Lepton-Hadron collisions in MadGraph5_aMC@NLO

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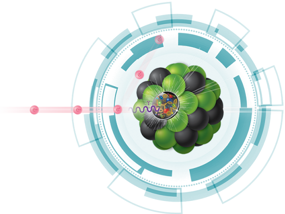
Motivation

- 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 (motivated towards EIC) performance within other constraints to study interesting physics scenarios.



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

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

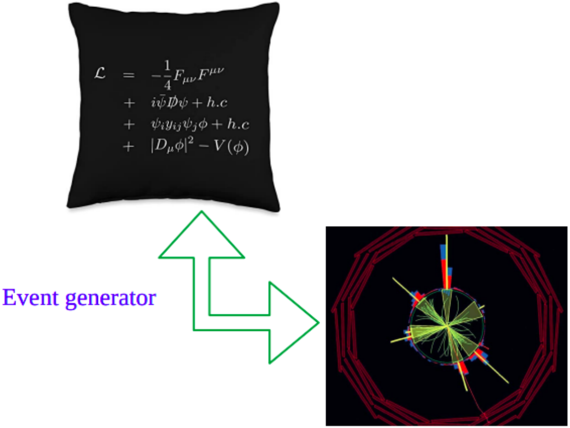
$d\hat{\sigma}$ = Partonic cross section, calculable within perturbation theory.
The partonic cross section can be expanded as:

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

* 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.



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

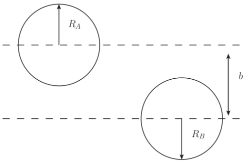
Missing: asymmetric collisions at next-to-leading (NLO)!

Photoproduction at LHC

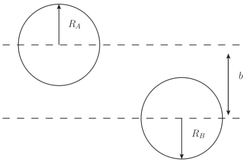
Ultra peripheral collisions

Photoproduction at LHC

Ultra peripheral collisions



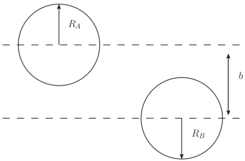
Ultra peripheral collisions



- b $> R_A + R_B$

Photoproduction at LHC

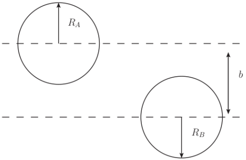
Ultra peripheral collisions



- b $> R_A + R_B$
- Photon induced

Photoproduction at LHC

Ultra peripheral collisions

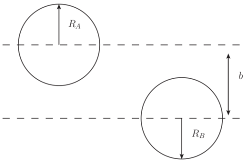


- $b > R_A + R_B$
- Photon induced

Inclusive Photoproduction

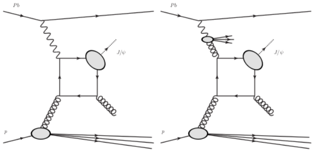
Photoproduction at LHC

Ultra peripheral collisions



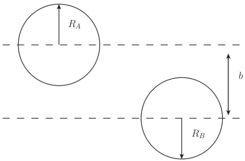
- b $> R_A + R_B$
- Photon induced

Inclusive Photoproduction



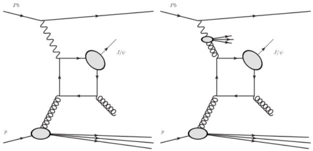
Photoproduction at LHC

Ultra peripheral collisions



- b > $R_A + R_B$
- Photon induced

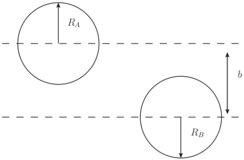
Inclusive Photoproduction



- Hard final state gluon

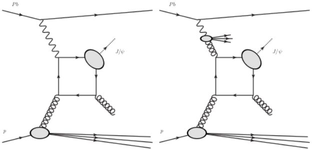
Photoproduction at LHC

Ultra peripheral collisions



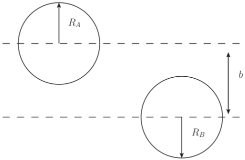
- b $> R_A + R_B$
- Photon induced

Inclusive Photoproduction



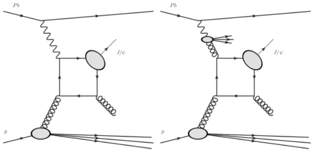
- Hard final state gluon
- Resolved vs. direct contribution

Ultra peripheral collisions



- b > $R_A + R_B$
- Photon induced

Inclusive Photoproduction



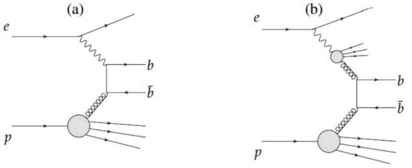
- Hard final state gluon
- Resolved vs. direct contribution
- Probe gluon PDF

