Lepton-hadron collisions in MadGraph5_aMC@NLO

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Synergies between LHC and EIC for quarkonium physics

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Overview

1. Photoproduction in electron-proton collision
2. Resolved Photoproduction
3. Heavy quark production for photo-nuclear collision

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.

$$Q^2 \leq m_H$$

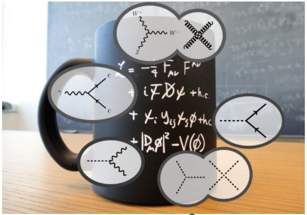
II) Deep-Inelastic-scattering (DIS):

Photon is off mass shell.

$$Q^2 >> m_H$$

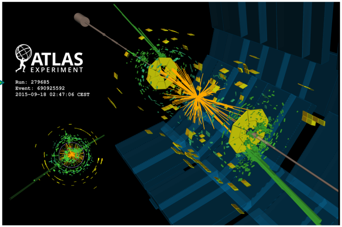
Introduction to MadGraph5

MadGraph_aMC@NLO (MG5) is an event generator which can generate matrix elements for any Lagrangian-based model at LO and NLO.

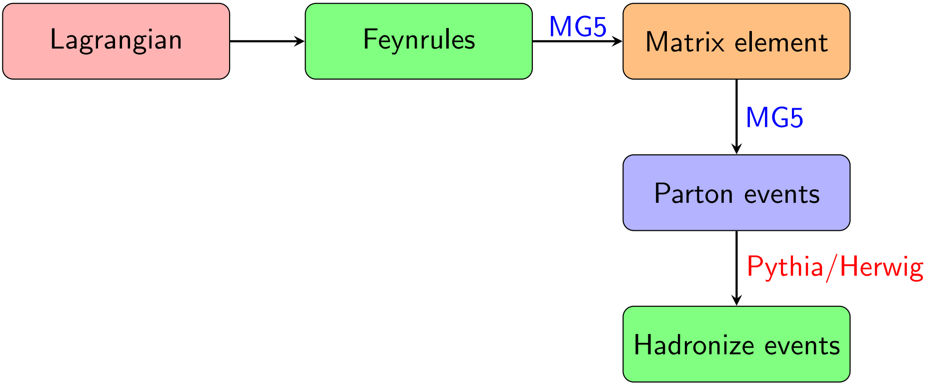


What we can get :

- Total cross section
- Differential cross section
- Un-weighted events



Framework


Lagrangian
Feynrules
MG5
Matrix element
MG5
Parton events
Pythia/Herwig
Hadronize events

Framework

Master integral for symmetric collision in MG5 (Already there):

$$\sigma_{AA\to X} = \sum_{i,j} \int \overbrace{dx_i dx_j d\phi}^{\text{Phase space integral}} \overbrace{f_i^A(x_i,\mu_F) f_j^A(x_j,\mu_F)}^{\text{PDFs}} \overbrace{\hat{\sigma}_{ab\to X}(x_i,x_j,\mu_F,\mu_R)}^{\text{Partonic cross section}}$$

How MG5 works:

- Identify all the partonic processes and calculate partonic cross section.
- Use PDFs
- Do the phase space integral and convolute with PDFs.
- Generate events

Photoproduction in MG5

In the case of asymmetric collision (New in MG5):

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

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

Issue : New parameter in the expression of the total cross section for photoproduction!

