Photon-induced and proton-nucleus collisions in MadGraph5_aMC@NLO

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On behalf of

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QCD@LHC 2022

November 30, 2022

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:

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

* 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]

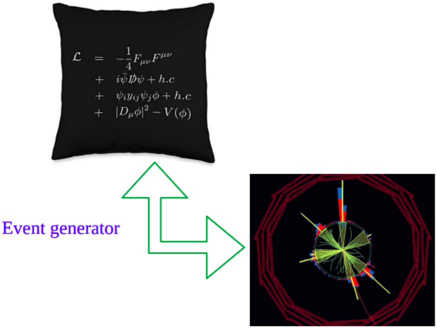
We can define Nuclear Modification Factors as,

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

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

$R_{pA} \approx 1$: No nuclear effects

- 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.

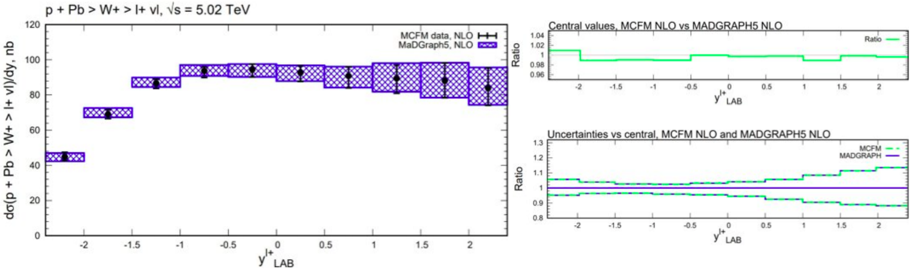


Initially, MadGraph5_aMC@NLO(MG5aMC) was developed for symmetric collisions.

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

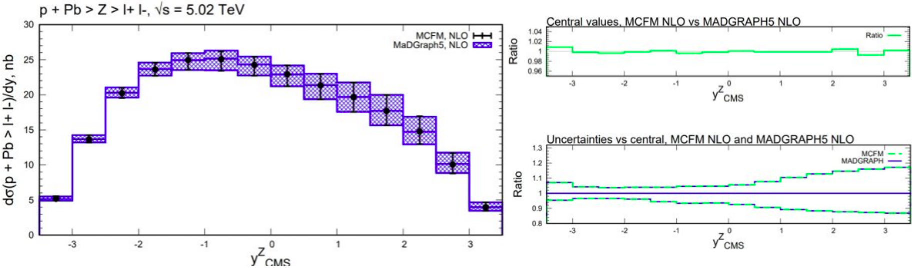


- Perfect agreement between MG5 and MCFM-based computations W production with nCTEQ15
- No difference in the uncertainty, if computation in MCFM-based code done with unsymmetric uncertainties

ICHEP 2022, A. Safronov

Validations of MG5 in asymmetric collisions

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



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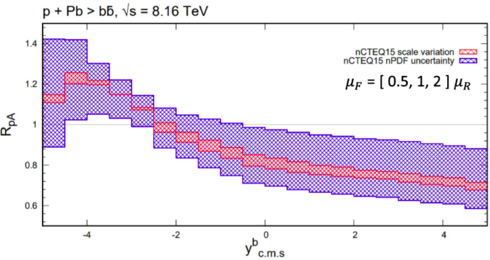
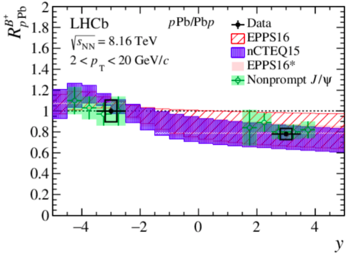
Validations of MG5 in asymmetric collisions

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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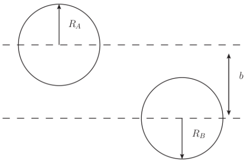
Photoproduction at LHC

