Pair production of particles in the Regge limit of QCD

Saleev V.[1,2]

[1]Samara University
[2]Joint Institute for Nuclear Research

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In collaboration with: Alimov L., Chernyshev A., Karpishkov A., Nefedov M., Shipilova A.

Introduction

QCD and hard inclusive production processes

$$p+p\to h+X$$

$$m_h \gg m_p, \qquad p_T \gg m_p$$

$$e+p\to e+X, (DIS) \qquad e+p\to e+h+X, \quad (SIDIS)$$

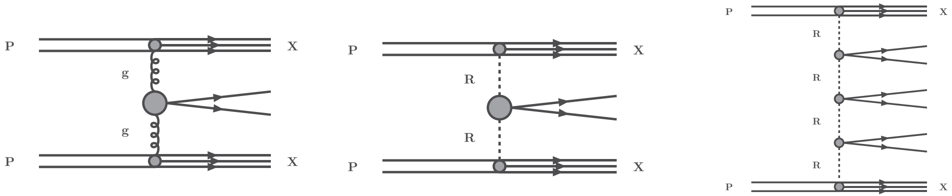
$$|q_\gamma^2| \gg m_p^2$$

Pair particle production and correlation observables

$$p+p\to h_1+h_2+X$$

- $d\sigma/dM_{12}$
- $d\sigma/dp_T, \qquad \vec{p}_T=\vec{p}_{1T}+\vec{p}_{2T}$
- $d\sigma/d\phi_{12}$
- We get new scale M_{12}, which separates two regions $p_T \ll M_{12}$ and $p_T \gg M_{12}$

Introduction



Conventional parton model and QCD

$$s = (p_1 + p_2)^2 > \hat{s} = (q_1 + q_2)^2, \qquad \hat{s} \sim \hat{t}, m_h^2, m_{ij} = (k_i + k_j)^2, p_{iT}^2, \ldots) \gg m_p^2 \gg \Lambda_{QCD}^2$$

Parton model in Multi-Regge kinematics or Quasi-Multi-Regge kinematics

$$s = (p_1 + p_2)^2 \gg \hat{s}_{ij} = (q_1 + q_2)^2, \qquad \hat{s}_{ij} \gg \hat{t}_{ij}(m_i^2, m_{ij} = (k_i + k_j)^2, p_{iT}^2, \ldots)$$

Resummation + Evolution + Factorization

Collinear parton model (CPM)

- $q^\mu_{1,2} = x_{1,2} p^\mu_{1,2}$, $q_{1,2T} = 0$, $p_T \sim Q \gg m_p$
- $d\sigma^{CPM} = \sum_{i,j} \int dx_1 \int dx_2 f_i(x_1, Q) \times f_j(x_1, Q) \times d\hat{\sigma}_{ij}$
- DGLAP evolution equation, transverse momentum ordering, $\alpha_S^\# \ln^\#(Q/\Lambda_{QCD})$

TMD parton model (TMD PM)

- $q^\mu_{1,2} = x_{1,2} p^\mu_{1,2} + q^\mu_{1,2T}$, $q^2_{1,2} \simeq 0$, $q_{1,2T} \neq 0$, $p_T \ll Q$, $Q = m_h, M_{12}$, $q\bar{q} \to Z$, $gg \to H$.
- $d\sigma^{TMD} = \sum_{i,j} \int dx_1 d^2 q_{1T} \int dx_2 d^2 q_{2T} F_i(x_1, q_{1T,} Q, \zeta_1) \times F_j(x_2, q_{2T,} Q, \zeta_2) \times d\hat{\sigma}_{ij}$
- Collins-Soper evolution equation for $\hat{F}(x_1, b_{T,} Q, \zeta)$, $\alpha_S^\# \ln^\#(Q/p_T)$.

