HiggsTools Mid-Term Review - ESR8

Stephen Jones

Supervisors:
Stefan Dittmaier (ALU-FR)
Gudrun Heinrich (MPI)

Background

Born: Liverpool, (1988)

Degree (MPhys): University of Liverpool, (2006-2010)

Proton Structure and Mellin Moments

(Supervisor: Prof. A. Vogt)

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Chemical Engineer, Wikimedia CC BY-SA 3.0

PhD: University of Liverpool, (2010-2014)

A Study of Exclusive Processes to NLO and Small-x PDFs from LHC Data

(Supervisor: Dr. T. Teubner)

Project 1-HH @ NLO

Goal: Total Cross-Section for $gg \to HH$ @ NLO (2-loop) with Top mass

WP2

M2.1.1

M2.1.2

Motivation:

$$\mathcal{L} \supset -\frac{m_H^2}{2} H^2 - \boxed{\frac{m_H^2}{2v} H^3} - \frac{m_H^2}{8v^2} H^4$$

- Stepping stone for $2 \to 2$ @ 2-loop (multiple scales)
- Large NLO correction, $K \approx 2$
- Known $m_T^2 \to \infty$ limit not completely well motivated
- Various approximations do not yield a coherent picture

Maltoni, Vryonidou, Zaro 14 -10%

Grigo, Hoff, Melnikov, Steinhauser 13; Grigo, Hoff, Steinhauser 15 $\pm 10\%$

Project 2-GoSam Multi-loop

Goal: Extend GoSam from automated calculation of 1-loop amplitudes to (some) multi-loop amplitudes

WP2
M2.3.3
WP3
M3.2.1

Motivation:

- Precision measurements at LHC are increasingly important

- Many NLO QCD processes now known & significant automation already achieved

- Many NNLO QCD processes have recently become tractable

Virtual: IBPs, DEs; Tkachov, Chetyrkin 81, Laporta 00 … Kotikov 91, Remiddi 97, Gehrmann 00 …

Real: Antenna, qT, N-jettiness; NLO: Kosower 98, Glover et al. 99 & NNLO 05, … Catani, Grazzini 07, Stewart, Tackmann et al. 10,…

- Automation should already be possible for a subset of NNLO QCD

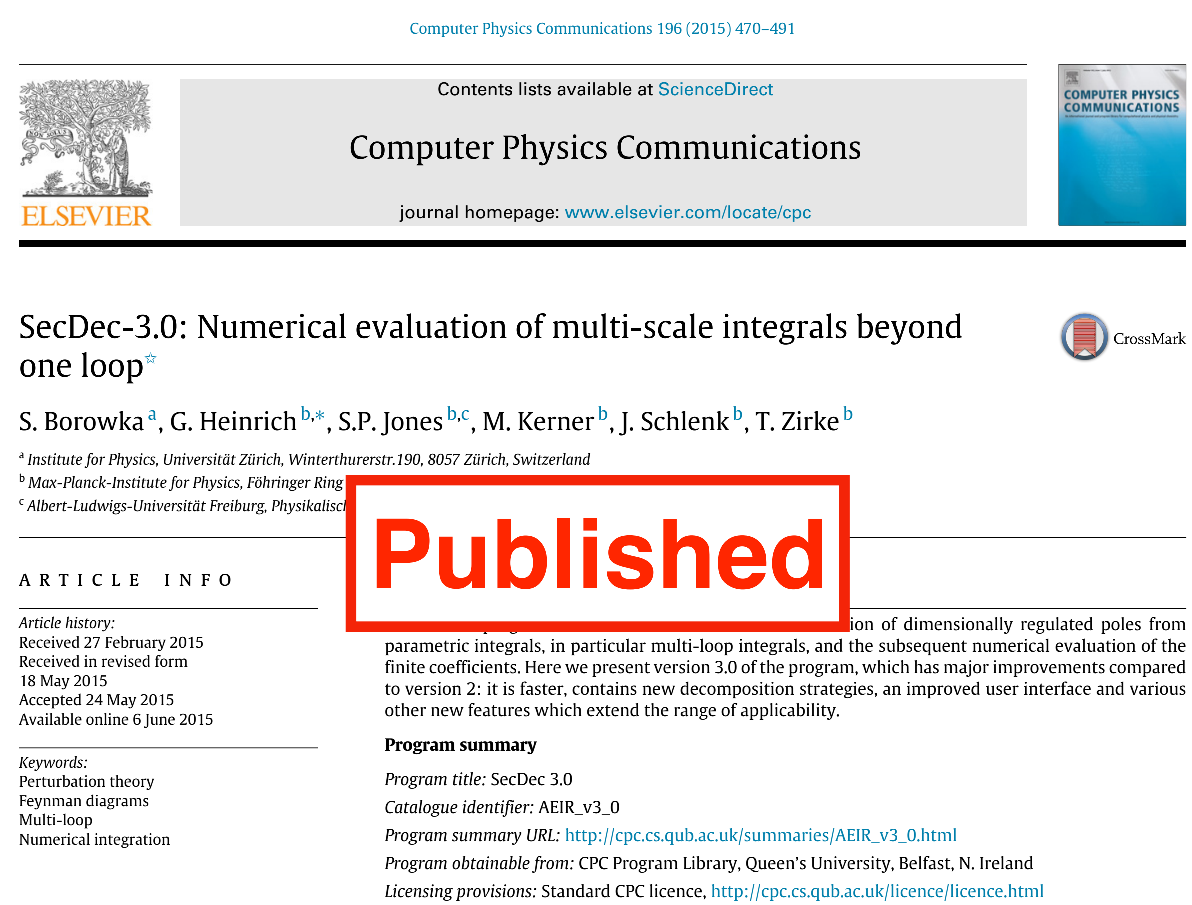
Project 3-SecDec

Goal: Improve SecDec, a tool for numerically evaluating dimensionally regulated parameter integrals

WP3
M3.2.1
Used in:
WP2

Achievements:

- New decomposition strategies (algebraic geometry)
- Support for inverse propagators
- Speed improvements
- Improved cluster mode
- Parameter scans



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SecDec-3.0: Numerical evaluation of multi-scale integrals beyond one loop☆

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Keywords:
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Feynman diagrams
Multi-loop
Numerical integration

ion of dimensionally regulated poles from parametric integrals, in particular multi-loop integrals, and the subsequent numerical evaluation of the finite coefficients. Here we present version 3.0 of the program, which has major improvements compared to version 2: it is faster, contains new decomposition strategies, an improved user interface and various other new features which extend the range of applicability.

