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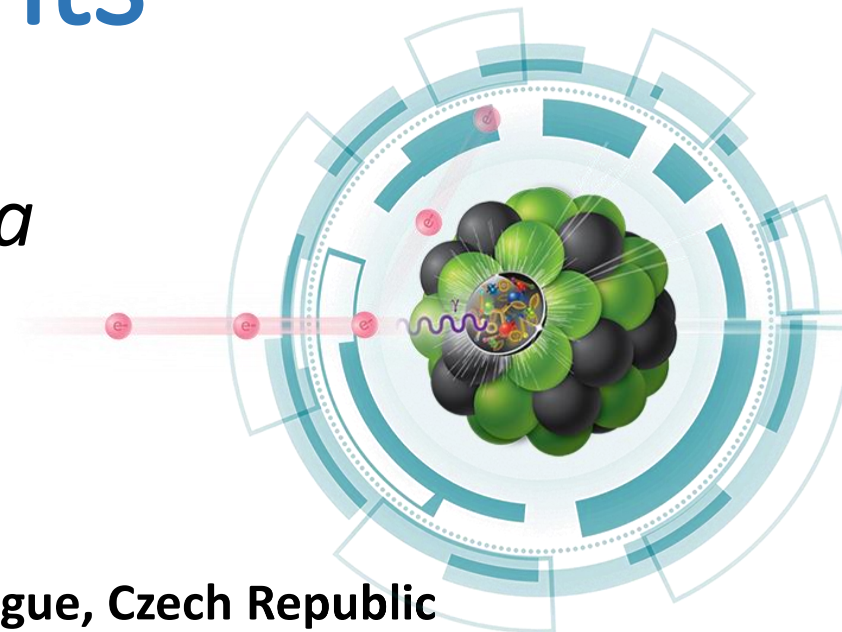
Physics at future EIC experiments



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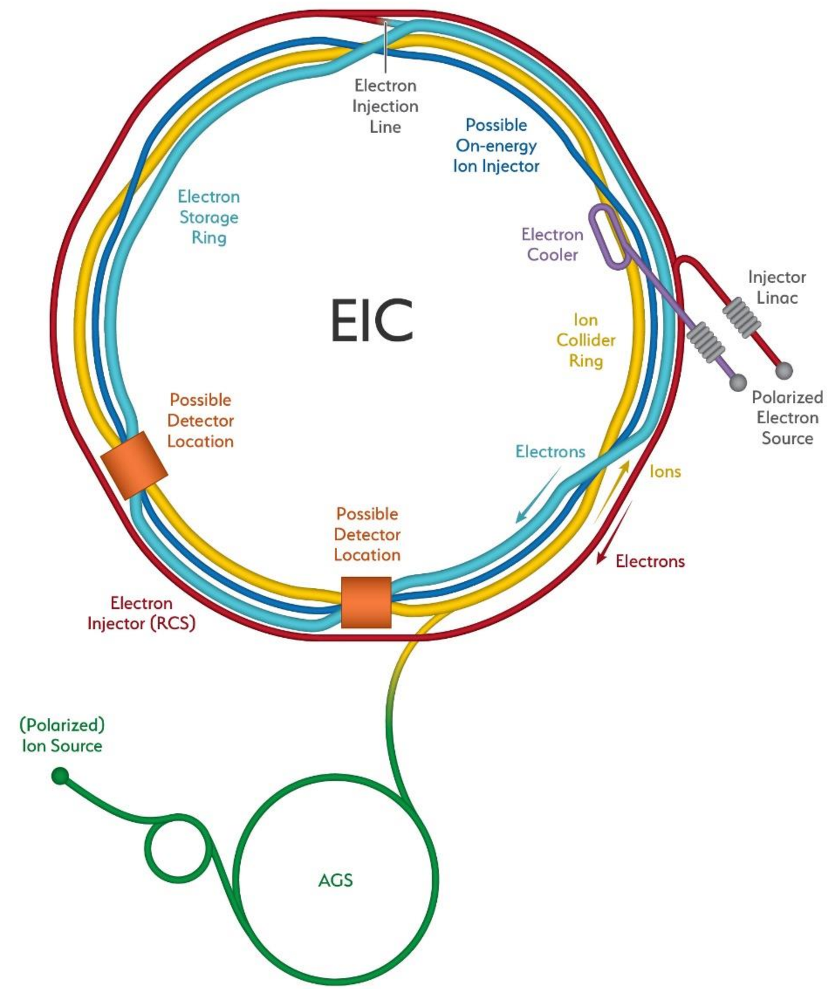
KCSF 2020 | Prague, 10 September 2020

Outline

- What is EIC?
- For what the EIC is useful?
- Vector mesons
  - On proton target
  - On nuclear target
- Nuclear shadowing

What is EIC

- **EIC** = **Electron-ion collid**er
- Particle accelerator colliding **polarized** beam of electrons and ions
- Will be build in Brookhaven National Laboratory (BNL)
- Possible ions: **p, d, He, Ca, C, Au, U, …** (all that worked at RHIC)
- Energies: $E_e = 15.9$ GeV, $E_A = 100$ GeV
- *Current status:* Yellow Report preparations



What will be studied at EIC

- Advantages:
  - Electron = **clear physics** (virtual photon scattering), elementary physics
  - **Low-x** DIS, nDIS
  - **Electroproduction** processes
- Physics program:
  - **Spin and 3D structure of the nucleon** (longitudinal spin, TMDs,...)
  - **Quark and gluon distribution in the nucleus** (nPDF, color charge propagation,...)
  - **High gluon density physics** (saturation scale, non-linear QCD evolution, diffractive physics,...)