Solution : Implement a new parameter to control Q^2

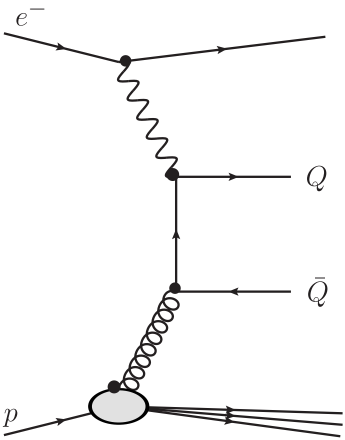
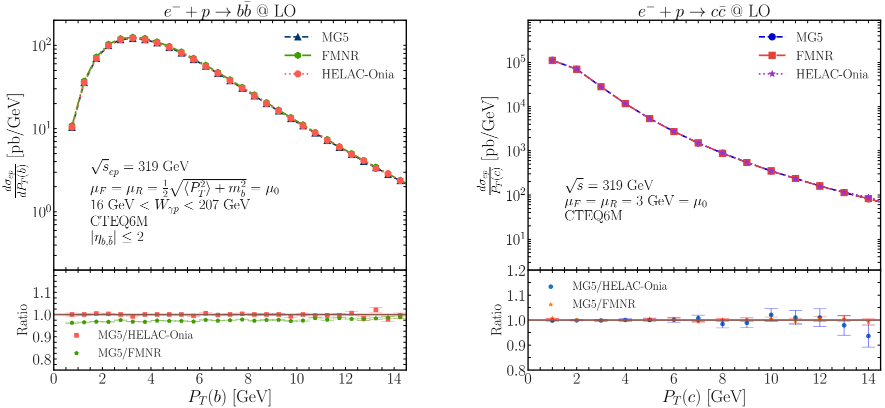


Figure: Direct photoproduction

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

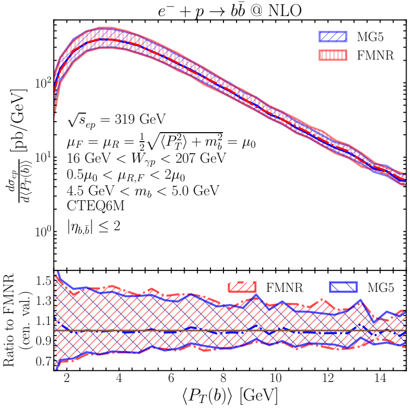
Validation of LO Results with FMNR

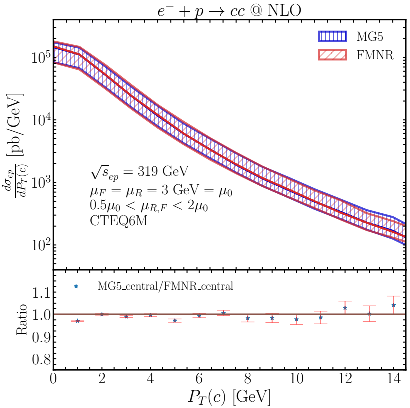


$\sim \mathcal{O}(1\%)$with HELAC-Onia for Charm and Beauty Quark photoproduction!

*FMNR : a private code by Stefano Frixione, Michelangelo L. Mangano, Paolo Nason, Giovanni Ridolfi