Program summary

Program title: SecDec 3.0
Catalogue identifier: AEIR_v3_0
Program summary URL: http://cpc.cs.qub.ac.uk/summaries/AEIR_v3_0.html
Program obtainable from: CPC Program Library, Queen's University, Belfast, N. Ireland
Licensing provisions: Standard CPC licence, http://cpc.cs.qub.ac.uk/licence/licence.html

Project 4-Exclusive Processes & PDFs

Goal: Investigate what may be learnt about the low-x gluon distribution from exclusive heavy vector-meson (HVM) photo-production

WP2

M2.3.2

WP3

M3.3.3

Durham Node

Achievements:

- Studied NLO MEs (recalculated & corrected Virtuals)
- Proposed a scale-fixing argument to absorb logs (high energy)
- Anticipate significant uncertainty reduction for PDFs if LHC data are included via Shuvaev transform

arXiv:1507.06942v1 [hep-ph] 24 Jul 2015

Exclusive J/ψ and Υ photoproduction and the low x gluon

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Submitted: 1507.06942

Abstract

We study exclusive vector meson photoproduction, $\gamma p \to V + p$ with $V = J/\psi$ or Υ, at NLO in collinear factorisation, in order to examine what may be learnt about the gluon distribution at very low x. We examine the factorisation scale dependence of the predictions. We argue that, using knowledge of the NLO corrections, terms enhanced by a large $\ln(1/\xi)$ can be reabsorbed in the LO part by a choice of the factorisation scale. (In these exclusive processes ξ takes the role of Bjorken-x.) Then, the scale dependence coming from the remaining NLO contributions has no $\ln(1/\xi)$ enhancements. As a result, we find that predictions for the amplitude of Υ production are stable to within about $\pm 15\%$. This will allow data for the exclusive process $pp \to p\Upsilon p$ at the LHC, particularly from LHCb, to be included in global

Feasibility - HH

Conceptually Clear:

~~LO + PS Generator~~

~~Real Radiation~~

~~Dipoles~~

~~Virtual Amplitude~~

Integral Reduction

Master Integrals (SecDec)

Now Sufficiently complete
(327 Integrals)

<u>Compute limited</u>

Priority on Max Planck CDF

Importance sample integrals

Maximise reuse of integrals

Basis change possible

Several integration techniques

Feasibility - GoSam

Achieved:

HH Amplitude (+ cross-checked)

REDUZE Interface

In Development:

SecDec Interface ← Collaboration: SecDec Developers

Under Consideration:

Projectors (Helicity Basis?)

Integral Families? ← Worst case scenario: process-by-process input

Slicing/Subtraction Method?

```
process_name=gghh
process_path=virtual

in=g,g,25,25
out=
order=QCD, none, 2, 4

# one quark flavour [t] running in the loops:
qgraf.verbatim=true=iprop[U,D,C,S,B,0,0];

extensions=reduze
```

Many experts in HiggsTools Network + Collaborators

Project Outlook

HH/GoSam/SecDec have many avenues for further work!

Strategy:

Get low hanging fruit & push methods to the limit

Devise new methods

HH

σ_{tot} → $\frac{\mathrm{d}\sigma}{\mathrm{d}m_{HH}}$, $\frac{\mathrm{d}\sigma}{\mathrm{d}p_T}$, $HH \to b\bar{b}\gamma\gamma$

Parton Shower, BSM/ EFT

GoSam

Automate projectors & Integral Families?

Process based, e.g.

$HZ,\ \gamma j,\ (Zj,\ Wj)$

SecDec

Alternative integration techniques & optimisation

Training & Conferences

Training:

HiggsTools YRM (Durham, 2015)

HiggsTools Summer School (Palleusieux, Italy, 2015)

School of Analytic Computing in THEP (Atrani, Italy, 2015)

HiggsTools + Node Journal Club (ongoing)

Conferences:

`Automated Virtual MEs for HH Production', HiggsTools Annual Meeting (Freiburg, 2015)

Talks:

`Examining Diffractive Processes at LO & NLO' (MPI Munich,13/10/14)

Secondments & Private Sector

Academic: MPI Munich (Months: 19-21)

- Worked closely with collaborators on HH @ NLO

- Involved in significant discussion/ prototyping of future GoSam extensions

- Further (upcoming) SecDec development

Private: Wolfram (Anticipated Months: 30-32)

- Experience developing a language/ tool I use every day

- Gauge applicability of my skills to other disciplines, learn where to focus my effort to broaden my skill set

- Participate in research outside academia

Career Outlook

Goal 1: Academia

Collaboration: Zurich, Geneva, Padova, Munich & Hamburg

Contacts: ESRs (EU wide) & Supervisors (Key institutions)

Individuality: Continued individual work from PhD

PostDoc & eventually permanent position in Europe/US

Goal 2: Private

Broadened horizons (first study/work out of Liverpool)

Concrete & demonstrable programming experience

New opportunities: Programming / Technology

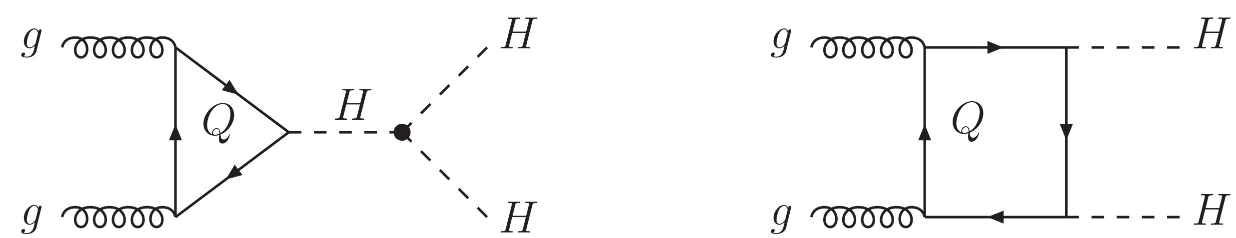
Programming/Tech/Research position

Thank you for listening!

