MAX-PLANCK-GESELLSCHAFT

GoSam 2.0: Automated One Loop Calculations within and beyond the SM

Nicolas Greiner
Max-Planck Institute for Physics

in collaboration with
G.Cullen,H.vanDeurzen,G.Heinrich,G.Luisoni,P.Mastrolia,E.Mirabella,G.Ossola,T.Peraro,J.Schlenk
JF.v.Soden-Fraunhofen,F.Tramontano

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

MC4BSM

Monte Carlo Tools for Physics Beyond the Standard Model

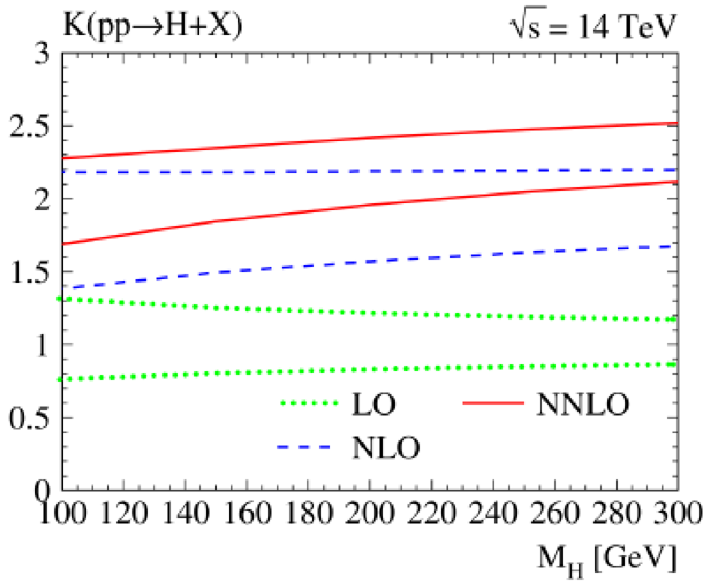
Motivation

The need for higher order corrections....

Motivation

The need for higher order corrections....

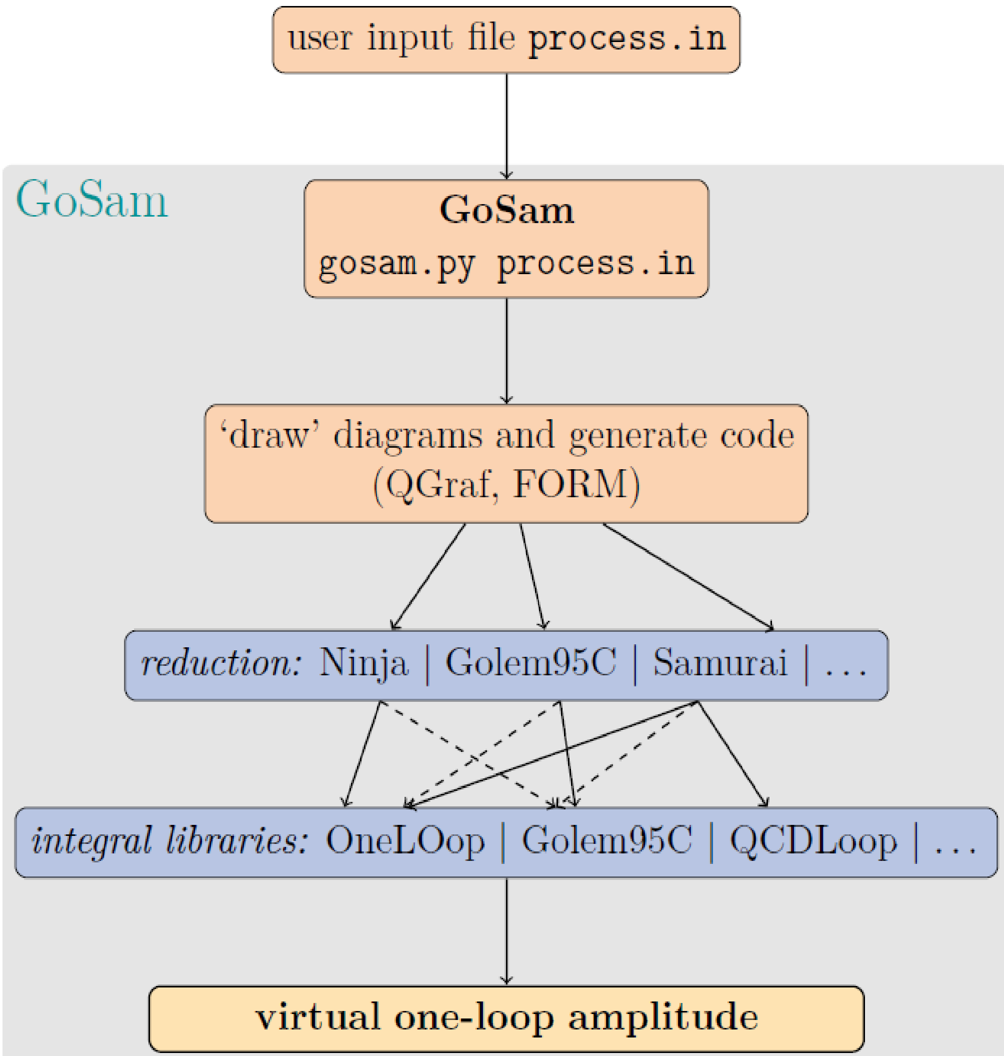
- Largely motivated by SM precision measurements and absence of new physics



