Inclusion of asymmetric hadronic collisions in MG5_aMC@NLO

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on behalf of

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Framework – Collinear factorization

Cross sections in collinear factorization and perturbative QCD

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

where the partonic cross section is calculated using:

$$\hat{\sigma} = \underbrace{\sigma^{Born}}_{\text{Leading order}}\Big(1 + \underbrace{\frac{\alpha_s}{2\pi}\sigma^{(1)}}_{\text{Next-to-leading order}} + \underbrace{\left(\frac{\alpha_s}{2\pi}\right)^2 \sigma^{(2)}}_{\text{Next-to-next-to leading order}} + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma^{(3)} + \ldots\Big)$$

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 - Nuclear 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 give information on:
- the **nuclear structure** in terms of quarks and gluons;
- the **initial state** of relativistic heavy-ion collisions,

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

- 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** are 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]

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

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

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

These factors are defined such that:

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

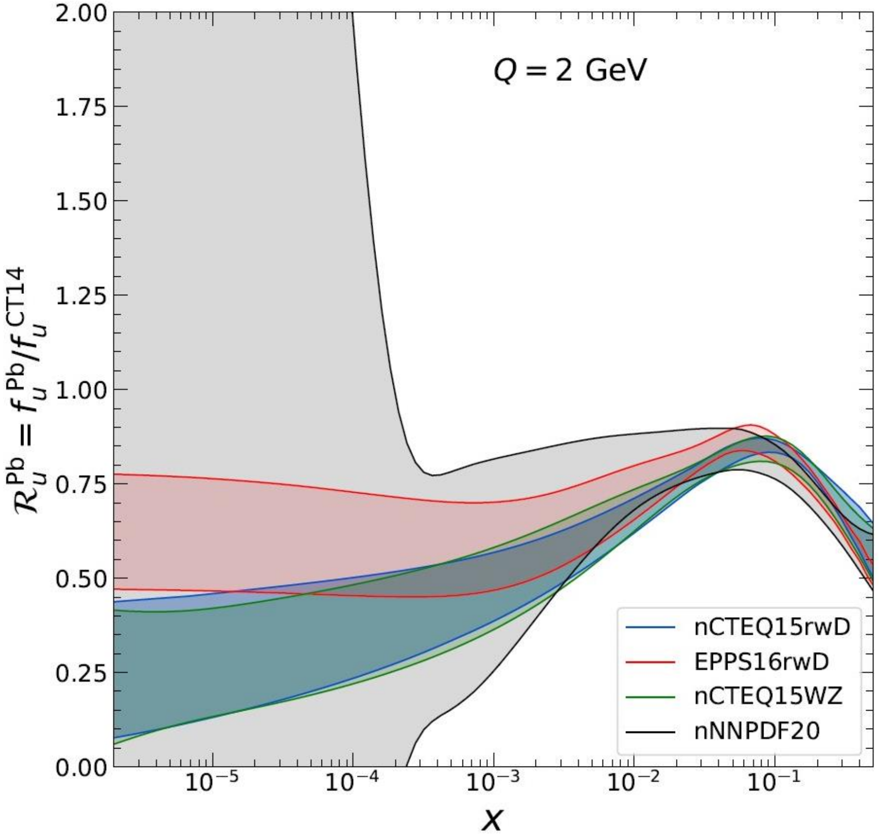
Quark nPDFs

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:

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

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

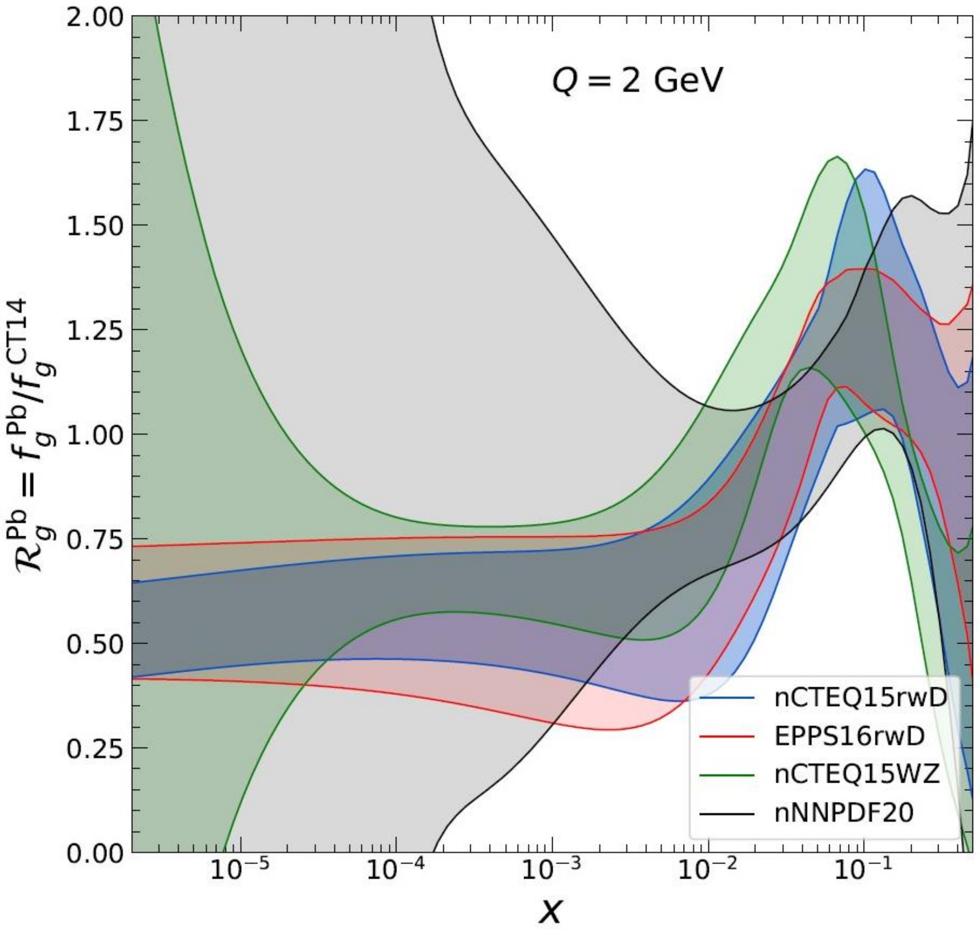
arXiv:1712.07024v2 [hep-ph]



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

Gluon nPDFs



Gluon nPDF are much **more complicated to measure** than quark nPDFs (only indirect constraint from DIS, DY data)

Because of **larger uncertainty** in the whole x region

The gluon nPDFs for $x \leq 10^{-3}$ obtained by **extrapolating** nPDFs.

Essentially depend on the **parametrizations** of the x-dependence of nPDFs at the initial scale μ_F

nPDFs and MG5

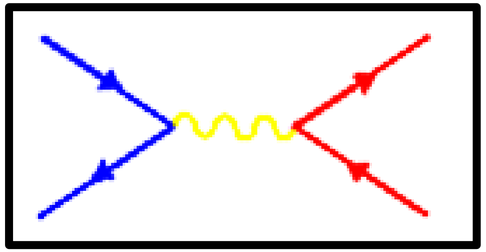
Nuclear **PDFs** can be used in **MG5 up to NLO** like *proton* **PDFs** with **LHAPDF** library

Currently only the symmetric mode is implemented

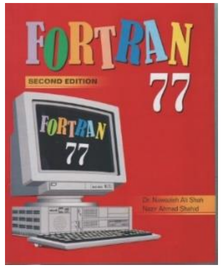
Reminder: we **assume** that

- **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…)**



python™

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*         VERSION 2.7.2                 2020-03-17         *
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*    The MadGraph5_aMC@NLO Development Team - Find us at   *
*    https://server06.fynu.ucl.ac.be/projects/madgraph     *
*                            and                           *
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*           Type 'tutorial' to learn how MG5 works         *
*    Type 'tutorial aMCatNLO' to learn how aMC@NLO works   *
*    Type 'tutorial MadLoop' to learn how MadLoop works    *
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set ninja to /projet/pth/safronov/MG5/MG5_aMC_v2_7_2/HEPTools/lib
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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~
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MG5_aMC>
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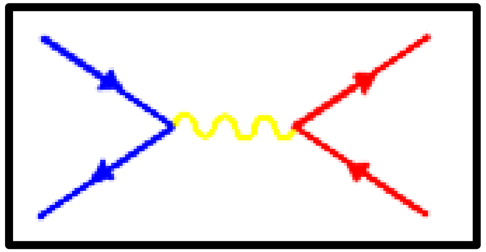
MadGraph



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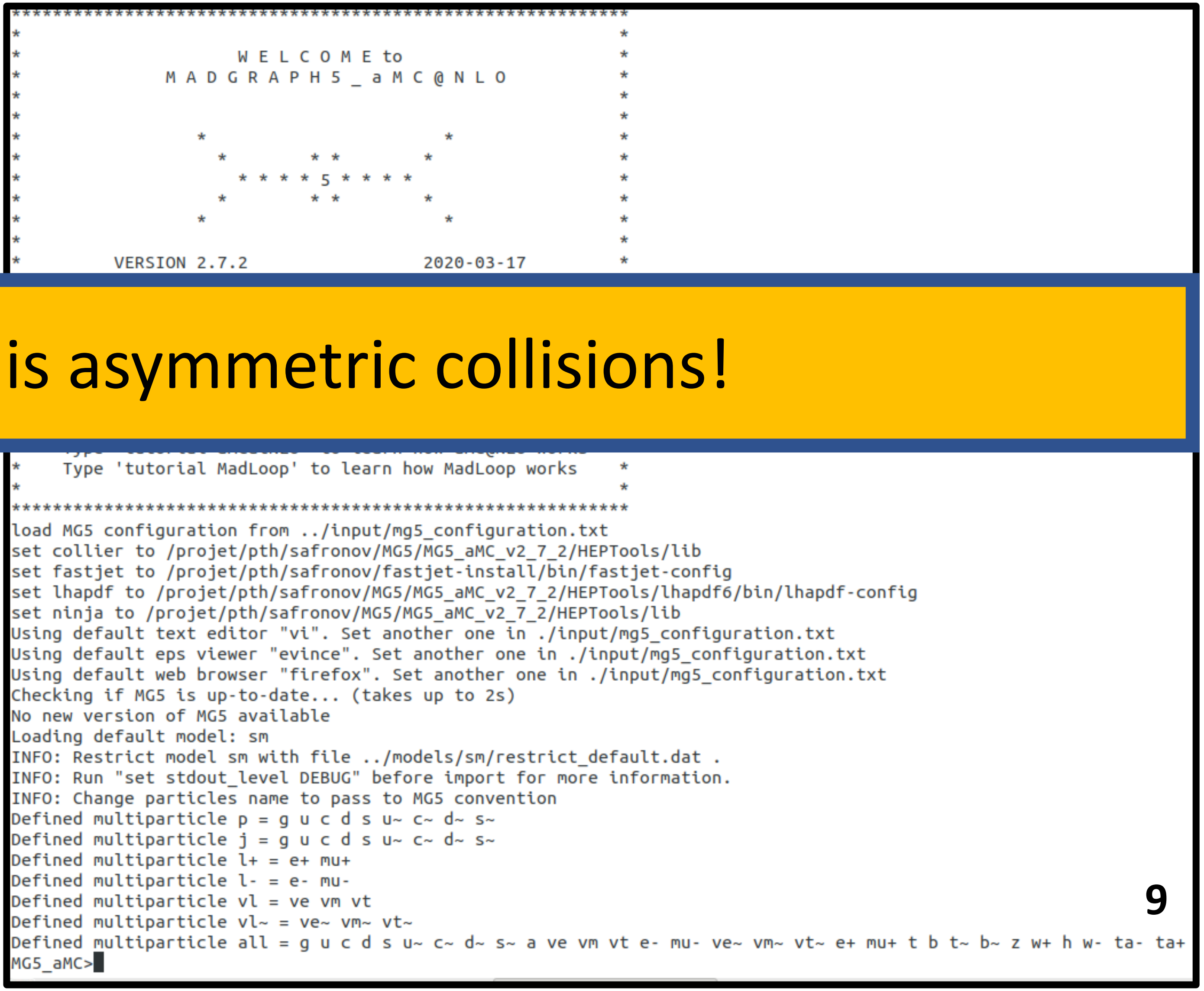
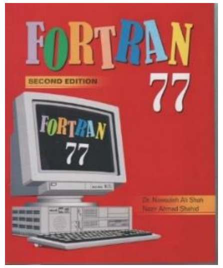


The missing part is asymmetric collisions!

