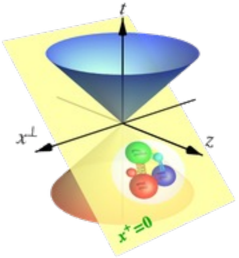

E1 radiative transition of charmonium on the light front

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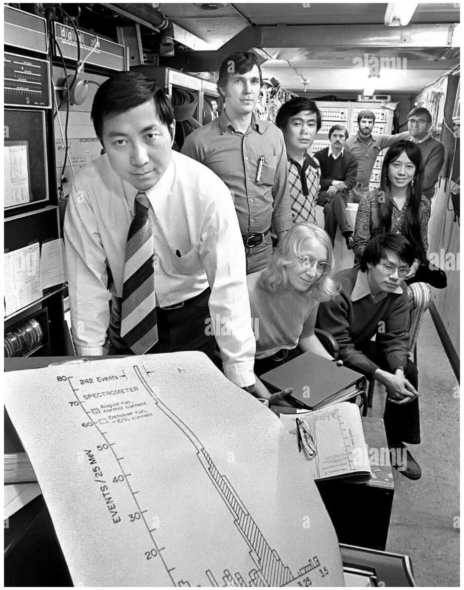
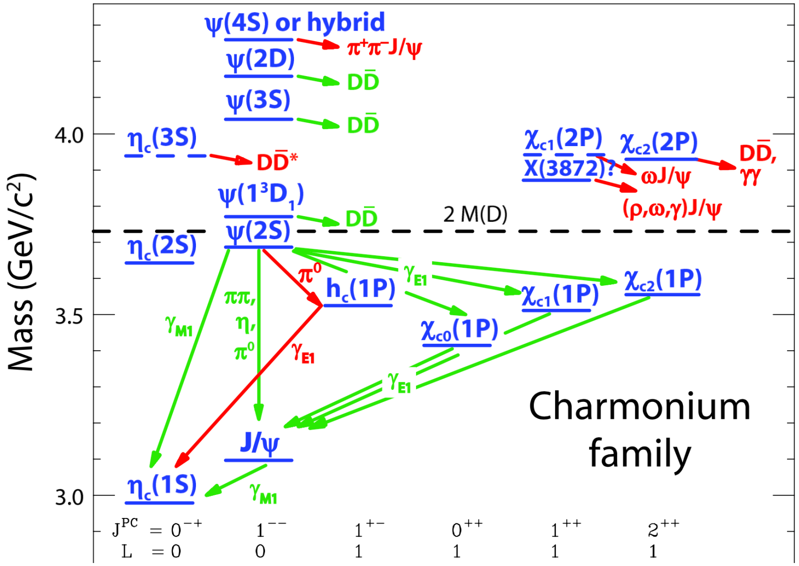
In cooperation with Meijian Li, Yang Li, James P. Vary

arXiv:2312.02604 [hep-ph]

Charmonium

- Charmonium spectroscopy
  - J/ψ discovered about 50 years ago by Ting at BNL and Richer at SLAC
  - Many mysteries:
    - X,Y,Z states [Brambilla '11]
    - Charmonium production puzzle
    - …
- Dynamics of charmonium should be tested in different regimes
  - Leptonic decay
  - Strong decay
  - **Radiative decay**
  - …

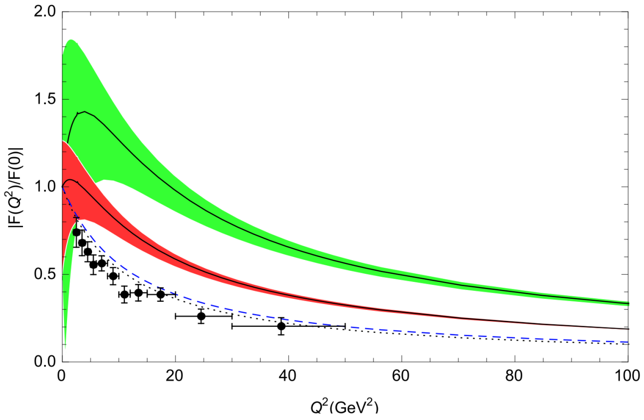




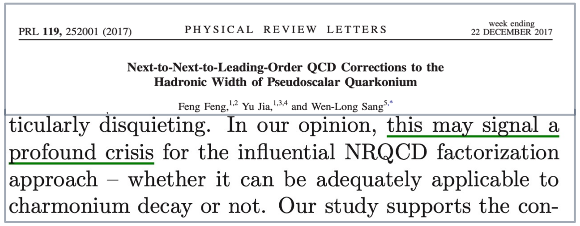
from Eichten'07

Challenges

- Quark model
  - Large relativistic correction [Barnes ‘05, Cao ‘12, Deng ’17, …]
  - Discrepancies between various potentials and relativistic approaches
  - Especially difficult for excited states with larger relativistic effect [Eichten ‘07]



