NLO QCD Corrections for $J/\psi + c + \bar{c}$ Production in Photon-Photon Collision

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Outline

- J/ψ Inclusive Production in Photon-Photon Collision
- NLO QCD Corrections to $\gamma + \gamma \to J/\psi + c + \bar{c}$
- $\gamma + \gamma \to J/\psi + g + g + g$ Process
- Summary

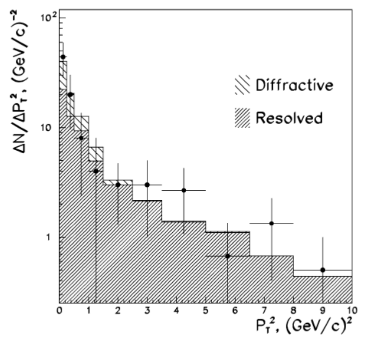
J/ψ Inclusive Production in Photon-Photon Collision

- LEPII $\gamma + \gamma \to J/\psi + \text{X}$ Data
- Mechanism
- COM&CSM
- $J/\psi + c + \bar{c}$ exclusive production

LEPII $\gamma + \gamma \to J/\psi + X$ Data

J. Abdallah *et al.*(DELPHI), Phys. Lett.B 565, 76 (2003):

- $\sqrt{s}$ of the LEP mechine ranged from 161 to 207 GeV.
- $N(J/\psi) = 36 \pm 7$ events.
- X contains at least two charged particle tracks (reject $\gamma + \gamma \to \chi_{c2} \to J/\psi + \gamma$).
- $\sigma = N(J/\psi)(Br \cdot \mathcal{L}\epsilon)^{-1} = 45 \pm 9 \pm 17$ pb.
- PYTHIA: $74 \pm 22\%$ from resolved photons.



$p_T^2(J/\psi)$ distribution from the LEPII DELPHI data.

Mechanism

The photons can interact either directly or via their quark and gluon content (resolved photoproduction):

i direct process:

$$\gamma\gamma \to c\bar{c}\left[{}^3S_1^{(8)}\right]g,$$

ii single-resolved process:

$$\gamma g \to c\bar{c}\left[{}^3S_1^{(1)}\right]g, c\bar{c}[8]g,$$
$$\gamma q \to c\bar{c}[8]q$$

iii double-resolved process:

$$gg \to c\bar{c}\left[{}^3S_1^{(1)}\right]g, c\bar{c}\left[{}^3P_J^{(1)}\right]g, c\bar{c}[8]g,$$
$$gq \to c\bar{c}\left[{}^3P_J^{(1)}\right]q, c\bar{c}[8]q,$$
$$q\bar{q} \to c\bar{c}\left[{}^3S_1^{(8)}\right]$$

Mechanism

Based on QCD parton model and NRQCD:

$$\begin{aligned} d\sigma(e^+e^- \to e^+e^- H + X) &= \int dx_+ f_{\gamma/e}(x_+) \int dx_- f_{\gamma/e}(x_-) \\ &\times \sum_{a,b,d} \int dx_a f_{a/\gamma}(x_a) \int dx_b f_{b/\gamma}(x_b) \\ &\times \sum_n d\hat{\sigma}(ab \to c\bar{c}[n] + d)\langle \mathcal{O}^H(n)\rangle \end{aligned}$$

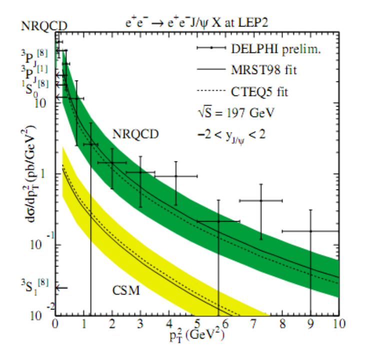
The PDFs of the photon have a leading behavior proportional to $\alpha \ln(M^2/\Lambda^2_{QCD}) \propto \alpha/\alpha_s$. Note, those three classes are same order in perturbative expansion.

NRQCD&CSM

Full LO result[1]:

- Dominant: single-resolved processes(NRQCD or CSM).
- From decays: 9%(NRQCD), 23%(CSM).
- Integrate over $1 \leq p_t^2 \leq 10\text{Gev}^2$,

DELPHI	(6.4 ± 2.0)pb
CSM	$0.39^{+0.16}_{-0.09}$pb
NRQCD	$4.7^{+1.9}_{-1.2}$pb



It was supposed to be a strong evidence for the CO mechanism.

[1] M. Klasen, B. A. Kniehl *et al.*, Phys. Rev. Lett. 89, 032001(2002).

NRQCD&CSM

The NLO analysis was performed, with the CO long-distance matrix elements fitted from 26 data sets (KEKB, LEPII, RHIC, HERA, Tevatron and LHC)[1].