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

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



What was implemented

Putting proton and Lead PDF into the run_card, you will get:

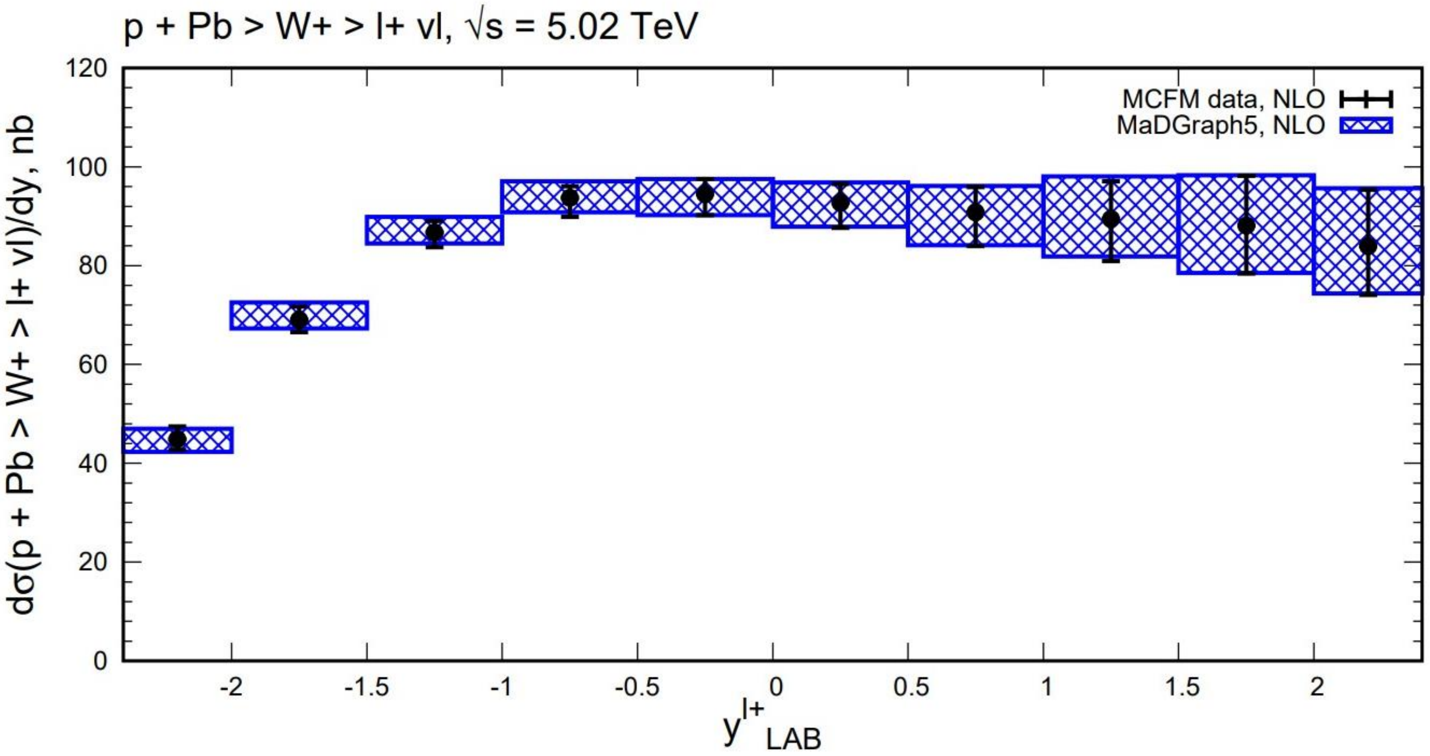
- Proton-proton collision for proton PDF:
- $d\sigma_{pp} = \sum_{p,p} \int dx_1 dx_2 f_p(x_1, \mu_F) f_p(x_2, \mu_F) d\hat{\sigma}_{pp\to K}(\hat{s}, \mu_F, \mu_R)$

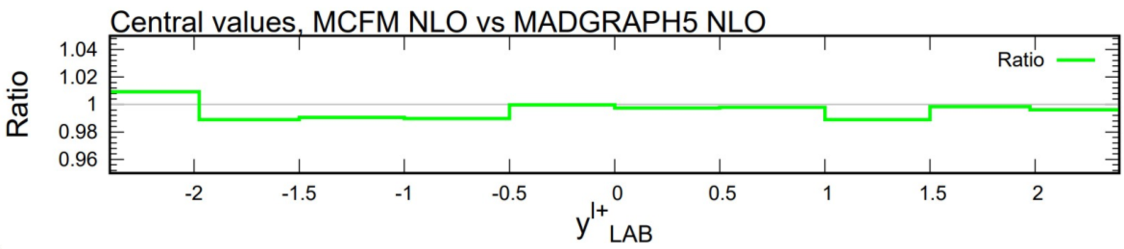
- Lead-Lead collision for Lead PDF:
- $d\sigma_{PbPb} = \sum_{Pb,Pb} \int dx_1 dx_2 f_{Pb}(x_1, \mu_F) f_{Pb}(x_2, \mu_F) d\hat{\sigma}_{PbPb\to K}(\hat{s}, \mu_F, \mu_R)$

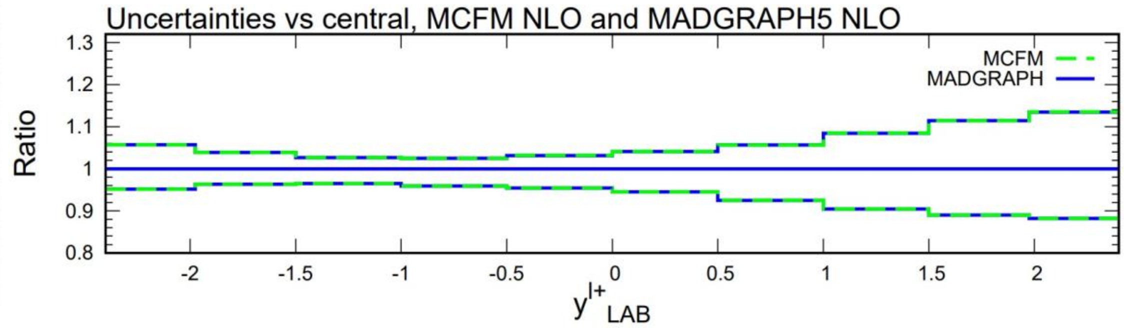
- Using it we can make p-Pb:
- $d\sigma_{pPb} = \sum_{p,Pb} \int dx_1 dx_2 f_p(x_1, \mu_F) f_{Pb}(x_2, \mu_F) d\hat{\sigma}_{pPb\to K}(\hat{s}, \mu_F, \mu_R)$

Validations of MG5 in asymmetric collisions

Validation vs MCFM for CT10 + nCTEQ15 for W production at NLO



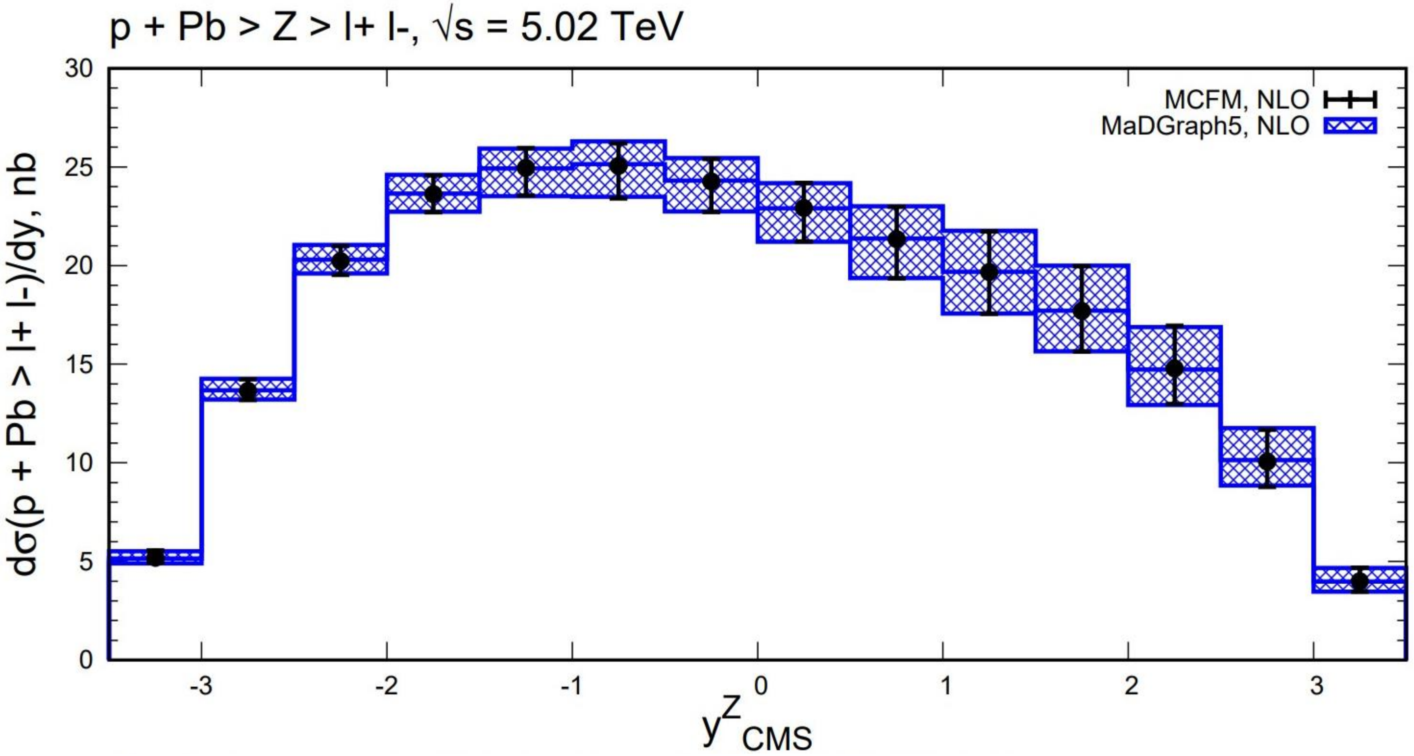


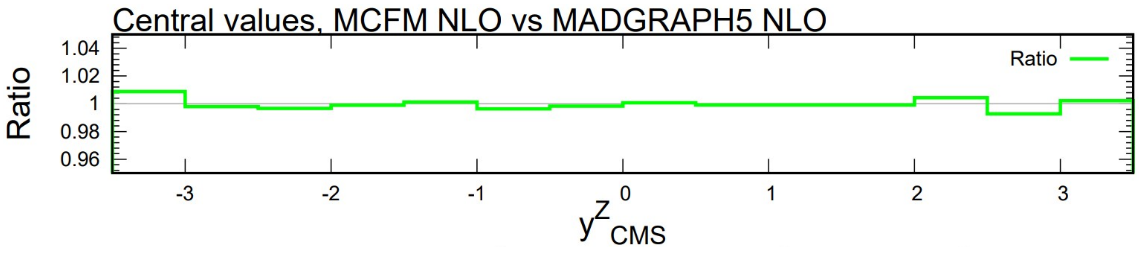


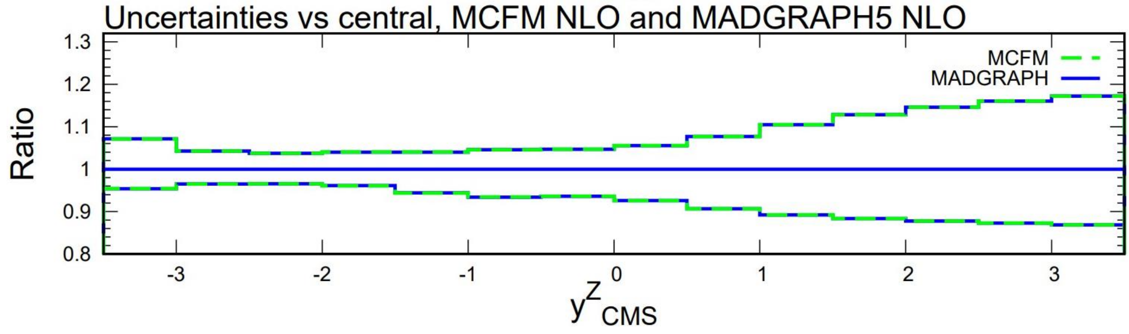
- **Perfect agreement** between **MG5** and **MCFM**-based computations W/Z production with nCTEQ15
- **No difference** in the uncertainty, if computation in **MCFM**-based code done with **unsymmetric** uncertainties