Ultra peripheral collisions

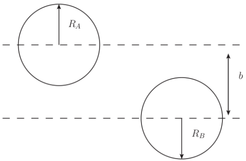
Photoproduction at LHC

Ultra peripheral collisions



Photoproduction at LHC

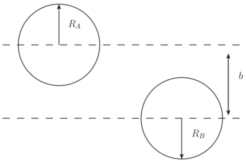
Ultra peripheral collisions



- b > $R_A + R_B$

Photoproduction at LHC

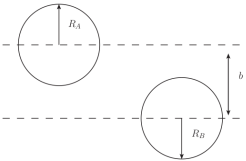
Ultra peripheral collisions



- b > $R_A + R_B$
- Photon induced

Photoproduction at LHC

Ultra peripheral collisions



- b > $R_A + R_B$
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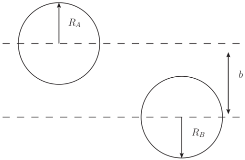
Inclusive Photoproduction

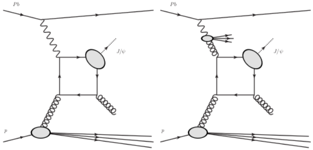
Photoproduction at LHC

Ultra peripheral collisions



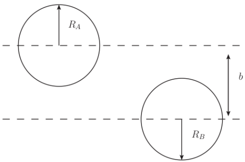
- b > $R_A + R_B$
- Photon induced

Inclusive Photoproduction



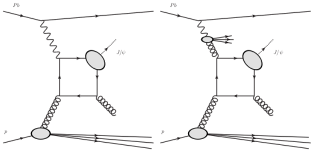
Photoproduction at LHC

Ultra peripheral collisions



- $b > R_A + R_B$
- Photon induced

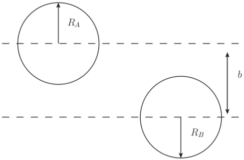
Inclusive Photoproduction



- Hard final state gluon

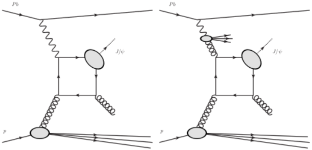
Photoproduction at LHC

Ultra peripheral collisions



- b > $R_A + R_B$
- Photon induced

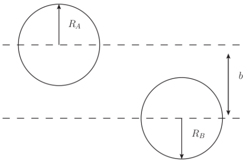
Inclusive Photoproduction



- Hard final state gluon
- Resolved vs. direct contribution

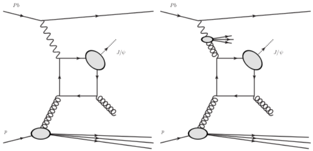
Photoproduction at LHC

Ultra peripheral collisions



- $b > R_A + R_B$
- Photon induced

Inclusive Photoproduction



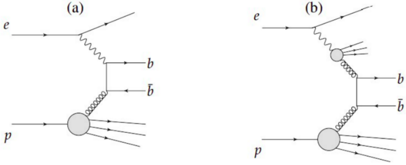
- Hard final state gluon
- Resolved vs. direct contribution
- Probe gluon PDF

- 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

Photoproduction at EIC

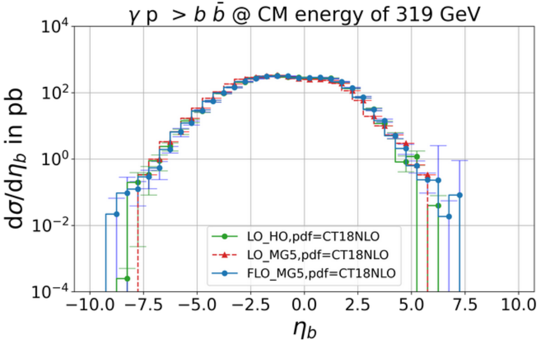
EIC (Electron-Ion Collider): first collider ever to study the inner structure of both protons and nuclei at high energy



