# Radiative decays of $\chi_{c1}$ states in effective field theory approach

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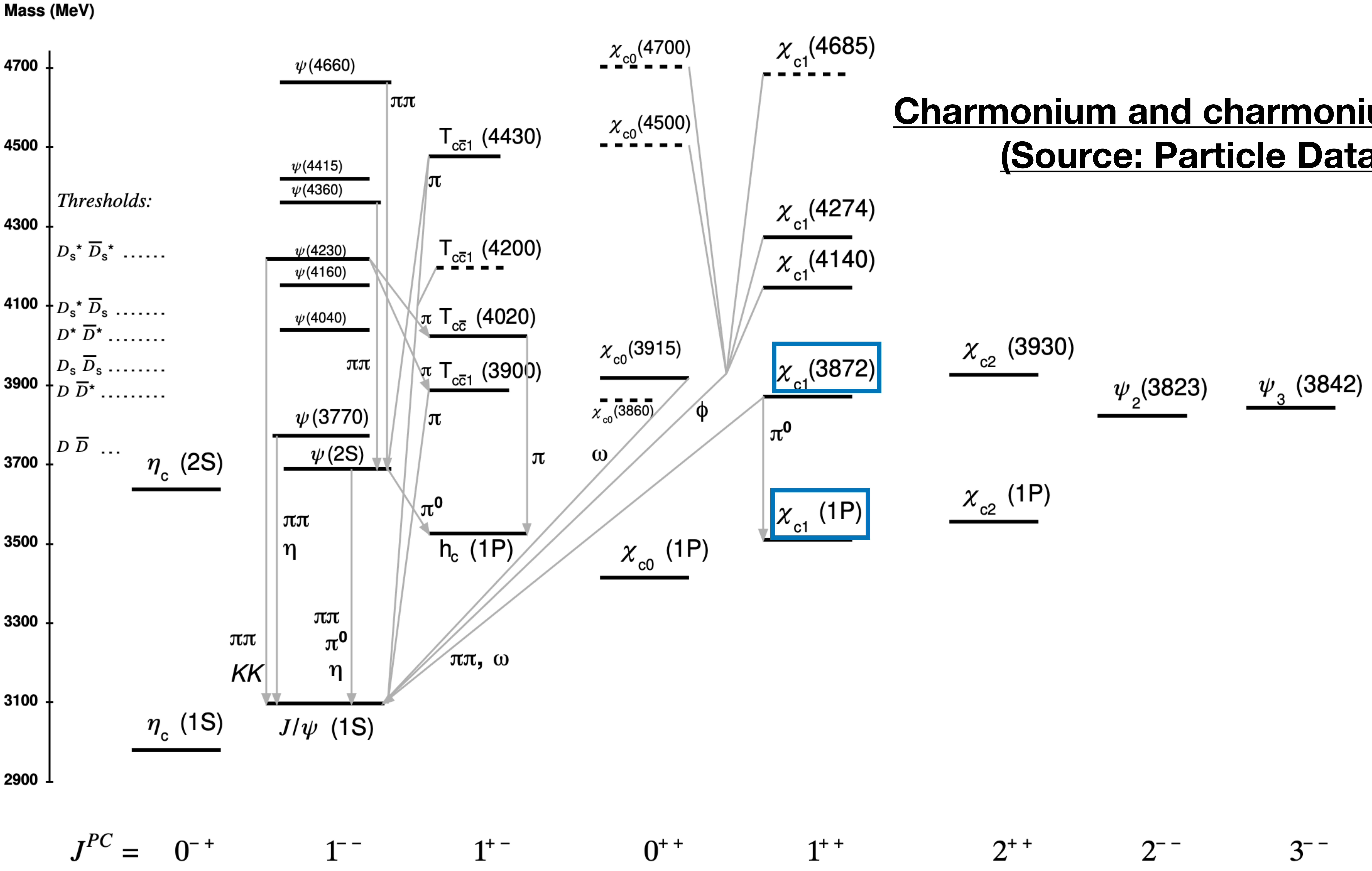
## Charmonium and charmonium-like states (Source: Particle Data Group)



