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Automated higher order corrections with GoSam

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On behalf of the GoSam collaboration

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Outline

- Very brief introduction to GoSam:
  Automated one-loop calculations within and beyond the SM

- Going beyond one-loop

GoSam = Golem + Samurai

General **O**ne **L**oop **E**valuator of **M**atrix elements +

Scattering **Am**plitudes from **U**nitarity based **R**eduction **A**t **I**ntegrand level

= **Automated generation of virtual amplitude.**

GoSam 1.0: arXiv: 1111.2034 [hep-ph] (EPJC 72, 2012)

[Cullen,NG,Heinrich,Luisoni,Mastrolia,Ossola,Reiter,Tramontano]

GoSam 2.0: arXiv: 1404.7096 [hep-ph] (EPJC 74, 2014)

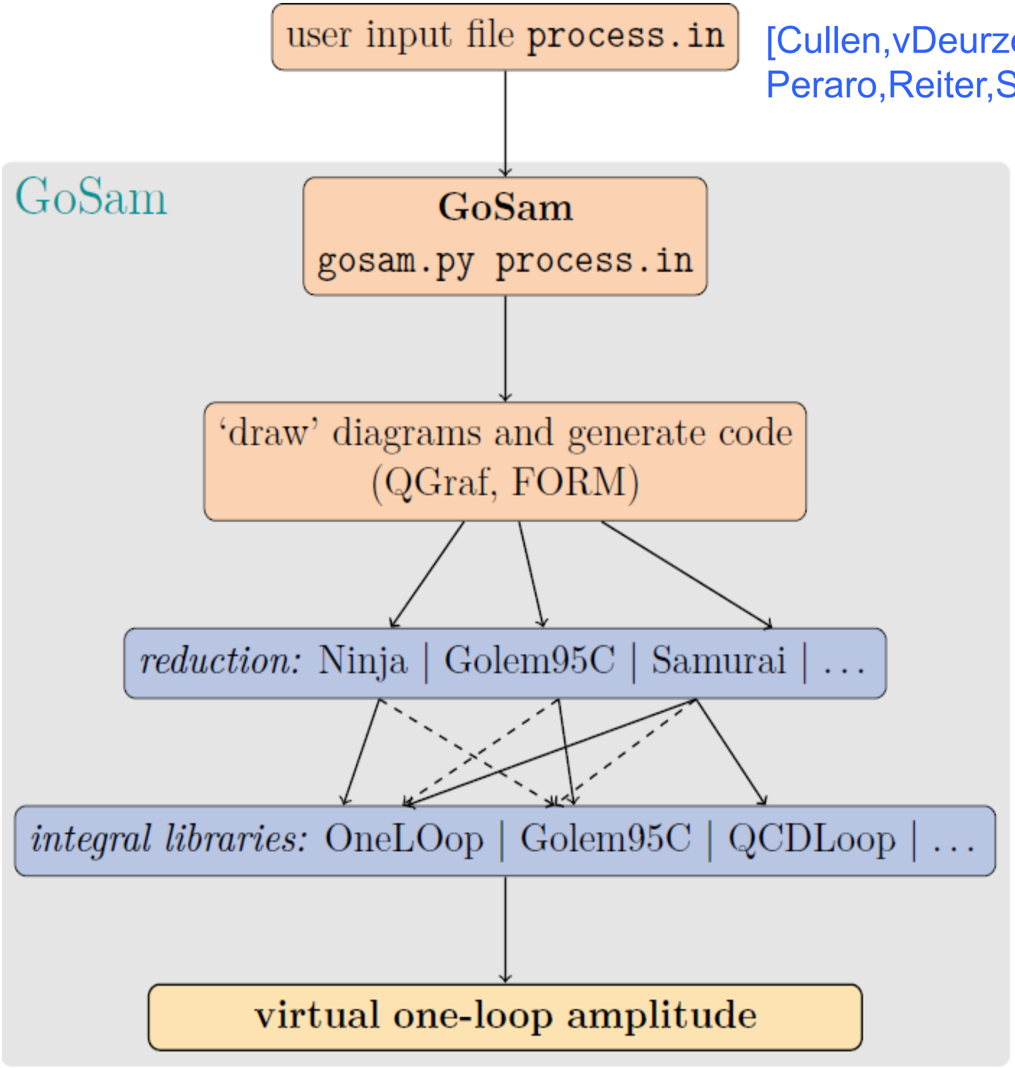
[Cullen,van Deurzen,NG,Heinrich,Luisoni,Mastrolia,Mirabella,Ossola,Peraro,Schlenk,von Soden-Fraunhofen,Tramontano]

- Based on **Feynman diagrams**
- Generates **Fortran95** code
- Can be used for **QCD**, **EW, effective Higgs coupling** and **BSM**
- Interface with existing tools for real radiation and integration (Herwig++, MadGraph, Sherpa, Powheg, Whizard)

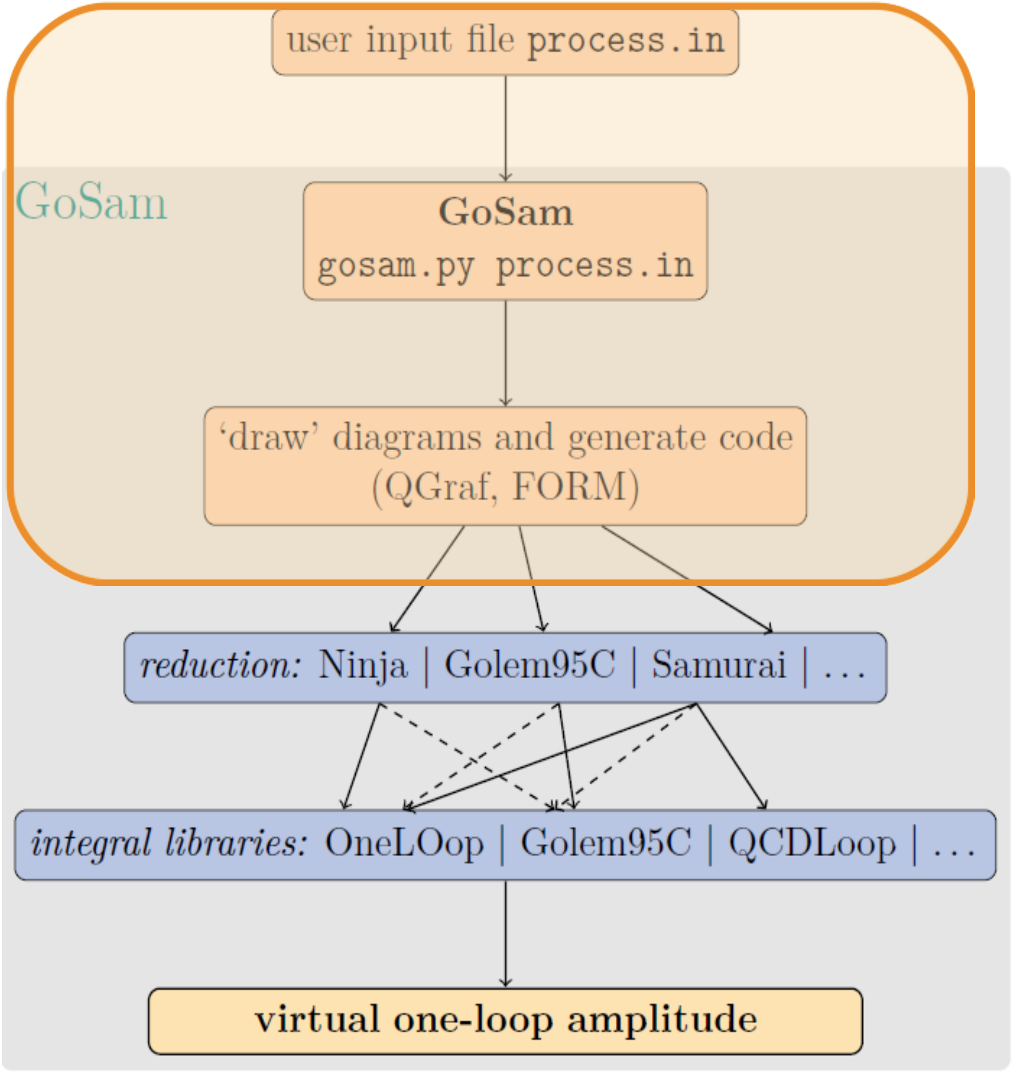
http://gosam.hepforge.org

GoSam 2.0 – A Quick Overview

[Cullen,vDeurzen,NG,Heinrich,Luisoni,Mastrolia,Mirabella,Ossola, Peraro,Reiter,Schlenk,vSoden-Fraunhofen,Tramontano]



GoSam 2.0 – A Quick Overview



GENERATION

- Specify process (process.in):
  in=g,g
  out=H,t,t~
  order=QCD,2,4
  model=smdiag
  (new models can be imported)
- Many additional options (Parameter settings, Filter)
- 'Draw' Feynman diagrams with Qgraf [Nogueira]
- Apply Feynman rules and optimize expression with FORM [Vermaseren,Kuipers,Ueda,Vollinga]
- Fortran code

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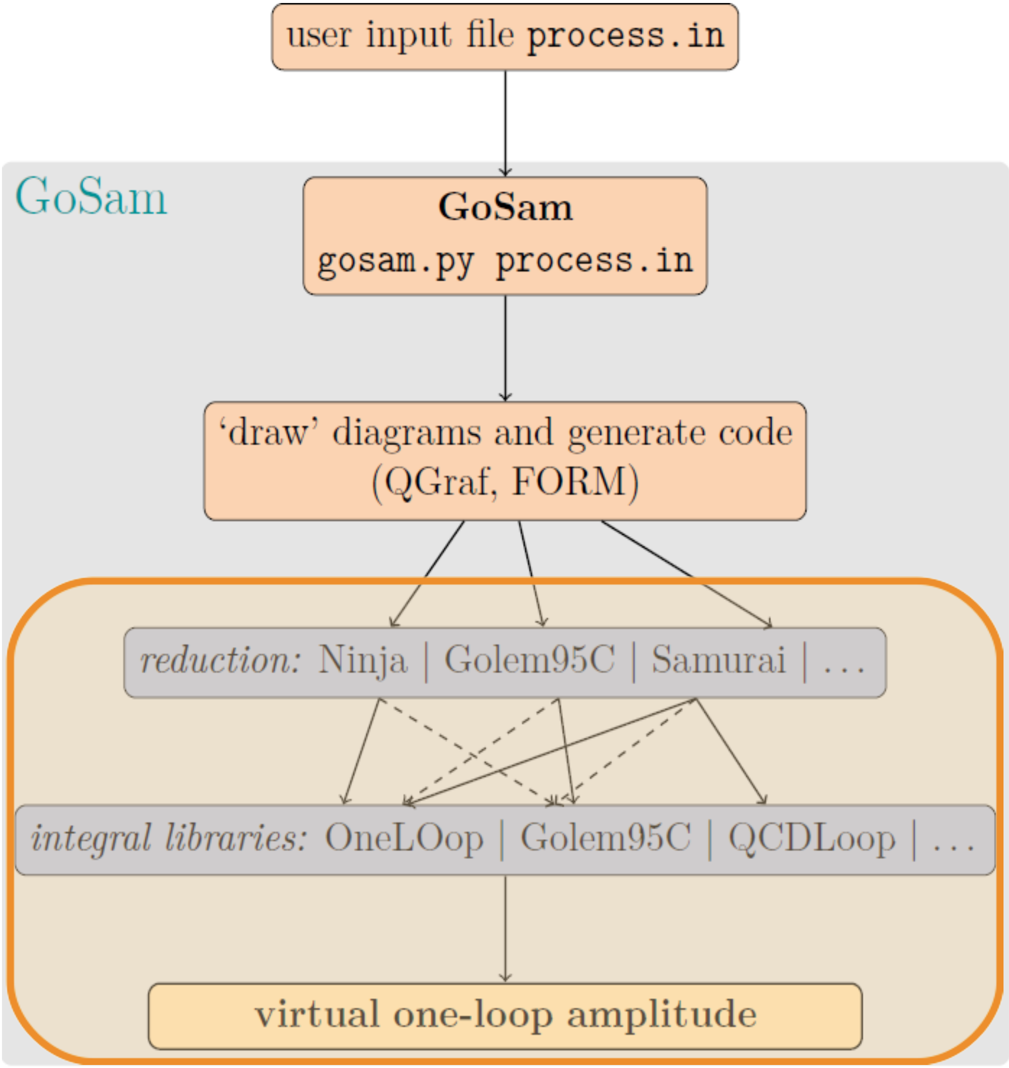
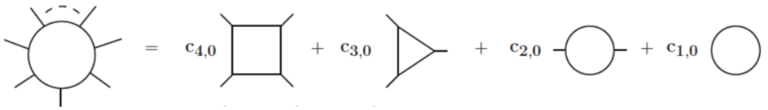


REDUCTION

- Any one loop amplitude can be written as combination of scalar integrals:



- Determine coefficients numerically, using either unitarity based methods Ninja [Mastrolia,Mirabella,Peraro] , Samurai [Mastrolia,Ossola,Reiter,Tramontano] or modified Passarino-Veltman reduction of Golem95 [Cullen et al.]
- Scalar integral libraries OneLoop [v.Hameren] ,QCDLoop [Ellis,Zanderighi] , Golem95

How to use GoSam

Preparation of input card

```
#!/bin/env  /home/pcl340b/greiner/GoSam/gosam.py

process_name=ttH
process_path=./ttH_virtual

#### physics options  #####

in=g,g              # accepts also PDG codes
out=H,t,t~
order=gs, 2, 4

model=smdiag
model.options= masses: mT mH, width: none, \
    alpha: 0.0072973525376, mZ: 91.1876, mW: 80.385, \
    mT: 172.4, mH: 125.0, Nf:5, Nfgen:1

zero=mU,mD,mC,mS,mB,wT,wB,wW,wZ,wH
one=gs,e
symmetries=family,generation
helicities=[+-][+-]0[+-][+-]

qgraf.options=onshell,notadpole,nosnail
qgraf.verbatim=true=iprop[D,S,C,B, 0, 0]
```

Example:
Higgs + Top quark pair

New models can be imported from FeynRules or LanHEP

Specify which parameters should be set ALGEBRAICALLY to zero or one

Options on helicity and loop diagrams

```
$ gosam.py --template process.in
```

generates **template input card**

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How to use GoSam

- **/matrix** directory contains test program for calculation of single phase space point.

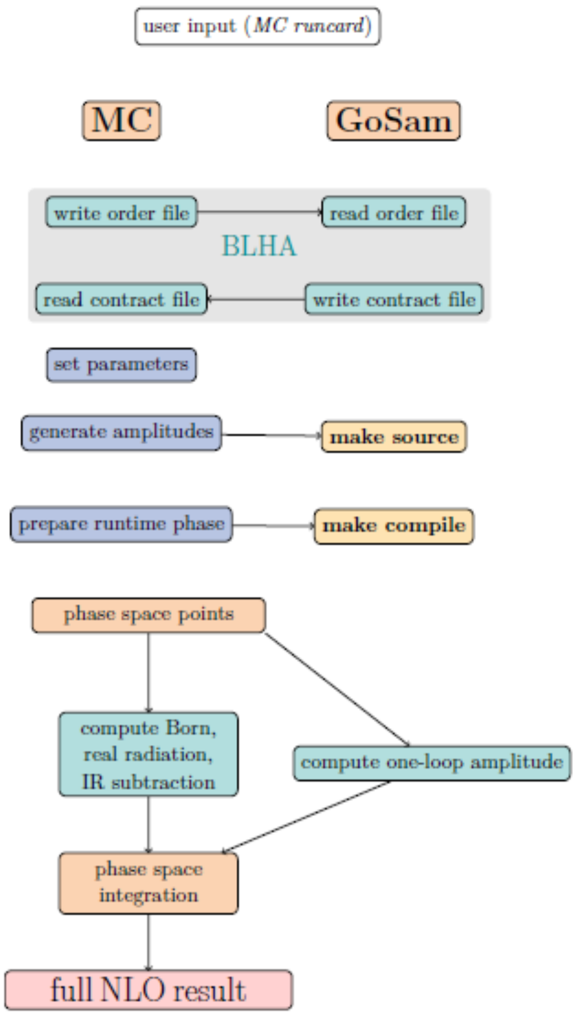
```
$ cd matrix
$ make test.exe
$ ./test.exe
```

```
#                   LO:   0.101314611282021 7E-03
# NLO, finite part:    17.31560363490869
# NLO, single pole:  -9.235244935244870
# NLO, double pole:  -6.000000000000000
# IR,  single pole:  -9.235244935222976
# IR,  double pole:  -6.000000000000001
#  Time/Event [ms]:                201.969
greiner@pcl340b:~/GoSam/gosam-1.0/ttH/matrix>
```

- Implementation of **infrared poles** allows for checking pole cancellation 'on the fly'.
  → Can be used to reject points during runtime. (PSP_check)

$$|\mathcal{M}|^2_{\text{1-loop}} = 2\,\Re\left(\mathcal{M}_B^\dagger \cdot \mathcal{M}_{Virt}\right)$$
$$= \frac{\alpha_{(s)}(\mu)}{2\pi}\frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \cdot (g_{(s)})^{2b} \cdot \left[c_0 + \frac{c_{-1}}{\epsilon} + \frac{c_{-2}}{\epsilon^2} + \mathcal{O}(\epsilon)\right]$$

Interface to Monte Carlo Programs



- Interface via **Binoth-Les-Houches-Accord (BLHA)** (both original and extended BLHA supported)
- Step 1: MC writes an **order file**

```
CorrectionType QCD
AmplitudeType Loop
2 -2 -> 1 -1
2 -2 -> 2 -2
```

- Step 2: OLP writes a **contract file**

```
CorrectionType QCD | OK
AmplitudeType Loop | OK
2 -2 -> 1 -1 | 0
2 -2 -> 2 -2 | 1
```

- Virtual amplitude called from within the MC during runtime (Sherpa,Powheg,Herwig++, aMC@NLO, Whizard)

New models from FeynRules

- Per default GoSam contains only different variations of the **Standard Model** (diagonal CKM, full CKM, effective Higgs theory, complex mass scheme)
- BSM models can be imported from **FeynRules** [Alloul,Christensen,Duhr,Degrande,Fuks] by exporting Lagrangian as **UFO (Universal FeynRules Output)** model file [Degrande,Duhr,Fuks,Grellscheid,Mattelaer,Reiter]
- UFO model: Python module that can be directly used by specifying

```
model = Feynrules, /path/to/ufo/model
```

- **Note:** UFO models usually do not contain renormalization (unrenormalized amplitude always possible)

  NB: Need renormalization constant in DRED (or conversion to DRED)

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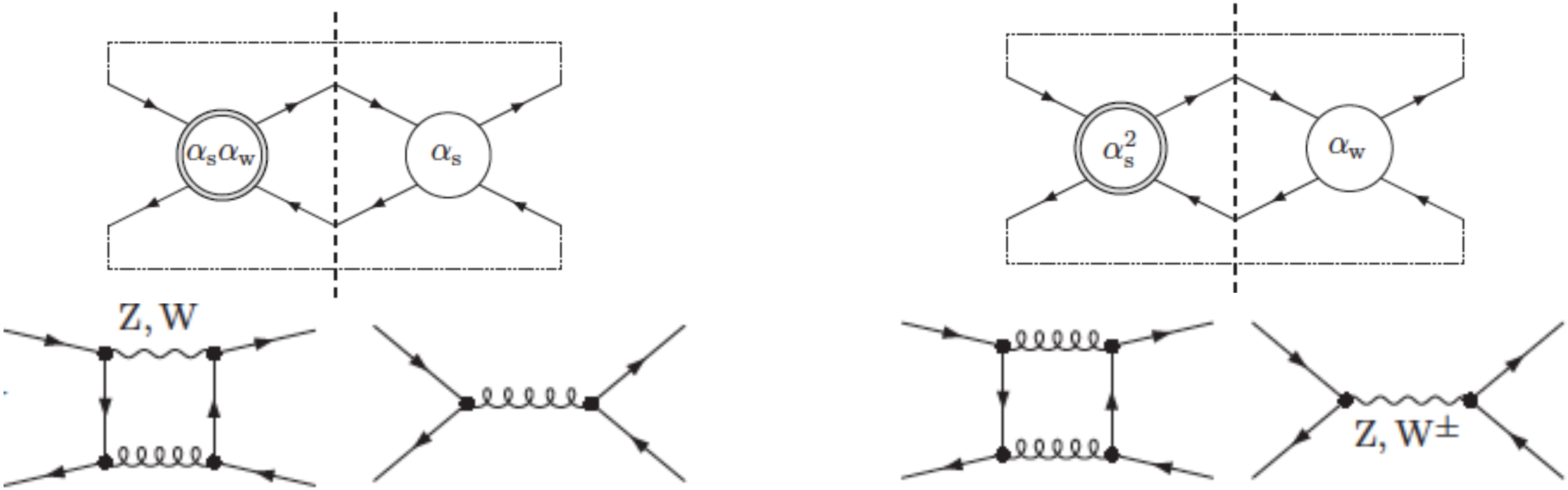
Electroweak corrections at NLO

Simplest example: **Dijet production** [Dittmaier,Huss,Speckner]

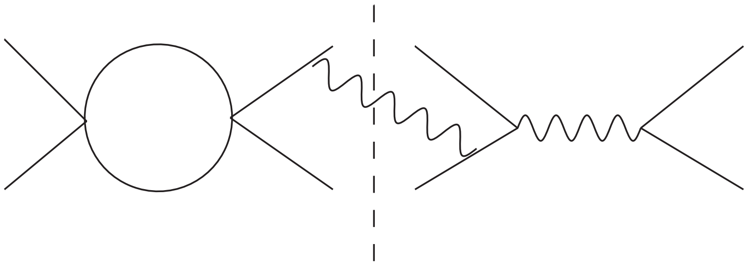


- Computation much more involved due to increased number of diagrams (photon/W/Z)
- Need to sum up all possible contributions at a given order
- Conceptually clear, but subtle difficulties (different types of loop diagrams, subtraction terms proportional to interference term, etc..)
- Fully automated and embedded in BLHA interface

Real-virtual and virtual-virtual

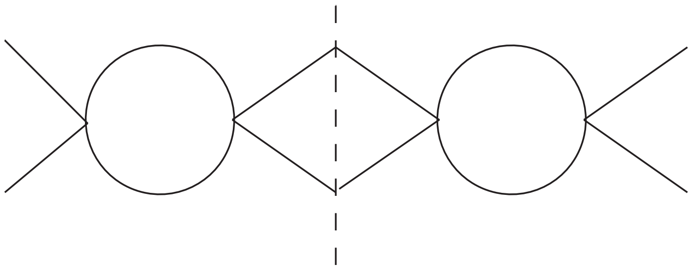
1-loop contributions to 2-loop calculations:

Real-virtual:



Equivalent to 'normal' one-loop contribution ✔
Option 'quadninja' allows for automatic switch to quadruple precision for numerical unstable points (for combination GoSam+Ninja)

virtual-virtual:



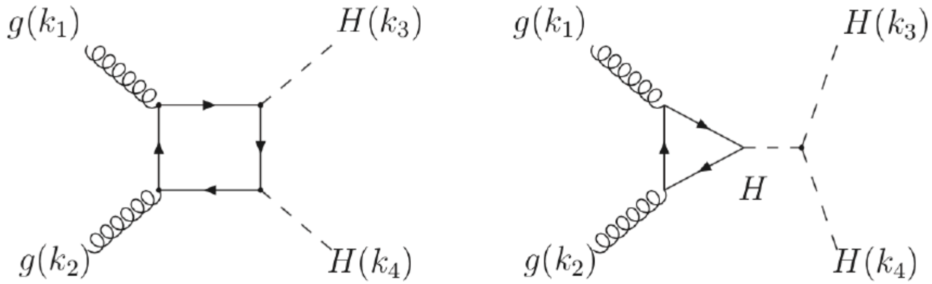
Corresponds to loop-induced process ✔

Includes color- and spin- correlation needed for NLO subtraction terms (needed for QCD only)

Beyond 1-loop

GoSam XL – Automation of 2loop

First successful application to **HH production @ NLO QCD**
[Borowka,NG,Heinrich,Jones,Kerner,Schlenk,Schubert,Zirke '16]



- 1- and 2-loop diagrams generated with **Qgraf**
- 2-loop diagrams: Use **Form** to bring **Qgraf** output into a form suitable for **Reduze** [Manteuffel, Studerus]
- Perform reduction of two-loop integrals as far as possible
- Remaining integrals are evaluated numerically using **SecDec** [Borowka,Carter,Heinrich,Jahn,Jones,Kerner,Schlenk,Zirke]
- Recently also applied to H+1jet [Jones,Kerner,Luisoni '18]

Example: HH production

$$g(p_1,\mu) + g(p_2,\nu) \to h(p_3) + h(p_4)$$

Amplitude can be written as: [Glover, v.d.Bij]

$$\mathcal{M}_{ab} = \delta_{ab}\,\epsilon^{\mu}(p_1,n_1)\epsilon^{\nu}(p_2,n_2)\,\mathcal{M}_{\mu\nu}$$
$$\mathcal{M}^{\mu\nu} = \frac{\alpha_s}{8\pi v^2}\left\{F_1(\hat{s},\hat{t},m_h^2,m_t^2,D)\,T_1^{\mu\nu} + F_2(\hat{s},\hat{t},m_h^2,m_t^2,D)\,T_2^{\mu\nu}\right\}$$

Only 2 Lorentz structures:

$$T_1^{\mu\nu} = g^{\mu\nu} - \frac{p_1^{\nu}\,p_2^{\mu}}{p_1\cdot p_2}$$
$$T_2^{\mu\nu} = g^{\mu\nu} + \frac{1}{p_T^2\,(p_1\cdot p_2)}\left\{m_h^2\,p_1^{\nu}\,p_2^{\mu} - 2\,(p_1\cdot p_3)\,p_3^{\nu}\,p_2^{\mu} - 2\,(p_2\cdot p_3)\,p_3^{\mu}\,p_1^{\nu} + 2\,(p_1\cdot p_2)\,p_3^{\nu}\,p_3^{\mu}\right\}$$
$$p_T^2 = (\hat{u}\,\hat{t} - m_h^4)/\hat{s}\ ,\ T_1\cdot T_2 = D-4\ ,\ T_1\cdot T_1 = T_2\cdot T_2 = D-2$$

Define projectors:

$$P_1^{\mu\nu}\mathcal{M}_{\mu\nu} = \frac{\alpha_s}{8\pi v^2}F_1(\hat{s},\hat{t},m_h^2,m_t^2,D) \qquad P_1^{\mu\nu} = \frac{1}{4}\frac{D-2}{D-3}T_1^{\mu\nu} - \frac{1}{4}\frac{D-4}{D-3}T_2^{\mu\nu}$$
$$P_2^{\mu\nu}\mathcal{M}_{\mu\nu} = \frac{\alpha_s}{8\pi v^2}F_2(\hat{s},\hat{t},m_h^2,m_t^2,D) \qquad P_2^{\mu\nu} = -\frac{1}{4}\frac{D-4}{D-3}T_1^{\mu\nu} + \frac{1}{4}\frac{D-2}{D-3}T_2^{\mu\nu}$$

Example: HH production

Reduction requires knowledge of integral families

Planar diagrams:

F_1	F_2	F_3
$k_1^2 - m_t^2$	$k_1^2 - m_t^2$	k_1^2
$k_2^2 - m_t^2$	$k_2^2 - m_t^2$	$(k_1 - k_2)^2 - m_t^2$
$(k_1 - k_2)^2$	$(k_1 - k_2)^2$	$(k_1 + p_1)^2$
$(k_1 + p_1)^2 - m_t^2$	$(k_1 + p_1)^2 - m_t^2$	$(k_2 + p_1)^2 - m_t^2$
$(k_2 + p_1)^2 - m_t^2$	$(k_2 + p_1)^2 - m_t^2$	$(k_1 - p_2)^2$
$(k_1 - p_2)^2 - m_t^2$	$(k_1 - p_3)^2 - m_t^2$	$(k_2 - p_2)^2 - m_t^2$
$(k_2 - p_2)^2 - m_t^2$	$(k_2 - p_3)^2 - m_t^2$	$(k_2 - p_2 - p_3)^2 - m_t^2$
$(k_1 - p_2 - p_3)^2 - m_t^2$	$(k_1 - p_2 - p_3)^2 - m_t^2$	$(k_1 + p_1 + p_3)^2$
$(k_2 - p_2 - p_3)^2 - m_t^2$	$(k_2 - p_2 - p_3)^2 - m_t^2$	$(k_2 + p_1 - p_2)^2$

F_4	F_5
$k_1^2 - m_t^2$	k_1^2
k_2^2	$k_2^2 - m_t^2$
$(k_1 - k_2)^2 - m_t^2$	$(k_1 - k_2)^2 - m_t^2$
$(k_1 + p_1)^2 - m_t^2$	$(k_1 + p_1)^2$
$(k_2 + p_1)^2$	$(k_2 + p_1)^2 - m_t^2$
$(k_1 - p_2)^2 - m_t^2$	$(k_1 - p_3)^2$
$(k_2 - p_2)^2$	$(k_2 - p_3)^2 - m_t^2$
$(k_1 - p_2 - p_3)^2 - m_t^2$	$(k_1 - p_2 - p_3)^2$
$(k_2 - p_2 - p_3)^2$	$(k_2 - p_2 - p_3)^2 - m_t^2$

Non-planar diagrams were evaluated directly as tensor integrals

General 2-loop process

General problems and difficulties:

- Projectors need to be constructed by hand
- Integral families need to be provided
- Renormalization for 2-loop
- Regularization scheme dependence
- Treatment of γ_5 :
  Larin – scheme $J_\mu^{5a} = \frac{1}{2}\overline{\psi}(\gamma_\mu\gamma_5 - \gamma_5\gamma_\mu)t^a\psi, \quad \gamma_5 = i\frac{1}{4!}\varepsilon_{\nu_1\nu_2\nu_3\nu_4}\gamma_{\nu_1}\gamma_{\nu_2}\gamma_{\nu_3}\gamma_{\nu_4}$

- Lorentz structure needs to be known
  e.g. ZH instead of HH: 115 possible Lorentz structures,
  only 7 contributing! (transversality, gauge invariance, Bose symmetry)
  [Kniehl]

  -> Affects number and size of projectors

Summary

- GoSam: Automated generation of one-loop amplitudes for SM and BSM
- Standardized interface allows to combine GoSam with any MC that supports the standard (Sherpa, Powheg, Herwig++,MG5_aMC@NLO, Whizard)
- All ingredients for NLO (QCD and EW) can be generated by GoSam
- First proves of concept for 2-loop: HH, H+j, but no conceptual issue with
- Next steps: Working towards automation

Backup slides

Additional useful features

- **Complex mass scheme:** allows gauge invariant inclusion of widths in heavy gauge bosons

$$m_V^2 \to \mu_V^2 = m_V^2 - i m_V \Gamma_v \quad \Rightarrow \quad \cos^2\theta_w = \mu_W^2/\mu_Z^2$$

- **Different EW schemes:** Minimal set of input parameters, remaining parameters derived

ewchoice	input parameters	derived parameters
1	$\mathrm{G_F}$, $\mathrm{m_W}$, $\mathrm{m_Z}$	e, sw
2	α, $\mathrm{m_W}$, $\mathrm{m_Z}$	e, sw
3	α, sw, $\mathrm{m_Z}$	e, $\mathrm{m_W}$
4	α, sw, $\mathrm{G_F}$	e, $\mathrm{m_W}$
5	α, $\mathrm{G_F}$, $\mathrm{m_Z}$	e, $\mathrm{m_W}$, sw
6	e, $\mathrm{m_W}$, $\mathrm{m_Z}$	sw
7	e, sw, $\mathrm{m_Z}$	$\mathrm{m_W}$
8	e, sw, $\mathrm{G_F}$	$\mathrm{m_W}$, $\mathrm{m_Z}$

- **Rescue system** to detect and (possibly) repair numerical instabilities

$$\delta_{pole} = \left|\frac{\mathcal{S}_{IR} - \mathcal{S}}{\mathcal{S}_{IR}}\right| \qquad \delta_{rot} = 2\left|\frac{\mathcal{A}^{fin}_{rot} - \mathcal{A}^{fin}}{\mathcal{A}^{fin}_{rot} + \mathcal{A}^{fin}}\right|$$

$\longrightarrow$ Estimation of obtained accuracy