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# *Nuclear effects in p-A interactions*

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# Outline

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  - Nuclear effects in *pA* collisions
- Calculation of the hadron production
  - QCD improved parton model
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  - Cross section for *pA* collisions
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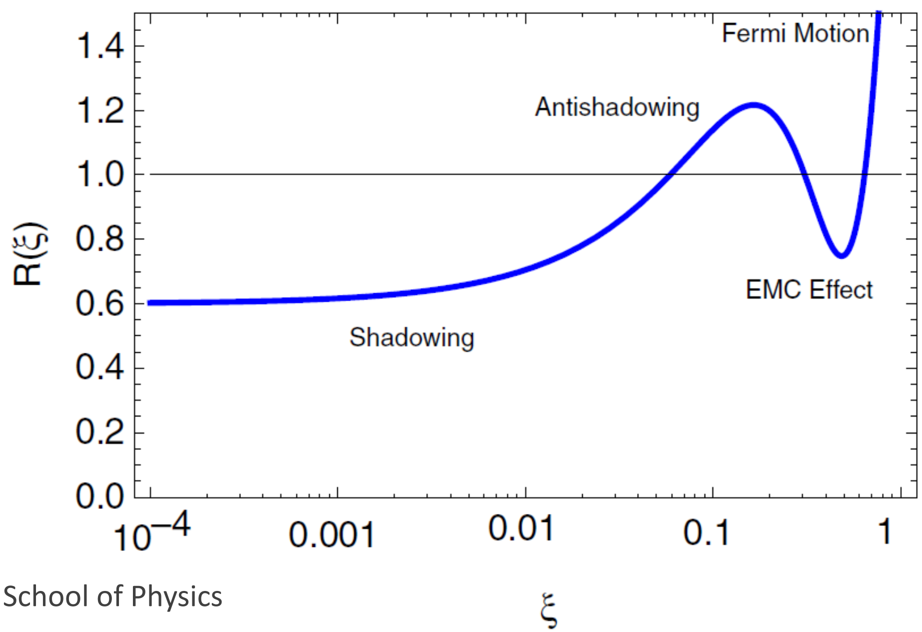
- Conclusions

