Pushing the precision frontier in Collider Physics

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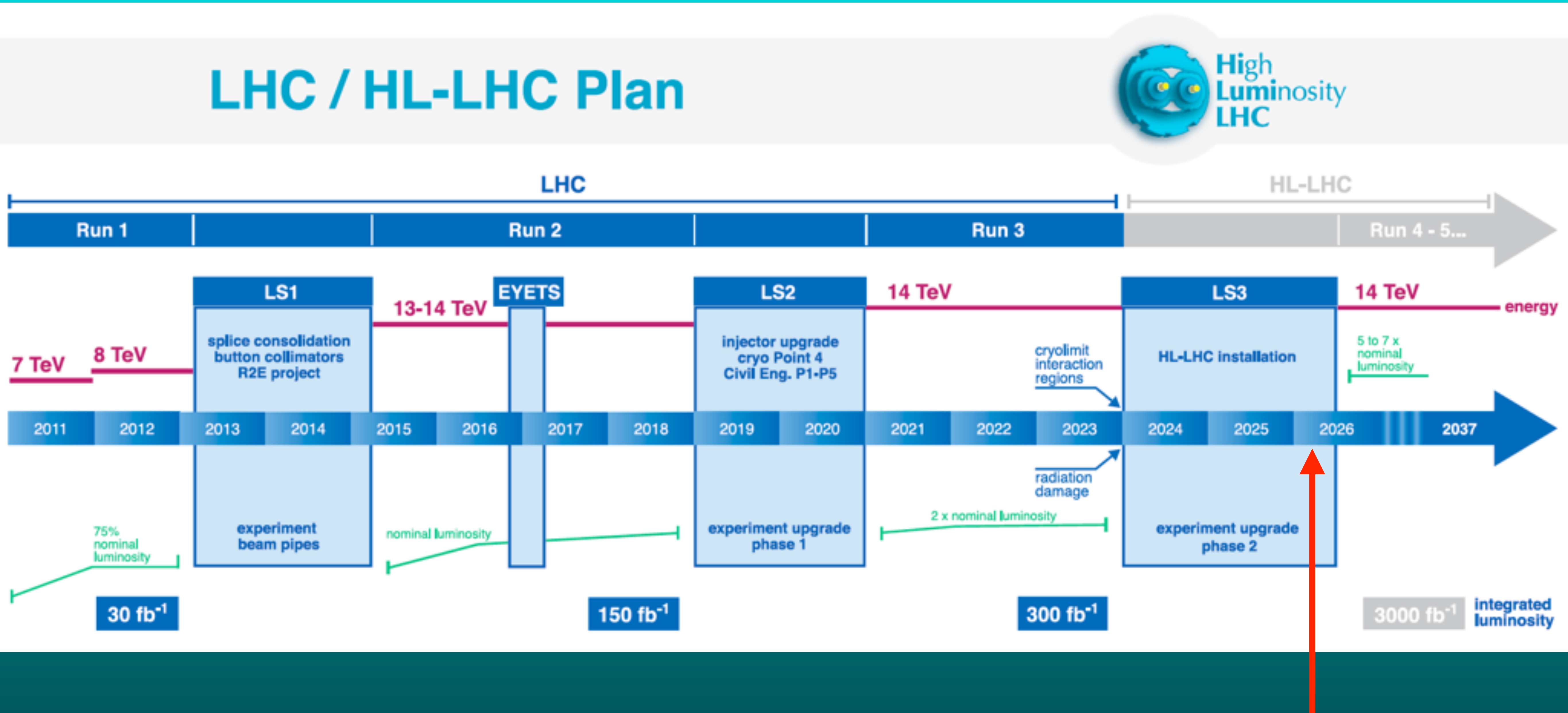
The experimental frontier(s)



Linear Collider?

The precision frontier

- LHC Run 2 and beyond:

  high statistics → 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) are required to match the experimental precision

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tedious calculations, automation desired !

current status:

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pretty advanced

NLO matched to parton shower is new state of the art

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pretty advanced

NLO matched to parton shower is new state of the art

- NNLO: still a long way to automation

status about 10 years ago:

Les Houches 05: NLO wishlist for LHC

process $(V \in \{Z, W, \gamma\})$	background to
1. $pp \to V\,V$ jet	$t\bar{t}H$, new physics
2. $pp \to H + 2$ jets	H production by VBF
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
5. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to V\,V + 2$ jets	VBF$\to H \to VV$
7. $pp \to V + 3$ jets	various new physics signatures
8. $pp \to V\,V\,V$	SUSY trilepton

Les Houches wishlist 2007

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [3]; Campbell/Ellis/Zanderighi [4] and Binoth/Karg/Kauer/Sanguinetti (in progress)
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [5]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [6,7]
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello [8] and WWZ by Hankele/Zeppenfeld [9]
Calculations remaining from Les Houches 2005	
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$
5. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$
6. $pp \to VV\,b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
7. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [10–12]
8. $pp \to V$+3jets	various new physics signatures
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Higgs and new physics signatures
Calculations beyond NLO added in 2007	
10. $gg \to W^*W^*$ $\mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
11. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
12. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
13. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

Les Houches wishlist 2009

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3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [11] and WWZ by Hankele/Zeppenfeld [12] (see also Binoth/Ossola/Papadopoulos/Pittau [13])
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini [14,15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16]
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]
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NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	$q\bar{q}$ channel calculated by Golem collaboration [23]
NLO calculations added to list in 2009	
10. $pp \to V$+4 jets	top pair production, various new physics signatures
11. $pp \to Wb\bar{b}j$	top, new physics signatures
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
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Les Houches 2011:

NLO QCD wishlist retired

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2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [31]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [32, 33] Interference QCD-EW in VBF channel [34, 35]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [36] and WWZ by Hankele/Zeppenfeld [37], see also Binoth/Ossola/Papadopoulos/Pittau [38] VBFNLO [39, 40] meanwhile also contains $WWW, ZZW, WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma, \gamma\gamma\gamma$ $WZj, W\gamma j, \gamma jj, W\gamma\gamma j$
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini [41, 42] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [43]
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7. $pp \to VV\,b\bar{b}$,	Pozzorini et al.[25],Bevilacqua et al.[23]
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Bevilacqua, Worek 2012

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↓

"NLO revolution"

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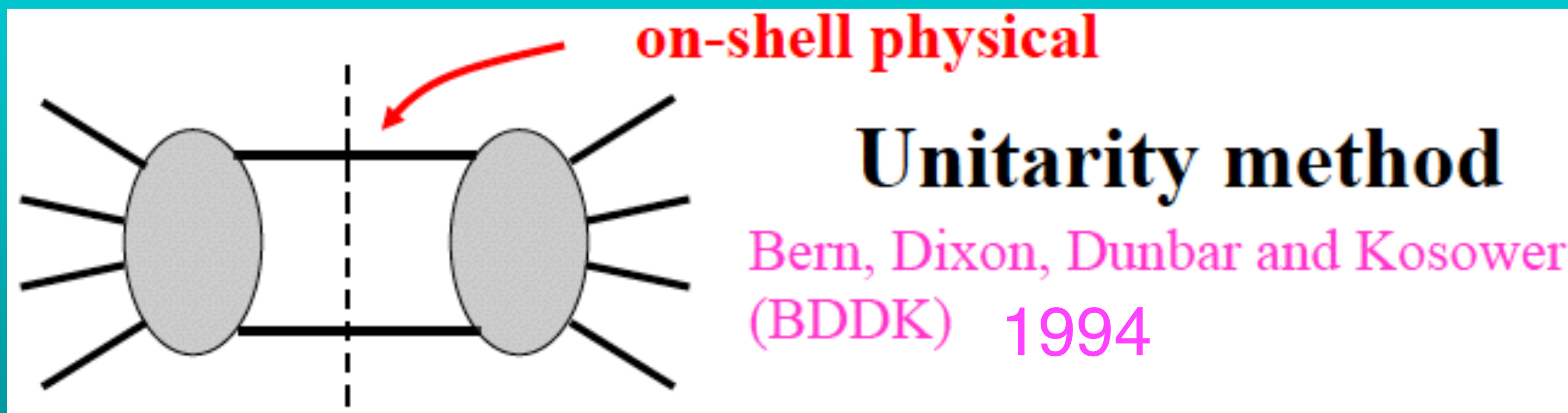
Bevilacqua, Worek 2012

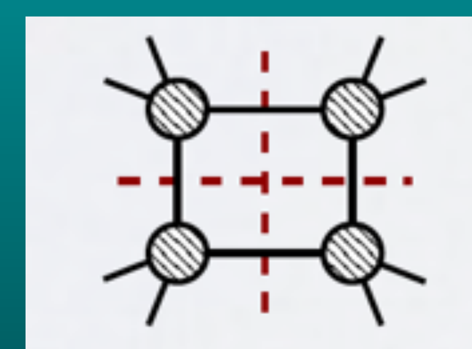
what caused the “NLO revolution”?

gauge dependent off-shell states introduce “spurious” terms

→ try to use on-shell quantities as building blocks

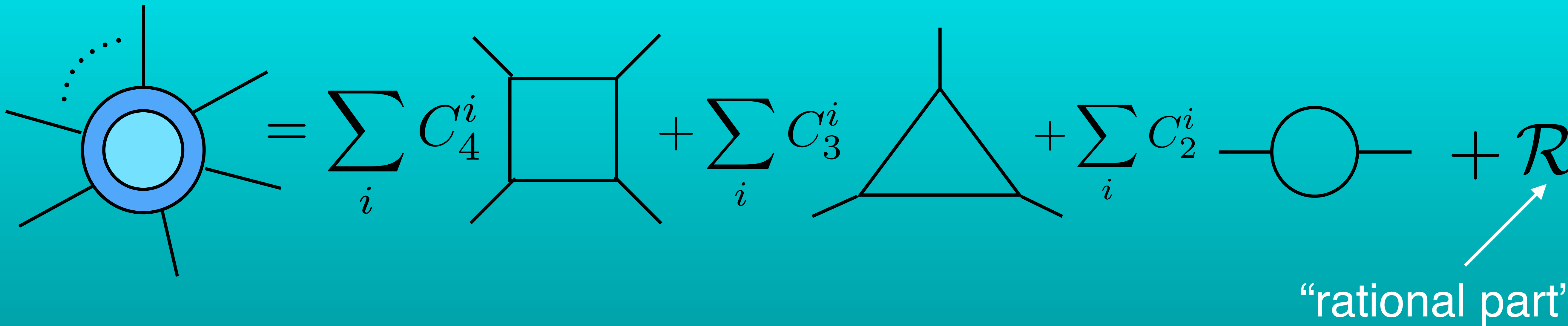


- construct N-point one-loop amplitudes from tree amplitudes
  Bern, Dixon, Kosower ‘98
- use of complex momenta in generalised cuts
  Britto, Cachazo, Feng ’04



- 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:



“master integrals”: boxes, triangles, bubbles

most complicated functions are dilogarithms

C_n^i can be obtained by numerical reduction at integrand level

automated tools:
- CutTools Ossola, Papadopoulos, Pittau
- Samurai Mastrolia, Ossola, Reiter, Tramontano, van Deurzen
- Ninja Mastrolia, Mirabella, **Peraro**

But …

… fulfilled wishes create more wishes …

Les Houches 2013: Higgs

Process	State of the Art	Desired
H	$d\sigma$ @ 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	$d\sigma$ @ 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
H + j	$d\sigma$ @ NNLO QCD (g only) and finite-quark-mass effects @ LO QCD and LO EW	$d\sigma$ @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
H + 2j	σ_{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	$d\sigma$(VBF) @ NNLO QCD + NLO EW $d\sigma$(gg) @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW σ_{tot}(gg) @ NLO QCD (infinite-m_t limit)	with $H \to b\bar{b}$ @ same accuracy $d\sigma$(gg) @ NLO QCD with full m_t/m_b dependence
tH and $\bar{t}$H	$d\sigma$(stable top) @ LO QCD	$d\sigma$(top decays) @ NLO QCD and NLO EW
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD and NLO EW
$gg \to HH$	$d\sigma$ @ NLO QCD (leading m_t dependence) $d\sigma$ @ NNLO QCD (infinite-m_t limit)	$d\sigma$ @ NLO QCD with full m_t/m_b dependence

Les Houches 2013: heavy quarks and jets

Process	State of the Art	Desired
$t\bar{t}$	σ_{tot}(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t} + j(j)$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t} + Z$	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW
$\gamma + j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW

Les Houches 2013: vector bosons

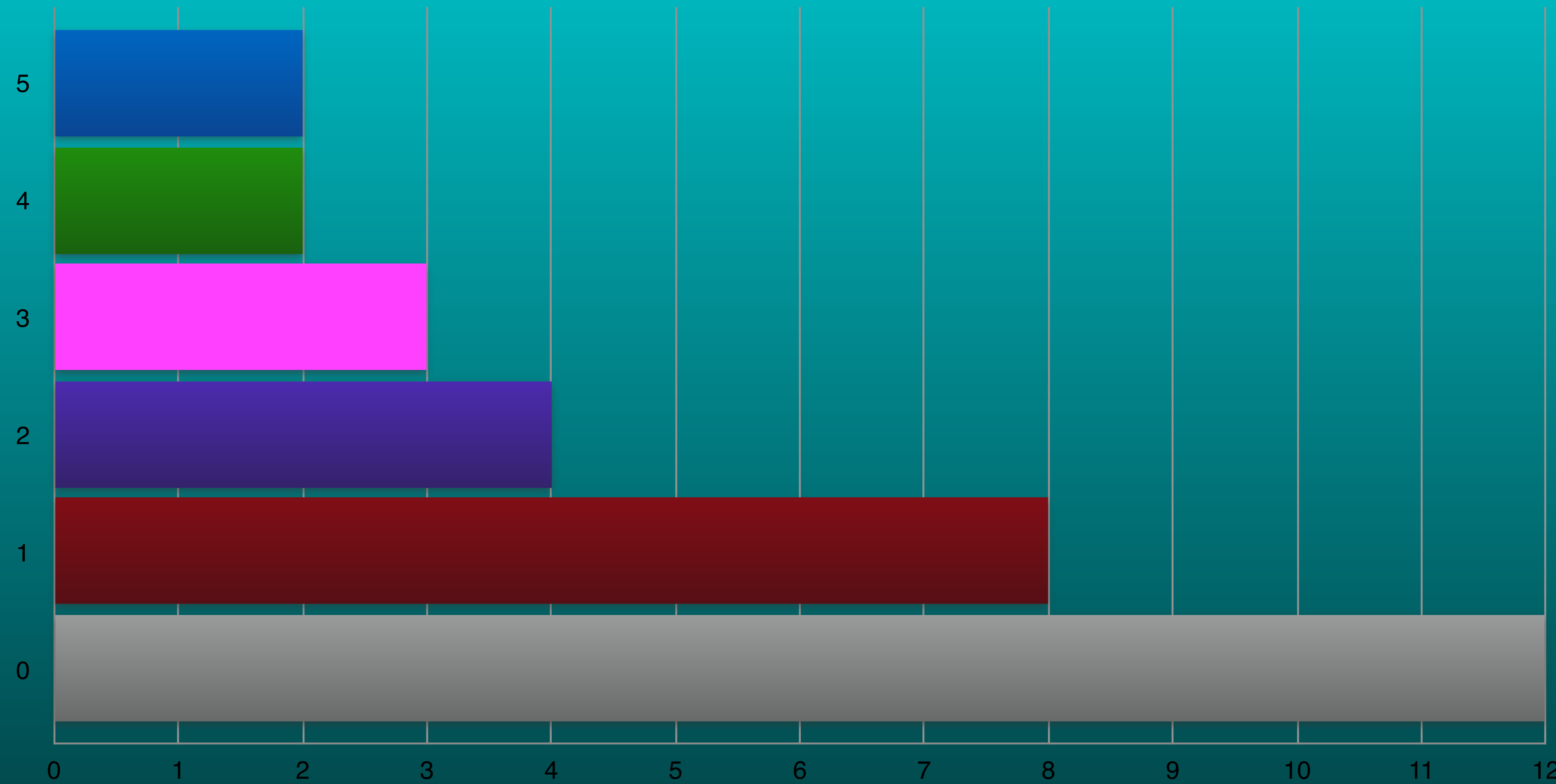
Process	State of the Art	Desired
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD and @ NNLO QCD+EW NNLO+PS
$\mathrm{V+j(j)}$	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW
$\mathrm{VV'}$	$d\sigma$(V decays) @ NLO QCD $d\sigma$(on-shell V decays) @ NLO EW	$d\sigma$(decaying off-shell V) @ NNLO QCD + NLO EW
$gg \to \mathrm{VV}$	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD
$\mathrm{V}\gamma$	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW
$\mathrm{Vb\bar{b}}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW, massless b
$\mathrm{VV'}\gamma$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
$\mathrm{VV'V''}$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
$\mathrm{VV'+j}$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
$\mathrm{VV'+jj}$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
$\gamma\gamma$	$d\sigma$ @ NNLO QCD + NLO EW	q_T resummation at NNLL matched to NNLO

measure of complexity

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

complexity does not scale linearly!

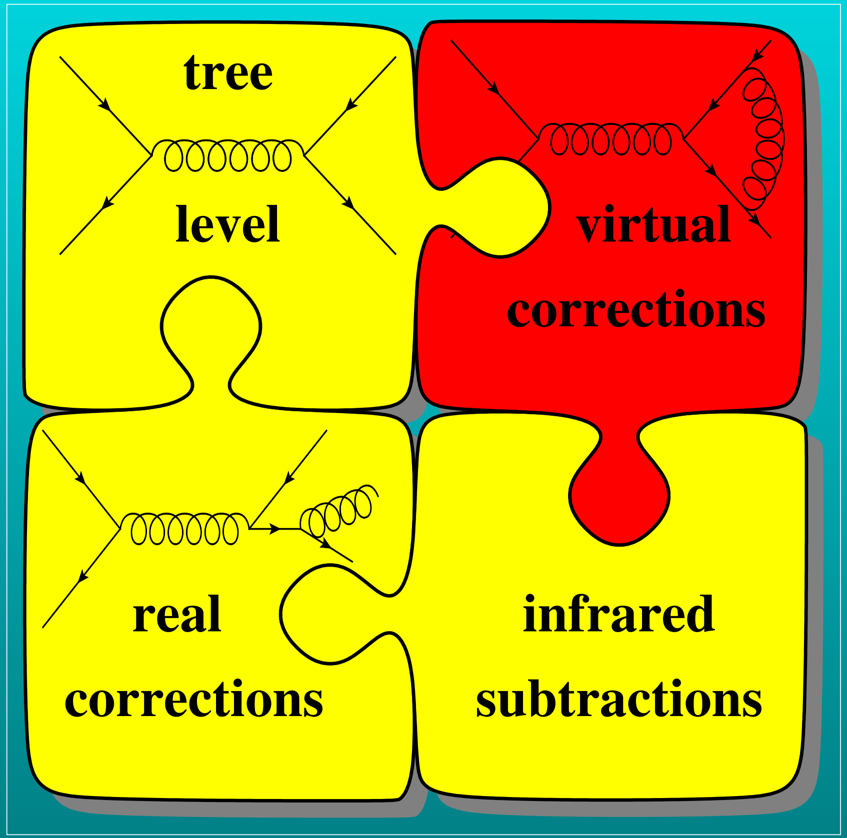
loops



legs

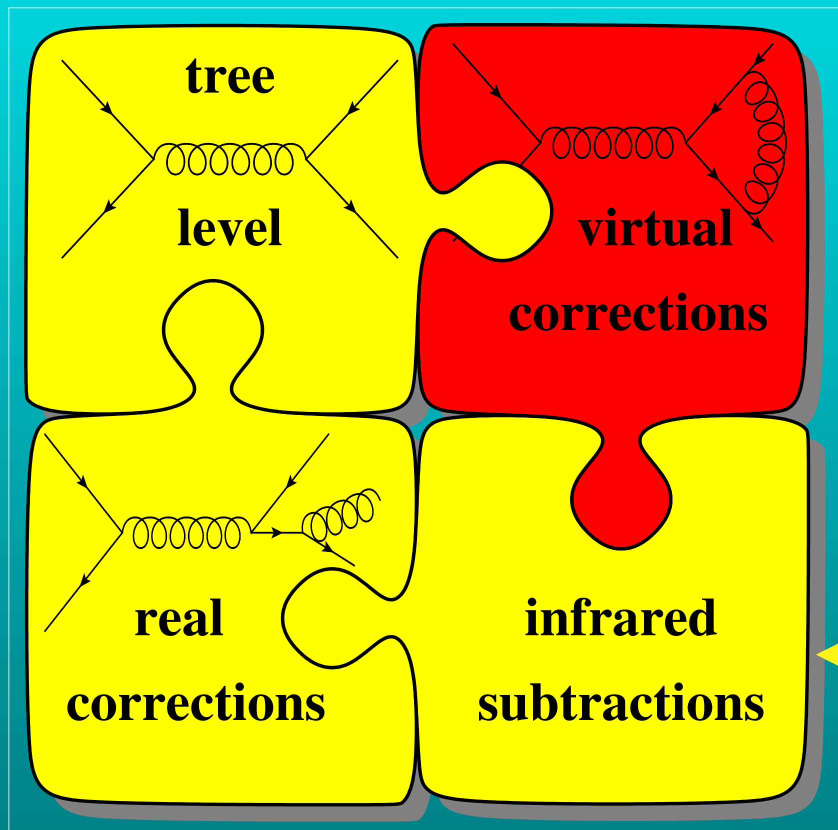
(refers to physical results, not individual integrals)

NLO automation



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

NLO automation



after the “NLO revolution” not the bottleneck anymore

automated tools exist at NLO

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

NLO automation

Monte Carlo program

- tree amplitudes
- infrared subtractions
- phase space integration/ event generation
- parton shower (optional)

BLHA or custom made

One-loop provider

- virtual amplitude

- Powheg
- Sherpa
- Herwig7/Matchbox
- Geneva
- Vincia

all in one:

- MG5_aMC@NLO
- Helac-NLO
- Grace

- Blackhat
- GoSam
- Madloop
- NJet
- OpenLoops
- Recola

collection of pre-computed processes:

- MCFM
- VBF_NLO

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NLO automation

one-loop reduction libraries:

unitarity-based:

- CutTools Ossola, Papadopoulos, Pittau
- Samurai Mastrolia, Ossola, Reiter, Tramontano
- Ninja Mastrolia, Mirabella, Peraro

tensor reduction and scalar integrals:

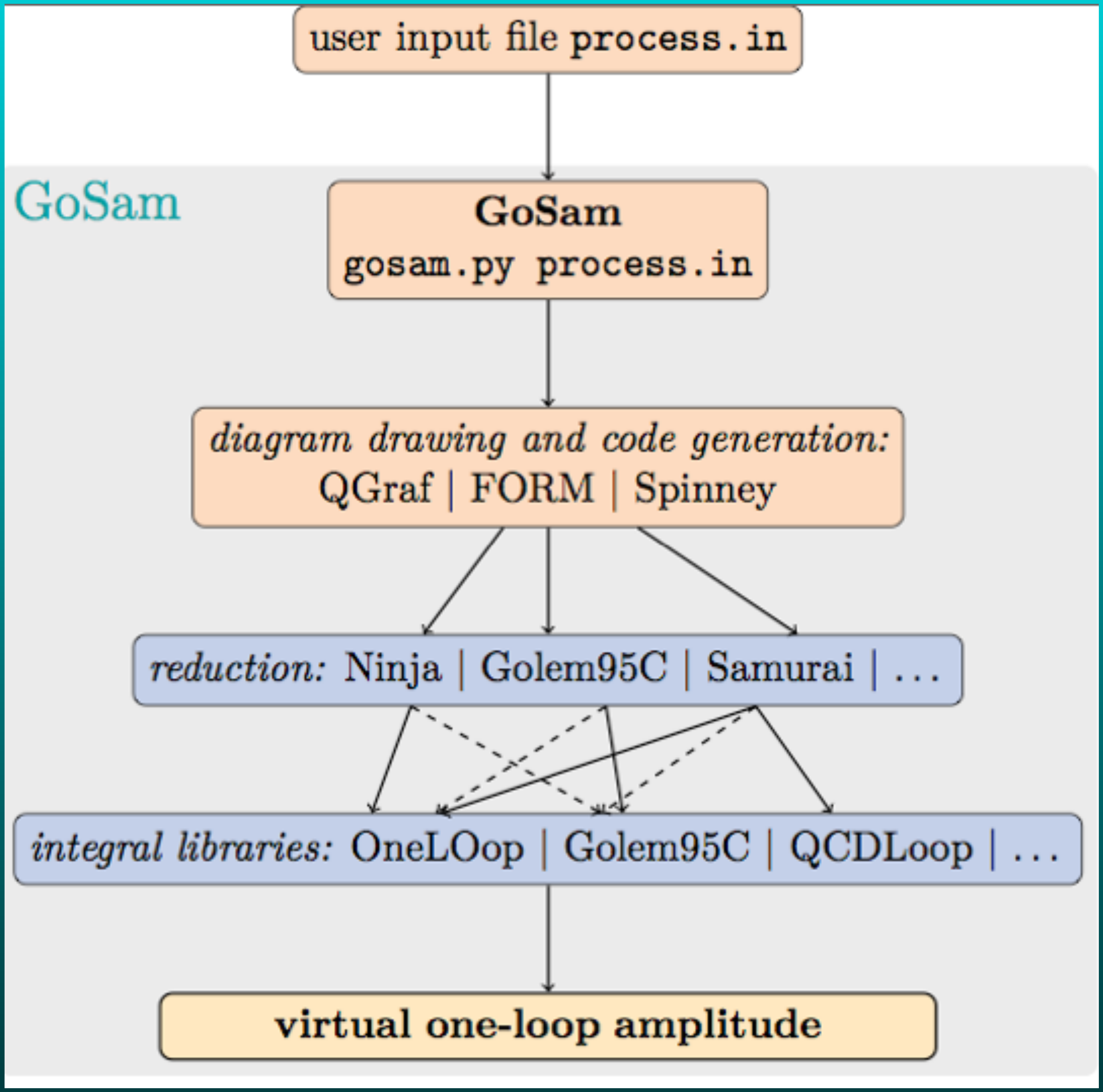
- LoopTools T.Hahn et al.
- golem95 Binoth, Guillet, GH, Reiter, von Soden
- PJFry Fleischer, Riemann, Yundin
- Collier Denner, Dittmaier, Hofer

scalar integrals:

- OneLoop van Hameren
- QCDLoop Ellis, Zanderighi
- FF van Oldenborgh, Vermaseren

GoSam @ 1-loop

T. Binoth, G.Cullen, H.van Deurzen, N.Greiner, GH, S.Jahn, G.Luisoni, P. Mastrolia, E.Mirabella, G. Ossola, T. Peraro, T. Reiter, J. Reichel, J. Schlenk, J.F. von Soden-Fraunhofen, F. Tramontano



http://gosam.hepforge.org

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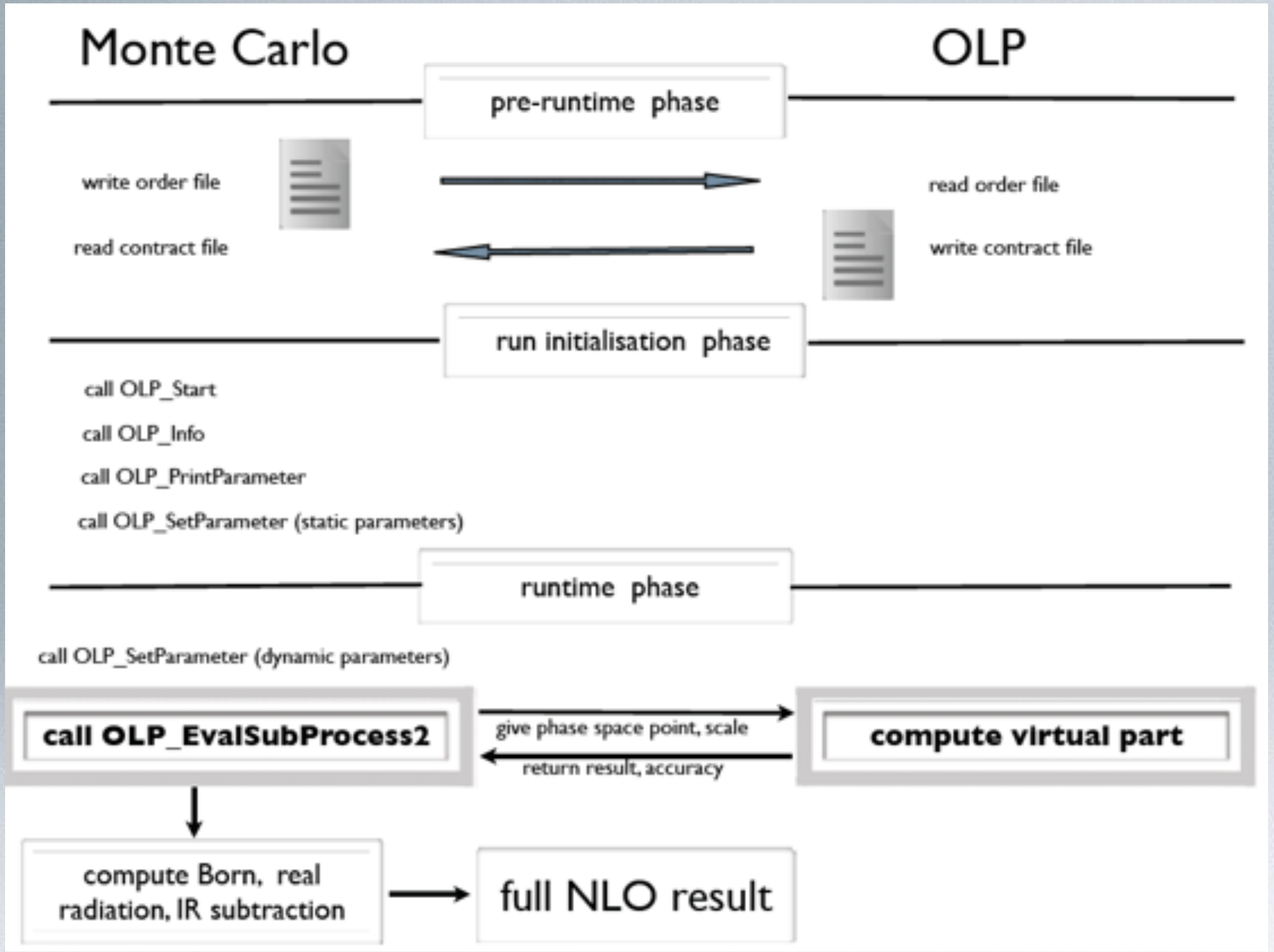
Interface to Monte Carlo programs

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



allows combination with different MC programs

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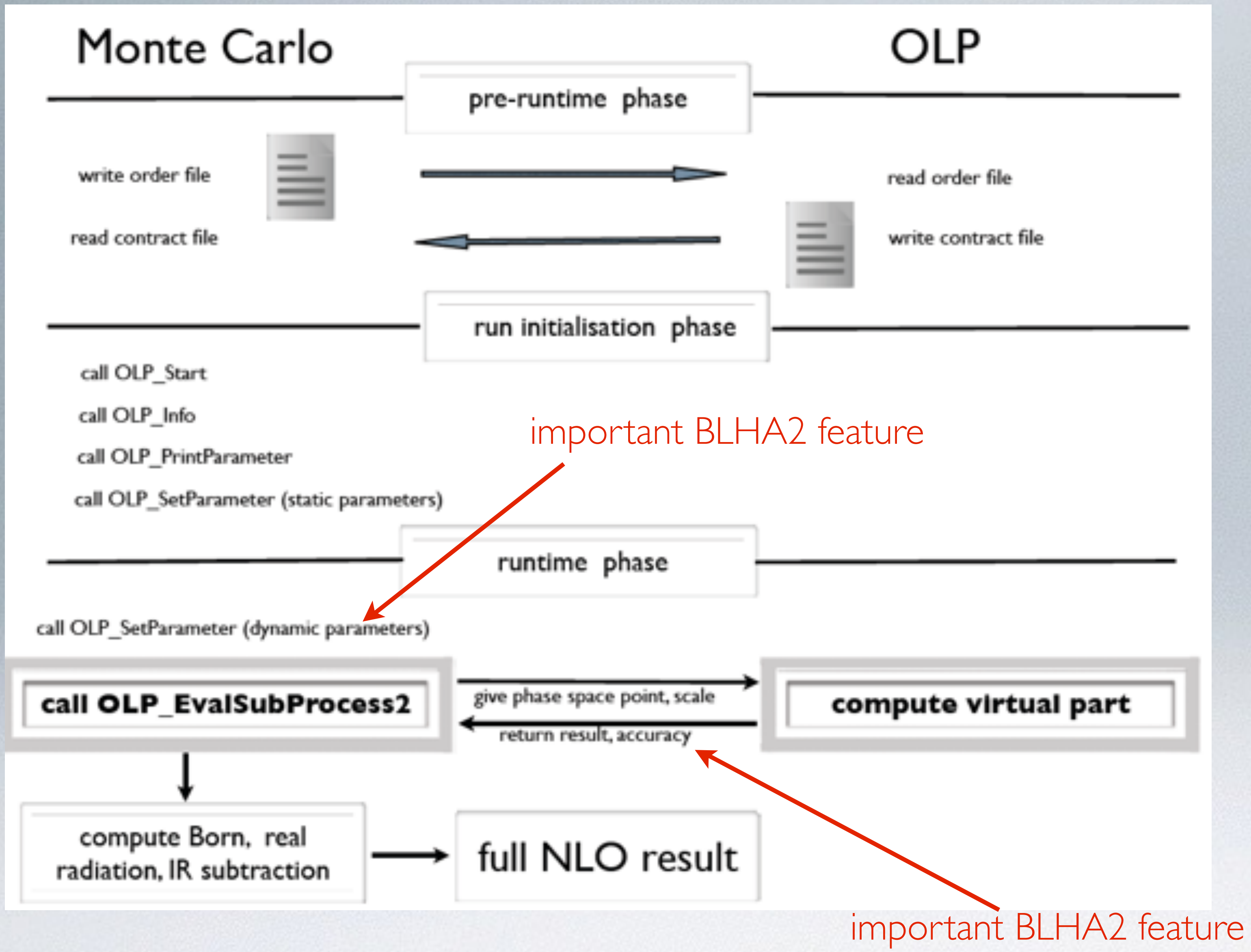

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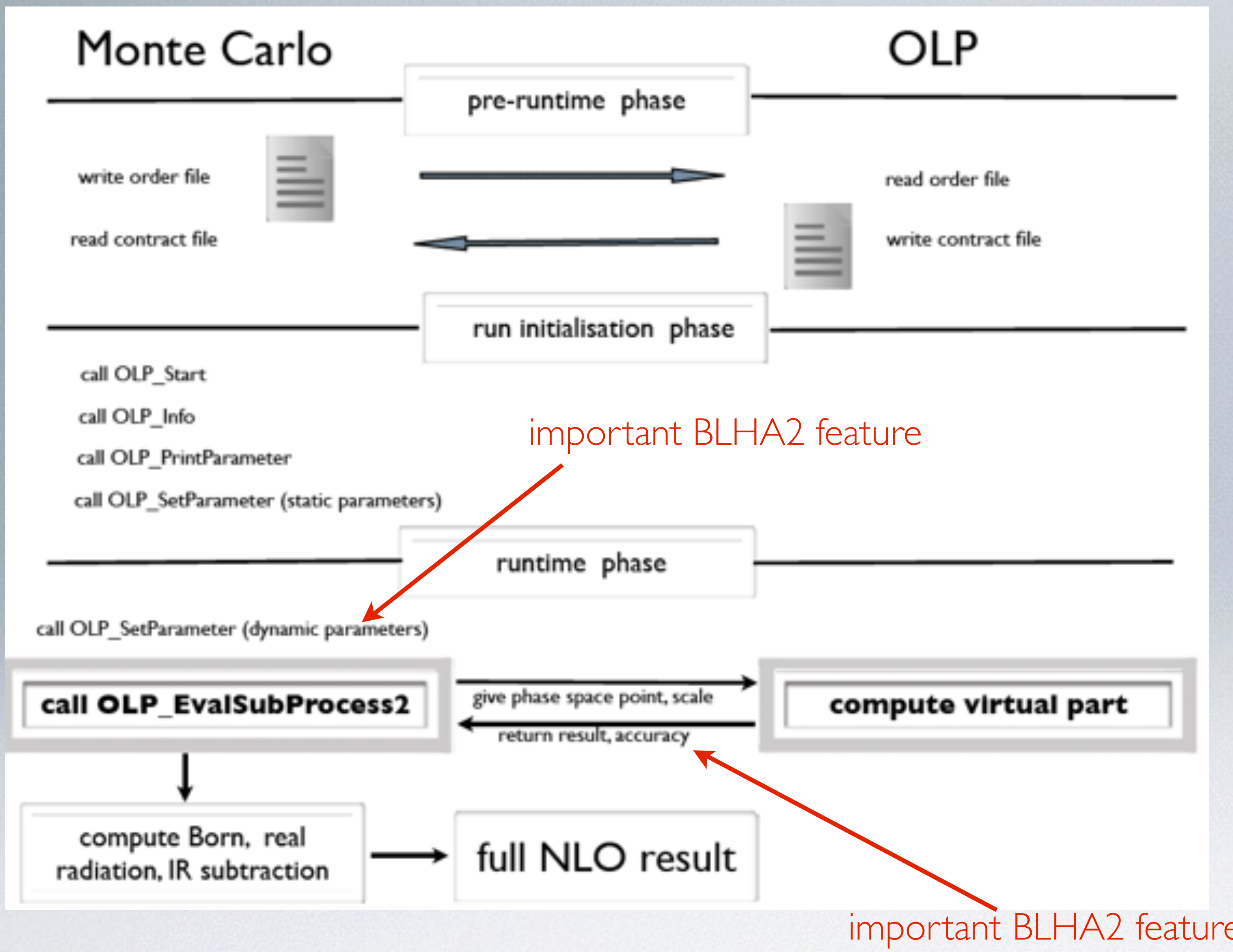

