Electron-Muon Scattering with GoSam

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Muon-electron scattering: Theory kickoff workshop
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Project in collaboration with
G. Luisoni, P. Mastrolia, A. Primo, W. J. Torres Bobadilla

Based on work with GoSam Collaboration

Introduction

- A brief introduction to the GoSam framework
- What can GoSam do for Electron-Muon Scattering **today**?
- What could GoSam do **"tomorrow"**? $\rightsquigarrow$ Updates and Upgrades

The GoSam Project

GoSam Collaboration (updated)

M. Chiesa, N. Greiner, G. Heinrich, S. Jahn, S. Jones, M. Kerner, G. Luisoni, P. Mastrolia, G.O., T. Peraro, J. Schlenk, L. Scyboz, F. Tramontano

http://gosam.hepforge.org/

GoSam 1.0

"Automated One-Loop Calculations with GoSam"
Cullen, Greiner, Heinrich, Luisoni, Mastrolia, G.O., Reiter, Tramontano
Eur.Phys.J. C72 (2012) 1889 [arXiv:1111.2034]

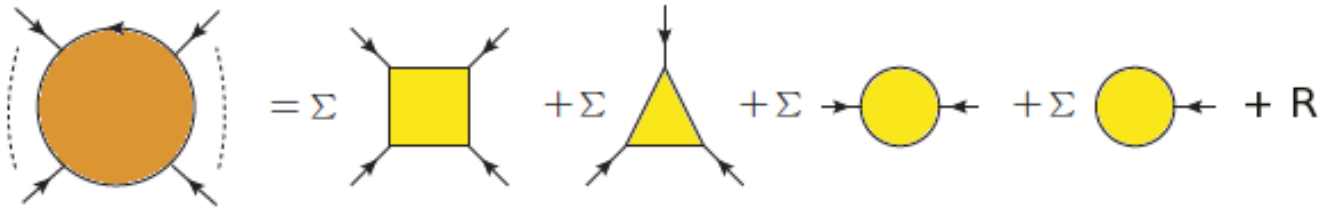
GoSam 2.0

"GOSAM-2.0: a tool for automated one-loop calculations within the Standard Model and beyond"
Cullen, van Deurzen, Greiner, Heinrich, Luisoni, Mastrolia, Mirabella, G.O., Peraro, Schlenk, von Soden-Fraunhofen, Tramontano
Eur.Phys.J. C74 (2014) 3001 [arXiv:1404.7096]

Virtual NLO: One-Loop "master" formula

$$\int d^d\bar{q}\,\frac{\mathcal{N}(\bar{q})}{\bar{D}_{i_0}\bar{D}_{i_1}\dots\bar{D}_{n-1}} = \sum_i d_i\ \mathrm{Box}_i + \sum_i c_i\ \mathrm{Triangle}_i + \sum_i b_i\ \mathrm{Bubble}_i + \sum_i a_i\ \mathrm{Tadpole}_i + \mathrm{R}\,,$$

1) **Generation**: Compute the unintegrated amplitudes for all diagrams
2) **Reduction**: Extract all coefficients and rational terms
3) **Master Integrals**: Calculate the Master Integrals (scalar integrals) and combine with the coefficients



There are several techniques available for Generation+Reduction and available codes to compute the one-loop Scalar Integrals

Virtual corrections with GoSam

1. Algebraic Generation
   - Amplitudes generated with **Feynman diagrams**
   - Optimization: **grouping of diagrams**, smart **caching**
   - Algebra in **dimension** d, different schemes
   - Suited for QCD, EW, effective Higgs coupling and BSM models$^{(*)}$

   GoSam employs a Python "wrapper" which:
   - $\rightsquigarrow$ generates analytic integrands from **Feynman diagrams** using QGRAF
   - $\rightsquigarrow$ manipulates and simplifies them with FORM
   - $\rightsquigarrow$ writes them into FORTRAN code for the reduction

Virtual corrections with GoSam

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2. Flexibility in the Reduction
   - Different reduction algorithms available at run-time
   - **Integrand-Level** and/or **Tensorial** Reduction available

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3. Selection of codes for the evaluation of the Master Integrals

OneLoop (**van Hameren**); QCDLoop (**Ellis, Zanderighi**)
Golem95C (**Binoth et al.**); LoopTools (**Hahn et al.**)

Virtual corrections with GoSam

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   Golem95C (**Binoth et al.**); LoopTools (**Hahn et al.**)
4. Fully interfaced within several Monte Carlo frameworks

Modular Structure $\rightarrow$ Ability to incorporate **new ideas** and **techniques**
The GoSam framework is in continuous evolution

