Towards a more accurate prediction of $W + b$ jets with an automatized approach to one-loop calculations

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Loops and Legs in Quantum Field Theory

Wernigerode, April 2012

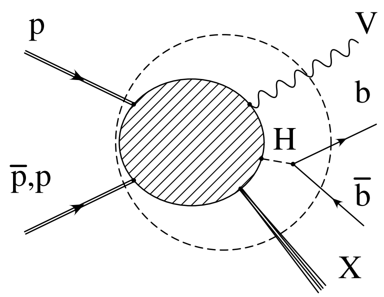
Outline

- Motivations:
  - ▷ $W + b$-jet and $W + 2\,b$-jets (plus light jets): important QCD test;
  - ▷ they are also crucial backgrounds in Higgs searches;
  - ▷ the NLO cross sections for $pp, p\bar{p} \to Wb\bar{b}$ production still suffer from large systematic uncertainty:
    - → contributes to both $1b$-jet and $2b$-jet signatures;
    - → main origin: $qg \to Wb\bar{b}q$ channel opening at NLO;
    - → more dramatic at the LHC in the $2b$-jet signature;
    - → less dramatic in the $1b$-jet signature (with 5FNS resummation).
- Main QCD studies:
  - ▷ $Wb\bar{b}$ at NLO, b massless/massive;
  - ▷ $Wb+$ jet: 4FNS and 5FNS at NLO;
  - ▷ NLO $Wb\bar{b}$ interfaced with parton shower Monte Carlo programs;
  - ▷ $Wb\bar{b} + j$ at NLO, b massive: one-loop contributions:
    - → meaning of adding this order of corrections;
    - → main technical challenges and what they entailed;
    - → ongoing and possible developments.

Motivations

a challenging background

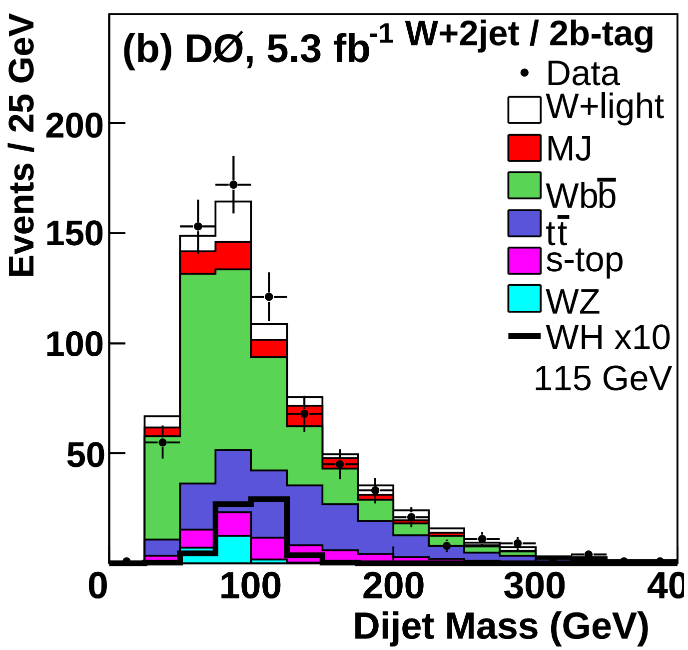
Associated production of SM Higgs with weak vector bosons

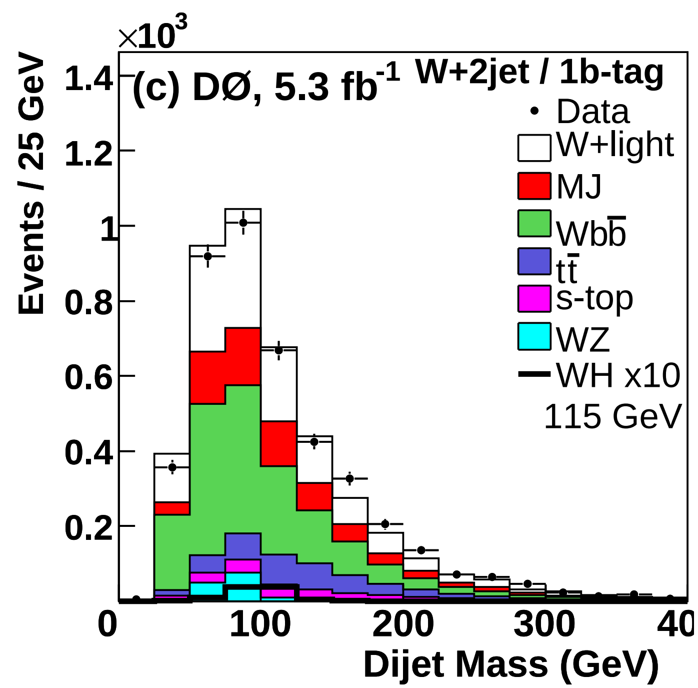


$\longrightarrow$ NNLO QCD corrections have been calculated for the signal [O.Brien, A.Djouadi and R.Harlander, 2004]