- 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

Photoproduction at EIC

EIC (Electron-Ion Collider): "The Electron-Ion Collider will be a discovery machine for unlocking the secrets of the **glue** that binds the building blocks of visible matter in the universe"



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–proton collisions

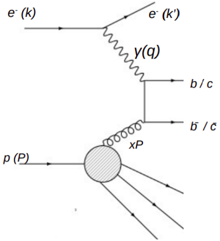
Electron - proton processes are traditionally classified according to the virtuality (Q^2) of the photon i.e four-momentum transfer to the photon from the electron (incoming outgoing),

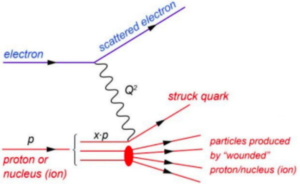
$Q^2 = -q^2 = -(k-k')^2$

I) Photoproduction:

Photon is nearly on mass shell.

$$Q^2 \leq m_H$$

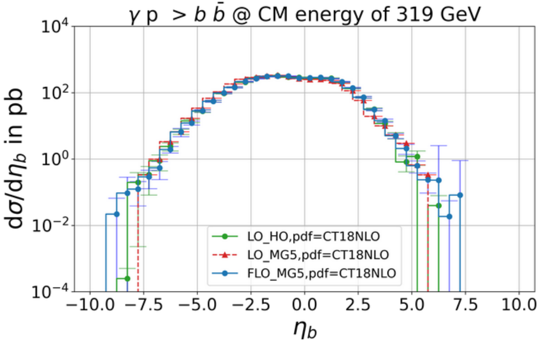




II) Deep-Inelastic-scattering (DIS):

Photon is off mass shell.

$$Q^2 >> m_H$$

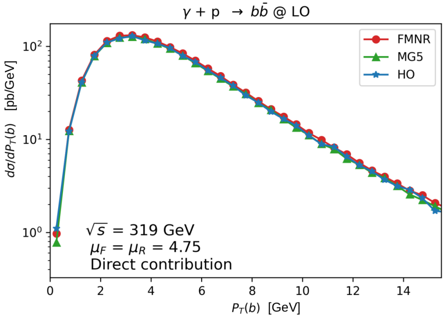


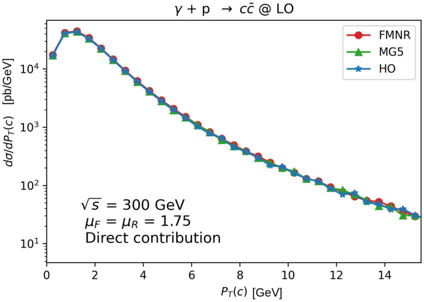
Comparison between pseudorapidity distribution of bottom quark pair production cross section obtained from MG5 at LO (FLO) and with another LO event generator called Helac-onia (HO).

	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 LO Results with FMNR

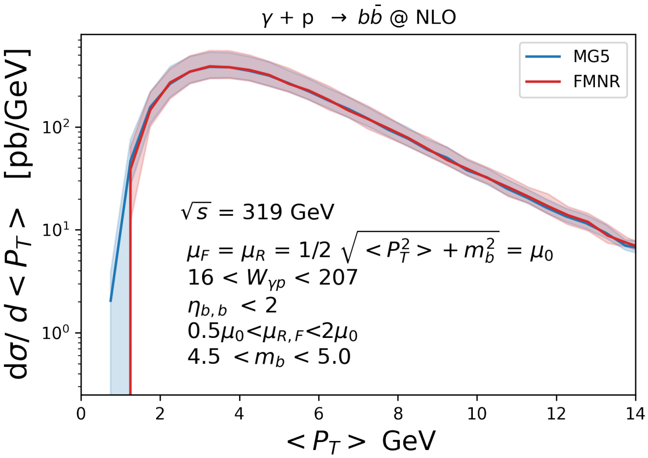
PDF = CTEQ6M





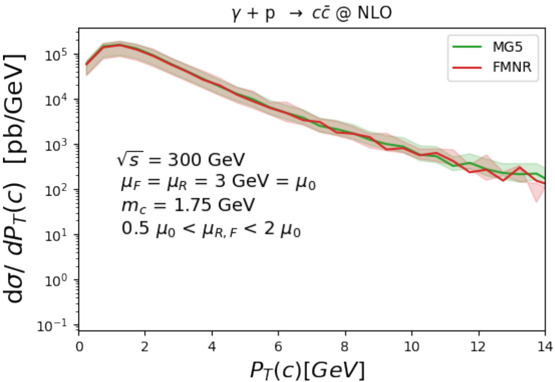
Good agreement from Charm and Beauty quark photoproduction!