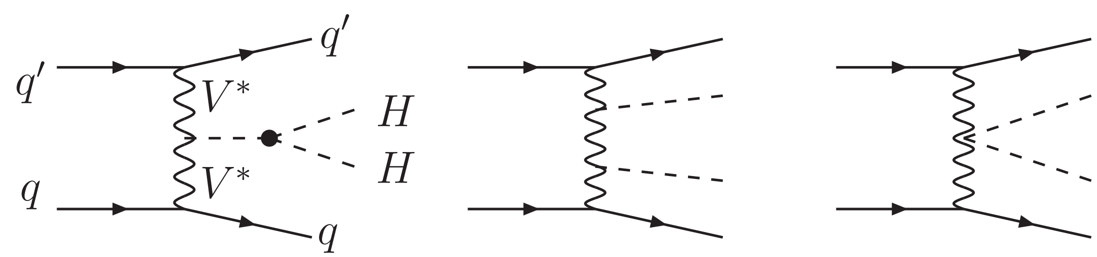
Production Channels

$\sigma(pp \to HH + X)$ @ 13TeV

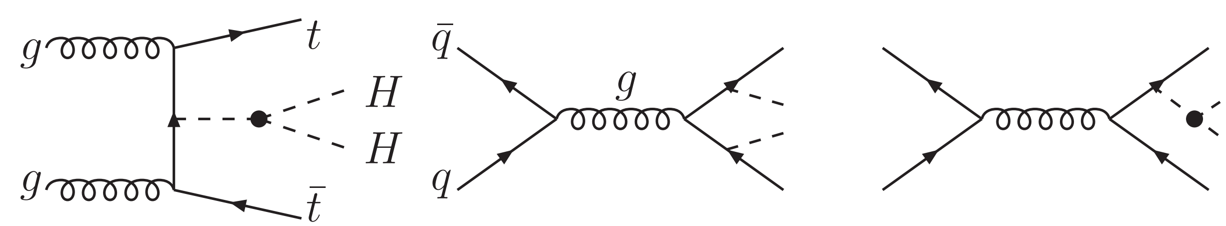
Gluon Fusion



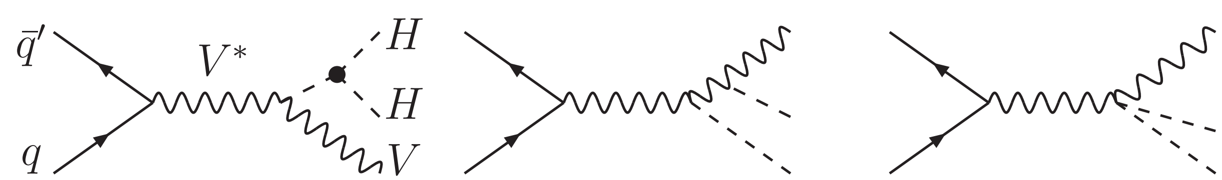
Vector Boson Fusion (VBF)



Associated top pair



Double Higgs-strahlung

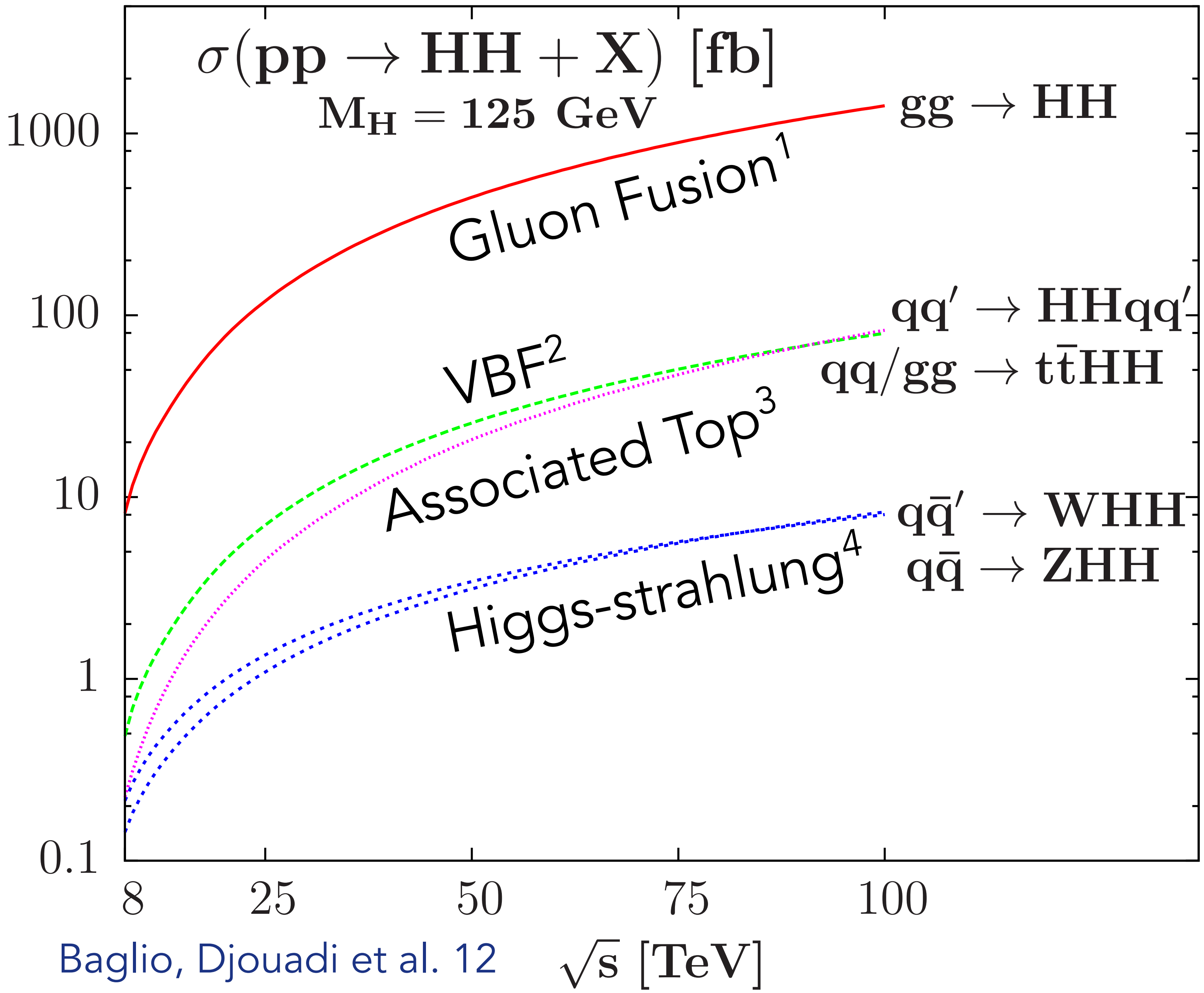


...

Baglio, Djouadi et al. 12

Production Channels

$$\sigma(pp \to HH + X) \sim \frac{1}{1000}\sigma(pp \to H + X)$$



Baglio, Djouadi et al. 12

[1] NLO QCD HEFT, `HPAIR`

Plehn, Spira, Zerwas 96, 98;
Dawson et al. 98

[2] NLO QCD, `VBFNLO`

Baglio, Djouadi et al. 12

[3] LO QCD (NLO, `aMC@NLO`)

