

GOLEM: Status and Progress

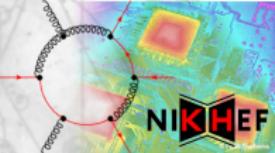
Thomas Reiter

in collaboration with

G. Cullen, A. Guffanti, J.P. Guillet, G. Heinrich, S. Karg,
N. Kauer, T. Kleinschmidt, E. Pilon, M. Rodgers, I. Wigmore

HO10, 21 June – 09 July 2010

Overview



The GOLEM Method

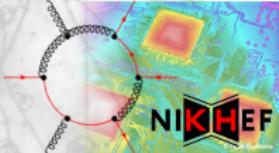
`golem-2.0`: Generator for Virtual Matrix Elements

`golem95`: Reduction of One-Loop Integrals

Application: Four-*b* Amplitude

Summary and Outlook

The GOLEM Method: Overview



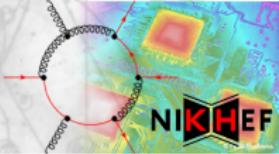
GOLEM: General One-Loop Evaluator for Matrix Elements

- ▶ GOLEM = a method for evaluating one-loop Feynman diagrams
- ▶ GOLEM = a library for one-loop integrals (`golem95`)
- ▶ GOLEM = a matrix element generator at the one-loop level

Why Feynman Diagrams?

- ▶ No distinction between cut-constructible and rational part
⇒ conceptually simple (one method for all parts)
- ▶ Gram determinant problem avoidable by dedicated tensor reduction (⇒ `golem95`)
- ▶ Combinatorial complexity of Feynman diagrams
⇒ problematic mainly beyond $2 \rightarrow 4$
- ▶ Tool of choice for many masses and few symmetries

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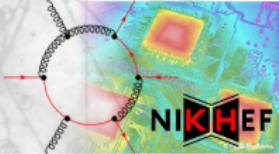
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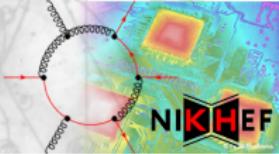
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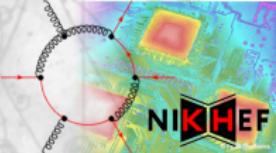


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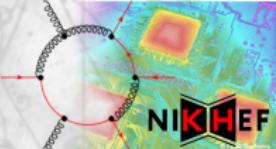
- ▶ Feynman diagrams
- ▶ Helicity projections
- ▶ Improved tensor reduction

The GOLEM method is designed for

- ▶ any number of ext. particles ($\lesssim 6$ feasable)
- ▶ massless and massive particles
- ▶ QCD and EW corrections
- ▶ physics within and beyond the Standard Model

The GOLEM method is aiming at

- ▶ NLO “Plug In” for MC generators



The GOLEM Method: Overview

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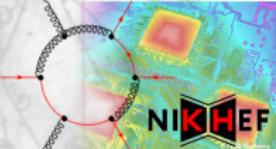
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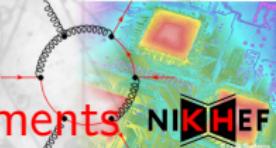
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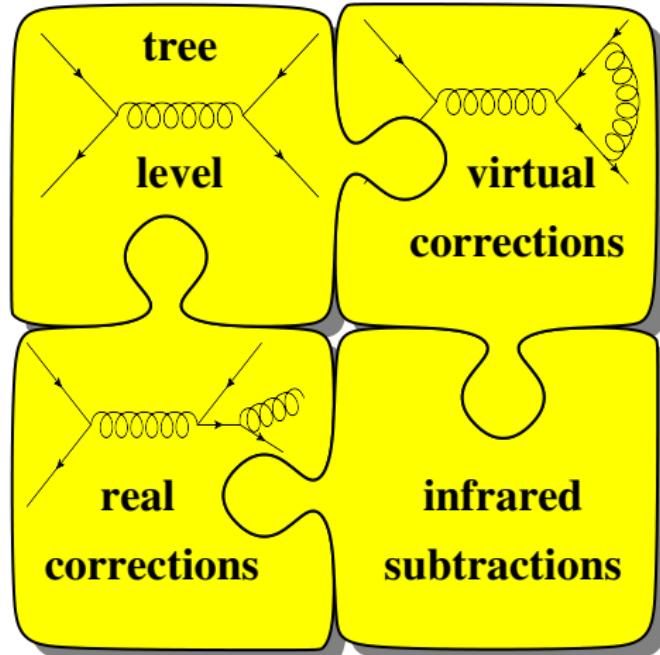
- ▶ NLO “Plug In” for MC generators

