Direct photon production in proton-nucleus and nucleus-nucleus collisions

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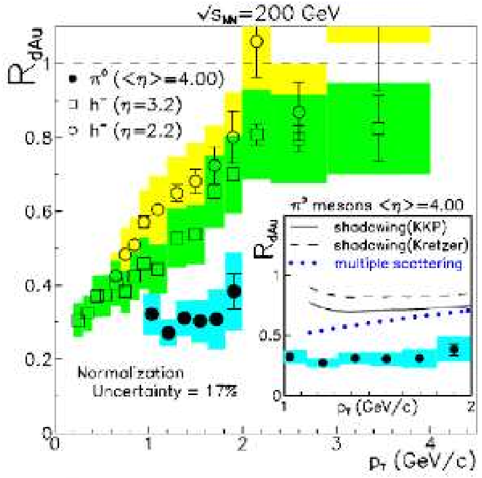
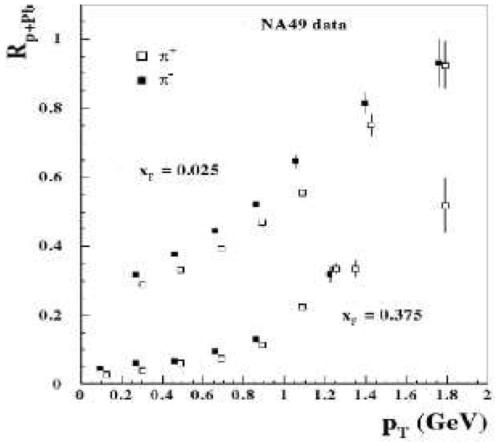
Outline of this talk

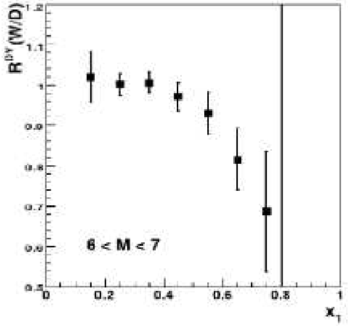
- Introduction and motivation
  - Nuclear suppression of various processes
  - Effects contributing to the suppression
- Calculation of the direct photon production
  - Direct photon production in pp via cda
  - Coherent scenario of the direct photon production in nuclear collisions
- Numerical Results
  - p(d)-A collisions
  - A-A collisions
- Conclusions

Introduction and motivation

- BRAHMS(RHIC) observed a suppression of particles produced at forward rapidity - described by coherence effects
- Data at lower energies - NA49(SPS), E772(FNAL) - suggest similar suppression where no CGC or shadowing is possible
- Kinematics
  - Light front momentum fraction of the projectile and the target
    $x_1 = \frac{m_T}{\sqrt{s}} e^{y} \quad x_2 = \frac{m_T}{\sqrt{s}} e^{-y}$
  - Feynman variable $x_F = x_1 - x_2$
- High x_1 can be achieved also at midrapidity at high p_T - at RHIC $p_T = 30 GeV \sim x_1 = 0.3$

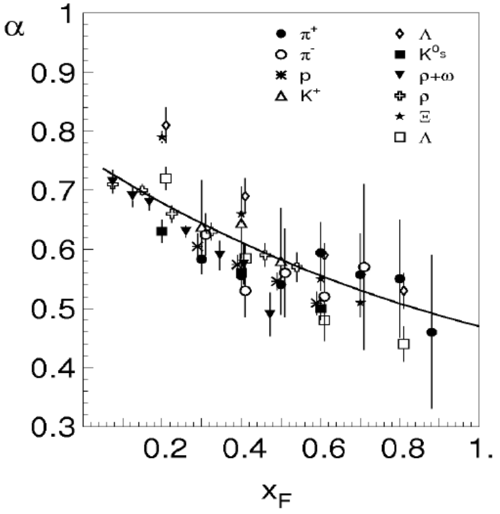






Introduction and motivation

- The magnitude of observed suppression grows with rapidity(or x_1)
- We propose energy independent mechanism based on energy sharing restrictions in multiple interactions that lead to x_1 scaling



- The suppression comes from interplay of several effects - coherence effects(quark and gluon shadowing) and energy sharing restrictions
- Each of them is dominant in certain kinematic region - all of them has to be included in the calculation.

Coherence effects

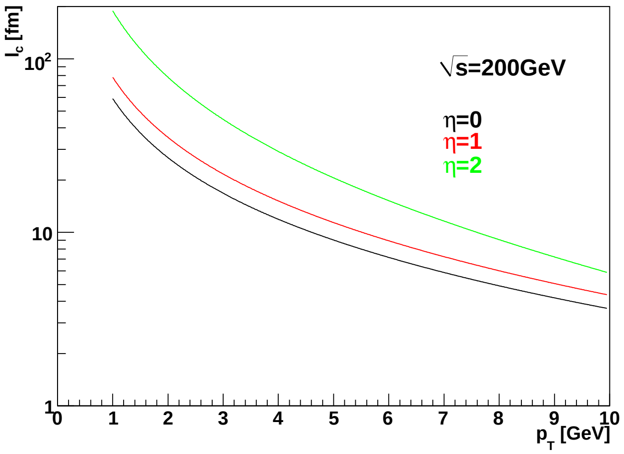
- Controlled by the coherence length

$$l_c = \frac{1}{q_L} = \frac{2E_q\alpha(1-\alpha)}{\alpha^2 m_q^2 + p_T^2}$$

  - p_T and α are transverse momentum and the fraction of the light-cone momentum of the quark carried our by the photon
  - $E_q = x_q \frac{s}{2m_N}$ and m_q are the energy and mass of the projectile quark
  - $q_L = \frac{M_{q\gamma}^2 - m_q^2}{2E_q}$ is the longitudinal momentum transfer

- Corresponds to lowest Fock component $|\bar{q}q>$ that represents the highest twist shadowing correction

