NLO QCD calculations of Higgs production at LHC with GoSam

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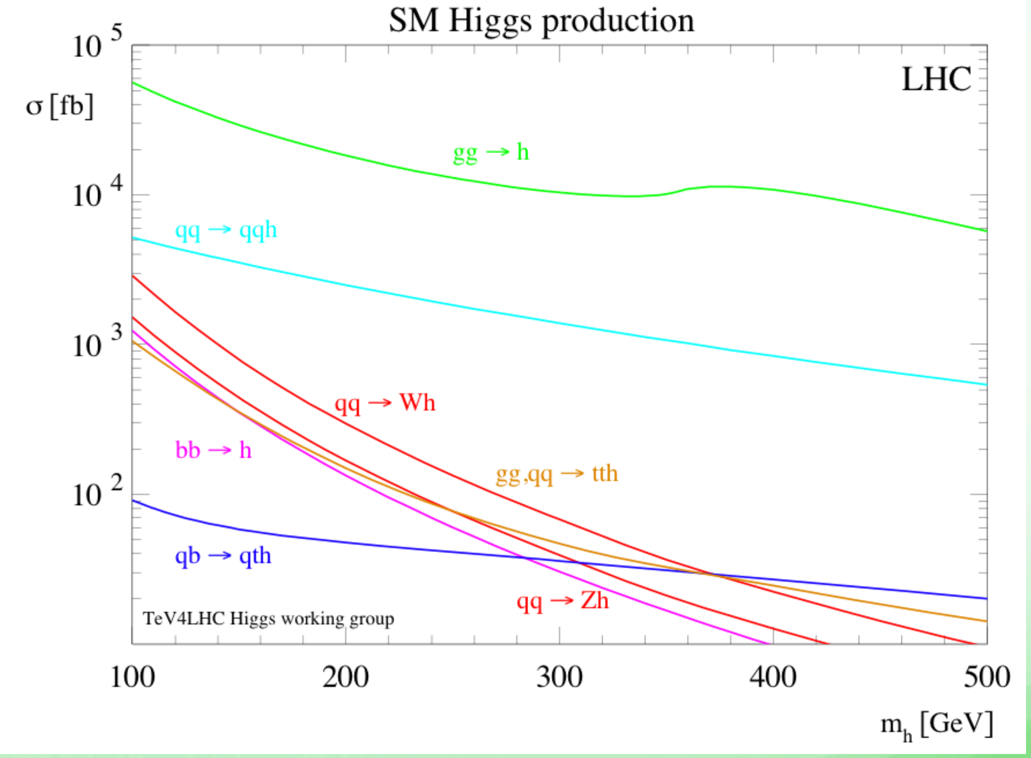
Outline

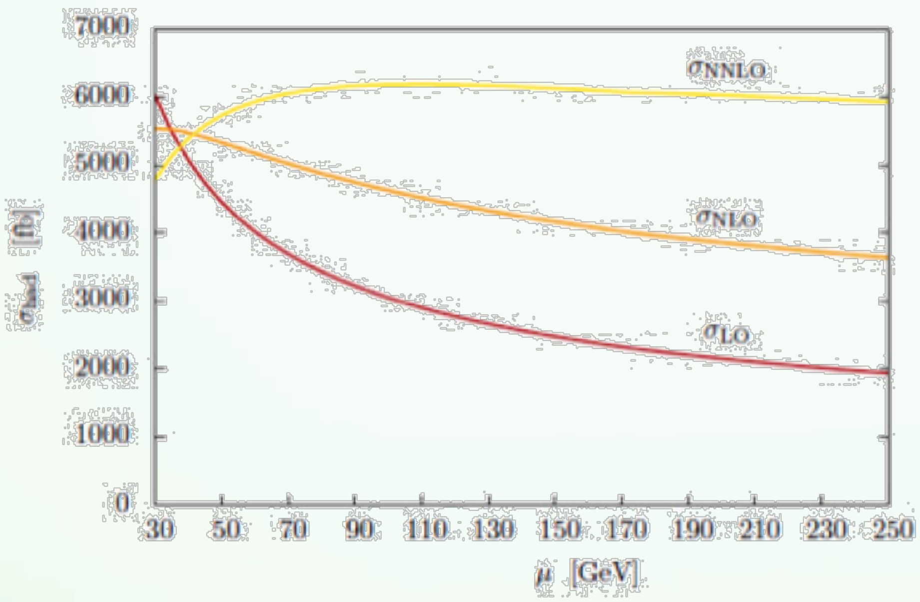
- Motivation, introduction GoSam
- Integrand decomposition
- Extension to higher rank
  - Computational strategy
  - Applications: H+2j, H+3j in GF
- Ninja
  - Improved algorithm
  - Applications: Httj

Motivation

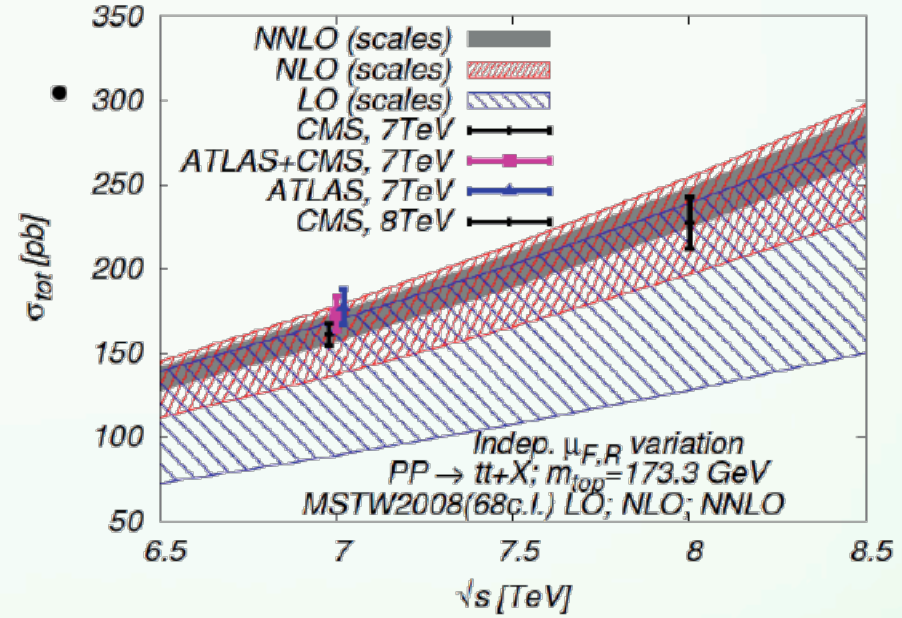
- Higgs discovery by Atlas and CMS
- Need to determine properties:
  - spin
  - CP properties
  - couplings



Motivation for NLO



Higgs+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

NLO calculations

$$\sigma^{NLO} = \int_m \left[d^{(4)}\sigma^B + \int_{loop} d^{(d)}\sigma^V + \int_1 d^{(d)}\sigma^S \right] + \int_{m+1} \left[d^{(4)}\sigma^R - d^{(4)}\sigma^S \right]$$

- NLO calculation consists of:
  - LO: Born diagram
  - Virtual corrections: loop diagrams ← GoSam
  - Real corrections: additional radiation
  - Subtraction terms to regulate infinities

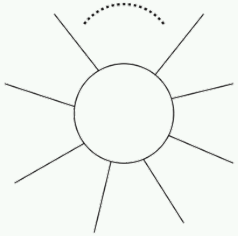
GoSam

Collaboration
Cullen, HvD, Greiner, Heinrich, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Reichel, Schlenk, von Soden-Fraunhofen, Tramontano

Reduction algorithms

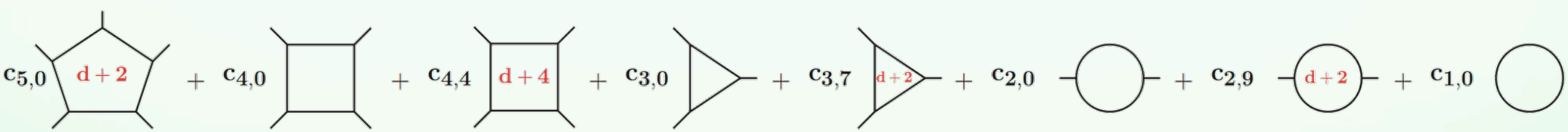
- *Samurai*, *Xsamurai*
  d-dimensional integrand-level reduction
  current default
  [Mastrolia, Ossola, Reiter, Tramontano]; [HvD (2013)]
- *Golem95*, *Golem95 higherrank extension*
  Tensorial reduction
  Numerically stable ➔ rescue system
  [Binoth, Guillet, Heinrich, Pilon, Reiter]; [Guillet, Heinrich, von Soden-Fraunhofen]
- *Ninja*
  Integrand-level+Laurent expansion
  Stable and fast
  [Mastrolia, Mirabella, Peraro]; [HvD, Luisoni, Mastrolia, Mirabella, Ossola, Peraro]

Amplitudes at one loop



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

Decompose:



$$\int d^{-2\epsilon}\mu^2 d^4q \mathcal{A}_n(q) = \int d\bar{q} \frac{c_{5,0}\mu^2}{D_0 D_1 D_2 D_3 D_4} + \int d\bar{q} \frac{c_{4,0} + c_{4,4}\mu^4}{D_0 D_1 D_2 D_3}$$
$$+ \int d\bar{q} \frac{c_{3,0} + c_{3,7}\mu^2}{D_0 D_1 D_2} + \int d\bar{q} \frac{c_{2,0} + c_{2,9}\mu^2}{D_0 D_1} + \int d\bar{q} \frac{c_{1,0}}{D_0}$$

