GoSam @ LHC

Algorithms and Applications to Higgs production

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GoSam team

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Alexander von Humboldt Stiftung / Foundation

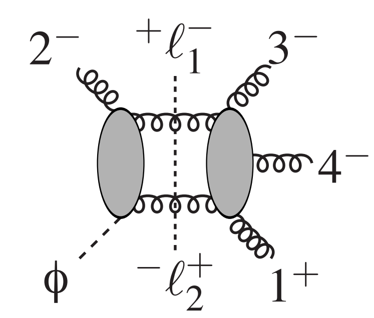
Outline

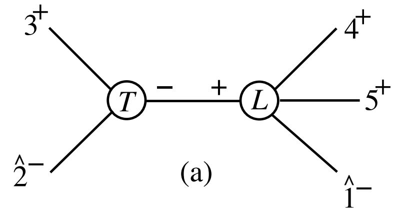
- The ***GoSam*** Project
- The code
- Applications: ***pp > Hjjj*** in gluon fusion @ NLO
- Novel integrand reduction :: ***Ninja***
- Applications :: ***pp > HtTj*** @ NLO
- Conclusions

Analytic Unitarity & Hjj @ NLO

::2006::
Berger del Duca Dixon
Badger Glower Risager
Glower Williams *P.M.*
Badger Glower Williams *P.M.*
Dixon Sofianatos
Badger Campbell Ellis Williams
::2009::

- 4D-Unitarity :: cut-constructible terms
- recurrence relation :: rational part
- PV Tensor-reduction :: rational part





(a)

$$
\begin{aligned}
B^\mu &= p_1^\mu B_1 \\
B^{\mu\nu} &= g^{\mu\nu} B_{00} + p_1^\mu p_1^\nu B_{11} \\
C^\mu &= p_1^\mu C_1 + p_2^\mu C_2
\end{aligned}
$$

Samurai... Ossola Reiter Tramontano *P.M.*

- *Integrand Reduction* for One-Loop Integrals Ossola Papadopoulos Pittau
- *Generalised D-dim Unitarity* Ellis Giele Kunszt Melnikov
  :: Complete reduction to D-reg Master Integrals
  :: cut-constructible & rational terms at once

...meets Golem Binoth Guillet Heinrich Pilon Reiter

- *Integrand Generation*
- *Tensor Reduction Library*

The GoSam Project

2.0 Cullen **van Deurzen** Greiner Heinrich Luisoni **Mirabella** Ossola **Peraro Reichel Schlenk von Soden-Fraunhofen** Tramontano *P.M.*

- *D-reg Feynman Diagrams* :: *algebraic generation* ::
  Qgraf Nogueira
  Form Vermaseren
  Spinney Cullen Koch-Janusz Reiter
- *Reduction* ::
  Samurai Ossola Reiter Tramontano *P.M.* + van Deurzen Mirabella Peraro
  Golem95 Binoth Guillet Heinrich Pilon Reiter
  Ninja Mirabella Peraro *P.M.*
- *Master Integrals* ::
  AvHOLO van Hameren
  QCDLoop Ellis Zanderighi
  Golem95C Binoth Guillet Heinrich Pilon Reiter von Soden-Fraunhofen
  Looptools Hahn

The GoSam Project

Cullen **van Deurzen** Greiner Heinrich Luisoni Mirabella Ossola **Peraro Reichel Schlenk von Soden-Fraunhofen** Tramontano *P.M.*

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

 Monte Carlo Generator

The GoSam Project

Cullen **van Deurzen** Greiner Heinrich Luisoni Mirabella Ossola **Peraro Reichel Schlenk von Soden-Fraunhofen** Tramontano *P.M.*

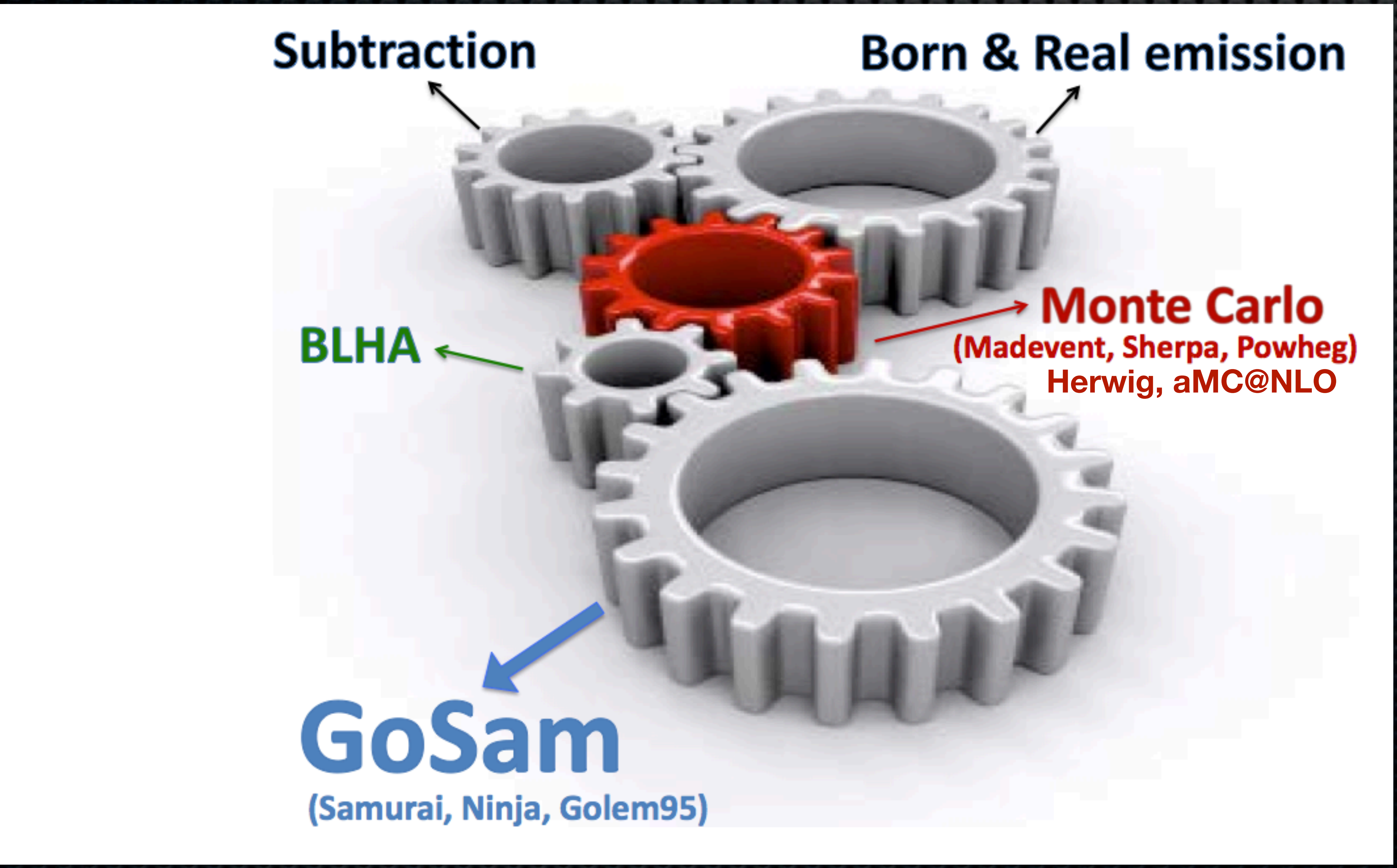
$$\sigma_{\text{NLO}} = \int_n \left(d\sigma_{\text{Born}} + d\sigma_{\text{Virtual}} + \int_1 d\sigma_{\text{Subtraction}} \right) + \int_{n+1} \left(d\sigma_{\text{Real}} - d\sigma_{\text{Subtraction}} \right)$$

 Monte Carlo Generator

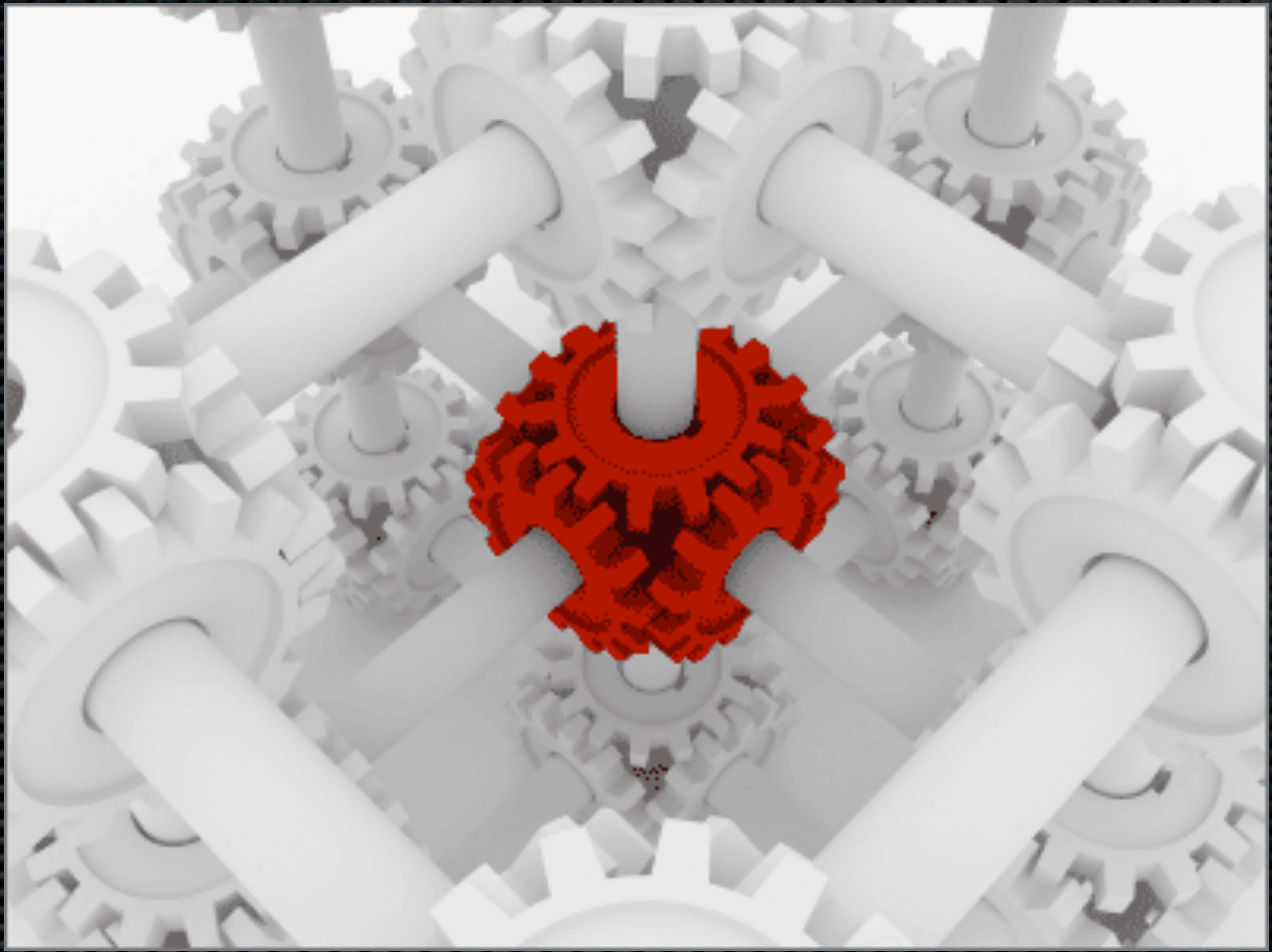
Multi Process One-Loop Provider 

The GoSam Project

Cullen **van Deurzen** Greiner Heinrich Luisoni
Mirabella Ossola **Peraro Reichel Schlenk**
von Soden-Fraunhofen Tramontano *P.M.*



...a deeper look into the code...