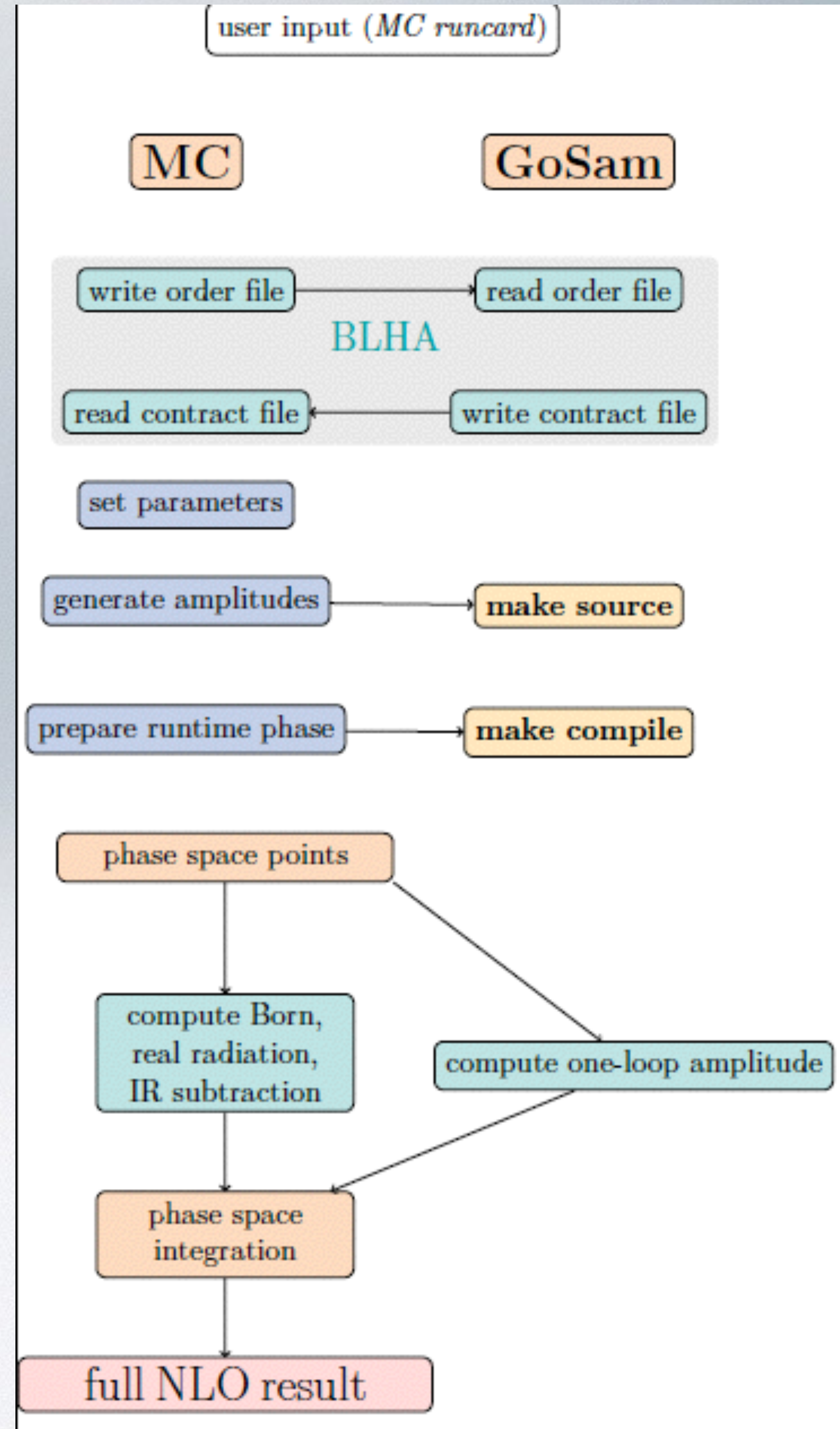

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Installation and usage of GoSam

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

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usage: create template for input file process.in:

gosam.py --template process.in

edit input file process.in

to generate amplitude (standalone):

gosam.py process.in

within BLHA:

gosam.py --olp order.lh

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

$pp \to W^+W^- + 2\, jets$ [Greiner, GH, Mastrolia, Ossola, Reiter, Tramontano '12]

$pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 + jet$ [Cullen, Greiner, GH '12]

$pp \to (G \to \gamma\gamma) + 1\, jet$ [Greiner, GH, Reichel, von Soden-Fraunhofen '13]

$pp \to \gamma\gamma + 1, 2\, jets$ [Gehrmann, Greiner, GH '13]

$pp \to HH + 2\, jets$ [Dolan, Englert, Greiner, Spannowsky '13]

- GoSam + Sherpa

$pp \to W^+W^+ + 2\, jets$ [Greiner, GH, Luisoni, Mastrolia, Ossola, Reiter, Tramontano '12]

$pp \to H + 2\, jets$ [van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano '13]

$pp \to W^+W^-\, b\bar{b}$ [GH, Maier, Nisius, Schlenk, Winter '13]

$pp \to t\bar{t} + 0, 1\, jet$ (includes shower) [Höche, Huang, Luisoni, Schönherr, Winter '13]

$pp \to H\, t\bar{t} + 0, 1\, jet$ [van Deurzen, Luisoni, Mastrolia, Mirabella, Ossola, Peraro '13]

- GoSam + Powheg (includes shower)

$pp \to HW/HZ + 0, 1\, jet$ [Luisoni, Nason, Oleari, Tramontano '13]

$pp \to W b\bar{b} + 1\, jet$ [Luisoni, Oleari, Tramontano '15]

- GoSam + Herwig++/Matchbox (includes shower)

$pp \to Z + jet$ [Bellm, Gieseke, Greiner, GH, Plätzer, Reuschle, von Soden-Fraunhofen ‘13]

- GoSam + MadDipole/MadGraph/MadEvent + Sherpa

$pp \to H + 3\, jets$ [Cullen, v.Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano ’13,’15]

Examples of processes calculated with GoSam

also: EW corrections, BSM [Greiner et al '15]

- GoSam + MadDipole/MadGraph/MadEvent

$pp \to W^+W^- + 2\,jets$ [Greiner, GH, Mastrolia, Ossola, Reiter, Tramontano '12]

$pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 + jet$ [Cullen, Greiner, GH '12]

$pp \to (G \to \gamma\gamma) + 1\,jet$ [Greiner, GH, Reichel, von Soden-Fraunhofen '13]

$pp \to \gamma\gamma + 1, 2\,jets$ [Gehrmann, Greiner, GH '13]

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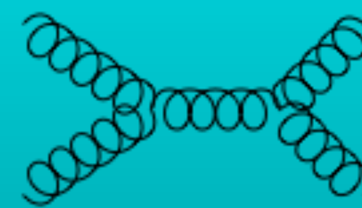
$pp \to H + 3\,jets$ [Cullen, v.Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano '13,'15]

beyond one loop

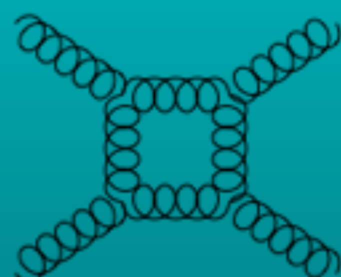
building blocks of higher order calculations

example 2 to 2 scattering

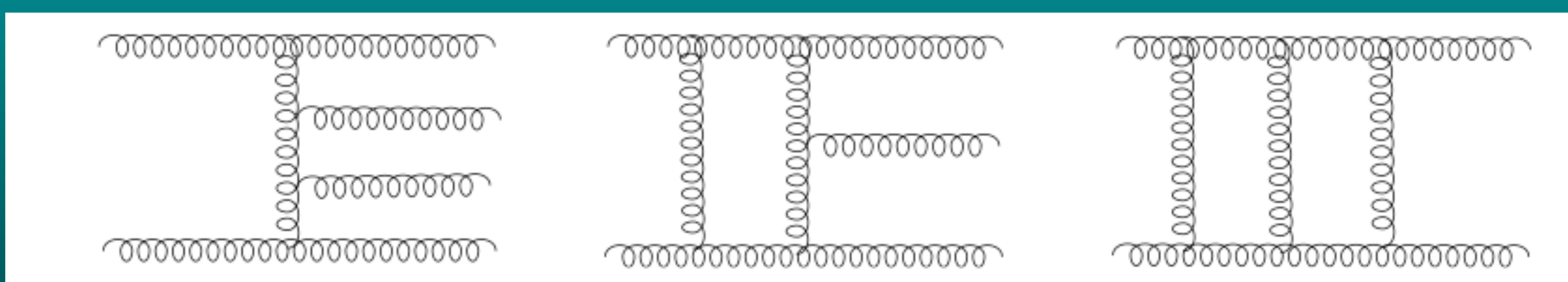
LO: usually tree level diagrams



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 ***divergent***

- requires the isolation of the singularities in epsilon

  (dimensional regularisation)

- need a good subtraction method for singularities of individual contributions

need efficient methods to

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SecDec

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

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(dimensional regularisation)

SecDec

- need a good subtraction method for singularities of individual contributions

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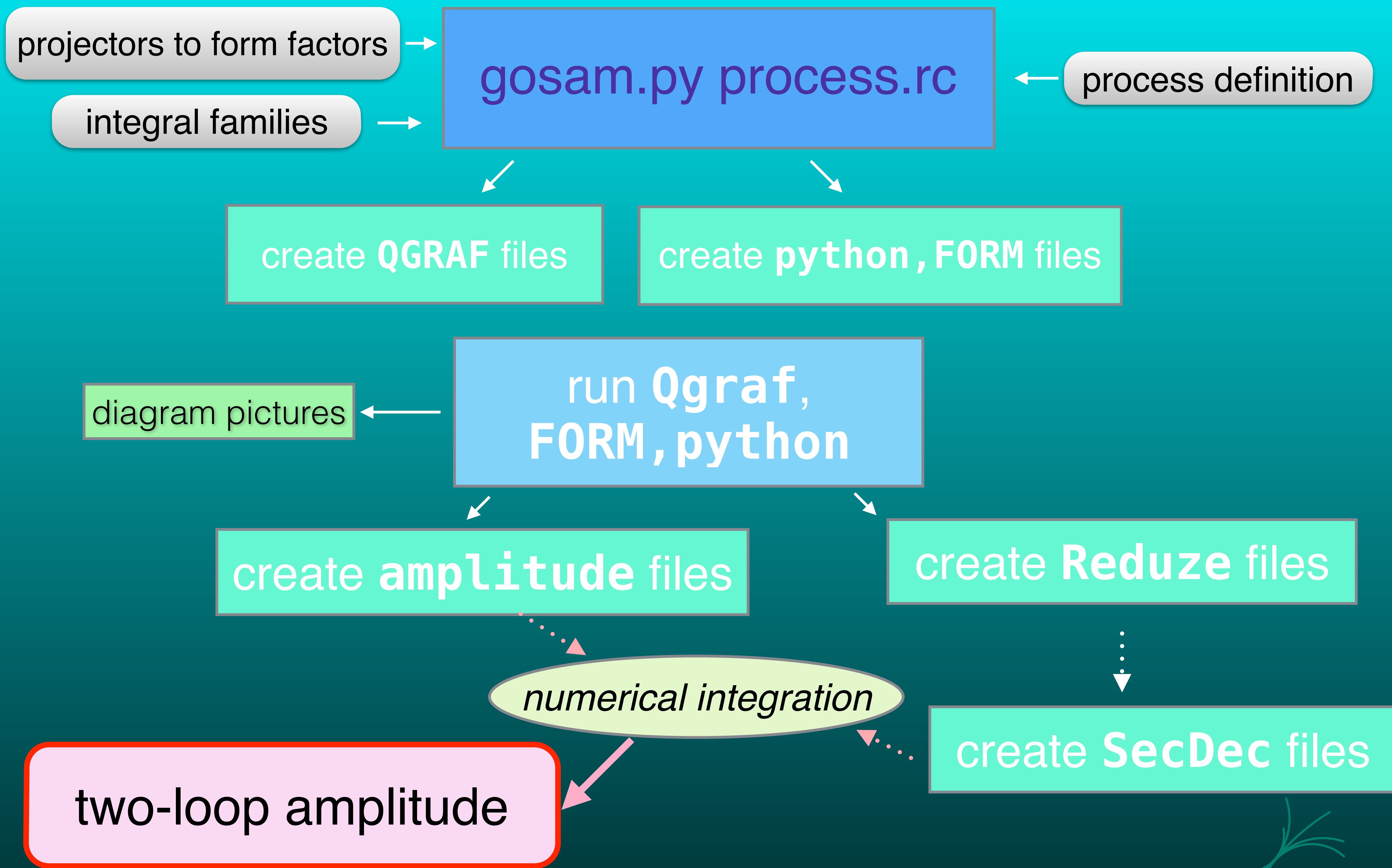
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

automated 2-loop amplitudes: GoSam @ 2 loops



credits

GoSam 2-loop N.Greiner, GH, S.Jahn, S.Jones, M.Kerner, P. Mastrolia, J.Schlenk, T.Zirke

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
- Stripper — Czakon (10); Boughezal et al (11)
- N-jettiness subtraction — Boughezal, Focke, Liu, Petriello (15); Gaunt, Stahlhofen, Tackmann, Walsh (15)

Each method has its advantages and disadvantages

	Analytic	FS Colour	IS Colour	Local
Antenna	✓	✓	✓	✗
qT	✓	✗	✓	✓
Colourful	✓	✓	✗	✓
Stripper	✗	✓	✓	✓
N-jettiness	✓	✓	✓	✓

