Investigating the inclusive D^0 and B^0 photoproduction in ultraperipheral collisions

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In collaboration with

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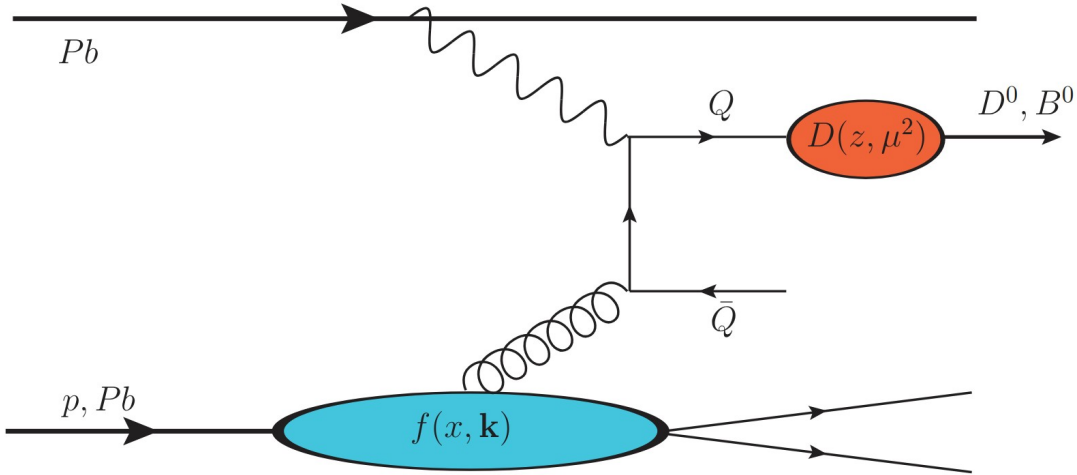
Introduction

- Investigate the description of Quantum Chromodynamics at high energies through pPb and PbPb collisions;
- **Exclusive processes:** both incident particles remain intact in the collision ⇒ largely investigated over the last years;
- **Inclusive processes:** at least one of the incident hadrons break up due the strong interaction ⇒ the first data in ultraperipheral collisions (UPCs) became available only recently by the ATLAS [1], CMS [2], and ALICE [3] collaborations.



[1] ATLAS Collaboration. Measurement of photonuclear jet production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with the ATLAS detector. Physical Review D, v. 111, n. 5, p. 052006, 2025.
[2] CMS Collaboration. Measurement of D^0 meson photoproduction in ultraperipheral heavy ion collisions. arXiv preprint arXiv:2509.08626, 2025.
[3] ALICE Collaboration. New probes of nuclear gluon dynamics through photoproduction of charm in inelastic ultra-peripheral PbPb collisions with ALICE. arXiv preprint arXiv:2509.11814, 2025.

Objectives

- Complement the investigation that has been carried out in exclusive processes;
- Describe the differential cross section in terms of the unintegrated gluon distribution (UGD);
- Constrain the **QCD dynamics and nuclear effects** using different models for the UGD.

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Letter

Investigating the inclusive D^0 photoproduction in ultraperipheral $PbPb$ collisions at the Large Hadron Collider

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In this seminar...

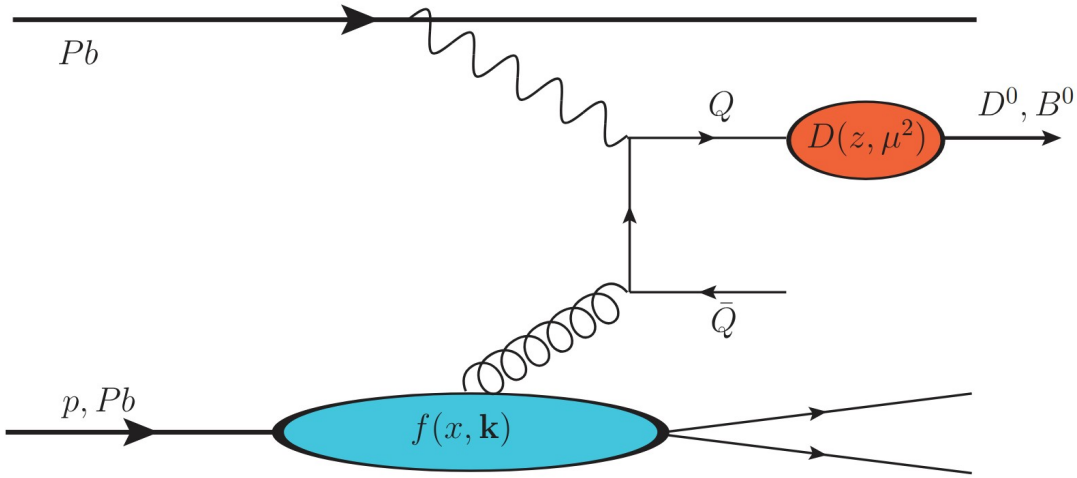
- Implementation of a new fragmentation function for the mesons;
- Investigation of pPb collisions;
- Update of the analyses including the B^0 meson;
- Comparison with the recent CMS and (preliminary) ALICE data.

The results discussed in this seminar will be available soon on arXiv!

Formalism

Differential cross section for the production of H (D^0 or B^0):

$$\frac{d^2\sigma(A+B\to A\otimes H+X)}{dY_H d^2p_{T,H}} = \int_{z_{min}}^{1}\frac{dz}{z^2}D_{Q/H}(z,\mu^2)\left[\frac{d^2\sigma(A+B\to A\otimes Q\bar{Q}+X)}{dY_Q d^2p_T}\right]_{p_T=\frac{p_{T,H}}{z}}$$



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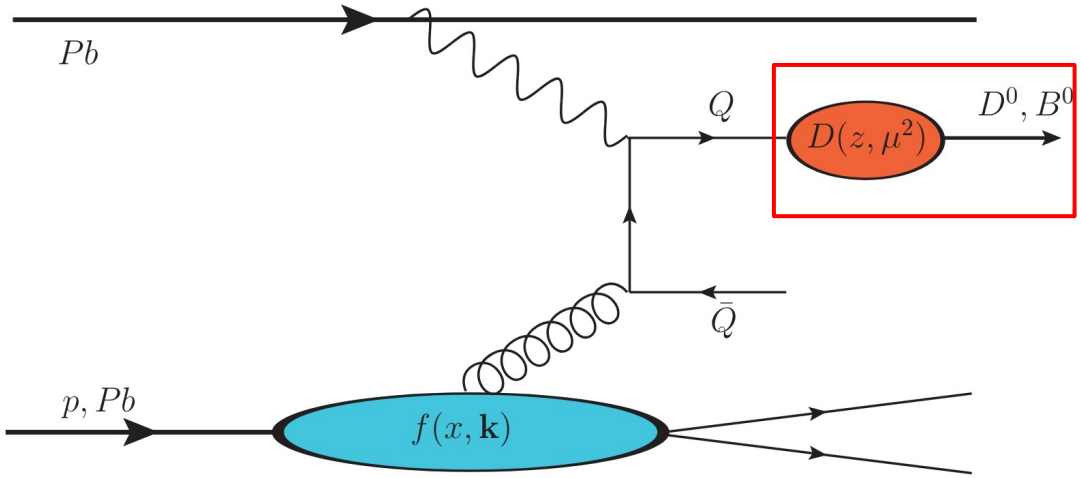
Fragmentation function $D_{Q/H}(z,\mu^2)$ $\Rightarrow$ KKKS model:

- non-perturbative fragmentation function for mesons D^0, D^+, and D^{*+} by fitting experimental data from the Belle, CLEO, ALEPH, and OPAL Collaborations [5]; and for B mesons through a global fit to e^+e^- data from CERN LEP1 and SLAC SLC [6].



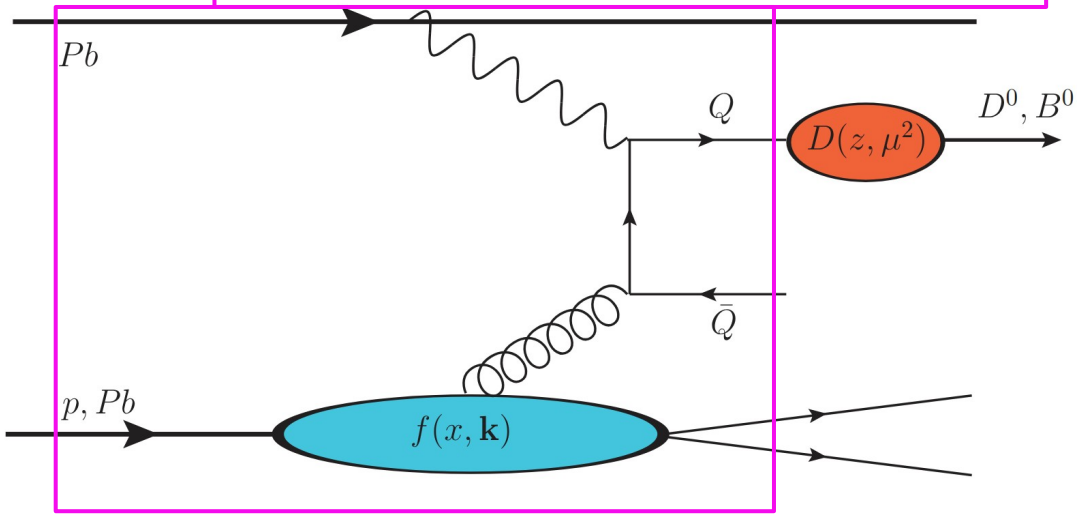
[5] KNEESCH, Torben et al. Charmed-meson fragmentation functions with finite-mass corrections. Nuclear Physics B, v. 799, n. 1-2, p. 34-59, 2008.
[6] KNIEHL, Bernd A. et al. Finite-mass effects on inclusive B-meson hadroproduction. Physical Review D, v. 77, n. 1, p. 014011, 2008.

Formalism

Differential cross section for the production of H (D^0 or B^0):

$$\frac{d^2\sigma(A+B\to A\otimes H+X)}{dY_H d^2p_{T,H}} = \int_{z_{min}}^{1}\frac{dz}{z^2}D_{Q/H}(z,\mu^2)\left[\frac{d^2\sigma(A+B\to A\otimes Q\bar{Q}+X)}{dY_Q d^2p_T}\right]_{p_T=\frac{p_{T,H}}{z}}$$

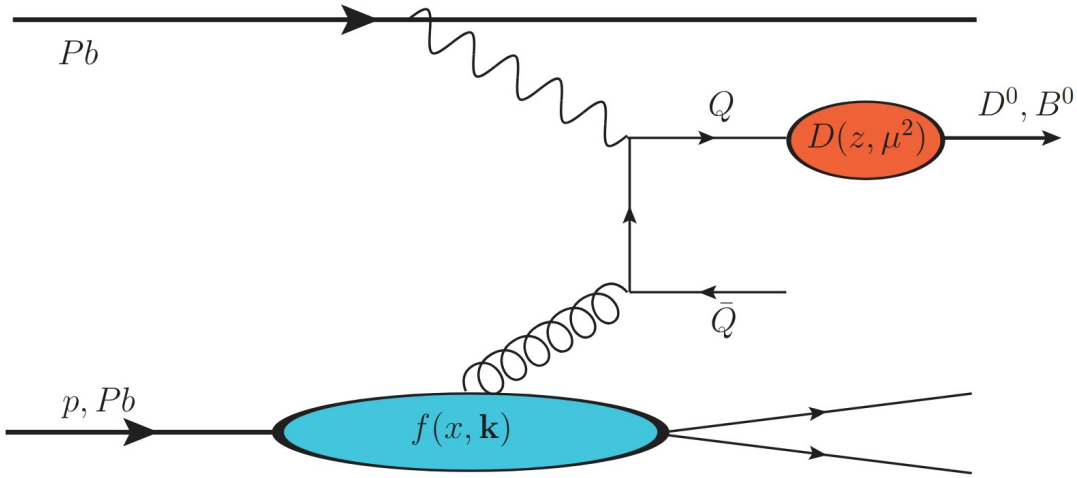
Differential cross section for heavy quark production!



Formalism

Differential cross section for heavy quark production in UPCs:

$$\frac{d\sigma(A+B\to A\otimes Q\bar{Q}+X)}{dY_Q d^2p_T}=\int_{x_Q}^{1}dz_Q\frac{x_Q}{z_Q}f^{\text{eff}}_{\gamma/A}\left(\frac{x_Q}{z_Q}\right)\frac{d\sigma(\gamma B\to Q\bar{Q}X)}{dz_Q d^2p_T}\qquad x_Q=\sqrt{\frac{p_T^2+m_Q^2}{s_{NN}}}\exp(+Y_Q)$$



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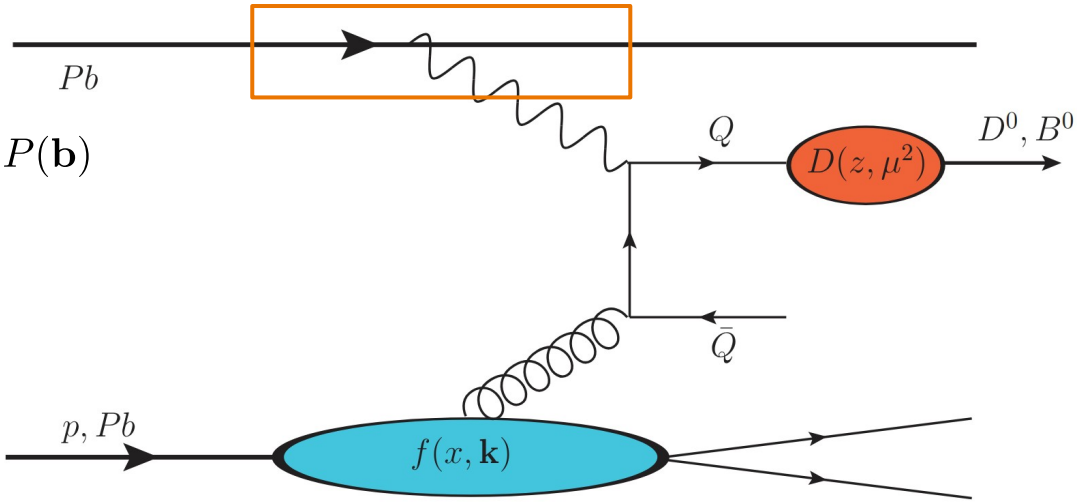
Effective photon flux [6]:

$$f^{eff}_{\gamma/A}(x)=\frac{Z^2\alpha_{em}}{\pi^2 x}\int_{R_A+R_B}^{\infty}\frac{d^2\mathbf{b}}{b^2}\left(\frac{\omega b}{\gamma}\right)^2 K_1^2\left(\frac{\omega b}{\gamma}\right)P(\mathbf{b})$$

where $x=2\omega/\sqrt{s_{NN}}$.



