

Higgs-Pair Production via Gluon Fusion: Top-Yukawa- and light-quark-induced electroweak Corrections

with A. Bhattacharya, L. Biermann, F. Campanario, J. Chang, J. Mazzitelli, M. M. Mühlleitner, J. Ronca, and M. Spira

Sauro Carlotti, ITP – KIT | HP2, Oct. 05, [JHEP 07, 057 \(2026\)2512.14823](#)

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Motivation

The Standard Model (SM) has been tested to highest accuracy, but there are open questions that call for new physics.

There are different ways to search for new physics:

- **Direct searches** of new phenomena, e.g. new particles
- **Indirect effects** by computing observables at high precision

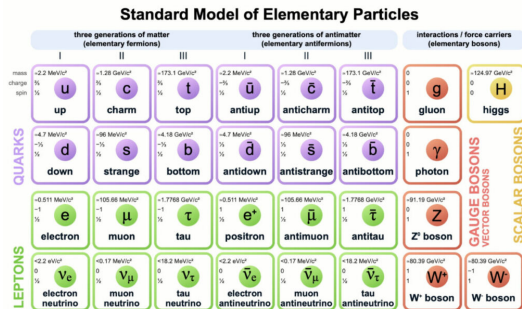


Figure: [\[Wikimedia\]](#)

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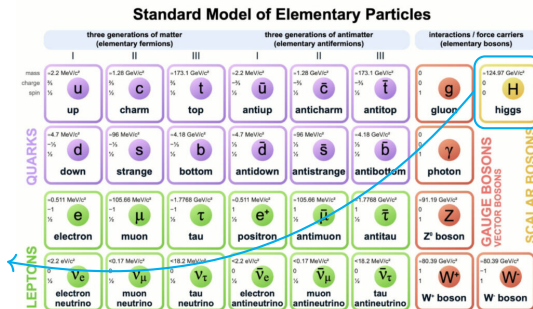


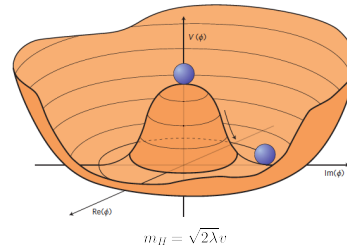
Figure: [\[Wikimedia\]](#)

Scalar Higgs Potential in the Standard Model

After the electroweak symmetry breaking (EWSB) the Higgs potential in the SM becomes:

$$V_{\text{SM}} = \frac{1}{2} m_H^2 H^2 + \frac{1}{3!} \lambda_{HHH} H^3 + \frac{1}{4!} \lambda_{HHHH} H^4$$

Figure: [J.Ellis '13]





$$\lambda_{HHH} = \frac{3m_H^2}{v}$$



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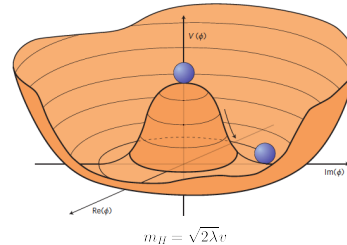
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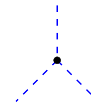
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- Measurement of the Higgs boson mass [ATLAS, CMS '12]

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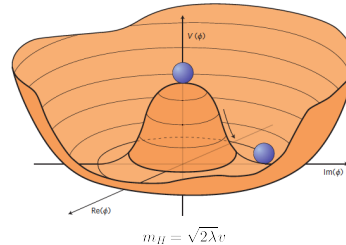
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- Test the shape of the Higgs potential

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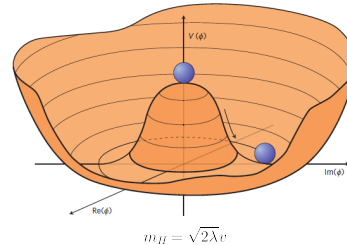
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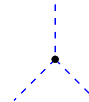
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λ_{HHH} is accessible through the Higgs boson pair production via gluon fusion at hadron colliders

Figure: [\[J.Ellis '13\]](#)





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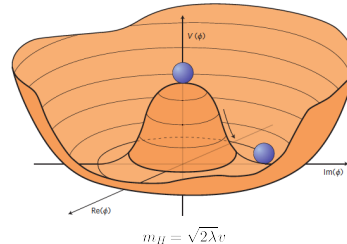
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- Test the shape of the Higgs potential

