Dispersive analysis of the $\gamma\gamma \to D\bar{D}$ data

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in coll. with Oleksandra Deineka,
Marc Vanderhaeghen

Phys. Lett. B 827, 136982 (2022)

EXCITED QCD 2022, October 28, Sicily

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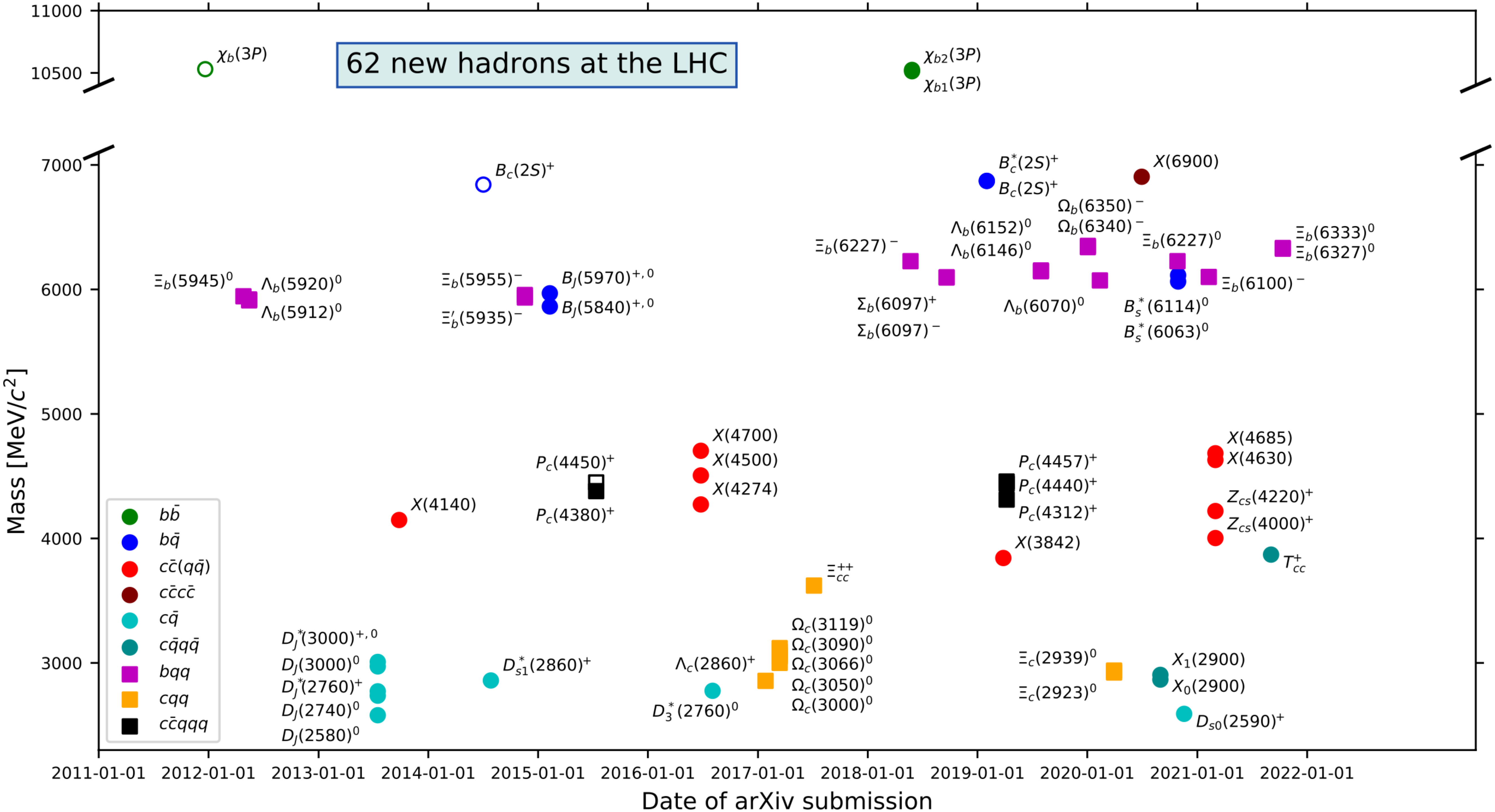
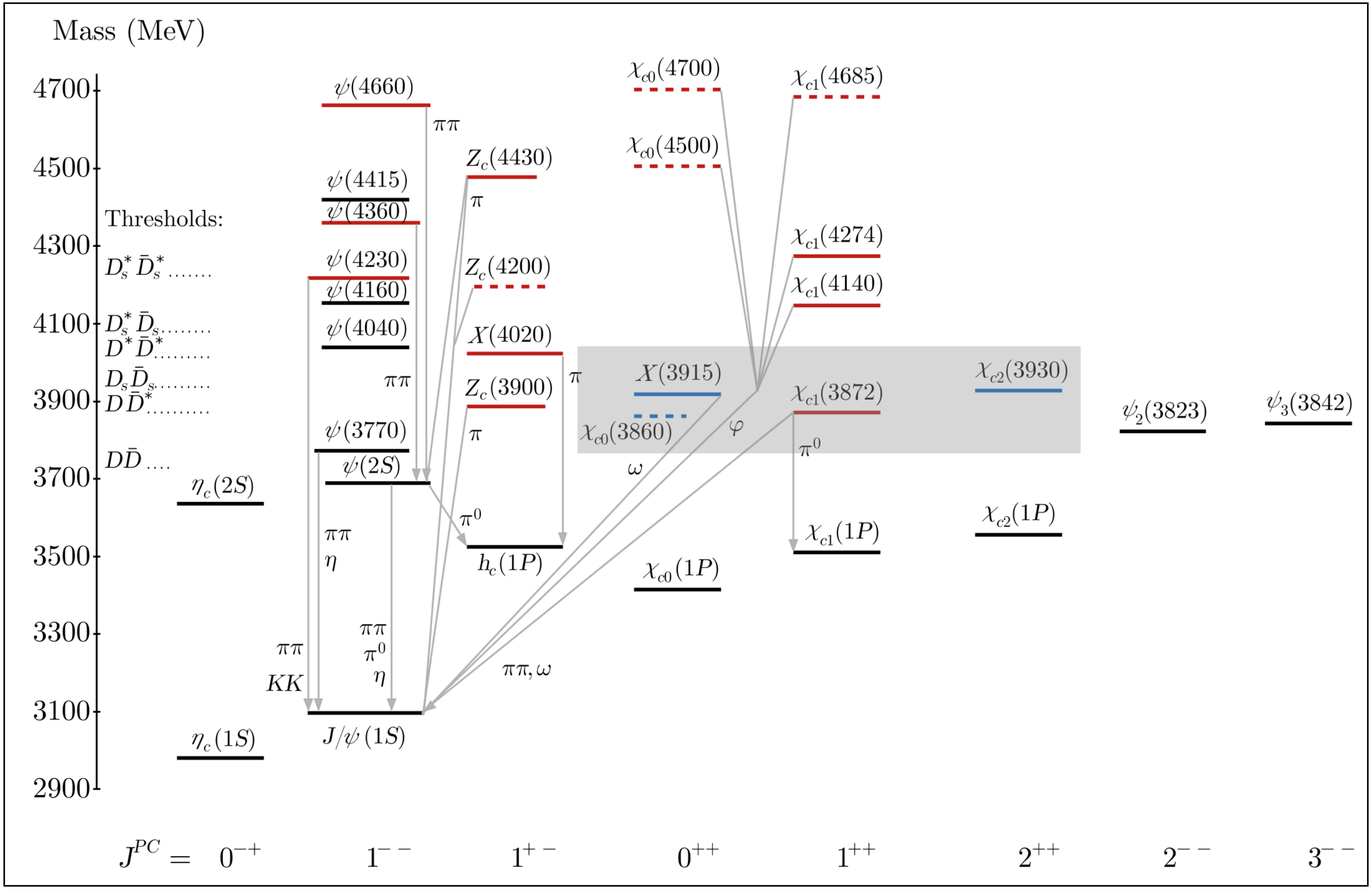


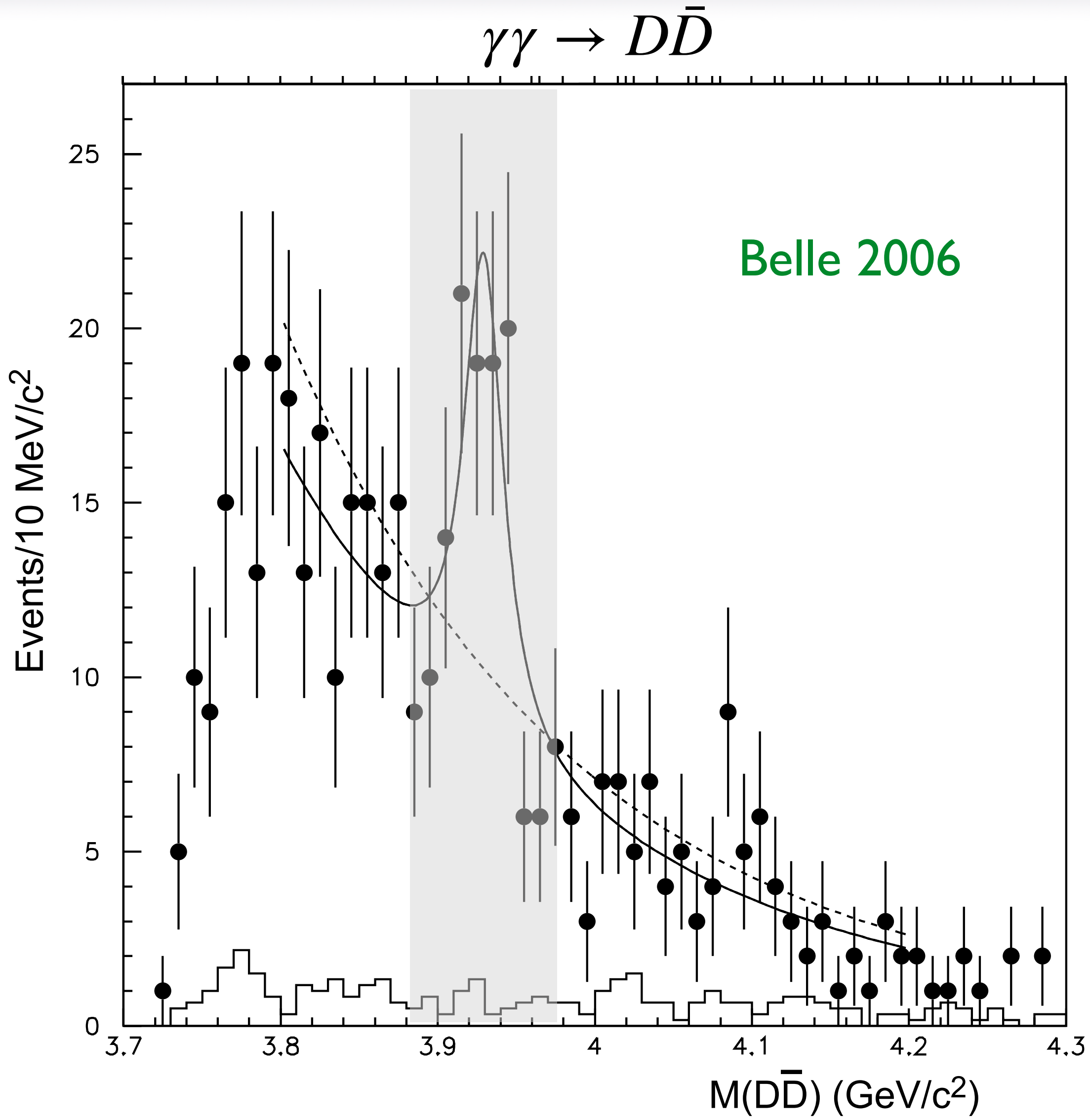
+ data from Babar, Belle, COMPASS, …

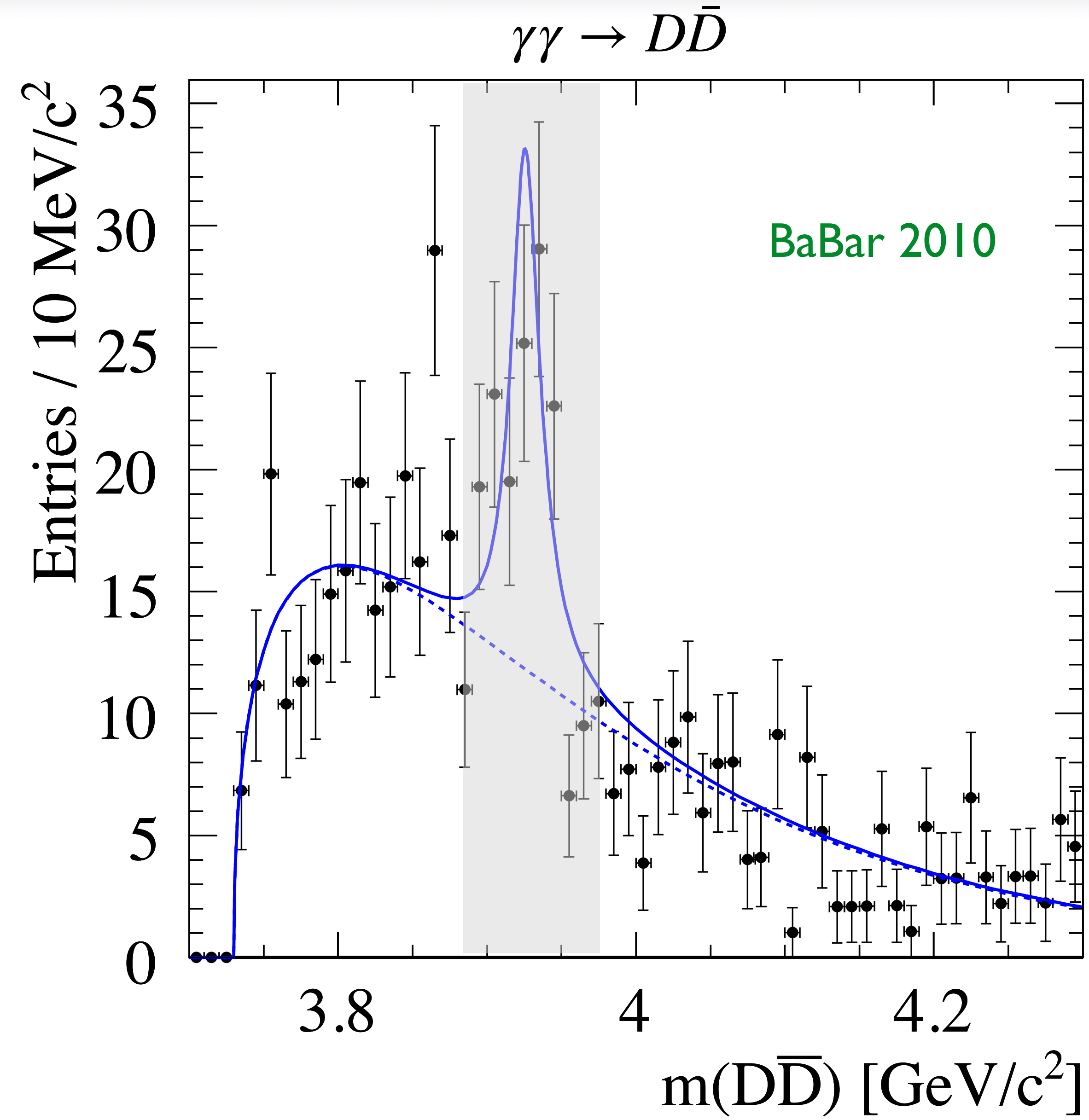
What are we looking for?