[7] BERTULANI, Carlos A.; BAUR, Gerhard. Electromagnetic processes in relativistic heavy ion collisions. Physics Reports, v. 163, n. 5-6, p. 299-408, 1988.
[8] KŁUSEK-GAWENDA, Mariola et al. Electromagnetic excitation of nuclei and neutron evaporation in ultrarelativistic ultraperipheral heavy ion collisions. Physical Review C, v. 89, n. 5, p. 054907, 2014.

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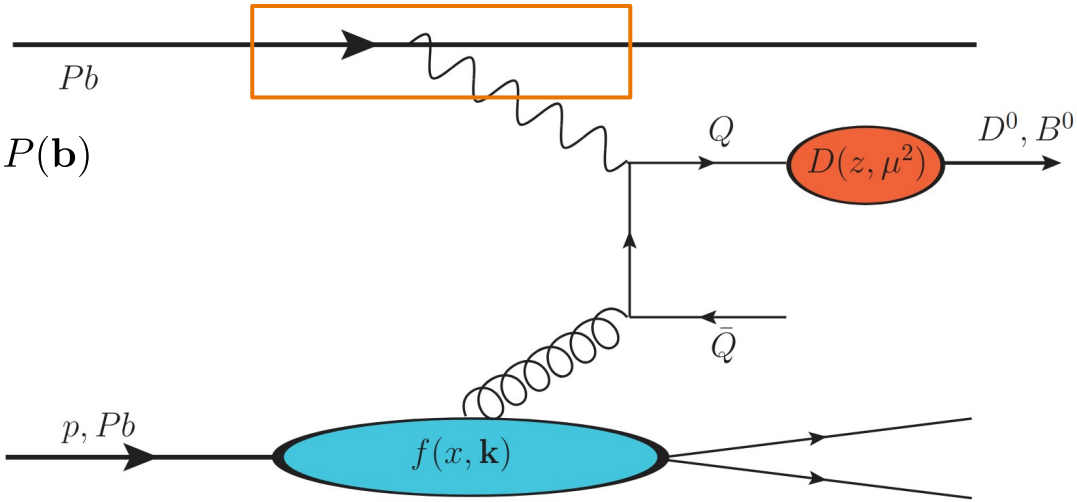
where $x=2\omega/\sqrt{s_{NN}}$.

Probability of no electromagnetic dissociation [7]: $P(\mathbf{b})=\exp(-S/b^2)$

$P(\mathbf{b})=1;\ S=(10.4\text{ fm})^2;\ S=(17.4\text{ fm})^2$



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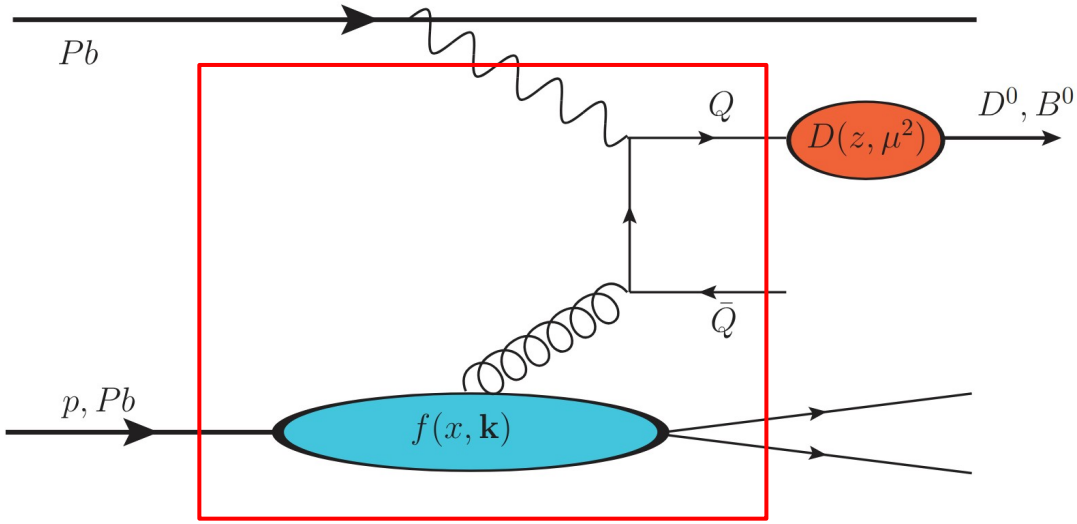
Differential cross section for heavy quark photoproduction!



Formalism

Differential cross section for heavy quark photoproduction:

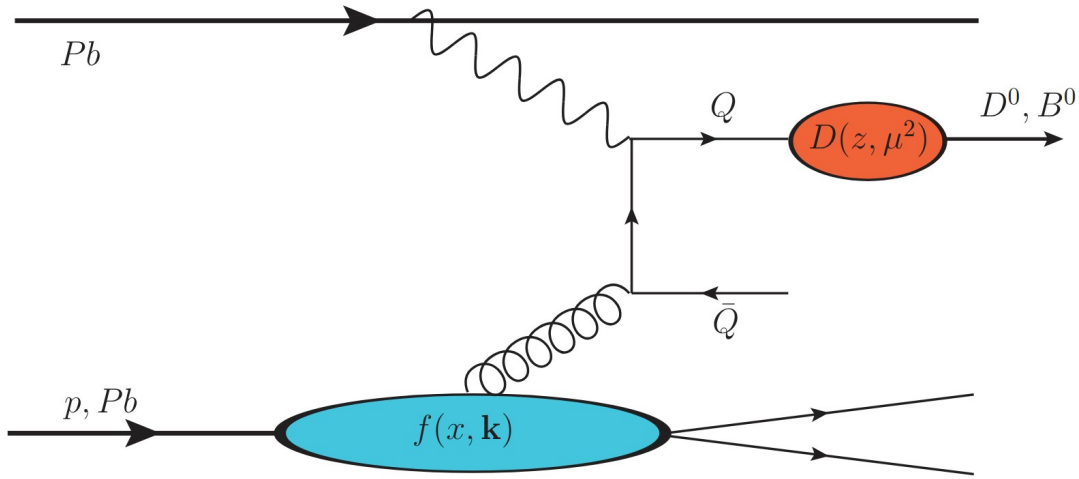
$m_c = 1.4$ GeV, $m_b = 4.5$ GeV

$$\frac{d\sigma_T(\gamma h \to Q\bar{Q}X)}{dz d^2\mathbf{p}} = \frac{N_c \alpha_{em} e_Q^2}{2\pi^2} \int d^2\mathbf{k} f(x,\mathbf{k}) \left\{ \left[z^2 + (1-z)^2 \right] \mathcal{B}_1(\mathbf{p}_T, \mathbf{k}) + m_Q^2 \mathcal{B}_2(\mathbf{p}_T, \mathbf{k}) \right\}$$

where

$$\mathcal{B}_1(\mathbf{p}_T, \mathbf{k}) = \frac{1}{2} \left[\frac{\mathbf{p}_T}{p_T^2 + m_Q^2} - \frac{\mathbf{p}_T + \mathbf{k}}{(\mathbf{p}_T + \mathbf{k})^2 + m_Q^2} \right]^2$$

$$\mathcal{B}_2(\mathbf{p}_T, \mathbf{k}) = \frac{1}{2} \left[\frac{1}{p_T^2 + m_Q^2} - \frac{1}{(\mathbf{p}_T + \mathbf{k})^2 + m_Q^2} \right]^2$$



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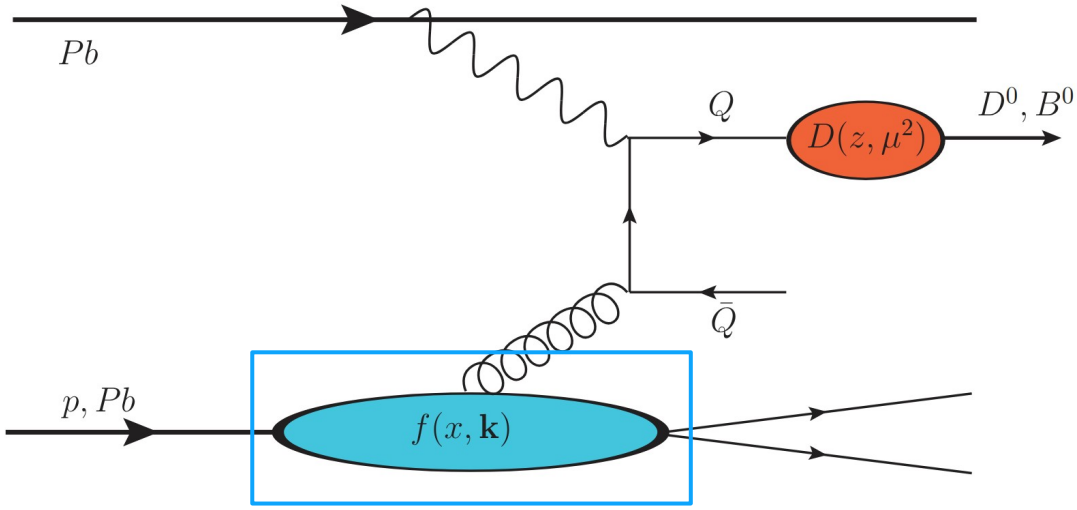


$\Rightarrow$ As a consequence, the heavy quark momentum spectrum is strongly dependent on the modeling of the unintegrated gluon distribution of the target, which is determined by the QCD dynamics.

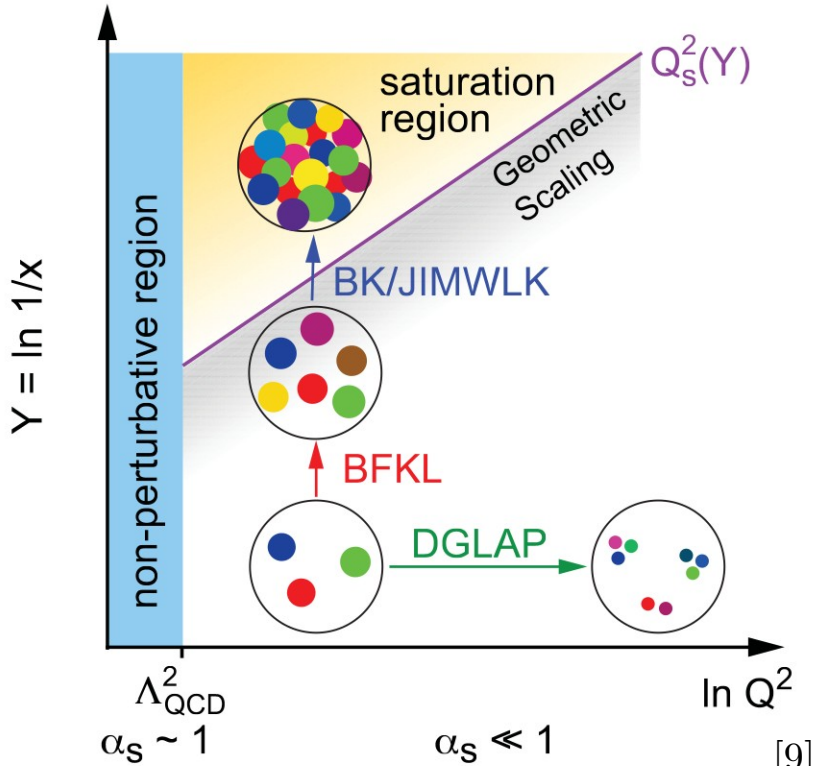
pPb collisions

Formalism

$$\frac{d\sigma_T(\gamma h \to Q\bar{Q}X)}{dz d^2\mathbf{p}} = \frac{N_c \alpha_{em} e_Q^2}{2\pi^2} \int d^2\mathbf{k} f(x,\mathbf{k}) \left\{ \left[z^2 + (1-z)^2 \right] \mathcal{B}_1(\mathbf{p}_T, \mathbf{k}) + m_Q^2 \mathcal{B}_2(\mathbf{p}_T, \mathbf{k}) \right\}$$

For the proton as a target:

$f(x,\mathbf{k})$	Evolution	Based on
CCFM	linear	BFKL and DGLAP equations
KS linear	linear	BFKL
KS nonlinear	nonlinear	BK
rcBK	nonlinear	BK



[9]

[9] Y. V. Kovchegov. Brief Review of Saturation Physics. Acta Phys. Polon., B45(12):2241–2256, 2014.