- But - coherence length drops with increasing p_T and at large quark masses as $1/m_q^2$ - almost no suppression from coherence effects at high p_T



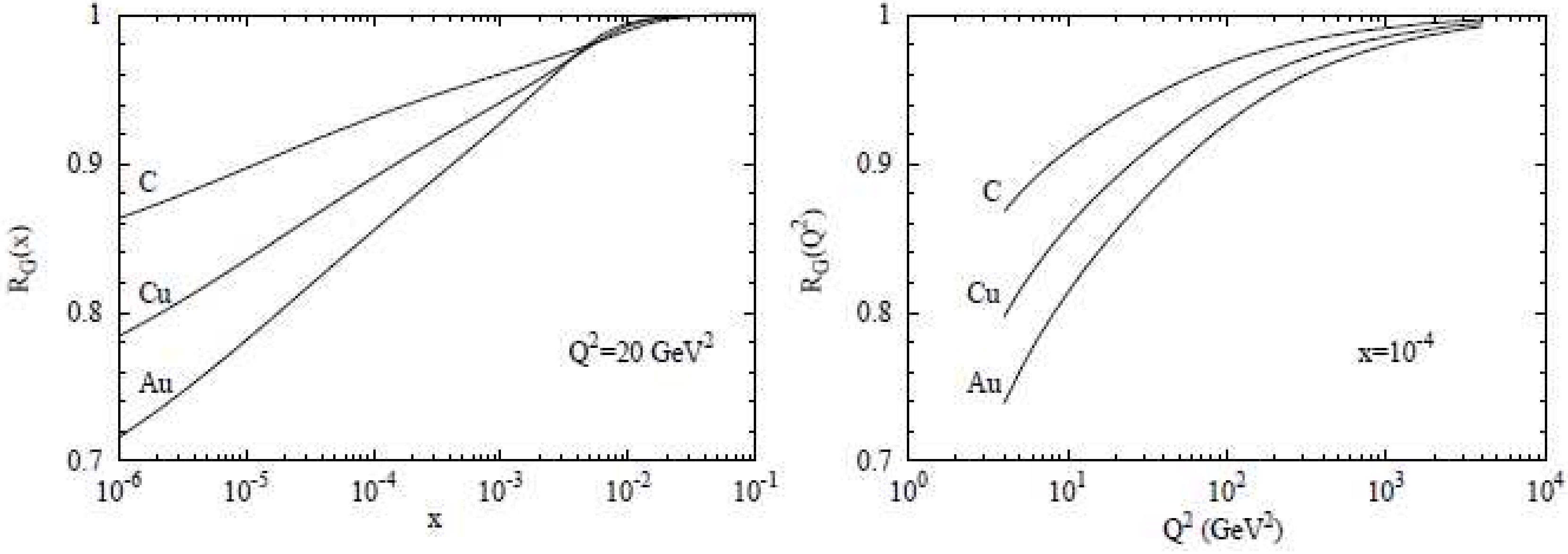
Gluon shadowing

- Guon shadowing added via $\sigma^N_{q\bar{q}}(\rho, x) \to \sigma^N_{q\bar{q}}(\rho, x) \times R_G(x, Q^2, b)$

$$R_G(x, Q^2, b) = \frac{G_A(x, Q^2, b)}{AG_N(x, Q^2, b)}$$

B.Z.Kopeliovich, A.Schaefer and A.V.Tarasov, Phys. Rev. D **62**, 054022 (2000)

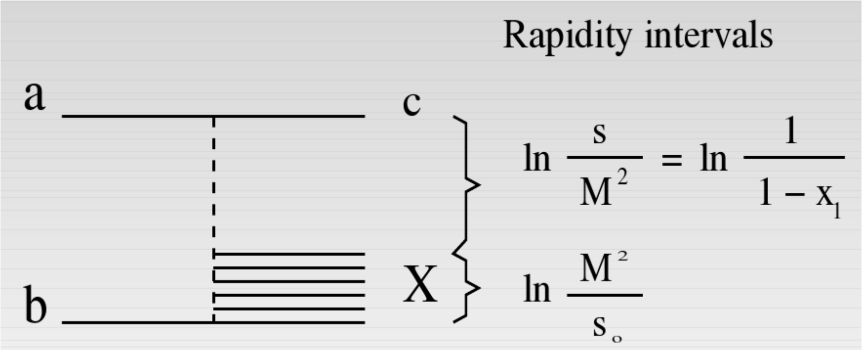
- Represents the leading twist correction to shadowing corresponding to higher Fock components with gluons
- Dominant at small scales and $x \lesssim 10^{-3}$



B.Z.Kopeliovich, J.Raufeisen, A.V.Tarasov and M.B.Johnson, Phys. Rev. C **67**, 014903 (2003)

Effective energy loss

- We propose mechanism based on the energy sharing problem at large p_T induced by multiple initial state interactions
- One can interpret the suppression as a survival probability of the LRG in multiple interactions inside the nucleus
- Any process a+b→ c+X at $x_1 \to 1$ is a LRG process



- The probability to radiate no gluons in the interval Δy is suppressed by Sudakov form factor $S(\Delta y)$
- Assuming an uncorrelated Poison distribution for gluons, the probability to have a rapidity gap Δy is $S(\Delta y) = e^{-<n_G(\Delta y)>}$, where the mean number of gluons is $< n_G(\Delta y) >= \Delta y \frac{dn_G}{dy}$
- Using a formula $\Delta y = ln(\frac{1}{1-x_1})$ one has $S(\Delta y) = (1 - x_1)^{\frac{dn_G}{dy}}$
- The height of the plateau in the gluon spectrum was estimated as

$$\frac{dn_G}{dy} = \frac{3\alpha_S}{\pi} ln(\frac{m_\rho^2}{\Lambda_{QCD}^2}) \sim 1$$

Gunion and Bertsch, Phys.Rev. D**25**, 746 (1982)

