IV Loopfest, Snowmass – 19 August 2005

Semi-numerical evaluation of one-loop corrections

A case study: Higgs + four partons

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☛ *In collaboration with Keith Ellis and Walter Giele*

Overview

- ✗ *Introduction*
  - status of one-loop predictions
  - what is the bottleneck?
- ✗ *Semi-numerical approach*
  - numerical reduction & analytical evaluation of basis integral
  - exceptional momentum configuration
- ✗ *New results*
  - Higgs plus di-jets at hadron colliders
    - ☛ comparison with analytical $4q$ result
    - ☛ numerical results in the $2q2g$, $4g$ cases
  - stability close to exceptional configurations

☛ References *R.K. Ellis, W. Giele, GZ*

hep-ph/0506196 [Higgs+4p NLO] & hep-ph/0507??? [details of the method]

Why do we need one loop corrections?

Well, for the usual reasons....

- reliable estimate of cross section normalization
- reduce scale dependencies
- understand the uncertainties due to the perturbative expansion
- for all searches of new physics it is crucial to understand backgrounds in great detail

☛ At LHC/ILC most processes/backgrounds involve multi-particle final states

Experimental NLO priorities [from Les Houches]

- $2 \to 3$
  - $p\bar{p} \to WW +$ jet
    [general background to NP]
  - $p\bar{p} \to VVV$
    [background to SUSY trilepton]
  - $p\bar{p} \to H + 2$jets
    [background to VBF H]
- $2 \to 4$
  - $p\bar{p} \to 4$jets
  - $p\bar{p} \to t\bar{t} + 2$jets
    [background to $t\bar{t}H$]
  - $p\bar{p} \to t\bar{t} + b\bar{b}$
    [background to $t\bar{t}H$]
  - $p\bar{p} \to V + 3$jets
    [general background to NP]
  - $p\bar{p} \to VV + 2$jets
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  - $p\bar{p} \to WW + b\bar{b}$
    [background to $t\bar{t}$]

Why do we still not know all this?

A full N-particle NLO calculation requires

- the calculation of the tree graph rates with $N+1$ partons
- the calculation of a set of subtraction terms
- the evaluation of the virtual corrections to N parton processes

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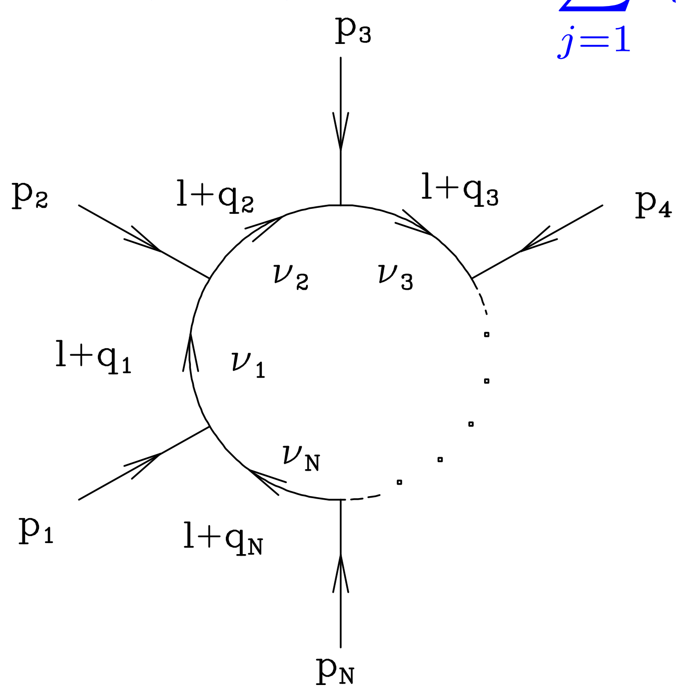
A similar automation of NLO calculations would constitute a major progress $\Rightarrow$ This is the aim of this project