golem-2.0: A Generator for Virtual Matrix Elements

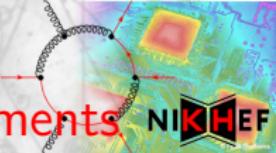


NLO calculations are modularized:

- ▶ tree level $2 \rightarrow N$
(Born)
- ▶ one-loop $2 \rightarrow N$
(virtual)
- ▶ tree level $2 \rightarrow N + 1$
(real)
- ▶ IR-subtraction
- ▶ At present very few automated tools for virtual part
- ▶ Aim of GOLEM:
automated generation of one-loop part



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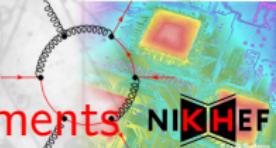


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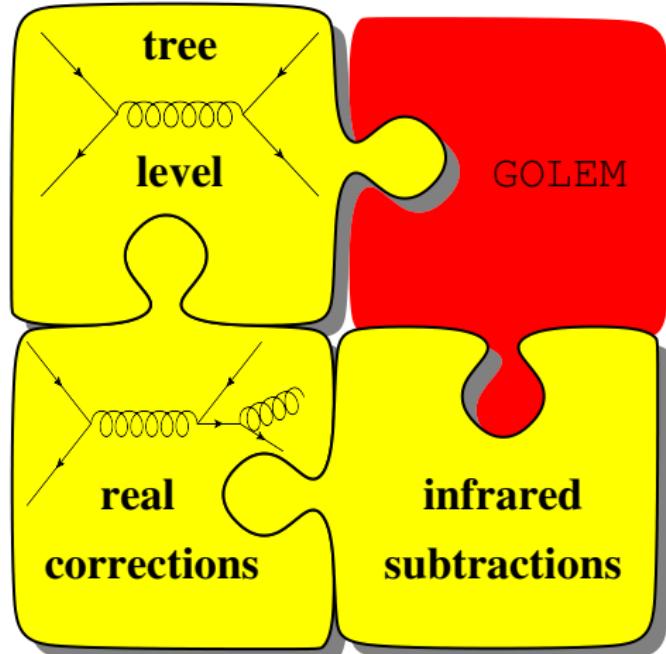
- ▶ **BlackHat** [Berger,Bern,Dixon,Febres Cordero,Forde,Gleisberg,Ita,Kosower,Maitre]
- ▶ **CutTools** [Ossola,Papadopoulos,Pittau]
- ▶ **FeynArts/FormCalc** [Hahn]
- ▶ **Grace one-loop** [Yasui et al.]
- ▶ **HAWK** [Denner,Dittmaier,Mück],
Prophecy4f [Bredenstein,Denner,Dittmaier,Weber]
- ▶ **Helac-1loop** [Bevilacqua,Czakon,v. Hameren,Papadopoulos,Pittau,Worek]
- ▶ **Rocket** [Ellis,Giele,Kunszt,Melnikov,Zanderighi]
- ▶ **Samurai** [Mastrolia,Ossau,TR,Tramontano]
- ▶ **VBF@NLO** [Arnold et al.]
- ▶ **Diana/OLOTIC** [Tentyukov,Fleischer/Diakonidis,Tausk]

