Saturation effects in single-inclusive heavy hadron production

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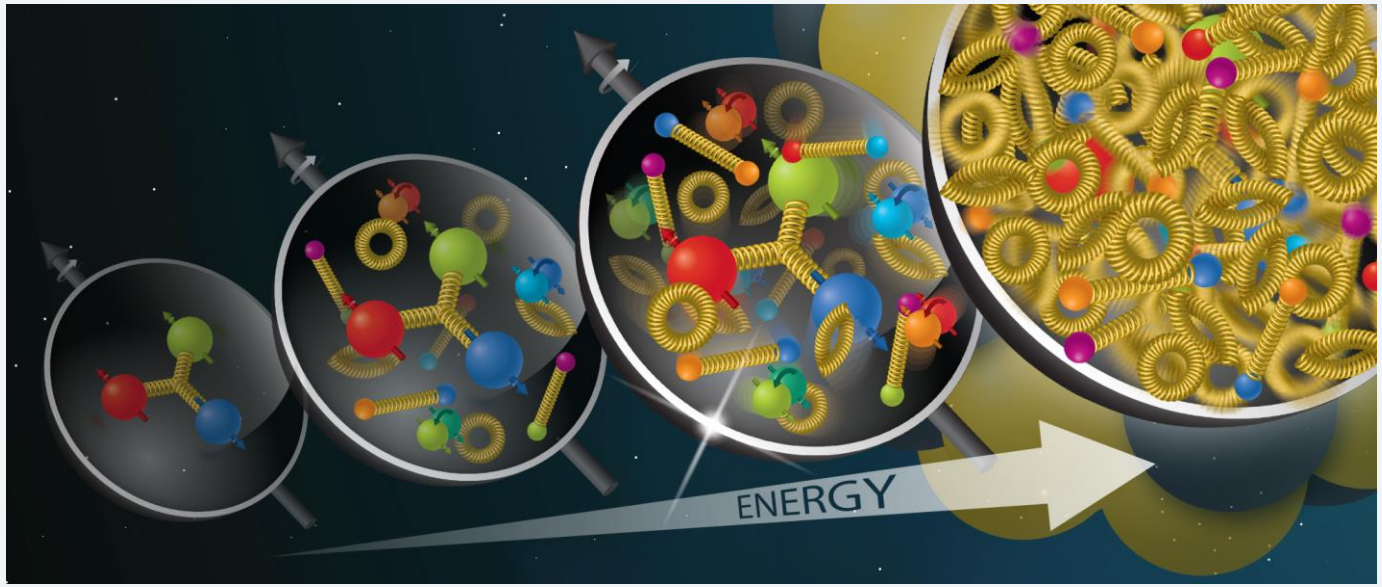
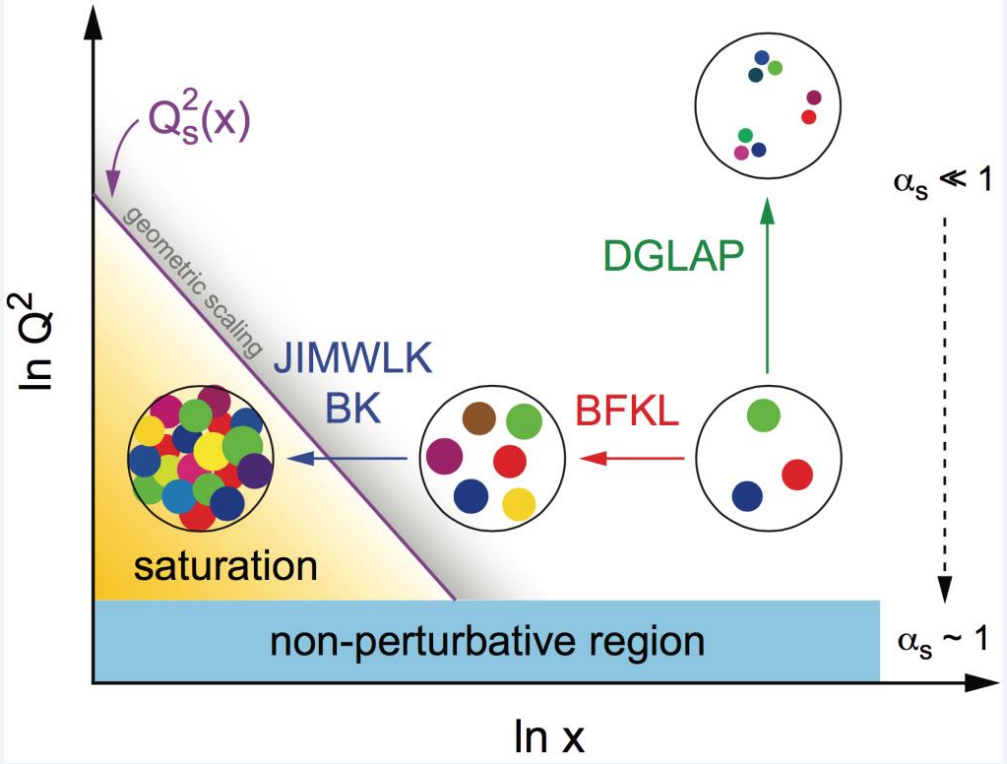
GLUON SATURATION

- An increase in energy scale leads to an increase in gluon density in nuclei due to gluon emissions
- This causes a sharp increase in the cross section of nucleus scattering
- Unlimited growth of gluon density would break unitarity of QCD
- To prevent this, gluon absorption must limit the growth of gluon density at some energy scale
- This is called gluon saturation



DETECTING GLUON SATURATION

- Gluon saturation is predicted by QCD
- There are models with and without saturation: BFKL, DGLAP, BK
- If a cross section measurement is better described by saturation models, it is evidence of gluon saturation
- However, past experiments have not led to clear evidence of saturation



INCLUSIVE QUARK PRODUCTION

- Gluon saturation could be observable in ultraperipheral heavy quark production at the LHC
- One hadron emits a photon, which oscillates into a heavy quark dipole
- The dipole exchanges a gluon with the target hadron, which dissociates
- The interaction between the dipole and the hadron is sensitive to the gluon density of the hadron