Amplitudes at one loop

$$\int d^{-2\epsilon}\mu^2 d^4 q \mathcal{A}_n(q) = \int d\bar{q} \frac{c_{5,0}\mu^2}{D_0 D_1 D_2 D_3 D_4} + \int d\bar{q} \frac{c_{4,0} + c_{4,4}\mu^4}{D_0 D_1 D_2 D_3} + \int d\bar{q} \frac{c_{3,0} + c_{3,7}\mu^2}{D_0 D_1 D_2} + \int d\bar{q} \frac{c_{2,0} + c_{2,9}\mu^2}{D_0 D_1} + \int d\bar{q} \frac{c_{1,0}}{D_0}$$

Integrand level:

$$\mathcal{A}_n(q) = \frac{c_{5,0}\mu^2 + f_{01234}(q,\mu^2)}{D_0 D_1 D_2 D_3 D_4} + \frac{c_{4,0} + c_{4,4}\mu^4 + f_{0123}(q,\mu^2)}{D_0 D_1 D_2 D_3} + \frac{c_{3,0} + c_{3,7}\mu^2 + f_{012}(q,\mu^2)}{D_0 D_1 D_2} + \frac{c_{2,0} + c_{2,9}\mu^2 + f_{01}(q,\mu^2)}{D_0 D_1} + \frac{c_{1,0} + f_0(q,\mu^2)}{D_0}$$

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

Parametric form integrand

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

- Residues multivariate polynomials
- Need rank to determine generic form
- Renormalizability requires rank ≤ propagators

Parametric form integrand

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

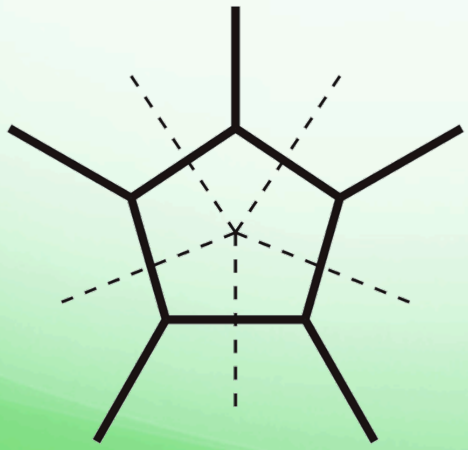
- Form residues process independent
- Values of coefficients process dependent

Integrand decomposition

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

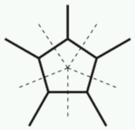
$$+ \sum_{ijk} \frac{\Delta_{ijk}(q,\mu^2)}{D_i D_j D_k} + \sum_{ij} \frac{\Delta_{ij}(q,\mu^2)}{D_i D_j} + \sum_{i} \frac{\Delta_{i}(q,\mu^2)}{D_i}$$

Quintuple cut



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

Integrand decomposition



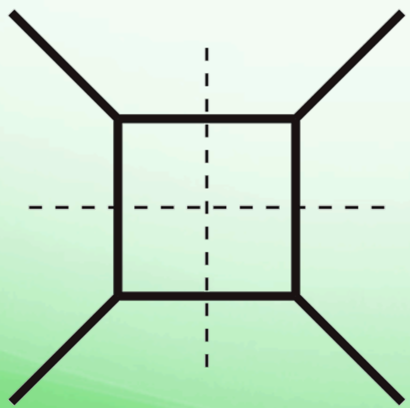
$$\Delta_{ijk\ell m}(\bar{q}) = \mathrm{Res}_{ijk\ell m}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}}\right\}$$

1 coefficient

$$\mathcal{A}_n = \sum_{ijklm}\frac{\Delta_{ijklm}(q,\mu^2)}{D_iD_jD_kD_lD_m}+\sum_{ijkl}\frac{\Delta_{ijkl}(q,\mu^2)}{D_iD_jD_kD_l}+$$

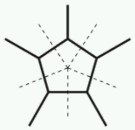
$$+\sum_{ijk}\frac{\Delta_{ijk}(q,\mu^2)}{D_iD_jD_k}+\sum_{ij}\frac{\Delta_{ij}(q,\mu^2)}{D_iD_j}+\sum_{i}\frac{\Delta_{i}(q,\mu^2)}{D_i}$$

Quadruple cut



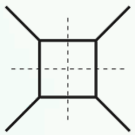
$$\Delta_{ijk\ell}(\bar{q}) = \mathrm{Res}_{ijk\ell}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m}\right\}$$

Integrand decomposition



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

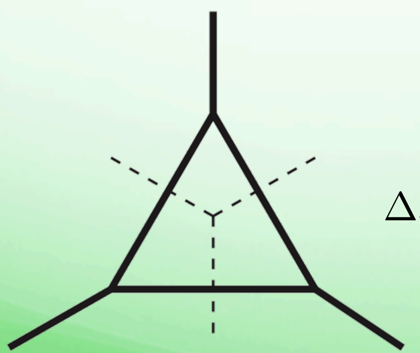
1 coefficient



$$\Delta_{ijk\ell}(\bar{q}) = \mathrm{Res}_{ijk\ell}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m}\right\}$$

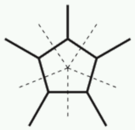
5 coefficients

Triple cut



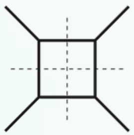
$$\Delta_{ijk}(\bar{q}) = \mathrm{Res}_{ijk}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m} - \sum_{i<<\ell}^{n-1}\frac{\Delta_{ijk\ell}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell}\right\}$$

Integrand decomposition



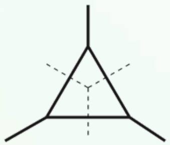
$$\Delta_{ijk\ell m}(\bar{q}) = \text{Res}_{ijk\ell m}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}}\right\}$$

1 coefficient



$$\Delta_{ijk\ell}(\bar{q}) = \text{Res}_{ijk\ell}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m}\right\}$$

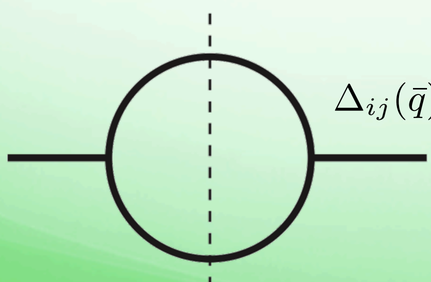
5 coefficients



$$\Delta_{ijk}(\bar{q}) = \text{Res}_{ijk}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m} - \sum_{i<<\ell}^{n-1}\frac{\Delta_{ijk\ell}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell}\right\}$$

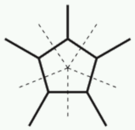
10 coefficients

Double cut



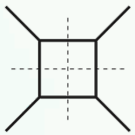
$$\Delta_{ij}(\bar{q}) = \text{Res}_{ij}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m} - \sum_{i<<\ell}^{n-1}\frac{\Delta_{ijk\ell}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell} - \sum_{i<<k}^{n-1}\frac{\Delta_{ijk}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k}\right\}$$

Integrand decomposition



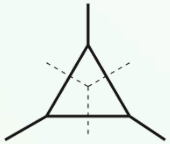
$$\Delta_{ijk\ell m}(\bar{q}) = \mathrm{Res}_{ijk\ell m}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}}\right\}$$

1 coefficient



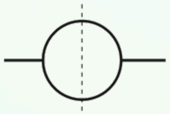
$$\Delta_{ijk\ell}(\bar{q}) = \mathrm{Res}_{ijk\ell}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m}\right\}$$

5 coefficients



$$\Delta_{ijk}(\bar{q}) = \mathrm{Res}_{ijk}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m} - \sum_{i<<\ell}^{n-1}\frac{\Delta_{ijk\ell}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell}\right\}$$

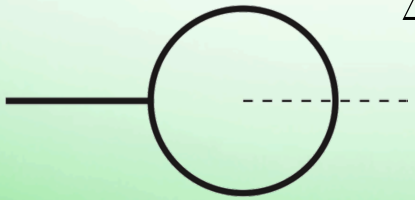
10 coefficients



$$\Delta_{ij}(\bar{q}) = \mathrm{Res}_{ij}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m} - \sum_{i<<\ell}^{n-1}\frac{\Delta_{ijk\ell}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell} - \sum_{i<<k}^{n-1}\frac{\Delta_{ijk}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k}\right\}$$

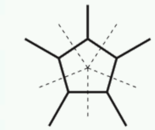
10 coefficients

Single cut



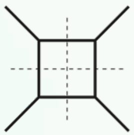
$$\Delta_i(\bar{q}) = \mathrm{Res}_i\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m} - \sum_{i<<\ell}^{n-1}\frac{\Delta_{ijk\ell}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell} + \right.$$
$$\left. - \sum_{i<<k}^{n-1}\frac{\Delta_{ijk}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k} - \sum_{i<j}^{n-1}\frac{\Delta_{ij}(\bar{q})}{\bar{D}_i\bar{D}_j}\right\}$$

Integrand decomposition



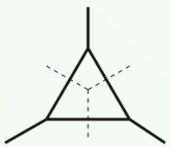
$$\Delta_{ijk\ell m}(\bar{q}) = \mathrm{Res}_{ijk\ell m}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}}\right\}$$

1 coefficient



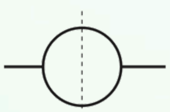
$$\Delta_{ijk\ell}(\bar{q}) = \mathrm{Res}_{ijk\ell}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m}\right\}$$

5 coefficients



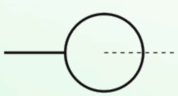
$$\Delta_{ijk}(\bar{q}) = \mathrm{Res}_{ijk}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m} - \sum_{i<<\ell}^{n-1}\frac{\Delta_{ijk\ell}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell}\right\}$$