We are interested in

- Detailed study of **vector meson** (VM) wave function
  - Electroproduction on proton target is an ideal tool
- **Nuclear effects**
  - Particularly nuclear shadowing including gluon shadowing
  - Proper coherence length treatment
- **Coherent and incoherent productions** on nucleus
  - Vector mesons, di-jets, deep virtual Compton scattering, di-lepton
  - Allow study high gluon density regime of QCD

Color Dipole Framework

- Reference frame: **rest frame** of the nucleus
- Virtual photon fluctuations:
  - Fock component expansion:
    $$|q\bar{q}\rangle + |q\bar{q}G\rangle + |q\bar{q}2G\rangle + |q\bar{q}3G\rangle + \cdots$$
  - For DIS at proton target **only the first** Fock component
- Cross section:
  $$\sigma_{tot}^{\gamma^* N}(x_{Bj}, Q^2) = \int d^2r \int_0^1 d\alpha \left|\Psi_{q\bar{q}}^{T,L}(\vec{r}, \alpha, Q^2)\right|^2 \sigma_{q\bar{q}}(\vec{r}, s)$$

  See more: arXiv:2003.04156

  - $\gamma^* \to q\bar{q}$ wave function:
    $$\Psi_{q\bar{q}}^{T,L}(\vec{r}, \alpha, Q^2) = \frac{\sqrt{N_c \alpha_{em}}}{2\pi} Z_q \, \bar{\chi}\hat{O}^{T,L}\chi K_0(\epsilon r)$$
  - *Improvement:* non-perturbative interaction $q - \bar{q}$

See more: Phys. Rev. D62, 054022 (2000)

Why to be interested in VM?

- **Vector Mesons (VM)** are used as a probe for example in heavy-ion collisions
- Mostly 1S states of heavy quarkonia are used J/ψ and Υ
- The size of heavy quarkonia is relatively small

But do we use the correct wave functions?

- Many publication uses the so called boosted-Gaussian light cone wave function
  - Uses photon-like vertex
  - Consider the HO $Q\bar{Q}$ potential

1^3S_1	1^{--}	$I=0,\ c\bar{c}$	0	$J/\psi(1S)$	3.0969
1^3S_1	1^{--}	$I=0,\ b\bar{b}$	0	$\Upsilon(1S)$	9.46030
1^3S_1	1^{--}	$I=1/2,\ u\bar{c},\bar{u}c$	0	D^*	2.00685
1^3S_1	1^{--}	$I=1/2,\ d\bar{c},\bar{d}c$	±1	D^*	2.01026
1^3S_1	1^{--}	$I=0,\ c\bar{s},\bar{c}s$	±1	$D_s^{*\pm}$	??
1^3S_1	1^{--}	$I=1/2,\ d\bar{b},\bar{d}b$	0	B^*	5.32465
1^3S_1	1^{--}	$I=1/2,\ u\bar{b},\bar{u}b$	±1	B^*	??
1^3S_1	1^{--}	$I=0,\ b\bar{s},\bar{b}s$	0	B_s^*	5.4154
1^3D_1	1^{--}	$I=0,\ c\bar{c}$	0	$\psi(3770)$	3.77313
1^3D_1	1^{--}	$I=0,\ c\bar{s},\bar{c}s$	±1	$D_{s1}^*(2700)^\pm$	2.7083
2^3S_1	1^{--}	$I=0,\ c\bar{c}$	0	$\psi(2S)$	3.686097
2^3S_1	1^{--}	$I=0,\ b\bar{b}$	0	$\Upsilon(2S)$	10.02326
3^3S_1	1^{--}	$I=0,\ b\bar{b}$	0	$\Upsilon(3S)$	10.3552
4^3S_1	1^{--}	$I=0,\ b\bar{b}$	0	$\Upsilon(4S)$	10.5794

VM wave function cookbook

1) Go to the rest frame of the quark-antiquark $Q\bar{Q}$ system
2) Solve the Schrödinger equation (SE)

   The potential in SE corresponds to the potential between both quark and antiquark

3) Boost it to the light cone (LC) frame
4) Use it for example within the color dipole framework