Reduction algorithms within GoSam

Ninja

$\rightsquigarrow$ **Default in GoSam 2.0**, more **Stable** and **Fast**

Integrand-Level Reduction + Laurent Expansion

Mastrolia, Mirabella, Peraro

Golem95

$\rightsquigarrow$ **Default Rescue System**

Tensorial Reduction

Binoth, Guillet, Heinrich, Pilon, Reiter, von Soden-Fraunhofen

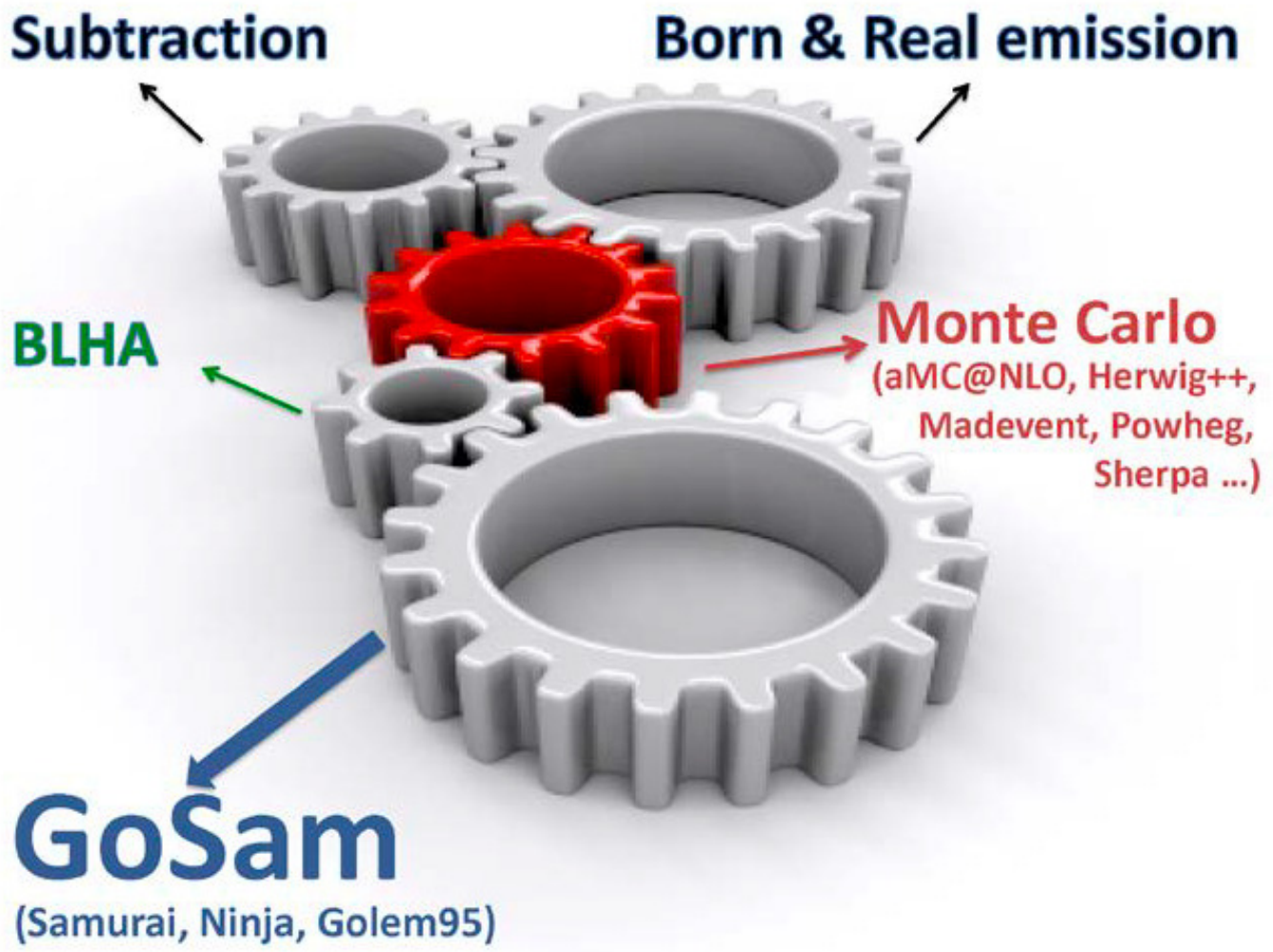
Samurai

$\rightsquigarrow$ **Default in GoSam 1.0**

$d-$dimensional Integrand-Level Reduction

Mastrolia, G.O., Reiter, Tramontano

The GoSam Project



GoSam – NLO Pheno Results (2011-2016)

