近阈奇特强子态的性质及其产生

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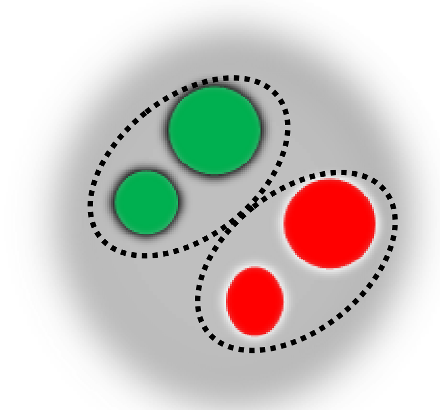
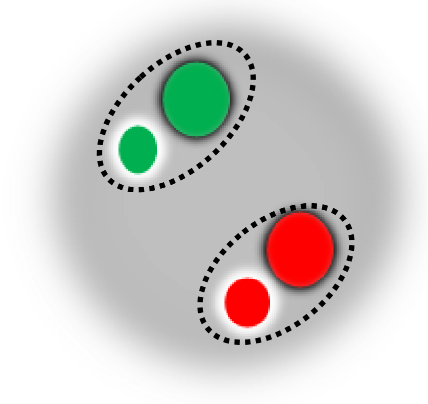
电子科技大学

第一届中国电子离子对撞机相关物理年会　青岛　2026/4/20

Multi-quark 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 $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, 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 *)

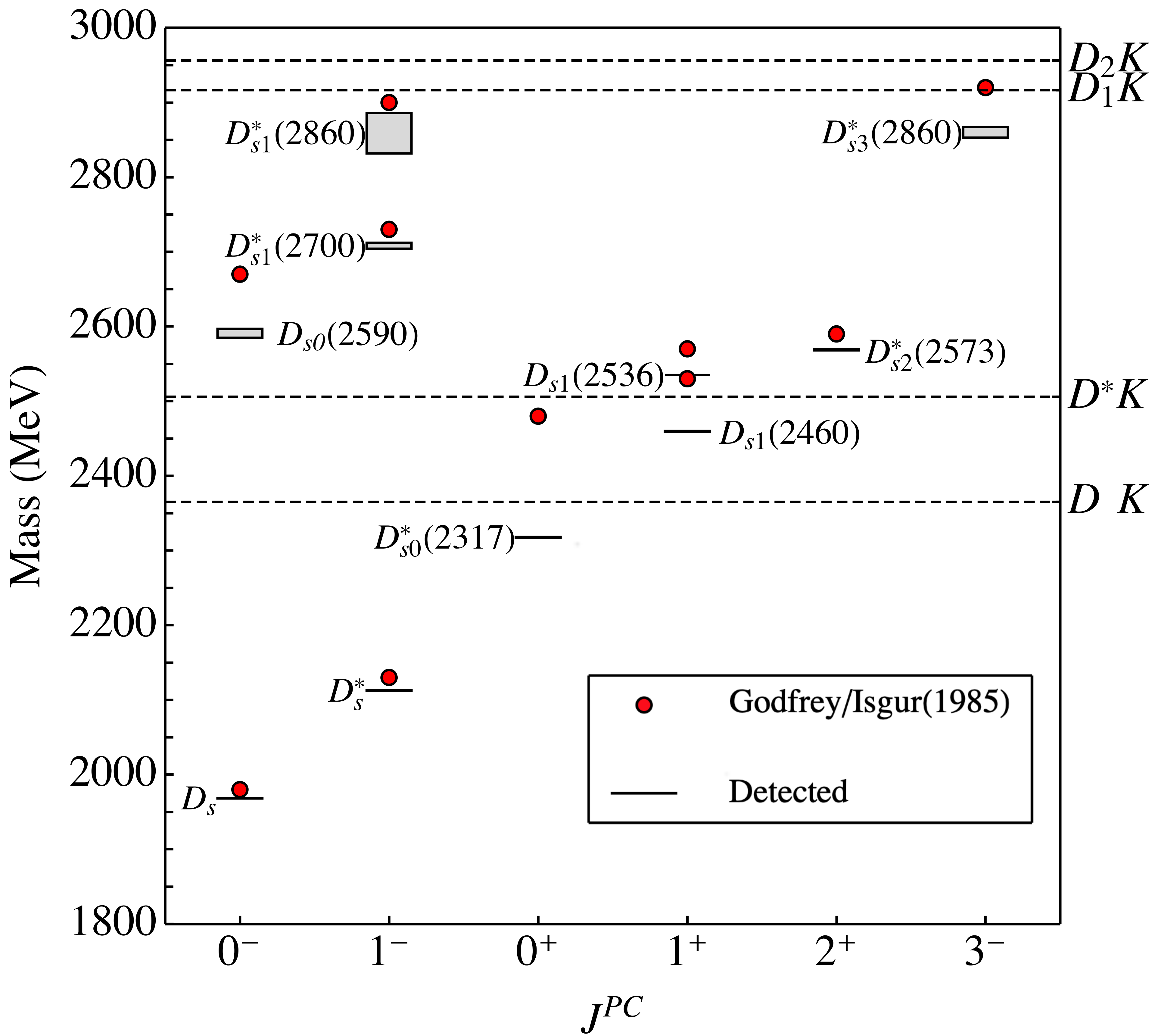
G. Zweig
CERN---Geneva

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

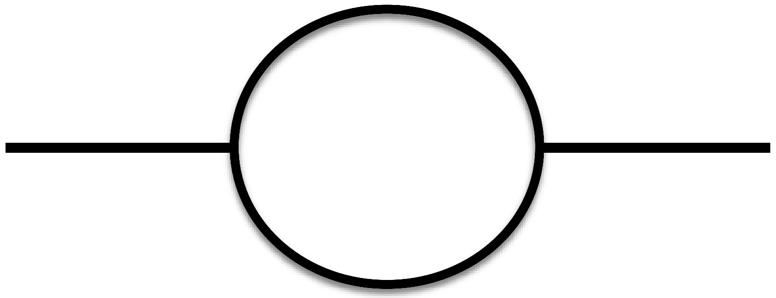
. . .