Results for total cross section in pPb collisions

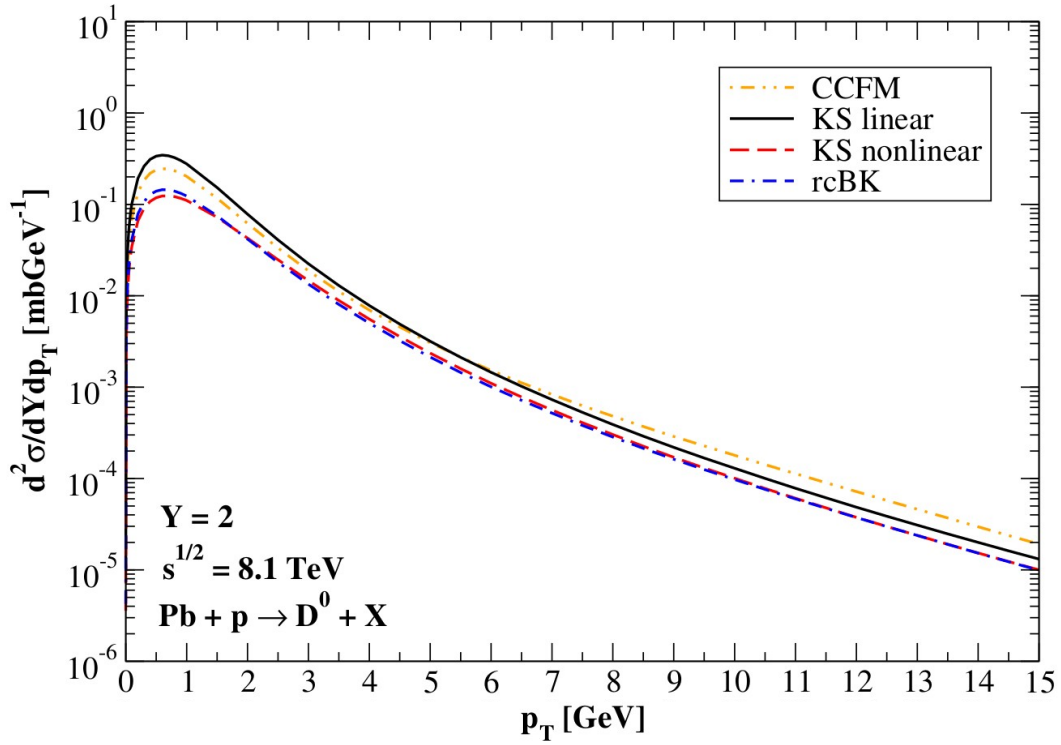
$\sqrt{s} = 8.1$ TeV

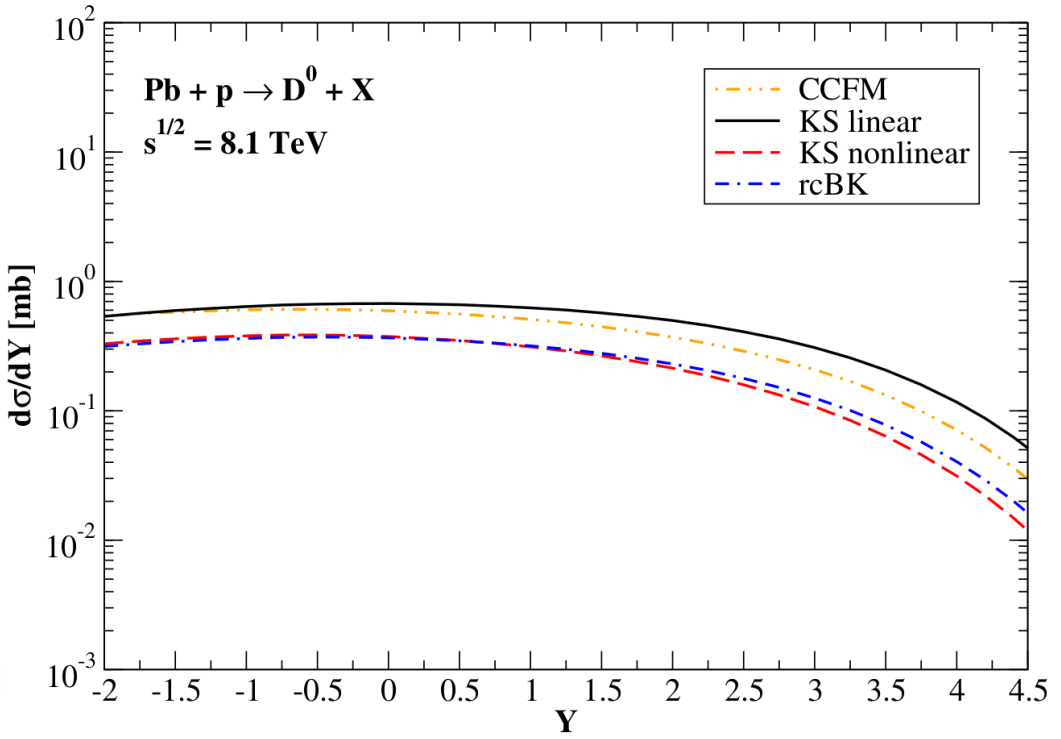
ALICE (-2 < Y < 2)	σ_{tot} for D^0 (mb)	σ_{tot} for B^0 (µb)
CCFM	2.18	26.1
KS linear	2.48	24.4
KS nonlinear	1.35	16.4
rcBK	1.33	14.9

LHCb (2 < Y < 4.5)	σ_{tot} for D^0 (mb)	σ_{tot} for B^0 (µb)
CCFM	0.449	2.41
KS linear	0.656	2.86
KS nonlinear	0.236	1.67
rcBK	0.271	1.62

Results for D^0 in pPb collisions

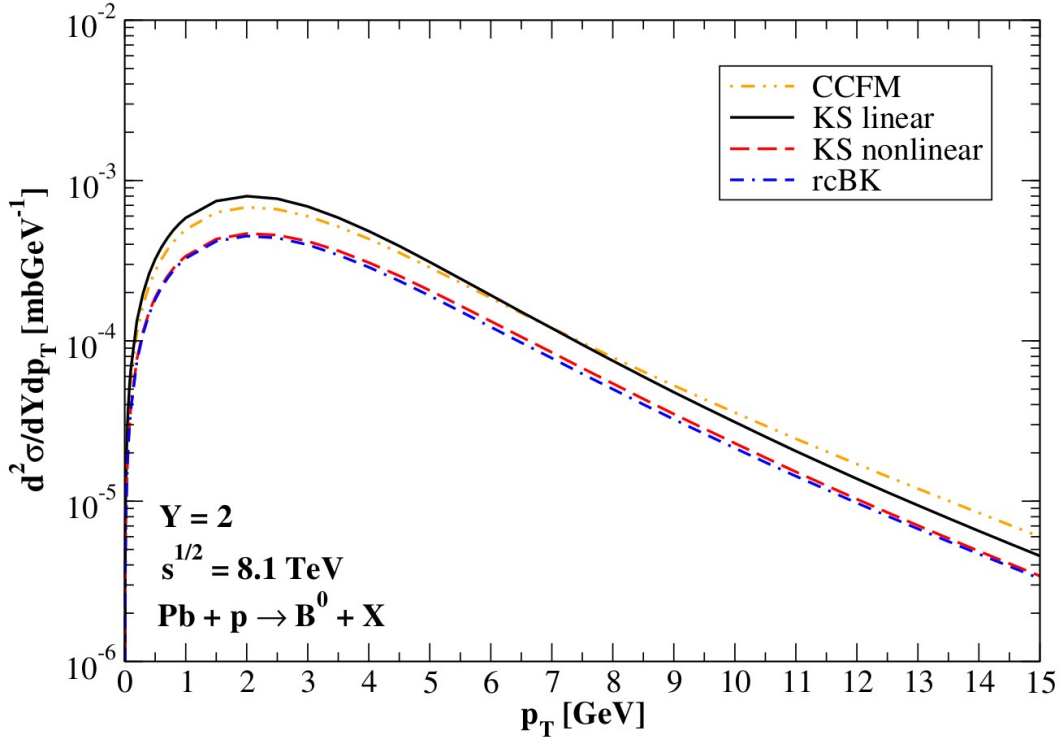
$f(x, \mathbf{k})$	CCFM	KS linear	KS nonlinear	rcBK
Evolution	linear	linear	nonlinear	nonlinear

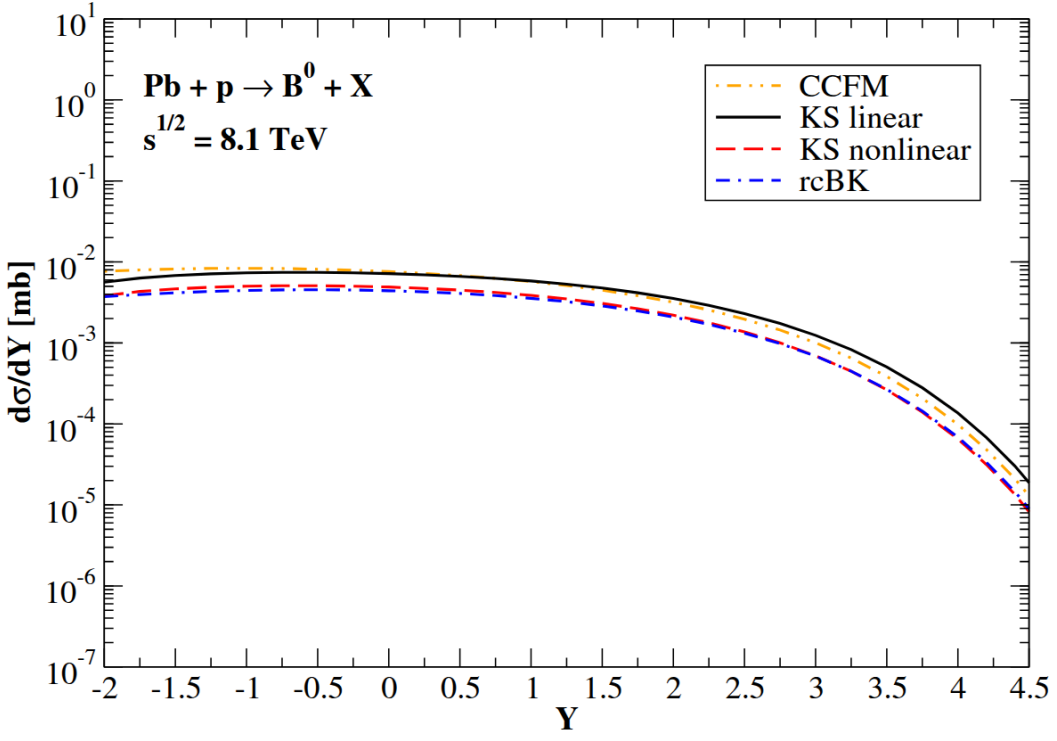




Results for B^0 in pPb collisions

$f(x, \mathbf{k})$	CCFM	KS linear	KS nonlinear	rcBK
Evolution	linear	linear	nonlinear	nonlinear





PbPb collisions

Formalism

$$\frac{d\sigma_T(\gamma h \to Q\bar{Q}X)}{dz d^2\mathbf{p}} = \frac{N_c \alpha_{em} e_Q^2}{2\pi^2} \int d^2\mathbf{k} f(x,\mathbf{k}) \left\{ \left[z^2 + (1-z)^2 \right] \mathcal{B}_1(\mathbf{p}_T, \mathbf{k}) + m_Q^2 \mathcal{B}_2(\mathbf{p}_T, \mathbf{k}) \right\}$$

For the lead as a target:

$f(x,\mathbf{k})$	Evolution	Nuclear effects?	Procedure
CCFM	linear	no	$Af_p(x,\mathbf{k})$
rcBK	nonlinear	yes	initial saturation scale scales with $Q_{s0}^2 = cA^{1/3}Q_{s0,p}^2$

Formalism

$$\frac{d\sigma_T(\gamma h \to Q\bar{Q}X)}{dz d^2\mathbf{p}} = \frac{N_c \alpha_{em} e_Q^2}{2\pi^2} \int d^2\mathbf{k} f(x,\mathbf{k}) \left\{ \left[z^2 + (1-z)^2 \right] \mathcal{B}_1(\mathbf{p}_T, \mathbf{k}) + m_Q^2 \mathcal{B}_2(\mathbf{p}_T, \mathbf{k}) \right\}$$

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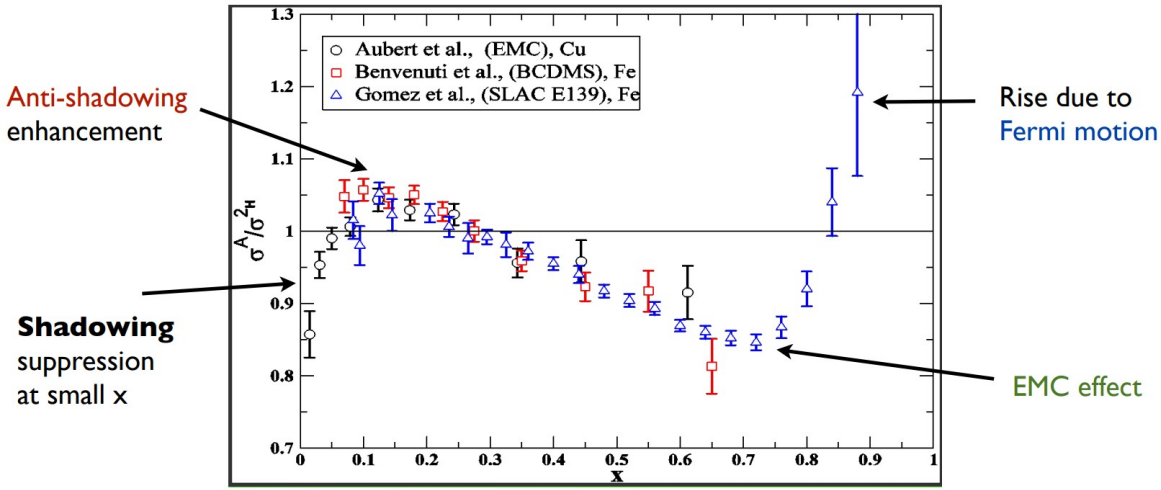
$f(x,\mathbf{k})$	Evolution	Nuclear effects?	Procedure
CCFM	linear	no	$A f_p(x,\mathbf{k})$
rcBK	nonlinear	yes	initial saturation scale scales with $Q_{s0}^2 = cA^{1/3} Q_{s0,p}^2$
EPPS	linear	yes	parton branching approach



[10]

[10] SCHIENBEIN, I. Nuclear PDFs. Presentation at the Workshop on "LHCb Heavy Ion and Fixed Target Physics", CERN, January 9–10, 2017. Université Grenoble Alpes, LPSC Grenoble, 2017.

