Lattice QCD calculation of the invisible decay $J/\psi \to \gamma\nu\bar{\nu}$

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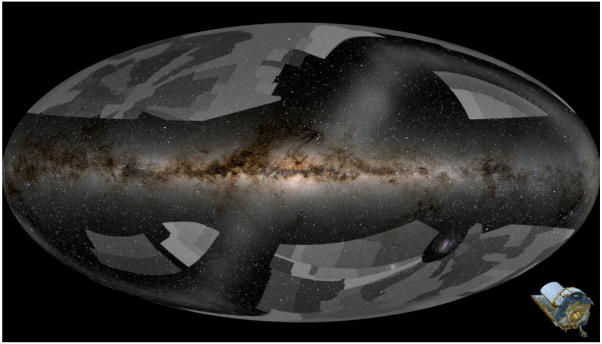
Outline

- Motivation
- Methodology: $\eta_c \to \gamma\gamma$
- Lattice studies on $J/\psi \to \gamma\nu\bar{\nu}$
- Summary

Motivation: search for the new physics



ESA

- Euclid space telescope: launching at 11:12 a.m, Sat July 1, 2023
- Mission: 3D map of the universe, with billions of galaxies that stretch 10 billion light-years away

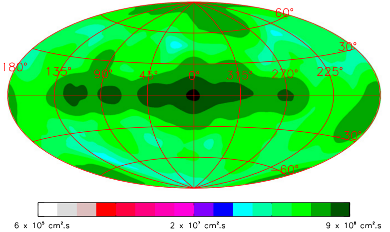
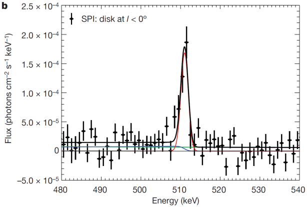


Figure 1. 508.25–513.75 keV *INTEGRAL* SPI exposure map. Units are in $cm^2 \times s$. This map takes into account the differential sensitivity of SPI across its field of view.



Nature,**451**,159(2008)

- First obervation, Astrophys.J. 172, L1(1972).
- One of the views: light dark matter (1-100MeV) annihilating into e^+e^- pairs PRL,92,101301(2004)

Current status of the dark matter search on the collider

- Remarkable candidates
  - Dark photon A': coupling to the photon through the kinetic mixing $\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$, free parameters are $m_{A'}$ and ϵ
  - CP-odd Higgs Boson A^0: m_{A^0} and $g_{al\bar{l}}$
  - Axion-like particle a: m_a and $g_{a\gamma\gamma}$
- Dark matter can be produced on the collider
  - Direct production: $e^+e^- \to \gamma X$
    BABAR,PRL119,131804(2017) BESIII,PLB839,137785(2023)
  - Resonant production: $e^+e^- \to J/\psi/\Upsilon(1S) \to \gamma + X$
    CLEO,PRD81,091101(2010) BABAR,PRL107,021804(2011)
    Belle,PRL122,011801(2019) Belle,PRL128,081804 (2022)
    BESIII,PRD101,112005(2020) BESIII,PRD105,012008(2022)
    BESIII,PLB838,137698(2023)

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CLEO 2010

PHYSICAL REVIEW D 81, 091101(R) (2010)

Search for the decay J/ψ→γ + invisible

(CLEO Collaboration)

$$J/\psi \to \gamma + X$$

invisible to detector

light dark matter ?

The upper limit corresponding to $m_X = 0$

is 4.3×10^{-6} at the 90% confidence level

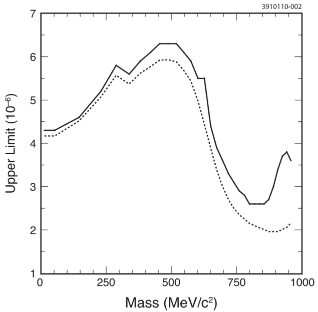


FIG. 4. The 90% confidence-level upper limits for $J/\psi \to \gamma X$, where X is invisible to the detector. The dashed line shows the results for statistical uncertainties alone, and the solid line includes systematic and statistical uncertainties.

