NLO QCD Corrections to J/ψ Inclusive Production in Photon-Photon Collision

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Outline

- Introduction
- J/ψ Inclusive Production in Photon-Photon Collision
- NLO QCD Corrections to $\gamma\gamma \to J/\psi + c\bar{c}$
- $J/\psi + ggg$ Final State Subprocess
- Summary

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- The test of NRQCD factorization is a exigent task in quarkonium physics. And the study of J/ψ inclusive production through $\gamma\gamma$ collision at LEPII unravel a rather confusing pattern.

J/ψ Inclusive Production in Photon-Photon Collision

- Experimental Data
  - LEPII $\gamma\gamma \to J/\psi + X$ Data
- Theoretical Calculations
  - Three Classes of Subprocesses
  - The LO Calculations
  - The NLO Corrections
  - $J/\psi + c\bar{c}$ Final State Subprocess
  - Full NLO Corrections
  - About Our Work

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

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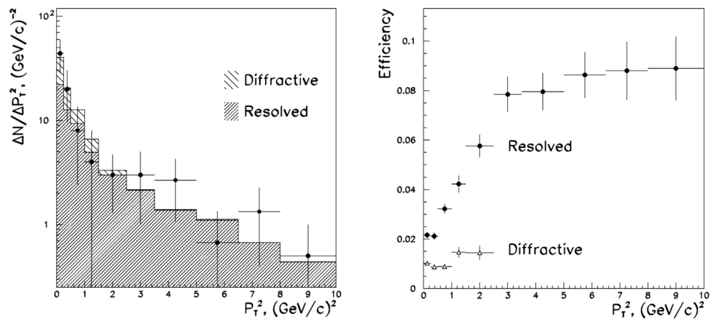

Figure: "DELPHI Collaboration, Phys. Lett. B 565(2003)76-86".

The requirement of at least 4 reconstructed tracks suppress the $J/\psi + \gamma$ final state.

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iii double-resolved process:

$$gg \to c\bar{c}\left[{}^3S_1^{(1)}\right]g, c\bar{c}\left[{}^3P_J^{(1)}\right]g, c\bar{c}[8]g,$$
$$gq \to c\bar{c}\left[{}^3P_J^{(1)}\right]q, c\bar{c}[8]q,$$
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- DELPHI (6.4 ± 2.0)pb
- CSM $0.39^{+0.16}_{-0.09}$pb
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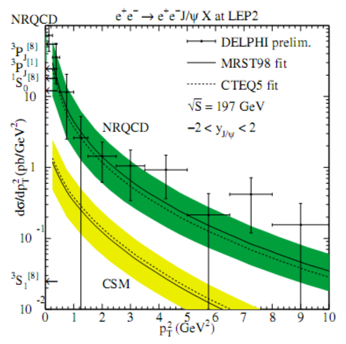

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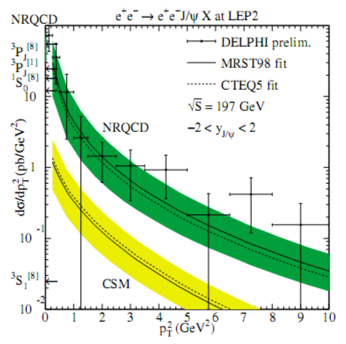

It seems that the CO mechanism is evidently supported by DELPHI data. However, the study is performed only on LO. Higher order corrections should be included before we draw a firm conclusion.

[1] Michael Klasen *et al.*, Nucl. Phys. B 609 (2001).

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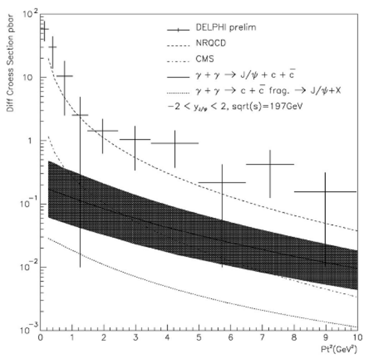
Although none of these analyses is performed in LEPII condition, people infer that similar corrections should not change the former conclusion, and shift their focus to a new subprocess: $J/\psi + c\bar{c}$ final state subprocess.

