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Nuclear effects of high-p_T hadrons in pA interactions

Michal Krelina

Czech Technical University in Prague, FNSPE, Prague, Czech Republic

High Energy Physics in the LHC Era, Valparaíso, Chile

Outline

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  - Nuclear effects in *pA* collisions
- Calculation of the hadron production
  - QCD improved parton model
  - Cross section for *pp* collisions
  - Cross section for *pA* collisions
  - Nuclear broadening
  - ISI effect
- Numerical Results
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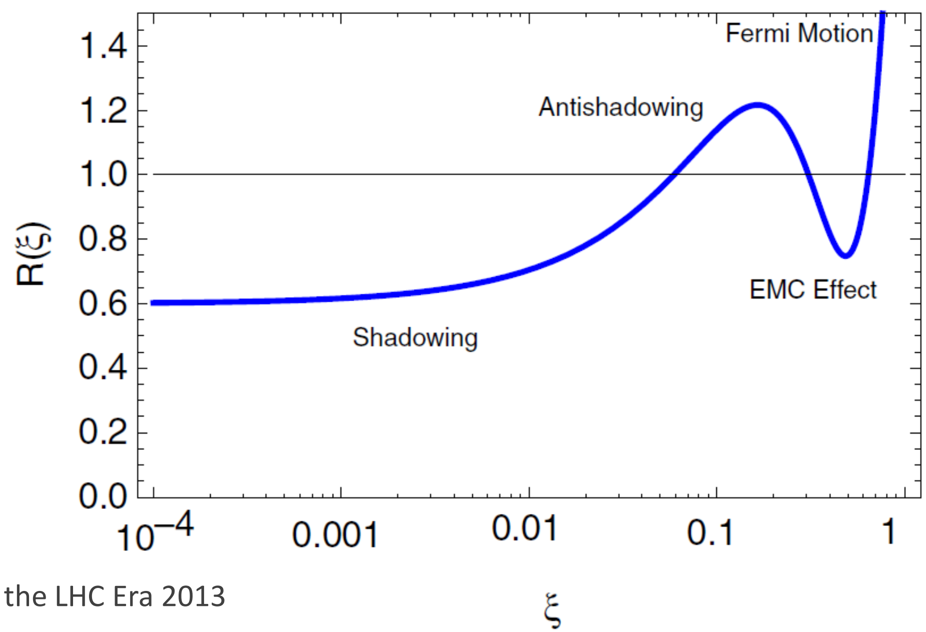
  - *pA* collisions
- Conclusions

Introduction & motivation

- Nuclear effects: suppression or enhancement of hadron production in *pA* vs hadron production in *pp*
- We study nuclear effects through the nuclear modification factor of inclusive hadron production
  - $R_{pA}(p_T) = \dfrac{\sigma^{pA\to h+X}(p_T)}{A\,\sigma^{pp\to h+X}(p_T)}$



