Lepton-Hadron collisions in MadGraph5_aMC@NLO

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On behalf of

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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.

Objective of our work

For the planning of our future measurements, detector optimization, and data collection campaigns, we need a reliable tool for the simulation of electron-proton and electron-nucleus collisions.

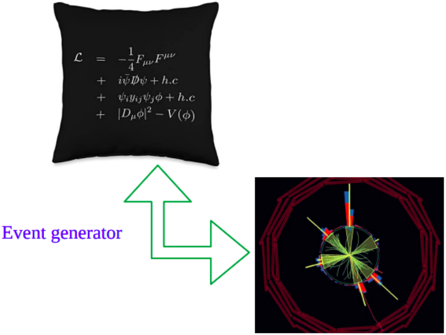
- There are few event generators available for electron-proton and electron-nucleus collisions that experimentalists could use.
- Most of them are working at the Leading Order.
- A convenient event generator development is crucial for our upcoming EIC.

Our goal :

- Implement a robust and user-friendly tool for the automated perturbative computations of heavy quark production, D mesons, and B mesons at a higher accuracy level.
- We will do so by implementing electron-proton and electron-nucleus collisions in MadGraph5_aMC@NLO.

Introduction to MadGraph5_aMC@NLO

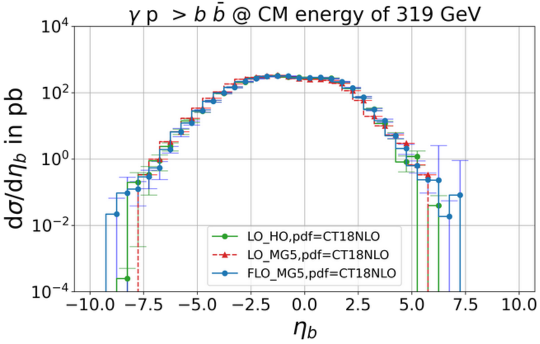
- It's an automated matrix element generator.
- It can support a huge class of particle physics models.
- The program can calculate amplitudes at the tree and one loop levels for arbitrary processes.
- A major feature is the computation of next-to-leading orders (NLO) at fixed order and with hadronization.



Initially, MadGraph5_aMC@NLO(MG5) was developed for (symmetric) proton-proton collisions.
Missing: electron-proton collisions at next-to-leading (NLO)!
Reason :

- Events and counter-events do not have the same kinematics since both need to have all the particles on the shell. If there are kinematic miss-match between events and counter events that can lead to preventing NLO event generation.
- A phase space mapping relating the two is required.