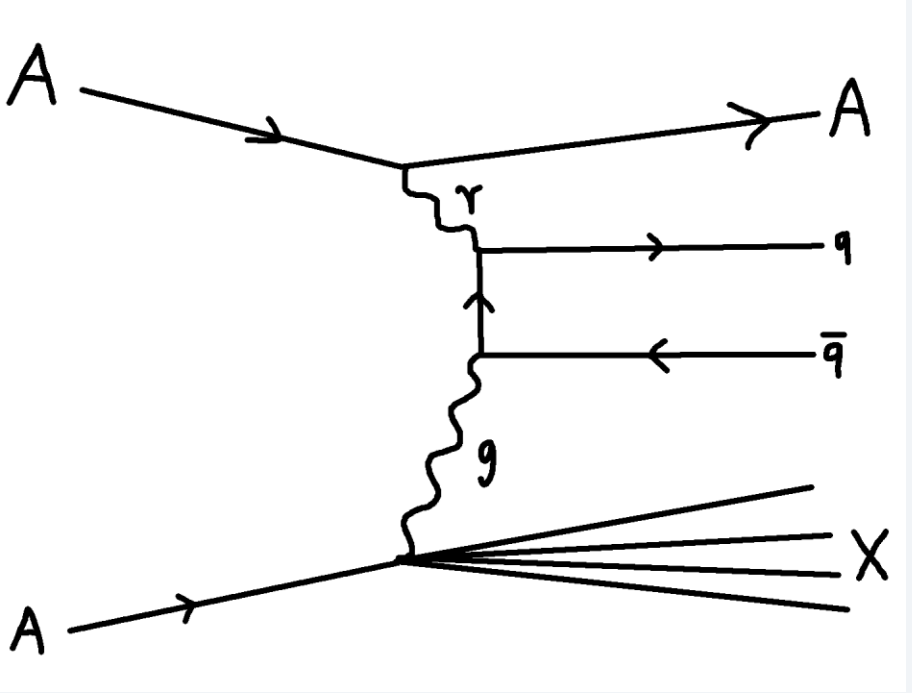
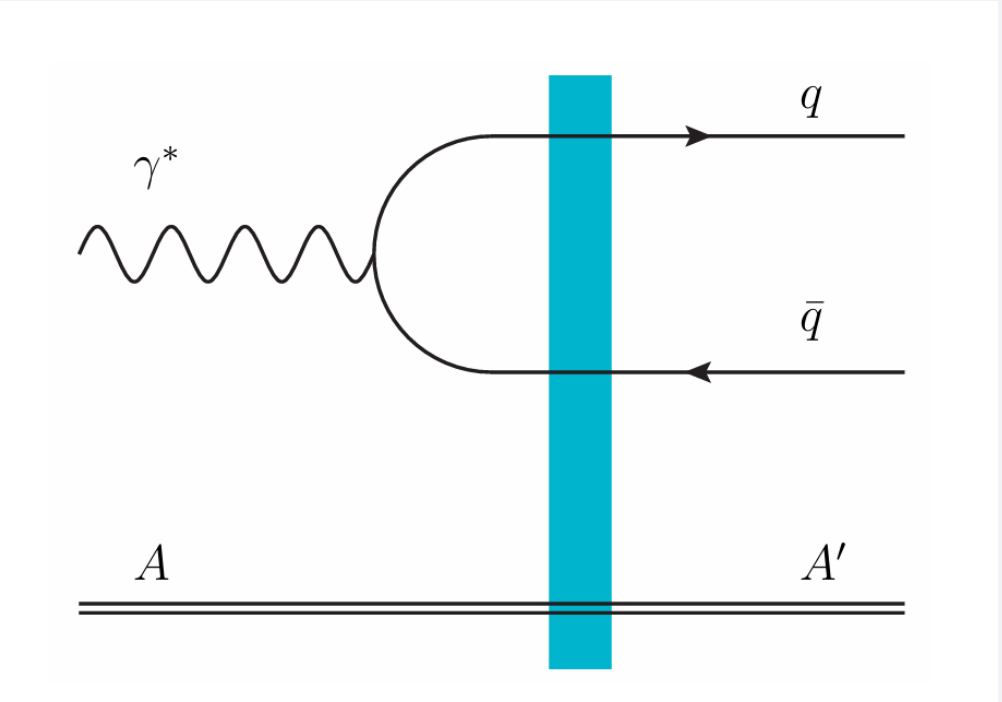


Diagram for quark production in inclusive photon nucleus scattering.

PROCESS FACTORIZATION

- The process can be factorized in two parts
  1. The photon fluctuates into a quark-antiquark pair
  2. The quark-antiquark pair interacts with the target hadron
- The first part is described by the light-cone wave function of the photon
- It can be calculated using perturbative QCD



Factorization of the process in the dipole picture. The blue rectangle depicts the nonperturbative interaction between the dipole and the target.

DIPOLE AMPLITUDE

- The second part of the process is given by the dipole scattering amplitude
- The dipole amplitude is a nonperturbative object
- However, its energy dependence can be described using perturbative evolution equation
- The dipole amplitude must be fitted to measurement data at some initial energy scale
- The evolution equations can then be used to calculate the dipole amplitude at other energy scales
  - ➢ The measurement at the initial scale affects predictions at all other scales

Evolution equations

- Balitsky-Fadin-Kuraev-Lipatov (BFKL) equation
  - Linear
  - Does not include saturation
- Balitsky-Kovchegov (BK) equation
  - Nonlinear
  - Does include saturation

