FACULTY OF NUCLEAR SCIENCES AND PHYSICAL ENGINEERING CTU IN PRAGUE

Study of Drell-Yan pair production on nuclear targets

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Outline

- **Introduction**
  - Motivation
  - Coherence length
  - Initial state interaction effects
- **Color dipole approach**
  - Basics
  - Green function method
  - Gluon shadowing
- **Results**
  - Fixed-target experiment
  - AFTER@LHC
  - RHIC
  - LHC (LHCb-gas program)
- **Conclusions**

Motivation

Motivation

- **Goal:**
  - Study initial-state effects (cold nuclear matter effects)
- **Tools:**
  - Drell-Yan (DY) process
    - No final-state interactions and fragmentation (no absorption or energy loss)
    - Variety of dilepton invariant masses $M_{l\bar{l}}$
- **Observable:**
  - Nuclear modification factor $$R_{pA} = \frac{\sigma^{pA}}{A \cdot \sigma^{pp}}$$
    - As a function of $M_{l\bar{l}}$, rapidity η,…
- **Method:**
  - Color dipole approach

Initial-state effects

- What are **initial-state effects**?
  - Effects occurring before the hard scattering

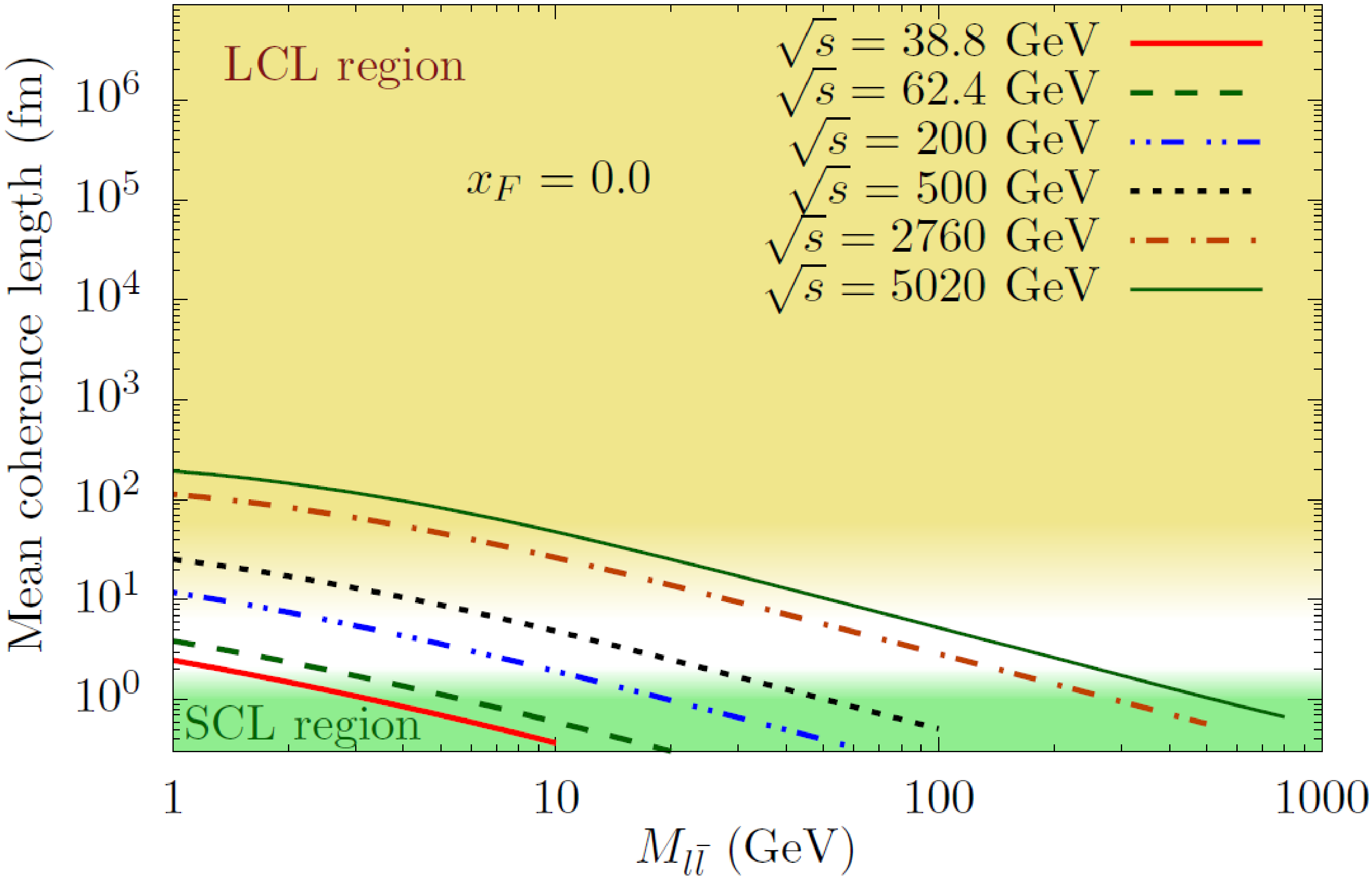
- Type of effects
  - **Coherence effects** (interaction with the nucleus as one object)
    - e.g.: **nuclear shadowing**, CGC
  - **Non-coherence effects** (interactions with inner structure of the nucleus)
    - e.g.: EMC effect, **initial state interactions effects**

