Asymmetric collisions in MadGraph5_aMC@NLO

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On behalf of

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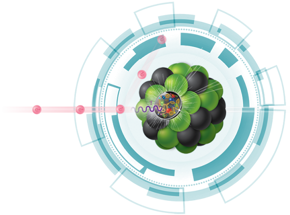
Electron-Ion Collider (EIC):

To know more about nucleons, Brookhaven lab is building a new machine - an Electron-Ion Collider - to look inside the nucleus and its protons and neutrons.

Motivation behind EIC :

- The origin of nucleonic properties like mass and spin lies in partons and their interactions.
- In momentum and position space, how are partons inside the nucleon distributed?
- How do color-charged quarks and gluons, and jets, interact with a nuclear medium?
- Does the density of gluons change? What happens at high energies?
- How do the quark-gluon interactions create nuclear binding?



Theoretical Overview

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

$$\sigma_{ab} = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 \int d\Phi_f \, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \frac{d\hat{\sigma}_{ab}(x_1, x_2, \mu_F^2, \Phi_f)}{dx_1 \, dx_2 \, d\Phi_f}$$

$d\hat{\sigma}$ = Partonic cross section, calculable within perturbation theory.
The partonic cross section can be expanded as:

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

* 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 as,

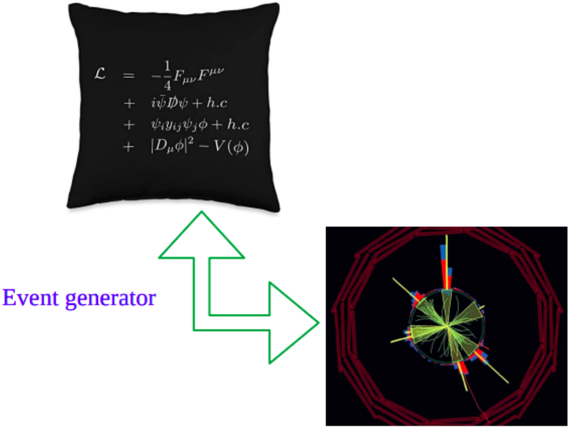
$$R_{AB} = \frac{\sigma_{AB}}{AB\sigma_{pp}}$$

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

$R_{pA} \approx 1$: No nuclear effects

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.



Initially, MadGraph5_aMC@NLO(MG5aMC) was developed for symmetric collisions.

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

Electron–proton collisions

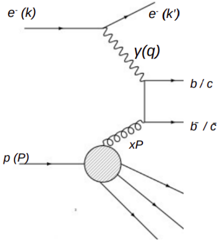
Electron-proton processes are traditionally classified according to the virtuality (Q^2) of the photon i.e four-momentum transfer to the photon from the electron (incoming outgoing),

$Q^2 = -q^2 = -(k-k')^2$

I) Photoproduction :

Photon is nearly on mass shell.

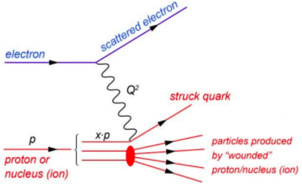
$$Q^2 \leq m_H$$



II) Deep-Inelastic-scattering (DIS):

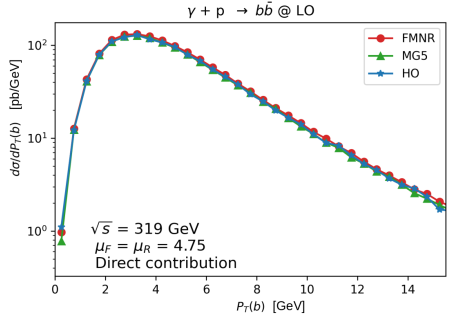
Photon is off mass shell.

