Dispersive analysis of the $\gamma\gamma \to D\bar{D}$ data and the confirmation of the $D\bar{D}$ bound state

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DFG Deutsche Forschungsgemeinschaft
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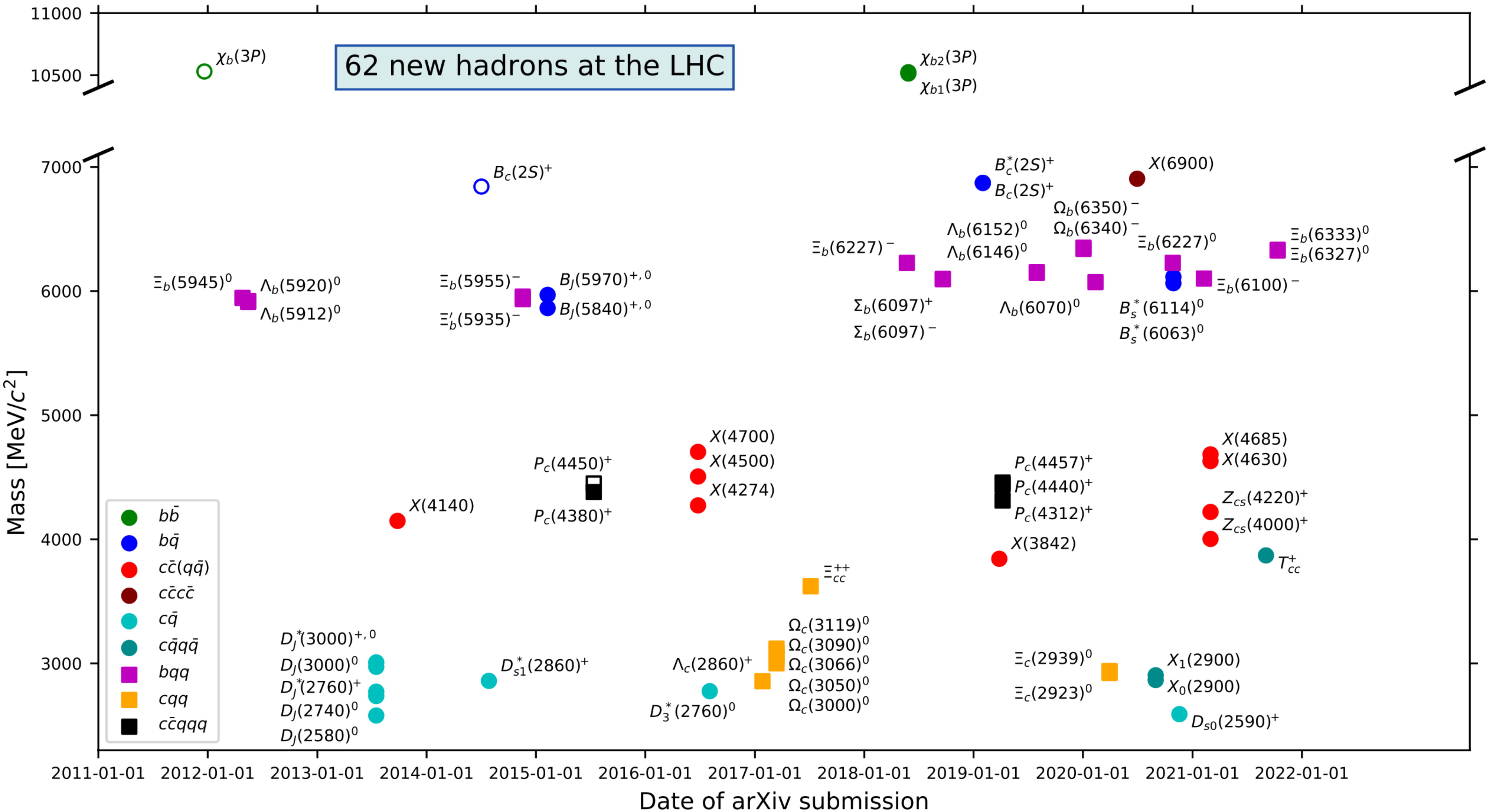
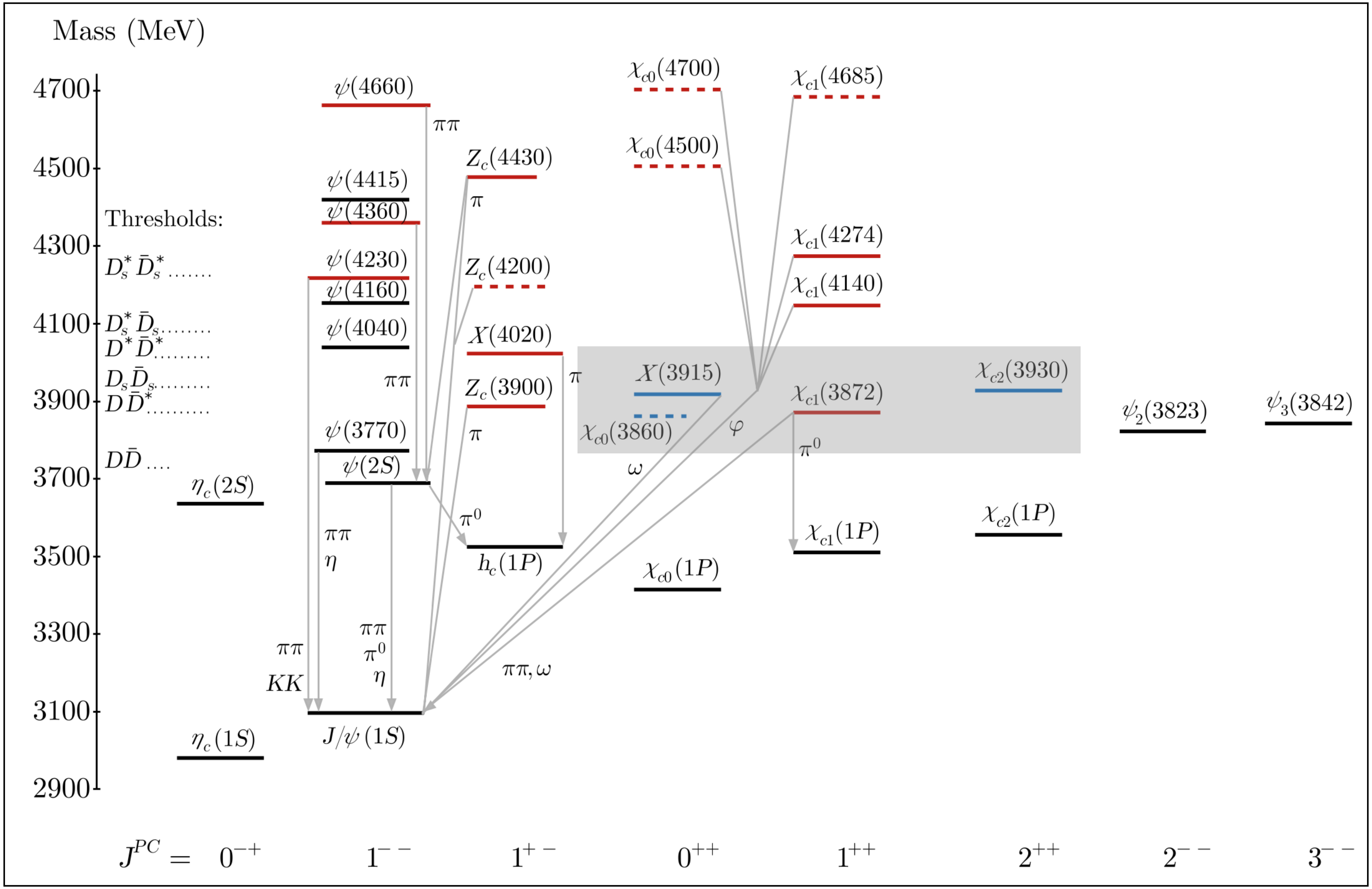
New states



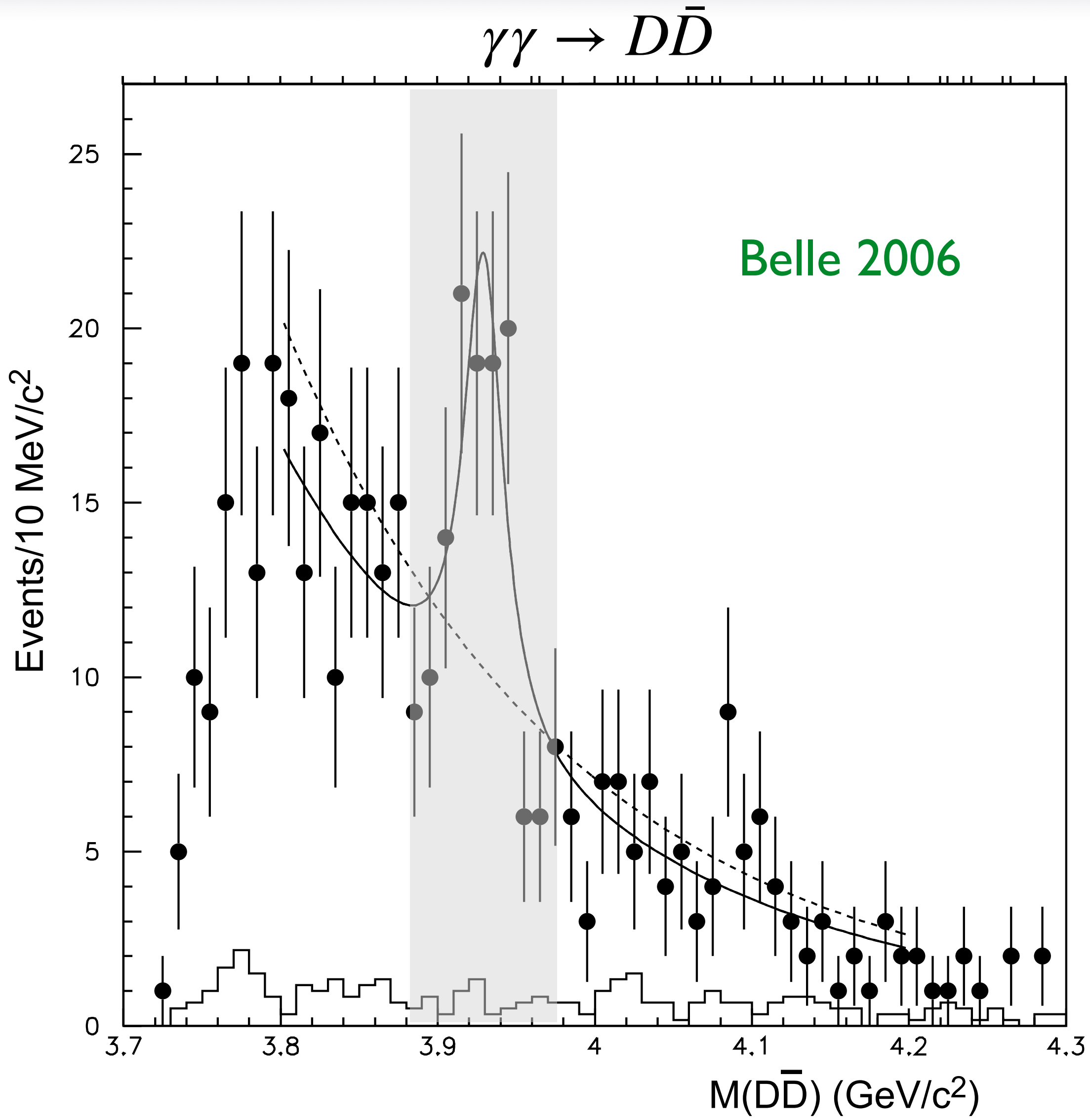
+ data from Babar, Belle, COMPASS, …

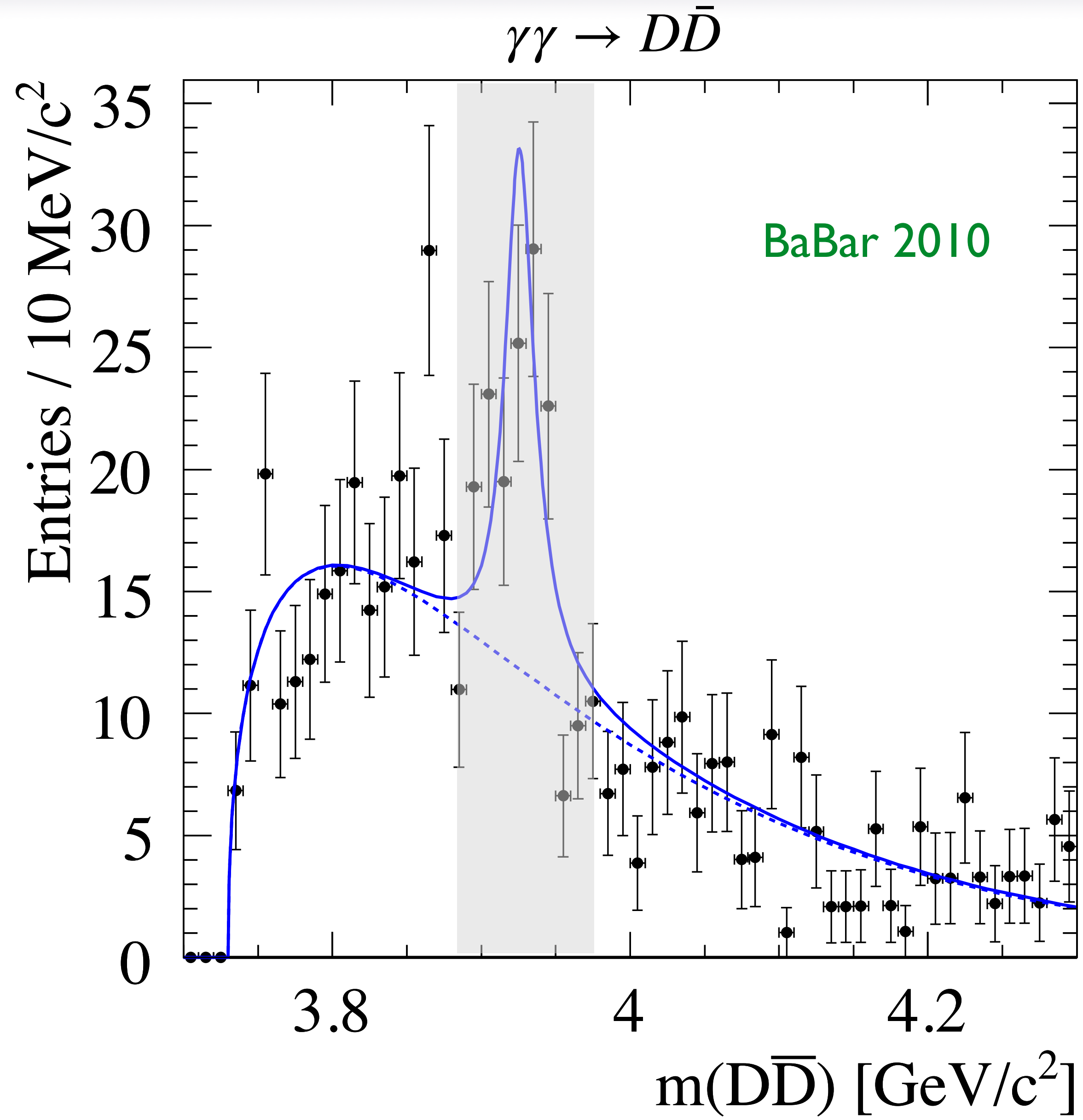
What are we looking for?



PDG 2021

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



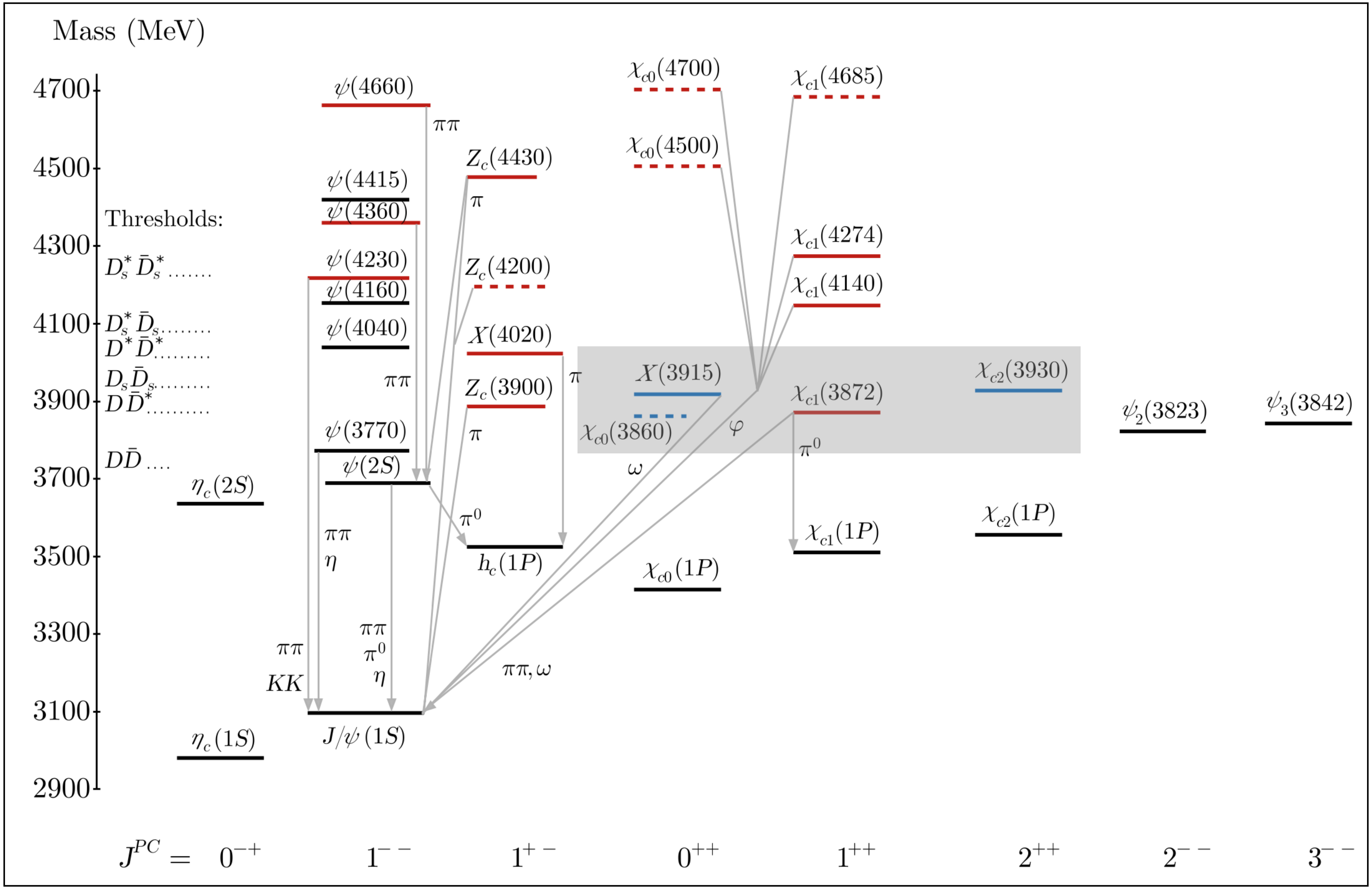


LHCb, 2019: $pp \to D\bar{D}$ + anything
LHCb, 2020: $B^+ \to D^+D^-K^+$

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

$\chi_{c2}(3930)$	$I^G(J^{PC}) = 0^+(2^{++})$	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, …]

