Asymmetric collisions in Madgraph5 Impact on nPDF of future D0 and B+ measurements with SMOG2

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PhD student (WUT, Poland)

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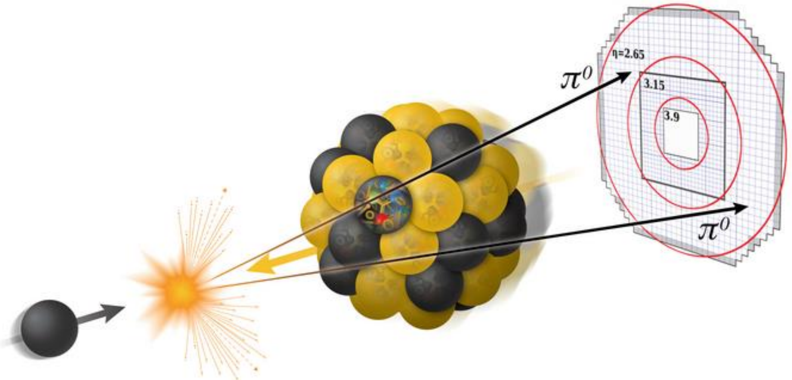
Synergies between LHC and EIC for quarkonium physics
08-13 July 2024, Trento, Italy

List of Content

Motivation

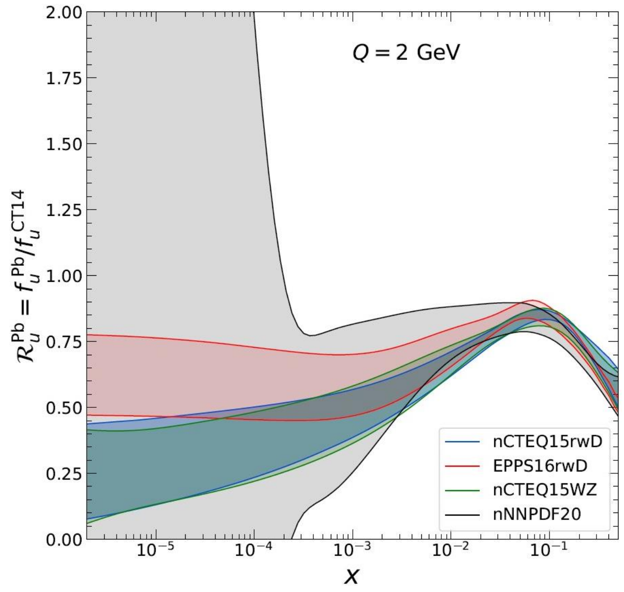
- Study quark and gluon content of nucleons and nuclei in
  - hadron-hadron scattering,
  - hadron-nucleus scattering,
  - or any asymmetric reactions (nucleus/hadron A + nucleus/hadron B),

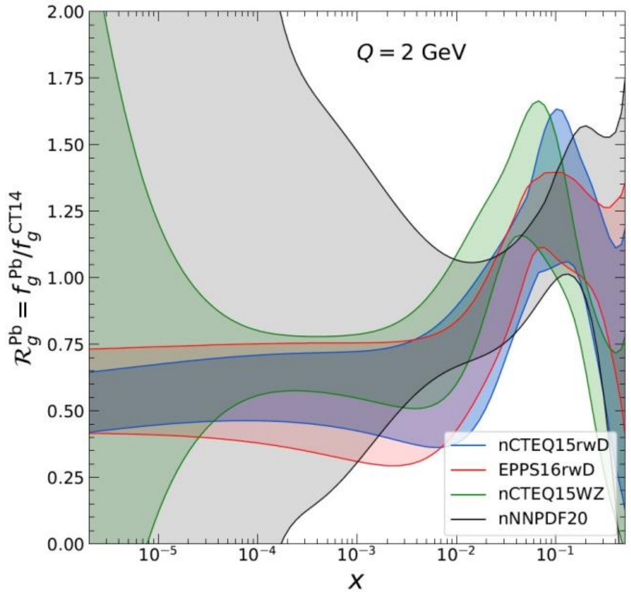
described by Parton Distribution Functions (PDF)



- Evaluate the baseline for more sophisticated studies, like:
  - new state of matter in heavy-ion collisions,
  - charm and beauty quark production,
  - quarkonium productions and
  - the interpretation of the LHC and RHIC data.

- Develop a reliable and high-precision tool for feasibility studies for future measurements and experimental programs





Context (State of art)

- There is **no NLO** code for **asymmetric hadron** collisions with **radiative corrections**
- Modified versions of
  - **MCFM** (Monte Carlo for FeMtobarn processes)
  - **FEWZ** (FEWZ: A Fully Exclusive Numerical Code for QCD and EW Correction to Drell-Yan Process)

are used by **High Energy Physics** community (they are **private** and **not** properly **validated**)

- It's important to provide such a **tool** for **phenomenology**

- The **code** should be **interfaceable** even with generators like **Pythia**

- It should be able to perform calculations at high orders of **QCD** (**Leading Order**, **Next-to-Leading Order**) for any types of **Parton Distribution Functions**, or example:
  - **nuclear**,
  - **nucleon**,
  - **pion**,
  - **photon**, etc.

Framework – Collinear factorization

Cross sections in collinear factorization and perturbative QCD

$$d\sigma = \sum_{a,b} \int dx_1 dx_2 \underbrace{f_a(x_1,\mu_F) f_b(x_2,\mu_F)}_{\text{Parton density functions}} \underbrace{d\hat{\sigma}_{ab\to K}(\hat{s},\mu_F,\mu_R)}_{\text{Parton-level (differential) Cross section}}$$

Parton density functions

Parton-level (differential) Cross section

where the partonic cross section is calculated using:

$$\hat{\sigma} = \sigma^{Born}\left(1 + \frac{\alpha_s}{2\pi}\sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma^{(3)} + \ldots\right)$$

Leading order

Next-to-leading order

Next-to-next-to-leading order

For **charm, beauty, quarkonium** production, the scales are small and α_s is large (0.15 ~ 0.25), **NLO corrections are very large and cannot be neglected**.

Such processes are usually accompanied with the **largest nuclear corrections** in proton-nucleus and nucleus-nucleus collisions

Framework - PDFs

Parton-distribution functions (PDFs): essential link between hadronic cross sections and perturbatively calculable partonic cross sections

Challenging situation for PDFs of nucleons inside nuclei (nPDFs): nuclear data significantly more complex to collect with two additional degrees of freedom (**protons** and **neutrons**)

nPDFs and PDFs give information on:

- the **nuclear / hadronic structure** in terms of quarks and gluons;
- the **initial state** of relativistic heavy-ion collisions,

to use **perturbative probes** of the **Q**uark **G**luon **P**lasma to study its properties

- **nPDFs** cannot be computed

and similarly, to the proton PDFs are **fit to experimental data**.

Only the evolution is perturbative

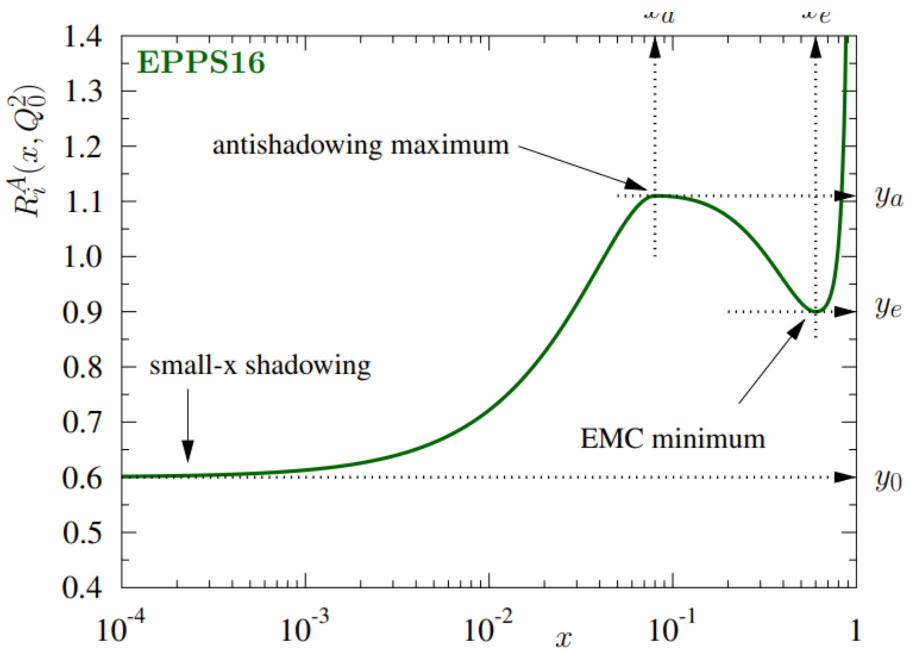
- Collinear **factorization** in terms of nPDFs is **assumed** and should be tested case by case
- **Automating** computations of cross sections with nPDFs up to **NLO** is highly **desirable**

Nuclear Modification Factors

For rare/hard probes $[\sigma_{NN}^{probe} \ll \sigma_{NN}^{inel}]$

$$\sigma_{AB}^{probe} = A \times B \times \sigma_{NN}^{probe}$$

[Each probe is produced independently]



arXiv:1612.05741v2 [hep-ph]

We can define **nuclear modification factors** (R_{AA}, R_{pA}):

$$R_{AB} = \frac{\sigma_{AB}}{AB\ \sigma_{pp}}$$

$$R_{pA} \equiv \frac{\sigma_{pA}}{(1 \times A \times \sigma_{pp})}$$

One expects:

- R_{pA}>1 for x $\gtrsim$ 0.8 (**Fermi-motion region**),
- R_{pA}<1 for 0.25 $\lesssim$ x $\lesssim$ 0.8 (**EMC region**),
- R_{pA}>1 for 0.1 $\lesssim$ x $\lesssim$ 0.25 (**antishadowing region**)
- R_{pA}<1 for x $\lesssim$ 0.1 (**shadowing region**)
- $R_{pA}\sim$ 1: **absence of nuclear effects**

nPDFs and MG5

Any **PDFs** can be used in **MG5 up to NLO** like *proton* **PDFs** with **LHAPDF** library

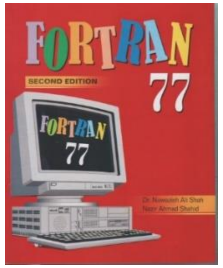
Currently only the symmetric mode is implemented

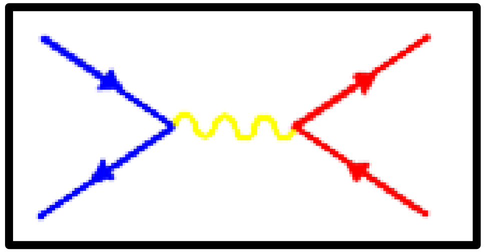
Reminder: we **assume** that

- **the factorization** of the **cross section** even in presence of **nuclear effects**
- all the **nuclear effects** can be accounted by **nPDFs** and thus **can be computed by MG5**.

MadGraph

- **MG5_aMC@NLO** is a **metacode,** i.e. a code generating **another code**
- **Matrix element generator** written in **Python**
- **Can compute cross section and generates events at NLO with QCD corrections automatically**
- Using **LHAPDF** can compute the cross section for **any PDF** in it with negligible additional CPU time (but **only** for **symmetrical** beam species)
- **Scale** and **PDF uncertainties** automatically computed and stored in **Histograms with Uncertainties** (HwU)
- **Output** in **multiple formats (root, HwU, gnuplot, etc…)**





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*                     W E L C O M E  to                    *
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*                   *        * *        *                  *
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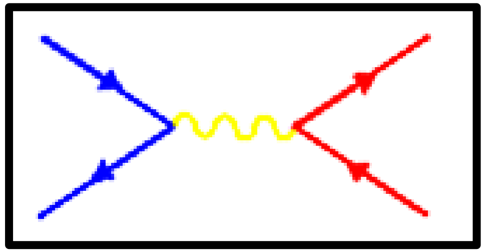
*                   *        * *        *                  *
*                 *                       *                *
*                                                          *
*         VERSION 2.7.2                 2020-03-17         *
*                                                          *
*    The MadGraph5_aMC@NLO Development Team - Find us at   *
*    https://server06.fynu.ucl.ac.be/projects/madgraph     *
*                            and                           *
*            http://amcatnlo.web.cern.ch/amcatnlo/         *
*                                                          *
*               Type 'help' for in-line help.              *
*           Type 'tutorial' to learn how MG5 works         *
*    Type 'tutorial aMCatNLO' to learn how aMC@NLO works   *
*    Type 'tutorial MadLoop' to learn how MadLoop works    *
*                                                          *
************************************************************
load MG5 configuration from ../input/mg5_configuration.txt
set collier to /projet/pth/safronov/MG5/MG5_aMC_v2_7_2/HEPTools/lib
set fastjet to /projet/pth/safronov/fastjet-install/bin/fastjet-config
set lhapdf to /projet/pth/safronov/MG5/MG5_aMC_v2_7_2/HEPTools/lhapdf6/bin/lhapdf-config
set ninja to /projet/pth/safronov/MG5/MG5_aMC_v2_7_2/HEPTools/lib
Using default text editor "vi". Set another one in ./input/mg5_configuration.txt
Using default eps viewer "evince". Set another one in ./input/mg5_configuration.txt
Using default web browser "firefox". Set another one in ./input/mg5_configuration.txt
Checking if MG5 is up-to-date... (takes up to 2s)
No new version of MG5 available
Loading default model: sm
INFO: Restrict model sm with file ../models/sm/restrict_default.dat .
INFO: Run "set stdout_level DEBUG" before import for more information.
INFO: Change particles name to pass to MG5 convention
Defined multiparticle p = g u c d s u~ c~ d~ s~
Defined multiparticle j = g u c d s u~ c~ d~ s~
Defined multiparticle l+ = e+ mu+
Defined multiparticle l- = e- mu-
Defined multiparticle vl = ve vm vt
Defined multiparticle vl~ = ve~ vm~ vt~
Defined multiparticle all = g u c d s u~ c~ d~ s~ a ve vm vt e- mu- ve~ vm~ vt~ e+ mu+ t b t~ b~ z w+ h w- ta- ta+
MG5_aMC>
```

MadGraph



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*            M A D G R A P H 5 _ a M C @ N L O             *
*                                                          *
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*                  * * * * 5 * * * *                       *
*                *        * *       *                      *
*              *                       *                   *
*                                                          *
*         VERSION 2.7.2                 2020-03-17         *
```

The missing part is asymmetric collisions!

- **Scale** and **PDF uncertainties** automatically computed and stored in **Histograms with Uncertainties** (HwU)