- NRQCD [Feng ’16&’17]
  - Discrepancies for two photon decay between NNLO predictions and BaBar measurement


PRL **119,** 252001 (2017) PHYSICAL REVIEW LETTERS week ending 22 DECEMBER 2017

Next-to-Next-to-Leading-Order QCD Corrections to the Hadronic Width of Pseudoscalar Quarkonium

Feng Feng,[1,2] Yu Jia,[1,3,4] and Wen-Long Sang[5,*]

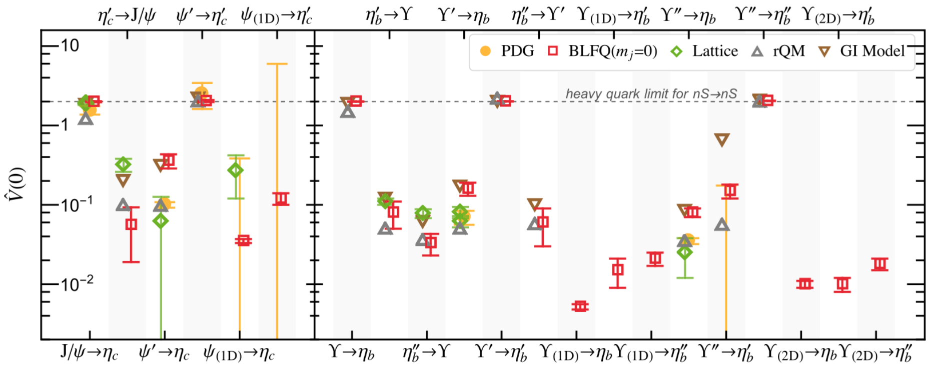
ticularly disquieting. In our opinion, this may signal a profound crisis for the influential NRQCD factorization approach – whether it can be adequately applicable to charmonium decay or not. Our study supports the con-

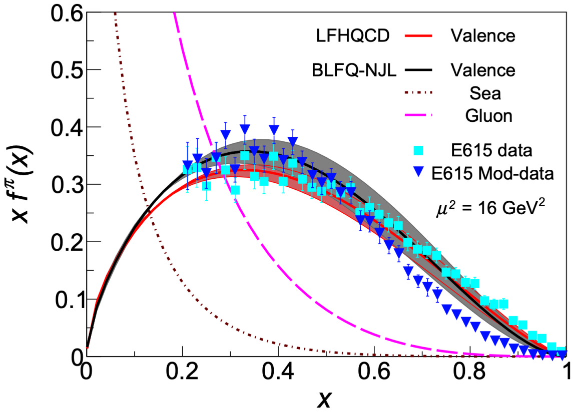
- Why charmonium so challenging? [Brembilla ‘12]
  - $\alpha_s \sim (0.3 - 0.6)$ Nonperturbative effect
  - $v_c^2 \sim 0.3$ relativistic effect

- A call for non-perturbative relativistic description
  - Lattice QCD
  - Dyson-Schwinger equation / Bethe-Salpeter equation
  - Light front QCD: Basis Light Front Quantization

Basis Light Front Quantization (BLFQ)