Validations of MG5 in asymmetric collisions

Validation vs MCFM for CT10 + nCTEQ15 for Z production at NLO







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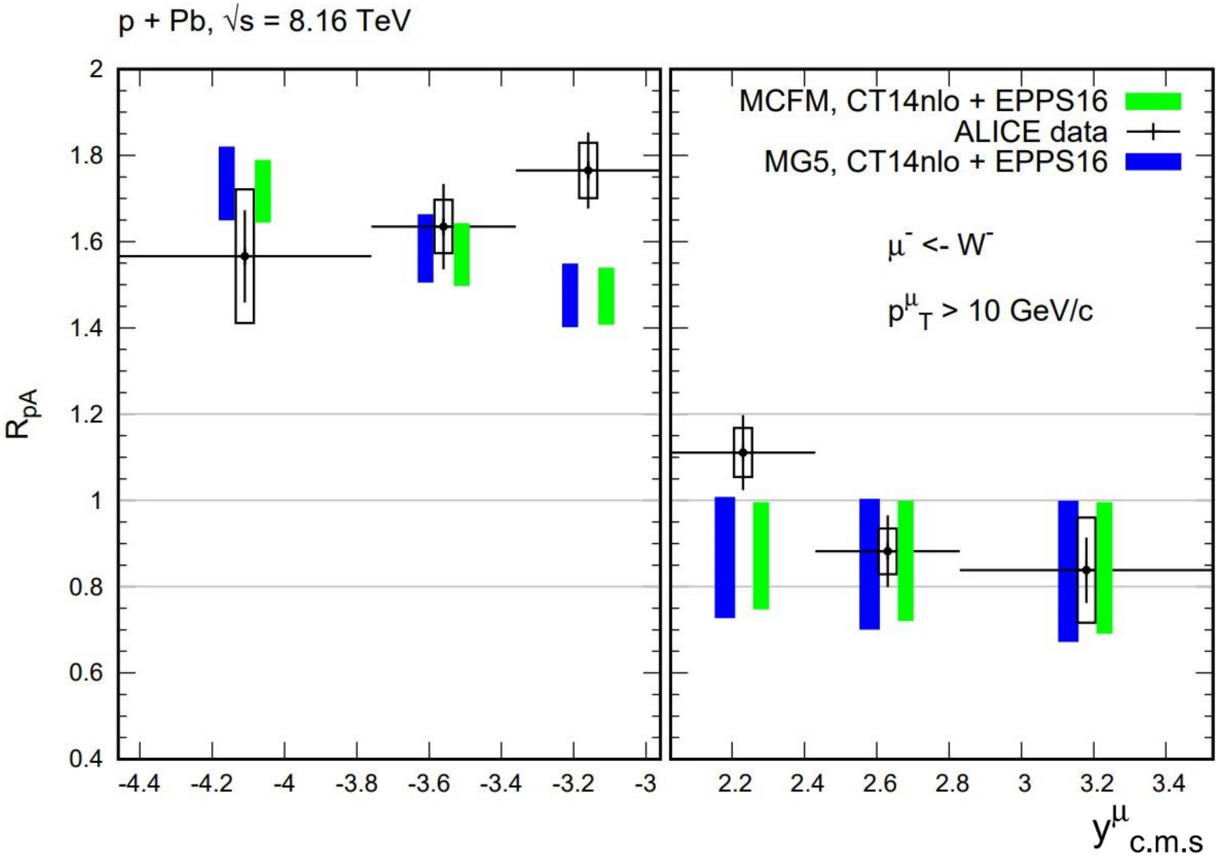
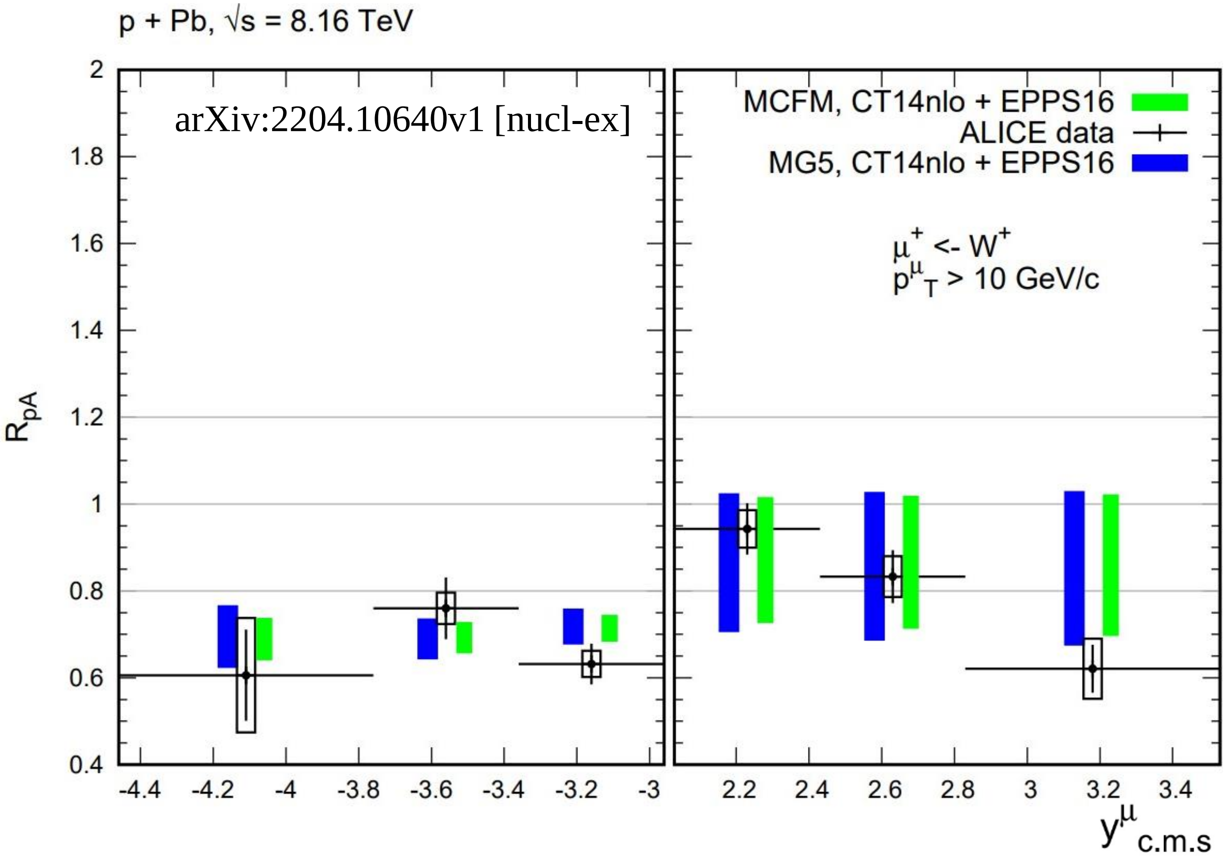
Validations of MG5 in asymmetric collisions

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

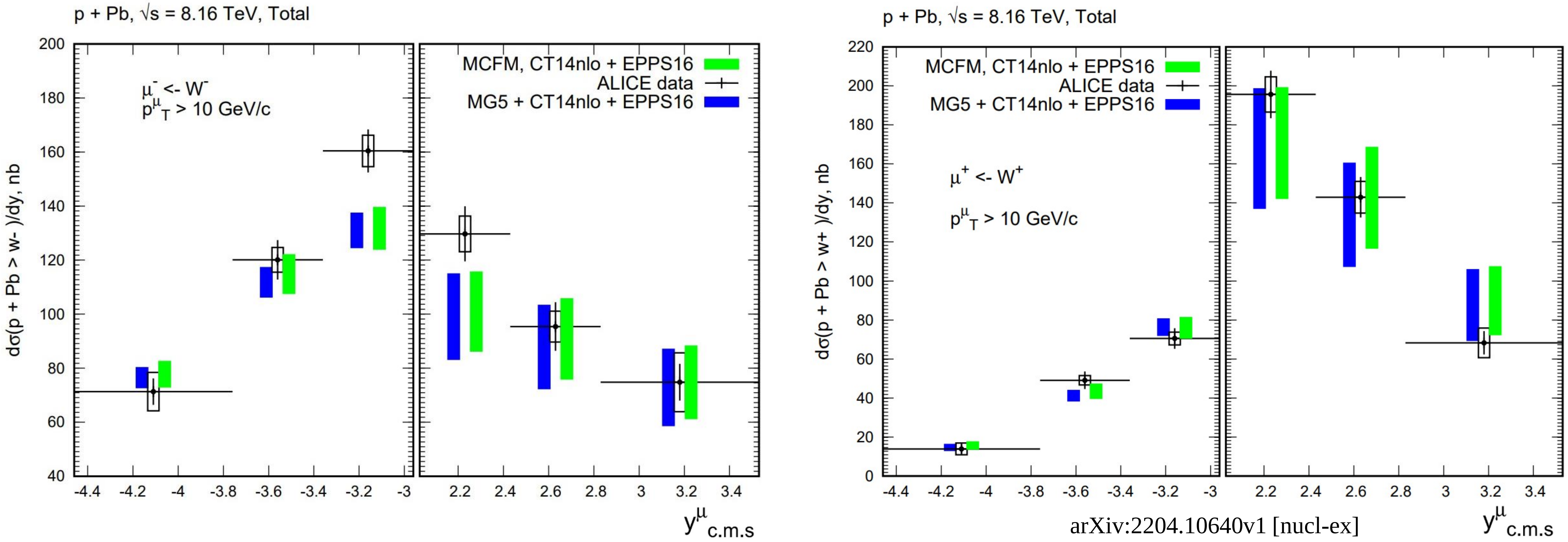




- **Good agreement** between **MG5** and **MCFM**-based computations for **EPPS16**
- Slight difference in the uncertainty since MCFM-based computation done with **symmetric uncertainties**
- More validations done vs FEWZ for :
  - **W** production with **nCTEQ15** for **CMS** kinematics
  - **Z** boson with **nCTEQ15** for **ATLAS/CMS** kinematics

Validations of MG5 in asymmetric collisions

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



arXiv:2204.10640v1 [nucl-ex]

