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GoSam: Automated One Loop Calculations within and beyond the SM

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in collaboration with
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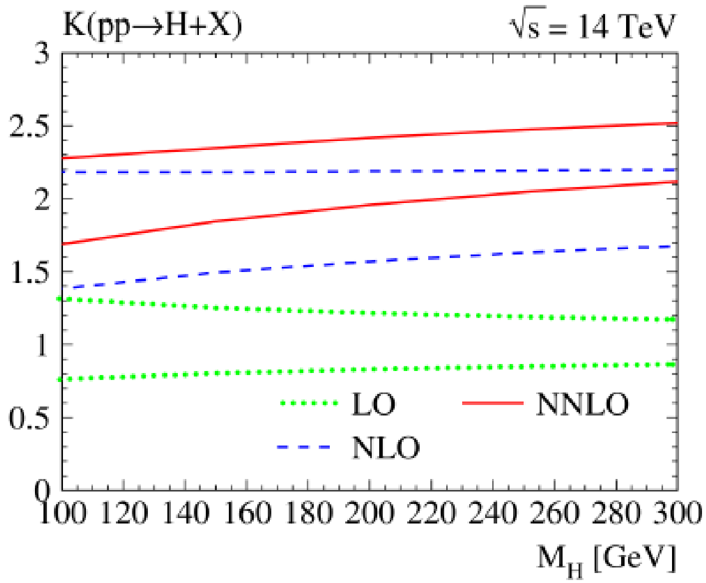
Motivation

The need for higher order corrections....