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

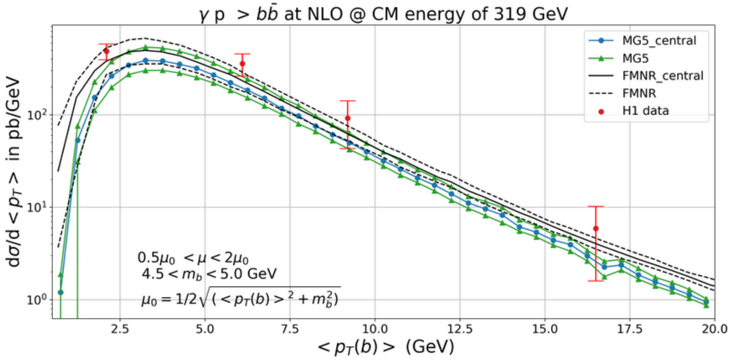
Validation of LO result



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	$2.40 \times 10^3 + 5.5 \times 10^2 - 4.9 \times 10^2$	$1.85 \times 10^3 \pm 1.14 \times 10^1$

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

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).
The research was funded by POB HEP of Warsaw University of Technology within the Excellence Initiative: Research University (IDUB) programme.

backup slides

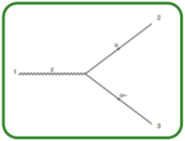
NLO calculation

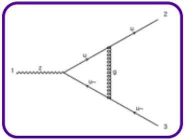
$$\sigma_{\text{NLO}} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$

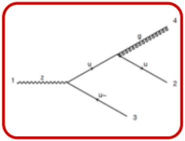
$\mathcal{O}(\alpha_s^b)$ — Born cross section

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

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







Finite — Divergent — Divergent

NLO Substraction

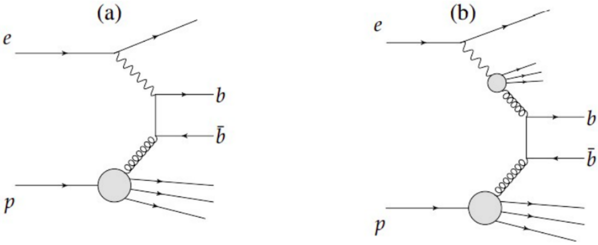
$$\sigma_{\text{NLO}} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$

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

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.

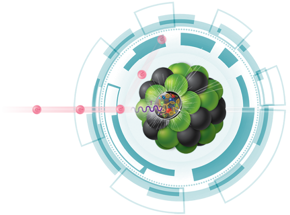
Experimental Overview

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 region

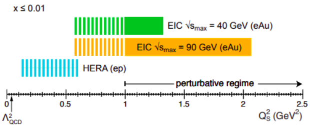


Fig. 1: Saturation scales Q_s^2 reached at the EIC in electron-nucleus collisions, compared to the ones accessed at HERA in electron-proton scattering. Figure from Ref. [3].

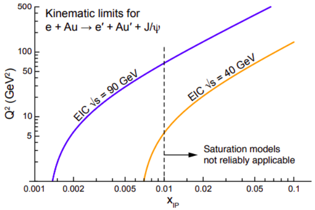


Fig. 2: Kinematical coverage for the exclusive J/Ψ production at the EIC. Figure from Ref. [3].

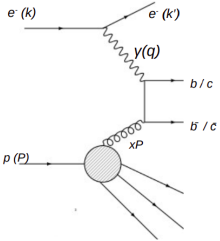
Electron–proton collisions

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),

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

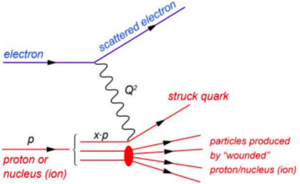
I) Photoproduction: Photon is nearly on mass shell.

$$Q^2 \leq m_H$$



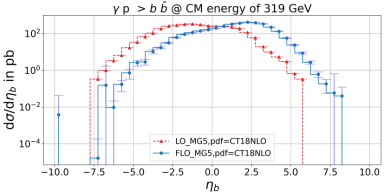
II) Deep-Inelastic-scattering (DIS): Photon is off mass shell.

