Isolated photon production in the Parton Reggeization Approach with real NLO corrections

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Outline

Introduction

Isolated single-photon production in CPM of QCD

- $K(exp/LO) \simeq 3$
- $K(exp/NLO) \simeq 1.5$ *[M. Fontannaz, J. P. Guillet and G. Heinrich, Isolated prompt photon photoproduction at NLO// Eur. Phys. J. C* ***21*** *(2001), 303-312]*
- $K(exp/NNLO) \simeq 1.0$ *[X. Chen, T. Gehrmann, N. Glover, M. Höfer and A. Huss, Isolated photon and photon+jet production at NNLO QCD accuracy // JHEP* ***04*** *(2020), 166]*

Parton Reggeization Approach (PRA)

Details of the LO PRA are presented in Refs.

- *Nefedov M.A., Saleev V.A., Shipilova A.V. Dijet azimuthal decorrelations at the LHC in the parton Reggeization approach. Phys. Rev. D. 2013. V. 87. P. 094030.*
- *Karpishkov A.V., Nefedov M.A. and Saleev V.A., B $B\bar{B}$ angular correlations at the LHC in parton Reggeization approach merged with higher-order matrix elements// Phys. Rev. D. 2017. V. 96. P. 096019.*
- *M. A. Nefedov and V. A. Saleev, High-Energy Factorization for Drell-Yan process in pp and $p\bar{p}$ collisions with new Unintegrated PDFs, Phys. Rev. D* ***102*** *(2020), 114018*

Developments of PRA in NLO can be found here

- M. A. Nefedov, Towards stability of NLO corrections in High-Energy Factorization via Modified Multi-Regge Kinematics approximation, JHEP **08** (2020), 055
- M. A. Nefedov, Computing one-loop corrections to effective vertices with two scales in the EFT for Multi-Regge processes in QCD," Nucl. Phys. B **946** (2019), 114715
- M. Nefedov and V. Saleev, On the one-loop calculations with Reggeized quarks," Mod. Phys. Lett. A **32** (2017) no.40, 1750207

Parton Reggeization Approach (PRA)

I. High-energy factorization

$$d\sigma = \sum_{i,j} \int_0^1 \frac{dx_1}{x_1} \int \frac{d^2\mathbf{q}_{T1}}{\pi} \Phi_i(x_1, t_1, \mu^2) \int_0^1 \frac{dx_2}{x_2} \int \frac{d^2\mathbf{q}_{T2}}{\pi} \Phi_j(x_2, t_2, \mu^2) \cdot d\hat{\sigma}_{ij}^{\mathrm{PRA}},$$

where $t_{1,2} = -\mathbf{q}_{T1,2}^2$, $i, j = R, Q, \bar{Q}$

$\Phi_{R/Q}(x, t, \mu^2)$ are gluon/quark unintegrated parton distribution functions (uPDFs)

$d\hat{\sigma}_{ij}^{\mathrm{PRA}}$ is patonic cross section which is written via off-shell squared matrix elements $\overline{|M^{\mathrm{PRA}}|^2}$ of PRA, and

$$\lim_{t_1, t_2 \to 0} \int \frac{d\phi_1}{2\pi} \int \frac{d\phi_2}{2\pi} \overline{|M^{\mathrm{PRA}}|^2} = \overline{|M^{\mathrm{CPM}}|^2}$$

Parton Reggeization Approach

II. Off-shell amplitudes as multi-Regge limit of auxiliary $(n+2)$ QCD amplitudes

The PRA hard-scattering amplitude is *gauge-invariant* because the initial-state off-shell partons are treated as Reggeized partons $(R, Q, \bar{Q})$ in a sense of gauge-invariant EFT for QCD processes in Multi-Regge Kinematics(MRK), introduced by L.N. Lipatov.

Feynman's rules of EFT:

- L. N. Lipatov, Gauge invariant effective action for high-energy processes in QCD, Nucl. Phys. B **452**, 369 (1995).
- L. N. Lipatov and M. I. Vyazovsky, QuasimultiRegge processes with a quark exchange in the t channel, Nucl. Phys. B **597**, 399 (2001).
- M. A. Nefedov, ReggeQCD model-file for FeynArts.