Energy conservation restrictions

- Every additional inelastic interaction then contributes an extra suppression factor $S(x_1) \sim 1 - x_1$
- The probability of an n-fold inelastic collision is related to the Glauber coefficients via AGK cutting rules

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

- Resuming over number of rescatterings leads to

$$f^A_{q/N}(x_1, Q^2, b, z) = \sum_{n=0}^{A} v_n(b,z) f^n_{q/N}(x_1, Q^2)$$

- Structure function acquire additional Sudakov factor for each scattering

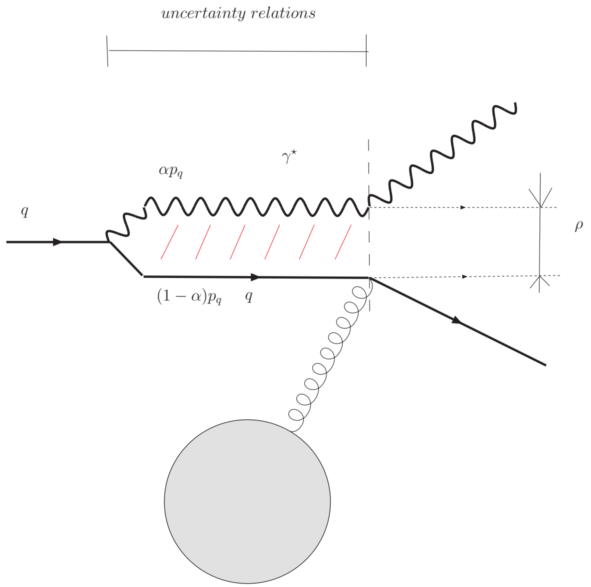
$$f^n_{q/N}(x_1, Q^2) = C_n f_{q/N}(x_1, Q^2) S^n(x_1)$$

- Structure function depends on the target → breakdown of the QCD factorization(leading twist effect)

B.Z.Kopeliovich, J.Nemchik, I.K.Potashnikova, M.B.Johnson and I.Schmidt, Nucl. Phys. Proc. Suppl. **146**, 171 (2005)

Direct photon production in pp

- We use the light-cone color dipole approach to calculate the direct photon production cross-section
- In the target rest frame, the photon production looks like the bremsstrahlung of a real massles photon



- The quark fluctuates into the coherent state $|q\gamma>$ that is disrupted by the color interaction with a nucleon
- Using LC wave functions and dipole cross section from DIS

$$\frac{d\sigma(qp\to\gamma X)}{dln\alpha d^2p_T} = \frac{1}{(2\pi)^2}\int d^2\rho_1 d^2\rho_2 e^{i\vec{p}_T(\rho_1-\rho_2)}\Psi_{\gamma q}(\alpha,\rho_1)\Psi^*_{\gamma q}(\alpha,\rho_2)\Sigma(\alpha,\rho_1,\rho_2)$$

$$\Sigma(\alpha,\rho_1,\rho_2) = \left(\sigma^N_{q\bar{q}}(\alpha\rho_1)+\sigma^N_{q\bar{q}}(\alpha\rho_2)-\sigma^N_{q\bar{q}}(\alpha|\rho_1-\rho_2|)\right)$$

$$\frac{d\sigma(pp\to\gamma X)}{d^2p_T} = \frac{x_1}{x_1+x_2}\int_{x_1}^{1}\frac{d\alpha}{\alpha^2}\sum_q Z_q^2(f_q(\frac{x_1}{\alpha})+f_{\bar{q}}(\frac{x_1}{\alpha}))\frac{d\sigma(qp\to\gamma X)}{dln\alpha d^2p_T}$$

B.Kopeliovich, In *Hirschegg 1995, Proceedings, Dynamical properties of hadrons in nuclear matter* 102-112 (arXiv:hep-ph/9609385)

Direct photon production in pp

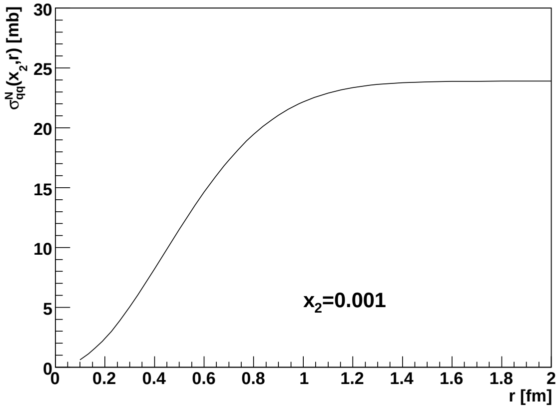
- Essential components for the calculation:
  - Dipole cross sections - revised GBW parametrization

$$\sigma^N_{q\bar{q}}(x,r) = 23.9mb\left(1 - e^{-\frac{r^2Q_0^2}{4r_0(x)}}\right)$$

$$Q_0^2 = 1GeV^2 \quad r_0(x) = \left(\frac{x}{x_0}\right)^\lambda$$

$$x_0 = 0.000111 \quad \lambda = 0.287$$

H.Kowalski, L. Motyka and G. Watt, Phys. Rev. D 74(2006)



  - Light-cone wave functions

$$\Psi_{\gamma q}(\alpha,\rho_1)\Psi^*_{\gamma q}(\alpha,\rho_2) = \frac{\alpha_{em}}{\pi^2}[(m_q^2\alpha^4)K_0(\epsilon\rho_1)K_0(\epsilon\rho_2) + (1+(1-\alpha)^2)\epsilon^2K_1(\epsilon\rho_1)K_1(\epsilon\rho_2)]$$