$J/\psi + c\bar{c}$ Final State Subprocess

The direct production of $J/\psi + c\bar{c}$, namely $\gamma\gamma \to J/\psi + c\bar{c}$ process, prove to be the dominant CS process[1].

A comparison is also made between pure fragmentation result and full calculation in [1]. It is found that this process cannot be mimicked by simple fragmentation scheme.



p

After including this process, the prediction of CS is doubled, but still insufficient to explain experiment data.

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

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These researches indicate that the contributions of single-resolved and double-resolved are significantly less important than the direct one with in the CS prescription. Their contributions do little to reduce the gap between CS prediction and experiment data.

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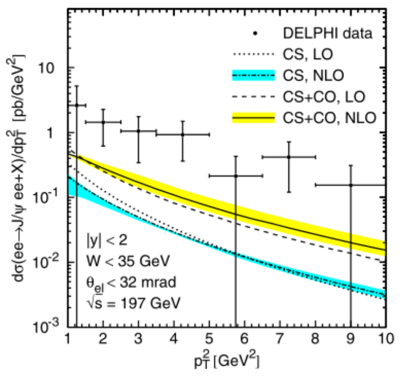

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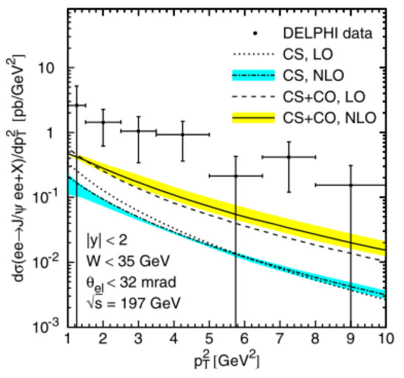

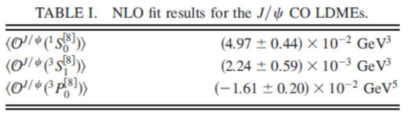

TABLE I. NLO fit results for the J/ψ CO LDMEs.

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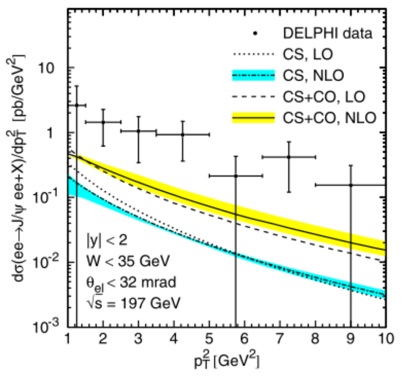

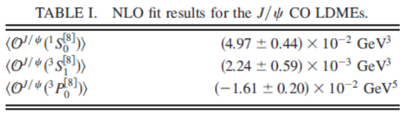

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Kniehl et al. started to emphasise that the data sample only consisted of 16 events above $p_t > 1$GeV.

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

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- This is the first true NLO calculation of 2 to 3 inclusive process in heavy quarkonium production.

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

- Formalism and Calculation
- Numerical Results

Formalism and Calculation

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- The quarkonium spin projection operator is

$$v(P/2)\bar{u}(P/2) = \frac{1}{4\sqrt{2}E(E+2m_c)}(\frac{\not{P}}{2} - m_c)\ \not{\epsilon}_S^*(\not{P} + 2E)(\frac{\not{P}}{2} + m_c)$$

Formalism and Calculation

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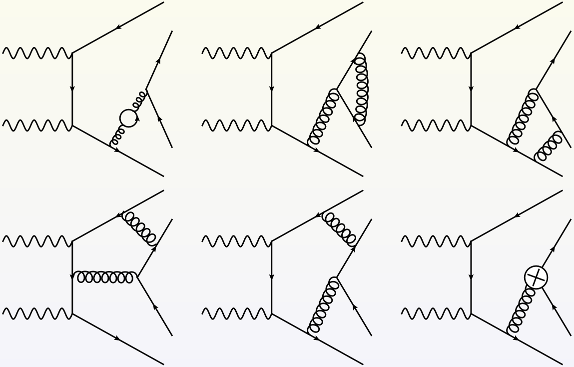
  Selfenergies, Triangles, Boxes, Pentagons, Hexagons and Counter terms



Masses of Feynman integrals are evaluated.

