Charmonium production at NLO in two-photon collisions

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[1] M. Klasen, B.A.K., L.N. Mihaila, M. Steinhauser, Nucl. Phys. **B713** (2005) 487.
[2] M. Klasen, B.A.K., L.N. Mihaila, M. Steinhauser, Phys. Rev. **D71** (2005) 014016.

1. Introduction

Heavy quarkonium H:

- useful testing ground for QCD
- simplest laboratory to study the binding of quarks to hadrons

Color Singlet Model: E.L. Berger, D. Jones, Phys. Rev. **D23** (1981) 1521; R. Baier, R. Rückl, Phys. Lett. **102B** (1981) 364.

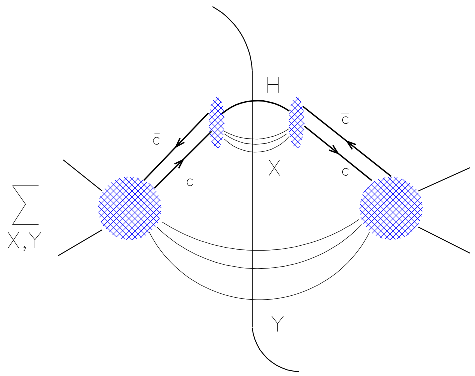
- Factorization in perturbative short-distance part $[\alpha_s(m_Q),\, m_Q]$ and nonperturbative long-distance part $[R_S(0),\, R'_P(0)]$.
- $Q\overline{Q}$ pair must be in CS state and have same ${}^{2S+1}L_J$ quantum numbers as H.
- No general argument for validity in higher orders; logarithmic IR divergences in P-wave decays to light hadrons and relativistic corrections to S-wave annihilation.
- Explains direct J/ψ photoproduction at HERA in NLO, but falls far short of Tevatron $p\overline{p}$, LEP2 $\gamma\gamma$, and HERA ep DIS data.

Color Evaporation Model: H. Fritzsch, Phys. Lett. **B67** (1977) 217; F. Halzen, Phys. Lett. **B69** (1977) 105; M. Glück, J.F. Owens, E. Reya, Phys. Rev. **D17** (1978) 2324.

Hard comover scattering: P. Hoyer, S. Peigné, Phys. Rev. **D59** (1999) 034011; N. Marchal, S. Peigné, P. Hoyer, Phys. Rev. **D62** (2000) 114001.

NRQCD factorization formalism

W. E. Caswell, G. P. Lepage, Phys. Lett. **B167** (1986) 437; G.T. Bodwin, E. Braaten, G.P. Lepage, Phys. Rev. **D51** (1995) 1125; D55 (1997) 5853 (E).



- Rigorous theoretical framework, renormalizable, predictive.
- Factorization in perturbative short-distance coefficients and long-distance matrix elements:

$$d\sigma(a+b\to H+d)=\sum_n\left\langle\mathcal{O}^H[n]\right\rangle d\sigma(a+b\to Q\overline{Q}[n]+d),$$

where $n={}^{2S+1}L_J^{(c)}$.

- Relative importance of $\langle \mathcal{O}^H[n] \rangle$ governed by velocity scaling rules. $\rightsquigarrow$ Double expansion in $\alpha_s(m_H)$ and $v \approx \alpha_s(m_H)$.
$v^2 \approx 0.3$ (0.1) for J/ψ (Υ).
- CSM recovered for $v \to 0$.
- Predicts CO processes, to be identified in other kinds of experiments.

$$\langle \mathcal{O}^H[n] \rangle \propto v^k$$

k	η_c	$\psi(nS)$	h_c	χ_{cJ}
3	${}^1S_0^{(1)}$	${}^3S_1^{(1)}$	—	—
5	—	—	${}^1P_1^{(1)}$, ${}^1S_0^{(8)}$	${}^3P_J^{(1)}$, ${}^3S_1^{(8)}$
7	${}^1S_0^{(8)}$, ${}^3S_1^{(8)}$, ${}^1P_1^{(8)}$	${}^1S_0^{(8)}$, ${}^3S_1^{(8)}$, ${}^3P_J^{(8)}$	—	—

Motivation for NLO:

- Reduction of renormalization and factorization scale dependence.
- Sizeable effects, e.g. due to opening of new partonic production channels.
- Ultimate test of NRQCD factorization by global NLO fit.
- High-statistics data from HERA II, Tevatron Run II, LHC, ILC.

Previous NLO calculations:

- $\gamma p \to J/\psi + X$ w/ direct γ and J/ψ for $p_T > 0$ in CSM M. Krämer, J. Zunft, J. Steegborn, P.M. Zerwas, Phys. Lett. **B348** (1995) 657; M. Krämer, Nucl. Phys. **B459** (1996) 3.
- $\gamma p \to J/\psi + X$ w/ direct γ and J/ψ for $p_T = 0$ in NRQCD F. Maltoni, M.L. Mangano, A. Petrelli, Nucl. Phys. **B519** (1998) 361.
- $p\bar{p} \to J/\psi + X$ for $p_T = 0$ in NRQCD A. Petrelli, M. Cacciari, M. Greco, F. Maltoni, M.L. Mangano, Nucl. Phys. **B514** (1998) 245.

