MAX-PLANCK-GESELLSCHAFT

Diphoton + jet at NLO with GoSam

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Based on
arxiv:1303.0824 [Gehrmann,NG,Heinrich]

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Outline

- Diphoton + jet: Motivation and setup
- GoSam: Introduction and new developments
- Diphoton + jet: Results and outlook

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Diphoton + Jet @ NLO

Diphoton + jet – Photon Fragmentation [Gehrmann,NG,Heinrich, '13]

- Background to H +jet, $H \to \gamma\gamma$ → need NLO QCD corrections!

More than just a normal NLO calculation...

Diphoton + Jet @ NLO

Diphoton + jet – Photon Fragmentation [Gehrmann,NG,Heinrich, '13]

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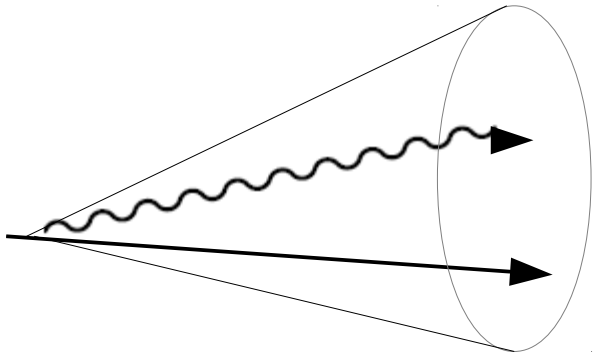
More than just a normal NLO calculation...

- Experiment: Photon accompanied by QCD stuff
- Collinear Limit between Photon and Quark resolved



Theory:

Quark and Photon collinear: Singularity!

- QED singularity → no cancellation with QCD virtuals

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Photon Fragmentation / Cone isolation

- Photon can have two origins:
  I. Direct radiation off quark/antiquark
  II. Fragmentation of hadronic jets into photons
    - Non-perturbative, described by photon fragmentation function (measured)
- Collinear singularity absorbed into photon fragmentation function

→ In cone around photon

$$z = \frac{p_{T,hadr}}{p_T(p_{hadr} + p_\gamma)} \leq z_{cut}$$

✔ Compatible with experiment
✗ Theoretically complicated

Frixione Isolation criterion [Frixione '98]

- The closer to the collinear limit, the less hadronic energy is allowed.

→ Inside cone around photon with radius Rγ

$$E_{\text{had,max}}(r_\gamma) = \epsilon_\gamma p_{T,\gamma} \left(\frac{1 - \cos r_\gamma}{1 - \cos R_\gamma} \right)^{n\gamma}$$

➡ In the limit, no hadronic energy is allowed

➡ **Finite!**

✔ Theoretically nice, no extra contributions needed
✗ Experimentally no smooth cut-off possible

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Diphoton + Jet @ NLO

Status: pp → $\gamma\,\gamma$: Diphox [Binoth et al. '99] cone / Frixione , MCFM [Campbell et al]

pp → γ j : Jetphox [Catani et al. '02], [Aurenche et al. '06], [Belghobsi et al. '09]

cone isolation / Frixione isolation

pp → $\gamma\,\gamma$ j : NLOJet++ [DelDuca,Maltoni,Nagy,Trocsanyi '03] Frixione isolation

Resbos: resummation contr. [Balazs et al.]
Gamma2MC: includes gg initial at NLO [Bern,Dixon,Schmidt, '02]
2GammaNNLO: NNLO corrections to diphoton [Catani et al. '12]

New: Comparison between the two methods (cone vs. Frixione)

Setup: Virtuals with GoSam
Tree level /real radiation with MadGraph
Subtraction terms for QCD with MadDipole
Phase space integration with MadEvent

➡ "normal" QCD

Additional subtraction terms for QED singularities with MadDipole
Include LO fragmentation from BFGW set.

Modular structure of automated building blocks allows easy combination.