GoSam: algorithms

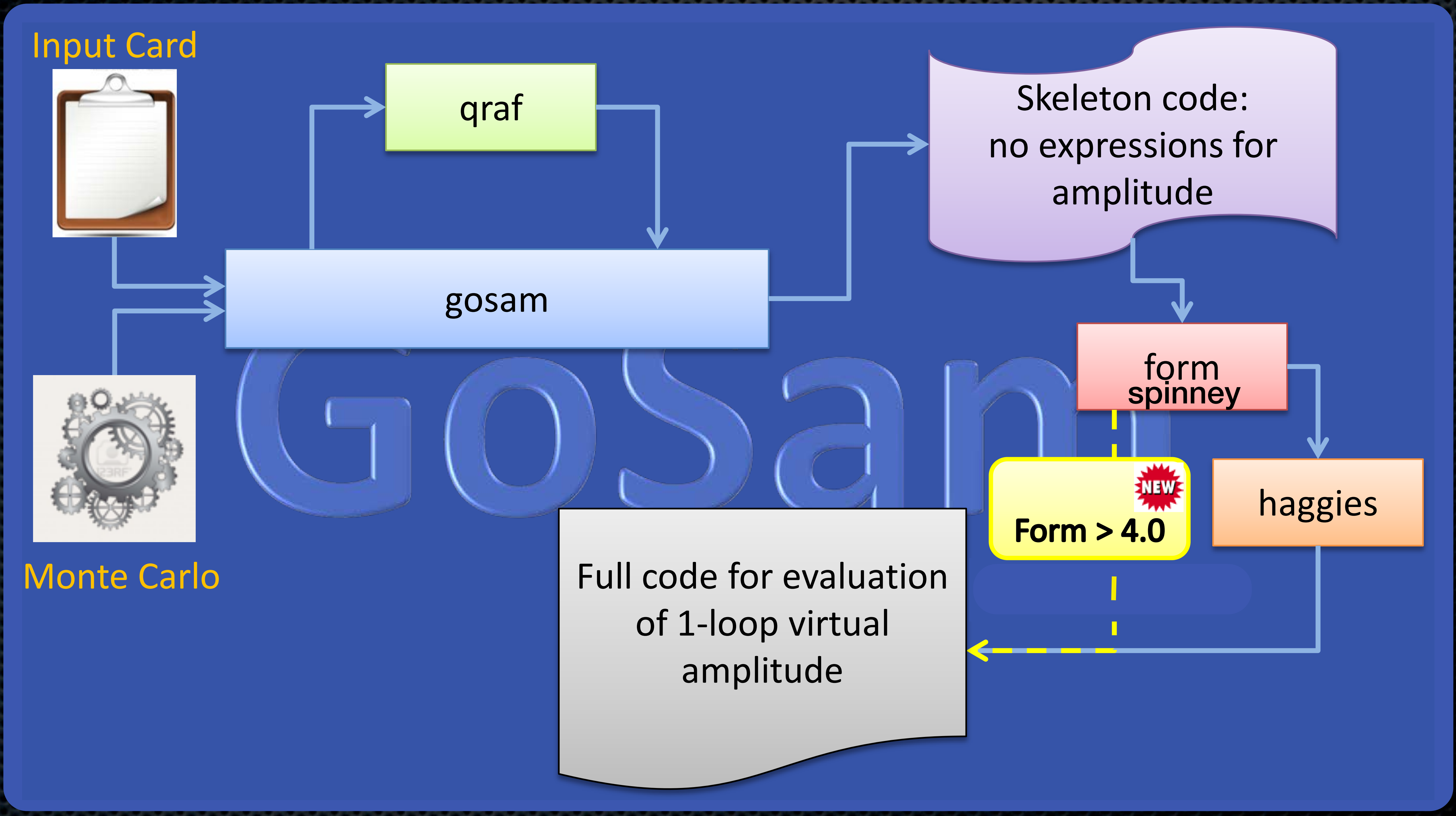
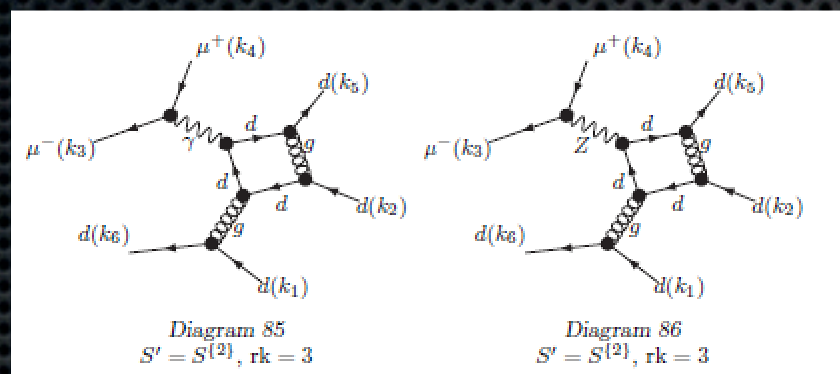
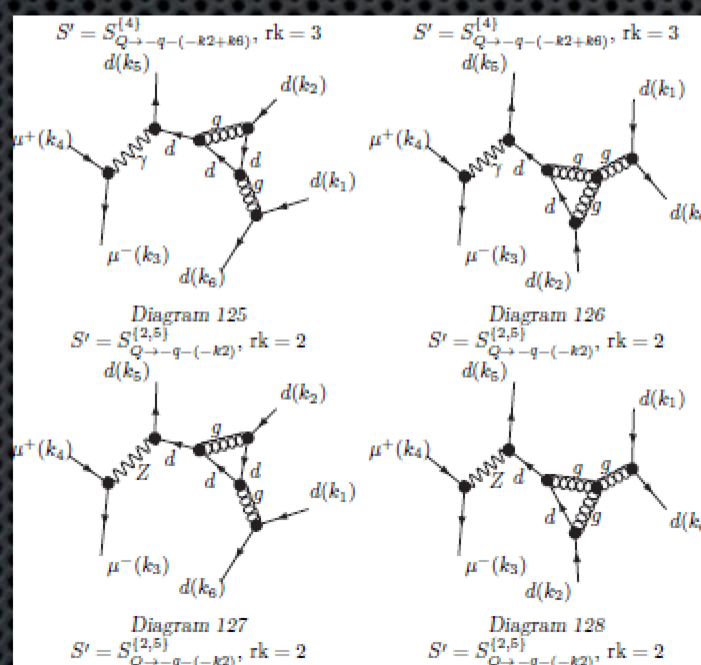


Diagram Generation





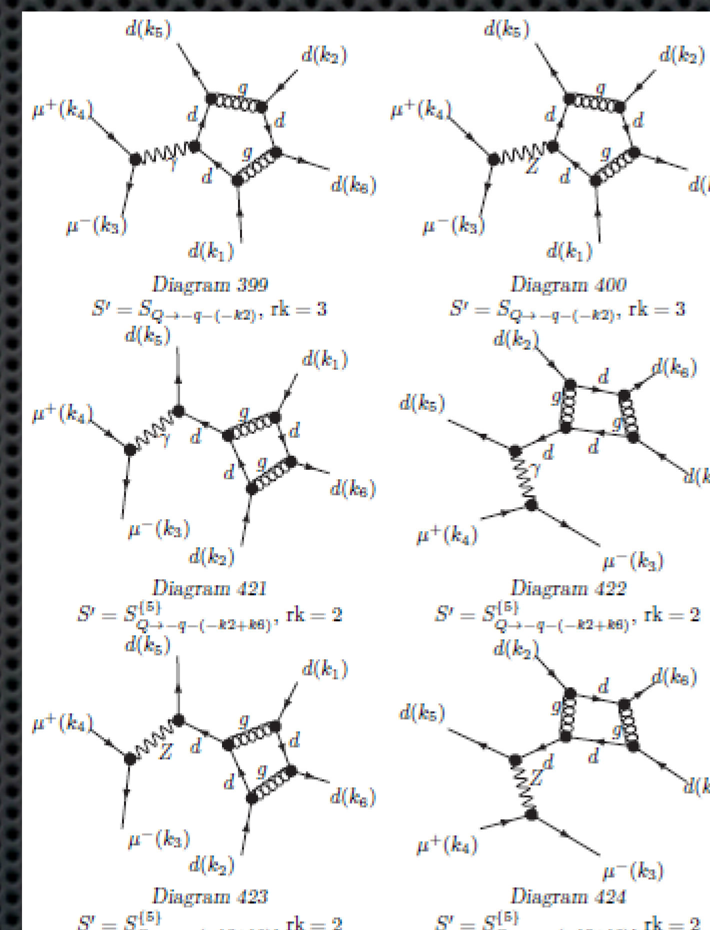


Diagram Generation

Diagrams are collected (orizzontally and vertically) according to their topologies:
maximal exploitation of the unitarity based integrand-reduction

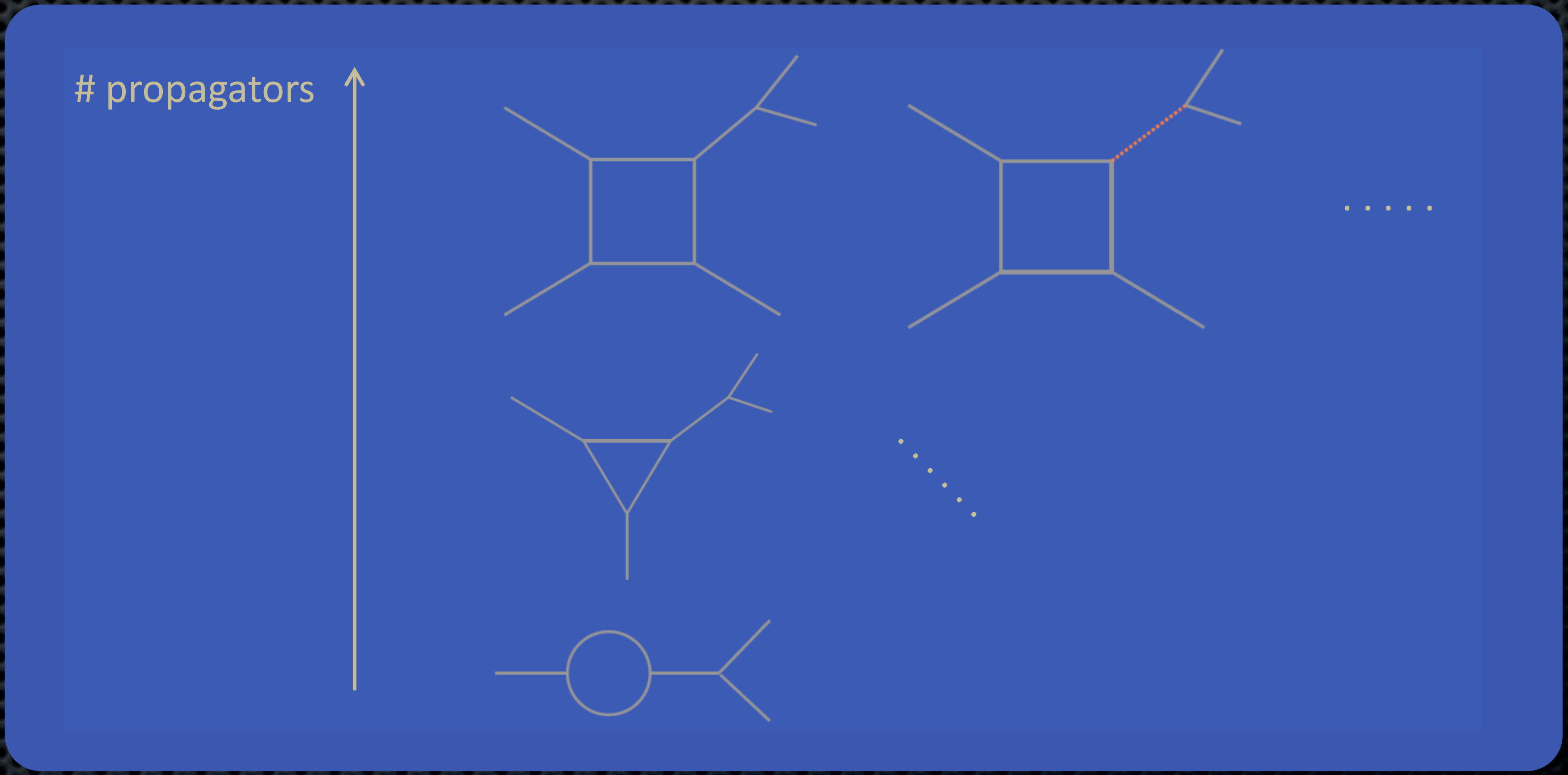


Diagram Generation

Diagsum :: common loop structure
- different tree appendices
- different particles in the loop, but same denominators

