NLO QCD Production of Higgs plus jets with GoSam

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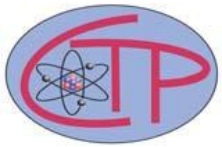


On behalf of the GoSam collaboration:
G. Cullen, **H. van Deurzen**, **N. Greiner**, **G. Heinrich**, **G. Luisoni**,
P. Mastrolia, **E. Mirabella**, **G.O.**, **T. Peraro**, **J. Reichel**,
J. Schlenk, **J.F. von Soden-Fraunhofer**, **F. Tramontano**

EPS HEP 2013 Stockholm
July 17-24, 2013

Outline

Credits

"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 2012-2013:

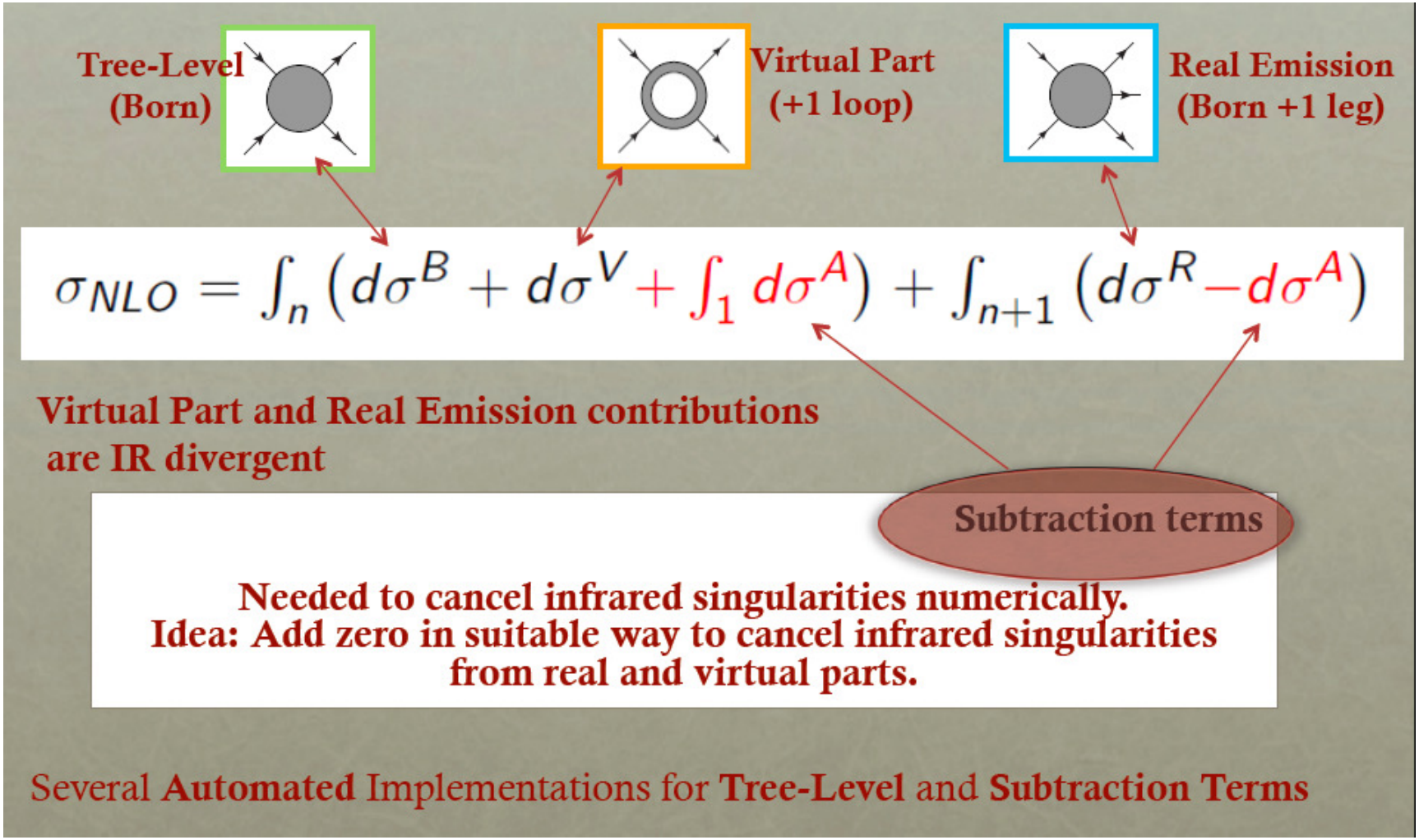
- G. Cullen, H. van Deurzen, N. Greiner, G. Luisoni, P. Mastrolia, E. Mirabella, G. O., T. Peraro, and F. Tramontano, "NLO QCD corrections to Higgs boson production plus three jets in gluon fusion," arXiv:1307.4737 [hep-ph].
- S. Hoeche, J. Huang, G. Luisoni, M. Schoenherr and J. Winter, "Zero and one jet combined NLO analysis of the top quark forward-backward asymmetry," arXiv:1306.2703 [hep-ph]
- G. Luisoni, P. Nason, C. Oleari and F. Tramontano, "Merging HW/HZ + 0 and 1 jet at NLO with no merging scale using the POWHEG BOX interfaced to GoSam," arXiv:1306.2542 [hep-ph]
- 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," arXiv:1305.6837 [hep-ph]
- 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 andF. Tramontano, "NLO QCD corrections to the production of W+ W- plus two jets at the LHC," Phys. Lett. B **713**, 277 (2012)

GoSam @ MPI Munich – January 2013

Cullen, Peraro, Schlenk, Tramontano, von Soden-Fraunhofen, Greiner, Mastrolia

GO, Reichel, van Deurzen, Heinrich, Luisoni, Mirabella

NLO calculations



GoSam provides the **Virtual Corrections**

One-Loop Virtual Corrections

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

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

One-Loop Master Integrals: Ellis, Zanderighi; van Oldenborgh; van Hameren; Binoth et al.; Hahn et al.

