The experimental frontier(s)

LHC / HL-LHC Plan

Linear Collider?
The precision frontier

• LHC Run 2 and beyond:
  high statistics $\rightarrow$ high experimental precision
  needs to be matched by theory predictions!

• means predictions at (at least) next-to-leading order (NLO)
  in the strong (and electro-weak) coupling

• there are cases where predictions at NNLO
  (or even beyond, and/or resummation)
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  tedious calculations, automation desired!
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- **NNLO:** still a long way to automation
**Les Houches 05: NLO wishlist for LHC**

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<tr>
<th>process $(V \in {Z, W, \gamma})$</th>
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<td>2. $pp \rightarrow H + 2$ jets</td>
<td>$H$ production by VBF</td>
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<td>7. $pp \rightarrow V + 3$ jets</td>
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<td>8. $pp \rightarrow VVV$</td>
<td>SUSY trilepton</td>
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<td>$(V \in {Z, W, \gamma})$</td>
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<td>4. $PP \to V+3$jets</td>
<td>VBF contributions calculated by (Bozzi)/Jäger/Oleari/Zeppenfeld [10–12]</td>
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<td>3. (pp \rightarrow VVV)</td>
<td>relevant for (t\bar{t}H) computed by Bredenstein/Denner/Dittmaier/Pozzorini [14, 15] and Bevilacqua/Czakon/Papadopoulos/Worek [16]. calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations.</td>
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<td>7. (pp \rightarrow VV b\bar{b}), (8. pp \rightarrow VV+2\text{jets})</td>
<td>relevant for VBF (\rightarrow H \rightarrow VV, t\bar{t}H) relevant for VBF (\rightarrow H \rightarrow VV) VBF contributions calculated by (Bozzi)Jäger/Oleari/Zeppenfeld [20–22].</td>
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Les Houches 2011:  

NLO QCD wishlist  

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### Les Houches 2011:

#### NLO QCD wishlist retired

“NLO revolution”

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what caused the “NLO revolution”?  

- gauge dependent off-shell states introduce “spurious” terms  
- try to use on-shell quantities as building blocks

- construct N-point one-loop amplitudes from tree amplitudes  
  Bern, Dixon, Kosower ‘98

- use of complex momenta in generalised cuts  
  Britto, Cachazo, Feng ’04

- numerical reduction at integrand level  
  Ossola, Papadopoulos, Pittau ’06

- D-dimensional unitarity  
  Anastasiou, Britto, Feng, Kunszt, Mastrolia ’06; Forde ’07; Giele, Kunszt, Melnikov ’08, Badger ’09, ...
one-loop N-point amplitude:

\[ = \sum_i C_i^4 + \sum_i C_i^3 + \sum_i C_i^2 + \mathcal{R} \]

