Open charm production in UPC

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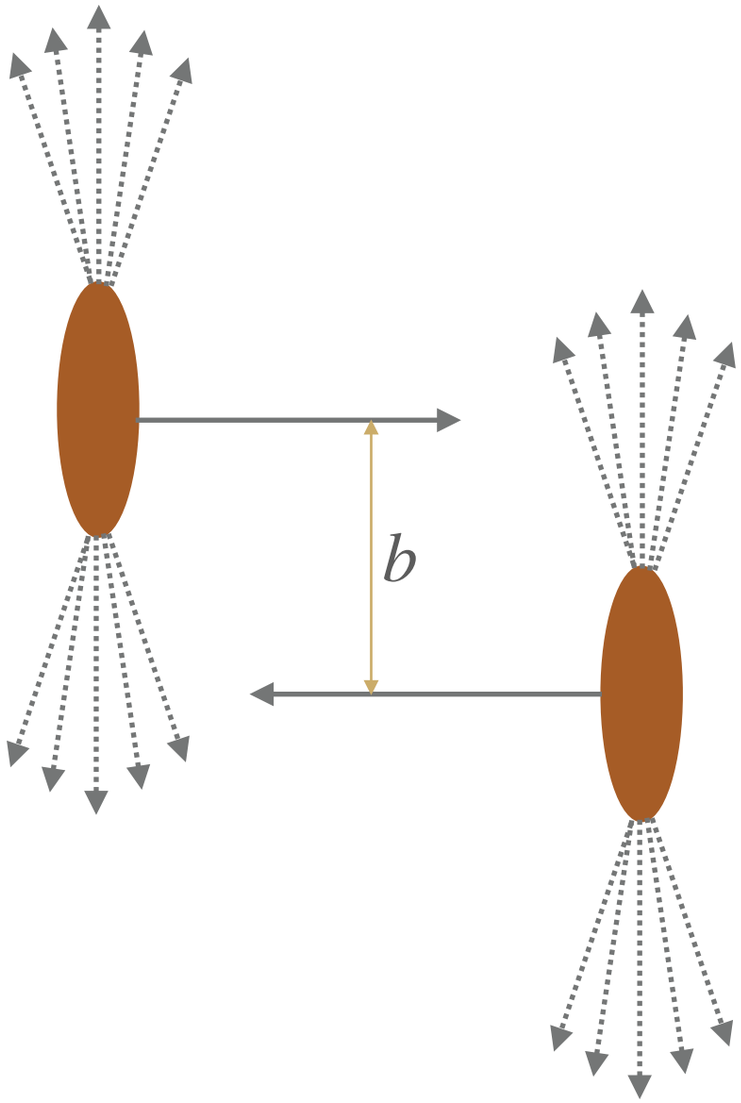
Outline

- Motivation : why UPC are interesting ?
- Photonuclear reactions as probes of nuclear structure
- Charm production cross section in FONLL approach
- Comparison with HERA inclusive D* data
- Prediction for D^0 production in UPC at LHC and comparison with preliminary CMS data
- Conclusions and outlook

Work in collaboration with **Gian-Michele Innocenti**

CMS measurement: see presentation by Gian-Michele tomorrow!

Ultraperipheral AA collisions



UPC: ultraperipheral AA collisions, $b > 2R_A$

Dominated by electromagnetic component

Cleaner environment than standard AA collisions

Equivalent photon approximation EPA

Photon flux enhanced by Z^2 of nucleus

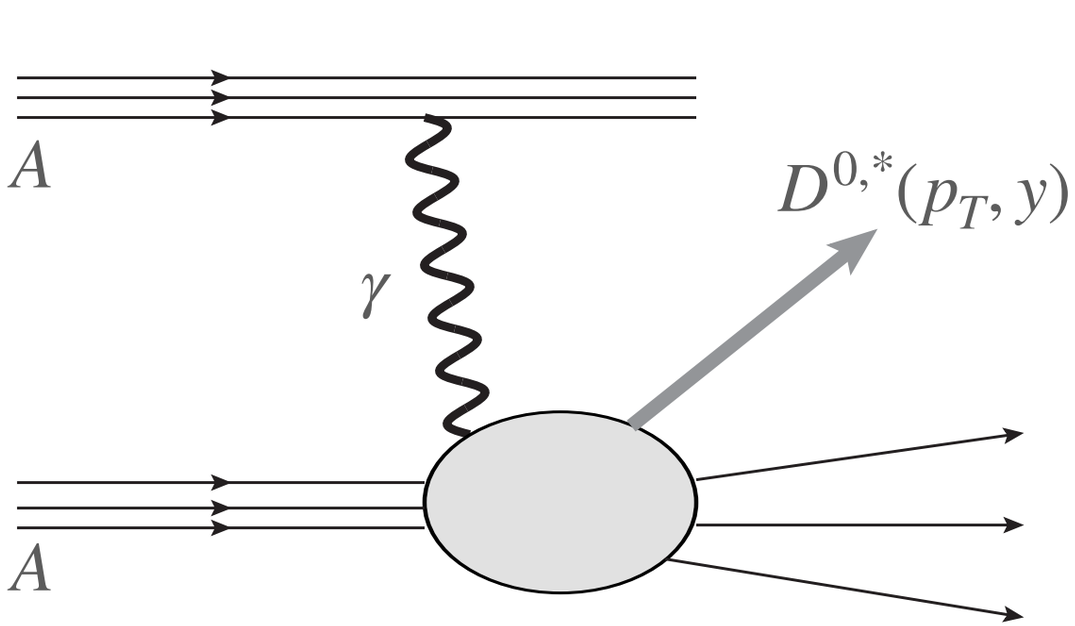
LHC :

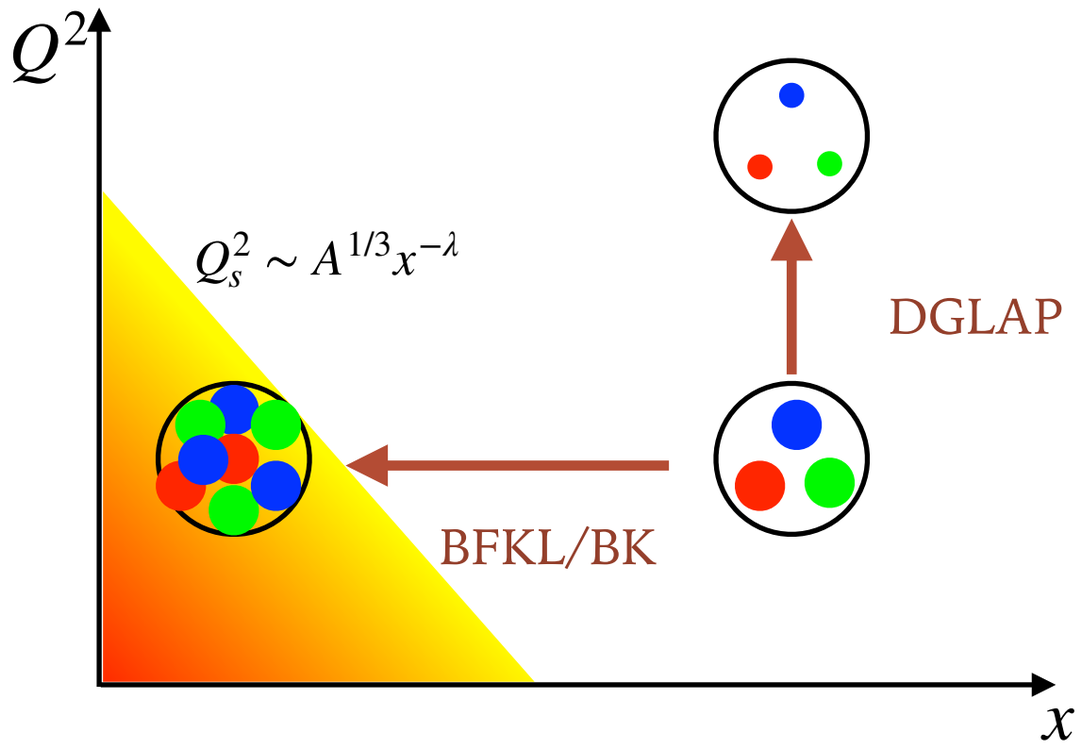
PbPb, Z=82, A=208

$\sqrt{s_{NN}} = 5.36\,\text{TeV}$

UPC with hard scale

- Photonuclear reactions with **hard scale**: **perturbative** methods applicable
- Examples:
  - **Dijet** photoproduction
  - **Exclusive heavy vector meson** production
- Excellent probes of **nuclear structure**, especially at **low Bjorken x**
- Focus of this talk: **inclusive charm photoproduction in UPC**





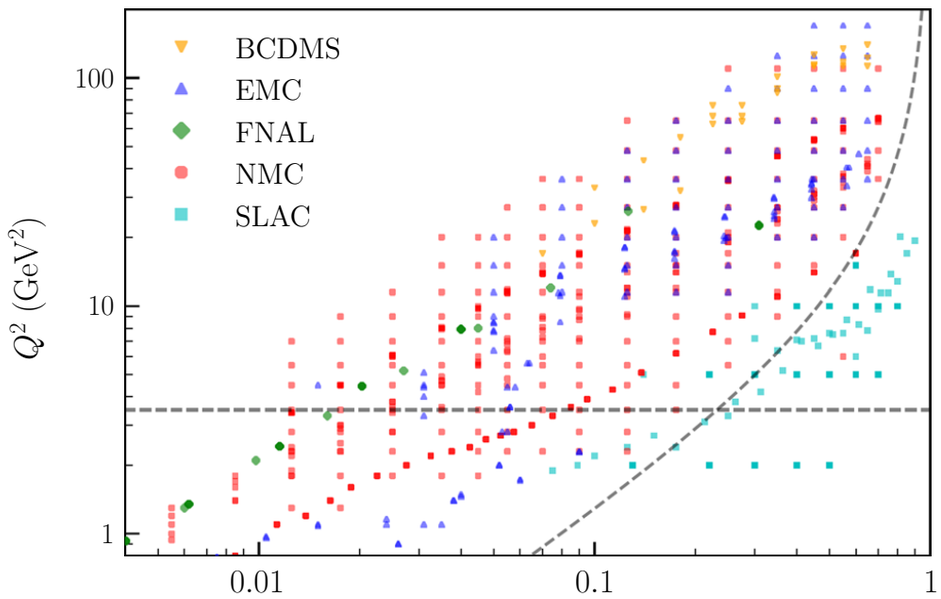
(x, Q^2) kinematic space in DIS and UPC with nuclei

Probing **nuclear structure**

Limited to fixed target DIS so far, moderate to large x

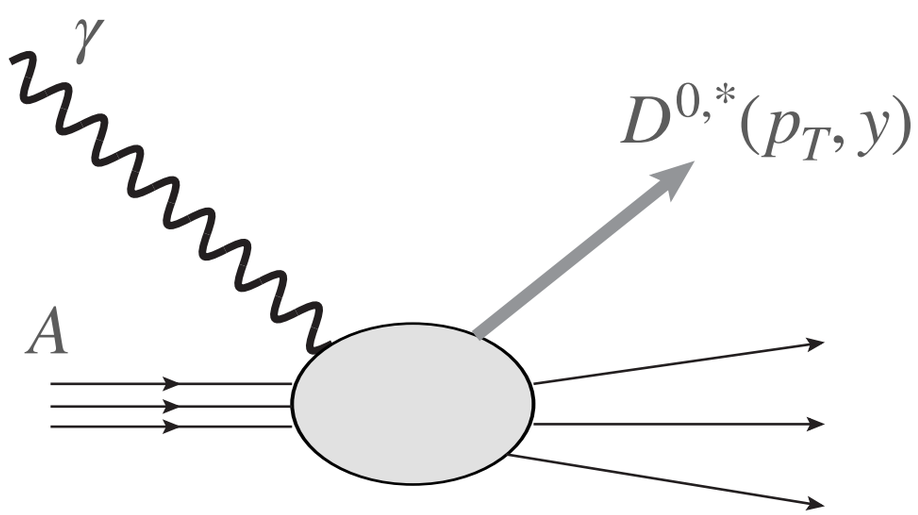
Electron Ion Collider will open new kinematics

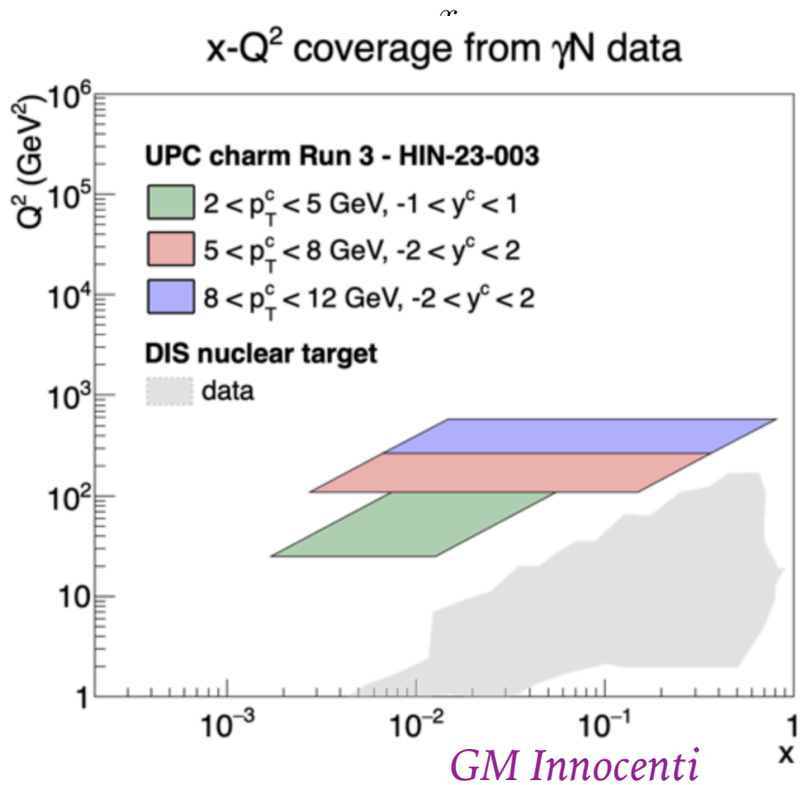
NNPDF, EPJC 79, 471, 2019



Charm photo-production in UPC

Charm produced mainly in γg **fusion**
Sensitive to the **nuclear gluon density**