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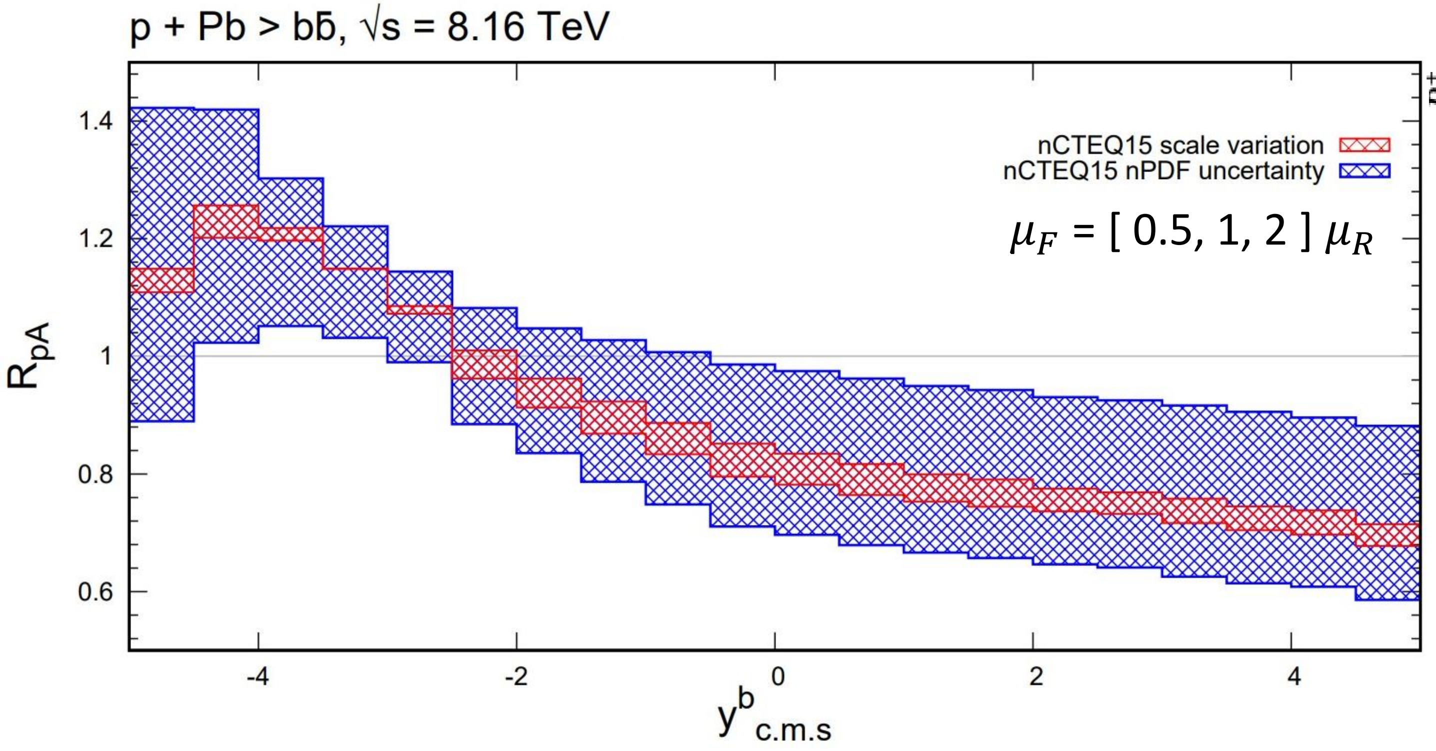
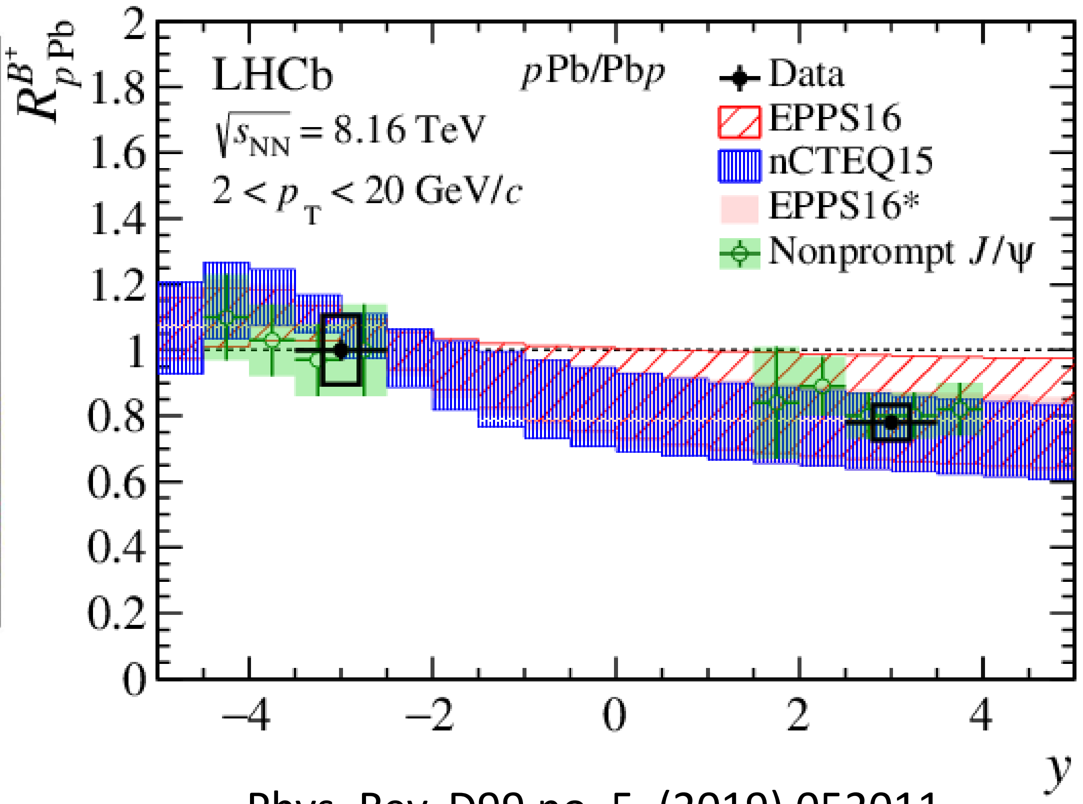
Example: *b* production in *p*Pb collision at LHC

Bottom quark production



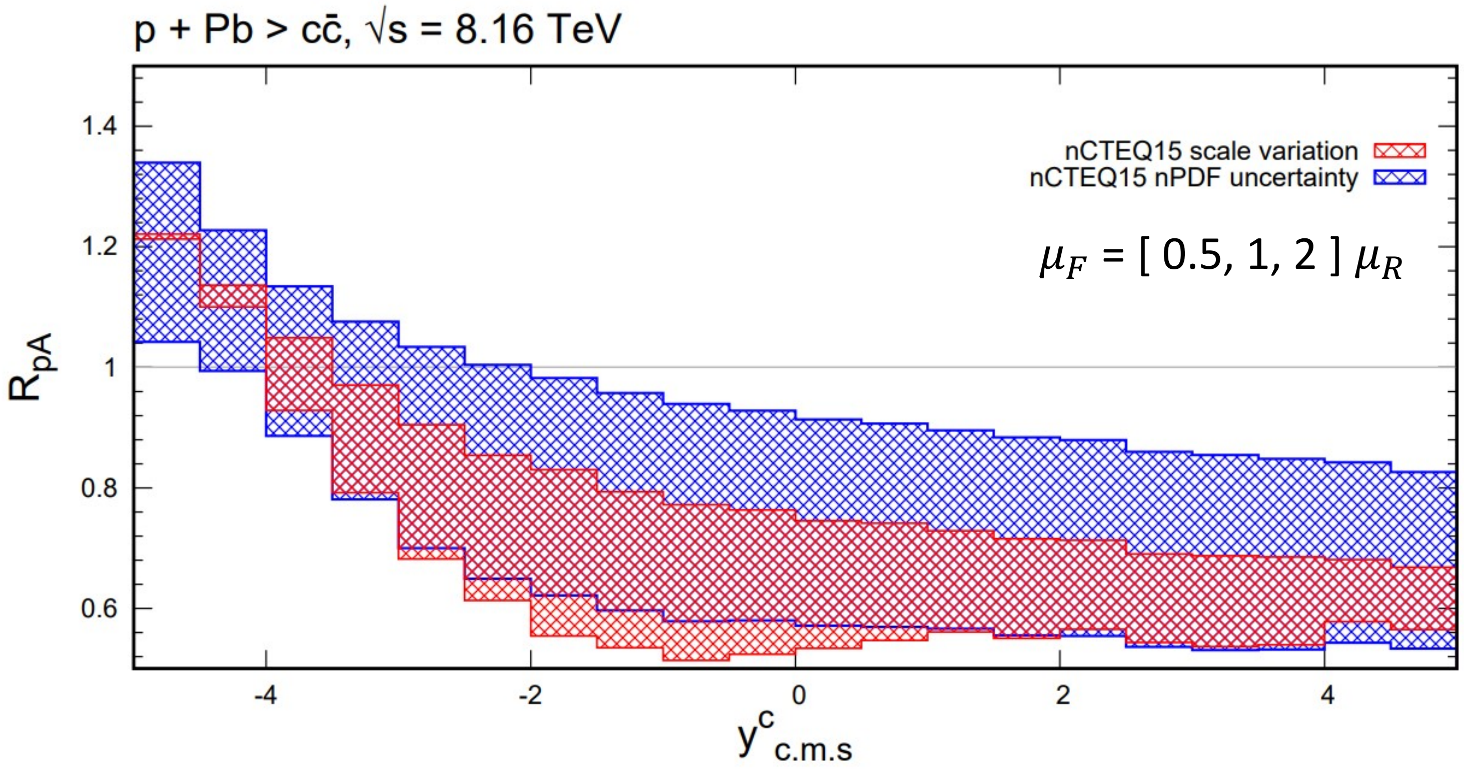


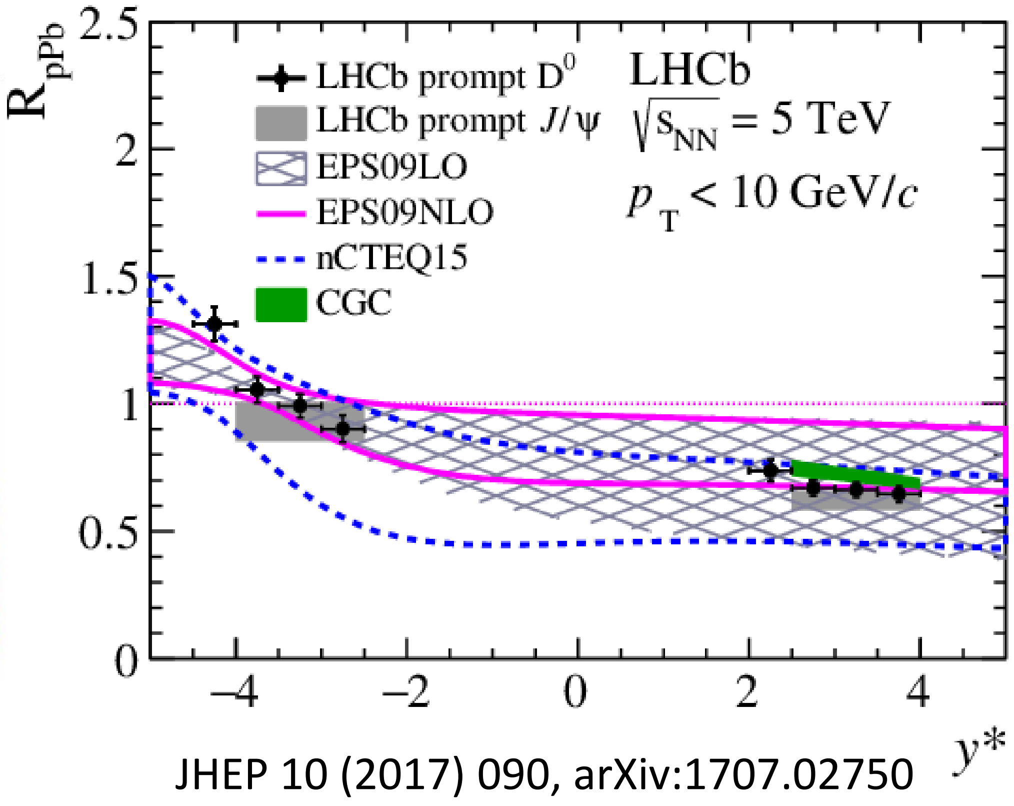
To make this plot, one just needs to input two numbers: **LHAPDF IDs** of proton and nCTEQ15 for Lead **Scale uncertainty can be automatically** computed.

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

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

Charm quark production



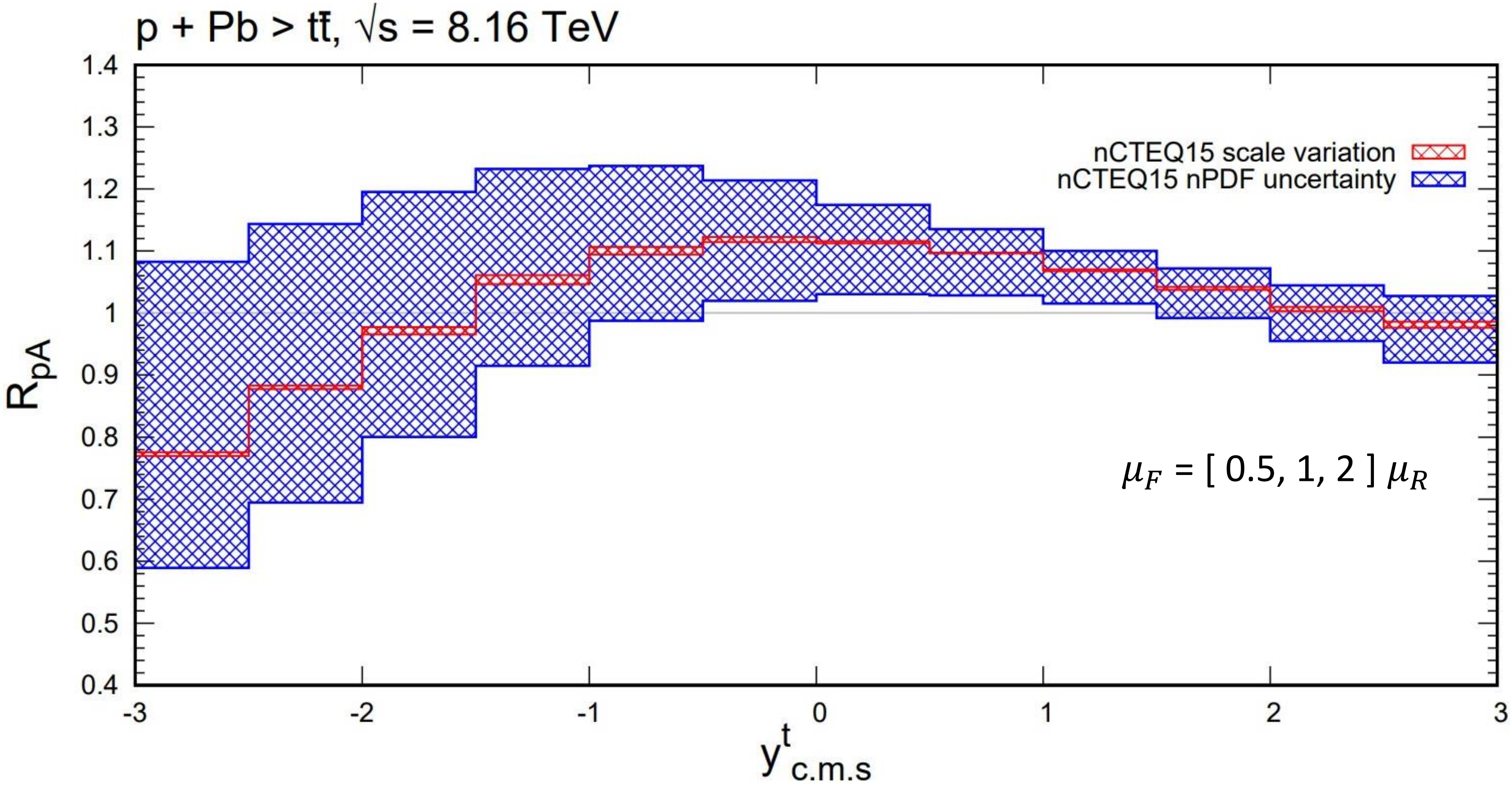


JHEP 10 (2017) 090, arXiv:1707.02750 [hep-ex].