λ_{HHH} is accessible through the Higgs boson pair production via gluon fusion at hadron colliders

$$-0.71 < \frac{\lambda_{\text{obs}}}{\lambda} < 6.1 \quad [\text{ATLAS, CMS, '26}]$$

Figure: [J.Ellis '13]





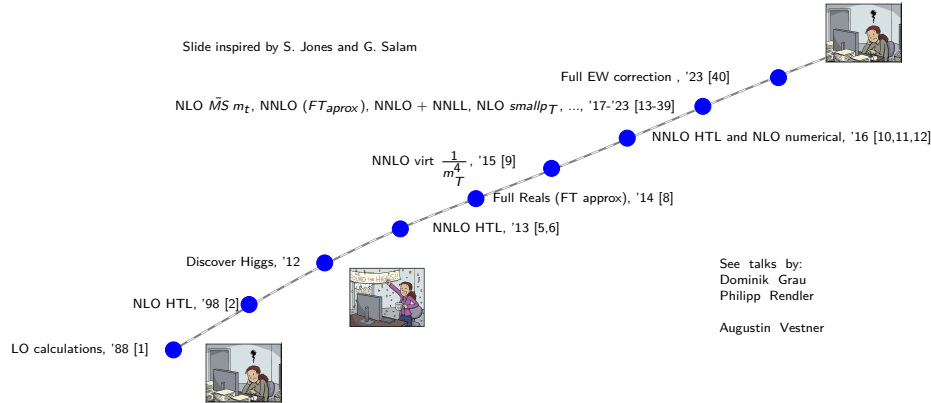
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Evolution of Theoretical Calculations for $gg \rightarrow HH$

Slide inspired by S. Jones and G. Salam



See talks by:
Dominik Grau
Philipp Rendler

Augustin Vestner

[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 96; [3] Shao, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowska, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zinke 16; [12] Borowska, Greiner, Heinrich, Jones, Kerner, Schlenk, Zinke 16; [13] Ferrera, Pires 16; [14] Heinrich, Jones, Kerner, Luisoni, Vryonidou 17; [15] Jones, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrandi, Giordano, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, Jones, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafante, Degrandi, Giordano, Gröber, Vitti 22; [30] Davies, Mishima, Schönwald, Steinhauser, Zhang 22; [31] Davies, Mishima, Schönwald, Steinhauser 23; [32] Davies, Schönwald, Steinhauser, Zhang 23; [34] Bagdasarian, Degrandi, Gröber 23; [35] Bi, Huang, Huang, Ma Yu 23; [36] Li, Si, Wang, Zhang, Zhao 24; [37] Davies, Schönwald, Steinhauser, Vitti 24; [38] Heinrich, Jones, Kerner, Stone, Vestner: [39] Li, Si, Wang, Zhang, Zhao 24; [40] Bi, Huang, Huang, Ma, Yu.: [41] M.Bonetti, P. Rendler, W.J. Torres., [42] J. Davies, K. Schönwald, M. Steinhauser, D. Stremmer, [43] Bhattacharya, Campanario, C., Chang, Mazzitelli, Mühlleitner, Ronca, and Spira

$gg \rightarrow HH$ NLO Overview
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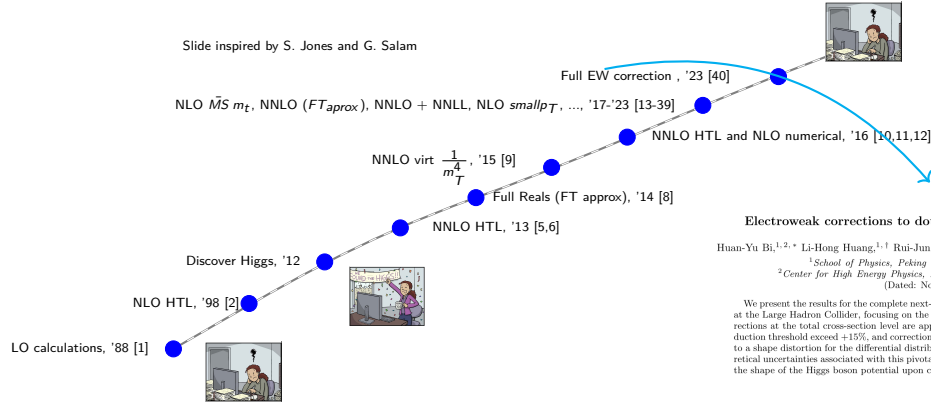
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Evolution of Theoretical Calculations for $gg \rightarrow HH$