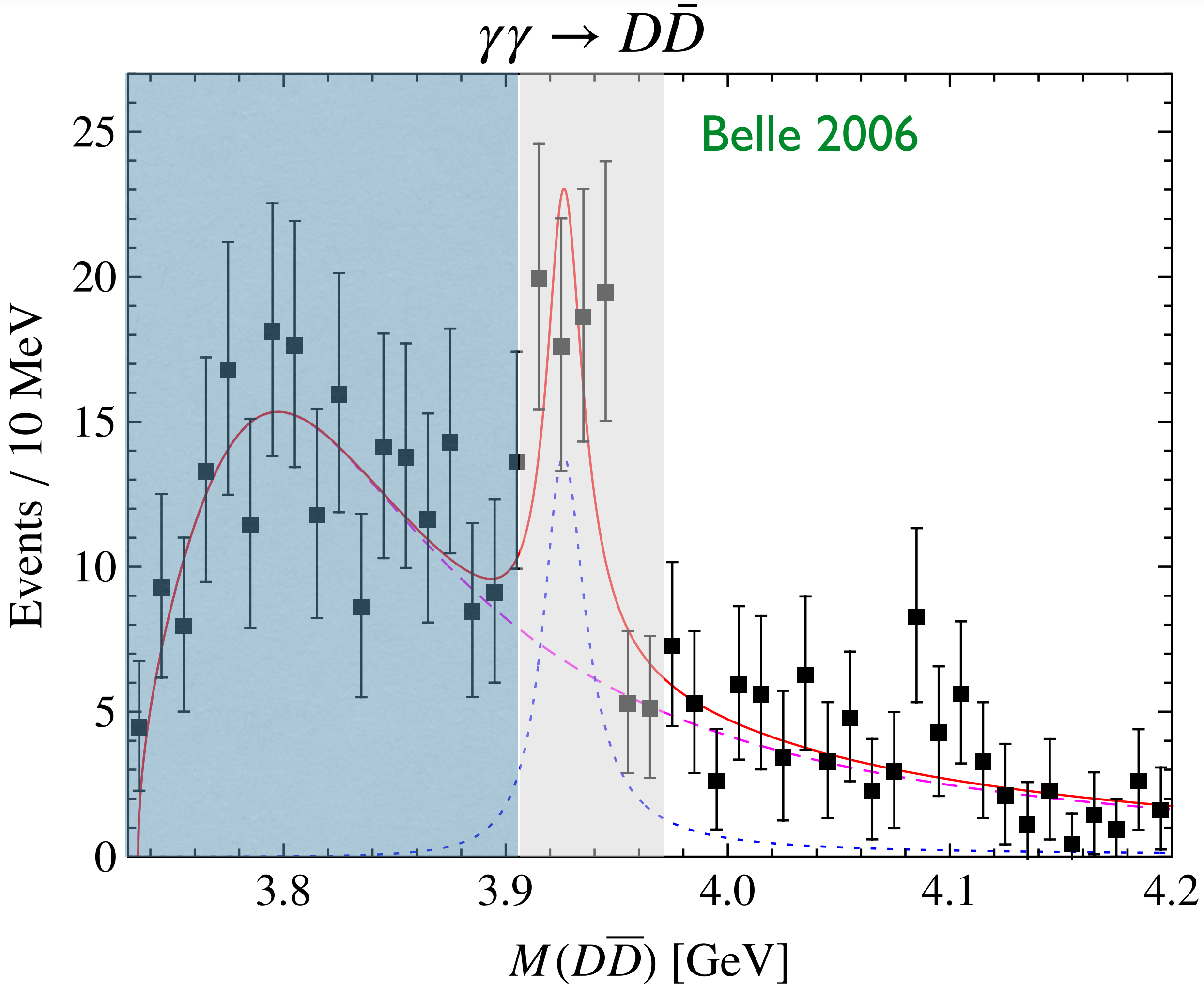
- No decay mode to DD (S-wave) was observed
- The $X(3915) \to J/\psi\omega$ decay should be OZI suppressed
- Narrow, width of ~20 MeV
- Small mass splitting with $\chi_{c2}(3930)$
- Might actually be the same state as $\chi_{c2}(3930)$ [Zhou et al. 2015]

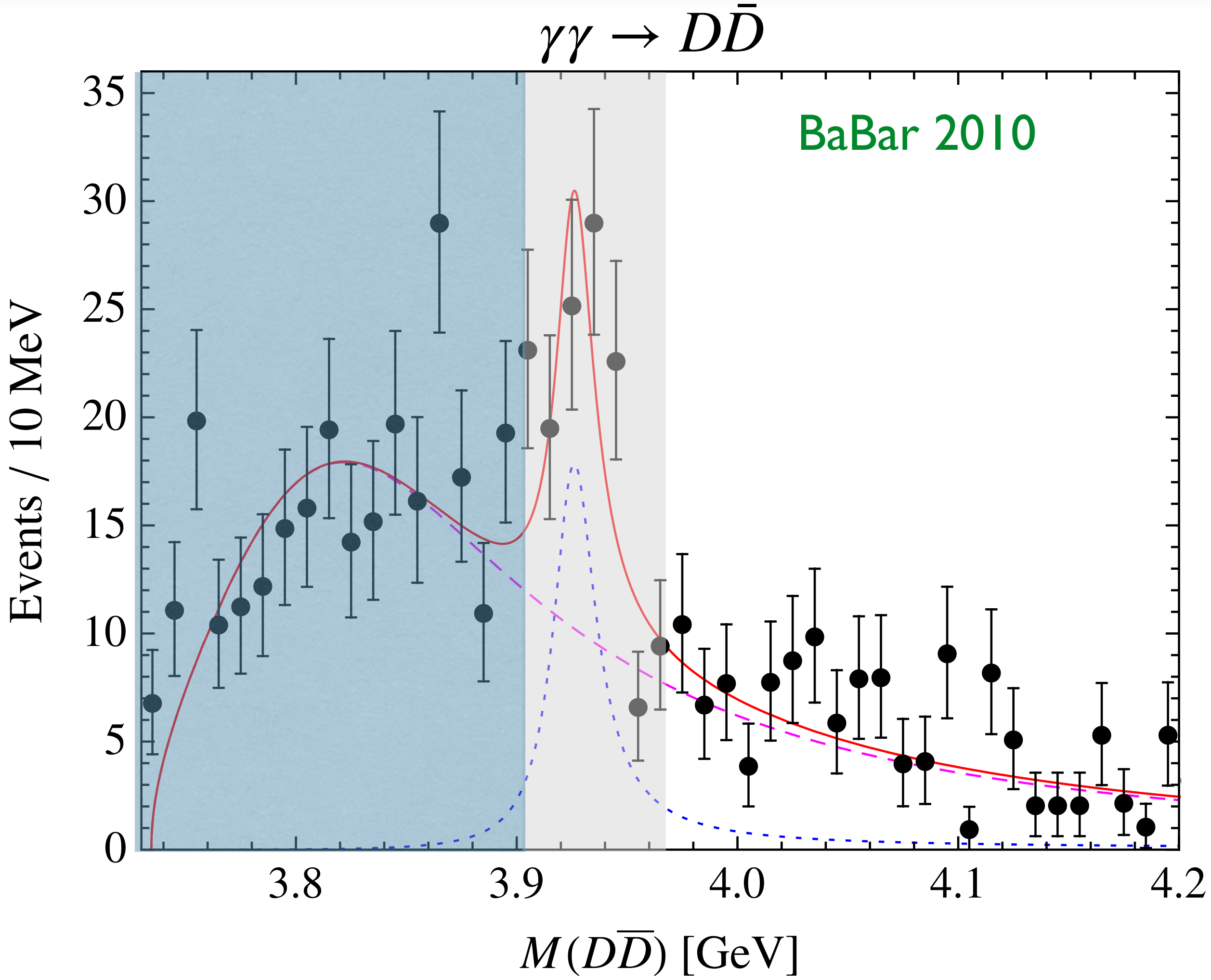
[LHCb 2021] $B^+ \to D^+D^-K^+$
found narrow $J^{PC} = 0^{++}$ resonance around ~3.92 GeV
(amplitude analysis)

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

$\chi_{c0}(3915)$	$I^G(J^{PC}) = 0^+(0^{++})$	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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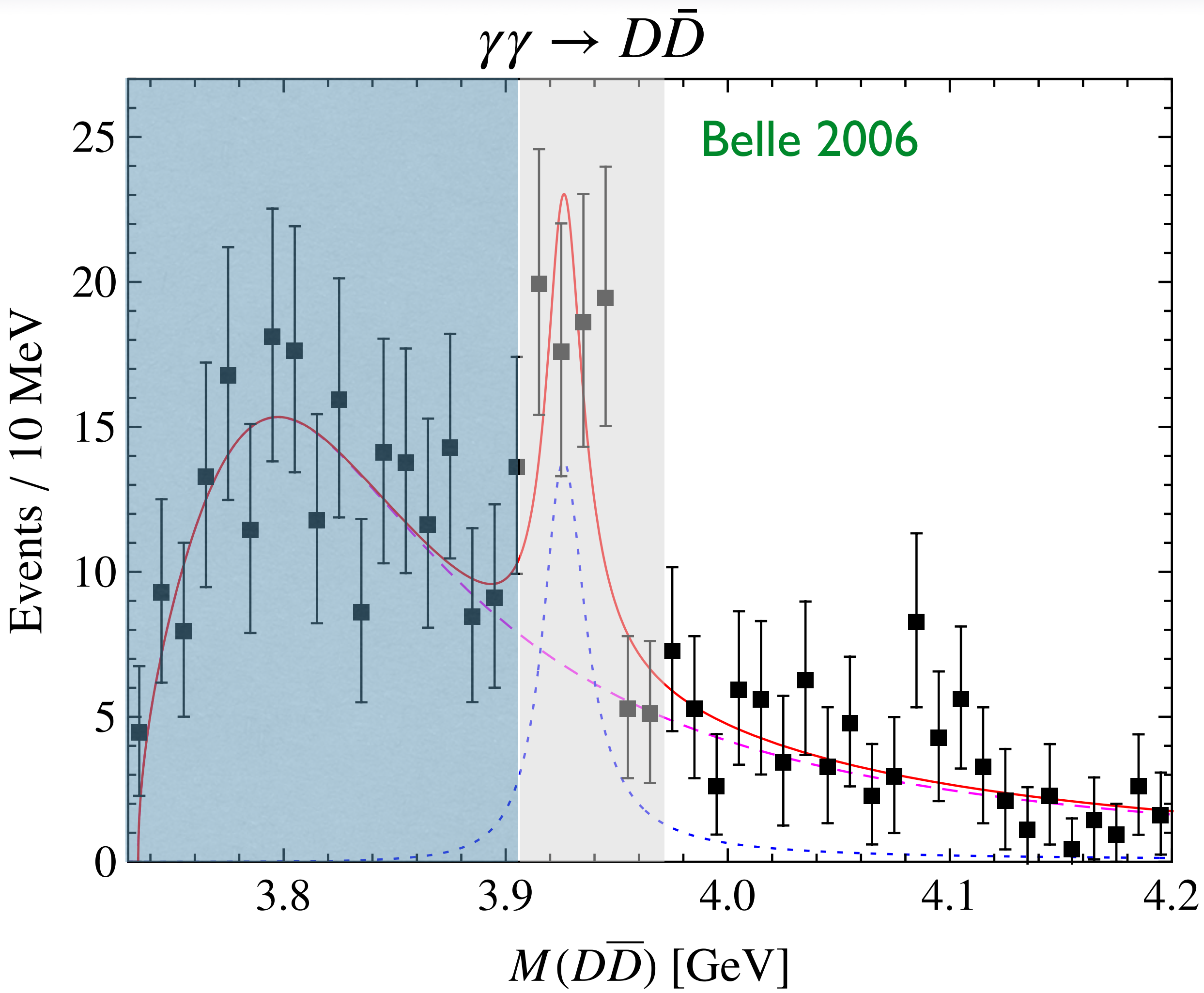
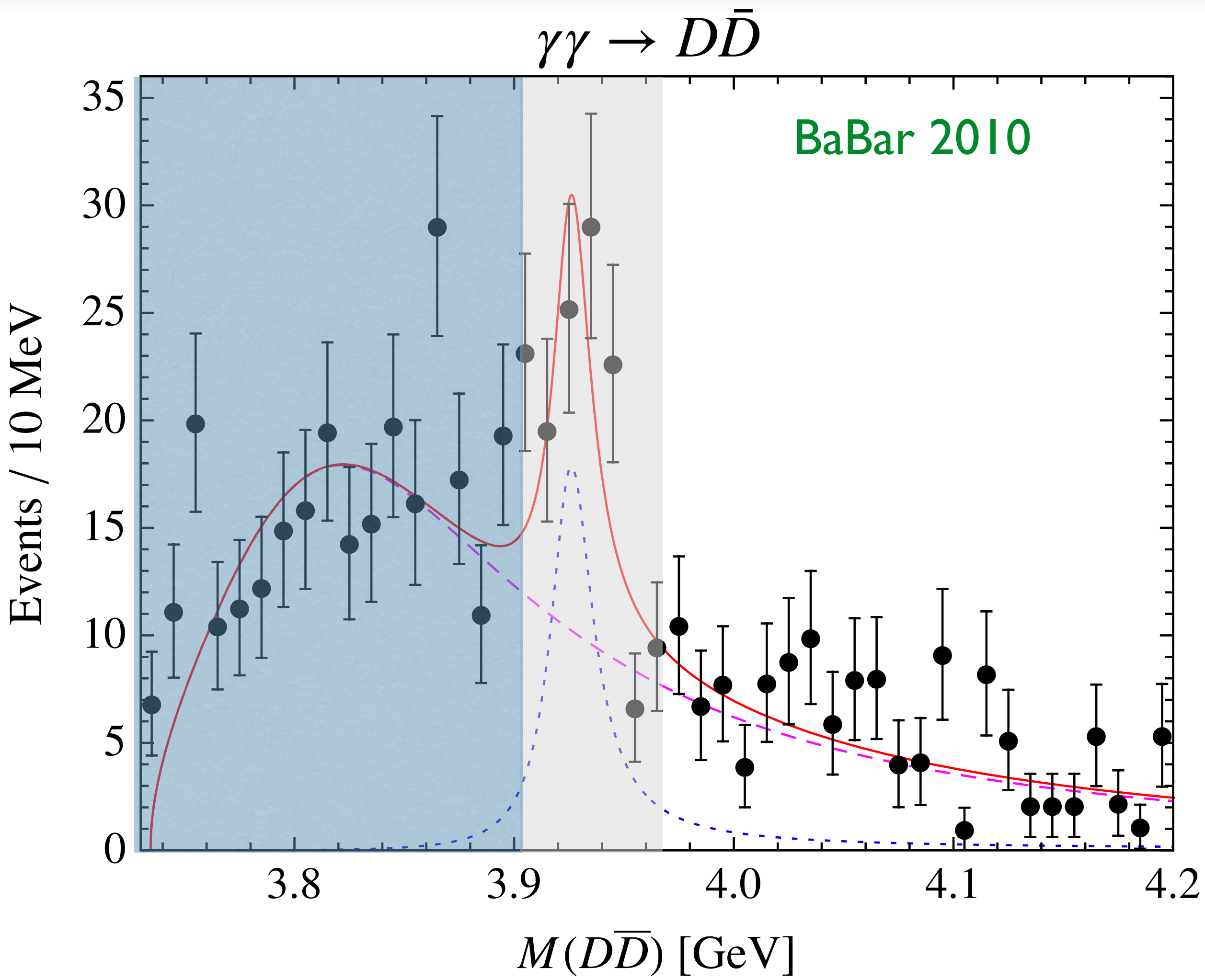




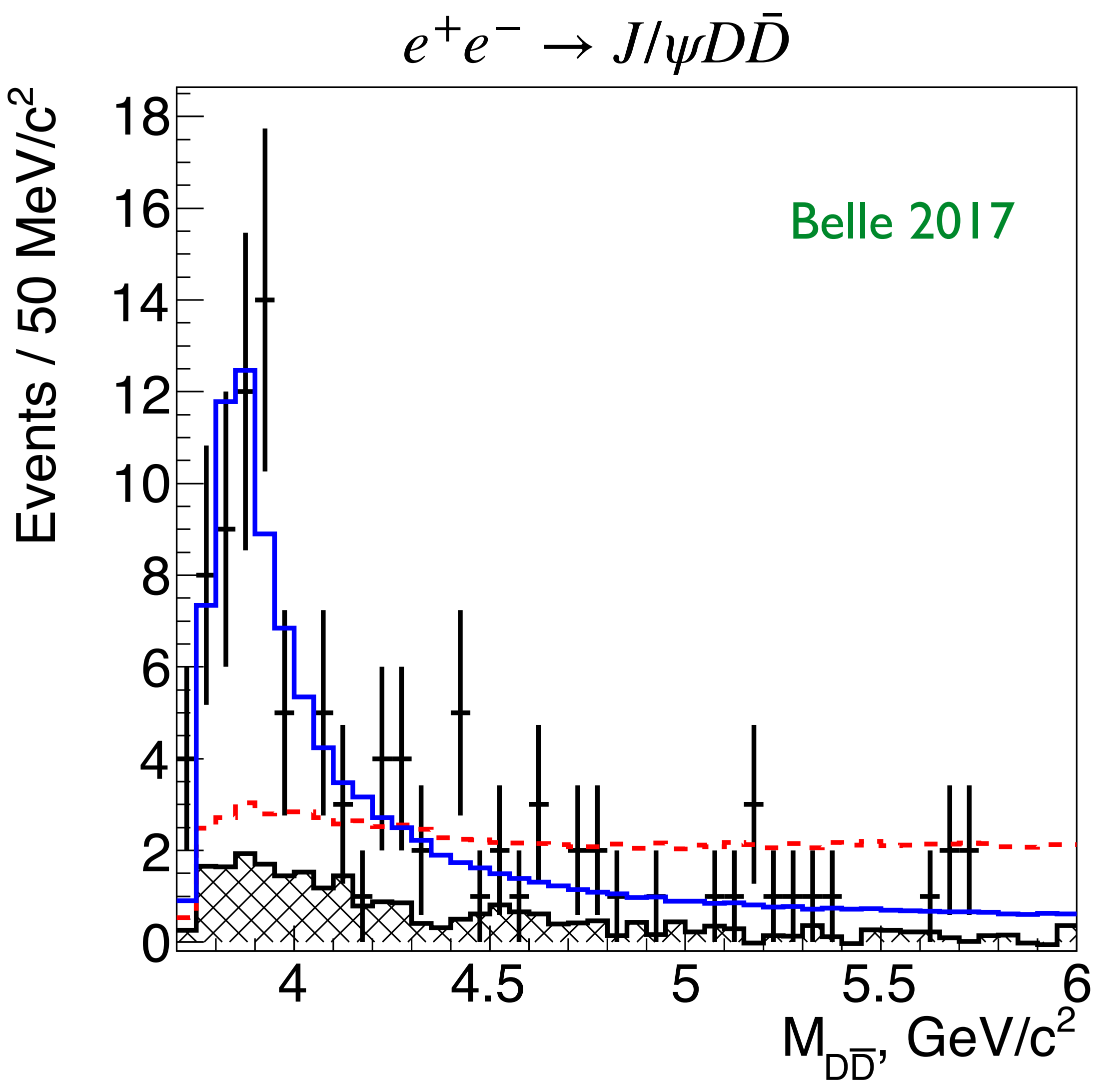
[Guo Meißner 2010]

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 $\chi_{c0}(2P)$?



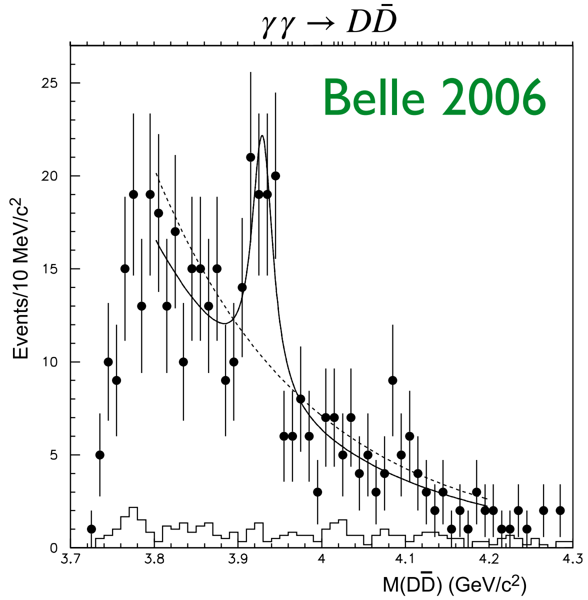
Problems:

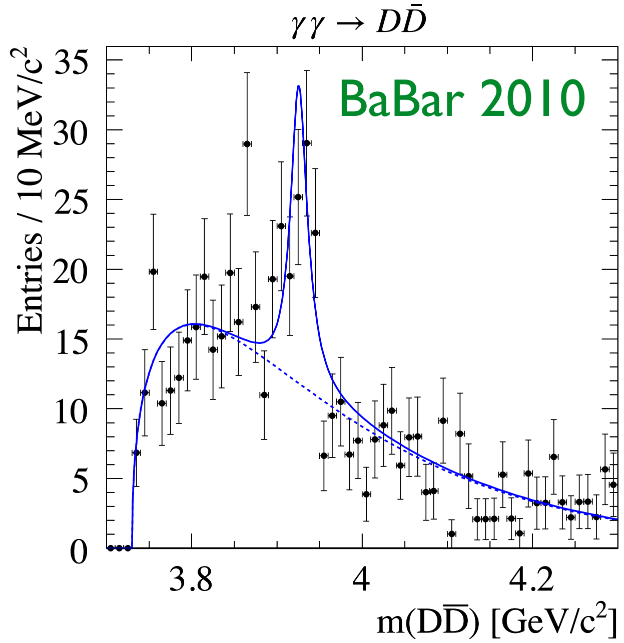
- The $e^+e^- \to J/\psi D\bar{D}$ statistics is rather limited
- LHCb 2021 amplitude analysis of $B^+ \to D^+D^-K^+$ see no evidence for broad $X(3860)$

