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

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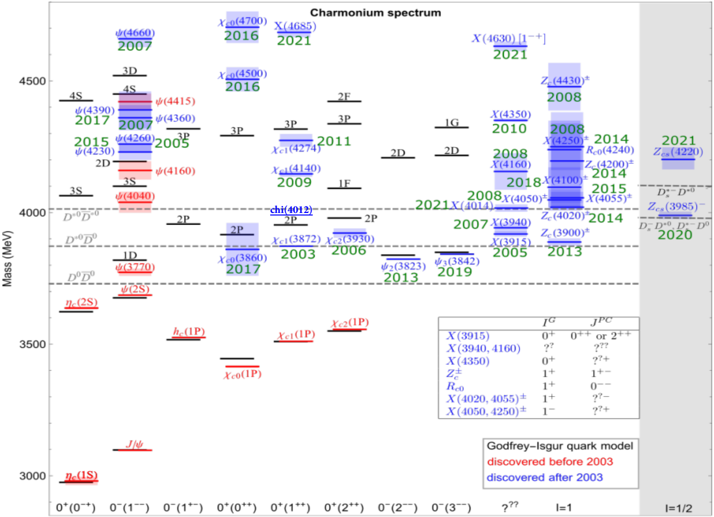
The 6th International Workshop on Future Tau Charm Facilities
@GuangZhou
19, November, 2024

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

Exotic states in the hidden-charm sector



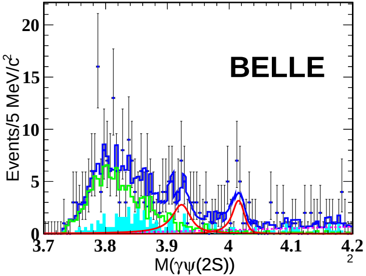
F.-K. Guo, PoS LATTICE2022 (2023) 232; PPS, *et al.*, arXiv:2410.19563

Experimental signal for $X(4014)$

In the process $\gamma\gamma \to \psi(2S)\gamma$, 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 2.8σ
  - $\Gamma_{\gamma\gamma}\mathrm{Br}[R_2 \to \psi(2S)\gamma]$:
    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
    $\Longleftrightarrow M_{X(4014)} - M_{X(3872)} \sim M_{D^*} - M_D \sim 140$ 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 $\eta_c P$ $[\mathcal{O}(1 \sim 10)\ \text{keV}]$; $\pi^0\chi_{c1}$ $[\mathcal{O}(1 \sim 10)\ \text{keV}]$

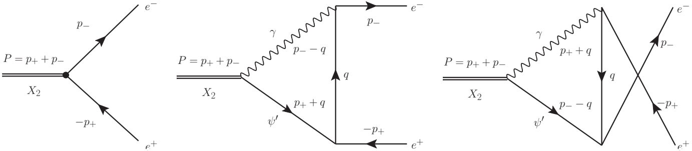
    M. Albaladejo, *et al.*, Eur.Phys.J.C 75(2015)547; Y.-X. Zheng, *et al.*, Phys.Rev.D 109(2024)014027; S.-D. Liu, *et al.*, Phys.Rev.D 110(2024)054048
- This state was also explored as a 0^{++} $D^*\bar{D}^*$ molecule

