Shedding light on X(3930) and X(3960) states with the $B^- \to K^- J/\psi\omega$ reaction

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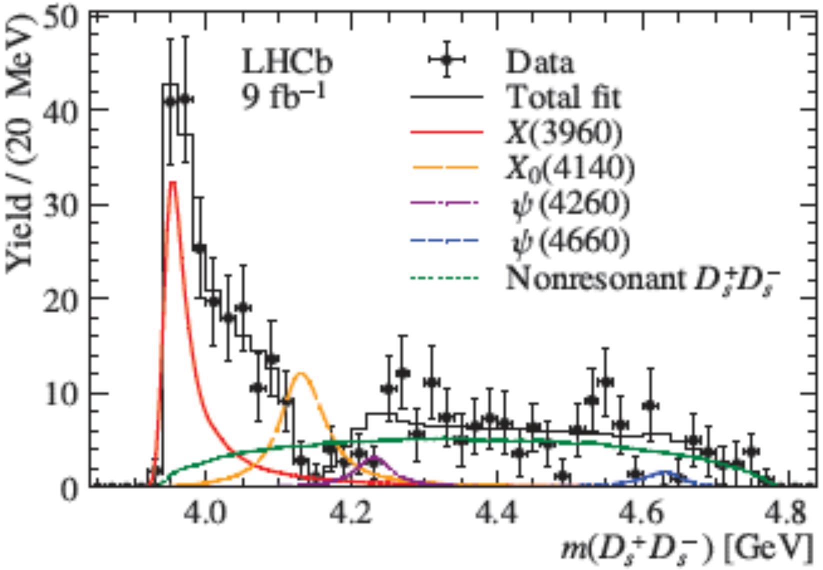
Observation of a resonant structure close to the $D_s^+ D_s^-$ threshold in $B^+ \to D_s^+ D_s^- K^+$ decay



$$J^{PC} = 0^{++}\ ;\ M = 3955 \pm 6 \pm 11\ MeV\ ;\ \Gamma = 48 \pm 17 \pm 10\ MeV$$

Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	$\mathcal{F}$ (%)	$\mathcal{S}$ (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 10$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 5.0$	12.6 (14.6)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 6$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 3.9$	3.8 (4.1)
$\psi(4260)$	1^{--}	4230 [59]	55 [59]	$3.6 \pm 0.4 \pm 3.2$	3.2 (3.6)
$\psi(4660)$	1^{--}	4633 [31]	64 [31]	$2.2 \pm 0.2 \pm 0.8$	3.0 (3.2)
NR	0^{++}	-	-	$46.1 \pm 13.2 \pm 11.3$	3.1 (3.4)

LHCb Collaboration, arXiv:2210.15153

Is there enough evidence to invoke a new $X_0(3960)$ state?

Introduction: facts to think about and plausible hypothesis

- Remarkable closeness to the $D_s^+ D_s^-$ threshold (3937 MeV) ➡ signal of a resonance below threshold

- LHCb collaboration observed a signal ($X_0(3930)$) in the D^+D^- measuring $B^+ \to D^+D^-K^+$ decay
  $J^{PC} = 0^{++};\ M_0' = 3924 \pm 2\ MeV\ ;\ \Gamma_0' = 17 \pm 5\ MeV$
  R. Aaij et al. (LHCb Collaboration), Phys. Rev. D 102, 112003 (2020); Phys. Rev. Lett. 125, 242001 (2020)

- If the $X_0(3930)$ state coupled also coupled to $D_s^+ D_s^-$, we would see a reflection of it in the $D_s^+ D_s^-$ invariant mass distribution…

