Search for $D\bar{D}$ bound state

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Outline

- Motivation
- $e^+e^- \to J/\psi D\bar{D}$ (EPJA57(2021)38)
- $\gamma\gamma \to D\bar{D}$ (PRD103(2021)054008)
- $\Lambda_\mathrm{b} \to D\bar{D}\Lambda$ (PRD103(2021)114013)
- $B^- \to K^-\eta\eta_c$(PRD109(2024)094014)
- Summary

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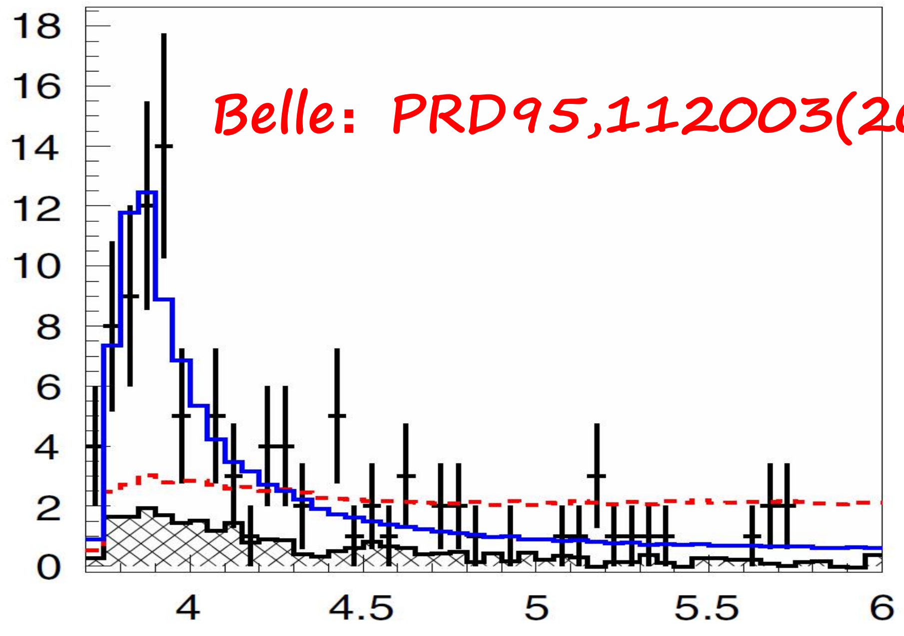
Belle: $e^+e^- \to J/\psi D\bar{D}$

$\chi_{c0}(3860)$ $\quad I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

The assignment $J^P = 0^+$ is preferred over 2^+ by 2.5 sigma.

Observed by CHILIKIN 17 using full amplitude analysis of the process $e^+e^- \to J/\psi D\bar{D}$, where $D = D^0$, D^+.



The X^* signal is described by the Breit-Wigner amplitude,

$$A_{X^*}(M) = \left(\frac{p(M)}{p(m)}\right)^L \frac{F_L(M)}{m^2 - M^2 - im\Gamma(M)}, \quad (11)$$

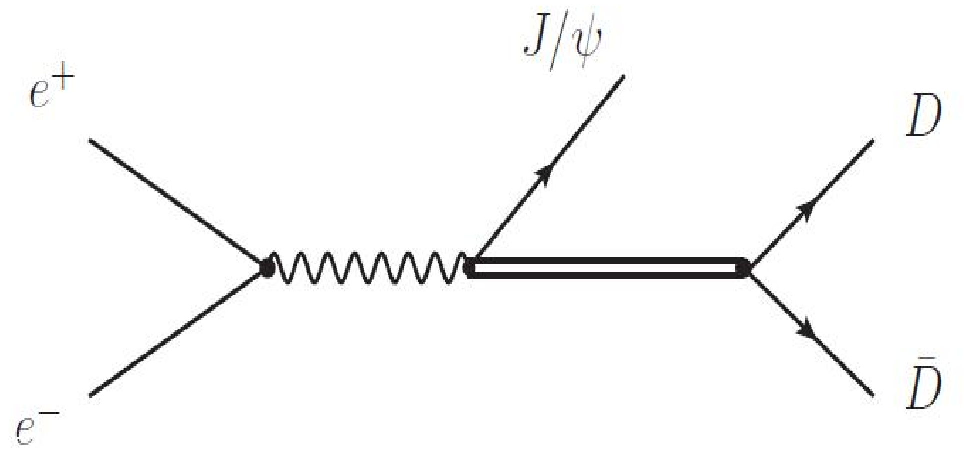
J^{PC}	Mass, MeV/c^2	Width, MeV	Significance
0^{++}	3862^{+26}_{-32}	201^{+154}_{-67}	9.1σ
2^{++}	3879^{+20}_{-17}	171^{+129}_{-62}	8.0σ
2^{++}	3879^{+17}_{-17}	148^{+108}_{-50}	8.0σ
2^{++}	3883^{+26}_{-24}	227^{+201}_{-125}	8.0σ

The results are presented in Table VI. The $J^{PC} = 0^{++}$ hypothesis is favored over the 2^{++} hypothesis at the level of 2.5σ.

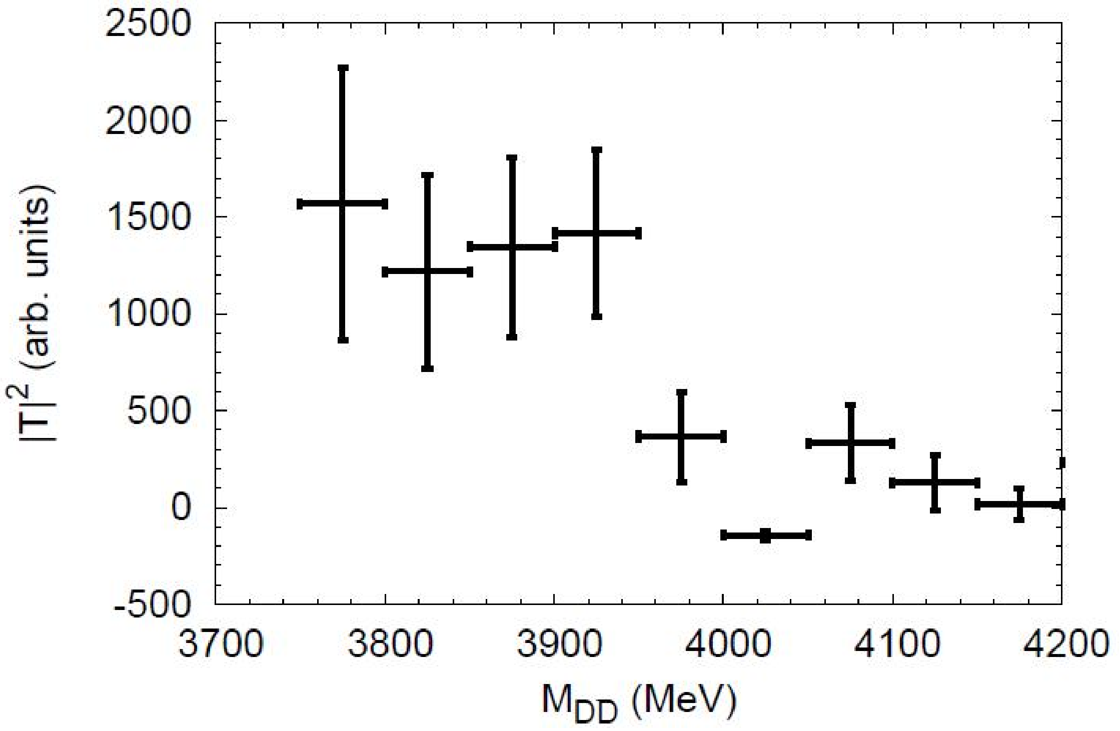
Production of New Charmoniumlike States in $e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}$ at $\sqrt{s} \approx 10.6$ GeV

P. Pakhlov *et al.* (Belle Collaboration)
Phys. Rev. Lett. **100**, 202001 – Published 19 May 2008

Belle: $e^+e^- \to J/\psi D\bar{D}$



$$\frac{d\sigma}{dM_{\text{inv}}(D\bar{D})} = \mathcal{C}\,\frac{1}{(2\pi)^3}\,\frac{m_e^2}{s\sqrt{s}}\,|\vec{p}|\,|\tilde{k}|\,|T|^2,$$



No significant signal around 3860MeV!!!

$\chi_{c0}(1P)$ & $\chi_{c0}(2P)$

$c\,\bar{c}$ MESONS
(including possibly non- $q\,\bar{q}$ states)

$\chi_{c0}(1P)$ $\quad I^G(J^{PC}) = 0^+(0^{++})$

$\chi_{c0}(1P)$ MASS	3414.71 ± 0.30 MeV
$\chi_{c0}(1P)$ WIDTH	10.8 ± 0.6 MeV

$c\,\bar{c}$ MESONS
(including possibly non- $q\,\bar{q}$ states)

INSPIRE se

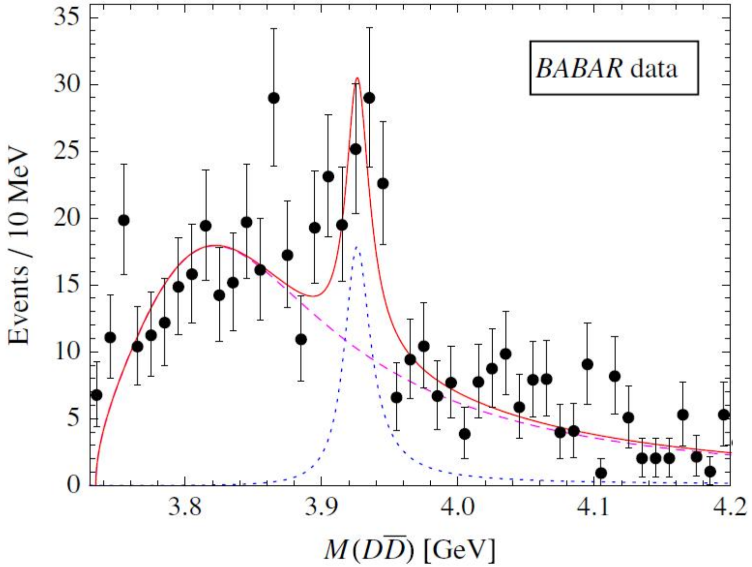
$\boldsymbol{X}(3915)$ $\quad I^G(J^{PC}) = 0^+(0 or 2^{++})$

