Asymmetric collisions in MadGraph5_aMC@NLO

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On behalf of

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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,

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

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

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

* 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.

nPDFs cannot be computed and similarly to the proton PDFs are fit to experimental data. Only evolution is perturbative

Nuclear Modification Factors:

For rare/hard probes [$\sigma_{NN}^{probe} << \sigma_{NN}^{inel}$]

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

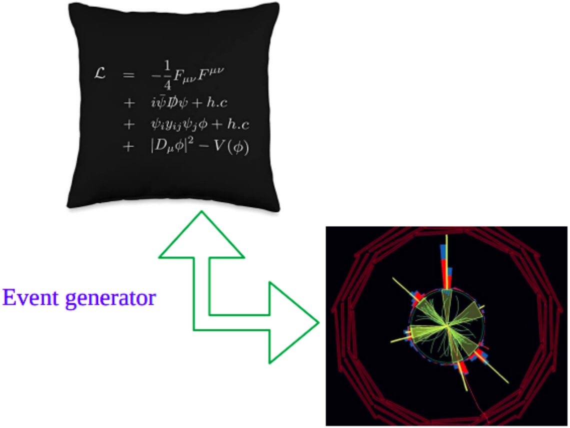
We can define Nuclear Modification Factors as,

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

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

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

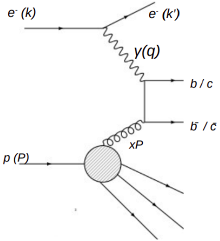
Electron-proton processes are traditionally classified according to the virtuality (Q^2) of the photon i.e four-momentum transfer to the photon from the electron (incoming outgoing),

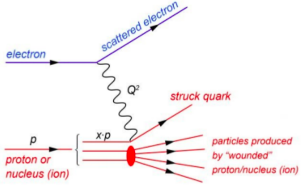
$Q^2 = -q^2 = -(k-k')^2$

I) Photoproduction :

Photon is nearly on mass shell.

$$Q^2 \leq m_H$$





II) Deep-Inelastic-scattering (DIS):

Photon is off mass shell.

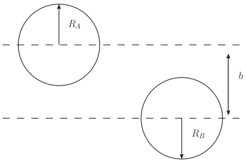
$$Q^2 >> m_H$$

Photoproduction at LHC

Ultra peripheral collisions

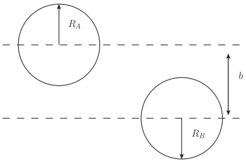
Photoproduction at LHC

Ultra peripheral collisions



Photoproduction at LHC

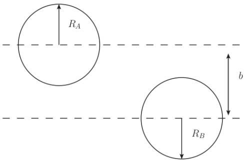
Ultra peripheral collisions



- b $> R_A + R_B$

Photoproduction at LHC

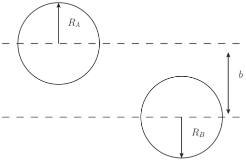
Ultra peripheral collisions



- b > $R_A + R_B$
- Photon induced

Photoproduction at LHC

Ultra peripheral collisions

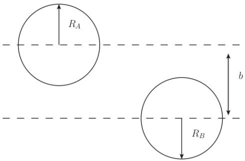


- b $> R_A + R_B$
- Photon induced

Inclusive Photoproduction

Photoproduction at LHC

Ultra peripheral collisions



- b $> R_A + R_B$
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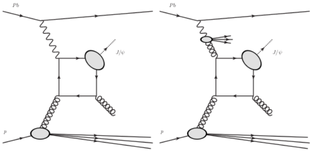
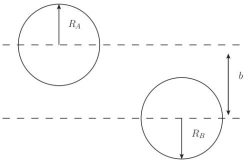
Inclusive Photoproduction



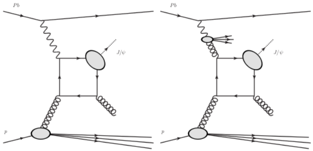
Photoproduction at LHC

Ultra peripheral collisions



- $b > R_A + R_B$
- Photon induced

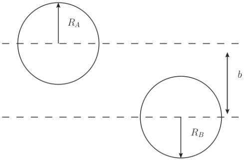
Inclusive Photoproduction



- Hard final state gluon

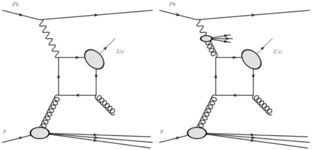
Photoproduction at LHC

Ultra peripheral collisions



- b > $R_A + R_B$
- Photon induced

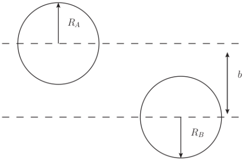
Inclusive Photoproduction



- Hard final state gluon
- Resolved vs. direct contribution

Photoproduction at LHC

Ultra peripheral collisions



- b $> R_A + R_B$
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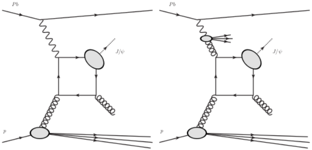