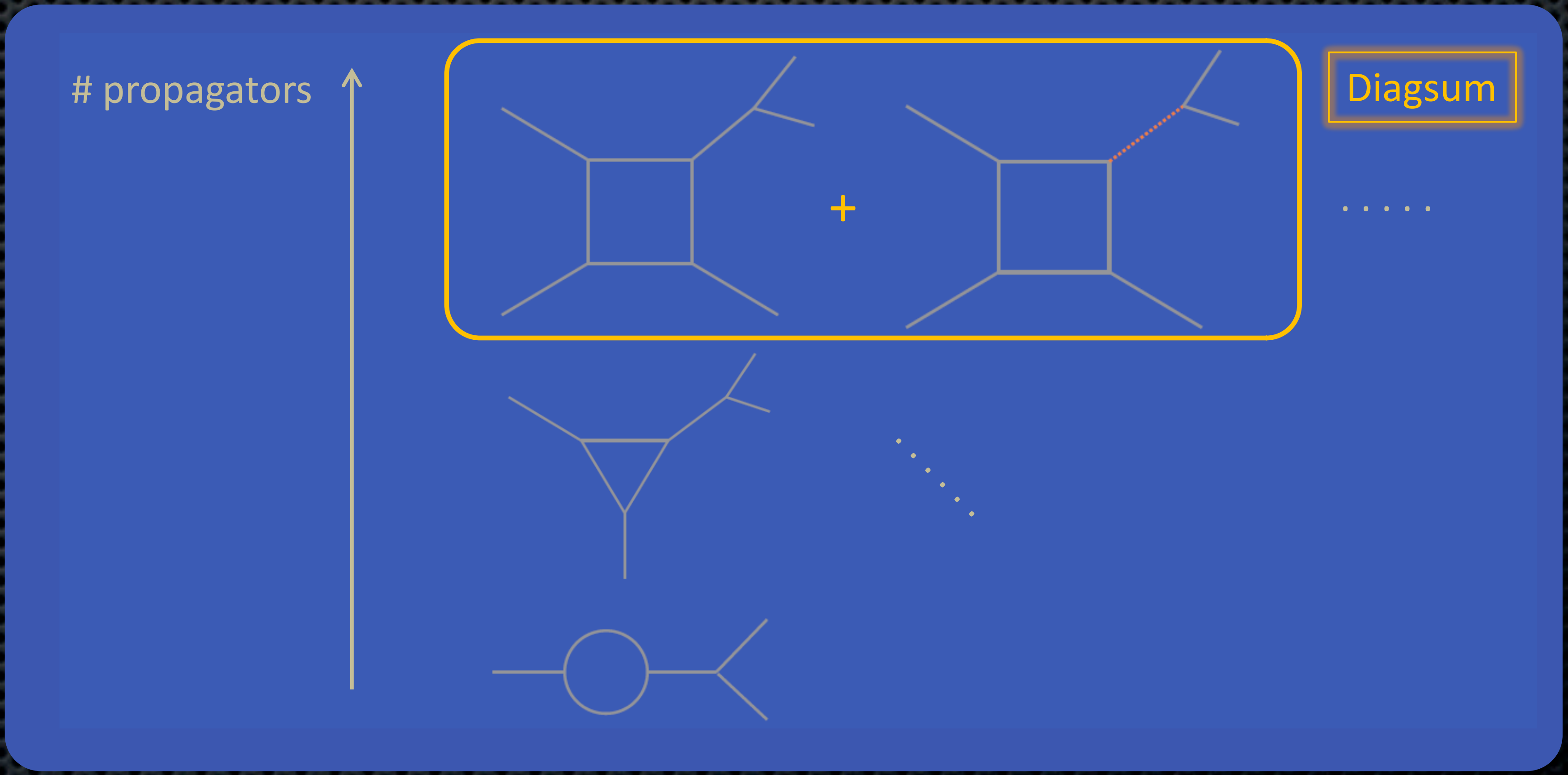


Diagram Generation

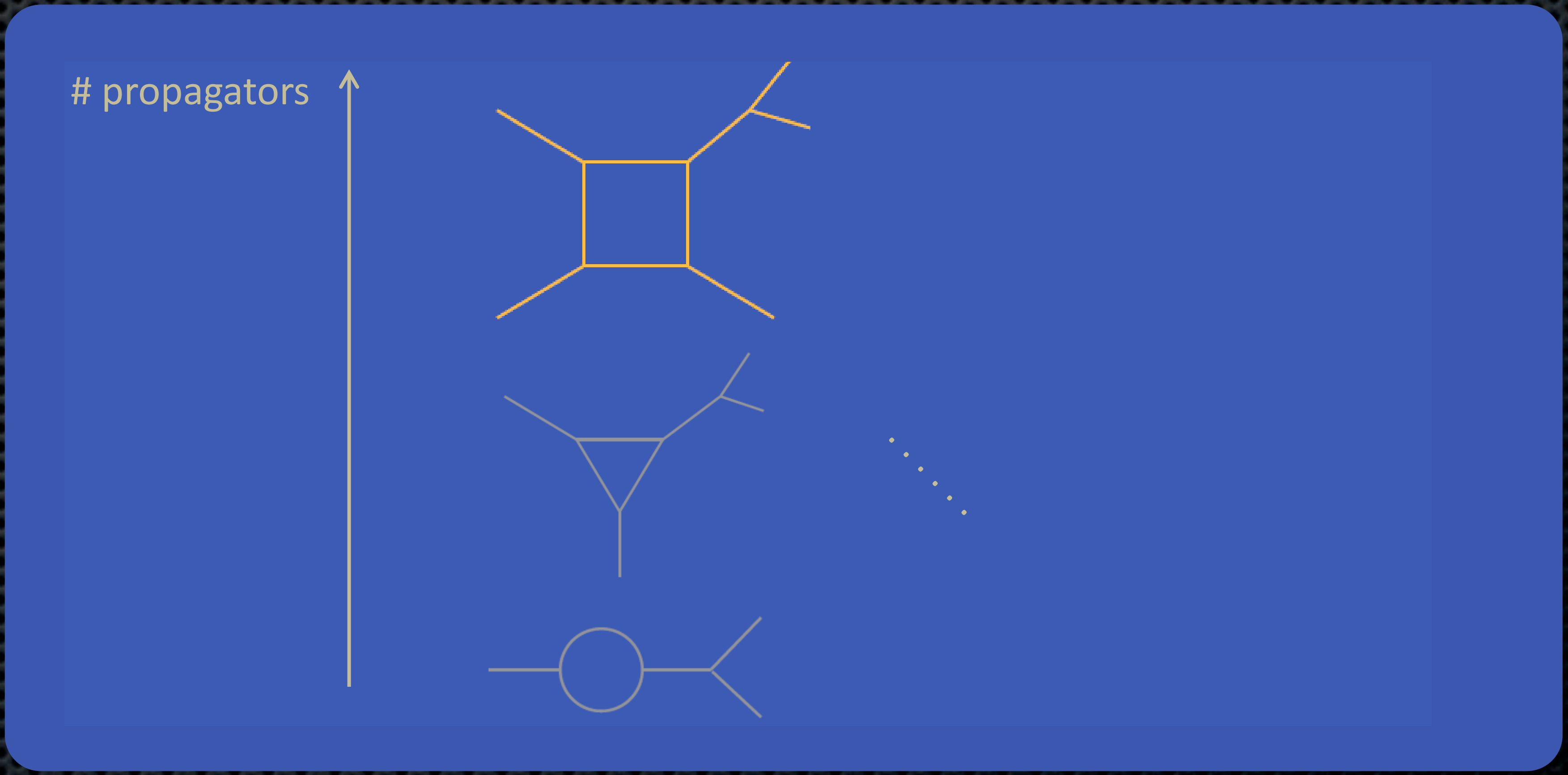


Diagram Generation

Grouping :: sub-topologies structure

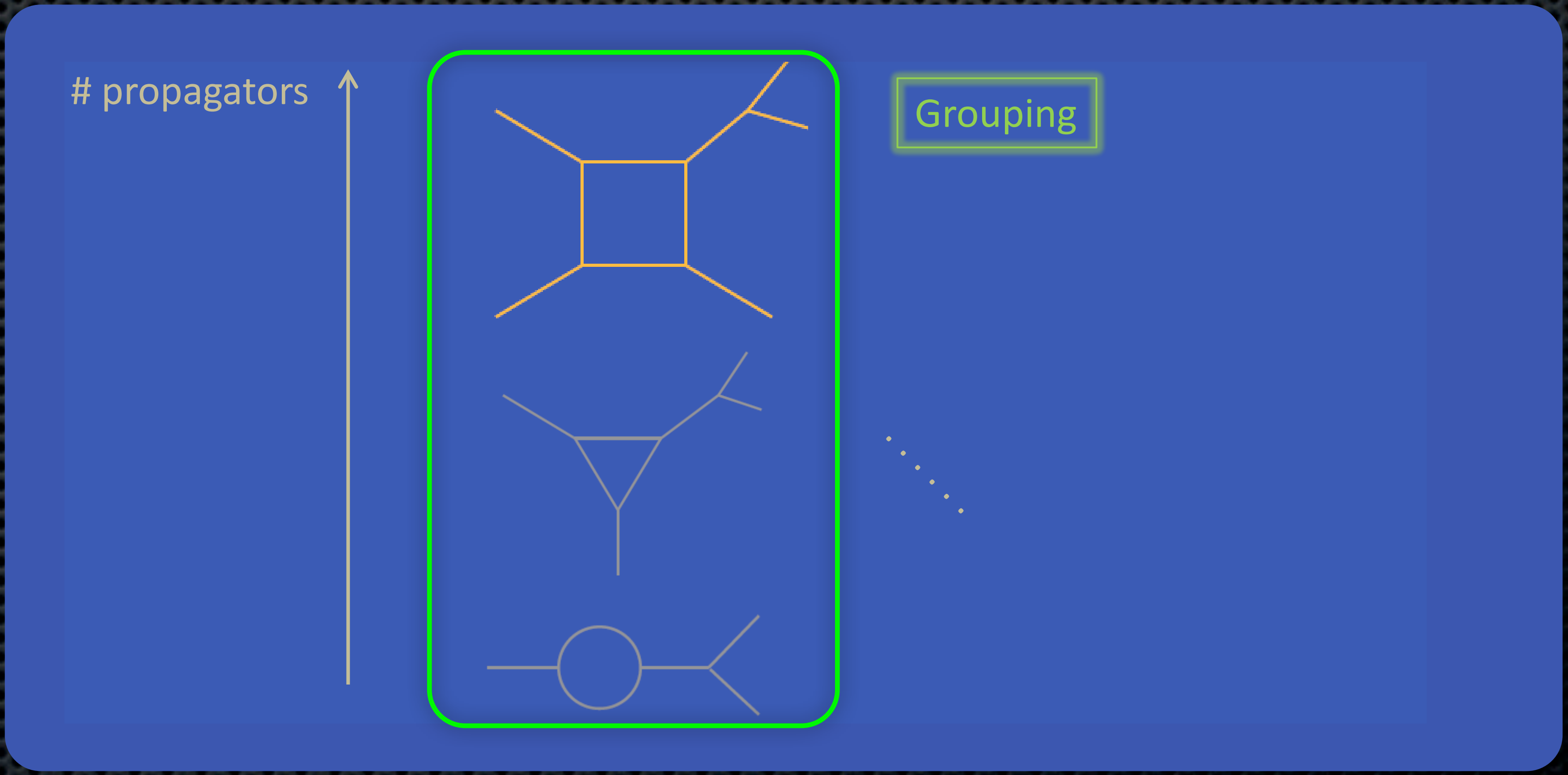
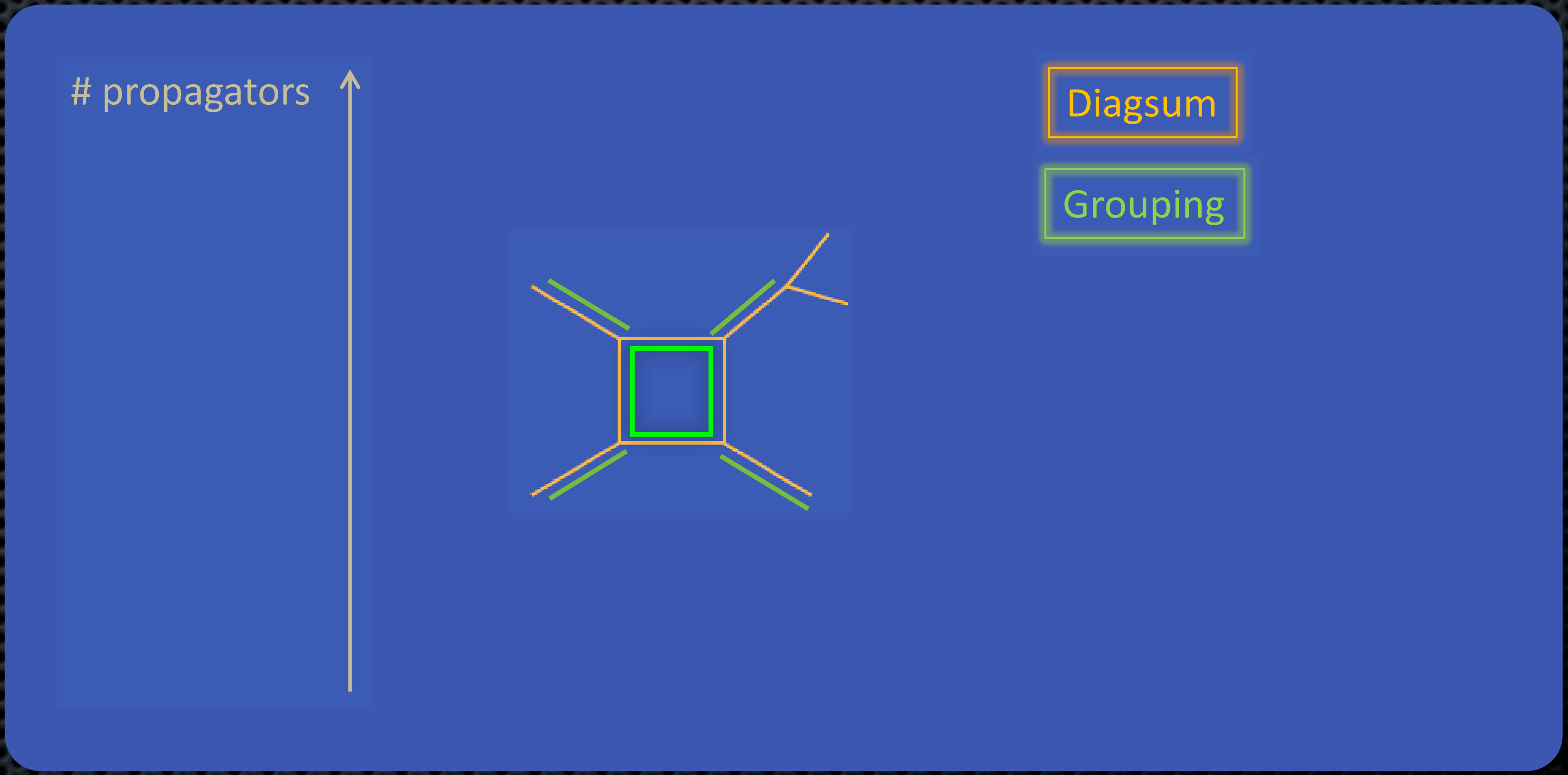
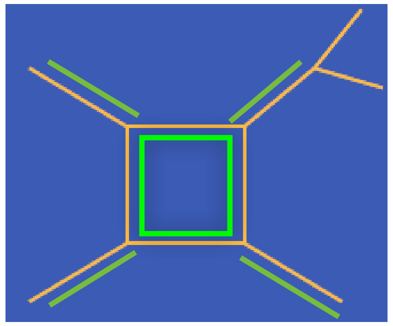


