J/Ψ radiative transitions to η_c

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based on

Nora Brambilla, Yu Jia and Antonio Vairo
Model-independent study of magnetic dipole transitions in quarkonium
PRD 73 054005 (2006) [arXiv:hep-ph/0512369]

*Nora Brambilla, Pablo **Roig** and Antonio Vairo*
(Work in progress)

Outline

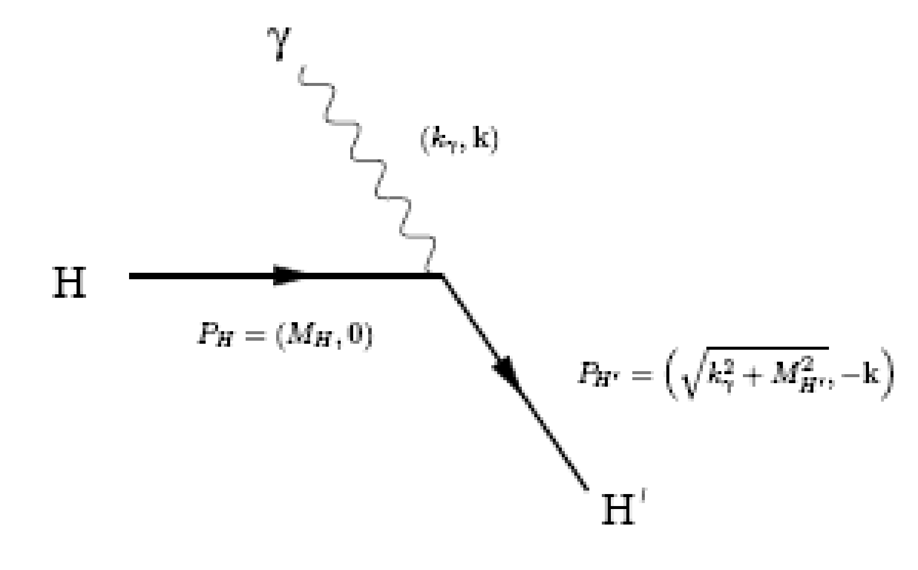
- Radiative transitions: Basics
- Experimental data on $J/\Psi \to \gamma\ \eta_c$
- EFT framework: pNRQCD
- Lineshape in $J/\Psi \to \gamma\ \eta_c$ using pNRQCD
- Conclusions and Outlook

Radiative transitions: Basics

Two dominant singe-photon transition processes:

i) Electric dipole transitions (E1)

ii) Magnetic dipole transitions (M1)



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In the non-relativistic limit

$$\Gamma_{n^3S_1\to n'^1S_0\gamma} = \frac{4}{3}\,\alpha\, e_Q^2\,\frac{k_\gamma^3}{m^2}\left|\int_0^\infty dr\, r^2\, R_{n'0}(r)\, R_{n0}(r)\, j_0\left(\frac{k_\gamma r}{2}\right)\right|^2$$

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If k_γ<r> << 1 $\longrightarrow$ $j_0(k_\gamma r/2) = 1 - (k_\gamma r)^2/24 + \ldots$

- n = n' Allowed transitions
- n ≠ n' Hindered transitions

Experimental data on $J/\Psi \to \gamma\, \eta_c$

Only one direct experimental measurement existed for long time:

$\Gamma(\mathbf{J/\Psi \to \gamma \eta_c}) = (1.14 \pm 0.23)$ keV *(Crystal Ball '86)*

There were also several measurements of the $BR(\mathbf{J/\Psi \to \gamma \eta_c \to \gamma \phi\, \phi})$

and one independent measurement of $BR(\mathbf{\eta_c \to \phi\, \phi})$ *(Belle '03)*

From them, one obtained $\Gamma(\mathbf{J/\Psi \to \gamma \eta_c}) = (2.9 \pm 1.5)$ keV

Recently, CLEO found $\Gamma(\mathbf{J/\Psi \to \gamma \eta_c}) = (1.85 \pm 0.08 \pm 0.28)$ keV *(CLEO '08)*

The combination of these independent measurements leads to $\Gamma(\mathbf{J/\Psi \to \gamma \eta_c}) = (1.44 \pm 0.18)$ keV with a 13% error

m_{η_c} = 2977.3 $\pm$ 1.3 MeV from $\Gamma(\mathbf{J/\Psi, \Psi(2S) \to \gamma \eta_c})$ vs.

