

NLO Cross Sections for the LHC using Golem: Status and Prospects

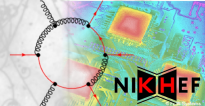
T. Reiter

in collaboration with

T. Binoth, G. Cullen, N. Greiner, A. Guffanti, J.P. Guillet, G. Heinrich, S. Karg,
N. Kauer, J. Reuter

Radiative Corrections, Ascona, 27 Oct. 2009

Overview



Motivation

GOLEM: An Overview

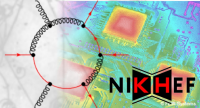
GOLEM95

GOLEM-2.0

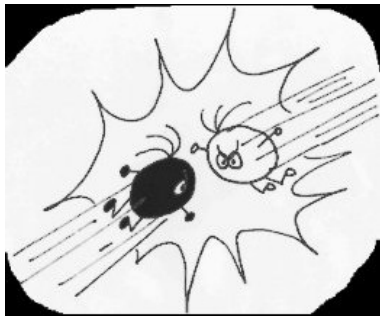
Results for $q\bar{q} \rightarrow b\bar{b}b\bar{b}$

Summary

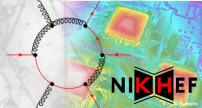
Motivation



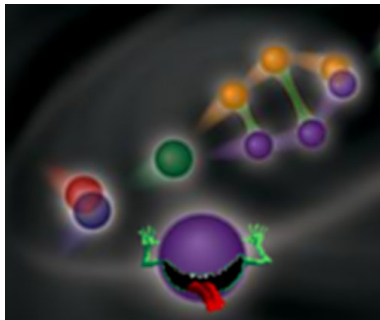
- ▶ LHC (re-)starts in < 1 month
- ▶ Expect 1st collisions this year
- ▶ 1st new particle < 1 year?
- ▶ Question: Are we ready?
 - ▶ reliable predictions start at NLO
 - ▶ required for signal and background
 - ▶ unknown model \Rightarrow unknown signal
- ▶ Can we produce NLO results quickly?
- ▶ For any new model?



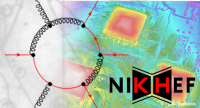
Motivation



- ▶ LHC (re-)starts in < 1 month
- ▶ Expect 1st collisions this year
- ▶ 1st new particle < 1 year?
- ▶ Question: Are we ready?
 - ▶ reliable predictions start at NLO
 - ▶ required for signal and background
 - ▶ unknown model \Rightarrow unknown signal
- ▶ Can we produce NLO results quickly?
- ▶ For any new model?



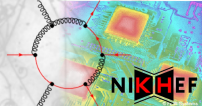
Motivation



- ▶ LHC (re-)starts in < 1 month
- ▶ Expect 1st collisions this year
- ▶ 1st new particle < 1 year?
- ▶ Question: Are we ready?
 - ▶ reliable predictions start at NLO
 - ▶ required for signal and background
 - ▶ unknown model \Rightarrow unknown signal
- ▶ Can we produce NLO results quickly?
- ▶ For any new model?



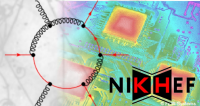
Motivation



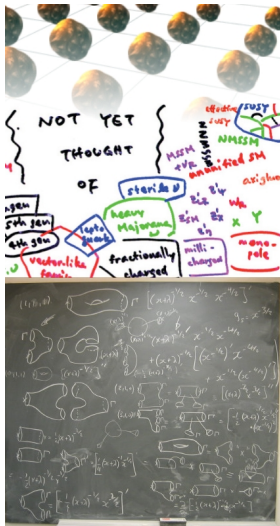
- ▶ LHC (re-)starts in < 1 month
- ▶ Expect 1st collisions this year
- ▶ 1st new particle < 1 year?
- ▶ Question: Are we ready?
 - ▶ reliable predictions start at NLO
 - ▶ required for signal and background
 - ▶ unknown model \Rightarrow unknown signal
- ▶ Can we produce NLO results quickly?
- ▶ For any new model?



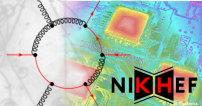
Motivation



- ▶ LHC (re-)starts in < 1 month
- ▶ Expect 1st collisions this year
- ▶ 1st new particle < 1 year?
- ▶ Question: Are we ready?
 - ▶ reliable predictions start at NLO
 - ▶ required for signal and background
 - ▶ unknown model \Rightarrow unknown signal
- ▶ Can we produce NLO results **quickly**?
- ▶ For any new model?



Motivation: recent progress... and things to do



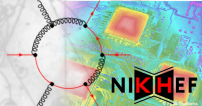
Recent results for multileg NLO corrections (QCD):

$pp \rightarrow WW + 2j$ (VBF)	talk by B. Jäger
$pp \rightarrow WW + j$	talk by S. Kallweit
$pp \rightarrow W\gamma + j$	talk by D. Zeppenfeld
$pp \rightarrow ZZ + j$	talk by S. Karg
$pp \rightarrow W + 3j$	talk by D. Maitre
$pp \rightarrow t\bar{t}b\bar{b}$	talk by S. Pozzorini
$pp \rightarrow V + b\bar{b}$	talk by D. Wackerroth
$pp \rightarrow W\gamma\gamma$	talk by M. Weber
$H \rightarrow f\bar{f}f'\bar{f}'$	[Denner, Dittmaier, Bredenstein]
$pp \rightarrow b\bar{b}b\bar{b}$	this talk ($q\bar{q}$ channel)

There is still work to be done:

$$\begin{array}{lll} pp \rightarrow t\bar{t} + 2j & pp \rightarrow Wb\bar{b}j & pp \rightarrow VV + b\bar{b} \\ pp \rightarrow 4j & pp \rightarrow VV + 2j & pp \rightarrow t\bar{t}t\bar{t} \\ pp \rightarrow W + 4j & & \end{array}$$

Motivation: recent progress... and things to do



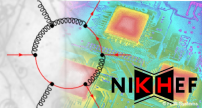
Recent results for multileg NLO corrections (QCD):

$pp \rightarrow WW + 2j$ (VBF)	talk by B. Jäger
$pp \rightarrow WW + j$	talk by S. Kallweit
$pp \rightarrow W\gamma + j$	talk by D. Zeppenfeld
$pp \rightarrow ZZ + j$	talk by S. Karg
$pp \rightarrow W + 3j$	talk by D. Maitre
$pp \rightarrow t\bar{t}b\bar{b}$	talk by S. Pozzorini
$pp \rightarrow V + b\bar{b}$	talk by D. Wackerroth
$pp \rightarrow W\gamma\gamma$	talk by M. Weber
$H \rightarrow f\bar{f}f'\bar{f}'$	[Denner, Dittmaier, Bredenstein]
$pp \rightarrow b\bar{b}b\bar{b}$	this talk ($q\bar{q}$ channel)

There is still work to be done:

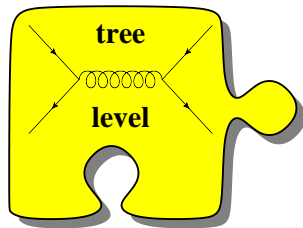
$$\begin{array}{lll} pp \rightarrow t\bar{t} + 2j & pp \rightarrow Wb\bar{b}j & pp \rightarrow VV + b\bar{b} \\ pp \rightarrow 4j & pp \rightarrow VV + 2j & pp \rightarrow t\bar{t}t\bar{t} \\ pp \rightarrow W + 4j & & \end{array}$$

Motivation: the missing link

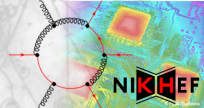


Full NLO calculation requires

- ▶ Born (LO) cross section
- ▶ virtual corrections
- ▶ real emission
- ▶ IR subtraction
(most common)
- ▶ What is the status?