N.Glover, Amplitudes 2015

- antenna subtraction

  e+e- $\rightarrow$ 3 jets [Gehrmann-DeRidder, Gehrmann, Glover, GH ’07; Weinzierl ’08]

  pp $\rightarrow$ 2 jets [Currie, Gehrmann-DeRidder, Gehrmann, Glover, Pires ‘13,’14]

  pp $\rightarrow$ H+jet [Chen, Gehrmann, Glover, Jaquier ’14]

  pp $\rightarrow$ t tbar [Abelof, Gehrmann-DeRidder, Maierhöfer, Pozzorini ‘13, ‘14]

  pp $\rightarrow$ Z+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 γ [Grazzini, Kallweit, Rathlev, Torre ’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+jet [Boughezal, Focke, Giele, Liu, Petriello ’15]

  pp $\rightarrow$ W+jet [Boughezal, Focke, Liu, Petriello ’15]

  pp $\rightarrow$ H+V [Campbell, Ellis, Williams ’16]

- sector-improved residue subtraction

  pp $\rightarrow$ t tbar [Czakon, Fiedler, Mitov ’13,’15]

  pp $\rightarrow$ H+jet [Boughezal, Caola, Melnikov, Petriello, Schulze ’14]

  pp $\rightarrow$ t+jet [Brucherseifer, Caola, Melnikov ’14]

- antenna subtraction

  e+e- $\to$ 3 jets [Gehrmann-DeRidder, Gehrmann, Glover, GH '07; Weinzierl '08]

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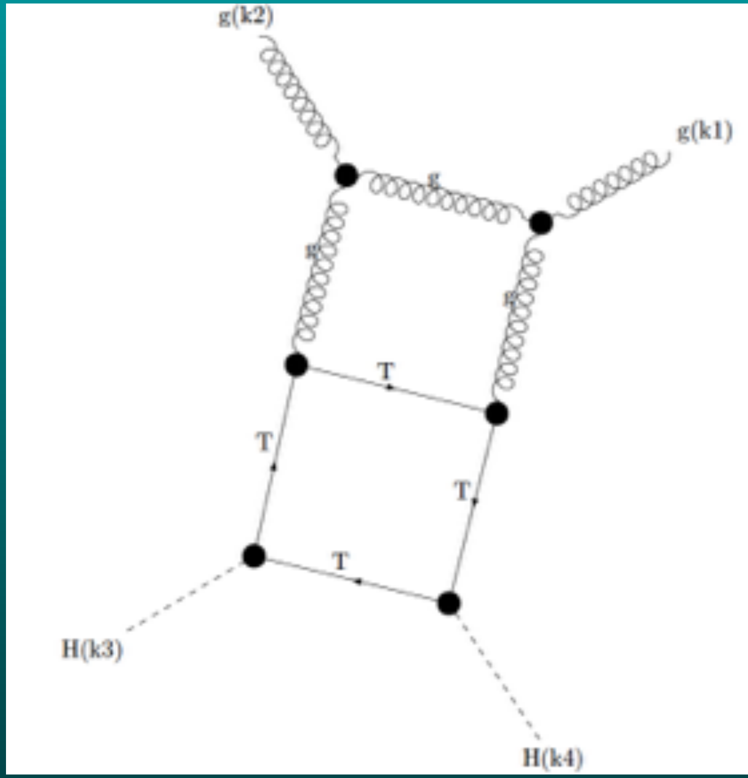
2 to 2 NNLO results are emerging rapidly!

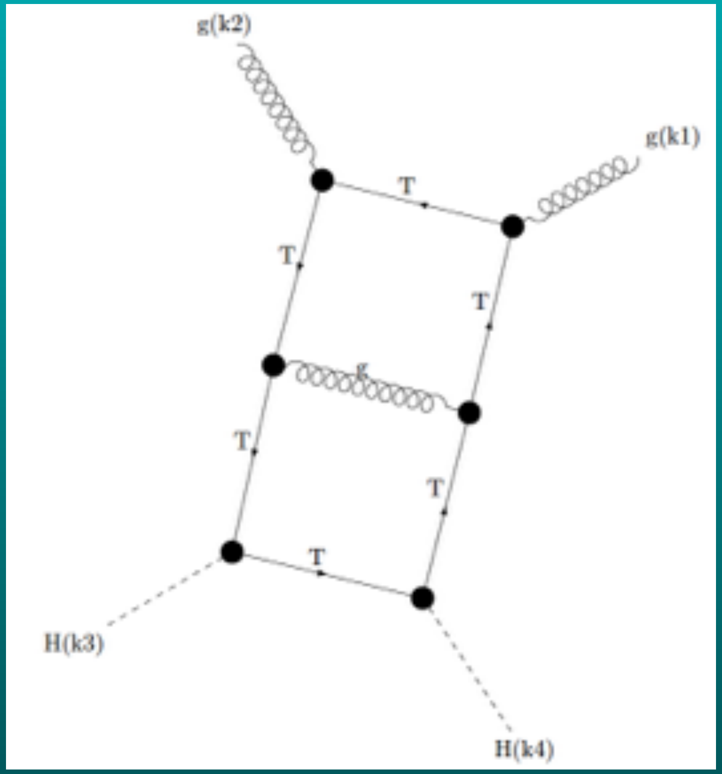
NNLO automation

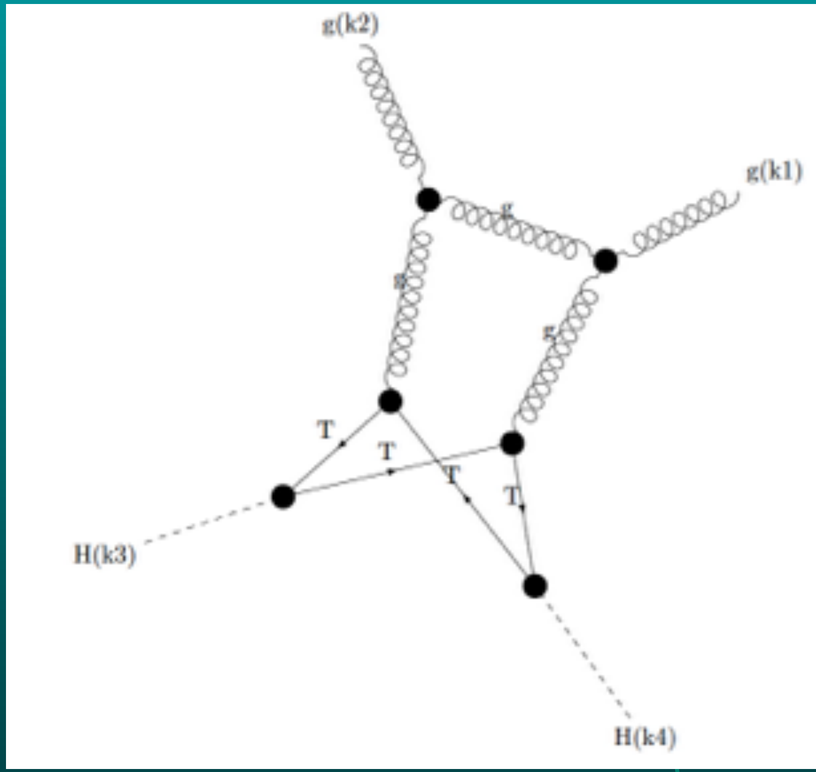
apart from double real radiation:

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

examples:







SecDec

http://secdec.hepforge.org


SecDec is hosted by Hepforge, IPPP Durham

- Home
- Subversion
- Tracker
- Wiki

SecDec

Sophia Borowka, Gudrun Heinrich, Stephan Jahn, Stephen Jones, Matthias Kerner, Johannes Schlenk, Tom Zirke

A program to evaluate dimensionally regulated parameter integrals numerically

home download program user manual faq changelog

NEW: Version 3.0 of the program can be downloaded as SecDec-3.0.8.tar.gz.

Version 2.1.6.1 of the program can be downloaded as SecDec-2.1.6.1.tar.gz.

To install the program:

- tar xzvf SecDec-3.0.8.tar.gz
- cd SecDec-3.0.8
- make

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

arXiv:1502.06595 (CPC 2015)

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

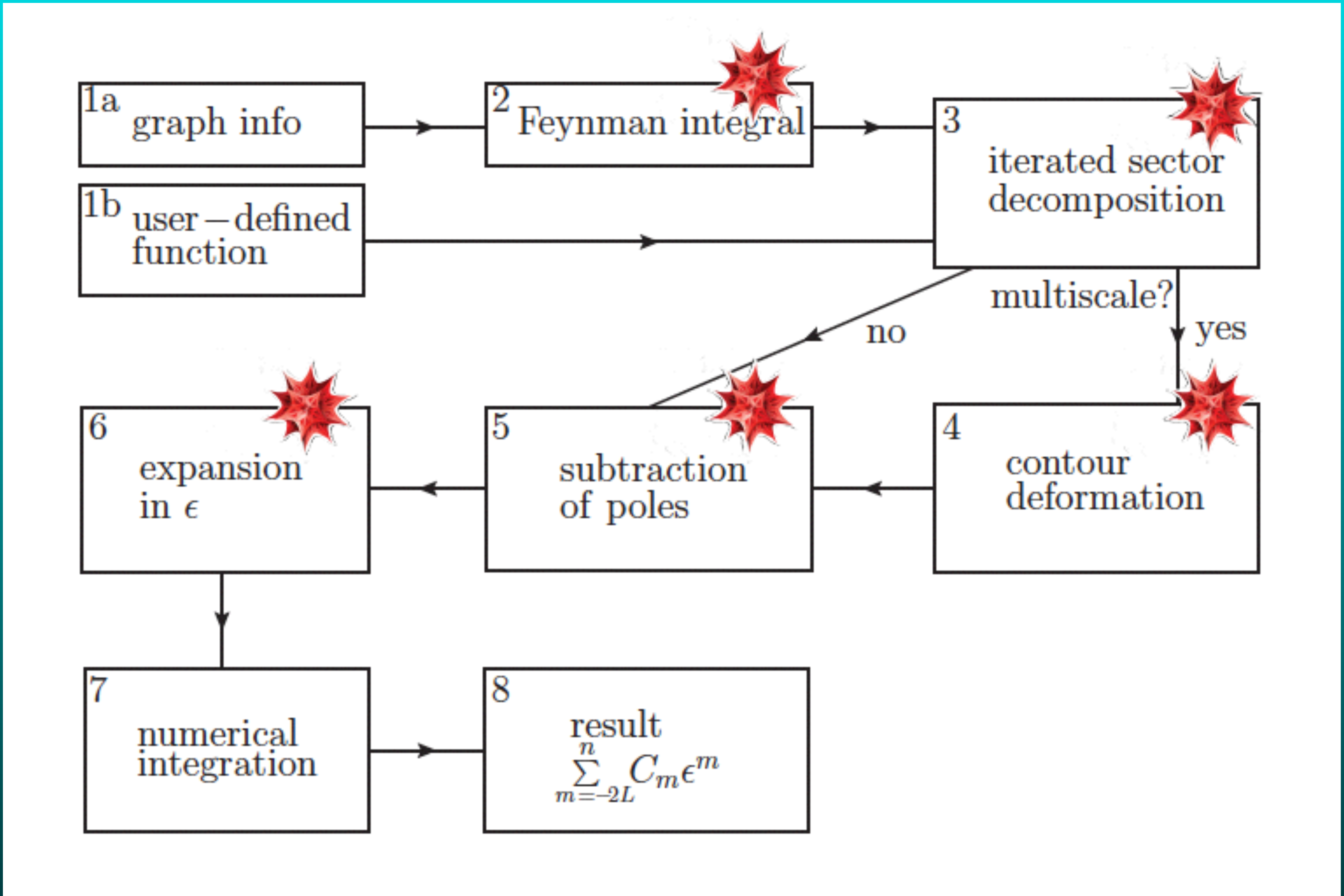
- produces Laurent series in epsilon, coefficients will be finite parametric integrals

- integrates coefficients numerically

  uses **Cuba** library (T.Hahn) or NIntegrate (Wolfram Research)

