EMMI Workshop: Mining for gluon saturation at the LHC and the future EIC

Heavy meson photoproduction in ultraperipheral collisions at the LHC

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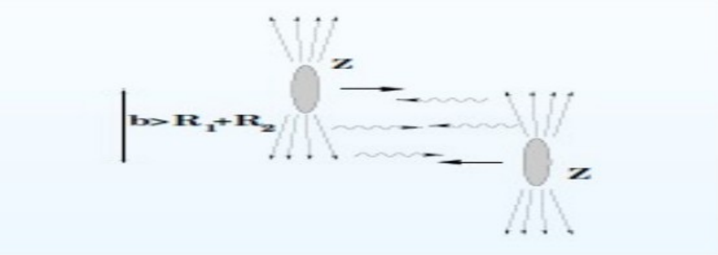
In collaboration with Luana Santana and Wolfgang Schäfer

Based on PLB869(2025)139859 and PRD113(2026)114003.

LHC as a photon collider



1. γh Processes: $\sigma(h_1 h_2 \to X) = n_h(\omega) \otimes \sigma^{\gamma h \to X}(W_{\gamma h})$
2. $\gamma\gamma$ Processes: $\sigma(h_1 h_2 \to X) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma \to X}(W_{\gamma\gamma})$

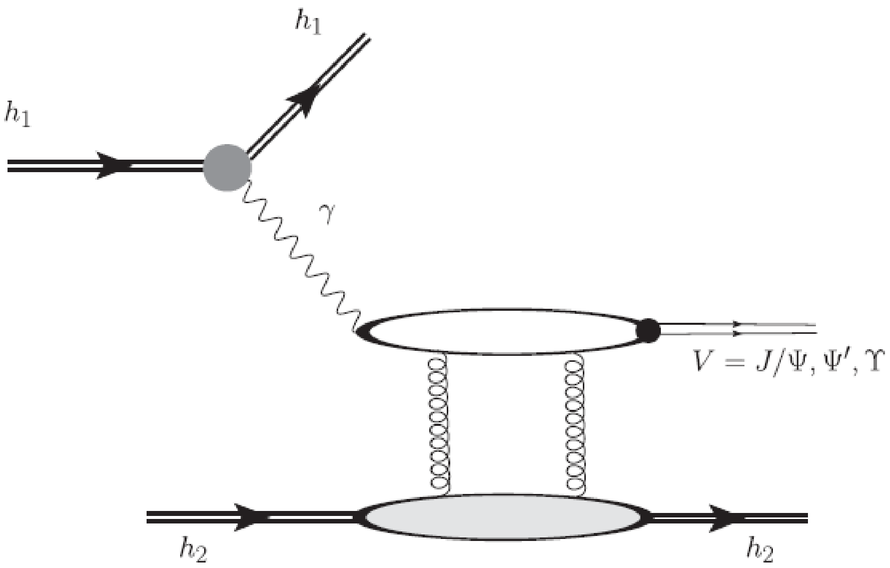
Center of mass energies

LHC	pp	$W_{\gamma p} \lesssim 8390$ GeV	$W_{\gamma\gamma} \lesssim 4504$ GeV
LHC	$pPb(Ar)$	$W_{\gamma A} \lesssim 1500\,(2130)$ GeV	$\lesssim 260\,(480)$ GeV
LHC	$PbPb$	$W_{\gamma A} \lesssim 950$ GeV	$W_{\gamma\gamma} \lesssim 160$ GeV
HERA	ep	$W_{\gamma p} \lesssim 200$ GeV	–

Photoproduction in pp, pA and AA collisions at LHC probes a unexplorated regime of photon – hadron center – of – mass energies.

Probing the hadronic structure in UPC's

- Over the last years, **exclusive processes** were largely investigated;



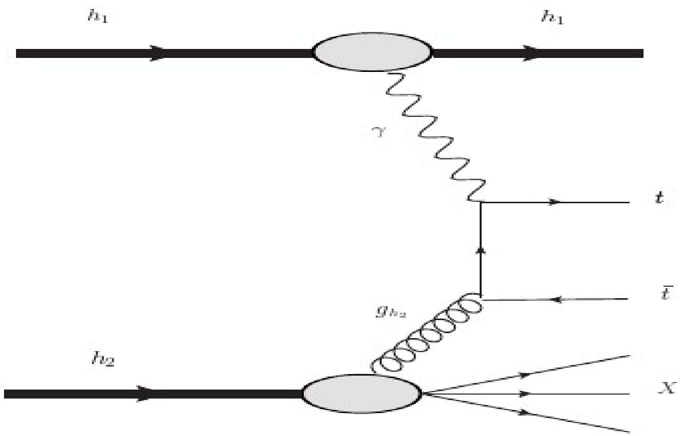
Main motivations:

- Cross section proportional to the square of the gluon distribution;
- Strongly sensitive to the description of the QCD dynamics;
- Very clean final state: two intact hadrons and two rapidity gaps.

[1] S. Klein, J. Nystrand. Exclusive vector meson production in relativistic heavy ion collisions. Physical Review C, v. 60, p. 014903, (1999).
[2] VPG, C. A. Bertulani. Peripheral heavy ion collisions as a probe of the nuclear distribution. Physical Review C, v. 65, p. 054905, (2002).
[3] L. Frankfurt, M. Strikman, M. Zhalov. Signals for black body limit in coherent ultraperipheral heavy ion collisions. Physics Letters B, v. 537, 51 (2002).
[4] VPG, M.V.T. Machado. The QCD pomeron in UPHICs. IV. Photonuclear production of vector mesons. Eur. Phys. J. C40, 519 (2005)

Probing the hadronic structure in UPC's

- However, the possibility of investigating the hadronic structure in UPC's was first proposed to be done in **inclusive processes**;



Characteristics:

- Cross section proportional to the gluon distribution;
- Sensitive to the description of the QCD dynamics;
- Final state characterized by one intact hadron and one rapidity gaps.
- Experimental separation is a challenge, specially in proton – proton collisions.

[5] G.Hofmann, G. Soff, A. Schafer, W. Greiner. Production of b and bbar quarks by photon – gluon fusion in HICs. Physics Letters B, v. 262, 210 (1991)
[6] N. Baron, G. Baur. Photon hadron interactions in relativistic HICs. Physical Review C, v. 48, p. 1999, (1993).
[7] VPG, C. A. Bertulani. Peripheral heavy ion collisions as a probe of the nuclear distribution. Physical Review C, v. 65, p. 054905, (2002).
[8] S. Klein, J. Nystrand, R. Vogt. Heavy quark photoproduction in UPCs. Physical Review C, v. 66, p. 044906, (2002).
[9] VPG, M.V.T. Machado. The QCD pomeron in UPHICs. III. Photonuclear production of heavy quarks. Eur. Phys. J. C31, 371 (2003).
[10] VPG. Photoproduction of top quarks in coherent hadron – hadron collisions. Physical Review D, v. 88, p. 054025, (2013).

Probing the hadronic structure in UPC's

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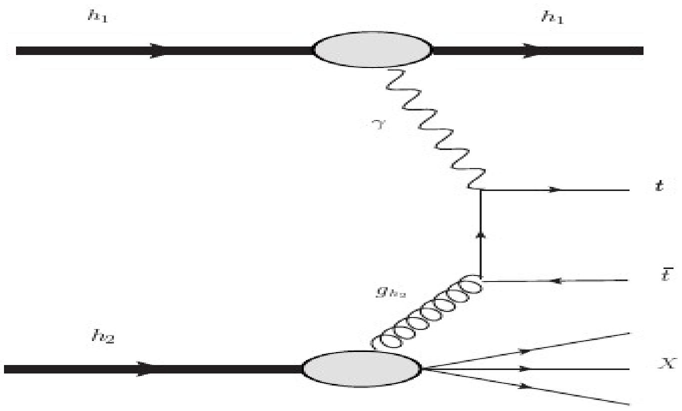


Characteristics:

- Cross section proportional to the gluon distribution;
- Sensitive to the description of the QCD dynamics;
- Final state characterized by one intact hadron and one rapidity gaps.
- Experimental separation is a challenge, specially in proton – proton collisions.

NEW: The first data for inclusive processes in UPC's were recently made available by the ATLAS[1], CMS [2], and ALICE [3] collaborations.

[11] 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.
[12] CMS Collaboration. Measurement of D^0 meson photoproduction in ultraperipheral heavy ion collisions. arXiv preprint arXiv:2509.08626, 2025.
[13] 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.

In this seminar...

- Focus on the results presented in PLB869(2025)139859, PRD113(2026)114003 (*).
- Heavy meson photoproduction in pPb and PbPb collisions within the S-matrix color dipole approach;
- Investigate the impact of the QCD dynamics on the predictions;
- Present, for the first time, results for the B^0 meson production and for pPb collisions;
- Present a comparison with the recent CMS and (preliminary) ALICE data for D^0 meson production in PbPb Collisions.

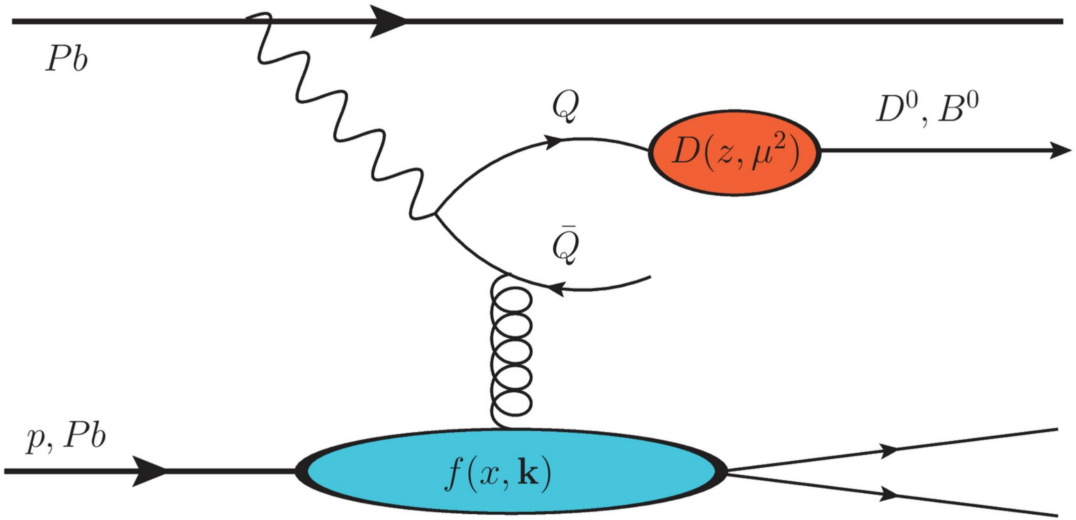
(*) See also Refs.:

[14]VPG, G. Dos Santos and C. Sena. Exclusive heavy quark photoproduction in pp, pPb and PbPb collisions at the LHC and FCC energies. Nuc. Phys. A1000, 121862 (2019)
[15] P. Gimeno, T. Lappi, H. Mantyssari, Inclusive D0 photoproduction in UPCs. Physical Review D, v. 111, n. 11, p. 114036, (2025).
[16] M. Cacciari, G. M. Innocenti, A. M. Stasto. Inclusive open charm photoproduction in UPCs at the LHC with the generalized photon – nucleus fixed – order NLL framework. Physical Review D, v. 112, n. 9, p. 094029, (2025).
[17] V. Guzey, G. M. Innocenti, A. M. Stasto, Diffractive open charm photproduction in ultraperipheral PbPb and pPb collisions at the LHC. Eprint: 2606.05469 [hep-ph]

Formalism

Differential cross section for the production of a heavy meson 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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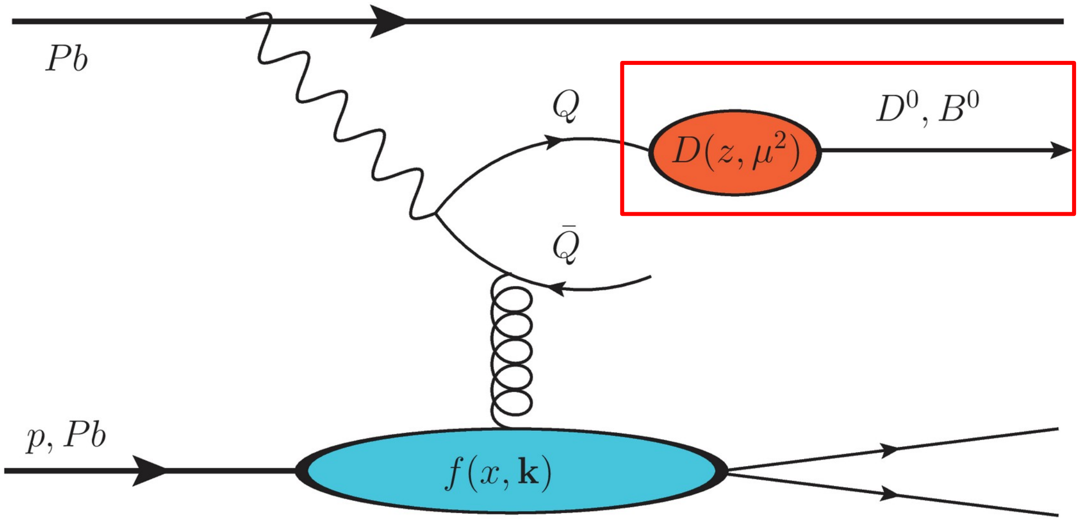
Fragmentation function $D_{Q/H}(z,\mu^2)$ $\Rightarrow$ KKSS model:

- non-perturbative fragmentation function for mesons D^0, D^+, and D^{*+} by fitting experimental data from the Belle, CLEO, ALEPH, and OPAL Collaborations [18]; and for B mesons through a global fit to e^+e^- data from CERN LEP1 and SLAC SLC [19].



