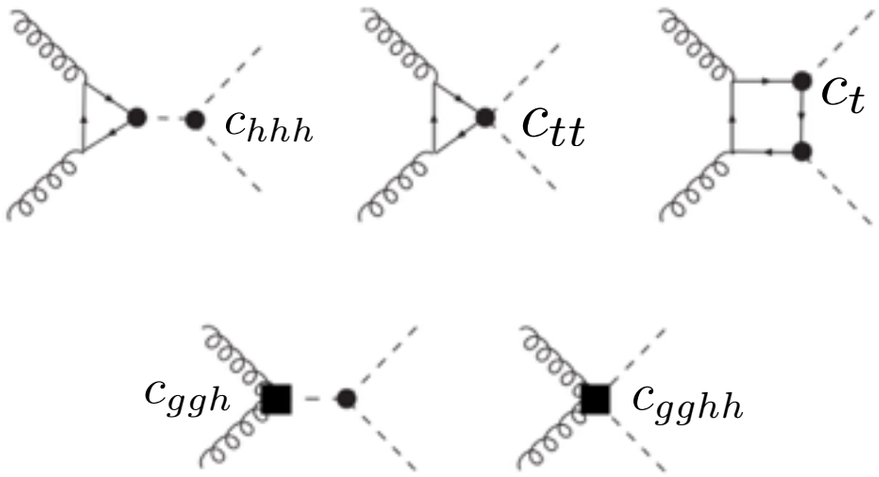
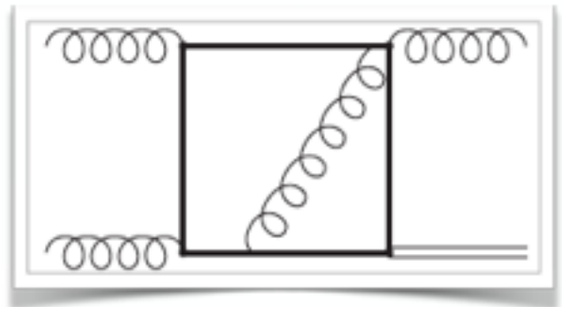
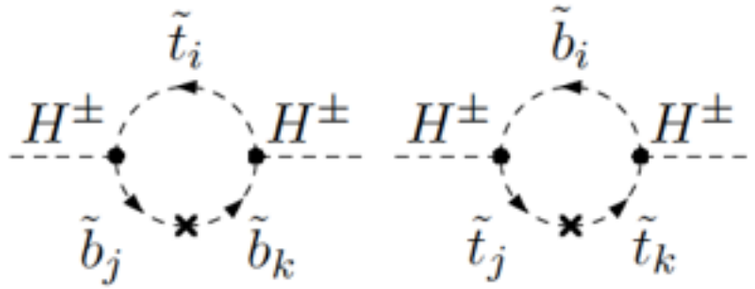
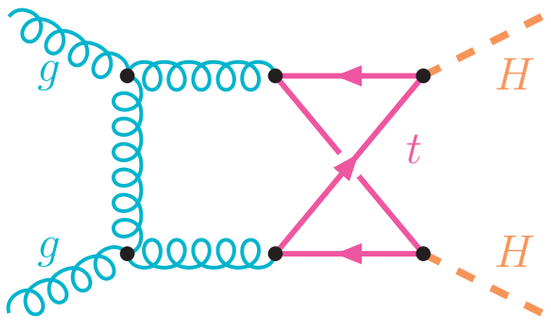
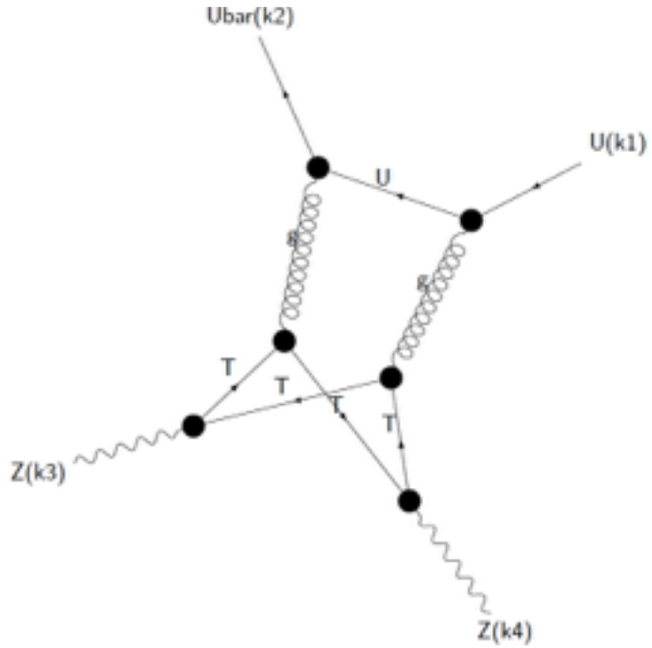
Phenomenology 2018: selected topics

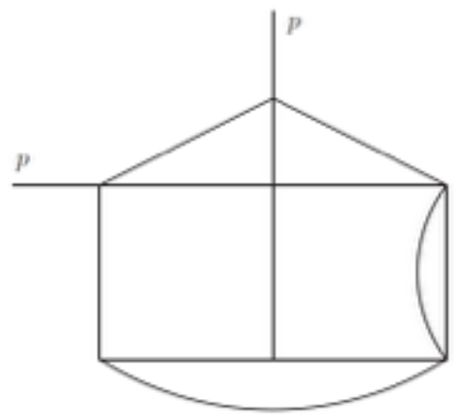












Gudrun Heinrich, MPP

Project Review 2018

MAX-PLANCK-GESELLSCHAFT

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

Phenomenology group before October 2018

- **Director:** *W. Hollik*
- **Senior staff:** *Thomas Hahn, Gudrun Heinrich*
- **Postdocs:** *Long Chen, Stephen Jones, Matthias Kerner, Gionata Luisoni*
- **PhD students**

  completed: *Henning Bahl, Stephan Hessenberger, Cyril Pietsch*

  ongoing: *Matteo Capozi, Stephan Jahn, Ludovic Scyboz (partial member)*

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new developments:

- **new directors:**

  Johannes Henn (October 2018)

  Giulia Zanderighi (January 2019)

- **independent research group:**

  Ulrich Haisch (October 2018)

New group members since October 2018

- Director: *Johannes Henn*
- Junior group leader: *Yang Zhang*
  (within ERC grant)
- Postdocs: *Taushif Ahmed*
  Dmitry Chicherin
  Kai Yan
- PhD Students: *Christoph Dlapa*
  Daniele Lombardi
  Leila Maestri
  Simone Zoia

Research directions

★ precision calculations

- Standard Model:
  - Higgs+jet production at NLO with full top quark mass dependence
    Stephen Jones, Matthias Kerner, Gionata Luisoni
  - Higgs-boson pair production at NNLO with top quark mass effects
    *Grazzini, Kallweit, **GH, Jones, Kerner**, Lindert, Mazzitelli*
  - NNLO predictions for Z-boson pair production at the LHC
    GH, Stephan Jahn, Stephen Jones, Matthias Kerner, Joao Pires
  - NLO and off-shell effects in top quark mass determinations
    ***GH,** A.A. Maier**, R. Nisius**, J. Schlenk, M. Schulze, **L. Scyboz**, J. Winter*
- Beyond the Standard Model: see next slide

★ tools development:

FeynArts, FormCalc, LoopTools, FeynHiggs, pySecDec, QMC, GoSam-Xloop, Loopedia

Beyond the Standard Model

- Higgs boson pair production beyond the SM

  effective field theory – generalized frame for Higgs physics

  Buchalla, Celis (LMU), *Capozi, Heinrich, Scyboz* (MPP)

- precision observables, non-standard Higgs bosons

  extra singlet, two doublets, supersymmetric Higgs

  Hessenberger, Hollik, Pietsch (MPP)

- SUSY Higgs boson spectrum calculations, FeynHiggs

  resummation of large $\log(M_{\rm SUSY}/m_t)$,

  SM or THDM as low-energy effective theory

  Bahl, Hahn, Hollik (MPP) *et al.*

- SUSY models in light of improved Higgs mass calculations

  global analysis

  Bahl, Hahn, Hollik (MPP) *et al.*

Research directions

- tools development

  - FeynArts/FormCalc/LoopTools http://www.feynarts.de

    Thomas Hahn

  - FeynHiggs http://www.feynhiggs.de

    Bahl, Hahn, Heinemeyer, Hollik, Paßehr, Rzehak, Weiglein

  - pySecDec https://github.com/mppmu/secdec/

    Borowka, GH, Jahn, Jones, Kerner, Schlenk installation movie: https://www.youtube.com/watch?v=Ughnr3EKgkk

  - GoSam(-Xloop) https://gosam.hepforge.org/

    Chen, Greiner, GH, Jahn, Jones, Kerner, Luisoni et al.