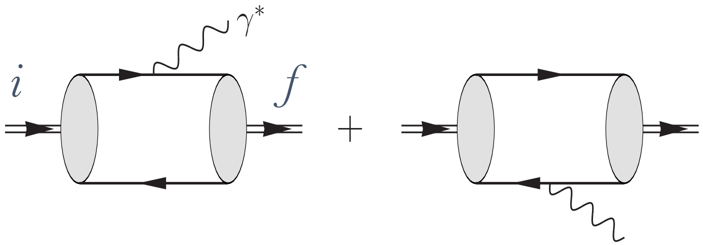
- Proposed by Vary et al. as a non-perturbative approach to QCD based on Hamiltonian field theory [Vary et al. PRC'09; Y. Li, Maris, Zhao, Vary, PLB'16]
- Application to a variety of systems:
  - Pion, nucleons, Λ, … [Lan, PRD'20; Mondal, PRD'20; Xu '21; Shuryak '21]
- Application to charmonium:
  - Holographic confinement and an effective one-gluon exchange interaction
  - Two free parameters m_c, κ fitted to the mass spectrum. [Y. Li, PLB'16&PRD '17]
- Access to a variety of observables:
  - Decay constant [Y. Li, PRD'17]
  - Radiative decay [Y. Li, PRD'22, M. Li, PRD '18]
  - PDFs/GPD [Xu PRD'23, Lan PRL'19, Adhikari PRC'18 & ' 21]
  - Diffractive production [Chen, PLB'17&PRC '18]
  - …





E1 Radiative transition

- Transition between charmonium states occurs by emission a photon



- The type of the radiative transition can be electric or magnetic depends on the dominating term in multipole expansion of the transition amplitude
  - Non-relativistic EM transition matrix element

$$\mathcal{A}_\lambda = -i\sqrt{\frac{\omega_\gamma}{2}}\langle J'\lambda'|h_e|J\lambda\rangle,$$

$$\mathcal{A}_\lambda^E = -i\sqrt{\frac{\omega_\gamma}{2}}\left\langle J'\lambda'\middle|\sum_j e_j\mathbf{r}_j\cdot\boldsymbol{\epsilon}e^{-i\mathbf{k}\cdot\mathbf{r}_j}\middle|J\lambda\right\rangle,$$

$$\mathcal{A}_\lambda^M = +i\sqrt{\frac{\omega_\gamma}{2}}\left\langle J'\lambda'\middle|\sum_j \frac{e_j}{2m_j}\boldsymbol{\sigma}_j\cdot(\boldsymbol{\epsilon}\times\hat{\mathbf{k}})e^{-i\mathbf{k}\cdot\mathbf{r}_j}\middle|J\lambda\right\rangle$$

  - Multipole contributions

$$\mathcal{A}_\lambda = \sum_l\left\{\frac{1+(-1)^{\pi_i\pi_f+l}}{2}\mathcal{A}_\lambda^{\mathrm{E}l} + \frac{1-(-1)^{\pi_i\pi_f+l}}{2}\mathcal{A}_\lambda^{\mathrm{M}l}\right\}.$$

[W. Deng PRD'17]

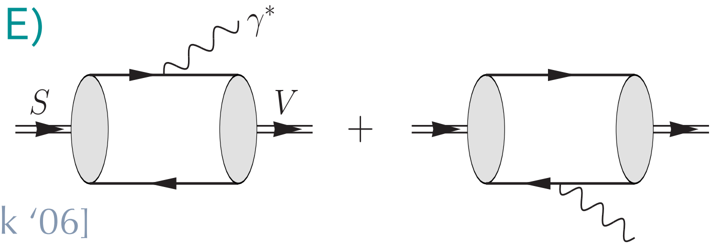
process	multipole contribution
$n^3S_1 \longleftrightarrow m^1S_0$	M1
$n^3P_J \longleftrightarrow m^3S_1$	E1, M2
$n^1P_1 \longleftrightarrow m^1S_0$	E1
$n^3D_J \longleftrightarrow m^3P_J$	E1, E3, M2, M4
$n^1D_1 \longleftrightarrow m^1P_1$	E1, E3
$n^3P_J \longleftrightarrow m^1P_1$	M1, M3

- Electric dipole (E1) transition (same spin, different orbital momentum)
  - Scalar meson $\chi_{c0}(1P), \chi_{c0}(2P)$, Vector meson $J/\psi(1S), \psi(2S), \psi(1D)$
  - Pseudovector $h_c(1P)$, Pseudoscalars: $\eta_c(1S), \eta_c(2S)$

E1 transition form factor

- Transition amplitude & current matrix element (CME)

$$\mathcal{M}_{\lambda_\gamma,\lambda'}(q^2) = e\mathcal{Q}_c\varepsilon^{\mu*}_{\lambda_\gamma}\langle V(p_V,\lambda')|J_\mu(0)|S(p_S)\rangle$$