10 coefficients



$$\Delta_{ij}(\bar{q}) = \mathrm{Res}_{ij}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m} - \sum_{i<<\ell}^{n-1}\frac{\Delta_{ijk\ell}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell} - \sum_{i<<k}^{n-1}\frac{\Delta_{ijk}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k}\right\}$$

10 coefficients



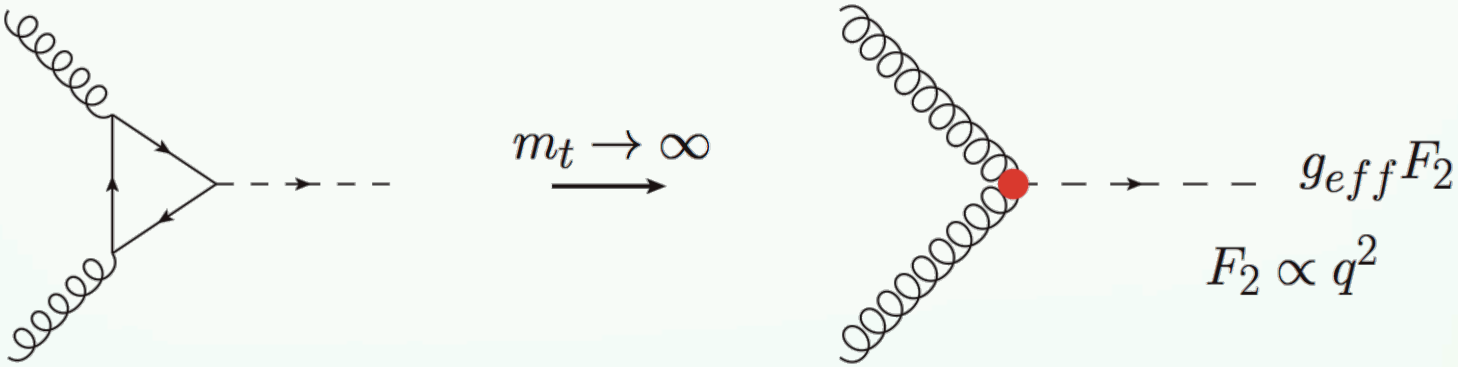
$$\Delta_{i}(\bar{q}) = \mathrm{Res}_{i}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m} - \sum_{i<<\ell}^{n-1}\frac{\Delta_{ijk\ell}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell} + \right.$$
$$\left. - \sum_{i<<k}^{n-1}\frac{\Delta_{ijk}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k} - \sum_{i<j}^{n-1}\frac{\Delta_{ij}(\bar{q})}{\bar{D}_i\bar{D}_j}\right\}$$

5 coefficients

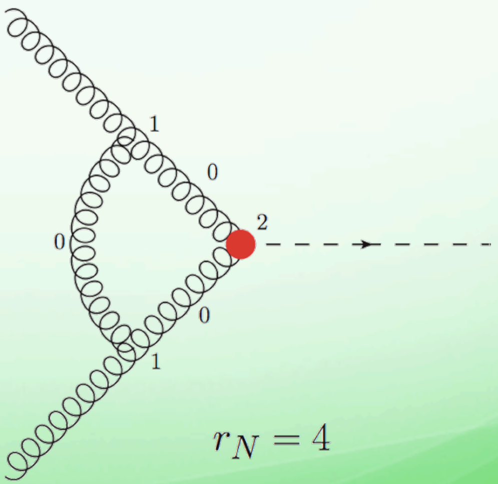
Hexagon:

$$\binom{6}{5}\cdot 1 + \binom{6}{4}\cdot 5 + \binom{6}{3}\cdot 10 + \binom{6}{2}\cdot 10 + \binom{6}{1}\cdot 5 = 461 \text{ coefficients}$$

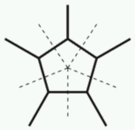
Effective vertices



- Effective vertex in loop adds two powers of q
- New rule: rank ≤ propagators + 1

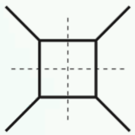


Integrand decomposition



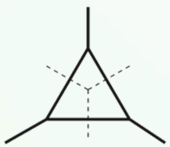
$$\Delta_{ijk\ell m}(\bar{q}) = \mathrm{Res}_{ijk\ell m}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}}\right\}$$

1➔1 coefficient



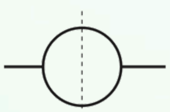
$$\Delta_{ijk\ell}(\bar{q}) = \mathrm{Res}_{ijk\ell}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m}\right\}$$

5➔6 coefficients



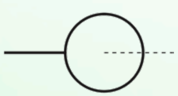
$$\Delta_{ijk}(\bar{q}) = \mathrm{Res}_{ijk}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m} - \sum_{i<<\ell}^{n-1}\frac{\Delta_{ijk\ell}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell}\right\}$$

10➔15 coefficients



$$\Delta_{ij}(\bar{q}) = \mathrm{Res}_{ij}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m} - \sum_{i<<\ell}^{n-1}\frac{\Delta_{ijk\ell}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell} - \sum_{i<<k}^{n-1}\frac{\Delta_{ijk}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k}\right\}$$

10➔20 coefficients



$$\Delta_{i}(\bar{q}) = \mathrm{Res}_{i}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m} - \sum_{i<<\ell}^{n-1}\frac{\Delta_{ijk\ell}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell} + \right.$$
$$\left. - \sum_{i<<k}^{n-1}\frac{\Delta_{ijk}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k} - \sum_{i<j}^{n-1}\frac{\Delta_{ij}(\bar{q})}{\bar{D}_i\bar{D}_j}\right\}$$

5➔15 coefficients

[Mastrolia, Mirabella, Peraro (2012)]; [HvD (2013)]

Hexagon:

$$\binom{6}{5}\cdot 1 + \binom{6}{4}\cdot 6 + \binom{6}{3}\cdot 15 + \binom{6}{2}\cdot 20 + \binom{6}{1}\cdot 15 = (461 \rightarrow)786 \text{ coefficients}$$

Discrete Fourier Transformation

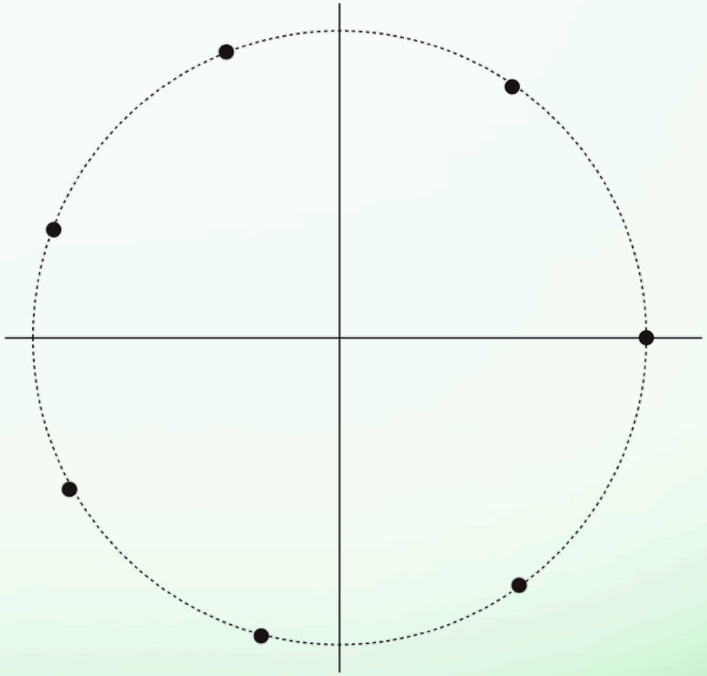
$$P(x) = c_0 + c_1 x + c_2 x^2 + \ldots + c_n x^n$$

$$x_k = \rho \exp\left[-2\pi i \frac{k}{n+1}\right]$$

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

$$\sum_{n=0}^{N-1} \exp\left[2\pi i \frac{k}{N} n\right] \exp\left[-2\pi i \frac{k'}{N} n\right] = N \delta_{kk'}$$

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



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

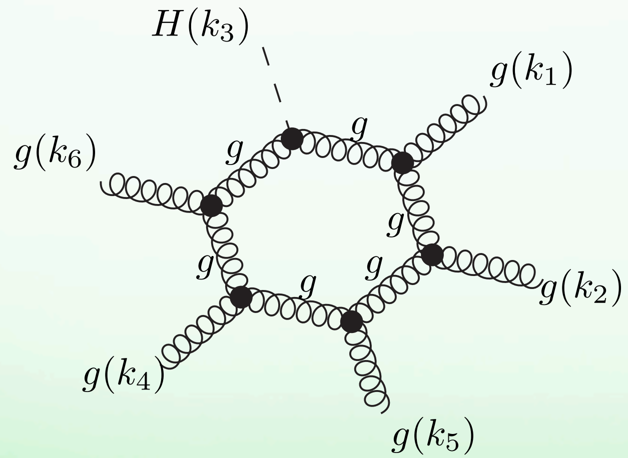
Sampling strategy

- Cuts impose conditions on the relation between variables
- These can lead to infinities when using the DFT naively
- Solution: Branch for each situation
- Especially in higherrank numerous instances
- Xsamurai: Systematic implementation

[HvD, Acta Phys. Polon. B44 (2013) 11, 2223-2230]

Higgs plus jets in GF@NLO

- Computational challenges
  - Over 10,000 diagrams
  - Higher-rank terms
  - 60 rank-7 hexagons