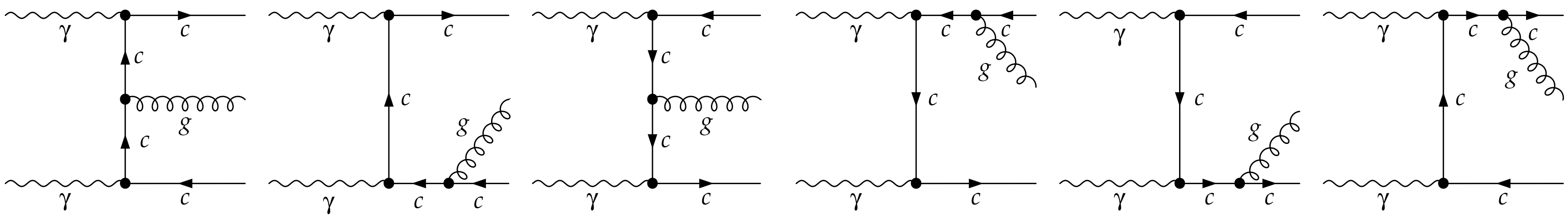
Here:

- $\gamma\gamma \to J/\psi + X$ w/ direct γ's and prompt J/ψ for $p_T > 0$ in NRQCD
- X purely hadronic: compensate μ_R dependence of LO single-resolved contribution
- X w/ prompt γ: direct photoproduction dominant

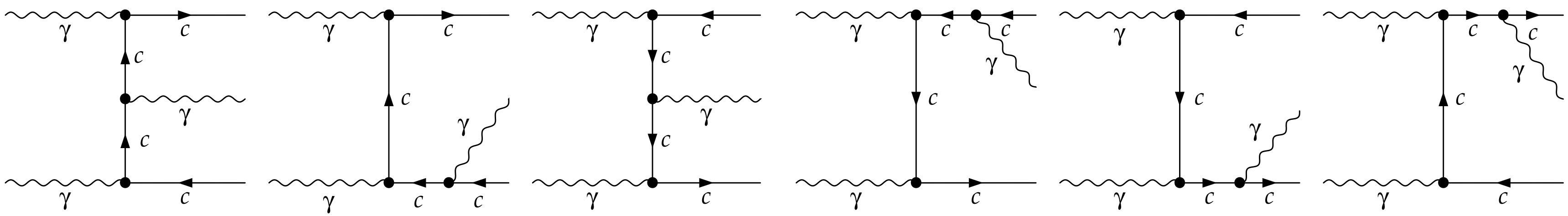
2. LO results

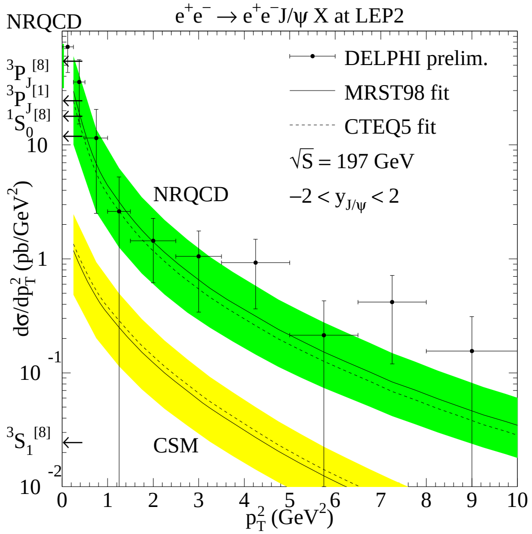
M. Klasen, B.A.K., L.N. Mihaila, M. Steinhauser, Phys. Rev. Lett. **89** (2002) 032001; R.M. Godbole, D. Indumathi, M. Krämer, Phys. Rev. **D65** (2002) 074003.

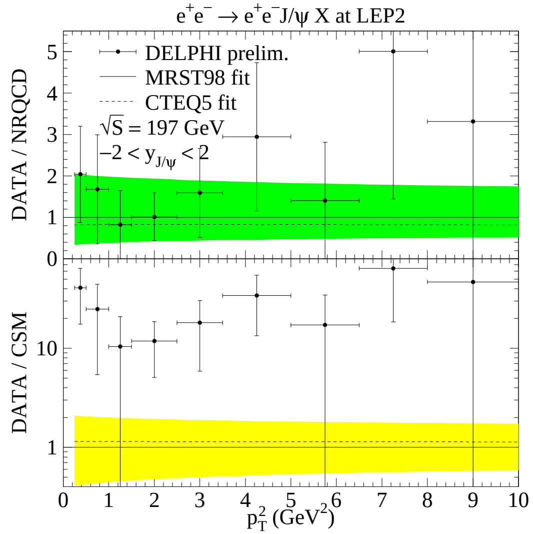
Subprocess: $\gamma + \gamma \to c\overline{c}\left[{}^3S_1^{(8)}\right] + g$

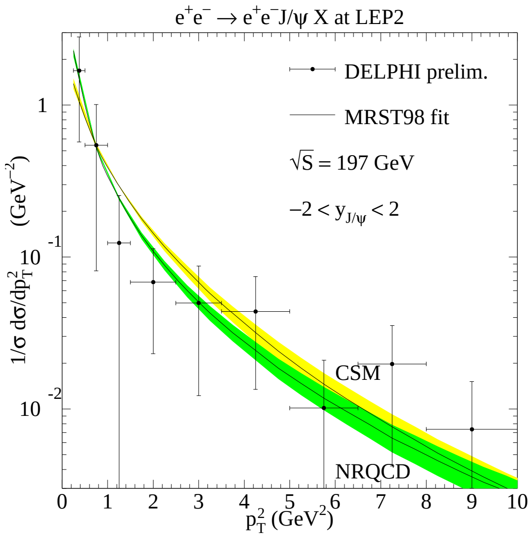


Subprocess: $\gamma + \gamma \to c\overline{c}\left[{}^3S_1^{(1)}\right] + \gamma$