- Lorentz (multipole) decomposition of CME [Dudek '06]

$$\begin{aligned}\langle V(p_V,\lambda')|J_\mu(0)|S(p_S)\rangle \\ &= \Omega^{-1}(q^2)\{E_1(q^2)[\Omega(q^2)e^{\mu*}_{\lambda'}(p_V) - (e^*_\lambda\cdot p_S)(p^\mu_V(p_S\cdot p_V) - m_V^2p^\mu_S)] \\ &\quad + C_1(q^2)\frac{m_V}{\sqrt{q^2}}(e^*_\lambda\cdot p_S)[(p_S\cdot p_V)(p_S+p_V)^\mu - m_S^2p^\mu_V - m_V^2p^\mu_S]\}\sim[m]^1,\end{aligned}$$

- Physical transition form factor $E_1(Q^2)$

$$\mathcal{M}_{\lambda_\gamma=\pm,\lambda'} = e\mathcal{Q}_cE_1(q^2)\delta_{\lambda_\gamma,-\lambda'}$$

- Decay width is related to $E_1(Q^2=0)$ by

$$\Gamma(i\to f\gamma) = \frac{Q_c^2\alpha_{em}}{2J_i+1}\frac{m_i^2-m_f^2}{2m_i^3}|E_1(0)|^2$$

Light front wave function representation

- In Drell-Yan frame ($q^+ = 0$), using J^+ component

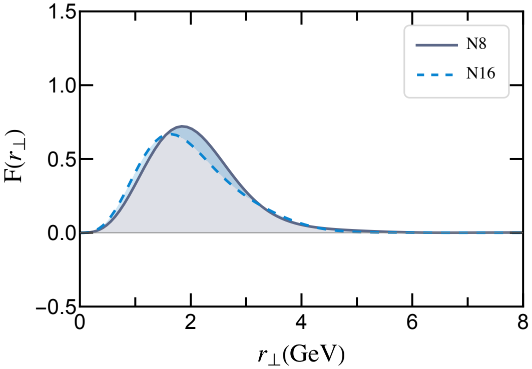
$$E_1(Q^2) = 4\sum_{s,\bar{s}}\int\frac{\mathrm{d}x}{2x(1-x)}\int\frac{\mathrm{d}^2k_\perp}{(2\pi)^3}\Big\{M_V\psi^{(\lambda=0)*}_{s\bar{s}/V}(x,\vec{k}_\perp)+ \frac{M_S^2-M_V^2+Q^2}{\sqrt{2}Q}\psi^{(\lambda=+1)*}_{s\bar{s}/V}(x,\vec{k}_\perp)\Big\}\psi_{s\bar{s}/S}\big(x,\vec{k}_\perp+(1-x)\vec{q}_\perp\big)$$

- At $Q^2 = 0$

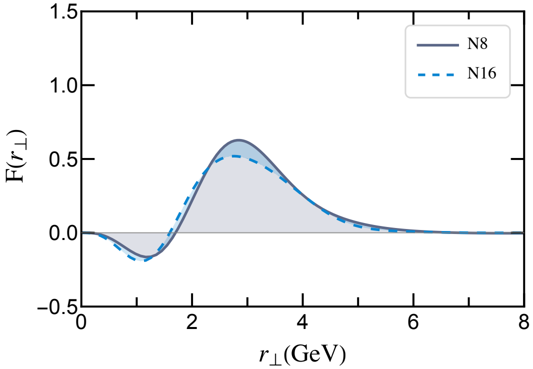
$$E_1(0) = -i\frac{M_S^2-M_V^2}{\sqrt{2}}\sum_{s,\bar{s}}\int_0^1\frac{\mathrm{d}x}{4\pi}\int\mathrm{d}^2\vec{r}_\perp\psi^{(\lambda=+1)*}_{s\bar{s}/V}(x,\vec{r}_\perp)(r_x+ir_y)\psi_{s\bar{s}/S}(x,\vec{r}_\perp)$$

$\mathrm{E}_1(0)$ is the overlap of LFWFs multiplied by a dipole in coordinate space, consistent with the nonrelativistic representation.

