Angular decorrelations in $\gamma + 2jet$ events at high energies in the parton Reggeization approach

A.V. Karpishkov, M.A. Nefedov, V.A. Saleev, A.V. Shipilova

Samara University

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Introduction

SPS and DPS in the CPM

PRA at LO

$\gamma + 2jet$ production

Summary and Conclusions

Outline

Introduction

SPS and DPS in the CPM

PRA at LO

$\gamma +$ 2*jet* production

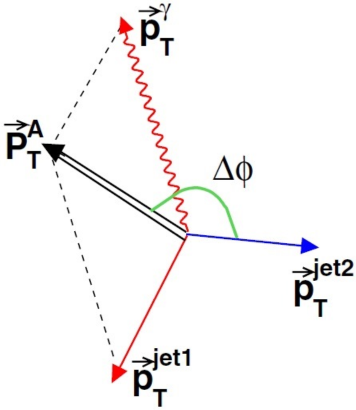
Summary and Conclusions

Motivation

- Multiple jet production is the dominant high transverse-momentum (p_T) process at high energies.
- Photon plus jet production is a testing ground for perturbative QCD (pQCD) with a hard colourless probe less affected by hadronisation effects than jet production.
- Azimuthal decorrelation is sensitive to the radiation of additional jets and probes the dynamics of multijet production.
- Particularly, the measurements of decorrelations in the azimuthal angle between the two most energetic jets, $\Delta\varphi$, as a function of number of produced jets, give the chance to separate directly leading order (LO) and next-to-leading orders (NLO) contributions in the strong coupling constant α_S.
- Observables such as $\Delta\varphi$ probe corners of phase space (that may not be well-described by event generators).
- A detailed understanding of events with large azimuthal decorrelations is important to searches for new physical phenomena with dijet signatures, such as supersymmetric extensions to the Standard Model.

Processes and variables

$$p + p \to a + b + X, \qquad p + p \to a + b + c + X$$

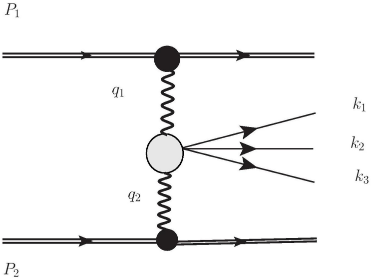


$$\frac{d\sigma}{d\Delta\phi}, \ \Delta\phi = \Delta\phi(\vec{P}_T^{a}, \vec{p}_T^{jet2})$$

Perturbation approach for hard processes

$$S, Q^2 >> \Lambda^2_{QCD} \qquad \alpha_S\left(Q^2/\Lambda^2_{QCD}\right) << 1$$

Collinear parton model is most suitable for Single-Scale hard process



$$d\sigma^{\rm CPM} = \sum_{i,j} \int dx_1\, f_i(x_1,\mu^2) \int dx_2\, f_j(x_2,\mu^2) d\hat{\sigma}^{CPM}_{ij}(x_1,x_2,\mu^2,Q^2) + \mathcal{O}\left(\frac{1}{Q^2}\right)^n, \tag{1}$$

$$\mu = Q, \qquad \ln\left[\frac{Q^2}{\mu^2}\right] \to 0$$

$$q_1 = x_1 P_1, \qquad q_2 = x_2 P_2, \qquad 0 < x_{1,2} < 1$$

Factorization formula of the CPM is proved in LLA for Drell-Yan pair production ($Q^2 = (p_{e^+} + p_{e^-})^2$), Deep Inelastic Scattering $ep-$scattering ($Q^2 = -q^2_{\gamma^*}$), Higgs boson production ($Q^2 = m^2_H$), heavy quark pair production ($Q^2 \sim m^2_q$, $p_T \leq m_q$), ..., i.e. for Single-Scale hard prosesses.

Large collinear $[\alpha_S \log(Q^2/\Lambda^2_{QCD})]^n$ are summed in Collinear Parton Distribution Functions (PDF) – $f(x, \mu^2_F), \quad \mu_F = Q$, which satisfy **DGLAP** evolution equation.

