Two-photon transitions of charmonia on the light front

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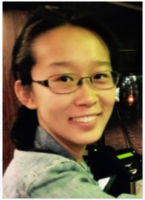
Outline

- Physics of two-photon transition of charmonium
- Light front dynamics and basis light-front quantization
- Numerical results: two-photon width and transition form factors
- Summary

Based on: YL, M. Li and J.P. Vary, arXiv:2111.14178 [hep-ph]
Nov. 28, 2021

In collaboration with:

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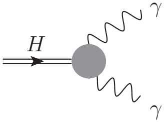
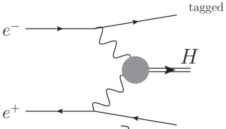
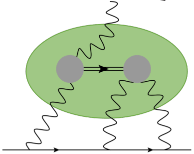
Two-photon physics

The two-photon to hadron transition amplitude $\mathcal{M}_{\gamma\gamma H}$ is associated with several important processes:

- Diphoton decay of quarkonia $H \to \gamma + \gamma$
  - *Selection rules: parity, charge conjugation, gauge symmetry, angular momentum conservation, ... (Landau-Yang theorem)*
  - *Hadron identification & hadron structure, diphoton width* $\Gamma_{\gamma\gamma}$
- Photoproduction $\gamma + \gamma \to H$, $\gamma \to H + \gamma$
  - *Resonances, exotica, ...*
  - *Exclusive photoproduction, hadroproduction via photon/gluon fusion*
- Experimental access:
  - e^+e^- *machines: BES, BELLE, BABAR, ... , (rich history)*
  - eA *&* AA *colliders: HERA, EIC, RHIC, LHCb, ...*
  - *Indirectly, high-precision QED measurements: HLbL in* g*-2*
- Theoretical approaches
  - *Lattice, NRQCD, Sum rules,* χ*PT, DSE/BSE, ...*







Reviews: Berger '87; Poppe '86; Lansberg '19; Hoferichter '20; Book: *The physics of the B factories* (2014)

Two-photon transitions of charmonia

Charmonium: ``a golden system to study strong interactions'' [Brambilla '14]

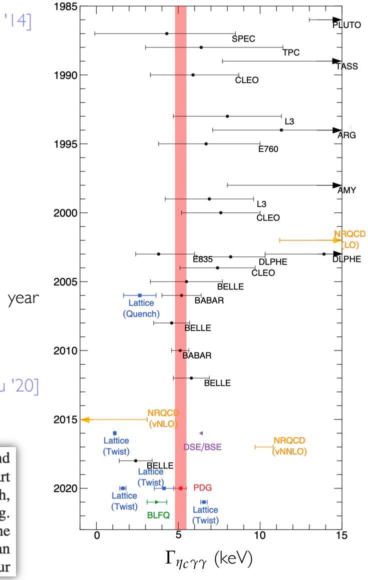
- Multi-scale: $\Lambda_{\text{QCD}} \lesssim \alpha_s^2 m_c < \alpha_s m_c < m_c$ where $\alpha_s \sim (0.3 - 0.6)$; Interplay between perturbative and nonperturbative dynamics
- Nonrelativistic system with considerable relativistic corrections $v_c^2 \sim 0.3$

Experimental measurements [Review of particle physics 2020]

- Diphoton width: extensive measurements for $\eta_c, \eta_c', \chi_{c0}, \chi_{c2}$;
- Transition form factors: $F_{\eta_c\gamma}(Q^2)$ by BABAR 2010; $F_{\chi_{c0}\gamma}(Q^2)$ by Belle 2017 with limited statistics

Theoretical predictions

- NRQCD: a ``crisis'' to describe charmonia? [Feng '15&'17]
- Lattice QCD: challenging to represent virtual photons on the Lattice [Liu '20]
- Potential model: large relativistic corrections [Babiarz '19]



PRL 115, 222001 (2015) PHYSICAL REVIEW LETTERS week ending 27 NOVEMBER 2015

Can Nonrelativistic QCD Explain the $\gamma\gamma^* \to \eta_c$ Transition Form Factor Data?