m_{η_c} = 2982.6 $\pm$ 1.0 MeV from $\gamma\gamma$ or $p\bar{p}$ production

EFT framework: pNRQCD

- The LO NR expressions for the M1 transitions do not account well enough for the data.
- So one needs to supplement them with higher order corrections.
- EFT provide a systematic and controlled way of doing that.
- In the case of Quarkonia they are NRQCD (Caswell, Lepage '86) (Bodwin, Braaten and Lepage '95), pNRQCD (Pineda, Soto '97) (Brambilla, Pineda, Soto, Vairo '99) that exploit the hierarchy of scales the problem has.

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$p \sim 1/r \sim Mv$

$E \sim Mv^2$

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k_γ

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pNRQCD already introduced by Antonio

EFT framework: pNRQCD

$$\mathcal{L}_{\gamma\,\mathrm{pNRQCD}} = \int d^3r\ \mathrm{Tr}\left\{ V_A^{\mathrm{em}}\,\mathrm{S}^\dagger \mathbf{r}\cdot ee_Q\mathbf{E}^{\mathrm{em}}\mathrm{S} \right.$$
$$+\frac{1}{2m}\,V_S^{\frac{\sigma\cdot B}{m}}\ \left\{\mathrm{S}^\dagger,\boldsymbol{\sigma}\cdot ee_Q\mathbf{B}^{\mathrm{em}}\right\}\mathrm{S}$$
$$+\frac{1}{16m}\,V_S^{(r\cdot\nabla)^2\frac{\sigma\cdot B}{m}}\ \left\{\mathrm{S}^\dagger,\mathrm{r}^i\mathrm{r}^j(\boldsymbol{\nabla}^i\boldsymbol{\nabla}^j\boldsymbol{\sigma}\cdot ee_Q\mathbf{B}^{\mathrm{em}})\right\}\mathrm{S}$$
$$+\frac{1}{2m}\,V_O^{\frac{\sigma\cdot B}{m}}\ \left\{\mathrm{O}^\dagger,\boldsymbol{\sigma}\cdot ee_Q\mathbf{B}^{\mathrm{em}}\right\}\mathrm{O}$$
$$+\frac{1}{4m^2}\,\frac{V_S^{\frac{\sigma\cdot(r\times r\times B)}{m^2}}}{r}\ \left\{\mathrm{S}^\dagger,\boldsymbol{\sigma}\cdot[\hat{\mathbf{r}}\times(\hat{\mathbf{r}}\times ee_Q\mathbf{B}^{\mathrm{em}})]\right\}\mathrm{S}$$
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$$-\frac{1}{16m^2}\,V_S^{\frac{\sigma\cdot\nabla_r\times r\cdot\nabla E}{m^2}}\ \left[\mathrm{S}^\dagger,\boldsymbol{\sigma}\cdot\left[-i\boldsymbol{\nabla}_r\times,\mathrm{r}^i(\boldsymbol{\nabla}^i ee_Q\mathbf{E}^{\mathrm{em}})\right]\right]\mathrm{S}$$
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$$\left.+\frac{1}{4m^3}\,V_S^{\frac{(\nabla_r\cdot\sigma)\,(\nabla_r\cdot B)}{m^3}}\ \left\{\mathrm{S}^\dagger,\boldsymbol{\sigma}^i\,ee_Q\mathbf{B}^{\mathrm{em}\,j}\right\}\boldsymbol{\nabla}_r^i\boldsymbol{\nabla}_r^j\mathrm{S}\right\}.$$

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E1 at $O(1)$

M1 at $O(1)$

The matching procedure gives the coefficients V that appear at a given order in the v expansion

For the **M1** potential (≡V_1):

V_1=(hard)x(soft)

(hard)=$c_F^{em}=1+2\alpha_s(m_c)/3\pi+\ldots$

(soft) = 1

No large quarkonium anomalous magnetic moment

EFT framework: pNRQCD

M1 at $\mathcal{O}(v^2)$

$$\frac{1}{4m^2}\frac{V_S^{\frac{\sigma\cdot(r\times r\times B)}{m^2}}}{r}\left\{S^\dagger,\boldsymbol{\sigma}\cdot\left[\hat{\mathrm{r}}\times(\hat{\mathrm{r}}\times ee_Q\mathrm{B}^{\mathrm{em}})\right]\right\}S \qquad \frac{1}{4m^2}\frac{V_S^{\frac{\sigma\cdot B}{m^2}}}{r}\left\{S^\dagger,\boldsymbol{\sigma}\cdot ee_Q\mathrm{B}^{\mathrm{em}}\right\}S$$