$\longrightarrow$ $O(\alpha)$ EW corrections have been calculated for the signal [M.L.Ciccolini, S.Dittmaier and M.Kramer, 2003]

$\rightarrow$ Results for WH associated production, Spring 2012





$W + b$ jets

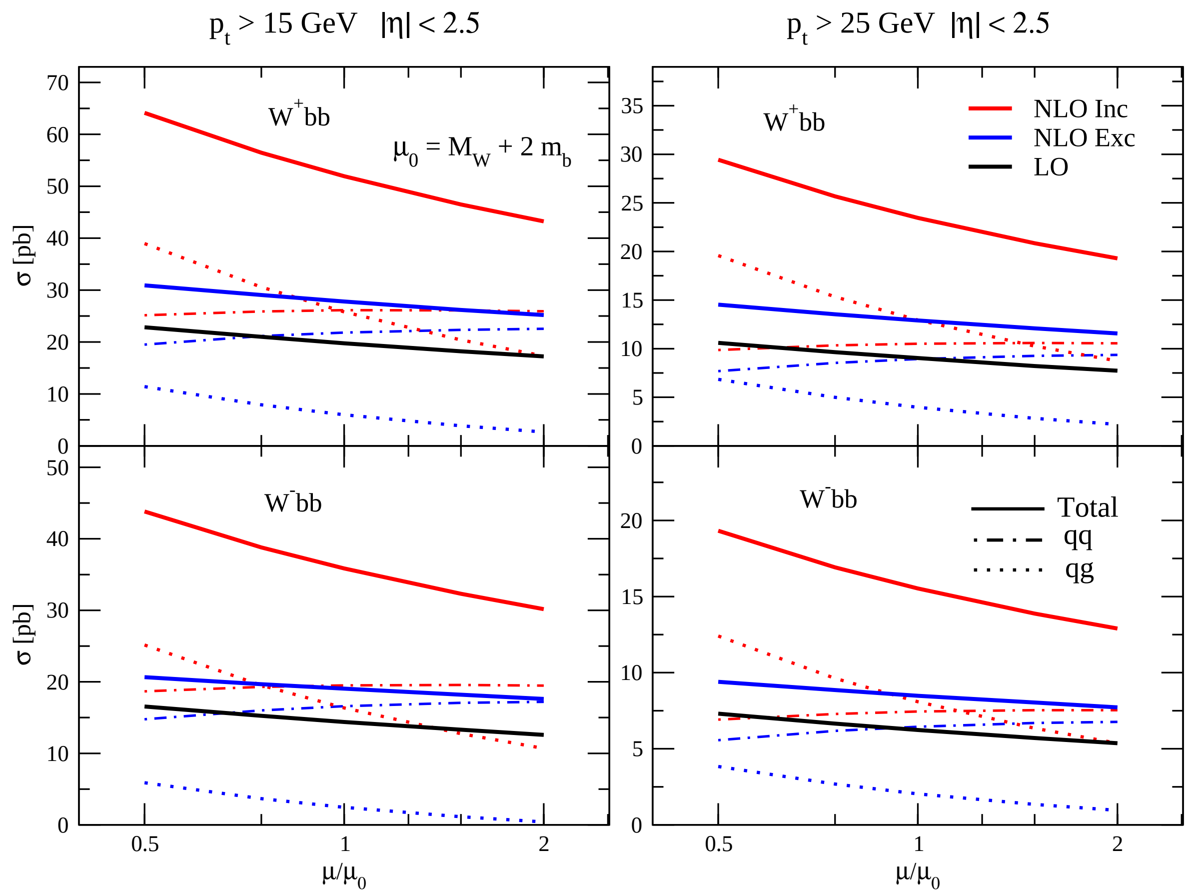
Studied at NLO in QCD/measured in experiments:

- $W + 2b$ jets ($m_b \neq 0$):
  - Febres Cordero, L. R., Wackeroth, hep-ph/0606102, arXiv:0906.1923
  - Badger, Campbell, Ellis, arXiv:1011.6647 (with $W \to l\nu$)
  - Oleari, L. R., arXiv.1105.4488 $\longrightarrow$ POWHEG
  - Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli, arXiv:1106.6019 $\longrightarrow$ MC@NLO