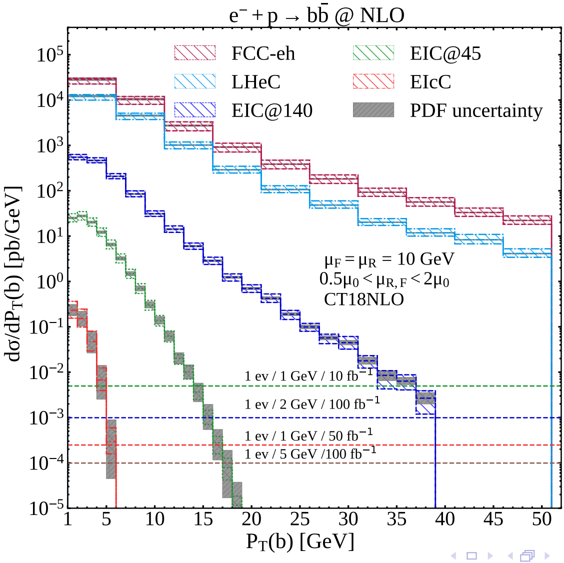
Validation of NLO Results with FMNR



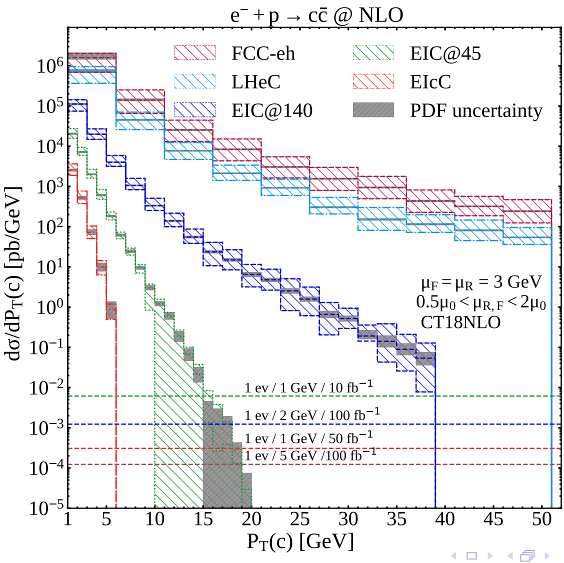


$\sim 2\%$ for Charm and $\sim \mathcal{O}(1\%)$ Beauty Quark photoproduction!
[10.1140/epjc/s10052-012-2148-1]

Bottom photoproduction at future *ep* experiment

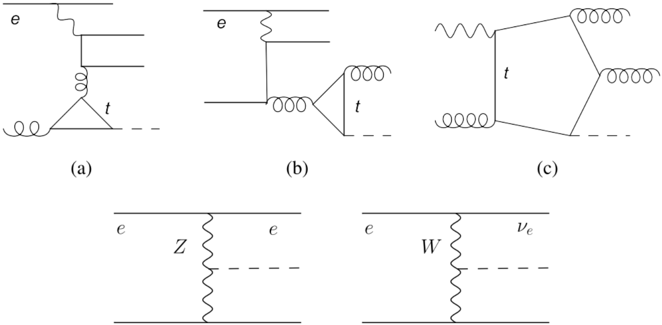


Charm production at future *ep* predictions



Higgs photoproduction

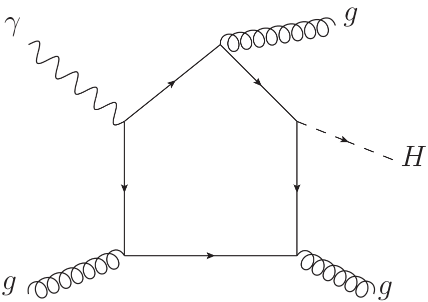
In the case of Higgs photoproduction, we have different diagrams
https://doi.org/10.1016/j.nuclphysb.2020.115134[1]



(a) (b) (c) (d) (e)

- Possibility to study Figure b and c.
- new diagram study for Higgs production with heavy quark-antiquark !

Higgs photopropduction



Partonic process	Calculated total cross section (fb)	Total cross section from paper [1] (fb)
a g $\to$ *hgg*	1.666 $\times 10^{-4}$	1.9 $\times 10^{-4}$

