Lattice QCD study on charmonia radiative decay

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Outline

- Introduction
  - Experiments(BESIII)
  - Theories
- Charmonium radiative decay
  - $\eta_c \to 2\gamma$
  - $\chi_{c_0} \to 2\gamma$
  - $J/\psi \to 3\gamma$
  - $J/\psi \to \gamma\nu\bar{\nu}$
- Conclusion and outlook

Motivation

Why charmonium decay ?

- Test the interplay of pert and non-pert QCD
  — intermediate energy scale
- More possibilities for the search of new physics
  — invisible decay of charmoinum
- BESIII experiment

For more charm physics on lattice, see Liu Zhaofeng's talk 14:00,08-22

Experiments : $\eta_c \to 2\gamma$

- Results

	$\mathrm{Br} \times 10^5$	Note
CLEO	$1.4^{+0.7}_{-0.5} \pm 0.3$	PRL 101,101801(2008)
BESIII	$2.7 \pm 0.8 \pm 0.6$	PRD 87,032003(2013)
World average	$1.9^{+0.7}_{-0.6}$	PDG-aver
Global fit	1.61 ± 0.12	PDG-fit

- Updated: 5.15(35) keV $\Rightarrow$ 5.43(+0.41-0.38) keV
  - Datas before 1995 unused
  - $J/\psi \to \gamma\eta_c$ unused
  - 97 datas,29 parameters,$\chi^2 = 86$

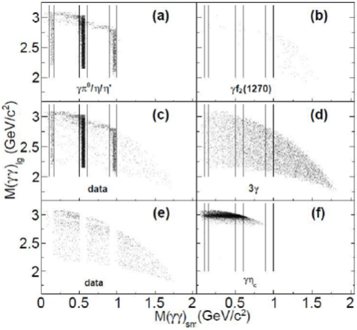
H-P.Wang and C-Z.Yuan,"New puzzle in charmonium decays" CPC**46**,071001(2022)

Experiments: $J/\psi \to 3\gamma$

- Results:

Exp	$\mathcal{B} \times 10^5$	$\delta\mathcal{B} \times 10^5$	Refs
Crystal Ball	< 5.5		PRL 44,712(1980)
CLEO	1.2	0.3± 0.2	PRL 101,101801(2008)
BESIII	1.13	0.18± 0.2	PRD 87,032003(2013)

- Difficulties:
  - (i) Multi-intermediate states
  - (ii) Poor knowledge of matrix element
- Opportunities: BESIII with 10^{10} J/ψ



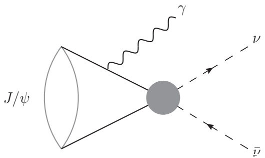
BESIII $\sim 3 \times 10^7 J/\psi$

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

- BSM predict CP-odd pseudoscalar Higgs boson A_0, which can be coupled with SM particle
- Dark matter from collider

CLEO,PRD.**81**,091101(2010)	$< 4.3 \times 10^{-6}$
BESIII,PRD.**101**,112005(2020)	$< 7.0 \times 10^{-7}$

- SM background: $J/\psi \to \gamma + \nu\bar{\nu}$
  - Perturbative calculation
    D.-N.Gao,Phys.Rev.D.**90**,077501(2014)
  - No lattice study, YM et al,in progress



Theories

- $\eta_c \to 2\gamma$

	$\Gamma(\mathrm{keV})$	Note
NRQCD	$9.9 \sim 10.6$	PRL**119**,252001(2017)
DSE	$6.32 \sim 6.39$	PRD**95**,016010(2017)
Lattice	$6.04(68)$	CLQCD(2020)
PDG-fit	$5.15(35)$	PDG
Lattice	$6.57(15)(8)$	YM et al,2109.09381

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

  (i) NRQCD+model inputs

  F. Feng, Y. Jia and W-L. Sang, PRD 87,051501(2013)

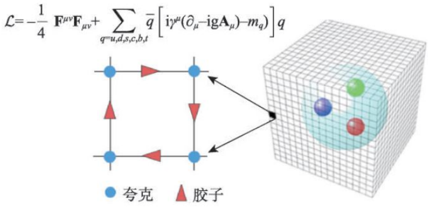
  (ii) Lattice QCD

  YM,C.Liu, K-L.Zhang Phys.Rev.D.**102**,054506(2020)