- $W + 2$ jets with at least one b jet:
  - Campbell, Ellis, Febres Cordero, Maltoni, L.R., Wackeroth, Willenbrock, arXiv:0809.3003
  - the CDF collaboration, arXiv:0909.1505,
    Campbell, Febres Cordero, L.R., arXiv:1001.3362, arXiv:1001.2954
  - the ATLAS collaboration, arXiv:1109.1470,
    Campbell, Caola, Febres Cordero, L.R., Wackeroth, arXiv:1107.3714

- $W + 2b+$ jet:
  - L.R., Schutzmeier, arXiv:1110.4438 (one-loop corrections)

$W + 2b$ jets@LHC: large theoretical uncertainty at NLO



(Febres Cordero, L.R., Wackeroth, arXiv:0906.1923)

⟶ NLO corrections very large, particularly for inclusive production;

⟶ large NLO scale-dependence (LO: 30%, NLO_{inc}: 50%, NLO_{exc}: 20%), induced by the opening of the $qg(\bar{q}g) \to Wb\bar{b} + q'(\bar{q}')$ channel;

⟶ theoretical uncertainty not only given by scale-dependence!

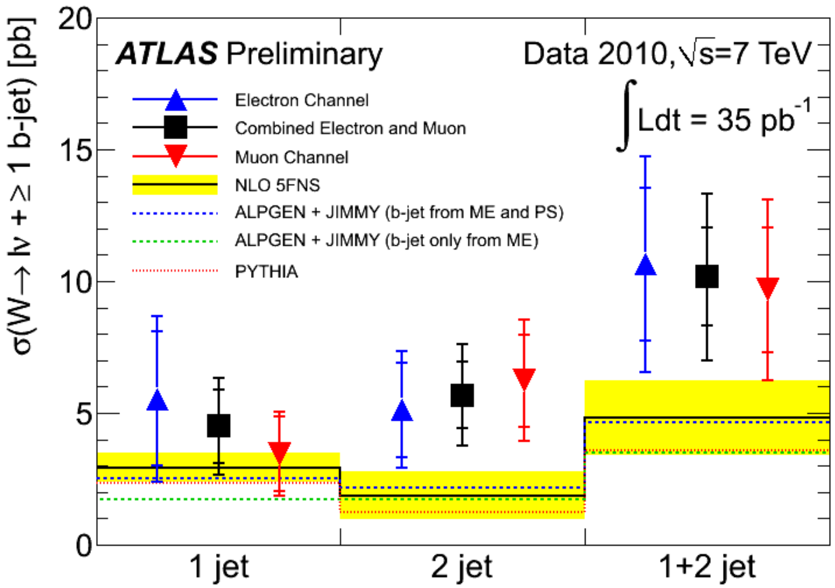
W plus at least one b jet, some tension:

$\longrightarrow$ Comparison with CDF (arXiv:0909.1505):

$$\sigma_{\mathrm{b-jet}}(W + b\,\mathrm{jets}) \cdot Br(W \to l\nu)|_{CDF} = 2.74 \pm 0.27(\mathrm{stat}) \pm 0.42(\mathrm{syst})\ \mathrm{pb}$$

$$\sigma_{\mathrm{b-jet}}(W + b\,\mathrm{jets}) \cdot Br(W \to l\nu)|_{theory} = 1.22 \pm 0.14\ \mathrm{pb}$$

$\longrightarrow$ Comparison with ATLAS (arXiv:1109.1470):



More statistics available

new results by Summer 2012

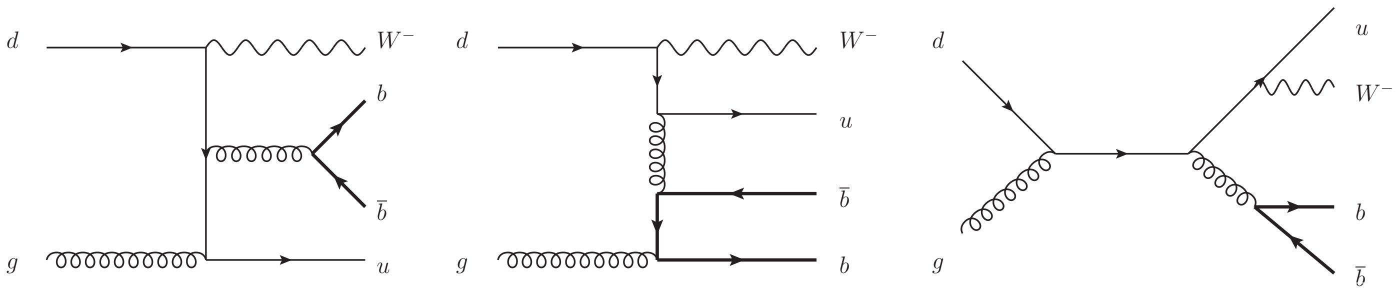
$Wb\bar{b} + j$ at NLO

challenges, results, future steps

with T. Schutzmeier

Overview

- One-loop QCD corrections to $qg \to Wb\bar{b} + q'$:



$+\cdots$

plus about 300 loop diagrams, keeping full m_b dependence.