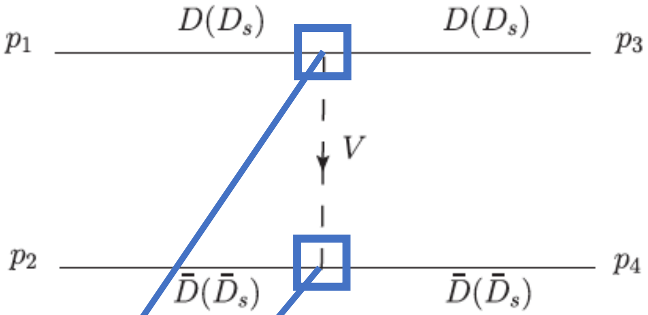
- A recent LQCD calculation obtained a bound state below $D_s^+ D_s^-$ threshold with quantum numbers 0^{++} coupling both to $D_s^+ D_s^-$ (strongly) and D^+D^- (weakly) channels
  S. Prelovsek, S. Collins, D. Mohler, M. Padmanath, and S. Piemonte, J. High Energy Phys. 06 (2021) 035

➡ **A dynamical calculation of the D^+D^- and the $D_s^+ D_s^-$ in coupled channels could make this state appear**

M. Bayar, A. Feijoo, E. Oset, Phys.Rev.D 107 (2023) 3, 034007

T. Ji, X.-K. Dong, M. Albaladejo, M.-L. Du, F.-K. Guo, J. Nieves, Phys. Rev. D Ser. 106, 094002 (2022)

Formalism: Dynamics of the $\bar{D}D$ and $\bar{D}_s D_s$ in coupled channels



$$\mathcal{L}_{VPP} = -ig\langle [P, \partial_\nu P] V^\mu \rangle$$

$$g = \frac{M_V}{2f} \quad (M_V \simeq 800\ MeV, f = 93\ MeV)$$

$$V_{ij} = -B_{ij} g^2 \frac{1}{2}\left[3s - (m_1^2 + m_2^2 + m_3^2 + m_4^2) - \frac{1}{s}(m_1^2 - m_2^2)(m_3^2 - m_4^2)\right]$$

$$B = \begin{pmatrix} \frac{1}{2}\left(\frac{3}{M_\rho^2} + \frac{1}{M_\omega^2} + \frac{2}{M_{J/\Psi}^2}\right) & \sqrt{2}\frac{1}{M_{K^*}^2} \\ \sqrt{2}\frac{1}{M_{K^*}^2} & \left(\frac{1}{M_\phi^2} + \frac{1}{M_{J/\Psi}^2}\right) \end{pmatrix} \begin{array}{l} (D\bar{D},\ I=0) = \frac{1}{\sqrt{2}}(D^+D^- + D^0\bar{D}^0) \\ D_s^+ D_s^- \end{array}$$

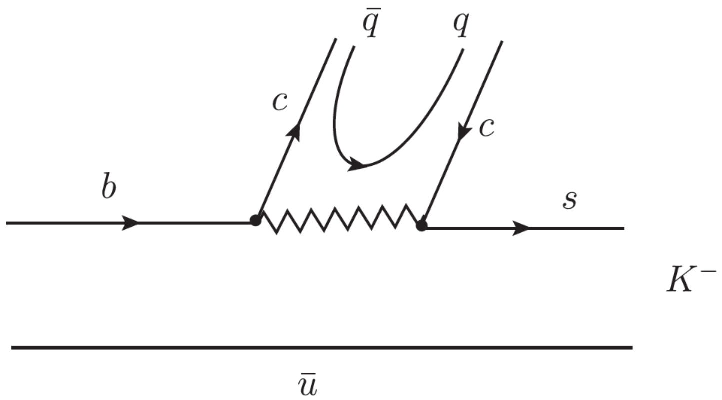
Unitarization via Bethe-Salpeter equation

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

(G loop function renormalized by means of dim. reg.)

	M [MeV]	Γ [MeV]	$\lvert g_{\bar{D}D}\rvert$ [MeV]	$\lvert g_{\bar{D}_s D_s}\rvert$ [MeV]
Pole I	3699.04	...	14509.0	5707.2
Pole II ($X_0(3930)$)	3932.72	12.32	2889.5	10018.0