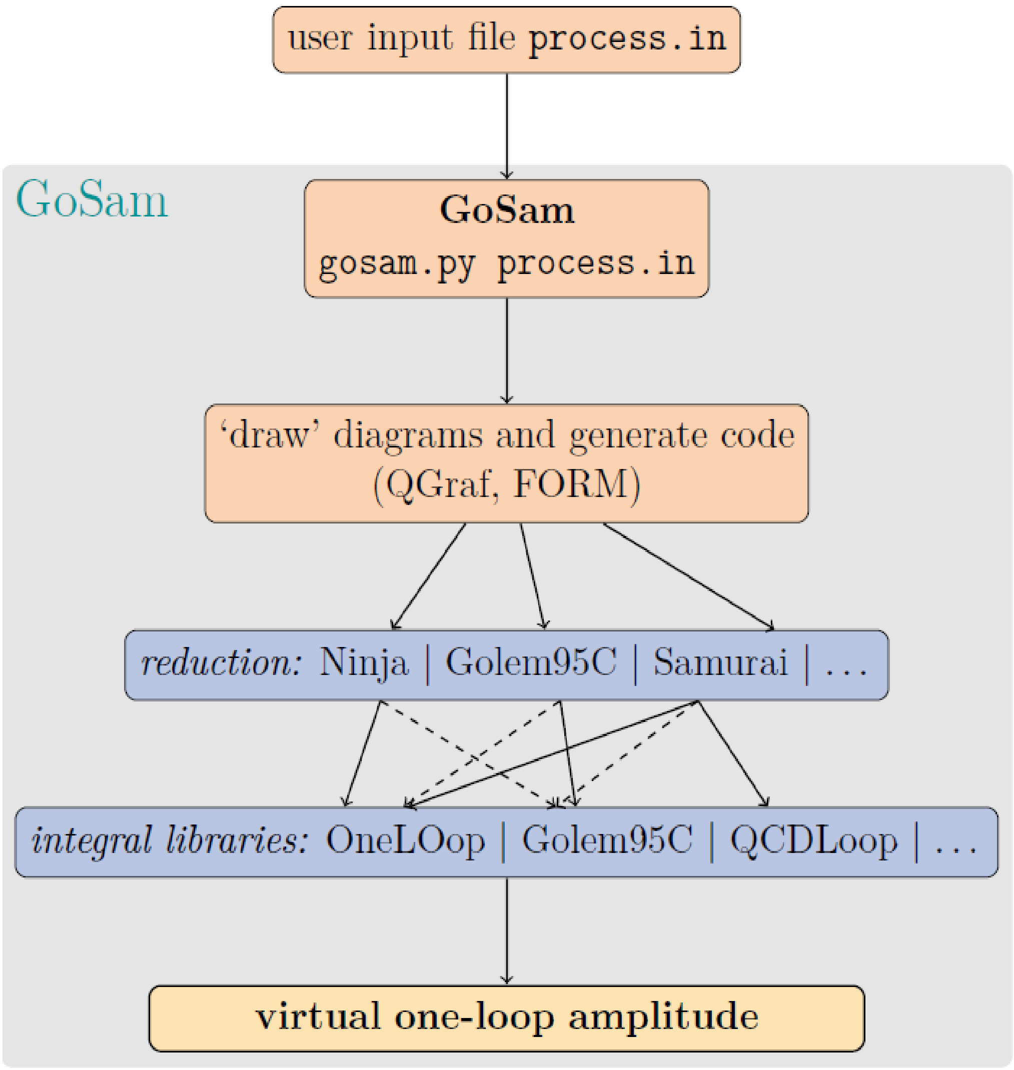
- Largely motivated by SM precision measurements and absence of new physics



[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]
```

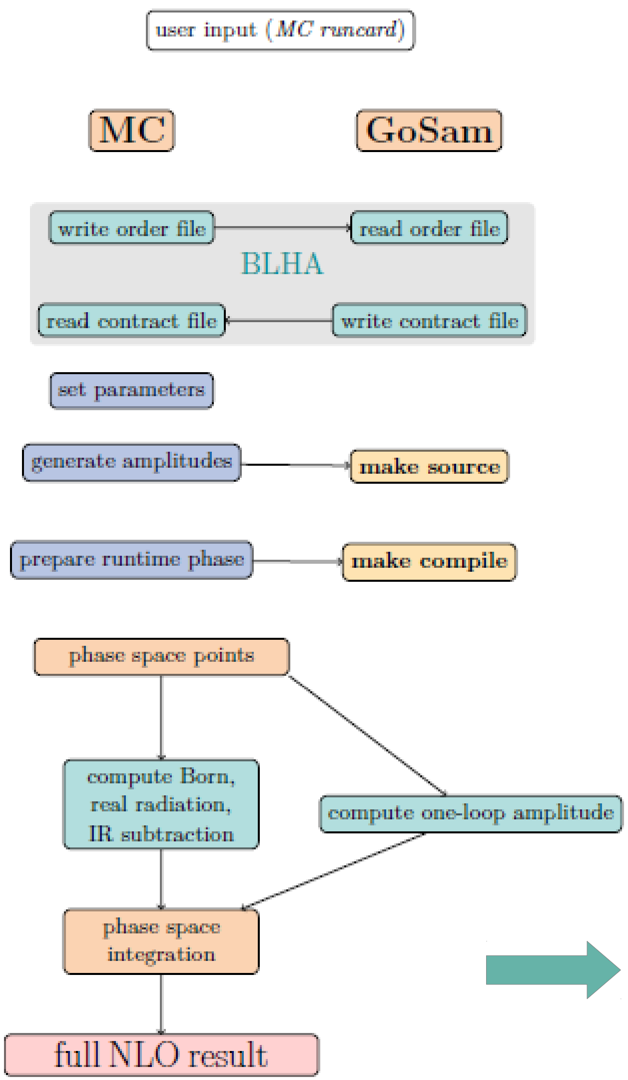
Example:
Higgs + Top quark pair

New models can be imported from FeynRules or LanHEP

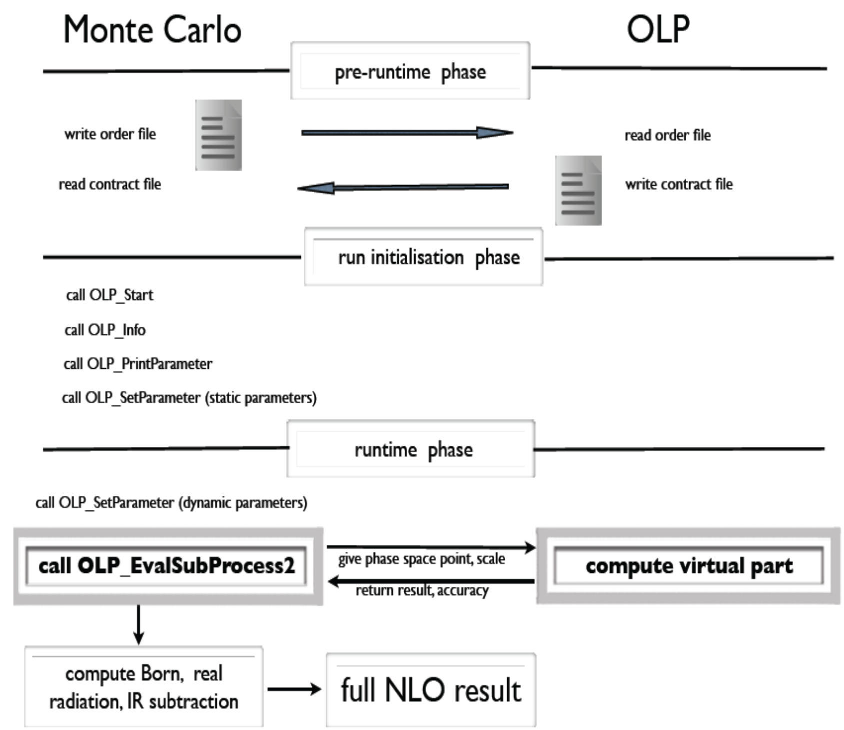