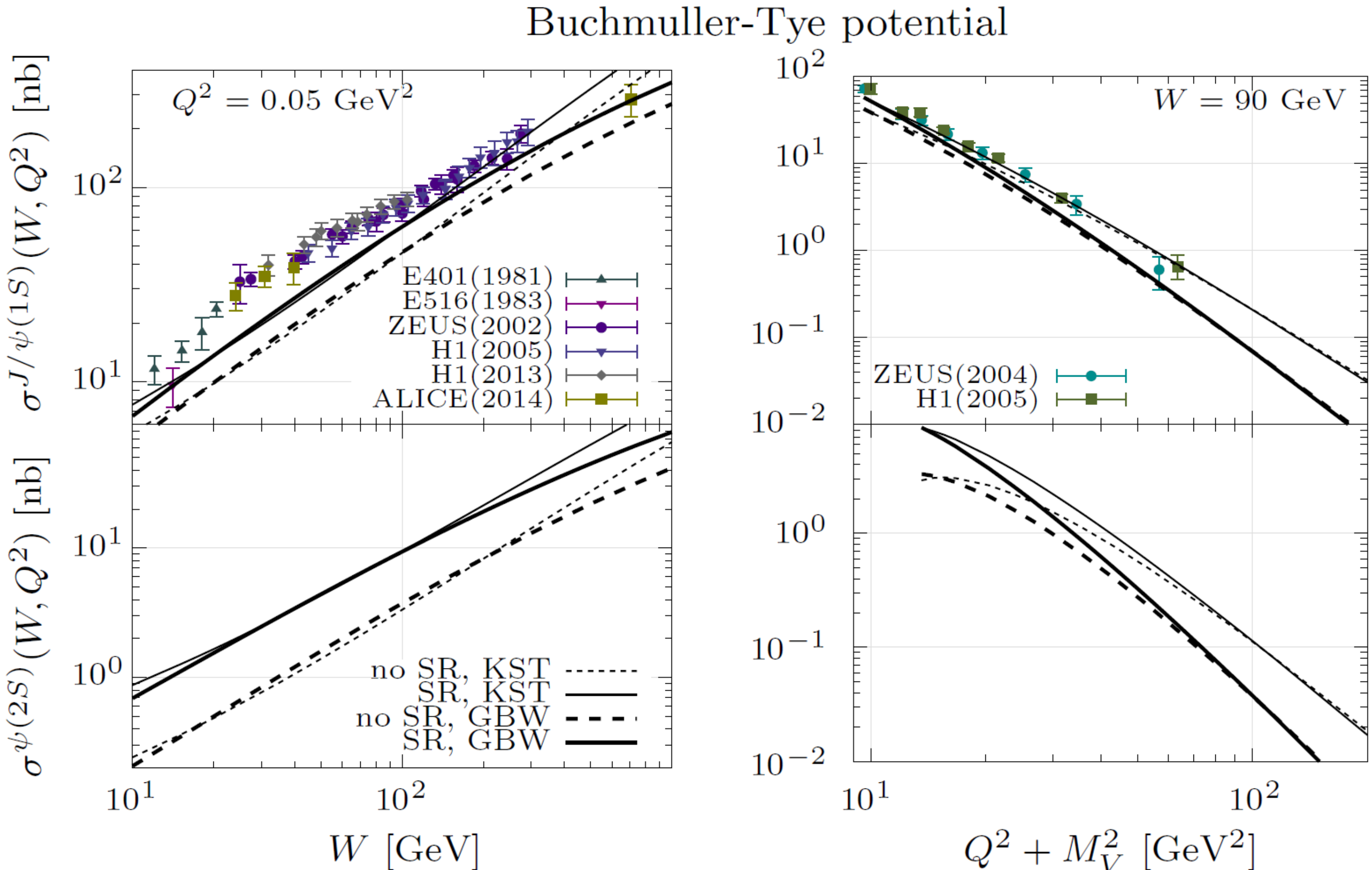
- In case of VM, we can factorize the radial and spin-orbital part
- In most cases, the spin-orbital part is omitted (only effect in normalization)
  - Application of Melosh spin rotation

    H.J. Melosh, Phys. Rev. D 9, 1095 (1974)

    J. Hufner, Y.P. Ivanov, B.Z. Kopeliovich, A.V. Tarasov, Phys. Rev. D 62, 094022 (2000)

Results – highlight of SR effect

- BT potential + KST/GBW dipole cross section
- Stronger effect of the spin rotation for $\psi(2S)$



