Isolated photon production and pion-photon correlations in high-energy pp and pA collisions

Michal Šumbera[a,b]

(a) *Nuclear Physics Inst. ASCR, 25068 Řež/Prague, Czech Republic*
(b) *In collaboration with Victor Goncalves, Yuri Lima and Roman Pasechnik*

International Conference on High Energy Physics,
Prague 28 July - 6 August, 2020

Isolated photon production in *pp* and *pA* collisions

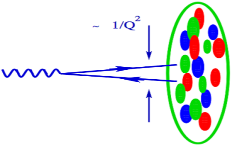
- The isolated (prompt) γ production in *pp* and *pA* high-energy collisions represents an attractive and clean probe in soft and pQCD regimes as well as nuclear effects and medium-induced QCD phenomena.
- It can be used to set constraints on PDFs in specific kinematic domains not sufficiently well explored by HERA (focus of ongoing and planned measurements at the LHC and RHIC).
- At very low-x the primordial transverse momentum evolution of incoming partons and non-linear QCD effects such as gluon saturation start to play a significant role whose reliable first-principle analysis represents a long-standing theoretical challenge.
- Experiments at the LHC [1] and at RHIC [2] are planning to extend their capabilities in the forward region to access low-x physics.

---

[1] S. Acharya *et al.* [ALICE Collaboration], Phys. Rev. C **99**, 024912 (2019).
[2] G. David, Rept. Prog. Phys. **83**, no.4, 046301 (2020).

Color dipole picture of low-x Deep Inelastic Scattering

- At low-x standard DIS proton structure functions $F_2 = F_T + F_L$ can be expressed in terms of total $\gamma^* p$ cross sections $\sigma_{\gamma^* p} = \sigma_T + \sigma_L$ [1] :



$$F_{T,L}(x, Q^2) = \frac{Q^2}{4\pi^2 \alpha_{em}} \sigma_{T,L}(x, Q^2)$$

$$\sigma_{T,L}(x, Q^2) = \int d^2\mathbf{r} \int_0^1 dz |\Psi_{T,L}(r, z, Q^2)|^2 \sigma^N_{q\bar{q}}(r, x) \quad (1)$$

where $\Psi_{T,L}$ is wave function for splitting of transverse (T) or longitudinal (L) polarized virtual photon into a $q\bar{q}$ dipole and $\sigma^N_{q\bar{q}}(r, x)$ is the dipole-proton cross section.

- Assumption $\sigma^N_{q\bar{q}}(r, x) = \sigma_0 g(\frac{r}{R_0(x)})$, where $R_0(x)$ is called saturation radius, leads to geometric scaling model of DIS [2].
- Rescaling the dipole size $r \to \hat{r} = r/R_0(x)$ in Eq.(1):

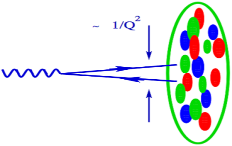
  $\Rightarrow \quad \sigma_{T,L}(x, Q^2) \;\to\; \sigma_{T,L}(\tau)$, where $\tau \equiv Q^2 R_0^2(x) \equiv Q^2/Q_s^2(x)$.
- For $\hat{r} \to \infty$ function $g(\hat{r}) \to 1$ (saturates) and $\sigma^N_{q\bar{q}}(r, x) \to \sigma_0$ becomes the energy independent constant, i.e. reaches the unitarity bound value.

[1] N. N. Nikolaev and B. G. Zakharov, Z. Phys. C49, 607 (1991)
[2] K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D 59, 014017 (1999); *ibid* 60, 114023 (1999); PRL 86, 596 (2001)

Color dipole picture of low-x Deep Inelastic Scattering

- At low-x standard DIS proton structure functions $F_2 = F_T + F_L$ can be expressed in terms of total $\gamma^* p$ cross sections $\sigma_{\gamma^* p} = \sigma_T + \sigma_L$ [1] :

$$F_{T,L}(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{em}}\sigma_{T,L}(x,Q^2)$$



$$\sigma_{T,L}(x,Q^2) = \int d^2\mathbf{r} \int_0^1 dz |\Psi_{T,L}(r,z,Q^2)|^2 \sigma_{q\bar{q}}^N(r,x) \quad (1)$$

where $\Psi_{T,L}$ is wave function for splitting of transverse (T) or longitudinal (L) polarized virtual photon into a $q\bar{q}$ dipole and $\sigma_{q\bar{q}}^N(r,x)$ is the dipole-proton cross section.

