Photon-induced and asymmetric collisions in MadGraph5_aMC@NLO

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Quarkonium as Tools 2023+

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Motivation

- To compute physical observables with higher accuracy.
- Apply a more fundamental interpretation to the phenomena observed in experimental data.
- Generating physics events using computer programs, as realistic as possible.
- To provide a tool that would help to understand detector performance within other constraints to study interesting physics scenarios.

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.

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

We can define Nuclear Modification Factors as,

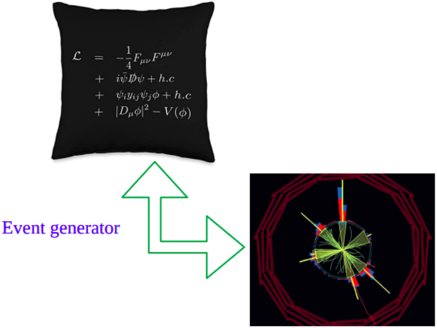
$$R_{AB} = \frac{\sigma_{AB}}{AB\sigma_{pp}}$$

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

$R_{pA} \approx 1$: 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.

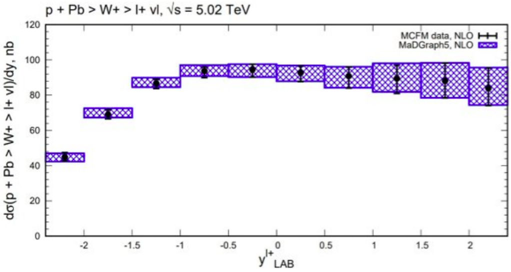


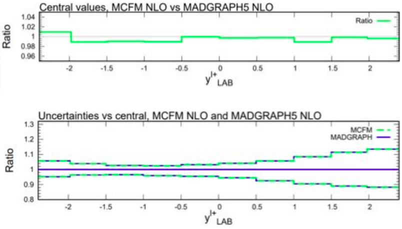
Initially, MadGraph5_aMC@NLO(MG5aMC) was developed for symmetric collisions.

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

Validations of MG5 in asymmetric collisions

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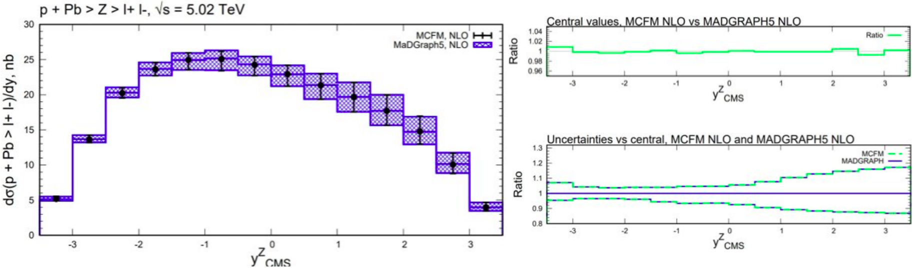
Validation vs MCFM for CT10 + nCTEQ15 for Z production at NLO



- 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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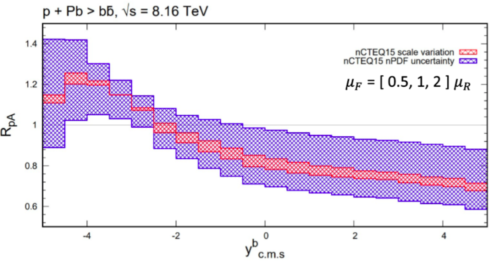
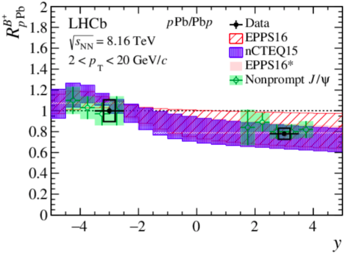
Example: bottom quark production in pPb collision at LHC





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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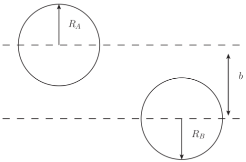
Photoproduction at LHC