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

Meson in quark model: D_s mesons



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 framework

The Hamiltonian reads

$$H = H_0 + H_I,$$

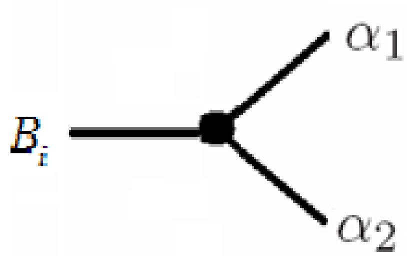
where the non-interacting one is

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

And the interacting one includes two parts

$$H_I = g + v$$

bare state core -> channel :



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

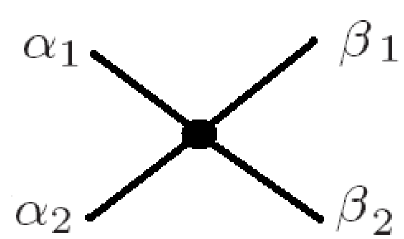
Quark pair creation model (QPC):

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

truncate the hard vertices given by usual QPC

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

channel -> channel :



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

Effective Lagrangian: (exchanging ρ/ω)

$$\begin{aligned} \mathcal{L} &= \mathcal{L}_{PPV} + \mathcal{L}_{VVV} \\ &= i g_v \mathrm{Tr}(\partial^\mu P[P, V_\mu]) + i g_v \mathrm{Tr}(\partial^\mu V^\nu [V_\mu, V_\nu]) \end{aligned}$$

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

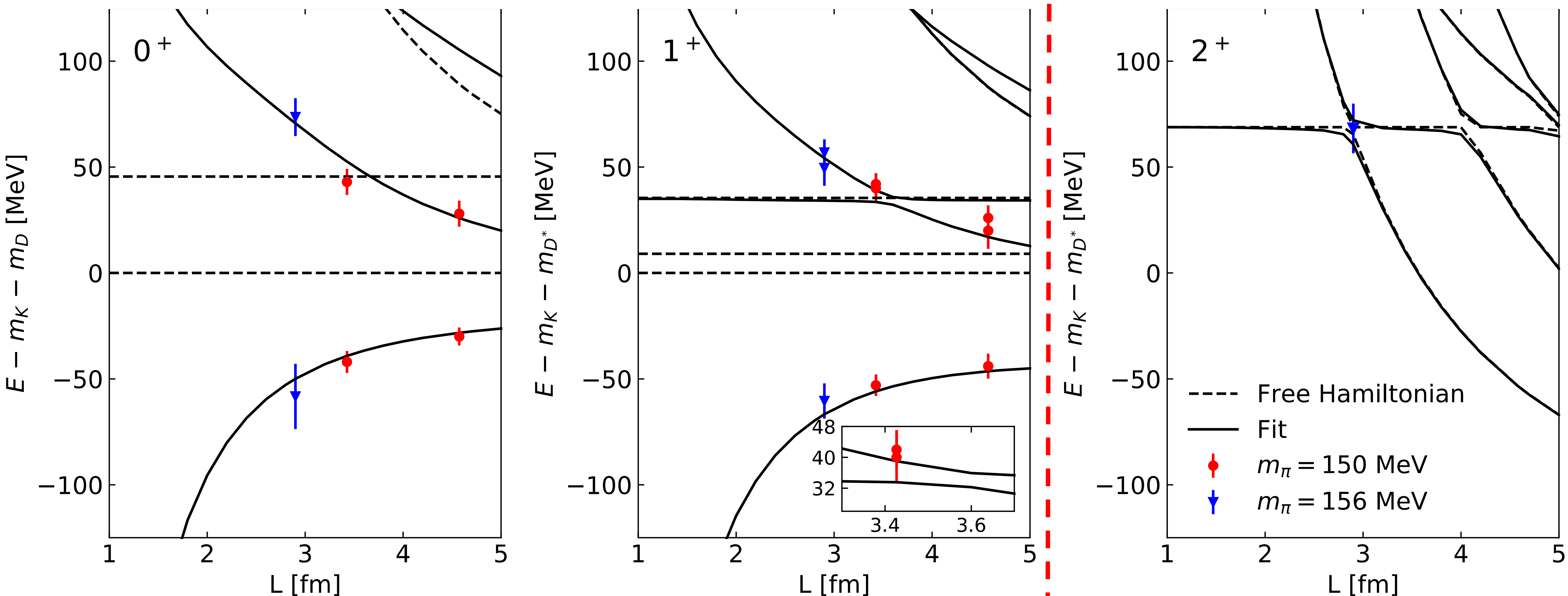
Fit the lattice data : $D_s(2317,2460,2536)$