Parton Reggeization Approach

III. Modified KMR unintegrated PDFs with exact normalization at arbitrary x

$$\Phi_i(x,t,\mu^2) = \frac{d}{dt}\left[T_i(t,\mu^2,x)F_i(x,t)\right],$$

where $T_i(t,\mu^2,x)$ is usually referred to as *Sudakov formfactor*, satisfying the boundary conditions $T_i(t=0,\mu^2,x)=0$ and $T_i(t=\mu^2,\mu^2,x)=1$.

$$\Phi_i(x,t,\mu_Y^2) = \frac{\alpha_s(t)}{2\pi}\frac{T_i(t,\mu^2,x)}{t}\sum_{j=q,\bar{q},g}\int\limits_x^1 dz\; P_{ij}(z)F_j\left(\frac{x}{z},t\right)\theta\left(\Delta(t,\mu_Y^2)-z\right).$$

Parton Reggeization Approach

Modified KMR unintegrated PDFs with exact normalization at arbitrary x

$$T_i(t,\mu^2,x) = \exp\left[-\int\limits_t^{\mu^2} \frac{dt'}{t'} \frac{\alpha_s(t')}{2\pi} \left(\tau_i(t',\mu^2) + \Delta\tau_i(t',\mu^2,x)\right)\right]$$

$$\tau_i(t,\mu^2) = \sum_j \int\limits_0^1 dz\; zP_{ji}(z)\theta(\Delta(t,\mu^2)-z),$$

$$\Delta\tau_i(t,\mu^2,x) = \sum_j \int\limits_0^1 dz\; \theta(z-\Delta(t,\mu^2)) \left[zP_{ji}(z) - \frac{F_j\left(\frac{x}{z},t\right)}{F_i(x,t)} P_{ij}(z)\theta(z-x)\right].$$

For details, see Ref.

- *M. A. Nefedov and V. A. Saleev, High-Energy Factorization for Drell-Yan process in pp and $p\bar{p}$ collisions with new Unintegrated PDFs, Phys. Rev. D **102** (2020), 114018*

Parton Reggeization Approach

Self agreement of the PRA is based on multi-Regge limit of the relevant QCD amplitudes and proved CPM formalism

- Factorization formula is obtained from relevant ones of CPM
- Reggeized amplitudes are gauge invariant
- Unintegrated PDFs are normalized on collinear PDFs

Single-photon production in the PRA

LO and most important real NLO correction to single-photon production in the PRA

- LO: $Q + \bar{Q} \to \gamma$
- NLO: $Q(\bar{Q}) + R \to \gamma + q(\bar{q})$

Negligible contributions to single-photon production in the PRA (see (*))

- NLO: $Q + \bar{Q} \to \gamma + g$
- NNLO: $R + R \to \gamma + q + \bar{q}$ and $R + R \to \gamma + g(quark\ \ box)$

(*) *[M. Nefedov and V. Saleev, Diphoton production at the Tevatron and the LHC in the NLO approximation of the parton Reggeization approach, Phys. Rev. D* ***92*** *(2015) no.9, 094033]*

MC event generator KaTie

As it has been shown in Refs.

- *Nefedov M.A., Saleev V.A., Shipilova A.V. Dijet azimuthal decorrelations at the LHC in the parton Reggeization approach. Phys. Rev. D. 2013. V. 87. P. 094030.*
- *Karpishkov A.V., Nefedov M.A. and Saleev V.A., B $B\bar{B}$ angular correlations at the LHC in parton Reggeization approach merged with higher-order matrix elements// Phys. Rev. D. 2017. V. 96. P. 096019.*
- *Kutak K., Maciula R., Serino M., Szczurek A. and van Hameren A., Four-jet production in single- and double-parton scattering within high-energy factorization// JHEP. 2016. V. 1604. P. 175,*

at the level of tree diagrams, analytical formalism based on Lipatov's EFT fully coincide with numerically generated off-shell amplitudes using MC event generator KaTie

- *van Hameren A., KaTie: For parton-level event generation with kT-dependent initial states. Comput.Phys.Commun. 2018. V. 224. P. 371.*

Single-photon production at the LHC

Setup of ATLAS measurements at 13 TeV

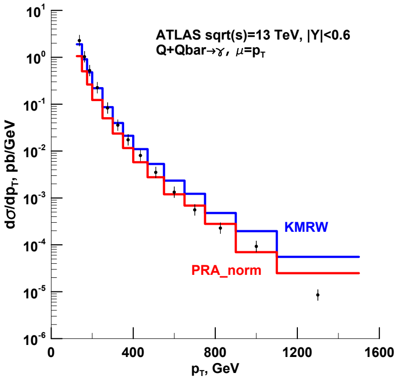
- For photons transverse momenta: $p_{T1} > 125$ GeV,
- For pseudorapidity all photons: $|\eta_\gamma| < 2.37$, excluding the range $1.37 < |\eta_\gamma| < 1.56$,
- For photon-jet separation conditions: $\Delta R_{\gamma j} = \sqrt{(\eta_\gamma - \eta_j)^2 + (\phi_\gamma - \phi_j)^2} > R_0 = 0.40$