[Harlander, Kilgore] '02

- Example: Higgs production via gluon fusion in the SM
  - Strong dependence on ren./fac. scale
- Bounds/Exclusion for BSM models, e.g. Susy
- If new physics is loop induced (leading order calculation)

GoSam



I. **Input card:** Specify process dependent information

II. **Code generation:**
- Uses QGraf [Nogueira] and
- FORM [Vermaseren]
- Writes Fortran code

III. **At runtime:**

Reduction of diagrams
- Integrand level with Ninja [Mastrolia,Mirabella,Peraro] or Samurai [Mastrolia,Ossola,Reiter,Tramontano]
- Passarino-Veltman with Golem95C [Cullen et al.]
- Can be chosen at runtime
- Several integral libraries available
  OneLoop [van Hameren]
  QCDLoop [Ellis,Zanderighi]
  Golem95C
- Can be linked to Monte Carlo via standardized interface (BLHA)

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

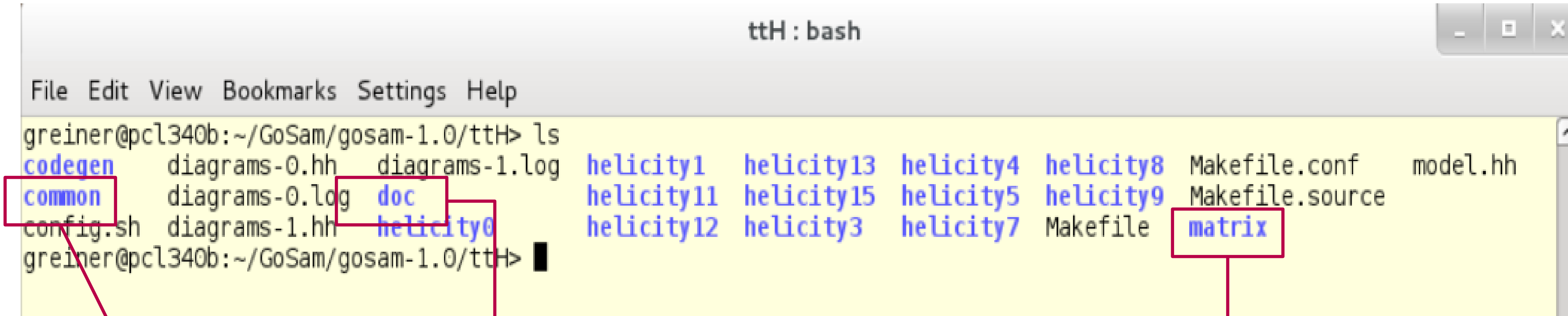
New models can be imported from FeynRules or LanHEP