Results for total cross section in PbPb collisions

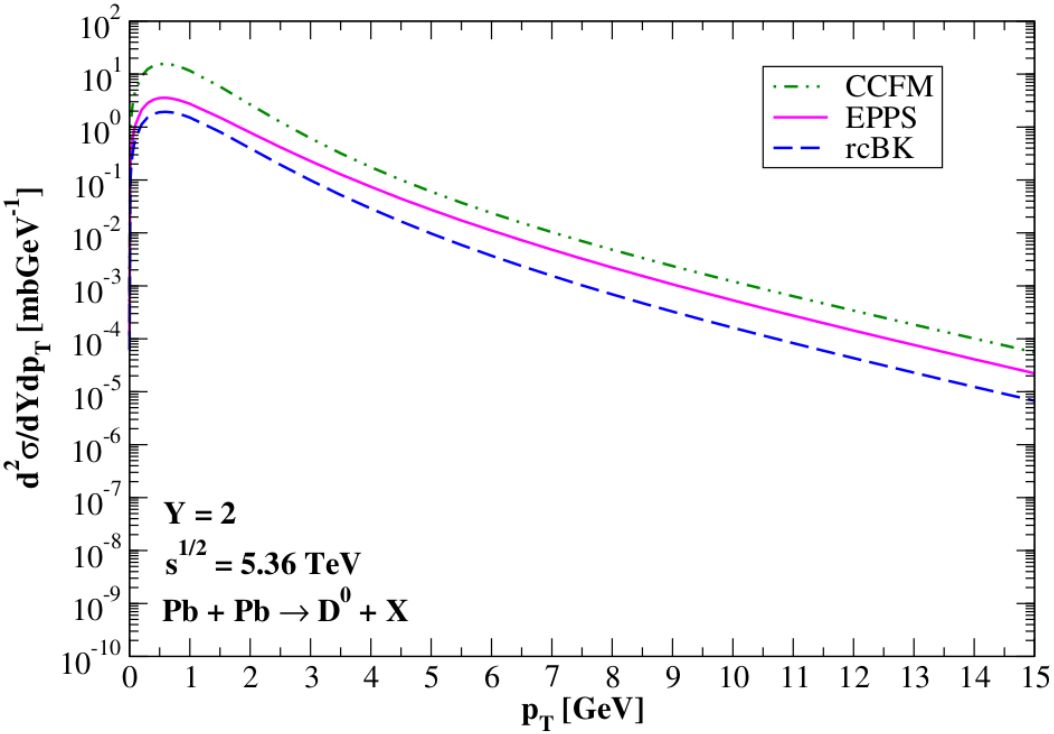
$\sqrt{s} = 5.36$ TeV

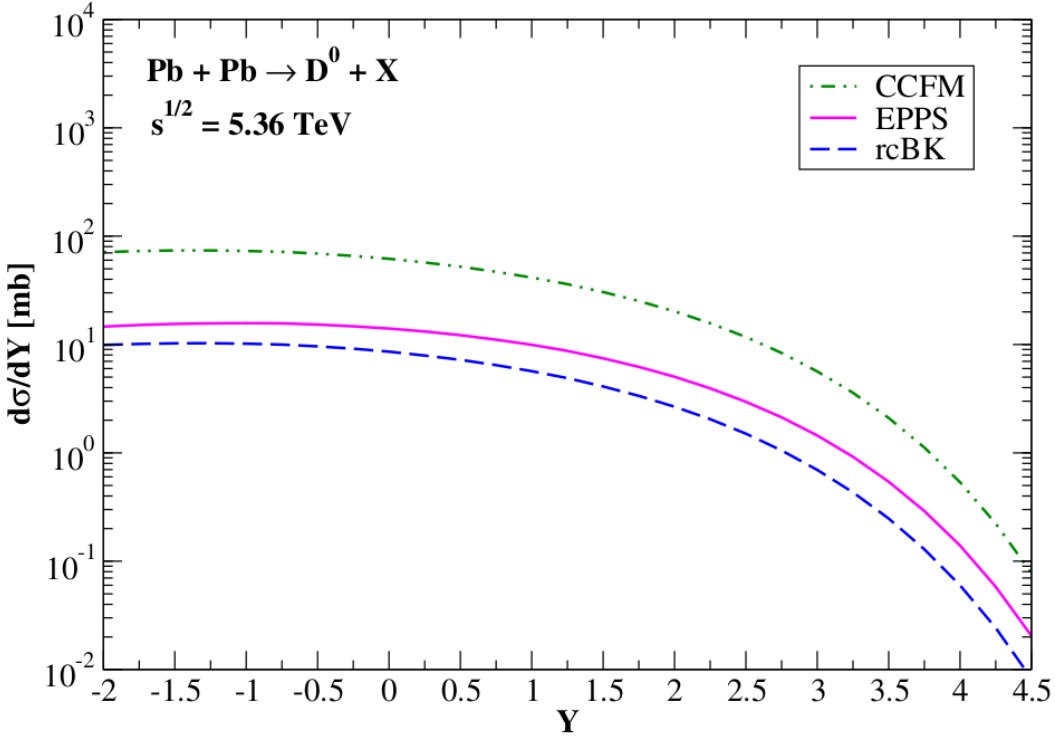
ALICE (-2 < Y < 2)	σ_{tot} for D^0 (mb)	σ_{tot} for B^0 (µb)
CCFM	287.7	2920
EPPS	65.03	851
rcBK	39.79	391

LHCb (2 < Y < 4.5)	σ_{tot} for D^0 (mb)	σ_{tot} for B^0 (µb)
CCFM	26.7	69.4
EPPS	6.82	24.1
rcBK	3.40	10.4

Results for D^0 in PbPb collisions

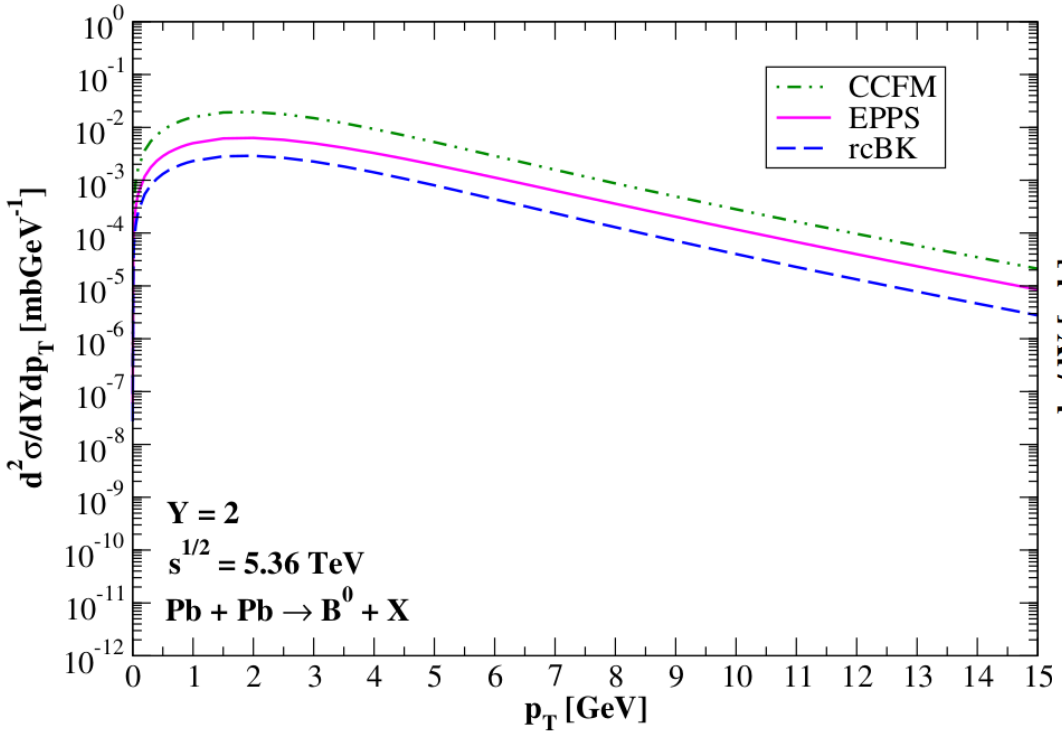
$f(x, \mathbf{k})$	CCFM	EPPS	rcBK
Evolution	linear	linear	nonlinear
Nuclear effects?	no	yes	yes

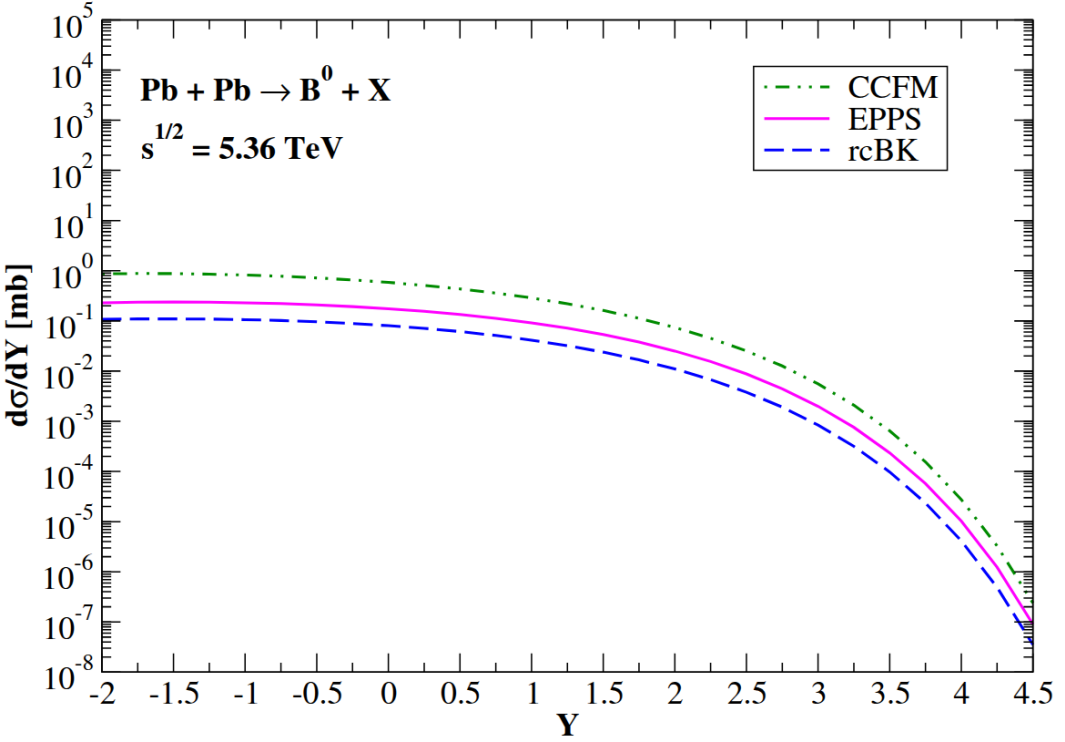




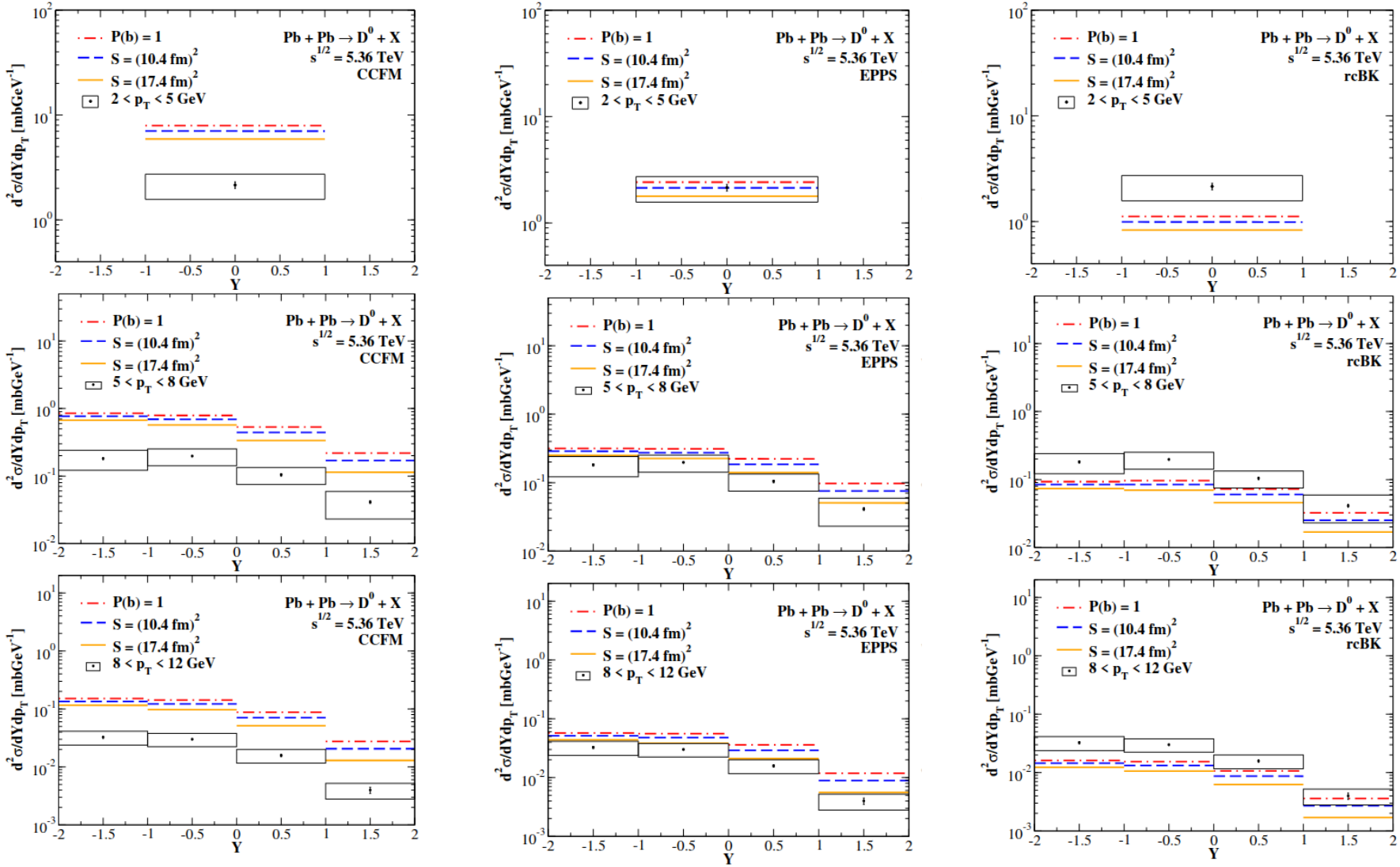
Results for B^0 in PbPb collisions

$f(x, \mathbf{k})$	CCFM	EPPS	rcBK
Evolution	linear	linear	nonlinear
Nuclear effects?	no	yes	yes

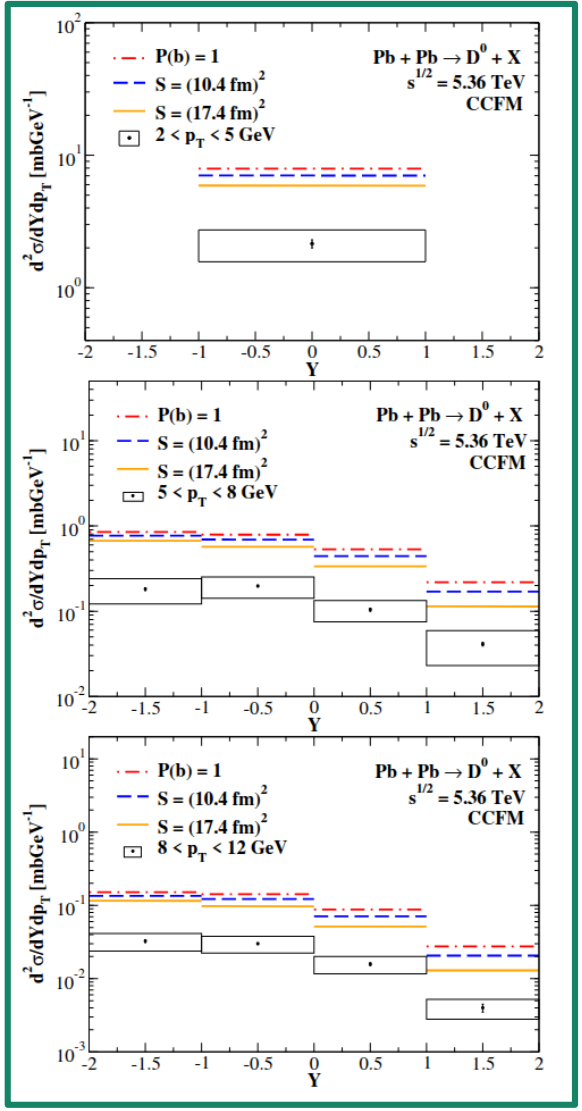




Comparison with data



CMS Collaboration. Measurement of D^0 meson photoproduction in ultraperipheral heavy ion collisions. arXiv preprint arXiv:2509.08626, 2025.



