Inclusion of pA collisions in MadGraph5

nPDF computation at NLO

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02 June 2021
Warsaw

Joint workshop "GDR-QCD/QCD@short distances and STRONG2020/PARTONS/FTE@LHC/NLOAccess"

Introduction

Cross sections in collinear factorization and perturbative QCD

$$d\sigma = \sum_{a,b} \int dx_1 dx_2 f_a(x_1, \mu_F) f_b(x_2, \mu_F) d\hat{\sigma}_{ab \to K}(\hat{s}, \mu_F, \mu_R)$$

Parton density functions

Parton-level (differential) Cross section

where the partonic cross section is calculated by:

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

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

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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:

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

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

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

This factors are defined such that
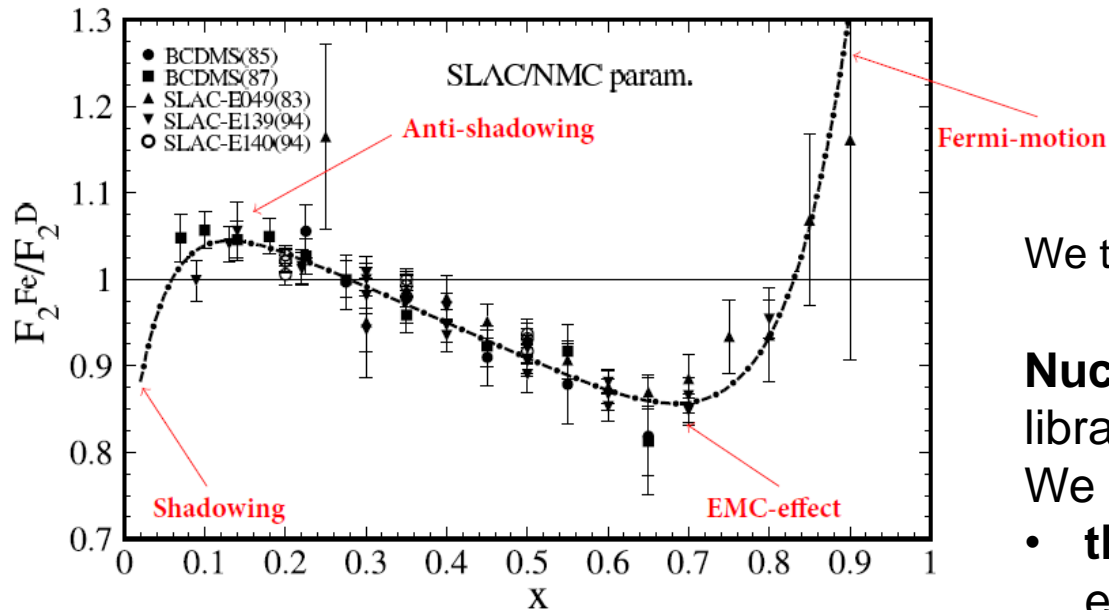
$R_{pA} \sim 1$: absence of nuclear effects

The reason to use R_{AB} (or R_{pA}) is that, for a rare/hard probe $\left[\sigma_{NN}^{probe} \ll \sigma_{NN}^{inel}\right]$, 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

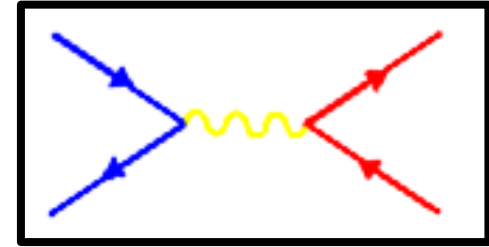We translate these **modifications** into universal quantities: **nuclear PDFs**

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**.