INCLUSIVE FORMULA

- The inclusive cross section is a function of two variables:
  - The Bjorken x
  - Photon virtuality Q^2
- The three integrations are done over:
  - The size and orientation of the dipole **r**
  - The impact parameter **b**
  - The fraction of photon momentum carried by the quark z
- The dipole amplitude depends on **r**, **b** and the shifted Bjorken x:

$$\tilde{x} = x\left(1 + \frac{4m_f^2}{Q^2}\right)$$

Dipole amplitude

$$\sigma^{\gamma_\lambda^* \to q_f \bar{q}_f \to X} = \frac{4\alpha_{\mathrm{em}} N_c e_f^2}{(2\pi)^2} \int d^2\mathbf{r} d^2\mathbf{b} \int_0^1 dz K_\lambda(\mathbf{r}, z) N_{\tilde{x}}(\mathbf{r}, \mathbf{b})$$

$$K_\lambda(\mathbf{r}, z) = \begin{cases} 4Q^2 z^2 (1-z)^2 K_0(\epsilon |\mathbf{r}|)^2 & \lambda = L \\ m_f^2 K_0(\epsilon |\mathbf{r}|)^2 + \epsilon^2 \left[z^2 + (1-z)^2\right] K_1(\epsilon |\mathbf{r}|)^2 & \lambda = T \end{cases}$$

$$\mathbf{r} = \mathbf{x} - \mathbf{y}$$

$$\mathbf{b} = \frac{1}{2}(\mathbf{x} + \mathbf{y})$$

$$\epsilon^2 = m_f^2 + z(1-z)Q^2$$

Modified Bessel function of the second kind

Locations of the quark and antiquark relative to the nucleus

Different cases for longitudinally and transversely polarized photons

COMPUTATION

- The dipole amplitudes have been computed from fits to vector meson data and stored in tables by Jani Penttala
- Different protons and lead ions have their own tables
- Due to the difference in their evolutions, the BK and BFKL models also have separate tables
- The integrals are computed using GSL VEGAS Monte Carlo integration

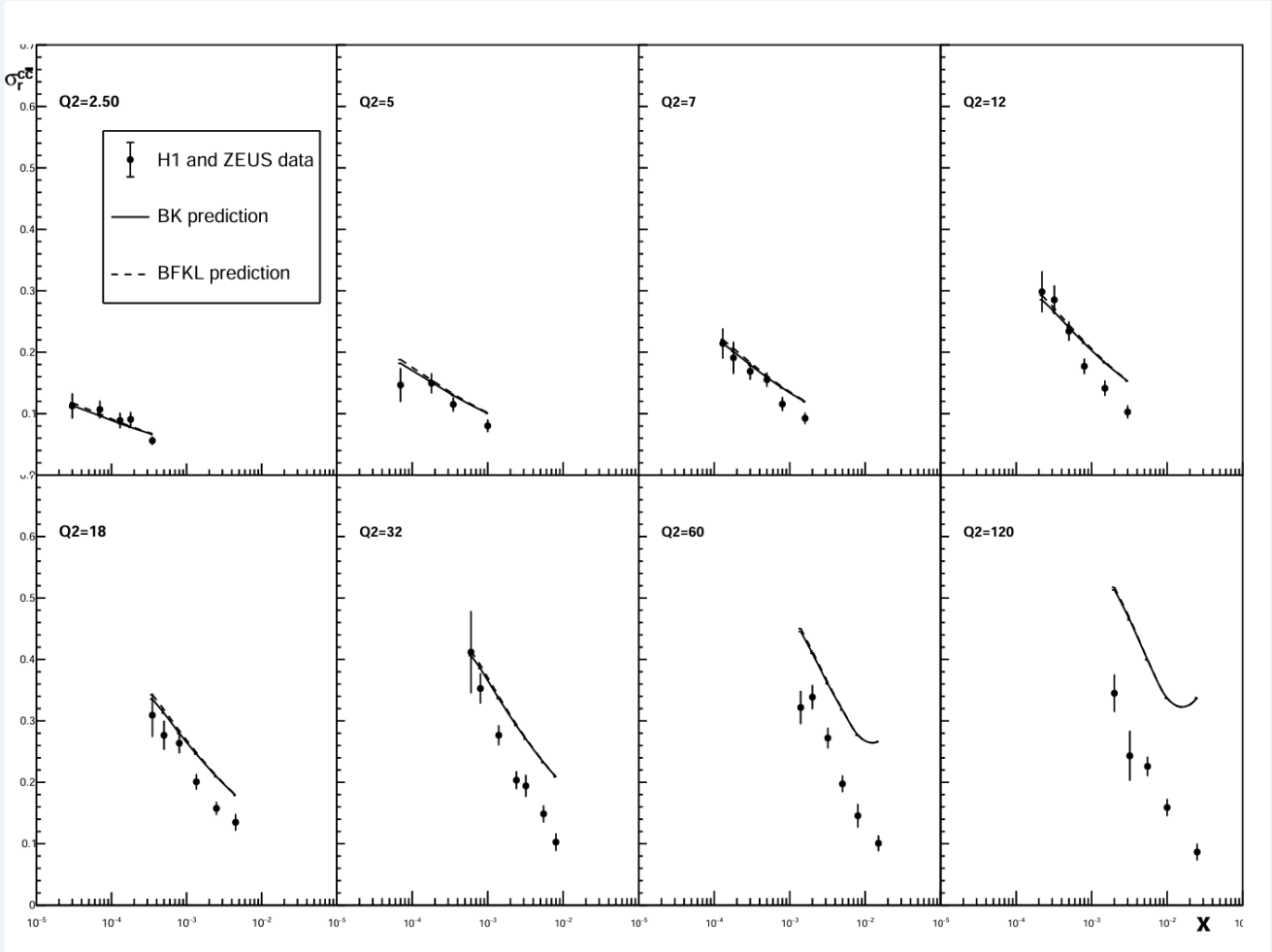
GNU Scientific Library (GSL)

INCLUSIVE $c\bar{c}$ DATA COMPARISON

- The formula can be tested by comparing it with measurements of the reduced cross section:

$$\sigma_r\left(y, x, Q^2\right) = \frac{Q^2}{4\pi^2\alpha_{\mathrm{em}}}\sigma^{\gamma_T^* \to q_f\bar{q}_f \to X} + \left(1 - \frac{y^2}{1+(1-y)^2}\right)\frac{Q^2}{4\pi^2\alpha_{\mathrm{em}}}\sigma^{\gamma_L^* \to q_f\bar{q}_f \to X}$$

- y is the inelasticity of the scattering
- The data on the right is from proton collisions at H1 and ZEUS
- The prediction is valid at small Q^2
- However, the Q^2 dependence is unexpected and requires further study
- The difference between BK and BFKL is negligible because no saturation is expected for protons at this low energies
- Note that no additional parameters are used to adjust any of the predictions in this presentation



Reduced $c\bar{c}$ production cross section measurements in inclusive photon proton scattering at H1 and ZEUS with varying Q^2.