- J. Bellm, S. Gieseke, N. Greiner, G. Heinrich, S. Platzer, C. Reuschle and J. F. von Soden-Fraunhofen, "Anomalous coupling, top-mass and parton-shower effects in $W + W-$ production," JHEP **1605**, 106 (2016)
- N. Greiner, S. Liebler and G. Weiglein, "Interference contributions to gluon initiated heavy Higgs production in the Two-Higgs-Doublet Model," Eur. Phys. J. C **76**, no. 3, 118 (2016)
- H. van Deurzen, R. Frederix, V. Hirschi, G. Luisoni, P. Mastrolia and G.O., "Spin Polarisation of $t\bar{t}\gamma\gamma$ production at NLO+PS with GoSam interfaced to MG5_aMC," Eur. Phys. J. C **76**, no. 4, 221 (2016)
- M. Chiesa, N. Greiner and F. Tramontano, "Automation of electroweak corrections for LHC processes," J. Phys. G **43**, no. 1, 013002 (2016)
- N. Greiner, S. Hoeche, G. Luisoni, M. Schoenherr, V. Yundin, J. Winter, "Phenomenological analysis of Higgs boson production through gluon fusion in association with jets", JHEP **1601**, 169 (2016)
- G. Luisoni, C. Oleari, F. Tramontano, "Wbbj production at NLO with POWHEG+MiNLO", JHEP 1504 (2015) 161
- M. J. Dolan, C. Englert, N. Greiner, M. Spannowsky, "Further on up the road: hhjj production at the LHC", Phys.Rev.Lett. 112 (2014) 101802
- G. Heinrich, A. Maier, R. Nisius, J. Schlenk, J. Winter, "NLO QCD corrections to WWbb production with leptonic decays in the light of top quark mass and asymmetry measurements", JHEP 1406 (2014) 158
- T. Gehrmann, N. Greiner, and G. Heinrich, "Precise QCD predictions for the production of a photon pair in association with two jets", Phys.Rev.Lett. 111 (2013) 222002
- N. Greiner, G. Heinrich, J. Reichel, and J. F. von Soden-Fraunhofen, "NLO QCD corrections to diphoton plus jet production through graviton exchange", JHEP 1311 (2013) 028
- H. van Deurzen, G. Luisoni, P. Mastrolia, E. Mirabella, G.O. and T. Peraro, "NLO QCD corrections to Higgs boson production in association with a top quark pair and a jet", Phys.Rev.Lett. 111 (2013) 171801
- G. Cullen, H. van Deurzen, N. Greiner, G. Luisoni, P. Mastrolia, E. Mirabella, G.O., T. Peraro, and F. Tramontano, "NLO QCD corrections to Higgs boson production plus three jets in gluon fusion," Phys.Rev.Lett. 111 (2013) 131801
- S. Hoeche, J. Huang, G. Luisoni, M. Schoenherr and J. Winter, "Zero and one jet combined NLO analysis of the top quark forward-backward asymmetry," Phys.Rev. D88 (2013) 014040
- G. Luisoni, P. Nason, C. Oleari and F. Tramontano,"HW/HZ + 0 and 1 jet at NLO with the POWHEG BOX interfaced to GoSam and their merging within MiNLO", JHEP 1310 (2013) 083
- M. Chiesa, G. Montagna, L. Barze', M. Moretti, O. Nicrosini, F. Piccinini and F. Tramontano, "Electroweak Sudakov Corrections to New Physics Searches at the CERN LHC," Phys.Rev.Lett. 111 (2013) 121801
- T. Gehrmann, N. Greiner, and G. Heinrich, "Photon isolation effects at NLO in gamma gamma + jet final states in hadronic collisions," JHEP 1306, 058 (2013)
- H. van Deurzen, N. Greiner, G. Luisoni, P. Mastrolia, E. Mirabella, G.O., T. Peraro, J. F. von Soden-Fraunhofen, and F. Tramontano, "NLO QCD corrections to the production of Higgs plus two jets at the LHC," Phys. Lett. B 721, 74 (2013)
- G. Cullen, N. Greiner, and G. Heinrich, "Susy-QCD corrections to neutralino pair production in association with a jet," Eur. Phys. J. C 73, 2388 (2013)
- N. Greiner, G. Heinrich, P. Mastrolia, G. O., T. Reiter and F. Tramontano, "NLO QCD corrections to the production of W+ W- plus two jets at the LHC," Phys. Lett. B 713, 277 (2012)

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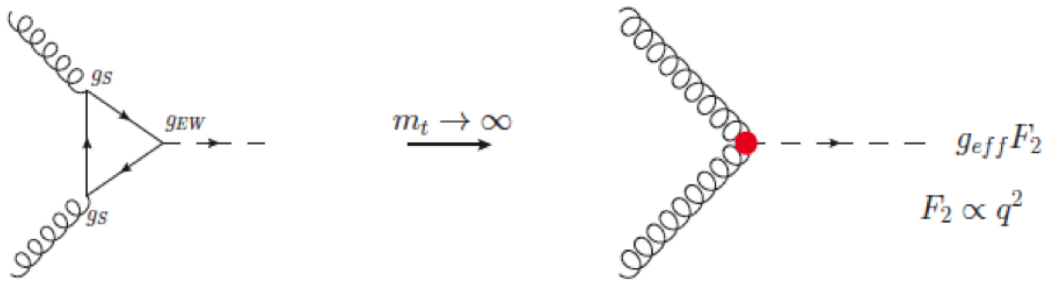
Main target: **NLO QCD**

