The η_c line shape

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work in progress with

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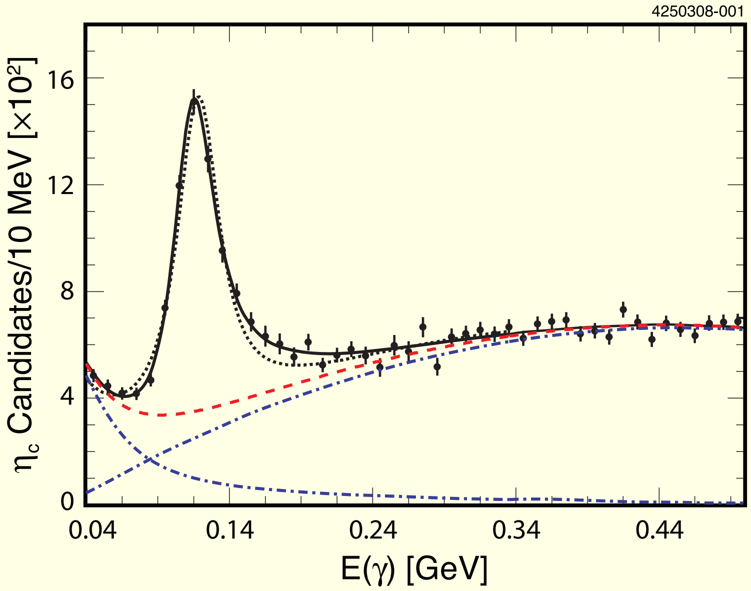
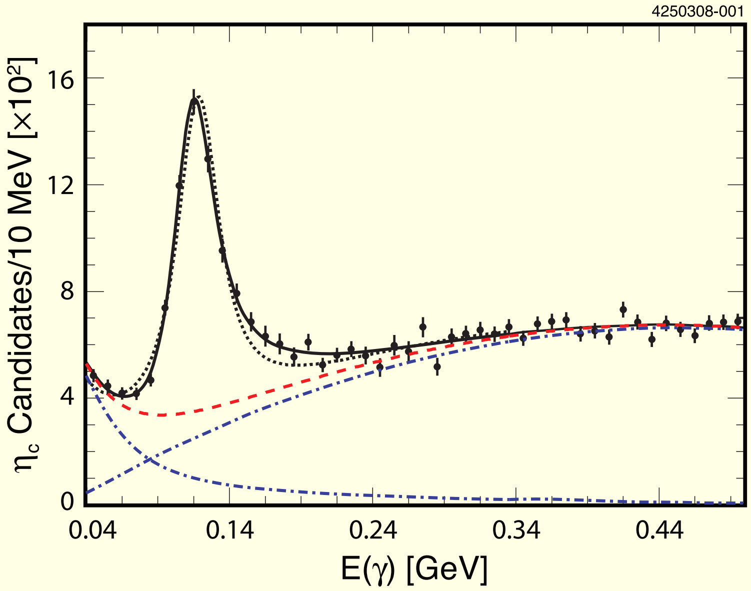
η_c line shape in the CLEO analysis



○ CLEO PRL 102(09)011801

- Input: two background sources
  - a MC modeled background for spurious $J/\psi \to X$:
    $\mathrm{bkg}^{(1)}(E_\gamma) = N[\exp(-5.720\,E_\gamma) + 10.441\,\exp(-33.567\,E_\gamma)]$
  - a freely fit background for $J/\psi \to \pi^0 X$ and non-signal $J/\psi \to \gamma X$:
    $\mathrm{bkg}^{(2)}(E_\gamma) = A + B\,E_\gamma + C\,E_\gamma^2$

