Lepton-hadron collisions in MadGraph5_aMC@NLO

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On behalf of

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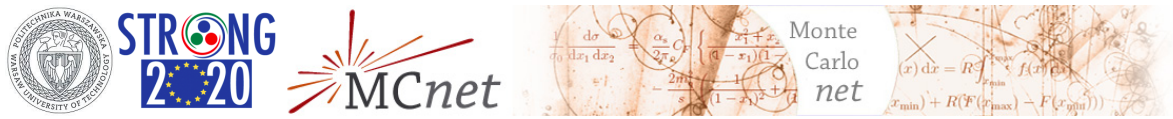


Theoretical Overview

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:

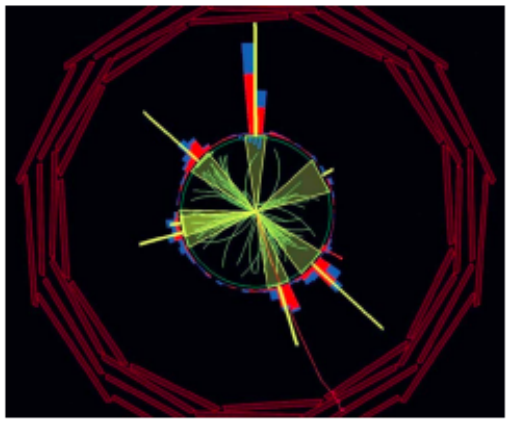
$$\hat{\sigma} = \overbrace{\sigma^{Born}\left(1 + \frac{\alpha_s}{2\pi}\sigma^1 + ..\right)}^{\text{NLO}} \quad \text{LO}$$

* 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.

Event generator



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

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

Electron–proton collisions

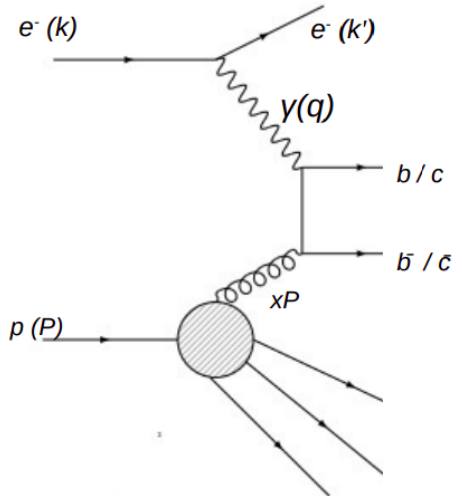
Electron-proton processes are traditionally classified according to the virtuality (Q^2) of the photon i.e four-momentum transfer to the photon from the electron (incoming outgoing),

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

I) Photoproduction :

Photon is nearly on mass shell.

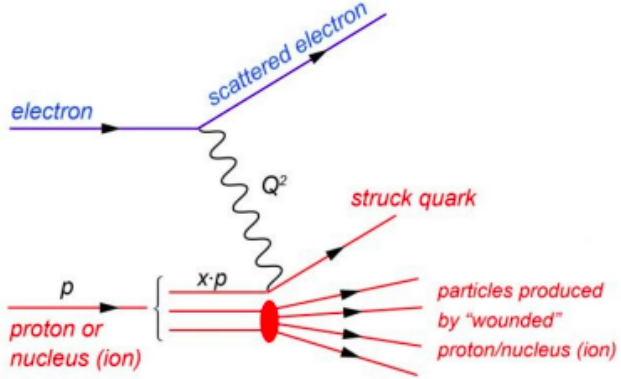
$$Q^2 \leq m_H$$



II) Deep-Inelastic-scattering (DIS):

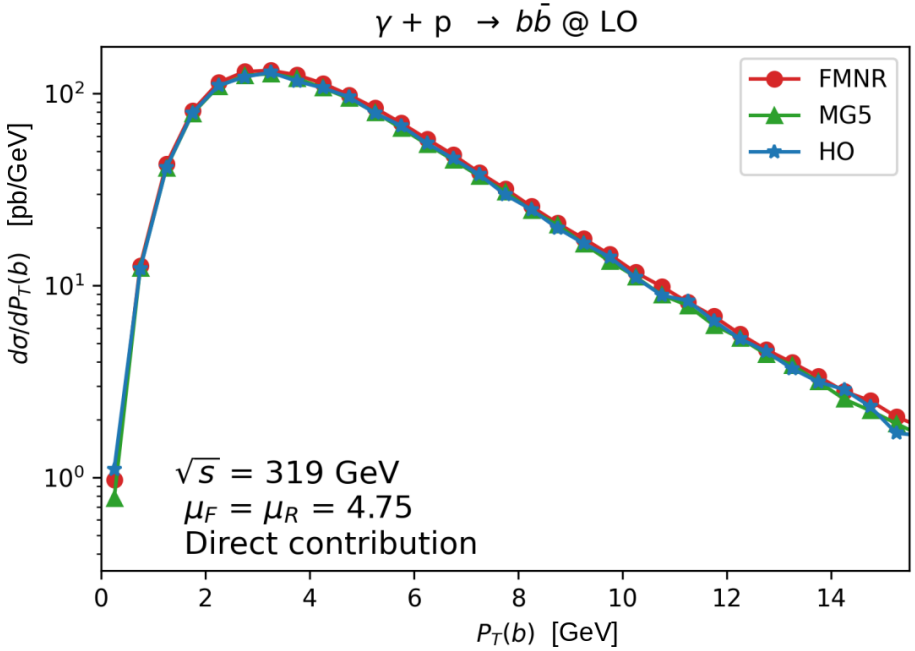
Photon is off mass shell.

