

Inclusion of pA collisions in MadGraph5

nPDF computation at NLO

Safronov Anton
24 June 2021
Warsaw

Aussois Quarkonium & QCD meeting

Introduction

Cross sections in collinear factorization and perturbative QCD

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

Parton density
functions

Parton-level
(differential)
Cross section

where the **partonic cross section** is calculated by:

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

Leading order

Next-to-leading order

Next-to-next-to leading order

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

Also such processes are usually accompanied with the largest nuclear PDF corrections

Introduction.

Parton-distribution functions (PDFs)

Parton-distribution functions (PDFs), provide the essential link between the measurable hadronic cross sections and the perturbatively calculable cross sections of high-energy processes induced by quarks and gluons.

The situation is challenging for PDFs of nucleons inside nuclei, nuclear data significantly more complex to collect with two additional degrees of freedom (protons and neutrons)

Nuclear PDFs (nPDFs) allow one to get information on:

- the **structure of the nuclei** in terms of quarks and gluons;
- the **initial state** of heavy-ion collisions at the LHC and RHIC
especially, to use **perturbative probes** of the QGP to study its properties
- nPDFs cannot be computed and similarly to the proton PDFs are
fit to experimental data. Only the evolution is perturbative

Introduction. Nuclear Modification Factors

In order to say are there any nuclear modifications we could use [nuclear modification factors](#) (R_{AA}, R_{pA})

This factors could be define in a following way:

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

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

which can be differential in the transverse momentum or the center-of-momentum rapidity of an any hadron

This factors are defined such that

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

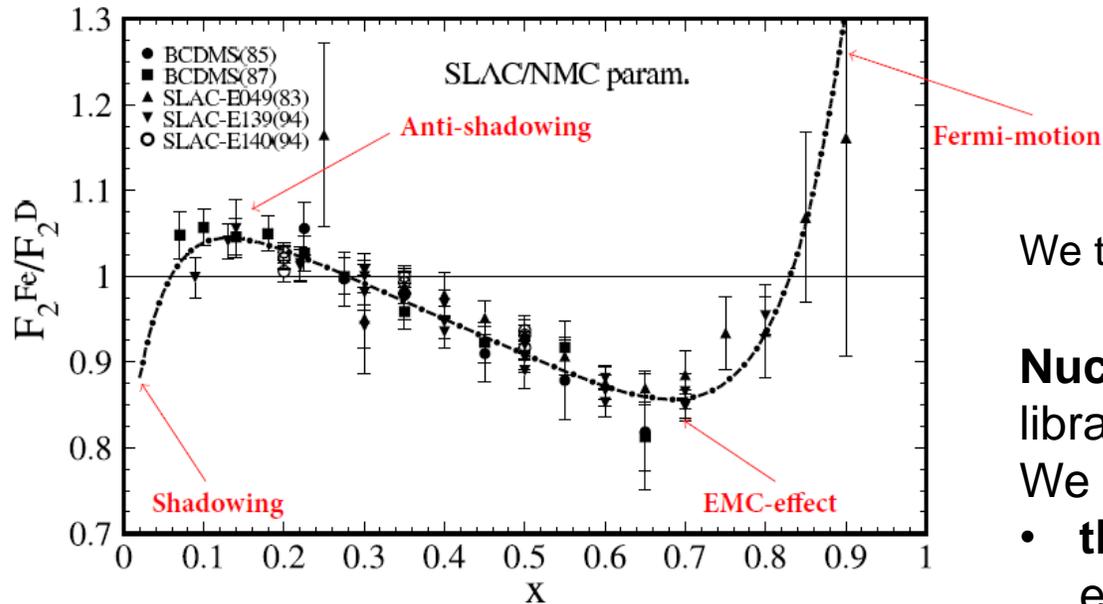
The reason to use R_{AB} (or R_{pA}) is that, for a rare/hard probe [$\sigma_{NN}^{probe} \ll \sigma_{NN}^{inel}$], the yield per AB collisions is proportional to the number of NN collisions

Introduction. Nuclear Modification Factors

Since the early 1980s, we know that the nuclei are not a simple collection of free nucleons, and nuclear PDFs are not equal to a sum of nucleon PDFs.

