University of Zurich[UZH]

Physik-Institut

SM/BSM physics with GoSam

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On behalf of the GoSam collaboration

Monte Carlo Tools for Physics Beyond the Standard Model

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Outline

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

- Applications to SM/BSM physics, recent developments

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Motivation

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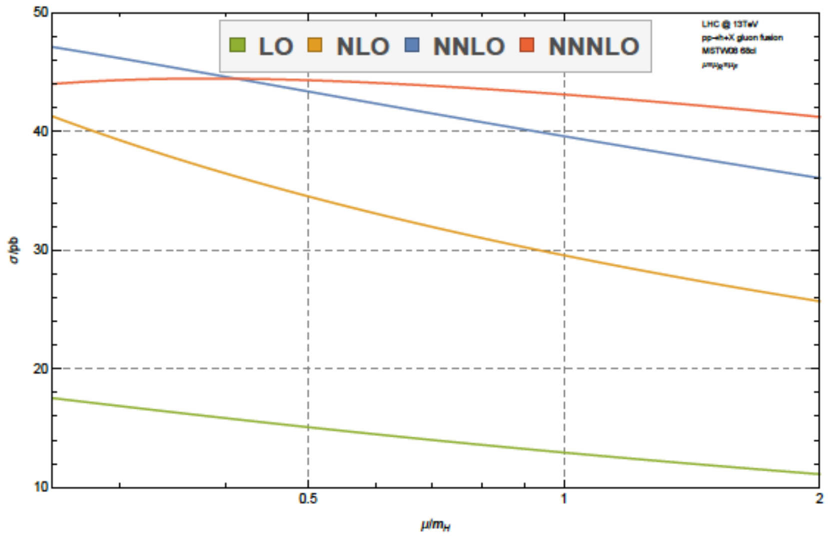
The need for higher order corrections....

- Largely motivated by SM precision measurements and absence of new physics



[Anastasiou,Duhr,Dulat,Herzog,Mistlberger '15]

- Example: Higgs production via gluon fusion in the SM
  ➡ Strong dependence on ren./fac. scales

- Bounds/exclusions on BSM models, e.g. Susy

- If new physics is loop induced (leading order calculation)

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)

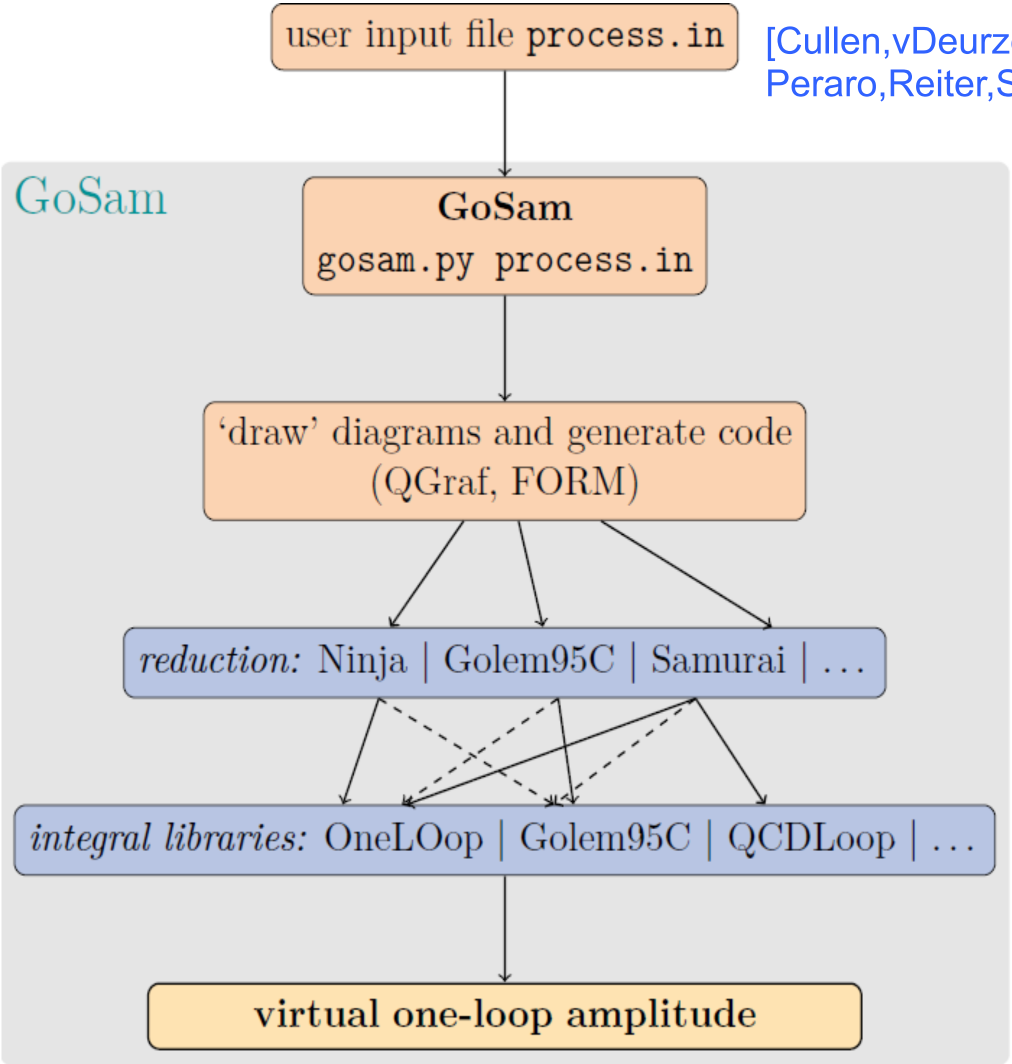
[Cullen,van Deurzen,NG,Heinrich,Luisoni,Mastrolia,Mirabella,Ossola,Peraro,Schlenk,von Soden-Fraunhofen,Tramontano]