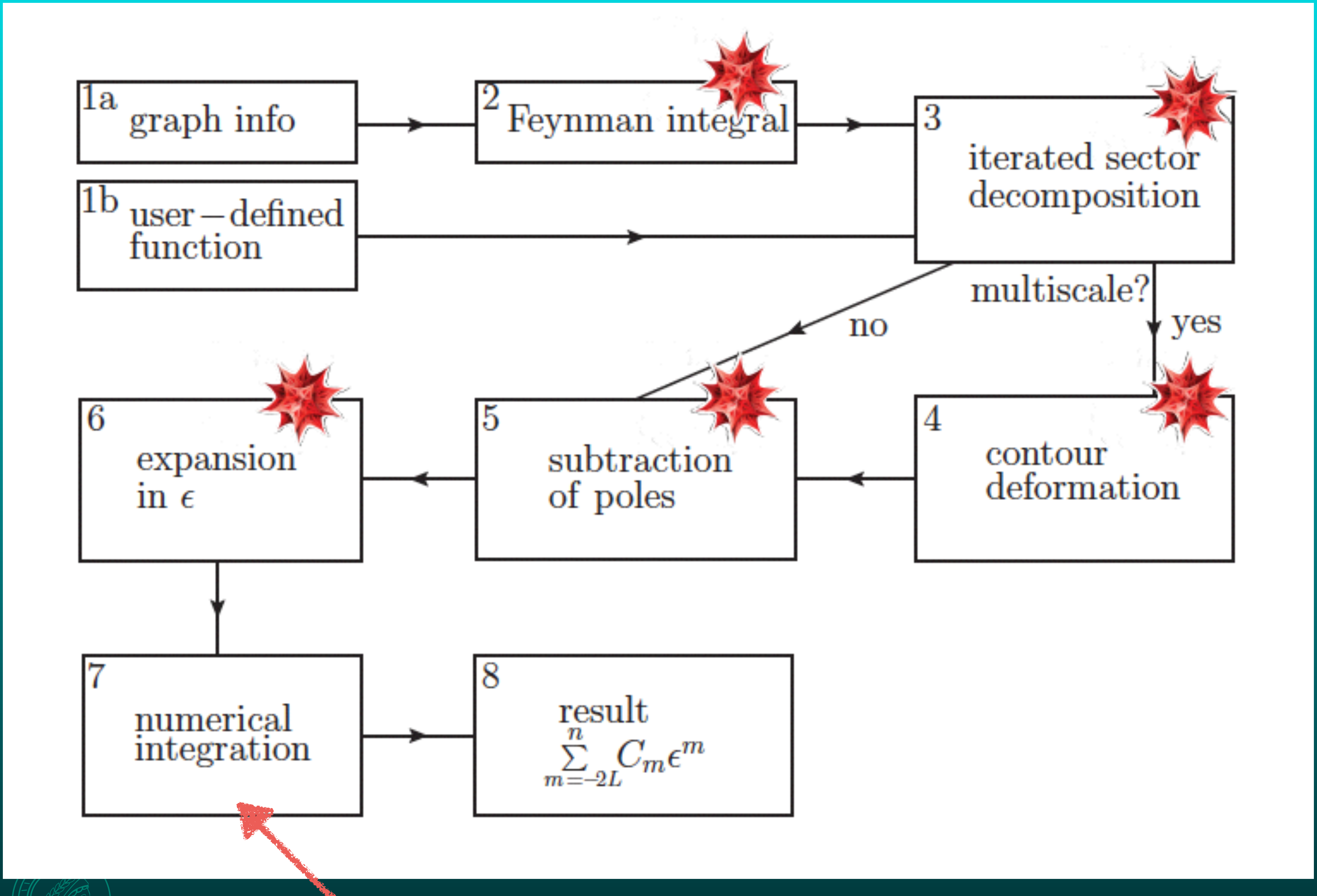
  1-dim: cquad (Gonnet)

SecDec basic workflow



graphics by S.Borowka

SecDec basic workflow



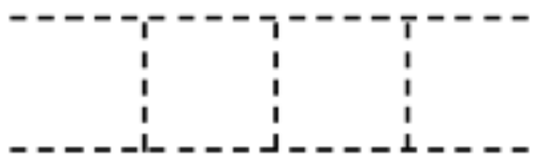
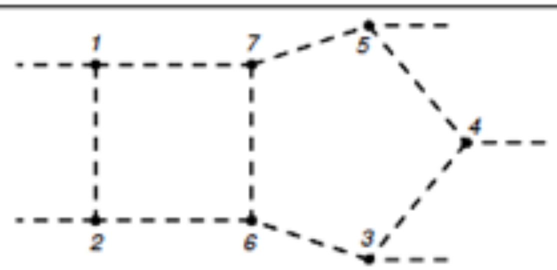
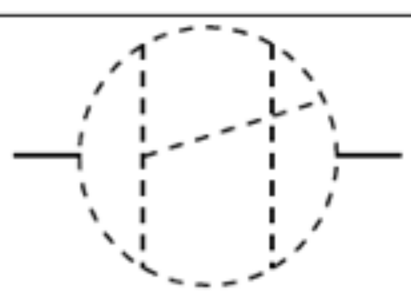
optionally on a cluster

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

Diagram	Strategy X	Strategy G1	Strategy G2
	282 sectors 1 s	266 sectors 8 s	166 sectors 4 s
	368 sectors 1 s	360 sectors 9 s	235 sectors 5 s
	548 sectors 3 s	506 sectors 15 s	304 sectors 4 s
	infinite recursion	72 sectors 5 s	76 sectors 1 s
	27336 sectrs 5510 s	32063 sectrs 11856 s	27137 sectrs 443 s

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

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

(Multi-)Loop integral repository

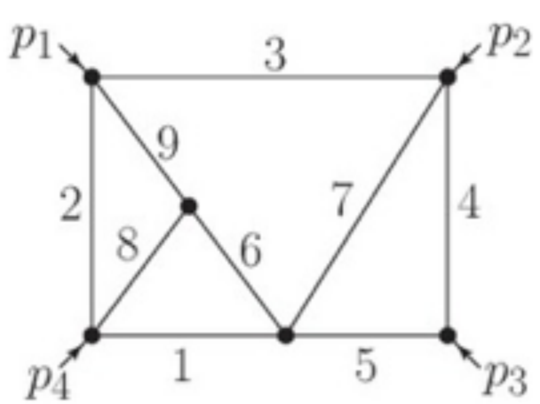
Loopedia | AN EASILY SEARCHABLE DATABASE OF FEYNMAN GRAPHS AND FEYNMAN INTEGRALS

Search this site

Home | Mindmap | Ideas | Existing databases | Admin | Help

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 ϵ-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.

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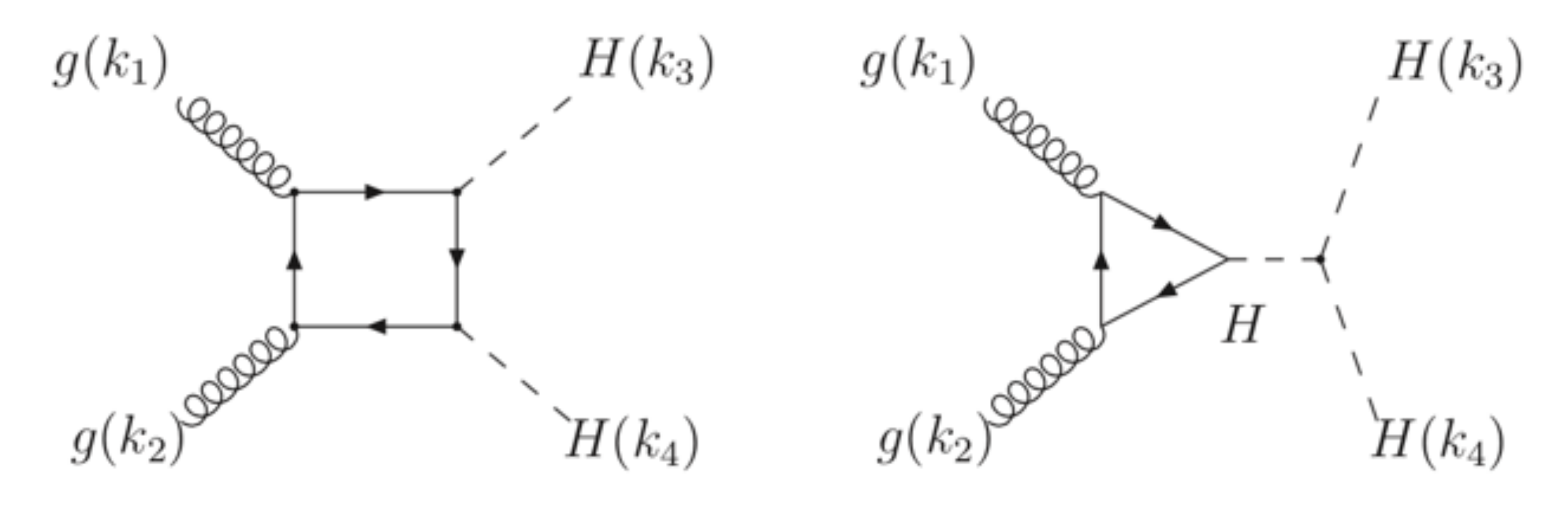
- :-) manteuffel
- :-) tluthe
- :-) gudrunh
- :-) wbkilgore
- :-) Dirk Kreimer
- :-) Andrea Ferroglia
- :-) mkompan

Watch: site | category | page

application to loop integrals with several mass scales

example $gg \to HH$: **4 independent scales s12, s23, mH, mt**

Leading Order already involves 1-loop diagrams



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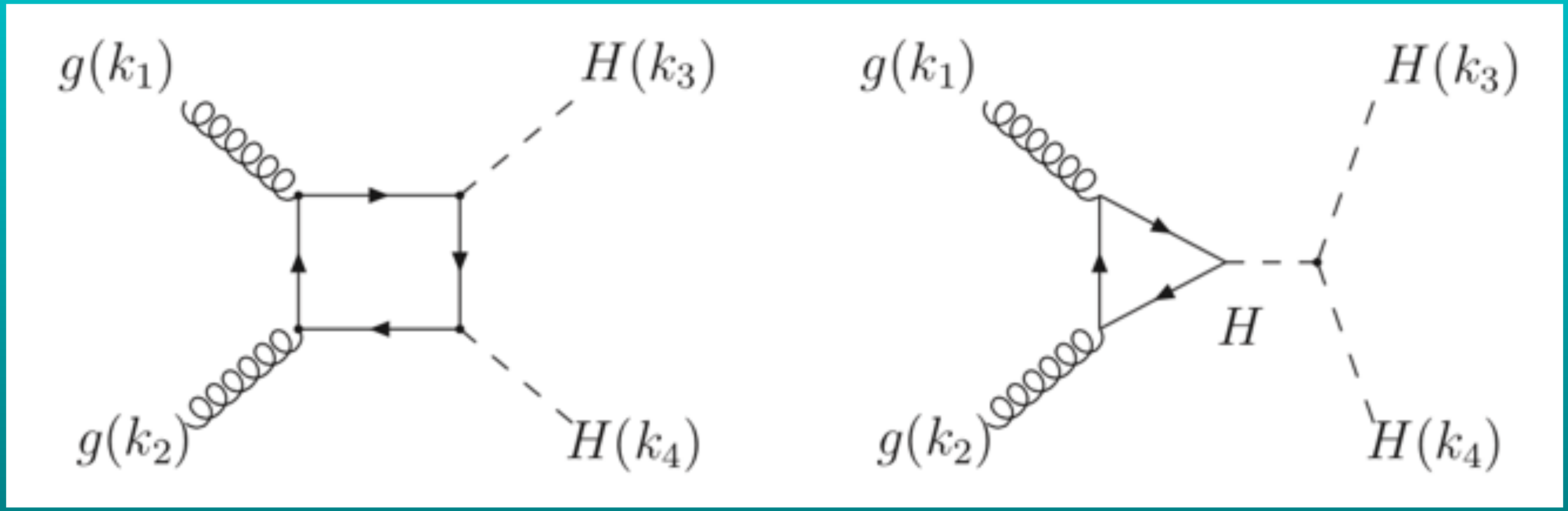
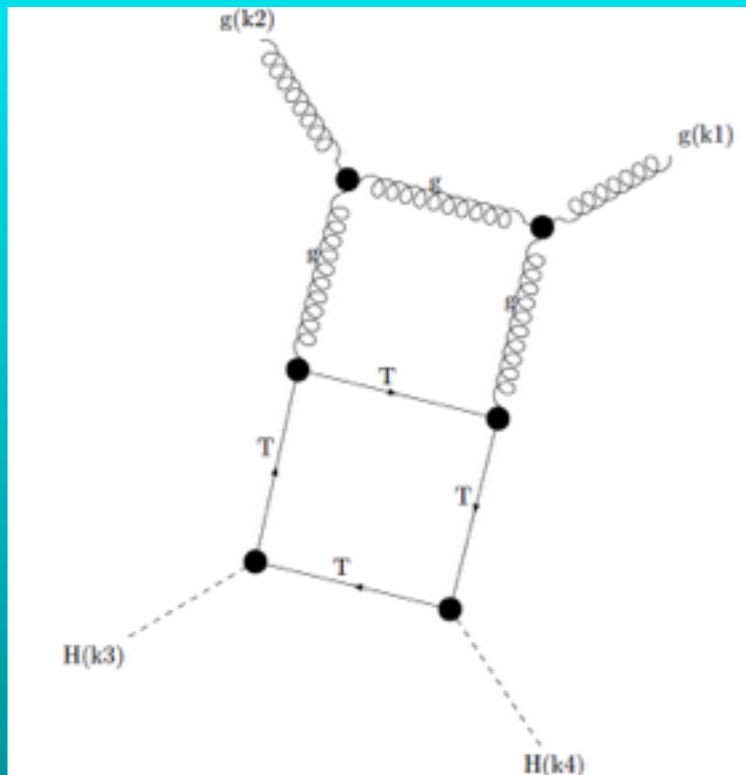


