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$X(3872) \to J/\psi\pi\gamma$ and $X(3872) \to J/\psi\pi\pi\gamma$ decays

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IISER Mohali, India

Outline

- Short review of X(3872)
- Theoretical framework
- Results and discussion
- Summary

Short review of $X(3872)$

The resonance parameters of the $X(3872)$ from PDG (in units of MeV)
R. L. Workman et al., PRD 108 (2023) 011103

Mass	Width	Threshold	ΔE
3871.65 ± 0.06	1.19 ± 0.21	$D^+D^{*-}/D^0\bar{D}^{*0}$	$-8/-0.04$

$X(3872)$: $D\bar{D}^*$ hadronic molecule

M.B. Voloshin, PLB 579, 316 (2004); E. S. Swanson, PLB 588, 189 (2004); N.A. Tornqvist, PLB 590, 209 (2004); S. Fleming, M. Kusunoki, T. Mehen, and U. van Kolck, PRD 76, 034006 (2007); Y. R. Liu, X. Liu, W.Z. Deng, and S.L. Zhu, EPJC 56, 63 (2008); N.A. Tornqvist, ZPC 61, 525 (1994).

The pure molecule models meet with difficulties:

- The ratio $\Gamma(B^0 \to K^0 X)/\Gamma(B^+ \to K^+ X)$ is about unity, which is about two times larger than measurements by the BABAR and Belle collaborations;
- The predicted branching ratios of $X(3872) \to D^0\bar{D}^0\gamma$ and $X(3872) \to J/\psi\gamma$ largely deviated from the experimental data;
- It is hard to explain the observed production rate in the high energy $p\bar{p}$ collisions at the Tevatron.

$X(3872)$: $D\bar{D}^*$ hadronic molecule $+c\bar{c}$

M. Suzuki, PRD 72, 114013 (2005); B. Q. Li and K.T. Chao, PRD 79, 094004 (2009).

Short review of $X(3872)$

The branching ratios (%) of $X(3872)$ from PDG
R. L. Workman et al., PRD 108 (2023) 011103

Decay channels	Branching ratios
$\pi^+\pi^- J/\psi$	3.8 ± 1.2
$\omega J/\psi$	4.3 ± 2.1
$D^0\bar{D}^0\pi^0$	49^{+18}_{-20}
$D^0\bar{D}^{*0}$	37 ± 9
$\pi^0\chi_{c1}$	3.4 ± 1.6
$\gamma J/\psi$	0.8 ± 0.4
$\gamma\psi(2S)$	4.5 ± 2.0

Check the decay modes of the $X(3872)$ list in PDG

- The dominant decay channel is the open-charm decay;
- The branching ratios of the radiative decays are of the same order as those of the hidden-charm decays;
- Other radiative decays of the $X(3872)$?

- Sizeable ω contribution to $X(3872) \to J/\psi\pi\pi$
  LHCb, PRD 108 (2023) 011103
- Dominant contributions to $X(3872) \to J/\psi\pi\pi$ and $X(3872) \to J/\psi\pi\pi\pi$ arise from the diagrams with the $X(3872)$ coupling to the $J/\psi\rho$ and $J/\psi\omega$
  H.N. Wang, Q. Wang, and J.J. Xie, PRD 106, 056022 (2022)

- Whether the same scenario still holds in the $X(3872) \to J/\psi\pi\gamma$ and $X(3872) \to J/\psi\pi\pi\gamma$?
- More importantly, compare with $X(3872) \to J/\psi\pi\pi$ and $X(3872) \to J/\psi\pi\pi\pi$, $X(3872) \to J/\psi\pi\gamma$ and $X(3872) \to J/\psi\pi\pi\gamma$ have an advantage in exploring the couplings of $X(3872)$ with $J/\psi\rho$ and $J/\psi\omega$.