# Introduction

## $\chi_{c1}(3872)$

$$I^G(J^{PC}) = 0^+(1^{++})$$

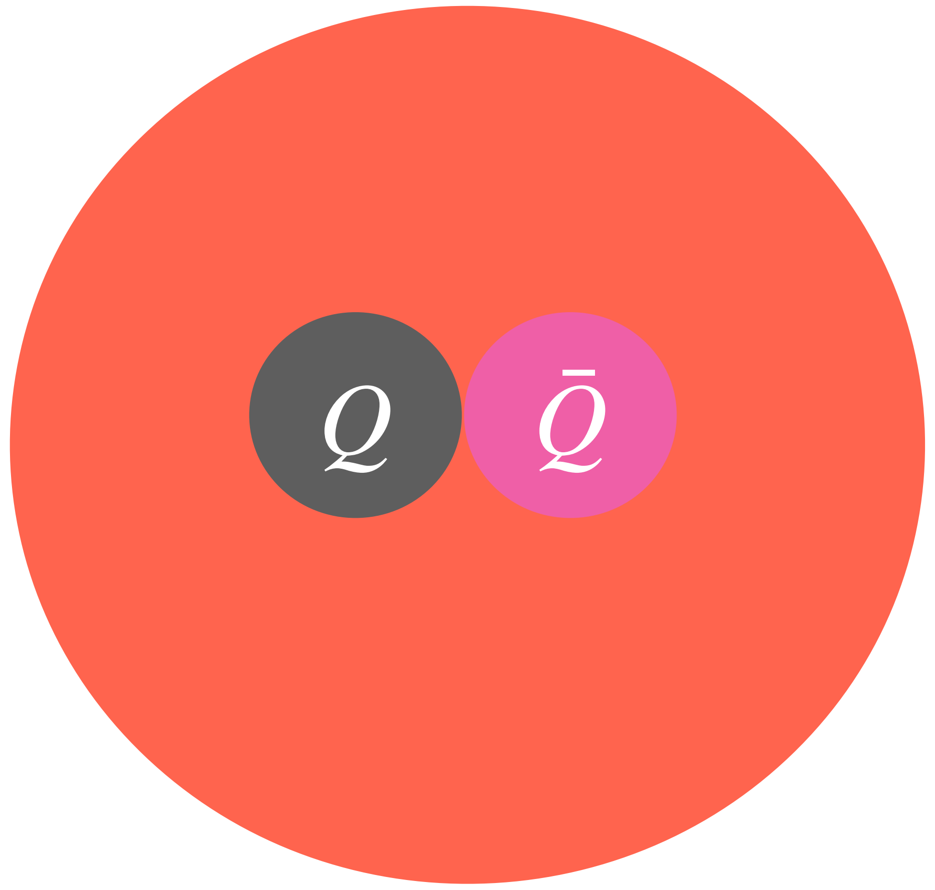
$$\left(m_{D^0} + m_{D^{*0}}\right) - m_{\chi_{c1}(3872)} = (0.00 \pm 0.18)\ \text{MeV}$$

$$\frac{\mathcal{B}\left[\chi_{c1}(3872) \to J/\psi\pi^+\pi^-\pi^0\right]}{\mathcal{B}\left[\chi_{c1}(3872) \to J/\psi\pi^+\pi^-\right]} = \begin{cases} 1.0 \pm 0.4 \pm 0.3 & \text{Belle,} \\ 1.6^{+1.4}_{-0.3} \pm 0.2 & \text{BESIII,} \\ 0.7 \pm 0.3 & B^+ \text{ events, BaBar,} \\ 1.7 \pm 1.3 & B^0 \text{ events, BaBar}. \end{cases}$$

Physics Reports 1019 (2023)