Specify which parameters should be set ALGEBRAICALLY to zero or one

Options on helicity and loop diagrams

Interface to Monte Carlo programs



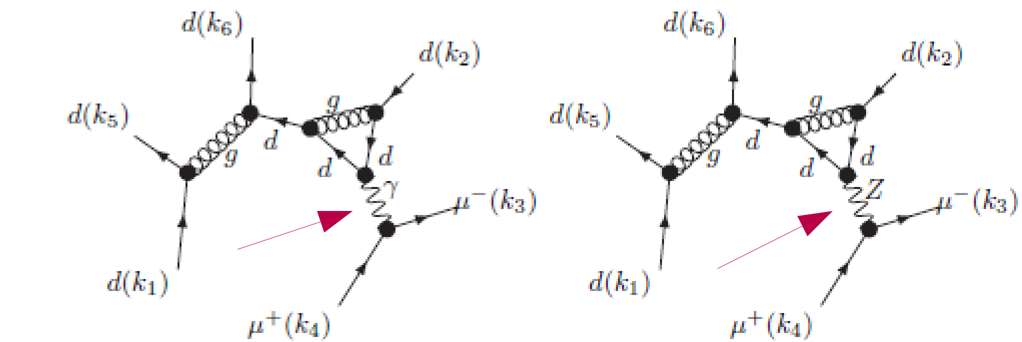
- Interface via Binoth-Les-Houches-Accord (both original and extended BLHA supported)



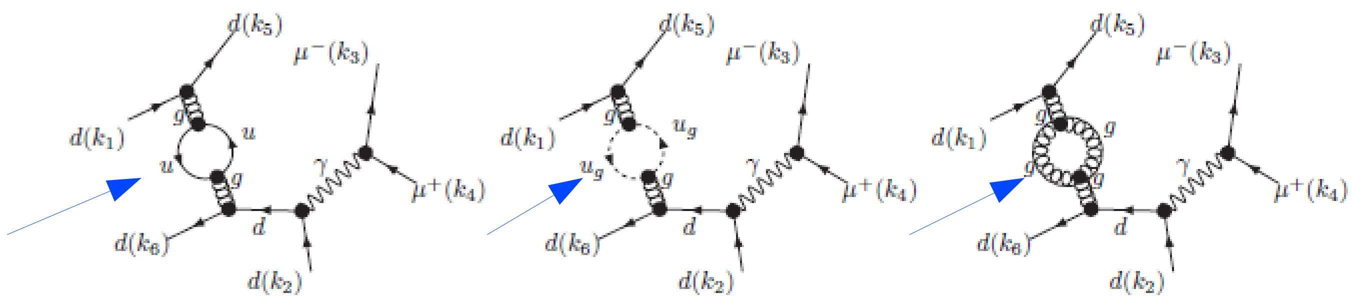
GoSam can be interfaced to ANY MC that supports this standard!

