High-p_T direct photons in nuclear collisions: from RHIC to LHC

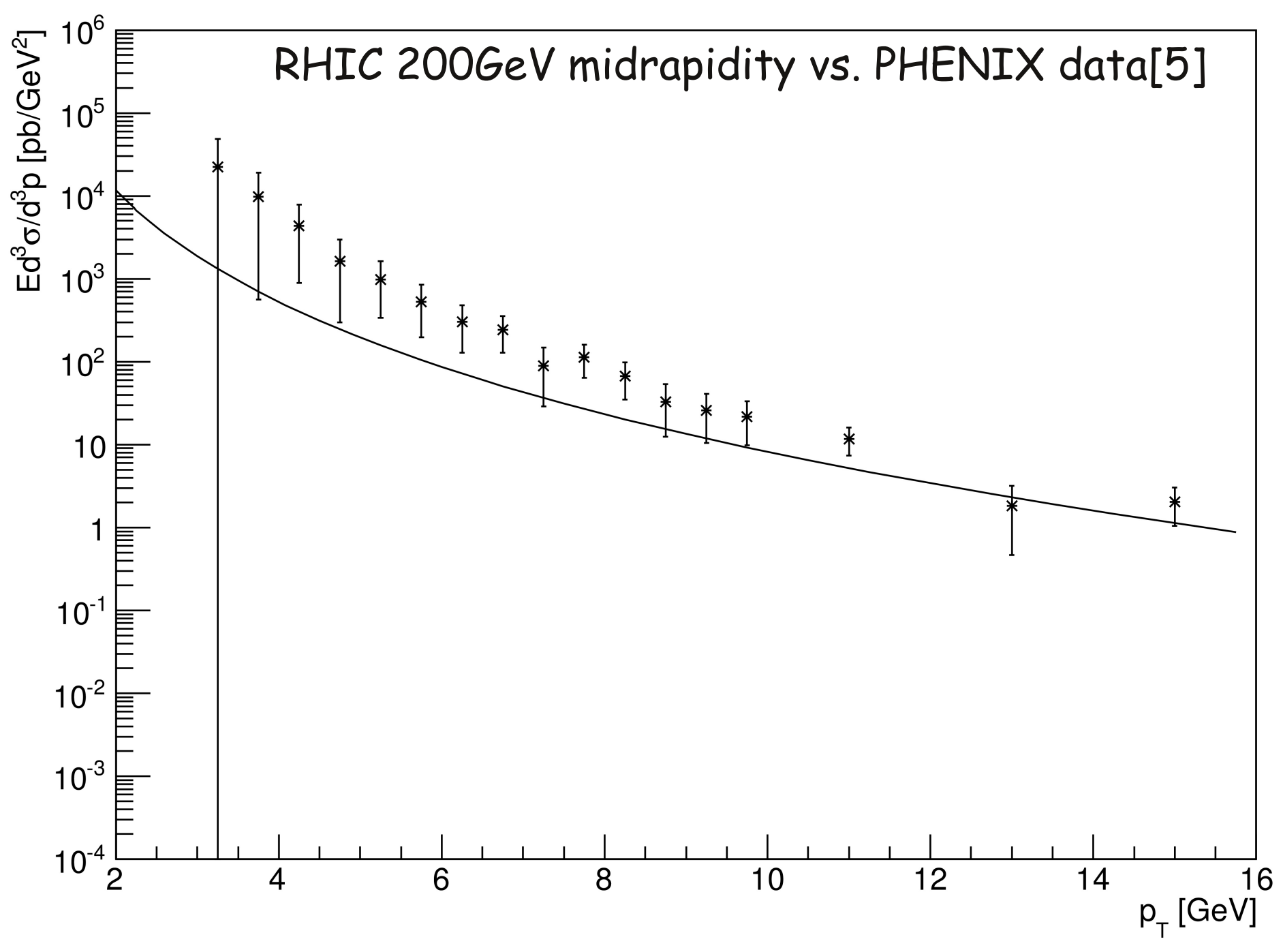
Jan Cepila[a], Jan Nemchik[a,b]

[a] CFRJS@FNSPE, Czech Technical University in Prague
[b] Institute of Experimental Physics SAS, Kosice