$$(H_0+H_I)|\Psi\rangle = E|\Psi\rangle$$

Eigenvalues ⟷ Lattice levels

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)**

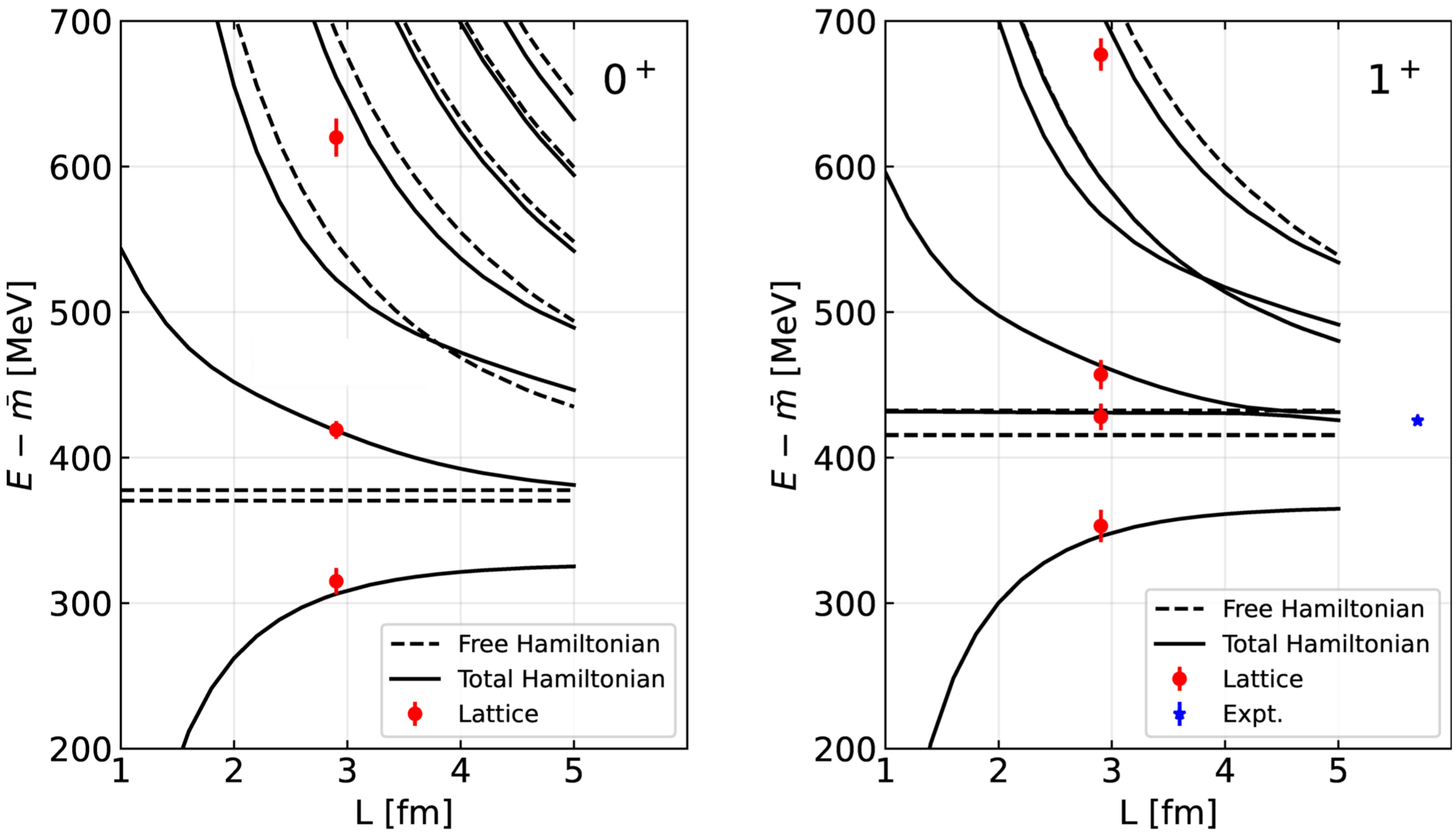
Fit | Postpredict



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)**

Component and pole mass

state | L=4.57 fm | Pole mass at $L \to \infty$

	$P(c\bar{s})[\%]$	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

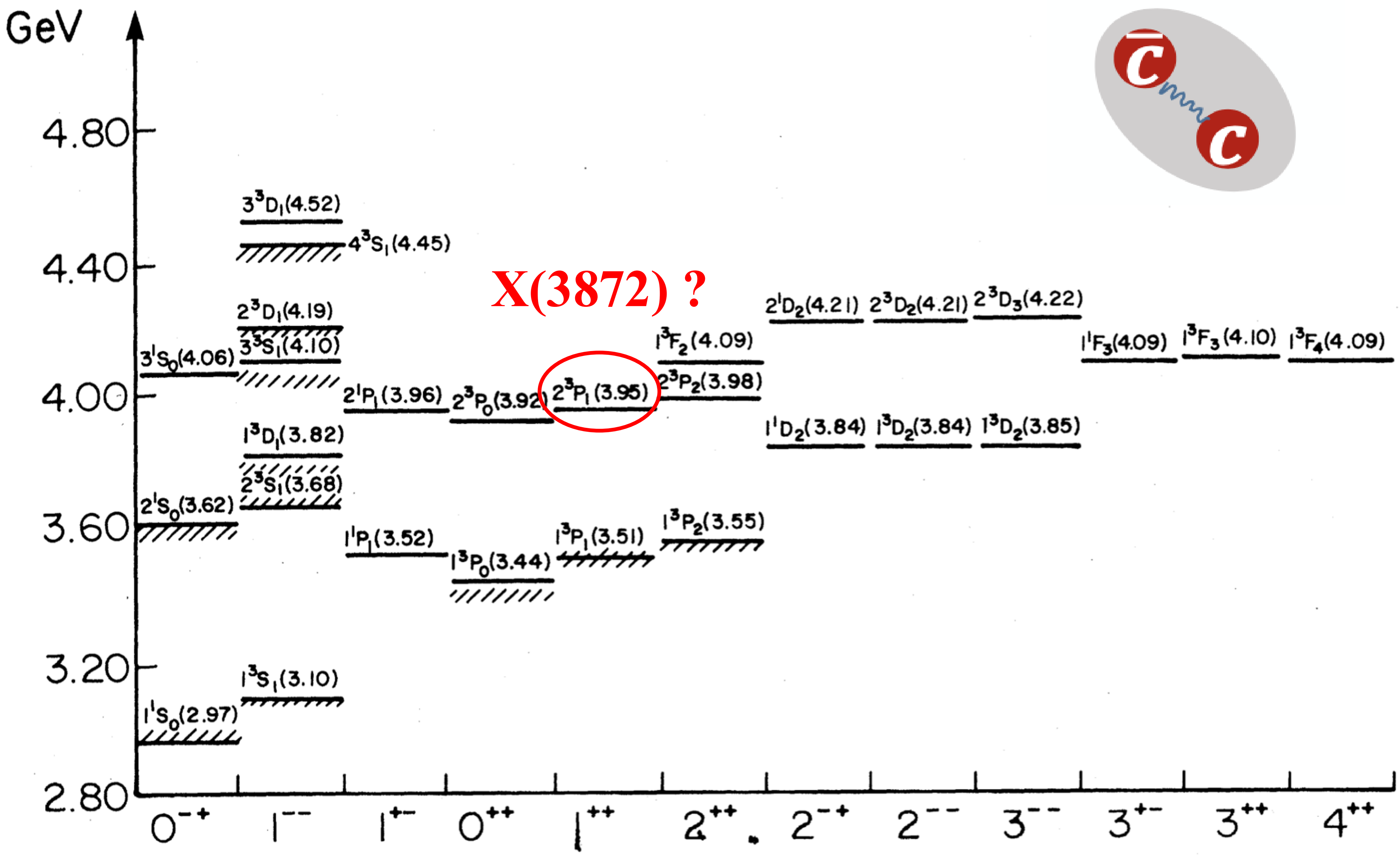
$D_{s0}(2317)$, $D_{s1}(2460)$

- 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 $c\bar{s}$.