Complexity $\rightsquigarrow$ Number of Diagrams, More Scales

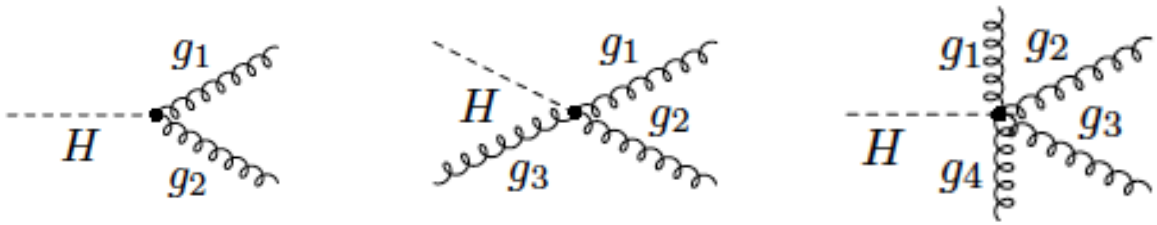
Automation $\rightsquigarrow$ Interfaces with MC

$pp \to H$+Jets in Gluon Fusion (GF)

Large Top-Mass Approximation ($m_t \to \infty$) : the Higgs coupling to gluons, mediated by a top-quark loop, can be described by an effective operator



$\to$ **new Feynman rules**: vertices involving the Higgs field and up to four gluons

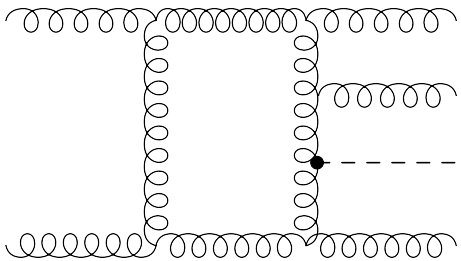


$pp \to H + 3$ jets @ NLO with GoSam + Sherpa

Huge Theoretical and Computational Challenges

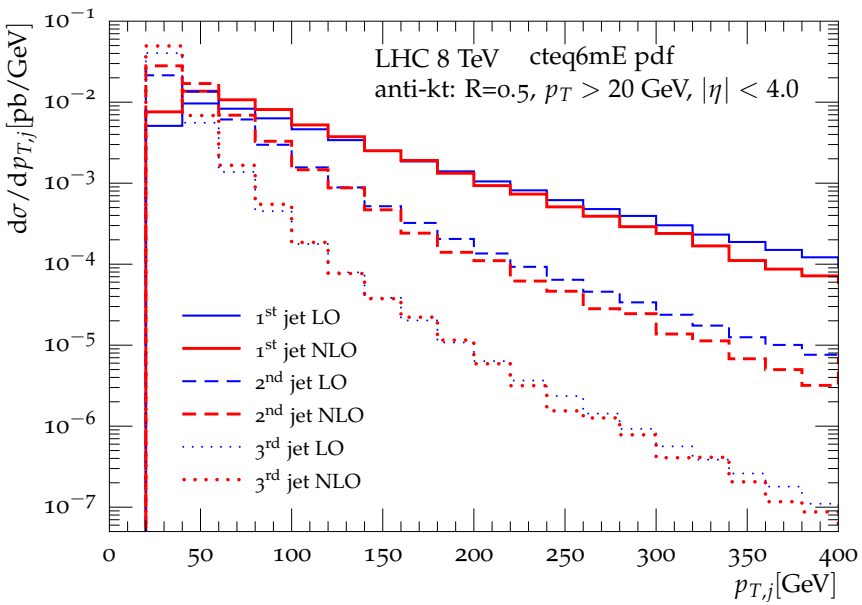
- ⇝ **Improvements in the reduction and in the code generation**
- ⇝ Upgrade Algorithms to include Higher-Rank Terms (effective couplings)
- ⇝ Ninja reduction based on Integrand reduction via Laurent expansion

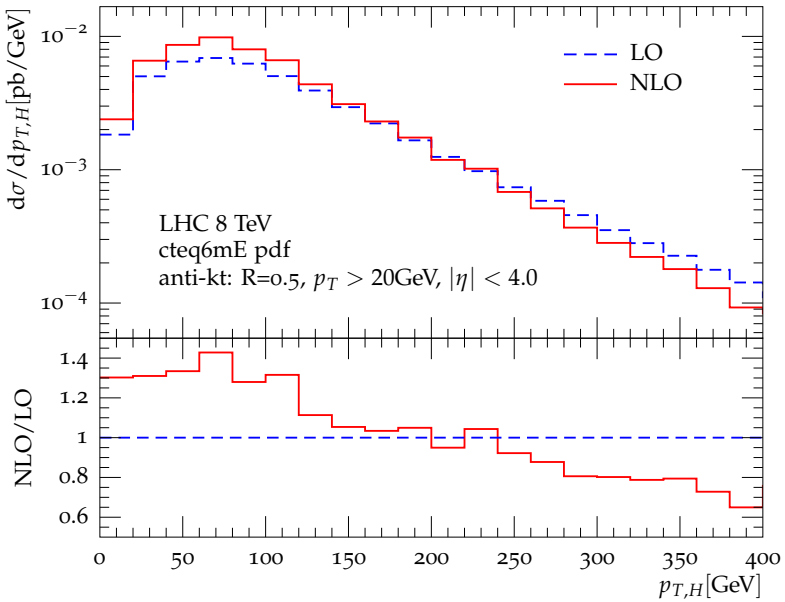
- More than 10,000 diagrams
- Higher-Rank terms
- Rank-7 hexagons