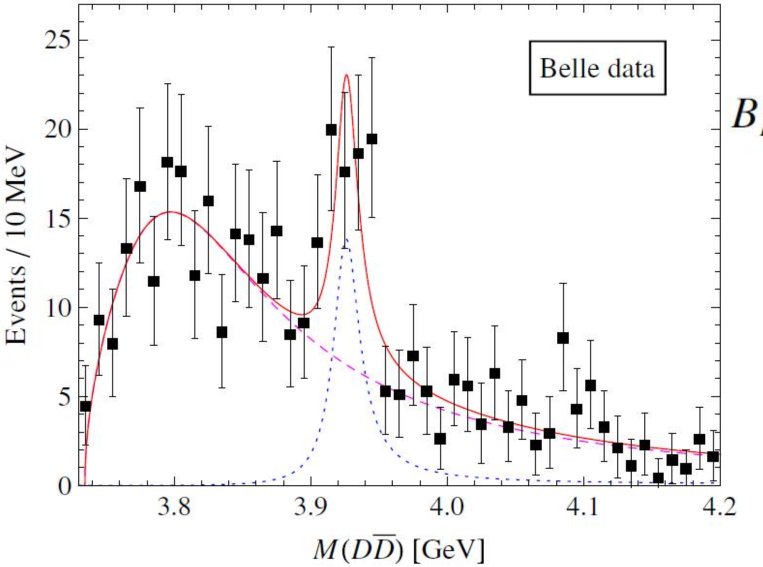
was $\chi_{c0}(3915)$

The experimental analysis prefers $J^{PC} = 0^{++}$. However, a reanalysis presented in ZHOU 2015C shows that if helicity-2 dominance assumption is abandoned and a sizable helicity-0 component is allowed, a $J^{PC} = 2^{++}$ assignment is possible.

$X(3915)$ MASS	3918.4 ± 1.9 MeV
$X(3915)$ WIDTH	20 ± 5 MeV (S = 1.1)

Belle&BABAR: $\gamma\gamma \to D\bar{D}$





$$B_L(w) = \left(\frac{p}{p_0}\right)^{2L+1} \frac{M}{w} \frac{F_L^2(w)}{(w^2 - M^2)^2 + \Gamma^2(w)M^2}$$

$$M_{\chi_{c0}(2P)} = (3837.6 \pm 11.5)\ \mathrm{MeV},$$

$$\Gamma_{\chi_{c0}(2P)} = (221 \pm 19)\ \mathrm{MeV}.$$

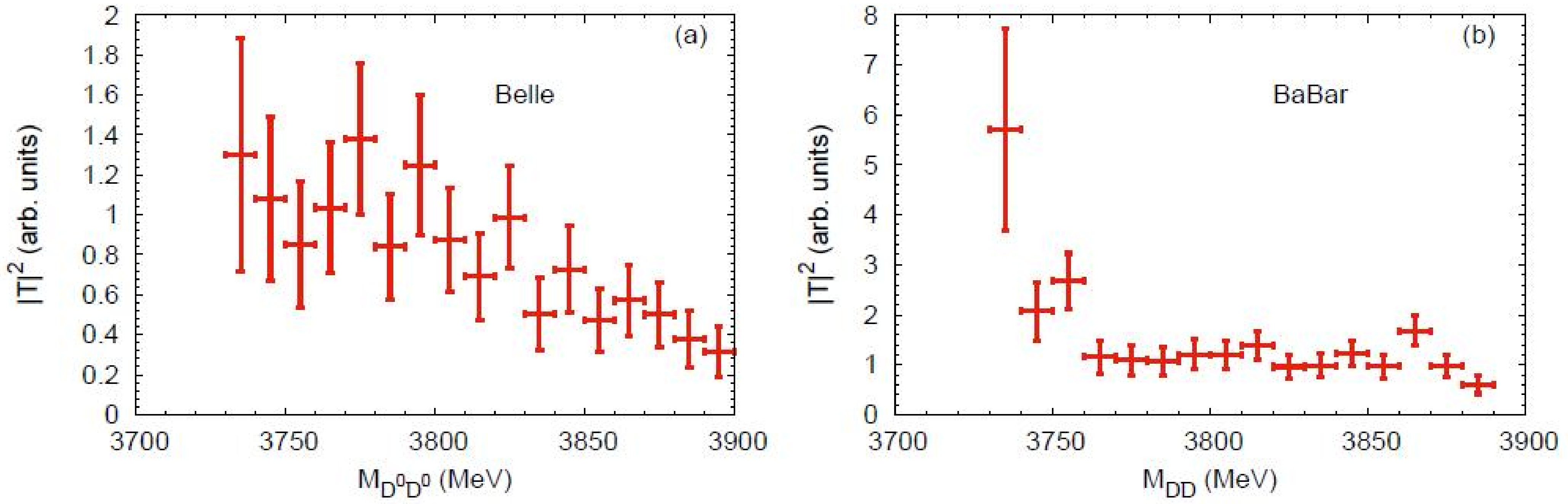
PHYSICAL REVIEW D **86,** 091501(R) (2012)

Where is the $\chi_{c0}(2P)$?

Feng-Kun Guo[1,*] and Ulf-G. Meißner[1,2,†]

$X(3915)$ is probably of exotic nature. There is an indication that the present data of the $\gamma\gamma \to D\bar{D}$ process already contain signals of the $\chi_{c0}(2P)$ with a mass and width around 3840 and 200 MeV, respectively. More refined analysis of the data with higher statistics is definitely necessary to confirm our assertion. In addition to the

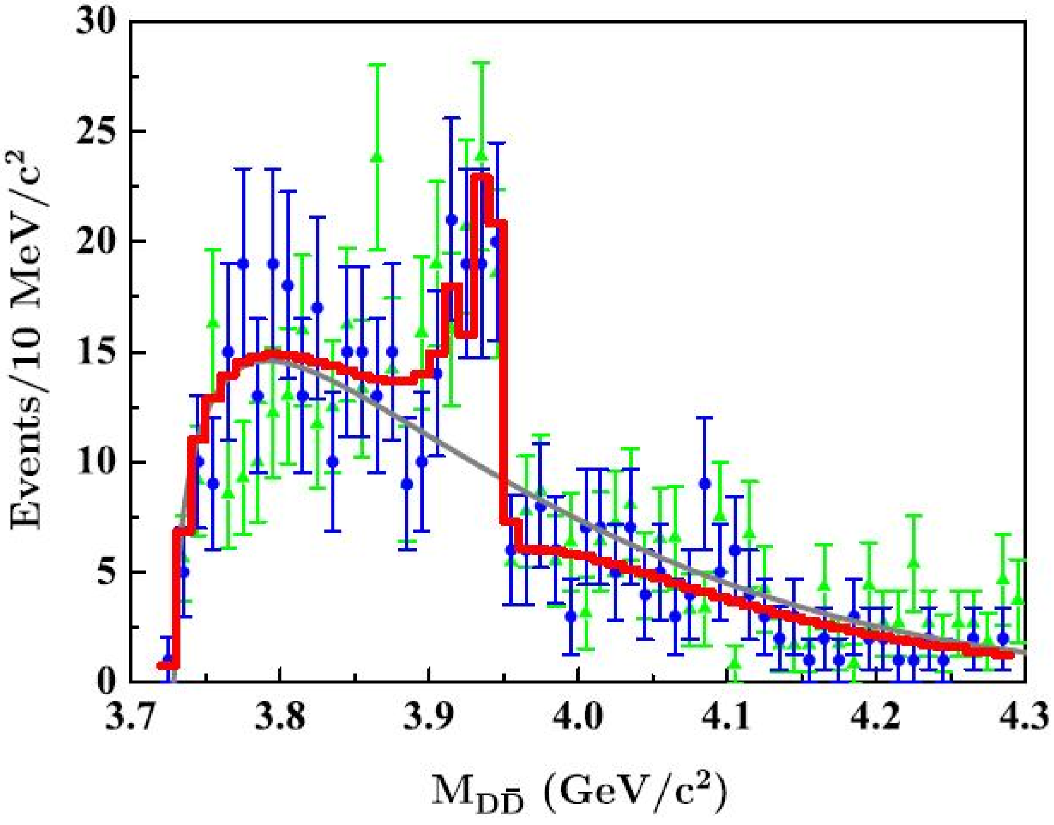
Belle&BABAR:$\gamma\gamma \to D\bar{D}$



$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2}\frac{1}{s}\frac{|\vec{p}'|}{|\vec{p}|}\bar{\sum}|\mathcal{M}|^2$$

No significant signal around 3840MeV!!!

Belle&BABAR:$\gamma\gamma \to D\bar{D}$



Eur. Phys. J. C (2012) 72:2226
DOI 10.1140/epjc/s10052-012-2226-4

THE EUROPEAN PHYSICAL JOUR

Regular Article - Theoretical Physics

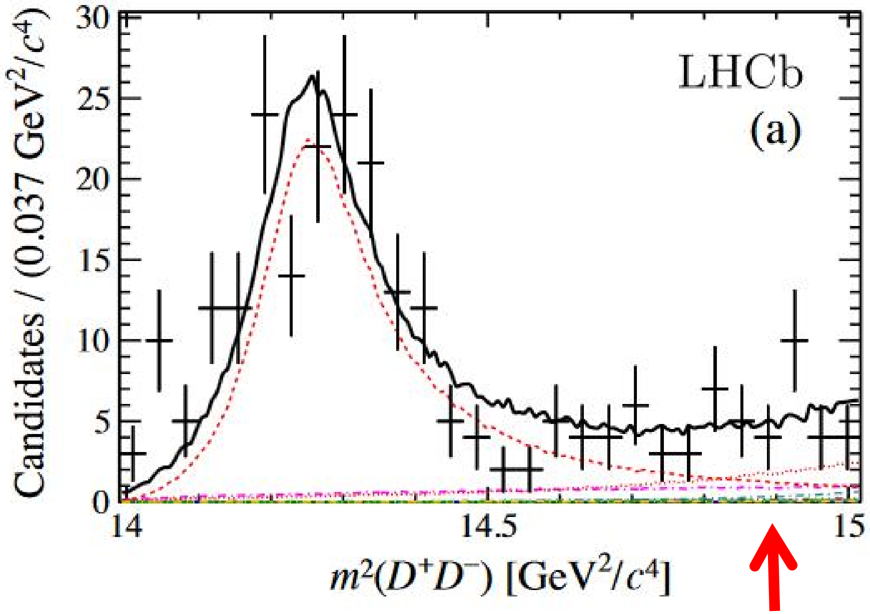
Does the enhancement observed in $\gamma\gamma \to D\bar{D}$ contain two P-wave higher charmonia?