Specify which parameters should be set ALGEBRAICALLY to zero or one

Options on helicity and loop diagrams

How to use GoSam

MAX-PLANCK-GESELLSCHAFT



parameters and setup in config.f90 / model.f90

main file matrix.f90

Index	1	2	3	4	5
0	−	−	0	−	−
1	+	−	0	−	−
2 → 1	−	+	0	−	−
3	+	+	0	−	−
4	−	−	0	+	−
5	+	−	0	+	−
6 → 5	−	+	0	+	−
7	+	+	0	+	−
8	−	−	0	−	+
9	+	−	0	−	+
10 → 9	−	+	0	−	+
11	+	+	0	−	+
12	−	−	0	+	+
13	+	−	0	+	+
14 → 13	−	+	0	+	+
15	+	+	0	+	+

GoSam 1.0: $gg \to Ht\bar{t}$

greiner

2013-02-27 (17:37:36)

Abstract

This process consists of 8 tree-level diagrams and 160 NLO diagrams. Golem has identified 15 groups of NLO diagrams by analyzing their one-loop integrals.

Detailed documention in process.ps

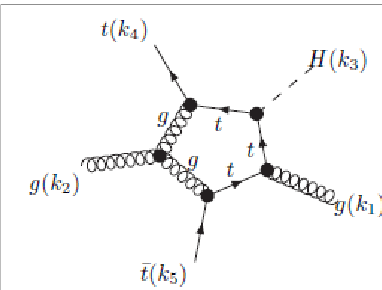


Diagram 158

$S' = S_{Q \to -q-(-k_3-k_4)}$, rk = 4

How to use GoSam

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

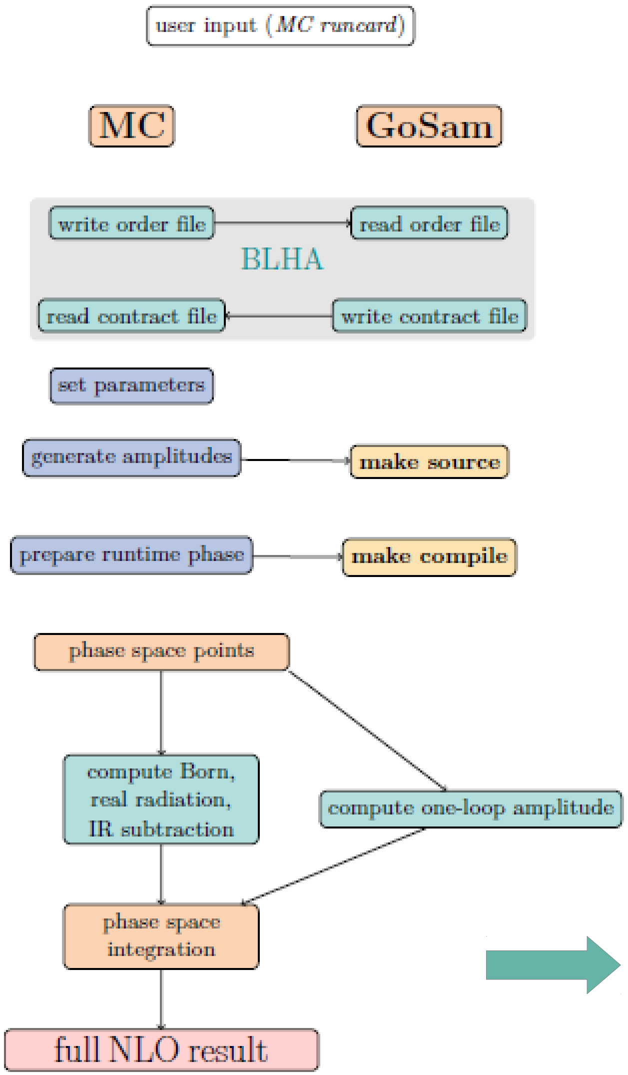
```
$ cd matrix
$ make test.exe
$ ./test.exe
```

```
#                  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>
```

