Associated Higgs production at NLO with GoSam

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Publications

Based on the work described in:

- S. Alioli, S. Badger, ..., HvD, ... et al., *"Update of the Binoth Les Houches Accord for a standard interface between Monte Carlo tools and one-loop programs"* arXiv: 1308.3462
- HvD, G. Luisoni, P. Mastrolia, E. Mirabella, G. Ossola and T. Peraro, arXiv:1308.3462 [hep-ph]. *"NLO QCD correction to Higgs boson production in association with a top quark pair and a jet"*, arXiv:1307.8437 [hep-ph].
- G. Cullen, HvD, N. Greiner, G. Luisoni, P. Mastrolia, E. Mirabella, G. Ossola., T. Peraro, and F. Tramontano, *"NLO QCD corrections to Higgs boson production plus three jets in gluon fusion"*, arXiv:1307.4737 [hep-ph].
- S. Heinemeyer, C. Mariotti, ..., HvD, ... et al., *"Handbook of LHC Higgs Cross Sections: 3. Higgs Properties"*, arXiv:1307.1347 [hep-ph]
- HvD, N. Greiner, G. Luisoni, P. Mastrolia, E. Mirabella, G. Ossola., T. Peraro, J.F. von Soden-Fraunhofen, and F. Tramontano, *"NLO QCD corrections to the production of Higgs plus two jets at the LHC,"* Phys. Lett. B **721**, 74 (2013).
- P. Mastrolia, E. Mirabella, G. Ossola., T. Peraro, HvD, *"The Integrand Reduction of One- and Two-Loop Scattering Amplitudes"* PoS LL2012 028 (2012).

Outline

Motivation

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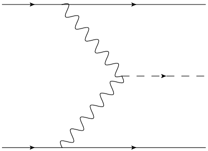
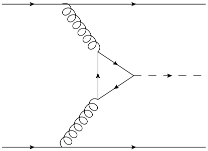


Vector Boson Fusion



Gluon Fusion via top loop

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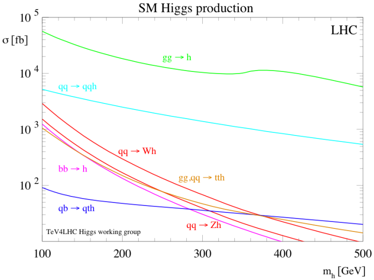

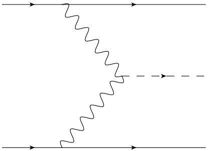

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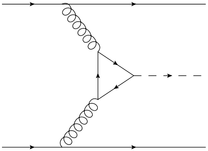
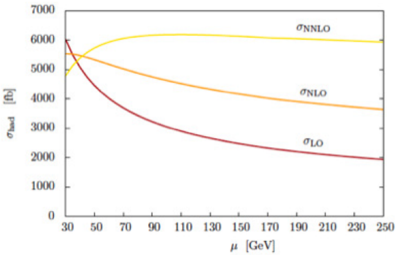


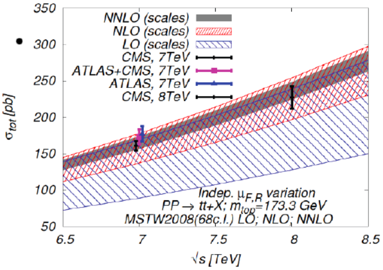
Gluon Fusion via top loop

Motivation for NLO



Higgs plus jet at NNLO

[Boughezal et al. (2013)]



Top pair production at NNLO

[Czakon, Fiedler, Mitov (2013)]

- Reduce theoretical error
- Strong dependence on renormalization and factorization scale

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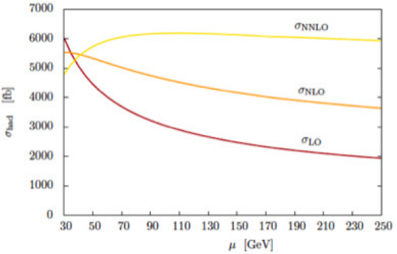