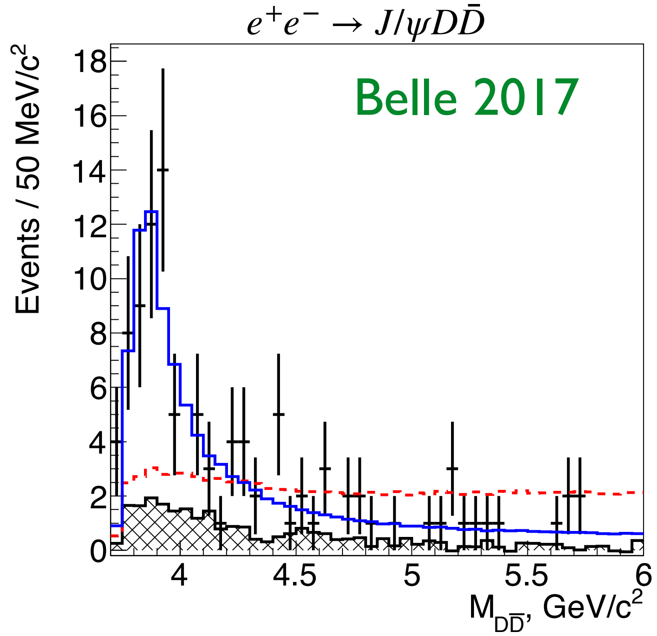
$X(3860)$
?
$\chi_{c0}(3860)$

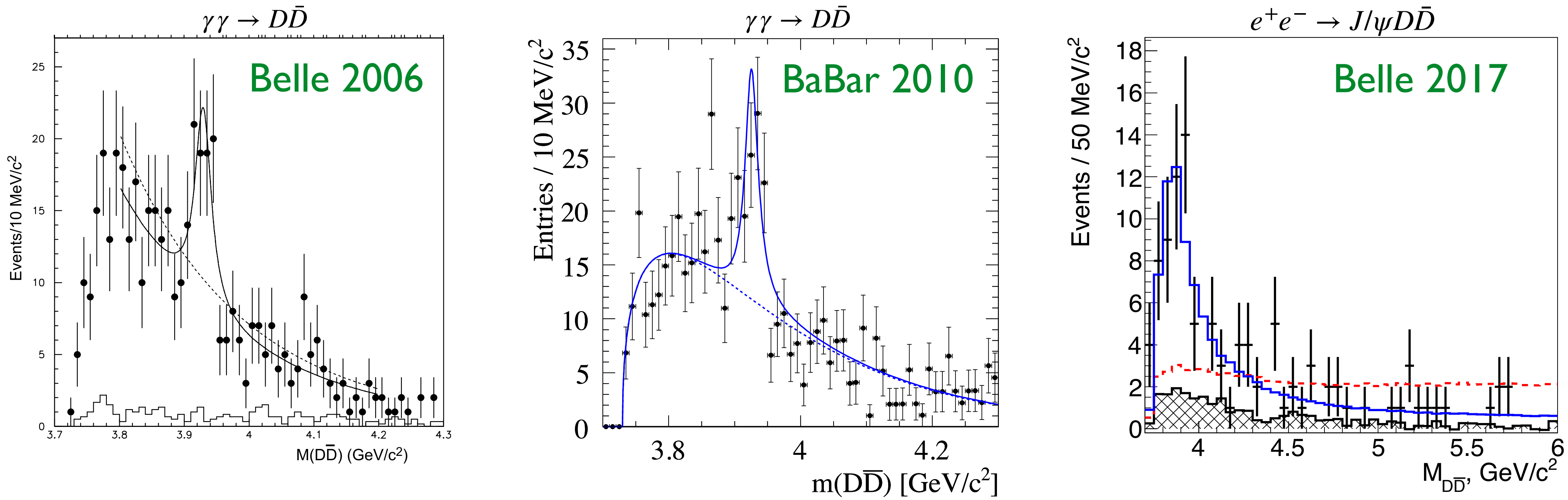
$\chi_{c0}(3860)$	$I^G(J^{PC}) = 0^+(0^{++})$	PDG 2022
$\chi_{c0}(3860)$ MASS		3862^{+50}_{-35} MeV
$\chi_{c0}(3860)$ WIDTH		201^{+180}_{-110} MeV

Theory overview

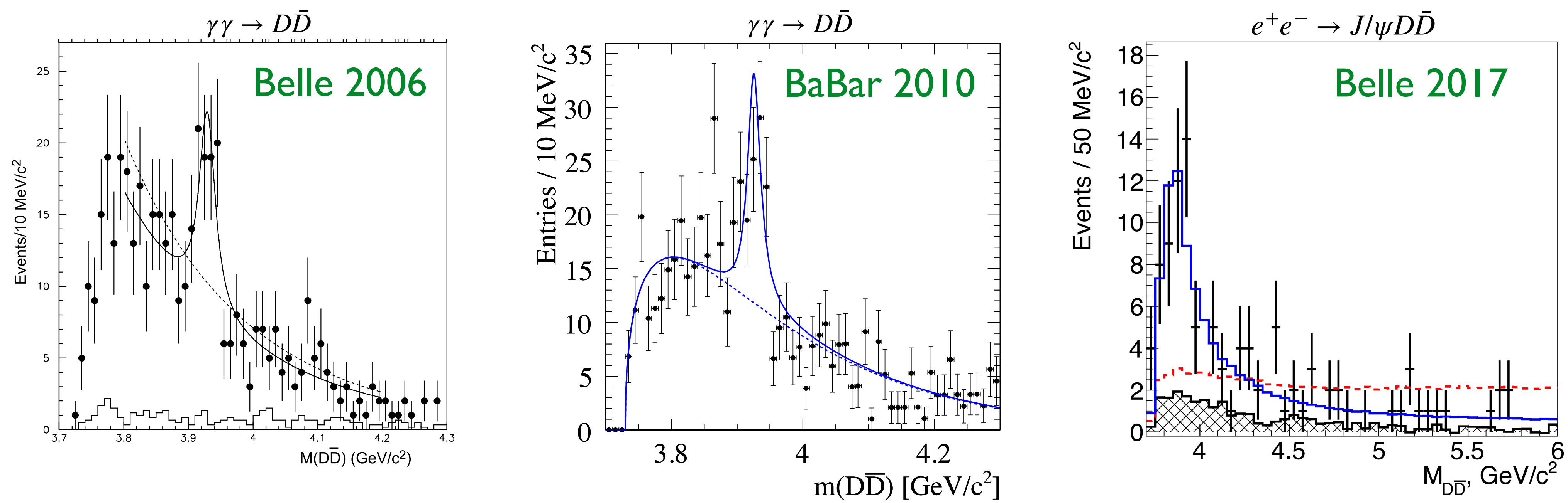




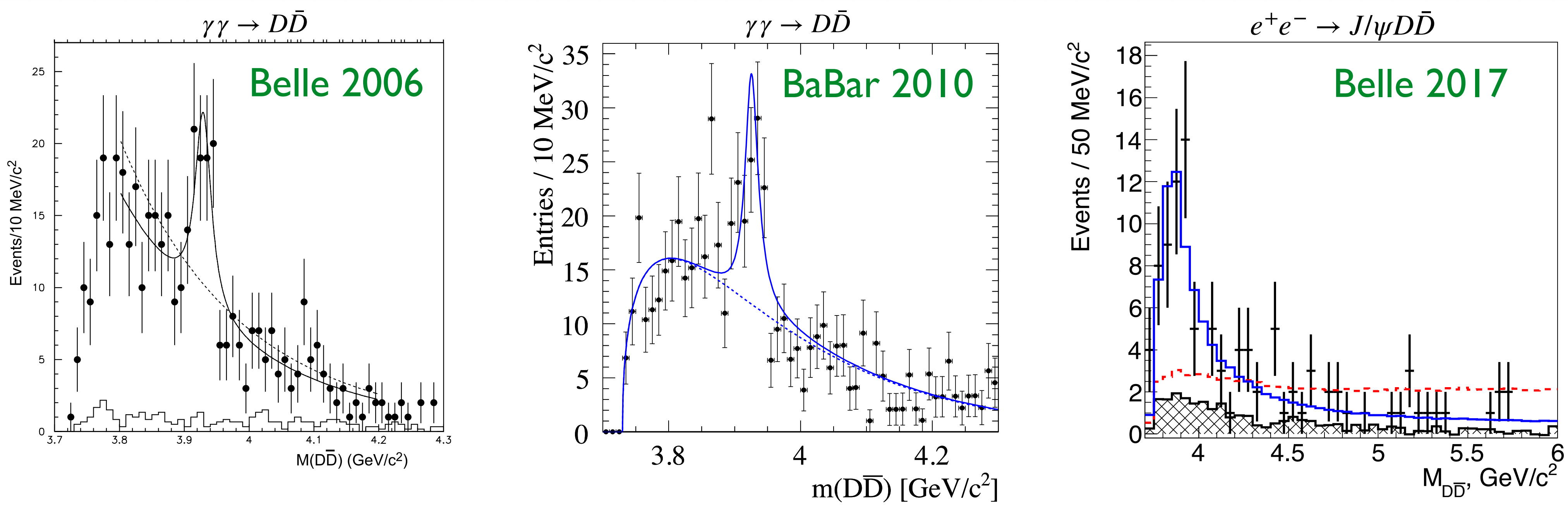




- [Guo Meißner 2010] Breit-Wigner analysis of $\gamma\gamma \to D\bar{D}$: found a broad $\chi_{c0}(3860)$



- [Guo Meißner 2010] Breit-Wigner analysis of $\gamma\gamma \to D\bar{D}$: found a broad $\chi_{c0}(3860)$
- [Wang et al. 2021, Gemerman et al. 2007] Unitary approach (BSE) found that $\gamma\gamma \to D\bar{D}$ & $e^+e^- \to J/\psi D\bar{D}$ data do not contradict dynamics with the encoded **bound state**: no broad $\chi_{c0}(3860)$ is needed



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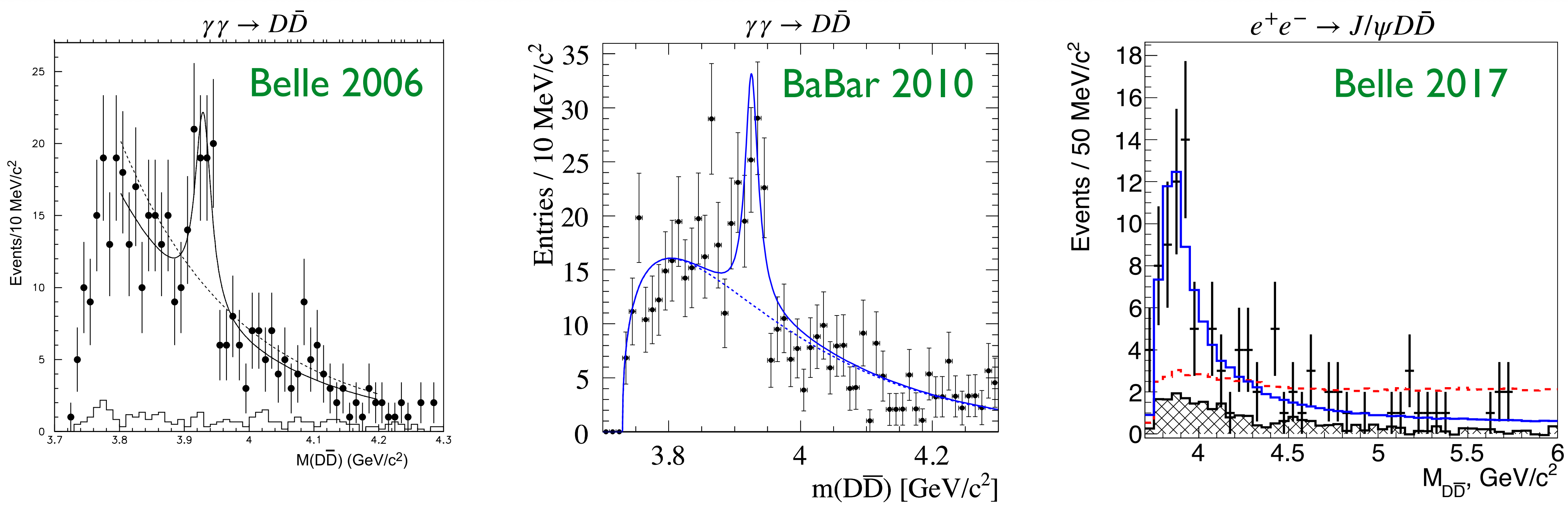
- [Prelovsek et al. 2022] Lattice analysis of $\{D\bar{D}, D_s\bar{D}_s\}$ with $m_\pi = 280\,\text{MeV}$ found 3 states with 0^{++}
  1) $D\bar{D}$ bound state
  2) broad state likely related to $\chi_{c0}(3860)$
  3) $D_s\bar{D}_s$ quasi-bound state (i.e. bound state if $D\bar{D}$ is off) which might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



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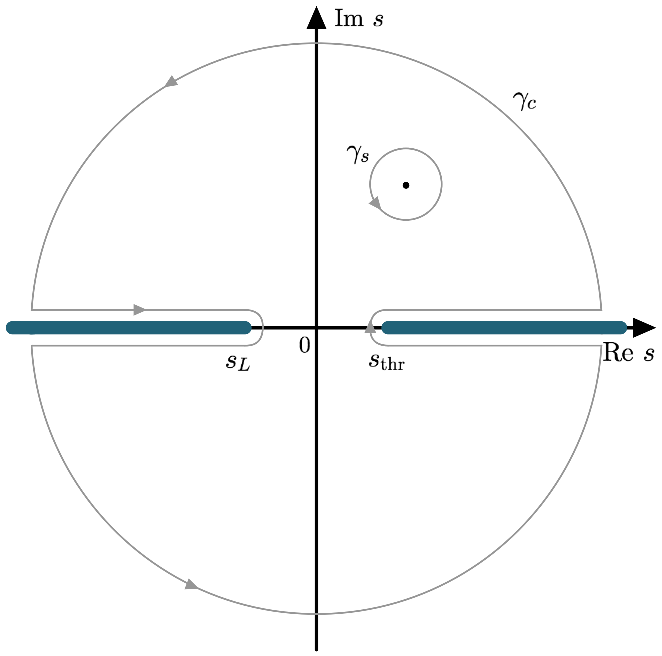
In order to figure out what is going on with 0^{++} we employ a data driven dispersive analysis of $\gamma\gamma \to D\bar{D}$ and $e^+e^- \to J/\psi D\bar{D}$

Formalism



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

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

- **Unitarity relation**

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

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

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

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

(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

partial wave dispersion relation (S wave)

- Once-subtracted p.w. dispersion relation

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- Bound state case

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

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

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

partial wave dispersion relation (S wave)

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- Neglect $\gamma\gamma$ intermediate states in the unitary relation
=> coupled-channel $\{\gamma\gamma, D\bar{D}, \ldots\}$ equations reduce to the **hadronic part** and **photon-fusion part**
Focus on energies $4m_D^2 < \sqrt{s} < 4.0\,\text{GeV}\ (\approx 4m_{D_s}^2)$

$$t_{DD}(s) = U_{DD}(s) + \frac{s}{\pi}\int_{4m_D^2}^{\infty} \frac{ds'}{s'} \frac{t_{DD}(s')\,\rho_D(s')\,t^*_{DD}(s')}{s'-s} = \frac{N_{DD}(s)}{D_{DD}(s)}$$

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

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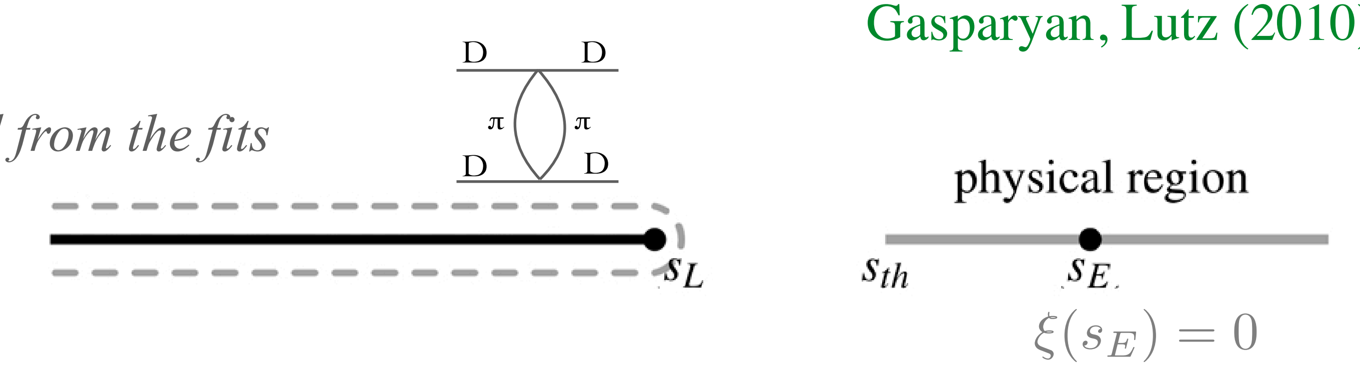
$$t_{\gamma\gamma,DD}(s) = U_{\gamma\gamma,DD}(s) + D_{DD}^{-1}(s)\left(-\frac{s}{\pi}\int_{4m_D^2}^{\infty}\frac{ds'}{s'}\frac{\mathrm{Im}\,D_{DD}(s')\,U_{\gamma\gamma,DD}(s')}{s'-s}\right)$$

- 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

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



partial wave dispersion relation (S wave)

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=> coupled-channel $\{\gamma\gamma,D\bar{D},\dots\}$ equations reduce to the **hadronic part** and **photon-fusion part**
Focus on energies $4m_D^2<\sqrt{s}<4.0\,\mathrm{GeV}\;(\approx 4m_{D_s}^2)$

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

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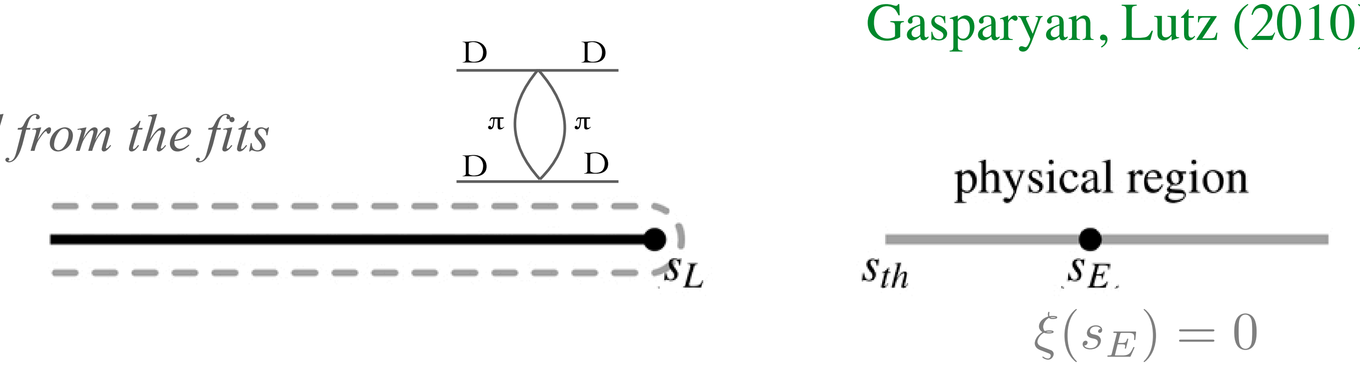
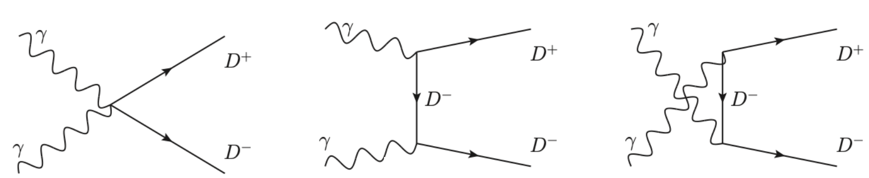


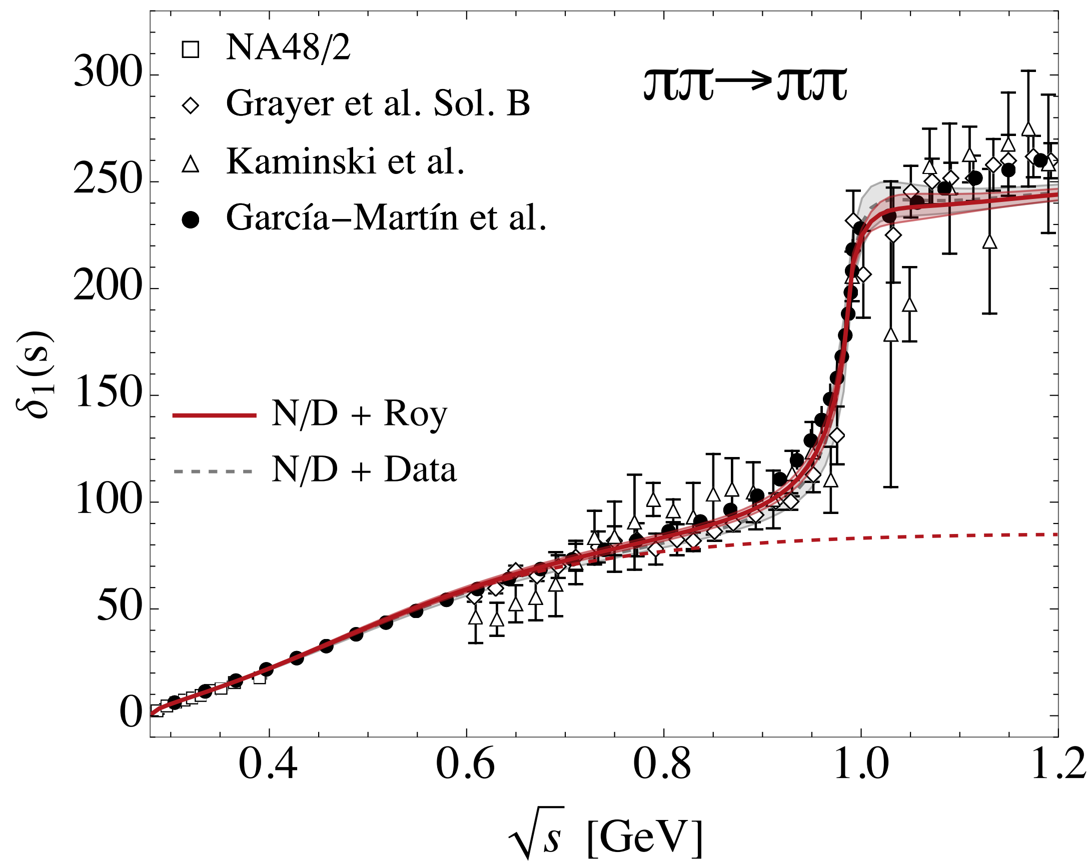
$$U_{\gamma\gamma,DD}(s)\approx\mathrm{Born}$$