High-energy factorization (HEF) or k_T-factorization

- $q^\mu_{1,2} = x_{1,2} p^\mu_{1,2} + q^\mu_{1,2T}$, $q^2_{1,2} = q^2_{1,2T} \neq 0$, $p_T \sim Q$, $Q = m_h, M_{12}$, $q^*\bar{q}^* \to Z$, $g^* g^* \to H$.
- $d\sigma^{KT} = \sum_{i,j} \int \frac{dx_1}{x_1} d^2 q_{1T} \int \frac{dx_2}{x_2} d^2 q_{2T} \Phi_i(x_1, q_{1T,}, Q) \times \Phi_j(x_2, q_{2T,} Q) \times d\hat{\sigma}^*_{ij}$
- Model dependent uPDFs, $\int dq_T^2 \Phi_i(x, q_{T,}, Q) \simeq x f_i(x, Q)$, $\alpha_S^\# \ln^\#(Q/\Lambda_{QCD})$, $\alpha_S^\# \ln^\#(s/Q^2)$, rapidity ordering

Parton Reggeization Approach (PRA)

PRA is gauge invariant version of the k_T-factorization

- Nefedov, Saleev, Shipilova, Phys. Rev. D **87**, no.9, 094030 (2013)
- Karpishkov, Nefedov, Saleev, Phys. Rev. D **96**, no.9, 096019 (2017)
- Nefedov, Saleev, Phys. Rev. D **102**, 114018 (2020)

Factorization

$d\sigma^{PRA} = \sum_{R,Q} \int \frac{dx_1}{x_1} d^2 q_{1T} \int \frac{dx_2}{x_2} d^2 q_{2T} \Phi_{R,Q}(x_1, q_{1T},, \mu) \times \Phi_{R,Q}(x_2, q_{2T}, \mu) \times d\hat{\sigma}^{PRA}$

Reggeized amplitudes are from L.N. Lipatov Effective Action in high-energy QCD

- Lipatov, Nucl. Phys. B **452**, 369-400 (1995)
- Lipatov, Vyazovsky, Nucl. Phys. B **597**, 399-409 (2001)

$$\hat{\sigma}^{PRA} \sim \overline{|A^{PRA}|^2}$$

$$R + R \to g + g, \quad R + R \to q + \bar{q}, \quad Q + \bar{Q} \to g + g, \quad ....$$

Parton Reggeization Approach (PRA)

Reggeized amplitude calculations

- In Ref. [Nefedov, Saleev, Shipilova, Phys. Rev. D **87**, no.9, 094030 (2013)] all squared Reggeized amplitudes for $2 \to 2$ processes were obtained and collected.
- In Ref. [Maxim Nefedov, 2017] ReggeQCD model file for FeynArts has been developed to obtain Reggeized amplitudes up to 4 particles in a final state
-
$$\lim_{q_{1,2T} \to 0} \int \frac{d\phi_1}{2\pi} \int \frac{d\phi_2}{2\pi} \overline{|A^{PRA}|^2} = \overline{|A^{CPM}|^2}$$

Parton Reggeization Approach (PRA)

Modified Kimber-Martin-Ryskin (KMR) uPDFs [Nefedov, SV, Phys. Rev. D **102**, 114018 (2020)]

$$\Phi_i(x,t,\mu^2) = \frac{\alpha_S(\mu)}{2\pi}\frac{T_i(t,\mu^2,x)}{t}\sum_j \int_x^1 \frac{dz}{z}\; P_{ij}(z)\, F_i(x,\mu^2)\,\theta\left(\Delta(t,\mu)-z\right), \quad F_i(x,\mu^2) = x\, f_i(x,\mu^2), \quad \Delta(t,\mu) = \sqrt{\mu^2}/\left(\sqrt{t}+\sqrt{\mu^2}\right)$$

$$\Phi_i(x,t,\mu^2) = \frac{d}{dt}\left[T_i(t,\mu^2,x)\, F_i(x,t)\right], \quad \int_0^{\mu^2} dt\; \Phi_i(x,t,\mu^2) \equiv F_i(x,\mu^2), \quad \forall x$$

$$T_i(t,\mu^2,x) = \exp\left[-\int_t^{\mu^2}\frac{dt'}{t'}\frac{\alpha_s(t')}{2\pi}\left(\tau_i(t',\mu^2)+\Delta\tau_i(t',\mu^2,x)\right)\right], \qquad \tau_i(t,\mu^2) = \sum_j \int_0^1 dz\; zP_{ji}(z)\theta(\Delta(t,\mu^2)-z),$$

$$\Delta\tau_i(t,\mu^2,x) = \sum_j \int_0^1 dz\;\theta(z-\Delta(t,\mu^2))\left[zP_{ji}(z) - \frac{F_j\left(\frac{x}{z},t\right)}{F_i(x,t)}P_{ij}(z)\theta(z-x)\right].$$