DIFFRACTIVE QUARK PRODUCTION

- In a diffractive process the target nucleus emits two gluons (a pomeron) and stays intact
- The cross section is much smaller than for the inclusive process
- However, sensitivity to gluon density is stronger
- Diffractive calculation uses a different dipole amplitude compared to inclusive

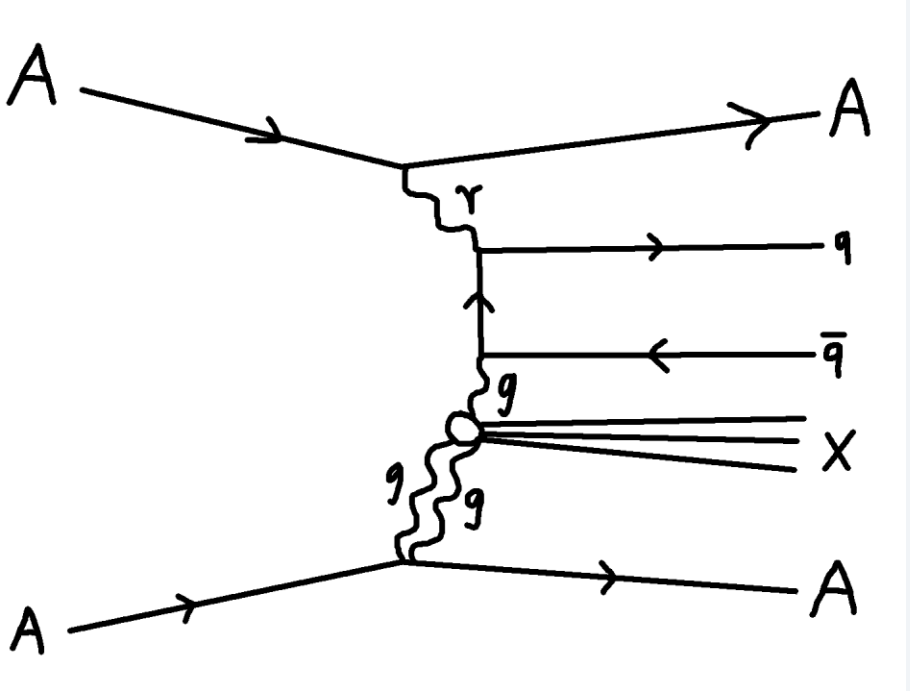


Diagram for quark production in diffractive photon nucleus scattering.

DIFFRACTIVE FORMULA

- Here the complex conjugate coordinates $\bar{r}$ and $\bar{b}$ must be integrated separately
- Due to the pomeron, the cross section depends on two new independent variables:
  - Invariant mass of the diffractive system M_X
  - Momentum transfer t
- In the diffractive case instead of the shifted Bjorken x, the x_{pom} variable is used:

$$\tilde{x}' = x_{\mathrm{pom}} = \frac{x}{\beta} = \left(Q^2 + M_X^2 - t\right)\frac{x}{Q^2}$$

Dipole amplitude appears twice

Bessel function of the first kind

Depends on two new variables

$$\frac{d\sigma^D}{dtdM_X^2} = \frac{1}{2(2\pi)^4}\alpha_{\mathrm{em}}N_c e_f^2 \int_0^1 dz \int d^2\mathbf{r} \int d^2\bar{\mathbf{r}} \int d^2\mathbf{b}$$

$$\int d^2\bar{\mathbf{b}} J_0\left(\sqrt{|t|}\left|\mathbf{b}-\bar{\mathbf{b}}\right|\right) J_0\left(\sqrt{z(1-z)M_X^2 - m_f^2}\,|\mathbf{r}-\bar{\mathbf{r}}|\right) \theta\left(\sqrt{z(1-z)M_X^2 - m_f^2}\right) z(1-z)\, H(\mathbf{r},\bar{\mathbf{r}},z)\, N_{\tilde{x}'}(\mathbf{r},\mathbf{b})\, N_{\tilde{x}'}\left(\bar{\mathbf{r}},\bar{\mathbf{b}}\right)$$

$$\mathbf{r} = \mathbf{x} - \mathbf{y}$$

$$\mathbf{b} = z\mathbf{x} + (1-z)\,\mathbf{y}$$

Different b definition

$$H_\lambda(\mathbf{r},\bar{\mathbf{r}},z) = \begin{cases} 4Q^2 z^2(1-z)^2 K_0(\epsilon|\mathbf{r}|) K_0(\epsilon|\bar{\mathbf{r}}|) & \lambda = L \\ m_f^2 K_0(\epsilon|\mathbf{r}|) K_0(\epsilon|\bar{\mathbf{r}}|) + \epsilon^2\left[z^2 + (1-z)^2\right]\frac{\mathbf{r}\cdot\bar{\mathbf{r}}}{|\mathbf{r}||\bar{\mathbf{r}}|} K_1(\epsilon|\mathbf{r}|) K_1(\epsilon|\bar{\mathbf{r}}|) & \lambda = T \end{cases}$$