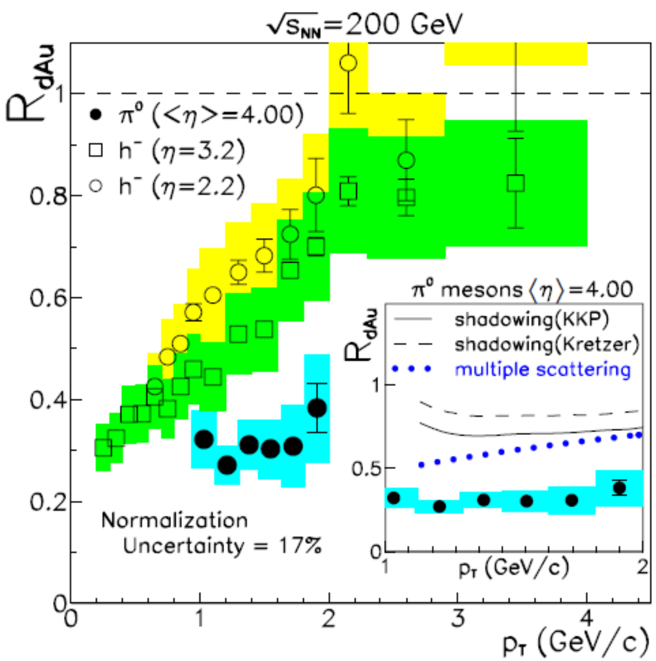
# Introduction & motivation

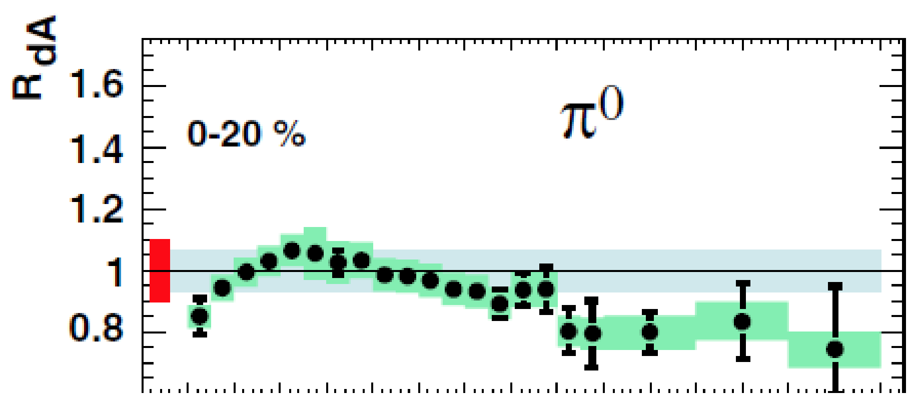
- Nuclear effects: suppression or enhancement of hadron production in *pA* vs hadron production in *pp*
- We study nuclear effects through the nuclear modification factor of inclusive hadron production
  - $R_{pA}(p_T) = \frac{\sigma^{pA \to h+X}(p_T)}{A\, \sigma^{pp \to h+X}(p_T)}$



# Introduction & motivation

- 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

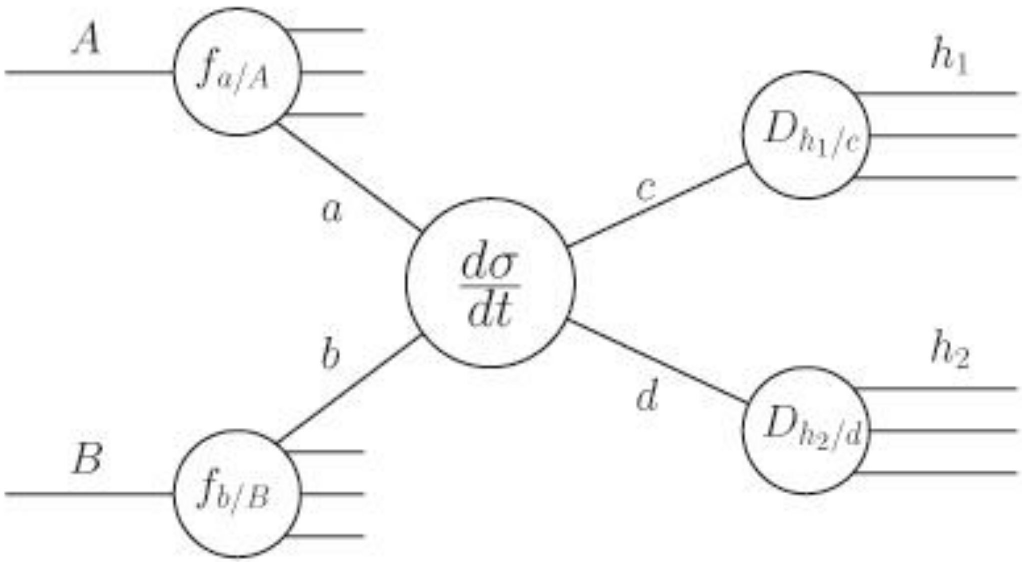



S.S. Adler, et al. (PHENIX Collaboration), Phys.Rev. Lett. **98**, 172302 (2007).
I. Arsene, et al. (BRAHMS Collaboration), Phys.Rev. Lett. **93**, 242303 (2004);
J. Adams, et al. (STAR Collaboration), Phys. Rev. Lett. **97**, 152302 (2006).

# 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)

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

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

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

$x_{Ri}^2 = x_i^2 + 4k_{Ti}^2/s$ is radial variable R. P. Feynman, R. D. Field and G. C. Fox, Phys. Rev. D18, 3320 (1978)

