Towards NLO predictions for 4 b-jets at the LHC

supported by the Scottish Universities Physics Alliance

in collaboration with T. Binoth, A. Guffanti, J.–Ph. Guillet, J. Reuter

▷ Thomas Reiter, The University of Edinburgh
▷ Loopfest VII, Buffalo, 16 May 2008

Overview

The Promise of the LHC

Structure of the Amplitude

Golem90: Numerical Reduction of Tensor Integrals

The Status of the Calculation

To–Do List

The Promise of the LHC

If the SM (MSSM) is implemented in nature

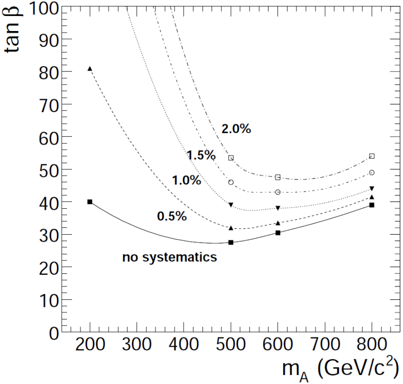
- the LHC will find the SM Higgs boson or ...
- ... at least one MSSM Higgs boson.
- "At large $\tan\beta$ the $b\bar{b}\tau^+\tau^-$ and $b\bar{b}b\bar{b}$ final states may provide the only access to two of the three neutral MSSM Higgs bosons." [Dai, Gunion, Vega (1995); also Richter-Was, Froidevaux]
- Number of assumptions about irreducible QCD backgrounds spoil the result.
- "Explicit calculations of the actual K factors are needed." [ibid.]

$b\bar{b}H \to b\bar{b}b\bar{b}$

Effect of background uncertainty on discovery reach (2σ contours)

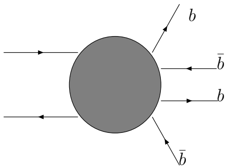
- big improvements possible by NLO background calculation
- in combination with $b\bar{b}\tau^+\tau^-$ good prospects

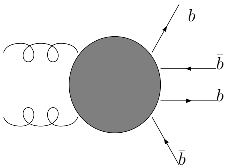
[Fig.: CMS Physics TDR]



The $q\bar{q} \to b\bar{b}b\bar{b}$ Process

- $pp \to b\bar{b}b\bar{b}$ irreducible background for SUSY Higgs searches.
- 4-b and 4-jet are on the Experimentalists' Wish List. [Les Houches 2007]
- $q\bar{q} \to b\bar{b}s\bar{s}$ is subprocess of 4-jets and (up to combinatorics) of $pp \to b\bar{b}b\bar{b}$.





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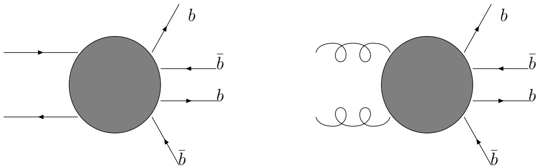

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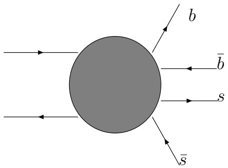

The Structure of the Amplitude

The full NLO cross-section can be written as

$$\sigma^{\mathsf{NLO}} = \int_N \mathrm{d}\sigma^{\mathsf{LO}} + \int_N \left(\mathrm{d}\sigma^{\mathcal{V}} + \int_1 \mathrm{d}\sigma^{\mathcal{A}} \right)_{\varepsilon=0} + \int_{N+1} \left(\mathrm{d}\sigma^{\mathcal{R}} - \mathrm{d}\sigma^{\mathcal{A}} \right)_{\varepsilon=0}$$

- leading order contribution
- virtual corrections
- real emission
- subtraction terms [Catani,Seymour]

This talk: mainly $\int_N \left(\mathrm{d}\sigma^{\mathcal{V}} + \int_1 \mathrm{d}\sigma^{\mathcal{A}} \right)_{\varepsilon=0}$

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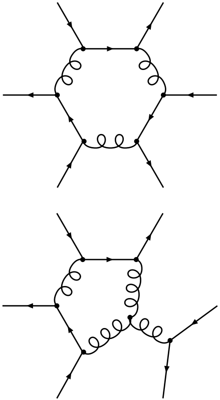
The Structure of the Virtual Corrections

- Feynman diagram based approach
- High complexity due to pentagons and hexagons
- Standard techniques typically fail
- Improved reduction method for tensor integrals
- No complete calculation of this complexity for LHC published yet