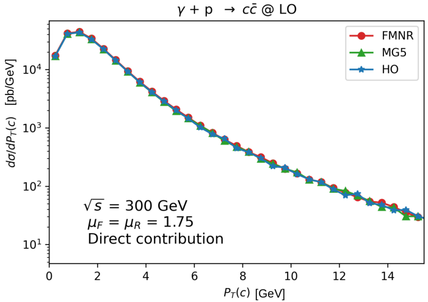
$$Q^2 >> m_H$$



Validation of LO Results with FMNR

PDF = CTEQ6M





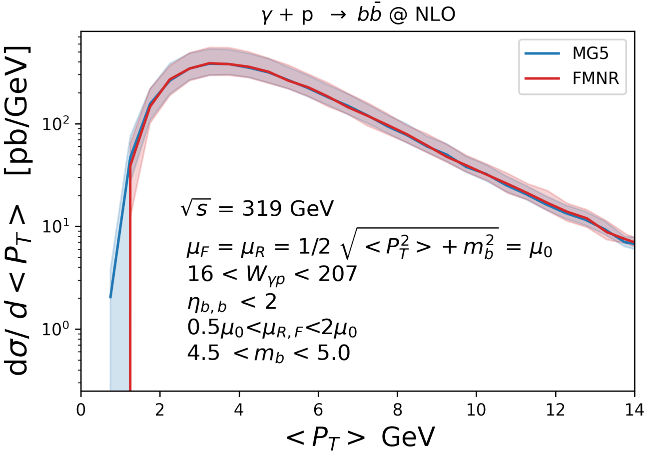
Good agreement for Charm and Beauty Quark photoproduction!

*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

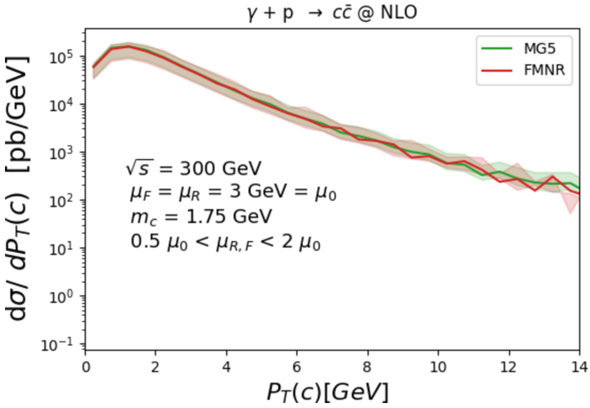
Validation of NLO result with FMNR program



Perfect agreement (direct contribution)!

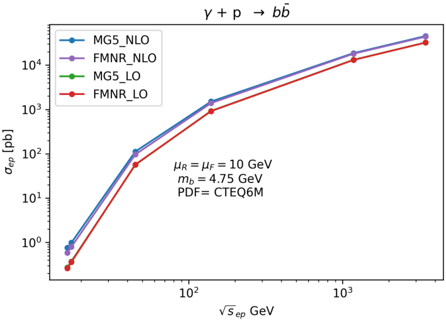
https://inspirehep.net/literature/1118830

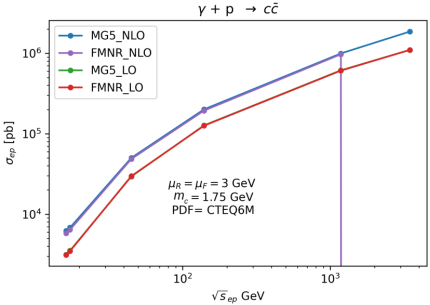
Validation of NLO result with FMNR program

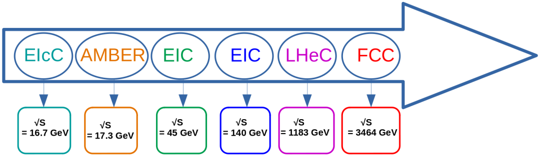


Perfect agreement (direct contribution)!