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

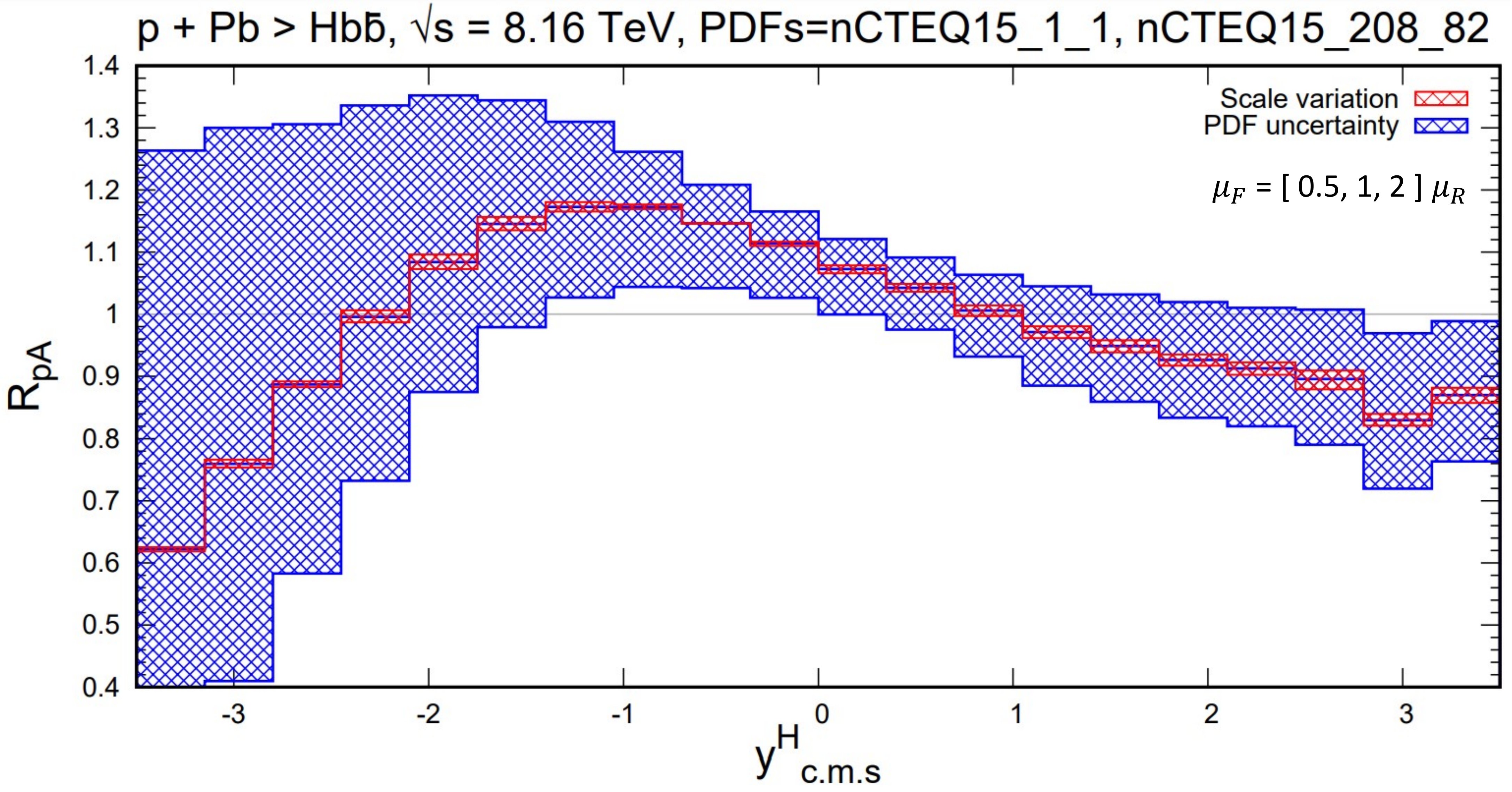
For charm production, $\boldsymbol{\mu_F}$ uncertainty nearly as **large** as the **nPDF uncertainty**.

Predictions for top production



- Scale uncertainty strongly reduced
- Very slight shadowing at $y^t_{CMS} = 3$
- Anti-shadowing down to $y^t_{CMS} = -1$
- Onset of gluon EMC effect for $y^t_{CMS} < -1$?

Fancier prediction: Higgs+$b\bar{b}$ at NLO



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

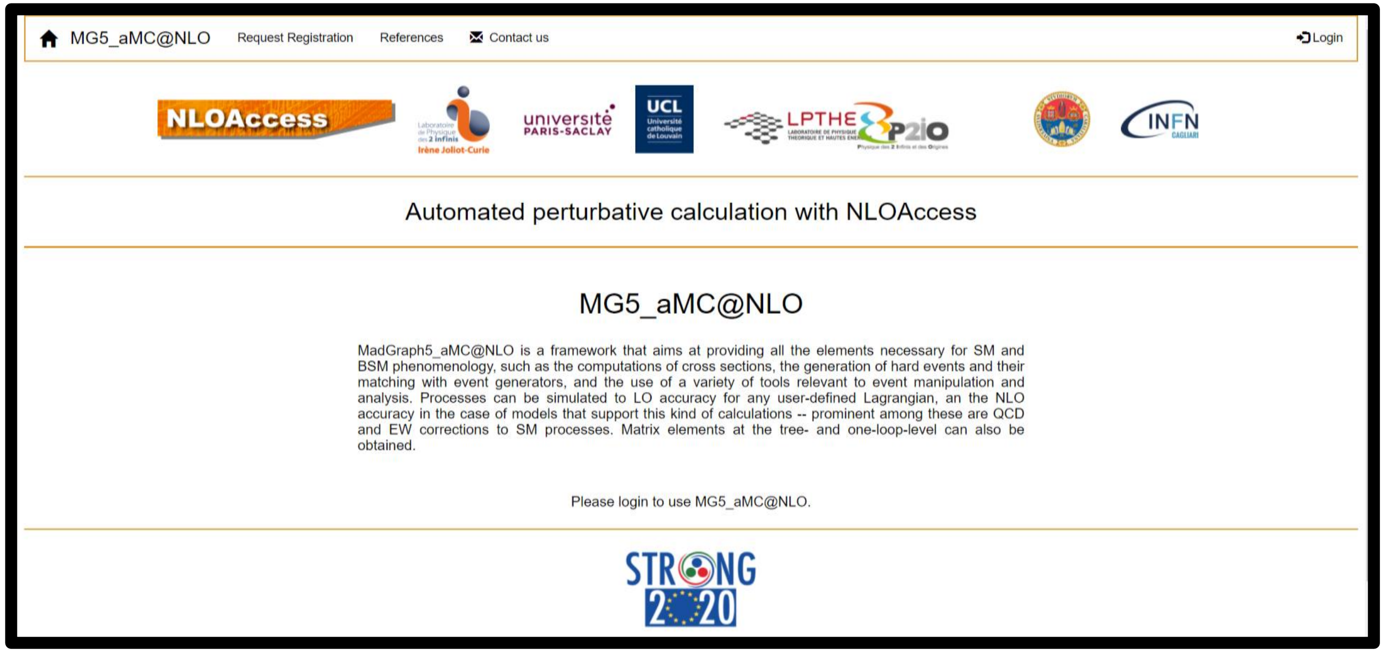
MadGraph in NLOAccess

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

Summary

- Asymmetric collisions in MadGraph5 have been implemented
- It can use various PDFs and nPDF (with their uncertainties) from LHAPDF library
- Nuclear modification factors are also computed automatically with their scale uncertainties
- Further possibilities are
  - Pion induced reactions
  - PDF reweighting “on the fly”
- In future, this upgrade of MG5 will be accessible via NLOAccess (https://nloaccess.in2p3.fr)

Backup

What was done

Basically:

Run_card:

- PDF set A
- PDF set B
- Or any number of the PDFs

$$d\sigma_{AA/BB} = \sum_{A1,A2\ /B1,B2} \int dx_1 dx_2 f_{A1/B1}(x_1, \mu_F) f_{A2/B2}(x_2, \mu_F) d\hat{\sigma}_{AA/BB \to K}(\hat{s}, \mu_F, \mu_R)$$

- We can derive 2 additional crossections: σ_{AB}, σ_{BA}
- Use analysis card to introduce cuts on any kinematic varibles
- Write down results in HwU file format
- Do plotting

Histogram output

Histogram With Uncertainty (HwU)

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##& 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 &
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+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 so as to account for scale, PDF and MC uncertainty.

The scale and PDF uncertainty 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 automatically by LHAPDF library according to special label inside PDF description (hessian, replicas etc.)

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)

