New developments on Monte-Carlo generation

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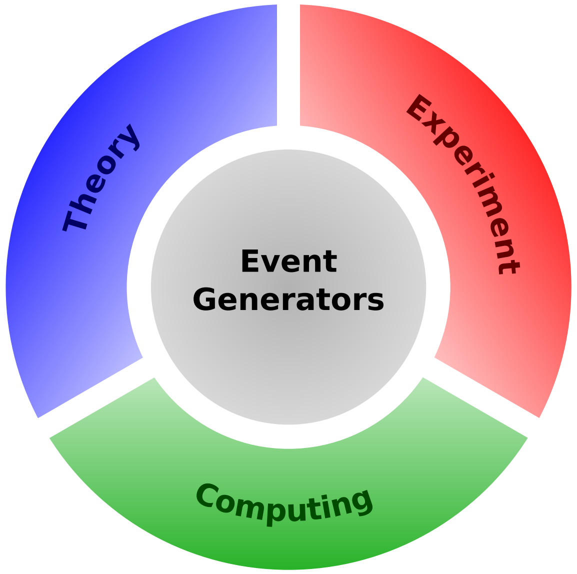
Monte Carlo tools

- MonteCarlo’s are essential tools in any branch of HEP
  - High-Energy (incl. lepton) colliders / Neutrino physics / Electron-Ion colliders / Forward physics
- They make state-of-the art predictions usable by experimental collaborations
- Require (and help setting) synergies between different communities
- This talk will cover some (very limited) aspects relative to parton-level (LHE) unweighted-event generators, relevant for hadron colliders
- More information in Snowmass ’22 paper 2203.11110

Event Generators for High-Energy Physics Experiments

We provide an overview of the status of Monte-Carlo event generators for high-energy particle physics. Guided by the experimental needs and requirements, we highlight areas of active development, and opportunities for future improvements. Particular emphasis is given to physics models and algorithms that are employed across a variety of experiments. These common themes in event generator development lead to a more comprehensive understanding of physics at the highest energies and intensities, and allow models to be tested against a wealth of data that have been accumulated over the past decades. A cohesive approach to event generator development will allow these models to be further improved and systematic uncertainties to be reduced, directly contributing to future experimental success. Event generators are part of a much larger ecosystem of computational tools. They typically involve a number of unknown model parameters that must be tuned to experimental data, while maintaining the integrity of the underlying physics models. Making both these data, and the analyses with which they have been obtained accessible to future users is an essential aspect of open science and data preservation. It ensures the consistency of physics models across a variety of experiments.



