

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

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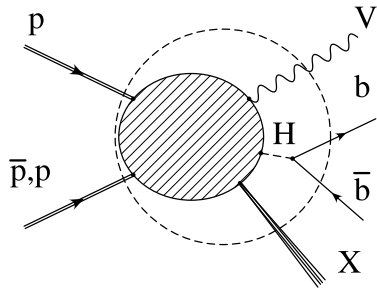
Outline

- 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 $pp, p\bar{p} \rightarrow W b\bar{b}$ production still suffer from large systematic uncertainty:
 - contributes to both $1b$ -jet and $2b$ -jet signatures;
 - main origin: $qg \rightarrow W b\bar{b}q$ 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:
 - ▷ $W b\bar{b}$ at NLO, b massless/massive;
 - ▷ $W b + \text{jet}$: 4FNS and 5FNS at NLO;
 - ▷ NLO $W b\bar{b}$ interfaced with parton shower Monte Carlo programs;
 - ▷ $W b\bar{b} + j$ 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

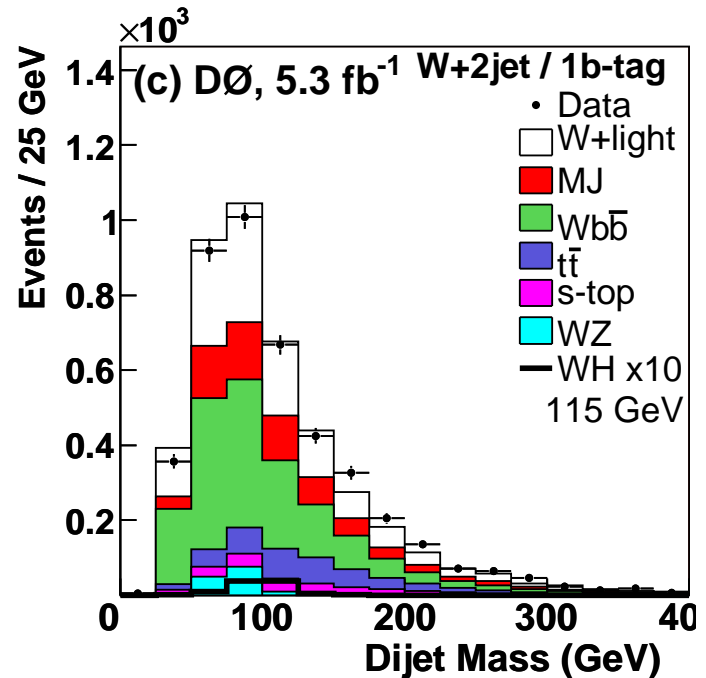
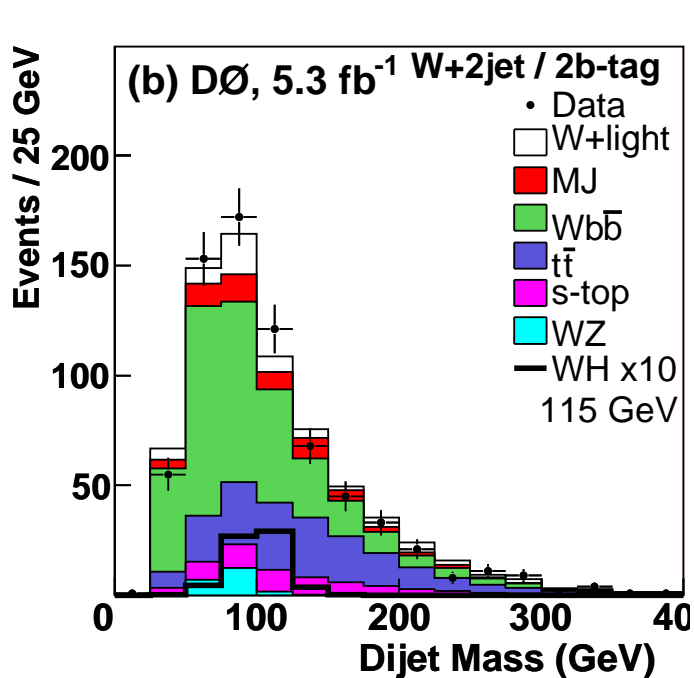
Associated production of SM Higgs with weak vector bosons