η_c line shape in the CLEO analysis



○ CLEO PRL 102(09)011801

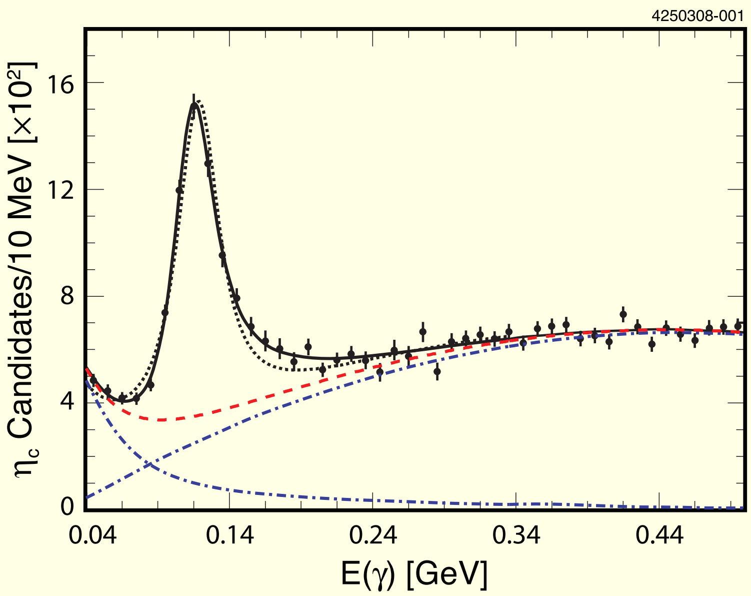
- Input: a theoretical line shape given by

$$E_\gamma^3 \times \mathrm{BW}^{\mathrm{rel}}(E_\gamma) \times \mathrm{damping}(E_\gamma)$$

where

- $\mathrm{BW}^{\mathrm{rel}}(E_\gamma) = \dfrac{1}{(M_{J/\psi}^2 - 2M_{J/\psi}E_\gamma - M_{\eta_c}^2)^2 + (M_{J/\psi}^2 - 2M_{J/\psi}E_\gamma)^2\Gamma_{\eta_c}}$
- $\mathrm{damping}(E_\gamma) = \exp[-E_\gamma^2/(8 \times (65.0 \pm 2.5\,\text{MeV})^2)]$

η_c line shape in the CLEO analysis

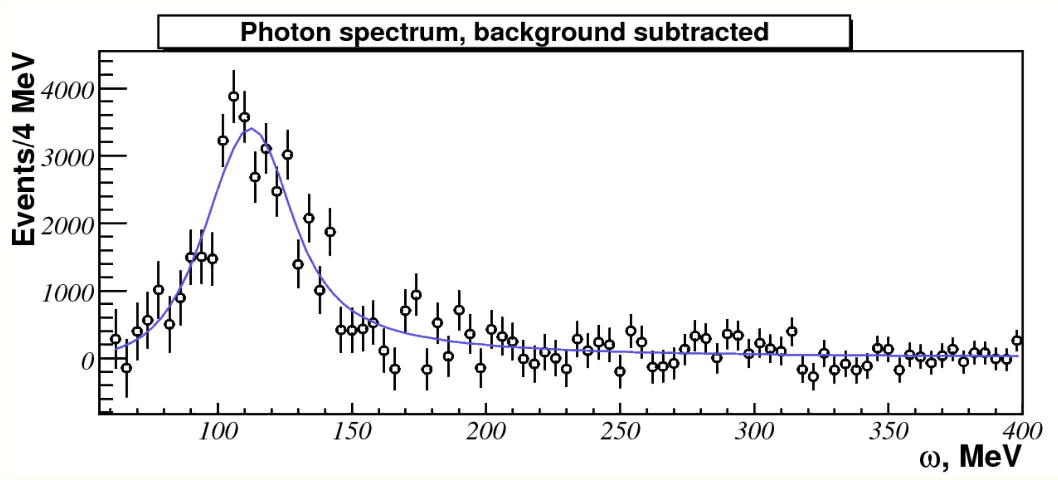


- CLEO PRL 102(09)011801

- Output:

$$M_{\eta_c} = 2982.2 \pm 0.6 \,\text{MeV}$$

η_c line shape in the KEDR analysis



○ `KEDR arXiv:1002.2071`

- Input: as before, but also

$$\text{damping}'(E_\gamma) = \frac{E_{\text{peak}}^2}{E_\gamma E_{\text{peak}} + (E_\gamma - E_{\text{peak}})^2}$$

- Output:

$$M_{\eta_c} = 2979.7 \pm 1.6\,\text{MeV} \qquad \Gamma_{\eta_c} = 26.9 \pm 4.8\,\text{MeV}$$

$$M'_{\eta_c} = 2979.4 \pm 1.5\,\text{MeV} \qquad \Gamma'_{\eta_c} = 27.8 \pm 5.1\,\text{MeV}$$