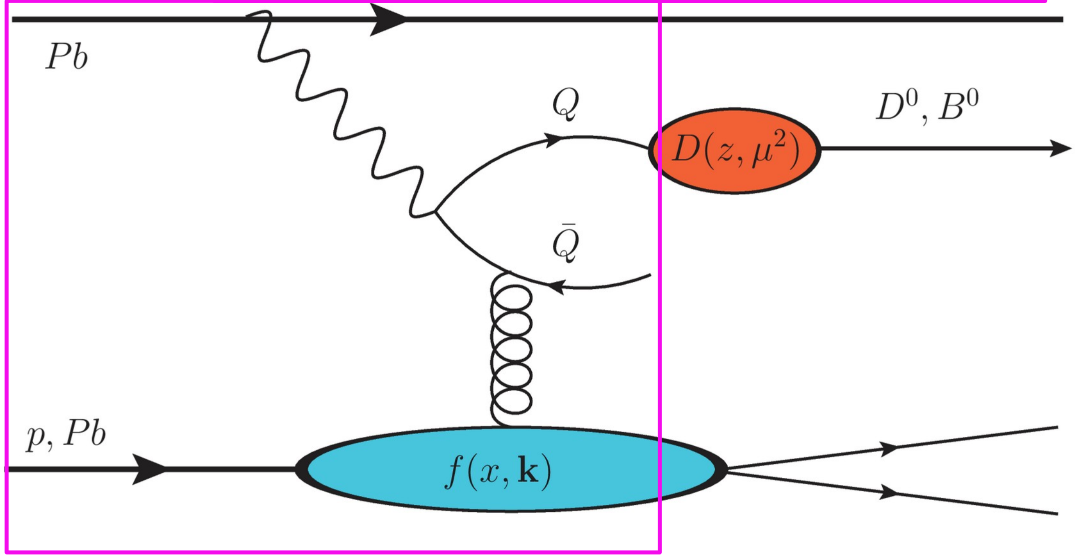
[18] KNEESCH, Torben et al. Charmed-meson fragmentation functions with finite-mass corrections. Nuclear Physics B, v. 799, n. 1-2, p. 34-59, 2008.
[19] KNIEHL, Bernd A. et al. Finite-mass effects on inclusive B-meson hadroproduction. Physical Review D, v. 77, n. 1, p. 014011, 2008.

Formalism

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

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

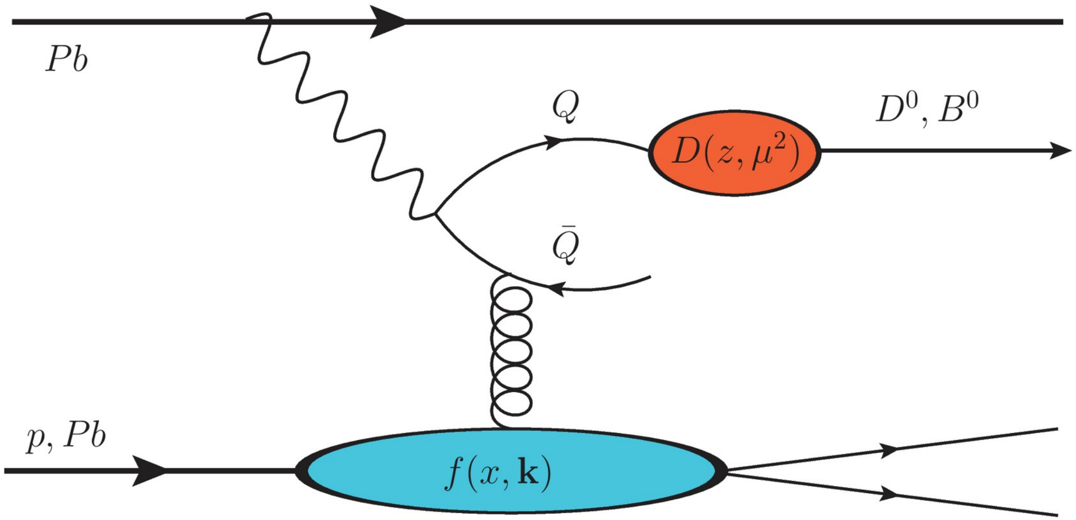
Differential cross section for heavy quark production!



Formalism

Differential cross section for heavy quark production in UPCs:

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



Formalism

Differential cross section for heavy quark production in UPCs:

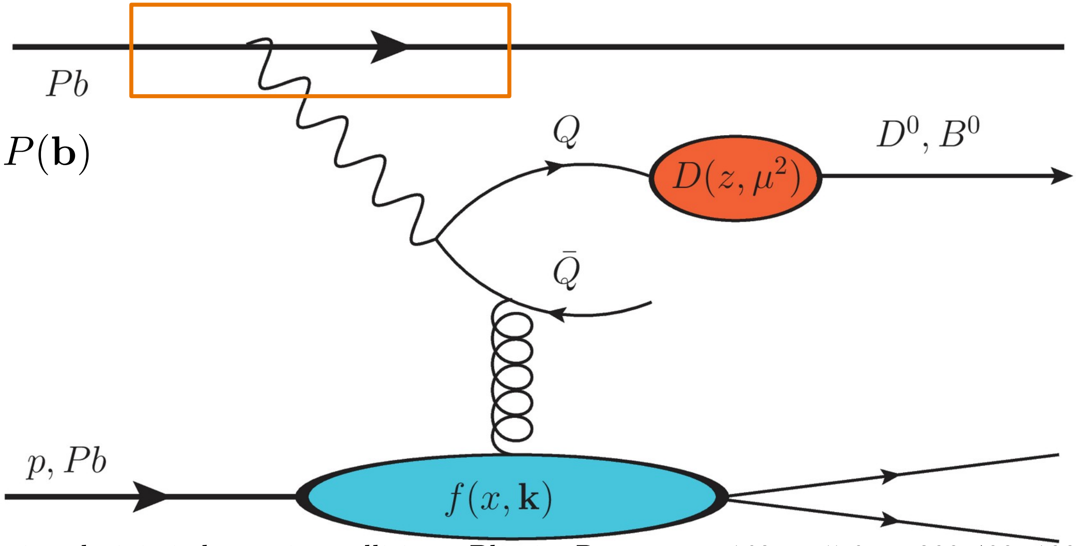
$$\frac{d\sigma(A+B\rightarrow A\otimes Q\bar{Q}+X)}{dY_Q d^2p_T} = \int_{x_Q}^{1} dz_Q \frac{x_Q}{z_Q} f^{\rm eff}_{\gamma/A}\left(\frac{x_Q}{z_Q}\right) \frac{d\sigma(\gamma B\rightarrow Q\bar{Q}X)}{dz_Q d^2p_T}$$

$$x_Q = \sqrt{\frac{p_T^2+m_Q^2}{s_{NN}}}\exp(+Y_Q)$$

Effective photon flux [19]:

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

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



[20] BERTULANI, Carlos A.; BAUR, Gerhard. Electromagnetic processes in relativistic heavy ion collisions. Physics Reports, v. 163, n. 5-6, p. 299-408, 1988.
[21] 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.

Formalism

Differential cross section for heavy quark production in UPCs:

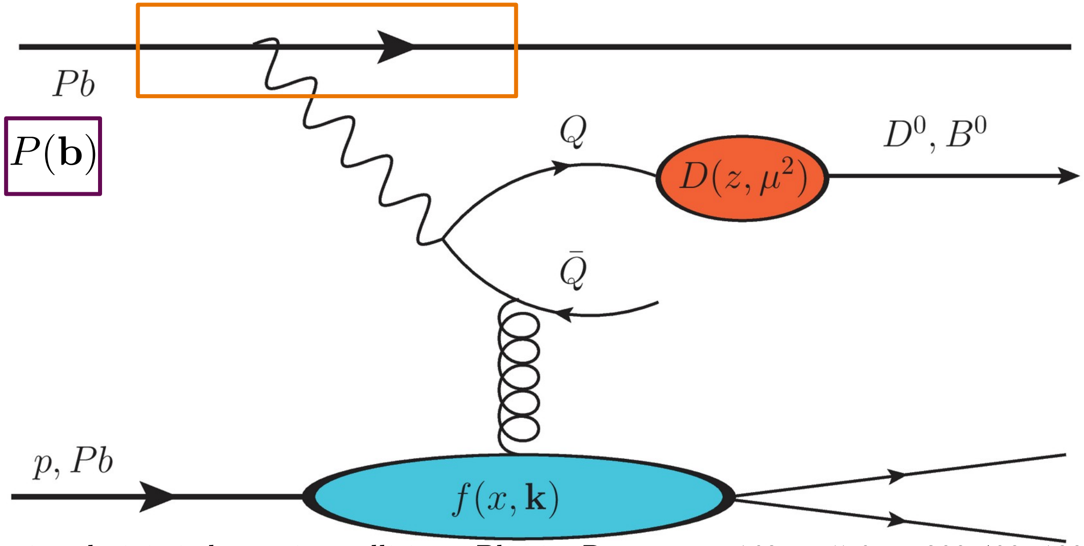
$$\frac{d\sigma(A+B\rightarrow A\otimes Q\bar{Q}+X)}{dY_Q d^2p_T} = \int_{x_Q}^{1} dz_Q \frac{x_Q}{z_Q} f^{\rm eff}_{\gamma/A}\left(\frac{x_Q}{z_Q}\right) \frac{d\sigma(\gamma B\rightarrow Q\bar{Q}X)}{dz_Q d^2p_T}$$

$$x_Q = \sqrt{\frac{p_T^2+m_Q^2}{s_{NN}}}\exp(+Y_Q)$$

Effective photon flux [19]:

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

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



Probability of no electromagnetic dissociation [20]: $P(\mathbf{b}) = \exp(-S/b^2)$

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

[20] BERTULANI, Carlos A.; BAUR, Gerhard. Electromagnetic processes in relativistic heavy ion collisions. Physics Reports, v. 163, n. 5-6, p. 299-408, 1988.
[21] 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.

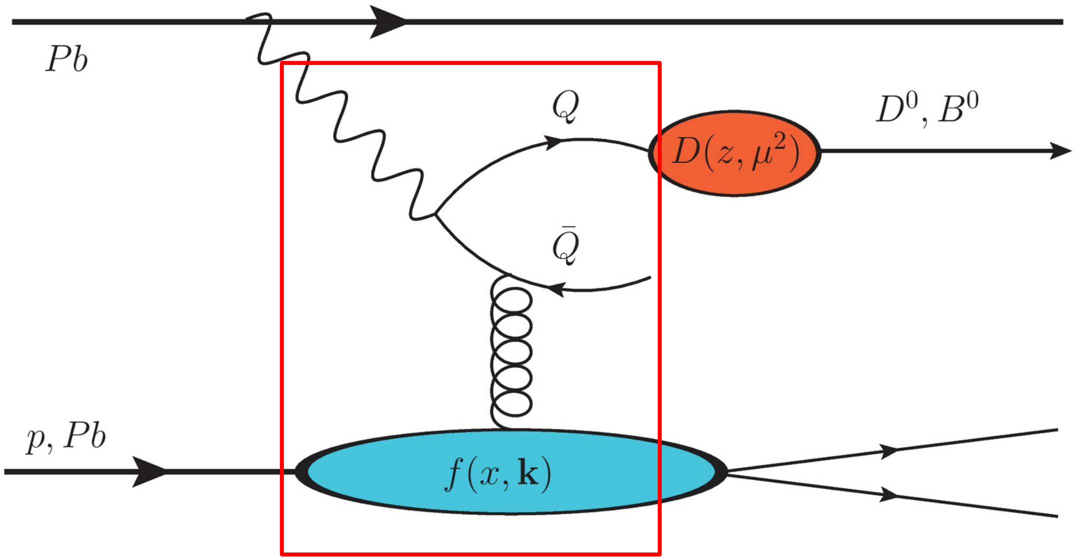
Formalism

Differential cross section for heavy quark production in UPCs:

$$\frac{d\sigma(A+B \to A \otimes Q\bar{Q} + X)}{dY_Q d^2p_T} = \int_{x_Q}^{1} dz_Q \frac{x_Q}{z_Q} f^{\rm eff}_{\gamma/A}\left(\frac{x_Q}{z_Q}\right) \frac{d\sigma(\gamma B \to Q\bar{Q}X)}{dz_Q d^2p_T}$$

$$x_Q = \sqrt{\frac{p_T^2 + m_Q^2}{s_{NN}}} \exp(+Y_Q)$$

Differential cross section for heavy quark photoproduction!



