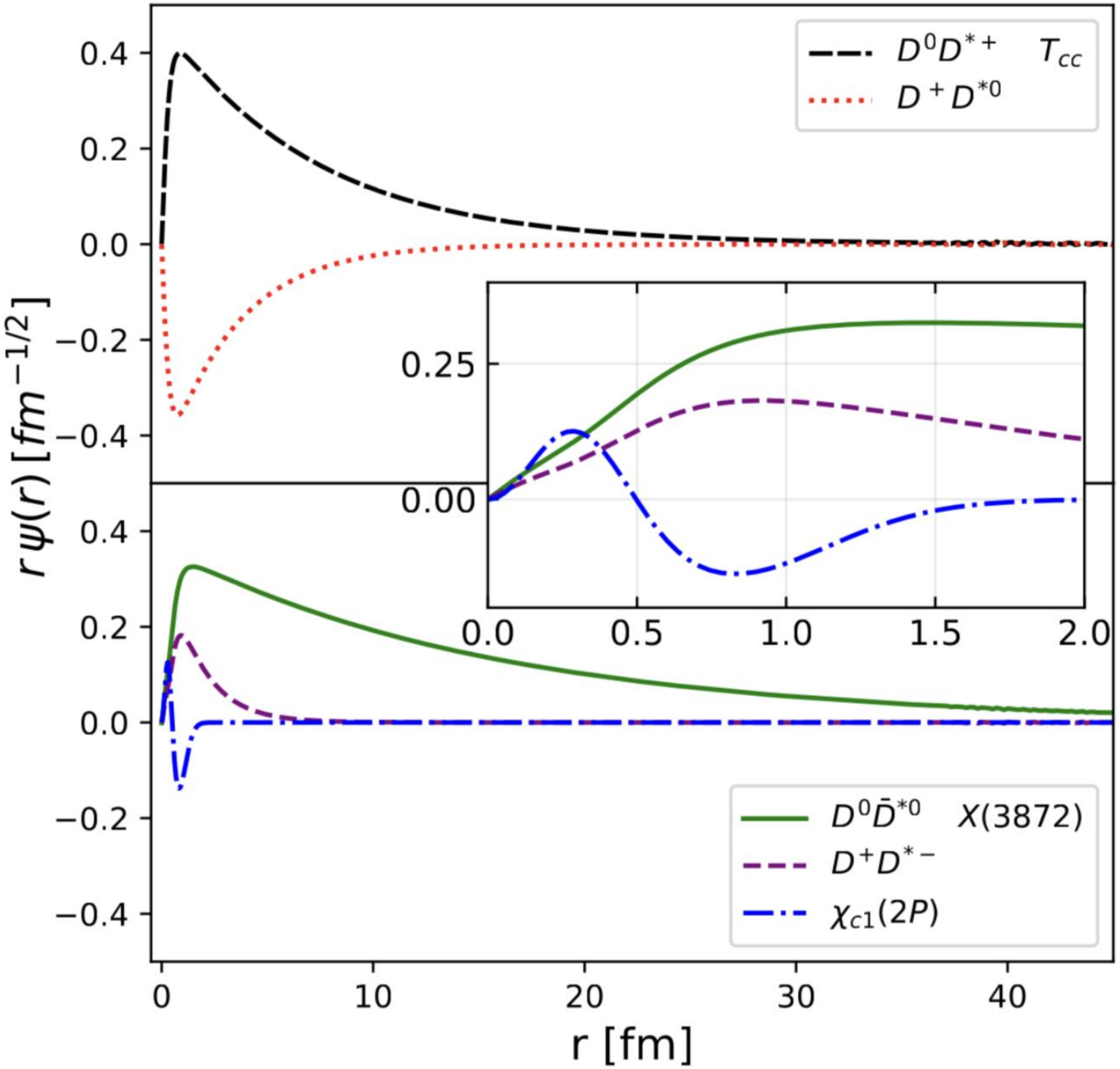
$$\gamma = 4.69$$

- 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 $\sqrt{\langle r^2 \rangle}$.

Compare with the lattice results

Ours: $\chi_{c1}(2P) \rightarrow M = 3957.9\text{MeV}$

Haozheng Li et al, arXiv: 2402.14541

m_π(MeV)	250(3)	307(2)	362(1)	417(1)
m_R(MeV)	3924(5)	3926(6)	3969(4)	3995(4)
Γ_R(MeV)	63(23)	57(18)	37(13)	57(10)

$X \approx 1$ and indicates a predominant $D\bar{D}^*$ component. This state may correspond to $X(3872)$. On the other hand, our results of the finite volume energies also hint at the existence of a 1^{++} resonance below 4.0 GeV with a width around 60 MeV.