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

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

→ Results for WH associated production, Spring 2012

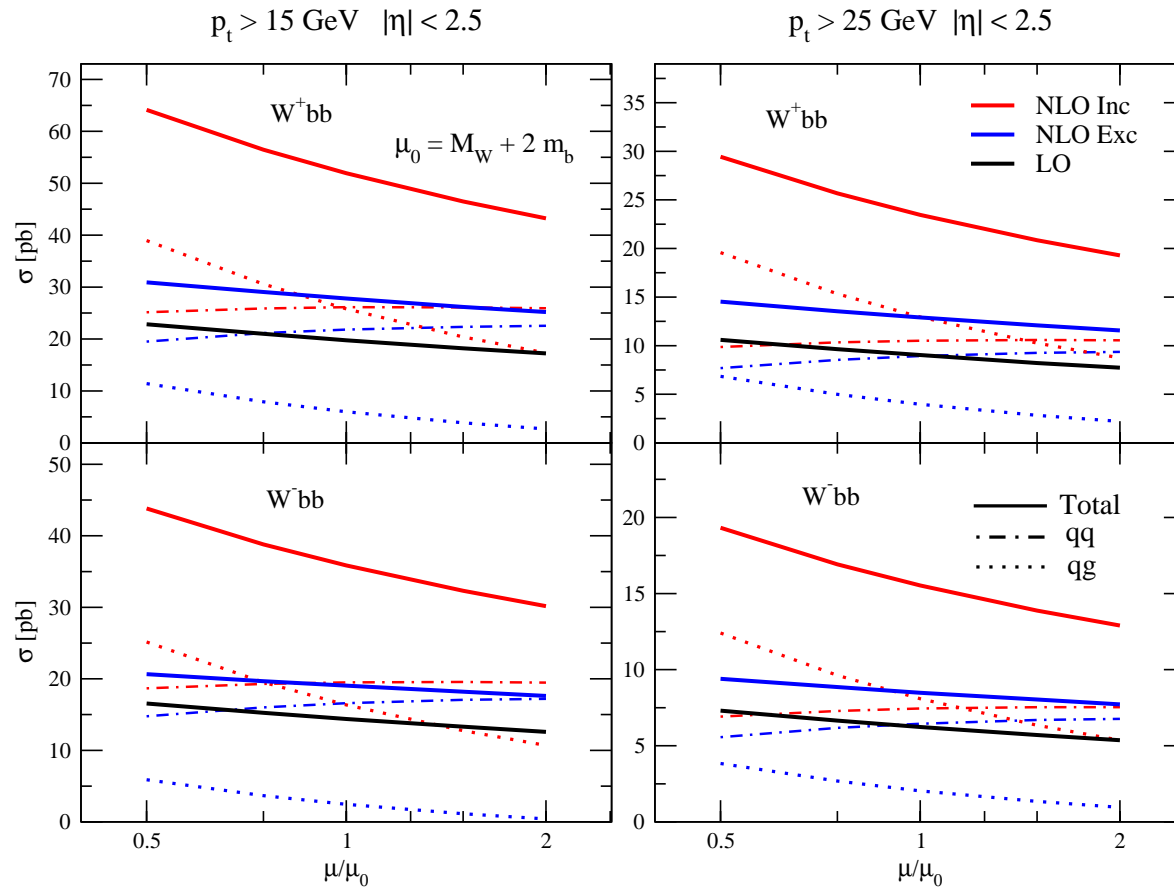


$W + b$ jets

Studied at NLO in QCD/measured in experiments:

- $W + 2b$ jets ($m_b \neq 0$):
 - Febres Cordero, L. R., Wackerth, hep-ph/0606102, arXiv:0906.1923
 - Badger, Campbell, Ellis, arXiv:1011.6647 (with $W \rightarrow l\nu$)
 - Oleari, L. R., arXiv.1105.4488 \rightarrow POWHEG
 - Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli, arXiv:1106.6019
 \rightarrow MC@NLO
- $W + 2$ jets with at least one b jet:
 - Campbell, Ellis, Febres Cordero, Maltoni, L.R., Wackerth, 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., Wackerth, arXiv:1107.3714
- $W + 2b + \text{jet}$:
 - L.R., Schutzmeier, arXiv:1110.4438 (one-loop corrections)

