Towards full NLO for Higgs pair production in gluon fusion

Gudrun Heinrich

Max Planck Institute for Physics, Munich

MITP workshop HPPC

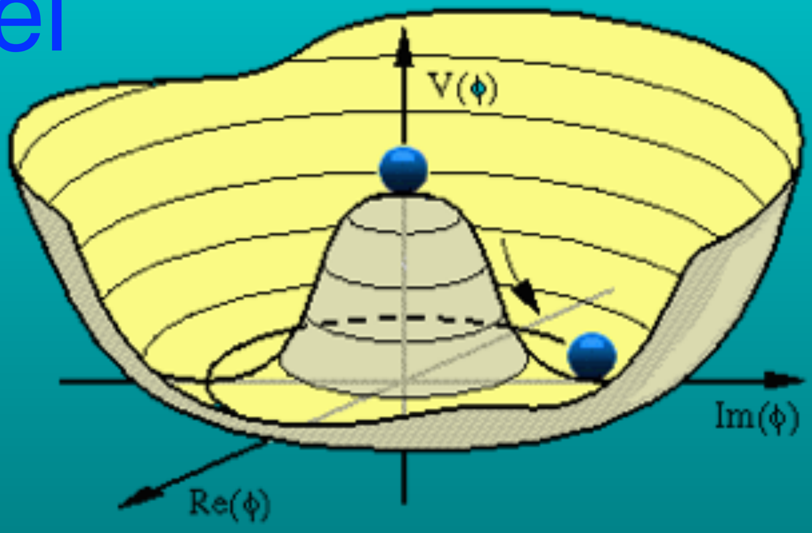
Johannes Gutenberg Universität Mainz, April 29, 2015

MAX-PLANCK-GESELLSCHAFT

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

Motivation

we need to find out whether the mechanism of EW symmetry breaking is the one predicted by the Standard Model



$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi)\ ,\ V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

$$\phi \to v + \sigma$$

$$\mathcal{L} = \frac{1}{2}\partial_\mu\sigma\,\partial^\mu\sigma - (-\mu^2)\,\sigma^2 - \sqrt{-\mu^2\lambda}\,\sigma^3 - \frac{\lambda}{4}\,\sigma^4 + \text{const.}$$

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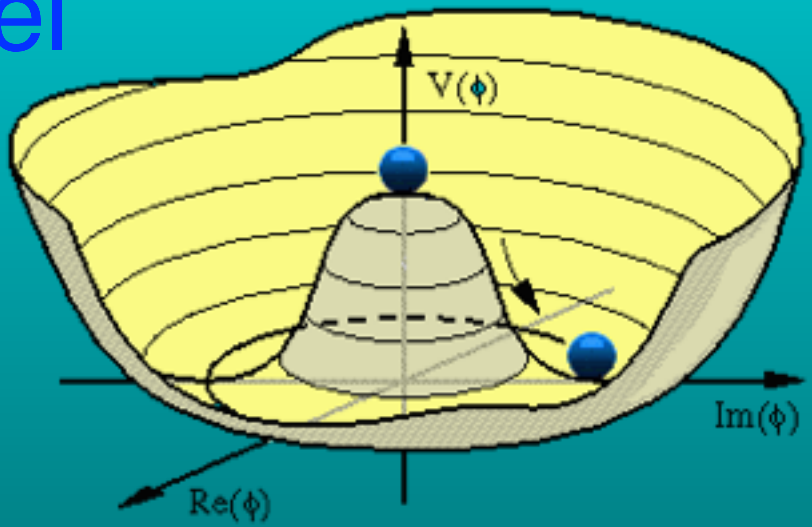

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so far we know nothing about λ

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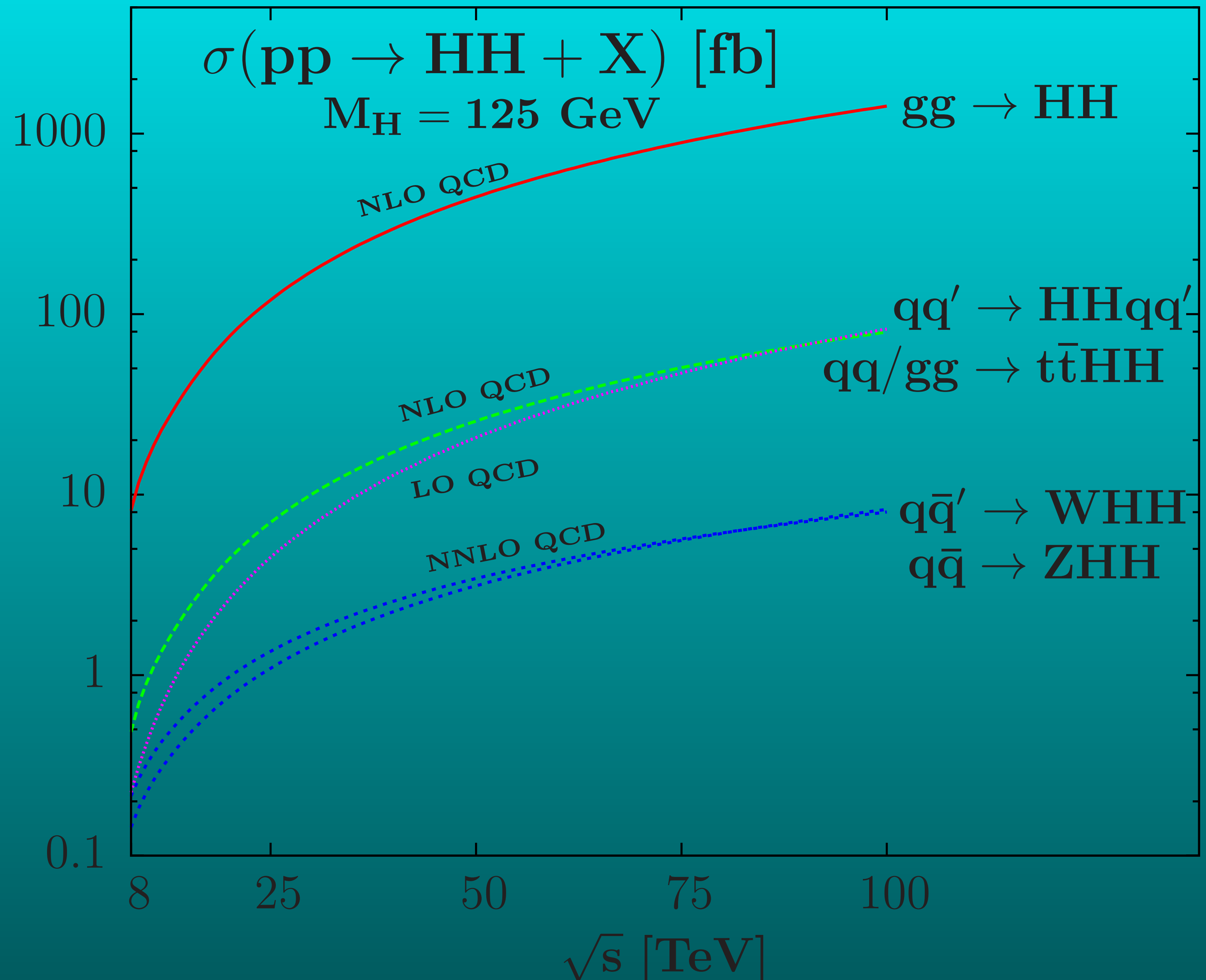
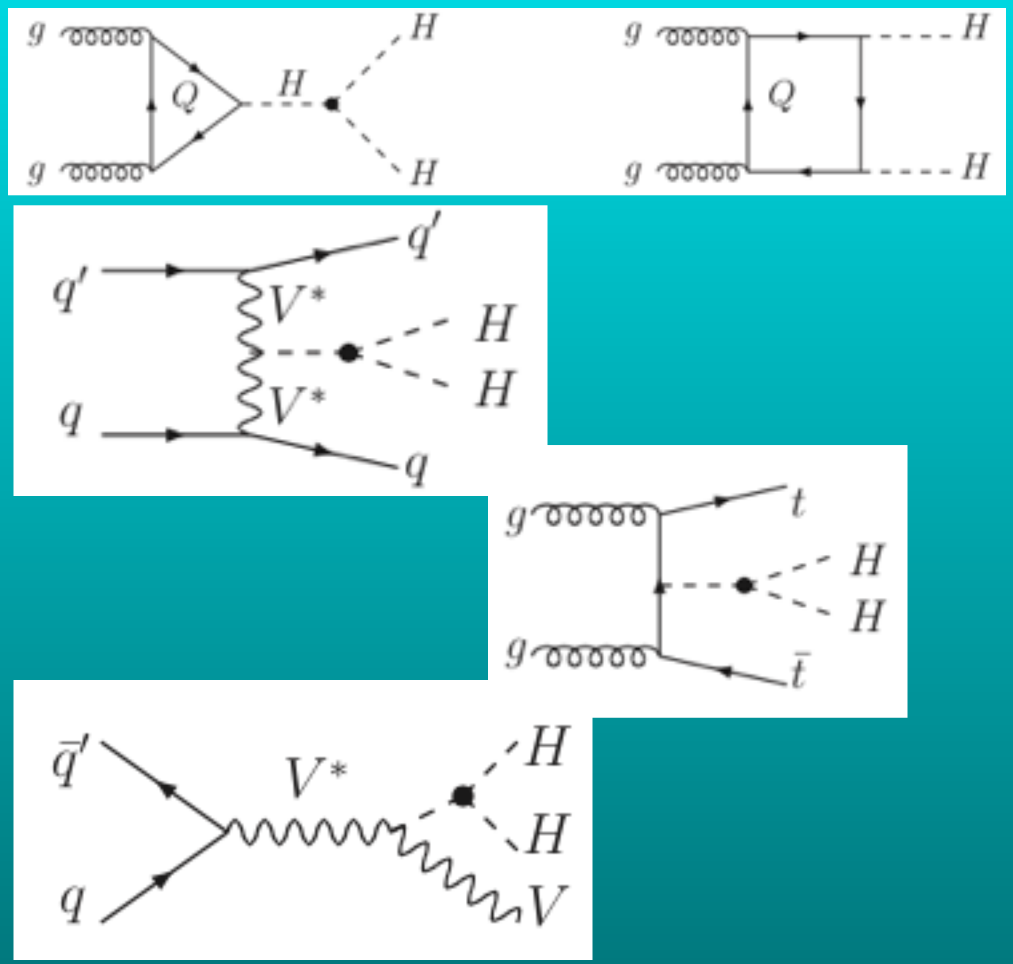
Higgs pair production channels