  - Loopedia loopedia.org

    Bogner, Borowka, Hahn, GH, Jahn, Jones, Kerner, von Manteuffel, Michel, Panzer, Papara

https://loopedia.mpp.mpg.de

loopedia

Multiple Upload (exp

Loopedia

Ex.: Edge list [(1,2),(2,3),(2,3),(3,4)] or 1 2 2 3 2 3 3 4 — Nickel index e11|e|

Enter your graph by its edge list (adjacency list) or Nickel index

or browse:

Loops = any Legs = any Scales = any

Fulltext must contain: must not contain:

Search Reset

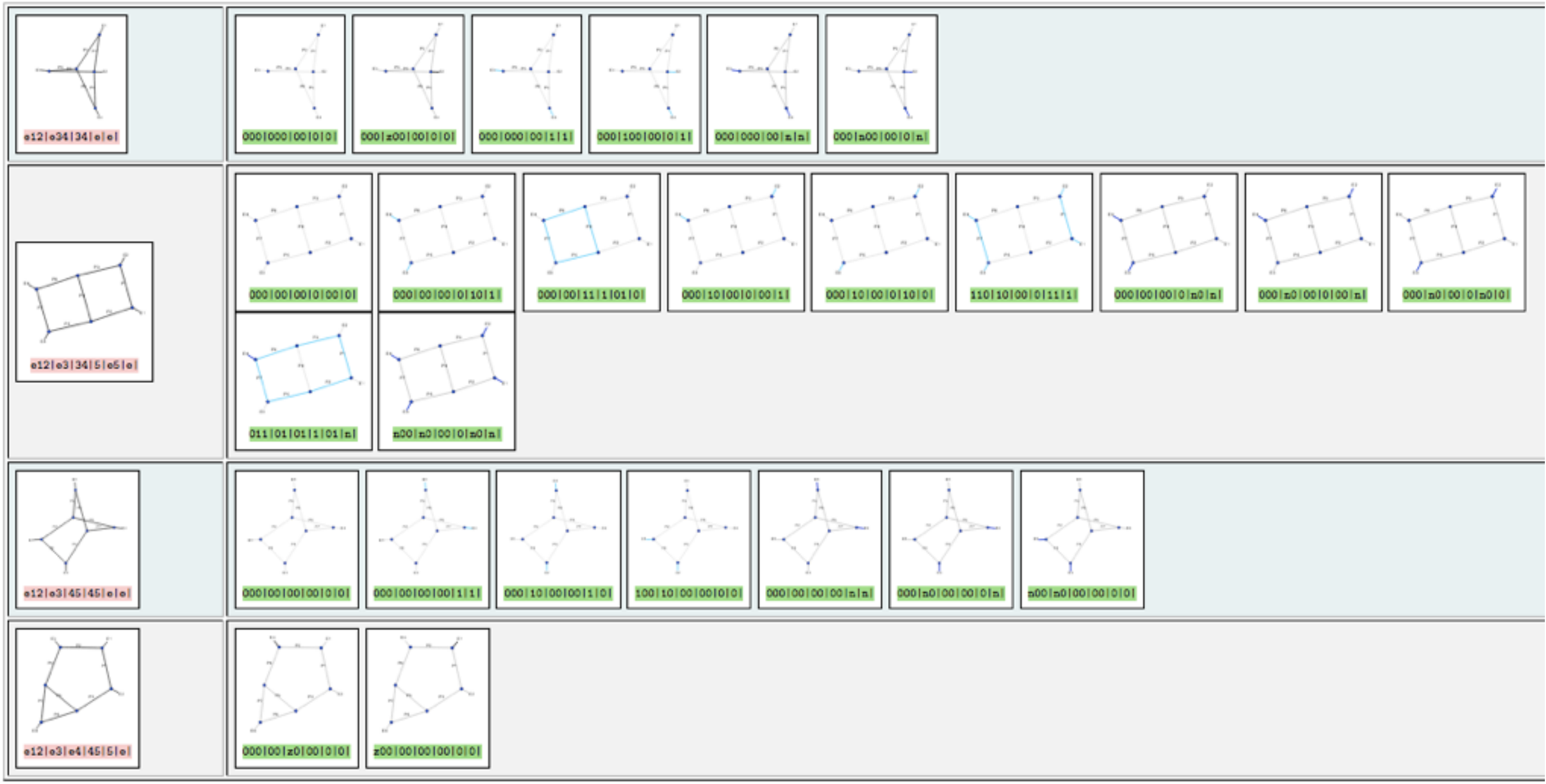
If you wish to add a new integral to the database, start by searching for its graph first.

The Loopedia Team is C. Bogner, S. Borowka, T. Hahn, G. Heinrich, S. Jones, M. Kerner, A. von Manteuffel, M. Michel, E. Panzer, V. Papara.
Software version of 23 May 2018 12:10 UTC. In case of technical difficulties with this site please contact Thomas Hahn or Viktor Papara.
This Web site uses the GraphState library [arXiv:1409.8227] for all graph-theoretical operations
and the neato component of Graphviz for drawing graphs.

Loopedia is free and open to everyone. To acknowledge and support the work put into keeping Loopedia up to date, please cite arXiv:1709.01266.
Data protection statement and Imprint

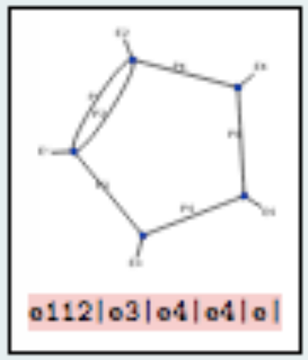
Loopedia

Results for loops = 2, legs = 4, all scales — Row 6»

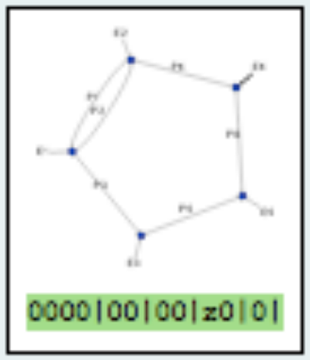


Loopedia

Results for loops = 2, legs = 5, all scales



e112|e3|e4|e4|e|



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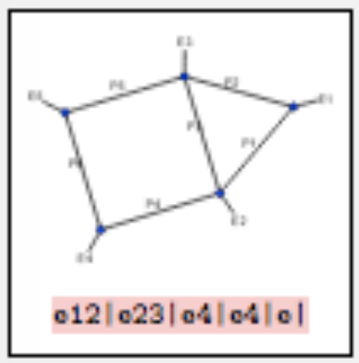

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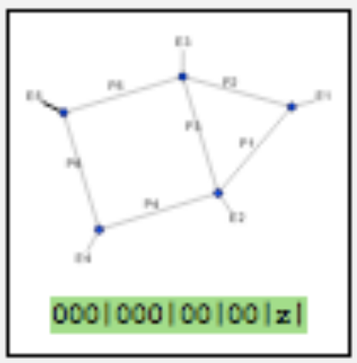

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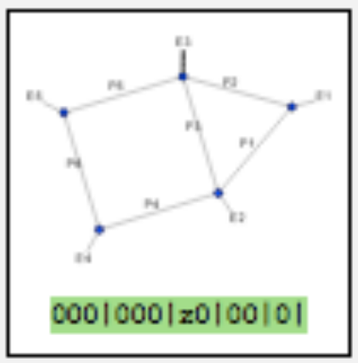

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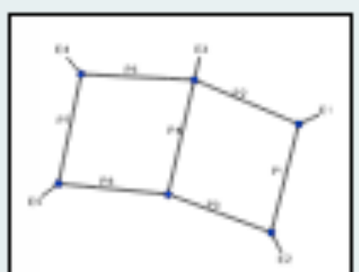