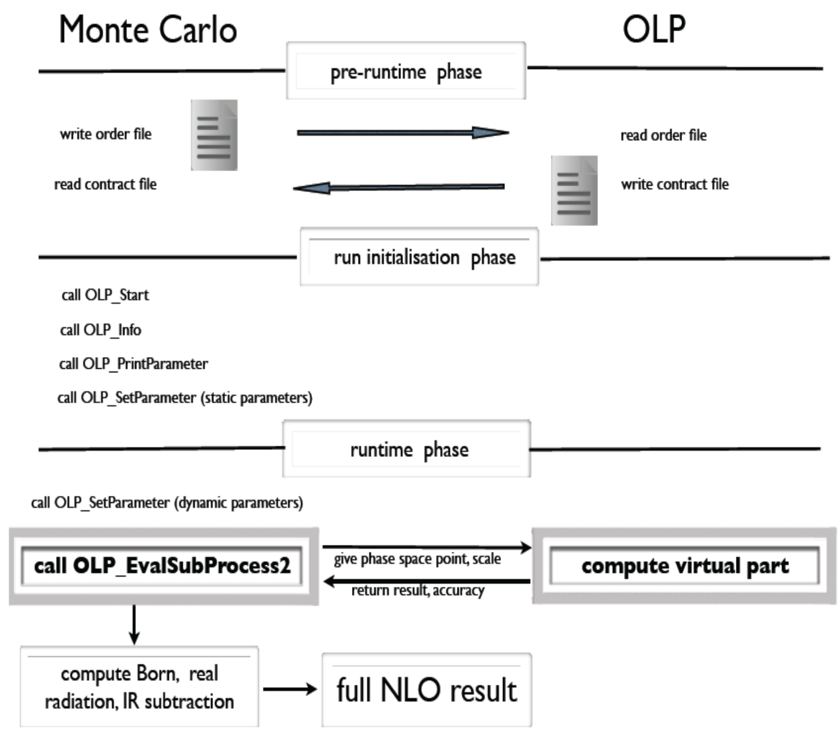
- Implementation of infrared poles allows for checking pole cancellation 'on the fly'.
  → Can be used to reject points during runtime. (PSP_check)

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

Interface to Monte Carlo programs



- Interface via Binoth-Les-Houches-Accord (both original and extended BLHA supported)

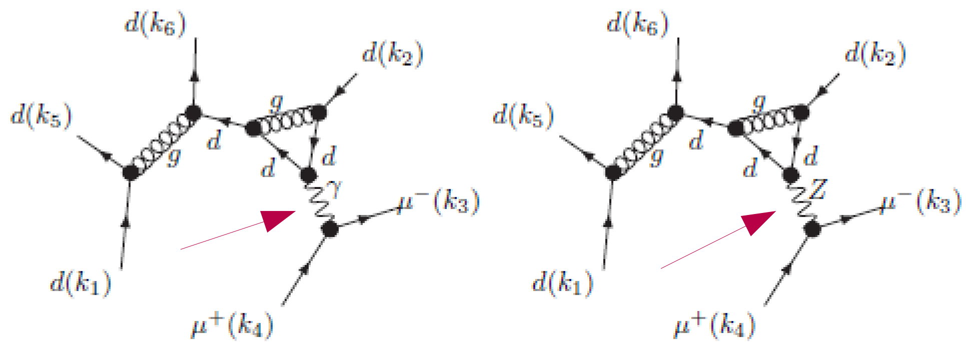


GoSam can be interfaced to ANY MC that supports this standard!

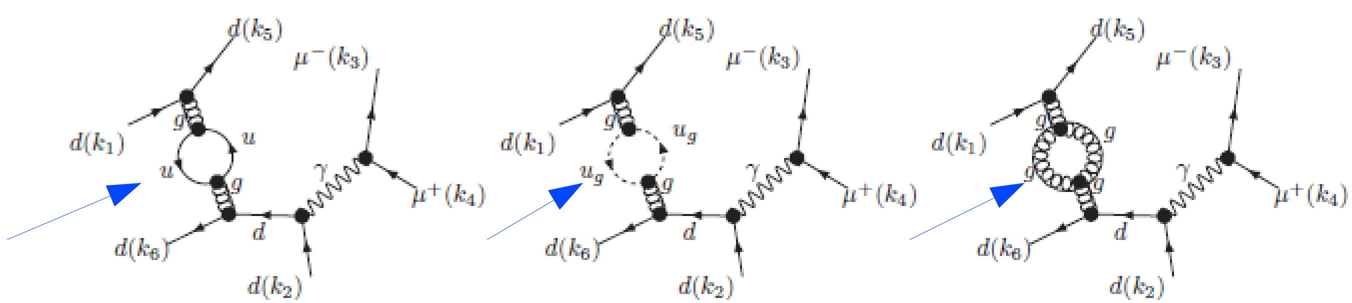
MAX-PLANCK-GESELLSCHAFT

New Features in GoSam 2.0

- Improvements in Code generation
  - Code optimisation with FORM 4 [Kuipers,Ueda,Vermaseren,Vollinga '12]
  - Summing diagrams sharing common substructures to 'meta-diagrams'.