Meson in quark model: charmonium states



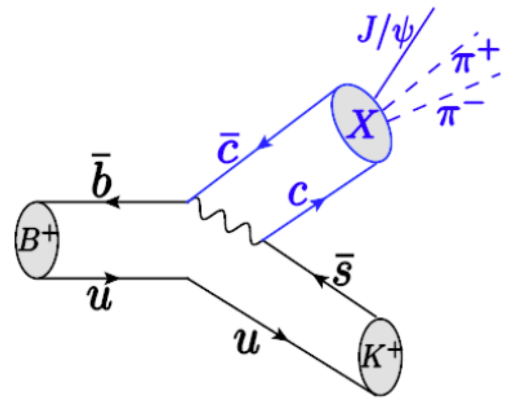
$X(3872)$

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

- 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

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...

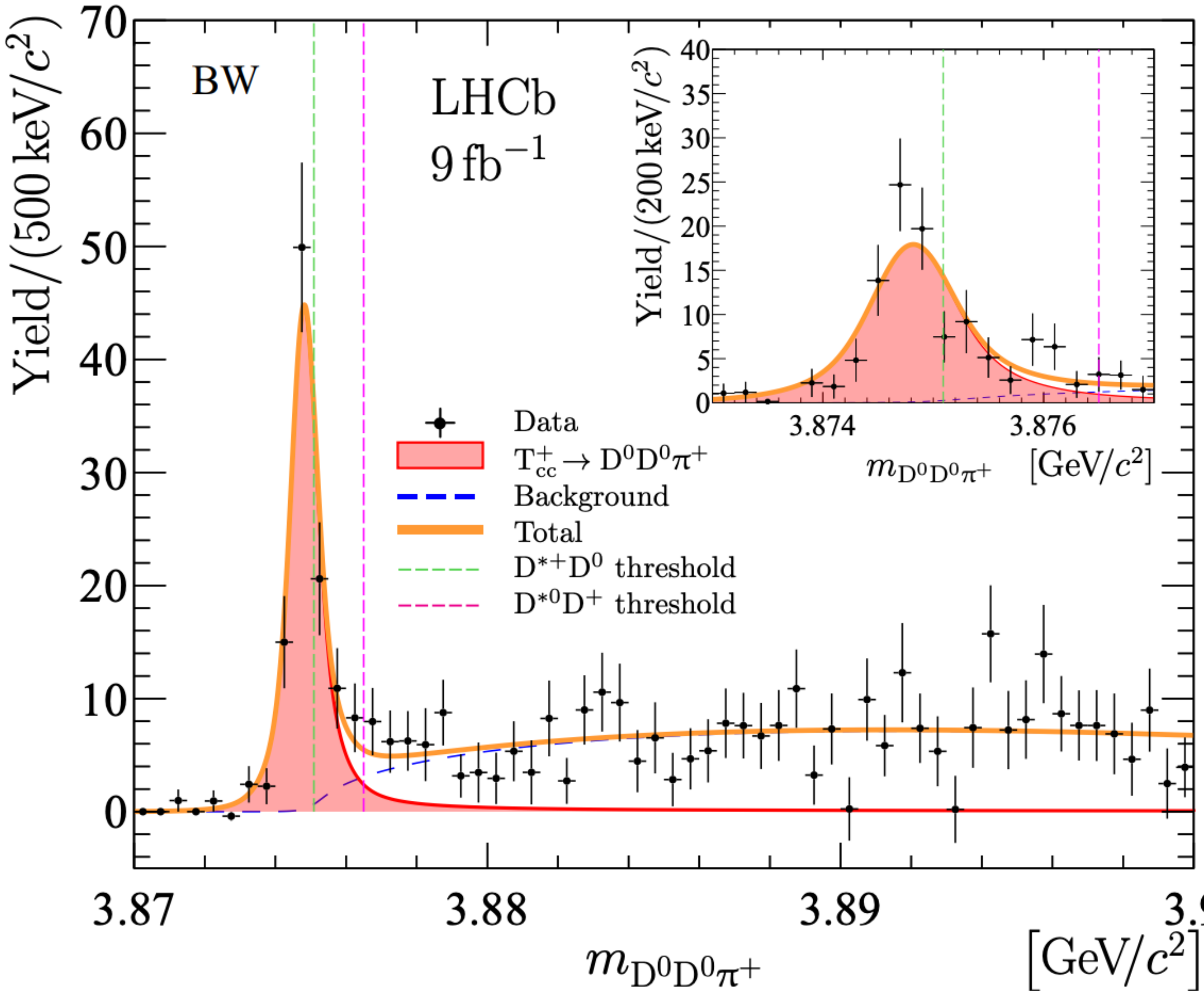
Close to charmonium $\chi_{c1}(2P)$: m=3953.5 MeV

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

$\rightarrow$ *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 T_{cc}



- $D^0D^0\pi^+$ 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:

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

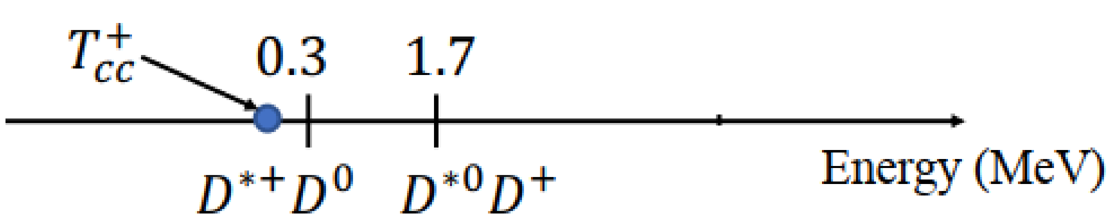
LHCb. Nature Commun. 13 (2022) 1. 3351

❖ Quark content: $cc\bar{u}\bar{d}$

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

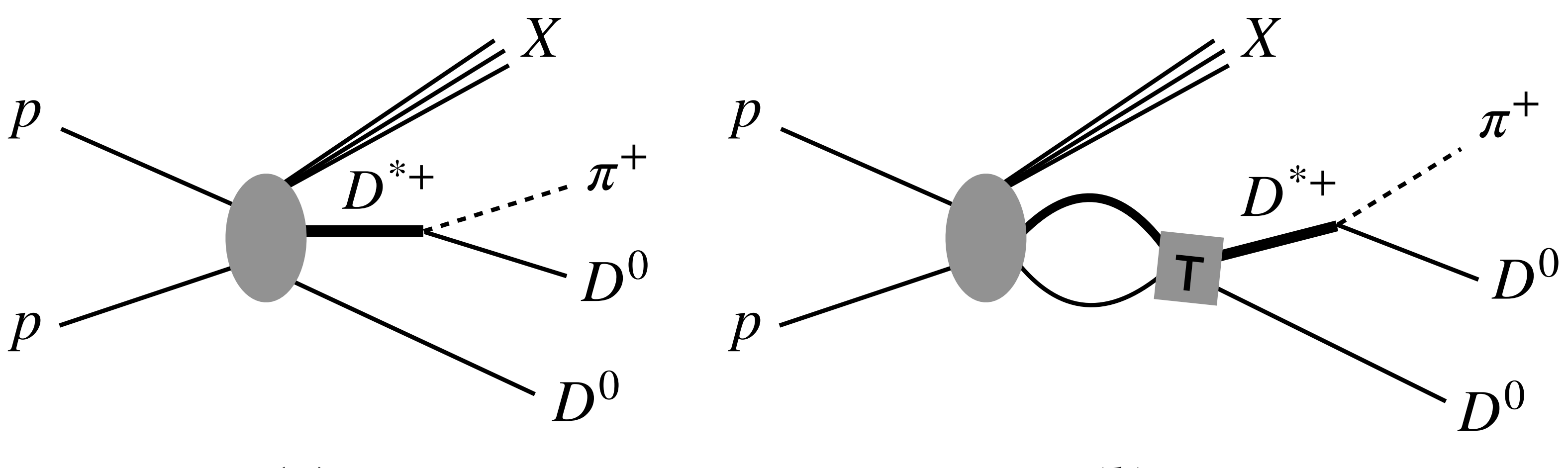
C-parity

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



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

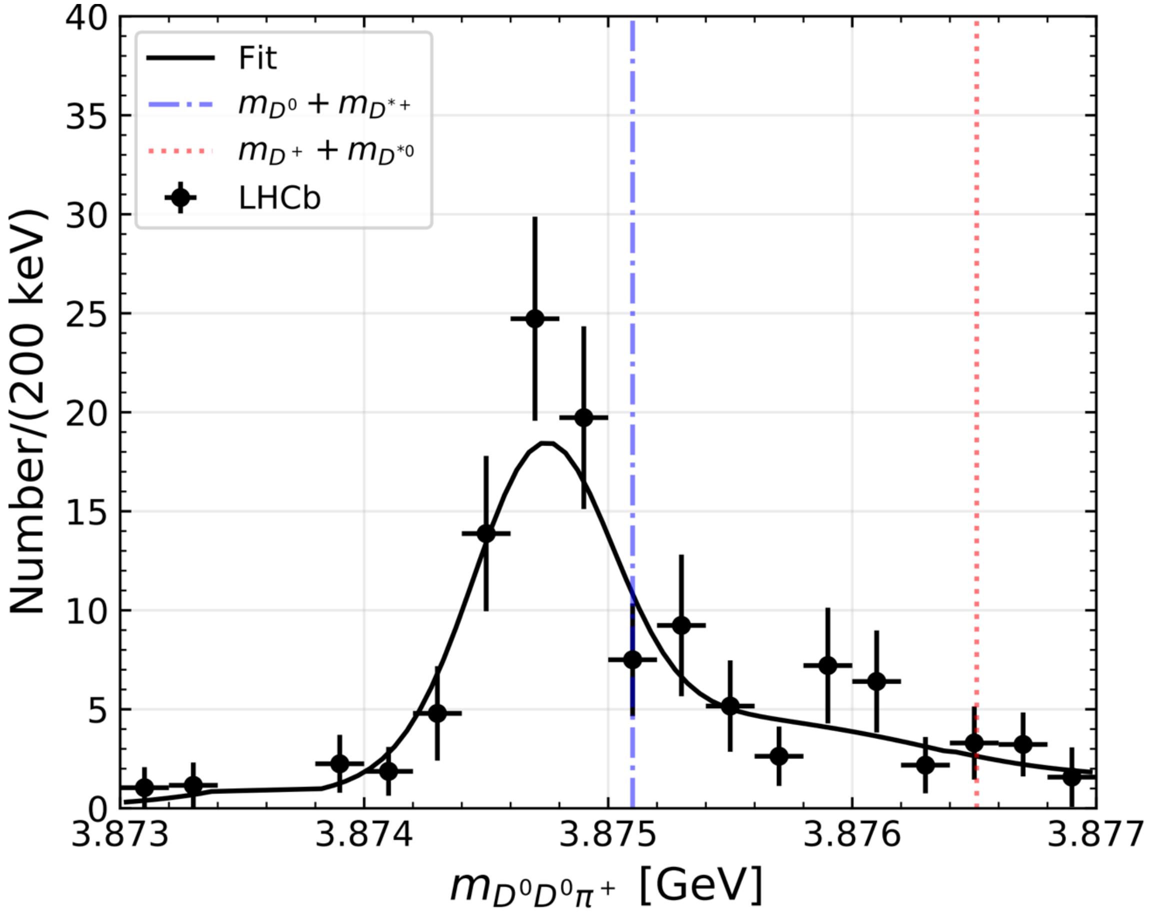
$$T(\vec{k}_{D^*},\vec{k}'_{D^*};E) = \mathcal{V}(\vec{k}_{D^*},\vec{k}'_{D^*};E) + \int d\,\vec{q}\,\frac{\mathcal{V}(\vec{k}_{D^*},\vec{q};E)T(\vec{q},\vec{k}'_{D^*};E)}{E-\sqrt{m_D^2+q^2}-\sqrt{m_{D^*}^2+q^2}+i\epsilon}$$