Dian-Yong Chen[1,3,a], Jun He[1,3,b], Xiang Liu[1,2,c], Takayuki Matsuki[4,d]

$\cos\theta^*$ distribution of $\gamma\gamma \to D\bar{D}$. Our study has illustrated that the experimental data of these quantities can be well reproduced when considering both $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$ in the $\gamma\gamma \to D\bar{D}$ process, which supports our conjecture of $Z(3930)$ structure. As indicated in Ref. [13], BaBar is carrying out the spin–parity analysis of $X(3915)$, which will be helpful to clarify whether it is suitable to explain $X(3915)$ as P-wave higher charmonium $\chi_{c0}(2P)$.

LHCb: $B^+ \to D^+ D^- h$

- **No evidence of the $\chi_{c0}(3860)$ in the $B^+ \to D^+ D^- h$**
- **LHCb,PRD102(2020)112003,PRL125(2020)242001**
- **A large strength of observed at the $D\bar{D}$ threshold.**



S wave in the baseline model. The broad $\chi_{c0}(3860)$ state reported by the Belle Collaboration [53] has been included in alternative fit models but is disfavored. Fits in which

Citation: S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)

$\boxed{\chi_{c0}(3860)}$ $\qquad I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

The assignment $J^P = 0^+$ is preferred over 2^+ by 2.5 sigma.

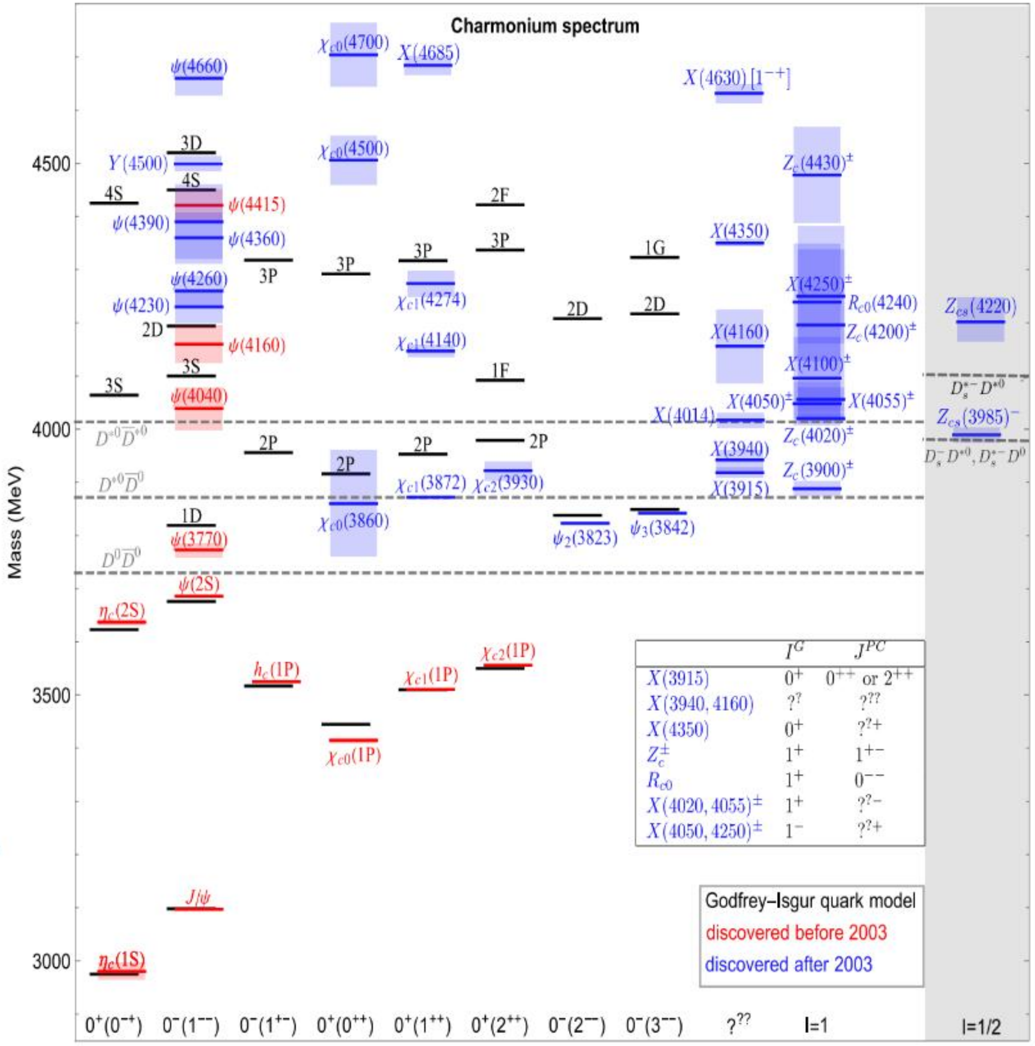
Observed by CHILIKIN 17 using full amplitude analysis of the process $e^+e^- \to J/\psi D\bar{D}$, where $D = D^0$, D^+. Not seen by AAIJ 20AI in the decay $B^+ \to D^+D^-K^+$.

Theoretical predictions for $\chi_{c0}(2P)$

- **3.92 GeV,** Godfrey-Isgur, PRD32(1985)189
- **3852 MeV(NR,LP), 3916MeV(GI),** Barnes-Godfrey-Swason, PRD72(2005)054026
- **3842 MeV, screening potentials,** BQLi-KTChao, PRD79(2009)094004
- **3869 MeV (LP), 3848MeV(SP), new paras,** WJDeng-Gui-Zhong,PRD95(2017)034026
- **Narrow width~20 MeV:** Gui-Lv-Zhong-Zhao, PRD98(2019)016010, Barnes-PRD72(2005)054026， Xiang Liu PRD101(2020)054029

$\chi_{c0}(3860)$ still needs to be confirmed by more experiments.

Theoretical predictions of $D\bar{D}$ states



- $D\bar{D}$, 0^{++}
  - 3700-3730 MeV Nieves, PRD86(2012) 056004, PRD87(2013)076006
  - 3720-3730MeV, Gamermann-Oset, PRD76(2007)074016, EPJA41(2009)85
  - B=4 MeV, LQCD, JHEP06(2021)035
  - 3734 MeV, Dong-Guo-Zou, Progr.Phys.4(2021)45
  - 3739 MeV, PPShi, ZHZhang-FKGuo-ZYang, PRD105(2022) 034024
  - 3.73 GeV HXChen, PRD105(2022)094003
  - ~3730 MeV, FZPeng-MJYan-Pavon, PRD108(2023)114001

Search for the $D\bar{D}$ bound state

- $B \to D\bar{D}K$, Dai-Xie-Oset, EPJC76(2016)121
- $\psi(3770) \to \gamma X(3700) \to \gamma\eta\eta'$, CWXiao-Oset, EPJA49(2013)52
- $\psi(4040) \to \gamma X(3700) \to \gamma\eta\eta'$, CWXiao-Oset, EPJA49(2013)52
- $e^+e^- \to J/\psi X(3700) \to J/\psi\eta\eta'$, CWXiao-Oset, EPJA49(2013)52
- $\Lambda_b \to D\bar{D}\Lambda$, EWang-Xie-DMLi, PRD103(2021)114013
- $B^- \to K^-\eta\eta_c$, Li-Liu-Wang-Wei(PRD109(2024)094014), Xie-Liu-Geng, PRD107(2023)016003
- $B^+ \to K^+\eta\eta$, Brandao-Song-Oset, PRD108 (2023) 054004
- $e^+e^- \to J/\psi D\bar{D}, \gamma\gamma \to D\bar{D}$

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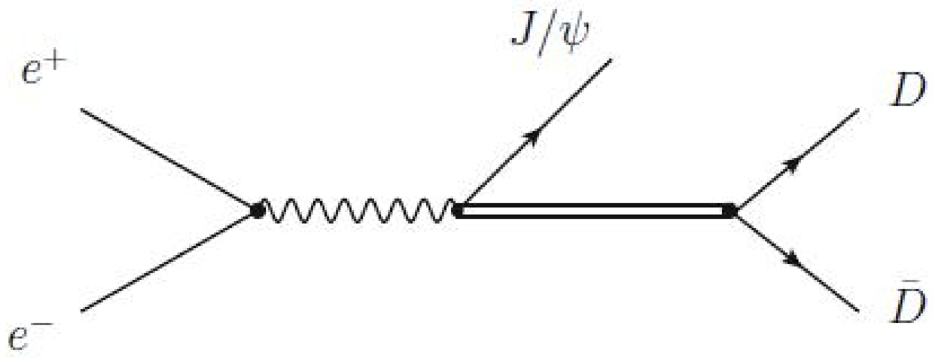
Formalism



$$\frac{\mathrm{d}\sigma}{\mathrm{d}M_{\mathrm{inv}}(D\bar{D})} = \mathcal{C}\,\frac{1}{(2\pi)^3}\,\frac{m_e^2}{s\sqrt{s}}\,|\vec{p}\,|\,|\tilde{k}|\,|T|^2,$$

$$T = [1 - VG]^{-1}\,V,$$

$$\mathcal{L}_{PPV} = -\frac{ig}{\sqrt{2}}\mathrm{Tr}([\partial_\mu \Phi, \Phi]V^\mu).$$

Phys. Rev. D **76**, 074016 (2007)

$$G_{ii} = i\int \frac{dq^4}{(2\pi)^4}\,\frac{1}{q^2 - m_1^2 + i\epsilon}\,\frac{1}{(P-q)^2 - m_2^2 + i\epsilon} = \tag{30}$$

$$\frac{1}{16\pi^2}\Big(\alpha_i + \log\frac{m_1^2}{\mu^2} + \frac{m_2^2 - m_1^2 + s}{2s}\log\frac{m_2^2}{m_1^2} + \frac{p}{\sqrt{s}}$$
$$\times\Big(\log\frac{s - m_2^2 + m_1^2 + 2p\sqrt{s}}{-s + m_2^2 - m_1^2 + 2p\sqrt{s}}$$
$$+ \log\frac{s + m_2^2 - m_1^2 + 2p\sqrt{s}}{-s - m_2^2 + m_1^2 + 2p\sqrt{s}}\Big)\Big). \tag{31}$$