Recent progress

More accurate 1

Cheaper 2

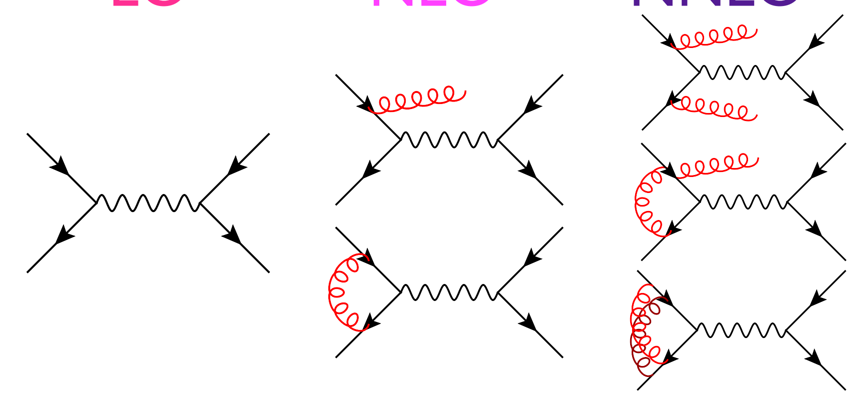
More versatile 4

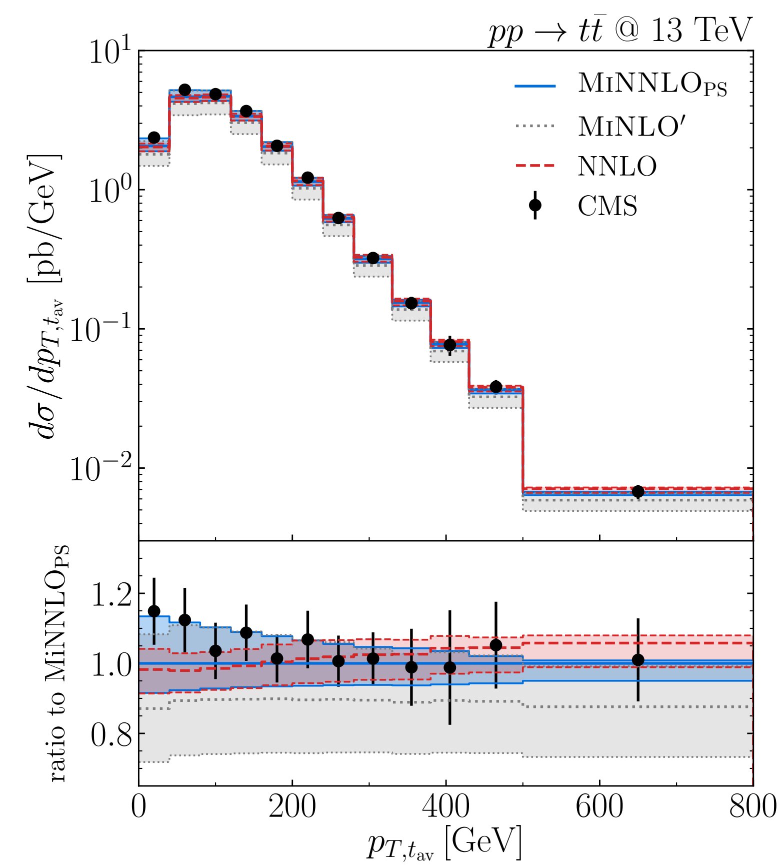
Faster 3

❶ More accurate

- NLO QCD+PS has been the golden standard for long time MG5_aMC/Sherpa/Powheg
- Going beyond NLO: NNLO
  See Giulia Zanderighi's plenary talk
  - NNLO+PS relies on rather mature technology (MiNNLOPS)
    Monni et al, 1908.06987
  - All currently-available NNLO QCD computation can (in principle) be included into a NNLO+PS generator
  - However, implementation is still process-dependent, and mostly done by hand

$$\hat{\sigma}_{ab\to X} = \underbrace{\hat{\sigma}^{(0)}_{ab\to X}}_{\text{LO}} + \underbrace{\alpha_s \hat{\sigma}^{(1)}_{ab\to X}}_{\text{NLO}} + \underbrace{\alpha_s^2 \hat{\sigma}^{(2)}_{ab\to X}}_{\text{NNLO}} + \ldots$$