# Cross section for *pp* collisions

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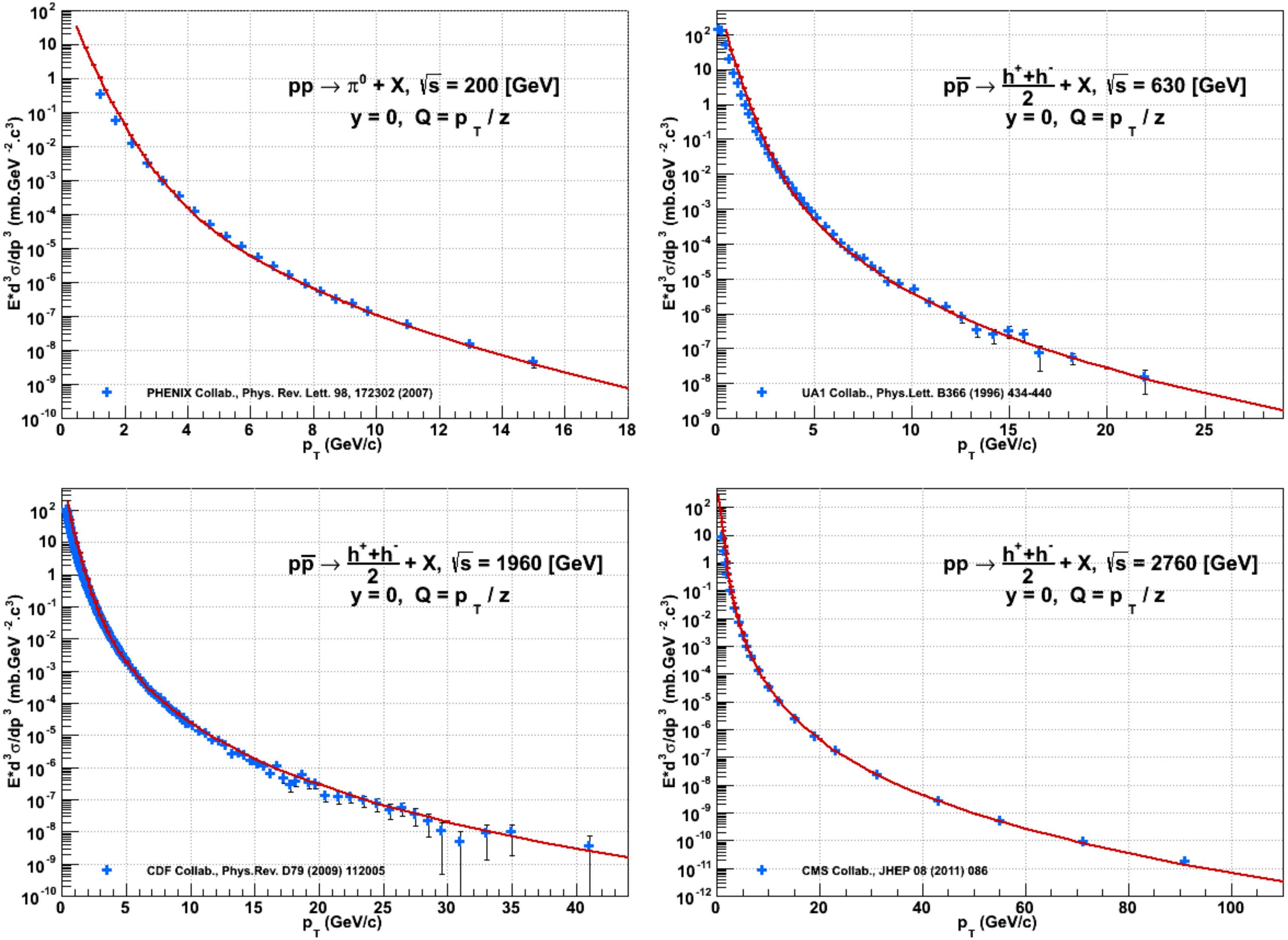
- Distribution of initial transverse momentum is described by the Gaussian distribution
  - $g_N(k_T, Q^2) = \dfrac{e^{-k_T^2/\langle k_T^2\rangle_N}}{\pi\langle k_T^2\rangle_N}$
- with non-perturbative parameter
  - $\langle k_T^2\rangle_p = \langle k_T^2\rangle_0 + 0.2\,\alpha_S(Q^2)\,Q^2$

    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



# Cross section for *pA* collisions

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

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

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

where

$T_A(b)$ is nuclear thickness function

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

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

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
  - $g_A(k_T, Q^2, b) = \dfrac{e^{-k_T^2/\langle k_T^2(b)\rangle_A}}{\pi\langle k_T^2\rangle}$

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

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

# 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)

- Initial State Interactions for $\xi \to 1$, where $\xi = \sqrt{x_F^2 + x_T^2}$, with $x_F = 2p_L/\sqrt{s}$ and $x_T = 2p_T/\sqrt{s}$, can be treated as a large rapidity gap (LRG) process where no particle is produced within rapidity interval $\Delta\mathrm{y} = -\ln(1-\xi)$
- The suppression factor as a survival probability for LRG was evaluated as $S(\xi) \approx 1 - \xi$
- Modification of the PDF

