One-loop QCD corrections to inclusive production of J/ψ and Υ in e^+e^- annihilation

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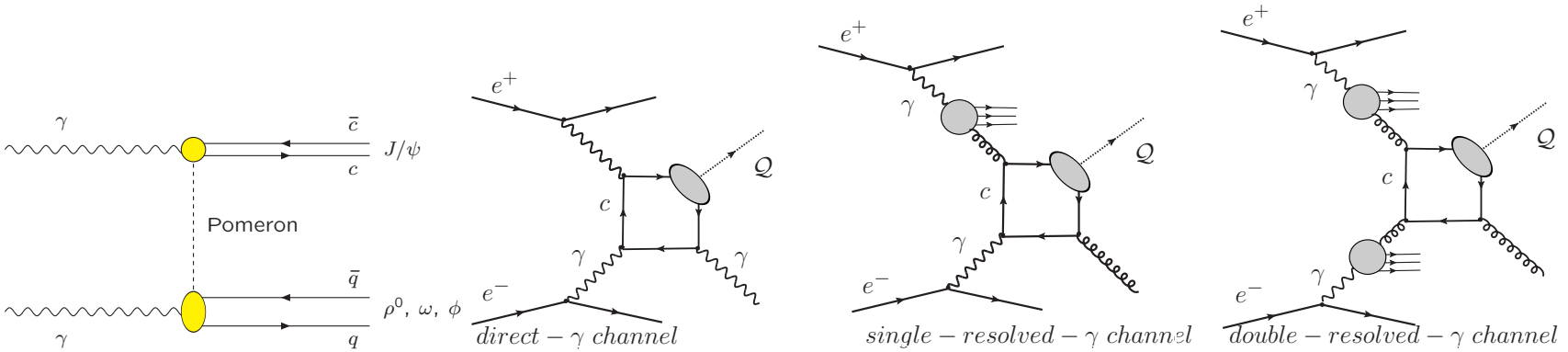
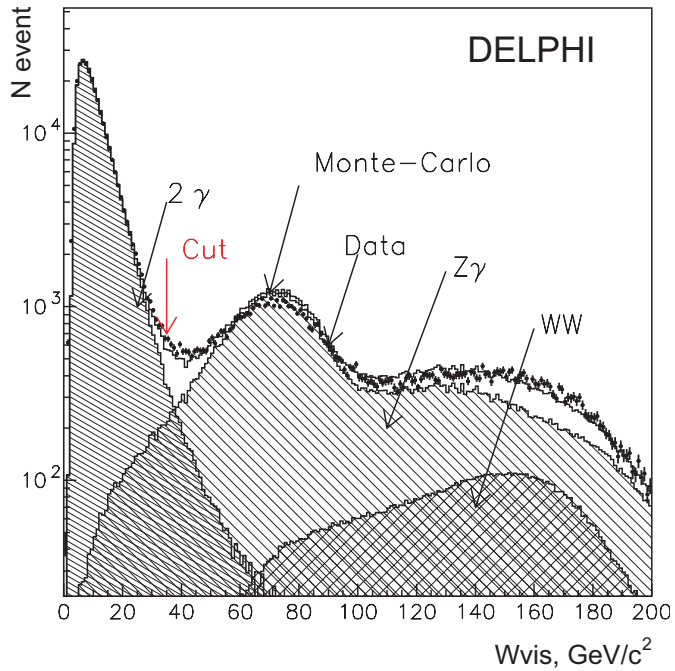
Introduction: inclusive J/ψ and Υ production in e^+e^- annihilation

Production channels: **diffraction**, **direct-photon, (single/double) resolved photon**



- Diffraction contributes at $p_T < 1$ GeV
- Double-resolved production is suppressed by α_s and one extra photon PDF
- Only direct-photon and single-resolved production significantly cotributes at $p_T > 1$ GeV
- To remove background from $e^+e^- \to \gamma Z$ and $e^+e^- \to W^+W^-$ DELPHI experiment puts $W^{(\gamma\gamma)}_{\text{vis.}} < 35$ GeV cut.



Quarkonium production mechanisms

- In quarkonium production physics one uses the fact that relative velocity of the bound state v is low: $v^2 \sim 0.3$ for charmonia and $v^2 \sim 0.1$ for bottomonia
- $\Rightarrow$ The colour-singlet $Q\bar{Q}$-state dominates the Fock-state decomposition of the physical S-wave bound state, e.g.:

$$|J/\psi\rangle = O(1)|c\bar{c}[^3S_1^{[1]}]\rangle + O(v)|c\bar{c}[^3P_J^{[8]}] + g\rangle + \dots$$