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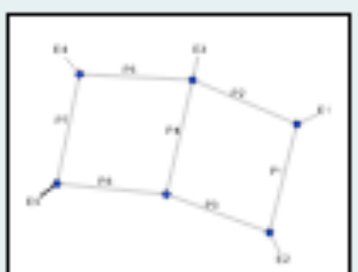

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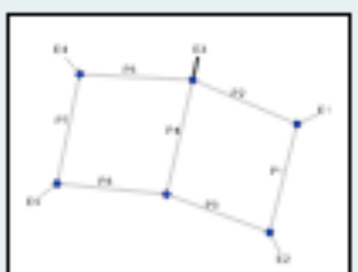

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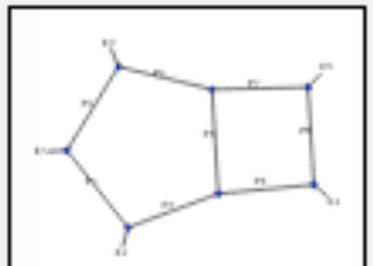

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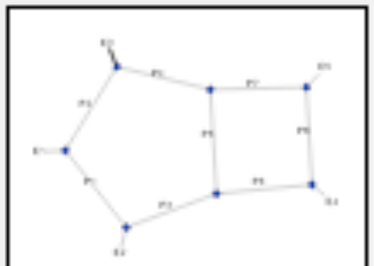

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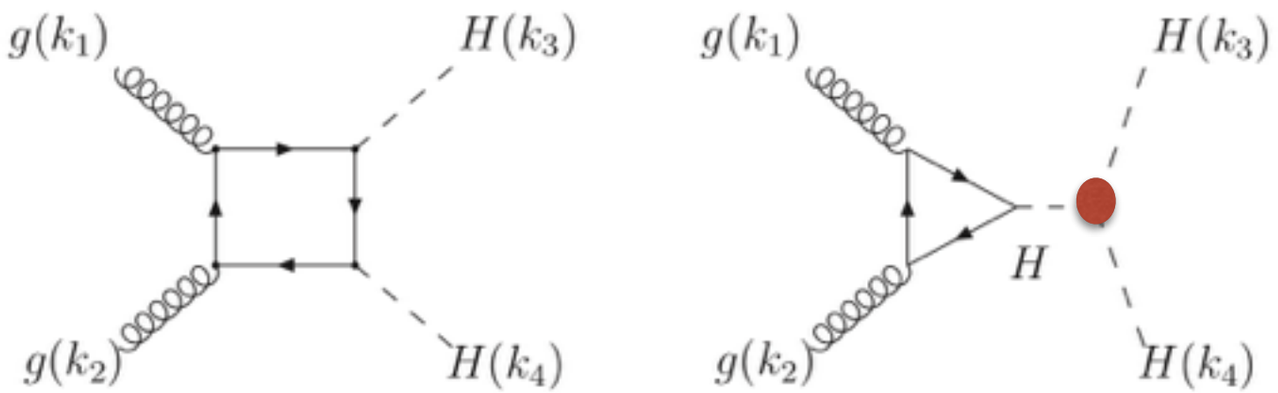
Precision calculations

Higgs boson pair production:

sensitive to Higgs boson self coupling ⟶ probe of EW symmetry breaking

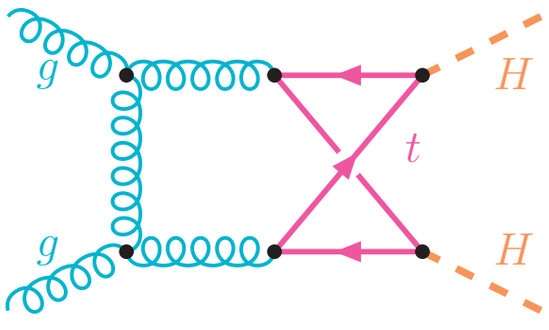
leading order (LO): *[Glover, van der Bij '88]*



next-to-leading order (NLO):

[Borowka, GH, Jahn, Jones, Kerner, Schlenk, Zirke, Schubert '16] (✳)

[Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher '18]



- multi-scale two-loop integrals hard
- both calculations based on numerical calculation of integrals

Precision calculations

Higgs boson pair production 2018: based on calculation (✳):

- extension to BSM within non-linear Effective Field Theory framework

  [Buchalla, Capozi, Celis, GH, Scyboz 1806.05162]

- combination with NNLO in $m_t \to \infty$ limit

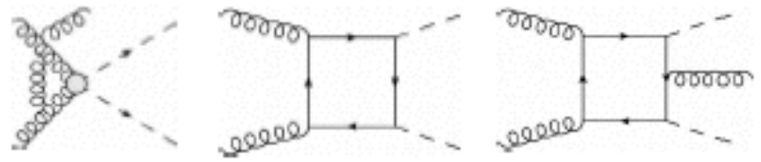
[Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli; 1803.02463]

- most precise perturbative prediction to date
- recommendation of LHC Higgs Cross Section Working Group
- scale uncertainties reduced by more than a factor 2 compared to NLO
- remaining top quark mass uncertainty hard to assess

Precision calculations

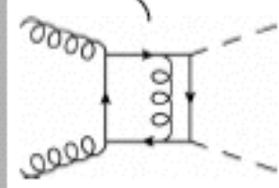
Higgs boson pair production NNLO_approx:

Technical ingredients

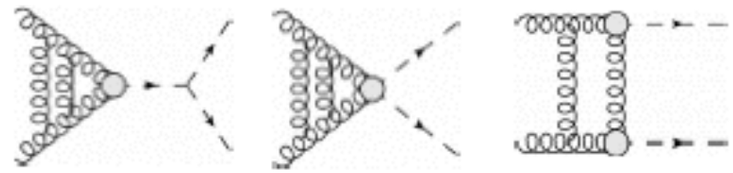


Tree-level and one-loop amplitudes (HEFT and full-M_t) → OpenLoops
[Cascioli, Lindert, Maierhofer, Pozzorini]

Full NLO (two-loop) virtual corrections → two dimensional grid + interpolation
[Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke, '16]



Analytical results for NNLO two-loop corrections in the HEFT
[de Florian, JM, '13]



NNLO subtraction formalism: q_T-subtraction
[Catani, Grazzini, '07]

Implementation based on public code MATRIX
[Kallweit, Grazzini, Wiesemann, '17]

slide by Javier Mazzitelli

Precision calculations (BSM)

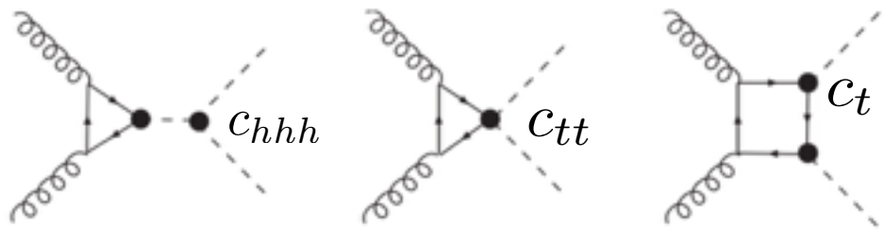
New Physics effects in Higgs-boson pair production

[Buchalla, Capozi, Celis, GH, Scyboz 1806.05162]

5 anomalous couplings play leading role in the Higgs sector within non-linear Effective Field Theory framework:

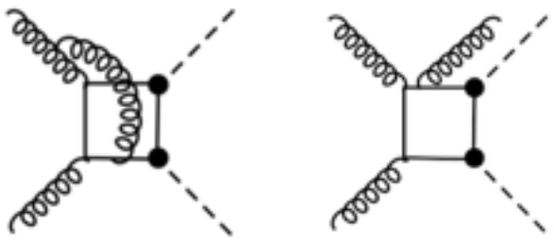
$$\mathscr{L} \supset -m_t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) \bar{t}\, t - c_{hhh} \frac{m_h^2}{2v} h^3$$

$$+ \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu}$$



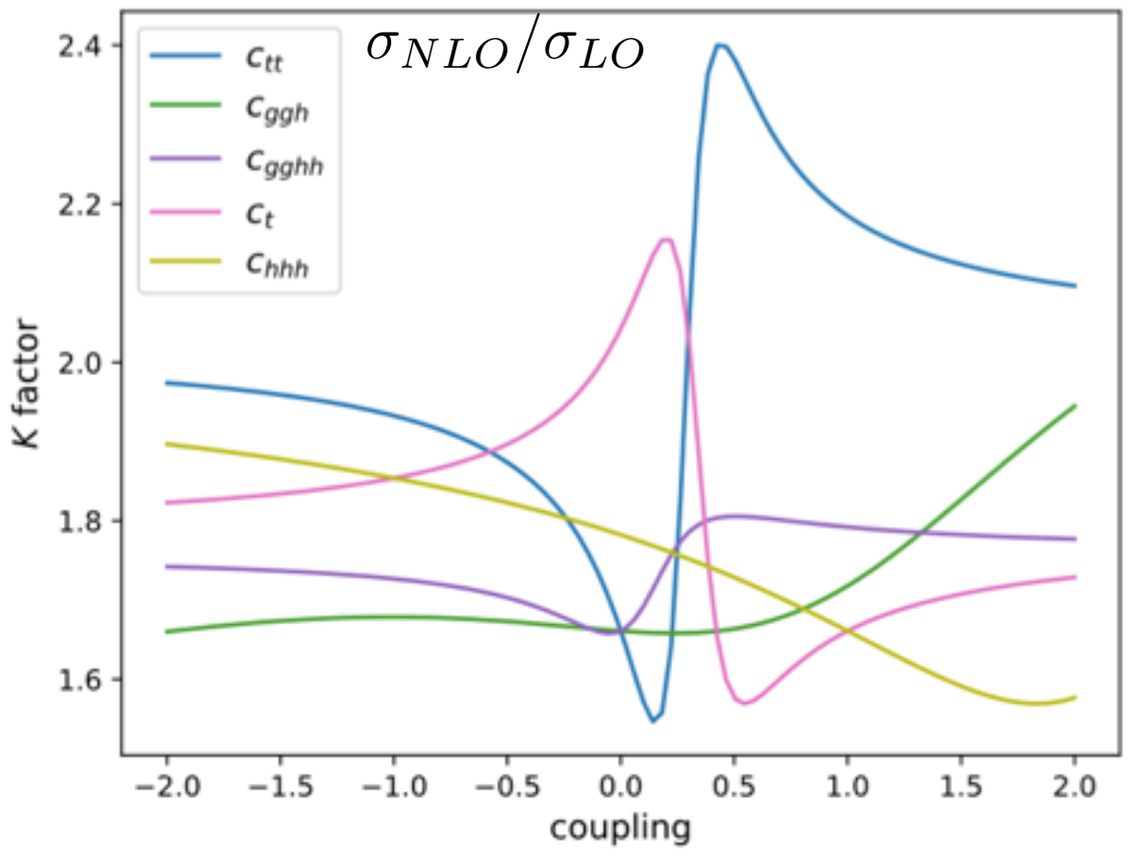
calculated NLO QCD corrections
with full top quark mass dependence

example NLO diagrams



result:

NLO corrections are large and
K-factors show significant dependence
on the couplings



Precision calculations

New Physics effects in Higgs-boson pair production

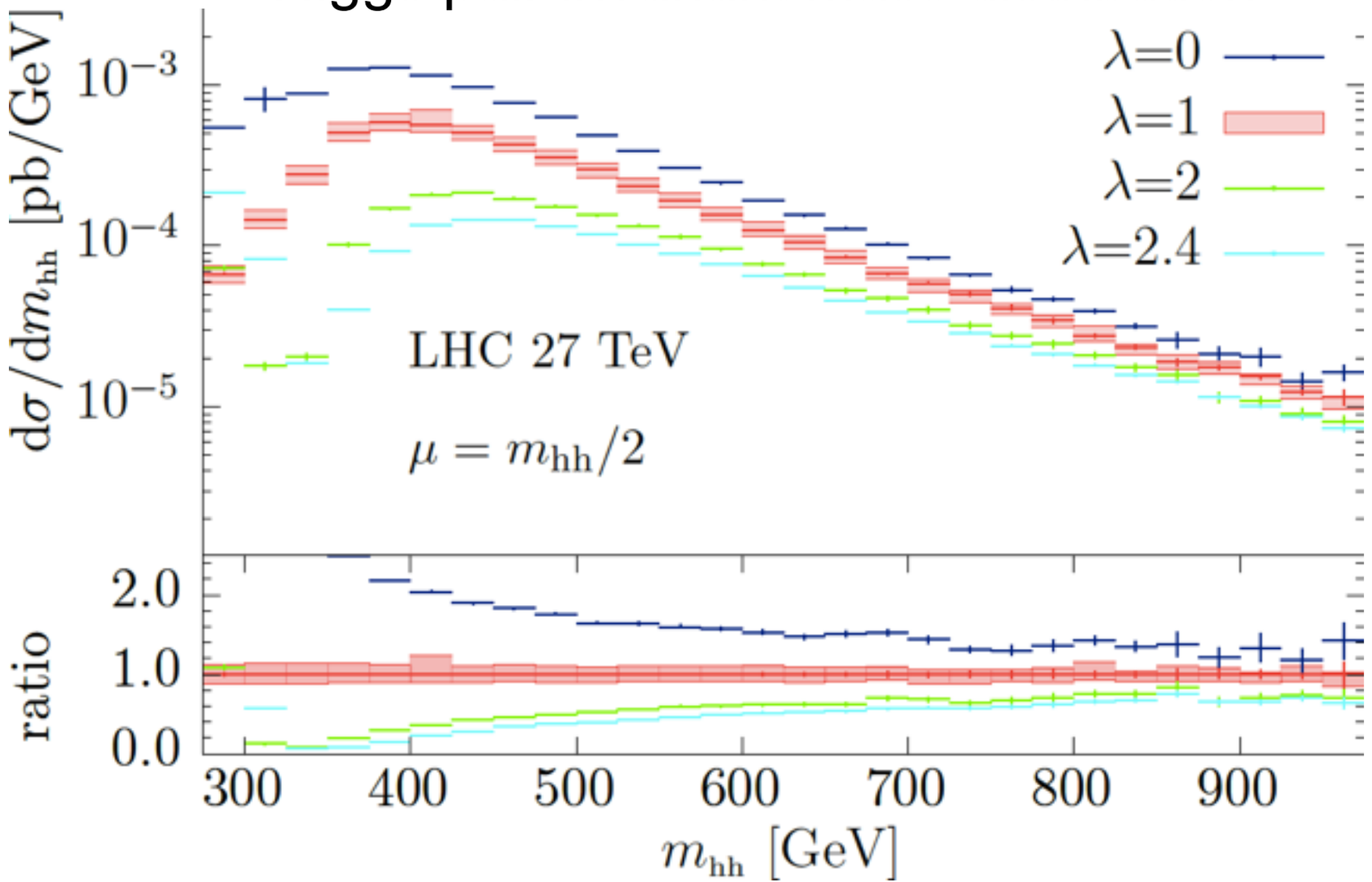
- variations of the trilinear Higgs boson coupling $\lambda = \lambda_{BSM}/\lambda_{SM}$

$pp \to HH$ with BSM effects on λ at full NLO implemented in POWHEG

[GH, Jones, Kerner, Scyboz]

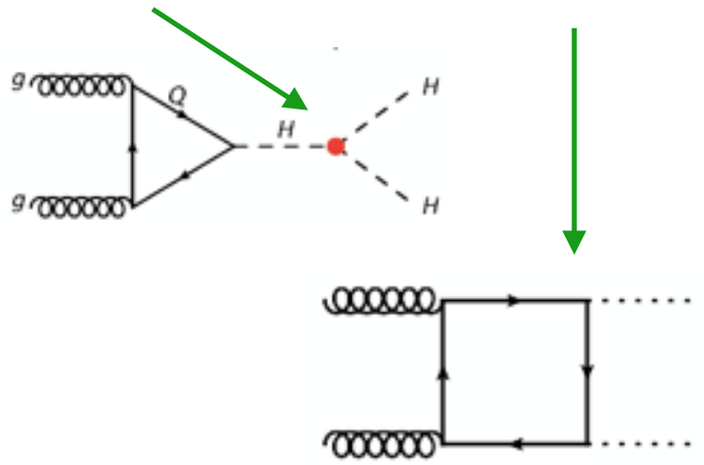
- entered CERN High Luminosity/High Energy Yellow Report, used by CMS