M. Klasen, B.A.K., L.N. Mihaila, M. Steinhauser, Phys. Rev. Lett. **89** (2002) 032001.

3. NLO calculation: (a) Virtual corrections

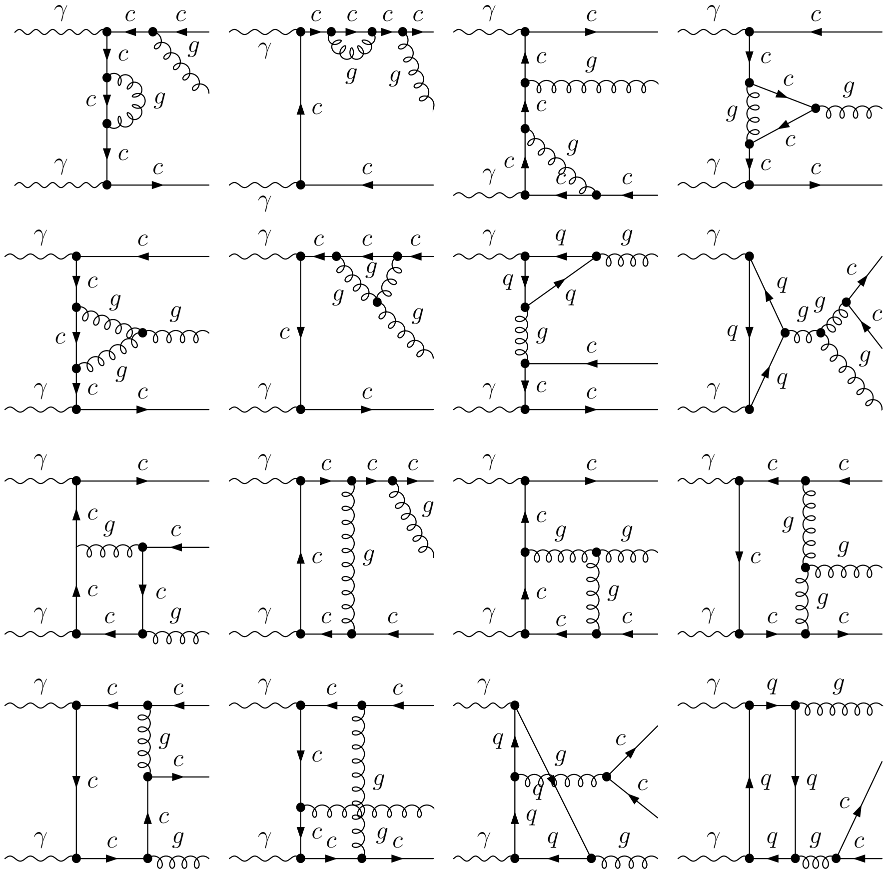
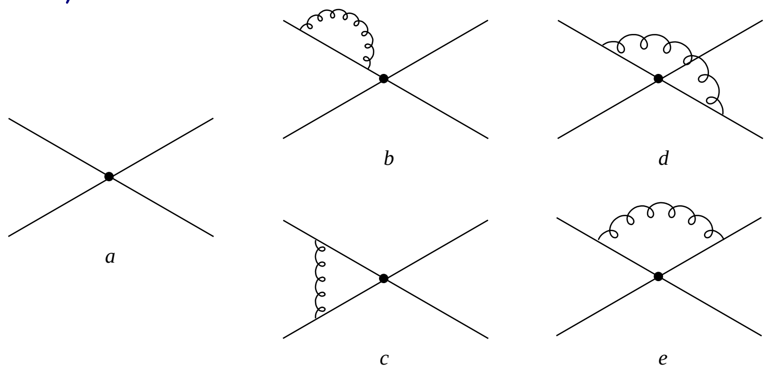


diagram	UV	IR	Coulomb
self energy	×		
triangle	×	×	
box		×	
pentagon		×	×

divergence	regularization	removal
UV	dim. reg. $(1/\epsilon_{\rm UV})$	renormalization of g_s, m_Q, ψ_Q, G_μ $(\rightsquigarrow \mu)$ and $\langle \mathcal{O}^H[n] \rangle$ $(\rightsquigarrow \lambda)$
IR	dim. reg. $(1/\epsilon_{\rm IR})$	real corrections
Coulomb	$1/v$	$\langle \mathcal{O}^H[n] \rangle$

Operator renromalization



$$\left\langle \mathcal{O}^H \left[{}^3S_1^{(8)} \right] \right\rangle_1 = \left\langle \mathcal{O}^H \left[{}^3S_1^{(8)} \right] \right\rangle_0 \left[1 + \left(C_F - \frac{C_A}{2} \right) \frac{\pi \alpha_s}{2v} \right] + \frac{4\alpha_s}{3\pi m^2} \left(\frac{4\pi\mu^2}{\lambda^2} \right)^\epsilon$$

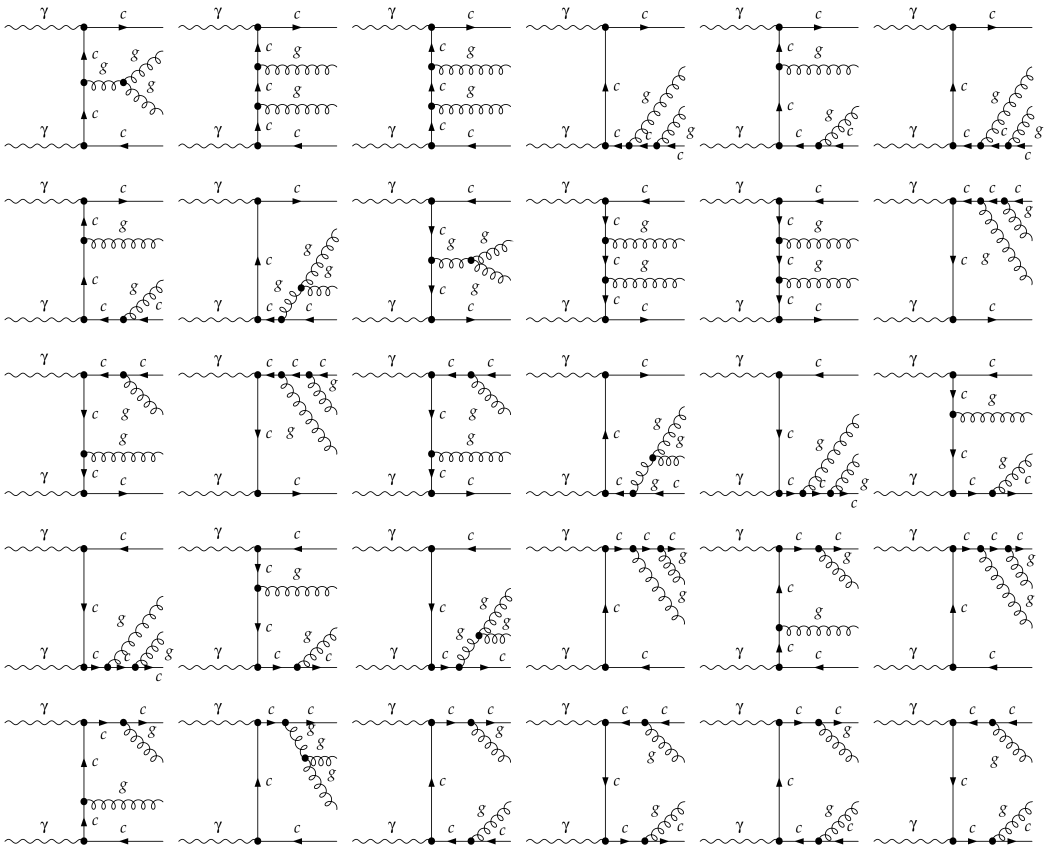
$$\times \exp(-\epsilon\gamma_E) \left(\frac{1}{\epsilon_{\rm UV}} - \frac{1}{\epsilon_{\rm IR}} \right) \sum_{J=0}^{2} \left(C_F \left\langle \mathcal{O}^H \left[{}^3P_J^{(1)} \right] \right\rangle + B_F \left\langle \mathcal{O}^H \left[{}^3P_J^{(8)} \right] \right\rangle \right)$$