Results – highlight of SR effect

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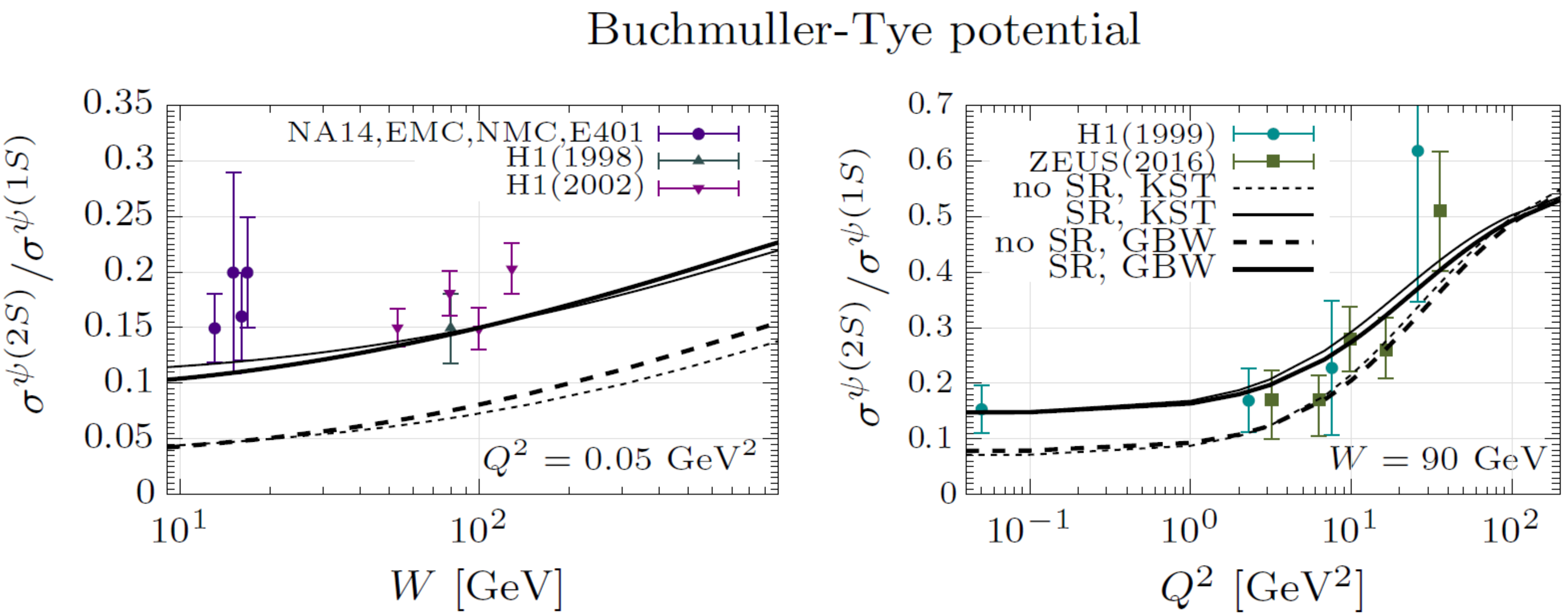


Nuclear shadowing

- **Nuclear shadowing:** shadowing of hadronic components of virtual photon caused by their multiple scattering inside the target
- Coherence length (CL)/time:
  - Controls the dynamics of nuclear shadowing
  - Photon fluctuation **lifetime**
  - For example: lowest Fock component $|q\bar{q}\rangle$

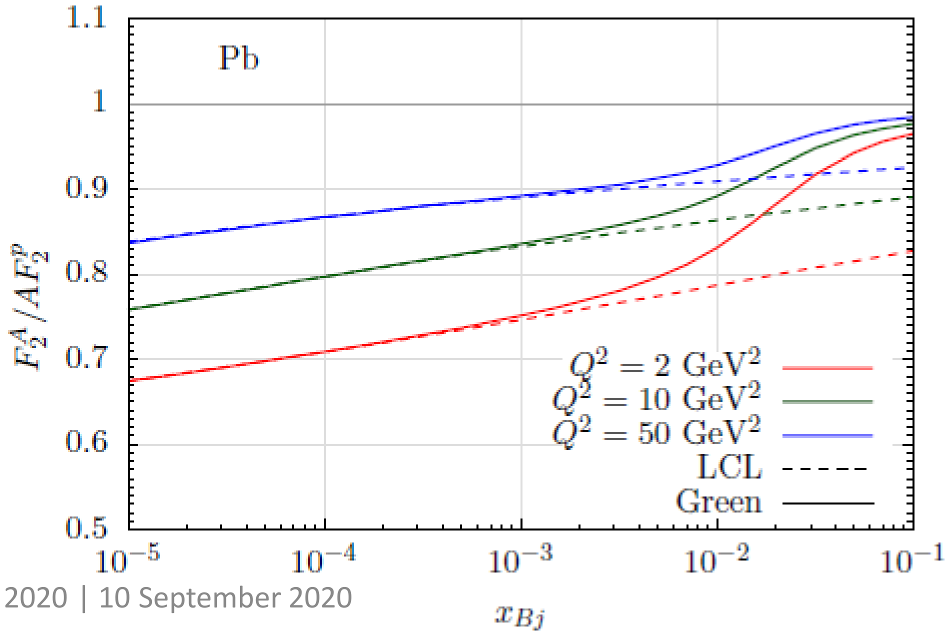
$$l_c = \frac{2\nu}{Q^2 + M_{q\bar{q}}^2}, \quad \nu = \frac{Q^2}{2m_N x_{Bj}}$$

  - CL is related to the longitudinal momentum $q_c = 1/l_c$

Nuclear shadowing limits

- **Eikonal approximation** (LCL – long coherence length)
  - $\sigma_{q\bar{q}} \to 2\left(1 - e^{-\frac{1}{2}T_A(b)\sigma_{q\bar{q}}}\right)$
  - This is valid for $\boldsymbol{l_c} \gg \boldsymbol{R_A}$
  - I.E.: for small x_{Bj}
- For all other $\boldsymbol{l_c}$ use the Green function technique
- This technique is more important for higher Fock components, because