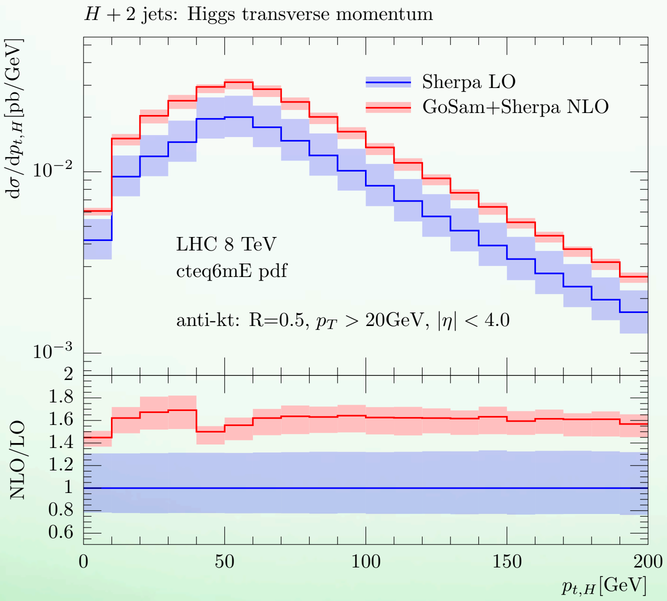
H+0j	**1 NLO**
$gg \to H$	1 NLO
H+1j	**62 NLO**
$qq \to Hg$	14 NLO
$gg \to Hg$	48 NLO
H+2j	**926 NLO**
$qq' \to Hqq'$	32 NLO
$qq \to Hqq$	64 NLO
$qg \to Hqg$	179 NLO
$gg \to Hgg$	651 NLO
H+3j	**13179 NLO**
$qq' \to Hqq'g$	467 NLO
$qq \to Hqqg$	868 NLO
$qg \to Hqgg$	2519 NLO
$gg \to Hggg$	9325 NLO

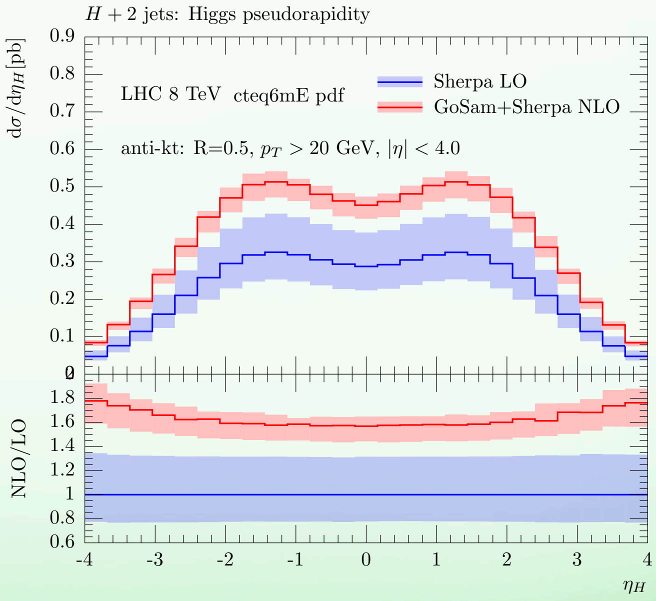
Complex calculations ➔ GoSam enhanced

grouping, optimization 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)]

Higgs + 3 jets GF@NLO: cross section

[Cullen, HvD, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano (2013)]

- Cross section obtained with hybrid setup:
  - GoSam + Sherpa for Born and virtual contributions
  - MadGraph+MadDipole+MadEvent for
    real contributions, subtraction terms, integrated dipoles

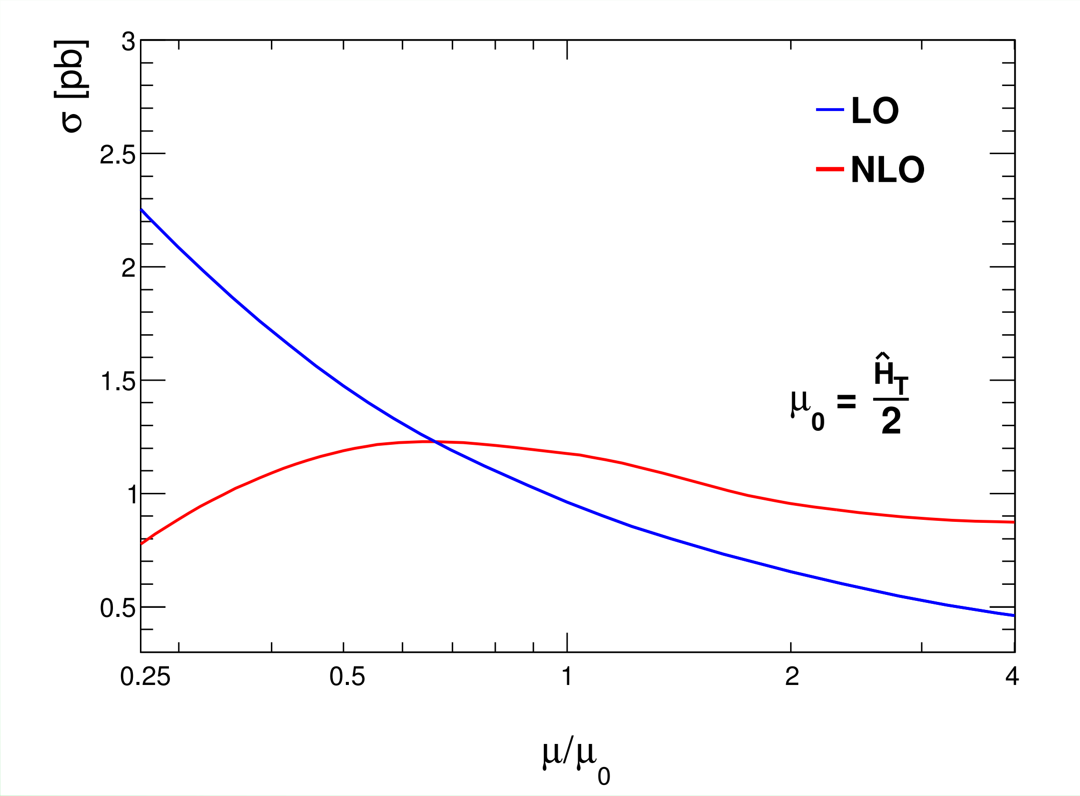
Higgs + 3 jets GF@NLO: cross section

[Cullen, HvD, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano (2013)]

- Tests performed on the cross section
  - NLO H+2j: Agreement between hybrid setup and GoSam+Sherpa
  - LO H+3j: Agreement MadGraph and Sherpa
  - NLO H+3j: Independence from α -parameter (subtr.+int.dipoles)

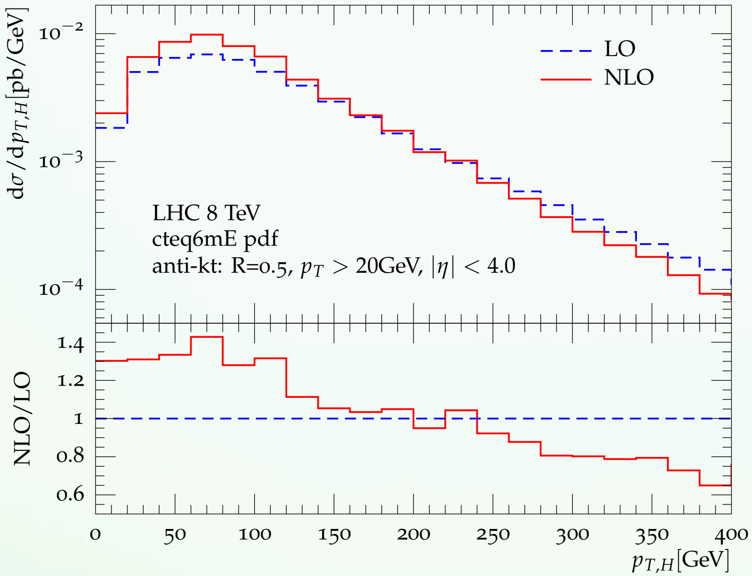
Higgs + 3 jets GF@NLO: results

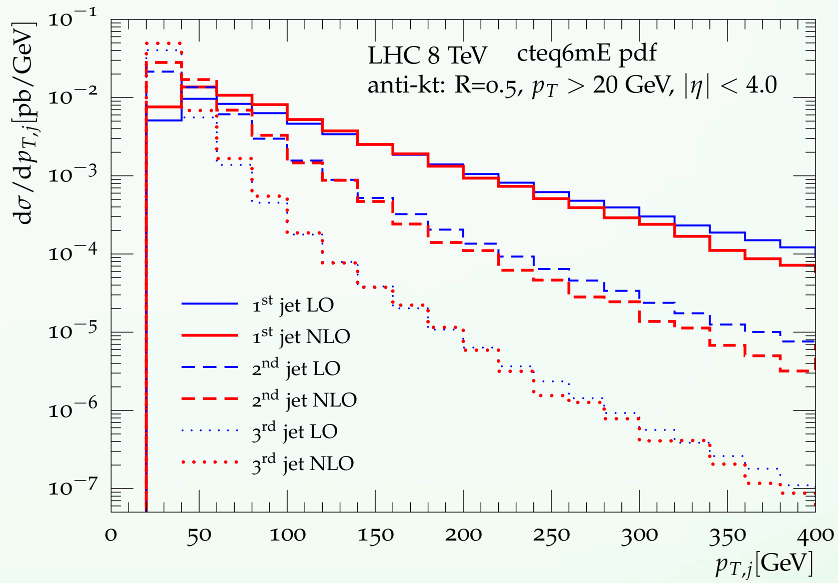
[Cullen, HvD, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano (2013)]



Higgs + 3 jets GF@NLO: distributions

[Cullen, HvD, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano (2013)]





- pp➔Hjjj can be paired with available MC programs for further phenomenological analyses

