Higgs physics with GoSam

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On behalf of the GOSAM collaboration:
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P. Mastrolia, EM, G. Ossola, T. Peraro, J. Reichel,
J. Schlenk, J.F. von Soden-Fraunhofen, F. Tramontano

Cullen Peraro Schlenk Tramontano von Soden-Fraunhofen Greiner Mastrolia
Ossola Reichel van Deurzen Heinrich Luisoni Mirabella

Outline

- The GoSam framework
- Interface with Monte Carlo
- Higgs production with GoSam
- Conclusions & Outlook

Outline

2013 Credits:

- T. Gehrmann, N. Greiner & G. Heinrich, "Precise QCD predictions for the production of a photon pair in association with two jets," arXiv:1308.3660 [hep-ph].
- N. Greiner, G. Heinrich, J. Reichel & J. F. von Soden-Fraunhofen, "NLO QCD corrections to diphoton plus jet production through graviton exchange," arXiv:1308.2194 [hep-ph].
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- S. Hoeche, J. Huang, G. Luisoni, M. Schoenherr & J. Winter, "Zero and one jet combined NLO analysis of the top quark forward-backward asymmetry," arXiv:1306.2703 [hep-ph]
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- Many papers from GoSam's . . .
- . . . Many topics involved
  - Beyond Standard Model
  - Interface with Monte Carlo
  - Electroweak Physics
  - Di-photon production
  - Higgs physics

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- . . . Many topics involved
- This talk:
  - Higgs production @ the LHC . . .
  - . . . and the code extensions needed

The GoSam framework

$$\sigma_{\text{NLO}} = \int_n \left(d\sigma_{\text{Born}} + d\sigma_{\text{Virtual}} + \int_1 d\sigma_{\text{Subtraction}} \right) + \int_{n+1} \left(d\sigma_{\text{Real}} - d\sigma_{\text{Subtraction}} \right)$$

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Ingredients @ NLO:

- Phase Space integration
- Tree-level contributions
- Virtual corrections
- IR & Collinear regularization
- Real corrections

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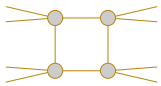
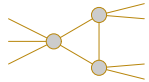
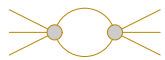
GoSam computes virtual contributions:

$$d\sigma_{\text{Virtual}} = \int d^d\ell \frac{\mathcal{N}}{D_1 \cdots D_k} = \sum_i$$  $$d_i + \sum_j$$  $$c_j + \sum_k$$  $$b_k$$

$$+ \sum_\ell$$  $$a_\ell + \mathcal{R}\text{ational}$$

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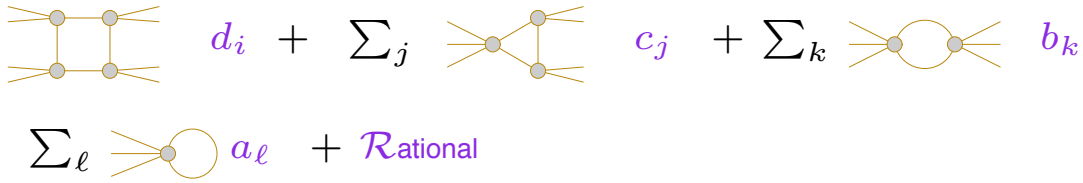

- Generation of $\mathcal{N}$
  - based on Feynman diagrams
  - separated from the numerical evaluation
  - optimized:
    - ↪ grouping of diagrams
    - ↪ smart caching
  - algebraic manipulations:
    - ↪ in d-dimensions in several schemes
    - ↪ performed before the reduction

The GoSam framework

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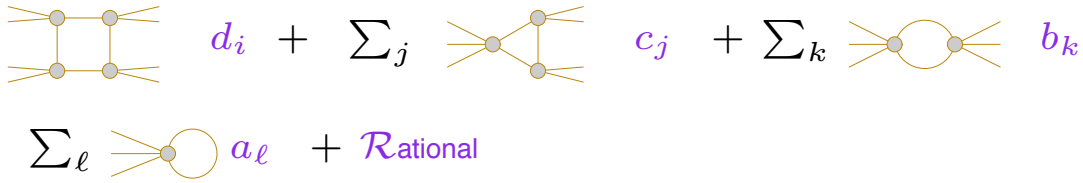

- Generation of $\mathcal{N}$
- Computation of the coefficients & $\mathcal{R}$
  - several reduction algorithm at run time
  - Samurai (current default) [Mastrolia, Ossola, Reiter, Tramontano]
    - ↪ d-dimensional integrand reduction
    - ↪ model-independent computation of $\mathcal{R}$
  - Golem95 (rescue system) [Binoth, Guillet, Heinrich, Pilon, Reiter]
    - ↪ tensorial reconstruction [Heinrich, Ossola, Reiter, Tramontano]
  - Ninja (stable and fast)
    - ↪ Laurent expansion +d-dimensional integrand reduction [Mastrolia, EM, Peraro]
    - ↪ more on this later!

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$$+ \sum_\ell \; a_\ell \; + \mathcal{R}\text{ational}$$

- Generation of $\mathcal{N}$
- Computation of the coefficients & $\mathcal{R}$
- Convolution with scalar integrals
  - AVHOLO [van Hameren]
  - QCDLOOP [Ellis, Zanderighi]
  - GOLEM95C [Cullen, Guillet, Heinrich, Kleinschmidt, Pilon, Reiter, Rodgers]

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- Generation of $\mathcal{N}$
- Computation of the coefficients & $\mathcal{R}$
- Convolution with scalar integrals
- Modular structure
  - new ideas and techniques are easily implemented
  - the GoSam framework evolves!