Possibility in Future Experiments

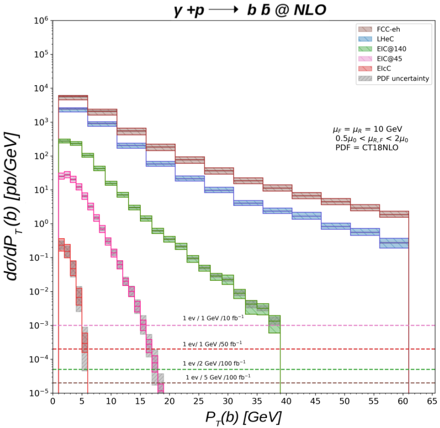


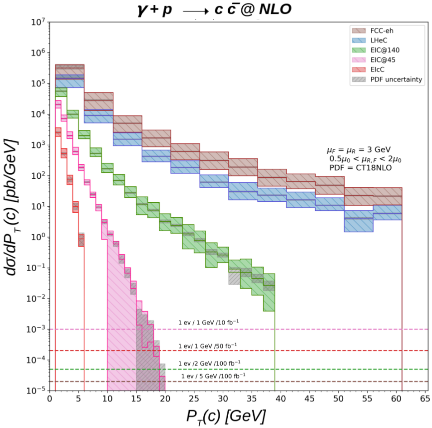




*EIcC → Electron-Ion Collider in China *AMBER → Apparatus for Meson and Baryon Experimental Research
*EIC → Electron-Ion Collider *LHeC → Large Hadron Electron Collider *FCC → Future Circular Collider

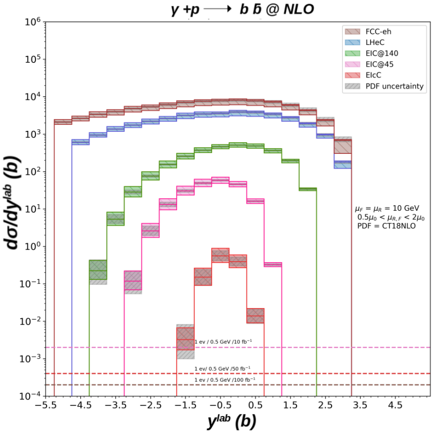
Preliminary Results

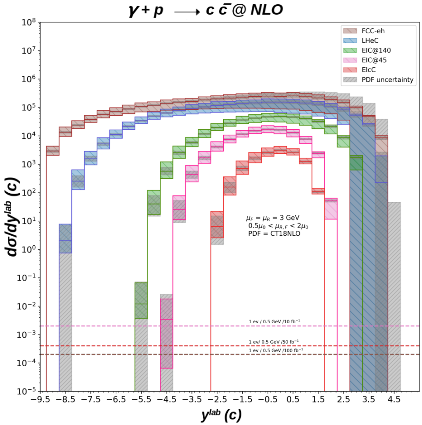




Transverse momenta distribution of Beauty and Charm quark

Preliminary Results



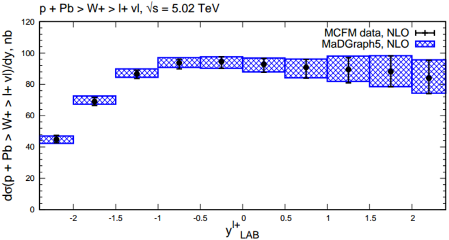


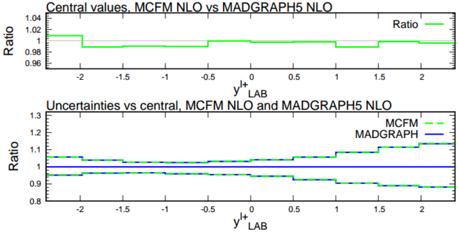
Rapidity distribution of Beauty and Charm quark

Proton-nucleus collision in MG_aMC

Validations of MG5_aMC in pA collisions

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 uncertainty, if computation in MCFM-based code done with asymmetric uncertainties

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

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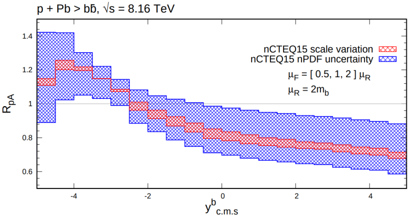
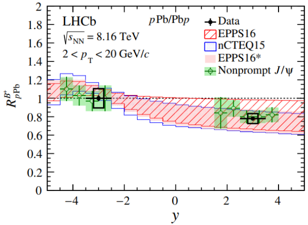
Validations of MG5_aMC in pA collisions

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 of proton and nCTEQ15 for Lead.

Scale uncertainty can be computed automatically .