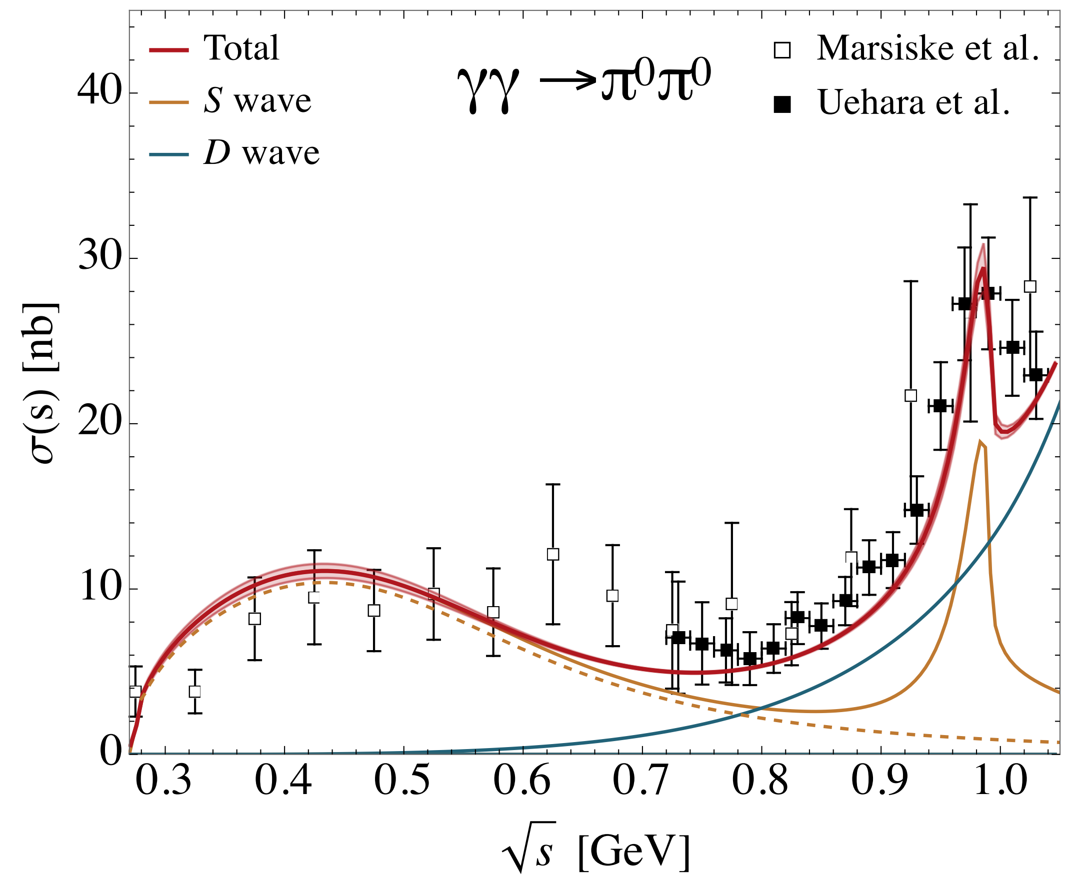
$t_{\gamma\gamma,DD}(s=0)=\mathrm{Born}$
(soft photon theorem)



How good is Born left-hand cut for $\{\gamma\gamma, \pi\pi, K\bar{K}\}$?

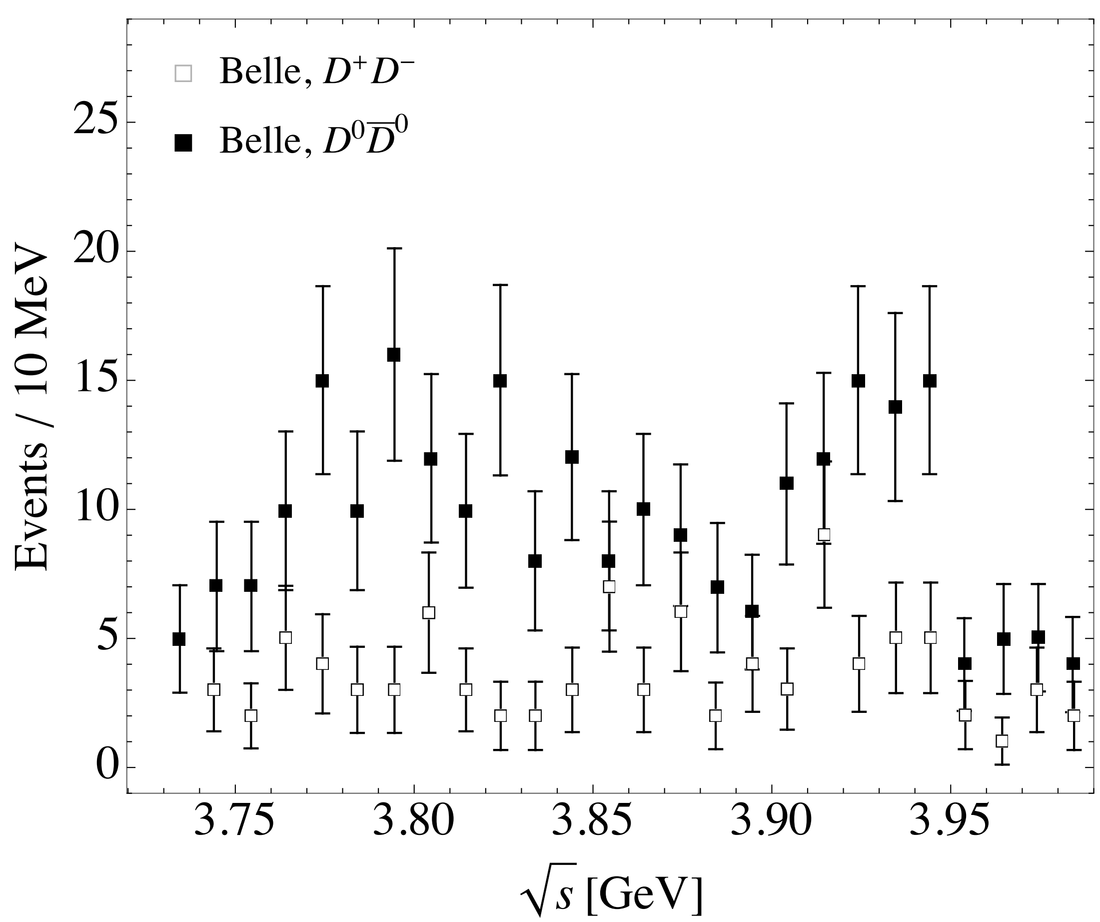
Fit to hadronic data → Post-diction based on Born left-hand cuts

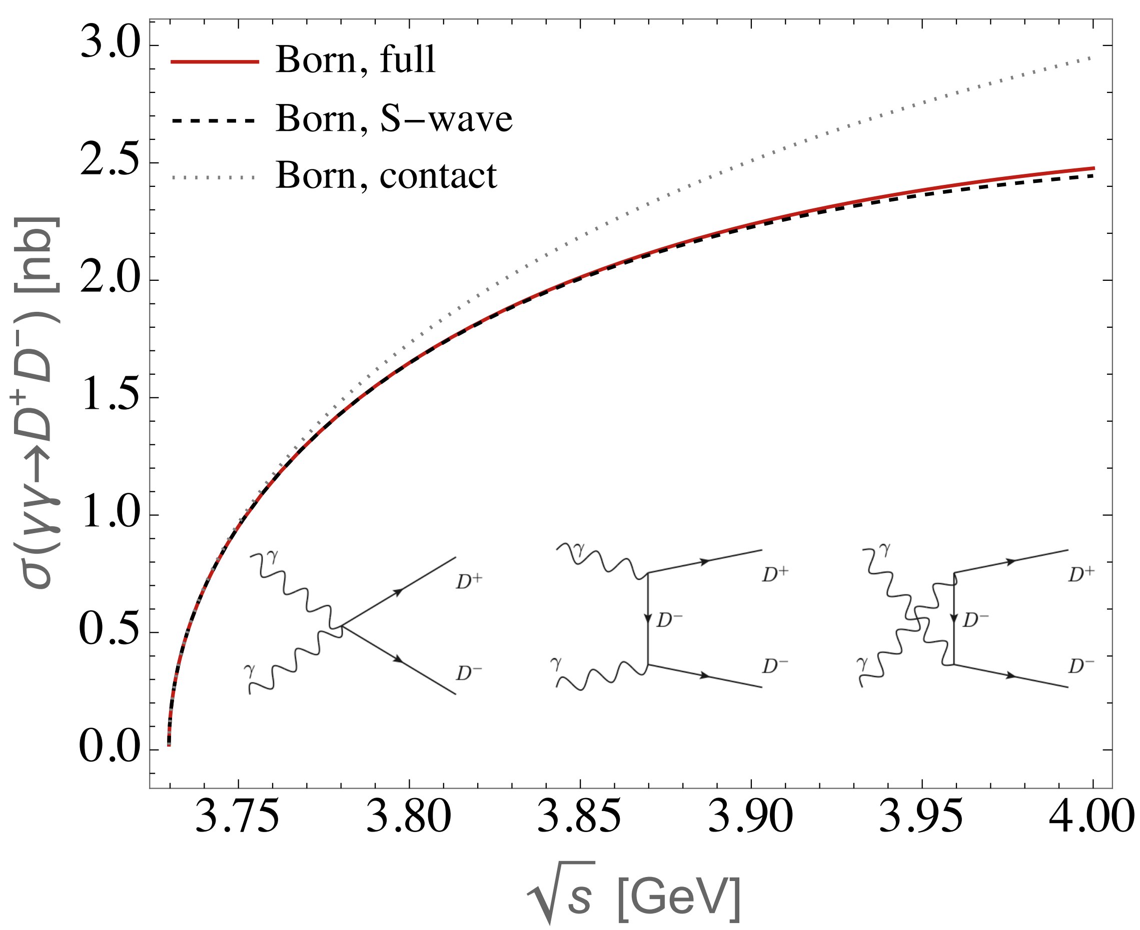




Analysis of $\gamma\gamma \to D^+D^-$ and $\gamma\gamma \to D^0\bar{D}^0$ data

$\sigma_c(s), \sigma_n(s)$



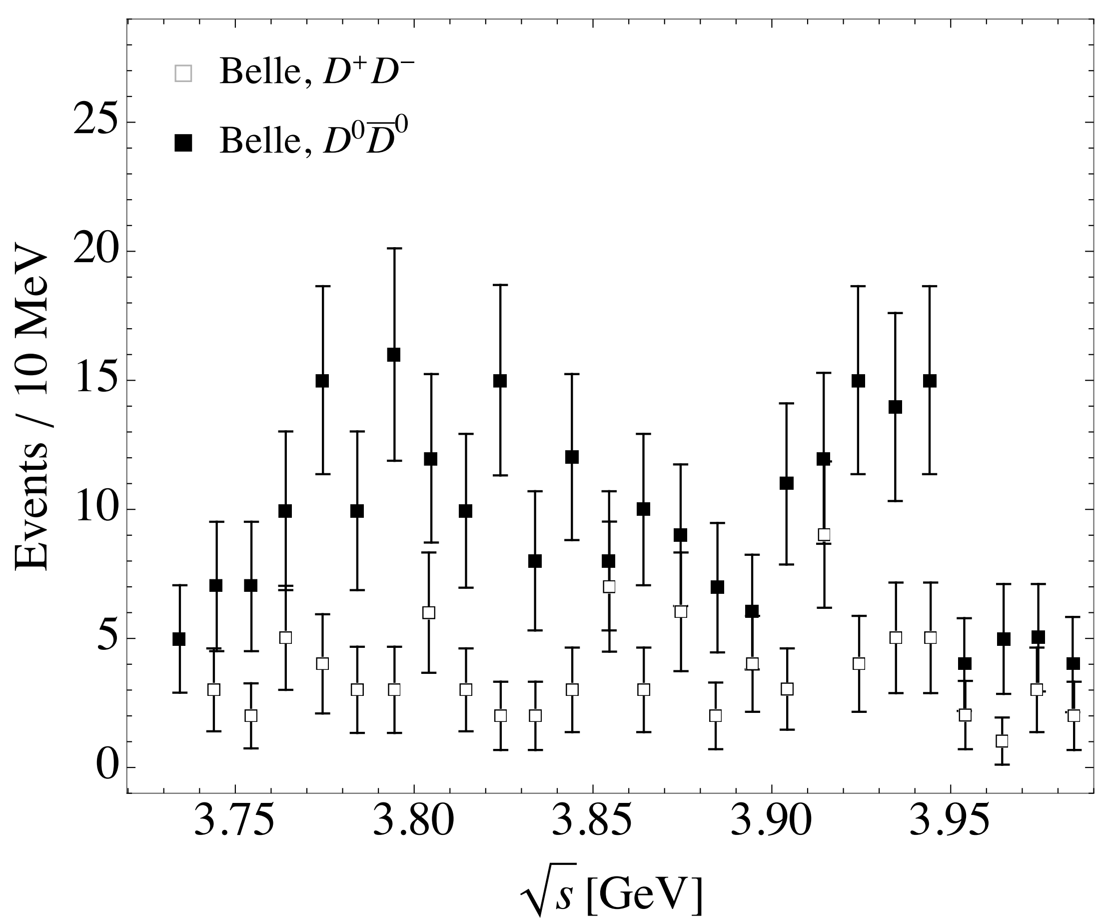


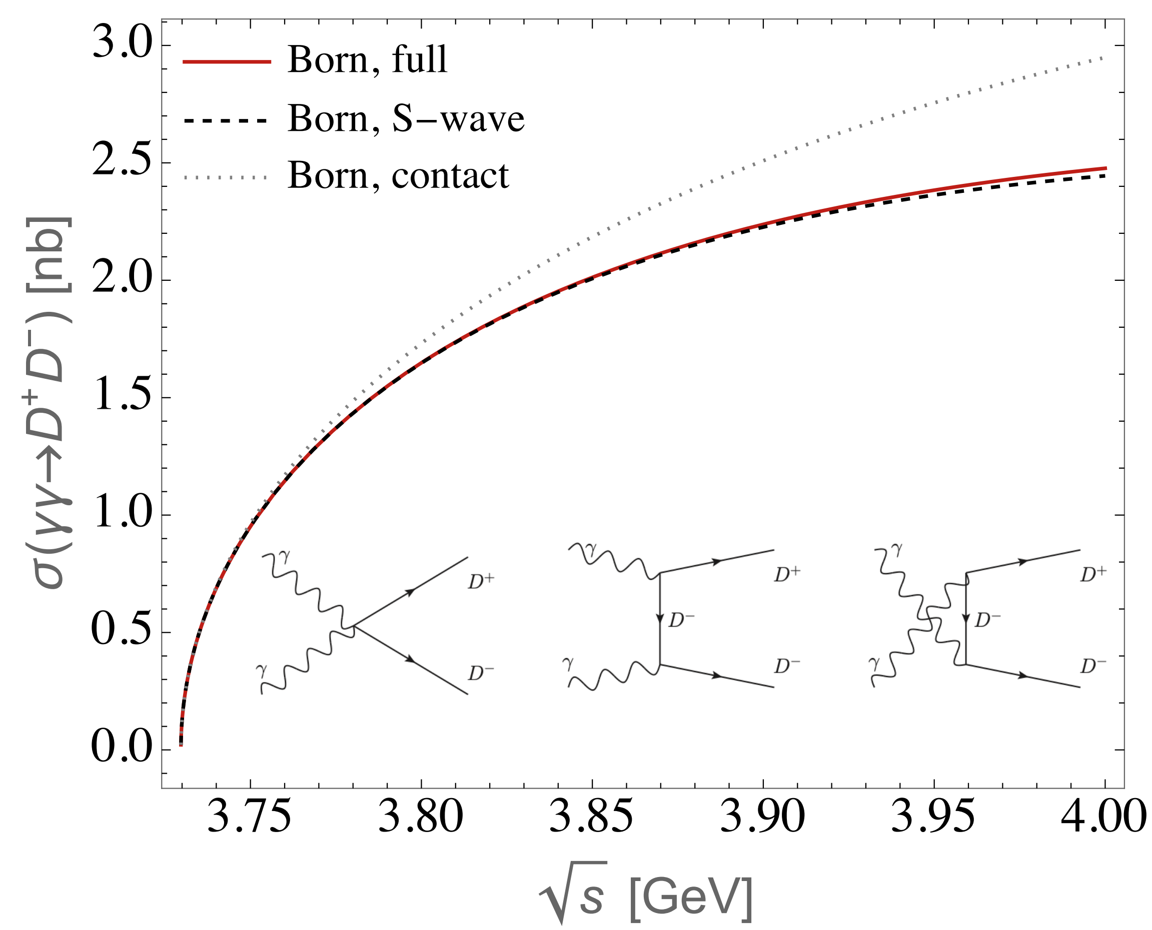
Analysis of $\gamma\gamma \to D^+D^-$ and $\gamma\gamma \to D^0\bar{D}^0$ data

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

$\Longrightarrow$ 3 parameters from N/D + normalisation ratio (S/D wave)

$\sigma_c(s), \sigma_n(s)$





Fit photon fusion data

↓

fix hadronic part

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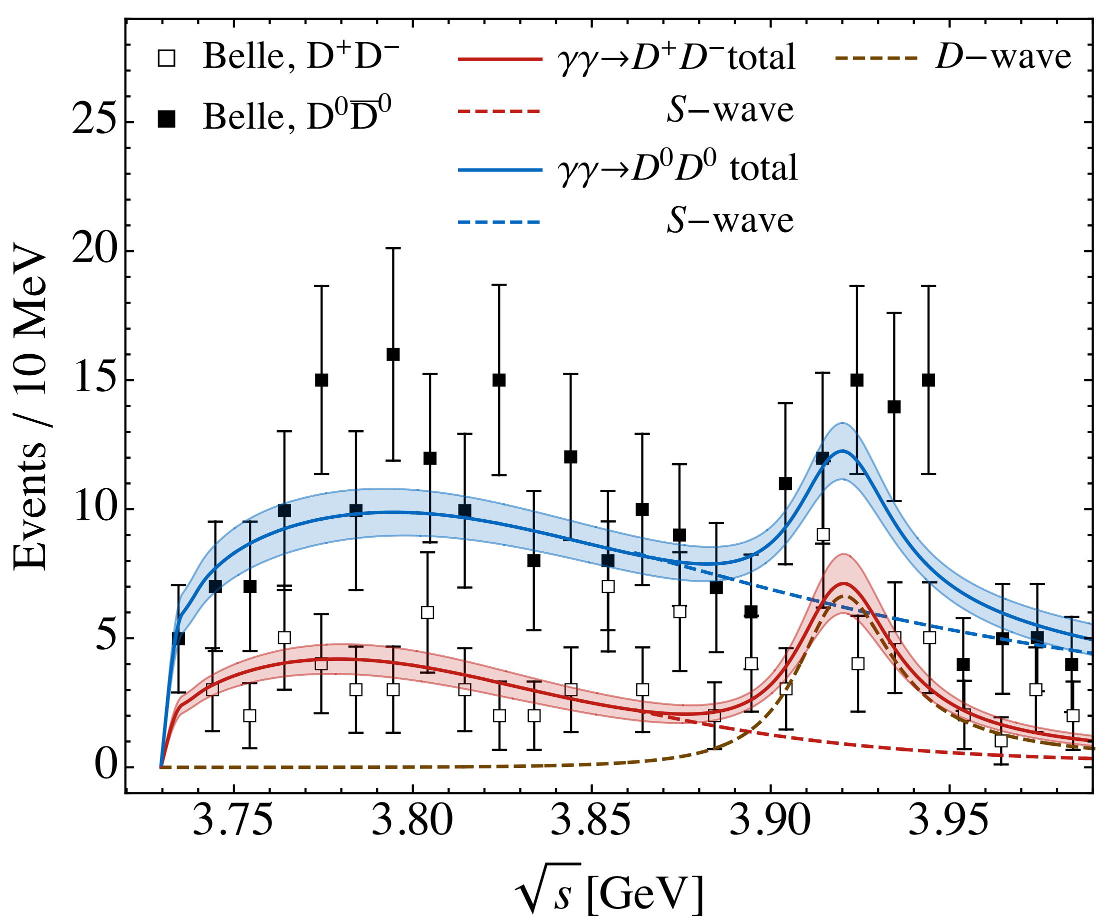