Virtual corrections with GoSam

1. Algebraic Generation
   - Amplitudes generated with **Feynman diagrams**
   - **Algebraic manipulations are allowed** before starting the numerical integration
   - The **generation** of numerators is executed **separately from the numerical reduction**
   - Optimization: **grouping of diagrams**, smart **caching**
   - Control over sub-parts of the calculation
   - Algebra in **dimension** d, different schemes

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

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Modular Structure $\rightarrow$ Ability to incorporate **new ideas** and **techniques**

The GoSam framework is in continuous evolution

Reduction algorithms within GoSam

Several Options for the Virtual Part:

Samurai

$d-$dimensional Integrand-Level Reduction → **Current default**

Automated Model-independent Computation of the full Rational Term

Mastrolia, G.O., Reiter, Tramontano

Golem95

Tensorial Reduction → **Rescue System**

Binoth, Guillet, Heinrich, Pilon, Reiter

Ninja → **Talk of T. Peraro**

Integrand-Level Reduction + Laurent Expansion → **Stable** and **Fast**!!

Mastrolia, Mirabella, Peraro

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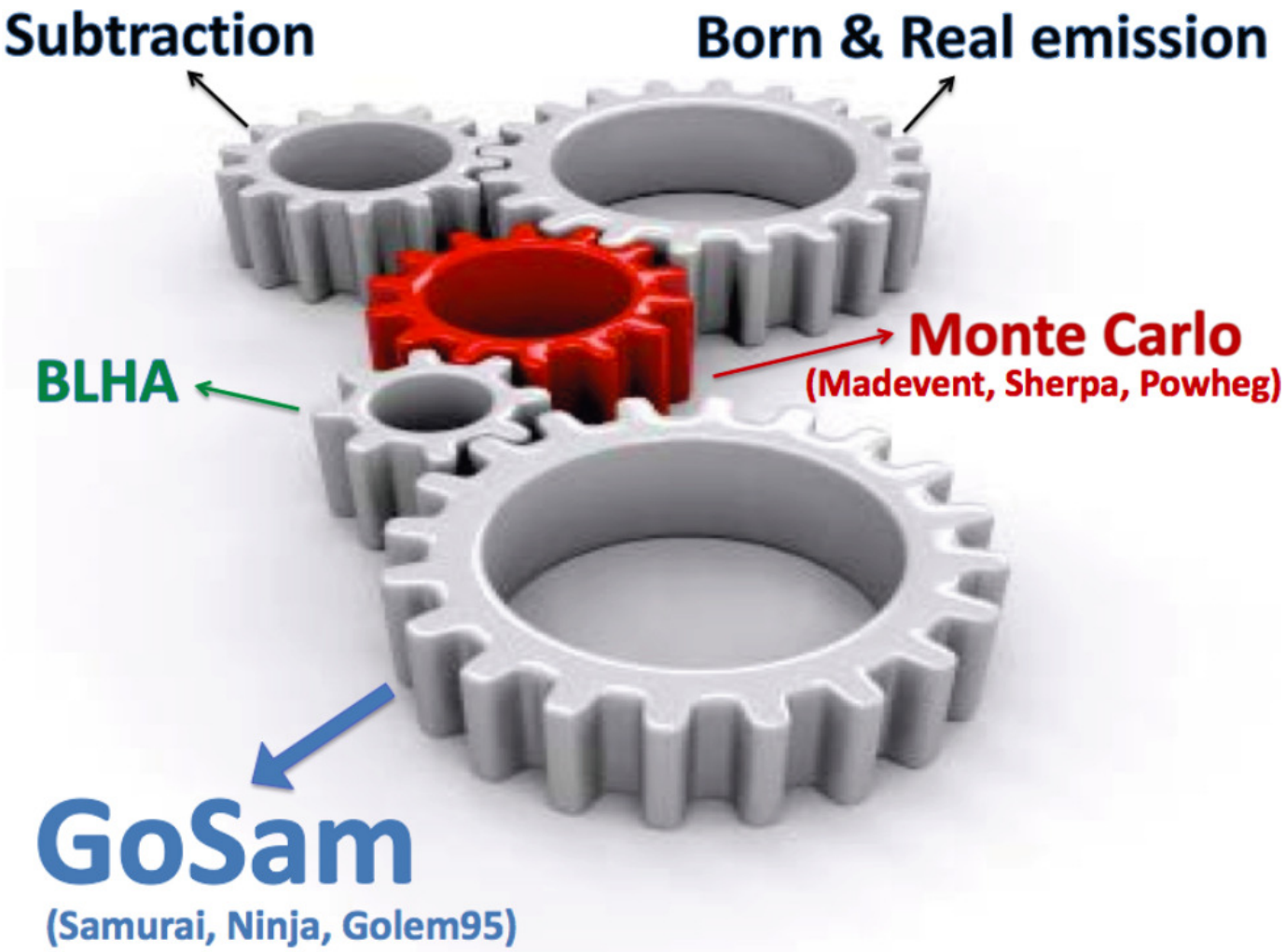
What about . . . Real Emission, Subtraction Terms, Integration ?