Fragmentation contribution is included using the Frixione condition for $QR \to q\gamma$ subprocesses

$$E_T^{iso}(\Delta R_{q\gamma}) = p_{Tq} < E_T^{max} \frac{1 - \cos(\Delta R_{q\gamma})}{1 - \cos(R_0)}, \text{ where } E_T^{max} = 10 \text{ GeV}$$

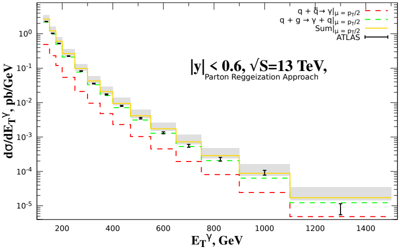
Single-photon production at the LHC

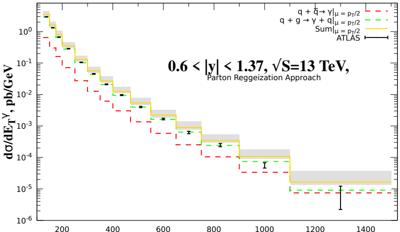
Comparison between KMRW and PRA PDFs. Only LO contributions are shown.



Single-photon production at the LHC

The differential cross sections for the production of one isolated photon as functions p_T. The hard scale in PRA calculations is taken as $\mu = p_T/2$.





Single-photon production at the LHC

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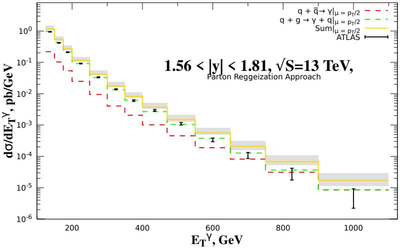
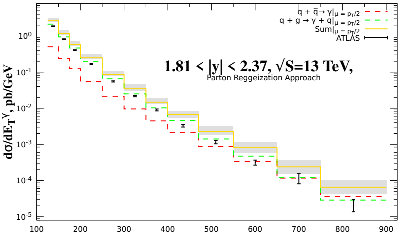
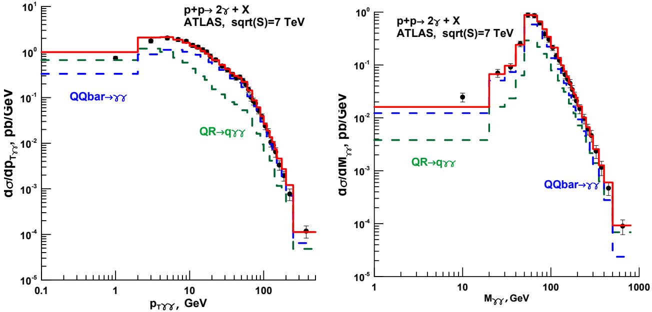




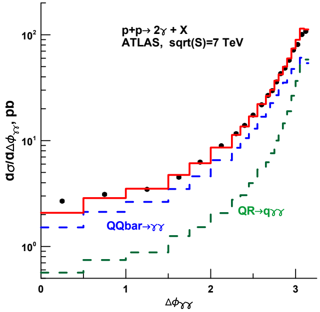
Two-photon production at the LHC

The differential cross sections for the production of two isolated photon as functions $p_{T\gamma\gamma}$ and $M_{\gamma\gamma}$.



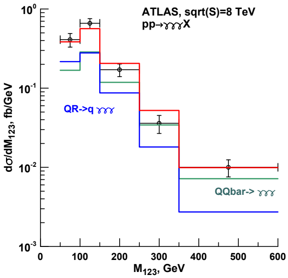
Two-photon production at the LHC

The differential cross sections for the production of one isolated photon as functions $\Delta\phi_{\gamma\gamma}$.



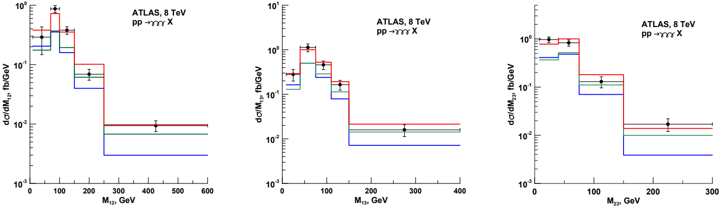
Three-photon production at the LHC

The differential cross sections for the production of three isolated photons as functions M_{123}. The hard scale in PRA calculations are taken as invariant mass of photons, $\mu = M_{3\gamma}$. The green histogram corresponds LO contribution from $Q\bar{Q} \to \gamma\gamma\gamma$ subprocess. The blue histogram corresponds NLO contribution from $QR \to q\gamma\gamma\gamma$ subprocess. The red histogram is their sum.