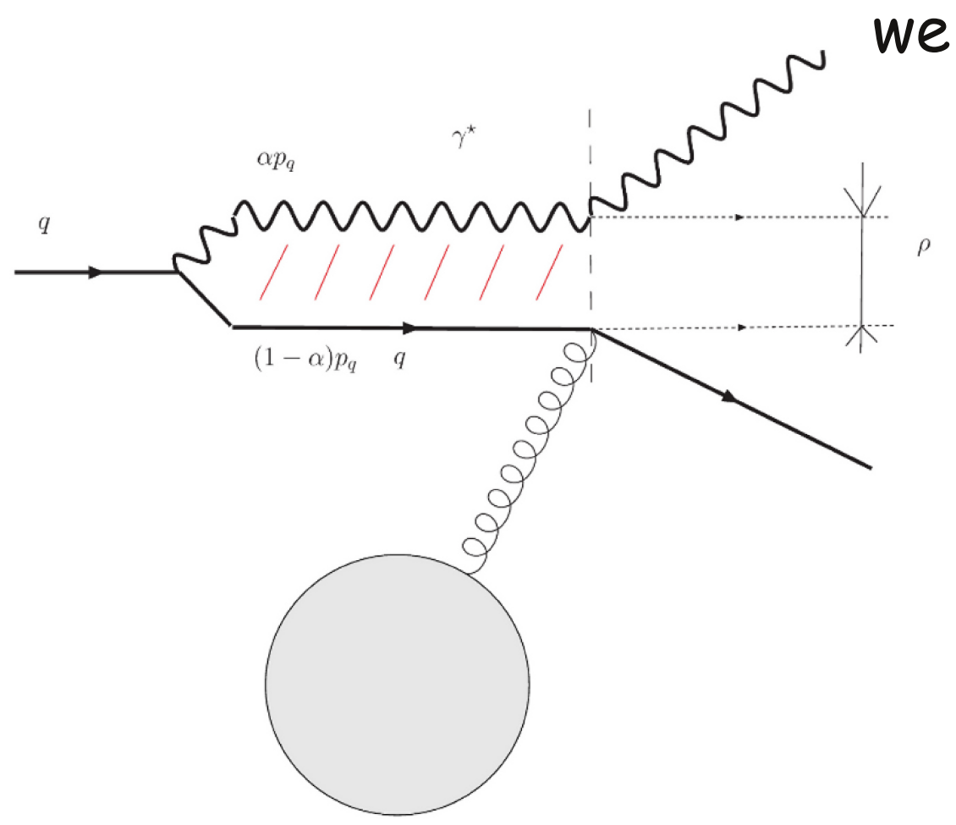
Abstract

We discuss a production of direct photons at large transverse momenta p_T in nuclear collisions at different energies and rapidities corresponding to RHIC and LHC experiments. Direct photons are very convenient tool for investigation of nuclear effects since they are not expected to be accompanied by any final state interaction, either energy loss or absorption. Therefore, besides the Cronin enhancement at medium-high p_T and small isotopic corrections at larger p_T, one should not expect any nuclear effects. However, data from the PHENIX experiment at mid-rapidities demonstrate a significant large-p_T suppression in central d+Au and Au+Au collisions that cannot be induced by coherent phenomena (gluon shadowing, Color Glass Condensate). We demonstrate that such an unexpected result is a subject to the energy conservation constraints (ECC) in initial state multiple parton interactions. The corresponding suppression factor falls steeply with p_T and leads to rather strong decrease with p_T of the nuclear modification factor violating so QCD factorization. In the RHIC kinematic region at forward rapidities we include also coherent phenomena as an additional source of nuclear suppression. In the LHC energy range ECC effects are irrelevant at mid rapidities, but they are going to be important with increasing rapidity. We study for the first time a relative contribution of both sources of nuclear suppression at different rapidities performing predictions that could be verified in the future by experiments at RHIC and LHC. We analyze also a contribution of gluon shadowing as a leading twist shadowing correction modifying nuclear effects especially at small p_T.