To all orders: (hard) = $2\,c_F - c_S = 1$; (soft) = $r^2\,V_s'/2$

(due to reparametrization/Poincaré invariance) (Brambilla, Gromes, Vairo '03)

EFT framework: pNRQCD

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$$V_2 = r^2 V_s'/2$$
$$V_3 = 0$$ (No scalar interaction)

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(hard) = 1 (due to reparametrization invariance) (Manohar '97)

$V_4 = 1 + \mathcal{O}(\alpha_S$ soft contributions$)$

Lineshape in $J/\Psi \to \gamma\ \eta_c$ using pNRQCD

$$\Gamma_{J/\Psi\to\eta_c\gamma} = \int \frac{\mathrm{d}^3k}{(2\pi)^3}(2\pi)\,\delta\left(E_p^{J/\Psi} - k - E_k^{\eta_c}\right)|\langle\gamma(k)\eta_c|\mathcal{L}_\gamma|J/\Psi\rangle|^2$$

Up to $\mathcal{O}(v^2)$ this transition is completely accesible to perturbation theory

$$\Gamma_{J/\psi\to\eta_c\gamma} = \frac{16}{3}\alpha e_c^2 \frac{k_\gamma^3}{M_{J/\psi}^2}\left[1 + C_F\frac{\alpha_s(M_{J/\psi}/2)}{\pi} + \frac{2}{3}\frac{\langle 1S|3V_S^{(0)} - rV_S^{(0)\prime}|1S\rangle}{M_{J/\psi}}\right]$$
$$= \frac{16}{3}\alpha e_c^2 \frac{k_\gamma^3}{M_{J/\psi}^2}\left[1 + C_F\frac{\alpha_s(M_{J/\psi}/2)}{\pi} - \frac{2}{3}(C_F\alpha_s(p_{J/\psi}))^2\right],$$

The normalization scale for α_s is the charm quark mass (in the contribution inherited from the quark magnetic moment) and the typical momentum transfer (for that one coming from the Coulomb potential).

$\alpha_s(M_{J/\psi}/2) \approx 0.35$ $\quad p_{J/\psi} \approx mC_F\alpha_s(p_{J/\psi})/2 \approx 0.8\ \mathrm{GeV}$

Lineshape in J/Ψ→γ η_c using pNRQCD

$$\Gamma_{J/\psi\to\gamma\eta_c} = \frac{16}{3}\alpha e_c^2 \frac{k_\gamma^3}{M_{J/\Psi}^2}\left(1 + \frac{4}{3}\frac{\alpha_s(M_{J/\Psi}/2)}{\pi} - \frac{2}{3}\frac{\langle 1|rV_s'|1\rangle}{M_{J/\Psi}} + 2\frac{\langle 1|V_s|1\rangle}{M_{J/\Psi}}\right)$$

