Extensions of MadGraph5_aMC@NLO for QCD studies

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Theoretical Overview

Parton distribution functions (PDFs) $= f(x, \mu_F^2) =$ momentum distribution of the quarks and gluons within a hadron.

In collinear factorization,

$$\sigma_{AB} = \sum_{i,j} \int dx_i \int dx_j \int d\Phi_f \, f_i^A(x_i, \mu_F^2) f_j^B(x_j, \mu_F^2) \frac{d\hat{\sigma}_{ab}(x_i, x_j, \mu_F^2, \Phi_f)}{dx_i dx_j d\Phi_f}$$

$d\hat{\sigma}_{ab} =$ Partonic cross section related to a & b , calculable within perturbation theory.

The partonic cross section can be expanded as:

$$\hat{\sigma} = \underbrace{\overbrace{\sigma^{Born}}^{\text{LO}} \left(1 + \frac{\alpha_s}{2\pi}\sigma^1\right.}_{\textbf{NLO}} \left. + ..\right)$$

* LO = Leading order, NLO = Next-to-leading order and so on.

Nuclear PDFs

Parton-distribution functions (PDFs): essential link between hadronic cross sections and partonic cross sections

Challenging situation for PDFs of nucleons inside nuclei (nPDFs)!

nPDFs give information on:

- The nuclear structure ;
- The initial state of relativistic heavy-ion collisions.

(n)PDFs cannot be computed and are fit to experimental data. Only their evolution is perturbative

Nuclear Modification Factors: For rare or hard probes [$\sigma_{NN}^{probe} << \sigma_{NN}^{inel}$]

$\sigma_{AB}^{probe} = A \times B \times \sigma_{NN}^{probe}$ [Each probe is produced independently]

We can define Nuclear Modification Factors R as,

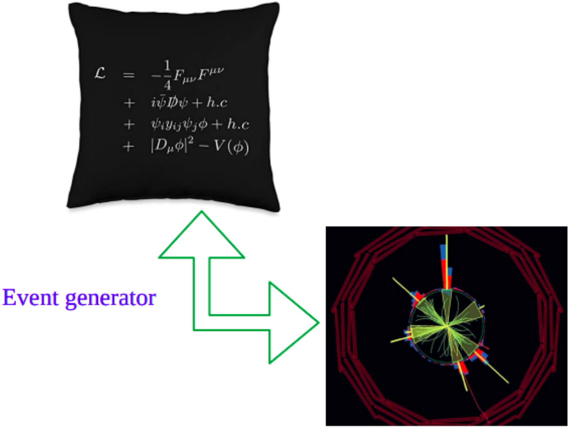
$$R_{AB} = \frac{\sigma_{AB}}{AB\sigma_{pp}}$$

$$R_{pA} = \frac{\sigma_{pA}}{1 \times A \times \sigma_{pp}} \qquad R \approx 1 : \text{ No nuclear effects}$$

$$R_{eA} = \frac{\sigma_{eA}}{1 \times A \times \sigma_{ep}}$$

Introduction to MadGraph5_aMC@NLO

- It's an automated matrix element generator.
- It can support a huge class of particle physics models.
- The program can calculate amplitudes at the tree and one loop levels for arbitrary processes.



Missing: asymmetric collisions at next-to-leading (NLO)!

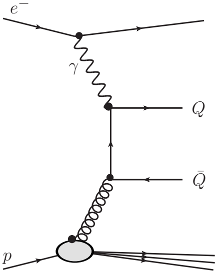
Asymmetric collisions implemented in MG5_aMC

- Photoproduction (L. Manna)
- Hadron A +Hadron B collision (A. Safronov)
- Quarkonium production (C. Flett & A. Colpani-Serri)

Electron–proton collisions

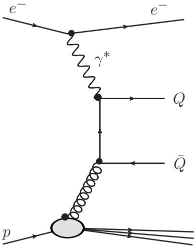
Electron-proton processes : Classified according to Q^2, the photon virtuality $Q^2 = -q^2 = -(k - k')^2$

I) Photoproduction :
Photon is nearly on mass shell.