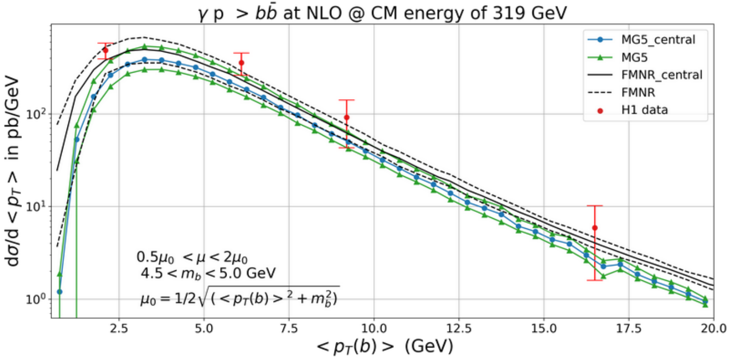
Validation of LO result



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

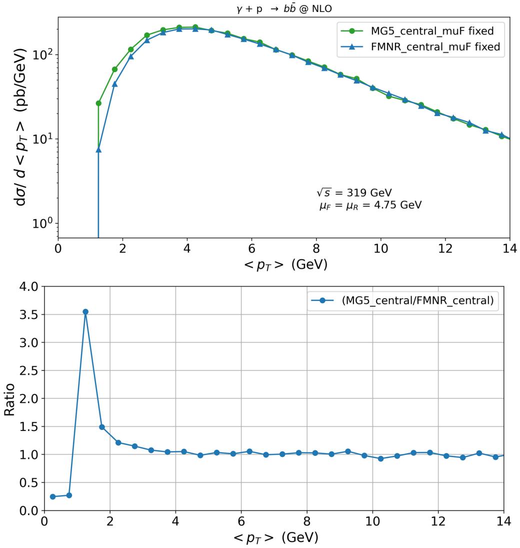
Validation of NLO result



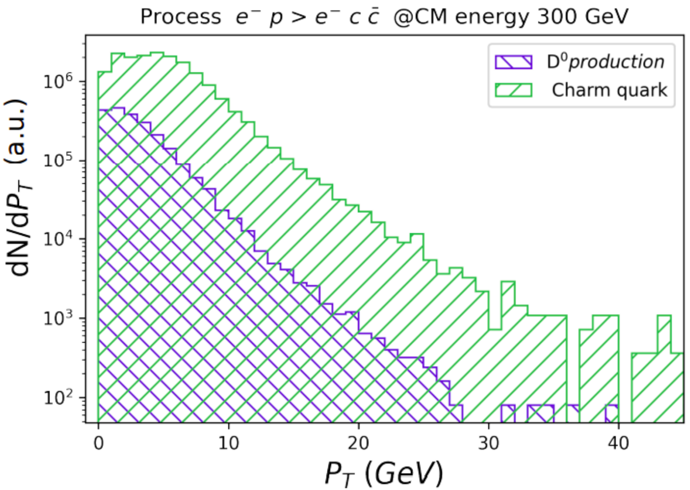
Comparison of cross section for the bottom pair production at NLO from MG5 with the experimental data HERA (H1) and a theoretical prediction from FMNR program.

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

Comparison with FMNR program (preliminary results)



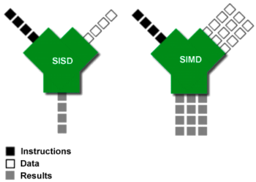
LO DIS + PS (work in progress):



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

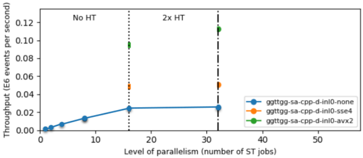
The next part of the talk is on behalf of
Stefan Roiser
Andrea Valassi
Olivier Mattelaer.

SIMD (Single Instruction Multiple Data):



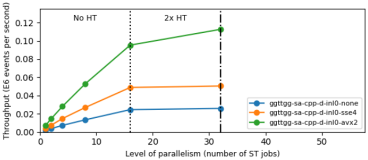
- Need a dedicated memory pattern to allow it.
- Speed-up on the same hardware.

Gain:



(a) Without SIMD

4x →



(b) With SIMD

Current status:

- We can reproduce the (differential) cross- section.
- Parton-shower and helicity-recycling are not yet supported.

New features of MG5aMC

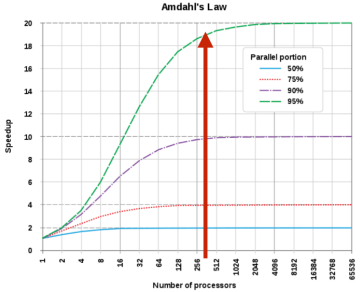
GPU:

- Thread parallelism.
- Memory management is critical.

Potential gain:

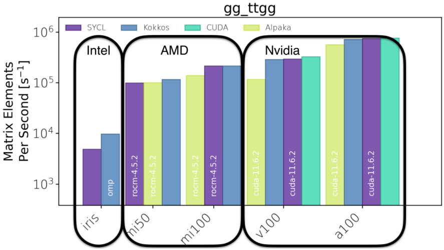
	$gg \to t\bar{t}$	$gg \to t\bar{t}gg$	$gg \to t\bar{t}ggg$
madevent	13G	470G	11T
matrix1	3.1G (23%)	450G (96%)	11T (>99%)

- Not full code is using GPU.
    - Gain limited by Amdahl's law,
        - Around 20x.