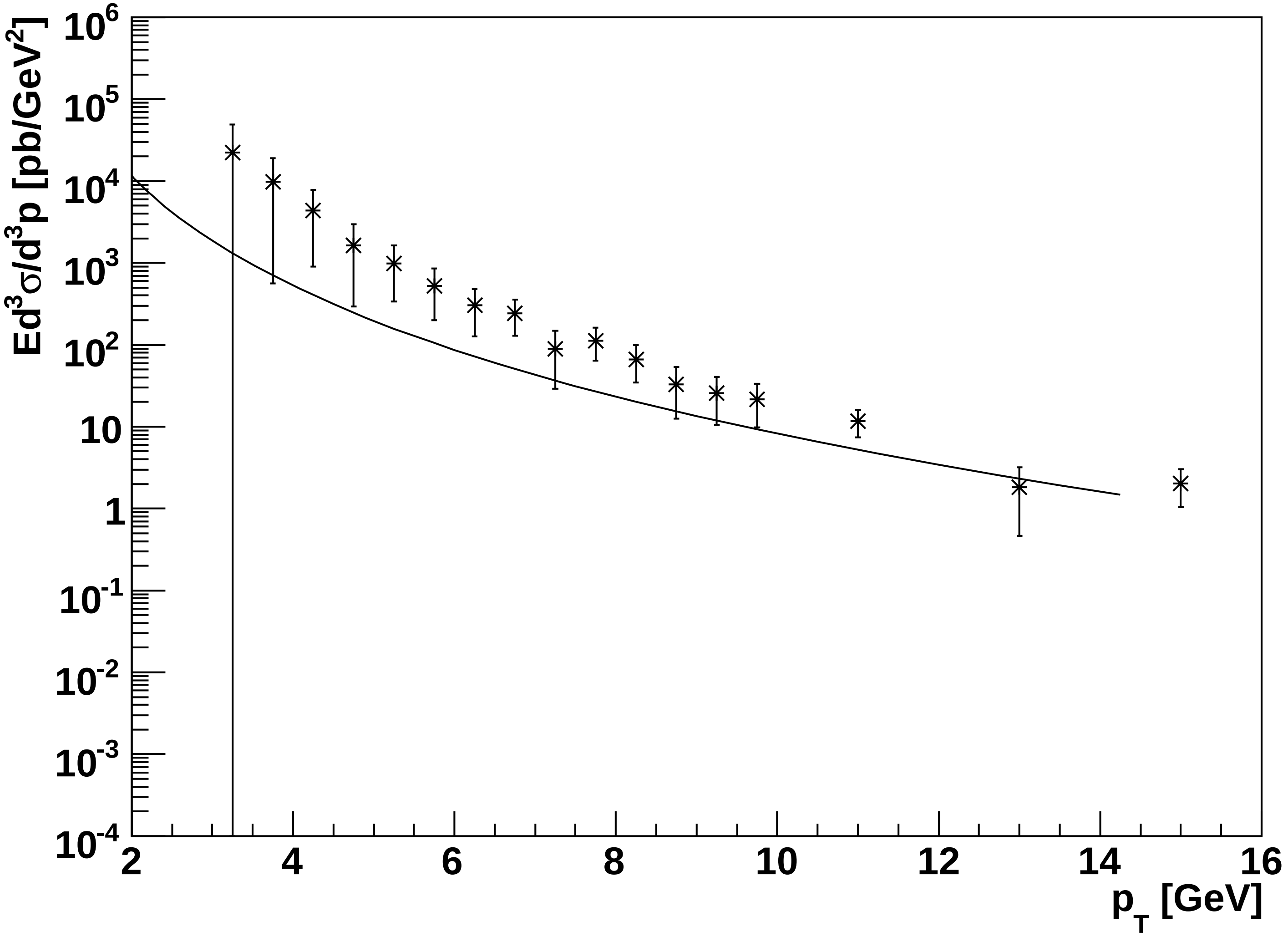
B.Z.Kopeliovich, A.Schaefer and A.V.Tarasov, Phys. Rev. D **62**, 054022 (2000)