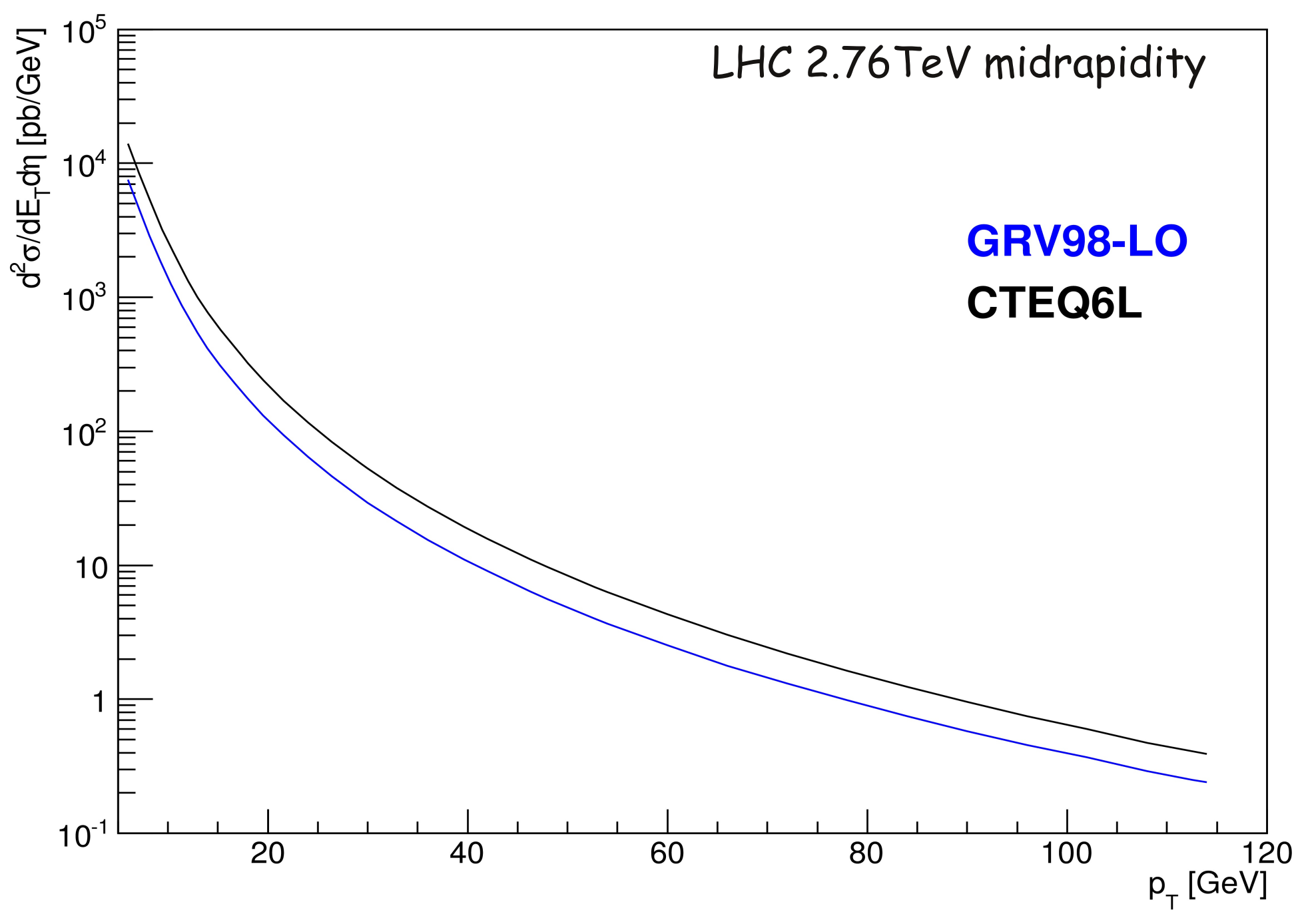
Proton-proton cross section calculation



In the color dipole approach the direct photon production is treated in the target rest frame[4] where photon emission looks like a bremsstrahlung from an incident quark. The quark fluctuates into the coherent state $|q\gamma>$ that is disrupted by the color interaction with a nucleon. The color dipole approach calculation of the p-p cross section agree reasonable well with RHIC data and can be used for the LHC kinematics.



$$\frac{d\sigma(qp\to\gamma X)}{d\ln\alpha d^2p_T}=\frac{1}{(2\pi)^2}\int d^2\rho_1 d^2\rho_2\, e^{ip_T(\rho_1-\rho_2)}\,\Psi^*_{\gamma q}(\alpha,\rho_1)\Psi_{\gamma q}(\alpha,\rho_2)\times$$
$$\times\frac{1}{2}\left(\sigma^N_{q\bar q}(\alpha\rho_1,x_2)+\sigma^N_{q\bar q}(\alpha\rho_2,x_2)-\sigma^N_{q\bar q}(\alpha(\rho_1-\rho_2),x_2)\right)$$
$$\frac{d\sigma(pp\to\gamma X)}{dx_F d^2p_T}=\frac{1}{x_1+x_2}\int_{x_1}^1\frac{d\alpha}{\alpha}F_2^p(\frac{x_1}{\alpha},Q)\frac{d\sigma^{qp}(q\to\gamma q)}{d\ln\alpha d^2p_T}$$
$$\sigma^N_{q\bar q}(\rho,x)=\sigma_0\left(1-e^{-\frac{\rho^2}{4\left(\frac{x}{x_0}\right)^{0.287}}}\right)\qquad\sigma_0=2.39fm^2, x_0=0.000111$$