Typical azimuthal angle spectrum

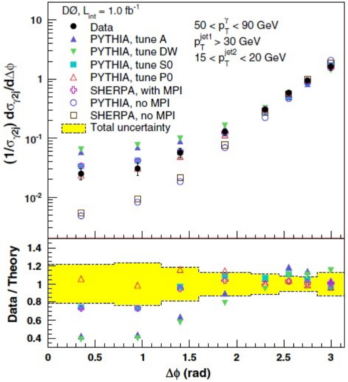


Figure 1: The azimuthal angle difference spectrum

MC: Pythia, SHERPA, *MC@NLO*, ..., - are different scheme of LO and NLO MC parton shower simulations. For ALL, the problem is to describe needed emission of partons with $p_T \sim Q$. There are a lot of data which can not been described in NLO PQCD and NLO-based MC generators.

To solve this task, the DPS approach has been suggested

P_1

$$\frac{d\sigma^{DPS}(pp \to q\bar{q}q\bar{q}X)}{d\Phi_1 d\Phi_2 d\Phi_3 d\Phi_4} = \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma^{SPS}(pp \to q\bar{q}X_1)}{d\Phi_1 d\Phi_2} \cdot \frac{d\sigma^{SPS}(pp \to q\bar{q}X_2)}{d\Phi_3 d\Phi_4}. \quad (2)$$

$$\sigma_{eff} \approx 15 \text{ mb}$$

Because of the nontrivial kinematics of correlation spectra, these correlation observables become Multi-Scale quantities

In the Multi-Scale hard processes, the perturbation series should be very complicated

The aim of PRA is to introduce the gauge-invariant scheme of QCD-factorization, which will take into account the leading part of the high-order corrections, which are needed to describe the spectra of multi-scale hard processes, already in the Leading Order and to improve, in such a way, order-by-order stability of the predictions

LO framework of PRA

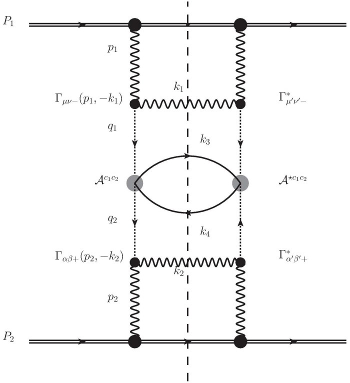
The parton Reggeization approach (PRA)

It is based on modified-MRK (mMRK) factorization

A. V. Karpishkov, M. A. Nefedov, V. A. Saleev, Phys.Rev. **D96** 096019 (2017)

M.A. Nefedov, V.A. Saleev, A. V Shipilova, Phys. Rev. D**87** 094030 (2013)

Auxiliary hard CPM subprocess
$(g(p_1) + g(p_2) \to g(k_1) + [q(k_3) + \bar{q}(k_4)] + g(k_2))$



$p_1^2 = 0,\ p_1^- = 0,\ p_2^2 = 0,\ p_2^+ = 0.$

Kinematic variables ($0 < z_{1,2} < 1$): $z_1 = \frac{p_1^+ - k_1^+}{p_1^+}$, $z_2 = \frac{p_2^- - k_2^-}{p_2^-}$

Two limits where $\overline{|\mathcal{M}|^2}$ factorizes:

1. **Collinear limit:** $\mathbf{k}_{T1,2}^2 \ll \mu^2$, $z_{1,2}$ – arbitrary,
2. **Multi-Regge limit:** $z_{1,2} \ll 1$, $\mathbf{k}_{T1,2}^2$ – arbitrary.

Collinear limit: $\mathbf{k}_{T1,2}^2 \ll \mu^2$, $z_{1,2}$ – arbitrary:

$$\overline{|\mathcal{M}|^2}_{\rm CL} \simeq \frac{4g_s^4}{\mathbf{k}_{T1}^2\mathbf{k}_{T2}^2} P_{gg}(z_1)P_{gg}(z_2)\frac{\overline{|\mathcal{A}_{CPM}|^2}}{z_1z_2},$$

where $\overline{|\mathcal{A}_{CPM}|^2}$ – amplitude $g+g \to q+\bar{q}$ with **on-shell** initial-state partons, $P_{gg}(z)$ – DGLAP $g \to g$ splitting function.

