# Extensions of MadGraph5_aMC@NLO for QCD studies

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work done in collaboration with
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*Present and future perspectives in Hadron Physics*

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# Theoretical Overview

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

$$\sigma_{AA\to X}=\sum_{i,j}\int dx_i dx_j f_i^A(x_i,\mu_F;\texttt{LHAID}) f_j^A(x_j,\mu_F;\texttt{LHAID})\hat{\sigma}_{ab\to X}(x_i,x_j,\mu_F,\mu_R)$$

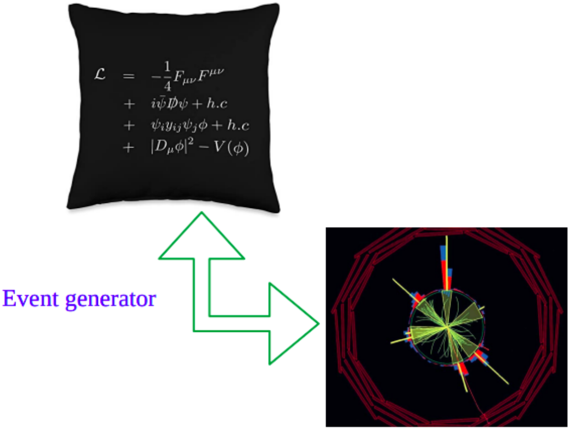
$\hat{\sigma}_{ab\to X}$ = Partonic cross section related to a & b , calculable within perturbation theory.
The partonic cross section can be expanded as:

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

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

# 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.



$$\begin{aligned}\mathcal{L} &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ &+ i\bar{\psi}\not{D}\psi + h.c \\ &+ \psi_i y_{ij}\psi_j\phi + h.c \\ &+ |D_\mu\phi|^2 - V(\phi)\end{aligned}$$

Event generator

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

Asymmetric collisions implemented in MG5_aMC

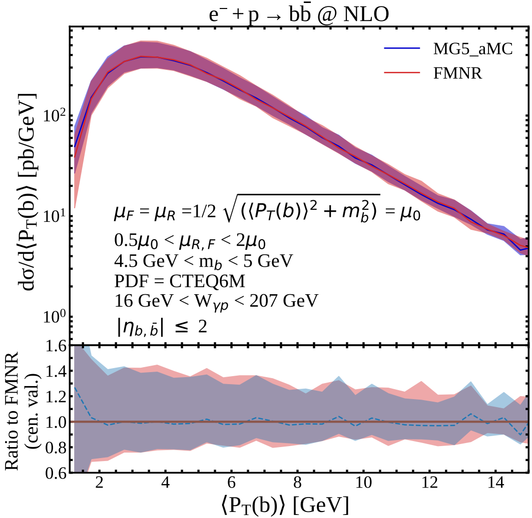
- Photoproduction (L. Manna)
- Hadron A +Hadron B collision (A. Safronov)
- Quarkonium production (C. Flett & A. Colpani-Serri)

# Photoproduction

$$\sigma_{eh\to X} = \sum_j \int dx_\gamma dx_j f_\gamma^e(x_\gamma, Q^2_{\max}) f_j^h(x_j, \mu_F; \texttt{LHAID}) \hat{\sigma}_{\gamma j\to X}(x_\gamma, x_j, \mu_F, \mu_R)$$

# Direct photoproduction: Validation at NLO

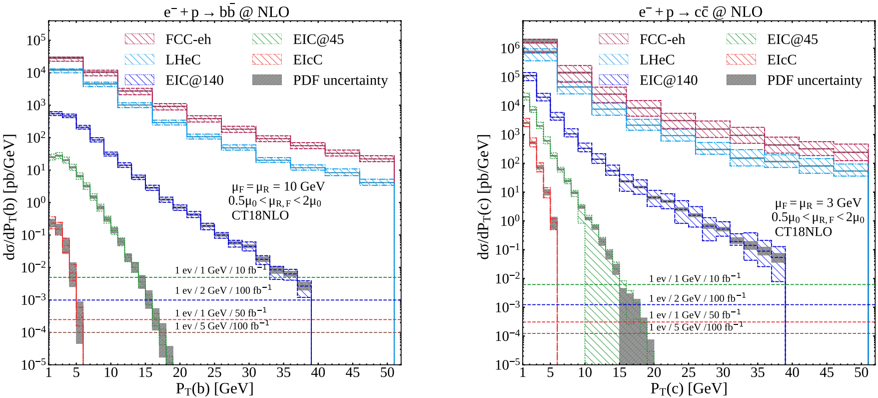
**H1 Collaboration**, 10.1140/epjc/s10052-012-2148-1