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

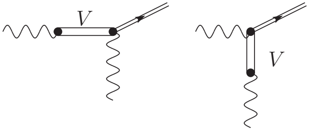
Next-to-Next-to-Leading-Order QCD Corrections to the Hadronic Width of Pseudoscalar Quarkonium

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

widths and the branching fractions for $\eta_{c,b} \to \gamma\gamma$. We find that severe tension arises between our state-of-the-art NRQCD predictions and the measured η_c hadronic width, and the tension in $\text{Br}(\eta_c \to \gamma\gamma)$ is particularly 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

Light-cone dominance

Physical understandings of the two-photon transition process [Berger '87]



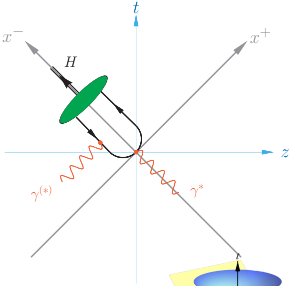
- Low Q^2:
  - *Light mesons: vector meson dominance (VMD)* [Sakurai '63, Novikov '78]
  - *Heavy flavors: nonrelativistic potential model (``wave function at origin'')*

$$i\mathcal{M} \sim \frac{1}{Q^2 + M_H^2}\psi(\vec{r}=0)$$

- Large Q^2: light-cone dominance [Lepage '80 & Chernyak '84]

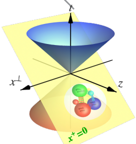
$$i\mathcal{M}^{\mu\nu} = \int \mathrm{d}^4x e^{iq\cdot z}\langle 0|J^\mu(z)J^\nu(0)|P\rangle \sim \int \mathrm{d}x\, T_H(x,Q^2)\underbrace{\phi_P(x;\mu)}_{\text{light-cone distribution amplitude}}$$

Large-Q^2 limit: $z^2 \sim 1/Q^2 \to 0$ (the light cone) [Gribov '83, Nandi '07 & Li '09]



- Extension to finite Q^2: allow contributions off the light cone $\to$ light front

$$i\mathcal{M}^{\mu\nu} \sim \int_0^1 \mathrm{d}x \int \frac{\mathrm{d}^2k_\perp}{16\pi^3} T_H(x,\vec{k}_\perp;Q^2)\underbrace{\psi_P(x,\vec{k}_\perp;\mu)}_{\text{light-front wave function}}$$



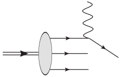
N.B. Brodsky-Lepage's collinear factorization goes beyond the naïve α_s expansion.

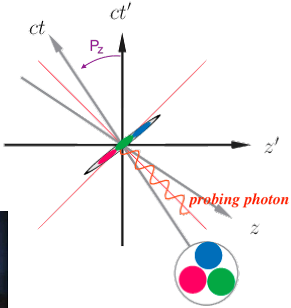
Physics on the light front

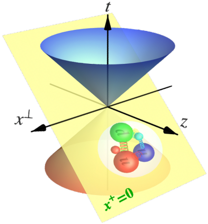
[Reviews: Brodsky '98, Burkardt '02, Bakker '14, Ji '21]

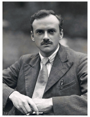
infinite momentum frame ($P_z \to \infty$)

light front quantization ($x^+ = 0$)



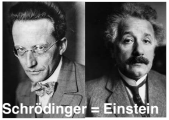






$$x^\pm = x^0 \pm x^3$$
$$P^\pm = P^0 \pm P^3$$
$$\underline{\mathcal{M}}^2 = P^+\underline{P}^- - \vec{P}_\perp^2$$

$$i\frac{\partial}{\partial x^+}|\psi(x^+)\rangle = \frac{1}{2}\underline{P}^-|\psi(x^+)\rangle$$
$$\Downarrow$$
$$\underline{\mathcal{M}}^2|\psi_h(P,j,m_j)\rangle = M_h^2|\psi_h(P,j,m_j)\rangle$$



Light-front wave functions (LFWFs) [Reviews: Brodsky '98, Diehl '03, Lorcé '11]

- LFWFs are frame independent

  Boosts & J_z are kinematical - maximal kinematical subgroup

  (partial) cluster decomposition (cf. FSDR & RGPEP)

- Direct access to hadronic observables

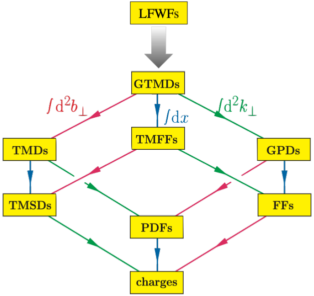
  OPE, PDFs (DAs, GPDs & TMDs) defined on the light front.

- Vacuum fluctuations are suppressed

  Indeed, hadronic densities can only be consistently defined on the light front.