(b) Real corrections

Subprocesses:

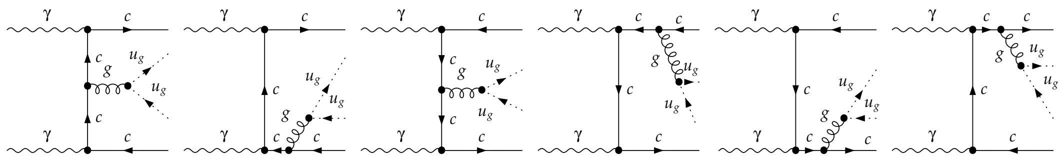
$$\gamma + \gamma \to c\overline{c}[n] + g + g$$

$$n = {}^3P_J^{(1)}, {}^1S_0^{(8)}, {}^3S_1^{(8)}, {}^3P_J^{(8)}$$



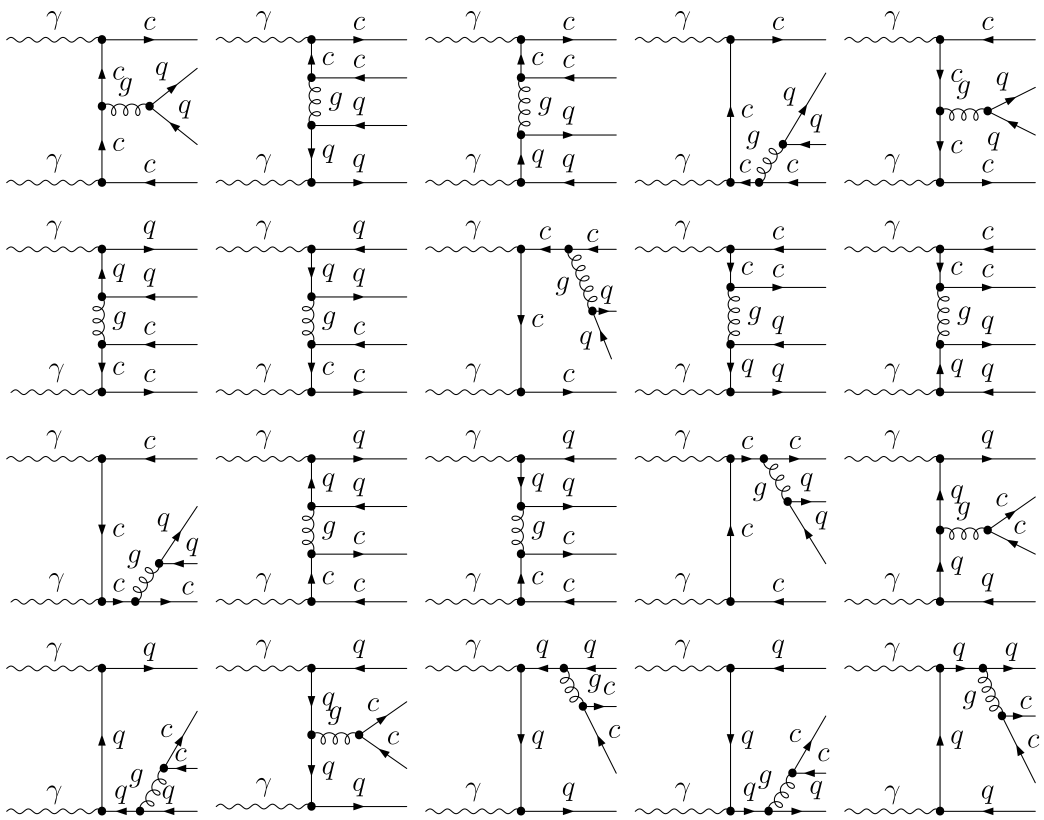
$$\gamma + \gamma \rightarrow c\overline{c}[n] + u_g + \overline{u}_g$$

$$n = {}^3S_1^{(8)}$$



$$\gamma + \gamma \rightarrow c\overline{c}[n] + q + \overline{q}$$

$$n = {}^1S_0^{(8)}, {}^3S_1^{(8)}, {}^3P_J^{(8)}$$



Soft and/or collinear singularities:

- Introduce IS and FS phase-space slicing parameters δ_i, δ_f.
- Integrate over soft and/or collinear regions analytically in d dimensions.
- Factorize IS collinear singularities into γ PDFs of single-resolved process ($\rightsquigarrow M$).
- Integrate over hard region numerically in 4 dimensions.