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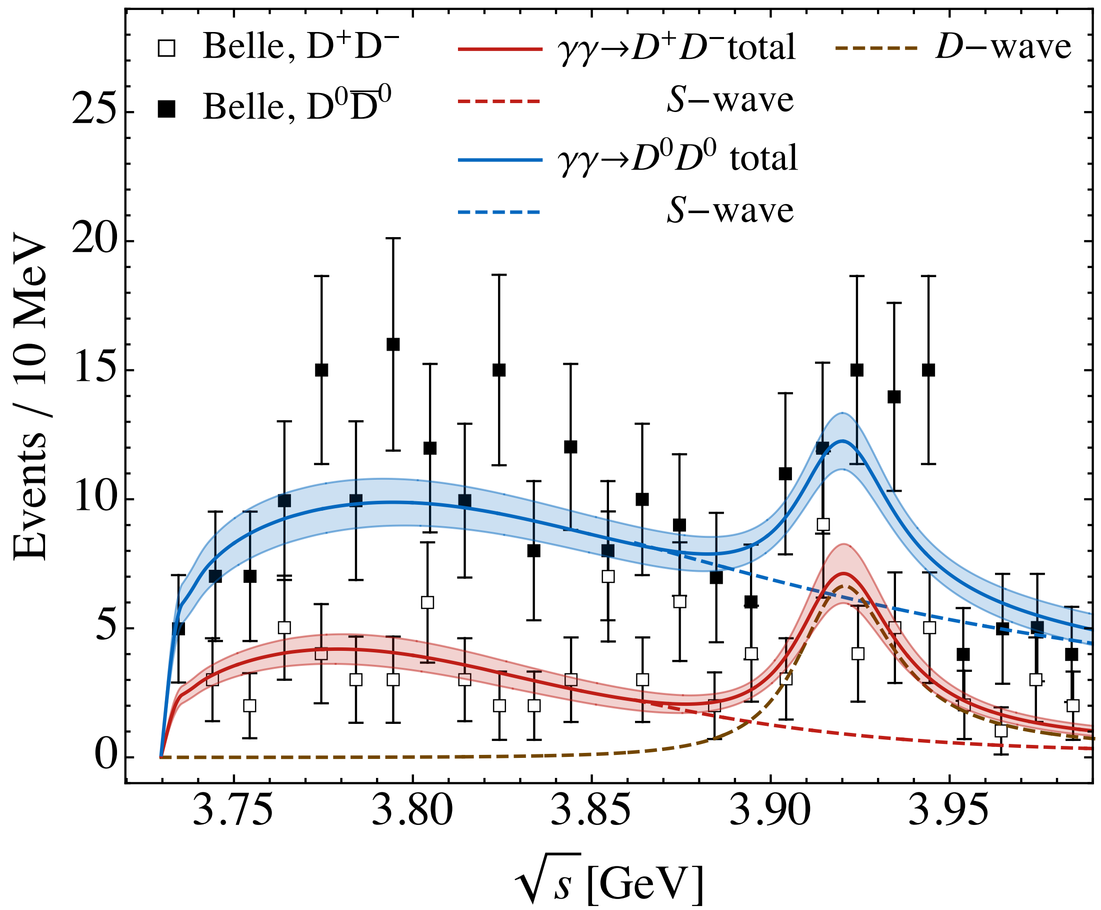
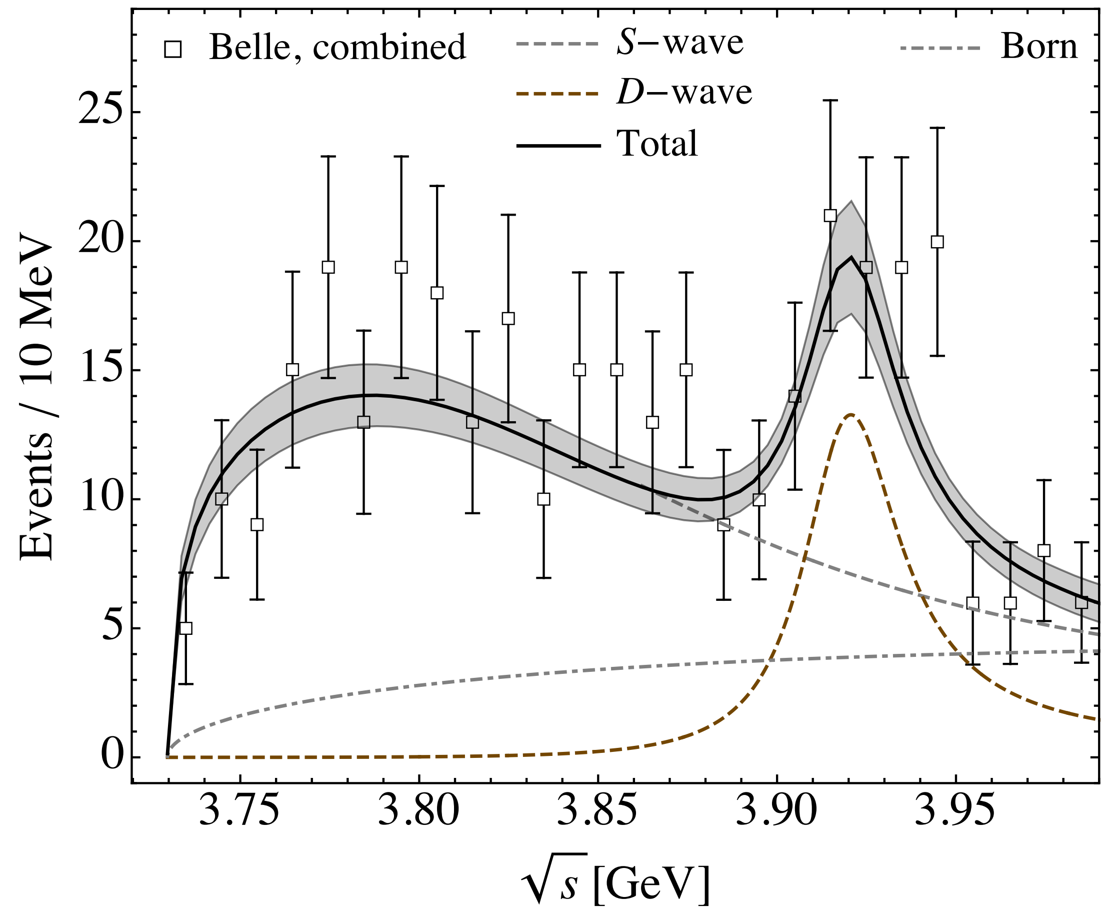
D-wave: $\chi_{c2}(3930)$ is a Breit-Wigner hel-2 with PDG mass/width

$\Longrightarrow$ 3 parameters from N/D + normalisation ratio (S/D wave)

$\sigma_c(s), \sigma_n(s)$



$\sigma_c(s) + \sigma_n(s)$



Bound state (BS):

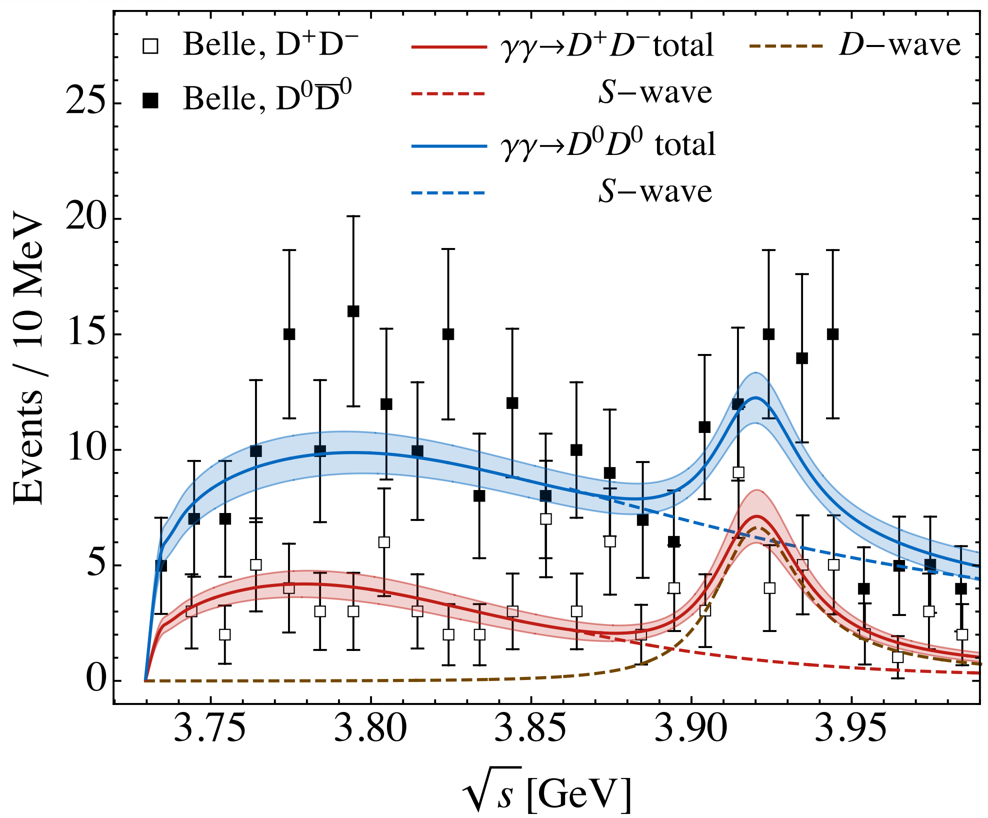
$$t_{ab} \sim \frac{g_a\, g_b}{s_B - s}$$

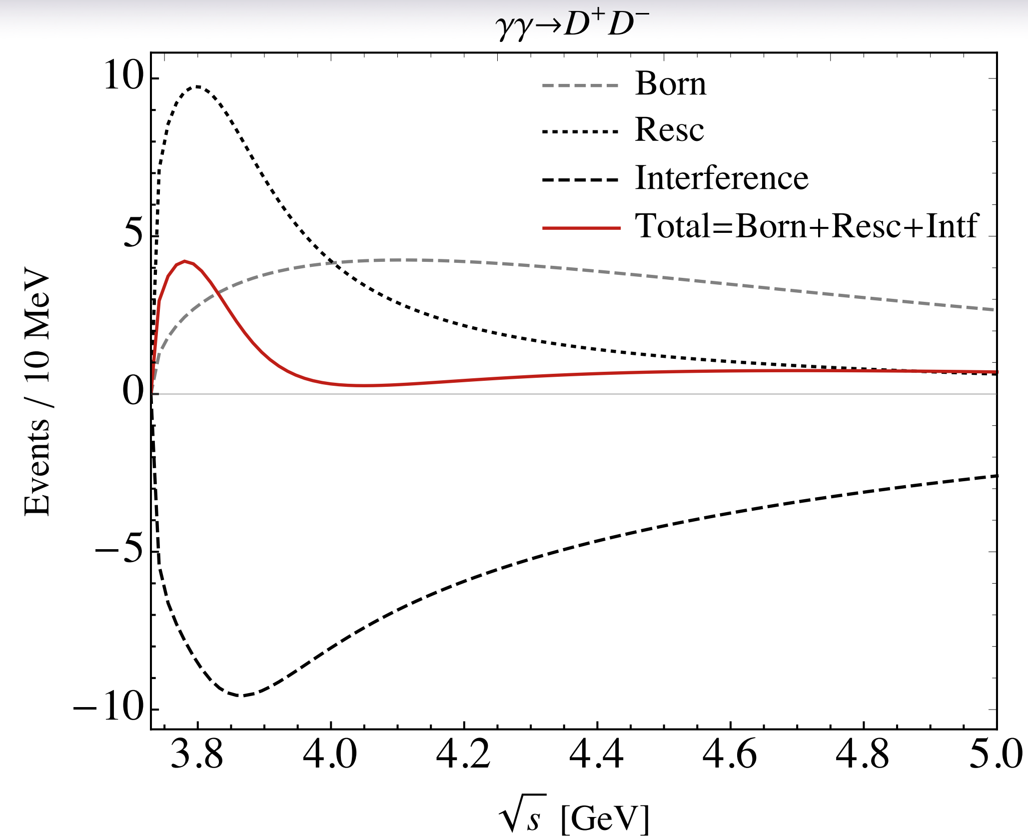
$$\sqrt{s_{BS}} = 3695(4)\ \text{MeV}$$

$$|g_{BS\to D\bar{D}}| = 27(1)\ \text{GeV}$$

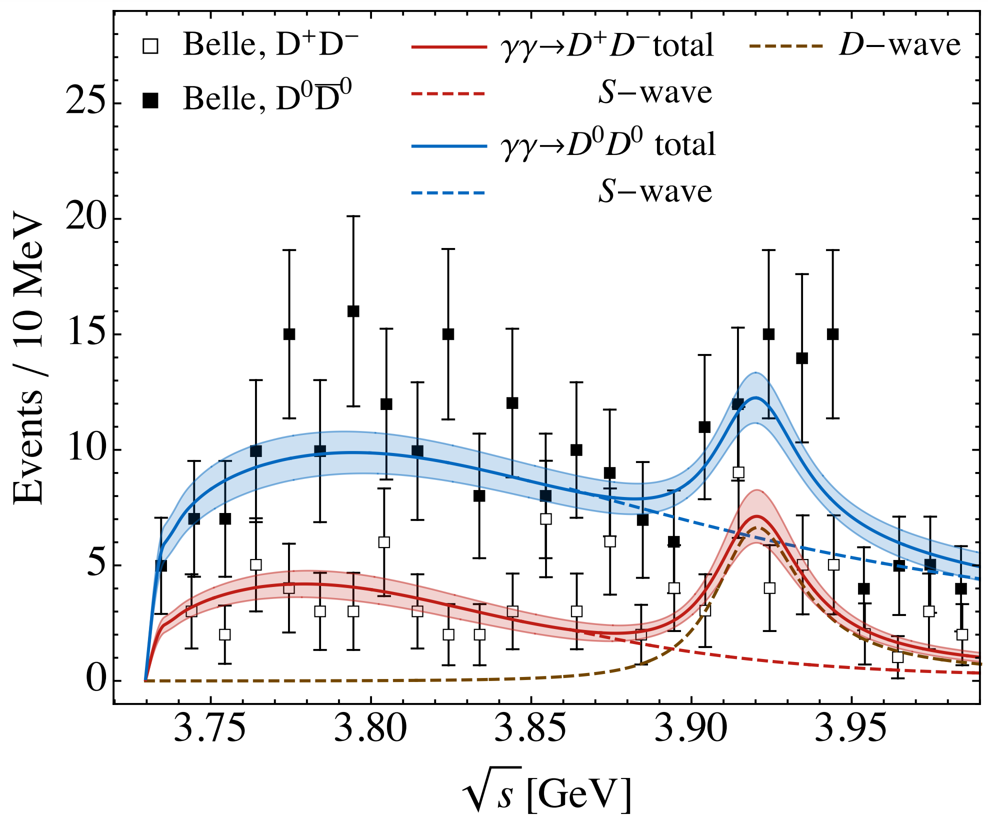
$$|g_{BS\to\gamma\gamma}| = 0.011(1)\ \text{GeV}$$

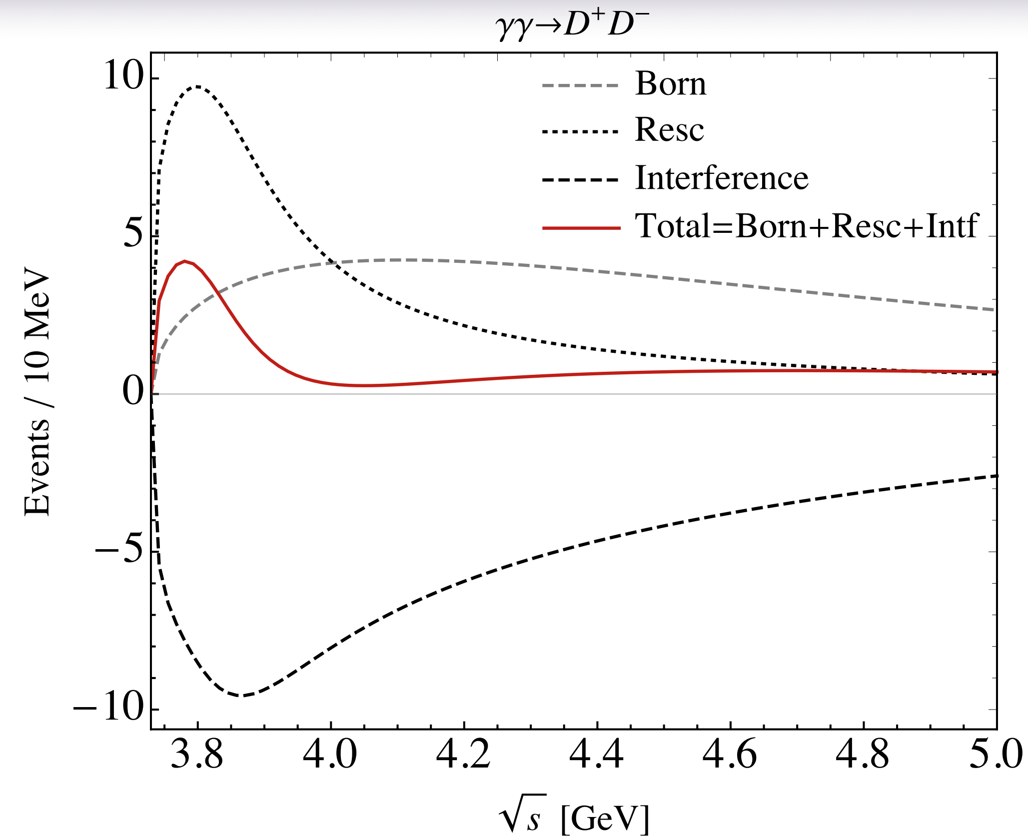
Destructive interference





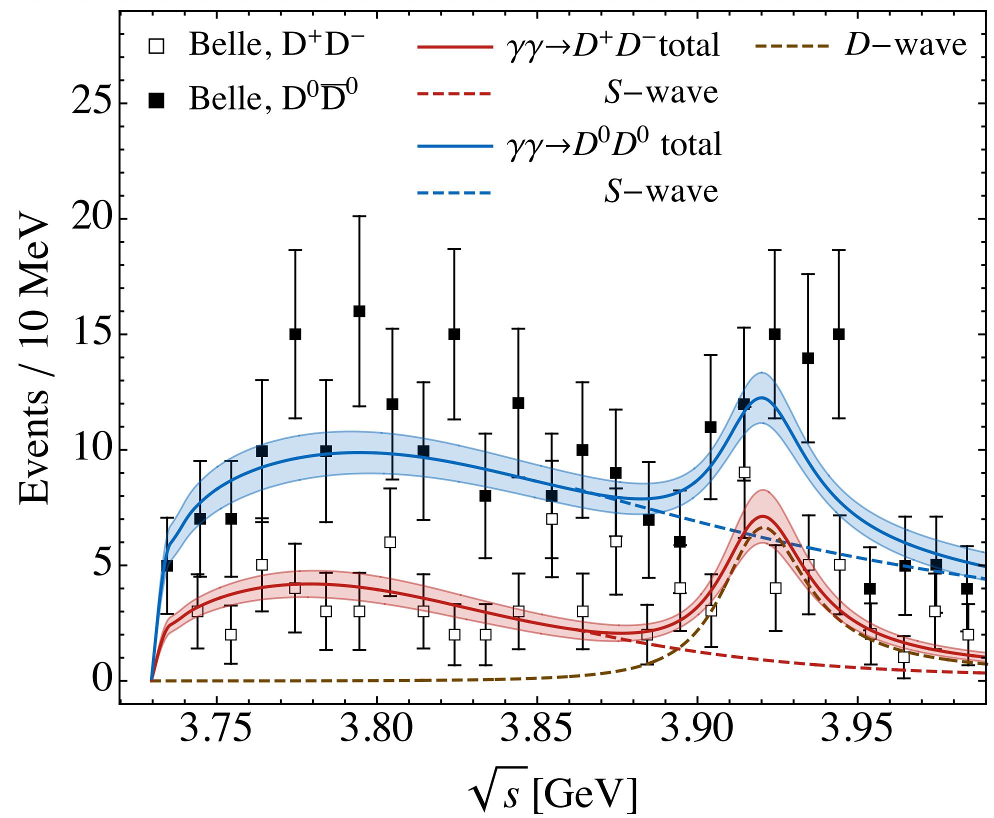
Destructive interference

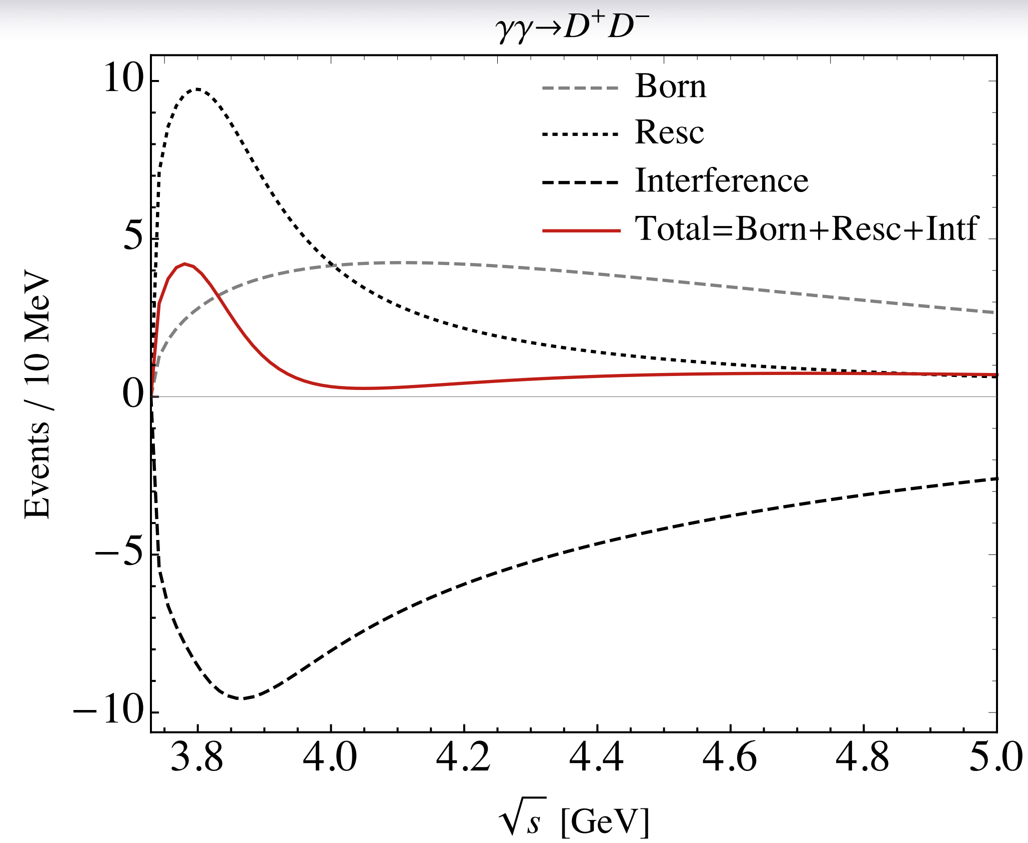




1) Consider again $\{\pi\pi, K\bar{K}\}$ coupled channel system $\sqrt{s_{f_0}} = 993 - i\,21$ MeV
2) Switch off $\pi\pi$ channel $\Longrightarrow f_0(980)$ becomes a $K\bar{K}$ bound state with $\sqrt{s_B} = 961$ MeV