Frederix, Frixione et al. 14

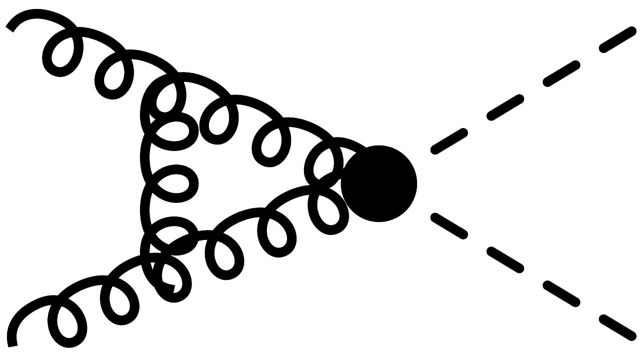
[4] NNLO QCD

Baglio, Djouadi et al. 12

Gluon Fusion

1. LO (1-loop), Dominated by $Q = t, b$ (b contributes 1%)
   Glover, van der Bij 88

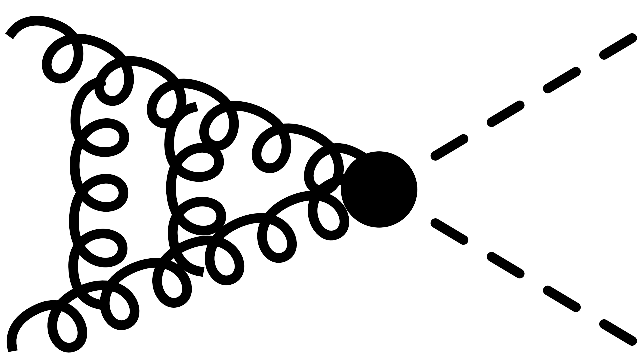
2. Born Improved NLO H(iggs)EFT $K \approx 2$
   Plehn, Spira, Zerwas 96; Dawson, Dittmaier, Spira 98



   A. Including m_T in Real radiation
      Maltoni, Vryonidou, Zaro 14

   B. Including $\mathcal{O}(1/m_T^{12})$ terms in Virtual MEs
      Grigo, Hoff, Melnikov, Steinhauser 13; Grigo, Hoff 14

3. Born Improved NNLO HEFT +20%
   De Florian, Mazzitelli 13



   Including matching coefficients
   Grigo, Melnikov, Steinhauser 14

   NNLL Soft Gluon Resummation +30%
   Shao, Li, Li, Wang 13; De Florian, Mazzitelli 15

Gluon Fusion (NLO HEFT)

Tension between corrections to HEFT!

Born Improved NLO QCD HEFT

$$\mathrm{d}\sigma^V_{\mathrm{NLO}}(m_T) \approx \mathrm{d}\bar{\sigma}^V_{\mathrm{NLO}}(m_T) = \frac{\sigma^V_{\mathrm{NLO}}(m_T \to \infty)}{\sigma^V_{\mathrm{LO}}(m_T \to \infty)} \sigma^V_{\mathrm{LO}}(m_T)$$

$$\mathrm{d}\sigma^R(m_T \to \infty)$$

$$K \approx 2$$

A. Maltoni et al.14

$$\mathrm{d}\bar{\sigma}^V(m_T)$$

$$\mathrm{d}\sigma^R(m_T)$$

$$-10\%$$

B. Grigo, Hoff 14

$$\mathrm{d}\sigma^V_{\mathrm{NLO}}(m_T) \approx \mathrm{d}\bar{\sigma}^V_0 + \mathrm{d}\bar{\sigma}^V_0 \frac{\lambda^2}{m_T^2} + \ldots + \mathrm{d}\bar{\sigma}^V_6 \frac{\lambda^{12}}{m_T^{12}}$$

$$\mathrm{d}\sigma^R(M_t \to \infty)$$

$$+10\%$$

Real-virtual Cancellations Spoilt?

Stable?

Shopping List

Virtual MEs (HH):

Channels:

$gg \to HH$ ~~$q\bar{q} \to HH$~~

Contributes at NNLO

	Diagrams
Tree	0
1-loop	8
2-loop	122

Real Radiation (HH + j…):

Huge simplification!

1-j Channels:

$gg \to HH + g$

$gq \to HH + q$ $g\bar{q} \to HH + \bar{q}$

$q\bar{q} \to HH + g$

	Diagrams
Tree ⊗ Double	0
1-loop ⊗ Single	54+8+8+8

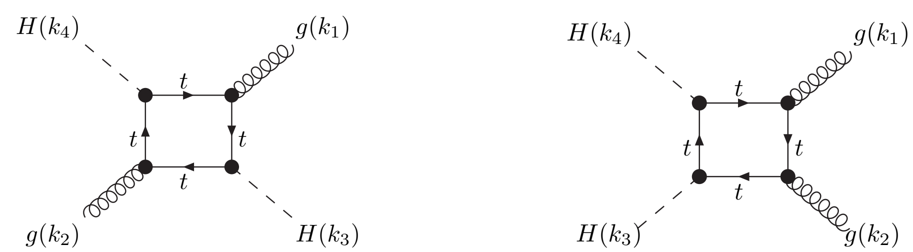
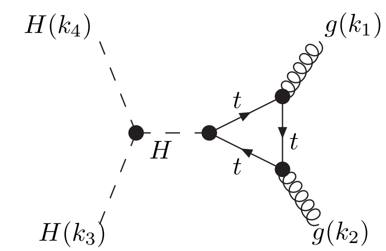
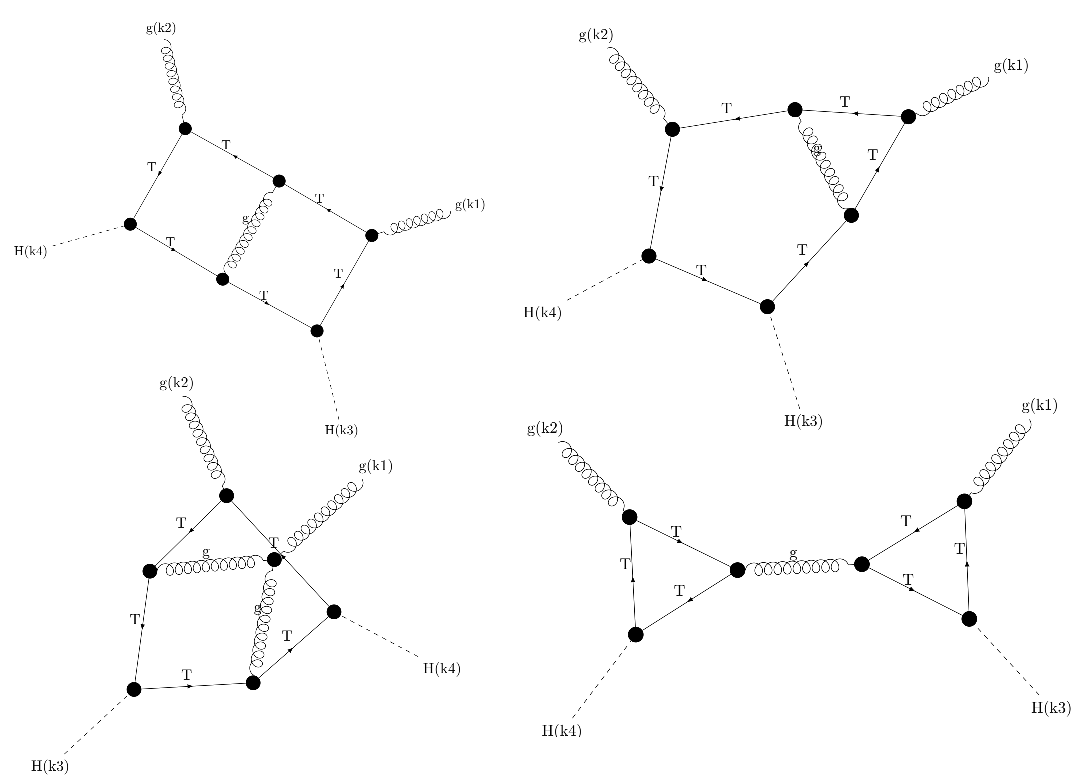
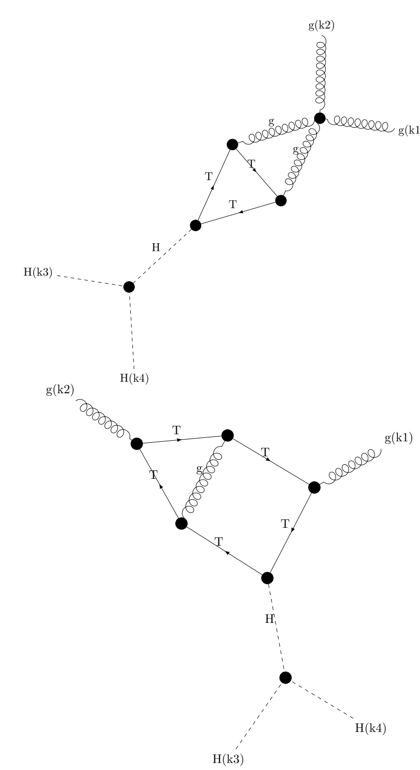
`GoSam` for MEs + Catani-Seymour Dipole Subtraction