  - Parton distribution functions - GRV98 LO parametrizations

M. Gluck, E. Reya and A. Vogt,Eur. Phys. J. C **5** (1998) 461

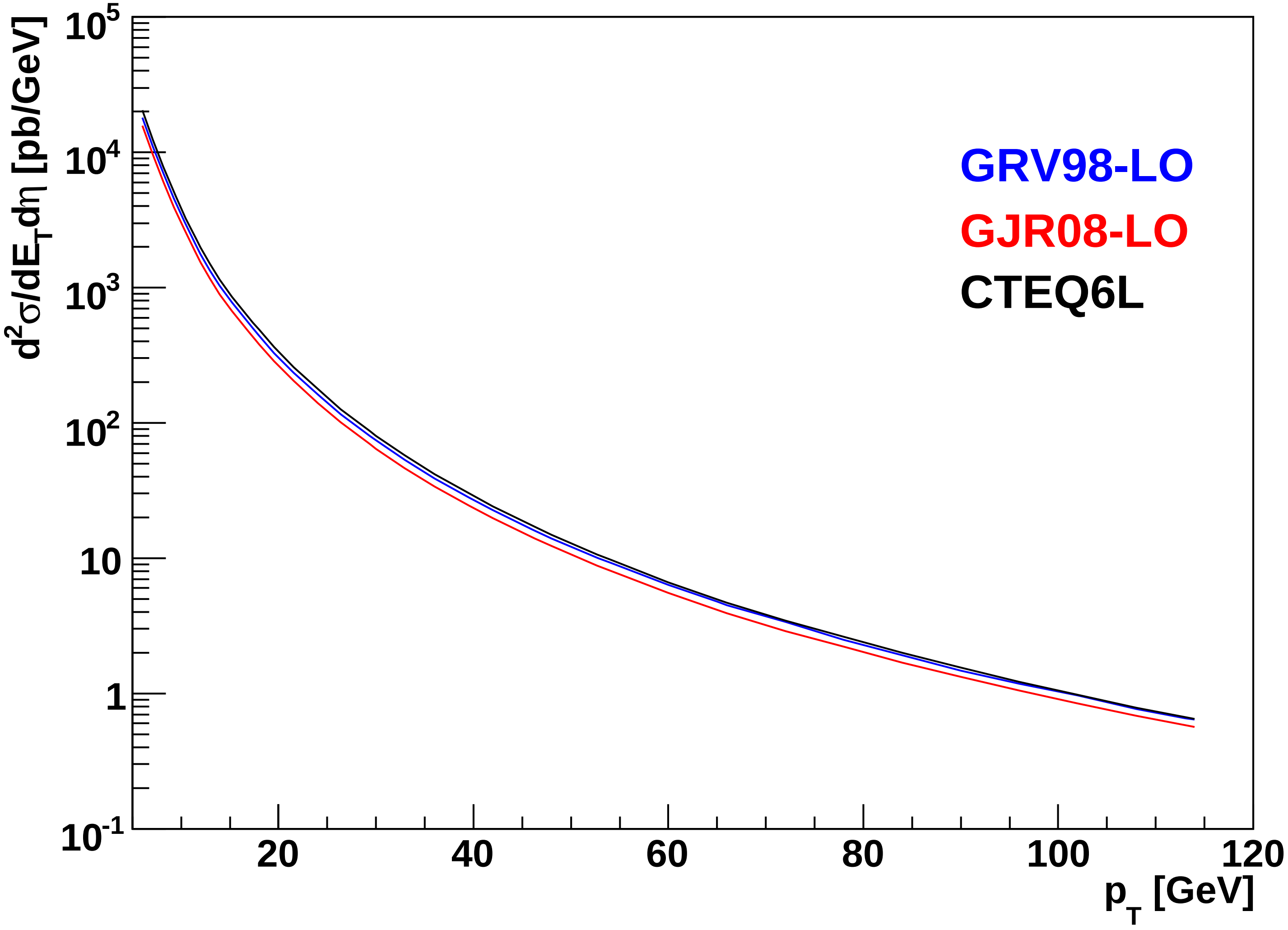
The direct photon production in pp

- Calculated cross section is in good agreement with data
- RHIC 200GeV at midrapidity



The direct photon production in pp

- No data yet available ..
- LHC 5.5TeV at midrapidity



Coherent scenario of p(d)-A collisions

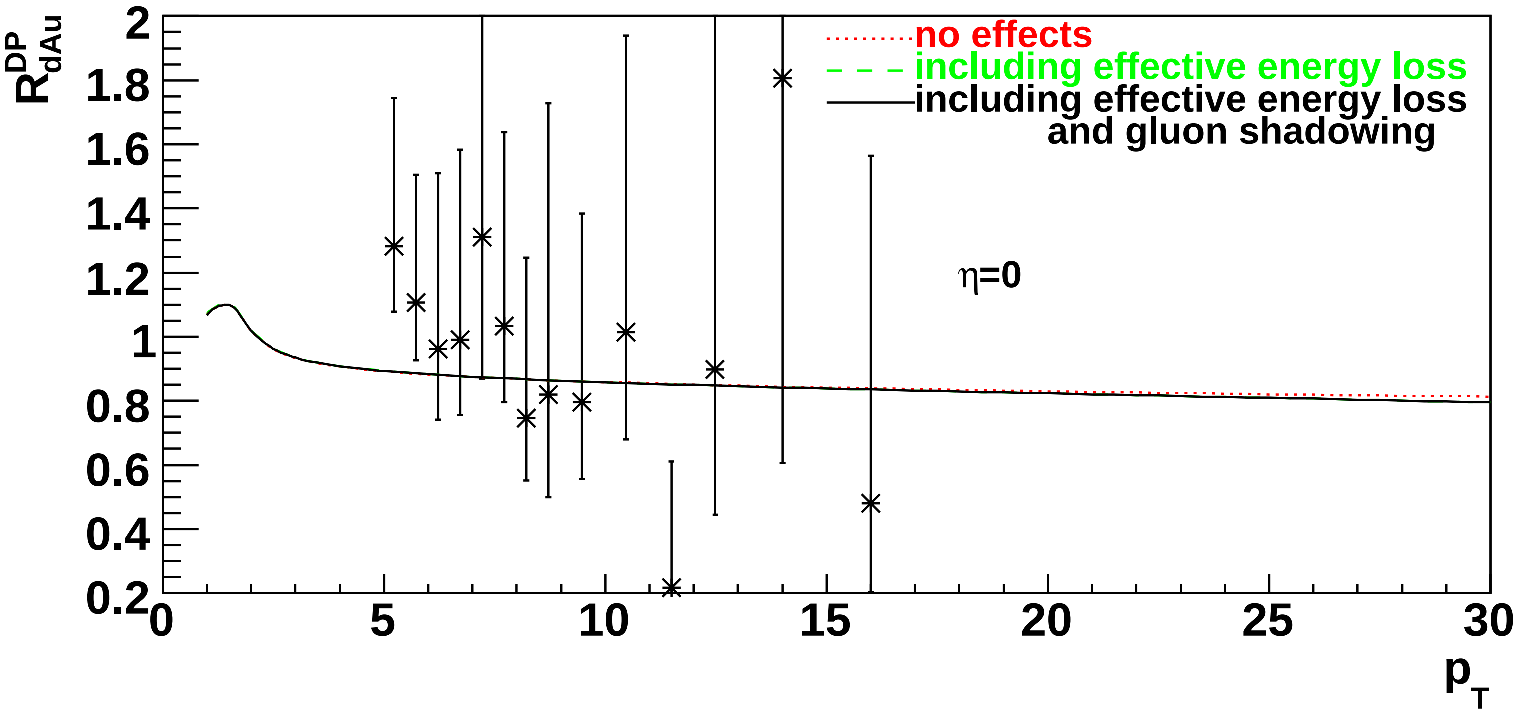
- Long coherence length limit - $< l_c > \gg \; R_A$
  - High energy limit
  - Fluctuation arises long before the quark enters the nucleus
  - Transverse separations of the fluctuation are "frozen" through the propagation - they form eigenstates of interaction
  - Interaction with the nucleons is coherent - maximal quark shadowing
  - Glauber eikonalization can be used to evaluate the σ^{NA}

$$\sigma_{q\bar{q}}^{N}(\rho, x) \rightarrow \sigma_{q\bar{q}}^{A}(\rho, x) = 2 \int d^2b \left(1 - (1 - \frac{1}{2A}\sigma_{q\bar{q}}^{N}(\rho, x)T_A(b))^A\right)$$