- Assumption $\sigma_{q\bar{q}}^N(r,x) = \sigma_0 g(\frac{r}{R_0(x)})$, where $R_0(x)$ is called saturation radius, leads to geometric scaling model of DIS [2].
- Rescaling the dipole size $r \to \hat{r} = r/R_0(x)$ in Eq.(1):

$$\Rightarrow \quad \sigma_{T,L}(x,Q^2) \ \to \ \sigma_{T,L}(\tau), \text{ where } \tau \equiv Q^2 R_0^2(x) \equiv Q^2/Q_s^2(x).$$

- For $\hat{r} \to \infty$ function $g(\hat{r}) \to 1$ (saturates) and $\sigma_{q\bar{q}}^N(r,x) \to \sigma_0$ becomes the energy independent constant, i.e. reaches the unitarity bound value.

[1] N. N. Nikolaev and B. G. Zakharov, Z. Phys. C49, 607 (1991)
[2] K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D 59, 014017 (1999); *ibid* 60, 114023 (1999); PRL 86, 596 (2001)

Color dipole model in *pp* and $p(d)A$ collisions

- **Color dipole model (CDM) in $dA \to \pi$**
  - J. Nemchik,*et al.*, *Nuclear suppression at large forward rapidities in d-Au collisions at relativistic and ultrarelativistic energies*, Phys. Rev. C **78**, 025213 (2008).
  - J. Nemchik and M. Sumbera, *Physics of Large-x Nuclear Suppression*, Nucl. Phys. A **830**, 611C-614C (2009).

- **CDM in $pp/pA \to \ell^+\ell^-$ and $pp/pA \to Z^0$**
  - E. Basso, *et al.*, *Drell-Yan phenomenology in the color dipole picture revisited*, Phys. Rev. D **93**, 034023 (2016).
  - E. Basso, *et al.*, *et al. 'Nuclear effects in Drell-Yan pair production in high-energy pA collisions*, Phys. Rev. D **93**, 094027 (2016).

- **CDM in heavy quark production in *pp***
  - V. P. Goncalves, *et al.*, *Heavy flavor production in high-energy pp collisions: color dipole description*, Phys. Rev. D **96**, 014010 (2017).

- **CDM in $pp/pA \to \gamma$**
  - V. P. Goncalves, *et al.*, *Isolated photon production and pion-photon correlations in high-energy pp and pA collisions*, Phys. Rev. D **101**, 094019 (2020).

Frame-dependent description of prompt γ production

- Cross section of prompt γ production is Lorentz invariant but its partonic interpretation is frame-dependent.
- In the cms frame it occurs via Compton scattering, in the lab frame it appears as photon Bremsstrahlung off a fast projectile quark q_f propagating through the low-x color field of the target T.p

Figure 1: Bremsstrahlung of photon off a projectile a quark (antiquark) of flavour *f* either after (left) and before (right) its interaction with the color field of the target (denoted by a shaded circle), respectively.

- N.B. Lifetime $\Delta\tau_{lab}$ of partonic fluctuation in the lab frame is enhanced with respect to that in the cms: $\Delta\tau_{lab} \approx \sqrt{s}/m_p \times \Delta\tau_{cms}$ effectively accounting for the higher-order QCD corrections [1,2].

[1] J. Raufeisen, J.-C. Peng and G. C. Nayak, Phys. Rev. D 66, 034024 (2002).

[2] M. B. Johnson *et al.*, Phys. Rev. C 75, 035206 (2007).