Ultra peripheral collisions

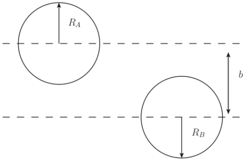
Photoproduction at LHC

Ultra peripheral collisions



Photoproduction at LHC

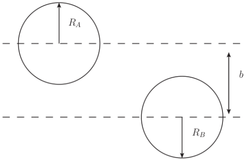
Ultra peripheral collisions



- b $> R_A + R_B$

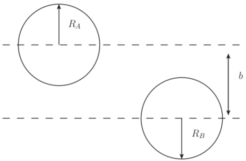
Photoproduction at LHC

Ultra peripheral collisions



- b $> R_A + R_B$
- Photon induced

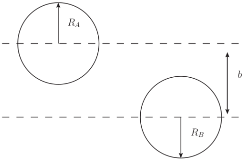
Ultra peripheral collisions



- b > $R_A + R_B$
- Photon induced

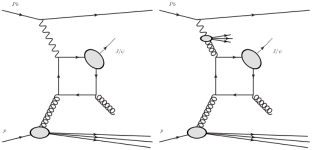
Inclusive Photoproduction

Ultra peripheral collisions



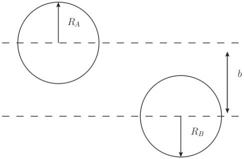
- b $> R_A + R_B$
- Photon induced

Inclusive Photoproduction



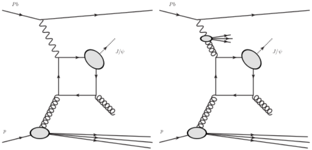
Photoproduction at LHC

Ultra peripheral collisions



- $b > R_A + R_B$
- Photon induced

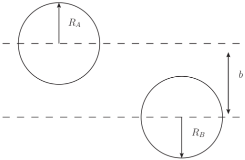
Inclusive Photoproduction



- Hard final state gluon

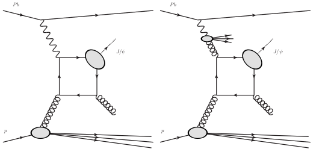
Photoproduction at LHC

Ultra peripheral collisions



- b > $R_A + R_B$
- Photon induced

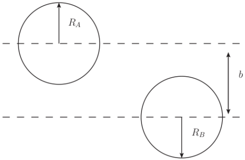
Inclusive Photoproduction



- Hard final state gluon
- Resolved vs. direct contribution

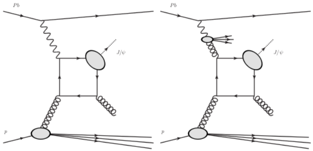
Photoproduction at LHC

Ultra peripheral collisions



- b > $R_A + R_B$
- Photon induced

Inclusive Photoproduction

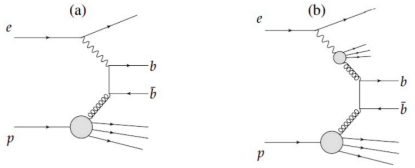


- Hard final state gluon
- Resolved vs. direct contribution
- Probe gluon PDF

- 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

EIC (Electron-Ion Collider): first collider ever to study the inner structure of both protons and nuclei at high energy



Photoproduction a) direct contribution b) resolved contribution

- Highly polarized electron ($\approx 70\%$) and proton ($\approx 70\%$) beams : spin structure studies
- Variable e+p center-of-mass energies from 20 to 100 GeV, upgradable to 140 GeV.
- It is possible to access the region where saturation scale is large and in the perturbative region by using heavy nuclei

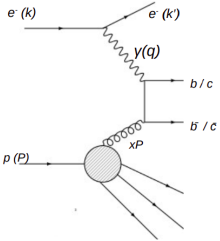
Electron (photon) - proton processes are traditionally classified according to the virtuality (Q^2) of the photon i.e four-momentum transfer to the photon from the electron (incoming outgoing),

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

I) Photoproduction:

Photon is nearly on mass shell.