Coherence length

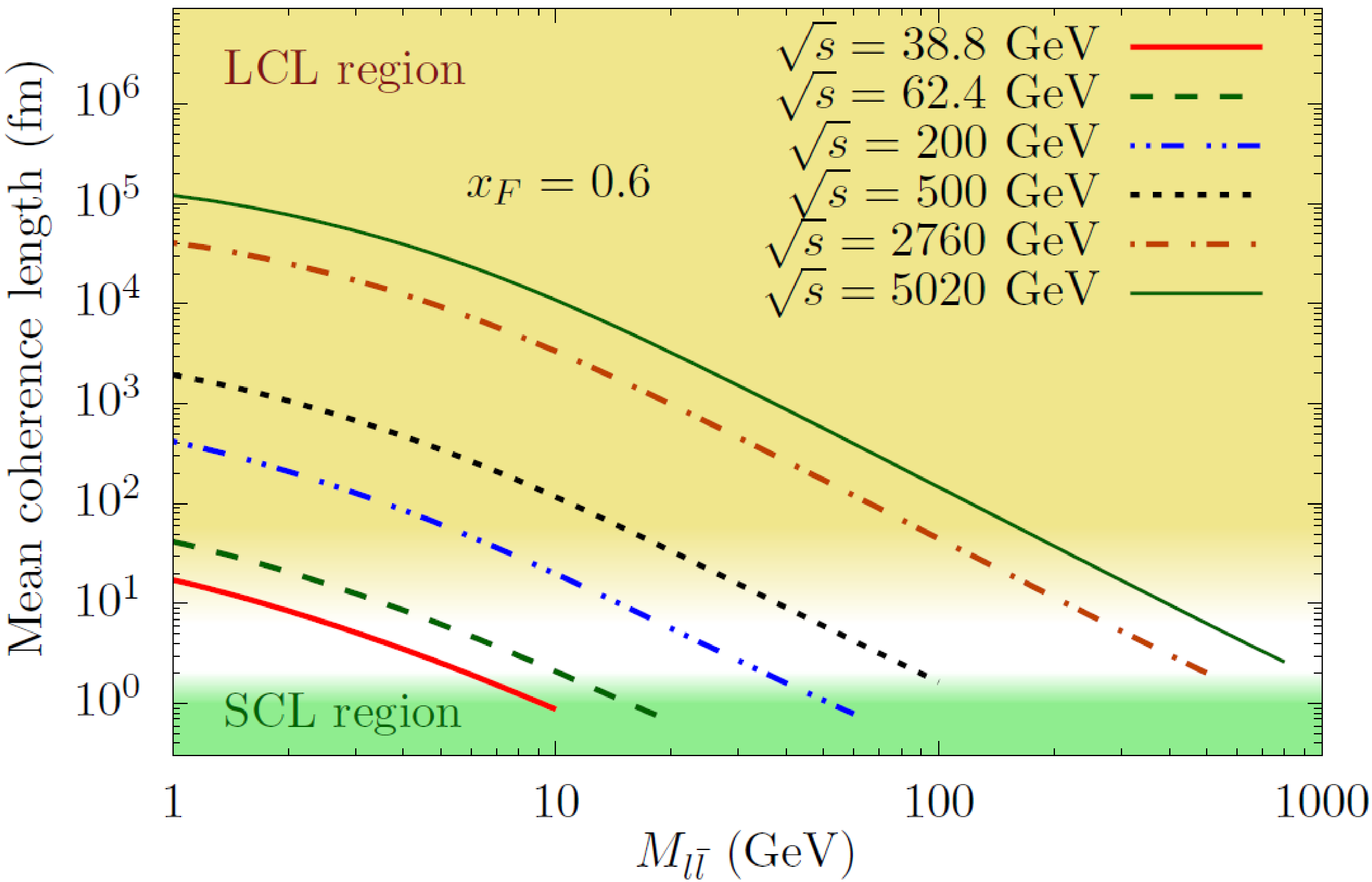
- The dynamics of coherence effects is controlled by the *coherence length (CL)*
  - coherence length = lifetime of $\gamma^* q$ fluctuation within the color dipole approach
- **Drell-Yan CL**
  - $$l_c = \frac{1}{x_2 m_N} \frac{(M_{l\bar{l}}^2 + p_T^2)(1-\alpha)}{(1-\alpha)M_{l\bar{l}}^2 + \alpha^2 m_N^2 + p_T^2}$$
- Coherence length
  - $l_c \gg R_A$ **, long coherence length (LCL)** limit
    - Nuclear shadowing is maximal
  - $l_c < 1 \div 2$ fm **, short coherence length (SCL)** limit
    - No nuclear shadowing

Mean CL – $x_F = 0.0$

$x_F = x_1 - x_2$, $x_F = 0$ corresponds to mid-rapidity



Mean CL – $x_F = 0.6$



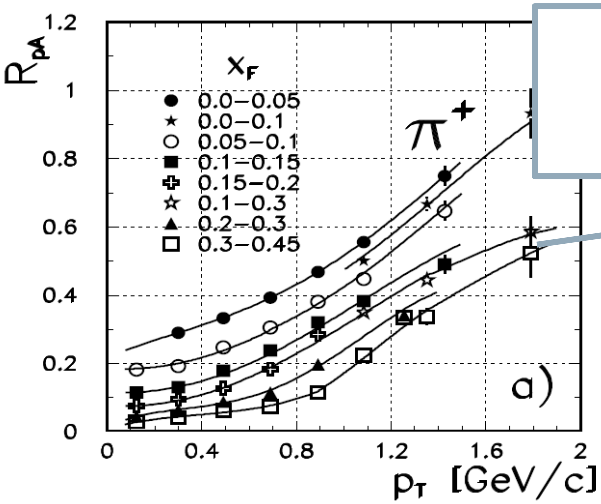
LCL region
SCL region
$x_F = 0.6$
$\sqrt{s} = 38.8$ GeV
$\sqrt{s} = 62.4$ GeV
$\sqrt{s} = 200$ GeV
$\sqrt{s} = 500$ GeV
$\sqrt{s} = 2760$ GeV
$\sqrt{s} = 5020$ GeV
Mean coherence length (fm)
10^0 10^1 10^2 10^3 10^4 10^5 10^6
1 10 100 1000
$M_{l\bar{l}}$ (GeV)

Coherence length

- What about the *white* area between the LCL and SCL regions?
  - Generalized path-integral (Green function) formulation should be used
  - This formulation **includes also SCL and LCL**
- **Usage and prospects**
  - Experiments: FNAL fixed-target experiments, AFTER@LHC, LHCb-gas program, RHIC, …
  - Calculation of gluon shadowing
  - Incorporation of absorption in the medium
    - Important for heavy-ion collisions and strongly interacting probes

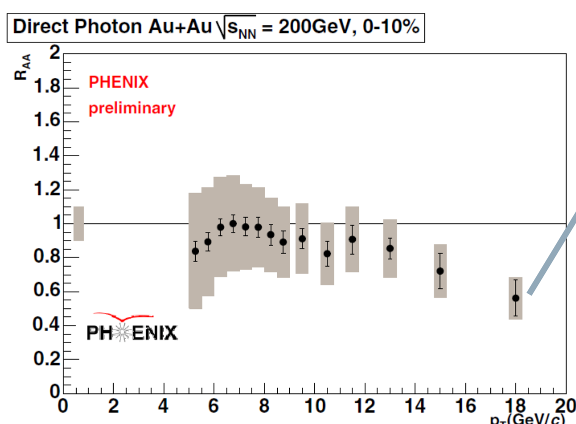
Initial state interactions effects

- ISI effects – type of **effective energy loss**
- Lead to the suppression of cross section
  - Dominates for $x_L = \frac{2p_L}{\sqrt{s}} \to 1$ and/or $x_T = \frac{2p_T}{\sqrt{s}} \to 1$
  - B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, I. Schmidt, Int. J. Mod. Phys. E23, 1430006 (2014)
- ISI effects **explain the nuclear suppression**
  - At high p_T particle production at RHIC
  - At forward rapidities at RHIC and fixed-target experiments
  - … where the coherence effects are not allowed