PDG 2021

Everything is fine with $\chi_{c2}(2P)$



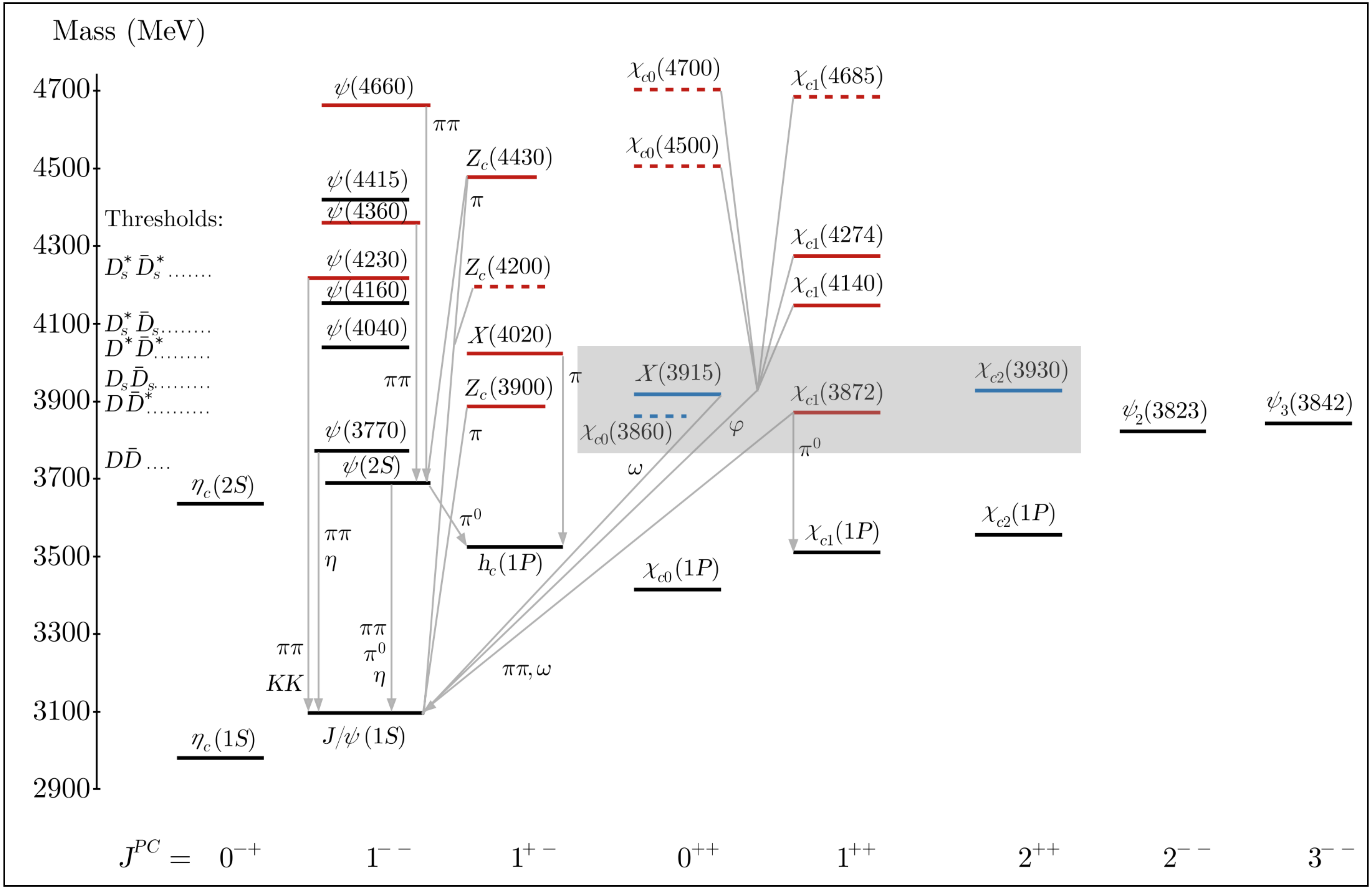


LHCb, 2019: $pp \to D\bar{D}$ + anything
LHCb, 2020: $B^+ \to D^+D^-K^+$

$X(3930)$
=
$\chi_{c2}(3930)$

$\chi_{c2}(3930)$	$I^G(J^{PC}) = 0^+(2^{++})$	PDG 2022
$\chi_{c2}(3930)$ MASS		3922.5 ± 1.0 MeV (S = 1.7)
$\chi_{c2}(3930)$ WIDTH		35.2 ± 2.2 MeV (S = 1.2)

What are we looking for?



PDG 2021

is $X(3915)$ a $\chi_{c0}(2P)$?

[Belle 2005] $B \to J/\psi \omega K$: $X(3915)$:
later confirmed by [BaBar 2008, 2010]

[Belle 2010] $\gamma\gamma \to X(3915) \to J/\psi\omega$
[BaBar 2012] spin-parity analysis : $J^{PC} = 0^{++}$
(assuming helicity-2 dominance of tensor resonance)

Problems: [Brambilla et al. 2011, Olsen 2015, …]

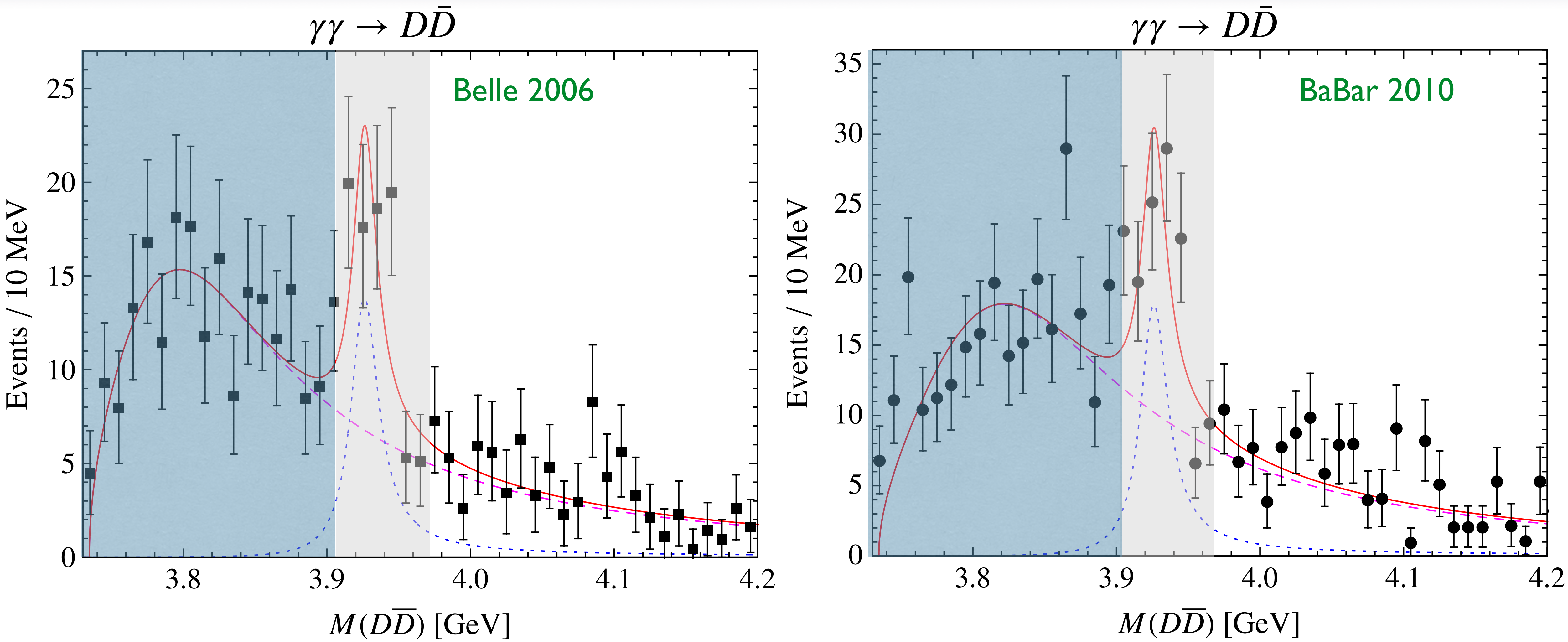
- No decay mode to DD (S-wave) was observed
- The $X(3915) \to J/\psi\omega$ decay should be OZI suppressed
- Narrow, width of ~20 MeV
- Small mass splitting with $\chi_{c2}(3930)$
- Might actually be the same state as $\chi_{c2}(3930)$ [Zhou et al. 2015]

[LHCb 2021] $B^+ \to D^+ D^- K^+$
found narrow $J^{PC} = 0^{++}$ resonance around ~3.92 GeV
(amplitude analysis)

$X(3915)$
?
$\chi_{c0}(3915)$

$\chi_{c0}(3915)$	$I^G(J^{PC}) = 0^+(0^{++})$	PDG 2022
$\chi_{c0}(3915)$ MASS		3921.7 ± 1.8 MeV
$\chi_{c0}(3915)$ WIDTH		18.8 ± 3.5 MeV

Another possibility for $\chi_{c0}(2P)$?



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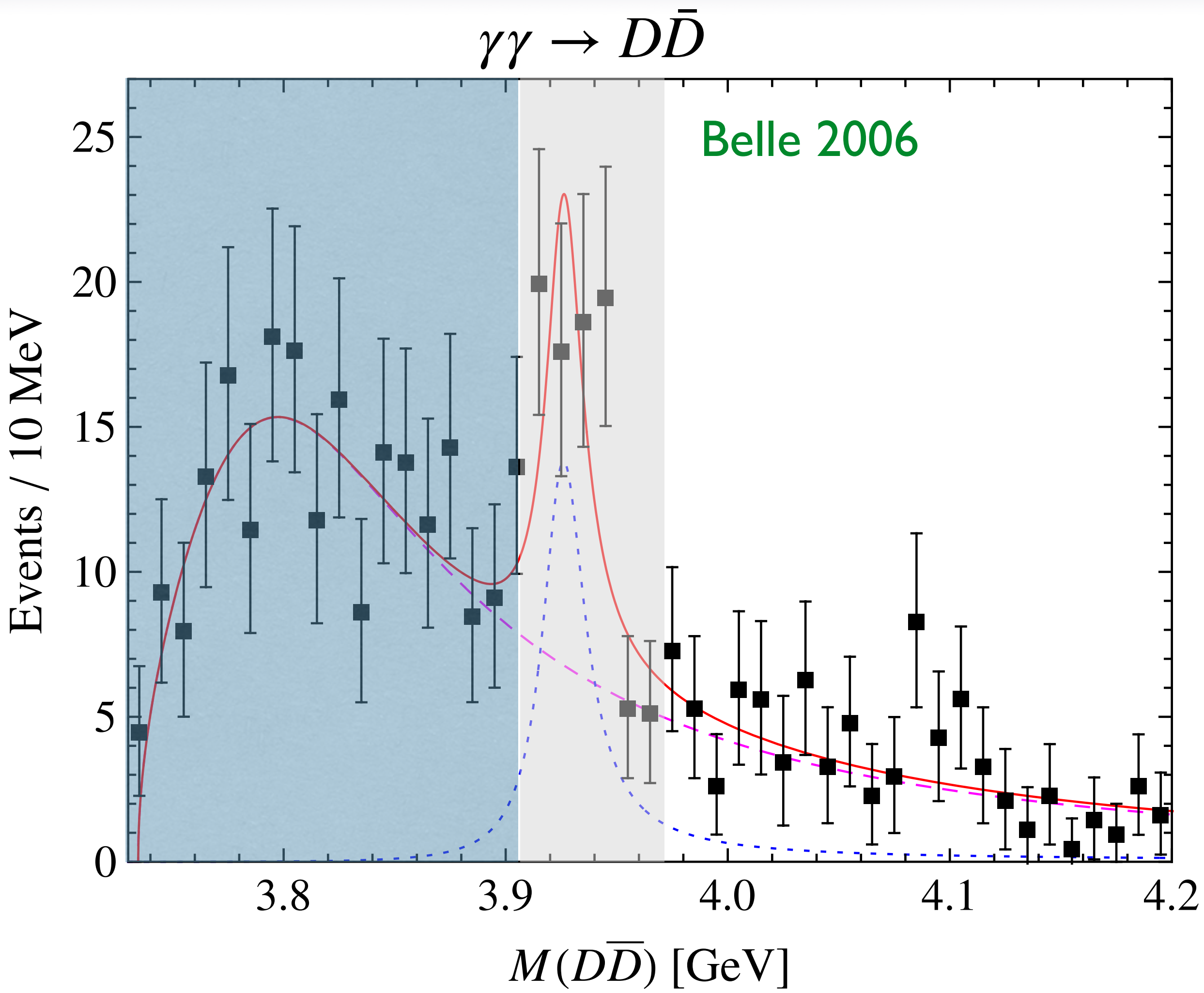
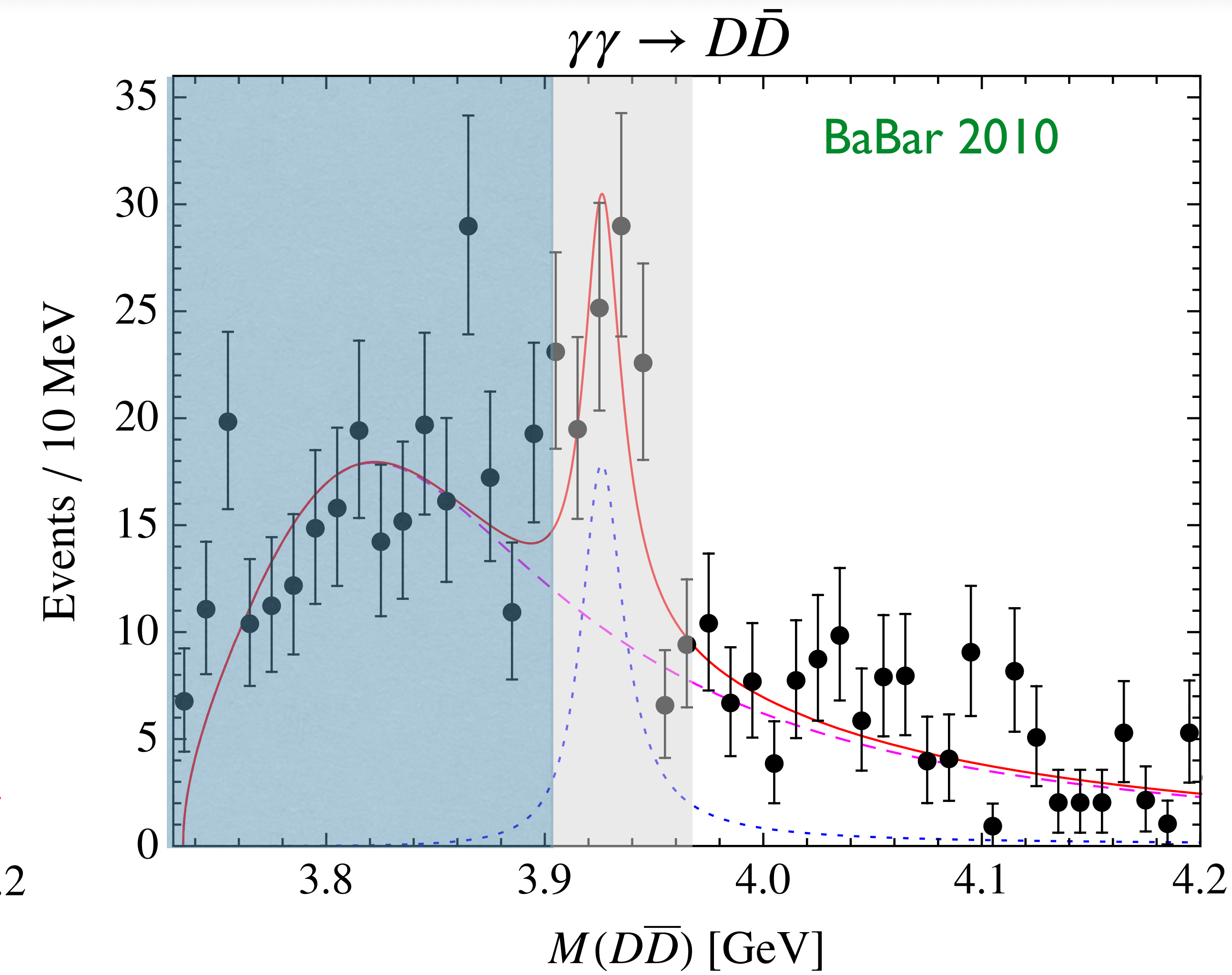