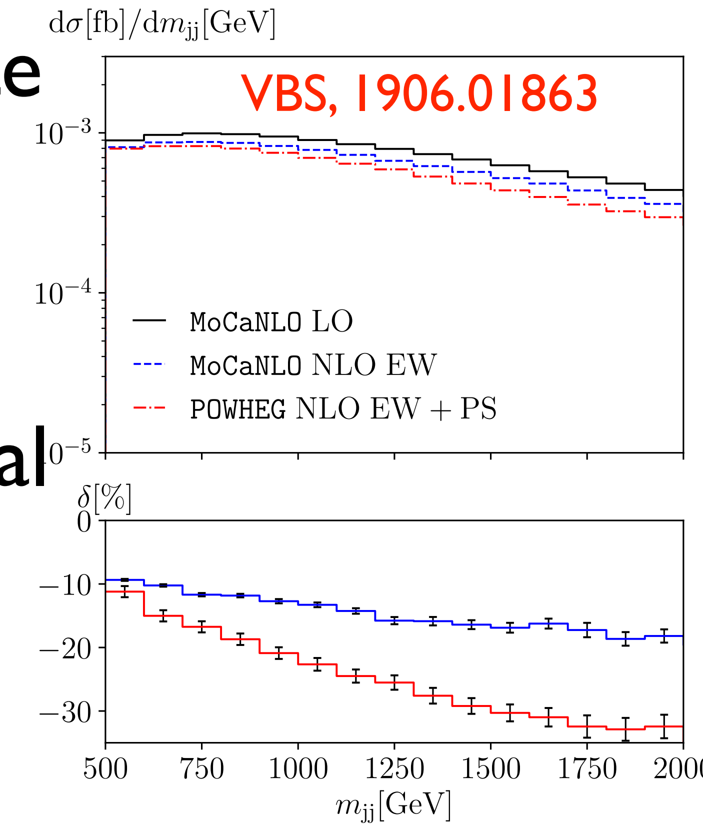


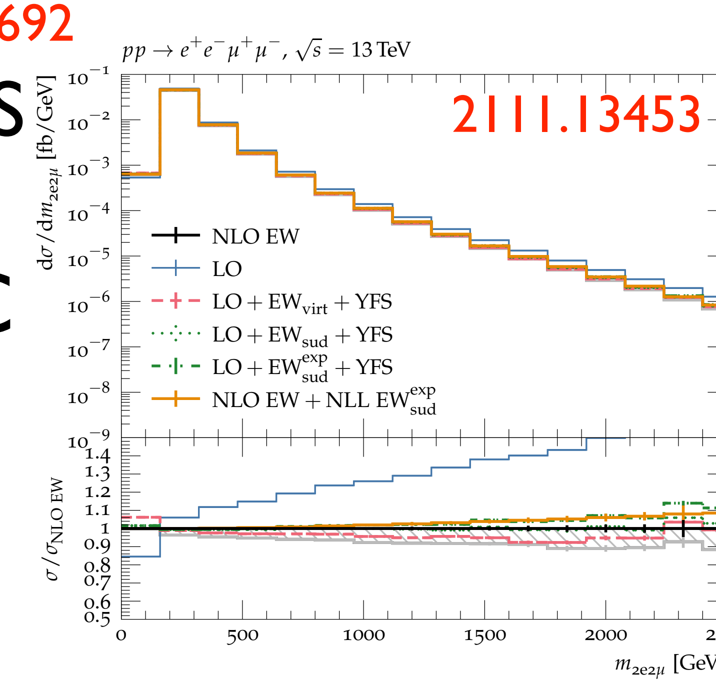


Mazzitelli et al, 2012.14267

I More accurate: beyond QCD

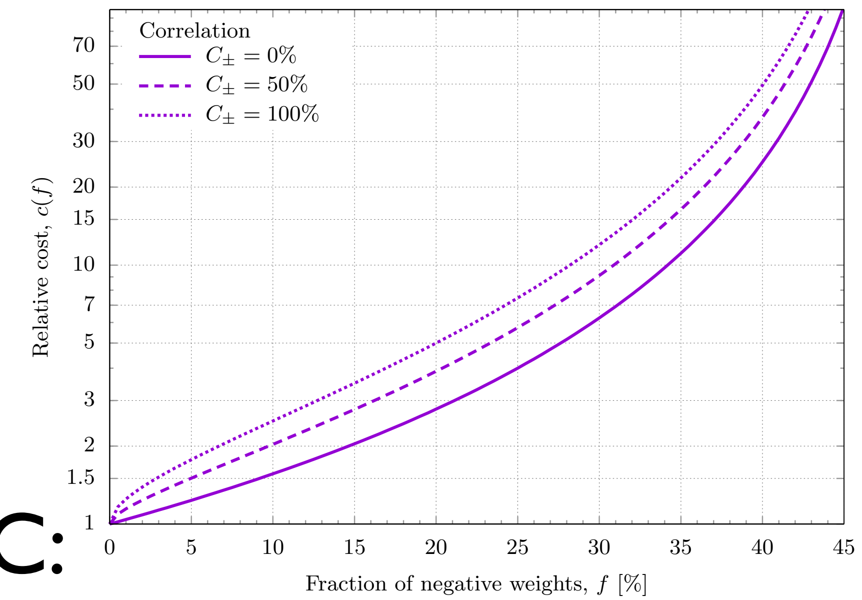
- NLO EW correction can violate the naive estimate due to couplings
  - Grow large and negative at high scales
  - Photon radiation distorts line-shapes
- Matching with QED shower is in general non trivial
- Few processes include exact matching
  DY: Barzè et al, 1302.4606; HV(+j): Granata et al, 1706.03522;
  VBS: Chiesa et al, 1906.01863
- Approximate NLO EW corrections may be sufficient for most applications see e.g Kallweit et al, 1511.08692
  - Including Sudakov approx. EW corrections + QED PS on top of NLO QCD
- EW Sudakov automated in Sherpa and MG5_aMC
  Bothmann et al, 2006.14635; Pagani, MZ, 2110.3714
- Ready for phenomenology!
  Bothmann et al, 2111.13453; Pagani, MZ, Vitos, in prep.





② Cheaper

- MC@NLO-matched MCs affected by negative weights
  - Reduce the statistical quality of the event sample
  - More events need to be generated than with positive-only events
- Recent progress both in Sherpa and MG5_aMC:
  - MG5_aMC: modify the matching by a term which improves the IR behaviour of the MC counterterms
    Frederix et al, 2002.12716
  - Sherpa: use leading-colour approximation+move K-factor to low-mult. processes in merged samples
    Danzinger et al, 2110.15211
- Other approaches (MC-agnostic):
  - Positive resampler: resample cross section to eliminate negative weights Andersen et al, 2005.09375

