

# Search for the $X(3872)$ spin partners: Production of the $X(4014)$ in $e^+e^-$ collisions

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PPS, V. Baru, F.-K. Guo, C. Hanhart, A. Nefediev, Chin.Phys.Lett.41 (2023) 031301

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Search for the  $X(3872)$  spin partners: Production of the  $X(4014)$  in  $e^+e^-$  collisions

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- ① Introduction
- ② Decay of  $X(4014) \rightarrow e^+e^-$
- ③ production of  $X(4014)$  in  $e^+e^-$  collisions
- ④ Summary

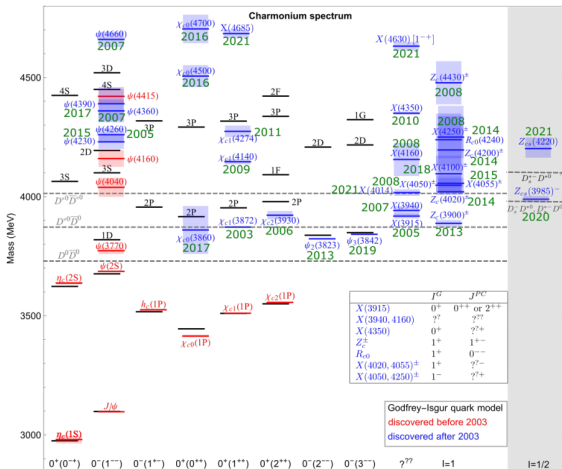
## ① Introduction

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## ④ Summary

## Exotic states in the hidden-charm sector

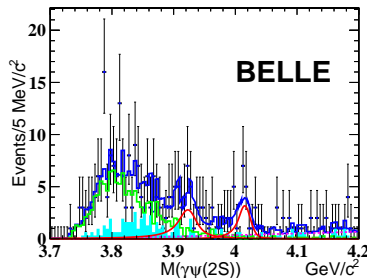
F.-K. Guo, PoS LAT'TICE2022 (2023) 232; PPS, *et al.*, arXiv:2410.19563

## Experimental signal for $X(4014)$

In the process  $\gamma\gamma \rightarrow \psi(2S)\gamma$ , two structures are reported by Belle

X.-L. Wang, *et al.* [Belle], *Phys. Rev. D* 105(2022)112011

- **first structure**  $M_1 = 3922.4 \pm 6.5 \pm 2.0$  MeV,  $\Gamma_1 = 2 \pm 17 \pm 4$  MeV which is consistent with  $\chi_{c0}(3915)$  or  $\chi_{c2}(3930)$
- **second structure**
  - $M_2 = 4014.3 \pm 4.0 \pm 1.5$  MeV
  - $\Gamma = 4 \pm 11 \pm 6$  MeV
  - global significance  $2.8\sigma$
  - $\Gamma_{\gamma\gamma}\text{Br}[R_2 \rightarrow \psi(2S)\gamma]$ :  
 $0^{++}: 6.2 \pm 2.2 \pm 0.8$  eV ;  
 $2^{++}: 1.2 \pm 0.4 \pm 0.2$  eV



## Properties of the second structure

- Second structure is the perfect candidate of  $2^{++} D^* \bar{D}^*$  molecule
  - **production in the  $\gamma\gamma$  process**: the quantum number  $0^{++}$  or  $2^{++}$
  - **close to  $D^* \bar{D}^*$  threshold**:  $D^{*0} \bar{D}^{*0}$  threshold 4014 MeV
  - **OBE**: more strong coupling for  $2^{++}$  molecule than  $0^{++}$  molecule