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MadGraph

- **MadGraph 5** is a **matrix element generator** written in **Python**

- **Can generate cross section for any process in LO**

- **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 CPU time**

- **Fast process** generation

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

- **User-friendly** command line **interfaces**


```
                    W E L C O M E  to
                M A D G R A P H 5 _ aMC @ N L O

              *          *  *          *
                 *    *  *  *  *    *
                   *  * * 5 * * *  *
                 *    *  *  *  *    *
              *          *  *          *

             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>
```


6
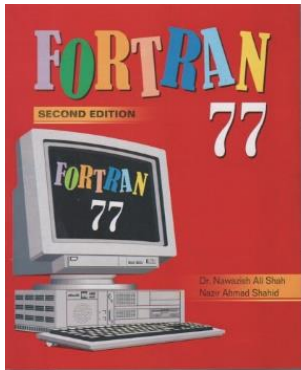
Histogram output

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
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+6.5251428e+02  +6.410858 3e+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  +4.2918732e+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
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```

- 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
```
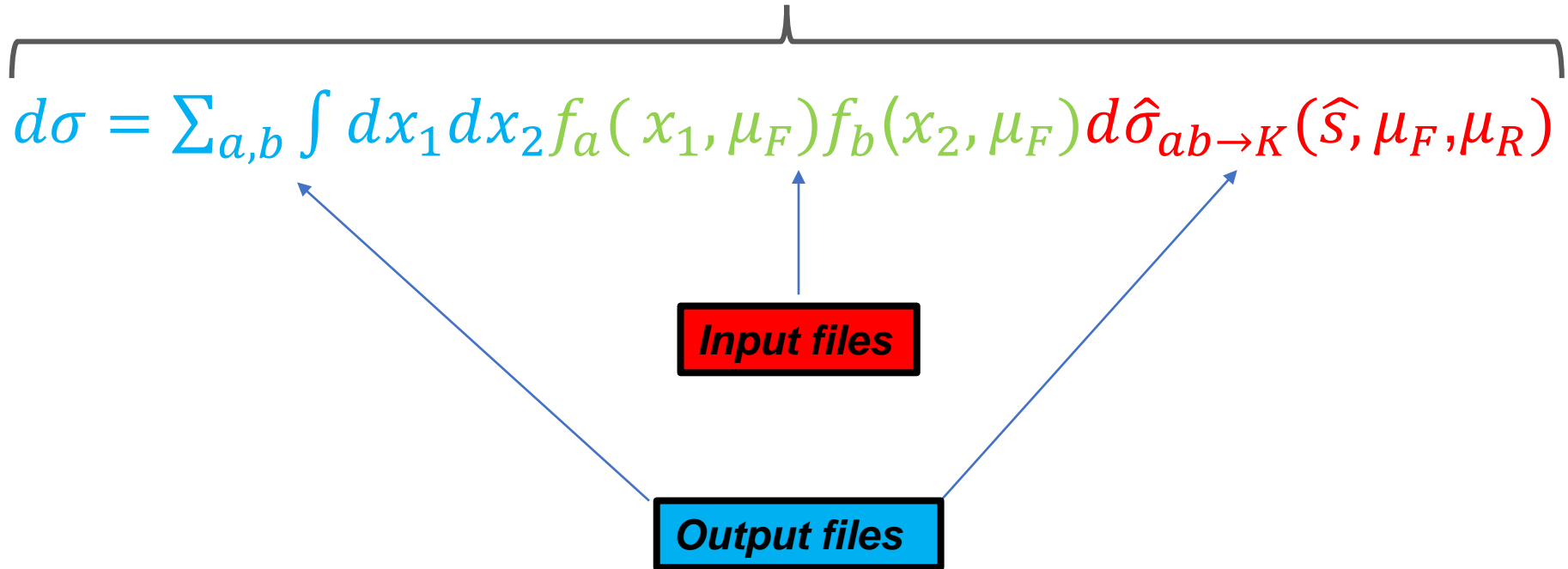
What should be done

Basically:

MADatNLO.HwU

$$\boxed{\begin{aligned} R_{pA} &\equiv \frac{\sigma_{pA}}{(1 \times A \times \sigma_{pp})} \\ R_{Ap} &\equiv \frac{\sigma_{Ap}}{(1 \times A \times \sigma_{pp})} \end{aligned}}$$

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

HwU

$$d\sigma = \sum_{a,b} \int dx_1 dx_2 f_a(x_1, \mu_F) f_b(x_2, \mu_F) d\hat{\sigma}_{ab \to K}(\hat{s}, \mu_F, \mu_R)$$

Input files

Output files

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Working examples