		Diagrams
H+0 jets	$g+g \longrightarrow H$	1
H+1 jets	$q+\bar{q} \longrightarrow H+g$	14
	$g+g \longrightarrow H+g$	48
		62
H+2 jets	$q+\bar{q} \longrightarrow H+q'+\bar{q}'$	32
	$q+\bar{q} \longrightarrow H+q+\bar{q}$	64
	$q+\bar{q} \longrightarrow H+g+g$	179
	$g+g \longrightarrow H+g+g$	651
		926
H+3 jets	$q+\bar{q} \longrightarrow H+q'+\bar{q}'+g$	467
	$q+\bar{q} \longrightarrow H+q+\bar{q}+g$	868
	$q+\bar{q} \longrightarrow H+g+g+g$	2519
	$g+g \longrightarrow H+g+g+g$	9325
		13179

$pp \to H + 3$ jets @ NLO with GoSam + Sherpa





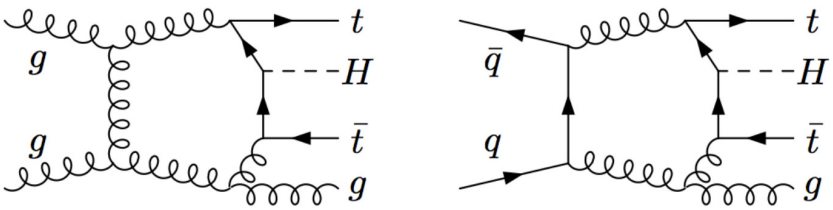
Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, G.O., Peraro, Tramontano
Phys. Rev. Lett. 111 (2013) 131801

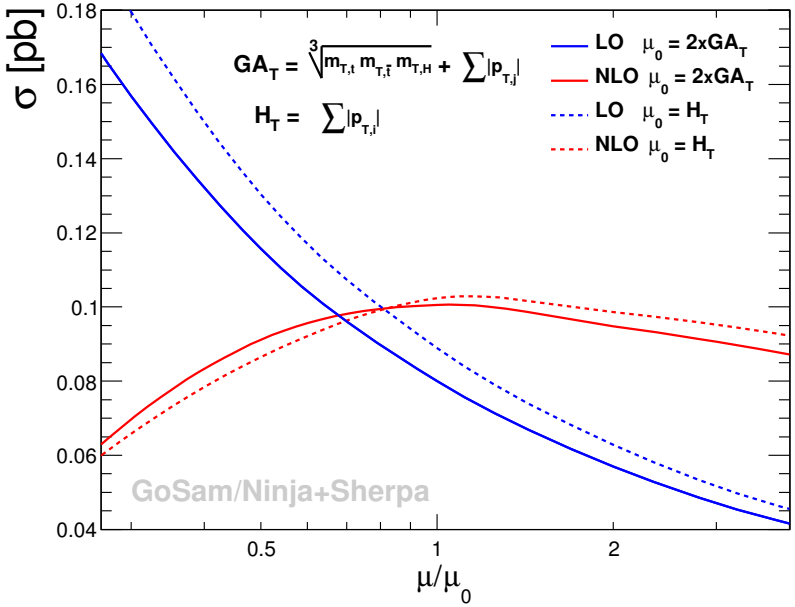
An updated analysis with GoSam + Sherpa appeared in:

N. Greiner, S. Hoeche, G. Luisoni, M. Schoenherr, V. Yundin, J. Winter,
"Phenomenological analysis of Higgs boson production through gluon fusion in association with jets", JHEP **1601**, 169 (2016)

$pp \to Ht\bar{t}$ + 1 jet @ NLO

		Diagrams
H t t +1 jets	$q+\bar{q} \longrightarrow H+t+\bar{t}+g$	320
	$g+g \longrightarrow H+t+\bar{t}+g$	1575
		1895





- Two different mass scales: Higgs and Top
- 51 hexagons in the gluon-gluon channel
- Timing/PS-point: $qq \to 0.2$ sec
  $gg \to 2.5$ sec