B.Z.Kopeliovich, J.Raufeisen, A.V.Tarasov and M.B.Johnson, Phys. Rev. C **67**, 014903 (2003)

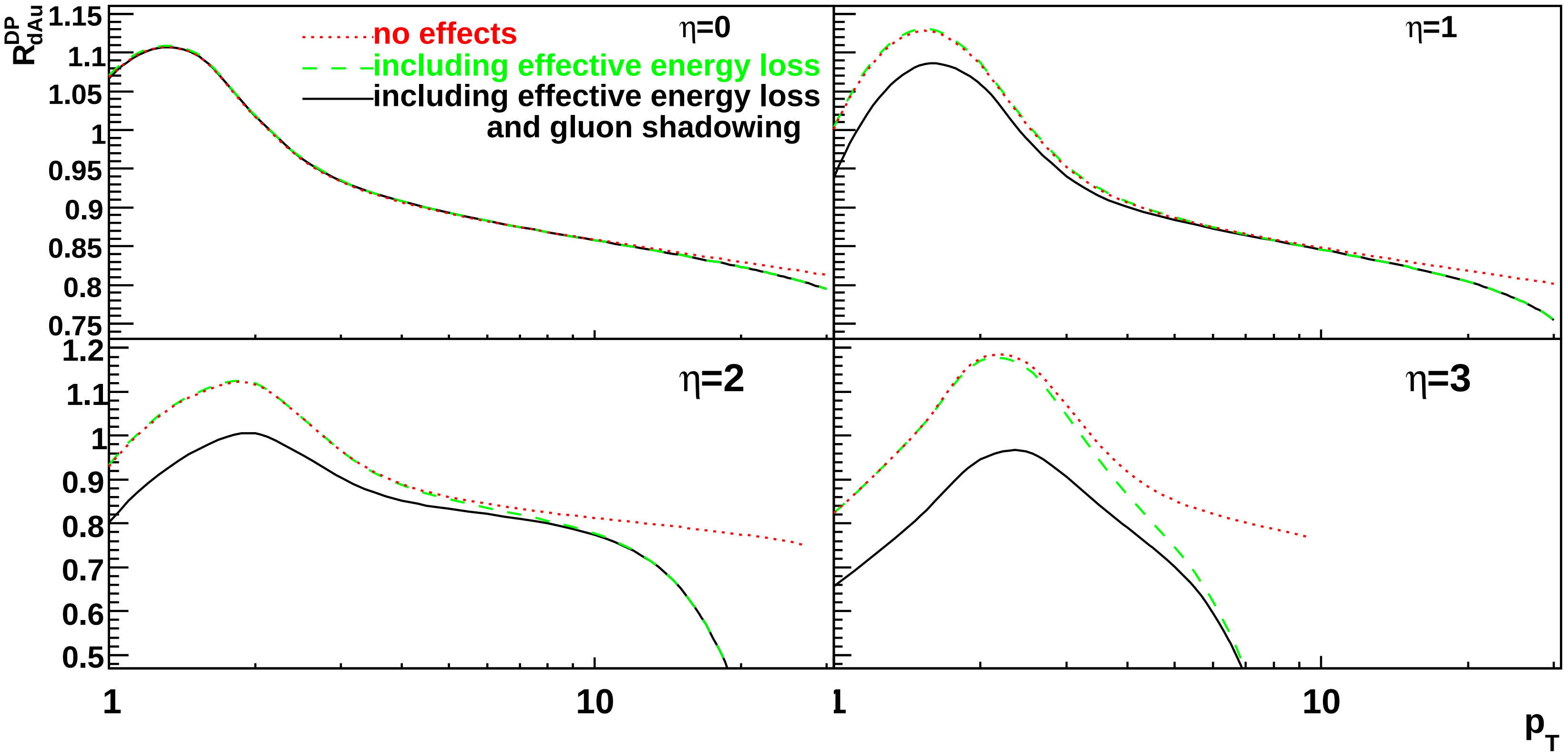
Numerical results - d+Au@RHIC(200GeV)

- The onset of isospin effects R→ 0.8 at high p_T
- Effective energy loss start to manifest themselves at $p_T \gtrsim 30$ GeV
- Gluon shadowing is negligible due to high x_2 at midrapidity