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



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

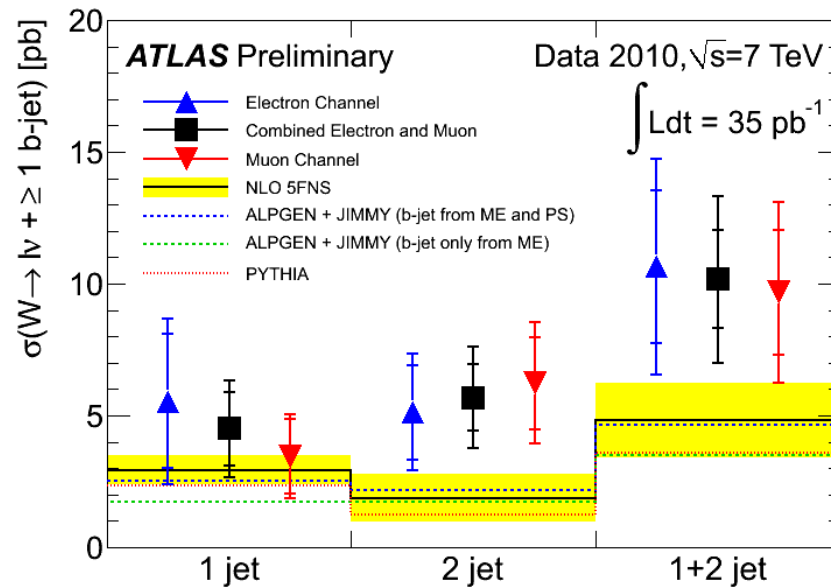
- NLO corrections very large, particularly for inclusive production;
- large NLO scale-dependence (LO: 30%, NLO_{inc} : 50%, NLO_{exc} : 20%), induced by the opening of the $qg(\bar{q}g) \rightarrow Wb\bar{b} + q'(\bar{q}')$ channel;
- theoretical uncertainty not only given by scale-dependence!

W plus at least one b jet, some tension:

→ Comparison with CDF ([arXiv:0909.1505](#)):

$$\begin{aligned}\sigma_{b\text{-jet}}(W + b\text{ jets}) \cdot Br(W \rightarrow l\nu)|_{CDF} &= 2.74 \pm 0.27(\text{stat}) \pm 0.42(\text{syst}) \text{ pb} \\ \sigma_{b\text{-jet}}(W + b\text{ jets}) \cdot Br(W \rightarrow l\nu)|_{theory} &= 1.22 \pm 0.14 \text{ pb}\end{aligned}$$

→ Comparison with ATLAS ([arXiv:1109.1470](#)):



More statistics available
new results by Summer 2012

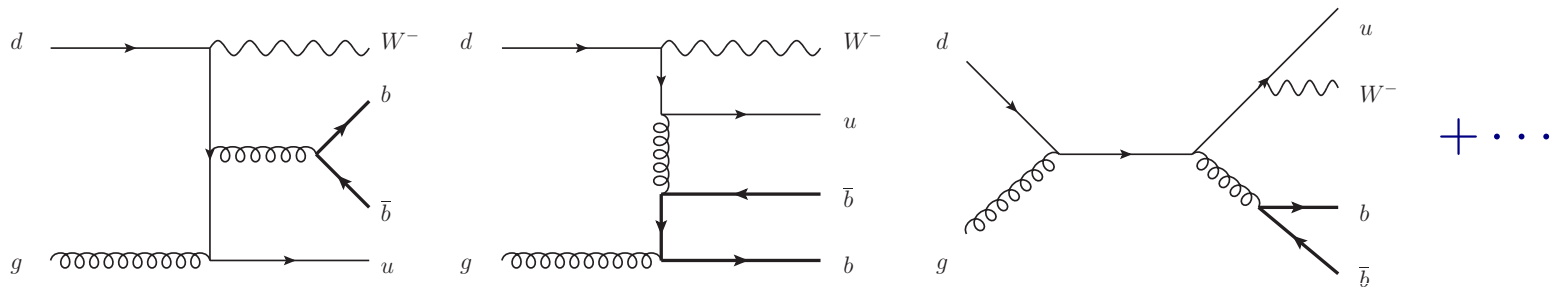
$Wb\bar{b} + j$ at NLO

challenges, results, future steps

with **T. Schutzmeier**

Overview

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



plus about 300 loop diagrams, keeping full m_b dependence.