Compare with the experimental results

Ours: virtual state with 1^{+-} and $M = 3870.2$ MeV

COMPASS: $\tilde{X}(3872)$ with $M = 3860.0 \pm 10.4$ MeV COMPASS, PLB783,334

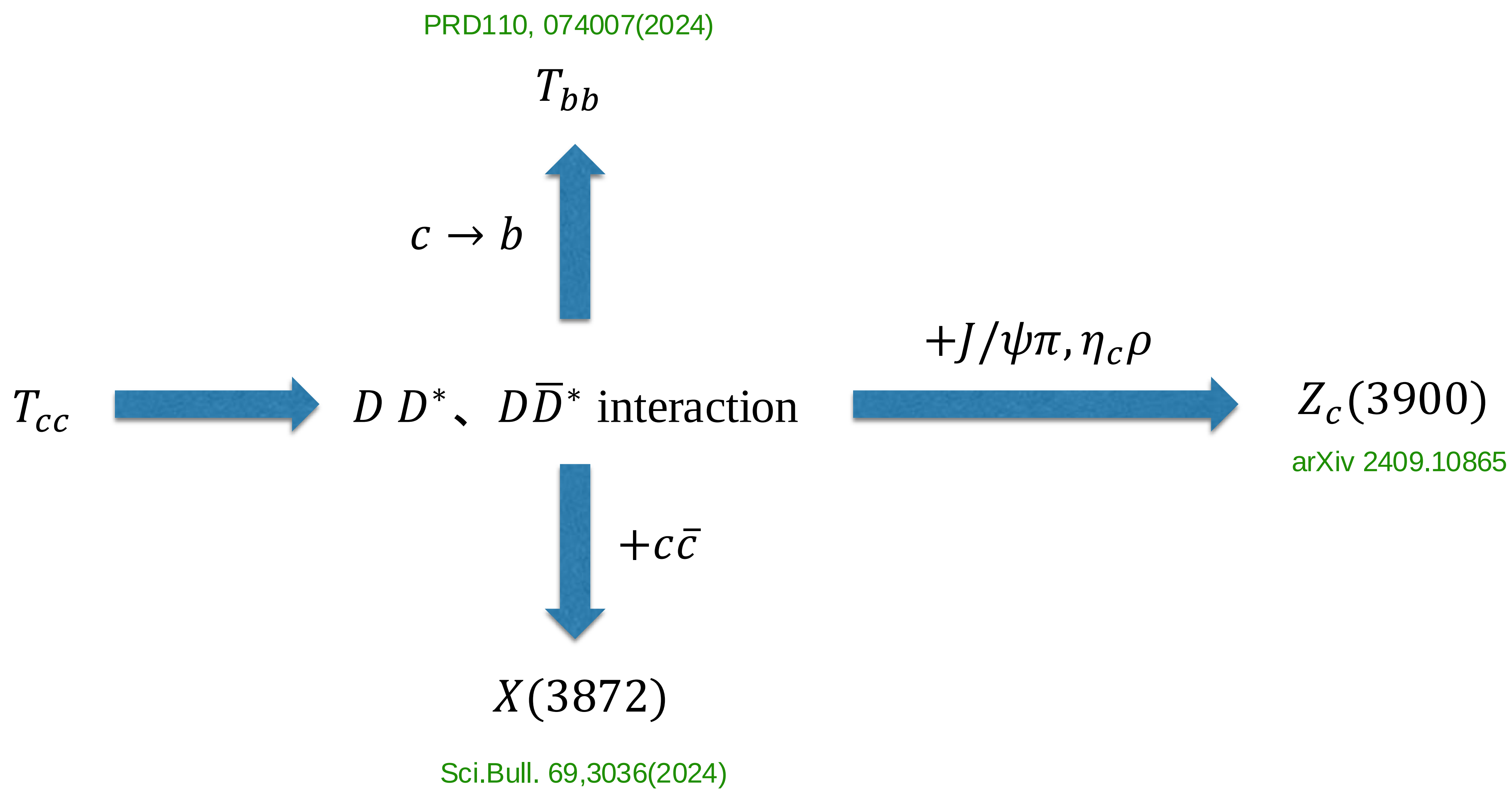
Ours: $h_c(2P) \rightarrow \; M = 3961.3$MeV

$\chi_{c1}(2P) \rightarrow M = 3957.9$MeV

LHCb, arXiv:2406.03156

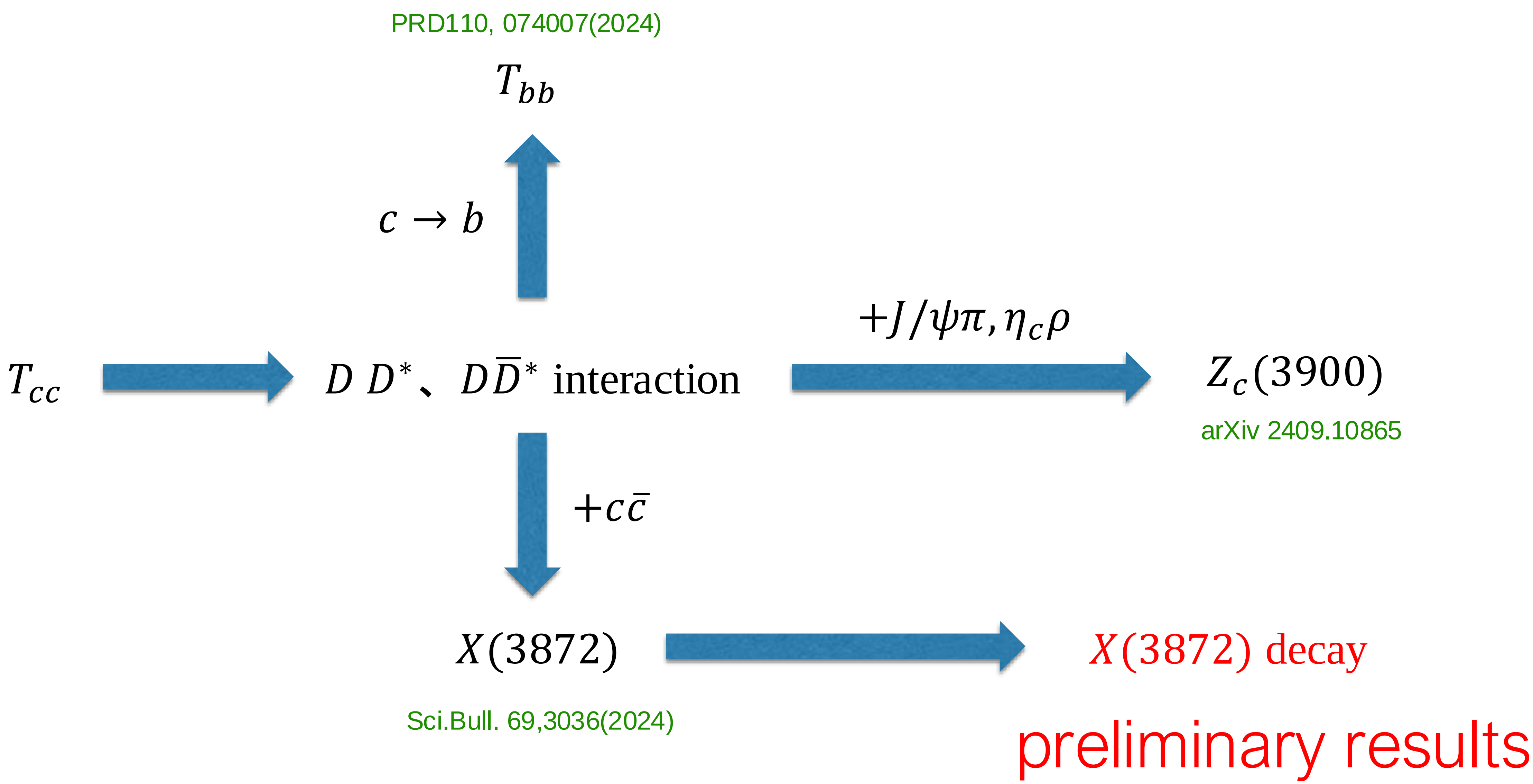
This work		Known states [6]		$c\bar{c}$ prediction [34]	
$\eta_c(3945)$	$J^{PC} = 0^{-+}$	$X(3940)$ [9, 10]	$J^{PC} = ?^{??}$	$\eta_c(3S)$	$J^{PC} = 0^{-+}$
$m_0 = 3945\,^{+28}_{-17}\,^{+37}_{-28}$	$\Gamma_0 = 130\,^{+92}_{-49}\,^{+101}_{-70}$	$m_0 = 3942 \pm 9$	$\Gamma_0 = 37\,^{+27}_{-17}$	$m_0 = 4064$	$\Gamma_0 = 80$
$h_c(4000)$	$J^{PC} = 1^{+-}$	$T_{c\bar{s}}(4020)^0$ [35]	$J^{PC} = ?^{?-}$	$h_c(2P)$	$J^{PC} = 1^{+-}$
$m_0 = 4000\,^{+17}_{-14}\,^{+29}_{-22}$	$\Gamma_0 = 184\,^{+71}_{-45}\,^{+97}_{-61}$	$m_0 = 4025.5\,^{+2.0}_{-4.7} \pm 3.1$	$\Gamma_0 = 23.0 \pm 6.0 \pm 1.0$	$m_0 = 3956$	$\Gamma_0 = 87$
$\chi_{c1}(4010)$	$J^{PC} = 1^{++}$			$\chi_{c1}(2P)$	$J^{PC} = 1^{++}$
$m_0 = 4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$	$\Gamma_0 = 62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$			$m_0 = 3953$	$\Gamma_0 = 165$