Precision test for QCD $\Leftarrow$ High precision lattice simulation $\Leftarrow$ new lattice method+systematic analysis

Lattice QCD

- K.G.Wilson, PRD 10, 2445(1974)
- Idea: put QCD on 4-d lattice
  - Quark field $\rightarrow$ site
  - Gauge filed $\rightarrow$ link



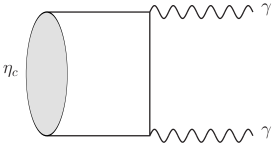
格点量子色动力学在中国 [J]. 现代物理知识,2020,32(01):36-44.

- “格点场论既是世界观 (非微扰的定义) 又是方法论 (非微扰的计算)”

  — 刘川,《格点量子色动力学导论》

  - 世界观 $\Rightarrow$ Non-perturbative definition of QCD,
    natural ultraviolet and infrared truncation
  - 方法论 $\Rightarrow$ Non-perturbative calculation of QCD,
    Monte-Carlo simulation

$\eta_c \to 2\gamma$



- Amplitude:

$$\begin{aligned} \mathcal{M} &= e^2 \epsilon_\mu(p) \epsilon_\nu(p') H_{\mu\nu}(p,q) \\ H_{\mu\nu}(p,q) &= \int d^4x e^{-ipx} \mathcal{H}_{\mu\nu}(x,q), \quad \mathcal{H}_{\mu\nu} = \langle 0 | \mathrm{Tr}[J_\mu(x) J_\nu(0)] | \eta_c(q) \rangle \end{aligned}$$

- Form factor: $$H_{\mu\nu}(p,q) = \epsilon_{\mu\nu\alpha\beta} p_\alpha q_\beta F(p^2)$$

- Decay width:

$$\Gamma_{\eta_c\gamma\gamma} = \alpha_{\mathrm{em}}^2 \frac{\pi}{4} m_{\eta_c}^3 |F_{\eta_c\gamma\gamma}|^2, \quad F_{\eta_c\gamma\gamma} = F(0)$$

Traditional vs New

- Off-shell form factors by projecting discrete momentum $\vec{p} = \frac{2\pi\vec{n}}{L}$

$$F(p^2) \xrightarrow{\text{Cont.Limit}} F(0), \quad |\vec{p}| = \frac{m_{\eta_c}}{2}$$

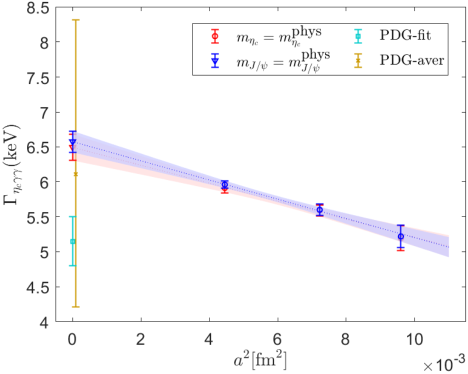
Y.Chen *et al*(CLQCD), CPC**44**,083108(2020)

  - Additional computation costs and extraplation error.
  - Lattice discretization effect: only two lattice spacings used
  - Excited-state contamination: without considering the excited-state effect on the lattice

- Scalar function method: calculate on-shell form factor directly

$$F_{\eta_c\gamma\gamma}(\Delta t) \quad = \quad -\frac{1}{2m_{\eta_c}} \int dt e^{m_{\eta_c} t/2} \int d^3\vec{x} \frac{j_1(|\vec{p}||\vec{\boldsymbol{x}}|)}{|\vec{p}||\vec{x}|} \epsilon_{\mu\nu\alpha 0} x_\alpha \mathcal{H}_{\mu\nu}(x, \Delta t)$$