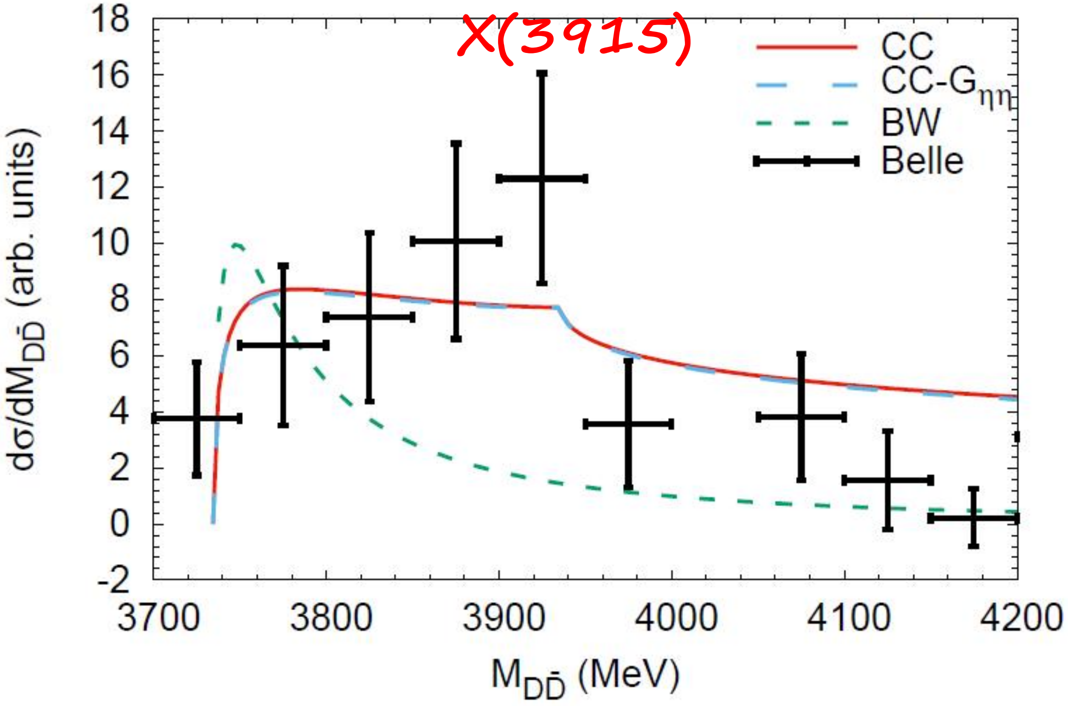
$\alpha = -1.3$

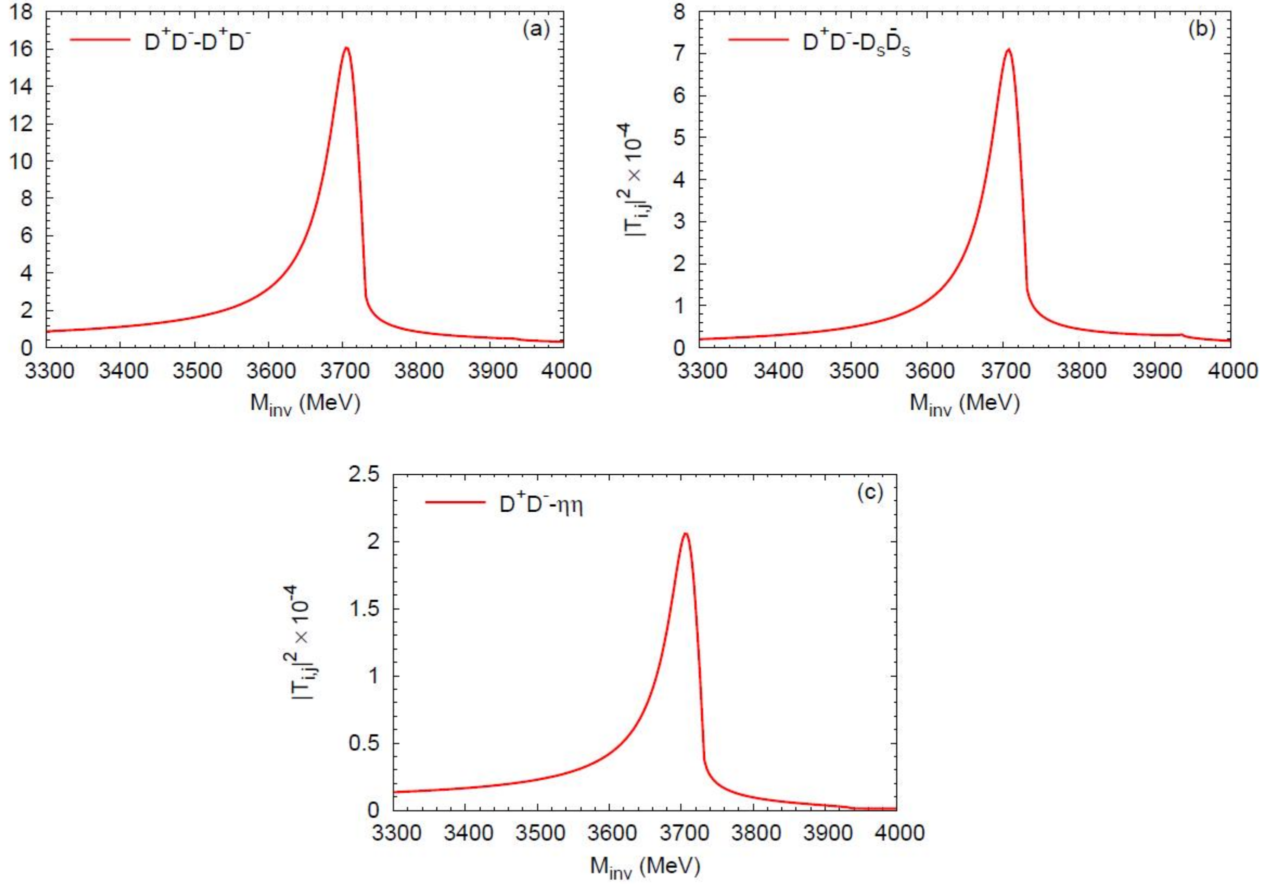
$\mu = 1500$ MeV,

TABLE VI. Residues for the poles in the C = 0, S = 0, I = 0 sector.

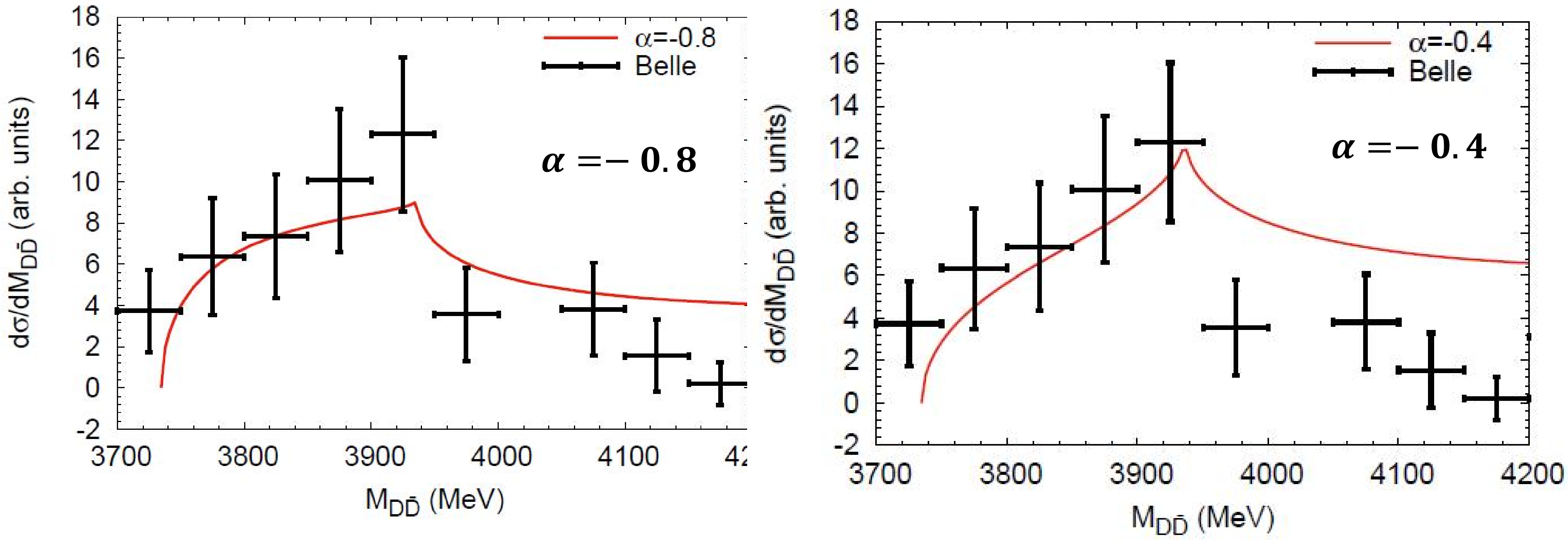
Channel	f_0 (GeV)	σ (GeV)	Heavy singlet (GeV)
$\pi\pi$	1.37	3.00	0.16 ± 0.05
$K\bar{K}$	3.80	1.25	0.05 ± 0.03
$\eta\eta$	3.14	0.36	0.01 ± 0.01
$D\bar{D}$	0.73	4.14	11.44 ± 4.42
$D_s\bar{D}_s$	3.73	0.49	7.55 ± 2.97
$\eta\eta_c$	1.97	0.98	0.12 ± 0.09

Results $\alpha = -1.3$





Results



- **The Belle data could be well described by considering the dynamically generated $D\bar{D}$ bound state in the process $e^+e^- \to J/\psi\, D\bar{D}$.**