GPU results :

1-core Standalone C++ scalar	1.84E3 **(x1.00)**
Standalone CUDA NVidia V100S-PCIE-32GB (TFlops*: 7.1 FP64, 14.1 FP32)	4.89E5 **(x270)**



Future prospects

- Validations on the photoproduction at NLO.
- Validation of DIS at LO work with available generator (Helac-Onia at LO) and with experimental results from HERA.
- Validation of photoproduction at LO + PS.
- Develop interface for photoproduction and DIS at NLO + PS.
- Extend our electron-proton work with electron-nucleus collisions by including nuclear PDFs.
- For **SIMD** , the work is still in progress.
- Waste of GPU
  - Solution under investigation (lhapdf, multi-process, un-weighting).

Timeline of our work

- i)Familiarisation with the automated tool Helac-Onia ii)Literature review — Oct, 2020
- i) Understanding MG5_aMC ii) Development of photoproduction at FNLO in MG5_aMC — Feb,2021
- i) Validating predictions for Heavy quarks photoproduction — Oct,2021
- i) Comparisons for Heavy quarks photoproduction ii) Development of LO+PS for ep collisions — Feb,2022
- i) Wrapping up previous work ii) Validations for LO+PS — Oct,2022 **I am here!**
- i) Development of NLO +PS for ep collisions — Feb,2023
- i) Finalise development of ep collisions ii) Extend the work for eA collisions — Oct,2023
- i) Finalise development of eA collisions — Feb,2024

By the end of Sept 2024 available for users!

Summary

- Our implementation of photoproduction at NLO in MG5 validation will be complete very soon.
- The validation of DIS at LO and photoproduction at LO is in progress.
- As soon as we finalize our previous works 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.
- Faster matrix-element using SIMD and GPU but still missing some pieces.

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

Part of this work has received funding from the European Union's Horizon 2020 research and innovation programme as part of the Marie Skłodowska-Curie Innovative Training Network MCnetITN3 (grant agreement no. 722104).
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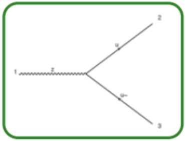
backup slides

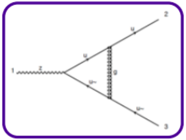
NLO calculation

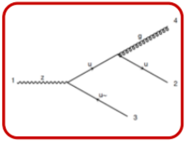
$$\sigma_{\text{NLO}} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$

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

Born cross section | Virtual correction | Real correction







Finite | Divergent | Divergent

NLO Substraction

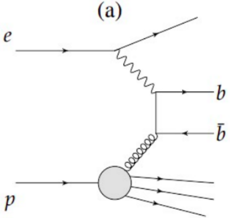
$$\sigma_{\mathrm{NLO}} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$

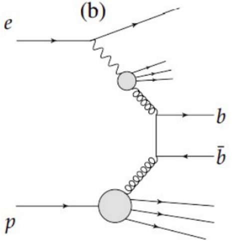
$$= \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\left[\mathcal{V} + \int d\Phi^{(1)} S\right] + \int d\Phi^{(n+1)}\left[\mathcal{R} - S\right]$$

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.

Theoretical Overview

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

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

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

$$\hat{\sigma} = \underbrace{\overbrace{\sigma^{Born}\Big(1}^{\text{LO}} + \frac{\alpha_s}{2\pi}\sigma^1}_{\textbf{NLO}} + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma^2 + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma^3 + ..\Big)$$

Why higher order correction?

- Leading Order (LO) predictions strongly depend on renormalization and factorization scales.
- Reliable estimate of theoretical uncertainties.