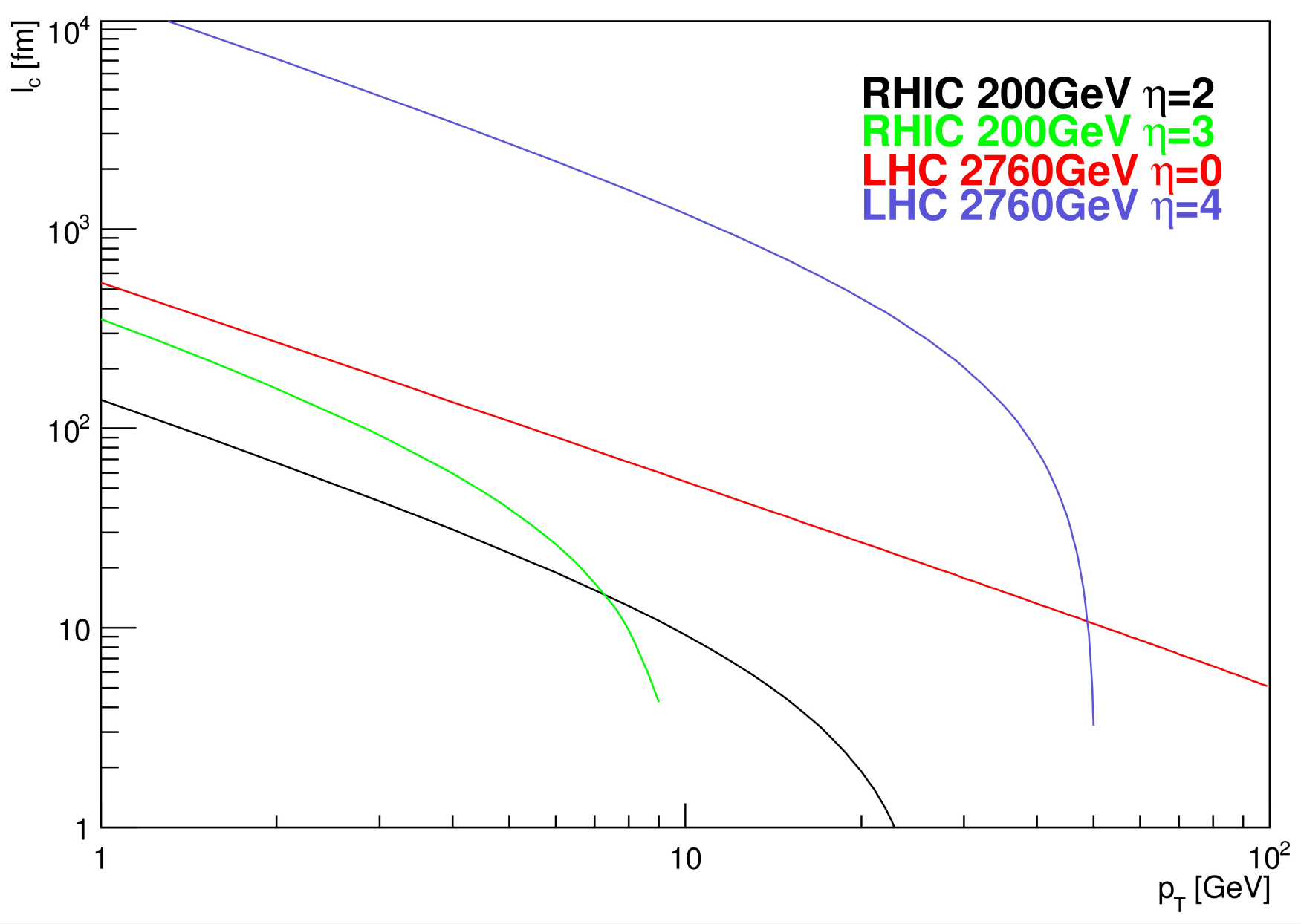


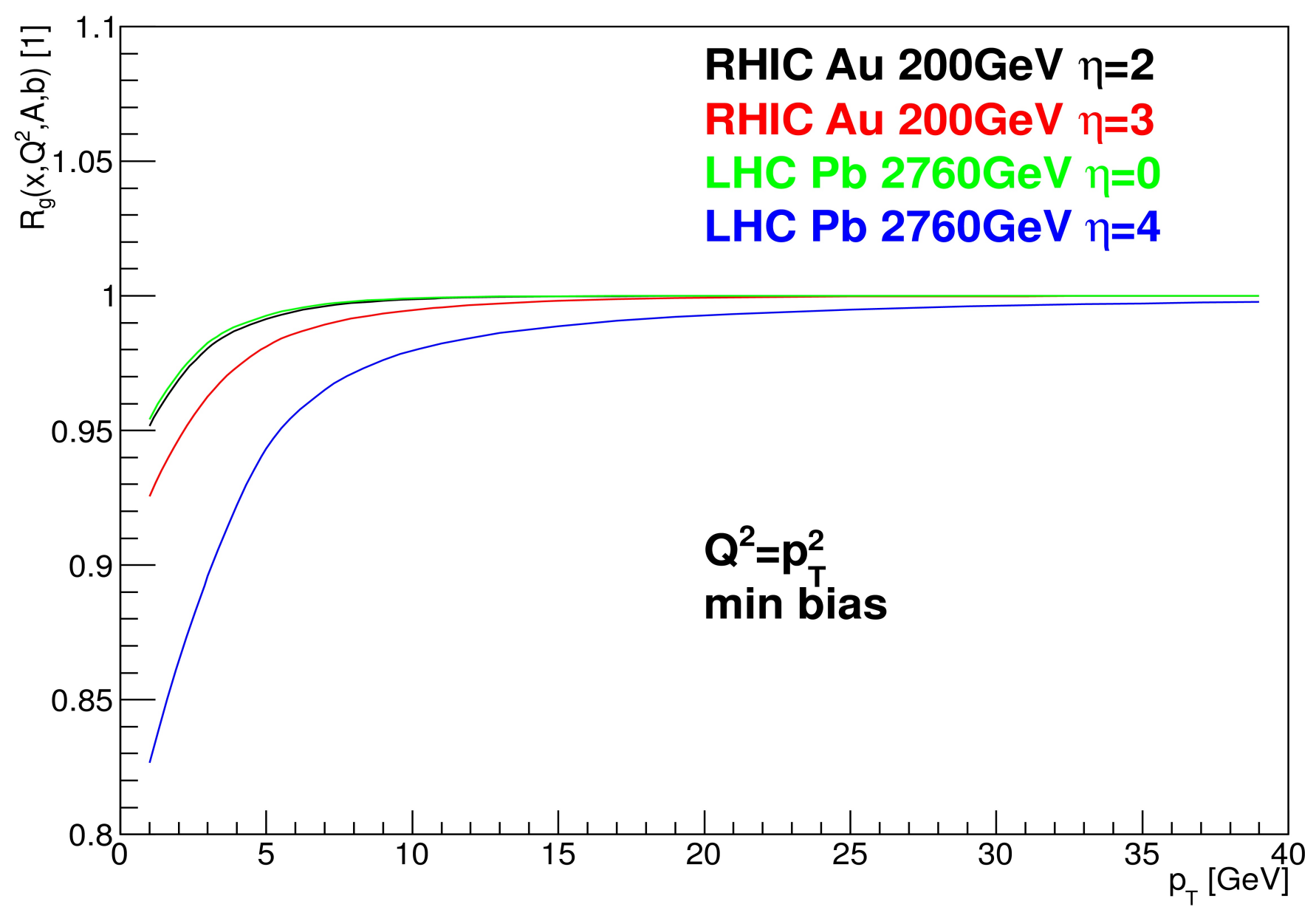
Cross section on the nucleus

The dynamics of the direct photon production in nuclear collisions is controlled by the mean coherence length(CL)

$$l_c=\left\langle\frac{2E_q\alpha(1-\alpha)}{\alpha^2 m_q^2+p_T^2}\right\rangle_\alpha$$

In the long coherence length (LCL) regime the CL is much longer than the nuclear radius. In the LCL limit(RHIC forward rapidity, LHC) the interference (shadowing) effects are maximal and all nucleons with the same impact parameter participate coherently.