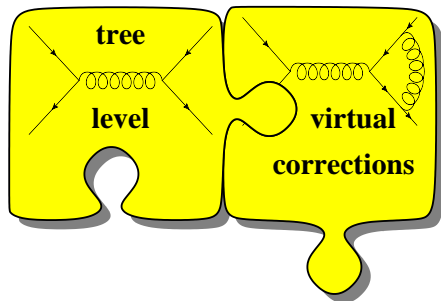


Motivation: the missing link

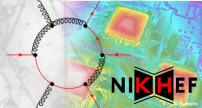


Full NLO calculation requires

- ▶ Born (LO) cross section
- ▶ virtual corrections
- ▶ real emission
- ▶ IR subtraction (most common)
- ▶ What is the status?

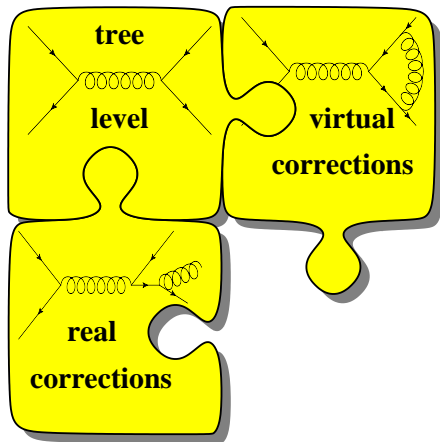


Motivation: the missing link

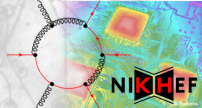


Full NLO calculation requires

- ▶ Born (LO) cross section
- ▶ virtual corrections
- ▶ real emission
- ▶ IR subtraction (most common)
- ▶ What is the status?

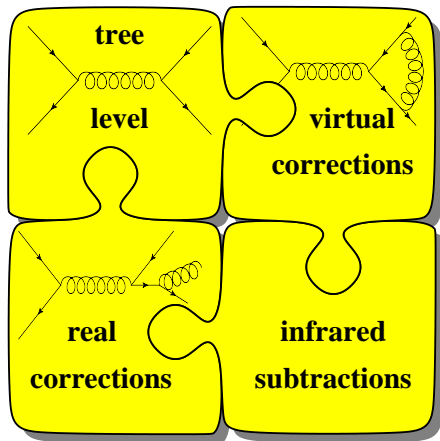


Motivation: the missing link

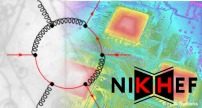


Full NLO calculation requires

- ▶ Born (LO) cross section
- ▶ virtual corrections
- ▶ real emission
- ▶ IR subtraction (most common)
- ▶ What is the status?

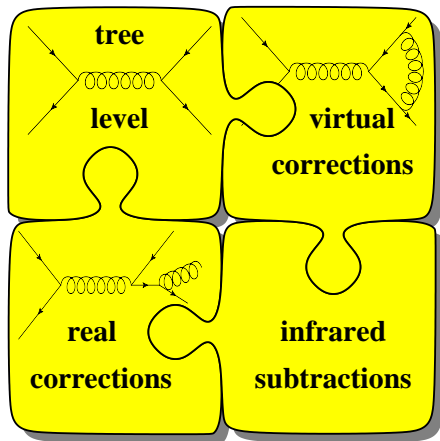


Motivation: the missing link

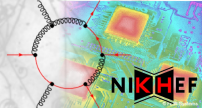


Full NLO calculation requires

- ▶ Born (LO) cross section
- ▶ virtual corrections
- ▶ real emission
- ▶ IR subtraction (most common)
- ▶ What is the status?

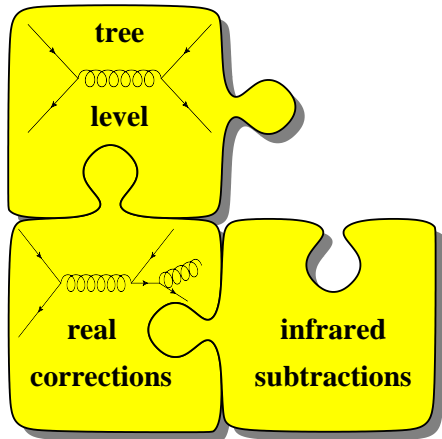


Motivation: the missing link

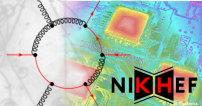


Tree-level parts:

- ▶ Many tools available
 - ▶ ALPGEN [Mangano et al.]
 - ▶ CalcHEP [Pukhov, Belyaev, Christensen]
 - ▶ CompHEP [Boos et al.]
 - ▶ FeynArts/FormCalc [Hahn]
 - ▶ Grace [Yuasa et al.]
 - ▶ HELAC-PHEGAS [Papadopoulos et al.]
 - ▶ MadGraph [Maltoni, Stelzer]
 - ▶ Sherpa (AMEGIC) [Krauss, Kuhn, Soff]
 - ▶ Whizard (O'Mega) [Kilian, Moretti, Ohl, Reuter]
- ▶ High level of automatisisation



Motivation: the missing link



Infrared subtraction:

- ▶ Catani-Seymour dipoles

- ▶ AutoDipole

[Hasegawa, Moch, Uwer]

- ▶ HELAC-DIPOLE

[Czakon, Papadopoulos, Worek]

- ▶ MadDipole

[Frederix, Gehrmann, Greiner]

- ▶ Sherpa [Gleisberg, Krauss]

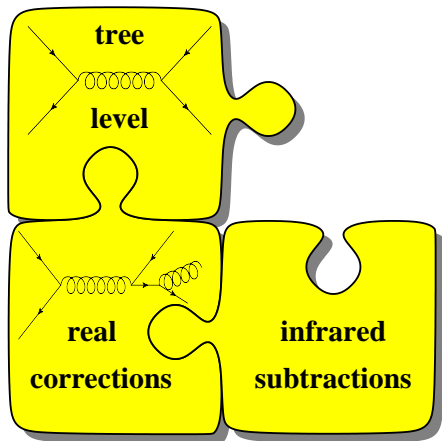
- ▶ TevJet [Seymour, Tevlin]