The Structure of the Virtual Corrections (II)

Using helicity projections:

$$\mathrm{d}\sigma^{\mathcal{V}} = \mathrm{d}\Phi^{(N)} \sum_{\{\lambda\}} \left(\mathcal{M}^{\mathsf{LO}}(\{\lambda\}, \{p\})^\dagger \otimes \mathcal{M}^{\mathcal{V}}(\{\lambda\}, \{p\}) + \text{h.c.} \right) F_J^{(N)}$$

$$\mathcal{M}_i^{\mathcal{V}} = c(\{\lambda\}, \{p\}) \sum_{\text{diagrams}} \sum_{\mathcal{F}} \mathrm{tr}^{\{\lambda\}}\{\{\not{p}\}_{i,\mathcal{F}}\} \mathcal{F}(S)$$

$$\mathcal{F}(S) \in \left\{ A^{N',r}(j_1, \ldots; S), B^{N',r}(j_1, \ldots; S), C^{N',r}(j_1, \ldots; S) \right\}$$

- Form factors $\mathcal{F}(S)$ from tensor integrals (see next slide).
- Coefficients products of Dirac traces $\mathrm{tr}^{\{\lambda\}}\{\{\not{p}\}_{i,\mathcal{F}}\}$.
- Non-trivial color structure $\Rightarrow$ Color flow decomposition

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The Structure of the Virtual Corrections(III)

Form factor representation for tensor integrals

$$\int \frac{\mathrm{d}^n k\, q_{a_1}^{\mu_1}\cdots q_{a_r}^{\mu_r}}{({q_1}^2-m_1^2)\cdots({q_N}^2-m_N^2)} = \sum_{j_1,\ldots,j_r} [\Delta_{j_1\bullet}^{\bullet}\cdots\Delta_{j_r\bullet}^{\bullet}]_{a_1,\ldots,a_r}^{\mu_1\ldots\mu_r} A_{j_1,\ldots,j_r}^{N,r}(S)$$
$$+ \sum_{j_1,\ldots,j_{r-2}} [g^{\bullet\bullet}\Delta_{j_1\bullet}^{\bullet}\cdots\Delta_{j_{r-2}\bullet}^{\bullet}]_{a_1,\ldots,a_r}^{\mu_1\ldots\mu_r} B_{j_1,\ldots,j_{r-2}}^{N,r}(S)$$
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$$q_i = k + r_i, \quad \Delta_{ij} = r_i - r_j, \quad S_{ij} = \Delta_{ij}\cdot\Delta_{ij} - m_i^2 - m_j^2$$

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Form factor representation for tensor integrals

$$\int \frac{\mathrm{d}^n k \, q_{a_1}^{\mu_1} \cdots q_{a_r}^{\mu_r}}{(q_1{}^2 - m_1^2) \cdots (q_N{}^2 - m_N^2)} = \sum_{j_1,\ldots,j_r} [\Delta_{j_1 \bullet}^{\bullet} \cdots \Delta_{j_r \bullet}^{\bullet}]_{a_1,\ldots,a_r}^{\mu_1 \ldots \mu_r} A_{j_1,\ldots,j_r}^{N,r}(S)$$
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Golem90: Tensor Reduction made Easy

Reduction of the tensor integrals:

- one of the main problems in (one) loop calculations:
- Either avoid it. . . [Unitarity methods: many names]
- . . . or do it in a smart way.
- We use algebraic/numerical approach.
  [Binoth, Guillet, Heinrich, Pilon, Schubert]
  - Reduction of 1- and 2-point integrals: trivial
  - Reduction of ($N \geq 5$) point integrals:
    always reduce to 3- and 4-point problems
- What about 3- and 4-point integrals?

