Quarkonium-nuclear-modification-factor computations for LHC and EIC

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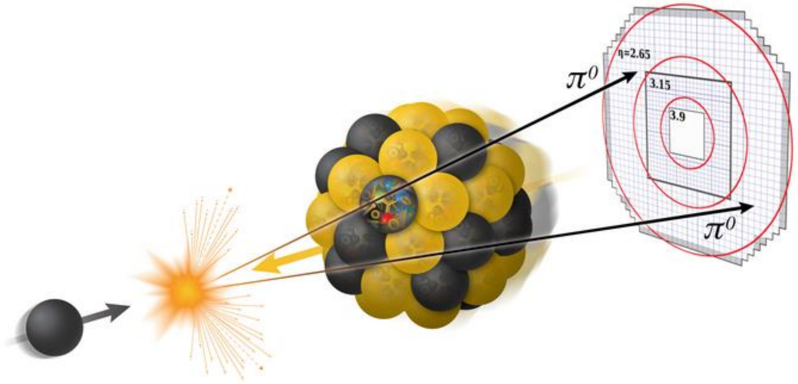
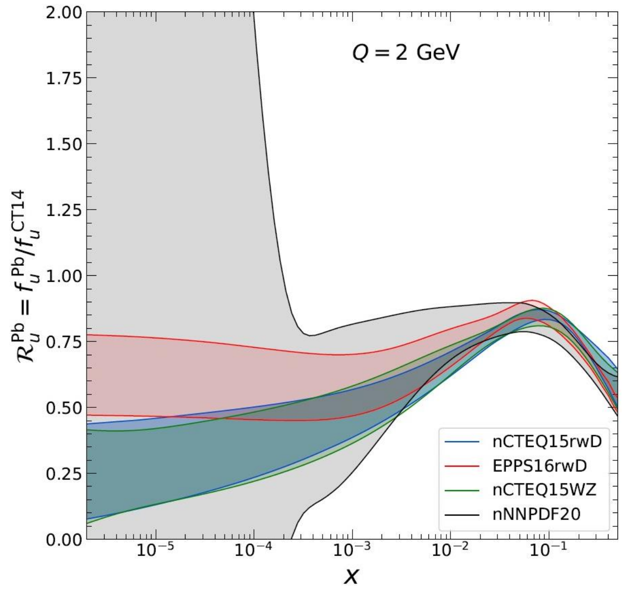
Centre Paul Langevin
Quarkonia as Tools 2024

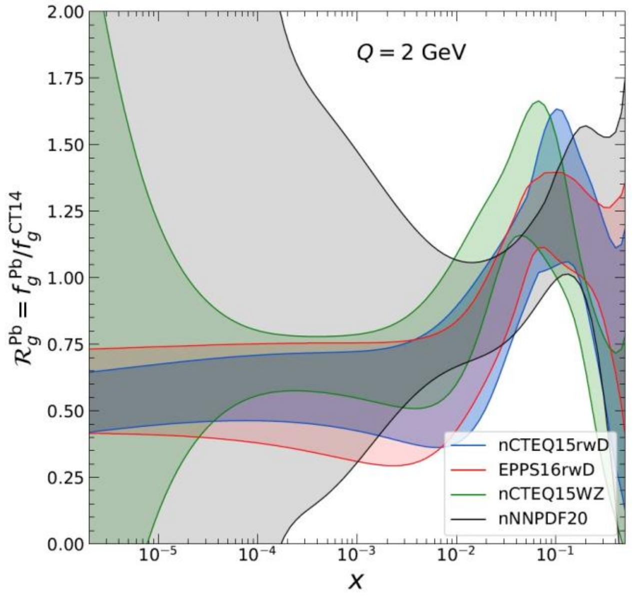
Motivation

- 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,RHIC, EIC data.

Framework – Collinear factorization

Cross sections in collinear factorization and perturbative QCD

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

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**

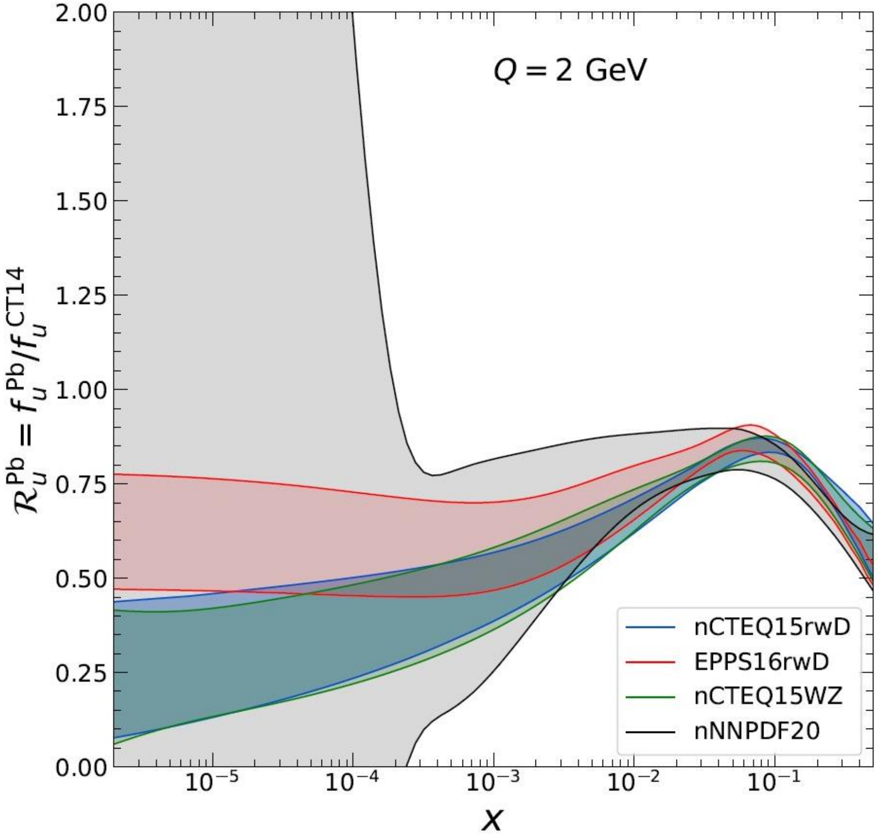
Quark nPDFs

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 ~ 1: absence of nuclear effects

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]

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

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

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

These factors are defined such that:

$R_{pA} \sim 1$: absence of nuclear effects

nPDFs and event generators

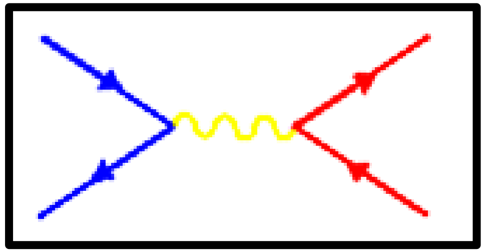
Any **PDFs** can be used in **up to NLO** like *proton* **PDFs** with **LHAPDF** library