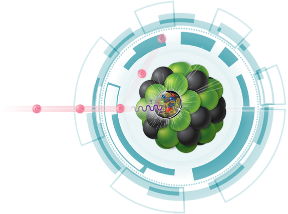
* LO = Leading order, NLO = Next-to-leading order and so on.

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?

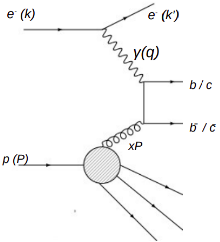


Electron–proton collisions

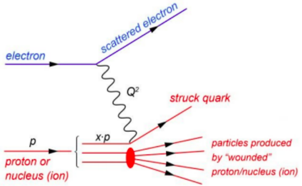
Electron (photon) - proton processes are traditionally classified according to the virtuality (Q^2) of the photon i.e four-momentum transfer to the photon from the electron (incoming outgoing),
$Q^2 = -q^2 = -(k-k')^2$

I) Photoproduction:Photon is nearly on mass shell.

$$Q^2 \leq m_H$$

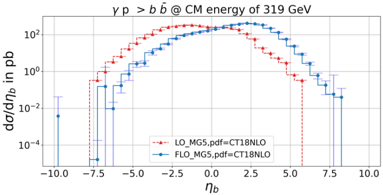


II) Deep-Inelastic-scattering (DIS): Photon is off mass shell. $Q^2 >> m_H$



Results

- Implementation of two scale choices (one for the photon flux and another for PDF) which is essential for electron-proton collisions
- We have added a new boost inside MG5 that can replicate the final results (spectrum of kinematic variables) in the laboratory frame.



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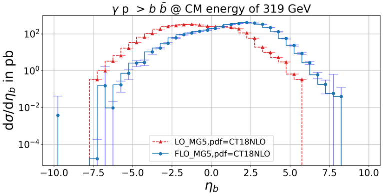

boost

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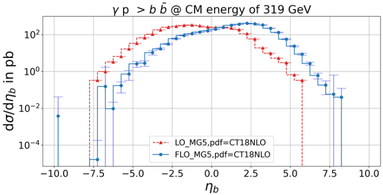
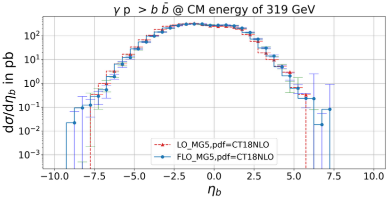
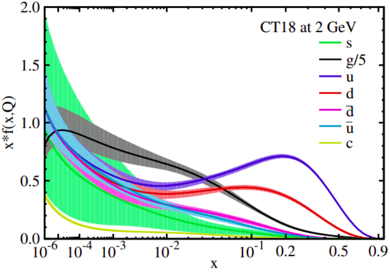
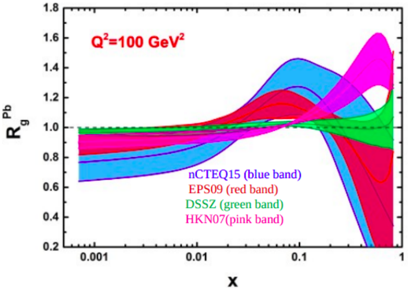


boost



Parton Distribution Functions





Parton distribution functions = f(x, Q)

x = Momentum carried by partons

Q = Energy scale(resolution of the probe)

R_g^{Pb}= nuclear modifications factor of the gluon PDF in Pb

nPDF's help us to understand the structure of hadrons by considering the contribution from partons inside nuclei.

DOI: 10.1103/PhysRevD.95.054002
https://arxiv.org/pdf/1912.10053.pdf

NLOAccess

MG5_aMC@NLO is now available online with its full NLO version on NLOAccess (https://nloaccess.in2p3.fr), a virtual access for automated perturbative NLO calculations for heavy ions and quarkonia.

Features :

- secure two-step registration process.
- protected OwnCloud storage.
- user input file as first way to submit a run
- guided input file creation and submission both for HELAC-Onia and MG5