Golem+ Samurai = GoSam

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.**

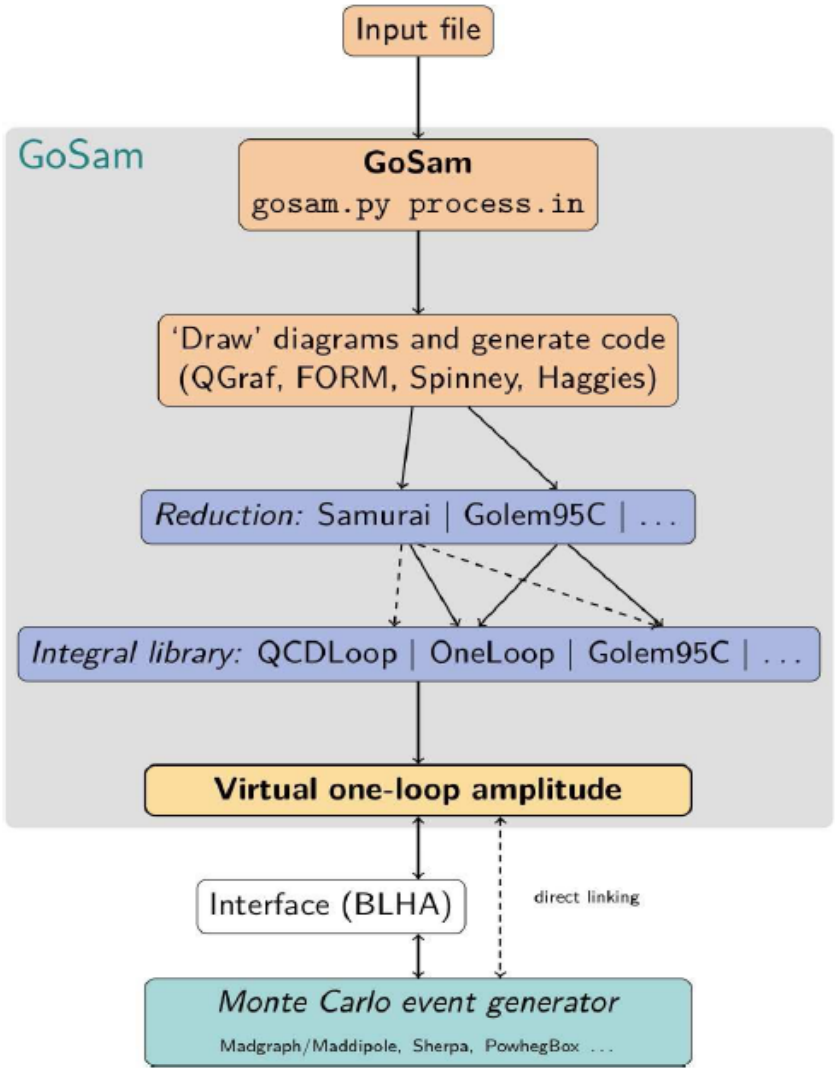
arXiv: 1111.2034 [hep-ph] (EPJC 72, 2012) [Cullen,NG,Heinrich,Luisoni,Mastrolia,Ossola,Reiter,Tramontano]
+H.vanDeurzen,J.F.v.Soden-Fraunhofen,E.Mirabella,T.Peraro,J.Reichel,J.Schlenk

- 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 (MadGraph, Sherpa, Powheg)

"15 minutes could save you 15 % or more
on your next NLO calculation."

Get a free quote: **http://gosam.hepforge.org**

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 (OPP) with Samurai [Mastrolia,Ossola,Reiter,Tramontano]
- Tensor reduction 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)

GoSam

```
ttH : bash
File  Edit  View  Bookmarks  Settings  Help
greiner@pcl340b:~/GoSam/gosam-1.0/ttH> ls
codegen     diagrams-0.hh   diagrams-1.log  helicity1   helicity13  helicity4  helicity8  Makefile.conf    model.hh
common      diagrams-0.log  doc             helicity11  helicity15  helicity5  helicity9  Makefile.source
config.sh   diagrams-1.hh   helicity0       helicity12  helicity3   helicity7  Makefile   matrix
greiner@pcl340b:~/GoSam/gosam-1.0/ttH>
```