Diagram Generation

Global Diagram :: diagsummed and grouped ~ super-amplitude



Numerator



$$\mathcal{A}_n = \int d^d\bar{q}\; A(\bar{q},\epsilon)\,, \qquad A(\bar{q},\epsilon) = \frac{\mathcal{N}(\bar{q},\epsilon)}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{n-1}}\,,$$

$$\mathcal{N}(\bar{q},\epsilon) = N_0(\bar{q}) + \epsilon N_1(\bar{q}) + \epsilon^2 N_2(\bar{q}).$$

We use a bar to denote objects living in $d = 4-2\epsilon$ dimensions

$$\bar{D}_i = (\bar{q}+p_i)^2 - m_i^2 = (q+p_i)^2 - m_i^2 - \mu^2$$

$$\bar{\not{q}} = \not{q} + \not{\mu}\,, \quad \text{with} \qquad \bar{q}^2 = q^2 - \mu^2\ .$$

$$\boxed{\mathcal{N}_i(\bar{q}) = \sum_{r=0}^{R} C_{\nu_1\ldots\nu_r}\; \bar{q}^{\nu_1}\cdots\bar{q}^{\nu_r} = \sum_{j=0}^{R/2}(\mu^2)^j \sum_{r=0}^{R-2j} C^{(j)}_{\nu_1\ldots\nu_r}\; q^{\nu_1}\cdots q^{\nu_r}}$$

separation of factors not depending on the loop-momentum
(computed once per ps-point)

Samurai

Ossola Reiter Tramontano *P.M.*

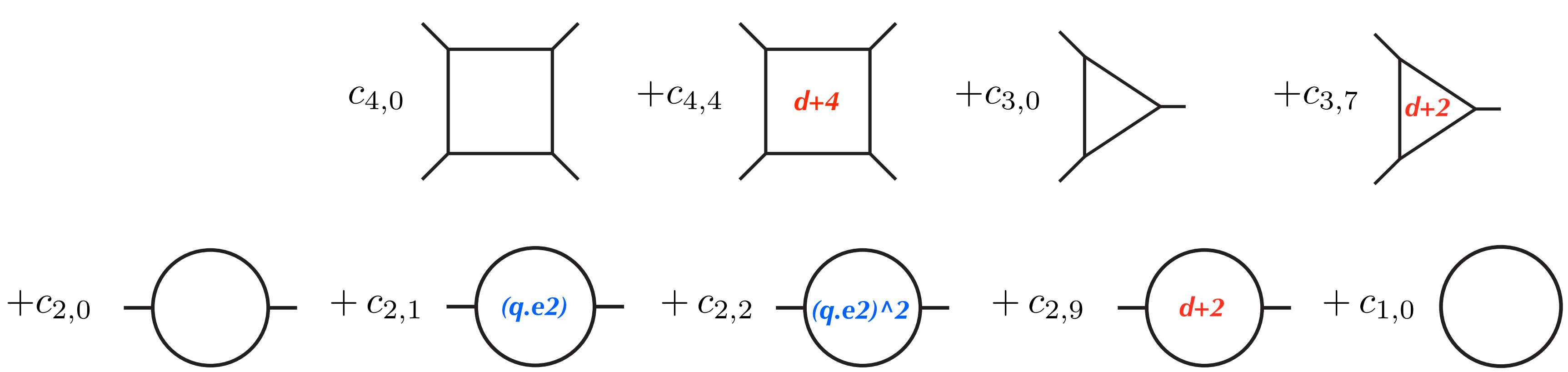
Numerator

$$\mathcal{N}_i(\bar{q}) = \sum_{r=0}^{R} C_{\nu_1 \dots \nu_r}\ \bar{q}^{\nu_1} \cdots \bar{q}^{\nu_r} = \sum_{j=0}^{R/2} (\mu^2)^j \sum_{r=0}^{R-2j} C^{(j)}_{\nu_1 \dots \nu_r}\ q^{\nu_1} \cdots q^{\nu_r}$$

m-cut residue (**universal** polynomial)

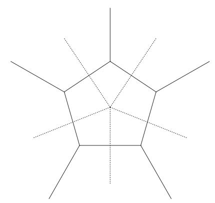
$$\Delta_{i_1 \dots i_m}(q,\mu^2) = \mathrm{Res}_{i_1 \dots i_m} \left\{ \frac{\mathcal{N}(q,\mu^2)}{\bar{D}_{i_1} \bar{D}_{i_2} \dots \bar{D}_{i_n}} - \sum_{k=(m+1)}^{5} \sum_{i_1 < i_2 < \dots < i_k} \frac{\Delta_{i_1 i_2 \dots i_k}(q,\mu^2)}{\bar{D}_{i_1} \bar{D}_{i_2} \dots \bar{D}_{i_k}} \right\}$$

Master Integrals



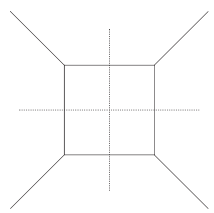
Samurai Ossola Reiter Tramontano *P.M.*

Polynomial Residues @ r ⩽ n (# of den’s)



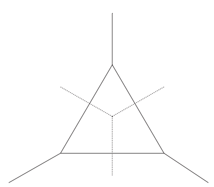
$$\Delta_{ijk\ell m}(\bar q) = \mathrm{Res}_{ijk\ell m}\left\{ \frac{N(\bar q)}{\bar D_0 \cdots \bar D_{n-1}} \right\}$$

1 coefficient



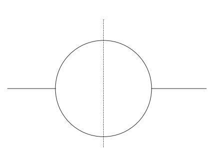
$$\Delta_{ijk\ell}(\bar q) = \mathrm{Res}_{ijk\ell}\left\{ \frac{N(\bar q)}{\bar D_0 \cdots \bar D_{n-1}} - \sum_{i<<m}^{n-1} \frac{\Delta_{ijk\ell m}(\bar q)}{\bar D_i \bar D_j \bar D_k \bar D_\ell \bar D_m} \right\}$$

5 coefficients



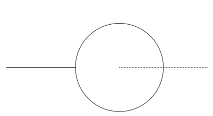
$$\Delta_{ijk}(\bar q) = \mathrm{Res}_{ijk}\left\{ \frac{N(\bar q)}{\bar D_0 \cdots \bar D_{n-1}} - \sum_{i<<m}^{n-1} \frac{\Delta_{ijk\ell m}(\bar q)}{\bar D_i \bar D_j \bar D_k \bar D_\ell \bar D_m} - \sum_{i<<\ell}^{n-1} \frac{\Delta_{ijk\ell}(\bar q)}{\bar D_i \bar D_j \bar D_k \bar D_\ell} \right\}$$

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 coefficients

Golem95

Binoth Guillet Heinrich Pilon Reiter von Soden-Fraunhofen

$$\mathcal{N}_i(\bar{q}) = \sum_{r=0}^{R} C_{\nu_1 \ldots \nu_r} \; \bar{q}^{\nu_1} \cdots \bar{q}^{\nu_r}$$

- *Tensor Reduction*
  more stable for degenerate kinematic configurations ::
  > suitable rescue system

The Rational Term in GoSam

$$\mathcal{N}_i(\bar{q}) = \sum_{r=0}^{R} C^{(0)}_{\nu_1 \ldots \nu_r}\, q^{\nu_1} \cdots q^{\nu_r} + \sum_{j=1}^{R/2} (\mu^2)^j \sum_{r=0}^{R-2j} C^{(j)}_{\nu_1 \ldots \nu_r}\, q^{\nu_1} \cdots q^{\nu_r}$$

- **implicit** mode ::
  Samurai reduces the whole $\boxed{\mathcal{N}_i(\bar{q})}$ $\Rightarrow$ R

The Rational Term in GoSam

$$\mathcal{N}_i(\bar{q}) = \sum_{r=0}^{R} C^{(0)}_{\nu_1\ldots\nu_r}\; q^{\nu_1}\cdots q^{\nu_r} + \sum_{j=1}^{R/2}(\mu^2)^j \sum_{r=0}^{R-2j} C^{(j)}_{\nu_1\ldots\nu_r}\; q^{\nu_1}\cdots q^{\nu_r}$$

- **implicit** mode ::
  Samurai reduces the whole $\mathcal{N}_i(\bar{q})$
- **explicit** mode::
  -analytic integration of $\sum_{j=1}^{R/2}(\mu^2)^j \sum_{r=0}^{R-2j} C^{(j)}_{\nu_1\ldots\nu_r}\; q^{\nu_1}\cdots q^{\nu_r}$ before any reduction $\Rightarrow$ R2

  -Samurai reduces only $\sum_{r=0}^{R} C^{(0)}_{\nu_1\ldots\nu_r}\; q^{\nu_1}\cdots q^{\nu_r}$ $\Rightarrow$ R1