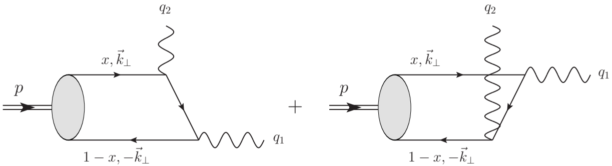
Hadron Physics without LFWFs is like Biology without DNA!

--- Stanley J. Brodsky



Adapted from C. Lorcé

LFWF representation of two-photon transitions



- The amplitude can be accessed in light-cone perturbation theory and also through hadronic matrix elements, [Lepage '80, Feldmann '97, Kroll '10, Babiarz '19]

$$\varepsilon^*_\mu(q_1,\lambda_1)\varepsilon^*_\nu(q_2,\lambda_2)e_\alpha(p,\lambda)\mathcal{M}^{\mu\nu\alpha} = \varepsilon^*_\nu(q_2,\lambda_2)\langle\gamma^*(q_1,\lambda_1)|J^\nu(0)|H(p,\lambda)\rangle.$$

It is convenient to adopt a frame in which $q_1^- = q_2^+ = 0$, i.e. with manifest light-cone dominance.

- Example: LFWF representation of a pseudoscalar meson (0^{-+}),

$$F_{P\gamma}(Q^2) = e_f^2 2\sqrt{2N_C}\int\frac{\mathrm{d}x}{2\sqrt{x(1-x)}}\int\frac{\mathrm{d}^2k_\perp}{(2\pi)^3}\frac{\psi^*_{\uparrow\downarrow-\downarrow\uparrow/P}(x,\vec{k}_\perp)}{k_\perp^2+m_f^2+x(1-x)Q^2}+\cdots$$

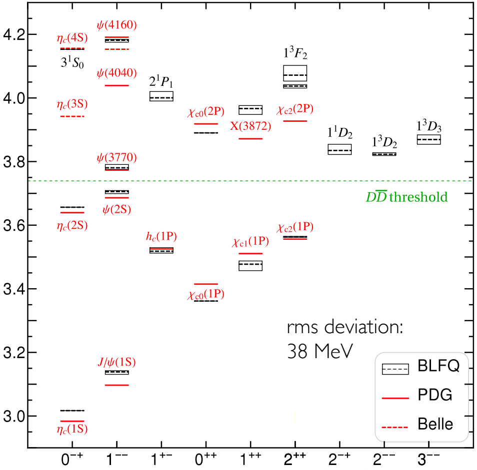
Intuitively, this is the overlap of the photon wave function with the meson wave function. [Beuf '16, Lappi '20]

Basis light-front quantization

[Vary et al. PRC '09; YL, Maris, Zhao, Vary, PLB '16]

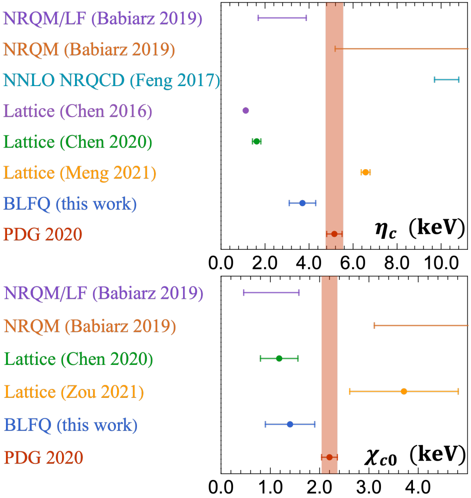
$$H_{\text{eff}} = \underbrace{\frac{\vec{k}_\perp^2 + m_c^2}{x(1-x)}}_{\text{LF kinetic energy}} + \underbrace{\kappa^4 \zeta_\perp^2 - \frac{\kappa^4}{4m_c^2}\partial_x\left[x(1-x)\partial_x\right]}_{\text{confinement}} - \underbrace{\frac{C_F 4\pi\alpha_s(Q^2)}{Q^2}\bar{u}_{s'}(k')\gamma_\mu u_s(k)\bar{v}_{\bar{s}}(\bar{k})\gamma^\mu v_{\bar{s}'}(\bar{k}')}_{\text{one-gluon exchange}}$$