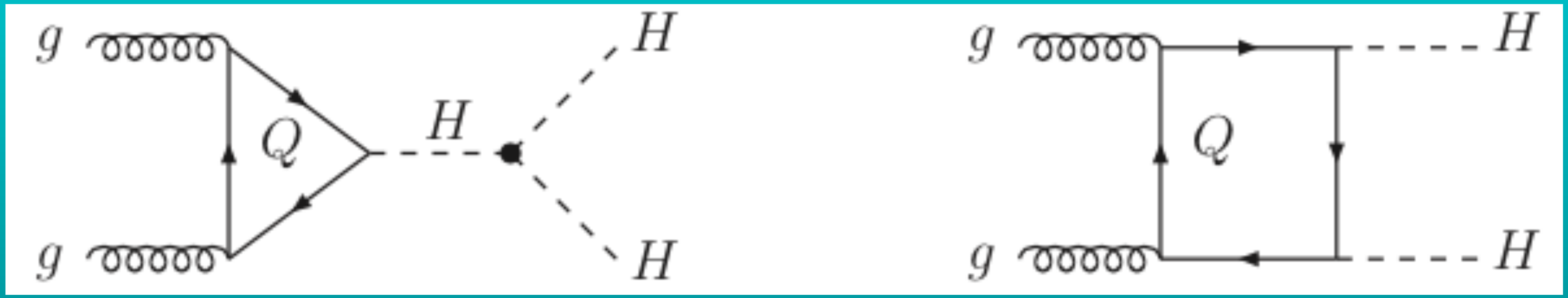
J. Baglio, A. Djouadi, R. Gröber, M. Mühlleitner, J. Quevillon, M. Spira '12

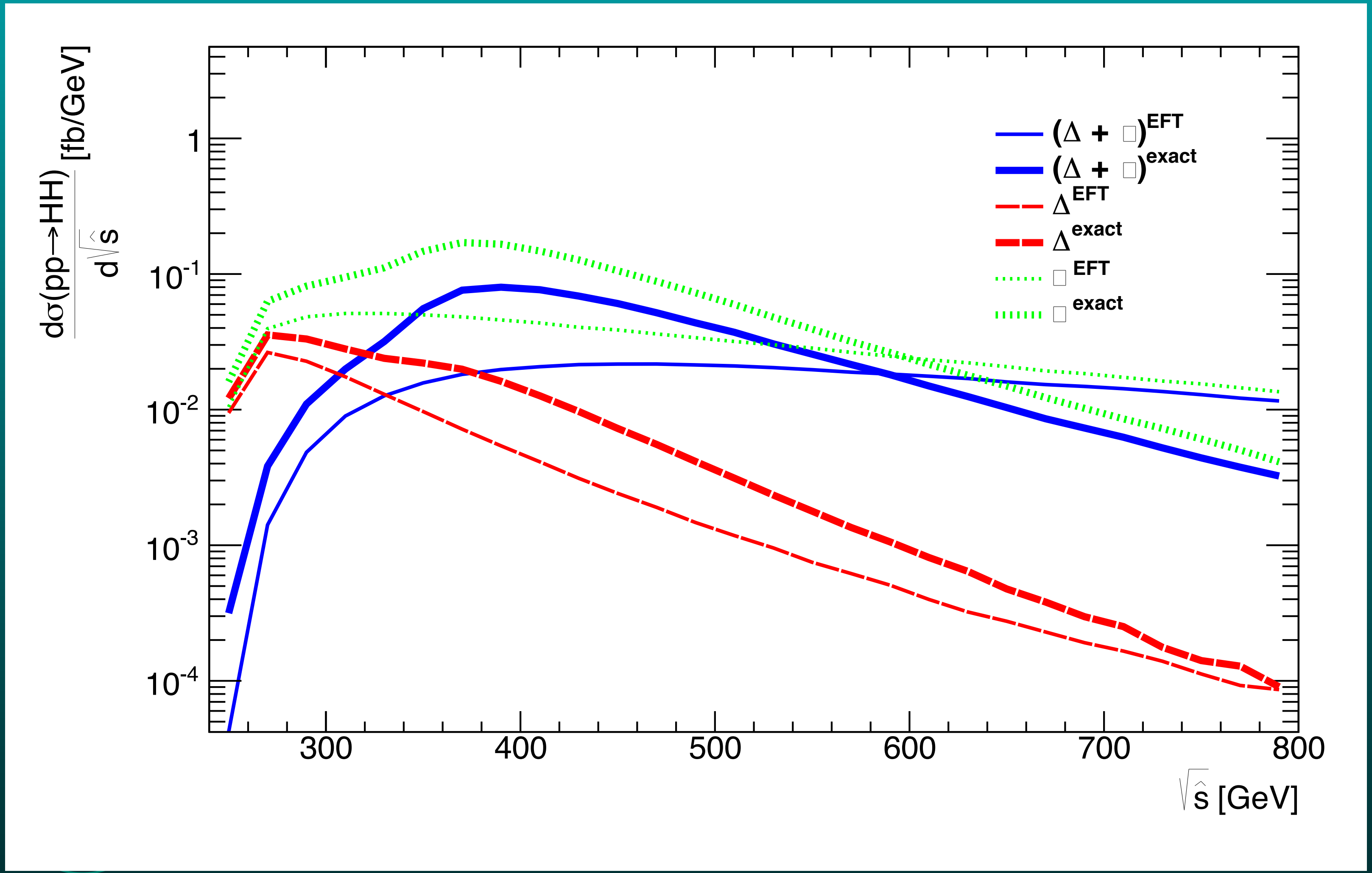
problem: $\sigma_{ggHH} \sim 10^{-3}\,\sigma_{ggH}$