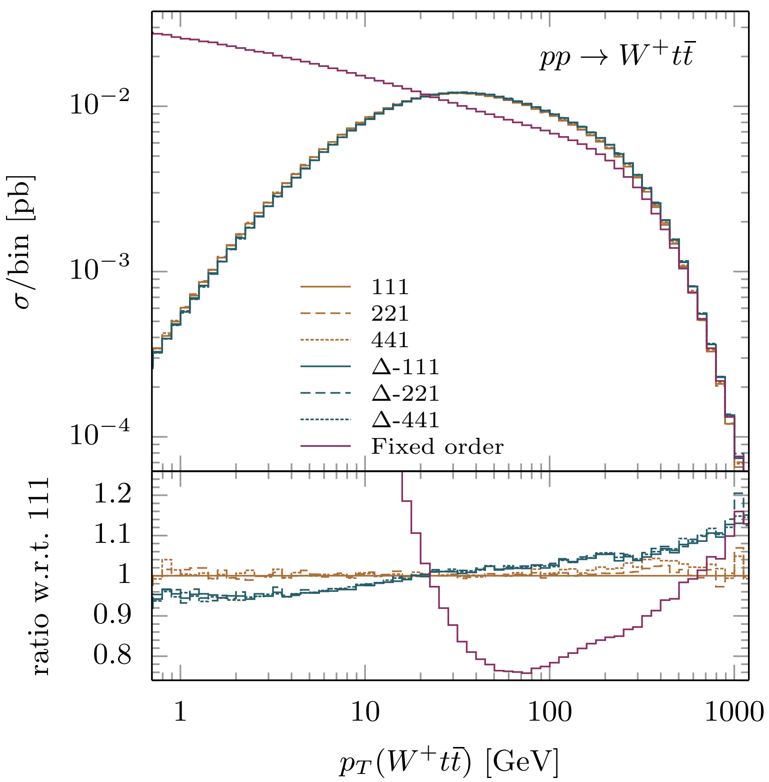


2002.12716

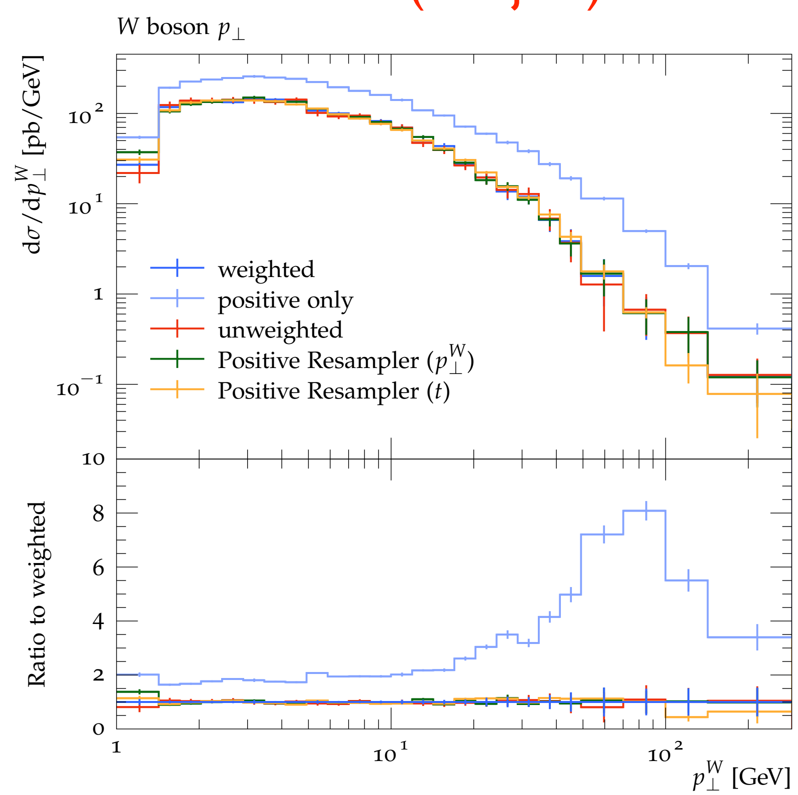
	MC@NLO	MC@NLO-Δ
$pp \to e^+e^-$	3.5% (1.2)	2.4% (1.1)
$pp \to e^+\nu_e$	3.8% (1.2)	2.5% (1.1)
$pp \to H$	4.9% (1.2)	2.0% (1.1)
$pp \to Hb\bar{b}$	38.4% (19)	32.6% (8.2)
$pp \to W^+j$	16.5% (2.2)	7.9% (1.4)
$pp \to W^+t\bar{t}$	15.2% (2.1)	11.9% (1.7)
$pp \to t\bar{t}$	20.2% (2.8)	9.3% (1.5)