Process	IS coll. (δ_i)	FS coll. (δ_f)	soft (δ_f)
$\gamma\gamma \to c\bar{c}\left[{}^3P_J^{(1)}, {}^3P_J^{(8)}\right] gg$			$\times$
$\gamma\gamma \to c\bar{c}\left[{}^1S_0^{(8)}\right] gg$			
$\gamma\gamma \to c\bar{c}\left[{}^3S_1^{(8)}\right] gg$		$\times$	$\times$
$\gamma\gamma \to c\bar{c}\left[{}^3S_1^{(8)}\right] q\bar{q}$	$\times$	$\times$	
$\gamma\gamma \to c\bar{c}\left[{}^1S_0^{(8)}, {}^3P_J^{(8)}\right] q\bar{q}$	$\times$		

Assembly of $\gamma\gamma \to H + X$ cross section:

$$d\sigma(\mu, \lambda, M) = d\sigma_0(\mu, \lambda)[1 + \delta_{\rm vi}(\mu; \epsilon_{\rm UV}, \epsilon_{\rm IR}, v) + \delta_{\rm ct}(\mu; \epsilon_{\rm UV}, \epsilon_{\rm IR}) + \delta_{\rm op}(\mu, \lambda; \epsilon_{\rm IR}, v) + \delta_{\rm fs}(\mu; \epsilon_{\rm IR}, \delta_f)] + d\sigma_{\rm is}(\mu, \lambda, M; \delta_i) + d\sigma_{\rm so}(\mu, \lambda; \epsilon_{\rm IR}, \delta_f) + d\sigma_{\rm ha}(\mu, \lambda; \delta_i, \delta_f)$$

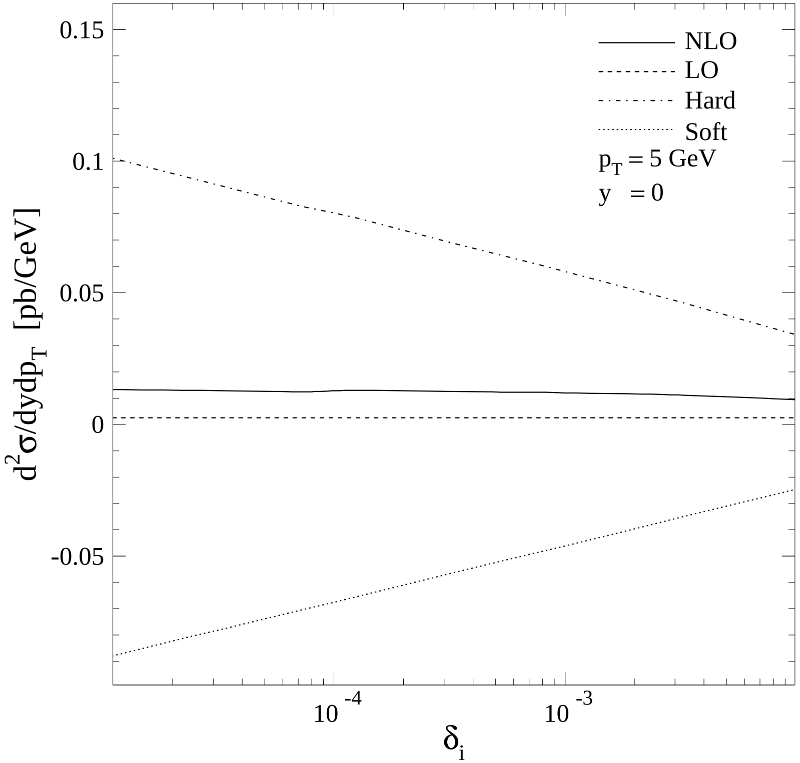
4. Phenomenology

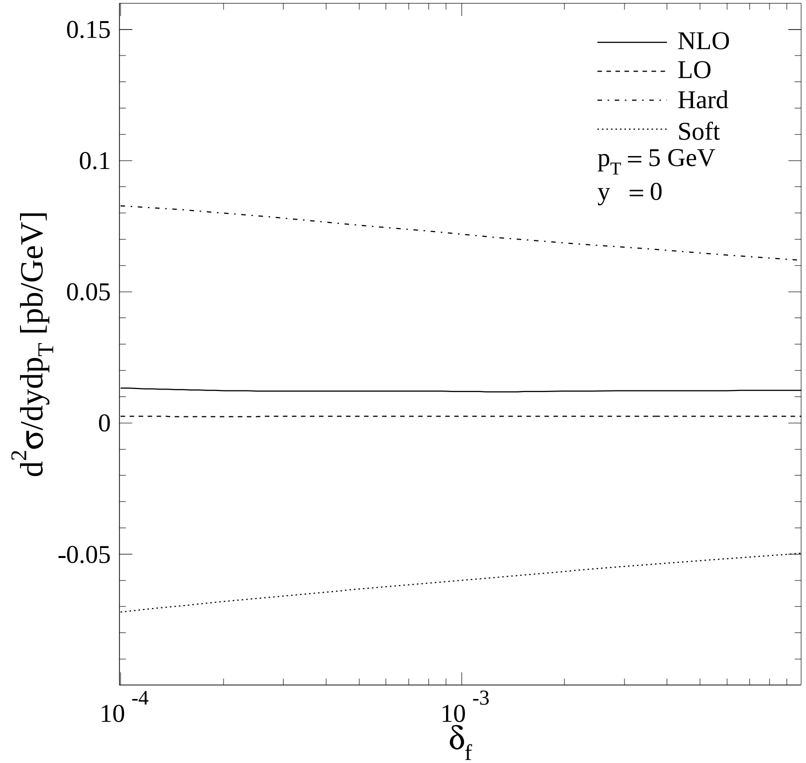
Input:

- e^+e^- linear collider with $\sqrt{S} = 500$ GeV
- IS bremsstrahlung with $\theta_{\max} = 25$ mrad
- Beamstrahlung with $\Upsilon = 0.053$ (TESLA)
- J/ψ, χ_{cJ}, and ψ' MEs from E. Braaten, B.A.K., J. Lee, Phys. Rev. **D62** (2000) 094005
- γ PDFs from M. Glück, E. Reya, I. Schienbein, Phys. Rev. **D60** (1999) 054019
- FS prompt γ: $p_T^\gamma > 3$ GeV, $|y^\gamma| < 2.79$