Light dark matter search on the collider

BESIII

PHYSICAL REVIEW D 101, 112005 (**2020**)

Search for the decay J/ψ→γ + invisible

Upper bound $\mathcal{B} \sim 7.0 \times 10^{-7}$

PHYSICAL REVIEW D 105, 012008 (**2022**)

Search for a CP-odd light Higgs boson in $J/\psi \to \gamma A^0$

Upper bound $\mathcal{B}(J/\psi \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-) \sim (1.2 - 778.0) \times 10^{-9}$

PHYSICS LETTERS B 838, 137698 (**2023**)

Search for an axion-like particle in radiative J/ψ decays

We search for an axion-like particle (ALP) a through the process $\psi(3686) \to \pi^+\pi^- J/\psi$, $J/\psi \to \gamma a$, $a \to \gamma\gamma$ in a data sample of $(2.71 \pm 0.01) \times 10^9$ $\psi(3686)$ events collected by the BESIII detector. No significant ALP signal is observed over the expected background, and the upper limits on the branching fraction of the decay $J/\psi \to \gamma a$ and the ALP-photon coupling constant $g_{a\gamma\gamma}$ are set at 95% confidence level in the mass range of $0.165 \le m_a \le 2.84$ GeV$/c^2$. The limits on $\mathscr{B}(J/\psi \to \gamma a)$ range from 8.3×10^{-8} to 1.8×10^{-6} over the search region, and the constraints on the ALP-photon coupling are the most stringent to date for $0.165 \le m_a \le 1.468$ GeV$/c^2$.

Future experiments in the search for dark matter

- Super $\tau-$ Charm Facility (STCF) arXiv:2303.15790

  Samples about 100 larger than the present largest τ-charm factory - BESIII

2.6 New light particles beyond the SM 52
2.6.1 Particles in the dark sector 52
2.6.2 Millicharged particles 54

- Belle II: The Belle II Physics Book arXiv:1808.10567

16.3 Experiment: Quarkonium Decay 569
16.3.1 Searches for BSM physics in invisible $\Upsilon(1S)$ decays 569
16.3.2 Probe of new light CP even Higgs bosons from bottomonium χ_{b0} decay 571
16.3.3 Search for a $CP-$odd Higgs boson in radiative $\Upsilon(3S)$ decays 572

- LHCb II: Physics case for an LHCb Upgrade II arXiv:1808.08865

8.6 Searches for prompt and detached dark photons 97
8.7 Searches for semileptonic and hadronic decays of long-lived particles 98

Standard model background in J/ψ invisible decay

Only after we exactly determine the standard model background can the precise experimental investigations of the $J/\psi \to \gamma + \mathrm{invisible}$ decay possibly provide us rigorous constraints on new physics

In the standard model, the background is

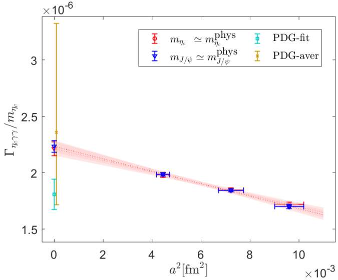
$$J/\psi \to \gamma + \nu + \bar{\nu}$$

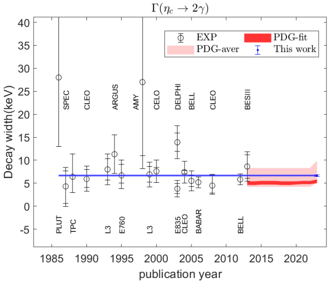
Since the neutrinos are only invisible particles

We target on an first-principle calculation on this invisible decay.