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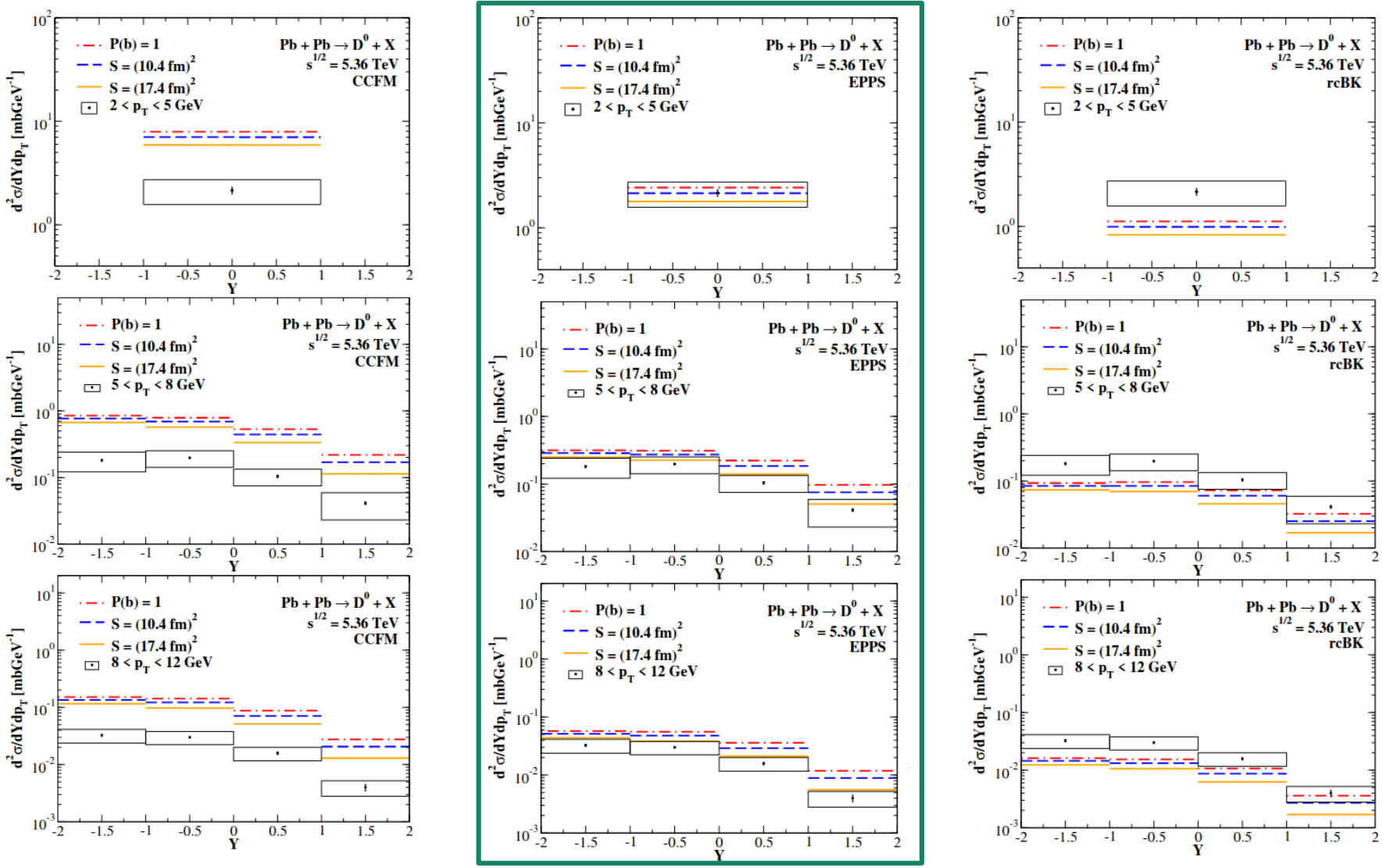

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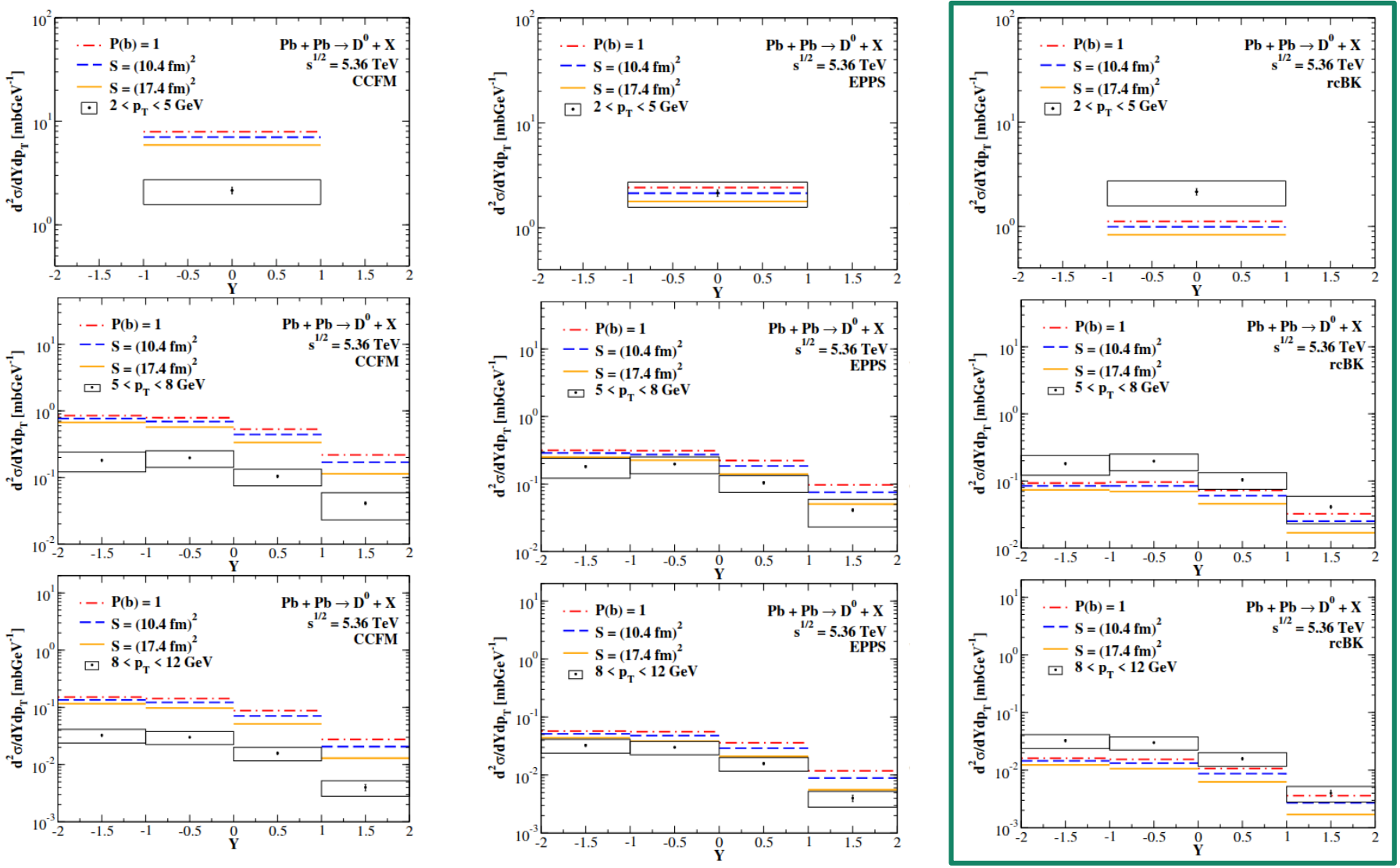
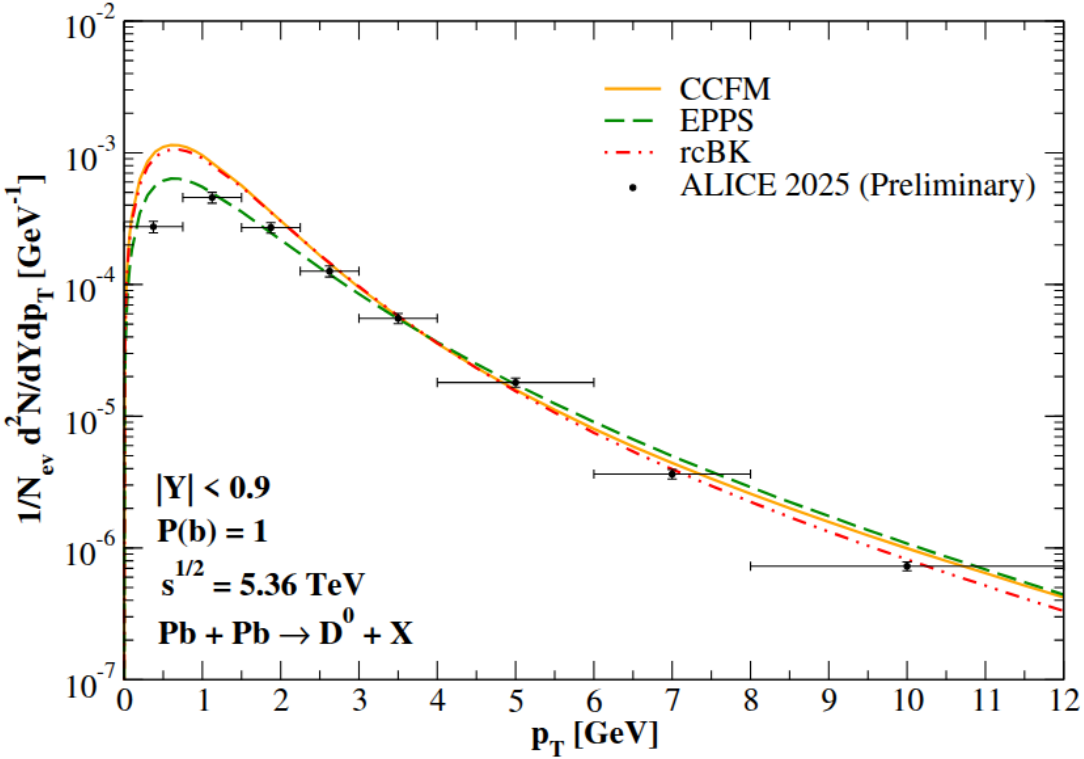


CMS Collaboration. Measurement of D^0 meson photoproduction in ultraperipheral heavy ion collisions. arXiv preprint arXiv:2509.08626, 2025.

Comparison with preliminary ALICE data

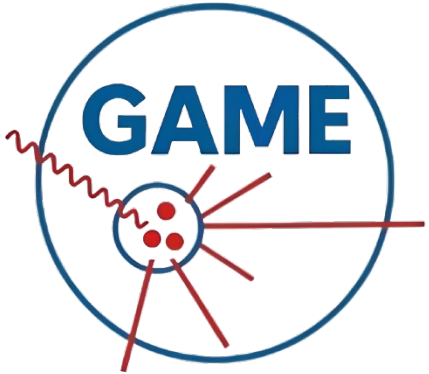


ALICE Collaboration. New probes of nuclear gluon dynamics through photoproduction of charm in inelastic ultra-peripheral PbPb collisions with ALICE. arXiv preprint arXiv:2509.11814, 2025.

Summary

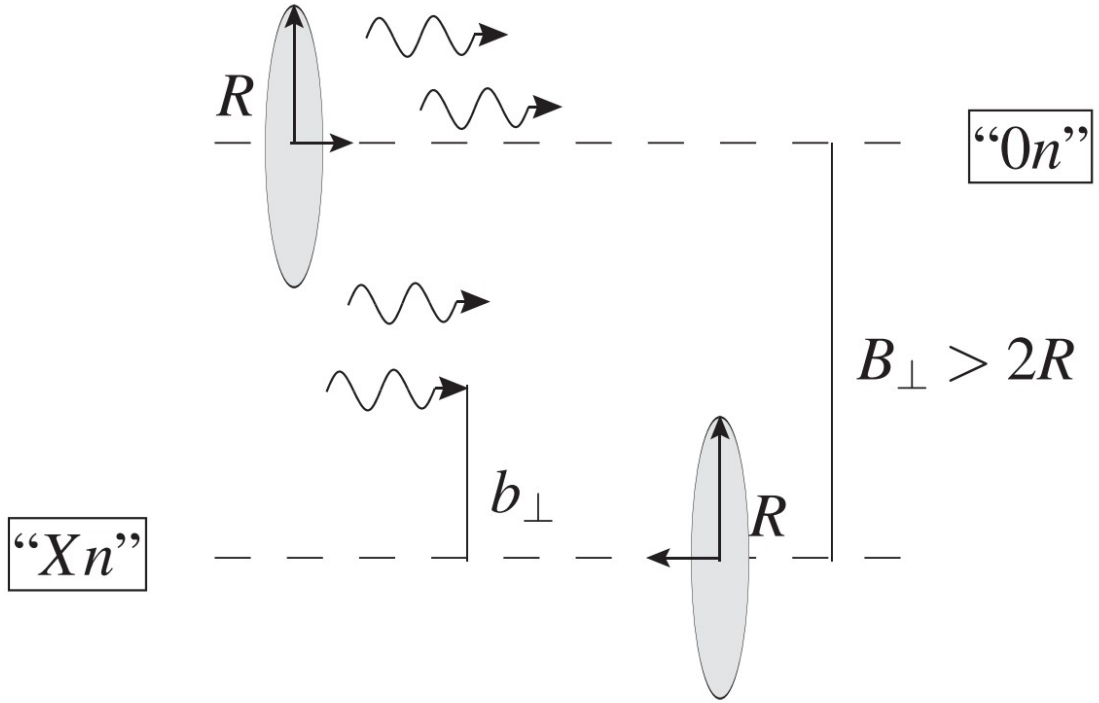
- The description of the QCD dynamics at high energies is still a theoretical challenge;
- Several models are available in the literature that consider distinct approaches and different underlying assumptions to treat the dynamics of a high gluon density system and how it is modified by the presence of a nuclear medium;
- In order to advance in our understanding, it is fundamental to have data for observables that are sensitity to these aspects;
- Our results indicate that precise experimental data for these observables will be very useful to improve our understanding of the strong interaction theory.