- **Output** in **multiple formats (root, HwU, gnuplot, etc…)**

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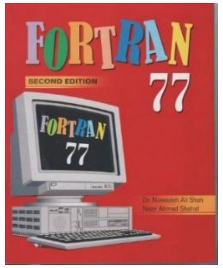
Defined multiparticle l+ = e+ mu+
Defined multiparticle l- = e- mu-
Defined multiparticle vl = ve vm vt
Defined multiparticle vl~ = ve~ vm~ vt~
Defined multiparticle all = g u c d s u~ c~ d~ s~ a ve vm vt e- mu- ve~ vm~ vt~ e+ mu+ t b t~ b~ z w+ h w- ta- ta+
MG5_aMC>
```



C++ python™

Framework – Collinear factorization

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Leading order

Next-to-leading order

Next-to-next-to-leading order

For **charm, beauty, quarkonium** production, the scales are small and α_s is large (0.15 ~ 0.25), **NLO corrections are very large and cannot be neglected**.

Such processes are usually accompanied with the **largest nuclear corrections** in proton-nucleus and nucleus-nucleus collisions

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Cross sections in collinear factorization and perturbative QCD

$$\sigma_{h_1 h_2 \to X} = \sum_{a,b} \int dx_a \, dx_b \, f_{a/h_1}(x_a, \mu_F; LHAID\_h_1) \, f_{b/h_2}(x_b, \mu_F; LHAID\_h_2) \hat{\sigma}_{ab \to X}(x_a, x_b, \mu_F, \alpha_S(\mu_R; LHAID\_h_2))$$

Parton density functions

Parton-level (differential) Cross section

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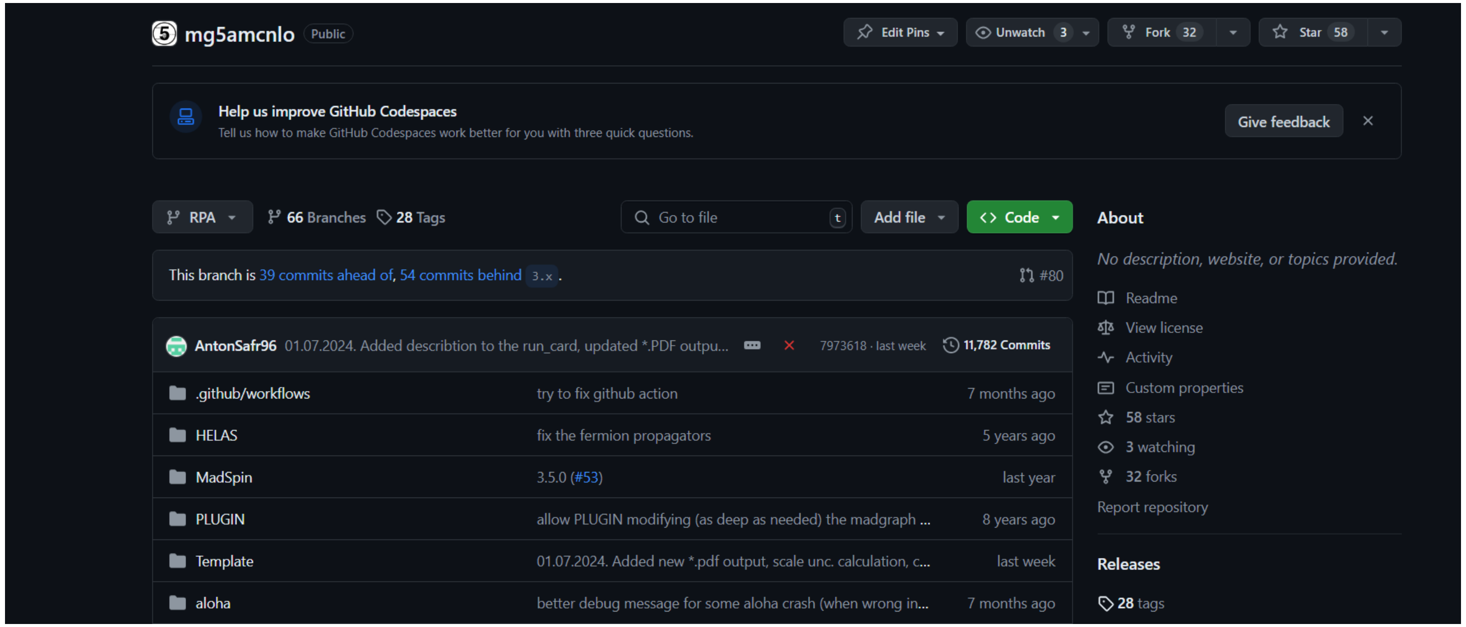
MadGraph in NLOAccess

MG5_aMC@NLO is now available online with its full NLO version on **NLOAccess** (https://nloaccess.in2p3.fr/MG5/)

The asymmetric version of the code is available at:
https://github.com/mg5amcnlo/mg5amcnlo.git

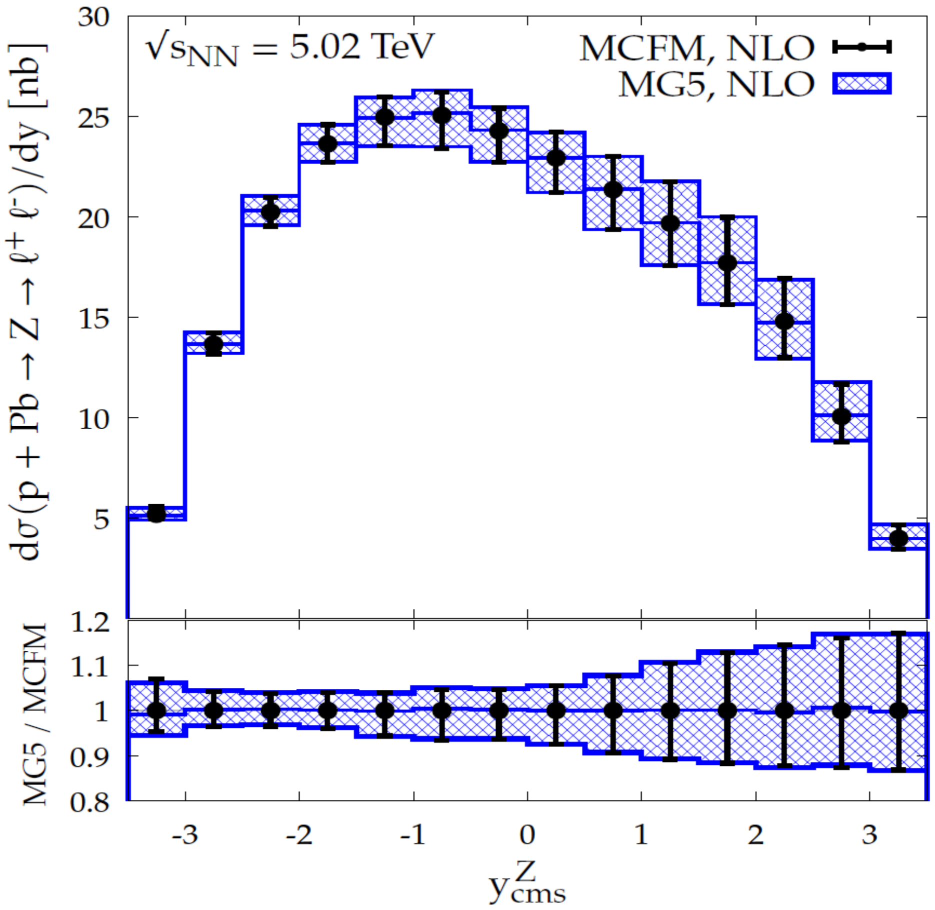
https://nloaccess.in2p3.fr/

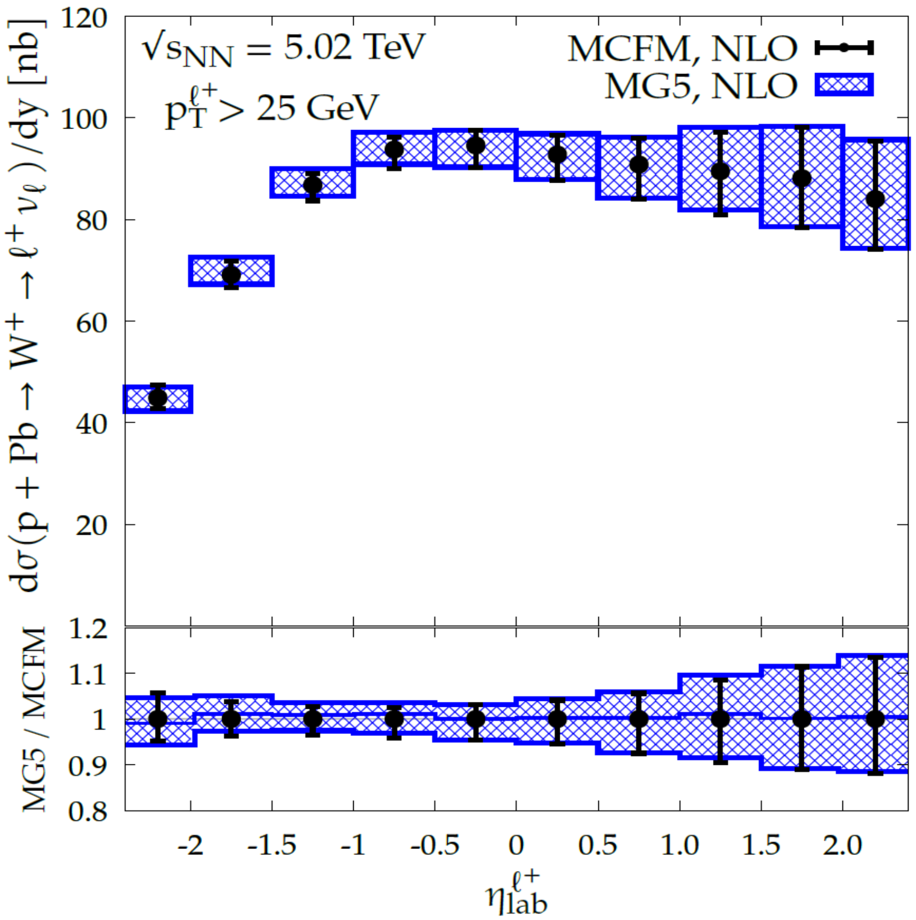


MG5 extension to asymmetric collisions will be included on NLOAccess

Validations of MG5 in asymmetric collisions

Validation vs MCFM for W and Z production in proton-lead collisions at NLO

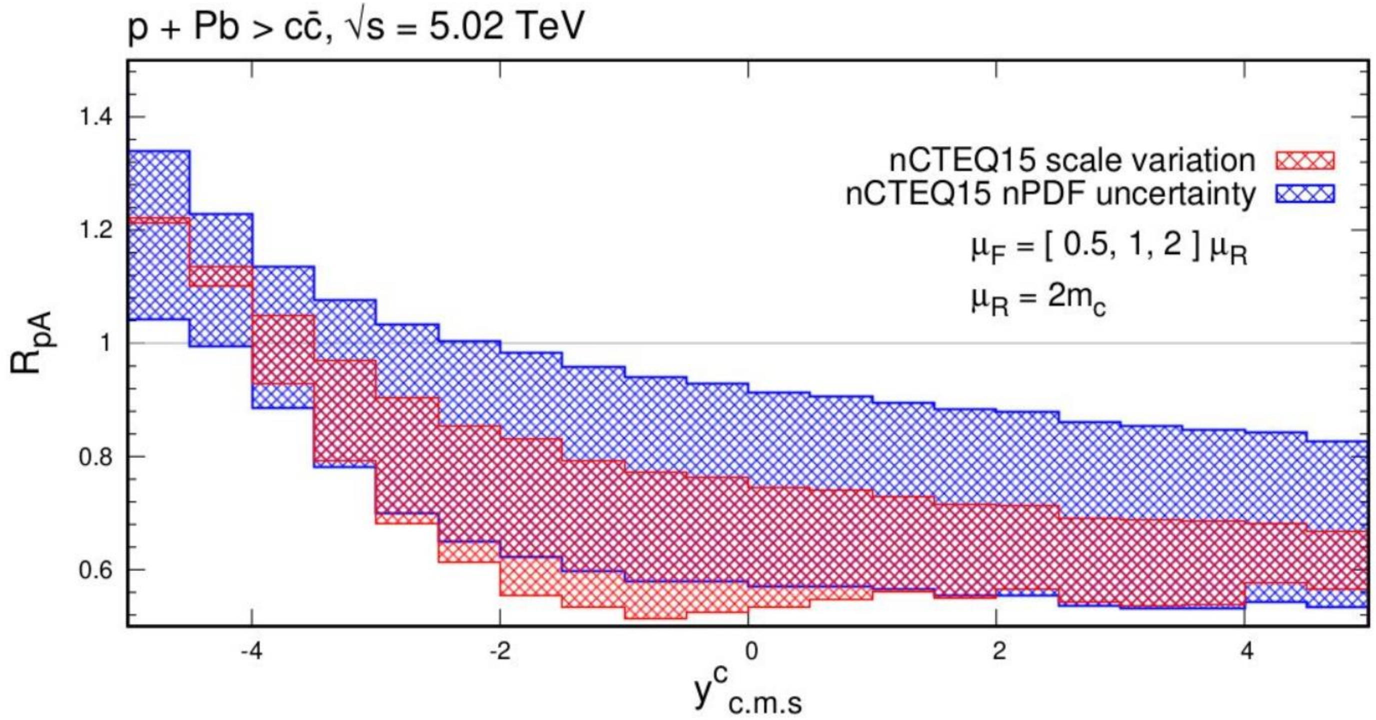


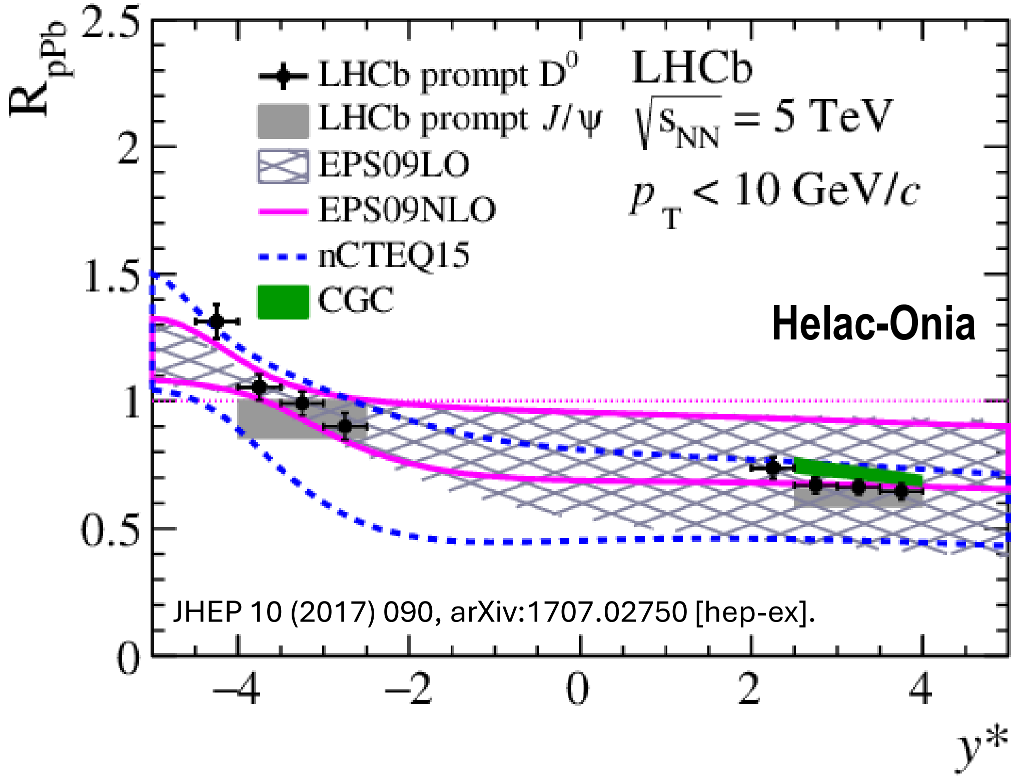


- **Very good agreement** between **MG5** and **MCFM**-based computations both for central value and uncertainties
- **Uncertainties match**, if **MCFM**-based computation done with **asymmetric** error estimation

Example: *c* production in *p*Pb collision at LHC

Charm quark production



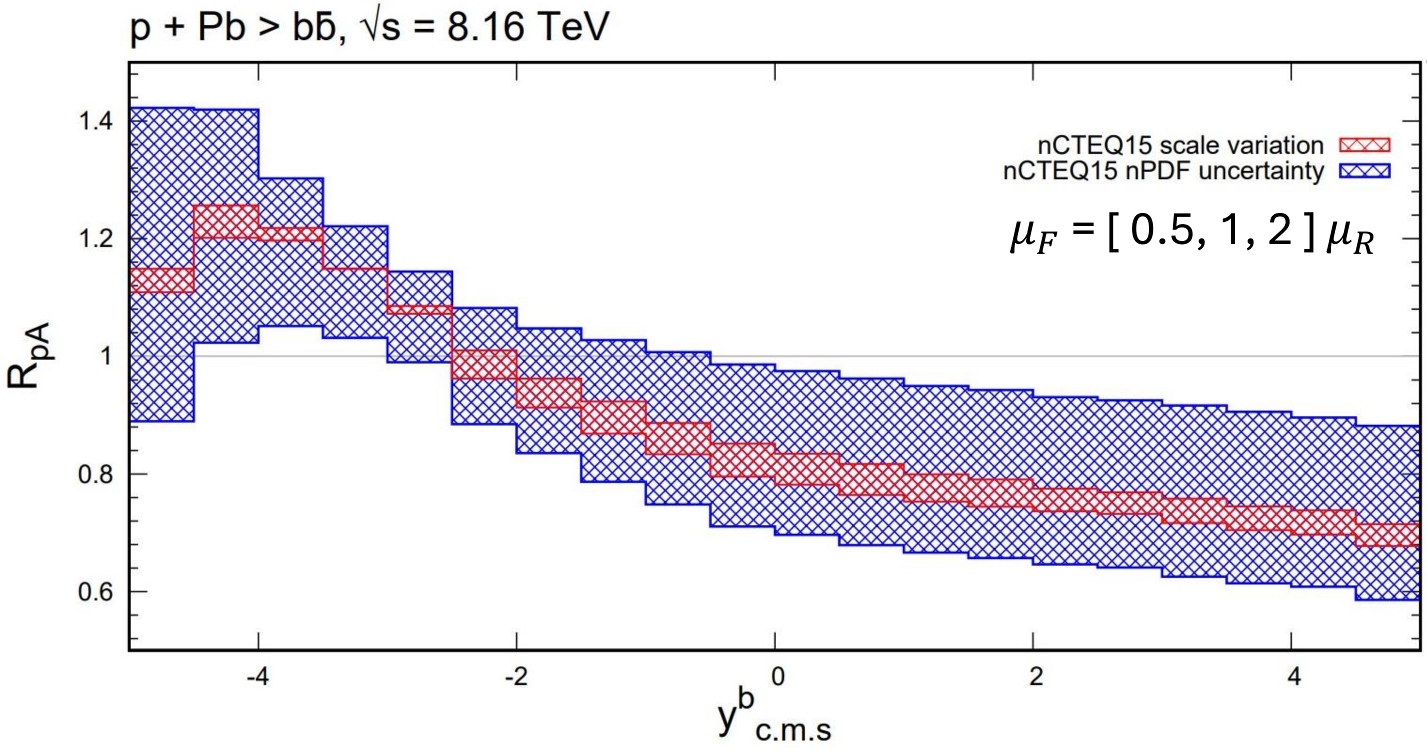


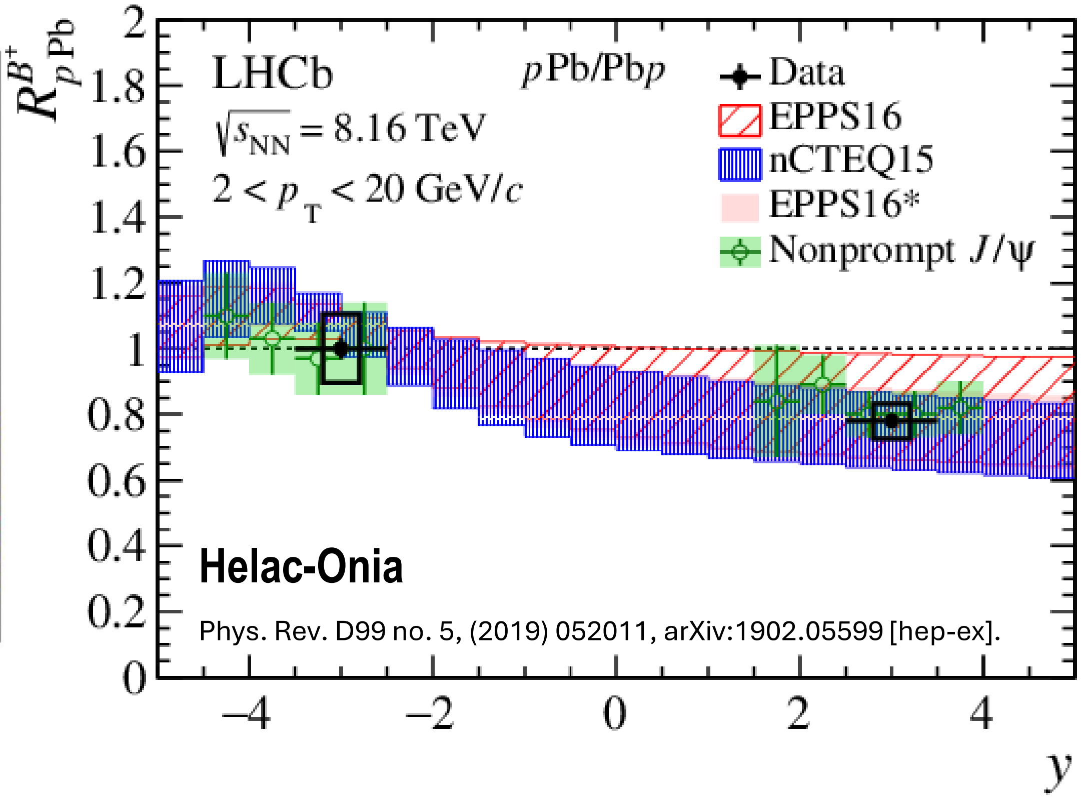
To make this plot, one just needs as input two numbers:
LHAPDF IDs of proton and nCTEQ15 for Lead
Scale uncertainty is automatically computed.