Notations

The generic N-point one-loop graph

$$I^{\mu_1\cdots\mu_M}(D;\nu_1,\ldots,\nu_N) \equiv \int \frac{d^D l}{i\pi^{D/2}} \frac{l^{\mu_1}\ldots l^{\mu_M}}{d_1^{\nu_1} d_2^{\nu_2}\cdots d_N^{\nu_N}}$$

$$D = 4 - 2\epsilon \qquad d_i \equiv (l+q_i)^2 \qquad q_i \equiv \sum_{j=1}^{i} p_j \qquad \sigma \equiv \sum_{i=1}^{N} \nu_i$$



☛ We consider only massless internal propagators, altough the method is more general

Semi-numerical method (I)

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$$\mathcal{A}(p_1, \ldots p_N) = \sum_{n=0}^{N} K_{\mu_1 \cdots \mu_M}(p_1, \ldots, p_N; \varepsilon_1, \ldots, \varepsilon_N) I_{\mu_1 \ldots \mu_n}(D; \nu_1, \ldots \nu_N)$$

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- use Davydychev's formula to reduce tensor integrals to scalar ones

$$I_{\mu_1 \dots \mu_M}(D; \{\nu_l\}) = \sum_{\substack{\lambda, \kappa_1, \kappa_2, \dots, \kappa_N \geq 0 \\ 2\lambda + \sum_i \kappa_i = M}} \left(-\frac{1}{2}\right)^{\lambda} \{[g]^{\lambda} [q_1]^{\kappa_1} \dots [q_N]^{\kappa_N}\}_{\mu_1 \dots \mu_M}$$
$$\times \quad (\nu_1)_{\kappa_1} \dots (\nu_N)_{\kappa_N} \; I(D + 2(M - \lambda); \{\nu_l + \kappa_l\})$$

Semi-numerical method (II)

Use integration-by-parts

$$\int \frac{d^D l}{i\pi^{D/2}} \frac{\partial}{\partial l^\mu} \left(\frac{\left(\sum_{i=1}^N y_i\right) l^\mu + \left(\sum_{i=1}^N y_i q_i^\mu\right)}{d_1^{\nu_1} d_2^{\nu_2} \cdots d_N^{\nu_N}} \right) = 0 \qquad \forall \{y_i\}_{i=1}^N$$

to derive the following reduction relations

[$n = D/2 - \sigma \Rightarrow$ degree of UV divergence]

$$(\nu_k - 1) I(D; \{\nu_l\}) = -\sum_{i=1}^N S_{ki}^{-1} I(D{-}2; \{\nu_l{-}\delta_{li} - \delta_{lk}\}) - b_k \,(D - \sigma)\, I(D; \{\nu_l{-}\delta_{lk}\})$$

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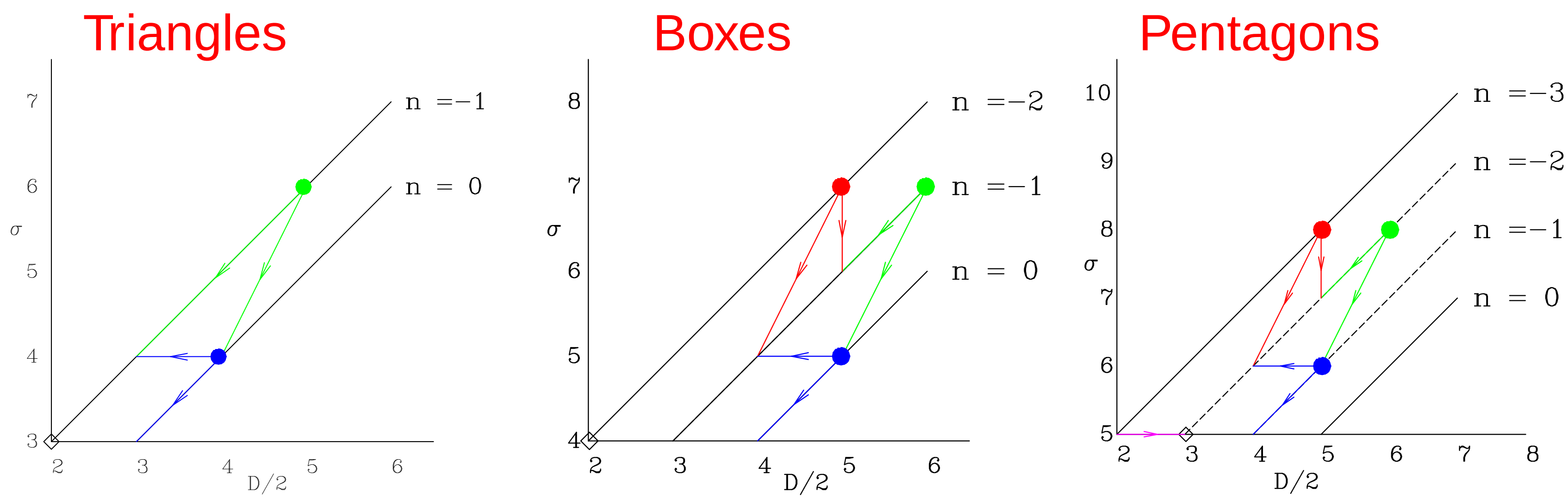