Ninja

- New reduction algorithm based on Laurent expansion [Mastrolia, Mirabella, Peraro (2012)]
- Improved in all directions
  - Faster (timings per PSP)
  - More stable (less bad points)
  - More precise (in correct digits)
- Higher rank included

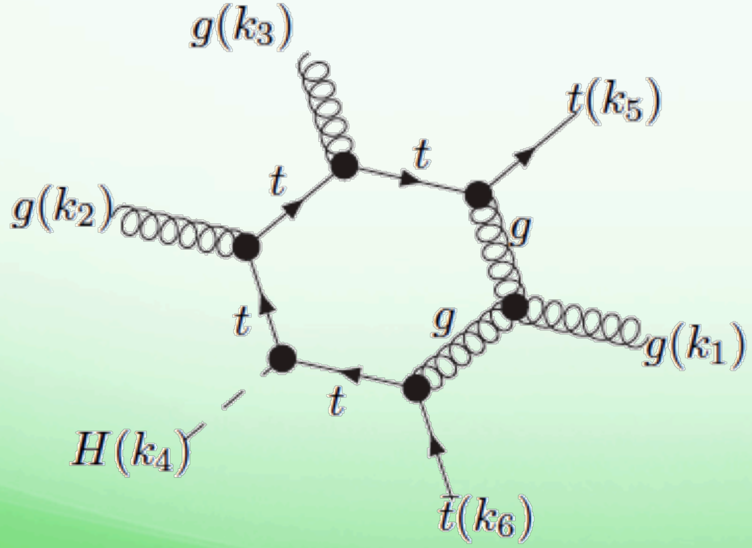
[Peraro (2014)]

[HvD, Luisoni, Mastrolia, Mirabella, Ossola, Peraro (2013)]

pp → Htt̄ +1 jet @ NLO

[HvD, Luisoni, Mastrolia, Mirabella, Ossola, Peraro (2013)]

- First application of GoSam+Ninja
- Two different mass scales: Higgs and top
- 51 hexagons in the gluon-gluon channel



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

pp → Htt̄ +1 jet results

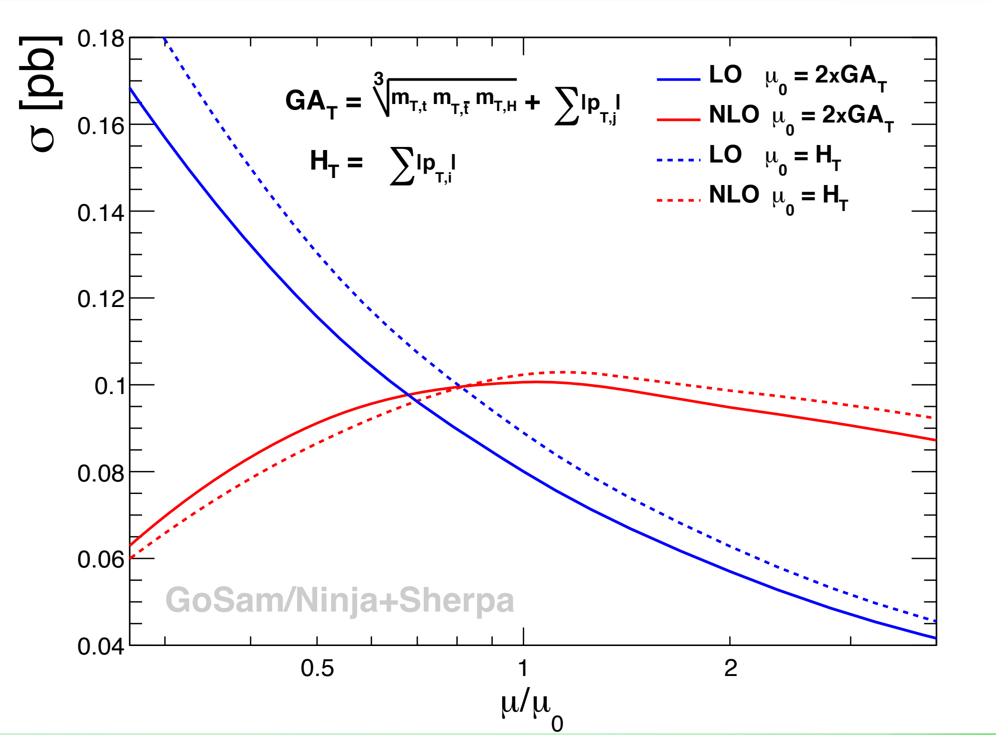
[HvD, Luisoni, Mastrolia, Mirabella, Ossola, Peraro (2013)]

$$\mu_R = \mu_F = \mu_0 \qquad H_T = \sum_i |p_T^i|$$

$$GA_T = (m_T^H m_T^t m_T^{\bar{t}})^{1/3} + \sum_{jets} |p_T^j|$$

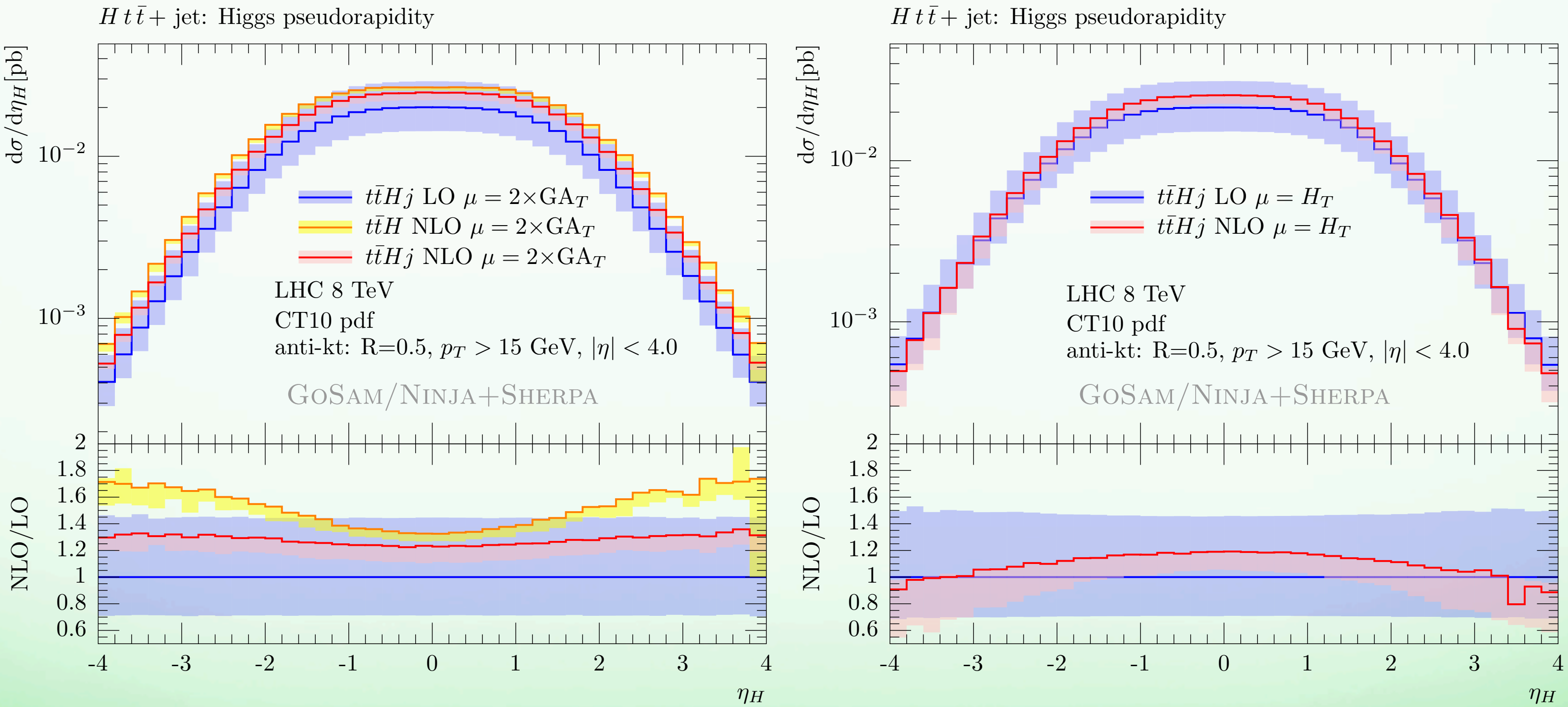
$$\mu_0 = 2GA_T \qquad \mu_0 = H_T$$

Central Scale	σ_{LO} [fb]	σ_{NLO} [fb]
$2GA_T$	$80.03^{+35.64}_{-23.02}$	$100.6^{+0.00}_{-9.43}$
H_T	$88.93^{+41.41}_{-26.13}$	$102.3^{+0.00}_{-15.82}$