CT14nnlo – proton PDF
nCTEQ15_208_82 - nucleon PDF

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

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

$\sqrt{S_{NN}} = 5.02$ TeV

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

Charm production (D^0)
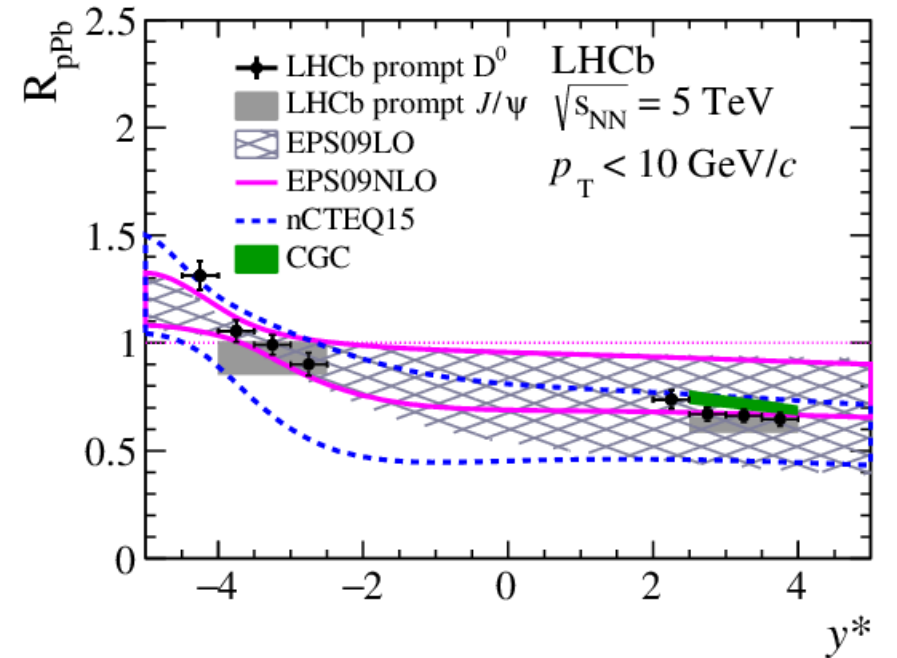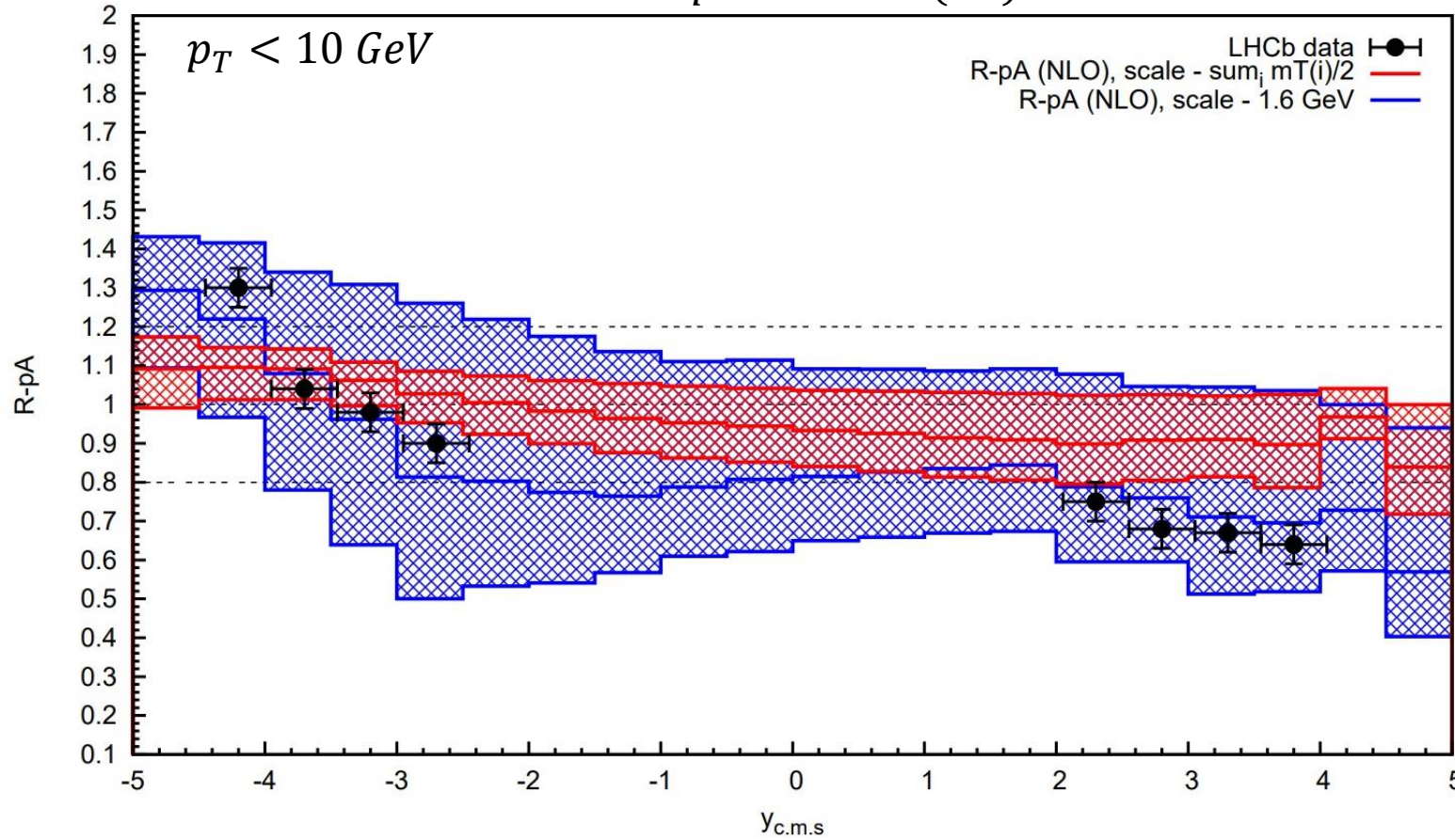
Data points from: JHEP 10 (2017) 090,
arXiv:1707.02750 [hep-ex].

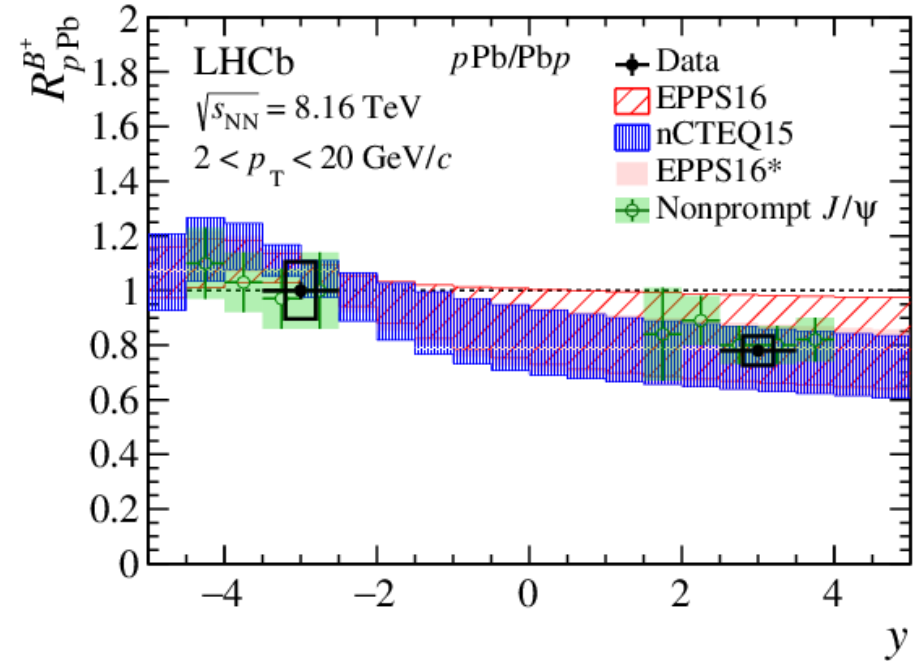# Working examples

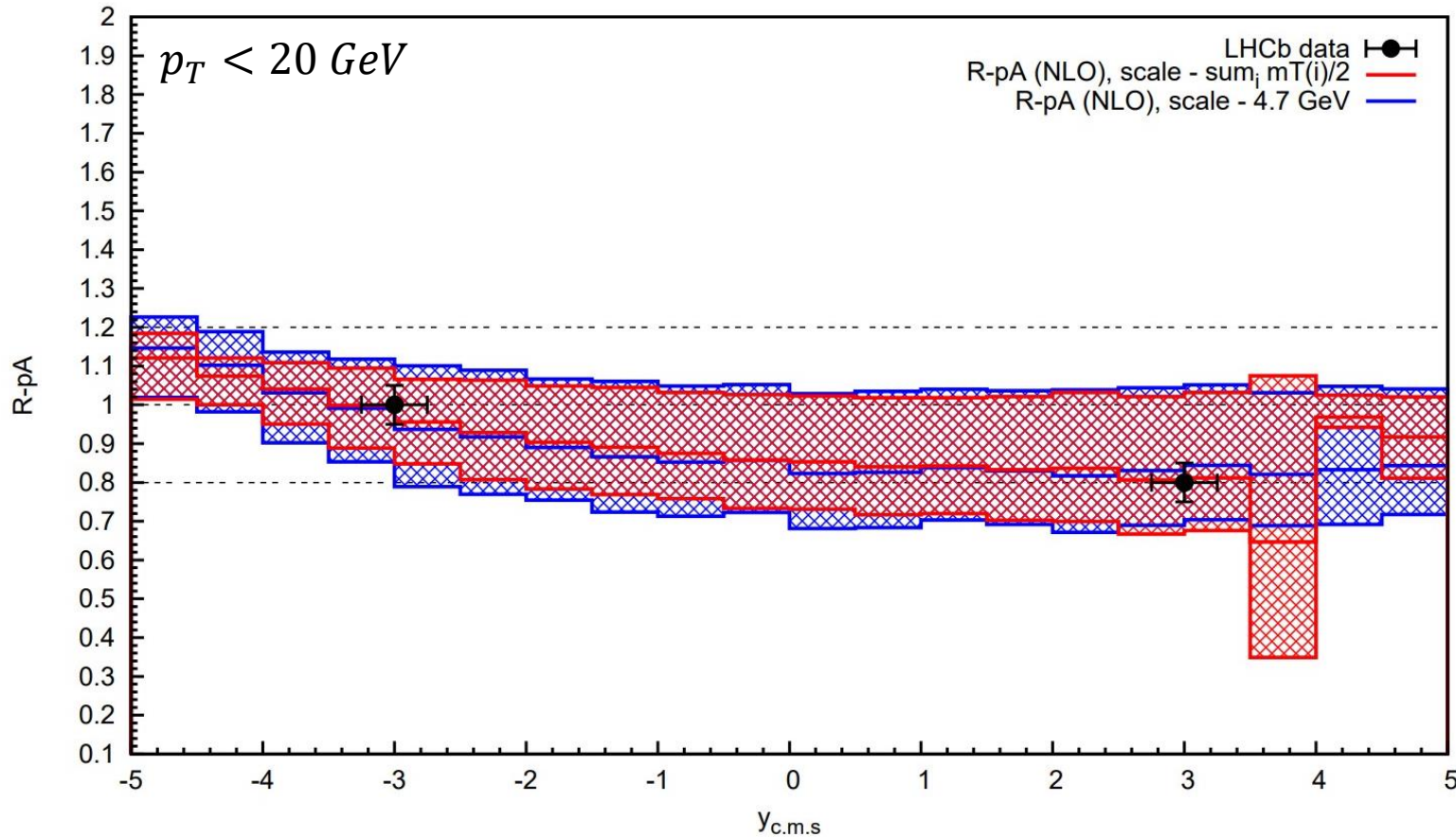CT14nnlo – proton PDF