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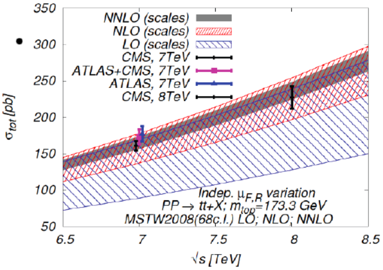

Top pair production at NNLO

[Czakon, Fiedler, Mitov (2013)]

- Reduce theoretical error
- Strong dependence on renormalization and factorization scale
- Development of more general framework for NLO automation

NLO cross section

$$\sigma^{NLO} = \int_{m+1}\left[d^{(4)}\sigma^{R} - d^{(4)}\sigma^{A}\right] + \int_{m}\left[d^{(4)}\sigma^{B} + \int_{loop} d^{(d)}\sigma^{V} + \int_{1} d^{(d)}\sigma^{A}\right]$$

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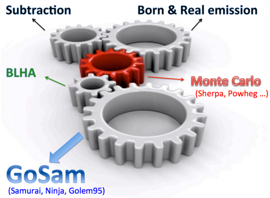
- NLO cross section consists of:
  - Leading Order: Born diagram
  - Virtual corrections: loop diagrams $\longleftarrow$ GoSam provides this part
  - Real corrections: Radiation
  - Subtraction terms to regulate infinities

GoSam

The GoSam collaboration:

G. Cullen, **HvD**, **N. Greiner**, **G. Heinrich**, **G. Luisoni**, **P. Mastrolia**, **E. Mirabella**, **G. Ossola**, **T. Peraro**, **J. Reichel**, **J. Schlenk**, **J.F. von Soden-Fraunhofen**, **F. Tramontano**

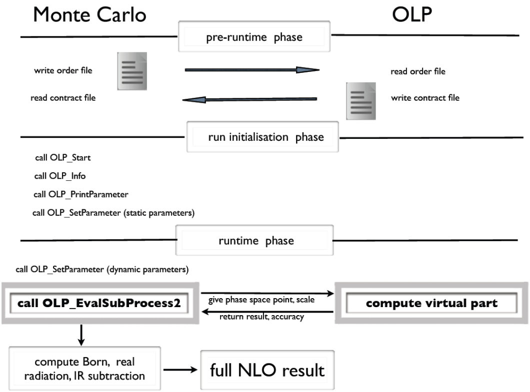


SAMURAI
$d-$dimensional Integrand-Level Reduction $\rightarrow$ **Current default**
Automated Model-independent Computation of the full Rational Term
Mastrolia, Ossola, Reiter, Tramontano

GOLEM95
Tensorial Reduction $\rightarrow$ **Rescue System**
Binoth, Guillet, Heinrich, Pilon, Reiter

NINJA $\rightarrow$ **Talk of T. Peraro**
Integrand-Level Reduction + Laurent Expansion $\rightarrow$ **Stable** and **Fast**!!
Mastrolia, Mirabella, Peraro

Binoth Les Houches Accord



"Update of the Binoth Les Houches Accord for a standard interface between Monte Carlo tools and one-loop programs", arXiv: 1308.3462

[Alioli, Badger, ..., HvD, ... et al. (2013)]

Interfaces with external MC

- GoSam + `MadGraph+MadDipole+MadEvent`
  → ad-hoc interface [Greiner]
- GoSam + Sherpa
  → via BLHA
- GoSam + POWHEG
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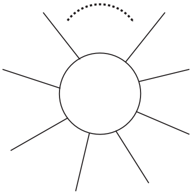
  → via BLHA [Luisoni, Nason, Oleari, Tramontano]
- GoSam + HERWIG
  → *work in progress* [Greiner, Heinrich, von Soden-Fraunhofen]
- GoSam + aMC@NLO
  → *work in progress*
  [HvD, Frederix, Frixione, Hirschi, Luisoni, Mastrolia, Ossola, Peraro]