sensitivity to Higgs self coupling

$gg \to HH$

two types of contributions: “triangle (λ)” and “box”

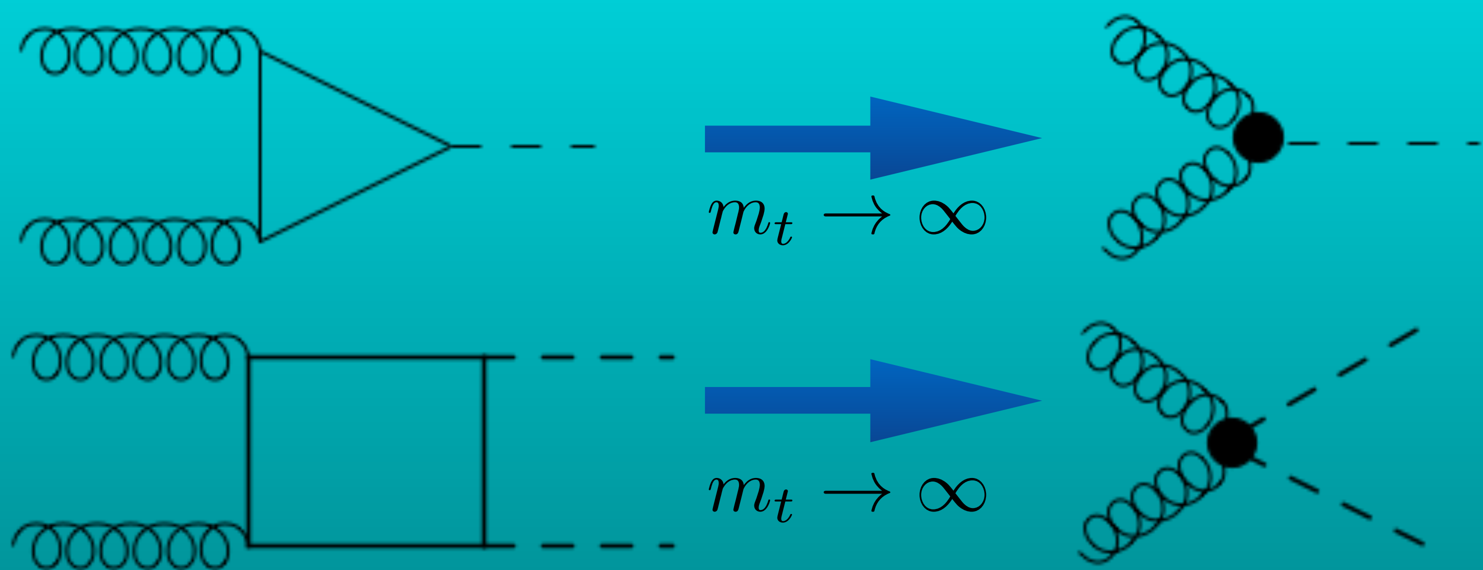




Slawinska,
van den Wollenberg,
van Eijk, Bentvelsen ‘14

(LO)

heavy top limit (EFT)



strictly only valid for $\sqrt{\hat{s}} \ll 2\,m_t$

$\sqrt{\hat{s}} > 2\,m_H$ for $gg \to HH$

→ $m_t \to \infty$ limit poor beyond threshold

→ need full m_t dependence → need 2-loop box integrals with m_t, m_H

current status

LO (1 loop): Glover, van der Bij '88 **(full heavy quark mass dependence)**

NLO in $m_t \to \infty$ limit (EFT): Plehn, Spira, Zerwas '96; Dawson, Dittmaier, Spira '98 (**HPAIR**)

NLO ($m_t \to \infty$) supplemented with $1/m_t$ expansion: Grigo, Hoff, Melnikov, Steinhauser '13

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NNLO + all matching coefficients ($m_t \to \infty$) Grigo, Melnikov, Steinhauser '14

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

study of BSM effects Dawson, Furlan, Lewis '12; Goertz, Papaefstathiou, Yang, Zurita '14; Dawson, Ismail, Low '15; Gröber, Mühlleitner, Spira, Streicher '15, …

soft gluon resummation NNLL in $m_t \to \infty$ limit: Shao, Li, Li, Wang '13

+ 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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+10%

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terminology

Born improved HEFT (Higgs Effective Field Theory) at NLO QCD

$$d\sigma^{virt}_{NLO} \approx \frac{d\sigma^{virt}_{NLO}(m_t \to \infty)}{d\sigma^{virt}_{LO}(m_t \to \infty)}\, d\sigma^{virt}_{LO}(m_t) =: d\sigma^{virt,HEFT}_{NLO}$$

HPAIR (Dawson, Dittmaier, Spira)

$$d\sigma^{real}_{NLO} = d\sigma^{real}_{NLO}(m_t \to \infty)$$

improvements towards "more mass dependence"

$$d\sigma^{virt,HEFT}_{NLO}$$

$$d\sigma^{real}_{NLO}(m_t)$$

Maltoni, Vryonidou, Zaro

-10%

$$d\sigma^{virt}_{NLO}(m_t) = \sum_n c_n(x) \left(\frac{m_H^2}{m_t^2}\right)^n \quad x = 4m_H^2/s\ ,\ n_{max} = 6$$

$$d\sigma^{real}_{NLO}(m_t \to \infty)$$

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$$d\sigma_{NLO}^{real} = d\sigma_{NLO}^{real}(m_t \to \infty)$$

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$$d\sigma_{NLO}^{real}(m_t \to \infty)$$