2 Results

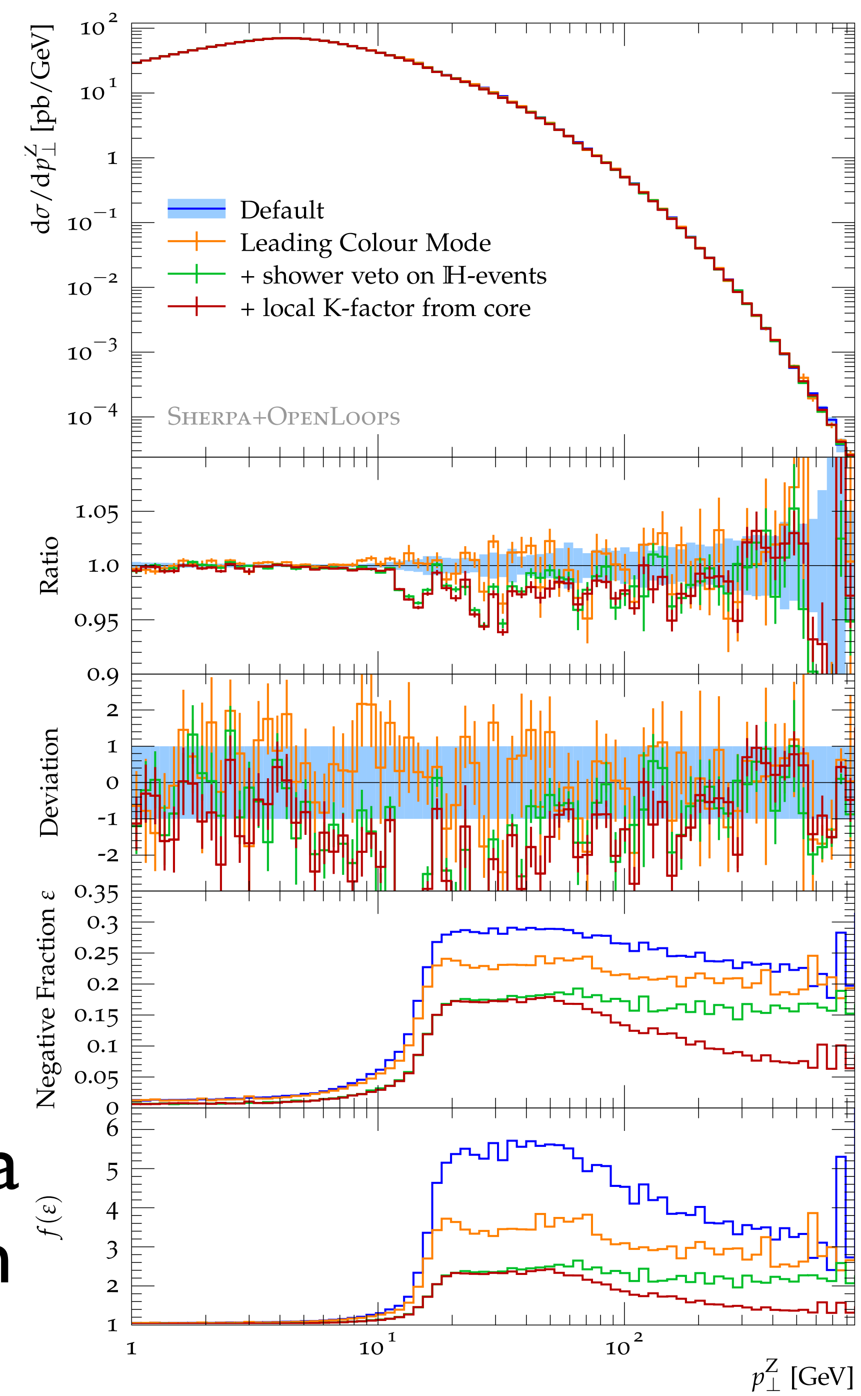
2002.12716 (ttW)



2005.09375 (W+jets)



2110.15211 (Z+jets)



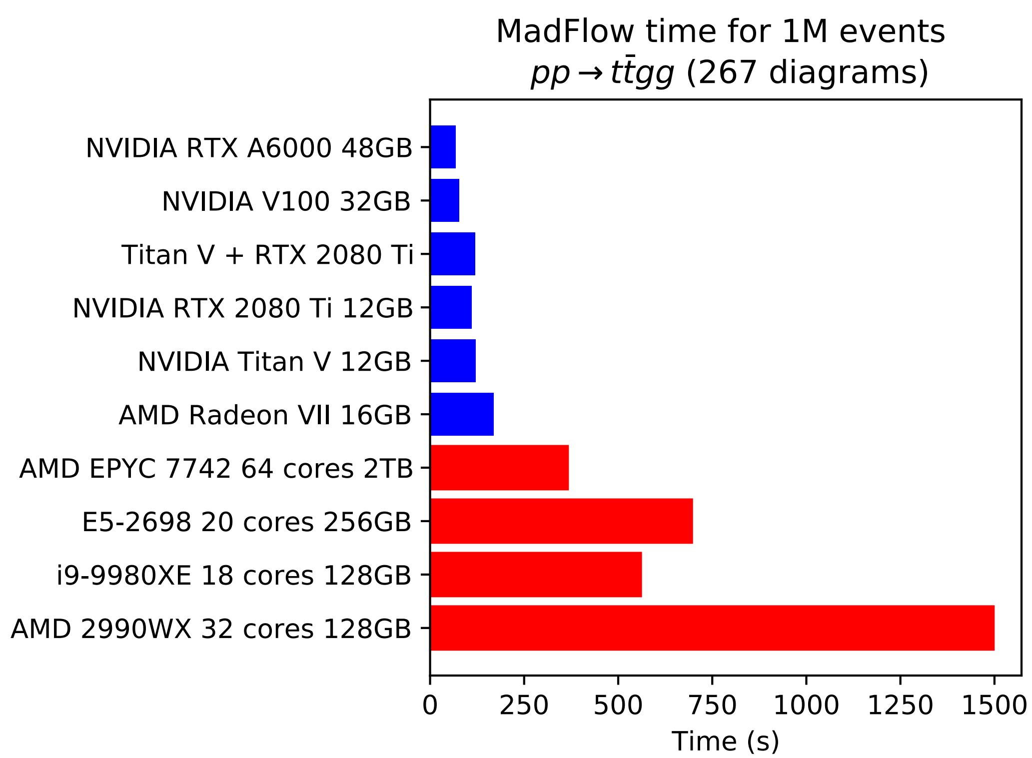
- Take home message: differences due to new matching/resampling are generally small (5%), with some exceptions
- Reduction of neg. weights may entail some extra cost (ie slower code) at event generation, which is (over)compensated with full sim.