$Q^2 \leq m_H$

II) Deep-Inelastic-scattering (DIS):
Photon is off mass shell.

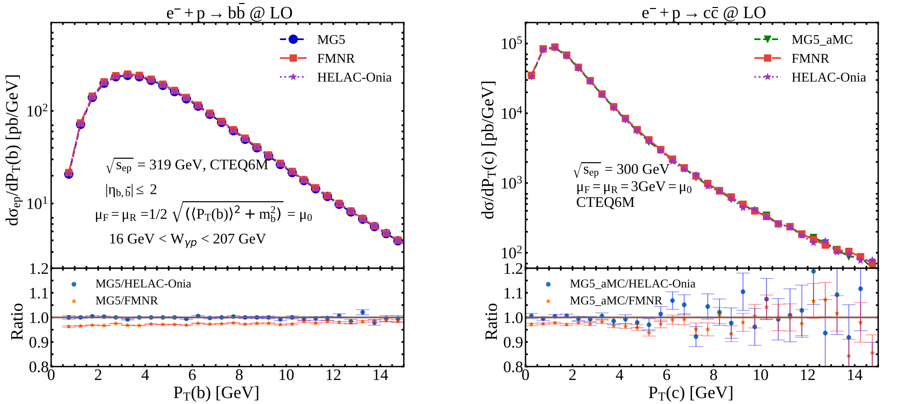


$Q^2 >> m_H$

Validations

- Photoproduction
- pA collisions

Direct Photoproduction: Validation of LO Results

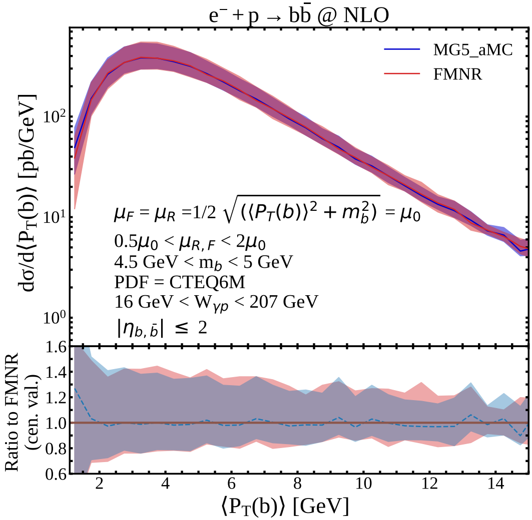


- Better agreement with HELAC-Onia than that of FMNR.

*HO = Helac-Onia
*FMNR : a private code by Stefano Frixione, Michelangelo L. Mangano, Paolo Nason, Giovanni Ridolfi
https://doi.org/10.1016/0550-3213(94)90501-0

Direct photoproduction: Validation at NLO

H1 Collaboration, 10.1140/epjc/s10052-012-2148-1

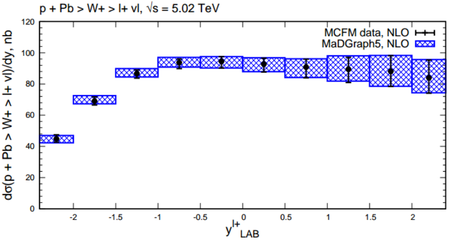


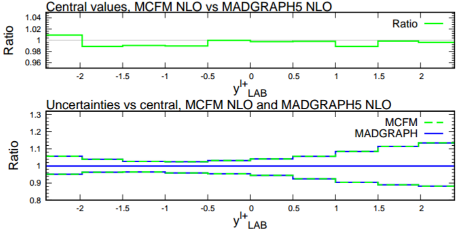
Approximately $\sim \mathcal{O}(1\%)$ agreement (direct photon contribution)!