Higgs pair invariant mass distribution



$\lambda = 2.4$:

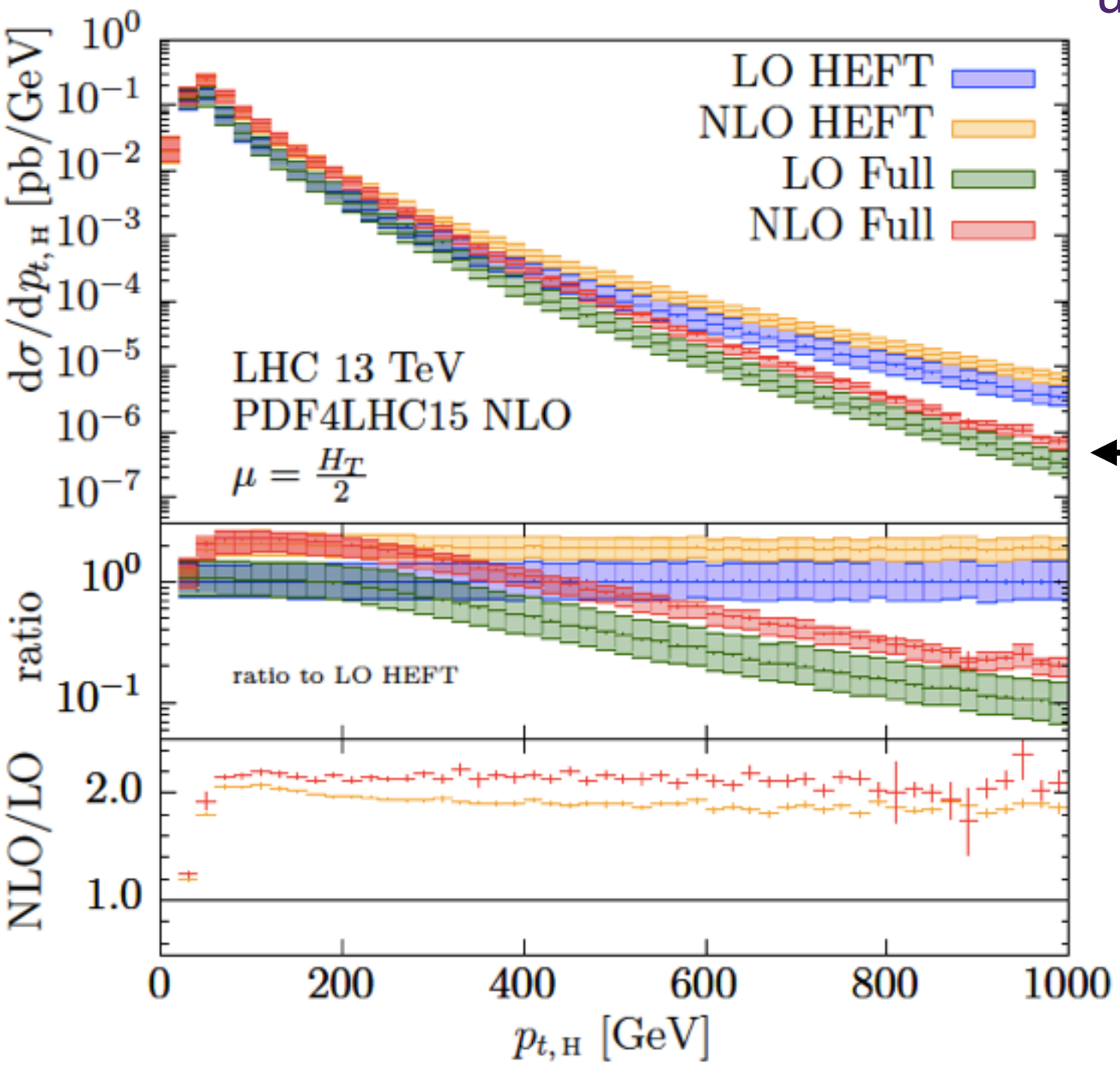
maximal destructive interference between "signal" and "background"



Precision calculations (SM)

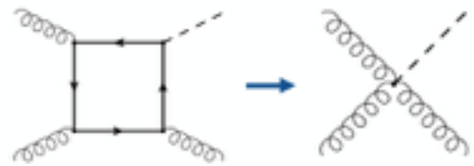
Higgs+jet at NLO including full top quark mass dependence

Jones, Kerner, Luisoni, 1802.00349

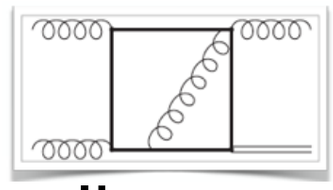


settles a longstanding question about the uncertainties due to unknown top mass effects at NLO

HEFT: $m_t \to \infty$ limit



← full NLO: different scaling behaviour at large pT



probing the loops at large pT important, can be modified by heavy BSM particles

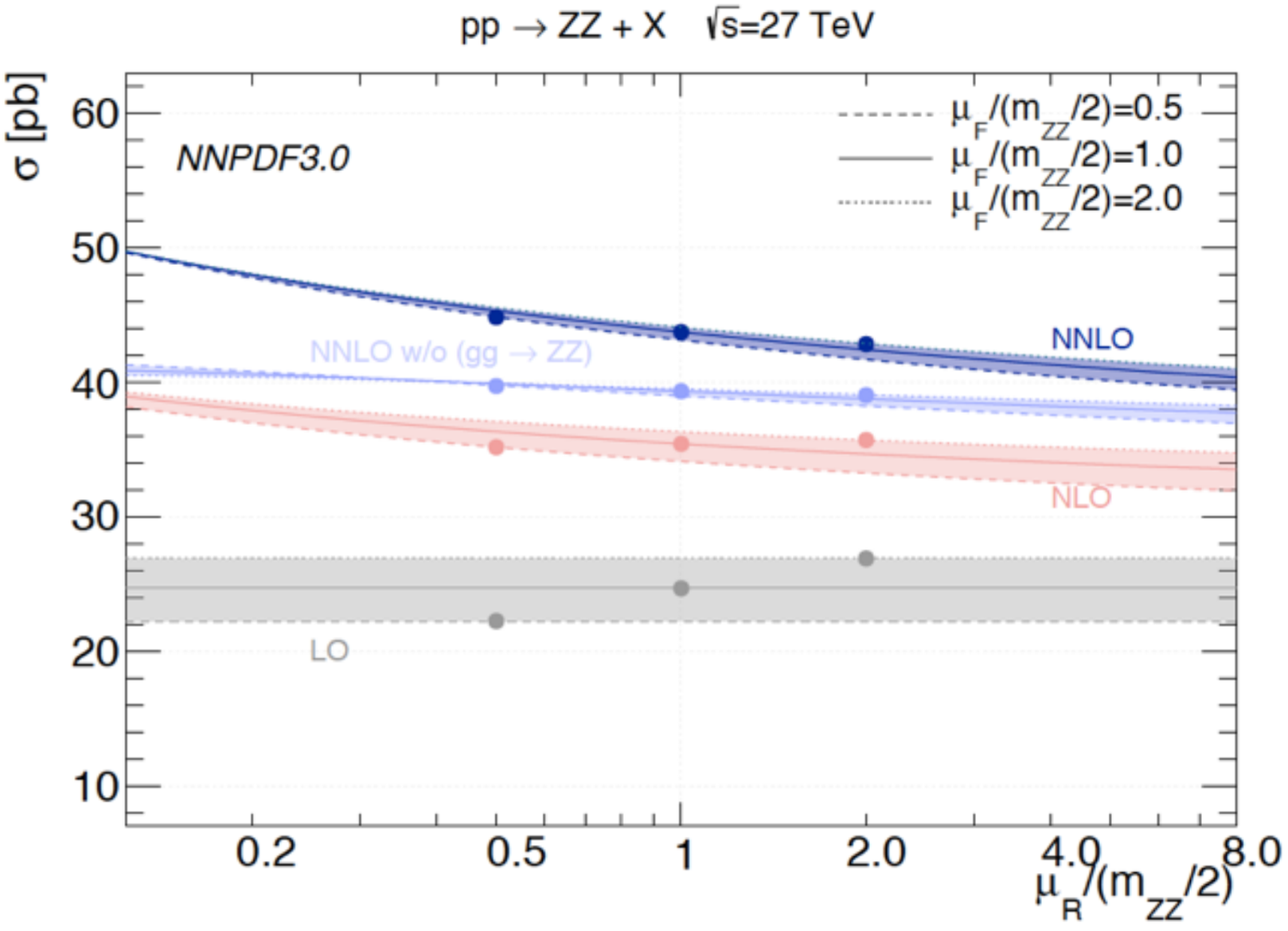
Precision calculations (SM)