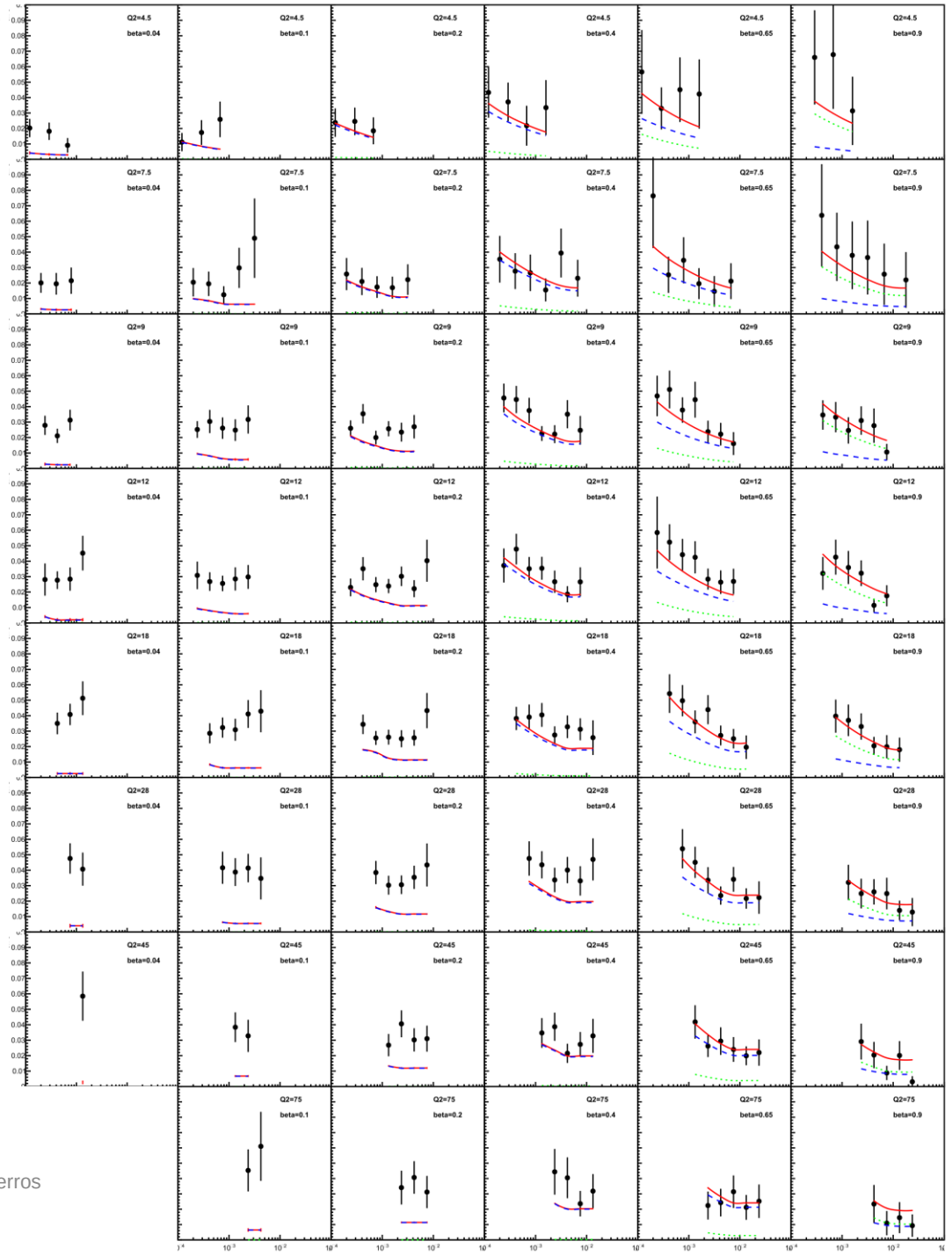
$$\epsilon^2 = z_0 z_1 Q^2 + m_f^2$$

$x_{pom}F_2^{D(3)}$

Total prediction

Transverse polarization

Longitudinal polarization



x_{Bj}

Measurements from H1 of the differential structure function $F_2^{D(3)}(x_{pom}, \beta, Q^2)$ multiplied with x_{pom} in diffractive photon proton scattering at varying β and Q^2.

Diffractive data comparison

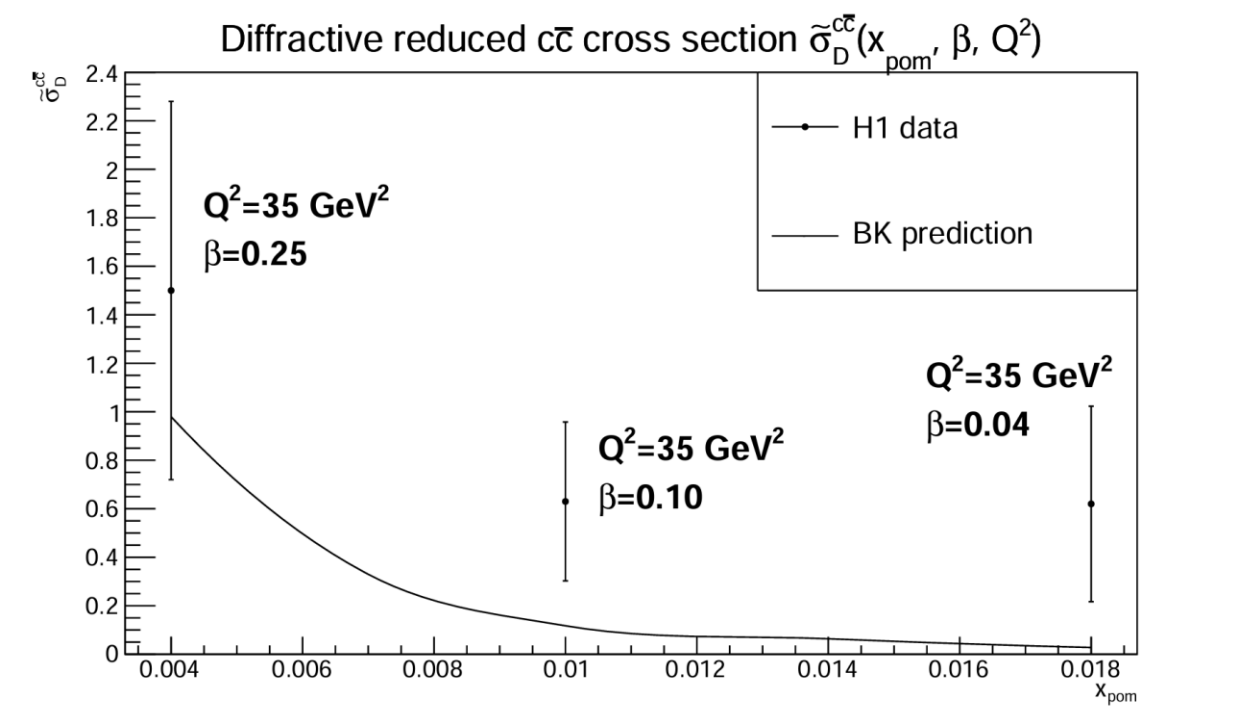
- Comparison between diffractive prediction and $x_{pom}F_2^{D(3)}$ measurements from H1
- The diffractive cross section is integrated over t
- M_X^2 dependence is replaced with β:

$$\beta \approx \frac{Q^2}{Q^2 + M_X^2}$$

- The prediction contains lightest quarks up to charm
- The prediction at low β is too small because of a large next to leading order contribution
- The agreement is good at high β