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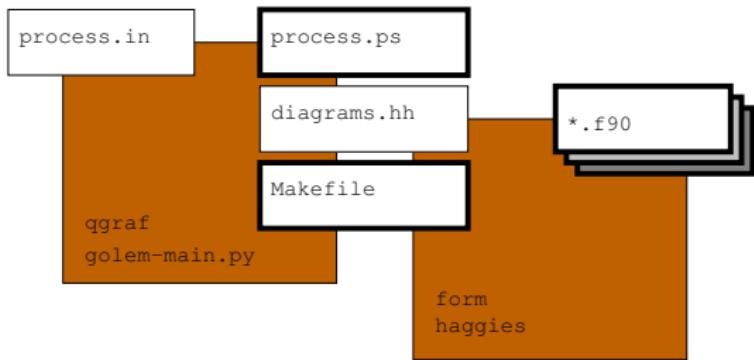


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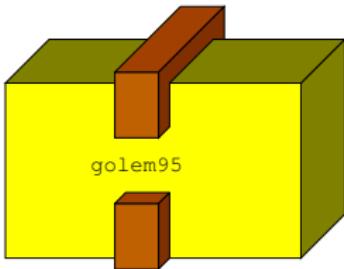
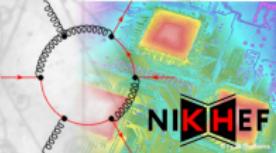
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golem-2.0: Structure



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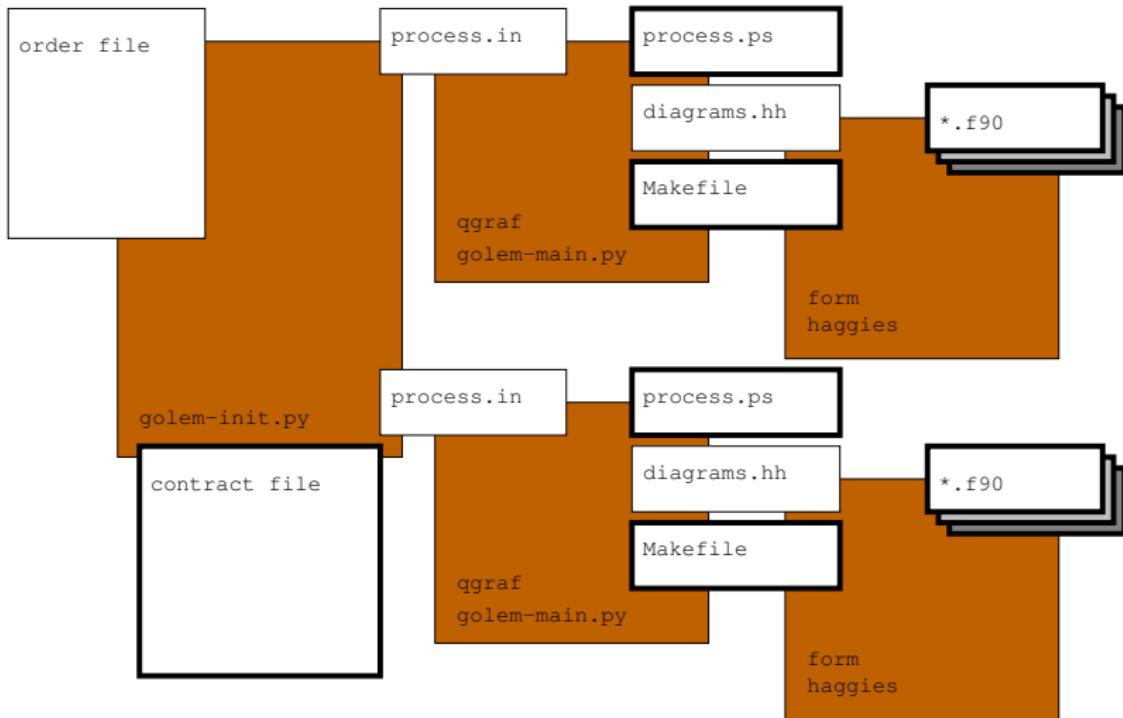
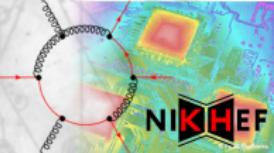


process.ps

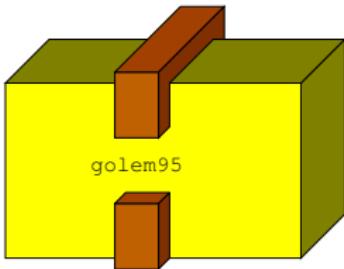
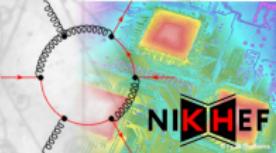
Makefile