- 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)

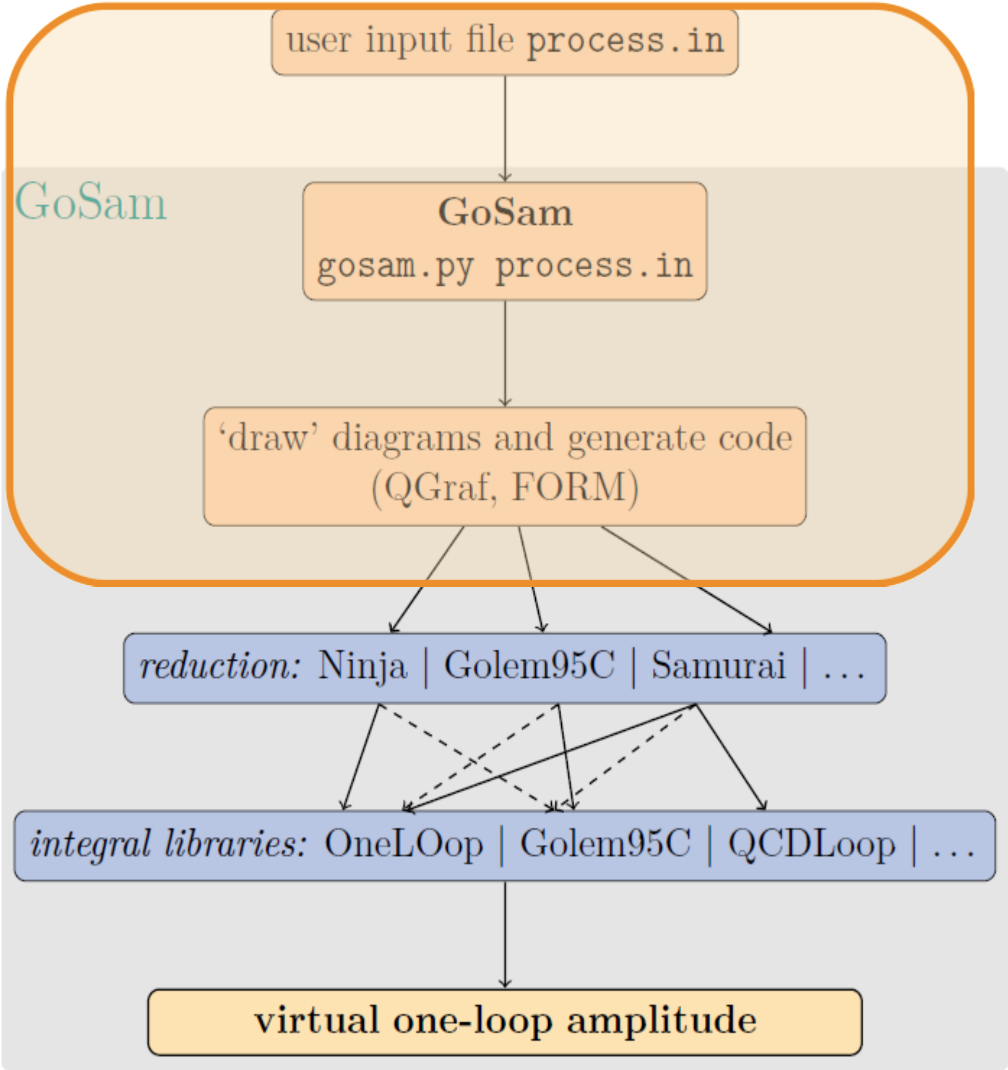
http://gosam.hepforge.org

GoSam 2.0 – A Quick Overview

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



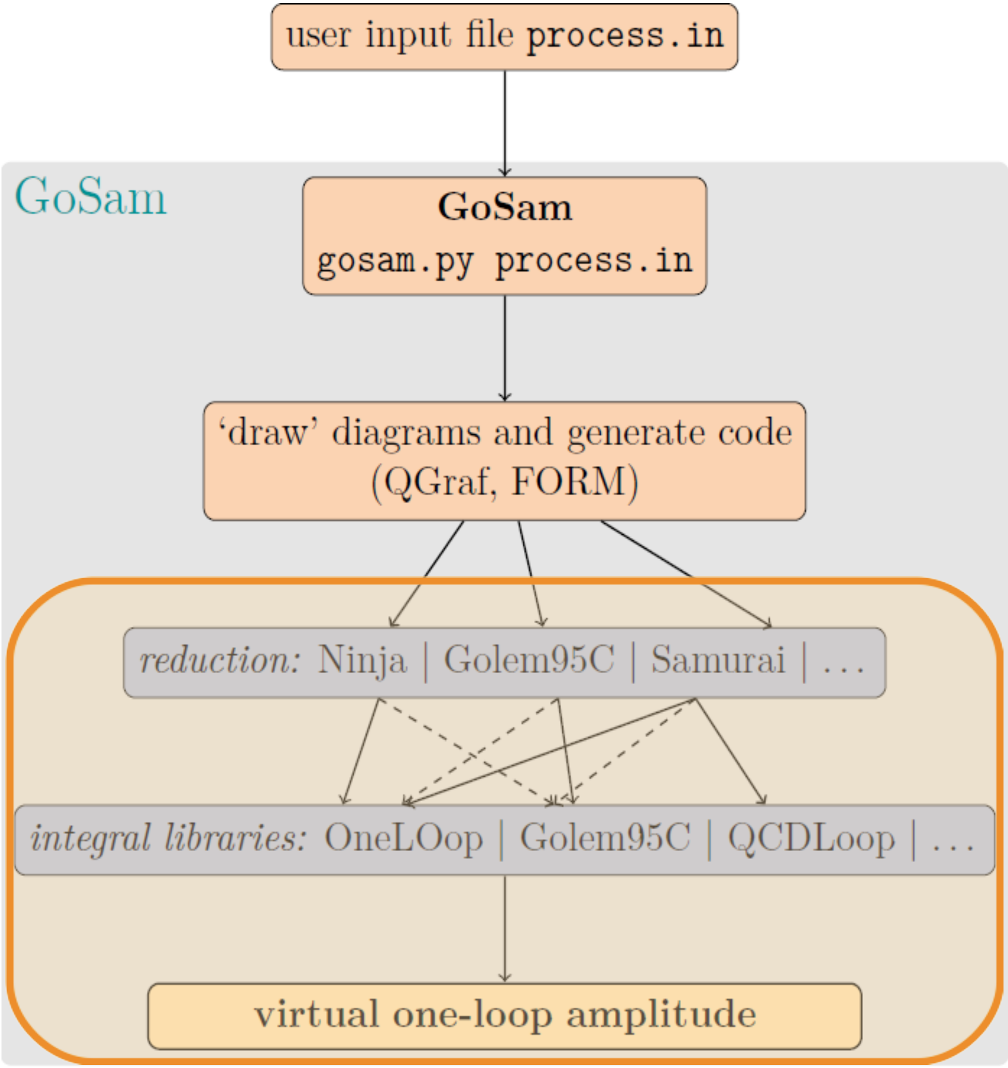
GoSam 2.0 – A Quick Overview



GENERATION

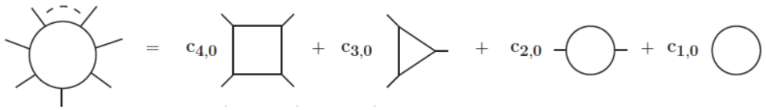
- Specify process (process.in):
  in=g,g
  out=H,t,t~
  order=QCD,2,4
  model=smdiag
  (new models can be imported)
- Many additional options (Parameter settings, Filter)
- 'Draw' Feynman diagrams with Qgraf [Nogueira]
- Apply Feynman rules and optimize expression with FORM [Vermaseren,Kuipers,Ueda,Vollinga]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