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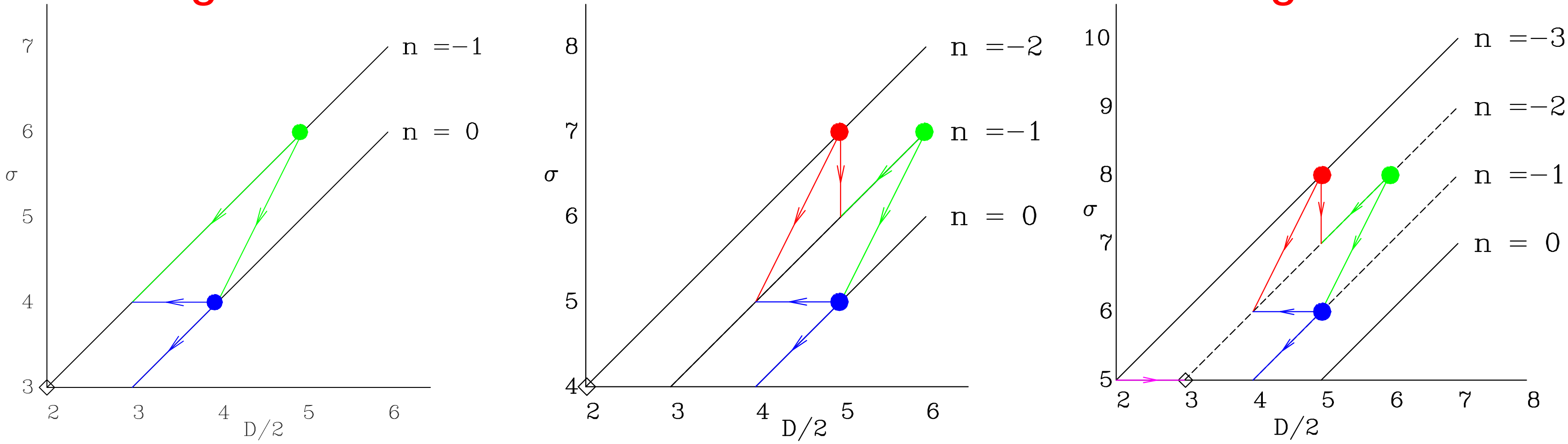
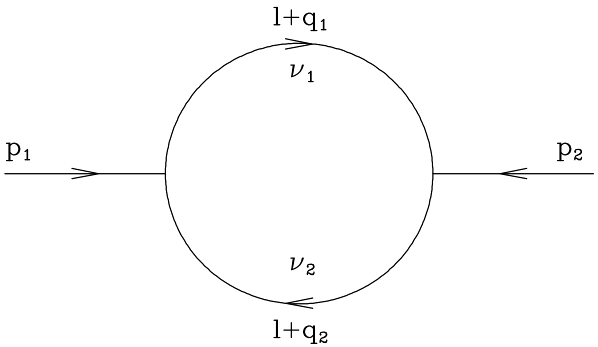
Triangles Boxes Pentagons