- ▶ other methods

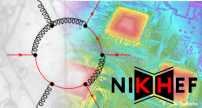
- ▶ Nagy-Soper dipoles

talk by T. Robens

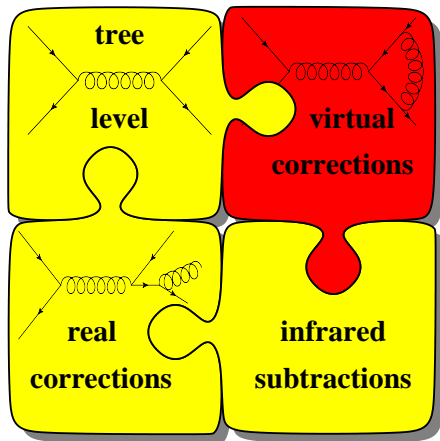
- ▶ MadFKS talk by R. Frederix

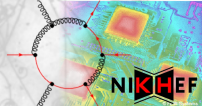


Motivation: the missing link



- ▶ Automatisisation beyond $2 \rightarrow 2$ in its infancy
- ▶ Many methods:
 - ▶ Unitarity based methods
talks by W. Giele, D. Kosower,
D. Maitre, S. Badger, P. Mastrolia,
A. Lazopoulos, C. Williams,
A. van Hameren
 - ▶ Feynman diagrammatic calculations
 ≈ 14 talks
 - ▶ Other methods
talk by T. Kleinschmidt

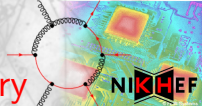




GOLEM: General One-Loop Evaluator for Matrix Elements

Golem Method	GOLEM95	GOLEM-2.0
<ul style="list-style-type: none">▶ Feynman diagrammatic▶ uses helicity projections▶ reduction method for tensor integrals <p>[hep-ph/0504267,0606318]</p>	<ul style="list-style-type: none">▶ implement. of integral reduction▶ Fortran 95 library▶ publicly available <p>[0810.0992]</p>	<ul style="list-style-type: none">▶ automatized matrix element generator▶ virtual part▶ under development

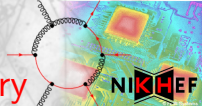
GOLEM95: A Generic Integral Form Factor Library



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

- ▶ Tensor Integrals from loop momentum

GOLEM95: A Generic Integral Form Factor Library



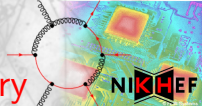
$$I_N^{d;\mu_1 \dots \mu_r}(S) = \int \frac{d^d k}{i\pi^{d/2}} \frac{k^{\mu_1} k^{\mu_2} \dots k^{\mu_r}}{[(k+r_1)^2 - m_1^2] \dots [(k+r_N)^2 - m_N^2]}$$




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

► Reduction to scalar basis $\Rightarrow (\det G)^{-1}$

GOLEM95: A Generic Integral Form Factor Library



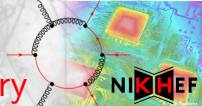
$$I_N^{d;\mu_1 \dots \mu_r}(S) = \int \frac{d^d k}{i\pi^{d/2}} \frac{k^{\mu_1} k^{\mu_2} \dots k^{\mu_r}}{[(k+r_1)^2 - m_1^2] \dots [(k+r_N)^2 - m_N^2]}$$


$$I_N^d(l_1, \dots, l_p; S) = (-1)^N \Gamma(N-d/2) \int_0^1 d^N z \frac{\delta(1 - \sum z_i) z_{l_1} \dots z_{l_p}}{\left(-\frac{1}{2} z^T S z - i\delta\right)^{N-d/2}}$$

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

- ▶ GOLEM basis: integrals with numerator

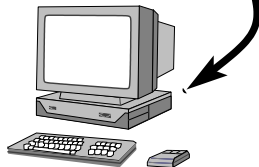
GOLEM95: A Generic Integral Form Factor Library



$$I_N^{d;\mu_1 \dots \mu_r}(S) = \int \frac{d^d k}{i\pi^{d/2}} \frac{k^{\mu_1} k^{\mu_2} \dots k^{\mu_r}}{[(k+r_1)^2 - m_1^2] \dots [(k+r_N)^2 - m_N^2]}$$

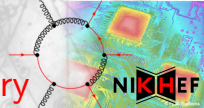
$$I_N^d(l_1, \dots, l_p; S) = (-1)^N \Gamma(N-d/2) \int_0^1 d^N z \frac{\delta(1 - \sum z_i) z_1 \dots z_{l_p}}{\left(-\frac{1}{2} z^T S z - i\delta\right)^{N-d/2}}$$

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



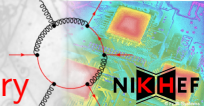
► numerical evaluation or algebraic reduction

GOLEM95: A Generic Integral Form Factor Library



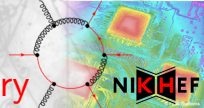
- ▶ Version without propagator masses
 - ▶ available as Fortran 95 code (open source)
[0810.0992]
 - ▶ safe in all phase space regions (avoids $(\det G)^{-1}$)
 - ▶ used successfully in actual calculations
e.g. $q\bar{q} \rightarrow b\bar{b}b\bar{b}$
 - ▶ numerical evaluation for small $\det G$:
1-dim. integral representations
- ▶ Version **with** propagator masses
 - ▶ all integrals (massive/massless, IR safe/IR finite)
 - ▶ LoopTools for IR finite massive integrals
 - ▶ some 1-dim. integrals missing
 $\Rightarrow (\det G)^{-1}$ not avoided everywhere
 - ▶ available in < 1 month
 - ▶ no changes in interface
- ▶ Next step: adding missing 1-dim. integrals

GOLEM95: A Generic Integral Form Factor Library



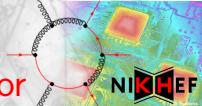
- ▶ Version without propagator masses
 - ▶ available as Fortran 95 code (open source)
[0810.0992]
 - ▶ safe in all phase space regions (avoids $(\det G)^{-1}$)
 - ▶ used successfully in actual calculations
e.g. $q\bar{q} \rightarrow b\bar{b}b\bar{b}$
 - ▶ numerical evaluation for small $\det G$:
1-dim. integral representations
- ▶ Version **with** propagator masses
 - ▶ all integrals (massive/massless, IR safe/IR finite)
 - ▶ LoopTools for IR finite massive integrals
 - ▶ some 1-dim. integrals missing
 $\Rightarrow (\det G)^{-1}$ not avoided everywhere
 - ▶ available in < 1 month
 - ▶ no changes in interface
- ▶ Next step: adding missing 1-dim. integrals