For charm production, $\boldsymbol{\mu_F}$ uncertainty nearly as **large** as the **nPDF uncertainty**.

Example: *b* production in *p*Pb collision at LHC

Bottom quark production





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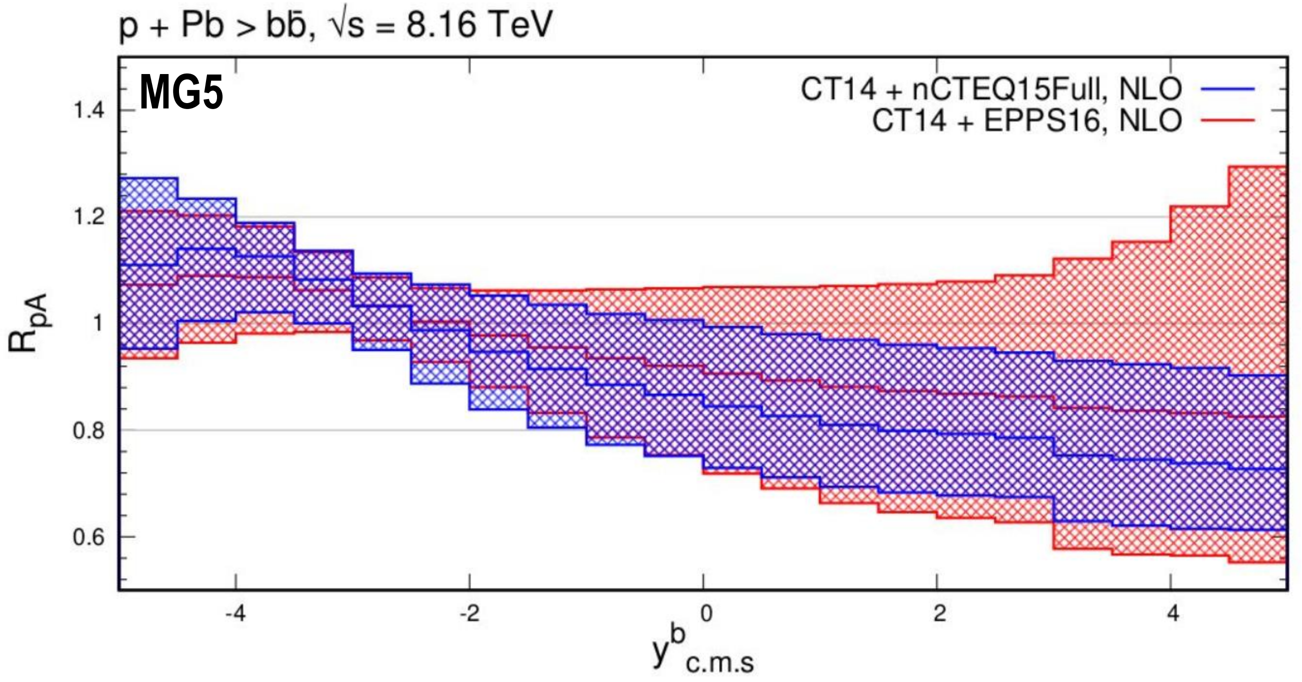
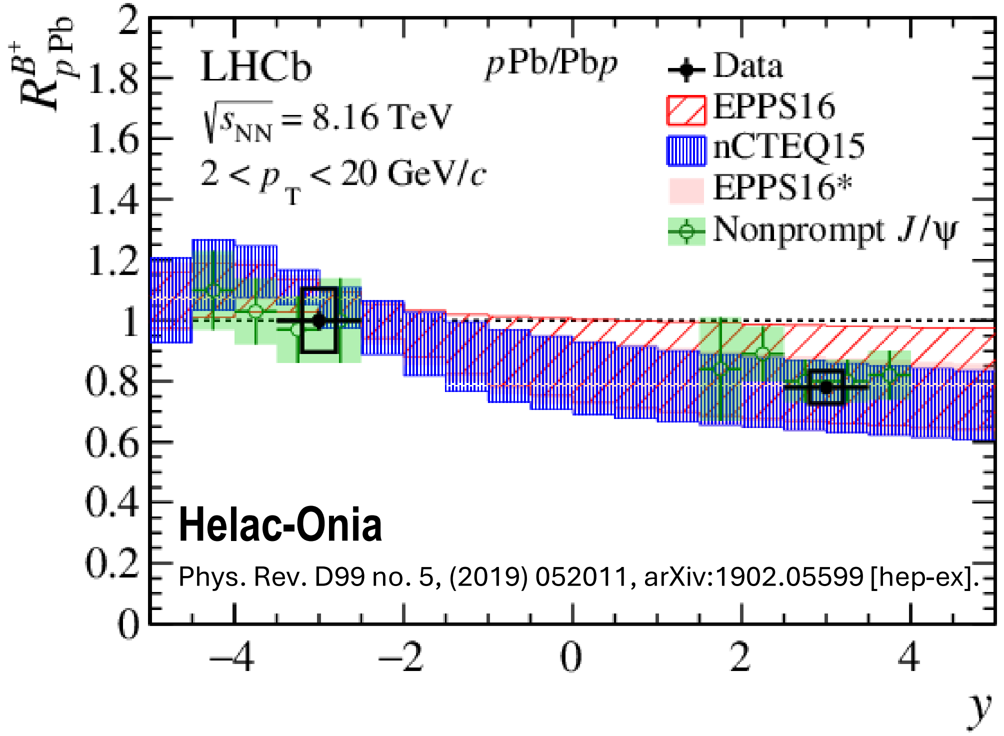
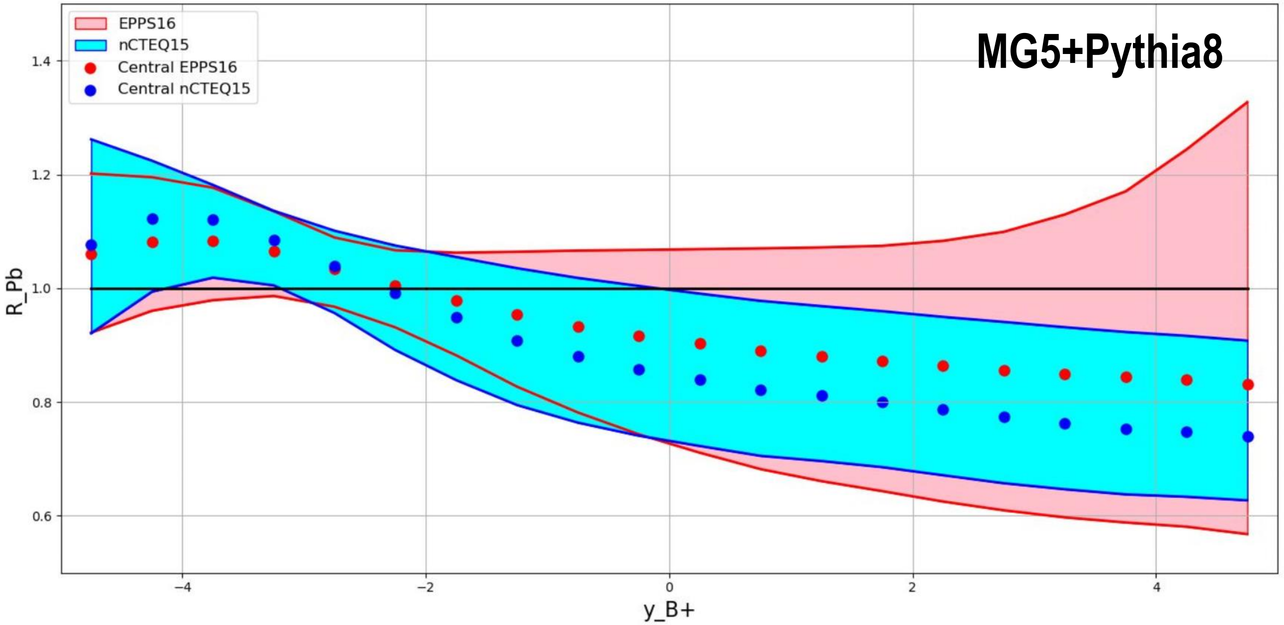
Example: *B*+ production in *p*Pb collision at LHC





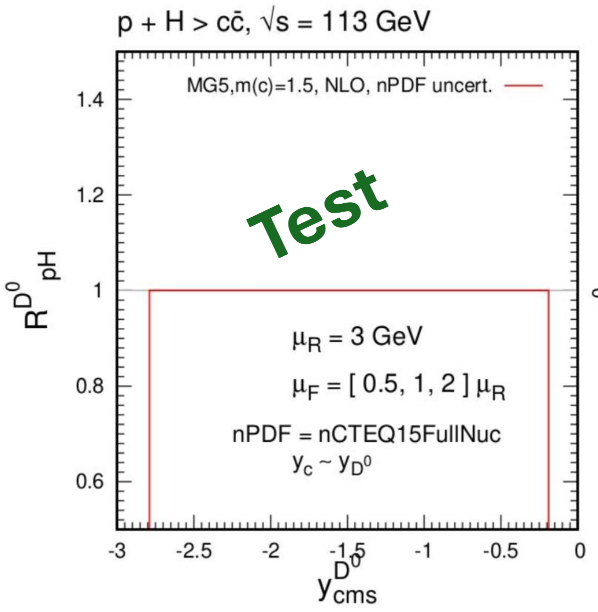


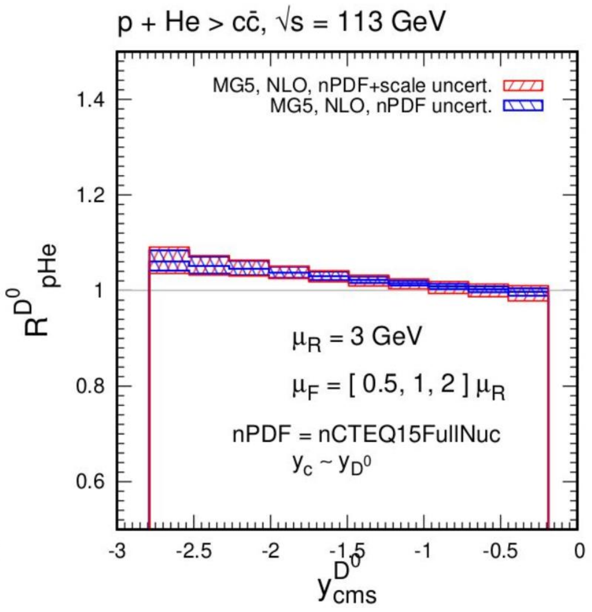
Impact on nPDF of future D0 and B+ measurements with SMOG2

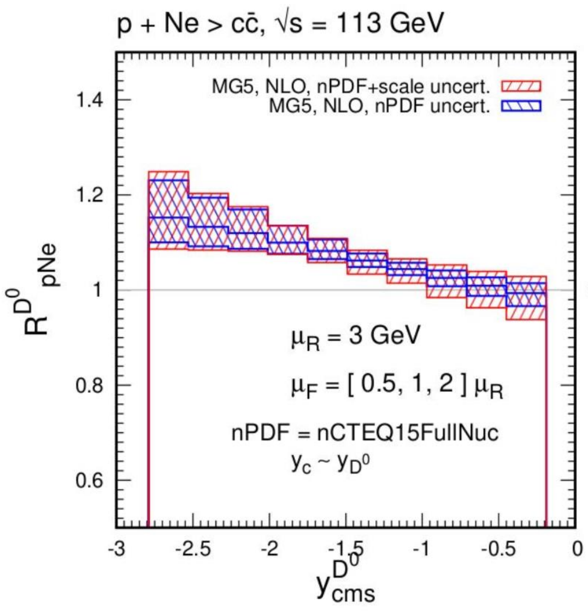
Directed by

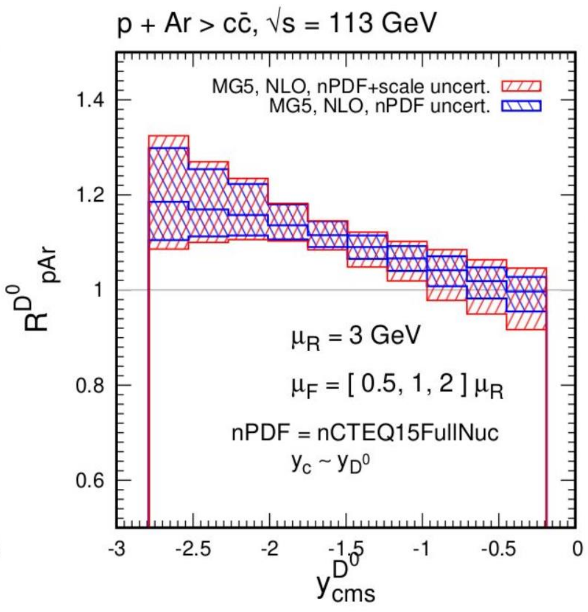
Cynthia Hadjidakis (IJClab)

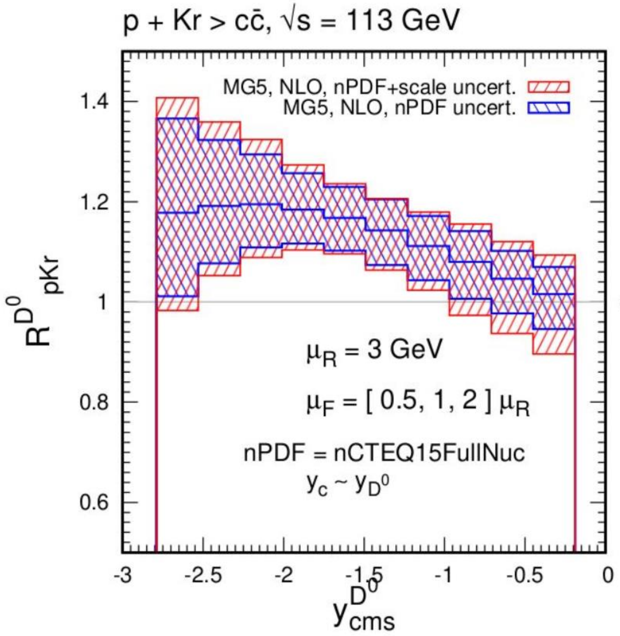
$R^{D^0}_{pA}$ for different nuclei (H, He, Ne, Ar, Kr, Xe): rapidity dependence

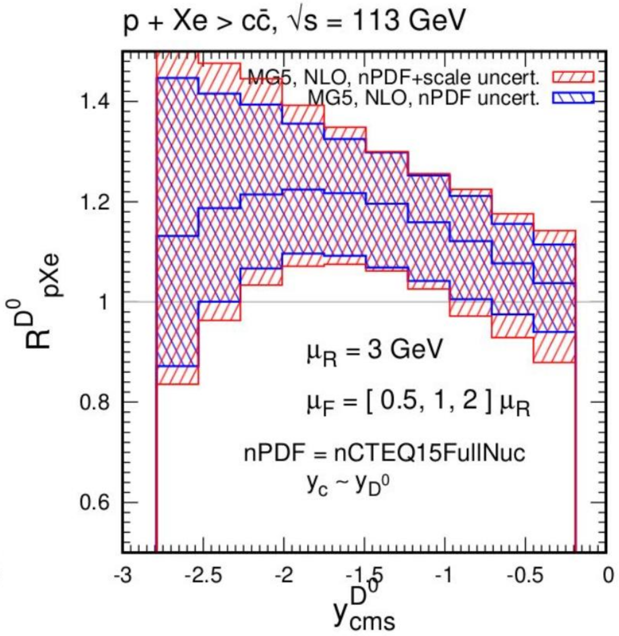










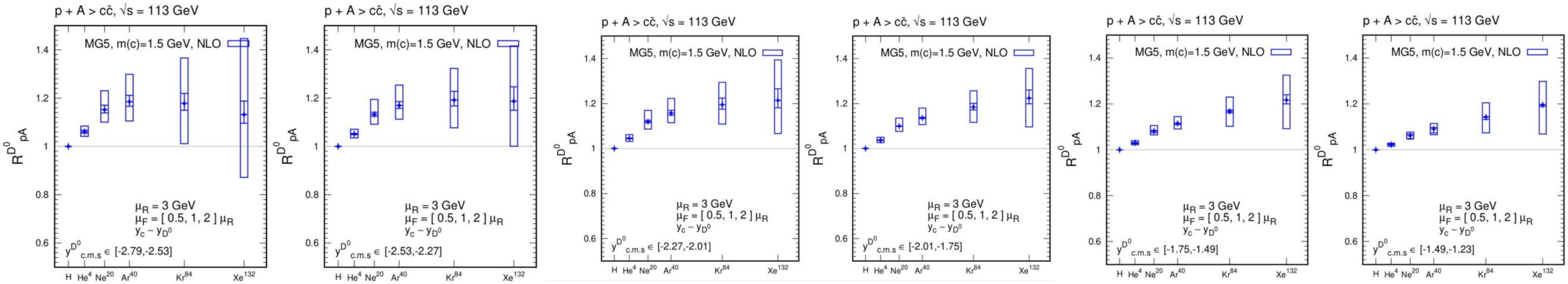


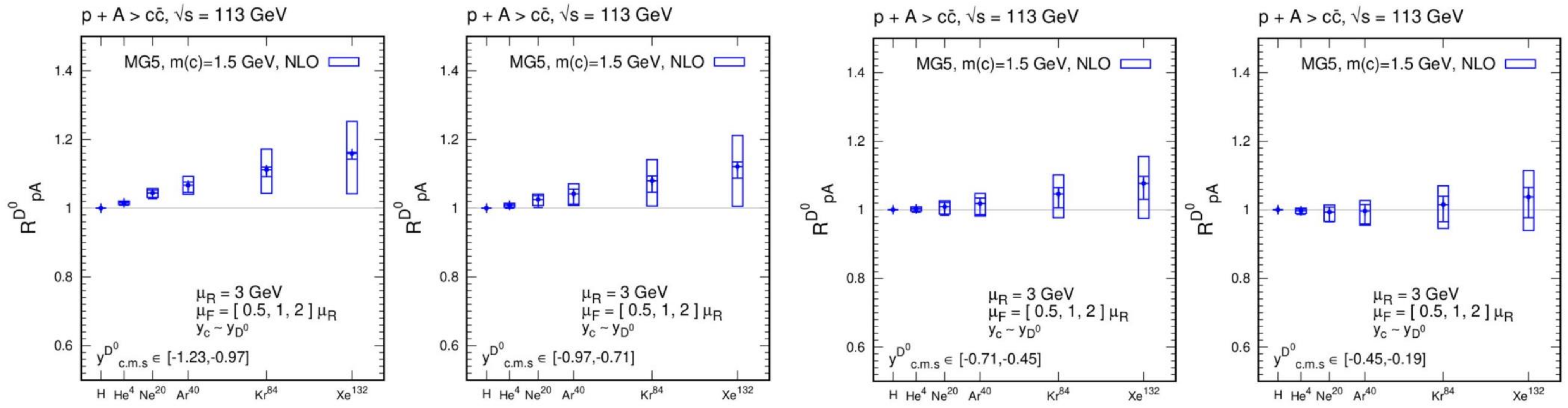
- **Uncertainties dominated by nPDFs ones**
- **Uncertainties for lower atomic mass number (He, Ne, Ar) probably too small.**

$R^{D^0}{}_{pA}$ for different nuclei (H, He, Ne, Ar, Kr, Xe): A dependence

Vertical bar – scale uncertainties

Boxes – nPDF uncertainties





Production of the D0 pseudo-data of SMOG2 LHCb using MG5 output

LHCb-PUB-2018-015
04/12/2018

$\sqrt{s} = 113\ GeV$

2.0 < y_lab <4.6

-2.79 < y_cms <-0.19

System	$\sqrt{s_{NN}}$ (GeV)	< pressure> (10^{-5} mbar)	ρ_S (cm^{-2})	$\mathcal{L}$ ($cm^{-2}s^{-1}$)	Rate (MHz)	Time (s)	$\int \mathcal{L}$ (pb^{-1})	
pH_2	115	4.0	2.0×10^{13}	6×10^{31}	4.6	2.5×10^6	150	
pD_2	115	2.0	1.0×10^{13}	3×10^{31}	4.3	0.3×10^6	9	
pAr	115	1.2	0.6×10^{13}	1.8×10^{31}	11	2.5×10^6	45	
pKr	115	0.8	0.4×10^{13}	1.2×10^{31}	12	2.5×10^6	30	
pXe	115	0.6	0.3×10^{13}	0.9×10^{31}	12	2.5×10^6	22	
pHe	115	2.0	1.0×10^{13}	3×10^{31}	3.5	3.3×10^3	0.1	40
pNe	115	2.0	1.0×10^{13}	3×10^{31}	12	3.3×10^3	0.1	40
pN_2	115	1.0	0.5×10^{13}	1.5×10^{31}	9.0	3.3×10^3	0.1	
pO_2	115	1.0	0.5×10^{13}	1.5×10^{31}	10	3.3×10^3	0.1	
PbAr	72	8.0	4.0×10^{13}	1×10^{29}	0.3	6×10^5	0.060	
PbH_2	72	8.0	4.0×10^{13}	1×10^{29}	0.2	1×10^5	0.010	
pAr	72	1.2	0.6×10^{13}	1.8×10^{31}	11	3×10^5	5	

$$\sigma_{D_0+\overline{D_0}} = 2 \times \sigma_c \times \varepsilon_{eff} \times Br \times f(c \to D0) \times \mathcal{L}$$

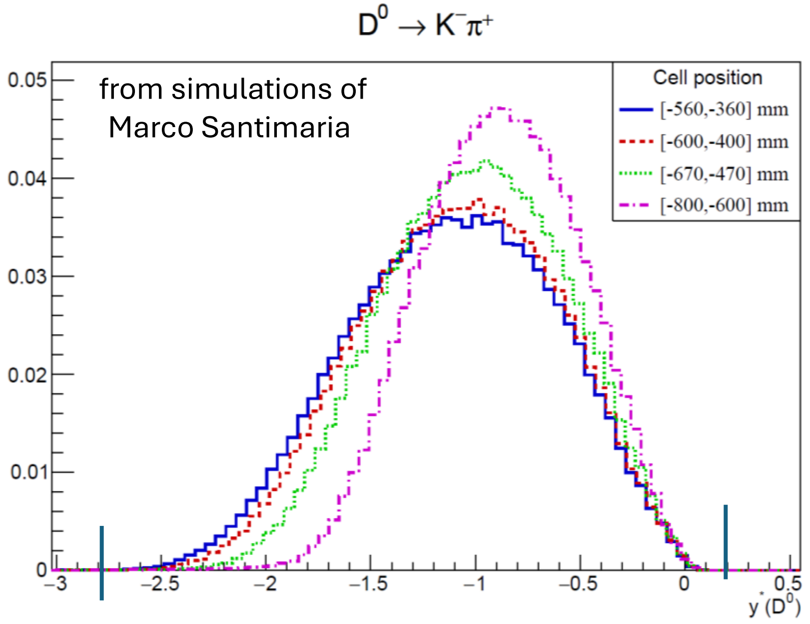
We have less statistics (limited by) for H_2

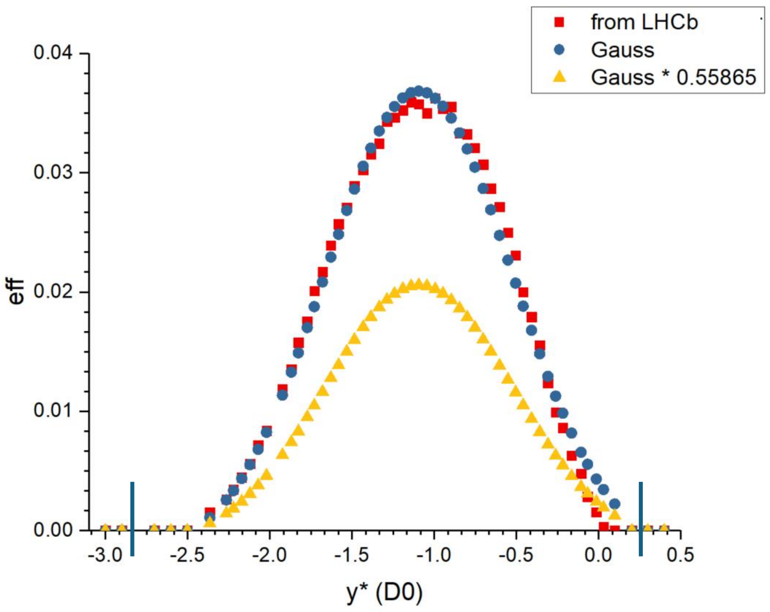
$$Br(D^0 \to K^-\pi^+) = (3.9\ \pm 0.09 \pm 0.12)\%$$

$\mathbf{f}(c \to \boldsymbol{D^0})$ = 0.542 ± 0.024