*.f90

golem-2.0: Structure



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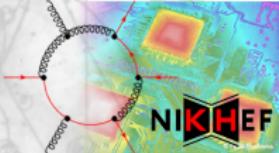
contract file

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golem-2.0: Matrix Elements Made Easy

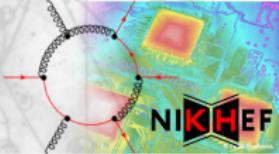


- ▶ create configuration file
- ▶ enter process, here: $gg \rightarrow s\bar{s} b\bar{b}$ @ NLO in QCD
- ▶ set up process directory
- ▶ generate code and draw diagrams

shell

```
$ golem-main.py --template process.in  
$
```

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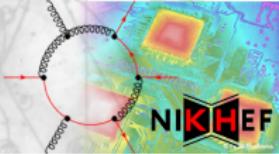
```
editor: process.in
```

```
process_path=<a directory>
in=g,g
out=s,s~,b,b~
order=gs,4,6
model=sm
```

```
# more settings optional
```

```
...
```

golem-2.0: Matrix Elements Made Easy

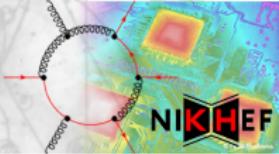


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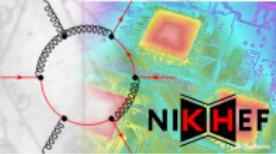


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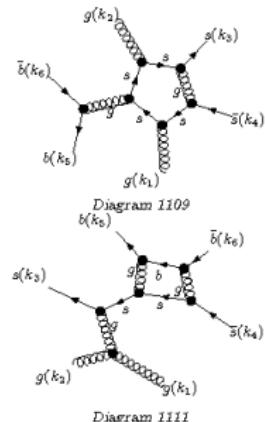
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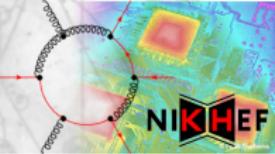
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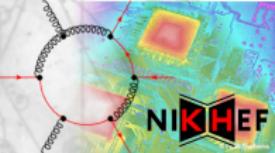
golem-2.0: Unfinished Features



Things to be finished in the near future:

- ▶ FeynRules model files
- ▶ Les Houches interface
- ▶ PowHeg-Box interface [Alioli,Nason,Oleari,Re]
- ▶ release after validation of $gg \rightarrow b\bar{b}b\bar{b}$

golem95: Reduction of One-Loop Integrals



golem95

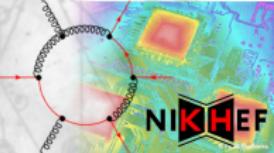
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The reduction method avoids instabilities induced by small Gram determinants.

News: golem95 Version 1.1.0 released.

- ▶ inclusion of internal masses
 - with link to LoopTools [Hahn,Perez-Victoria] for some infrared finite integrals
 - ▶ scale μ has been added
 - ▶ installation uses AutoTools
 - ▶ better routine for matrix inversion
- ⇒ suitable for all processes up to 6 legs with real masses!

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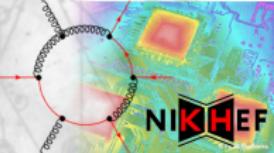
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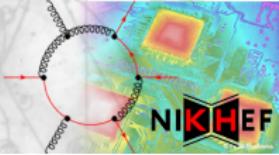
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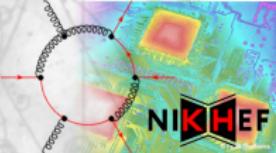


golem95: Reduction of One-Loop Integrals

$$I_N^{d;\mu_1 \dots \mu_r}(S) = \int \frac{d^d k}{i\pi^d/2} \frac{k^{\mu_1} k^{\mu_2} \dots k^{\mu_r}}{[(k+r_1)^2 - m_1^2] \dots [(k+r_N)^2 - m_N^2]}$$
$$S_{ij} = (r_i - r_j)^2 - m_i^2 - m_j^2$$
$$G_{ij} = 2r_i \cdot r_j$$