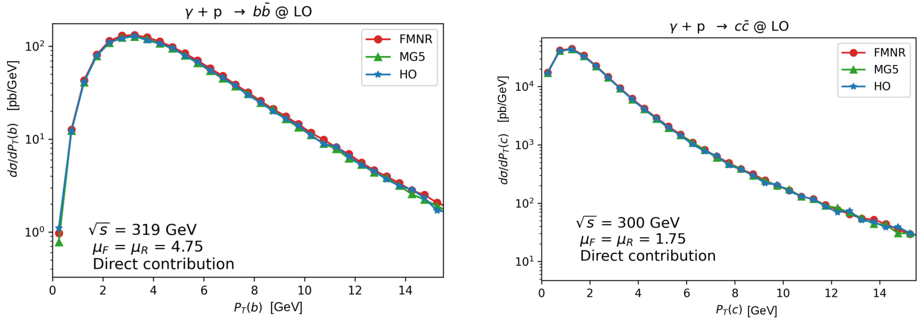
- Hard final state gluon
- Resolved vs. direct contribution
- Probe gluon PDF

- Photoproduction is simpler than hadroproduction should be easier to extract PDFs.
- Photon PDF is not well known
- UPC @ LHC $\sqrt{s_{\gamma p}} \approx 1$ TeV vs. HERA $\sqrt{s_{\gamma p}} \approx 0.2$ TeV
- Future study @ EIC has the advantage of reduced resolved contributions.

HF 2022, K.lynch

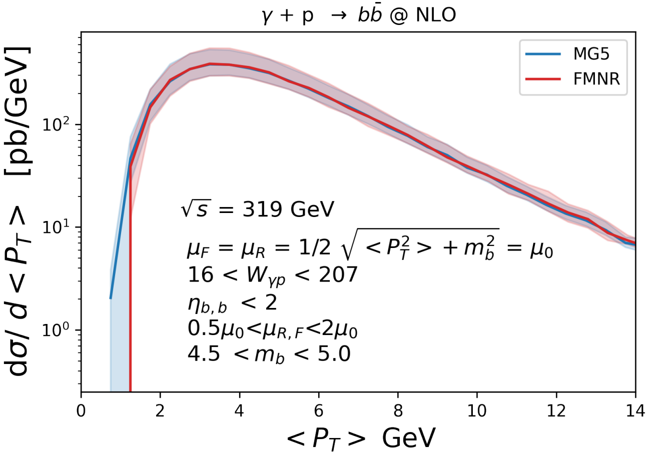
Validation of LO Results with FMNR

PDF = CTEQ6M



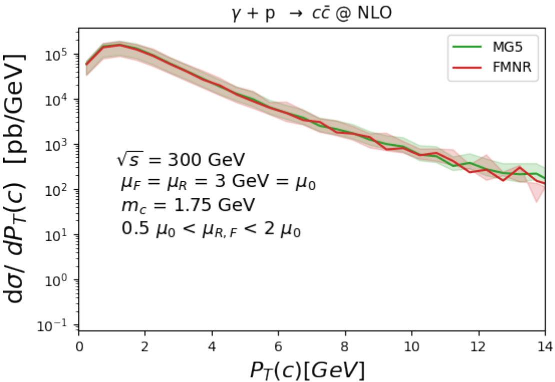
Good agreement from Charm and Beauty Quark photoproduction!

Validation of NLO result with FMNR program



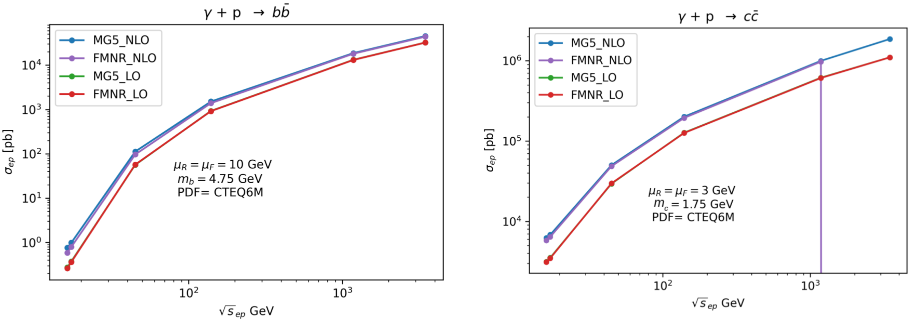
Perfect agreement (direct contribution)!