“master integrals”: boxes, triangles, bubbles

most complicated functions are dilogarithms

\( C_i^n \) can be obtained by numerical reduction at integrand level

automated tools: CutTools, Samurai, Ninja

Ossola, Papadopoulos, Pittau

Mastrolia, Ossola, Reiter, Tramontano, van Deurzen

Mastrolia, Mirabella, Peraro
But …

… fulfilled wishes create more wishes …
Les Houches 2013: Higgs

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<th>Process</th>
<th>State of the Art</th>
<th>Desired</th>
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<td>H</td>
<td>$d\sigma @ NNLO$ QCD (expansion in $1/m_t$) full $m_t/m_b$ dependence @ NLO QCD and @ NLO EW NNLO+PS, in the $m_t \to \infty$ limit</td>
<td>$d\sigma @ NNNLO$ QCD (infinite-$m_t$ limit) full $m_t/m_b$ dependence @ NNLO QCD and @ NNLO QCD+EW NNLO+PS with finite top quark mass effects</td>
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<td>H + j</td>
<td>$d\sigma @ NNLO$ QCD (g only) and finite-quark-mass effects @ LO QCD and LO EW</td>
<td>$d\sigma @ NNLO$ QCD (infinite-$m_t$ limit) and finite-quark-mass effects @ NLO QCD and NLO EW</td>
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<td>H + 2j</td>
<td>$\sigma_{tot}(VBF) @ NNLO(DIS)$ QCD $d\sigma(VBF) @ NLO$ EW $d\sigma(gg) @ NLO$ QCD (infinite-$m_t$ limit) and finite-quark-mass effects @ LO QCD</td>
<td>$d\sigma(VBF) @ NNLO$ QCD + NLO EW $d\sigma(gg) @ NNLO$ QCD (infinite-$m_t$ limit) and finite-quark-mass effects @ NLO QCD and NLO EW</td>
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<td>$d\sigma @ NNLO$ QCD $d\sigma @ NLO$ EW $\sigma_{tot}(gg) @ NLO$ QCD (infinite-$m_t$ limit)</td>
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<td>$t\bar{t}H$ and $t\bar{t}$</td>
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<td>$d\sigma$(top decays) @ NLO QCD and NLO EW</td>
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| $t\bar{t}$ | $\sigma_{\text{tot}}$ (stable tops) @ NNLO QCD  
$\sigma$(top decays) @ NLO QCD  
$\sigma$(stable tops) @ NLO EW | $\sigma$(top decays)  
@ NNLO QCD + NLO EW |
| $t\bar{t} + j(j)$ | $\sigma$(NWA top decays) @ NLO QCD | $\sigma$(NWA top decays)  
@ NNLO QCD + NLO EW |
| $t\bar{t} + Z$ | $\sigma$(stable tops) @ NLO QCD | $\sigma$(top decays) @ NLO QCD  
+ NLO EW |
| single-top | $\sigma$(NWA top decays) @ NLO QCD | $\sigma$(NWA top decays)  
@ NNLO QCD + NLO EW |
| dijet | $\sigma$ @ NNLO QCD (g only)  
$\sigma$ @ NLO EW (weak) | $\sigma$ @ NNLO QCD + NLO EW |
| 3j | $\sigma$ @ NLO QCD | $\sigma$ @ NNLO QCD + NLO EW |
| $\gamma + j$ | $\sigma$ @ NLO QCD  
$\sigma$ @ NLO EW | $\sigma$ @ NNLO QCD + NLO EW |
Les Houches 2013: vector bosons

<table>
<thead>
<tr>
<th>Process</th>
<th>State of the Art</th>
<th>Desired</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$</td>
<td>$d\sigma(\text{lept. } V \text{ decay})$ @ NNLO QCD</td>
<td>$d\sigma(\text{lept. } V \text{ decay})$ @ NNNLO QCD and @ NNLO QCD + EW</td>
</tr>
<tr>
<td></td>
<td>$d\sigma(\text{lept. } V \text{ decay})$ @ NLO EW</td>
<td>$d\sigma(\text{lept. } V \text{ decay})$ @ NNLO QCD + NLO EW</td>
</tr>
<tr>
<td>$V + j(j)$</td>
<td>$d\sigma(\text{lept. } V \text{ decay})$ @ NLO QCD</td>
<td>$d\sigma(\text{decaying off-shell } V)$ @ NNLO QCD + NLO EW</td>
</tr>
<tr>
<td></td>
<td>$d\sigma(\text{lept. } V \text{ decay})$ @ NLO EW</td>
<td>@ NNLO QCD + NLO EW</td>
</tr>
<tr>
<td>$VV'$</td>
<td>$d\sigma(V \text{ decays})$ @ NLO QCD</td>
<td>$d\sigma(V \text{ decays})$ @ NLO QCD</td>
</tr>
<tr>
<td></td>
<td>$d\sigma(\text{on-shell } V \text{ decays})$ @ NLO EW</td>
<td>@ NNLO QCD + NLO EW</td>
</tr>
<tr>
<td>$g g \rightarrow V V$</td>
<td>$d\sigma(V \text{ decays})$ @ LO QCD</td>
<td>$d\sigma(V \text{ decays})$ @ NLO QCD</td>
</tr>
<tr>
<td>$V\gamma$</td>
<td>$d\sigma(V \text{ decay})$ @ NLO QCD</td>
<td>$d\sigma(V \text{ decay})$ @ NNLO QCD + NLO EW</td>
</tr>
<tr>
<td></td>
<td>$d\sigma(\text{PA, } V \text{ decay})$ @ NLO EW</td>
<td>@ NNLO QCD + NLO EW</td>
</tr>
<tr>
<td>$V b b$</td>
<td>$d\sigma(\text{lept. } V \text{ decay})$ @ NLO QCD</td>
<td>$d\sigma(\text{lept. } V \text{ decay})$ @ NNNLO QCD + NLO EW</td>
</tr>
<tr>
<td></td>
<td>massive $b$</td>
<td>+ NLO EW, massless $b$</td>
</tr>
<tr>
<td>$VV'\gamma$</td>
<td>$d\sigma(V \text{ decays})$ @ NLO QCD</td>
<td>$d\sigma(V \text{ decays})$ @ NLO QCD + NLO EW</td>
</tr>
<tr>
<td>$VV''$</td>
<td>$d\sigma(V \text{ decays})$ @ NLO QCD</td>
<td>$d\sigma(V \text{ decays})$ @ NLO QCD + NLO EW</td>
</tr>
<tr>
<td>$V V' + j$</td>
<td>$d\sigma(V \text{ decays})$ @ NLO QCD</td>
<td>$d\sigma(V \text{ decays})$ @ NLO QCD + NLO EW</td>
</tr>
<tr>
<td>$V V' + j j$</td>
<td>$d\sigma(V \text{ decays})$ @ NLO QCD</td>
<td>$d\sigma(V \text{ decays})$ @ NLO QCD + NLO EW</td>
</tr>
<tr>
<td>$\gamma \gamma$</td>
<td>$d\sigma$ @ NNLO QCD + NLO EW</td>
<td>$q_{T}$ resummation at NNLL matched to NNLO</td>
</tr>
</tbody>
</table>
Measure of complexity