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- Generation of $\mathcal{N}$
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What about the other ingredients?

Interface with Monte Carlo

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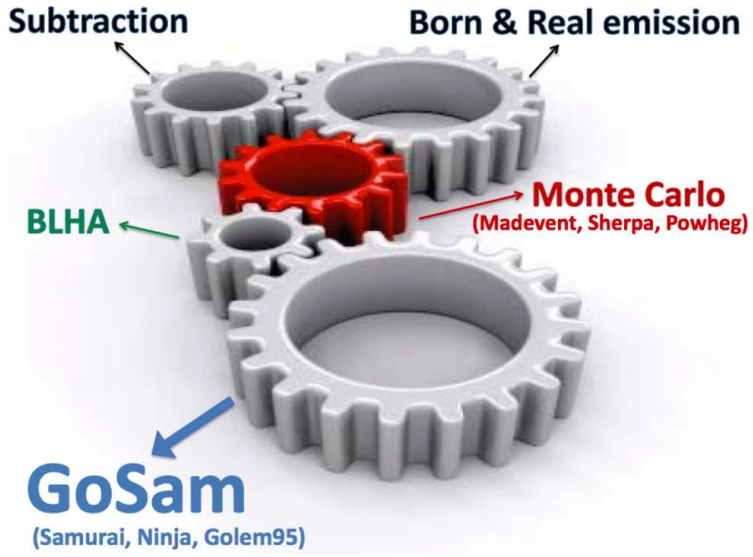
Monte Carlo computes the other ingredients



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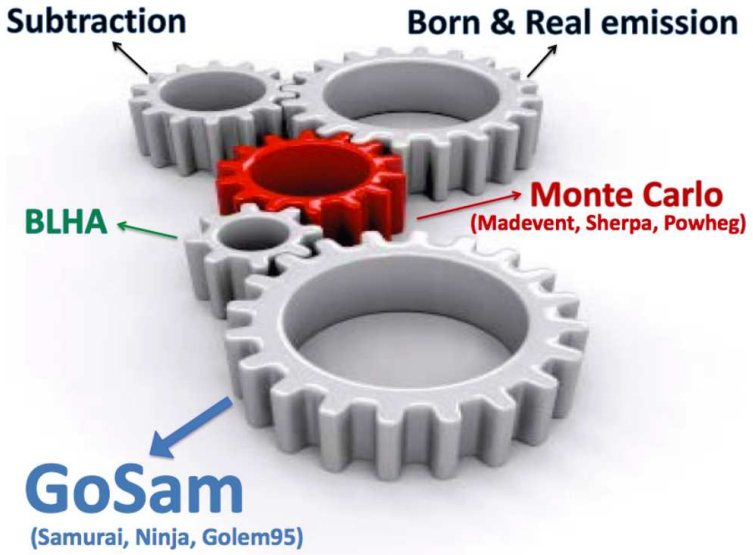
Monte Carlo computes the other ingredients

- GoSam + MadGraph/MadDipole/MadEvent
  - ad-hoc interface [Greiner]
    - ↪ $pp \to b\bar{b}b\bar{b}$ [Binoth, Greiner, Guffanti, Reiter, Reuter]
    - ↪ $pp \to W^+W^- jj$ [Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano]
    - ↪ $pp \to \chi^0\chi^0 j$ [Cullen, Greiner, Heinrich]
    - ↪ $pp \to \gamma\gamma j \ (j)$ [Gehrmann, Greiner, Heinrich]
    - ↪ $pp \to (G \to \gamma\gamma) j$ [Greiner, Heinrich, Reichel, von Soden-Fraunhofen]
    - ↪ $pp \to W^+W^- b\bar{b}$ [Heinrich, Schlenk, Winter (w.i.p.)]



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- GoSam + Sherpa
  - BLHA interface
    - ↪ $pp \to Hjj$ in GF [van Deurzen, Greiner, Luisoni, Mastrolia, EM, Ossola., Peraro, von Soden-Fraunhofen, Tramontano]
    - ↪ $pp \to t\bar{t}\,(j)$ [Hoeche, Huang, Luisoni, Schönherr, Winter]
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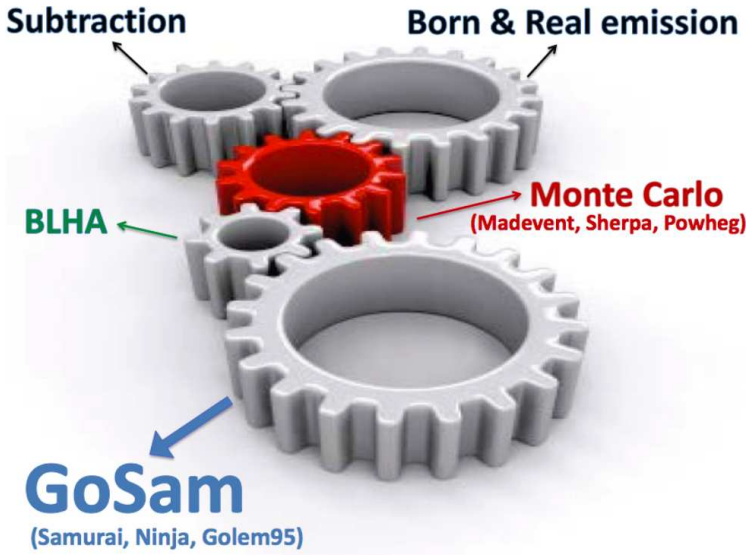