Starting point: one-loop tensor integrals

golem95: Reduction of One-Loop Integrals

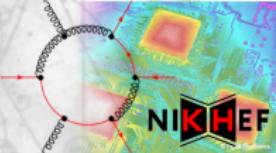


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$$I_N^d(S) = (-1)^N \Gamma(N-d/2) \int_0^d z \frac{\delta(1 - \sum z_i)}{\left(-\frac{1}{2} z^\top S z - i\delta\right)^{N-d/2}}$$

Full reduction to scalar integral \Rightarrow Gram determinants



golem95: Reduction of One-Loop Integrals

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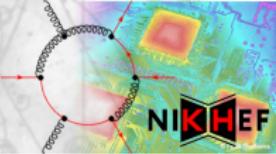


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form factor decomposition: non-scalar Feynman param. integrals

golem95: Reduction of One-Loop Integrals



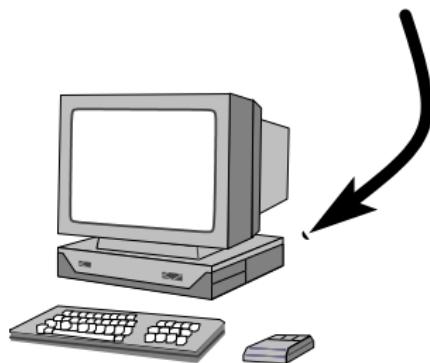
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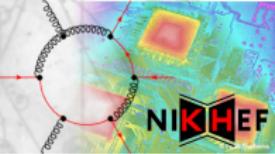


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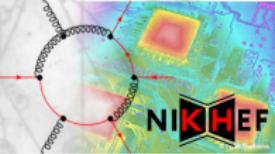
$\det G$ small \Rightarrow numerical evaluation of non-scalar integrals.

golem95: Status and outlook



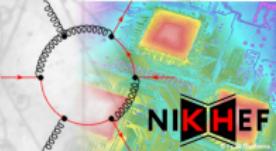
- ▶ Current version (1.1.0) contains all massive and massless one-loop integrals up to 6 legs
- ▶ well tested, many examples
- ▶ for some massive integrals only algebraic branch available
- ▶ future plans include
 - ▶ completion of numerical integration for all integrals
 - ▶ removal of dependence on 3rd party libraries
 - ▶ complex masses
- ▶ <http://lappweb.in2p3.fr/lapth/Golem/golem95.html>

The four-*b* amplitude



... for an overview of recent NLO results see Lance Dixon's talk...
... or Francesco Tramontano's talk...

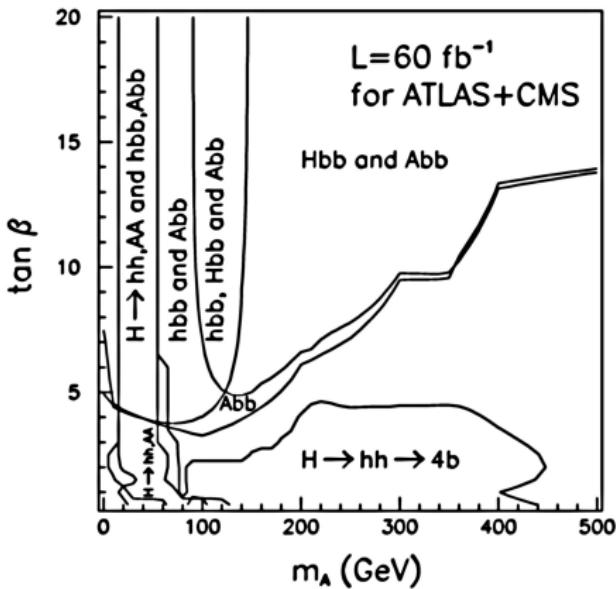
$b\bar{b}b\bar{b}$: An Important Background