An EFT approach: scales

Scales:

- $\langle p \rangle \sim 1/\langle r \rangle \sim m_c v \sim$ 700 MeV - 1 GeV $\gg \Lambda_{\rm QCD}$
- $E_{J/\psi} \equiv M_{J/\psi} - 2m_c \sim m_c v^2 \sim$ 400 MeV - 600 MeV $\ll 1/\langle r \rangle$
- $M_{J/\psi} - M_{\eta_c} \sim m_c v^4 \sim$ 120 MeV $\ll E_{J/\psi}$
- 0 MeV $\leq E_\gamma \lesssim$ 400 MeV - 500 MeV $\ll 1/\langle r \rangle$
- $\Gamma_{\eta_c} \sim$ 30 MeV $\ll m_c v^4$

It follows that the system is

(i) non-relativistic,
(ii) weakly-coupled at the scale $1/\langle r \rangle$: $v \sim \alpha_{\rm s}$,
(iii) that we may mutipole expand in the external photon energy.

An EFT approach: degrees of freedom

Degrees of freedom at scales lower than mv:

- c-$\bar{c}$ states, with energy $\sim \Lambda_{\rm QCD}$, $m_c v^2$ and momentum $\lesssim m_c v$
  $\Rightarrow$ (i) singlet $\rm S$ (ii) octet $\rm O$
- Gluons with energy and momentum $\sim \Lambda_{\rm QCD}$, $m_c v^2$
- Photons of energy and momentum lower than $m_c v$

An EFT approach: the Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm pNRQCD} + \mathcal{L}_\gamma$$

- $$\mathcal{L}_{\rm pNRQCD} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu\, a} - \frac{1}{4} F^{\rm em}_{\mu\nu} F^{\mu\nu\, \rm em} + {\rm Tr}\left\{ {\rm S}^\dagger \left(i\partial_0 - h_s\right) {\rm S} + {\rm O}^\dagger \left(iD_0 - h_o\right) {\rm O} \right\} + \dots$$

$$h_s = {\rm Re}\, h_s + i{\rm Im}\, h_s, \quad {\rm Re}\, h_s = \mathbf{p}^2/m_c + {\rm Re}\, V_s, \quad \langle H|{\rm Im}\, h_s|H\rangle = -\Gamma_H/2$$

  - Pineda Soto NP PS 64(98)428, Brambilla et al NPB 566(00)275 Brambilla et al PRD 67(03)034018

- $$\mathcal{L}_\gamma = {\rm Tr}\left\{ \overbrace{V_A^{\rm em}\, {\rm S}^\dagger \mathbf{r}\cdot ee_Q \mathbf{E}^{\rm em} {\rm S}}^{\rm E1} + \overbrace{\frac{1}{2m_c} V_1 \left\{ {\rm S}^\dagger, \boldsymbol{\sigma}\cdot ee_Q \mathbf{B}^{\rm em} \right\} {\rm S}}^{\rm M1} + \dots \right\}$$

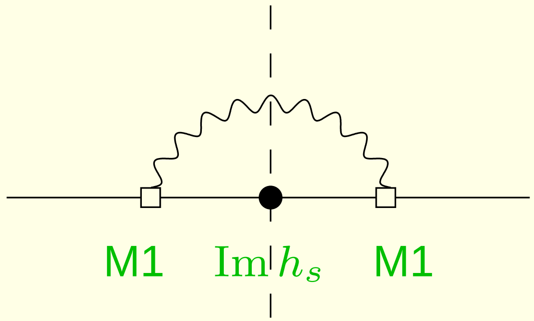
$$V_A^{\rm em} = 1 + \dots, \qquad V_1 = 1 + \dots$$

  - Brambilla Jia Vairo PRD 73(06)054005

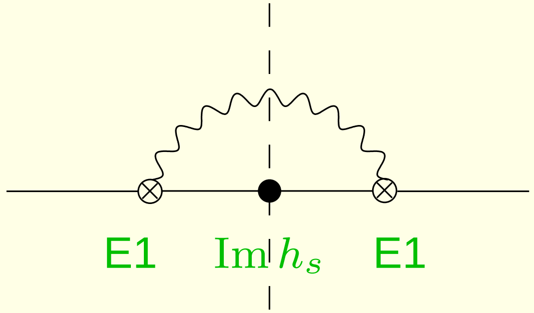
$J/\psi \to X\,\gamma$ for 0 MeV $\leq E_\gamma \lesssim$ 500 MeV