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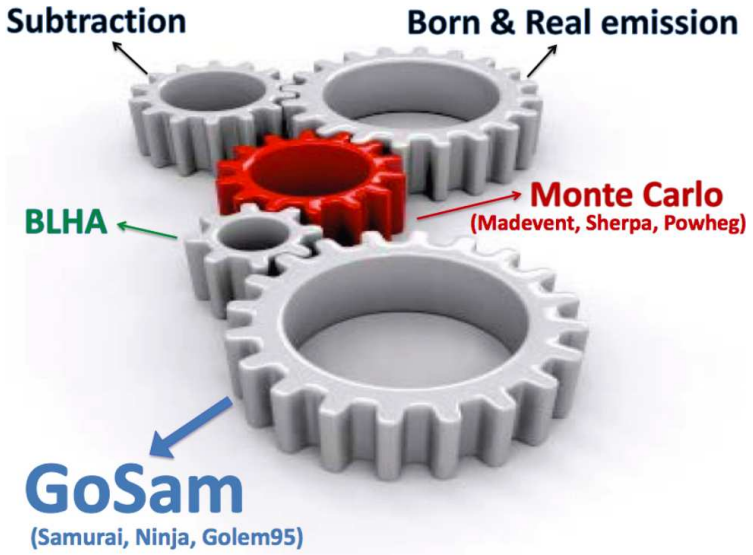

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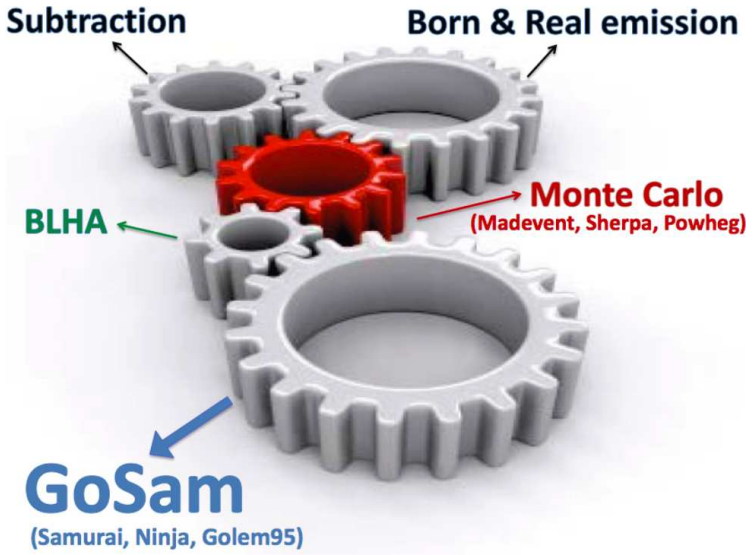

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  - ad-hoc interface [Greiner]
- GoSam + Sherpa
  - BLHA interface
- GoSam + Powheg
  - BLHA interface [Luisoni, Nason, Oleari, Tramontano]
- GoSam + Herwig
  - w.i.p. [Greiner, Heinrich, von Soden-Fraunhofen]
- GoSam + aMC@NLO
  - w.i.p. [van Deurzen, Frederix, Frixione, Hirschi, Luisoni, Mastrolia, Ossola, Peraro]

Higgs plus jets in gluon fusion

Motivation: Higgs via gluon fusion

- main production process @ the LHC
- contaminates other channels (e.g. VBF)

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Approximation: large top mass ($m_t \to \infty$)

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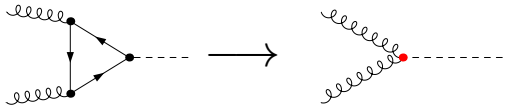
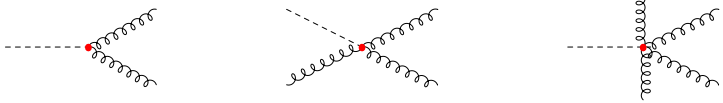


$\rightsquigarrow$ integrands with (numerator rank) = (# denominators) +1

- new Feynman rules:



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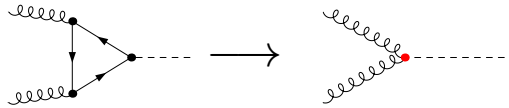

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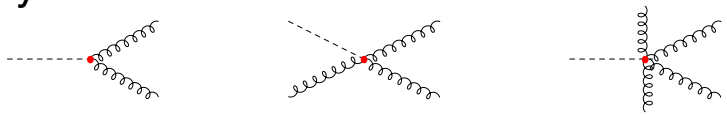


Extension of the integrand reduction . . .