Thank you for your attention!



luanasntna@gmail.com

Backup



GIMENO-ESTIVILL, Patricia; LAPPI, Tuomas; MÄNTYSAARI, Heikki. Inclusive D^0 photoproduction in ultraperipheral collisions. Physical Review D, v. 111, n. 11, p. 114036, 2025.

Backup

$$P(\boldsymbol{b}) = \exp[-\bar{n}(\boldsymbol{b})] \qquad \bar{n}(\boldsymbol{b}) = \int_{E_{\min}}^{\infty} dE\, N(E, \boldsymbol{b})\, \sigma_{\text{tot}}(\gamma Pb; E),$$

Here, $_{\min}$ is the neutron separation energy, denotes the photon energy in the nucleus rest frame. (,) should therefore be evaluated with the boost parameter $_{\text{rf}} = 2^{2}{}_{\text{cm}} - 1$. One then observes that, to a with a good approximation,

$$\frac{Eb}{\gamma_{\text{rf}}} K_1\left(\frac{Eb}{\gamma_{\text{rf}}}\right) \approx 1,$$

so that

$$\bar{n}(\boldsymbol{b}) = \frac{S}{b^2}, \qquad S = \frac{Z^2 \alpha_{\text{em}}}{\pi^2} \int_{E_{\min}}^{\infty} \frac{dE}{E} \sigma_{\text{tot}}(\gamma Pb; E)\,.$$

We obtain for the contribution from the excitation of the giant dipole resonance $\approx (11.4\ \text{fm})^2$, while integrating out to $= 10$ GeV, we obtain $\approx (14.9\ \text{fm})^2$. These values lie between $= (10.4\ \text{fm})^2$ and $= (17.4\ \text{fm})^2$, which we adopt in our numerical results.

Backup

$$\frac{d\sigma_T(\gamma h \to c\bar{c}X)}{dzd^2\boldsymbol{p}} = \frac{N_c\alpha_{em}e_c^2}{2\pi^2}\left\{\left[z^2+(1-z)^2\right]\epsilon^2\mathcal{A}_1(z,p_T,\epsilon)+\left[zm_c+(1-z)m_c\right]^2\mathcal{A}_2(z,p_T,\epsilon)\right\}$$

where

$$\mathcal{A}_1(z,p_T,\epsilon) = \frac{p_T}{\epsilon(p_T^2+\epsilon^2)}I_3(z,p_T) - \frac{1}{2\epsilon^2}I_1(z,p_T) + \frac{1}{4\epsilon}I_2(z,p_T)$$

$$\mathcal{A}_2(z,p_T,\epsilon) = \frac{1}{p_T^2+\epsilon^2}I_1(z,p_T) - \frac{1}{4\epsilon}I_2(z,p_T)$$

with the auxiliary functions I_i being defined by

$$I_1(z,p_T) = \int r\mathrm{d}r\; J_0(p_T r)K_0(\epsilon r)\sigma(\mathbf{r},x)$$

$$I_2(z,p_T) = \int \mathrm{d}r\; r^2 J_0(p_T r)K_1(\epsilon r)\sigma(\boldsymbol{r},x)$$

$$I_3(z,p_T) = \int \mathrm{d}r\; rJ_1(p_T r)K_1(\epsilon r)\sigma(\mathbf{r},x)$$

$$\sigma(\mathbf{r},x) = \frac{4\pi}{3}\int\frac{\mathrm{d}^2\mathbf{k}}{k^2}\alpha_s\mathcal{F}(x,\mathbf{k})\left(1-e^{i\mathbf{k}\cdot\mathbf{r}}\right) = \int \mathrm{d}^2\mathbf{k}f(x,\mathbf{k})\left(1-e^{i\mathbf{k}\cdot\mathbf{r}}\right)$$

Backup

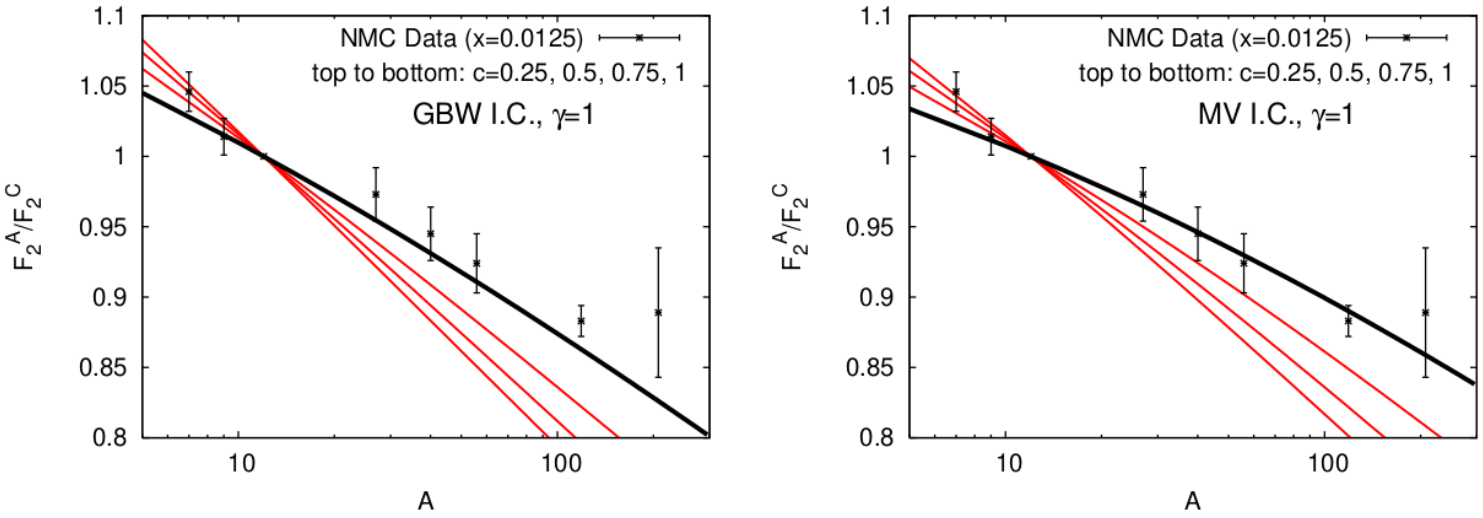


Figure 8: DIS fixed target e+A data on the ratio of structure functions as a function of A for fixed $x = 0.0125$. The plots correspond to (right) MV model initial condition having $\gamma = 1$ and (left) GBW initial condition.

DUSLING, Kevin et al. Long range two-particle rapidity correlations in A+ A collisions from high energy QCD evolution. Nuclear Physics A, v. 836, n. 1-2, p. 159-182, 2010.

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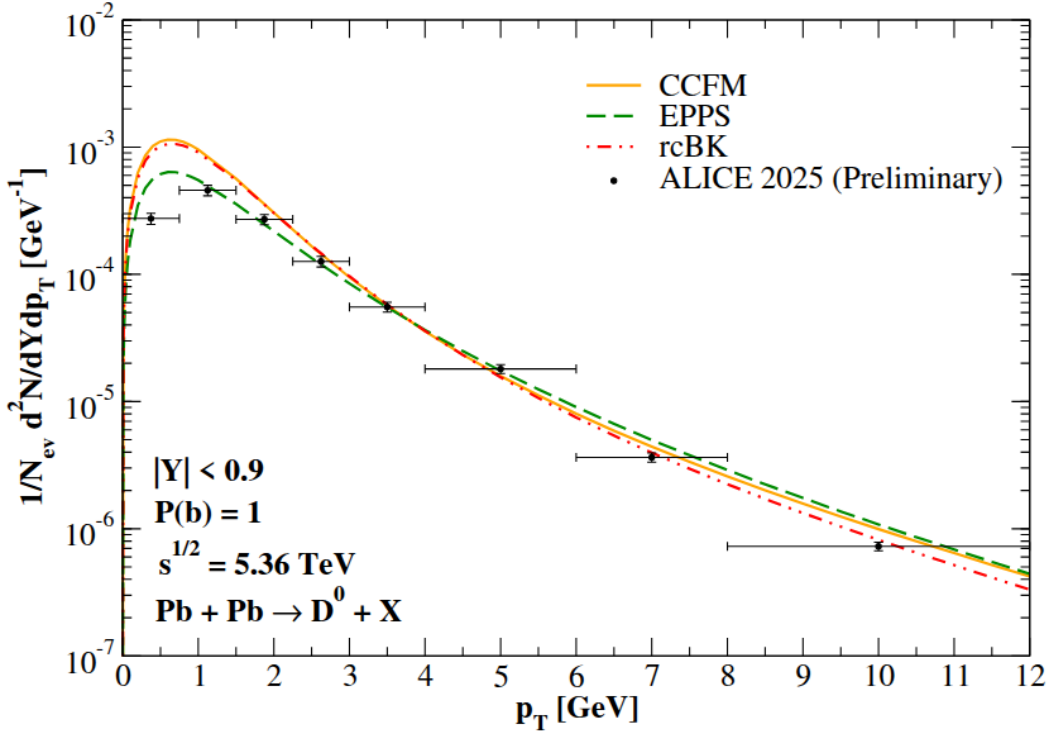
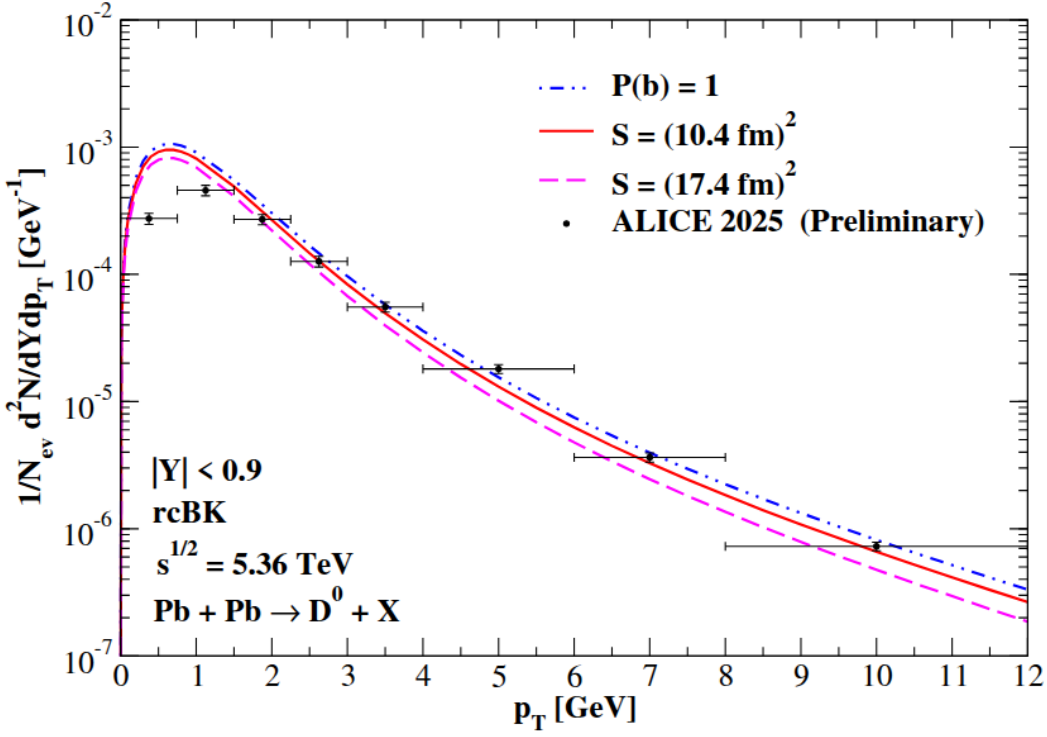