GM Innocenti

Cross section for charm photoproduction

FONLL framework for **heavy flavor photoproduction and hadroproduction**
Cacciari, Frixione, Nason; Cacciari, Greco, Nason

FONLL code for heavy quark photoproduction by *M. Cacciari*

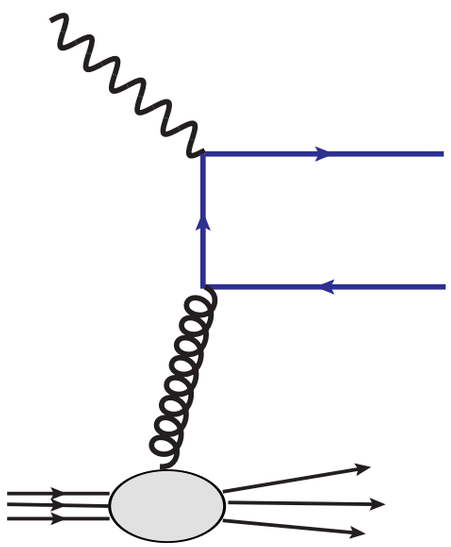
Connects **small transverse momenta** with mass effects to the **large transverse momentum** region with logarithmically enhanced terms $\ln p_T/m$

Accurate up to NLO, i.e. $\alpha_{\rm em}\alpha_s$, $\alpha_{\rm em}\alpha_s^2$ terms exact

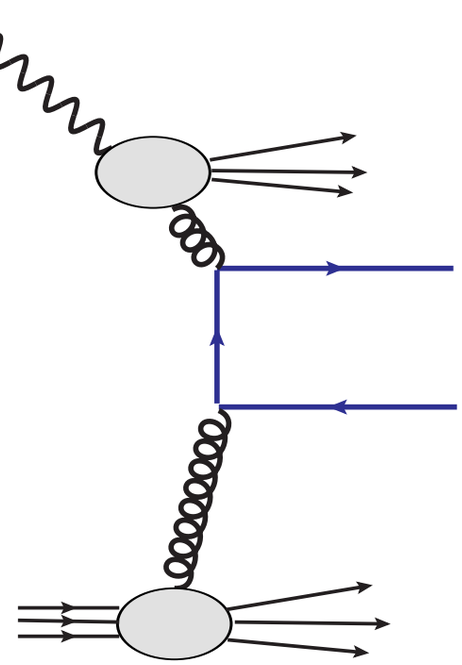
Includes terms: $\alpha_{\rm em}\alpha_s(\alpha_s \ln p_T/m)^k$, $\alpha_{\rm em}\alpha_s^2(\alpha_s \ln p_T/m)^k$

Both ***direct*** and ***resolved*** contributions included

direct



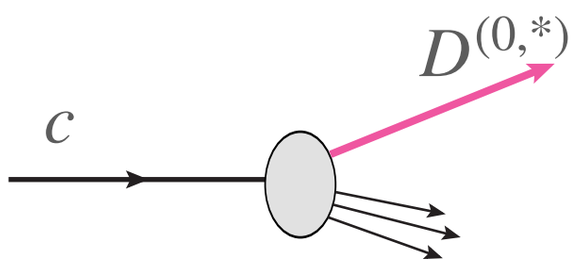
resolved

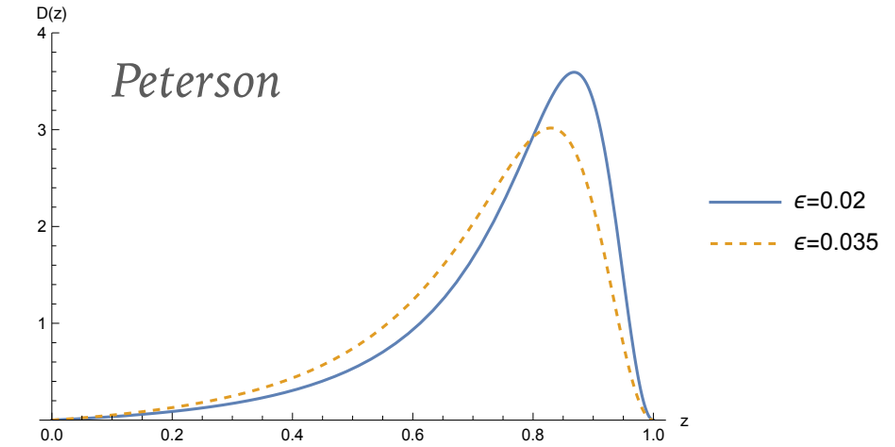


Both related beyond LO

Only sum is observable

Fragmentation functions: from c to D





D* production at HERA

Use **Peterson** function: $D(z) = \mathcal{N}\frac{1}{z}\left(1 - \frac{1}{z} - \frac{\varepsilon}{1-z}\right)^{-2}$

Parameter choice: $\varepsilon = 0.02, 0.035$ *Frixione, Nason*

D^0 production in UPC

In addition to Peterson function, use **Braaten-Cheung-Fleming-Yuan (BCFY)**

Two component model: direct decays $c \to D^0$ and decays from D* states

Parameter choice: $r = 0.1, 0.06$

Cacciari, Nason ; Cacciari, Frixione, Houdeau,Mangano,Nason, Ridolfi

Comparison with HERA data on D*

Reproduce FONLL results by *Frixione & Nason* with **updated** PDFs
Compute both FONLL and fixed order FO at NLO

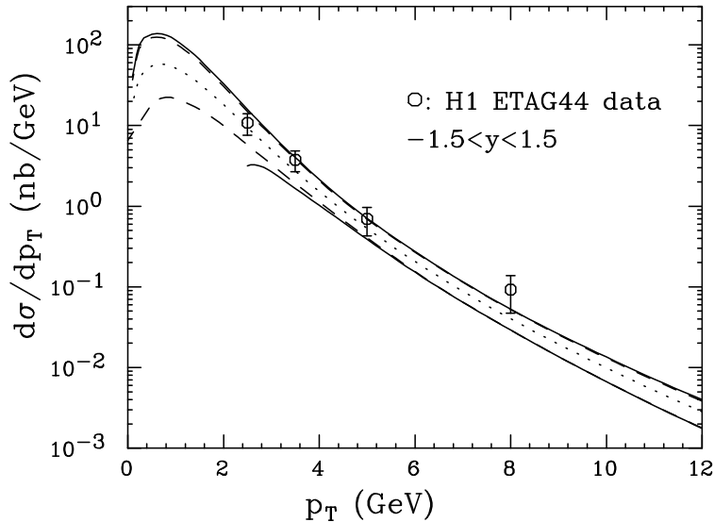
Proton PDF sets: CTA18NLO, HERAPDF2.0, nNNPDF3.0_p

Photon PDF sets: GRV, AFG

Fragmentation: Peterson with $\varepsilon = 0.02,0.035$

Scale variation: $\mu_r = 0.5 \div 2.0\,\mu_0$, $\mu_f = 0.5 \div 2.0\,\mu_0$, $\mu_0 = \sqrt{m_c^2 + p_T^2}$

Charm mass: 1.3-1.5 GeV

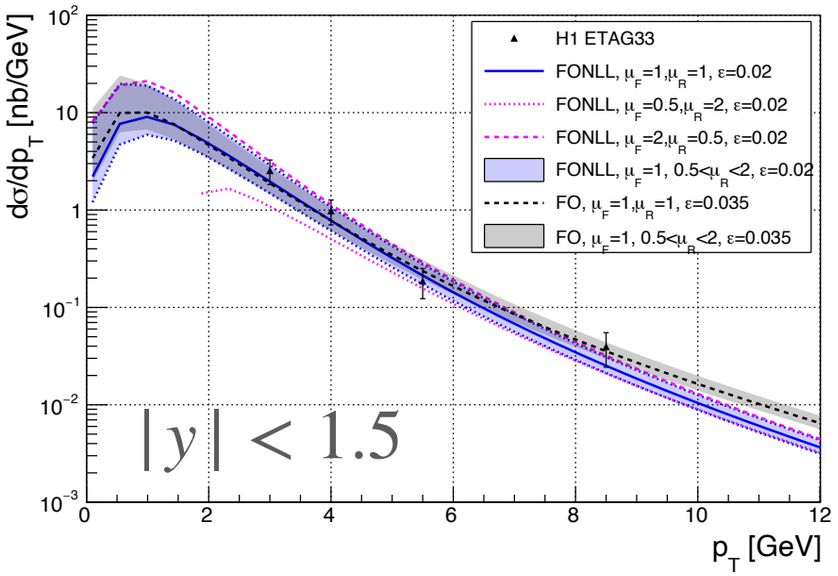


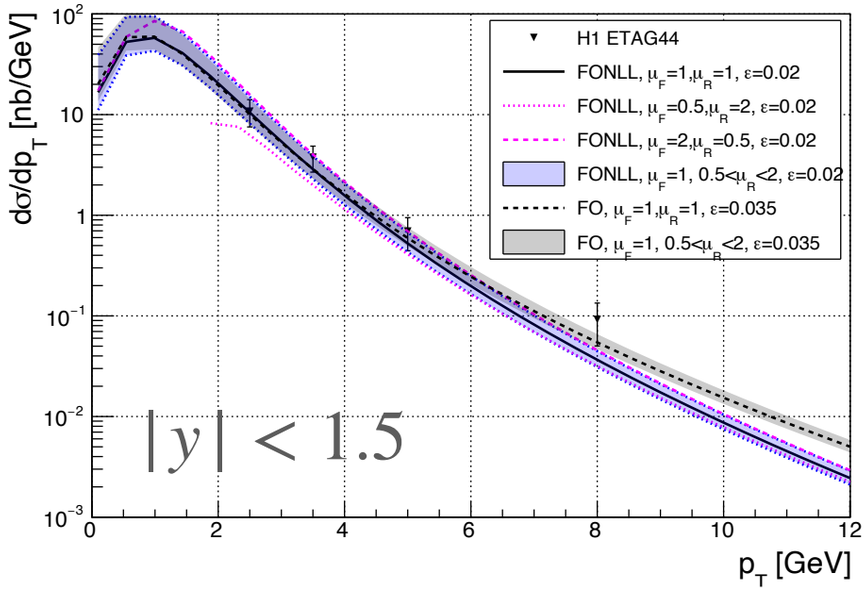
Frixione, Nason 2002

Ratio of photon energy to incoming electron (usually denoted by y)

	Data set	$Q^2_{\max}$	z_{min}	z_{max}	p_T	(pseudo)rapidity
H1 NPB 545 (1999) 21	H1 ETAG44	0.009	0.02	0.32	$p_T > 2\,\text{GeV}$	$\lvert y\rvert < 1.5$
	H1 ETAG33	0.01	0.29	0.62	$p_T > 2\,\text{GeV}$	$\lvert y\rvert < 1.5$
ZEUS EPJC 6 (1999) 67	ZEUS	1	0.187	0.869	$p_T > 2\,\text{GeV}$	$\lvert \eta\rvert < 1.5$
H1 EPJC 72 (2012) 1995	H1 2012	2	0.09	0.8	$p_T > 1.8\,\text{GeV}$	$\lvert \eta\rvert < 1.5$