Three main processes contribute to $J/\psi \to X\,\gamma$ for 0 MeV $\leq E_\gamma \lesssim$ 500 MeV:

- $J/\psi \to \eta_c\,\gamma \to X\,\gamma$



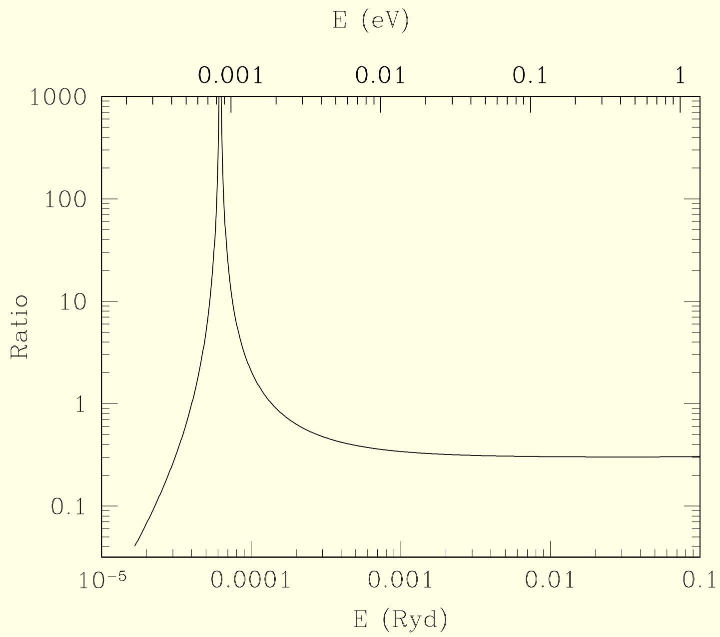
- $J/\psi \to \chi_{c0,2}(1P)\,\gamma \to X\,\gamma$



- fragmentation and other background processes, included in the bkg functions.

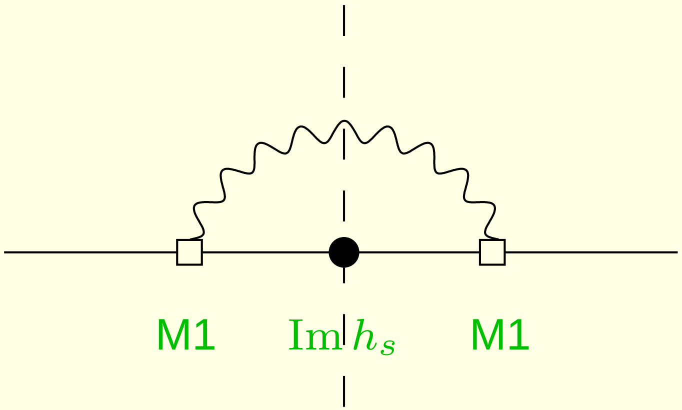
The orthopositronium decay spectrum

The problem is analogous to the photon spectrum in orthopositronium $\rightarrow 3\gamma$ that also exhibits a characteristically asymmetric spectrum.



- Manohar Ruiz-Femenia PRD 69(04)053003
  Ruiz-Femenia NPB 788(08)21, arXiv:0904.4875

$$J/\psi \to \eta_c\,\gamma \to X\,\gamma$$

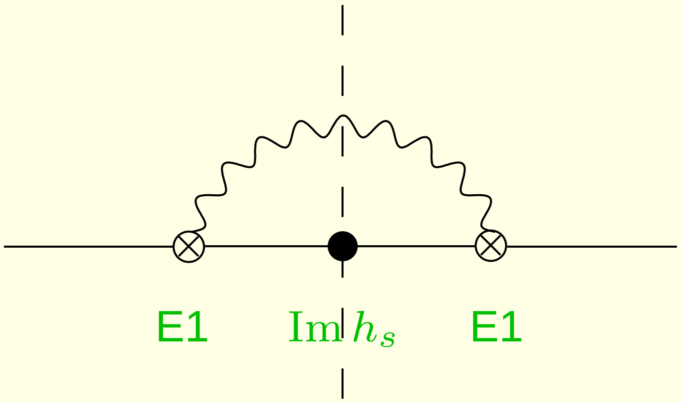


$$\frac{d\Gamma}{dE_\gamma} = \frac{64}{27}\,\frac{\alpha}{M_{J/\psi}^2}\,\frac{E_\gamma}{\pi}\,\frac{\Gamma_{\eta_c}}{2}\,\frac{E_\gamma^2}{(M_{J/\psi}-M_{\eta_c}-E_\gamma)^2+\Gamma_{\eta_c}^2/4}$$