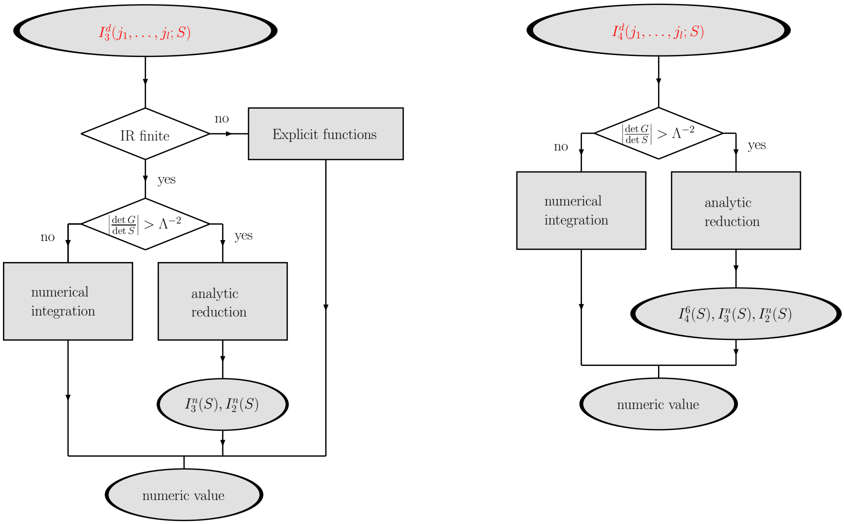
Golem90: Tensor Reduction made Easy (II)

Use of extended set of basis functions

$$A^{N,r}(S), B^{N,r}(S), C^{N,r}(S) \rightsquigarrow I_N^d(j_1, \ldots, j_l; S)$$

$$I_N^d(j_1, \ldots, j_l; S) = (-1)^N \Gamma(N - d/2) \times \int_0 \mathrm{d}z_1 \cdots \mathrm{d}z_N \delta(1 - \sum z_i) \frac{z_{j_1} \cdots z_{j_l}}{(-\frac{1}{2} z_i S_{ik} z_k - i\delta)^{N-d/2}}$$

- Required for $N \in \{3, 4\}$ only
- Reduction and numerical calculation possible



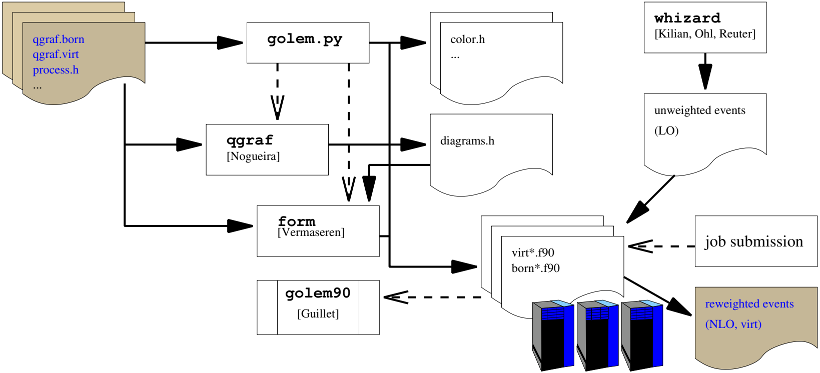
$I_3^d(j_1,\dots,j_l;S)$
IR finite
no
Explicit functions
yes
$\left|\frac{\det G}{\det S}\right| > \Lambda^{-2}$
no
yes
numerical integration
analytic reduction
$I_3^n(S), I_2^n(S)$
numeric value
$I_4^d(j_1,\dots,j_l;S)$
$\left|\frac{\det G}{\det S}\right| > \Lambda^{-2}$
no
yes
numerical integration
analytic reduction
$I_4^6(S), I_3^n(S), I_2^n(S)$
numeric value

Preliminary Setup

Tensor reduction is only part of a larger setup:

- Formfactors $A^{N,r}, B^{N,r}, C^{N,r}$ implemented in `Golem90`
- Automated framework to build amplitude (see next slides)
- Aim: start from minimal set of input files

Preliminary Setup



Results: $u\bar{u} \to b\bar{b}s\bar{s}$ (virtual)

Results are based on

- 200,000 unweighted LO-events, generated from Whizard [Ohl,Kilian,Reuter]
- reweighted with local K-factor
- cuts: $p_T > 50\,\mathrm{GeV}$, $\eta < 3$, $\Delta R > 0.3$
- $\mu = \sum p_T/4$, $\mu_F = 100\,\mathrm{GeV}$, CTEQ6m, $\sqrt{s} = 14\,\mathrm{TeV}$

$$\langle O\rangle_{\mathrm{LO}} = \frac{\sigma^{\mathrm{LO}}}{N}\sum_E O(E)$$

$$\langle O\rangle_{\mathcal{V}} = \frac{\sigma^{\mathrm{LO}}}{N}\sum_E \frac{\mathrm{d}\sigma^{\mathrm{LO}} + \mathrm{d}\sigma^{\mathcal{V}} + \int_1 \mathrm{d}\sigma^{\mathcal{A}}}{\mathrm{d}\sigma^{\mathrm{LO}}} O(E)$$