Multi-Regge limit: $z_{1,2} \ll 1$ ($\Leftrightarrow \Delta y_{1,2} \gg 1$), $\mathbf{k}_{T1,2}^2$ – arbitrary:

$$\overline{|\mathcal{M}|^2}_{\rm MRK} \simeq \frac{4g_s^4}{\mathbf{k}_{T1}^2\mathbf{k}_{T2}^2} \tilde{P}_{gg}(z_1)\tilde{P}_{gg}(z_2)\frac{\overline{|\mathcal{A}_{PRA}|^2}}{z_1z_2},$$

where $\tilde{P}_{gg}(z) = 2C_A/z$ and $\overline{|\mathcal{A}_{PRA}|^2}$ is the **gauge-invariant** amplitude $R_+(q_1) + R_-(q_2) \to q + \bar{q}$ with **Reggeized** (**off-shell**) partons in the initial state.

Modified MRK approximation: $z_{1,2}$ and $\mathbf{k}_{T1,2}^2$ – arbitrary:

$$\overline{|\mathcal{M}|^2}_{\rm mMRK} \simeq \frac{4g_s^4}{q_1^2 q_2^2} P_{gg}(z_1) P_{gg}(z_2) \frac{\overline{|\mathcal{A}_{PRA}|^2}}{z_1 z_2},$$

where $q_{1,2}^2 = \mathbf{q}_{T1,2}^2/(1-z_{1,2})$, has correct **collinear** and **Multi-Regge** limits!

$$d\sigma = \int \frac{dk_1^+ d^2\mathbf{k}_{T1}}{2k_1^+} \int \frac{dk_2^- d^2\mathbf{k}_{T2}}{2k_2^-} \int_0^1 d\tilde{x}_1 d\tilde{x}_2 f_g(\tilde{x}_1,\mu^{)} f_g(\tilde{x}_2,\mu^{)} \times$$

$$\times \quad \frac{\overline{|M_{mMRK}|^2}}{2S\tilde{x}_1\tilde{x}_2} d\Phi(k_3,k_4)$$

$$(\tilde{x}_1, k_1^+, \mathbf{k}_{T1}) \to (x_1, z_1, \mathbf{q}_{T1}), \quad (\tilde{x}_2, k_2^-, \mathbf{k}_{T2}) \to (x_2, z_2, \mathbf{q}_{T2})$$

Derive a factorization formula

$$d\sigma^{PRA} = \int_0^1 \frac{dx_1}{x_1} \int \frac{d^2q_{T1}}{\pi} \tilde{\Phi}_g(x_1,t_1,\mu^{)} \int_0^1 \frac{dx_2}{x_2} \int \frac{d^2q_{T2}}{\pi} \tilde{\Phi}_g(x_2,t_2,\mu^2) \times$$

$$\times \quad \frac{\overline{|A_{PRA}|^2}}{2Sx_1x_2} (2\pi)^4 \delta\left(\frac{1}{2}\left(q_1^+ n_- + q_2^- n_+\right) + q_{T1} + q_{T2} - P_{\mathcal{A}}\right) d\Phi(k_3,k_4)$$

where $x_1 = q_1^+/P_1+$, $x_2 = q_2^-/P_2^-$, $\tilde{\Phi}(x,t,\mu^2)$ – “tree-level” **unintegrated PDFs**