Shadowing effects are incorporated via a simple eikonalization. For p-A collisions one substitutes

$$\sigma^N_{q\bar q}\to 2\int d^2b(1-(1-\frac{1}{2A}\sigma^N_{q\bar q}T_A(b))^A)$$

and for A-B collisions one substitutes

$$\sigma^N_{q\bar q}\to 2\int d^2b(1-(1-\frac{1}{2AB}\sigma^N_{q\bar q}T_{AB}(b))^{AB})$$

where $T_{AB}(b)=\int d^2sT_A(s)T_B(b-s)$ is nuclear overlap function and integration over impact parameter b is performed for each centrality class. Gluon shadowing added (for p-A and A-B resp.)via [4]

$$\sigma^N_{q\bar q}(\rho,x)\to\sigma^N_{q\bar q}(\rho,x)\times R_G(x_2,Q^2,b)$$
$$\sigma^N_{q\bar q}(\rho,x)\to\sigma^N_{q\bar q}(\rho,x)\times R_G(x_2,Q^2,b)\times R_G(x_1,Q^2,b-s)$$

Energy conservation constraints

Each of multiple inelastic parton rescatterings leads to effective energy loss and produces an extra suppression factor $S(x_1)$ representing the probability to produce a particle with x_1. At forward rapidities (x_1->1) this factor was estimated in [3], $S(x_1)$ ~ 1-x_1. This formula leads to $x_1(x_F)$ scaling of the suppression. Quark distribution function in the nucleus can be calculated as a sum over multiple interactions using a probability of n-fold inelastic collision related to the Glauber model via AGK cutting rules

$$f_q^A(x,Q^2,b)=\sum_{n=0}^{A}C_n v_n(b)f_{q/N}(x,Q^2)S^n(x)$$

with coefficients in case of pA collisions

$$v_n(b)=e^{-\sigma_{eff}T_A(b)}\frac{(\sigma_{eff}T_A(b))^n}{n!}\qquad\sigma_{eff}=20mb$$

and in case of AB collisions

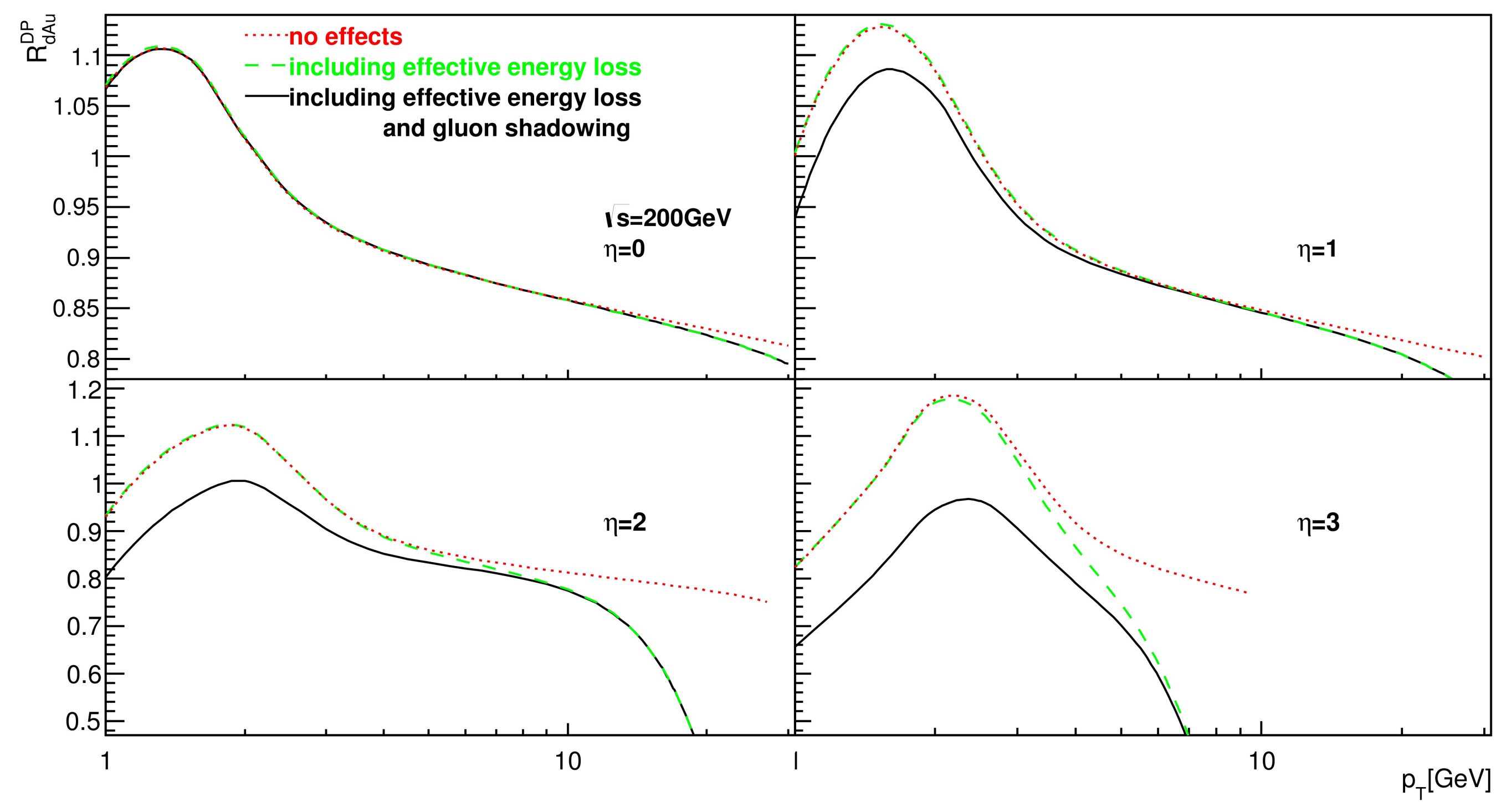
$$v_n(b)=e^{-\sigma_{eff}T_{AB}(b)}\frac{(\sigma_{eff}T_{AB}(b))^n}{n!}\qquad\sigma_{eff}=20mb$$