NA49, *pPb*,
E_{LAB} = 158 AGeV
$l_c < R_A$ (5.5 fm)

PHENIX, *dAu*,
$\sqrt{s_{NN}}$ = 200 GeV
$l_c < R_A$ (5.3 fm)

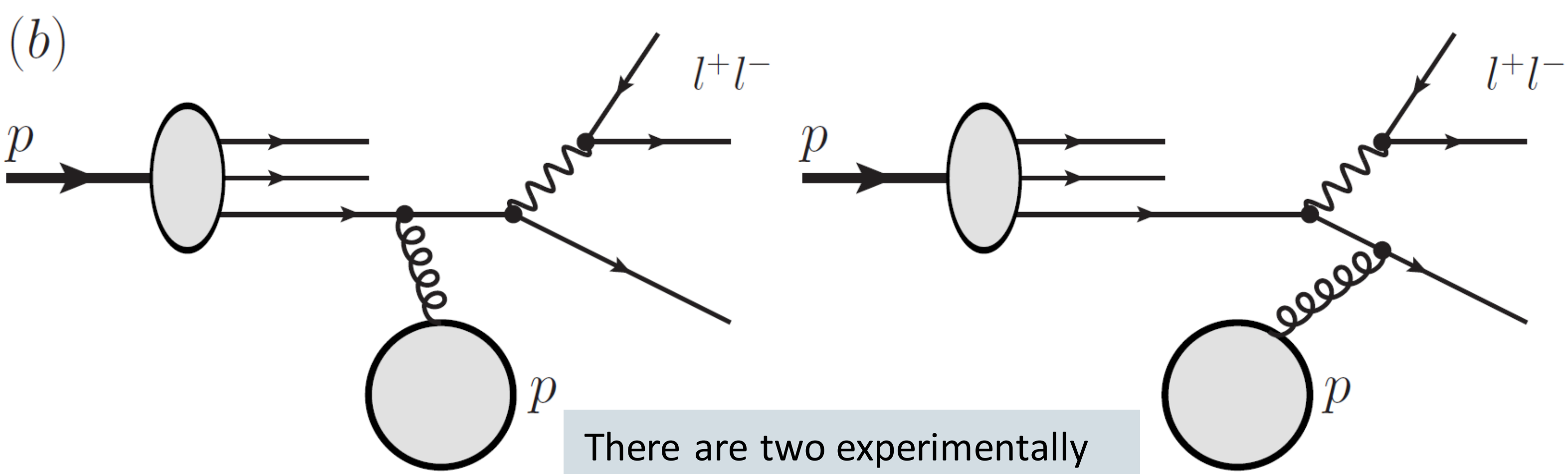


NA49 Collaboration, B. Boimska, Ph.D. Thesis (Warsaw 2004), CERN-THESIS-2004-035.
T. Sakaguchi (PHENIX Collab.) Nucl. Phys. A 805, 355 (2008).

Color dipole approach

Color dipole approach (CDA)

- Formulated in the target rest frame
- Drell-Yan process looks like $\boldsymbol{\gamma^*}$-**Bremsstrahlung** off a projectile quark
- Cross section = **convolution** of PDFs, light-cone wave function (of the lowest Fock state $|q\gamma^*\rangle$) and dipole cross section



There are two experimentally undistinguishable contributing diagrams.

Color dipole approach (CDA)

- Dipole cross section
  - Extracted from DIS, more parametrizations on the market
  - The weakest part of CDA
  - GBW - K.J. Golec-Biernat, M. Wusthoff, Phys. Rev. D59, 014017 (1998)
  - BGBK (DGLAP evolution) - J. Bartels, K. Golec-Biernat, and H. Kowalski, Phys. Rev. D66, 014001 (2002)
  - rcBK (BK evolution) - J.L. Albacete, N. Armesto, J.G. Milhano and C.A. Salgado, Phys. Rev. D80, 034031 (2009)

- pp cross section
  - $\frac{d^2\sigma^{(pp\to llX)}}{dM^2 dx_F} = \frac{d\sigma^{(\gamma^*\to ll)}}{dM^2}\frac{x_1}{x_1+x_2}\int_{x_1}^{1}\frac{d\alpha}{\alpha^2}\sum_q\left(f_q\left(\frac{x_1}{\alpha}\right)+f_{\bar{q}}\left(\frac{x_1}{\alpha}\right)\right)\frac{d\sigma^{(qN\to\gamma^* X)}}{d\ln\alpha}$
  - $\frac{d\sigma^{(qN\to\gamma^* X)}}{d\ln\alpha} = \int d^2\rho\left|\Psi_{\gamma^* q}(\alpha,\vec{\rho},M^2)\right|^2\sigma_{q\bar{q}}^{N}(\alpha\vec{\rho},x)$

- Advantages of CDA
  - Parametrizations from DIS only (no nPDF, …)
  - No K factor
  - No limitation by pQCD

Proton-nucleus collisions

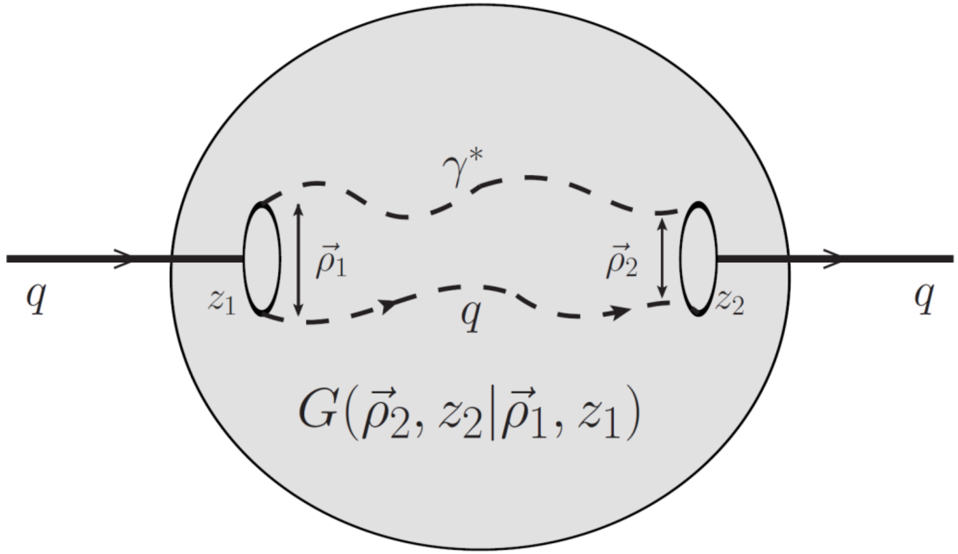
- Well-known formulas for LCL, SCL
- General expression