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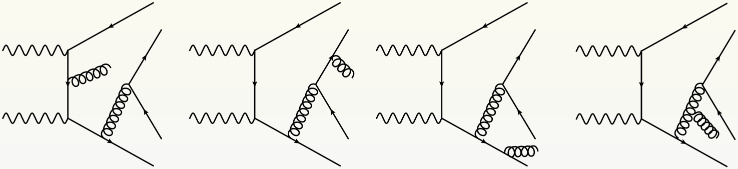

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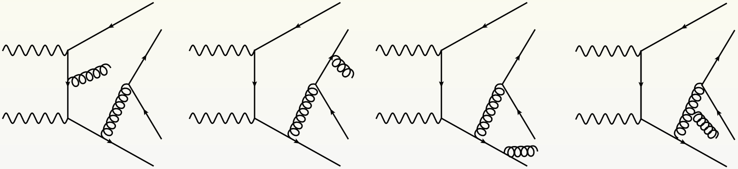

According to B. W. Harris and J. F. Owens, "Two cutoff phase space slicing method", Phys. Rev. D 65, 094032 (2002),

$$d\sigma_{real} = d\sigma^{IR}_{soft}\Big|_{p^0_g<\delta\frac{\sqrt{s}}{2}} + d\sigma^{IR-free}_{hard}\Big|_{p^0_g>\delta\frac{\sqrt{s}}{2}}$$

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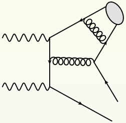

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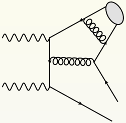

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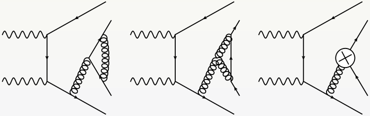

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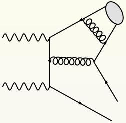

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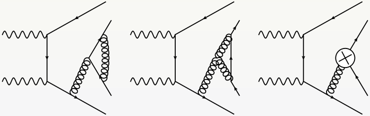
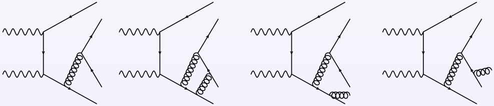


  - iii Infrared singularities involved in virtual corrections and real emissions are canceled each other



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- LEPII collider energy

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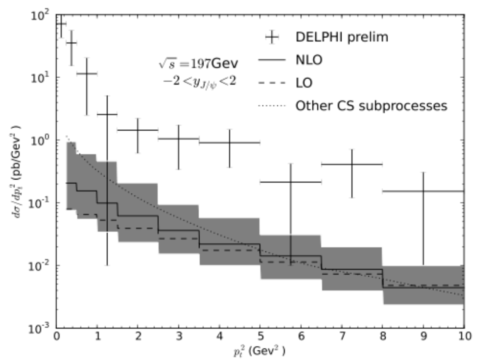

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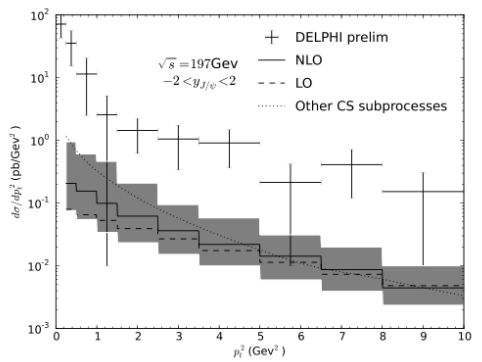

The shaded band is the NLO result of $\gamma\gamma \to J/\psi + c\bar{c}$ process with its upper bound obtained at $r = 0.5$, $m_c = 1.4$GeV and lower bound at $r = 2$, $m_c = 1.6$GeV. The solid and dashed lines represent the NLO and LO results with $r = 1$, $m_c = 1.5$GeV.