Relating γ production to DIS via color dipole model

- For $\sqrt{s} \gg m_c, m_b$ the prompt γ production can be formulated in the lab frame using the same color dipole cross section used in low-x DIS [1].
- The amplitudes for scattering of $|q\rangle$ and $|q\gamma\rangle$ Fock states off the target T, see Fig. 1, interfere. The matrix element squared integrated over the impact parameter of the initial quark expressed in terms of the universal dipole-target cross section $\sigma^T_{q\bar{q}}(\Delta\mathbf{r}, x)$ gives:

$$\frac{d\sigma^f(qT \to q\gamma X)}{d\ln\alpha d^2 p_T} = \frac{1}{(2\pi)^2}\int d^2\rho_1\, \mathrm{d}^2\rho_2 e^{i\mathbf{p}_T\cdot(\boldsymbol{\rho}_1-\boldsymbol{\rho}_2)}\Psi(\alpha, \boldsymbol{\rho}_1, m_f)\Psi^*(\alpha, \boldsymbol{\rho}_2, m_f) \times\frac{1}{2}\left[\sigma^T_{q\bar{q}}(\alpha\boldsymbol{\rho}_1, x_2) + \sigma^T_{q\bar{q}}(\alpha\boldsymbol{\rho}_2, x_2) - \sigma^T_{q\bar{q}}(\alpha|\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2|, x_2)\right]$$

where m_f is the constituent quark mass, and $\Psi(\alpha, \boldsymbol{\rho}, m_f)$ is the LC wave function of the real photon radiation off a quark with flavor f.

- N.B. Due to the γ Bremsstrahlung the final quark gets a transverse shift relative to the initial one, $\Delta\mathbf{r} = \alpha\boldsymbol{\rho}$, where α is the fractional LC momentum taken by the radiated photon off the projectile quark and $\boldsymbol{\rho}$ is the transverse separation between quark and photon.

Cross section of p-induced prompt γ production

$$\frac{d\sigma(p\,T\to\gamma X)}{\mathrm{d}^2 p_T d\eta} = \frac{2p_T\cosh(\eta)}{\sqrt{s}}\frac{x_1}{x_1+x_2}\sum_f\int_{x_1}^1\frac{d\alpha}{\alpha^2}\left[q_f(\tfrac{x_1}{\alpha},\mu_F^2)+\bar{q}_f(\tfrac{x_1}{\alpha},\mu_F^2)\right]\frac{d\sigma^f(q\,T\to q\gamma X)}{d\ln\alpha\, d^2p_T}$$

p_T, η and $x_F = x_1 - x_2$ are the transverse momentum, pseudorapidity and the Feynman variable of the photon.

$x_{1,2} = \frac{p_T}{\sqrt{s}}e^{\pm\eta}$ – LC (longitudinal) momentum fractions of the isolated photon, taken from the incoming proton momenta $p_{1,2}$.

$q_f(\bar{q}_f), f = u, d, s, c$ – unpolarised projectile quark (antiquark) collinear PDFs as functions of the momentum fraction of the projectile quark taken from the parent nucleon $x_q = x_1/\alpha$ and the QCD factorisation scale $\mu_F = p_T \equiv |\mathbf{p}_T|$.

Color dipole cross section models: proton target

- Dipole cross section models used: GBW, CGC, AAMQS.

GBW: K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D **59**, 014017 (1999); **60**, 114023 (1999); PRL **86**, 596 (2001)

$$\sigma_{q\bar{q}}^{p}(r,x) = \sigma_0 \left[1 - e^{-\frac{r^2 Q_{s,p}^2(x)}{4}}\right], \; Q_{s,p}^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^{\lambda}$$

CGC: Saturation model for $\sigma_{q\bar{q}}^{p}(r,x)$ based upon the Color Glass Condensate
E. Iancu, K. Itakura, S. Munier, Phys. Lett. B **590**, 199 (2004)

$$\sigma_{q\bar{q}}^{p}(r,x) = \sigma_0 \times \begin{cases} \mathcal{N}_0 \left(\frac{r\,Q_{s,p}}{2}\right)^{2\left(\gamma_s + \frac{\ln(2/rQ_{s,p})}{\kappa\,\lambda\,Y}\right)} & r\,Q_{s,p} \le 2 \\ 1 - \exp^{-A\,\ln^2(B\,r\,Q_{s,p})} & r\,Q_{s,p} > 2 \end{cases} \quad (1)$$

$\kappa = \chi''(\gamma_s)/\chi'(\gamma_s)$, where χ is the LO BFKL characteristic function. The coefficients A and B are uniquely determined from the continuity condition for the dipole cross section and its derivative with respect to $r\,Q_{s,p}$ at $r\,Q_{s,p} = 2$.