Formalism

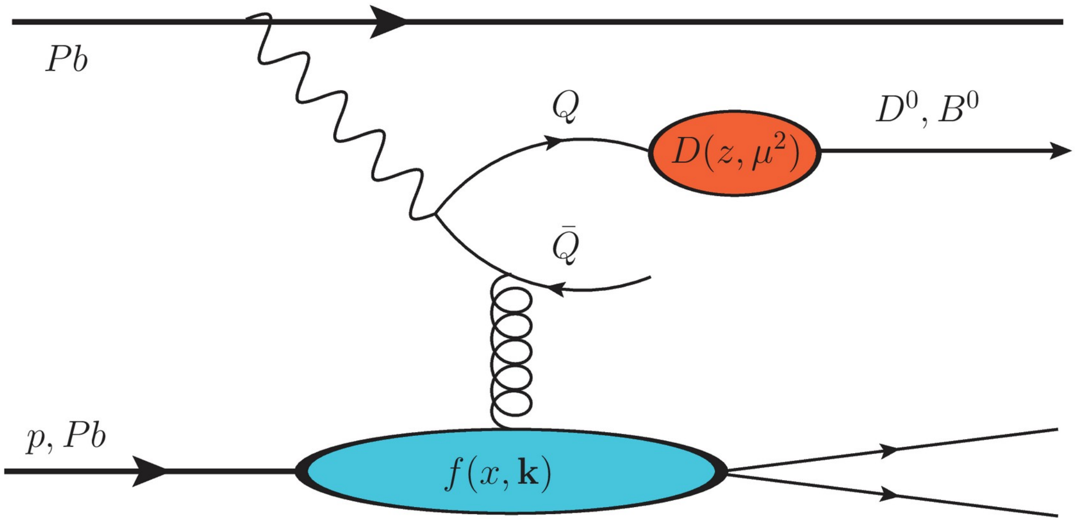
Differential cross section for heavy quark photoproduction within the S-matrix color dipole approach:

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

where

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

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



[22] N. N. Nikolaev, W. Schafer, B. G. Zakharov. Nonuniversality aspects of nonlinear kT factorization for hard dijets. Physical Review Letters, v. 95, p. 221803, (2005).

Formalism

Differential cross section for heavy quark photoproduction:

$$x = \sqrt{\frac{p_T^2 + m_Q^2}{s_{NN}}} \exp(-Y)$$

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

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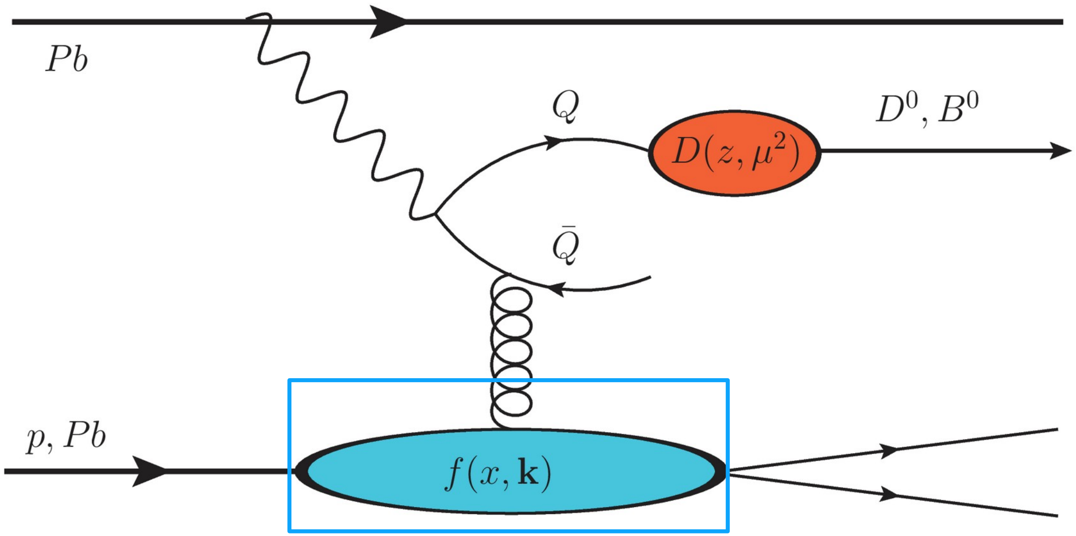
$$\mathcal{B}_2(\mathbf{p}_T,\mathbf{k}) = \frac{1}{2}\left[\frac{1}{p_T^2 + m_Q^2} - \frac{1}{(\mathbf{p}_T + \mathbf{k})^2 + m_Q^2}\right]^2$$



$\Longrightarrow$ 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.

Results for pPb collisions

Formalism

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

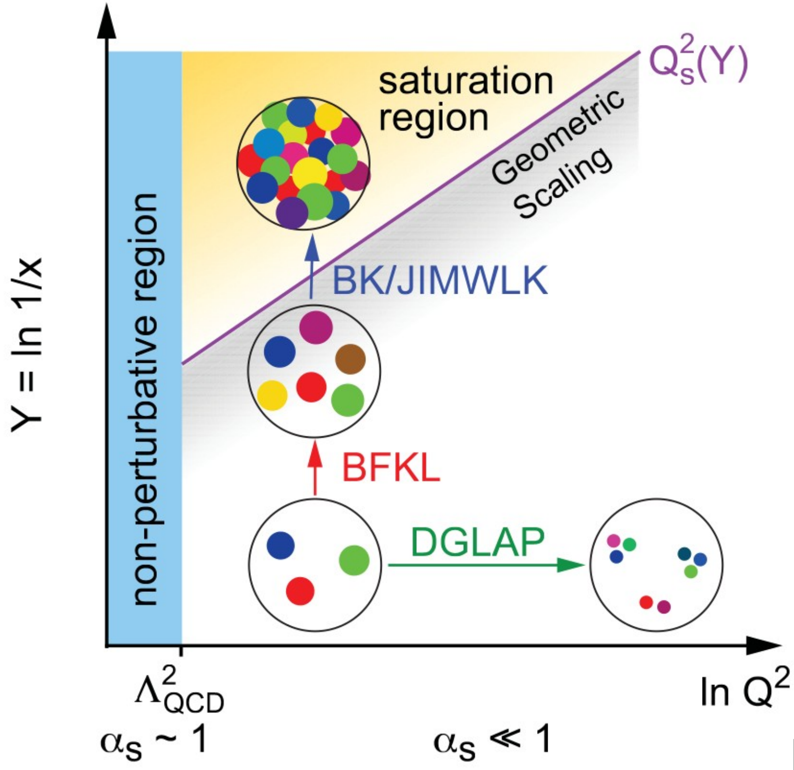
For the proton as a target:

Formalism

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

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



[23]

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

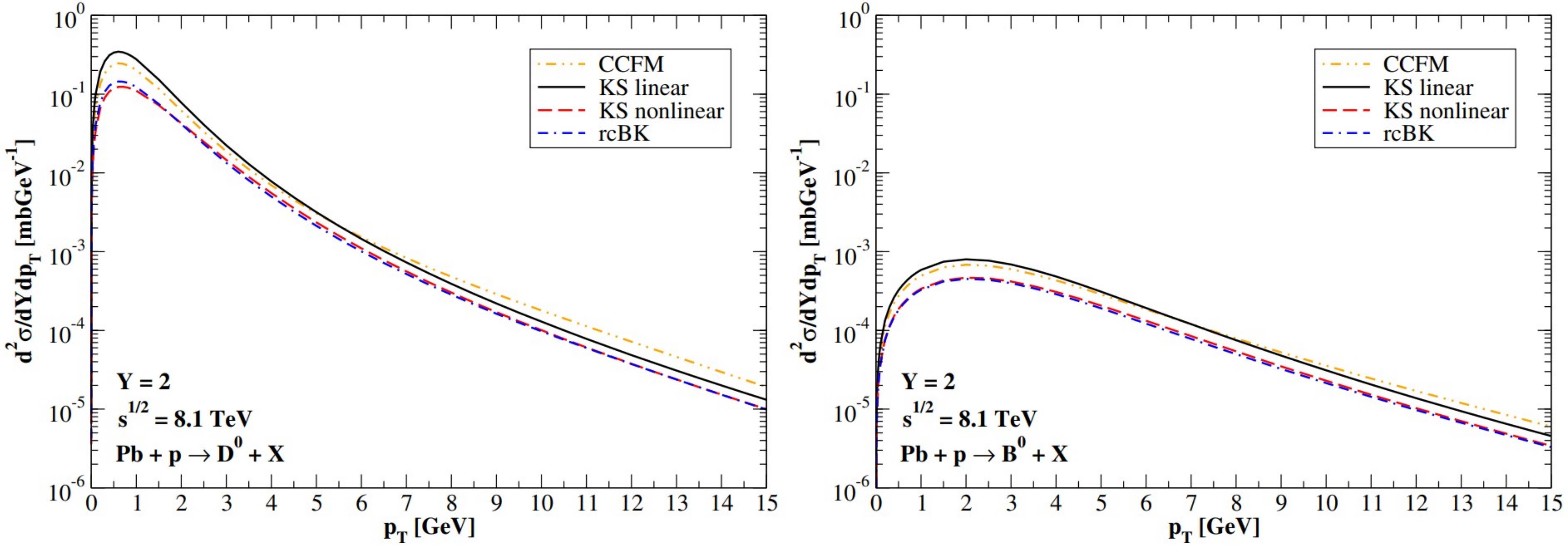
Total cross section in pPb collisions

ALICE (-2 < Y < 2)	D^0 (mb)	B^0 (mb)
CCFM	2.18	0.0261
KS linear	2.48	0.0244
KS nonlinear	1.35	0.0164
rcBK	1.33	0.0149

LHCb (2 < Y < 4.5)	D^0 (mb)	B^0 (mb)
CCFM	0.449	0.00241
KS linear	0.656	0.00286
KS nonlinear	0.236	0.00167
rcBK	0.271	0.00162

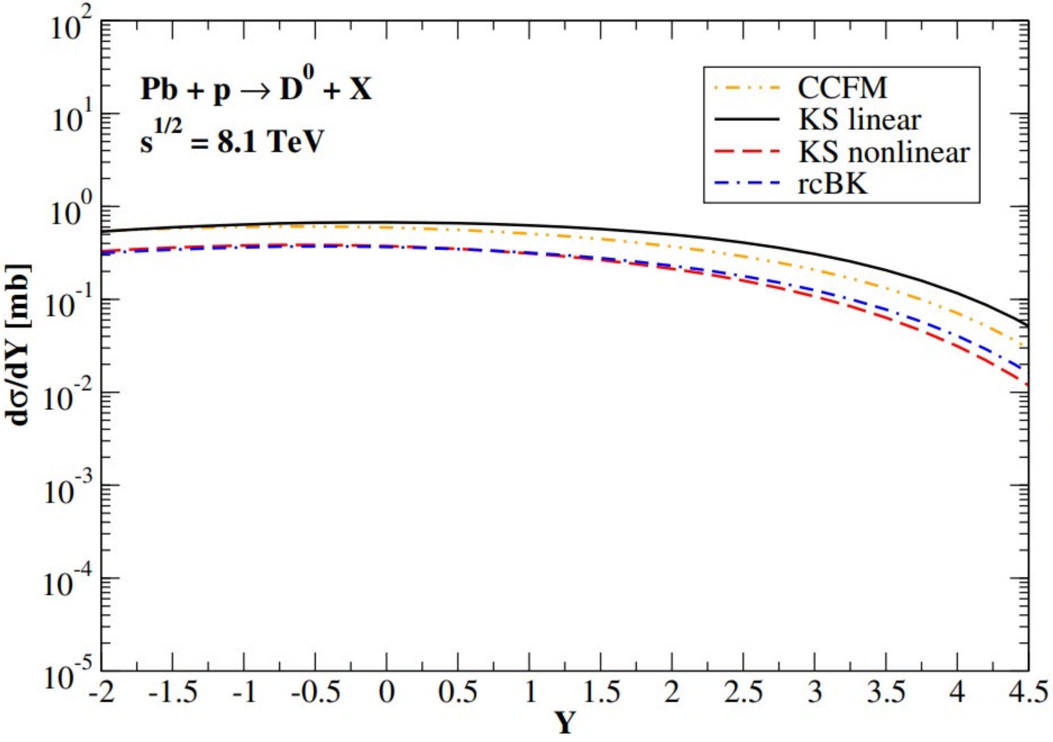
$$\sqrt{s} = 8.1 \text{ TeV}$$

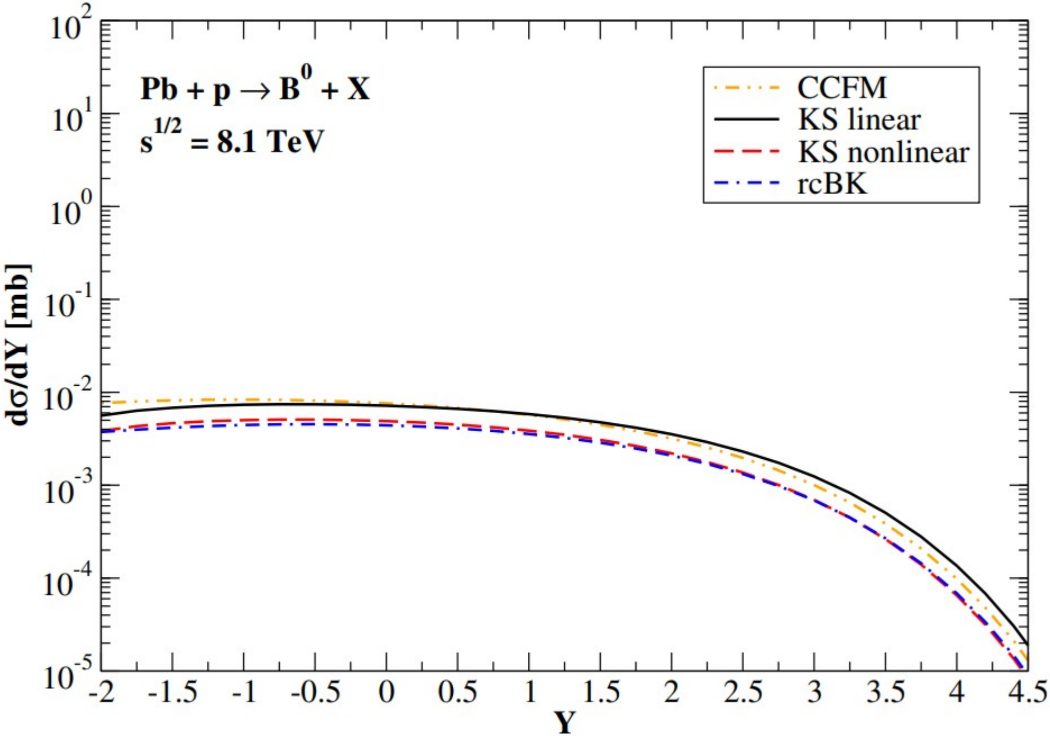
Tranverse momentum distributions in pPb collisions