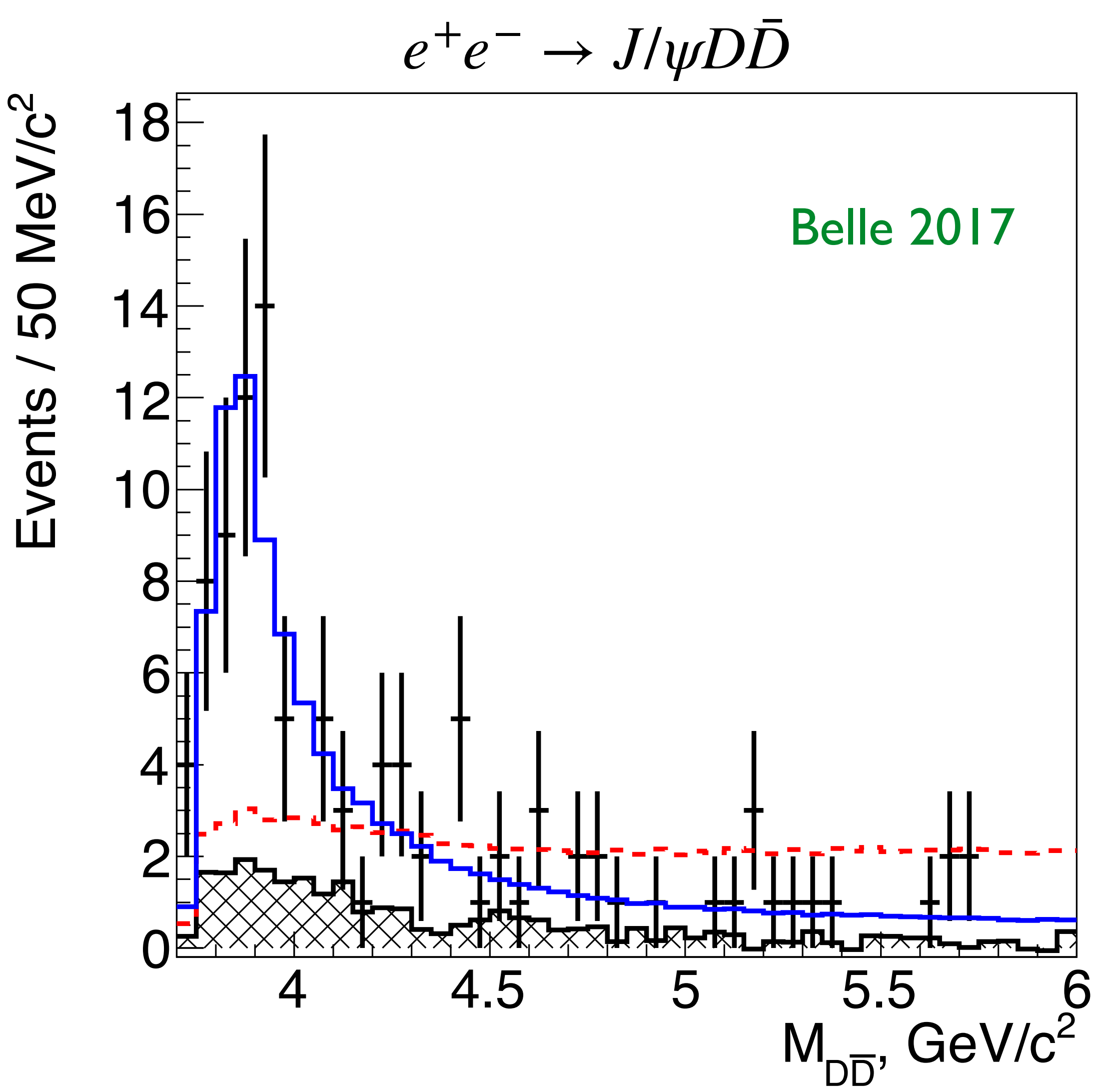
[Guo Meißner 2010]

two Breit-Wigner functions: mass and width of $\chi_{c2}(3930)$ is fixed, and $\chi_{c0}(2P)$ is fitted

$$B_L(s) = \left(\frac{p(s)}{p(m_R^2)}\right)^{2L+1} \frac{m_R}{\sqrt{s}} \frac{F_L^2(s)}{(s-m_R^2)^2 + m_R^2\Gamma^2(s)}, \quad \Gamma(s) = \Gamma_R \left(\frac{p(s)}{p(m_R^2)}\right)^{2L+1} \frac{m_R}{\sqrt{s}} F_L^2(s)$$

$$M_{\chi_{c0}(2P)} = 3837.6 \pm 11.5\,\text{MeV}, \quad \Gamma_{\chi_{c0}(2P)} = 221 \pm 19\,\text{MeV}$$

is $X(3860)$ a $\chi_{c0}(2P)$?



Problems:

- The $e^+e^- \to J/\psi D\bar{D}$ statistics is rather limited
- LHCb 2021 amplitude analysis of $B^+ \to D^+D^-K^+$ see no evidence for broad $X(3860)$

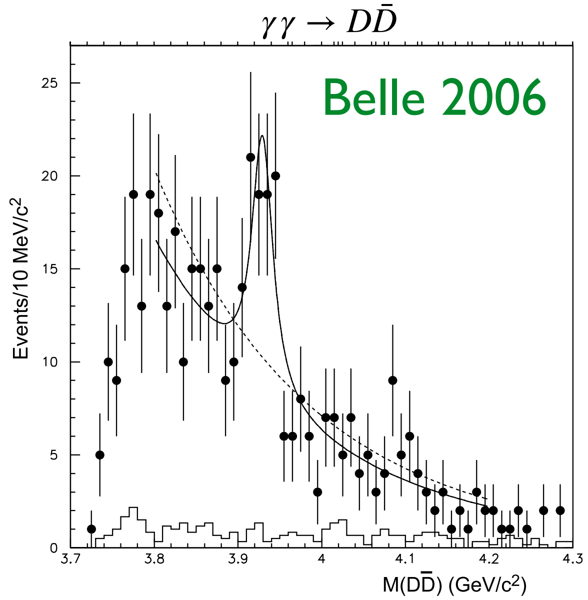
$X(3860)$

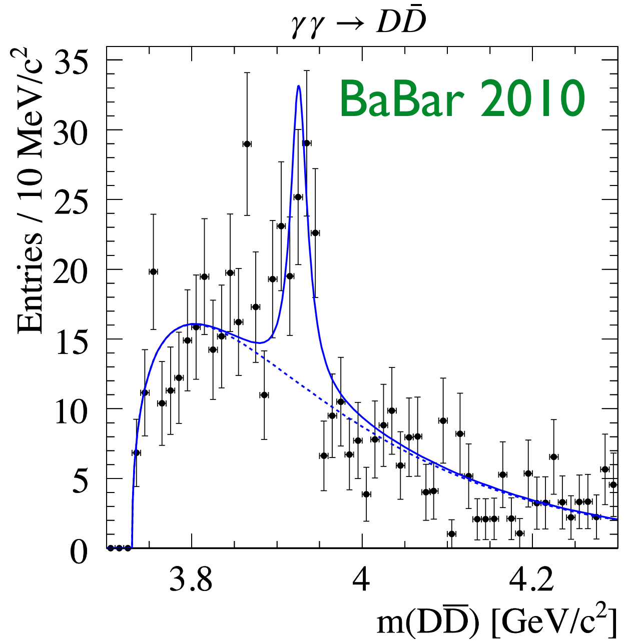
?

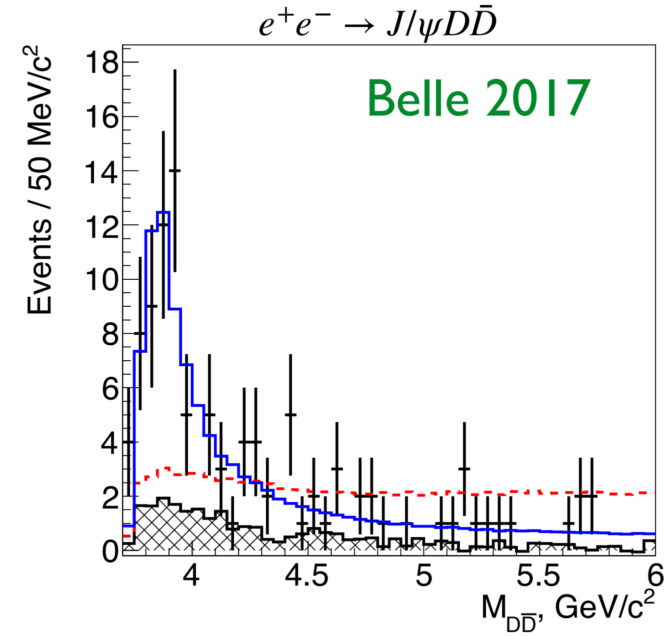
$\chi_{c0}(3860)$

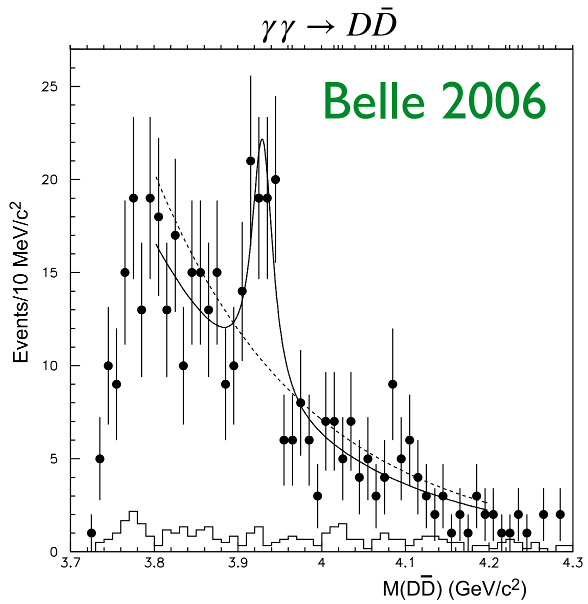
$\chi_{c0}(3860)$	$I^G(J^{PC}) = 0^+(0^{++})$	PDG 2022
$\chi_{c0}(3860)$ MASS		3862^{+50}_{-35} MeV
$\chi_{c0}(3860)$ WIDTH		201^{+180}_{-110} MeV

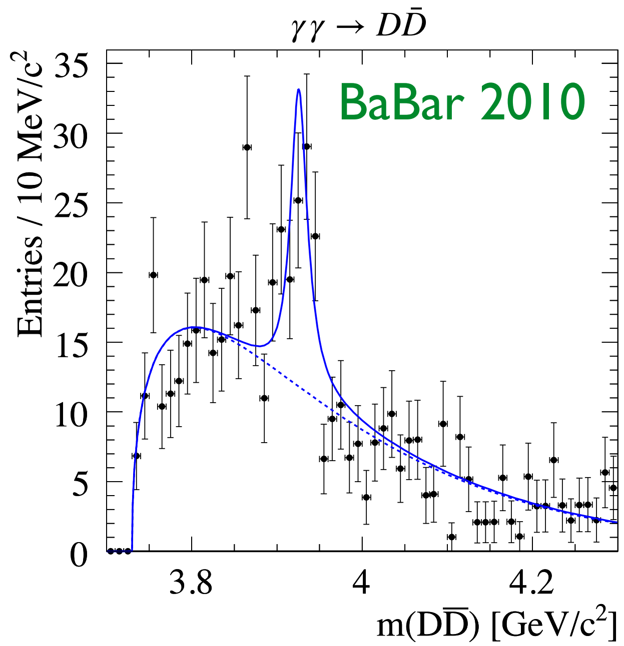
Theory overview

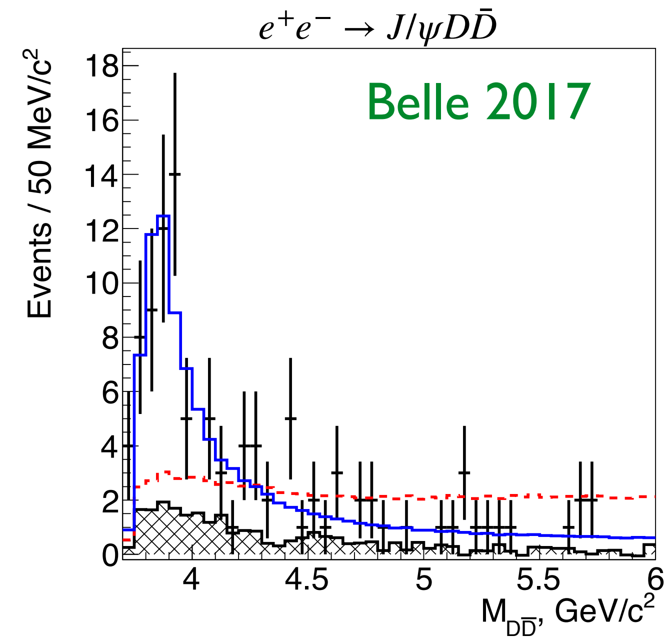












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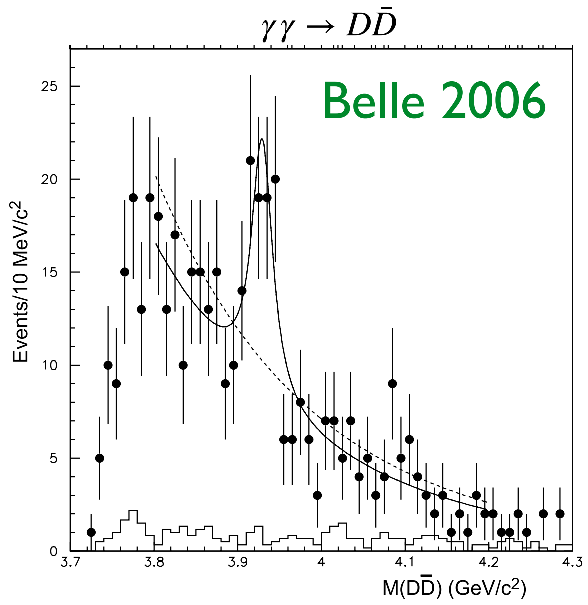

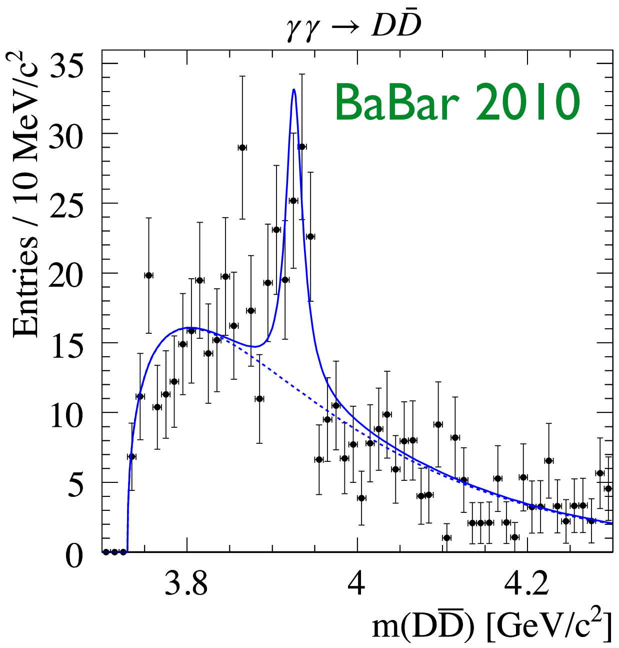

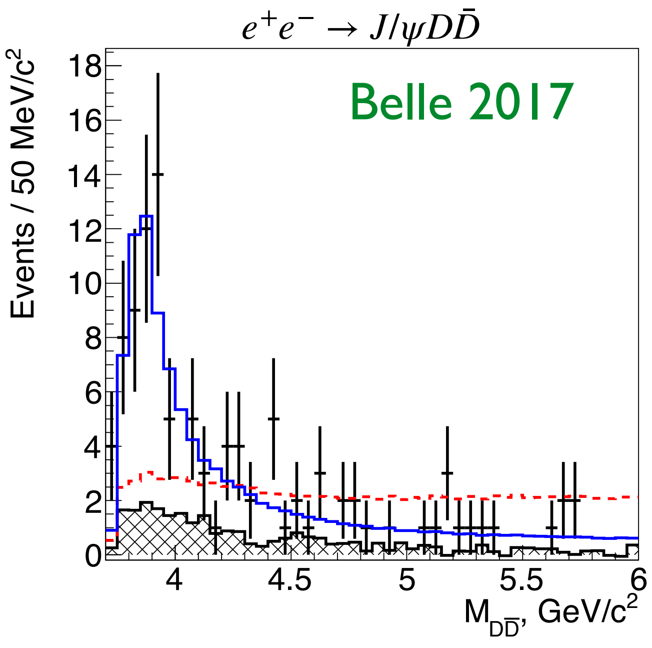

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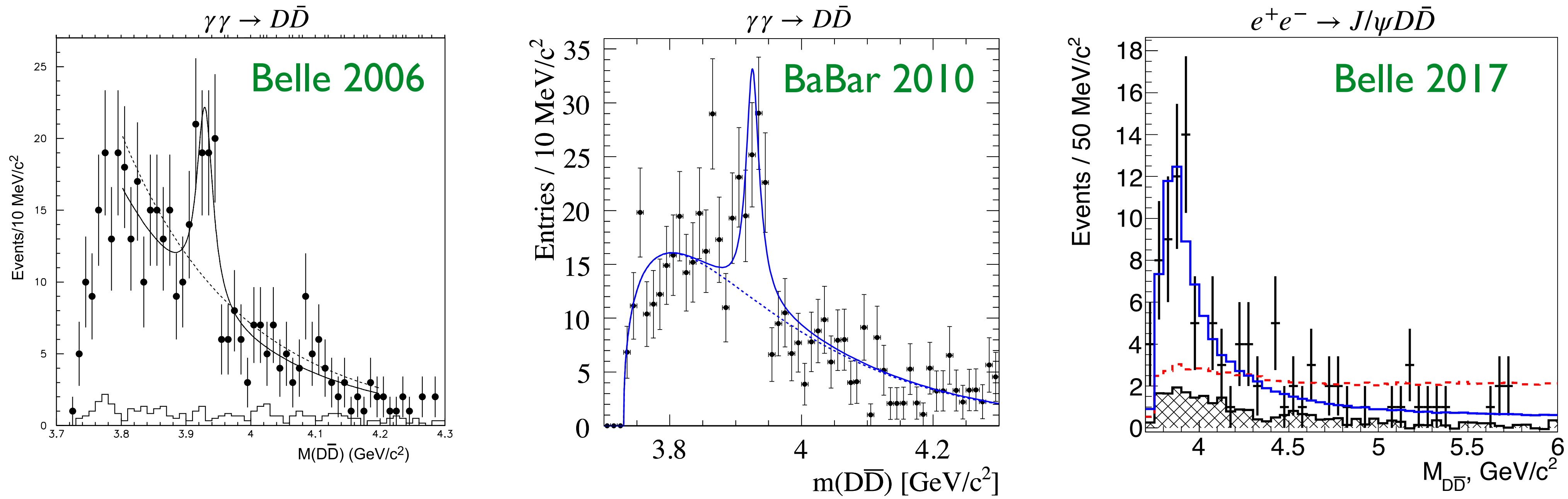

