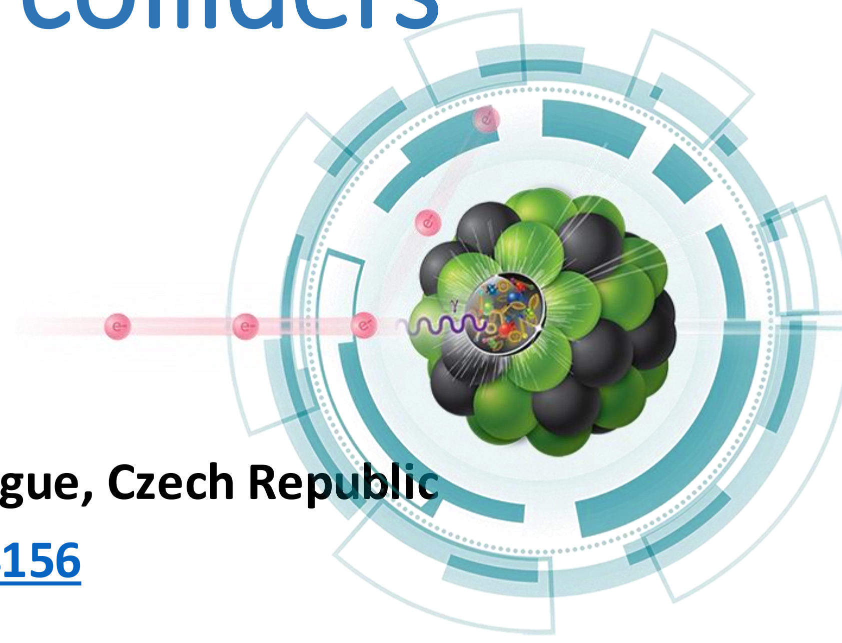
EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

CTU
CZECH TECHNICAL
UNIVERSITY
IN PRAGUE

Nuclear shadowing in DIS for future electron-ion colliders



Michal Krelina

FNSPE, Czech Technical University in Prague, Czech Republic

Based on [arXiv:2003.04156]

1st EIC Yellow Report Workshop at Temple University, 19-21 March 2020

Outline

- **Nuclear shadowing** in terms of **color dipole formalism**
- Results for F_2^A
- Preliminary results for centralities, $F_L^A, F_2^{(c)A}, \sigma_L/\sigma_T$
- What we can offer to **EIC**?
- Conclusions

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)

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 $|q\bar{q}\rangle$

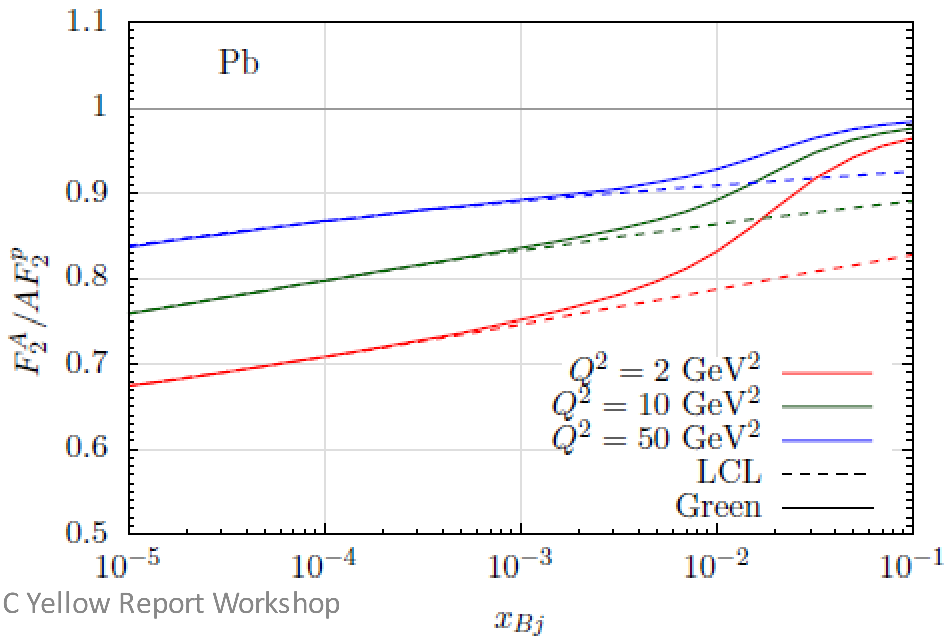
$$l_c = \frac{2\nu}{Q^2+M_{q\bar{q}}^2}, \quad \nu = \frac{Q^2}{2m_N x_{Bj}}$$

  - 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

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



Green Function Formalism

- For equations, see arXiv:2003.04156
- In high energy limit, the Green function takes a eikonalized form

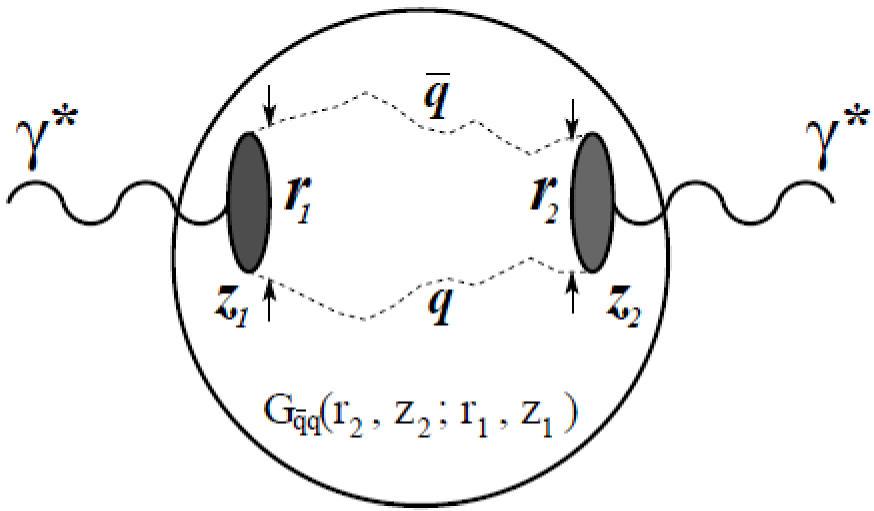


FIG. 1: A cartoon [5, 6, 10] for the first shadowing term $\Delta\sigma_{tot}(x_{Bj}, Q^2) = \Delta\sigma_{tot}(q\bar{q})$ in Eq. (2.1). The Green function $G_{q\bar{q}}(\vec{r_2}, z_2; \vec{r_1}, z_1)$ describes the propagation of the $q\bar{q}$ pair through the nucleus, which results from the summation over different paths of the $q\bar{q}$ pair.