- Holographic light-front QCD confinement plus a longitudinal confinement [Review: Brodsky '14]
- Solved in basis function approach, $\Lambda_{\text{UV}} \approx b\sqrt{N_{\max}}$.
- Two free parameters m_c, κ fitted to the mass spectrum. Posterior rms deviation: $\lesssim$ 40 MeV
- Application to a variety of systems:
  - $c\bar{c}, b\bar{b}$: YL, PLB '16 & PRD '17
  - $b\bar{c}, b\bar{q}, c\bar{q}$: Tang, PRD '18 & EPJC '20
  - $q\bar{q}$: Jia, PRC '19; Qian, PRC '20; YL, '21
  - Baryons: Mondal, PRD '20; Xu, '21; Shuryak, PRD '21
- Access to a variety of observables
  - Form factors: YL, PRD '18; Mondal, PRD '20
  - (Semi-)leptonic decay: Li, PRD '18 & '19; Tang, PRD '21
  - PDFs/GPDs: Lan, PRL '19 & PRD '20; Adhikari, PRC '18 & '21
  - Diffractive production: Chen, PLB '17 & PRC '18

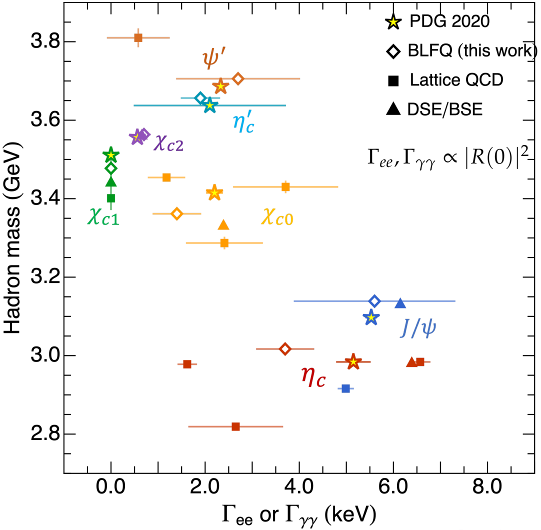


Numerical results: diphoton widths

Our results are extremely competitive!



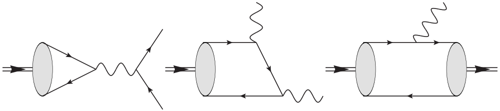
[Lattice: Dudek '06, Chen '16, Chen '20, Meng '21, Zou '21; DSE: Chen '16]



Radiative transitions

Leptonic and radiative transitions probe the fundamental structure of the hadrons:

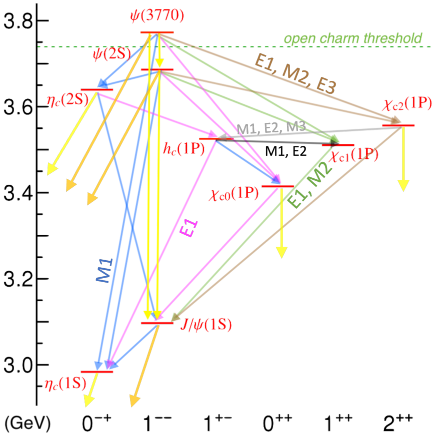
[Review: Barnes & Yuan, Int. J. Mod. Phys. A 2009]



decay width (keV)		Γ_{ee}	$\Gamma_{\gamma\gamma}$	$\Gamma_{\eta_c\gamma}$	$\Gamma_{J/\psi\gamma}$
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)	-	$15(1)\times10^3$
	BLFQ	-	1.9(4)	-	in progress
χ_{c1}	PDG	-	-	-	288(16)
	BLFQ	-	-	-	in progress
⋮					

[YL, PRD '17; Li, PRD '18; Chen, in progress]

[PDG, PTEP '20 + '21(update)]

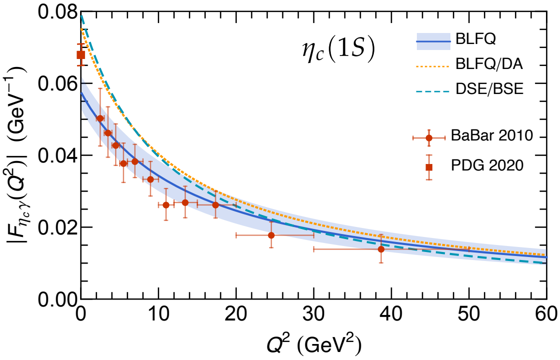


Transition form factor: η_c

$$\mathcal{M}^{\mu\nu} = 4\pi\alpha_{\rm em}\varepsilon^{\mu\nu\rho\sigma}q_{1\rho}q_{2\sigma}F_{P\gamma\gamma}(q_1^2,q_2^2), \quad F_{P\gamma}(Q^2) \equiv F_{P\gamma\gamma}(Q^2,0) = F_{P\gamma\gamma}(0,Q^2)$$