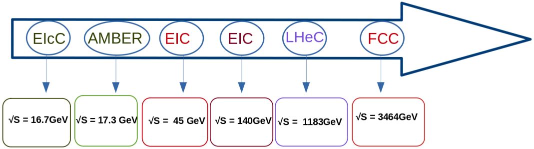
Validation of NLO result with FMNR program



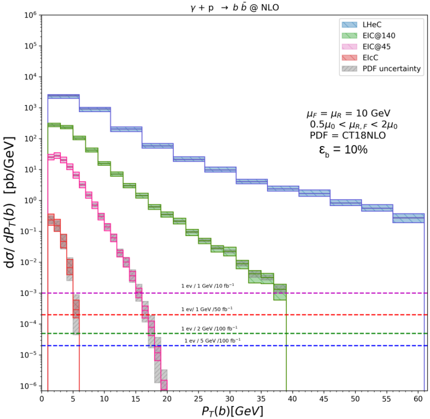
Perfect agreement (direct contribution)!

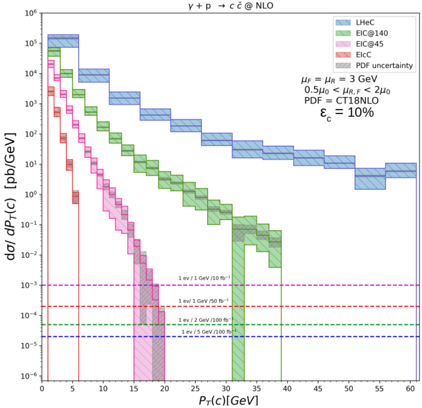
Possibility in Future Experiments





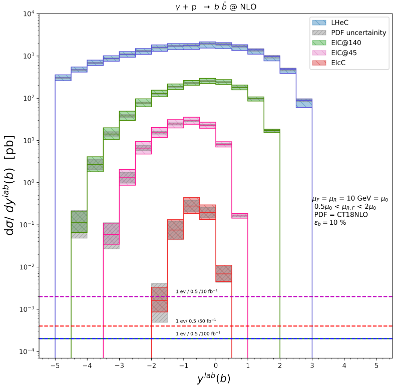
Preliminary Results

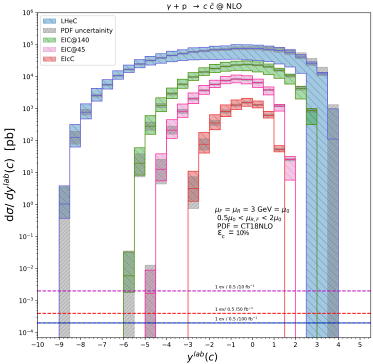




Transverse momenta distribution of Beauty and Charm quark

Preliminary Results





Rapidity distribution of Beauty and Charm quark

Proton-nucleus collision in MG5aMC

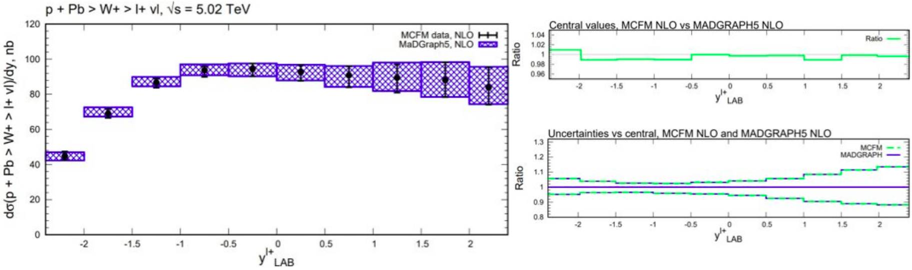
nPDF's and MG5

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

Reminder: we assume that

- The factorization of the cross section even in the presence of nuclear effects
- All the nuclear effects can be accounted by nPDFs and thus can be computed by MG5.

