Two-Photon Exclusive Production of Fully-Charmed Tetraquarks at the LHC

Longjie Chen, Wolfgang Schäfer, Antoni Szczurek

IFJ PAN

arXiv:2605.22500

June 24, 2026

THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

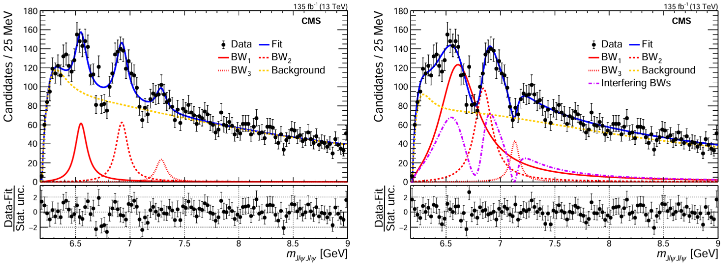
NARODOWE CENTRUM NAUKI

Outline

Introduction

Motivation: The $X(6900)$ and its family

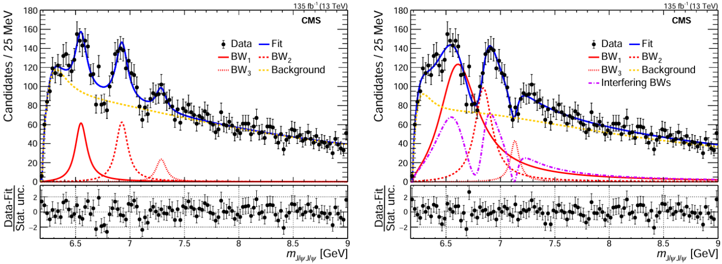
- Observation of $X(6900) \to J/\psi J/\psi$ by LHCb , confirmed by ATLAS and CMS, established the existence of fully-charmed tetraquark states T_{4c}.



A. Hayrapetyan *et al.*, the $J/\psi J/\psi$ invariant mass spectrum.

Motivation: The $X(6900)$ and its family

- Observation of $X(6900) \to J/\psi J/\psi$ by LHCb , confirmed by ATLAS and CMS, established the existence of fully-charmed tetraquark states T_{4c}.

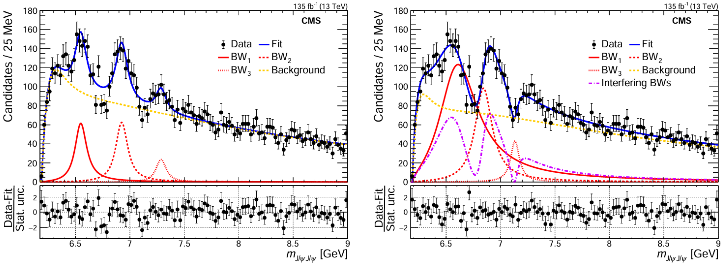


A. Hayrapetyan *et al.*, the $J/\psi J/\psi$ invariant mass spectrum.

- The leading interpretation is a compact diquark–antidiquark bound state.

Motivation: The $X(6900)$ and its family

- Observation of $X(6900) \to J/\psi J/\psi$ by LHCb , confirmed by ATLAS and CMS, established the existence of fully-charmed tetraquark states T_{4c}.



A. Hayrapetyan *et al.*, the $J/\psi J/\psi$ invariant mass spectrum.

- The leading interpretation is a compact diquark–antidiquark bound state.
- Recent CMS determination: $J^{PC} = 2^{++}$ for $X(6600)$ and $X(6900)$.

Photon–Photon Fusion as a Clean Probe

- UPCs provide intense fluxes of quasi-real photons $\Rightarrow$ access $\gamma\gamma \to T_{4c}$.

Photon–Photon Fusion as a Clean Probe

- UPCs provide intense fluxes of quasi-real photons ⇒ access $\gamma\gamma \to T_{4c}$.
- Cross section is directly proportional to the two-photon decay width:

$$\sigma(\gamma\gamma \to T_{4c}) \propto \Gamma(T_{4c} \to \gamma\gamma)$$

Photon–Photon Fusion as a Clean Probe

- UPCs provide intense fluxes of quasi-real photons $\Rightarrow$ access $\gamma\gamma \to T_{4c}$.
- Cross section is directly proportional to the two-photon decay width:

$$\sigma(\gamma\gamma \to T_{4c}) \propto \Gamma(T_{4c} \to \gamma\gamma)$$

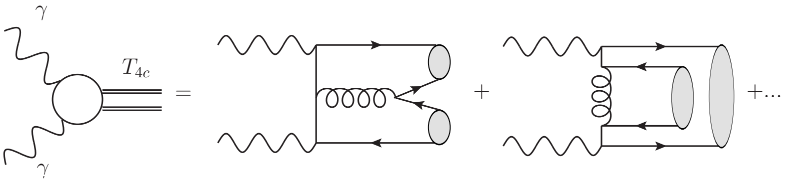
- $\Gamma_{\gamma\gamma}$ is highly sensitive to the internal structure:
  - Compact tetraquark $\to$ calculable, $\mathcal{O}(0.1\text{–}1\ \text{keV})$.
  - Point-like diquark $\to$ much larger, $\mathcal{O}(10\text{–}100\ \text{keV})$.