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

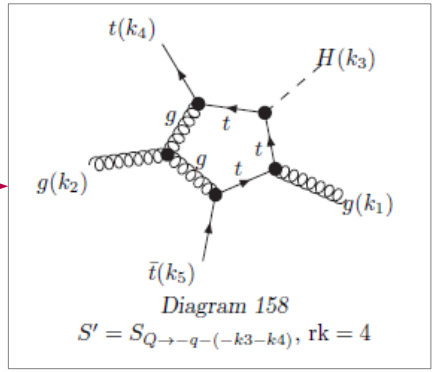


Diagram 158
$S' = S_{Q\to -q-(-k3-k4)}$, rk = 4

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Interfacing GoSam

- GoSam + MadDipole [Frederix,Gehrmann,NG '08, '10] + MadGraph/MadEvent [Stelzer,Long, '94], [Maltoni,Stelzer, '02]
  - NLO QCD corrections to pp → bbbb

    [Binoth, NG, Guffanti, Guillet, Reiter, Reuter '10, '11]
  - NLO QCD corrections to pp → W+ W- + 2 jets

    including massive top loops

    [NG, Heinrich, Mastrolia, Ossola, Reiter, Tramontano '12]
  - SUSY QCD corrections to neutralino pair + jet in MSSM

    [Cullen, NG, Heinrich '12]
- GoSam + Sherpa
  - H + 2 jets in gluon fusion

    [van Deurzen,NG,Luisoni,Mastrolia,Mirabella,Ossola,Peraro,von Soden-Fraunhofen,Tramontano '13]
  - More ready-to-go packages at **http://gosam.hepforge.org/proc**

    [Luisoni, Tramontano]

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Towards GoSam 2.0

- Continous developments in code generation and reduction have led to significant improvements. → Will be made public in **GoSam 2.0**

Code generation

- New optimization strategy (use new features of FORM >4.0 to optimize algebraic expressions).
  → Leads to faster generation, smaller code, and better run-time!
- Numerical polarization vectors reduce code size.
- Parallelization of diagram generation: Each diagram can be generated independently. → Enormous reduction of generation time.
- Diagsum option: Diagrams with identical denominators are summed on FORM level algebraically.

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Towards GoSam 2.0

Improvements on the reduction side

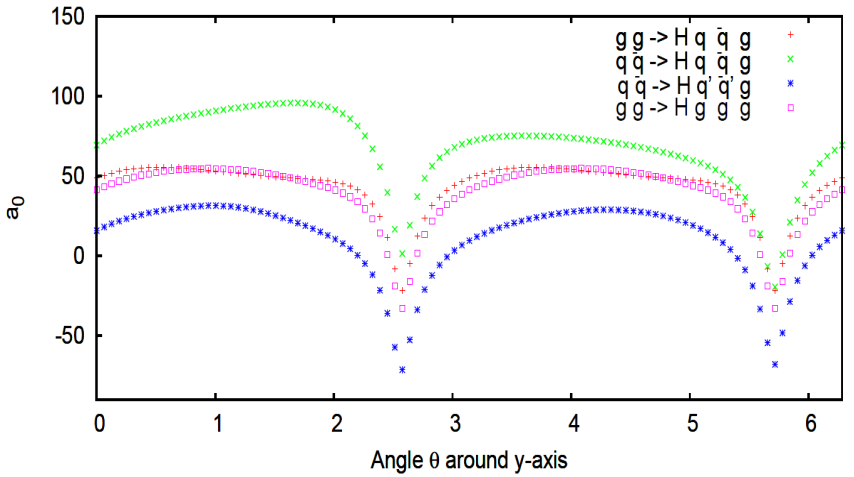
- Implementation of higher rank integrals in Samurai [van Deurzen, Mastrolia] and in Golem95 [Guillet, Heinrich, v.Soden-Fraunhofen].
  → Needed for effective Higgs couplings, BSM scenarios.
- Alternative reduction with NINJA (C++ library) [Mastrolia,Mirabella,Peraro '12]
  Idea: Combining Integrand reduction and Laurent expansion, implemented through polynomial division for triple, double and single cuts, allows to determine coefficients without the sampling as in OPP
- Interface for NINJA implemented in GoSam.