Performing summation we get

$$f^A_{q/N}(x,Q^2,b)=C_N f_{q/N}(x,Q^2)e^{-(1-S(x))\sigma_{eff}T_A(b)}$$
$$f^A_{q/A}(x,Q^2,b)=C_A f_{q/N}(x,Q^2)e^{-(1-S(x))\sigma_{eff}T_{AB}(b)}$$

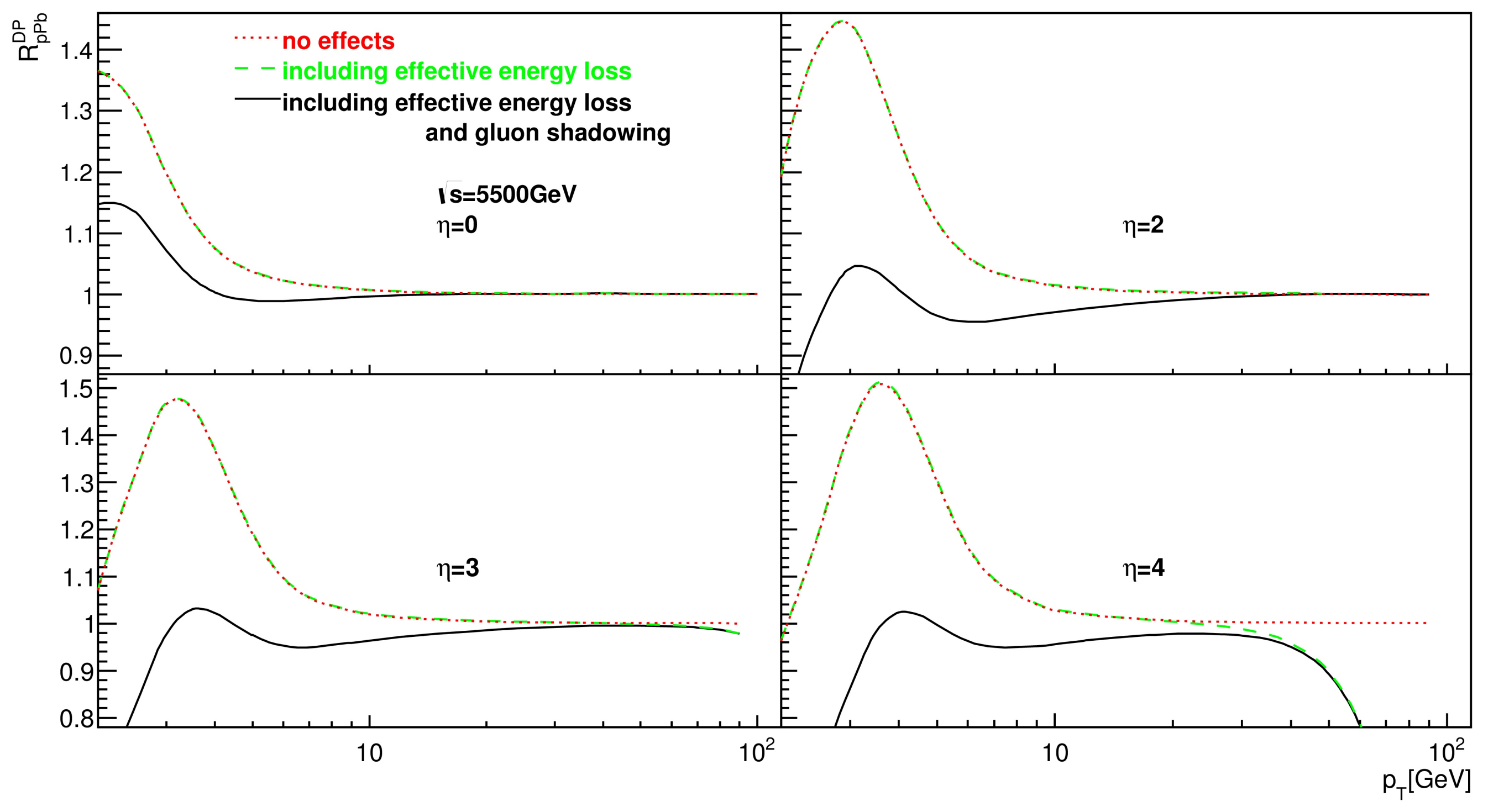
where normalization factors are fixed by the Gottfried sum rules. The correlation between the projectile distribution functions and the target results in the QCD factorization breakdown at forward rapidities.

