Production of isolated and virtual photons and pion-photon correlations in high-energy pp and pA collisions

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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.

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[1] S. Acharya *et al.*, [ALICE Collaboration], CERN-LHCC-2020-009.
[2] G. David, Rept. Prog. Phys. **83**, no.4, 046301 (2020).

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

- **Color dipole model 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).
- **Color dipole model 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.*, *Nuclear effects in Drell-Yan pair production in high-energy pA collisions*, Phys. Rev. D **93**, 094027 (2016).
- **Color dipole model 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).
- **Color dipole model 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).

Relating γ^* production to DIS via color dipole model

- *In the kinematical region $\sqrt{s} \gg$ all other scales (e.g. m_c, m_b), the DY process can be formulated in the target rest frame in terms of the same color dipole cross section used in low-x DIS [1]:*

$$\boxed{\frac{d\sigma(qN\to\gamma^*X)}{d\ln\alpha} = \int d^2\rho\, |\Psi_{\gamma^*q}(\alpha,\rho)|^2\, \sigma^N_{q\bar q}(\alpha\rho, x)}$$

$\Psi_{\gamma^*q}(\alpha,\rho)$ – LC wave function. Provides rate of $q\to\gamma^*q$ EM radiation, is PT calculable.
$\sigma^N_{q\bar q}$ – dipole cross section. Has NP origin, comes from phenomenology (GBW [2] *etc.*)
$\alpha = p^+_\gamma/p^+_q$ – LC momentum fraction of parent quark taken away by γ^*.
ρ – transverse separation between γ^* and final quark.

$$\frac{d^2\sigma(pN\to\gamma^*X)}{dM^2dx_F} = \frac{\alpha_{em}}{3\pi M^2}\frac{x_1}{x_1+x_2}\int_{x_1}^1\frac{d\alpha}{\alpha^2}\sum_{f=1}^{N_f}Z_f^2\left[q_f\left(\frac{x_1}{\alpha},\mu_F^2\right)+\bar q_f\left(\frac{x_1}{\alpha},\mu_F^2\right)\right]\frac{d\sigma(qN\to\gamma^*X)}{d\ln\alpha}$$

$x_1 = \frac{2P_2\cdot p}{s}$, $x_2 = \frac{2P_1\cdot p}{s}$, $s=(P_1+P_2)^2$, $p^2 = M^2 \equiv M^2_{\ell\bar\ell}$, $x_F = x_1 - x_2 = 2p_L/\sqrt{s}$
$\mu_F^2 = (1-x_1)M_T^2$ – hard scale at which the projectile parton distribution q_f is probed.

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[1] J. Raufeisen *et al.*, Phys. Rev. D **66**, 034024 (2002)

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.

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

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.

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[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).

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)

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

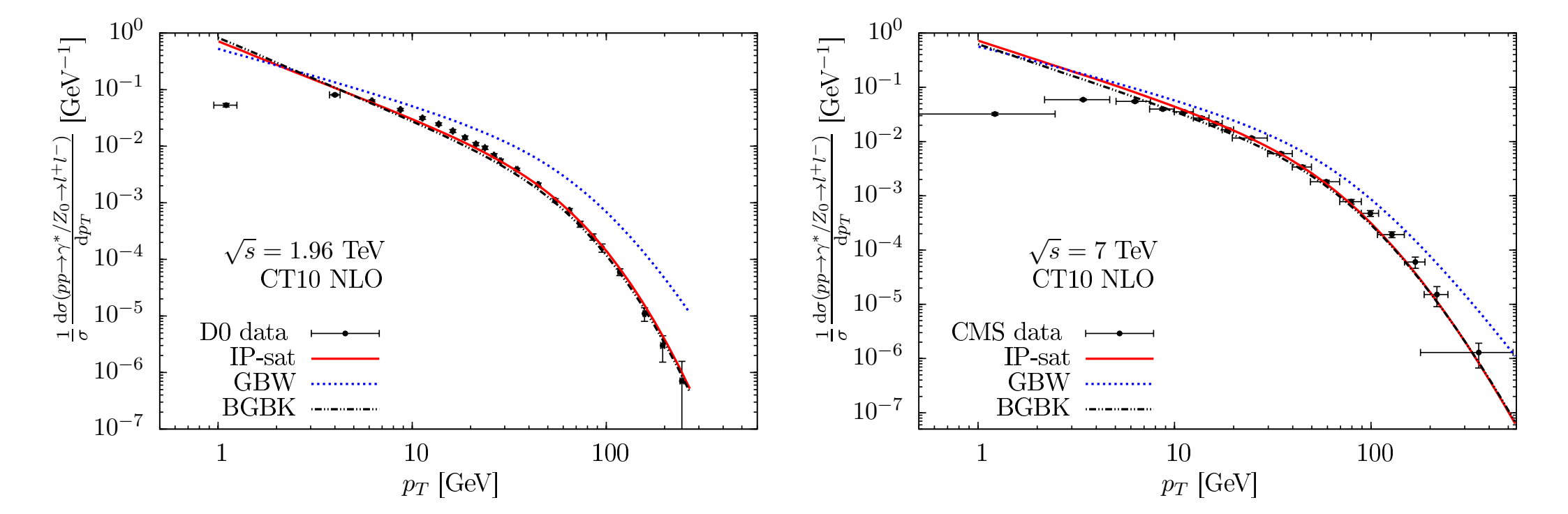
CGC: Saturation model for $\sigma^p_{q\bar q}(r,x)$ based upon the Color Glass Condensate E. Iancu, K. Itakura, S. Munier, Phys. Lett. B **590**, 199 (2004)