- Together with analogous corrections to $q\bar{q}' \to Wb\bar{b} + g$ (obtained by crossing), they represent a well-defined piece of the NNLO QCD corrections to $pp, p\bar{p} \to Wb\bar{b}$: the one-loop virtual corrections from $2 \to 4$ processes.

- They provide the $O(\alpha_s)$ virtual corrections for $pp, p\bar{p} \to W + 2b\,\text{jets} + j$.

- In a fixed-flavor scheme, they also provide the $O(\alpha_s)$ virtual corrections for $pp, p\bar{p} \to W + b\,\text{jet} + j$.

Approach

- Based on traditional Feynman diagrams evaluation

$$\Gamma = \mathrm{Re}\left\{ \sum_{ij} \sum_{\mathrm{color}} C_i C_j^* \sum_{\mathrm{spin,pol}} \sum_n c_{in}\, \hat{\mathcal{M}}_n^{(1)} \hat{\mathcal{M}}_j^{(0)*} \right\}$$

- UV and IR divergences extracted in $d = 4 - 2\epsilon$ using dimensional regularization,
  - ▷ UV divergent QCD subdiagrams are standard: can be isolated and matched with a suitable choice of counterterms;
  - ▷ IR divergences' structure well known and matched exactly by corresponding real emission contributions.
- New techniques developed to
  - ▷ reduce diagram structure to small/minimal set of standard spinor structures using graph techniques;
  - ▷ combine different reduction methods to optimize calculation of numerically stable tensor integral coefficient.

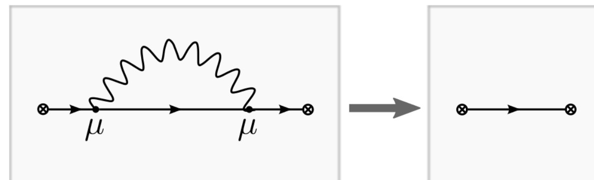
- Each level of evaluation automatized within an overall interface (`Python`) that only takes as input the desired process:
  - ▷ diagram generated with a very modified version of `QGRAPH`;
  - ▷ algebraic manipulations to extract first level of SME and tensor structures done with `FORM`;
  - ▷ reduction of tensor integral coefficients and spinor structures use `C++`;
  - ▷ numerical stability checks use library of scalar integrals based on `QCDLoop` and `LoopTools`;
  - ▷ amplitude square calculation uses `C++` interface to facilitate
    - – selection of terms (e.g. individual diagrams or groups of),
    - – extraction of divergences,
    - – extensive numerical checks,
    - – connection with a phase space generator,
    - – and more.

Reduction of spinor structures

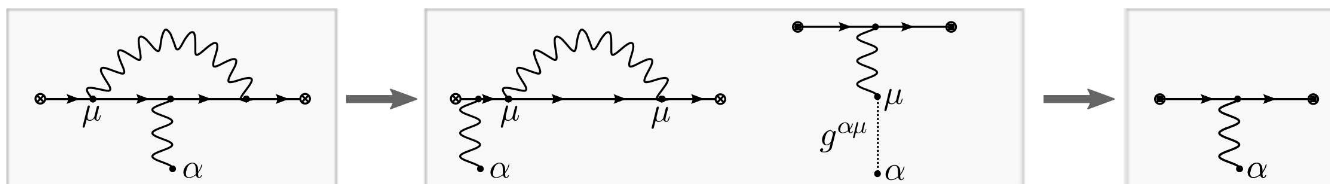
spinor structures (standard matrix element or SME) $\rightarrow$ oriented graphs:

- nodes $\rightarrow$ spinor, gamma matrices, projectors, polarizations, ...
- links $\rightarrow$ contraction of indices and direction.