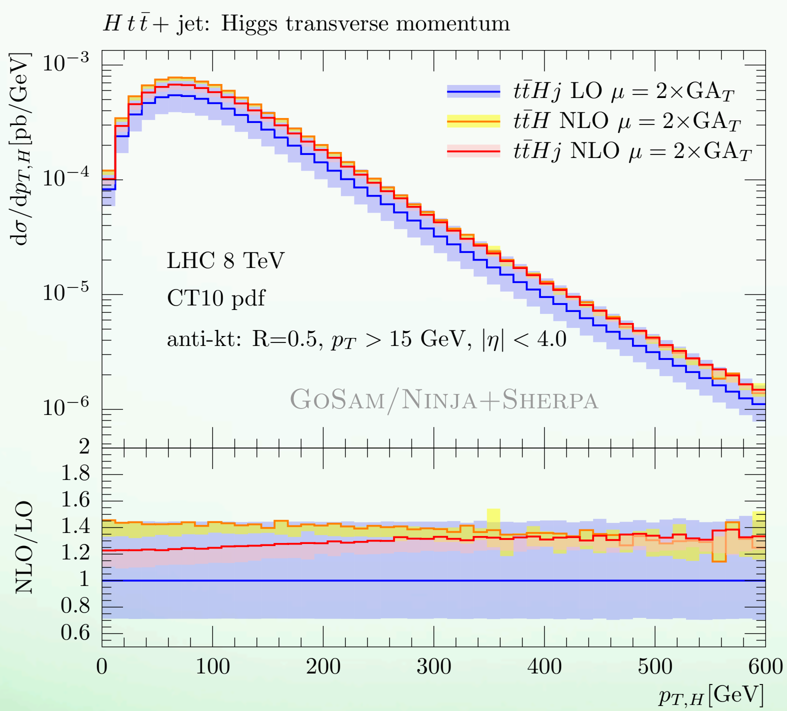
pp → H$t\bar{t}$ +1 jet results

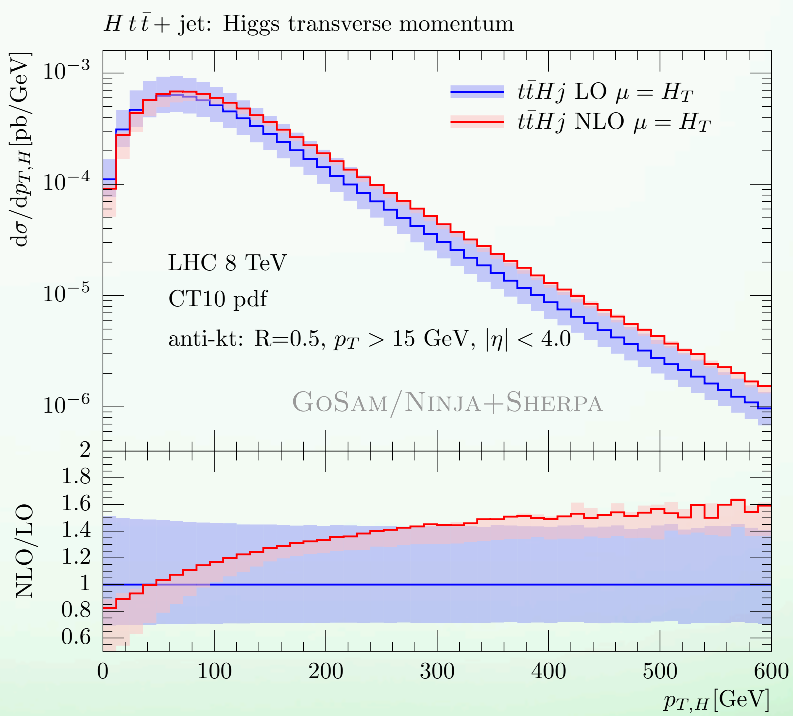
[HvD, Luisoni, Mastrolia, Mirabella, Ossola, Peraro (2013)]



pp → $Ht\bar{t}$ +1 jet results

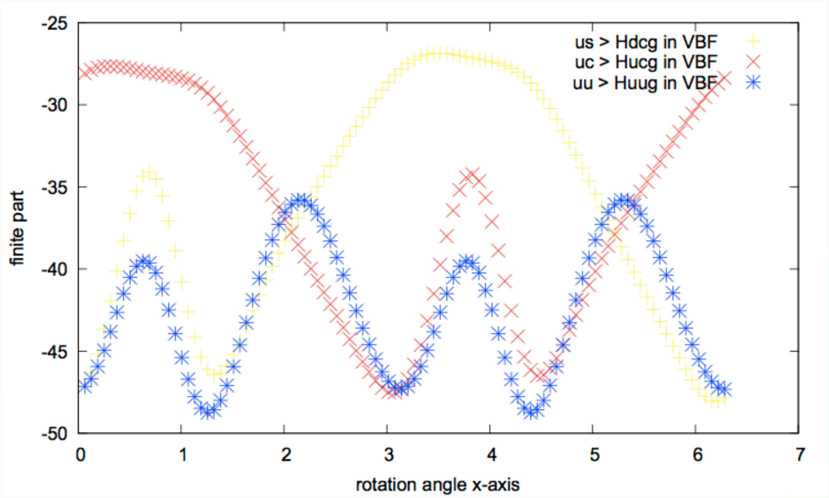
[HvD, Luisoni, Mastrolia, Mirabella, Ossola, Peraro (2013)]

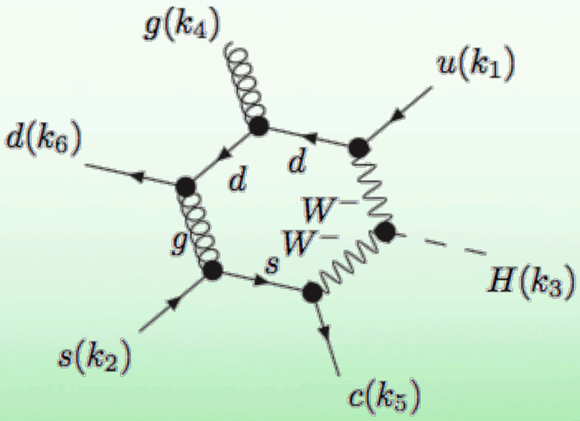




Vector Boson Fusion

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



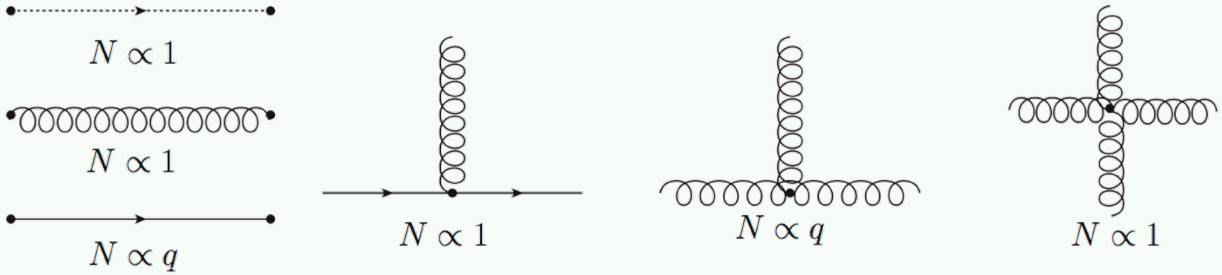


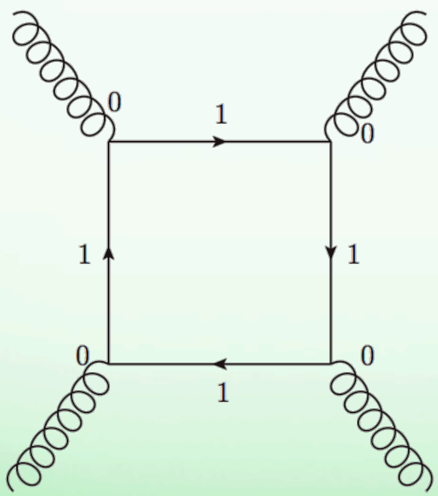
Conclusions

- Samurai has been extended to higher rank: Xsamurai
- Higgs plus two and three jets in GF have been calculated
- Ninja has been introduced as new algorithm
- $Ht\bar{t}j$ has been calculated
- Higgs plus jets in VBF is no problem