Validation of NLO result with FMNR program



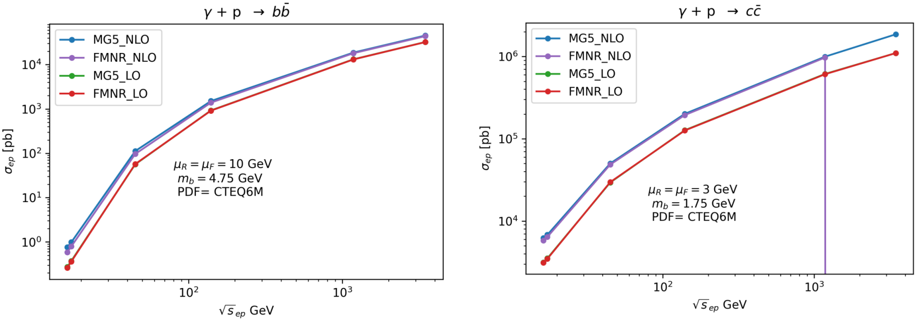
Perfect agreement (direct contribution)!

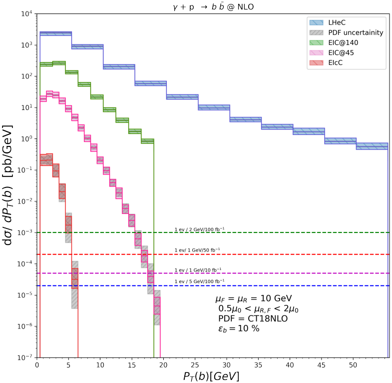
Validation of NLO result with FMNR program

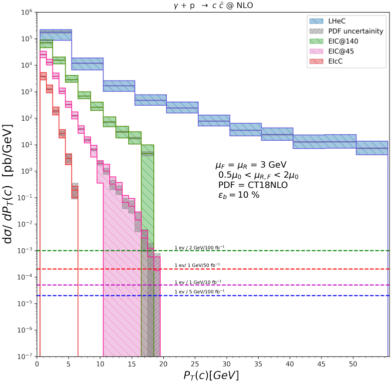


Perfect agreement (direct contribution)!

Possibility of future predictions

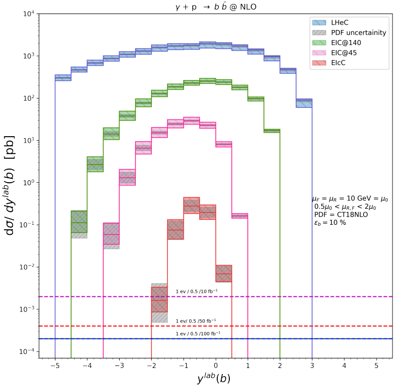


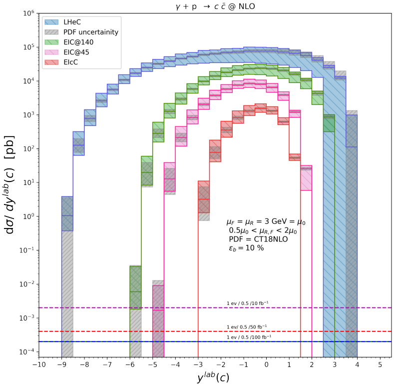




Transverse momenta distribution of Beauty and charm quark

Preliminary Results





Rapidity distribution of Beauty and charm quark

Future prospects

- 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.

Summary

- Our implementation of photoproduction at NLO in MG5 validation is completed and will be available very soon for users.
- We are also focusing 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
Fixed order	√√	√√	√	In progress
Parton shower	√√	√	Development will be starting soon	Development will be starting soon

Thank you for your attention!

Acknowledgment

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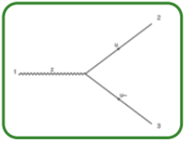
backup slides

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

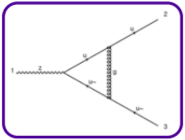
$\mathcal{O}(\alpha_s^b)$ | $\mathcal{O}(\alpha_s^{b+1})$ | $\mathcal{O}(\alpha_s^{b+1})$

Born cross section



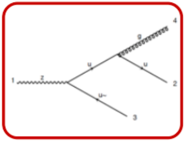
Finite

Virtual correction



Divergent

Real correction



Divergent

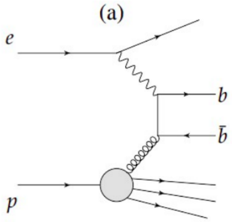
NLO Substraction

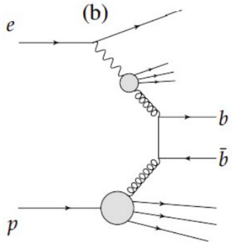
$$\sigma_{\rm NLO} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$
$$= \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\left[\mathcal{V} + \int d\Phi^{(1)}S\right] + \int d\Phi^{(n+1)}\left[\mathcal{R} - S\right]$$

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.