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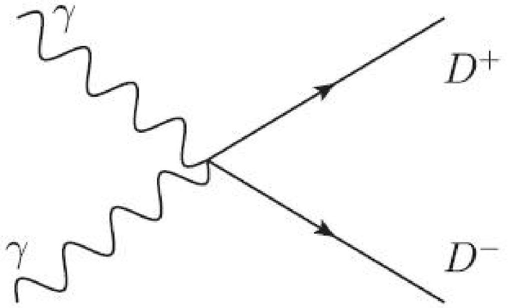
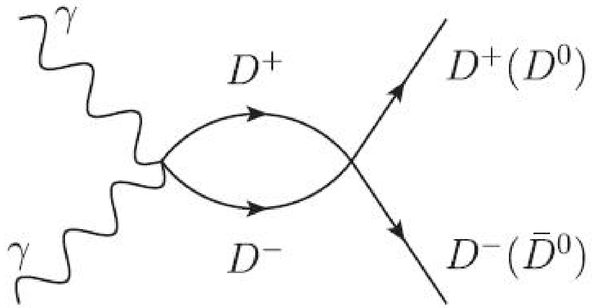
Formalism

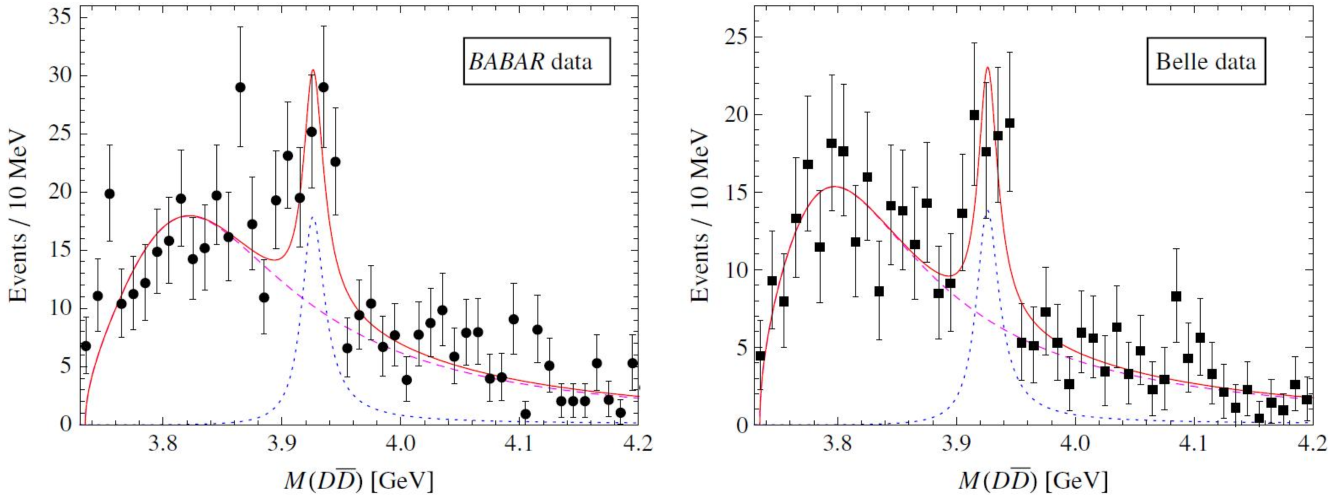
- **Tree diagram+ FSI**



(a)



(b)



$$|t_{\mathrm{Belle}}|^2 = \mathcal{C}_{\mathrm{Belle}} |t_{D^0\bar{D}^0}|^2,$$

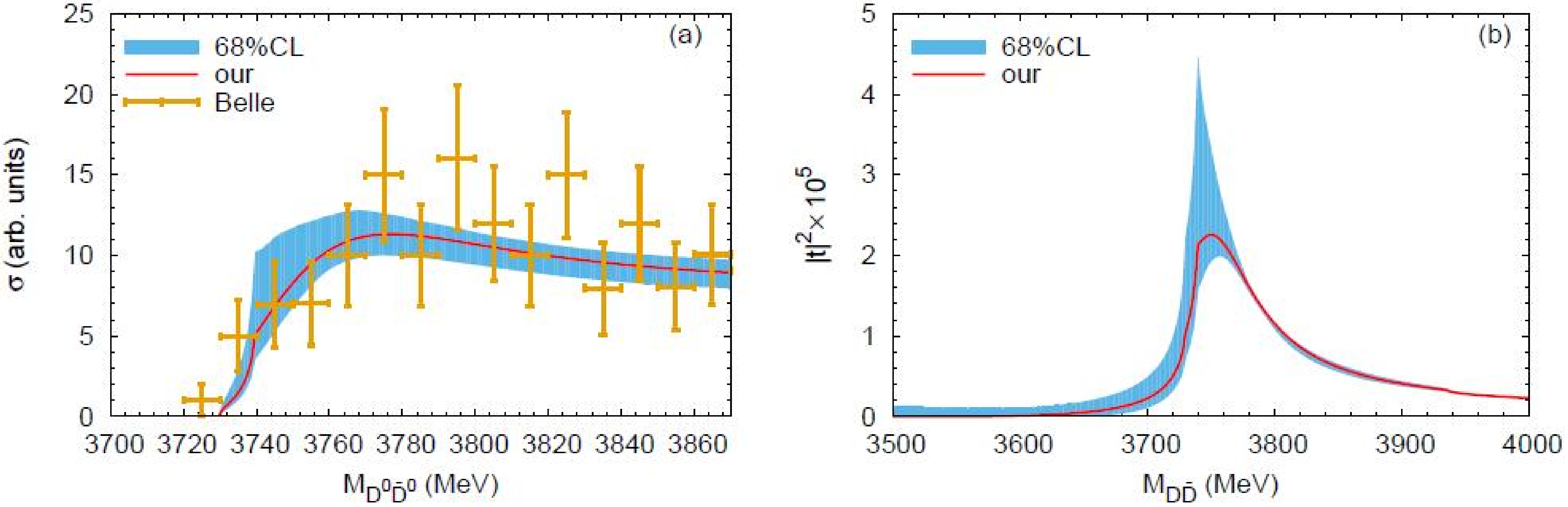
$$|t_{BABAR}|^2 = \mathcal{C}_{BABAR} (|t_{D^0\bar{D}^0}|^2 + B|t_{D^+D^-}|^2),$$

$$\mathcal{M} = 2e^2 \vec{\epsilon}_1 \cdot \vec{\epsilon}_2 \times t,$$

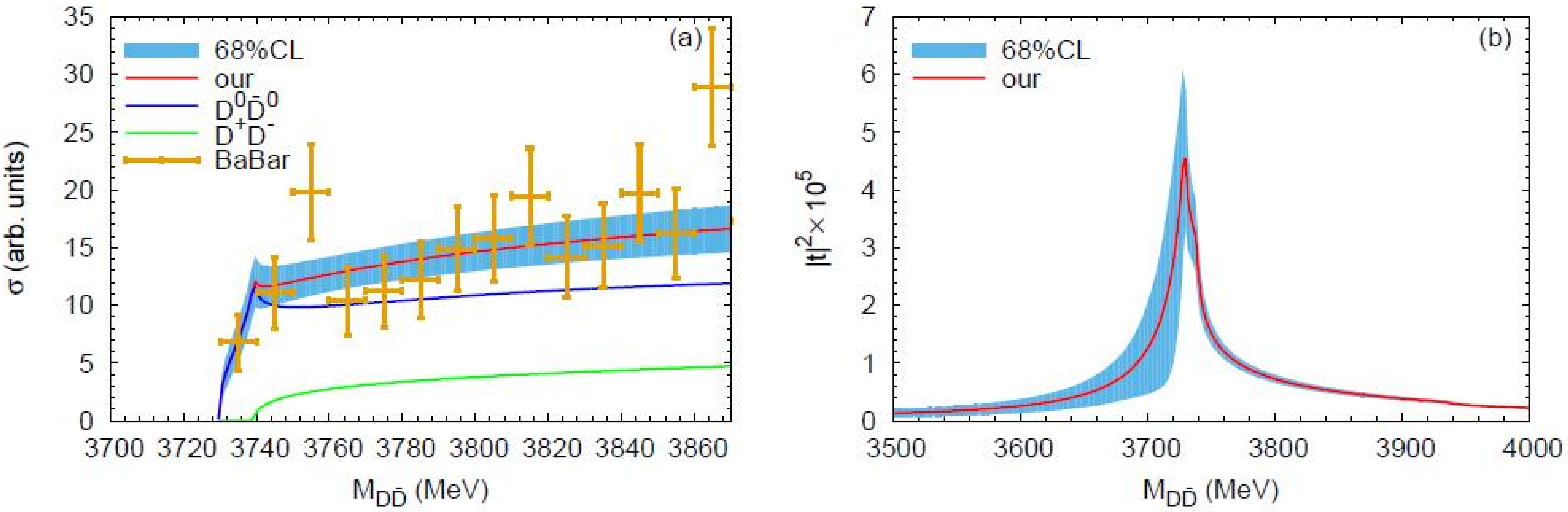
$$t_{D^+D^-} = \left(1 + \frac{1}{2} G_{D^+D^-} t^{I=0}_{D\bar{D},D\bar{D}}\right),$$