L. Manna et. al, PoS EPS-HEP 2023 449 https://doi.org/10.22323/1.449.0274

Validation of calculations for pA collisions at NLO

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



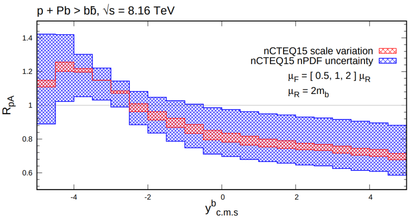


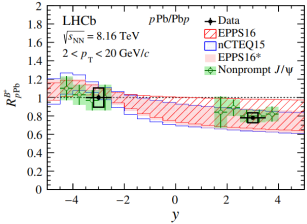
- Perfect agreement between MG5_aMC and MCFM-based computations W production with nCTEQ15
- No difference in the PDF uncertainty, if computation in MCFM-based code done with asymmetric uncertainties

*MCFM → Monte Carlo for FeMtobarn processes
10.1007/JHEP12(2019)034

A. Safronov et al., PoS ICHEP2022 (2022) 494 (https://doi.org/10.22323/1.414.0494)

Example: bottom quark production in pPb collision at LHC





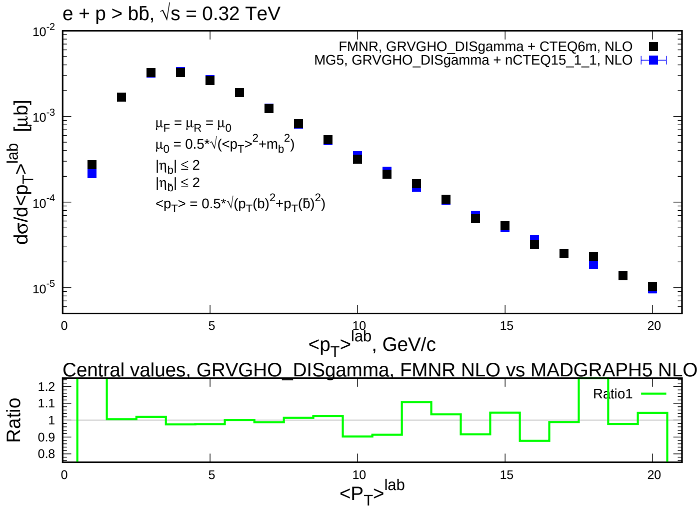
Phys. Rev. D99 no. 5, (2019) 052011, arXiv:1902.05599 [hep-ex].

To make this plot, one just needs to input two numbers: LHAPDF IDs for the proton and nCTEQ15 for the lead.

Scale uncertainty can be computed automatically .

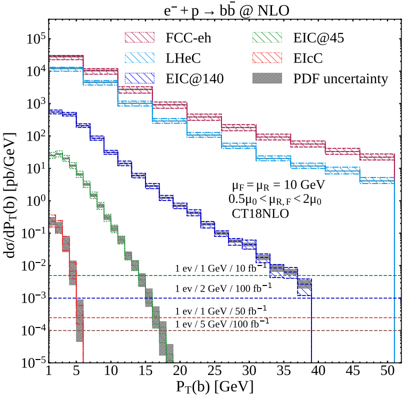
A. Safronov et al., PoS ICHEP2022 (2022) 494 (`https://doi.org/10.22323/1.414.0494`)

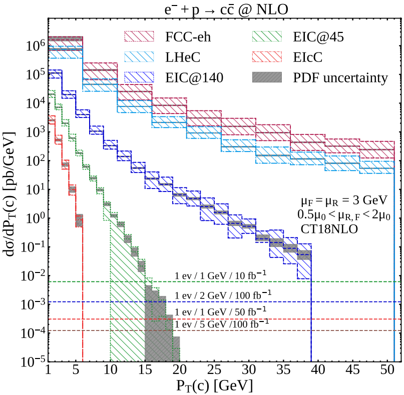
Resolved photoproduction: Validation at NLO



Approximately $\sim \mathcal{O}(1\%)$ agreement for 1 GeV $< \langle P_T \rangle <$ 10 GeV (resolved photon contribution)!