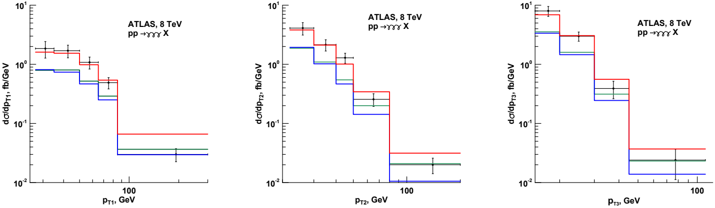
Three-photon production at the LHC

The differential cross sections for the production of three isolated photons as functions of M_{12} (left panel), M_{13} (central panel), and M_{23} (right panel).



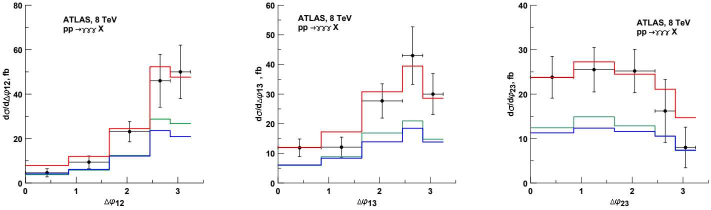
Three-photon production at the LHC

The differential cross sections for the production of three isolated photons as functions of p_{T1} (left panel), p_{T2} (central panel) and p_{T3} (right panel).



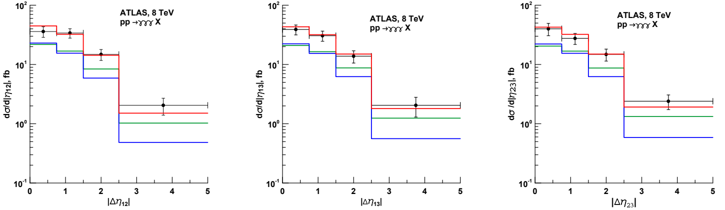
Three-photon production at the LHC

The differential cross sections for the production of three isolated photons as functions of $|\Delta\phi_{12}|$ (left panel), $|\Delta\phi_{13}|$ (central panel) and $\Delta\phi_{23}$ (right panel).



Three-photon production at the LHC

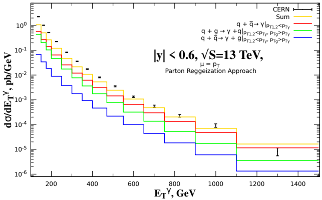
The differential cross sections for the production of three isolated photons as functions of $|\Delta y_{12}|$ (left panel), $|\Delta y_{13}|$ (central panel) and $|\Delta y_{23}|$ (right panel).

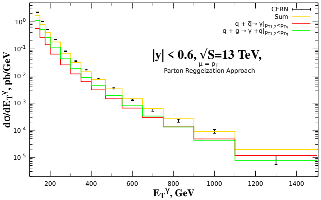


On double counting between LO and real NLO contributions

Subtraction scheme based on k_T−ordering

- *Karpishkov A.V., Nefedov M.A. and Saleev V.A., B $B\bar{B}$ angular correlations at the LHC in parton Reggeization approach merged with higher-order matrix elements// Phys. Rev. D. 2017. V. 96. P. 096019.*
- *A. Karpishkov, V. Saleev and A. Shipilova, Angular decorrelations in $\gamma + 2$jet events at high energies in the parton Reggeization approach, Mod. Phys. Lett. A **34** (2019) no.32, 1950266*
- *R. Maciula and A. Szczurek, Consistent treatment of charm production in higher-orders at tree-level within k_T-factorization approach, Phys. Rev. D **100** (2019) no.5, 054001*

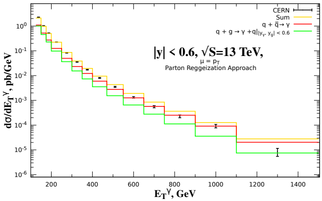


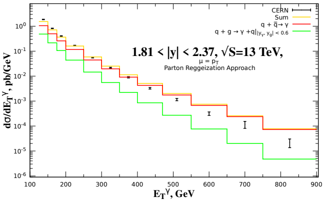


On double counting between LO and real NLO contributions

Subtraction scheme based on rapidity-ordering

- *[M. Nefedov and V. Saleev, Diphoton production at the Tevatron and the LHC in the NLO approximation of the parton Reggeization approach, Phys. Rev. D* ***92*** *(2015) no.9, 094033]*





Conclusions

- We describe cross sections and spectra for 1-2-3-photon production in LO PRA with real NLO corrections
- We demonstrate advantages of normalized PRA uPDFs instead of KMRW PDFs, especially for quarks uPDFs
- PRA results in LO+NLO approximation are roughly coincide with full NNLO predictions of CPM
- Double counting between LO and real NLO contributions in k_T-factorization should be small.

Thank you for your attention!