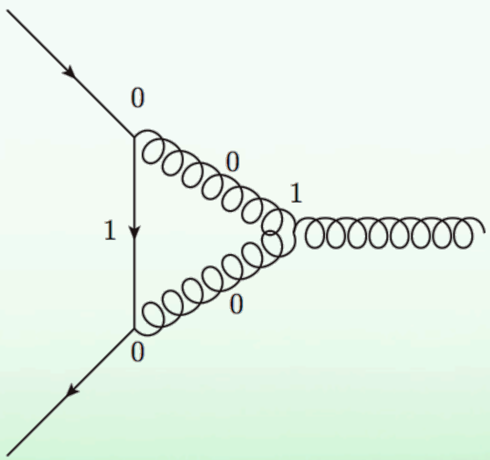
Backup slides

Rank of the numerator



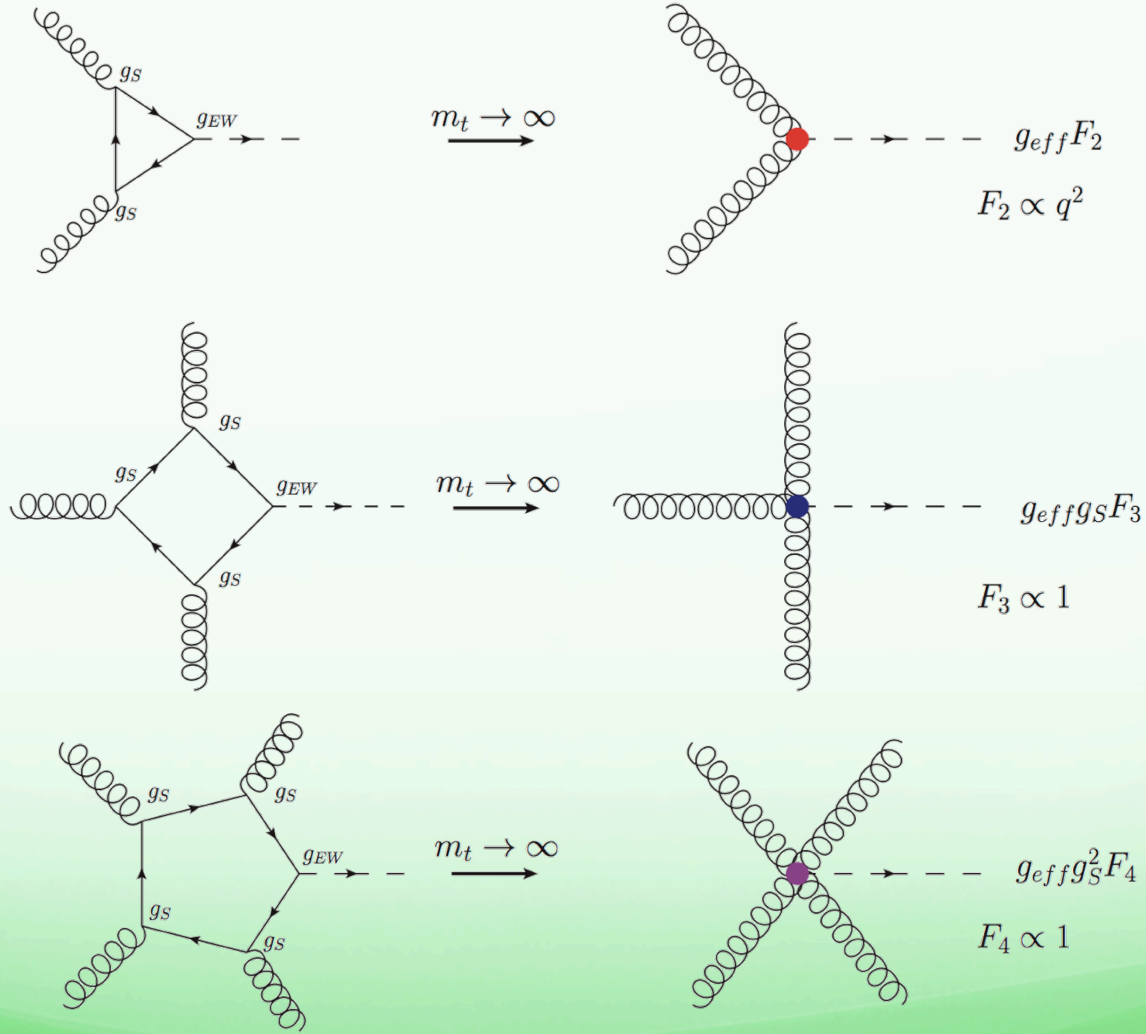


$r_N = 4$



$r_N = 2$

Effective vertices



Sampling strategy

$$\Lambda(\mu^2, q) \quad q^\mu = \sum x_i e_i^\mu \rightarrow (\mu^2, x_1, x_2, x_3, x_4)$$

- Five variables
- Quintuple cut: 5 conditions on 5 variables
  ➔ Everything constrained
- Quadruple cut: 4 conditions on 5 variables
  ➔ 1 free variable

$$\Lambda(\mu^2)$$

[HvD, Acta Phys. Polon. B44 (2013) 11, 2223-2230]

Sampling strategy

- Triple cut: 3 conditions on 5 variables
  ➔ 2 free variables

- One of those conditions constrains the product

$$x_3 x_4 = C(\mu^2)$$

$$\Lambda(\mu^2, x_3) \quad \overset{\text{DFT}}{\rightarrow} \quad c_i \propto \frac{1}{C}$$

$$\left.\begin{array}{l}\Lambda(\mu^2, x_3)\\ \Lambda(\mu^2, x_4)\end{array}\right\} \quad \overset{\text{DFT}}{\rightarrow} \quad c_i \propto \frac{1}{1-C}$$

[HvD, Acta Phys. Polon. B44 (2013) 11, 2223-2230]

Sampling strategy

Quadruple cut		Triple cut	$C=0$	$C\neq 0$
$\Lambda(0,q)$	2	$\Lambda(0,x_3,C/x_3)$	5	9
		$\Lambda(0,C/x_4,x_4)$	4	0
$\Lambda(+\mu_s^2,q)$	2	$\Lambda(+\mu_s^2,x_3,C/x_3)$	5	5
$\Lambda(-\mu_s^2,q)$	2	$\Lambda(-\mu_s^2,1,C)$	1	1

[HvD, Acta Phys. Polon. B44 (2013) 11, 2223-2230]

Sampling strategy

- Double cut: 2 conditions on 5 variables
➔ 3 free parameters

- One of those constraints the product

$$x_3 x_4 = F(\mu^2, x_1) = A\, x_1^2 + B\, x_1 + C(\mu^2)$$

- Numerous branchings: F can be zero/non-zero, equation can have 0,1 or 2 solutions

[HvD, Acta Phys. Polon. B44 (2013) 11, 2223-2230]

Sampling strategy

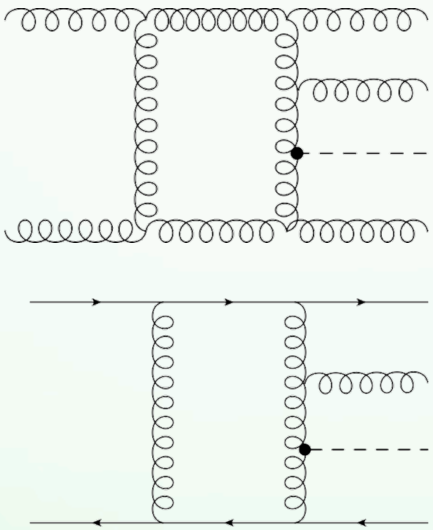
Double cut	$F=0$	$F\neq 0$	Single cut	$G=0$	$G\neq 0$
$\Lambda(0,0,x_3,F/x_3)$	4	7	$\Lambda(0,x_1,G/x_1,0,0)$	3	5
$\Lambda(0,0,F/x_4,x_4)$	3	0	$\Lambda(0,G/x_2,x_2,0,0)$	2	0
$\Lambda(0,x_{1a},x_3,F/x_3)$	3	5	$\Lambda(0,0,0,x_3,G/x_3)$	3	5
$\Lambda(0,x_{1a},F/x_4,x_4)$	2	0	$\Lambda(0,0,0,G/x_4,x_4)$	2	0
$\Lambda(0,x_{1b},x_3,F/x_3)$	2	3	$\Lambda(0,x_1,-G/x_1,1,0)$	1	2
$\Lambda(0,x_{1b},F/x_4,x_4)$	1	0	$\Lambda(0,-G/x_2,x_2,1,0)$	1	0
$\Lambda(0,x_{1c},1,F)$	1	1	$\Lambda(0,x_1,-G/x_1,0,1)$	1	2
			$\Lambda(0,-G/x_2,x_2,0,1)$	1	0
$\Lambda(\mu_s^2,0,x_3,F/x_3)$	2	3	$\Lambda(\mu_s^2,0,0,0,0)$	1	0
$\Lambda(\mu_s^2,0,F/x_4,x_4)$	1	0	$\Lambda(\mu_s^2,1,G,0,0)$	0	1
$\Lambda(\mu_s^2,1,1,F)$	1	1			

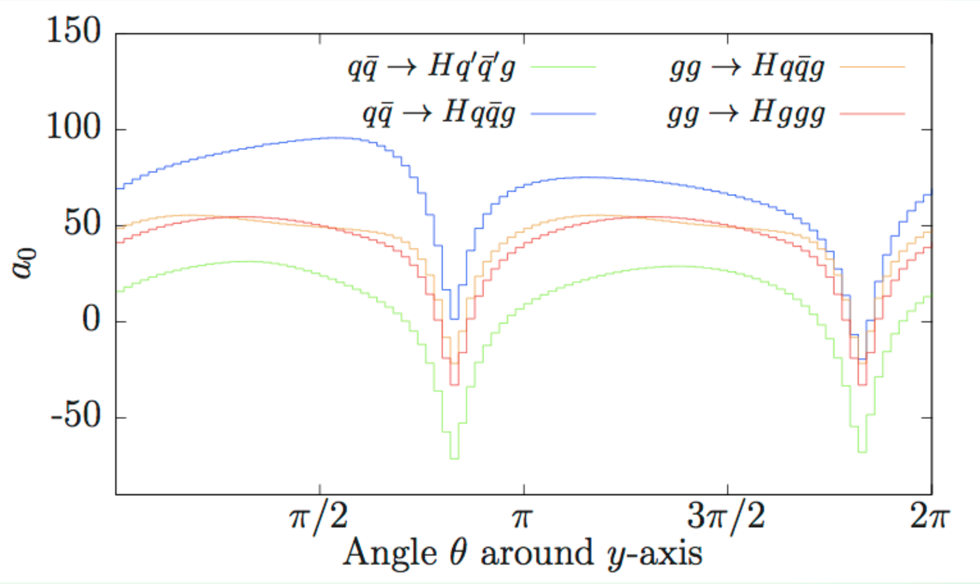
[HvD, Acta Phys. Polon. B44 (2013) 11, 2223-2230]

Higgs + 3 jets in GF: virtual part

[Cullen, HvD, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano (2013)]