R. Molina, E. Oset, *Phys.Rev.D* 80(2009)114013

- **mass**: its mass is identical to the prediction of the HQSS; at heavy quark limit,  $X(3872)$  and  $X(4014)$ : the same potentials

$$\iff M_{X(4014)} - M_{X(3872)} \sim M_{D^*} - M_D \sim 140 \text{ MeV}$$

J. Nieves, *et al.*, *Phys.Rev.D* 86(2012)056004; T. J., *et al.*, *Phys.Rev.D* 106(2022)094002

- **decay width**: based on the HQSS,  $D\bar{D}$  and  $D\bar{D}^*[\mathcal{O}(1 \text{ MeV})]$ ,  $D\bar{D}^*\gamma[\mathcal{O}(1 \text{ keV})]$ ;  $J/\psi V [\mathcal{O}(10 \sim 10^3 \text{ keV})]$  and  $\eta_c P [\mathcal{O}(1 \sim 10) \text{ keV}]$ ;  $\pi^0 \chi_{c1} [\mathcal{O}(1 \sim 10) \text{ keV}]$

M. Albaladejo, *et al.*, *Eur.Phys.J.C* 75(2015)547; Y.-X. Zheng, *et al.*, *Phys.Rev.D*

109(2024)014027; S.-D. Liu, *et al.*, *Phys.Rev.D* 110(2024)054048

- This state was also explored as a  $0^{++} D^* \bar{D}^*$  molecule

M.-Y. Duan, *et al.*, *Eur.Phys.J.C* 82(2022)968; Z.-L. Yue, *et al.*, *Phys.Rev.D* 106(2022)054008

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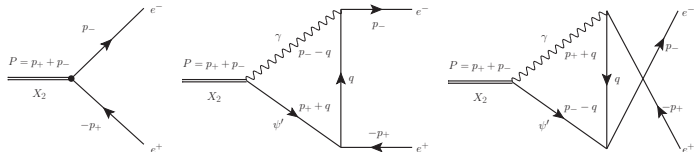
Decay process for  $X(4014) \rightarrow e^+e^-$ 

The same amplitudes for  $X(4014) \rightarrow e^+e^-$  and  $e^+e^- \rightarrow X(4014)$  due to **time reversal** and  **$P$ -parity** (the principle of detailed balance)

- decay process  $X(4014) \rightarrow \psi'/V\gamma \rightarrow e^+e^-$   
with  $\psi' = J/\psi$ ,  $\psi(2S)$  and  $V = \rho, \omega$
- light vector meson & charmonium in  $X(3872) \rightarrow e^+e^-$

A. Denig, *et al.*, Phys.Lett.B 736(2014)221

- $\Gamma[X(3872) \rightarrow V\gamma \rightarrow e^+e^-] \sim 10^{-7}$  eV
- $\Gamma[X(3872) \rightarrow \psi'\gamma \rightarrow e^+e^-] \sim 10^{-3} - 10^{-2}$  eV
- as the spin-2 partner of  $X(3872)$ , contributions from the light vector mesons to  $X(4014) \rightarrow e^+e^-$  are ignorable



## Parameters

- interaction between  $X(4014)$  and  $\psi'\gamma$  is

$$\mathcal{L}_{X\psi'\gamma} = g_{X\psi'\gamma} X_2^{\rho\sigma} F_{\sigma\beta} \psi'^{\beta}_{\rho},$$

where the coupling is extracted from the partial width  $X(4014) \rightarrow \psi'\gamma$

- estimation of the partial width for  $X(4014) \rightarrow \psi'\gamma$ 
  - $\Gamma_{X(4014)}^{\gamma\gamma} \text{Br}(X(4014) \rightarrow \psi(2S)\gamma) = (1.2 \pm 0.4 \pm 0.2) \text{ eV}$   
X.-L. Wang, *et al.* [Belle], *Phys. Rev. D* 105(2022)112011
  - $\Gamma_{X(4014)}^{\gamma\gamma} = 0.1 \text{ keV}$  to estimate the branch ratio for  $X(4014) \rightarrow \psi(2S)\gamma$   
V. Baru, C. Hanhart, A. V. Nefediev, *JHEP* 06(2017)010
  - $\Gamma[X(4014) \rightarrow \psi(2S)\gamma]/\Gamma[X(4014) \rightarrow J/\psi\gamma] \sim 1$   
PPS, J. M. Dias, F.-K. Guo, *Phys.Lett.B* 843(2023)137987
- VMD model is utilized to estimate the vertex  $\psi' \rightarrow \gamma^* \rightarrow e^+e^-$

$$\mathcal{L}_{\psi'\gamma} = -\frac{e f_{\psi'} Q_c}{2 M_{\psi'}} F^{\mu\nu} \psi_{\mu\nu}$$