Summary



- T_{cc} is used to fix the $D\bar{D}^*$ interactions in $X(3872)$.
- Short-range interactions and structures of $X(3872)$ should be studied by considering the $c\bar{c}$ core.

Content


PRD110, 074007(2024)
T_{bb}
$c \to b$
T_{cc}
$D\,D^*$、$D\bar{D}^*$ interaction
$+J/\psi\pi, \eta_c\rho$
$Z_c(3900)$
arXiv 2409.10865
$+c\bar{c}$
$X(3872)$
$X(3872)$ decay
Sci.Bull. 69,3036(2024)
preliminary results

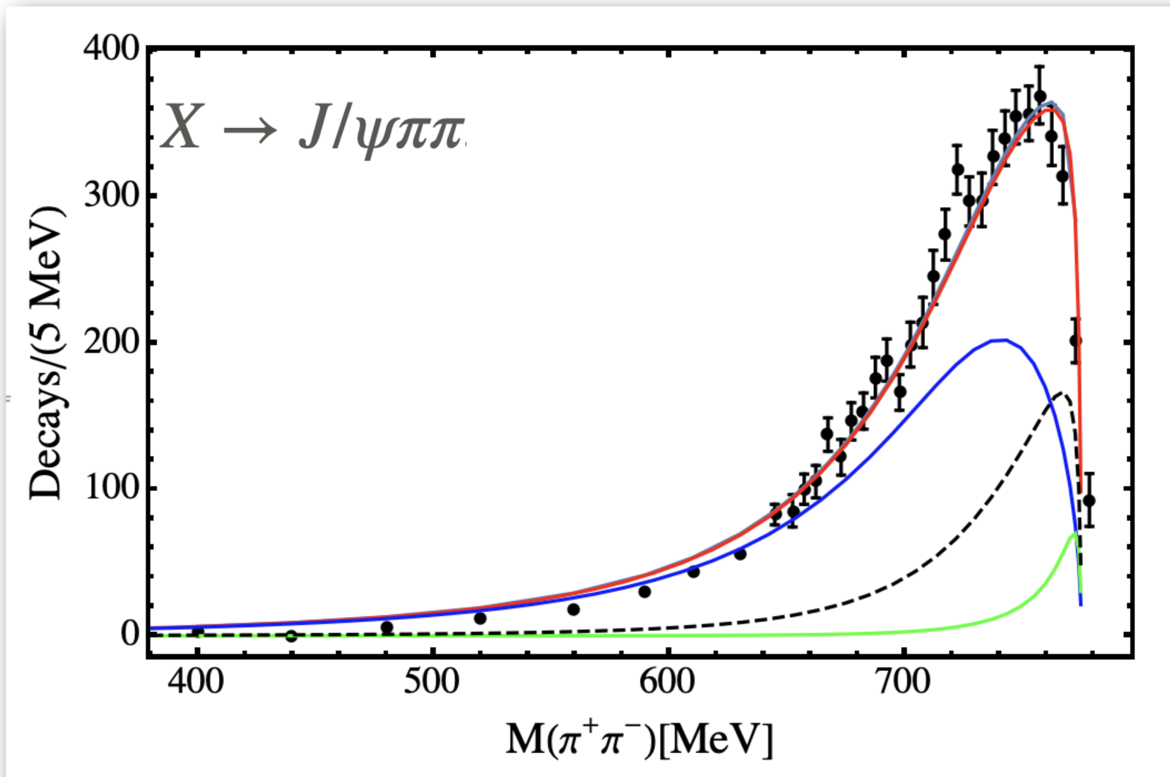
Preliminary results of $X(3872)$ decay

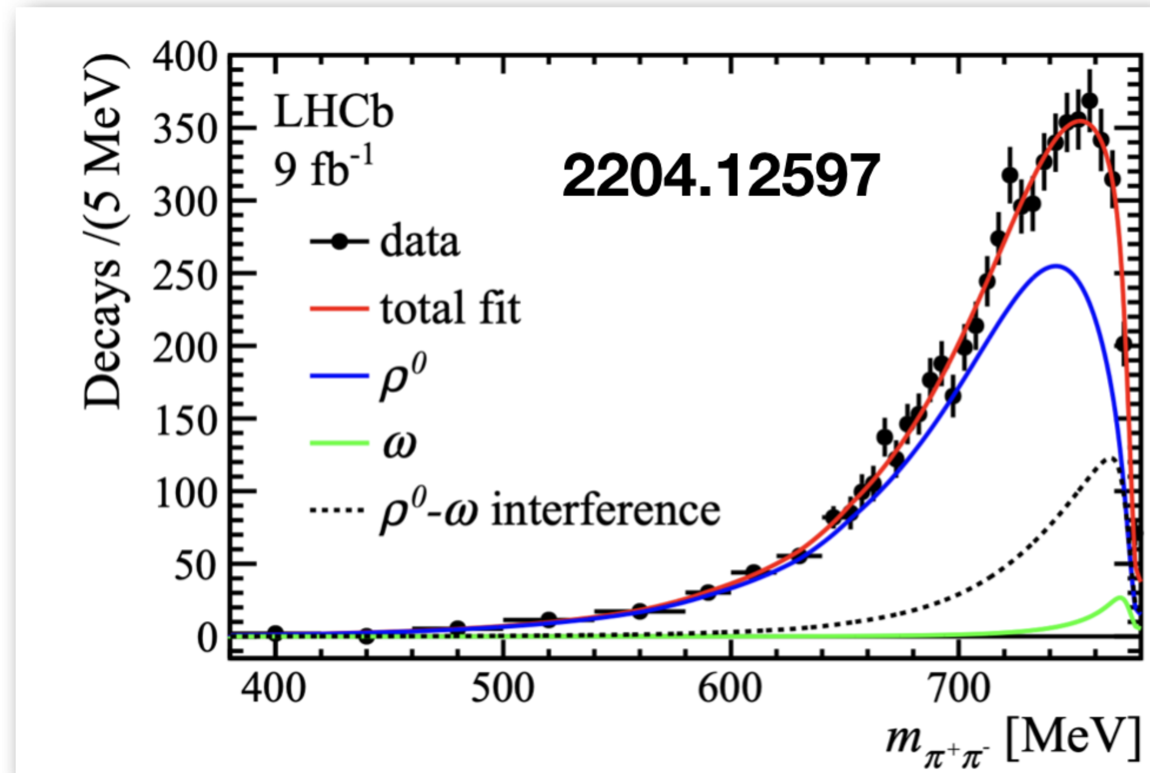
The Quark exchanging model

$\Gamma_i/\Gamma_{\text{total}}$	PDG	Our result with $\Gamma_{D^*} = 55.9\text{keV}$	C.-H. Li, C.-Z. Yuan [PRD100 094003]
$\Gamma(\chi_{c1}(3872) \to \pi^+\pi^- J/\psi(1S))$	0.035 ± 0.009	0.03	$(4.1^{+1.9}_{-1.1})\%$
$\Gamma(\chi_{c1}(3872) \to \rho(770)^0 J/\psi(1S))$	$(2.8 \pm 0.7)\%$	3.7%	-
$\Gamma(\chi_{c1}(3872) \to \omega J/\psi(1S))$	$(4.1 \pm 1.4)\%$	12.4%	$(4.4^{+2.3}_{-1.3})\%$
$\Gamma(\chi_{c1}(3872) \to \pi\pi\pi J/\psi(1S))$	not seen	6.4%	-
$\Gamma(\chi_{c1}(3872) \to D^0 \bar{D}^0 \pi^0)$	$(45 \pm 21)\%$	10.3%	-
$\Gamma(\chi_{c1}(3872) \to \bar{D}^{*0} D^0)$	$(34 \pm 12)\%$	52.6%	$(52.4^{+25.3}_{-14.3})\%$
$\Gamma(\chi_{c1}(3872) \to \pi^0 \chi_{c2})$	$< 4\%$	1.6%	-
$\Gamma(\chi_{c1}(3872) \to \pi^0 \chi_{c1})$	$(3.1^{+1.5}_{-1.3})\%$	2.0%	$(3.6^{+2.2}_{-1.6})\%$
$\Gamma(\chi_{c1}(3872) \to \pi^0 \chi_{c0})$	$< 13\%$	1.3%	-
$\Gamma(\chi_{c1}(3872) \to \gamma D^+ D^-)$	$< 3.5\%$	0.1%	-
$\Gamma(\chi_{c1}(3872) \to \gamma \bar{D}^0 D^0)$	$< 6\%$	5.8%	-
$\Gamma(\chi_{c1}(3872) \to \gamma J/\psi)$ [VMD]	$(7.8 \pm 2.9) \times 10^{-3}$	0.9×10^{-3}	$(1.1^{+0.6}_{-0.3})\%$
$\Gamma(\chi_{c1}(3872) \to \gamma \psi(2S))$	possibly seen	$(7.0) \times 10^{-3}$	$(2.4^{+1.3}_{-0.8})\%$