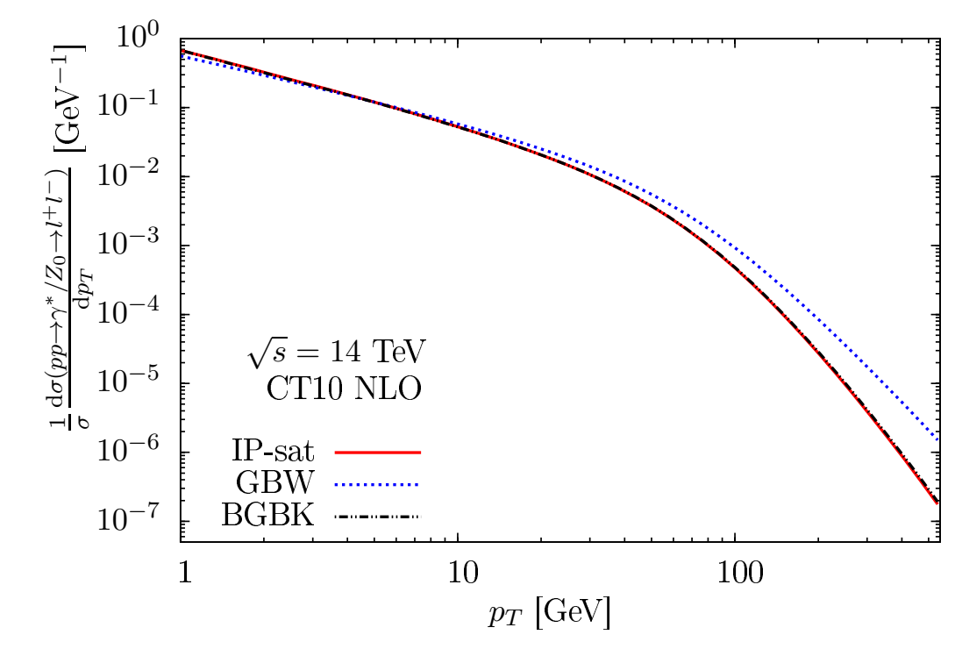
$$\sigma^p_{q\bar q}(r,x) = \sigma_0\times\begin{cases}\mathcal{N}_0\left(\frac{r\,Q_{s,p}}{2}\right)^{2\left(\gamma_s+\frac{\ln(2/rQ_{s,p})}{\kappa\,\lambda\,Y}\right)} & r\,Q_{s,p}\le 2\\ 1-\exp^{-A\,\ln^2(B\,r\,Q_{s,p})} & r\,Q_{s,p}>2\end{cases}\qquad(1)$$

$\kappa = \chi''(\gamma_s)/\chi'(\gamma_s)$, 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.