- For $\Gamma_{\eta_c} \to 0$ one recovers $\Gamma(J/\psi \to \eta_c\,\gamma) = \dfrac{64}{27}\alpha\dfrac{E_\gamma^3}{M_{J/\psi}^2}$
- The non-relativistic Breit–Wigner distribution goes like:

$$\frac{E_\gamma^2}{(M_{J/\psi}-M_{\eta_c}-E_\gamma)^2+\Gamma_{\eta_c}^2/4} = \begin{cases} 1 & \text{for } E_\gamma \gg m_c\alpha_{\mathrm{s}}^4 \sim M_{J/\psi}-M_{\eta_c} \\ \dfrac{E_\gamma^2}{(M_{J/\psi}-M_{\eta_c})^2} & \text{for } E_\gamma \ll m_c\alpha_{\mathrm{s}}^4 \sim M_{J/\psi}-M_{\eta_c} \end{cases}$$

$$J/\psi \to \chi_{c0,2}(1P)\,\gamma \to X\,\gamma$$



$$\frac{d\Gamma}{dE_\gamma} = \frac{32}{81}\,\frac{\alpha}{M^2_{J/\psi}}\,\frac{E_\gamma}{\pi}\left[\frac{21\,\alpha_s^2}{2\,\pi\,\alpha^2}\right]|a(E_\gamma)|^2$$

- $a(E_\gamma) = \dfrac{(1-\nu)(3+5\nu)}{3(1+\nu)^2} + \dfrac{8\nu^2(1-\nu)}{3(2-\nu)(1+\nu)^3}\;{}_2F_1(2-\nu,1;3-\nu;-(1-\nu)/(1+\nu))$
  $\nu = \sqrt{-E_{J/\psi}/(E_\gamma - E_{J/\psi})}$