Preliminary results of $X(3872)$ decay

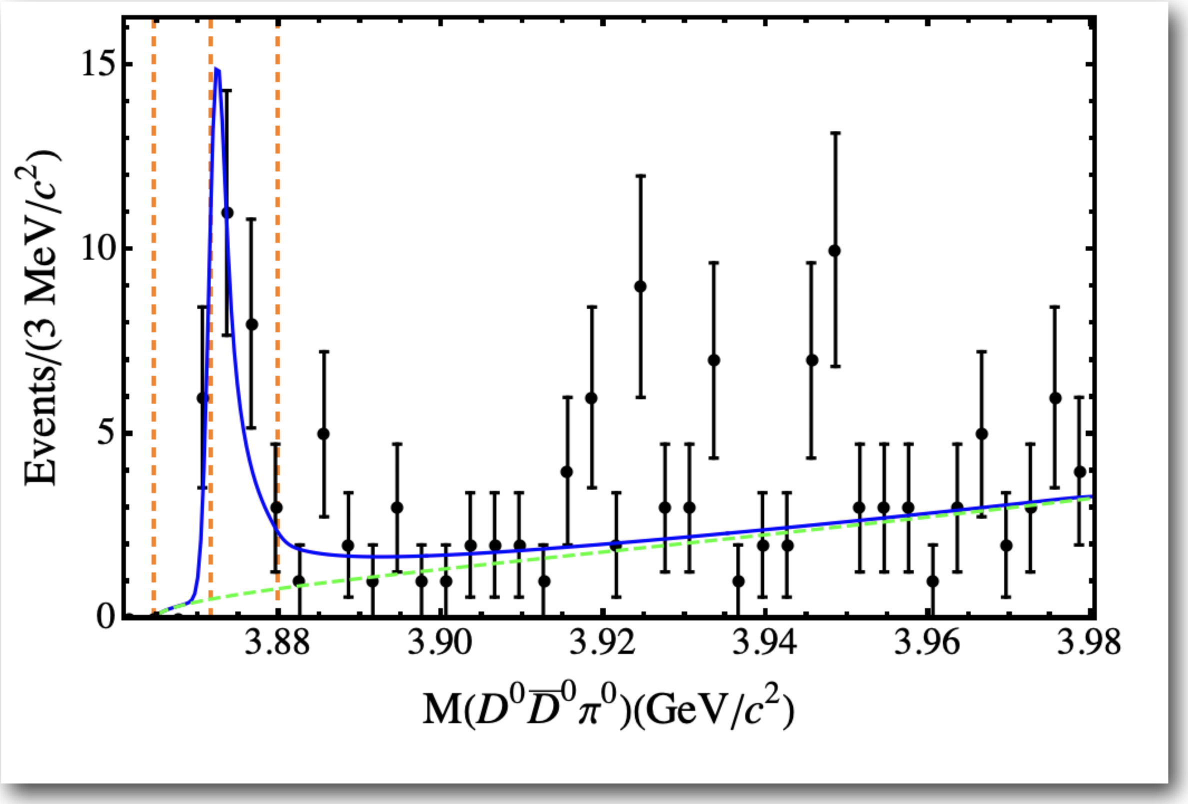
We obtain the distribution of the $\pi\pi$ without any fitting
except a normalization factor !