LO unintegrated PDF

The “tree-level” unPDF:

$$\tilde{\Phi}_g(x,t,\mu^2) = \frac{1}{t}\frac{\alpha_s}{2\pi}\int\limits_x^1 dz\, P_{gg}(z)\cdot\frac{x}{z} f_g\left(\frac{x}{z},\mu^2\right).$$

contains collinear divergence at $t \to 0$ and IR divergence at $z \to 1$.
In the “dressed” unPDF collinear divergence is regulated by **Sudakov formfactor** $T(t,\mu^2)$:

$$\Phi_i(x,t,\mu^2) \quad = \quad \frac{T_i(t,\mu^2,x)}{t}\times\frac{\alpha_s(t)}{2\pi}\int\limits_x^1 dz\, \theta_z^{\rm cut} P_{ij}(z)\frac{x}{z} f_j\left(\frac{x}{z},t\right)$$

where: $\theta_z^{\rm cut} = \theta\left((1-\Delta_{KMR}(t,\mu^2)) - z\right)$, and the Kimber-Martin-Ryskin(KMR) **cut condition** [KMR, 2001]:

$$\Delta_{KMR}(t,\mu^2) = \frac{\sqrt{t}}{\sqrt{\mu^2}+\sqrt{t}},$$

follows from the **rapidity ordering** between the last emission and the hard subprocess.

LO unintegrated PDF

$$\begin{aligned}\Phi_i(x,t,\mu^2) &= \frac{T_i(t,\mu^2,x)}{t}\times\frac{\alpha_s(t)}{2\pi}\int\limits_x^1 dz\, \theta_z^{\text{cut}} P_{ij}(z)\frac{x}{z} f_j\left(\frac{x}{z},t\right) \\ &= \boxed{\frac{\partial}{\partial t}\left[T_i(t,\mu^2,x)\cdot xf_i(x,t)\right]} \leftarrow \text{derivative form of unPDF}\end{aligned}$$

$\Rightarrow$ **LO normalization condition:**

$$\boxed{\int_0^{\mu^2} dt\ \Phi_i(x,t,\mu^2) = xf_i(x,\mu^2)} \leftarrow \textbf{Holds exactly}!$$

Because $T(0,\mu^2,x) = 0$ and $T(\mu^2,\mu^2,x) = 1$.

The KMR unPDF is actively used in the phenomenological studies employing k_T-factorization. We have found, at first time, it's relationships with MRK limit of the QCD amplitudes.

Advantages of the Parton Reggeization Approach

- In case of Single-Scale hard process predictions obtained in the LO PRA coincide with results of NLO calculations in the CPM. In most cases, the leading processes are $2 \to 1$ instead of $2 \to 2$, as in CPM.
- For Multi-Scale hard processes, in which multiple hard jet emission play a principal role, the LO PRA describes data better than NLO and even NNLO CPM.
- NLO level of calculations in PRA can be achieved.

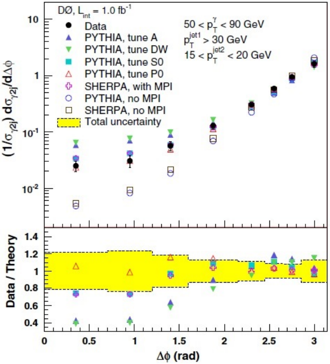
The basics of calculations in PRA

Gauge-invariant off-shell amplitudes $\overline{|\mathcal{A}_{\mathrm{PRA}}|^2}$ is obtained from Lipatov's **gauge-invariant effective theory for MRK processes in QCD**.

- The Effective Field Theory contains field of Reggeized gluons [*Lipatov, 1995.]*
- The Effective action with Reggeized quarks [*Lipatov, Vyazovky, 2001.*]
- Feynman rules for Reggeized gluons [*Antonov, Kuraev, Lipatov, Cherednikov, 2005.]*
- ReggeQCD package for generation Reggeized amplitudes $2 \rightarrow 2, \quad 3, \quad 4$ [*Nefedov, 2016.]*
  ReggeQCD + FeynArts + FeynCalc + FormCalc

Multijet production

Experimental studies of D0 Collaboration: *V. Khachatryan at al.* Azimuthal Decorrelations and Multiple parton interactions in $\gamma + 2jet$ and $\gamma + 3jet$ events in $p\bar{p}$ collisions at $\sqrt{S} = 1.96\ TeV$ Phys. Rev. D **83**, 052008 (2011).
Event generators with and without MPI-effects