3 Faster

- Computing demand requires to move away from single-core jobs, and to access more powerful hardware tools
- While multi-threading (multiple jobs on different cores) is in general possible (up to memory availability), multiprocessing (single job on many cores) is in general rare
- The usage of SIMD paradigm is taking place in some collaboration, making MP possible together with code offloading on different architectures (GPUs)
- This requires rewriting (old) codes, it may not be particularly appealing to physicists, but it is necessary and pays back
- See also:
  "Challenges in Monte Carlo event generator software for High-Luminosity LHC", 2004.13687

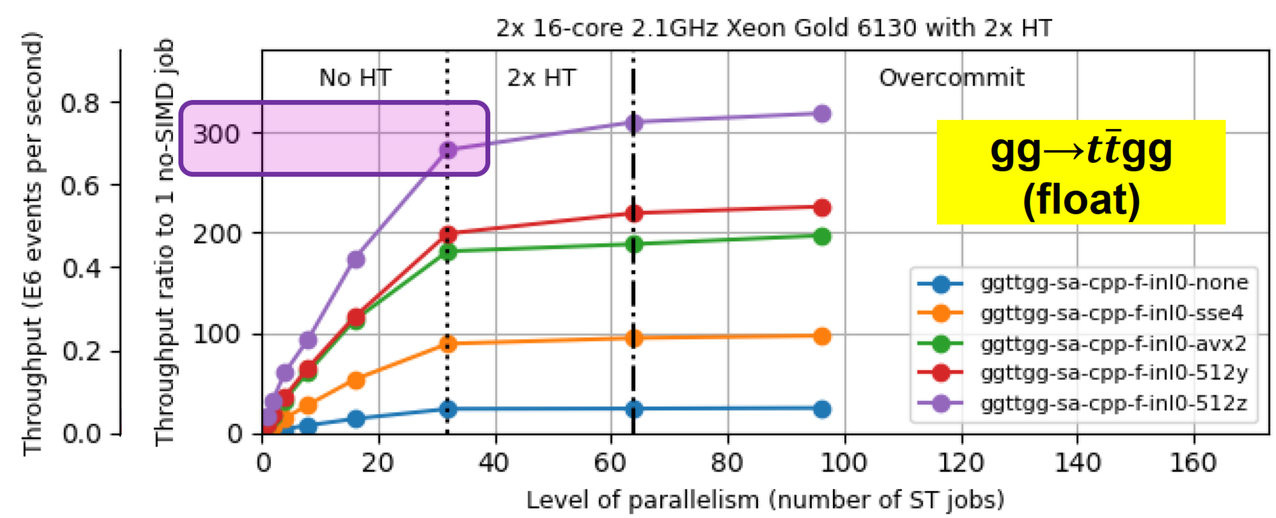
3 Speed gain on different architectures

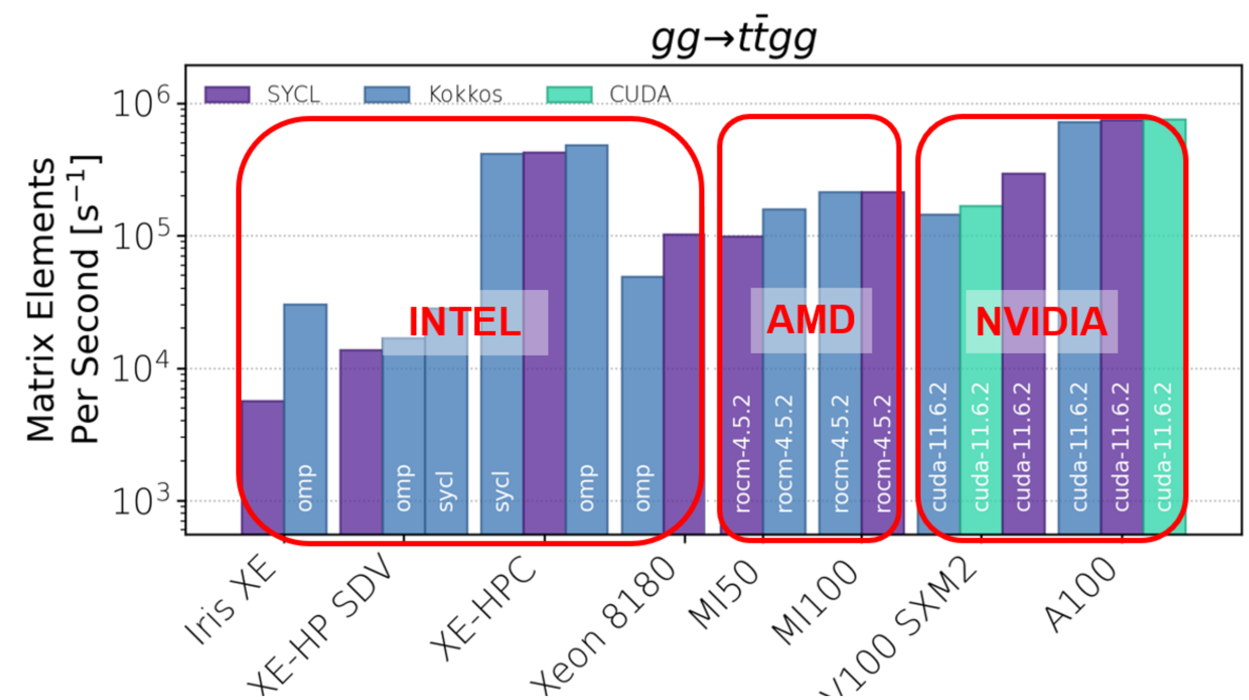
MadFlow:
Carrazza, Cruz-Martinez, Rossi, MZ, 2106.10279