Destructive interference





1) Consider again $\{\pi\pi, K\bar{K}\}$ coupled channel system $\sqrt{s_{f_0}} = 993 - i\,21$ MeV

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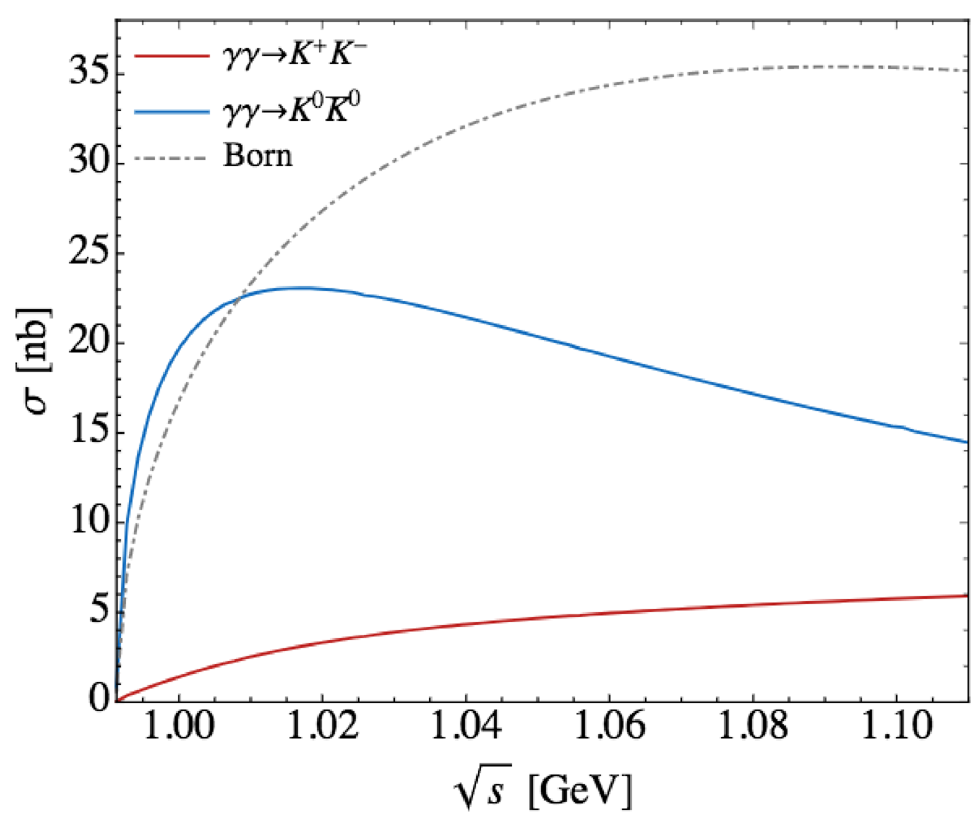
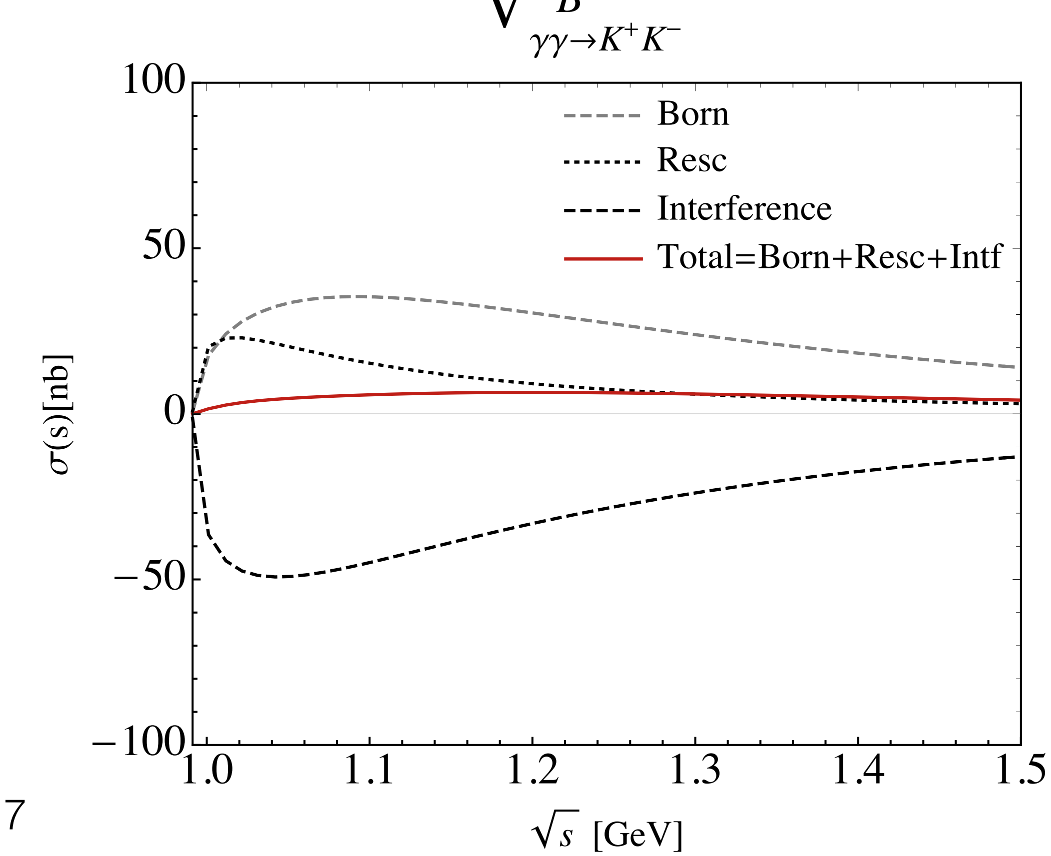
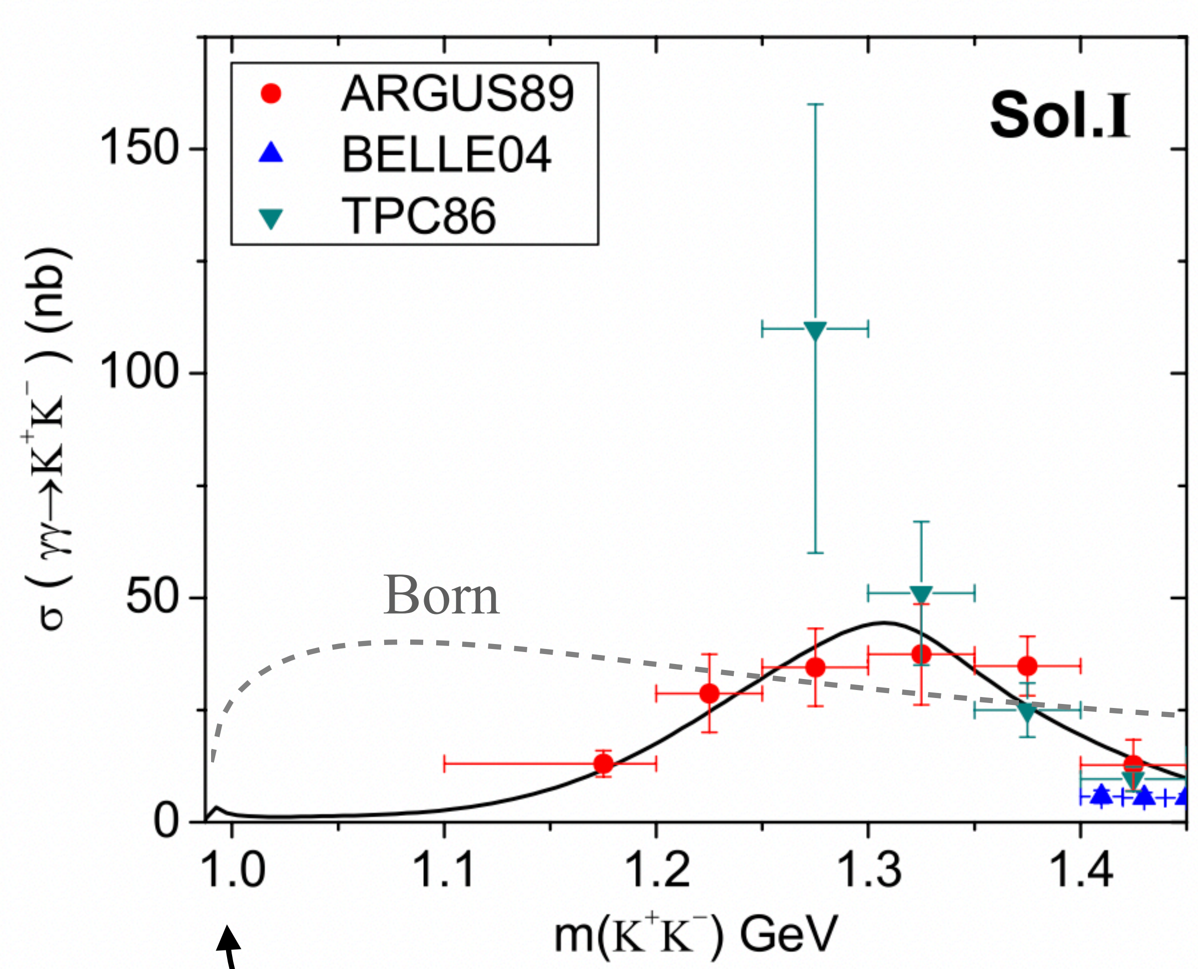
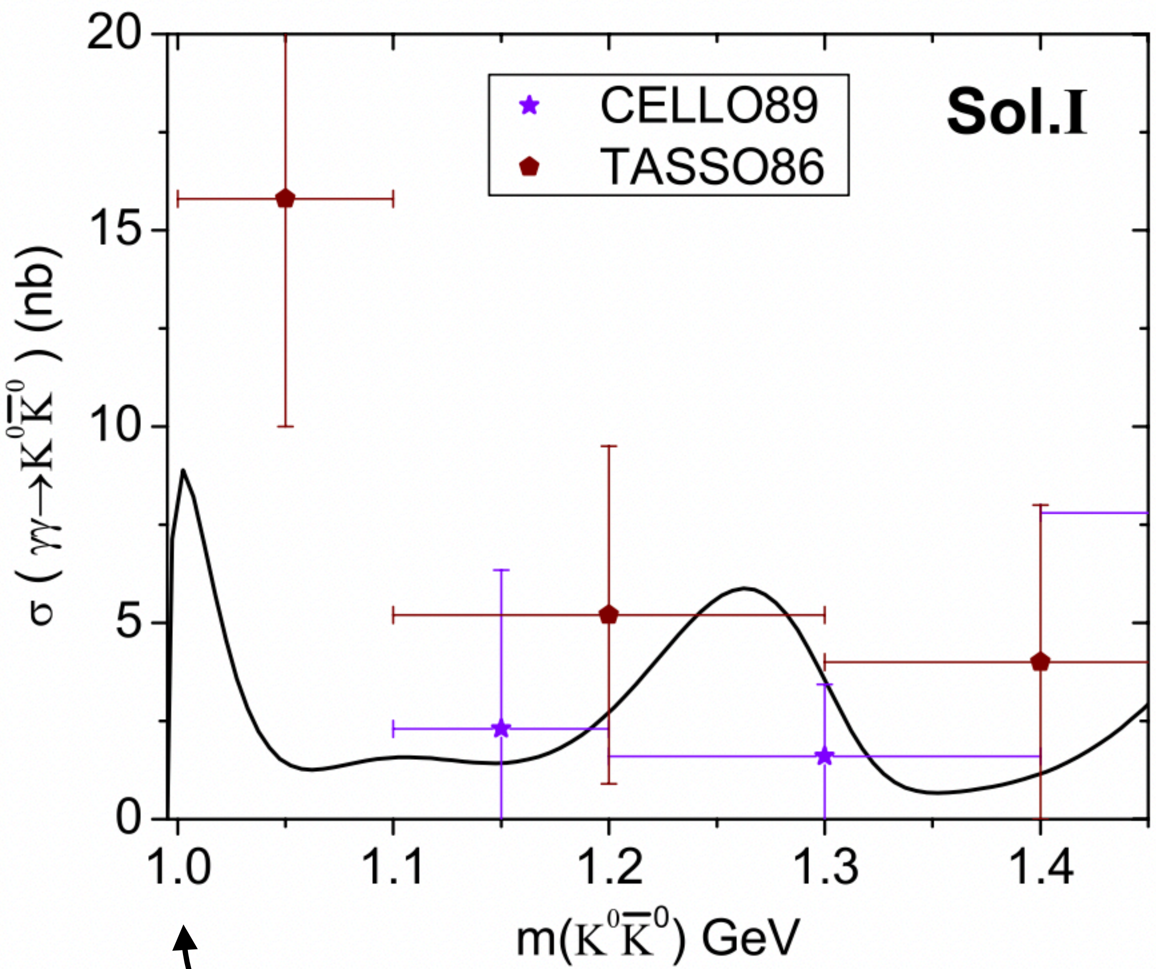




Suppression of K^+K^- channel compared to $K^0\bar{K}^0$ is also seen in the full amplitude analysis of [Dai Pennington 2014]



$\sigma \sim 5\,\mathrm{nb}$

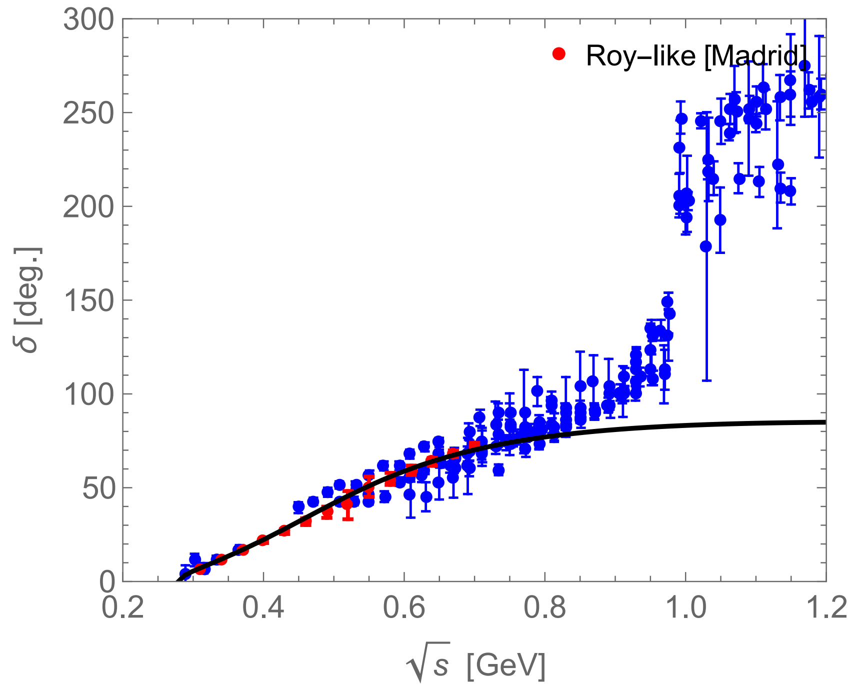


$\sigma \sim 10\,\mathrm{nb}$

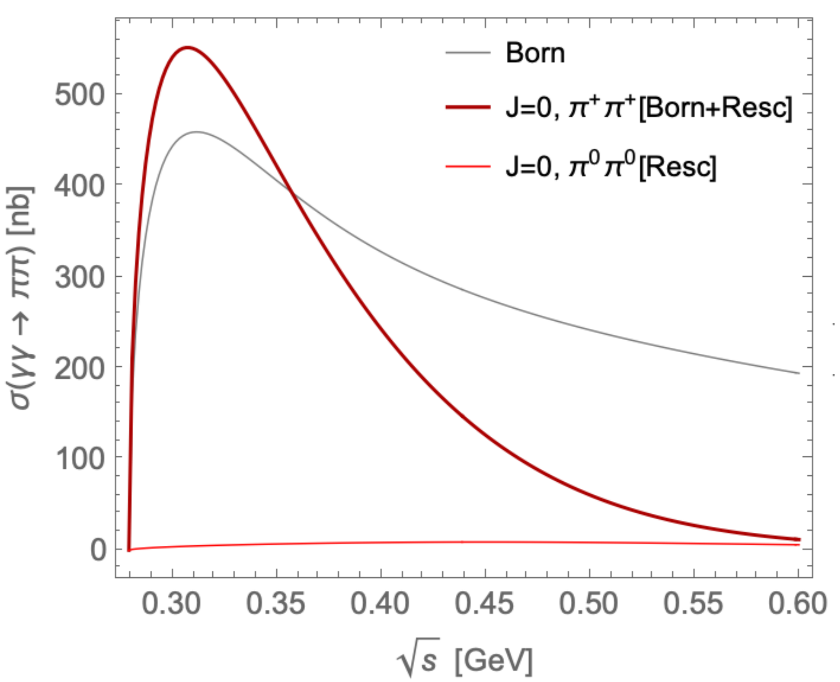
future BESIII data

Prediction for $\gamma\gamma \to \pi\pi$ cross section for unphysical m_π

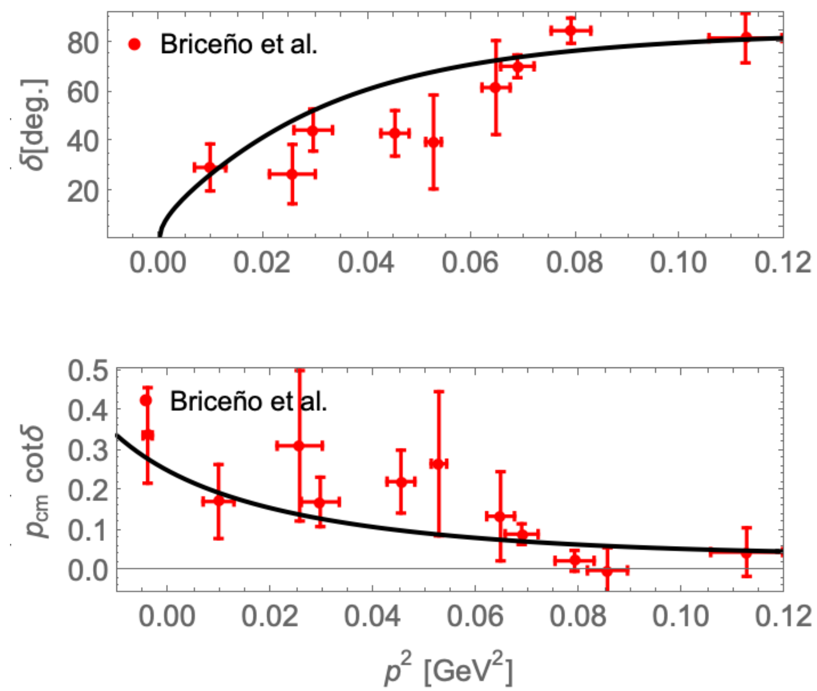
$m_\pi = phys$



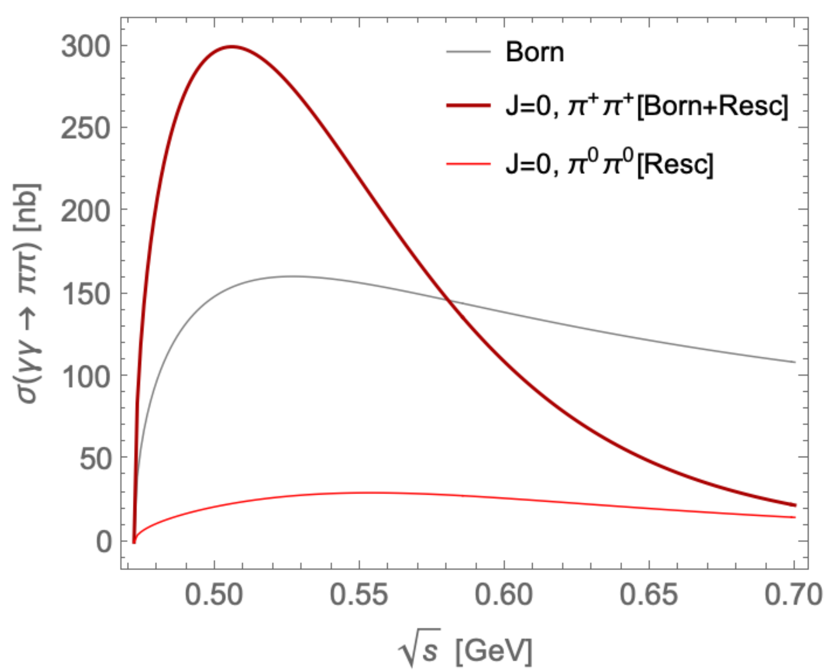
$\sqrt{s_\sigma} = 0.458 - i\,0.244\,\mathrm{GeV}$



