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A tool for automated perturbative cross section computations of asymmetric hadronic collisions at next-to-leading order using the MadGraph5_aMC@NLO framework

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Automated perturbative computations of cross sections for hard processes in asymmetric hadronic collisions at next-to-leading order in α_s will offer a wide range of applications, such as more robust predictions for new experimental codes, the phenomenology of heavy-ion collisions, and the interpretation of the LHC and RHIC data. Such a goal can now be achieved using MadGraph5_aMC@NLO, a well-established tool for automatic generation of matrix elements and event generation for high energy physics processes in elementary collisions. We report here about the extension of MadGraph5_aMC@NLO, done by implementing computations for asymmetric collisions. These new capabilities will be made available via the EU Virtual Access NLOAccess (https://nloaccess.in2p3.fr).

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1. Introduction

A reliable code for computing the cross section for a given process, colliding system and energy is an indispensable tool in feasibility studies for future experiments and in phenomenological analyses. To be of use for the experimental physics community, it should be possible to run such a tool without in-depth knowledge of the underlying theory (in this case Quantum Chromodynamics) and computing techniques. Such codes exist (MadGraph5_aMC@NLO [1], HERWIG [2], PYTHIA [3], SHERPA [4]) but not yet for asymmetric reactions. Moreover, in the case of nuclear collisions, their applicability for heavy-quark (namely charm and beauty) production is limited.

Our main motivation for the project presented here is to develop a reliable and high-precision tool for automated perturbative computation of cross sections for Standard Model processes in any asymmetric hadronic reaction, such as proton-nucleus or nucleus A + nucleus B collisions, at the Relativistic Heavy Ion Collider (RHIC) [5, 6] and the Large Hadron Collider (LHC) [7], including the fixed-target programs at LHCb and ALICE [8]. Such computations, performed at the next-to-leading (NLO) order in α_s, will offer a wide range of applications, such as more robust predictions for new experimental programs, for the phenomenology of heavy-ion collisions, and for the interpretation of the LHC and RHIC data. One example is the study of heavy flavor production in proton-lead collisions which probes the nuclear gluon distribution, that is poorly known and yet crucial for modelling and interpretation of experimental data.

2. The framework: collinear factorization

The standard approach for computing the cross section for hard processes (processes with large energy transfer) is the collinear factorization. In this approach the cross section is calculated as a convolution of parton level matrix element (which can be calculated using perturbative QCD) and non-perturabtive objects, representing the distributions of partons in hadrons, called Parton Distribution Functions (PDFs):

$$\sigma_{AB\to X} = \sum_{a,b} \int dx_1 dx_2 f_a^A(x_1, \mu_F) f_b^B(x_2, \mu_F) \widehat{\sigma}_{ab\to X}(x_1, x_2, \mu_F, \mu_R) \tag{1}$$

where f_a^A, f_b^B are the PDFs of the incoming hadrons/nuclei, μ_F and μ_R are, respectively, the factorization and renormalization scales, x_1 and x_2 are longitudinal momentum fractions carried by the partons compared to the hadrons, $\widehat{\sigma}_{ab\to X}$ is the partonic cross section. The PDFs encode information about the parton flux as a function of x and, in case of nuclear PDFs, also information about possible modifications in nucleus [9–11].

Since (n)PDFs are non-perturbative objects, they are obtained by fitting experimental data with theoretical inputs. Ratios of cross sections are usually used for this purpose because some (theoretical and experimental) uncertainties are expected to cancel to some extent for such observables. In the case of nPDFs studies, an example of such a ratio is the nuclear modification factor (NMF) R_{pA}, defined as:

$$R_{pA} \equiv \frac{1}{A}\frac{d\sigma_{pA}}{d\sigma_{pp}}, \tag{2}$$

where σ_{pA} and σ_{pp} are the cross sections for proton-nucleus and proton-proton collisions respectively and A is the number of the nucleons in a nucleus A. The NMF could be differential in the transverse momentum $P_{T,\mathcal{H}}$ or the center-of-mass system (c.m.s.) rapidity $y_{cms,\mathcal{H}}$ of the observed hadron $\mathcal{H}$, as well as a function of the collision centrality.