# Introduction

**<u>Theoretical interpretations</u>** Radial excitation of the axial vector charmonium



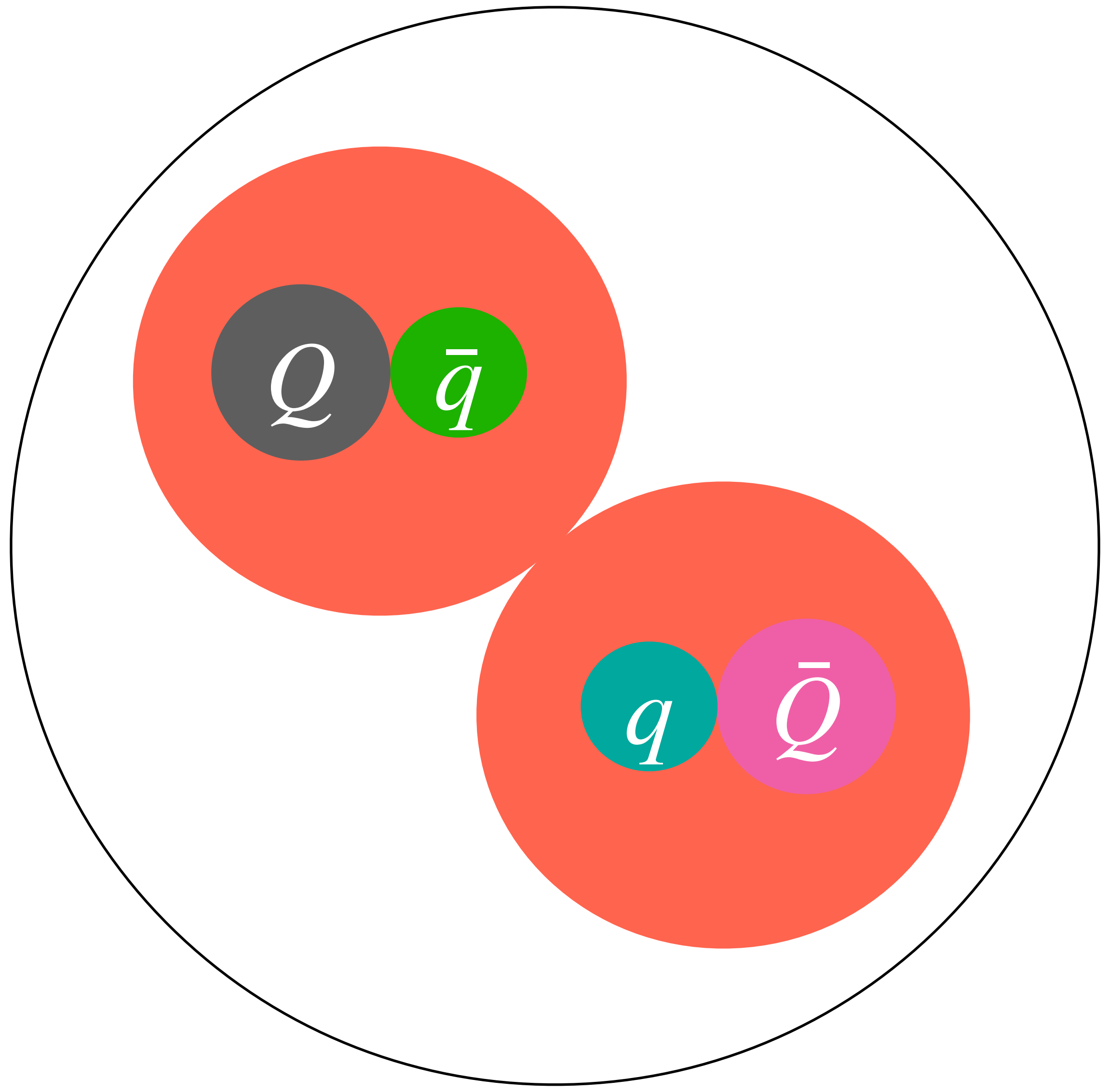

- $\chi_{c1}(3872)$ is hypothesized to be the first radial excitation of the axial vector charmonium $\chi_{c1}(2P)$, aligning with the traditional $c\bar{c}$ quark model
- Models predict the $\chi_{c1}(2P)$ state near the mass of $\chi_{c1}(3872)$, though theoretical mass predictions often differ from experimental results
- Spin-parity $J^{PC} = 1^{++}$ is consistent with quark model expectations for a $\chi_{c1}(2P)$ assignment

<u>Issues</u>

- The experimentally observed mass of X(3872) precisely coincides with the $D^0\bar{D}^{*0}$ threshold, which is unexplained in the pure charmonium model
- The quark model fails to account for large isospin-violating decays (e.g., $J/\psi\rho$ and $J/\psi\omega$) that suggest strong $D^0\bar{D}^{*0}$ dynamics