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Introduction & motivation

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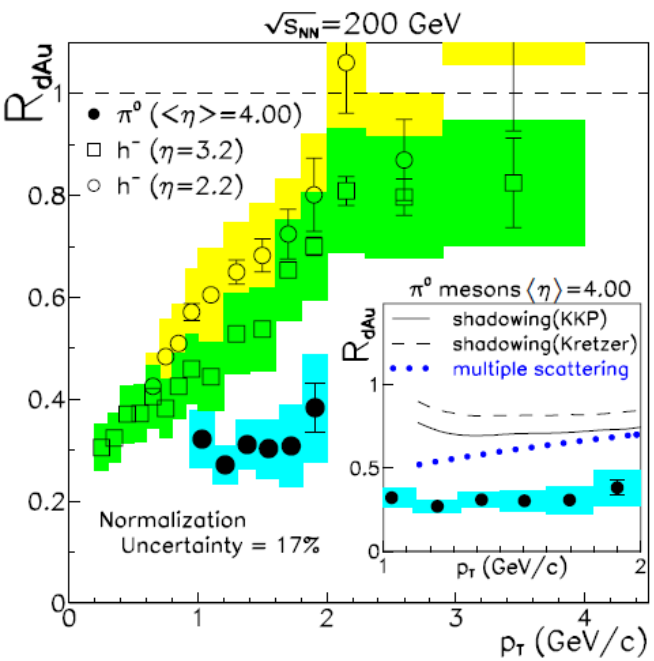
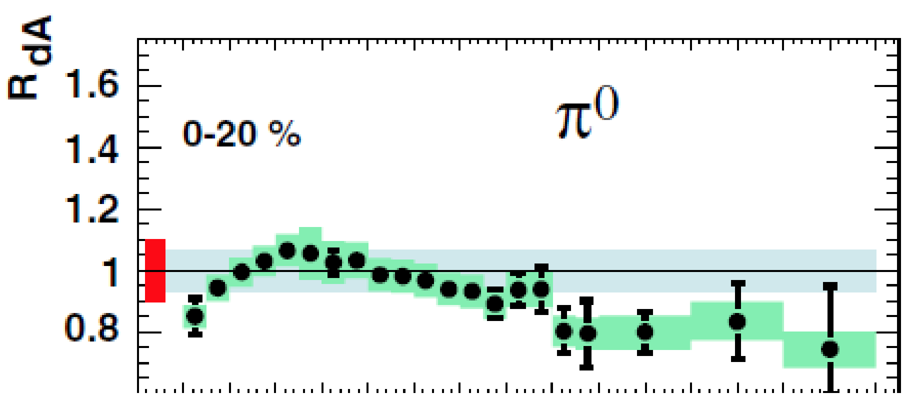
- We focused on three effects:
  - Cronin effect, $R_{pA}(p_T)$>1 at medium-high p_T
  - Suppression at small-p_T - nuclear shadowing
  - Suppression at large-p_T and forward rapidity, indicated by the PHENIX, STAR and BRAHMS





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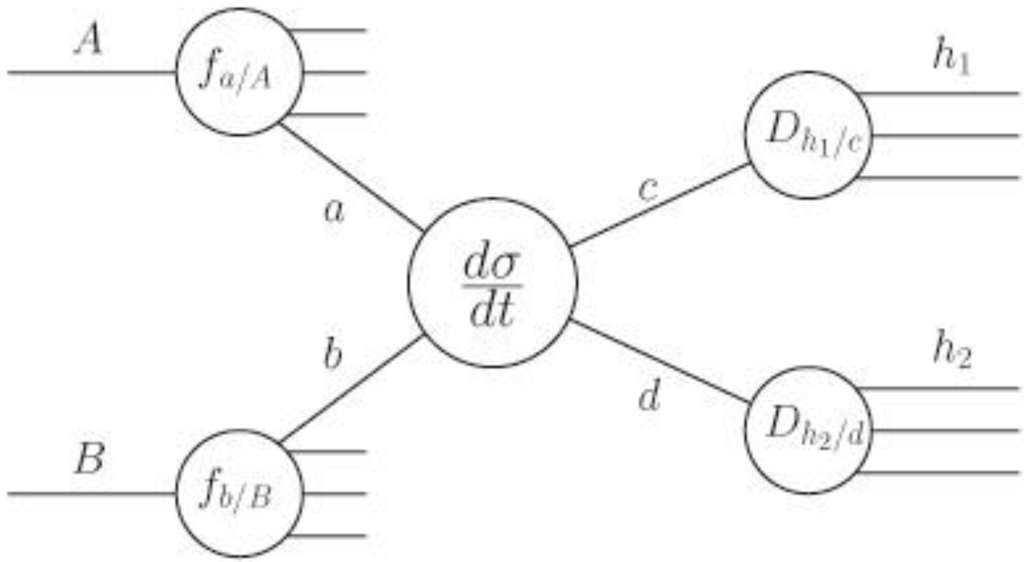
S.S. Adler, et al. (PHENIX Collaboration), Phys.Rev. Lett. **98**, 172302 (2007).
I. Arsene, et al. (BRAHMS Collaboration), Phys.Rev. Lett. **93**, 242303 (2004);
J. Adams, et al. (STAR Collaboration), Phys. Rev. Lett. **97**, 152302 (2006).