$$M_{q\bar{q}}^2 \ll M_{q\bar{q}G}^2 \ll M_{q\bar{q}2G}^2 \ll \cdots$$



Gluon shadowing

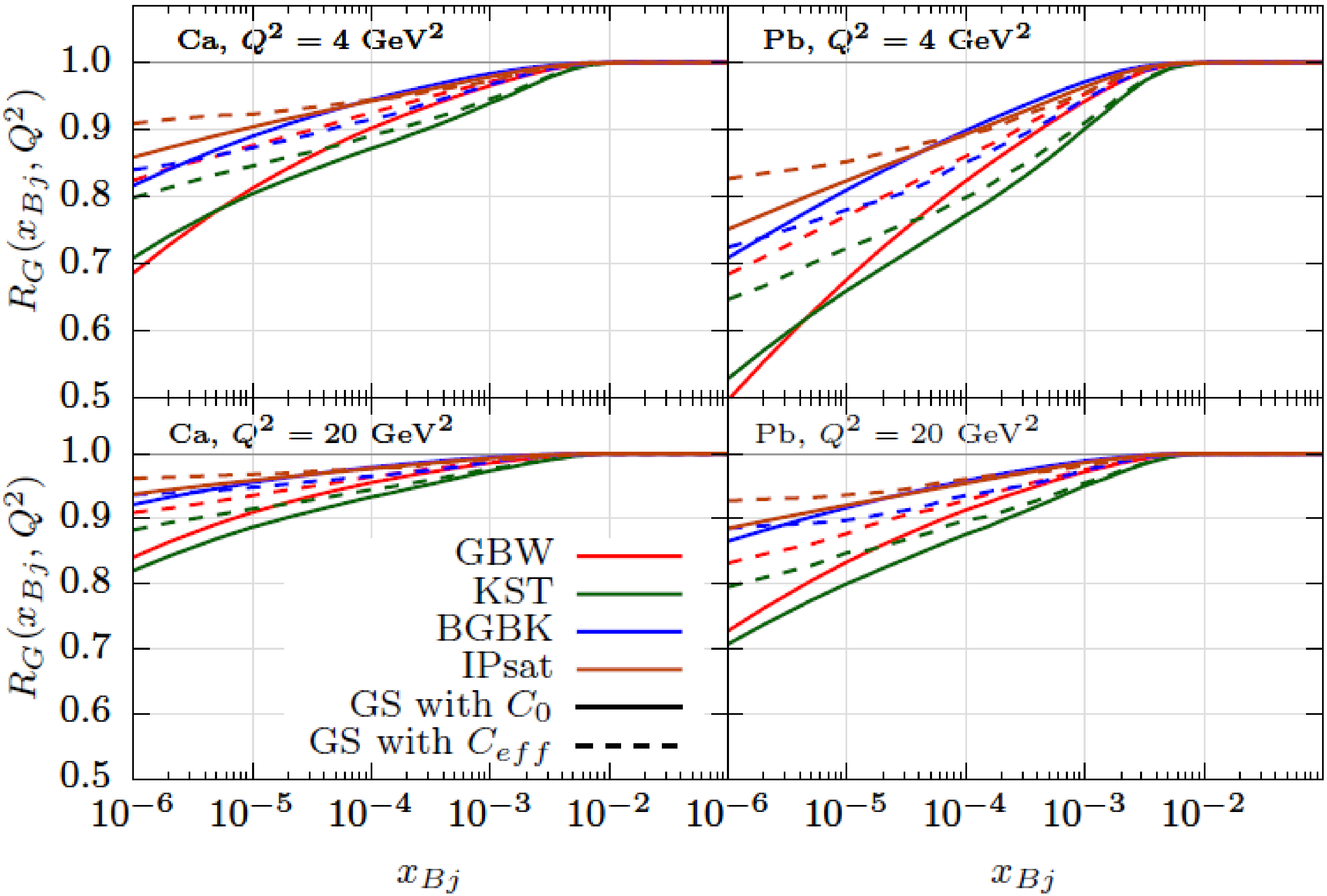
- $\boldsymbol{\gamma^* \rightarrow q\bar{q}G}$ wave function
  - $\gamma^* \rightarrow GG$ approximation, valid for higher Q^2
  - The full $\gamma^* \rightarrow q\bar{q}G$ wave function in progress
- Small $\sigma_{q\bar{q}}(\vec{r}, s)$ approximation, i.e., $\sigma_{q\bar{q}} \sim C r^2$
  - Various ways to get factor C
  - We discuss two of them denotes as C_0 and more realistic C_{eff}
- **Green function considered only** because
  - $M^2_{q\bar{q}G} = \frac{p_T^2}{\alpha_G(1-\alpha_G)} + \frac{M^2_{q\bar{q}}}{1-\alpha_G} \gg M^2_{q\bar{q}}$

See more: Phys. Rev. C62, 035204 (2000)