The effective potential is obtained with light-meson exchange potentials

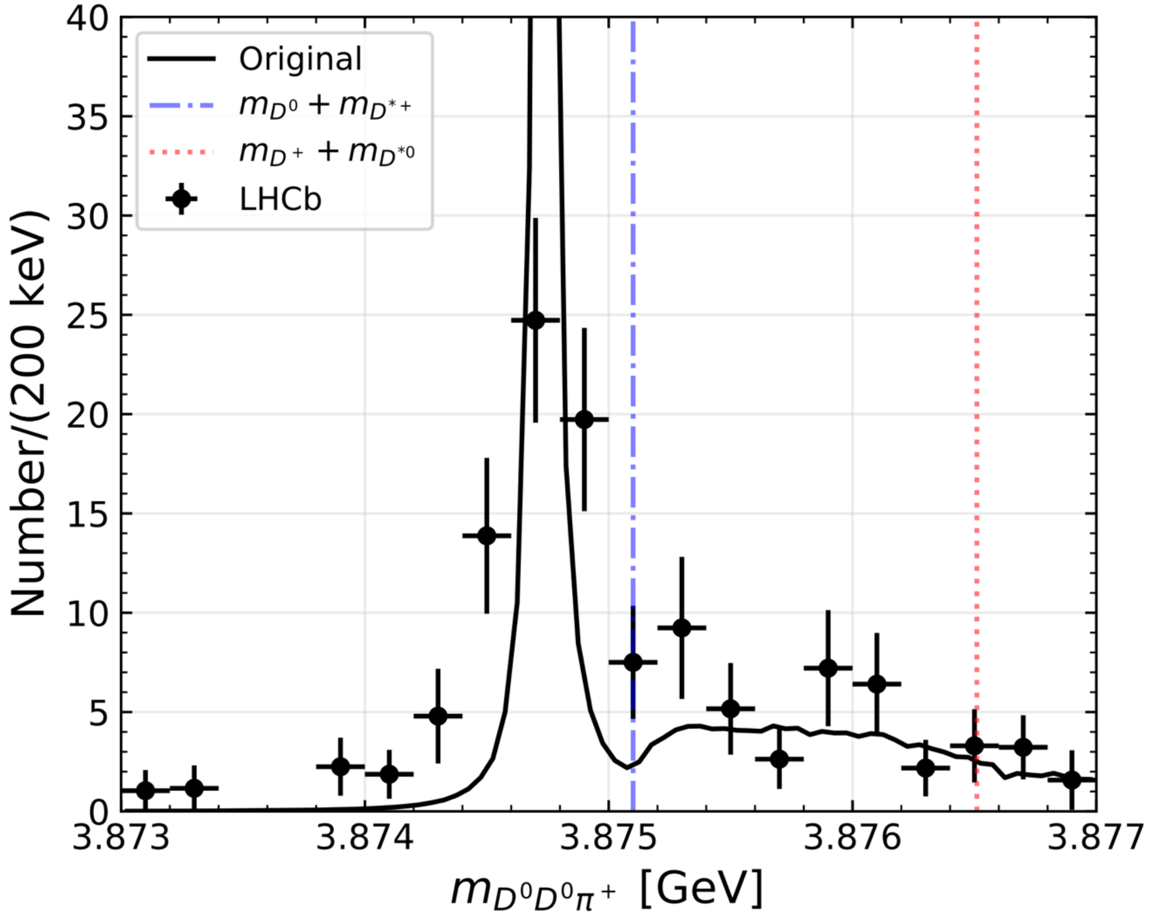
$$\mathcal{V} = (V_\pi + V^t_{\rho/\omega} + V^u_{\rho/\omega})\left(\frac{\Lambda^2}{\Lambda^2+p_f^2}\right)^2\left(\frac{\Lambda^2}{\Lambda^2+p_i^2}\right)^2$$

Fitting result and T_{cc} properties

χ^2/dof =0.76



Without resolution function



- 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$^*(I=1)$

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

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

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

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

- 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:

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

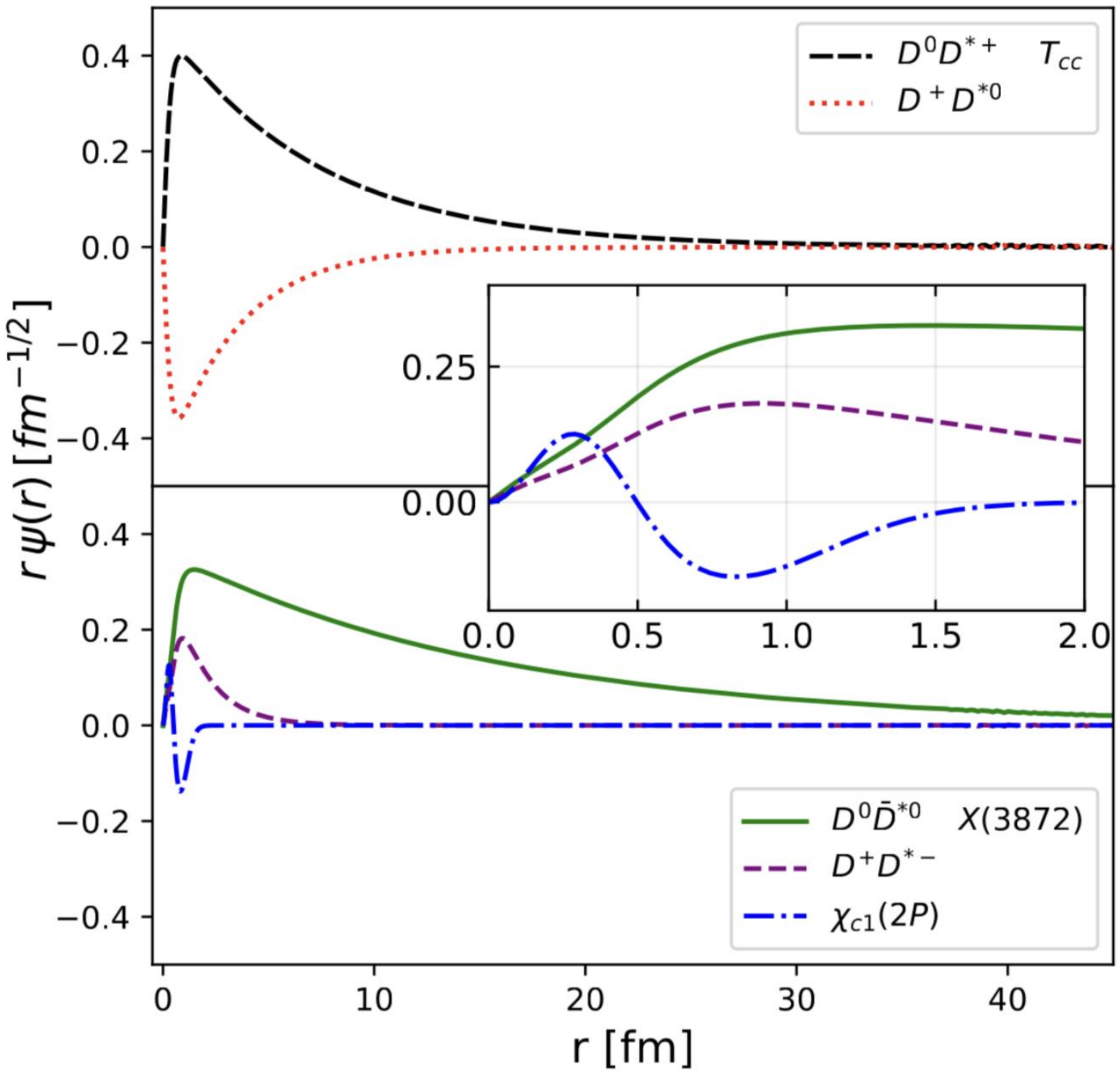
$I_{D\bar{D}^*,cc}(|\vec{k}_{D\bar{D}^*}|)$ is the overlap of the meson wave functions $\leftarrow$ GI quark model