The GoSam interface



Interfaces with external MC

- GoSam + MadGraph+MadDipole+MadEvent
  → ad-hoc interface [Greiner]
  - $pp \to b\bar{b}b\bar{b}$ [Greiner, Guffanti, Reiter, Reuter (2011)]
  - $pp \to W^+W^-$ + 2 jets [Greiner, Heinrich, Mastrolia, G.O., Reiter, Tramontano (2012)]
  - $pp \to \chi^0\chi^0$ + jet [Cullen, Greiner, Heinrich (2012)]
  - $pp \to \gamma\gamma$ + jet [Gehrmann, Greiner, Heinrich (2013)]
  - $pp \to W^+W^- b\bar{b}$ [Heinrich, Schlenk, Winter (in progress)]

Interfaces with external MC

- GoSam + MadGraph+MadDipole+MadEvent
  → ad-hoc interface [Greiner]
- GoSam + Sherpa
  → via BLHA [Luisoni, Schönherr, Winter]
  Standalone packages publicly available: `http://gosam.hepforge.org/proc/`
  H+2 jets in GF [van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, G.O., Peraro, von Soden-Fraunhofen, Tramontano (2013)]
  $t\bar{t} + 0, 1$ jet [Hoeche, Huang, Luisoni, Schönherr, Winter (2013)] → **Talk of M. Schönherr**

Interfaces with external MC

- GoSam + MadGraph+MadDipole+MadEvent
  → ad-hoc interface [Greiner]
- GoSam + Sherpa
  → via BLHA [Luisoni, Schönherr, Winter]
- GoSam + Powheg
  → via BLHA [Luisoni, Nason, Oleari, Tramontano]
  HW/HZ + 0,1 jet [Luisoni, Nason, Oleari, Tramontano (2013)]

Interfaces with external MC

- GoSam + MadGraph+MadDipole+MadEvent
  → ad-hoc interface [Greiner]
- GoSam + Sherpa
  → via BLHA [Luisoni, Schönherr, Winter]
- GoSam + Powheg
  → via BLHA [Luisoni, Nason, Oleari, Tramontano]
- GoSam + Herwig
  → *work in progress* [Greiner, Heinrich, von Soden-Fraunhofen]
- GoSam + aMC@NLO
  → *work in progress* [van Deurzen, Frederix, Frixione, Hirschi, Luisoni, Mastrolia, GO, Peraro]

Example 1: $pp \to W^+W^- +$ 2 jets

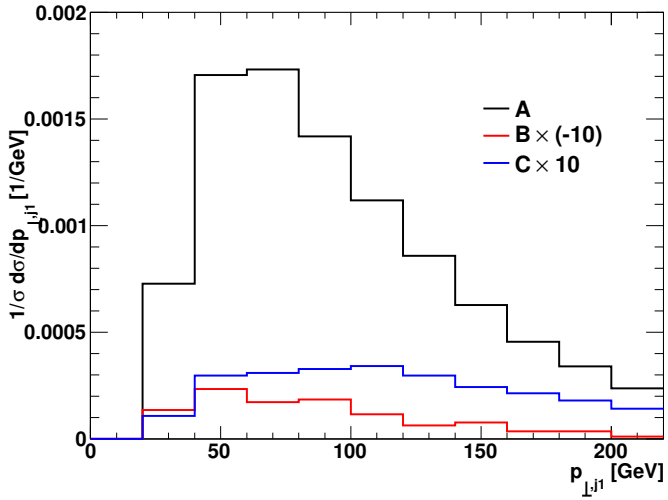
Greiner, Heinrich, Mastrolia, G.O., Reiter, Tramontano (2012)

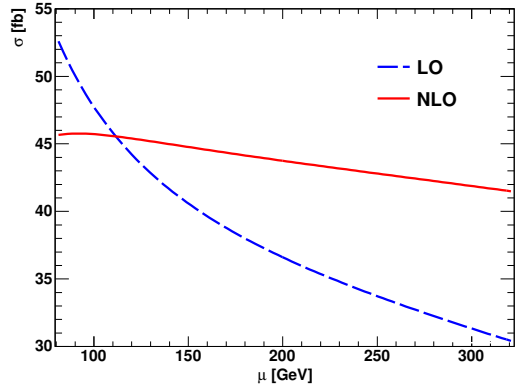
Virtual contributions divided in 3 parts:

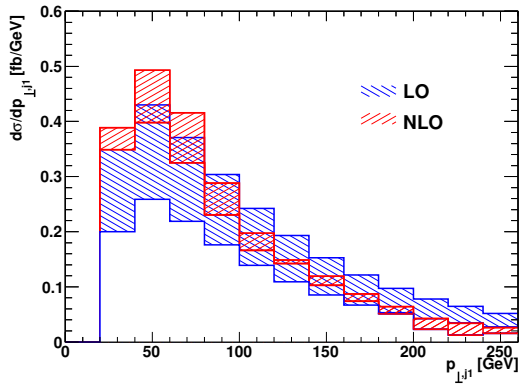
- A same setup as Melia et al. (2011)
- B W's attached to a fermion loop (2%)
- C third generation in the loops (4%)

Reduction of scale uncertainty at NLO

$\sigma_{\rm lo} = 39.57^{+34\%}_{-23\%}$ fb $\quad \sigma_{\rm nlo} = 44.51^{+2.5\%}_{-7.4\%}$ fb