$$\frac{d\sigma^{(qA\to\gamma^* X)}}{d\ln\alpha} = \mathrm{A}\frac{d\sigma^{(qN\to\gamma^* X)}}{d\ln\alpha}$$
$$-\frac{1}{2}Re\int_{-\infty}^{\infty}dz_1\int_{z_1}^{\infty}dz_2\int d^2b\,d^2\rho_1 d^2\rho_2$$
$$\times\,\Psi^*_{\gamma q}(\alpha,\vec{\rho}_2)\rho_A(b,z_2)\sigma^N_{q\bar{q}}(\alpha\rho_2)\ G(\vec{\rho}_2,z_2|\vec{\rho}_1,z_1)$$
$$\times\,\rho_A(b,z_1)\sigma^N_{q\bar{q}}(\alpha\rho_1)\Psi_{\gamma q}(\alpha,\vec{\rho}_1)$$

  - b… impact parameter
  - $\rho_A(b,z_1)$… nuclear density
  - B. Z. Kopeliovich, A. V. Tarasov, and A. Schafer, Phys.Rev. C59, 1609 (1999)

- Terms:
  - *First*, *A*-times single scattering cross section
  - *Second*, represents correction term

Green function technique



- $G(\vec{\rho}_2, z_2|\vec{\rho}_1, z_1)$… Green function
  - Describes propagation of a $|\boldsymbol{\gamma}^* \boldsymbol{q}\rangle$ Fock state from longitudinal position $\boldsymbol{z_1}$ to $\boldsymbol{z_2}$ through the nucleus with initial and final separation $\vec{\boldsymbol{\rho}}_{\boldsymbol{1}}$ and $\vec{\boldsymbol{\rho}}_{\boldsymbol{2}}$**,** where $|\boldsymbol{\gamma}^* \boldsymbol{q}\rangle$ interacts with bound nucleons via dipole cross section $\boldsymbol{\sigma}^{\boldsymbol{N}}_{\boldsymbol{q\bar{q}}}(\vec{\boldsymbol{\rho}})$ which depends on the local transverse separation $\vec{\boldsymbol{\rho}}$
  - Treats the **coherence length exactly**

Green function

- Corresponds to the two-dimensional **Schrödinger equation** with potential

$$\left[i\frac{\partial}{\partial z_2}+\frac{\Delta_T(\vec{\rho}_2)-\eta^2}{2E_q\alpha(1-\alpha)}-V(z_2,\vec{\rho}_2,\alpha)\right]G(\vec{\rho}_2,z_2|\vec{\rho}_1,z_1)=0$$

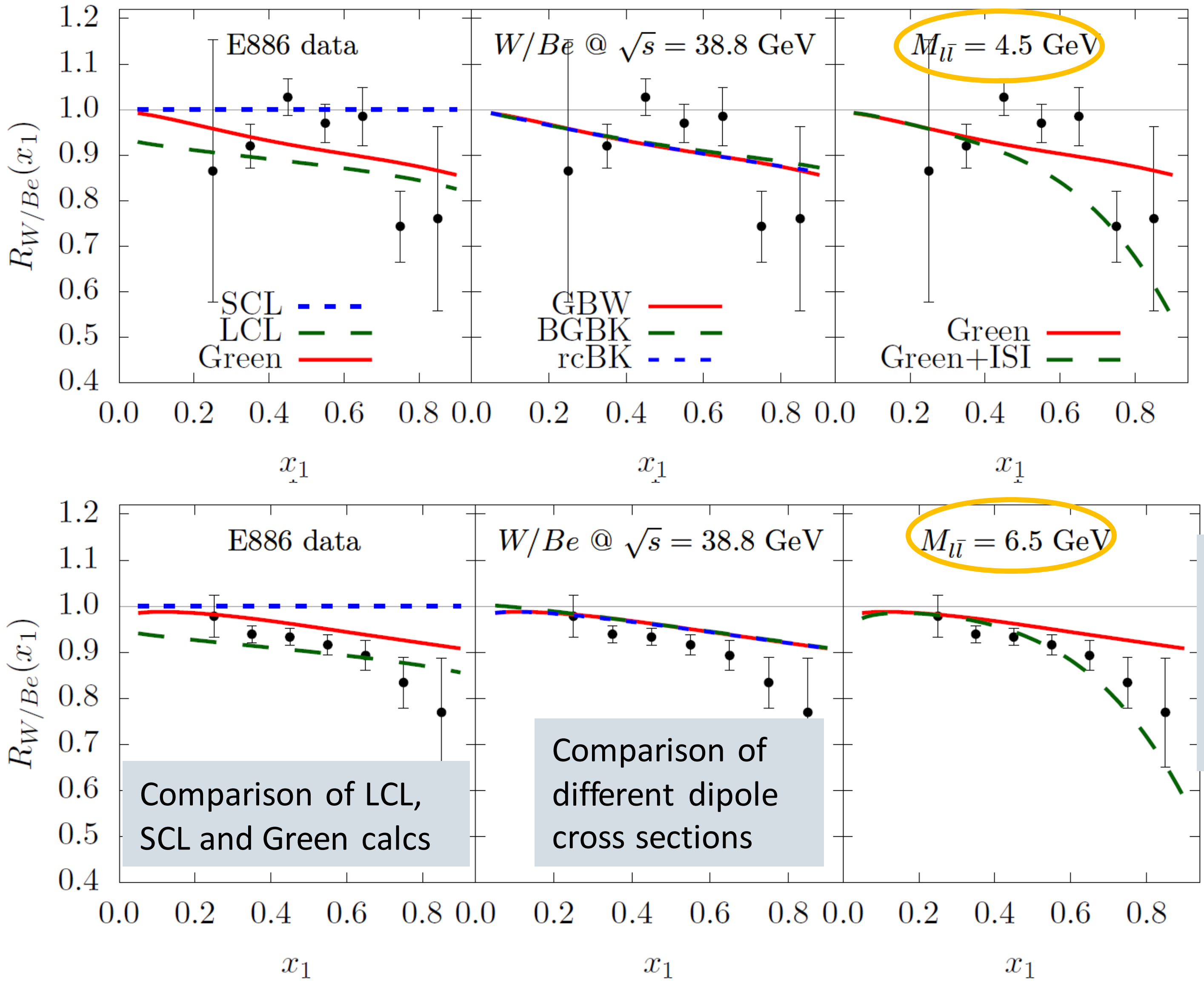
  - z_2… plays a role of the time
  - $\Delta_T(\vec{\rho}_2)$… 2D Laplacian acts on $\vec{\rho}_2$
  - **Boundary condition**:
    - $G(\vec{\rho}_2,z_2|\vec{\rho}_1,z_1)|_{z_1=z_2}=\delta^2(\vec{\rho}_2-\vec{\rho}_1)$
  - **Imaginary potential**
    - $V(z_2,\vec{\rho}_2,\alpha)=-\frac{i}{2}\rho_A(b,z_2)\sigma^N_{q\bar{q}}(\alpha\vec{\rho}_2,x)$