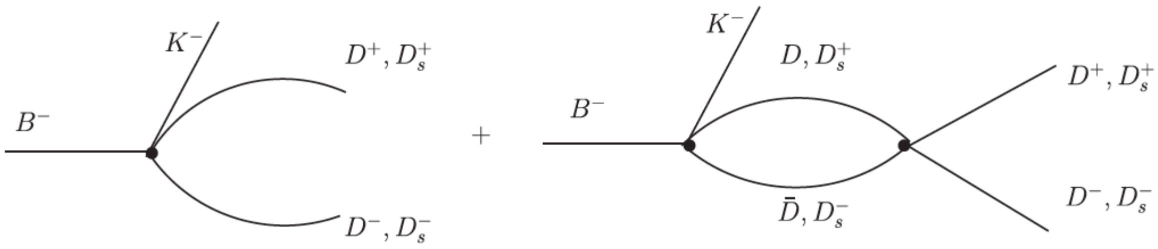
$B^- \to D^+ D^- K^-$ and $B^- \to D_s^+ D_s^- K^-$ decay processes



B^- decay via internal emission at the quark level

$c\bar{c}$ pair is hadronized to finally obtain:

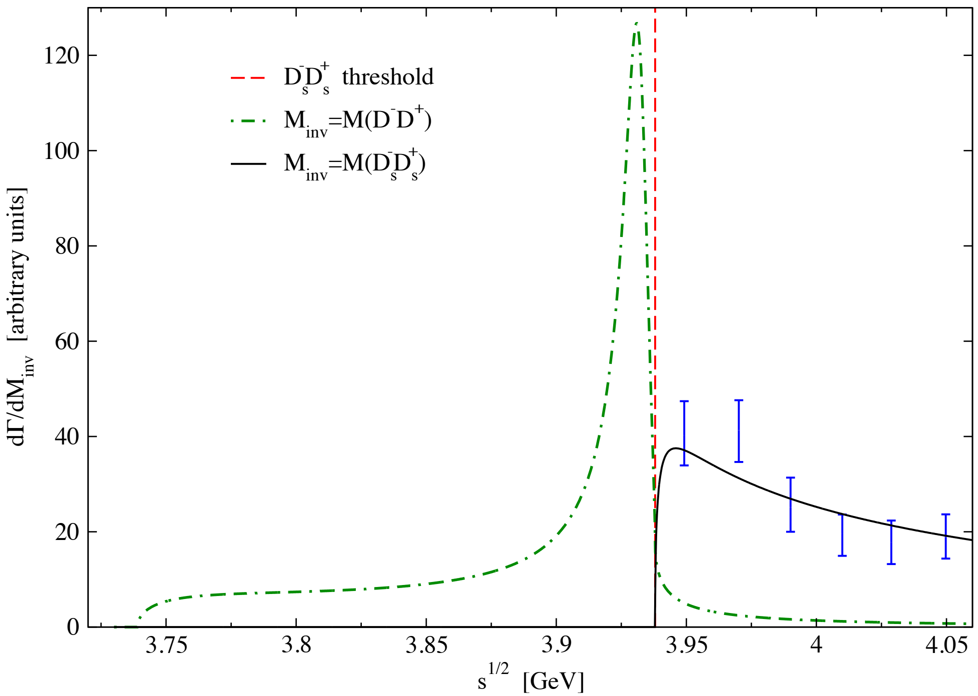
$$c\bar{c} \to \sum_i c\bar{q}_i q_i \bar{c} \to \sum_i P_{4i} P_{i4} = D^0 \bar{D}^0 + D^+ D^- + D_s^+ D_s^-$$
$$= \sqrt{2} D\bar{D} + D_s^+ D_s^-$$



Tree-level contribution + Primary production of pair $D^+ D^-$ and the $D_s^+ D_s^-$ followed by rescattering

Invariant mass distributions

$$\frac{d\,\Gamma}{dM_{\rm inv}} = \frac{1}{(2\pi)^3}\,\frac{1}{4M_B^2}\;p_{K^-}\;p_{\tilde{D}_i}\;|\tilde{t}_i|^2$$