Dijet production (central rapidity region) [Nefedov,Shipilova,SV,2013]

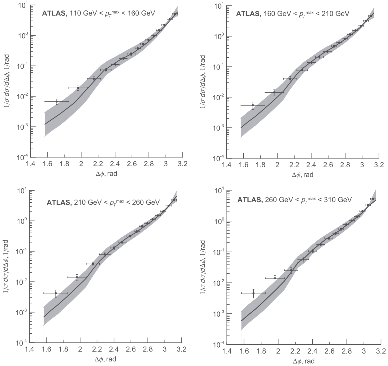


FIG. 2. Normalized $F(\Delta\phi)$ distributions in several $p_T^{\max}$ regions at $\sqrt{S} = 7$ TeV, $|y| < 0.8$ and $p_T > 100$ GeV. The data are from the ATLAS Collaboration [3]. The curves correspond to the LO parton Reggeization approach.

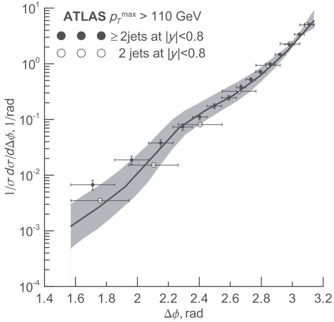


FIG. 3. Normalized $F(\Delta\phi)$ distribution for 2 (open circles) and ≥ 2 (black circles) jets with $p_T > 100$ GeV, $|y| < 0.8$, $p_T^{\max} > 110$ GeV and $\sqrt{S} = 7$ TeV. The data are from the ATLAS Collaboration [3]. The curve corresponds to the LO parton Reggeization approach.

Dijet production (central rapidity region) [Nefedov,SV, 2018]

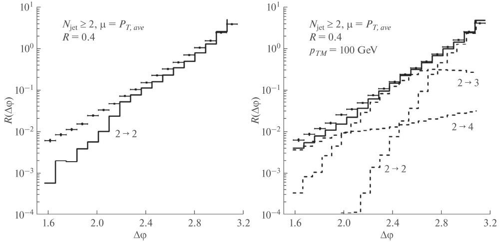


Fig. 1. Distribution on the difference of azimuthal angles between the leading jets $R^{(n\geq 2)}(\Delta\phi)$. The calculations are performed at $\mu = p_{T,ave}$ and $R = 0.4$. Left panel: calculation in the PRA LO. Right panel: calculation by formula (4) at $p_{T\mathcal{M}} = 100$ GeV. Different histograms correspond to the contributions $R^{(2,3,4)}(\Delta\phi)$ and their sum (continuous histogram).

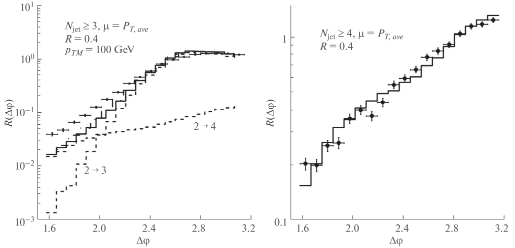
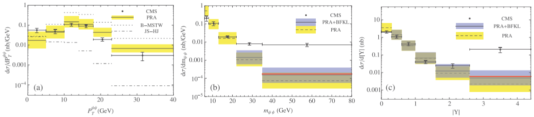


Fig. 2. Left panel: distribution on the difference of azimuthal angles between the leading jets $R^{(n\geq 3)}(\Delta\varphi)$. The calculations are performed at $\mu = p_{T,ave}$, $p_{T\mathcal{M}} = 100$ GeV, and $R = 0.4$. Different histograms correspond to the contributions $R^{(3,4)}(\Delta\phi)$ and their sum (continuous histogram). Right panel: azimuthal spectrum $R^{(n\geq 4)}(\Delta\phi)$, the histogram corresponds to the calculation only with consideration of the contribution $R^{(4)}(\Delta\phi)$ to the PRA LO.