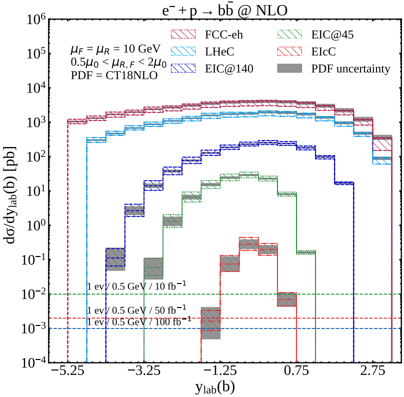
Prediction for future *ep* experiments

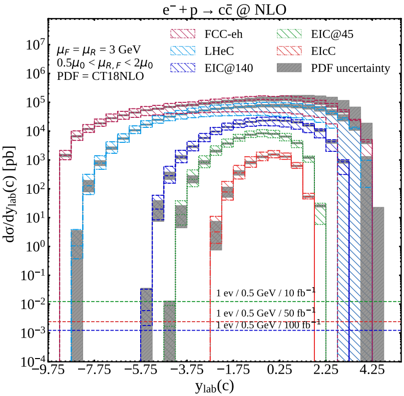




Transverse momenta distribution of Bottom and Charm quark

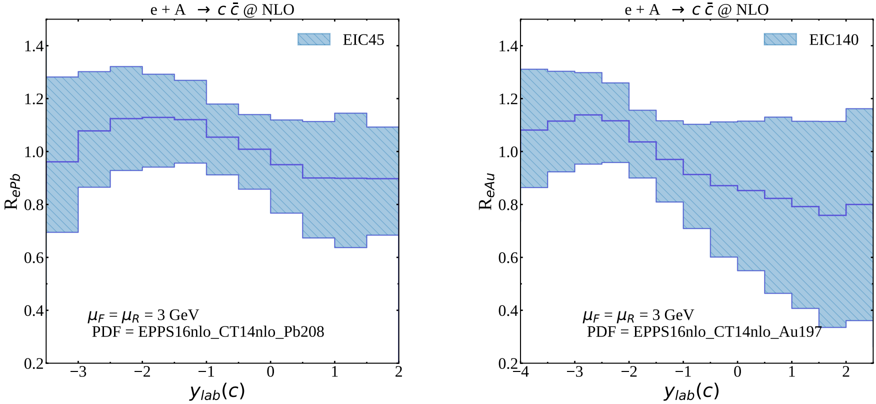
Prediction for future *ep* experiments





Rapidity distribution of Bottom and Charm quark

Nuclear modification factor for the EIC



R_{eA} distribution at two different energies as a function of the rapidity of charm quark

Quarkonium production in MG5_aMC

- Currently, no quarkonium cross sections or event generation in MG5_aMC
- Quarkonium computations important for e.g. QCD studies and resolving internal structure of nucleons
- In collinear factorisation,

$$\sigma(pp \to \mathcal{Q}+X) = \sum_{i,j,n} \int \mathrm{d}x_1 \mathrm{d}x_2 f_{i/p}(x_1) f_{j/p}(x_2) \hat{\sigma}(ij \to Q\bar{Q}[n]+X) \langle O_n^{\mathcal{Q}} \rangle$$

New ingredients:

- $\langle O_n^{\mathcal{Q}} \rangle$: non-pert. long-distance matrix element
- $Q\bar{Q}[n]$: open $Q\bar{Q}$ pair in quantum state $n = {}^{2s+1}L_J^c$.
  L: orbital angular momentum ($L = 0$ (S-wave), $L = 1$ (P-wave), . . .), **s:** spin ($s = 0$ (pseudoscalar), $s = 1$ (vector)), **c:** colour ($c = 1$ (singlet), $c = 8$ (octet)), **J:** total angular momentum ($L + s$).