$$Q^2 >> m_H$$



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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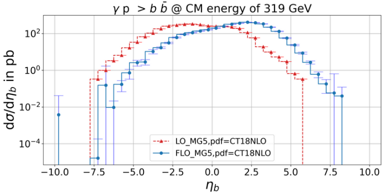

boost

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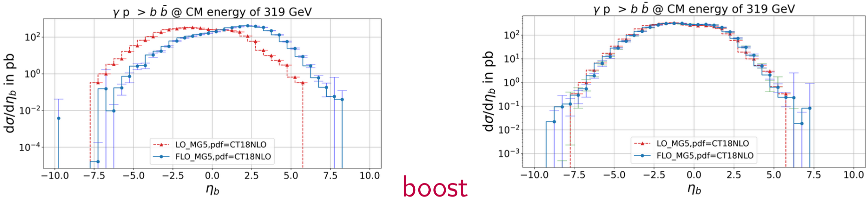
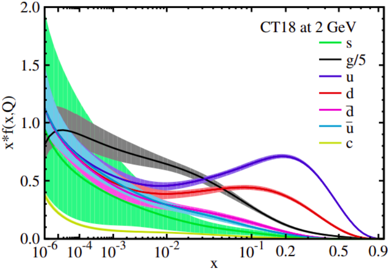
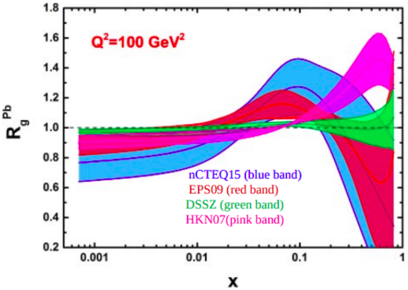


Parton Distribution Functions





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

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.

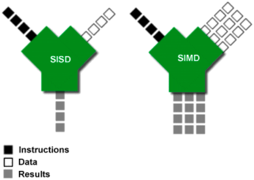
- There are few event generators available for electron-proton and electron-nucleus collisions that experimentalists could use.
- Most of them are working at the Leading Order.
- A convenient event generator development is crucial for our upcoming EIC.

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.

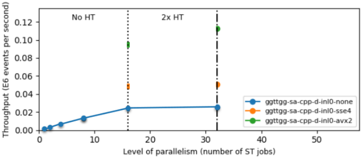
The next part of the talk is on behalf of
Stefan Roiser
Andrea Valassi
Olivier Mattelaer.

SIMD (Single Instruction Multiple Data):



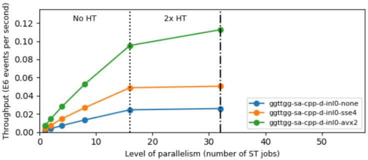
- Need a dedicated memory pattern to allow it.
- Speed-up on the same hardware.

Gain:



(a) Without SIMD

$\xrightarrow{4x}$



(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

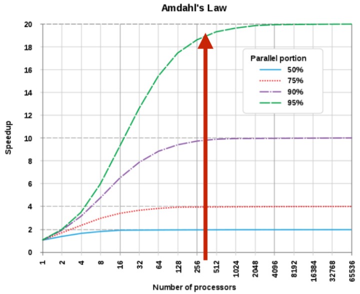
GPU:

- Thread parallelism.
- Memory management is critical.

Potential gain:

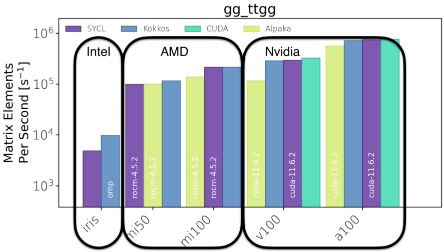
	$gg \to t\bar{t}$	$gg \to t\bar{t}gg$	$gg \to t\bar{t}ggg$
madevent	13G	470G	11T
matrix1	3.1G (23%)	450G (96%)	11T (>99%)

- 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)



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) Developmer
NLO +PS fc
collisions
Feb,2023

By the end of Sept 2024 available for users!