M. Bayar, A. Feijoo, E. Oset, Phys.Rev.D 107 (2023) 3, 034007

$$\tilde{t}_{D^+D^-} = C\left(1 + G_{D\bar{D}}(M_{inv})T_{D\bar{D},D\bar{D}}(M_{inv}) + \frac{1}{\sqrt{2}}G_{D_s\bar{D}_s}(M_{inv})T_{D_s\bar{D}_s,D\bar{D}}(M_{inv})\right)$$

$$\tilde{t}_{D_s^+D_s^-} = C\left(1 + \sqrt{2}G_{D\bar{D}}(M_{inv})T_{D\bar{D},D_s^+D_s^-}(M_{inv}) + G_{D_s\bar{D}_s}(M_{inv})T_{D_s^+D_s^-,D_s^+D_s^-}(M_{inv})\right)$$

Partial width ratio assuming the same X resonance decaying to different final states:

$$\frac{\Gamma(X \to D^+D^-)}{\Gamma(X \to D_s^+D_s^-)} = \frac{\mathcal{B}^{(1)}\,\mathcal{F}_X^{(1)}}{\mathcal{B}^{(2)}\,\mathcal{F}_X^{(2)}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$$

LHCb Collaboration, arXiv:2210.15153

$B^- \to K^- J/\psi\omega$ decay

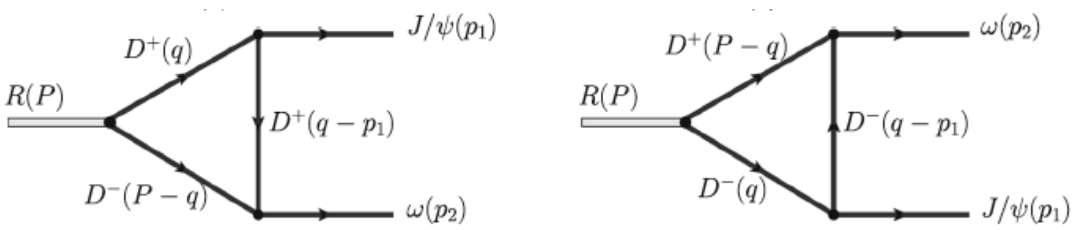
The measurement of the $J/\psi\omega$ invariant mass in the $B^+ \to K^+ J/\psi\omega$ decay can provide valuable information about the existence of the X(3960)

- unpublished data available for this reaction yet with poor statistics
  Andreassi, Master's thesis, Rome U., 11 (2014)

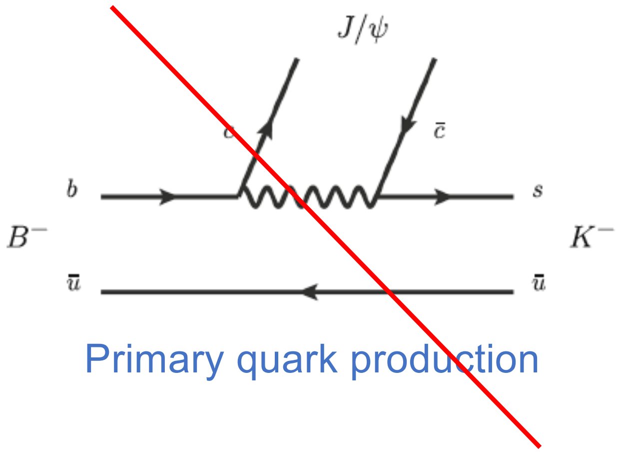
- The $J/\psi\omega$ threshold (3880 MeV) is open well below the region of interest, therefore one can see either one peak or two peaks, refuting or proving the single signal hypothesis

Assuming that only one state, X(3930), is present in that energy region, we study $B^- \to K^- J/\psi\omega$ decay that after comparison with future observations can or cannot rule out the need of new X(3960)
L. M. Abreu, M. Albaladejo, A. F., E. Oset and J. Nieves, *Eur.Phys.J.C* 83 (2023) 4, 309