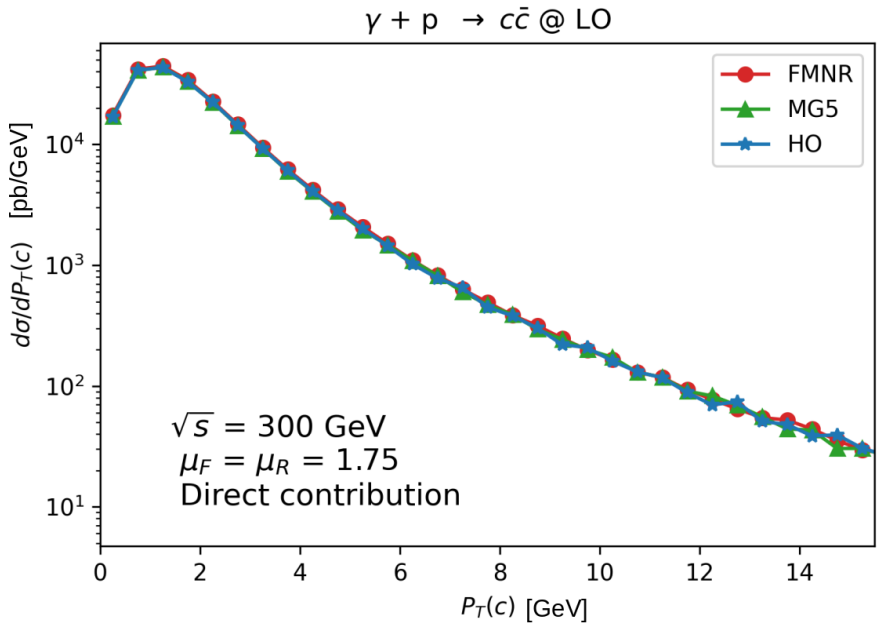
$$Q^2 >> m_H$$



Validation of LO Results with FMNR

PDF = CTEQ6M

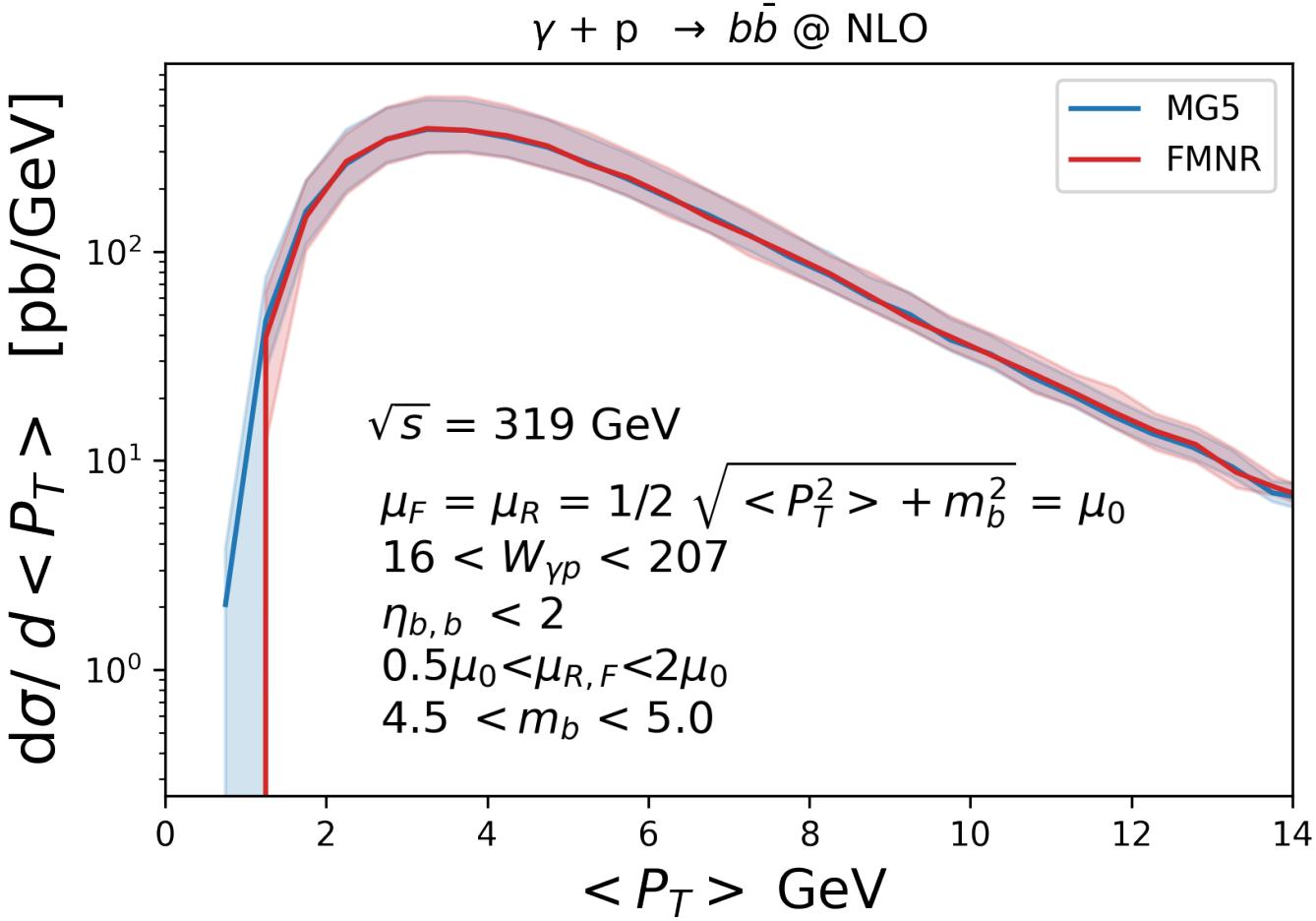




Good agreement for Charm and Beauty Quark photoproduction!