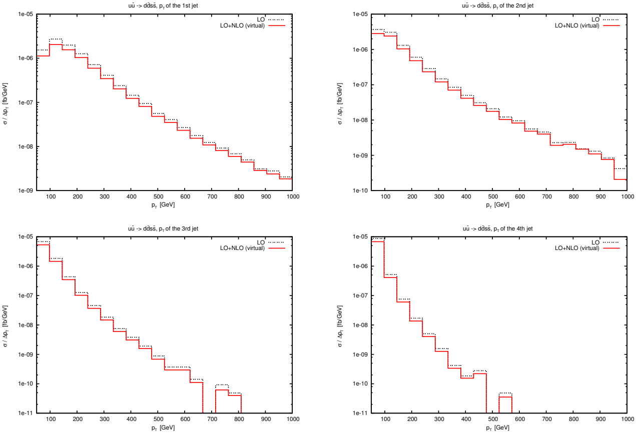
$E \in$ unweighted events

Results: $u\bar{u} \to b\bar{b}s\bar{s}$ (virtual)

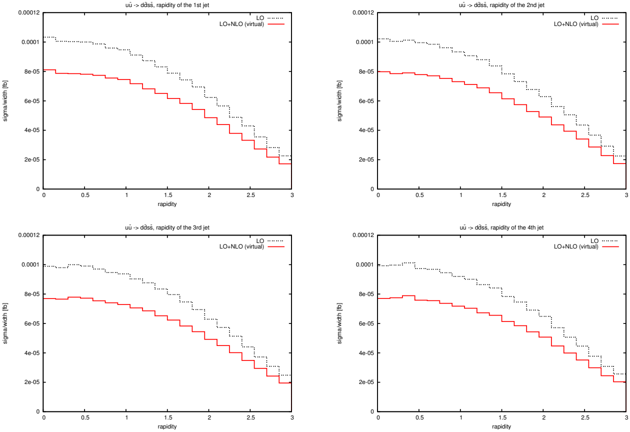
We find

- Numerical evaluation very stable:
  1. cancellation of IR-poles
     all points passed test
  2. "suspicious" points (i.e. $K > 10$)
     2.4‰ failed, re-evaluated with quadruple precision
- K-factor contribution: 0.78 ($\pm$0.22% stat.)

p_T Distributions: $u\bar{u} \to b\bar{b}s\bar{s}$ (virtual)



Rapidity Distributions: $u\bar{u} \rightarrow b\bar{b}s\bar{s}$ (virtual)



Tests

- Comparison diagram by diagram for single phase space points by two independent codes:

	This Code	Alternative
Diagram Generation	QGraf	Feynarts
Simplification	Form	Form, Maple
Representation	numerical	analytic
	form factors	basis integrals
Numerical Evaluation	Fortran90	Maple

- Cancellation of infrared poles
- Independent analytic calculation for up to 3-point diagrams.

Nowadays people ask about ...

On a single computer (4× Intel® Xeon®, 3 GHz)

- $\mathcal{O}(1s)$ per phase space point.
  (includes all helicities, all colors: no hidden cost)
- 200k points took 60 CPUh.
- My opinion: performance debate is overrated:
  - Problem is "Embarrassingly Parallel"
  - Edinburgh Compute and Data Facility (ECDF)
  - 200k points took 12 minutes (on 345 nodes).
  - CPU time is relatively cheap: 400g of peanuts
  - ...compared to a PhD-student: ≈ 20 tons of peanuts.

Nowadays people ask about run time

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  (includes all helicities, all colors: no hidden cost)
- 200k points took 60 CPUh.
- My opinion: performance debate is overrated:
  - Problem is "Embarrassingly Parallel"
  - Edinburgh Compute and Data Facility (ECDF)
  - 200k points took 12 minutes (on 345 nodes).
  - CPU time is relatively cheap: 400g of peanuts
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Conclusion

I have presented

- first results for 6-quark amplitude
- outline of a (fairly) automated, Feynman diagram based, NLO matrix element generator (aka GOLEM)
- application of a Fortran90 library for reduction of tensor integrals (`Golem90`)

Currently in progress:

- real emission and dipoles
- tighter integration into MC program
- full $b\bar{b}b\bar{b}$ amplitude
- Further (long term) targets:
  - generality (e.g. masses, particle content)
  - easier setup, more automation
  - improved performance