Quark vs gluon shadowing

- **Quark shadowing:** from $|q\bar{q}\rangle$ Fock component
- **Gluon shadowing:** from $|q\bar{q}G\rangle + |q\bar{q}2G\rangle + |q\bar{q}3G\rangle + \cdots$ Fock components

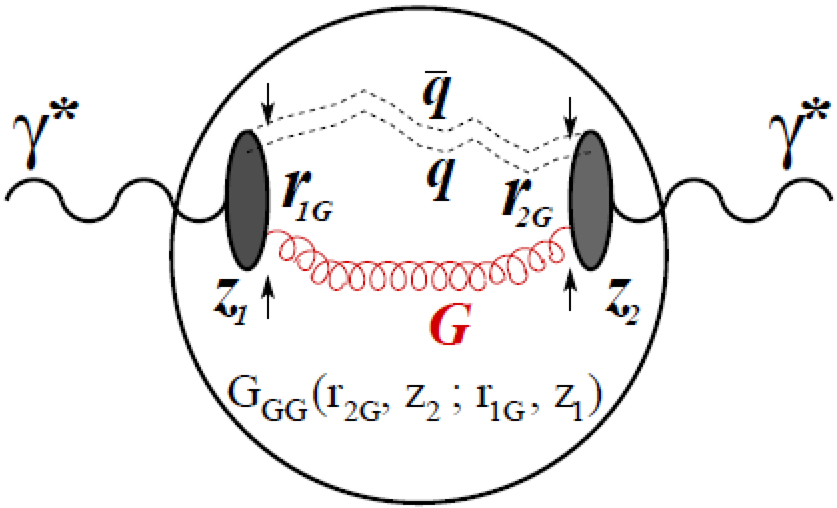


FIG. 3: A cartoon [52] for the shadowing term $\Delta\sigma_{tot}(x_{Bj}, Q^2) = \Delta\sigma_{tot}(q\bar{q}G)$. The Green function $G_{GG}(\vec{r}_{2G}, z_2; \vec{r}_{1G}, z_1)$ describes the propagation of the $q\bar{q}G$ system through the nucleus as a propagation of the effective gluon-gluon (color octet-octet) dipole neglecting the small transverse size of the color-octet $G \equiv q\bar{q}$ fluctuation.

Gluon shadowing

- $\boldsymbol{\gamma^* \to q\bar{q}G}$ wave function
  - $\gamma^* \to GG$ approximation, valid for higher Q^2
  - The full $\gamma^* \to q\bar{q}G$ wave function in progress
- Small $\sigma_{q\bar{q}}(\vec{r}, s)$ approximation, i.e., $\sigma_{q\bar{q}} \sim Cr^2$
  - 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)

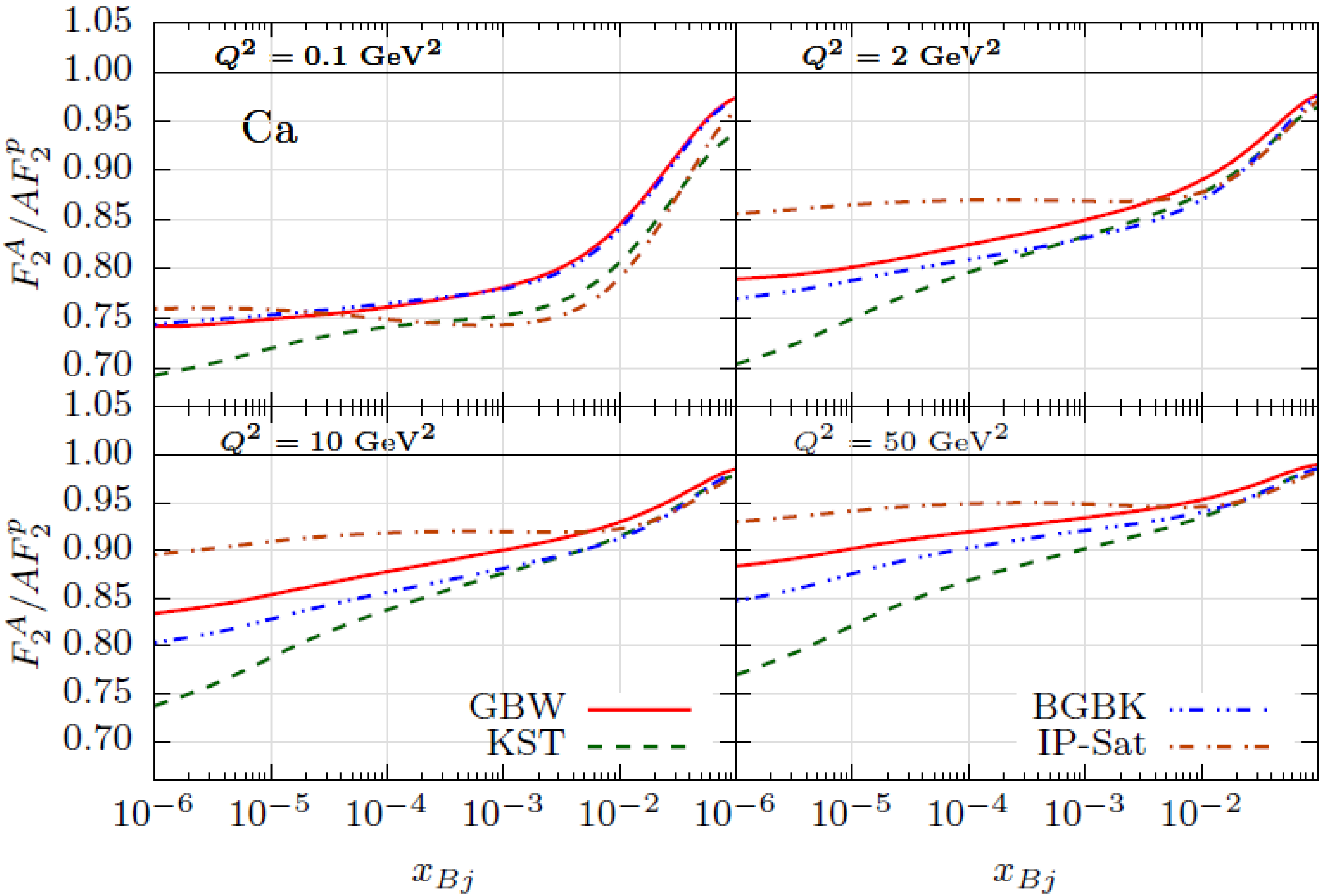
- Implemented as $\sigma_{q\bar{q}}(\vec{r}, s) \to R_G\left(b, x_{Bj}, Q^2\right)\sigma_{q\bar{q}}(\vec{r}, s)$