nCTEQ15_208_82 - nucleon PDF

$\sqrt{S_{NN}} = 8.16$ 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:
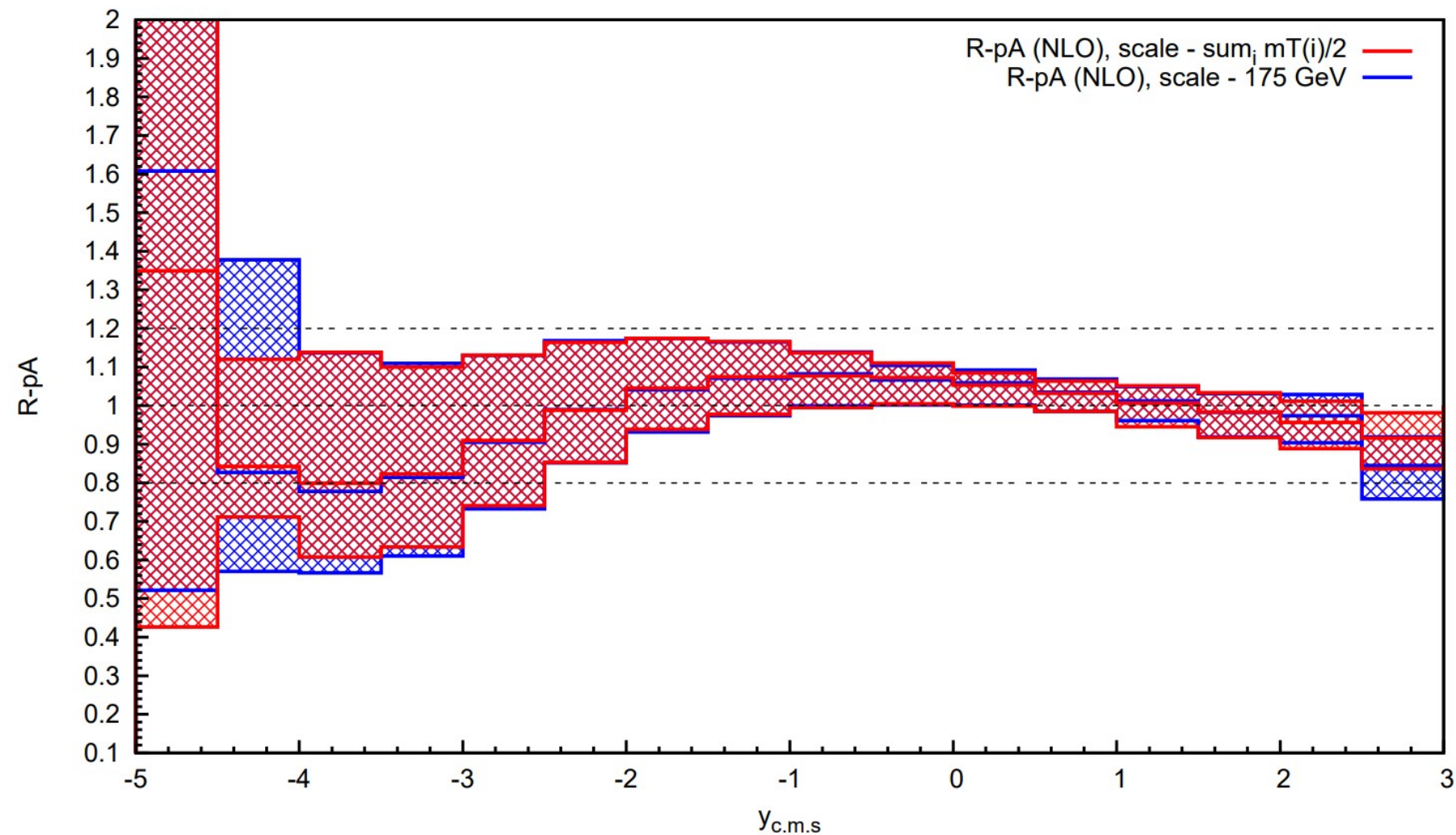Phys. Rev. D99 no. 5, (2019) 052011,
arXiv:1902.05599 [hep-ex].

Working examples

CT14nnlo – proton PDF
nCTEQ15_208_82 - nucleon PDF

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

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

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

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

Top production

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)