In fact, often analyses rather bear on nuclear-modification factors (NMF), like in lepton-nucleus (ℓA) collisions for the deep-inelastic scattering (DIS) structure function F_2 and parton-level NMFs, instead of the absolute nuclear PDFs

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



Based on earlier studies, for the quarks:

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

We translate these **modifications** into universal quantities: **nuclear PDFs**

Nuclear PDFs can be used like **original PDFs** with **LHAPDF** library.

We **assume** that

- **the factorization** of the **cross section** is supposed to **hold** even in presence of **nuclear effects**
- all the **nuclear effects** can be accounted by **nPDFs** and thus **can be computed** with **process generators**.

Histogram output

Histogram With Uncertainty (HwU)

```
##& xmin & xmax & central value & dy & delta_pdf_cen CT10nnlo @aux & delta_pdf_min CT10nnlo @aux & delta_pdf_max CT10nnlo @aux & delta_pdf_cen CJ12min @aux & delta_pdf_min CJ12min @aux & delta_pdf_max CJ12min @aux & PDF=11200 CT10nnlo & PDF=11201 CT10nnlo & PDF=11202 CT10nnlo & PDF=11203 CT10nnlo & PDF=11204 CT10nnlo & PDF=11205 CT10nnlo & PDF=11206 CT10nnlo & PDF=11207 CT10nnlo & PDF=11208 CT10nnlo & PDF=11209 CT10nnlo & PDF=11210 CT10nnlo & PDF=11211 CT10nnlo & PDF=11212 CT10nnlo & PDF=11213 CT10nnlo & PDF=11214 CT10nnlo & PDF=11215 CT10nnlo & PDF=11216 CT10nnlo & PDF=11217 CT10nnlo & PDF=11218 CT10nnlo & PDF=11219 CT10nnlo & PDF=11220 CT10nnlo & PDF=11221 CT10nnlo & PDF=11222 CT10nnlo & PDF=11223 CT10nnlo & PDF=11224 CT10nnlo & PDF=11225 CT10nnlo & PDF=11226 CT10nnlo & PDF=11227 CT10nnlo & PDF=11228 CT10nnlo & PDF=11229 CT10nnlo & PDF=11230 CT10nnlo & PDF=11231 CT10nnlo & PDF=11232 CT10nnlo & PDF=11233 CT10nnlo & PDF=11234 CT10nnlo & PDF=11235 CT10nnlo & PDF=11236 CT10nnlo & PDF=11237 CT10nnlo & PDF=11238 CT10nnlo & PDF=11239 CT10nnlo & PDF=11240 CT10nnlo & PDF=11241 CT10nnlo & PDF=11242 CT10nnlo & PDF=11243 CT10nnlo & PDF=11244 CT10nnlo & PDF=11245 CT10nnlo & PDF=11246 CT10nnlo & PDF=11247 CT10nnlo & PDF=11248 CT10nnlo & PDF=11249 CT10nnlo & PDF=11250 CT10nnlo & PDF=12000 CJ12min & PDF=12001 CJ12min & PDF=12002 CJ12min & PDF=12003 CJ12min & PDF=12004 CJ12min & PDF=12005 CJ12min & PDF=12006 CJ12min & PDF=12007 CJ12min & PDF=12008 CJ12min & PDF=12009 CJ12min & PDF=12010 CJ12min & PDF=12011 CJ12min & PDF=12012 CJ12min & PDF=12013 CJ12min & PDF=12014 CJ12min & PDF=12015 CJ12min & PDF=12016 CJ12min & PDF=12017 CJ12min & PDF=12018 CJ12min & PDF=12019 CJ12min & PDF=12020 CJ12min & PDF=12021 CJ12min & PDF=12022 CJ12min & PDF=12023 CJ12min & PDF=12024 CJ12min & PDF=12025 CJ12min & PDF=12026 CJ12min & PDF=12027 CJ12min & PDF=12028 CJ12min & PDF=12029 CJ12min & PDF=12030 CJ12min & PDF=12031 CJ12min & PDF=12032 CJ12min & PDF=12033 CJ12min & PDF=12034 CJ12min & PDF=12035 CJ12min & PDF=12036 CJ12min & PDF=12037 CJ12min & PDF=12038 CJ12min

<histogram> 5 "total rate [X AXIS@LIN |Y AXIS@LOG |TYPE@#1"
+5.0000000e-01 +1.5000000e+00 +6.4455281e+02 +4.3419843e+00 +6.4455281e+02 +6.2143878e+02 +6.7107467e+02 +4.2906822e+02 +4.2779946e+02 +4.3003940e+02 +6.4455281e+02 +6.4604128e+02 +6.4332700e+02 +6.4597039e+02 +6.4293137e+02
+6.3831395e+02 +6.5116992e+02 +6.4096476e+02 +6.4709037e+02 +6.4394706e+02 +6.4494423e+02 +6.6334370e+02 +6.2933691e+02 +6.3907321e+02 +6.4972477e+02 +6.5075482e+02 +6.3889098e+02 +6.4760126e+02 +6.4007826e+02 +6.4516553e+02
+6.4389586e+02 +6.4303981e+02 +6.4713320e+02 +6.4185914e+02 +6.4982644e+02 +6.3922225e+02 +6.4827573e+02 +6.4624972e+02 +6.4189352e+02 +6.3891140e+02 +6.5134116e+02 +6.4261936e+02 +6.4578236e+02 +6.4876317e+02 +6.4054837e+02
+6.5251428e+02 +6.4108583e+02 +6.3853410e+02 +6.4787213e+02 +6.4357447e+02 +6.4767052e+02 +6.4384709e+02 +6.4349553e+02 +6.4559302e+02 +6.4361312e+02 +6.4486493e+02 +6.4467228e+02 +6.4865253e+02 +6.4224500e+02 +6.4603112e+02
+6.4127512e+02 +4.2906822e+02 +4.2904609e+02 +4.2908709e+02 +4.2897610e+02 +4.2918732e+02 +4.2826083e+02 +4.2935126e+02 +4.2901049e+02 +4.2911847e+02 +4.2863095e+02 +4.2945180e+02 +4.2905660e+02 +4.2908437e+02 +4.2921634e+02
+4.2892264e+02 +4.2939985e+02 +4.2873980e+02 +4.2911867e+02 +4.2901068e+02 +4.2878712e+02 +4.2931146e+02 +4.2880671e+02 +4.2929100e+02 +4.2883058e+02 +4.2927473e+02 +4.2916949e+02 +4.2896695e+02 +4.2843305e+02 +4.2969922e+02
+4.2907660e+02 +4.2905983e+02 +4.2906275e+02 +4.2907409e+02 +4.2905829e+02 +4.2907831e+02 +4.2913175e+02 +4.2900471e+02 +4.2906155e+02 +4.2907510e+02
```