Towards GoSam 2.0

Improvements allowed for the calculation of virtual amplitude for H+ 3 jets:

Process	# diags	#diags (diagsum true)	timing
$q + \bar{q} \to H + q' + \bar{q}' + g$	467	202	~ 290 ms
$q + \bar{q} \to H + q + \bar{q} + g$	868	344	~ 600 ms
$g + g \to H + q + \bar{q} + g$	2519	645	~ 3900 ms
$g + g \to H + g + g + g$	9325	1814	~ 20100 ms

- Check gauge invariance:
  Replace polarization vector by momentum
  → Contribution numerically zero !
  → Strong consistency check !



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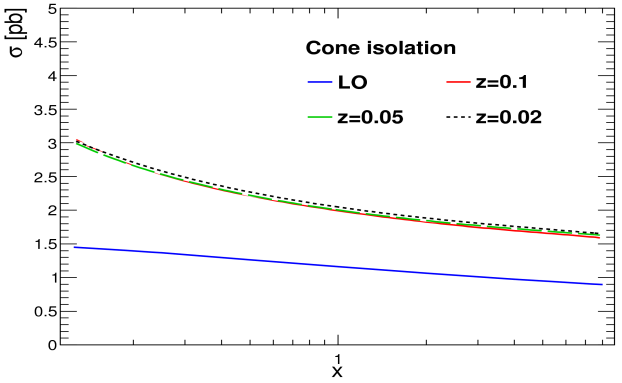
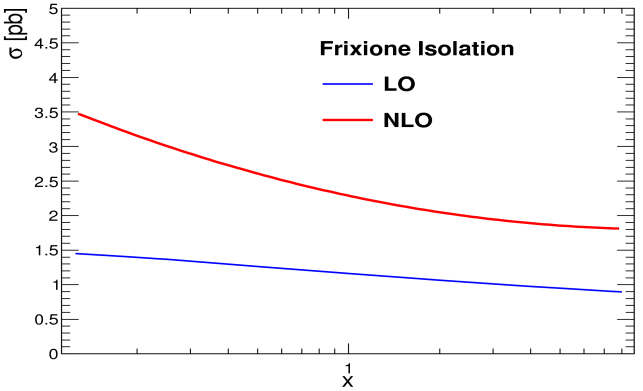
Diphoton + Jet @ NLO

Scale variation: $\mu_0^2 = \frac{1}{4}\left(m_{\gamma\gamma}^2 + \sum_j p_{T,j}^2\right)$ $\mu_r = \mu_f = \mu_F$ $\sqrt{s} = 8$ TeV

$p_T^{\text{jet}} > 40\,\text{GeV}, p_T^{\gamma} > 20, |\eta^{\gamma}, \eta^{j}| \leq 2.5,$ $R \geq 0.4$ $100\,\text{GeV} \leq m_{\gamma\gamma} \leq 140\,\text{GeV}.$

Inclusive cuts:





$\epsilon = 0.5,\ n = 1$

- Large K-factor ~2
- No reduction of scale uncertainty

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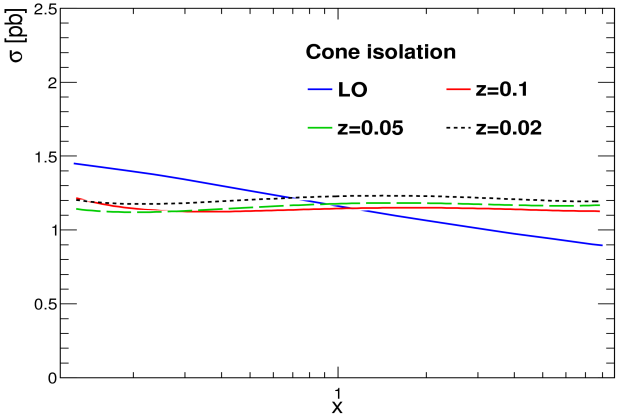
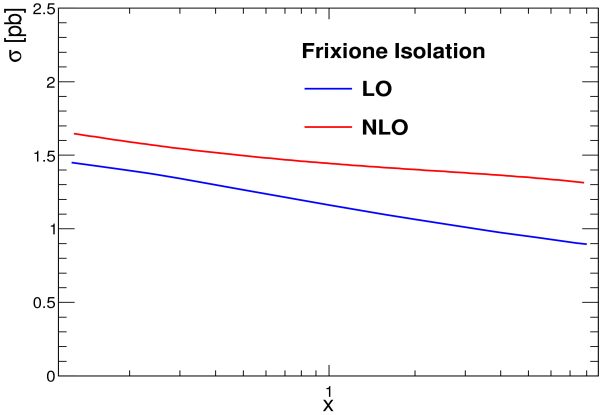
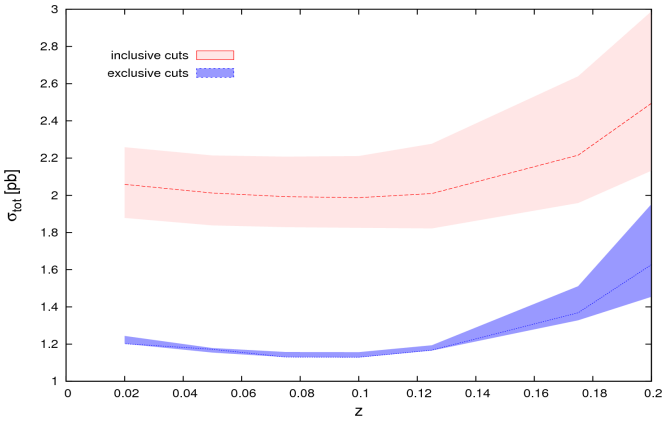
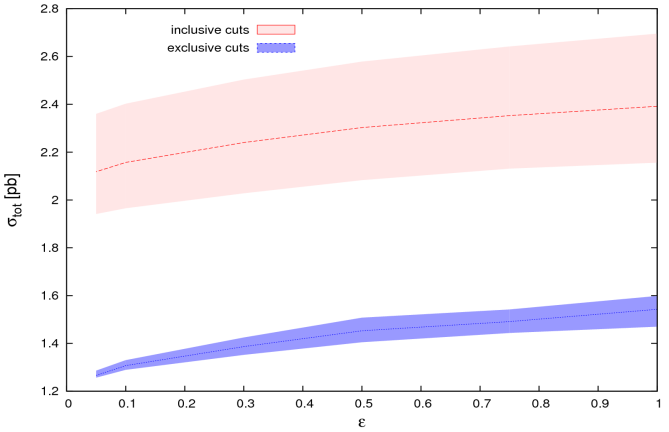
Impose veto on second jet (exclusive cuts): $p_{T,j2} \leq 30\ \mathrm{GeV}$









- Reduction of scale uncertainty compared to LO.
- Strong reduction of K-factor compared to inclusive cuts.
- Cone isolation more stable under scale variation

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Diphoton + Jet @ NLO

What is not included:

- Gluon to Photon fragmentation: Regarded as higher order contribution
- NLO fragmentation: Only LO fragmentation included. Sizeable ?
- Virtuals for gluon-gluon initial state: One-loop squared, higher order, but gluon-pdf enhanced. Sizeable ?

The whole package is made public as a complete stand alone code

http://gosam.hepforge.org/diphoton

- Installation with ./setup.py install
- Generation of results with ./integrate.py
- Short README with more information.

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Summary

- Diphoton + jet important background to H + jet.
- Photon Fragmentation vs. Frixione isolation: Differences decrease when the allowed hadronic energy around the photon is reduced.
- Process made public as fully stand alone package ready to use.
- GoSam: fully automated generation of one-loop amplitudes.
- GoSam 2.0 contains multiple improvements, will be made public later this year.