GOLEM95: A Generic Integral Form Factor Library



- ▶ Version without propagator masses
 - ▶ available as Fortran 95 code (open source)
[0810.0992]
 - ▶ safe in all phase space regions (avoids $(\det G)^{-1}$)
 - ▶ used successfully in actual calculations
e.g. $q\bar{q} \rightarrow b\bar{b}b\bar{b}$
 - ▶ numerical evaluation for small $\det G$:
1-dim. integral representations
- ▶ Version **with** propagator masses
 - ▶ all integrals (massive/massless, IR safe/IR finite)
 - ▶ LoopTools for IR finite massive integrals
 - ▶ some 1-dim. integrals missing
 $\Rightarrow (\det G)^{-1}$ not avoided everywhere
 - ▶ available in < 1 month
 - ▶ no changes in interface
- ▶ Next step: adding missing 1-dim. integrals

GOLEM-2.0: One-Loop Matrix Element Generator



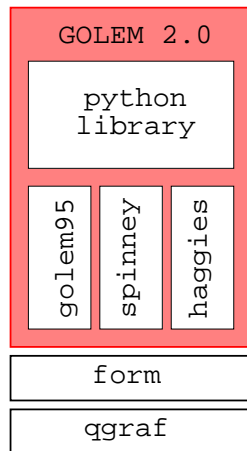
Overview

- ▶ implementation of the Golem method
- ▶ very modular
 - ▶ python library (command line tools)
 - ▶ spinney: helicity spinors in Form
 - ▶ haggies: optimizing code generator
 - ▶ golem95: integral library
- ▶ based on Form and QGraf
- ▶ Fortran 95 matrix element code

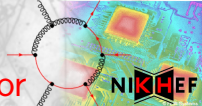
Recent addition: BSM interface

- ▶ import of CalcHep Feynman rules
- ▶ implementation of Majorana fermions and higher spins

Goal: public and open source in 2010



GOLEM-2.0: One-Loop Matrix Element Generator



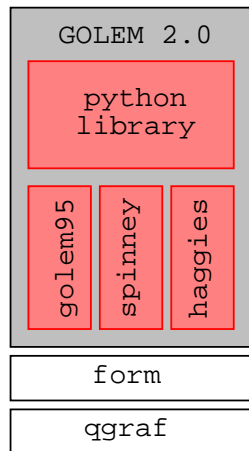
Overview

- ▶ implementation of the Golem method
- ▶ very modular
 - ▶ python library (command line tools)
 - ▶ spinney: helicity spinors in Form
 - ▶ haggies: optimizing code generator
 - ▶ golem95: integral library
- ▶ based on Form and QGraf
- ▶ Fortran 95 matrix element code

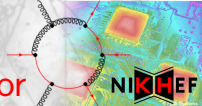
Recent addition: BSM interface

- ▶ import of CalcHep Feynman rules
- ▶ implementation of Majorana fermions and higher spins

Goal: public and open source in 2010



GOLEM-2.0: One-Loop Matrix Element Generator



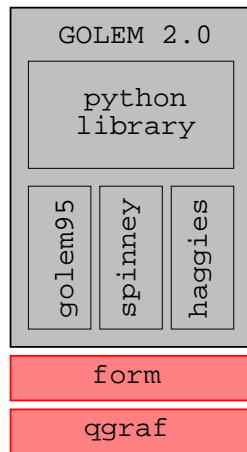
Overview

- ▶ implementation of the Golem method
- ▶ very modular
 - ▶ python library (command line tools)
 - ▶ spinney: helicity spinors in Form
 - ▶ haggies: optimizing code generator
 - ▶ golem95: integral library
- ▶ based on Form and QGraf
- ▶ Fortran 95 matrix element code

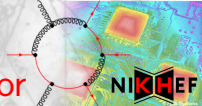
Recent addition: BSM interface

- ▶ import of CalcHep Feynman rules
- ▶ implementation of Majorana fermions and higher spins

Goal: public and open source in 2010



GOLEM-2.0: One-Loop Matrix Element Generator



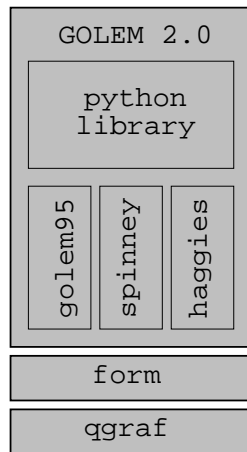
Overview

- ▶ implementation of the Golem method
- ▶ very modular
 - ▶ python library (command line tools)
 - ▶ spinney: helicity spinors in Form
 - ▶ haggies: optimizing code generator
 - ▶ golem95: integral library
- ▶ based on Form and QGraf
- ▶ Fortran 95 matrix element code

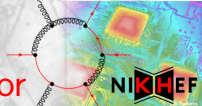
Recent addition: BSM interface

- ▶ import of CalcHep Feynman rules
- ▶ implementation of Majorana fermions and higher spins

Goal: public and open source in 2010



GOLEM-2.0: One-Loop Matrix Element Generator

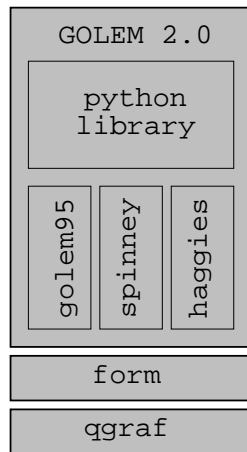


Overview

- ▶ implementation of the Golem method
- ▶ very modular
 - ▶ python library (command line tools)
 - ▶ spinney: helicity spinors in Form
 - ▶ haggies: optimizing code generator
 - ▶ golem95: integral library
- ▶ based on Form and QGraf
- ▶ Fortran 95 matrix element code

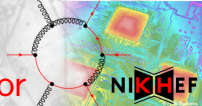
Recent addition: BSM interface

- ▶ import of CalcHep Feynman rules
- ▶ implementation of Majorana fermions and higher spins



Goal: public and open source in 2010

GOLEM-2.0: One-Loop Matrix Element Generator



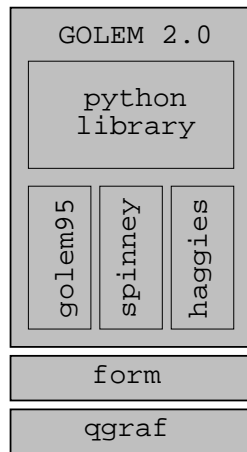
Overview

- ▶ implementation of the Golem method
- ▶ very modular
 - ▶ python library (command line tools)
 - ▶ spinney: helicity spinors in Form
 - ▶ haggies: optimizing code generator
 - ▶ golem95: integral library
- ▶ based on Form and QGraf
- ▶ Fortran 95 matrix element code