Z-boson pair production at NNLO (2-loop massless so far)

GH, Stephan Jahn, Stephen Jones, Matthias Kerner, Joao Pires

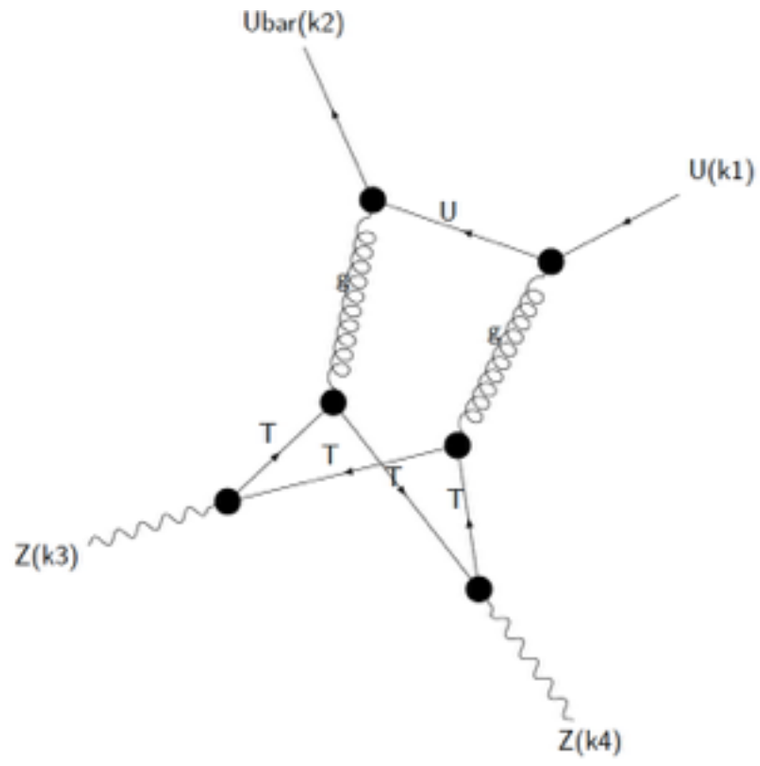
also entered CERN High Luminosity/High Energy Yellow Report

(results at $\sqrt{s} = 27\,\mathrm{TeV}$)



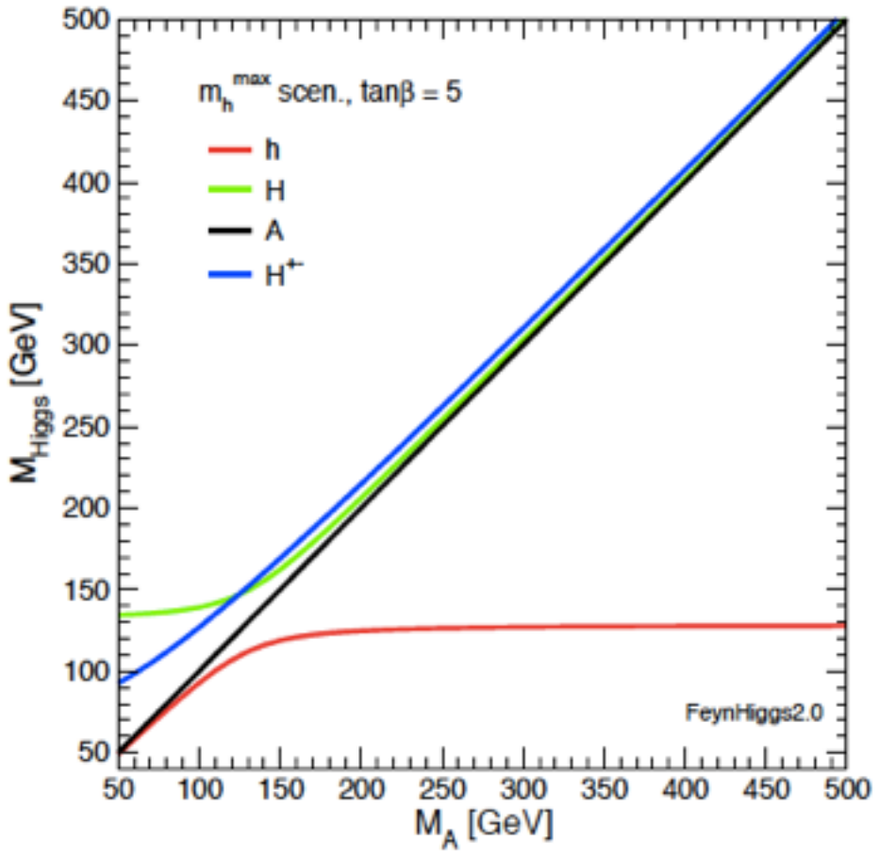
planned:

include top quarks at 2-loops



Precision calculations (BSM)

Higgs bosons in the MSSM: $h^0,\ H^0,\ A^0,\ H^\pm$



- *light Higgs boson* h^0

  $m_h \leq m_Z |\cos(2\beta)| + \Delta m_{h^0}$

- *for heavy* $A^0,\ H^0,\ H^\pm$*:*

  h^0 *like Standard Model Higgs boson,*

  but mass m_h *is a prediction*

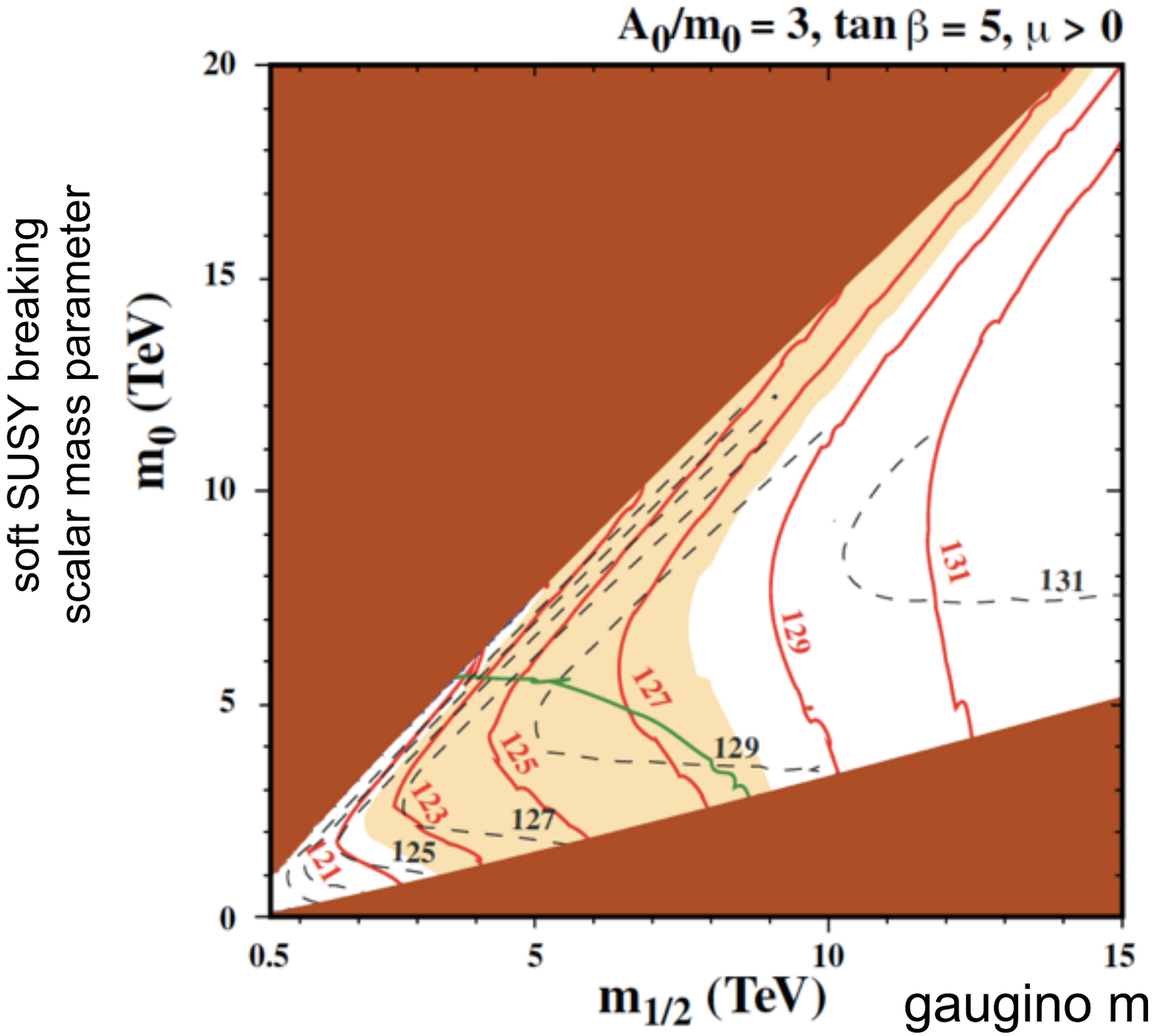
m_h strongly influenced by virtual particles, entire SUSY spectrum