Process	MadFlow CPU	MadFlow GPU	MG5_aMC
$gg \to t\bar{t}$	9.86 μs	1.56 μs	20.21 μs
$pp \to t\bar{t}$	14.99 μs	2.20 μs	45.74 μs
$pp \to t\bar{t}g$	57.84 μs	7.54 μs	93.23 μs
$pp \to t\bar{t}gg$	559.67 μs	121.05 μs	793.92 μs

MG5onGPU:
Valassi et al, 2106.12631, 2303.18244





4 More versatile

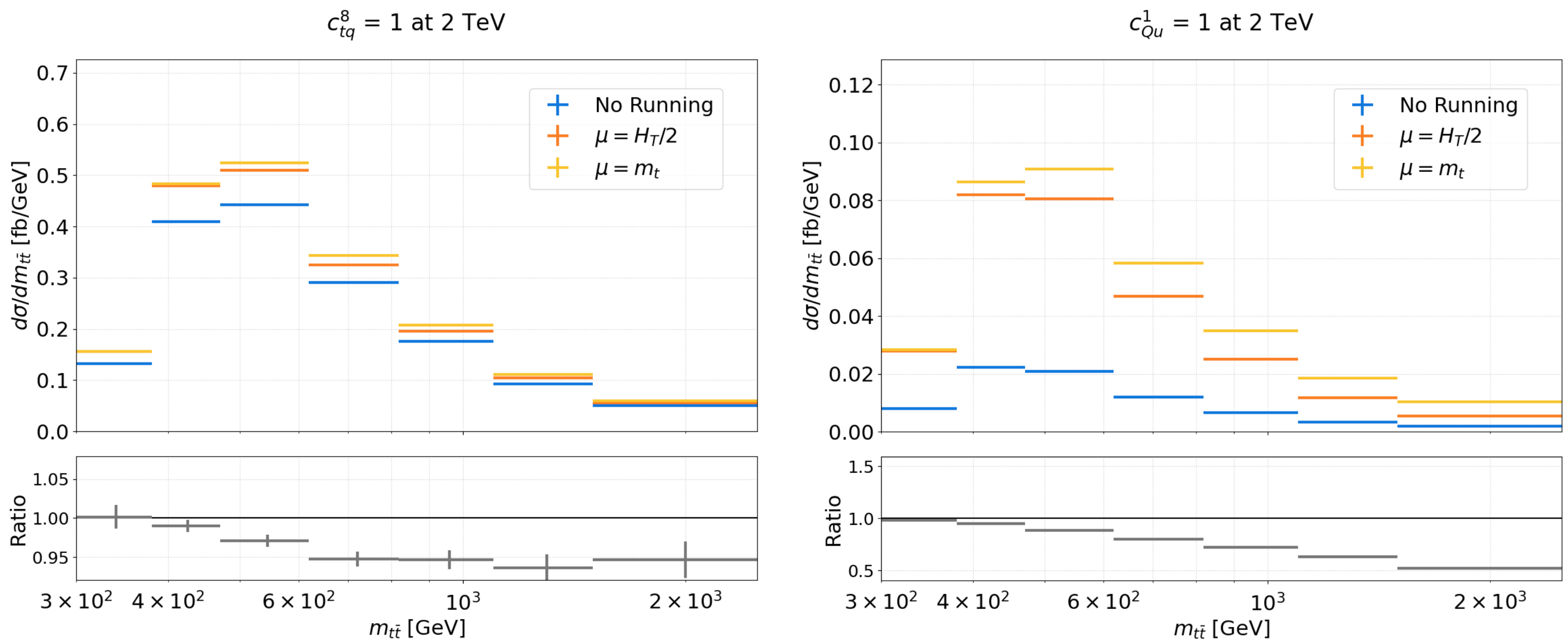
UFO 2.0 - The 'Universal Feynman Output' format