## Decay width

- branch ratio for  $X(4014) \rightarrow e^+e^-$  as the function of the energy scale  $\mu$

PPS, V. Baru, F.-K. Guo, C. Hanhart, A. Nefediev, arXiv:2312.05389

$\mu$ [GeV]	2.0	4.0	6.0
$\text{Br}_{\text{loop}}[X(4014) \rightarrow e^+e^-] \times 10^9$	2	7	11

- branch ratios for  $X(4014)$  and  $\chi_{c2}(2P)$ :  $\Gamma_{\chi_{c2}(3930)}^{\gamma\gamma} = 1.0$  keV (quark model) and  $\Gamma_{\chi_{c2}(1P)}^{ee} \sim \Gamma_{\chi_{c2}(2P)}^{ee} = 0.07$  eV (NRQCD)

C. M. A., R. Dhir, (2023), arXiv:2311.05274; N. Kivel and M. Vanderhaeghen, JHEP 02(2016)032;

E. J. Eichten, C. Quigg, Phys.Rev.D 52(1995)1726

Channel	$J/\psi\gamma$	$\psi(2S)\gamma$	$\gamma\gamma$	$e^+e^-$
$(D^*\bar{D}^*)_{J=2}$	$10^{-2}$	$10^{-2}$	$10^{-4}/10^{-5}$	$10^{-9}$
$\chi_{c2}(2P)$	$10^{-3}$	$10^{-3}$	$10^{-4}$	$10^{-9}$

- because of large uncertainty of  $X(4014)$  width ( $\Gamma_{X(4014)} = 4 \pm 11 \pm 6$  MeV), we take different values for  $\Gamma_{X(4014)}$ :
  - $\Gamma[X(4014) \rightarrow e^+e^-] \sim \mathcal{O}(10^{-2})$  eV for  $\Gamma_{X(4014)} \sim 10$  MeV
  - $\Gamma[X(4014) \rightarrow e^+e^-] \sim \mathcal{O}(10^{-3})$  eV for  $\Gamma_{X(4014)} \sim 1$  MeV

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production cross section for  $X(4014)$ 

- based on the principle of detailed balance, the cross section for the directly production of  $X(4014)$  is

PPS, *et al.*, Phys.Rev.D 105(2022)034024

$$\sigma_C \simeq \frac{20\pi\Gamma_{X(4014)}^{ee}}{\Gamma_{X(4014)}M_{X(4014)}^2} = \frac{20\pi}{M_{X(4014)}^2} \text{Br}[X(4014) \rightarrow e^+e^-] \simeq 7 \text{ pb},$$

- search for  $X(4014)$  in the  $\psi'\gamma$  invariant mass distribution ( $\psi(2S)$  and  $J/\psi$  are reconstructed by following decay processes)

$$\text{Br}[\psi(2S) \rightarrow \pi^+\pi^- J/\psi] \simeq (34.68 \pm 0.30)\%,$$

$$\text{Br}[J/\psi \rightarrow \ell^+\ell^-] \simeq (11.93 \pm 0.07)\% \quad (\ell = e, \mu),$$

Search for  $X(4014)$  in the  $e^+e^-$  collisions

Search for  $X(4014)$  in BESIII and STCF:

- **BESIII:** During the period from 2011 to 2014, BESIII accumulated an integrated luminosity of around  $53 \text{ pb}^{-1}$  at the centre-of-mass energy  $\sqrt{s} = 4090 \text{ MeV}$  and we expect that  $\mathcal{O}(10^2)$  events can be produced
- **STCF:** considering the integrated luminosity of a year is  $1 \text{ ab}^{-1}$ , at  $\sqrt{s} \simeq 4014 \text{ MeV}$ , the number of events constructed in  $\psi'\gamma$  final state can be
  - $\mathcal{O}(10^2)$  for  $\chi_{c2}(2P)$
  - $\mathcal{O}(10^3)$  for  $X(4014)$  as a molecule