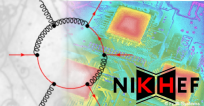
Recent addition: BSM interface

- ▶ import of CalcHep Feynman rules
- ▶ implementation of Majorana fermions and higher spins

Goal: public and open source in 2010



GOLEM-2.0: Matrix Elements Made Easy

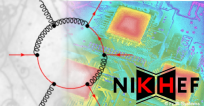


- ▶ create configuration file
- ▶ enter process, here: $gg \rightarrow s\bar{s}b\bar{b}$ @ NLO in QCD
- ▶ set up process directory
- ▶ generate code and draw diagrams

```
shell
```

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

GOLEM-2.0: Matrix Elements Made Easy

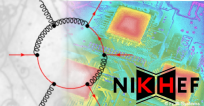


- ▶ create configuration file
- ▶ enter process, here: $gg \rightarrow s\bar{s}b\bar{b}$ @ NLO in QCD
- ▶ set up process directory
- ▶ generate code and draw diagrams

```
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

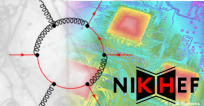


- ▶ create configuration file
- ▶ enter process, here: $gg \rightarrow s\bar{s}b\bar{b}$ @ NLO in QCD
- ▶ set up process directory
- ▶ generate code and draw diagrams

shell

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

GOLEM-2.0: Matrix Elements Made Easy

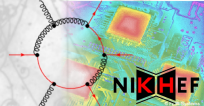


- ▶ create configuration file
- ▶ enter process, here: $gg \rightarrow s\bar{s}b\bar{b}$ @ NLO in QCD
- ▶ set up process directory
- ▶ generate code and draw diagrams

shell

```
$ golem-main.py --template process.in
$ edit process.in
$ golem-main.py process.in
$ make dist # -> matrix.tar.gz
$
```

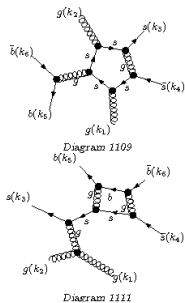
GOLEM-2.0: Matrix Elements Made Easy



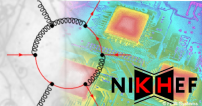
- ▶ create configuration file
- ▶ enter process, here: $gg \rightarrow s\bar{s}b\bar{b}$ @ NLO in QCD
- ▶ set up process directory
- ▶ generate code and draw diagrams

shell