QCD improved parton model

- Factorization theorem: separate perturbative and non-perturbative QCD



$$d\sigma^{pp\to h+X} = \sum_{abcd} f_{a/p}(x_a, Q^2) \otimes f_{b/p}(x_b, Q^2) \otimes \hat{\sigma}^{ab\to cd} \otimes D_{h/c}\,(z_c, \mu_F^2)$$

Cross section for *pp* collisions

- We use the QCD improved parton model + initial transverse momentum (k_T-smearing)

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

R. P. Feynman, R. D. Field and G. C. Fox, Phys. Rev. D**18**, 3320 (1978)

where

$f_{i/p}(x_i,Q^2)$ are parton distribution functions (PDF),

$D_{h/c}(z_c,\mu_F^2)$ is fragmentation function (FF),

$g_p(k_{Ta},Q^2)$ are distributions of initial transverse momentum

$d\hat{\sigma}^{ab\to cd}/d\hat{t}$ is partonic cross section

Cross section for *pp* collisions

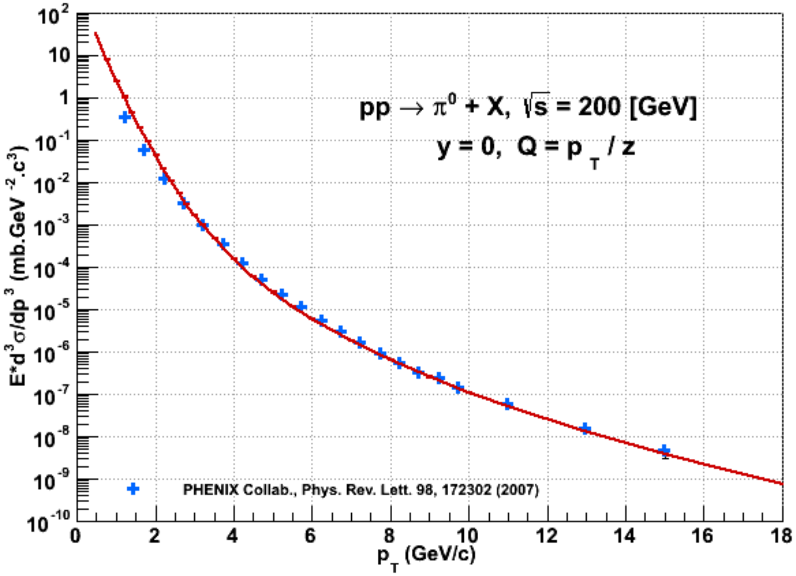
- Distribution of initial transverse momentum is described by the Gaussian distribution
  - $g_N(k_T, Q^2) = \dfrac{e^{-k_T^2/\langle k_T^2\rangle_N}}{\pi\langle k_T^2\rangle_N}$
- with non-perturbative parameter
  - $\langle k_T^2\rangle_p = \langle k_T^2\rangle_0 + 0.2\, \alpha_S(Q^2)\, Q^2$

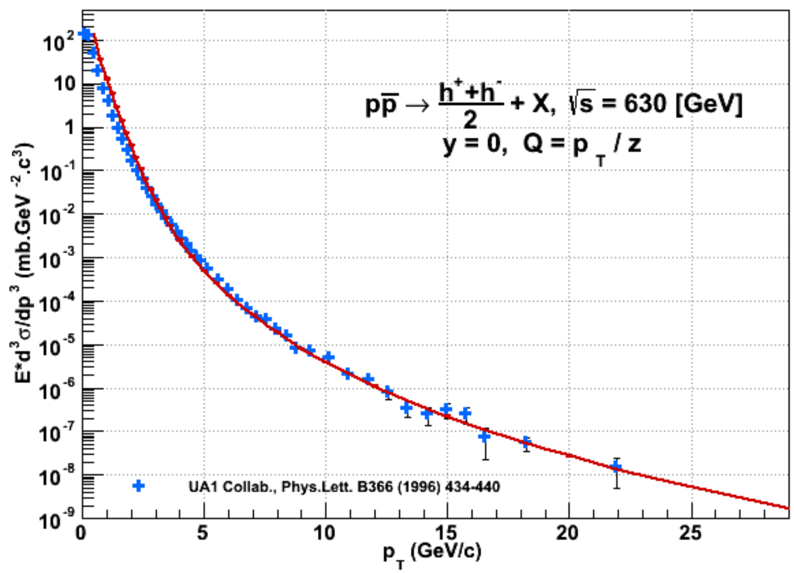
    X.-N. Wang, Phys. Rev.C **61** (2000) 064910
  - where $\langle k_T^2\rangle_0 = 0.2$ GeV^2 for quarks