- A new standard for creating histograms
- A single histogram can store many different weights at once to account for scale, PDF and MC uncertainty.

The scale and PDF uncertainty envelope computation is done automatically by the module when output

Error estimation:

If we refer to the PDF uncertainty:

The PDF uncertainty is obtained by computing the cross section with the different PDFs of the PDF set and deriving the uncertainty for these numbers

For the scales:

μ_R and μ_F are varied inside MadGraph code and the different pieces of the cross-section are reweighted with different values of alphas(μ_R) and PDF(μ_F)

```
##& xmin & xmax & central value & dy & delta_mu_cen -1 @aux & delta_mu_min -1 @aux & delta_mu_max -1 @aux & dyn=-1 muR= 1.000 muF= 1.000 & dyn=-1 muR= 2.000 muF= 1.000 & dyn=-1 muR= 0.500 muF= 1.000 & dyn=-1 muR= 1.000 muF= 2.000 & dyn=-1 muR= 2.000 muF= 2.000 & dyn=-1 muR= 0.500 muF= 2.000 & dyn=-1 muR= 1.000 muF= 0.500 & dyn=-1 muR= 2.000 muF= 0.500 & dyn=-1 muR= 0.500 muF= 0.500

<histogram> 5 "total rate [X AXIS@LIN |Y AXIS@LOG |TYPE@#1"
+5.0000000e-01 +1.5000000e+00 +6.9118832e+02 +5.1215007e+00 +6.9118832e+02 +6.0732421e+02 +7.6418582e+02 +6.9118832e+02 +6.3336687e+02 +7.4424264e+02 +6.6694792e+02
+6.0732421e+02 +7.2487765e+02 +7.1527317e+02 +6.5884776e+02 +7.6418582e+02
+1.5000000e+00 +2.5000000e+00 +0.0000000e+00 +0.0000000e+00 +0.0000000e+00 +0.0000000e+00 +0.0000000e+00 +0.0000000e+00 +0.0000000e+00 +0.0000000e+00 +0.0000000e+00
```