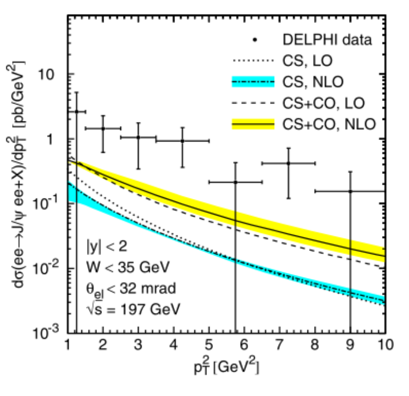


TABLE I. NLO fit results for the J/ψ CO LDMEs.

$\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle$	$(4.97 \pm 0.44) \times 10^{-2}$ GeV^3
$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle$	$(2.24 \pm 0.59) \times 10^{-3}$ GeV^3
$\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle$	$(-1.61 \pm 0.20) \times 10^{-2}$ GeV^5

Owing to the negative value of $\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle$, the DELPHI data cannot be reproduced even with the CO contributions.

Unlike CO LDME, there is less uncertainties in the value of CS LDME. So higher order corrections for CS process might be useful for clarifying the situation.

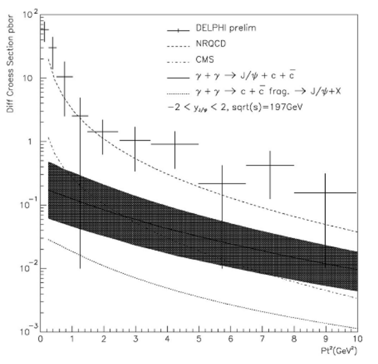
[1] M.Butenschoen and B.A.Kniehl, Phys. Rev. D 84, 051501(2011).

$\gamma + \gamma \to J/\psi + c + \bar{c}$

This important CS process[1] was omitted in previous analysises.

The results shows:

- It is the dominant process among all the CS subprocesses with $p_t^2 > 1\text{GeV}^2$.
- This process cannot be mimicked by the simple fragmentation scheme.



[1] C.F. Qiao and J.X. Wang, Phys. Rev. D 69, 014015(2004).

Resolved Production of $J/\psi + c + \bar{c}$

Further researches indicate that the contributions of single-resolved and double-resolved are significantly less important than the direct one:

1. R. Li and K.-T. Chao, Phys. Rev. D 79, 114020(2009)
2. G. Chen, X.-G. Wu, *et al.* Phys. Rev. D 90, 034004(2014)
3. Z. Sun, X.-G. Wu and H.-F. Zhang, Phys. Rev. D 92, 074021(2015)
4. M. Klasen and J.P.Lansberg, Nucl. Phys. B 179-180 (2008) 226-231
5. ...

NLO QCD Corrections to $\gamma + \gamma \to J/\psi + c + \bar{c}$

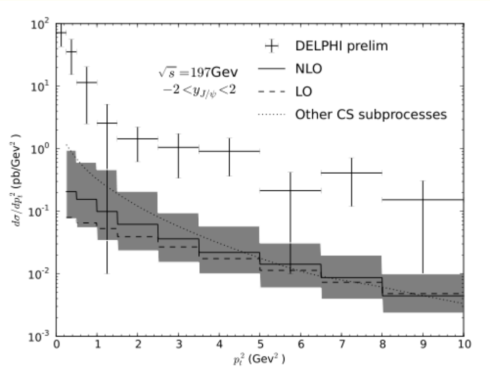
- Motivation
- Numerical Results

Motivation

- An attempt to clarify the contributions of CO processes in LEP2 $\gamma + \gamma \to J/\psi +$ X.
- Provide a more precise cross section for $\gamma + \gamma \to J/\psi + c + \bar{c}$ process, which can be measured at the planned e^+e^- colliders.
- Try to find a efficient way to deal with true 2 to 3 process in heavy quarkonium production. This type of process had never been calculated to NLO before.

Numerical Results[1]

In LEPII collider energy:



- Dash line:
  LO $\gamma\gamma \to J/\psi + c + \bar{c}$.
- Solid line:
  NLO $\gamma\gamma \to J/\psi + c + \bar{c}$
- Upper bound:
  $r = 0.5, m_c = 1.4$GeV;
  Lower bound:
  $r = 2, m_c = 1.6$GeV.
  Where r is introduced in $\mu = r\sqrt{4m_c^2 + p_t^2}$.

Along the p_t increase direction, the NLO correction decreases and eventually turns to be negative.

[1] Z.Q. Chen, L.B. Chen and C.F. Qiao, Phys. Rev. D 95, 036001(2017).

Numerical Results

While integrated over the range $1 \leq p_t^2 \leq 10\text{GeV}^2$,

σ(pb)	$m_c = 1.4$GeV	$m_c = 1.5$GeV	$m_c = 1.6$GeV
$r = 0.5$	$0.766(0.436)$	$0.459(0.283)$	$0.299(0.187)$
$r = 1$	$0.363(0.236)$	$0.227(0.156)$	$0.152(0.105)$
$r = 2$	$0.216(0.152)$	$0.138(0.101)$	$0.093(0.069)$

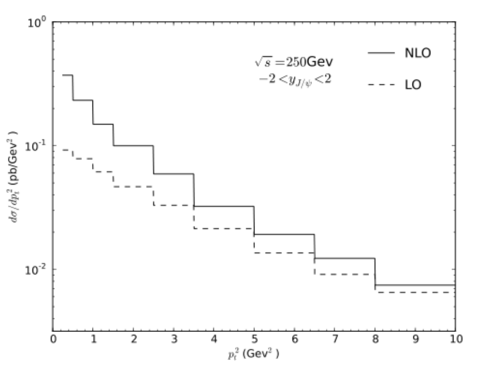
Table: NLO(LO) results of total cross sections with different renormalization scale and charm quark mass. The K factor of central value is about 1.46.