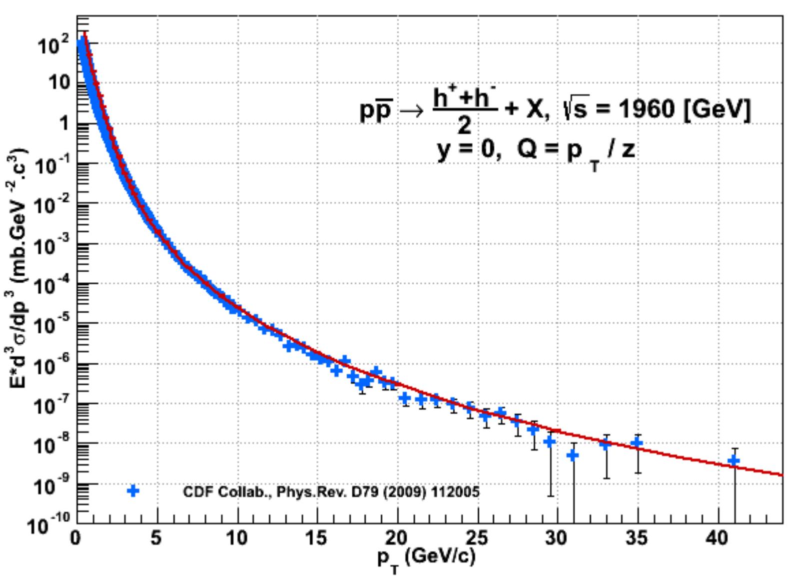
    and $\langle k_T^2\rangle_0 = 2.0$ GeV^2 for gluons

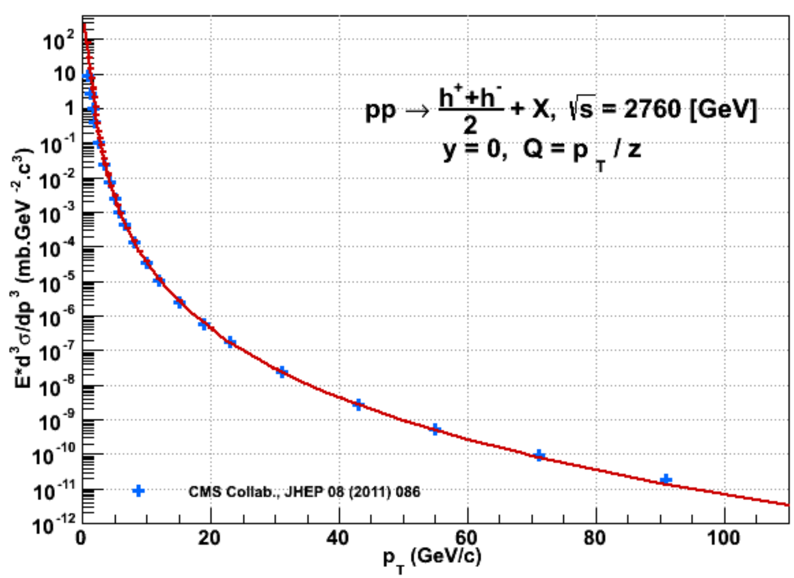
- In all calculations we took the scale $Q^2 = \mu_F^2 = p_T^2/z_c^2$
- The PDF and FF were taken from MSTW2008 and DSS, respectively

Results: *pp* cross section









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Cross section for *pA* collisions