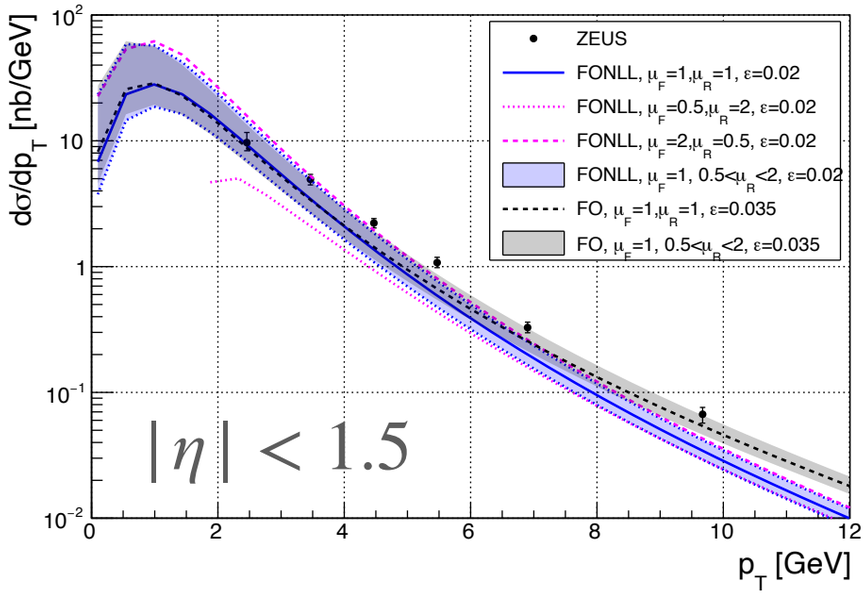
Comparison with HERA: p_T distributions

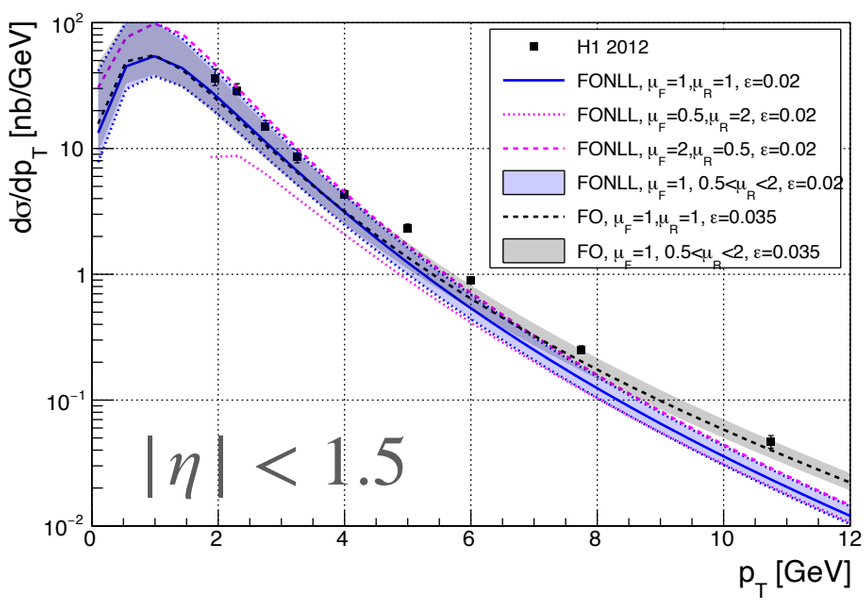




Note: these are ep cross sections

CTA18NLO



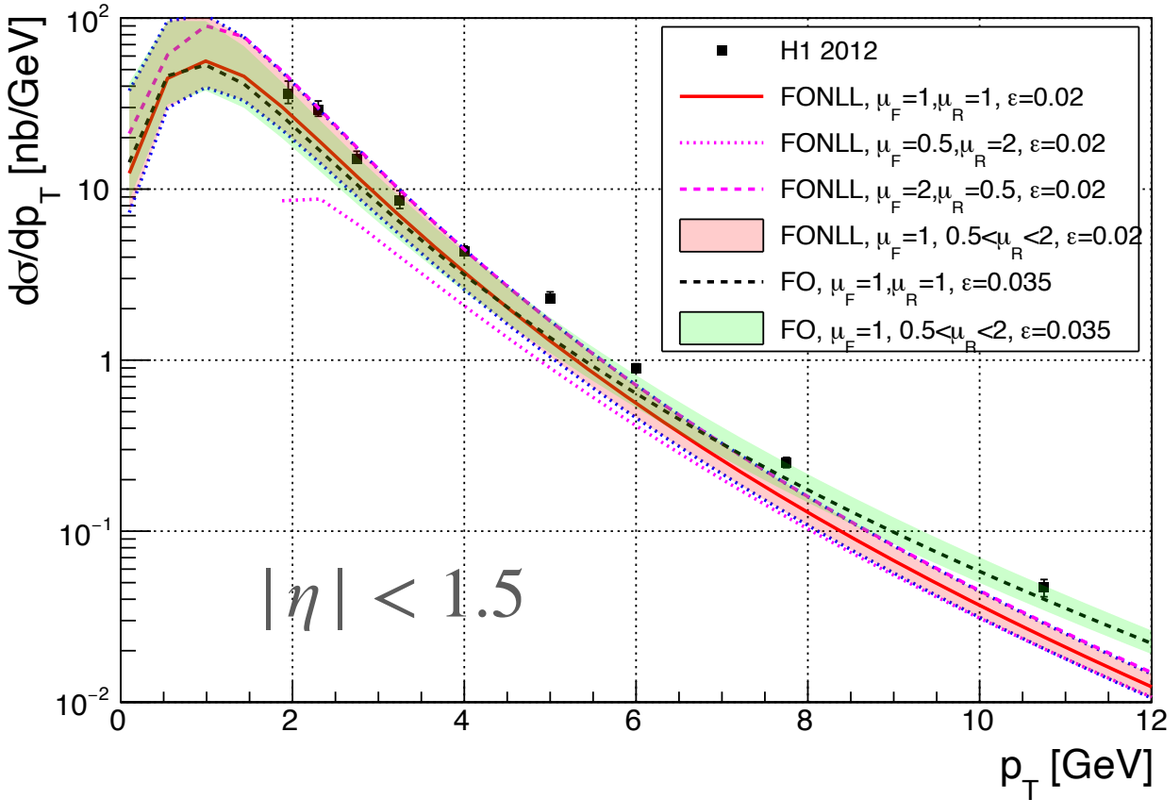


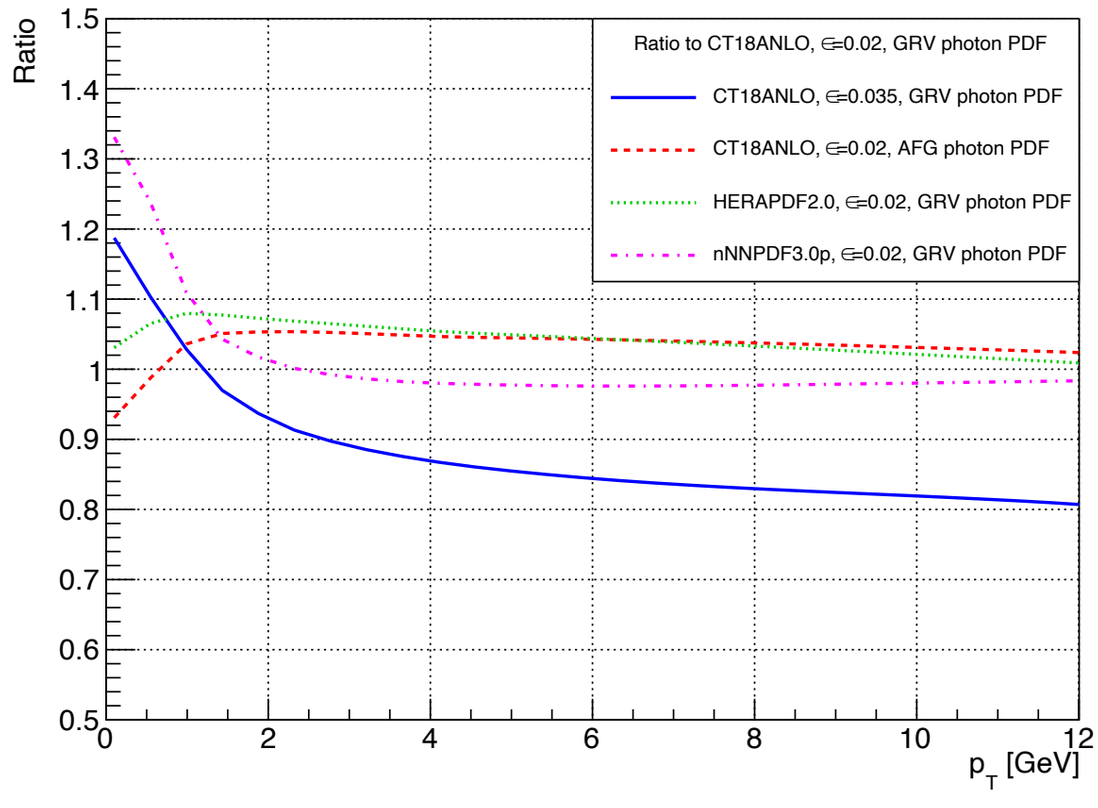
Reproducing *Frixione&Nason* calculations, results with CTA18NLO consistent with previous ones

Good description, FO leads to harder spectrum than FONLL

Renormalization scale dependence most significant

Comparison with HERA: p_T distributions



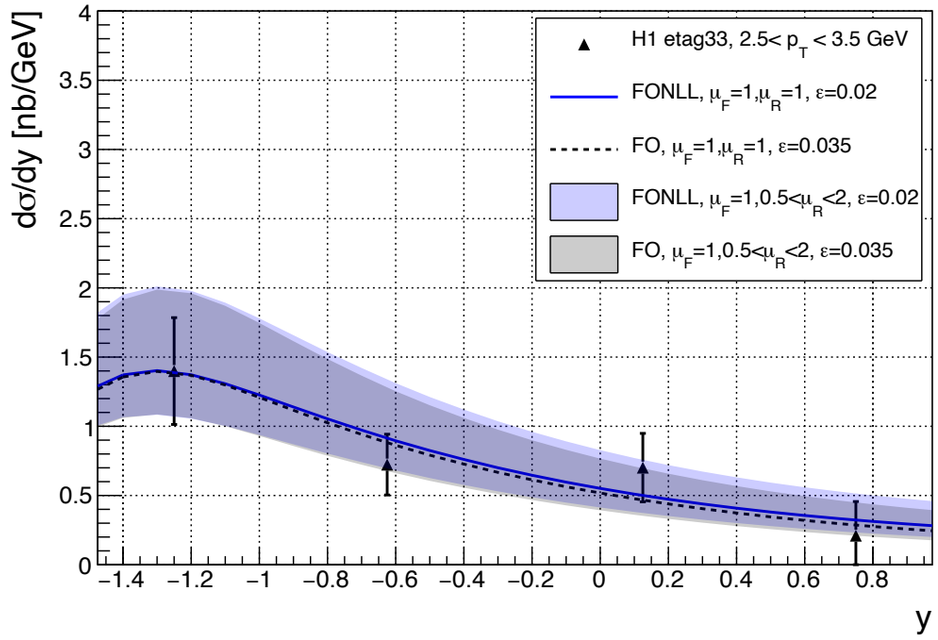


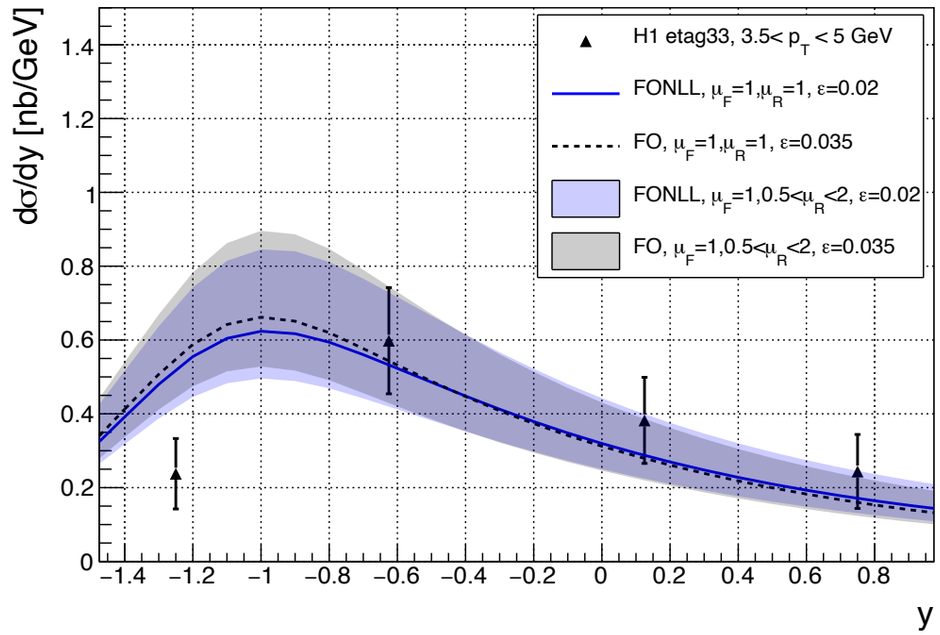
Different photon and proton PDFs lead to the similar results

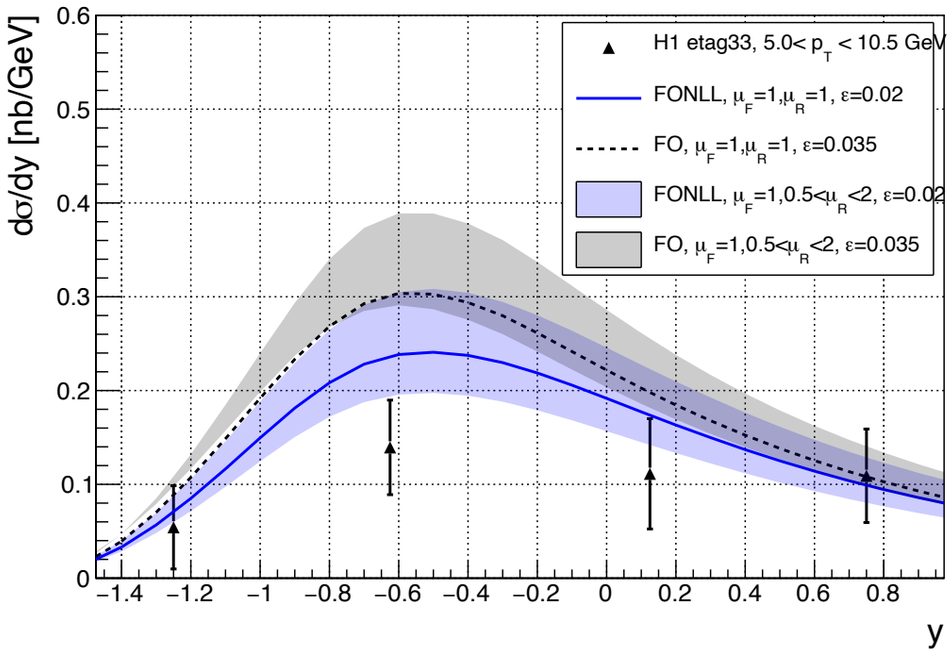
Slight difference when Peterson function parameter changed from $\varepsilon = 0.02$ to $\varepsilon = 0.035$