AAMQS: Solution of the Balitsky-Kovchegov equation with running coupling obtained in J. L. Albacete *et al.*, Eur. Phys. J. C **71**, 1705 (2011) and initial conditions constrained by a fit to the HERA DIS data.

Color dipole cross section models: nuclear target

1. Glauber-Mueller (GM) approach [1, 2]: resummation of all the multiple elastic rescattering diagrams for the $q\bar{q}$ dipole propagation through the nuclear target.

$$\sigma^A_{q\bar{q}}(r,x) = 2\int d^2b_A \left\{1 - \exp\left[-\frac{1}{2}\sigma^p_{q\bar{q}}(r,x)\, T_A(b_A)\right]\right\}$$

where $T_A(b_A)$ is the nuclear thickness function and b_A is the impact parameter of the dipole with respect to the nucleus centre with the amplitude of $q\bar{q}-A$ scattering given by:

$$\Gamma^A_{q\bar{q}}[\vec{b_A};(\vec{s_j},z_j)] = 1 - \prod_{k=1}^{A}\left[1 - \Gamma^p_{q\bar{q}}(\vec{b_A} - \vec{s_k})\right]; \quad \sigma^p_{q\bar{q}} = 2\int d^2b\, \mathrm{Re}\Gamma^p_{q\bar{q}}$$

2. Solution the running-coupling Balitsky-Kovchegov (rcBK) equation for the nuclear case [3, 4] which takes into account mutual interactions of the gluonic ladders exchanged between the dipole and the nucleus.

[1] R. J. Glauber and G. Matthiae, Nucl. Phys. B **21**, 135 (1970).
[2] A. H. Mueller, Nucl. Phys. B **335**, 115 (1990).
[3] K. Dusling *et al.*, Nucl. Phys. A **836**, 159 (2010).
[4] T. Lappi and H. Mantysaari, Phys. Rev. D **88**, 114020 (2013).

Isolated photons at midrapidity: RHIC at $\sqrt{s} = 0.2$ TeV

V. P. Goncalves *et. al.*, Phys. Rev. D **101**, 094019 (2020)

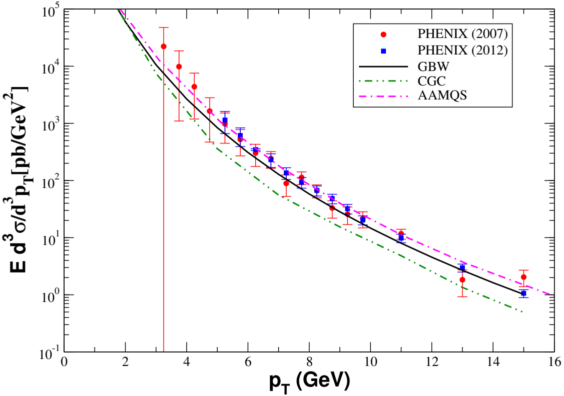
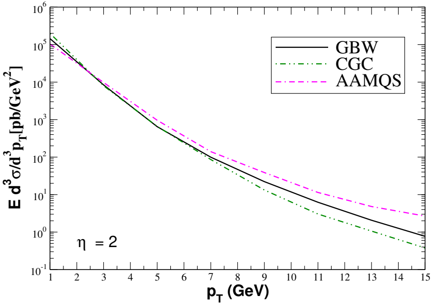


Figure 2: The isolated photon p_T-spectra in *pp* collisions at $\sqrt{s} = 0.2$ TeV and $\eta = 0$, obtained using the different models for the dipole cross section. Experimental data are from S. S. Adler *et al.*, Phys. Rev. Lett. **98**, 012002 (2007) and A. Adare *et al.*, Phys. Rev. D **86**, 072008 (2012).

Isolated photons at large η: RHIC at $\sqrt{s} = 0.5$ TeV

V. P. Goncalves *et. al.*, Phys. Rev. D **101**, 094019 (2020)



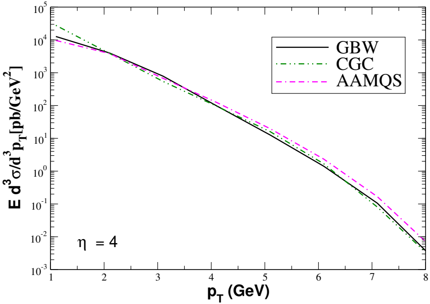


Figure 3: The isolated photon p_T-spectra in pp collisions at $\sqrt{s} = 0.5$ TeV for $\eta = 2$ (left) and $\eta = 4$ (right) using the different models for the dipole cross section.