- *pA* cross section is modification of *pp* cross section

$$E\frac{d^3\sigma^{pA\to h+X}}{d^3p} = K\sum_{abcd}\int d^2b\,T_A(b)\int d^2k_{Ta}d^2k_{Tb}dx_a dx_b dz_c\, g_A(k_{Ta},Q^2,b)g_p(k_{Tb},Q^2)$$

$$\times f_{a/p}(x_a,Q^2)f_{b/A}(x_b,Q^2,b)D_{h/c}(z_c,\mu_F^2)\frac{\hat{s}}{z_c^2\pi}\frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}\delta(\hat{s}+\hat{t}+\hat{u}),$$

where

$T_A(b)$ is nuclear thickness function

$f_{b/A}(x,Q^2)$ is nuclear parton distribution function (NPDF)

$$f_{b/A}(x,Q^2) = R_{b/A}(x,Q^2)\left[\frac{Z}{A}f_{b/p}(x,Q^2)+\left(1-\frac{Z}{A}\right)f_{b/n}(x,Q^2)\right]$$

where for $R_{b/A}(x,Q^2)$ we use EPS09 and nDS nuclear modification factor including the nuclear shadowing

Cross section for *pA* collisions

- *Nuclear broadening* represents propagation of the high-energy parton through a nuclear medium that experiences multiple soft scatterings
- Nuclear initial transverse momenta distribution
  - $g_A(k_T, Q^2, b) = \frac{e^{-k_T^2/\langle k_T^2(b)\rangle_A}}{\pi\langle k_T^2\rangle}$

where

  - $\langle k_T^2(b)\rangle_A = \langle k_T^2\rangle_N + \Delta k_T^2(b)$

and

  - $\Delta k_T^2(b) = 2CT_A(b)$

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

The variable *C* is defined as

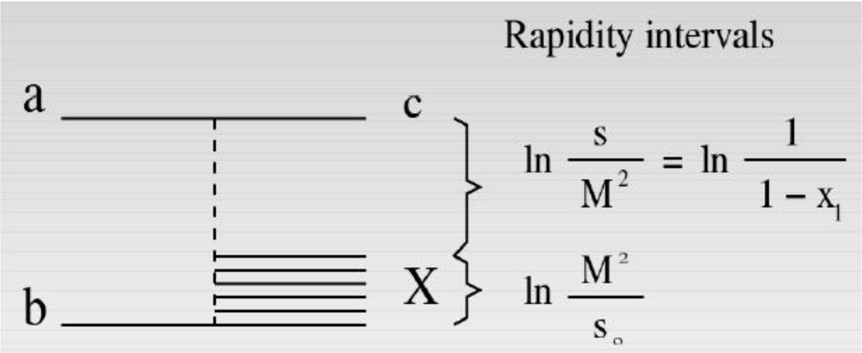
- $C = \left.\frac{d\sigma_{q\bar{q}}^N}{dr^2}\right|_{r^2=0}$

Color dipole cross sections

- We use three parameterizations
- for low c.m. energy:
  - Kopeliovich-Schäfer-Tarasov (KST)
    - B. Z. Kopeliovich, A. Schäfer and A. V. Tarasov,, Phys. Rev. D62 (2000) 054022.
- for high c.m. energy:
  - Golec-Biernat - Wüsthoff (GBW)
    - K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D59, 014017 (1998).
  - Impact-Parameter dependent Saturation Model (IP-Sat)
    - A. H. Rezaeian, at al., Phys. Rev. D87, 034002 (2013).

Initial State Interactions (ISI)

- 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)

