One-loop corrections to inclusive production of J/ψ and Υ in high-energy photon-photon collisions in NRQCD at LO in v^2

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Sep. 27, 2023

Assemblée Générale 2023 du GDR QCD

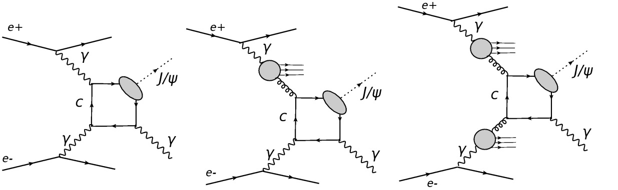
Part I

Introduction

Introduction: inclusive J/ψ and Υ production in photon fusion

In this work we discuss **direct-photon and single-resolved photon $J/\psi(\Upsilon)$ production in $\gamma\gamma$ fusion**:

- as a reminder, $J/\psi(\Upsilon)$ is a $c\bar{c}$ ($b\bar{b}$) bound state with $J = 1,\ L = 0,\ S = 1$; vector particle

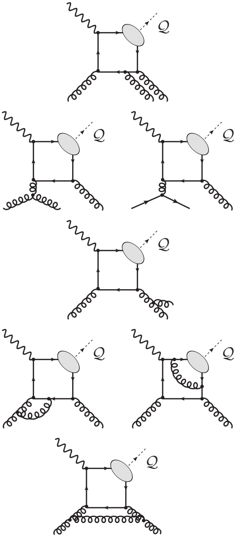


direct-photon *single-resolved photon* *double-resolved photons*

- One supposes **factorisation**:
  1. **collinear**, in which the hadronic cross section can be written as the convolution of the photon flux (WWA) and PDFs (for resolved-photon) with the partonic cross section;
  2. **between the hard part** (a perturbative amplitude, which describes the $Q\bar{Q}$ pair production) and **the soft part** (a non-perturbative matrix element, which describes hadronisation - LDME):
- **Colour Singlet (CS):** the Taylor series expansion of the ampl. in the $Q\overline{Q}$ relative momentum (v) to the 1st non-vanishing term. Colour Octet (CO): higher-v^2 ord.

General structure of NLO corrections

M. Krämer, Nucl.Phys., B459, 3 (96')

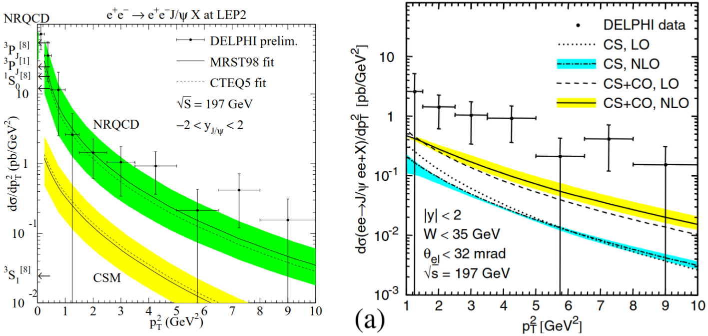


Singularities at NLO [and how they are removed]:

- Real emission
  - Infrared divergences: Soft [cancelled by loop IR contr.]
  - Infrared divergences: Collinear
    - ★ initial state [subtracted by Altarelli-Parisi counter-terms (AP-CT) in the factorised PDFs]
    - ★ final state [cancelled by loop IR contr.]
- Virtual (loop) contribution
  - Ultraviolet divergences: [removed by renormalisation]
  - Infrared divergences: [cancelled by real Infrared contribution]

[The quark and antiquark attached to the ellipsis are taken as on-shell and their relative velocity v is set to zero.]