4b Final State 5σ LHC Discovery Contours

$m_{stop} = 1 \text{ TeV}$, no squark mixing

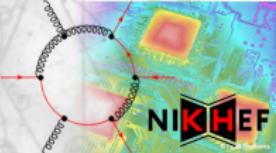
$m_t = 175 \text{ GeV}$, $\varepsilon_{b-tag} = 0.6$, $\varepsilon_{mis-tag} = 0.01$



- ▶ Uncertainty on $b\bar{b}b\bar{b}$ crucial for BSM Higgs searches
- ▶ for certain MSSM scenarios: $H \rightarrow b\bar{b}b\bar{b}$ enhanced
- ▶ maybe only discovery channel
- ▶ also important for other BSM models

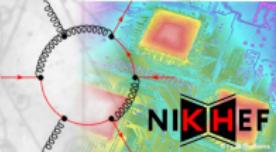
[Dai, Gunion, Vega]

$pp \rightarrow b\bar{b}b\bar{b}$: Overview



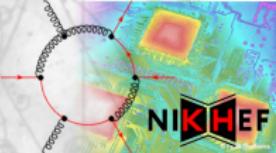
- ▶ Born part and virtual corrections
 - ▶ $q\bar{q} \rightarrow b\bar{b}b\bar{b}$ (done)
 - ▶ $gg \rightarrow b\bar{b}b\bar{b}$
- ▶ real corrections
 - ▶ $q\bar{q} \rightarrow b\bar{b}b\bar{b} + g$ (done)
 - ▶ $gg \rightarrow b\bar{b}b\bar{b} + g$ (done)
 - ▶ $gq \rightarrow b\bar{b}b\bar{b} + q$ (done)
- ▶ Approximations: $m_b = 0, m_t \rightarrow \infty, q \in \{u, d, s, c\}$
- ▶ LHC kinematics and cuts:
 - ▶ $\sqrt{s} = 14 \text{ TeV}$
 - ▶ p_T cut: $p_T > 30 \text{ GeV}$
 - ▶ rapidity cut: $|\eta| < 2.5$
 - ▶ separation cut: $\Delta R > 0.8$

$pp \rightarrow b\bar{b}b\bar{b}$: Overview



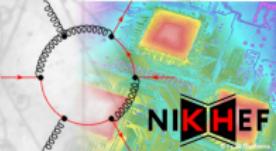
- ▶ Born part and virtual corrections
 - ▶ $q\bar{q} \rightarrow b\bar{b}b\bar{b}$ (done)
 - ▶ $gg \rightarrow b\bar{b}b\bar{b}$
- ▶ real corrections
 - ▶ $q\bar{q} \rightarrow b\bar{b}b\bar{b} + g$ (done)
 - ▶ $gg \rightarrow b\bar{b}b\bar{b} + g$ (done)
 - ▶ $gq \rightarrow b\bar{b}b\bar{b} + q$ (done)
- ▶ Approximations: $m_b = 0, m_t \rightarrow \infty, q \in \{u, d, s, c\}$
- ▶ LHC kinematics and cuts:
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$pp \rightarrow b\bar{b}b\bar{b}$: Overview

