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Challenges of direct photon production at forward rapidities and large p_T

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HPT2014, Nantes, France

Outline

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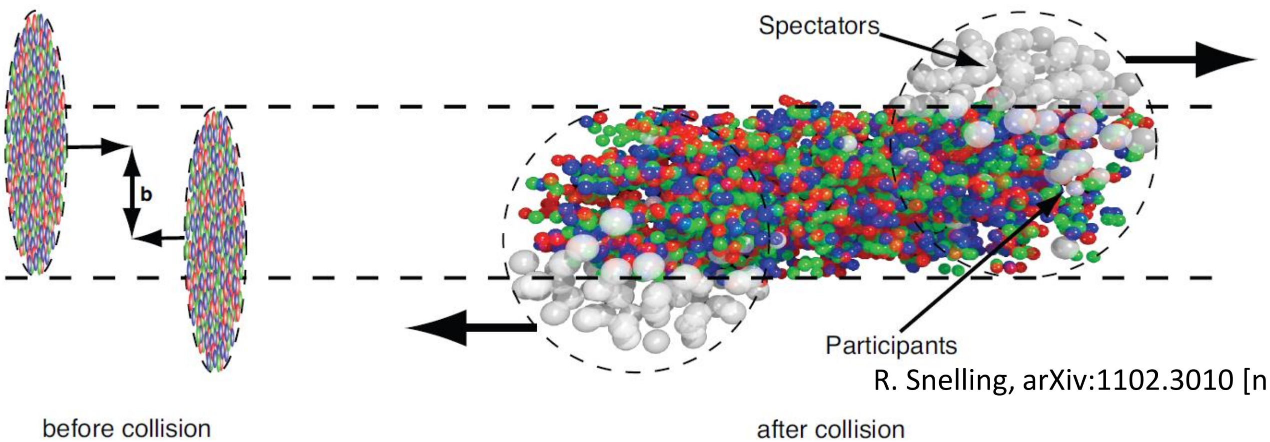
- Introduction and motivation
  - Motivation for direct photons
  - Aspects of direct photons
  - Initial state effects
- Calculation of the direct photon
  - QCD factorization calculation
  - Color dipole approach calculation
- Numerical Results
  - *pA* collisions
  - *AA* collisions
- Conclusions

Introduction & motivation

- Motivation for HIC is to discover and study strong interaction at high temperature
- Unfortunately, *AA* collisions, besides final state effects, includes also initial state effects
- Baseline is needed for recognition of both effects
  - Study *pA* collisions
    - Jets, hadrons, **photons**, …
  - Strongly non-interacting probes in *AA* collisions
    - **Direct (prompt) photons**



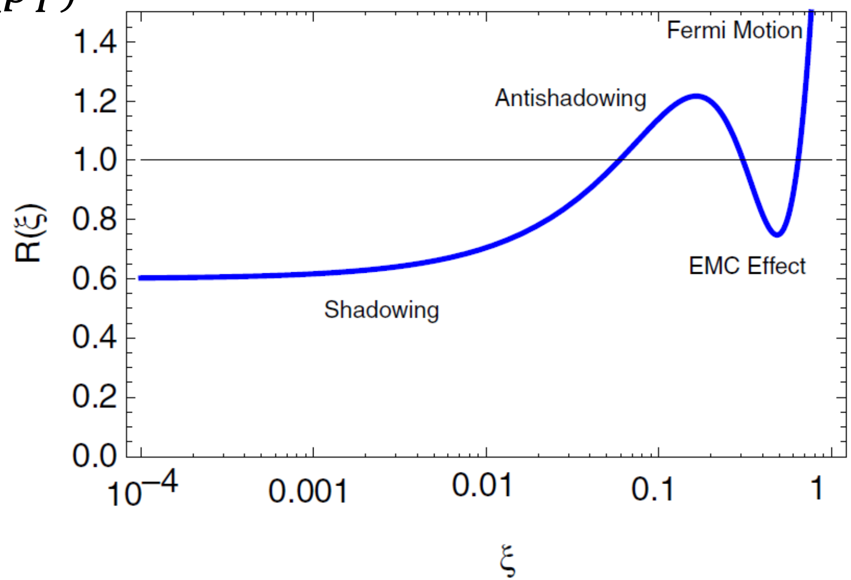
R. Snelling, arXiv:1102.3010 [nucl-ex]

Introduction & motivation

- Advantages of direct (prompt) photons
  - Just EM interaction
  - Just initial state effects
  - No fragmentation
  - No energy loss
  - No absorption

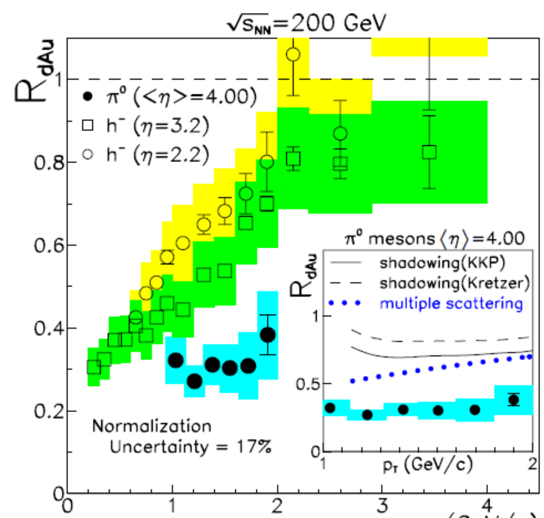
Introduction & motivation

- Initial/Final state effects: suppression or enhancement of photon production in *pA or AA* vs photon production in *pp*
- We study initial state effects through the nuclear modification factor of inclusive photon production
  - $R_{pA/AA}(p_T) = \frac{\sigma^{pA/AA \to h+X}(p_T)}{A\,\sigma^{pp \to h+X}(p_T)}$



Introduction & motivation

- We can focus on three effects:
  - Cronin effect, $R_{pA}(p_T)$>1 at medium-high p_T
    - Quite understood, existence of different mechanisms
  - Suppression at small-p_T - nuclear shadowing
    - Large theoretical uncertainties
  - Suppression at large-p_T and forward rapidity, indicated by the PHENIX, STAR and BRAHMS



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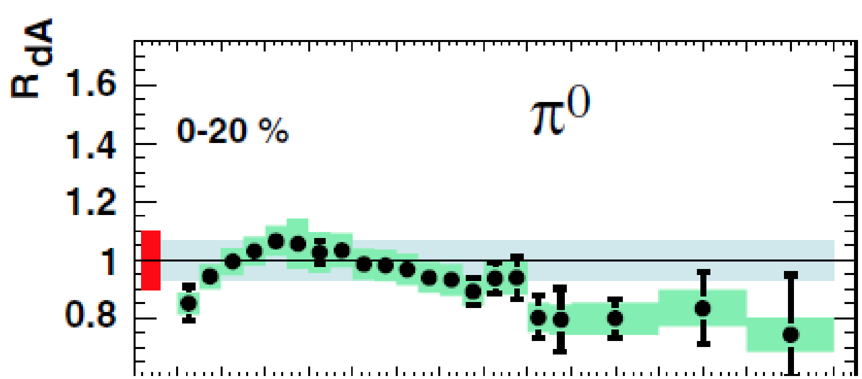

S.S. Adler, et al. (PHENIX Collaboration), Phys.Rev. Lett. **98**, 172302 (2007).
I. Arsene, et al. (BRAHMS Collaboration), Phys.Rev. Lett. **93**, 242303 (2004);
J. Adams, et al. (STAR Collaboration), Phys. Rev. Lett. **97**, 152302 (2006).