What should be done

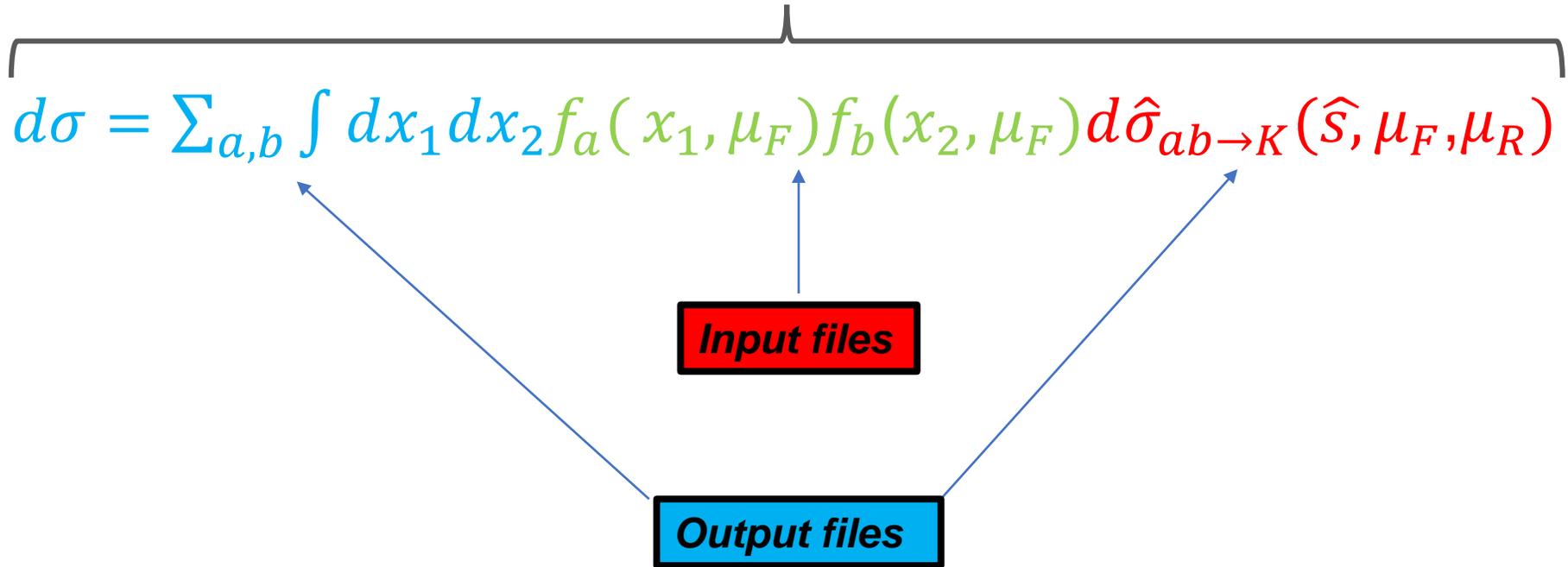
Basically:

MADatNLO.HwU

HwU

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

$$R_{pA}(y_{c.m.s}) = R_{Ap}(-y_{c.m.s})$$



Working examples

CT14nnlo – proton PDF
 nCTEQ15_208_82 - nucleon PDF

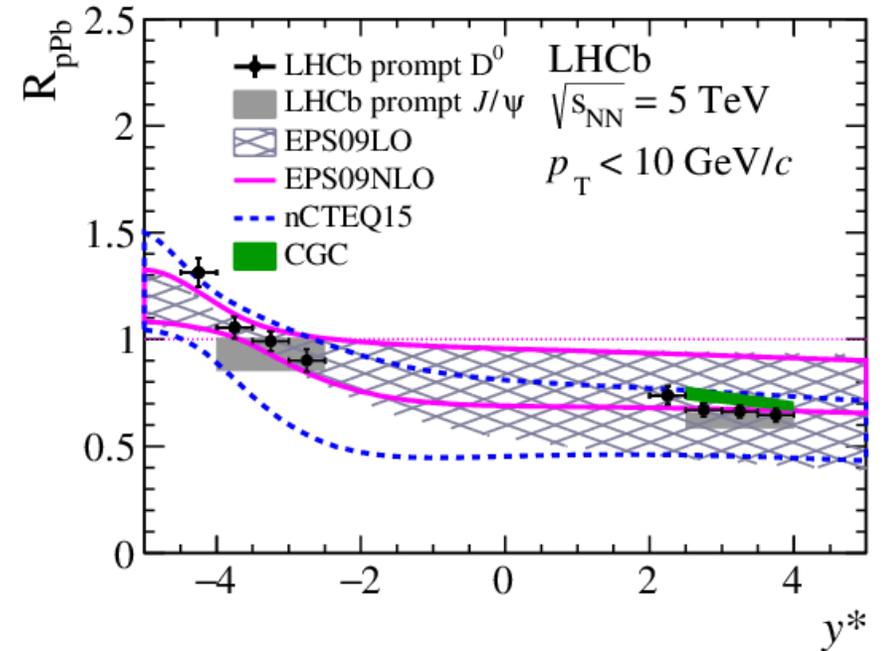
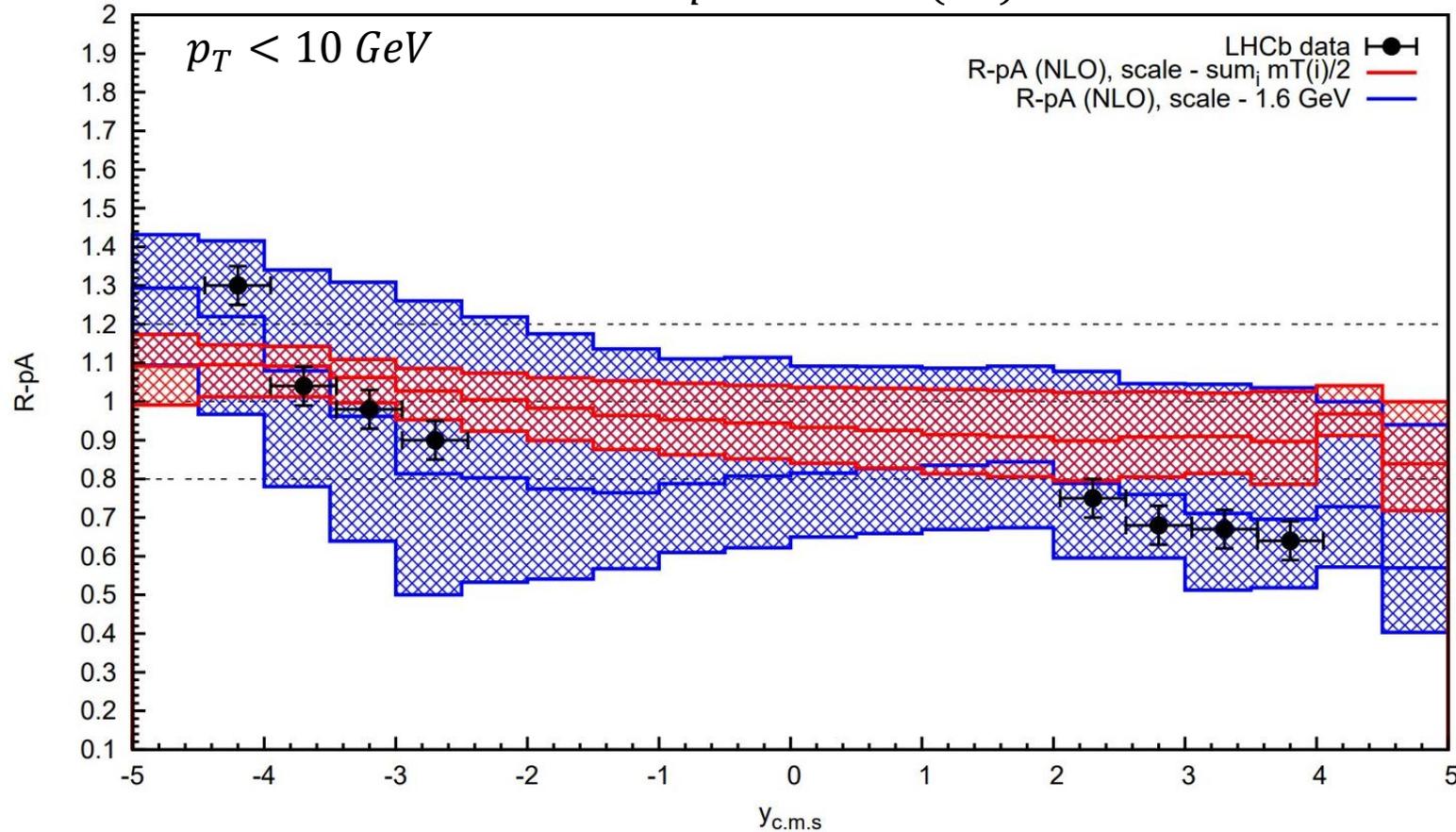
$$\sqrt{s_{NN}} = 5.02 \text{ TeV}$$