3. MadGraph5_aMC@NLO and implementation of nuclear effects

MadGraph5_aMC@NLO (MG5aMC) is a well-established flexible, robust, high-accuracy (NLO) tool for the automated generation of matrix elements and events for High Energy Physics processes, such as decays and $2 \rightarrow N$ scatterings for any Standard Model and Beyond the Standard Model process. In its standard version, MG5aMC supports computations for symmetric reactions, where the flux for both incoming partons is given by the convolution of two PDFs of the same kind (*i.e.* two proton PDFs or two nPDFs).

To allow for the study of nuclear effects at NLO with MG5aMC, we have extended the existing algorithm to use two different PDF sets and calculate cross sections or NMFs as a function of user-defined kinematical variables, for instance rapidity (y), transverse momentum (p_T) of a particle, or relative azimuthal angle ($\Delta\phi$). This new algorithm provides all relevant uncertainties (statistical, scale and PDF) automatically.

This developement of MG5aMC includes the modification of the Fortran routines, responsible for handling the parton luminosity, and the modification the of Python code, responsible for the histograms generation and calculation of uncertainties. For the NMFs (e.g. R_{pA}), we assume that the nPDF uncertainty dominates over the proton PDF one. As such, we consider only the uncertainty on the nuclear PDF. To properly include uncertainties on both the numerator and the denominator of the NMF, one needs to know their possible correlations, which we leave for future work.

4. Validation

To validate the new algorithm, we have compared our results to those obtained using the MCFM [12] code. We have considered Z and W^+ boson production in proton-lead collisions at the LHC, at a c.m.s. energy per nucleon-nucleon collision $\sqrt{s_{NN}} = 5.02$ TeV. we have applied the following selection criteria: $|y_Z^{\rm cms}| < 3.5$ and $66 < m_{l^+l^-} < 116$ GeV for the Z rapidity in the c.m.s. and the invariant mass of produced lepton pairs, respectively; $|p_T^{l^+}| < 3.5$ GeV and $|\eta_{\rm lab}^{l+}| < 2.4$ for the transverse momentum and the pseudorapidity in the laboratory frame of leptons produced in the W^+ boson decay. All calculations were performed in the center-of-mass frame at NLO accuracy. The top plots in Figure 1 show the comparison between the results obtained with a modified version of MG5aMC and MCFM using the CT10nlo proton PDFs [13] and the nCTEQ15 lead PDFs [11]. Note that only the nPDF uncertainty is shown, in blue for MG5aMC and in black for MCFM, respectively. The green curve in the middle plots of Figure 1 is the ratio between the central values of MG5aMC and MCFM, while the bottom plots in Figure 1 represent the ratio of uncertainties to the central value for each generator. All plots show excellent agreement between our new algorithm and the results from MCFM. The validation of this modified MG5aMC version against another NLO code, FEWZ [14, 15], also yielded very satisfactory results.