Catani, Seymour 96

Project 1-HH @ NLO (II)

Boxes & Triangles

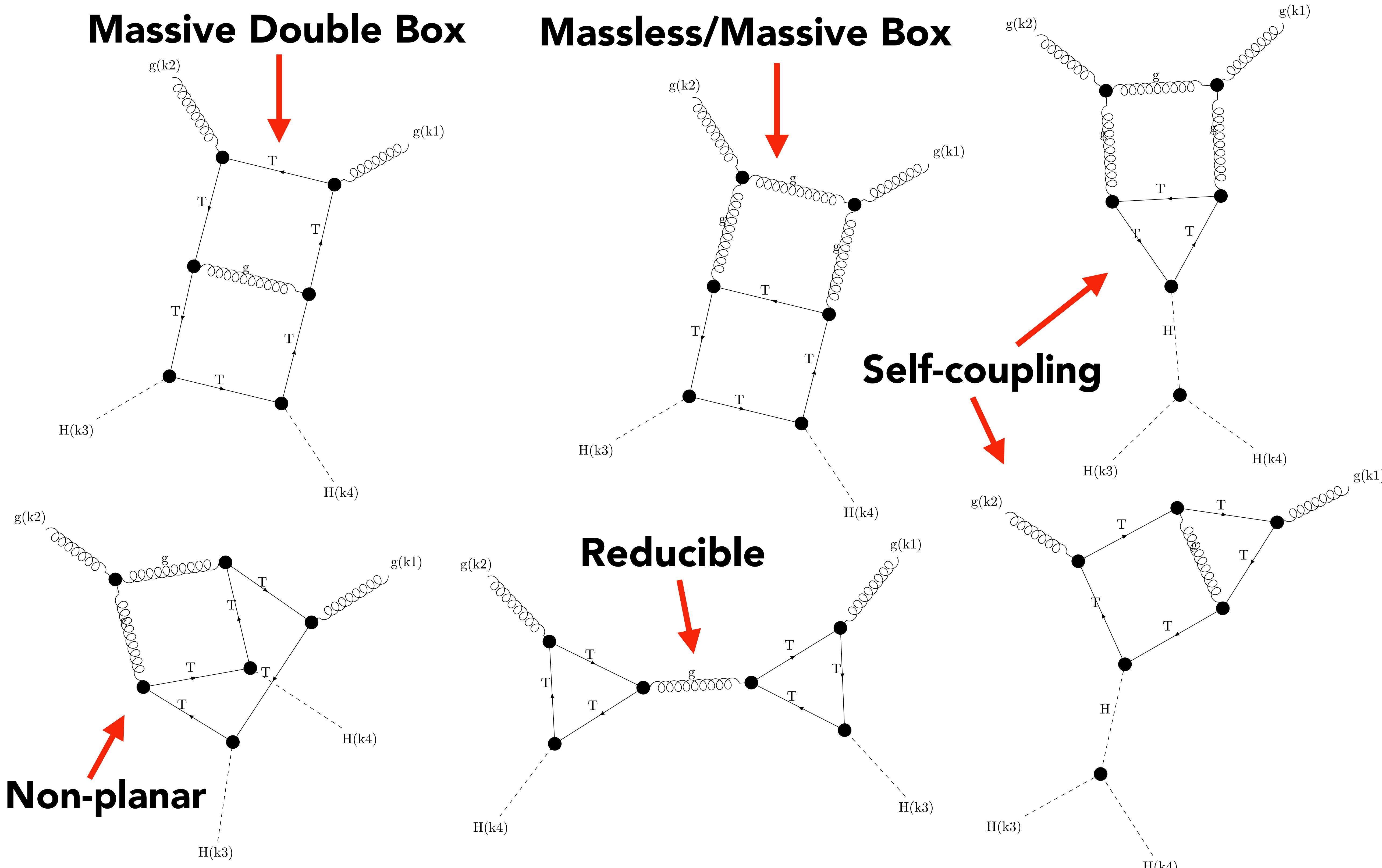
<table>
<tr><th></th><th>Yukawa only (≤ 4-point)</th><th>Self-coupling (3-point)</th></tr>
<tr><td>LO

Glover, van der Bij 88</td><td>
6 Diagrams</td><td>
2 Diagrams</td></tr>
<tr><td>NLO</td><td>
101 Diagrams</td><td>
Known
$gg \to H$

Spira et al.93, 95;
P. Mastrolia et al. 03;
Beerli et al. 06;
...