Grigo, Hoff, Melnikov, Steinhauser

+10%

full mass dependence needed!

tools development

GoSam

N. Greiner, GH, G. Luisoni, S.Jones, M.Kerner, G.Ossola, P. Mastrolia,
J. Schlenk, J.F. von Soden-Fraunhofen, T. Zirke

SecDec

S. Borowka, GH, S. Jones, M. Kerner, J. Schlenk, A. Stoyanov, T. Zirke

new analytic techniques

P. Mastrolia, T. Peraro, U. Schubert, S. di Vita, V. Yundin

build on GoSam (one loop)

arXiv:1404.7096

Cullen, Greiner, GH, Luisoni, Mastrolia, Mirabella,
Ossola, Peraro, Schlenk, van Deurzen,
von Soden-Fraunhofen, Tramontano

program available at

http://gosam.hepforge.org

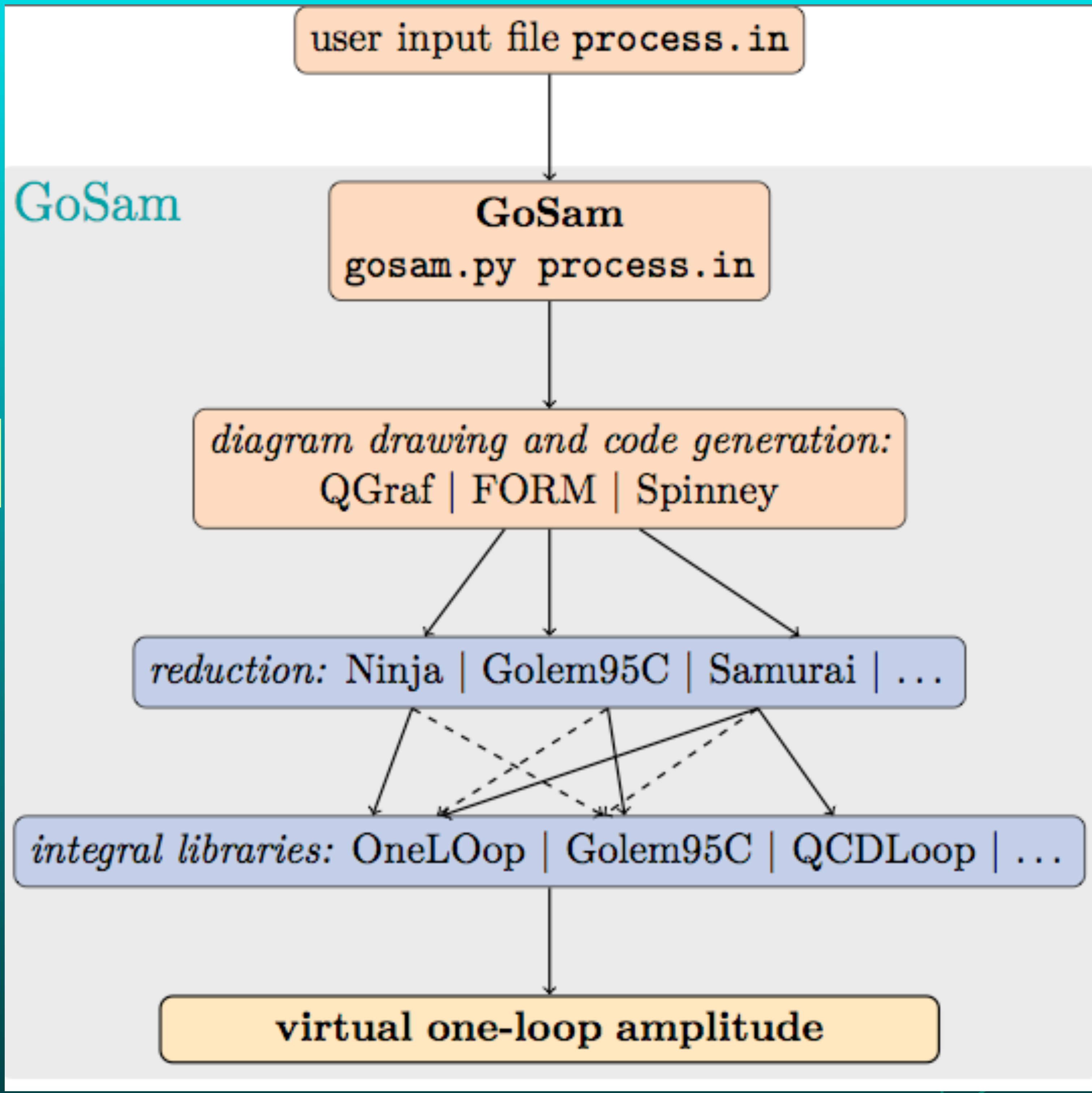
very simple usage

example input file for

$$e^+e^- \rightarrow t\,\bar{t}$$

```
process_path=eett
in=     e+, e-
out=    t, t~
order= gs, 0, 2
```

LO (↑ 0) NLO (↖ 2)