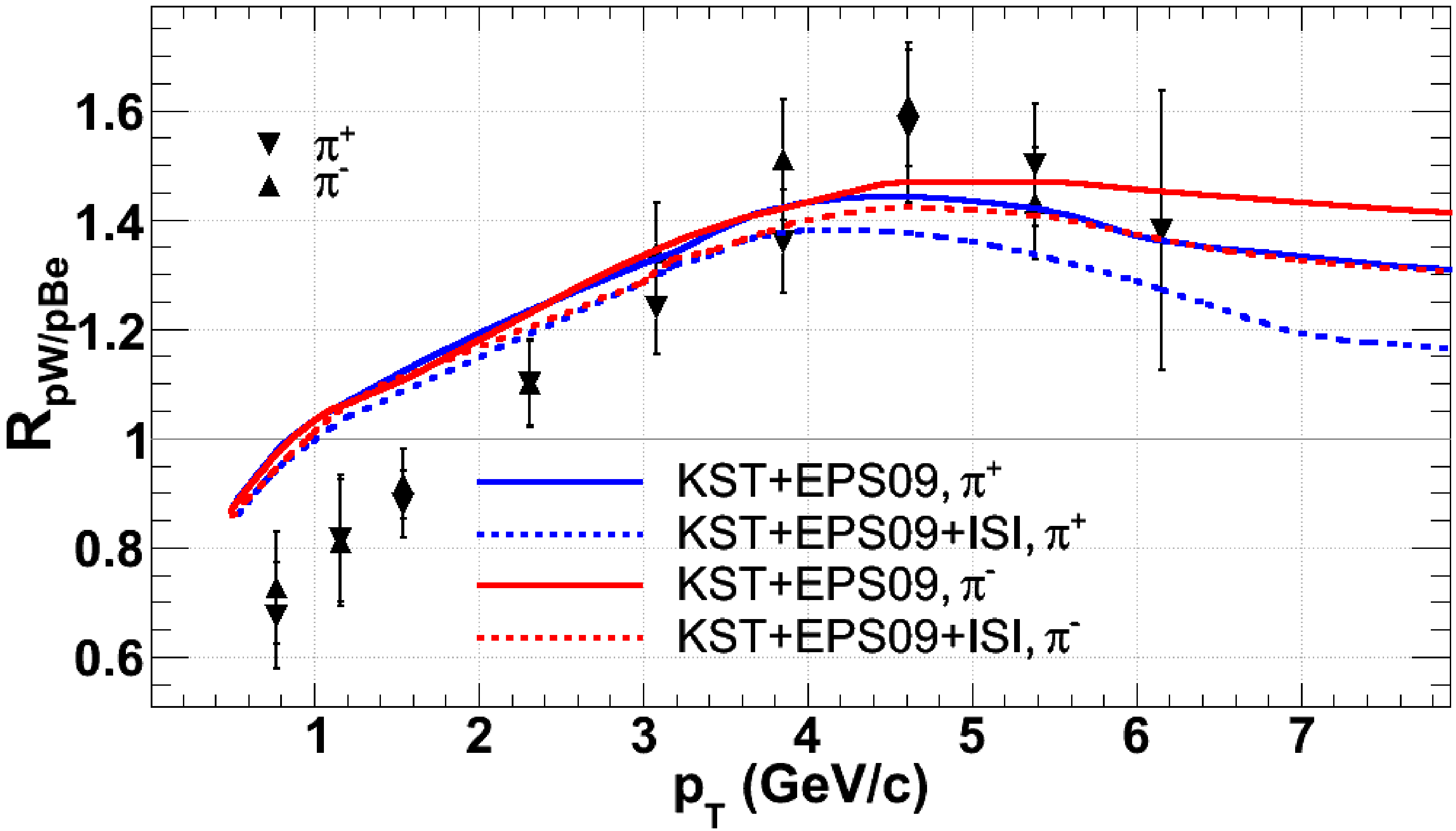
- The probability of an n-fold inelastic collision is related to the Glauber coefficients via AGK cutting rules
- Implementation as the modification of the PDF