Theoretical framework： Feynman diagram and Lagrangian

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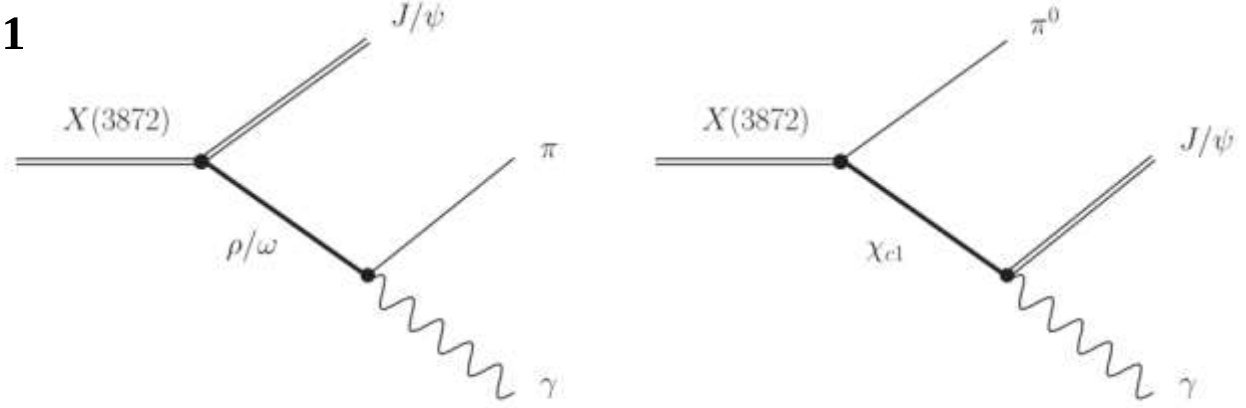

(a) (b)

$$\mathcal{L}_{XJ/\psi V} = g_{X\psi V}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu X_\nu \psi_\alpha V_\beta,$$

$$\mathcal{L}_{X\chi_{c1}\pi} = \frac{g_{X\chi_{c1}\pi}}{m_X}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu X_\nu \chi_{c1\alpha}\partial_\beta \pi,$$

$$\mathcal{L}_{X\psi'\gamma} = g_{X\psi'\gamma}\varepsilon^{\mu\nu\alpha\beta}X_\mu \psi'_\nu \partial_\alpha A^\gamma_\beta,$$

$$\mathcal{L}_{\omega\rho\pi} = g_{\omega\rho\pi}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu \omega_\alpha \partial_\nu \rho_\beta \phi_\pi,$$

$$\mathcal{L}_{V\pi\gamma} = g_{V\pi\gamma}\varepsilon^{\mu\nu\alpha\beta}F_{\mu\nu}V_{\alpha\beta}\phi_\pi,$$

$$\mathcal{L}_{\chi_{c1}\psi\gamma} = g_{\chi_{c1}\psi\gamma}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu \chi_{c1\nu} \upsilon^\xi \psi_\alpha F_{\beta\xi},$$

G. Janssen, K. Holinde, and J. Speth, PRC 49, 2763 (1994).

J. L. Lucio-Martinez, M. Napsuciale, M. D. Scadron, and V. M. Villanueva, PRD 61, 034013 (2000).

R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio, and G. Nardulli, PLB 302, 95 (1993).