GoSam 2.0 – A Quick Overview



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**

How to use GoSam

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

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

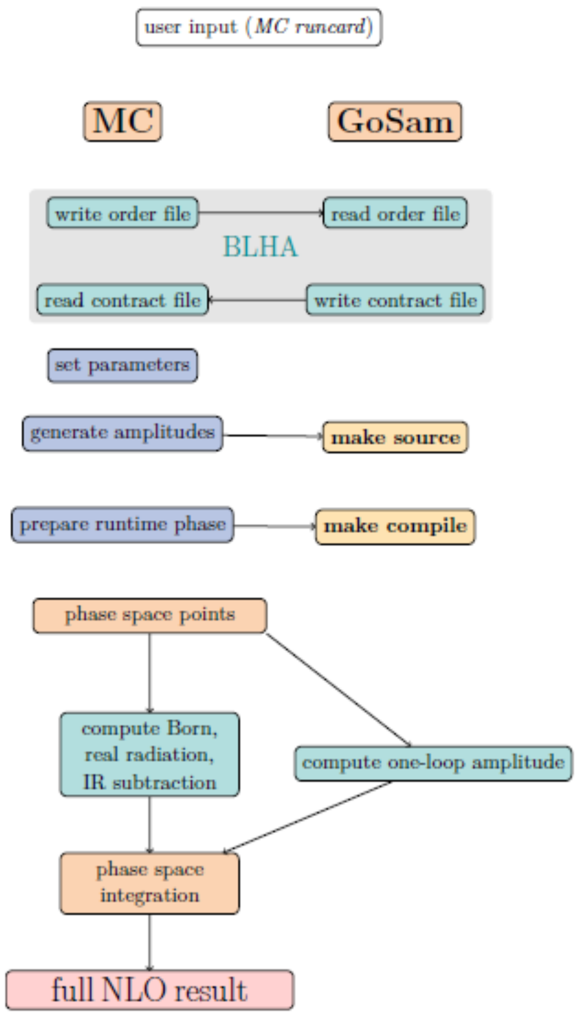
```
#                  LO:   0.1013146112820217E-03
# NLO, finite part:    17.31560363490869
# NLO, single pole:   -9.235244935244870
# NLO, double pole:   -6.000000000000000
# IR,  single pole:   -9.235244935222976
# IR,  double pole:   -6.000000000000001
#  Time/Event [ms]:                 201.969
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)

$$|\mathcal{M}|^2_{\text{1-loop}} = 2\,\Re\left(\mathcal{M}_B^\dagger \cdot \mathcal{M}_{Virt}\right)$$

$$= \frac{\alpha_{(s)}(\mu)}{2\pi}\,\frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)}\cdot\left(g_{(s)}\right)^{2b}\cdot\left[c_0 + \frac{c_{-1}}{\epsilon} + \frac{c_{-2}}{\epsilon^2} + \mathcal{O}(\epsilon)\right]$$

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
```

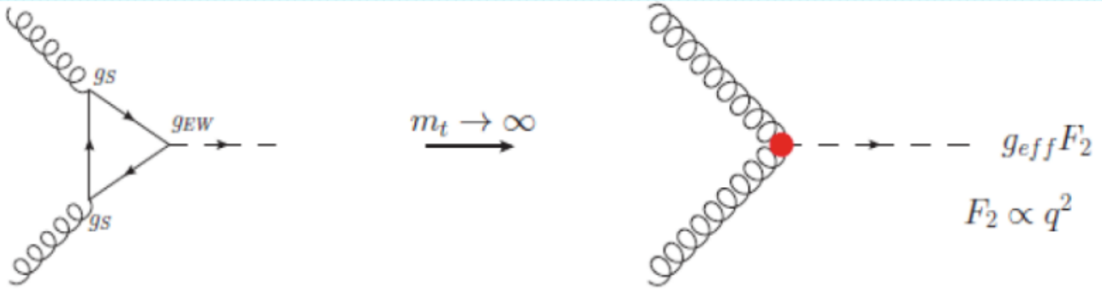
- Virtual amplitude called from within the MC during runtime (Sherpa,Powheg,Herwig++, aMC@NLO, Whizard)