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

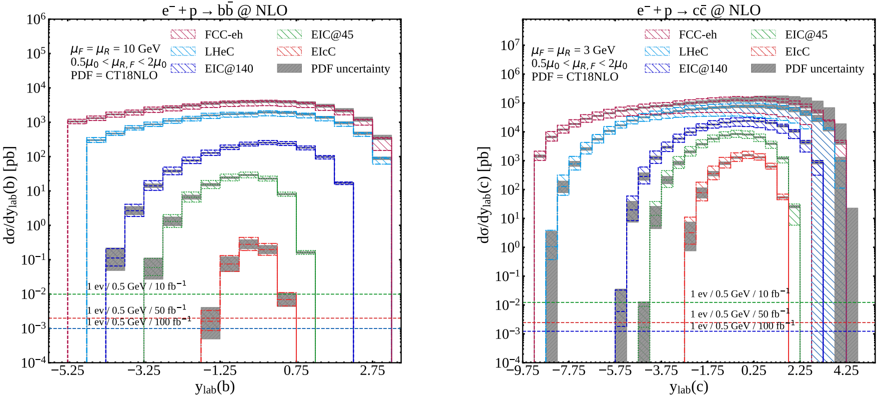
**L. Manna et. al, PoS EPS-HEP 2023 449** https://doi.org/10.22323/1.449.0274

# 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

# pA collisions

$$\sigma_{AB\to X} = \sum_j \int dx_i dx_j f_j^A(x_j, \mu_F; \texttt{LHAID1}) f_j^B(x_j, \mu_F; \texttt{LHAID2}) \hat{\sigma}_{ij\to X}(x_i, x_j, \mu_F, \mu_R)$$

# 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,

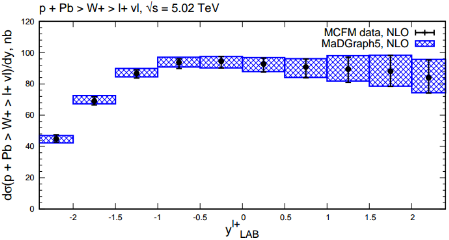
$$R_{AB} = \frac{\sigma_{AB}}{AB\sigma_{pp}}$$

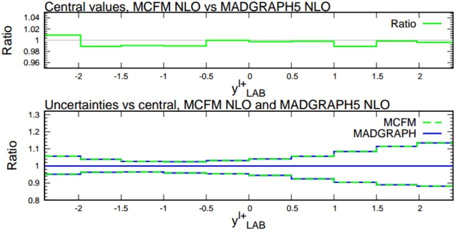
$$R_{pA} = \frac{\sigma_{pA}}{1 \times A \times \sigma_{pp}}$$

$R \approx 1$ : No nuclear effects

# Validation of calculations for pA collisions at NLO

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





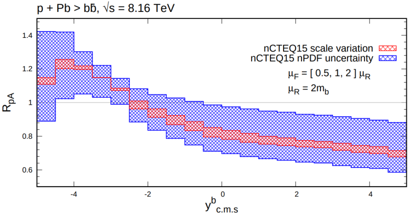
- Perfect agreement between MG5_aMC and MCFM-based computations W production with nCTEQ15
- No difference in the PDF uncertainty, if computation in MCFM-based code done with asymmetric uncertainties

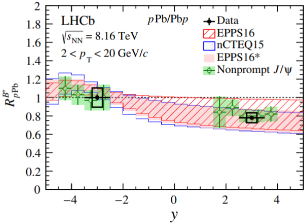
*MCFM → Monte Carlo for FeMtobarn processes
`10.1007/JHEP12(2019)034`

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

# Validations of calculations for pA collisions

Example: bottom quark production in pPb collision at LHC





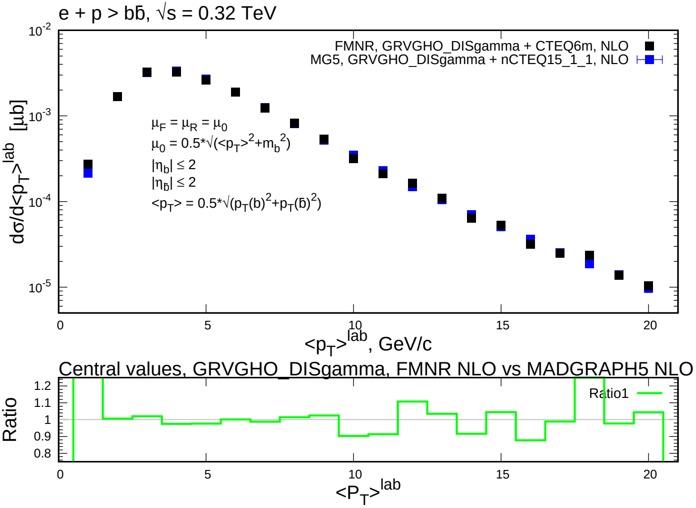
Phys. Rev. D99 no. 5, (2019) 052011, arXiv:1902.05599 [hep-ex].