$f = \frac{A}{B}$	$\sigma_f^2 \approx f^2 \left[\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2 - 2\frac{\sigma_{AB}}{AB}\right]$ [17]

Calculation of the AccxEff and uncertainties





Acceptance efficiency integrated over y is taken as 0.5-1% (we took 1%) (priv. comm. Emilie Maurice)

To achieve this, we have to scale Gaussian from the LHCb by factor 0.56 (yellow distribution)

Uncertainties are considered as uncorrelated over y!

Systematic uncertainty estimations are based on pPb systematics for D0 production:
arXiv:1707.02750v1 (5 TeV)
arXiv:2205.03936v4 (8.16 TeV)

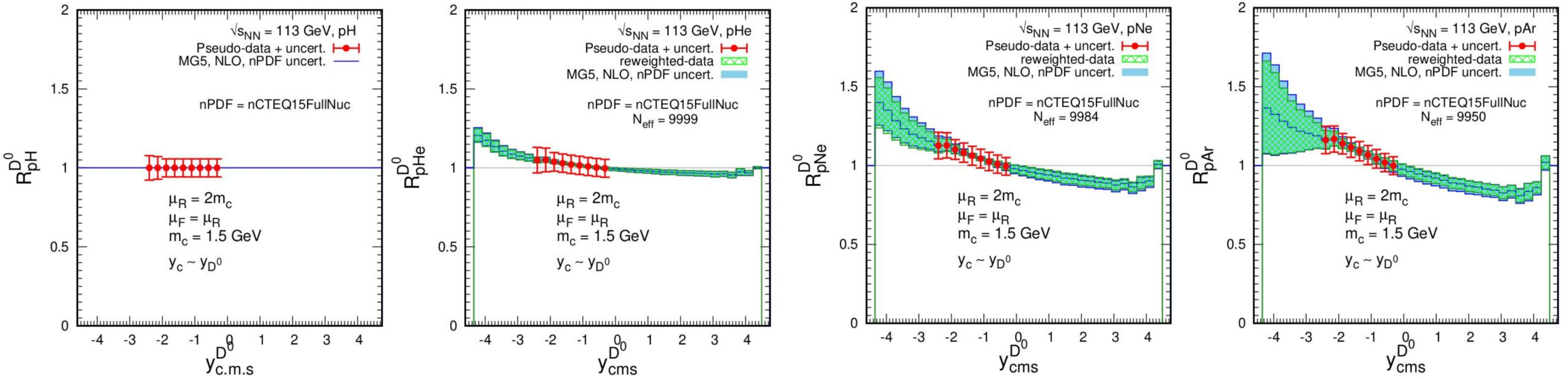
PID	Lum	Tracking	Signal	Prompt	Sim.sample	BR
1%	2%	3%	1%	0.1%	1%	0.8%

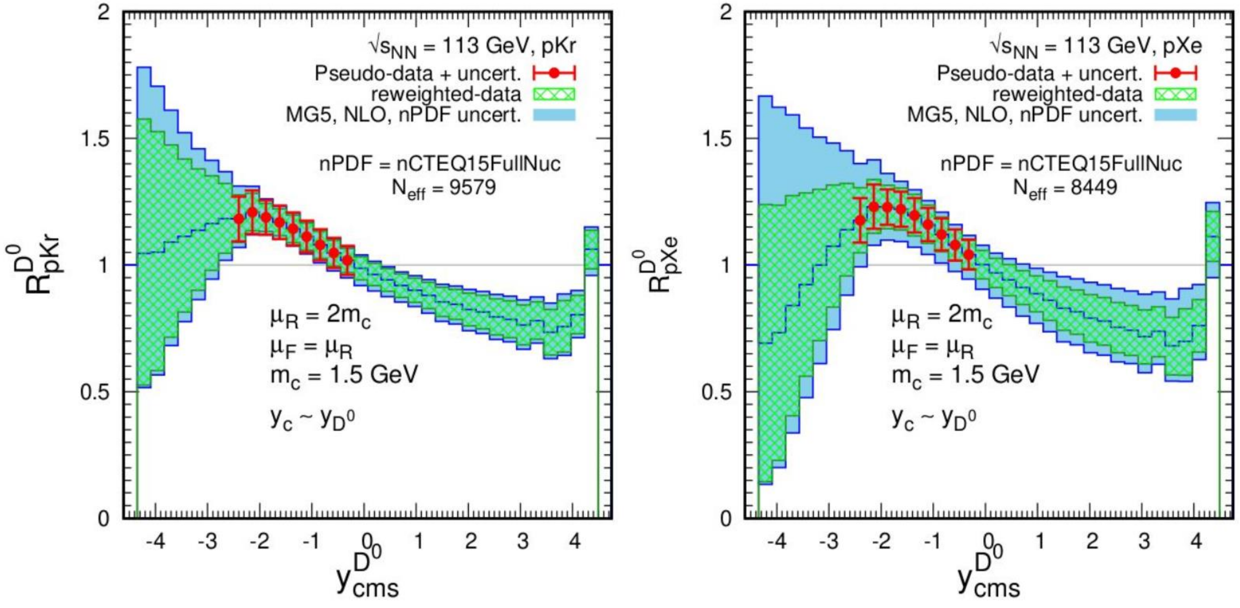
$$\frac{\delta\sigma_{syst}}{\sigma_{syst}} = 4\%$$

Except for bins
-2.5 < **y_cms** < -2.0

$$\frac{\delta\sigma_{syst}}{\sigma_{syst}} = 5\%$$

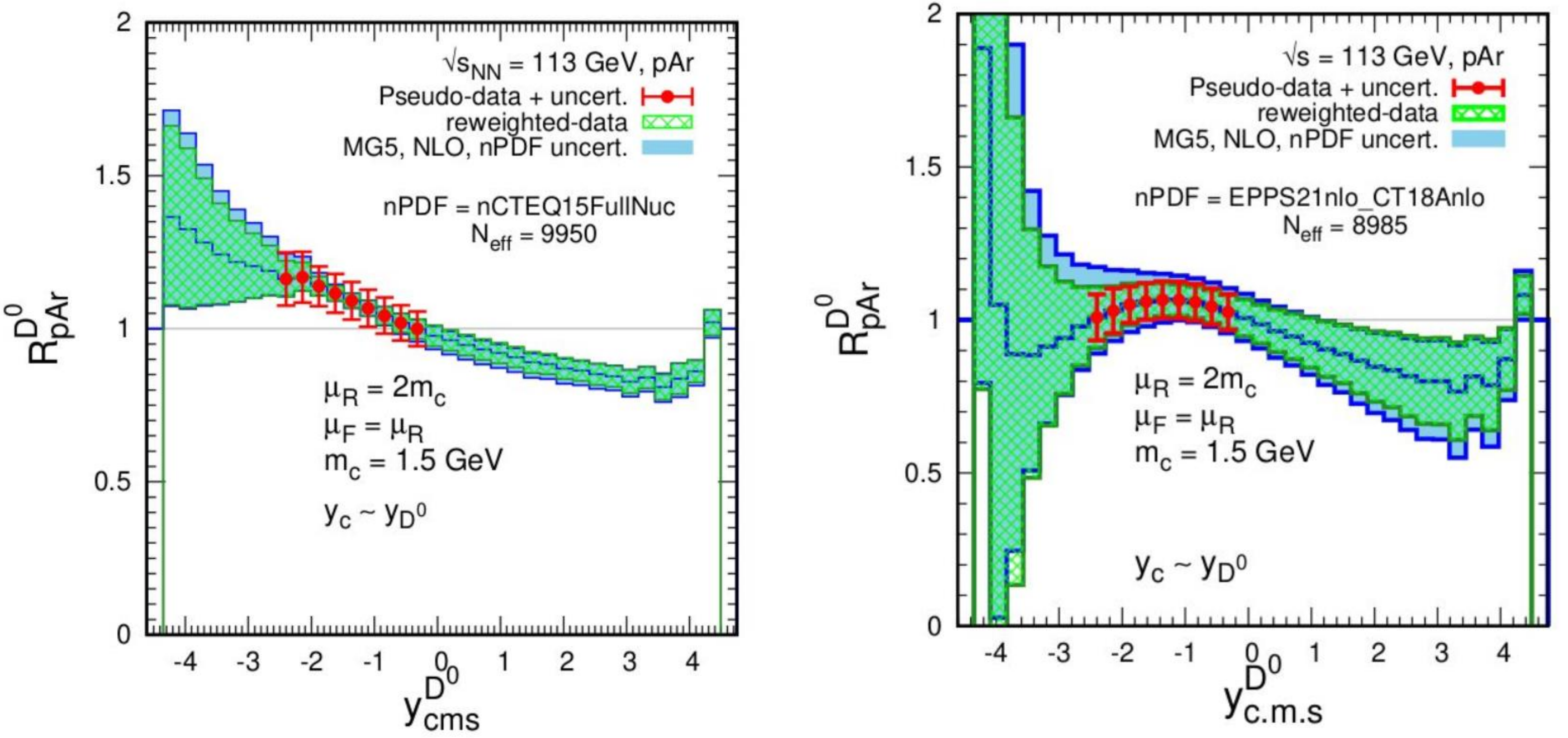
$R^{D^0}{}_{pA}$ for different nuclei (H, He, Ne, Ar, Kr, Xe): reweighing of the nPDFs



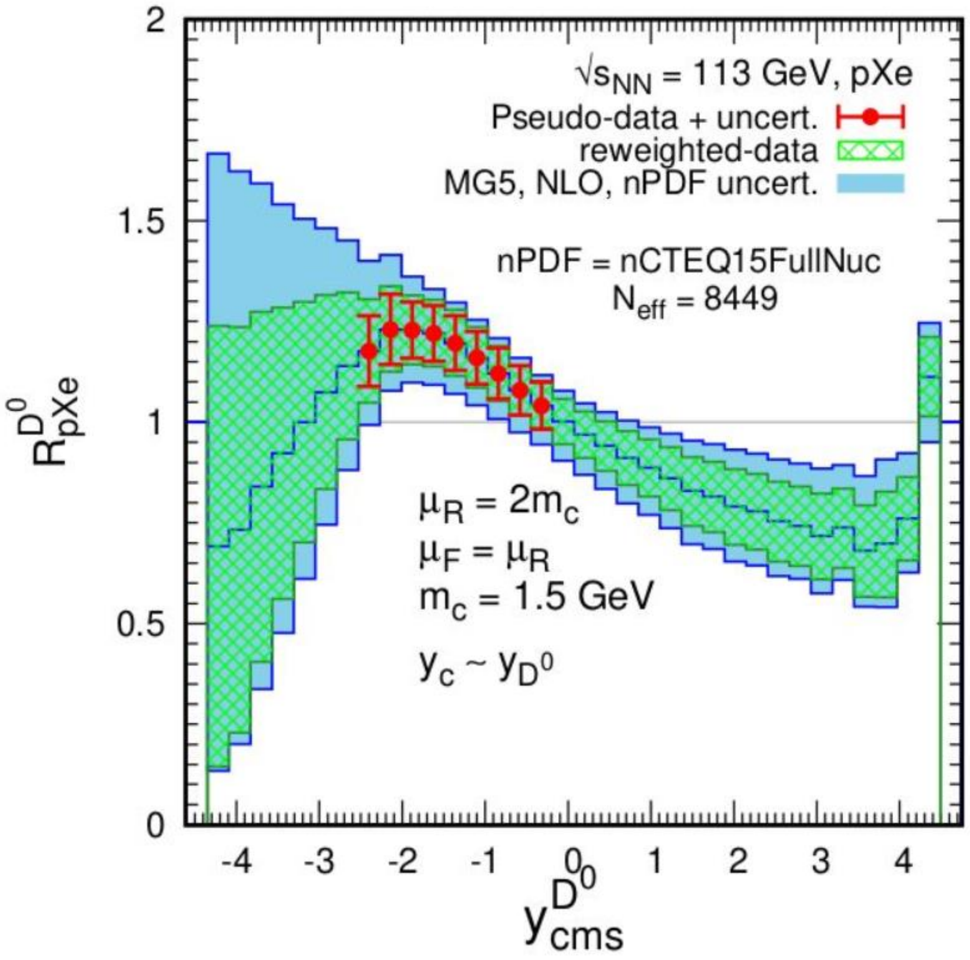


Steps for the reweighting were taken from arXiv:1610.02925v2

${R^{D^0}}_{pA}$ for Ar: reweighing of the nPDFs, nCTEQ vs EPPS21



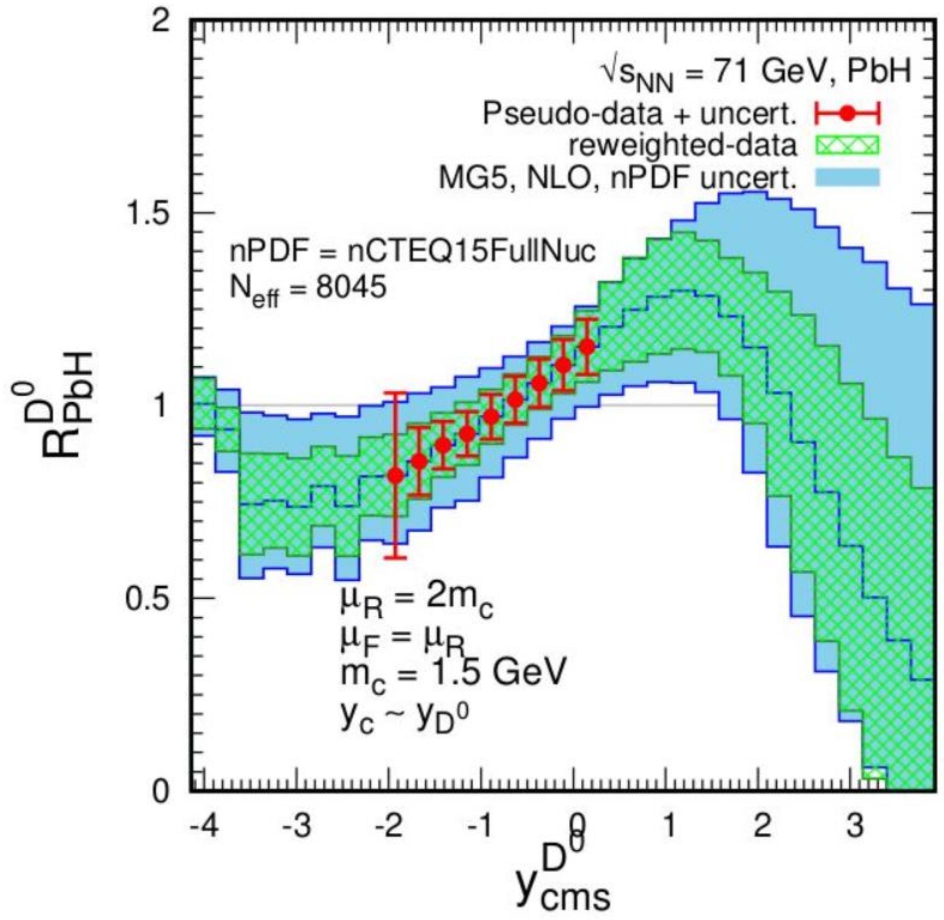
Reweighing of the nPDFs:
proton beam on Xe target vs Pb beam on H target



$x_2 \in [0.032, 0.33]$

$$x2 = \frac{2m_c}{113} e^{-y}$$

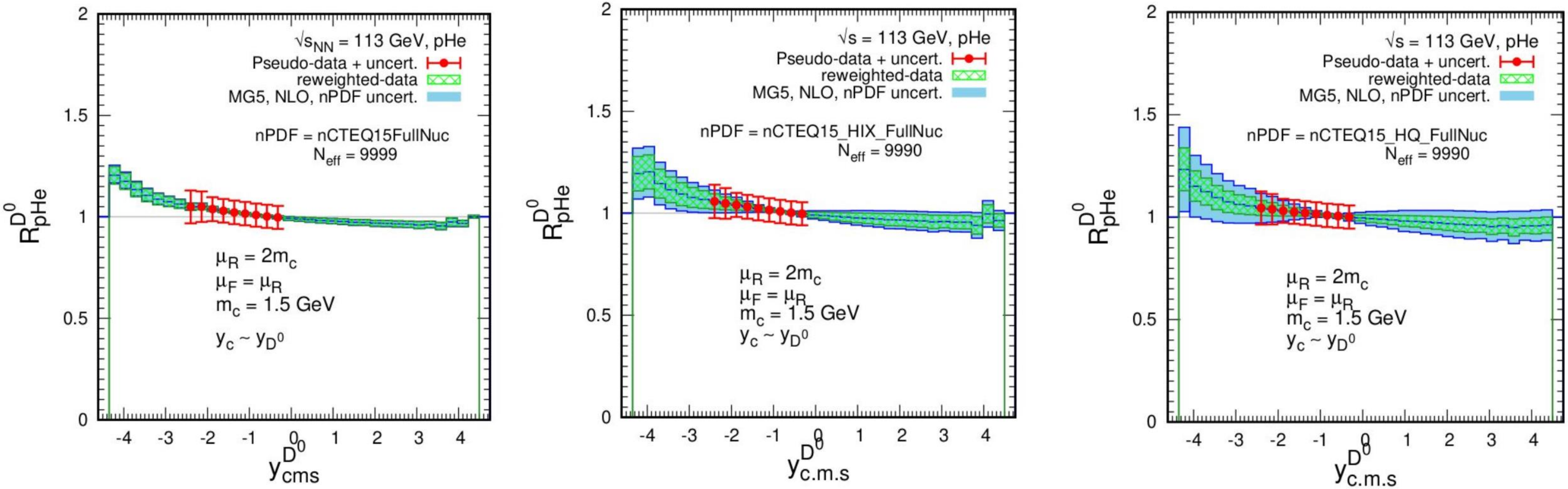
SMOG2
probes different
regions of the rapidity



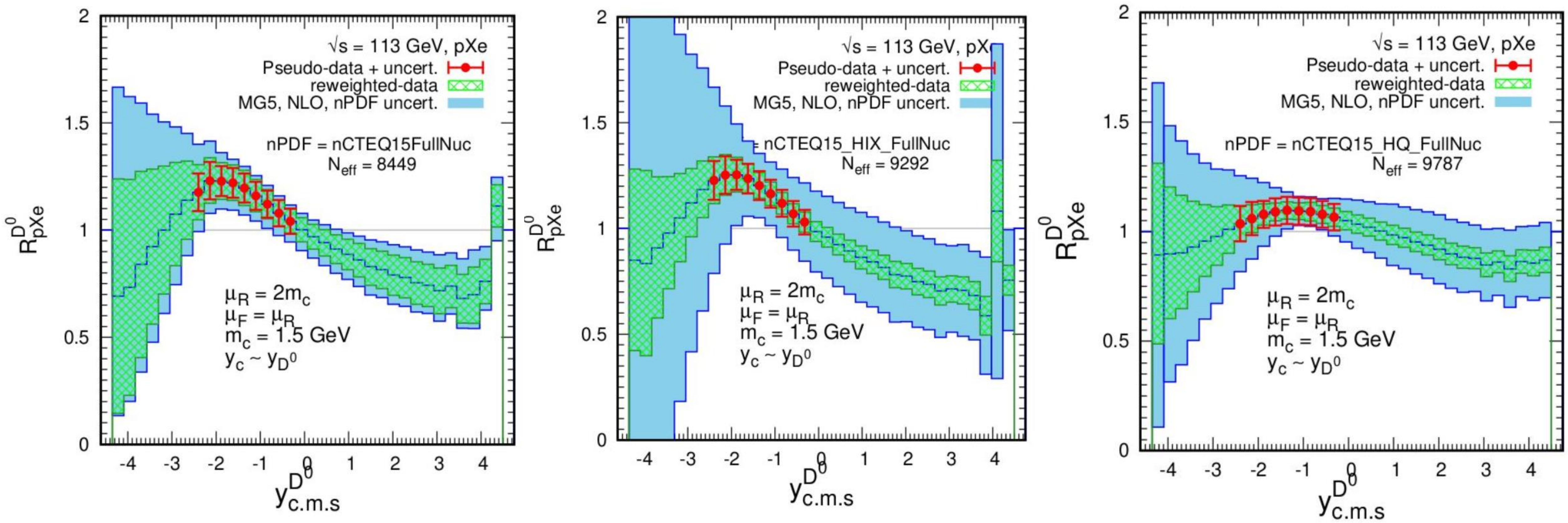
$x_1 \in [0.0053, 0.056]$

$$x1 = \frac{2m_c}{71} e^{y}$$

$R^{D^0}{}_{pA}$ for He and newer nPDFs: reweighing



$R^{D^0}{}_{pA}$ for Xe for newer nPDFs: reweighing



Production of the B+ pseudo-data of SMOG2 LHCb using MG5 output

LHCb-PUB-2018-015
04/12/2018

System	$\sqrt{s_{NN}}$ (GeV)	< pressure> (10^{-5} mbar)	ρS (cm^{-2})	$\mathcal{L}$ ($cm^{-2}s^{-1}$)	Rate (MHz)	Time (s)	$\int \mathcal{L}$ (pb^{-1})	
pH_2	115	4.0	2.0×10^{13}	6×10^{31}	4.6	2.5×10^6	150	
pD_2	115	2.0	1.0×10^{13}	3×10^{31}	4.3	0.3×10^6	9	
pAr	115	1.2	0.6×10^{13}	1.8×10^{31}	11	2.5×10^6	45	
pKr	115	0.8	0.4×10^{13}	1.2×10^{31}	12	2.5×10^6	30	
pXe	115	0.6	0.3×10^{13}	0.9×10^{31}	12	2.5×10^6	22	
pHe	115	2.0	1.0×10^{13}	3×10^{31}	3.5	3.3×10^3	0.1	40
pNe	115	2.0	1.0×10^{13}	3×10^{31}	12	3.3×10^3	0.1	40
pN_2	115	1.0	0.5×10^{13}	1.5×10^{31}	9.0	3.3×10^3	0.1	
pO_2	115	1.0	0.5×10^{13}	1.5×10^{31}	10	3.3×10^3	0.1	
PbAr	72	8.0	4.0×10^{13}	1×10^{29}	0.3	6×10^5	0.060	
PbH_2	72	8.0	4.0×10^{13}	1×10^{29}	0.2	1×10^5	0.010	
pAr	72	1.2	0.6×10^{13}	1.8×10^{31}	11	3×10^5	5	

$\sqrt{s} = 113\ GeV$

2.0 < y_lab <4.5