Methodology: $\eta_c \to 2\gamma$

Scalar function method: YM et al, Sci.Bull 68,1880(2023),2109.09381





$$\Gamma(\eta_c \to 2\gamma) = \begin{cases} 6.67(16)(6)\,\text{keV} \\ 5.4(4)\,\text{keV} \quad \text{PDG-fit} \\ 7.04^{+2.9}_{-1.9}\,\text{keV} \quad \text{PDG-aver} \end{cases}$$

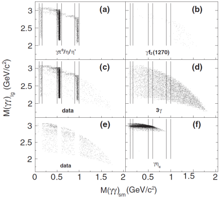
- HPQCD, $\Gamma_{\eta_c\gamma\gamma} = 6.788(45)_{\rm fit}(41)_{\rm syst}$ keV, PRD108,014513(2023),2305.06231

Discussion

- CLEO(08) and BESIII(13) extract the branching fraction of $\eta_c \to 2\gamma$ by

$$J/\psi \to \gamma\eta_c \to 3\gamma$$

- Using 1.06×10^8 $\psi(3686) \to \pi^+\pi^- J/\psi$



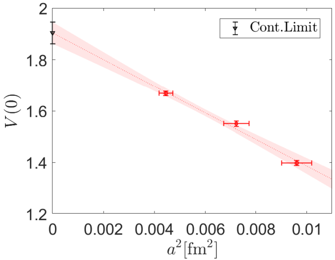
VALUE (10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{1.68 \pm 0.12}$ OUR FIT					
$\mathbf{2.2^{+0.9}_{-0.6}}$ OUR AVERAGE					
$2.7 \pm 0.8 \pm 0.6$			[1] ABLIKIM 2013I	BES3	
$0.7\ ^{+1.6}_{-0.7} \pm 0.2$		$1.2\ ^{+2.8}_{-1.1}$	[2] ADAMS 2008	CLEO	$\psi(2S) \to \pi^+\pi^- J/\psi$
• • We do not use the following data for averages, fits, limits, etc. • •					
$2.0\ ^{+0.9}_{-0.7} \pm 0.2$		13	[3] WICHT 2008	BELL	$B^\pm \to K^\pm\gamma\gamma$
$2.80\ ^{+0.67}_{-0.58} \pm 1.0$			[4] ARMSTRONG 1995F	E760	$\bar{p}\,p \to \gamma\gamma$
< 9	90		[5] BISELLO 1991	DM2	$J/\psi \to \gamma\gamma\gamma$
$6\ ^{+4}_{-3} \pm 4$			[4] BAGLIN 1987B	SPEC	$\bar{p}\,p \to \gamma\gamma$
< 18	90		[6] BLOOM 1983	CBAL	$J/\psi \to \eta_c\gamma$

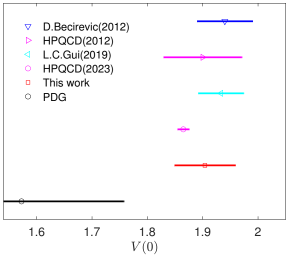
[1] ABLIKIM 2013I reports $[\Gamma(\eta_c(1S) \to \gamma\gamma)/\Gamma_{\rm total}] \times [B(J/\psi(1S) \to \gamma\eta_c(1S))] = (4.5 \pm 1.2 \pm 0.6) \times 10^{-6}$ which we divide by our best value $B(J/\psi(1S) \to \gamma\eta_c(1S)) = 0.017 \pm 0.004$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[2] ADAMS 2008 reports $[\Gamma(\eta_c(1S) \to \gamma\gamma)/\Gamma_{\rm total}] \times [B(J/\psi(1S) \to \gamma\eta_c(1S))] = (1.2\ ^{+2.7}_{-1.1} \pm 0.3) \times 10^{-6}$ which we divide by our best value $B(J/\psi(1S) \to \gamma\eta_c(1S)) = 0.017 \pm 0.004$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

The contribution of $J/\psi \to \gamma\eta_c$ is crucial

$\eta_c \to 2\gamma$ & $J/\psi \to \gamma\eta_c$





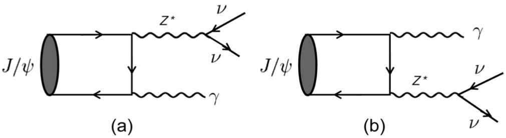
- Our result $\text{Br}(J/\psi \to \gamma\eta_c) = 2.31(13)\%$ [To appear] $\Leftarrow 1.7(4)\%$ PDG
- Combining BESIII(13), $\Gamma(\eta_c \to 2\gamma) = 6.2(1.7)(0.9)\text{keV} \Leftarrow 8.64(2.56)(1.92)\text{keV}$