DY: Color dipole approach @ Tevatron and LHC





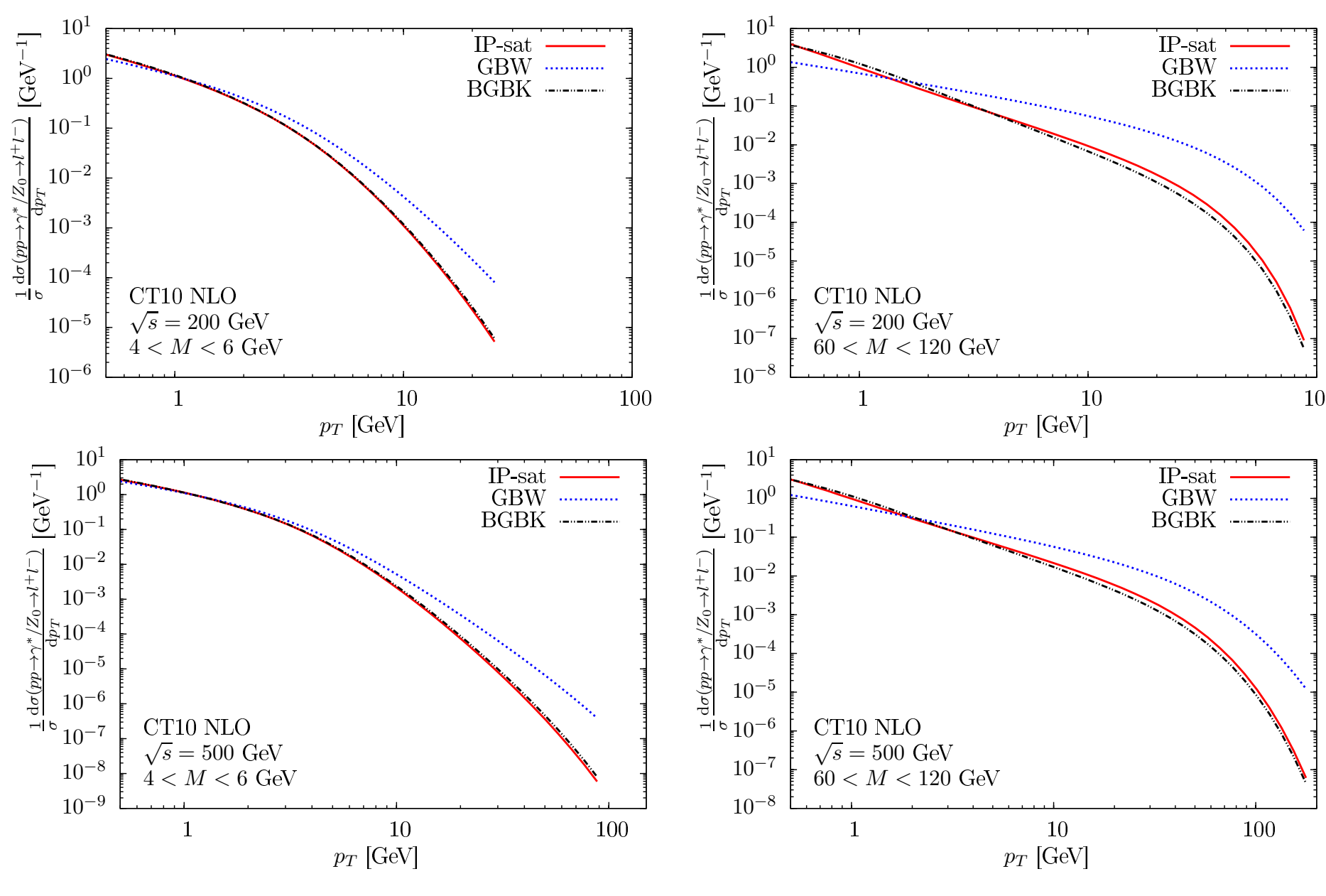
E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)

Three different parametrizations of dipole cross section:

GBW:	K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D **59**, 014017 (1999); 60, 114023 (1999); PRL **86**, 596 (2001).
BGBK:	J. Bartels, K. Golec-Biernat and H. Kowalski, Phys. Rev. D **66**, 014001 (2002).
IP-sat:	H. Kowalski, L. Motyka and G. Watt, Phys. Rev. D **74**, 074016 (2006); G. Watt and H. Kowalski, Phys. Rev. D **78**, 014016 (2008).

Color dipole predictions for DY@RHIC

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



- Sensitive to different parametrizations of dipole cross section $\sigma^N_{q\bar q}$