Gluon shadowing (GS)

- We use the lowest Fock component - $|\boldsymbol{\gamma}^{*}\boldsymbol{q}\rangle$
  - Therefore the nuclear CDA formalism contains quark shadowing only
- **Gluon shadowing** dominates at **very small** $\boldsymbol{x_2}$
  - At very high collision energies, e.g. LHC
  - At lower energies in combination with forward rapidities
- GS is calculated externally and implemented as a correction of the dipole cross section
  - Considering $|\boldsymbol{\gamma}^{*}\boldsymbol{qG}\rangle$ Fock state
  - B.Z. Kopeliovich, A. Schaefer, and A.V. Tarasov, Phys. Rev. D62, 054022 (2000)

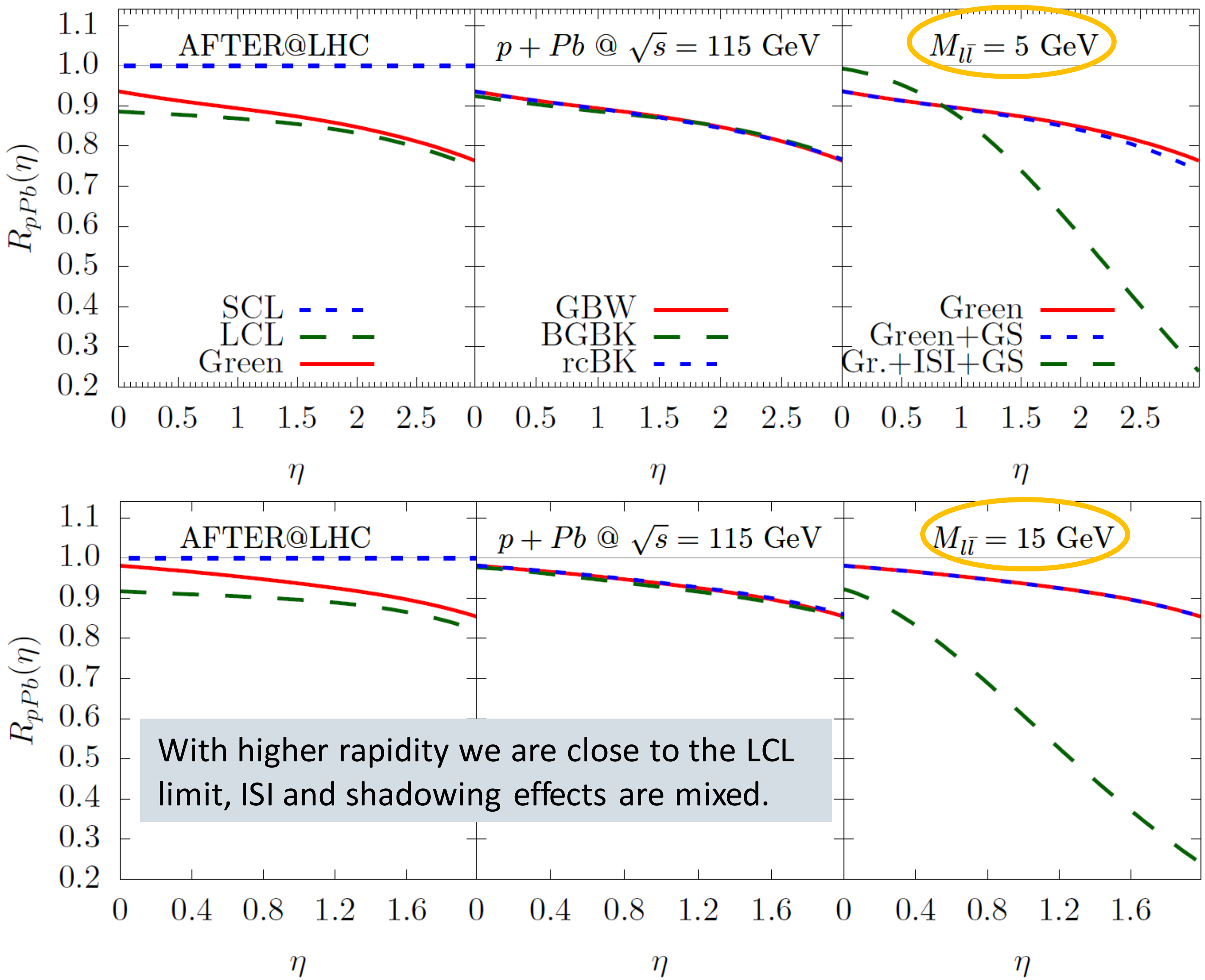
Results

Results: $R_{pA}(x_1)$ – E886, $\sqrt{s} = 38.8$ GeV



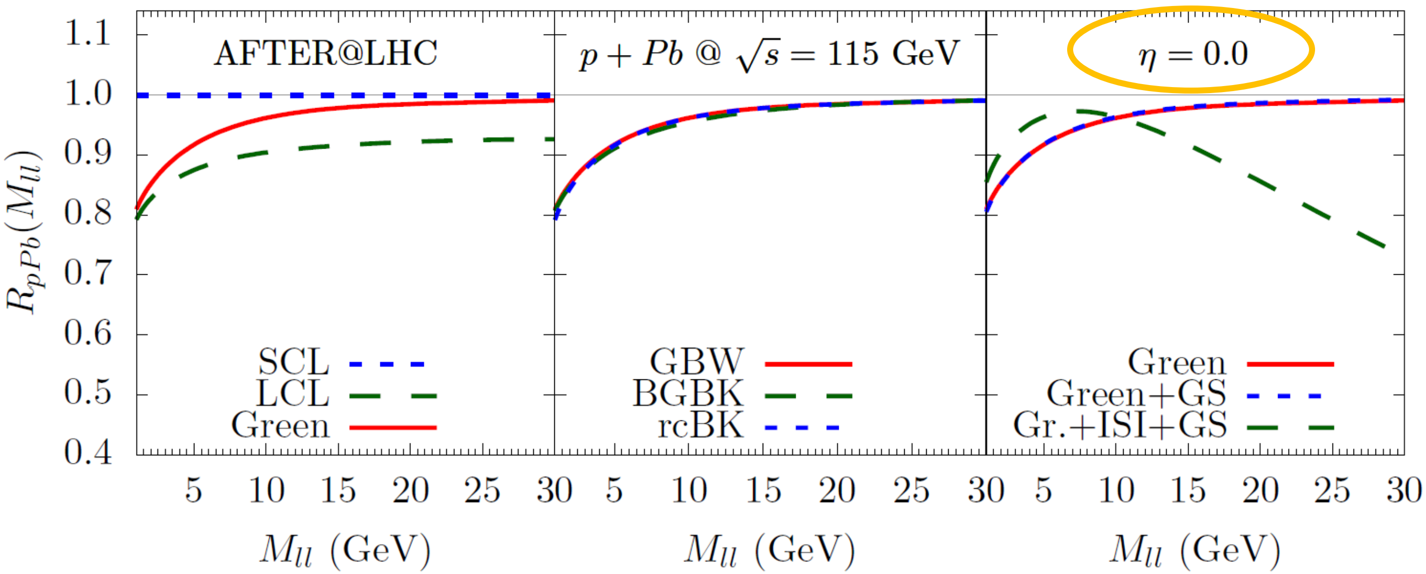
Comparison of quark shadowing (green), gluon shadowing and ISI effects