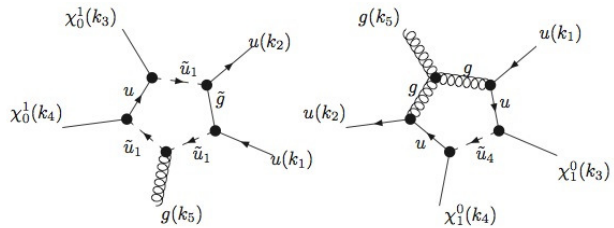




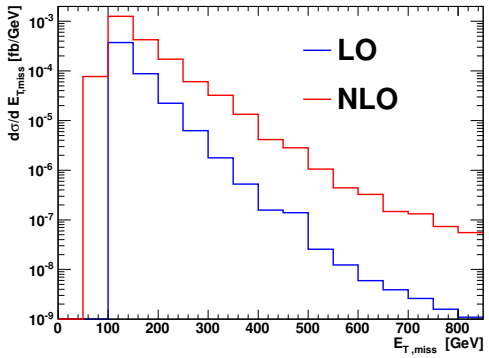
Example 2 (BSM): neutralino pair +jet

Cullen, Greiner, Heinrich (2012)

- Susy-QCD corrections to neutralino pair production in association with a jet
- FeynRules produces a UFO model file that can be read by GoSam
- About 1400 diagrams: rank-3 pentagons, up to 4 internal masses



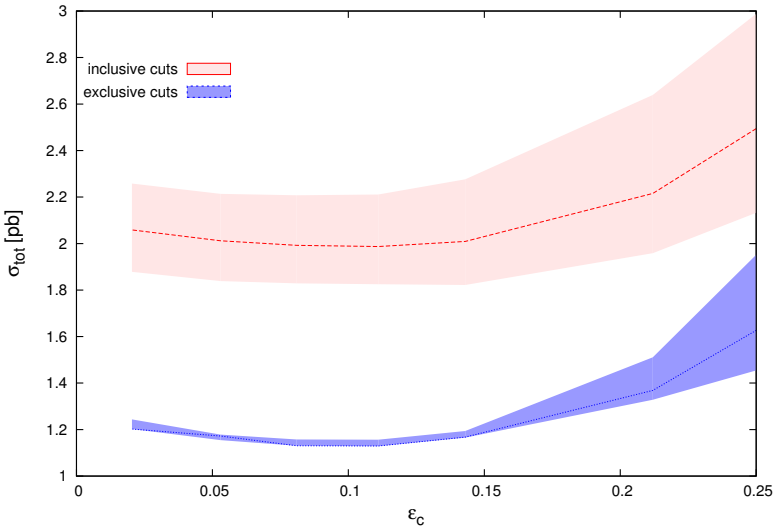
- Missing transverse energy for the process $pp \to \chi^0\chi^0$ + jet at 8TeV

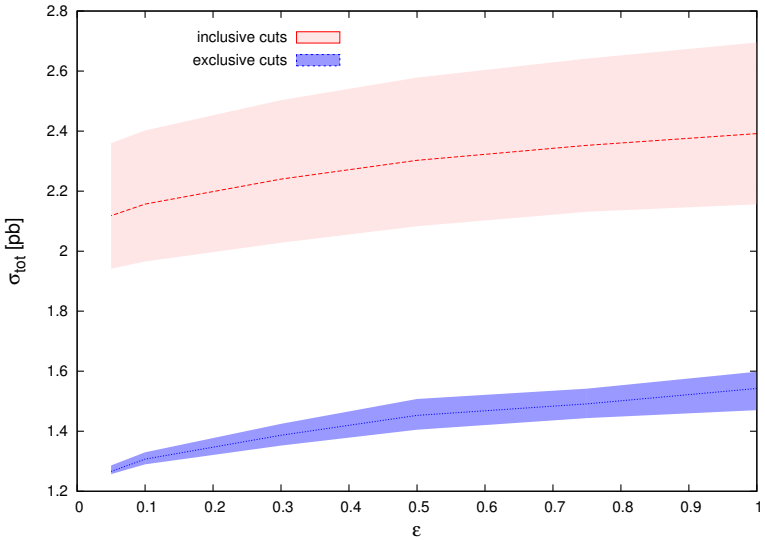


Example 3: Di-Photon + Jet

Gehrmann, Greiner, Heinrich (2013)

- NLO QCD corrections to diphoton plus jet production at hadron colliders
- Comparison of different photon isolation criteria
- Detailed study of the dependence of the cross section on the photon isolation parameters