# Introduction

**<u>Theoretical interpretations</u>** Molecular scheme




- Treats $\chi_{c1}(3872)$ as a bound $D^0\bar{D}^{*0}$ state, where the mass proximity to the $D^0\bar{D}^{*0}$ threshold is natural
- Explains large isospin-violating decay ratios through the mixing of charged and neutral components
- Weinberg's compositeness criterion indicates a dominant molecular component (~70%)

<u>Issues</u>

- The extremely narrow width and high production rates in high-energy experiments challenge the molecular interpretation
- Precise fine-tuning is required to explain the shallow binding energy near the threshold

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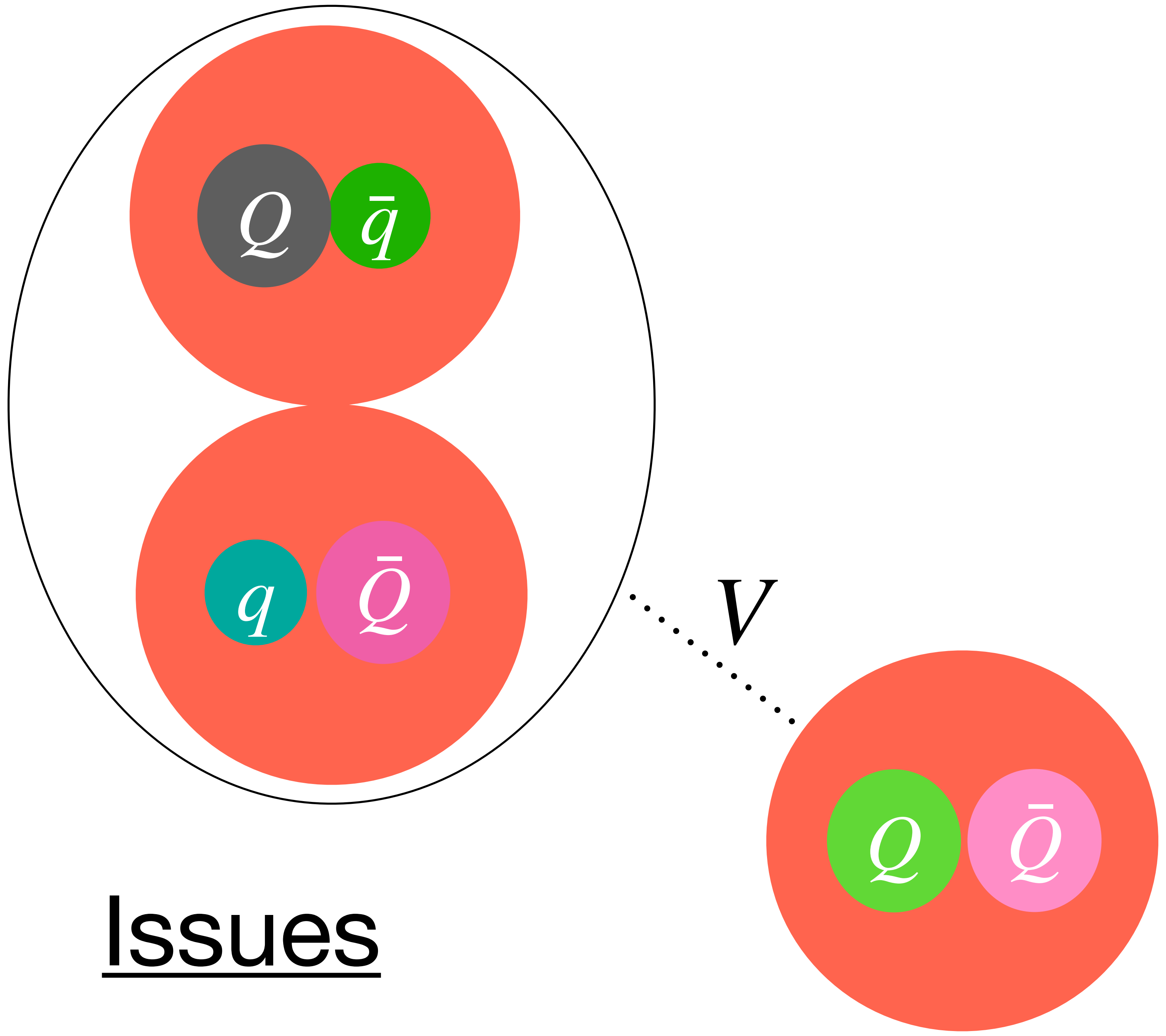
# Introduction