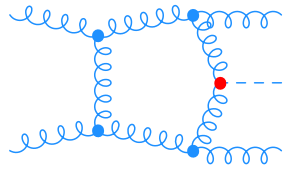
- integrand-level parametrization of the numerator
  - $\hookrightarrow$ obtained using the Gram determinant [Mastrolia, EM, Peraro]
  - $\hookrightarrow$ simple exercise using multivariate polynomial division [Mastrolia, EM, Ossola, Peraro]
- sampling of the numerator
- decomposition in term of master integrals

. . . implemented in SAMURAI [van Deurzen *et al.*]

Higgs plus jets in gluon fusion

Higgs plus two jets [van Deurzen, Greiner, Luisoni, Mastrolia, EM, Ossola, Peraro, von Soden-Fraunhofen, Tramontano]

- Computation using GoSam + Sherpa
- Agreement with MCFM (v6.4) [Campbell, Ellis, Williams]



+ 925 diagrams

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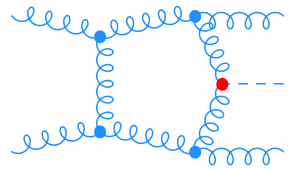

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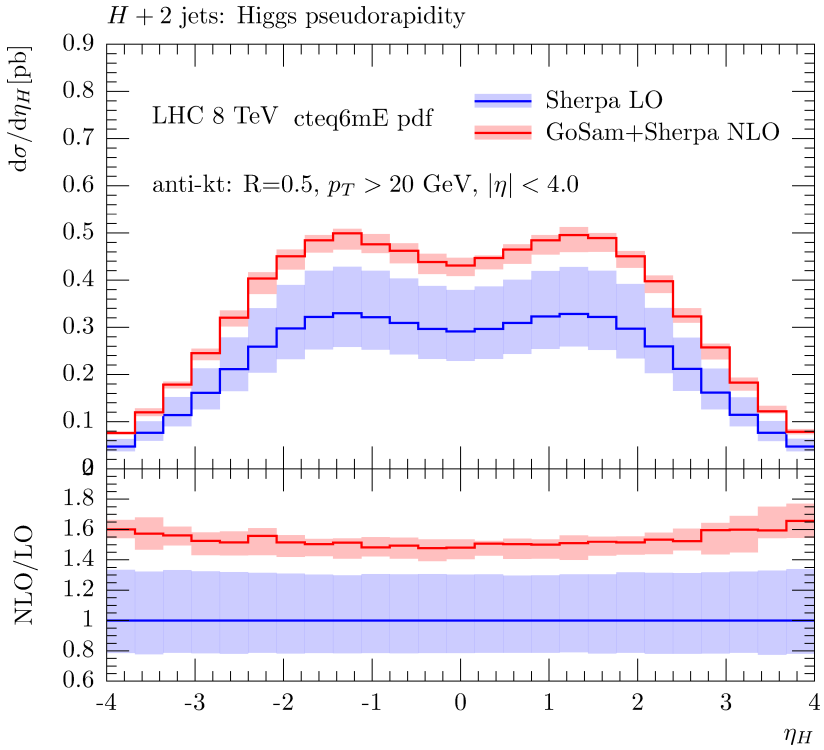
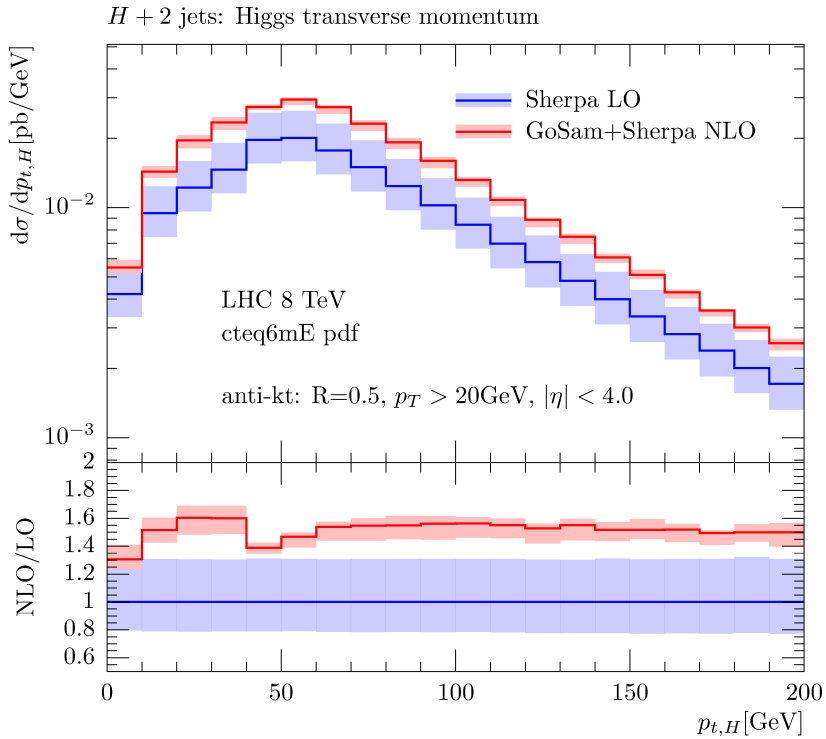
Differential distributions:



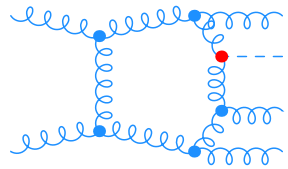


Higgs plus jets in gluon fusion

Higgs plus three jets

[Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, EM, Ossola, Peraro, Tramontano]

- Computational challenges
  - ↪ $\geq 10,000$ diagrams
  - ↪ higher rank terms (60 rank-7 hexagons)



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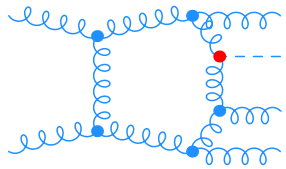

