The Discrete Contribution to ψ(2S) Decay into J/ψ+2γ

Zhi-Guo He

Universitat de Barcelona

In collaboration with Xiao-Rui Lu (GUCAS)

Joan Soto(UB) , Yangheng Zheng (GUCAS)

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Outline

- Background and Motivation
- The Theoretical Framework
- Discrete Contribution to Two Photon Transition
- Comparison with the MC simulation
- Conclusions and Summary

Motivation and Background

Why the two photon transition Process?

On theoretical side:

- **Two-photon transition among hydrogen system is helpful to study the hydrogen recombination in universe. (Kholupenko, Ivanchik, 2006)**
- **Similar decay $D^* \to D + 2\gamma$ to extract the couplings $g_{D^* D\gamma}$ and $g_{D^* D\pi}$. (D.Guetta and P.Singer, 2000)**
- **Radiative transition may help to test the meson-loop effect in heavy quarkonium states, however its uncertainty is large in one-photon transition. (T.Barnes, 2010)**

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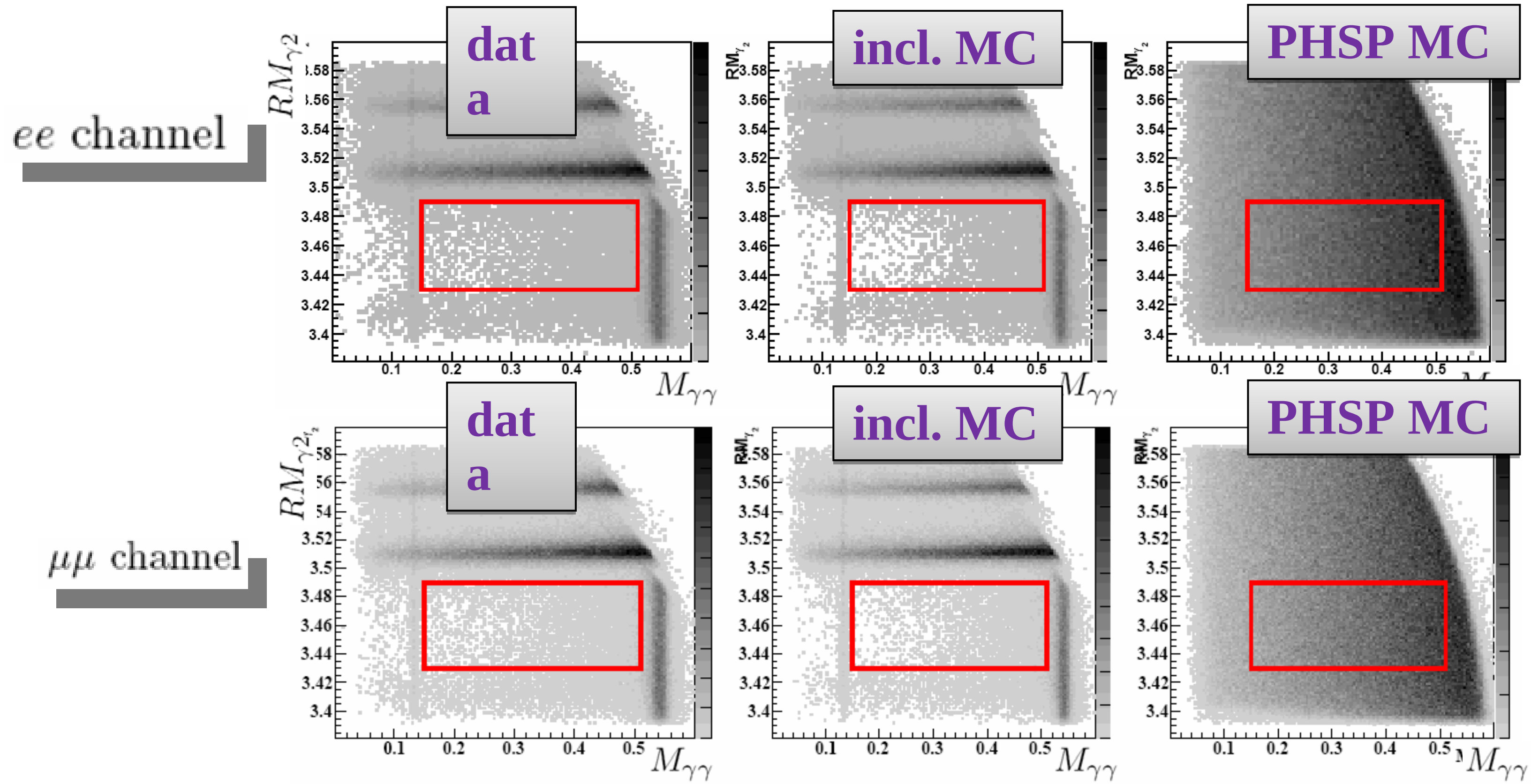
- **Radiative transition may help to test the meson-loop effect in heavy quarkonium states, however its uncertainty is large in one-photon transition. (T.Barnes, 2010)**