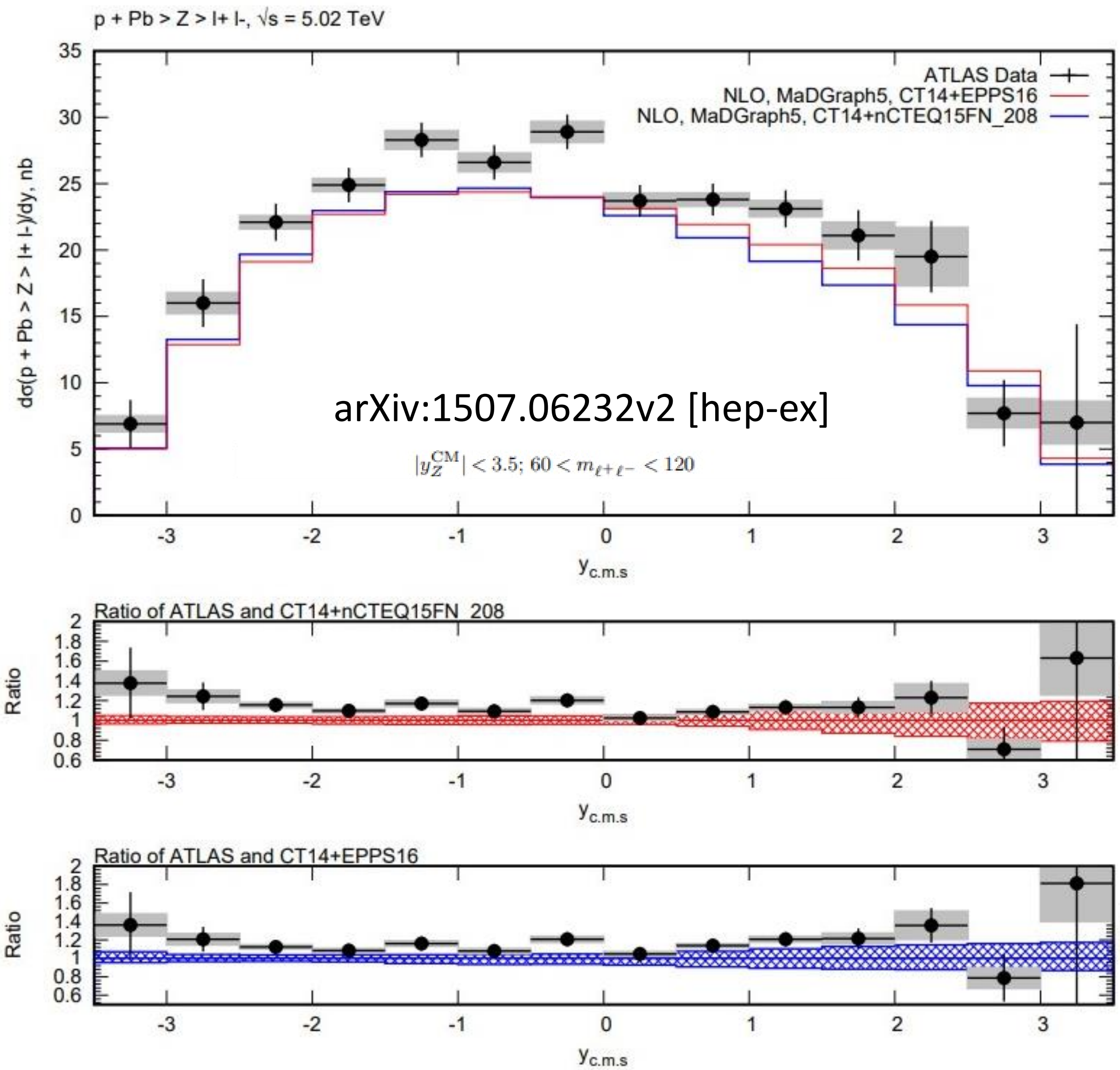
```
##& xmin & xmax & central value & dy & delta_mu_cen -1 @aux & delta_mu_min -1 @aux & delta_mu_max -1 @aux & dyn=-1 muR= 1.000 muF= 1.000 & dyn=-1 muR= 2.000 muF= 1.000 & dyn=-1 muR= 0.500 muF=
1.000 & dyn=-1 muR= 1.000 muF= 2.000 & dyn=-1 muR= 2.000 muF= 2.000 & dyn=-1 muR= 0.500 muF= 2.000 & dyn=-1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

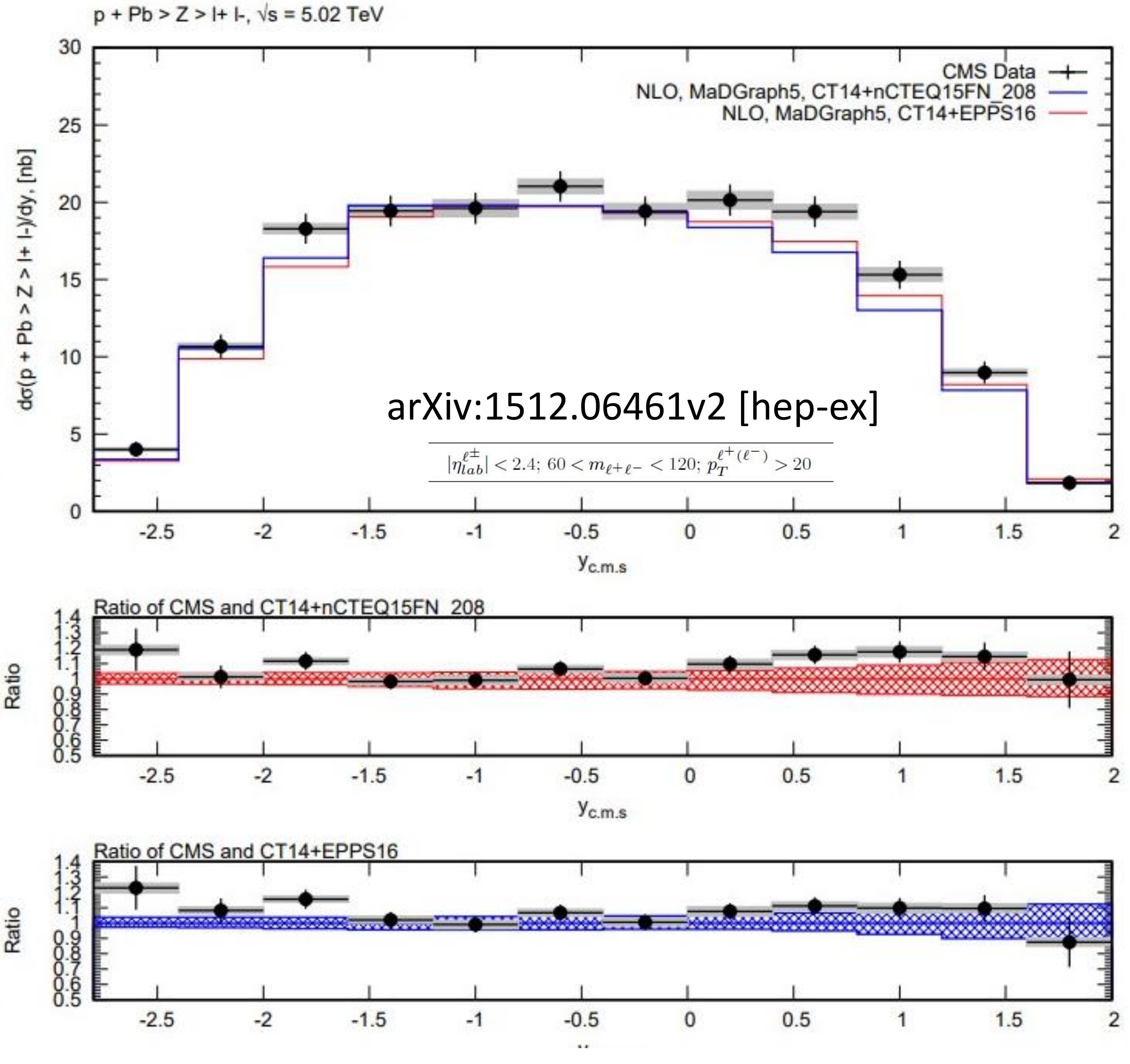
<histogram> 5 "total rate |X_AXIS@LIN |Y_AXIS@LOG |TYPE@#1"