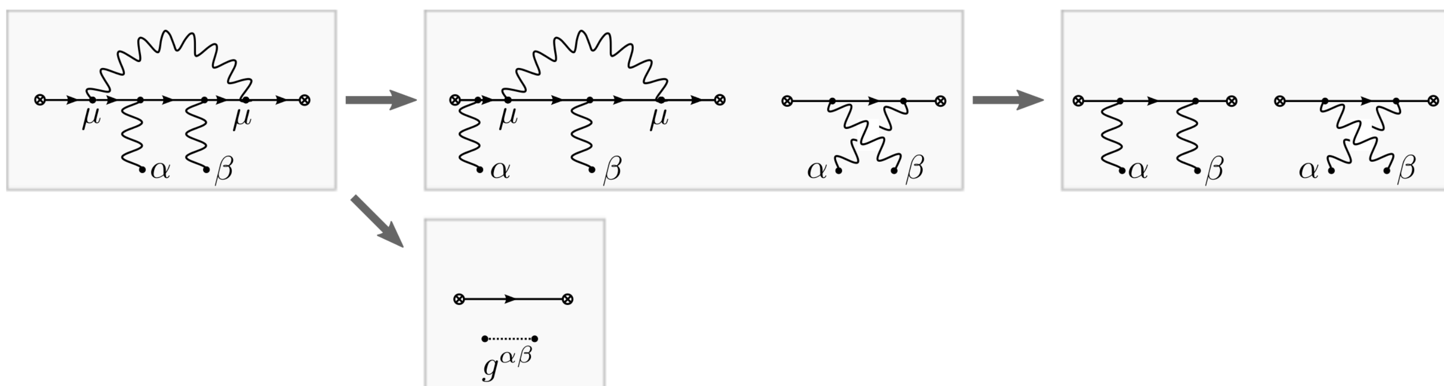
$\gamma^\mu \gamma_\mu$



$\gamma^\mu \gamma^\alpha \gamma_\mu$

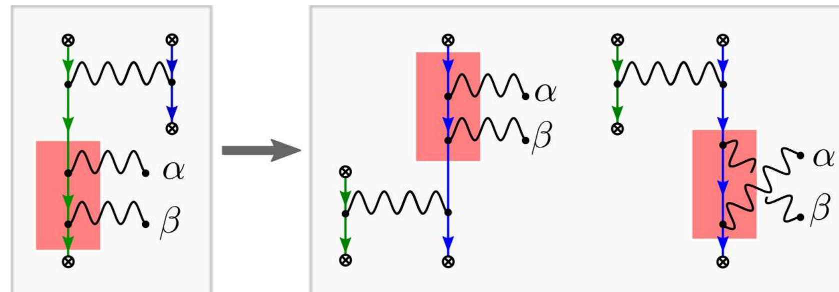


$\gamma^\mu \gamma^\alpha \gamma^\beta \gamma_\mu$



oriented graphs → stored as relations and graph operations that are automatically implemented over the entire structure of a diagram at once,

$$\gamma^\mu \gamma^\alpha \gamma^\beta P_+ \times \gamma_\mu =$$
$$\gamma^\mu P_+ \times (\gamma_\mu \gamma^\beta \gamma^\alpha P_+ + \gamma^\alpha \gamma^\beta \gamma_\mu P_-)$$



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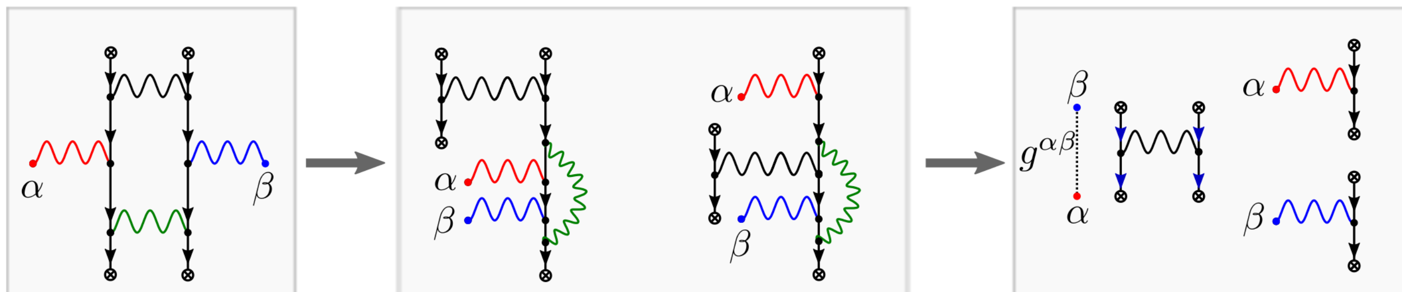