- γ is determined to reproduce the $\psi(3770)$
- 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 T_{cc} and $X(3872)$



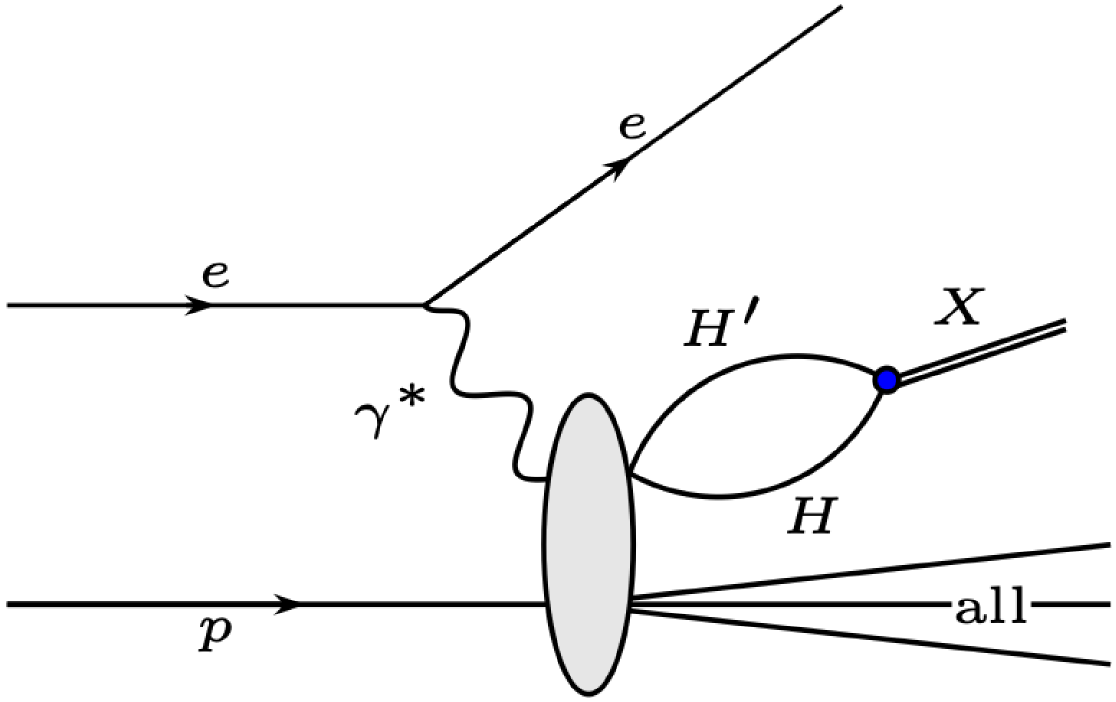
- Long tails for the radius distribution.
- $X(3872)$ has a even longer tails than T_{cc}

✓ $r < 2$ 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 $\sqrt{\langle r^2 \rangle}$.

Production of near-threshold exotic state at EicC



Coalescence Model in pp and heavy ion collider

Cho, Lee, Phys. Rev. C 101, 024902
Yun and Park, Noh, at al, Phys. Rev. C 107, 014906;
Chen, Yang, Chen, Zhao and Liu, Phys. Rev. C 109, 064909;
Wu and Geng, Phys. Rev. D 109, 014006;
Zhang, Liao, Wang, Wang and Xing, Phys. Rev. Lett. 126, 012301

Factorization: $$\mathcal{M}[X+\text{all}] = \mathcal{M}[HH'+\text{all}]\cdot G\cdot T_X,$$

Hadron pair production: $$d\sigma[HH'(k)]_{\text{MC}} = K_{HH'}\frac{1}{\text{flux}}\sum_{\text{all}}\int d\phi_{HH'+\text{all}}\left|\mathcal{M}[HH'+\text{all}]\right|^2\frac{d^3k}{(2\pi)^3 2\mu},$$