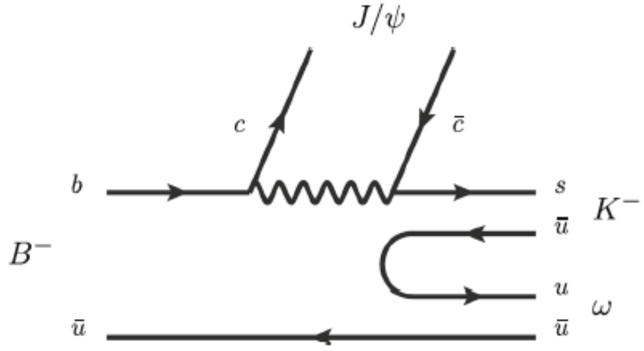
- A triangle loop diagram can connect the $J/\psi\omega$ with the $\bar{D}D$ and the $D_s^+ D_s^-$ components (and their inherent dynamics)



$B^- \to K^- J/\psi\omega$ decay formalism: internal emission mechanism



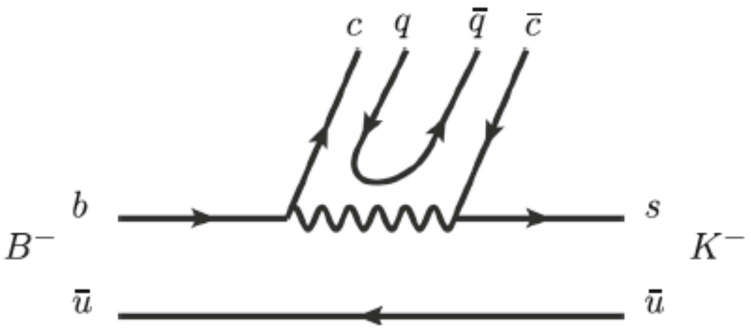
Primary quark production



$s\bar u$ pair hadronization:

$$s\bar u \to \sum_i s\bar q_i q_i \bar u = (PV)_{31}$$

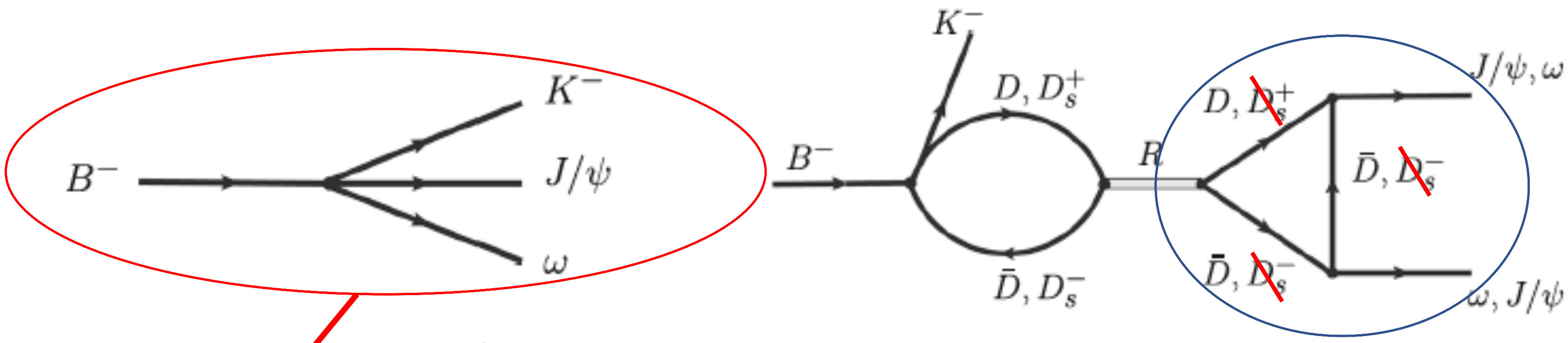
$$= K^- \left(\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega \right) + \dots$$



$c\bar c$ pair hadronization:

$$c\bar c \to \sum_i c\bar q_i q_i \bar c \to \sum_i P_{4i}P_{i4} = D^0\bar D^0 + D^+D^- + D_s^+D_s^-$$