Diagrams differ only by propagator outside the loop



Same set of propagators, different particles in the loop

New Features in GoSam 2.0

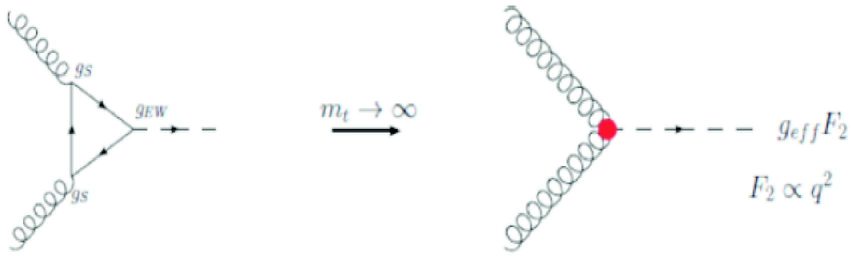
- Improvements in reduction

  - **New reduction method Ninja** [Peraro '14]. Idea: Extract coefficients of the residues of a loop integral by performing a Laurent expansion of the integrand.
    [Mastrolia,Mirabella,Peraro '12]
    → Less numerical sampling compared to OPP reduction.
    → Leads to faster and more stable reduction!

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

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

needed for effective theories, BSM (e.g. Spin-2)



MAX-PLANCK-GESELLSCHAFT

New Features in GoSam 2.0

- New ranges of applicability
  - New BLHA 2 standard, includes color- and spin-correlated matrix elements

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

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

⇒ GoSam contains **ALL** ingredients for a full NLO calculation!

  - Complex mass scheme, different EW schemes, rescue system for unstable points

BSM Physics with GoSam

- $pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 j$ [Cullen,NG,Heinrich '13]

Susy QCD corrections to Neutralino Pair production plus one jet in MSSM

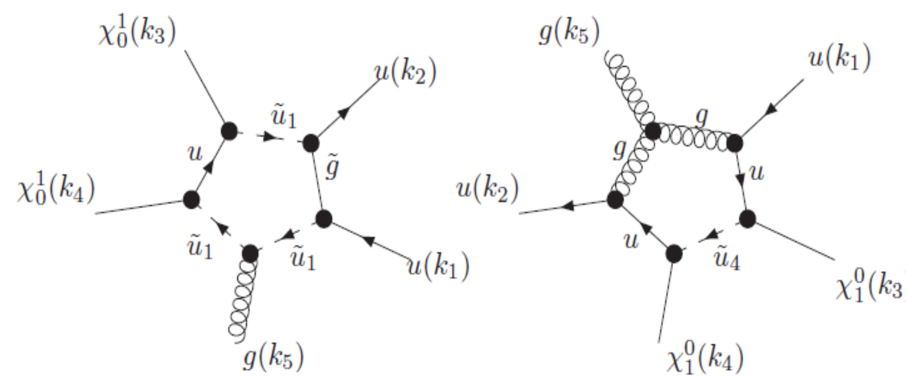
Signature: Monojet + Missing Energy

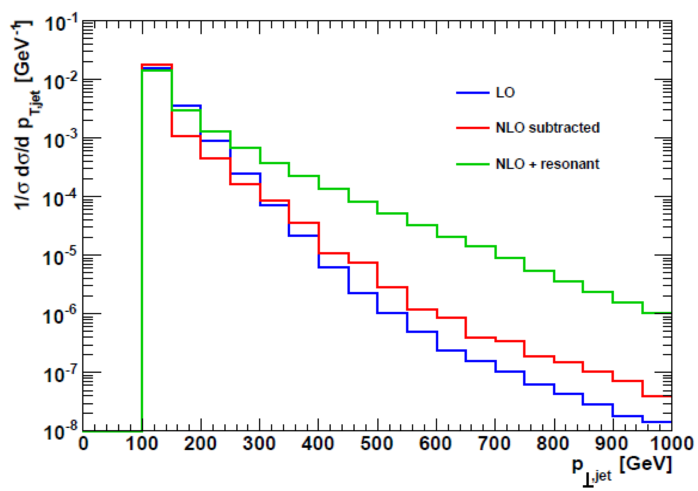
Non-trivial process, multiple scales, full off shell effects taken into account.