R=R1+R2

Evolving GoSam: outward

- MC interfaces
- Applications

2013 Activities

Beyond SM
MC Interfaces >>> *Luisoni's talk*
EW Physics
Top Physics >>> *Schlenk's talk*
Diphoton and jets >>> *Greiner's talk*
Higgs & Jets

- 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].
- H. van Deurzen, G. Luisoni, P. Mastrolia, EM, G. Ossola & T. Peraro, "NLO QCD corrections to Higgs boson production in association with a top quark pair and a jet," arXiv:1307.8437 [hep-ph].
- G. Cullen, H. van Deurzen, N. Greiner, G. Luisoni, P. Mastrolia, EM, G. Ossola, T. Peraro & F. Tramontano, "NLO QCD corrections to Higgs boson production plus three jets in gluon fusion," arXiv:1307.4737 [hep-ph].
- 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]
- G. Luisoni, P. Nason, C. Oleari & F. Tramontano, HW/HZ + 0 and 1 jet at NLO with the POWHEG BOX interfaced to GoSam and their merging within MiNLO arXiv:1306.2542 [hep-ph]
- M. Chiesa, G. Montagna, L. Barze', M. Moretti, O. Nicrosini, F. Piccinini & F. Tramontano, "Electroweak Sudakov Corrections to New Physics Searches at the CERN LHC,"arXiv:1305.6837 [hep-ph]
- T. Gehrmann, N. Greiner & G. Heinrich, "Photon isolation effects at NLO in gamma gamma + jet final states in hadronic collisions," JHEP **1306**, 058 (2013)
- H. van Deurzen, N. Greiner, G. Luisoni, P. Mastrolia, EM, G. Ossola, T. Peraro, J. F. von Soden-Fraunhofen & F. Tramontano, "NLO QCD corrections to the production of Higgs plus two jets at the LHC," Phys. Lett. B **721**, 74 (2013)
- G. Cullen, N. Greiner & G. Heinrich, "Susy-QCD corrections to neutralino pair production in association with a jet," Eur. Phys. J. C **73**, 2388 (2013)

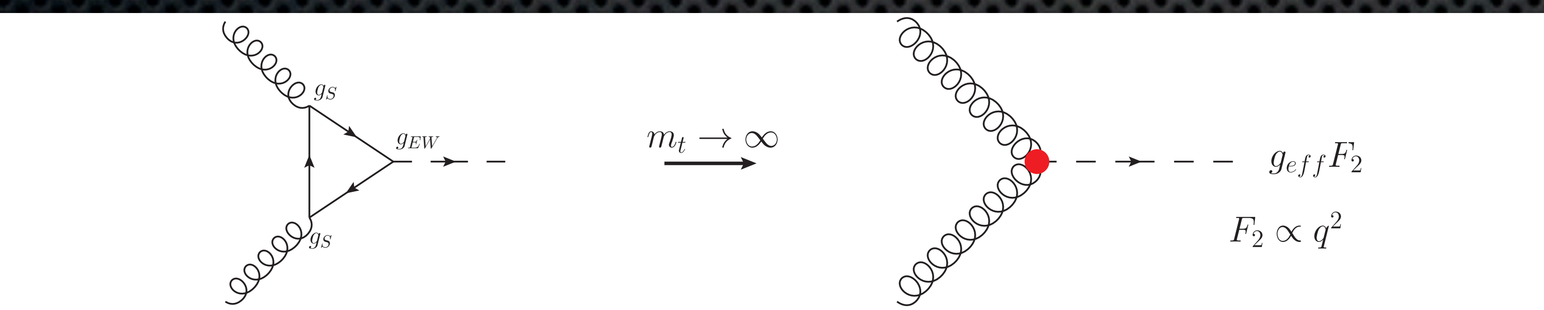
Higgs & Jazz ?

The path to Hjjj @ NLO

Challenges

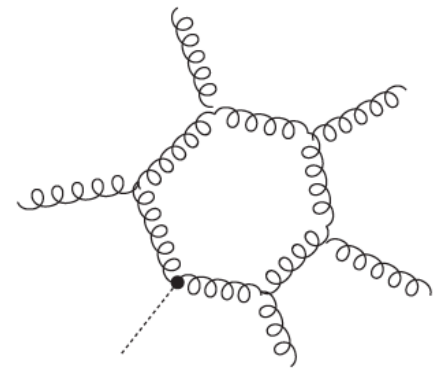
- reducing the **code size**
  FORM > 4.0 optimized algebraic expressions
  :: faster generation, smaller code, better runtime
  :: we enjoyed FORM **O2** *>>> Vermaseren's talk*

- *effective Hgg-coupling*:



higher rank :: r ⩽ n+1

the rank *r* of the numerator can be larger than the number *n* of denominators



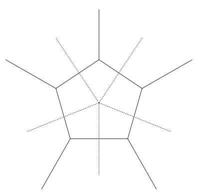
H+0j	1 NLO
$gg \to H$	1 NLO
H+1j	**62 NLO**
$qq \to Hqq$	14 NLO
$qg \to Hqg$	48 NLO
H+2j	**926 NLO**
$qq' \to Hqq'$	32 NLO
$qq \to Hqq$	64 NLO
$qg \to Hqg$	179 NLO
$gg \to Hgg$	651 NLO
H+3j	**13179 NLO**
$qq' \to Hqq'g$	467 NLO
$qq \to Hqqg$	868 NLO
$qg \to Hqgg$	2519 NLO
$gg \to Hggg$	9325 NLO

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

Extended Integrand Red'n

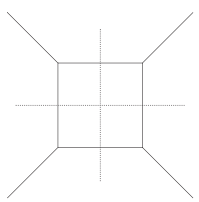
Mirabella Peraro *P.M.*

Extending the Polynomial Residues @ r ⩽ n+1



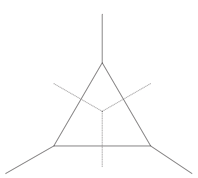
$$\Delta_{ijk\ell m}(\bar{q}) = \mathrm{Res}_{ijk\ell m}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}}\right\}$$

1→1 coefficient



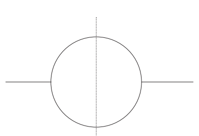
$$\Delta_{ijk\ell}(\bar{q}) = \mathrm{Res}_{ijk\ell}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m}\right\}$$

5→6 coefficients



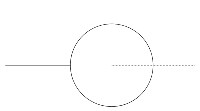
$$\Delta_{ijk}(\bar{q}) = \mathrm{Res}_{ijk}\left\{\frac{N(\bar{q})}{\bar{D}_0\cdots\bar{D}_{n-1}} - \sum_{i<<m}^{n-1}\frac{\Delta_{ijk\ell m}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell\bar{D}_m} - \sum_{i<<\ell}^{n-1}\frac{\Delta_{ijk\ell}(\bar{q})}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_\ell}\right\}$$

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



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

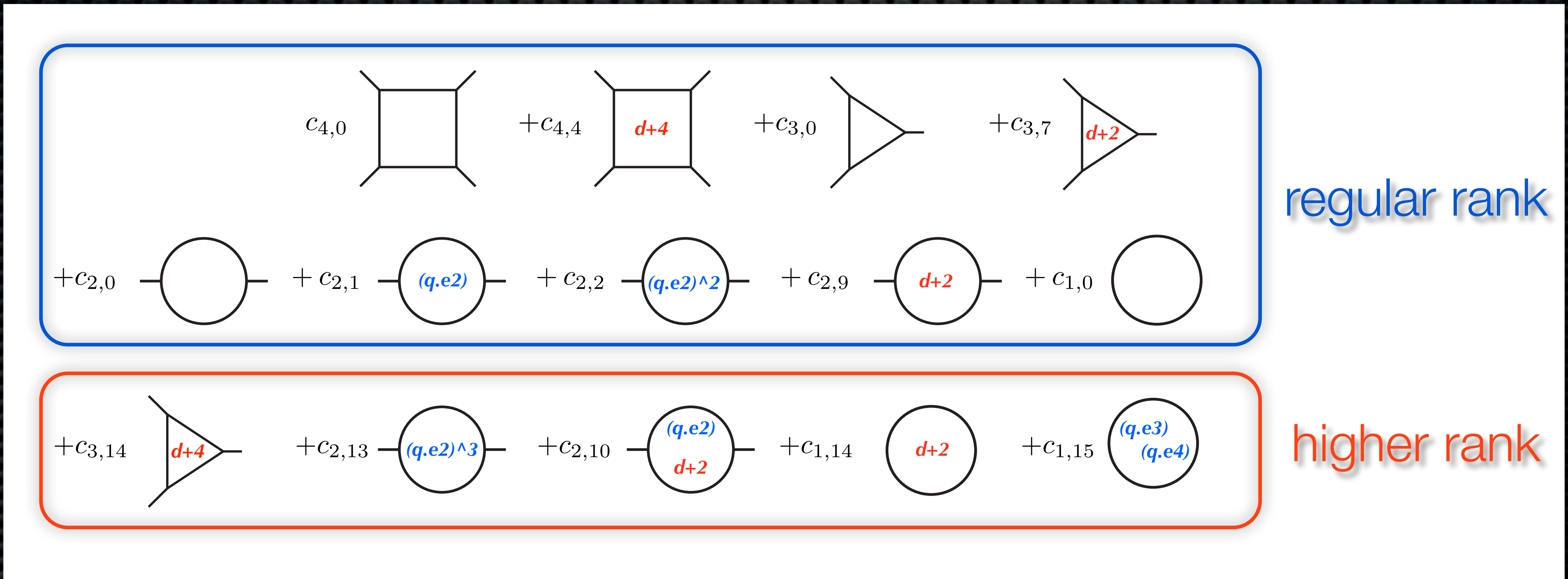
5→15 coefficients

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

Extended Integrand Red'n

Mirabella Peraro *P.M.*

Extending the Master Integrals @ $r \leqslant n+1$

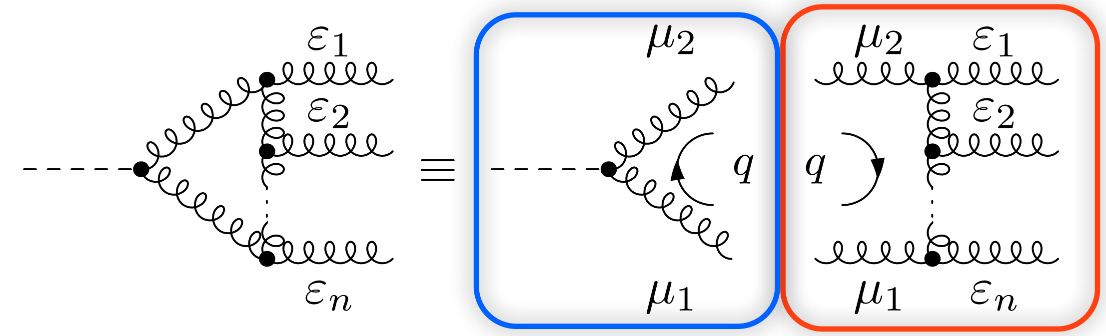


Samurai > XSamurai van Deurzen

Hjj @ NLO :: a nice surprise

- **explicit** mode
  :: higher-rank terms needed

- **implicit** mode
  :: higher-rank terms do not contribute!!!
  they contain always powers of $\bar{q}^2 = q^2 - \mu^2$ which cancel against denominators.