- Together with analogous corrections to $q\bar{q}' \rightarrow Wb\bar{b} + g$ (obtained by crossing), they represent a well-defined piece of the NNLO QCD corrections to $pp, p\bar{p} \rightarrow Wb\bar{b}$: the one-loop virtual corrections from $2 \rightarrow 4$ processes.
- They provide the $O(\alpha_s)$ virtual corrections for $pp, p\bar{p} \rightarrow W + 2b \text{ jets} + j$.
- In a fixed-flavor scheme, they also provide the $O(\alpha_s)$ virtual corrections for $pp, p\bar{p} \rightarrow W + b \text{ jet} + j$.

Approach

- Based on traditional Feynman diagrams evaluation

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

- 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.

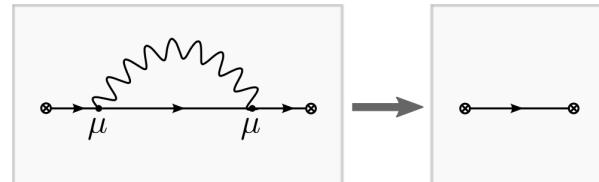
- Each level of evaluation automatized within an overall interface (Python) that only takes as input the desired process:
 - ▷ diagram generated with a very modified version of QGRAPH;
 - ▷ algebraic manipulations to extract first level of SME and tensor structures done with FORM;
 - ▷ reduction of tensor 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

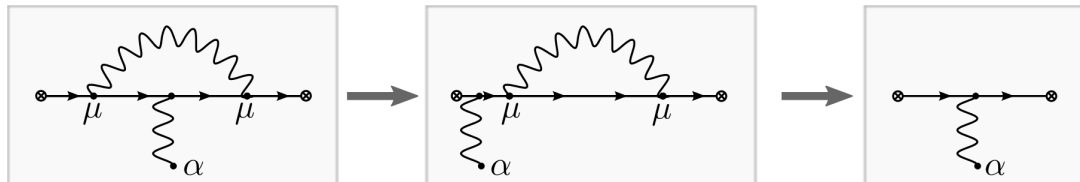
spinor structures (standard matrix element or SME) \rightarrow oriented graphs:

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

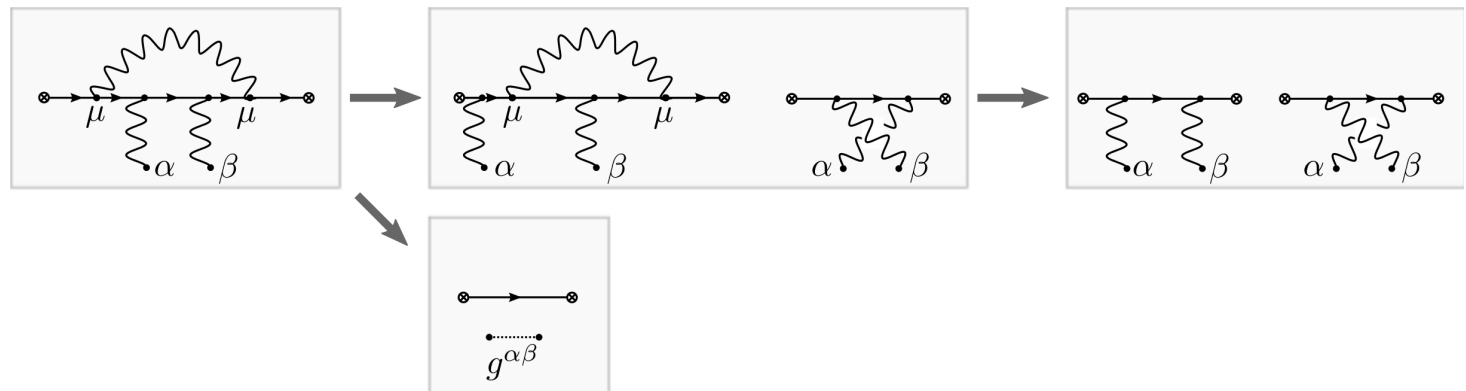
$$\gamma^\mu \gamma_\mu$$



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

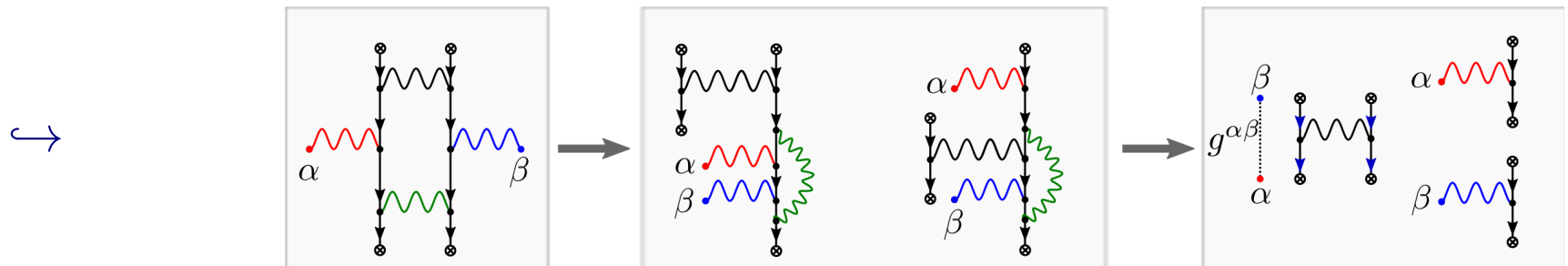
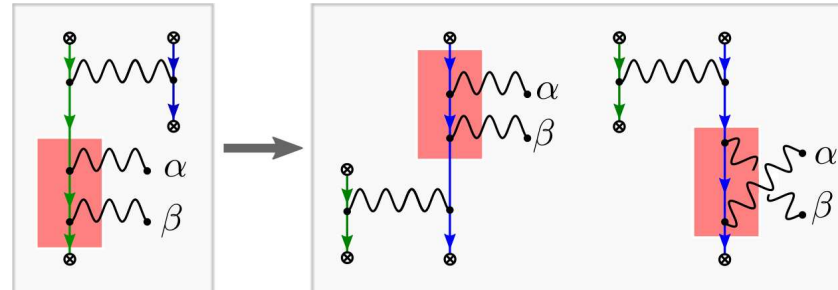


$$\gamma^\mu \gamma^\alpha \gamma^\beta \gamma_\mu$$



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

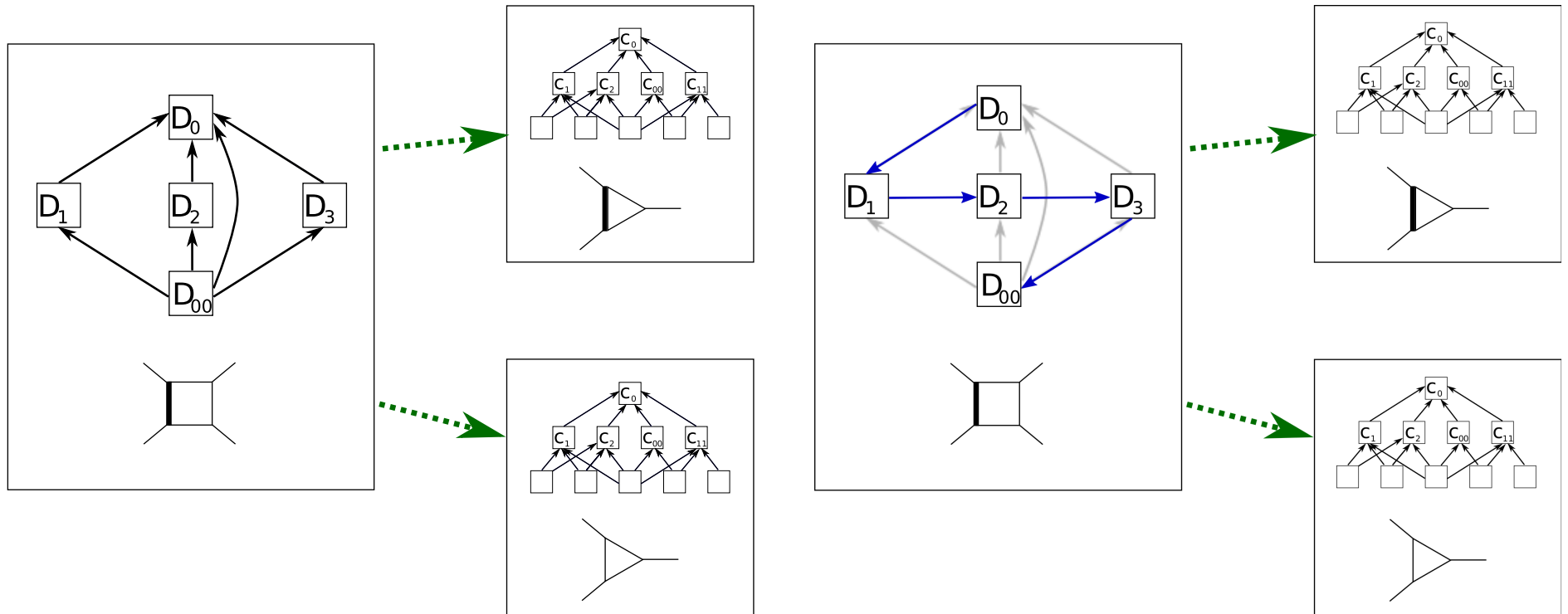
$$\gamma^\mu \gamma^\alpha \gamma^\beta P_+ \times \gamma_\mu = \gamma^\mu P_+ \times (\gamma_\mu \gamma^\beta \gamma^\alpha P_+ + \gamma^\alpha \gamma^\beta \gamma_\mu P_-)$$