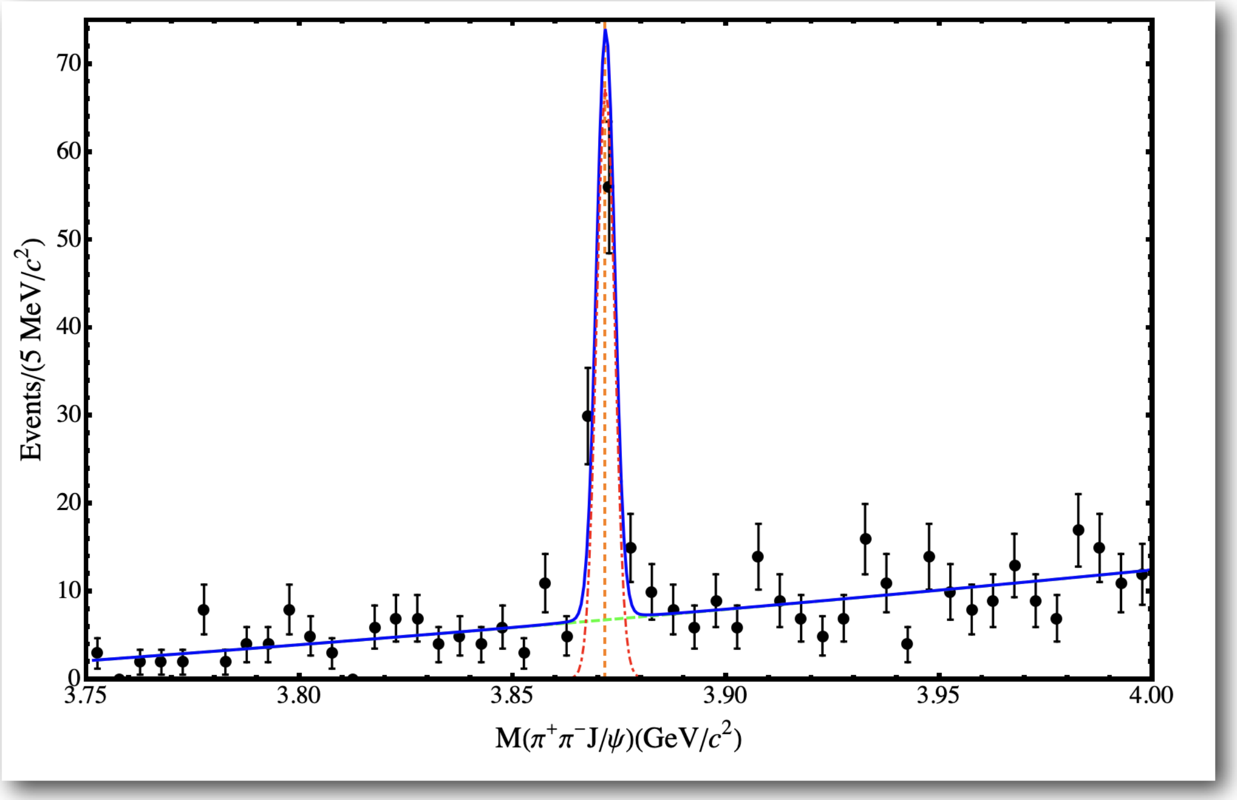




Preliminary results of $X(3872)$ decay

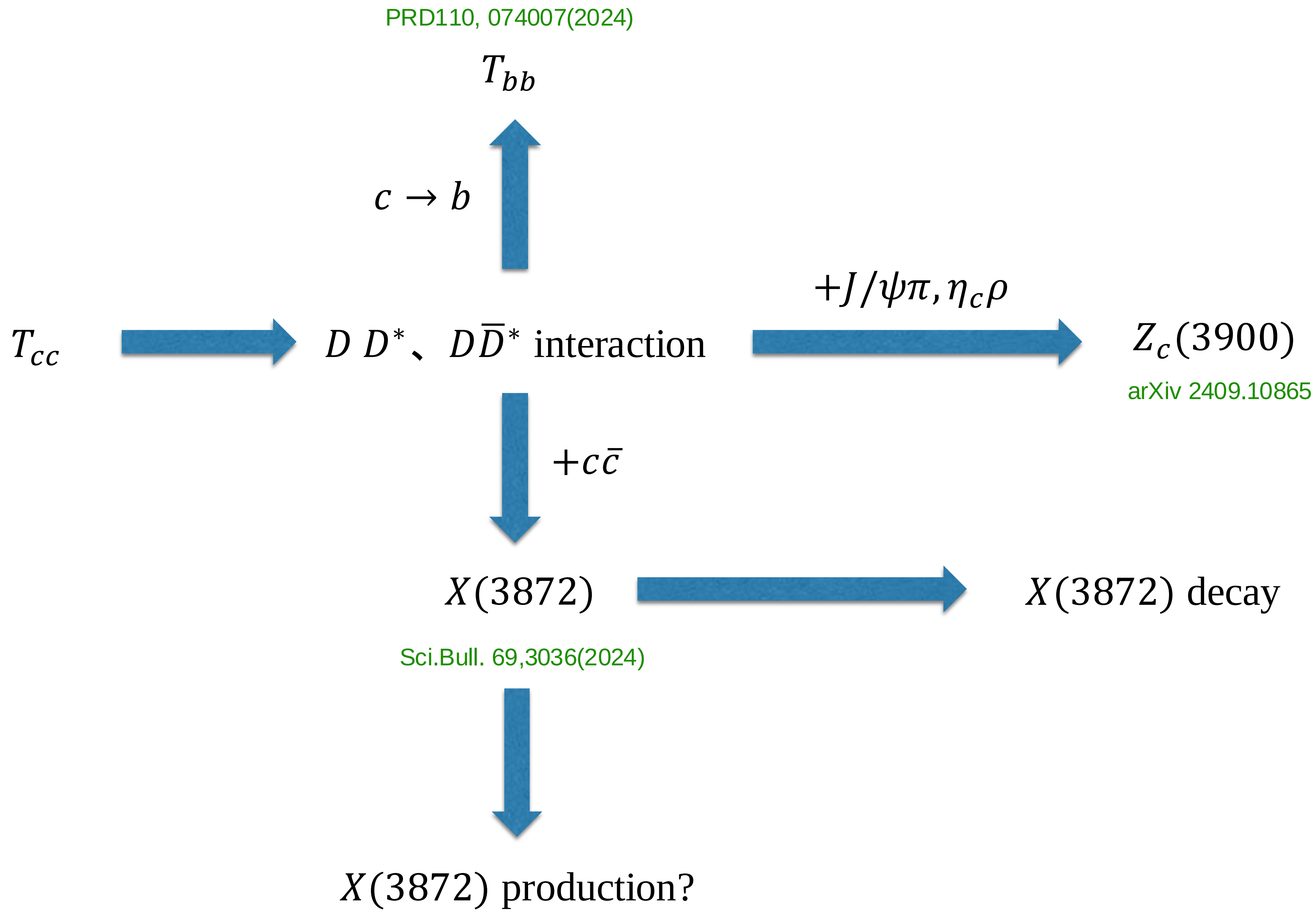
Without any fitting except a normalization factor!





BESIII, Phys. Rev. Lett. 124, 242001 (2020)

Discussion



- What important role the $c\bar{c}$ core can play in the production of the $X(3872)$?

Discussion

The probability of the $c\bar{c}$ component in the $X(3872)$ can be obtained from fitting its production:

$$d\sigma(pp \to X(J/\psi\pi^+\pi^-)) = d\sigma(pp \to \chi'_{c1}) \cdot k, \quad k = Z_{c\bar{c}} \cdot Br_0$$

$$\longrightarrow Z_{c\bar{c}} = (28\text{-}44)\%$$

C. Meng, H. Han, K.T. Chao, Phys. Rev. D 96, 074014

Thank you !