Model imported from Feynrules [Alloul, Christensen,Duhr,Degrande,Fuks] via UFO model file [Degrande,Duhr,Fuks, Grellscheid,Mattelaer,Reiter]

Interfaced with MadGraph/MadDipole/ MadEvent [Stelzer,Long][Frederix,Gehrmann, NG][Maltoni,Stelzer]

Renormalisation done separately





SUSY Parameters	
$M_{\tilde{\chi}_1^0} = 299.5$	$\Gamma_{\tilde{\chi}_1^0} = 0$
$M_{\tilde{g}} = 415.9$	$\Gamma_{\tilde{g}} = 4.801$
$M_{\tilde{u}_L} = 339.8$	$\Gamma_{\tilde{u}_L} = 0.002562$
$M_{\tilde{u}_R} = 396.1$	$\Gamma_{\tilde{u}_R} = 0.1696$
$M_{\tilde{d}_L} = 348.3$	$\Gamma_{\tilde{d}_L} = 0.003556$
$M_{\tilde{d}_R} = 392.5$	$\Gamma_{\tilde{d}_R} = 0.04004$
$M_{\tilde{b}_L} = 2518.0$	$\Gamma_{\tilde{b}_L} = 158.1$
$M_{\tilde{b}_R} = 2541.8$	$\Gamma_{\tilde{b}_R} = 161.0$
$M_{\tilde{t}_L} = 2403.7$	$\Gamma_{\tilde{t}_L} = 148.5$
$M_{\tilde{t}_R} = 2668.6$	$\Gamma_{\tilde{t}_R} = 182.9$

BSM Physics with GoSam

- $pp \to G(\to \gamma\gamma) + j$ [NG,Heinrich,Reichel,v.Soden-Fraunhofen '13]

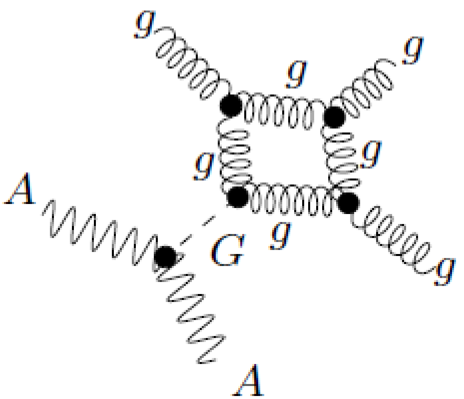
  Graviton production in ADD model

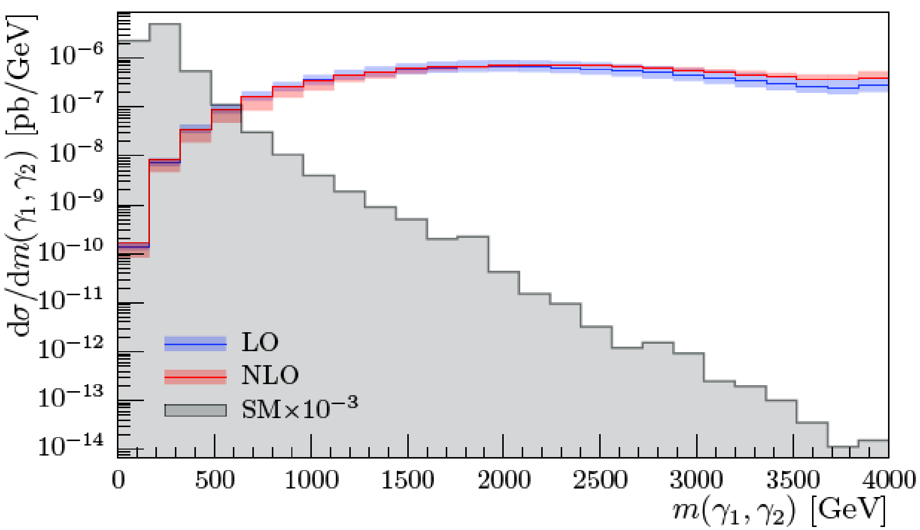
  Non-standard propagator for gravitons, sum over KK modes approximated by integral over mass density