Table: Cross section for LHeC study at 1.3 TeV for fig. c

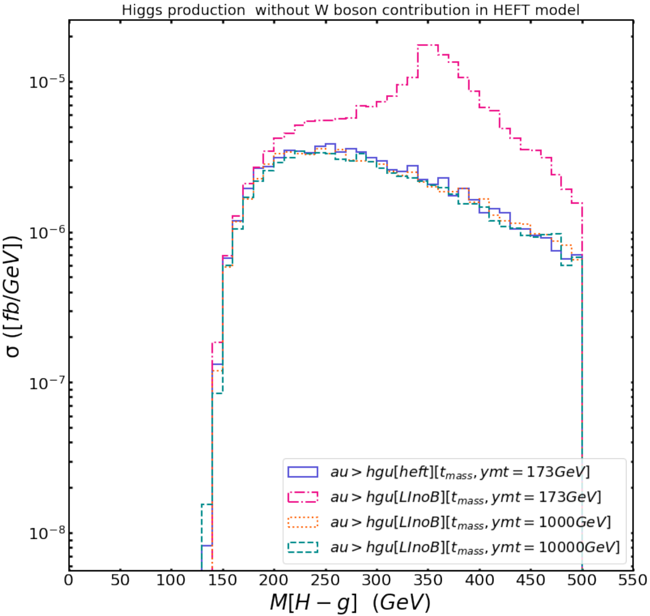
Higgs photoproduction

In the case of Fig b, we can study both EFT and SM at LO.

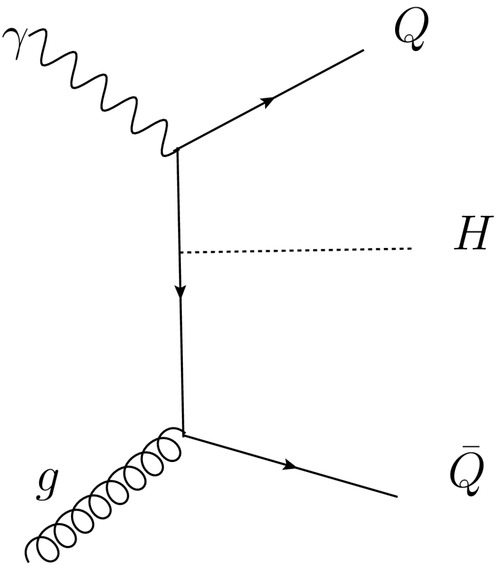
Partonic process	model	Calculated in MG5 (fb)	From paper [1] (fb)
a p → h g j	Loop_induced	$2.739 \times 10^{-4} \pm 1.066 \times 10^{-6}$	7.5×10^{-4}
	HEFT	9.998e $\times 10^{-5} \pm 3.415 \times 10^{-7}$	

Table: Cross section for LHeC at 1.3 TeV

$p/j = u\ d\ s\ \bar{u}\ \bar{d}\ \bar{s}$


Higgs production without W boson contribution in HEFT model
σ ([fb/GeV])
10−5
10−6
10−7
10−8
0
50
100
150
200
250
300
350
400
450
500
550
M[H − g] (GeV)
au > hgu[heft][tmass, ymt = 173GeV]
au > hgu[LInoB][tmass, ymt = 173GeV]
au > hgu[LInoB][tmass, ymt = 1000GeV]
au > hgu[LInoB][tmass, ymt = 10000GeV]

Higgs photoproduction



Higgs photoproduction

$E_e(GeV)$	$E_p(GeV)$	Mass of Higgs (GeV)	Scale (GeV)	PDF used
60	7000 / 50000	125	125	CT18NLO

Partonic process	LO (fb)	NLO (fb)
a p $\rightarrow hb\bar{b}$	9.194 x $10^{-3} \pm 8.35 \times 10^{-5}$	1.03 x $10^{-2} \pm 3.5 \times 10^{-5}$
a p $\rightarrow hc\bar{c}$	1.06 x $10^{-3} \pm 2.54x10^{-5}$	2.19 x $10^{-3} \pm 1.14x10^{-4}$
a p $\rightarrow ht\bar{t}$	5.722x $10^{-3} \pm 3.82 \times 10^{-5}$	6.11 x $10^{-3} \pm 6.19 \times 10^{-5}$

Table: Cross section for Higgs Photoproduction at LHeC energy 1.3 TeV

Partonic process	LO (fb)	NLO (fb)
a p $\rightarrow hb\bar{b}$	8.10 $\times 10^{-2} \pm 8.80 \times 10^{-4}$	9.03 x $10^{-2} \pm 4.51 \times 10^{-3}$
a p $\rightarrow hc\bar{c}$	1.04 $\times 10^{-2} \pm 1.95x10^{-4}$	2.49 $\times 10^{-2} \pm 1.44x10^{-4}$
a p $\rightarrow ht\bar{t}$	0.492 $\pm 2.81 \times 10^{-3}$	0.4701 $\pm 6.16 \times 10^{-3}$