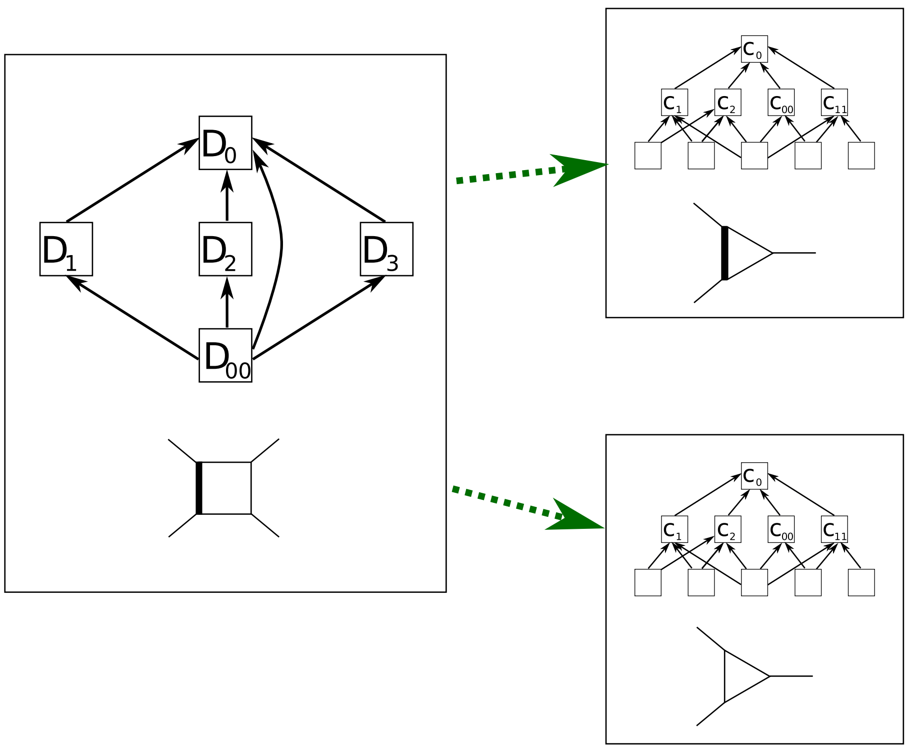
- ▷ algebraic relations (based on d=4 identities) translate into graph operations (e.g. shrinking of edges, exchange or addition of nodes, ...) and result into disconnected elementary graphs;
- ▷ number of final SME much smaller (from thousands to a a few hundreds);
- ▷ coefficients of single elementary graphs collected via systematic labeling .

Reduction of tensor-integral coefficients

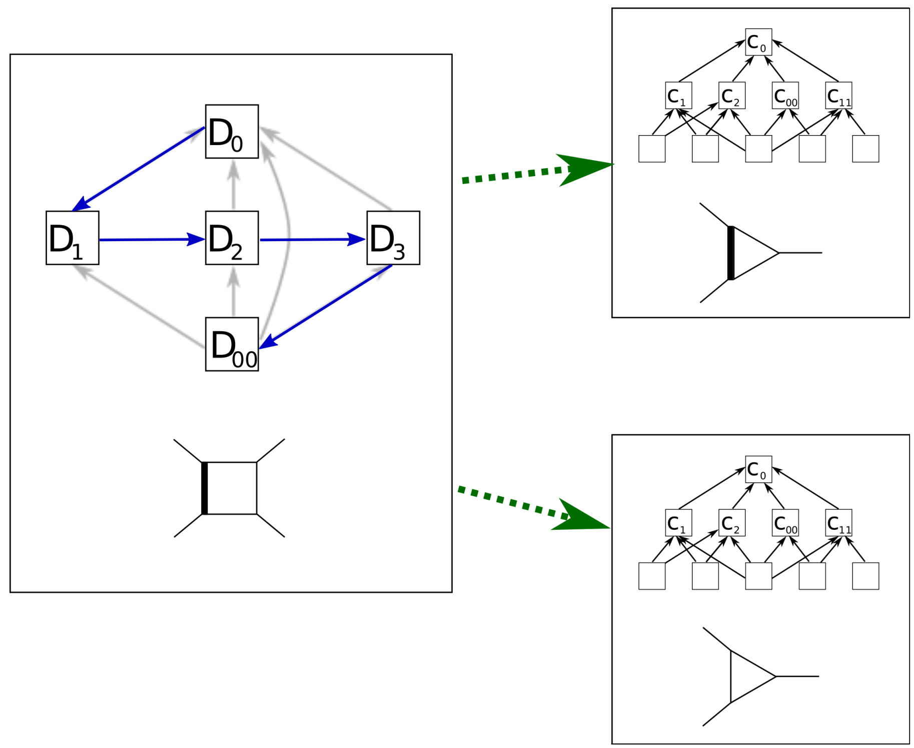
– reduce to standard pattern of momenta and masses;