- ▷ 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 few hundreds);
- ▷ coefficients of single elementary graphs collected via systematic labeling .

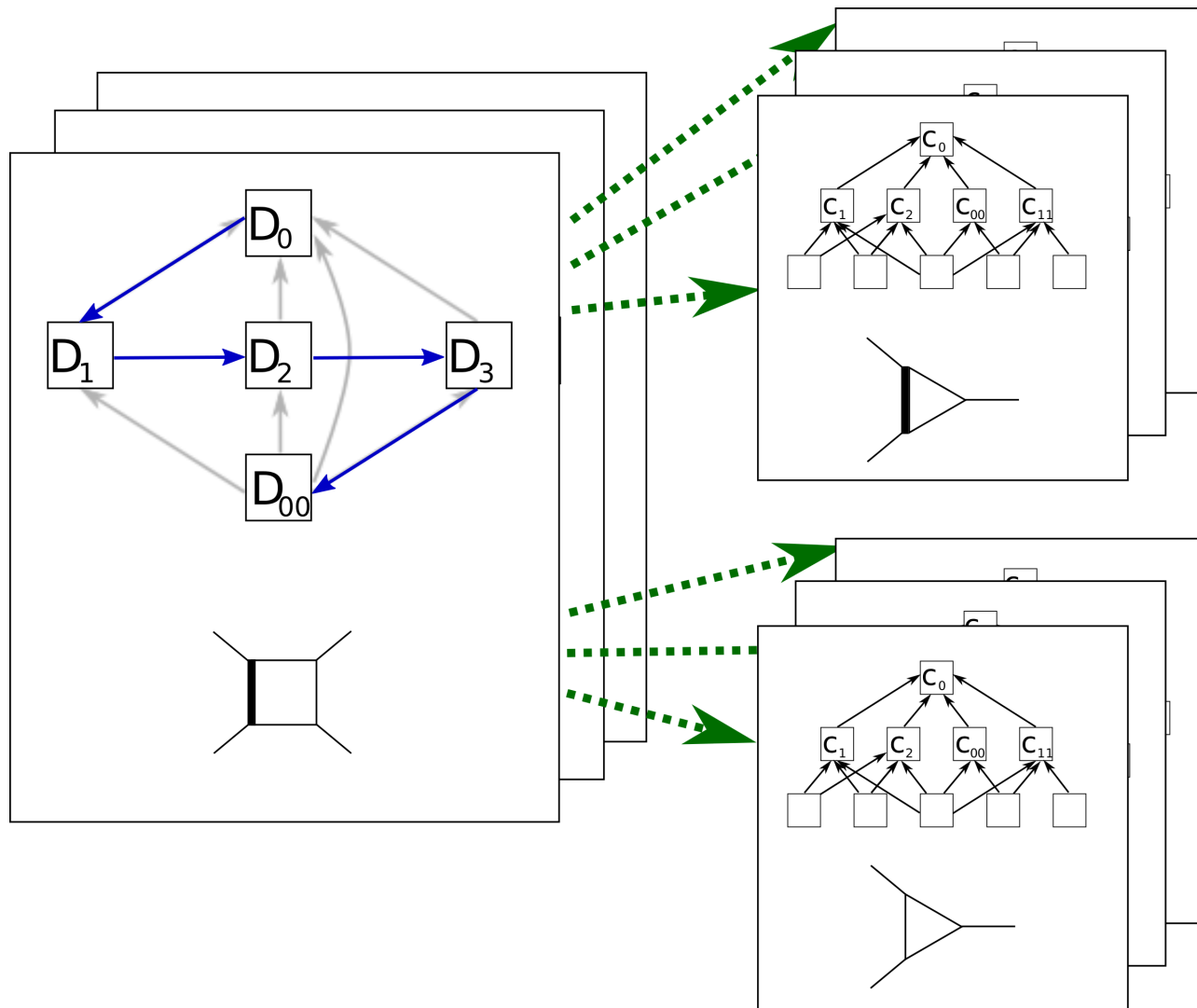
Reduction of tensor-integral coefficients