- If $V_s = -\frac{4}{3}\frac{\alpha_s(\mu)}{r}$: $-\frac{2}{3}\frac{\langle 1|rV_s'|1\rangle}{M_{J/\Psi}} + 2\frac{\langle 1|V_s|1\rangle}{M_{J/\Psi}} = -\frac{32}{27}\alpha_s(\mu)^2 < 0$
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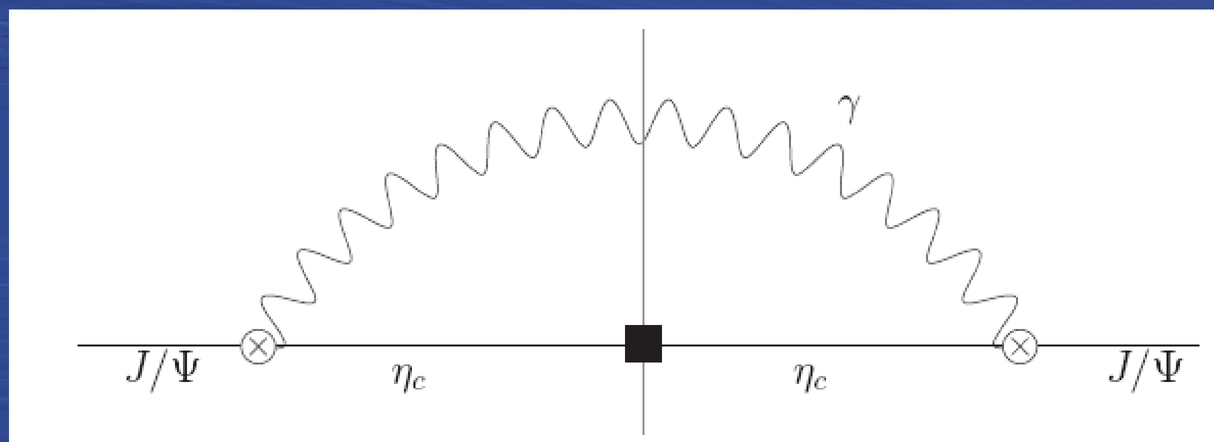
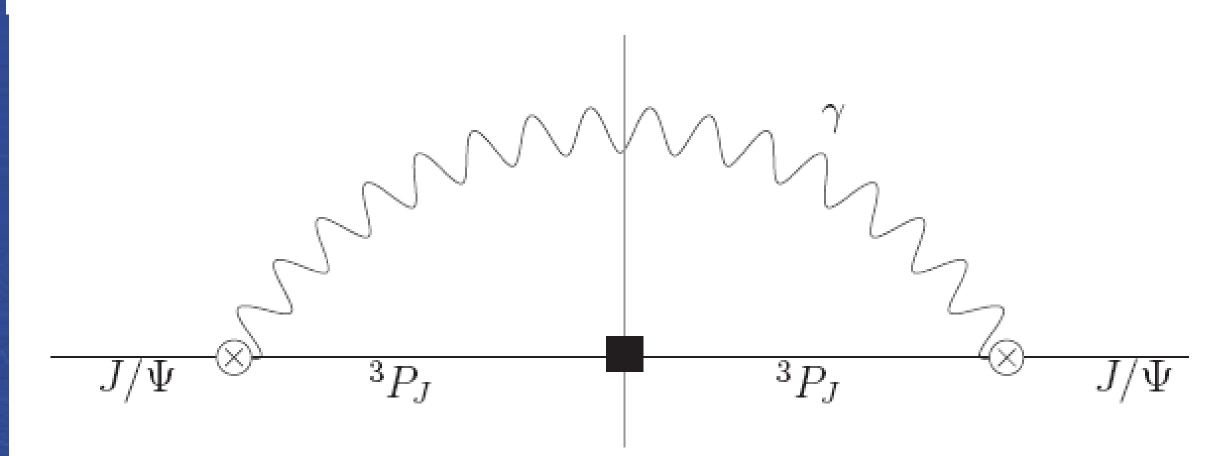
M1



E1



Lineshape in $J/\Psi \to \gamma\ \eta_c$ using pNRQCD

$$\frac{d\Gamma^{\rm mag}_{J/\Psi\to\eta_c\gamma}}{dk_\gamma} = \frac{4}{3}\frac{c_F^{em\,2}\alpha e_Q^2}{m^2}\frac{k_\gamma^3}{\pi}\frac{\frac{\Gamma_{\eta_c}}{2}}{\left(E_{J/\Psi}-k_\gamma-E_{\eta_c}\right)^2+\frac{\Gamma^2_{\eta_c}}{4}}$$

$$\frac{d\Gamma^{\rm el}_{J/\Psi\to\eta_c\gamma}}{dk_\gamma} = \frac{8}{9}\frac{\alpha e_Q^2}{\pi}k_\gamma\left|\phi_{J/\Psi}(0)\right|^2\frac{\left|a_e(k_\gamma)\right|^2}{m^4}\left[C_A\Im m f_1\left({}^3P_0\right)+5C_A\Im m f_1\left({}^3P_2\right)\right]$$

The function $a_e(k_\gamma)$ has been discussed in (Manohar, Ruiz-Femenía '03, Ruiz-Femenía '07, '09) (Voloshin '03)

We have checked the results in these papers for the orthopositronium decay spectrum in (p)NRQED.