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

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

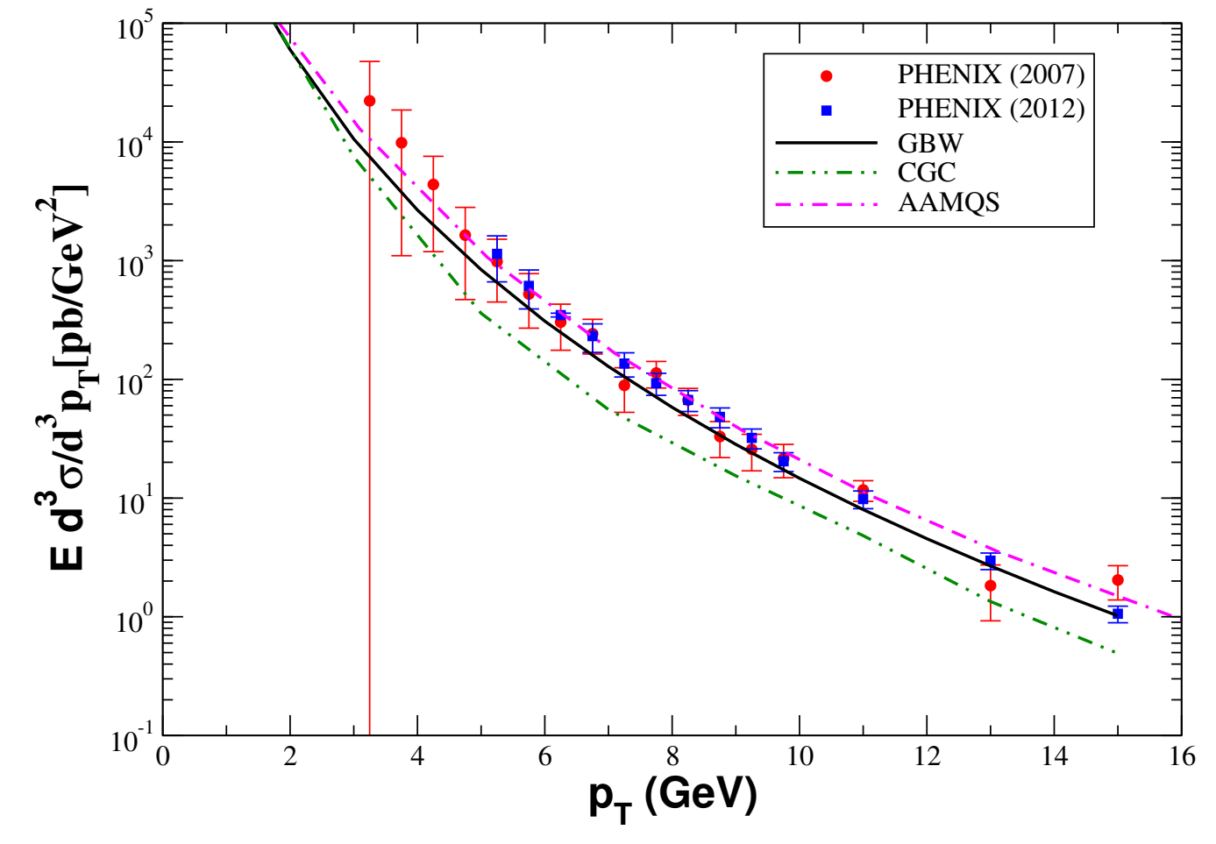


Figure 1: The isolated photon p_T-spectra in *pp* collisions at $\sqrt{s} = 0.2$ TeV and $\eta = 0$, obtained using the different models for the dipole cross section. Experimental data are from S. S. Adler *et al.*, Phys. Rev. Lett. **98**, 012002 (2007) and A. Adare *et al.*, Phys. Rev. D **86**, 072008 (2012).