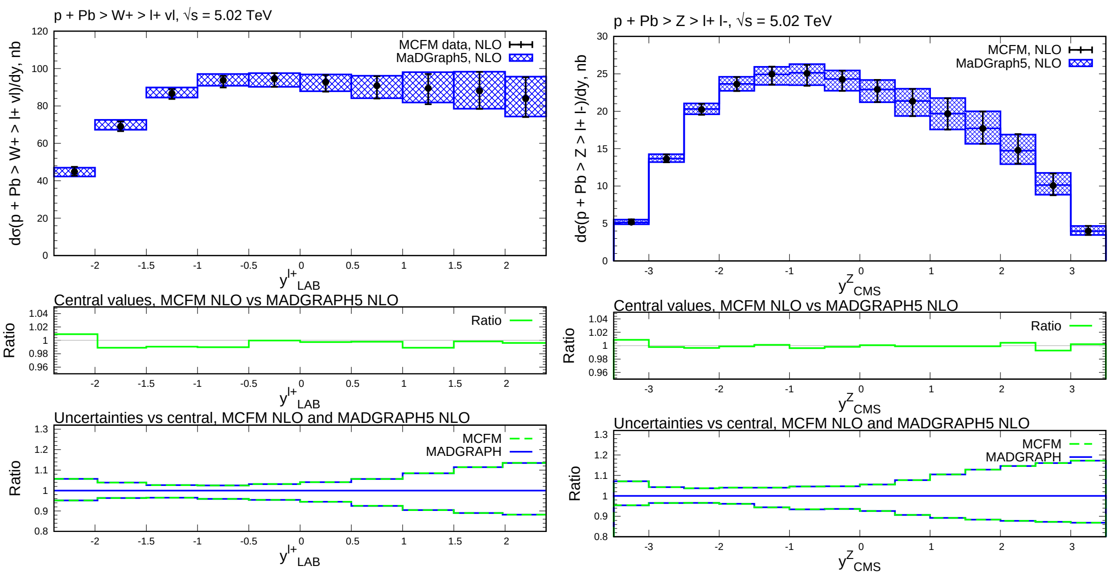

Figure 1: Validation of the `MadGraph5_aMC@NLO` asymmetric code versus `MCFM` using cross sections of W^+ and Z bosons production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

5. Predictions

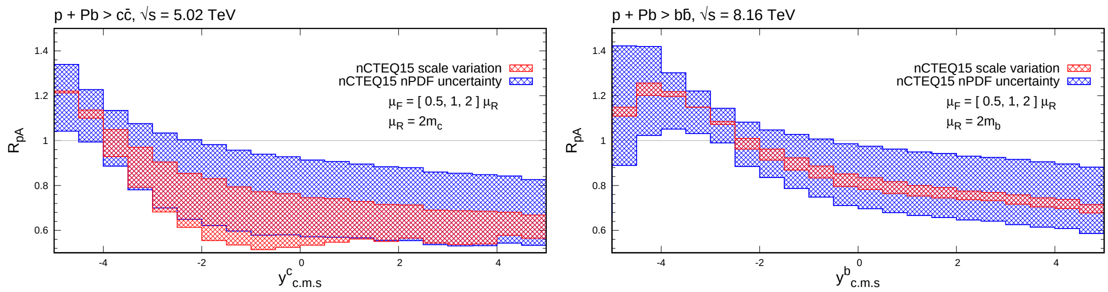

Figure 2: NMFs for charm- and bottom-quark production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 8.16$ TeV. The factorization scale and the PDF uncertainties are shown with red and blue bands, respectively.

Thanks to the automation of the `MG5aMC` framework, we are virtually able to provide predictions including nPDF effects for any hard process in proton-nucleus or nucleus-nucleus reactions. Figure 2 shows cross section for charm- and bottom-quark production in proton-lead collisions at a c.m.s energy per nucleon-nucleon collision $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 8.16$ TeV respectively. In both cases, we used the nCTEQ15 PDF for the proton and for the lead. The factorization scale and the nuclear PDF uncertainties are shown with red and blue bands. We stress that, from the user perspective, one just needs to provide the `LHAPDF` [16] IDs for the proton and for each nucleus of interest, and all calculations (including uncertainties) will be performed automatically by `MG5aMC`. Our results match very well with the data measured by the LHCb collaboration [17, 18], although our computations do not include the hadronization process yet. Our updated `MG5aMC` is also capable of delivering predictions for more exotic processes as top-quark or even $H^0 + b\bar{b}$ production at NLO accuracy. For each of these results MG5aMC provides production cross section, NMFs (as a function of any kinematic variable) and scale and PDFs uncertainties.

6. Conclusion

To summarize, we have extended the capabilities of MadGraph5_aMC@NLO by implementing the computation of cross sections for asymmetric nuclear collisions. This allows using any PDFs and nPDFs (with their uncertainties) from the LHAPDF library. Nuclear modification factors are also computed automatically with their scale and nPDF uncertainties. We have validated our results against the broadly used MCFM and FEWZ codes and we have observed excellent agreement. The predictions obtained for heavy-quark production in p-Pb collisions at different c.m.s. energies are in agreement with the data from the LHCb experiment [17, 18] and other theory predictions therein. In the near future we plan to validate the MadGraph5_aMC@NLO framework for pion-induced reactions. All these new capabilities will be available via the EU Virtual Access NLOAccess (https://nloaccess.in2p3.fr). We expect our new tool to be useful for theoretical predictions, for the phenomenological exploration of current and new data collected at the LHC or RHIC, and for feasibility studies for new experimental endeavours like a fixed-target program at the LHC [8].

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