- Remark: direct measurement with no-dependence on $J/\psi \to \gamma\eta_c$ is urgent, or much improved $J/\psi \to 3\gamma$, both statistically and systematically.
  - Model-independent input for $J/\psi \to 3\gamma$ amplitude with full Dalitz space. YM et al, PRD 102,054506(2020)

$J/\psi \to \gamma\nu\bar{\nu}$ decay from lattice QCD

arXiv:2309.15436

$J/\psi \to \gamma\nu\bar{\nu}$: Formalism



- Amplitude

$$i\mathcal{M} \quad = \quad -i\frac{(q_c e)G_F}{\sqrt{2}}[H_{\mu\nu\alpha}(q,p)\epsilon^{\alpha}_{J/\psi}(p)\epsilon^{\nu*}(q)\bar{u}(q_1)\gamma^{\mu}(1-\gamma_5)v(q_2)]$$

- Hadroinc function

$$H_{\mu\nu\alpha}(q,p) \quad = \quad \int d^4x e^{-iqx}\langle 0|T\{J^{\mathrm{em}}_{\mu}(x)J^{Z}_{\nu}(0)\}|J/\psi(p)_{\alpha}\rangle$$
$$\equiv \quad \epsilon_{\mu\nu\alpha\beta}q_{\beta}F_{\gamma\nu\bar{\nu}} \qquad \text{PRD } \mathbf{90}, 077501(2014)$$

- Decay width

$$\Gamma(J/\psi \to \gamma\nu\bar{\nu}) \quad = \quad \frac{\alpha G_F^2}{3\pi^2}\int_0^{\frac{m_{J/\psi}}{2}} |\vec{q}|^3(m_{J/\psi}-|\vec{q}|)|F_{\gamma\nu\bar{\nu}}|^2 d|\vec{q}|$$

Methodology

- Form factor

$$
\begin{aligned}
F_{\gamma\nu\bar{\nu}}(E_\gamma, \Delta t) &= \frac{1}{6p \cdot q}\epsilon_{\mu\nu\alpha\beta} p_\beta H_{\mu\nu\alpha}(q,p) \\
&= -\frac{i}{6E_\gamma}\int e^{E_\gamma t} dt \int d^3\vec{x} j_0(E_\gamma|\vec{x}|)\epsilon_{\mu\nu\alpha 0}\mathcal{H}_{\mu\nu\alpha}(x, \Delta t)
\end{aligned}
$$

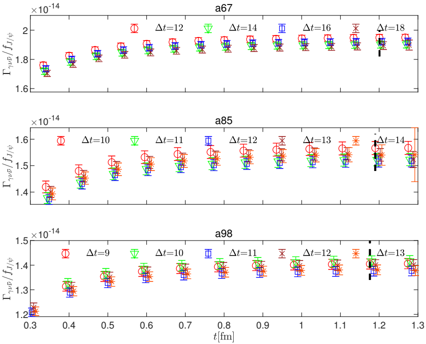
- Decay width evaluated by a Monte-Carlo method

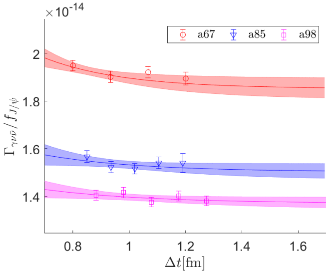
$$
\Gamma_{\gamma\nu\bar{\nu}}(\Delta t) = \frac{\alpha G_F^2}{3\pi^2}\frac{m_{J/\psi}}{2N_{MC}}\sum_{i=1}^{N_{MC}}\left(E_\gamma^3(m_{J/\psi} - E_\gamma)|F_{\gamma\nu\bar{\nu}}(E_\gamma, \Delta t)|^2\right)_i
$$

- Dimensionless quantity $R_f \equiv \Gamma_{\gamma\nu\bar{\nu}}/f_{J/\psi}$ and Δt dependence

$$
R_f(\Delta t) = R_f + \zeta \cdot e^{-(m_{J/\psi}^{(1)} - m_{J/\psi})\Delta t}
$$