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

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

$$R_{pA}(y_{c.m.s}) = R_{Ap}(-y_{c.m.s})$$

Charm production (D^0)



Data points from: JHEP 10 (2017) 090,
 arXiv:1707.02750 [hep-ex].

Working examples

CT14nnlo – proton PDF
nCTEQ15_208_82 - nucleon PDF

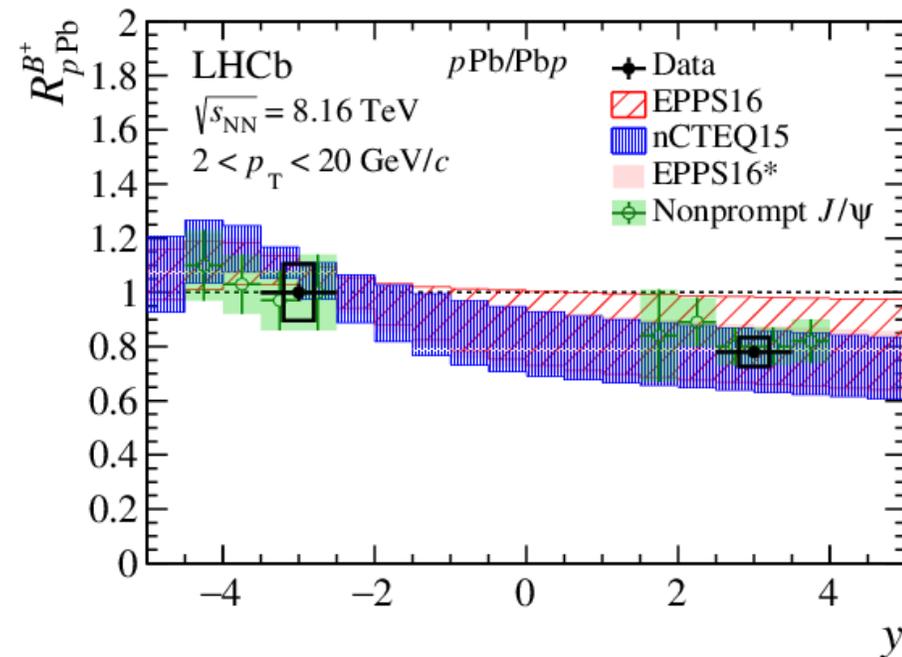
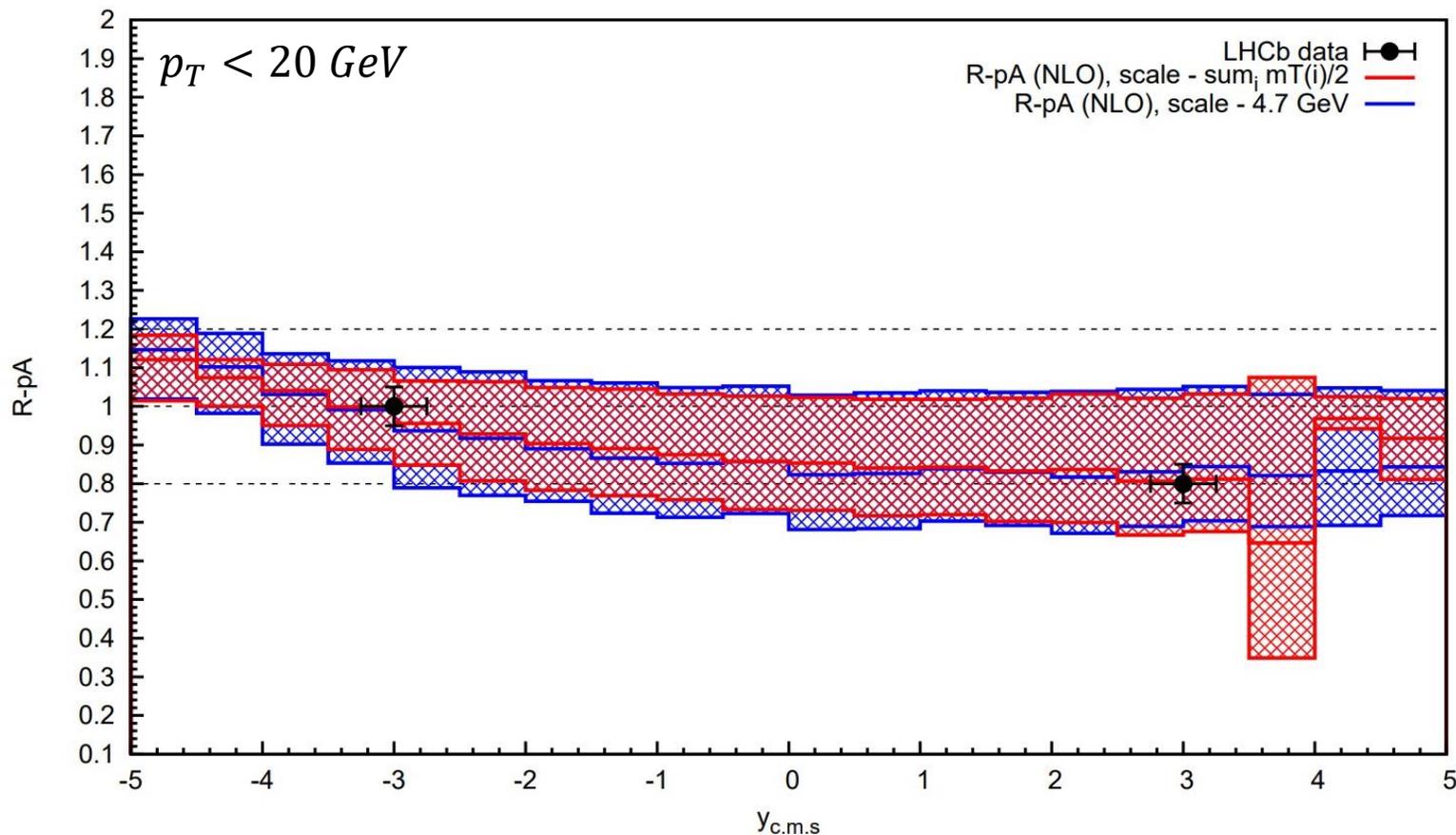
$$\sqrt{s_{NN}} = 8.16 \text{ TeV}$$

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

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

$$R_{pA}(y_{c.m.s}) = R_{Ap}(-y_{c.m.s})$$

Bottom production (B^+)