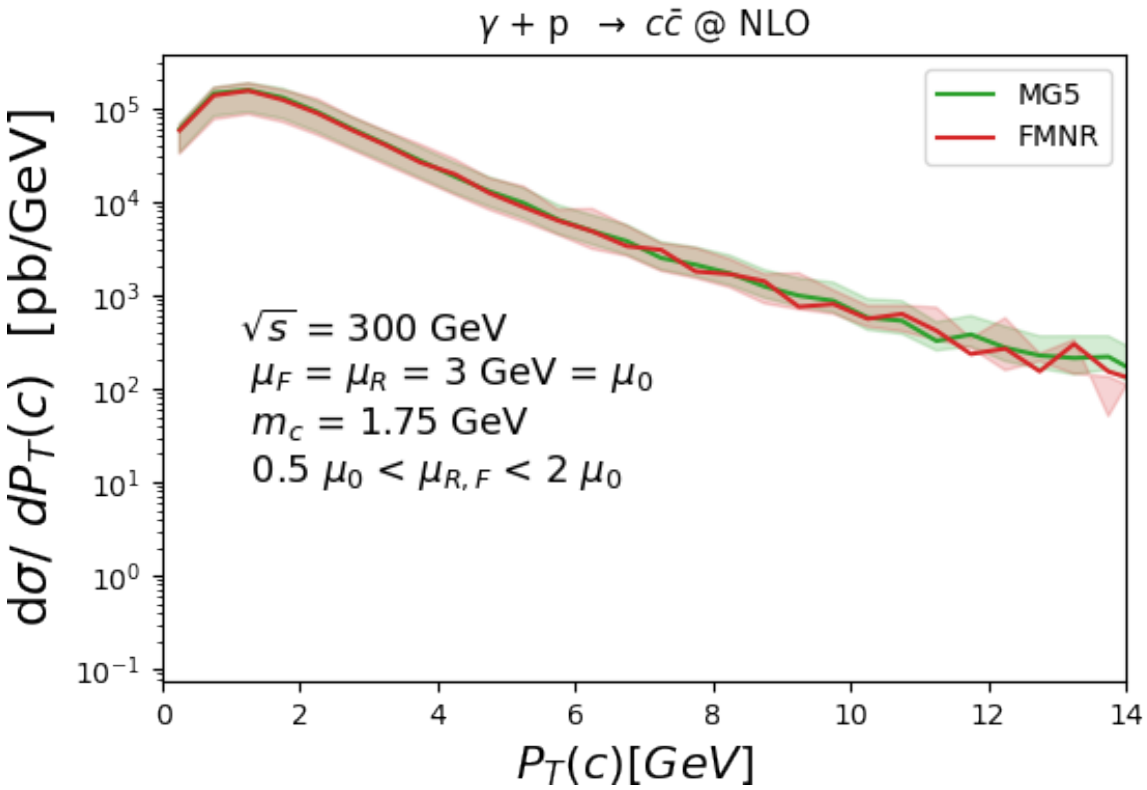
*HO = Helac-Onia

Validation of NLO result with FMNR program



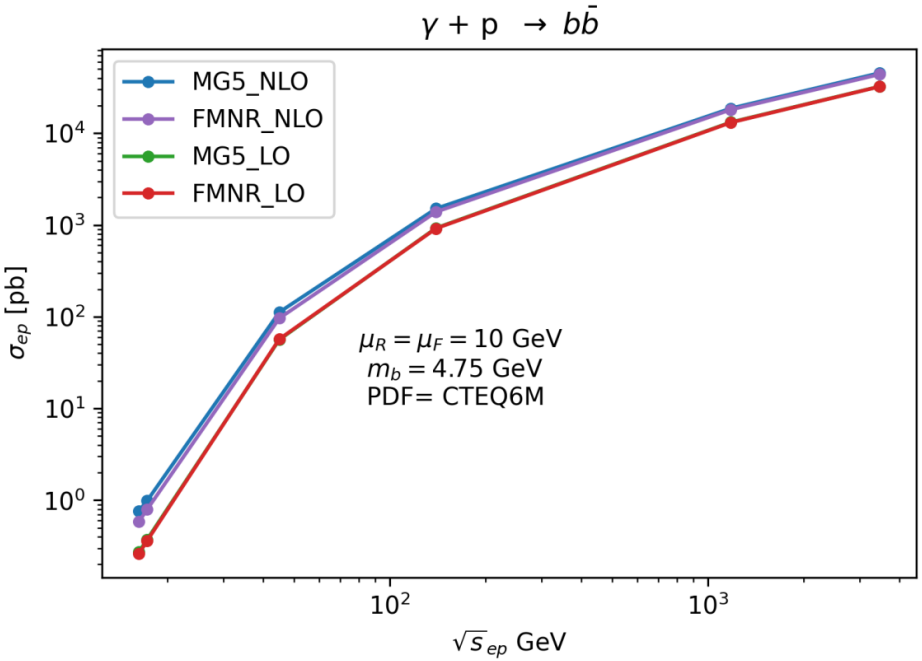
Perfect agreement (direct contribution)!