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 event generators.**

MG5_aMC@NLO



- **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

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*                     W E L C O M E  to                    *
*              M A D G R A P H 5 _ a M C @ N L O           *
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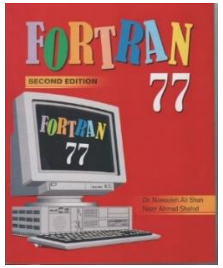
*         VERSION 2.7.2                 2020-03-17         *
*                                                          *
*    The MadGraph5_aMC@NLO Development Team - Find us at   *
*    https://server06.fynu.ucl.ac.be/projects/madgraph     *
*                            and                           *
*            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>
```



Framework – Collinear factorization

Cross sections in collinear factorization and perturbative QCD

$$d\sigma = \sum_{a,b} \int dx_a dx_b f_a(x_a, \mu_F; LHAID) f_b(x_b, \mu_F; LHAID)\, d\hat{\sigma}_{ab\to X}(\hat{s}, \mu_F, \mu_R)$$

↓

- Asymmetric collisions for hadron-hadron — done by Anton Safronov

$$d\sigma_{AB\to X} = \sum_{a,b} \int dx_a dx_b \; f_a^A(x_a, \mu_F; LHAID1) f_a^B(x_b, \mu_F; LHAID2)\; d\hat{\sigma}_{ab\to X}(\hat{s}, \mu_F, \mu_R)$$

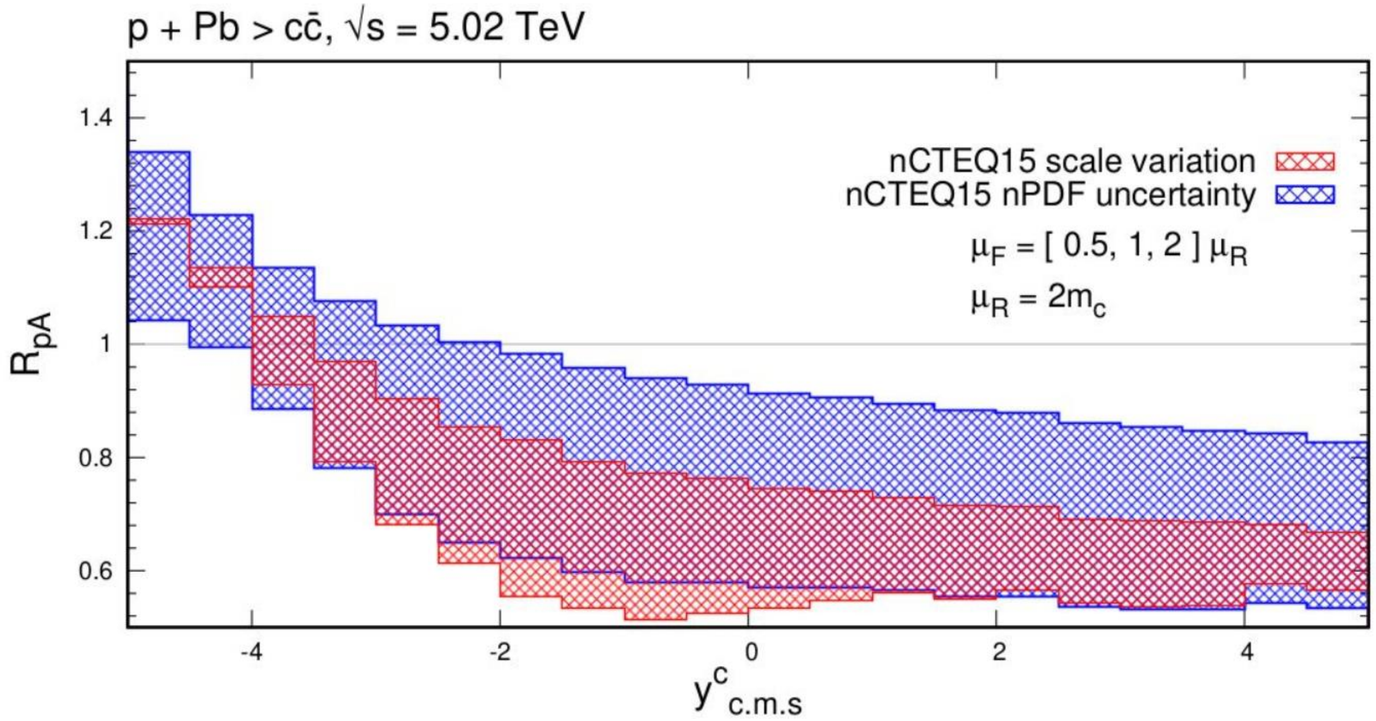
- Photoproduction — done by Laboni Manna

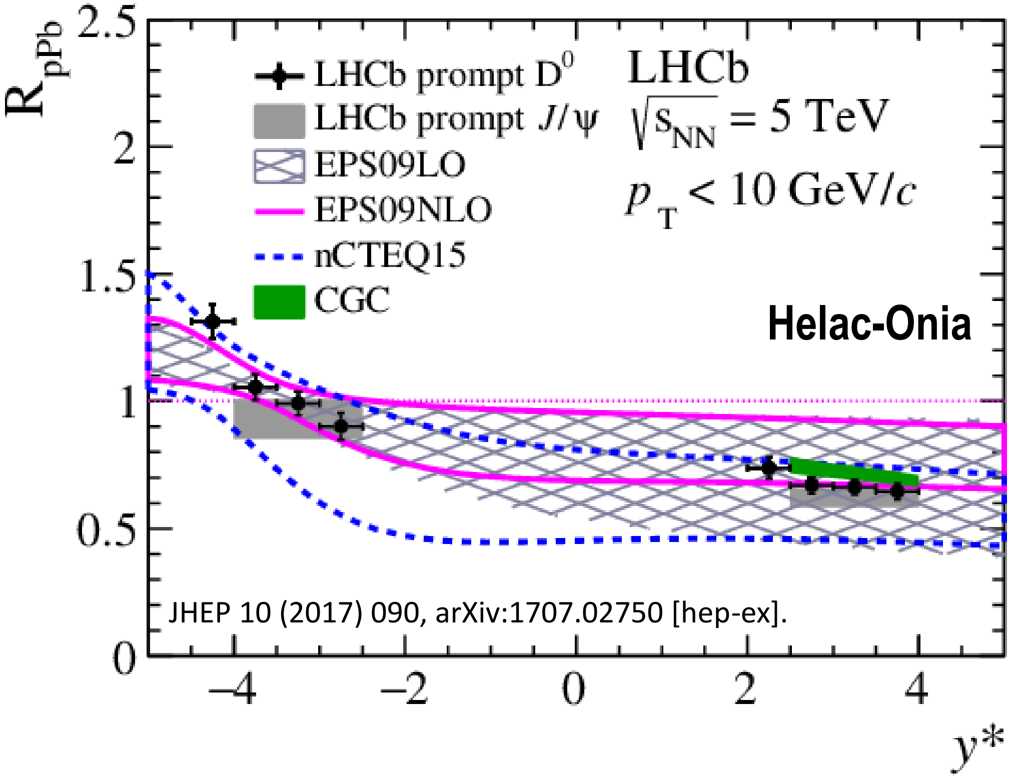
$$d\sigma_{\gamma H\to X} = \sum_{e,h} \int dx_\gamma dx_h f_\gamma^e\,(x_\gamma; Q^2_{max}) f_h^H(x_b, \mu_F; LHAID) d\hat{\sigma}_{\gamma h\to X}(x_\gamma, x_h, \mu_F, \mu_R)$$

PoS(EPS-HEP2023)274

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

Charm quark production



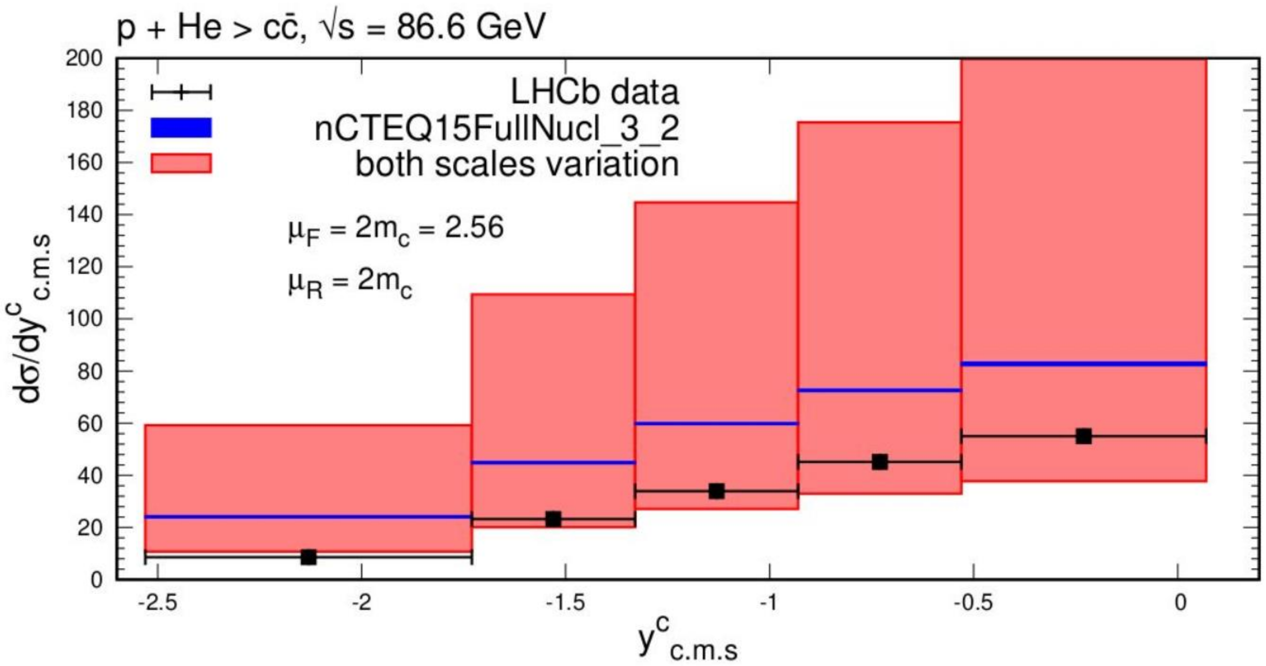


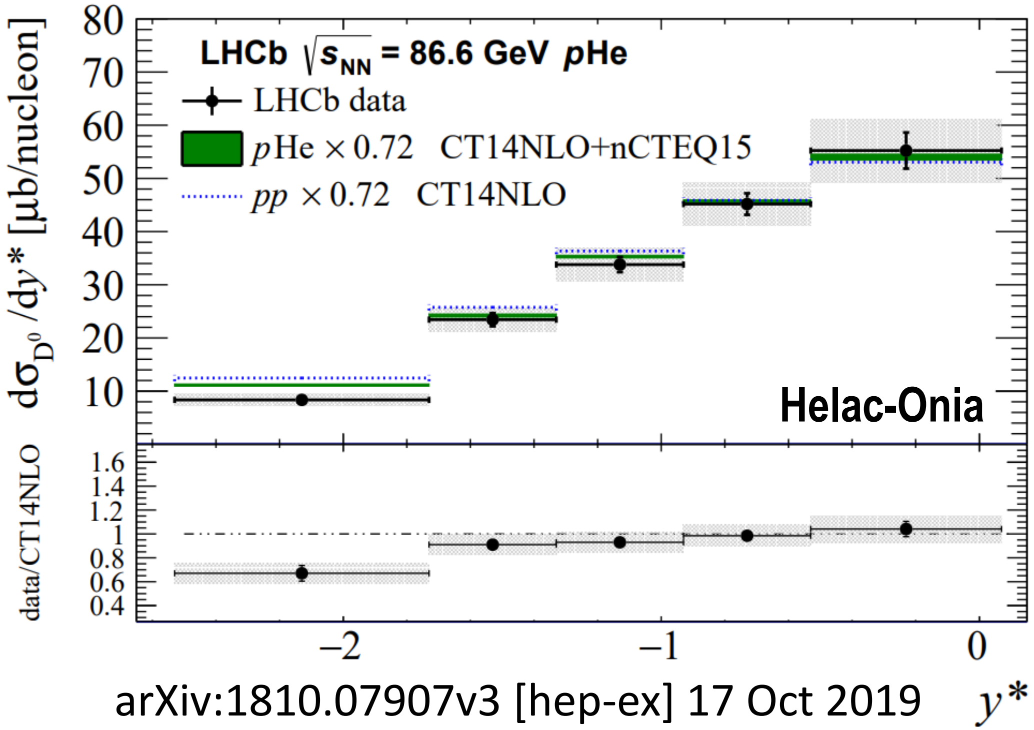