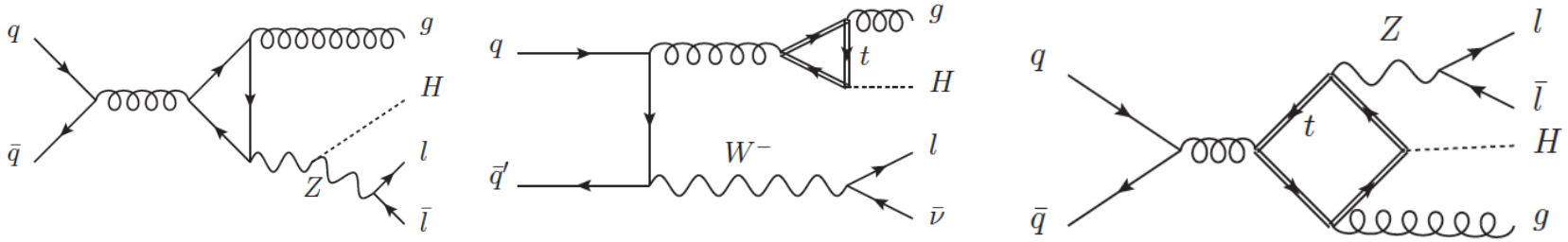




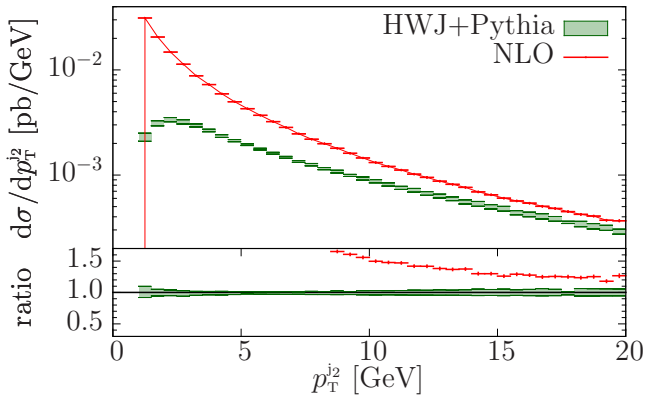
Example 4: GoSam + Powheg : HW/HZ + 0,1 jet

Luisoni, Nason, Oleari, Tramontano (2013)

- Interface of the POWHEG BOX to GoSam based on BLHA
- Higgs boson in association with a vector boson (with decays) plus 0,1 jets



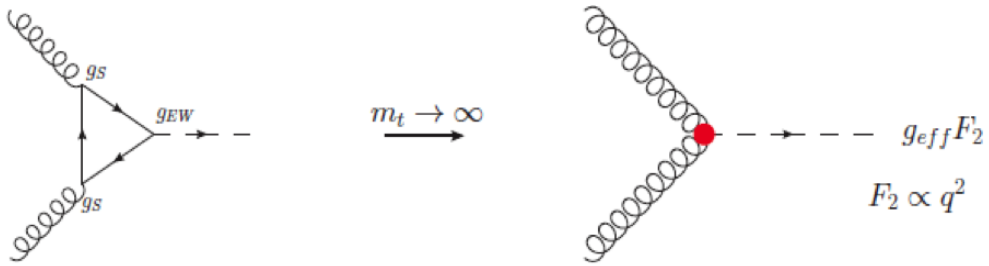
- NLO+parton shower event generators for the HV and HV + 1 jet processes



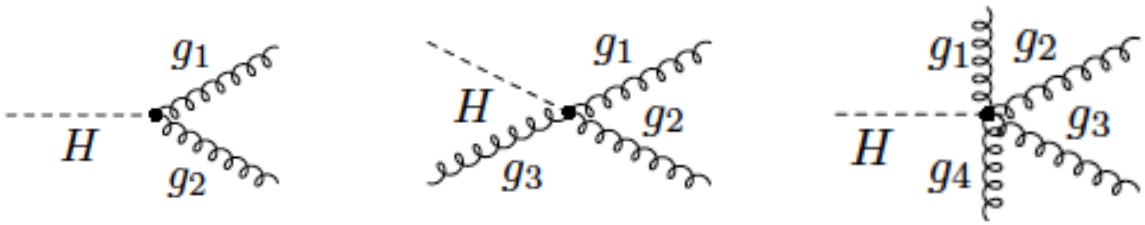
Higgs + Jets in Gluon Fusion

Motivation: determine the properties of the Higgs boson
→ study of all possible production/decay channels and background processes
Many ongoing studies: i.e. contamination of VBF sample by GF events (see YR3).

Large Top-Mass Approximation ($m_t \to \infty$) : the Higgs coupling to gluons, which at LO is mediated by a top-quark loop, becomes independent of m_t, and it can be described by an effective operator



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



Higher Rank Extension → XSamurai

Theoretical Challenge: Effective Hgg coupling leads to **numerators with rank r larger than the number n of the denominators**, i.e. $r \leq n+1$

- The form of the integrand-level identity for the numerator has to be extended Mastrolia, Mirabella, Peraro (2012)
- The decomposition of any one-loop n-point amplitude in terms of master integrals (MIs) acquires new contributions

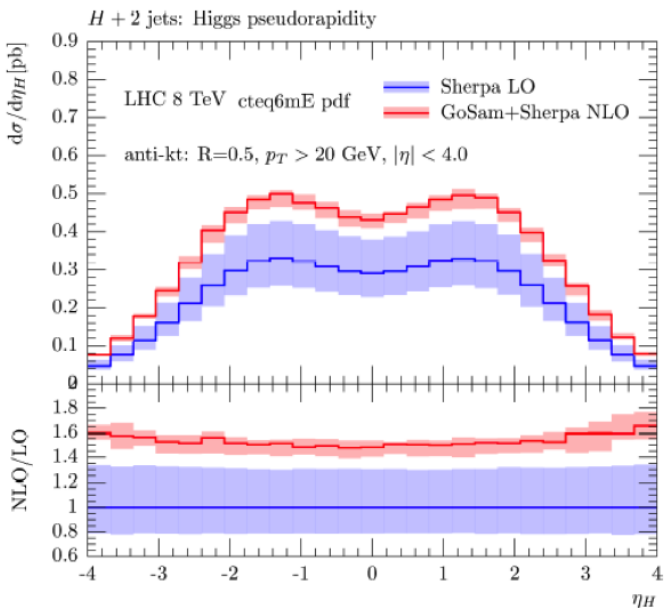
$$\mathcal{M}_n^{\text{one-loop}} = \mathcal{A}_n + \delta\mathcal{A}_n$$

