Two-loop EW Corrections to Higgs Boson Pair Production: Yukawa and Self-coupling corrections

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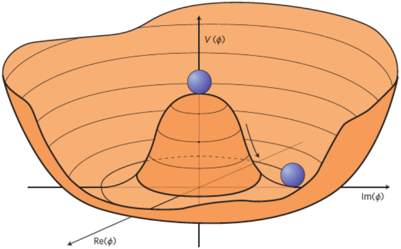
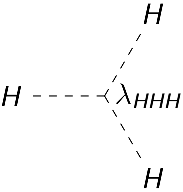
Introduction & Motivation

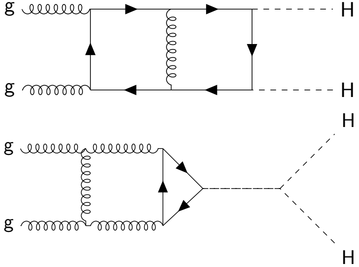
- Investigating Higgs properties in run 3 of the LHC requires precision calculations in the SM
- Gluon fusion is the dominant mechanism for producing Higgs bosons at the LHC
- Higgs pair production provides a direct way to measure the Higgs self-coupling through $\kappa_\lambda := \lambda_{HHH}/\lambda_{HHH}^{SM}$ (currently $-1.4 < \kappa_\lambda < 6.1$ [ATLAS 23] & $-1.24 < \kappa_\lambda < 6.49$ [CMS 22])





NLO Corrections

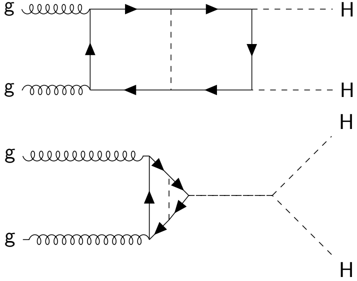
NLO QCD: $\mathcal{O}\left(\alpha_s^2\alpha\right)$



Full top mass dependence

[S. Borowka, N. Greiner, G. Heinrich, S.P. Jones, M. Kerner, J. Schlenk, U. Schubert, T. Zirke 16]

NLO EW: $\mathcal{O}\left(\alpha_s\alpha^2\right)$



Heavy top mass expansion

[J. Davies, K. Schönwald, M. Steinhauser, H. Zhang 23]

Amplitude Structure

- To any number of loops, there exists a decomposition of the amplitude for gg → HH into form factors

Form Factor Decomposition

$$\mathcal{M}_{ab} = \delta_{ab}\, \epsilon_1^{\mu}\epsilon_2^{\nu}\, \mathcal{M}_{\mu\nu}$$
$$\mathcal{M}^{\mu\nu} = F_1\left(s, t, m_h^2, m_t^2, d\right)\, T_1^{\mu\nu} + F_2\left(s, t, m_h^2, m_t^2, d\right)\, T_2^{\mu\nu}$$

- The form factors F_1 and F_2 correspond to the helicity amplitudes $\mathcal{M}^{++} = \mathcal{M}^{--}$ and $\mathcal{M}^{+-} = \mathcal{M}^{-+}$ respectively

Coupling Structures

$$F_i \sim \left(y_t^2 F^{(0)}_{i,y_t^2} + y_t\lambda F^{(0)}_{i,y_t\lambda} + y_t^4 F^{(1)}_{i,y_t^4} + y_t^3\lambda F^{(1)}_{i,y_t^3\lambda} + y_t^2\lambda^2 F^{(1)}_{i,y_t^2\lambda^2} + \ldots\right)$$

Master Integrals

- Obtain F_1 & F_2 from $\mathcal{M}_{\mu\nu}$ using projectors [Glover, van der Bij 88]
- Form factors are linear combinations of scalar Feynman integrals ($\Sigma_{i=1}^{\mathcal{O}(10000)} c_i I_i$)
- We can express each complicated Feynman integral in terms of a finite set of master integrals

Master Integral Decomposition

$$\forall i : I_i = \Sigma_{j=1}^{494} \alpha_{ij} M_j$$

Integral Reduction

- How do we determine $\{\alpha_{ij}\}$?
- We can use integration-by-parts (IBP) reduction rules to rewrite integrals in terms of others