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Summary

- Our implementation of photoproduction at NLO in MG5_aMC validation is completed and will be available very soon for users.
- We can study Ultra peripheral collisions as well.
- Asymmetric proton-nucleus collisions in MG5_aMC have been implemented.
- Inclusion of resolved photoproduction.
- Nuclear modification factors are also computed automatically with their scale uncertainties.
- **MG5_aMC capabilities :**

Mode	LO (SM)	LO (ep collision) (DIS+Direct Photoproduction)	NLO (Direct Photoproduction)	NLO (Resolved Photoproduction)	NLO (DIS)	NLO (pA collisions)
Fixed order	√√	√√	√	√	In progress	√
Parton shower	√√	√	Development will be starting soon	Not implemented yet	Development will be starting soon	Not implemented yet

Future prospects

- Further possibilities for proton-nucleus collisions are,
  - Pion induced reactions
  - PDF reweighting "on the fly"
- Future work for electron-proton collisions,
  - Develop interface for photoproduction and DIS at NLO + Hadronization .
  - Extend our electron-proton work with electron-nucleus collisions by including nuclear PDFs.

Thank you for your attention!

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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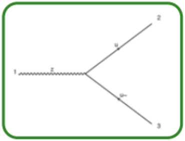
backup slides

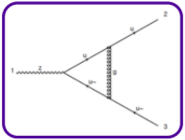
NLO calculation

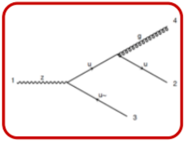
$$\sigma_{\text{NLO}} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$

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

Born cross section | Virtual correction | Real correction







Finite | Divergent | Divergent

NLO Substraction

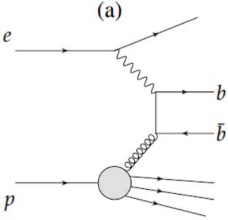
$$\sigma_{\rm NLO} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$

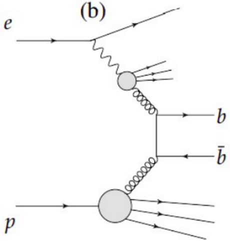
$$= \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\left[\mathcal{V} + \int d\Phi^{(1)} S\right] + \int d\Phi^{(n+1)}\left[\mathcal{R} - S\right]$$

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





Photoproduction a) direct contribution b) resolved contribution

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

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

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

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

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

Photoproduction vs DIS

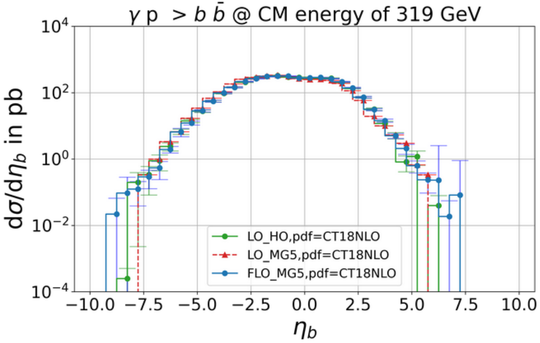
DIS	Photoproduction
Photon is highly virtual	Photon is quasi-real
Scattered e^- observed	Scattered e^- not observed due to low virtuality
Direct	Direct & resolved photon contribution due to partonic structure of photon

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

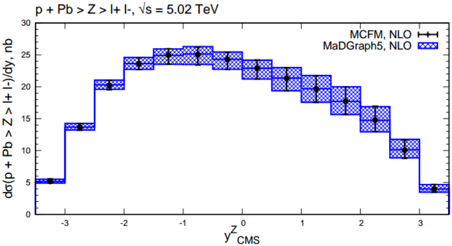


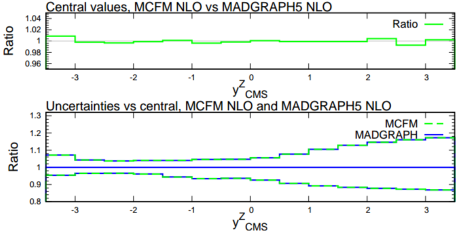
Comparison between pseudorapidity distribution of bottom quark pair production cross section obtained from MG5 at LO (FLO) and with another LO event generator called Helac-onia (HO).

	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





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