GoSam-2Loop

Greiner, GH, Jones, Kerner, Luisoni, Mastrolia, Schlenk, Zirke

generic extension of GoSam, not limited to $gg \rightarrow hh$

use projectors on tensor structures rather than helicity amplitudes

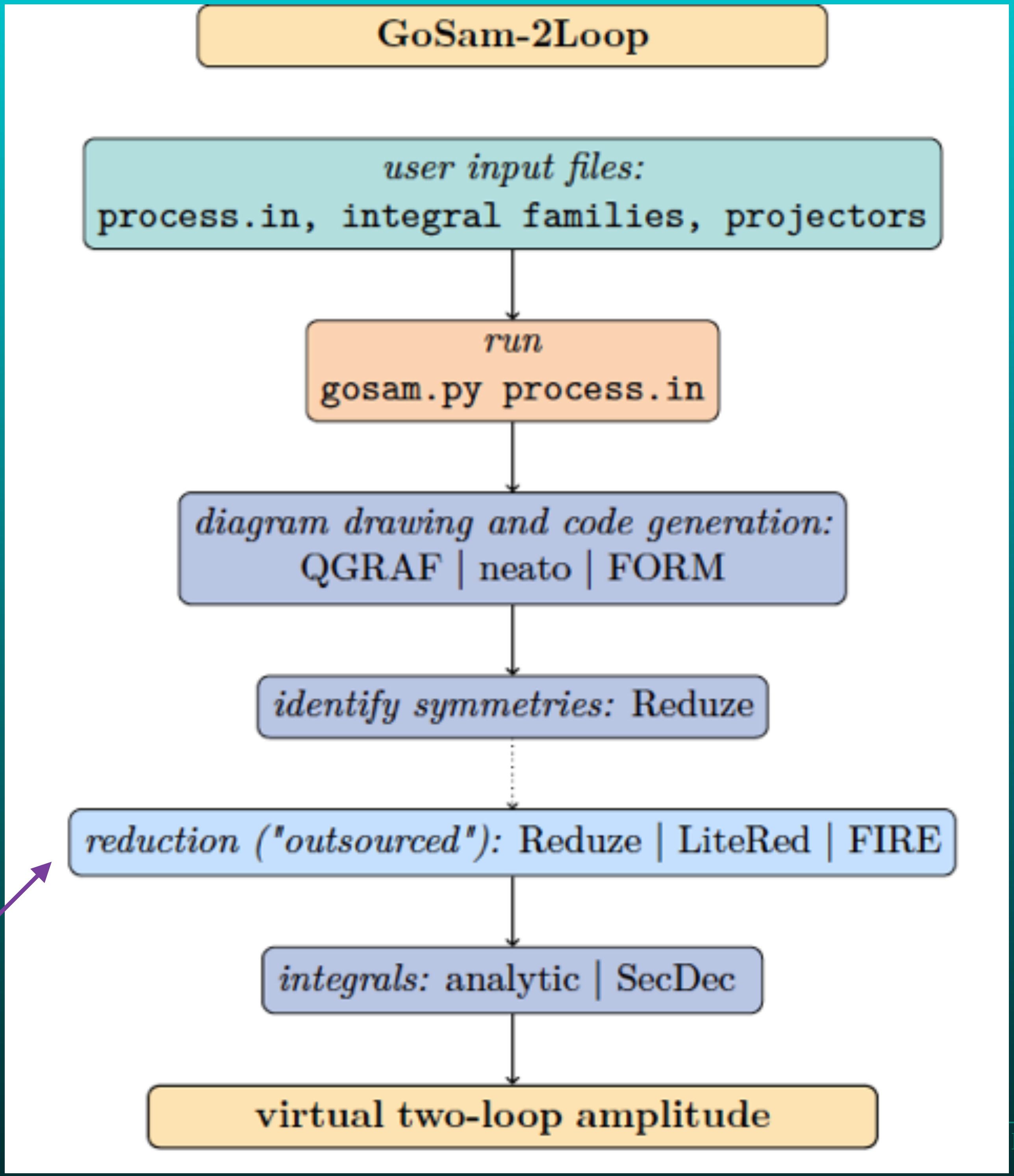
process.in for

$gg \rightarrow hh$

```
in=g,g
out=h,h
model=smdiag
order=QCD,none,2,4
```

tree 1-loop 2-loop

Manteuffel, Studerus; R.N.Lee; A.V.Smirnov



example $gg \to hh$

amplitude structure: (independent of #loops)

$$\mathcal{M} = \epsilon_\mu(p_1,n_1)\epsilon_\nu(p_2,n_2)\,\mathcal{M}^{\mu\nu}$$

$$\mathcal{M}^{\mu\nu} = A_1(s,t,m_H^2,m_t^2,D)\,T_1^{\mu\nu} + A_2(s,t,m_H^2,m_t^2,D)\,T_2^{\mu\nu}$$

choose tensor decomposition such that

$$\mathcal{M}^{++} = \mathcal{M}^{--} = -A_1$$

$$\mathcal{M}^{+-} = \mathcal{M}^{-+} = -A_2$$

← diagrams with trilinear couplings enter only here

$$T_1^{\mu\nu} = g^{\mu\nu} - \frac{p_1^\nu\, p_2^\mu}{p_1\cdot p_2}$$

$$T_2^{\mu\nu} = g^{\mu\nu} + \frac{1}{p_T^2\,(p_1\cdot p_2)}\left\{m_H^2 p_1^\nu\, p_2^\mu - 2\,(p_1\cdot p_3)\,p_3^\nu\, p_2^\mu - 2\,(p_2\cdot p_3)\,p_3^\nu\, p_1^\mu + 2\,(p_1\cdot p_2)\,p_3^\nu\, p_3^\mu\right\}$$

$$p_T^2 = (u\,t - m_H^4)/s$$

Glover, van der Bij '88

form factors/reduction

construct projectors $P_j^{\mu\nu}$ such that

$$\begin{aligned} P_1^{\mu\nu}\mathcal{M}_{\mu\nu} &= A_1(s,t,m_H^2,m_t^2,D) \\ P_2^{\mu\nu}\mathcal{M}_{\mu\nu} &= A_2(s,t,m_H^2,m_t^2,D) \end{aligned}$$

current status:

projectors as input to GoSam-2L

algebra done automatically by GoSam-2L (FORM)

interface to Reduze to identify integral symmetries

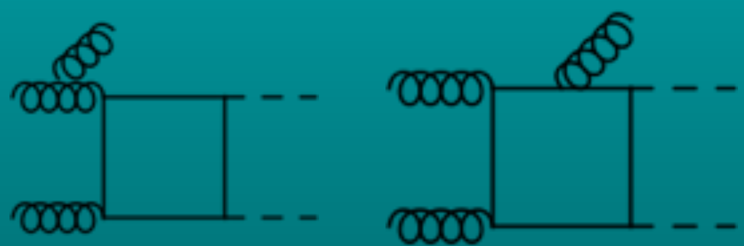
reduction: interface to Reduze, LiteRed, FIRE

building blocks

loop diagrams:

	# diagrams
tree	0
1-loop	8
2-loop	122

real radiation:



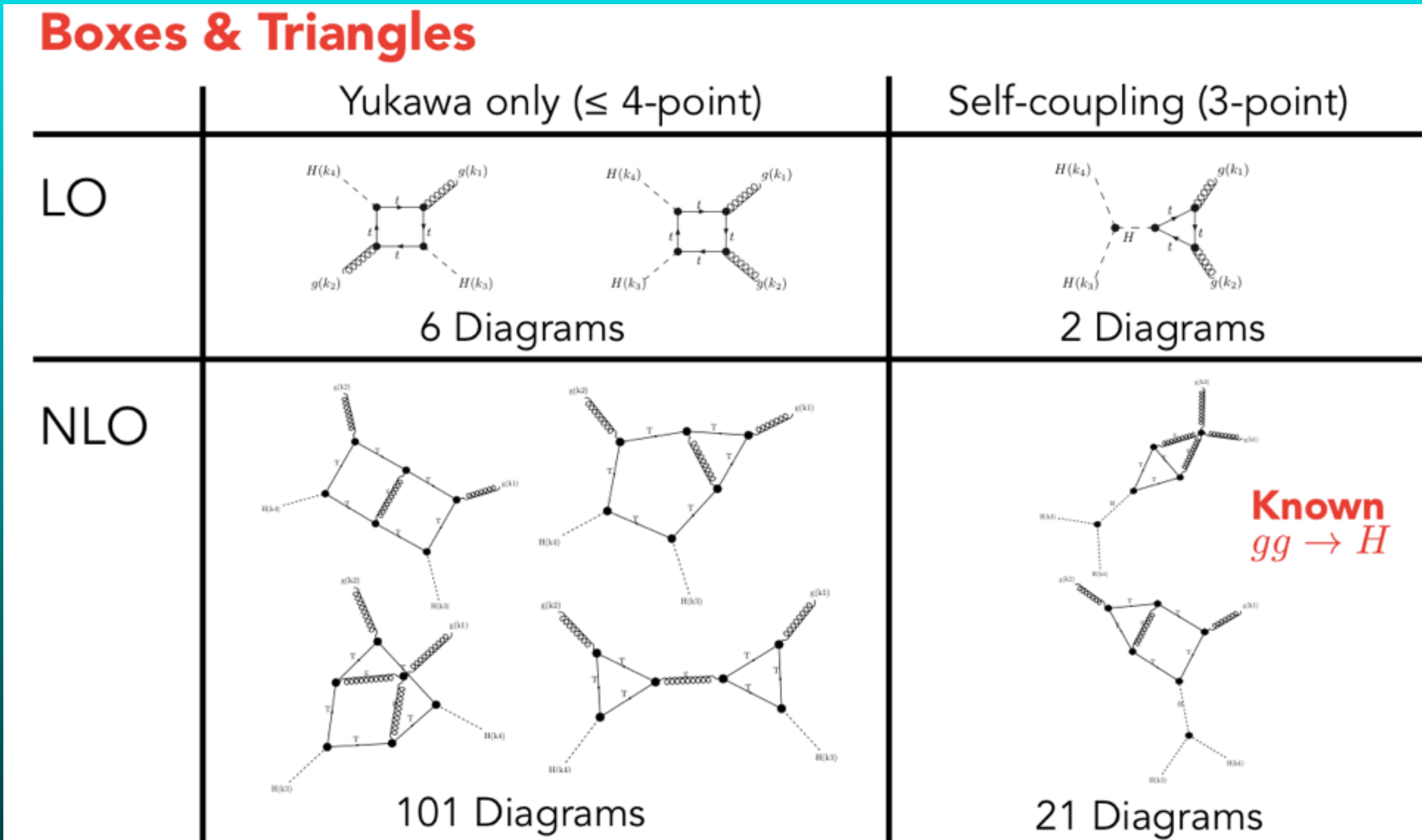
$$gg \to hh\,g$$
$$gq \to hh\,q$$
$$g\bar{q} \to hh\,\bar{q}$$
$$q\bar{q} \to hh\,g$$