Scattering amplitudes at one-loop



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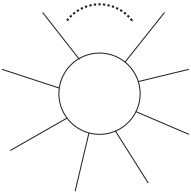

$$\mathcal{M}_n \equiv \int \mathcal{A}_n(\bar{q})\, d\bar{q}$$

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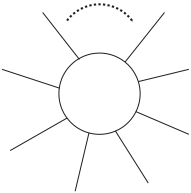

$$\mathcal{M}_n \equiv \int \mathcal{A}_n(\bar{q})\, d\bar{q} \equiv \int d^{-2\epsilon}\mu \int d^4 q \frac{N(q,\mu^2)}{\bar{D}_0 \ldots \bar{D}_{n-1}}$$

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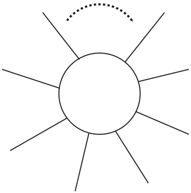

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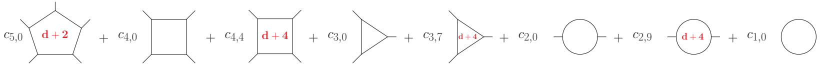
- Decompose:



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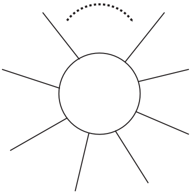

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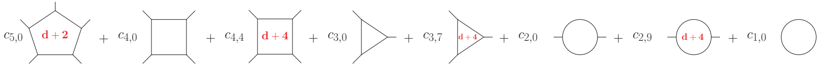

$$\int d^{-2\epsilon}\mu^2 d^4 q \mathcal{A}_n(q) = \int d\bar{q} \frac{c_{5,0}\mu^2}{D_0 D_1 D_2 D_3 D_4} + \int d\bar{q} \frac{c_{4,0} + c_{4,4}\mu^4}{D_0 D_1 D_2 D_3}$$
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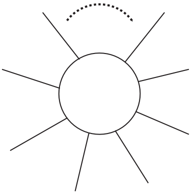

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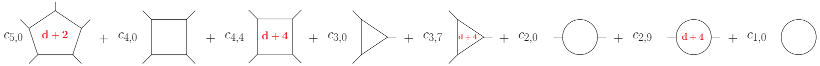

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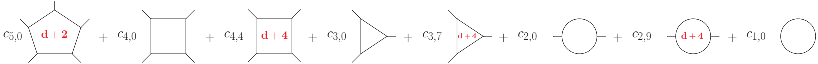
- computation of $\mathcal{M}_n \rightarrow$ computation of coefficients

Integral to Integrand



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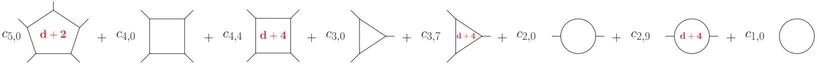

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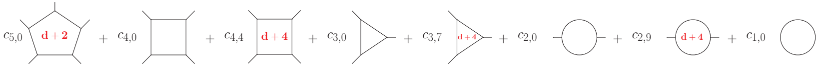

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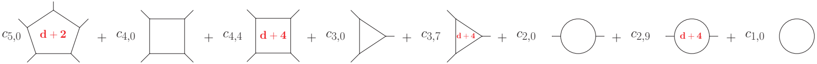

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$$\int d^{-2\epsilon}\mu^2 \int d^4 q \quad \frac{f_{ij\ldots}(q,\mu^2)}{D_i D_j \ldots} = 0$$

Determining the parametric form of the numerator

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$$\mathcal{A}_n = \sum_{ijklm} \frac{\Delta_{ijklm}(q,\mu^2)}{D_i D_j D_k D_l D_m} + \sum_{ijkl} \frac{\Delta_{ijkl}(q,\mu^2)}{D_i D_j D_k D_l} + \sum_{ijk} \frac{\Delta_{ijk}(q,\mu^2)}{D_i D_j D_k} + \sum_{ij} \frac{\Delta_{ij}(q,\mu^2)}{D_i D_j} + \sum_{i} \frac{\Delta_{i}(q,\mu^2)}{D_i}$$