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

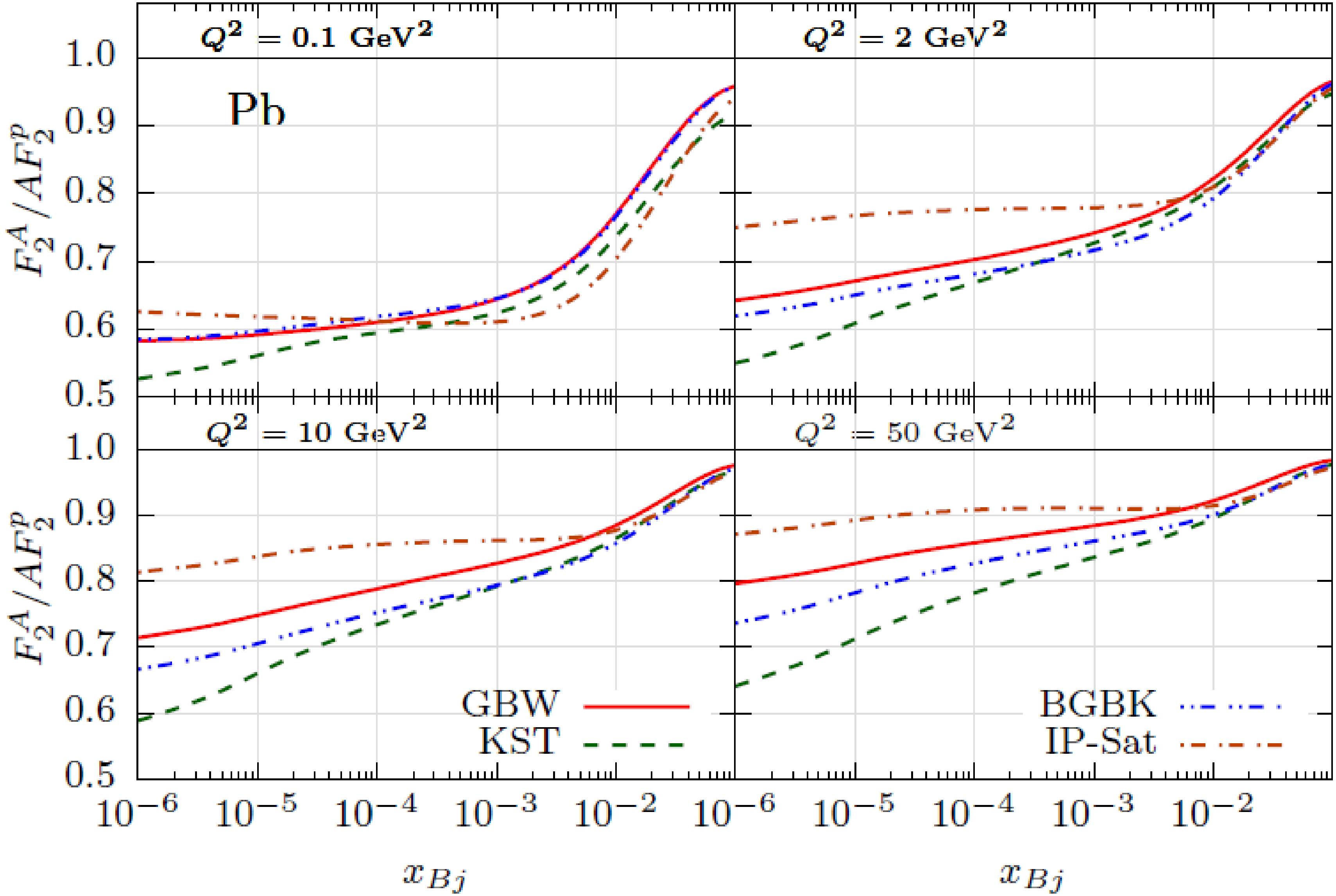
BK equation note

- Balitsky-Kovchegov (BK) evolution equation
  - Summation of all Fock components with gluons is inherent
  - Usually, the interaction is treated in high energy limit, i.e., the eikonalized form is used
  - That is $l_c^{q\bar{q}}, l_c^{q\bar{q}G}, \dots, l_c^{q\bar{q}nG} \gg R_A$
  - Leading to **overestimated nuclear shadowing**
  - This is not reliable at kinematics covered by EIC