For charm production, μ_F uncertainty nearly as **large** as the **nPDF uncertainty**

Scale and PDF uncertainties are automatically computed

Example: *c* production at *fixed-target* collisions at LHC

Charm quark production



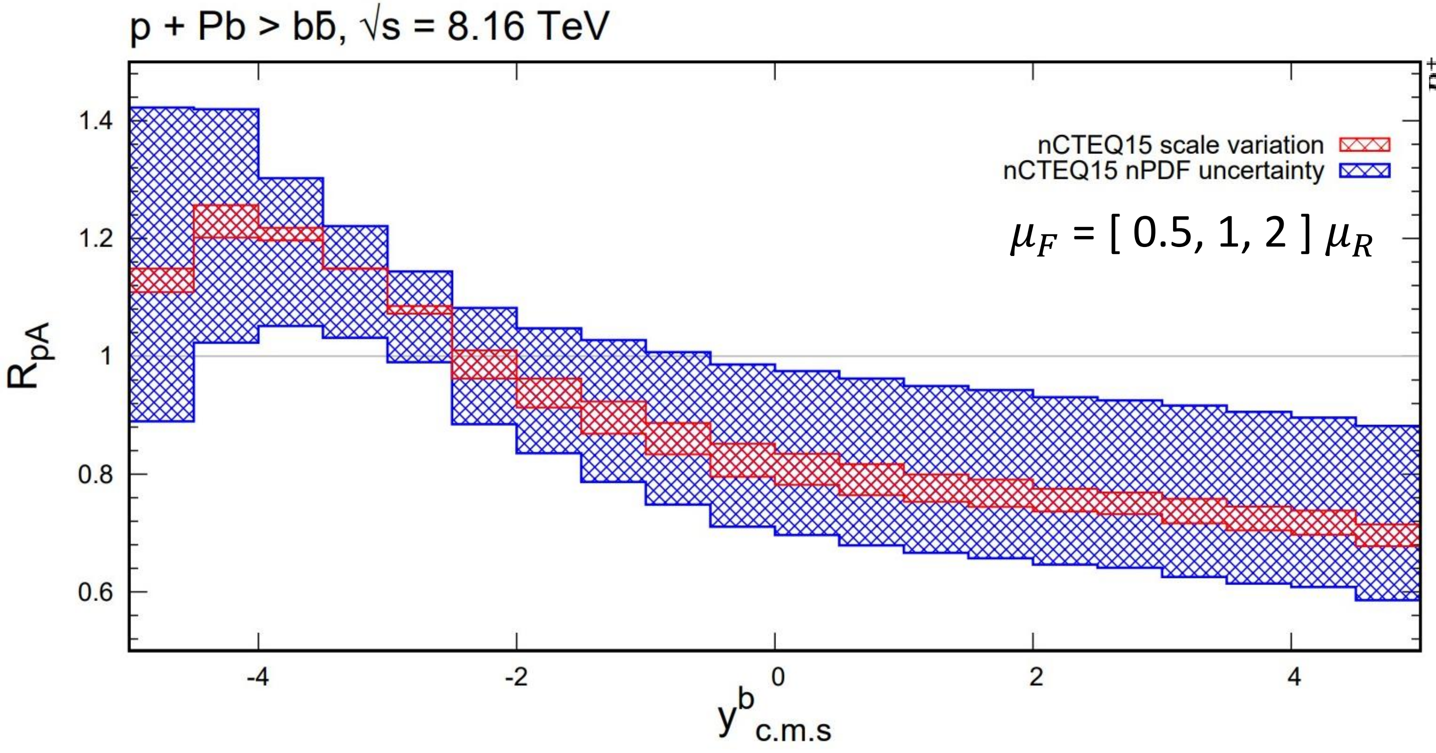


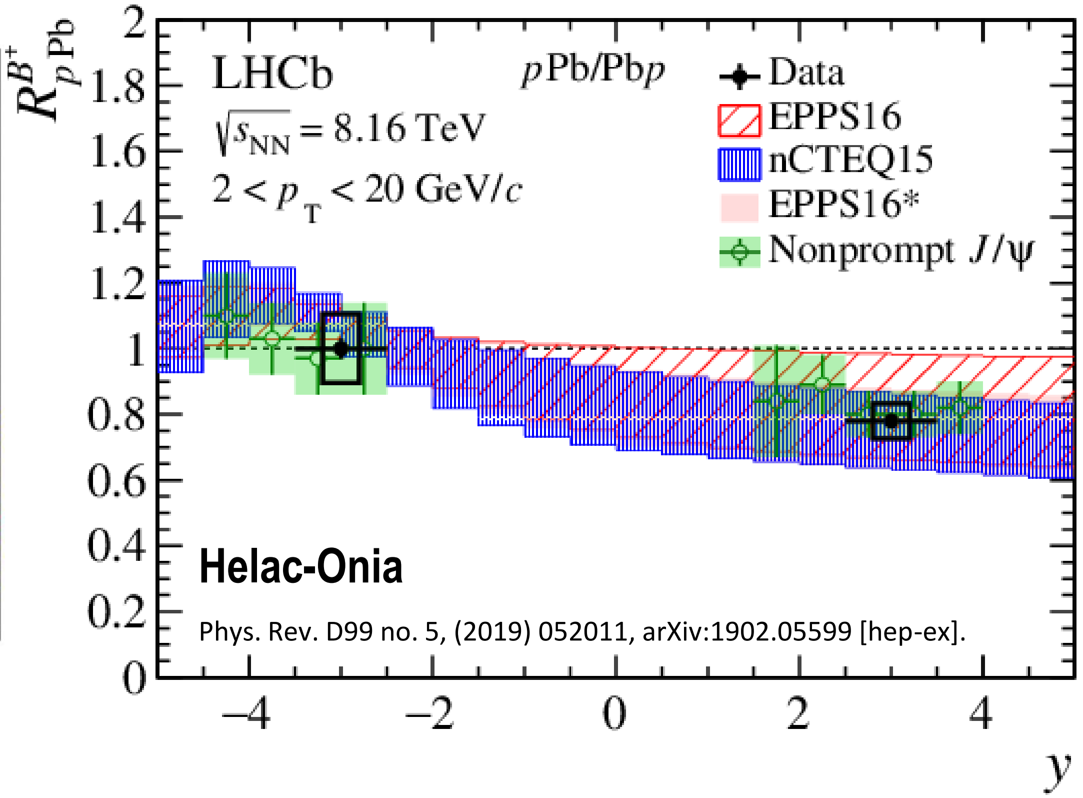
arXiv:1810.07907v3 [hep-ex] 17 Oct 2019

In this case,
Both **scale variation (μ_F, μ_R)** is much **larger** then **nPDF uncertainty**

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

Bottom quark production

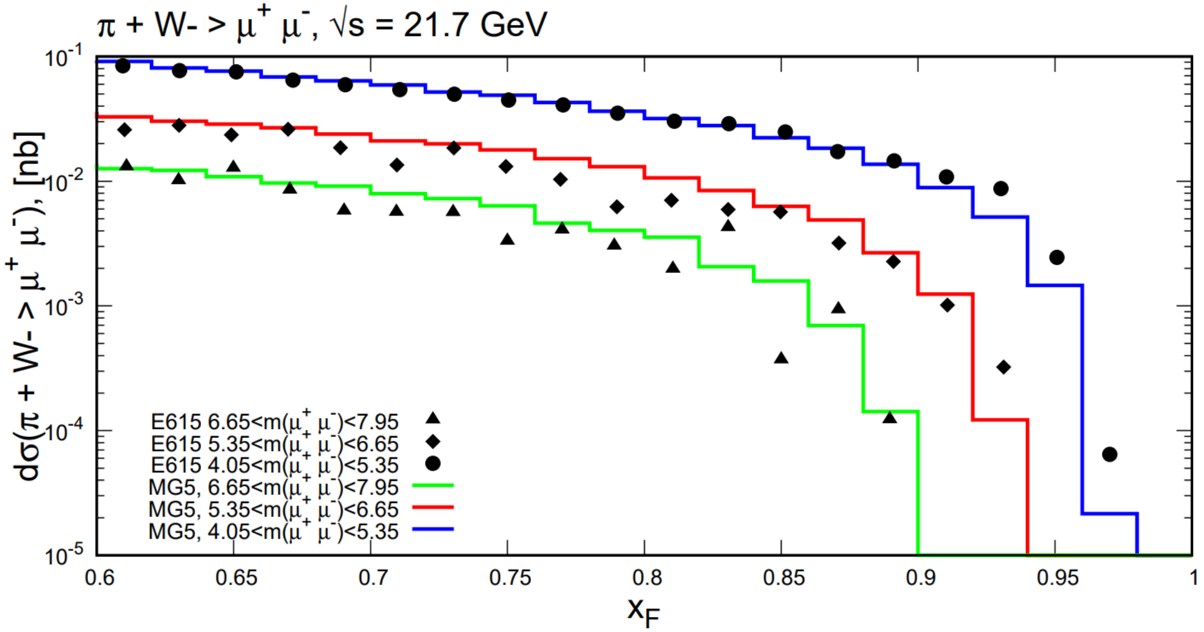


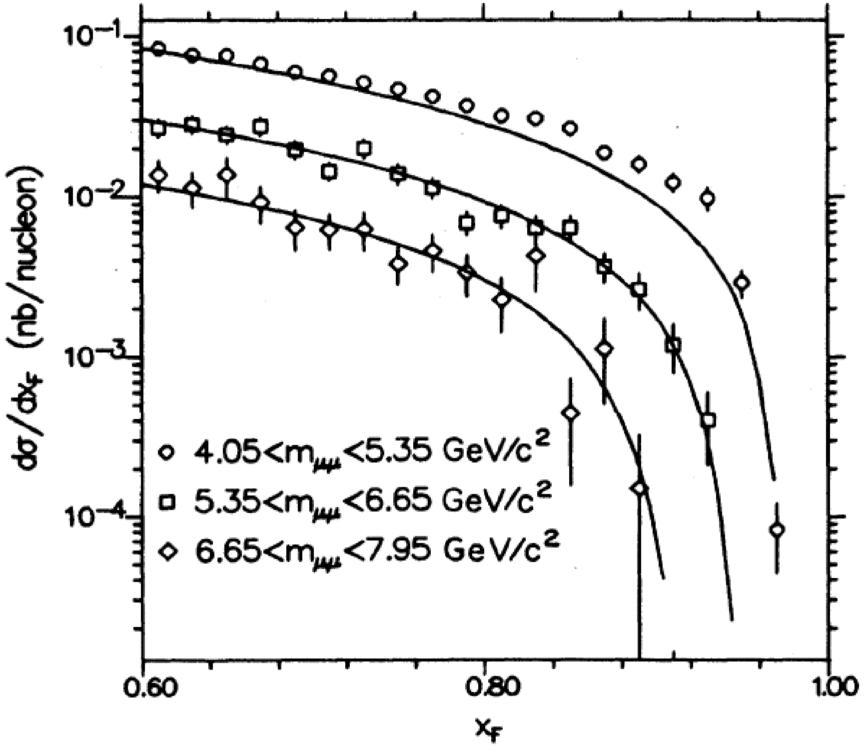


Phys. Rev. D99 no. 5, (2019) 052011, arXiv:1902.05599 [hep-ex].

Example: *Drell-Yan* production in πW collision

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





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

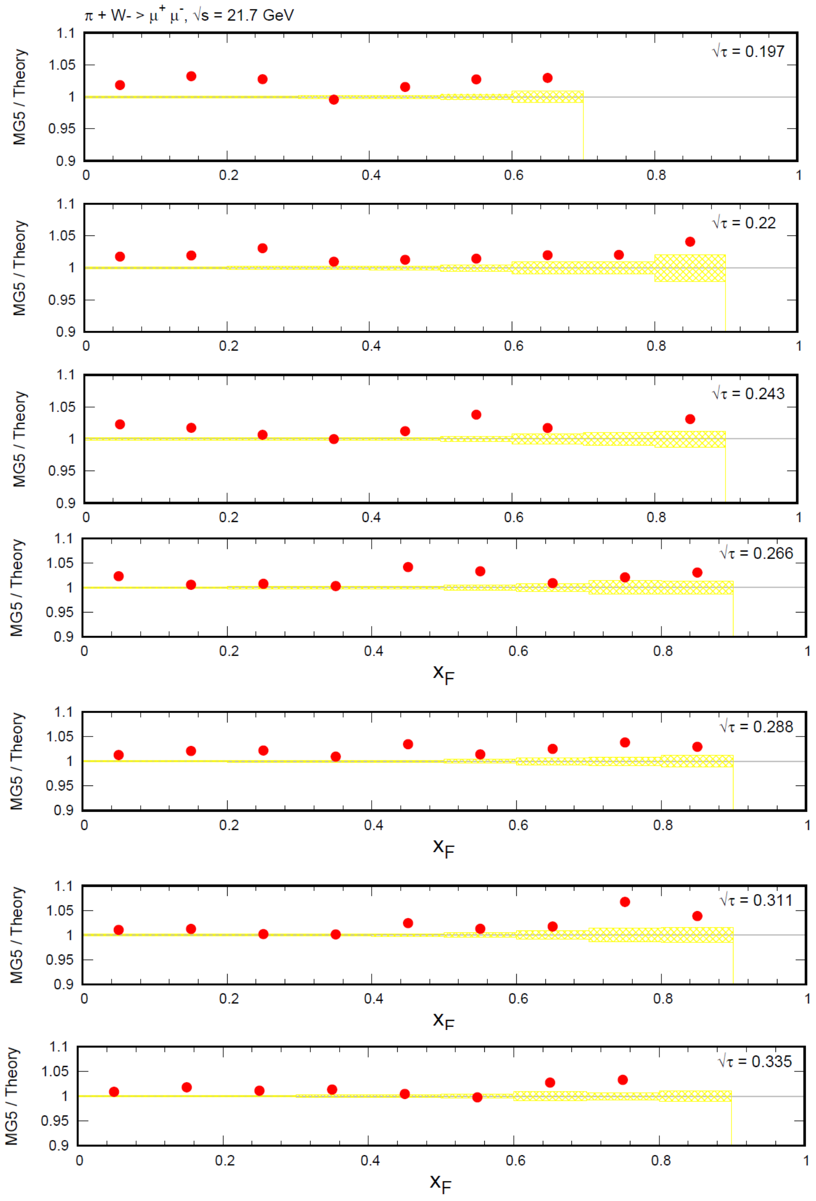