```
$ golem-main.py --template process.in
$ edit process.in
$ golem-main.py process.in
$ make dist # -> matrix.tar.gz
$ make doc # -> process.ps
$
```



spinney: Helicity Spinors for Form



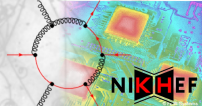
Common tasks in many helicity spinor calculations:

- ▶ translating from explicit spinor indices: $\gamma_{\alpha\beta}^{\mu} |p\rangle_{\beta} \rightarrow \gamma^{\mu} |p\rangle$
- ▶ dimension splitting ('t Hooft algebra)
- ▶ decomposition of massive spinors
- ▶ contraction of Lorentz indices (Chisholm identities)
- ▶ Schouten identities
- ▶ **new:** Flipping rules for Majorana fermions

spinney

- ▶ Form implementation of above algorithms
- ▶ works independent from GOLEM
- ▶ Goal: public and open source in 2009

spinney: Helicity Spinors for Form



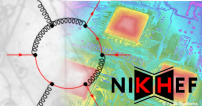
Common tasks in many helicity spinor calculations:

- ▶ translating from explicit spinor indices: $\gamma_{\alpha\beta}^{\mu} |p\rangle_{\beta} \rightarrow \gamma^{\mu} |p\rangle$
- ▶ dimension splitting ('t Hooft algebra)
- ▶ decomposition of massive spinors
- ▶ contraction of Lorentz indices (Chisholm identities)
- ▶ Schouten identities
- ▶ **new:** Flipping rules for Majorana fermions

spinney

- ▶ Form implementation of above algorithms
- ▶ works independent from GOLEM
- ▶ Goal: public and open source in 2009

haggies: Optimizing Code Generation

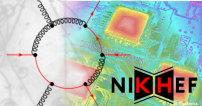


- ▶ Problem: carrying out algebra \rightarrow large expressions
- ▶ e.g. $gg \rightarrow b\bar{b}b\bar{b}$, most complicated diagram: 52,313 terms (2.8 MB ASCII)
- ▶ direct translation to Fortran
 - ▶ very/too large for compiler
 - ▶ inefficient code: many arithmetic operations

Code Generation with haggies:

- ▶ same example:
 - ▶ before optimization: 225,079 multiplications
 - ▶ after haggies: 57,653 multiplications
 - ▶ splitting into manageable compilation units
- ▶ haggies independent of GOLEM
- ▶ source and target language independent
- ▶ public, open source, available for download [0907.3714]

haggies: Optimizing Code Generation

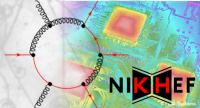


- ▶ Problem: carrying out algebra \rightarrow large expressions
- ▶ e.g. $gg \rightarrow b\bar{b}b\bar{b}$, most complicated diagram: 52,313 terms (2.8 MB ASCII)
- ▶ direct translation to Fortran
 - ▶ very/too large for compiler
 - ▶ inefficient code: many arithmetic operations

Code Generation with haggies:

- ▶ same example:
 - ▶ before optimization: 225,079 multiplications
 - ▶ after haggies: 57,653 multiplications
 - ▶ splitting into manageable compilation units
- ▶ haggies independent of GOLEM
- ▶ source and target language independent
- ▶ public, open source, available for download [0907.3714]

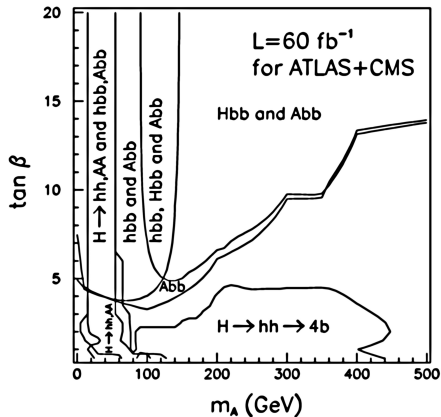
$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: An Important Background



4b Final State 5σ LHC Discovery Contours

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

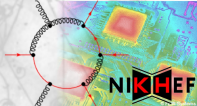
$m_t = 175$ GeV, $\epsilon_{b\text{-tag}} = 0.6$, $\epsilon_{\text{mis-tag}} = 0.01$



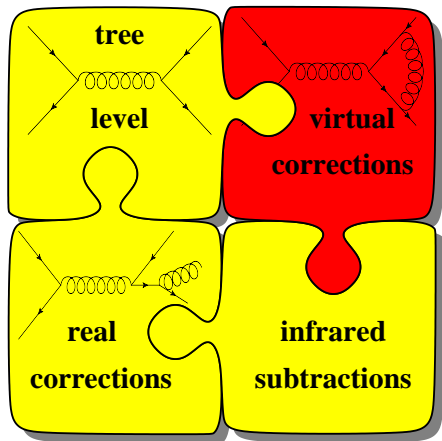
- ▶ Uncertainty on $b\bar{b}b\bar{b}$ crucial for BSM Higgs searches
- ▶ for MSSM at large $\tan \beta$: $H \rightarrow b\bar{b}b\bar{b}$ enhanced
- ▶ maybe only discovery channel
- ▶ also important for other BSM models

[Dai, Gunion, Vega]

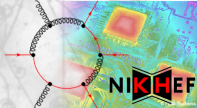
$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Setup



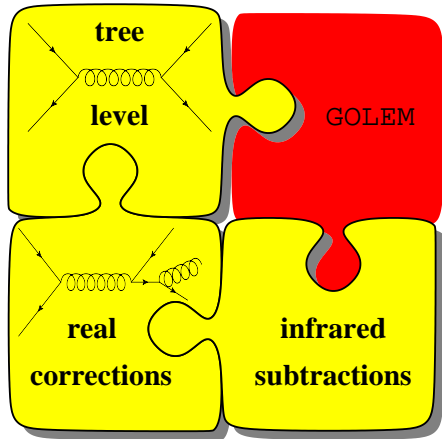
- ▶ virtual corrections: GOLEM
- ▶ Born part: MadGraph
[F. Maltoni, T. Stelzer]
- ▶ real corrections: MadGraph
- ▶ subtractions: MadDipole
[R. Frederix, T. Gehrmann, N. Greiner]
- ▶ integration/analysis
(MadEvent [Maltoni, Stelzer])
- ▶ “plug and play”: single subroutine call from MadEvent to GOLEM



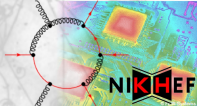
$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Setup



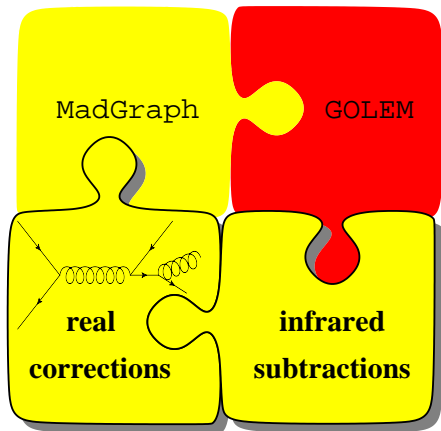
- ▶ virtual corrections: GOLEM
- ▶ Born part: MadGraph
[F. Maltoni, T. Stelzer]
- ▶ real corrections: MadGraph
- ▶ subtractions: MadDipole
[R. Frederix, T. Gehrmann, N. Greiner]
- ▶ integration/analysis
(MadEvent [Maltoni, Stelzer])
- ▶ “plug and play”: single subroutine call from MadEvent to GOLEM



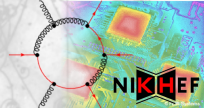
$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Setup



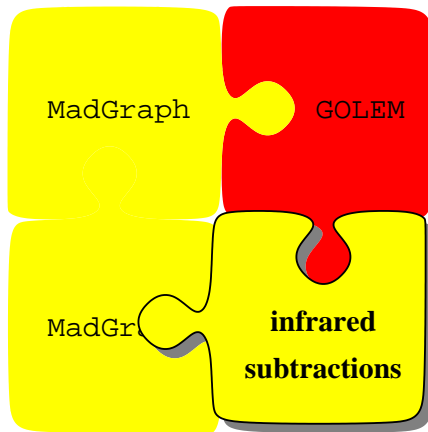
- ▶ virtual corrections: GOLEM
- ▶ Born part: MadGraph
[F. Maltoni, T. Stelzer]
- ▶ real corrections: MadGraph
- ▶ subtractions: MadDipole
[R. Frederix, T. Gehrmann, N. Greiner]