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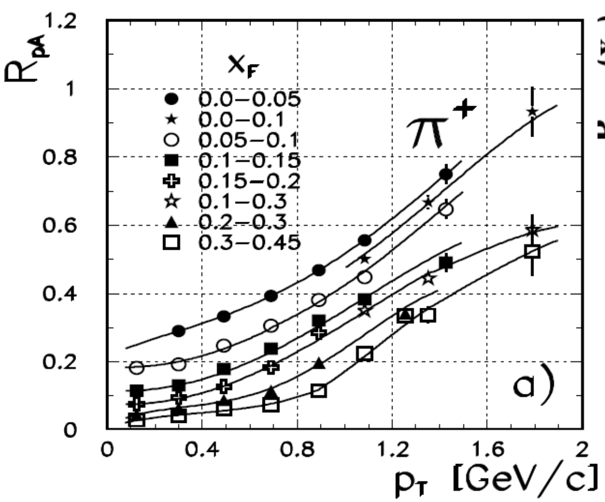
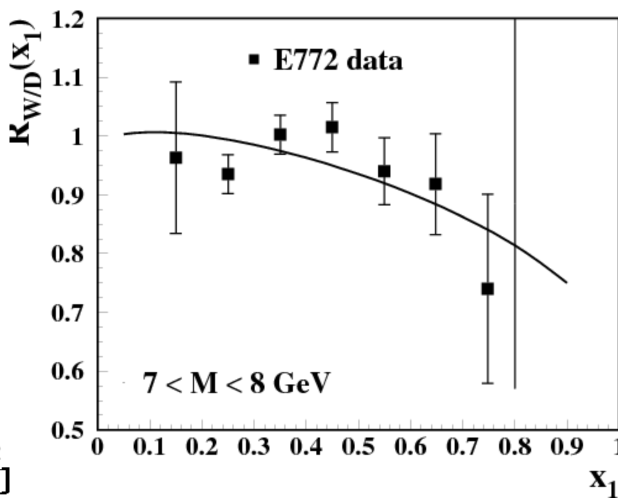
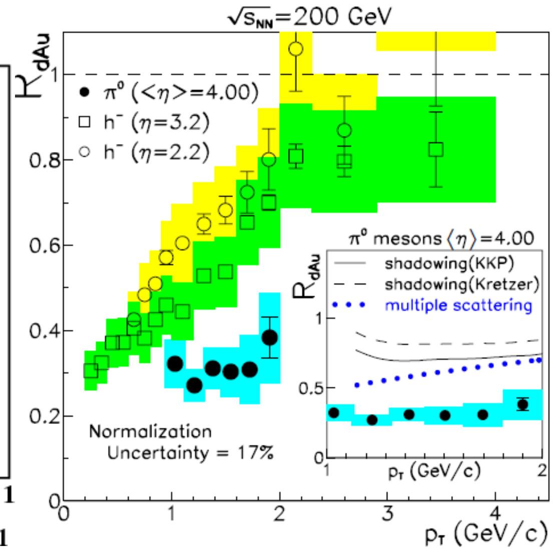
Introduction & motivation

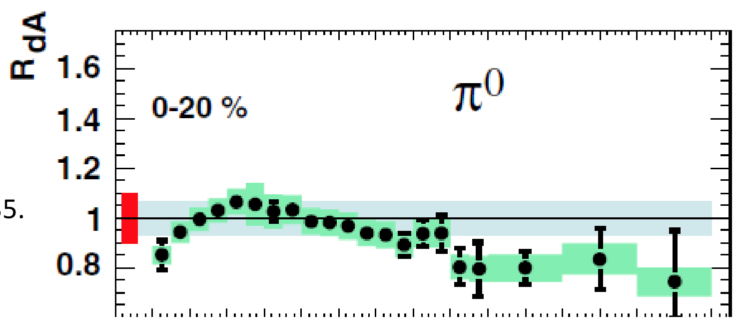
- Data at forward rapidity at STAR and BRAHMS can be explain by CGC, where x_F is large $\leftrightarrow$ x_2 is small
  - But similar suppression at lower energies cannot be explain by coherence effects







- Data at large-p_T - no coherence effects are possible, no CGC



NA49 Collaboration, B. Boimska, Ph.D. Thesis (Warsaw 2004), CERN-THESIS-2004-035.
E772 Collaboration, D.M. Alde at al., Phys. Rev. Lett 64, 2479 (1990).

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Introduction & motivation

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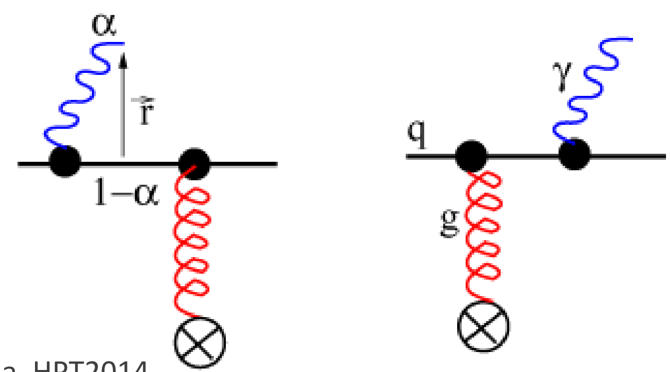
- Previous presented suppressions can be explained by **initial state interactions**
- Multiple interactions of the projectile hadron and its debris propagating through the nucleus should cause a dissipation of energy.
- The suppression factor for each of multiple interactions was evaluated as
  - $S(\xi) \approx 1 - \xi$, where $\xi = \sqrt{x_L^2 + x_T^2}$
    - $x_L = \frac{2p_L}{\sqrt{s}}$, $x_T = \frac{2p_T}{\sqrt{s}}$
- This factor leads to a suppression of the cross section of large-p_T photon production at forward rapidities.
- More in
  - B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, M.B. Johnson and I. Schmidt, Phys.Rev.C **72** (2005) 054606

Calculation of the direct photon

- QCD factorization (LO):
  - Centre-of-mass system
  - Dominate quark-antiquark annihilation

- Color dipole approach:
  - Laboratory system (rest frame) of nucleus/hadron
  - Bremsstrahlung of incoming parton



Calculation of the direct photon

- QCD factorization (LO):
  - Hadrons collision: collision of non-interacting partons in infinite momentum frame
  - Cross section = QCD factorization of pQCD + PDFs + k_T-smearing
  - More details in following refs or at backups slides
    - R. P. Feynman, R. D. Field and G. C. Fox, Phys. Rev. D18, 3320 (1978)
    - X.-N. Wang, Phys. Rev. C 61 (2000) 064910
    - M. Krelina, J. Nemchik, Nucl. Phys. B (Proc. Suppl.) 245 (2013) 239-242