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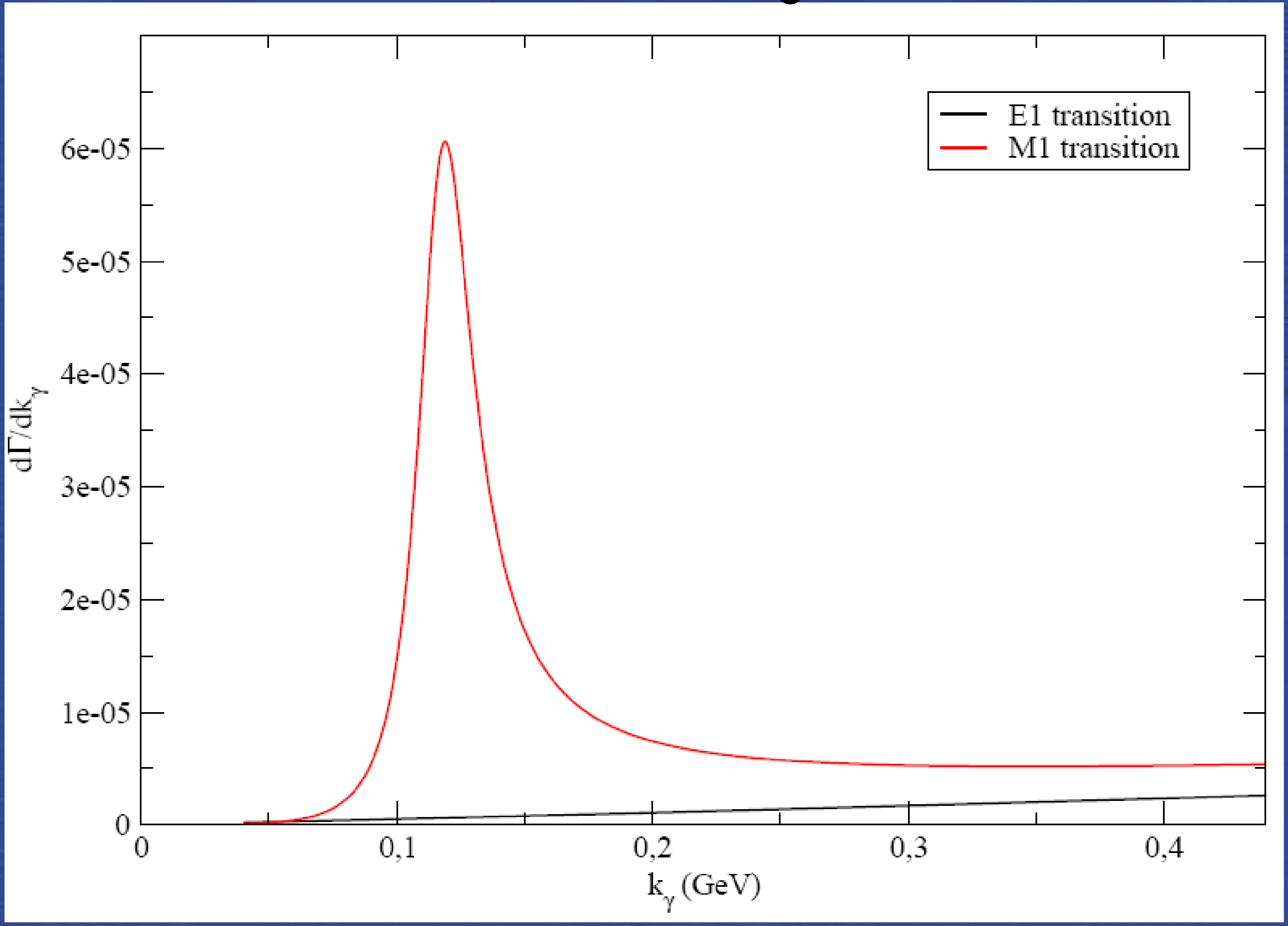