- Form residues process independent
- Values of coefficients process dependent

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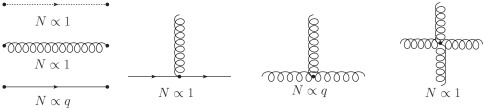
- Form residues process independent
- Values of coefficients process dependent
- Implemented in Samurai
  [Ossola, Reiter, Tramontano, Mastrolia, 2010]

Rankcounting, normal rank



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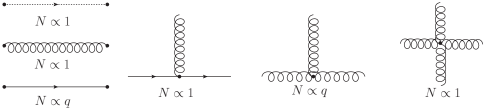

- Only q propagators and 3-gluon-vertices contribute one power of q to numerator

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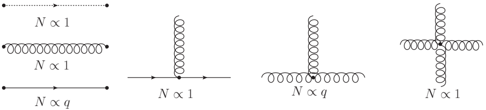

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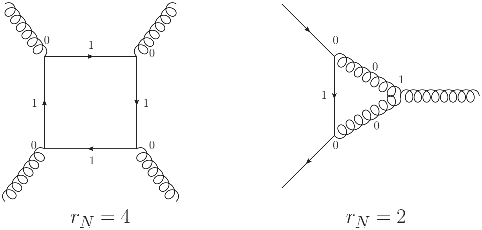

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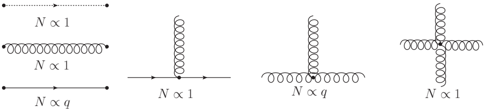

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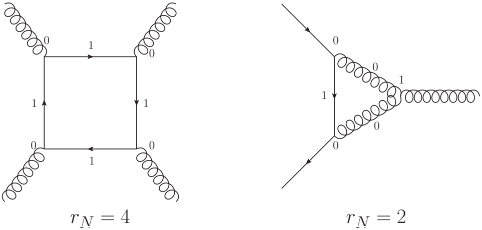
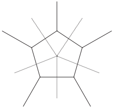


- $r_N \leq \#D$

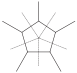
Integrand decomposition algorithm



$$\Delta_{ijk\ell m}(\bar{q}) = \mathrm{Res}_{ijk\ell m}\left\{\frac{N(\bar{q})}{\bar{D}_0 \cdots \bar{D}_{n-1}}\right\}$$

1 coefficient

Integrand decomposition algorithm



$$\Delta_{ijk\ell m}(\bar{q}) = \mathrm{Res}_{ijk\ell m}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}}\right\}$$

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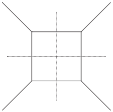

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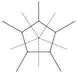
5 coefficients

Integrand decomposition algorithm



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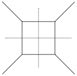

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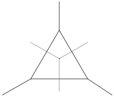

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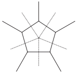
Integrand decomposition algorithm



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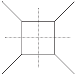

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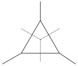

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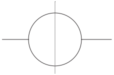

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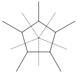

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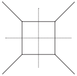

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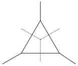

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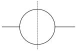

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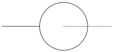

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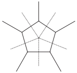
Integrand decomposition algorithm



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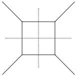

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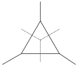

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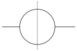