On experimental side:

- **An α^2 order subtle QED transition process.**
- **The two-photon transition has been observed among positronium 1S and 2S states in 80s. (S.Chu, A.P.Mills, 1982)**
- **CLEO reported $Br(\Upsilon(3S) \to \Upsilon(2S) + 2\gamma) = (5.0 \pm 0.7)\%$. (PDG 2010)**
- **In charmonium systems, it is observed by BESIII recently.**

Preliminary Experimental Result



box cut:

$0.15 < M_{\gamma\gamma} < 0.51$ GeV
$3.43 < RM_{\gamma 2} < 3.49$ GeV

X. R. Lu talk, Meson 2010

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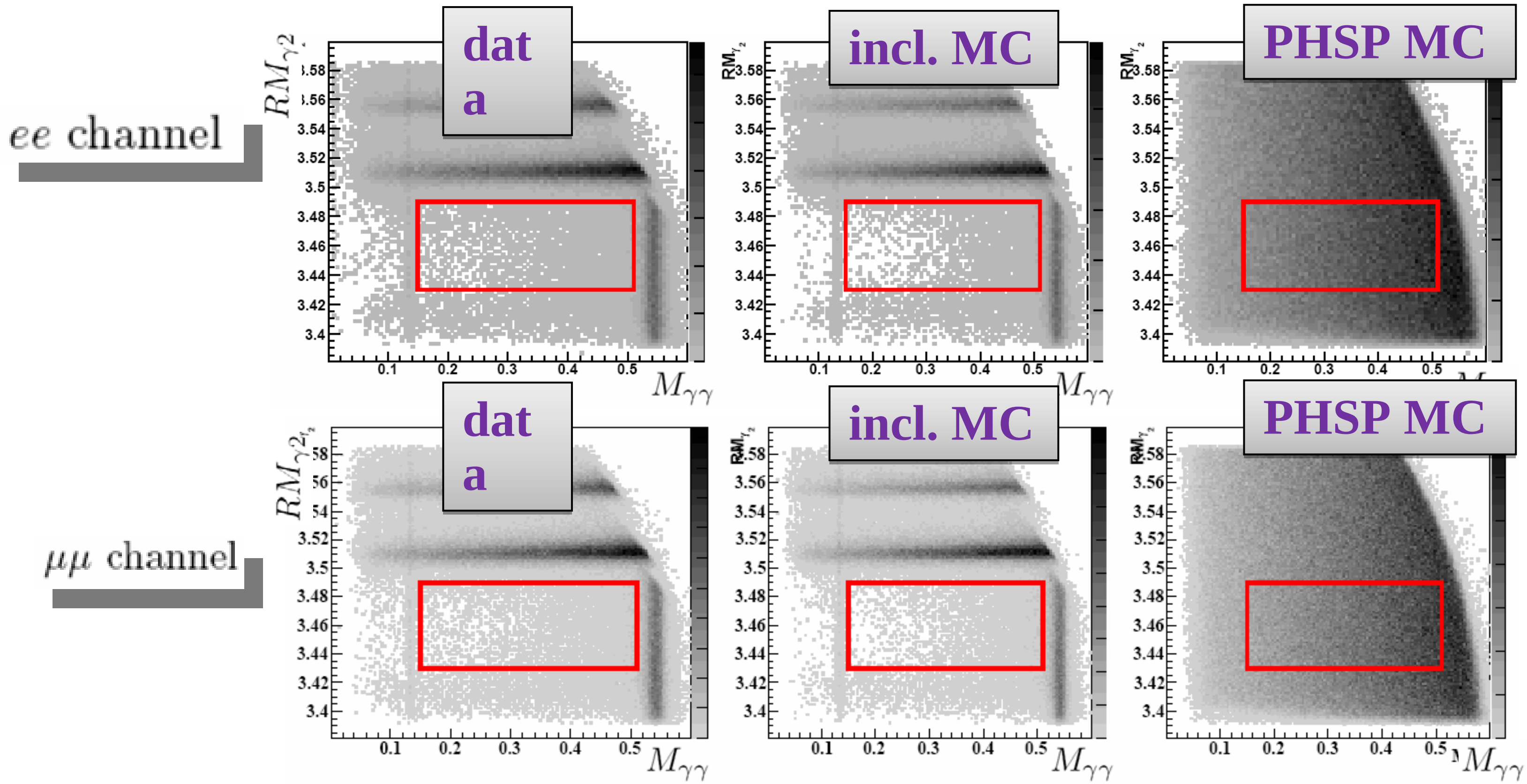

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$$Br(\psi(2S) \to J/\psi + 2\gamma) \sim 1 \times 10^{-3}$$

compatible with CLEO data. (CLEO 2008)