Diphoton width: $\Gamma_{\gamma\gamma} = \frac{\pi}{4}\alpha_{\rm em}^2 M_P^3 \big|F_{P\gamma\gamma}(0,0)\big|^2$. [Lepage '81, Babiarz '19, Hoferichter '20]

$$F_{P\gamma}(Q^2) = e_f^2 2\sqrt{2N_C}\int\frac{{\rm d}x}{2\sqrt{x(1-x)}}\int\frac{{\rm d}^2k_\perp}{(2\pi)^3}\frac{\psi^*_{\uparrow\downarrow-\downarrow\uparrow/P}(x,\vec{k}_\perp)}{k_\perp^2+m_f^2+x(1-x)Q^2}$$



- BABAR data: $F_{\eta_c\gamma} \propto 1/(Q^2+\Lambda^2)$, where the pole mass $\Lambda^2 = 8.5 \pm 0.6 \pm 0.7\,{\rm GeV}^2$; width $\Gamma_{\gamma\gamma} = 5.12(53)\,{\rm keV}$.
- BLFQ: using $N_{\max} = 8$, corresponding to $\mu \approx 2m_c$. Basis sensitivity band is taken as the difference between the $N_{\max} = 8, 16$ results.
- BLFQ/DA: prediction using the LCDA obtained first from the LFWF
- Theoretical prediction in good agreement with both the width and the form factor.

[DSE/BSE: Chen, PRD '17]

Transition form factor: η_c

$$\mathcal{M}^{\mu\nu} = 4\pi\alpha_{\rm em}\varepsilon^{\mu\nu\rho\sigma}q_{1\rho}q_{2\sigma}F_{P\gamma\gamma}(q_1^2,q_2^2), \quad F_{P\gamma}(Q^2) \equiv F_{P\gamma\gamma}(Q^2,0) = F_{P\gamma\gamma}(0,Q^2)$$

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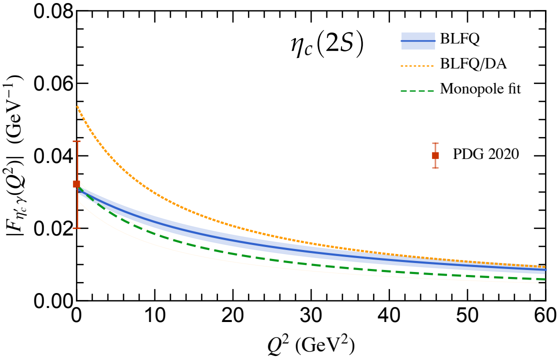


- No experimental measurement yet.
- A monopole fit using $\Lambda^2 = M_{\psi'}^2$ is included for comparison.
- Note that a VMD prediction requires the off-shell coupling $g_V(Q^2) = V_{PV\gamma}(Q^2)$: [Lakhina '06]

$$F_{P\gamma}^{(\rm VMD)}(Q^2) = \sum_V \frac{e_f^2 f_V}{1+\frac{M_P}{M_V}}\left[\frac{g_V(0)}{M_V^2+Q^2}+\frac{g_V(Q^2)}{M_V^2}\right]$$

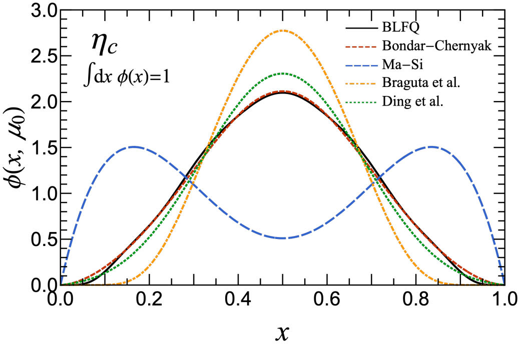
Light cone distribution amplitude (LCDA)

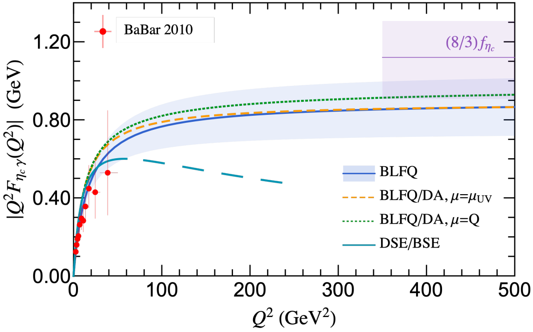
At large-Q^2, viz. $Q^2 + \langle m_f^2/x(1-x)\rangle \gg \langle k_\perp^2/x(1-x)\rangle$,

$$F_{P\gamma}(Q^2) \approx e_f^2 f_P \int_0^1 \mathrm{d}x \frac{\phi_P(x,\mu)}{x(1-x)Q^2 + m_f^2} \xrightarrow{Q\to\infty} \frac{6e_f^2 f_P}{Q^2}.$$