#loops + #legs + #scales (masses, off-shellness)

Complexity does not scale linearly!

(refers to physical results, not individual integrals)
NLO automation

\[
\sigma^{NLO} = \int_{m+1} \left[ d\sigma^R - d\sigma^S \right]_{\epsilon=0}^{\epsilon=0} + \int_m \left[ \frac{d\sigma^V}{\text{cancel poles}} + \int_s d\sigma^S \right]_{\epsilon=0}^{\epsilon=0} 
\]

- tree level
- virtual corrections
- real corrections
- infrared subtractions
NLO automation

After the "NLO revolution" not the bottleneck anymore

Automated tools exist at NLO

\[ \sigma^{NLO} = \int_{m+1} \left[ d\sigma^R - d\sigma^S \right]_{\epsilon=0} + \int_m \left[ \begin{array}{c} d\sigma^V \text{ cancel poles} \\ \text{analytically} \\ \int_s d\sigma^S \text{ numerically} \end{array} \right]_{\epsilon=0} \]
NLO automation

Monte Carlo program
• tree amplitudes
• infrared subtractions
• phase space integration/ event generation
• parton shower (optional)

One-loop provider
• virtual amplitude
  BLHA or custom made

all in one:
• Powheg
• Sherpa
• Herwig7/Matchbox
• Geneva
• Vincia

collection of pre-computed processes:
• MCFM
• VBF_NLO

• MG5_aMC@NLO
• Helac-NLO
• Grace
• Blackhat
• GoSam
• Madloop
• NJet
• OpenLoops
• Recola
NLO automation

one-loop reduction libraries:

unitarity-based:
- CutTools
- Samurai
- Ninja

• Ossola, Papadopoulos, Pittau
• Mastrolia, Ossola, Reiter, Tramontano
• Mastrolia, Mirabella, Peraro

tensor reduction and scalar integrals:
- LoopTools
- golem95
- PJFry
- Collier

• T. Hahn et al.
• Binoth, Guillet, GH, Reiter, von Soden
• Fleischer, Riemann, Yundin
• Denner, Dittmaier, Höfer

scalar integrals:
- OneLoop
- QCDLoop
- FF

• van Hameren
• Ellis, Zanderighi
• van Oldenborgh, Vermaseren
GoSam @ 1-loop


http://gosam.hepforge.org
Interface to Monte Carlo programs

both original Binoth-Les-Houches-Accord
and extended standards [CPC 185 (2014)]
are supported

allows combination with
different MC programs
Interface to Monte Carlo programs

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Interface to Monte Carlo programs

both original Binoth-Les-Houches-Accord and extended standards [CPC 185 (2014)] are supported

allows combination with different MC programs
Installation and usage of GoSam

installation:  installation script downloads GoSam and reduction libraries and installs everything

```
wget http://gosam.hepforge.org/gosam-installer/gosam_installer.py
chmod +x gosam_installer.py
./gosam_installer.py  [--prefix=installation_path]
```

installation script will also install FORM [J.Vermaseren et al.] and QGraf [P. Nogueira] if not present already
Installation and usage of GoSam