	# diagrams
doubly unresolved (tree)	0
singly unresolved (1-loop)	54 + 3 x 8

no NNLO-type subtraction needed!

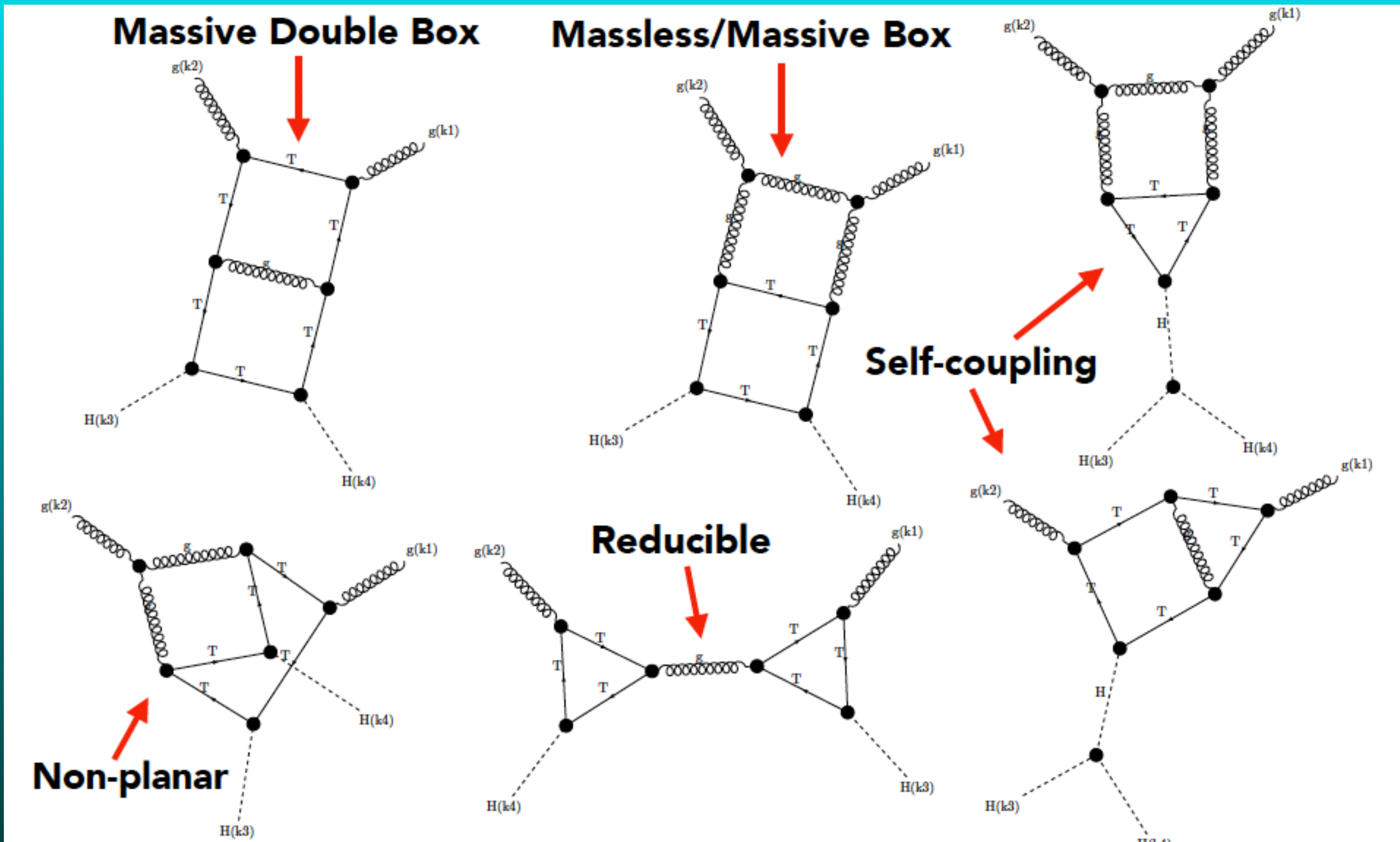
use GoSam (1-loop) + dipole subtraction

some loop diagrams (drawn by GoSam-2L)



thanks: Stephen Jones

some types of 2-loop diagrams



thanks: Stephen Jones

2-loop integrals

- maximal number of propagators in diagrams obtained from Feynman rules: ***N***=7
- maximal number of scalar products in numerator: ***S***=9

$$S = \frac{l(l+1)}{2} + lm$$

`m`: *number of (independent) external momenta*
`l`: *number of loops*

- define integral family: add propagators such that all numerators can be expressed in terms of inverse propagators

→ input for Reduze/FIRE5/LiteRed

master integrals:

triangle type: partly known analytically

Bonciani, Mastrolia, Remiddi; Harlander et al; Anastasiou, Beerli et al

box type: scales s, t ,(u), m_H, m_t → **SecDec**

note: SecDec can also do integrals with numerators

SecDec

http://secdec/hepforge.org

- Home
- Subversion
- Tracker
- Wiki

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University of Zurich[UZH]

SecDec

Sophia Borowka, Gudrun Heinrich, 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-3.0.5.tar.gz.

version 3.0: arXiv:1502.06595

S.Borowka, GH, S.Jones, M.Kerner, J.Schlenk, T.Zirke

SecDec

new features (version 3.0):

- implementation of two new decompositions strategies based on a geometric algorithm (guaranteed to stop!)
- improved user interface
- linear propagators can be treated
- option to use numerical integrators from Mathematica (and Cquad)
- propagators with negative indices are possible
- usage on a cluster facilitated