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



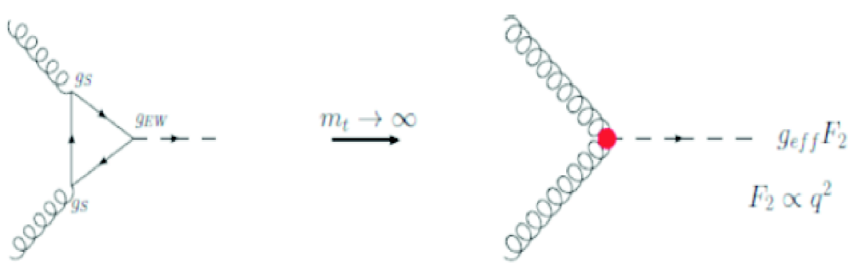
Same set of propagators, different particles in the loop

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)



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

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Higgs + jets in Gluon Fusion

- Dominant production mechanism at LHC
- Direct study of the Higgs without jet vetoes difficult due to large QCD background
- Nevertheless important for reliable estimation of theoretical uncertainty with jet veto, need inclusive and exclusive results, H+2 irreducible background to Higgs production in VBF
- Computed using **GoSam**+ **Sherpa** + **MadGraph/MadDipole/Madevent** [Cullen et al. – Les Houches proceedings '14]
- **Setup:**
  LHC 8 TeV anti-kt: R=0.4
  p_T >30 GeV $|\eta| < 4.4$
  PDFs: cteq6l1 @ LO
  CT10NLO @ NLO

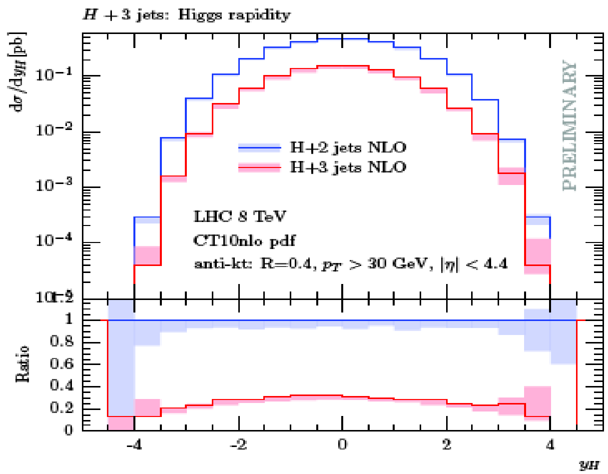
$$\mu_r = \mu_f = \frac{\hat{H}_t}{2} = \frac{1}{2}\sqrt{M_H^2 + p_{t,H}^2} + \sum_j p_{T,j}$$

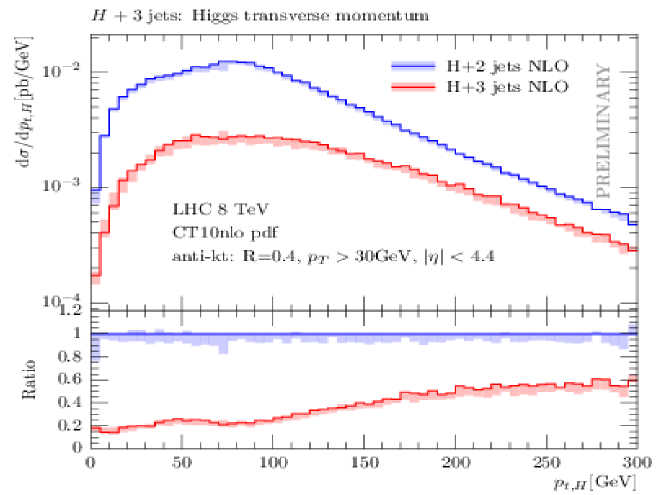
- Looking at ratio H+3/H+2

Sample K-factor	Cross sections for Higgs boson plus ≥ 2 jets	f_3	≥ 3 jets	$r_{3/2}$