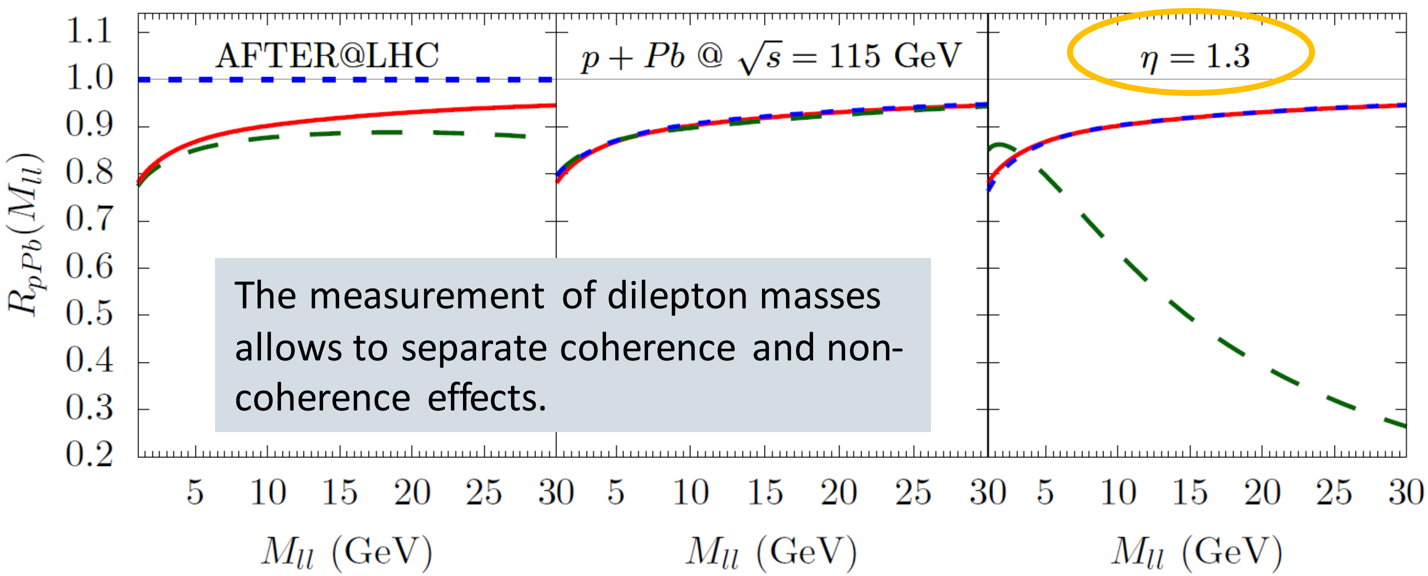
Results: $R_{pA}(\eta)$ – AFTER, $\sqrt{s} = 115$ GeV



With higher rapidity we are close to the LCL limit, ISI and shadowing effects are mixed.

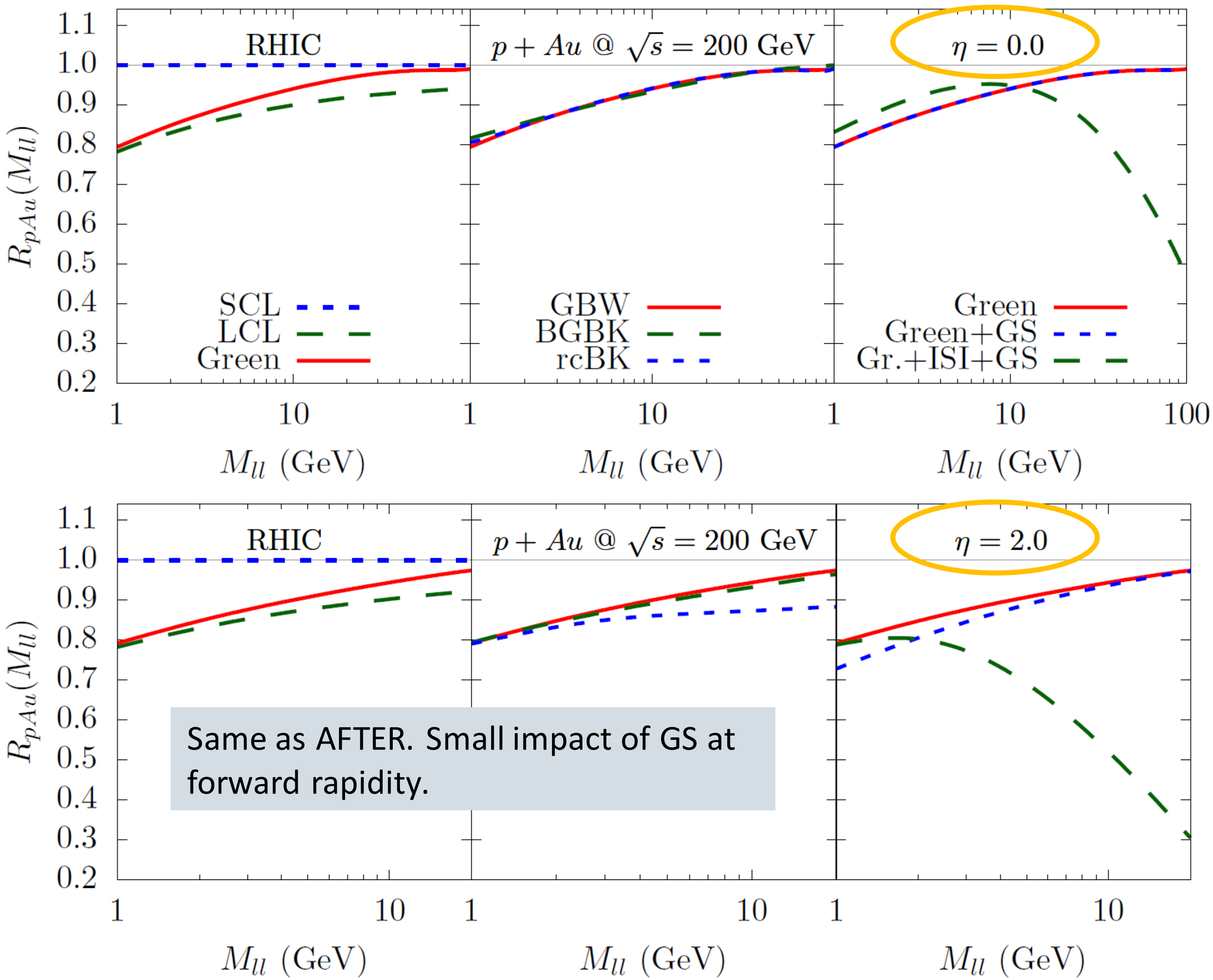
Results: $R_{pA}(M_{l\bar{l}})$ – AFTER, $\sqrt{s} = 115$ GeV





