

Applications of NLO automation with GoSam

Johann Felix von Soden-Fraunhofen

Max Planck Institute for Physics, Munich

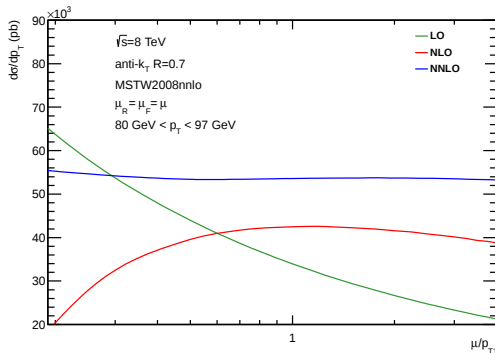
 **DPG** Frühjahrstagung Mainz, 25.03.2014



Overview

- ① Introduction
- ② GoSam
- ③ BLHA2
- ④ $pp \rightarrow \gamma\gamma + \text{jet}$ through graviton exchange
- ⑤ Summary

Why do we need higher order calculations?



$$gg \rightarrow gg + X$$

[J. Pires RADCOR 2013]

GoSam

- calculates virtual NLO corrections (one-loop multi-leg amplitudes)
- fully automated
- open source and uses only public tools

Release 2.0 coming soon

GoSam Collaboration: G. Cullen, H. van Deurzen, N. Greiner, G. Heinrich, G. Luisoni, P. Mastrolia, E. Mirabella, G. Ossola, T. Peraro, J. Reichel, J. Schlenk, JFvS, F. Tramontano

<http://gosam.hepforge.org/>

[Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano (1111.2034)]

GoSam + MadDipole/MadGraph4

- $pp \rightarrow b\bar{b}b\bar{b}$ [Greiner, Guffanti, Reiter, Reuter (1105.3624)]
- $pp \rightarrow W^+ W^- + 2 \text{ jets}$
including massive top loops [Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano (1202.6004)]
- SUSY QCD corrections to $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + \text{jet}$
[Cullen, Greiner, Heinrich (1212.5154)]
- $pp \rightarrow \gamma\gamma + 1 \text{ \& } 2 \text{ jets}$ [Gehrmann, Greiner, Heinrich (1303.0824); Gehrmann, Greiner, Heinrich (1308.3660)]
- $pp \rightarrow H H + 2 \text{ jets}$ [Dolan, Englert, Greiner, Spannowsky (1310.1084)]
- QCD corrections to $pp \rightarrow (G \rightarrow \gamma\gamma) + \text{jet}$
[Greiner, Heinrich, Reichel, JFvS (1308.2194)]

GoSam + MadDipole/MadGraph4 + Sherpa

- $pp \rightarrow H + 3 \text{ jets (gluon fusion)}$ [Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, et al. (1307.4737)]

GoSam + Sherpa

- $pp \rightarrow H + 2 \text{ jets (gluon fusion)}$ [van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, et al. (1301.0493)]
- $pp \rightarrow W^+ W^- b\bar{b}$ [Heinrich, Maier, Nisius, Schlenk, Winter (1312.6659)]
- $pp \rightarrow t\bar{t} + 0 \text{ \& } 1 \text{ jet}$ [Hoeche, Huang, Luisoni, Schoenherr, Winter (1306.2703)]
- $pp \rightarrow H t\bar{t} + 0 \text{ \& } 1 \text{ jet}$ [van Deurzen, Luisoni, Mastrolia, Mirabella, Ossola, Peraro (1307.8437)]
- $pp \rightarrow W + 0 \text{ to } 3 \text{ jets}$
[<http://gosam.hepforge.org/proc/> or in prep.]
- $pp \rightarrow Z/\gamma^* + 0 \text{ to } 2 \text{ jets}$
[<http://gosam.hepforge.org/proc/>]
- $pp \rightarrow W b\bar{b}$ [<http://gosam.hepforge.org/proc/>]
- $pp \rightarrow W^+ W^-$ [<http://gosam.hepforge.org/proc/>]
- $pp \rightarrow W^+ W^+ + 2 \text{ jets}$
[<http://gosam.hepforge.org/proc/>]

GoSam + POWHEG

- $pp \rightarrow HW/HZ + 0 \text{ \& } 1 \text{ jet}$ [Luisoni, Nason, Oleari, Tramontano (1306.2542)]

GoSam + MadDipole/MadGraph4

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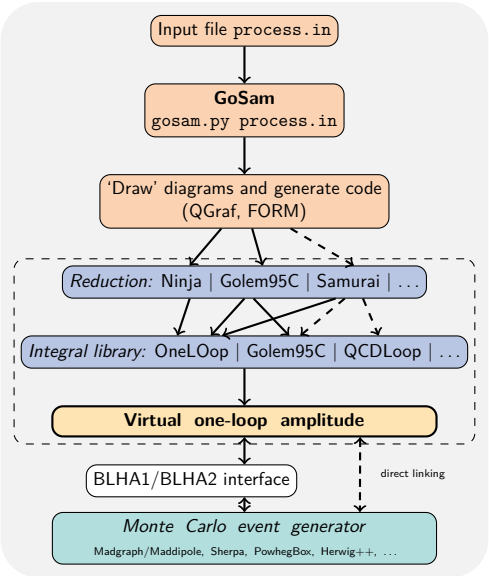
GoSam + Sherpa

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GoSam + POWHEG

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A look into GoSam



GoSam 2.0 Features

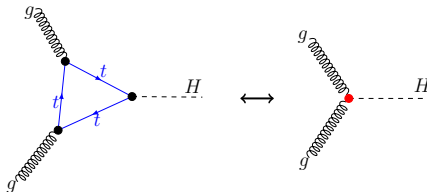
- new integrand-level reduction method: NINJA [Peraro (1403.1229)]
 - faster and more precise
- user-interface simplified
 - [new install script](#), installs all dependencies
 - input card improved
- BLHA2 interface to Monte-Carlo programs
- code generation improved
 - use new FORM features
- higher rank support

Higher tensor rank extension

$$I_{\mathbf{N}}^{n, \mu_1 \dots \mu_r}(S) = \int d^n k \frac{k^{\mu_1} \dots k^{\mu_r}}{\prod_{i \in S} ((k + r_i)^2 - m_i^2 + i\delta)}$$

with $\boxed{r = \mathbf{N} + 1}$ (general $r \geq \mathbf{N} + 1$)

- effective couplings like ggH-vertices (top-loops integrated out)

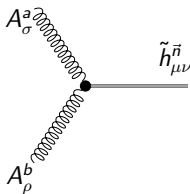


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with $\boxed{r = \mathbf{N} + 1}$ (general $r \geq \mathbf{N} + 1$)

- effective couplings like ggH-vertices (top-loops integrated out)
- spin-2 particles (gravitons)

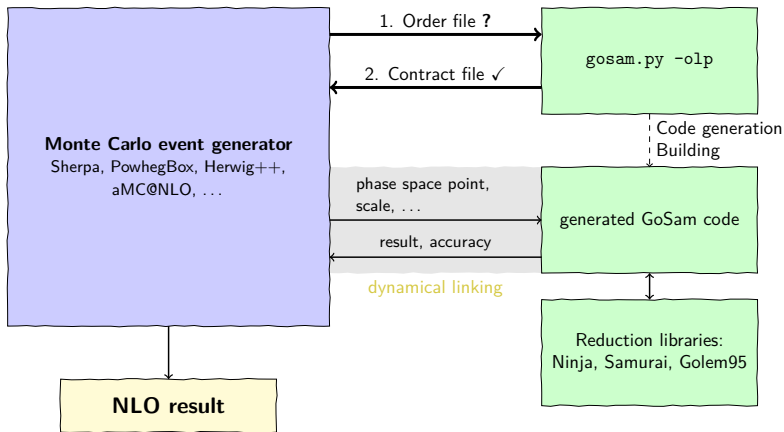


$$\propto \delta^{ab} ((m_A^2 + k_1 \cdot k_2) C_{\mu\nu, \rho\sigma} + \dots)$$

[Han, Lykken, Zhang (hep-ph/9811350)]

BLHA interface

- Binoth Les Houches Accord
- Interface between Monte Carlo programs and one-loop-provider



[Binoth, Boudjema, et al. (1001.1307); Alioli, Badger, et al. (1308.3462)]

New features of BLHA2 Interface

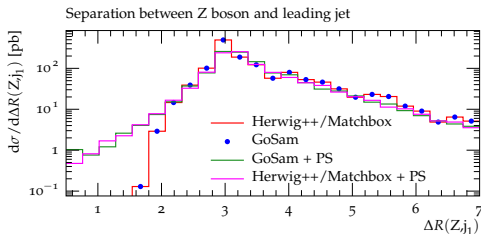
- processes with different multiplicities and settings in one order file
- including color/spin-correlated LO matrix elements
- dynamical parameter setting (coupling, masses)
- OLP can return (numerical) accuracy of results

[Alioli, et al. (47 authors), (1308.3462)]

Herwig++

An BLHA2 example

- Linking GoSam with Herwig++/Matchbox
- GoSam provides additionally all tree-level matrix elements
- fully automated
- $pp \rightarrow Z/\gamma^* + \text{jet} \rightarrow e^+e^- + \text{jet}$



[Bellm et al., Les Houches 2013 proceedings]

$\gamma\gamma + \text{jet}$ through graviton exchange

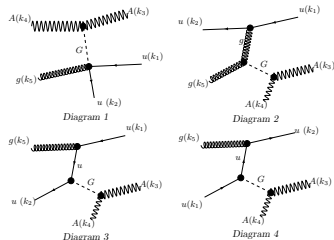
A higher rank example

- Diphoton+Jet production through graviton bridge
- ‘automated’ QCD NLO calculation with GoSam and MadGraph4
- ADD model [Arkani-Hamed, Dimopoulos, Dvali (hep-ph/9803315)] from Universal Feynrules Output (UFO) file imported [Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (1108.2040)]

- non-standard propagator (sum over KK modes)

$$D(s) = \sum_{\vec{n}} \frac{i}{s - m_{\vec{n}}^2 + i\epsilon}$$
simplified to density function

‘NLO QCD corrections to diphoton plus jet production through graviton exchange’ [Greiner, Heinrich, Reichel, JFvS; arXiv: (1308.2194)]



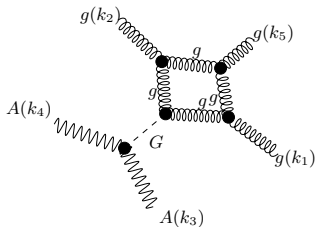


Diagram 108

rk = 5

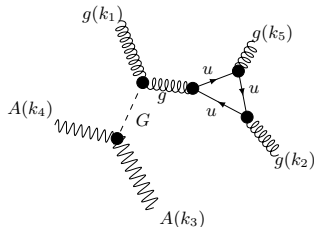


Diagram 109

rk = 3

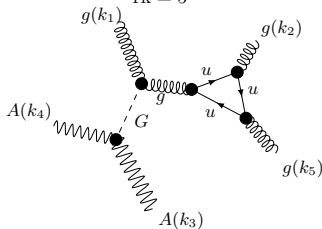


Diagram 110

rk = 3

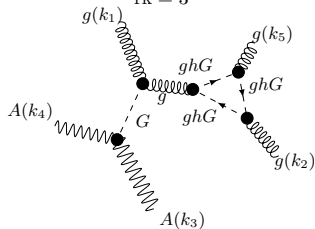
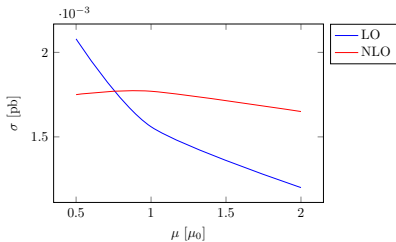


Diagram 113

rk = 3

Cuts and cross section

	cross section [fb]	MC error [fb]	scale uncertainty [fb]	
LO	1.561	$\pm 6.5 \times 10^{-4}$	0.522 -0.363	$\mu = \mu_0/2$ $\mu = 2\mu_0$
NLO	1.767	$\pm 7.1 \times 10^{-3}$	-0.02 -0.11	$\mu = \mu_0/2$ $\mu = 2\mu_0$



Cuts and parameters

$$p_{T,\gamma} \geq 25 \text{ GeV} \quad |\eta_\gamma| \leq 2.5 \quad 0.4 \leq \Delta R_{\gamma\gamma}$$

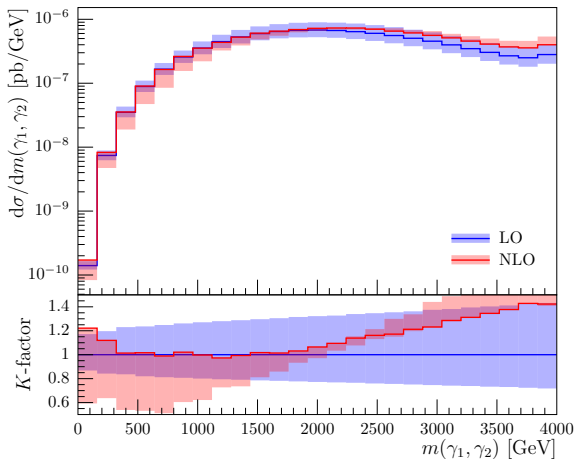
$$140 \text{ GeV} \leq m_{\gamma\gamma} < 3.99 \text{ TeV}$$

$$p_{T,\text{leading jet}} \geq 30 \text{ GeV} \quad |\eta_{\text{jet}}| \leq 4 \quad 0.4 \leq \Delta R_{\text{jet},\gamma}$$

$$\mu_0^2 = \mu_R^2 = \mu_F^2 = \frac{1}{4} (m_{\gamma\gamma}^2 + p_{T,\text{jet}}^2)$$

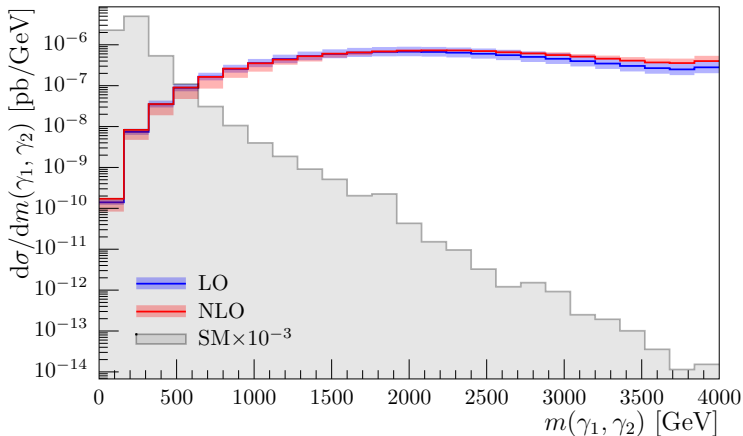
$$4 \text{ (5 u. 6) extra dimensionens} \quad M_s = 4 \text{ TeV}$$

Results



$$\text{invariant di-photon-mass } m_{\gamma\gamma} = \sqrt{(p_{\gamma_1} + p_{\gamma_2})^2}$$

Results



invariant di-photon-mass – compared with Standard Model

Conclusion

- soon GoSam 2.0: flexible automated tool for one-loop multi-leg amplitudes within and beyond the Standard Model.
- extended standard interface to Monte Carlo programs (BLHA2)
- has been used to calculate various NLO QCD $2 \rightarrow 4$ processes and BSM $2 \rightarrow 3$ processes
- phenomenological results for di-photon + jet production through graviton exchange

<http://gosam.hepforge.org/>

Thank you!

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Code generation

- General problem: Expression too huge for compilers $\Rightarrow$ need to be cleverly split into sub-expressions

old way: using HAGGIES [Reiter (0907.3714)]

new way: optimizing expressions with FORM (≥ 4.0)

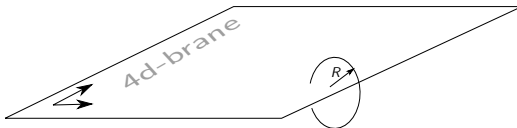
- factorisation of expression / Horner scheme
- smaller code, faster generated
 $\Rightarrow$ better performance

ADD model

- large extra-dimensions model (LED)
- offers solution to the hierarchy problem
- 'large' means $\gg \frac{1}{M_P}$, up to mm-range
- gravitation effects at TeV scale

$$\boxed{M_P^2 \sim R^\delta M_D^{\delta+2}} \text{ in } 4 + \delta \text{ dimensions}$$

- SM particles on 4-dim brane
- Kaluza-Klein modes in full dimensions (bulk)
- changes short-range Gravitation law



Graviton propagator

- “Graviton” = sum over KK modes
⇒ effective propagator needed

$$\sum_k \frac{i}{s - m_k^2 + i\epsilon} \approx \frac{s^{n/2-1}}{2M_s^{n+2}G_N} \left(\pi + 2i I(M_s/\sqrt{s}, n) \right)$$

where $I(x, n)$ is a smooth function.

- in GoSam 2.0 handled by new `customspin2propagator` extension

[Gleisberg, Krauss, Matchev, Schaliche, Schumann, Soff (hep-ph/0306182); Han, Lykken, Zhang (hep-ph/9811350)]

Graviton propagator

$$\sum_k \frac{i}{s - m_k^2 + i\epsilon} \approx \frac{s^{n/2-1}}{2M_s^{n+2}G_N} \left(\pi + 2i I(M_s/\sqrt{s}, n) \right)$$

$$I(x, n) = \begin{cases} -\sum_{k=1}^{n/2-1} \frac{1}{2k} x^{2k} - \frac{1}{2} \log(x^2 - 1) & \text{if } n = \text{even} \\ -\sum_{k=1}^{(n-1)/2} \frac{1}{2k-1} x^{2k-1} + \frac{1}{2} \log\left(\frac{x+1}{x-1}\right) & \text{if } n = \text{odd} \end{cases}$$

in $4 + n$ dimensions.

[Han, Lykken, Zhang (hep-ph/9811350); Gleisberg, Krauss, Matchev, Schaliche, Schumann, Soff (hep-ph/0306182)]