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

Rapidity distributions in pPb collisions





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

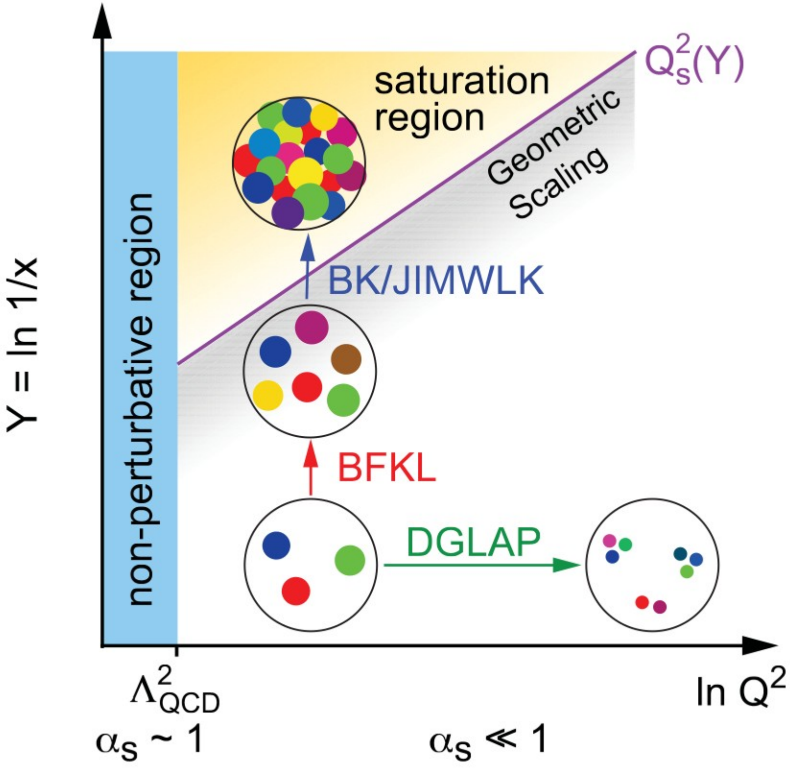
Results for PbPb collisions

Formalism

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

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: $Q_{s0}^2 = cA^{1/3}Q_{s0,p}^2$



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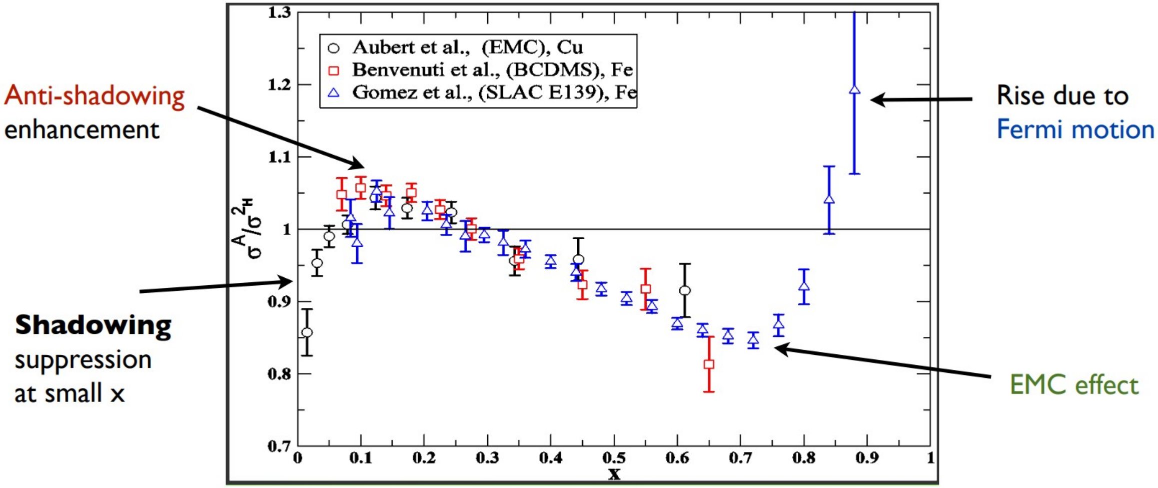
$f(x,\mathbf{k})$	Evolution	Nuclear effects?	Procedure
CCFM	linear	no	$Af_p(x,\mathbf{k})$
rcBK	nonlinear	yes	initial saturation scale: $Q_{s0}^2 = cA^{1/3}Q_{s0,p}^2$
EPPS	linear	yes	parton branching approach



[24]

[24] 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.

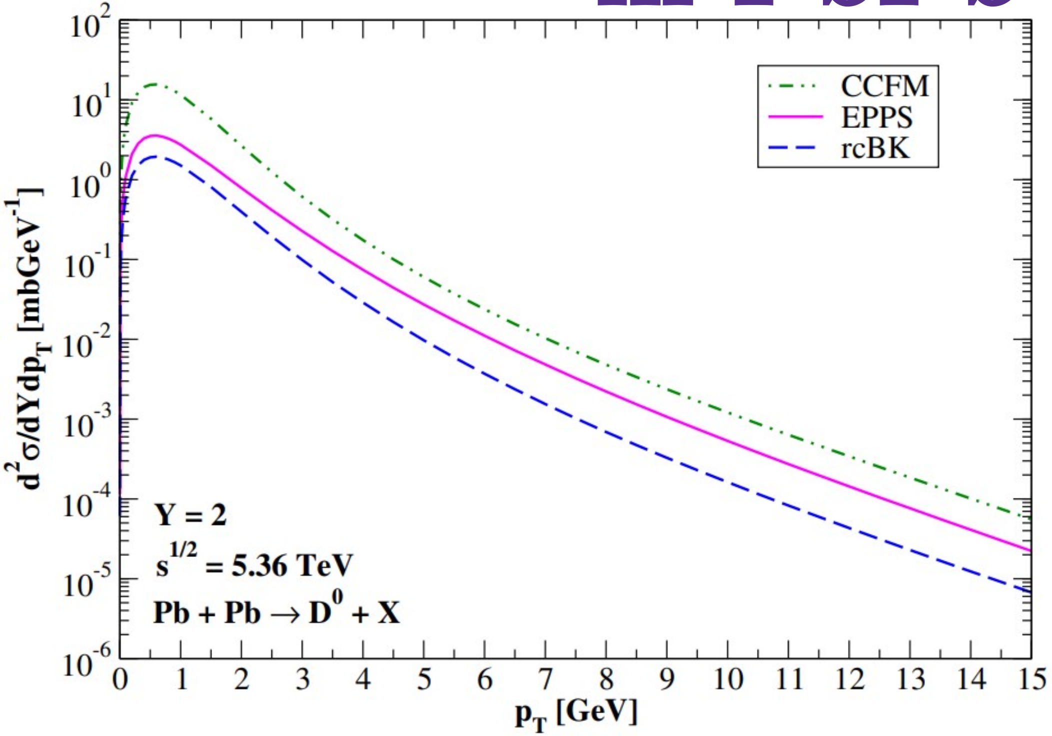
Total cross section in PbPb collisions

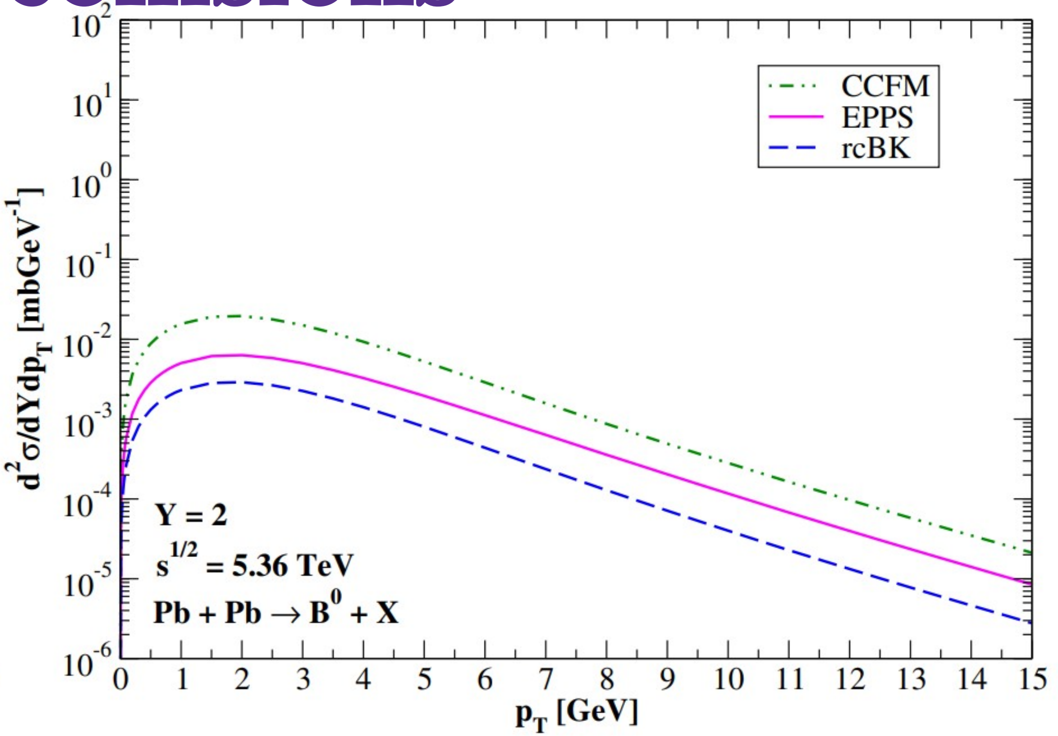
ALICE (-2 < Y < 2)	D^0 (mb)	B^0 (mb)
CCFM	225.1	2.138
EPPS	50.31	0.615
rcBK	31.11	0.284

LHCb (2 < Y < 4.5)	D^0 (mb)	B^0 (mb)
CCFM	14.69	0.0310
EPPS	3.717	0.0107
rcBK	1.867	0.0046

$$\sqrt{s} = 5.36 \text{ TeV}$$

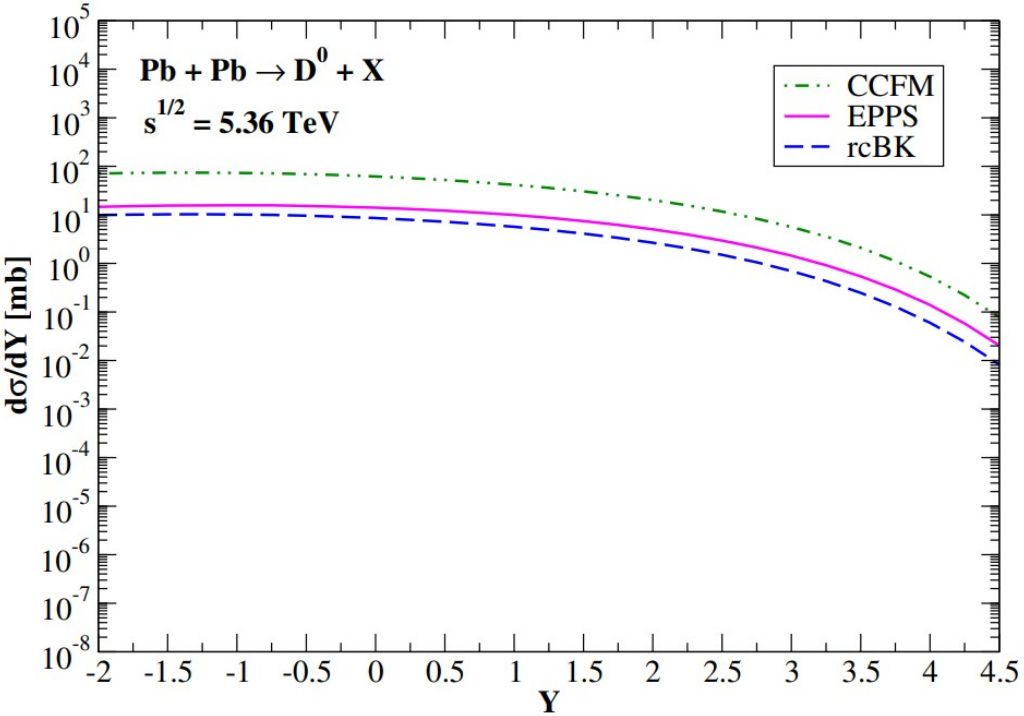
Transverse momentum distributions in PbPb collisions