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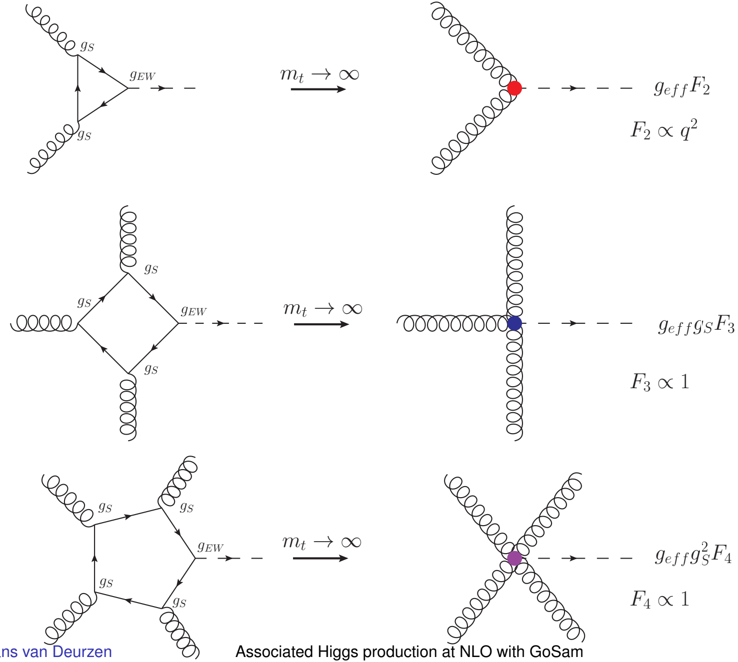
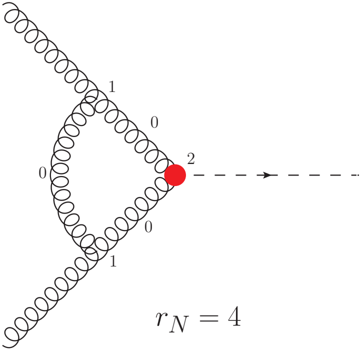
Hexagon: $\binom{6}{5}\cdot 1+\binom{6}{4}\cdot 5+\binom{6}{3}\cdot 10+\binom{6}{2}\cdot 10+\binom{6}{1}\cdot 5 = 386$ coefficients

Effective Vertices

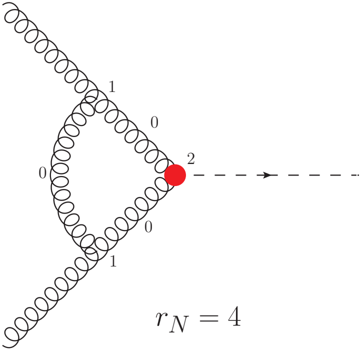


Rankcounting, higher rank



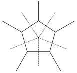
$r_N = 4$

Rankcounting, higher rank



- One effective vertex: $r_N \leq \#D + 1$

Extended rank Integrand decomposition algorithm



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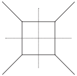
1→1 coefficient



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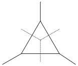
5→6 coefficients



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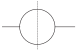
10→15 coefficients



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10→20 coefficients

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5→15 coefficients

[Mastrolia, Mirabella, Peraro, 2012]

Hexagon: $\binom{6}{5}\cdot 1 + \binom{6}{4}\cdot 6 + \binom{6}{3}\cdot 15 + \binom{6}{2}\cdot 20 + \binom{6}{1}\cdot 15 = (386 \rightarrow) 786$ coefficients

- Samurai → XSamurai [HvD et al.]

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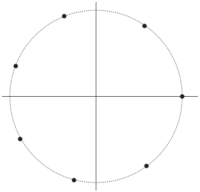

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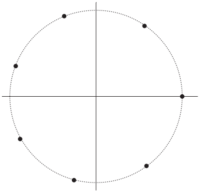

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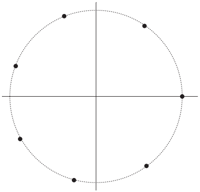

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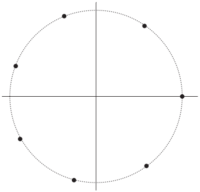
$$c_l = \frac{\rho^{-l}}{n+1} \sum_{k=0}^{n} P_k \exp\left[2\pi i \frac{k}{n+1} l\right]$$



[Mastrolia, Ossola, Papadopoulos, Pittau (2008)]