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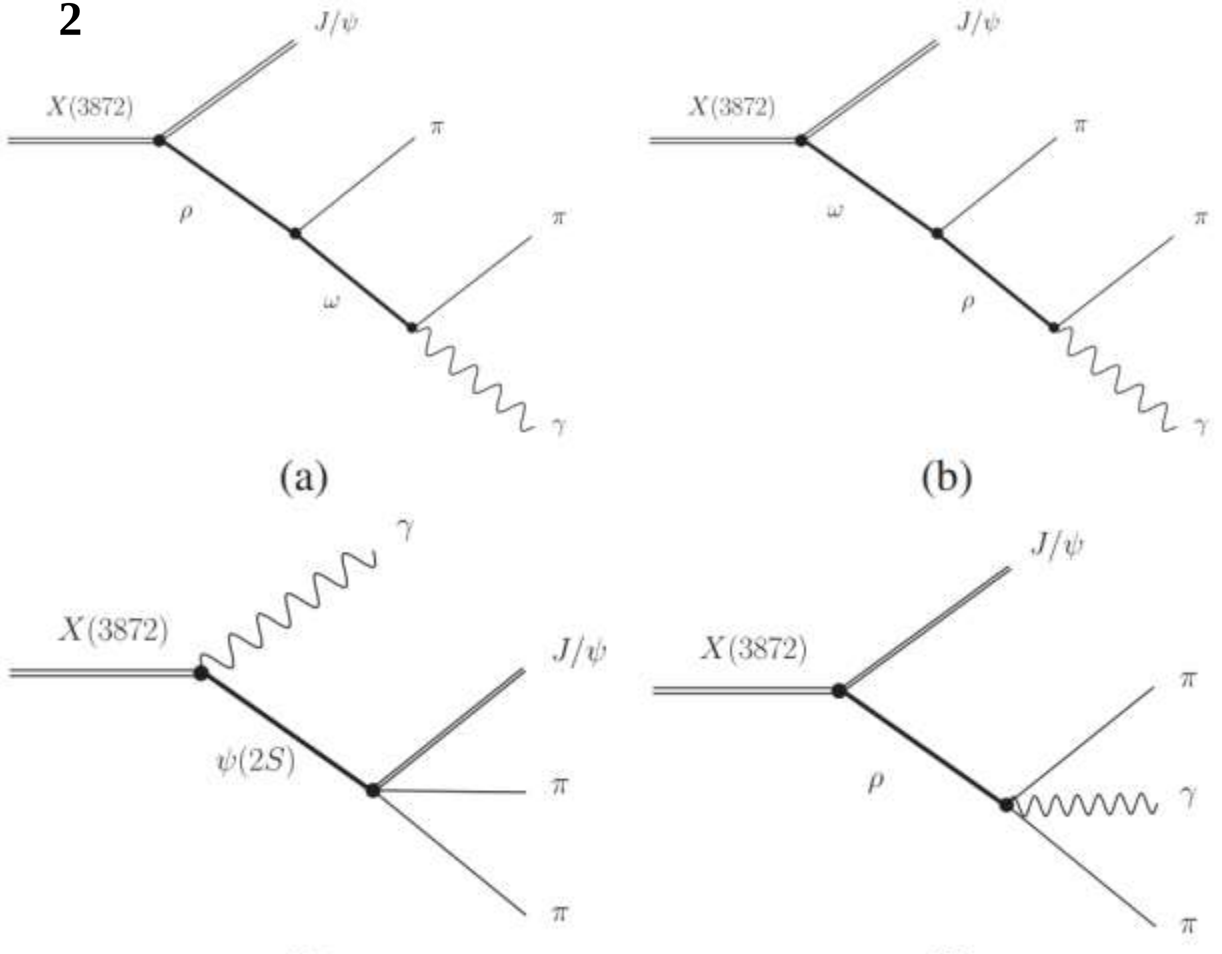


(a) (b) (c) (d)

Theoretical framework: $X(3872) \to J/\psi\pi\gamma$

$$F_{\rho/\omega}(q^2) = \frac{\Lambda^4_{\rho/\omega}}{\Lambda^4_{\rho/\omega} + (q^2 - m^2_{\rho/\omega})^2}$$

$$\mathcal{M}^{\pi\gamma}_{\rho} = (g_{X\psi\rho}\varepsilon_{\xi\kappa\phi\theta} i p^{\xi}\epsilon^{\kappa}(p)p_1^{\phi}q^{\theta})\frac{-g^{\theta\sigma} + q^{\theta}q^{\sigma}/m_{\rho}^2}{D_{\rho}(q^2)} \times (g_{\rho\pi\gamma}\varepsilon_{\mu\nu\alpha\beta}(p_3^{\mu}g^{\sigma\nu} - p_3^{\nu}g^{\sigma\mu})(q^{\alpha}g^{\sigma\beta} - q^{\beta}g^{\sigma\alpha})\epsilon_{\rho}(p_3)) \times F_{\rho}(q^2),$$

$$\mathcal{M}^{\pi\gamma}_{\chi_{c1}} = \left(\frac{g_{X\chi_{c1}\pi}}{m_X}\varepsilon_{\xi\kappa\phi\theta} i p^{\xi}\epsilon^{\kappa}(p) i p_2^{\theta}\right)\frac{-g^{\phi\nu} + q^{\phi}q^{\nu}/m_{\rho}^{\chi_{c1}}}{D_{\chi_{c1}}(q^2)} \times \left(\frac{\sqrt{2}g_{\chi_{c1}\psi\gamma}}{m_{\chi_{c1}}}\varepsilon_{\mu\nu\alpha\beta}(-i)q^{\mu}v^{\xi}\epsilon^{\alpha}(p_1)i(p_3^{\beta}\epsilon^{\xi}(p_3) - p_3^{\xi}\epsilon^{\beta}(p_3))\right)F_{\chi_{c1}}(q^2),$$