Goal: LO automation with NLO automation in sight. So far:

- Colour singlet & octet and S-wave spin projectors implemented
- Building blocks of interface at level of MG5's `generate` command for quarkonium processes
- Agreement of S-wave quarkonium *single* and *associated* colour singlet and octet matrix-element squared with `Helac-Onia` H-S. Shao, https://doi:10.1016/j.cpc.2013.05.023. See also (albeit deprecated) `MadOnia` P. Artoisenet, F. Maltoni, T. Stelzer https://doi:10.1088/1126-6708/2008/02/102
- Some examples checked: `generate g g > b b~(1S01), g g > b b~(1S08)` & `g g > b b~(1S01) g`

To do: For LO, need to finalise user interface and phase-space-integration adaptation, and incorporation into NLOAccess

Future: NLO automation (see H-S. Shao, A. Hamed, L. Simon arXiv:2402.19221)

Summary

- Our implementation of photoproduction at NLO in MG5_aMC is completed and will be available very soon for users.
- We can study Ultra peripheral collisions as well.
- Asymmetric hadron A + hadron B collisions in MG5_aMC have been implemented.
- Resolved photoproduction has been studied.
- Nuclear modification factors are computed automatically with their scale uncertainties.
- Inclusion of hadronisation for both asymmetric collisions (future work!).
- Finalising LO automation of S-wave quarkonium in MG5_aMC with NLO in sight.

Acknowledgment

Part of this work has received funding from the European Union's Horizon 2020 research and innovation programme as part of the Marie Skłodowska-Curie Innovative Training Network MCnetITN3 (grant agreement no. 722104).
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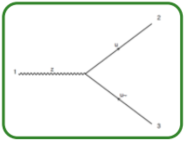
backup slides

NLO calculation

$$\sigma_{\rm NLO} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$

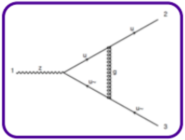
$\mathcal{O}(\alpha_s^b)$ $\mathcal{O}(\alpha_s^{b+1})$ $\mathcal{O}(\alpha_s^{b+1})$

Born cross section



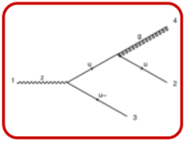
Finite

Virtual correction



Divergent

Real correction



Divergent

NLO Subtraction

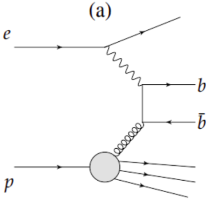
$$\sigma_{\mathrm{NLO}} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$

$$= \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\left[\mathcal{V} + \int d\Phi^{(1)} S\right] + \int d\Phi^{(n+1)}\left[\mathcal{R} - S\right]$$

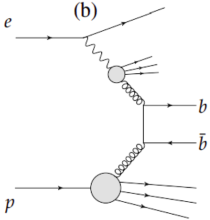
The subtraction counterterm S should be chosen:

- It exactly matches the singular behavior of real ME
- It can be integrated numerically in a convenient way
- It can be integrated exactly in the d dimension
- It is process independent (overall factor times Born ME)

Photoproduction



a) Direct photoproduction



b) Resolved photoproduction

$$\sigma_{ep} = \int dx_\gamma f_\gamma{}^{(e)}(x_\gamma, \mu_{WW}) \sigma_{\gamma p}$$

$$\sigma_{\gamma p} = \sum_i \int_0^1 dx_i \int d\Phi_f f_i(x_i, \mu_F^2) \frac{d\hat{\sigma}_{\gamma i}(x_i, \mu_F^2, \Phi_f)}{dx_i d\Phi_f}$$

$$\sigma_{\gamma p}^{Total} = \sigma_{\gamma p}^{pointlike} + \sigma_{\gamma p}^{hadronic}$$