**installation:** installation script downloads GoSam and reduction libraries and installs everything

```bash
wget http://gosam.hepforge.org/gosam-installer/gosam_installer.py
chmod +x gosam_installer.py
./gosam_installer.py [--prefix=installation_path]
```

installation script will also install FORM [J. Vermaseren et al.] and QGraf [P. Nogueira] if not present already

**usage:** create template for input file `process.in`:

```bash
gosam.py --template process.in
```

edit input file `process.in` to generate amplitude (standalone):

```bash
gosam.py process.in
```

within BLHA:

```bash
gosam.py --olp order.lh
```

example input file:

```
# example input file:
process_name=eett
process_path=eett
in= e+, e-
out= t, t~
model= smdiag
model.options=ewchoose
order= gs, 0, 2
zero=me
one=gs, e
regularisation_scheme=dred
```

many more options available, will take defaults if not set
Examples of processes calculated with GoSam

- **GoSam + MadDipole/MadGraph/MadEvent**
  
  \[ pp \rightarrow W^+W^- + 2 \text{jets} \quad \text{[Greiner, GH, Mastrolia, Ossola, Reiter, Tramontano '12]} \]
  
  \[ pp \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1 + \text{jet} \quad \text{[Cullen, Greiner, GH '12]} \]
  
  \[ pp \rightarrow (G \rightarrow \gamma\gamma) + 1 \text{jet} \quad \text{[Greiner, GH, Reichel, von Soden-Fraunhofen '13]} \]
  
  \[ pp \rightarrow \gamma\gamma + 1, 2 \text{jets} \quad \text{[Gehrmann, Greiner, GH '13]} \]
  
  \[ pp \rightarrow HH + 2 \text{jets} \quad \text{[Dolan, Englert, Greiner, Spannowsky '13]} \]

- **GoSam + Sherpa**
  
  \[ pp \rightarrow W^+W^+ + 2 \text{jets} \quad \text{[Greiner, GH, Luisoni, Mastrolia, Ossola, Reiter, Tramontano '12]} \]
  
  \[ pp \rightarrow H + 2 \text{jets} \quad \text{[van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano '13]} \]
  
  \[ pp \rightarrow W^+W^- b\bar{b} \quad \text{[GH, Maier, Nisius, Schlenk, Winter '13]} \]
  
  \[ pp \rightarrow t\bar{t} + 0, 1 \text{jet} \quad \text{(includes shower) [Höche, Huang, Luisoni, Schönherr, Winter '13]} \]
  
  \[ pp \rightarrow H t\bar{t} + 0, 1 \text{jet} \quad \text{[van Deurzen, Luisoni, Mastrolia, Mirabella, Ossola, Peraro '13]} \]

- **GoSam + Powheg (includes shower)**
  
  \[ pp \rightarrow HW/HZ + 0, 1 \text{jet} \quad \text{[Luisoni, Nason, Oleari, Tramontano '13]} \]
  
  \[ pp \rightarrow Wb\bar{b} + 1 \text{jet} \quad \text{[Luisoni, Oleari, Tramontano '15]} \]

- **GoSam + Herwig++/Matchbox (includes shower)**
  
  \[ pp \rightarrow Z + \text{jet} \quad \text{[Bellm, Gieseke, Greiner, GH, Plätzer, Reuschle, von Soden-Fraunhofen '13]} \]

- **GoSam + MadDipole/MadGraph/MadEvent + Sherpa**
  
  \[ pp \rightarrow H + 3 \text{jets} \quad \text{[Cullen, v.Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano '13,'15]} \]
Examples of processes calculated with GoSam

• GoSam + MadDipole/MadGraph/MadEvent
  \[ pp \rightarrow W^+W^- + 2 \text{ jets} \quad \text{[Greiner, GH, Mastrolia, Ossola, Reiter, Tramontano '12]} \]
  \[ pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + \text{jet} \quad \text{[Cullen, Greiner, GH '12]} \]
  \[ pp \rightarrow (G \rightarrow \gamma\gamma) + 1 \text{ jet} \quad \text{[Greiner, GH, Reichel, von Soden-Fraunhofen '13]} \]
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  \[ pp \rightarrow H + t\bar{t} + 0, 1 \text{ jet} \quad \text{[van Deurzen, Luisoni, Mastrolia, Mirabella, Ossola, Peraro '13]} \]