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

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

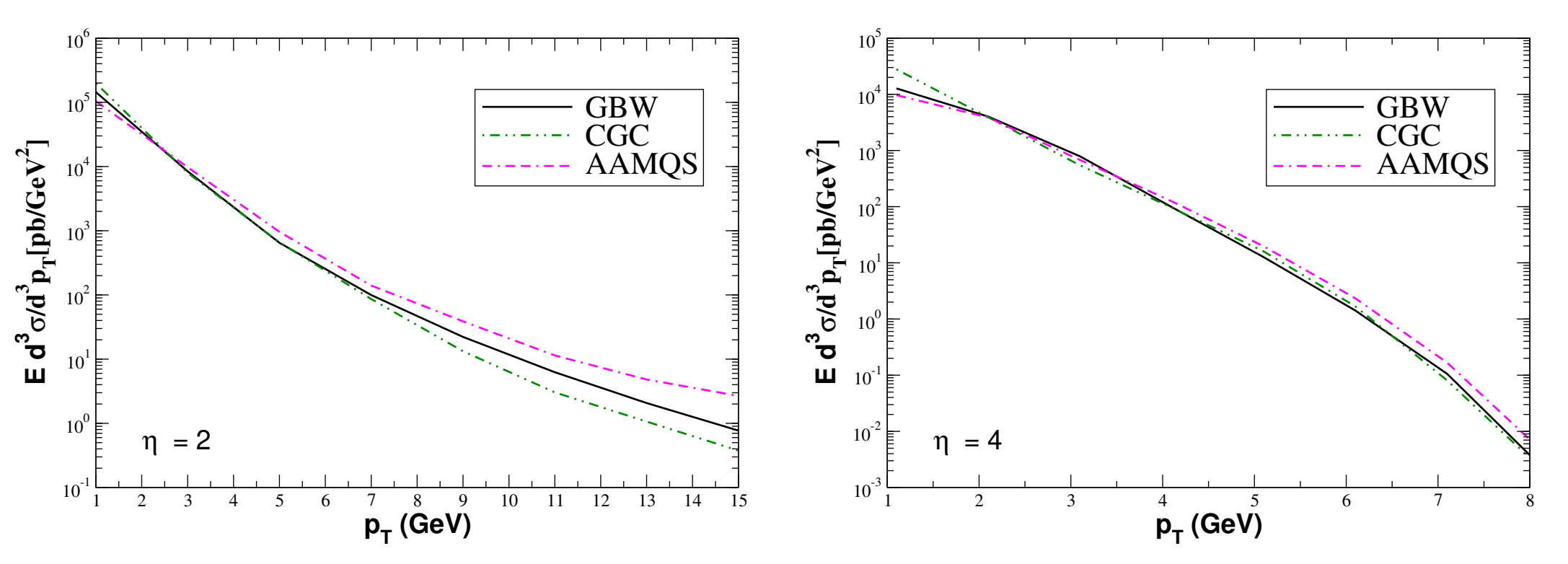


Figure 2: The isolated photon p_T-spectra in *pp* collisions at $\sqrt{s} = 0.5$ TeV for $\eta = 2$ (left) and $\eta = 4$ (right) using the different models for the dipole cross section.

- Note change of the curvature when moving from mid-rapidity to forward rapidity.

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

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

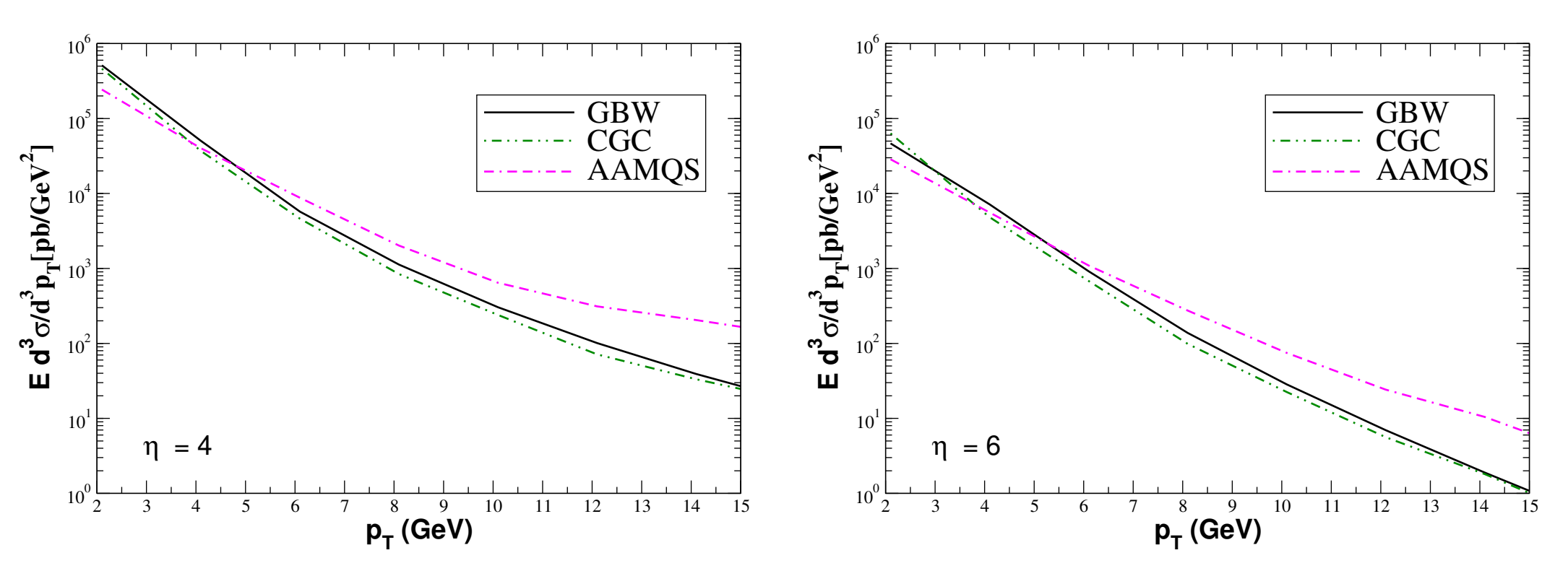


Figure 3: The isolated photon transverse-momentum spectra in *pp* collisions at $\sqrt{s} = 14$ TeV for $\eta = 4$ (left) and $\eta = 6$ (right) using the different models for the dipole cross section..