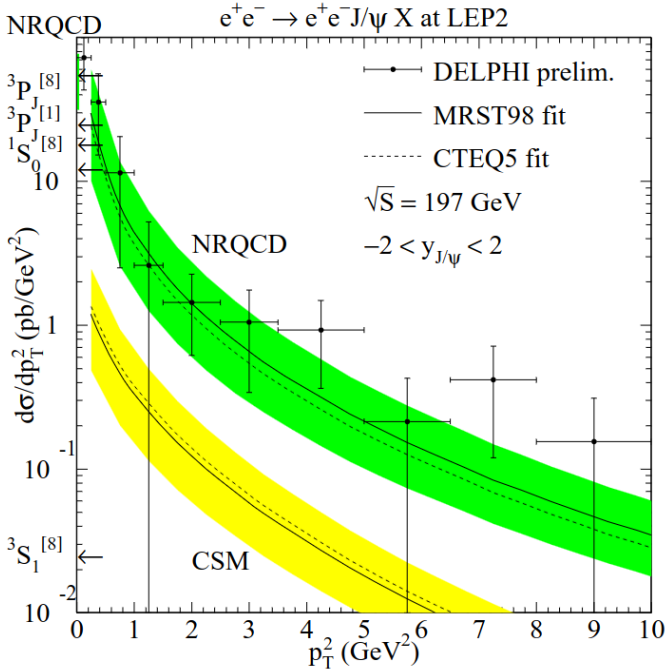
- So in the leading-order in v the production cross section is (**colour-singlet model (CSM)**):

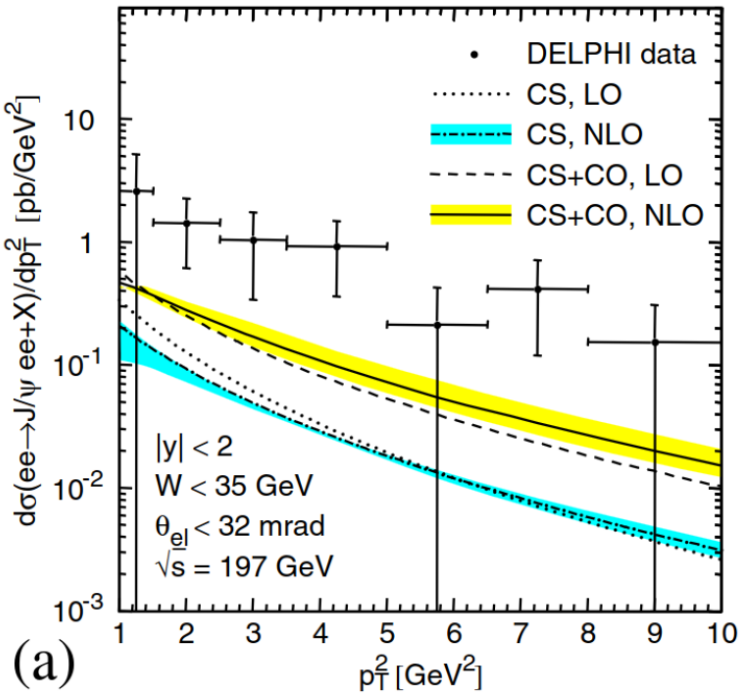
$$d\sigma(J/\psi + X) = d\sigma(c\bar{c}[^3S_1^{[1]}] + X) \times \frac{|R(0)|^2}{4\pi} + O(v^2)$$

- Colour-octet states contribute (**NRQCD**), but corresponding **long-distance matrix elements** are supressed by v^2.

In the present work we revisit main **CSM** production channels at NLO in α_s and provide predictions for future high-energy e^+e^- facilities.