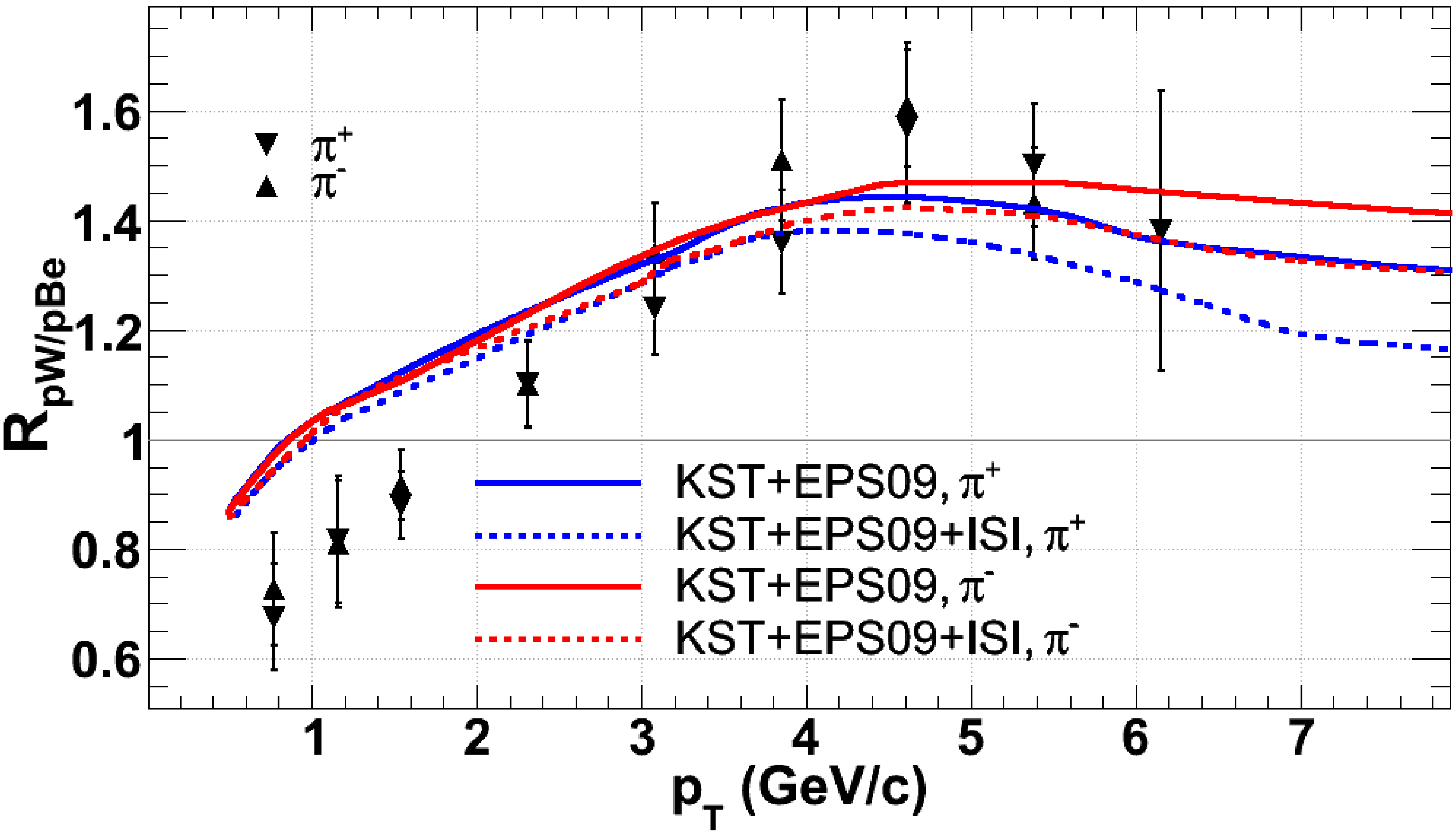
$$f_{a/p}^{(A)}(x, Q^2, b) = C_v f_{a/p}(x, Q^2) \frac{e^{-\xi\sigma_{eff}T_A(b)} - e^{-\sigma_{eff}T_A(b)}}{(1-\xi)\left(1-e^{-\sigma_{eff}T_A(b)}\right)},$$