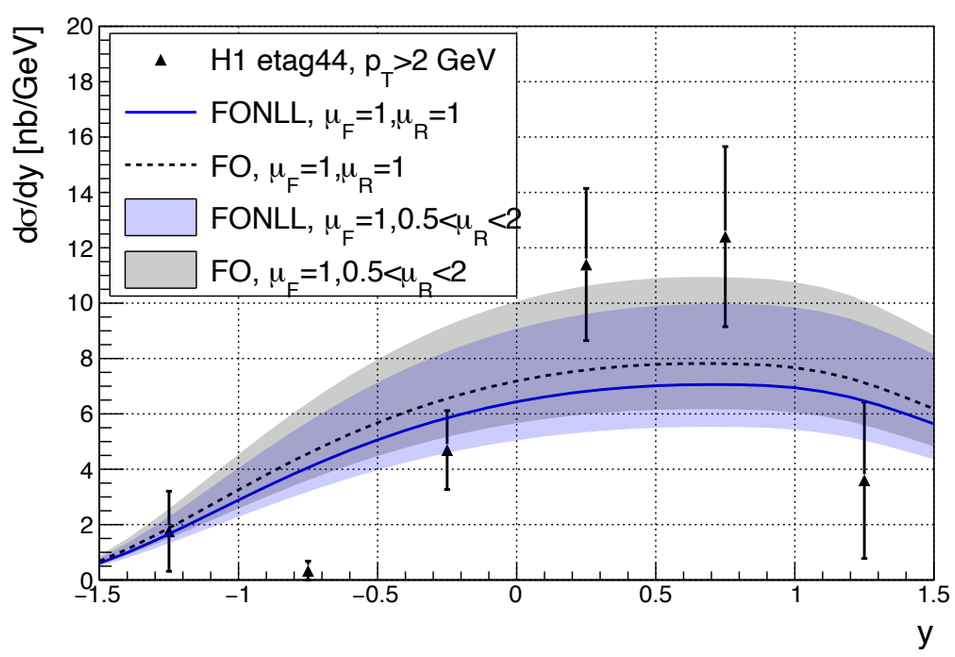
Comparison with H1 data: rapidity distributions

Data set	$Q^2_{\max}$	z_{min}	z_{max}
H1 ETAG44	0.009	0.02	0.32
H1 ETAG33	0.01	0.29	0.62
ZEUS	1	0.187	0.869
H1 2012	2	0.09	0.8