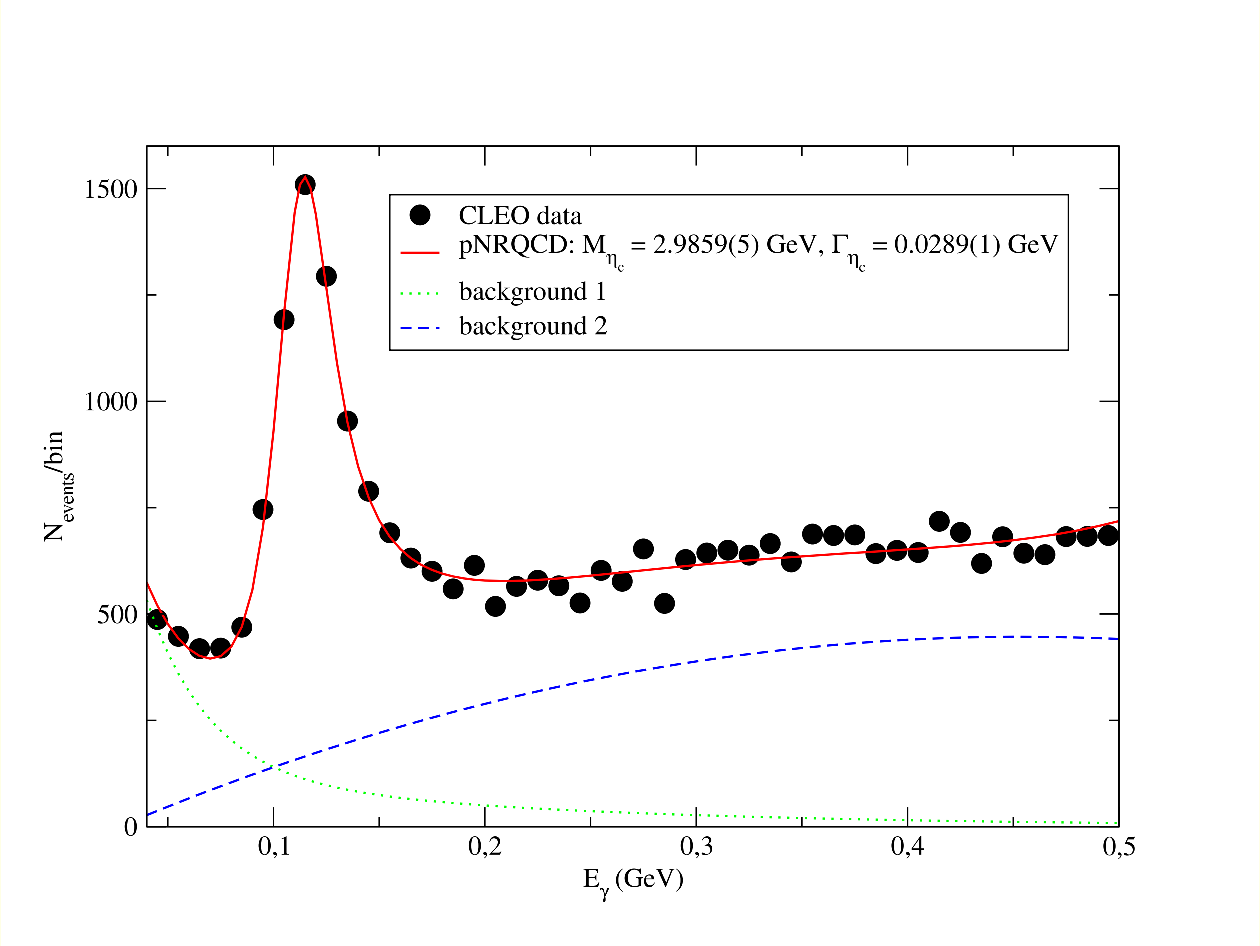
○ Voloshin MPLA 19(04)181

- $|a(E_\gamma)|^2 = \begin{cases} 1 & \text{for } E_\gamma \gg m_c\alpha_s^2 \sim E_{J/\psi} \\ E_\gamma^2/(2E_{J/\psi})^2 & \text{for } E_\gamma \ll m_c\alpha_s^2 \sim E_{J/\psi} \end{cases}$

- The two contributions are of equal order for $m_c\alpha_{\mathrm{s}} \gg E_\gamma \gg m_c\alpha_{\mathrm{s}}^2 \sim -E_{J/\psi}$;

- the magnetic contribution dominates for $-E_{J/\psi} \sim m_c\alpha_{\mathrm{s}}^2 \gg E_\gamma \gg m_c\alpha_{\mathrm{s}}^4 \sim M_{J/\psi} - M_{\eta_c}$;

- it also dominates by a factor $E_{J/\psi}^2/(M_{J/\psi} - M_{\eta_c})^2 \sim 1/\alpha_{\mathrm{s}}^4$ for $E_\gamma \ll m_c\alpha_{\mathrm{s}}^4 \sim M_{J/\psi} - M_{\eta_c}$.



$$M_{\eta_c} = 2985.9 \pm 0.5\,\text{MeV} \qquad \Gamma_{\eta_c} = 28.9 \pm 0.1\,\text{MeV}$$

- Besides M_{η_c} and Γ_{η_c} the fitting parameters are the overall normalization N, the signal normalization, and the background parameters a, b and c.

Differences with the CLEO fit

- No damping functions, which do not seem to have a theoretical justification. They account for about 50% difference in the η_c mass.
- Damping functions require a larger background above the η_c peak. The absence of the damping functions accounts for a background about 30% smaller than in the CLEO analysis.
- The use of the non-relativistic Breit–Wigner $\times E_\gamma^3$ distribution instead of the relativistic Breit–Wigner $\times E_\gamma^3$ distribution used in the CLEO analysis accounts for about 50% difference in the η_c mass.

Outlook

- We plan to include the first relativistic correction of order E_γ/m_c ($\sim \alpha_{\rm s}^4$ around the η_c peak). Note that relativistic corrections of order $\langle p\rangle^2/m_c^2$ are reabsorbed in the overall normalization while corrections coming form the multipole expansion are of order $E_\gamma^2\langle r\rangle^2$ ($\sim \alpha_{\rm s}^6$ around the η_c peak) and therefore suppressed in the peak region.