$$\tau = \frac{{m_{ll}}^2}{s}$$

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

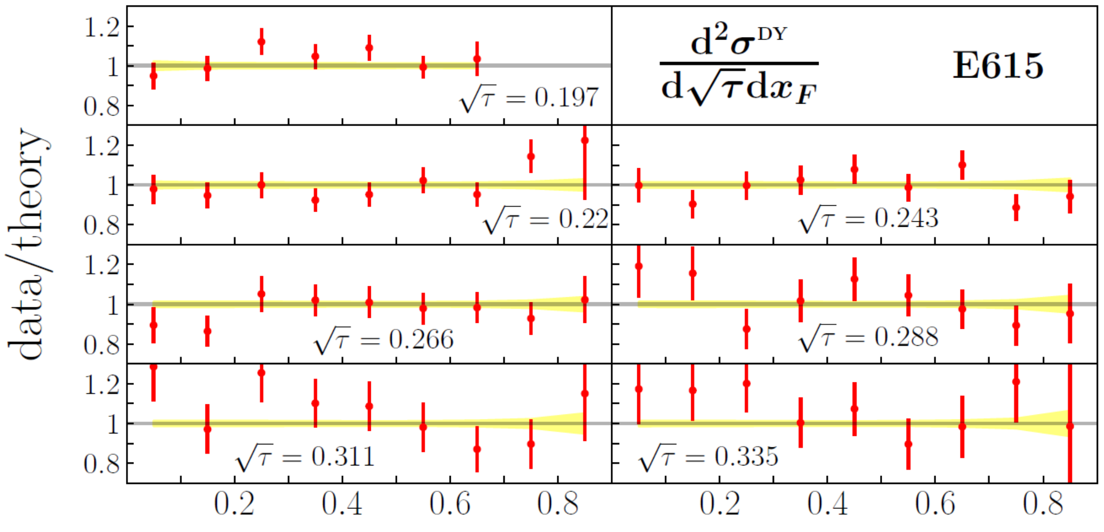
$$x_{pion} = \sqrt{\tau}e^{Y}$$

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

Example: *Drell-Yan* production in πW collision



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

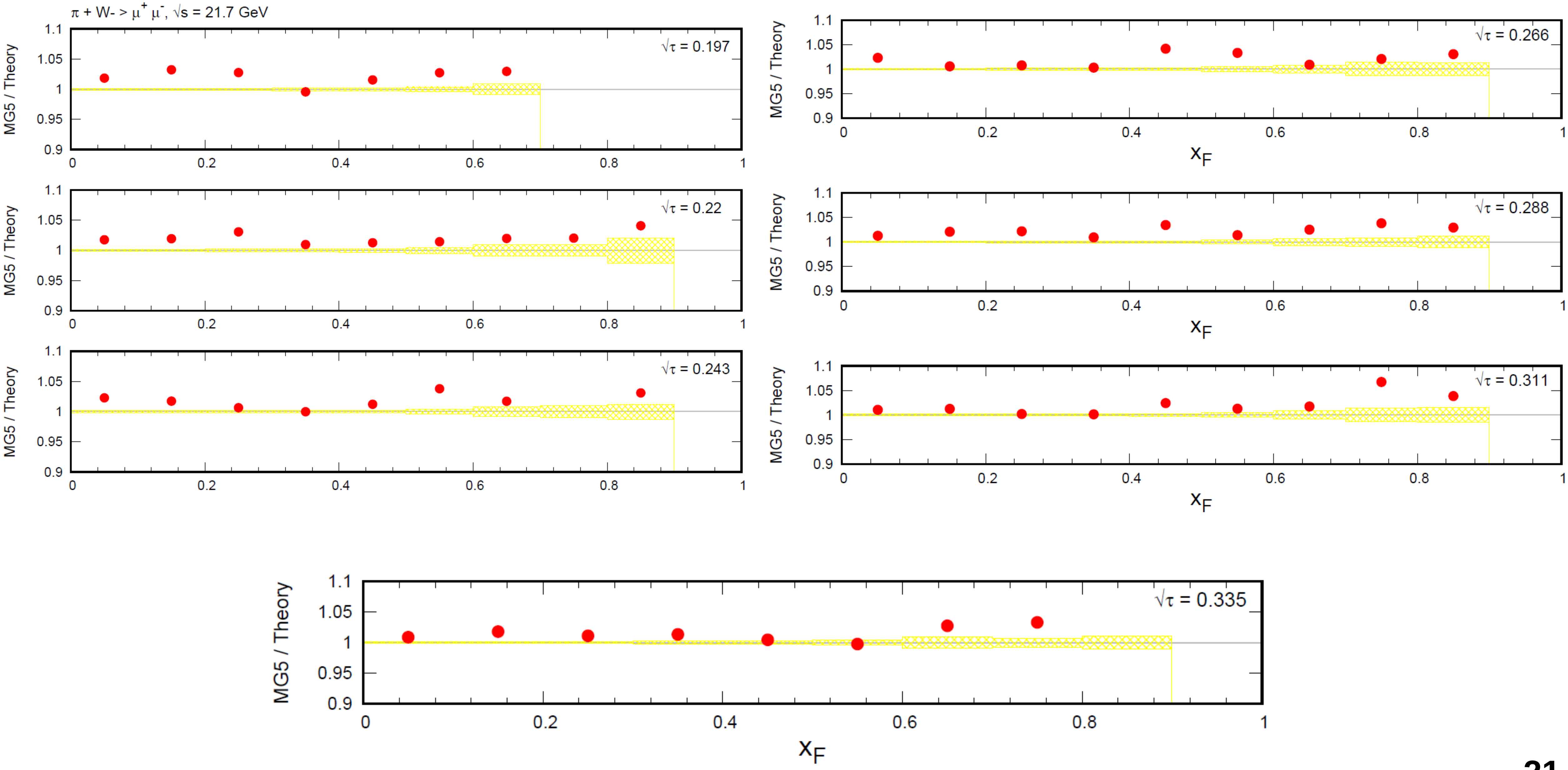


arXiv:2103.02159v2 [hep-ph] 30 Nov 2021

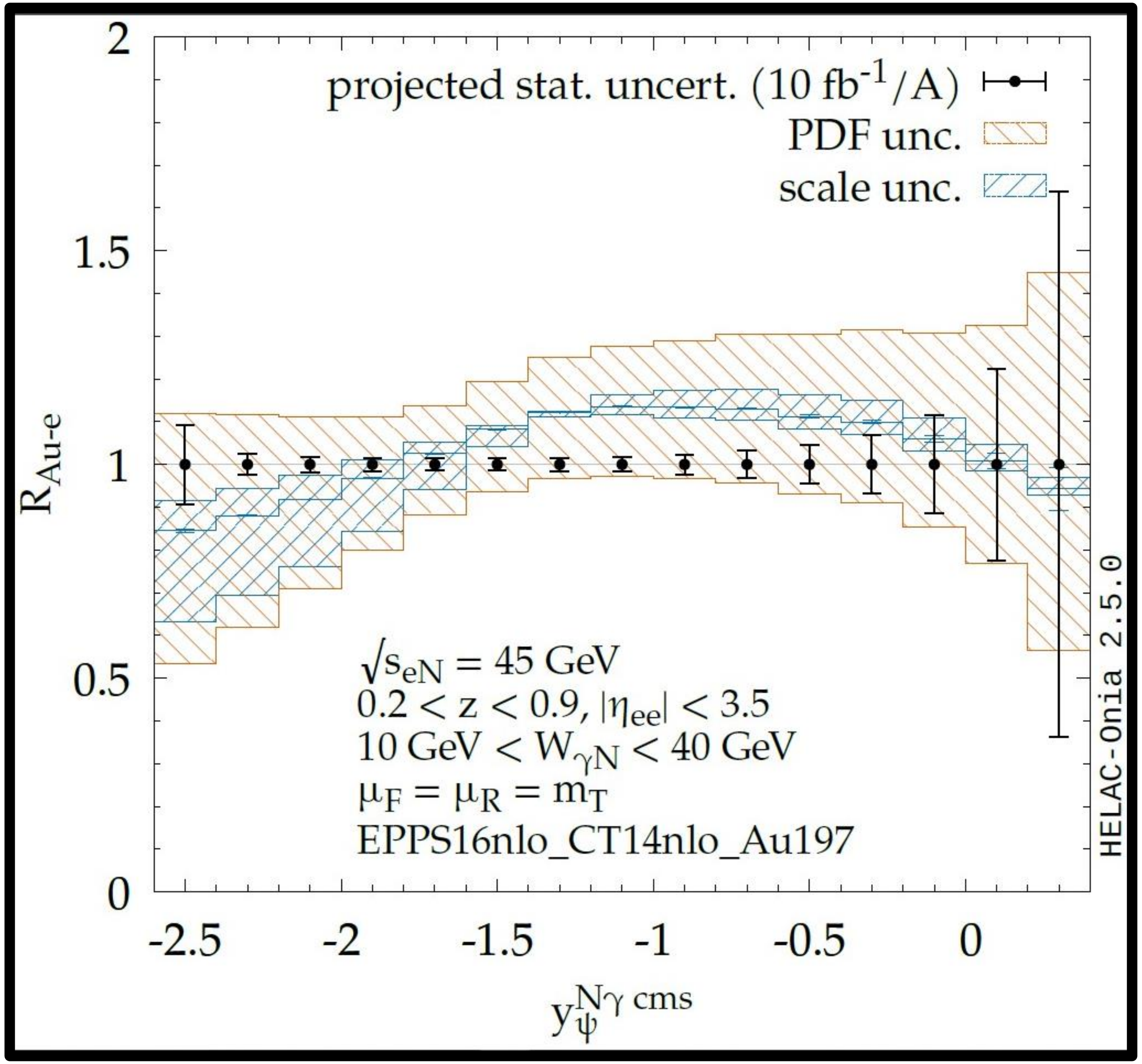
***Phys.Rev.D* 39 (1989) 92-122**

- **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

Example: *Drell-Yan* production in πW collision



Photoproduction at EIC



$$R_{eA} = \frac{\sigma_{eA}}{A\,\sigma_{ep}} \equiv R_g \text{ (at LO)}$$

$$z = \frac{P_Q \cdot P_p}{P_\gamma \cdot P_p}$$

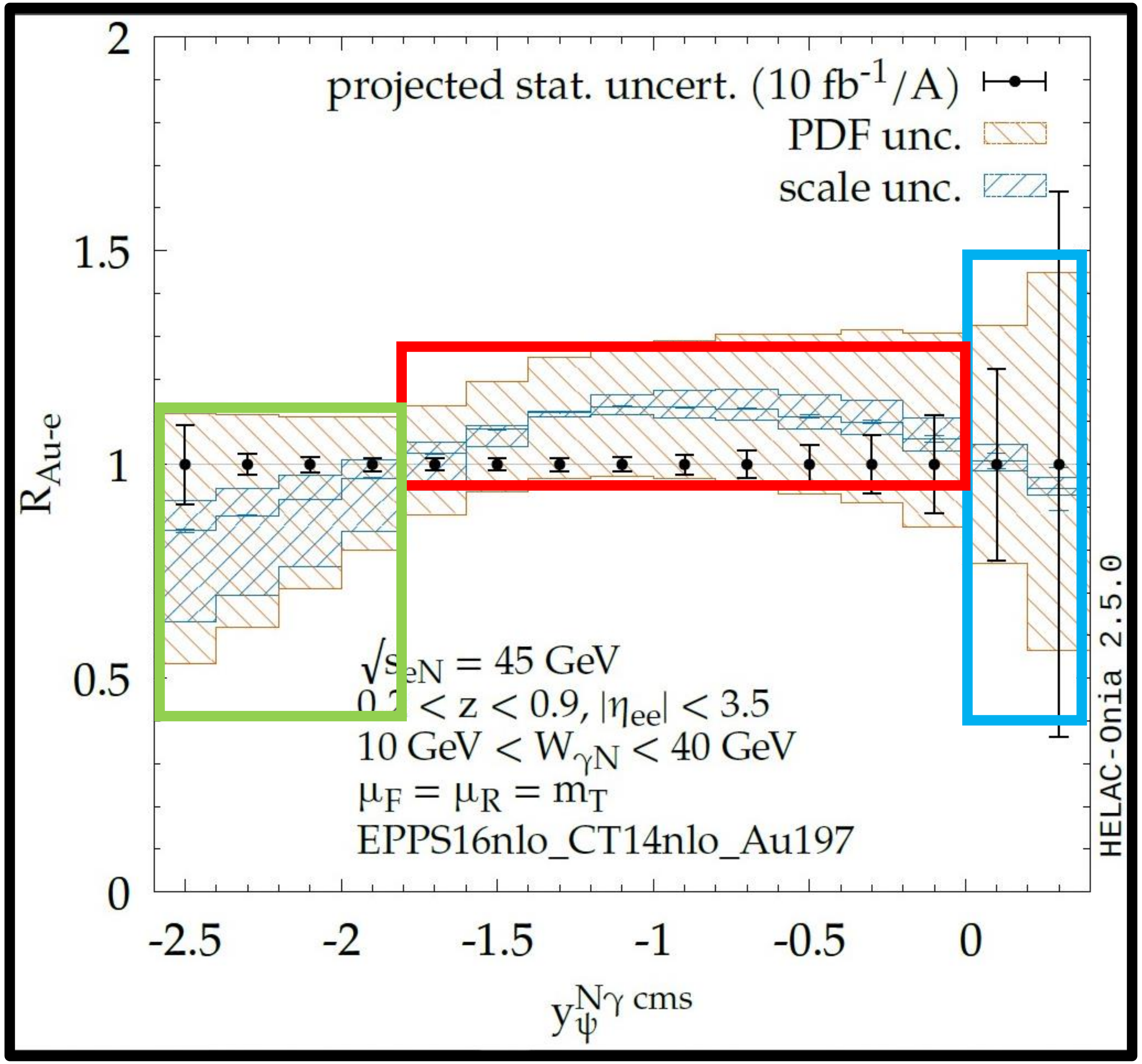
$$W_{\gamma N} = (P_\gamma + P_N)$$

EMC

Anti-shadowing

Shadowing

Photoproduction at EIC