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`)

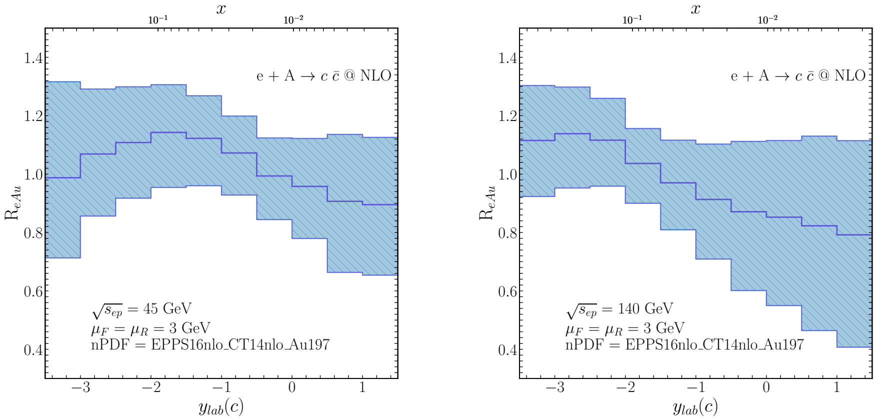
# Another Asymmetric Collisions: Resolved Photoproduction



$\sim \mathcal{O}(1\%)$ agreement for 1 GeV $< \langle P_T \rangle <$ 10 GeV

# $R_{eAu}$@NLO of charm at EIC

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



Automatic generation of uncertainty (both scale and nPDF)

# Quarkonium production

# 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), $\ldots$), **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 complete, and the testing version is available on GitHub.
- We can study Ultra peripheral collisions (UPC) as well.
- Asymmetric hadron A + hadron B collisions in MG5_aMC have been implemented and are also available on GitHub (testing).
- 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.
- All our developments will be available in NLOAccess.

# Acknowledgment

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# backup slides

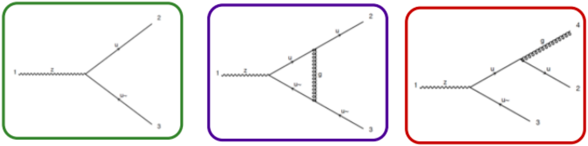
# NLO calculation

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

Born cross section

Virtual correction

Real correction



Finite

Divergent

Divergent

# NLO Subtraction

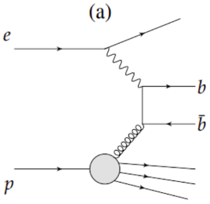
$$\sigma_{\mathrm{NLO}} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$

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

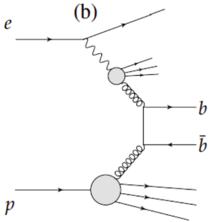
The subtraction counterterm S should be chosen:

- 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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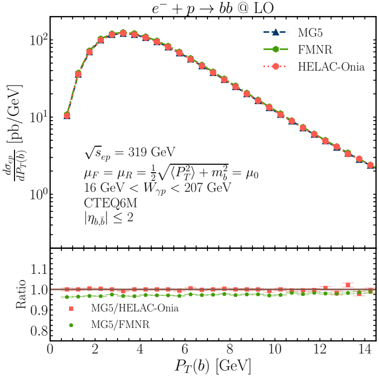
## NLO calculations and approaches:

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 $\alpha_s$) 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.

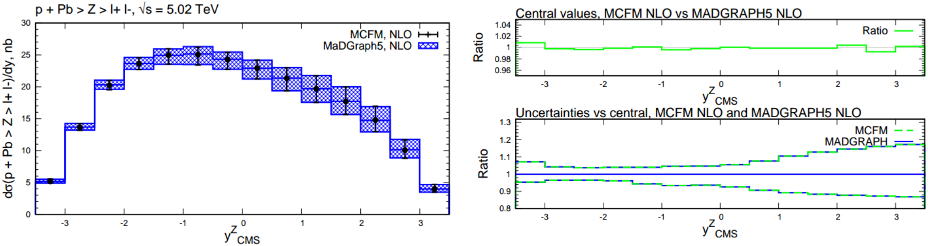
# Validation of LO result



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

# 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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