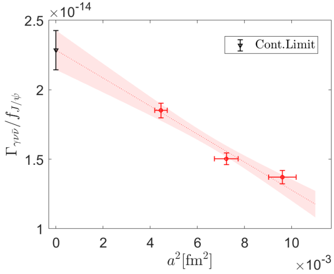
Excited-state contamination

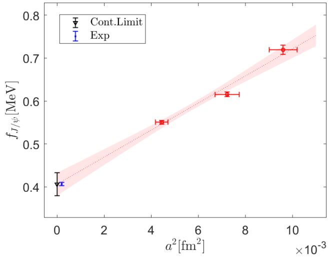




- A slight dependence on the excited-state of J/ψ (Δt-dependence).
- Dashed black line: a suitable time truncation $t_{\mathrm{cut}} \sim 1.2$ fm.
- The right: an extrapolation for Δt at t_{cut}.

Continuous limit





- The first lattice QCD calculation arXiv:2309.15436

$$\mathrm{Br}[J/\psi \to \gamma\nu\bar{\nu}] = 1.00(9)(7) \times 10^{-10}$$

- Phenomenological estimation $\sim 0.7 \times 10^{-10}$
  Dao-Neng Gao,PRD **90**,077501(2014)

Discussion: next generation experiments

- Dark matter search by $J/\psi \to \gamma + \mathrm{invisible}$[STCF]
  - STCF has the potential to improve the upper limit to 10^{-8}, even possibly 10^{-9} level.
  - Standard model background $J/\psi \to \gamma\nu\bar{\nu}$ is calculated on the lattice with a branching fraction of $1.00(9)(7) \times 10^{-10}$.
- Dark matter search by $\Upsilon \to \gamma + \mathrm{invisible}$[Belle II]
  - The design luminosity of Belle II is 80 times larger than Belle, which has an upper limit of 10^{-6}.
  - Naive phenomenological estimation $\mathcal{B}(\Upsilon(1S) \to \gamma\nu\bar{\nu}) \sim 10^{-9}$ considering $\mathcal{B} \sim M^2$.
  - No lattice calculation of $\mathcal{B}(\Upsilon(1S) \to \gamma\nu\bar{\nu}$.

Summary

- We present first lattice calculation on the invisible decay $J/\psi \to \gamma\nu\bar{\nu}$ using a scalar function method.
- Various systematics are examined, including finite-volume effects, excited-state contamination, and discretization effects.
- An exact branching fraction $\mathrm{Br}[J/\psi \to \gamma\nu\bar{\nu}] = 1.00(9)(7) \times 10^{-10}$ is determined, providing theoretical support for the dark matter search in future experiments.

Thank you for attention!

Back-up

Hadronic function in Minkowski and Euclidean space

- Minkowski

$$H_{\mu\nu\alpha}(q,p) = i\sum_{n,\vec{q}} \frac{1}{E_\gamma - E_n + i\epsilon}\langle 0|J_\mu^{\rm em}(0)|n(\vec{q})\rangle\langle n(\vec{q})|J_\nu^Z(0)|J/\psi(p)_\alpha\rangle$$
$$-i\sum_{n',\vec{q}} \frac{1}{E_\gamma + E_{n'} - m_{J/\psi} - i\epsilon}\langle 0|J_\nu^Z(0)|n'(-\vec{q})\rangle\langle n'(-\vec{q})|J_\mu^{\rm em}(0)|J/\psi(p)_\alpha\rangle$$

- Euclidean

$$H^E_{\mu\nu\alpha}(q,p) = i\sum_{n,\vec{q}} \frac{1-e^{-(E_n - E_\gamma)T/2}}{E_\gamma - E_n + i\epsilon}\langle 0|J_\mu^{\rm em}(0)|n(\vec{q})\rangle\langle n(\vec{q})|J_\nu^Z(0)|J/\psi(p)_\alpha\rangle$$
$$-i\sum_{n',\vec{q}} \frac{1-e^{-(E_\gamma + E_{n'} - m_{J/\psi})T/2}}{E_\gamma + E_{n'} - m_{J/\psi} - i\epsilon}\langle 0|J_\nu^Z(0)|n'(-\vec{q})\rangle\langle n'(-\vec{q})|J_\mu^{\rm em}(0)|J/\psi(p)_\alpha\rangle$$