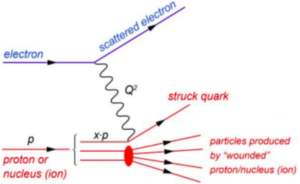
$$Q^2 \leq m_H$$



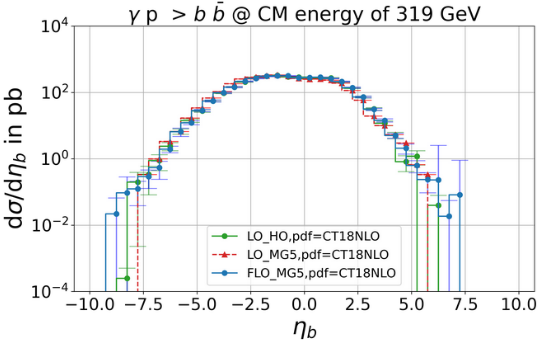
II) Deep-Inelastic-scattering (DIS):

Photon is off mass shell.

$$Q^2 >> m_H$$



Validation of LO result

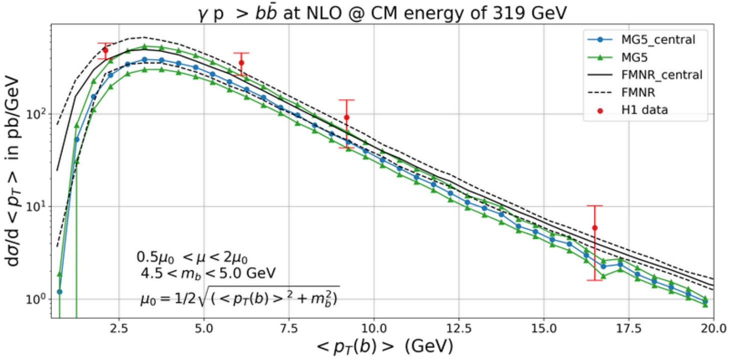


Comparison between pseudorapidity distribution of bottom quark pair production cross section obtained from MG5 at LO (FLO) and with another LO event generator called Helac-onia (HO).

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

Validation of NLO result

$16 < W\gamma p < 207$ and $|\eta_b|$,$|\eta_{\bar{b}}| \leq 2$; $PDF = CTEQ6M$

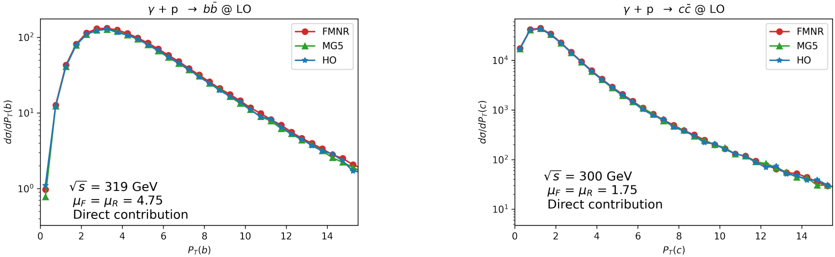


Comparison of cross section for the bottom pair production at NLO from MG5 with the experimental data HERA (H1) and a theoretical prediction from FMNR program.

NLO	FMNR(pb)	MG5 (pb)
cross section	$2.40 \times 10^3 + 5.5 \times 10^2$ -4.9×10^2	$1.85 \times 10^3 \pm 1.14 \times 10^1$

Validation of LO Results with FMNR

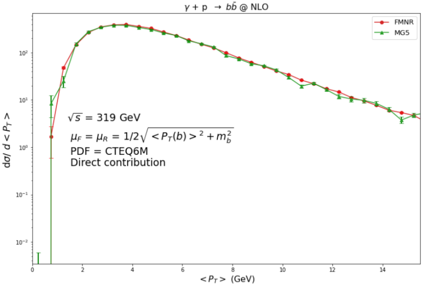
PDF = CTEQ6M

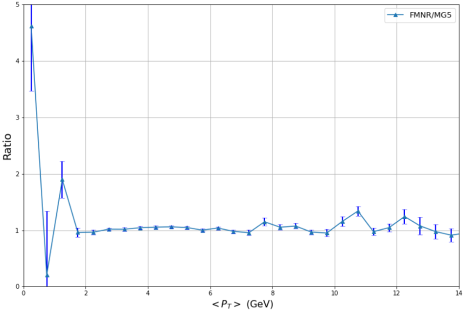


Good agreement from charm and beauty quark photoproduction!

Validation of NLO result with FMNR program

$16 < W\gamma p < 207$ and $|\eta_b|$,$|\eta_{\bar{b}}| \leq 2$





Perfect agreement!