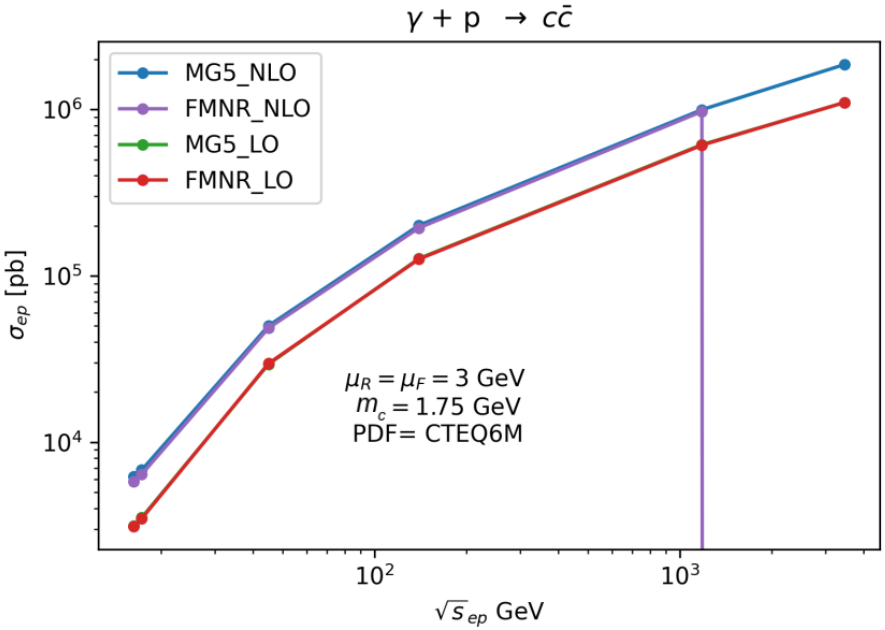
Validation of NLO result with FMNR program

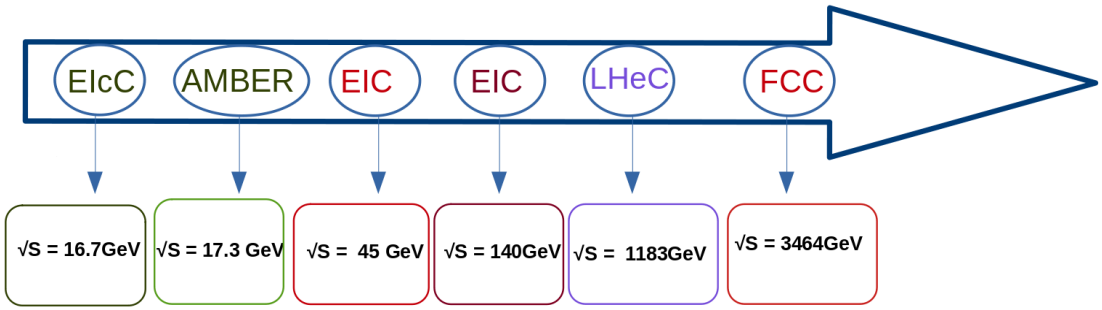


Perfect agreement (direct contribution)!