Sampling strategy

- $q = \sum_{i=1}^{4} x_i e_i \Rightarrow \mu^2, x_1, x_2, x_3, x_4$ variables

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  - Use DFT twice, $\Delta(\mu^2, x3, C/x3)$ and $\Delta(\mu^2 C/x_4, x_4)$
    solutions $\propto \frac{1}{1-C}$, problem if $C = 1$

Sampling strategy

- $q = \sum_{i=1}^{4} x_i e_i \Rightarrow \mu^2, x_1, x_2, x_3, x_4$ variables
- At quintuple cut: Everything constrained
- At quadruple cut: $\Delta(\mu^2)$
- At triple cut: $\Delta(\mu^2, x_3, x_4)$ Condition: $x_3 x_4 = C(x_1, x_2) = C \Rightarrow \Delta(\mu^2, x_3, C/x_3)$
  - Use DFT: solutions $\propto \frac{1}{C}$, problem if $C = 0$
  - Use DFT twice, $\Delta(\mu^2, x3, C/x3)$ and $\Delta(\mu^2 C/x_4, x_4)$
    solutions $\propto \frac{1}{1-C}$, problem if $C = 1$
  - Branching:
    if(C=0): Use $\Delta(\mu^2, x_3, C/x_3)$ and $\Delta(\mu^2 C/x_4, x_4)$
    else: Use $\Delta(\mu^2, x_3, C/x_3)$

Sampling strategy

- At double cut: $\Delta(\mu^2, x_1, x_3, x_4)$ with $x_3 x_4 = F(x_1) = A x_1^2 + B x_1 + C$ lot of branchings:

Sampling strategy

- At double cut: $\Delta(\mu^2, x_1, x_3, x_4)$ with $x_3 x_4 = F(x_1) = A x_1^2 + B x_1 + C$ lot of branchings:
  - F=0 has no solutions
  - F=0 has one zero solution
  - F=0 has one non-zero solution
  - F=0 has two zero solutions
  - F=0 has two non-zero solutions

Sampling strategy

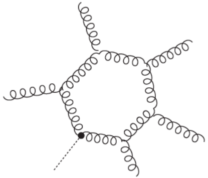
- At double cut: $\Delta(\mu^2, x_1, x_3, x_4)$ with $x_3 x_4 = F(x_1) = A x_1^2 + B x_1 + C$ lot of branchings:
  - F=0 has no solutions
  - F=0 has one zero solution
  - F=0 has one non-zero solution
  - F=0 has two zero solutions
  - F=0 has two non-zero solutions
- At single cut: $\Delta(\mu^2, x_1, x_2, x_3, x_4)$ with $x_3 x_4 - x_1 x_2 = G$
  similar to the triple cut

Towards Higgs jets in GF @ NLO

H+0j	**1 NLO**
$gg \to H$	1 NLO
H+1j	**62 NLO**
$qq \to Hqq$	14 NLO
$qg \to Hqg$	48 NLO
H+2j	**926 NLO**
$qq' \to Hqq'$	32 NLO
$qq \to Hqq$	64 NLO
$qg \to Hqg$	179 NLO
$gg \to Hgg$	651 NLO
H+3j	**13179 NLO**
$qq' \to Hqq'g$	467 NLO
$qq \to Hqqg$	868 NLO
$qg \to Hqgg$	2519 NLO
$gg \to Hggg$	9325 NLO

Computational Challenges:

- Over 10,000 diagrams
- Higher-Rank terms
- 60 Rank-7 hexagons

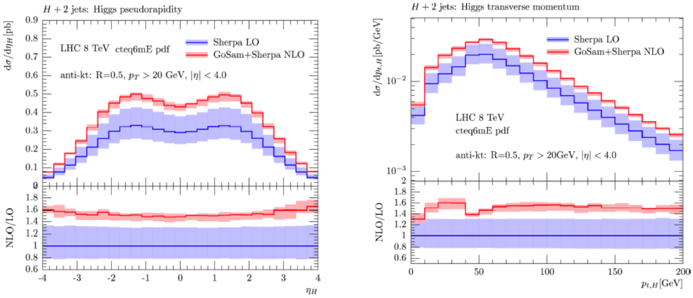


Complex calculations $\to$ GoSam enhanced

grouping, optimalization through Form4.0, numerical polarization vectors, parallelization