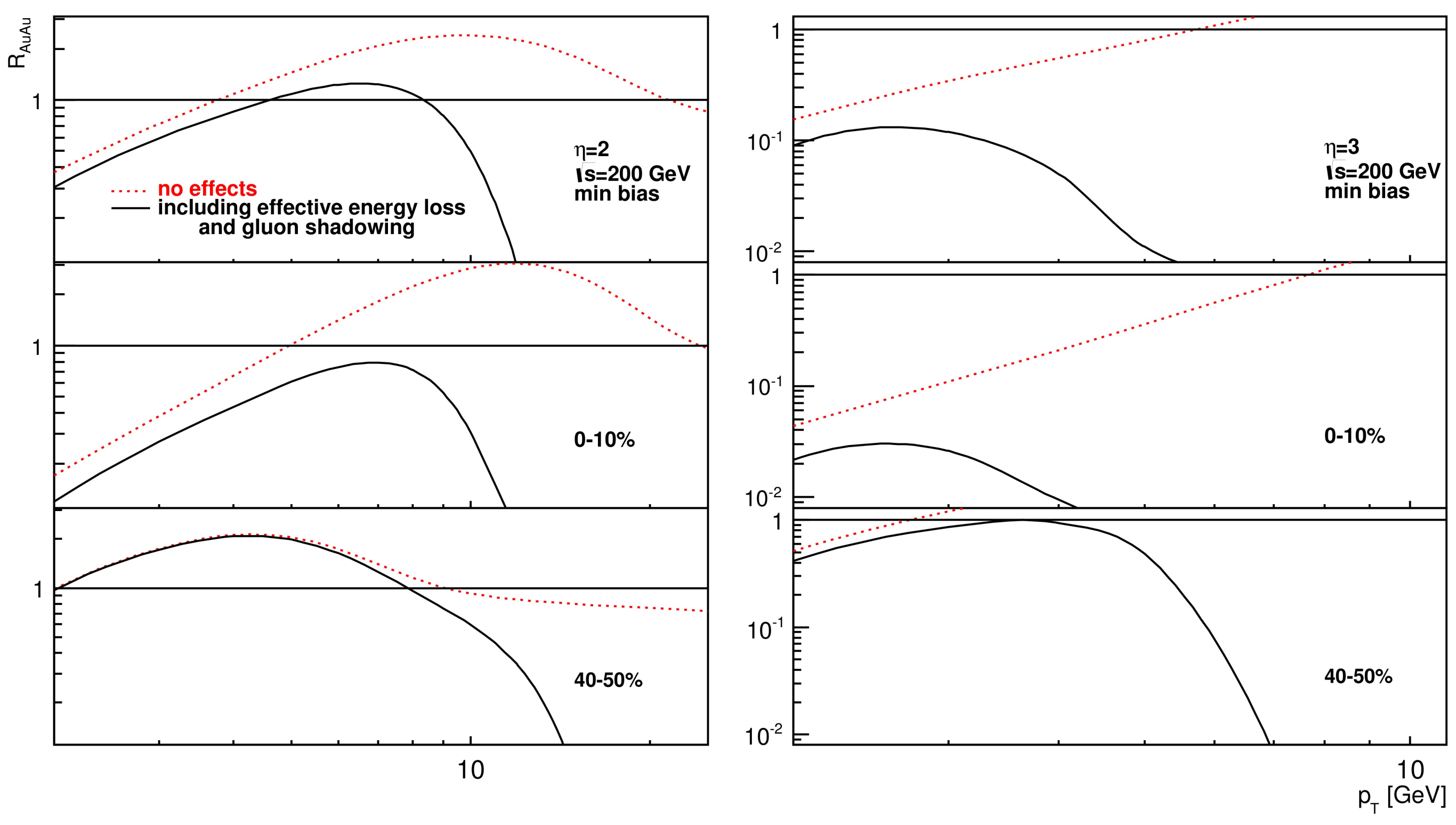
Predictions for RHIC at mid and forward rapidity