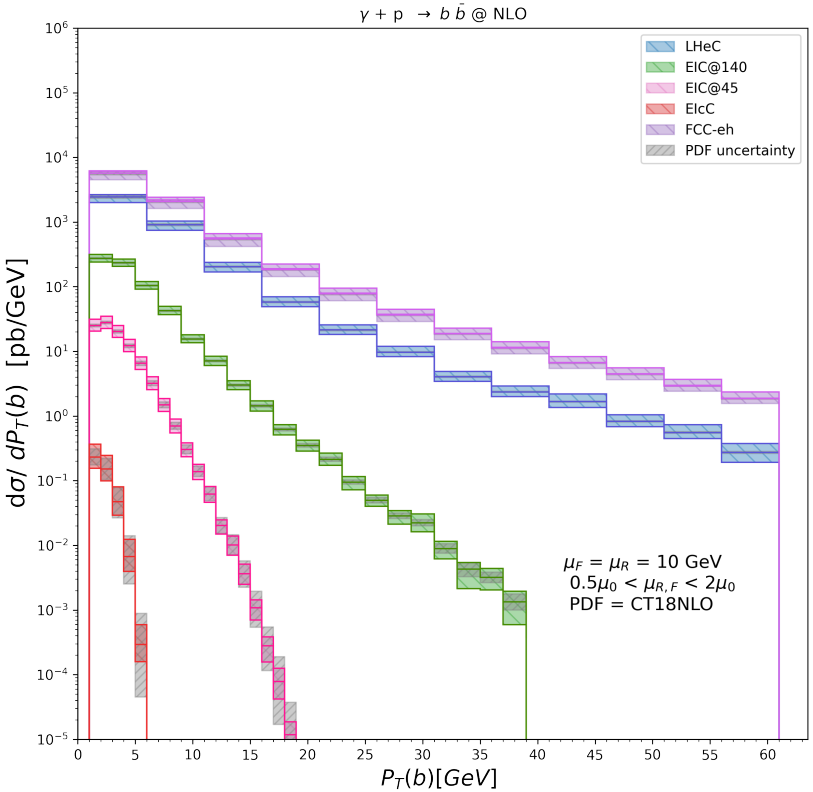
Possibility in Future Experiments

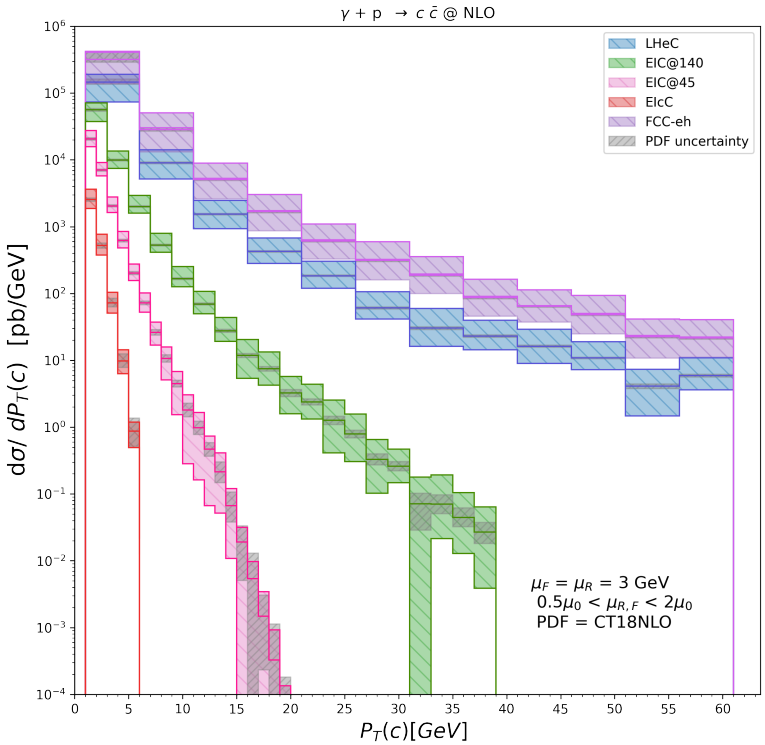






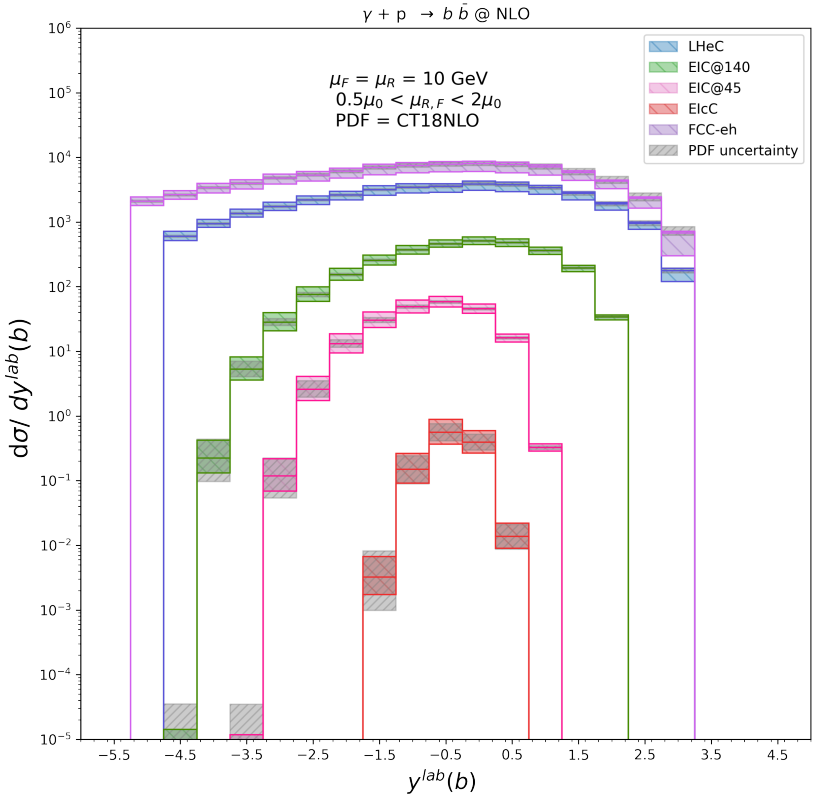
Preliminary Results

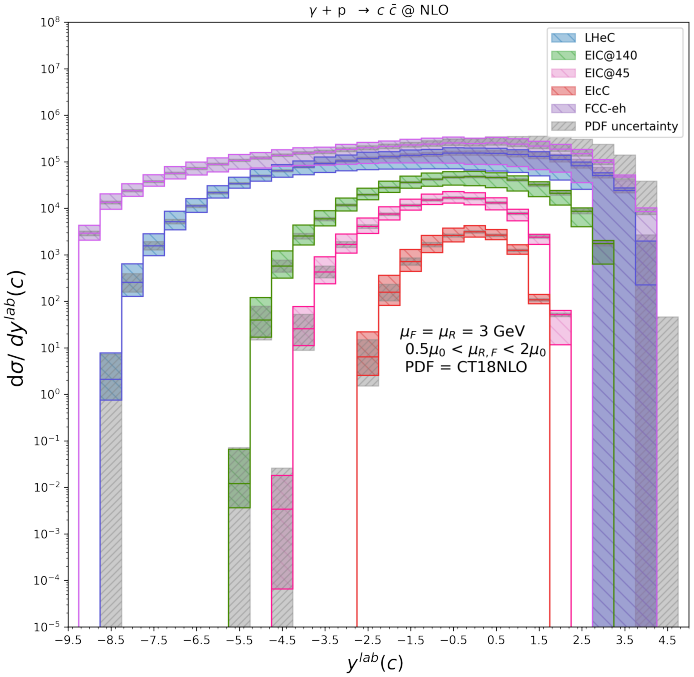




Transverse momenta distribution of Beauty and Charm quark

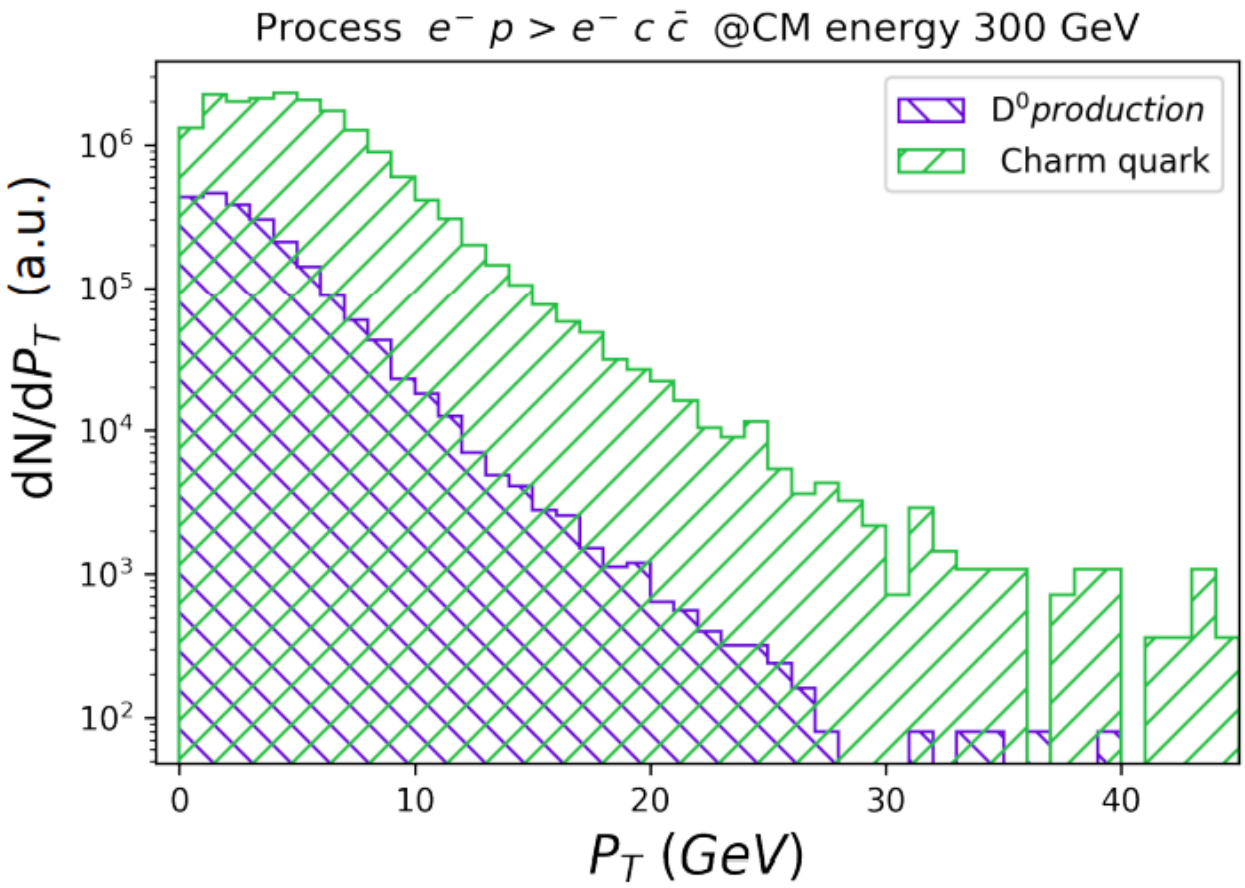
Preliminary Results





Rapidity distribution of Beauty and Charm quark

LO DIS + hadronization (work in progress):