DIFFRACTIVE CHARM DATA COMPARISON

- The diffractive formula can be compared with specifically charm production cross section measurements from H1
- Here again t is integrated and M_X^2 is replaced with β
- The precision of the measurements is not sufficient to tell much about the validity of the prediction



Reduced $c\bar{c}$ production cross section in diffractive photon proton scattering measurements from H1

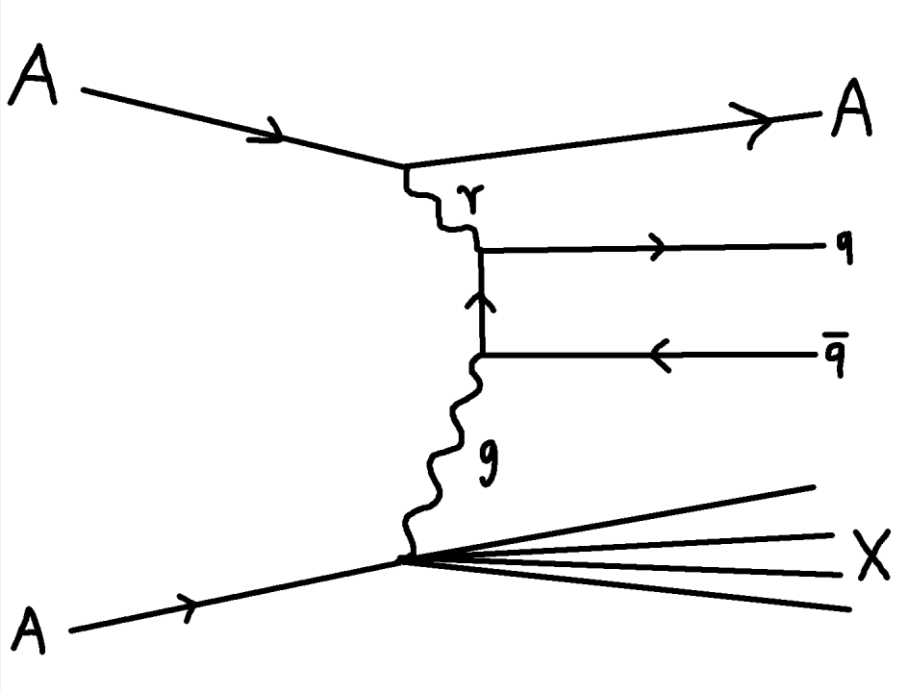
LHC MEASUREMENT

- MIT is analyzing charm quark production cross section measurements in photon lead scattering in the CMS detector
- Due to the large center of mass energy at the LHC and the use of lead ions there is a chance of detecting saturation effects
- The LHC measurement is ultraperipheral, so the photon virtuality is effectively zero: $Q^2 = 0$
- For the diffractive process both t and M_X^2 are integrated
- Bottom quark measurements may also be analyzed later