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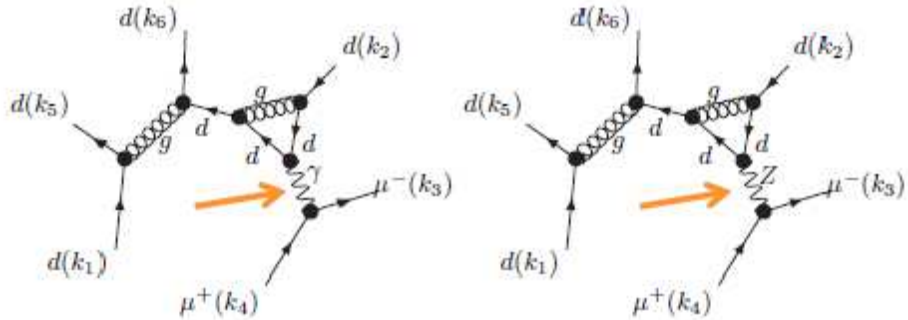
Complexity of the calculation $\Longrightarrow$ enhancement of GoSam

- sum over equal propagators
  - ↪ at generation time
- new abbreviations of Form 4.0
  - ⇝ faster generation, smaller code & better runtime
- numerical polarization vectors
  - ⇝ reduced code size
- parallelization of diagram generation
  - ⇝ reduced generation time



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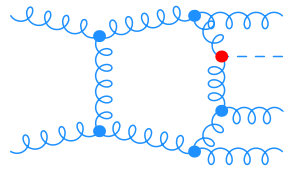

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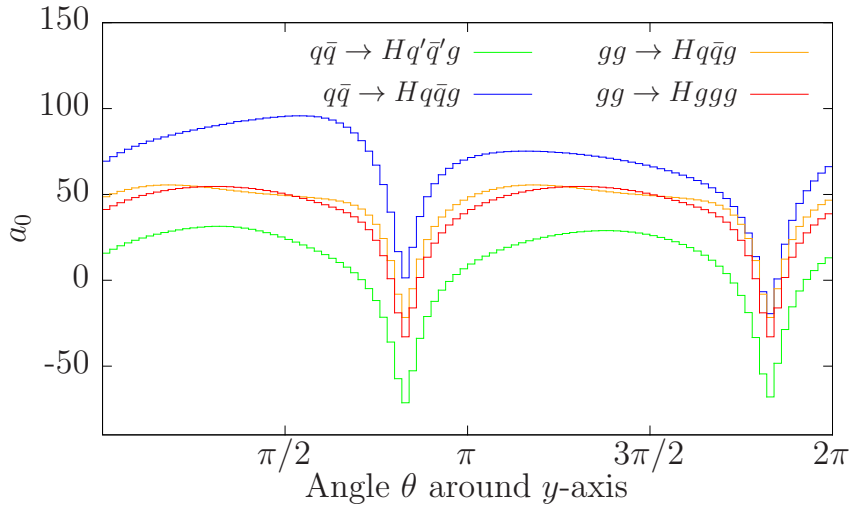
Virtual contributions with GoSam

- Timings:

Subprocess	Diagrams	Time/PS-point
$q\bar{q} \to Hq'\bar{q}'g$	467	0.29 s
$q\bar{q} \to Hq\bar{q}g$	868	0.60 s
$gg \to Hq\bar{q}g$	2519	3.9 s
$gg \to Hggg$	9325	20 s

- Tests:
  - ↪ IR poles reconstructions
  - ↪ gauge invariance



$$\frac{2\,\Re\mathrm{e}\left\{\mathcal{M}^{\text{tree-level}*}\,\mathcal{M}^{\text{one-loop}}\right\}}{\left|\mathcal{M}^{\text{tree-level}}\right|^2} \equiv \frac{a_{-2}}{\epsilon^2} + \frac{a_{-1}}{\epsilon} + a_0$$

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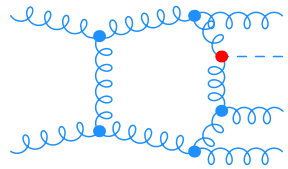

+ 13,178 diagrams

- Computational challenges
  - ↪ $\geq 10,000$ diagrams
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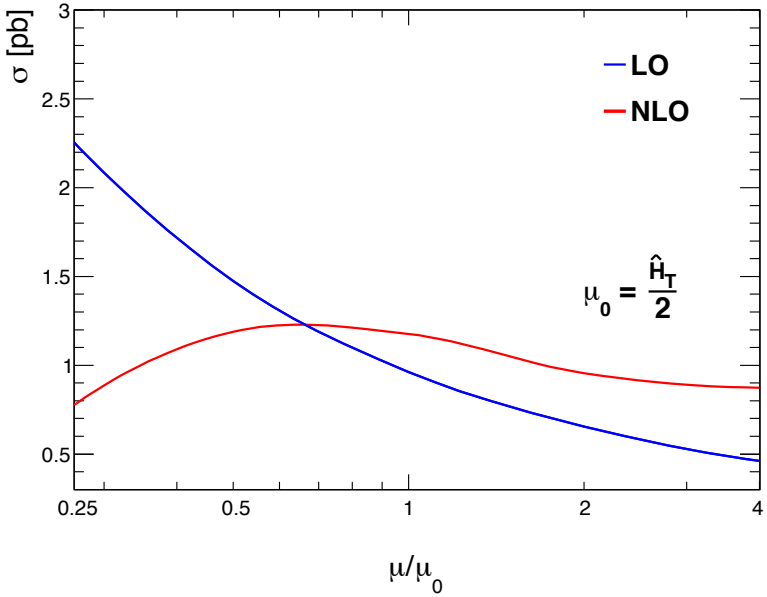
Observables via a *"hybrid" setup*