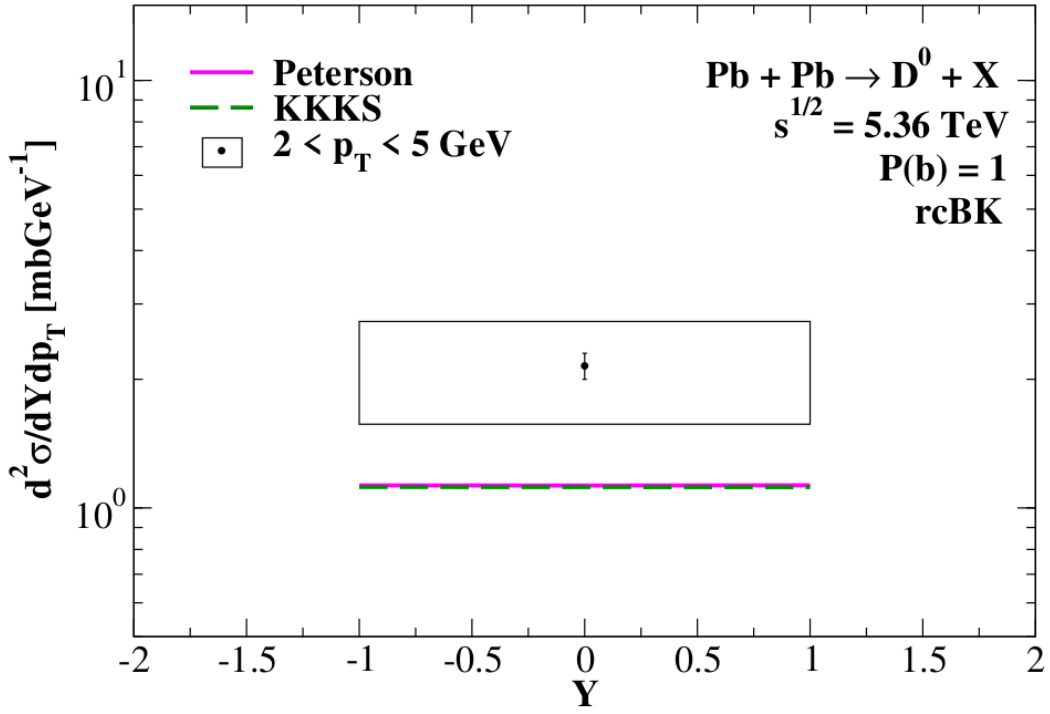


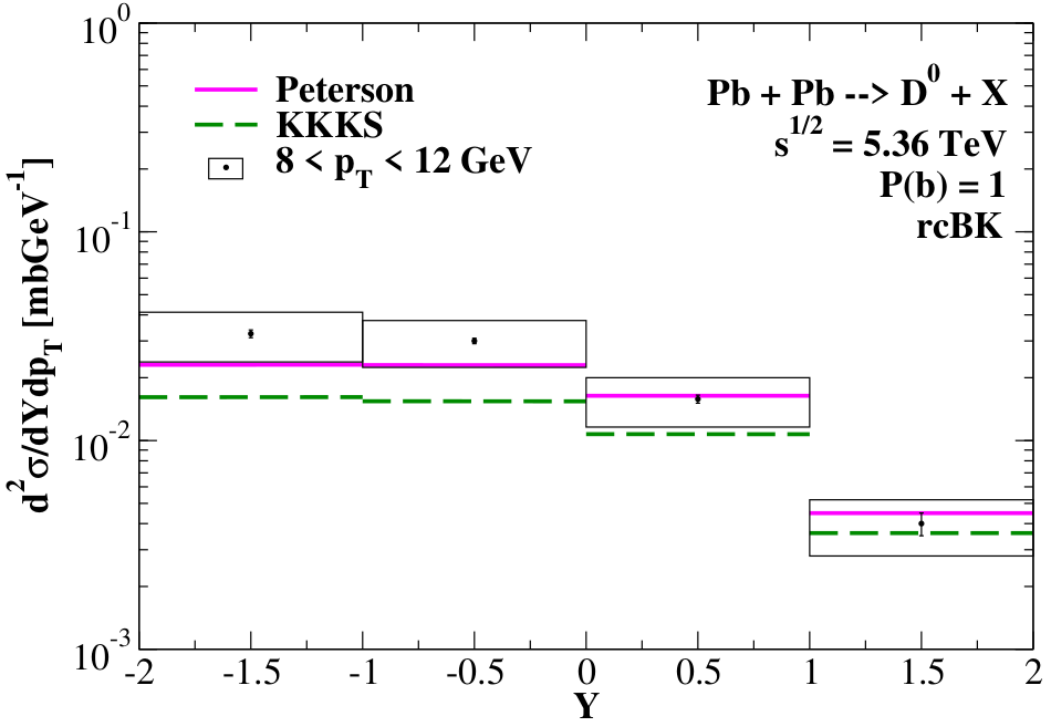
ALICE Collaboration. New probes of nuclear gluon dynamics through photoproduction of charm in inelastic ultra-peripheral PbPb collisions with ALICE. arXiv preprint arXiv:2509.11814, 2025.

Backup

Peterson x KKKS model:

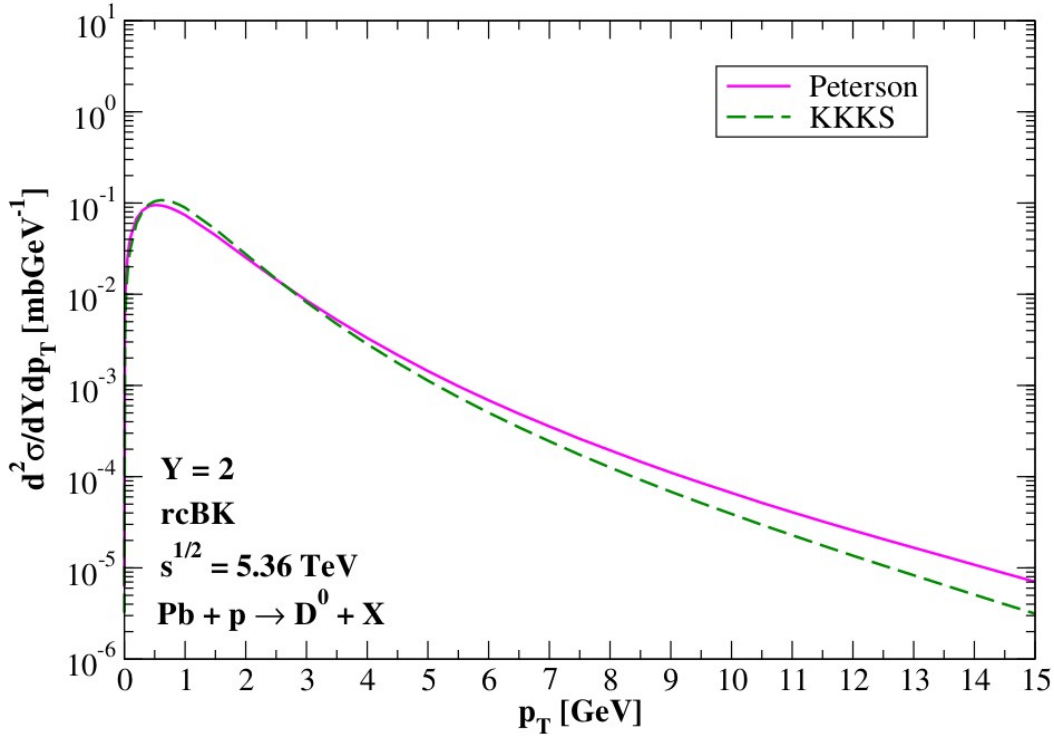
$$D^{q/H}(z,\mu^2) = \frac{n(H)}{z\left(1-\frac{1}{z}-\frac{\epsilon_q}{1-z}\right)^2}$$

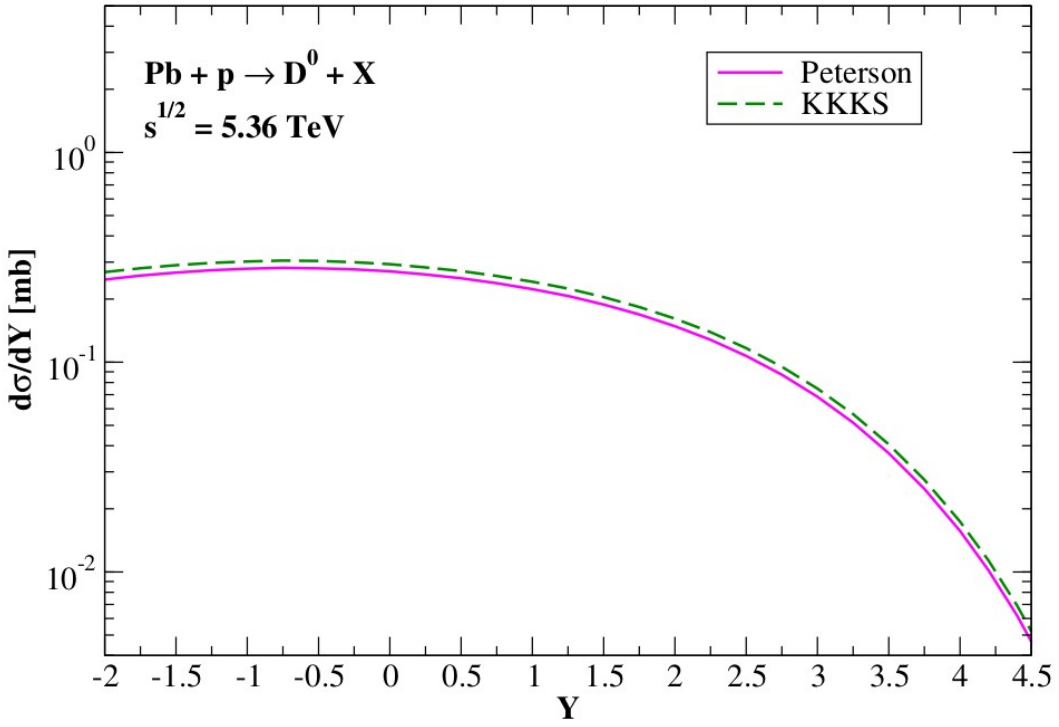




Backup

Peterson x KKKS model:





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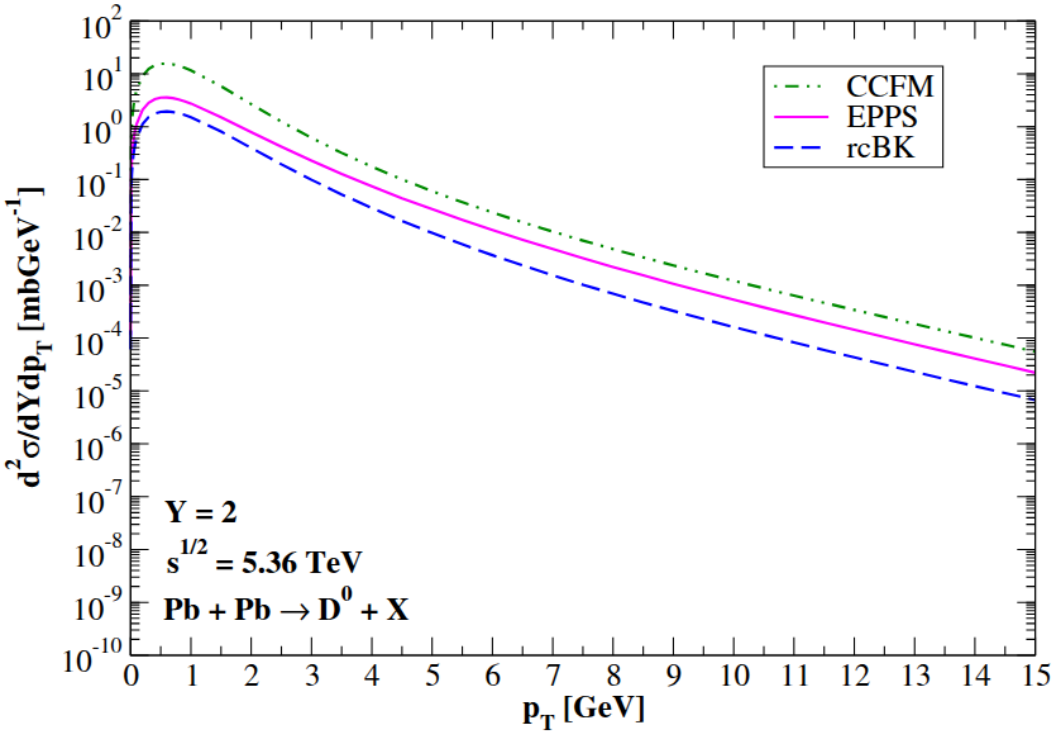
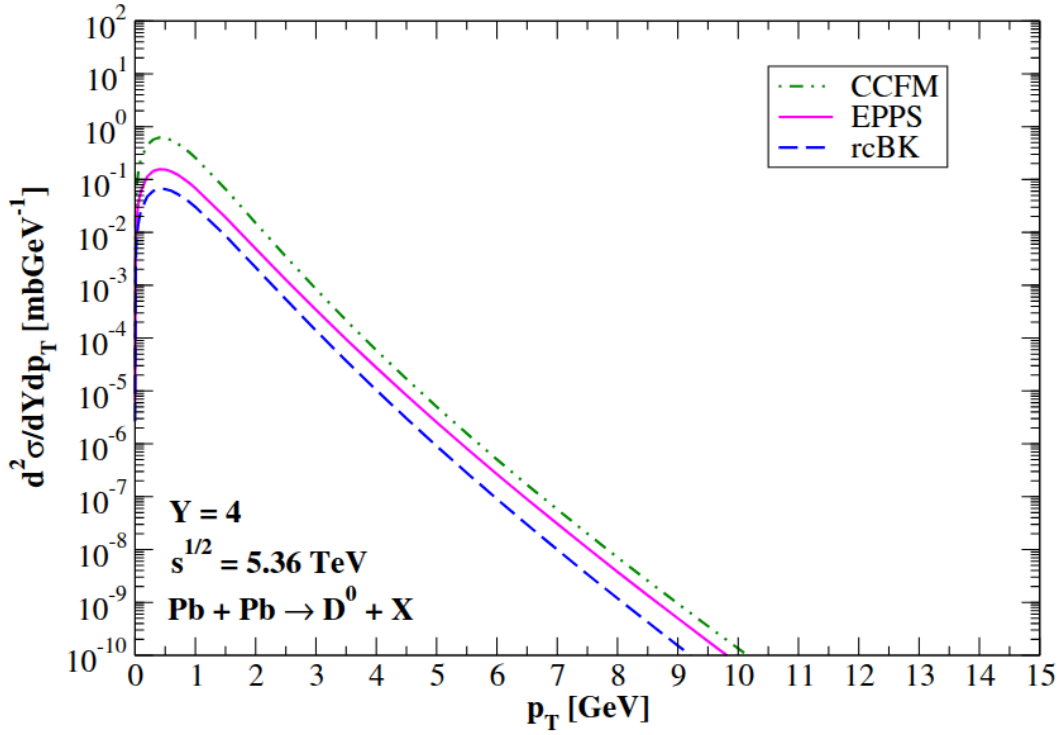

CCFM
EPPS
rcBK
Y = 2
$s^{1/2}$ = 5.36 TeV
Pb + Pb → D^0 + X
$d^2\sigma/dYdp_T$ [mbGeV^{-1}]
p_T [GeV]

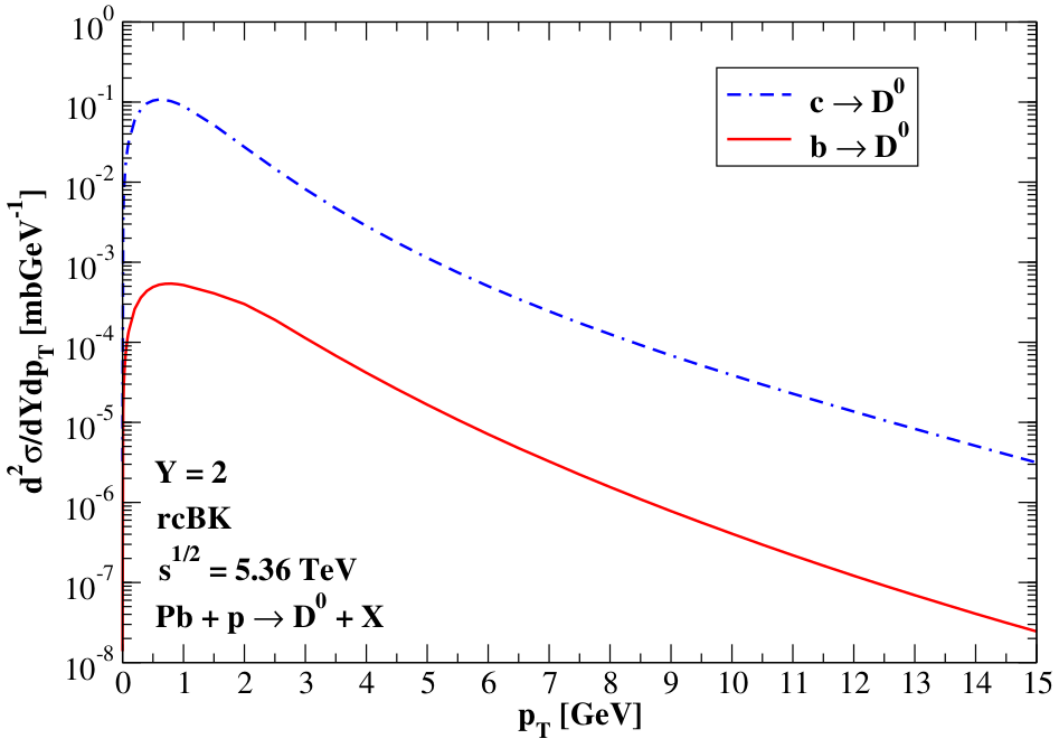

CCFM
EPPS
rcBK
Y = 4
$s^{1/2}$ = 5.36 TeV
Pb + Pb → D^0 + X
$d^2\sigma/dYdp_T$ [mbGeV^{-1}]
p_T [GeV]