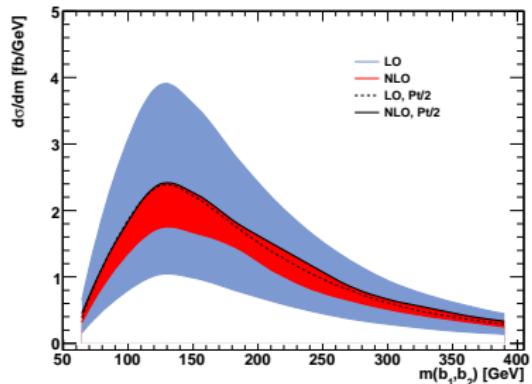


- ▶ Born part and virtual corrections
 - ▶ $q\bar{q} \rightarrow b\bar{b}b\bar{b}$ (done)
 - ▶ $gg \rightarrow b\bar{b}b\bar{b}$
- ▶ real corrections
 - ▶ $q\bar{q} \rightarrow b\bar{b}b\bar{b} + g$ (done)
 - ▶ $gg \rightarrow b\bar{b}b\bar{b} + g$ (done)
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- ▶ Approximations: $m_b = 0, m_t \rightarrow \infty, q \in \{u, d, s, c\}$
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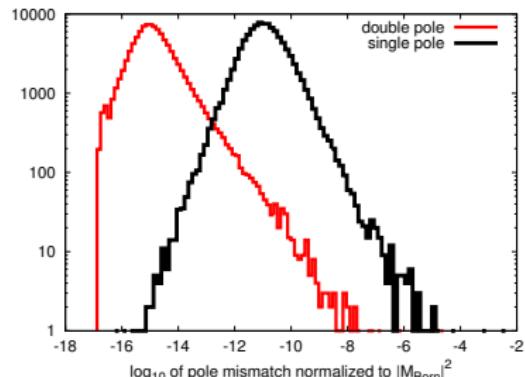
$q\bar{q} \rightarrow b\bar{b} b\bar{b}$



- ▶ computed with different setups:
 - ▶ golem-2.0+golem95+MadGraph/MadEvent/MadDipole
[Long,Stelzer/Maltoni,Stelzer/Frederix,Gehrman,Greiner]
 - ▶ golem-2.0+golem95+Whizard [Kilian,Ohl,Reuter]
 - ▶ golem-2.0+Samurai+MadGraph/MadEvent/MadDipole
 - ▶ FeynArts/Form/Maple for cross-check of virtual part

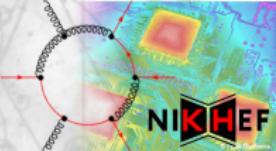


$q\bar{q}$ channel complete



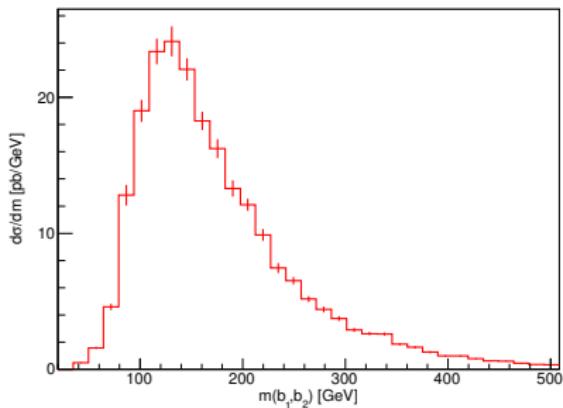
$q\bar{q}$ channel, pole cancellation of virtual part using
Samurai on 10^5 points

$pp \rightarrow b\bar{b}b\bar{b}$: Real Emission

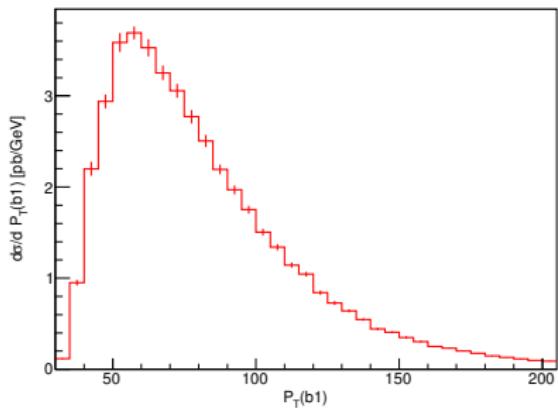


- ▶ real emission implemented for all channels using MadEvent/MadDipole
- ▶ integration cross-checked with HELAC-PHEGAS

[Cafarella, Papadopoulos, Worek]



invariant bb -mass (real only)



p_T of the hardest jet (real only)

Summary and Outlook

golem-2.0:

- ▶ interfaces for FeynRules, PowHeg-Box and Les Houches Accord planned
- ▶ interface for golem95 and Samurai ready
- ▶ release after further validation

golem95:

- ▶ all integrals up to hexagons in latest release
- ▶ AutoTools for installation/configuration
- ▶ complex masses and completion of numerical branch coming in future release

$$pp \rightarrow b\bar{b}b\bar{b}$$

- ▶ last missing piece: gg-channel, virtual
- ▶ comparison with independent code under way
- ▶ stability and speed promising