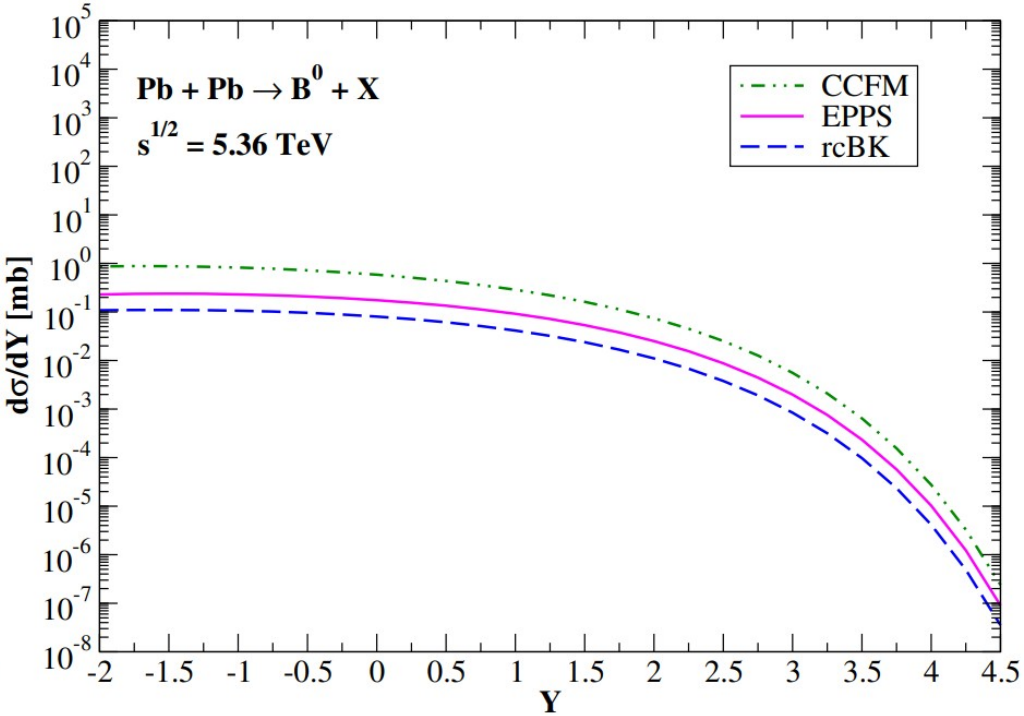




$f(x, \mathbf{k})$	CCFM	EPPS	rcBK
Evolution	linear	linear	nonlinear
Nuclear effects?	no	yes	yes

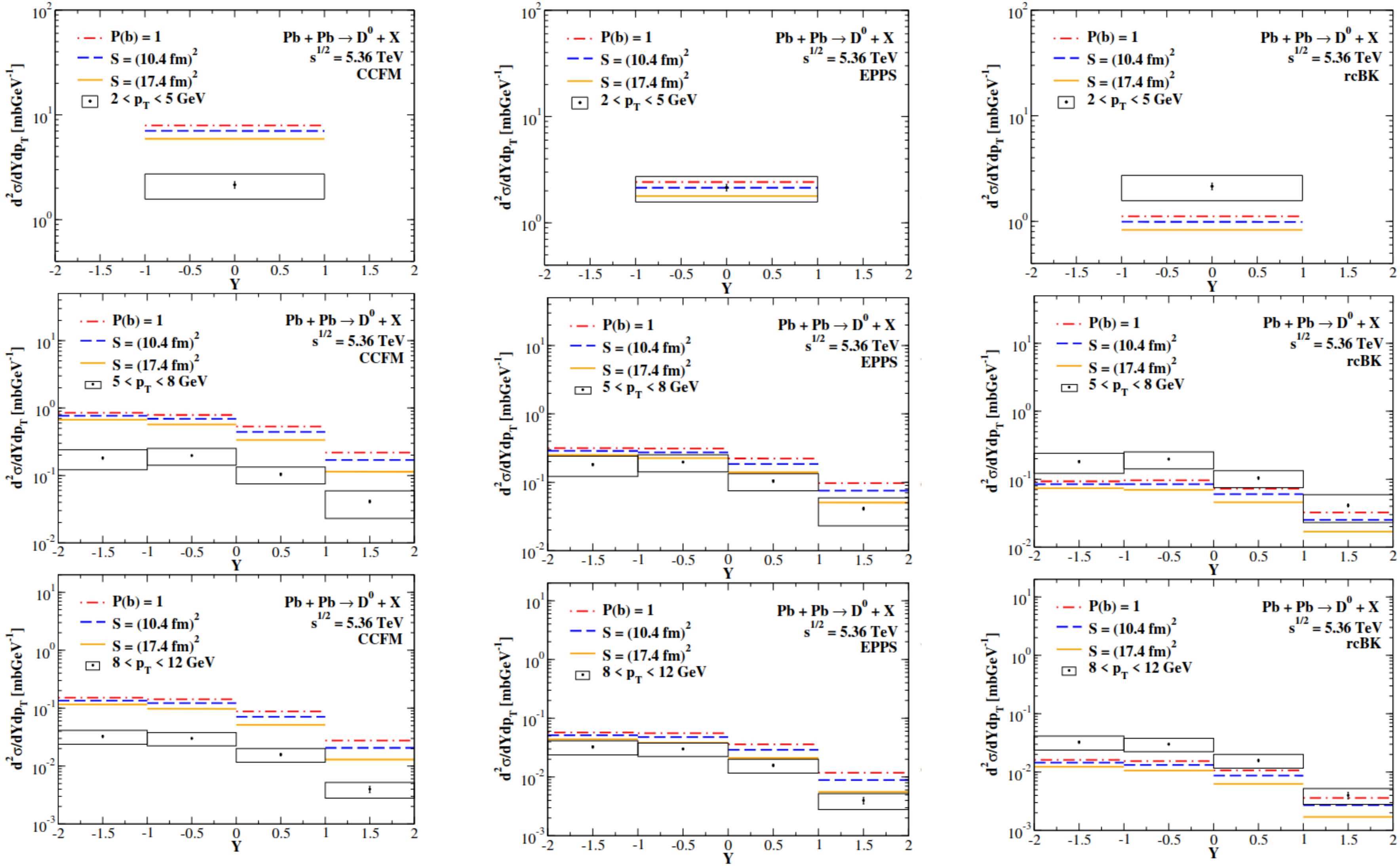
Rapidity distributions in PbPb collisions



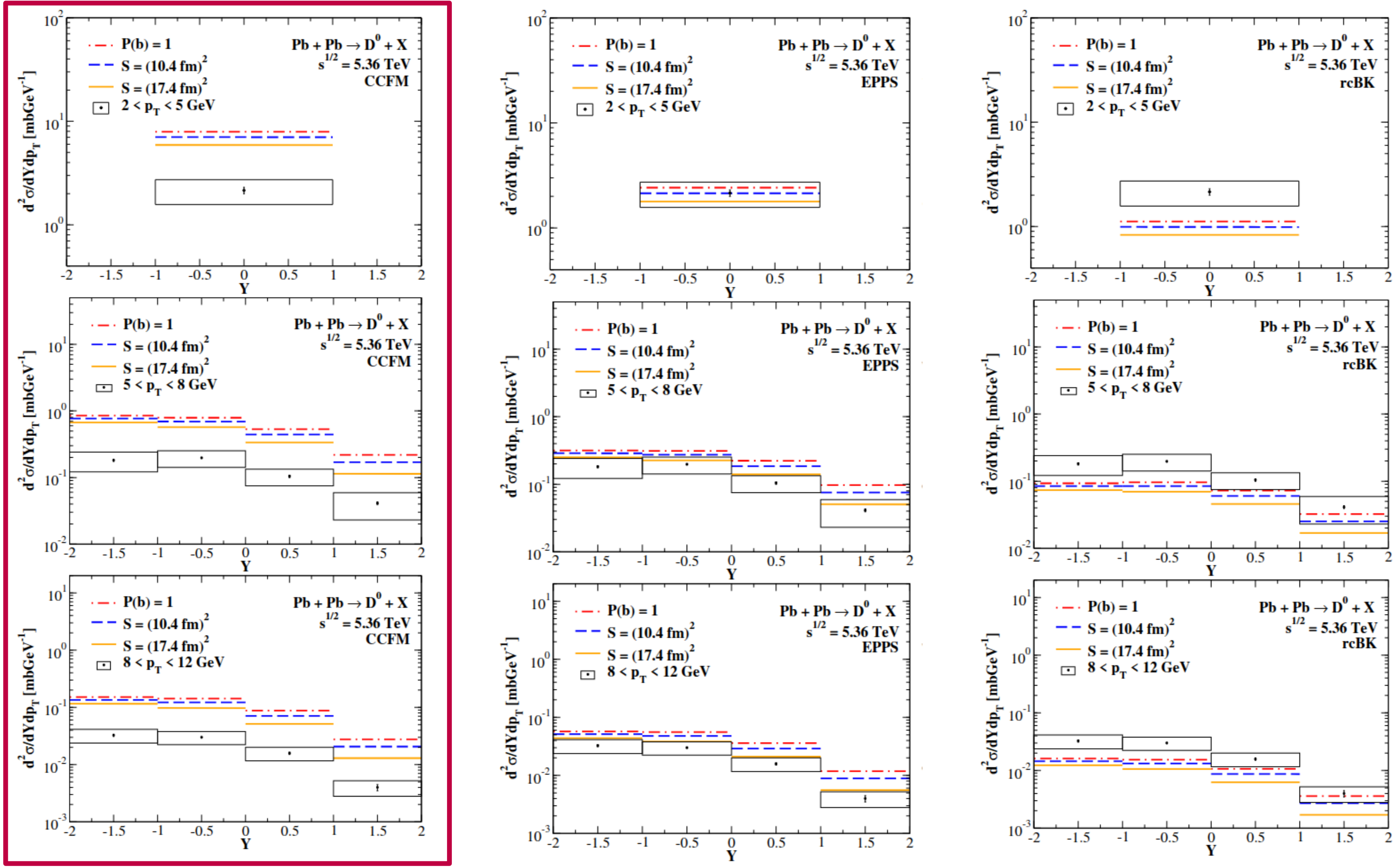


$f(x, \mathbf{k})$	CCFM	EPPS	rcBK
Evolution	linear	linear	nonlinear
Nuclear effects?	no	yes	yes