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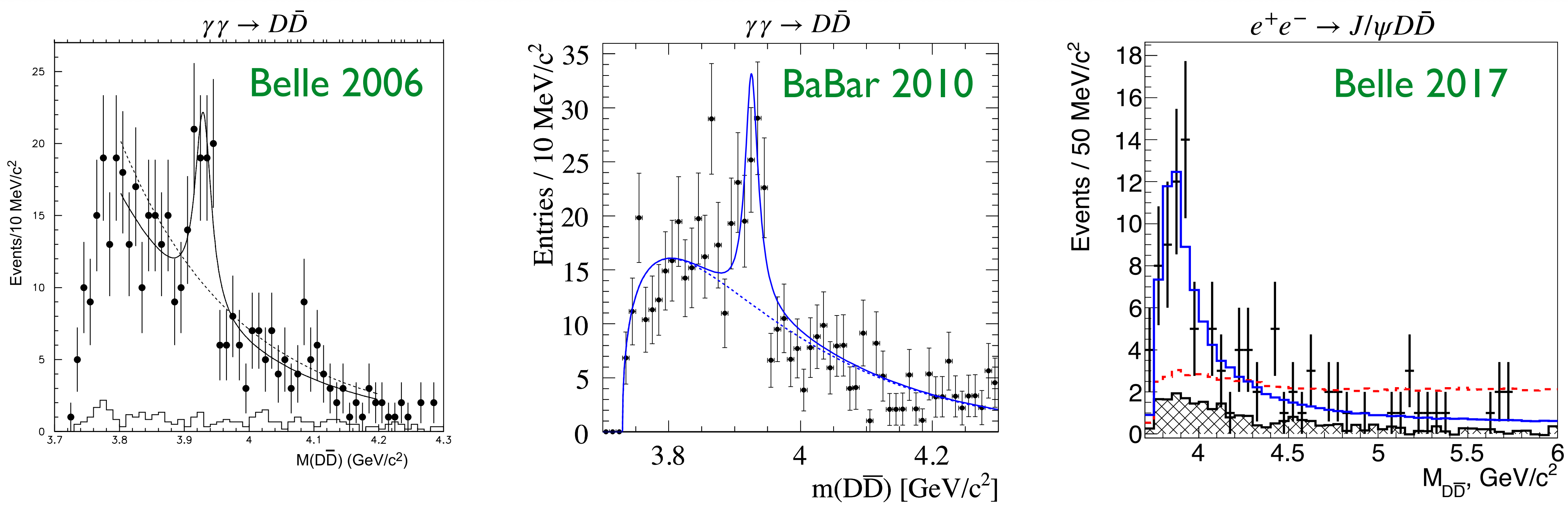
no broad $\chi_{c0}(3860)$ is needed

- [Prelovsek et al. 2022] Lattice analysis of $\{D\bar{D}, D_s\bar{D}_s\}$ with $m_\pi = 280\,\text{MeV}$ found 3 states with 0^{++}
1) $D\bar{D}$ bound state
2) broad state likely related to $\chi_{c0}(3860)$
3) $D_s\bar{D}_s$ quasi bound state which might be $\chi_{c0}(3915)$ or $X(3960)$



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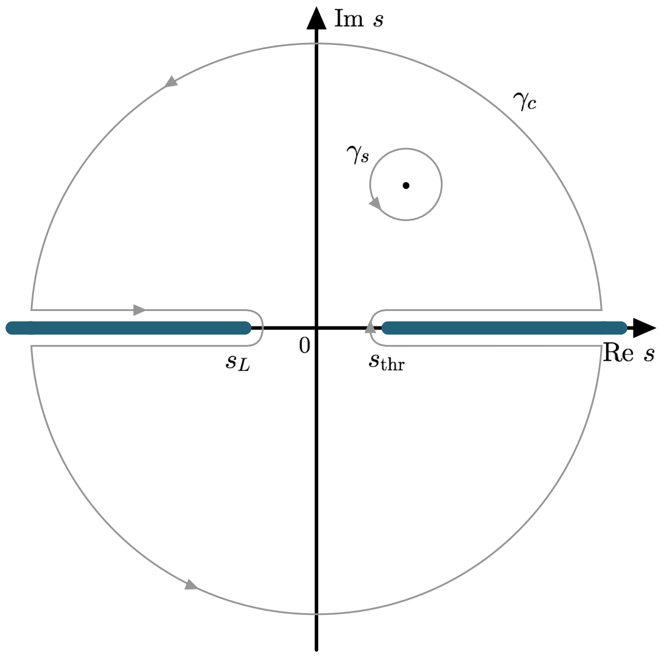
In order to figure out what is going on with 0^{++} we employ a data driven dispersive analysis of $\gamma\gamma \to D\bar{D}$ and $e^+e^- \to J/\psi D\bar{D}$

Formalism

partial wave dispersion relation (S wave)

- Full **p.w. dispersion relation** (causality, crossing, unitarity)

$$t_{ab}(s) = \int_{-\infty}^{s_L} \frac{ds'}{\pi} \frac{\text{Im}\, t_{ab}(s')}{s'-s} + \int_{s_{th}}^{\infty} \frac{ds'}{\pi} \frac{\text{Im}\, t_{ab}(s')}{s'-s}$$



- **Unitarity relation**

$$\text{Im}\, t_{ab}(s) = \sum_c t_{ac}(s)\, \rho_c(s)\, t^*_{cb}(s)$$

$$-\frac{1}{2\rho_1} \leq \text{Re}\, t_{11}(s) \leq \frac{1}{2\rho_1}, \quad 0 < \text{Im}\, t_{11}(s) \leq \frac{1}{\rho_1}, \quad \ldots$$

- Assuming $t(\infty) \to const$ we subtract the dispersion relation once

$$t_{ab}(s) = \underbrace{t_{ab}(0) + \frac{s}{\pi} \int_{-\infty}^{s_L} \frac{ds'}{s'} \frac{\text{Im}\, t_{ab}(s')}{s'-s}}_{U_{ab}(s)} + \frac{s}{\pi} \sum_c \int_{s_{th}}^{\infty} \frac{ds'}{s'} \frac{t_{ac}(s')\, \rho_c(s')\, t^*_{cb}(s')}{s'-s}$$

$U_{ab}(s)$ (asymptotically bounded unknown function)

- Once-subtracted p.w. dispersion relation

$$t_{ab}(s) = \underbrace{t_{ab}(0) + \frac{s}{\pi}\int_{-\infty}^{s_L} \frac{ds'}{s'} \frac{\text{Im}\ t_{ab}(s')}{s'-s}}_{U_{ab}(s)} + \frac{s}{\pi}\sum_c \int_{s_{th}}^{\infty} \frac{ds'}{s'} \frac{t_{ac}(s')\,\rho_c(s')\,t^*_{cb}(s')}{s'-s}$$

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can be solved using N/D method with input from $U_{ab}(s)$ **above threshold**

Chew, Mandelstam (1960)
Luming (1964)
Johnson, Warnock (1981)

$$t_{ab}(s) = \sum_c D^{-1}_{ac}\, N_{cb}(s)$$

$$N_{ab}(s) = U_{ab}(s) + \frac{s}{\pi}\sum_c \int_{s_{th}}^{\infty} \frac{ds'}{s'} \frac{N_{ac}(s')\,\rho_c(s')\,(U_{cb}(s') - U_{cb}(s))}{s'-s}$$

$$D_{ab}(s) = \delta_{ab} - \frac{s}{\pi}\int_{s_{th}}^{\infty} \frac{ds'}{s'} \frac{N_{ab}(s')\,\rho_b(s')}{s'-s}$$

the obtained N/D solution can be checked that it **fulfils** the p.w. dispersion relation

- Once-subtracted p.w. dispersion relation

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- Bound state case

$$\det(D_{ab}(s_B)) = 0$$

$$t_{ab}(s) = U_{ab}(s) + \frac{s}{s_B}\frac{g_a\,g_b}{s_B - s} + \frac{s}{\pi}\sum_c \int_{s_{th}}^{\infty}\frac{ds'}{s'}\frac{t_{ac}(s')\,\rho_c(s')\,t^*_{cb}(s')}{s'-s}$$

partial wave dispersion relation (S wave)

- $I = 0$ has $\{\gamma\gamma, \pi\pi, K\bar{K}, \ldots, D\bar{D}\}$ channels, but the coupling of charmed $\{D\bar{D}\}$ with uncharmed $\{\pi\pi, K\bar{K}, ..\}$ are strongly suppressed: separately focus on $\{\gamma\gamma, D\bar{D}\}$ and $\{\gamma\gamma, \pi\pi, K\bar{K}\}$

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- Neglect $\gamma\gamma$ intermediate states in the unitary relation and put $U_{\gamma\gamma\to\gamma\gamma} = 0 \ (\sim e^4)$
=> coupled-channel $\{\gamma\gamma, D\bar{D}\}$ equations reduce to the **hadronic part** and **photon-fusion part**

$$t_{DD}(s) = U_{DD}(s) + \frac{s}{\pi}\int_{4m_D^2}^{\infty} \frac{ds'}{s'} \frac{t_{DD}(s')\,\rho_D(s')\,t_{DD}^*(s')}{s'-s} = \frac{N_{DD}(s)}{D_{DD}(s)}$$

$$t_{\gamma\gamma,DD}(s) = U_{\gamma\gamma,DD}(s) + D_{DD}^{-1}(s)\left(-\frac{s}{\pi}\int_{4m_D^2}^{\infty} \frac{ds'}{s'} \frac{\mathrm{Im}\, D_{DD}(s')\, U_{\gamma\gamma,DD}(s')}{s'-s}\right)$$

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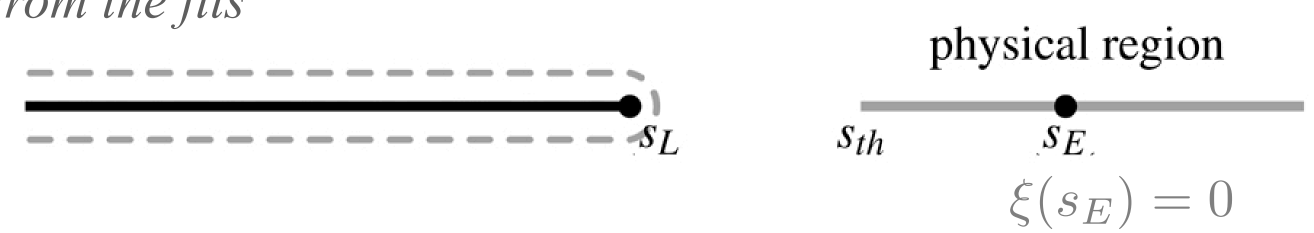
- Using the known analytical structure of **left-hand cuts**, one can approximate $U_{ab}(s)$ as an expansion in a conformal mapping variable $\xi(s)$ Gasparyan, Lutz (2010)

to be determined from the fits

$$U_{DD}(s) \simeq \sum_{n=0}^{\infty} C_n\, \xi^n(s)$$



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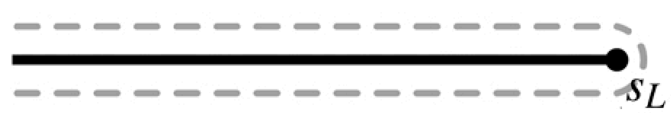
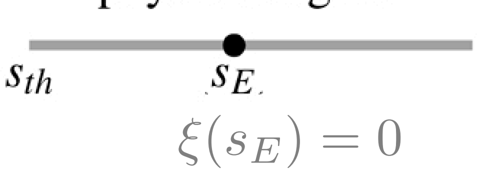
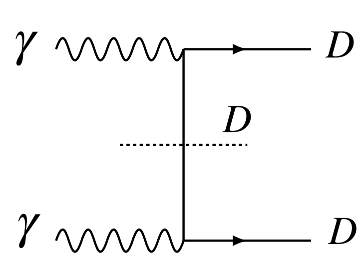
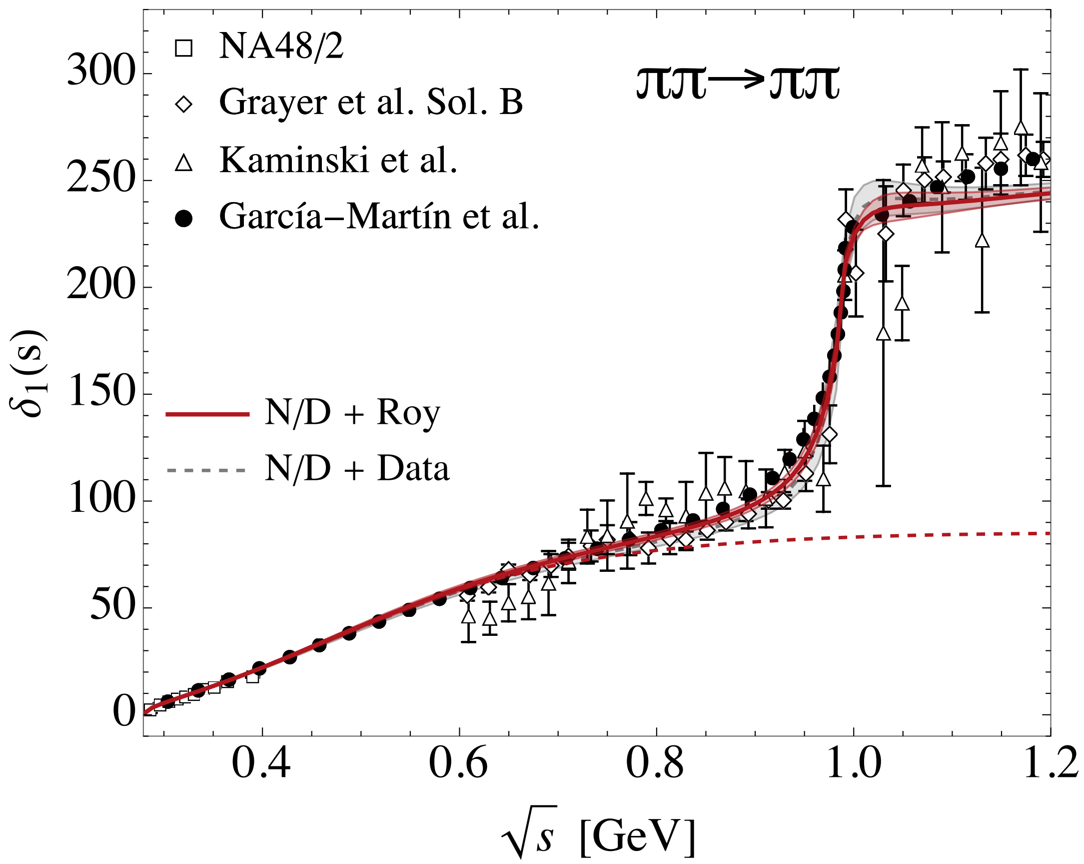
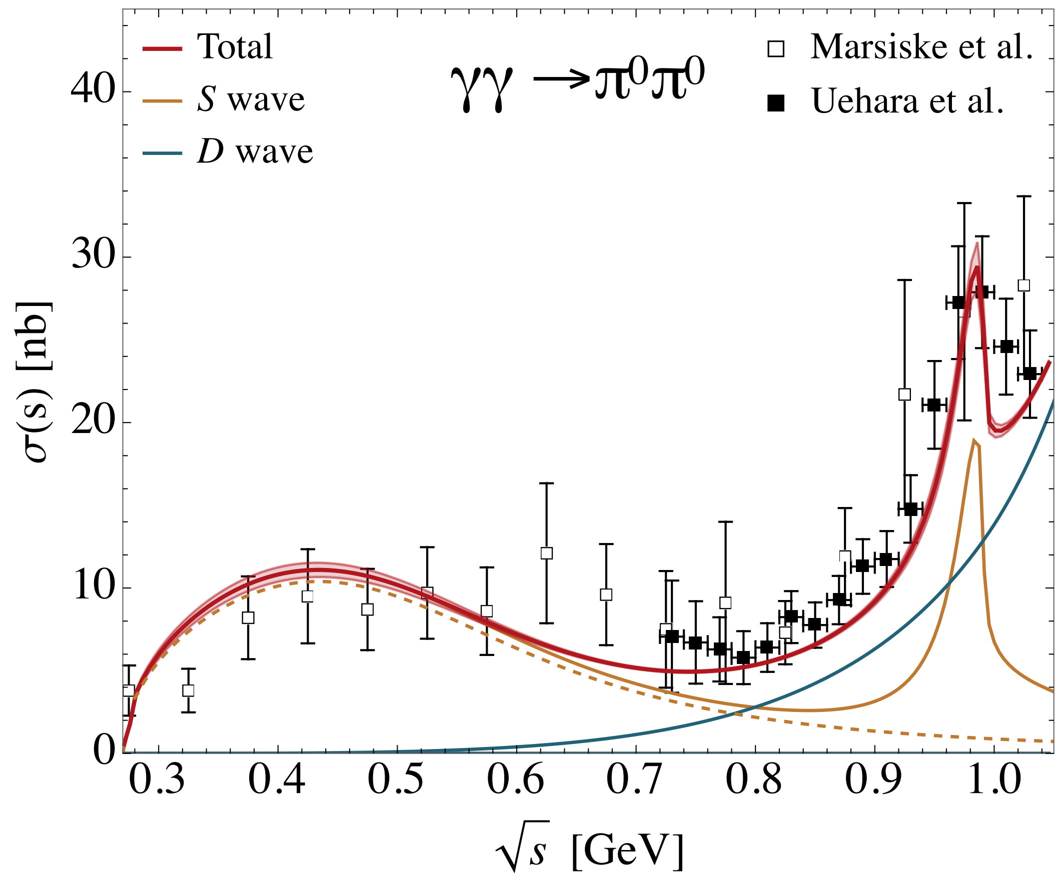




$$U_{\gamma\gamma,DD}(s) \approx \text{Born}$$







Input: experimental data/Roy analysis + threshold parameters NNLO + Adler zero NLO