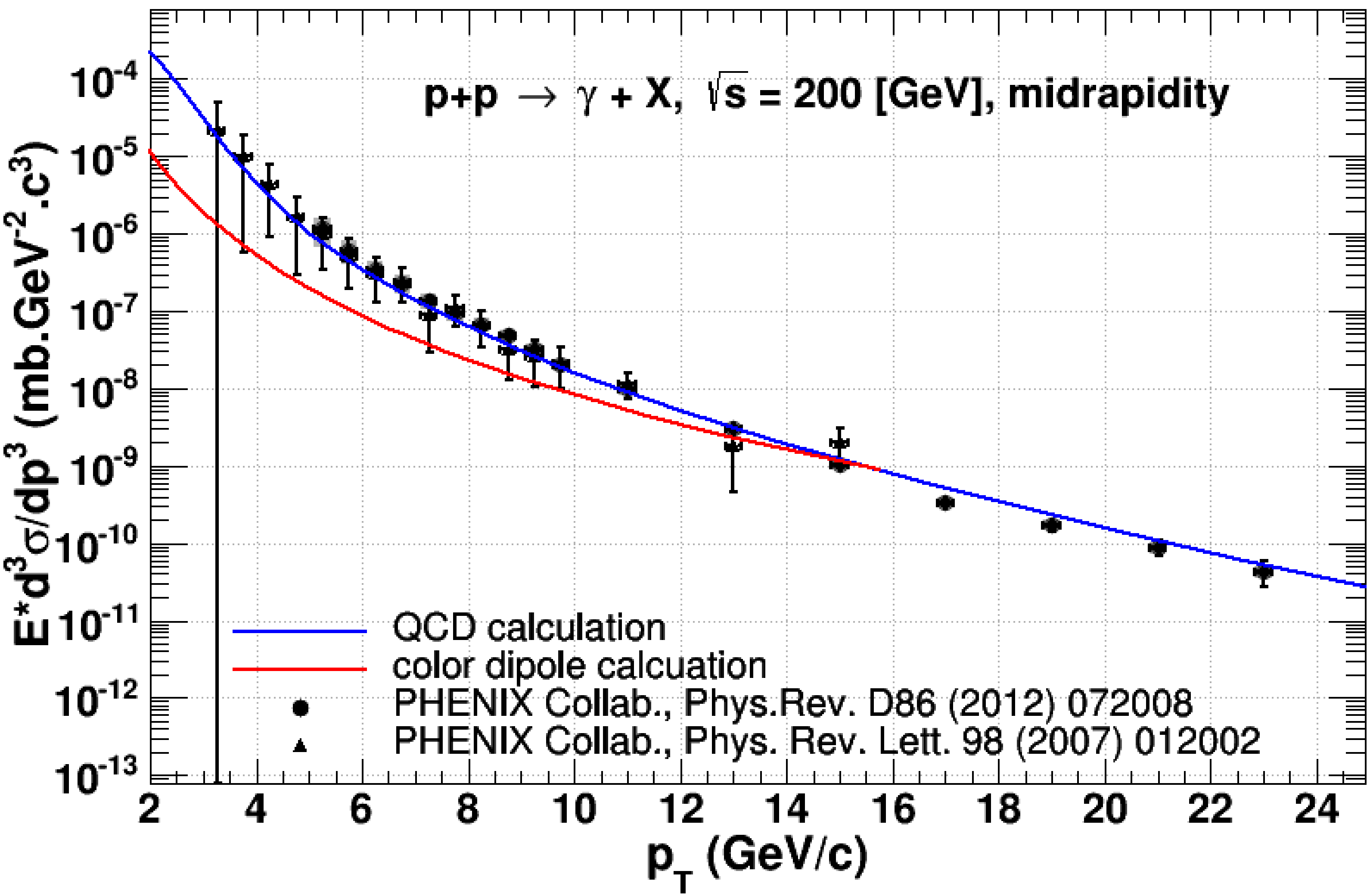
- Color dipole approach:
  - Hadrons collision: interaction of non-interacting partons with hadron in its rest frame
  - Cross section = convolution of PDF and Fock's state wave function and dipole cross section
  - More details in following refs or at backups slides
    - B.Kopeliovich, In *Hirschegg 1995, Proceedings, Dynamical properties of hadrons in nuclear matter* 102-112 [arXiv:hep-ph/9609385]
    - B.Z.Kopeliovich, A.Schaefer and A.V.Tarasov, Phys. Rev. D 62, 054022 (2000)
    - J. Cepila, J. Nemchik, EPJ Web of Conf. 66, 04006 (2014)

Calculation of the direct photon

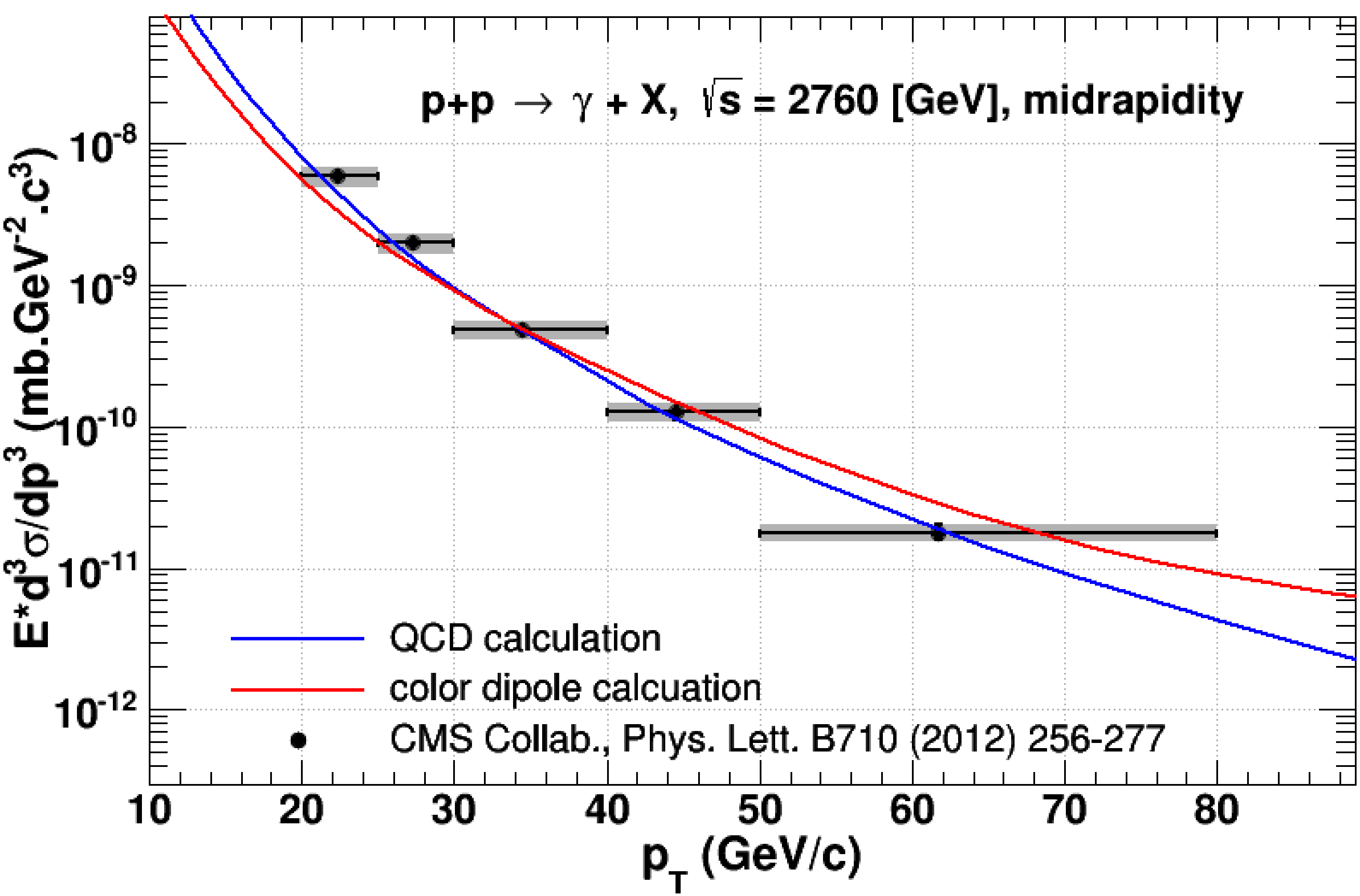
- QCD factorization (LO) - the pros and cons:
  - \+ Based on QCD Lagrangian
  - \+ Very good description (shape) of p_T spectra, Cronin peak, …
  - \- Need for K-factor (naive NLO compensation)
  - \- Choice of renorm. and factor. scale, usually $Q = p_T$
  - \- Divergence for $p_T \to 0$

- Color dipole approach - the pros and cons:
  - \+ Easier transition to *pA* and *AA* formulas
  - \+ Quark shadowing automatically included
  - \- Strong dependence on unintegrated gluon density function
  - \- Not based on QCD Lagrangian

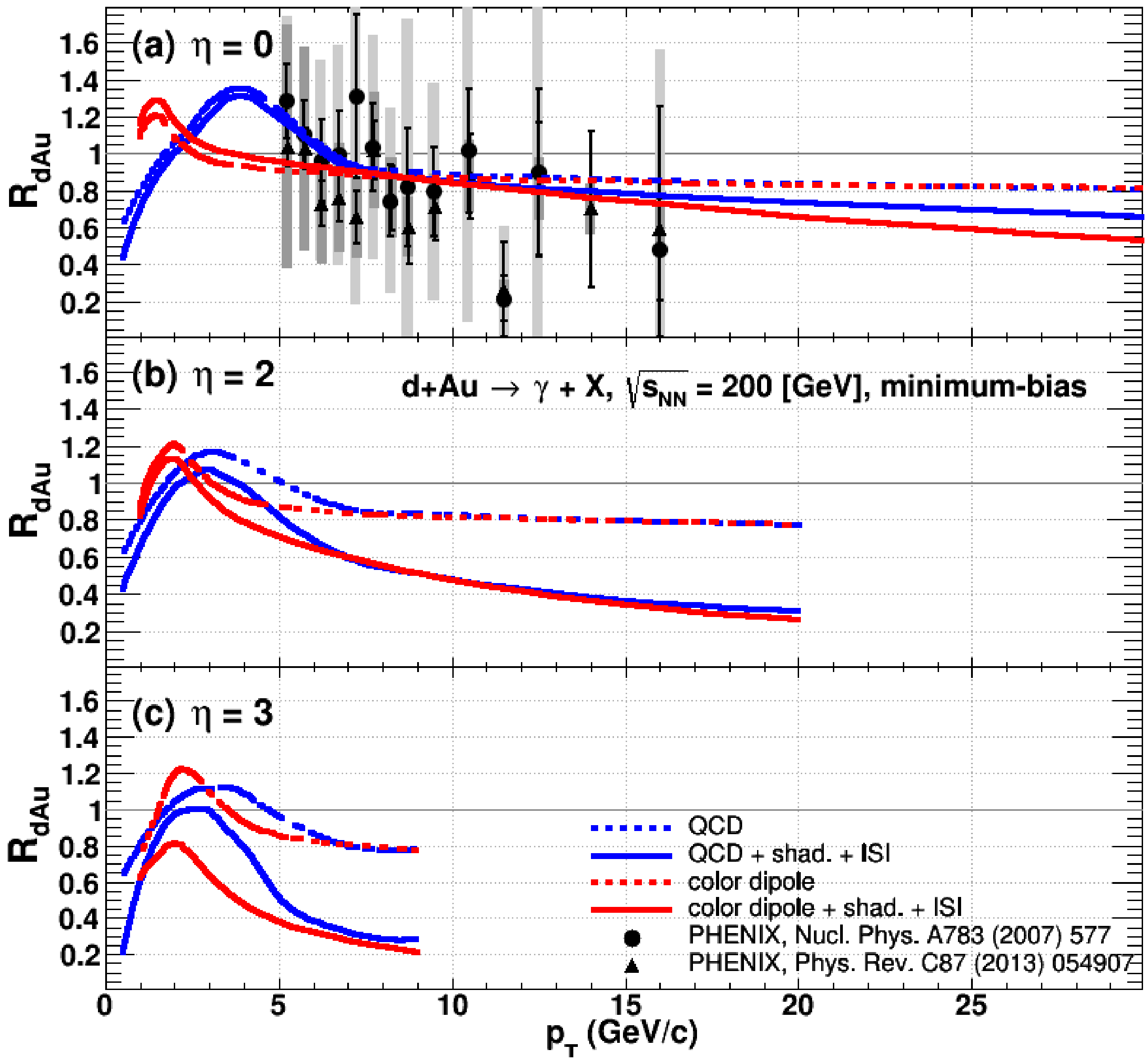
Results: *pp* cross section



Results: *pp* cross section



Results: RHIC



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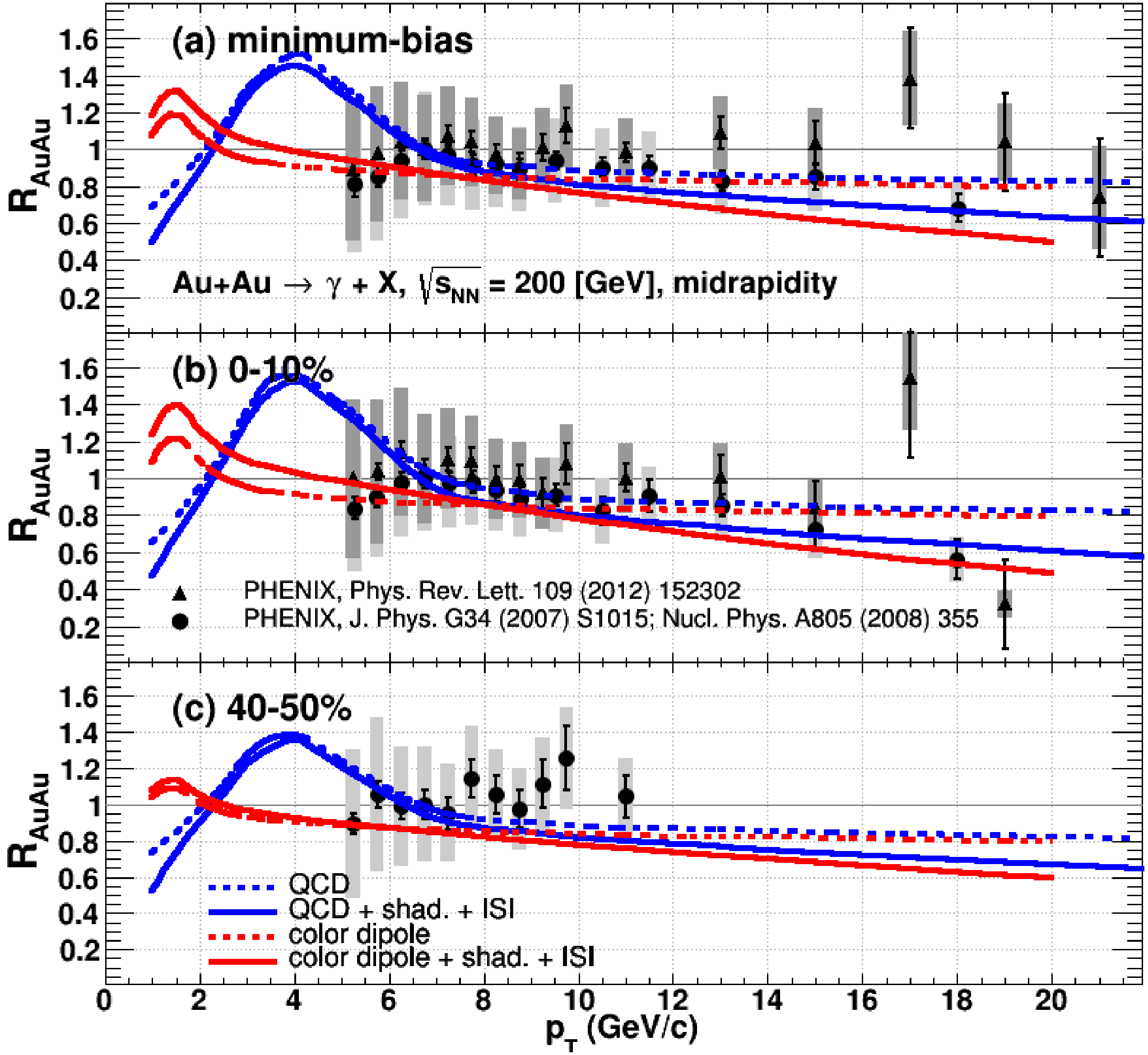
Results: RHIC



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Results: RHIC

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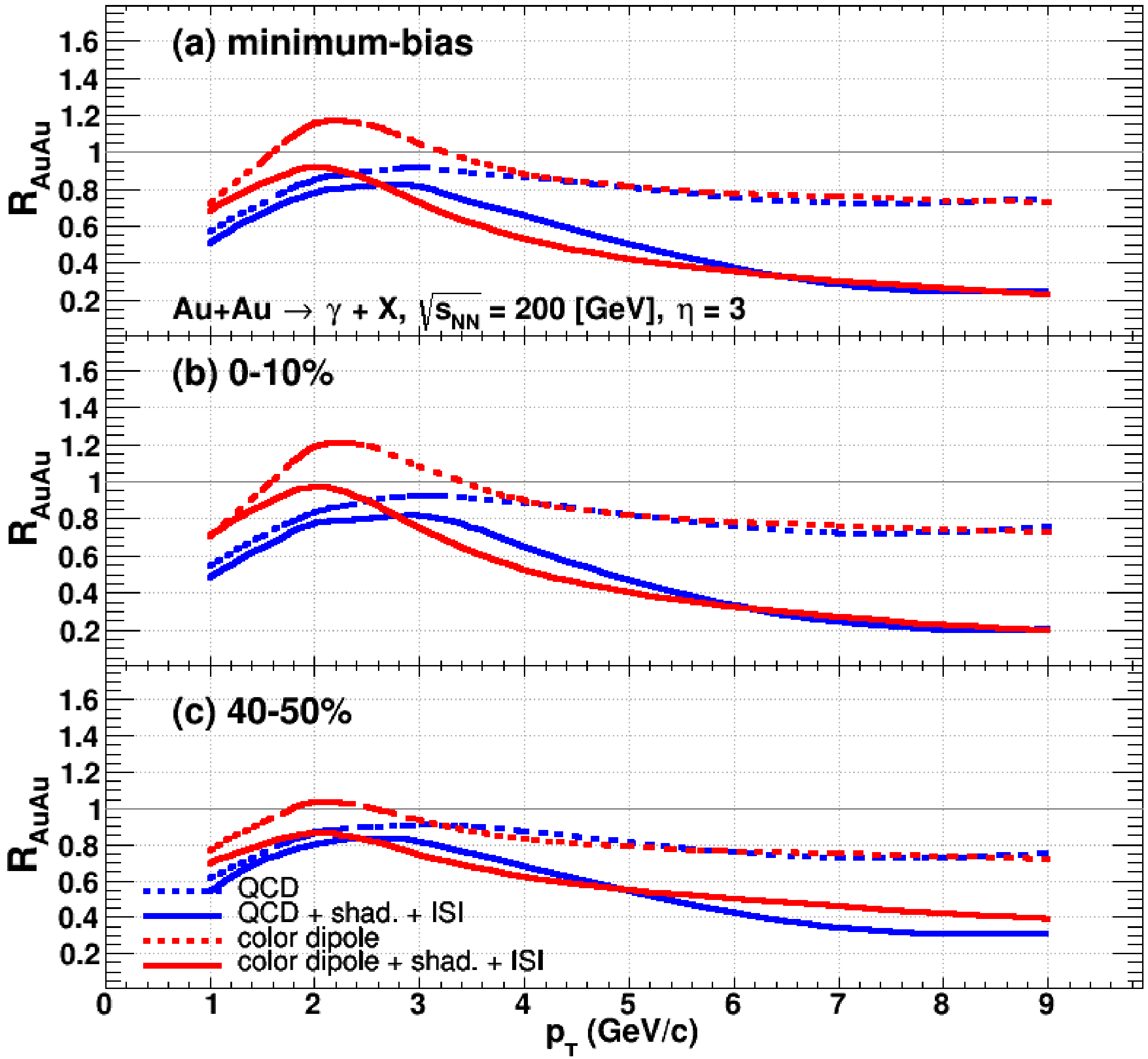

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Results: RHIC

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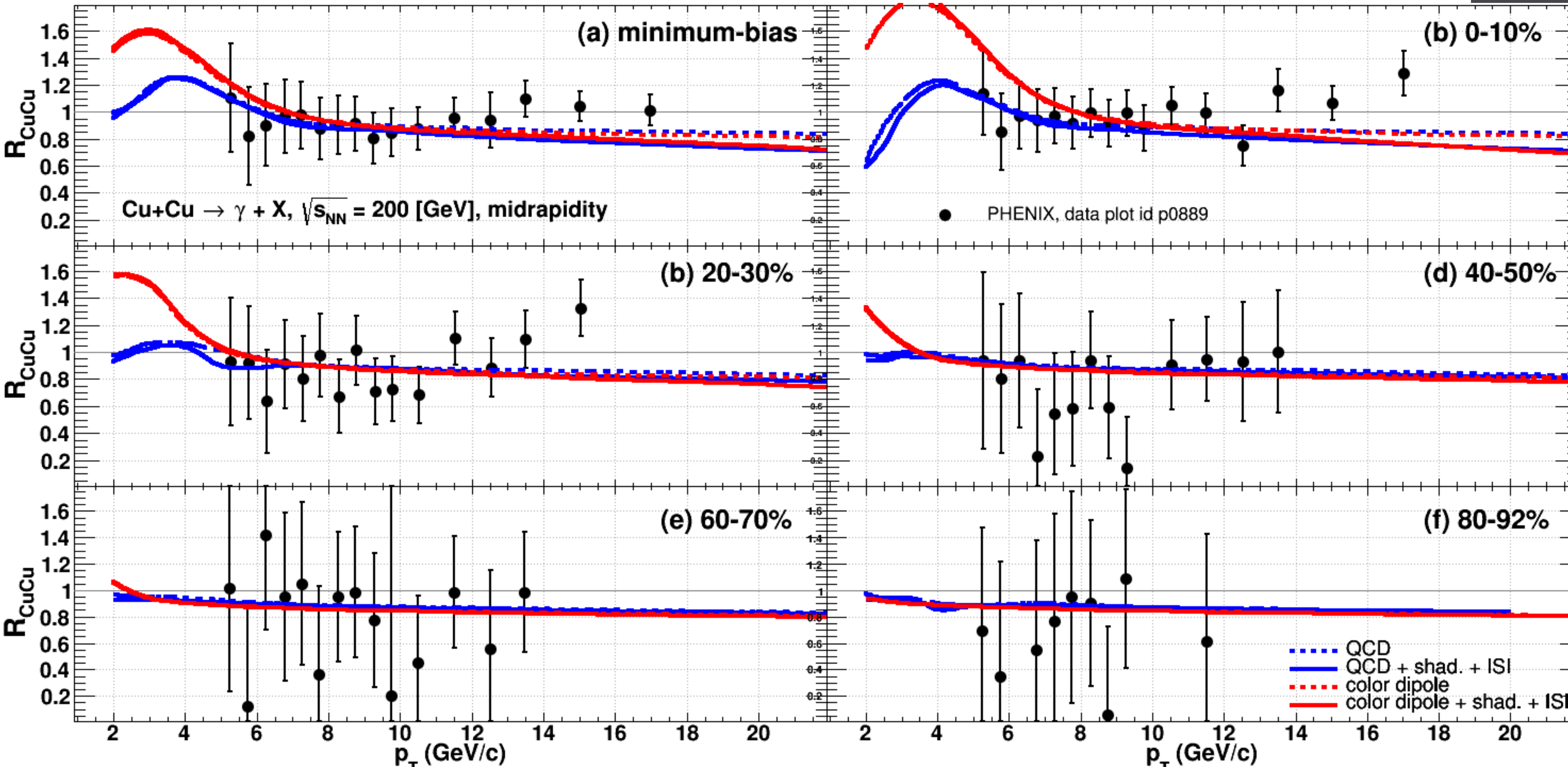

Results: RHIC

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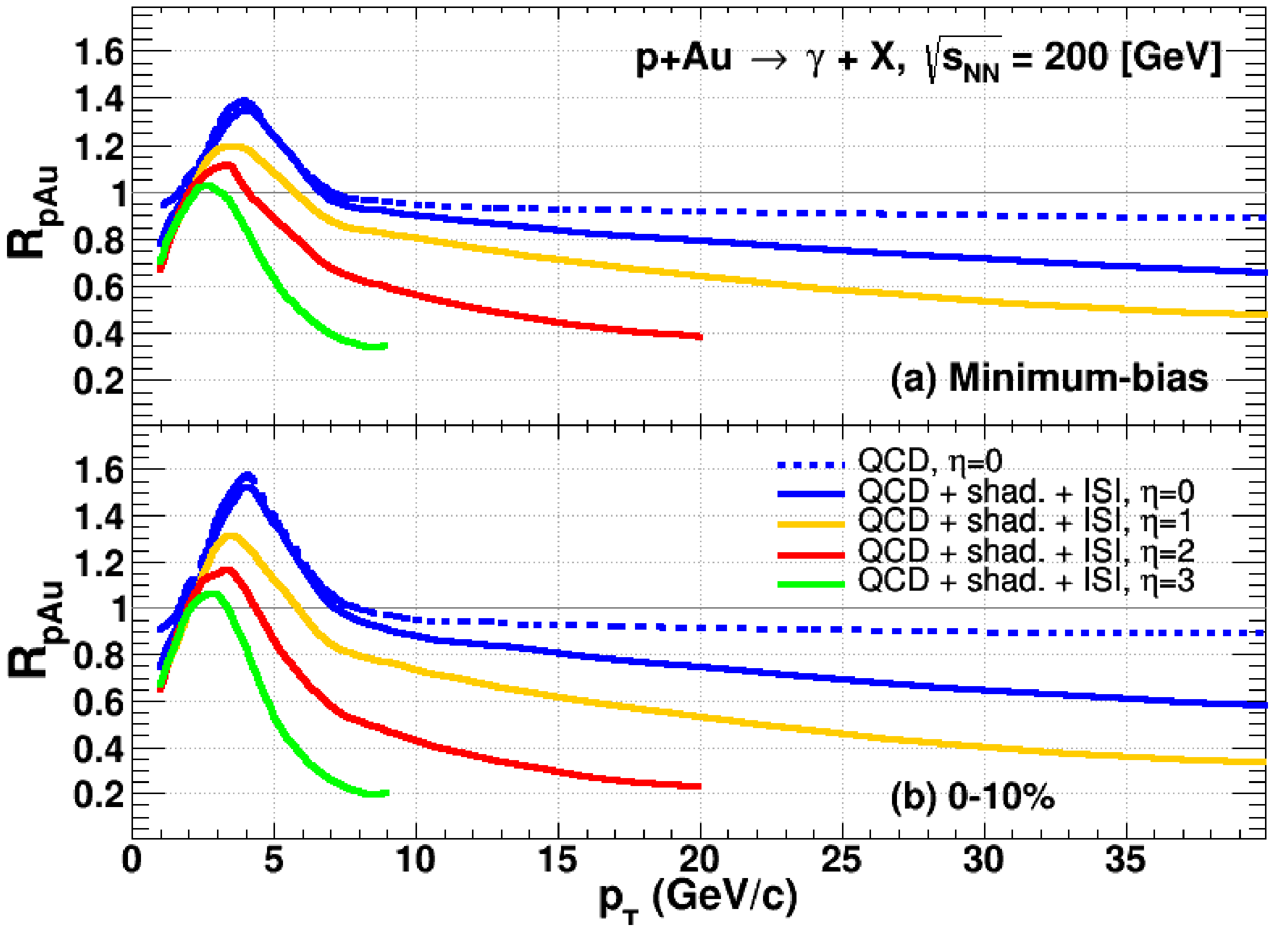

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Results: LHC

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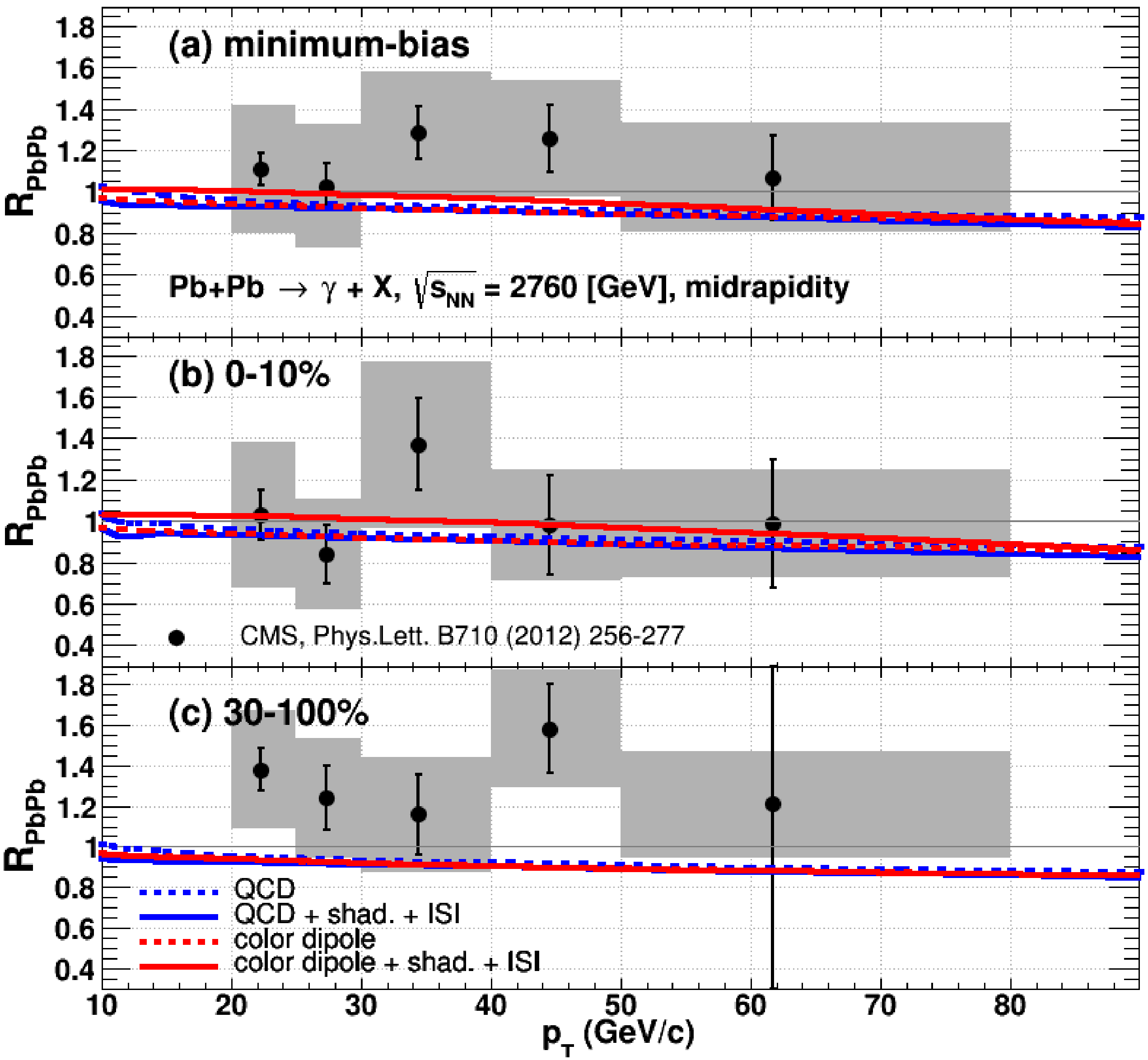

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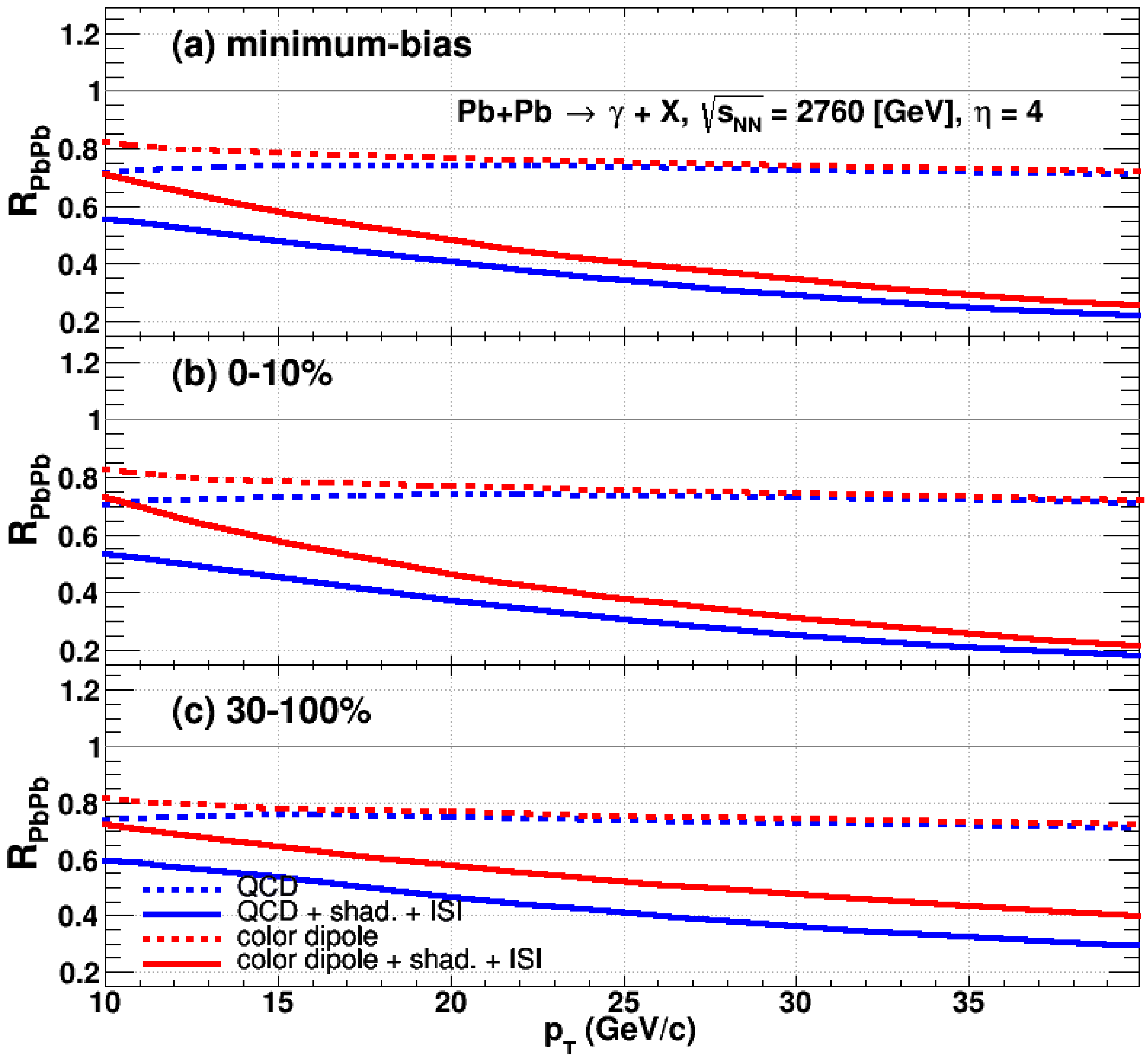
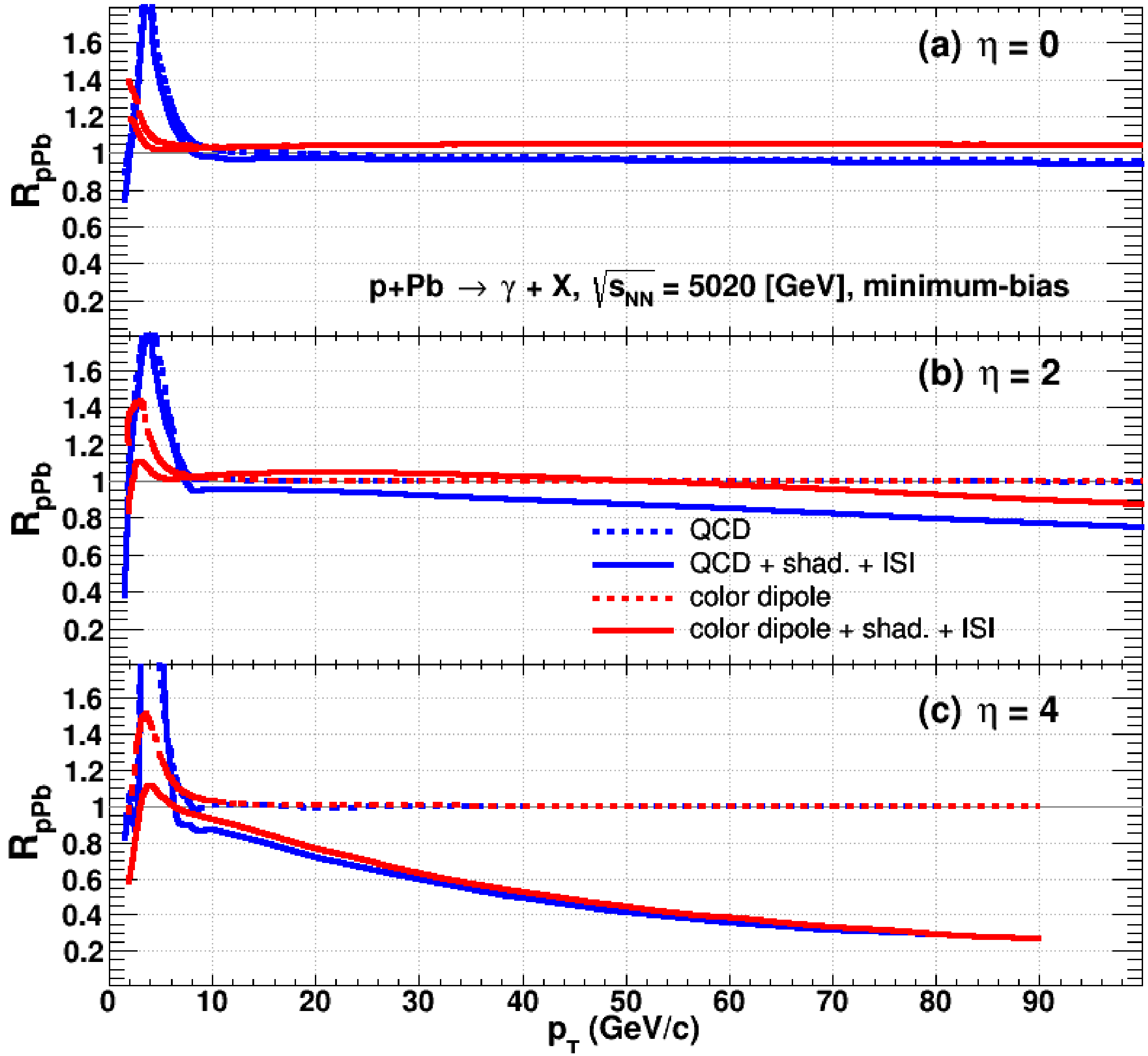
Results: LHC



M. Krelina, HPT2014

Results: LHC



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Conclusions

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- Direct photon production cross sections were calculated within the QCD factorization scheme with k_T-smearing and in color dipole approach
- We included Cronin peak, shadowing and corrections for energy conservation and isospin correction
- At the RHIC energy
  - Agreement with available data
  - ISI effects cause a strong suppression at large-p_T and lead so to violation of the QCD factorization
    - Indication of ISI for R_{AuAu} for 0-10%
- At the LHC energy
  - $R_{pA/AA}(p_T) \to 1$ at $y = 0$ – in accordance with QCD factorization
  - We predict a strong suppression at forward rapidities and large-p_T that can be verified by the future measurements at LHC

Thanks for your attention.

Backups slides

pQCD factorization - *pp* x-section

- Factorization theorem: separate perturbative and non-perturbative QCD

- Inclusive cross section for prompt photons production

  - $$E\,\frac{d^3\sigma^{pp\to\gamma+X}}{d^3p} = K\sum_{abcd}\int d^2k_{Ta}d^2k_{Tb}dx_a dx_b\, g_p(k_{Ta},Q^2)g_p(k_{Tb},Q^2) \times f_{a/p}(x_a,Q^2)f_{b/p}(x_b,Q^2)\frac{\hat{s}}{z_c^2\pi}\frac{d\hat{\sigma}^{ab\to\gamma d}}{d\hat{t}}\delta(\hat{s}+\hat{t}+\hat{u}),$$

- Distribution of initial transverse momentum $g_N(k_T,Q^2)$ is described by the Gaussian distribution with non-perturbative parameter
  - $\langle k_T^2\rangle_p = \langle k_T^2\rangle_0 + 0.2\,\alpha_S(Q^2)\,Q^2$

    where $\langle k_T^2\rangle_0 = 0.2$ GeV^2 for quarks

    and $\langle k_T^2\rangle_0 = 2.0$ GeV^2 for gluons

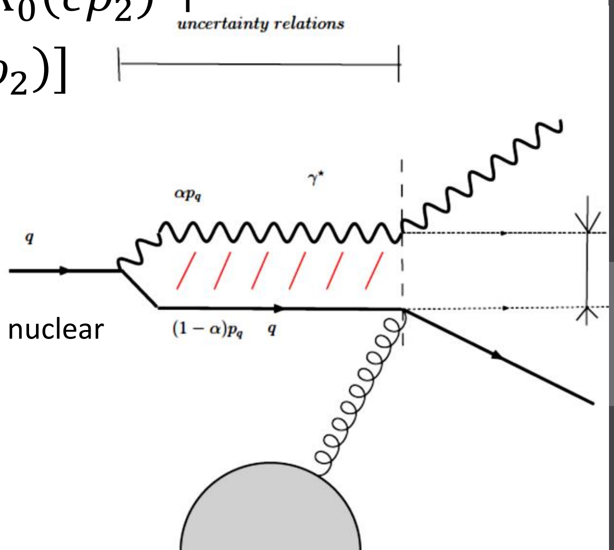
R. P. Feynman, R. D. Field and G. C. Fox, Phys. Rev. D**18**, 3320 (1978)
X.-N. Wang, Phys. Rev. C **61** (2000) 064910

Color dipole approach – *pp* x-section

- Using LC wave functions and dipole cross section from DIS
  - $$\frac{d^2\sigma^{qp\to\gamma+X}}{d\ln\alpha d^2p_T} = \frac{1}{(2\pi)^2}\int d^2\rho_1 d^2\rho_2 e^{i\vec{p}_T(\rho_1-\rho_2)}\Psi_{\gamma q}(\alpha,\rho_1)\Psi^*_{\gamma q}(\alpha,\rho_2)\Sigma(\alpha,\rho_1,\rho_2)$$
    $$\Sigma(\alpha,\rho_1,\rho_2) = \sigma^N_{q\bar{q}}(\alpha\rho_1) + \sigma^N_{q\bar{q}}(\alpha\rho_2) - \sigma^N_{q\bar{q}}(\alpha|\rho_1-\rho_2|)$$
  - $$\frac{d^2\sigma^{pp\to\gamma+X}}{d^2p_T} = \frac{x_1}{x_1+x_2}\int_{x_1}^{1}\frac{d\alpha}{\alpha^2}\sum_q Z_q^2\left(f_{q/p}\left(\frac{x_1}{\alpha},Q^2\right) + f_{\bar{q}/p}\left(\frac{x_1}{\alpha},Q^2\right)\right)\frac{d^2\sigma^{qp\to\gamma+X}}{d\ln\alpha d^2p_T}$$

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

- Dipole cross section $\sigma^N_{q\bar{q}}(\rho,x)$: GBW



B.Kopeliovich, In *Hirschegg 1995, Proceedings, Dynamical properties of hadrons in nuclear matter* 102-112 [arXiv:hep-ph/9609385]
B.Z.Kopeliovich, A.Schaefer and A.V.Tarasov, Phys. Rev. D **62**, 054022 (2000)
H.Kowalski, L. Motyka and G. Watt, Phys. Rev. D **74** (2006)

pQCD factorization – *pA, AA* x-section

- Cross section for *pA* collisions:
  - $E\frac{d^3\sigma^{pA\to\gamma+X}}{d^3p} = \int d^2b\, T_A(\vec{b})\left(E\frac{d^3\sigma^{pp\to\gamma+X}}{d^3p}\right)$
- Cross section for *AA* collisions:
  - $E\frac{d^3\sigma^{AB\to\gamma+X}}{d^3p} = \int d^2b d^2s\, T_A(\vec{b})T_B(\vec{b}-\vec{s})\left(E\frac{d^3\sigma^{pp\to\gamma+X}}{d^3p}\right)$
- Nuclear modification of PDF -> nPDF:
  - $f_{a/A}(x,Q^2) \; = R_{a/A}(x,Q^2)\left[\frac{Z}{A}f_{a/p}(x,Q^2) + \left(1-\frac{Z}{A}\right)f_{a/n}(x,Q^2)\right]$
- Nuclear modification of initial transverse momenta $g_A(k_T,Q^2,b)$:
  - $\langle k_T^2(b)\rangle_A = \langle k_T^2\rangle_N + \Delta k_T^2(b)$
  - $\Delta k_T^2(b) = 2CT_A(b)$

M. B. Johnson, B. Z. Kopeliovich and A. V. Tarasov, Phys. Rev. C**63**, 035203 (2001).

The variable *C* is defined through color dipole cross section (GBW) as:

- $C = \left.\frac{d\sigma_{q\bar{q}}^N}{dr^2}\right|_{r^2=0}$

Color dipole approach – *pA, AA* x-section

- For long coherence length:
  - $\sigma^{A}_{q\bar{q}}(\rho,\vec{s}) = \left(1 - \left(1 - \frac{1}{2A}\sigma^{N}_{q\bar{q}}(\rho)T_A(\vec{s})\right)^{A}\right)$
- Cross section for *pA* collisions:
  - $\sigma^{N}_{q\bar{q}}(\rho) \rightarrow \sigma^{A}_{q\bar{q}}(\rho) = 2\int d^2s\sigma^{A}_{q\bar{q}}(\rho,\vec{s})$
- Cross section for *AA* collisions:
  - $\sigma^{N}_{q\bar{q}}(\rho,x) \rightarrow \sigma^{AB}_{q\bar{q}}(\rho,x) = \int d^2b d^2s\big(\sigma^{A}_{q\bar{q}}(\rho,\vec{s})T_B\big(\vec{b}-\vec{s}\big) +$

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

Initial State Interactions (ISI)

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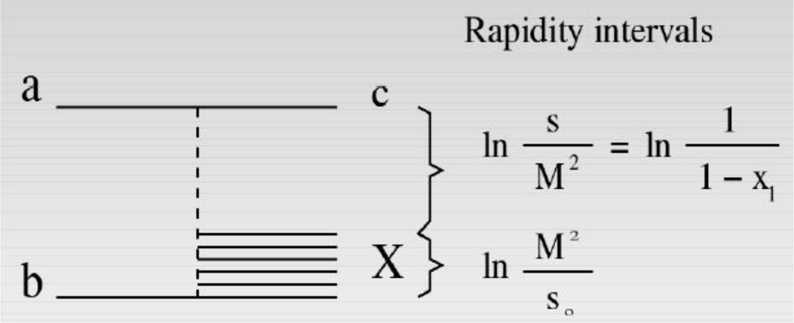
- We propose mechanism based on the energy sharing problem at large-p_T induced by multiple initial state interactions
- One can interpret the suppression as a survival probability of the LRG in multiple interactions inside the nucleus
- Considering LRG process $a + b \to c + X$ for $x \to 1$, probability 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 $S(\Delta y) = e^{-\langle n_G(\Delta y) \rangle}$ where the mean number of gluons is $\langle n_G(\Delta y) \rangle = \Delta y \frac{dn_G}{dy}$
- 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, Bertsch, Phys.Rev. D**25**, 746 (1982)

Initial State Interactions (ISI)

- The probability of an n-fold inelastic collision is related to the Glauber coefficients via AGK cutting rules
- Implementation as the modification of the PDF

$$f_{a/p}^{(A)}(x, Q^2, b) = C_v f_{a/p}(x, Q^2) \frac{e^{-\xi \sigma_{eff} T_A(b)} - e^{-\sigma_{eff} T_A(b)}}{(1-\xi)\left(1 - e^{-\sigma_{eff} T_A(b)}\right)},$$

B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, M.B. Johnson and I. Schmidt, Phys.Rev.C **72** (2005) 054606

  - where $\xi = \sqrt{x_F^2 + x_T^2}$, $\sigma_{eff} = 20$ mb, C_v is fixed by the Gottfried sum rule
- Structure function depends on the target → breakdown of the QCD factorization