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

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

$$\boxed{C(\Delta\phi) = \frac{2\pi\displaystyle\int_{p_T,p_T^h>p_T^{\rm cut}} dp_Tp_T\,dp_T^hp_T^h\,\frac{d\sigma(pT\to h\gamma X)}{d\eta dy_hd^2p_Td^2p_T^h}}{\displaystyle\int_{p_T>p_T^{\rm cut}} dp_Tp_T\,\frac{d\sigma(pT\to\gamma X)}{d\eta d^2p_T}}}$$

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

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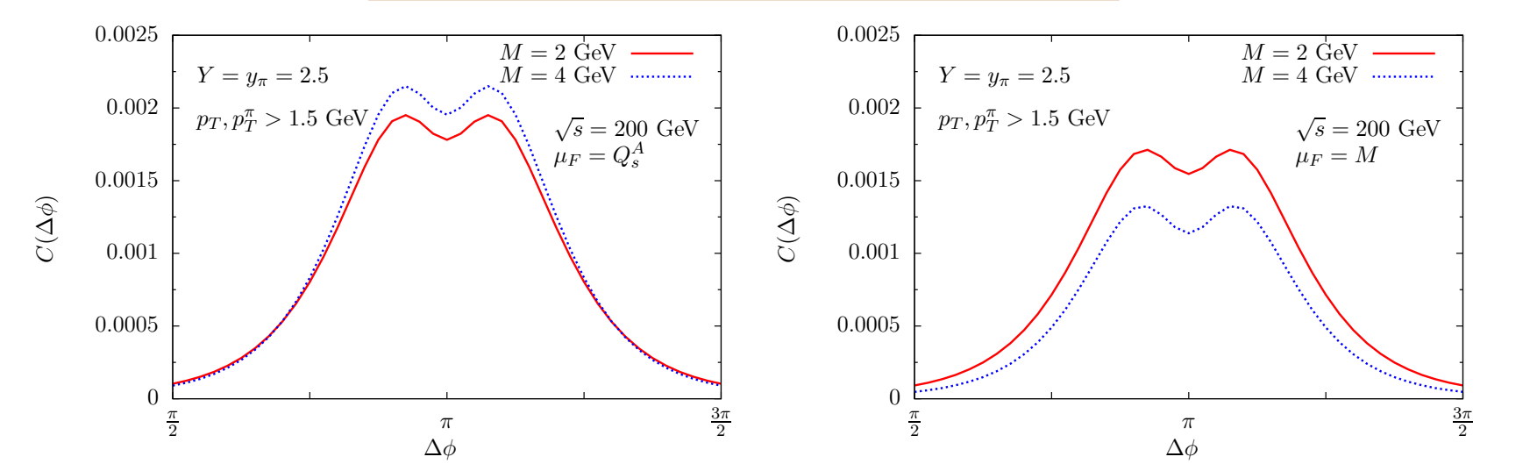
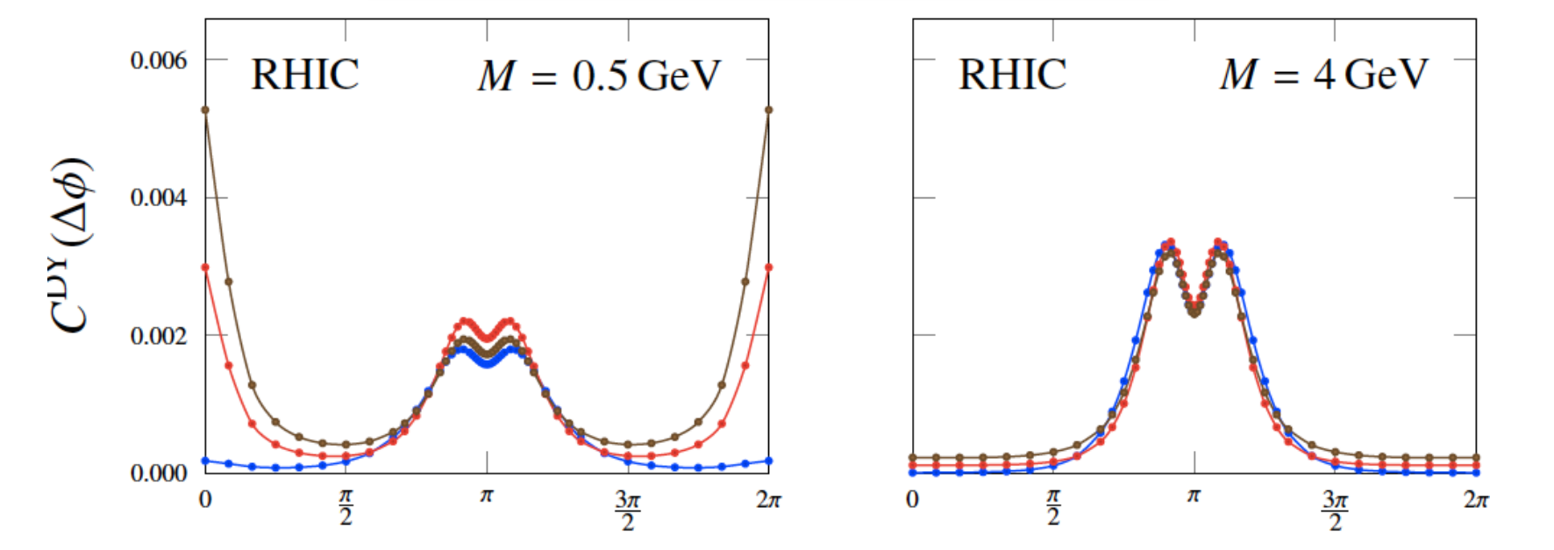
[1] $Q_0^2 = 1$ GeV^2, $x_0 = 3.04\times10^{-4}$, $\lambda = 0.288$, $\sigma_0 = 23.03$ mb from fit to DIS data.
[2] B. A. Kniehl, G. Kramer and B. Potter, Nucl. Phys. B **582**, 514 (2000).