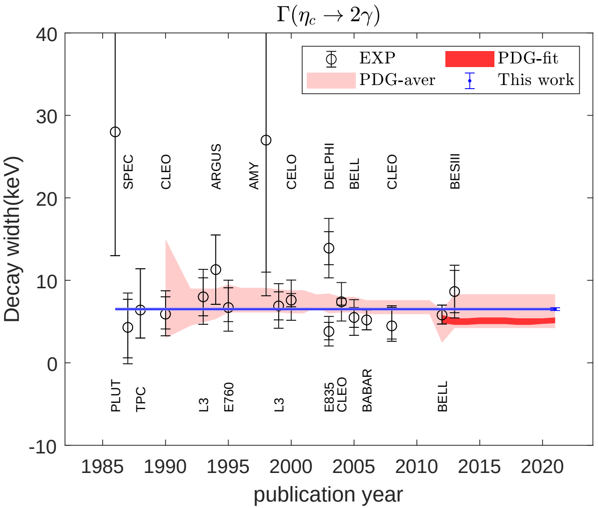
- NRQCD(NLO) ~ 6.2
  K.-T.Chao *et al*, PRD**56**,368(1997)
- NRQCD(NNLO) ~ 10
  F.Feng *et al*, PRL**119**,252002(2017)
- DSE ~ 6.4
  J.Chen *et al*, PRD**95**,016010(2017)
- CLQCD $\sim 6.0(7)$
  Y.Chen *et al*, CPC**44**,083108(2020)



$$
\Gamma(\eta_c \to 2\gamma) = \begin{cases} 6.57(15)(8)\,\text{keV} & \text{YM } et\ al, \text{2109.09381} \\ 5.15(35)\,\text{keV} & \text{PDG-fit} \\ 6.11^{+2.2}_{-1.9}\,\text{keV} & \text{PDG-aver} \end{cases}
$$

- HPQCD-preliminary, $\Gamma_{\eta_c \to 2\gamma} = 6.78(13)\text{keV}$, Lattice 2022

Lattice & Experiments

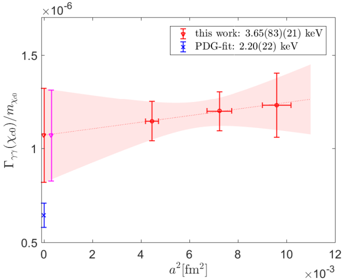


$\chi_{c_0} \to 2\gamma$

- Overviews

Method	$\Gamma(\text{keV})$	$\delta\Gamma(\text{keV})$	Refs
CLEO	2.36	0.35$\pm$ 0.22	PRD 78,091501(2008)
BESIII	2.03	0.08$\pm$ 0.14	PRD 96,092007(2013)
Dudek	2.41	0.58$\pm$ 0.86	PRL 97,172001(2006)
CLQCD	3.72	0.76$\pm$ 1.0	CPC 44,083108(2020)

- Notes:
  - (a) Continuous extrapolation
  - (b) Improved lattice method
  - (c) Twm Ens $\to$ parity violation
    $\Rightarrow$ GEVP $\to$ statistical error

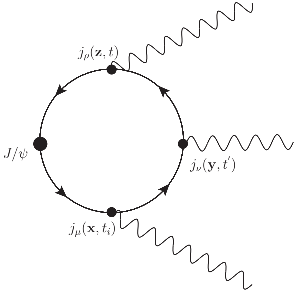


- Our result: $\Gamma_{\gamma\gamma}(\chi_{c0}) = 3.65(83)_{\text{stat}}(21)_{\text{lat.syst}}(66)_{\text{syst}}\ \text{keV}$
  Z.-H.Zou,YM,C.Liu,CPC 46,053102(2022)

$J/\psi \to 3\gamma$

- Decay width

$$\Gamma_{3\gamma} = \frac{m_{J/\psi}}{1536\pi^3}\int_0^1 dx \int_{1-x}^1 dy\mathcal{T}(x,y)$$
$$\mathcal{T} = \frac{1}{3}\sum_{\mu\nu\rho\alpha}|\mathcal{M}_{\mu\nu\rho\alpha}|^2$$
$$x \equiv 1-2q_2\cdot q_3/m^2, y \equiv 1-2q_1\cdot q_2/m^2$$