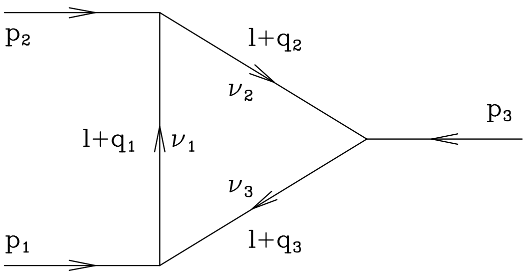


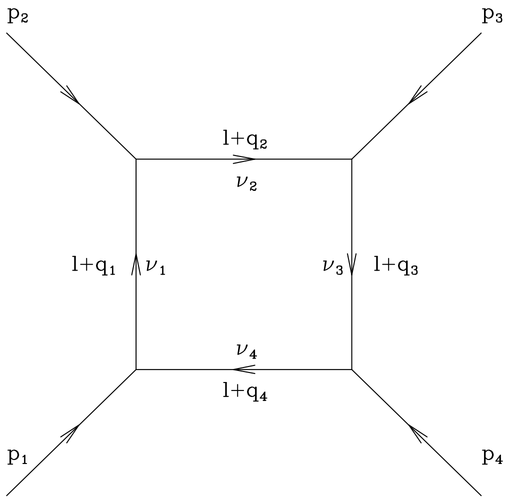
➥ One obtains a complete set of recursion relations which allows one to reduce any integral to a set of known basis integrals

Master integrals

- End-points of the recursions are
  - two-point functions $I(D;\nu_1,\nu_2)$ for arbitrary D and $\{\nu_k\}$
  - one-mass triangles $I(D;\nu_1,\nu_2,\nu_3)$ for arbitrary D and $\{\nu_k\}$
  - three-mass triangles $I(D=4-2\epsilon;1,1,1)$
  - boxes $I(D=4-2\epsilon;1,1,1,1)$
  - pentagons $I(D=6-2\epsilon;1,1,1,1,1)$







Semi-numerical method (sumr.)

❶ use qgraf/form/mathematica to generate the amplitude for the specific process

❷ use Davydychev to reduce tensor integrals to scalar integrals

❸ use a complete set of recurions relations to reduce all integrals to a set of analytically known basis integrals

Notice:

- since recursion relations involve D, the result of each integral is *not* a number but a Laurent series in ϵ (a derived type in F95)
- since analytical expressions for the basis integrals are used no loss of accuracy is expected
- however one encouters unphysical divergences in the physical region

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A closer look at the recursion relations

$$(\nu_k - 1) I(D;\{\nu_l\}) = -\sum_{i=1}^{N} S^{-1}_{ki} I(D-2;\{\nu_l - \delta_{li} - \delta_{lk}\}) - b_k\,(D-\sigma)\,I(D;\{\nu_l - \delta_{lk}\})$$

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These exceptional configurations have generally zero measure, but standard recursions are unstable close to those points

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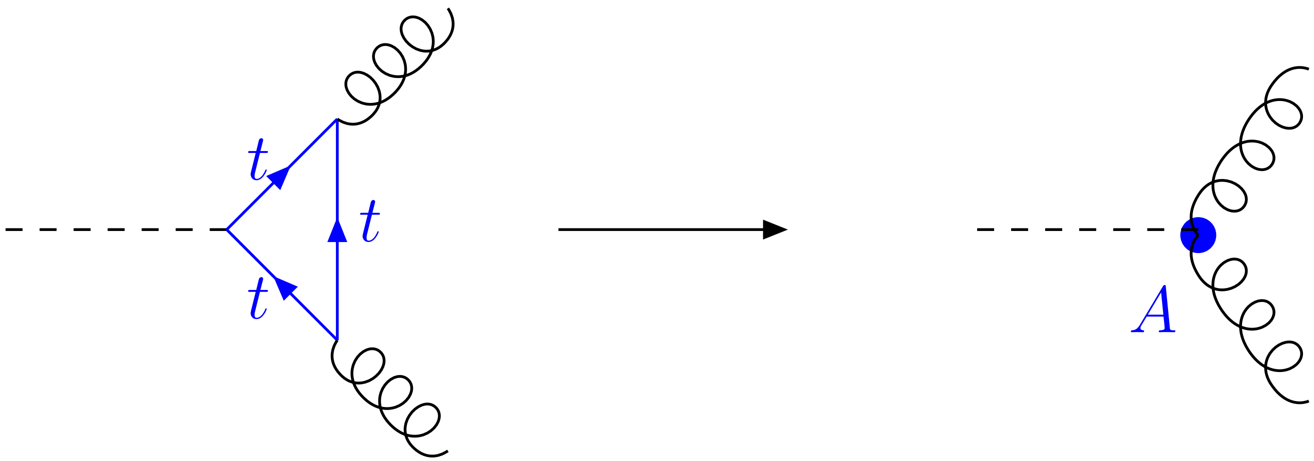
Higgs plus four partons