Recent LHC results: High-ET isolated-photon plus jets production in pp collisions at $\sqrt{S} = 8\ TeV$ with the ATLAS detector, Nucl. Phys. B **918, 257, 316(2017).**

Subprocesses in PRA

SPS: $QR \to qg\gamma$, $RR \to q\bar{q}\gamma$, $Q\bar{Q} \to q\bar{q}\gamma$, $q = u, d, s, c$

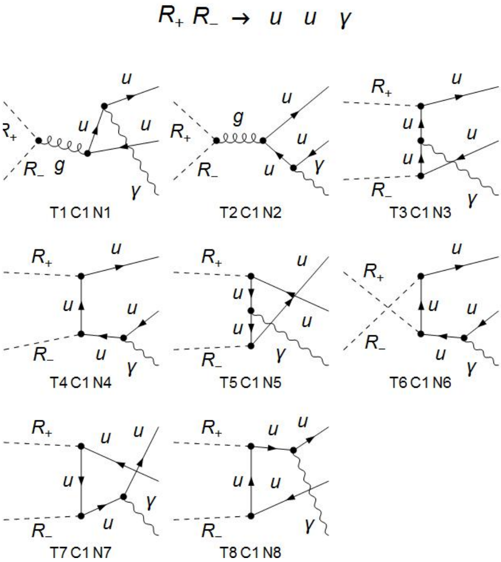
The closely related subprocess $RR \to q\bar{q}g$ firstly was calculated in the recent work *A.V. Karpishkov, M.A. Nefedov, and V.A. Saleev, $B\bar{B}$* ***angular correlations at the LHC in the parton Reggeization approach merged with higher-order matrix elements*** *Phys. Rev. D 96, 096019.* This result finds a full agreement with the result obtained in the approach of automatic amplitude generation implemented in the works *A. van Hameren and M. Serino, BCFW recursion for TMD parton scattering, J. High Energy Phys. 07 (2015) 010 and K. Kutak, A. Hameren, and M. Serino, QCD amplitudes with 2 initial spacelike legs via generalised BCFW recursion, J. High Energy Phys. 02 (2017) 009.*

For the subprocess $RR \to q\bar{q}\gamma$ we perform calculations both in FORMCALC and FEYNCALC using the package *ReggeQCD* which will be published in the separate paper. Such a cross-check demonstrates that both results are coincide.

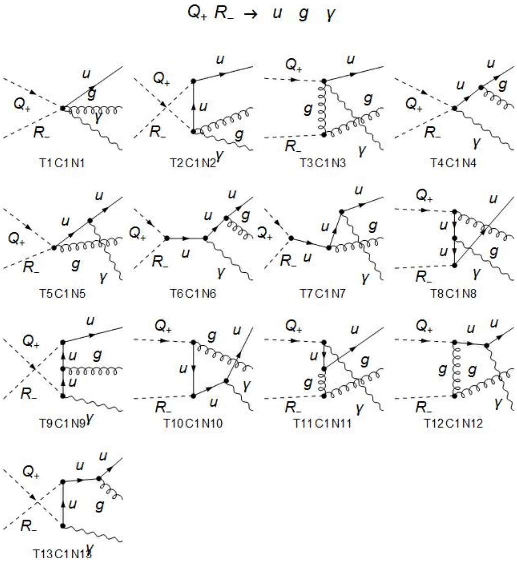
DPS: the convolution of subprocesses $RR \to g$ and $QR \to q\gamma$, $q = u, d, s, c$

The gauge invariance of each amplitude is accurately proved and the PM limit of the corresponding matrix elements is carefully checked.