$$t_{D^0\bar{D}^0} = \frac{1}{2} G_{D^+D^-} t^{I=0}_{D\bar{D},D\bar{D}}.$$

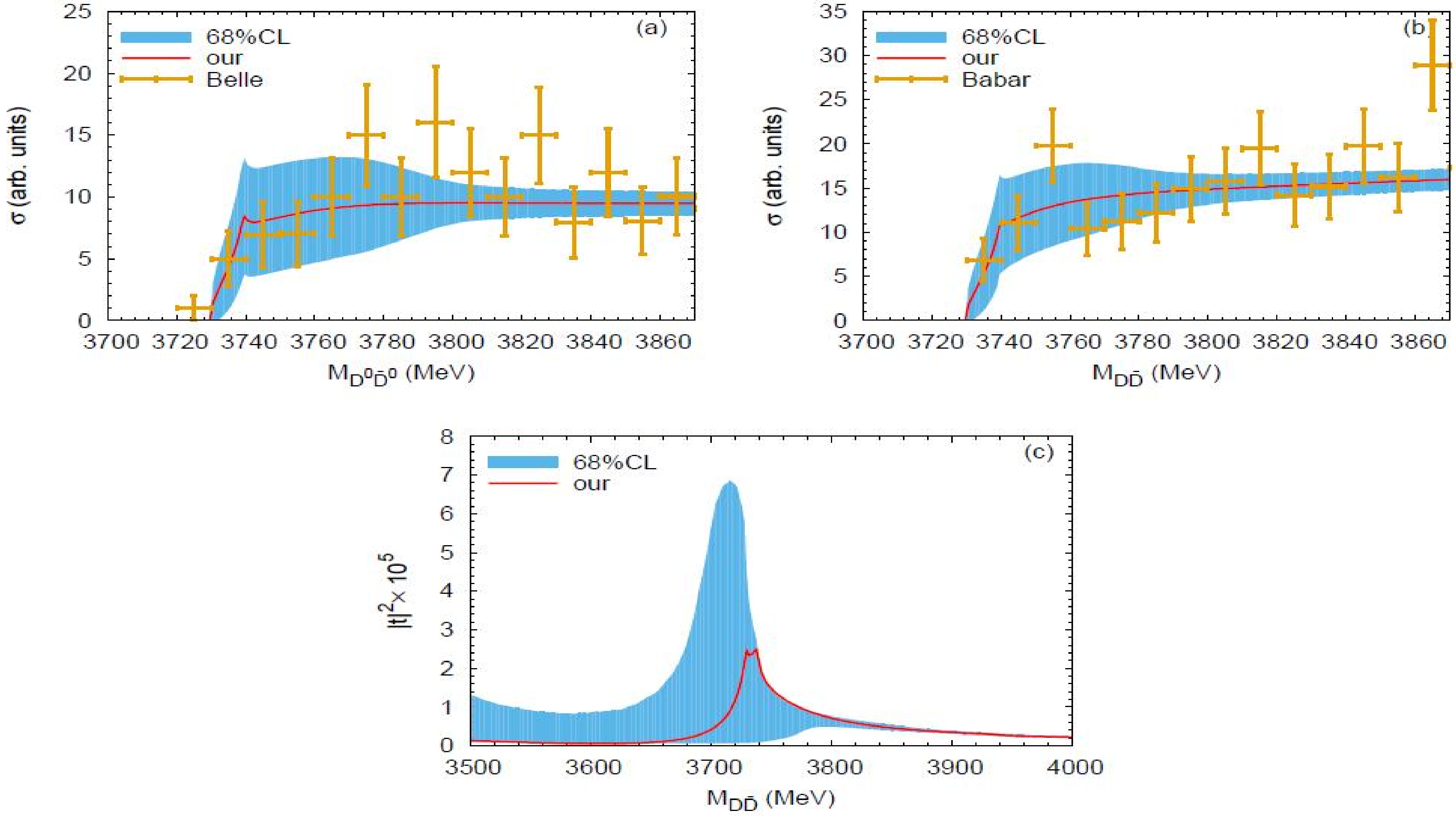
Fit A-only Belle



Fit B-only BABAR



Fit C-Both Belle and BABAR



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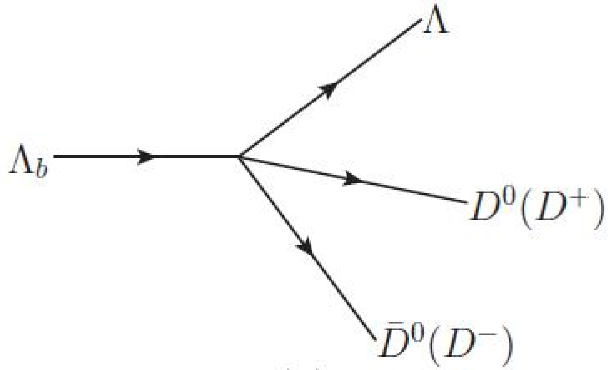
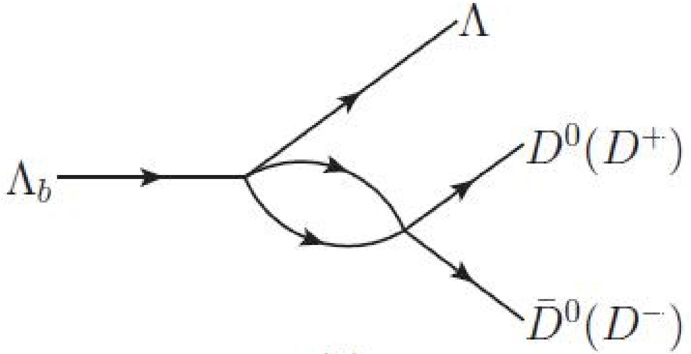
$\boldsymbol{\Lambda_b \to D\bar{D}\Lambda}$

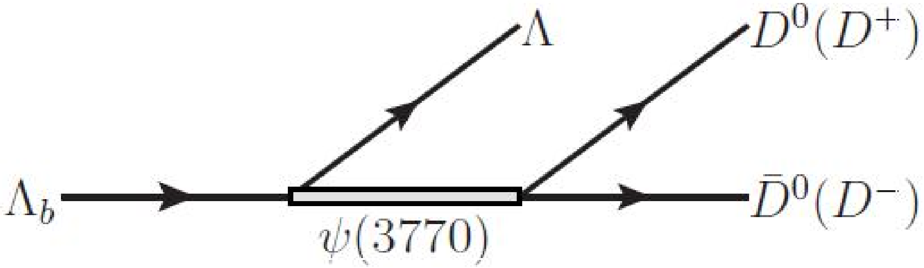


(a)



(b)

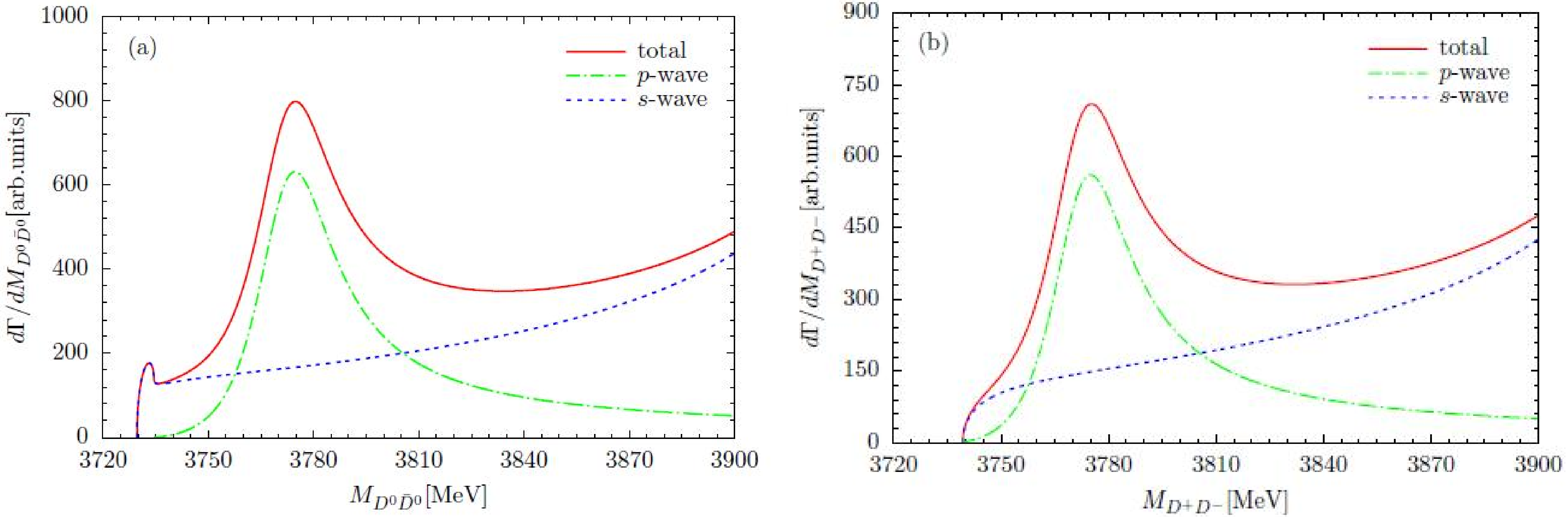
$$
\begin{aligned}
t^{s\text{-wave}}_{\Lambda_b\to\Lambda D^0\bar{D}^0} &= V_p\,[1 + G_{D^+D^-}t_{D^+D^-\to D^0\bar{D}^0} \\
&\quad + G_{D^0\bar{D}^0}t_{D^0\bar{D}^0\to D^0\bar{D}^0} \\
&\quad + (1+C)G_{D_s^+D_s^-}t_{D_s^+D_s^-\to D^0\bar{D}^0}\Big], \\
t^{s\text{-wave}}_{\Lambda_b\to\Lambda D^+D^-} &= V_p\,[1 + G_{D^+D^-}t_{D^+D^-\to D^+D^-} \\
&\quad + G_{D^0\bar{D}^0}t_{D^0\bar{D}^0\to D^+D^-} \\
&\quad + (1+C)G_{D_s^+D_s^-}t_{D_s^+D_s^-\to D^+D^-}\Big],
\end{aligned}
$$



$$
t^{p\text{-wave}} = \frac{\beta V_p \times M_{\psi(3770)}\tilde{p}_D}{M^2_{D\bar{D}} - M^2_{\psi(3770)} + iM_{\psi(3770)}\tilde{\Gamma}_{\psi(3770)}},
$$