- A naive relation requires
  - $\delta E_n \equiv E_n - E_\gamma > 0$
  - $\delta E_{n'} \equiv E_\gamma + E_{n'} - m_{J/\psi} > 0$

Hadronic function in Minkowski and Euclidean space

- Minkowski

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- A naive relation requires
  - $\delta E_n \equiv E_n - E_\gamma > 0$ ☑ $|n\rangle \overset{\text{lowest}}{=\!=} |J/\psi\rangle$
  - $\delta E_{n'} \equiv E_\gamma + E_{n'} - m_{J/\psi} > 0$ ☐ $|n'\rangle \overset{\text{lowest}}{=\!=} |\eta_c\rangle$

Note: a general approach to exponentially growing terms

Norman H. Christ et al, PRD 103,014507(2021)

Gauge ensembles

- $N_f = 2$ twisted mass ensembles

Ens	a (fm)	$L^3 \times T$	$N_{\text{conf}} \times T$	m_π(MeV)	t
a67	0.0667(20)	$32^3 \times 64$	197×64	300	12-18
a85	0.085(2)	$24^3 \times 48$	200×48	315	10-14
a98	0.098(3)	$24^3 \times 48$	236×48	365	9-13

- Numerical results: $\delta E_{\eta_c}(\vec{n} \neq 0) > 0$

Ensemble	a67	a85	a98
$a\delta E_{\eta_c}(\lvert\vec{n}\rvert^2 = 0)$	-0.0343(2)	-0.0372(3)	-0.0387(3)
$a\delta E_{\eta_c}(\lvert\vec{n}\rvert^2 = 1)$	0.1781(2)	0.2446(3)	0.2380(4)
$a\delta E_{\eta_c}(\lvert\vec{n}\rvert^2 = 2)$	0.2758(3)	0.3737(3)	0.3611(4)
$a\delta E_{\eta_c}(\lvert\vec{n}\rvert^2 = 3)$	0.3544(3)	0.4751(4)	0.4587(4)
$a\delta E_{\eta_c}(\lvert\vec{n}\rvert^2 = 4)$	0.4223(4)	0.5636(5)	0.5426(5)

Note that $\langle 0|J_\nu^Z(0)|\eta_c(\vec{0})\rangle\langle\eta_c(\vec{0})|J_\mu^{\text{em}}(0)|J/\psi(\vec{0})_\alpha\rangle = 0$

Hadronic function in Minkowski and Euclidean space

- Minkowski

$$H_{\mu\nu\alpha}(q,p) = i\sum_{n,\vec{q}} \frac{1}{E_\gamma - E_n + i\epsilon} \langle 0|J_\mu^{\rm em}(0)|n(\vec{q})\rangle\langle n(\vec{q})|J_\nu^Z(0)|J/\psi(p)_\alpha\rangle$$
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$$-i\sum_{n',\vec{q}} \frac{1-e^{-(E_\gamma+E_{n'}-m_{J/\psi})T/2}}{E_\gamma + E_{n'} - m_{J/\psi} - i\epsilon} \langle 0|J_\nu^Z(0)|n'(-\vec{q})\rangle\langle n'(-\vec{q})|J_\mu^{\rm em}(0)|J/\psi(p)_\alpha\rangle$$

- A naive relation requires
  - $\delta E_n \equiv E_n - E_\gamma > 0$ ☑ $|n\rangle \xlongequal{\text{lowest}} |J/\psi\rangle$
  - $\delta E_{n'} \equiv E_\gamma + E_{n'} - m_{J/\psi} > 0$ ☑ $|n'\rangle \xlongequal{\text{lowest}} |\eta_c\rangle$

Finite-volume effects

- Examining the finite-volume effects ($R \equiv |\vec{x}|$)

$$F_{\gamma\nu\bar{\nu}}(E_\gamma, \Delta t) = -\frac{i}{6E_\gamma}\int e^{E_\gamma t}dt \int_0^R d^3\vec{x}\; j_0(E_\gamma|\vec{x}|)\epsilon_{\mu\nu\alpha 0}\mathcal{H}_{\mu\nu\alpha}(x, \Delta t)$$