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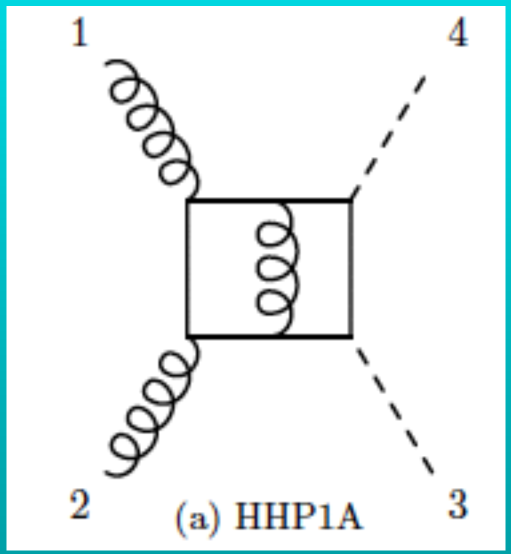
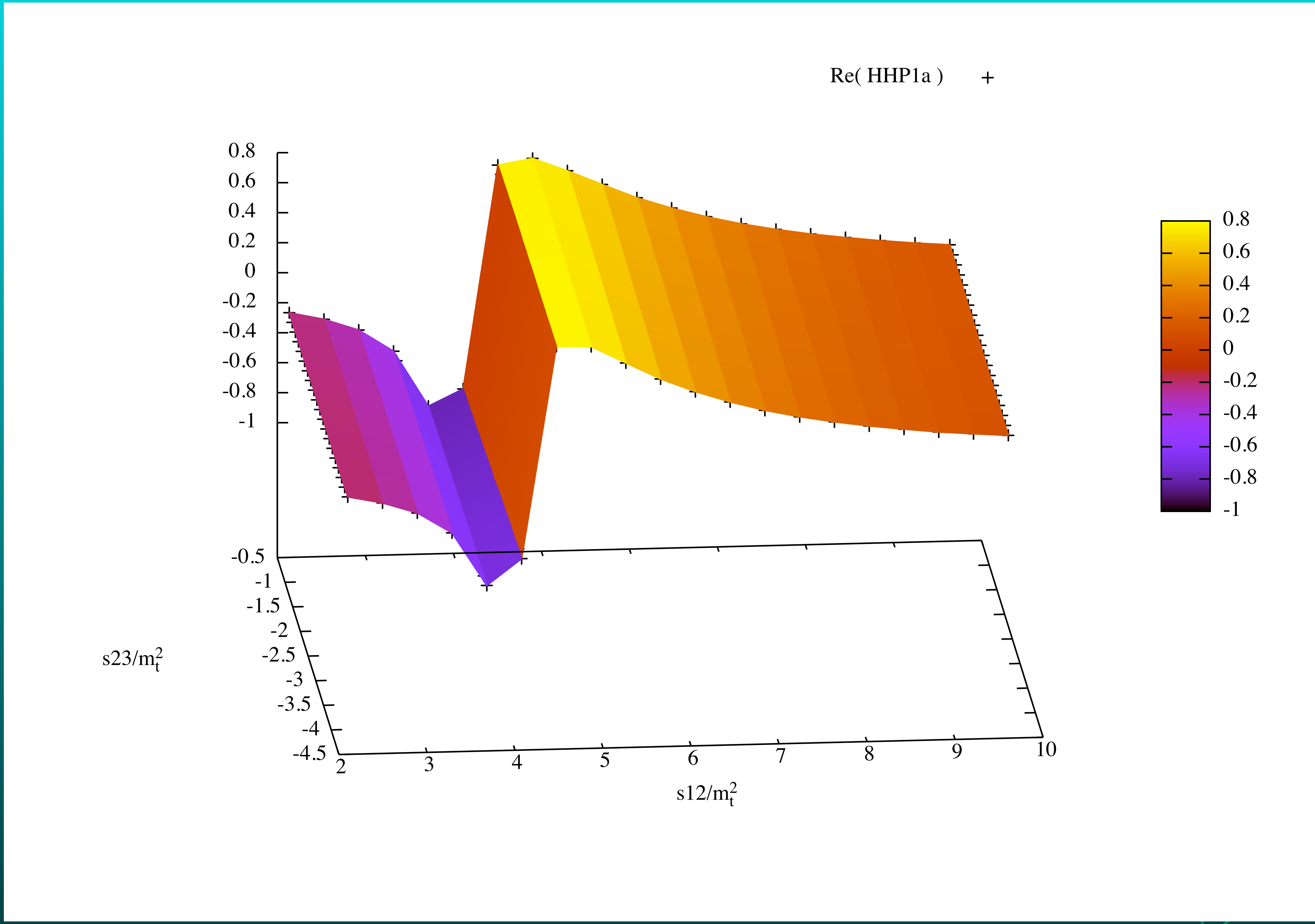
efficient tool, make it part of GoSam-2Loop

master integrals: examples



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



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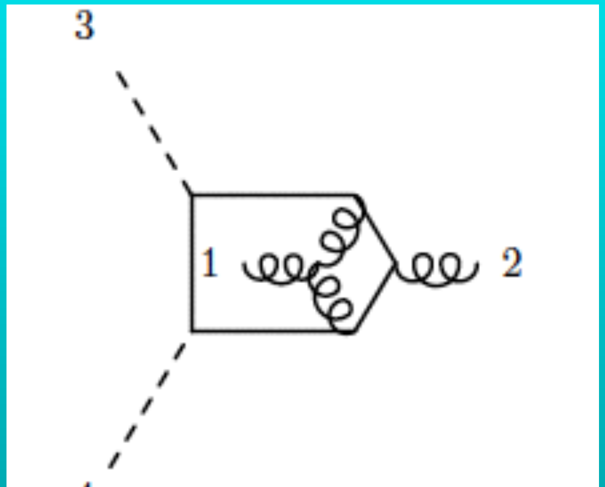
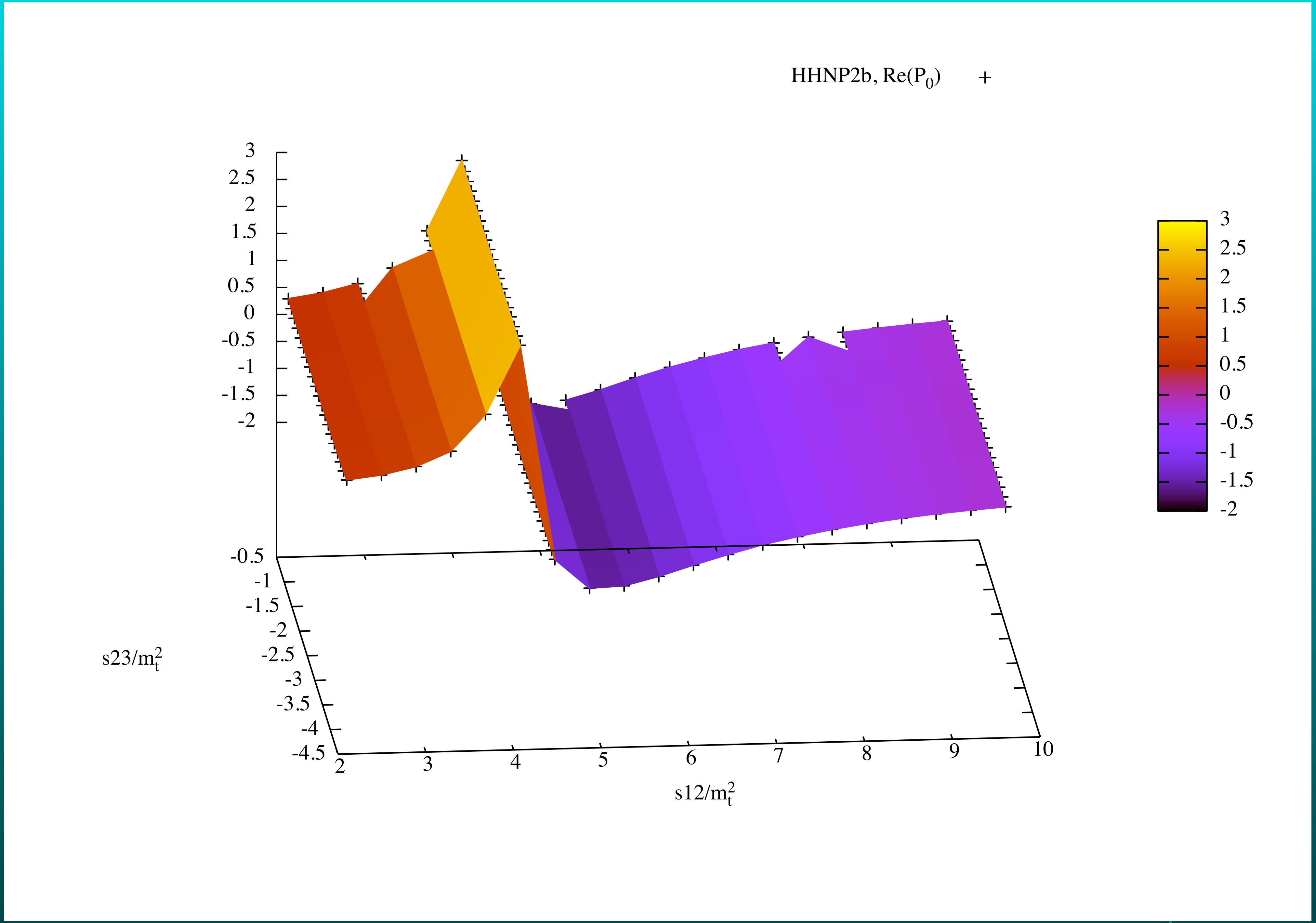