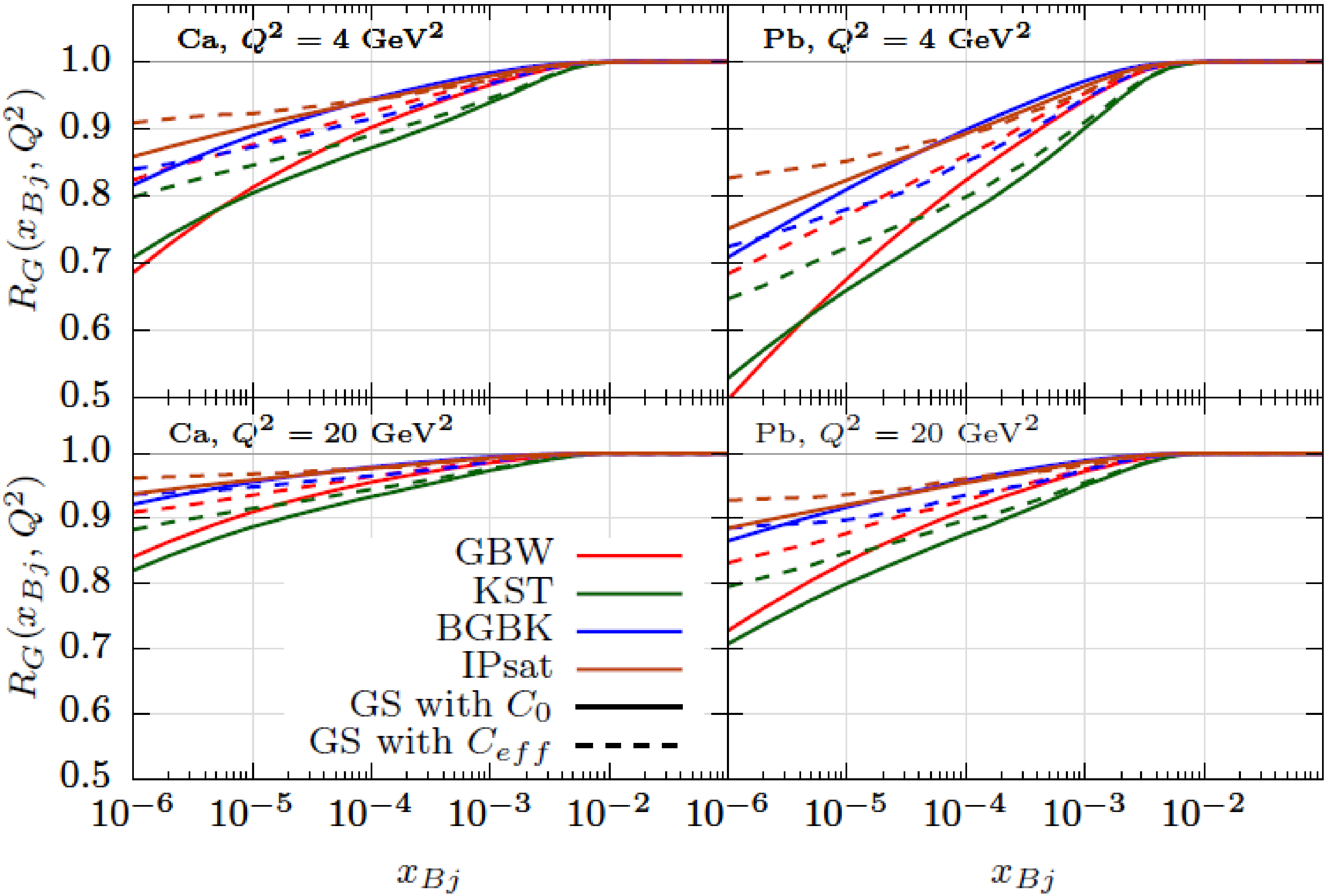
Results: quark shadowing only



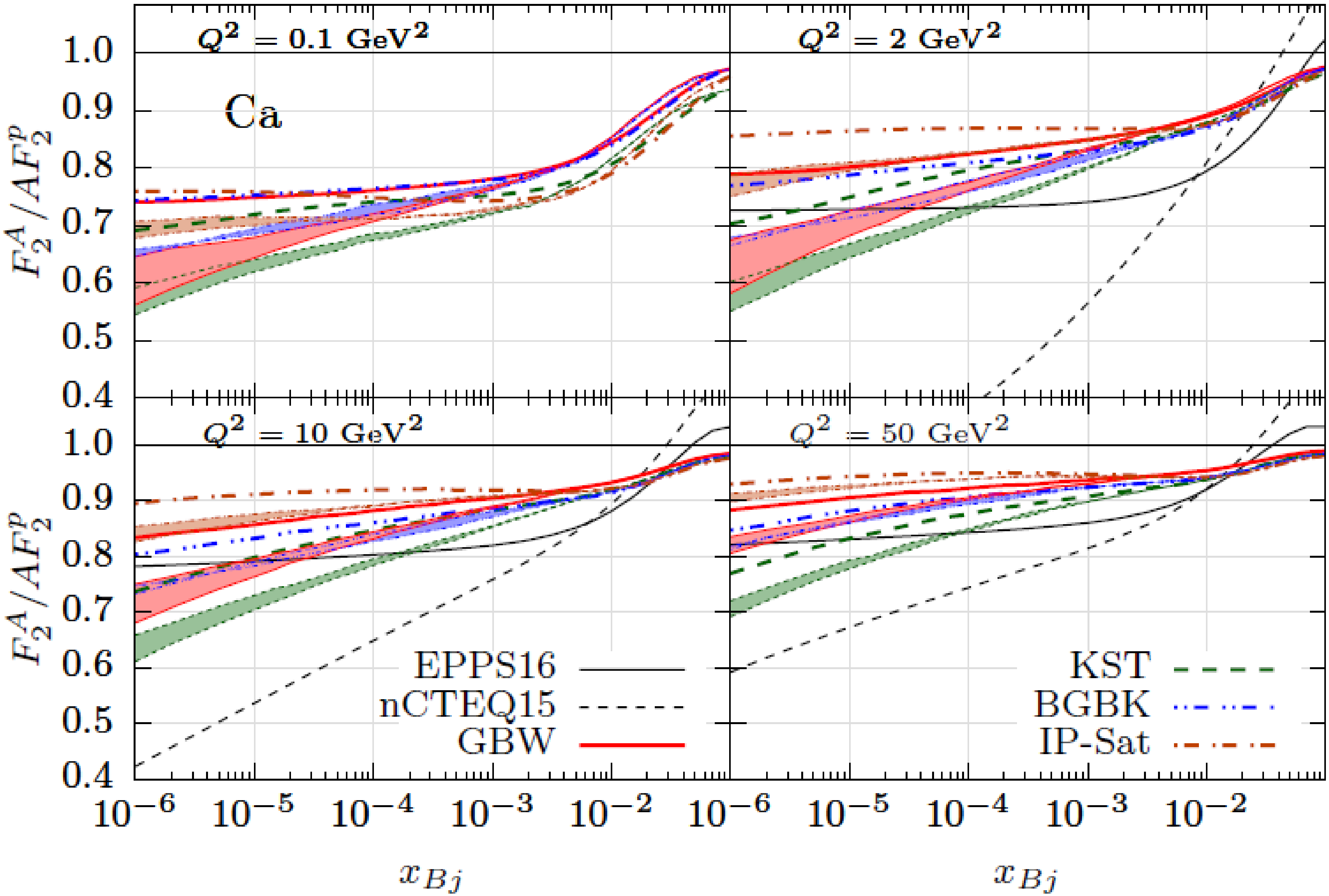
Results: quark shadowing only



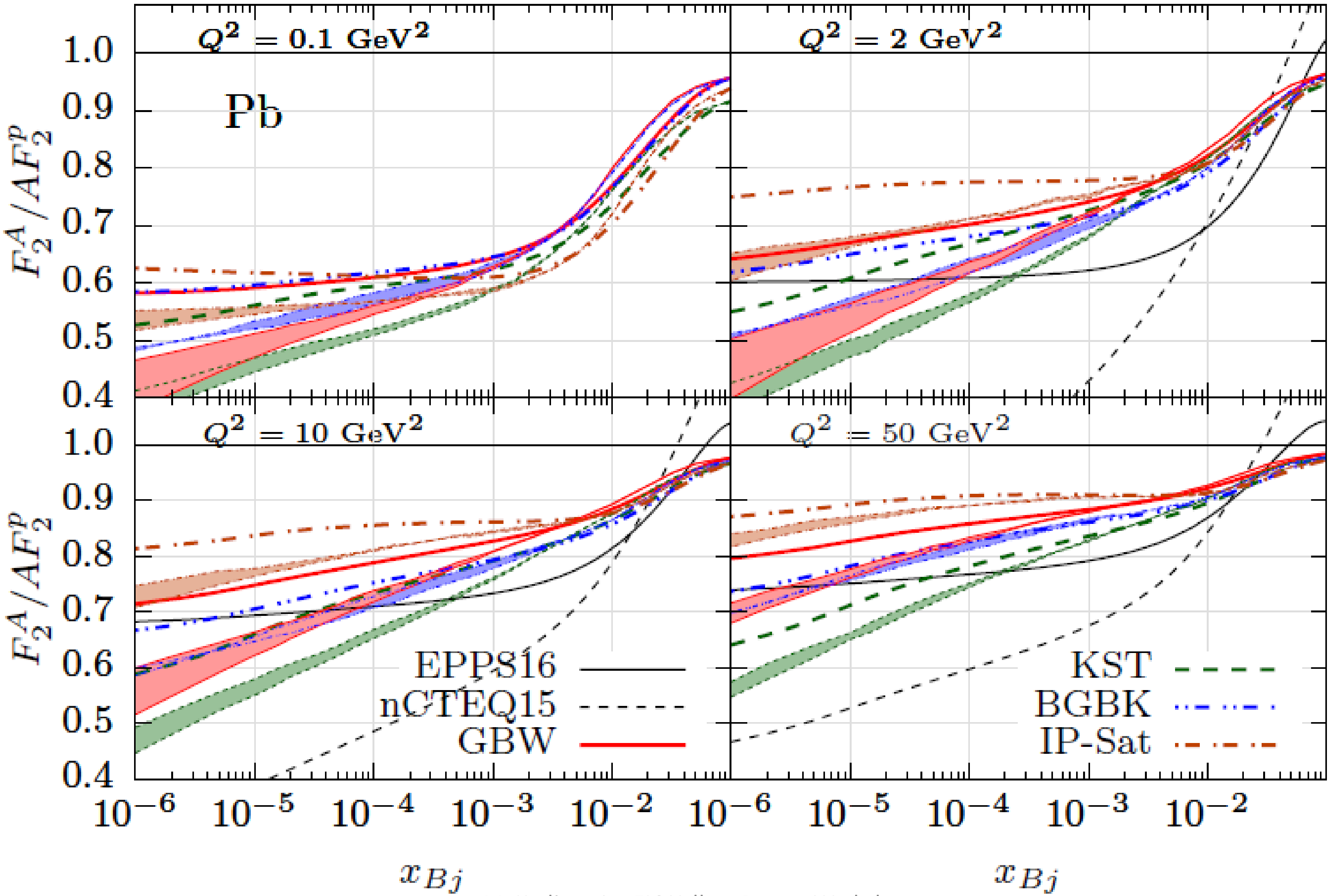