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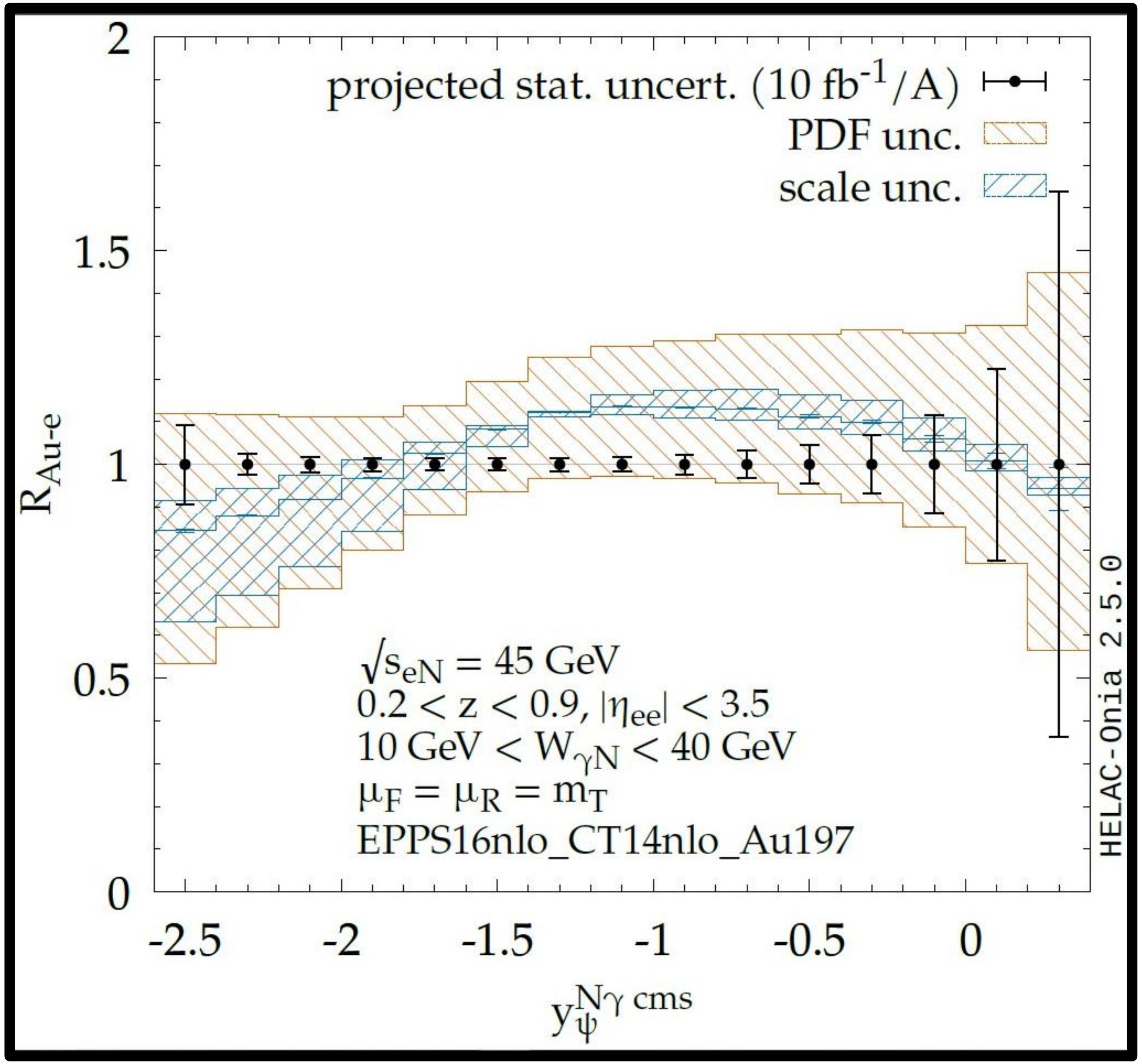
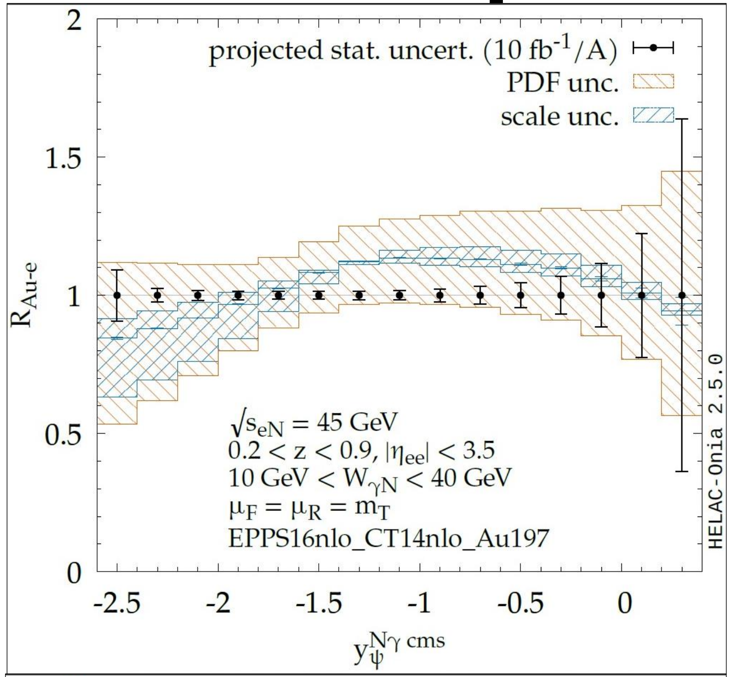


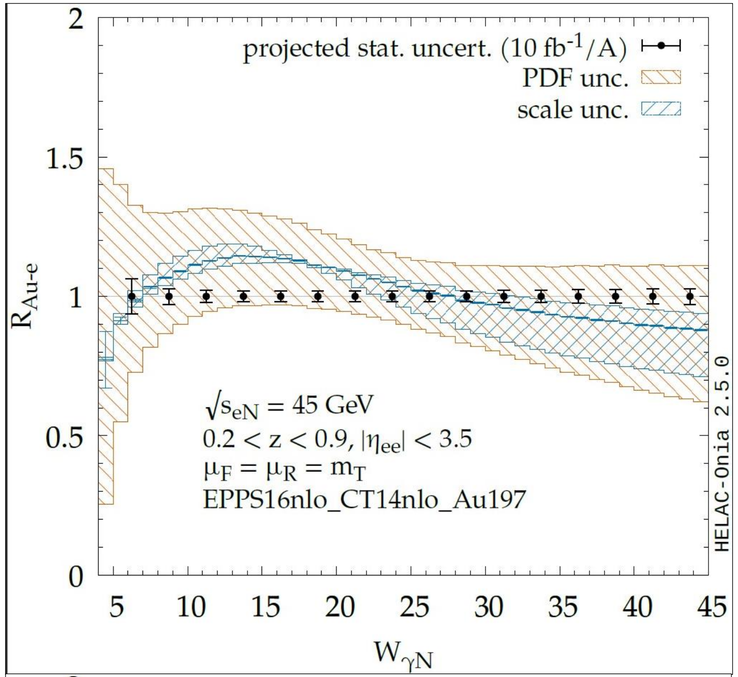
$$R_{eA} = \frac{\sigma_{eA}}{A\,\sigma_{ep}} \equiv R_g \text{ (at LO)}$$

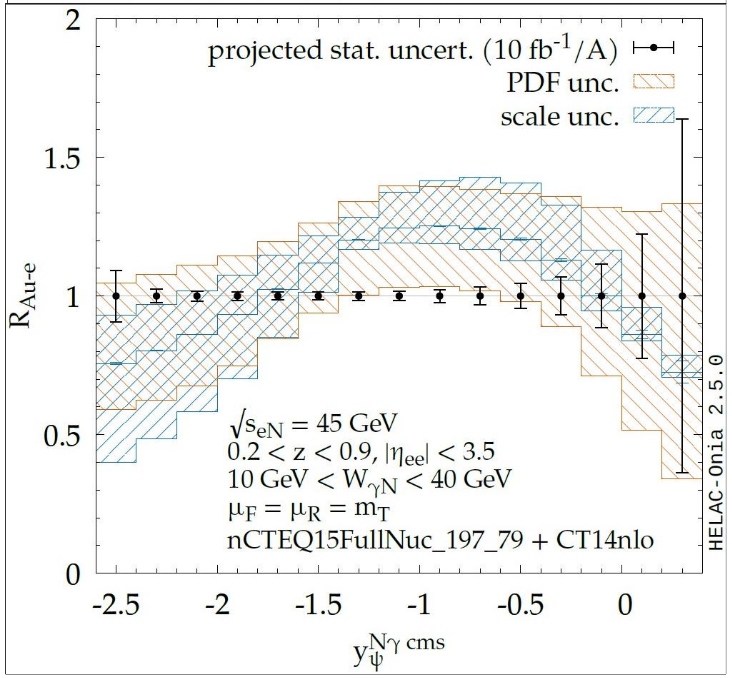
Measurement of the J/Psi production leads to accuracy improvements of the PDFs (reweighting)

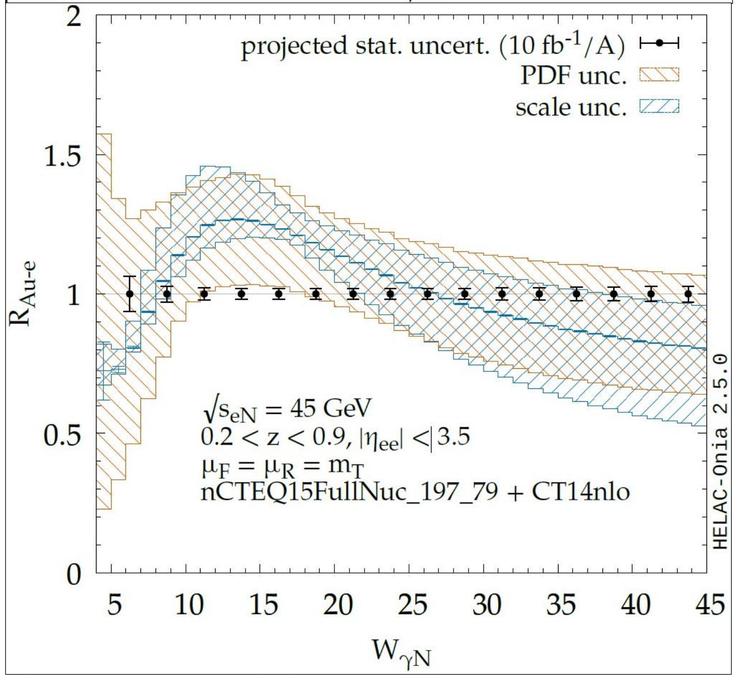
arXiv:2012.11462v2 [hep-ph] 8 Jan 2021

Photoproduction at EIC

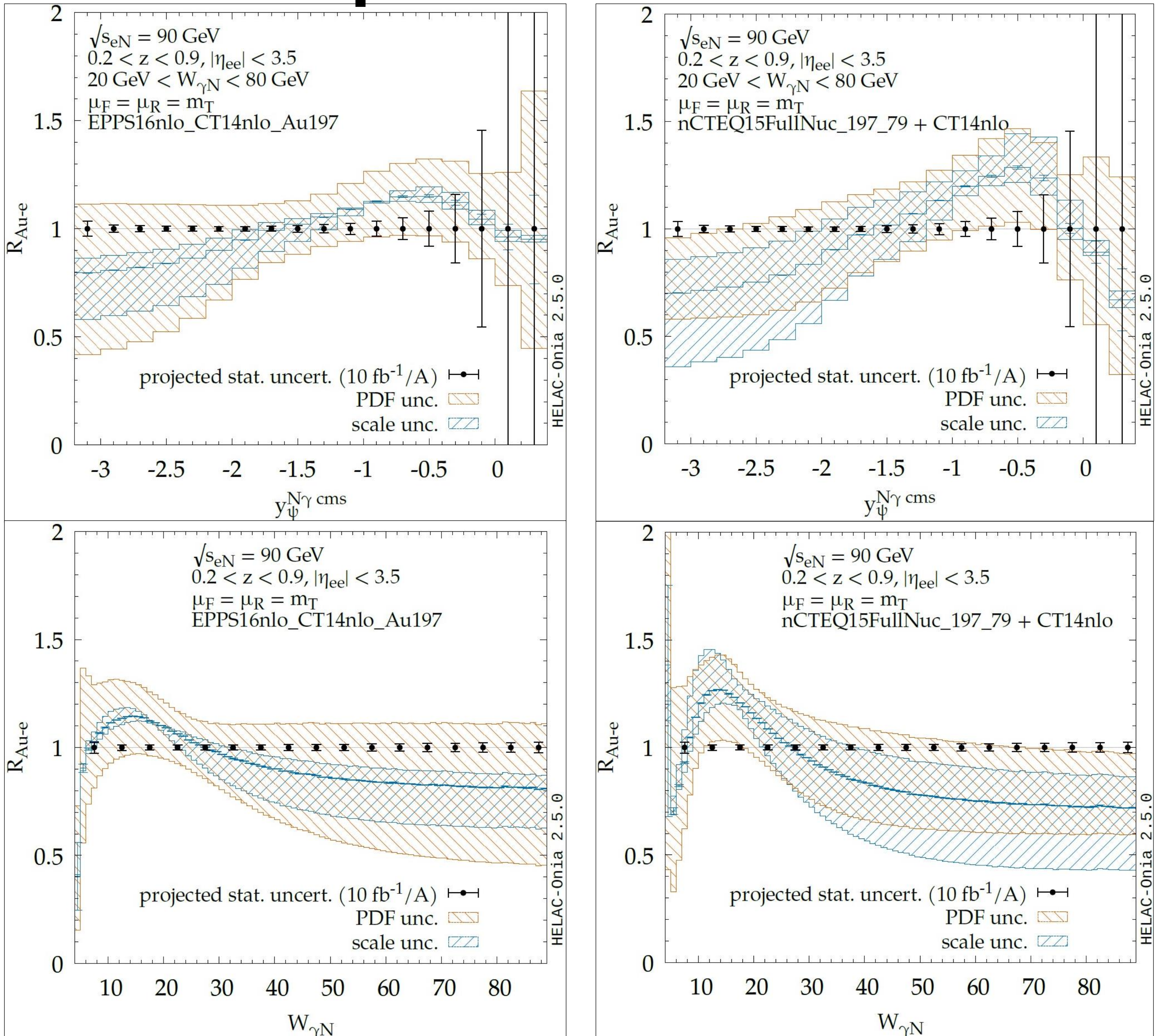








Photoproduction at EIC



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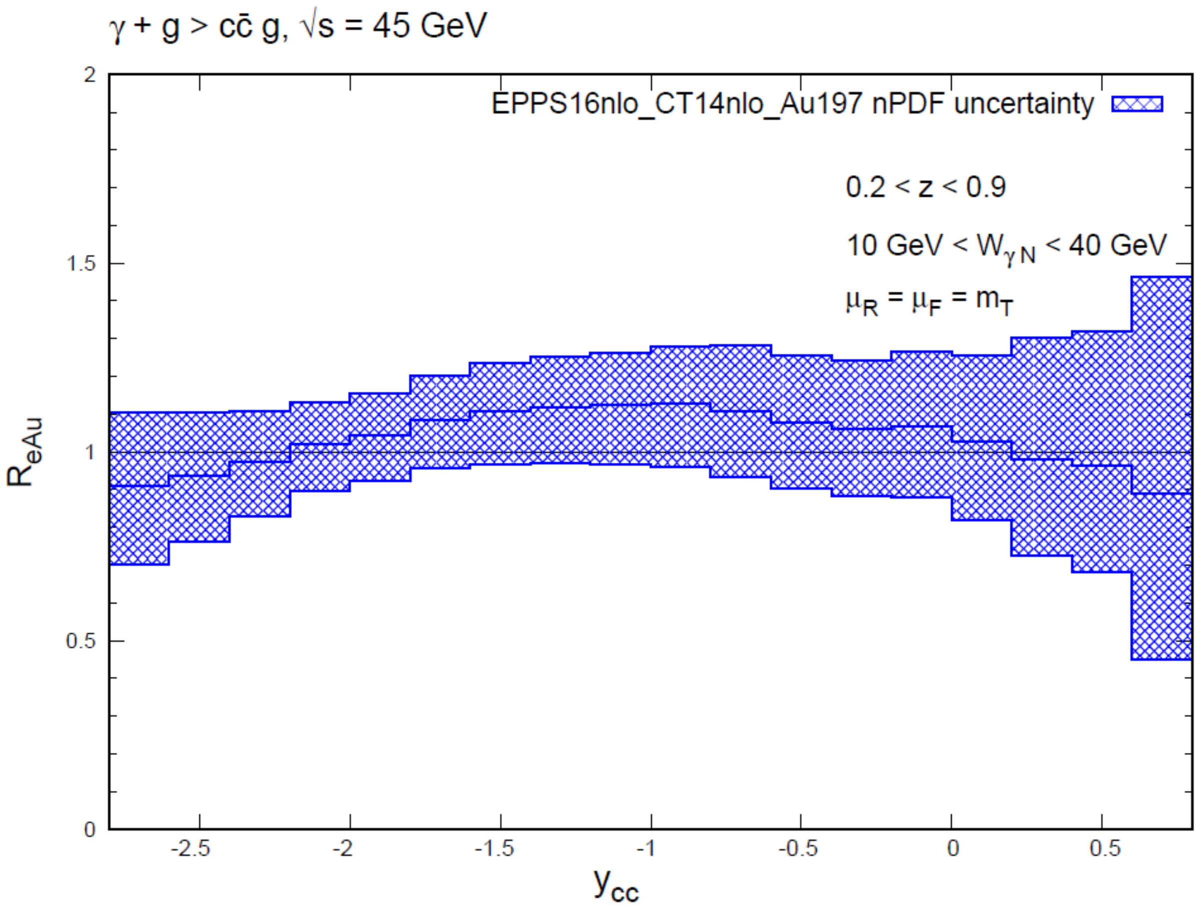

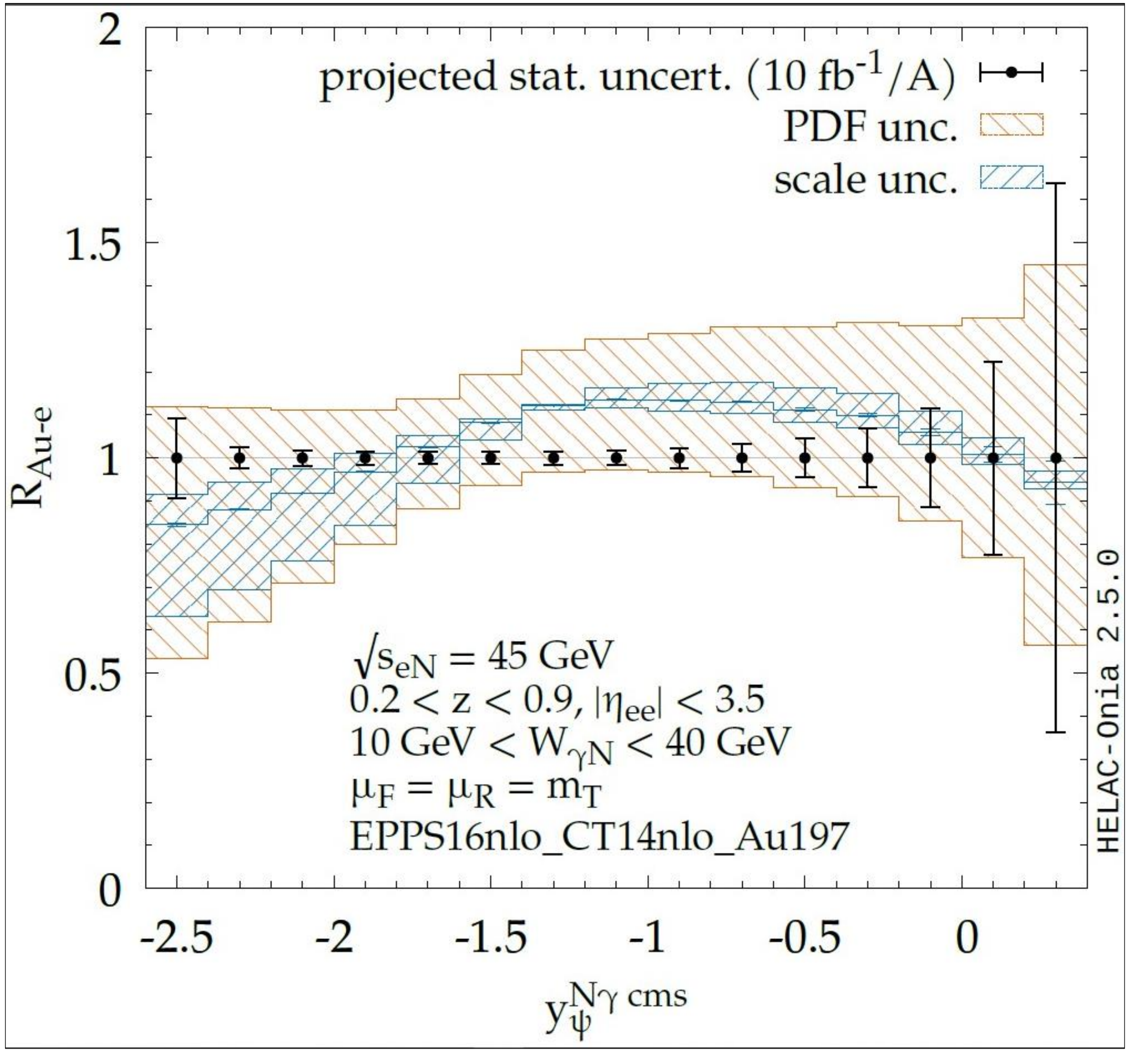

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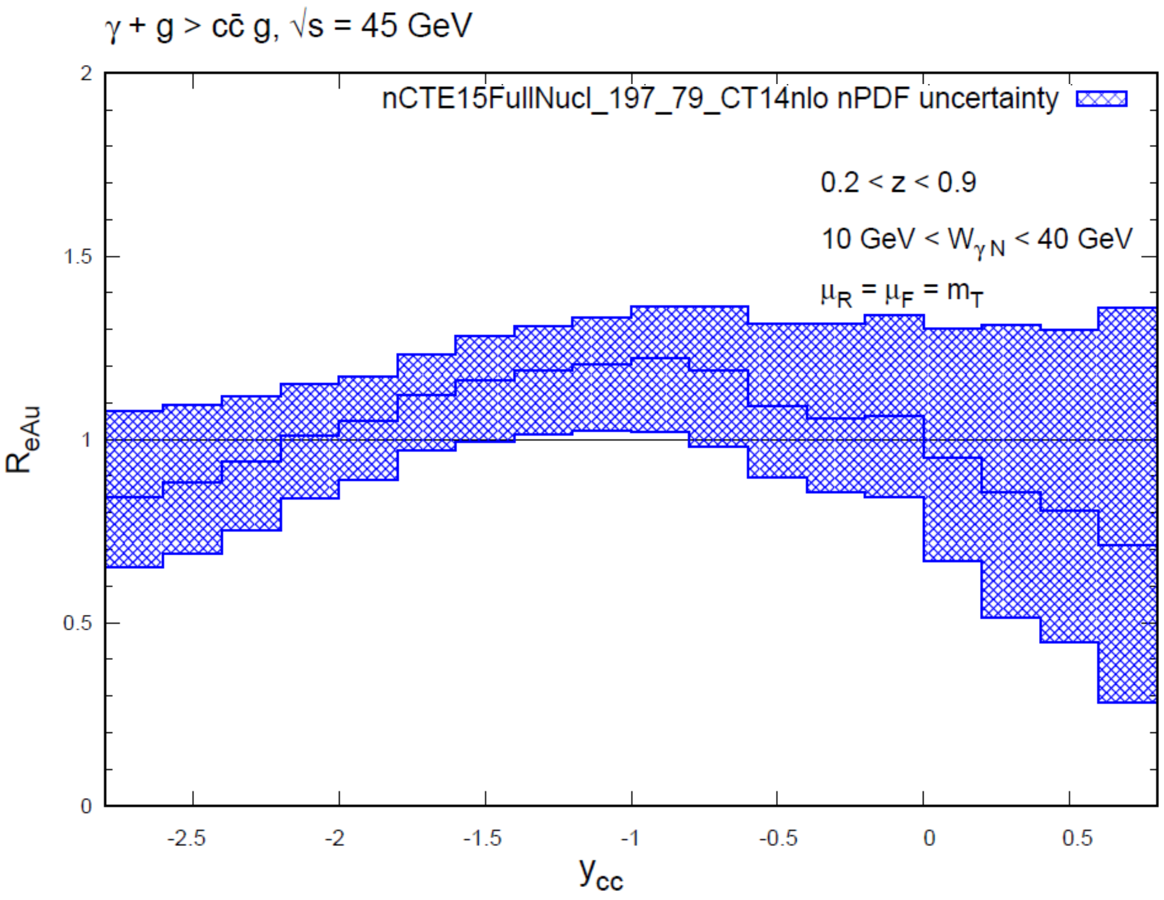
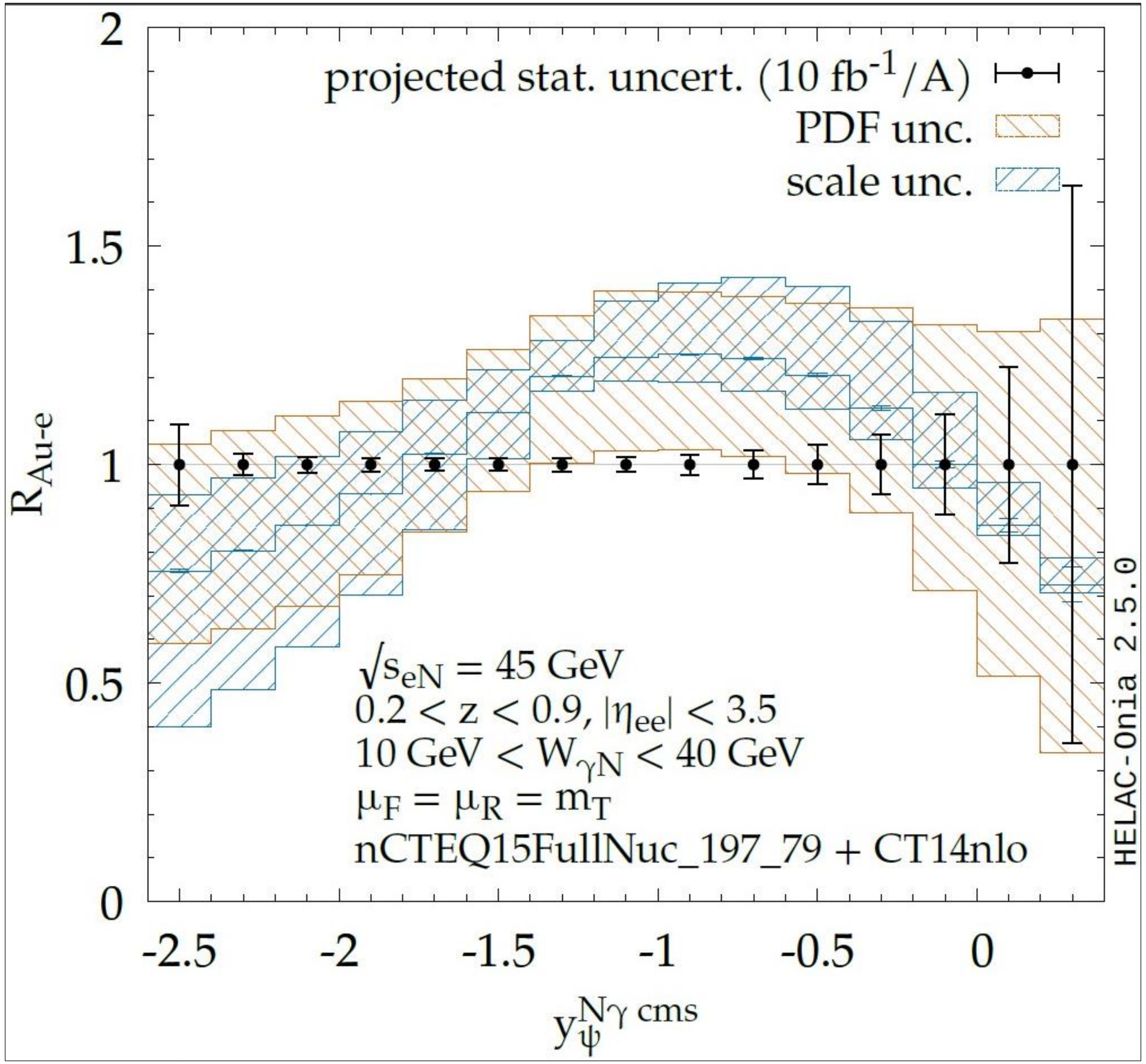




Conclusions