a) $\chi_{c0}(1P)\to J/\psi(1S)+\gamma$

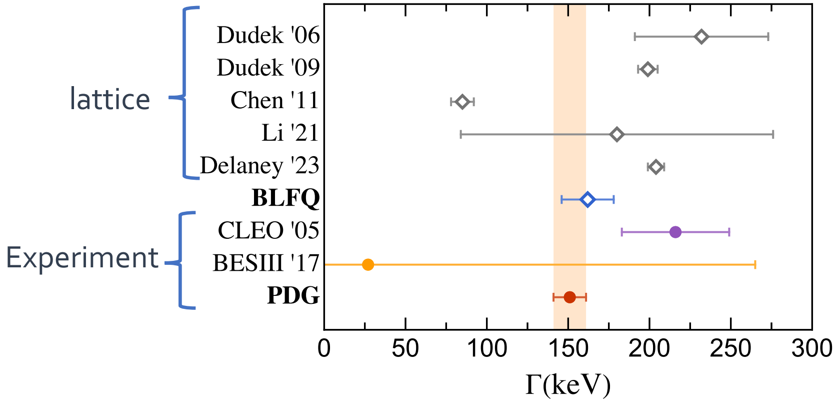


$b)$ $\psi(2S)\to\chi_{c0}+\gamma$

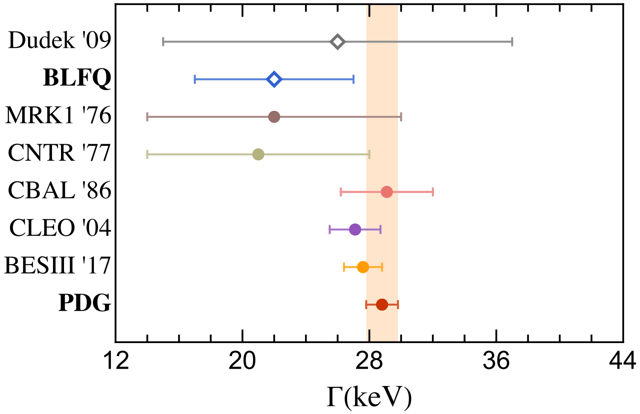


E1 radiative decay widths

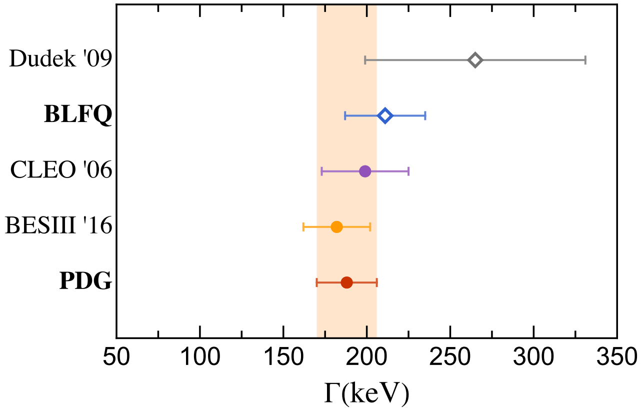
a) $\chi_{c0}(1P) \rightarrow J/\psi(1S) + \gamma$



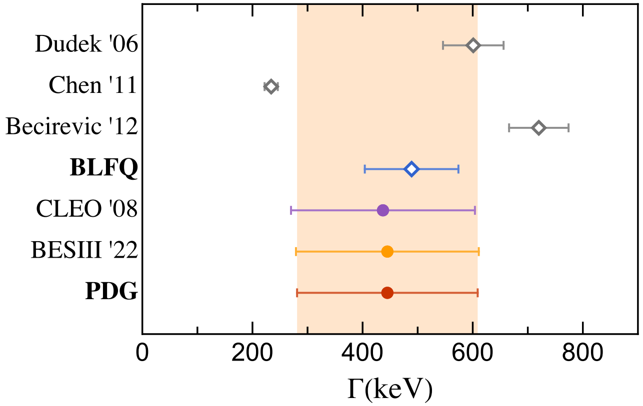
b) $\psi(2S) \rightarrow \chi_{c0} + \gamma$



c) $\psi(1D) \rightarrow \chi_{c0} + \gamma$



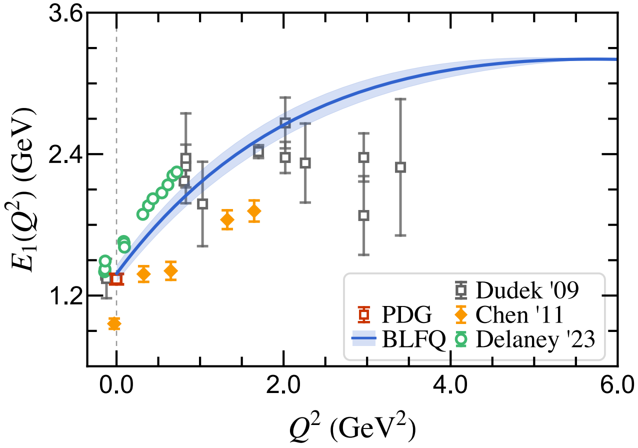
d) $h_c(1P) \rightarrow \eta_c(1S) + \gamma$