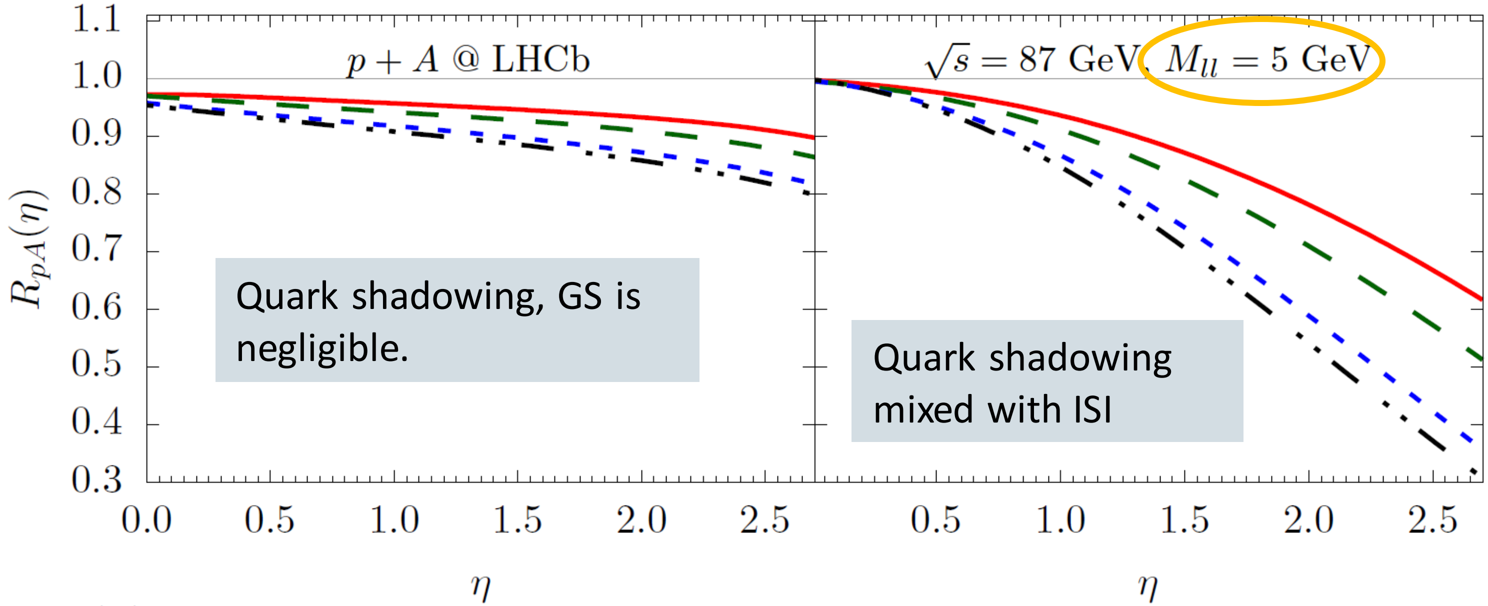
The measurement of dilepton masses allows to separate coherence and non-coherence effects.

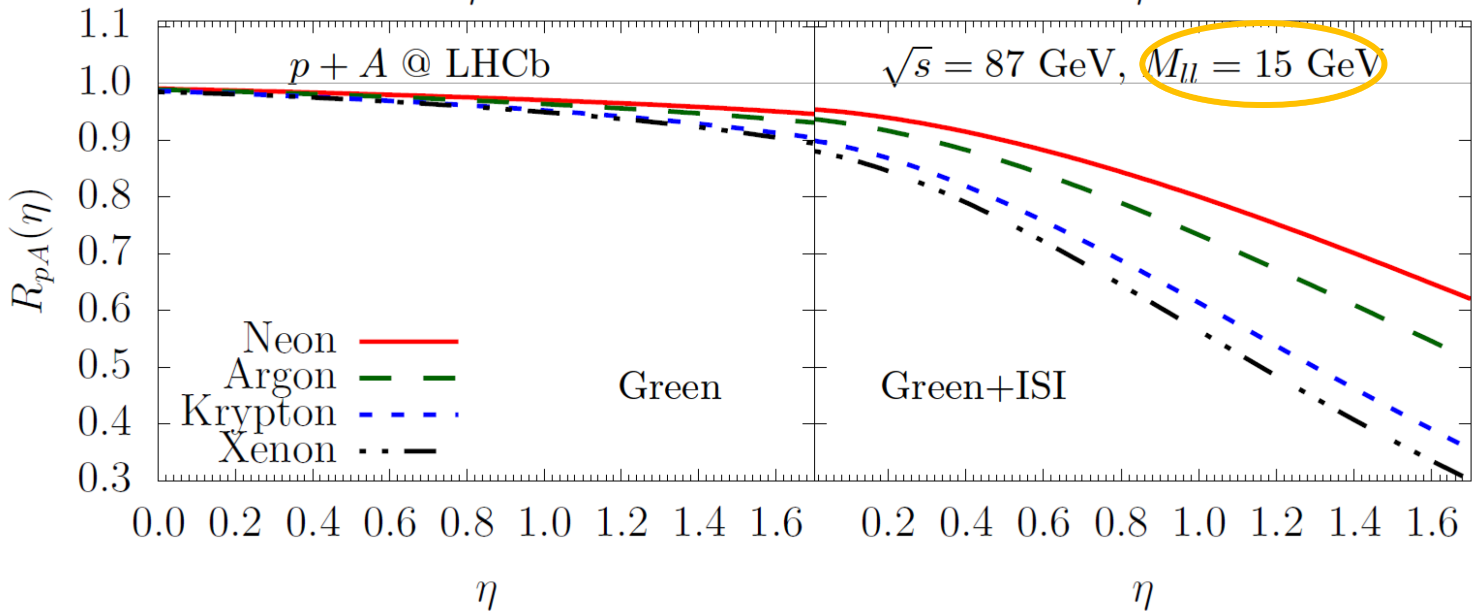
Results: $R_{pA}(M_{l\bar{l}})$ – RHIC, $\sqrt{s}$ = 200 GeV