21 Diagrams</td></tr>
</table>

Diagrams


Massive Double Box
Massless/Massive Box
Self-coupling
Reducible
Non-planar
g(k1)
g(k2)
H(k3)
H(k4)
T
g
H

Form Factor Decomposition

Expose tensor structure: $\mathcal{M} = \epsilon^1_\mu \epsilon^2_\nu \mathcal{M}^{\mu\nu}$

Decomposition:

Form Factors (Contain integrals)

$$\mathcal{M}^{\mu\nu} \propto A_1(s,t,m_H^2,m_T^2,d)T_1^{\mu\nu} + A_2(s,t,m_H^2,m_T^2,d)T_2^{\mu\nu}$$

(Tensor) Basis

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

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

$$T_1^{\mu\nu} = g^{\mu\nu} - \frac{p_2^\mu p_1^\nu}{p_1 \cdot p_2} \qquad p_T^2 = \frac{ut - m_H^4}{s}$$

$$T_2^{\mu\nu} = g^{\mu\nu} + \frac{m_H^2 p_2^\mu p_1^\nu}{p_T^2 p_1 \cdot p_2} - \frac{2p_1 \cdot p_3 p_2^\mu p_3^\nu}{p_T^2 p_1 \cdot p_2} - \frac{2p_2 \cdot p_3 p_3^\mu p_1^\nu}{p_T^2 p_1 \cdot p_2} + \frac{2p_3^\mu p_3^\nu}{p_T^2}$$

Glover, van der Bij 88

Form Factor Decomposition

Construct Projectors:

No Integrals

$$P_j^{\mu\nu} = \sum_{i=1}^{2} B_{ji}(s,t,m_H^2,d) T_i^{\mu\nu}$$

Same Basis as amplitude

Such that:

$$P_{1\,\mu\nu}\mathcal{M}^{\mu\nu} = A_1$$

$$P_{2\,\mu\nu}\mathcal{M}^{\mu\nu} = A_2$$

Explicitly; separately calculate the contraction of each projector with $\mathcal{M}^{\mu\nu}$

Recall:

$$\mathcal{M}^{++} = \mathcal{M}^{--} = -A_1$$
$$\mathcal{M}^{+-} = \mathcal{M}^{-+} = -A_2$$

- Self-coupling diagrams are 1PR by cutting a scalar propagator
- By angular momentum conservation they contribute only to A_1

Current Status: Projectors constructed/ input by hand

Integral Reduction

Integral Reduction (dramatically) reduces the number of integrals!

Integrals	1-loop	2-loop
Direct	63	9865
+ Symmetries	21	1601
+ IBPs	8	~260-270 (currently 327)

3 Finite Boxes, 4 Finite Triangles + (d-4) x Bubble!

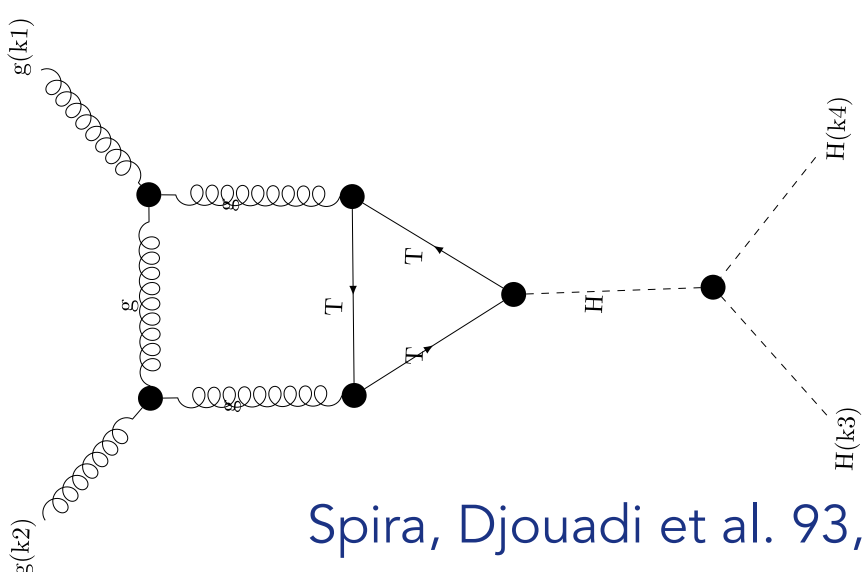
Current Status: Writing `GoSam` interface to existing Integral Reduction tools: `Reduze`, `LiteRed`, `FIRE`

Manteuffel, Studerus 12; Lee 13; Smirnov, Smirnov 13

Master Integrals

Double Higgs Production Master Integrals are tough!

- Massive propagators
- Off-shell legs

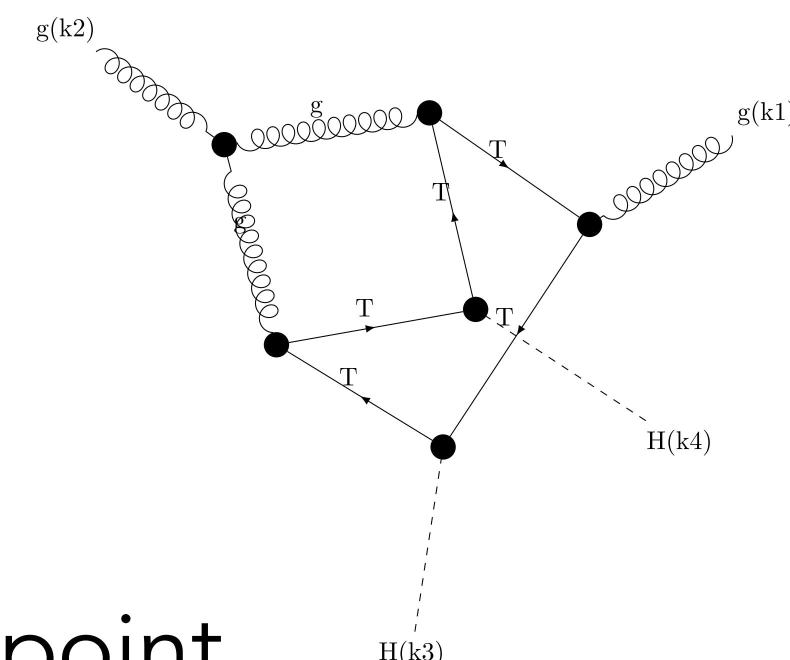


Spira, Djouadi et al. 93, 95;
Bonciani, P. Mastrolia 03,04;
Anastasiou, Beerli et al. 06;
…