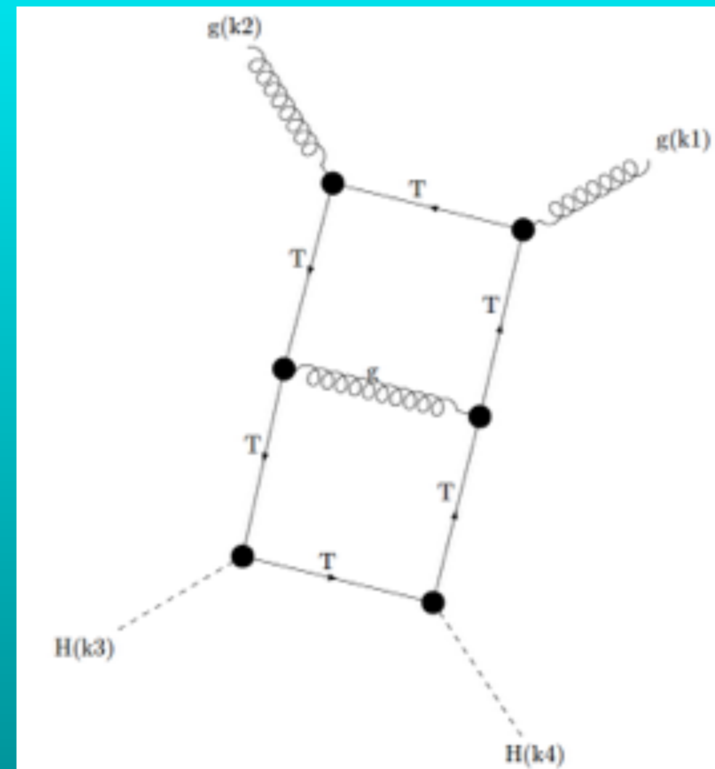
NLO (= 2 loops):

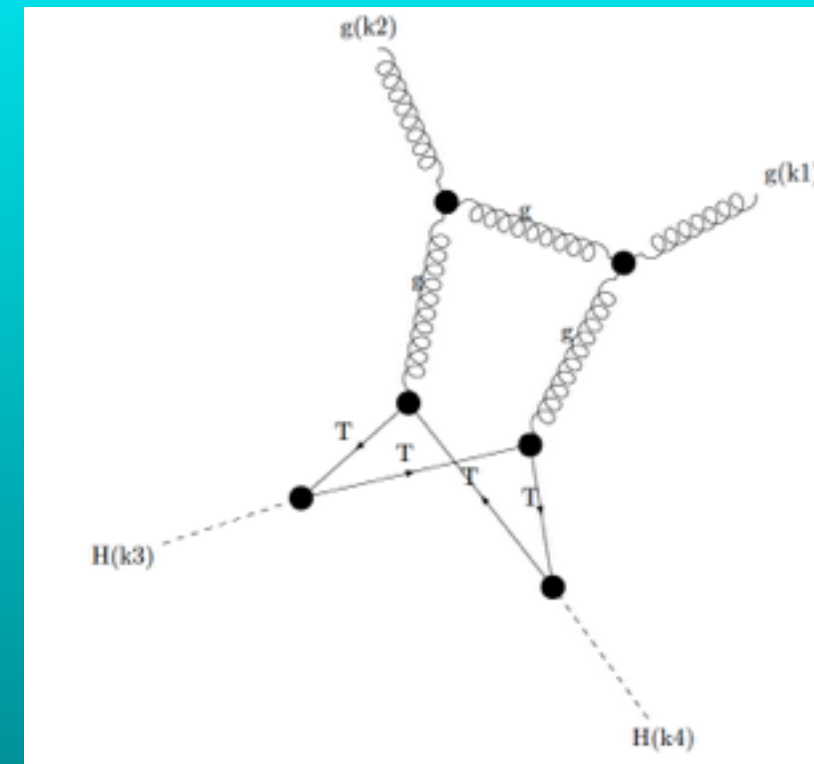
(most) 2-loop diagrams not known analytically

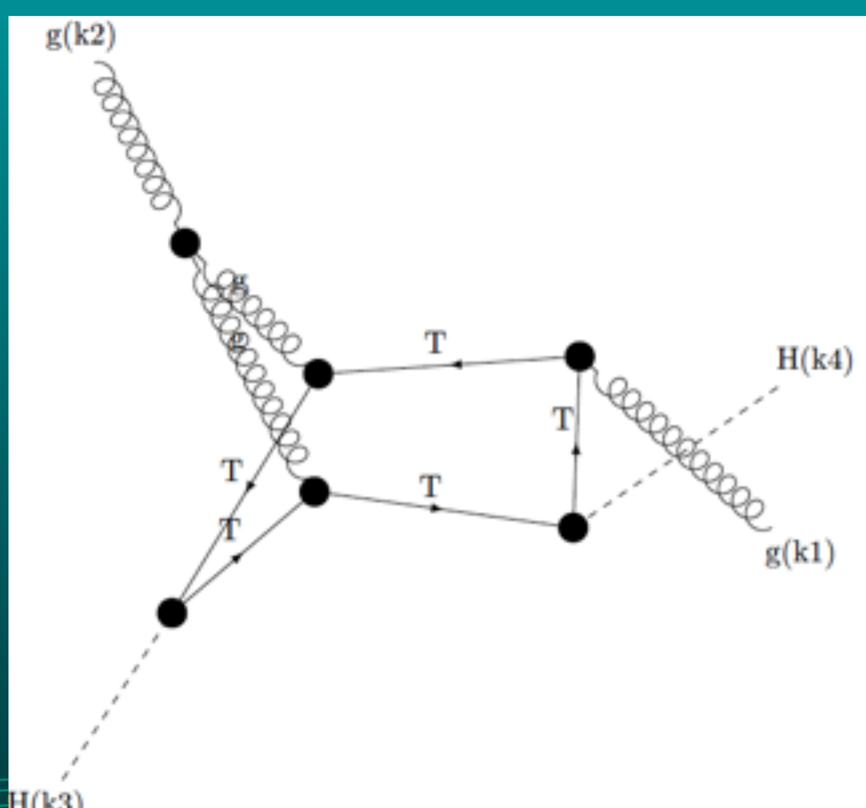
with full mass dependence

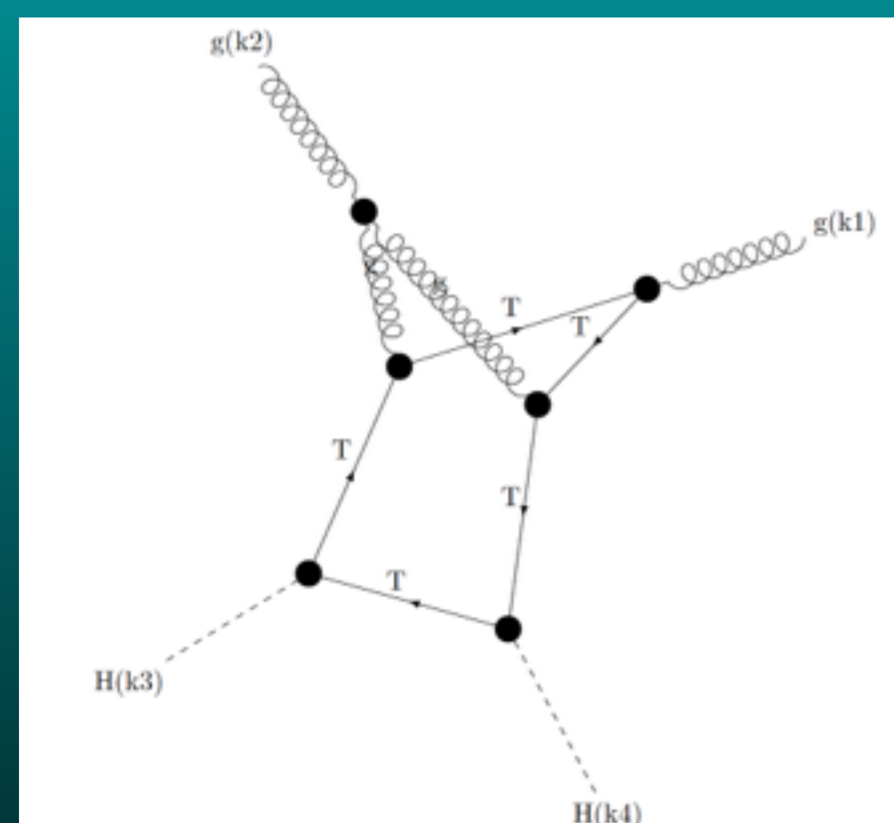
examples of 2-loop box diagrams







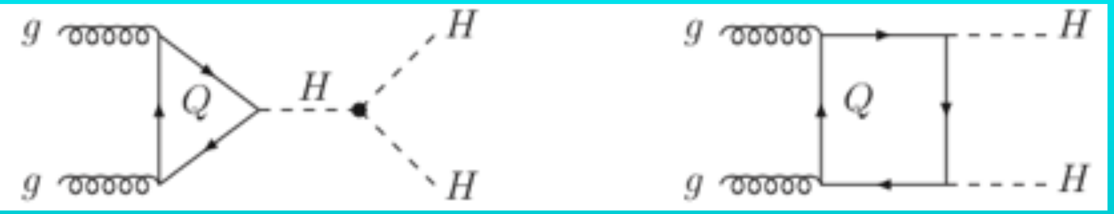




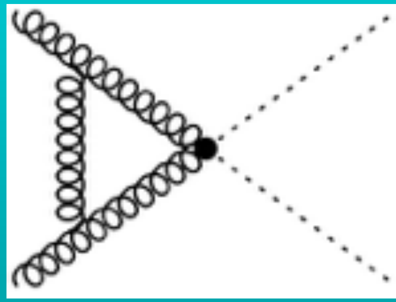
results in the literature so far

LO with full heavy quark mass dependence

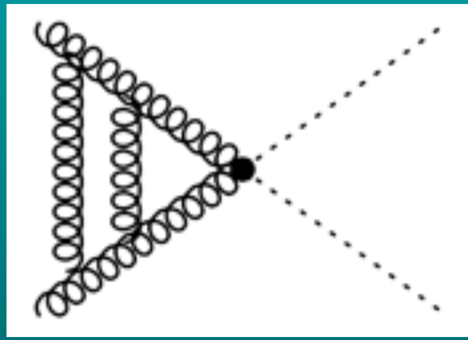
Glover, van der Bij '88, Plehn, Spira, Zerwas '96



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
- **supplemented with $1/m_t$ expansion:** Grigo, Hoff, Steinhauser '15
- **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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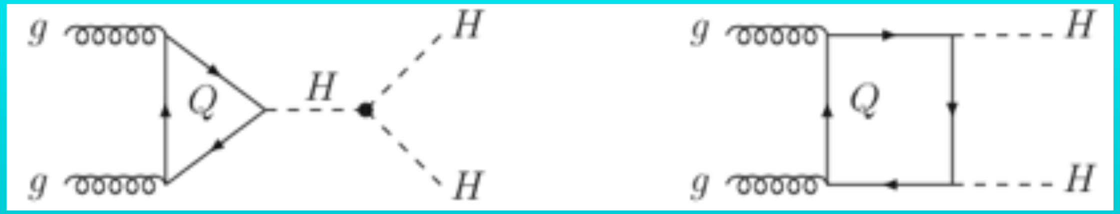

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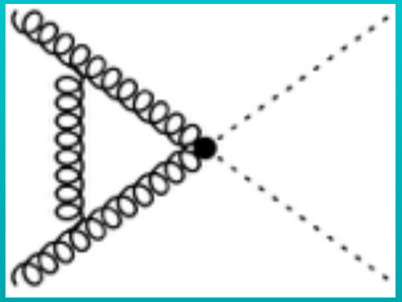

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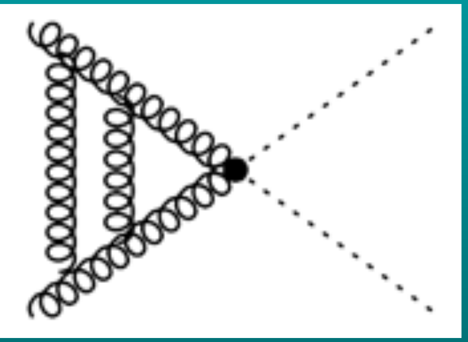

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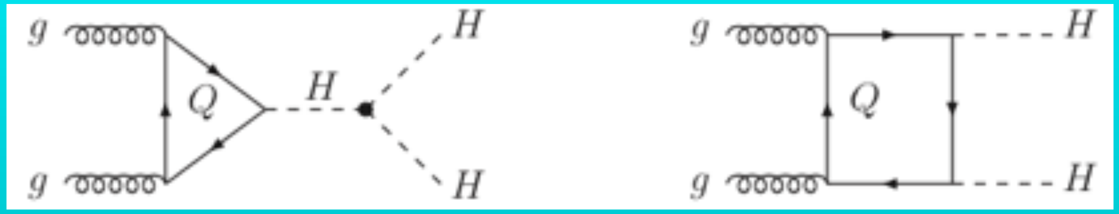
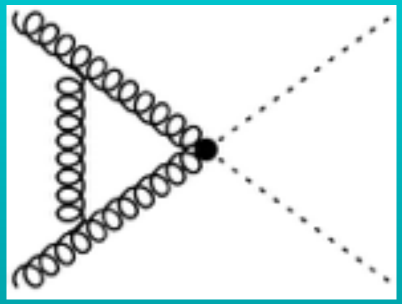
LO with full heavy quark mass dependence