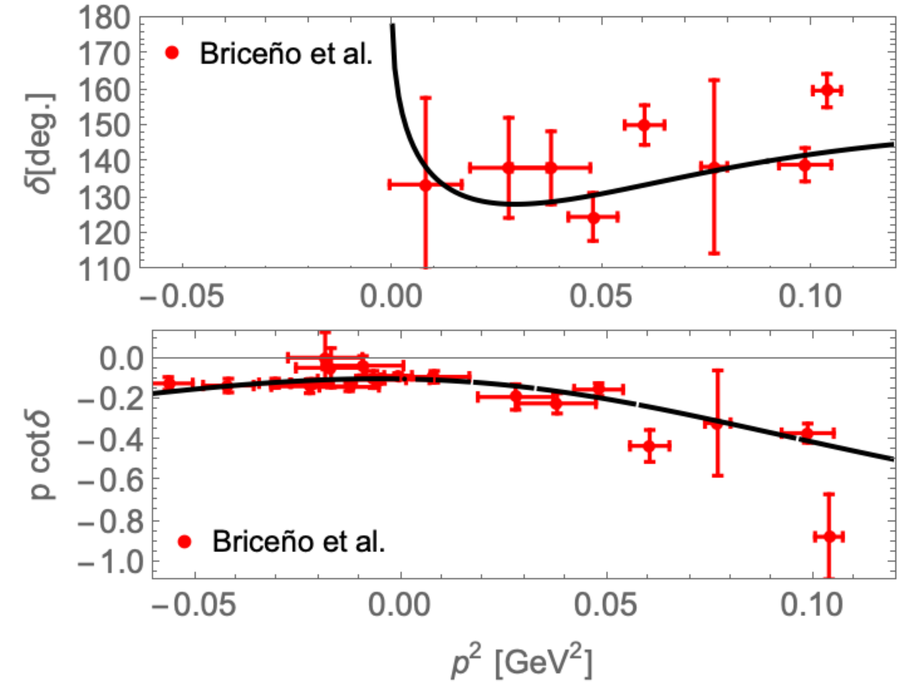
$m_\pi = 239\,\mathrm{MeV}$



$\sqrt{s_\sigma} = 0.502 - i\,0.140\,\mathrm{GeV}$

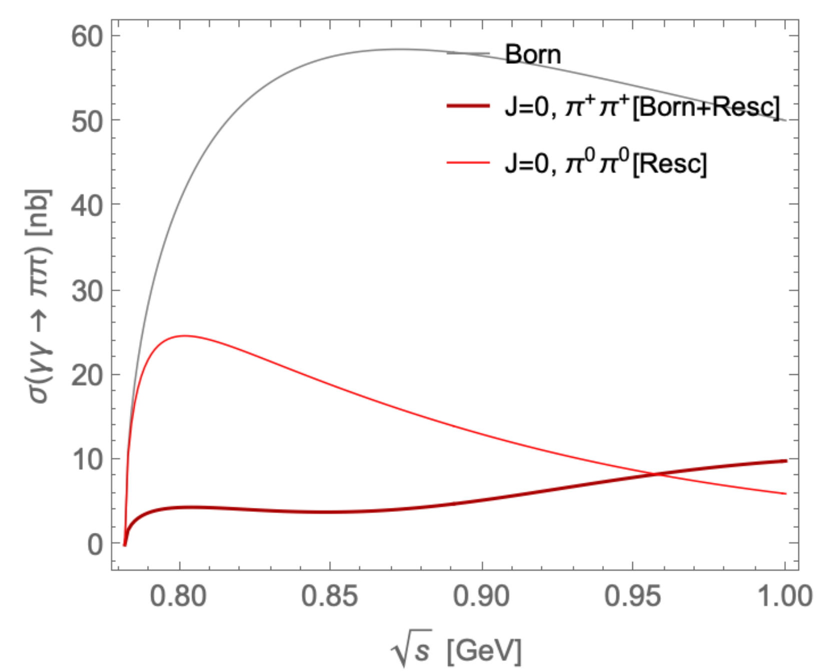


$m_\pi = 391\,\mathrm{MeV}$



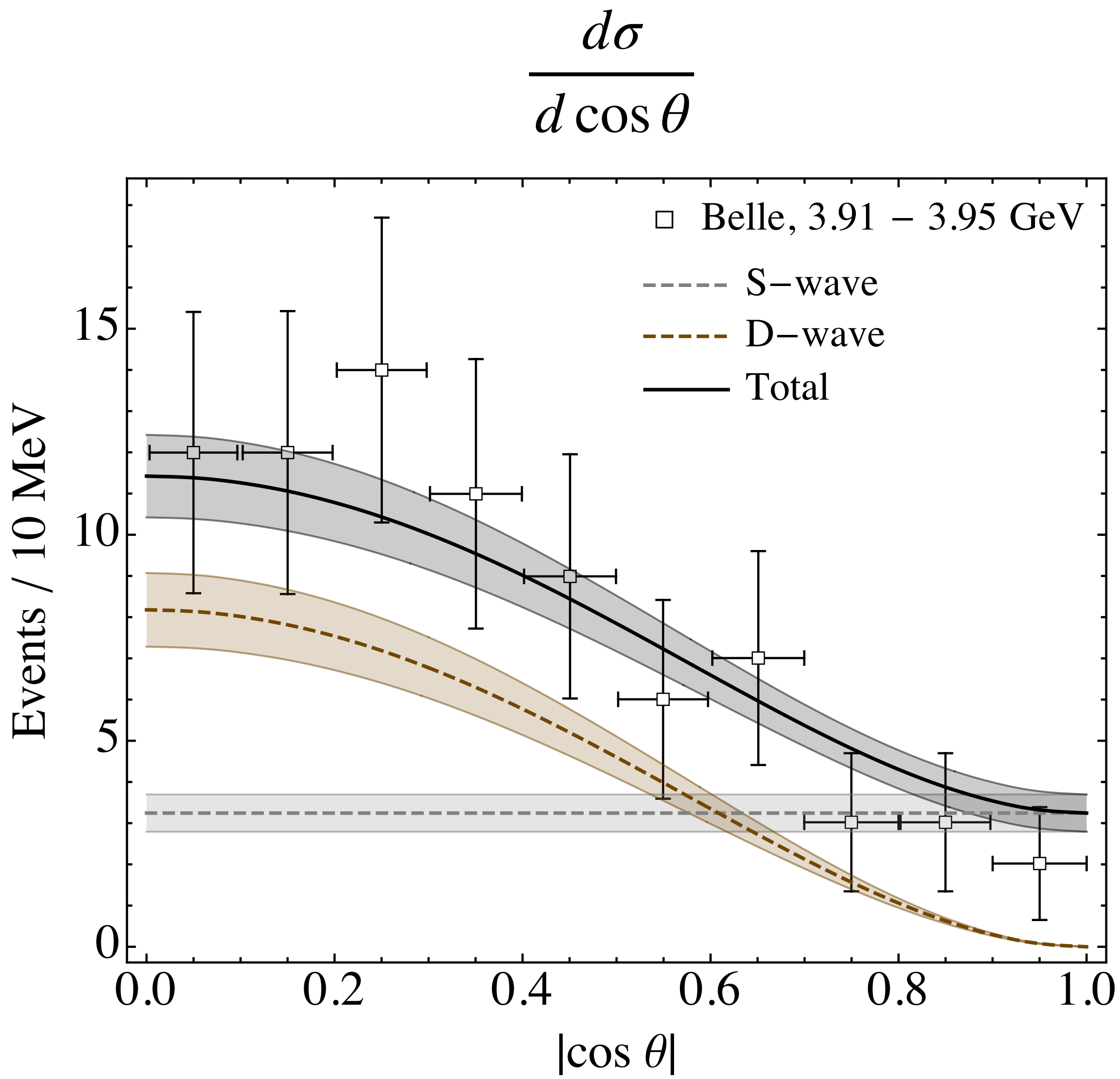
$\sqrt{s_\sigma} = 0.758\,\mathrm{GeV}$

(bound state)



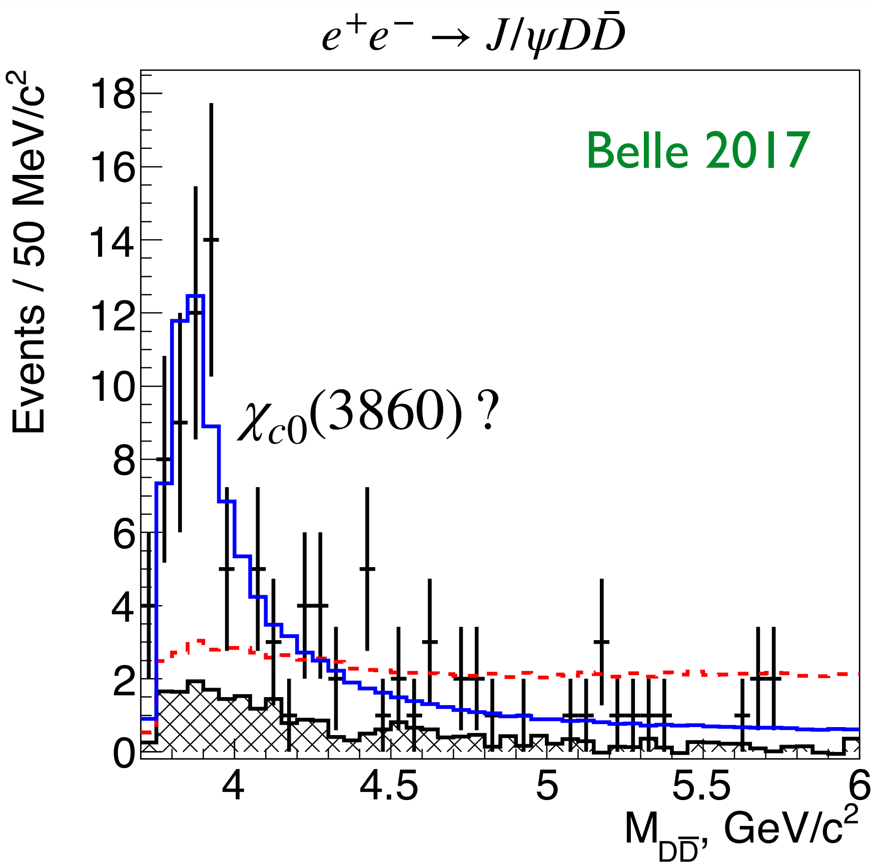
in the case of a **bound state**: charged channel is suppressed compared to neutral

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

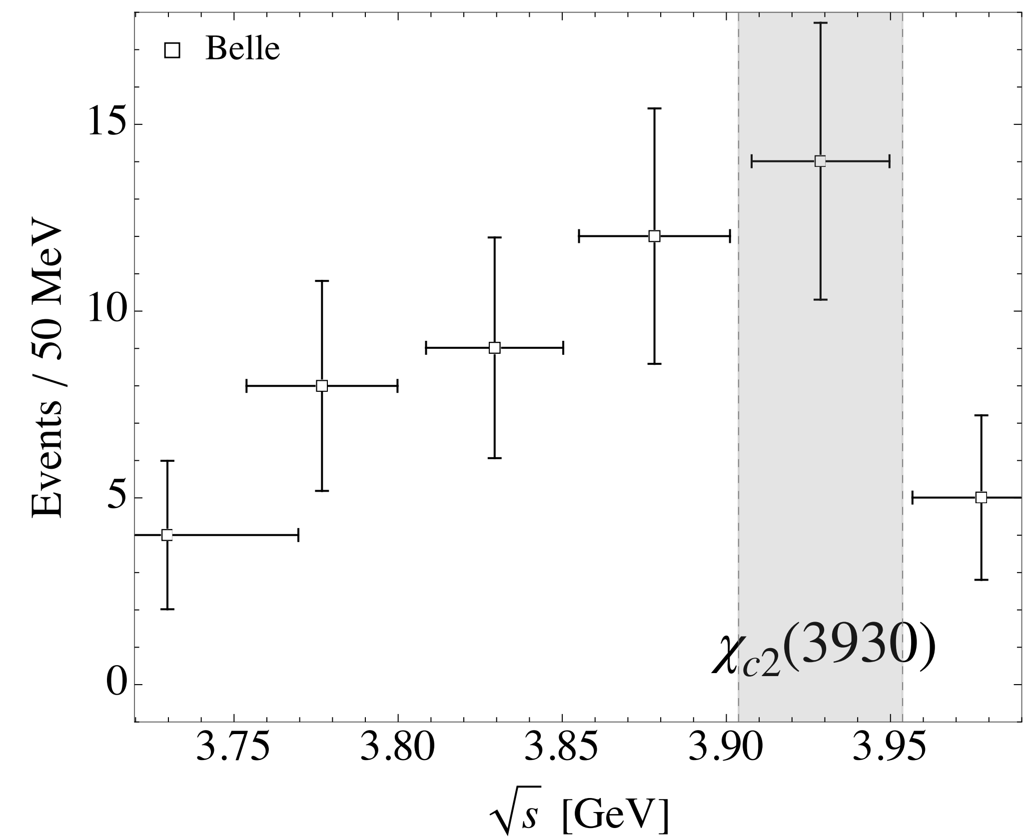


Angular distribution is mainly D-wave: however, one cannot exclude an additional small S-wave contribution from $\chi_{c0}(3915)$

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

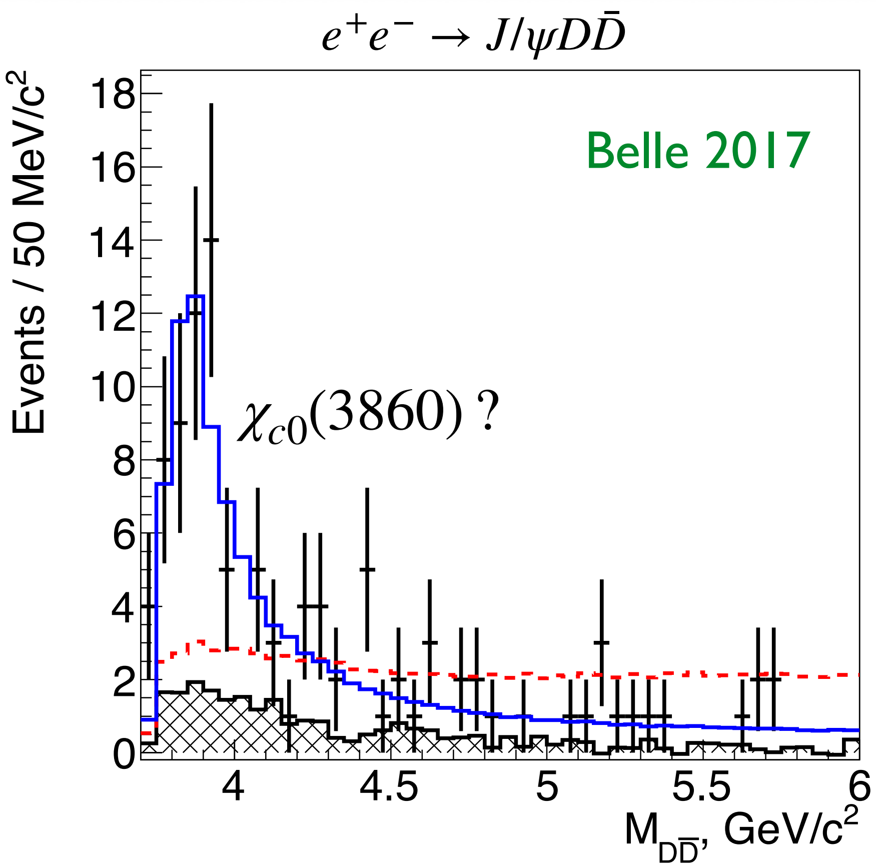


only 6 data points below 4 GeV

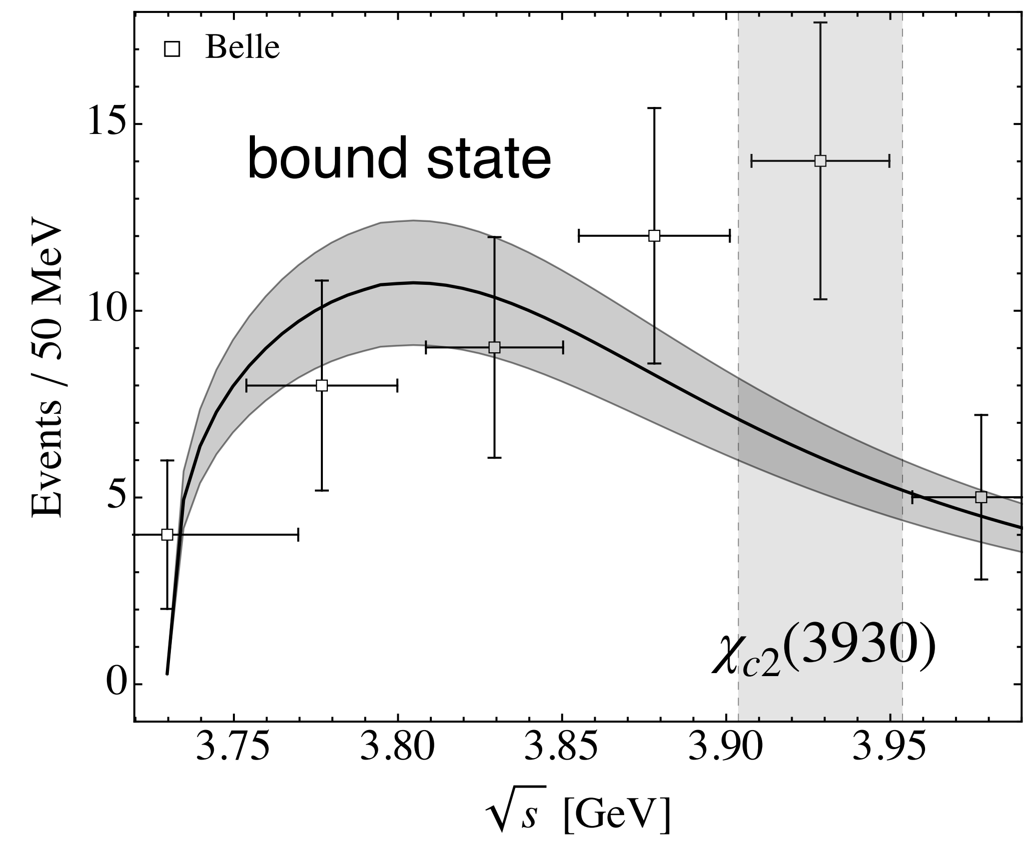


- No realistic estimates can be done from this data alone; full experimental dataset is needed