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

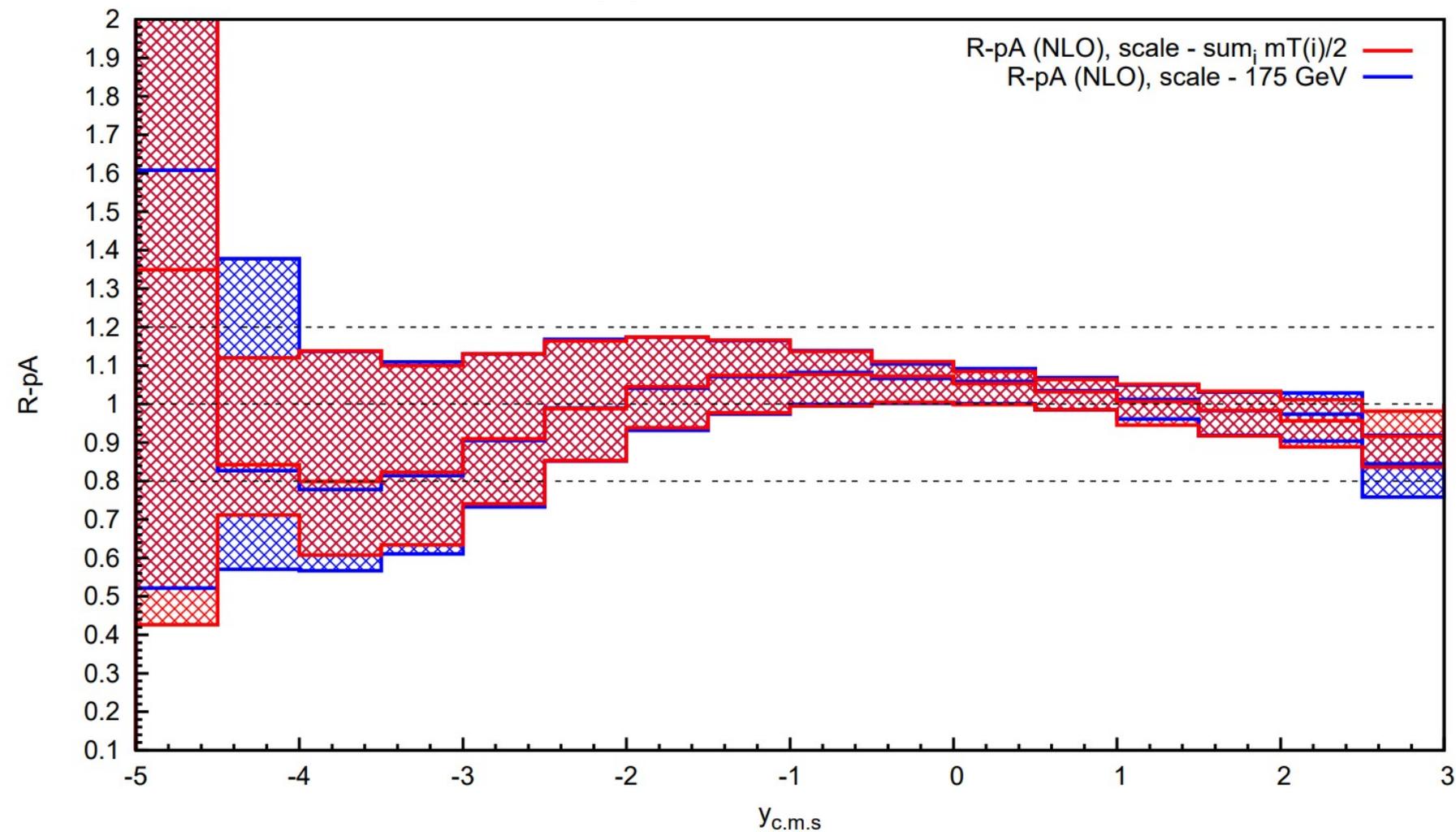
Working examples

CT14nnlo – proton PDF
nCTEQ15_208_82 - nucleon PDF

$$\sqrt{S_{NN}} = 8.16 \text{ TeV}$$

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

Top production



$$R_{pA}(y_{c.m.s}) = R_{Ap}(-y_{c.m.s})$$

Summary

- **The first NLO fixed-order calculation of p-A collisions was done using MadGraph5**
- **It can use various PDFs and nPDF from LHAPDF libraries**
- **Also, pA collisions can be calculated with different scales**
- **Uncertainties are calculated “on fly”**
- **Every output data will be stored in HwU files, which has high functionality**
- **In future, it will be implemented into NLOAccess (<https://nloaccess.in2p3.fr>)**

Acknowledgments

Research was funded by POB HEP of Warsaw University of Technology within the Excellence Initiative: Research University (IDUB) programme.