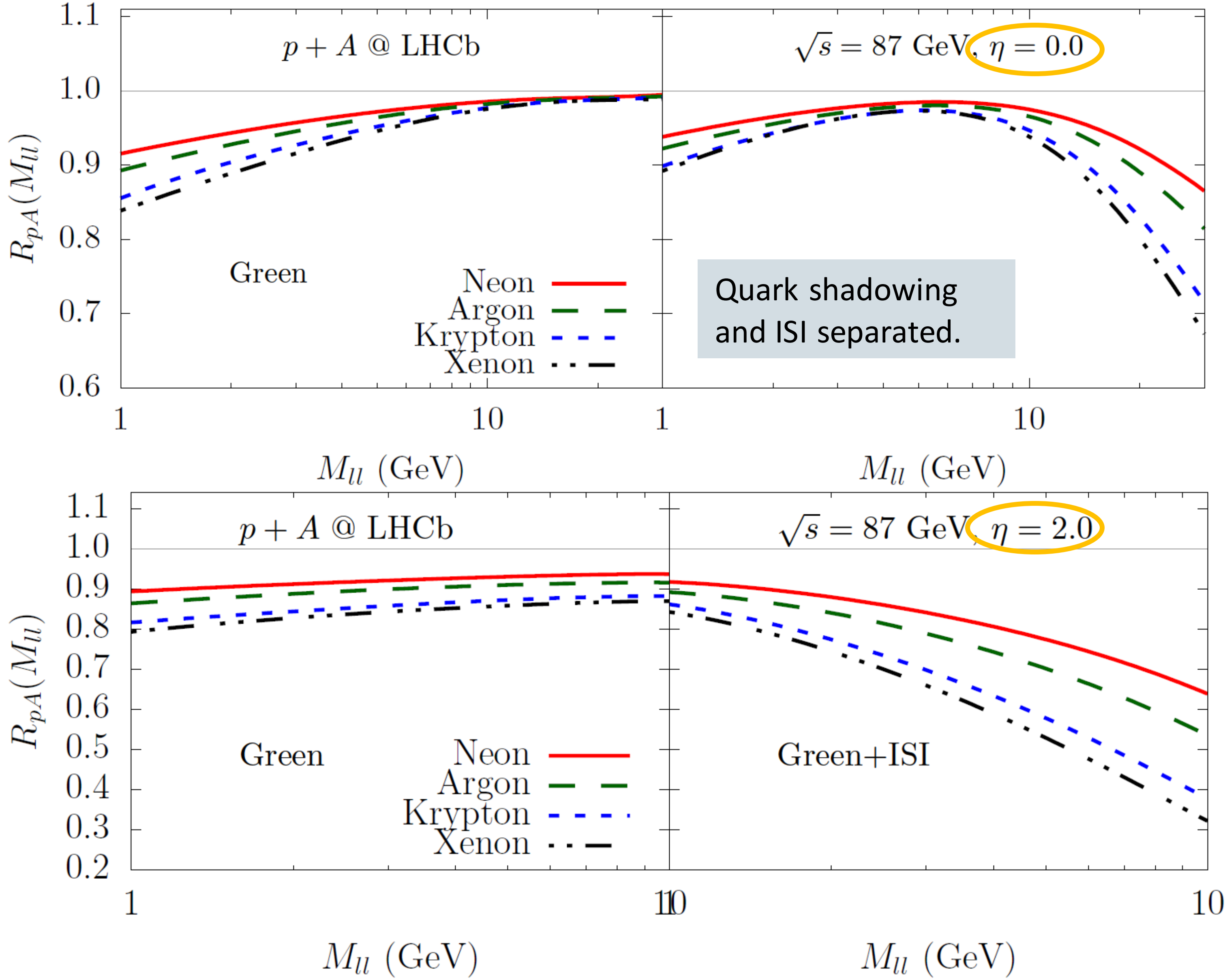
Same as AFTER. Small impact of GS at forward rapidity.

Results: $R_{pA}(\eta)$ – LHCb-gas, $\sqrt{s} = 87$ GeV





Results: $R_{pA}(M_{l\bar{l}})$ – LHCb-gas, $\sqrt{s} = 87$ GeV



Conclusions

Conclusions

- DY is an **ideal tool** for study of nuclear effects
- R_{pA} is controlled by the **coherence length** which is correlated with the nuclear shadowing
- Green function formalism **is important for $\sqrt{s} \leq 200$** GeV
- Green function method successfully **reproduces the SCL and LCL predictions** in the corresponding kinematic regimes
- ISI effects cause a **strong suppression at forward rapidities**
- We presented predictions
  - **RHIC,** and **LHCb-gas** program and for planned experiment **AFTER@LHC**,
- The R_{pA} as a function of dilepton invariant mass $M_{l\bar{l}}$ is a **good probe** for both the **coherence and non-coherence sources of suppression** allowing to reduce or eliminate the shadowing-ISI mixing

Thanks for your attention.

Backups slides

Kinematics

- Fractions kinematics

$$x_1 = \frac{1}{2}\left(\sqrt{x_F^2 + 4\tau} + x_F\right) = \sqrt{\tau}\exp(y),$$
$$x_2 = \frac{1}{2}\left(\sqrt{x_F^2 + 4\tau} - x_F\right) = \sqrt{\tau}\exp(-y),$$

$$\tau = \frac{M^2 + p_T^2}{s} = x_1 x_2,$$
$$x_F = x_1 - x_2.$$

- Scale

$$Q^2 = p_T^2 + (1 - x_1)M^2$$

- Gluon shadowing

$$\sigma_{q\bar{q}}^N(\alpha\rho, x) \Rightarrow \sigma_{q\bar{q}}^N(\alpha\rho, x) R_G(x, Q^2)$$