First new results

$H \to k_1\, k_2\, k_3\, k_4$ in the large m_t limit

The Higgs is produced using the effective coupling to gluons



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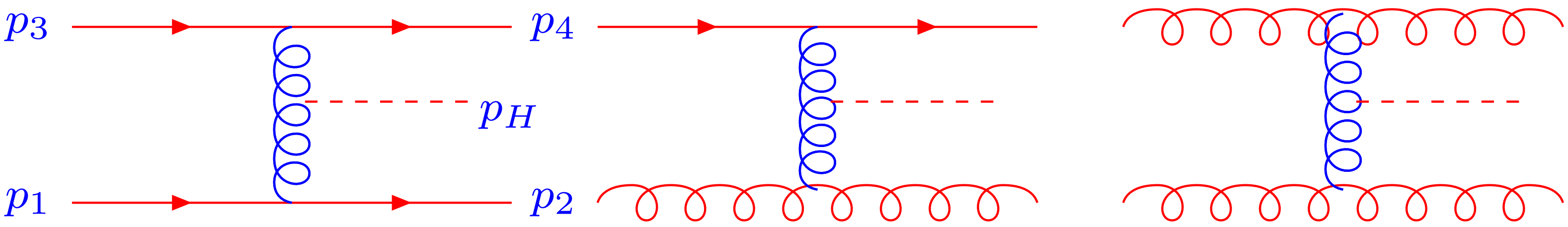

@NLO

Processes

$A:$	H	$\rightarrow q\bar{q}q'\bar{q}'$	30 diags.
$B:$	H	$\rightarrow q\bar{q}q\bar{q}$	60 diags.
$C:$	H	$\rightarrow q\bar{q}gg$	191 diags.
$D:$	H	$\rightarrow gggg$	739 diags.