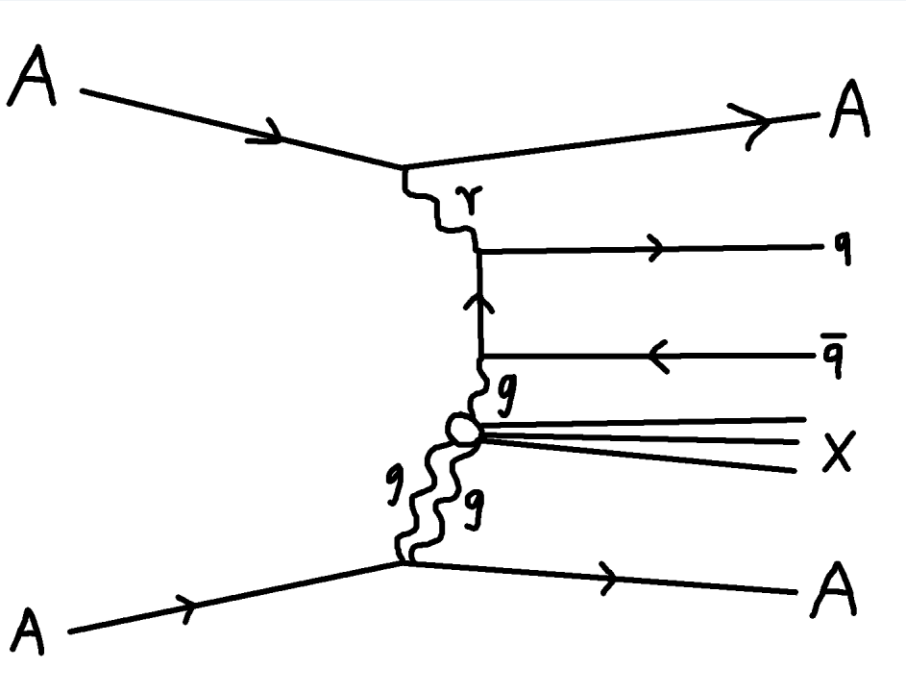
Massachusetts Institute of Technology

REMINDER: PROCESSES

Inclusive process

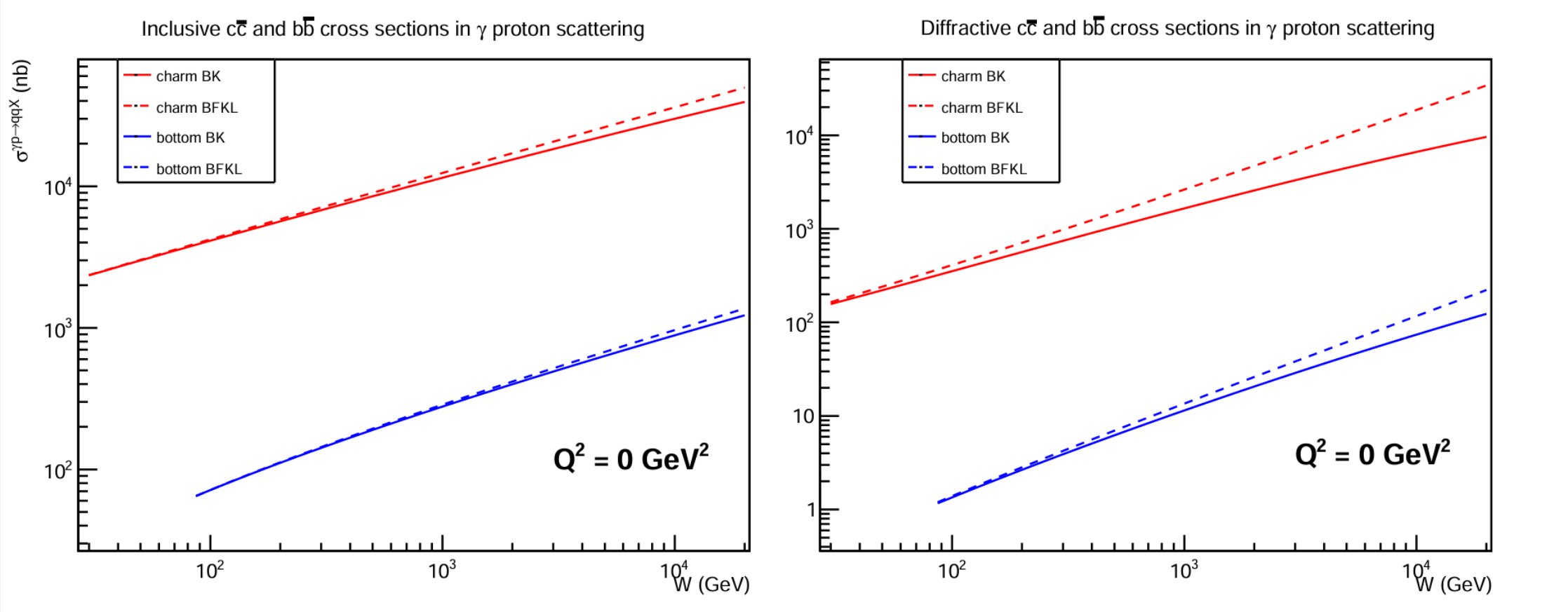


Diffractive process



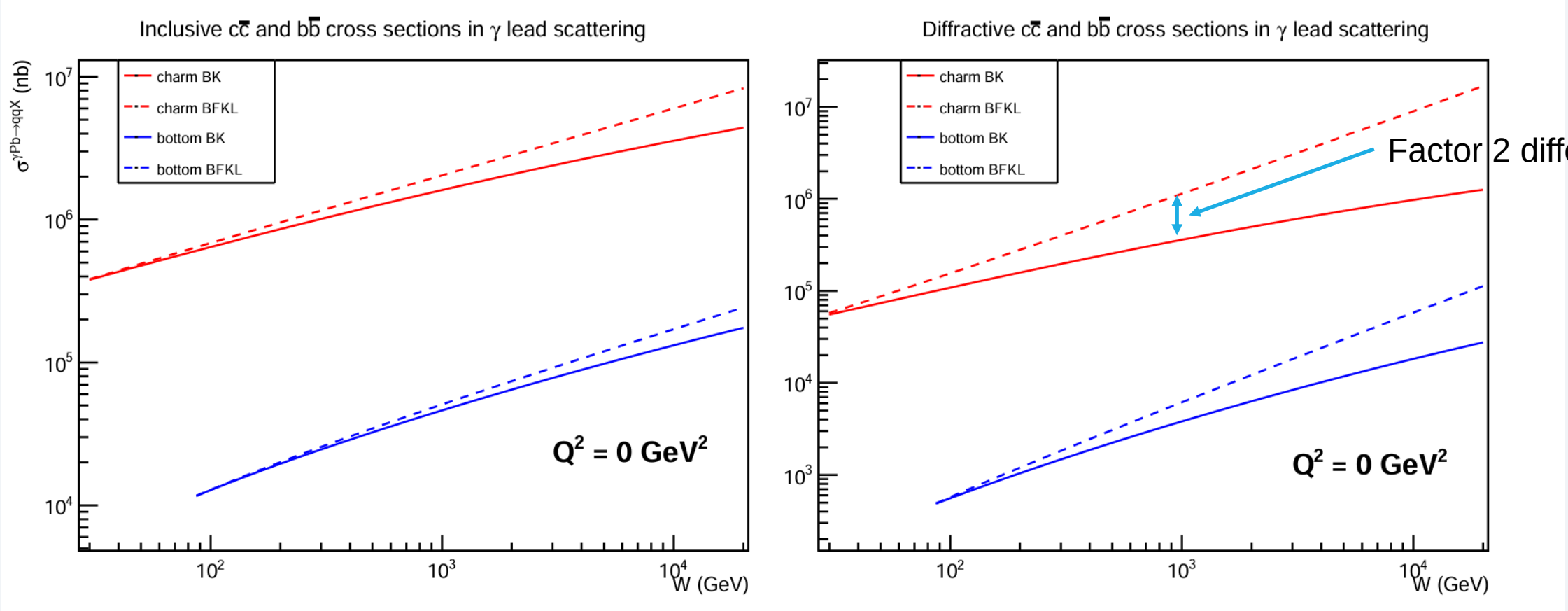
In the diffractive process the target nucleus interacts with a gluon twice, so the dipole amplitude is squared. This amplifies the difference between the BK and BFKL evolutions.

LHC PROTON SCATTERING PREDICTION



Predictions for heavy quark production cross sections in photon proton scattering with BK evolution (saturation) and BFKL evolution (no saturation).