– create list of dependences that are then reused every time the same pattern appears,including subdiagrams;

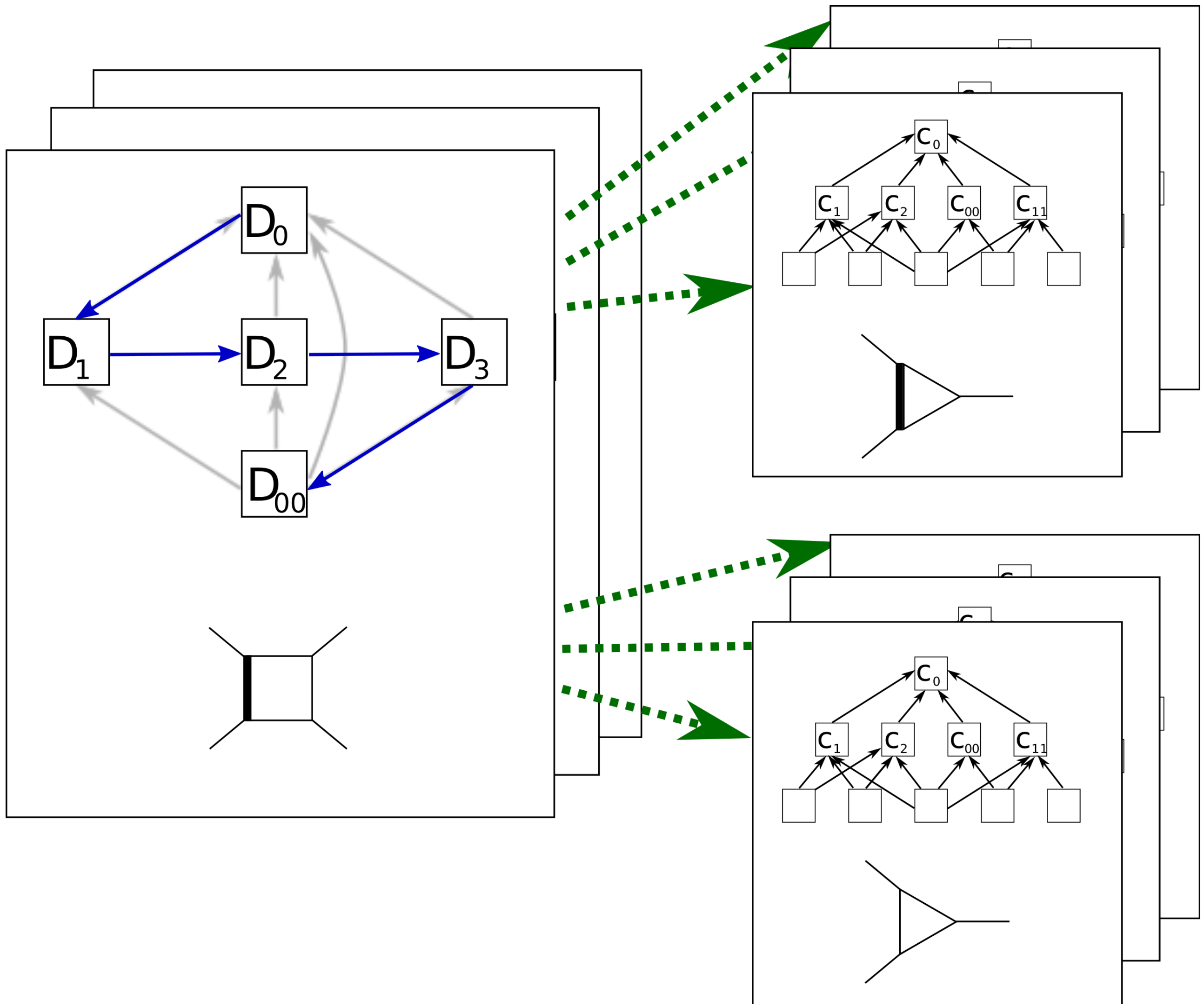
– choose evaluation order.



automated dependency creation



evaluation order determination



On-the-fly generation and evaluation of alternatives reduction methods if needed.

– presence of numerical instabilities detected from behavior of double and single pole parts (checked against analytical library);

– if detected, switch to different reduction method.

For $N \leq 4$ we implement:

– no instabilities: PV reduction

– if unstable:

  – PV in multiple precision (quadruple or double quadruple);

  – reduction with modified Cayley determinant (Denner and Dittmaier, arXiv:hep-ph/0509141);

  – expansion around small quantities (e.g. Gram or Cayley determinant) (Denner and Dittmaier, arXiv:hep-ph/0509141).