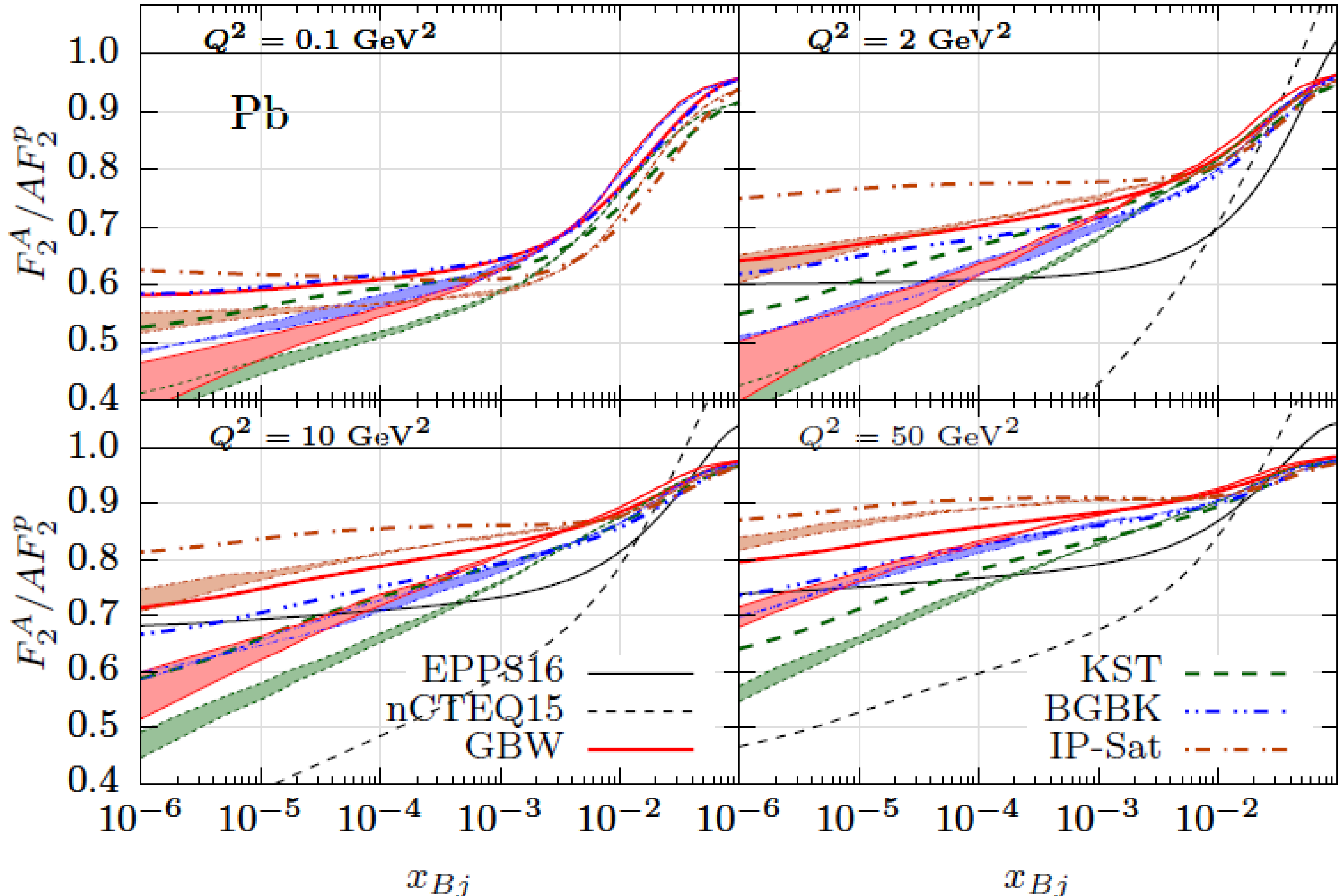
- Implemented as $\sigma_{q\bar{q}}(\vec{r}, s) \rightarrow R_G\left(b, x_{Bj}, Q^2\right)\sigma_{q\bar{q}}(\vec{r}, s)$

See more: Nucl. Phys. A696, 669 (2001)