Important features for BSM at NLO

- **Higher rank integrals: r >= N+1**

$$I_N^{n,\mu_1\dots\mu_r}(S) = \int d^n k \frac{k^{\mu_1}\dots k^{\mu_r}}{\prod_{i=1}^{N}\left((k+r_i)^2 - m_i^2 + i\delta\right)}$$

needed for effective theories (HEFT, dim-6) and spin-2



- **Inclusion of color- and spin-correlated matrix elements**

$$C_{ij} = \langle \mathcal{M}|\mathbf{T}_i\mathbf{T}_j|\mathcal{M}\rangle \qquad S_{ij} = \langle \mathcal{M},-|\mathbf{T}_i\mathbf{T}_j|\mathcal{M},+\rangle$$

$$\langle \mathcal{M}_{i,-}|\mathbf{T}_i\cdot\mathbf{T}_j|\mathcal{M}_{i,+}\rangle = \sum_{\lambda_1,\dots,\lambda_{i-1},\lambda_{i+1},\dots,\lambda_n} \langle \mathcal{M}_{\lambda_1,\dots,\lambda_{i-1},-,\lambda_{i+1},\dots,\lambda_n}|\mathbf{T}_i\cdot\mathbf{T}_j|\mathcal{M}_{\lambda_1,\dots,\lambda_{i-1},+,\lambda_{i+1},\dots,\lambda_n}\rangle$$

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	G_F, m_W, m_Z	e, s_W
2	α, m_W, m_Z	e, s_W
3	α, s_W, m_Z	e, m_W
4	α, s_W, G_F	e, m_W
5	α, G_F, m_Z	e, m_W, s_W
6	e, m_W, m_Z	s_W
7	e, s_W, m_Z	m_W
8	e, s_W, G_F	m_W, m_Z