LEP2 Puzzle: the DELPHI data overshoot CS+CO

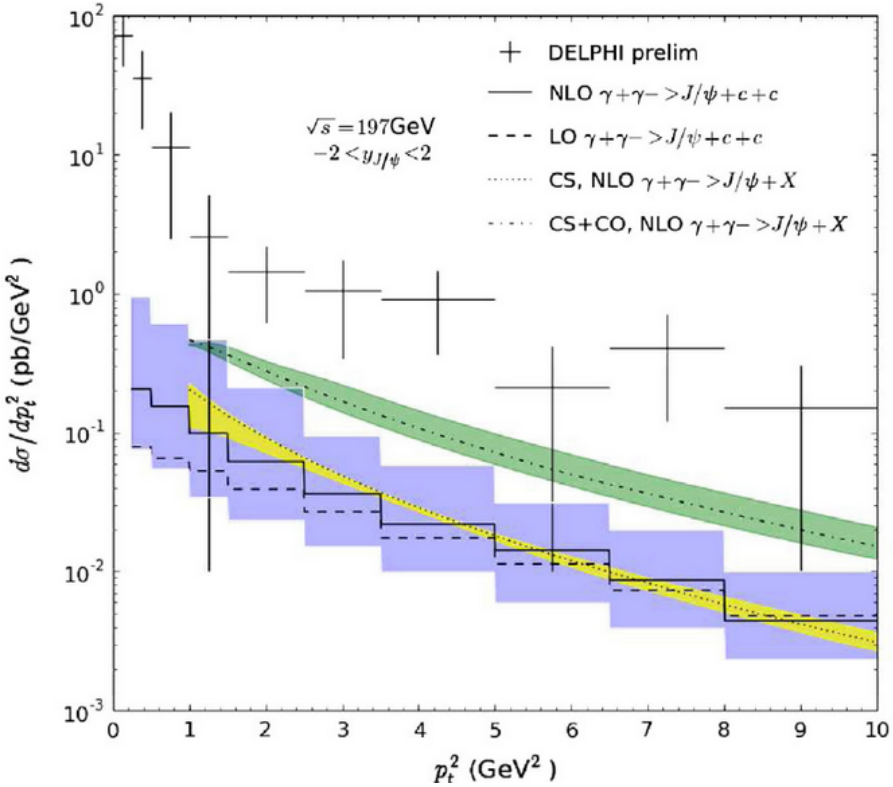




- M. Klasen, B.A. Kniehl, L.N. Mihaila, M. Steinhauser (Phys.Rev.Lett.89:032001,2002): at low p_T LO CS+CO prediction reproduces the **DELPHI** data (J. Abdallah et al., PLB 565, 76 (2003))
- M. Butenschoen,B.A.Kniehl: (PRD84, 051501(R),2011): At NLO in α_s-order CS+CO these data do not agree anymore with NRQCD
- DELPHI: the absolute p_T-spectrum was not published in PLB
- CO: perturbatively unstable?
- In QCD calculations we put $W^{(\gamma\gamma)} < 35$ GeV but $W^{(\gamma\gamma)} > W^{(\gamma\gamma)}_{\text{vis.}}$!

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
- 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 enough to reproduce the data
- the QED (direct-photon) contribution to the inclusive yield was never considered for DELPHI

Subprocesses in CSM

- **Direct-photon (QED)** channel:

$$\gamma + \gamma \to Q\bar{Q}\left[{}^3S_1^{[1]}\right] + \gamma,$$

recieves finite one-loop correction at $O(\alpha_s)$. [Klasen, Kniehl, Michaila, Steinhauser, PRD 2004]
No publicly available implementation exists.

- **Single-resolved** channel at LO:

$$\gamma + g \to Q\bar{Q}\left[{}^3S_1^{[1]}\right] + g,$$

and NLO, one-loop + real-emission corrections:

$$\begin{aligned}
\gamma + g &\to Q\bar{Q}\left[{}^3S_1^{[1]}\right] + g + g \text{ (or } + q + \bar{q}), \\
\gamma + q &\to Q\bar{Q}\left[{}^3S_1^{[1]}\right] + g + q,
\end{aligned}$$

[Kraemer, NPB 1995] No publicly available implementation exists.

- **Direct-photon (QCD)** channels (so far at LO in our calculation, using HelacOnia):

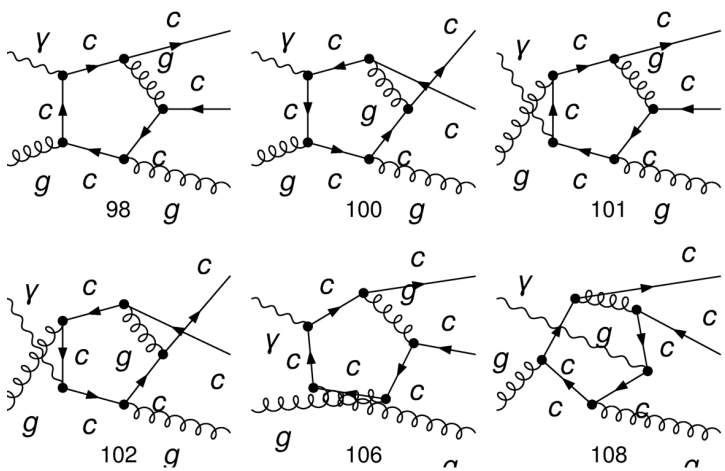
$$\begin{aligned}
\gamma + \gamma &\to Q\bar{Q}\left[{}^3S_1^{[1]}\right] + Q + \bar{Q}, \\
\gamma + \gamma &\to Q\bar{Q}\left[{}^3S_1^{[1]}\right] + g + g + g.
\end{aligned}$$

Virtual NLO corrections

- 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 projector on the colour-singlet state with total spin 1 and put $p_1 = p_2 = p_{J/\psi}/2$.
- FeynCalc: tensor reduction & mapping to master topologies
- Solve linear dependence in propagators introduced by the non-relativistic limit $\rightarrow$ partial-fractioning, leads to squared denominators in Coulomb-divergent diagrams
- FIRE, KIRA - IBP reduction to standard basis of one-loop Feynman integrals
- LoopTools library: numerical evaluation of master integrals

Subset of diagrams containing Coulomb divergence:

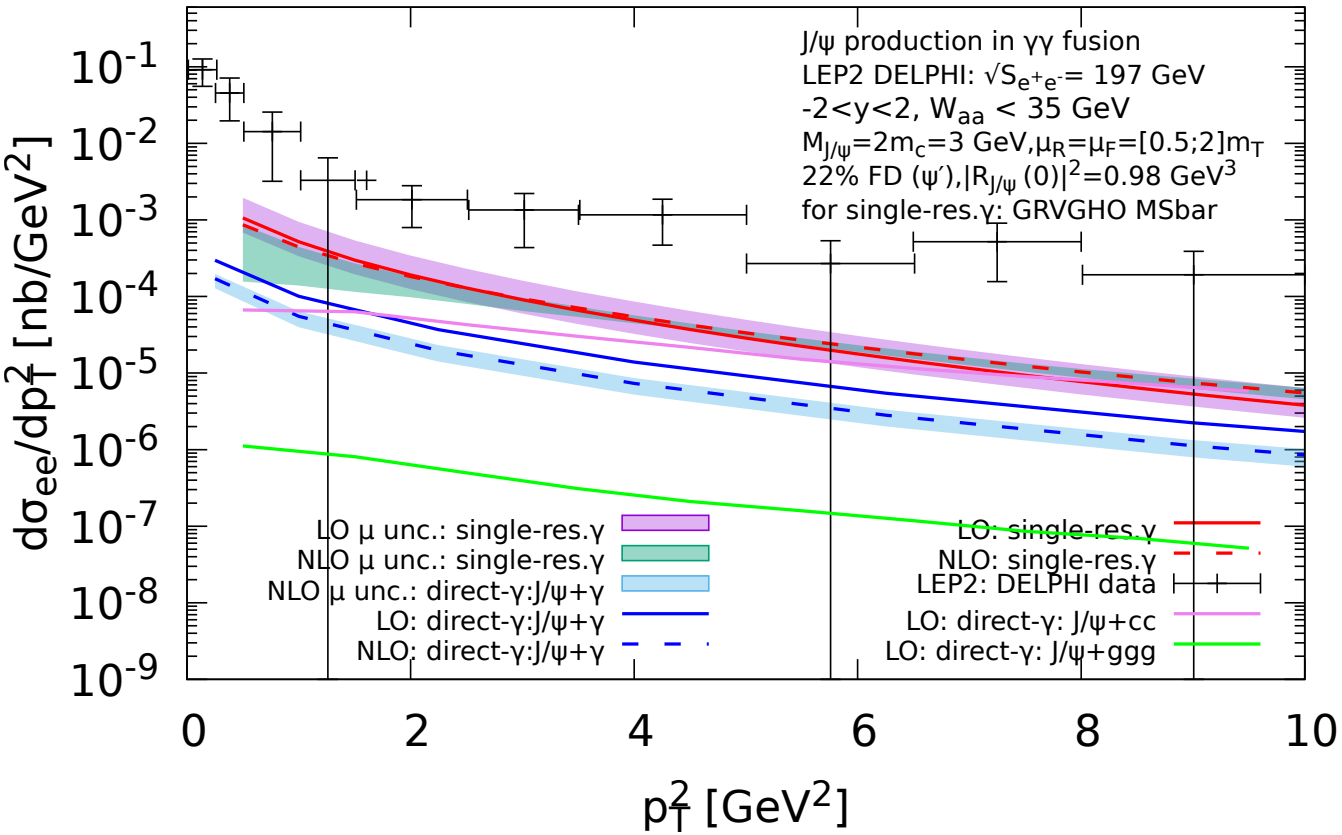
$\gamma\ g \rightarrow c\ c\ g$



Real-emission NLO corrections

- The $2 \to 3$ matrix elements generated with FormCalc
- The **Catani-Seymour** dipole subtraction algorithm is used to deal with infra-red and collinear divergences in the $2 \to 3$ phase-space integration
- The most numerically demanding part of the NLO computation: the $2 \to 3$ **PS integration** is separated from the **convolution with photon PDF and photon fluxes** using intermadiate interpolation $\Rightarrow$ **fast and stable evaluation of NLO cross sections**
- Numerous cross checks against other existing implementations of the quarkonium photoproduction process (thanks to **M. Butenschön**, **Yu Feng** and **C. Flore**!)