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

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

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

- decay process $X(4014) \to \psi'/V\gamma \to e^+e^-$
  with $\psi' = J/\psi,\ \psi(2S)$ and $V = \rho,\ \omega$
- light vector meson & charmonium in $X(3872) \to e^+e^-$
  A. Denig, *et al.*, Phys.Lett.B 736(2014)221
  - $\Gamma[X(3872) \to V\gamma \to e^+e^-] \sim 10^{-7}$ eV
  - $\Gamma[X(3872) \to \psi'\gamma \to e^+e^-] \sim 10^{-3} - 10^{-2}$ eV
- as the spin-2 partner of $X(3872)$, contributions from the light vector mesons to $X(4014) \to e^+e^-$ 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 $X(4014) \to \psi'\gamma$
- estimation of the partial width for $X(4014) \to \psi'\gamma$
  - $\Gamma^{\gamma\gamma}_{X(4014)} \mathrm{Br}(X(4014) \to \psi(2S)\gamma) = (1.2 \pm 0.4 \pm 0.2)$ eV
    X.-L. Wang, *et al.* [Belle], Phys. Rev. D 105(2022)112011
  - $\Gamma^{\gamma\gamma}_{X(4014)} = 0.1$ keV to estimate the branch ratio for $X(4014) \to \psi(2S)\gamma$
    V. Baru, C. Hanhart, A. V. Nefediev, JHEP 06(2017)010
  - $\Gamma[X(4014) \to \psi(2S)\gamma]/\Gamma[X(4014) \to J/\psi\gamma] \sim 1$
    PPS, J. M. Dias, F.-K, Guo, Phys.Lett.B 843(2023)137987
- VMD model is utilized to estimate the vertex $\psi' \to \gamma^* \to e^+e^-$

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

Decay width

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

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

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

- branch ratios for $X(4014)$ and $\chi_{c2}(2P)$: $\Gamma^{\gamma\gamma}_{\chi_{c2}(3930)} = 1.0$ keV (quark model) and $\Gamma^{ee}_{\chi_{c2}(1P)} \sim \Gamma^{ee}_{\chi_{c2}(2P)} = 0.07$ 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 $\Gamma_{X(4014)}$:
  - $\Gamma[X(4014) \to e^+e^-] \sim \mathcal{O}(10^{-2})$ eV for $\Gamma_{X(4014)} \sim 10$ MeV
  - $\Gamma[X(4014) \to e^+e^-] \sim \mathcal{O}(10^{-3})$ eV for $\Gamma_{X(4014)} \sim 1$ MeV

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

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

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

$$\mathrm{Br}[\psi(2S) \to \pi^+\pi^- J/\psi] \simeq (34.68 \pm 0.30)\%,$$
$$\mathrm{Br}[J/\psi \to \ell^+\ell^-] \simeq (11.93 \pm 0.07)\% \quad (\ell = e,\ \mu),$$

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 pb^{-1} at the centre-of-mass energy $\sqrt{s} = 4090$ MeV and we expect that $\mathcal{O}(10^2)$ events can be produced
- STCF: considering the integrated luminosity of a year is 1 ab^{-1}, at $\sqrt{s} \simeq 4014$ 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

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

Summary

- $X(4014)$: A hint, observed by Belle in the process $\gamma\gamma \to \psi(2S)\gamma$ 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 $X(4014) \to e^+e^-$ 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

$$\mathcal{S}^{(1)}_{\rho\sigma} = g_{\rho\sigma}(\partial_\alpha F_{\mu\nu})(\partial^\alpha \psi^{\mu\nu}),$$
$$\mathcal{S}^{(2)}_{\rho\sigma} = (\partial_\rho F_{\mu\nu})(\partial_\sigma \psi^{\mu\nu}) + (\partial_\sigma F_{\mu\nu})(\partial_\rho \psi^{\mu\nu}) - \frac{1}{2} g_{\rho\sigma}(\partial_\alpha F_{\mu\nu})(\partial^\alpha \psi^{\mu\nu}),$$
$$\mathcal{S}^{(3)}_{\rho\sigma} = (\partial_\rho \partial_\sigma F_{\mu\nu})\psi^{\mu\nu} + F_{\mu\nu}(\partial_\rho \partial_\sigma \psi^{\mu\nu}),$$
$$\mathcal{S}^{(4)}_{\rho\sigma} = F_{\rho\beta}\psi^\beta_\sigma + F_{\sigma\beta}\psi^\beta_\rho - \frac{1}{2} g_{\rho\sigma} F_{\mu\nu}\psi^{\mu\nu},$$

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

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

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

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