LO				
H+2-jet2 (LO PDFs)	$1.23\ ^{+37\%}_{-24\%}$			
H+3-jets (LO PDFs)	(0.381)	1.0	$0.381\ ^{+53\%}_{-32\%}$	$0.310\ ^{0.347}_{0.278}$
H+2-jets (NLO PDFs)	$0.970\ ^{+33\%}_{-23\%}$			
H+3-jets (NLO PDFs)	(0.286)	1.0	$0.286\ ^{+50\%}_{-31\%}$	$0.295\ ^{0.332}_{0.265}$
NLO				
H+2-jets	$1.590\ ^{-4\%}_{-7\%}$	0.182	$0.289\ ^{+49\%}_{-31\%}$	
H+3-jets	(0.485)	1.0	$0.485\ ^{-3\%}_{-13\%}$	$0.305\ ^{0.307}_{0.284}$
K_2, K_3 (LO PDFs for LO)	$1.29\ ^{0.911}_{1.59}$		$1.27\ ^{0.806}_{1.63}$	
K_2, K_3 (NLO PDFs for LO)	$1.64\ ^{1.19}_{1.98}$		$1.70\ ^{1.10}_{2.13}$	

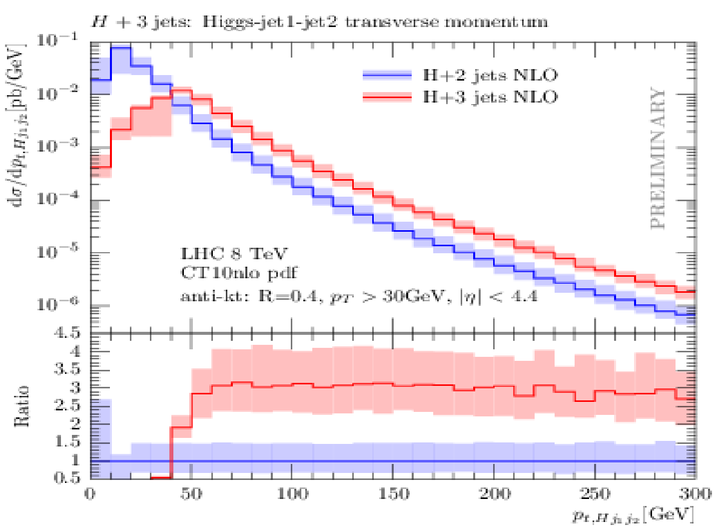
Higgs + jets in Gluon Fusion

- Rapidity and transverse momentum distribution of the Higgs





- Hj_1j_2 transverse momentum distribution



More phenomenology to follow (including parton shower)

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

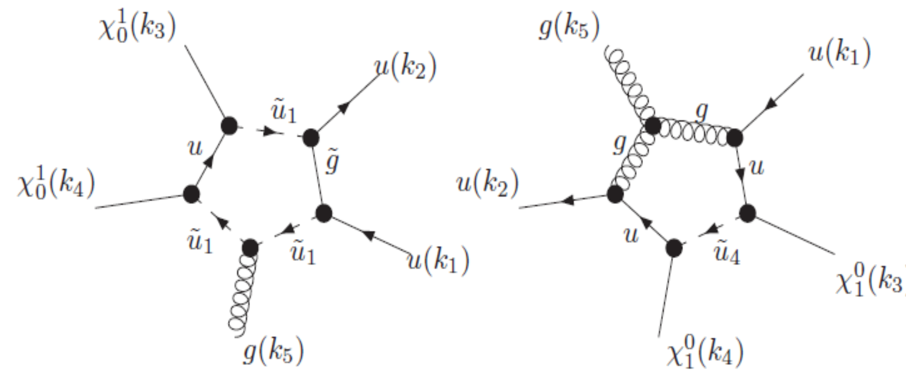
Signature: Monojet + Missing Energy

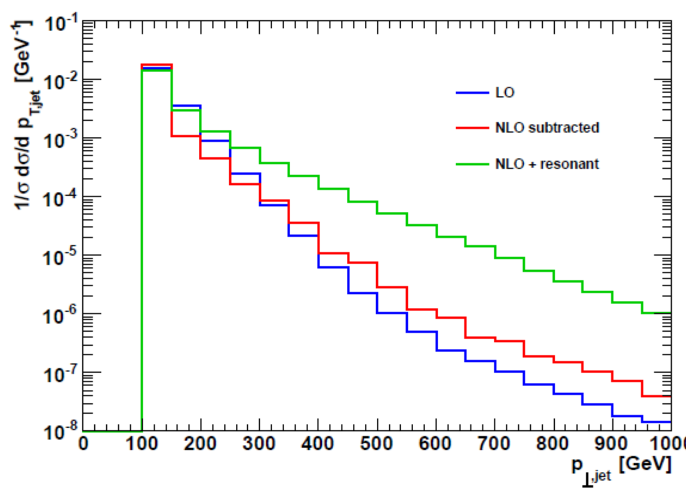
Non-trivial process, multiple scales, full off shell effects taken into account.

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

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