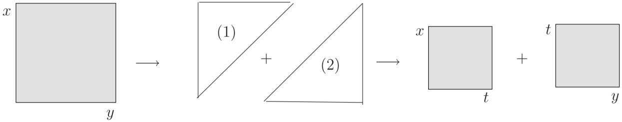
Integration-by-Parts Identity

$$\forall j, n : \int \prod_{i=1}^{L} [\mathrm{d}k_i] \frac{\partial}{\partial k_j^\mu} \frac{q^\mu}{\mathcal{D}_{1,n}^{\alpha_{1,n}} \ldots \mathcal{D}_{p,n}^{\alpha_{p,n}}} = 0$$ [Tkachov 81; Chetyrkin 81]

- We reduce these integrals using Kira [Maierhoefer, Usovitsch, Uwer 17; Maierhofer, Usovitsch 18; Klappert, Lange, Maierhofer, Usovitsch 20] and Ratracer [Magerya 22] via functional reconstruction with finite fields

Numerical Evaluation of Master Integrals

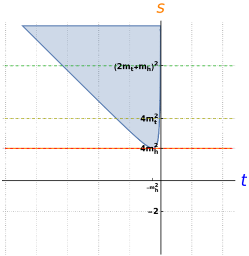
- Sector Decomposition (pySecDec [SecDec Collaboration 22])



- Series Solutions of Differential Equations (DiffExp [Hidding 20])

Differential Equation System

$$\mathrm{d}\vec{f} = \mathrm{d}\tilde{\mathbf{A}}\vec{f}$$



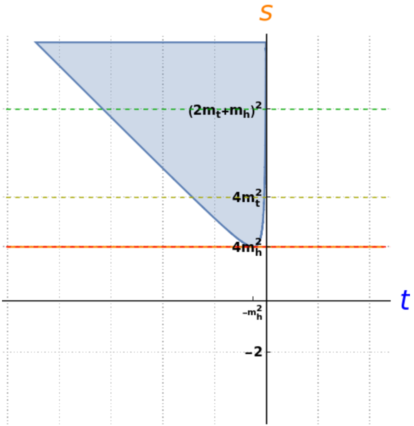
Differential Equations

- It was noted that master integrals could be solved as a system of differential equations [Kotikov 91]

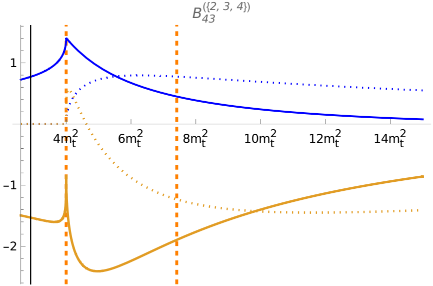
Differential Equation System

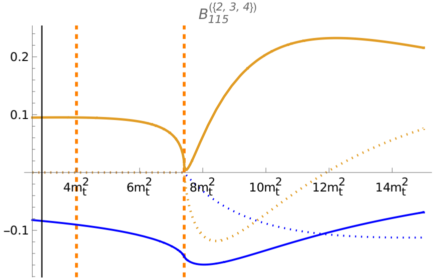
$$\mathrm{d}\vec{f} = \left(\sum_{x\in\{s,t,m_h^2\}} \mathbf{A}_{\mathbf{x}}\,\mathrm{d}x\right)\vec{f}$$

- DiffExp [Hidding 20] is a Mathematica package which solves the differential equation system using a generalised series expansion solution



DiffExp Master Integral Example Results





Two master integrals in the same integral family evaluated along a contour in the positive s-direction

Current Status

- We have the reduced differential equations and amplitude for an improved basis of master integrals

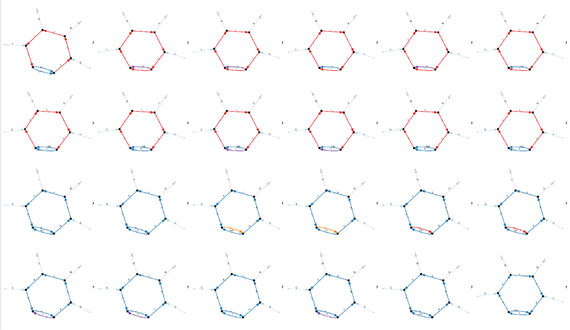
Basis Comparison for Virtual Correction (“Good” Point)

- Old Basis (2022): $T(F_1) = 45$ hours $T(F_2) = 347$ hours
- New Basis (2023): $T(F_1) \sim 5$ mins $T(F_2) \sim 5$ mins

- Old basis did not even converge on a “bad” phase space point!

Outlook

- We are currently performing the UV renormalisation using the one-loop result we have already calculated
- We will also begin looking at the full electroweak corrections (∼17000 diagrams!) and make progress on them



DiffExp Error Plot