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  \[ pp \rightarrow HW/HZ + 0, 1 \text{ jet} \quad \text{[Luisoni, Nason, Oleari, Tramontano '13]} \]
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• GoSam + MadDipole/MadGraph/MadEvent + Sherpa
  \[ pp \rightarrow H + 3 \text{ jets} \quad \text{[Cullen, v.Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano '13,'15]} \]

also: EW corrections, BSM [Greiner et al '15]
beyond one loop
building blocks of higher order calculations

example 2 to 2 scattering

LO: usually tree level diagrams

NLO: one loop (virtual) + extra real radiation + subtraction terms

NNLO:

double real

1-loop virtual

× single real

2-loop virtual
need efficient methods to

- generate the amplitudes
- reduce the loop amplitudes to coefficients \( \otimes \) master integrals
- calculate the master integrals

individual contributions to an amplitude (virtual/real) are usually \textit{divergent}

- requires the isolation of the singularities in epsilon
  
  (dimensional regularisation)

- \textbf{need a good subtraction method for singularities of individual contributions}
need efficient methods to

• generate the amplitudes
• reduce the loop amplitudes to coefficients $\otimes$ master integrals
• calculate the master integrals

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- reduce the loop amplitudes to coefficients \( \otimes \) master integrals
- calculate the master integrals

individual contributions to an amplitude (virtual/real) are usually *divergent*

- requires the isolation of the singularities in epsilon (dimensional regularisation)

- need a good subtraction method for singularities of individual contributions
automated 2-loop amplitudes: GoSam @ 2 loops

- Projectors to form factors
- Integral families
- GoSam.py process.rc
- Process definition

Create:
- QGRAF files
- Python, FORM files
- Qgraf, FORM, Python

Run:
- Create amplitude files
- Create Reduce files
- Create SecDec files

Diagram pictures

Numerical integration

Two-loop amplitude
credits

GoSam 2–loop

QGRAF
P. Nogueira

FORM
J. Vermaseren, J. Kuipers, T. Ueda, J. Vollinga

Reduze
C. Studerus, A. von Manteuffel

GoSam 1–loop
see above

SecDec
see later
NNLO automation

- need an efficient method to isolate and subtract infrared singularities from the double real radiation part

Five main methods:

- **Antenna subtraction**
  - Gehrmann, Gehrmann-De Ridder, NG (05)

- **$q_T$ subtraction**
  - Catani, Grazzini (07)

- **Colourful subtraction**
  - Del Duca, Somogyi, Tronsanyi
  - Czakon (10); Boughezal et al (11)

- **Stripper**
  - Boughezal, Focke, Liu, Petriello (15); Gaunt, Stahlhofen, Tackmann, Walsh (15)

Each method has its advantages and disadvantages

<table>
<thead>
<tr>
<th>Method</th>
<th>Analytic</th>
<th>FS Colour</th>
<th>IS Colour</th>
<th>Local</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>$q_T$</td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Colourful</td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Stripper</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>N-jettiness</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
antenna subtraction

\[ \text{e+e-} \rightarrow 3 \text{ jets} \quad \text{[Gehrmann-DeRidder, Gehrmann, Glover, GH '07; Weinzierl '08]} \]

\[ \text{pp} \rightarrow 2 \text{ jets} \quad \text{[Currie, Gehrmann-DeRidder, Gehrmann, Glover, Pires '13,'14]} \]

\[ \text{pp} \rightarrow \text{H+jet} \quad \text{[Chen, Gehrmann, Glover, Jaquier '14]} \]

\[ \text{pp} \rightarrow \text{t \overline{t} bar} \quad \text{[Abelof, Gehrmann-DeRidder, Maierhöfer, Pozzorini '13, '14]} \]

\[ \text{pp} \rightarrow \text{Z+jet} \quad \text{[Gehrmann-DeRidder, Gehrmann, Glover, Huss, Morgan '15]} \]

qt subtraction (colourless final states)

\[ \text{pp} \rightarrow \text{H, pp} \rightarrow \text{V, pp} \rightarrow \text{HV, pp} \rightarrow \gamma \gamma \]