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)

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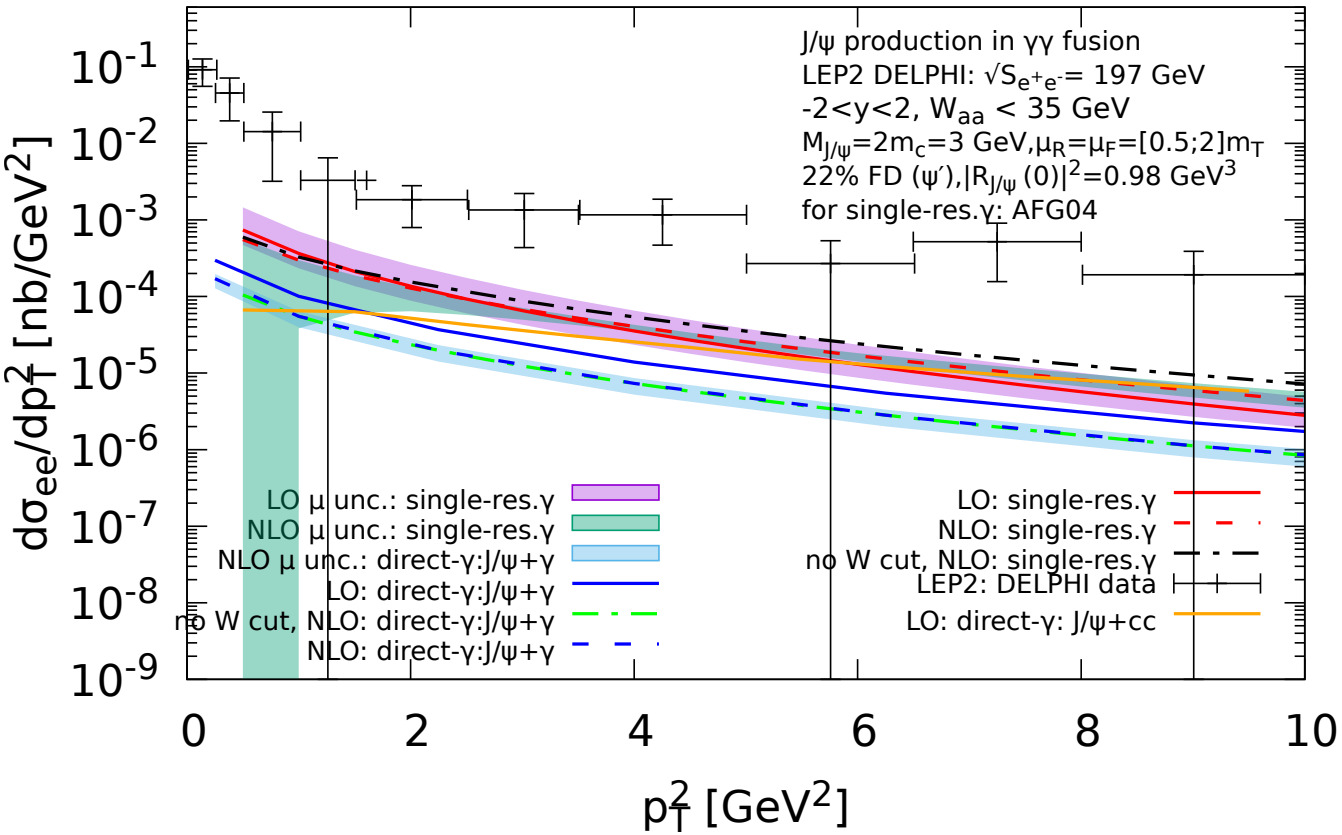

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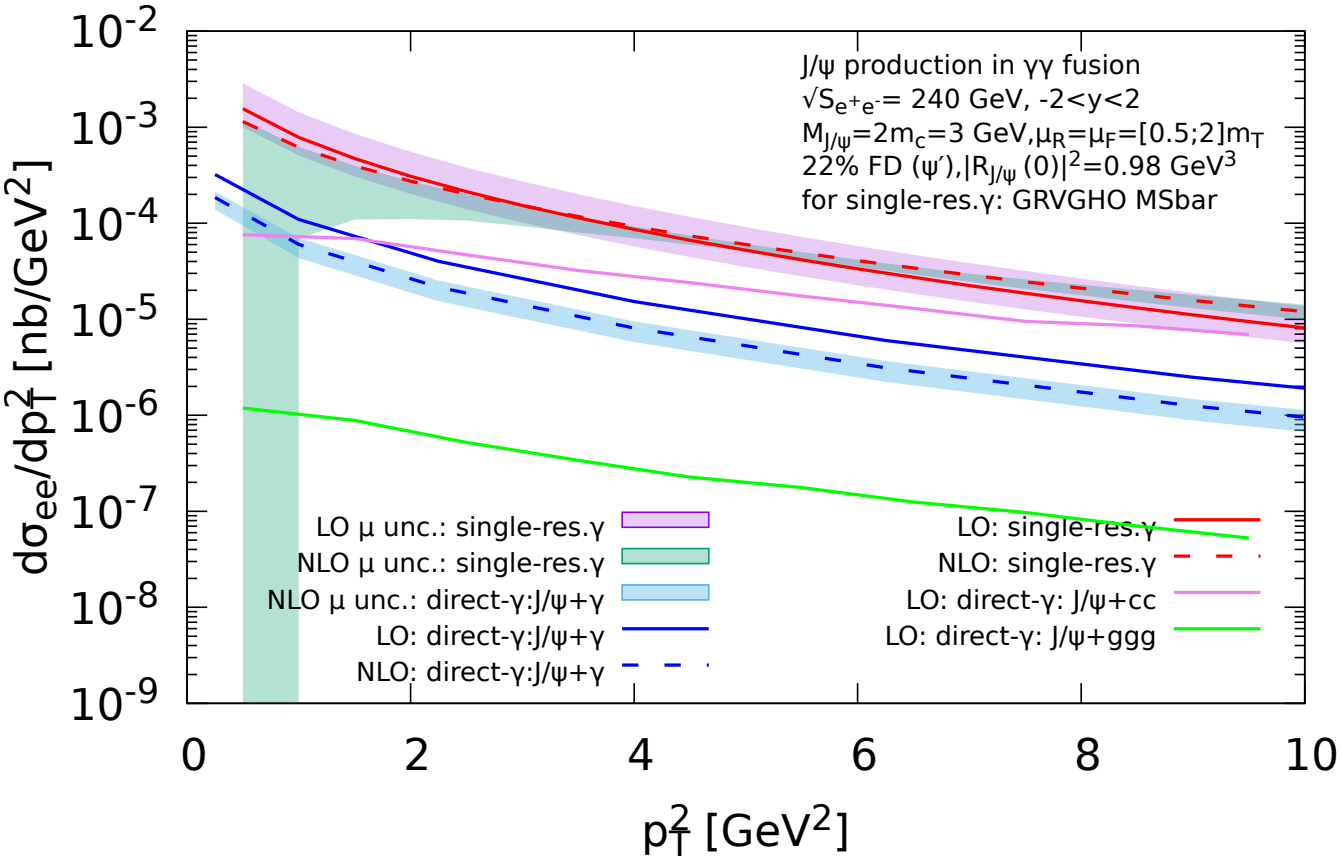
Future high-energy e^+e^- colliders