Theoretical Picture

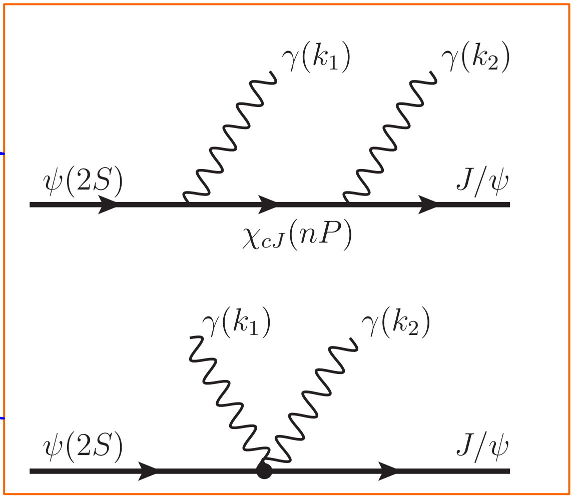
Discrete part contribution:

Leading order:

double E-1 transition via discrete nP (n=1,2…) states (virtual and real parts).
(including main source of the background)

Relativistic corrections:

relatively higher order v^2 operator corrections



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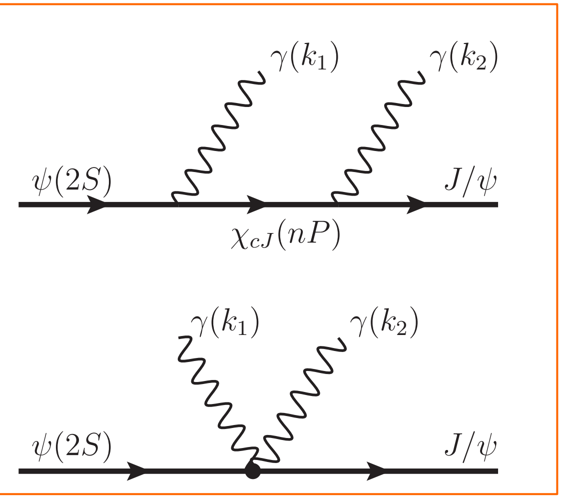
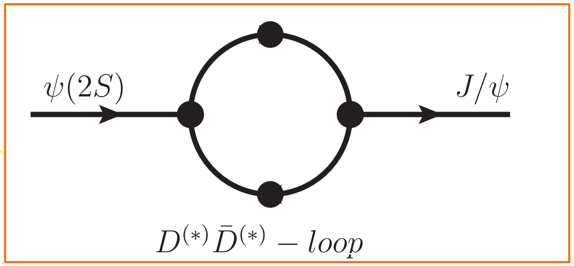


Hadron-loop contribution:

besides discrete contribution, the $DD^{(*)}$ meson loop effect can also contribute.



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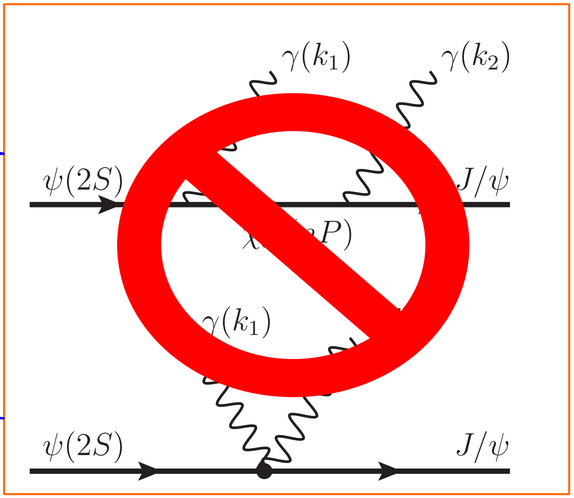

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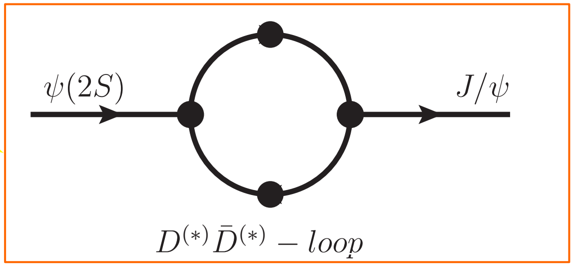

Our idea

Pin down the discrete part contribution, there may left signal of meson loop effect!!