[Catani, Cieri, De Florian, Ferrera, Grazzini, Tramontano '07 - '14]

\[ \text{pp} \rightarrow \text{Z} \gamma \quad \text{[Grazzini, Kallweit, Rathlev, Torre '13]} \]

\[ \text{pp} \rightarrow \text{Z Z, pp} \rightarrow \text{W+W-} \quad \text{[Cascioli, T.Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '13,'14]} \]

N-jettiness

\[ \text{pp} \rightarrow \text{H+jet} \quad \text{[Boughezal, Focke, Giele, Liu, Petriello '15]} \]

\[ \text{pp} \rightarrow \text{W+jet} \quad \text{[Boughezal, Focke, Liu, Petriello '15]} \]

\[ \text{pp} \rightarrow \text{H+V} \quad \text{[Campbell, Ellis, Williams '16]} \]

sector-improved residue subtraction

\[ \text{pp} \rightarrow \text{t \overline{t} bar} \quad \text{[Czakon, Fiedler, Mitov '13,'15]} \]

\[ \text{pp} \rightarrow \text{H+jet} \quad \text{[Boughezal, Caola, Melnikov, Petriello, Schulze '14]} \]

\[ \text{pp} \rightarrow \text{t+jet} \quad \text{[Brucherseifer, Caola, Melnikov '14]} \]
• antenna subtraction
  \( e^+e^- \rightarrow 3 \text{ jets} \) [Gehrmann-DeRidder, Gehrmann, Glover, GH ’07; Weinzierl ’08]
  \( pp \rightarrow 2 \text{ jets} \) [Currie, Gehrmann-DeRidder, Gehrmann, Glover, Pires ‘13,’14]
  \( pp \rightarrow H+\text{jet} \) [Chen, Gehrmann, Glover, Jaquier ’14]
  \( pp \rightarrow t \overline{t} \) [Abelof, Gehrmann-DeRidder, Maierhöfer, Pozzorini ‘13, ‘14]
  \( pp \rightarrow Z+\text{jet} \) [Gehrmann-DeRidder, Gehrmann, Glover, Huss, Morgan ’15]

• qt subtraction (colourless final states)
  \( pp \rightarrow H, pp \rightarrow V, pp \rightarrow HV, pp \rightarrow \gamma \gamma \)
  [Catani, Cieri, De Florian, Ferrera, Grazzini, Tramontano ’07 - ’14]
  \( pp \rightarrow Z \gamma \) [Grazzini, Kallweit, Rathlev, Tancredi ’13]
  \( pp \rightarrow Z Z, pp \rightarrow W+W- \) [Cascioli, T.Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs ’13,’14]

• N-jettiness
  \( pp \rightarrow H+\text{jet} \) [Boughezal, Focke, Giele, Liu, Petriello ’15]
  \( pp \rightarrow W+\text{jet} \) [Boughezal, Focke, Liu, Petriello ’15]
  \( pp \rightarrow H+V \) [Campbell, Ellis, Williams ’16]

• sector-improved residue subtraction
  \( pp \rightarrow t \overline{t} \) [Czakon, Fiedler, Mitov ’13,’15]
  \( pp \rightarrow H+\text{jet} \) [Boughezal, Caola, Melnikov, Petriello, Schulze ’14]
  \( pp \rightarrow t+\text{jet} \) [Brucherseifer, Caola, Melnikov ’14]

2 to 2 NNLO results are emerging rapidly!
NNLO automation

apart from double real radiation:

- need an efficient method to calculate 2-loop integrals, in particular with several mass scales

examples:
SecDec

http://secdec.hepforge.org

algorithm: T. Binoth, GH ‘00
version 1.0: J. Carter, GH ‘10
version 2.0: S. Borowka, J. Carter, GH ‘12
version 3.0: S. Borowka, GH, S. Jones, M. Kerner, J. Schlenk, T. Zirke ‘15
other public programs based on sector decomposition:

- **sector_decomposition** (uses Ginac) (only Euclidean region)  
  [Bogner, Weinzierl ’07]

  supplemented with **CSectors**  
  for construction of integrand in terms of Feynman parameters  
  [Gluza, Kajda, Riemann, Yundin ’10]

- **FIESTA** (versions 1,2,3,4) (use Mathematica, C++)  
  [A.Smirnov, V.Smirnov, Tentyukov, ’08,’09,’13,’15]
SecDec

based on method of sector decomposition
   (Hepp 66; Denner & Roth 96; Binoth & GH 00)