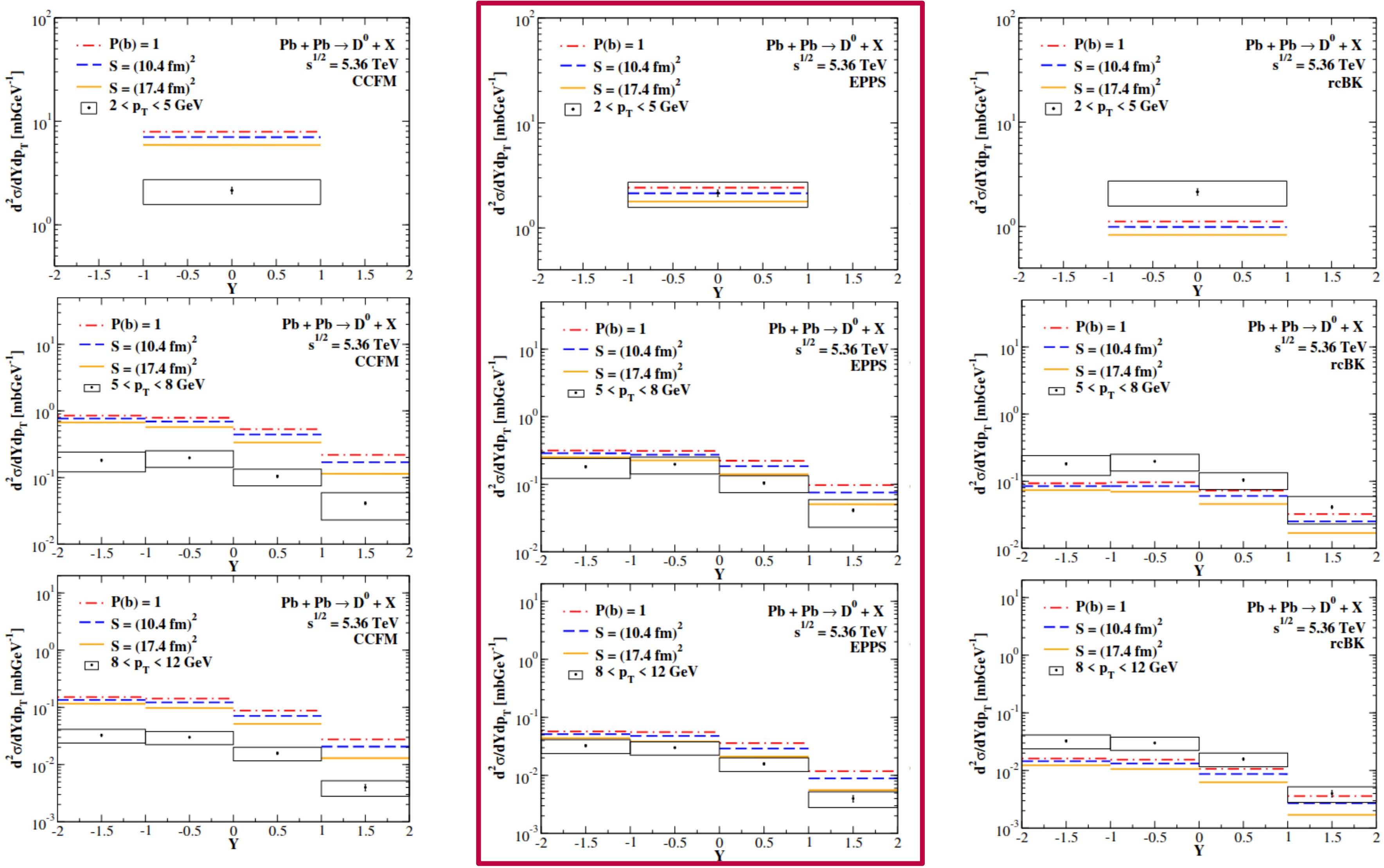
Comparison with data



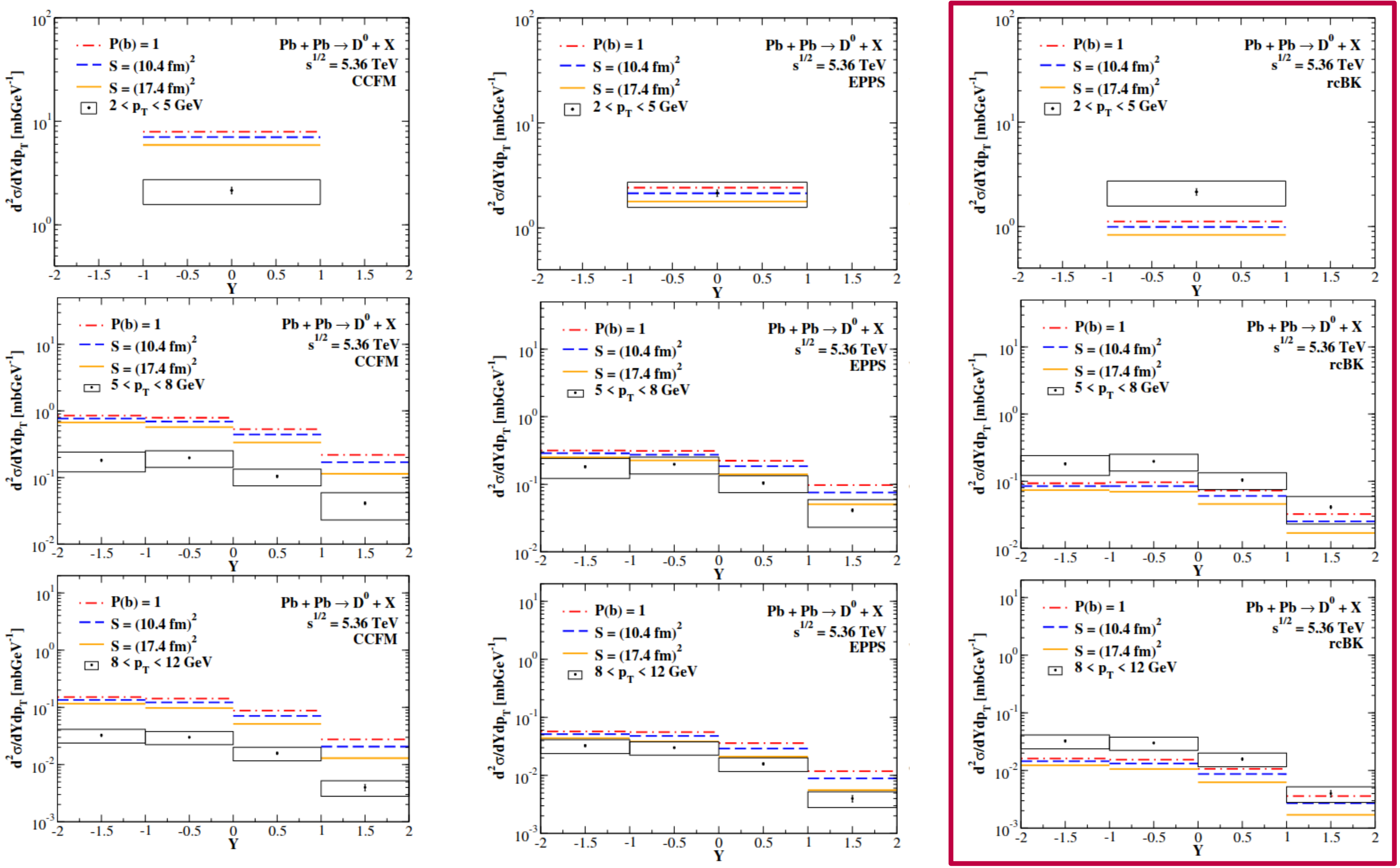
CMS Collaboration. Measurement of D^0 Meson Photoproduction in Ultraperipheral Heavy Ion Collisions. Phys. Rev. Lett. 136, 122303, 2026.



CMS Collaboration. Measurement of D^0 Meson Photoproduction in Ultraperipheral Heavy Ion Collisions. Phys. Rev. Lett. 136, 122303, 2026.

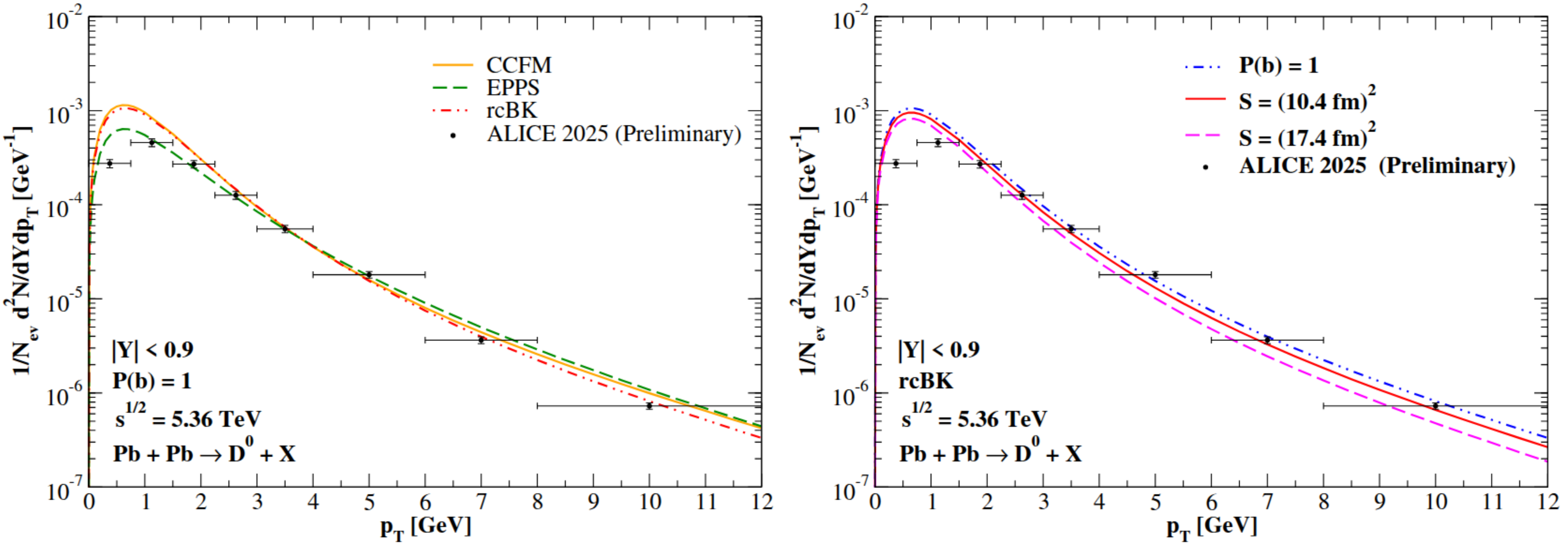


CMS Collaboration. Measurement of D^0 Meson Photoproduction in Ultraperipheral Heavy Ion Collisions. Phys. Rev. Lett. 136, 122303, 2026.



CMS Collaboration. Measurement of D^0 Meson Photoproduction in Ultraperipheral Heavy Ion Collisions. Phys. Rev. Lett. 136, 122303, 2026.

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 inclusive observables will be very useful to improve our understanding of the strong interaction theory.

Thank you for your attention!

Extra

S-matrix approach: the heavy quark photoproduction at high energies is determined by the $\gamma g \to c\bar{c}$ subprocesses. In the laboratory frame, such a process can be viewed as an excitation of the perturbative $|c\bar{c}\rangle$ Fock state of the physical projectile $|\gamma\rangle$ by a one-gluon exchange with the target proton. At high energies, the photon can be assumed to propagate along a straight line with a fixed impact parameter. The perturbative transition $\gamma \to c\bar{c}$ can be described in terms of the Fock state expansion for the physical state $|\gamma\rangle_{phys}$, which at the lowest order is given by

$$|\gamma\rangle_{phys} = |\gamma\rangle_0 + \Psi(z, \boldsymbol{r})|c\bar{c}\rangle_0,$$

where $|...\rangle_0$ refers to a bare photon and $\Psi(zc,\boldsymbol{r})$ is the probability amplitude to find the $c\bar{c}$ system with separation $\boldsymbol{r}$ in the two-dimensional impact parameter space. The impact parameter of the photon is assumed to be $\boldsymbol{b}$, which implies $\boldsymbol{b}c = \boldsymbol{b} + z\boldsymbol{r}$ and $\boldsymbol{b}\bar{c} = \boldsymbol{b} - z\boldsymbol{r}$. The corresponding cross section for the charm production is a particular case of the master formula for the $a \to bc$ transition, and is given by

$$\frac{d\sigma_{T,L}(\gamma \to c(p_c)\bar{c}(p_{\bar{c}}))}{dz d^2\boldsymbol{k} d^2\Delta} = \frac{1}{2(2\pi)^4} \int d^2\boldsymbol{r} d^2\boldsymbol{r}' \exp[i\boldsymbol{k}\cdot(\boldsymbol{r}-\boldsymbol{r}')]\Psi_{T,L}(z,\boldsymbol{r})\, \Psi^*_{T,L}(z,\boldsymbol{r}')$$
$$\times \int d^2\boldsymbol{s} \exp[i\Delta\cdot\boldsymbol{s}]\Big\{\sigma(\boldsymbol{s}+z\boldsymbol{r}') + \sigma(\boldsymbol{s}-z\boldsymbol{r}) - \sigma(\boldsymbol{s}-z(\boldsymbol{r}-\boldsymbol{r}')) - \sigma(\boldsymbol{s})\Big\},$$

Extra

where $\boldsymbol{k} = (1 - z)\boldsymbol{p}c - z\boldsymbol{p}\bar{c}$ is the light-cone relative momentum, which is the conjugate variable to $\boldsymbol{r} - \boldsymbol{r}'$, and $\Delta = \boldsymbol{p}c + \boldsymbol{p}\bar{c}$ is the transverse momentum decorrelation. The inclusive charm production has a cross section that can be derived integrating the equation over the transverse momentum of the anticharm in the final state or, equivalently, integrating over Δ. As a consequence, the corresponding cross section will be given by

$$\frac{d\sigma_{T,L}(\gamma h \to c\bar{c}X)}{dz\, d^2\mathbf{p}} = \frac{1}{(2\pi)^2} \int d^2\mathbf{r}\, d^2\mathbf{r}' \, \exp[i\mathbf{p}\cdot(\mathbf{r}-\mathbf{r}')]\, \Psi_{T,L}(z,\mathbf{r})\, \Psi^*_{T,L}(z,\mathbf{r}')$$
$$\times \frac{1}{2}\left[\sigma(\mathbf{r},x) + \sigma(\mathbf{r}',x) - \sigma(|\mathbf{r}-\mathbf{r}'|,x)\right],$$

with $\boldsymbol{p} = \boldsymbol{p}c$ and x is the Bjorken variable. The products of wave functions are given by

$$\Psi_T(z,\mathbf{r})\Psi^*_T(z,\mathbf{r}') = \frac{N_c\alpha_{\mathrm{em}}e_c^2}{2\pi^2}\left\{\left[z^2 + (1-z)^2\right]\epsilon^2 K_1(\epsilon r)K_1(\epsilon r')\frac{\mathbf{r}\cdot\mathbf{r}'}{rr'} + m_c^2 K_0(\epsilon r)K_0(\epsilon r')\right\},$$

$$\Psi_L(z,\mathbf{r})\Psi^*_L(z,\mathbf{r}') = \frac{N_c\alpha_{\mathrm{em}}e_c^2}{2\pi^2}\left\{4z^2(1-z)^2Q^2 K_0(\epsilon r)K_0(\epsilon r')\right\},$$

In our case, we are interested in the photoproduction limit, where the longitudinal contribution vanishes.