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

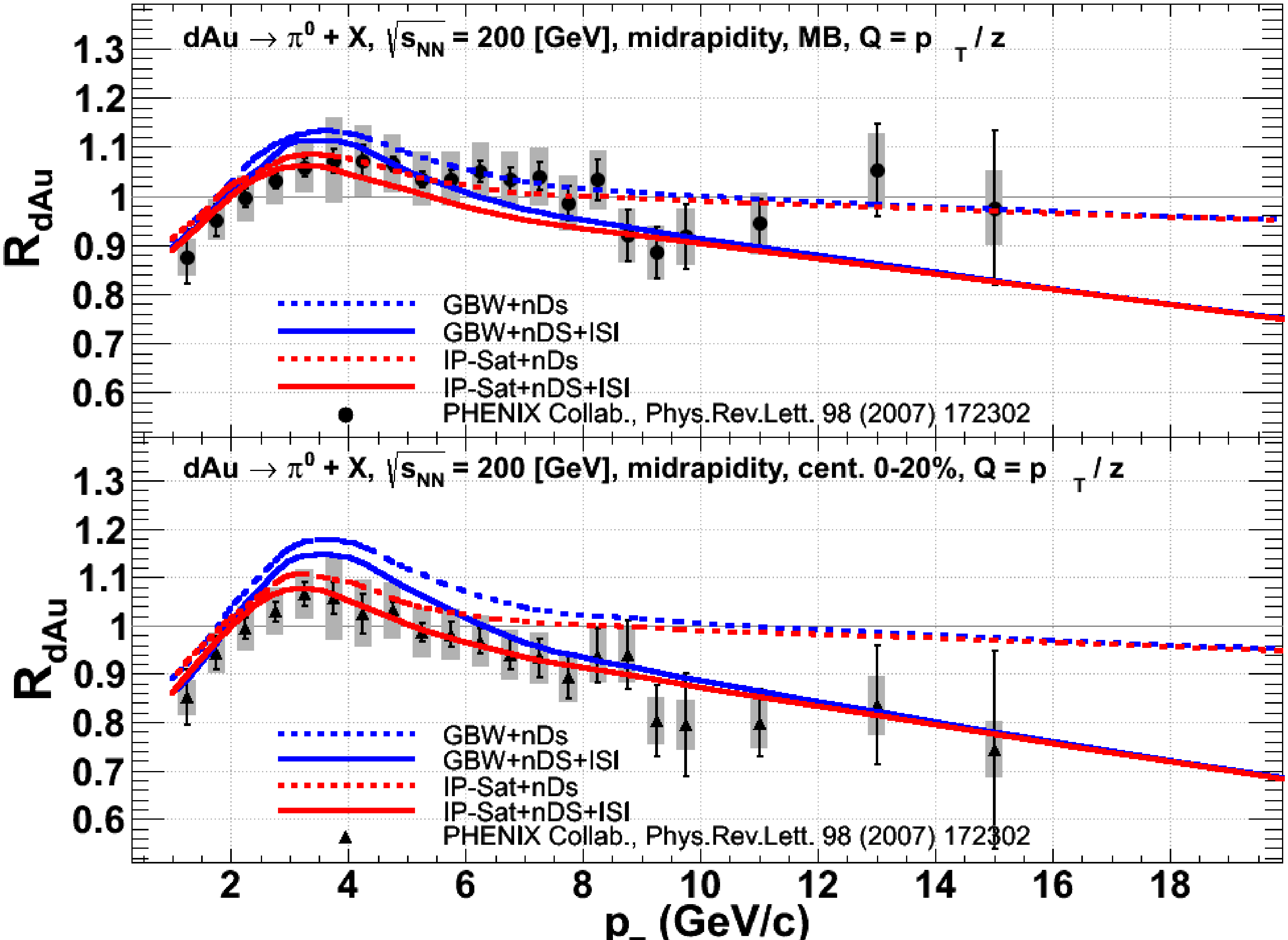
B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, M.B. Johnson and I. Schmidt, Phys.Rev.C **72** (2005) 054606