	Our results		Roy-like analyses	
	pole position, MeV	couplings, GeV	pole position, MeV	couplings, GeV
$\sigma/f_0(500)$	$458(10)^{+7}_{-15} - i\,256(9)^{+5}_{-8}$	$\gamma\gamma : 5.6(1)(1)\cdot 10^{-3}$ $\pi\pi : 3.33(8)^{+0.12}_{-0.20}$ $K\bar{K} : 2.11(17)^{+0.27}_{-0.11}$	$449^{+22}_{-16} - i\,275(15)$	$\gamma\gamma : 6.1(7)\cdot 10^{-3}$ $\pi\pi : 3.45^{+0.25}_{-0.29}$ $K\bar{K} : -$
$f_0(980)$	$993(2)^{+2}_{-1} - i\,21(3)^{+2}_{-4}$	$\gamma\gamma : 4.0(8)^{+0.3}_{-1.1}\cdot 10^{-3}$ $\pi\pi : 1.93(15)^{+0.07}_{-0.12}$ $K\bar{K} : 5.31(24)^{+0.04}_{-0.24}$	$996^{+7}_{-14} - i\,25^{+11}_{-6}$	$\gamma\gamma : 3.8(1.4)\cdot 10^{-3}$ $\pi\pi : 2.3(2)$ $K\bar{K} : -$

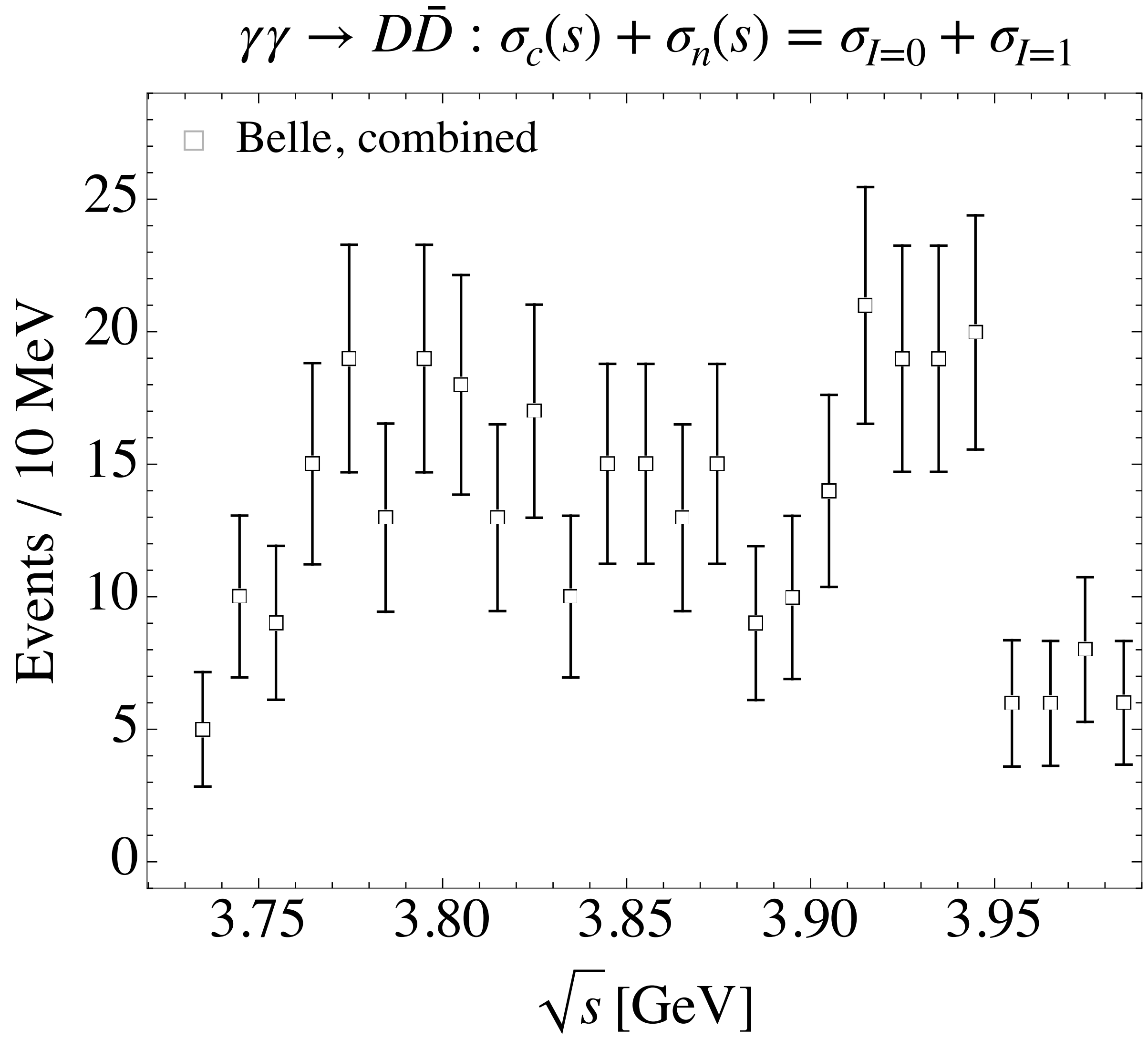
I.D, Deineka, Vanderhaeghen (2020)

Caprini et al. (2006), Garcia-Martin et al. (2011)
Moussallam (2011), Dai Pennington (2016)

Naïve analysis of the combined $\gamma\gamma \to D\bar{D}$ data

S-wave: $I = 0$ with dispersive rescattering, $I = 1$ only Born
D-wave: $\chi_{c2}(3930)$ as a Breit-Wigner hel-2 with PDG mass/width

$\Longrightarrow$ 2 parameters from N/D + normalisation ratio (S/D wave)



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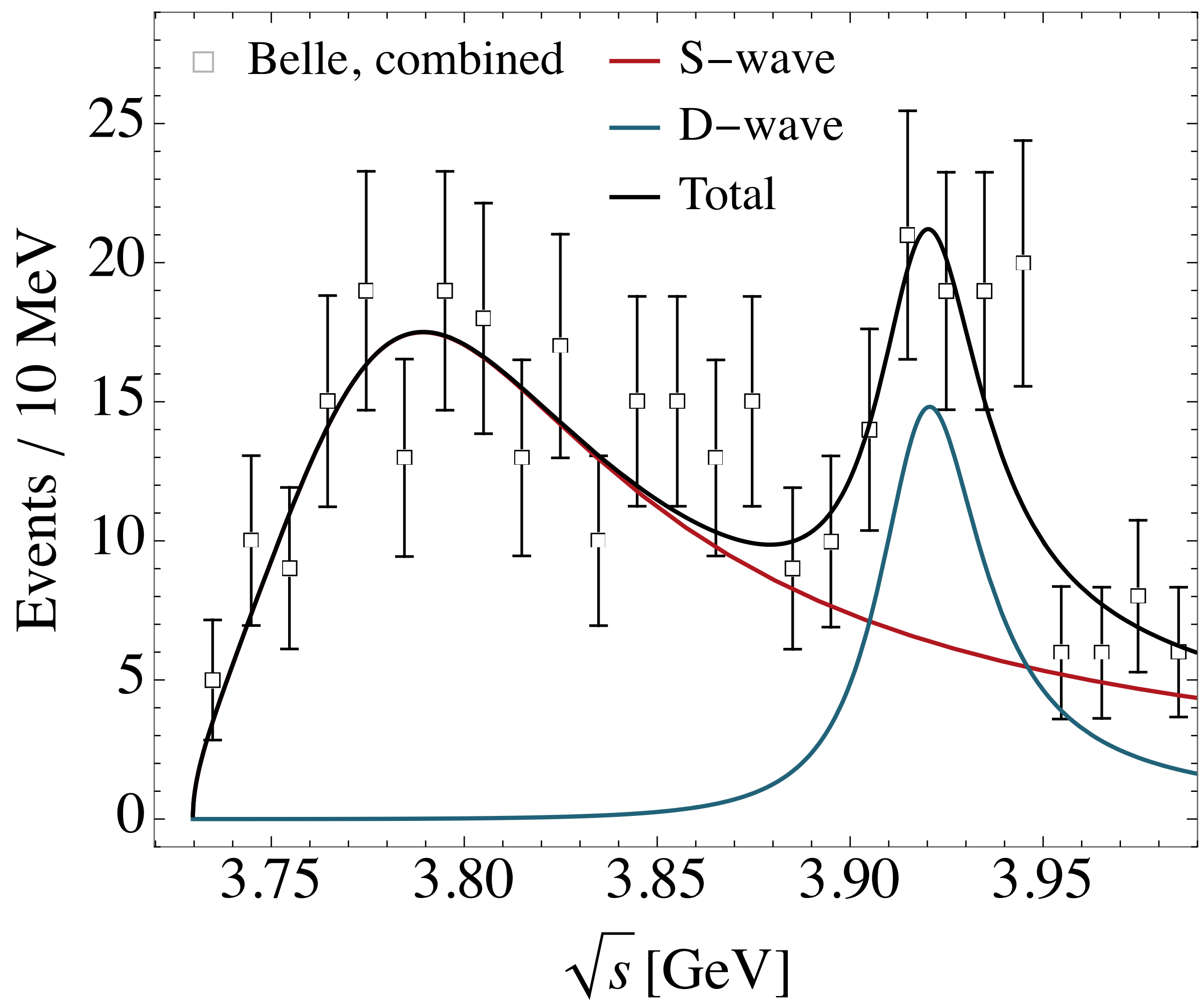
$\Longrightarrow$ 2 parameters from N/D + normalisation ratio (S/D wave)

$\gamma\gamma \to D\bar{D} : \sigma_c(s) + \sigma_n(s) = \sigma_{I=0} + \sigma_{I=1}$



$$\sqrt{s_p} = 3772.2 - 50\,i\ \text{MeV}$$

Naïve analysis of the combined $\gamma\gamma \to D\bar{D}$ data

S-wave: $I = 0$ with dispersive rescattering, $I = 1$ only Born
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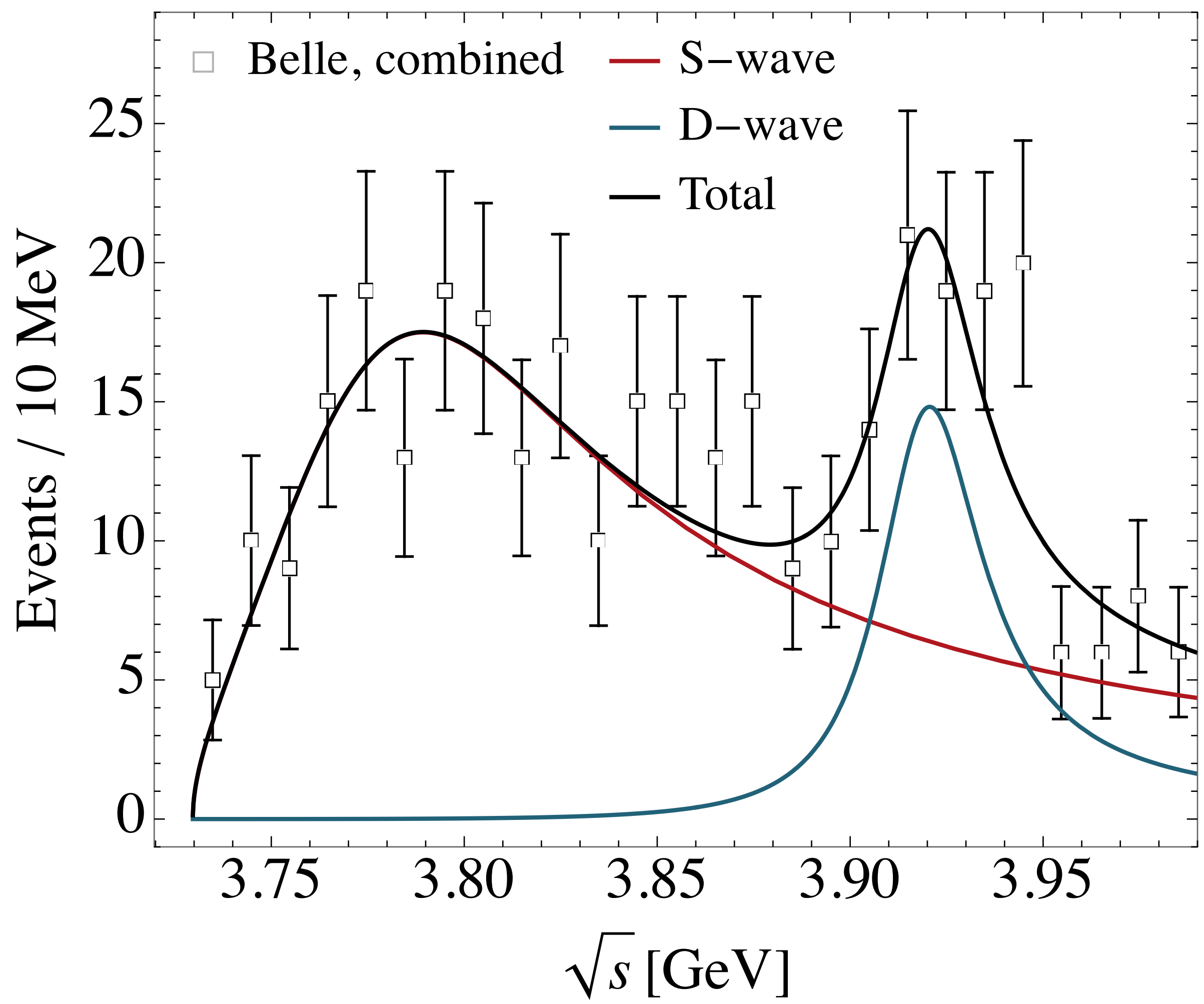
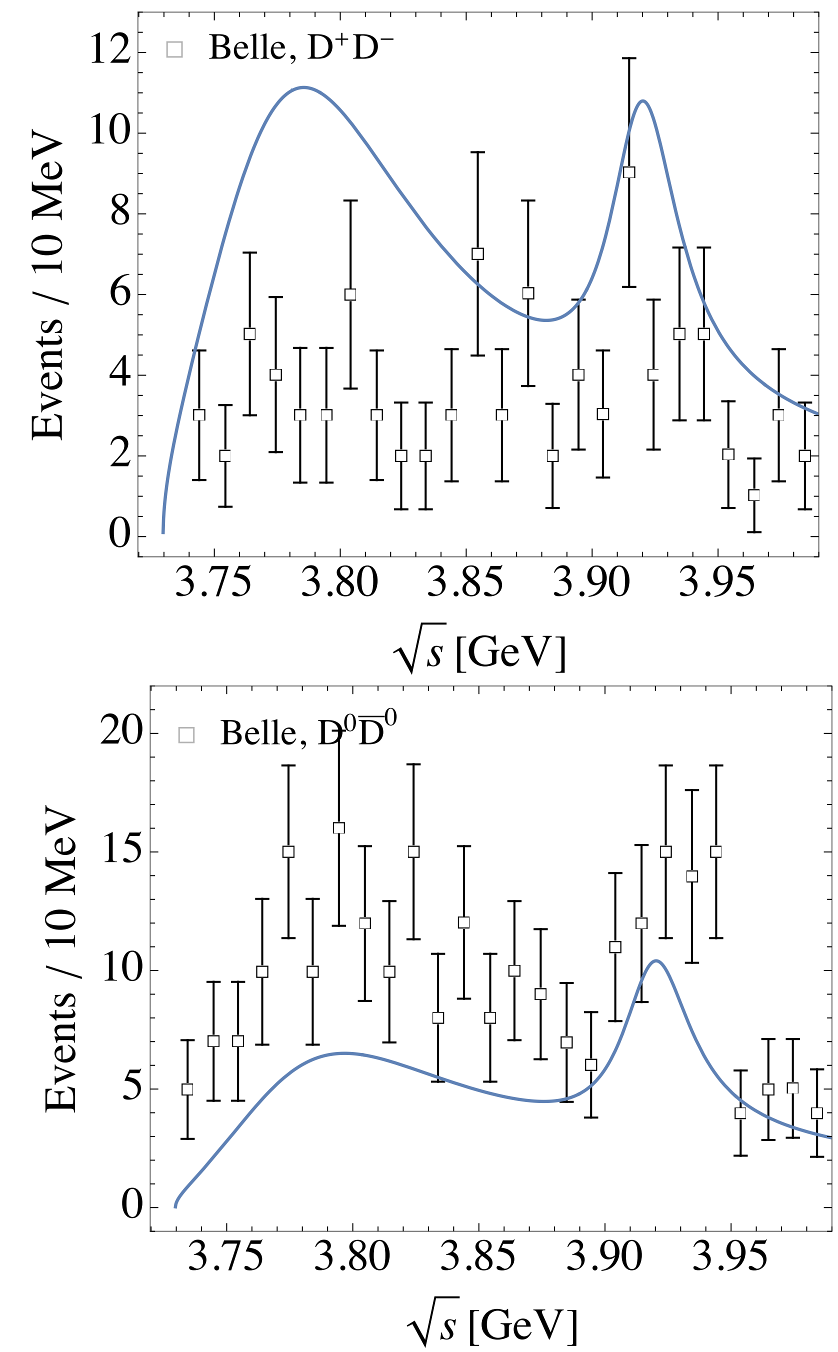
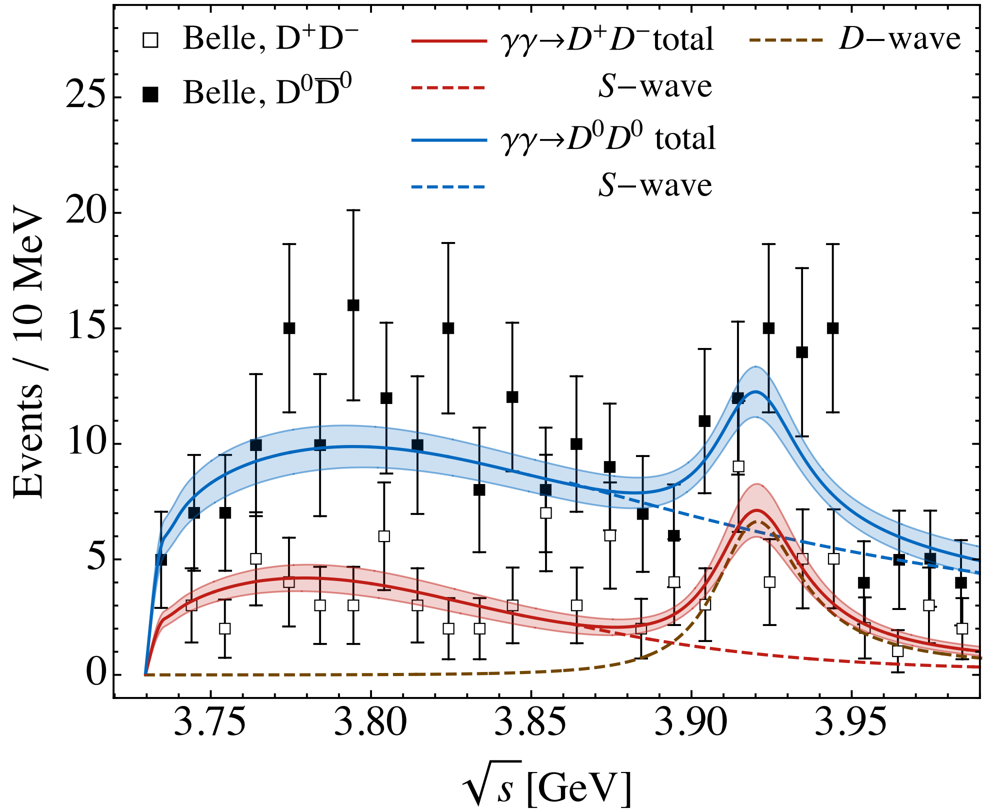