Isolated photons at large η: LHC at $\sqrt{s} = 14$ TeV

V. P. Goncalves *et. al.*, Phys. Rev. D **101**, 094019 (2020)

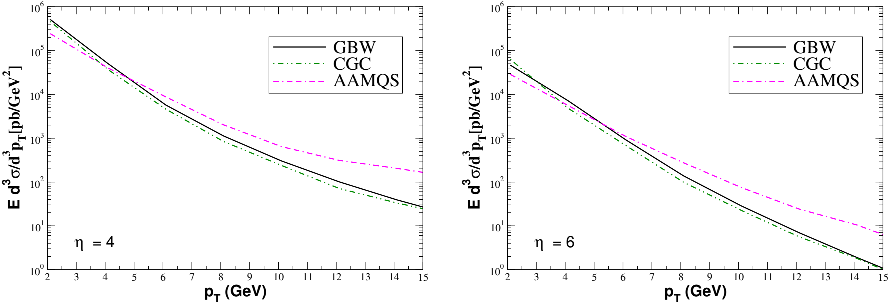


Figure 4: The isolated photon transverse-momentum spectra in *pp* collisions at $\sqrt{s} = 14$ TeV for $\eta = 4$ (left) and $\eta = 6$ (right) using the different models for the dipole cross section..

Nuclear modification factor R_{pA} at $\sqrt{s_{\rm NN}} = 8.8$ TeV

$$R_{pA} = \frac{\sigma_{inel}^{pp}}{<N_{bin}>\sigma_{hadr}^{pA}} \frac{E\frac{d^3\sigma}{dp^3}(p+A\to\gamma+X)}{E\frac{d^3\sigma}{dp^3}(p+p\to\gamma+X)}$$

V. P. Goncalves *et. al.*, Phys. Rev. D **101**, 094019 (2020)

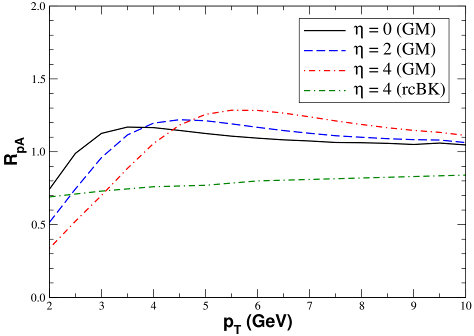


Figure 5: p_T-dependence of the nuclear modification factor R_{pA} for isolated photon production in pPb collisions at the LHC ($\sqrt{s_{\rm NN}} = 8.8$ TeV) for several selected values of the photon pseudorapidity η and for two distinct (GM and rcBK) models of the dipole-nucleus cross section.

Photon/dilepton - hadron correlations: Motivation

- In both pA and pp collisions photon/DY production is accompanied by hadron production from fragments of the quark which radiated γ/γ^*.

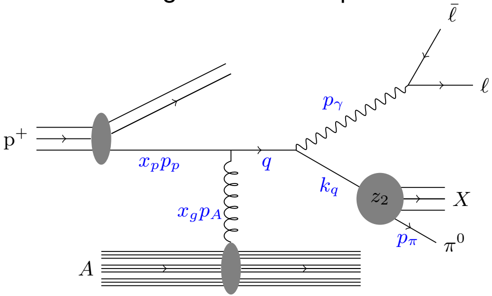


Figure from A. Staśto *et al.*, Phys. Rev. D **86**, 014009 (2012).

- Quark, in order to radiate the photon, has to acquire its p_T via multiple gluon exchanges with the target. When the target color field becomes dominated by low-x gluons with $k_T^g \sim Q_s$ one expects that for $m_T(x) \gtrsim Q_s(x)$ suppression of $\gamma^* - h$ correlation at $\Delta\phi \approx \pi$ takes place⋆.

$\Rightarrow$ Study γ^*-h azimuthal correlations.