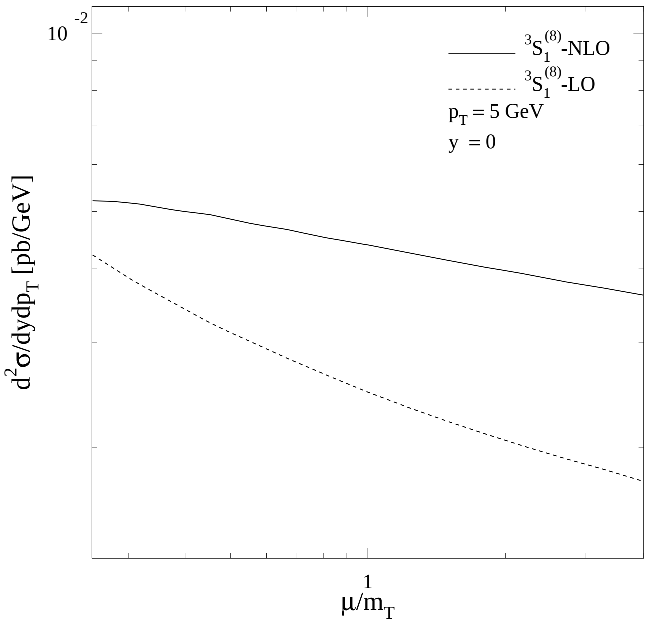
(a) $\gamma\gamma \to J/\psi + j + X$

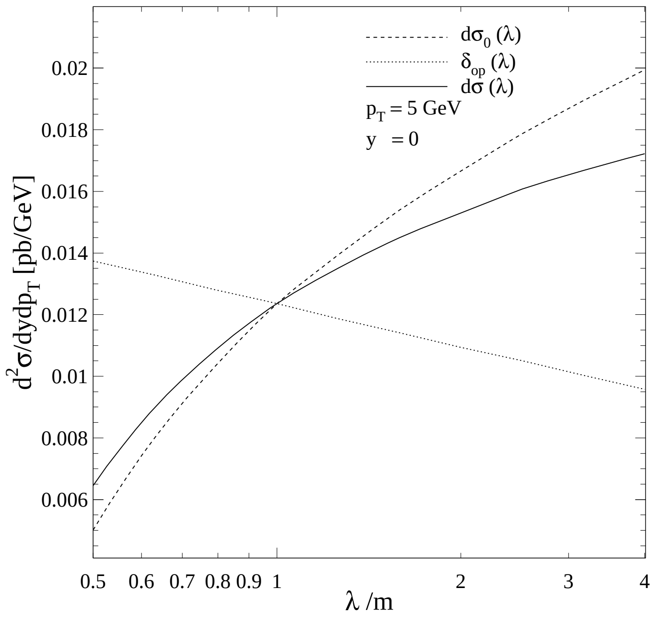
δ_i, δ_f dependences

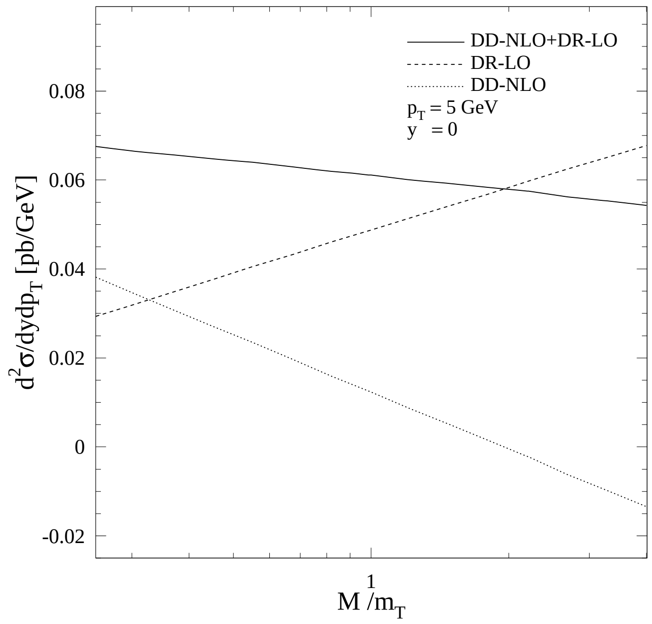


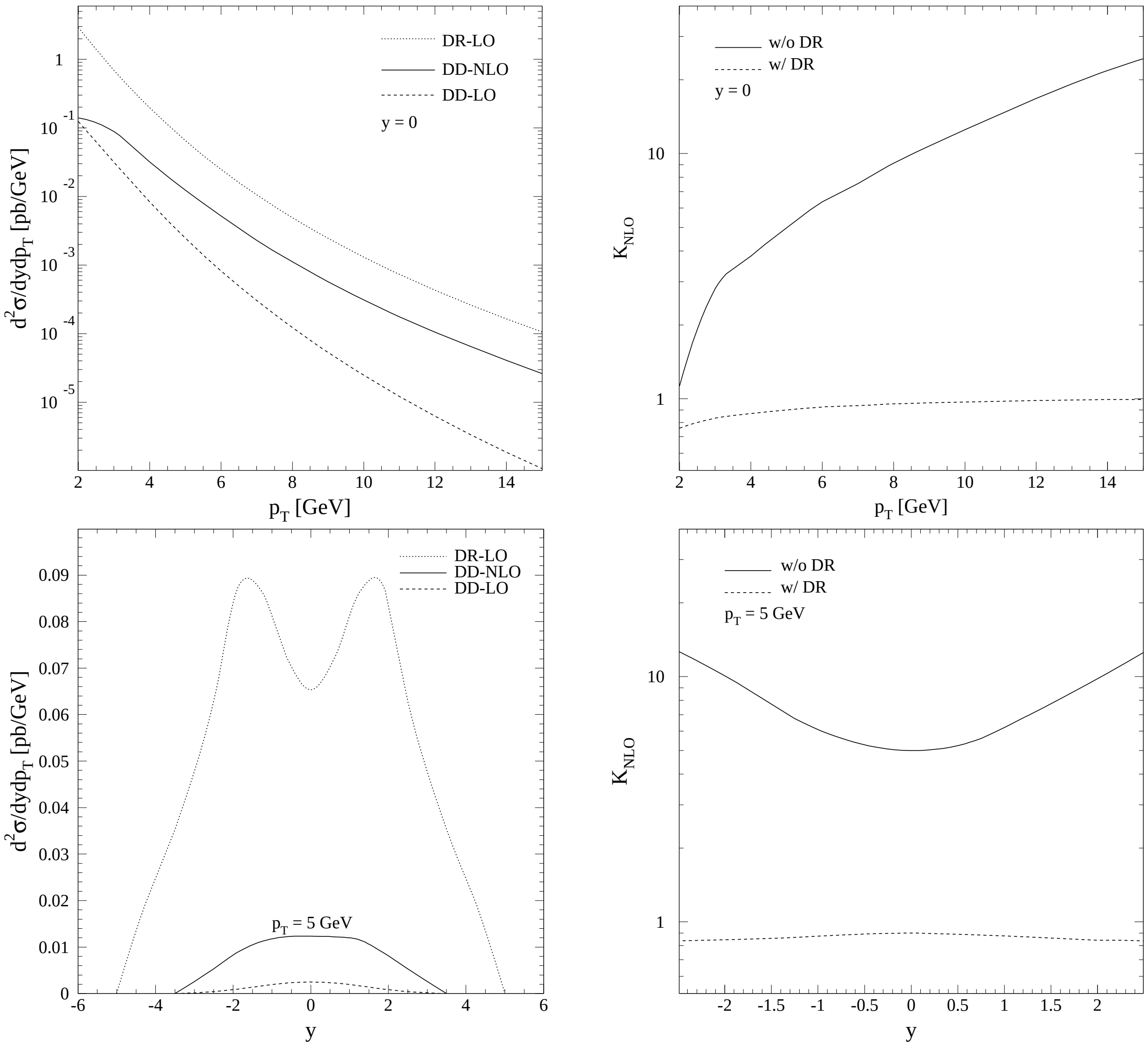


μ, λ, M dependences



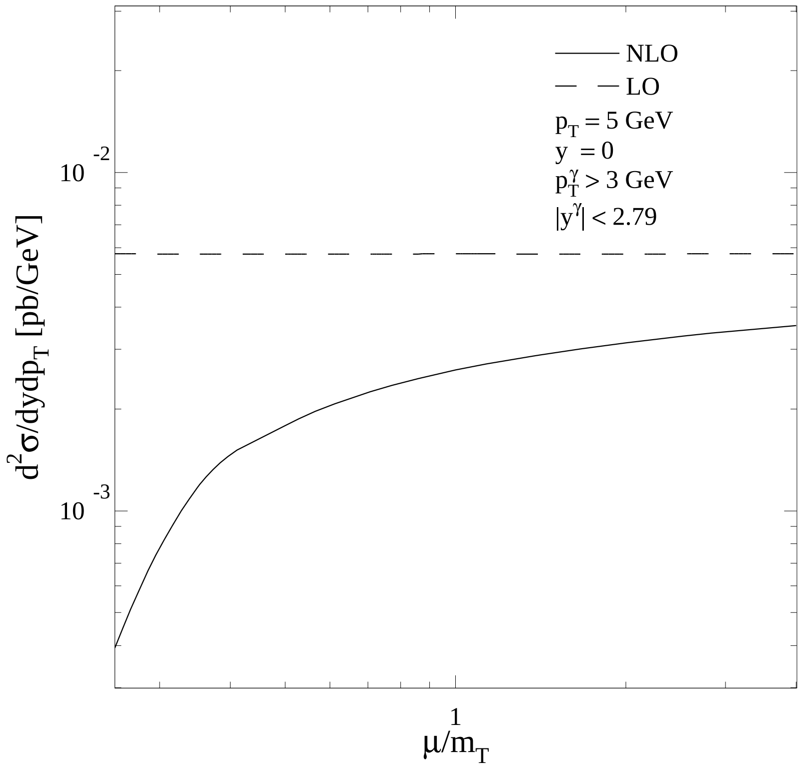


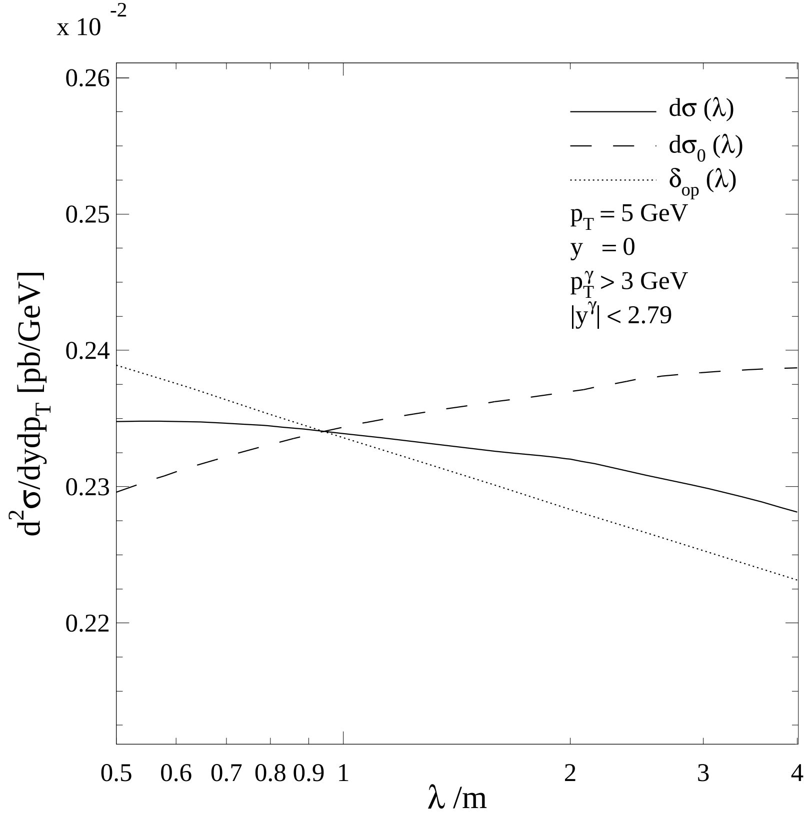


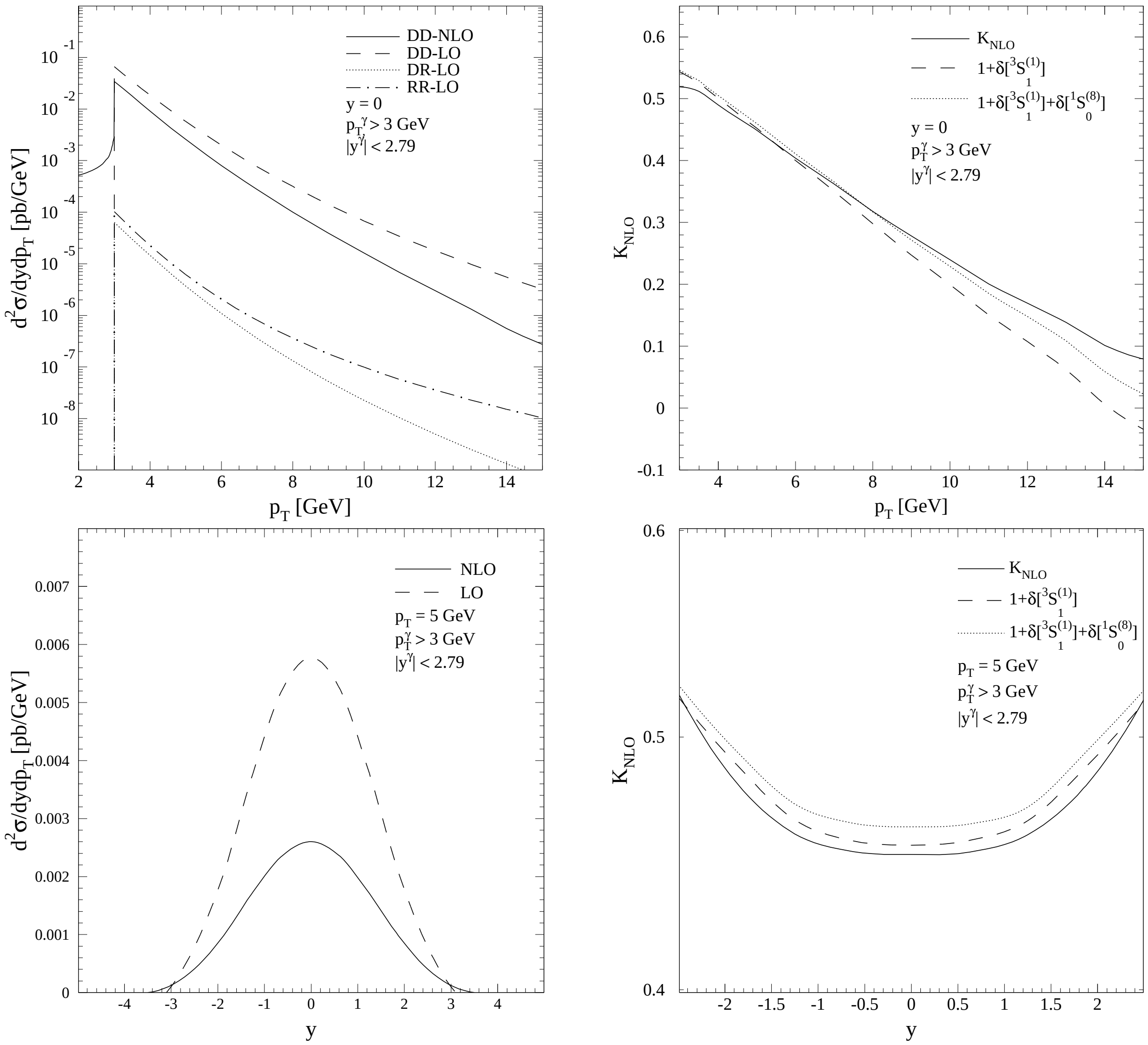

DR-LO
DD-NLO
DD-LO
y = 0
$d^2\sigma/dydp_T$ [pb/GeV]
p_T [GeV]
w/o DR
w/ DR
y = 0
K_{NLO}
p_T [GeV]
DR-LO
DD-NLO
DD-LO
p_T = 5 GeV
$d^2\sigma/dydp_T$ [pb/GeV]
y
w/o DR
w/ DR
p_T = 5 GeV
K_{NLO}
y