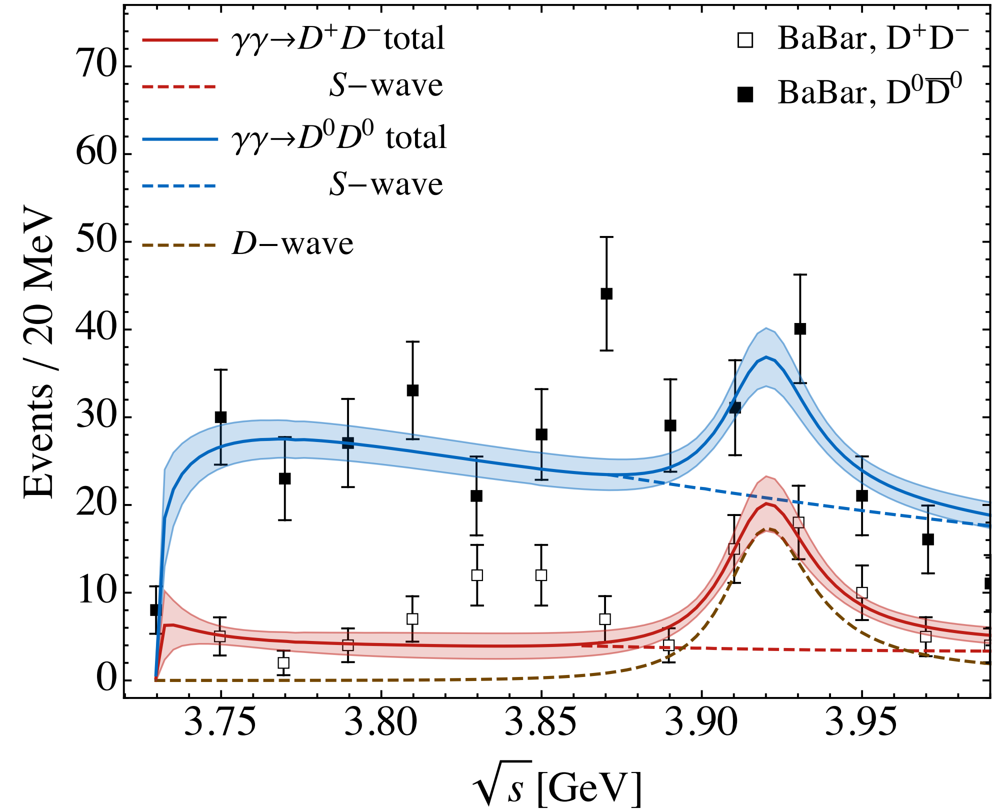
~~$\sqrt{s_p} = 3772.2 - 50\,i$ MeV~~



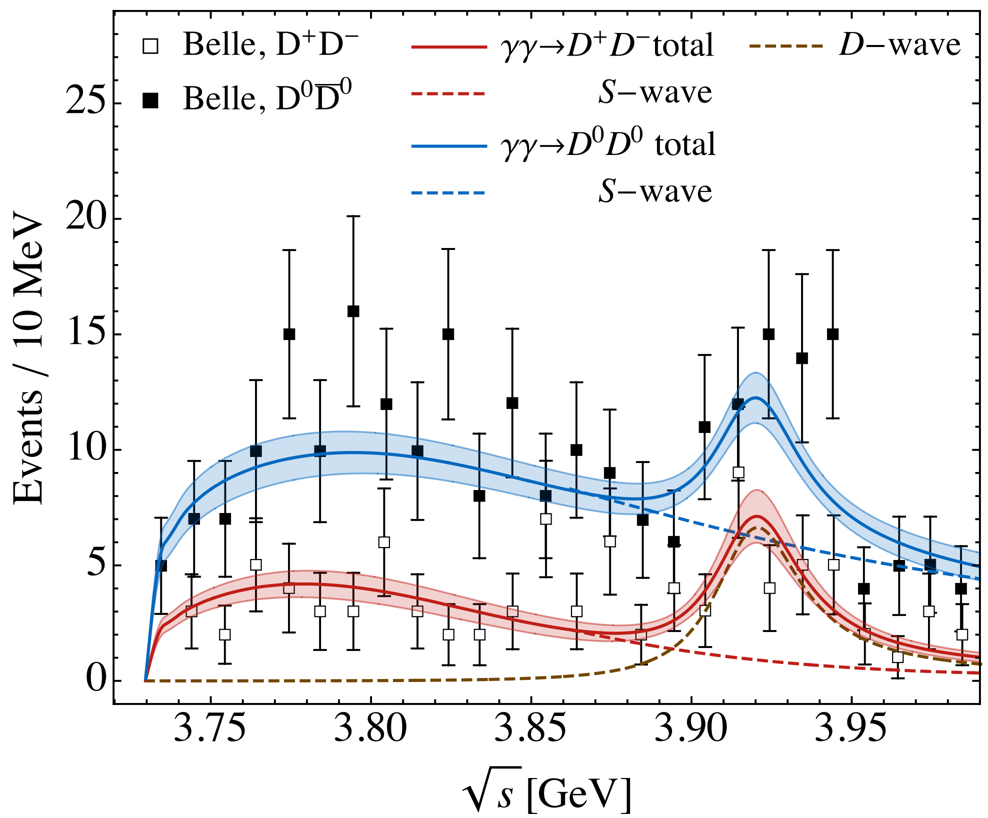
The fit to combined $\sigma_c(s) + \sigma_n(s)$ data **does not** describe individually $\sigma_c(s), \sigma_n(s)$

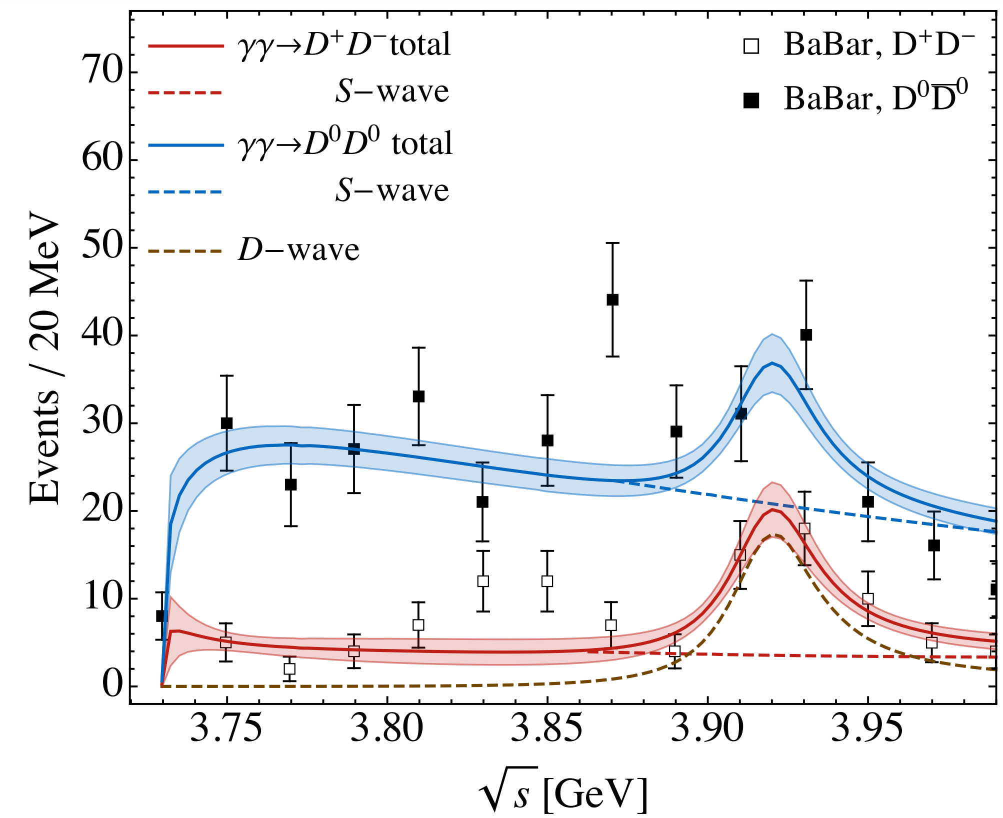
Analysis of $\gamma\gamma \to D^+D^-$ and $\gamma\gamma \to D^0\bar{D}^0$ data





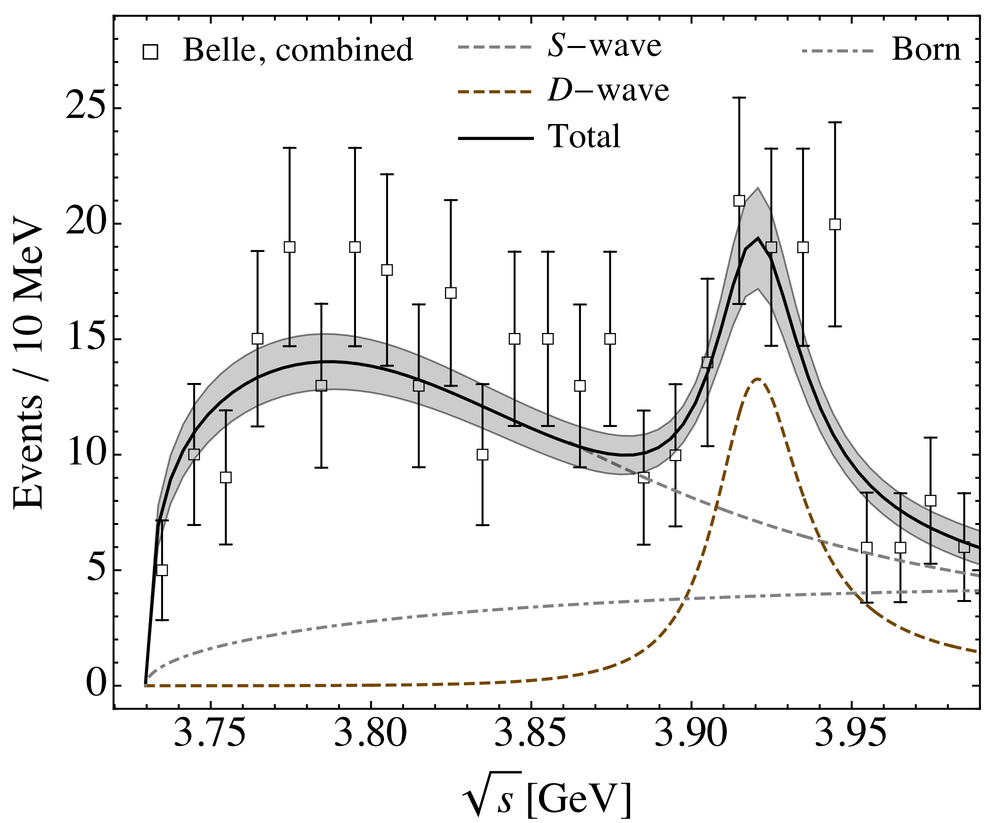
Analysis of $\gamma\gamma \to D^+D^-$ and $\gamma\gamma \to D^0\bar{D}^0$ data