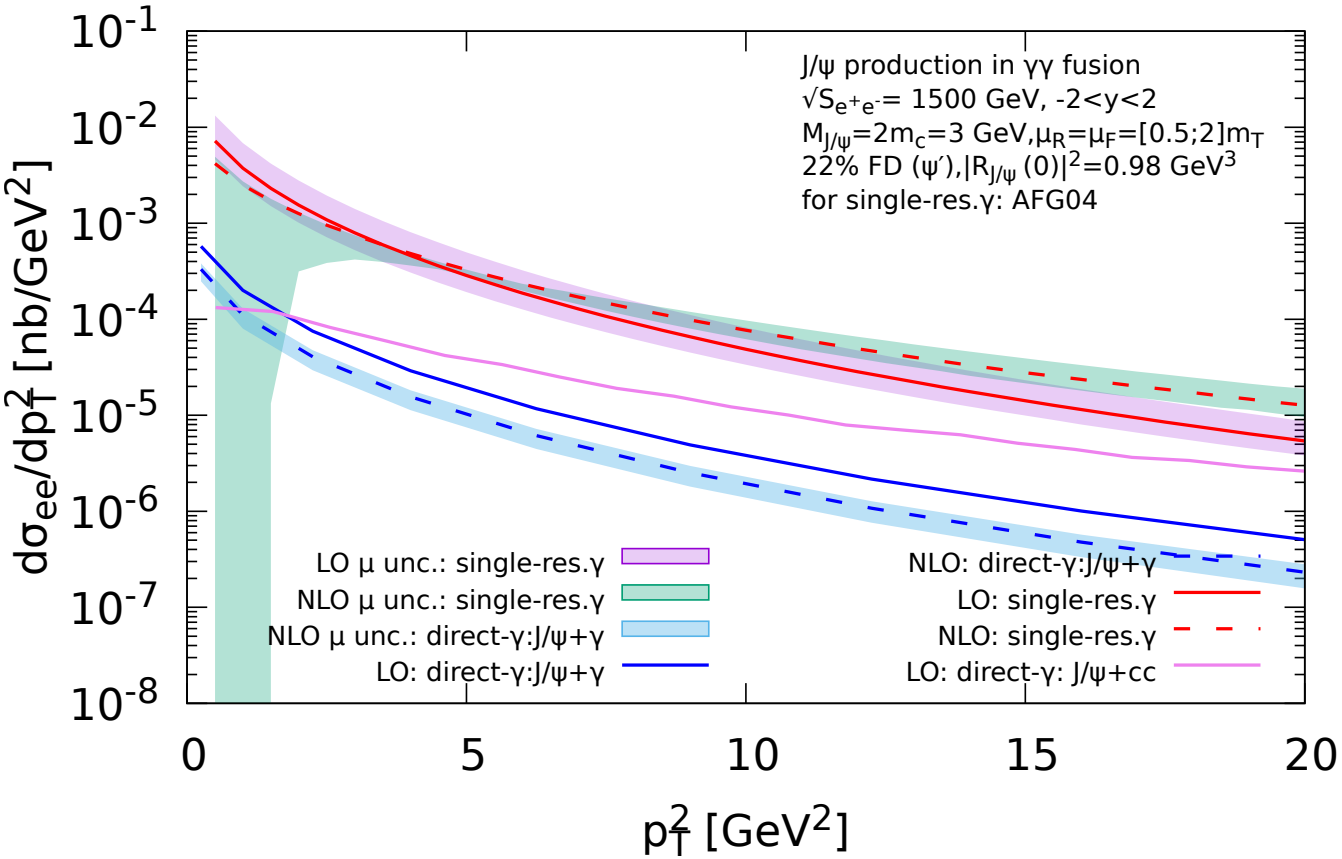
experiment	int. lumi. (ab^{-1})	$\sqrt{s}(GeV)$	"golden" prod. mode
CEPC	5.6	240	H
CEPC	5.6	240	H
CEPC	16	91.2	Z
CEPC	2.6	160	$W^{\pm}$
FCC-ee	5	240	H
FCC-ee	150	91	Z
FCC-ee	12	160	$W^{\pm}$
FCC-ee	1.7	350	$t\bar{t}$
CLIC	0.1	350	$Z, t\bar{t}, H$
CLIC	0.5	380	$t\bar{t}, H$
CLIC	1.5	1500	$t\bar{t}, H$
CLIC	3.0	3000	$t\bar{t}, H$