Heavy quarkonium pair production in the NRQCD [He,Nefedov,Kniehl,SV]

- Phys. Rev. Lett. **123**, no.16, 162002 (2019); Mod. Phys. Lett. A **36**, no.19, 2130018 (2021)
- SPS, PRA + LL BFKL for large $|Y|$ region
- DPS calculation is in progress till now



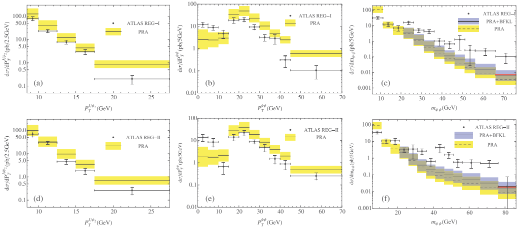
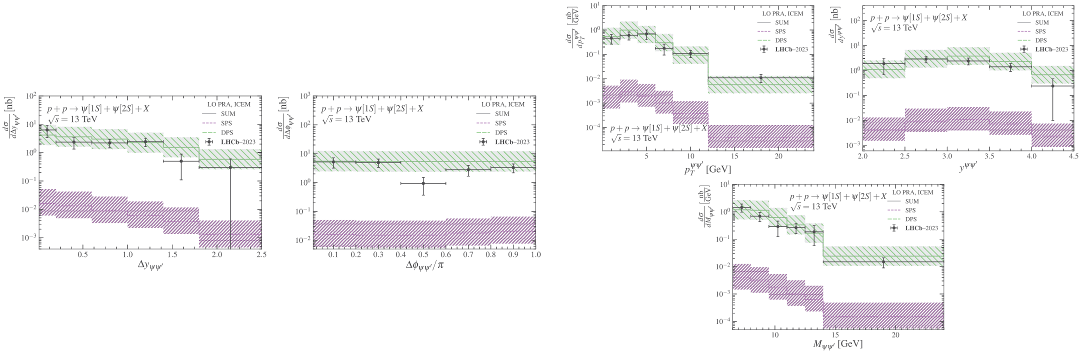


FIG. 3. As in Fig. 2, but for the p_{2T} (left column), $p_T^{\psi\psi}$ (middle column), and $m_{\psi\psi}$ (right column) distributions measured by the ATLAS Collaboration [11] in regions I (upper row) and II (lower row).

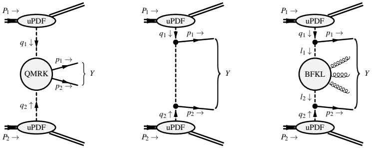
Heavy quarkonium pair production in the ICEM [Chernyshev,SV]

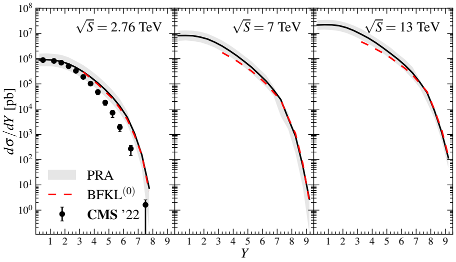
- Phys. Rev. D **106**, no.11, 114006 (2022); Modern Physics Letters A (2024) 2450207
- SPS versus DPS with $\sigma_{eff} \simeq 11$ mb.

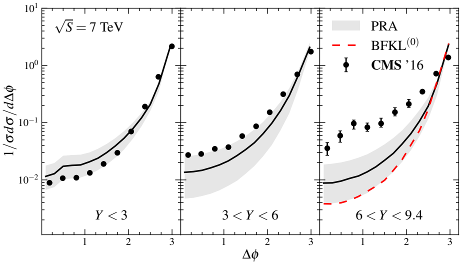


Dijet production with large rapidity gap [Chernyshev,SV, 2024]

PRA ⇒ PRA+BFKL(0) ⇒ PRA+BFKL



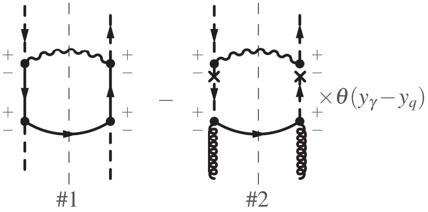


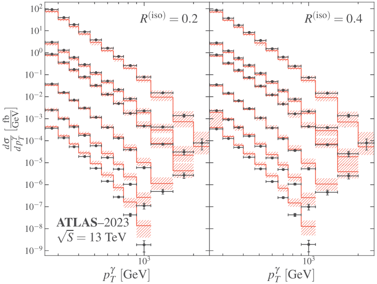


Parton Reggeization Approach in the NLO*

Single isolated photon production in the NLO* of the PRA [Chernyshev, SV, 2024]