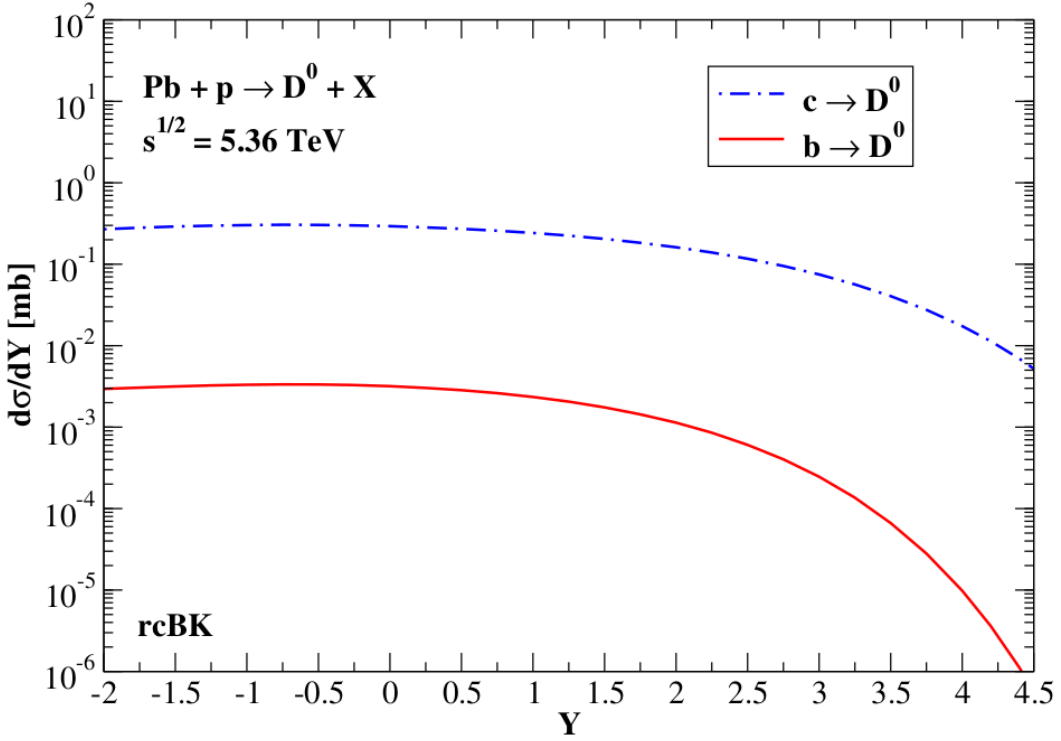
Backup

$f(x, \mathbf{k}_T)$	Evolution
CCFM	linear
KS linear	linear
KS nonlinear	nonlinear
rcBK	nonlinear

Feed down $b \to D^0$:

pPb collisions



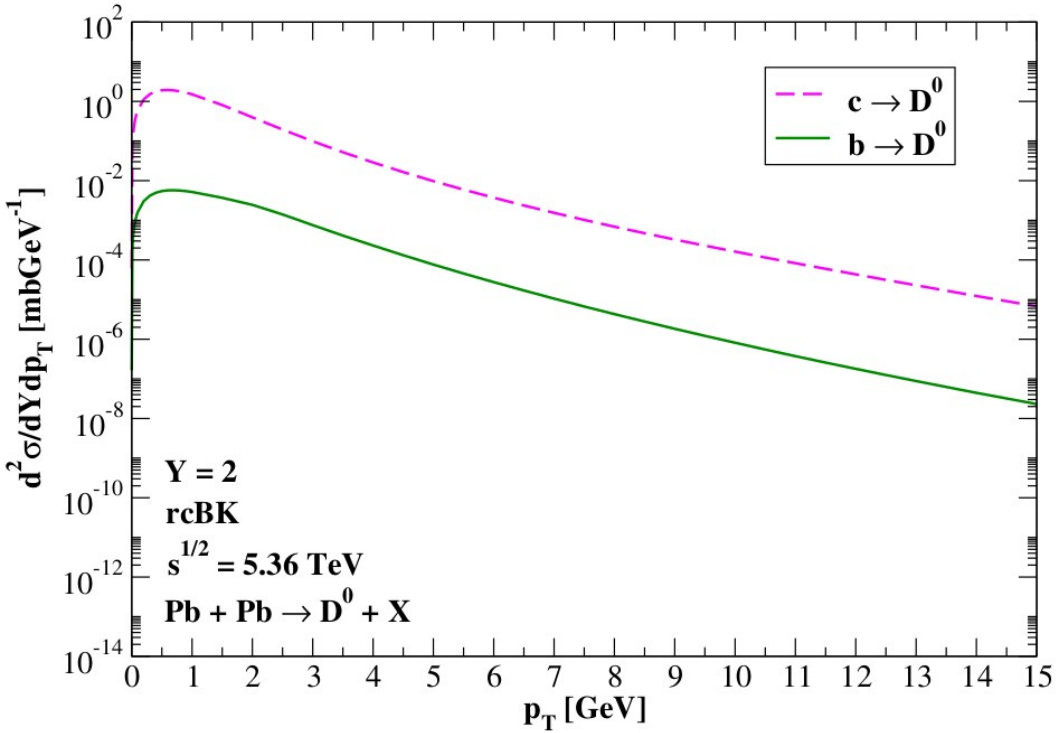


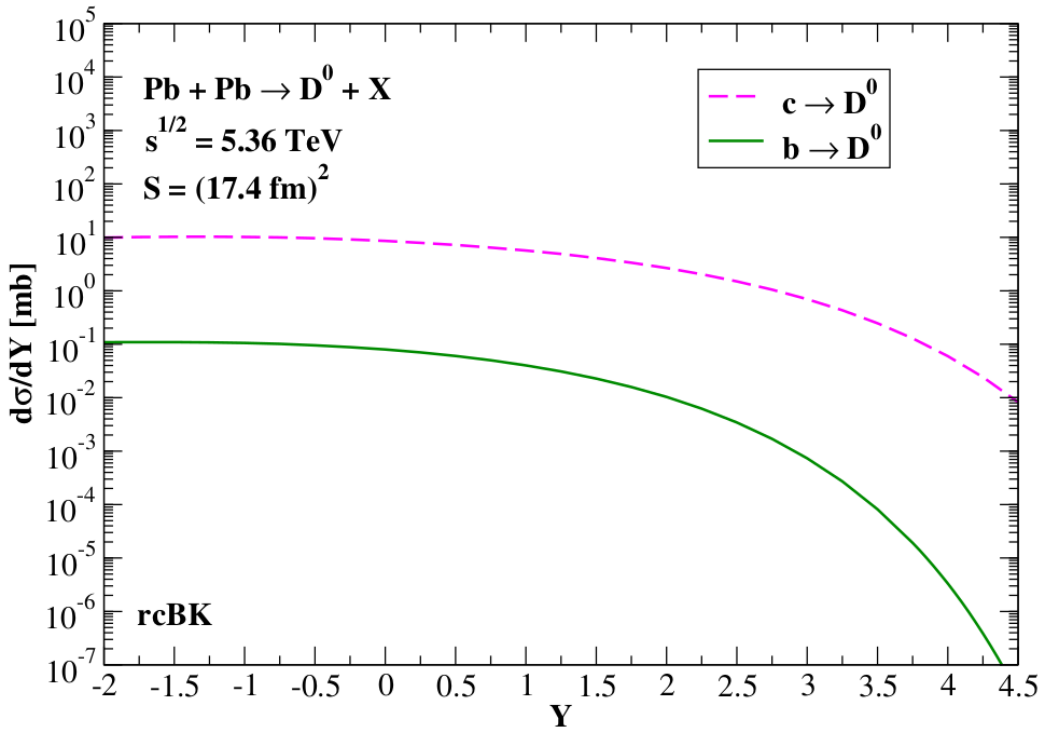
Backup

$f(x, \mathbf{k}_T)$	Evolution	Nuclear effects?
CCFM	linear	no
EPPS	linear	yes
rcBK	nonlinear	yes

Feed down $b \to D^0$: using the KKKS model, we can estimate this contribution.

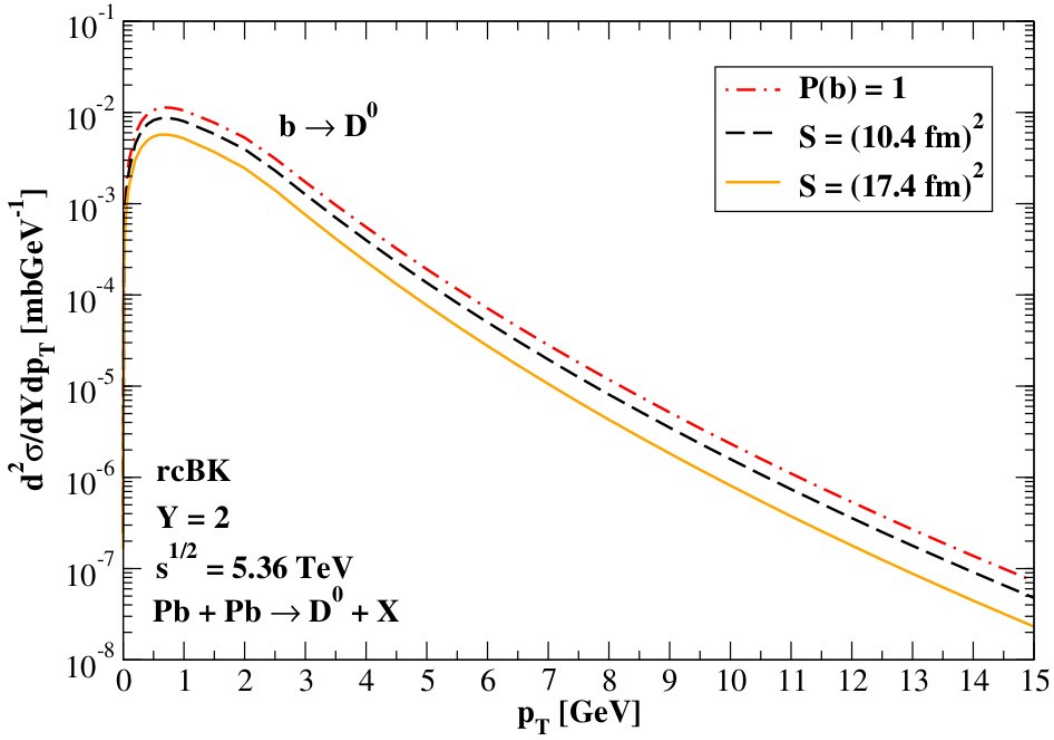
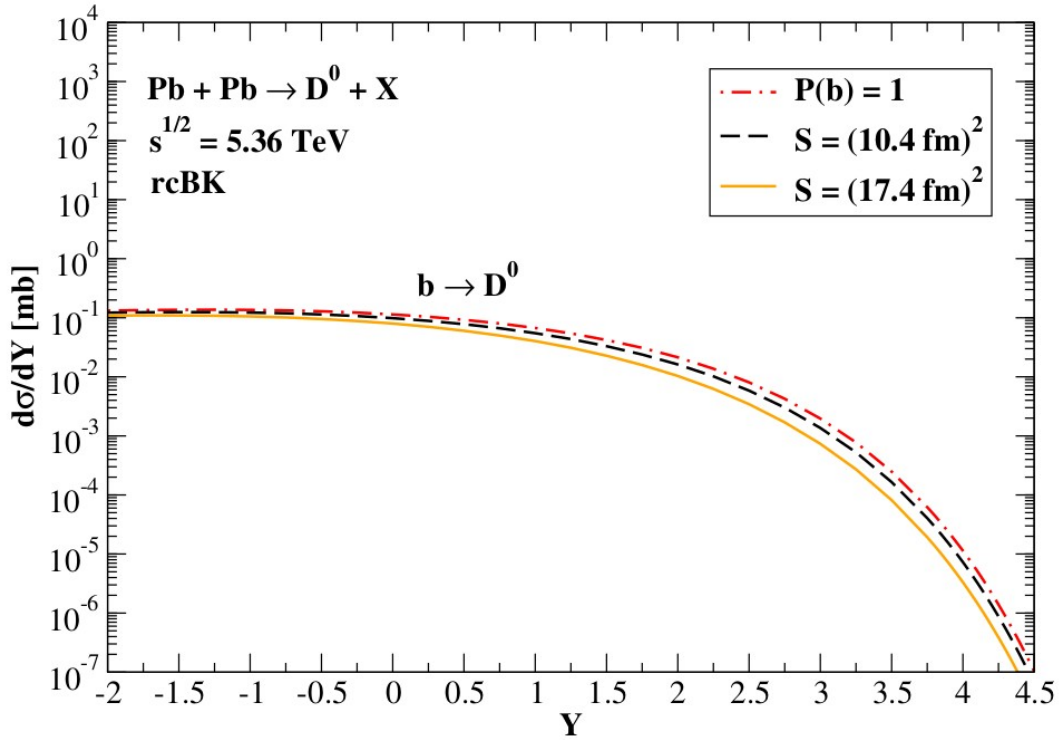
PbPb collisions:





Backup

$f(x, \mathbf{k}_T)$	Evolution	Nuclear effects?
CCFM	linear	no
EPPS	linear	yes
rcBK	nonlinear	yes

Feed down $b \to D^0$:

PbPb collisions