- Traditional: $\mathcal{M}_{\mu\nu\rho\alpha}(q_1,q_2,q_3)$

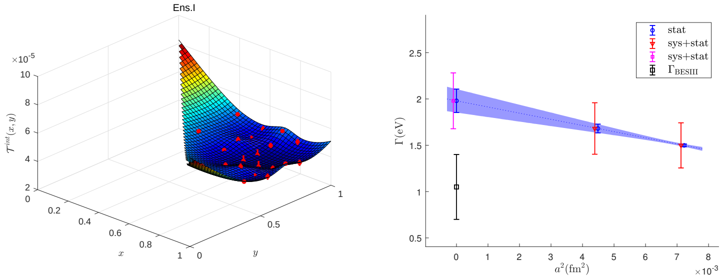
$$\mathcal{T}(x,y,Q_1^2,Q_2^2,Q_3^2) = \mathcal{T}(x,y) + \text{const} \times \sum_i Q_i^2$$

- Scalar function method

YM et al,in progress

$$\mathcal{M}^{\mu\nu\rho\alpha}(q_1,q_2,q_3) = \sum_{[123]}\sum_{i=1}^{3} F_i(s_1,s_2,s_3)\Pi_i^{[\mu\nu\rho]\alpha}(q_1,q_2,q_3)$$

Traditional calculation



YM,C.Liu, K-L.Zhang Phys.Rev.D.**102**,054506(2020)

- Naive continuum extrapolation;
- The intermediate contribution $J/\psi \to \gamma\eta_c \to 3\gamma$;
- Excited-state contamination;
- Systematical error by the region without data covered;

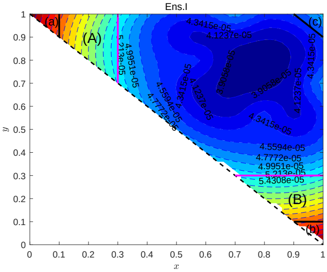
Dalitz analysis

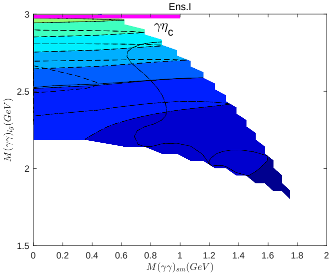
- Dalitz variables:

$$\frac{M(\gamma\gamma)_{lg/sm}}{m_{J/\psi}} = \begin{matrix}\max\\\min\end{matrix}\left\{\sqrt{1-x}, \sqrt{1-y}, \sqrt{x+y-1}\right\}$$

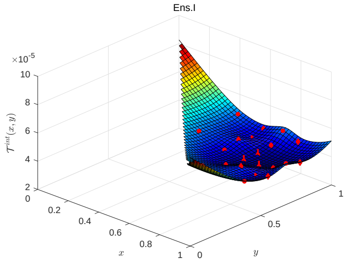
  - Dalitz plot is the direct observable for the experiments.
  - Bands in Dalitz plot indicate the intermediate two-body states.

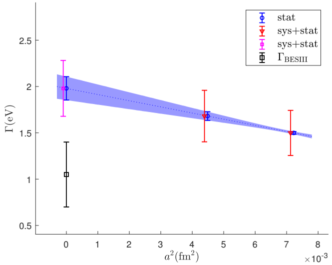
- Dalitz plot





Toward a systematic study





YM,C.Liu, K-L.Zhang Phys.Rev.D.**102**,054506(2020)

- Naive continuum extrapolation; ☑Three lattice spacings
- The intermediate contribution $J/\psi \to \gamma\eta_c \to 3\gamma$; ☑
- Excited-state contamination; ☑
- Systematical error by the region without data covered; ☑ Scalar function method

Summary and outlook

- Summary
  - Lattice calculation on $\eta_c/\chi_{c_0} \to 2\gamma$ with new method
  - An explorative calculation on $J/\psi \to 3\gamma$ by traditional way
- Outlook
  - Systematic study on $J/\psi \to \gamma\nu\bar{\nu}$ and $J/\psi \to 3\gamma$
  - QCD precision test + new physics in charmonium physics

BESIII,etc & Lattice QCD & Phenomenological

特别致谢：BESIII 项目组及实验同行