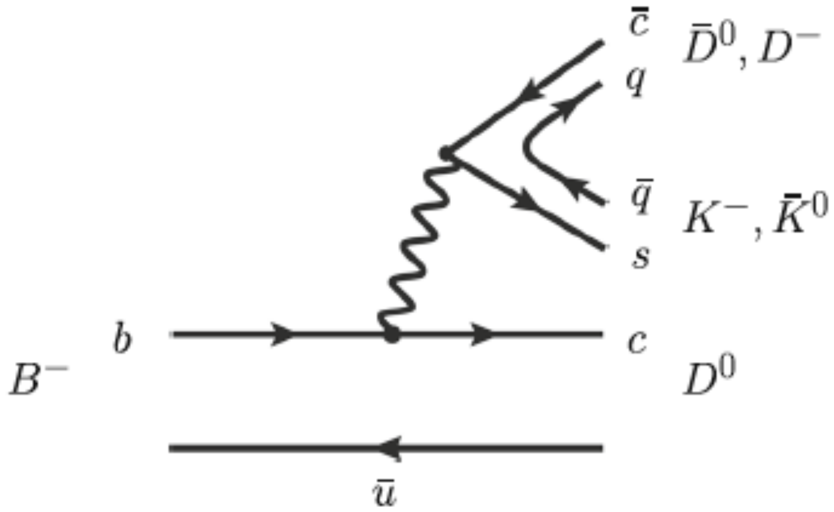
$$= \sqrt{2}D\bar D + D_s^+D_s^-$$



$$\tilde{t}_{J/\psi\,\omega} = \frac{1}{\sqrt{2}} C\,\vec{\epsilon}_{J/\psi}\cdot\vec{\epsilon}_{\omega} + C' \Bigg(\left[\sqrt{2} G_{D\overline{D}}(M_{\rm inv})\, T_{D\overline{D},D\overline{D}}(M_{\rm inv}) + G_{D_s^+ D_s^-}(M_{\rm inv})\, T_{D_s^+ D_s^-,D\overline{D}}(M_{\rm inv})\right]$$

$$\times \left(\frac{1}{\sqrt{2}}\widetilde{V}_{D^+D^-} + \frac{1}{\sqrt{2}}\widetilde{V}_{D^0\overline{D}^0}\right)\Bigg) .$$

$$\boxed{\widetilde{V}^{(a)}_{D^+D^-} = i\left(\frac{m_{D^*}}{m_{K^*}}\right)^2 \int \frac{d^4q}{(2\pi)^4} \frac{(-2g\,\epsilon_{J/\psi}\cdot q)\left(\frac{g}{\sqrt{2}}\,\epsilon_\omega\cdot(2q-P-p_1)\right)\theta\,(q_{\rm max}-|\vec{q}|)}{[q^2-m_D^2+i\varepsilon]\,[(P-q)^2-m_D^2+i\varepsilon]\,[(q-p_1)^2-m_D^2]}}$$