3-point

2 scales s, m_T^2

Known analytically



4-point

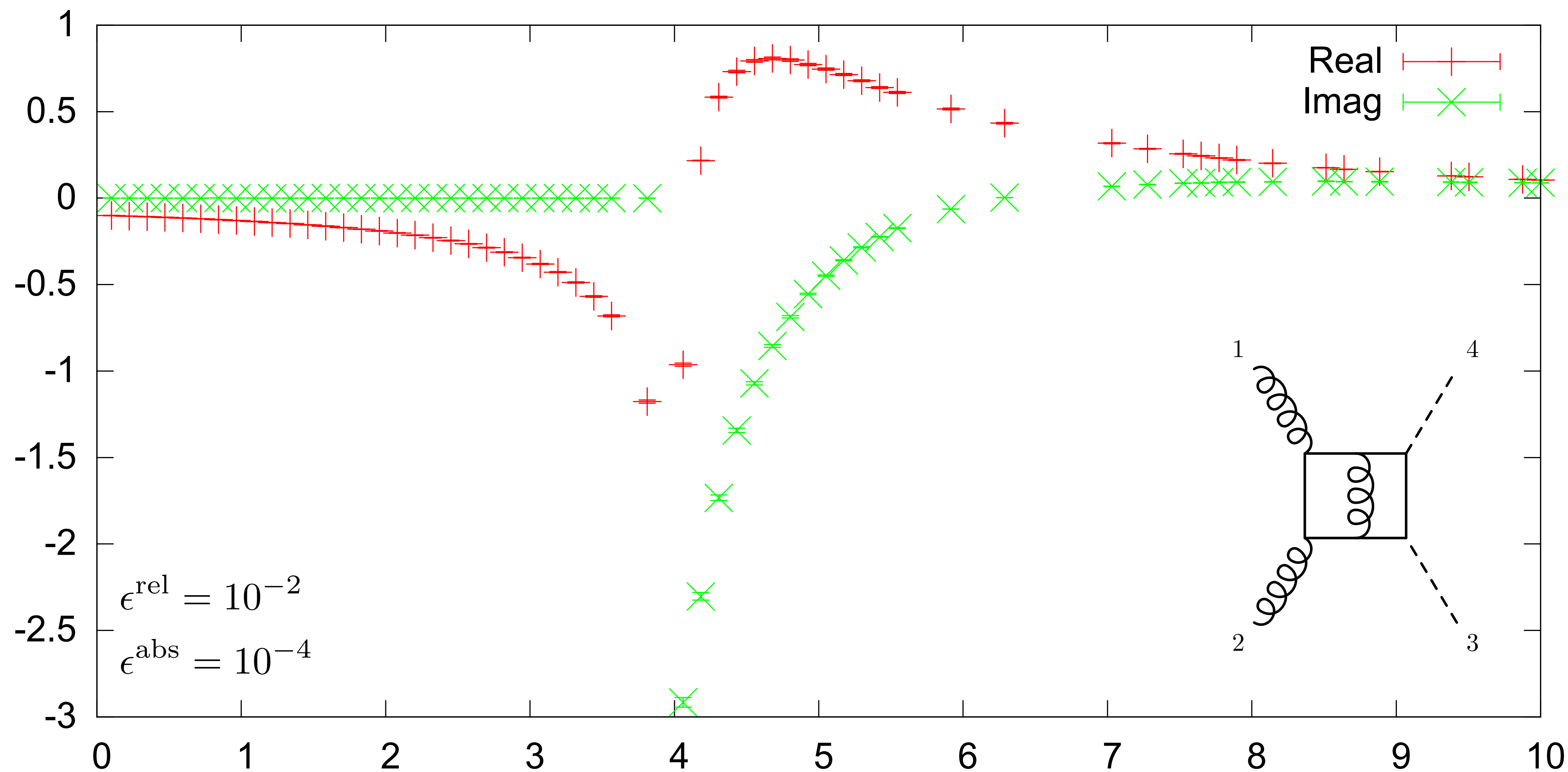
4 scales s, t, m_T^2, m_H^2

Numerical (`SecDec`)

Master Integrals (Numerical)

SecDec (https://secdec.hepforge.org)

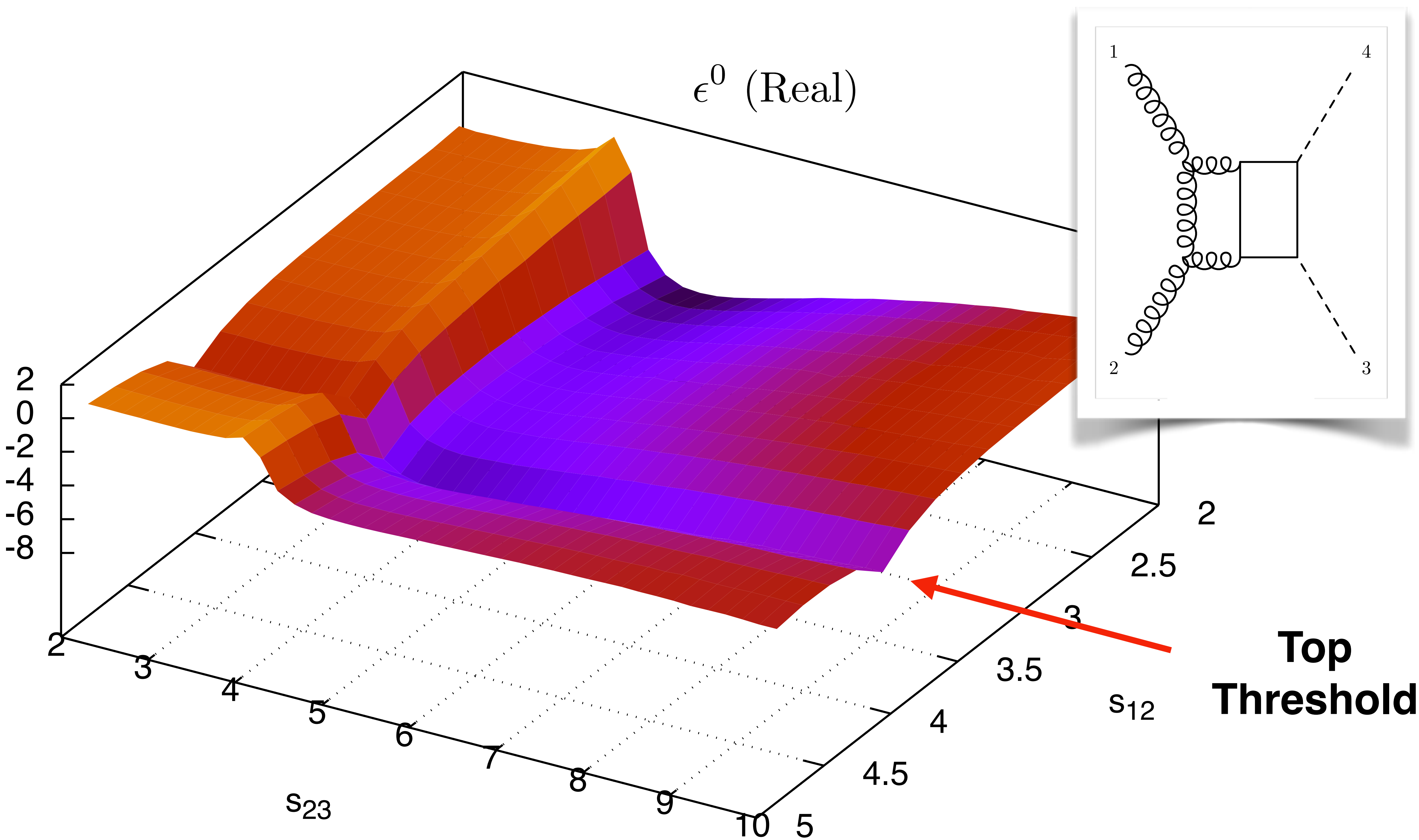
Evaluate Dimensionally regulated parameter integrals numerically