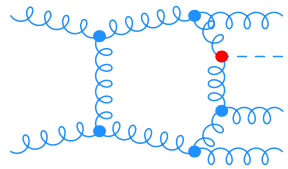
- GoSam+ Sherpa
  - ↪ Born & Virtual
- MadGraph/MadDipole/MadEvent
  - ↪ Real & dipole subtraction
- Tests performed:
  - ↪ $H + 2j$: hybrid scheme - GoSam + Sherpa agree
  - ↪ $H + 3j$ @ LO: Sherpa & MadGraph agree
  - ↪ $H + 3j$ @ NLO: α-independence (subtraction)



$$\hat{H}_T \equiv \sqrt{m_H^2 + p_{t,H}^2} + \Sigma_i \left| p_{t,i} \right|$$

Higgs plus jets in gluon fusion

Higgs plus three jets [Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, EM, Ossola, Peraro, Tramontano]



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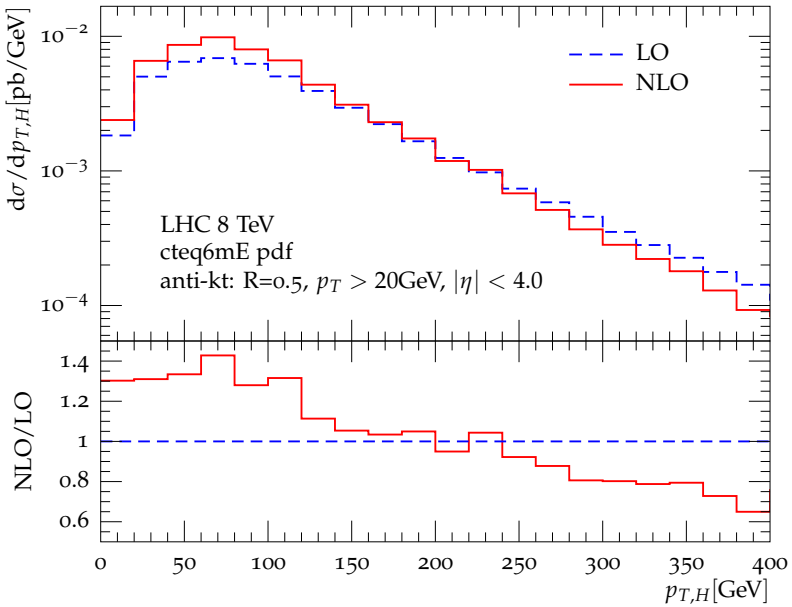

Higgs plus jets in gluon fusion

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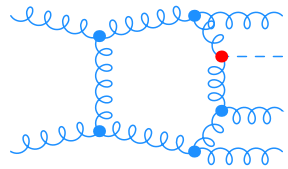

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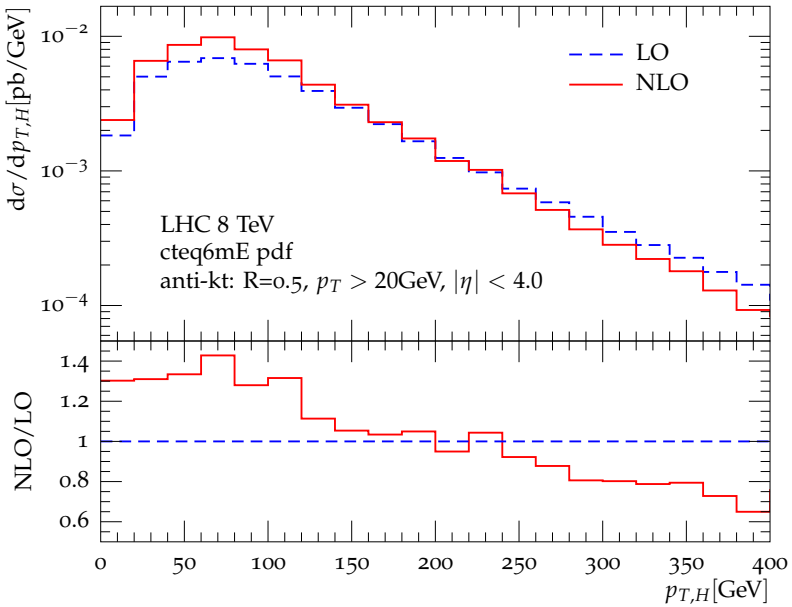
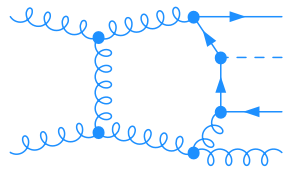


GoSam's virtual corrections available for any MC ⇝ further phenomenological analyses.