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.

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

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

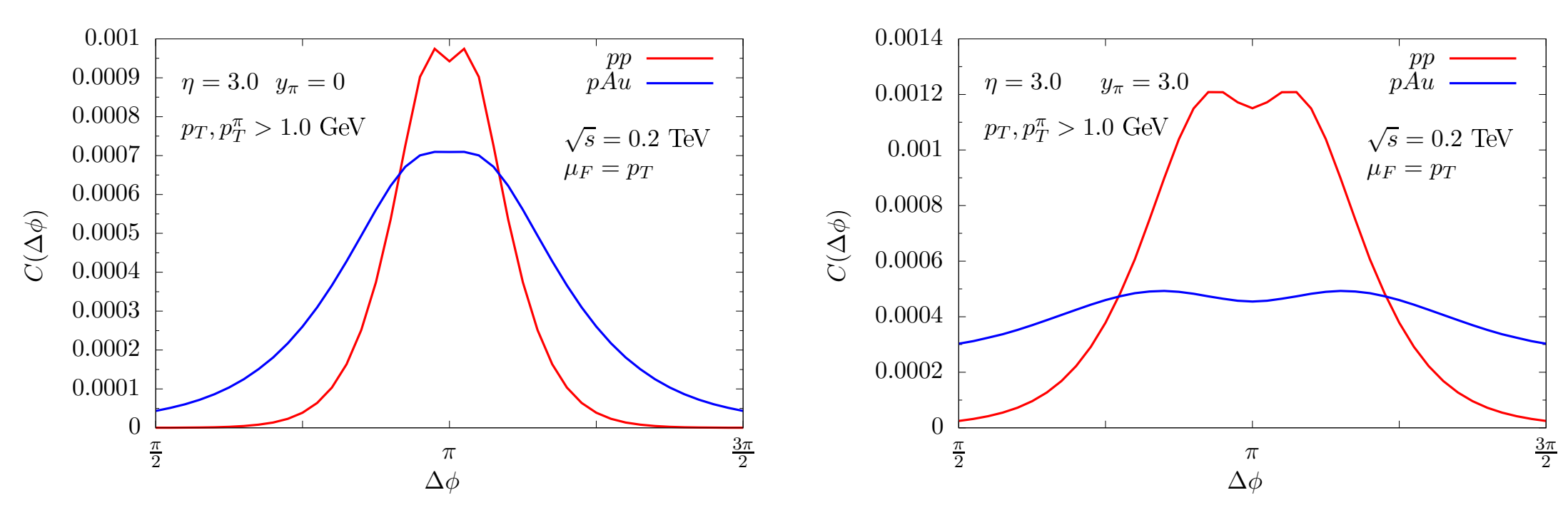


Figure 5: The correlation function $C(\Delta\phi)$ for the associated isolated photon at forward rapidity $\eta = 3$ and pion production at midrapidity (left) and at forward rapidity (right) in *pp* and *pAu* collisions at RHIC $\sqrt{s_{\rm NN}} = 0.2$ TeV.