- ▶ integration/analysis
(MadEvent [Maltoni, Stelzer])
- ▶ “plug and play”: single subroutine call from MadEvent to GOLEM



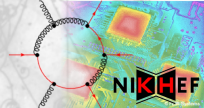
$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Setup



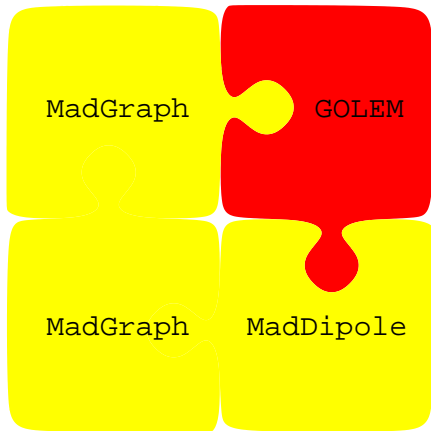
- ▶ virtual corrections: GOLEM
- ▶ Born part: MadGraph
[F. Maltoni, T. Stelzer]
- ▶ real corrections: MadGraph
- ▶ subtractions: MadDipole
[R. Frederix, T. Gehrmann, N. Greiner]
- ▶ integration/analysis
(MadEvent [Maltoni, Stelzer])
- ▶ “plug and play”: single
subroutine call from
MadEvent to GOLEM



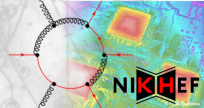
$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Setup



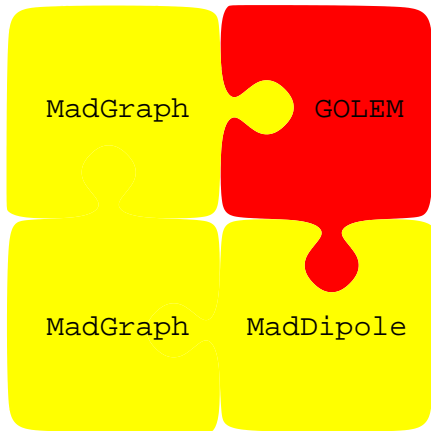
- ▶ virtual corrections: GOLEM
- ▶ Born part: MadGraph
[F. Maltoni, T. Stelzer]
- ▶ real corrections: MadGraph
- ▶ subtractions: MadDipole
[R. Frederix, T. Gehrmann, N. Greiner]
- ▶ integration/analysis
(MadEvent [Maltoni, Stelzer])
- ▶ “plug and play”: single
subroutine call from
MadEvent to GOLEM



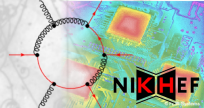
$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Setup



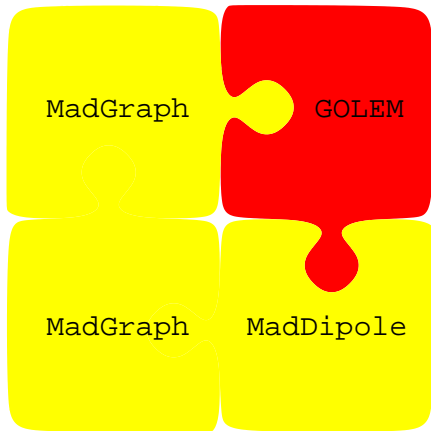
- ▶ virtual corrections: GOLEM
- ▶ Born part: MadGraph
[F. Maltoni, T. Stelzer]
- ▶ real corrections: MadGraph
- ▶ subtractions: MadDipole
[R. Frederix, T. Gehrmann, N. Greiner]
- ▶ integration/analysis
(MadEvent [Maltoni, Stelzer])
- ▶ “plug and play”: single
subroutine call from
MadEvent to GOLEM



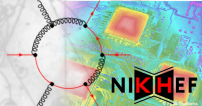
$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Setup



- ▶ virtual corrections: GOLEM
- ▶ Born part: MadGraph
[F. Maltoni, T. Stelzer]
- ▶ real corrections: MadGraph
- ▶ subtractions: MadDipole
[R. Frederix, T. Gehrmann, N. Greiner]
- ▶ integration/analysis
(MadEvent [Maltoni, Stelzer])
- ▶ “plug and play”: single
subroutine call from
MadEvent to GOLEM



$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Alternative Setup

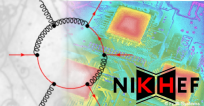


- ▶ Born part, real emission and IR-subtractions:
Whizard [Kilian,Moretti,Ohl,Reuter]
- ▶ virtual part: stand-alone GOLEM
- ▶ reweighting of unweighted LO events

$$\sigma = \frac{\sigma_{LO}}{|U|} \sum_{u \in U} \left(\frac{d\sigma_{virt}(u)}{d\sigma_{LO}(u)} + 1 \right)$$

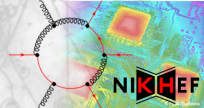
- ▶ very efficient integration method

$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Checks



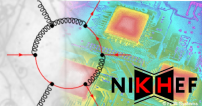
- ▶ LO contribution and real emission
 - ▶ two independent calculations:
 - ▶ MadEvent/MadGraph
 - ▶ Whizard
- ▶ IR-subtractions
 - ▶ two independent calculations:
 - ▶ MadDipole
 - ▶ implementation in Whizard
 - ▶ cut-off independence (α_{Nagy})
- ▶ virtual corrections
 - ▶ two independent implementations:
 - ▶ GOLEM-2.0 (QGraf, Form, Fortran/GOLEM95)
 - ▶ FeynArts/FeynCalc, Form, algebraic reduction
 - ▶ cancellation of poles in $1/(d-4)$
 - ▶ symmetry properties of the amplitude

$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Checks



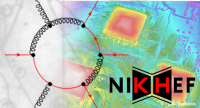
- ▶ LO contribution and real emission
 - ▶ two independent calculations:
 - ▶ MadEvent/MadGraph
 - ▶ Whizard
- ▶ IR-subtractions
 - ▶ two independent calculations:
 - ▶ MadDipole
 - ▶ implementation in Whizard
 - ▶ cut-off independence (α_{Nagy})
- ▶ virtual corrections
 - ▶ two independent implementations:
 - ▶ GOLEM-2.0 (QGraf, Form, Fortran/GOLEM95)
 - ▶ FeynArts/FeynCalc, Form, algebraic reduction
 - ▶ cancellation of poles in $1/(d-4)$
 - ▶ symmetry properties of the amplitude

$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Checks

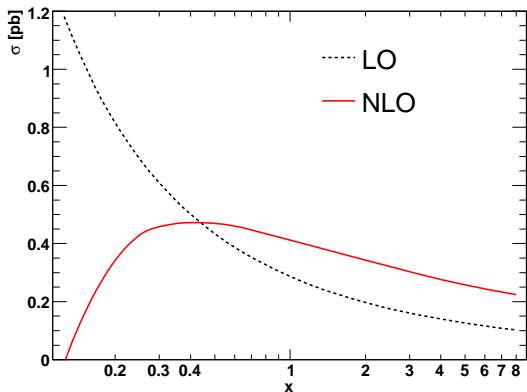


- ▶ LO contribution and real emission
 - ▶ two independent calculations:
 - ▶ MadEvent/MadGraph
 - ▶ Whizard
- ▶ IR-subtractions
 - ▶ two independent calculations:
 - ▶ MadDipole
 - ▶ implementation in Whizard
 - ▶ cut-off independence (α_{Nagy})
- ▶ virtual corrections
 - ▶ two independent implementations:
 - ▶ GOLEM-2.0 (QGraf, Form, Fortran/GOLEM95)
 - ▶ FeynArts/FeynCalc, Form, algebraic reduction
 - ▶ cancellation of poles in $1/(d - 4)$
 - ▶ symmetry properties of the amplitude

$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Results



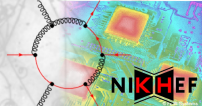
$$\mu_R = x\mu_0$$



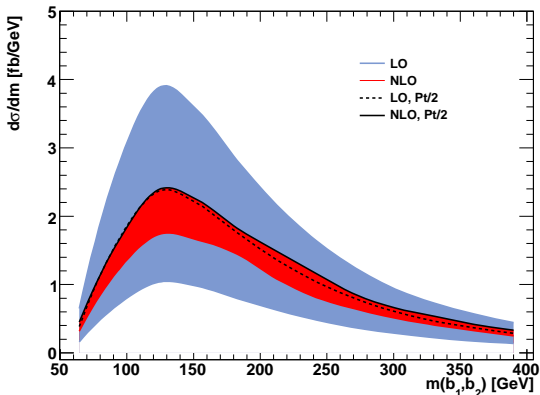
$$\sqrt{s} = 14 \text{ TeV}, \mu_0 = \sqrt{\sum_j p_T^2(b_j)}, \mu_F = 100 \text{ GeV}, m_b = 0$$

- ▶ significant reduction of scale dependence
- ▶ plateau region around $x = 0.5$
- ▶ stabilization of result
- ▶ error bands:
 $\mu_0/4 < \mu_R < 2\mu_0$