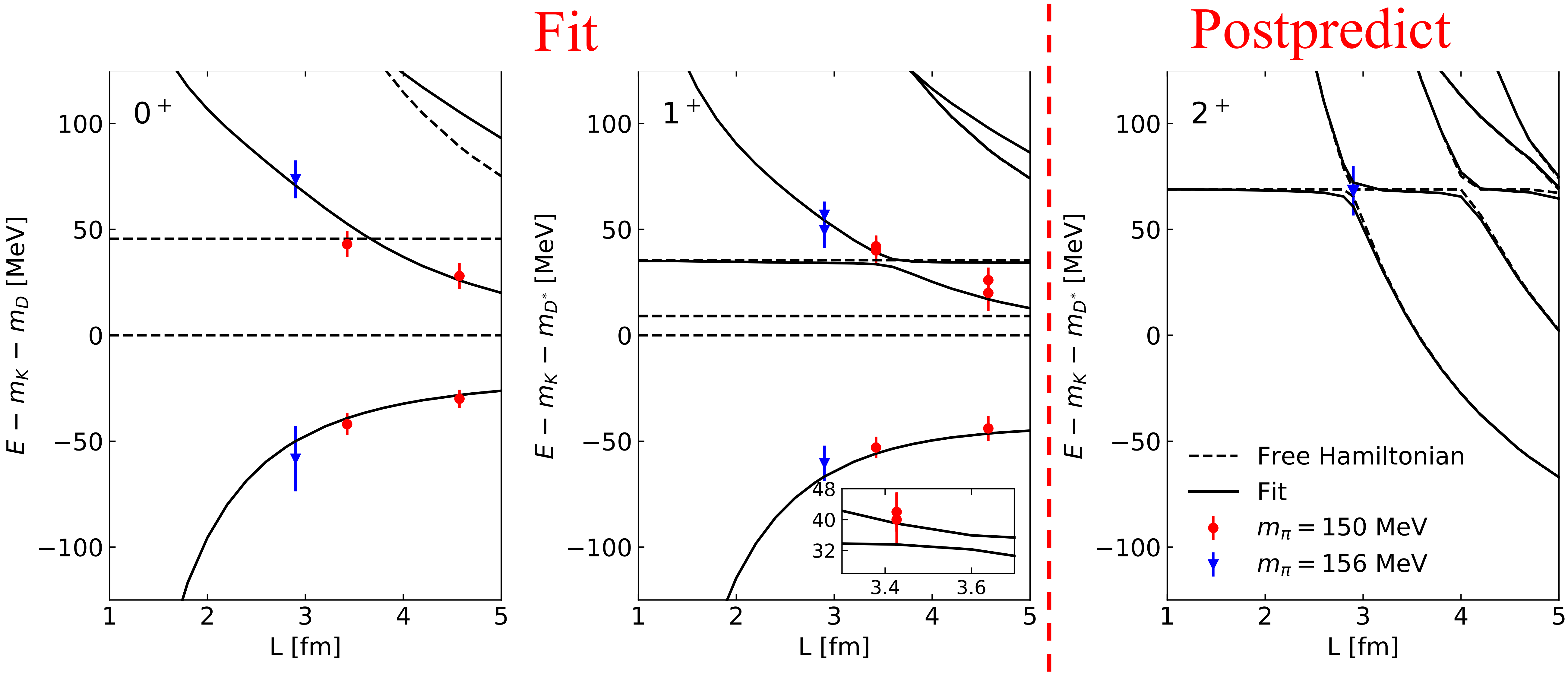
Backup

- With fixed $\Lambda = 1.0$ GeV, $\chi^2/\text{dof} = 0.95$

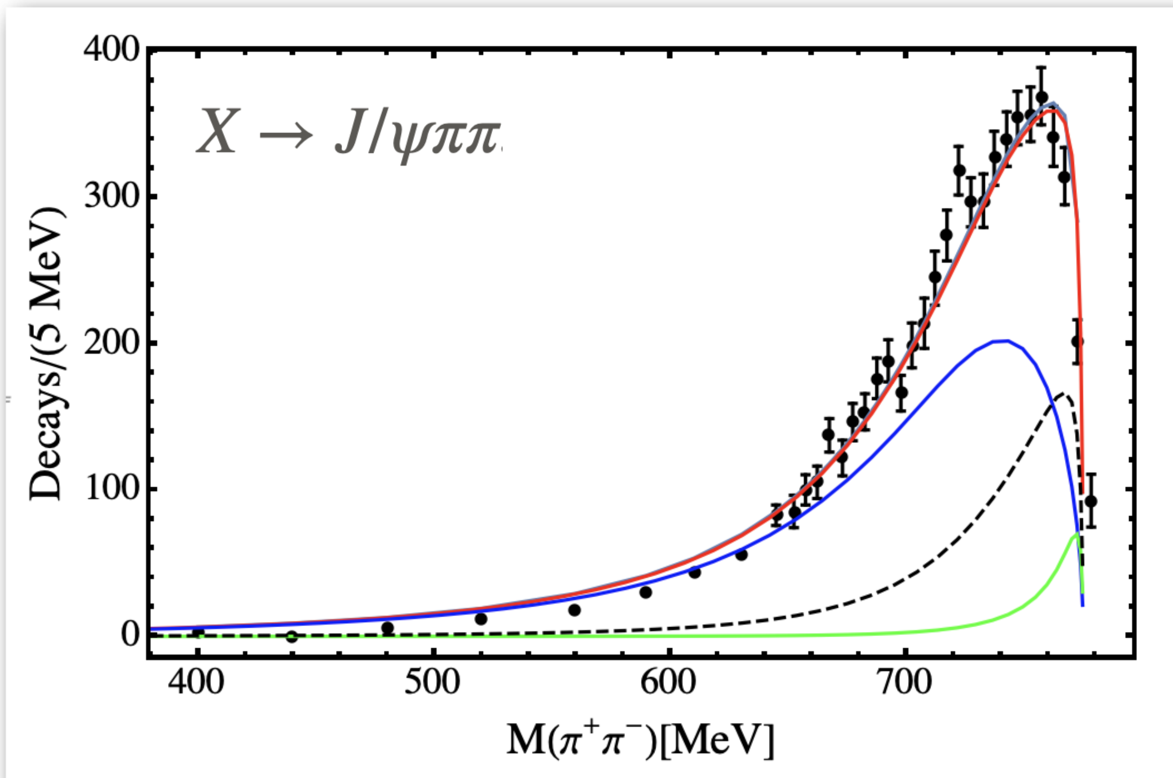
$$g_c = 4.2^{+2.2}_{-3.1}\ ,\ \Lambda' = 0.323^{+0.033}_{-0.031}\ \text{GeV},$$