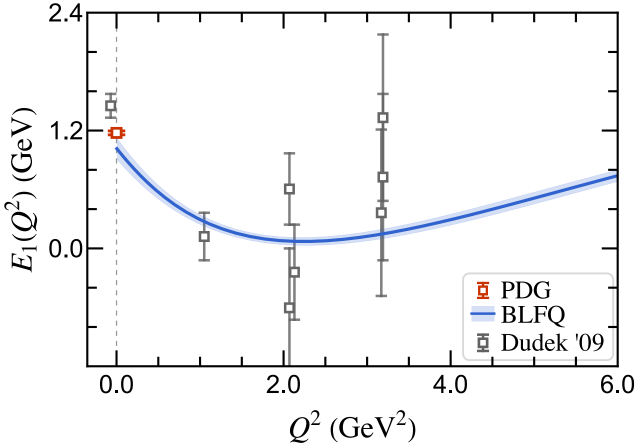
- Good agreement with experiments and Lattice.

Transition form factors $E_1(Q^2)$

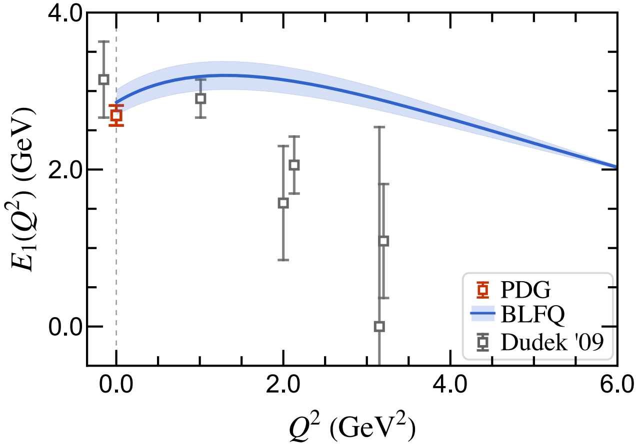
a) $\chi_{c0} \to J/\psi + \gamma$



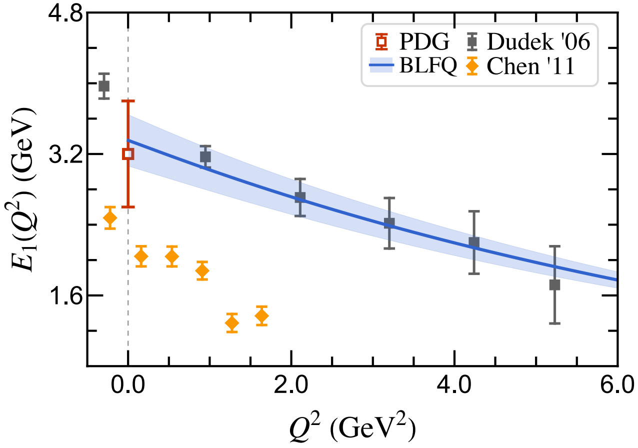
b) $\psi(2S) \to \chi_{c0} + \gamma$



c) $\psi(3770) \to \chi_{c0} + \gamma$



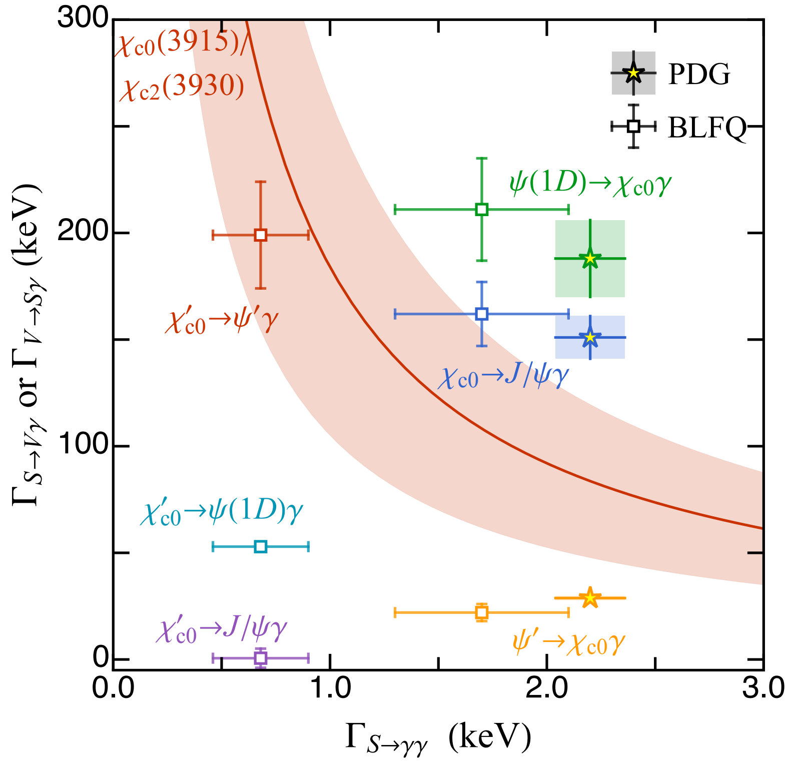
d) $h_c(1P) \to \eta_c(1S) + \gamma$



Good agreement with Lattice, especially at small Q^2 region.

$\chi_{c0}(3915)$

- $\chi_{c0}(3915)$ discovered by Belle in 2005, is one of the prime 2P candidates
- Last year, Belle measured the product of its E1 width and diphoton width [Wang PRD '22]
- Our BLFQ prediction for the 2P $c\bar{c}$ state is consistent with the Belle measurement
- More measurements are needed



Radiative decay of charmonium

Along with other parameter free predictions

		Leptonic Decay	Diphoton Decay	Radiative transitions							
decay width (keV)		Γ_{ee}	$\Gamma_{\gamma\gamma}$	$\Gamma_{\eta_c\gamma}$	$\Gamma_{J/\psi\gamma}$	$\Gamma_{\chi_{c0}\gamma}$	$\Gamma_{\chi_{c1}\gamma}$	$\Gamma_{h_c\gamma}$	$\Gamma_{\chi_{c2}\gamma}$	$\Gamma_{\eta_c'\gamma}$	$\Gamma_{\psi'\gamma}$