The result of DELPHI and other CS processes read (6.4 ± 2.0)pb and $0.39^{+0.16}_{-0.09}$pb[1], respectively. And the DELPHI data still overshoot the theoretical prediction.

[1] M. Klasen, B. A. Kniehl *et al.*, Phys. Rev. Lett. 89, 032001(2002).

Numerical Results

In CEPC energy ($\sqrt{s} = 250$GeV),



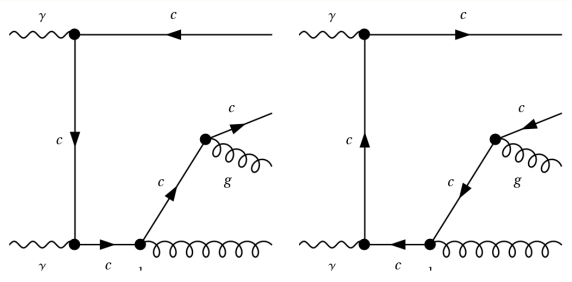
Integrate over $p_t^2 > 1\text{GeV}^2$, we obtain the total cross section 0.245pb(LO) and 0.432pb(NLO), and K factor: 1.76.

$\gamma + \gamma \to J/\psi + g + g + g$ Process

- $\gamma + \gamma \to J/\psi + g + g + g$

$\gamma + \gamma \to J/\psi + g + g$

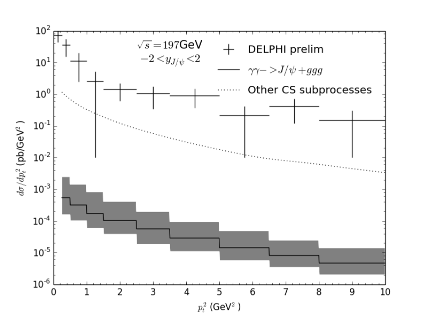
Process $\gamma + \gamma \to J/\psi + g + g$ is of the same order as $\gamma + \gamma \to J/\psi + c + \bar{c}$. But this process is forbidden by Furry's theorem based on charge conjugation invariance.



The color factors of these two diagram are equal: $\mathrm{Tr}(T_a T_b) = \mathrm{Tr}(T_b T_a)$, we may apply Furry's theorem like in QED.

$\gamma + \gamma \to J/\psi + g + g + g$

- LEPII collider energy (197GeV)



upper bound: $r = 0.5$, $m_c = 1.4$GeV
lower bound: $r = 2$, $m_c = 1.6$GeV
solid lines: $r = 1$, $m_c = 1.5$GeV

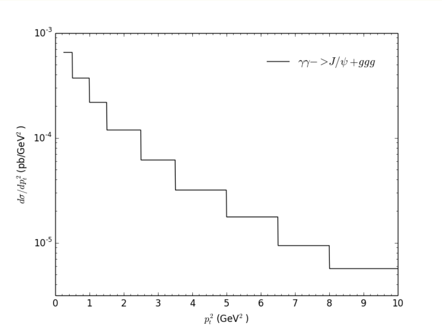
Integrated over the range $1 \le p_t^2 \le 10\text{GeV}^2$,

σ(fb)	$m_c = 1.4$GeV	$m_c = 1.5$GeV	$m_c = 1.6$GeV
$r = 0.5$	1.32	0.82	0.54
$r = 1$	0.52	0.33	0.22
$r = 2$	0.26	0.17	0.12

$\gamma + \gamma \to J/\psi + g + g + g$

- CEPC collider energy (250GeV)

At the e^+e^- collider CEPC,



Integrated over $p_t^2 \geq 1\text{GeV}^2$, we obtain the total cross section 0.39fb.

Summary

- We calculate the NLO QCD corrections to $\gamma + \gamma \rightarrow J/\psi + c + \bar{c}$ process. This is the first truly NLO calculation of 2 to 3 inclusive process for heavy quarkonium production.
- Numerical results shows that the cross section of this process at LEPII can be enhanced with a K factor of about 1.46. And the discrepancy between theoretical prediction and experiment data reduced accordingly.
- The results indicate that the NLO corrections are even significant at CEPC energy, and the K factor can reach up to about 1.76.
- According to Furry's theorem, CS process $\gamma + \gamma \rightarrow J/\psi + g + g$ is forbidden, and contribution from $\gamma + \gamma \rightarrow J/\psi + g + g + g$ process is relatively small.