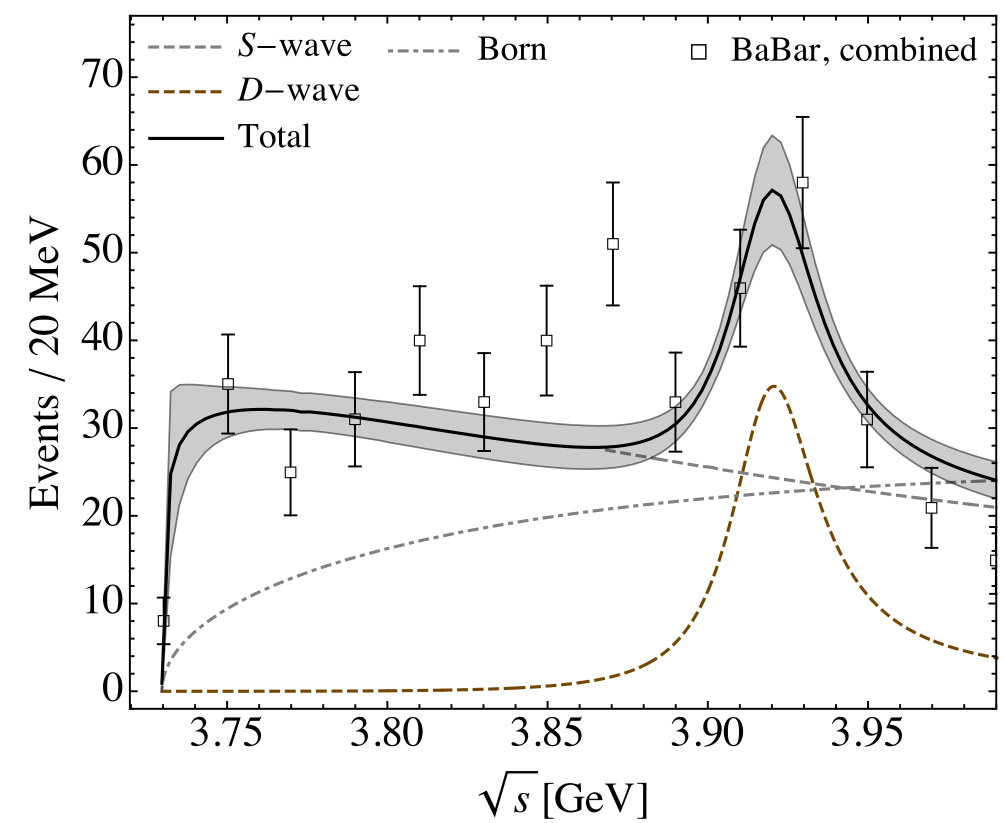




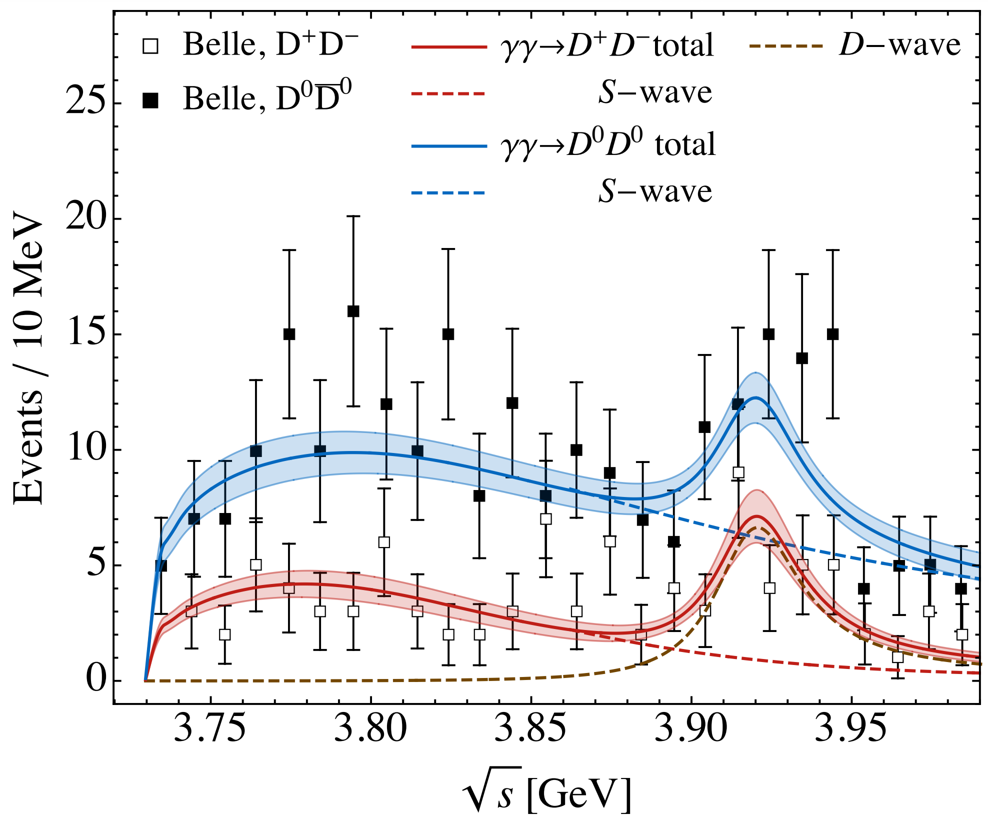
Bound state: $\sqrt{s_B} = 3695(4)$ MeV

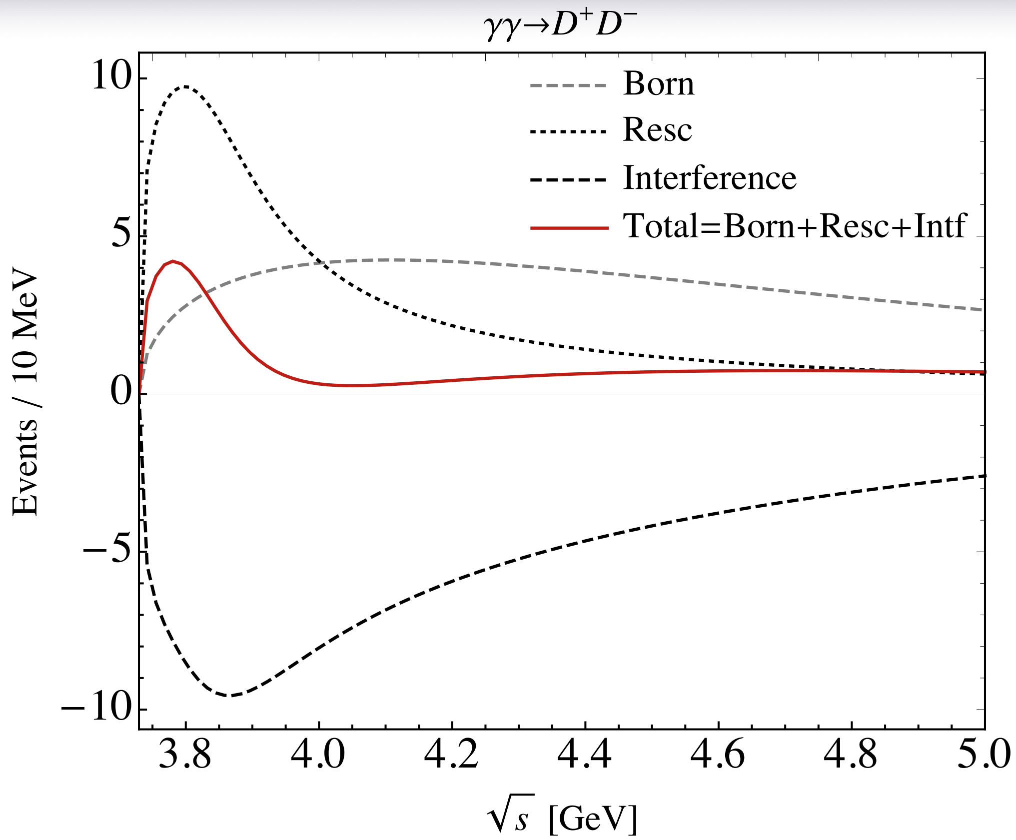
Bound state: $\sqrt{s_B} = 3669(18)$ MeV