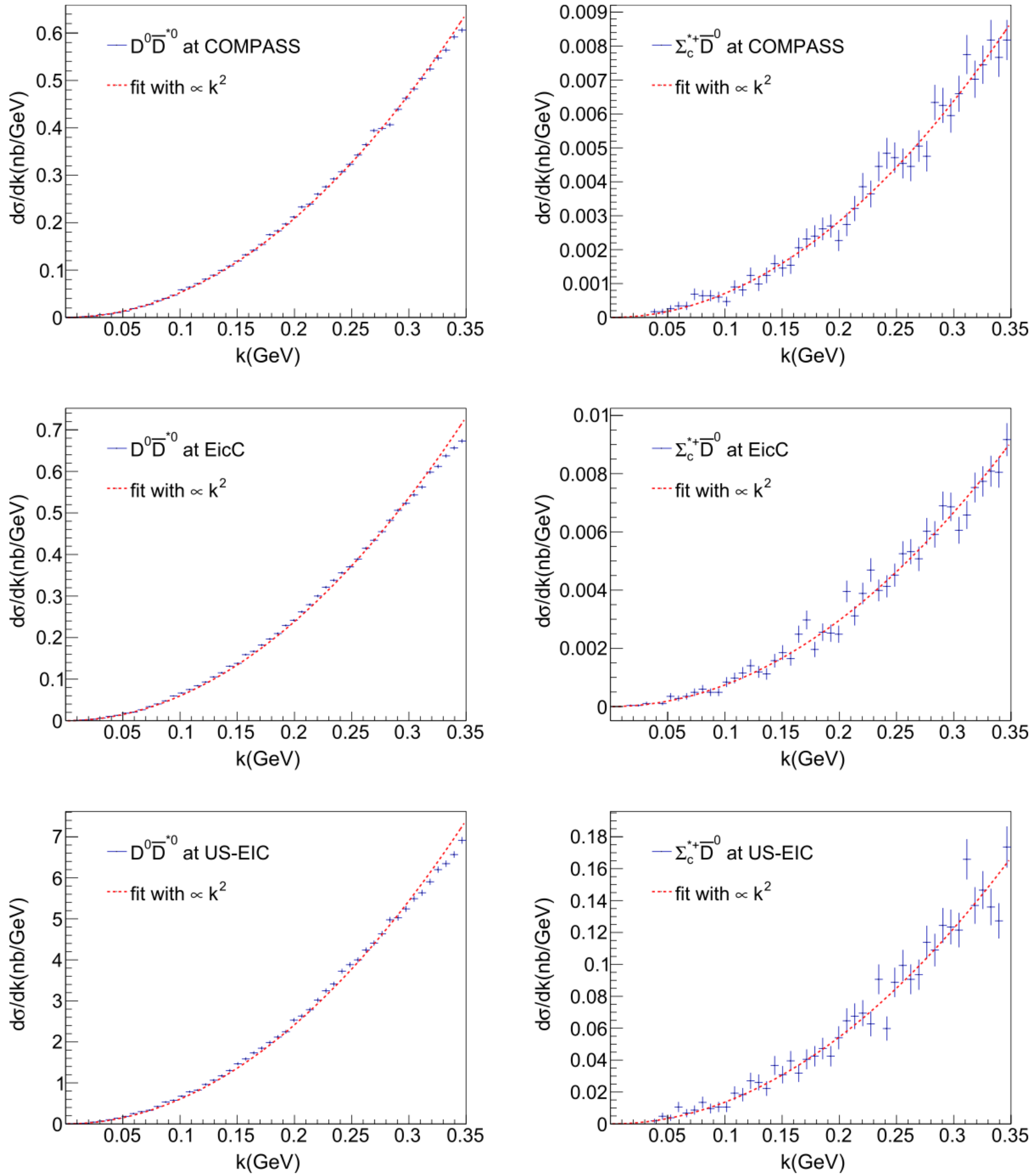
Molecule production: $$\sigma[X+\text{all}] \simeq \frac{\mathcal{N}}{4m_H m_{H'}}\left|GT_X\right|^2\left(\frac{d\sigma[HH'+\text{all}]}{dk}\right)_{\text{MC}}\frac{4\pi^2\mu}{k^2},$$

Yang, Guo, Chin.Phys.C 45 (2021) 12, 123101
Shi, Guo, Yang, Phys.Rev.D 106 (2022) 11, 114026

Production of near-threshold exotic state at EicC

Hadron pair production:

$$\left(\frac{d\sigma[HH'+\text{all}]}{dk}\right)_{\text{MC}} \propto k^2$$



Production of near-threshold exotic state at EicC

cross sections (in units of pb)

	Constituents	EicC	US-EIC
$X(3872)$	$D\bar{D}^*$	21(89)	216(904)
$Z_c(3900)^0$	$D\bar{D}^*$	$0.4\times10^3(1.3\times10^3)$	$3.8\times10^3(14\times10^3)$
$Z_c(3900)^+$	$D^{*+}\bar{D}^0$	$0.3\times10^3(1.0\times10^3)$	$2.7\times10^3(9.9\times10^3)$
$Z_c(4020)^0$	$D^*\bar{D}^*$	$0.2\times10^3(0.6\times10^3)$	$1.7\times10^3(6.3\times10^3)$
Z_{cs}^-	$D^{*0}D_s^-$	19(69)	253(901)
Z_{cs}^{*-}	$D^{*0}D_s^{*-}$	14(51)	192(679)
$P_c(4312)$	$\Sigma_c\bar{D}$	0.8(4.1)	15(73)
$P_c(4440)$	$\Sigma_c\bar{D}^*$	0.7(4.7)	11(79)
$P_c(4457)$	$\Sigma_c\bar{D}^*$	0.6(2.2)	9.9(36)
$P_c(4380)$	$\Sigma_c^*\bar{D}$	1.6(8.4)	30(155)
$P_c(4524)$	$\Sigma_c^*\bar{D}^*$	0.8(3.9)	14(67)
$P_c(4518)$	$\Sigma_c^*\bar{D}^*$	1.2(6.9)	22(123)
$P_c(4498)$	$\Sigma_c^*\bar{D}^*$	1.2(9.8)	21(173)

$X(3872)$ per day	EicC (2×10^{33})	US-EIC (10^{34})
production	8×10^3	4×10^5
detection	20	1000

$\mathcal{B}(X(3872)\to J/\psi\pi\pi) = (3.8\pm1.2)\%$, $\mathcal{B}(J/\psi\to l^+l^-) = 12\%$ and assume the detection efficiency of 50%

Summary

- A coupled-channel framework is necessary to study the components and pole masses of the physical $D_s(2317)$, $D_s(2460)$, and $X(3872)$.

- Combined studies on the mass spectrum and production is difficult so far.

- An order-of-magnitude estimation of exotic state production has been performed at EicC. EicC can produce a large number of events for the near-threshold hidden-charm molecular states.

Thank you !