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

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

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

Conclusion and outlook

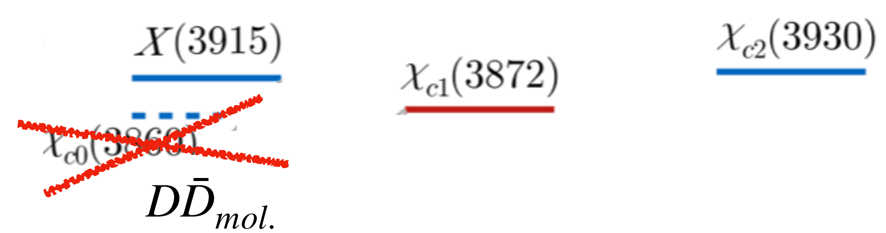
☑ Dispersive analysis of the $\gamma\gamma \to D^+D^-, D^0\bar{D}^0$ data, consistency check with the $e^+e^- \to J/\psi D\bar{D}$ data

☑ 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

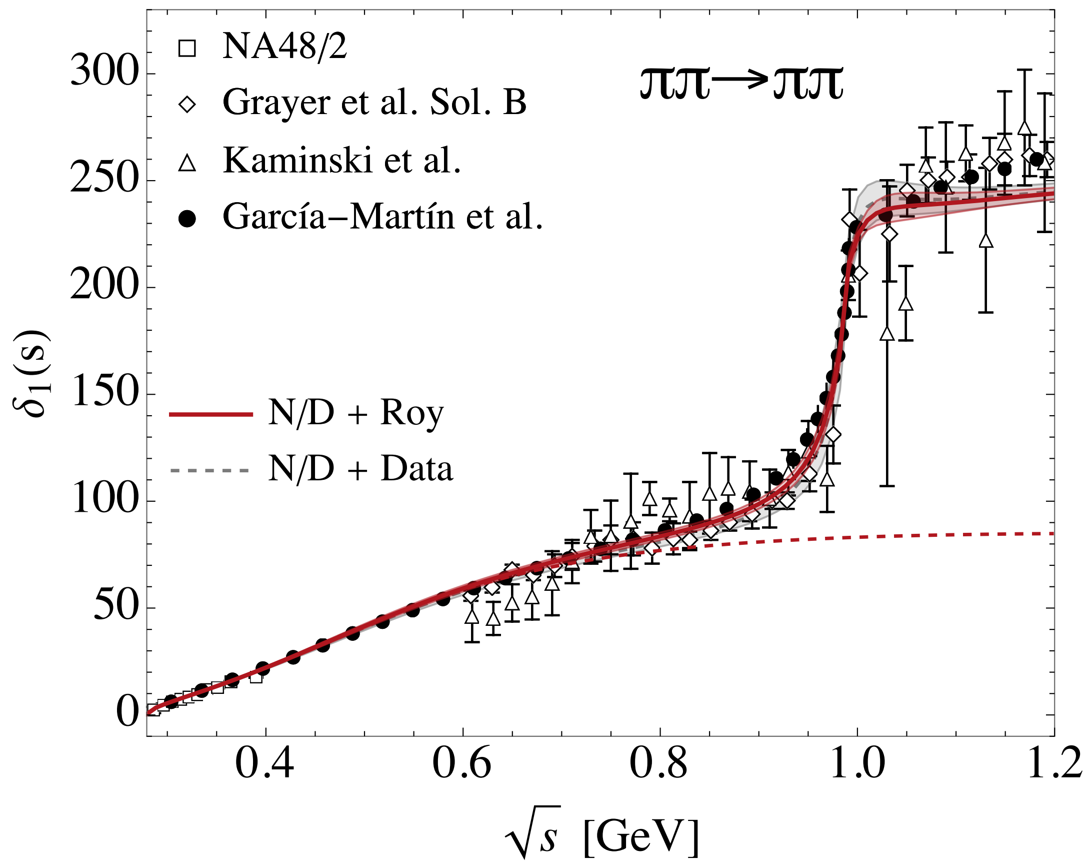
☐ Light: $\gamma\gamma \to \pi^0\eta, K\bar{K}$; $(g-2)_\mu$ HLBL contributions

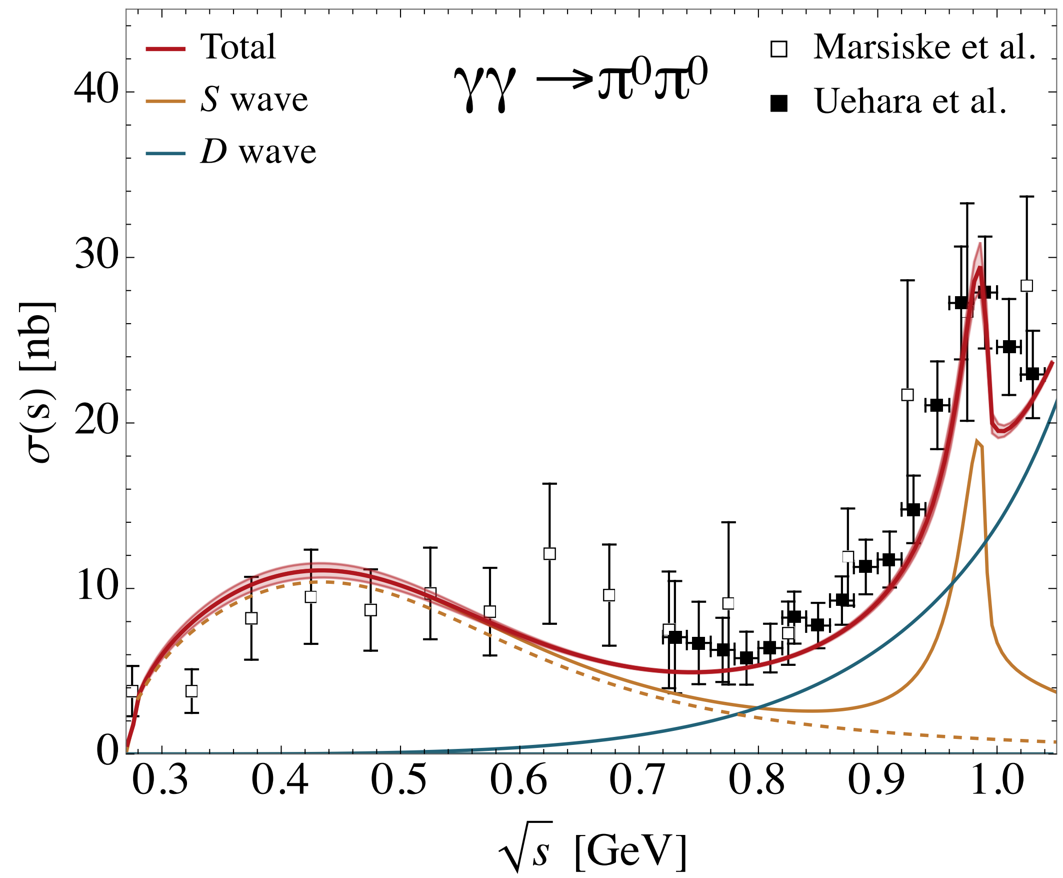
☐ $\{J/\psi J/\psi,\ J/\psi\ \psi(2S)\}$ scattering LHCb

Thank you!

Extra slides

Fit to hadronic data ⟶ Post-diction based on Born left-hand cuts





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

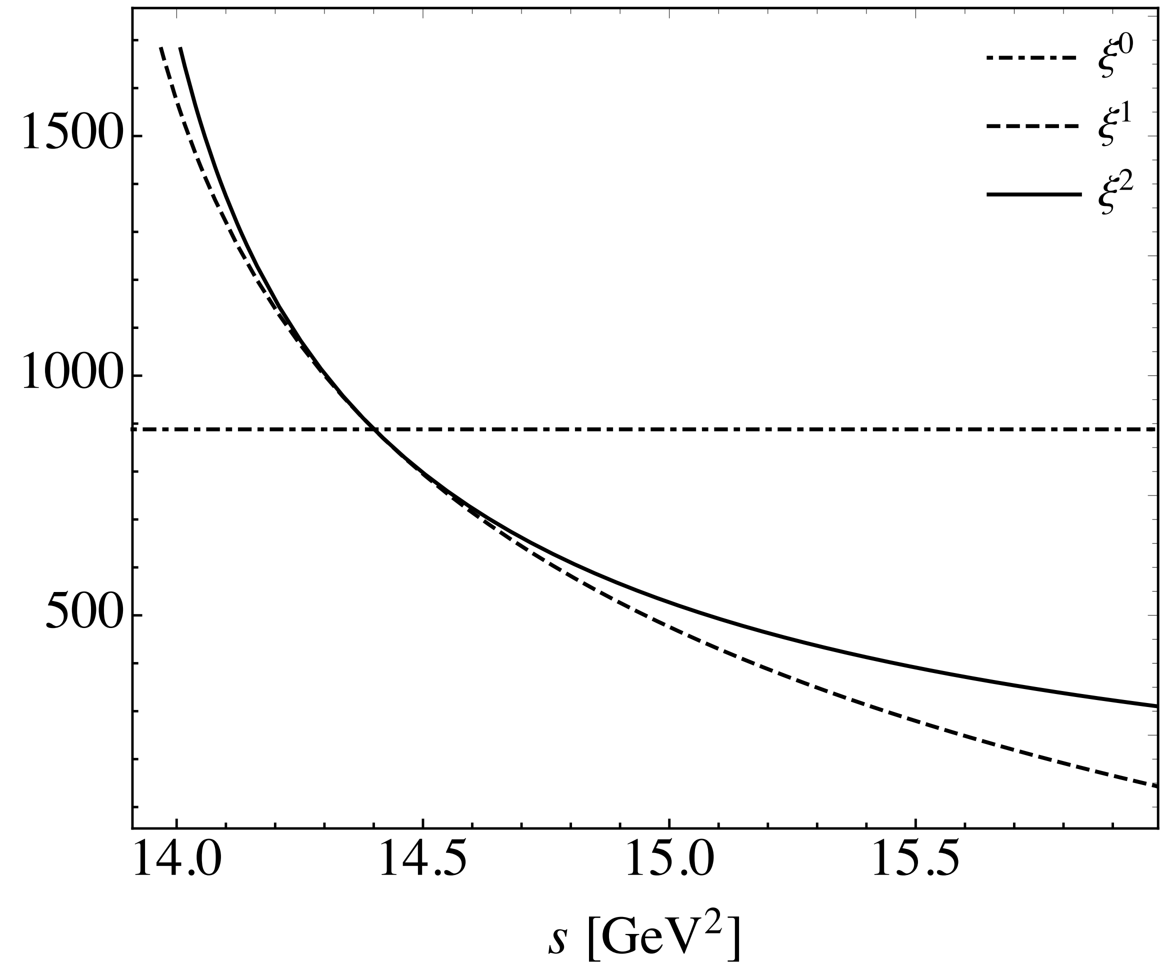
I.D, Deineka, Vanderhaeghen (2020)

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

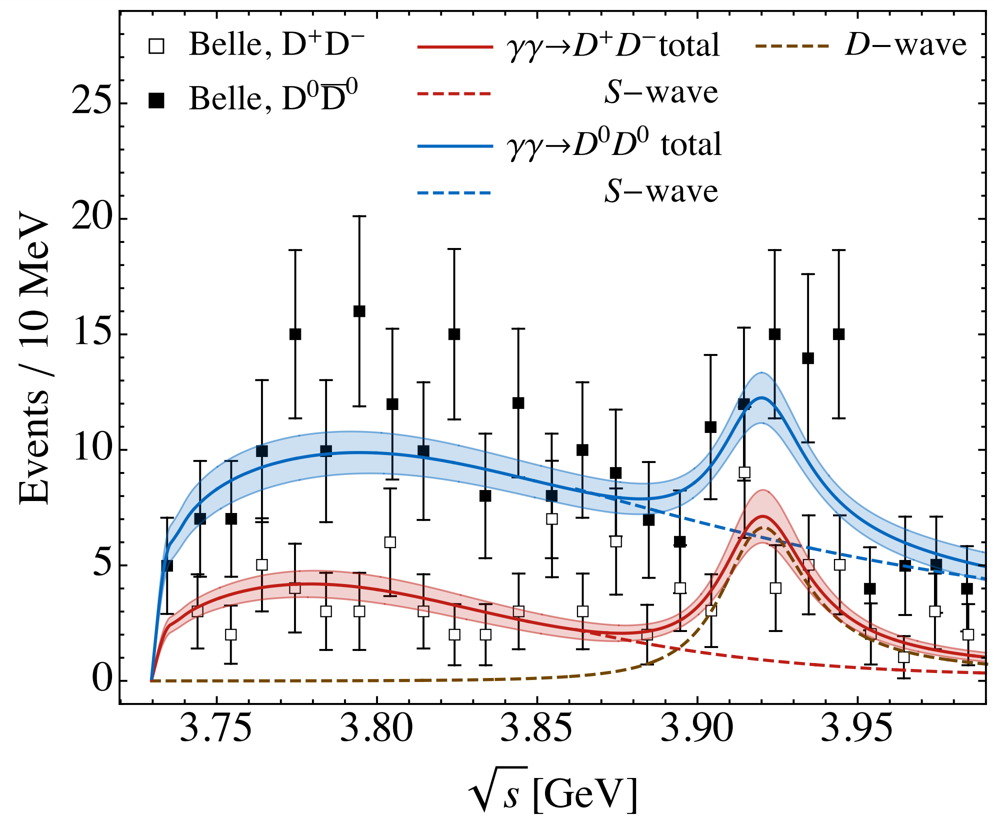
Convergence of conformal expansion

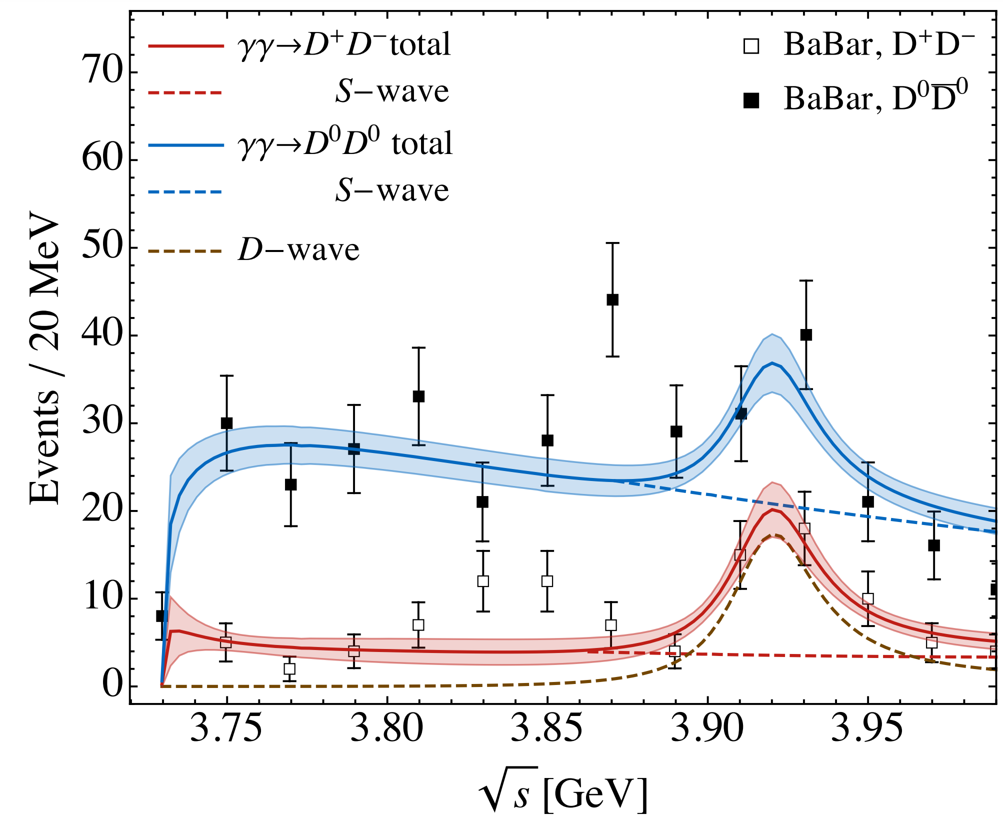
Good convergence with 3 parameters in conformal mapping expansion $\Longrightarrow$ there is no need for more parameters

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

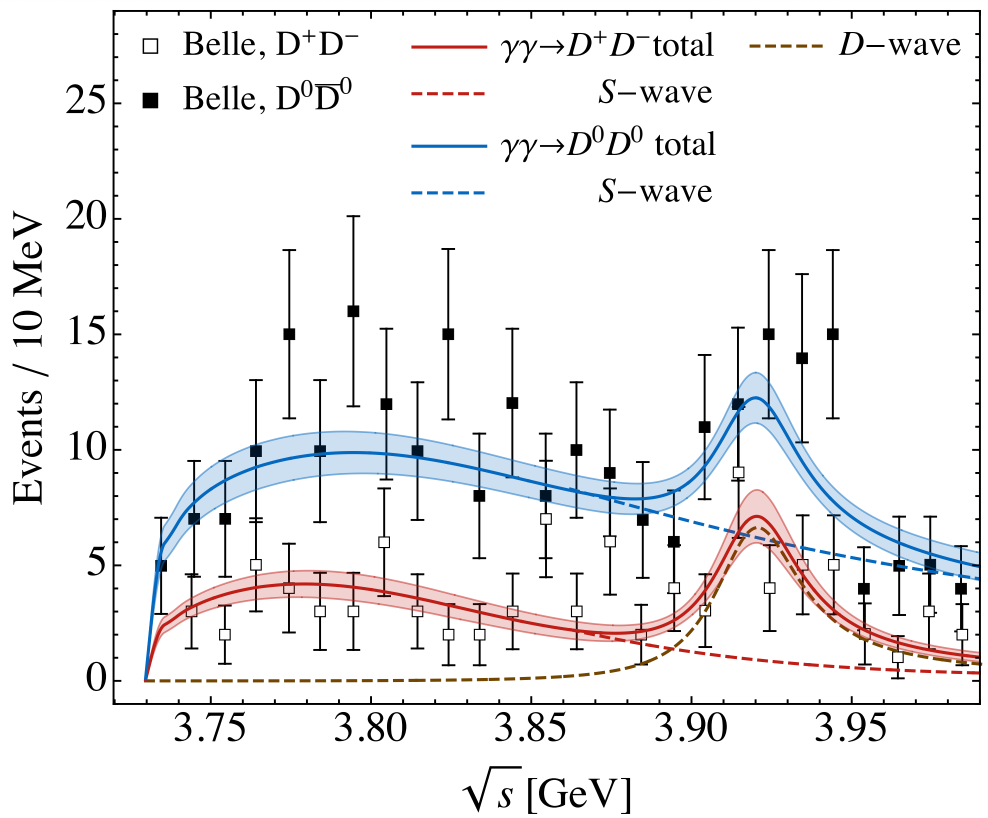


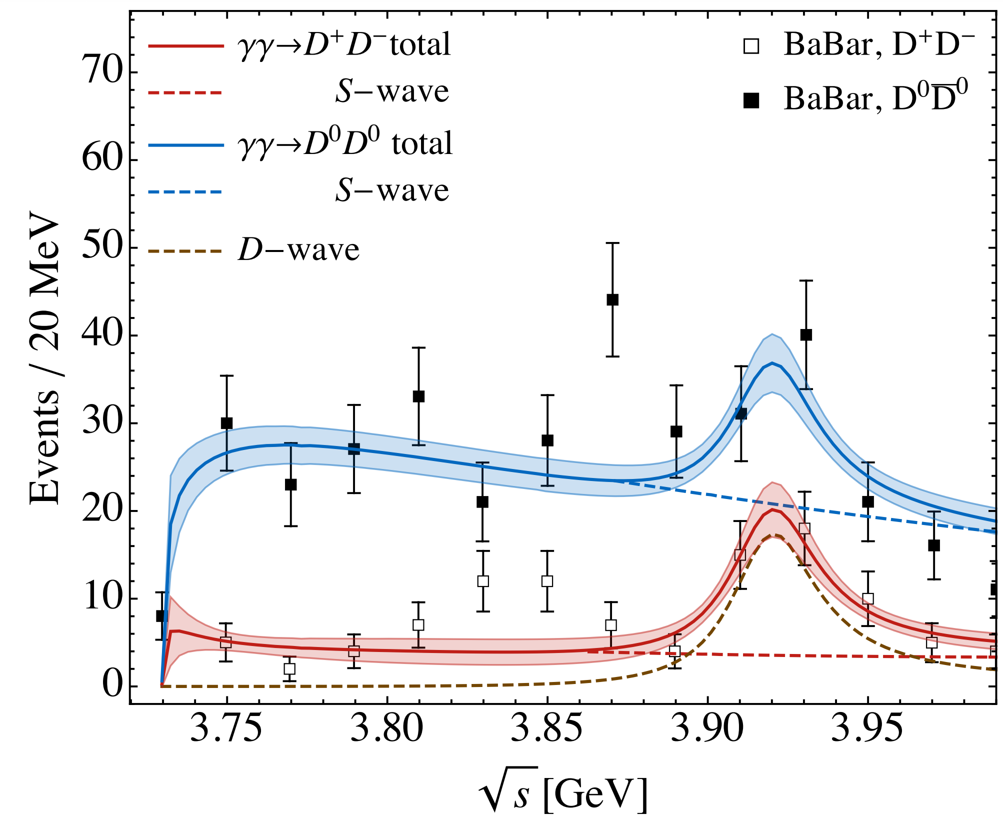
Analysis of $\gamma\gamma \to D^+D^-$ and $\gamma\gamma \to D^0\bar{D}^0$ data





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