$$\mathcal{M}_{X\to J/\psi\pi\gamma} = \mathcal{M}^{\pi\gamma}_{\rho} + e^{i\phi_{\omega}}\mathcal{M}^{\pi\gamma}_{\omega} + e^{i\phi_{\chi_{c1}}}\mathcal{M}^{\pi\gamma}_{\chi_{c1}}$$

$$\Gamma_{\rho\to\pi\gamma} = \frac{4g^2_{\rho\pi\gamma}p^3_{f\rho}}{3\pi},$$

$$\Gamma_{\omega\to\pi\gamma} = \frac{4g^2_{\omega\pi\gamma}p^3_{f\omega}}{3\pi},$$

$$\Gamma_{X\to\psi'\gamma} = \frac{g^2_{X\psi'\gamma}p^3_{fX}}{12\pi m_X^2 m_{\psi'}^2}(m_X^2 + m_{\psi'}^2),$$

$$\Gamma_{X\to\chi_{c1}\pi} = \frac{g^2_{X\psi'\gamma}p^3_{fX}}{12\pi m_X^2},$$

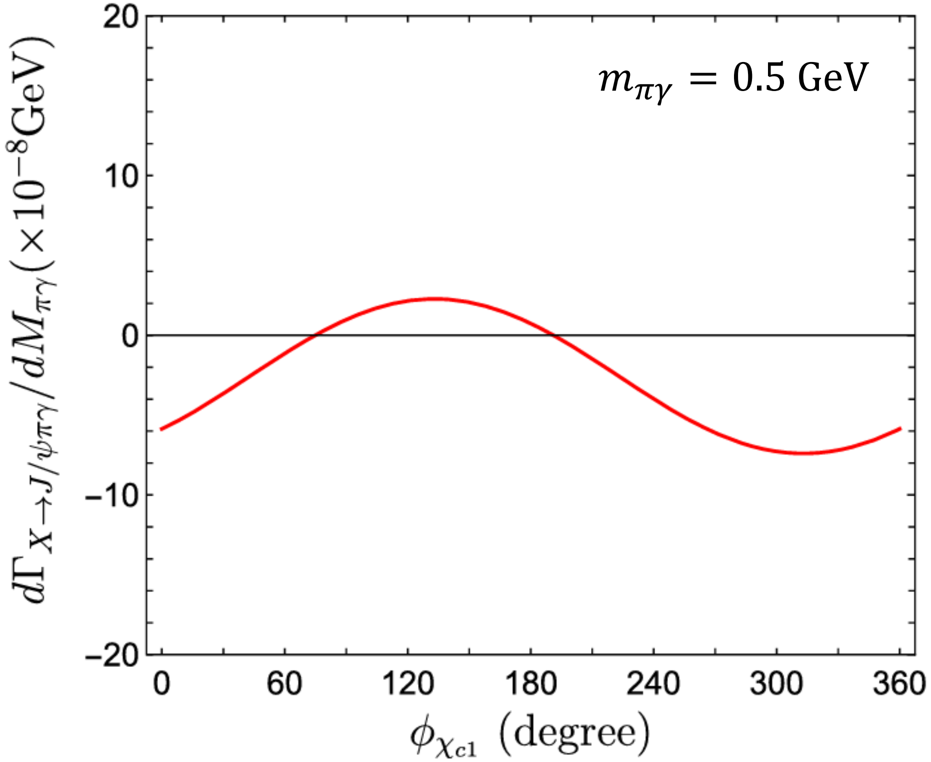
$$\Gamma_{\chi_{c1}\to J/\psi\gamma} = \frac{g^2_{\chi_{c1}\psi\gamma}p^3_{f\chi_{c1}}m_{\psi}}{3\pi m_{\chi_{c1}}},$$