The Theoretical Frame work

Heavy Quarkonium Multiplet Ⅰ

- **For those states have the same n and L, they can expressed by a single multiplet $J^{\mu_1\cdots\mu_L}$:**

$$J^{\mu_1\ldots\mu_L} = \frac{1+\not{v}}{2}\Bigg(H_{L+1}^{\mu_1\ldots\mu_L\alpha}\gamma_\alpha + \frac{1}{\sqrt{L(L+1)}}\sum_{i=1}^{L}\epsilon^{\mu_i\alpha\beta\gamma}v_\alpha\gamma_\beta H_{L\gamma}^{\mu_1\ldots\mu_{i-1}\mu_{i+1}\ldots\mu_L}$$

$$+\frac{1}{L}\sqrt{\frac{2L-1}{2L+1}}\sum_{i=1}^{L}(\gamma^{\mu_i}-v^{\mu_i})H_{L-1}^{\mu_1\ldots\mu_{i-1}\mu_{i+1}\ldots\mu_L} - \frac{2}{L\sqrt{(2L-1)(2L+1)}}$$

$$\times\sum_{i<j}(g^{\mu_i\mu_j}-v^{\mu_i}v^{\mu_j})\gamma_\alpha H_{L-1}^{\alpha\mu_1\ldots\mu_{i-1}\mu_{i+1}\ldots\mu_{j-1}\mu_{j+1}\ldots\mu_L} + K_L^{\mu_1\ldots\mu_L}\gamma^5\Bigg)\frac{1-\not{v}}{2},$$

v^μ **is the four-velocity of the multiplet state and**

$$v_{\mu_i}K_L^{\mu_1\cdots\mu_i\cdots\mu_L}=0,\ v_{\mu_i}H_L^{\mu_1\cdots\mu_i\cdots\mu_L}=0$$

Heavy Quarkonium Multiplet Ⅱ

Explicit Expression for L=S,P case:

- **For L=S:** $$J=\frac{1+\not{v}}{2}(H_1^{\mu}\gamma_{\mu}-K_0\gamma^5)\frac{1-\not{v}}{2}$$
- **For L=P:**

$$J^{\mu}=\frac{1+\not{v}}{2}(H_2^{\mu\alpha}\gamma_{\alpha}+\frac{1}{\sqrt{2}}\varepsilon^{\mu\alpha\beta\gamma}v_{\alpha}\gamma_{\beta}H_{1\gamma}+\frac{1}{\sqrt{3}}(\gamma^{\mu}-v^{\mu})+K_0\gamma^5)\frac{1-\not{v}}{2}$$

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Effective Lagrangian for radiative transition among S- and P-wave states:

$$L=\sum_{m,n}\delta^{nP,mS}Tr[\bar{J}(mS)J_{\mu}(nP)]v_{\nu}F^{\mu\nu}+H.c.$$

Preserve CPT, gauge invariance, and heavy quark spin symmetry

coupling constant

Electromagnetic tensor

E1 Transition Formula

- **Decay widths for the one-photon emission:**
  - **mS--->nP+ γ :**

$$\Gamma(m^3S_1 \to n^3P_J + \gamma) = (2J+1)\frac{(\delta_J^{nP,mS})^2}{144} k_\gamma^3 \frac{(M_{mS} + M_{nP})^4}{M_{mS}^3 M_{nP}}$$

  - **nP--->mS+ γ :**

$$\Gamma(n^3P_J \to m^3S_1 + \gamma) = \frac{(\delta_J^{nP,mS})^2}{48} k_\gamma^3 \frac{(M_{mS} + M_{nP})^4}{M_{mS} M_{nP}^3}$$

J-dependent

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J-dependent

- **Numerical result of coupling constant:**

TABLE I. The numerical values of the coupling constants $\delta_J^{nP,mS}$(GeV ^{1}) are shown. For the $n = 1$ case, the results are obtained by fitting the experimental data, and for $n = 2$, the results are determined by comparing with the potential model predictions [26].

	$\chi_{c0}(1P)$	$\chi_{c1}(1P)$	$\chi_{c2}(1P)$	$\chi_{c0}(2P)$	$\chi_{c1}(2P)$	$\chi_{c2}(2P)$
J/ψ	0.211	0.230	0.228	$5.27 \times 10^{\ 2}$	$5.30 \times 10^{\ 2}$	$5.34 \times 10^{\ 2}$
$\psi(2S)$	0.224	0.235	0.273	0.410	0.413	0.416

Discrete Contribution to Two Photon Transition

Feynman Diagrams and Amplitude

Two Feynman diagrams

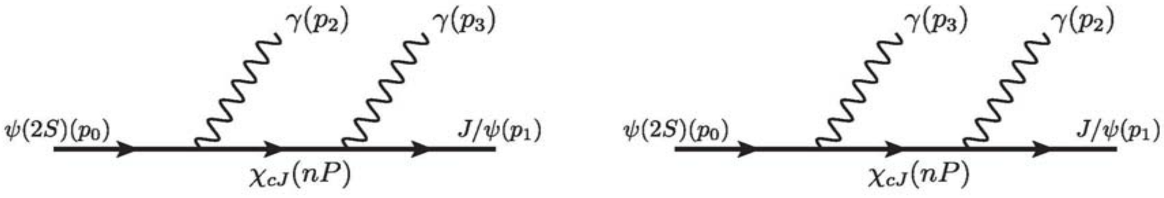

FIG. 1. The Feynman diagrams for $\psi(2S)$ decay into $J/\psi + 2\gamma$ via intermediate states $\chi_{cJ}(nP)$.