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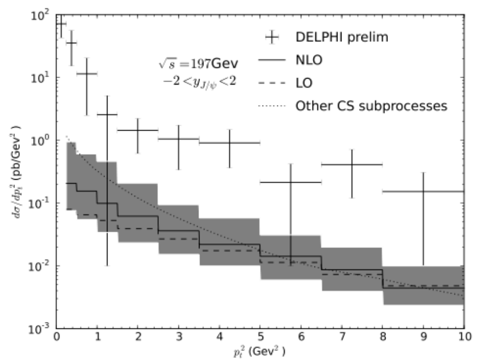

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The NLO correction is moderate but not big enough to remove the huge discrepancy between theoretical prediction and experimental observation.

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

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

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.

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The result of DELPHI and other CS processes read (6.4 ± 2.0)pb and $0.39^{+0.16}_{-0.09}$pb, respectively. And the DELPHI data can not be reproduced by CS model (according to [1] NRQCD neither) after including our corrections.

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

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- CEPC collider energy

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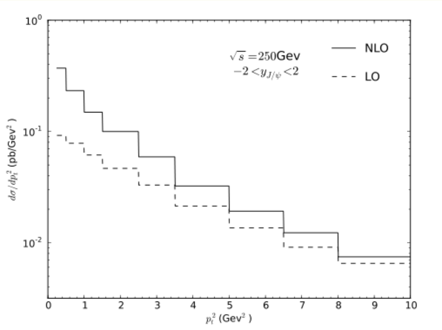

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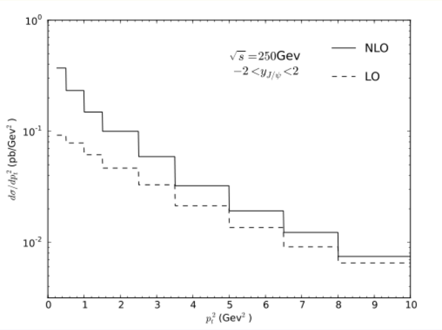

The p_t^2 distribution of $J/\psi + c\bar{c}$ production through $\gamma\gamma$ collision at CEPC. The solid and dashed lines represent the NLO and LO results with $r = 1, m_c = 1.5\text{GeV}$.

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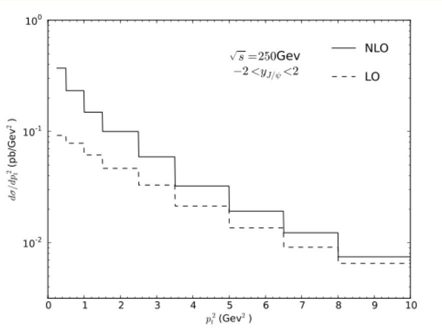

The p_t^2 distribution of $J/\psi + c\bar{c}$ production through $\gamma\gamma$ collision at CEPC. The solid and dashed lines represent the NLO and LO results with $r = 1, m_c = 1.5$GeV. Integrated over $p_t^2 \geq 1$GeV^2, the total NLO(LO) cross section is 0.432pb(0.245pb). The K factor is about 1.76.

$J/\psi + ggg$ Final State Subprocess

- $\gamma\gamma \to J/\psi + gg$ Process and Furry's Theorem
- Feynman Diagrams
- Numerical Results

$\gamma\gamma \to J/\psi + gg$ Process and Furry's Theorem

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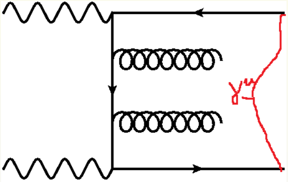

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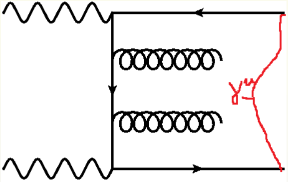