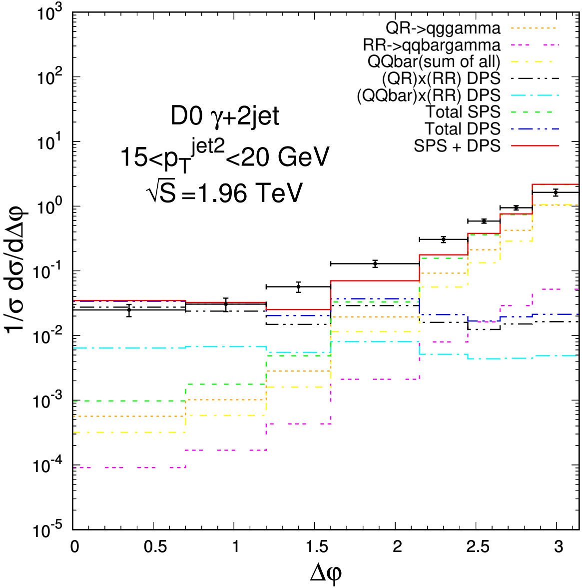
Diagrams for $RR \to q\bar{q}\gamma$



Diagrams for $QR \to qg\gamma$



The normalized azimuthal decorrelations at $\sqrt{S} = 1.96$ TeV



Summary

- We performed the calculation of azimuthal decorrelations in $\gamma + 2jet$ production at Tevatron in the LO of PRA taking into account the main subprocess, for the first time. We find a good agreement with the experimental data for the region $\pi/2 < \Delta\phi < \pi$.
- Our results in LO PRA reproduce the results obtained in NLO of Collinear Parton Model. That fact once again proves this correspondence found in our previous works.
- The agreement with experimental data becomes better with the enlargement of p_T, as it is expected, and following the general tendency. Nevertheless there remains a room for the multi-parton scattering in the region of $0 < \Delta\phi < \pi/2$.

- *Jet and Dijet production at the LHC*

  B. A. Kniehl, V. A. Saleev, A. V. Shipilova, E. V. Yatsenko. Single jet and prompt-photon inclusive production with multi-Regge kinematics: From Tevatron to LHC. Phys. Rev. D **84**, 074017 (2011);
  M. A. Nefedov, N. N. Nikolaev, V. A. Saleev. Drell-Yan lepton pair production at high energies in the parton Reggeization approach. Phys. Rev. D **87**, 014022 (2013).
  *M.A. Nefedov, V.A. Saleev, A. V Shipilova.*Dijet azimuthal decorrelations at the LHC in the parton Reggeization approach. Phys. Rev. D**87** (2013) 094030.
- *b−jet production at the LHC*

  B. A. Kniehl, A. V. Shipilova and V. A. Saleev. Inclusive b and b anti-b production with quasi-multi-Regge kinematics at the Tevatron. Phys. Rev. D **81**, 094010 (2010);
  V. A. Saleev and A. V. Shipilova. Inclusive b-jet and bb-dijet production at the LHC via Reggeized gluons. Phys. Rev. D **86**, 034032 (2012).
- *Heavy quarkonium production at the LHC*

  *M.A. Nefedov, V.A. Saleev, A. V. Shipilova.*Prompt Upsilon(nS) production at the LHC in the Regge limit of QCD. Phys. Rev. D**87** (2013)
  *M.A. Nefedov, V.A. Saleev, A. V. Shipilova.*Prompt J/psi production in the Regge limit of QCD: From Tevatron to LHC Phys. Rev. D**85** (2012) 074013.

  Karpishkov A. V., Nefedov M. A., Saleev V. A. $B\bar{B}$ angular correlations at the LHC in the parton Reggeization approach merged with higher-order matrix elements Phys. Rev. D**96**, (2017) 096019.
- *Open heavy flavored meson production* *Karpishkov A. V., Nefedov M. A., Saleev V. A., Shipilova A. V.* B-meson production in the Parton Reggeization Approach at Tevatron and the LHC Int. J. Mod. Phys. A, V. **30**, 1550023 (2015); Open charm production in the parton Reggeization approach: Tevatron and the LHC Phys.Rev. D **91** (2015) 054009.
- *Prompt-photon plus jet associated photoproduction; Drell-Yan pair production;...*

Thank you for attention!