  +5.0000000e-01   +1.5000000e+00   +6.9118832e+02   +5.1215007e+00  +6.9118832e+02   +6.0732421e+02   +7.6418582e+02   +6.9118832e+02   +6.3336687e+02   +7.4424264e+02   +6.6694792e+02
+6.0732421e+02   +7.2487765e+02   +7.1527317e+02   +6.5884776e+02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

Results

Z boson production

arXiv:1610.02925v2 [nucl-th]

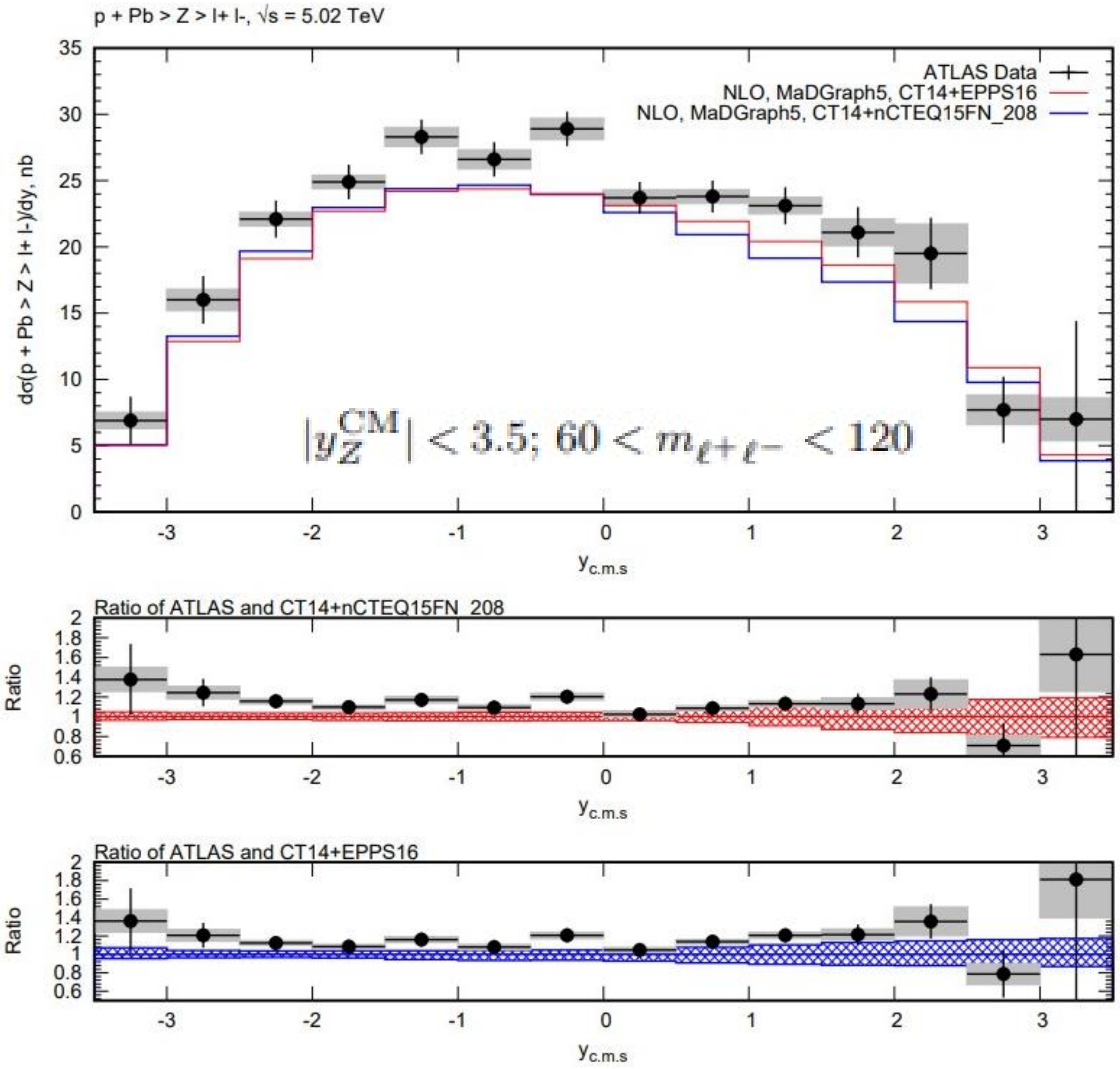


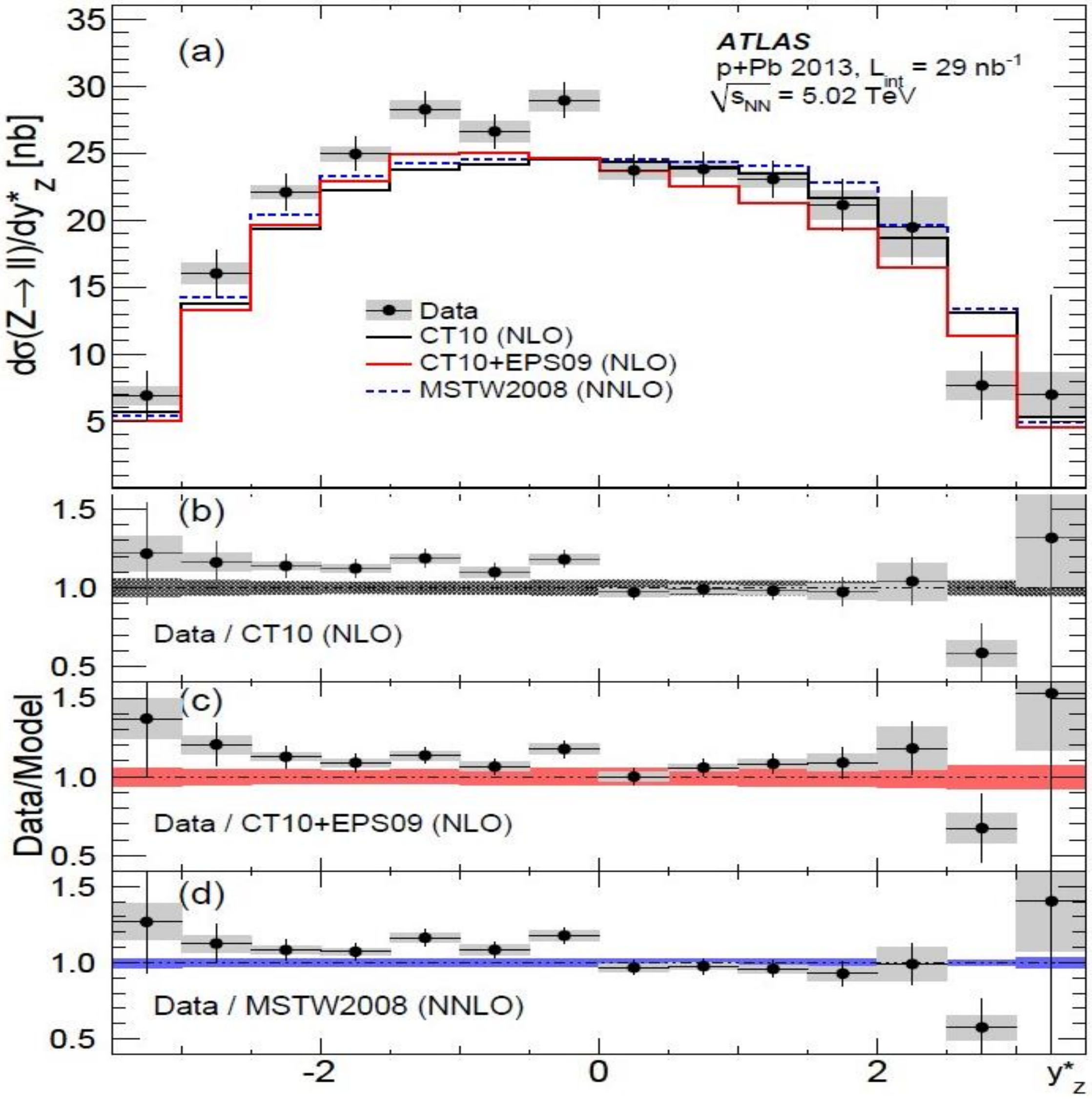


Results

Z boson
production

arXiv:1507.06232v2 [hep-ex]