• factorizes poles in dim. regulator epsilon from
  * multi-loop integrals
  * multi-dimensional parameter integrals

• produces Laurent series in epsilon, coefficients will be finite parametric integrals

• integrates coefficients numerically
   uses Cuba library (T.Hahn) or NIntegrate (Wolfram Research)
   1-dim: cquad (Gonnet)
SecDec basic workflow

1a graph info

1b user-defined function

2 Feynman integral

3 iterated sector decomposition

no

multiscale?

yes

4 contour deformation

5 subtraction of poles

6 expansion in $\epsilon$

7 numerical integration

8 result

$$\sum_{m=-2L}^{n} C_m \epsilon^m$$
SecDec basic workflow

1a. graph info → 2. Feynman integral → 3. iterated sector decomposition
1b. user-defined function → 2. Feynman integral

3. iterated sector decomposition → no → 6. expansion in $\epsilon$
3. iterated sector decomposition → yes → 4. contour deformation → 4. contour deformation

4. contour deformation → 5. subtraction of poles
4. contour deformation

5. subtraction of poles → 2. Feynman integral
5. subtraction of poles

2. Feynman integral → 3. iterated sector decomposition
2. Feynman integral

3. iterated sector decomposition → no → 6. expansion in $\epsilon$
3. iterated sector decomposition

6. expansion in $\epsilon$ → 7. numerical integration
6. expansion in $\epsilon$

7. numerical integration → 8. result
7. numerical integration

8. result

 optionally on a cluster  graphics by S.Borowka
new features in SecDec-3.0

- implementation of two new decompositions strategies G1, G2 based on a geometric algorithm ([J. Schlenk], inspired by Kaneko/Ueda ’10)
- uses Normaliz (for triangulation) (Bruns, Ichim, Römer, Söger)

→ guaranteed to stop, produces less sectors than original strategy X

<table>
<thead>
<tr>
<th>Diagram</th>
<th>Strategy X</th>
<th>Strategy G1</th>
<th>Strategy G2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>282 sectors 1s</td>
<td>266 sectors 8s</td>
<td>166 sectors 4s</td>
</tr>
<tr>
<td></td>
<td>368 sectors 1s</td>
<td>360 sectors 9s</td>
<td>235 sectors 5s</td>
</tr>
<tr>
<td></td>
<td>548 sectors 3s</td>
<td>506 sectors 15s</td>
<td>304 sectors 4s</td>
</tr>
<tr>
<td></td>
<td>infinite recursion</td>
<td>72 sectors 5s</td>
<td>76 sectors 1s</td>
</tr>
<tr>
<td></td>
<td>27336 sectrs 5510s</td>
<td>32063 sectrs 11856s</td>
<td>27137 sectrs 443s</td>
</tr>
</tbody>
</table>
new features in SecDec-3.0

• improved user interface → easy input files, custom definition of kinematics

• propagators with zero or negative powers are possible
  → easy interface to reduction programs

• linear propagators can be treated

• usage on a cluster facilitated

• speed improvements

• option to use numerical integrators from Mathematica

• complex masses
coming soon:

algebraic part in python

new IBP method

numerical part on GPU

speedup by sampling adjustment for (sub-)dominant sectors

SecDec as a library to be linked to any amplitude calculation

S. Borowka, GH, S. Jahn, M. Kerner, S. Jones, J. Schlenk, T. Zirke
(Multi-)Loop integral repository

Loopedia
AN EASILY SEARCHABLE DATABASE OF FEYNMAN GRAPHS AND FEYNMAN INTEGRALS

Loopedia

Name proposed by Sophia Borowka

Idea

Have a database containing Feynman graphs that is easily searchable, provides links to literature, and ideally also explicit e-expansions accessible in well-defined, uniform, customizable formats.

Here is the Online test version of Loopedia  (Viktor Papara)

Please contribute your thoughts to the Mindmap. More detailed suggestions can be collected on the Ideas page.