⋆) A. Staśto *et al.*, Phys. Rev. D**86**, 014009 (2012)

Photon - hadron azimuthal correlation function $C(\Delta\phi)$

- $C(\Delta\phi)$ – coincidence probability per trigger particle γ:

$$C(\Delta\phi) = \frac{2\pi \int_{p_T, p_T^h > p_T^{\rm cut}} dp_T p_T \; dp_T^h p_T^h \; \frac{d\sigma(pT \to h\gamma X)}{d\eta dy_h d^2 p_T d^2 p_T^h}}{\int_{p_T > p_T^{\rm cut}} dp_T p_T \; \frac{d\sigma(pT \to \gamma X)}{d\eta d^2 p_T}}$$

  where $p_T^{\rm cut}$ is experimental lower cut-off on p_T of γ and of hadron p_T^h and $\Delta\phi$ is the angle between them.

- To describe interactions of the incoming quark with the target color field we employ unintegrated gluon distribution function (UGDF):

  $F(x_g, k_T^g) = [\pi Q_s^2(x_g)]^{-1} \, exp(-k_T^{g\,2}/Q_s^2(x_g)) \, , Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$ [1]

  $x_g = x_1 \, e^{-2Y} + \frac{x_h}{z_h} \, e^{-2y_h}, \quad \mathbf{k}_T^q = \frac{\mathbf{p}_T^h}{z_h}, \quad \mathbf{k}_T^g = \mathbf{p}_T + \mathbf{k}_T^q, \quad \mathbf{P}_T = (1-z)\mathbf{p}_T - z\mathbf{k}_T^q$

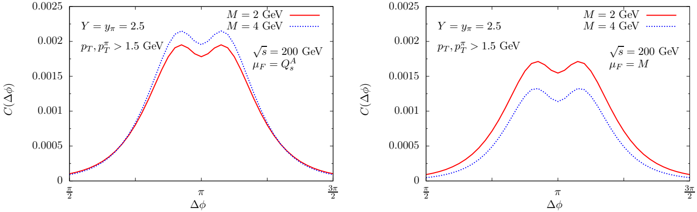
- KKP fragmentation function $D_{h/f}(z_h, \mu_F^2)$ of a quark with a flavor f into a neutral pion $h = \pi^0$ was used [2]. We assume $\mu = \mu_F$.

---

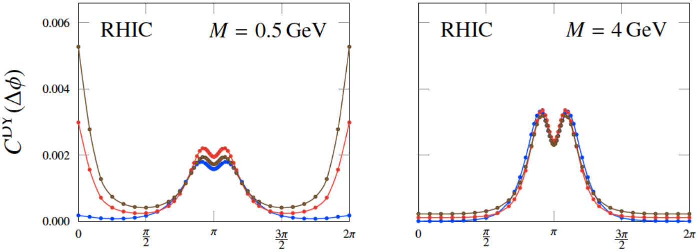
[1] $Q_0^2 = 1$ GeV^2, $x_0 = 3.04 \times 10^{-4}$, $\lambda = 0.288$, $\sigma_0 = 23.03$ mb from fit to DIS data.
[2] B. A. Kniehl, G. Kramer and B. Potter, Nucl. Phys. B **582**, 514 (2000).

γ^*-π azimuthal correlations in *dAu*@RHIC

E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)



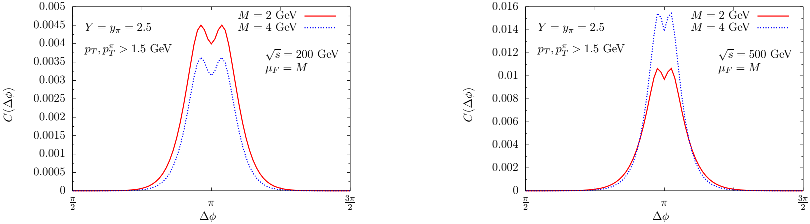
A. Staśto et al., Nucl. Phys. A 904-905, 837c (2013)



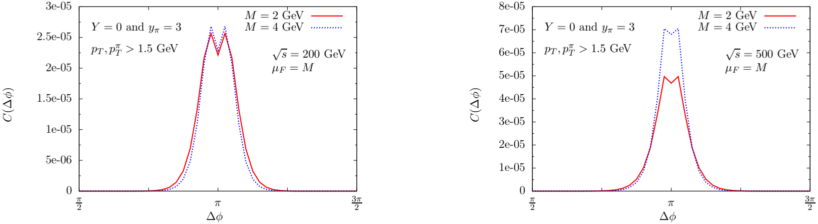
- Similarly to Staśto *et al.* the away-side double-peak structure shows up in dAu.
- Independently of the factorization scale μ_F choice $\Rightarrow$ it is expected also for pp.