**Theoretical interpretations** Coupled-channel picture of the $c\bar{c}$ and di-meson degrees of freedom




- Combines $c\bar{c}$ and $D^0\bar{D}^{*0}$ components, treating $\chi_{c1}(3872)$ as a dynamically mixed state
- Explains both the near-threshold behavior and isospin-violating decays as arising from the interplay between molecular and charmonium degrees of freedom
- Provides a unified framework that includes the quarkonium core and molecular structure

Issues

- Highly dependent on model assumptions and parameter tuning to balance the contributions of molecular and quarkonium components
- The exact mechanism of coupled-channel effects and their impact on decays remains experimentally unverified

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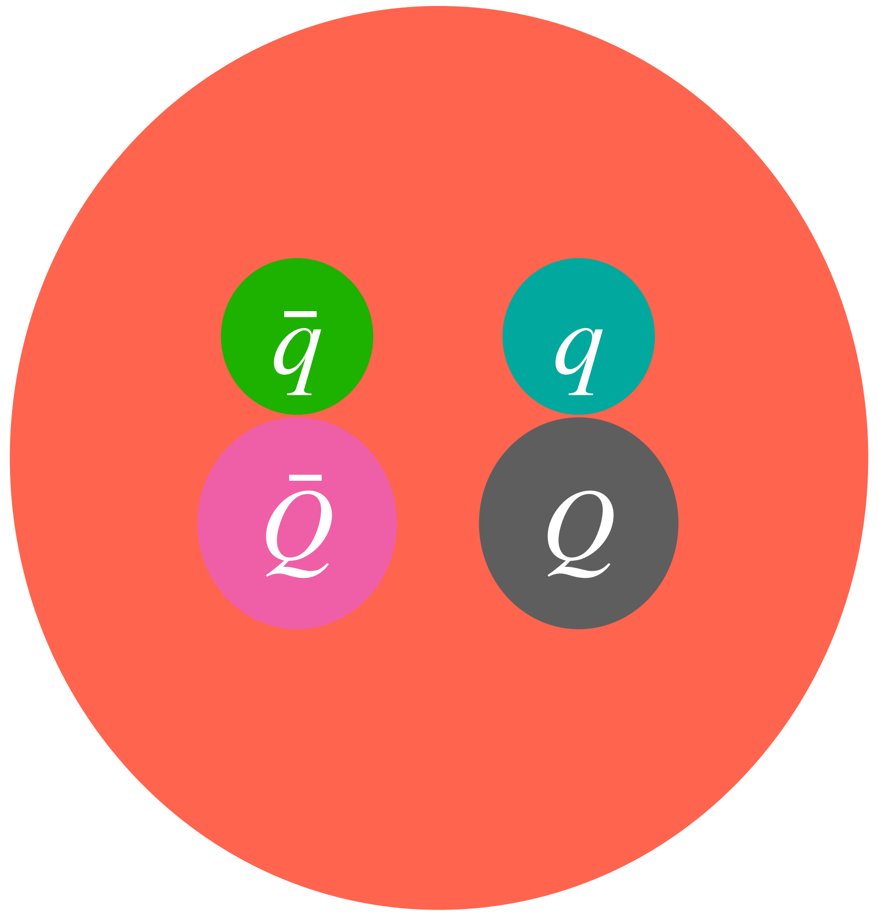
# Introduction

**<u>Theoretical interpretations</u>** Compact tetraquark state




- $\chi_{c1}(3872)$ is viewed as a tightly bound $c\bar{c}q\bar{q}$ tetraquark with diquark-antidiquark configurations
- Explains exotic quantum numbers and stability through strong color correlations between quarks
- High production rates in high-energy processes align well with the compact nature of tetraquarks

<u>Issues</u>

- Cannot easily explain the proximity of the mass to the $D^0\bar{D}^{*0}$ threshold
- Fails to naturally account for large isospin-violating decay ratios or the dominant $D^0\bar{D}^{*0}$ decay mode