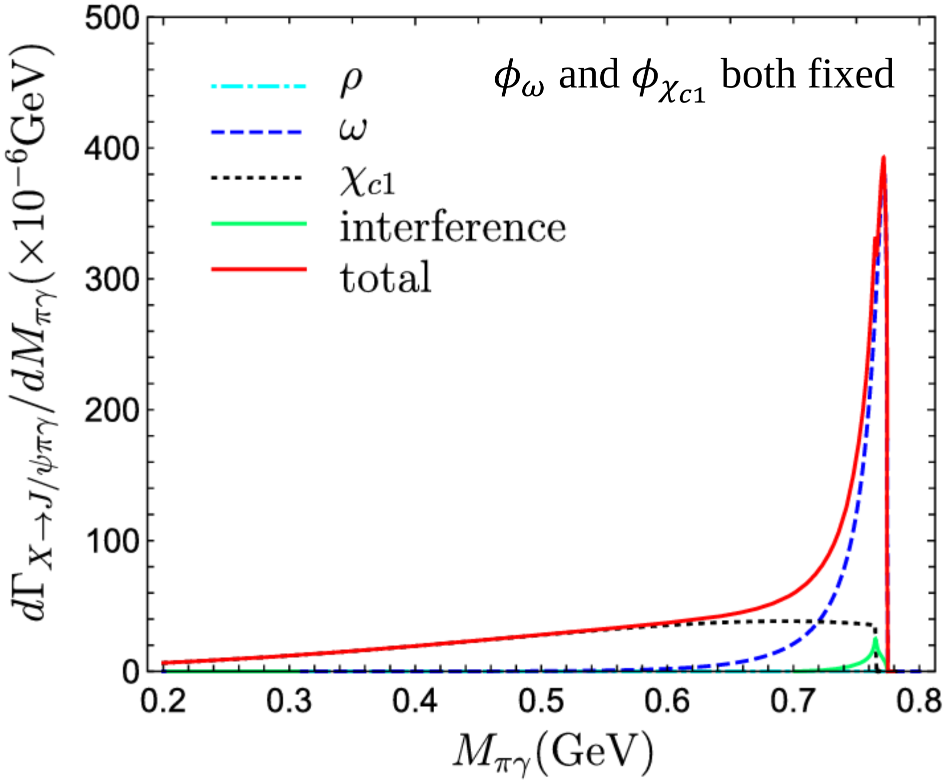
$g_{X\psi\rho}$	$g_{X\psi\omega}$	$g_{\rho\pi\gamma}$	$g_{\omega\pi\gamma}$	$g_{X\psi'\gamma}$	$g_{X\chi_{c1}\pi}$	$g_{\chi_{c1}\psi\gamma}$	$g_{\omega\rho\pi}$
0.09 ± 0.02	0.31 ± 0.06	$0.06\mathrm{GeV}^{-1}$	$0.18\mathrm{GeV}^{-1}$	1.56	$0.84^{+0.18}_{-0.23}$	$0.31\mathrm{GeV}^{-1}$	$50\mathrm{GeV}^{-1}$

H.N. Wang, Q. Wang, and J.J. Xie, PRD 106, 056022 (2022).