Higgs + 2 jets in GF @ NLO

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



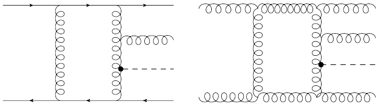
HvD, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano (2013)

(also appeared in *Handbook of LHC Higgs Cross Sections: 3. Higgs Properties*)

Higgs + 3 jets in GF: virtual part

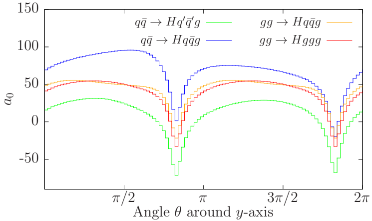
Cullen, HvD, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano, **arXiv:1307.4737**

Virtual parts computed with GoSam



$$\frac{2\,\mathfrak{Re}\left\{\mathcal{M}^{\text{tree-level}*}\mathcal{M}^{\text{one-loop}}\right\}}{(\alpha_s/2\pi)\left|\mathcal{M}^{\text{tree-level}}\right|^2} \equiv \frac{a_{-2}}{\epsilon^2} + \frac{a_{-1}}{\epsilon} + a_0$$

SUBPROCESS	DIAGRAMS	TIME/PS-POINT [sec]
$q\bar{q} \to Hq'\bar{q}'g$	467	0.29
$q\bar{q} \to Hq\bar{q}g$	868	0.60
$gg \to Hq\bar{q}g$	2519	3.9
$gg \to Hggg$	9325	20



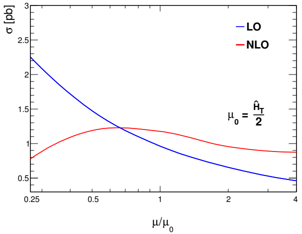
Number of Feynman diagrams and time per PS-point point for each subprocess

Tests: gauge invariance and IR poles

Higgs + 3 jets GF @ NLO: cross-section

Cross sections are obtained with a hybrid setup:

- GoSam + Sherpa for Born and of the virtual contributions
- `MadGraph+MadDipole+MadEvent` for reals/subtraction/integrated dipoles



$$\mu_F = \mu_R = \frac{\hat{H}_T}{2} = \mu_0$$

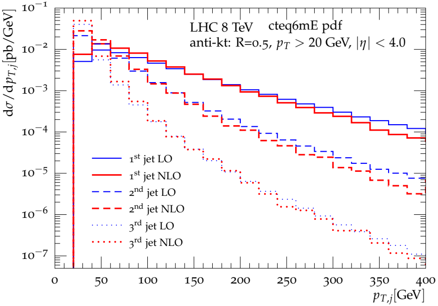
$$\hat{H}_T = \sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}|$$

Tests performed on the cross section:

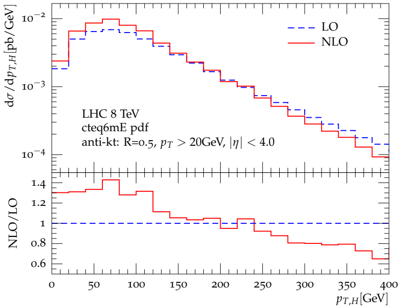
- NLO H+2 jets: Agreement between hybrid scheme and GoSam+Sherpa
- LO H+3 jets: Agreement between MADGRAPH and Sherpa
- NLO H+3 jets: Independence from $\alpha-$parameter (subtraction+int. dipoles)

Cullen, HvD, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano **arXiv:1307.4737**

Higgs + 3 jets GF @ NLO: distributions



p_T of the Jets



p_T of the Higgs boson

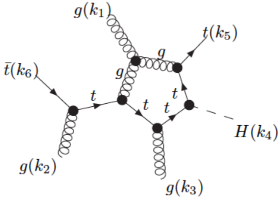
$pp \to Hjjj$ generated by GoSam can be paired with available MC programs for further phenomenological analyses.