- Phys. Rev. D **110**, no.11, 11 (2024)
- LO: $Q\bar{Q} \to \gamma$
- NLO*: $QR \to q\gamma$
- $\sigma^{NLO} = \sigma^{LO} + \sigma^{NLO} - \sigma^{NLO}_{sub}$





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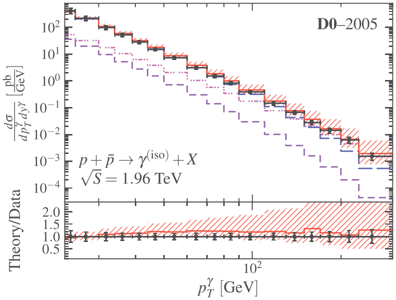
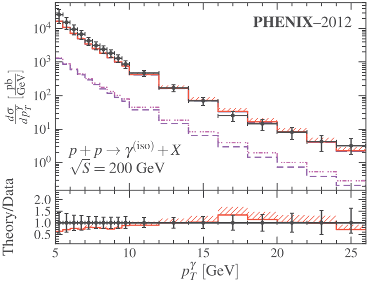
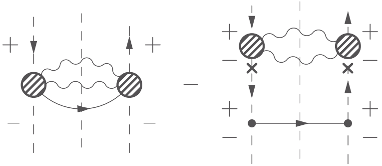


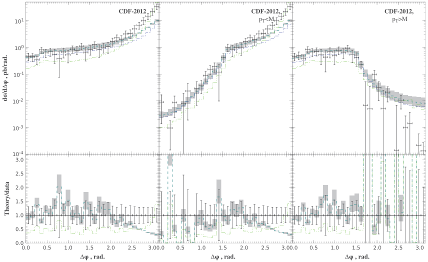


Parton Reggeization Approach in the NLO*

Pair photon production in the NLO* of the PRA [Nefedov, SV, 2015]

- Phys. Rev. D **92**, no.9, 094033 (2015)
- LO: $Q\bar{Q} \to \gamma\gamma$
- NLO*: $QR \to q\gamma\gamma$
- $\sigma^{NLO} = \sigma^{LO} + \sigma^{NLO} - \sigma^{NLO}_{sub}$





Parton Reggeization Approach in the NLO

[Nefedov,SV, 2017-2019], [Nefedov, 2020-2024], [Nefedov, Hameren, 2025]

- A. van Hameren and M. Nefedov, "Hybrid high-energy factorization and evolution at NLO from the high-energy limit of collinear factorization," [arXiv:2501.02619 [hep-ph]].
- M. A. Nefedov, "One-loop impact factors for heavy quarkonium production: S-wave case," JHEP **12**, 129 (2024)
- M. Nefedov, "Sudakov resummation from the BFKL evolution," Phys. Rev. D **104**, no.5, 054039 (2021)
- M. A. Nefedov, "Towards stability of NLO corrections in High-Energy Factorization via Modified Multi-Regge Kinematics approximation," JHEP **08**, 055 (2020)
- M. Nefedov and V. Saleev, "From LO to NLO in the parton Reggeization approach," EPJ Web Conf. **191**, 04007 (2018)
- M. Nefedov and V. Saleev, "On the one-loop calculations with Reggeized quarks," Mod. Phys. Lett. A **32**, no.40, 1750207 (2017)
- M. Nefedov and V. Saleev, "DIS structure functions in the NLO approximation of the Parton Reggeization Approach," EPJ Web Conf. **158**, 03011 (2017) doi:10.1051/epjconf/201715803011

Conclusions

- For single inclusive particle production, the LO PRA $\simeq$ NLO (+ NNLO) CPM, if the real NLO corrections are dominant
- For pair particle production, the LO PRA $\simeq$ NLO CPM for the large kinematic domain
- For pair particle production, the LO PRA agrees with data better than NLO CPM for some correlation spectra
- For multi particle production $(2 \to 3,\ 4, ..)$, the LO PRA is unique way to take into account main part of HO corrections
- The NLO PRA is in progress: loop corrections with Reggeized partons, new uPDFs with evolution, subtraction scheme for real NLO corrections.

THANK YOU FOR YOUR ATTENTION!