$$\Gamma^{\varepsilon_1 \cdots \varepsilon_n} \equiv \mathcal{F}_{\mu_1 \mu_2} \, \mathcal{G}^{\mu_1 \mu_2 \varepsilon_1 \cdots \varepsilon_n}$$

$$\mathcal{F}_{\mu_1 \mu_2} = q_{\mu_1} \, q_{\mu_2} + \mathcal{O}(q^2)$$

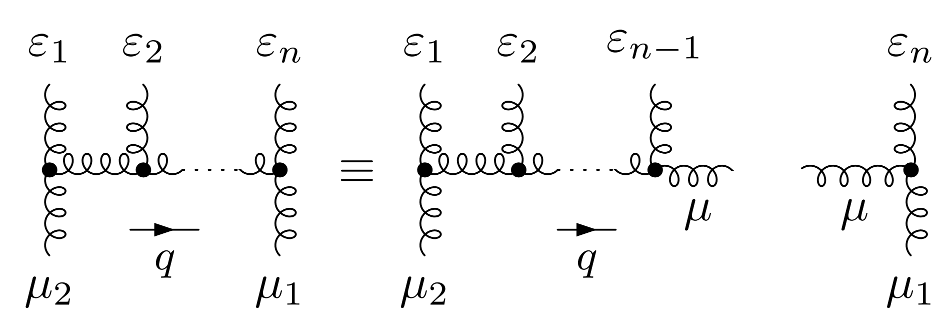
$$\mathcal{G}^{\mu_1 \mu_2 \varepsilon_1 \cdots \varepsilon_n} = q^{\mu_1} \mathcal{T}_1^{\mu_2 \varepsilon_1 \cdots \varepsilon_n} + q^{\mu_2} \mathcal{T}_2^{\mu_1 \varepsilon_1 \cdots \varepsilon_n} + g^{\mu_1 \mu_2} \mathcal{T}_g^{\varepsilon_1 \cdots \varepsilon_n} + \mathcal{O}(q^2)$$

where $\mathcal{T}_1, \mathcal{T}_2$, and $\mathcal{T}_g$ are tensors which may depend on q as well. Indeed Eq. (B.3) is fulfilled for $n = 0, 1$,

$$\begin{aligned} \mathcal{G}^{\mu_1 \mu_2} &= g^{\mu_1 \mu_2} \\ \mathcal{G}^{\mu_1 \mu_2 \varepsilon_1} &= g^{\mu_1 \varepsilon_1} q^{\mu_2} + g^{\mu_2 \varepsilon_1} q^{\mu_1} - 2 g^{\mu_2 \mu_1} q^{\varepsilon_1} \, , \end{aligned}$$

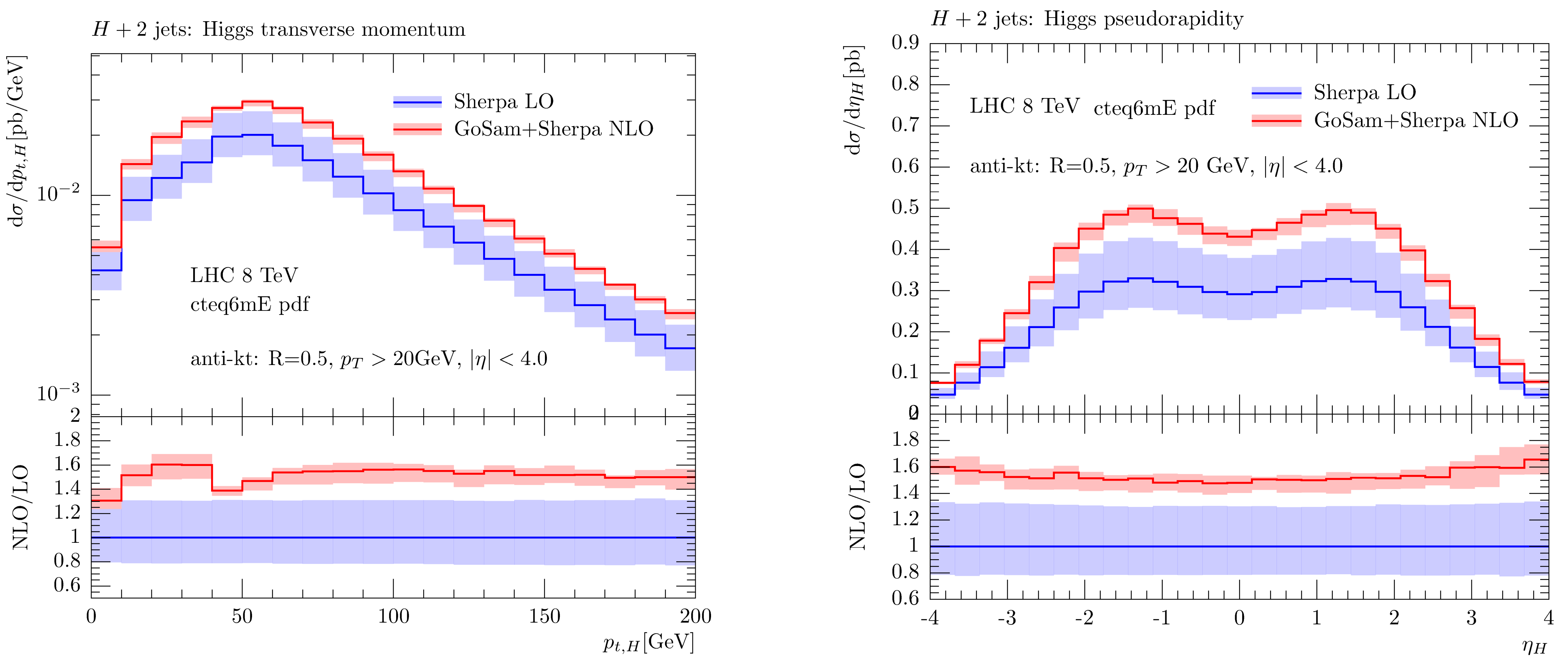
while for $n > 1$ it can be proven by induction over n by using

$$\mathcal{G}^{\mu_1 \mu_2 \varepsilon_1 \cdots \varepsilon_n} = \mathcal{G}_\mu{}^{\mu_2 \varepsilon_1 \cdots \varepsilon_{n-1}} \mathcal{G}^{\mu_1 \mu \varepsilon_n} \, ,$$



Hjj @ NLO :: GoSam+Sherpa

v. Deurzen Greiner Luisoni Mirabella Ossola
Peraro v. Soden-Fraunhofen Tramontano *P.M.*
Phys.Lett. B721 (2013) 74-81, 1301.0493 [hep-ph]



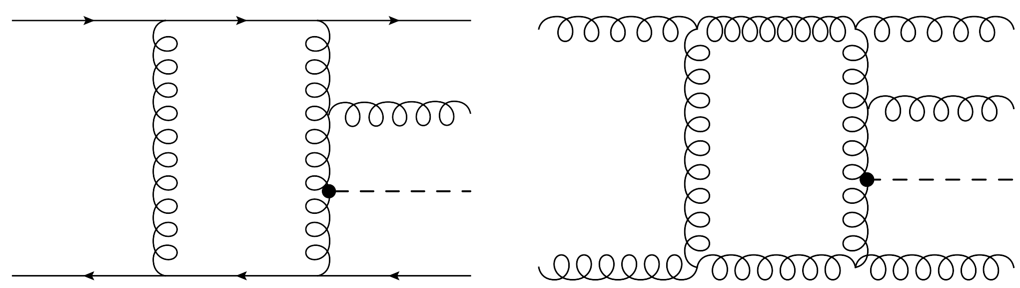
$$\mu = \mu_R = \mu_F = \hat{H}_t \qquad \hat{H}_t = \sqrt{M_H^2 + p_{t,H}^2} + \sum_j p_{t,j} \,,$$

- our amplitudes confirmed by MCFM (v6.4) Campbell, Ellis, Williams

Hjjj @ NLO :: GoSam+Sherpa+MadDipole

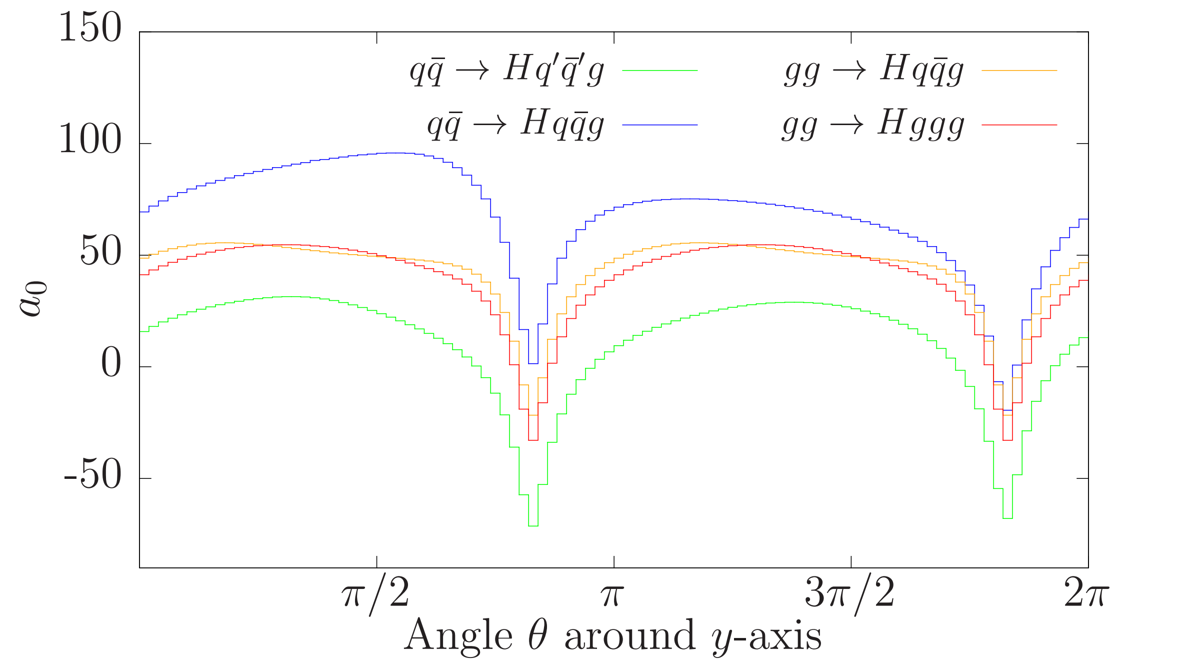
Cullen v. Deurzen Greiner Luisoni
Mirabella Ossola Peraro Tramontano *P.M.*
1307.4737 to appear in PRL

Virtual Contributions



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

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



Hjjj @ NLO :: GoSam+Sherpa+MadDipole

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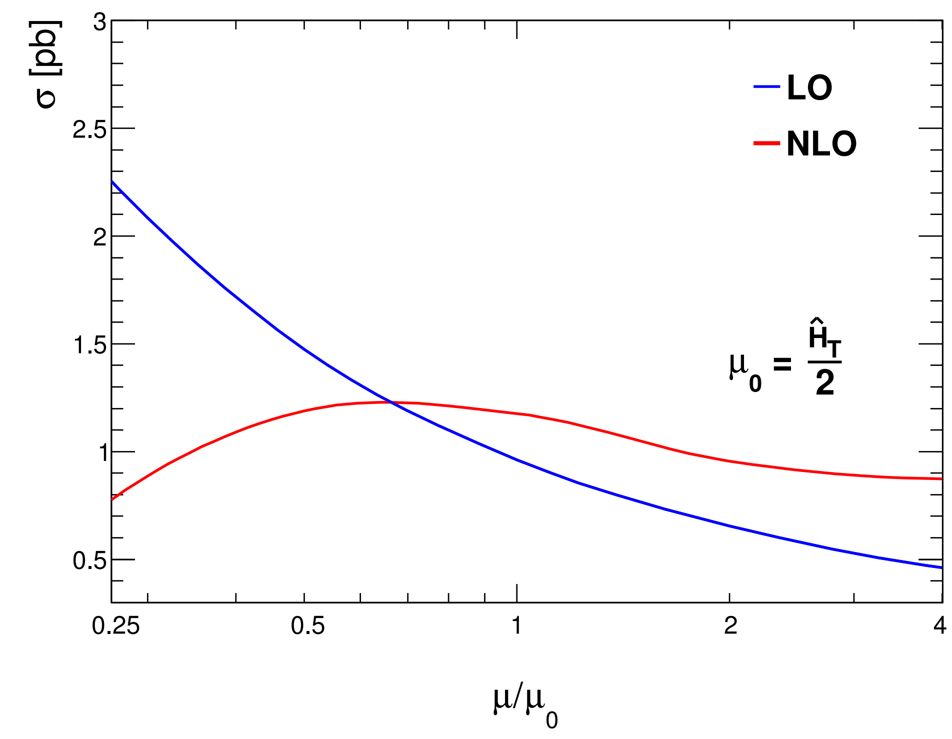
Hybrid MC setup (HMC)

- GoSam+Sherpa: *Born & Virtuals*
- Mad-{Graph/Dipole/Event}
  Reals, Subtractions, Int'ed Dipoles