-2.79 < y_cms <-0.29

We have less statistics (limited by) H_2 and Xe

$$\sigma_{B+} = \sigma_b \times \varepsilon_{eff} \times Br \times f(b \to B^+) \times \mathcal{L}$$

$$f = \frac{A}{B} \qquad \sigma_f^2 \approx f^2 \left[\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2 - 2\frac{\sigma_{AB}}{AB} \right]$$ [17]

$$Br(B^+ \to J/\psi\, K^+) = (1.020 \pm 0.019) \times 10^{-3}$$
$$Br(J/\psi \to \mu^+\mu^-) = (5.961 \pm 0.033)\%$$

$\mathbf{f}(b \to \boldsymbol{B^0})$ = 40.4 ± 0.6 %

Production of the pseudo-data of SMOG2 LHCb using MG5 output

Target			LHCb							
			Proton beam ($\sqrt{s_{NN}}$ = 115 GeV)				Pb beam ($\sqrt{s_{NN}}$ = 72 GeV)			
			$\mathcal{L}$ [cm^{-2} s^{-1}]	$\sigma_{\text{inel.}}$ [mb]	$\Gamma_{inel.}$ [kHz]	$\int\mathcal{L}$ [pb^{-1}]	$\mathcal{L}$ [cm^{-2} s^{-1}]	$\sigma_{\text{inel.}}$ [mb]	$\Gamma_{inel.}$ [kHz]	$\int\mathcal{L}$ [nb^{-1}]
Internal gas target	Gas-Jet	$H^{\uparrow}$	4.3×10^{30}	39	168	43	5.6×10^{26}	1.8	1	5.6×10^{-1}
		H_2	1.0×10^{33}	39	40000	1.0×10^{4}	1.2×10^{29}	1.8	212	1.2×10^{2}
		$D^{\uparrow}$	4.3×10^{30}	72	309	43	5.6×10^{26}	2.2	1	5.6×10^{-1}
		$^3He^{\uparrow}$	3.4×10^{32}	117	40000	3.4×10^{3}	4.7×10^{28}	2.5	118	47
		Xe	3.1×10^{31}	1300	40000	3.1×10^{2}	2.3×10^{28}	6.2	186	23
	Storage Cell	$H^{\uparrow}$	9.2×10^{32}	39	35880	9.2×10^{3}	1.2×10^{29}	1.8	212	1.2×10^{2}
		H_2	1.0×10^{33}	39	40000	1.0×10^{4}	1.2×10^{29}	1.8	212	1.2×10^{2}
		$D^{\uparrow}$	5.6×10^{32}	72	40000	5.6×10^{3}	8.8×10^{28}	2.2	194	88
		$^3He^{\uparrow}$	1.3×10^{33}	117	40000	1.3×10^{4}	8.3×10^{28}	2.5	206	83
		Xe	3.1×10^{31}	1300	40000	3.1×10^{2}	3.0×10^{28}	6.2	186	30
Internal solid target on beam halo	Wire Target	C (500 μm)	2.8×10^{30}	271	760	28	5.6×10^{26}	3.3	2	5.6×10^{-1}
		Ti (500 μm)	1.4×10^{30}	694	972	14	2.8×10^{26}	4.7	1	2.8×10^{-1}
		W (500 μm)	1.6×10^{30}	1700	2720	16	3.1×10^{26}	6.9	2	3.1×10^{-1}
Beam splitting	E1039	$NH_3^{\uparrow}$	7.2×10^{31}	420	30240	7.2×10^{2}	1.4×10^{28}	19	259	14
		$ND_3^{\uparrow}$	7.2×10^{31}	519	37368	7.2×10^{2}	1.4×10^{28}	22	314	14
	Unpolarised solid target	C (5 mm)	2.8×10^{31}	271	7600	2.8×10^{2}	5.6×10^{27}	3.3	18	5.6
		Ti (5 mm)	1.4×10^{31}	694	9720	1.4×10^{2}	2.8×10^{27}	4.7	13	2.8
		W (5 mm)	1.6×10^{31}	1700	27200	1.6×10^{2}	3.1×10^{27}	6.9	21	3.1

A Fixed-Target Programme at the LHC:
Physics Case and Projected Performances for Heavy-Ion, Hadron, Spin and Astroparticle Studies