Top Threshold ↑ s_{12} (s/m_T^2)

Thanks: Anton Stoyanov

Master Integrals (Numerical)



Thanks: Anton Stoyanov
S. Jones ESR8, Freiburg

Integrals

k_i Loop momenta, p_i L.I. External momenta,

$N_i = (q_i^2 - a)$ Propagator^{-1}, $q_i = \sum_{i=1}^{j} b_i k_i + \sum_{i=1}^{m} c_i p_i$

After Dirac algebra (Traces):

$$A_j \supset \int \mathrm{d}^d k_1 \int \mathrm{d}^d k_2 \frac{f(k_1 \cdot k_1, k_1 \cdot k_2, \ldots, k_2 \cdot p_3)}{N_1 \cdots N_7}$$

(Max) 7 Propagators in Diagram

$S >$ **#Propagators: Irreducible Numerators**

Number of Scalar products:

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

$l = 2$ # Loops

$m = 3$ # L.I External momenta

$S = 9$

Integral Reduction

Integral family: Add propagators s.t. all scalar products can be expressed in terms of (inverse) propagators

$$A_j \supset \int \mathrm{d}^d k_1 \int \mathrm{d}^d k_2 \frac{1}{N_1^{\alpha_1} \dots N_9^{\alpha_9}} \equiv I(\alpha_1, \dots, \alpha_9)$$

Encode all integrals by their propagator powers

Current Status: Integral families input by hand

Symmetries: $I(\alpha_1, \dots, \alpha_9) = I(\sigma(\alpha_1), \dots, \sigma(\alpha_9))$ ← **For some** $\alpha_i > 0$

Integration-by-parts (IBP) /Lorentz Invariance (LI) Identities

Tkachov 81; Chetyrkin, Tkachov 81 Gehrmann, Remiddi 99

Laporta/ S-Bases algorithms to automate application of

Laporta 01; Smirnov, Smirnov 06

these identities

Uncertainties

Total Cross Section:

Born Improved NLO HEFT

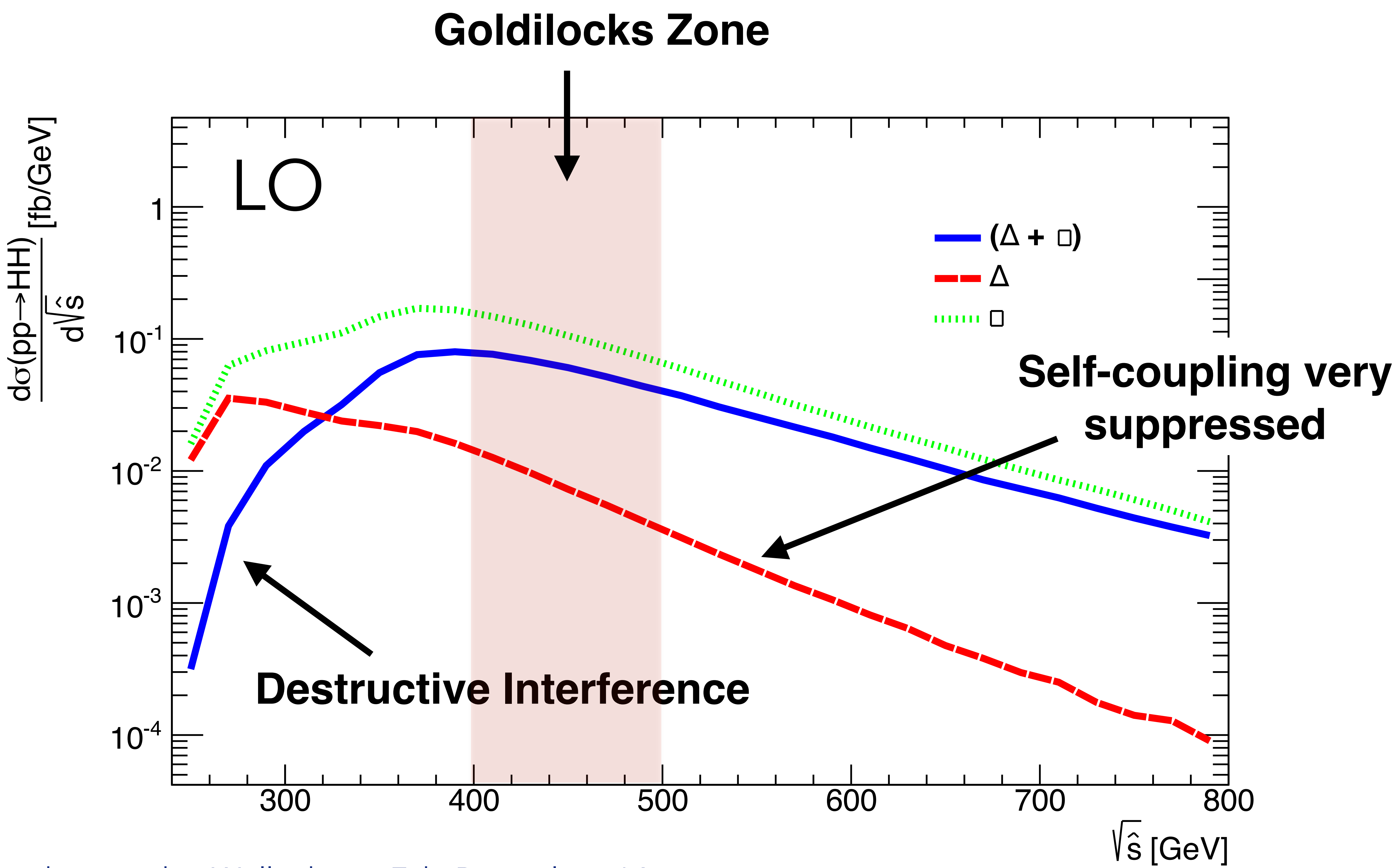
Scale $\mu_0 = \mu_R = \mu_F = M_{HH}$, Variation: $[\frac{\mu_0}{2}, 2\mu_0]$

Some arguments for switching to $\mu_0 = M_{HH}/2$ **or** $\mu_0 = 2m_H$ **(account for NNLL?)**

Scale	15-20%
PDF + α_s	6-7%
EFT (NLO)	~10%
Total	30-40%

See: Eg… Baglio, Djouadi et al. 12

Self-Coupling Sensitivity



Slawinska, van den Wollenberg, Eijk, Bentvelsen 14