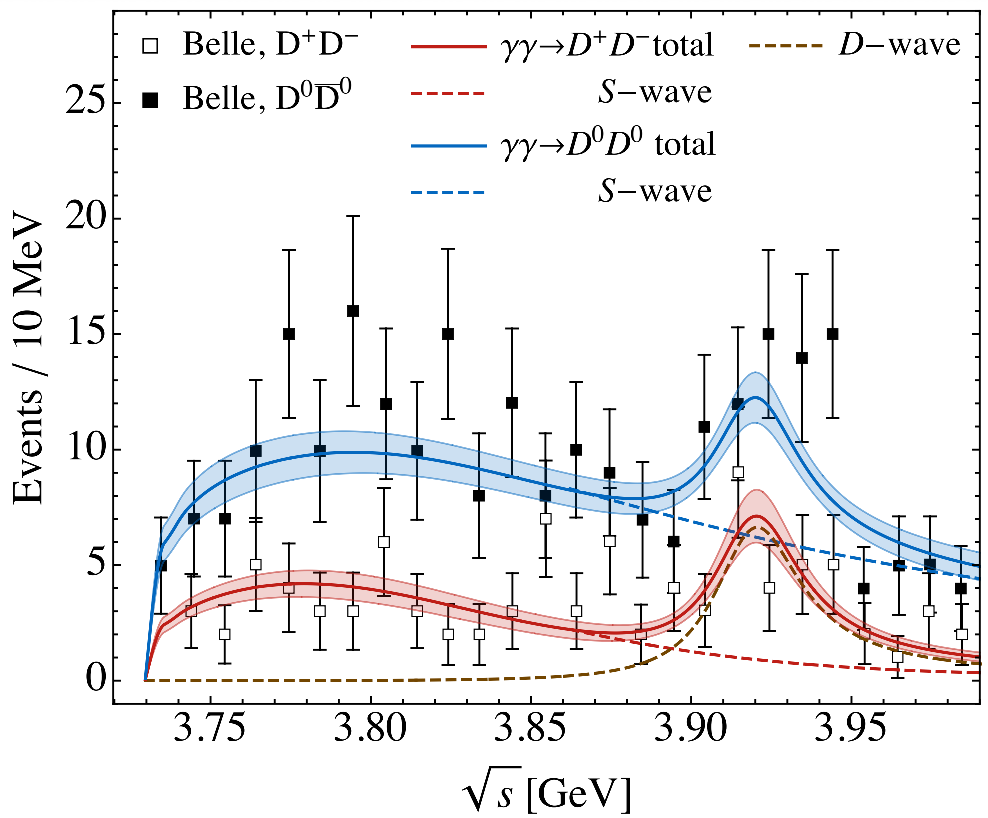


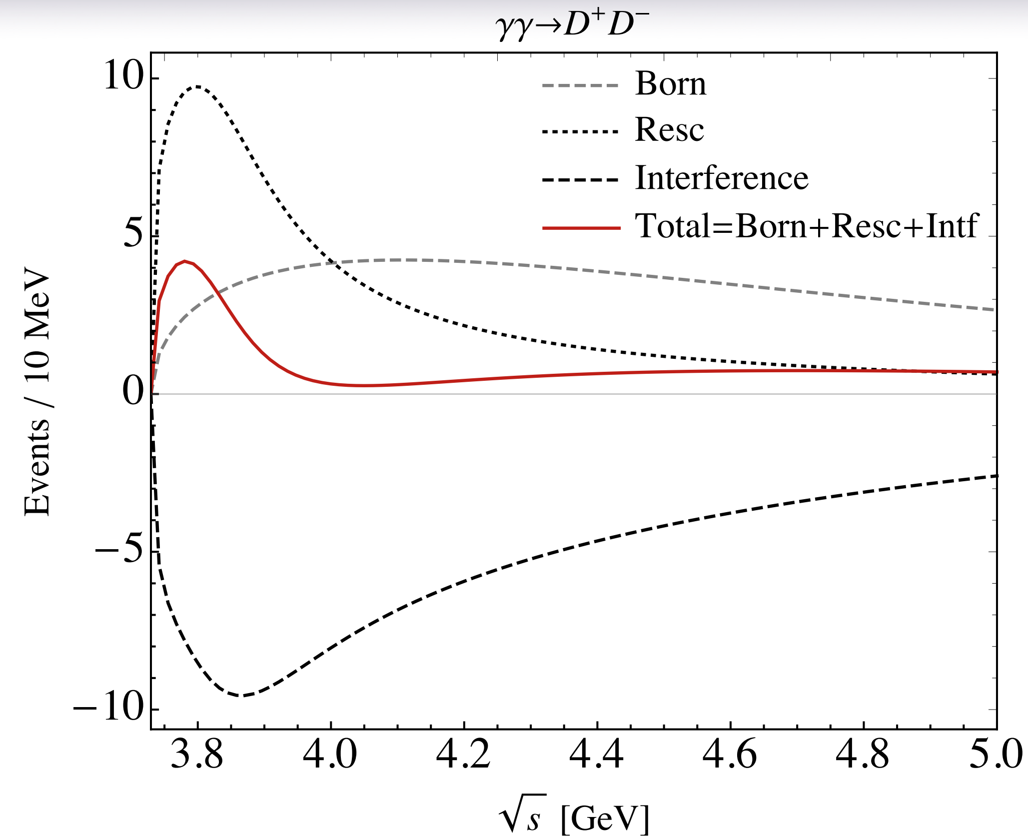
Destructive interference





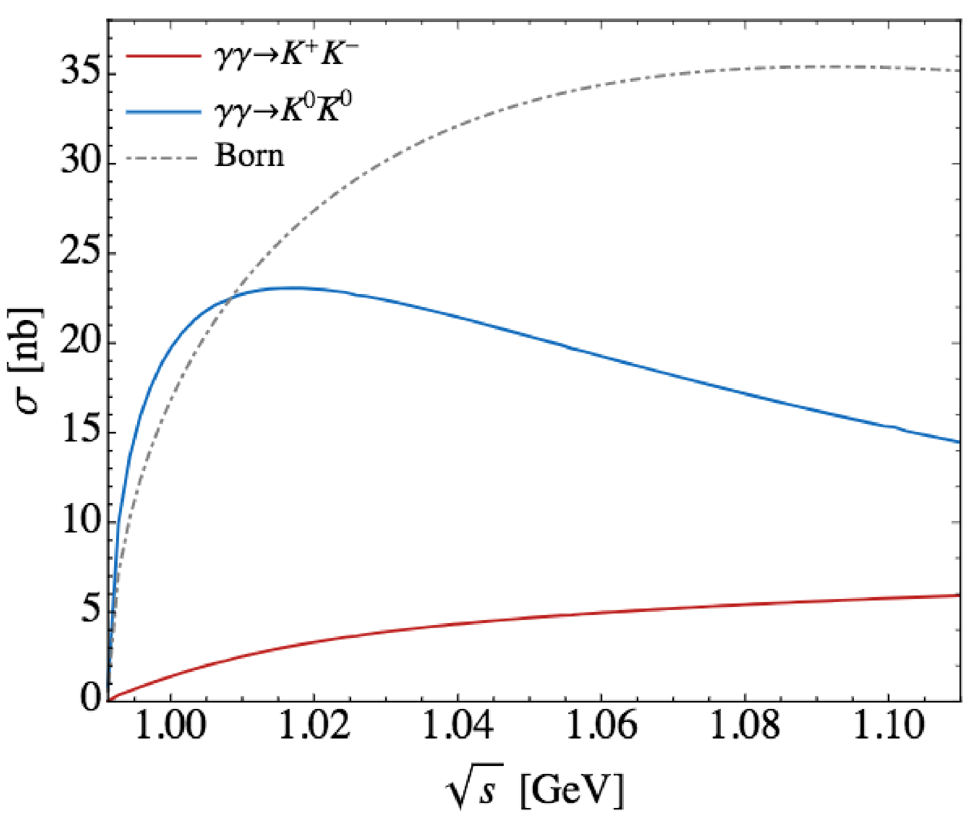
Destructive interference

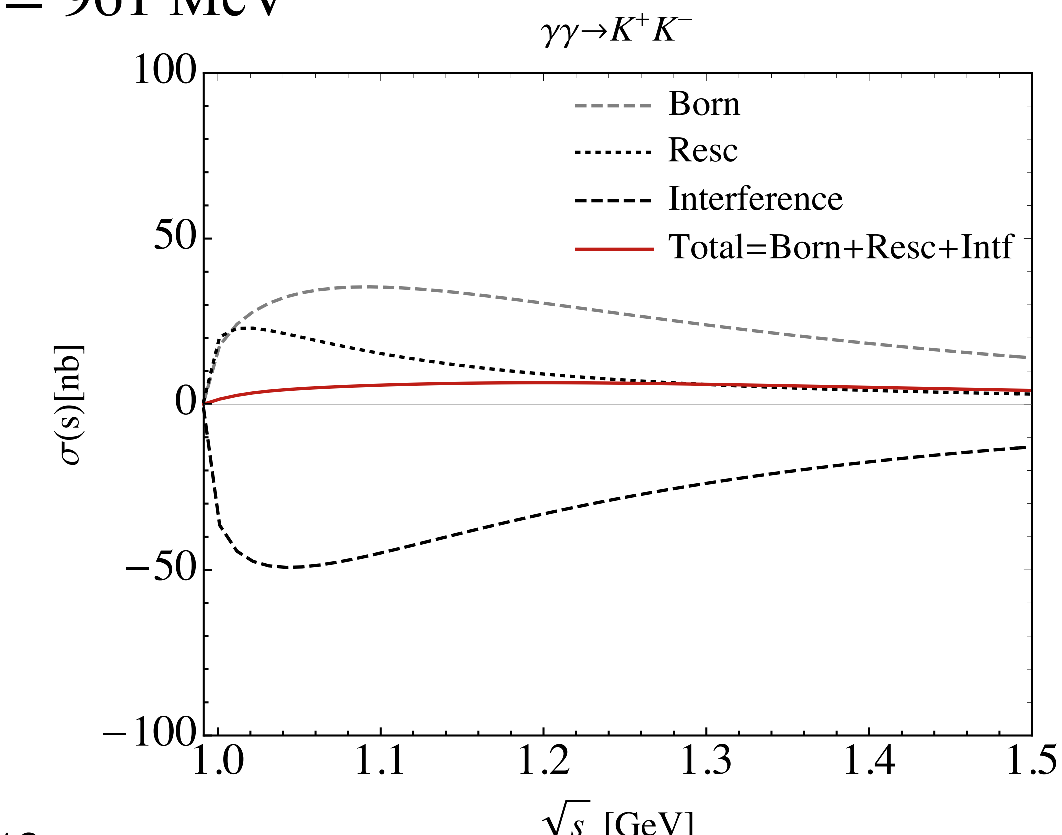




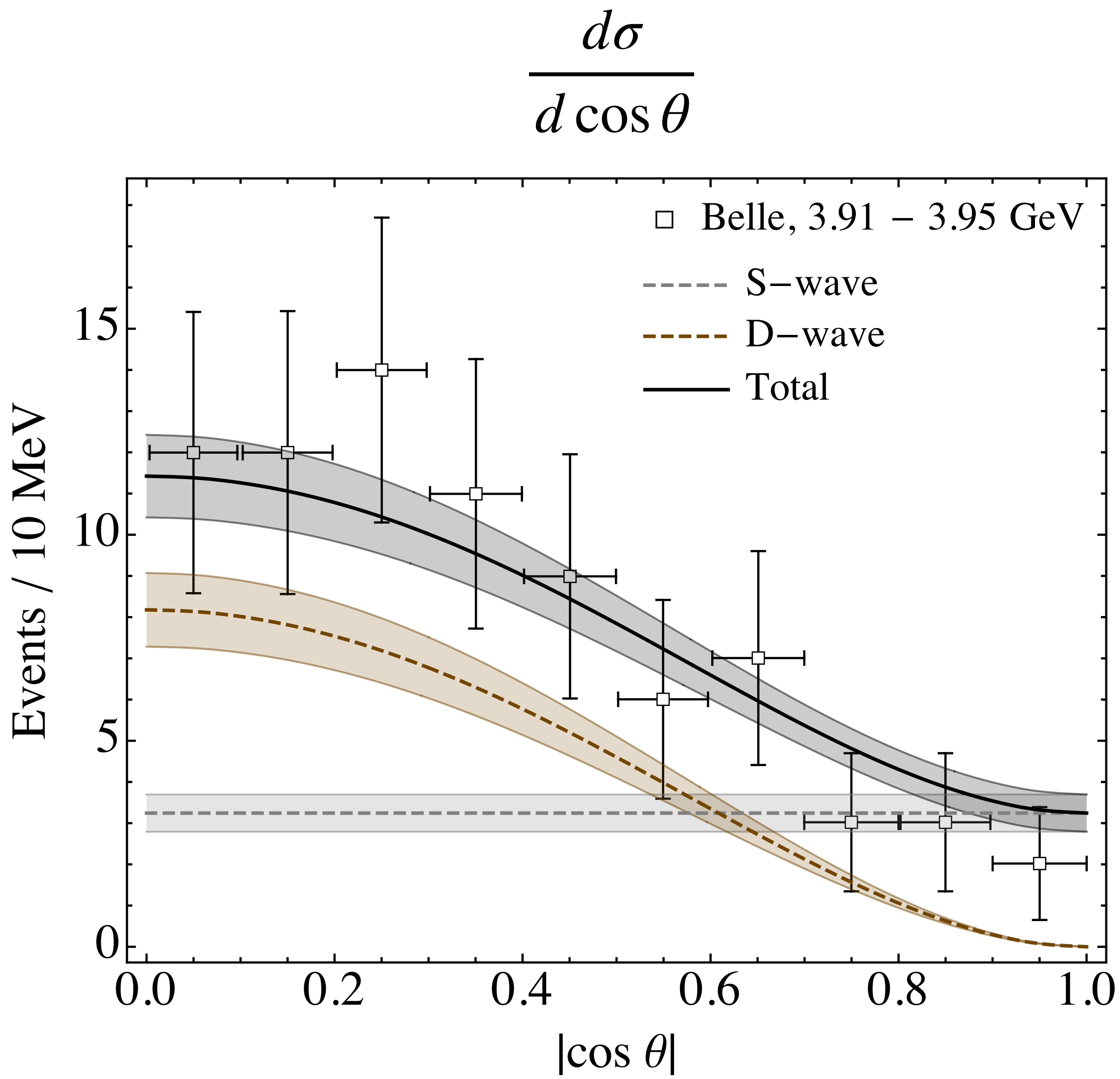
Consider again $\{\pi\pi, K\bar{K}\}$ coupled channel system and switch off $\pi\pi$ channel

$\Longrightarrow f_0(980)$ becomes a $K\bar{K}$ bound state with $\sqrt{s_B} = 961$ MeV

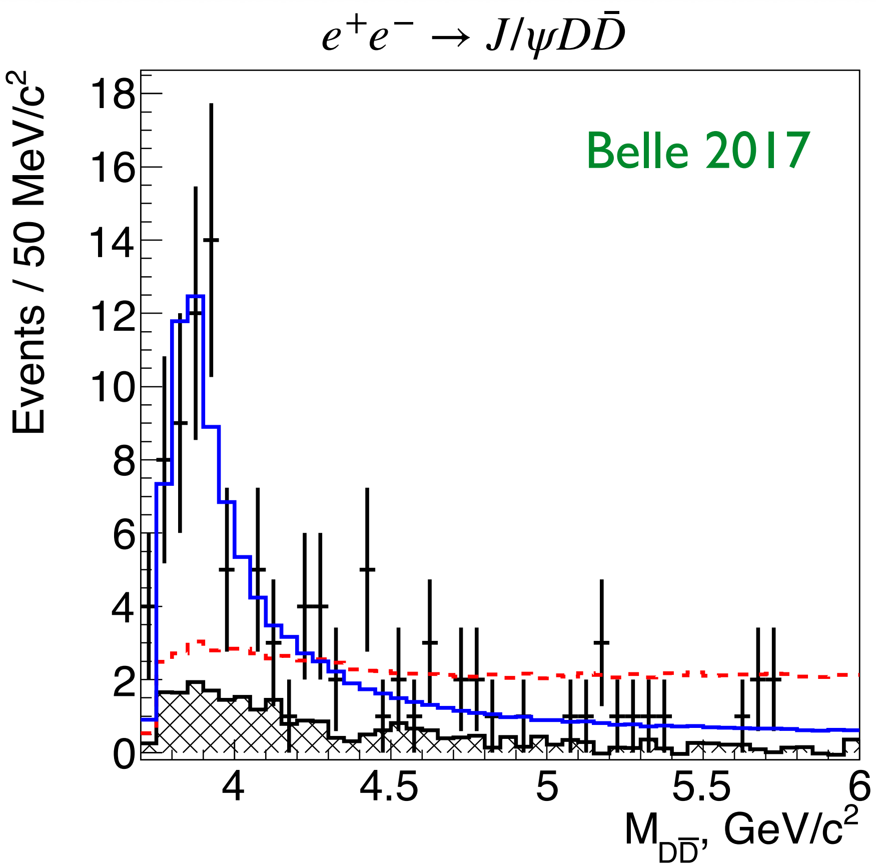




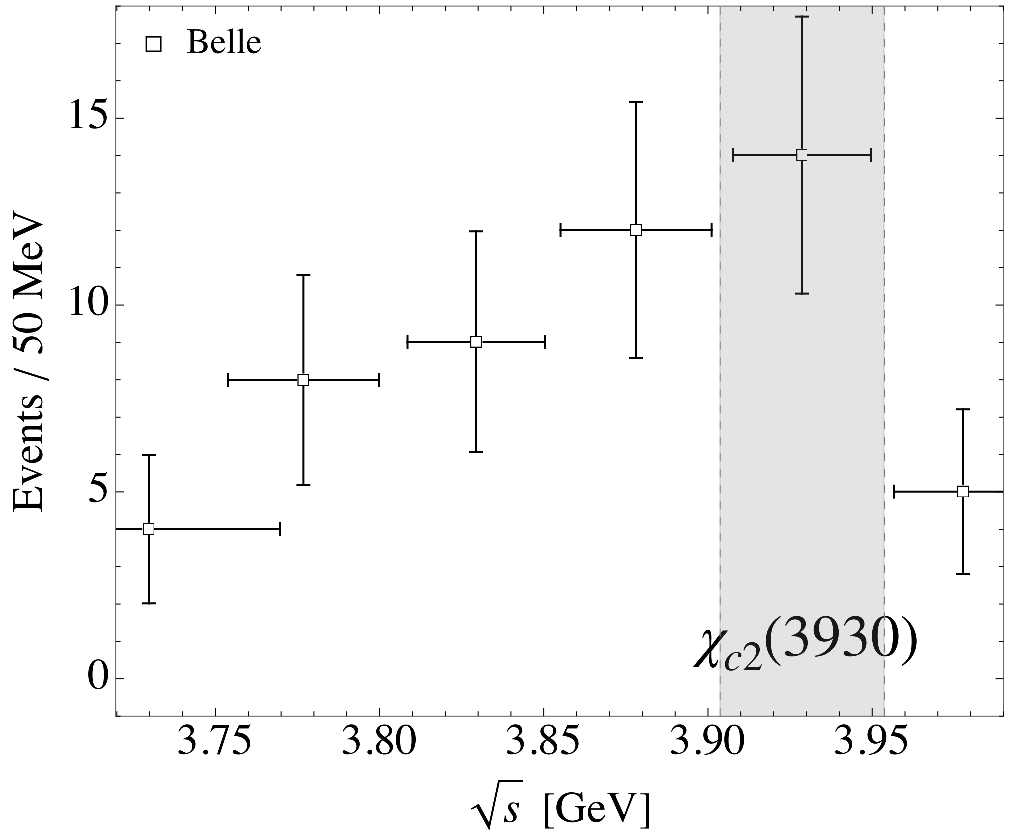
$\gamma\gamma \to D\bar{D}$ angular distribution



Angular distribution is mainly D-wave: however, one cannot exclude an additional small S-wave contribution from $\chi_{c0}(3915)$

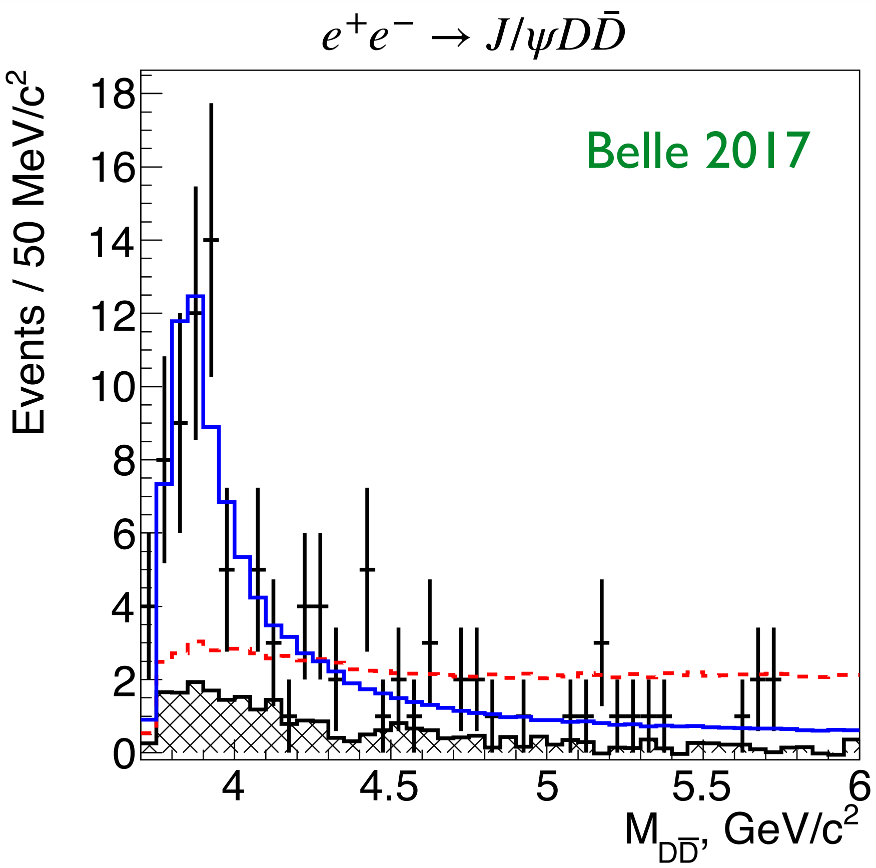


only 6 data points below 4 GeV

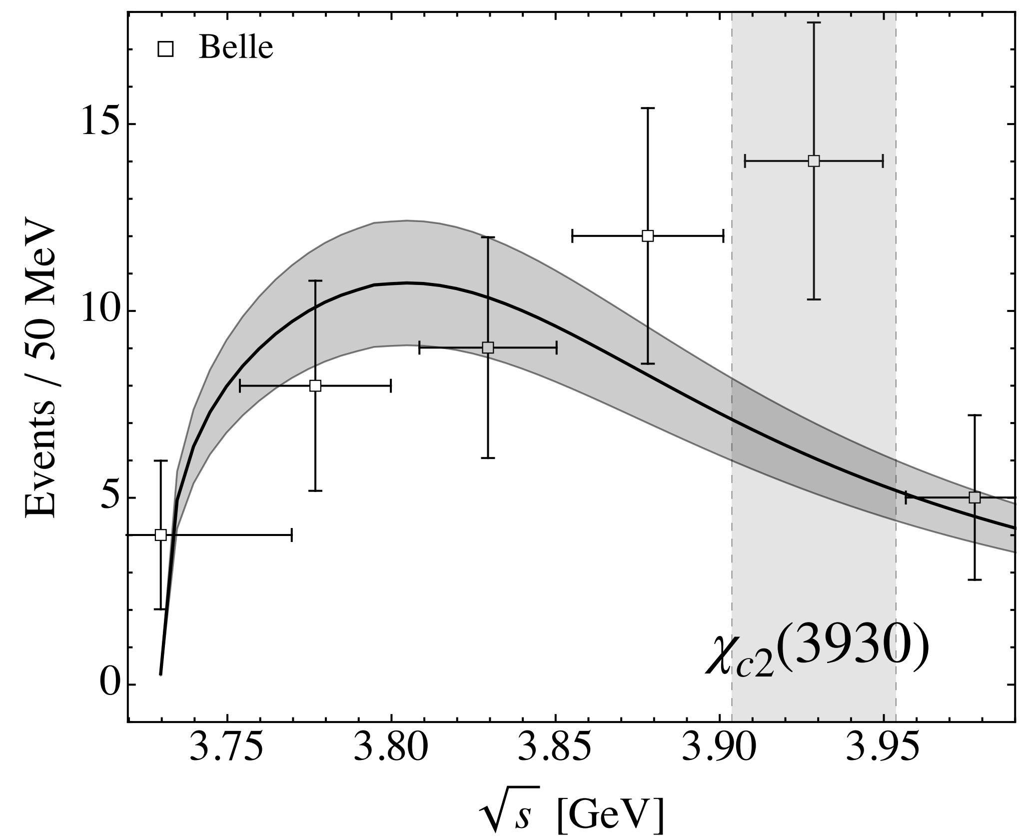


- No realistic estimates can be done from this data alone; full experimental dataset is needed

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



only 6 data points below 4 GeV



- No realistic estimates can be done from this data alone; full experimental dataset is needed
- Post-diction based on the obtained $D\bar{D}$ Omnes function shows a good description of the S-wave region

$$\frac{d\sigma}{d\sqrt{s}} = N \frac{\lambda^{1/2}(s, q^2, m_{J/\psi}^2)\, \lambda^{1/2}(s, m_D^2, m_D^2)}{q^6 \sqrt{s}} \left| D_{D\bar{D}}^{-1}(s) \right|^2$$

the only fitting parameter

- Our results based on $\gamma\gamma \to D\bar{D}$ data are consistent with $e^+e^- \to J/\psi D\bar{D}$ data

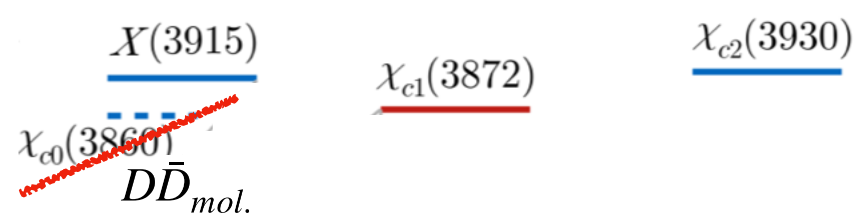
☑ Dispersive analysis of the $\gamma\gamma \to D^+D^-, D^0\bar{D}^0$ data, consistency check with the $e^+e^- \to J/\psi D\bar{D}$ data

☑ No broad resonance corresponding to $X(3860)$ found

☑ Bound state below the $D\bar{D}$ threshold, $\sim D\bar{D}$ molecule

☑ More data is needed: Belle II $\gamma\gamma \to D\bar{D}$, BESIII decay $\psi(3770) \to D\bar{D}\gamma$, PANDA …

Still an open question about $\chi_{c0}(2P)$:
is it a $D\bar{D}$ molecular or it is a X(3915)?



☐ Dispersion theory can be applied to many other exciting processes

☐ Light: $\gamma\gamma \to \pi^0\eta, K\bar{K}$; $(g-2)_\mu$ HLBL contributions

☐ $\{J/\psi J/\psi,\ J/\psi\ \psi(2S)\}$ scattering LHCb

Thank you!

Extra slides

Convergence of conformal expansion

Good convergence with 3 parameters in conformal mapping expansion $\Longrightarrow$ there is no need for more parameters

$$U_{DD}(s) \simeq \sum_{n=0}^{\infty} C_n \xi^n(s)$$