Comparison between the transverse momentum spectrum of D^0 mesons produced from DIS with that of charm quarks. (preliminary result)

Summary

- Our implementation of photoproduction at NLO in MG5 validation is completed and will be available very soon for users.
- The validation of DIS at LO and photoproduction at LO with hadronization is in progress.
- We can do UPC study as well.
- **MG5_aMC capabilities :**

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

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.

Thank you for your attention!

Acknowledgment

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backup slides

NLO calculation

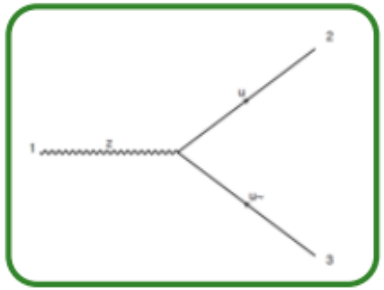
$$\sigma_{\mathrm{NLO}} = \int d\Phi^{(n)} \mathcal{B} + \int d\Phi^{(n)} \mathcal{V} + \int d\Phi^{(n+1)} \mathcal{R}$$

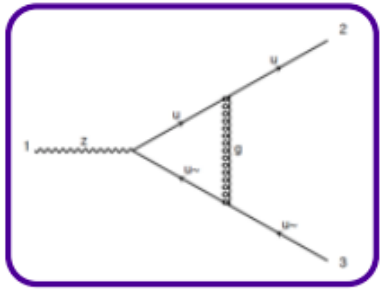
$$\mathcal{O}(\alpha_s^b) \qquad \mathcal{O}(\alpha_s^{b+1}) \qquad \mathcal{O}(\alpha_s^{b+1})$$