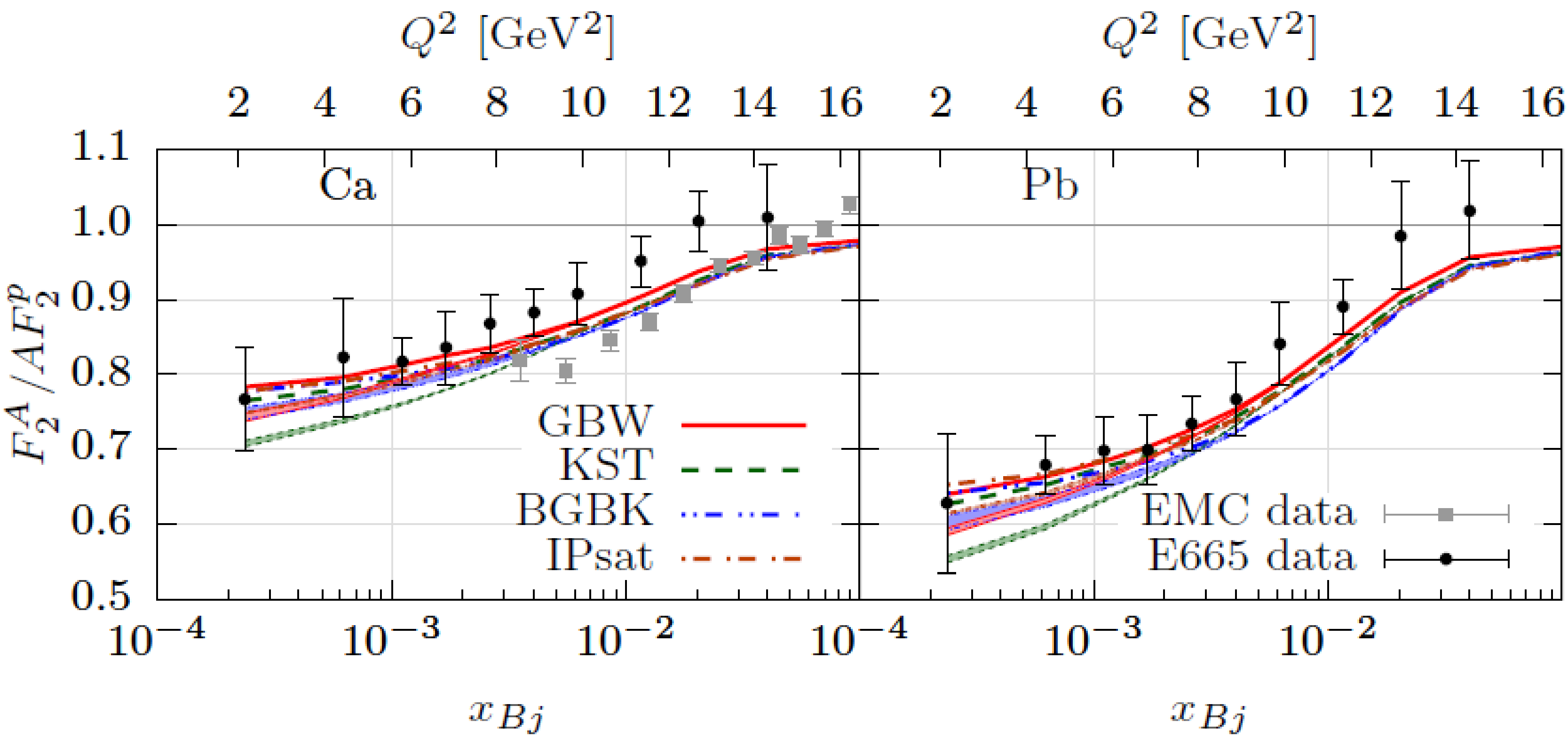
Results: Gluon shadowing standalone



Results: Full shadowing



Results: Data comparison

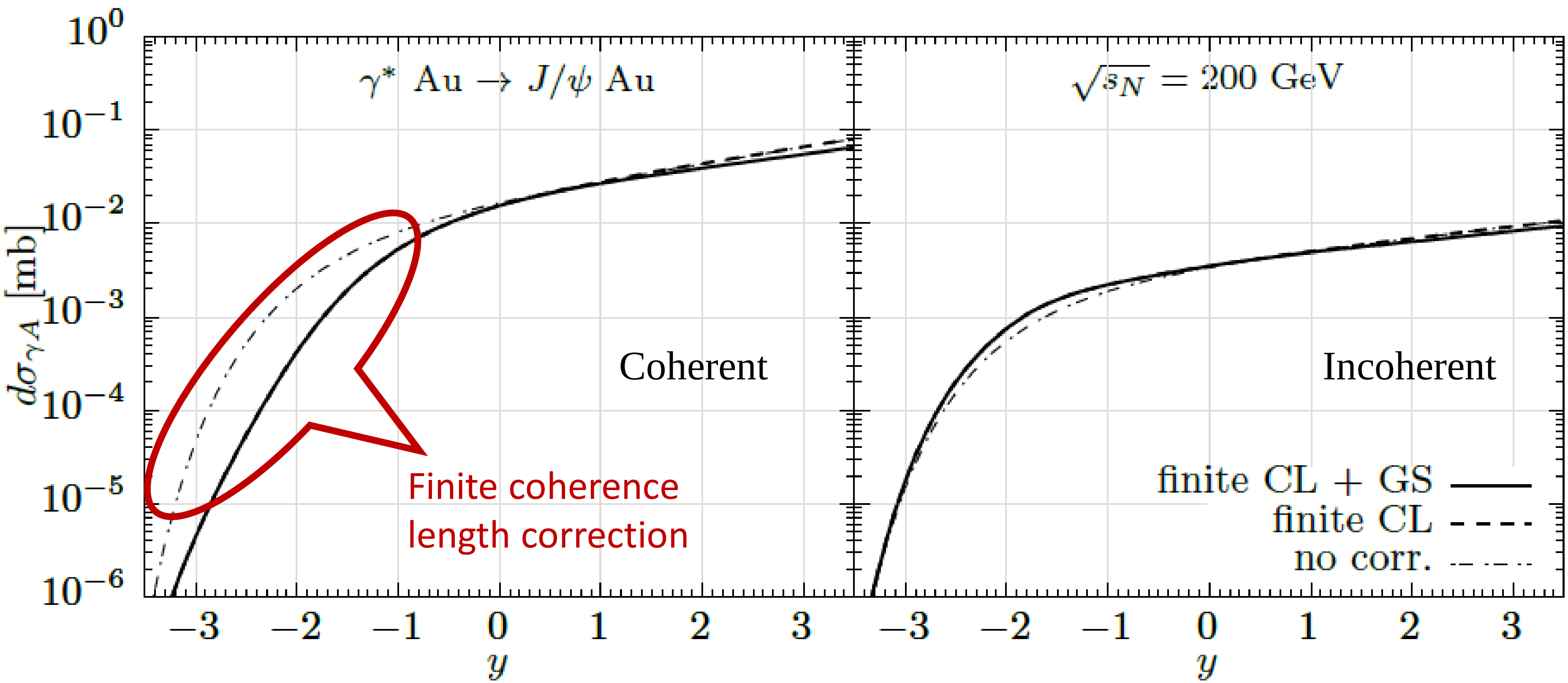


Coherence correction applications

- **About coherence length we should care for all processes on nuclear target**
  - At least at lower $\sqrt{s_{NN}}$ energies (∼RHIC, EIC), or
  - At LHC energies and large rapidities