Extracted from the experimental data

Results and discussion: $X(3872) \to J/\psi\pi\gamma$

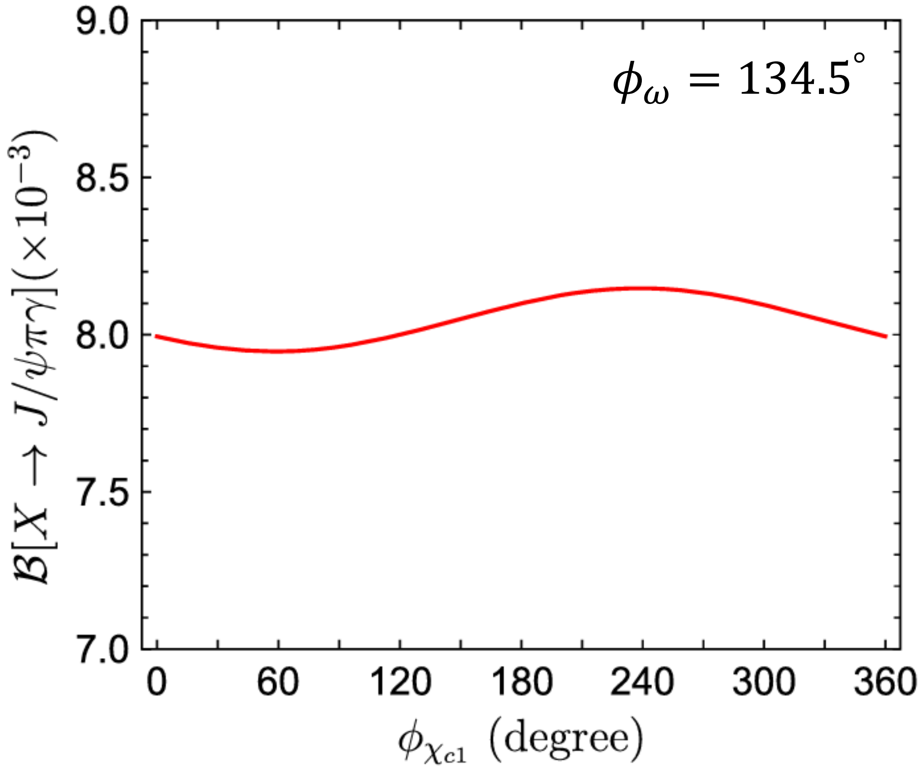




- ϕ_ω: same as in $X(3872) \to J/\psi\pi\pi$;
- The interference term is not drastically dependent on the $\phi_{\chi_{c1}}$;
- Choose $\phi_{\chi_{c1}} = 223^\circ$: the central value of the interference term.

- $X(3872) \to J/\psi\pi\gamma$ is dominated by the ω meson;
- χ_{c1}: the non-resonance contribution;
- $X(3872) \to J/\psi\pi\gamma$: clean and ideal process to explore the isospin conservation channel $J/\psi\omega$ of $X(3872)$.

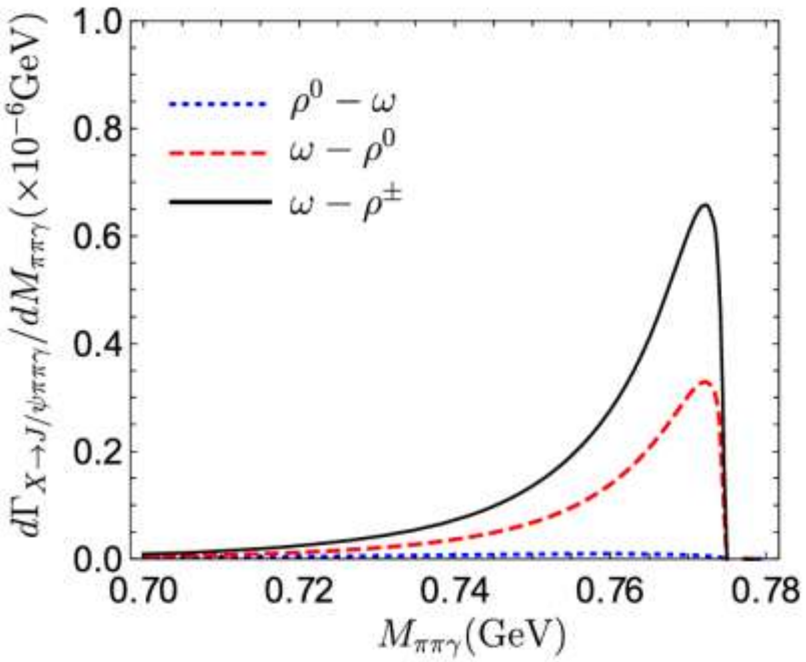
Results and discussion： $X(3872) \to J/\psi\pi\gamma$



- The $\phi_{\chi_{c1}}$ dependence of the total branching ratio of $X(3872) \to J/\psi\pi\gamma$ is fairly stable;
- $Br[X(3872) \to J/\psi\pi\gamma] = (8.10^{+3.59}_{-2.89}) \times 10^{-3}$, the same order as those of the hidden-charm and radiative decays, which is **large enough to be detected** experimentally;
- Similar with [E. Braaten and M. Kusunoki, PRD 72, 054022 (2005)]

Results and discussion: $X(3872) \to J/\psi\pi\pi\gamma$

- $X(3872) \to J/\psi\pi\pi\pi$: $g_{\rho\pi\pi} > g_{\omega\pi\pi}$;
- $X(3872) \to J/\psi\pi\pi\gamma$: $g_{\rho\pi\gamma} < g_{\omega\pi\gamma}$;



- $J/\psi\omega$ channel is still larger than $J/\psi\rho$ channel, similar to $X(3872) \to J/\psi\pi\pi\pi$;
- How about the Br of $X(3872) \to J/\psi\pi\pi\gamma$ for Fig. a and b?