Tests

- NLO H+2: HMC *vs* Gosam+Sherpa
- LO H+3: Madgraph *vs* Sherpa
- NLO H+3: alpha-independence
  (Subtr'ns + Int'ed Dipoles)

xsection



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

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

Hjjj @ NLO :: GoSam+Sherpa+MadDipole

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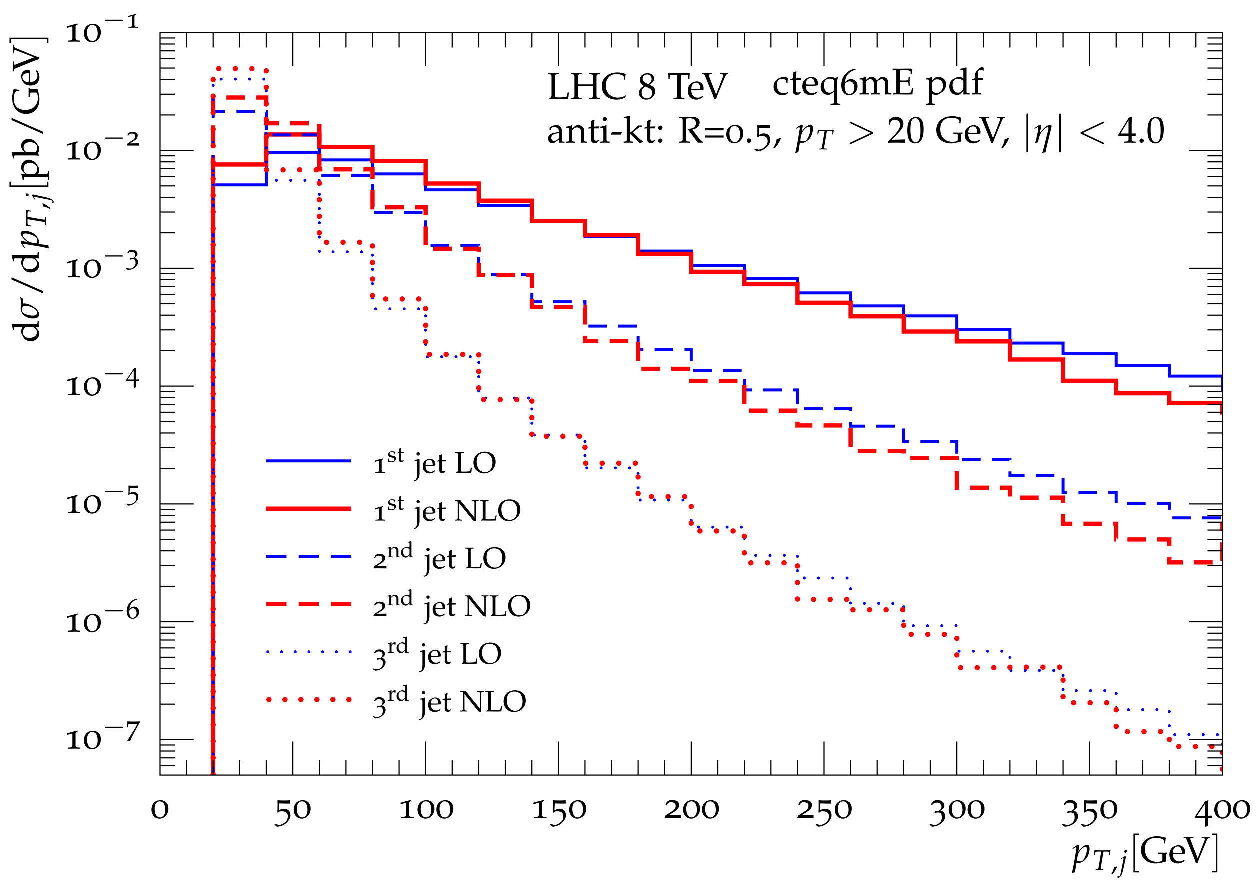

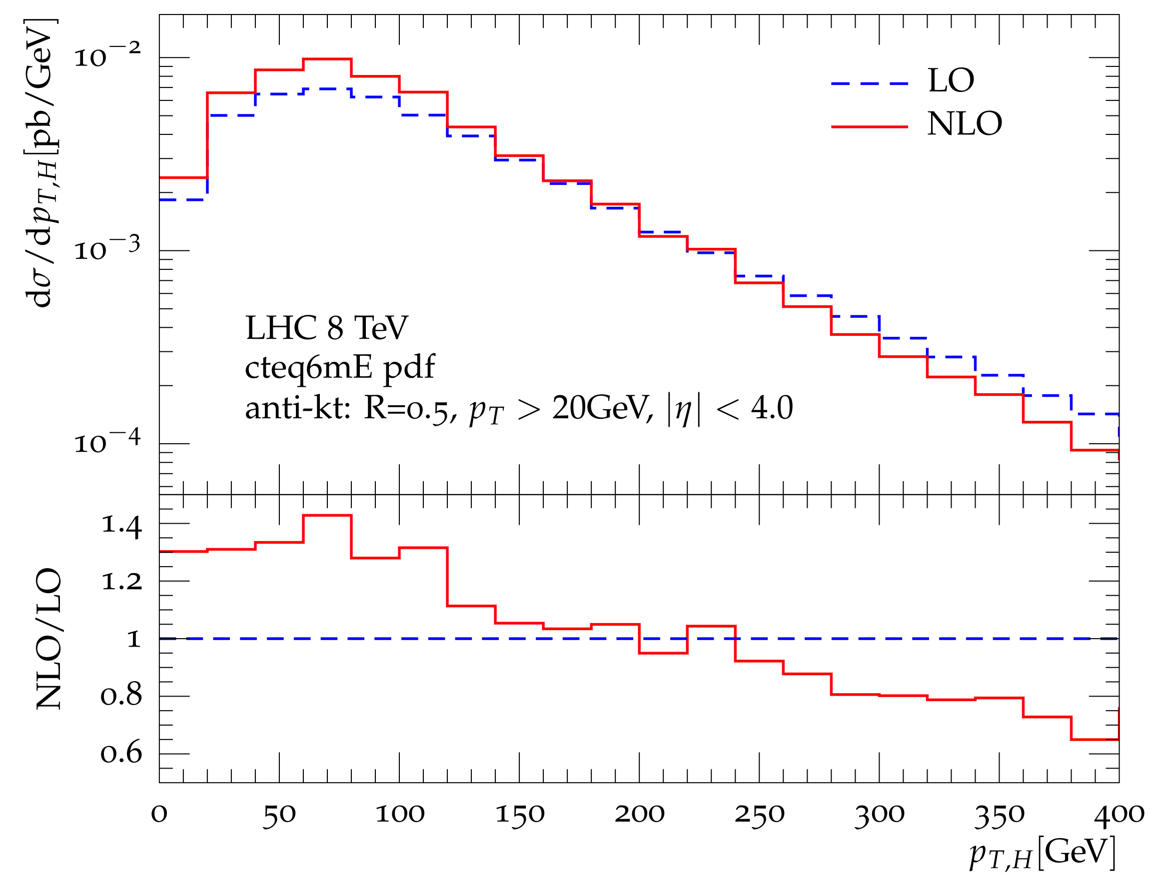

pp > Hjjj GoSam-generated code available for pairing with any MC for further common studies

Evolving GoSam: inward

- Improving and Extending the Integrand Reduction

Improved Integrand Red'n

- **Integrand Reduction** Algorithm ...

universal

$$\Delta_{i_1\ldots i_m}(q,\mu^2) = \mathrm{Res}_{i_1\ldots i_m}\left\{\frac{\mathcal{N}(q,\mu^2)}{\bar{D}_{i_1}\bar{D}_{i_2}\ldots\bar{D}_{i_n}} - \sum_{k=(m+1)}^{5}\sum_{i_1<i_2<\ldots<i_k}\frac{\Delta_{i_1 i_2\ldots i_k}(q,\mu^2)}{\bar{D}_{i_1}\bar{D}_{i_2}\ldots\bar{D}_{i_k}}\right\}$$

polynomial

a + b x + c x^2 + ...

non-polynomial

non-polynomial

Ossola Papadopoulos Pittau

- known Delta-residues allow for polynomial sampling
- mandatory integrand subtraction
- multiple cuts are nested
- triangular system solving (chained algorithm)

Improved Integrand Red'n

- **Integrand Reduction** Algorithm ...
- ...in combination with **Laurent series expansion** Forde; Kilgore; Badger

∞ universal ∞

$$\Delta_{i_1\ldots i_m}(q,\mu^2) = \mathrm{Res}_{i_1\ldots i_m}\left\{\frac{\mathcal{N}(q,\mu^2)}{\bar{D}_{i_1}\bar{D}_{i_2}\ldots\bar{D}_{i_n}} - \sum_{k=(m+1)}^{5}\sum_{i_1<i_2<\ldots<i_k}\frac{\Delta_{i_1 i_2\ldots i_k}(q,\mu^2)}{\bar{D}_{i_1}\bar{D}_{i_2}\ldots\bar{D}_{i_k}}\right\}$$

polynomial polynomial polynomial

a + b x + c x^2 + ... a'+ b' x + c' x^2 + ... a" + b" x + c" x^2 + ...

Mirabella Peraro *P.M.*

- each term becomes independent from the others
- expansion of Delta => universal counterterms :: a"
- expansion of N on the multiple cuts can be performed independently cut by cut :: a'
- coefficients of MI's :: a = a'+ a"
- diagonal system solving

Ninja :: Quasi-Analytic Int'nd Red'n

Mirabella Peraro *P.M.*

- lighter reduction algorithm: faster and more stable
- sampling replaced by series expansion
- integrand subtraction replaced by coefficient corrections
- less coefficient to be determined
- 5-cut not needed
- 4-cut decoupled from lower cuts
- coefficients of 3-, 2- and 1-cut obtained by Laurent expansion (+ coefficients corrections)
- Laurent expansions of 3-, 2- and 1-cut independent of each other (unchained algorithm)

Hexagon: $\binom{6}{4} \cdot 2 + \binom{6}{3} \cdot 10 + \binom{6}{2} \cdot 10 + \binom{6}{1} \cdot 1 = \boxed{(461 \to)\, 386 \text{ coefficients}}$

Ninja :: Quasi-Analytic Int'nd Red'n

Mirabella Peraro *P.M.*

- lighter reduction algorithm: faster and more stable
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- integrand subtraction replaced by coefficient corrections
- less coefficient to be determined
- 5-cut not needed
- 4-cut decoupled from lower cuts
- coefficients of 3-, 2- and 1-cut obtained by Laurent expansion (+ coefficients corrections)
- Laurent expansions of 3-, 2- and 1-cut independent of each other (unchained algorithm)
- Laurent expansion implemented by **Polynomial Division**

Ninja C++ library Peraro + GoSam...