γ^*-π azimuthal correlations in *pp*@RHIC

Forward-Forward



Central-Forward



E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)

- Away-side double-peak structure is present also in pp collisions at RHIC.
- Shows up both in Fwd-Fwd and Centr-Fwd correlations $\Rightarrow$ is measurable!
- Centr-Fwd correlations are by two orders in magnitude smaller than Fwd-Fwd.

$\gamma - \pi^0$ azimuthal correlations in *pp* and *pAu* at RHIC

V. P. Goncalves *et. al.*, Phys. Rev. D **101**, 094019 (2020)

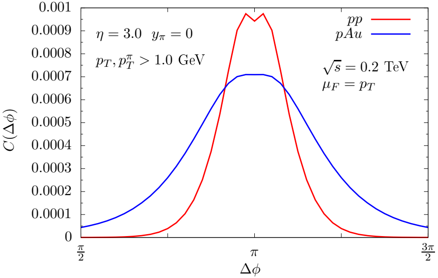


Figure 6: The correlation function $C(\Delta\phi)$ for the associated isolated photon at forward rapidity $\eta = 3$ and pion production at midrapidity (left) and at forward rapidity (right) in *pp* and *pAu* collisions at RHIC $\sqrt{s_{\rm NN}} = 0.2$ TeV.

$\gamma - \pi^0$ azimuthal correlations in *pA* at the LHC

V. P. Goncalves *et. al.*, Phys. Rev. D **101**, 094019 (2020)

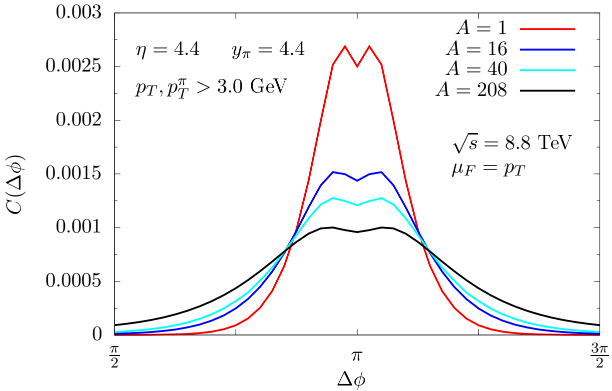


Figure 7: The correlation function $C(\Delta\phi)$ for the associated photon and pion production in *pA* collisions at the LHC ($\sqrt{s_{\rm NN}} = 8.8$ TeV) for different nuclei.

Growth of the saturation scale $Q_{s,A}(x) \propto A^{1/3}$ leads to de-correlation and hence to $C(\Delta\phi = \pi) \sim A^{-0.2}$.

Dependence of $C(\Delta\phi)$ on the model of UGDF

V. P. Goncalves *et. al.*, Phys. Rev. D **101**, 094019 (2020)

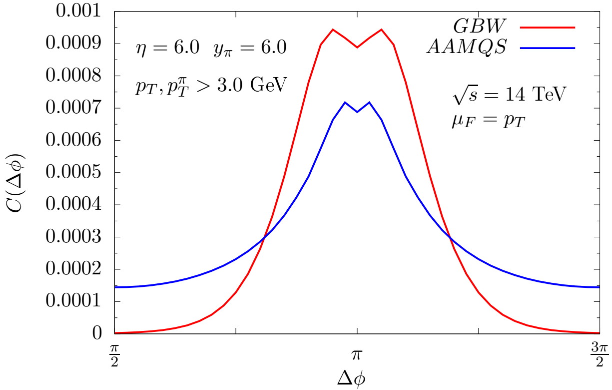


Figure 8: $C(\Delta\phi)$ in *pp* collisions at the LHC for two different models (GBW and AAMQS) of the UGDF in the proton target.