(b) $\gamma\gamma \to J/\psi + \gamma + X$

μ, λ dependences






DD-NLO
DD-LO
DR-LO
RR-LO
y = 0
$p_T^\gamma > 3$ GeV
$|y^\gamma| < 2.79$
$d^2\sigma/dydp_T$ [pb/GeV]
p_T [GeV]
K_{NLO}
$1+\delta[^3S_1^{(1)}]$
$1+\delta[^3S_1^{(1)}]+\delta[^1S_0^{(8)}]$
NLO
LO
$p_T = 5$ GeV
y

5. Summary and outlook

- $\gamma\gamma \to J/\psi + j + X$ w/ direct γ's and prompt J/ψ for $p_T > 0$ at NLO in NRQCD
  - Sizeable K factor due to opening of $g \to c\overline{c}\left[{}^3S_1^{(8)}\right]$ *fragmentation-prone* subprocesses $\gamma\gamma \to c\overline{c}\left[{}^3S_1^{(8)}\right] g$ and $\gamma\gamma \to c\overline{c}\left[{}^3S_1^{(8)}\right] q\overline{q}$ (proportional to e_q^2)
  - M dependence of LO cross section (dominantly single-resolved) considerably reduced
- $\gamma\gamma \to J/\psi + \gamma + X$ at NLO in NRQCD
  - Direct photproduction dominant
  - Unscreened μ dependence
  - No M dependence $\rightsquigarrow$ formally independent of single-resolved photoproduction
  - Small K factor from virtual corrections
- Extend analysis to ep photoproduction and hadroproduction
- Test NRQCD factorization by global NLO fit to high-statistics data from HERA II, Tevatron Run II, LHC, ILC,. . .