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



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

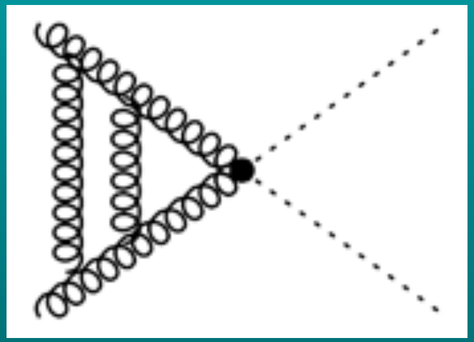


- **supplemented with $1/m_t$ expansion:** $(\pm 10\%)$

  Grigo, Hoff, Melnikov, Steinhauser '13, '15

- **full mass dependence in NLO real radiation part and matching to parton shower** **-10%**

  Frederix, Hirschi, Mattelaer, Maltoni, Torrielli, Vryonidou, Zaro '14;
  Maltoni, Vryonidou, Zaro '14



NNLO in $m_t \to \infty$ limit: **+20%**

De Florian, Mazzitelli '13

- **including all matching coefficients** Grigo, Melnikov, Steinhauser '14
- **supplemented with $1/m_t$ expansion:** Grigo, Hoff, Steinhauser '15
- **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

calculation of the 2-loop amplitude

S.Borowka, N.Greiner, GH, S.Jones, M.Kerner, J.Schlenk, U.Schubert, T.Zirke

- 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

integrals	1-loop	2-loop
direct	63	~10000
use symmetries	21	~1600
use IBP's	8	~300

# of sampling points determined by

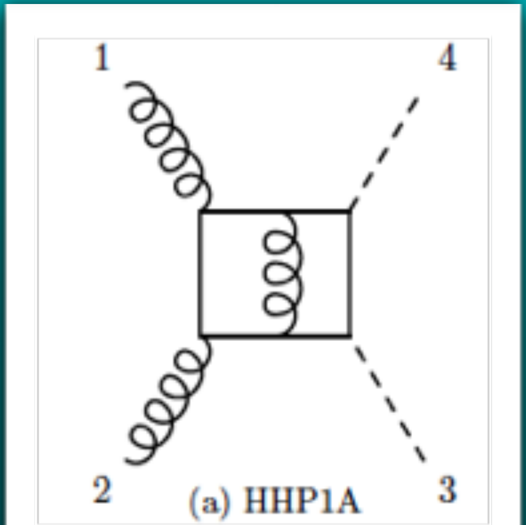
- contribution to amplitude
- time per sampling point

target accuracy set at amplitude level

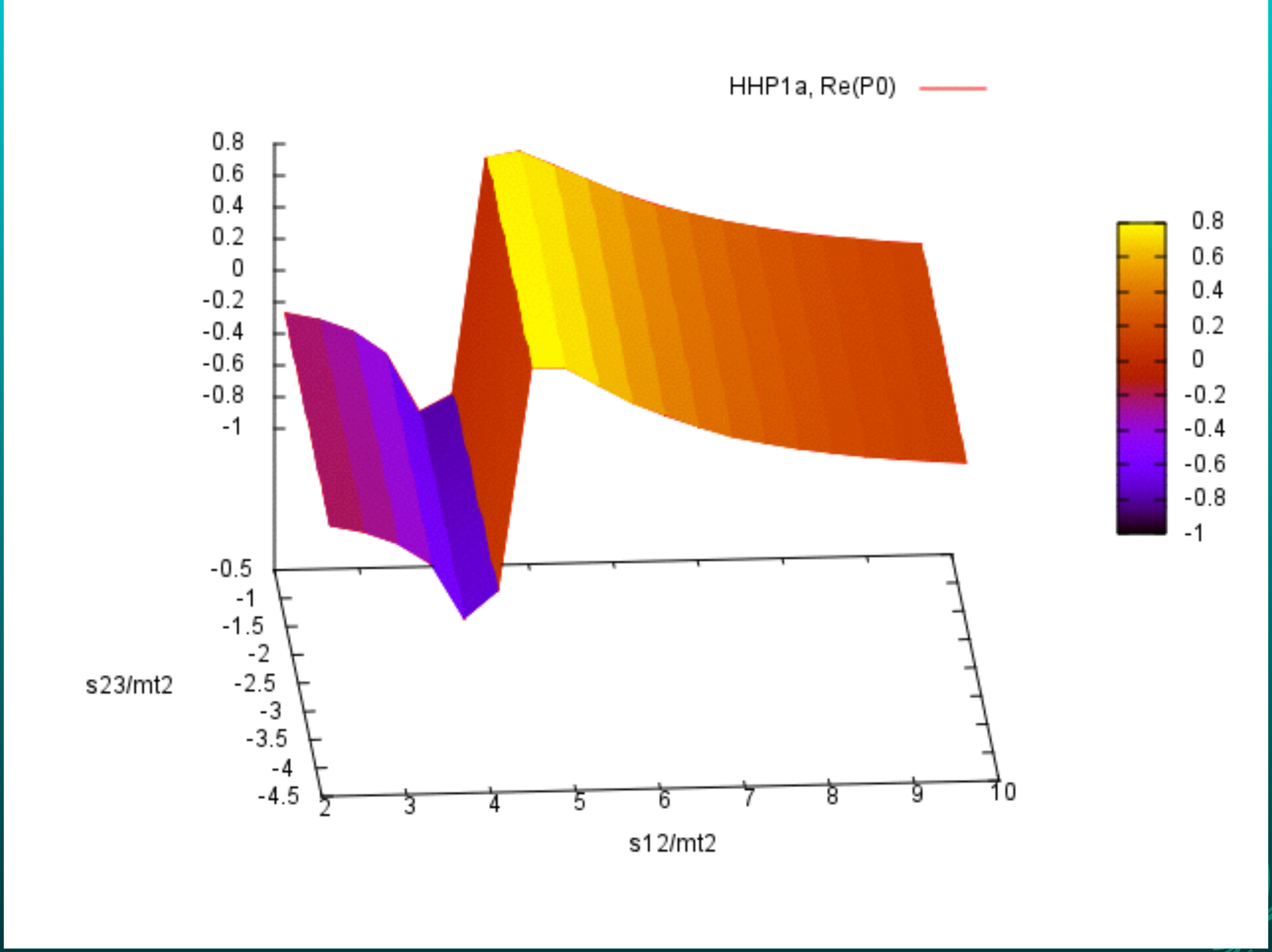
examples of master integrals

a planar 7 propagator integral:

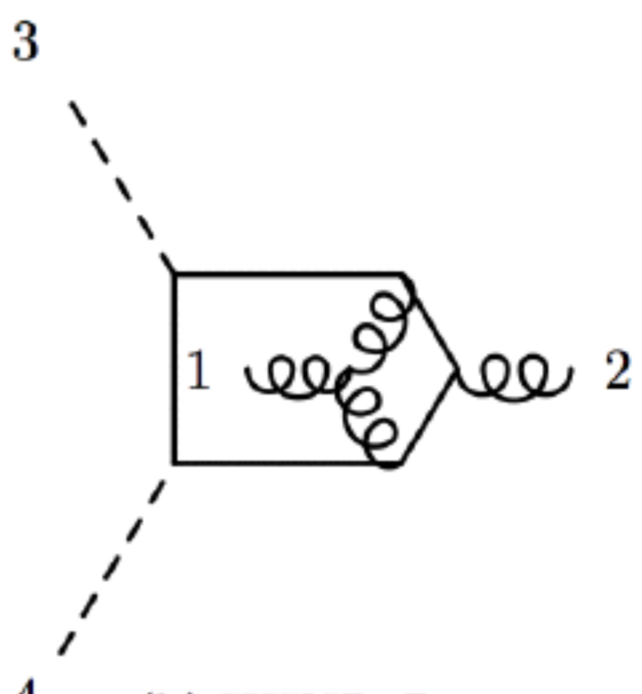
$$m_H = 125\,GeV$$
$$m_t = 173\,GeV$$



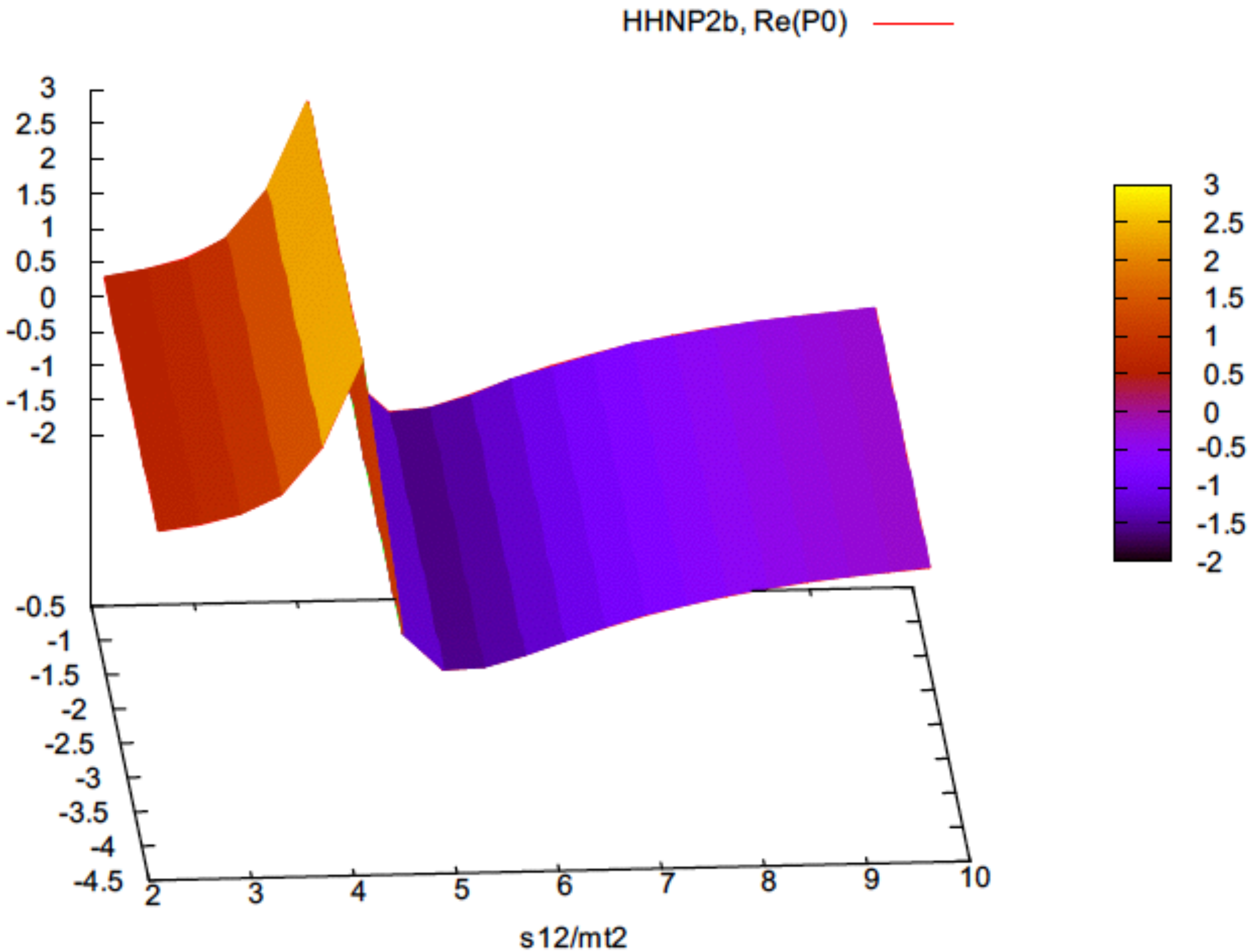
(a) HHP1A



a non-planar 7 propagator integral:



(b) HHNP2B



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

$$m_H = 125\,\text{GeV}$$
$$m_t = 173\,\text{GeV}$$

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.

$$I^{-1,0}_{NP2B} = \frac{\int d^D p_1 \int d^D p_2 \quad (p_1+k_1)^2}{(p_2^2-m_t^2)((p_2+k_1+k_2)^2-m_t^2)((p_2+k_1+k_2+k_3)^2-m_t^2)(p_2-p_1)^2(p_2-p_1+k_1)^2(p_1^2-m_t^2)((p_1+k_2)^2-m_t^2)}$$

- integrals with contracted tensor numerators, e.g.

$$I^{t2}_{NP2B} = \frac{\int d^D p_1 \int d^D p_2 \quad (p_1\cdot k_1)\,(p_2\cdot k_3)}{(p_2^2-m_t^2)((p_2+k_1+k_2)^2-m_t^2)((p_2+k_1+k_2+k_3)^2-m_t^2)(p_2-p_1)^2(p_2-p_1+k_1)^2(p_1^2-m_t^2)((p_1+k_2)^2-m_t^2)}$$

$\longrightarrow$ no need for a scalar integral basis