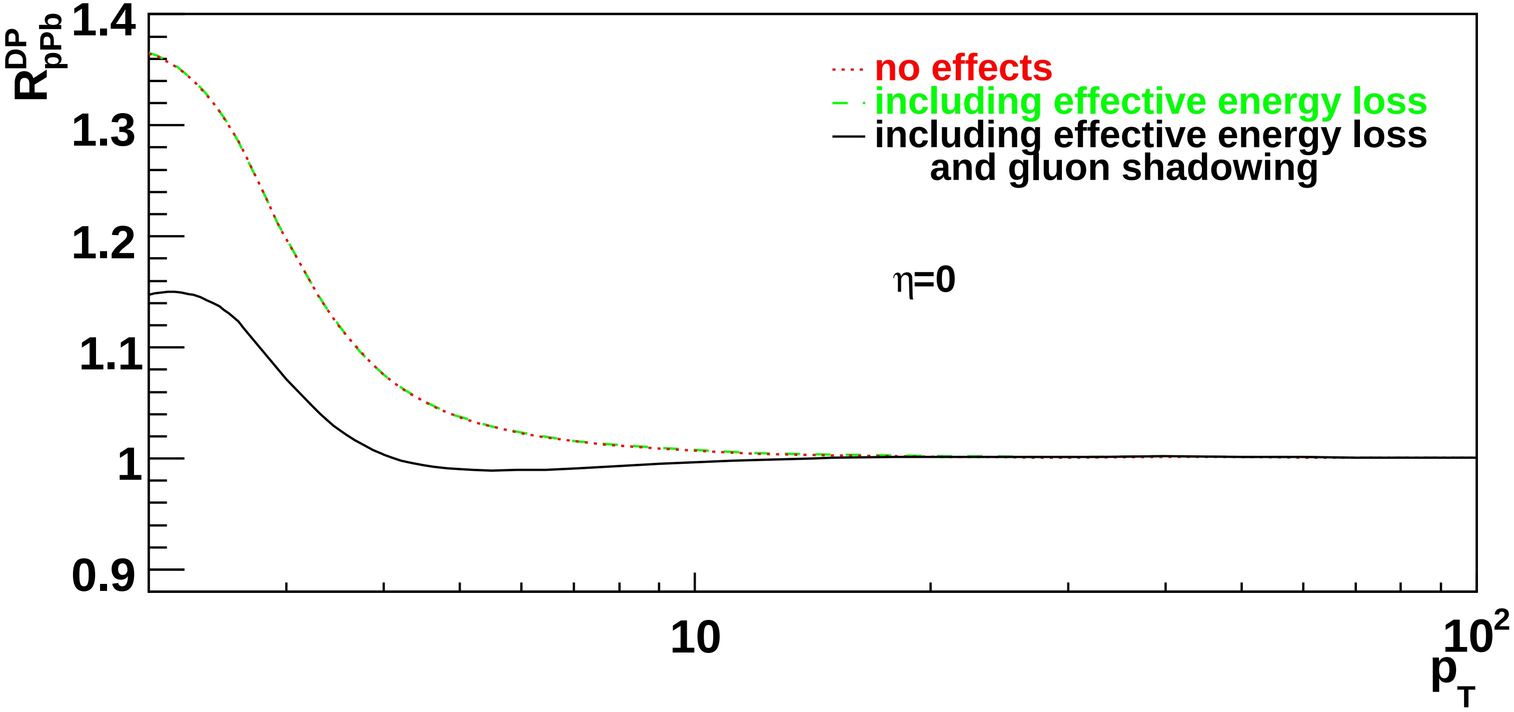
Numerical results - d+Au@RHIC(200GeV)

- Magnitude of energy loss effects rises with rapidity - dominates at high p_T
- Gluon shadowing rises from almost 0% at $\eta = 0$ to ~ 10% at $\eta = 3$ and gradually decreases with p_T



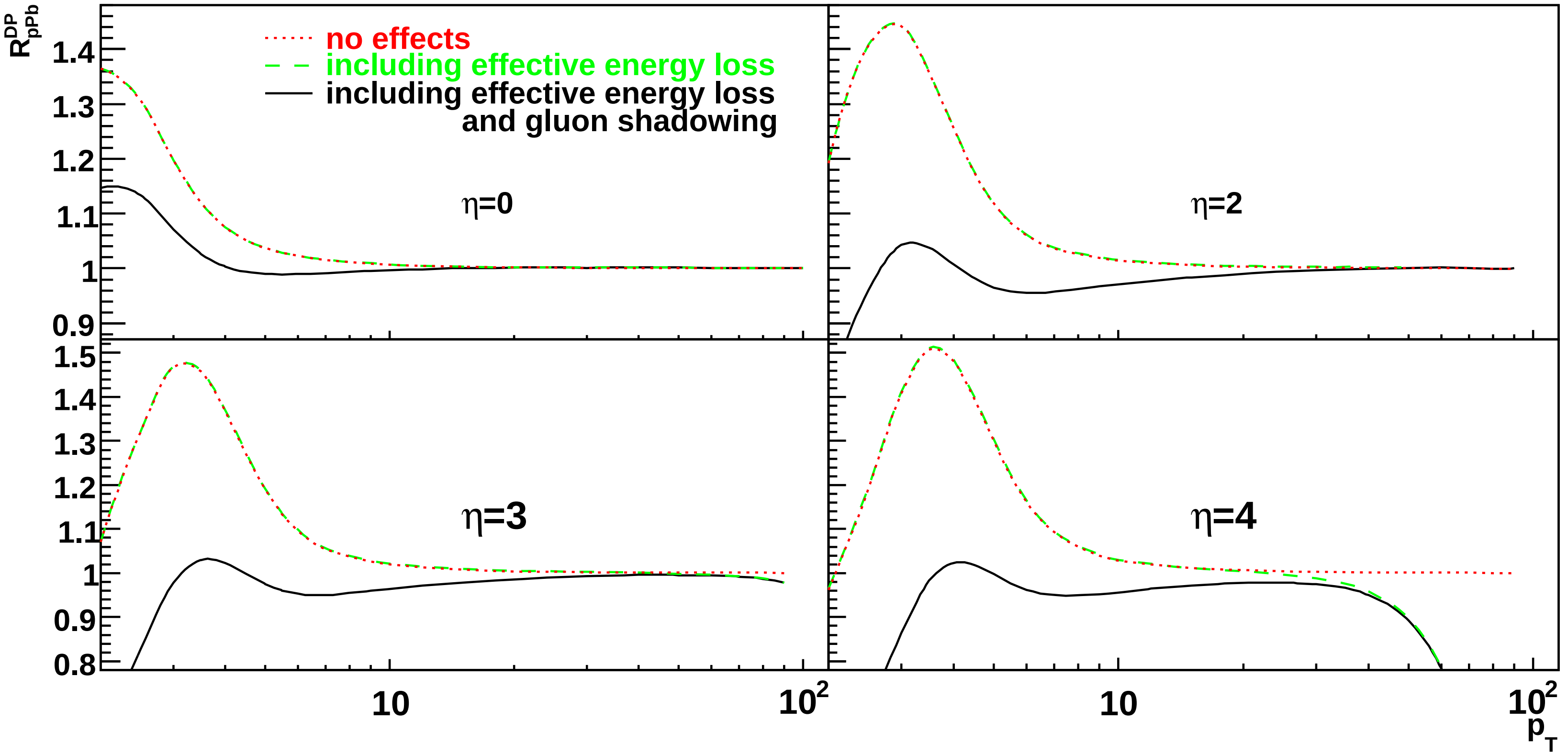
Numerical results - p+Pb@LHC(5.5TeV)