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



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

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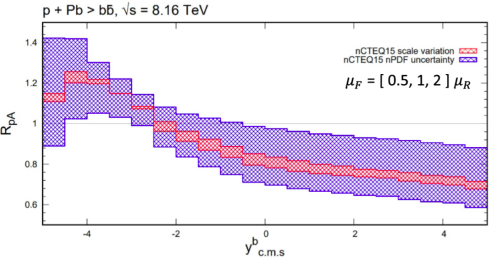
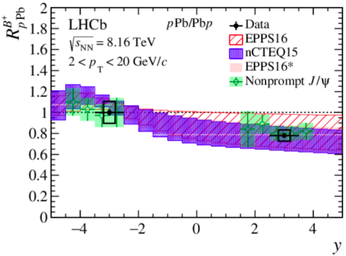
Validations of MG5 in asymmetric collisions

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 validation is completed and will be available very soon for users.
- Asymmetric proton-nucleus collisions in MadGraph5 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 is,
  - PDF reweighting "on the fly"
- Future work for electron-proton collisions,
  - Develop interface for photoproduction and DIS at NLO + PS.
  - Extend our electron-proton work with electron-nucleus collisions by including nuclear PDFs.

Thank you for your attention!

Acknowledgment

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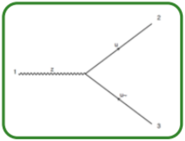
backup slides

NLO calculation

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

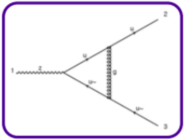
$\mathcal{O}(\alpha_s^b)$ $\mathcal{O}(\alpha_s^{b+1})$ $\mathcal{O}(\alpha_s^{b+1})$

Born cross section



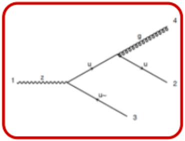
Finite

Virtual correction



Divergent

Real correction



Divergent

NLO Substraction

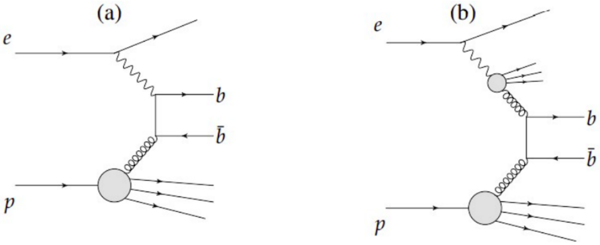
$$\sigma_{\text{NLO}} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$

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

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

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

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

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

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

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

Photoproduction vs DIS

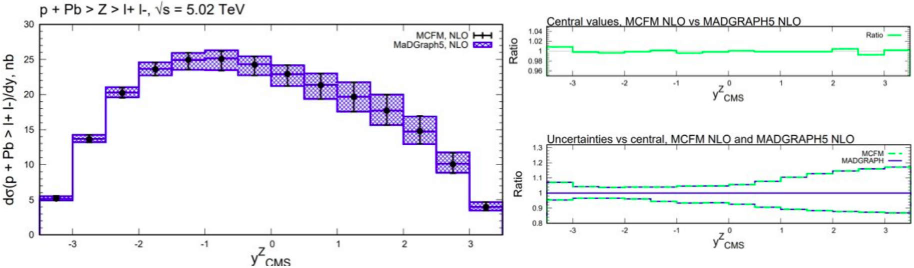
DIS	Photoproduction
Photon is highly virtual	Photon is quasi-real
Scattered e^- observed	Scattered e^- not observed due to low virtuality
Direct	Direct & resolved photon contribution due to partonic structure of photon

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 vs MCFM for CT10 + nCTEQ15 for Z production at NLO



- Perfect agreement between MG5 and MCFM-based computations Z production with nCTEQ15
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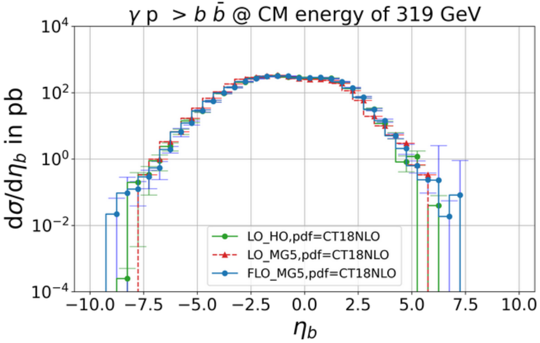
Validation of LO result



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	$3.34 \pm 4.4 \times 10^{-3}$	$3.34 \pm 19 \times 10^{-3}$	$3.34 \pm 10.08 \times 10^{-3}$