Feynman amplitude:

$$M^{\mathrm{Tot}} = M^{\chi_{c0}(1P)} + M^{\chi_{c1}(1P)} + M^{\chi_{c2}(1P)} + M^{\chi_c(2P)}$$

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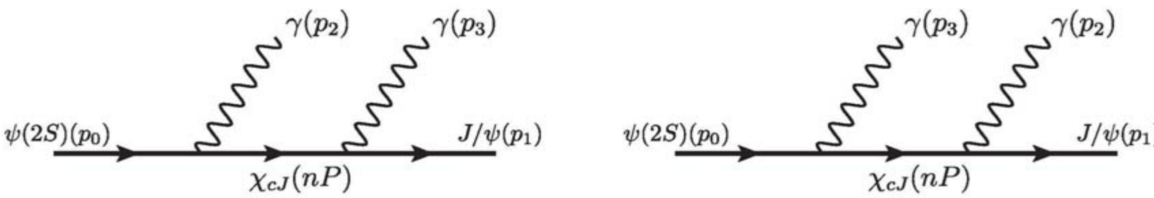

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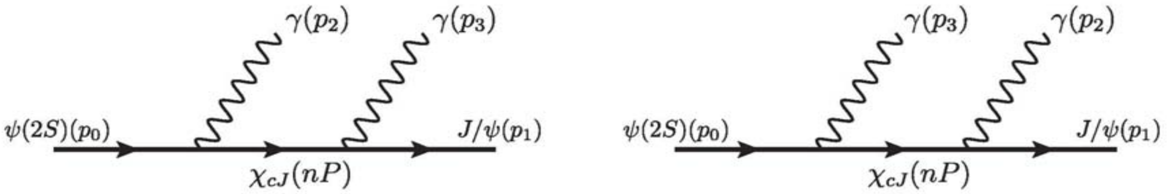
Decay width is divided into four part:

$$\Gamma_{\mathrm{dis}}(\psi(2S) \to J/\psi + \gamma\gamma) = \Gamma^{1P}_{\mathrm{ind}} + \Gamma^{1P}_{\mathrm{int}} + \Gamma^{2P} \pm \Gamma^{1,2P}_{\mathrm{int}}$$

Feynman Diagrams and Amplitude

- **Two Feynman diagrams**



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Account for the relative phase

Sum of three individual 1P

1P interferences

Only 2P

1P,2P Interference

Numerical Result Ⅰ

- **Whole phase space region result:**

$$\Gamma^{1P}_{\mathrm{ind}} = 15.14\,keV \simeq \sum_J \Gamma(\psi(2S) \to \chi_{cJ} + \gamma) \times Br(\chi_{cJ} \to J/\psi + \gamma)$$

$$\Gamma^{1P}_{\mathrm{int}} = 5.95 \times 10^{-2}\,keV,\ \Gamma^{1,2P}_{\mathrm{int}} = 4.13 \times 10^{-2}\,keV, \Gamma^{2P} = 2.80 \times 10^{-3}\,keV$$

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$$0.15 GeV < M_{\gamma\gamma} < 0.51 GeV,\ 3.43 GeV < M_{J/\psi\gamma} < 3.49 GeV,$$

$$\Gamma_{\rm ind}^{1P} = 4.68 \times 10^{-2} keV,\ \Gamma_{\rm int}^{1P} = 6.5 \times 10^{-3} keV$$

$$\Gamma^{2P} = 1.82 \times 10^{-4} keV,\ \Gamma_{\rm int}^{1,2P} = 4.78 \times 10^{-3} keV$$

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In cut region the interference effect can reach 20%!!

Numerical Result Ⅱ

- **Branching ratio in cut region:**

$$Br_{\mathrm{dis}}^{\mathrm{cut}}(\psi(2S)\to J/\psi+2\gamma)=\begin{cases}1.92\times10^{-4} & \text{for } \theta=0,\\ 1.60\times10^{-4} & \text{for } \theta=\pi.\end{cases}$$

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- **The polarization of J/ψ in final state:**

$$\alpha=\frac{\Gamma_T-2\Gamma_L}{\Gamma_T+2\Gamma_L},\quad \alpha=\left\{\begin{array}{c}-1,\ \text{Longitudinal}\\ 0,\text{Unpolarized}\\ 1,\ \text{Transverse}\end{array}\right\}$$

  - If we use the same V^μ, α =0.
  - In the whole region: α = -0.16.
  - In the cut region, α = -0.122 and α =-0.107 for θ =0 and $\theta=\pi$,respectively. If only include three individual 1P contribution, α =-0.078.

J/ ψ tends to be in longitudinal polarization state!!