- The QCD factorization predicts R→ 1 at high p_T
- Effective energy loss negligible at this p_T range - manifest themselves at much higher p_T
- Gluon shadowing $\sim$ 20% at low p_T



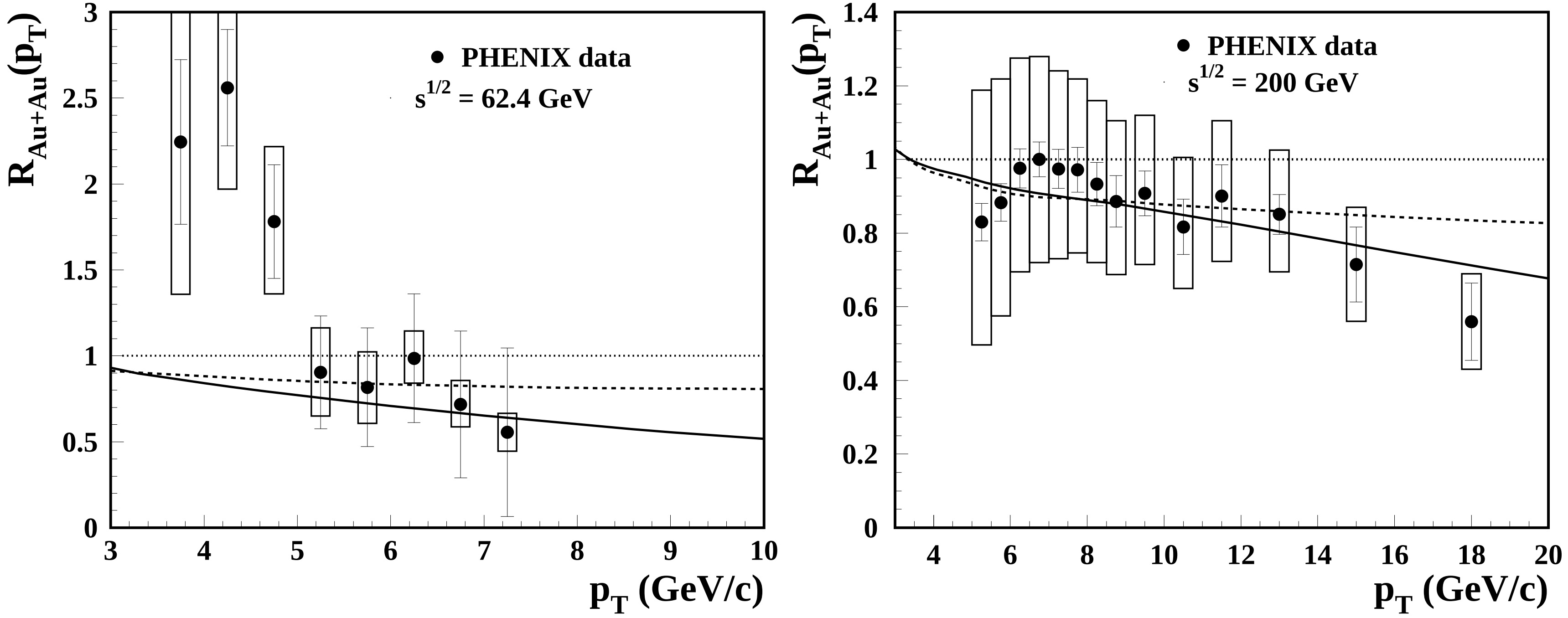
Numerical results - p+Pb@LHC(5.5TeV)

- Effects of energy conservation rise with rapidity and are clearly observable at $p_T >$30GeV at $\eta = 3 - 4$ - they can be verified at LHC
- Gluon shadowing rises from $\sim$ 20% at $\eta = 0$ to $\sim$ 50% at $\eta = 4$ at low p_T



Numerical results - Au+Au@RHIC(200GeV)

- The onset of isospin effects - R→ 0.8 at high p_T
- Effective energy loss mechanism gives a stronger suppression at high p_T - in a better agreement with data



Conclusions

- Direct photon production cross-sections were calculated within the color dipole approach in the RHIC and LHC kinematic regions
- We included coherence effects (quark and gluon shadowing) and corrections for energy conservation in our calculations to evaluate nuclear effects.
- At RHIC energy
  - Calculations of the dAu/pp production rate show $\sim$20% effect of isospin
  - The suppression driven by energy sharing problem in multiple initial state interactions is weak at midrapidity at high p_T but rapidly rises with rapidity
  - The effect of the gluon shadowing is $\sim$5-10%

Conclusions

- At LHC energy
  - Calculations of the pPb/pp production rate show no isospin effects and consequently one should expect R $\to$ 1 in accord with QCD factorization.
  - The suppression driven by energy sharing problem in multiple initial state interactions is very weak at midrapidity at high p_T and starts to play role at very forward rapidity $\eta \sim 3-4$
  - The effect of the gluon shadowing is ∼20-50%
- In central Au-Au collisions at RHIC the effective energy loss mechanism mechanism represents a significant effect and describes well available data also at high p_T
- Data from RHIC and LHC at forward rapidity needed (FoCal@ALICE) for better comparison

Thank you for your attention!