Extra

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

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

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

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

$$I_3(z, p_T) = \int \mathrm{d}r\; r J_1(p_T r) K_1(\epsilon r) \sigma(\mathbf{r}, x)$$

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

Extra

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

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

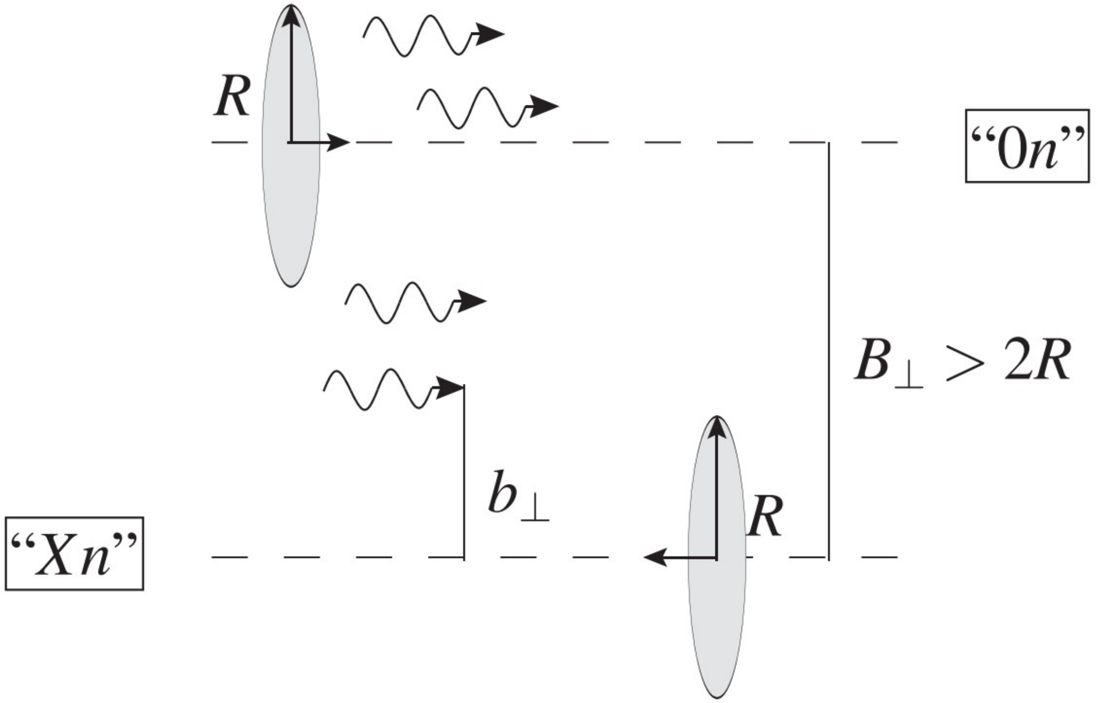
$$\frac{Eb}{\gamma_{\rm rf}} K_1\left(\frac{Eb}{\gamma_{\rm rf}}\right) \approx 1,$$

so that

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

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

Extra



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

Extra

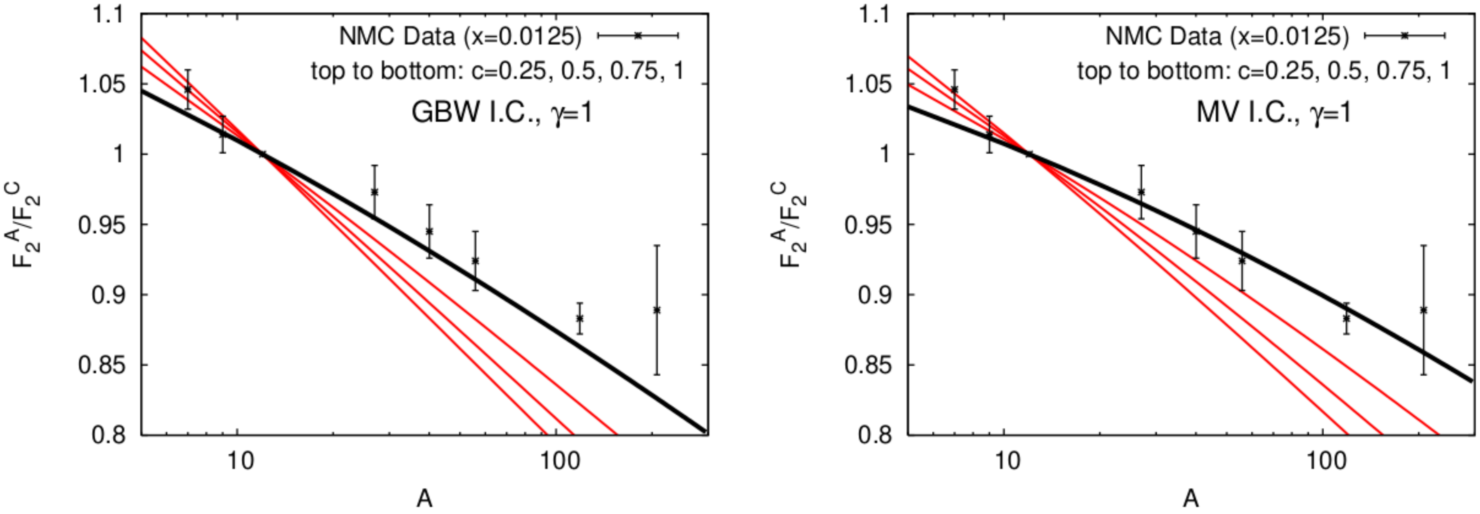


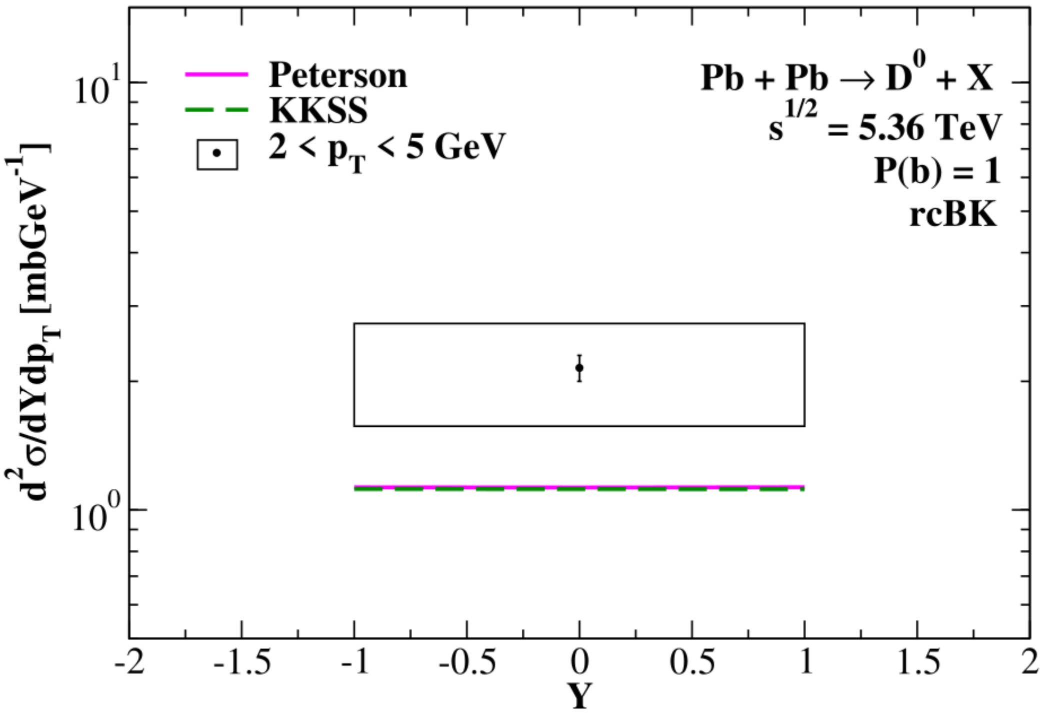
Figure 8: DIS fixed target e+A data on the ratio of structure functions as a function of A for fixed $x = 0.0125$. The plots correspond to (right) MV model initial condition having $\gamma = 1$ and (left) GBW initial condition.

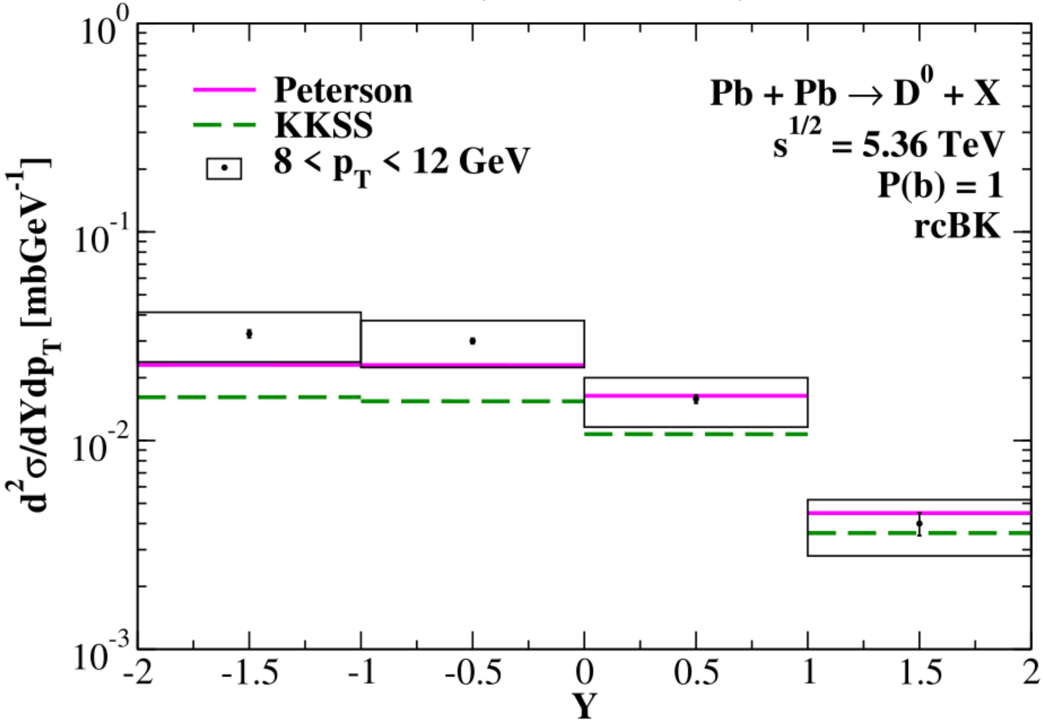
DUSLING, Kevin et al. Long range two-particle rapidity correlations in A+ A collisions from high energy QCD evolution. Nuclear Physics A, v. 836, n. 1-2, p. 159-182, 2010.

Extra

Peterson x KKSS model:

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





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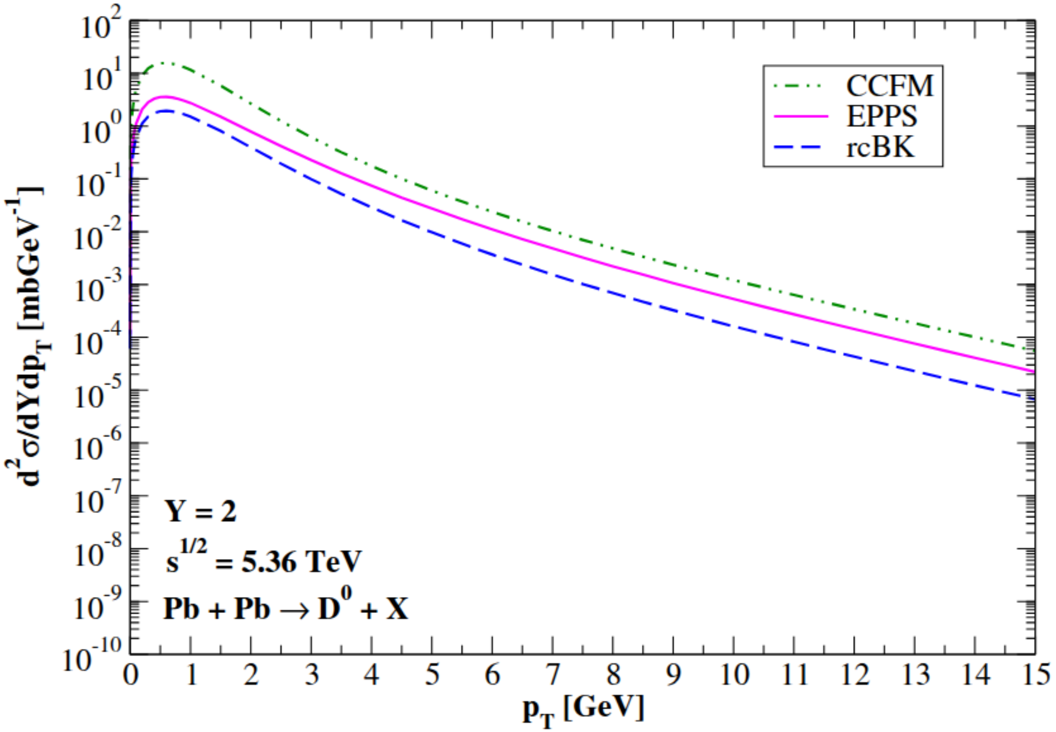
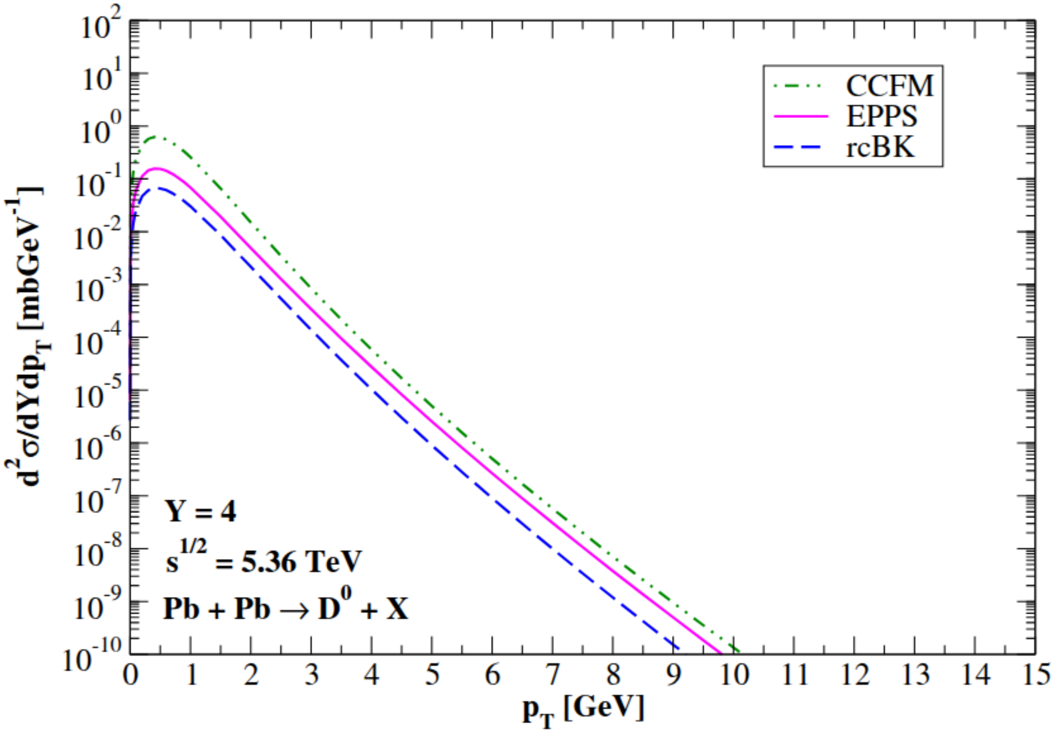


CCFM
EPPS
rcBK
Y = 2
s^1/2 = 5.36 TeV
Pb + Pb → D^0 + X
d^2σ/dYdp_T [mbGeV^-1]
p_T [GeV]



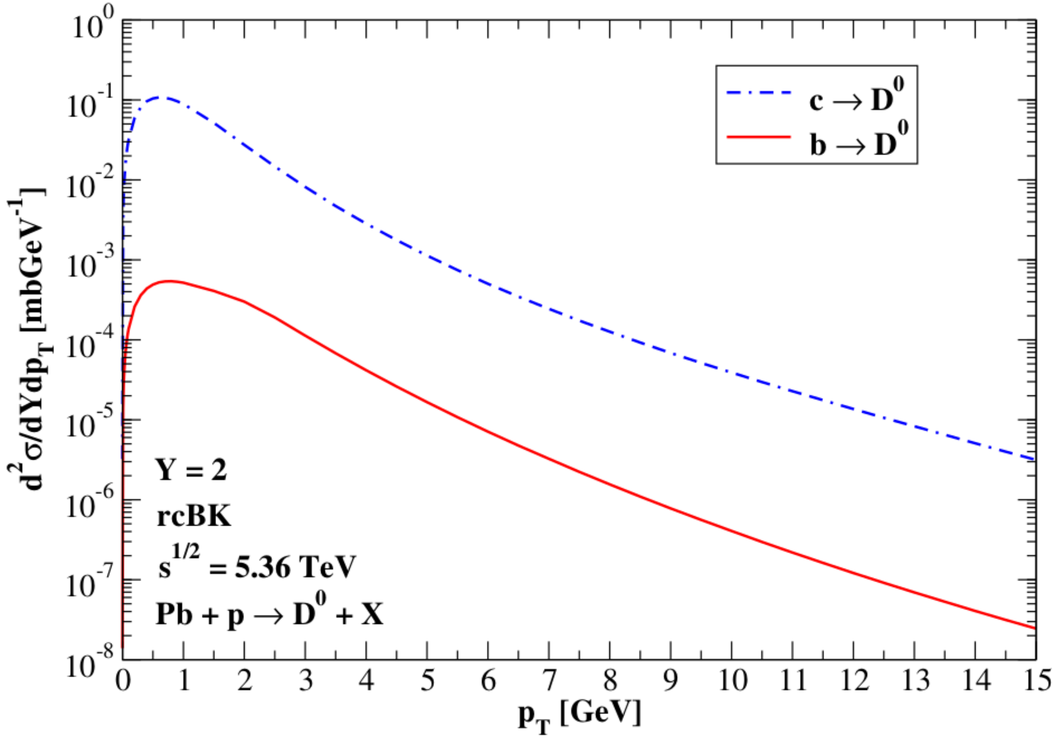
CCFM
EPPS
rcBK
Y = 4
s^1/2 = 5.36 TeV
Pb + Pb → D^0 + X
d^2σ/dYdp_T [mbGeV^-1]
p_T [GeV]

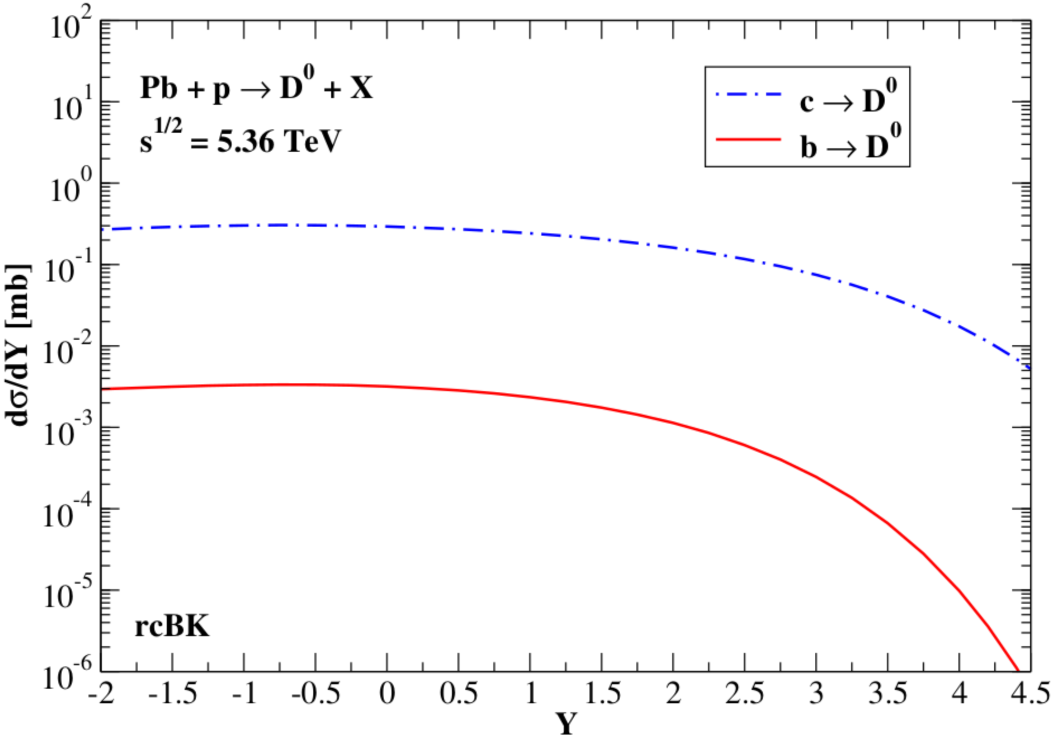
Extra

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

Feed down b→D⁰:

pPb collisions

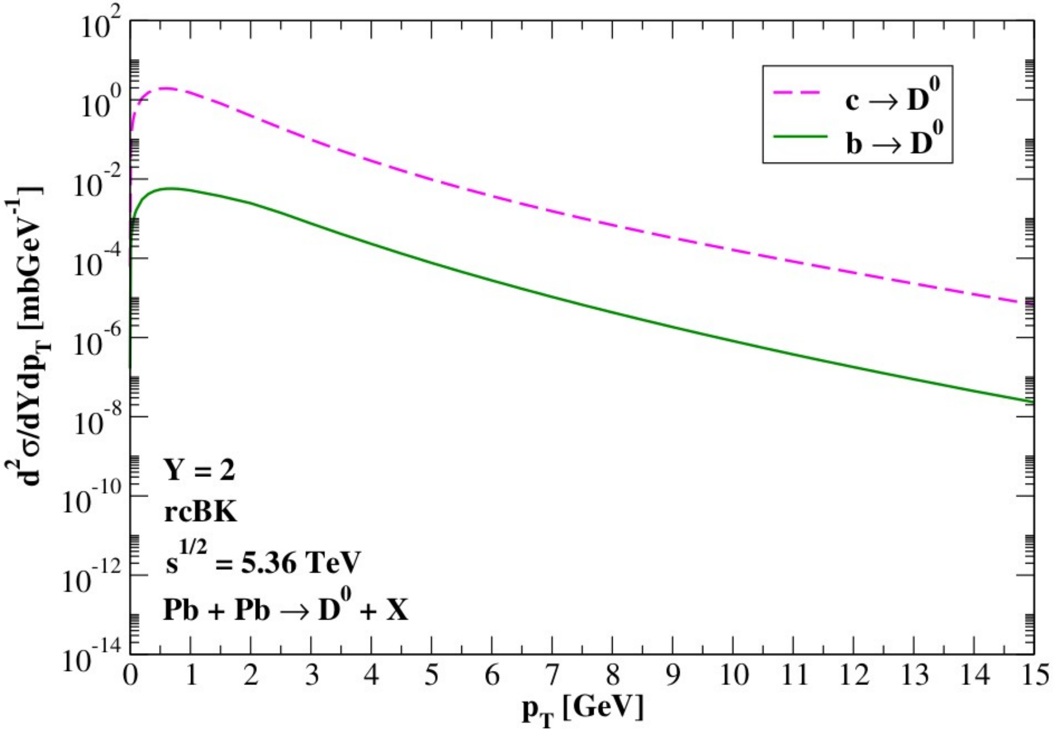


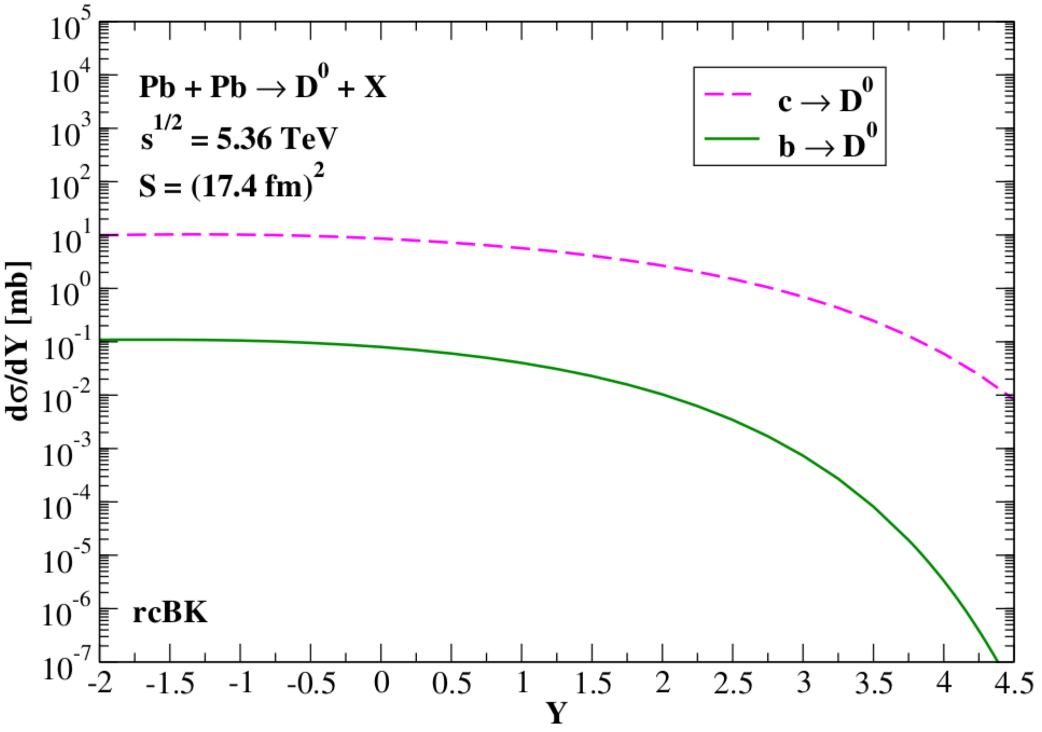


Extra

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

Feed down b $\rightarrow$ D^0:





Extra

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

Feed down $b \to D^0$: