Applications of NLO automation with GoSam

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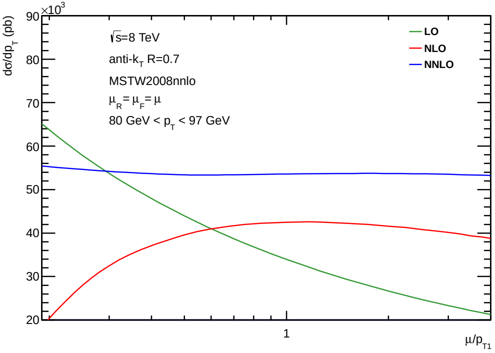
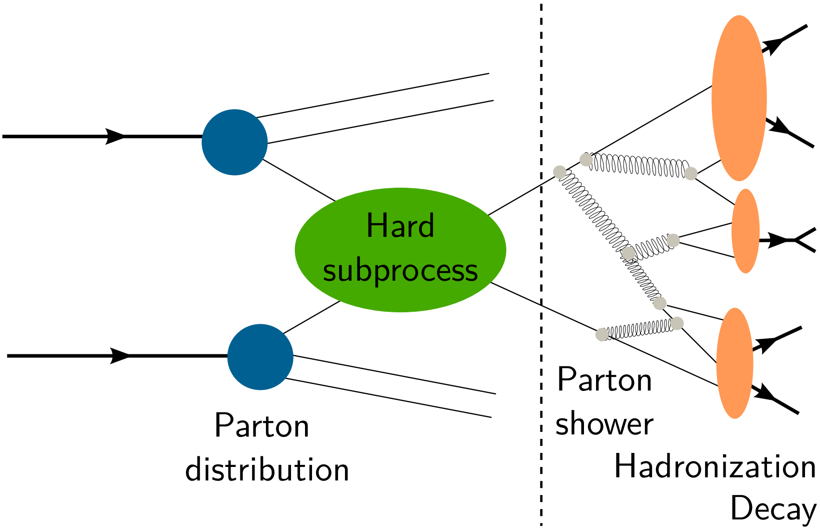
Overview

Why do we need higher order calculations?

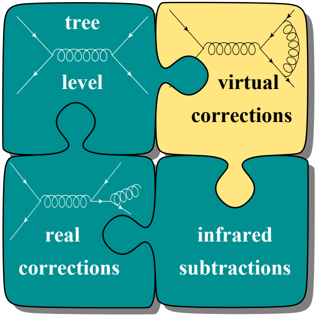


$$gg \to gg + X$$

[J. Pires RADCOR 2013]


Hard subprocess
Parton distribution
Parton shower
Hadronization
Decay

NLO calculation



$$\sigma^{NLO} = \int_m d\sigma^B + \int_m \left[d\sigma^V + \int_1 d\sigma^A \right] + \int_{m+1} \left[d\sigma^R - d\sigma^A \right]$$

GoSam

- calculates virtual NLO corrections (one-loop multi-leg amplitudes)
- fully automated
- open source and uses only public tools
- core: Ninja/Samurai and Golem95C
- written in Python

Release 2.0

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

http://gosam.hepforge.org/

[Cullen, van Deurzen, Greiner, Heinrich, et al. (1404.7096)]

GoSam + MadDipole/MadGraph4

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

GoSam + MadDipole/MadGraph4 + Sherpa

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

GoSam + Herwig++/Matchbox

GoSam + Sherpa

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

GoSam + POWHEG

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

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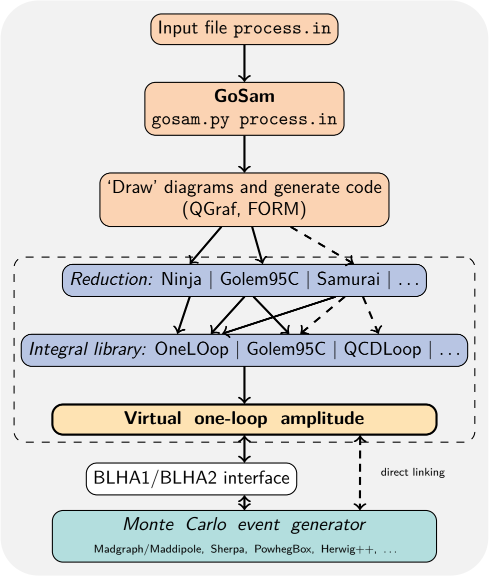
A look into GoSam



GoSam 2.0 Features

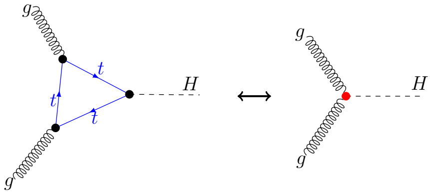
- new integrand-level reduction method: NINJA [Peraro (1403.1229)]
  - faster and more precise
- user-interface simplified
  - new install script, installs all dependencies
  - input card improved
- BLHA2 interface to Monte-Carlo programs
- Electroweak corrections
  - several options for EW scheme choice
  - complex mass scheme fully supported
- code generation improved
  - use new FORM features
- higher rank support

Higher tensor rank extension

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

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

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



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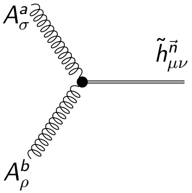
- effective couplings like ggH-vertices (top-loops integrated out)
- spin-2 particles (gravitons)

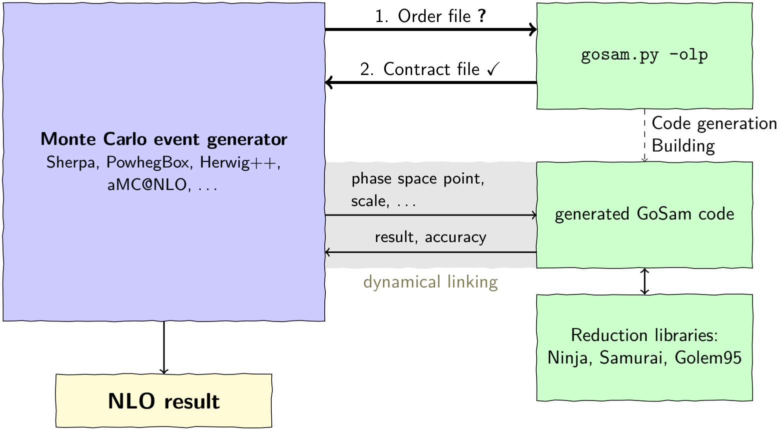


$\propto \delta^{ab}\left((m_A^2 + k_1\cdot k_2)C_{\mu\nu,\rho\sigma} + \ldots\right)$

[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

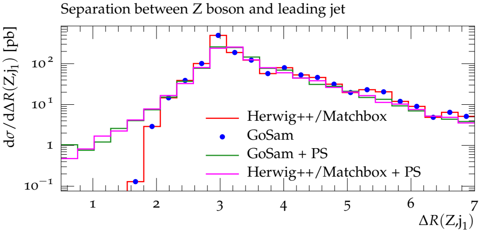
- processes with different multiplicities and settings in one order file
- including color/spin-correlated LO matrix elements
- dynamical parameter setting (coupling, masses)
- OLP can return (numerical) accuracy of results

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

Herwig++

A BLHA2 example

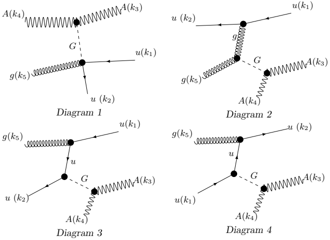
- Linking GoSam with Herwig++/Matchbox
- GoSam provides additionally all tree-level matrix elements
- fully automated
- $pp \to Z/\gamma^* + \text{jet} \to e^+e^- + \text{jet}$



[Bellm et al., Les Houches 2013 proceedings]

$\gamma\gamma$ + 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

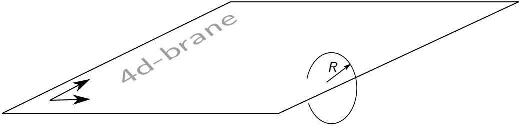
‘NLO QCD corrections to diphoton plus jet production through graviton exchange’ [Greiner, Heinrich, Reichel, JFvS; arXiv: (1308.2194)]

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

$\boxed{M_P^2 \sim R^\delta M_D^{\delta+2}}$ in $4 + \delta$ 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
  $\Rightarrow$ 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, Schalicke, 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, Schalicke, Schumann, Soff (hep-ph/0306182)]

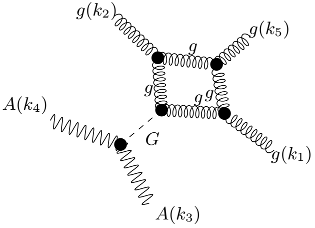


Diagram 108
rk = 5

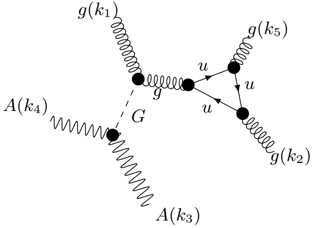


Diagram 109
rk = 3

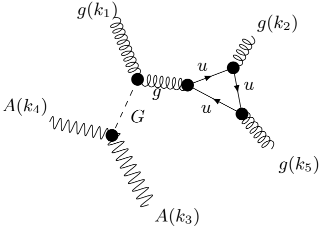


Diagram 110
rk = 3

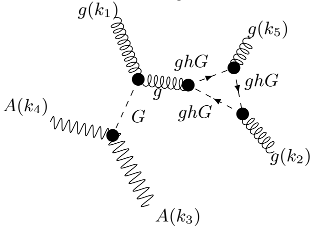
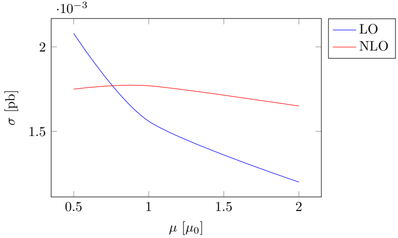


Diagram 113
rk = 3

Cuts and cross section

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



Cuts and parameters

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

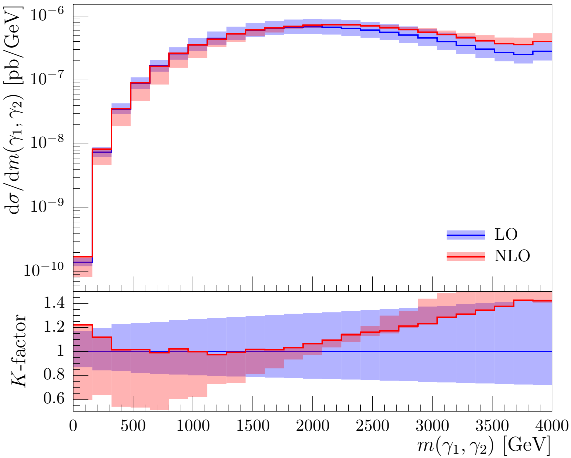
$140\text{ GeV} \leq m_{\gamma\gamma} < 3.99\text{ TeV}$

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

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

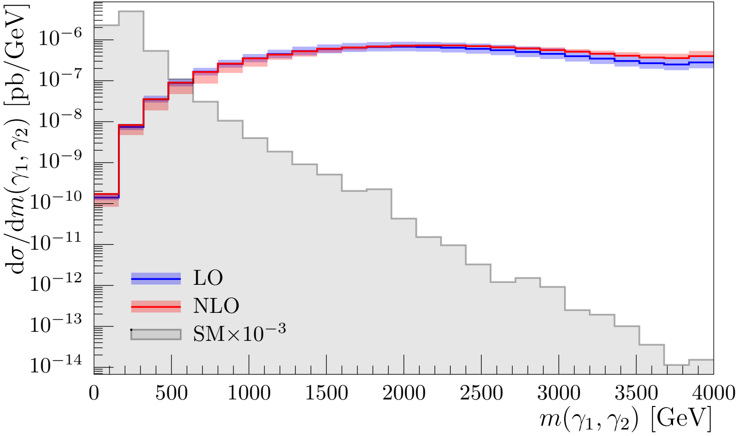
4 (5 u. 6) extra dimensionens $\quad M_s = 4$ TeV

Results



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

- 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 $2 \to 4$ processes and BSM $2 \to 3$ 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 to huge for compilers ⇒ 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
  ⇒ better performance