JLAB-THY-23-3848

# Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab

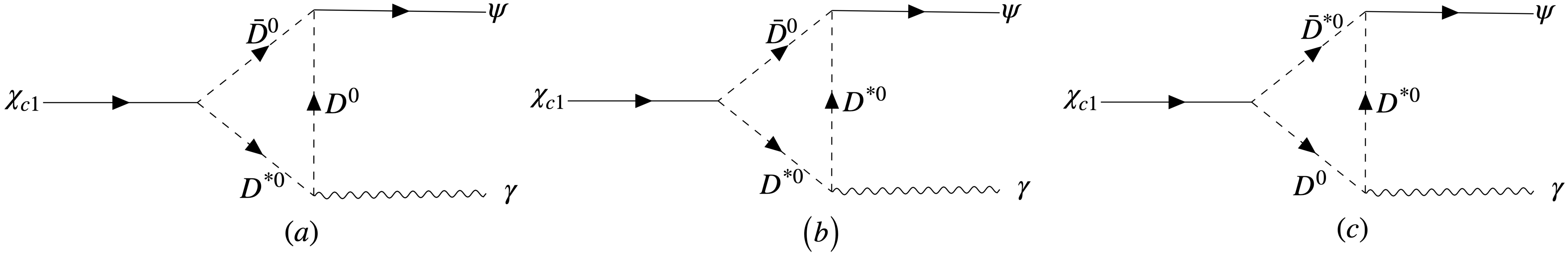
(arXiv:2306.09360v2)

**CEBAF: Continuous Electron Beam Accelerator Facility**

- Experimental programs
  - CLAS12 experiment: $\gamma^* p$ interaction
  - GlueX experiment: $\gamma p$ interaction
- A comparison of photoproduction mechanisms of the $\chi_{c1}(1P)$ and $\chi_{c1}(3872)$ may provide insights into the nature of the $\chi_{c1}(3872)$ state

# Formalism

Radiative decay modes of $\chi_{c1}$ states in effective field theory method



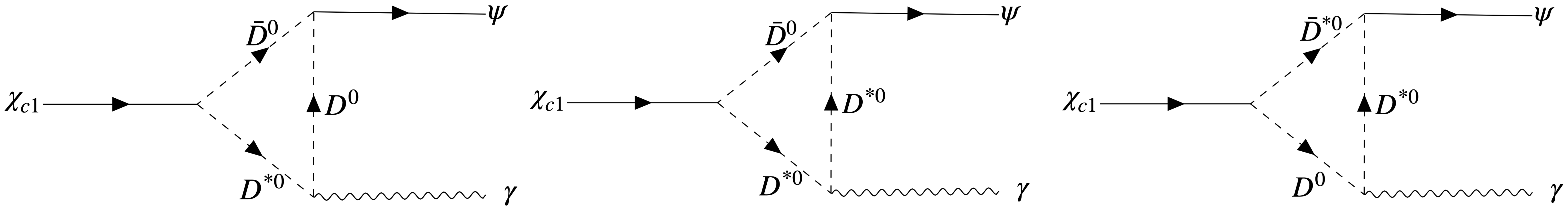

Fix the cutoff parameters to reproduce the observed fraction $R_{\chi_{c1}(1P)\to J/\psi\gamma}$

Predict the branching fractions $R_{\chi_{c1}(3872)\to J/\psi\gamma}$, $R_{\chi_{c1}(3872)\to \psi(2S)\gamma}$

**Form factor:** $$F(\Lambda_i, q_i^2, m_i) = \frac{\Lambda_i^2 - m_i^2}{\Lambda_i^2 - q_i^2}$$

Phys.Rev.D75, 114002 (2007)
Phys.Rev.D77, 094013 (2008)

# Formalism




$(a)$ $(b)$ $(c)$

**Effective Lagrangians**

$$\mathscr{L}_{\chi DD^*} = g_\chi \chi^\mu \left( D_\mu D^\dagger - D D_\mu^\dagger \right)$$

$$\mathscr{L}_{\psi DD} = i g_{\psi DD} \psi_\mu \left( \partial^\mu D D^\dagger - D \partial^\mu D^\dagger \right)$$

$$\mathscr{L}_{\gamma DD^*} = \frac{e}{4} g_{\gamma DD^*} D \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} D_{\alpha\beta}^\dagger$$

$$\mathscr{L}_{\psi DD^*} = - g_{\psi DD^*} \epsilon^{\mu\nu\alpha\beta} \partial_\mu \psi_\nu \left( D \partial_\alpha D_\beta^\dagger + \partial_\alpha D_\beta D^\dagger \right)$$

$$\mathscr{L}_{\gamma D^* D^*} = - i e A^\mu \left( D^\nu D_{\mu\nu}^\dagger - D_{\mu\nu} D^{\nu\dagger} \right)$$

$$\mathscr{L}_{\psi D^* D^*} = - i g_{\psi D^* D^*} \left\{ \psi^\mu \left( \partial_\mu D^\nu D_\nu^\dagger - D^\nu \partial_\mu D_\nu^\dagger \right) + \psi^\nu D^\mu \partial_\mu D_\nu^\dagger - \psi_\nu \partial_\mu D^\nu D^{\mu\dagger} \right\}$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

and $D_{\mu\nu} = \partial_\mu D_\nu - \partial_\nu D_\mu$

Phys.Rev.D75, 114002 (2007)
Phys.Rev.D77, 094013 (2008)
Phys.Rev.D109, 094002 (2024)

# Formalism

**Coupling constants for $\chi_{c1}$**

$$g_\chi = \begin{cases} 21.5\ \text{GeV} & \text{for } \chi_{c1}(1P), \\ 23\ \text{GeV} & \text{for } \chi_{c1}(3872)\,. \end{cases}$$

$\longrightarrow$

$B^-$ decay

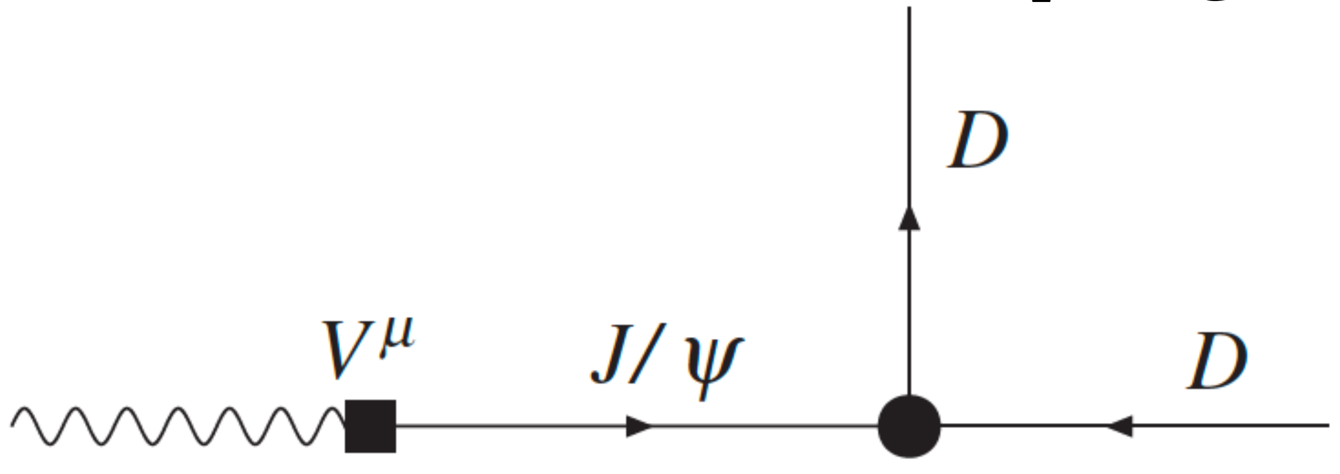
$$g_\chi = 2\sqrt{m_{D^0} m_{D^{*0}} m_\chi}\, g_1(2P)$$

with $g_1(2P) \approx g_1(1P) = \sqrt{\frac{m_{\chi_{c0}}}{3}}\frac{1}{f_{\chi_{c0}}}$

**Coupling constants for $J/\psi$**

$$g_{\psi DD} = 8$$
$$g_{\psi DD^*} = 4.3\ \text{GeV}^{-1}$$
$$g_{\psi D^* D^*} = 8$$

$\longrightarrow$ VMD Mechanism




HQS relations: $g_{\psi D^* D^*} = m_D g_{\psi DD^*} = g_{\psi DD}$

**Coupling constants for $\psi(2S)$**

$$g_{\psi DD} = 12.39$$
$$g_{\psi DD^*} = 3.49\ \text{GeV}^{-1}$$
$$g_{\psi D^* D^*} = 13.33$$

$\longrightarrow$ VMD Mechanism

with $g_2 = \frac{1}{2m_D f_\psi}\sqrt{m_\psi}$

$$g_{\psi DD} = 2g_2\sqrt{m_\psi}\, m_D,\ g_{\psi DD^*} = 2g_2\sqrt{\frac{m_D m_{D^*}}{m_\psi}},\ g_{\psi D^* D^*} = 2g_2\sqrt{m_\psi}\, m_{D^*}$$

$g_{\gamma DD^*} = 2\ \text{GeV}^{-1}$ $\longrightarrow$ From radiative decay mode $D^{*0} \to D^0\gamma$

# Formalism

**Decay width:** $$\Gamma = \frac{1}{32\pi^2}\frac{q}{m_\chi^2}\int d\Omega \left\langle \left| \mathscr{M} \right|^2 \right\rangle$$

with $$\left\langle \left| \mathscr{M} \right|^2 \right\rangle = \frac{1}{3}\sum_{\lambda_1,\lambda_2,\lambda_3} \left| \mathscr{M} \right|^2$$ and $$\mathscr{M} = \mathscr{M}_a + \mathscr{M}_b + \mathscr{M}_c$$

**Free parameters:** $\Lambda_D, \Lambda_{D*}$ **Branching fraction:** $$R_i = \frac{\Gamma_i}{\Gamma_t}$$

# Results

We fix the parameters $\Lambda_D$ and $\Lambda_{D*}$ to reproduce the branching fraction of $\chi_{c1}(1P)$

**Observed branching fraction:** $R_{\chi_{c1}(1P)\to J/\psi\gamma} = 0.343 \pm 0.013$

**Result:** $R^{(t)}_{\chi_{c1}(1P)\to J/\psi\gamma} = 0.357 \pm 0.017$

with $\Lambda_D = \Lambda_{D*} = 2.23$ GeV

# Results

**Predictions for the fractions** $R_{\chi_{c1}(3872)\to J/\psi\gamma}$, $R_{\chi_{c1}(3872)\to\psi(2S)\gamma}$

**Observed branching fraction:** $R_{\chi_{c1}(3872)\to J/\psi\gamma} = (7.8 \pm 2.9) \times 10^{-3}$

**Our predictions:**

$$R^{(t)}_{\chi_{c1}(3872)\to J/\psi\gamma} = \left(3.2 \pm 0.6\right) \times 10^{-1}$$

$$R^{(t)}_{\chi_{c1}(3872)\to\psi(2S)\gamma} = \left(3.5 \pm 0.6\right) \times 10^{-2}$$

# Results

**Comparison of the predicted fraction** $R_{\chi_{c1}(3872)\to J/\psi\gamma}$

**Our work:** $\left(3.2 \pm 0.6\right) \times 10^{-1}$

**Phys.Rev.D109, 094002 (2024):** $4 \times 10^{-3}$
(Molecular picture)

**Phys.Lett.B848, 138404 (2024):** $(7.6^{+1.8}_{-2.0}) \times 10^{-1}$
($c\bar{c}$ picture)

**Eur. Phys. J. C, 75:26 (2015):** $(2.0 \pm 0.4) \times 10^{-2}$
($c\bar{c} - D\bar{D}*$ mixing scheme)

# Summary

- We have studied the radiative decays of $\chi_{c1}(1P)$ and $\chi_{c1}(3872)$ states in effective field theory method

- To reproduce the observed fraction $R_{\chi_{c1}(1P)\to J/\psi\gamma}$, the cutoff parameters $\Lambda_D$ and $\Lambda_{D*}$ are fixed to be $2.23$ GeV

- The branching fraction $R_{\chi_{c1}(3872)\to J/\psi\gamma}$ and $R_{\chi_{c1}(3872)\to \psi(2S)\gamma}$ are predicted to be about $(3.2 \pm 0.6) \times 10^{-1}$and $(3.5 \pm 0.6) \times 10^{-2}$, respectively

- Our predicted fraction is about two orders of magnitude higher than the observed fraction of the decay mode $\chi_{c1}(3872) \to J/\psi\gamma$

Thank you