J/ψ production at $\sqrt{s_{ee}} = 240\text{GeV}$



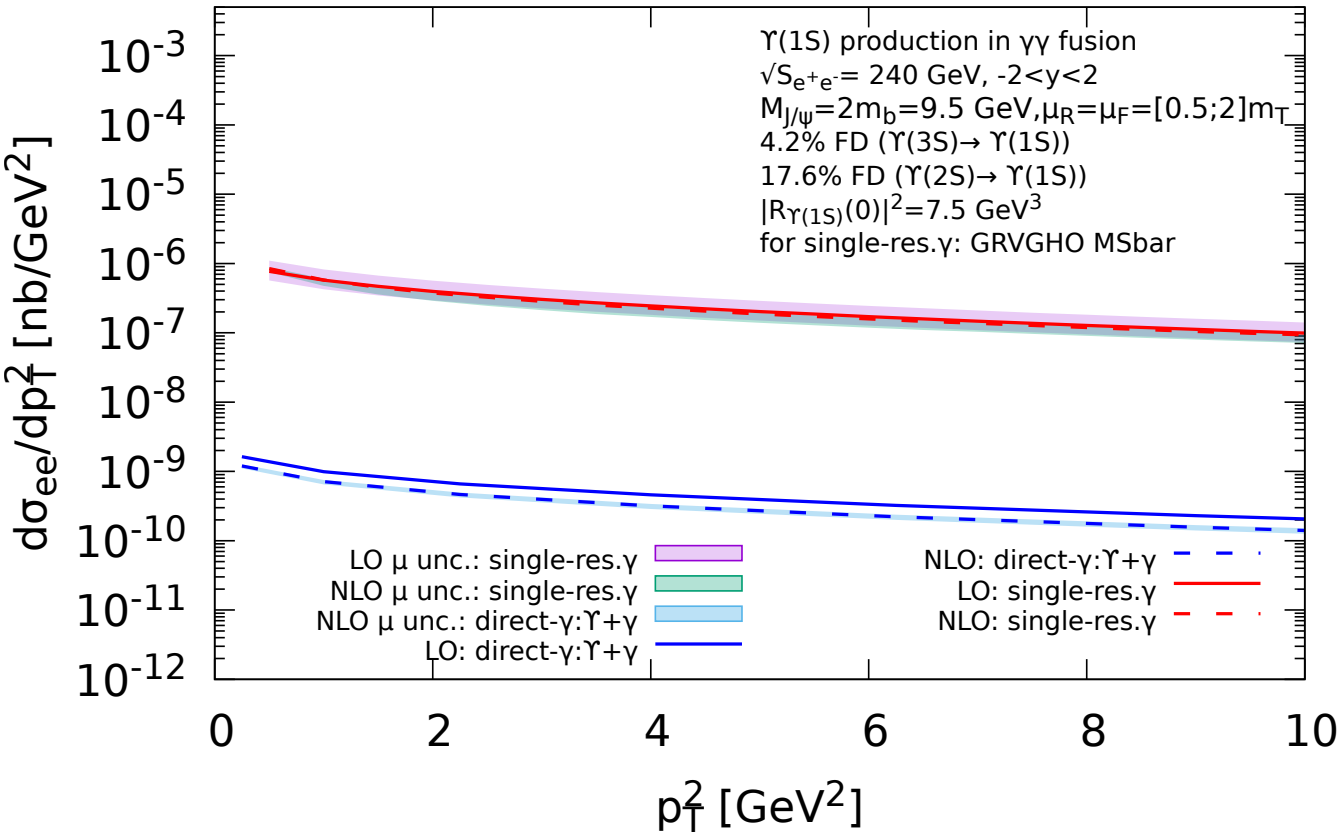
- We computed CS 1-loop QED direct-γ predictions for the 1st time for CEPC
- QED contribution is relevant at low p_T
- CS channels ($J/\psi + ggg$) and ($J/\psi + c\bar{c}$) included at LO in α_s