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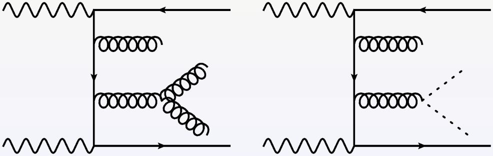
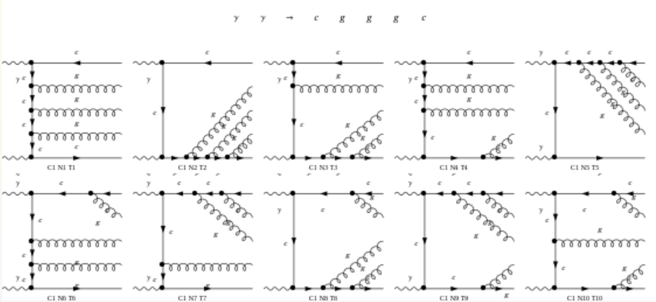


This was also verified by explicit calculation.

Feynman Diagrams

There are 120 Feynman diagrams for $\gamma\gamma \to J/\psi + ggg$.



Other diagrams can be obtained by exchange gluons and photons.

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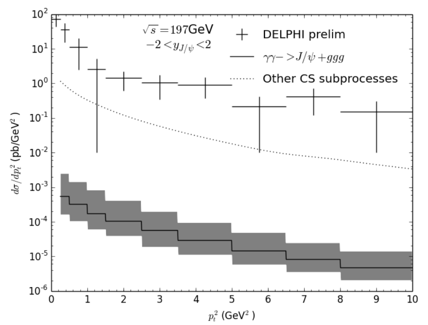

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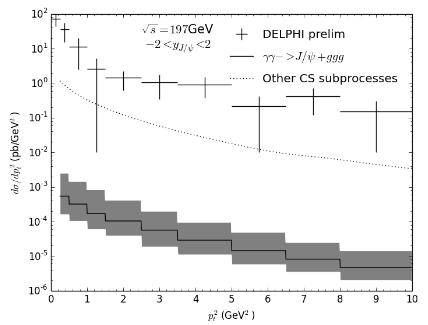

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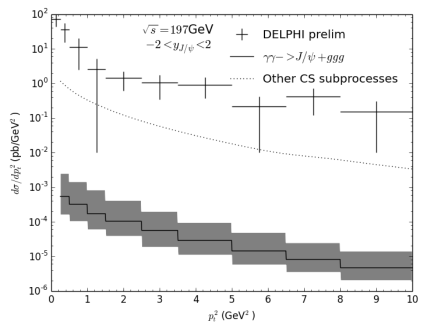

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Integrated over the range $1 \leq p_t^2 \leq 10\text{GeV}^2$,

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

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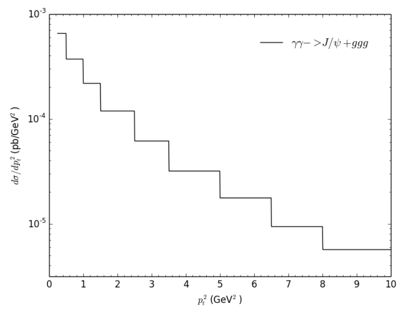

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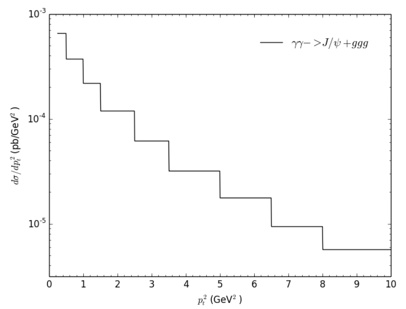

The p_t^2 distribution of $J/\psi + ggg$ production through $\gamma\gamma$ collision at CEPC. The solid lines represent the cross section with $r = 1$, $m_c = 1.5$GeV. Integrated over $p_t^2 \geq 1\text{GeV}^2$, the total cross section is 0.39fb.

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- As a experimentally distinguishable final state process, It is meaningful to predict its cross section at CEPC. Our results indicate that The NLO corrections is more significant there. And the K factor can reach up to 1.76.
- According to Furry's theorem, CS process $\gamma\gamma \rightarrow J/\psi + gg$ is forbidden. The cross section of $\gamma\gamma \rightarrow J/\psi + ggg$ is relatively small.