Higgs with a top–anti-top pair

$t\bar{t}Hj$ production [van Deurzen, Luisoni, Mastrolia, EM, Ossola, Peraro]

- signal for LHC studies
  - ↪ Higgs properties
  - ↪ $Ht\bar{t}$ coupling
- Computation using GoSam + Sherpa
- two scales (m_t & m_H) & 51 hexagons



+ 1,895 diagrams

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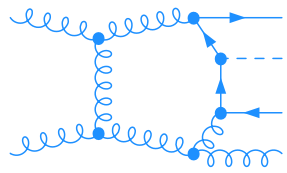
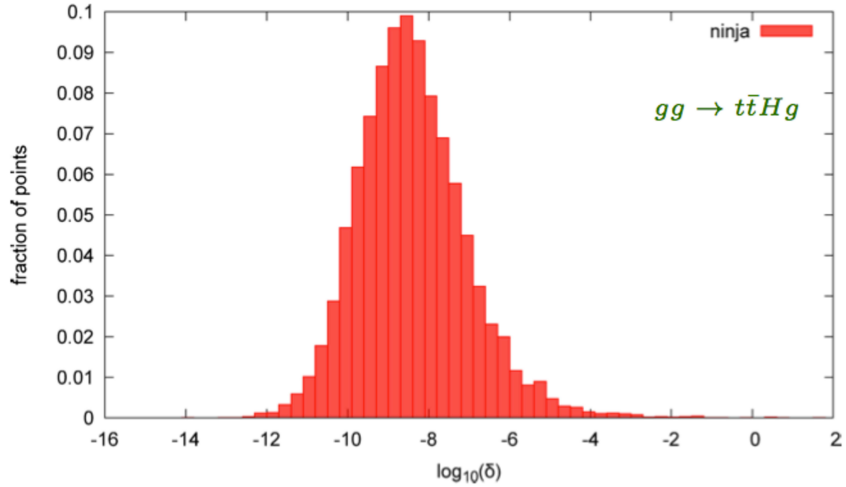


+ 1,895 diagrams

First application of the C++ library NINJA

- integrand reduction via Laurent expansion. . .
  [Mastrolia, EM, Peraro]
  - ↪ asymptotic limits to simplify the reconstruction
  - ↪ fewer coefficients have to be determined
  - ↪ subtraction works at the coefficient level
- . . . implemented via polynomial division
  - ↪ semi-numerical implementation
  - ↪ interfaced with GOSAM
- Timings $\frac{t_{\text{Samurai}}}{t_{\text{Ninja}}} \sim 2$

SUBPROCESS	DIAGRAMS	TIME/PS-POINT
$gg \to Ht\bar{t}g$	1575	2.5 s
$q\bar{q} \to Ht\bar{t}g$	320	0.2 s



$$\delta = \frac{2\,|A_{\text{rotated}} - A|}{|A_{\text{rotated}} + A|}$$

- 0.6% events with $\delta > 10^{-4}$

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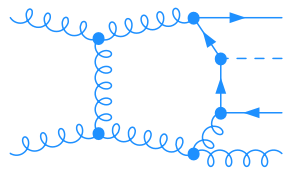

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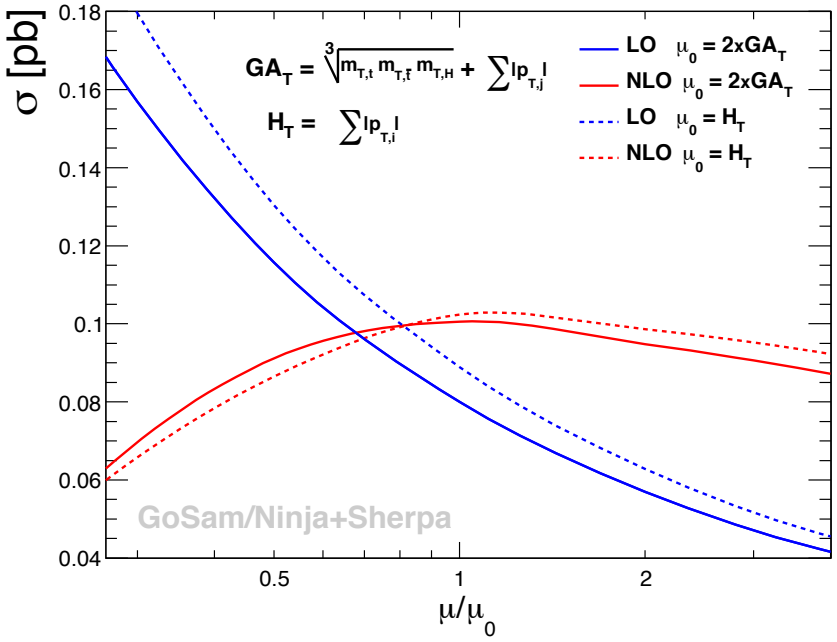
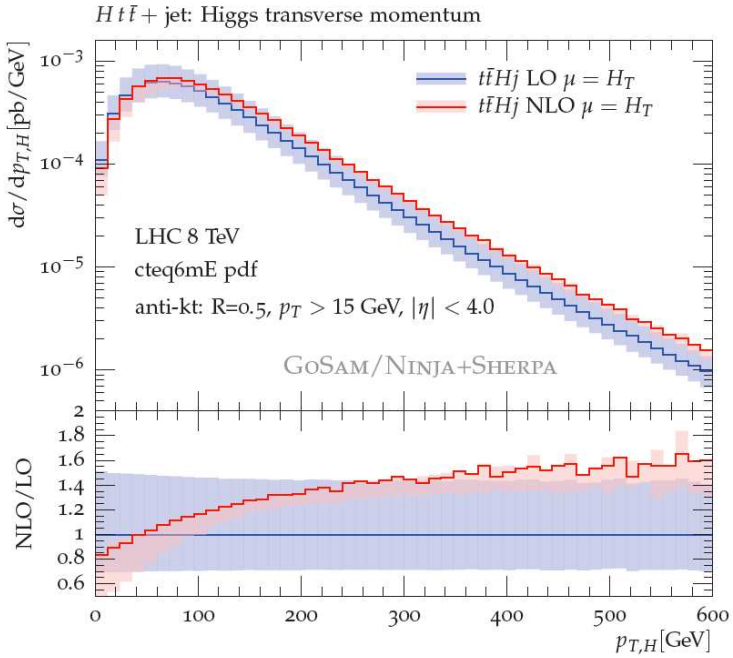
Some results:

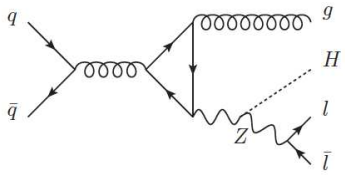


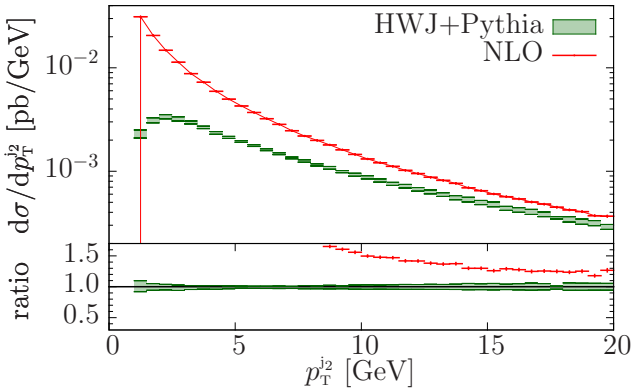


More Higgs-relevant processes

HW / HZ plus one jet [Luisoni, Nason, Oleari, Tramontano]

- allow to measure $H \to b\bar{b}$ / invisible
- NLO event generator using GoSam + Powheg
  - ↪ `GoSam` ⇝ virtual
  - ↪ `Powheg` ⇝ parton shower
- V-decay & m_t retained
- use of MiNLO [Hamilton, Nason, Zanderighi] ⇝ HW / HZ





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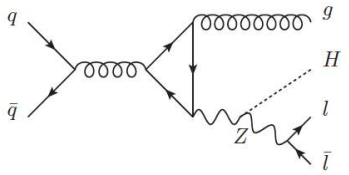
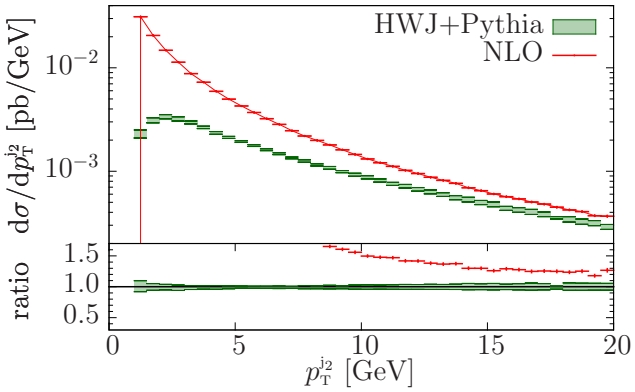
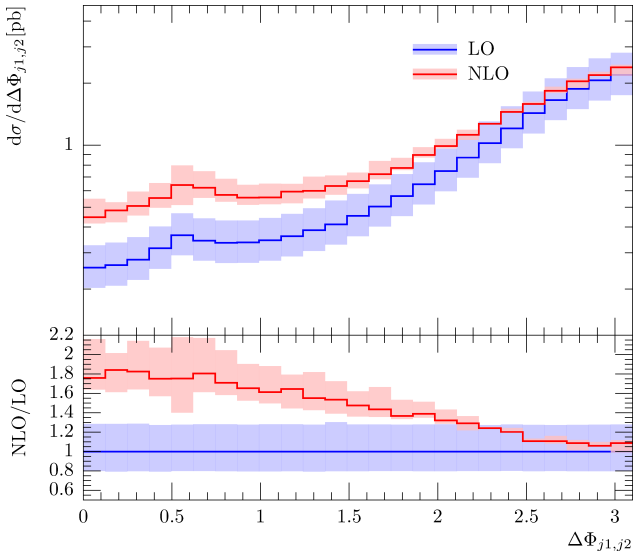




$\gamma\gamma$ plus two jets [Gehrmann, Greiner, Heinrich]

- background for $H + 2\,j$
- computed using GoSam + MadGraph/MadDipole/MadEvent
- smooth cone isolation criterion [Frixione]
- NLO corrections important:
  - ↪ proper normalization of the total rate
  - ↪ shape of the distributions



Conclusions

GoSam

- Automatic computation of virtual corrections @ one loop
  - Feynman diagram & d-dimensional algebra
  - several reduction procedures
- Interfaced to several Monte Carlo
- Computation of several Higgs-relevant processes
- Beside QCD, works for EW and BSM corrections
- "Dynamic“ framework
  - new ideas $\rightsquigarrow$ new techniques $\rightsquigarrow$ exciting results!
- Interface with Ninja
  - implements integrand reduction via Laurent expansion
  - faster and more stable reduction algorithm

Outlook

- More phenomenology:
  - interaction with Monte Carlo & experimental collaborations
- code improvements $\rightsquigarrow$ GoSam 2.0
- multi-loop extension under investigation