  - 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

Results: FNAL



Results: RHIC



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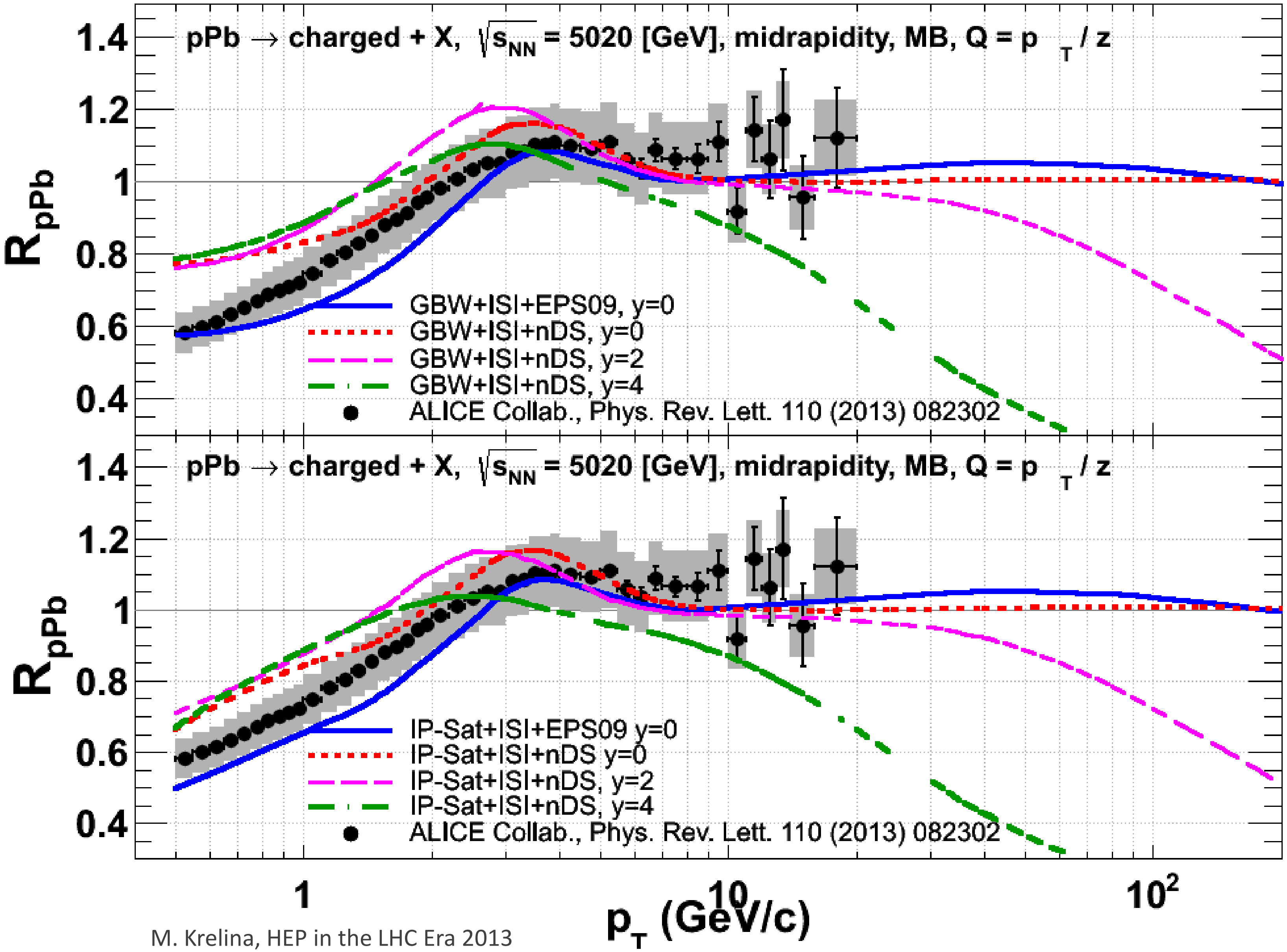
Results: LHC


pPb → charged + X, $\sqrt{s_{NN}}$ = 5020 [GeV], midrapidity, MB, Q = p_T / z
R_{pPb}
GBW+ISI+EPS09, y=0
GBW+ISI+nDS, y=0
GBW+ISI+nDS, y=2
GBW+ISI+nDS, y=4
ALICE Collab., Phys. Rev. Lett. 110 (2013) 082302
pPb → charged + X, $\sqrt{s_{NN}}$ = 5020 [GeV], midrapidity, MB, Q = p_T / z
R_{pPb}
IP-Sat+ISI+EPS09 y=0
IP-Sat+ISI+nDS y=0
IP-Sat+ISI+nDS, y=2
IP-Sat+ISI+nDS, y=4
ALICE Collab., Phys. Rev. Lett. 110 (2013) 082302
p_T (GeV/c)

Conclusions

- Hadron production cross sections were calculated within the QCD improved parton model with k_T-smearing
- We included nuclear broadening evaluated within the color dipole formalism and corrections for energy conservation
- At the FNAL energy
  - Reasonable agreement with data, no effects of shadowing
- At the RHIC energy
  - The magnitude and shape of the Cronin effect is described in accordance with data
  - ISI effects cause a strong suppression at large-p_T and lead so to violation of the QCD factorization
- At the LHC energy
  - The effect of shadowing ~10-30% dominates at small and medium p_T
  - $R_{pA}(p_T) \to 1$ 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 measurements at LHC

Thanks for your attention.