- LCDA plays a pivotal role in hard exclusive charmonium production. [See, e.g., Braguta '12]
- Our LCDA agrees with the Bondar-Chernyak model. Both fit the BABAR normalized TFF well.

[LCDAs: Ma '04, Bondar '05, Braguta '07, Ding '16]



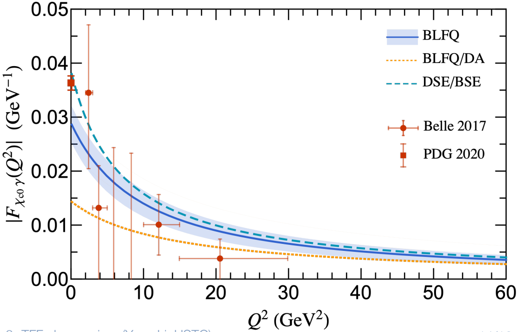


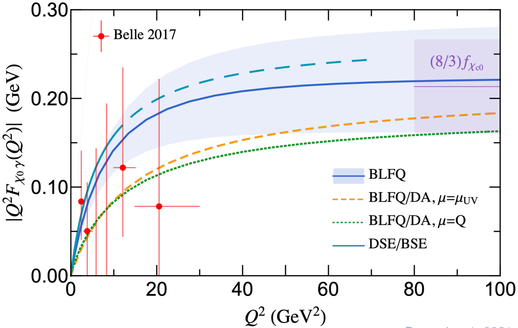
Transition form factor: χ_{c0}

[Babiarz '20, Hoferichter '20; DSE/BSE: Chen '17]

$$\mathcal{M}^{\mu\nu} = 4\pi\alpha_{\rm em}\Big\{\big[(q_1\cdot q_2)g^{\mu\nu} - q_2^\mu q_1^\nu\big]F_1^S(q_1^2,q_2^2) + \frac{1}{M_S^2}\big[q_1^2q_2^2g^{\mu\nu} + (q_1\cdot q_2)q_1^\mu q_2^\nu - q_1^2 q_2^\mu q_2^\nu - q_2^2 q_1^\mu q_1^\nu\big]F_2^S(q_1^2,q_2^2)\Big\}$$

Single-tag TFF: $F_{S\gamma}(q^2) = F_1^S(q^2,0) = F_1^S(0,q^2)$. Width $\Gamma_{\gamma\gamma} = \frac{\pi\alpha_{\rm em}^2}{4}M_S^3|F_{S\gamma}(0)|^2$. Belle provides the first measurement of the TFF, albeit with limited statistics. [Belle, PRD 2017]



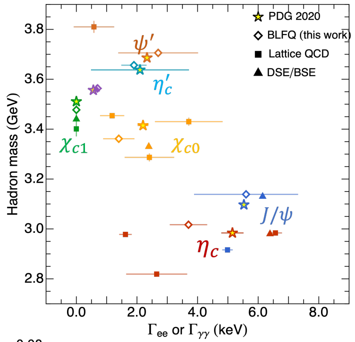


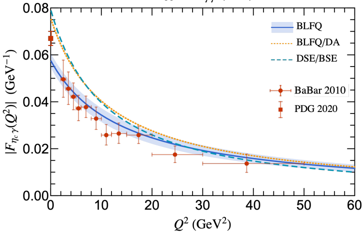
Summary

- Light-front Hamiltonian formalism provides unique tools to access the hadronic observables
  - Light-cone dominance
  - Collinear factorization and k_T factorization
- We computed the two-photon width and transition form factors of charmonia within the basis light-front quantization approach.
  - Excellent agreements with the available experimental measurements.
  - No parameters are dialed to obtain these results.
  - Reveal relativistic nature of charmonium system
- The obtained wave functions await further experimental measurements and further applications.

Based on: YL, Meijian Li, J.P. Vary, arXiv:2111.14178 [hep-ph].

LFWFs available on Mendeley Data & arXiv (visualizations)





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Thank you for your attention.