Results: Gluon shadowing standalone



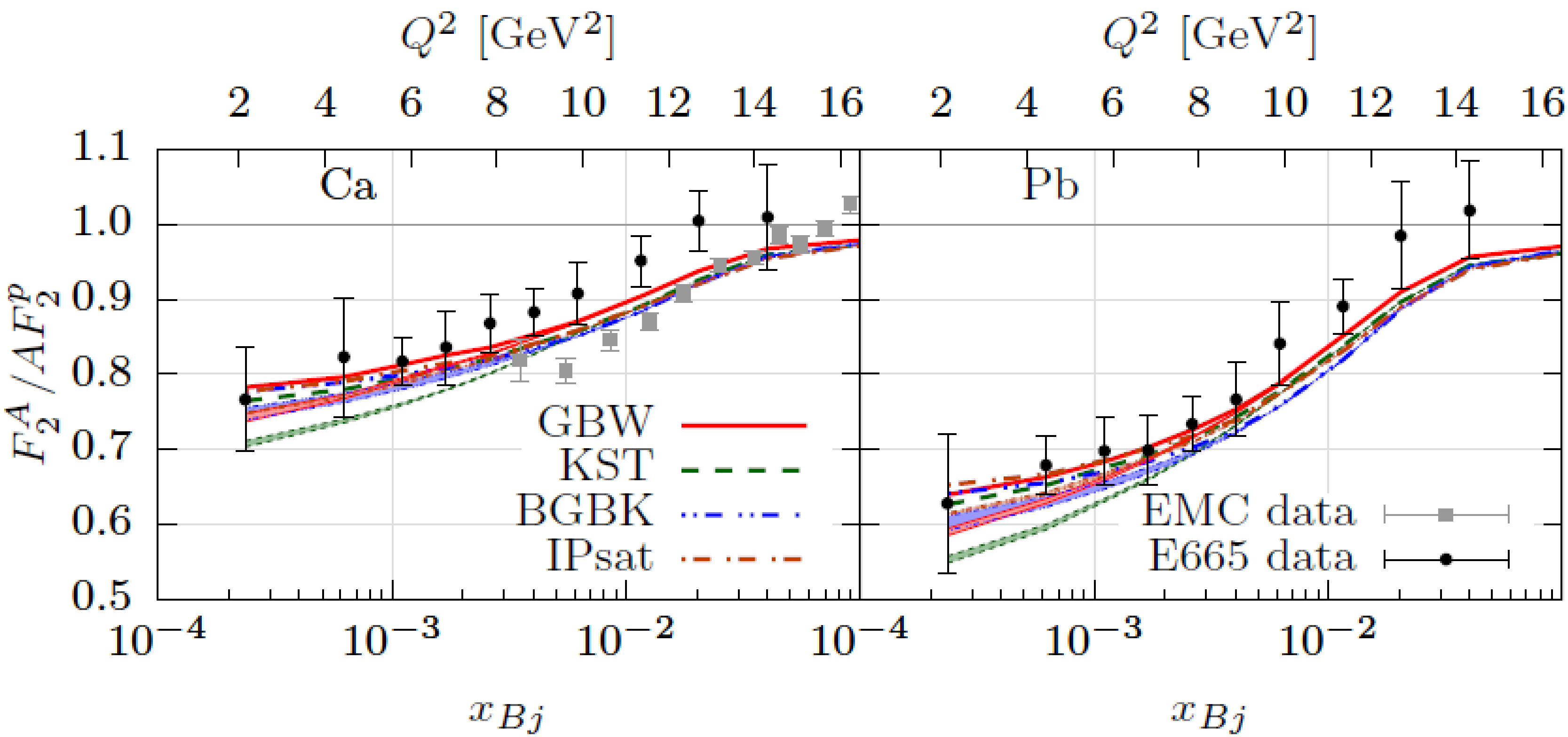
Results: Full shadowing



Results: Full shadowing



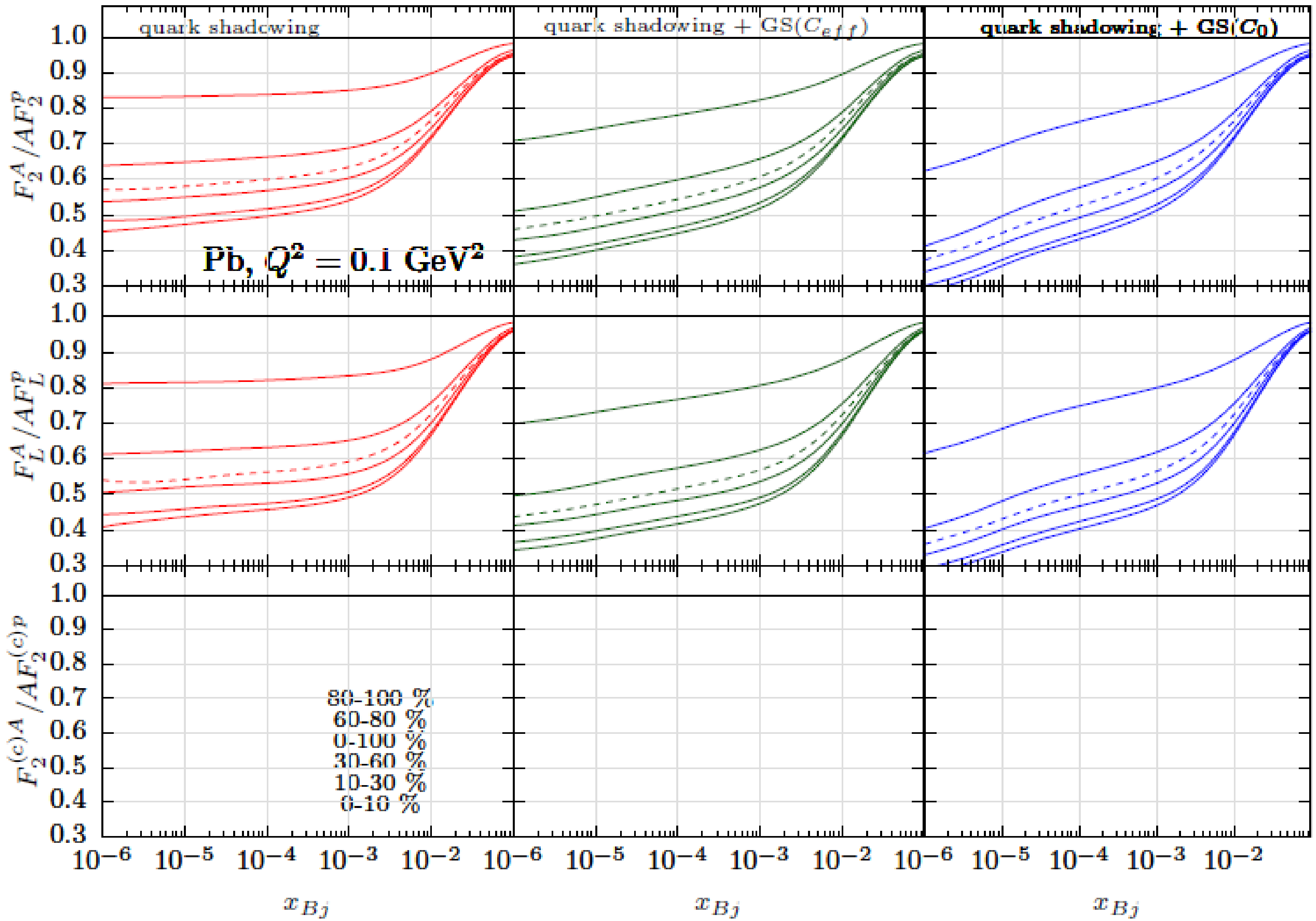
Results: Data comparison