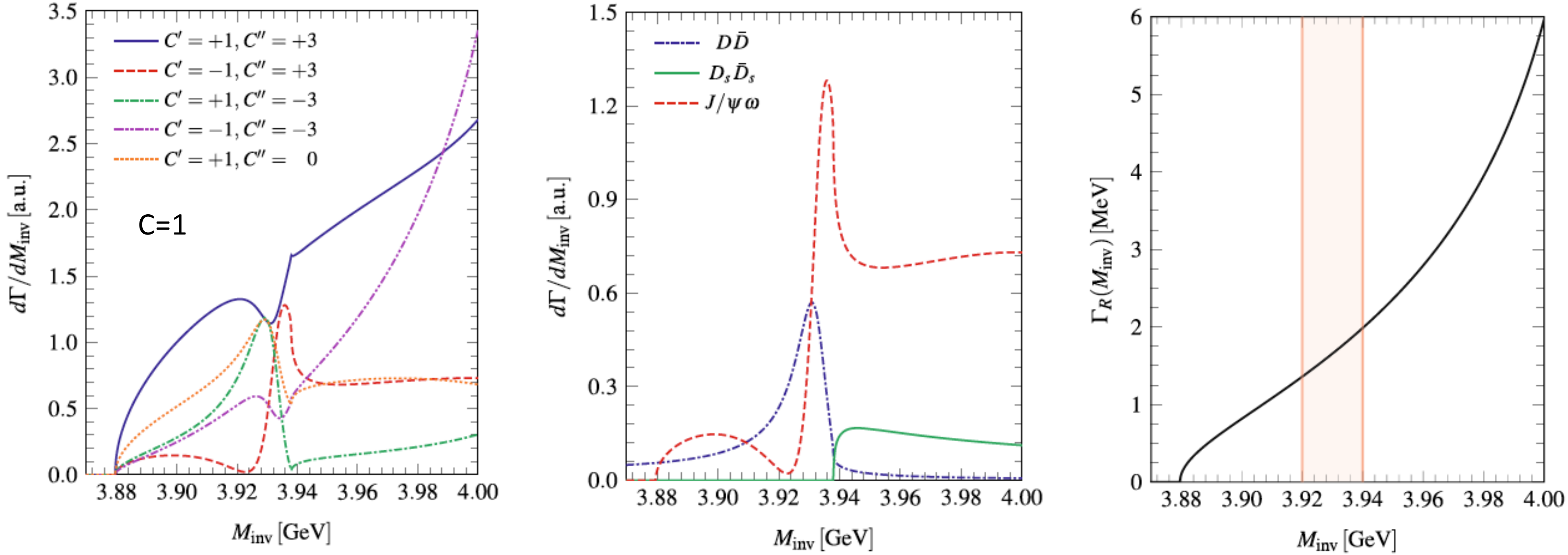
$s\bar{c}$ pair hadronization:

$$s\bar{c} \to \sum_i s\bar{q}_i q_i \bar{c} = (P^2)_{34} = K^-\overline{D}^0 + \overline{K}^0 D^- - \frac{1}{\sqrt{3}}\eta D_s^- + \sqrt{\frac{2}{3}}\eta' D_s^- + \eta_c D_s^-$$

$$C'\sqrt{2}G_{D\overline{D}}(M_{\text{inv}})T_{D\overline{D},D\overline{D}}(M_{\text{inv}}) \to \left(C'\sqrt{2} + \frac{1}{\sqrt{2}}C''\right) \times G_{D\overline{D}}(M_{\text{inv}})T_{D\overline{D},D\overline{D}}(M_{\text{inv}}$$

$B^- \to K^- J/\psi\omega$ decay: $J/\psi\omega$ invariant mass and its contribution to the X(3930) width

$$\frac{d\Gamma}{dM_{\rm inv}} = \frac{3}{(2\pi)^3}\frac{1}{4m_B^2}p_{K^-}\tilde{p}_\omega|\tilde{t}'_{J/\psi\,\omega}|^2$$



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We have performed a study of the $\bar{D}D$, $\bar{D}_s D_s$ dynamics in coupled channels, two states found, one of them identified with the $X_0(3930)$ coupling mostly to $D_s^+ D_s^-$ and more weakly to $\bar{D}D$.

The D^+D^-, $D_s^+ D_s^-$ invariant mass distributions in $\mathrm{B}^- \to \mathrm{D}^+\mathrm{D}^-\mathrm{K}^-$ and $\mathrm{B}^- \to \mathrm{D}_s^+\mathrm{D}_s^-\mathrm{K}^-$ decays have been calculated and showed that:

- the $X_0(3930)$ produces and enhancement in the $D_s^+ D_s^-$ invariant mass distribution close to its threshold
- The shape and the relative integrated strength (compared to the D^+D^-one) is in agreement with the experimental one

➡ **There is no need to invoke a new $X_0(3960)$ state**

The study of the $\mathrm{B}^- \to \mathrm{K}^-\ \mathrm{J}/\psi\omega$ decay as a tool to see if the $X_0(3930)$ state is the same or not as the $X_0(3960)$. We present results for our assumption (no need of $X_0(3960)$) for the $\mathrm{J}/\psi\omega$ invariant mass distribution for different parametrizations finding clear effects produced by the $X_0(3930)$ in all cases.

Future comparison with experimental measurements could confirm or refute our hypothesis.

Thank you for your attention!