  Higher rank integrals needed (up to rank 5 boxes)

  Model imported from UFO

  Interfaced with MadGraph/MadDipole/ MadEvent using modified model





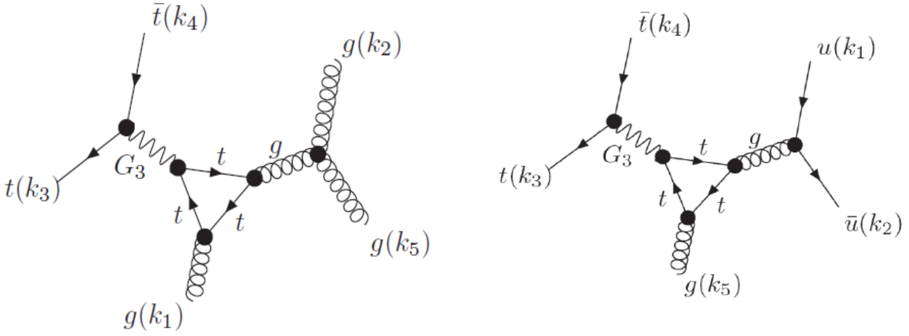
BSM Physics with GoSam

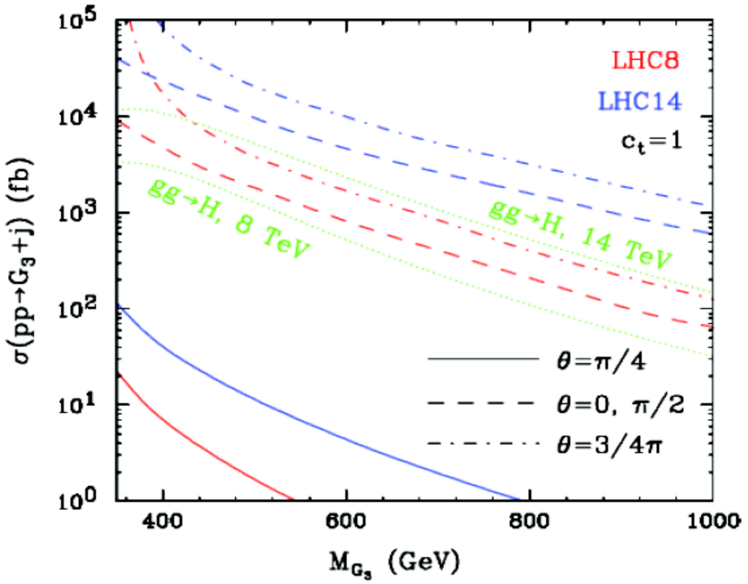
- Model independent t-tbar resonance [NG,Kong,Park,Winter] work in progress
  Massive Color singlet that couples only to top quarks

$$\mathcal{L} = \bar{t}\,\gamma_\mu \left(c_L^t P_L + c_R^t P_R\right) t\, G_3^\mu \,,$$
$$= c_t \bar{t}\,\gamma_\mu \left(\cos\theta P_L + \sin\theta P_R\right) t\, G_3^\mu$$

$$\Gamma\left(G_3 \to t\bar{t}\right) = \frac{c_t^2 M_G}{8\pi}\sqrt{1 - \frac{4M_t^2}{M_G^2}}\left[1 + \frac{Mt^2}{M_G^2}\left(3\sin 2\theta - 1\right)\right]$$

Produced via loop induced process





- PS integration with MadEvent
- Strong dependence on angle Θ (Landau-Yang theorem)
- Comparable to Higgs production
- Interference with SM ?

Summary

- GoSam: Automated generation of one-loop amplitudes for SM and BSM
- GoSam 2.0: Improvements on code generation and reduction
  → Faster and more stable
- Many new features: Easy installation, complex mass scheme, rescue system, electroweak scheme choices
- Standardized interface allows to combine GoSam with any MC that supports the standard (Sherpa, Powheg, Herwig++,aMC@NLO)
- All ingredients for NLO can be generated by GoSam
- BSM models can easily be imported via UFO format