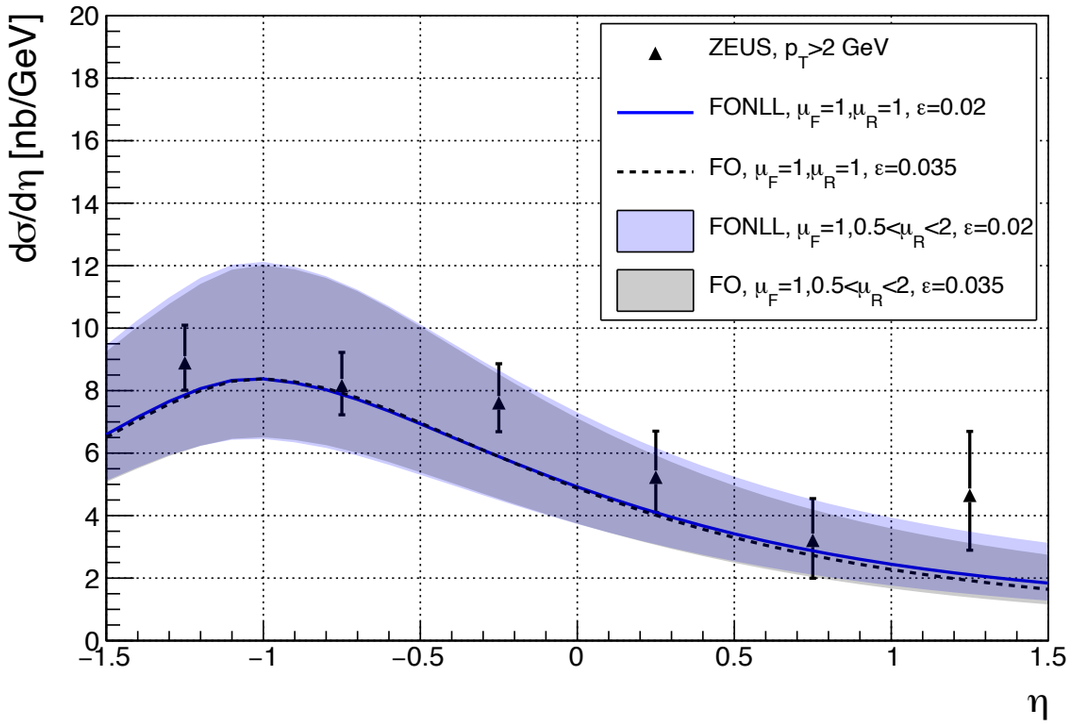


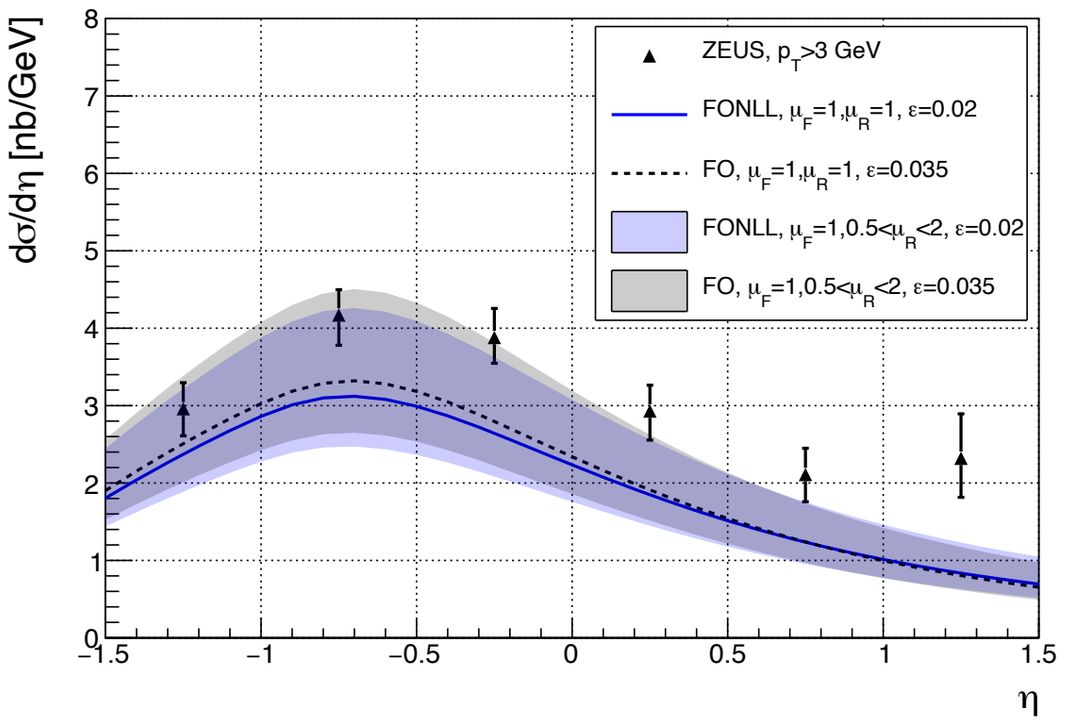


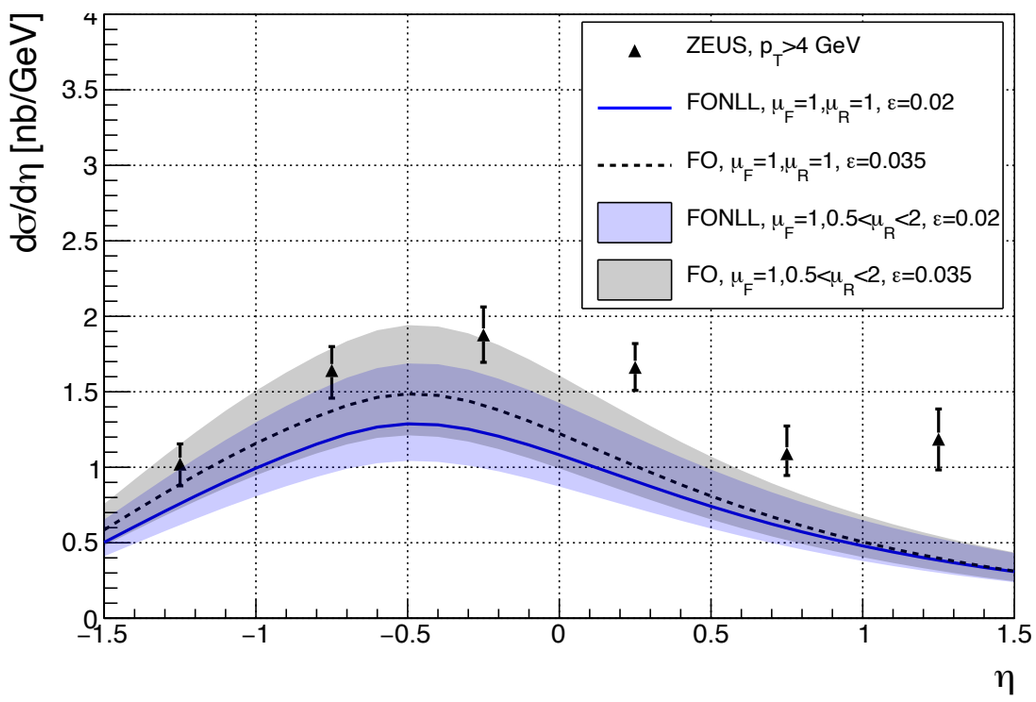


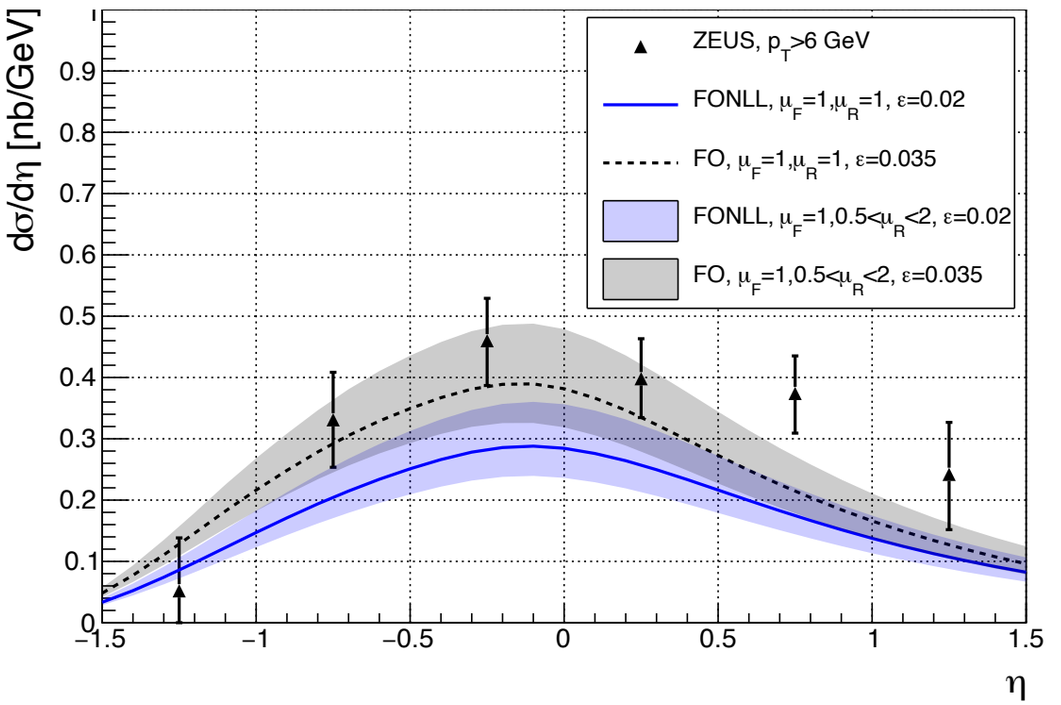


Comparison with ZEUS data: pseudorapidity distributions

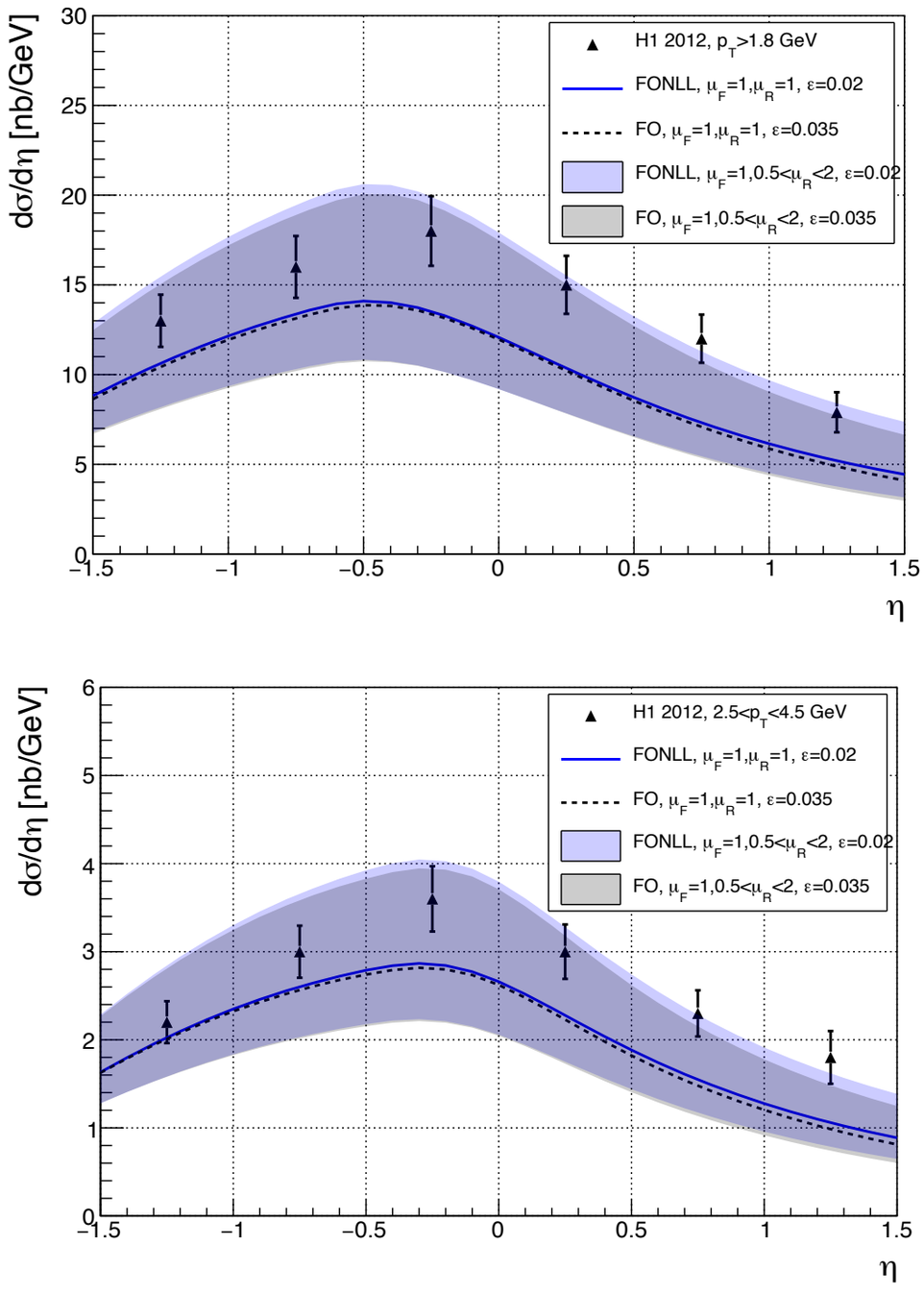


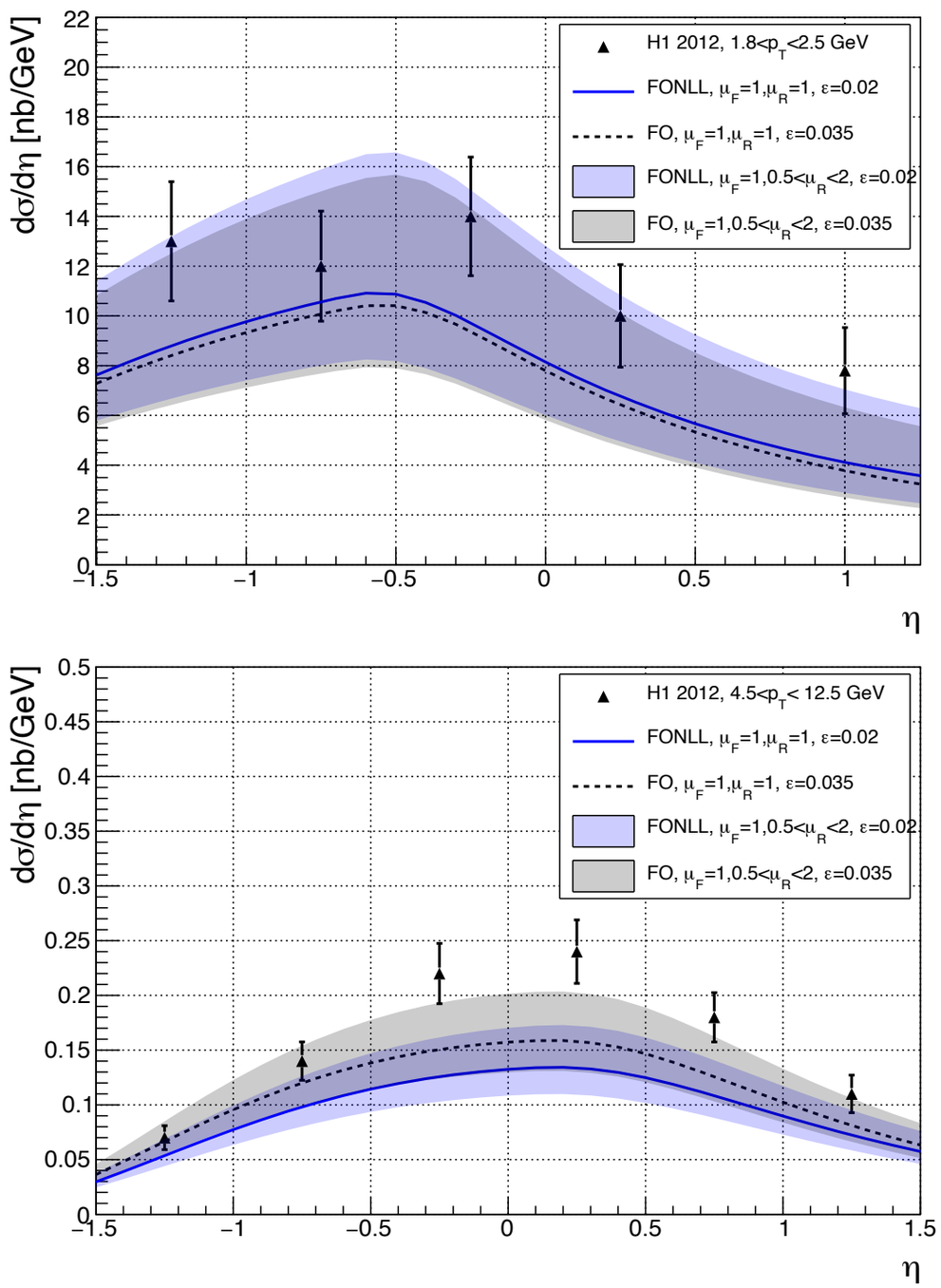






Comparison with H1 2012 data: pseudorapidity distributions





Overall good description of the (pseudo)rapidity distributions, within scale uncertainties

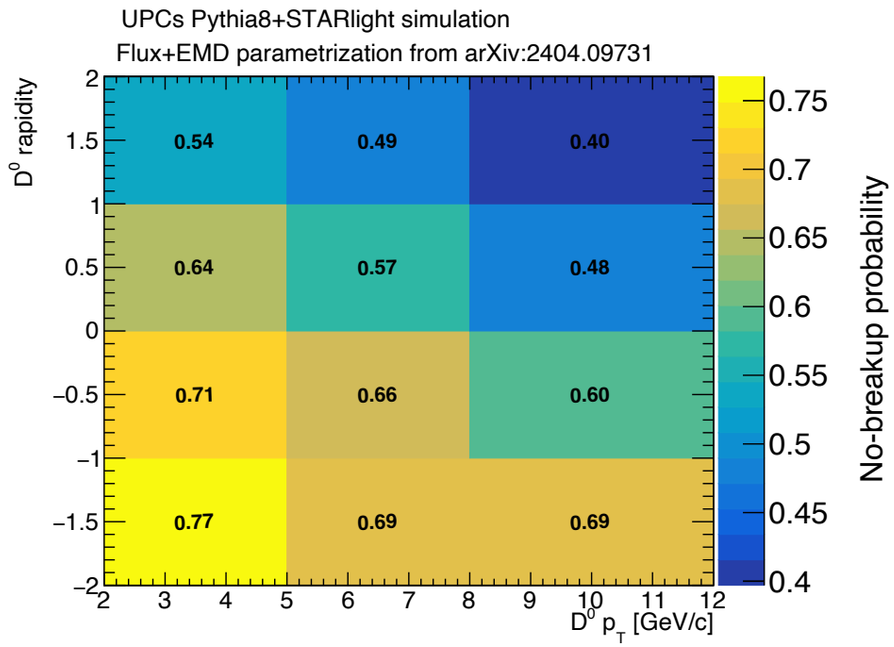
HERA ep vs LHC UPC AA

Differences between ep and UPC AA

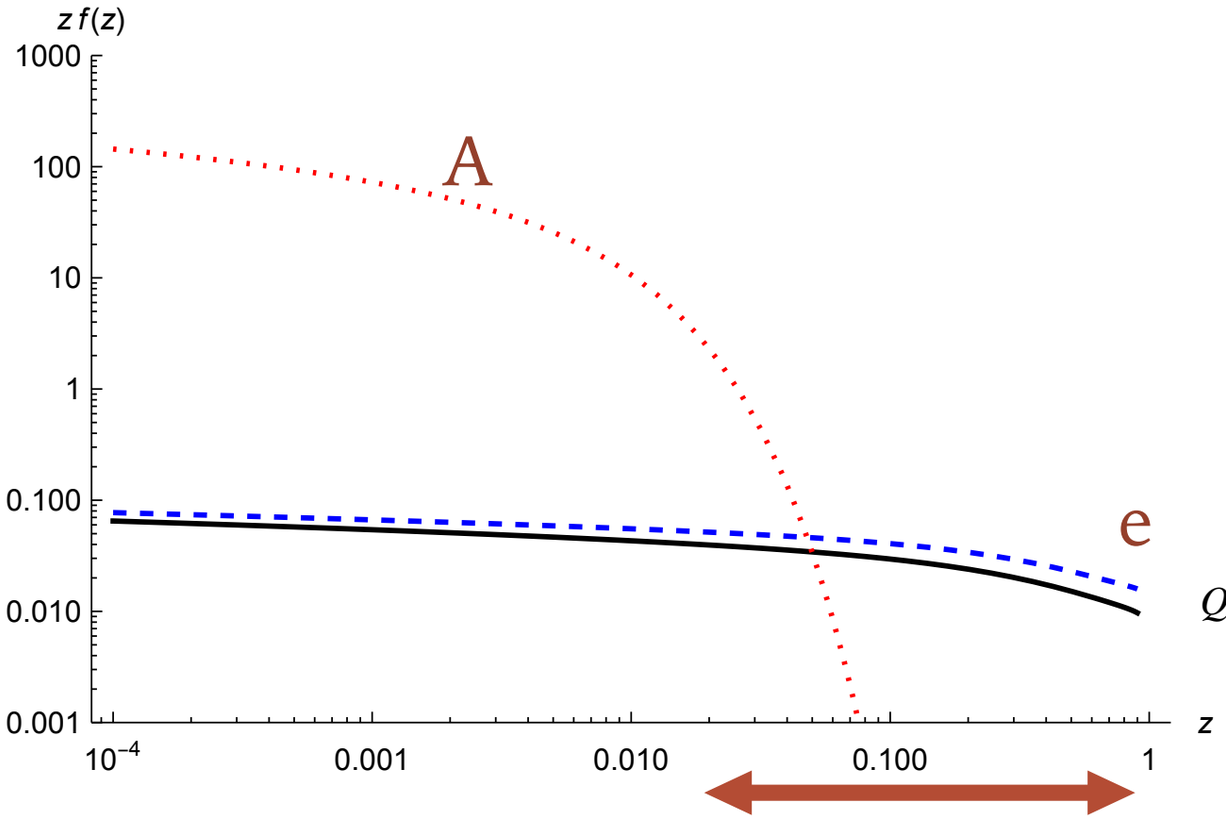
- **Electron** vs **nucleus** photon flux: different behavior
- In ep: **photon energy** (W in DIS) can be measured. In UPC it is **integrated** over
- In ep: some data sets have larger range of $Q^2(\sim 2\,\mathrm{GeV}^2)$

CMS PAS HIN-24-003

- **Proton** vs **nuclear** target: **nuclear shadowing** expected
- AA: selection of UPC events with **0nXn** (zero neutrons in one ZDC, at one neutron in opposite ZDC), requires accounting for **survival probability** factor for nucleus due to possibility of **electromagnetic dissociation (EMD)**
- In UPC: **0nXn** selection means **coherent diffraction** is rejected. In ep it is included: theoretical calculation is for **inclusive** process