C. Hadjidakis[a,1], D. Kikoła[b,1], J.P. Lansberg[a,1], L. Massacrier[a,1], M.G. Echevarria[c,d,2], A. Kusina[e,2], I. Schienbein[f,2], J. Seixas[g,h,i,2], H.S. Shao[j,2], A. Signori[k,c,l,2], B. Trzeciak[m,n,2], S.J. Brodsky[o], G. Cavoto[p], C. Da Silva[q], F. Donato[r], E.G. Ferreiro[s,t], I. Hřivnáčová[a], A. Klein[q], A. Kurepin[u], C. Lorcé[v], F. Lyonnet[w], Y. Makdisi[x], S. Porteboeuf Houssais[y], C. Quintans[h], A. Rakotozafindrabe[z], P. Robbe[a], W. Scandale[aa], N. Topilskaya[u], A. Uras[ab], J. Wagner[ac], N. Yamanaka[a,af,ad,ae], Z. Yang[ag], A. Zelenski[x]

arXiv:1807.00603v3 [hep-ex] 28 Jan 2021

$\sqrt{s} = 113\ GeV$

2.0 < y_lab <4.5

-2.79 < y_cms <-0.29

Calculation of the AccxEff and uncertainties

Table 3: Measured ε_{tot} of $B^{\pm}$ events at 13 TeV, in the bins of $B^{\pm}$ p_T and y. The efficiencies and uncertainties are in percent.

p_T [GeV/c]	$2.0 < y < 2.5$	$2.5 < y < 3.0$	$3.0 < y < 3.5$	$3.5 < y < 4.0$	$4.0 < y < 4.5$
0.0 – 0.5	0.8±0.1	4.7±0.1	7.6±0.2	6.8±0.2	2.3±0.1

AccxEff is Different for each of the y region

Systematic uncertainty estimations are based on pPb and pp systematics for B+ production:
arXiv:1902.05599v2 (8.16 TeV)
arXiv:1710.04921v2 (13 TeV)

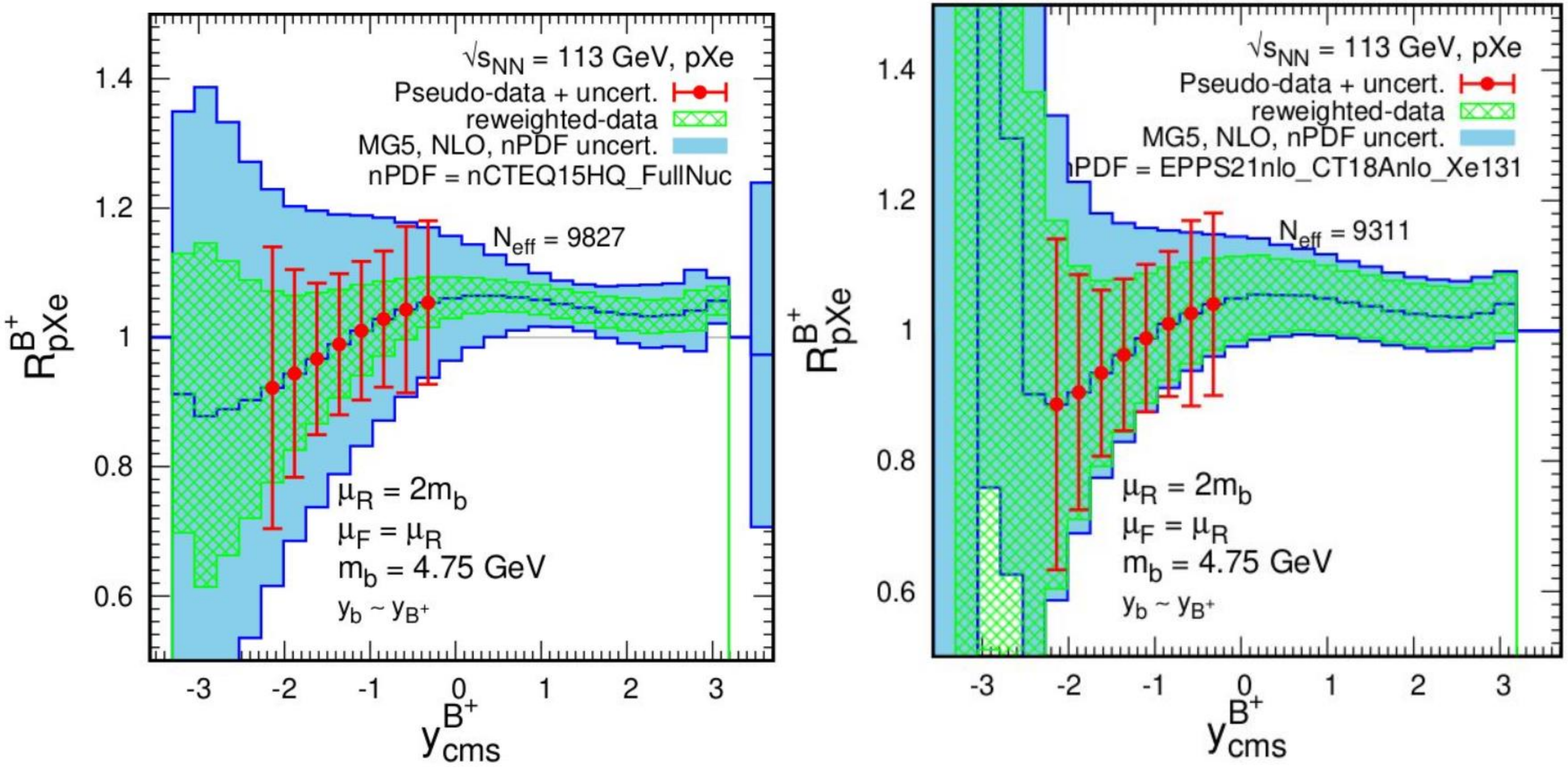
PID	Lum	BR	Binning	mass-fits	Acc	Rec	Track	Trigger
0.4%	2%	2.8%	2.5%	2%	0.2%	0.1%	2%	3%

GEC	Selection	Weighting
0.7%	1%	0.2%

$$\frac{\delta\sigma_{syst}}{\sigma_{syst}} = 6.1\%$$

Uncertainties are considered as uncorrelated over y!

$R^{B^+}{}_{pA}$ for Xe nPDF: reweighing



Conclusions

- Asymmetric collisions in MadGraph5 have been implemented and successfully validated
- The code is available at GitHub right now!
- Also, it will be a part of NLOAccess and official MadGraph5

- Reweighting is working with chosen D0-meson pseudo-data with SMOG2:
  - Pseudo-data uncertainties dominated by the systematic ones
  - If data-point uncertainties lower than nPDF uncertainties (Xe target), data can constrain gluon nPDF in and outside the probed rapidity interval

- Pseudo-data has the strong impact on the nPDF, for
  Xe target ($x_2 \in [0.032, 0.33]$)
  and
  Pb-beam ($x_1 \in [0.0053, 0.056]$)
- For lighter target it's not clear how reliable are uncertainties for nPDFs.

- Very similar situation with B+-meson pseudo-data
- Except that statistic uncertainties are much larger, due to the low luminosities of the Hydrogen and a target

- Some pseudo-data systematic uncertainties can be correlated over *y*
  assuming some experimental correlation could improve the reweighting picture.

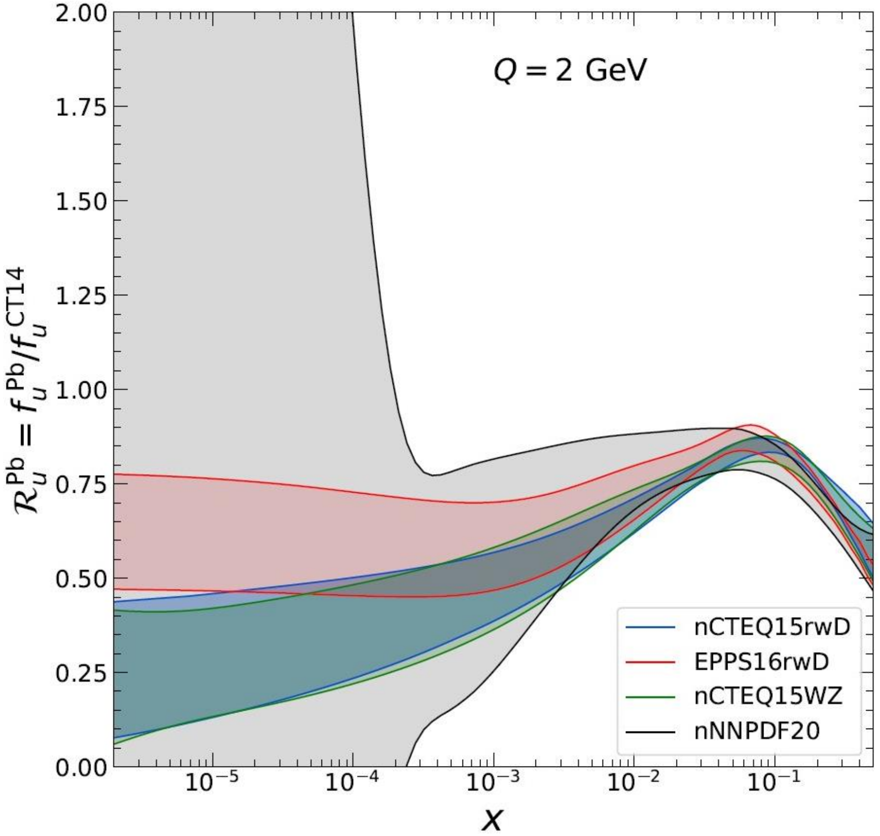
Backup

Quark nPDFs

Since the early 1980s, from the ratio of structure functions F_2 , we know that the **nuclei** are **not** a simple collection of **free nucleons**.