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

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

$\longrightarrow$ Estimation of obtained accuracy

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
```

- **Work in progress:** Using NLOCT package [Degrande] to provide counter terms to renormalize amplitude (in-house renormalization only for QCD)
  ➡ One-loop phenomenology for **ANY** renormalizable theory
  (unrenormalized amplitudes always possible)

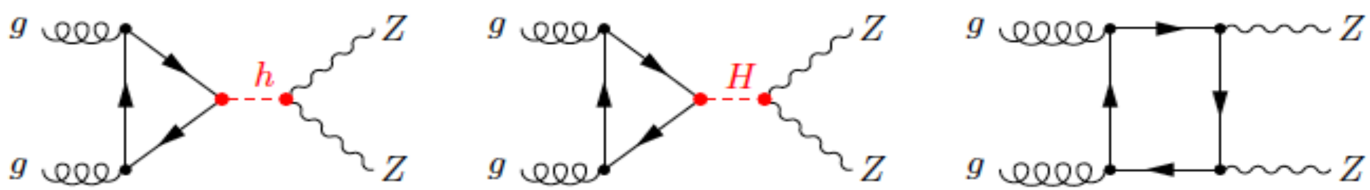
→ C. Degrande's talk

Recent applications to BSM physics

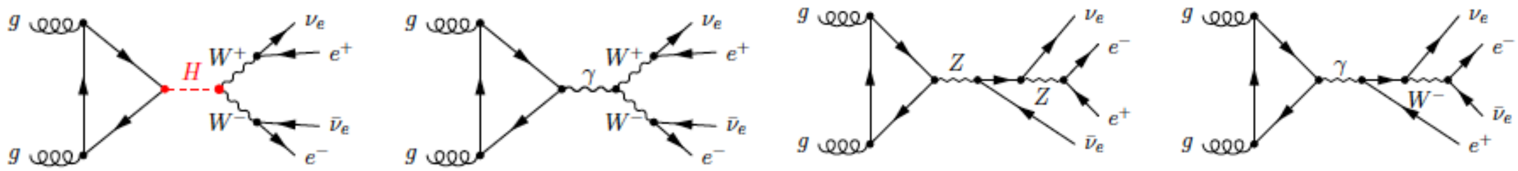
Interference effects in 2HDM

Investigate interference of **heavy CP-even Higgs** with background in various **2HDM** scenarios. [NG,Liebler,Weiglein '15]

$$gg \to ZZ \quad gg \to VV \to e^+e^-\mu^+\mu^-,\ e^+e^-\nu_{e,\mu\tau}\bar{\nu}_{e,\mu,\tau}$$



Including **decays** into 4 lepton final state also requires intermediate W, photon



4-particle final state amplitudes generated with **GoSam**, integration with **MadEvent**

ZZ amplitude generated with **Feynarts** [Hahn], added to **vh@NNLO** [Harlander,Liebler,Zirke]