Join
application to loop integrals with several mass scales

example $gg \rightarrow HH$ : 4 independent scales $s_{12}, s_{23}, m_H, m_t$

Leading Order already involves 1-loop diagrams
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Example \( gg \rightarrow HH \): 4 independent scales \( s_{12}, s_{23}, m_H, m_t \)

NLO \((= 2 \text{ loops})\):

(most) 2-loop diagrams not known analytically with full mass dependence
examples of 2-loop box diagrams
results in the literature so far

**LO with full heavy quark mass dependence**

Glover, van der Bij '88, Plehn, Spira, Zerwas '96

**NLO in $m_t \to \infty$ limit (EFT):** Dawson, Dittmaier, Spira '98 (HPAIR)

- supplemented with $1/m_t$ expansion: $\pm 10\%$
  - Grigo, Hoff, Melnikov, Steinhauser '13, '15
- full mass dependence in NLO real radiation part and matching to parton shower
  - Frederix, Hirschi, Mattelaer, Maltoni, Torrielli, Vryonidou, Zaro '14;
    Maltoni, Vryonidou, Zaro '14

**NNLO in $m_t \to \infty$ limit:**

De Florian, Mazzitelli '13

- including all matching coefficients
  - Grigo, Melnikov, Steinhauser '14
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- soft gluon resummation NNLL matched to NNLO
  - De Florian, Mazzitelli '15
+ lots of phenomenological studies

Baglio, Barr, Dolan, Englert, Ferreira de Lima, Goncalves-Netto, Greiner, Gröber, Krauss, Maierhöfer, Maltoni, Mühlleitner, Papaefstathiou, Spannowsky, Spira, Thompson, Vryonidou, Zaro, Zurita, ... '12,'13,'14,'15
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calculation of the 2-loop amplitude


• use GoSam-2loop to generate the amplitude
• reduction with Reduze2 [C. Studerus, A. von Manteuffel]

(Fire5 [A.V. Smirnov], LiteRed [R.N. Lee])

→ 8 integral families with 9 propagators each
→ partly finite basis

• produce input files for SecDec with GoSam-2loop
• independent implementation with Qgraf, Reduze2, Mathematica [M. Kerner]
• evaluate integrals (SecDec) & coefficients
# 2-loop amplitude

<table>
<thead>
<tr>
<th></th>
<th>1-loop</th>
<th>2-loop</th>
</tr>
</thead>
<tbody>
<tr>
<td>direct</td>
<td>63</td>
<td>~10000</td>
</tr>
<tr>
<td>use symmetries</td>
<td>21</td>
<td>~1600</td>
</tr>
<tr>
<td>use IBP’s</td>
<td>8</td>
<td>~300</td>
</tr>
</tbody>
</table>

# of sampling points determined by

- contribution to amplitude
- time per sampling point

Target accuracy set at amplitude level
examples of master integrals

a planar 7 propagator integral:

\[ m_H = 125 \text{ GeV} \]
\[ m_t = 173 \text{ GeV} \]
a non-planar 7 propagator integral:

\[ I = \frac{P_{-1}}{\varepsilon} + P_0 \]

\[ m_H = 125 \text{ GeV} \]
\[ m_t = 173 \text{ GeV} \]
Summary and Outlook

• LHC Run II and beyond is a precision game!
• NNLO techniques are advancing rapidly
  → automation feasible!
• tools towards this aim presented here:
  ➡ GoSam  GoSam-1loop: public, 2-loop extension underway
  ➡ SecDec
  ✓ can do integrals with several mass scales numerically
  ✓ is being made ready for large scale phenomenological applications
try out the tools!

http://gosam.hepforge.org

http://secdec.hepforge.org
SecDec can also do

- integrals with inverse propagators (numerators), e.g.

\[ I_{NP2B}^{1,0} = \int d^D p_1 \int d^D p_2 \frac{(p_1 + k_1)^2}{(p_2 - m_t^2)((p_2 + k_1 + k_2)^2 - m_t^2)((p_2 + k_1 + k_2 + k_3)^2 - m_t^2)(p_2 - p_1)^2(p_2 - p_1 + k_1)^2(p_1^2 - m_t^2)((p_1 + k_2)^2 - m_t^2)} \]

- integrals with contracted tensor numerators, e.g.

\[ I_{NP2B}^{k2} = \int d^D p_1 \int d^D p_2 \frac{(p_1 \cdot k_1)(p_2 \cdot k_3)}{(p_2 - m_t^2)((p_2 + k_1 + k_2)^2 - m_t^2)((p_2 + k_1 + k_2 + k_3)^2 - m_t^2)(p_2 - p_1)^2(p_2 - p_1 + k_1)^2(p_1^2 - m_t^2)((p_1 + k_2)^2 - m_t^2)} \]

→ no need for a scalar integral basis