In other words, **nPDFs deviate** from a simple **sum of nucleon PDFs**. To **study** such deviations, it is customary to rely on **NMFs**, like:

$$R\left[F_2^{\ell A}\right] = \frac{F_2^{\ell A}}{(ZF_2^{\ell p} + (A-Z)F_2^{\ell n})}$$

$$R_i^A(x, \mu_F) = \frac{Zf_i^{p/A} + (A-Z)f_i^{n/A}}{Zf_i^p + (A-Z)f_i^n}$$



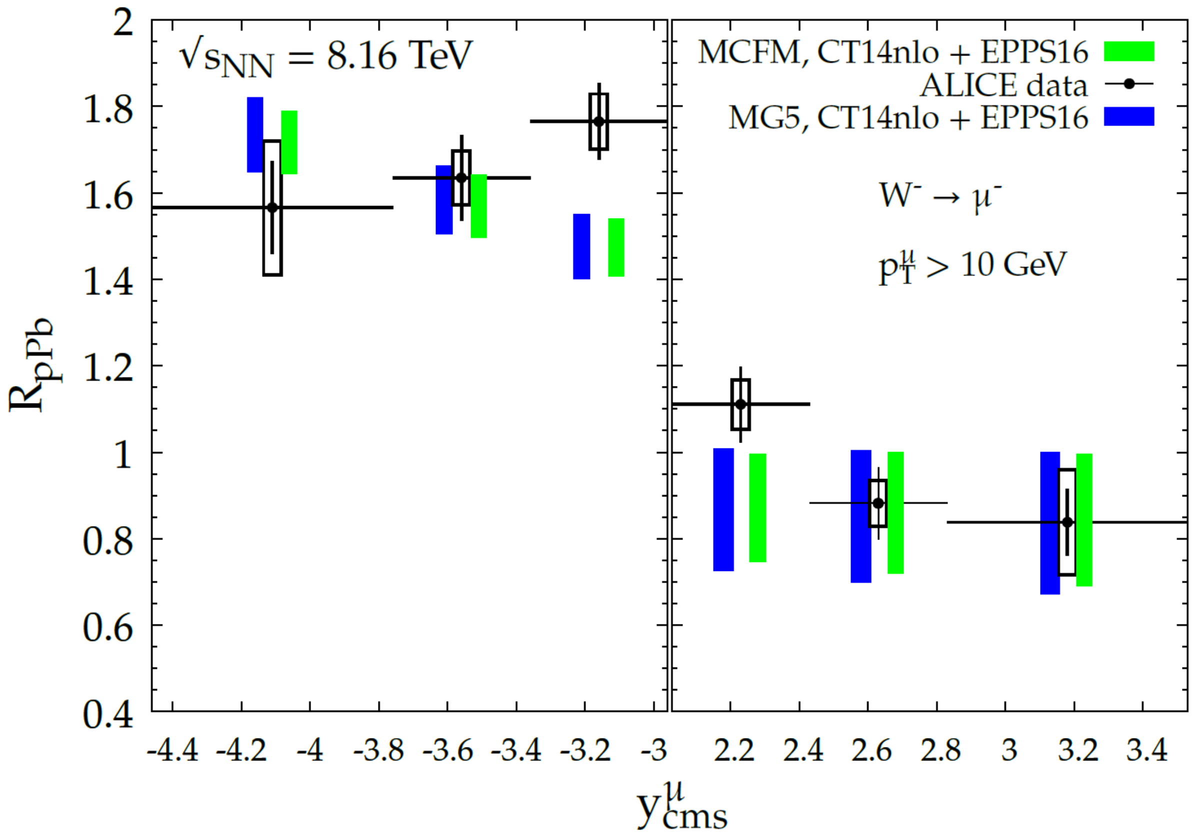
arXiv:1712.07024v2 [hep-ph]

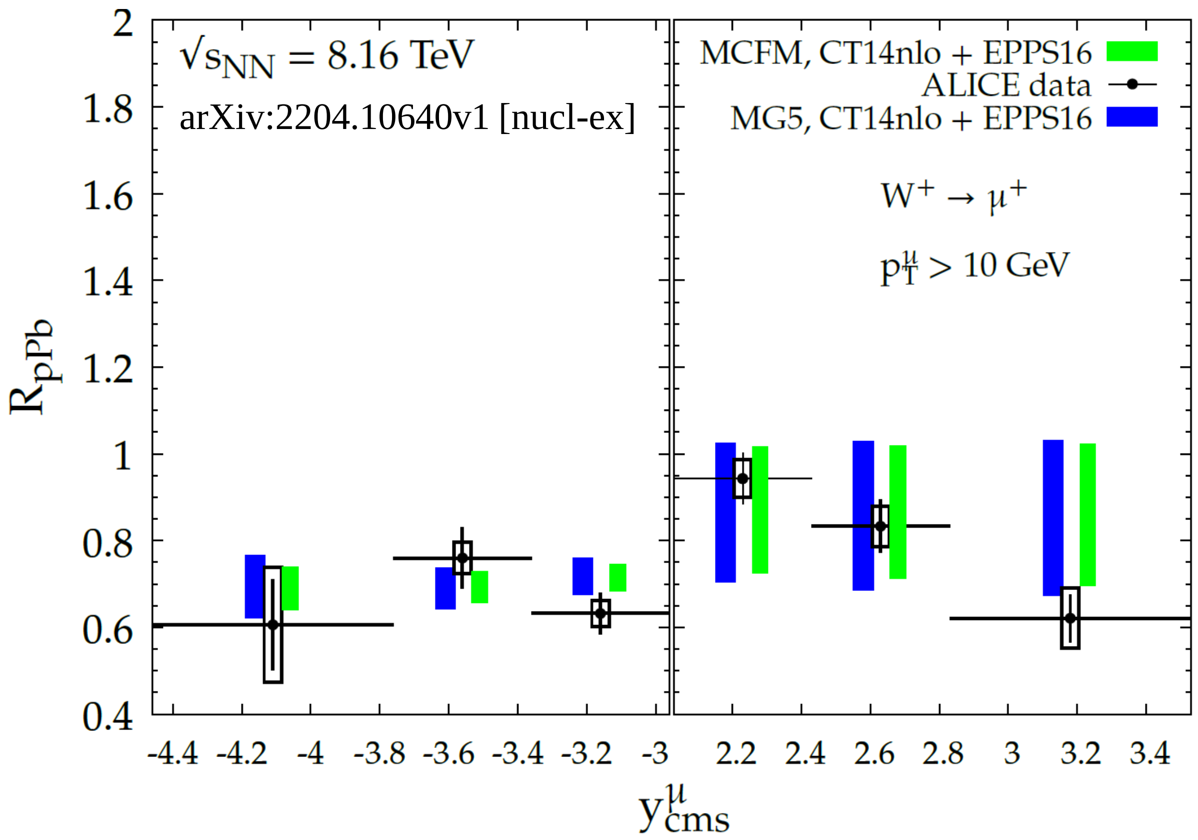
One expects:

- R_q^A >1 for x ≳ 0.8 (Fermi-motion region),
- R_q^A <1 for 0.25 ≲ x ≲ 0.8 (EMC region),
- R_q^A >1 for 0.1 ≲ x ≲ 0.25 (antishadowing region)
- R_q^A <1 for x ≲ 0.1 (shadowing region)
- $R_q^A \sim 1$: absence of nuclear effects

Validations of MG5 in asymmetric collisions

Validation vs MCFM for CT14 + EPPS16 for W production at NLO

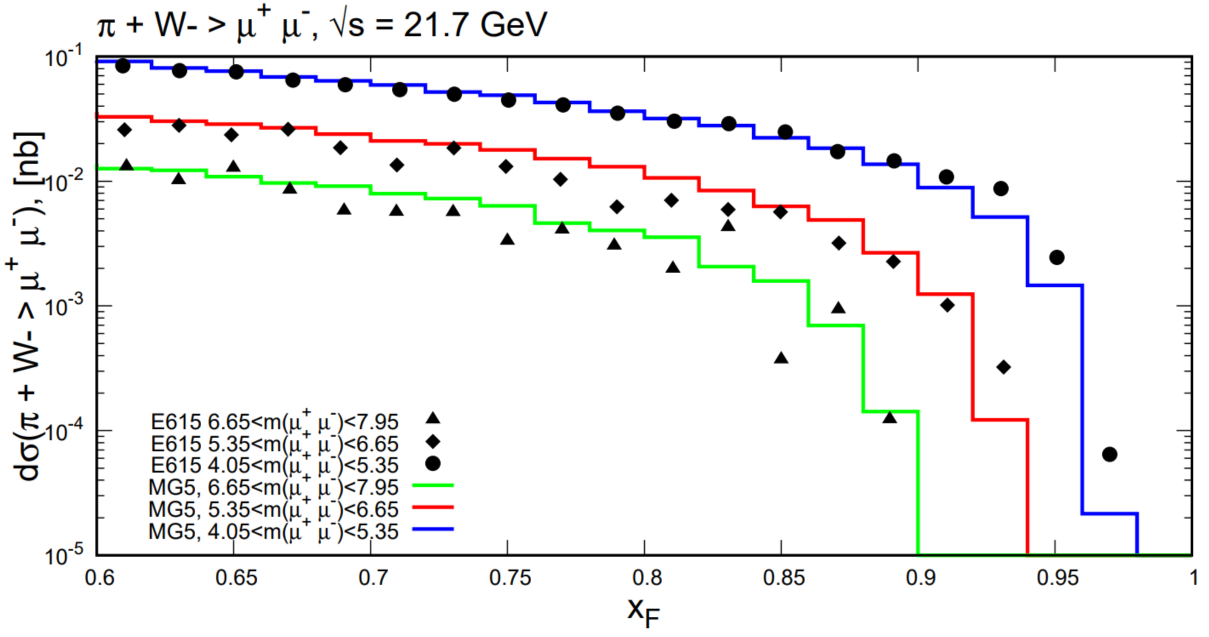


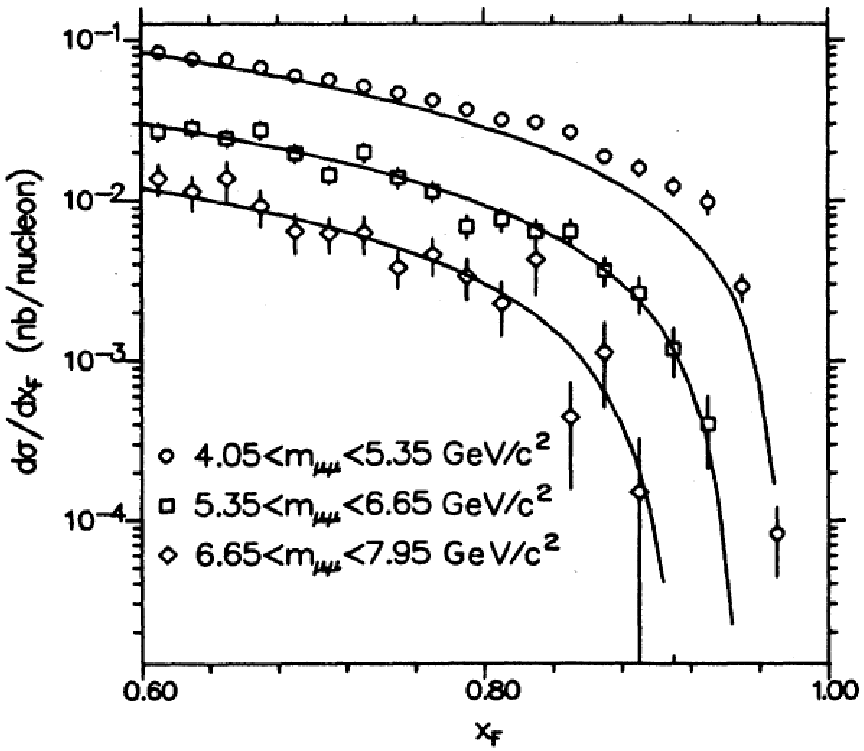


- **Good agreement** between **MG5** and **MCFM**-based computations for **EPPS16**
- **Good agreement** between **MG5** and experimental data
- Slight difference in the uncertainty since MCFM-based computation done with **symmetric uncertainties**

Example: *Drell-Yan* production in πW collision

4.05 GeV/c < m_{ll}< 8.55 GeV/c





Phys.Rev.D **39 (1989) 92-122**

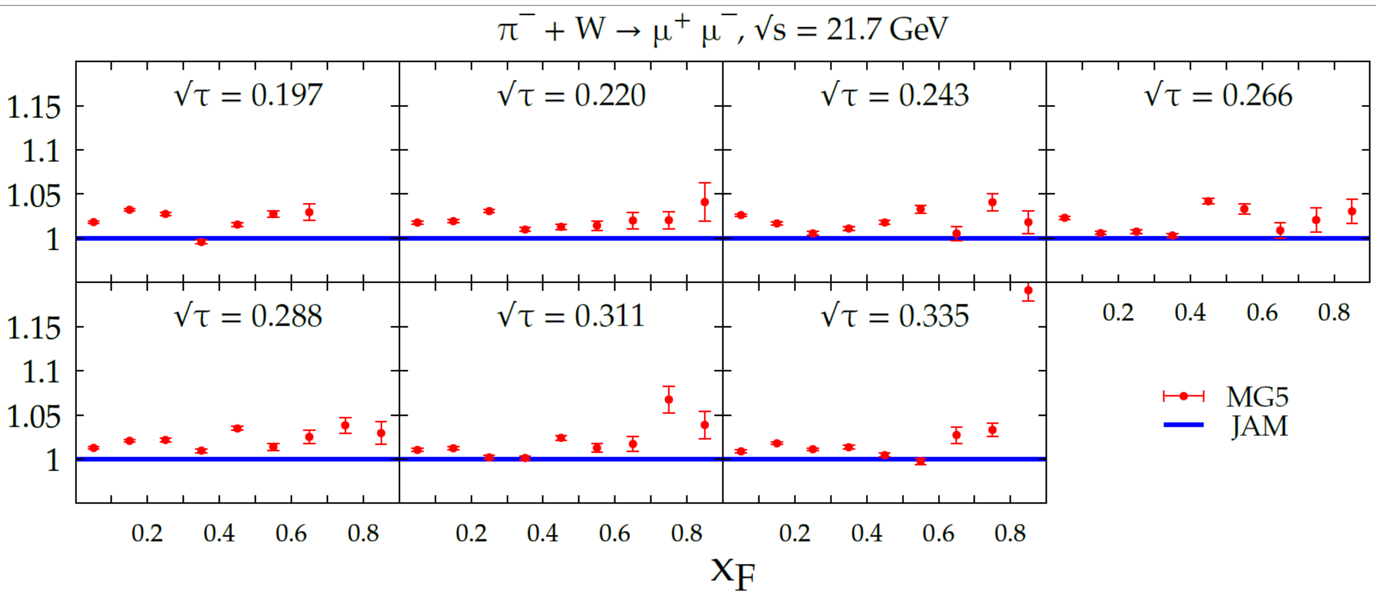
$$\tau = \frac{{m_{ll}}^2}{s}$$

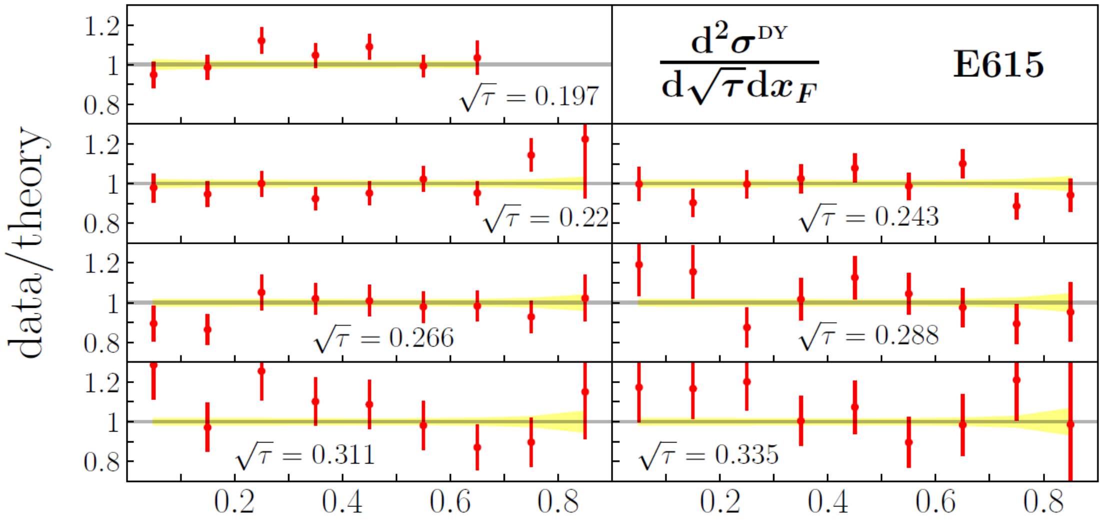
$$x_F = x_{pion} - x_{nucleus}$$

$$x_{pion} = \sqrt{\tau} e^{Y}$$

$$x_{nucleus} = \sqrt{\tau} e^{-Y}$$

Example: *Drell-Yang* production in πW collision





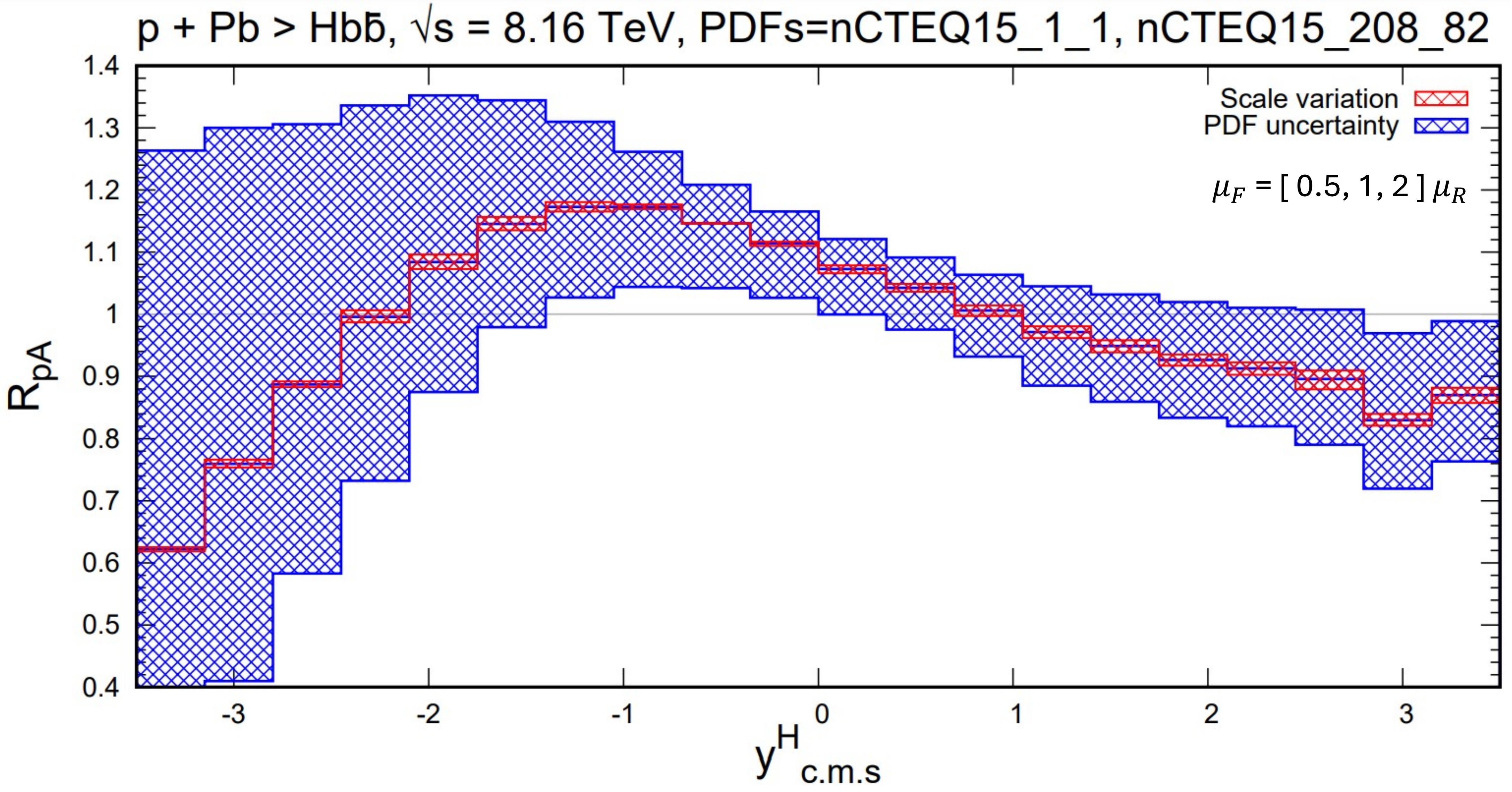
arXiv:2103.02159v2 [hep-ph] 30 Nov 2021

***Phys.Rev.D* 39 (1989) 92-122**

- **For all $\sqrt{\tau}$ regions and bins, differences do not exceed 5-10% percent range**
- Results **match** well those produced by the **JAM collaboration**
- Small **differences**, could **arise** from **instabilities** that relate to **Monte-Carlo algorithms** and very **narrow regions** of invariant masses of muon pairs

$$\tau = \frac{m_{ll}^2}{s}$$

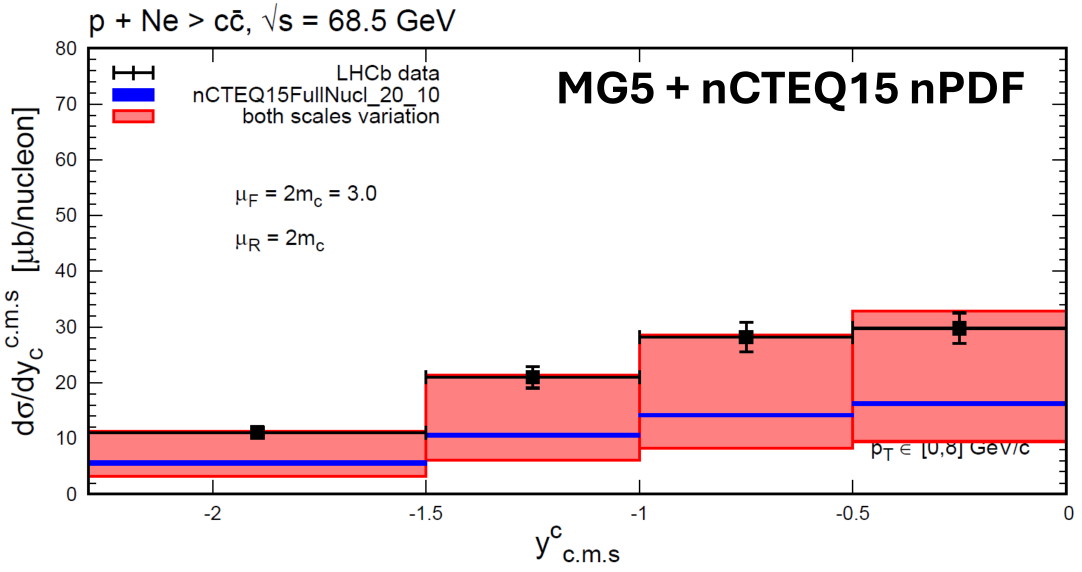
“Un”real prediction: Higgs+$b\bar{b}$ at NLO

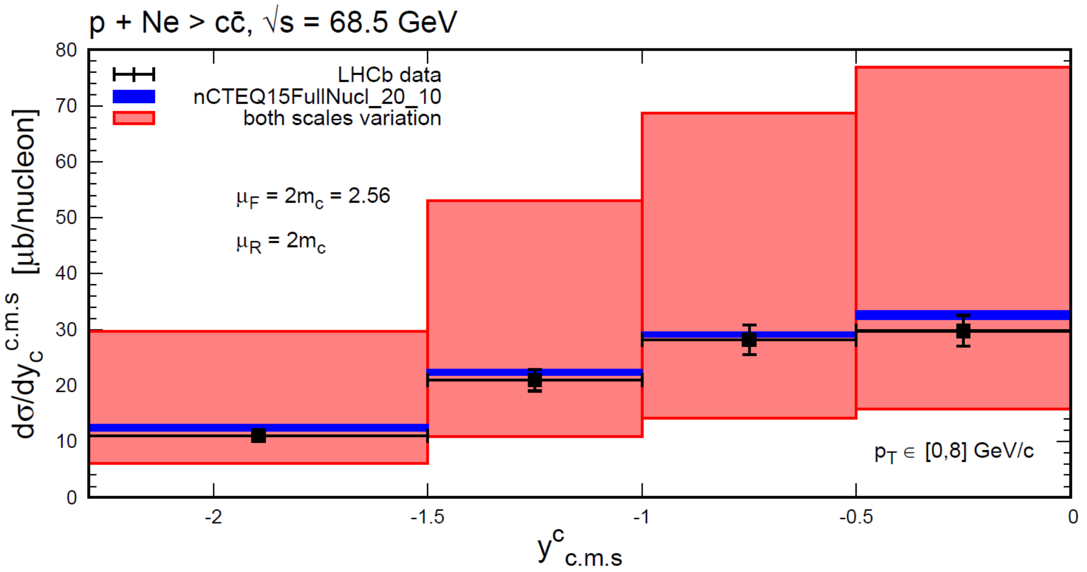


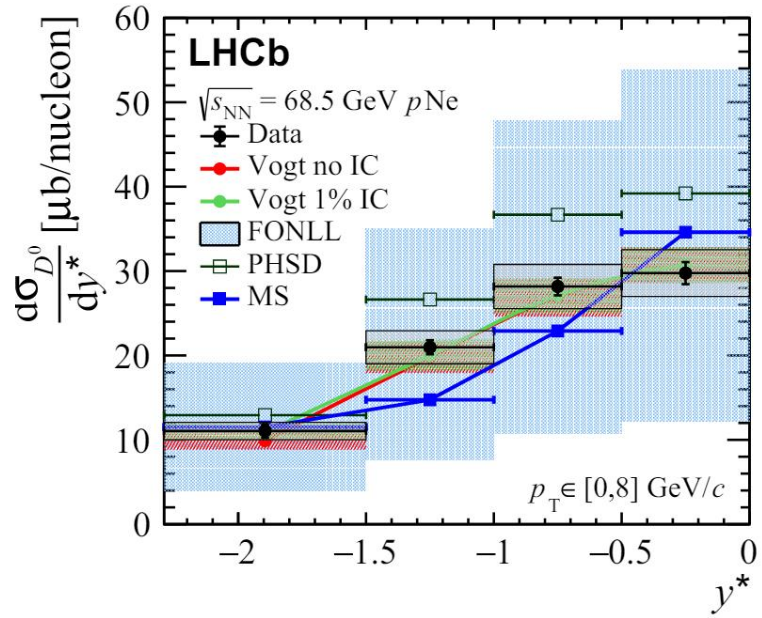
- Rapidity dependence for other particles can be obtained by changing a single line in the analysis file

D^0 production for the proton-Ne collisions, for two different masses for m_c

LHCb data: arXiv:2211.11633v3 [hep-ex] 20 Feb 2024







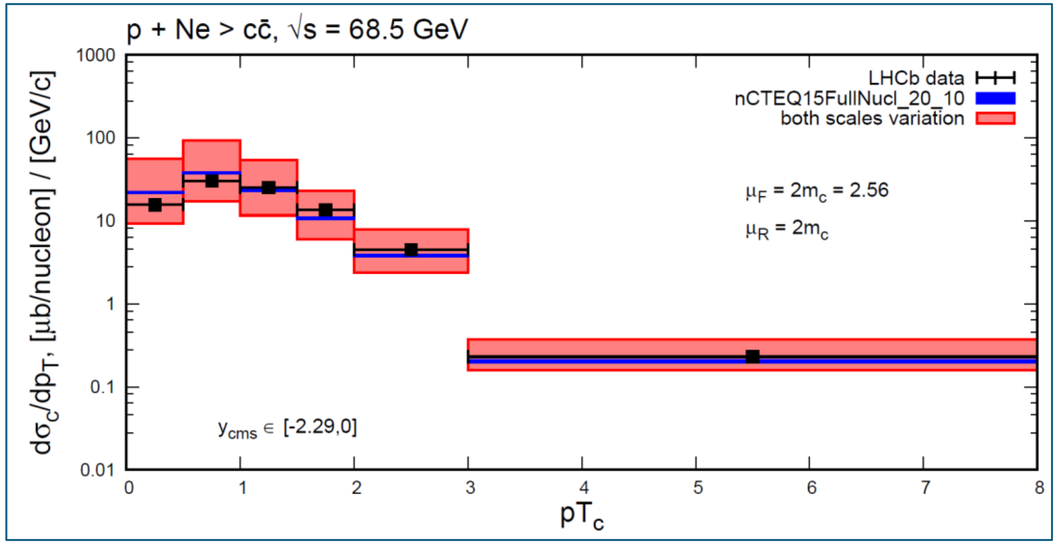
Assumption: $y_c \sim y_{D^0}$