where

- $\sigma_{eff} = 20$ mb, $C_v$ is fixed by the Gottfried sum rule

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

# Results: FNAL



# Results: RHIC

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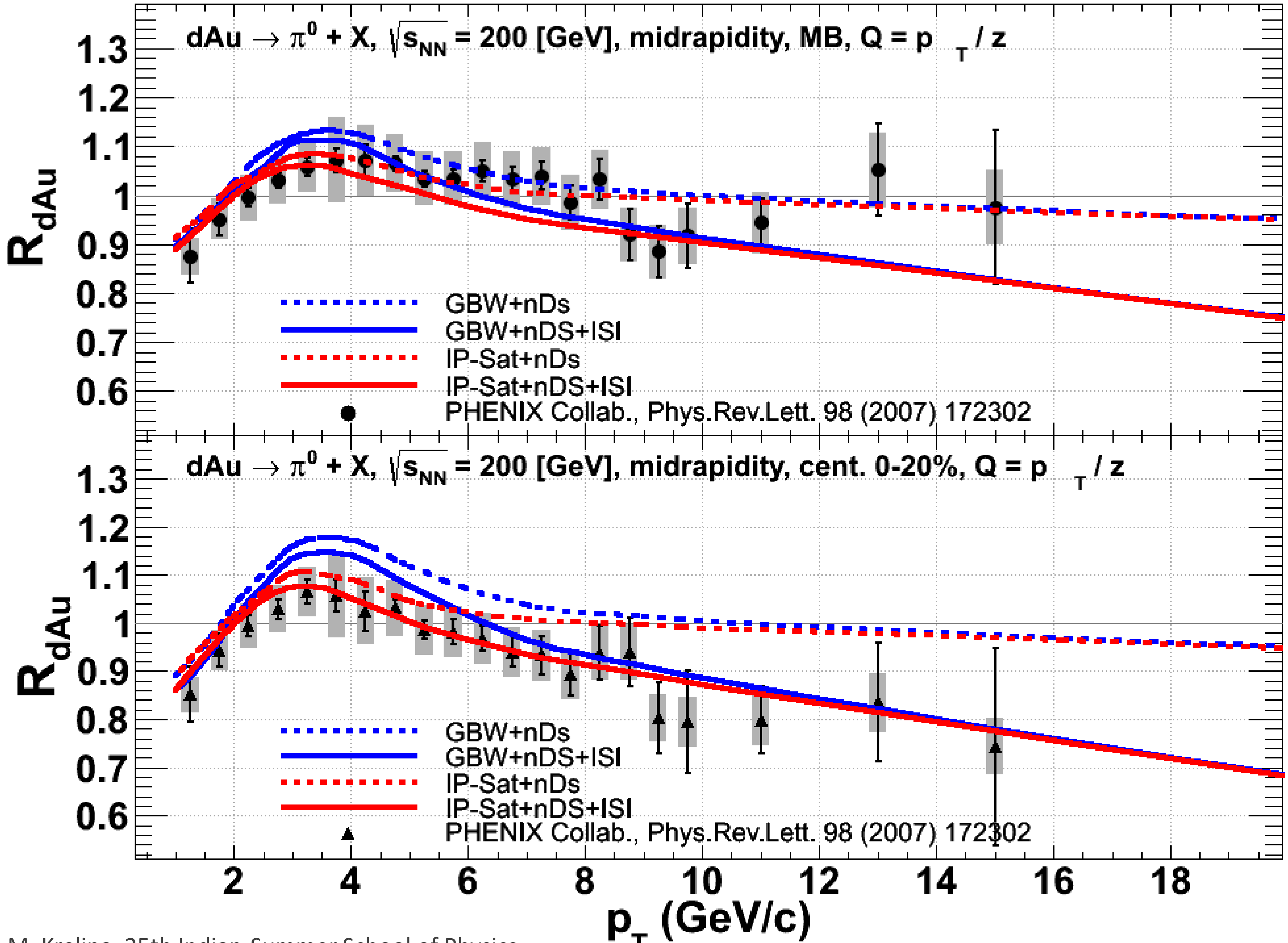
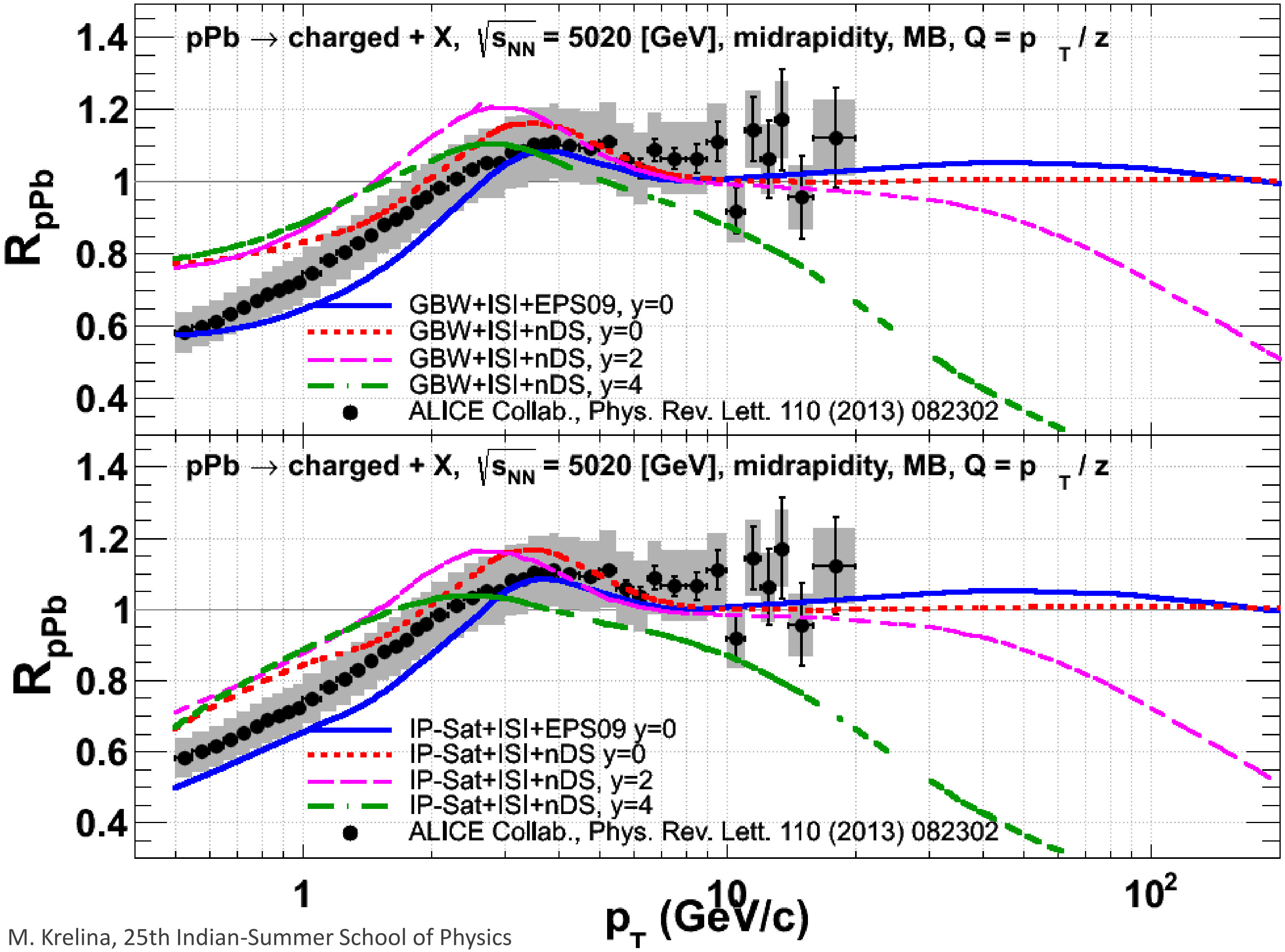


# Results: LHC



pPb → charged + X, $\sqrt{s_{NN}}$ = 5020 [GeV], midrapidity, MB, Q = $p_T$ / z
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
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
$R_{pPb}$
$p_T$ (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.