η_c	PDG	-	5.15(35)								
	BLFQ	-	3.7(6)								
J/ψ	PDG	5.53(10)	-	1.6(4)							
	BLFQ	5.7(1.9)	-	2.6(1)							
χ_{c0}	PDG	-	2.1(1.6)	-	151(10)						
	BLFQ	-	1.9(4)	-	162(16)						
χ_{c1}	PDG	-	-	-	288(16)	-					
	BLFQ	-	-	-	in progress	-					
h_c	PDG	-	-	445(164)	-						
	BLFQ	-	-	489(85)		in progress	in progress				
χ_{c2}	PDG	-	0.56(5)	-	374(20)	-	-				
	BLFQ	-	0.021(4)	-	in progress	-	-	in progress			
η_c'	PDG	-	2.1(1.6)	-	<195	-	-		-		
	BLFQ	-	1.9(4)	-	0.5(6)	-	-	26.4(1.1)	-		
ψ'	PDG	2.33(81)	-	1.00(16)	-	28.8(1.0)	28.7(1.1)	-	28(1)	0.23(17)	
	BLFQ	2.7(1.3)	-	13(5)	-	22(5)	in progress	-	in progress	0.148(13)	
$\psi(1D)$	PDG	0.261(21)	-	<19	-	188(18)	80(7)	-	<17	<24.9	-
	BLFQ	0.051(19)	-	0.164(19)	-	211(24)	in progress	-	in progress	0.011(4)	-

🟩 M1

🟥 E1

Summary

- We computed E1 transition width of charmonium with basis light front quantization approach
- The obtained results are in good agreements with the experimental measurements as well as lattice results whenever available
- Our results are consistent with recent Belle measurement for $\chi_{c0}(3915)$ and can be used to discern the structure of this particle when further experimental data are available

Thank you!