Interference effects in 2HDM

$$g_t^H = \frac{\sin\alpha}{\sin\beta} = -s_{\beta-\alpha}\frac{1}{t_\beta} + c_{\beta-\alpha}$$

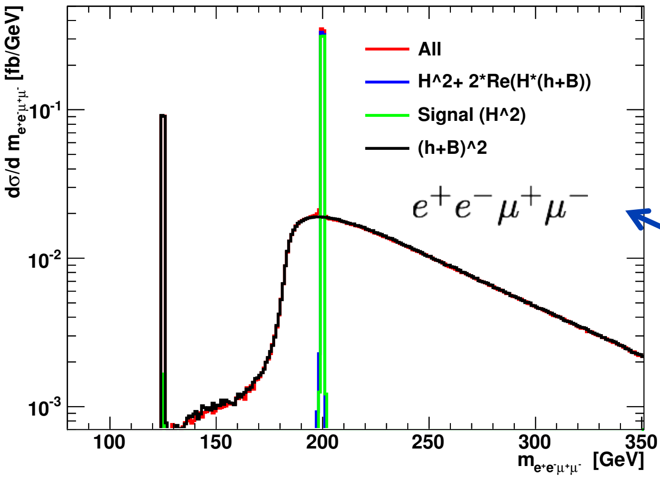
$$\text{Type I: } g_b^H = \frac{\sin\alpha}{\sin\beta} = -s_{\beta-\alpha}\frac{1}{t_\beta} + c_{\beta-\alpha}$$

$$\text{Type II: } g_b^H = \frac{\cos\alpha}{\cos\beta} = s_{\beta-\alpha}t_\beta + c_{\beta-\alpha}$$

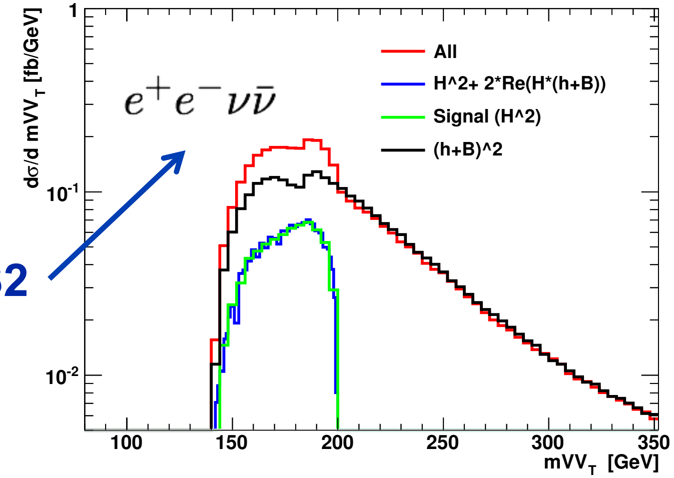
$$g_V^h = \sin(\beta-\alpha) =: s_{\beta-\alpha}, \qquad g_V^H = \cos(\beta-\alpha) =: c_{\beta-\alpha}$$

Scenario	2HDM type	t_β	$s_{\beta-\alpha}$	m_H	Γ_H
S1	II	1	0.990	400 GeV	3.605 GeV
S2	II	2	−0.995	200 GeV	0.0277 GeV
S3	II	2	0.600	400 GeV	20.32 GeV
S4	I	5	0.950	400 GeV	2.541 GeV
S5	I	5	0.96695	200 GeV	0.0882 GeV
S6	II	20	0.990	400 GeV	5.120 GeV

$$m_{VV,T}^2 = (E_{T,ll} + E_{T,\nu\nu})^2 - |\vec{p}_{T,ll} + \vec{p}_{T,\nu\nu}|^2$$



S2



Recent developments

Electroweak corrections at NLO

- Electroweak corrections important for Run 2

- NLO corrections mostly small for total cross section, but easily supersede QCD corrections in high pT tail
  (mostly due to incomplete cancellation of large logarithms)
  -> interesting region for new physics