- Virtual parts computed by GoSam





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

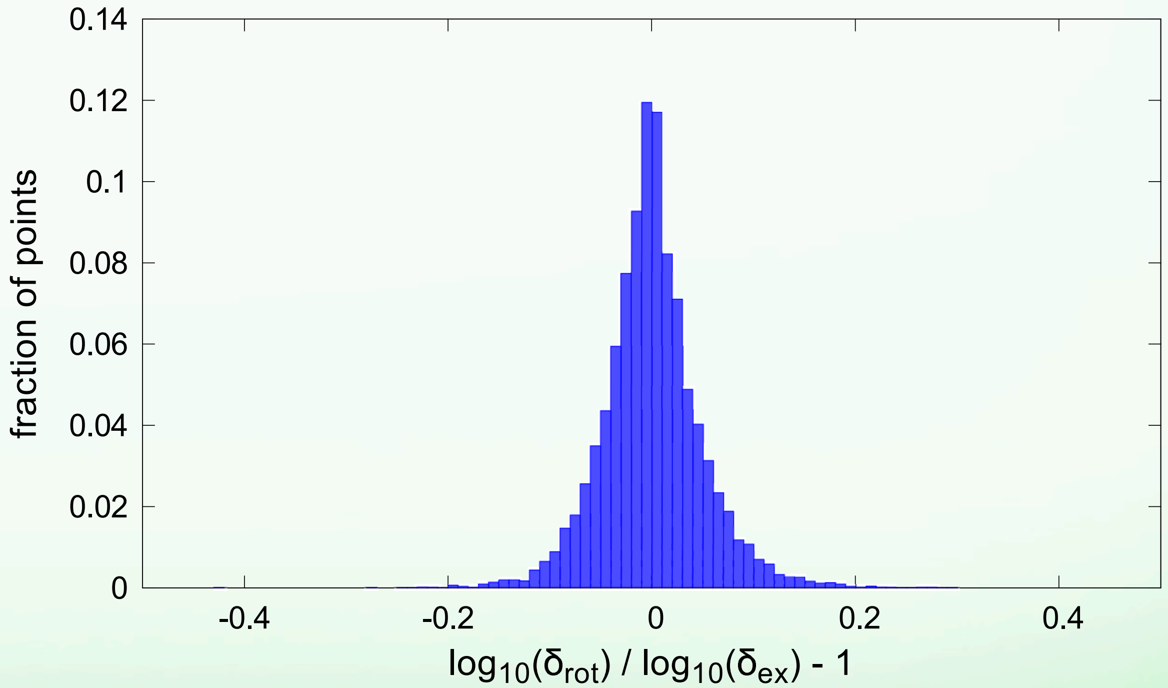
- gauge invariance
- IR poles

Ninja: precision correlation

$$\delta_{ex} = \left| \frac{A_{quad} - A}{A_{quad}} \right|$$

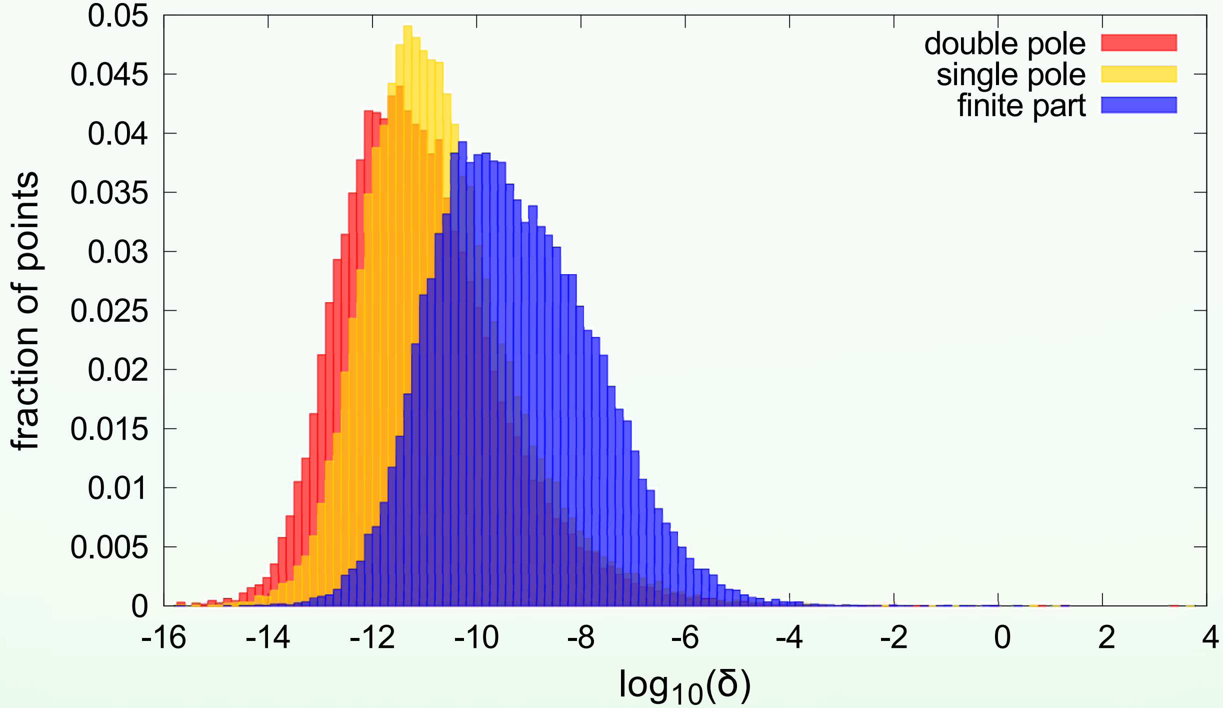
$$\delta_{rot} = 2 \left| \frac{A_{rot} - A}{A_{rot} + A} \right|$$

$$\mathcal{C} = \frac{\log_{10}(\delta_{rot})}{\log_{10}(\delta_{ex})} - 1$$



[HvD, Luisoni, Mastrolia, Mirabella, Ossola, Peraro (2013)]

Ninja: precision

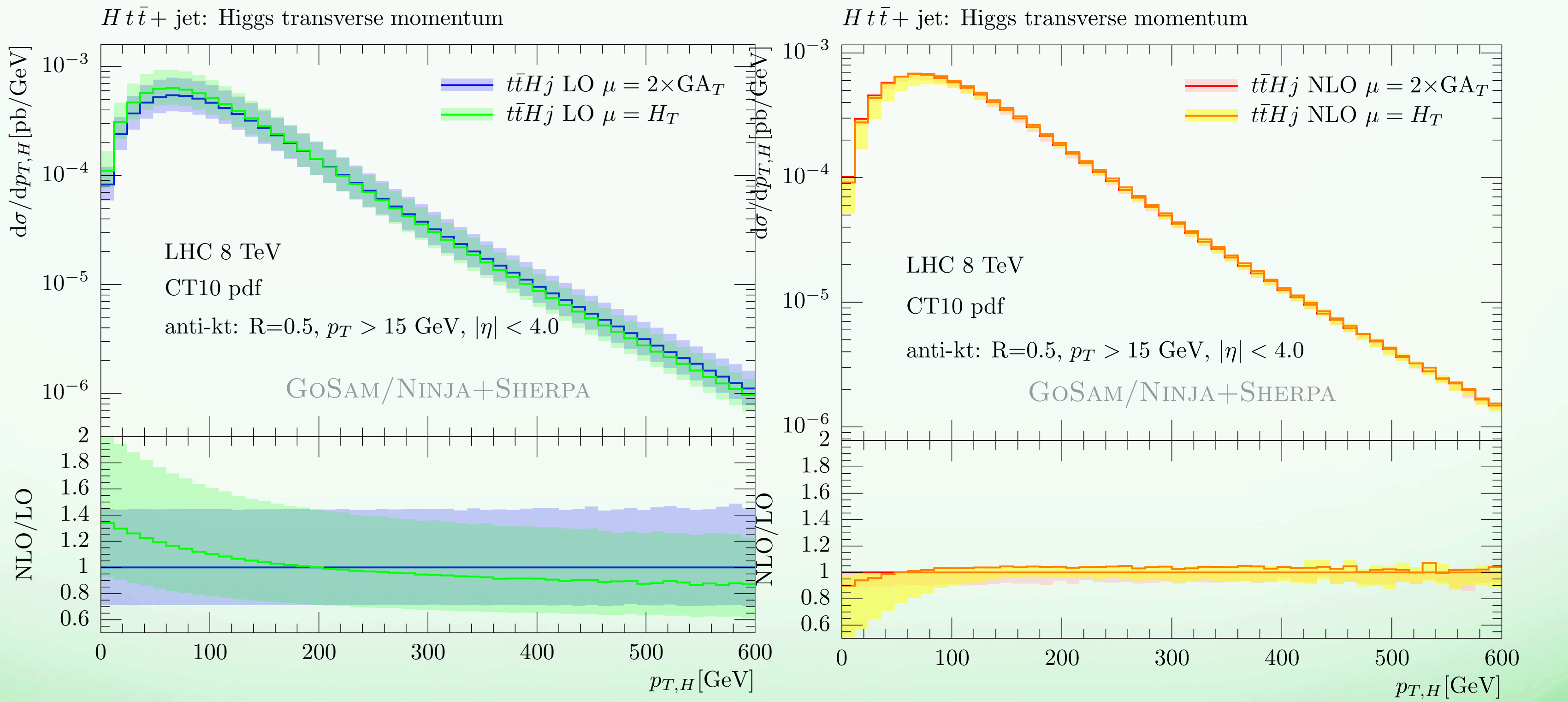


Precision Plot for $gg \to t\bar{t}Hg$: the distributions are obtained using $5 \cdot 10^4$ randomly

[HvD, Luisoni, Mastrolia, Mirabella, Ossola, Peraro (2013)]

pp → Htt̄ +1 jet results

[HvD, Luisoni, Mastrolia, Mirabella, Ossola, Peraro (2013)]



NLO calculations

$$\sigma^{NLO} = \int_m \left[d^{(4)}\sigma^B + \int_{loop} d^{(d)}\sigma^V + \int_1 d^{(d)}\sigma^S \right] + \int_{m+1} \left[d^{(4)}\sigma^R - d^{(4)}\sigma^S \right]$$

- NLO calculation consists of:
  - LO: Born diagram
  - Virtual corrections: loop diagrams ← GoSam
  - Real corrections: additional radiation
  - Subtraction terms to regulate infinities

Interfaces with external MC

- GoSam+MadGraph+MadDipole+MadEvent
  - ad-hoc interface
- GoSam+Sherpa
  - via BLHA
- GoSam+Powheg
  - via BLHA
- GoSam+Herwig
  - work in progress
- GoSam+aMC@NLO
  - Work in progress