Photon fluxes for electron and nucleus



HERA photon energy, extending to large energies

UPC: flux steeply falling beyond z=0.01

$Q^2_{\max} = 0.01, 2\ \mathrm{GeV}^2$

electron

$$f_{\gamma/e}(z) = \frac{\alpha_{em}}{2\pi}\left[\frac{1+(1-z)^2}{z}\log\left(\frac{Q^2_{\max}(1-z)}{(m_e z)^2}\right) + 2m_e^2 z\left(\frac{1}{Q^2_{\max}} - \frac{1-z}{(z m_e)^2}\right)\right]$$

Improved formula derived by Frixione, Mangano, Nason, Ridolfi

nucleus

$$f_{\gamma/A}(z) = \frac{2Z^2\alpha_{em}}{\pi z}\left[\eta K_0(\eta)K_1(\eta) - \frac{\eta^2}{2}(K_1(\eta)^2 - K_0(\eta)^2)\right]$$

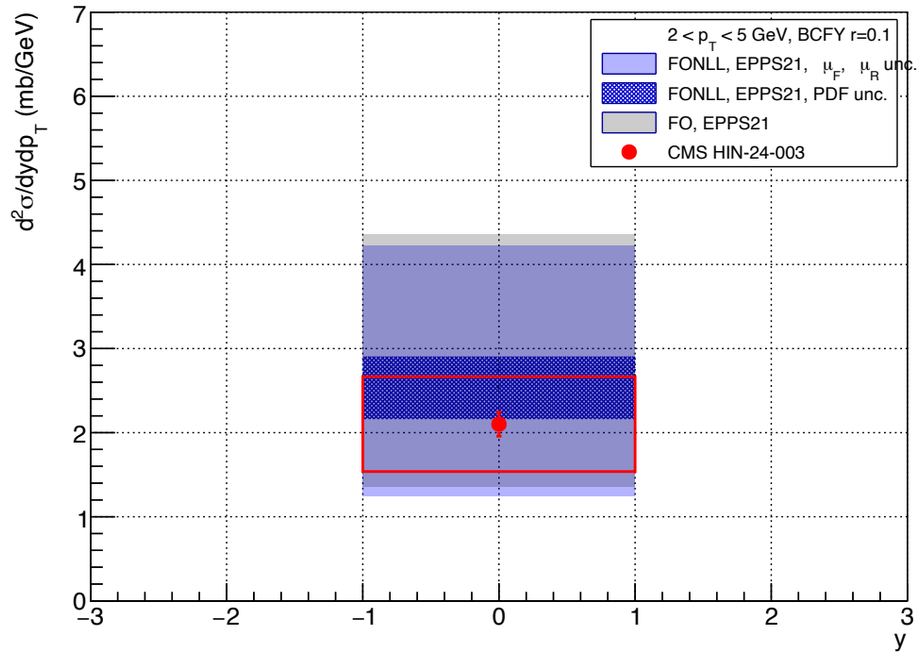
$\eta = z m_p b_{\min}/(\hbar c)$

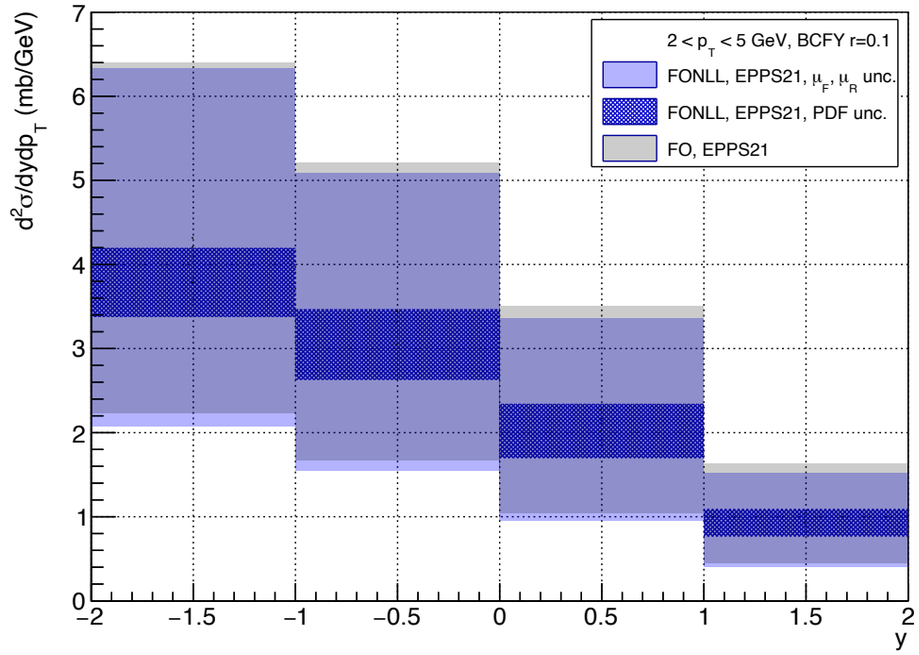
$Z = 82,\ b_{\min} = 2R_A = 2\times 7.1\ \mathrm{fm}$

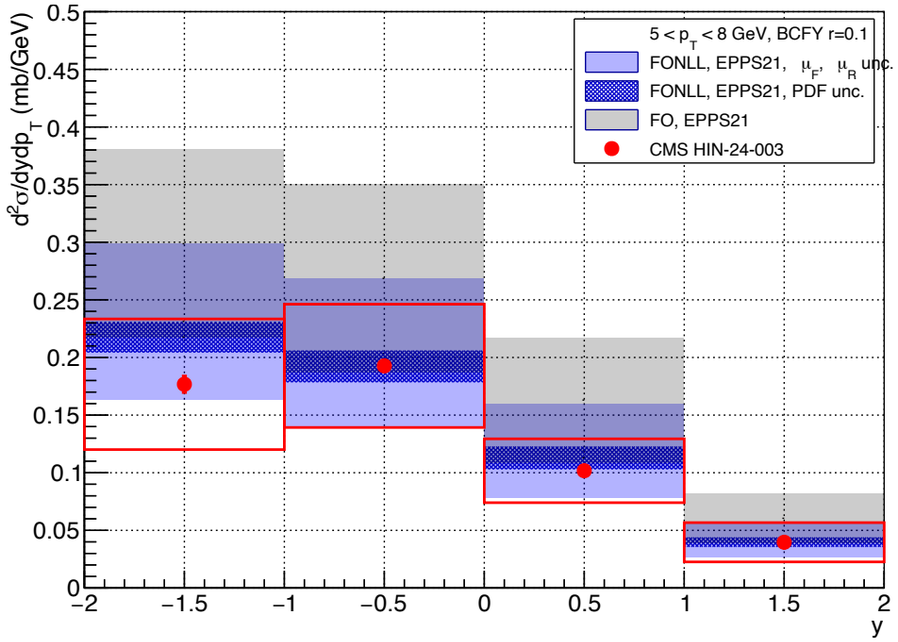
Comparison of FONLL with preliminary CMS data on D^0