J/ψ production at $\sqrt{s_{ee}} = 1.5\text{TeV}$



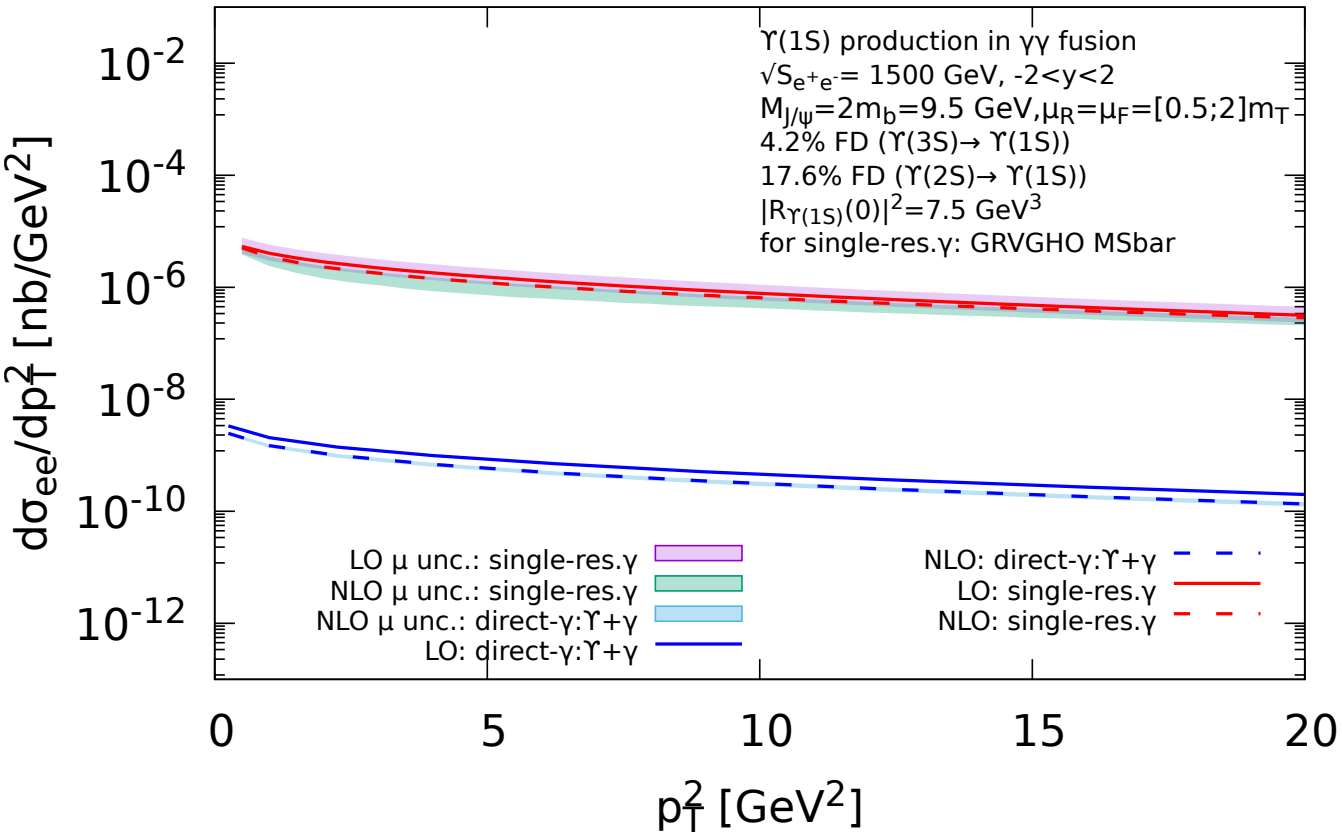
- We computed CS 1-loop QED direct-γ predictions for the 1st time for CEPC
- QED contribution is relevant at low p_T
- CS channel ($J/\psi + c\bar{c}$) included at LO in α_s

Υ production at $\sqrt{s_{ee}} = 240$GeV



- 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

Υ production at $\sqrt{s_{ee}} = 1.5$TeV



- 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 $J/\psi + X$ 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
- direct-photon processes in CSM ($J/\psi + \gamma$, $J/\psi + c\bar{c}$) are not negligible
- We obtained the predictions for CS one-loop QED direct-photon production and single-resolved photon contributions for J/ψ production for DELPHI and future high-energy e^+e^- colliders
- Predictions for Υ production also had been obtained
- Exclusive direct-photon ($J/\psi + \gamma$) can be measured in ultra-peripheral heavy-ion collisions at the LHC