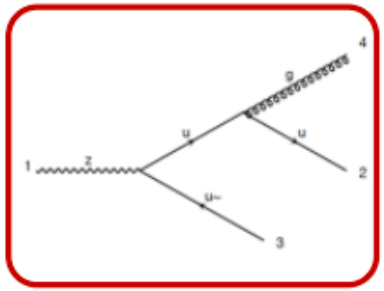
Born cross section

Virtual correction

Real correction







Finite

Divergent

Divergent

NLO Substraction

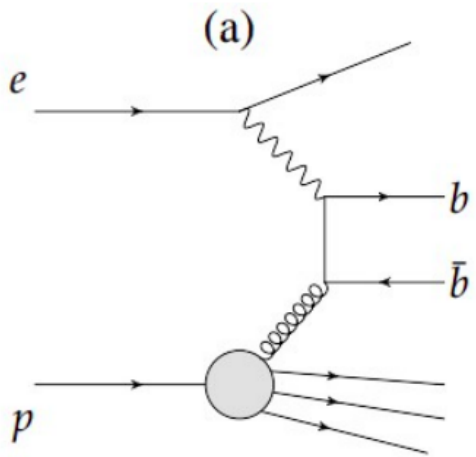
$$\sigma_{\mathrm{NLO}} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$

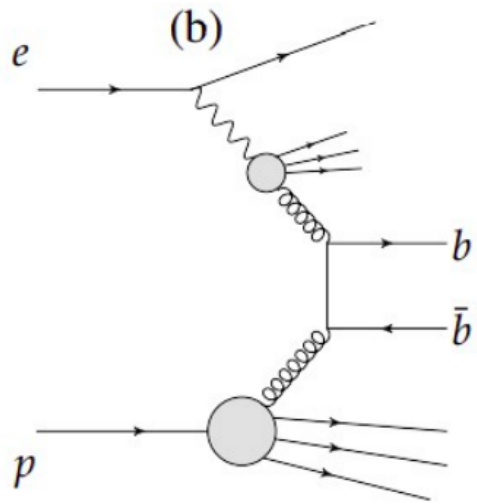
$$= \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\left[\mathcal{V} + \int d\Phi^{(1)}S\right] + \int d\Phi^{(n+1)}\left[\mathcal{R} - S\right]$$

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

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

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

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

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

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

Photoproduction vs DIS

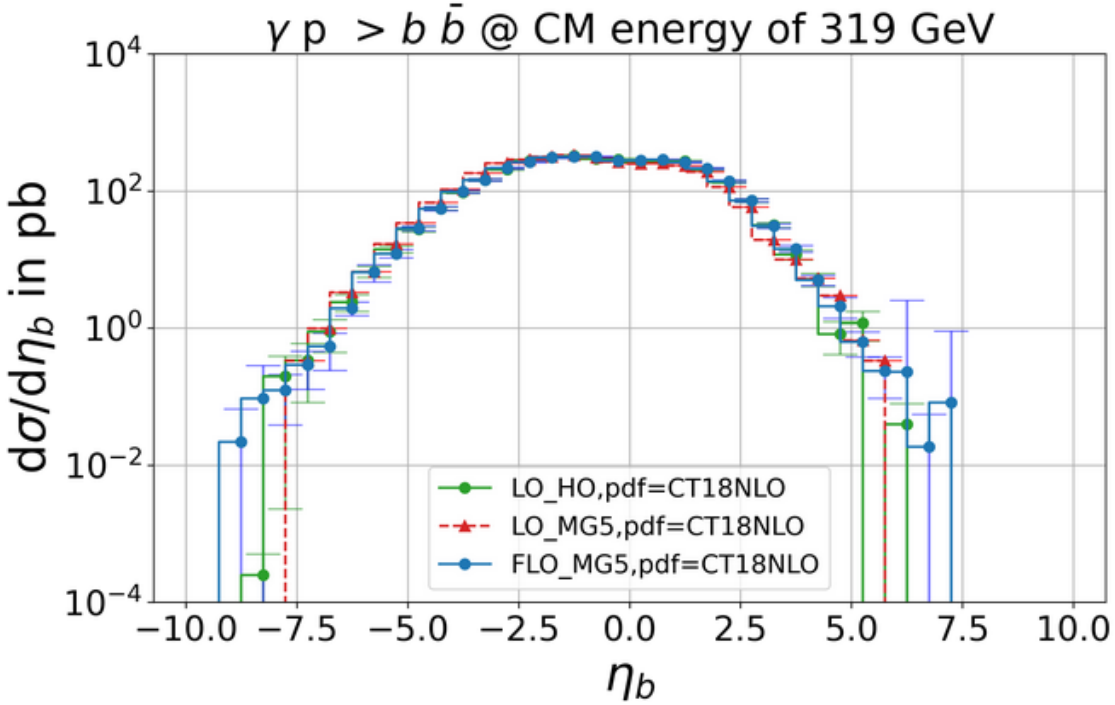
DIS	Photoproduction
Photon is highly virtual	Photon is quasi-real
Scattered e^- observed	Scattered e^- not observed due to low virtuality
Direct	Direct & resolved photon contribution due to partonic structure of photon

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