Photon–Photon Fusion as a Clean Probe

- UPCs provide intense fluxes of quasi-real photons $\Rightarrow$ access $\gamma\gamma \to T_{4c}$.
- Cross section is directly proportional to the two-photon decay width:

$$\sigma(\gamma\gamma \to T_{4c}) \propto \Gamma(T_{4c} \to \gamma\gamma)$$

- $\Gamma_{\gamma\gamma}$ is highly sensitive to the internal structure:
  - Compact tetraquark $\to$ calculable, $\mathcal{O}(0.1\text{–}1\ \text{keV})$.
  - Point-like diquark $\to$ much larger, $\mathcal{O}(10\text{–}100\ \text{keV})$.
- Some of the 40 tree-level diagrams for $\gamma\gamma \to cc\bar{c}\bar{c}$:



Theoretical Framework

NRQCD Factorisation

- We employ the Non-Relativistic QCD (NRQCD) effective field theory, which provides a rigorous expansion in α_s and the heavy-quark velocity v.

NRQCD Factorisation

- We employ the Non-Relativistic QCD (NRQCD) effective field theory, which provides a rigorous expansion in α_s and the heavy-quark velocity v.
- NRQCD factorisation separates the decay amplitude into:

$$\mathcal{M}(\gamma\gamma \to T_{4c}) = \sum_n \mathcal{A}_n(\gamma\gamma \to cc\bar{c}\bar{c})\ \langle 0|\mathcal{O}_n|T_{4c}\rangle$$

NRQCD Factorisation

- We employ the Non-Relativistic QCD (NRQCD) effective field theory, which provides a rigorous expansion in α_s and the heavy-quark velocity v.
- NRQCD factorisation separates the decay amplitude into:

$$\mathcal{M}(\gamma\gamma \to T_{4c}) = \sum_n \mathcal{A}_n(\gamma\gamma \to cc\bar{c}\bar{c})\, \langle 0|\mathcal{O}_n|T_{4c}\rangle$$

- Short-Distance Coefficients (SDCs):
  Perturbative $cc\bar{c}\bar{c} \to \gamma\gamma$ at the hard scale $\mu \sim 4m_c$, generated with FEYNCALC.

NRQCD Factorisation

- We employ the Non-Relativistic QCD (NRQCD) effective field theory, which provides a rigorous expansion in α_s and the heavy-quark velocity v.
- NRQCD factorisation separates the decay amplitude into:

$$\mathcal{M}(\gamma\gamma \to T_{4c}) = \sum_n \mathcal{A}_n(\gamma\gamma \to cc\bar{c}\bar{c}) \, \langle 0|\mathcal{O}_n|T_{4c}\rangle$$

- Short-Distance Coefficients (SDCs):
  Perturbative $cc\bar{c}\bar{c} \to \gamma\gamma$ at the hard scale $\mu \sim 4m_c$, generated with FeynCalc.

  We calculate these at Leading Order (LO) in α_s.

NRQCD Factorisation

- We employ the Non-Relativistic QCD (NRQCD) effective field theory, which provides a rigorous expansion in α_s and the heavy-quark velocity v.
- NRQCD factorisation separates the decay amplitude into:

$$\mathcal{M}(\gamma\gamma \to T_{4c}) = \sum_n \mathcal{A}_n(\gamma\gamma \to cc\bar{c}\bar{c})\ \langle 0|\mathcal{O}_n|T_{4c}\rangle$$

- Short-Distance Coefficients (SDCs):
  Perturbative $cc\bar{c}\bar{c} \to \gamma\gamma$ at the hard scale $\mu \sim 4m_c$, generated with FeynCalc.

  We calculate these at Leading Order (LO) in α_s.
- Long-Distance Matrix Elements (LDMEs):
  Non-perturbative, universal matrix elements of 4-quark NRQCD operators that parametrize the hadronization dynamics.

NRQCD Factorisation

- We employ the Non-Relativistic QCD (NRQCD) effective field theory, which provides a rigorous expansion in α_s and the heavy-quark velocity v.
- NRQCD factorisation separates the decay amplitude into:

$$\mathcal{M}(\gamma\gamma \to T_{4c}) = \sum_n \mathcal{A}_n(\gamma\gamma \to cc\bar{c}\bar{c}) \, \langle 0|\mathcal{O}_n|T_{4c}\rangle$$

- Short-Distance Coefficients (SDCs):
  Perturbative $cc\bar{c}\bar{c} \to \gamma\gamma$ at the hard scale $\mu \sim 4m_c$, generated with FeynCalc.

  We calculate these at Leading Order (LO) in α_s.
- Long-Distance Matrix Elements (LDMEs):
  Non-perturbative, universal matrix elements of 4-quark NRQCD operators that parametrize the hadronization dynamics.

  Extracted from four-body wave functions at the origin.

Diquark Operators and Colour Configurations

- Assume S-wave diquark–antidiquark structure. According to the Pauli principle we can have the following diquarks:

$$D_{kl} = S_{kl,rs}\, \psi_r^T i\sigma_2 \psi_s \quad \text{(spin-0, colour } \mathbf{6}\text{)},$$
$$D_{kl}^j = A_{kl,rs}\, \psi_r^T i\sigma_2 \sigma^j \psi_s \quad \text{(spin-1, colour } \bar{\mathbf{3}}\text{)}.$$

Diquark Operators and Colour Configurations

- Assume S-wave diquark–antidiquark structure. According to the Pauli principle we can have the following diquarks:

$$D_{kl} = S_{kl,rs}\,\psi_r^T i\sigma_2\psi_s \quad \text{(spin-0, colour } \mathbf{6}\text{)},$$
$$D^j_{kl} = A_{kl,rs}\,\psi_r^T i\sigma_2\sigma^j\psi_s \quad \text{(spin-1, colour } \bar{\mathbf{3}}\text{)}.$$

- Tetraquark operators:

$$\mathcal{O}^{(0)}_{6\otimes\bar{6}} = D_{kl}\bar{D}_{kl}, \qquad \mathcal{O}^{(0)}_{\bar{3}\otimes 3} = \frac{1}{\sqrt{3}}\delta_{ij}D^i_{kl}\bar{D}^j_{kl},$$
$$\mathcal{O}^{(2)}_{\bar{3}\otimes 3} = E^*_{ij}(J_z)D^i_{kl}\bar{D}^j_{kl}.$$