The STCF is expected to search for  $X(4014)$  in the  $\psi(2S)\gamma$  and  $J/\psi\gamma$  invariant mass distribution

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## Summary

- $X(4014)$ : A hint, observed by Belle in the process  $\gamma\gamma \rightarrow \psi(2S)\gamma$  process, is a candidate of isoscalar  $2^{++} D^*\bar{D}^*$  molecule;
- production of  $X(4014)$  in  $e^+e^-$  collision (principle of detailed balance):
  - the partial width for  $X(4014) \rightarrow e^+e^-$  is at  $\mathcal{O}(10^{-3}) - \mathcal{O}(10^{-2})$  eV level in terms of the value of  $\Gamma_{X(4014)}$
  - STCF can be used to search for  $X(4014)$  in the  $\psi'\gamma$  invariant mass distribution

Thanks for your attention!

## Backup

The independent and gauge invariant structure coupled with the tensor polarization is

$$\mathcal{S}_{\rho\sigma}^{(1)} = g_{\rho\sigma}(\partial_\alpha F_{\mu\nu})(\partial^\alpha \psi^{\mu\nu}),$$

$$\mathcal{S}_{\rho\sigma}^{(2)} = (\partial_\rho F_{\mu\nu})(\partial_\sigma \psi^{\mu\nu}) + (\partial_\sigma F_{\mu\nu})(\partial_\rho \psi^{\mu\nu}) - \frac{1}{2}g_{\rho\sigma}(\partial_\alpha F_{\mu\nu})(\partial^\alpha \psi^{\mu\nu}),$$

$$\mathcal{S}_{\rho\sigma}^{(3)} = (\partial_\rho \partial_\sigma F_{\mu\nu})\psi^{\mu\nu} + F_{\mu\nu}(\partial_\rho \partial_\sigma \psi^{\mu\nu}),$$

$$\mathcal{S}_{\rho\sigma}^{(4)} = F_{\rho\beta}\psi_\sigma^\beta + F_{\sigma\beta}\psi_\rho^\beta - \frac{1}{2}g_{\rho\sigma}F_{\mu\nu}\psi^{\mu\nu},$$

with  $\psi^{\mu\nu} \equiv \partial^\mu \psi^\nu - \partial^\nu \psi^\mu$ . Since  $\mathcal{S}_{\rho\sigma}^{(1)}$ ,  $\mathcal{S}_{\rho\sigma}^{(2)}$  and  $\mathcal{S}_{\rho\sigma}^{(3)}$  are suppressed by the third power of momentum at heavy quark limit, and the the last term of  $\mathcal{S}_{\rho\sigma}^{(4)}$  vanishes due to the traceless tensor polarization. Then the Lagrangian is

$$\mathcal{L}_{X\psi\gamma} = g_{X\psi\gamma} X^{\rho\sigma} F_{\sigma\beta}\psi_\rho^\beta.$$

Applying the narrow-width approximation, the cross section of  $AB \rightarrow C$  in the center-of-mass frame is

$$\begin{aligned}
 \sigma_C &= \frac{1}{2E_A 2E_B |v_A - v_B|} \int \frac{dp_C^3}{(2\pi)^3 2E_C} |\mathcal{M}_{AB \rightarrow C}|^2 (2\pi)^4 \delta^4(p_A + p_B - p_C) \\
 &= \frac{1}{4 |E_B \mathbf{p} + E_A \mathbf{p}|} \frac{2\pi \delta(E_A + E_B - E_C)}{2(E_A + E_B)} |\mathcal{M}_{AB \rightarrow C}|^2 \\
 &\simeq \frac{1}{\Gamma \sqrt{s \lambda(s, m_A^2, m_B^2)}} |\mathcal{M}_{AB \rightarrow C}|^2. \tag{1}
 \end{aligned}$$