- 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](https://arxiv.org/abs/hep-ph/0509141));
 - expansion around small quantities (e.g. Gram or Cayley determinant) (Denner and Dittmaier, [arXiv:hep-ph/0509141](https://arxiv.org/abs/hep-ph/0509141)).

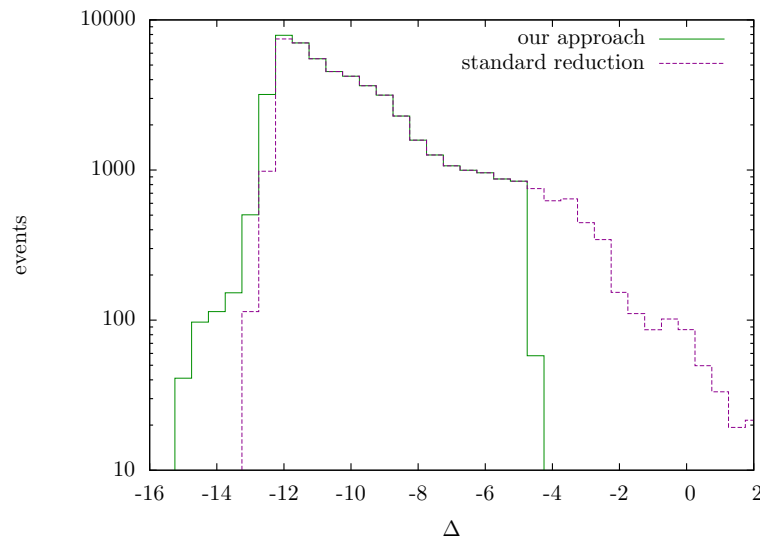
For $N > 4$ we implement:

- Gram determinant free (GDF) procedure (Diakonidis, Fleischer, Gluza, Kajda, Riemann, and Tausk, [arXiv:0812,2134](https://arxiv.org/abs/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 (Γ_{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.



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

- Moreover: reproduced results for several $2 \rightarrow 3$ processes (e.g. $W/Zb\bar{b}$, $\gamma t\bar{t}$), and $2 \rightarrow 4$ ($\bar{u}d \rightarrow d\bar{d}gW$ channel of $W + 3j$ calculation). Also, results for $ug \rightarrow Wb\bar{b} + d$ 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	$t_q^{\text{full}}/\text{ms}$
$q\bar{q} \rightarrow \gamma t\bar{t}$	99.6%	0.4%	0	9.5	8.9	153	0	1069
$gg \rightarrow \gamma t\bar{t}$	98.9%	1.1%	0	12.0	10.1	182	0	1972
$q\bar{q}' \rightarrow W b\bar{b}$	99.7%	0.3%	0	10.9	10.4	167	0	1264
$q\bar{q} \rightarrow Z b\bar{b}$	99.8%	0.1%	0.1%	17.7	14.4	217	3161	2290
$gg \rightarrow Z b\bar{b}$	98.3%	1.6%	0.1%	22.5	15.7	233	3314	2706
$\bar{u}d \rightarrow d\bar{d}gW$	95.4%	3.6%	1.0%	90.3	37.5	306	4358	5503
$ug \rightarrow b\bar{b}dW$	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 $2 \rightarrow 3$ and $2 \rightarrow 4$ processes with vector bosons and several massive particles.
- Effort now focused on:
 - ↪ documenting existing package, adding useful options or improving existing ones;
 - ↪ implementing interface to real corrections' generator;
 - ↪ studying impact of calculated QCD effects.