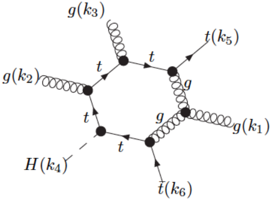
Cullen, HvD, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano **arXiv:1307.4737**

$pp \to Ht\bar{t}$ + 1 jet @ NLO

First Application of GoSam/Ninja + Sherpa → **Talk of T. Peraro**

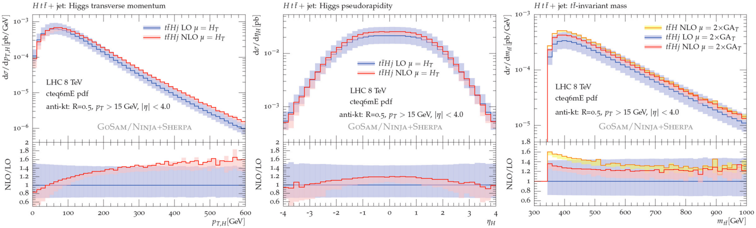
$t\bar{t}H + 1j$	**1895 NLO**
$qq \to Ht\bar{t}g$	320 NLO
$gg \to Ht\bar{t}g$	1575 NLO

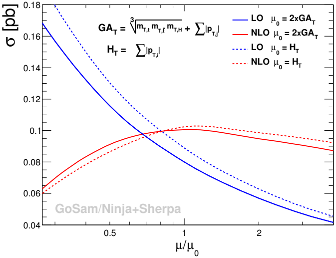




- Two different mass scales: Higgs and Top
- 51 hexagons in the gluon-gluon channel

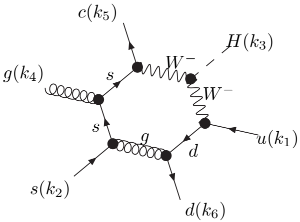
$Ht\bar{t}j$ results

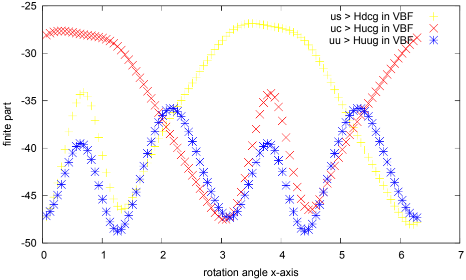




Vector Boson Fusion

H+2j	240 NLO
$us \to Hdc$	24 NLO
$uc \to Huc$	24 NLO
$us \to Hus$	24 NLO
$ds \to Hds$	24 NLO
$ud \to Hud$	48 NLO
$uu \to Huu$	48 NLO
$dd \to Hdd$	48 NLO
H+3j	**2160 NLO**
$us \to Hdcg$	216 NLO
$uc \to Hucg$	216 NLO
$us \to Husg$	216 NLO
$ds \to Hdsg$	216 NLO
$ud \to Hudg$	432 NLO
$uu \to Huug$	432 NLO
$dd \to Hddg$	432 NLO





Conclusions

- GoSam is a powerful framework for the automatic computation of one loop virtual amplitudes
- Samurai has been extended to deal with higher rank numerators: Xsamurai
- GoSam is interfaced to a lot of Monte Carlo Programs
- GoSam has been used for a lot of different phenomenology studies, among which
  - Higgs plus two jet in GF
  - Higgs plus three jet in GF
  - Higgs $t\bar{t}$ jet
  - Higgs plus two and three jet in VBF in progress

Outlook

- Even more processes on the way
- Interaction with MC and experimental collaborations
- Additional code improvements towards GoSam 2.0
- Multi-loop integrand reduction in the making (talk T.Peraro on Thursday)

BACKUP SLIDES