public tool: `FeynHiggs` *newest:* `FeynHiggs2.14.3` (2018)

Bahl, Hahn, Hollik (MPP) *+ Heinemeyer, Paßehr, Rzehak, Weiglein*

Precision calculations (BSM)

constrained-MSSM parameters and Higgs boson mass



3-loop RGEs

2-loop threshold corrections

dashed lines:
FeynHiggs 2.10.0

solid brown lines:
FeynHiggs 2.14.1

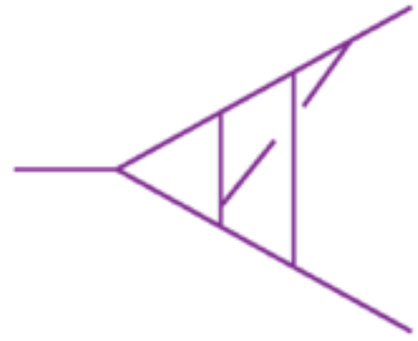
brown regions:
excluded

Bagnaschi, ... Bahl, Hahn, Hollik (MPP) *arXiv:1810.10905*

Tools development

pySecDec

SecDec is hosted by Hepforge, IPPP Durham



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! The latest version of pySecDec is available on github. The manual is available on readthedocs.

moved from hepforge to github: https://github.com/mppmu/secdec/releases

number of users increasing (more than constantly)

new: pySecDec-1.4 *S.Borowka, GH, S.Jahn, S.Jones, M.Kerner, J.Schlenk*

+ Quasi-Monte Carlo integrator *1811.11720*

pySecDec Documentation

pySecDec

pySecDec [PSD17] is a toolbox for the calculation of dimensionally regulated parameter integrals using the sector decomposition approach [BH00]; see also [Hei08], [BHJ+15].

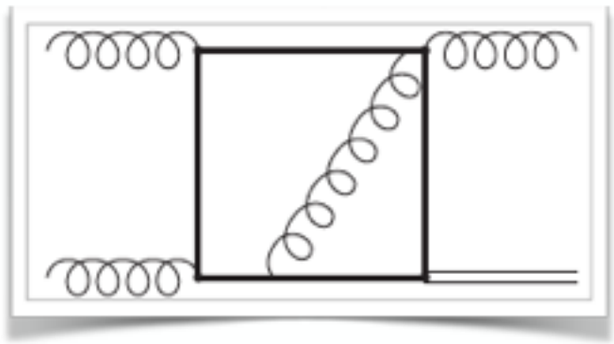
Tools development/high performance computing

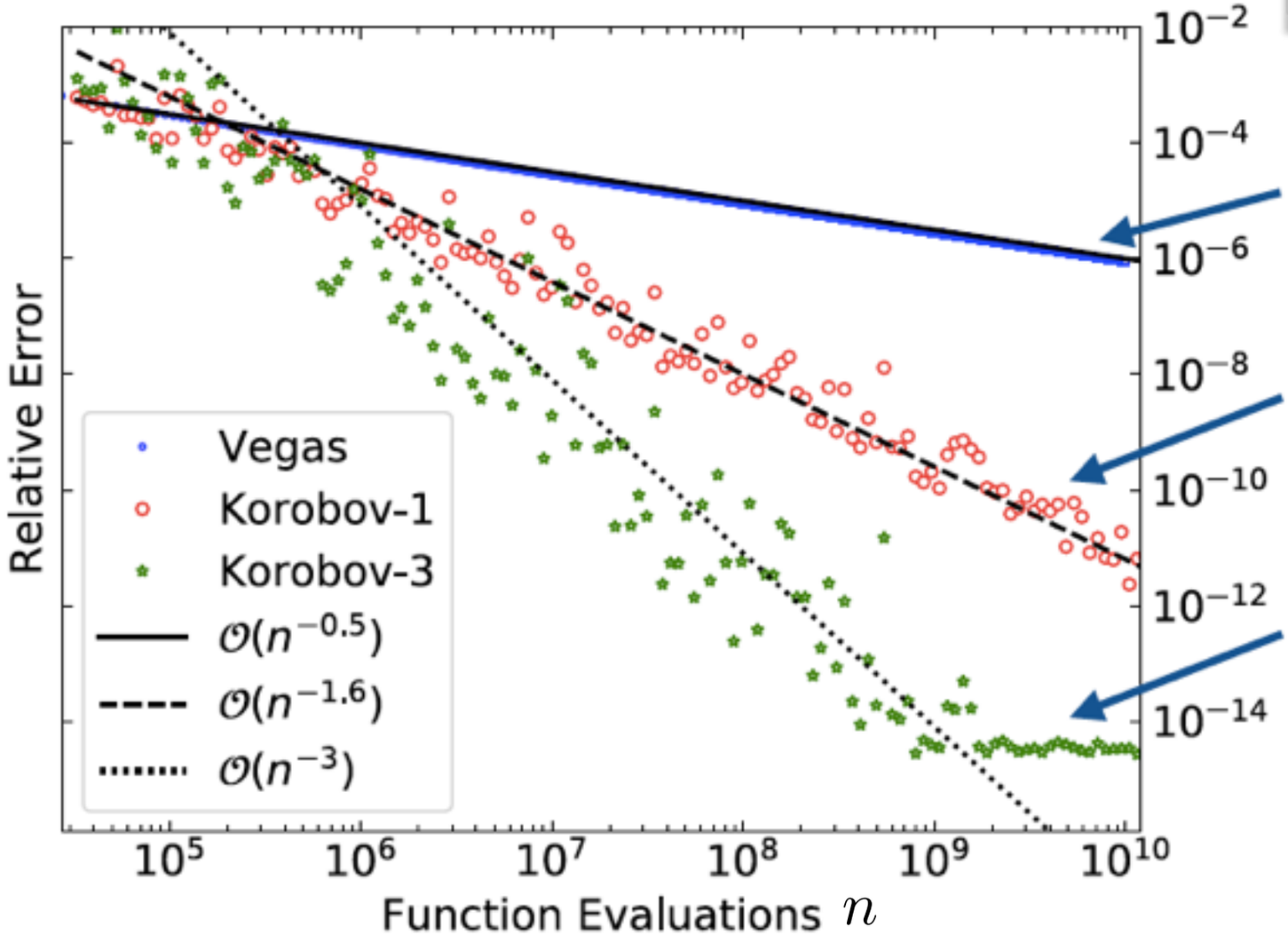
Quasi-Monte Carlo integration:

error scales like 1/n or better
(Monte Carlo int. scales like $1/\sqrt{n}$)

- GPU compatible
- published as standalone library and with interface to pySecDec

Example: *(S.Jones, M.Kerner)*
Sector Decomposed HJ Integral





Monte Carlo scaling

Better than "guaranteed" n^{-1} scaling

Limited by machine precision (double)