Both models predict a similar behavior and differ mainly in the region dominated by the leading jet fragmentation.

Conclusions

- Detailed phenomenological analysis of prompt photon production at RHIC and LHC energies in the framework of color dipole approach was presented.
- Three/two different phenomenological saturation models for the dipole--target scattering (GBW, CGC, AAMGS) / (GM, rcBK) were used to analyse p_T spectra of prompt photons in pp/pA collisions.
- Both in *pA* and *pp* we have found a characteristic double-peak structure of the correlation function $C(\Delta\phi)$ around $\Delta\phi \approx \pi$ between back-to-back produced real photons and hadrons (pions) emerging either at large forward rapidities or, to a lesser extent, when one of the particles is at midrapidity.
- The double peak around $\Delta\phi \approx \pi$ appears to be strongly sensitive to the details of theoretical modelling of the saturation phenomena in QCD.
- Measurement of $C(\Delta\phi)$ at different energies at the RHIC and the LHC can be useful when probing the underlying dynamics by setting even stronger constraints on the saturation physics.

Back up slides

Mapping the k_T^g contribution to $C(\Delta\phi)$

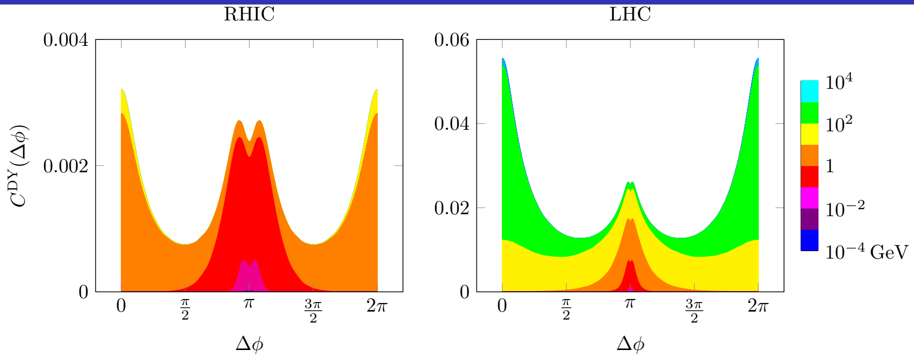


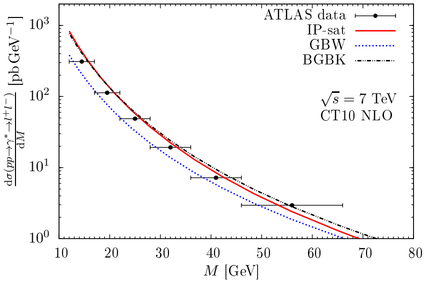
Figure from D. Zaslavsky, arXiv:1409.8259 [hep-ph].

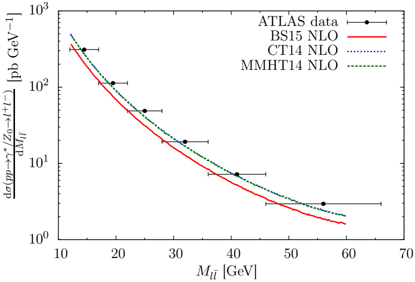
- Contributions of different k_T^g, the transverse momentum acquired by the quark as it interacts with the gluon field of the target, to $C(\Delta\phi)$. Left RHIC ($M = 0.5$GeV), right LHC ($M = 4.$GeV).
- There is a sharp transition between the momenta that contribute to the central back-to-back emission peak and those that contribute to the parallel emission peak. For the RHIC that transition is around 1 GeV and for the LHC between 10 GeV and 100 GeV.

DY: Color dipole approach vs. NLO pQCD calculations

E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)

E. Basso *et. al.*, Nucl. Phys. A **948**, 63 (2016)





ATLAS data: G. Aad *et al.*, JHEP **1406**, 112 (2014)

- Confirms previous observation[1,2] that
  dipole approach effectively accounts for higher order pQCD corrections

[1] J. Raufeisen, J.-C. Peng and G. C. Nayak, Phys. Rev. D **66**, 034024 (2002);
[2] M. B. Johnson *et al.* Phys. Rev. C **75**, 035206 (2007); M. B. Johnson *et al.* ibid C **75**, 064905 (2007).