HtTj @ NLO :: GoSam+Ninja+Sherpa

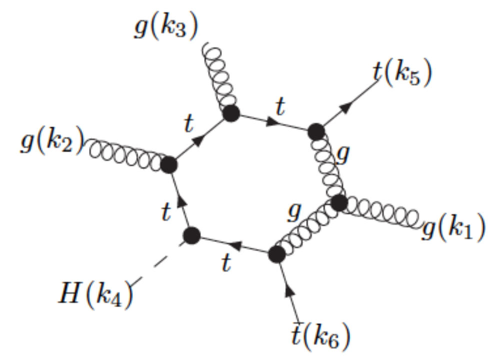
van Deurzen Luisoni Mirabella Ossola Peraro *P.M.*

1307.8437

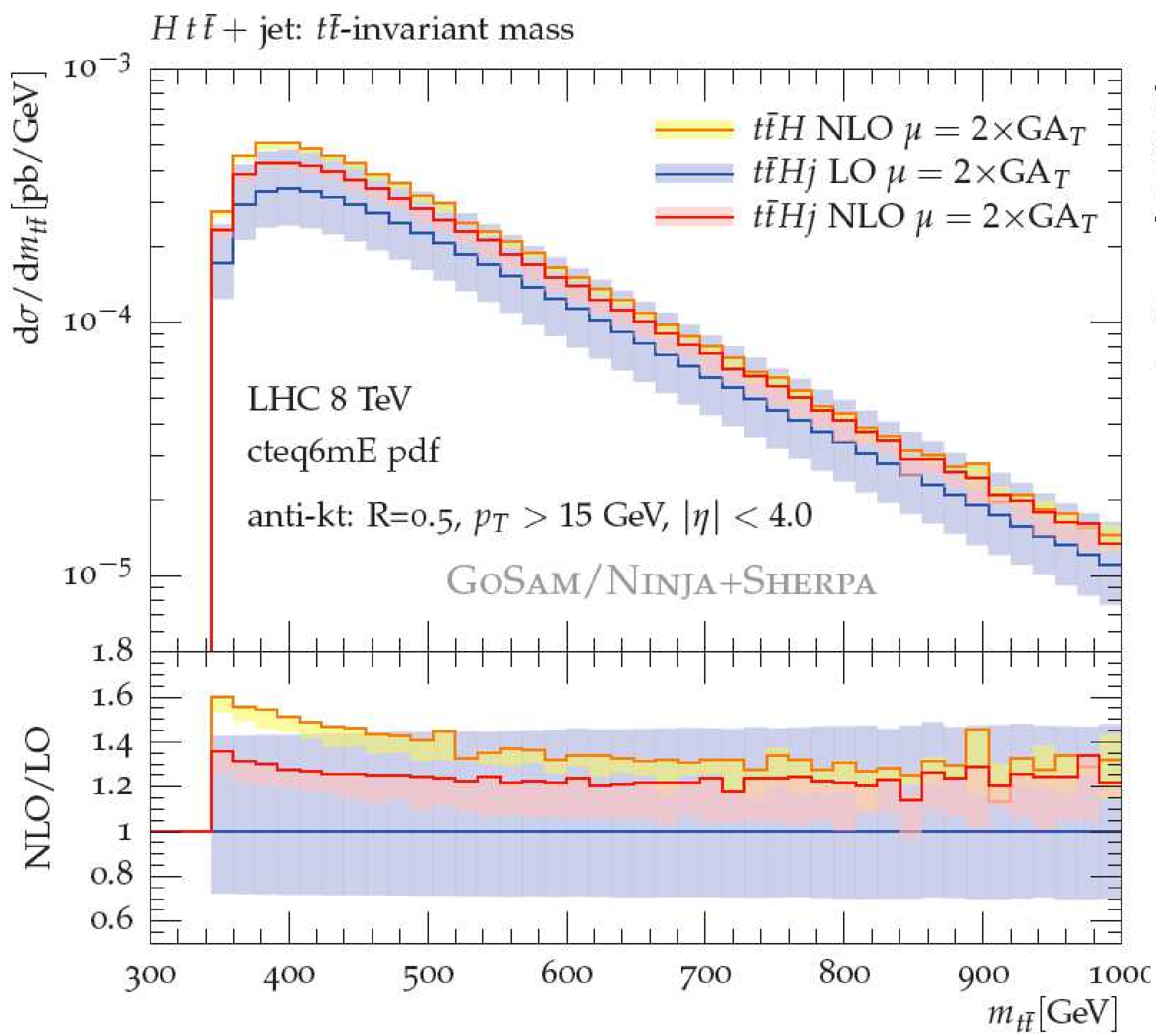
First application of Ninja

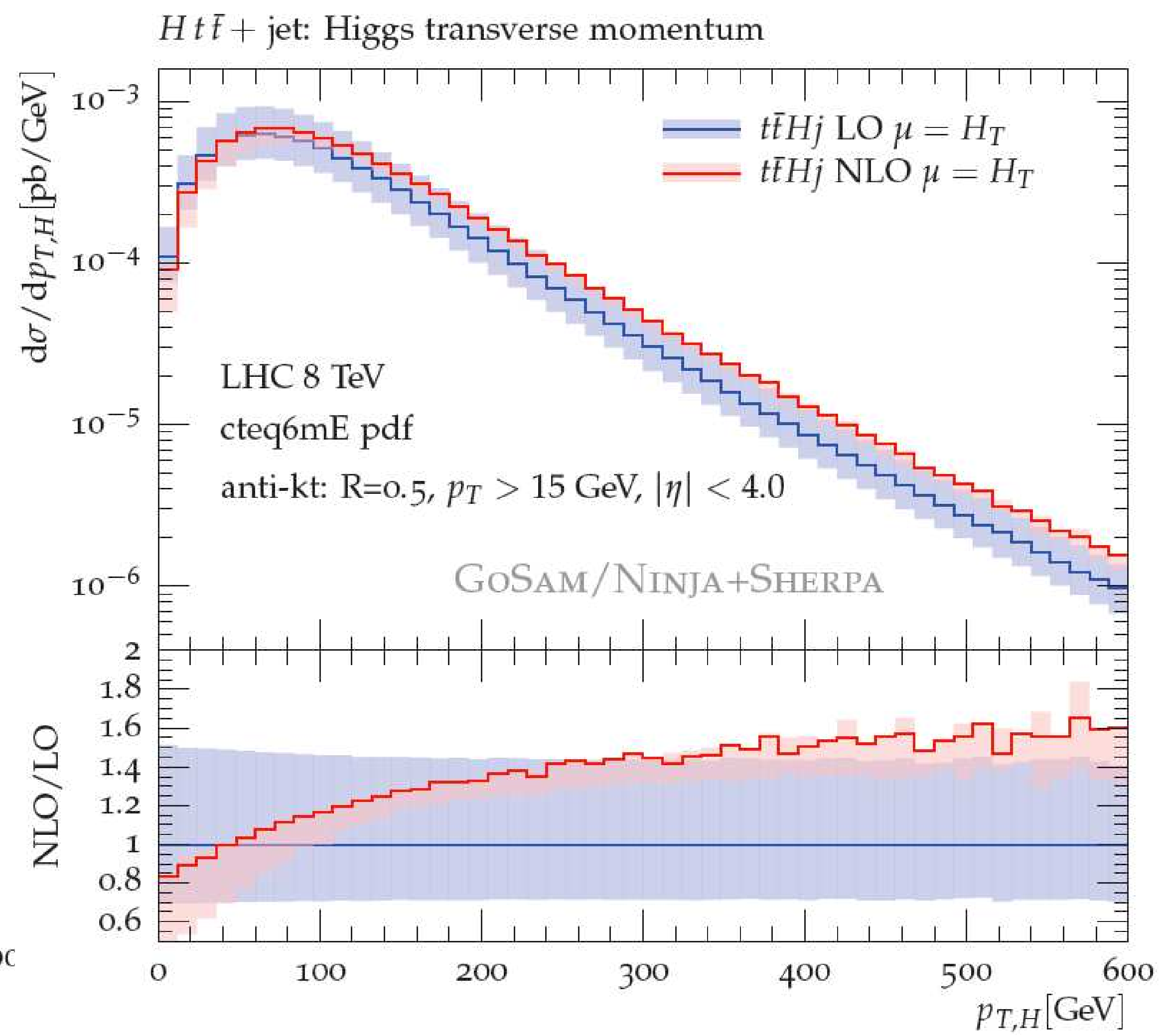
Massive Dipoles

Catani, Dittmaier, Seymour, Tocszany



$t\bar{t}H + 1j$	1895 NLO	Time/psp
$qq \to Ht\bar{t}g$	320 NLO	80 ms
$gg \to Ht\bar{t}g$	1575 NLO	1685 ms





$$\mathrm{GA}_T = \sqrt[3]{m_{T,H}\, m_{T,t}\, m_{T,\bar{t}}} + \sum_{\text{jets } j} |p_{T,j}|$$

$$H_T = \sum_{\substack{\text{final}\\ \text{states } f}} |p_{T,f}|$$

GoSam + Ninja: more app's

van Deurzen Luisoni Mirabella Ossola Peraro *P.M.*

SUBPROCESS	TIME/PS-POINT [ms]
$\mathbf{pp \to Wjjj}$	
$d\bar{u} \to \bar{\nu}_e e^- ggg$	226
$\mathbf{pp \to Zjjj}$	
$d\bar{d} \to e^+ e^- ggg$	1911.4
$\mathbf{pp \to t\bar{t}b\bar{b}} \quad (\mathbf{m_b \neq 0})$	
$d\bar{d} \to t\bar{t}b\bar{b}$	178
$gg \to t\bar{t}b\bar{b}$	5685
$\mathbf{pp \to Wb\bar{b}j} \quad (\mathbf{m_b \neq 0})$	
$u\bar{d} \to e^+ \nu_e b\bar{b}g$	67
$\mathbf{pp \to Hjjj} \quad (\mathbf{GF, m_t \to \infty})$	
$gg \to Hggg$	11266
$gg \to Hgu\bar{u}$	999
$u\bar{u} \to Hgu\bar{u}$	157
$u\bar{u} \to Hgd\bar{d}$	68
$\mathbf{pp \to Hjjj} \quad (\mathbf{VBF})$	
$u\bar{u} \to Hgu\bar{u}$	101
$\mathbf{pp \to Hjjjj} \quad (\mathbf{VBF})$	
$u\bar{u} \to Hggu\bar{u}$	669
$u\bar{u} \to Hu\bar{u}u\bar{u}$	600

Intel i7 960 (3.20GHz) CPU + Intel fortran compiler ifort (with optimization O2).

- faster,
  higher accuracy,
  more stable,
  no-problem with
  multiple masses

Conclusions

- **GoSam**: ideas >> technical improvements >> exciting results
- **GoSam**: automatic computation of one-loop amplitudes
  - algebraic generation of integrands from Feynman diagrams
  - based on d-dim integrand reduction and tensor reduction
  - built-in rational term
- Interfaced to several MC for pheno studies
- Applications within and beyond SM: QCD, EW, BSM, extra-D
- Successful computation of H+n jets (n=1,2,3) in GF
- Ninja :: the new integrand reduction
- GoSam + Ninja :: pp > HtTj

http://gosam.hepforge.org

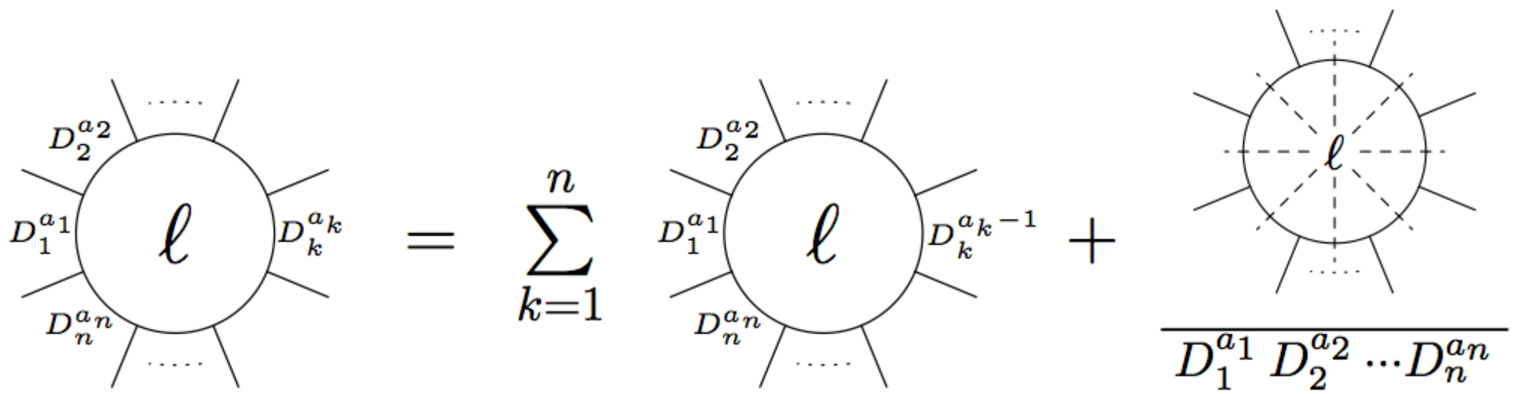
Outlook

- Toward **Gosam2.0** ::
  - faster code generation
  - lighter executable [thanks to Form > 4.0]
  - new reduction algorithm: Ninja
  - faster and more stable evaluation of virtual amp’s
  - extended and more flexible MC-interface

Outlook

- Toward **Gosam2.0**
- *a new horizon*:
  Analytic Integrand Reduction *via* Multivariate Polynomial Division

All-loop Integrand Decomposition



Mirabella Ossola Peraro *P.M.*

>>> Peraro's talk

...one-loop to begin with

I would like to thank Hans, Tiziano, Gionata, Edoardo and Giovanni, for providing some of the shown material