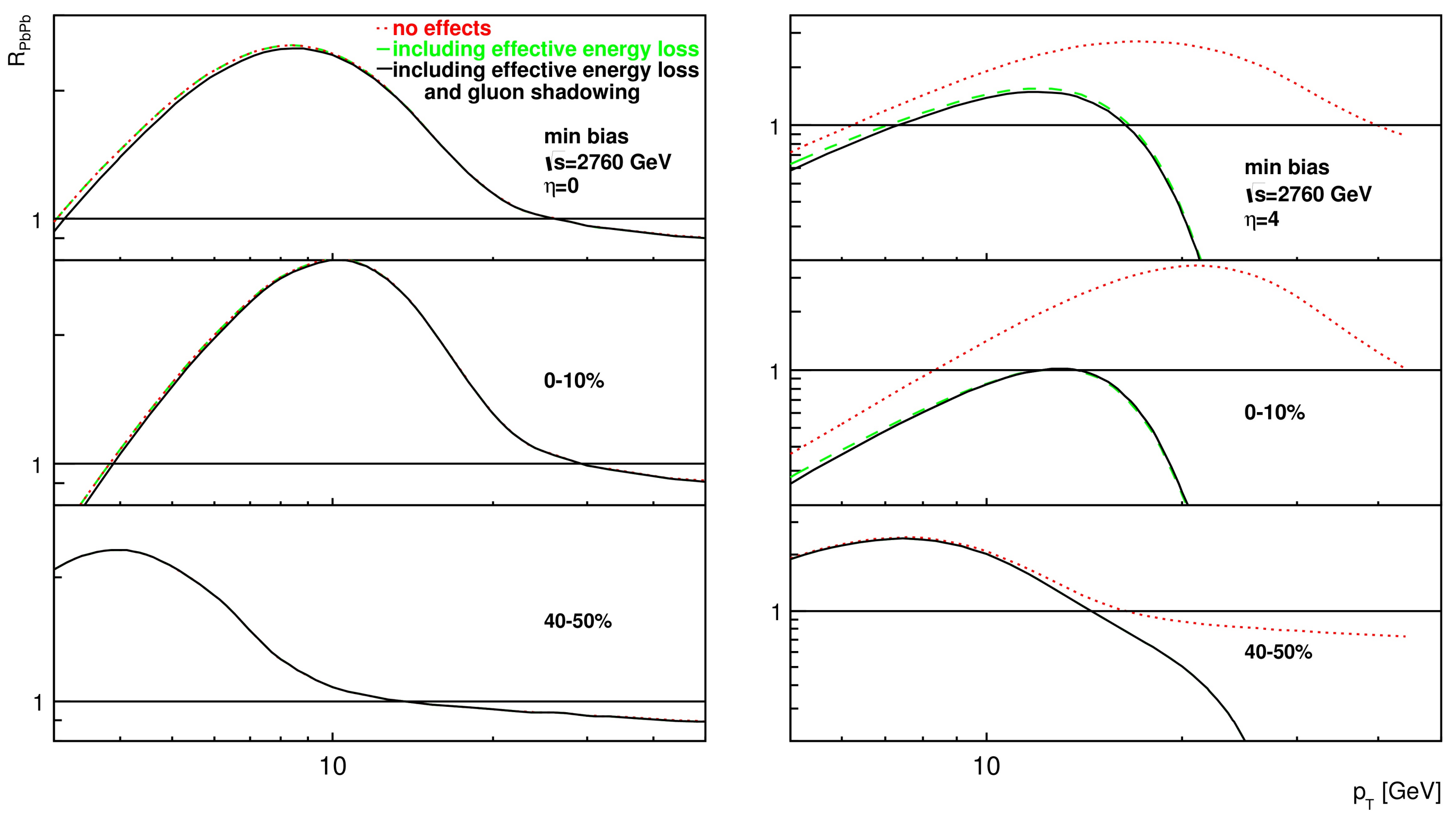
In case of p(d)A collisions at midrapidity the onset of isospin effects shows R -> 0.8 at RHIC at high p_T while no effect is expected at LHC. At midrapidity energy conservation constraints are negligible at this p_T range but they manifest themselves at much higher p_T. Magnitude of this effect rises with rapidity and dominates at high p_T. Suppression induced by the gluon shadowing rises from almost 0% at η = 0 to 10% at η = 3 at RHIC and gradually decreases with p_T. At LHC gluon shadowing rises from ~ 20% at η = 0 to ~ 50% at η = 4 at low p_T. Effects of energy conservation are clearly observable at p_T > 30GeV at η = 3 – 4 and so they can be verified at LHC.

Predictions for LHC at mid and forward rapidity





Suppression from isospin effects at AA collisions grows with rapidity from R -> 0.7 to R -> 0.9 both at RHIC and LHC at high p_T. Suppression coming from energy conservation constraints is negligible at midrapidity at this p_T range but it grows with rapidity and dominates at high p_T at forward rapidity. Suppression induced by the gluon shadowing rises from ~3% at η = 2 to ~5% at η = 3 at RHIC and gradually decreases with p_T. At LHC gluon shadowing rises from ~4% at η = 0 to ~15% at η = 4 at low p_T. Effects of energy conservation are clearly observable at p_T > 10GeV at η = 2 - 4 at RHIC and LHC and so they can be verified by future data.



Conclusions

Using the color dipole approach the study of production of direct photons in collisions on nucleon and nuclear targets in the RHIC and LHC kinematic regions is presented. The cross section for pp collisions in RHIC kinematics shows good agreement with PHENIX data at midrapidity and also the cross section for pp collisions in LHC kinematics is shown. We present predictions of p_T behavior of nuclear effects at different rapidities. We included coherence effects (quark and gluon shadowing) and corrections for energy conservation constraints in multiple parton rescatterings in our calculations to evaluate nuclear effects. Since photons are not accompanied by final state interactions, no suppression at high p_T is expected(besides an onset of isospin effects). We demonstrate that the nuclear suppression at small and medium p_T is dominated by coherence effects and the suppression at high p_T is clearly induced by corrections for energy conservation constraints in initial state parton rescatterings. Both effects grow strongly with rapidity. Quite strong suppression at high p_T that is in contrast with the QCD factorization can be tested by future data from RHIC and LHC.

References

1) B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, M.B. Johnson and I. Schmidt, Phys. Rev. C72, 054606 (2005); e-Print: hep-ph/0501260
2) B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, M.B. Johnson and I. Schmidt, Nucl. Phys. Proc. Suppl. 146, 171 (2005).
3) J. Nemchik, V. Petracek, I. K. Potashnikova and M. Sumbera, PhysRevC78025213 (2008); ePrint: arXiv:08054267 [hepph]
4) B.Z.Kopeliovich, A.Schaefer and A.V.Tarasov, Phys. Rev. D 62, 054022 (2000)
5) S.S. Adler et al., [PHENIX Collaboration], Phys. Rev. Lett. 98, 012002 (2007)