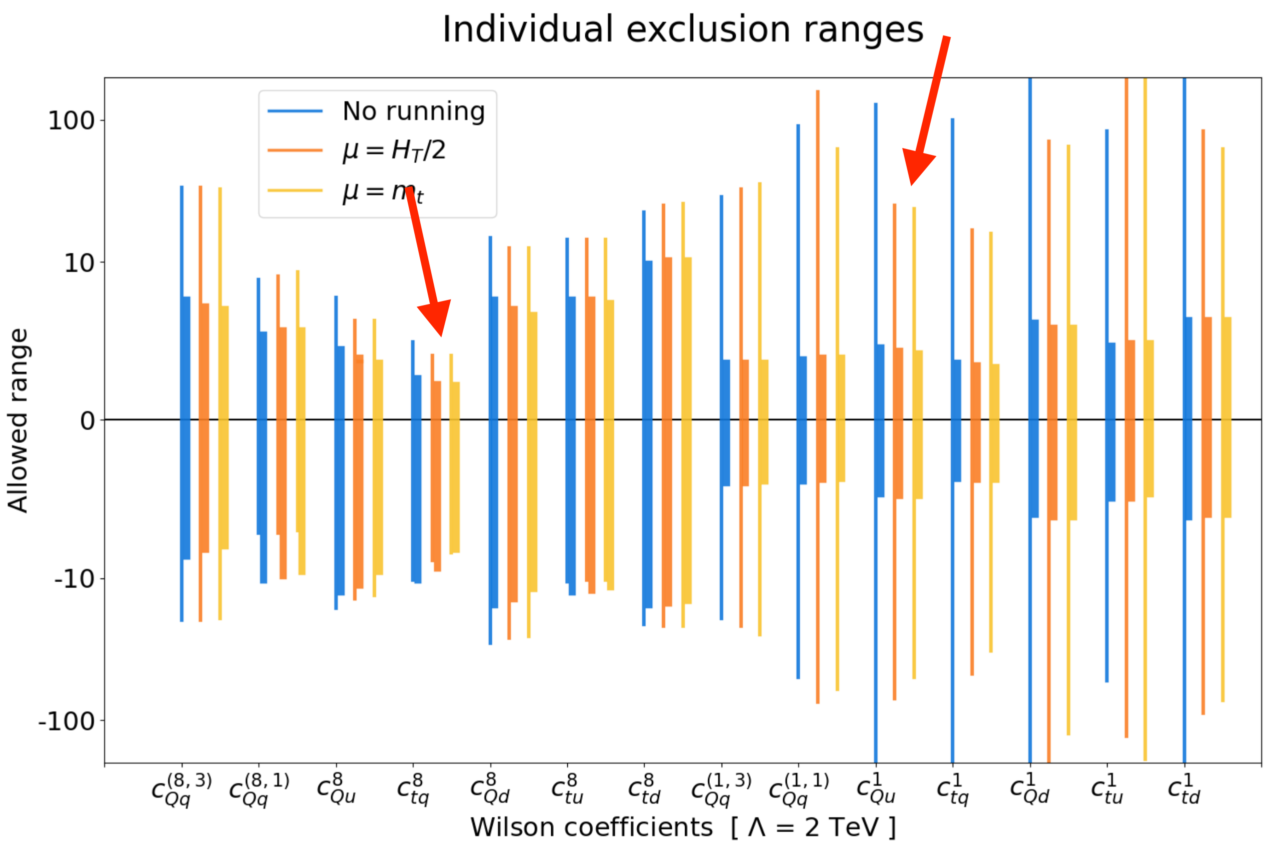
2304.09883

Luc Darmé[1], Céline Degrande[2], Claude Duhr[3], Benjamin Fuks[a,4], Mark Goodsell[4], Gudrun Heinrich[5], Valentin Hirschi[6], Stefan Höche[7], Marius Höfer[5], Joshua Isaacson[7], Olivier Mattelaer[2], Thorsten Ohl[8], Davide Pagani[9], Jürgen Reuter[10], Peter Richardson[11], Steffen Schumann[12], Hua-Sheng Shao[4], Frank Siegert[13], Marco Zaro[14]

- UFO2 updates the UFO standard to ship the information about any physics model Degrande et al, 1108.2040
- Python-based format, particles/interactions/parameters/… as objects
- Since UFO, many new features required extensions
  - Analytic expression for partial decay widths
  - Parameter running
  - NLO counterterms (including possible infos on analytic continuation)
  - Form factors / custom propagators
  - …
- Makes it possible to benefit of current MC's for a wider class of models

4 Example:
Running of parameters in EFT fits





Aoude et al, 2212.05067

Outlook

- Understanding and improving MC tools is crucial for a proper and efficient collaboration between theory and experiments
- Lot of recent activity, only a glimpse of it in these slides
  - Inclusion of higher orders beyond NLO QCD
  - Reduction of negative weights leads to reduction in needed n of events
  - Faster simulations can profit of modern hardwares (GPUs)
  - More flexibility in model formats leads to more possibility for BSM studies

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Thank you!