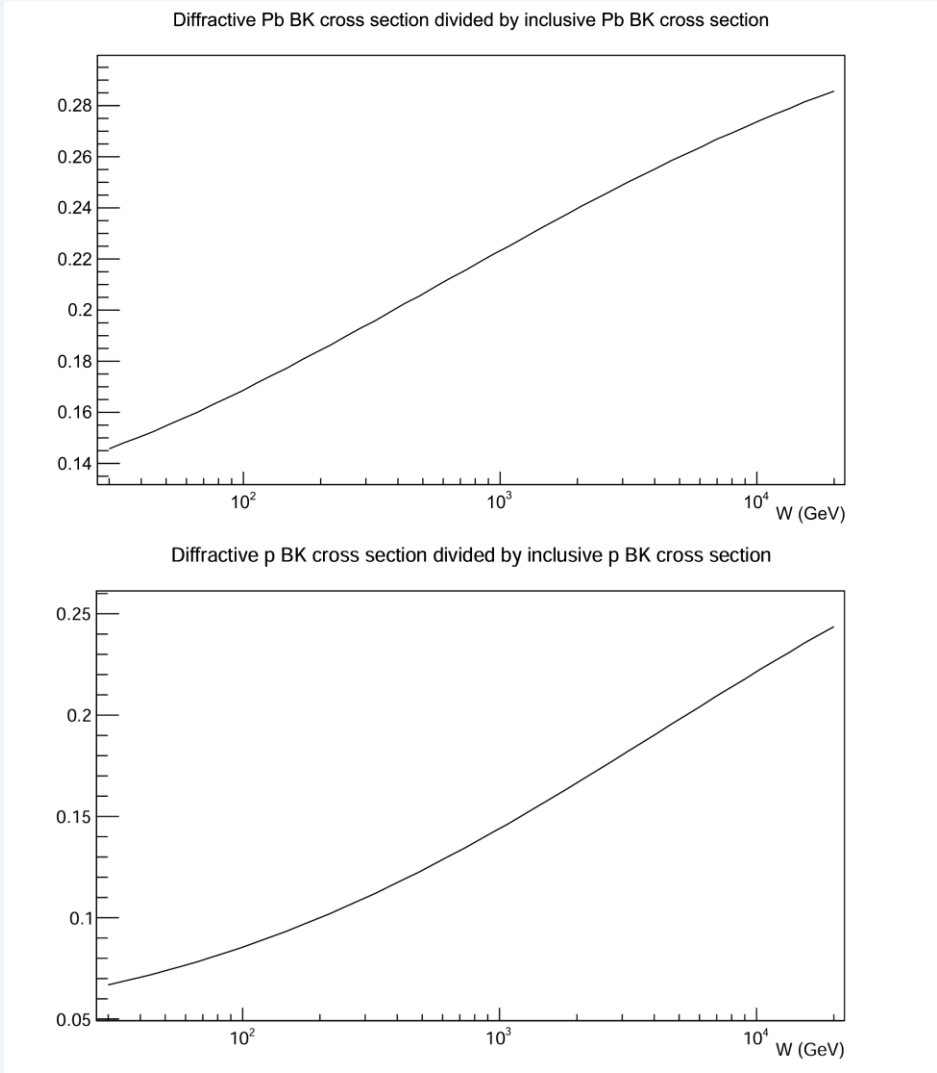
LHC LEAD SCATTERING PREDICTION



Predictions for heavy quark production cross sections in photon lead scattering with BK evolution (saturation) and BFKL evolution (no saturation).

DIFFRACTIVE INCLUSIVE RATIO

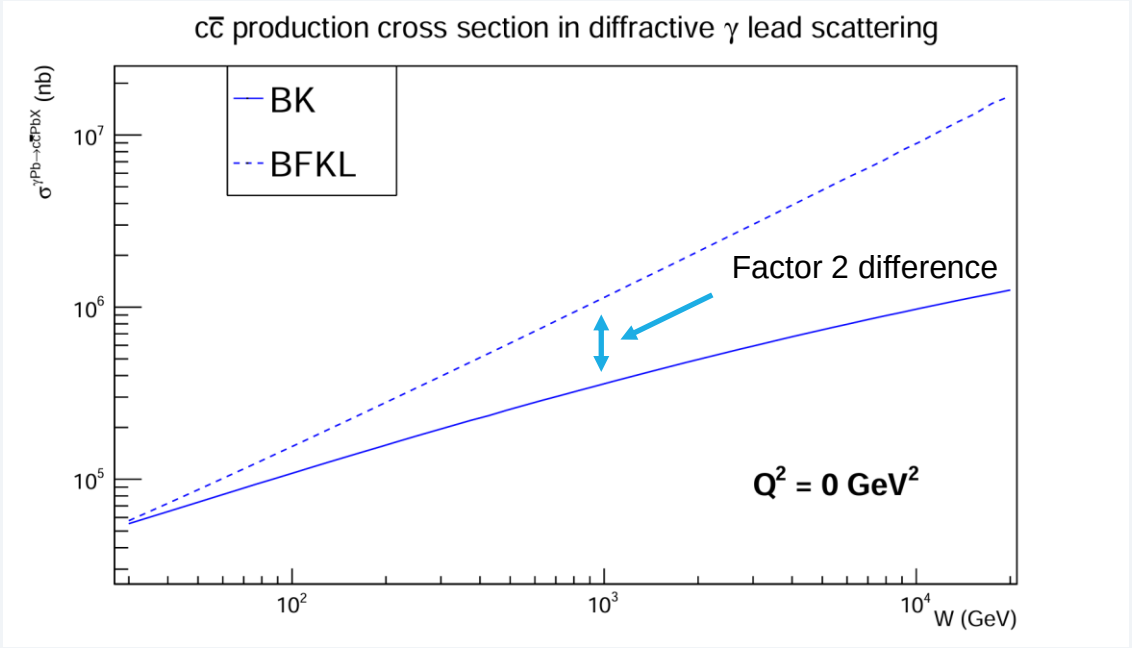
- With BK evolution, the diffractive $c\bar{c}$ cross section is predicted to be a large contribution to the inclusive $c\bar{c}$ cross section
- This is a surprising result
- However, a similar observation has been made by ATLAS



For lead, the diffractive cross section is a fourth of the inclusive cross section at high energy. For protons it is a fifth instead.

CONCLUSION

- Confirmation of saturation observations made for J/ψ and Υ would be a major achievement
- A significant difference between BK and BFKL in diffractive charm production cross section in photon lead scattering is predicted
- However, it will depend on measurement precision if the difference can be distinguished
- The prediction can be improved further:
  - Adding contribution from $q\bar{q}g$ final state to improve prediction at small β and large Q^2
  - Better dipole amplitude fits
  - Full next to leading order calculation is in progress



Predictions for charm quark production cross sections in photon lead scattering with BK evolution (saturation) and BFKL evolution (no saturation).

SOURCES

- Inclusive $c\bar{c}$ cross section measurement
  - Abramowicz, H., Abt, I., Adamczyk, L. et al. Combination and QCD analysis of charm and beauty production cross-section measurements in deep inelastic ep scattering at HERA. Eur. Phys. J. C 78, 473 (2018).
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  - Aktas, A., Andreev, V., Anthonis, T. et al. Diffractive open charm production in deep-inelastic scattering and photoproduction at HERA. Eur. Phys. J. C 50, 1–20 (2007).
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