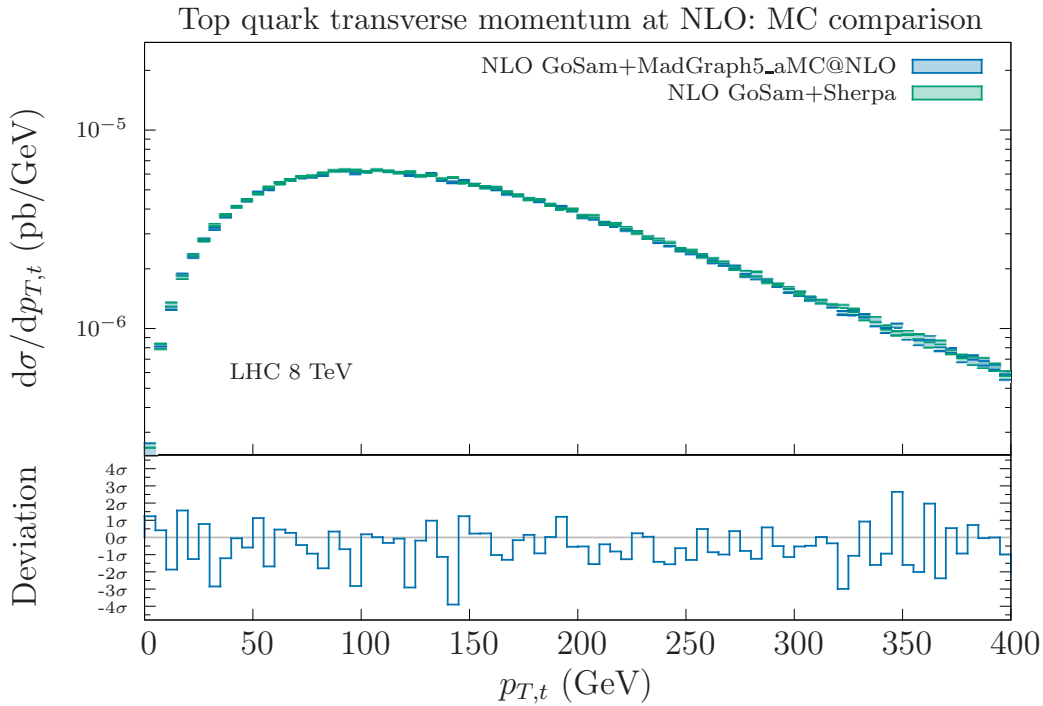
Central Scale	σ_{LO} [fb]	σ_{NLO} [fb]
$2\times GA_T$	$80.03^{+35.64}_{-23.02}$	$100.6^{+0.00}_{-9.43}$
H_T	$88.93^{+41.41}_{-26.13}$	$102.3^{+0.00}_{-15.82}$

van Deurzen, Luisoni, Mastrolia, Mirabella, G.O., Peraro

Phys. Rev. Lett. 111 (2013) 171801

$pp \to t\bar{t}\gamma\gamma$ @ NLO

- Interface between the MG5_aMC and GoSam
- As a first application of this framework, we computed the NLO corrections to $pp \to t\bar{t}H$ and $pp \to t\bar{t}\gamma\gamma$ matched to a parton shower



NLO comparison between GoSam+MG5_aMC and GoSam+Sherpa

van Deurzen, Frederix, Hirschi, Luisoni, Mastrolia, G.O. (2016)

GoSam – More Recent Results (2016-2017)

- Additional QCD Pheno

  ⇝ D. Faeh and N. Greiner, "Diphoton production in association with two bottom jets," arXiv:1706.08309 [hep-ph]

  ⇝ S. Alioli, F. Caola, G. Luisoni and R. Röntsch, "ZZ production in gluon fusion at NLO matched to parton-shower," Phys. Rev. D **95**, no. 3, 034042 (2017)

  ⇝ N. Greiner, S. Höche, G. Luisoni, M. Schönherr and J. C. Winter, "Full mass dependence in Higgs boson production in association with jets at the LHC and FCC," JHEP **1701**, 091 (2017)

GoSam – More Recent Results (2016-2017)

- Additional QCD Pheno
- NLO Electro-Weak

  ⇝ M. Chiesa, N. Greiner, M. Schoenherr and F. Tramontano, "Electroweak corrections to diphoton plus jets," arXiv:1706.09022 [hep-ph].

GoSam – More Recent Results (2016-2017)

- Additional QCD Pheno
- NLO Electro-Weak
- NLO QED predictions for muon decays (in Fermi Theory)

  ⇝ G. M. Pruna, A. Signer and Y. Ulrich, "Fully differential NLO predictions for the radiative decay of muons and taus," Phys. Lett. B **772**, 452 (2017)

  ⇝ G. M. Pruna, A. Signer and Y. Ulrich, "Fully differential NLO predictions for the rare muon decay," Phys. Lett. B **765**, 280 (2017)

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- Hard functions for NNLL ($t\bar{t}H$, $t\bar{t}V$)

  ⇝ A. Broggio, A. Ferroglia, G.O., B.D. Pecjak, and R.D. Sameshima, "Associated production of a top pair and a Z boson at the LHC to NNLL accuracy", JHEP 1704, 105 (2017)

  ⇝ A. Broggio, A. Ferroglia, B. D. Pecjak and L. L. Yang, "NNLL resummation for the associated production of a top pair and a Higgs boson at the LHC," JHEP **1702**, 126 (2017)

  ⇝ A. Broggio, A. Ferroglia, G.O., and B.D. Pecjak, "Associated production of a top pair and a W boson at next-to-next-to-leading logarithmic accuracy", JHEP 1609, 089 (2016)