Table: Cross section for Higgs Photoproduction at FCC-eh energy 3.4 TeV

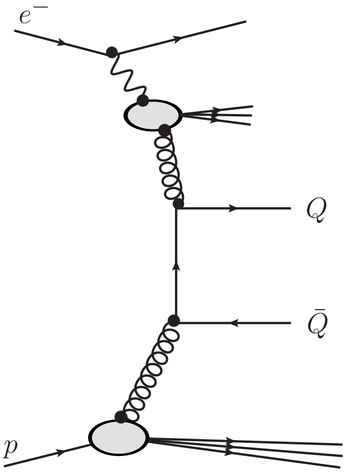
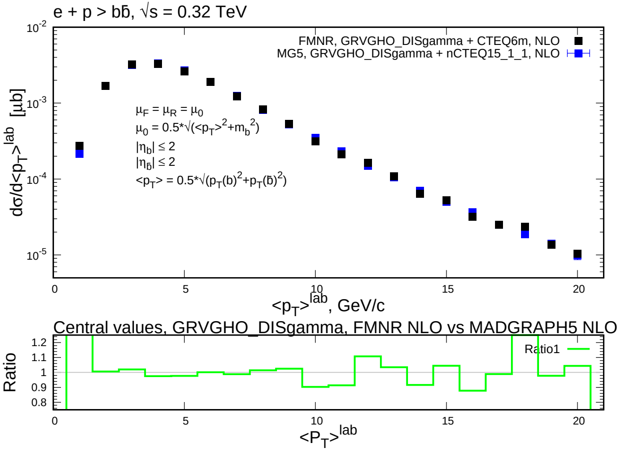


Figure: Resolved photoproduction

$$\sigma_{\gamma h \to X} = \sum_{i,j} \int dx_i dx_j d\phi f_i^{\gamma}(x_i, \mu_F, \texttt{LHAID1}) f_j^{h}(x_j, \mu_F, \texttt{LHAID2}) \hat{\sigma}_{ab \to X}(x_i, x_j, \mu_F, \mu_R)$$