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

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

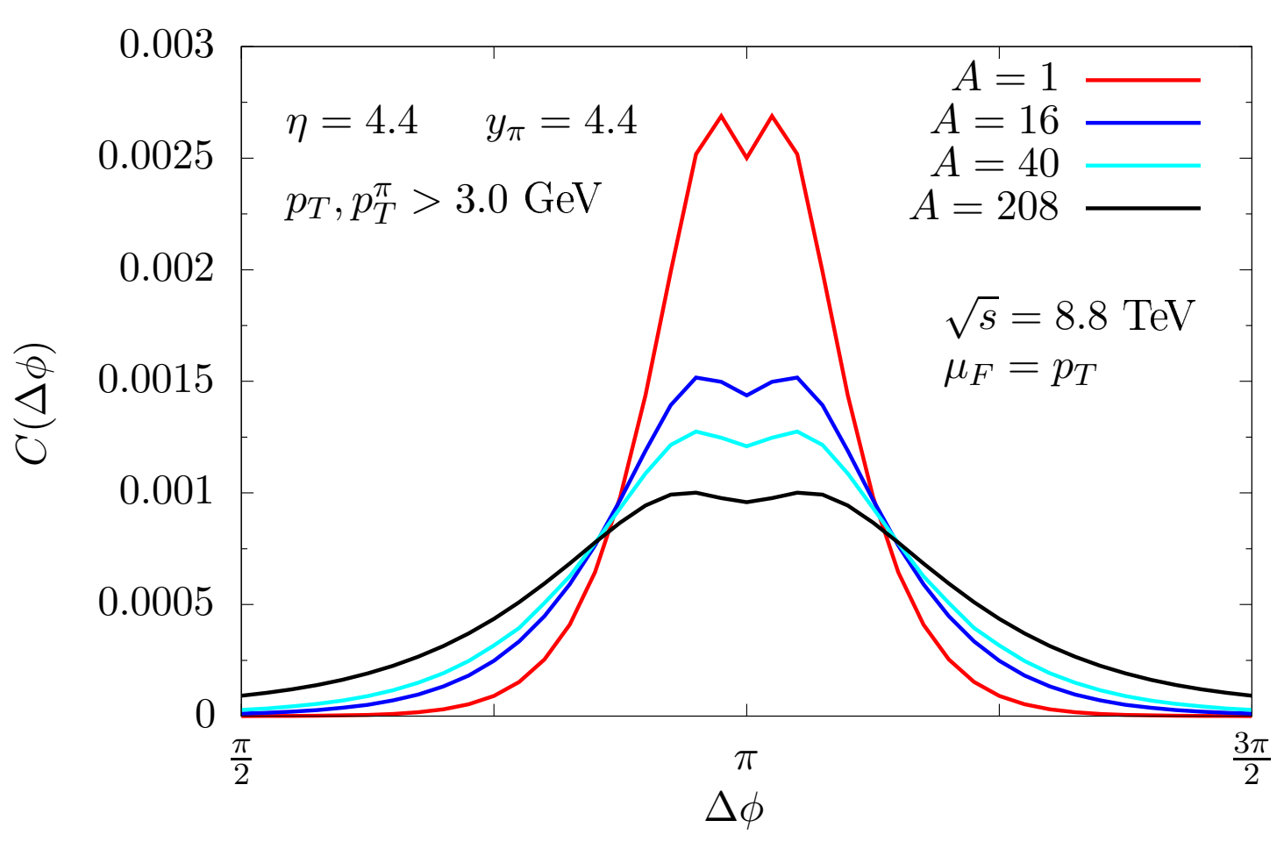


Figure 6: The correlation function $C(\Delta\phi)$ for the associated photon and pion production in *pA* collisions at the LHC ($\sqrt{s_{\rm NN}} = 8.8$ TeV) for different nuclei.

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

Conclusions

- ► Detailed phenomenological analysis of prompt and virtual 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 the 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/virtual 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.

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