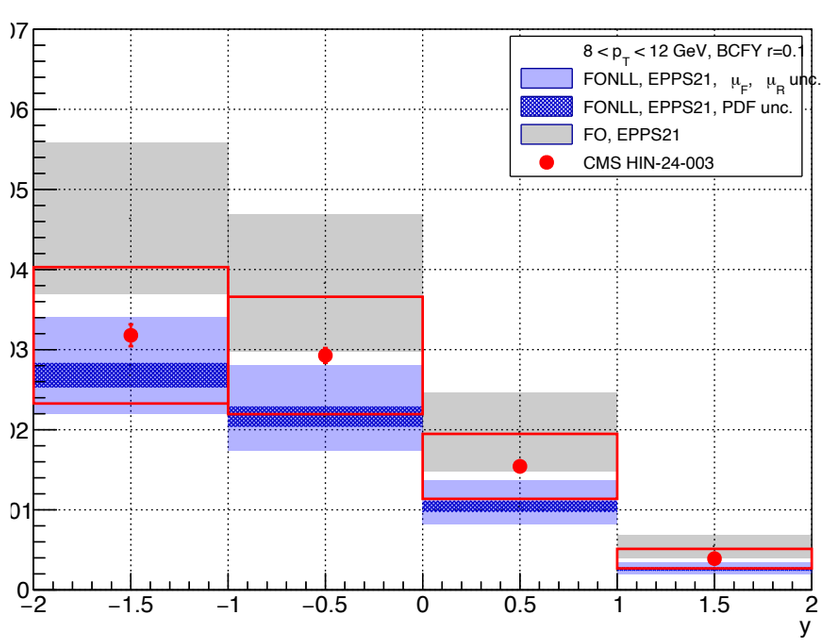
$Pb(\gamma)$ → ← Pb

Preliminary CMS data extracted from CMS PAS HIN-24-003









EPPS21 nPDF

FONLL, FO

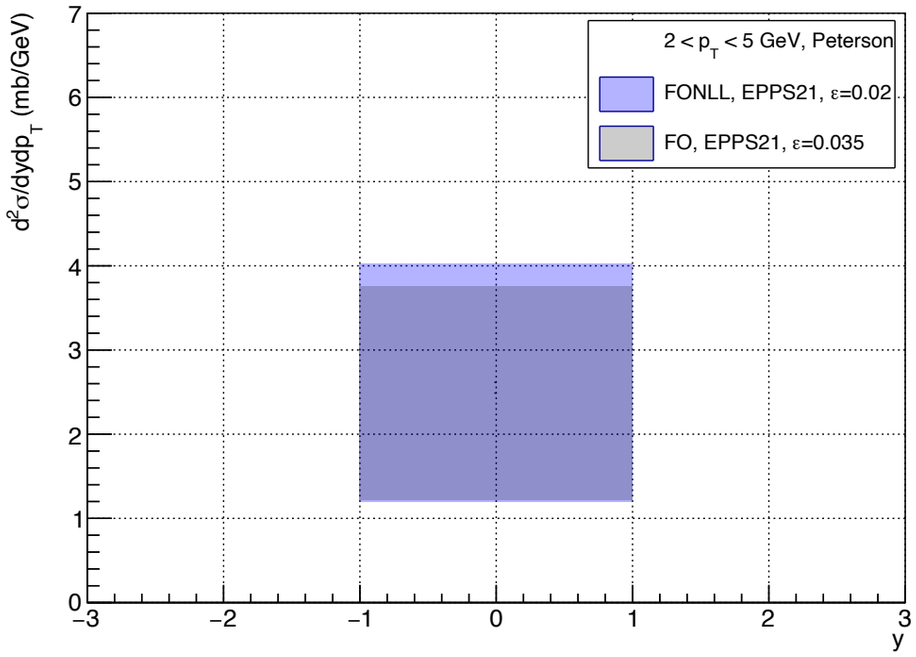
BCFY, r=0.1

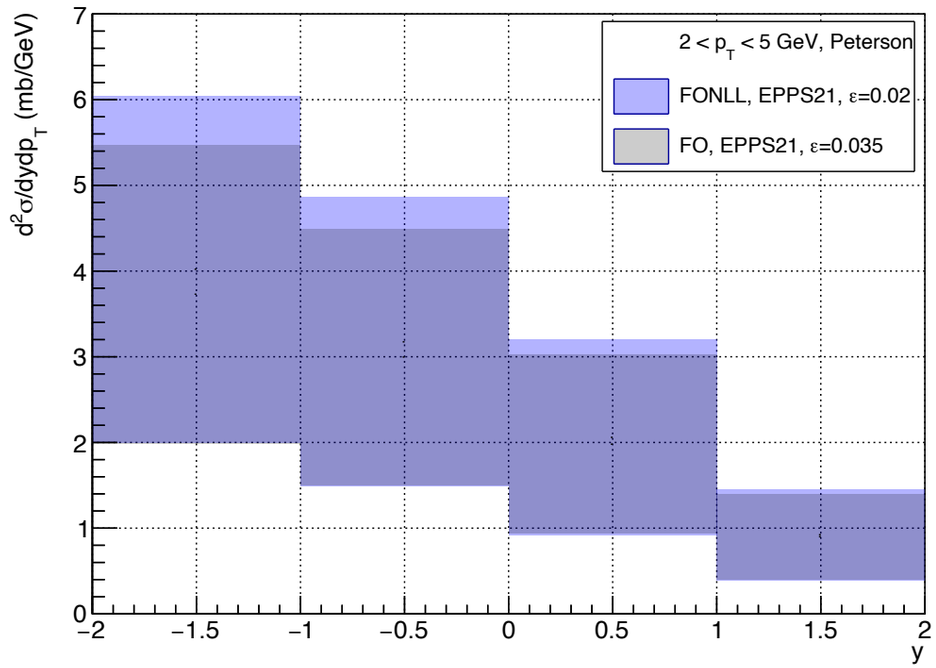
Scale, PDF uncertainty

Comparison of FONLL with preliminary CMS data

Very good agreement within the theoretical/ experimental uncertainties

Rapidity distributions: different FF



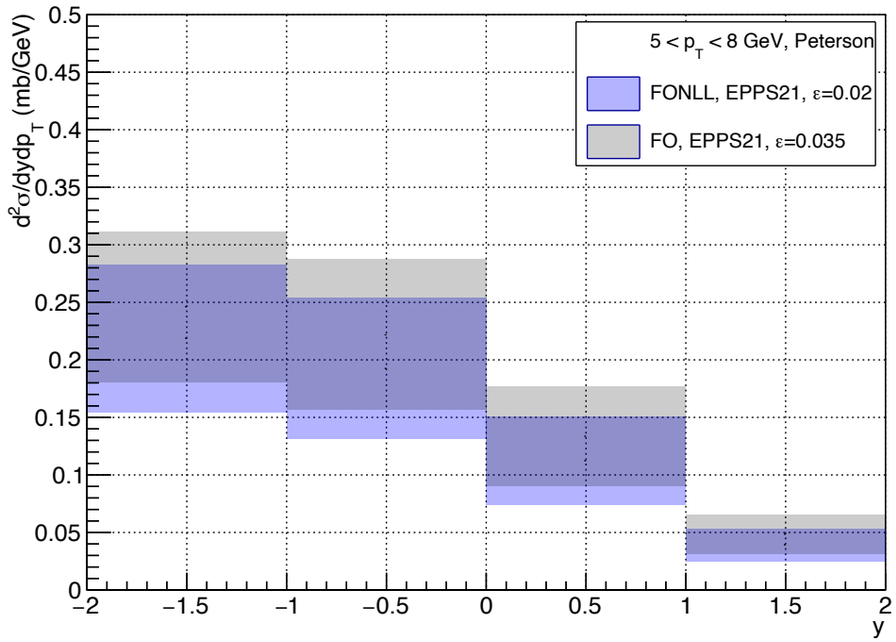


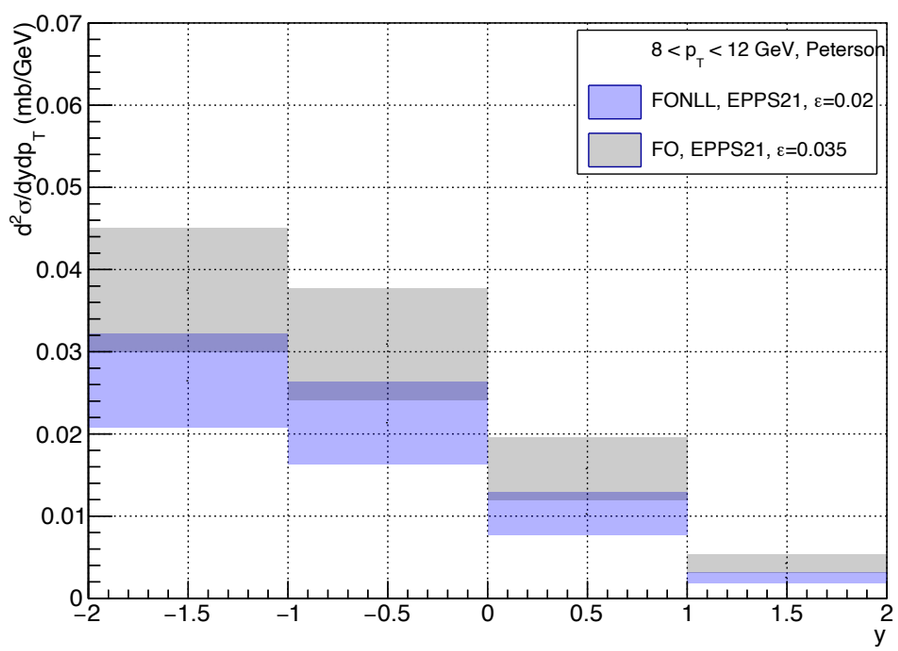
EPPS21

FONLL, FO

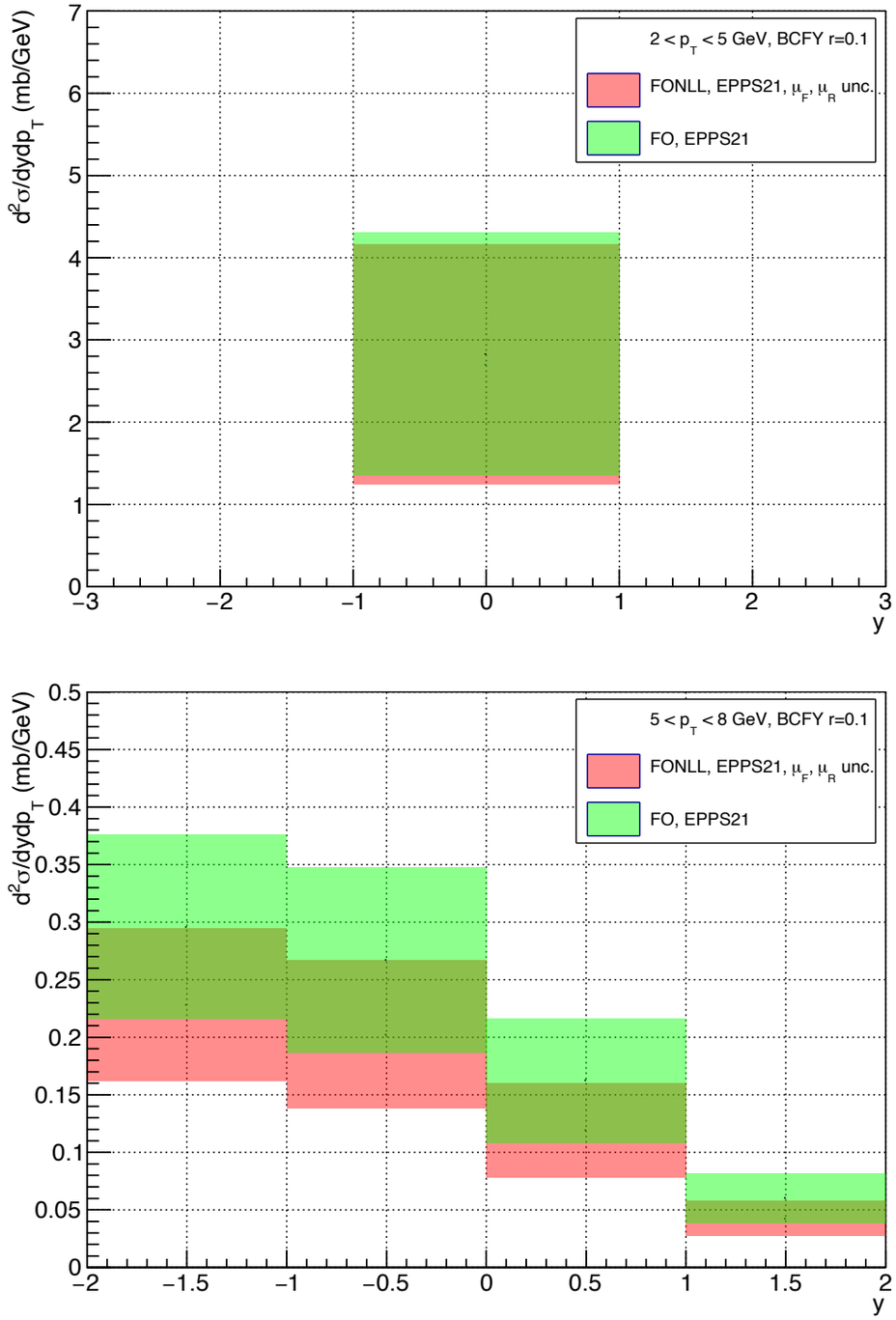
Peterson FF

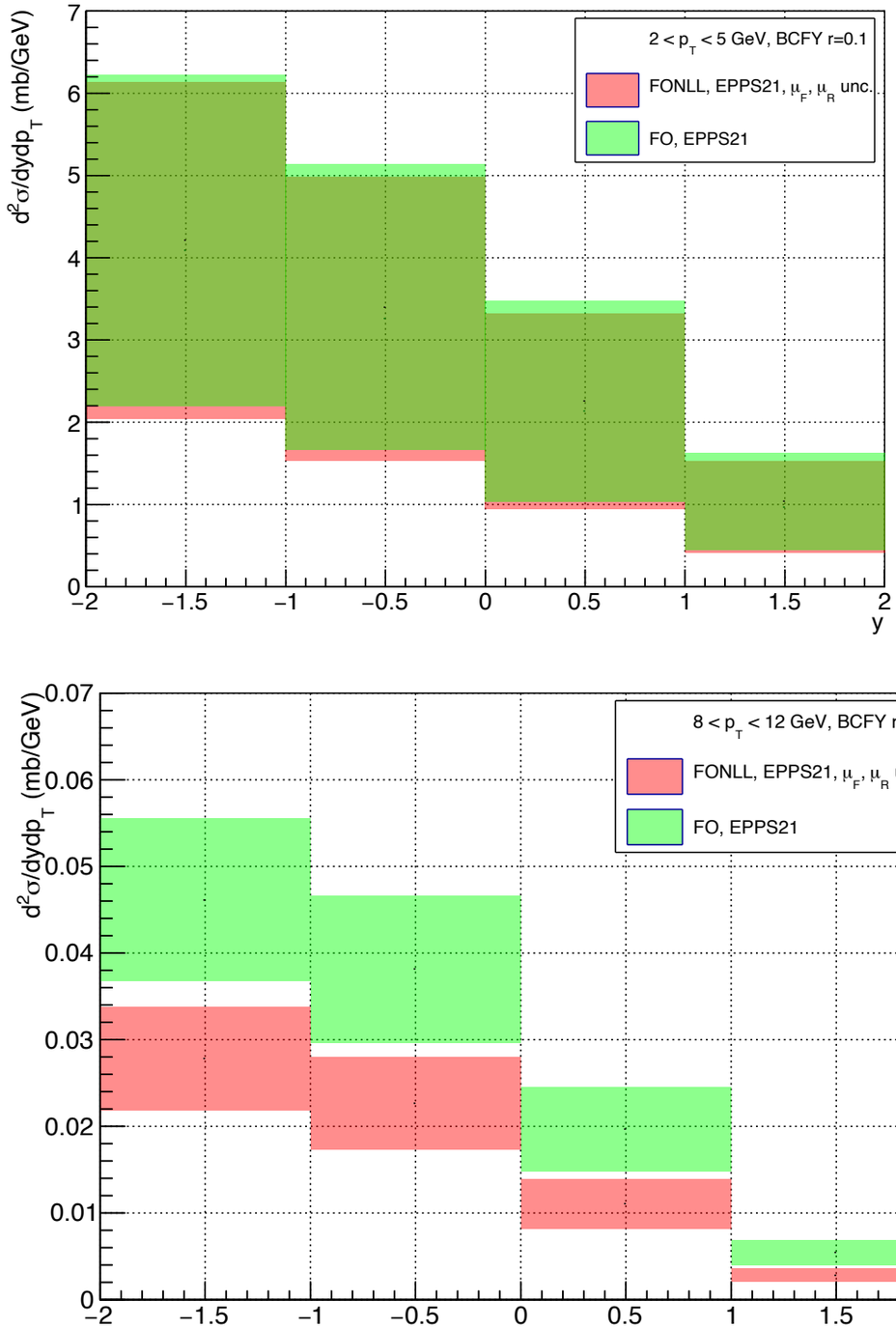
Scale, PDF uncertainty

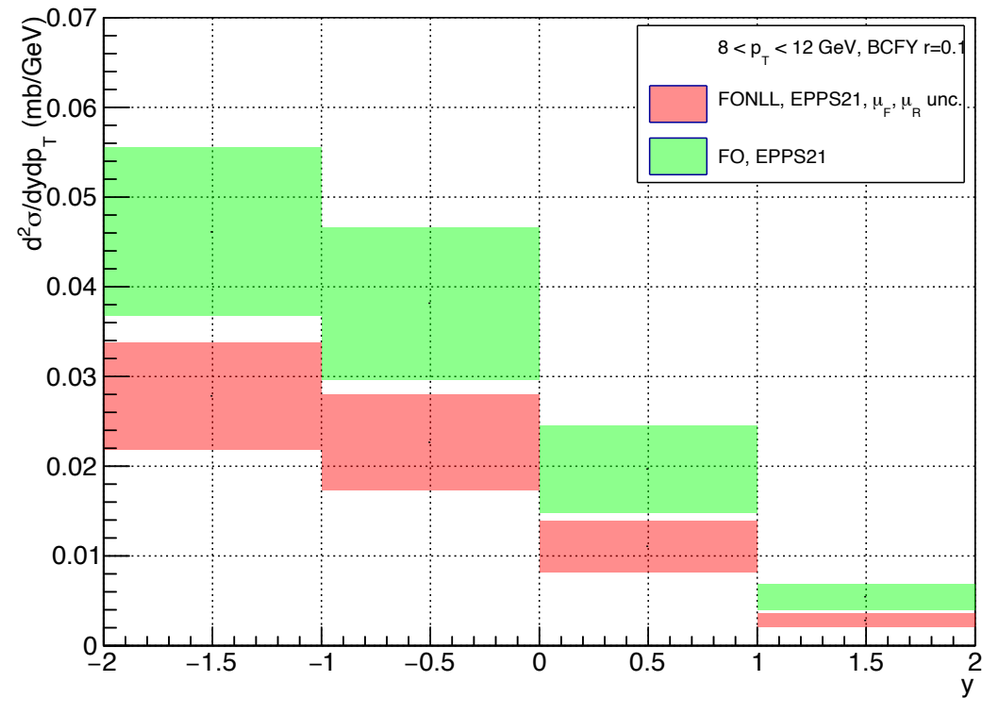




Rapidity distributions: EPPS21 and AFG







EPPS21

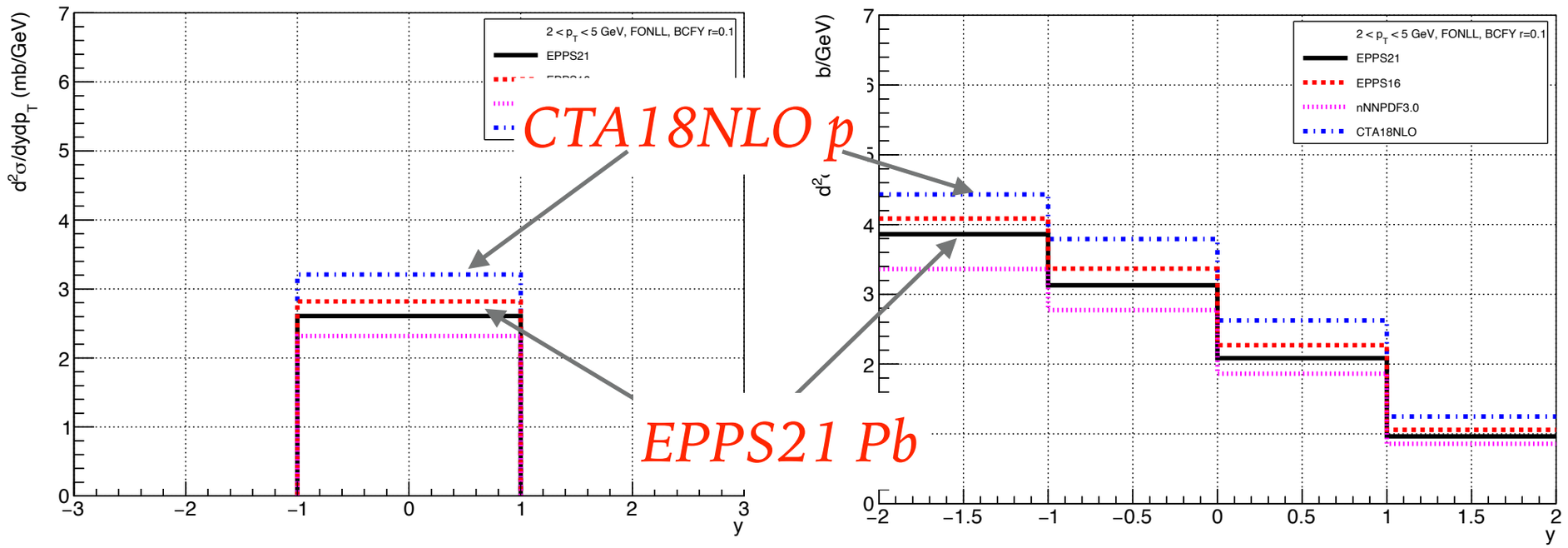
FONLL, FO

Photon AFG

BCFY, r=0.1

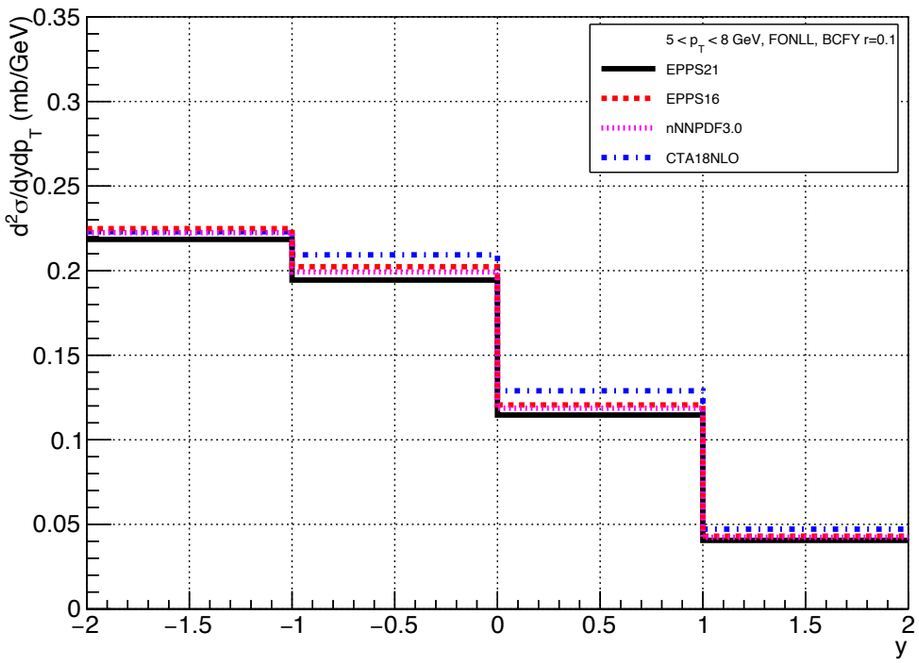
Scale, PDF uncertainty

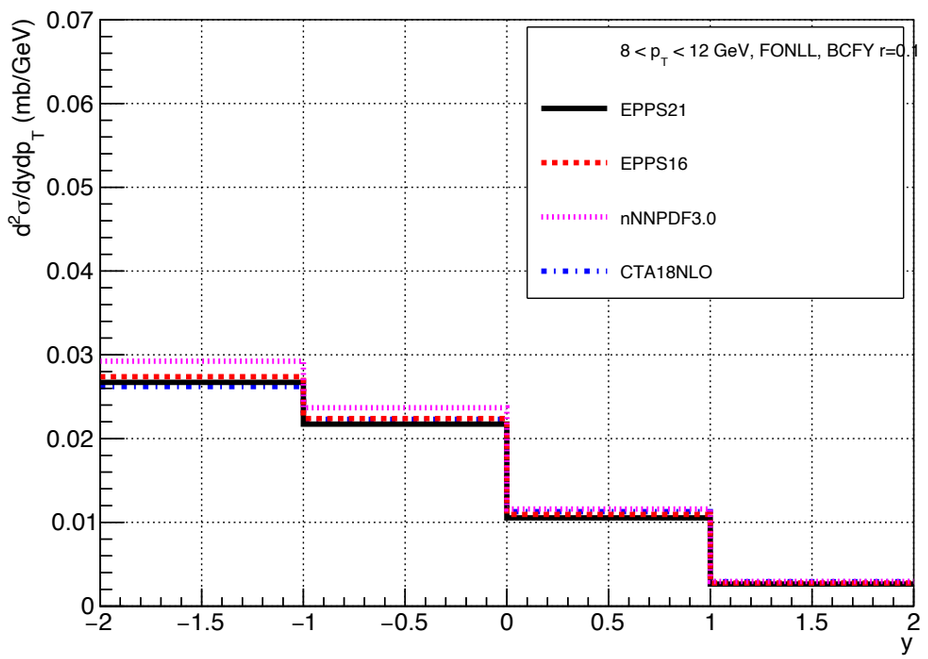
Rapidity distributions: PDF choices



CTA18NLO p

EPPS21 Pb





Shadowing is moderate

20-30% lowest pT bin

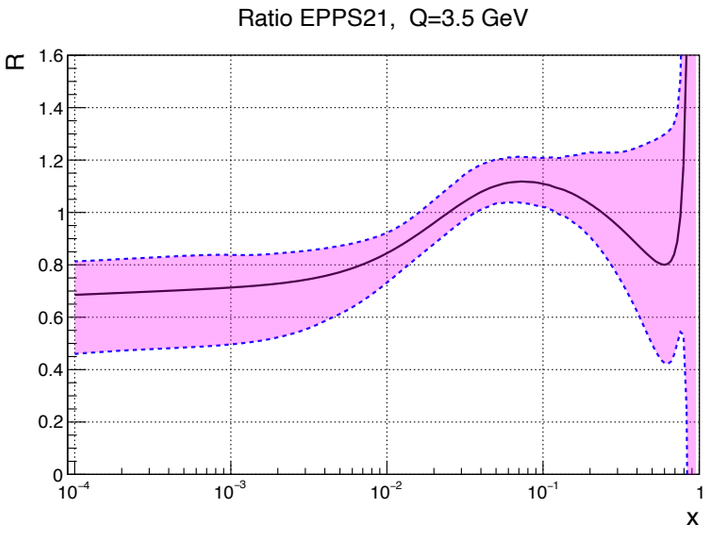
EPPS21, EPPS16, CTA18NLO,nNNPDF3.0

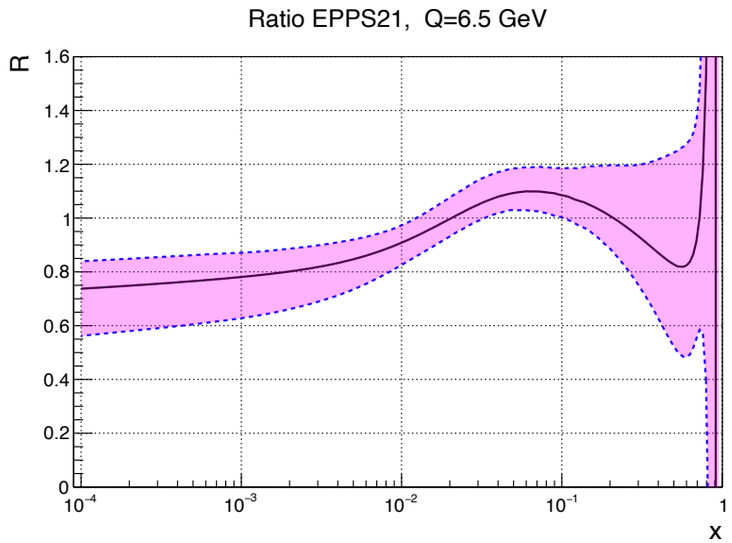
BCFY, r=0.1