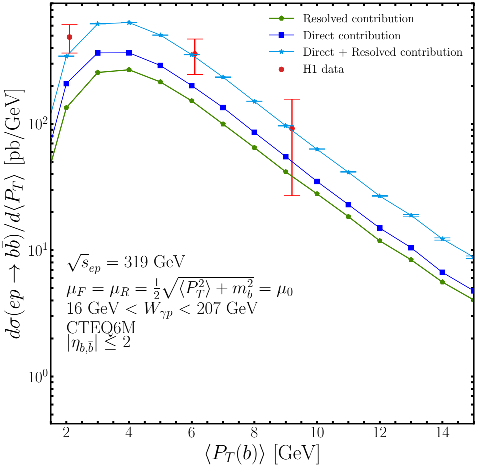
Resolved photoproduction

1 GeV $< \langle P_T(b) \rangle <$ 10 GeV agreement of $\sim \mathcal{O}$ (1%) with FMNR



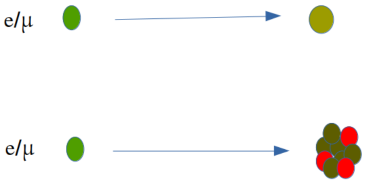
Direct vs Resolved photoproduction

Direct photoproduction > Resolved photoproduction



10.1140/epjc/s10052-012-2148-1

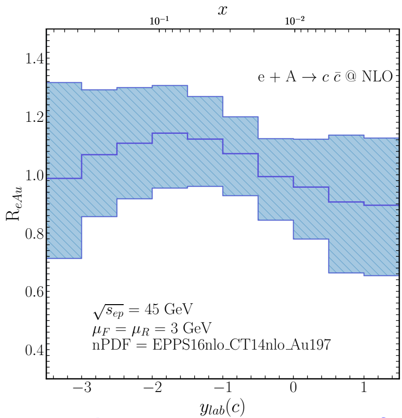
Photo-nuclear collision

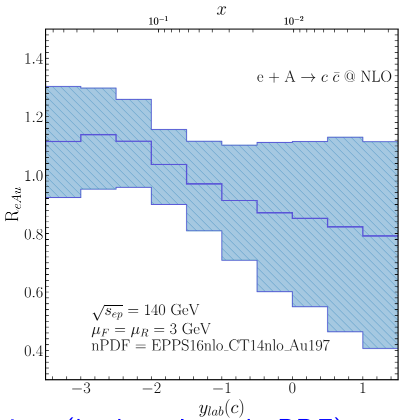


R_{eAu}@NLO of charm at EIC

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

$$e + Au \rightarrow c\bar{c}$$





Automatic generation of uncertainty (both scale and nPDF)

Conclusion and future plans

- Our implementation of photoproduction at NLO in MG5_aMC is complete, and the testing version is available on GitHub (https://github.com/mg5amcnlo/mg5amcnlo/tree/ep_collision).
- We can study Ultra peripheral collisions (UPC) as well.
- Resolved photoproduction has been studied.
- Nuclear modification factors are computed automatically with their scale and PDF uncertainties.
- DIS at LO+PS working and needs to be validated.
- Publish our code officially.
- Work on the interface for photoproduction + Hadronization at NLO.
- Work on DIS+PS at NLO

Backup Slides

Future predictions for Rapidity at different *ep* facility

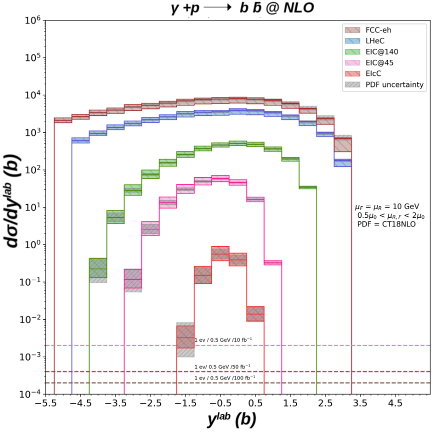


Figure: Rapidity of bottom

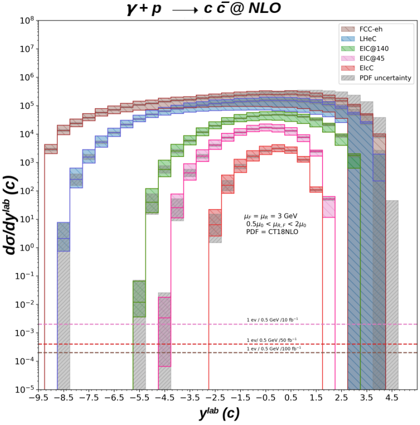


Figure: Rapidity of charm

Higgs production for pp

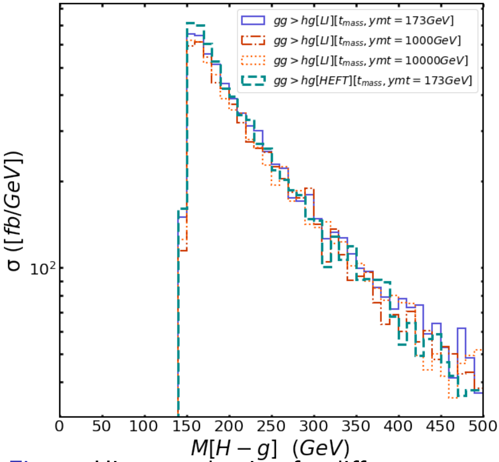


Figure: Higgs production for different top mass