Diquark Operators and Colour Configurations

- Assume S-wave diquark–antidiquark structure. According to the Pauli principle we can have the following diquarks:

$$D_{kl} = S_{kl,rs}\,\psi_r^T i\sigma_2\psi_s \quad \text{(spin-0, colour } \mathbf{6}),$$
$$D_{kl}^j = A_{kl,rs}\,\psi_r^T i\sigma_2\sigma^j\psi_s \quad \text{(spin-1, colour } \bar{\mathbf{3}}).$$

- Tetraquark operators:

$$\mathcal{O}^{(0)}_{6\otimes\bar{6}} = D_{kl}\bar{D}_{kl}, \qquad \mathcal{O}^{(0)}_{\bar{3}\otimes 3} = \frac{1}{\sqrt{3}}\delta_{ij}D^i_{kl}\bar{D}^j_{kl},$$
$$\mathcal{O}^{(2)}_{\bar{3}\otimes 3} = E^*_{ij}(J_z)D^i_{kl}\bar{D}^j_{kl}.$$

- For the scalar (0^{++}): both $\bar{3}\otimes 3$ and $6\otimes\bar{6}$ contribute and mix.
- For the tensor (2^{++}): only $\bar{3}\otimes 3$ (spin-1 diquarks, S-wave).

Extracted Short-Distance Coefficients

- The factorised amplitudes F_{TT}, $F_{TT,0}$, $F_{TT,2}$ relating SDCs to LDMEs are given in the backup. Matching at LO yields the SDCs:

$$\tilde{F}_{TT,0} = \frac{4\pi\alpha_s e_Q^2}{\sqrt{3}\, m_Q^4}, \qquad \tilde{F}_{TT,2} = \frac{128\pi\alpha_s e_Q^2}{\sqrt{3}\, m_Q^2},$$

$$\tilde{F}_{TT}^{66} = -\frac{8\sqrt{2}\pi\alpha_s e_Q^2}{\sqrt{3}\, m_Q^2}, \qquad \tilde{F}_{TT}^{33} = \frac{48\pi\alpha_s e_Q^2}{m_Q^2}.$$

Extracted Short-Distance Coefficients

- The factorised amplitudes F_{TT}, $F_{TT,0}$, $F_{TT,2}$ relating SDCs to LDMEs are given in the backup. Matching at LO yields the SDCs:

$$\tilde{F}_{TT,0} = \frac{4\pi\alpha_s e_Q^2}{\sqrt{3}\, m_Q^4}, \qquad \tilde{F}_{TT,2} = \frac{128\pi\alpha_s e_Q^2}{\sqrt{3}\, m_Q^2},$$

$$\tilde{F}_{TT}^{66} = -\frac{8\sqrt{2}\pi\alpha_s e_Q^2}{\sqrt{3}\, m_Q^2}, \qquad \tilde{F}_{TT}^{33} = \frac{48\pi\alpha_s e_Q^2}{m_Q^2}.$$

- Decay widths in terms of LDMEs:

$$\Gamma(2^{++} \to \gamma\gamma) = \frac{128\pi^3\alpha_{em}^2\alpha_s^2 e_Q^4}{15\, m_Q^8}\left[1 + \frac{1}{6}\left(\frac{M}{4m_Q}\right)^4\right]\left|\langle\mathcal{O}^{(2)}_{\bar{3}\otimes 3}\rangle\right|^2,$$

$$\Gamma(0^{++} \to \gamma\gamma) = \frac{\pi^3\alpha_{em}^2\alpha_s^2 e_Q^4}{m_Q^8}\Big[18|\langle\mathcal{O}_{\bar{3}3}\rangle|^2 + \frac{1}{3}|\langle\mathcal{O}_{6\bar{6}}\rangle|^2 - 2\sqrt{6}\,\mathrm{Re}\big(\langle\mathcal{O}_{\bar{3}3}\rangle\langle\mathcal{O}_{6\bar{6}}\rangle^*\big)\Big].$$

Calculation & Inputs

Inputs I: Running of α_s

- 2-loop RG evolution with RunDec.
- Flavour thresholds:
  $\alpha_s^{(5)}(m_Z) \to \alpha_s^{(5)}(m_b) \to \alpha_s^{(4)}(m_b) \to \alpha_s^{(4)}(m_c) \to \alpha_s^{(3)}(m_c)$.

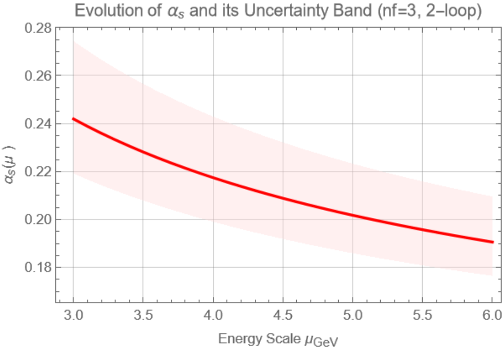


Figure: $\alpha_s(\mu)$ in the $n_f = 3$ theory.

- Central scale $\mu_0 = 3$ GeV $\simeq 2m_c$.
- Scale variation $\mu \in [2m_c, 4m_c]$ estimates theory uncertainty ($\sim 30\%$).

Inputs II: Wave Functions at the Origin

- LDMEs extracted from 4-body wave functions, obtained via the **Gaussian Expansion Method** applied to the extended relativized quark model from Q. F. Lü, D. Y. Chen and Y. B. Dong, "Masses of fully heavy tetraquarks $QQ\bar{Q}\bar{Q}$ in an extended relativized quark model," Eur. Phys. J. C **80** (2020) no.9, 871
- For scalar states: colour mixing leads to two physical eigenstates.

Mass (J^{PC})	State	Eigenvector	$\psi_{\bar{3}3}(0)$	$\psi_{6\bar{6}}(0)$	$\psi_{\text{phys}}(0)$
6435 (0^{++})	1s	[0.62, 0.79]	0.0466	0.0283	0.0510
6542 (0^{++})	1s	[0.79, -0.62]	0.0466	0.0283	0.0189
6849 (0^{++})	2s	[0.50, 0.87]	0.0721	0.0466	0.0764
6940 (0^{++})	2s	[0.87, -0.50]	0.0721	0.0466	0.0391
6543 (2^{++})	1s	1	0.0300	—	0.0300
6928 (2^{++})	2s	1	0.0471	—	0.0471

- Note: $\psi(0)$ of $2s$ states is larger than $1s$ – counterintuitive! For $3s$, $\psi(0) \simeq 0$.

Results & Discussion

Predictions for $\Gamma(T_{4c} \to \gamma\gamma)$

- We identify: $X(6600) \equiv (2^{++}, 1s)$, $X(6900) \equiv (2^{++}, 2s)$, $X(7100) \equiv (2^{++}, 3s)$.

Mass (J^{PC})	State	Description	$\Gamma_{\gamma\gamma}$ (keV)
6435 (0^{++})	1s	Mixture 1 (ground)	$0.106^{+0.03}_{-0.02}$
6542 (0^{++})	1s	Mixture 2 (ground)	$0.245^{+0.07}_{-0.05}$
6849 (0^{++})	**2s**	**Mixture 1 (radial)**	$\mathbf{0.149^{+0.05}_{-0.03}}$
6940 (0^{++})	**2s**	**Mixture 2 (radial)**	$\mathbf{0.688^{+0.21}_{-0.15}}$
6543 (2^{++})	1s	$X(6600)$	$0.088^{+0.03}_{-0.02}$
6928 (2^{++})	**2s**	$\boldsymbol{X(6900)}$	$\mathbf{0.217^{+0.07}_{-0.05}}$

- The $X(7100)$ candidate, identified with $(2^{++}, 3s)$, has vanishing $\Gamma_{\gamma\gamma}$.
- $\Gamma_{\gamma\gamma}$ spans 0.1–0.7 keV. Uncertainties dominated by scale variation.

Comparison with Literature

- Our results: $\mathcal{O}(0.1\text{–}0.7\ \text{keV})$. The literature spans an enormous range.

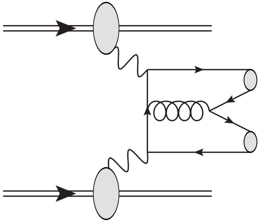
Approach	**Reference**	$\Gamma_{\gamma\gamma}$ (keV)	Note
Quark model (1987)	Badalian et al.	$\sim 10^{-3}$	$10^{-4}\,\Gamma(\eta_c \to \gamma\gamma)$
NRQCD (this work)	**This work**	$\mathbf{0.1\text{–}0.7}$	LDMEs from GEM wave fns.
NRQCD LO+NLO	Sang et al. / Liu et al.	$0.1\text{–}0.5$	Similar ballpark
VDM	Esposito et al.	$0.086 \times B_\psi$	$B_\psi \sim 1 \Rightarrow 0.086$
Point-Like Diquark	Kalamidas et al.	$\mathbf{5\text{–}82}$	Two orders larger
LbL fit	Biloshytskyi et al.	$45\text{–}67$	Spin-0 only

- The point-like diquark model overestimates by ~ 2 orders of magnitude – treats diquarks as elementary fields.
- VDM model implicitly assumes $B_\psi \equiv \mathrm{Br}(T_{4c} \to J/\psi J/\psi) \sim \mathcal{O}(1)$. However model calculations of decays and hadronic production rather suggest $B_\psi \sim \mathcal{O}(10^{-3})$.

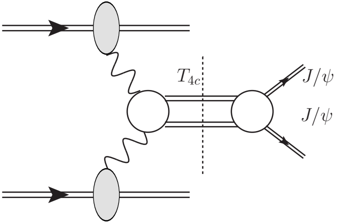
Phenomenology: UPCs

Two mechanisms for T_{4c} production in UPCs

We discuss two different final states $J/\psi J/\psi$ and $\gamma\gamma$ through which fully-charmed tetraquarks can be accessed in AA ultraperipheral collisions. Both final states receive direct continuum *and* resonant contributions:



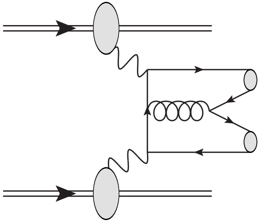
(a) : $\gamma\gamma \to J/\psi J/\psi$ and $\gamma\gamma \to \gamma\gamma$.



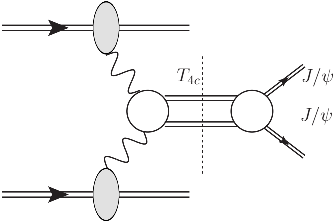
(b) : $\gamma\gamma \to T_{4c} \to J/\psi\, J/\psi$ and $\gamma\gamma \to T_{4c} \to \gamma\gamma$.

Two mechanisms for T_{4c} production in UPCs

We discuss two different final states $J/\psi J/\psi$ and $\gamma\gamma$ through which fully-charmed tetraquarks can be accessed in AA ultraperipheral collisions. Both final states receive direct continuum *and* resonant contributions:



(a) : $\gamma\gamma \to J/\psi J/\psi$ and $\gamma\gamma \to \gamma\gamma$.

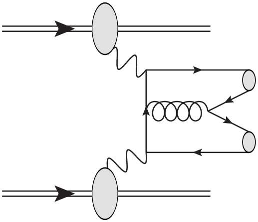


(b) : $\gamma\gamma \to T_{4c} \to J/\psi\, J/\psi$ and $\gamma\gamma \to T_{4c} \to \gamma\gamma$.

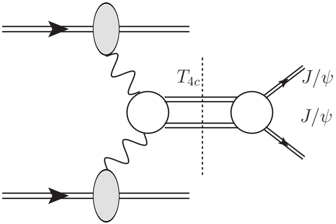
- The direct $\gamma\gamma \to \gamma\gamma$ continuum is the QED light-by-light box diagram.
- The direct $\gamma\gamma \to T_{4c} \to \gamma\gamma$ continuum is computed in LO NRQCD.

Two mechanisms for T_{4c} production in UPCs

We discuss two different final states $J/\psi J/\psi$ and $\gamma\gamma$ through which fully-charmed tetraquarks can be accessed in AA ultraperipheral collisions. Both final states receive direct continuum *and* resonant contributions:



(a) : $\gamma\gamma \to J/\psi J/\psi$ and $\gamma\gamma \to \gamma\gamma$.



(b) : $\gamma\gamma \to T_{4c} \to J/\psi\, J/\psi$ and $\gamma\gamma \to T_{4c} \to \gamma\gamma$.

- The direct $\gamma\gamma \to \gamma\gamma$ continuum is the QED light-by-light box diagram.
- The direct $\gamma\gamma \to T_{4c} \to \gamma\gamma$ continuum is computed in LO NRQCD.
- The resonant contributions scale as $\Gamma_{\gamma\gamma} \times B_\psi$ (for $J/\psi J/\psi$) and $\Gamma^2_{\gamma\gamma}/\Gamma_{\rm tot}$ (for $\gamma\gamma$).

T_{4c} Production in UPCs

- The UPC cross section is:

$$\sigma(AA \to T_{4c}AA) = \int dW^2 \, \frac{d\mathcal{L}_{\gamma\gamma}}{dW^2} \, \sigma(\gamma\gamma \to T_{4c}; W)$$

- Photon–photon luminosity is given in terms of the Weizsäcker–Williams fluxes of photons as

$$\frac{d\mathcal{L}_{\gamma\gamma}}{dW^2} = \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} \delta(W^2 - x_1 x_2 s_{\rm NN}) \int d^2\boldsymbol{b}_1 d^2\boldsymbol{b}_2 \, S^2(|\boldsymbol{b}_1 - \boldsymbol{b}_2|) N(x_1, \boldsymbol{b}_1) N(x_2, \boldsymbol{b}_2),$$

T_{4c} Production in UPCs

- The UPC cross section is:

$$\sigma(AA \to T_{4c}AA) = \int dW^2 \, \frac{d\mathcal{L}_{\gamma\gamma}}{dW^2} \, \sigma(\gamma\gamma \to T_{4c}; W)$$

- Photon–photon luminosity is given in terms of the Weizsäcker–Williams fluxes of photons as

$$\frac{d\mathcal{L}_{\gamma\gamma}}{dW^2} = \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} \delta(W^2 - x_1 x_2 s_{\rm NN}) \int d^2\boldsymbol{b}_1 d^2\boldsymbol{b}_2 \, S^2(|\boldsymbol{b}_1 - \boldsymbol{b}_2|) N(x_1, \boldsymbol{b}_1) N(x_2, \boldsymbol{b}_2),$$

- Partonic cross section: Breit–Wigner form

$$\sigma(\gamma\gamma \to T_{4c}(J); W) = 8\pi(2J+1) \frac{M}{W} \, \frac{\Gamma_{\rm tot} \, \Gamma_{\gamma\gamma}}{(W^2 - M^2)^2 + M^2 \Gamma_{\rm tot}^2}$$

T_{4c} Production in UPCs

- The UPC cross section is:

$$\sigma(AA \to T_{4c}AA) = \int dW^2 \, \frac{d\mathcal{L}_{\gamma\gamma}}{dW^2} \, \sigma(\gamma\gamma \to T_{4c}; W)$$

- Photon–photon luminosity is given in terms of the Weizsäcker–Williams fluxes of photons as

$$\frac{d\mathcal{L}_{\gamma\gamma}}{dW^2} = \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} \delta(W^2 - x_1 x_2 s_{\mathrm{NN}}) \int d^2\boldsymbol{b}_1 d^2\boldsymbol{b}_2 \, S^2(|\boldsymbol{b}_1 - \boldsymbol{b}_2|) N(x_1, \boldsymbol{b}_1) N(x_2, \boldsymbol{b}_2),$$

- Partonic cross section: Breit–Wigner form

$$\sigma(\gamma\gamma \to T_{4c}(J); W) = 8\pi(2J+1) \frac{M}{W} \, \frac{\Gamma_{\mathrm{tot}} \, \Gamma_{\gamma\gamma}}{(W^2 - M^2)^2 + M^2 \Gamma_{\mathrm{tot}}^2}$$

- Total widths: $\Gamma_{\mathrm{tot}} = 0.446$ GeV for $X(6600)$, 0.135 GeV for $X(6900)$[A. Hayrapetyan *et al.*], 0.1 GeV for others.

Total Cross Sections in $^{208}Pb + ^{208}Pb$ UPC, $\sqrt{s_{NN}} = 5.5\,\mathrm{TeV}$

Mass (MeV)	J^{PC}	State	$\sigma(\gamma\gamma \to T_{4c})$ (nb)	$\sigma(AA \to T_{4c}AA)$ (μb)
6435	0^{++}	1s	0.251	0.351
6542	0^{++}	1s	0.560	0.769
6849	0^{++}	2s	0.311	0.396
6940	0^{++}	2s	1.398	1.738
6543	2^{++}	1s	1.006	1.164
6928	$\mathbf{2^{++}}$	**2s**	**2.212**	**2.733**

- Tensor states profit from $(2J+1) = 5$ spin factor.
- Total $\sigma(AA \to T_{4c}AA) \sim \mu$b; must be compared with UPC luminosities of a few nb^{-1}.

$J/\psi J/\psi$ Channel

- Simplified $T_{4c} \to J/\psi J/\psi$ couplings (following Esposito et al.):

$$\langle T_{4c}(0^{++})|V_1 V_2\rangle = \alpha_0\, \varepsilon_1 \cdot \varepsilon_2, \quad \langle T_{4c}(2^{++})|V_1 V_2\rangle = \alpha_2\, E_{\mu\nu}\, \varepsilon_1^{\mu} \varepsilon_2^{\nu}.$$

$J/\psi J/\psi$ Channel

- Simplified $T_{4c} \to J/\psi J/\psi$ couplings (following Esposito et al.):

$$\langle T_{4c}(0^{++})|V_1 V_2\rangle = \alpha_0\, \varepsilon_1 \cdot \varepsilon_2, \quad \langle T_{4c}(2^{++})|V_1 V_2\rangle = \alpha_2\, E_{\mu\nu}\, \varepsilon_1^\mu \varepsilon_2^\nu.$$

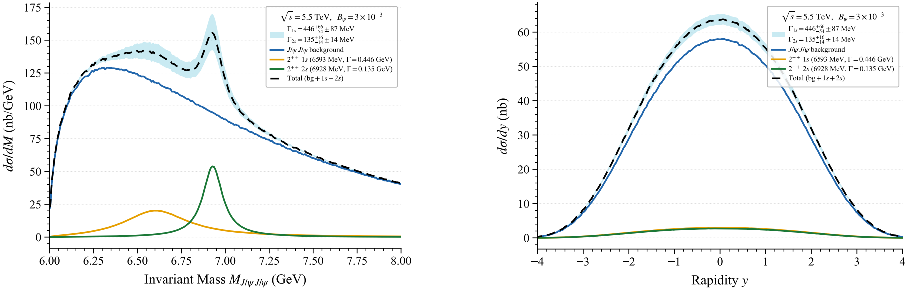
- The continuum is computed in LO NRQCD with $\mathrm{B}_\psi = 3 \times 10^{-3}, |\psi(0)|^2 = 0.08$ GeV^3, $m_c = 1.5$ GeV, $\alpha_s = 0.24$.

$J/\psi J/\psi$ Channel

- Simplified $T_{4c} \to J/\psi J/\psi$ couplings (following Esposito et al.):

$$\langle T_{4c}(0^{++})|V_1 V_2\rangle = \alpha_0\,\varepsilon_1\cdot\varepsilon_2, \quad \langle T_{4c}(2^{++})|V_1 V_2\rangle = \alpha_2\,E_{\mu\nu}\,\varepsilon_1^{\mu}\varepsilon_2^{\nu}.$$

- The continuum is computed in LO NRQCD with $\mathrm{B}_\psi = 3\times 10^{-3}, |\psi(0)|^2 = 0.08$ GeV^3, $m_c = 1.5$ GeV, $\alpha_s = 0.24$.



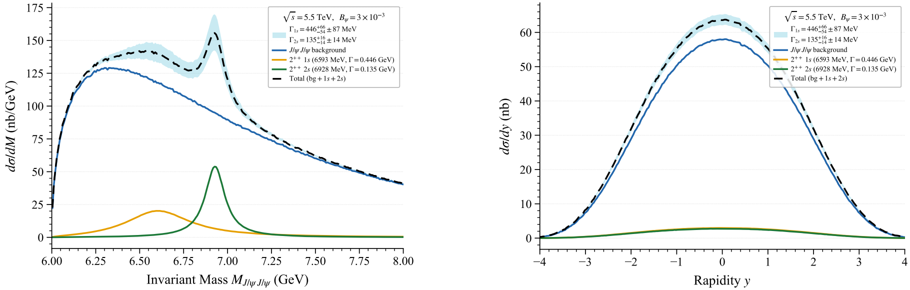
Invariant mass (left) and rapidity (right) for J/ψ pairs, with $B_\psi = 3\times 10^{-3}$.

$J/\psi J/\psi$ Channel

- Simplified $T_{4c} \to J/\psi J/\psi$ couplings (following Esposito et al.):

$$\langle T_{4c}(0^{++})|V_1 V_2\rangle = \alpha_0\, \varepsilon_1 \cdot \varepsilon_2, \quad \langle T_{4c}(2^{++})|V_1 V_2\rangle = \alpha_2\, E_{\mu\nu}\, \varepsilon_1^{\mu} \varepsilon_2^{\nu}.$$

- The continuum is computed in LO NRQCD with $\mathrm{B}_{\psi} = 3 \times 10^{-3}, |\psi(0)|^2 = 0.08$ GeV^3, $m_c = 1.5$ GeV, $\alpha_s = 0.24$.



Invariant mass (left) and rapidity (right) for J/ψ pairs, with $B_{\psi} = 3 \times 10^{-3}$.

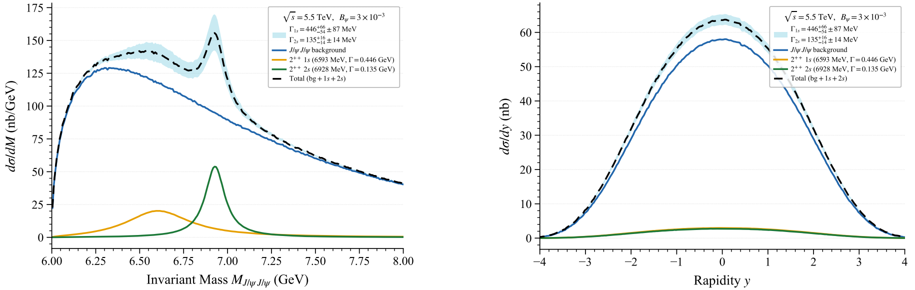
- The broad $1s$ (6593 MeV) spans 6.3–7.0 GeV; the narrow $2s$ (6928 MeV) forms a sharp peak.

$J/\psi J/\psi$ Channel

- Simplified $T_{4c} \to J/\psi J/\psi$ couplings (following Esposito et al.):

$$\langle T_{4c}(0^{++})|V_1 V_2\rangle = \alpha_0\, \varepsilon_1 \cdot \varepsilon_2, \quad \langle T_{4c}(2^{++})|V_1 V_2\rangle = \alpha_2\, E_{\mu\nu}\, \varepsilon_1^{\mu} \varepsilon_2^{\nu}.$$

- The continuum is computed in LO NRQCD with $\mathrm{B}_{\psi} = 3 \times 10^{-3}, |\psi(0)|^2 = 0.08$ GeV^3, $m_c = 1.5$ GeV, $\alpha_s = 0.24$.



Invariant mass (left) and rapidity (right) for J/ψ pairs, with $B_\psi = 3 \times 10^{-3}$.

- The broad $1s$ (6593 MeV) spans 6.3–7.0 GeV; the narrow $2s$ (6928 MeV) forms a sharp peak.
- Resonant signal exceeds the continuum $\Rightarrow$ promising for HL-LHC.

$\gamma\gamma$ Channel

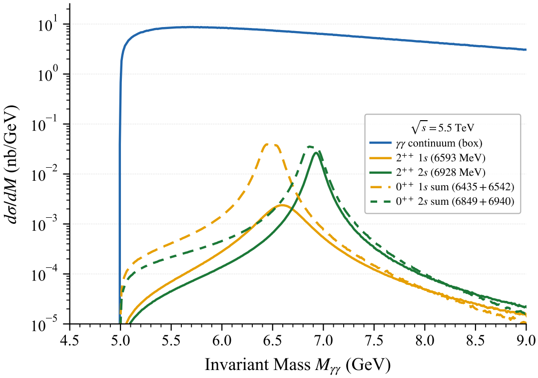


Figure: Diphoton invariant-mass distribution.

- QED box continuum dominates by ~ 2 orders of magnitude.

$\gamma\gamma$ Channel

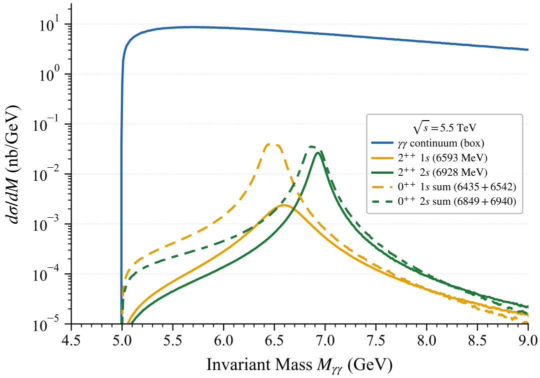


Figure: Diphoton invariant-mass distribution.

- QED box continuum dominates by ~ 2 orders of magnitude.
- All resonant contributions are at the level of a few $\times 10^{-2}$ nb.

$\gamma\gamma$ Channel

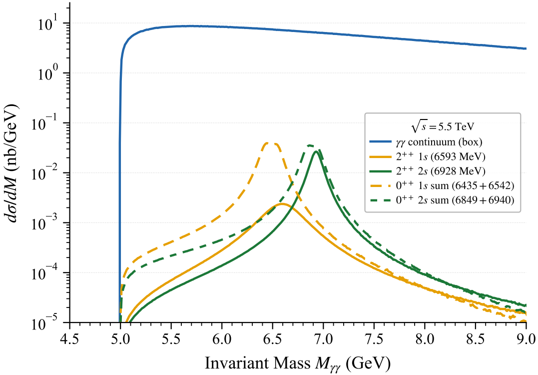


Figure: Diphoton invariant-mass distribution.

- QED box continuum dominates by ~ 2 orders of magnitude.
- All resonant contributions are at the level of a few $\times 10^{-2}$ nb.
- In clear disagreement with the VDM-based result of Biloshytskyi et al.

Summary

Summary and Outlook

Summary

- Presented LO NRQCD predictions for $\Gamma(T_{4c} \to \gamma\gamma)$ of 0^{++} and 2^{++} states.
- LDMEs extracted from realistic 4-body wave functions (GEM).
- Key results: $\Gamma(2^{++}_{2s}) \approx 0.22$ keV, $\Gamma(0^{++}_{2s}) \approx 0.15$–$0.69$ keV.
- $J/\psi J/\psi$ channel: resonant signal exceeds continuum – promising.
- $\gamma\gamma$ channel: resonant contributions much smaller than continuum – contradicts VDM predictions.

Summary and Outlook

Summary

- Presented LO NRQCD predictions for $\Gamma(T_{4c} \to \gamma\gamma)$ of 0^{++} and 2^{++} states.
- LDMEs extracted from realistic 4-body wave functions (GEM).
- Key results: $\Gamma(2^{++}_{2s}) \approx 0.22$ keV, $\Gamma(0^{++}_{2s}) \approx 0.15$–$0.69$ keV.
- $J/\psi J/\psi$ channel: resonant signal exceeds continuum – promising.
- $\gamma\gamma$ channel: resonant contributions much smaller than continuum – contradicts VDM predictions.

Outlook

- NLO calculation of SDCs needed to reduce $\sim 30\%$ scale uncertainty.
- Larger UPC luminosity at HL-LHC would be highly valuable.
- LDMEs can be used for other NRQCD-factorized processes.
- Matching between high p_T regions and low p_T regions in pp collisions.

Thank You!

Backup: Four-Body Schrödinger Equation

- The LDMEs are determined by $|\psi(0)|^2$, obtained by solving the 4-body Schrödinger equation:

$$H = \sum_{i=1}^{4} \sqrt{p_i^2 + m_i^2} + \sum_{i<j} V_{ij}(\mathbf{r}_{ij}),$$
$$V_{ij} = \mathbf{F}_i \cdot \mathbf{F}_j \left[V_{\rm conf}(r_{ij}) + V_{\rm OGE}(r_{ij})\right].$$

- Solved via the **Gaussian Expansion Method** (GEM).

$$\Psi(\mathbf{r}_{12}, \mathbf{r}_{34}, \mathbf{r}) = \sum_{n_{12},\, n_{34},\, n} C_{n_{12} n_{34} n}\, \psi_{n_{12}}(\mathbf{r}_{12})\, \psi_{n_{34}}(\mathbf{r}_{34})\, \psi_n(\mathbf{r}),$$
$$\psi_n(\mathbf{r}) = \left(\frac{2\nu_n}{\pi}\right)^{3/4} e^{-\nu_n r^2}\, Y_{00}(\hat{\mathbf{r}}),$$
$$\nu_n = \frac{1}{r_1^2\, a^{2(n-1)}}, \quad n = 1, \ldots, N_{\rm max}.$$

- $C_{n_{12} n_{34} n}$ and the tetraquark mass are obtained by solving the generalized eigenvalue problem $(H_{ij} - E\, N_{ij})\, \mathbf{C}_j = 0$.

Backup: Branching ratio B_ψ

- Total widths of the three $X \to J/\psi J/\psi$ peaks are known from CMS/LHCb, but B_ψ is not measured.
- Two conflicting pictures in the literature:
  - Several early works (VDM, LbL fits) assume $B_\psi \sim \mathcal{O}(1)$ [arXiv:2109.10359, arXiv:2207.13623].
  - Ref. [arXiv:2006.14388] evaluates the dimuon final states: $\mathcal{B}(T_{4c}(2^{++}) \to \mu^+\mu^-\mu^+\mu^-) \sim 10^{-5}$.
    Using $\mathcal{B}(J/\psi \to \mu^+\mu^-) \approx 0.06$, then obtain $B_\psi \sim 3 \times 10^{-3}$.
- Such small values are also required to explain the observed pp event rates [arXiv:2510.02085].
- Nevertheless, model calculations with larger $B_\psi \sim 10\%$ or more do exist [arXiv:2512.18569].
- Our choice: we adopt the representative value

$$B_\psi = 0.003$$

for *all* resonances, although B_ψ may strongly depend on the state [arXiv:2006.11952].

Backup: Analytic Results for SDCs

$$\tilde{F}_{TT,0} = \frac{4\pi\alpha_s e_Q^2}{\sqrt{3}\, m_Q^4}, \qquad \tilde{F}_{TT,2} = \frac{128\pi\alpha_s e_Q^2}{\sqrt{3}\, m_Q^2},$$

$$\tilde{F}_{TT}^{66} = -\frac{8\sqrt{2}\pi\alpha_s e_Q^2}{\sqrt{3}\, m_Q^2}, \qquad \tilde{F}_{TT}^{33} = \frac{48\pi\alpha_s e_Q^2}{m_Q^2}.$$

Decay width factorisation:

$$F_{TT} = \tilde{F}_{TT}^{66} \cdot \frac{\sqrt{2M}\langle \mathcal{O}^{(0)}_{6\otimes\bar{6}}\rangle}{4(2m_Q)^2} + \tilde{F}_{TT}^{33} \cdot \frac{\sqrt{2M}\langle \mathcal{O}^{(0)}_{\bar{3}\otimes 3}\rangle}{4(2m_Q)^2},$$

$$F_{TT,0} = \tilde{F}_{TT,0} \cdot \frac{\sqrt{2M}\langle \mathcal{O}^{(2)}_{\bar{3}\otimes 3}\rangle}{4(2m_Q)^2}, \quad F_{TT,2} = \tilde{F}_{TT,2} \cdot \frac{\sqrt{2M}\langle \mathcal{O}^{(2)}_{\bar{3}\otimes 3}\rangle}{4(2m_Q)^2}.$$

Backup: Comparison of LDMEs (GeV^9)

Mass (J^{PC})	State	$\langle \mathcal{O}_{\bar{3}3} \rangle$	$\langle \mathcal{O}_{6\bar{6}} \rangle$	$\langle \mathcal{O}_{\text{mix}} \rangle$	$\Gamma_{\gamma\gamma}$ (keV)
6435 (0^{++})	1s	0.01323	0.00794	0.010	0.106
6542 (0^{++})	1s	0.02152	0.00488	-0.010	0.245
6849 (0^{++})	2s	0.02078	0.02605	0.023	0.149
6940 (0^{++})	2s	0.06234	0.00868	-0.023	0.688
6543 (2^{++})	1s	0.01442	—	—	0.088
6928 (2^{++})	2s	0.03546	—	—	0.217

- Mixing term enters with different SDC weight $\Rightarrow$ constructive/destructive interference in decay width.