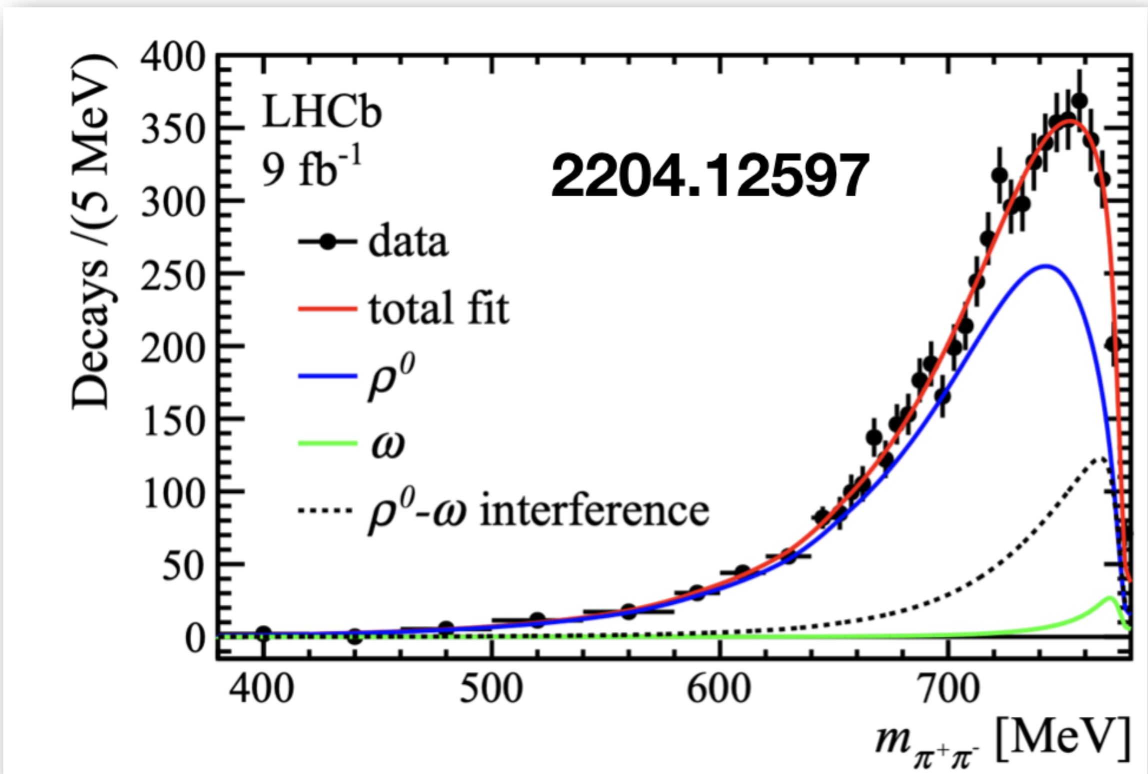
$$\gamma = 10.3^{+1.1}_{-1.0}$$

Lattice data from: C. B. Lang et al., **Phys. Rev. D 90, 034510 (2014);**
G. S. Bali et al., **Phys. Rev. D 96, 074501 (2017)**



Backup



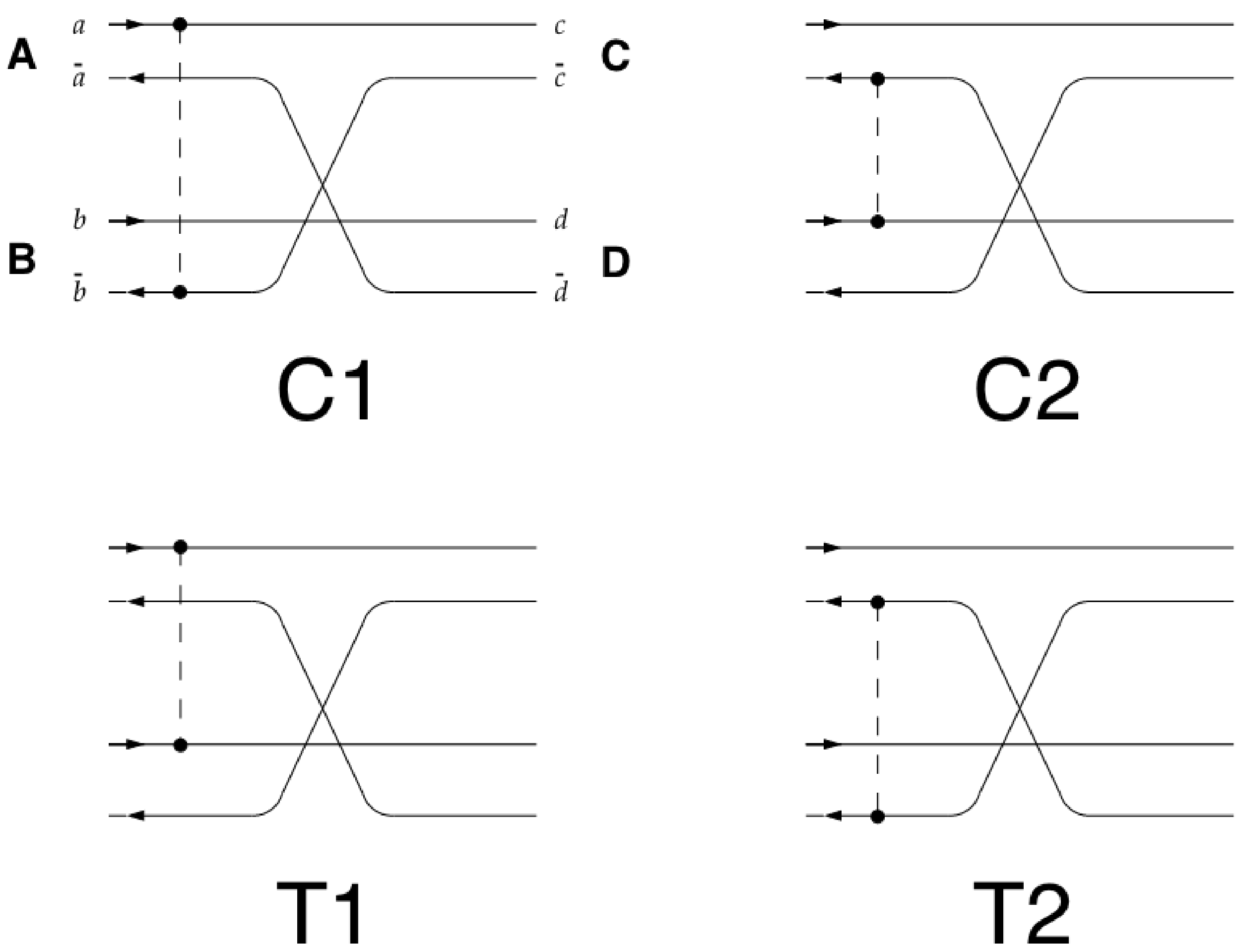


$R_X \sim 0.21$

$$A_{\omega\to 2\pi} = \varepsilon G_\rho A_{\rho\to 2\pi}$$

$$\epsilon \approx \sqrt{m_\omega m_\rho \Gamma_\rho \Gamma_{\omega\to 2\pi}} \approx 3.4 \times 10^{-3}\mathrm{GeV}^2$$

Backup



C.-Y. Wong, E.S. Swanson, Ted Barnes, PhysRevC.66.029901;
Z.-Y. Zhou, M.-T. Yu, Z.-G. Xiao, PhysRevD.100.094025;
G.-J. Wang, X.-H. Liu et al, Eur.Phys.J. C79 (2019) no.7, 567