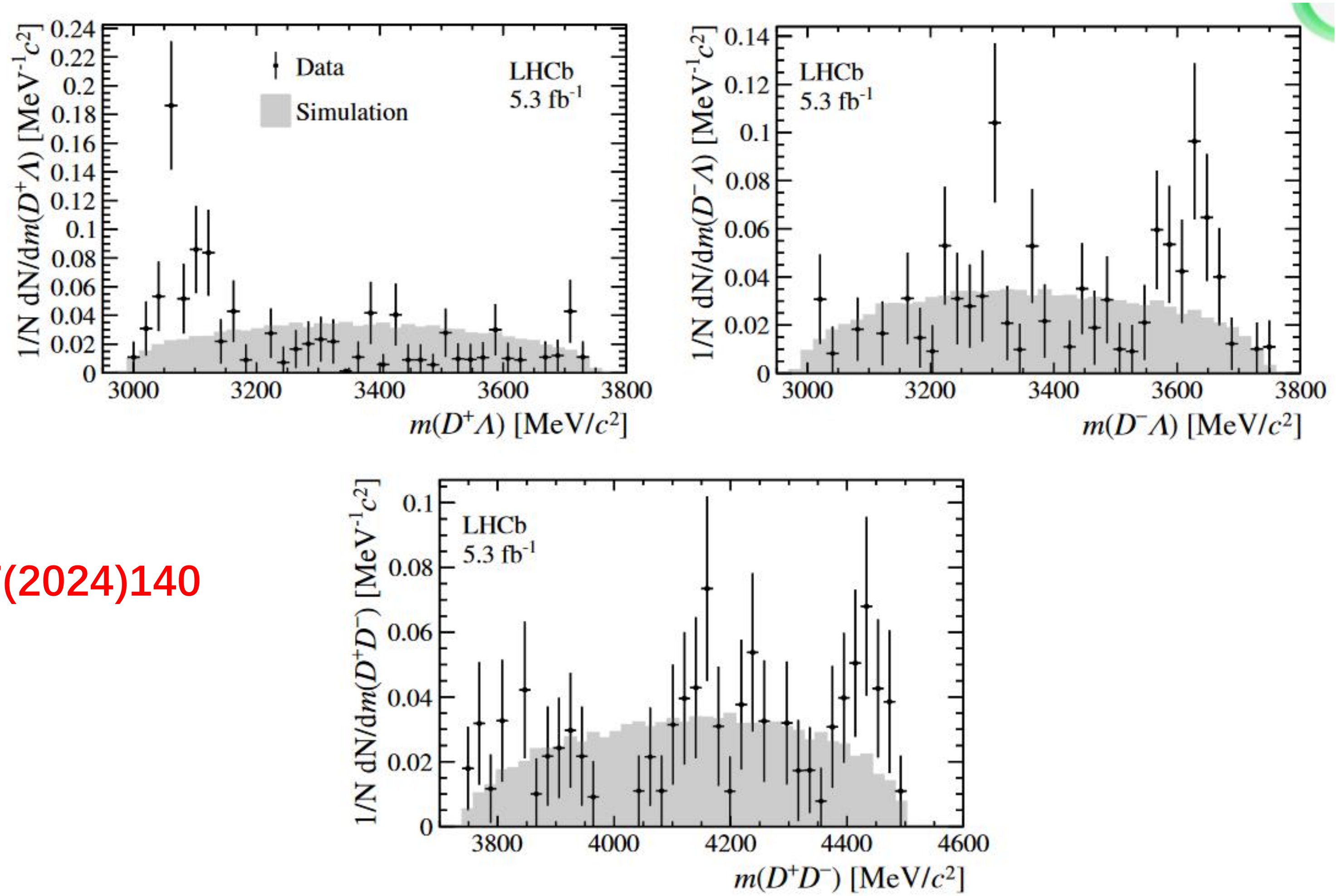
Results

□ $M(D^+D^-) = 3739$ **MeV,** $M(D^0\overline{D}^0) = 3730$ **MeV**



The enhancement near the $D^0\overline{D}^0$ threshold is more significant.

LHCb measurements about $\Lambda_b \to D\bar{D}\Lambda$



JHEP07(2024)140

$$\mathcal{B}(\Lambda_b^0 \to D^+ D^- \Lambda) = (1.24 \pm 0.15 \pm 0.10 \pm 0.28 \pm 0.11) \times 10^{-4}$$

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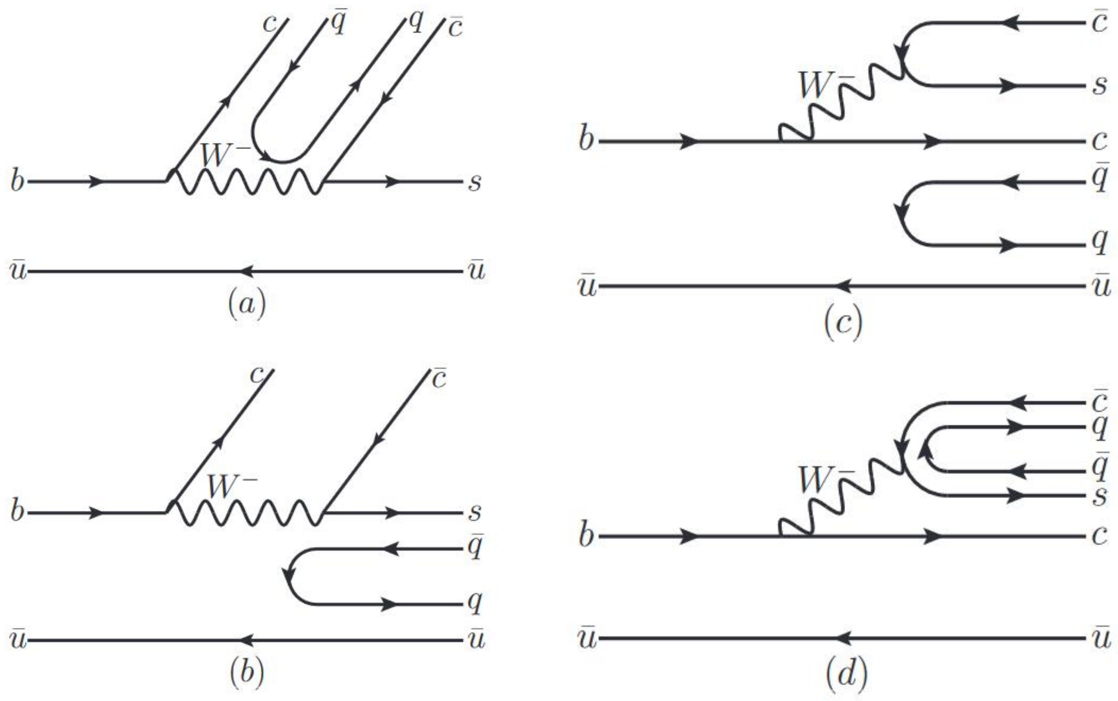
$B^- \to K^-\eta\eta_c$

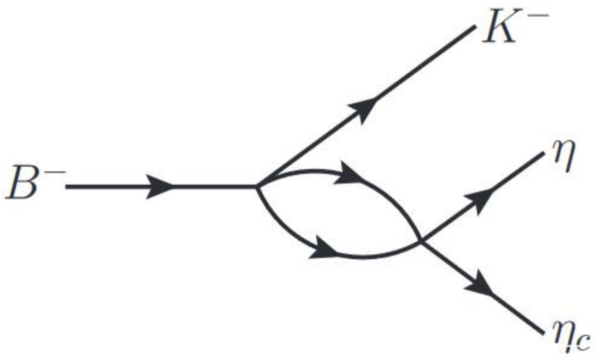
□Quark level diagrams

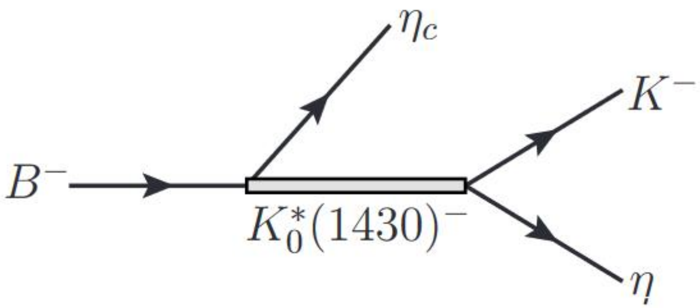


$$
\begin{aligned}
|H\rangle^{\mathrm{a}} &= V_p V_{cb} V_{cs}^{*} c(\bar{u}u + \bar{d}d + \bar{s}s)\bar{c}s\bar{u} \\
&= V_p V_{cb} V_{cs}^{*} \left(M^2\right)_{44} K^- \\
&= V_p V_{cb} V_{cs}^{*} \left(D^0 \bar{D}^0 + D^+ D^- + D_s^+ D_s^-\right) K^-, \\
|H\rangle^{\mathrm{b}} &= V_p V_{cb} V_{cs} c\bar{c}s(\bar{u}u + \bar{d}d + \bar{s}s)\bar{u} \\
&= V_p V_{cb} V_{cs}^{*} \left(M^2\right)_{31} \eta_c \\
&= V_p V_{cb} V_{cs}^{*} \left(\frac{1}{\sqrt{2}} K^- \pi^0 + \frac{3}{\sqrt{6}} K^- \eta'\right) \eta_c,
\end{aligned}
$$

$$
\begin{aligned}
|H\rangle^{\mathrm{c}} &= V_p V_{cb} V_{cs}^{*} \times C \times \left(K^- D_s^+\right) D_s^-, \\
|H\rangle^{\mathrm{d}} &= V_p V_{cb} V_{cs}^{*} \times C \times \left(K^- \bar{D}^0\right) D^0,
\end{aligned}
$$

☐Final state interactions



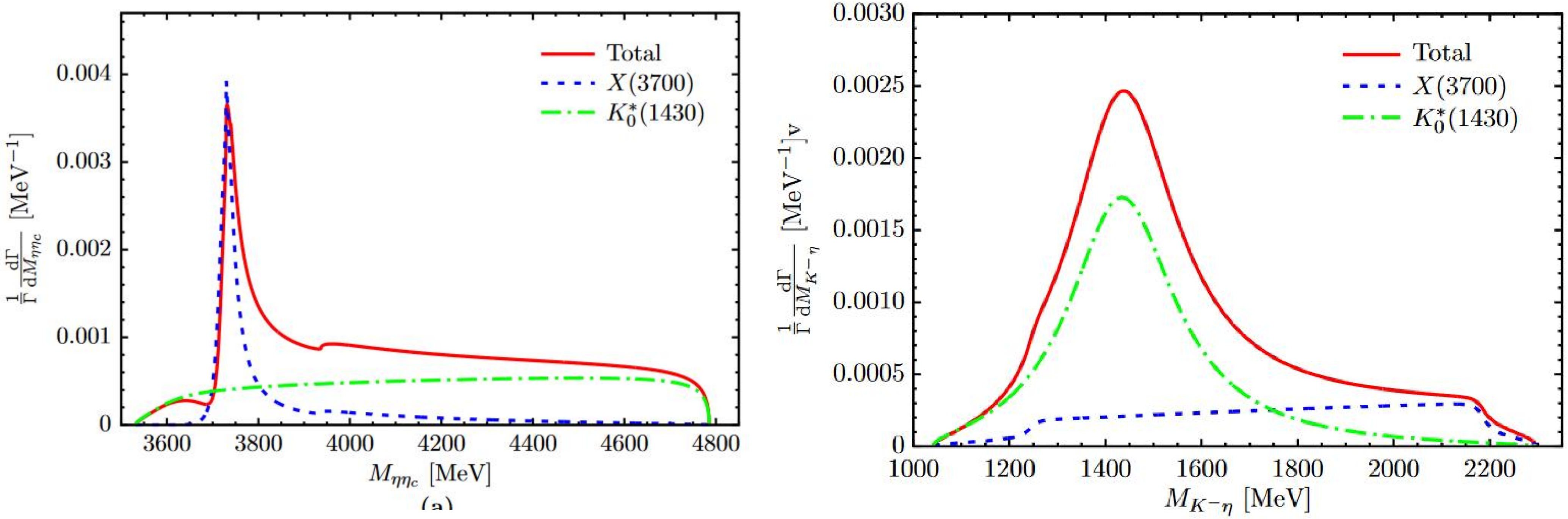


$$
\begin{aligned}
\mathcal{T}_X = V_p V_{cb} V_{cs}^* \Big[& G_{D^+D^-}\, t_{D^+D^-\to\eta\eta_c} \\
& + (1+C)\times G_{D^0\bar{D}^0}\, t_{D^0\bar{D}^0\to\eta\eta_c} \\
& + (1+C)\times G_{D_s^+D_s^-}\, t_{D_s^+D_s^-\to\eta\eta_c} \\
& + \frac{3}{\sqrt{6}}\times G_{\eta'\eta_c}\, t_{\eta'\eta_c\to\eta\eta_c} \Big],
\end{aligned}
$$