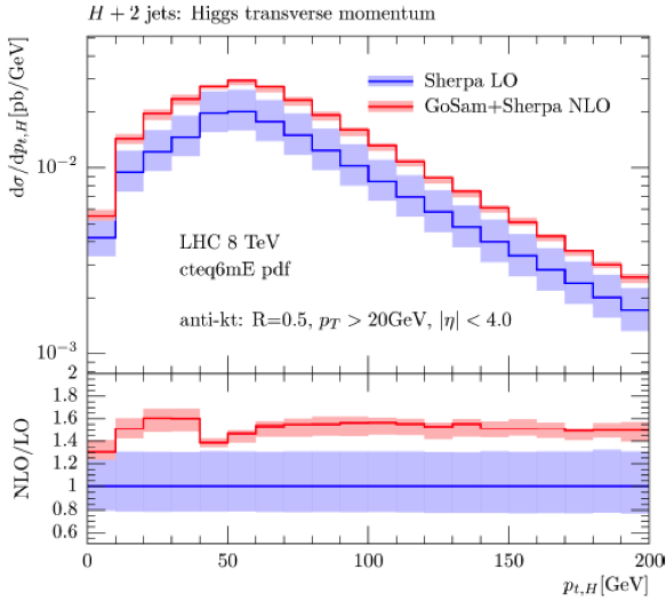
  $\mathcal{A}_n$ corresponds to the standard decomposition ($r \leq n$)
  $\delta\mathcal{A}_n$ enters only if $r \leq n+1$

- The **extended** integrand decomposition has been implemented in the SAMURAI library. van Deurzen et al. (2012)

Warm-up: Higgs + 2 jets in GF @ NLO

- Results obtained with GoSam+Sherpa
- Agreement with MCFM (v6.4) [Campbell, Ellis, Williams]





van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, G.O., Peraro, von Soden-Fraunhofen, Tramontano (2013)

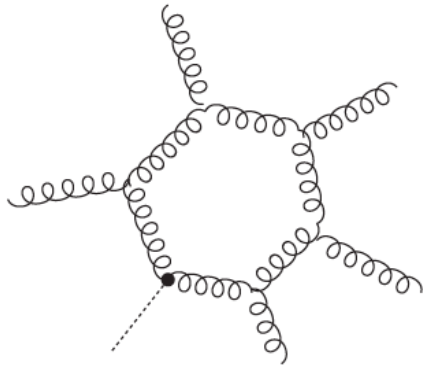
(also appeared in *Handbook of LHC Higgs Cross Sections: 3. Higgs Properties*)

Towards Higgs+3 jets in GF @ NLO

		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

Further Theoretical and Computational Challenges:

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

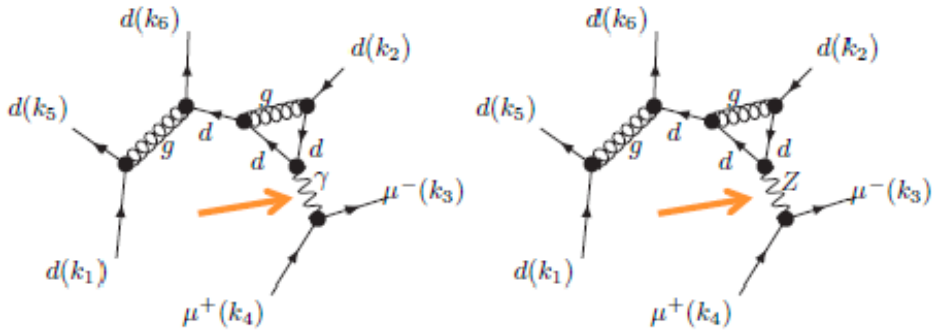


In order to deal with the complexity level of this calculation, the GoSam code has been enhanced

Beyond GoSam 1.0

Improvements on the Code generation:

- Diagrams with identical sets of denominators are summed algebraically during generation.

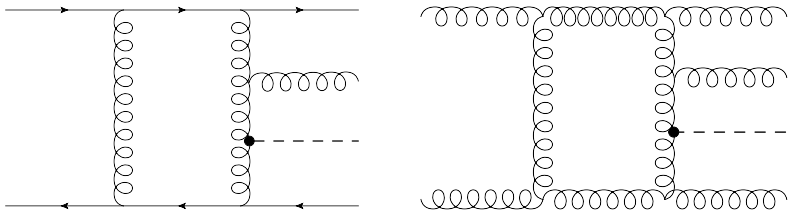


- New optimization strategy: new features of FORM 4.0 allow to optimize algebraic expressions → Faster generation, smaller code, and better runtime!
- Numerical polarization vectors → Reduced code size.
- Parallelization of diagram generation → Reduction of generation time.

Higgs + 3 jets in GF: virtual part

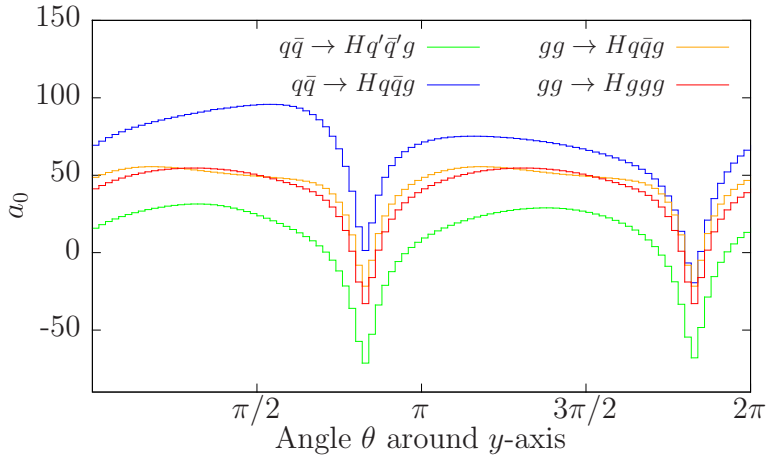
Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, GO, Peraro, Tramontano, **arXiv:1307.4737**

Virtual parts computed with GoSam



$$\frac{2\,\Re\mathrm{e}\left\{\mathcal{M}^{\text{tree-level}*}\,\mathcal{M}^{\text{one-loop}}\right\}}{(\alpha_s/2\pi)\left|\mathcal{M}^{\text{tree-level}}\right|^2} \equiv \frac{a_{-2}}{\epsilon^2} + \frac{a_{-1}}{\epsilon} + a_0$$

Subprocess	Diagrams	Time/PS-point [sec]
$q\bar{q} \to Hq'\bar{q}'g$	467	0.29
$q\bar{q} \to Hq\bar{q}g$	868	0.60
$gg \to Hq\bar{q}g$	2519	3.9
$gg \to Hggg$	9325	20



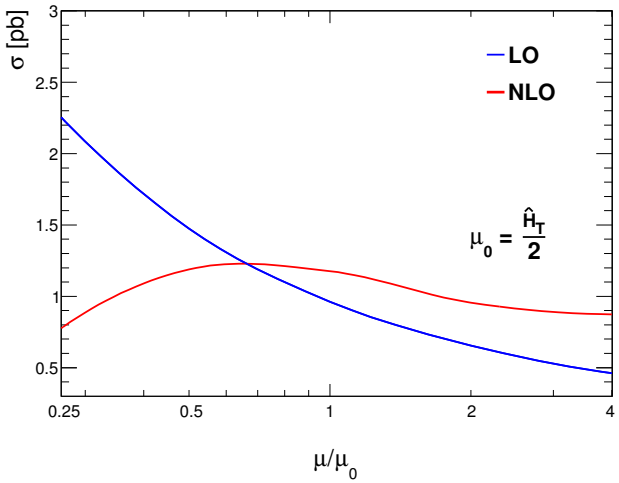
Number of Feynman diagrams and time per PS-point point for each subprocess

Tests: gauge invariance and IR poles

Higgs + 3 jets GF @ NLO: cross-section

Cross sections are obtained with a hybrid setup:

- GoSam+ Sherpa for Born and of the virtual contributions
- MadGraph+MadDipole+MadEvent for reals/subtraction/integrated dipoles



$$\mu_F = \mu_R = \frac{\hat{H}_T}{2} = \mu_0$$

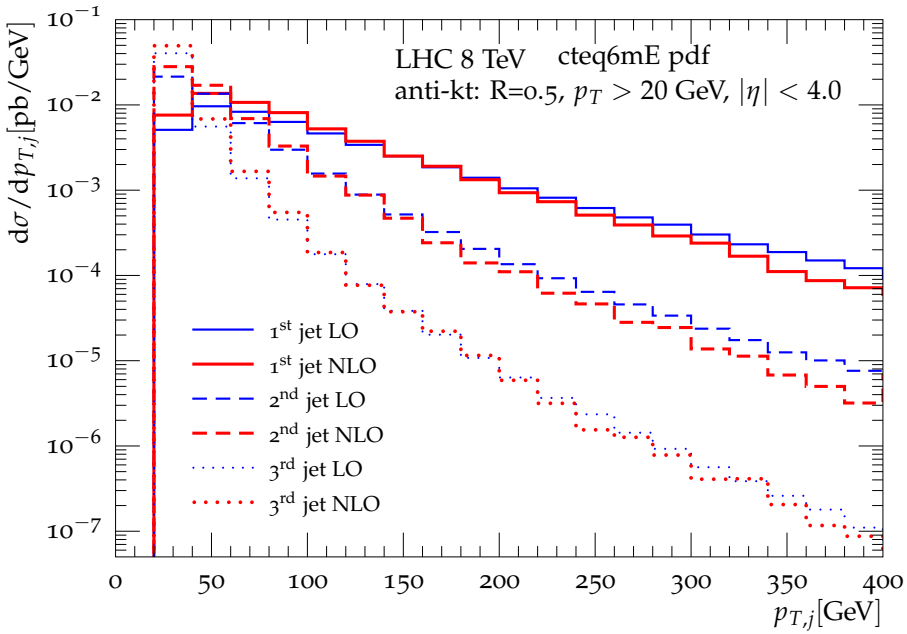
$$\hat{H}_T = \sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}|$$

Tests performed on the cross section:

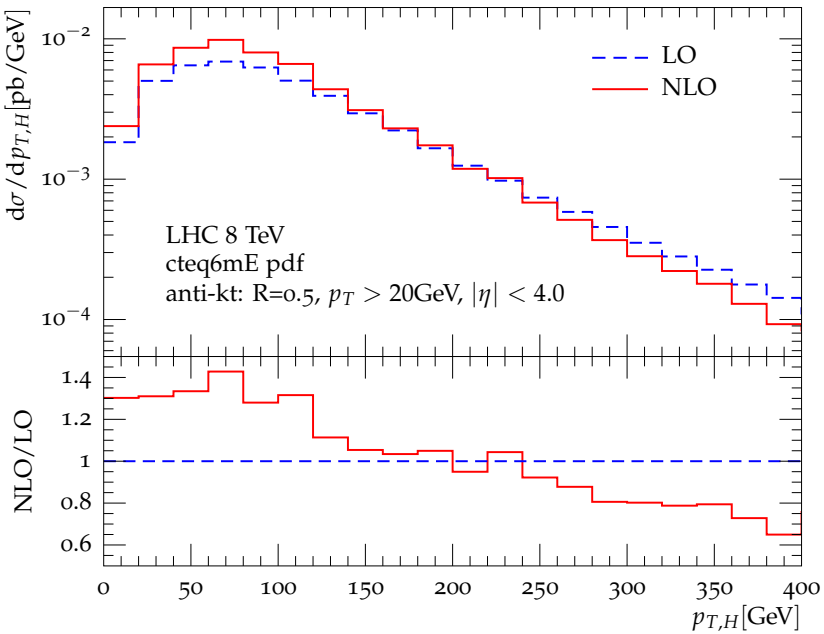
- NLO H+2 jets: agreement between hybrid scheme and GoSam+Sherpa
- LO H+3 jets: agreement between MadGraph and Sherpa
- NLO H+3 jets:Independence from $\alpha-$parameter (subtraction+int. dipoles)

Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, GO, Peraro, Tramontano **arXiv:1307.4737**

Higgs + 3 jets GF @ NLO: distributions



p_T of the Jets



p_T of the Higgs boson

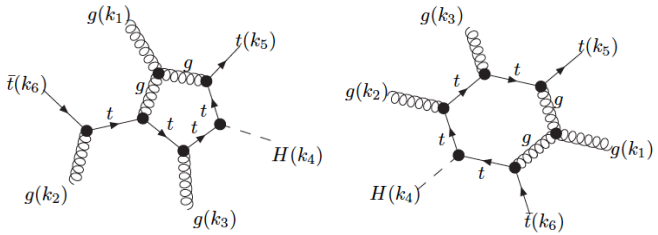
$pp \to Hjjj$ generated by GoSam can be paired with available MC programs for further phenomenological analyses.

Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, GO, Peraro, Tramontano **arXiv:1307.4737**

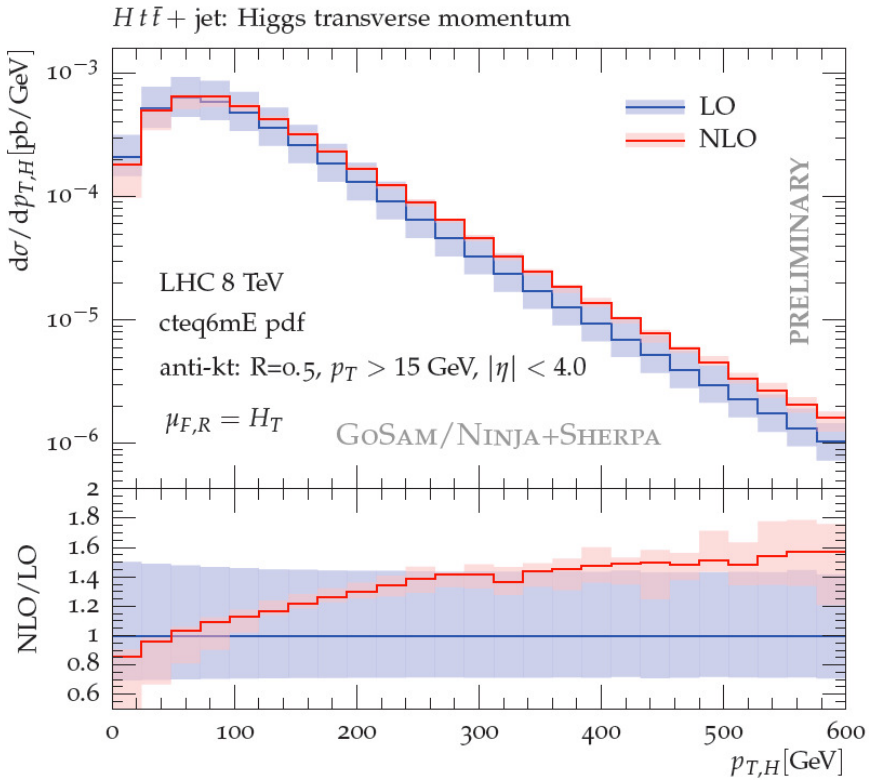
$pp \to Ht\bar{t} + 1$ JET @ NLO

First Application of GoSam/Ninja + Sherpa→ **Talk of T. Peraro**

		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



Conclusions

- GoSam is a dynamic code → new ideas became technical improvements, which turned into exciting results
- GoSam allows for the automatic computation of 1-loop virtual amplitudes
  - *Algebraic generation of d-dimensional integrands via Feynman diagrams*
  - *Reduction using d-dimensional OPP and/or tensorial reduction*
  - *Automated computation of full rational term*
- Interfaced to several external MC for pheno studies
- Applications beyond QCD, in EW and BSM models
- Successful computation of $H + n$ jets ($n = 1, 2, 3$) processes in Gluon Fusion

Outlook

- more **processes** on the way
- **interaction** with MC and experimental collaborations
- additional **code improvements** towards GoSam 2.0
- **multi-loop** integrand reduction in the making