  ⇝ A. Broggio, A. Ferroglia, B. D. Pecjak, A. Signer and L. L. Yang, "Associated production of a top pair and a Higgs boson beyond NLO," JHEP **1603**, 124

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- Additional QCD Pheno
- NLO Electro-Weak
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- Hard functions for NNLL ($t\bar{t}H$, $t\bar{t}V$)
- Double Higgs production (Two-loop Virtual)

  ⇝ G. Heinrich, S. P. Jones, M. Kerner, G. Luisoni and E. Vryonidou, "NLO predictions for Higgs boson pair production with full top quark mass dependence matched to parton showers," JHEP **1708**, 088 (2017)

  ⇝ S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk and T. Zirke, "Full top quark mass dependence in Higgs boson pair production at NLO," JHEP **1610**, 107 (2016)

  ⇝ S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk, U. Schubert and T. Zirke, "Higgs Boson Pair Production in Gluon Fusion at Next-to-Leading Order with Full Top-Quark Mass Dependence," Phys. Rev. Lett. **117**, no. 1, 012001 (2016)

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- Double Higgs production (Two-loop Virtual)

The focus shifted $\rightsquigarrow$ Going **beyond** NLO QCD

GoSam Today

What can GoSam do for Electron-Muon Scattering **today**?
(`Work in Progress`)

$\rightsquigarrow$ Talks of Carloni Calame, Fael, Vicini

$\mu^- e^- \to \mu^- e^-$ @ NLO

GoSam 2.0.4: $\mu^- e^- \to \mu^- e^-$

This process consists of one LO diagram and 6 NLO diagrams.

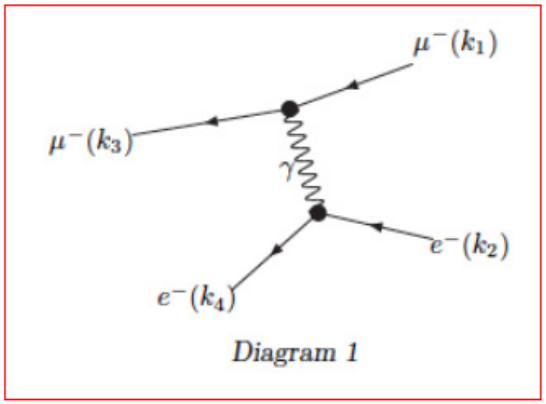
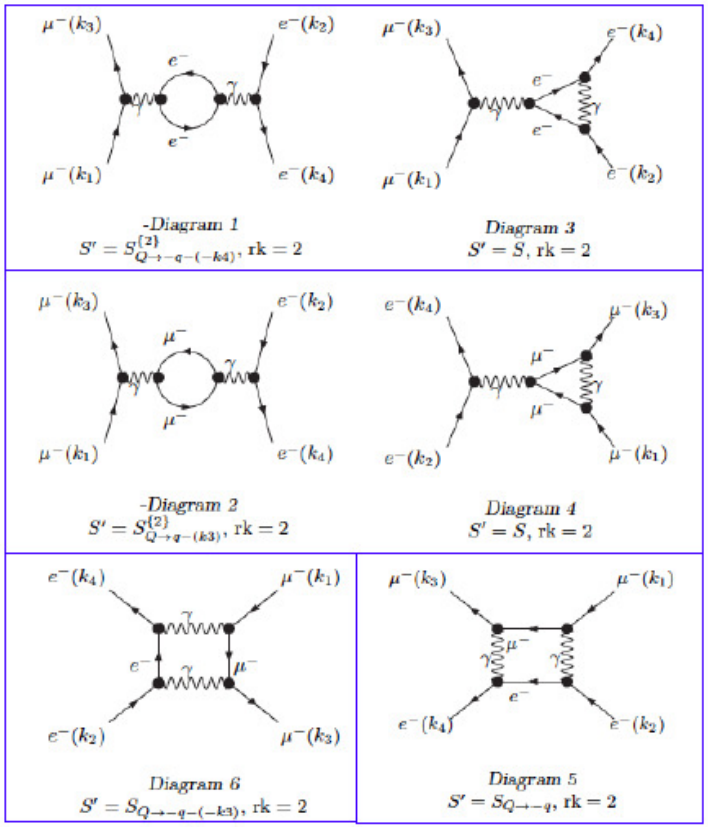


Diagram 1

Timing: 1.2 ms / phase space



Analytic Expressions are available $\rightsquigarrow$ Do we need a numerical code?