$$
\mathcal{T}_{K_0^*} = \frac{V_p \times \beta \times M^2_{K_0^*(1430)}}{M^2_{K^-\eta} - M^2_{K_0^*(1430)} + iM_{K_0^*(1430)}\Gamma_{K_0^*(1430)}};
$$

$$
\frac{\mathrm{d}^2\Gamma}{\mathrm{d}M_{\eta\eta_c}\mathrm{d}M_{K^-\eta}} = \frac{1}{(2\pi)^3}\frac{M_{\eta\eta_c}M_{K^-\eta}}{8M^3_{B^-}}\left|\mathcal{T}_X + \mathcal{T}_{K_0^*}\right|^2
$$

Results



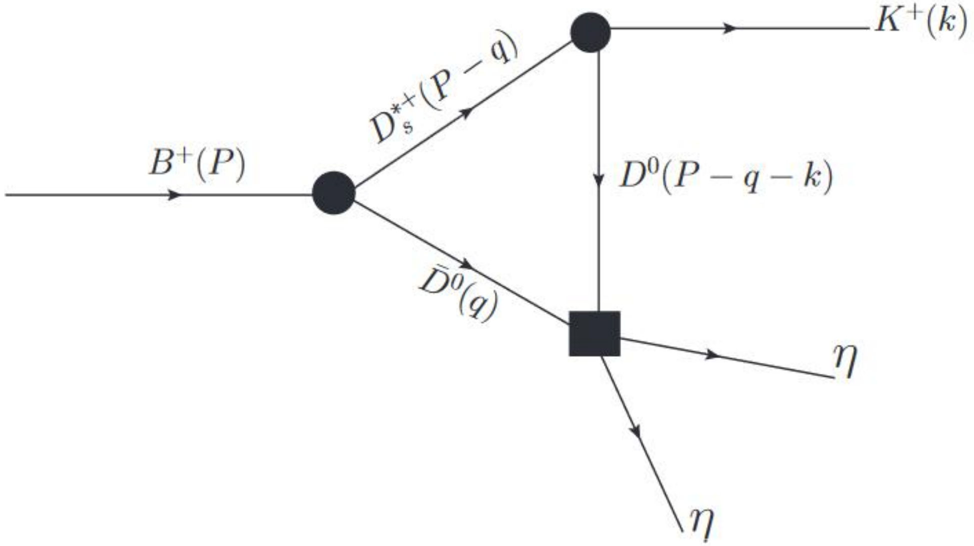
(b)

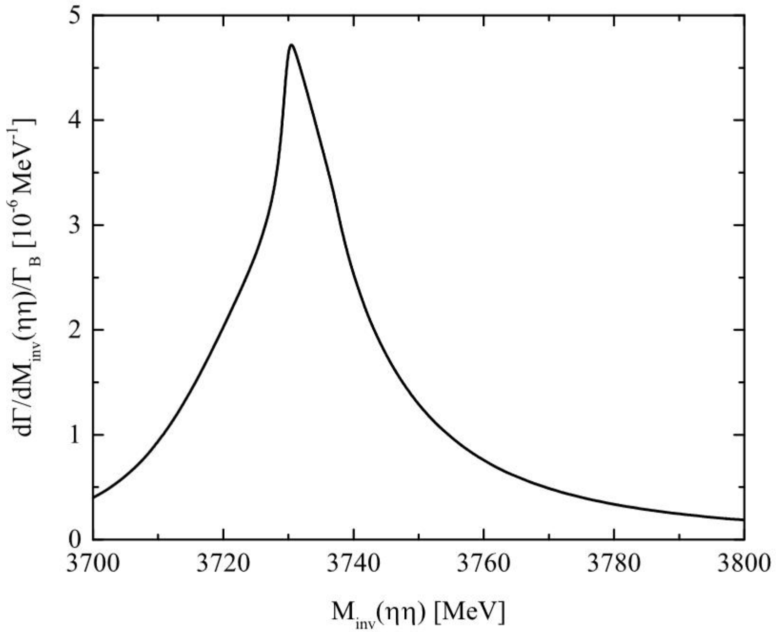
$B^+ \to (X_{q\bar{q}} \to \eta_c\eta)K^+ \qquad (0.9 \sim 6.7) \times 10^{-4} \qquad \mathrm{Br}(B^+ \to \eta_c\eta K^+) < 2.2 \times 10^{-4}$

- JMXie-Mzliu-LSGeng, Phys.Rev.D 107 (2023) 1, 016003
- Belle: JHEP06(2015)132, 772 × 10^6 $B\bar{B}$ pairs at $\Upsilon(4S)$
- Belle II: 50ab^{-1}

$B^+ \to K^+\eta\eta$

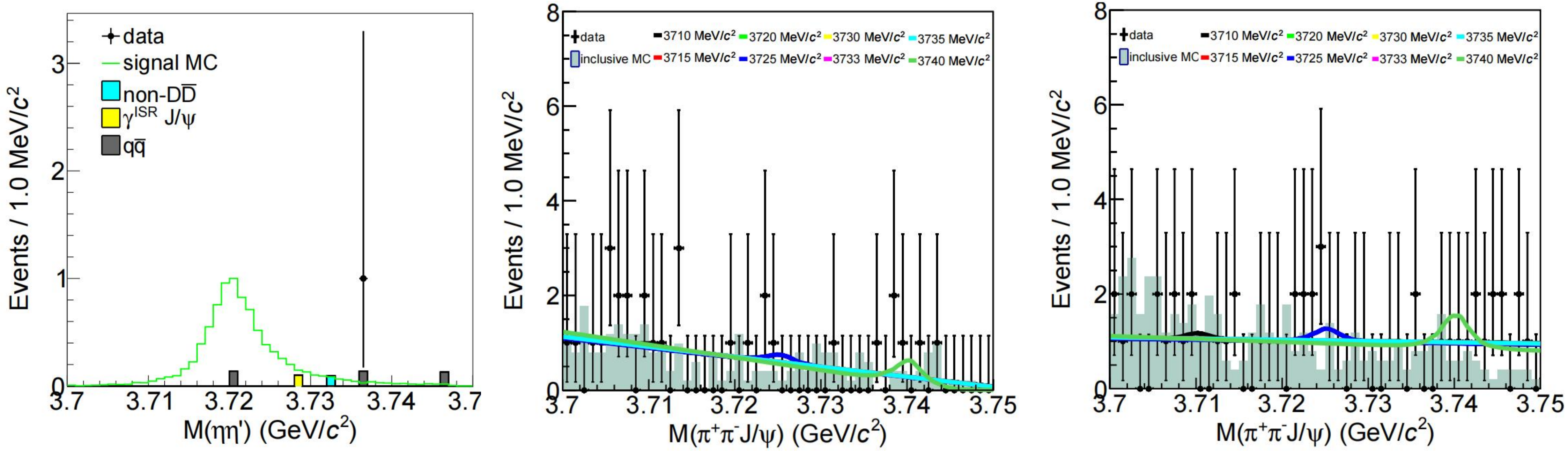
- **2307.05351,** Brandao, J. Song, Abreu, Oset





$$Br[B^+ \to K^+ D\bar{D}|_b;\ D\bar{D}|_b \to \eta\eta] = 1.47 \times 10^{-4}$$

BESIII, $\psi(3770) \to \gamma X(3700)$ PRD108 (2023) 052012



$M(X(3700))$ (MeV/c^2)		3710	3715	3720	3725	3730	3733	3735	3740
$\psi(3770) \to \gamma\eta\eta'$	ε_0 (%)	10.35	10.32	9.94	9.58	9.11	8.74	8.49	7.93
	$\mathcal{B}^{\rm up}(\times 10^{-6})$	7.9	8.0	8.2	8.6	9.1	16	17	18
$\psi(3770) \to \gamma\pi^+\pi^- J/\psi$	ε_0^{ee} (%)	15.68	15.59	15.88	15.50	15.38	15.32	14.83	13.76
	$\varepsilon_0^{\mu\mu}$ (%)	24.10	23.97	24.02	23.93	23.67	23.54	23.16	21.80
	$\mathcal{B}^{\rm up}(\times 10^{-5})$	2.2	1.2	1.8	3.0	0.86	1.0	1.3	3.4

The photon energies are about 30~40 MeV for M(eta eta')=3720 MeV。

Summary

- The $D\bar{D}$ bound state was predicted in many theoretical works.
- The present experimental data of $e^+e^- \to J/\psi D\bar{D}$ and $\gamma\gamma \to D\bar{D}$ support the existentce of the $\mathrm{D\bar{D}}$ state.
- Some processes are proposed to search for $\mathrm{D\bar{D}}$ state
  - $\Lambda_b \to D\bar{D}\Lambda$
  - $B^- \to K^-\eta\eta_c$
  - $B^+ \to K^+\eta\eta$

Thanks for your attention!