- **Using collinear factorization and MadGraph5 it became possible to make:**
  - **The first NLO fixed-order calculation of A-B and γN collisions**
  - **Quarkonium production is still not possible by MG5,**

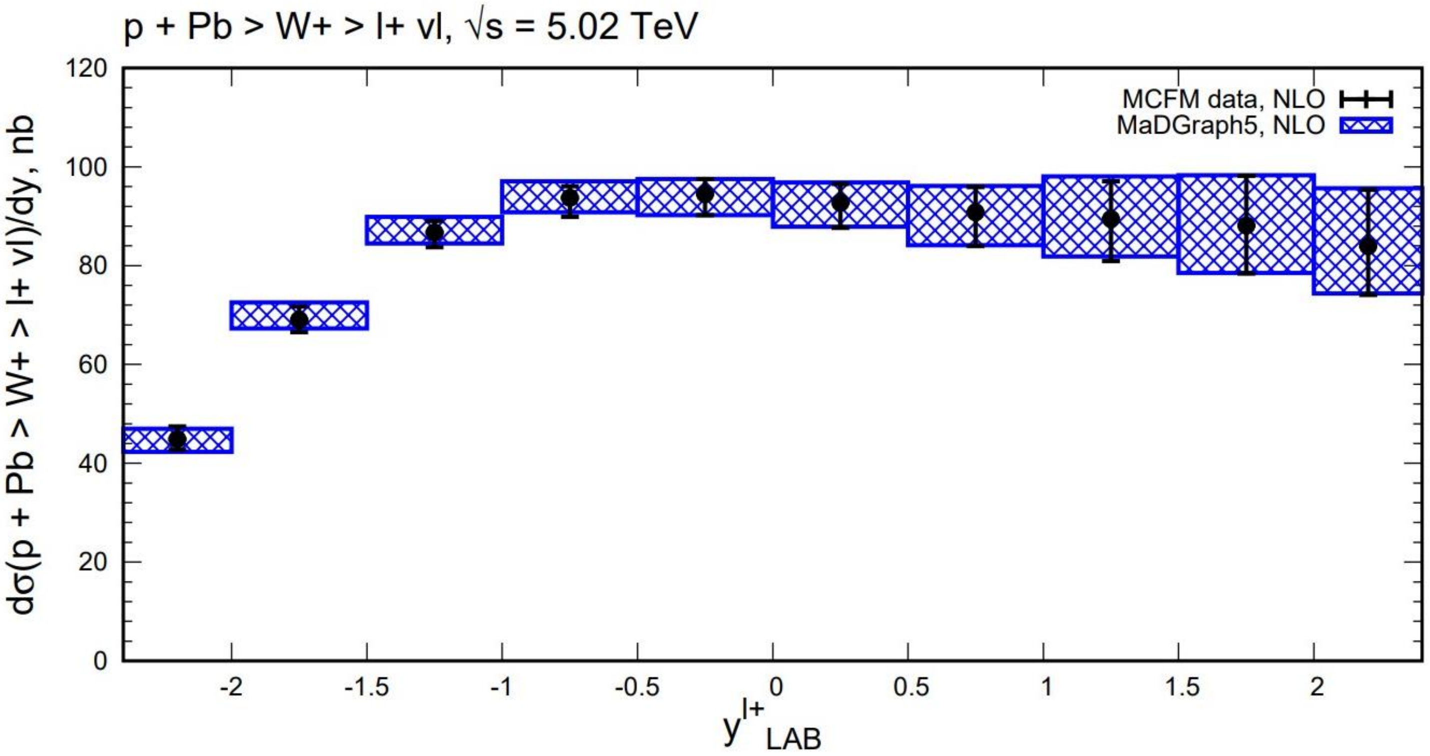
    but soon will be developed by Chris and Alice
- **New codes are flexible in terms of PDFs due to the usage of the LHAPDF libraries**
  - **This makes possible NLO predictions for charm mesons (like D0) or bottom mesons (like B+, B0) productions at LHC**
  - **Usage of PDFs for photon or pion is also possible**
- **Predictions done by Helac-Onia and MG5 for**

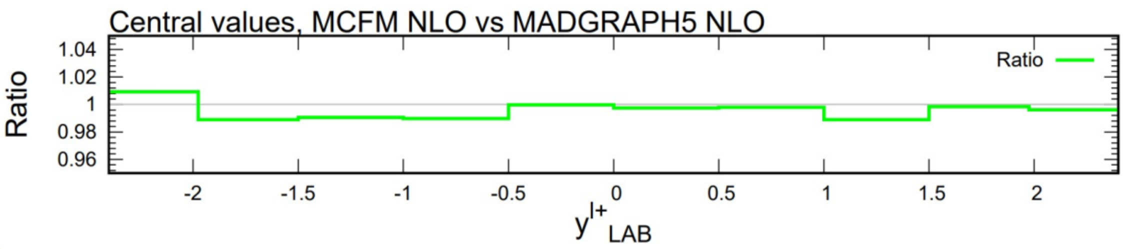
  NMFs in $\mathbf{e}Au$ collisions (photoproduction at EIC) shown in terms of:
  - **rapidity of the J/ψ and**
  - **c.m.s energy of the γN**

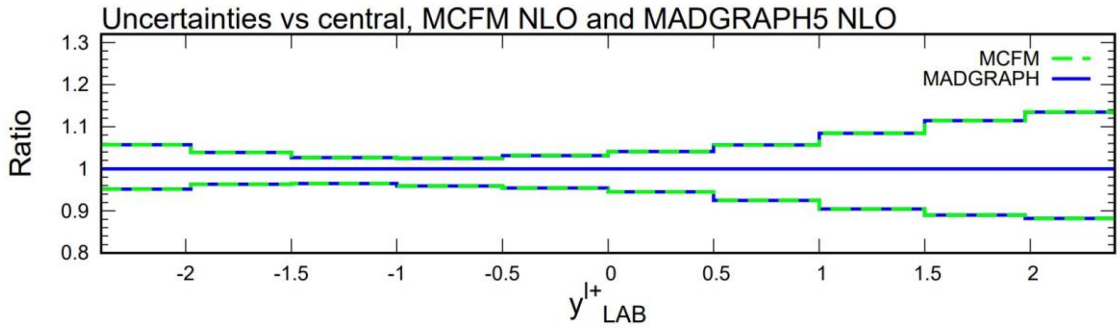
Backup

Validations of MG5 in asymmetric collisions