For $N > 4$ we implement:

– Gram determinant free (GDF) procedure (Diakonidis, Fleischer, Gluza, Kajda, Riemann, and Tausk, arXiv:0812,2134).

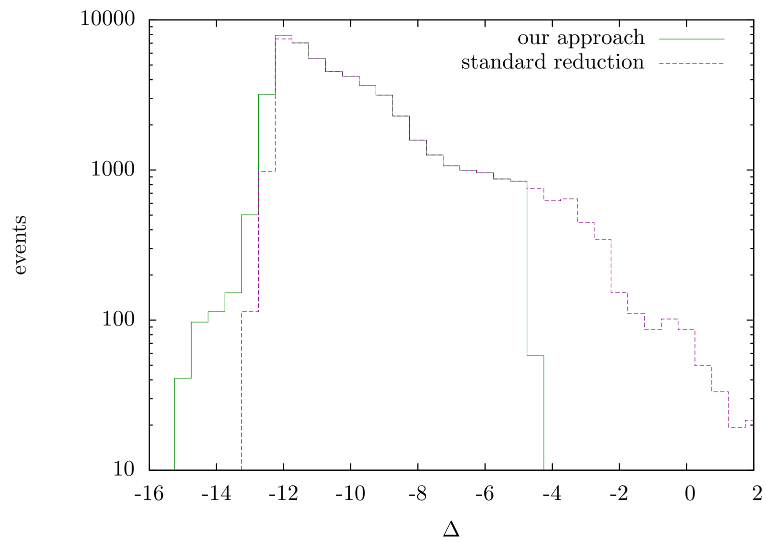
Moreover, if numerical instabilities arise when combining various terms at the amplitude square level, the entire calculation is switched to multiple precision.

Some checks

– Using the high precision set of points previously generated as reference points ($\Gamma_{\rm ref}$), compute the square amplitude for the same set of points using two different strategies:

  – standard reduction of 5- and 6-point tensor coefficients,

  – GDF reduction of 5- and 6-point tensor integrals switches to multiple precision when needed.



$$\Delta = \log_{10}\left(\frac{|\Gamma - \Gamma_{\rm ref}|}{|\Gamma_{\rm ref}|}\right)$$

– Moreover: reproduced results for several $2 \to 3$ processes (e.g. $W/Zb\bar{b}$, $\gamma t\bar{t}$) , and $2 \to 4$ ($\bar{u}d \to d\bar{d}gW$ channel of $W + 3j$ calculation). Also, results for $ug \to Wb\bar{b} + d$ checked with GoSam collaboration.

Some benchmarks

Benchmarks of the numerically stabilized method applied to various NLO amplitudes for the evaluation of $5 \cdot 10^4$ phase-space points.

Process	r_s	r_q	r_{dq}	t_m/ms	t_s/ms	t_q/ms	t_{dq}/ms	t_q^{full}/ms
$q\bar{q} \to \gamma t\bar{t}$	99.6%	0.4%	0	9.5	8.9	153	0	1069
$gg \to \gamma t\bar{t}$	98.9%	1.1%	0	12.0	10.1	182	0	1972
$q\bar{q}' \to Wb\bar{b}$	99.7%	0.3%	0	10.9	10.4	167	0	1264
$q\bar{q} \to Zb\bar{b}$	99.8%	0.1%	0.1%	17.7	14.4	217	3161	2290
$gg \to Zb\bar{b}$	98.3%	1.6%	0.1%	22.5	15.7	233	3314	2706
$\bar{u}d \to d\bar{d}gW$	95.4%	3.6%	1.0%	90.3	37.5	306	4358	5503
$ug \to b\bar{b}dW$	93.1%	5.6%	1.3%	95.4	29.7	311	3870	5192

The above numbers were obtained on an Intel i7 950 CPU at 3.07GHz.

Summary and Outlook

- Calculated $O(\alpha_s)$ virtual corrections to $Wb\bar{b}+j$ and $Wb+j$ (in fixed-flavor scheme).
- This also provides a self-contained piece of NNLO virtual corrections to $Wb\bar{b}$.
- New automatized package developed (based on improved Feynman-diagram techniques) to calculate $2 \to 3$ and $2 \to 4$ processes with vector bosons and several massive particles.
- Effort now focused on:
  - $\hookrightarrow$ documenting existing package, adding useful options or improving existing ones;
  - $\hookrightarrow$ implementing interface to real corrections' generator;
  - $\hookrightarrow$ studying impact of calculated QCD effects.