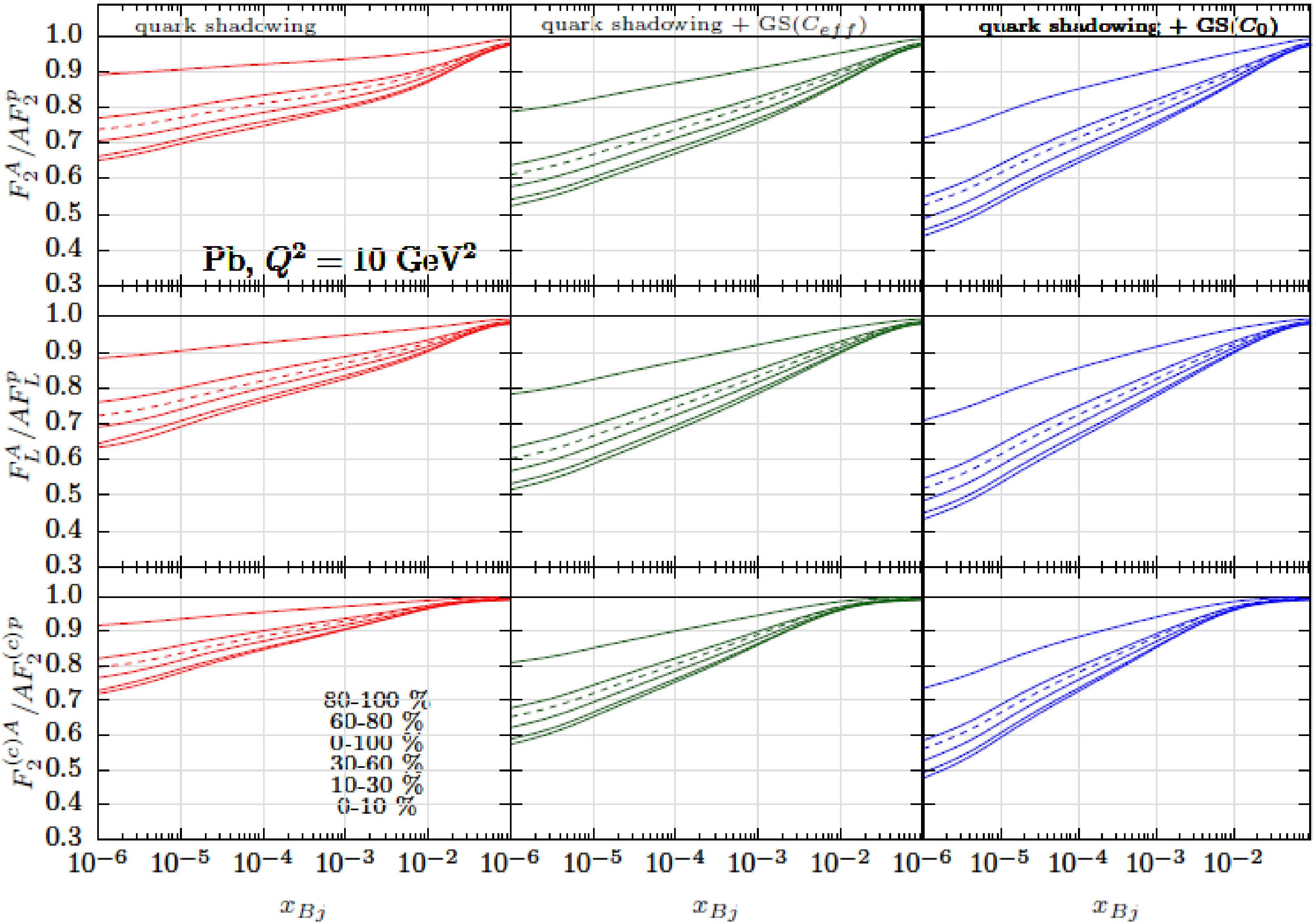
Dipole Formalism allows more

- So far, we studied F_2^A only
- **We can study more**:
  - Centrality dependence
  - $F_L^A, \sigma_L^A/\sigma_T^A$
  - $F_2^{c,A}, F_L^{c,A}, \sigma_L^{c,A}/\sigma_T^{c,A}$
  - $F_2^{b,A}, F_L^{b,A}, \sigma_L^{b,A}/\sigma_T^{b,A}$
- Note, the following results are preliminary and for GBW dipole cross section parametrization only