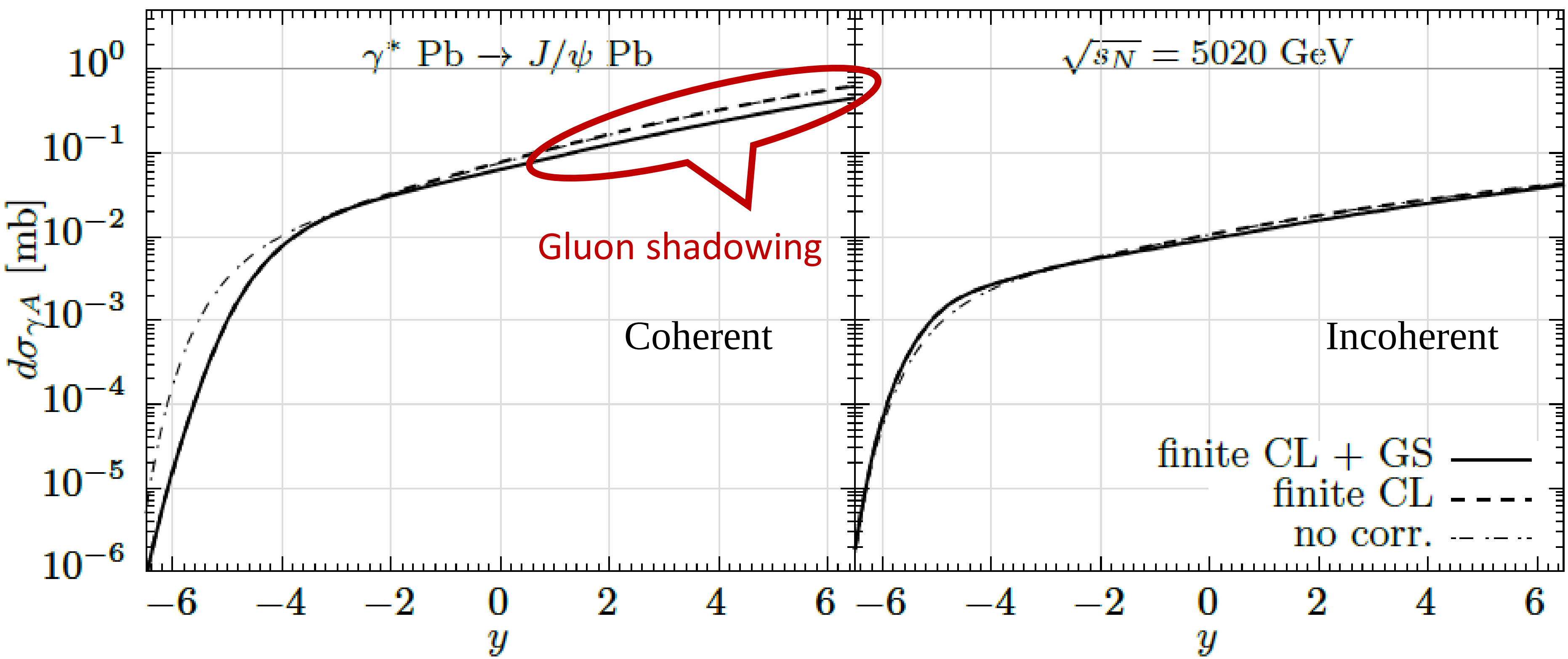
- *Example:*
  - Currently, the correct finite coherence length is **hot topic** for EIC that will probe energies, where the eikonal form is **not more safe**
    - VM photo/electro production, DVCS, di-jets, …
  - Other **hot topic** are UPC, see next slides…

Application for VM photoproduction



PRELIMINARY (RHIC energy)

Application for VM photoproduction



PRELIMINARY (LHC energy)

Conclusions and outlooks

- **Vector mesons**
  - Proper wave function calculation
  - Spin rotation effects contribute to obtain a reasonable agreement with available data without any adjusted parameter (e.g. skewedness);
  - Spin rotation effects lead to a rise of the higher state VM photoproduction cross section by a factor of $2 \div 3$
- **Nuclear shadowing**
  - Non-perturbative effects in $q - \bar{q}$ interaction
  - Exact treatment of coherence length
  - Green function technique
  - **Gluon shadowing**
- **Main source of uncertainty:** dipole cross section $\sigma_{q\bar{q}}(\vec{r}, s)$
  - $\sigma_{q\bar{q}}(\vec{r}, s)$ is fitted from DIS
  - Nuclear DIS can help to exclude some of them
- **Color dipole formalism** offers **nature** calculations for nuclear targets

Thank you for your attention!

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The work was supported from European Regional Development Fund-Project

"Center of Advanced Applied Science"

No. CZ.02.1.01/0.0/0.0/16-019/0000778.

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