On the plots we have a cross-section of c-quark production,
multiplied by the factor: $2 * \mathbf{f}(c \to D^0)$

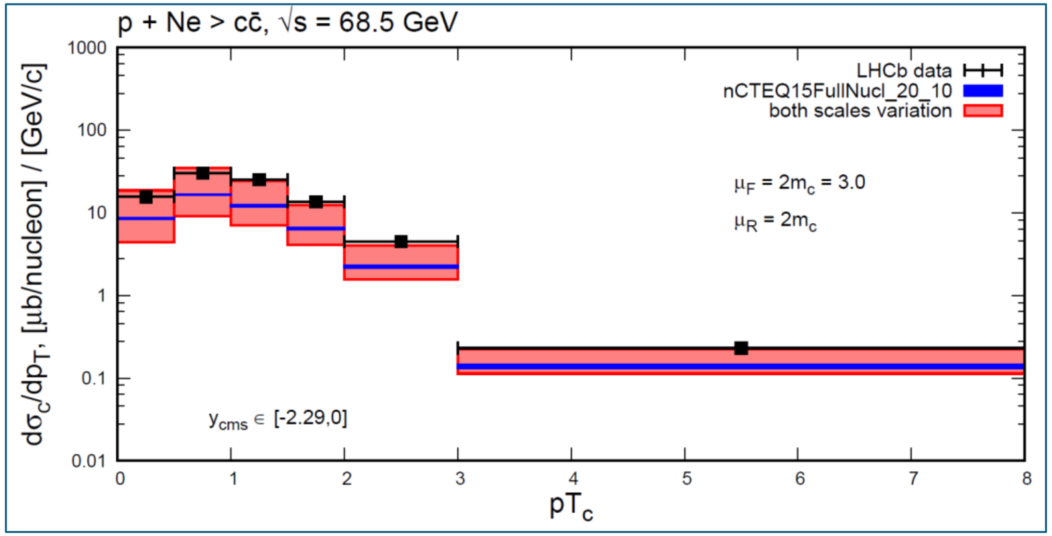
$\mathbf{f}(c \to D^0) = 0.542 \pm 0.024$

Charm mass significant for the scale variation

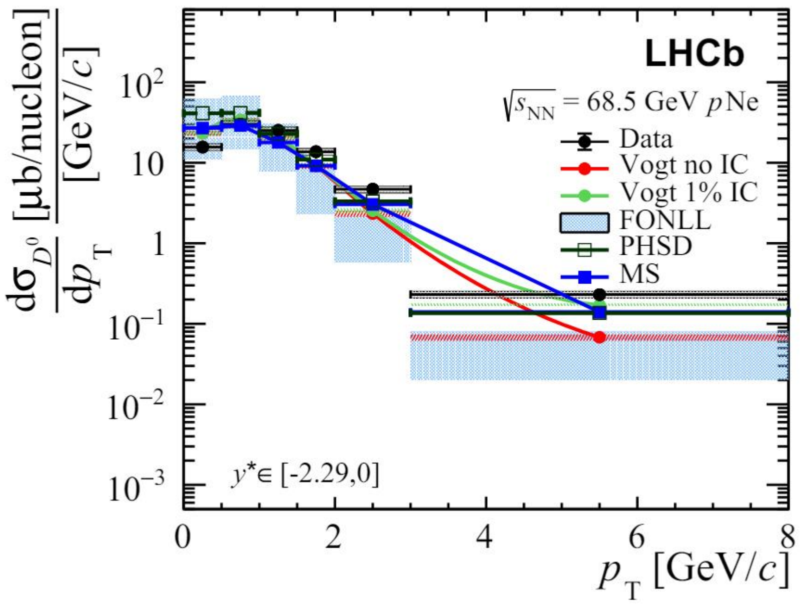
D^0 production for the proton-Ne collisions, for two different masses of m_c



MG5 + nCTEQ15 nPDF



LHCb data: arXiv:2211.11633v3 [hep-ex] 20 Feb 2024



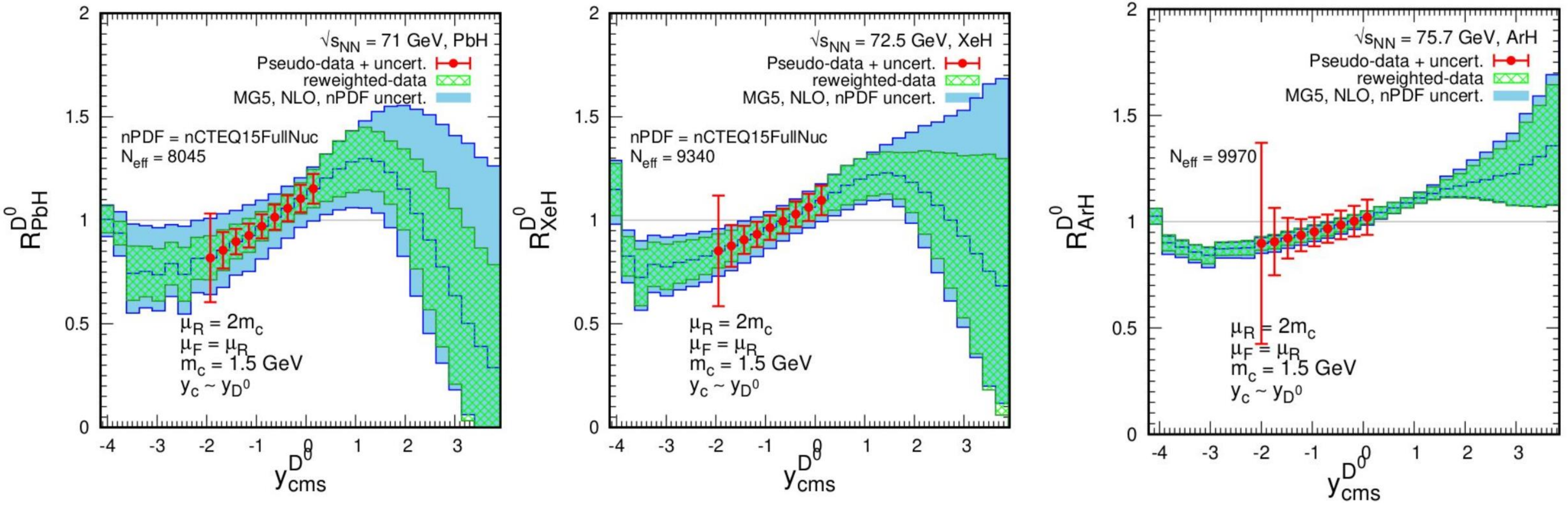
On the plots we have a cross-section of c-quark production, multiplied by the factor:

$$2*\mathbf{f}(c \rightarrow D^0)$$

$$\mathbf{f}(c \rightarrow D^0) = 0.542 \pm 0.024$$

Assumption that $pT_c \sim pT_{D^0}$ not correct for **large pT**: one can try to use **Pythia** to compute decay kinematics

Reweighing of the nPDFs: Heavy-Ion beams



Reweighting process

Def. of PDF replicas f_k:

$$f_k = f_0 + \sum_{i=1}^{N} \frac{f_i^{(+)} - f_i^{(-)}}{2} R_{ki}$$

f_0 – best fit (central) PDF

$f_i^{(+)}$, $f_i^{(-)}$ – are the plus and minus error PDFs corresponding to the eigenvector direction i

Def. of weight:

$$w_k = \frac{e^{-\frac{1}{2}\chi_k^2/T}}{\frac{1}{N_{\mathrm{rep}}}\sum_i^{N_{\mathrm{rep}}} e^{-\frac{1}{2}\chi_i^2/T}}$$

T – is the tolerance criterion used when defining Hessian error PDFs

$\chi_k^2 - \chi^2$ for a given replica k.

Def. of χ^2 :

$$\chi_k^2 = \sum_j^{N_{\mathrm{data}}} \frac{(D_j - T_j^k)^2}{\sigma_j^2}$$

j – runs over all data points in the data set(s)

N_{data} – total number of data points,

D_j – the experimental measurement at point j

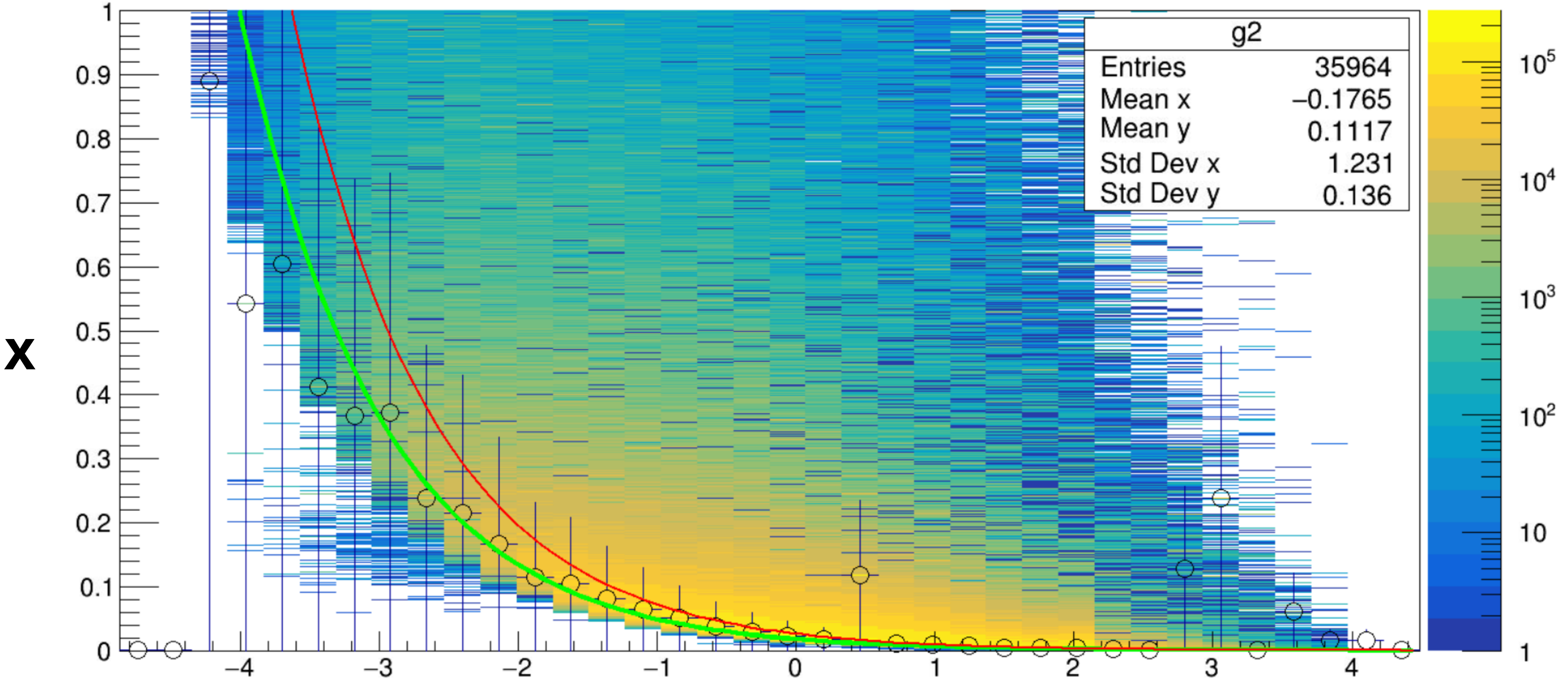
σ_j – experimental uncertainty

T_k^j – theoretical prediction calculated with PDFs given by replica k.

$$\langle \mathcal{O} \rangle_{\mathrm{new}} = \frac{1}{N_{\mathrm{rep}}} \sum_{k=1}^{N_{\mathrm{rep}}} w_k \mathcal{O}(f_k),$$

$$\delta \langle \mathcal{O} \rangle_{\mathrm{new}} = \sqrt{\frac{1}{N_{\mathrm{rep}}} \sum_{k=1}^{N_{\mathrm{rep}}} w_k \left(\mathcal{O}(f_k) - \langle \mathcal{O} \rangle_{\mathrm{new}}\right)^2}$$

$x2\ vs\ \ y$
$for\ \ pXe$



Red: $m_c = 1.5\ GeV$

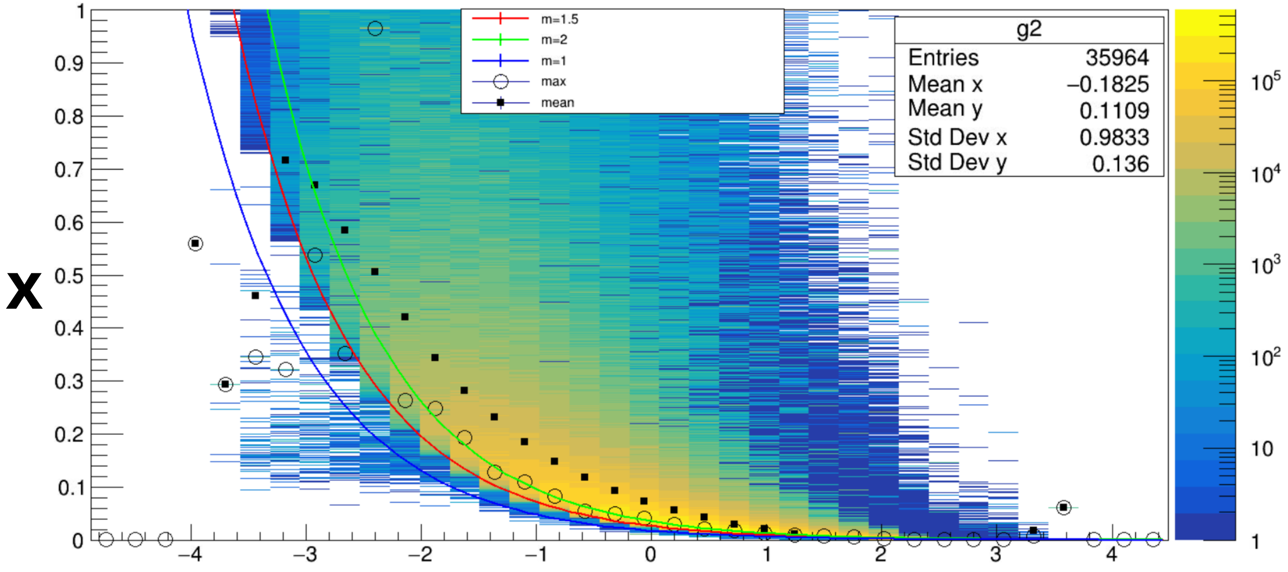
Green: $m_c = 1$ GeV (fit)

Open-points: **maximum** of the **distribution** per bin of **y**

$$x2 = \frac{2m_c}{113}e^{-y}$$

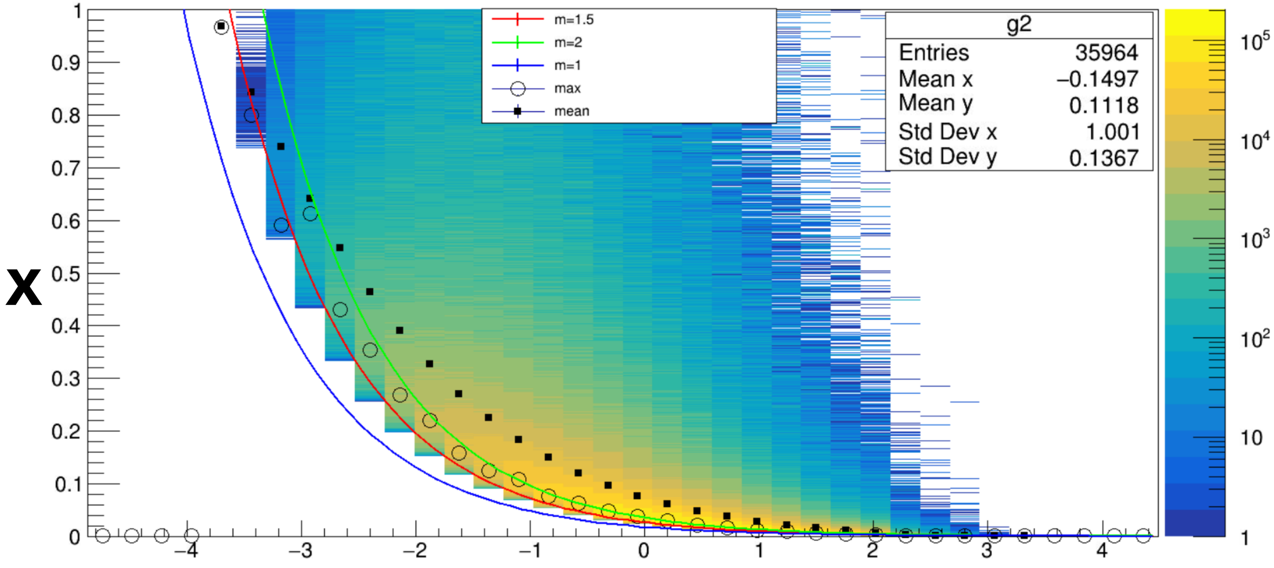
$x2\ vs\ \ y$
$for\ \ pXe$

NLO



y^{cc}_{cms}

LO



y^{cc}_{cms}

Red: $m_c = 1.5\ GeV$

Green: $m_c = 1\ \mathrm{GeV}$ (fit)

Open-points: **maximum** of the **distribution** per bin of **y**

$$x2 = \frac{2m_c}{113} e^{-y}$$