Photon Spectrum Ⅰ

1P contribution in whole region:

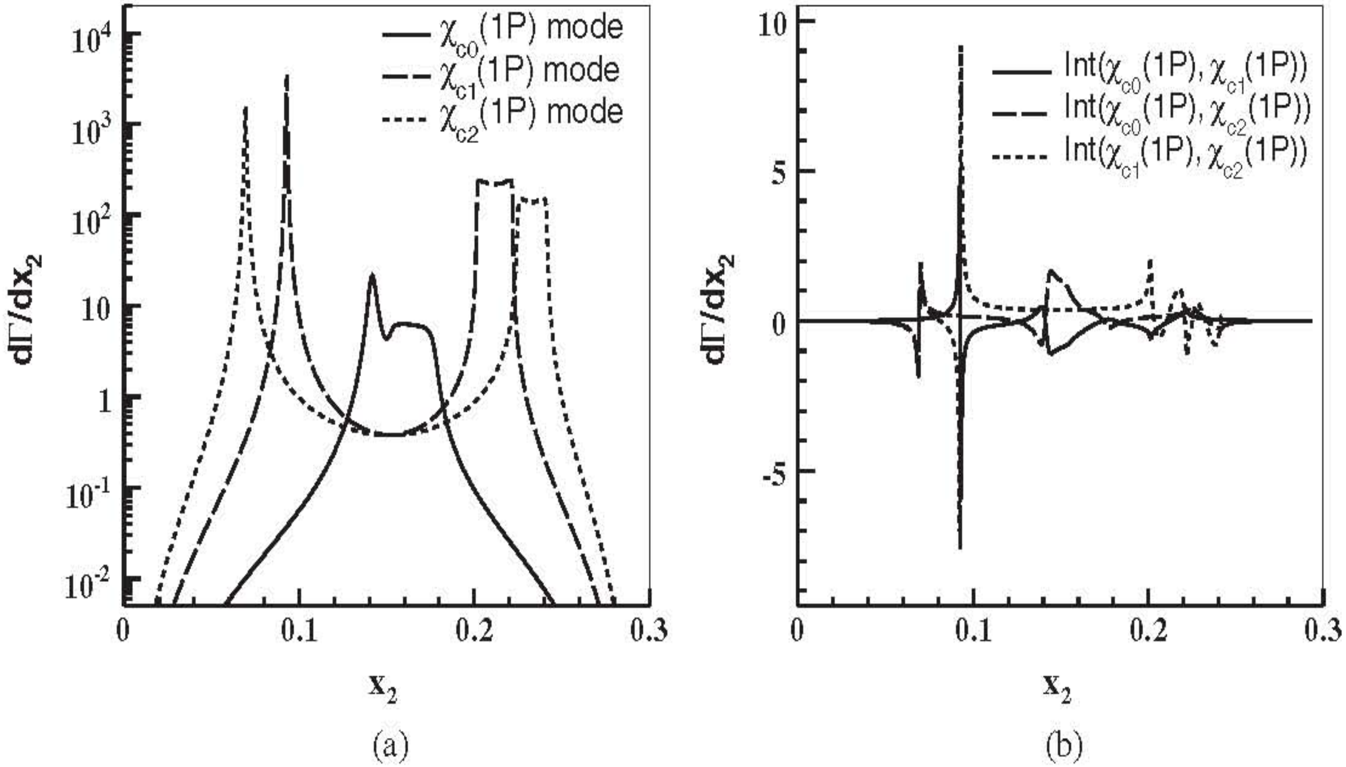

FIG. 2. The partial decay width as a function of the photon energy fraction x_2: (a) the individual contribution of the three χ_{cJ} ($J = 0, 1, 2$) states, corresponding to $\Gamma^{1P}_{\rm Ind}$ in (15), (b) the contribution of the interference terms between the three χ_{cJ} ($J = 0, 1, 2$) states, corresponding to $\Gamma^{1P}_{\rm Int}$ in (15).

Photon Spectrum Ⅱ

◈ 2P effect in whole region:

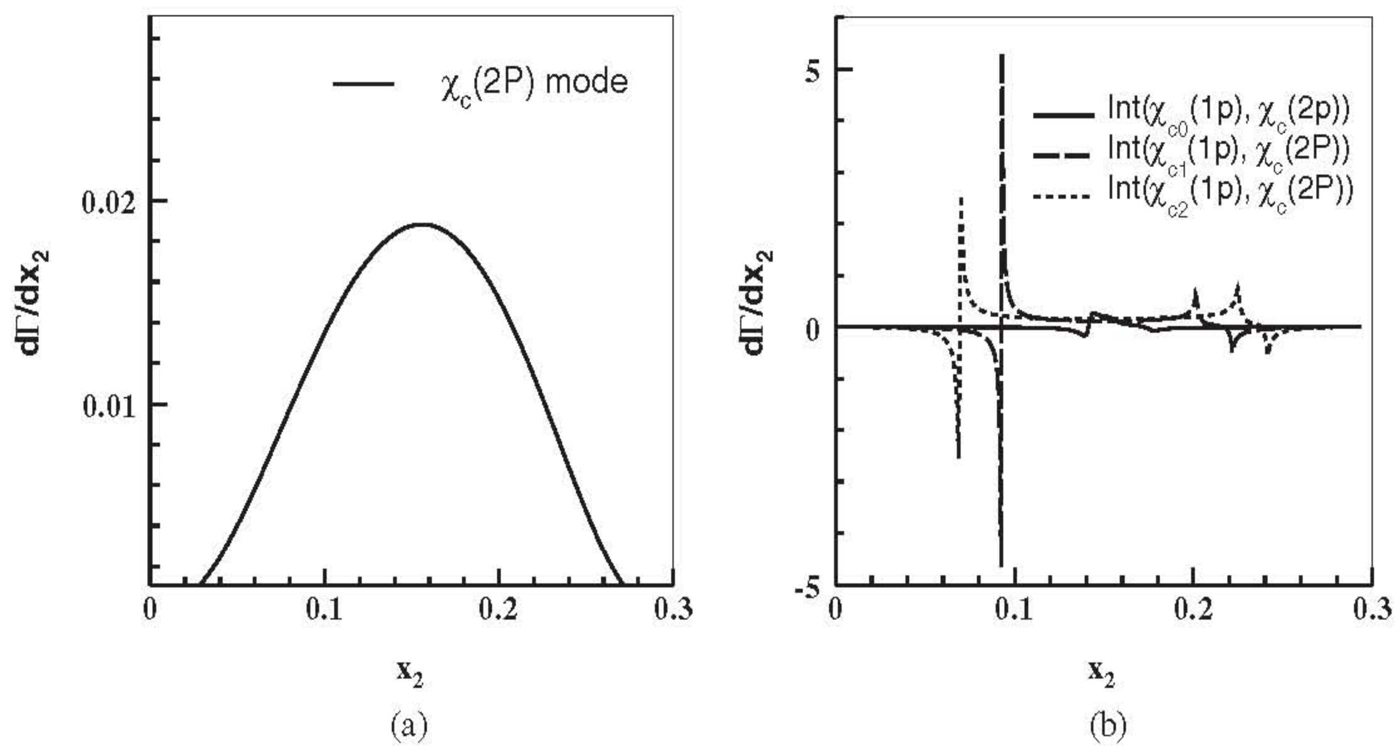

FIG. 3. The partial decay width as a function of the photon energy fraction x_2: (a) the contribution of the $2P$ states, corresponding to Γ^{2P} in (15), (b) the contribution of the interference terms between the $2P$ and the three $1P$ states, corresponding to $\Gamma^{1,2P}_{\mathrm{Int}}$ in (15).

Photon Spectrum Ⅲ

◈ Summary in cut region:

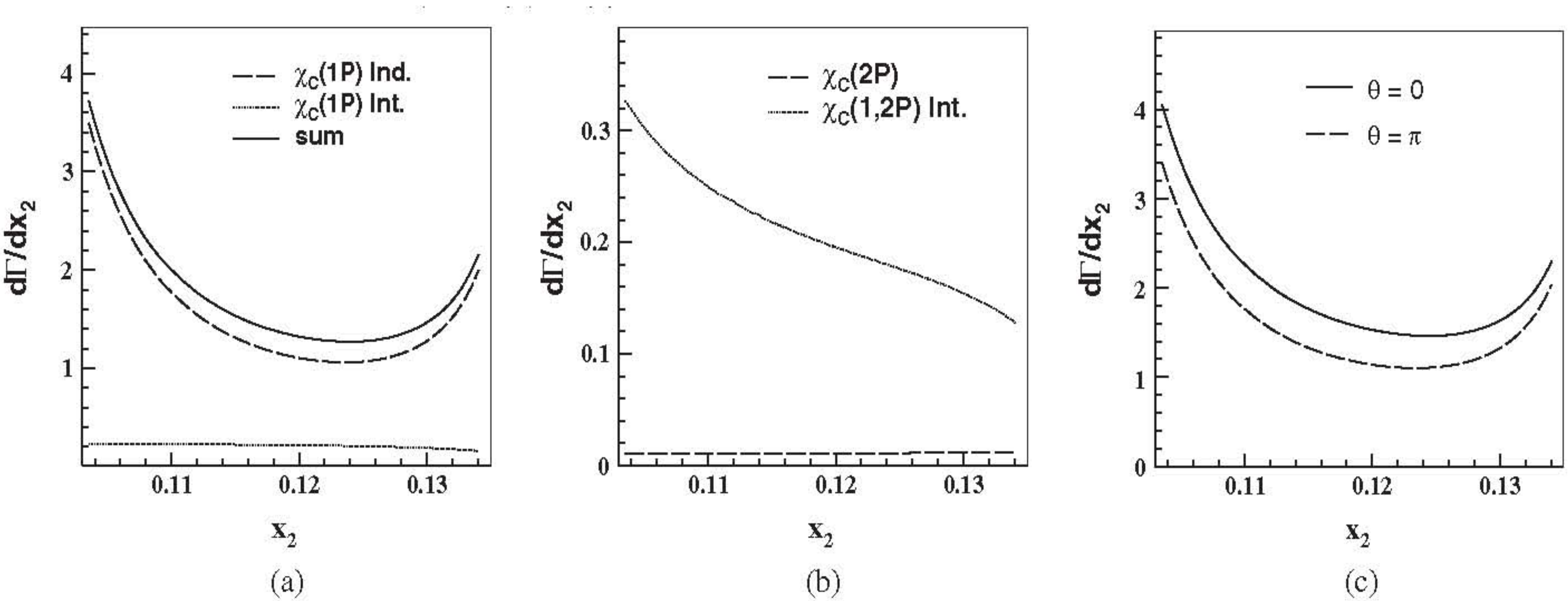

FIG. 4. The discrete contributions to the photon energy spectrum of the $\psi(2S) \to J/\psi + \gamma\gamma$ process in the cut region: (a) the contribution of the $1P$ states, corresponding to $\Gamma^{1P}_{\rm Ind}$ and $\Gamma^{1P}_{\rm Int}$ in (15), (b) the contribution of the $2P$ states and of the interference terms between $1P$ and $2P$ states, corresponding to Γ^{2P} and to $\Gamma^{1,2P}_{\rm Int}$ in (15), (c) the total contribution for a different relative phase angle θ, corresponding to the $\pm$ sign in (15).

Comparison with MC simulation

Description about the MC

- **In MC simulation, normally, only the individual part $\Gamma^{1P}_{\mathrm{ind}}$ is taken into account.**
- **The non-relativistic Breit-Wigner is used to describe the line shape of χ_{cJ}(1P) state.**
- **Double E1 transition factor $k^3_{\gamma 1} k^3_{\gamma 2}$ should be included.**
- **The decay widths and masses are from PDG 2010.**

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- Double E1 transition factor $k_{\gamma 1}^{3} k_{\gamma 2}^{3}$ should be included.
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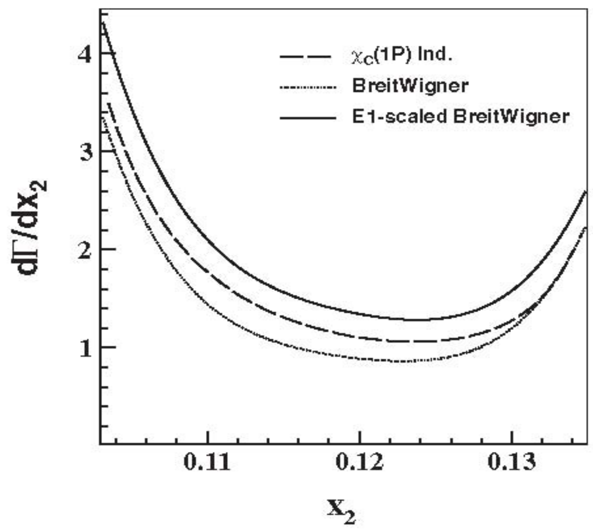
- Two questions left:
  - Effect of the interference and higher excited states.
  - Is the non-relativistic Breit-Wigner a good approximation in cut region?

Comparison in Cut Region

◆ Photon spectrum in cut region:



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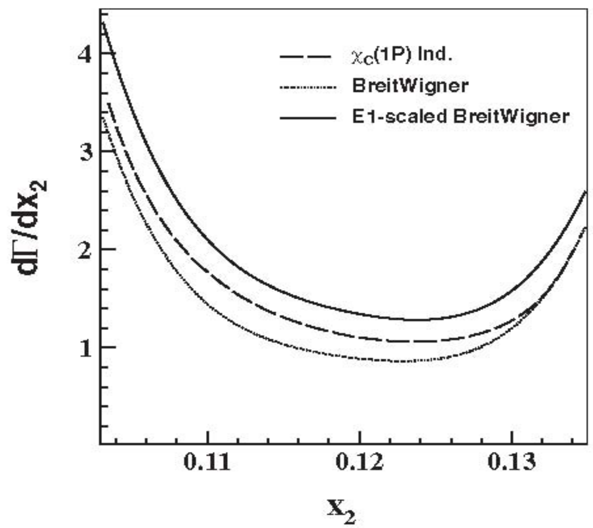

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In cut region, the non-relativistic together with energy factor is not enough to study the individual contribution.

Conclusions and Summary

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- **In the two photon transition process, the effect of interference and higher excited states (2P) are very tiny.**
- **In the experimental cut region, the contribution of the interference and higher excited states is sizeable.**
- **The J/ψ tends to be in longitudinal polarization state.**
- **The experimental MC simulation still gets potential to be improved in the cut region.**
- **Large deviation between our prediction and experimental data will indicate the signal of meson-loop effect.**

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谢谢！