Future prospects

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

Summary

- Asymmetric proton-nucleus collisions in MadGraph5 have been implemented
- Nuclear modification factors are also computed automatically with their scale uncertainties
- Our implementation of photoproduction at NLO in MG5 validation will be complete very soon.
- As soon as we finalize our previous works on photoproduction, we will focus on the development of photoproduction and DIS at NLO in Parton shower mode.
- After the complete development and validation of electron-proton collisions in MG5, it will be extended for electron-nucleus collisions.

MG5_aMC capabilities :

Mode	LO (SM)	LO (ep collision) (Photoproduction + DIS)	NLO (γp collision) Photoproduction	NLO (ep collision) DIS	NLO (pA collsion)
Fixed order	✓✓	✓✓	✓	In progress	✓
Parton shower	✓✓	✓	Development will be starting soon	Development will be starting soon	Not implemented yet

Thank you for your attention!

Acknowledgment

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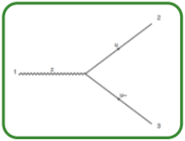
backup slides

NLO calculation

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

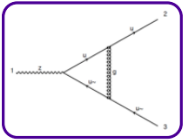
$\mathcal{O}(\alpha_s^b)$ $\mathcal{O}(\alpha_s^{b+1})$ $\mathcal{O}(\alpha_s^{b+1})$

Born cross section



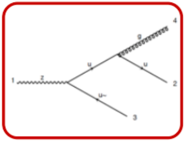
Finite

Virtual correction



Divergent

Real correction



Divergent

NLO Substraction

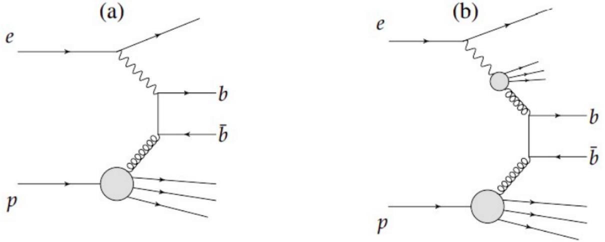
$$\sigma_{\mathrm{NLO}} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$

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

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



Photoproduction a) direct contribution b) resolved contribution

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

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

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

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

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

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.

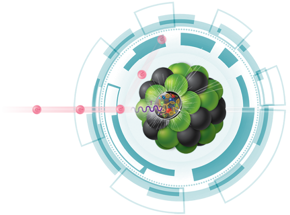
- The massive approach is a fixed order calculation (in α_s) with $m_Q \neq 0$
- The massless approach sets $m_Q = 0$. Therefore the heavy quark is treated as an active flavor in the proton.
- In a third approach (FONLL) the features of both methods are combined. The matched scheme adjusts the number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

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?



Saturation region

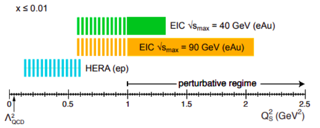


Fig. 1: Saturation scales Q_s^2 reached at the EIC in electron-nucleus collisions, compared to the ones accessed at HERA in electron-proton scattering. Figure from Ref. [3].

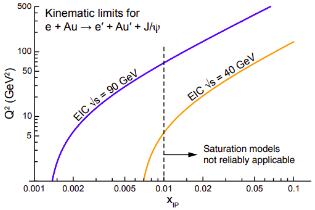
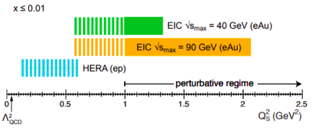


Fig. 2: Kinematical coverage for the exclusive J/Ψ production at the EIC. Figure from Ref. [3].

K.lynch

Saturation region



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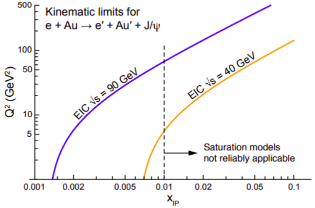

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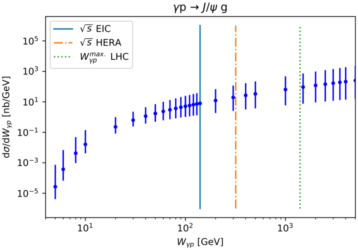

Figure 16: Resolved photon cross section as a function of $W_{\gamma p}$.