Sample results for a non-exceptional point

	$1/\epsilon^2$	$1/\epsilon$	1
A_B	0	0	12.9162958212387
$A_{V,N}$	-68.8869110466063	-114.642248172519	120.018444115458
$A_{V,A}$	-68.8869110466064	-114.642248172523	120.018444115429
B_B	0	0	858.856417157052
$B_{V,N}$	-4580.56755817094	-436.142317955208	26470.9608978350
$B_{V,A}$	-4580.56755817099	-436.142317955660	26470.9608978346
C_B	0	0	968.590160211857
$C_{V,N}$	-8394.44805516930	-19808.0396331354	-1287.90574949112
$C_{V,A}$	-8394.44805516942	-19808.0396331363	not known
D_B	0	0	3576991.27960852
$D_{V,N}$	-4.29238953553022 $\cdot 10^7$	-1.04436372655580 $\cdot 10^8$	-6.79830911471604$\cdot 10^7$
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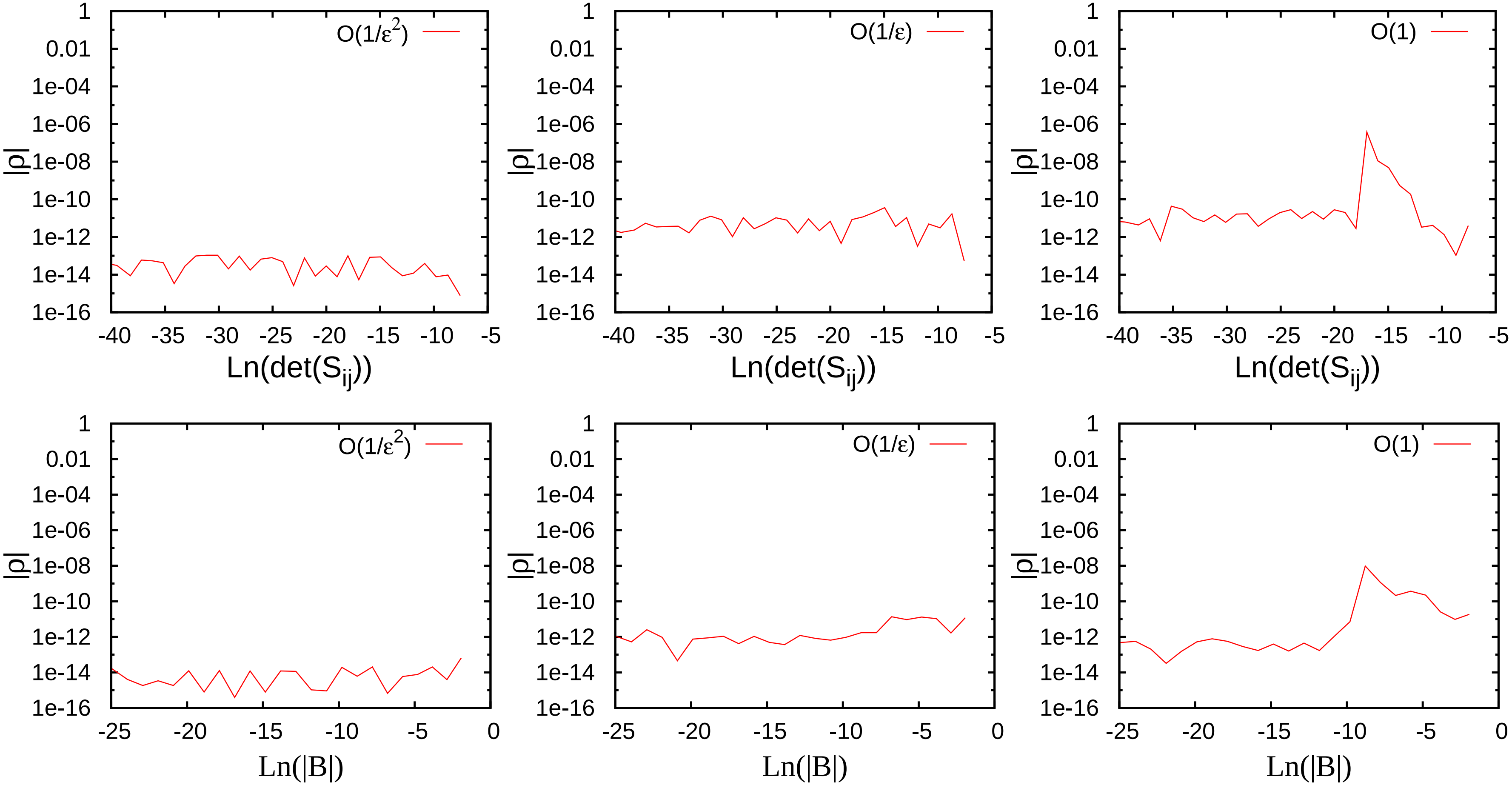
➥ relative accuracy of $\mathcal{O}\left(10^{-13}\right)$!

Results for exceptional phase space points



➥ relative accuracy $|\rho|$ of $\mathcal{O}\left(10^{-6}\right)$!

☚ <u>Notice:</u> in principle any accuracy can be reached at the price of including more terms in the expansion

Conclusions

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[SAMPER – Semi-Analitycal aMPlitude EvaluatoR

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➥ Remarks:

- analytical evaluation of basis integrals $\Rightarrow$ no loss of accracy
- "expanded" recursion relations $\Rightarrow$ results stable close to exceptional phase space points
- a key point of the algorithm: a record is kept of all previously computed scalar integrals, so that each one is computed only once $\Rightarrow$ efficient method

Four lines of research

Outlook

Four lines of research

- completion of Higgs boson plus two jet at NLO
  - calculation of the tree level Higgs + 5 partons ✓
  - calculation of the subtraction terms [✓]
  - phase space integration and phenomenology
  - true proof of principle of the method

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  - true proof of principle of the method
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  - tri-boson production (V_1, V_2, V_3)
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