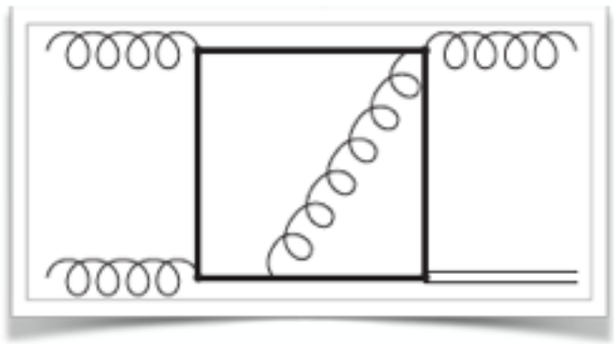
Tools development/high performance computing

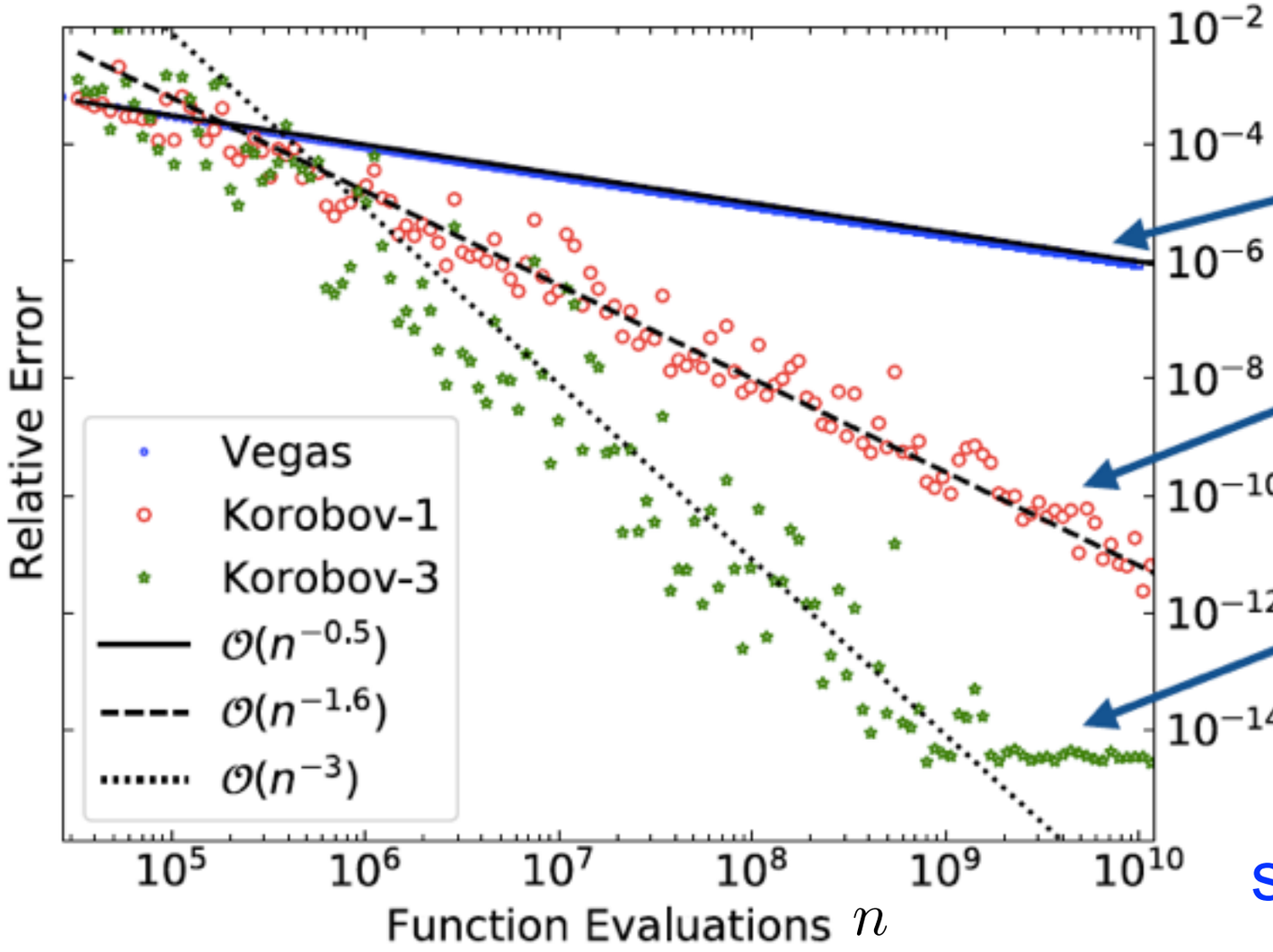
Quasi-Monte Carlo integration:

error scales like 1/n or better
(Monte Carlo int. scales like $1/\sqrt{n}$)

- GPU compatible
- published as standalone library and with interface to pySecDec

Example: *(S.Jones, M.Kerner)*
Sector Decomposed HJ Integral





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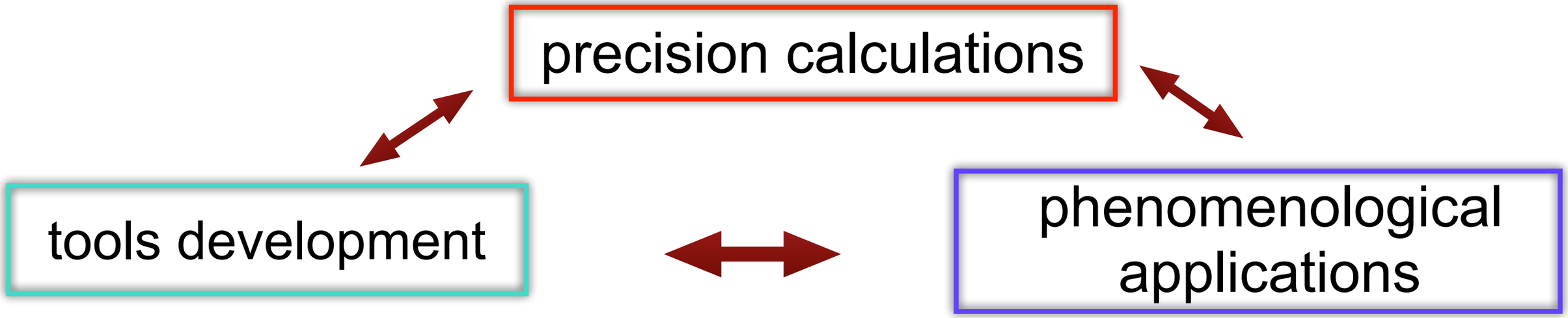
see also talk by Oliver Schulz

Summary

- 2018 has been a successful year in terms of precision calculations within and beyond the Standard Model

- important interplay



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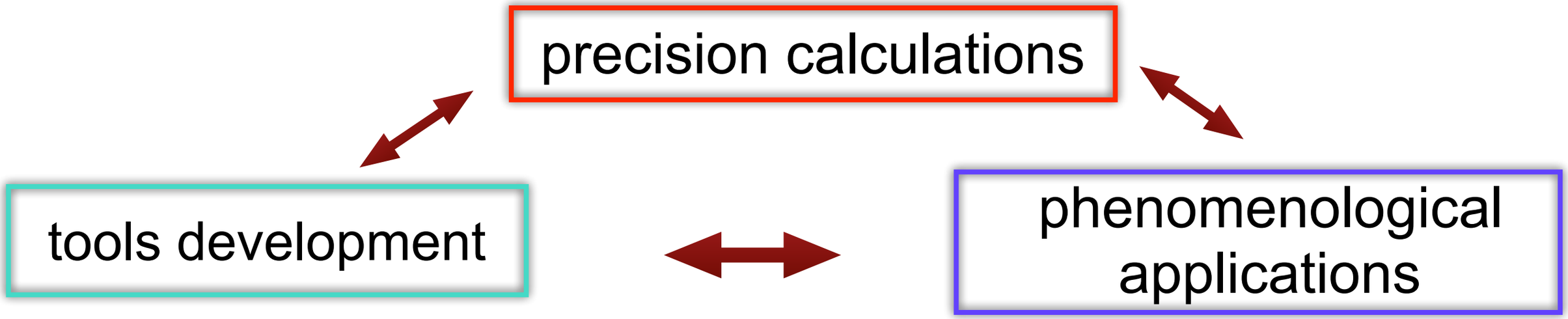

- the new group members bring in important additional/complementary expertise

- we are looking forward to fruitful collaborations in the future!

Let’s stick to tree level for Christmas!