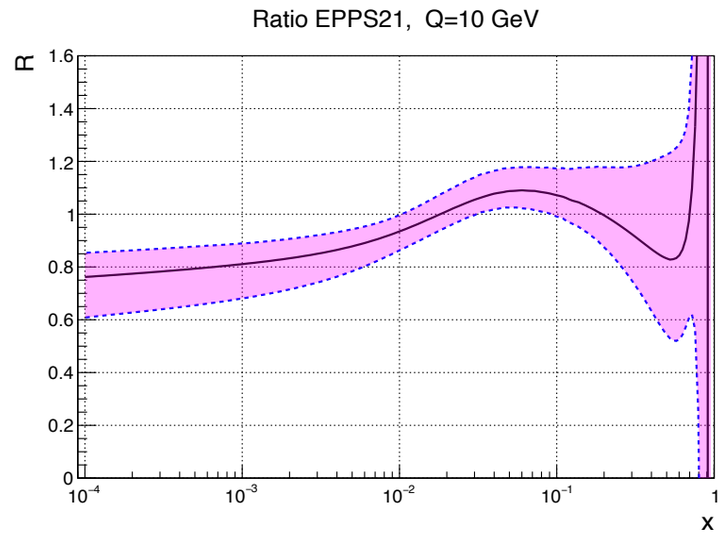
Nuclear gluon distribution: shadowing effects

Nuclear ratios for gluon EPPS21 evaluated at the middle of the pT bins

(2,5), (5,8), (8,12)

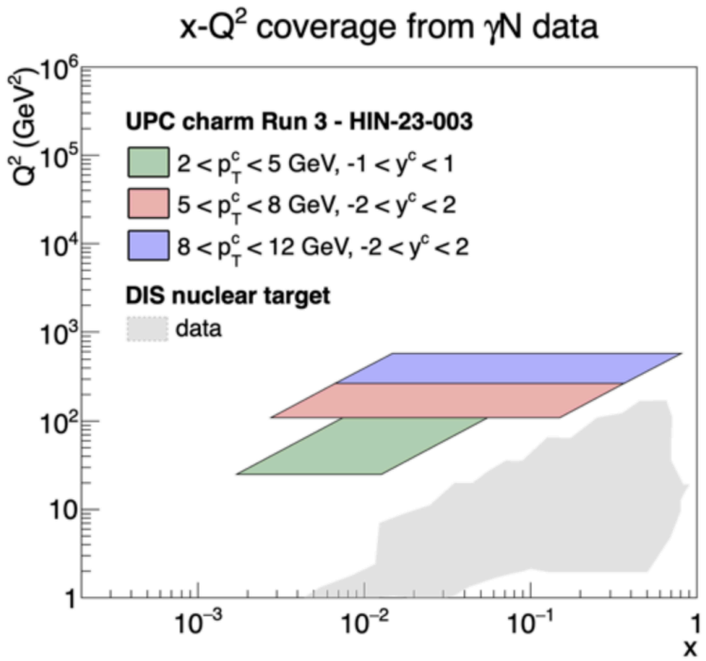






Shadowing ratio at most 70% for lowest pT bin and low x, evaluated at the gluon(parton) level

Indeed, only slight reduction visible in lowest bin in CMS measurement: about 75-80%



Summary

FONLL prediction on **charm production in PbPb UPC at LHC**, $\sqrt{s_{NN}} = 5.36$ TeV

Results checked against **HERA data on D***, good description, large p_T slightly underestimated with FONLL, better with NLO FO. Studied PDF/scale/FF variations

For the description of the UPC tested different **nuclear PDFs**. EMD included

Very good agreement of the calculations with preliminary data on **D^0 production from CMS**, within theoretical and experimental uncertainties

Effects of **nuclear shadowing** in the CMS kinematics correctly captured by nuclear PDFs, about **20-30%**, in the lowest p_T bin.

Outlook:

Test other models for gluon density at small x…

Extension to lower p_T values : should be more sensitive to nuclear shadowing, low x effects