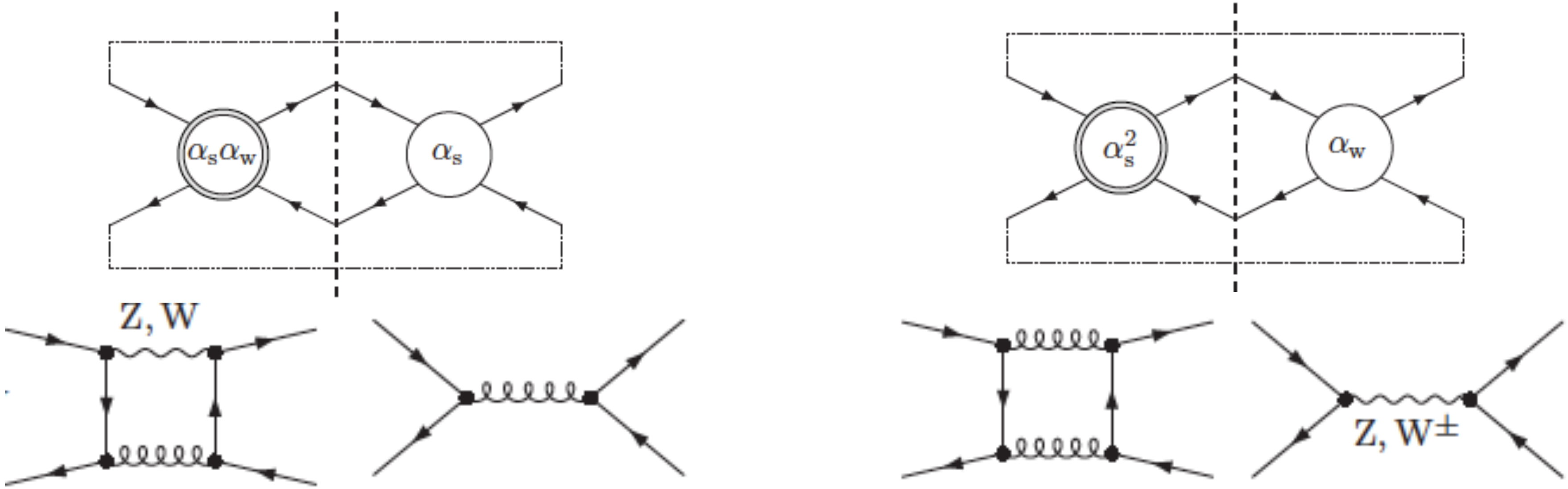
✓ Reduction strategies can applied to EW calculations without modification

BUT:

- Computation much more involved due to increased number of diagrams (photon/W/Z)
- In general mixing between QCD and EW corrections
  Need to sum up ALL contributions at a given order

Electroweak corrections at NLO

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



- 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..)
- First application to **W+2j** [Chiesa,NG,Tramontano '15]

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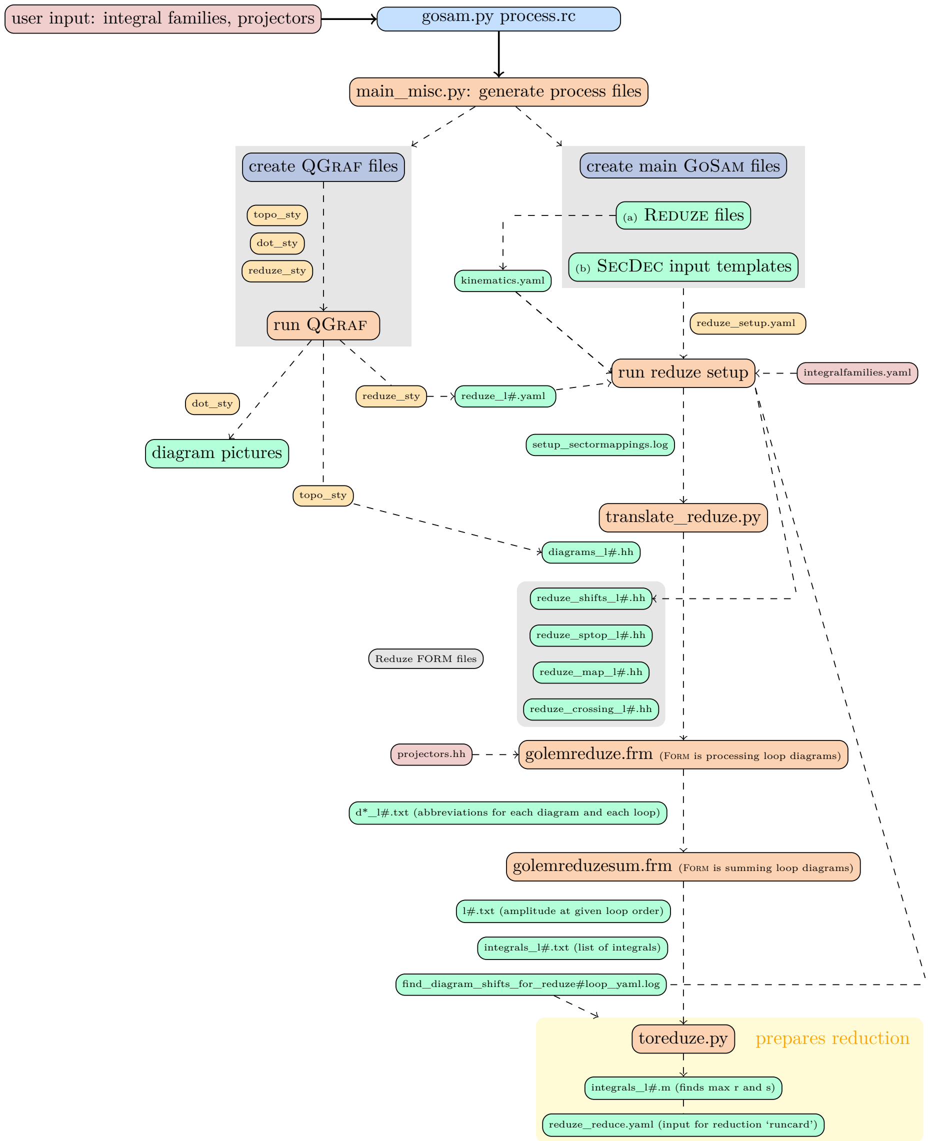
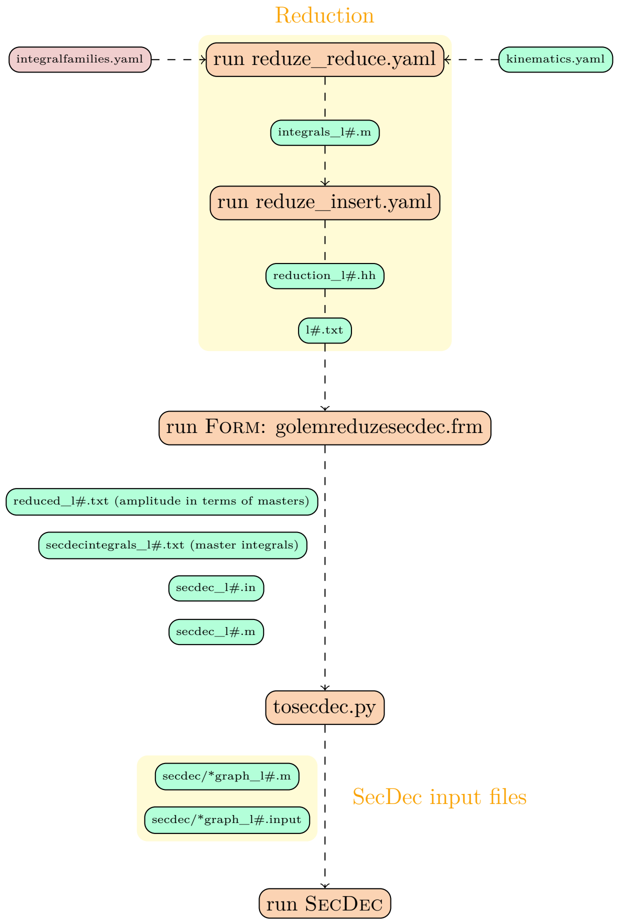
GoSam XL – Automation of 2loop



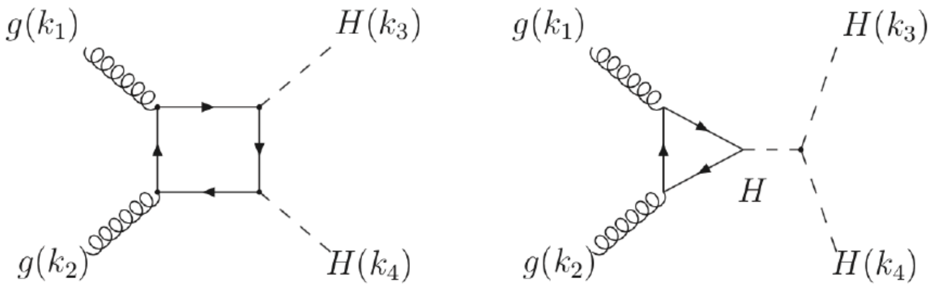


[GoSam coll. + Jahn,Jones,Kerner,Zirke]

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]

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 can be generated by GoSam
- Several applications to BSM physics (Interference effects in 2HDM models)
- BSM models can easily be imported via UFO format
- Ongoing developments: Generation of counter terms for UFO models, EW automation, towards 2-loop automation