$$\sigma_{\gamma p}^{pointlike} = \sum_i \int_0^1 dx_i \int d\Phi_f f_i(x_i, \mu_F^2) \frac{d\hat{\sigma}_{\gamma i}(x_i, \mu_F^2, \Phi_f)}{dx_i d\Phi_f}$$

$$\sigma_{\gamma p}^{hadronic} = \sum_{ij} \int_0^1 dx_i \int_0^1 dy_j \int d\Phi_f f_i(x_i, \mu_F^2) f_j^{(\gamma)}(y_j, \mu_F^2) \frac{d\hat{\sigma}_{ij}(x_i, \mu_F^2, \Phi_f)}{dx_i d\Phi_f dy_i}$$

Photoproduction vs DIS

$$\sigma_{ep} = \int dx_\gamma f_\gamma^{(e)}(x_\gamma, \mu_{WW}) \sigma_{\gamma p}$$

$$\sigma_{\gamma p}^{pointlike} = \sum_i \int_0^1 dx_i \int d\Phi_f f_i(x_i, \mu_F^2) \frac{d\hat{\sigma}_{\gamma i}(x_i, \mu_F^2, \Phi_f)}{dx_i d\Phi_f}$$

$$\sigma_{\gamma p} = \sum_i \int_0^1 dx_i \int d\Phi_f f_i(x_i, \mu_F^2) \frac{d\hat{\sigma}_{\gamma i}(x_i, \mu_F^2, \Phi_f)}{dx_i d\Phi_f}$$

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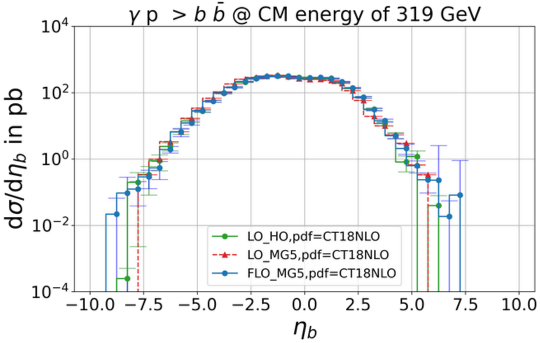
NLO calculations and approaches:

NLO calculations are performed in several schemes. All approaches assume a scale to be hard enough to apply pQCD and to guarantee the validity of the factorization theorem.

- The massive approach is a fixed order calculation (in α_s) with $m_Q \neq 0$
- The massless approach sets $m_Q = 0$. Therefore the heavy quark is treated as an active flavor in the proton.
- In a third approach (FONLL) the features of both methods are combined. The matched scheme adjusts the number of partons, nf, in the proton according to the relevant scale.
- Our work is focused on the first approach, massive heavy quark.

Validation of LO result

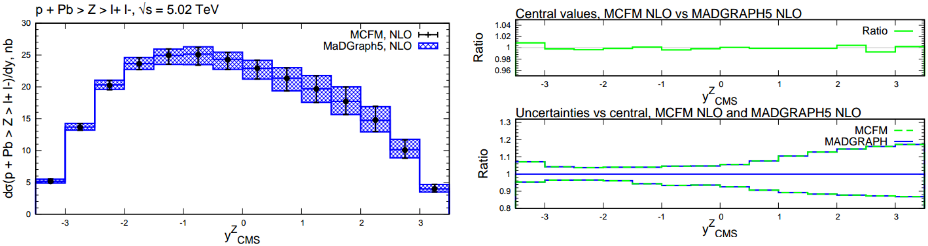


Comparison between pseudorapidity distribution of bottom quark pair production cross section obtained from MG5 at LO (FLO) and with another LO event generator called Helac-onia (HO).

	MG5(nb) (LO)	MG5(nb) (FLO)	HO (nb) (LO)
cross section	$3.34 \pm 4.4 \times 10^{-3}$	$3.34 \pm 19 \times 10^{-3}$	$3.34 \pm 10.08 \times 10^{-3}$

Validations of MG5 in asymmetric collisions

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



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

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