- ▶ complete analysis after inclusion of all channels

$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Results



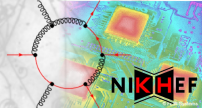
m_{bb} of leading b -jets



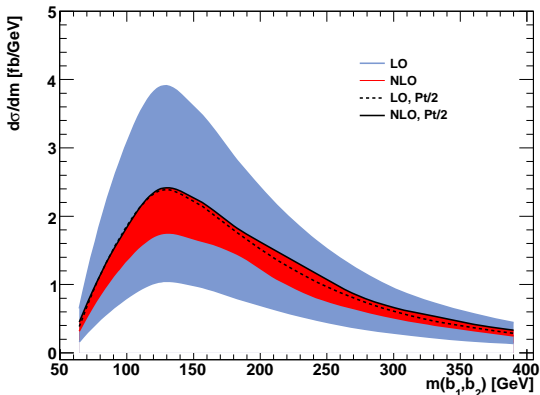
- ▶ significant reduction of scale dependence
- ▶ plateau region around $x = 0.5$
- ▶ stabilization of result
- ▶ error bands:
 $\mu_0/4 < \mu_R < 2\mu_0$
- ▶ complete analysis after inclusion of all channels

$$\sqrt{s} = 14 \text{ TeV}, \mu_R = \frac{1}{2} \sqrt{\sum_j p_T^2(b_j)}, \mu_F = 100 \text{ GeV}, m_b = 0$$

$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Results



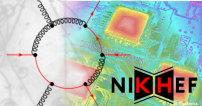
m_{bb} of leading b -jets



- ▶ significant reduction of scale dependence
- ▶ plateau region around $x = 0.5$
- ▶ stabilization of result
- ▶ error bands:
 $\mu_0/4 < \mu_R < 2\mu_0$
- ▶ complete analysis after inclusion of all channels

$$\sqrt{s} = 14 \text{ TeV}, \mu_R = \frac{1}{2} \sqrt{\sum_j p_T^2(b_j)}, \mu_F = 100 \text{ GeV}, m_b = 0$$

Summary

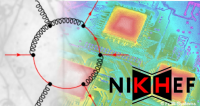


- ▶ full NLO automatism important for LHC
- ▶ missing piece: virtual part
- ▶ GOLEM approach fills a gap
- ▶ GOLEM95 already there
- ▶ successfully applied
- ▶ massive version soon
- ▶ GOLEM-2.0 works
- ▶ spin-offs: spinney, haggies
- ▶ BSM important goal
- ▶ first results $q\bar{q} \rightarrow b\bar{b}b\bar{b}$
- ▶ important background to BSM Higgs searches
- ▶ benchmark for GOLEM-2.0
- ▶ proof of interoperability

Outlook

- ▶ all components of GOLEM public ASAP
- ▶ careful testing required
- ▶ full $pp \rightarrow b\bar{b}b\bar{b}$ results expected soon

Summary

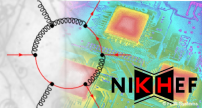


- ▶ full NLO automatism important for LHC
- ▶ missing piece: virtual part
- ▶ GOLEM approach fills a gap
- ▶ GOLEM95 already there
- ▶ successfully applied
- ▶ massive version soon
- ▶ GOLEM-2.0 works
- ▶ spin-offs: spinney, haggies
- ▶ BSM important goal
- ▶ first results $q\bar{q} \rightarrow b\bar{b}b\bar{b}$
- ▶ important background to BSM Higgs searches
- ▶ benchmark for GOLEM-2.0
- ▶ proof of interoperability

Outlook

- ▶ all components of GOLEM public ASAP
- ▶ careful testing required
- ▶ full $pp \rightarrow b\bar{b}b\bar{b}$ results expected soon

Summary

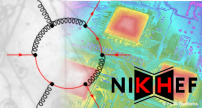


- ▶ full NLO automatism important for LHC
- ▶ missing piece: virtual part
- ▶ GOLEM approach fills a gap
- ▶ GOLEM95 already there
- ▶ successfully applied
- ▶ massive version soon
- ▶ GOLEM-2.0 works
- ▶ spin-offs: spinney, haggies
- ▶ BSM important goal
- ▶ first results $q\bar{q} \rightarrow b\bar{b}b\bar{b}$
- ▶ important background to BSM Higgs searches
- ▶ benchmark for GOLEM-2.0
- ▶ proof of interoperability

Outlook

- ▶ all components of GOLEM public ASAP
- ▶ careful testing required
- ▶ full $pp \rightarrow b\bar{b}b\bar{b}$ results expected soon

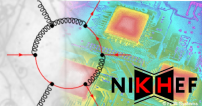
Summary



- ▶ full NLO automatism important for LHC
- ▶ missing piece: virtual part
- ▶ GOLEM approach fills a gap
- ▶ GOLEM95 already there
- ▶ successfully applied
- ▶ massive version soon
- ▶ GOLEM-2.0 works
- ▶ spin-offs: spinney, haggies
- ▶ BSM important goal
- ▶ first results $q\bar{q} \rightarrow b\bar{b}b\bar{b}$
- ▶ important background to BSM Higgs searches
- ▶ benchmark for GOLEM-2.0
- ▶ proof of interoperability

Outlook

- ▶ all components of GOLEM public ASAP
- ▶ careful testing required
- ▶ full $pp \rightarrow b\bar{b}b\bar{b}$ results expected soon

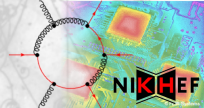


- ▶ full NLO automatism important for LHC
- ▶ missing piece: virtual part
- ▶ GOLEM approach fills a gap
- ▶ GOLEM95 already there
- ▶ successfully applied
- ▶ massive version soon
- ▶ GOLEM-2.0 works
- ▶ spin-offs: spinney, haggies
- ▶ BSM important goal
- ▶ first results $q\bar{q} \rightarrow b\bar{b}b\bar{b}$
- ▶ important background to BSM Higgs searches
- ▶ benchmark for GOLEM-2.0
- ▶ proof of interoperability

Outlook

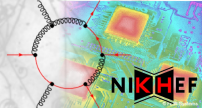
- ▶ all components of GOLEM public ASAP
- ▶ careful testing required
- ▶ full $pp \rightarrow b\bar{b}b\bar{b}$ results expected soon

Backup Slides

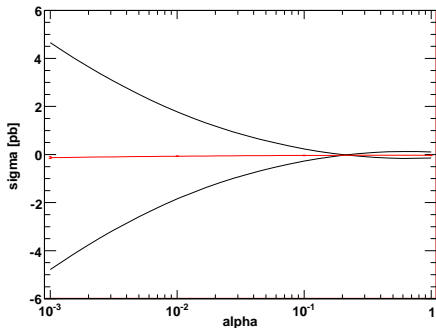


More Results

$q\bar{q} \rightarrow b\bar{b}b\bar{b}$: Results



(In-)dependence on α_{Nagy}



Cuts and Parameters

- ▶ $q \in \{u, d, s, c\}$
- ▶ $m_b = 0$
- ▶ $\sqrt{s} = 14 \text{ TeV}$
- ▶ $p_T(b_j) > 30 \text{ GeV}$
- ▶ $|\eta(b_j)| < 2.5$
- ▶ $\Delta R(b_i, b_j) > 0.8$
- ▶ $\mu_0 = \sqrt{\sum_j p_T^2(b_j)}$
- ▶ $\mu_F = 100 \text{ GeV}$
- ▶ CTEQ6M pdfs/2-loop running of α_s