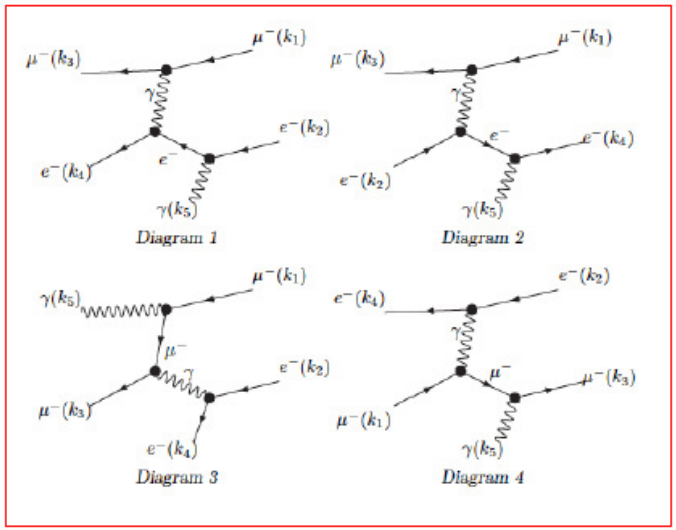
$\rightsquigarrow$ Talk of Carloni Calame

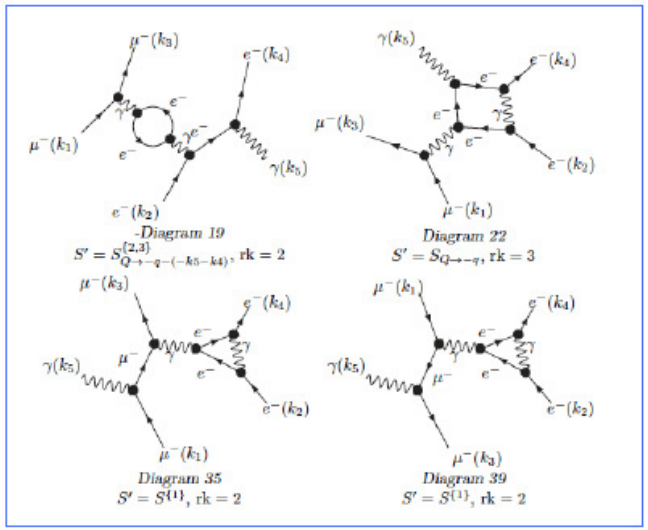
$\mu^- e^- \to \mu^- e^- \gamma$ @ NLO

Needed as part of the NNLO calculation

GoSam 2.0.4: $\mu^- e^- \to \mu^- e^- \gamma$

This process consists of 4 tree-level diagrams and 44 NLO diagrams.





Timing: about 30 ms / phase space

⇝ In which form will the **MC** incorporate this contributions?

⇝ Can we do better (analytic)? Shall we use the numerical result for cross-checks?

NLO Automation

$$\sigma_{NLO} = \int_n \left(d\sigma^B + d\sigma^V + \int_1 d\sigma^A \right) + \int_{n+1} \left(d\sigma^R - d\sigma^A \right)$$

Monte Carlo Tools (MC) $\rightsquigarrow$

Tree-level Contributions

Subtraction Terms

Integration over phase-space

One-Loop Programs (OLP) $\rightsquigarrow$

The values of the Virtual Contributions (at each given phase-space point)

Strategies to full NLO automation:

- $\rightsquigarrow$ **MC** controls the **OLP** via Binoth Les Houches Accord interface (BLHA)
- $\rightsquigarrow$ **OLP** is fully incorporated within the **MC**

NNLO Automation

$$\sigma_{NNLO} = \int_n (d\sigma^V + \ldots) \quad + \quad \int_{n+1} (d\sigma^{RV} + \ldots) \quad + \quad \int_{n+2} (d\sigma^R + \ldots)$$

- **Monte Carlo Tools**
- **Leading-Order Contributions**
- **One-Loop Numerical Programs**
- **One-Loop Analytic Results**
- **Two-Loop Virtual Contributions**
- **Subtraction Terms**

$\rightsquigarrow$ The **MC** should guide us in the development of the various contribution

GoSam Tomorrow

What **could/should/will** GoSam do **tomorrow**?

$\rightsquigarrow$ Updates and Upgrades

$\rightsquigarrow$ Talks of Mastrolia, Primo, Schubert

GoSam Tomorrow

What **could/should/will** GoSam do **tomorrow**?

$\rightsquigarrow$ Updates and Upgrades

- Several development are under way within GoSam, as the code is evolving beyond NLO
- EW renormalization (see `arXiv:1706.09022`) should be merged in the main public branch of the code
- There is an existing version of two-loop generator (see `arXiv:1604.06447`), as used in double Higgs production.
- The Feynman integrand generator can be updated to provide input for a new reduction code
- New techniques for NLO are available (analytic results!)
- Further support to NNLO developments

Conclusions/Outlook

Electron-Muon Scattering at NLO is available analytically $\rightsquigarrow$ GoSam can contribute to the calculation of Electron-Muon Scattering at NNLO
(*"MC, what shall we do?"*)

The GoSam framework is in continuous evolution
Its modular structure allows to incorporate new ideas and techniques

Over the past year, *the focus in GoSam has shifted*
Early applications $\rightsquigarrow$ NLO QCD, automation
Recent attempts beyond NLO QCD $\rightsquigarrow$ electroweak, calculations beyond one loop

Electron-Muon Scattering is a wonderful opportunity
for further GoSam development