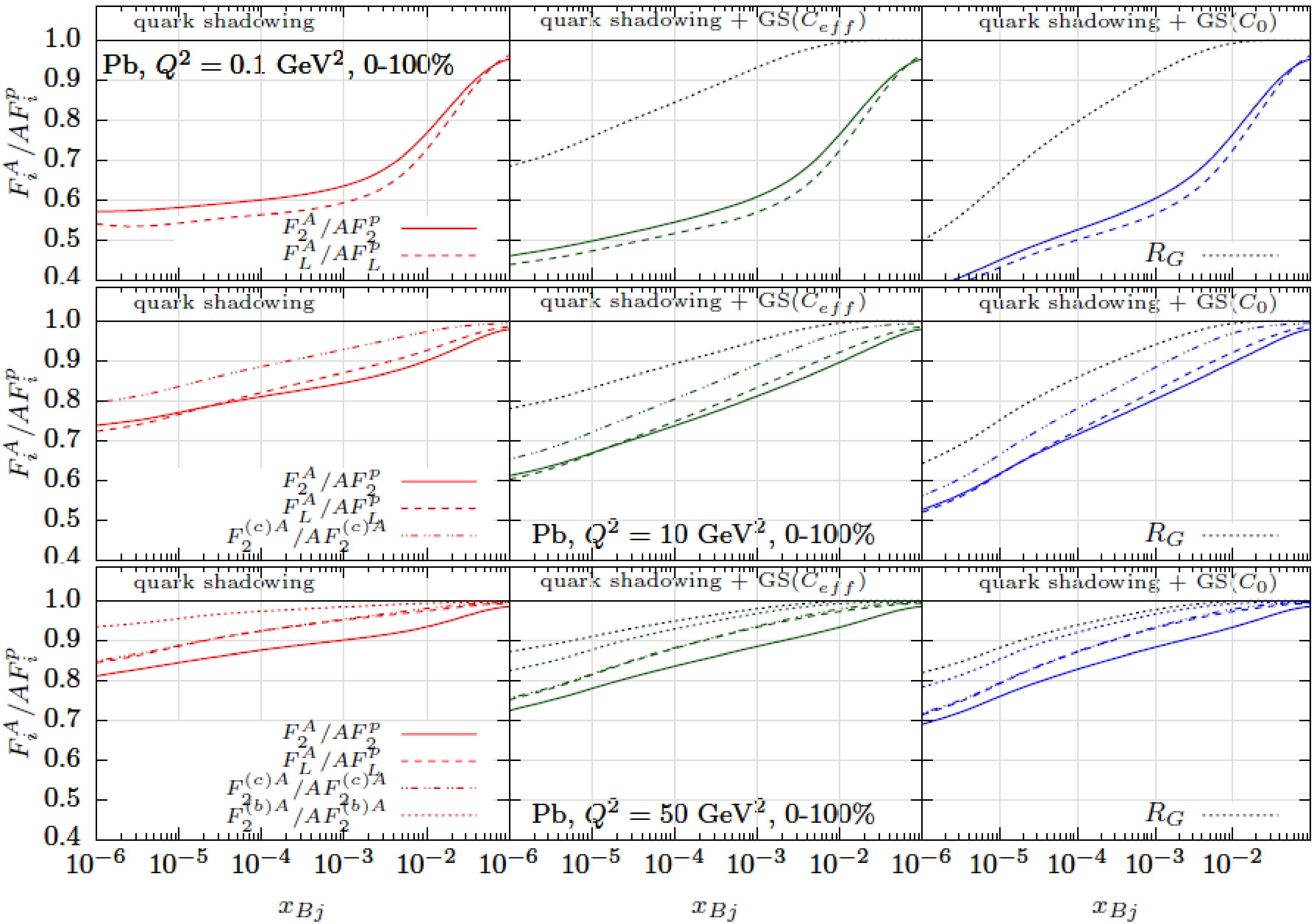
Results: Centrality



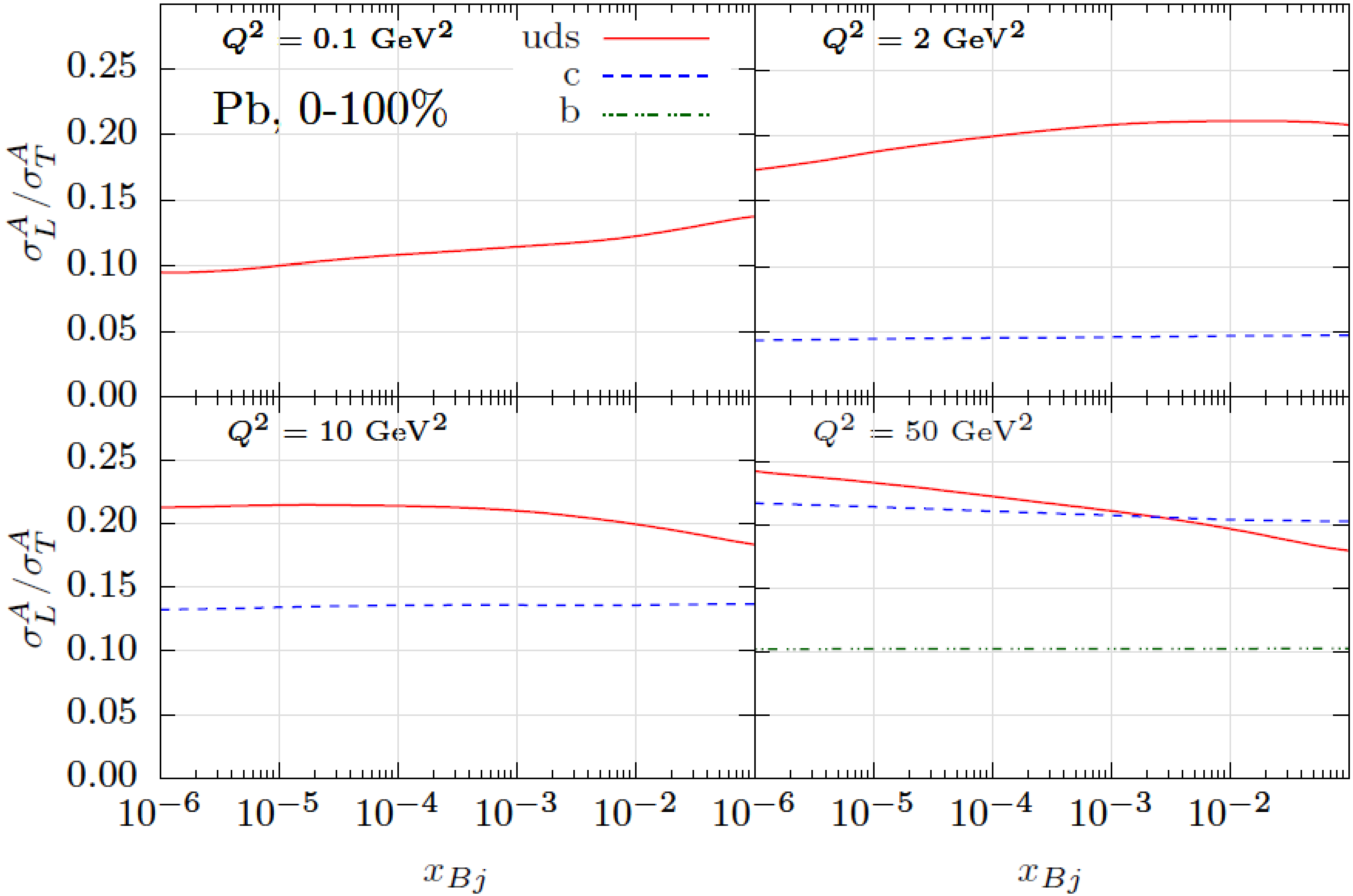
Results: Centrality



Results: Various observables



Results: Ratios



What we offer to EIC?

- **For EIC collaboration**, we offer help with development color dipole framework based MC event generators such as **Sartre**
  - Implementation of Green function formalism
  - Exclusive processes involving VM
  - Other related features…

- **Gluon shadowing grids:**
  - https://zenodo.org/record/3470138

Conclusions and outlooks

- **Improvements**
  - Non-perturbative effects in $q - \bar{q}$ interaction
  - Exact treatment of coherence length
  - Green function technique
- **Gluon shadowing**
  - Green function formalism important
  - Studied uncertainties of applied approximations
- **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 the **nature** calculations at nuclear targets

Thank you for your attention!

CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

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.

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

MINISTRY OF EDUCATION, YOUTH AND SPORTS