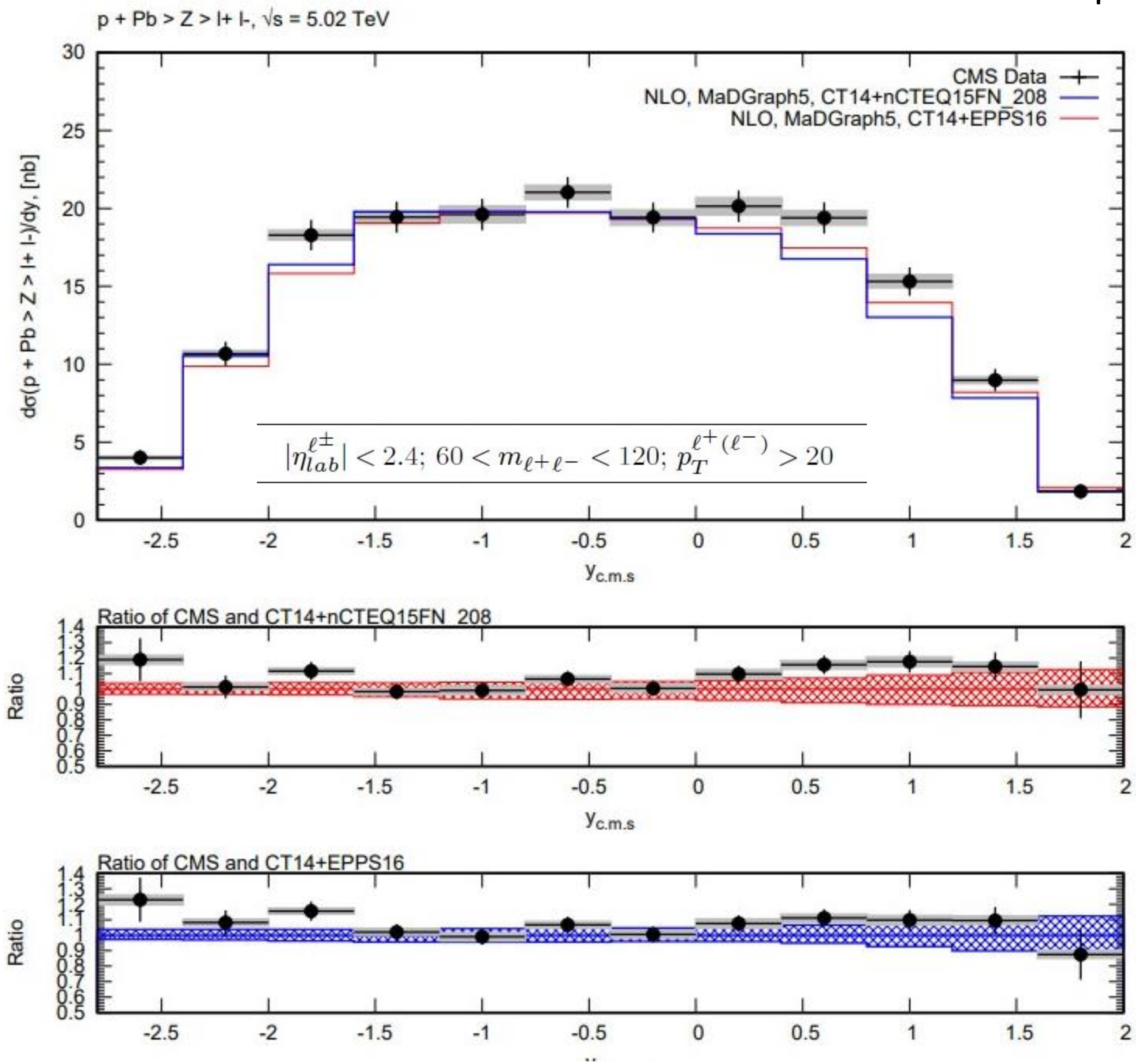


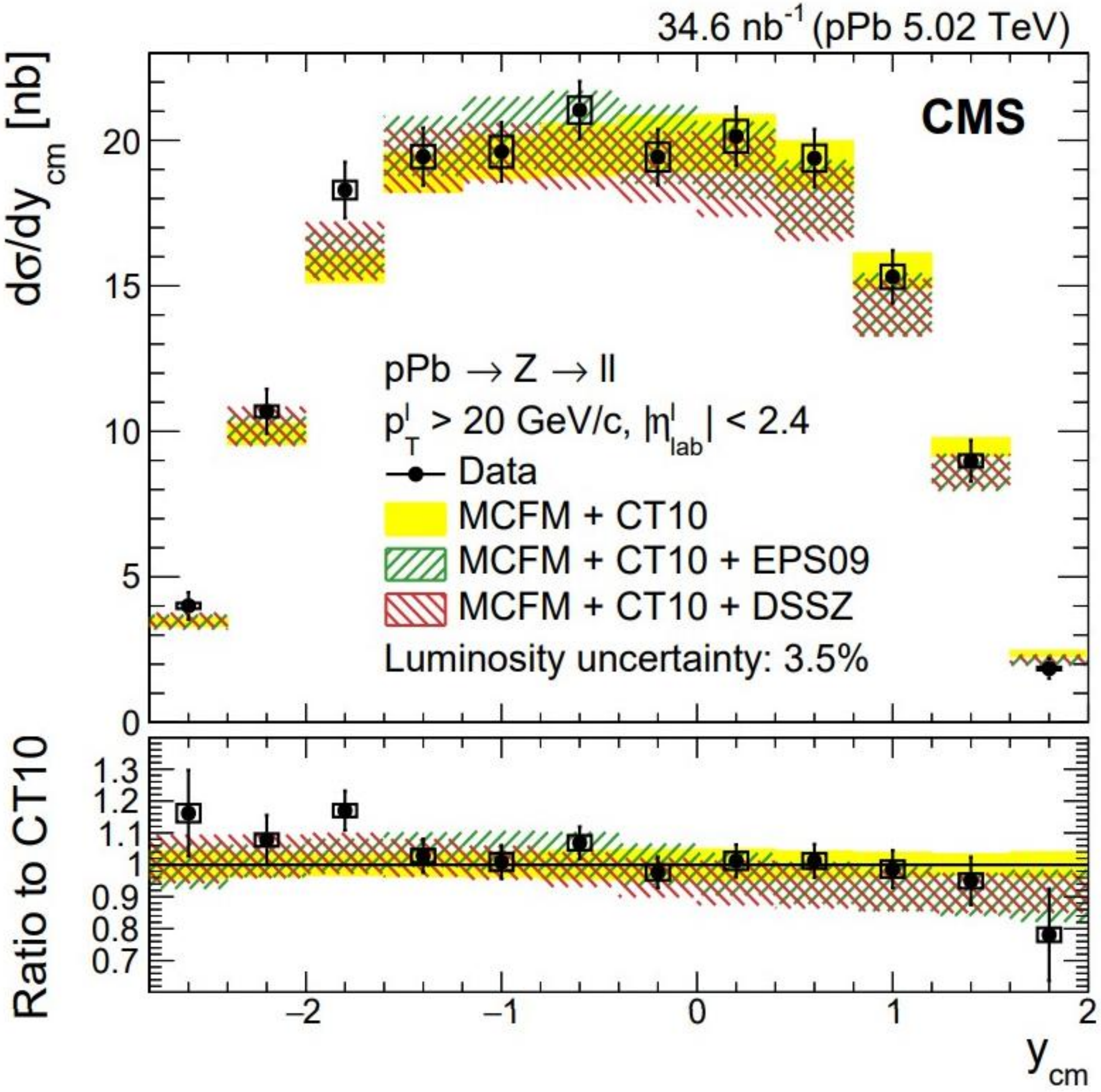


Results

Z boson production

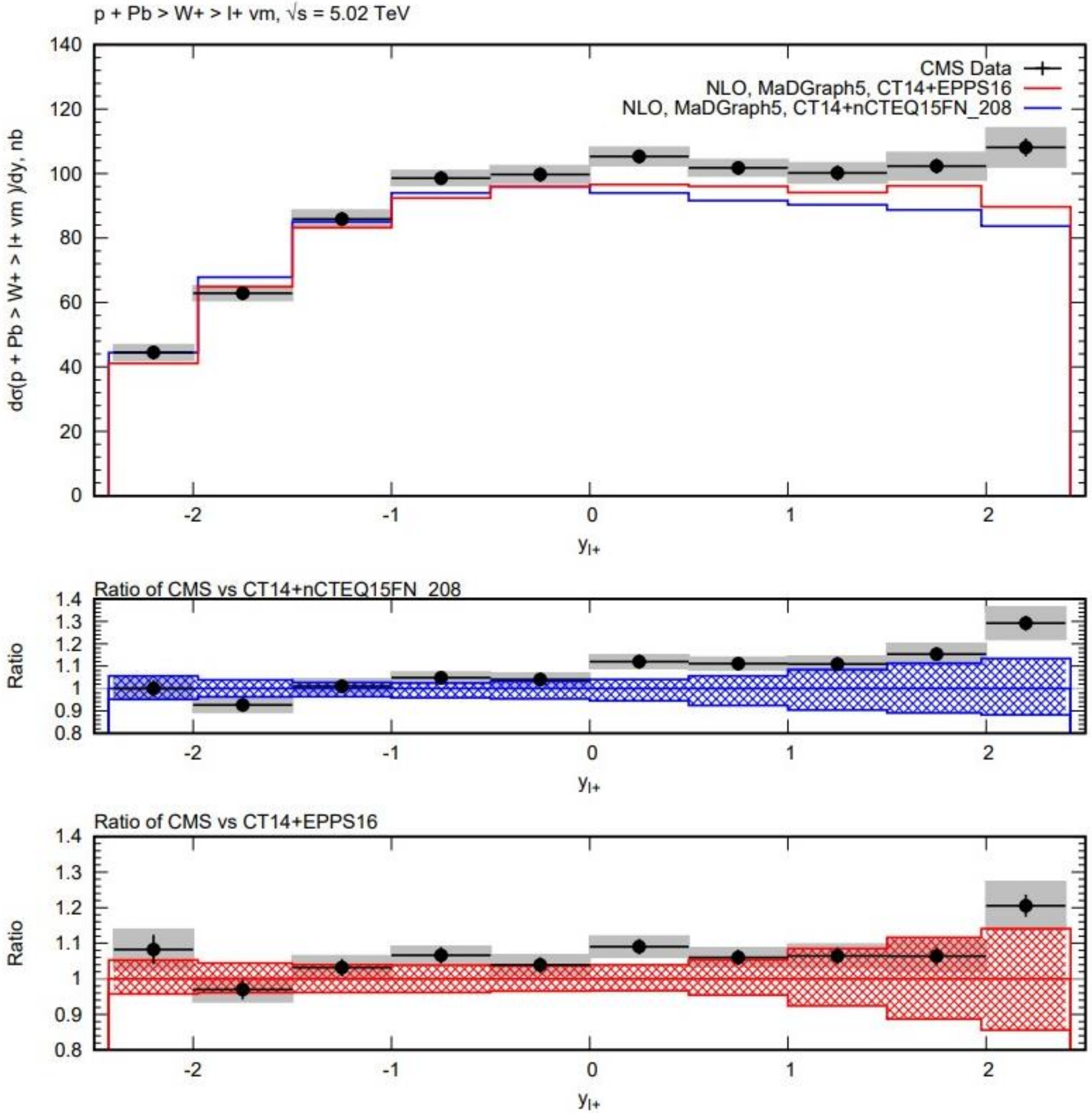
arXiv:1512.06461v2 [hep-ex]

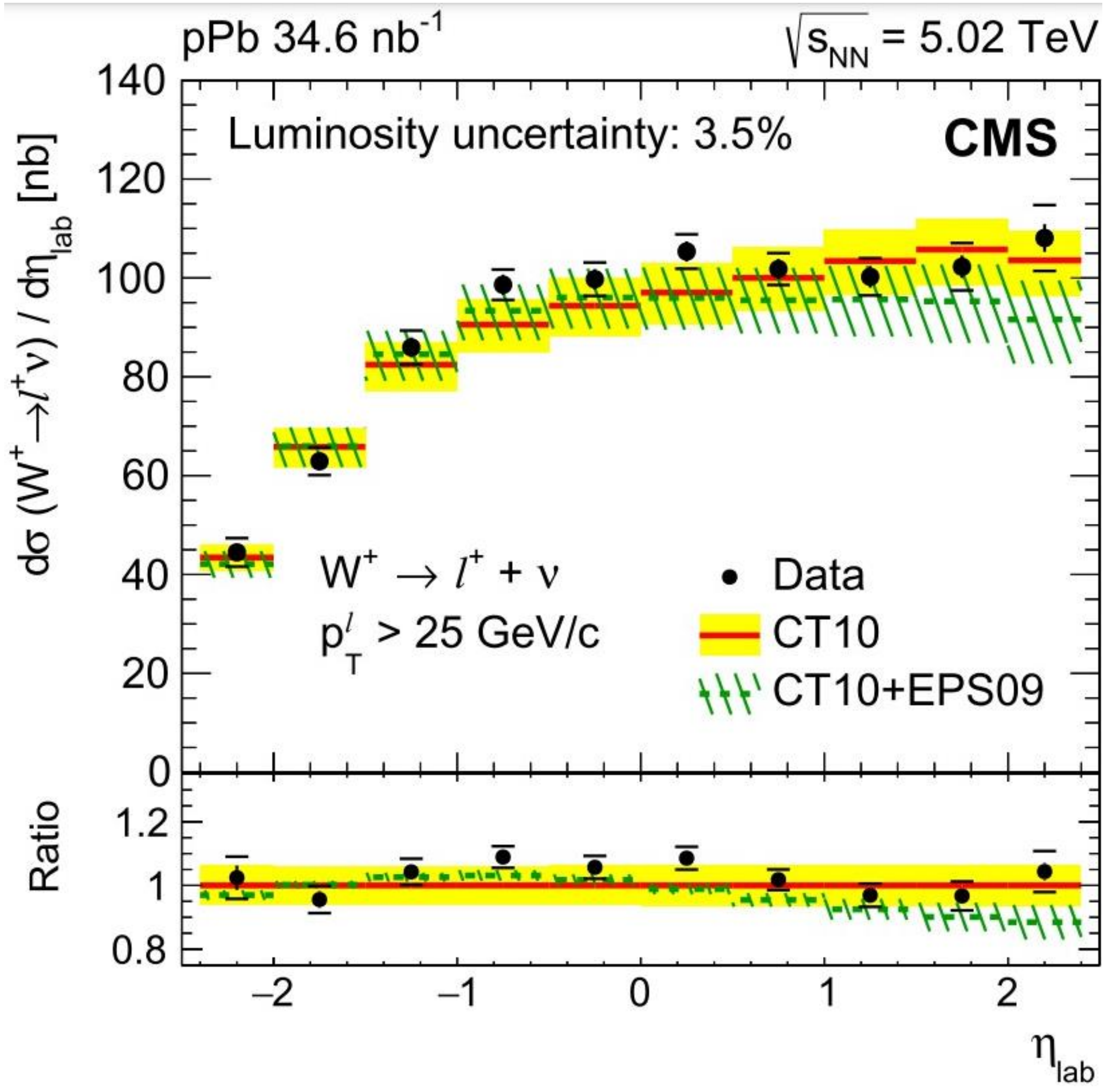




Results

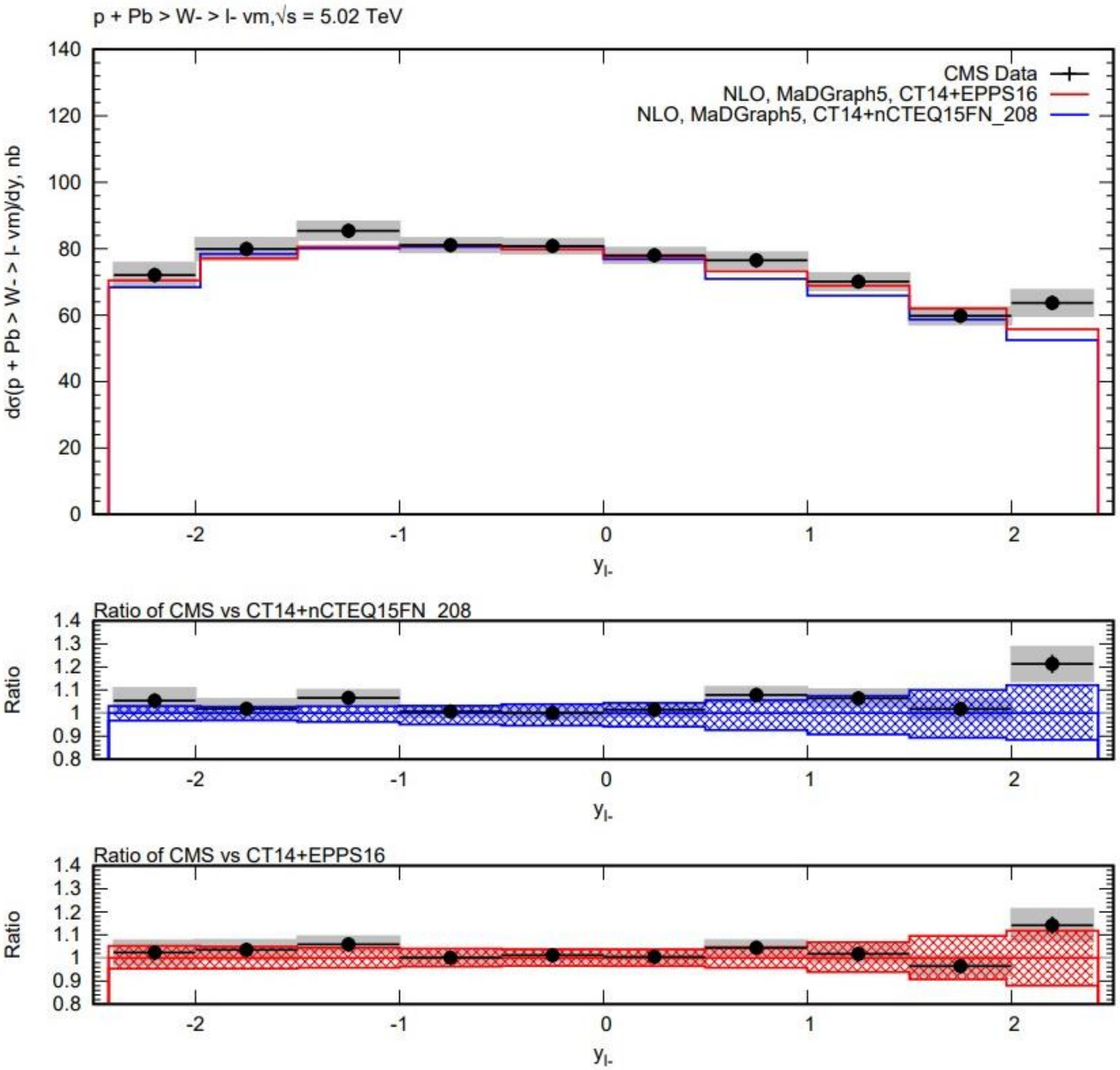
CMS Collaboration / Physics Letters B 750 (2015) 565–586

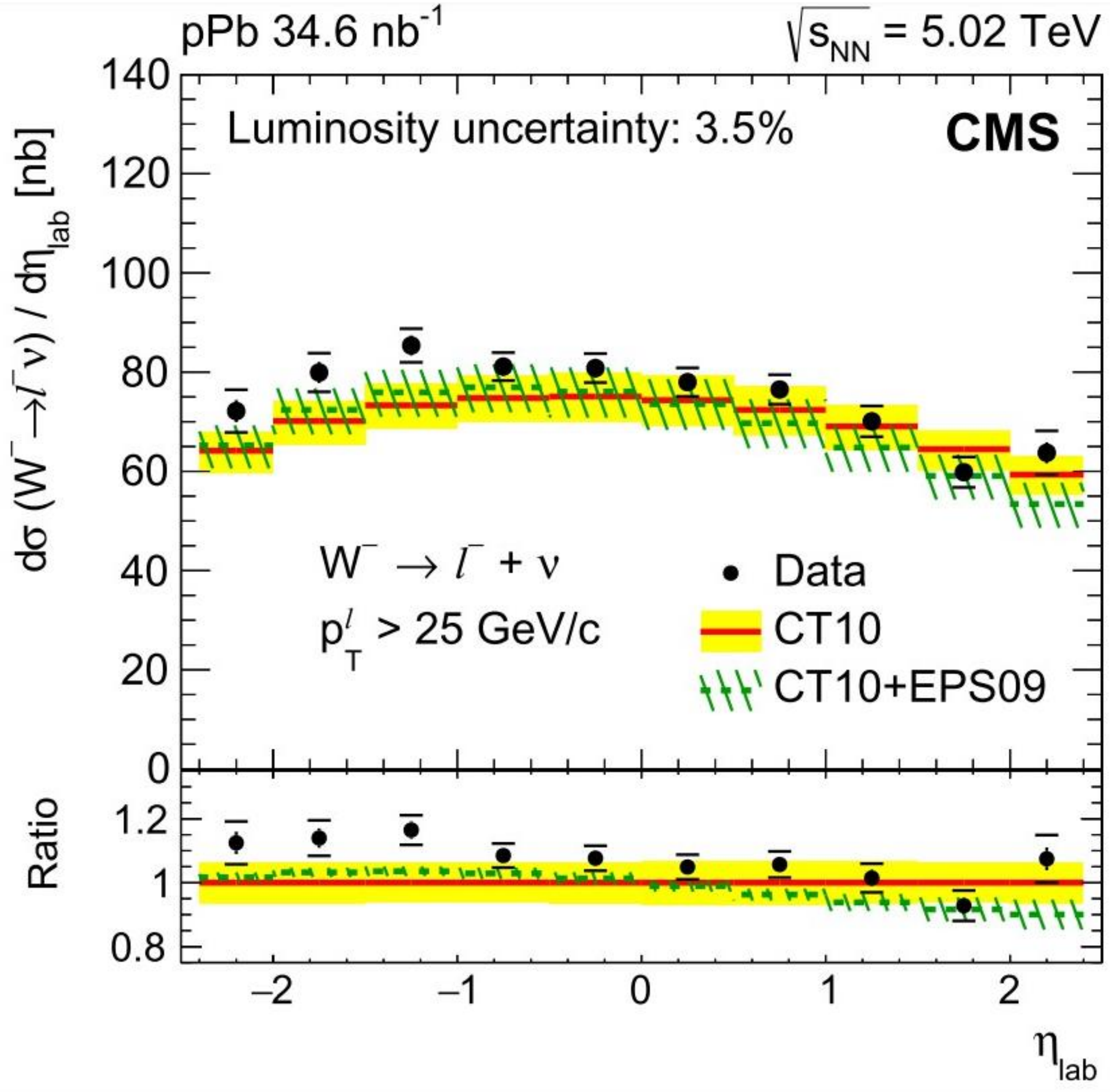




Results

CMS Collaboration / Physics Letters B 750 (2015) 565–586





Results

CMS Collaboration / Physics Letters B 750 (2015) 565–586