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



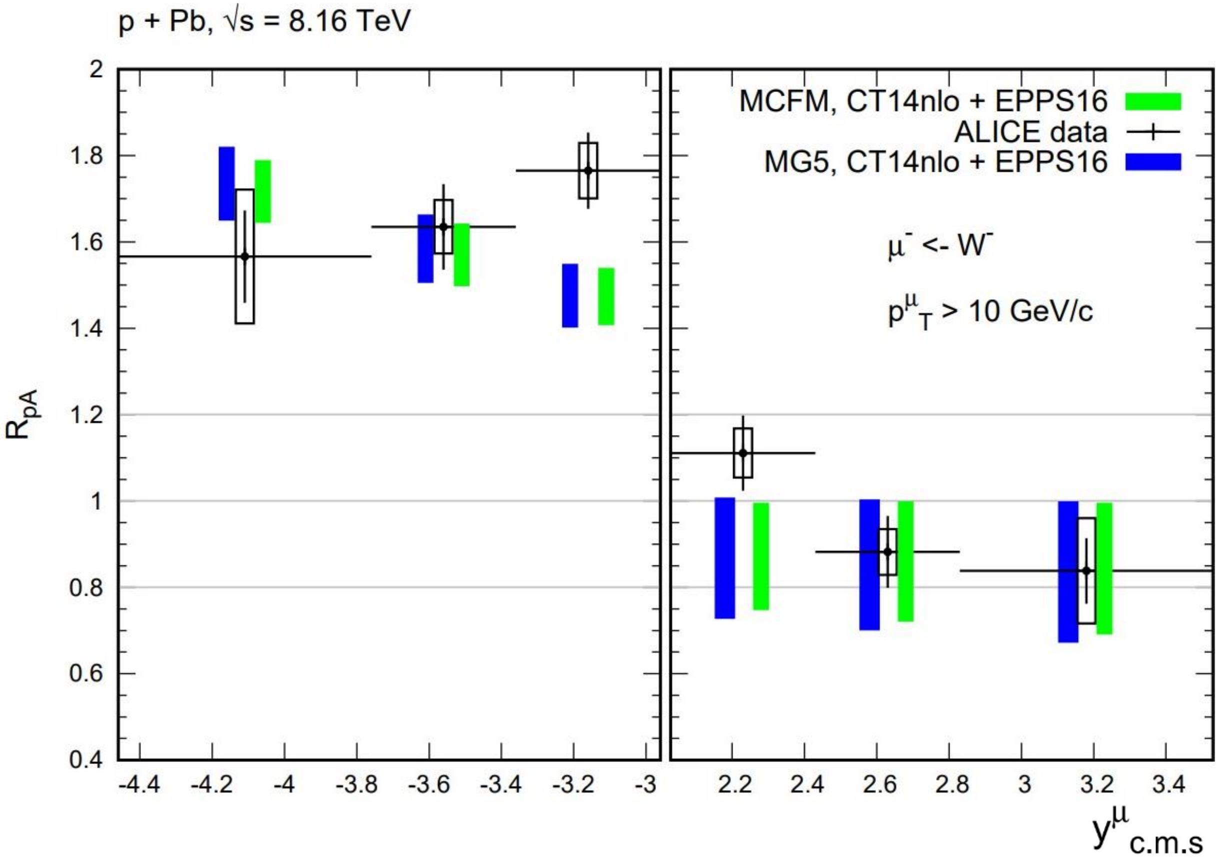


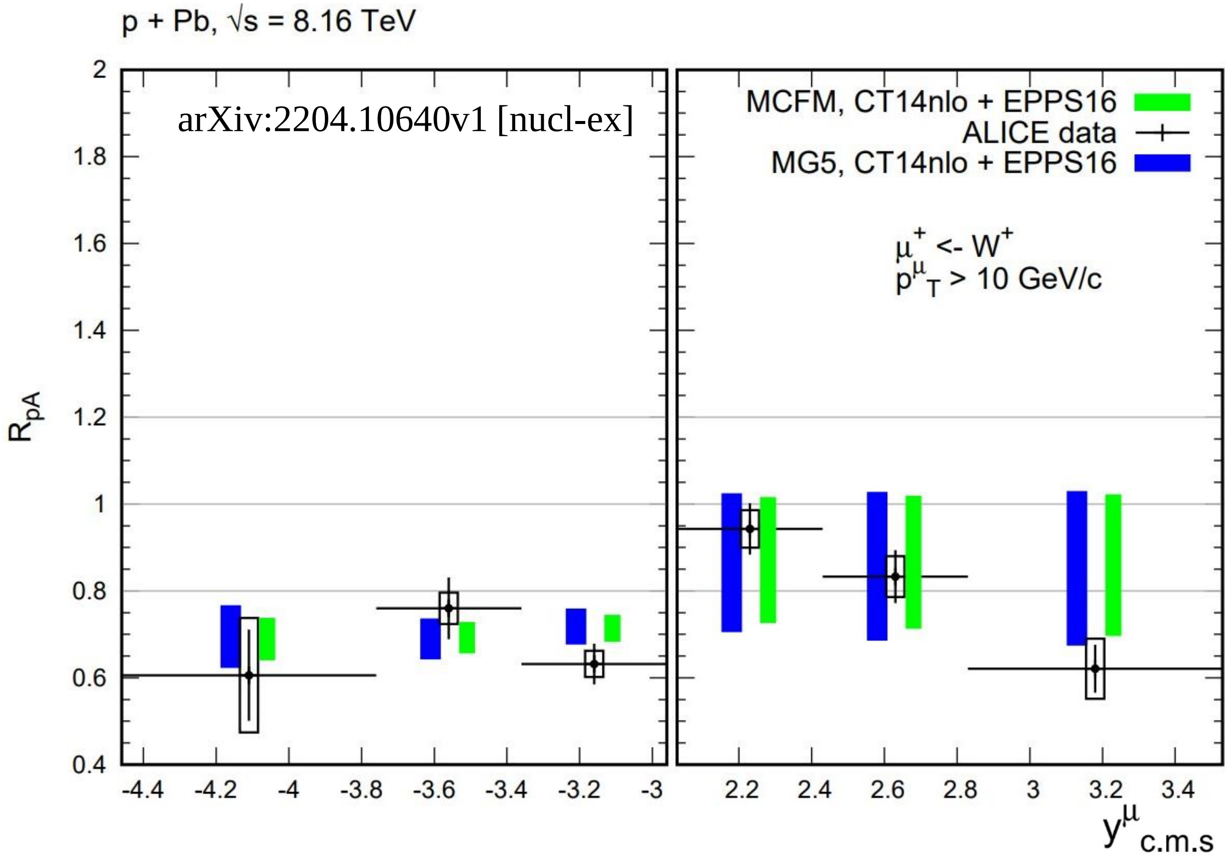


- **Very good agreement** between **MG5** and **MCFM**-based computations both for central value and uncertainties
- **Uncertainties match**, if **MCFM**-based computation done with **asymmetric** error estimation

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**

MadGraph in NLOAccess

https://nloaccess.in2p3.fr/

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

About NLOAccess:

- available tools: HELAC-Onia, MG5_aMC@NLO
- secure two-step registration process
- protected **OwnCloud** storage is given
- file input as first way to submit a run
- live user run status
- user run history
- guided input file creation and submission both for HELAC-Onia and MG5

MG5 extension to asymmetric collisions will be included on NLOAccess