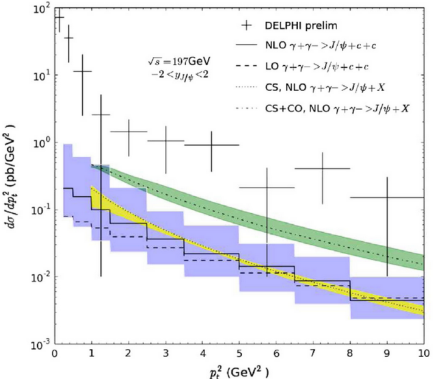
LEP2 Puzzle: the DELPHI data overshoot CS+CO



- M. Klasen, B.A. Kniehl, L.N. Mihaila, M. Steinhauser (Phys.Rev.Lett.89:032001,2002): at low p_T LO CS+CO prediction reproduces the **DELPHI** data (J. Abdallah et al., PLB 565, 76 (2003))
- M. Butenschoen,B.A.Kniehl: (PRD84, 051501(R),2011): At NLO in α_S-order CS+CO these data do not agree anymore with NRQCD
- DELPHI: the normalisation of the data may be wrong: only 16ev. with $p_T > 1$GeV and it was not confirmed by any of the 3 LEPII exp.
- CO: perturbatively unstable

LEP2 Puzzle: more direct photon processes

Z.Q.Chen, L.B. Chen and C.F. Qiao: PRD 95, 036001 (2017)



- Given the current situation $\rightarrow$ direct photon processes matter
- In PRD 95: dominant direct $\gamma\gamma \rightarrow J/\psi c\bar{c}$ was computed up to NLO in α_s in CS $\rightarrow$ but it's not enought to reproduce the data
- the QED contribution to the inclusive yield was never considered for DELPHI and CEPC

DEPLHI data: J. Abdallah et al., PLB 565, 76 (2003)

Part II

Computation of direct-photon $J/\psi(\Upsilon) + \gamma$ in $\gamma\gamma$ fusion process

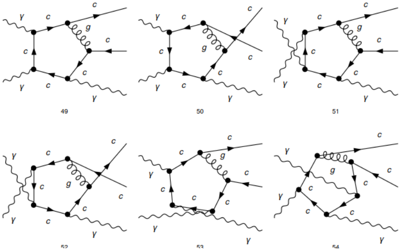
Squared amplitude

- FeynArts: to generate expressions for Feynman diagrams
- In the amplitudes for the bound state of $c\bar{c}$ we replace heavy-quark spinors $\bar{u}(p_1)$ and $v(p_2)$ with the Colour Singlet spin projector + contracted colour indices + one momenta:

$$c(p_1) + \bar{c}(p_2) \to c\bar{c}\left[{}^3S_1^{(1)}\right](k_3)$$

- FeynCalc: tensor reduction & find master topologies (7/48 total)
- Solve linear dependence in propagators introduced with NRQCD limit $\to$ partial-fractioning

Partial-fractioning



1. Equation with linearly-dependant denominators $(1/(D_1 D_2 D_3))$:
   $Eq = aD_1(l) + bD_2(l) + cD_3(l) + f = 0$, where $a, b, c, f \neq a(l), b(l), c(l), f(l)$

2. Two cases

   1. If $f = 0$, then $Eq/(cD_3)/(D_1 D_2 D_3)$:
      $$\frac{1}{D_1 D_2 D_3} = -\frac{b}{c}\frac{D_2}{D_3}\frac{1}{D_1 D_2 D_3} - \frac{a}{c}\frac{D_1}{D_3}\frac{1}{D_1 D_2 D_3}$$
      $$= -\frac{b}{c}\frac{1}{D_1 D_3^2} - \frac{a}{c}\frac{1}{D_2 D_3^2}$$
   2. If $f \neq 0$, then $Eq/(f)/(D_1 D_2 D_3)$:
      $$\frac{1}{D_1 D_2 D_3} = -\frac{b}{f}\frac{D_2}{D_1 D_2 D_3} - \frac{a}{f}\frac{D_1}{D_1 D_2 D_3} - \frac{c}{f}\frac{D_3}{D_1 D_2 D_3}$$

Evaluation of the master integrals

- Feynman integrals:

$$I(\vec{s};\nu;D) = \int \left(\prod_{j=1}^{L} e^{\gamma_E \epsilon} \frac{d^D l_j}{i\pi^{D/2}} \right) \frac{N(l_j \cdot l_l, l_j \cdot p_l; D)}{\prod_{j=1}^{p} (m_j^2 - q_j^2 - i\epsilon)^{\nu_j}},$$

- **Master integrals** (MI): integrals with $\nu_j = 0, 1$ for each $j-$denominator and $N(l_j \cdot l_l, l_j \cdot p_l; D) = 1$
- IBP reduction: follow from translation invariance of the loop momentum.
- LiteRed, FIRE, KIRA, FiniteFlow - IBP reduction of Feynman integrals to master integrals
- LoopTools library: Feynman integrals are evaluated in an efficient and numerically-stable way

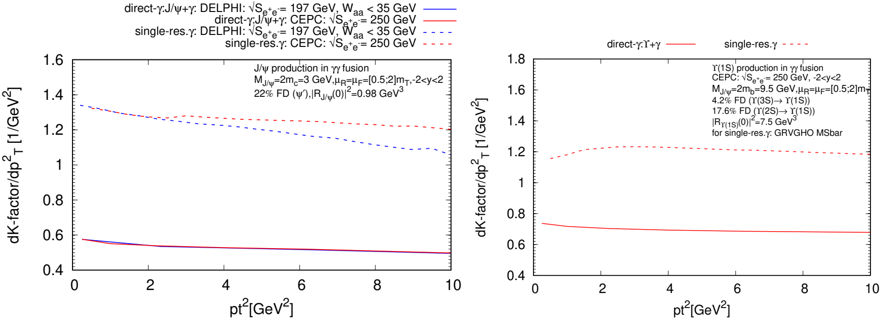
Evaluation of the amplitudes

- UV renormalisation: wave-function and quark mass renormalisation counter-terms (in On-shell scheme) restore gauge invariance and cancel μ_R dependence of the $J/\psi + \gamma$ amplitudes
- Fortran: to get differential hadronic cross-section, phase-space integration was performed numerically using CUBA packages (MC integration routines)
- Helac-Onia+MadAnalysis: we generate .lhe files + apply experimental cuts to plot LO cross sections for $\gamma\gamma \to J/\psi + ggg$ and $\gamma\gamma \to J/\psi + c\bar{c}$
- One of the goals is to work on helicity amplitudes, which could be used to implement α_s-order cross-section computation in MC generators
- In future the one-loop helicity amplitudes for the similar process $gg \to J/\psi + \gamma$ are relevant for TMD factorization computations at NLO

Part III

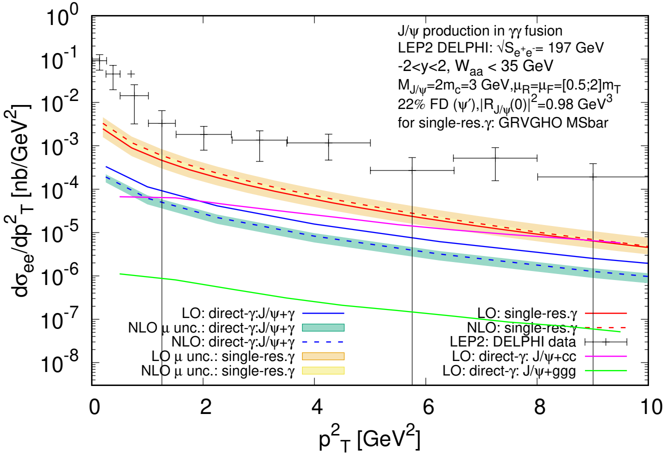
Phenomenology study of quarkonium production

K factors for DELPHI and CEPC predictions



- For single-resolved photon contribution K-factor > 1, direct-photon ($J/\psi + \gamma$) contribution < 1
- Detailed comparison with the results from Klasen et al. (PRD71, 014016 (2005)) - in progress

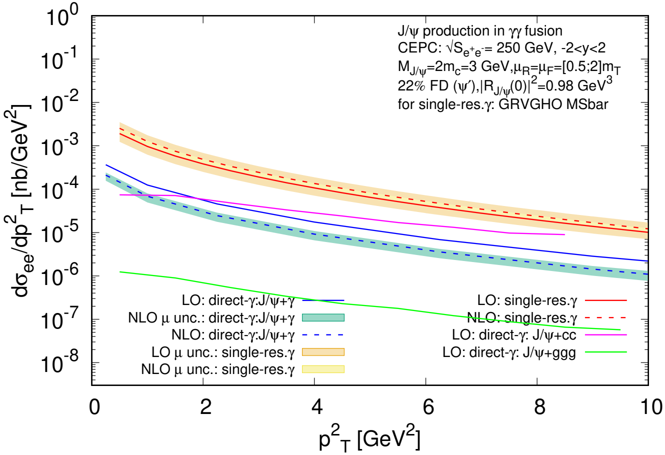
Results with LEP2 DELPHI cuts for J/ψ



- We computed CS 1-loop QED direct-γ predictions for the 1st time for DELPHI
- QED contribution is relevant at low p_T
- CS channels ($J/\psi + ggg$) and ($J/\psi + c\bar{c}$) included at LO in α_s

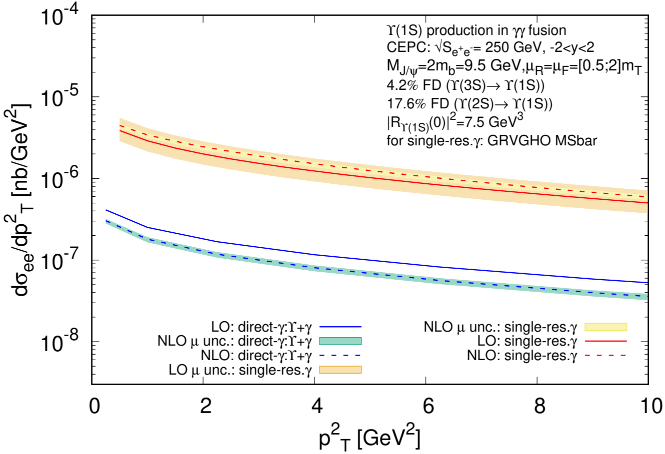
DEPLHI data: J. Abdallah et al., PLB 565, 76 (2003)

Predictions with CEPC cuts for J/ψ



- We computed CS 1-loop QED direct-γ predictions for the 1st time for CEPC
- QED contribution is relevant at low p_T
- CS channels ($J/\psi + ggg$) and ($J/\psi + c\bar{c}$) included at LO in α_s

Predictions with CEPC cuts for Υ



- We computed CS 1-loop QED direct-photon and single-resolved photon predictions for Υ for the 1st time for CEPC
- For Υ CO-contribution is smaller
- QED contribution is relevant at low p_T

Exclusive $\gamma + \gamma \to J/\psi + \gamma$ is within the LHC reach

Thanks to D. d'Enterria and K.Lynch

- Photon efficiency:
  - $2.5 < p_T^\gamma < 3$GeV: O(0.5) due to trigger, expected to grow close to 1 if associated with a J/ψ
  - $p_T^\gamma > 3$GeV=O(1)
- Cross section in UPC PbPb collisions in the CMS at $\sqrt{s} = 5.02$TeV for
  - $1.2 < |y^\psi| < 2.4$
  - $|\eta^\gamma| < 2.4$
  - $p_T^\psi > 2.5$GeV
- $\sigma_{LO} = O(10)$nb, ($K_{NLO} = O(1)$)
- Expected event counts: $\sigma \times \epsilon \times Br \times L_{PbPb} = 10 \times 0.06 \times 13 = O(10)$ events
- Conclusion: exclusive direct-photon ($J/\psi + \gamma$) can be measured in ultra-peripheral heavy-ion collisions at the LHC
- This gives us confidence that inclusive $J/\psi + \gamma$ and $J/\psi + X$ from photon fusion can be measured at LHC if UPC can be identified in inclusive reactions

Summary

- LEP puzzle: the experimental data from DELPHI LEP2 overshoots CS+CO NLO-α_s leading $\gamma\gamma \to J/\psi + X$ contributions
- It may indicate that we have issues with the normalisation of the data or with the CO model
- CS is more perturbatively stable: direct-photon processes ($J/\psi + \gamma$, $J/\psi + c\bar{c}$) are not negligible
- We computed the first predictions for CS one-loop QED direct-photon production for CEPC and DELPHI and single-resolved photon contributions for J/ψ production for CEPC
- We computed the first predictions for CS one-loop QED direct-photon and single-resolved photon contributions for Υ production for CEPC
- For the computations we used self-written codes based on FeynArts, FeynCalc, KIRA, LoopTools, Fortran - CUBA
- Exclusive direct-photon ($J/\psi + \gamma$) can be measured in ultra-peripheral heavy-ion collisions at the LHC