Lineshape in J/Ψ→γ η_c using pNRQCD

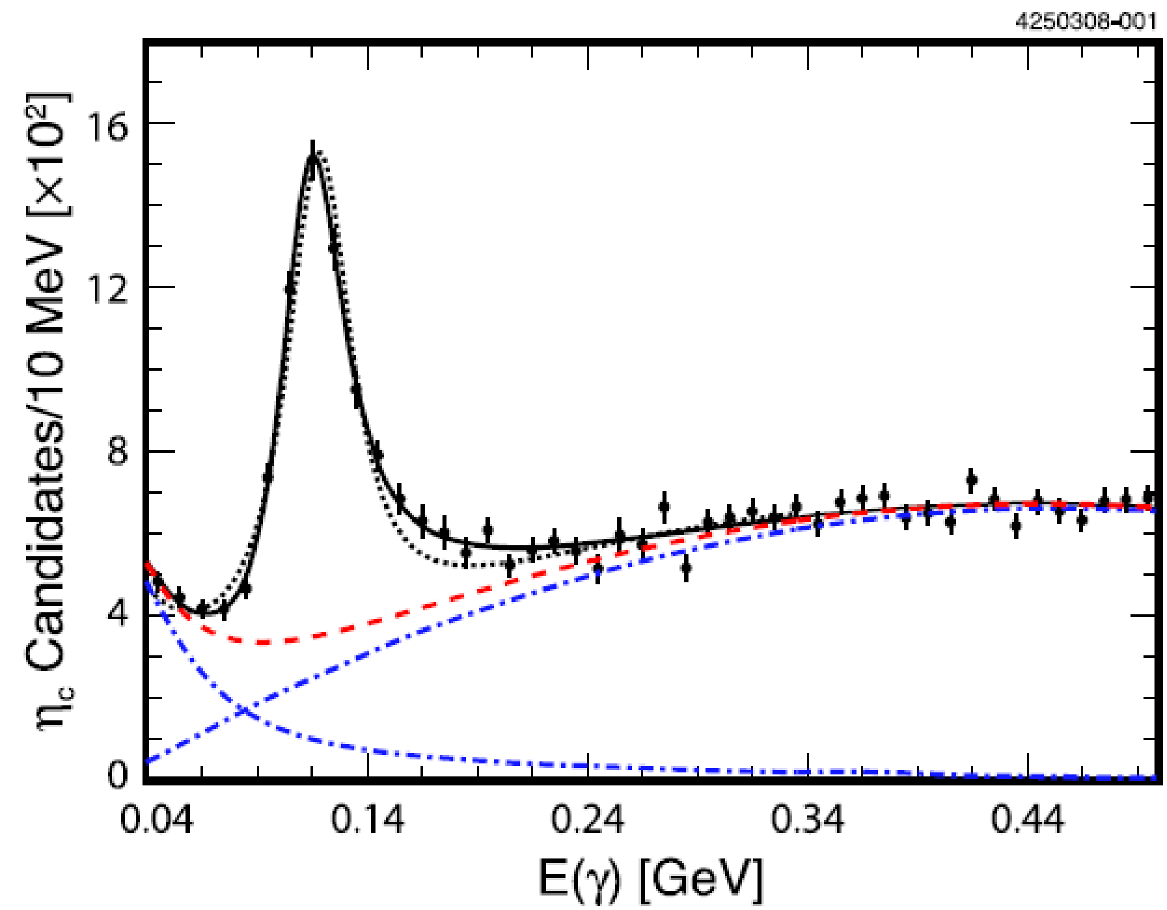

FIG. 1: Fits to the photon spectrum in exclusive $J/\psi \to \gamma\eta_c$ decays using relativistic Breit-Wigner (dotted) and modified (solid) signal line shapes convolved with a 4.8 MeV wide resolution function. Total background is given by the dashed line. The dot-dashed curves indicate two major background components described in the text.

Conclusions and Outlook

- Radiative decays of quarkonia are/will be subject of research in CLEO-c, BaBar, Belle, BES-III.
- One can take advantage of the hierarchy of scales the problem has and develop an EFT approach (pNRQCD) able to study them systematically.
- Within pNRQCD at $\mathcal{O}(v^2)$ one obtains $\Gamma(\mathbf{J/\Psi\to\gamma\eta_c})$ in agreement with experiment.
- A description of the lineshape of this process is currently in progress: $\Gamma(\mathbf{J/\Psi\to\gamma\eta_c})$ and $\mathbf{m}_{\eta_c}$.
- We find that the M1 contribution overcomes completely that of E1.
- We still have to get the background subtracted data to compare our predictions to it.
- We are also considering the importance of fragmentation contributions in the low-E region.