Narrow width approximation: $\psi(2S)$

$$Br[X(3872) \to \psi(2S)\gamma \to J/\psi\pi\pi\gamma]$$
$$= Br[X(3872) \to \psi(2S)\gamma] \times Br[\psi(2S) \to J/\psi\pi\pi]$$

ρ is almost on shell with a large width& $J/\psi\rho$ near threshold

$$\Gamma_{X\to J/\psi\rho\to J/\psi\pi\pi\gamma} = \int_{(2m_\pi)^2}^{(m_X-m_{J/\psi})^2} ds\, f(s, m_\rho, \Gamma_\rho) \times \frac{|\vec{p}|}{24\pi m_X^2} |\overline{\mathcal{M}^{\text{tot}}_{X\to J/\psi\rho}(m_\rho \to \sqrt{s})}|^2 \times \mathcal{B}[\rho \to \pi\pi\gamma],$$

$$\frac{1}{\pi}\frac{m_\rho\Gamma_\rho}{(s-m_\rho^2)^2 + m_\rho^2\Gamma_\rho^2}$$

Results and discussion: $X(3872) \to J/\psi\pi\pi\gamma$

BR	a	b	c	d	Total
$X(3872) \to J/\psi\pi^0\pi^0\gamma$	$(3.84^{+1.90}_{-1.52}) \times 10^{-7}$	$(4.58^{+1.94}_{-1.60}) \times 10^{-6}$	$(0.82 \pm 0.37)\%$	$(2.07 \pm 0.52) \times 10^{-6}$	$(2.38 \pm 1.06)\%$
$X(3872) \to J/\psi\pi^+\pi^-\gamma$	0	$(9.16^{+3.89}_{-3.20}) \times 10^{-6}$	$(1.56 \pm 0.69)\%$	$(4.55 \pm 1.09) \times 10^{-4}$	

The $X(3872) \to J/\psi\pi\gamma$ and $X(3872) \to J/\psi\pi\pi\gamma$ decays are very helpful for constraining the coupling constants

$$\mathcal{B}[X \to J/\psi\pi\gamma] = 0.002 g_{X\psi\rho}^2 + \boxed{0.083 g_{X\psi\omega}^2} + 0.004 g_{X\psi\rho} g_{X\psi\omega} + 0.012,$$

Extract $g_{X\psi\omega}$ in $X \to J/\psi\omega \to J/\psi\pi\gamma$

$$\mathcal{B}[X \to J/\psi\pi^0\pi^0\gamma], = \boxed{(3.03 \pm 1.16) \times 10^{-4} g_{X\psi\rho}^2 + (4.77 \times 10^{-5}) g_{X\psi\omega}^2} + (0.82 \pm 0.37)\%,$$

Extract $g_{X\psi\rho}$ and $g_{X\psi\omega}$ in $X \to J/\psi\pi^0\pi^0\gamma$

$$\mathcal{B}[X \to J/\psi\pi^+\pi^-\gamma], = \boxed{(5.62 \pm 2.22) \times 10^{-2} g_{X\psi\rho}^2} + (9.53 \times 10^{-5}) g_{X\psi\omega}^2 + (1.56 \pm 0.69)\%.$$

Extract $g_{X\psi\omega}$ in $X \to J/\psi\pi^+\pi^-\gamma$

Summary

- The $X(3872) \to J/\psi\pi\gamma$ is dominated by the ω meson. As for the $X(3872) \to J/\psi\pi\pi\gamma$, the contributions of the cascade decays through the ρ and ω mesons are strongly suppressed with respect to the diagrams which proceed either through the $\psi(2S)$ or the three body decay of ρ;
- The branching ratios of $X(3872) \to J/\psi\pi\gamma$ and $X(3872) \to J/\psi\pi\pi\gamma$ are predicted to be in order $10^{-3} \sim 10^{-2}$, which may be accessible by the BESIII and LHCb collaborations;
- The $X(3872) \to J/\psi\pi\gamma$ and $X(3872) \to J/\psi\pi\pi\gamma$ decays can be employed to extract the couplings $g_{X\psi\omega}$ and $g_{X\psi\rho}$, which probe the isoscalar and isovector components of the $X(3872)$ wave function, respectively.

Thank you for your attention!