(b) HHNP2B

$$I = \frac{P_1}{\epsilon} + P_0$$



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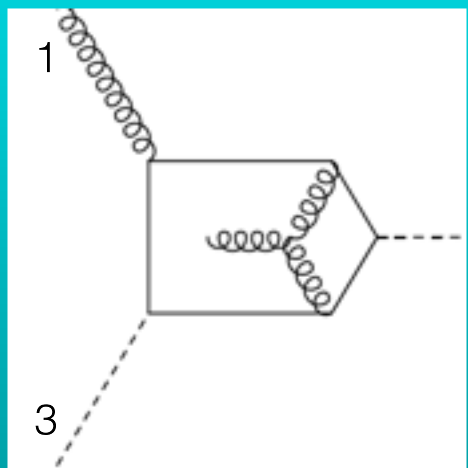

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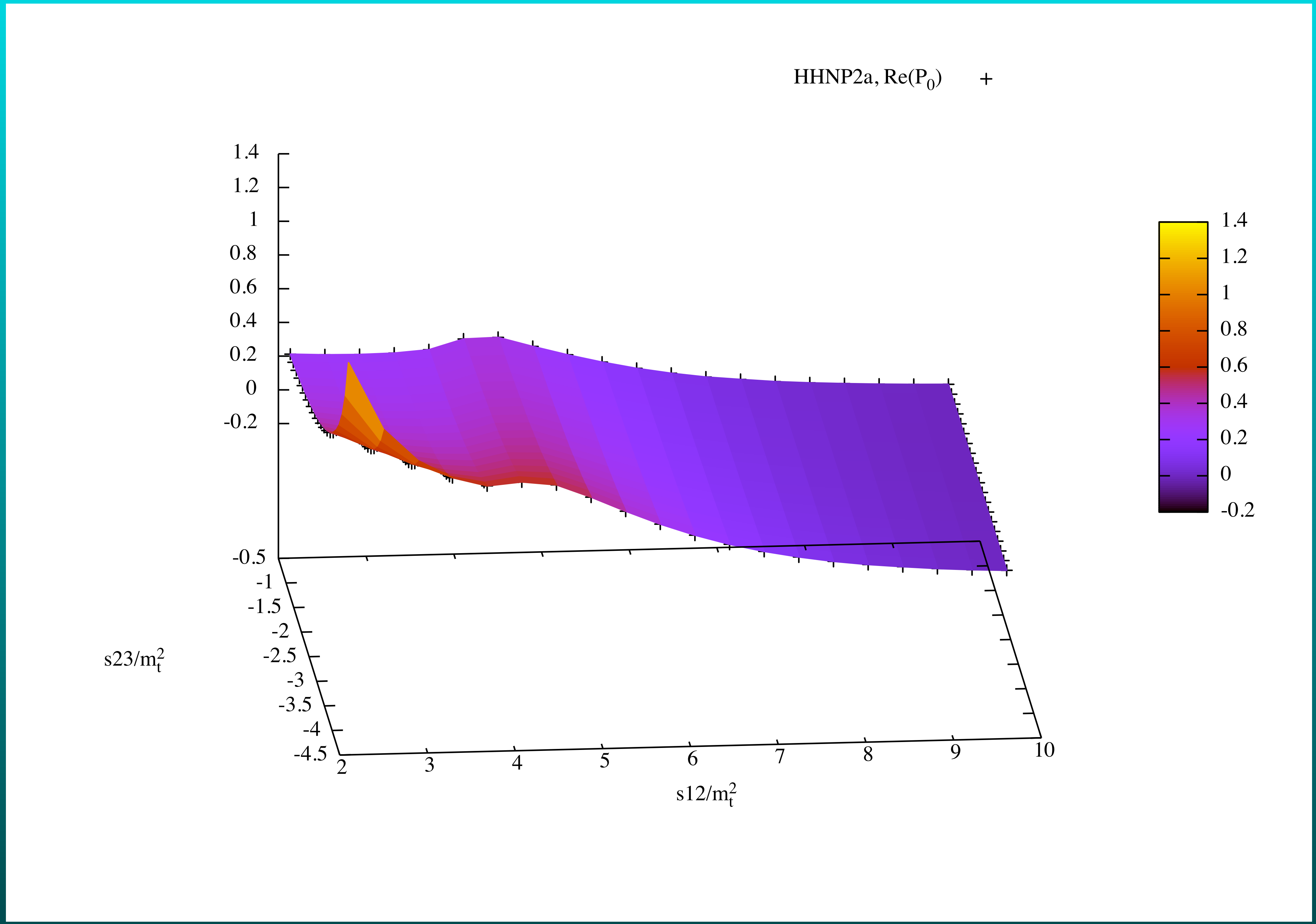

Conclusions/Outlook

- measurement of **Higgs pair production vital** to understand mechanism of EW symmetry breaking

- heavy top approximation for gg to HH not satisfactory

- NLO with full top mass dependence for HH in gluon fusion well underway

- GoSam-2Loop setup quite generic, can be applied to other processes

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extra slides