Slide inspired by S. Jones and G. Salam



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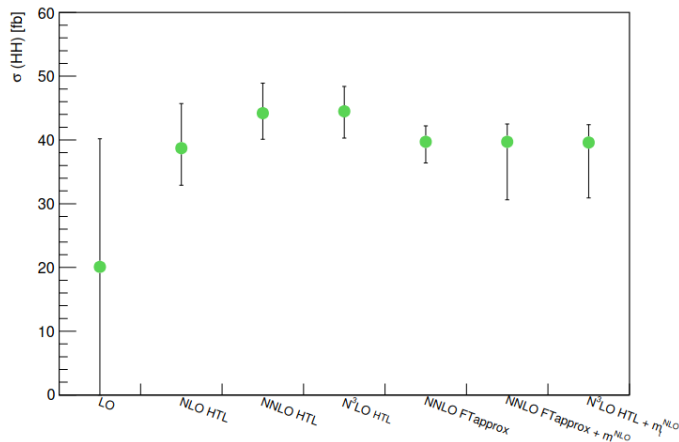
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Evolution of the Cross Section over the Years



Taken from M. Spira

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NLO EW Corrections

$gg \rightarrow HH$ is a loop-induced process where we have two types of diagrams



Sizeable contributions of the EW corrections come from the top-Yukawa coupling

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Our framework

- Gaugeless limit $\rightarrow$ presence of massless Goldstone bosons

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Sizeable contributions of the EW corrections come from the top-Yukawa coupling

Our framework

- Gaugeless limit $\rightarrow$ presence of massless Goldstone bosons
- Massive top and bottom quarks, light quarks massless
- Only top-Yukawa-induced corrections + light quark loops

Top-Yukawa Model + QCD

$$\mathcal{L} = -\frac{1}{4} G^{a,\mu\nu} G_{a,\mu\nu} + \bar{t} i \not{D} t + \bar{b} i \not{D} b + |\partial_\mu \Phi|^2 - Y_t \bar{Q}_L \Phi^c t_R - Y_b \bar{Q}_L \Phi b_R - V(\Phi),$$

$$V(\Phi) = \mu^2 |\Phi|^2 + \frac{\lambda}{2} |\Phi|^4 =$$

$$= -\frac{m_H^2}{8} v^2 + \frac{m_H^2}{2} H^2 + \frac{m_H^2}{v} \left[\frac{H^3}{2} + \frac{H}{2} (G^0)^2 + H G^+ G^- \right]$$

$$+ \frac{m_H^2}{2v^2} \left[\frac{H^4}{4} + \frac{H^2}{2} (G^0)^2 + H^2 G^+ G^- + (G^+ G^-)^2 + (G^0)^2 G^+ G^- + \frac{(G^0)^4}{4} \right],$$

with

$$\Phi = \begin{pmatrix} G^+ \\ \frac{v + H + iG^0}{\sqrt{2}} \end{pmatrix}.$$

Top-Yukawa-Induced Corrections

Matrix element split into tensor structures

$$\mathcal{M}^{\mu\nu} = F_1 T_1^{\mu\nu} + F_2 T_2^{\mu\nu}$$

The cross section can be written as

$$d\sigma \sim \text{Re} \left[(C_\Delta F_{1\Delta} + F_{1\Box})^* (C_\Delta F_{1\Delta} + F_{1\Box}) + F_{2\Box}^* F_{2\Box} \right]$$

Since only virtual corrections are involved, the corrections can be added by shifting the LO terms

$$C_\Delta F_{1\Delta} \rightarrow C_\Delta F_{1\Delta} (1 + \delta_1 + \Delta_{HHH})$$

$$F_{1\Box} \rightarrow F_{1\Box} (1 + \Delta_{1\Box})$$

$$F_{2\Box} \rightarrow F_{2\Box} (1 + \Delta_{2\Box})$$

→ Expand $d\sigma$ properly to next-to-leading order (NLO)

$$T_1^{\mu\nu} = g^{\mu\nu} - \frac{p_1^\nu p_2^\mu}{p_1 \cdot p_2} \quad \text{with } p_T = \sqrt{\frac{tu - m_H^4}{s}}$$

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

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

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Contributions computed

$$C_\Delta F_{1\Delta} \rightarrow C_\Delta F_{1\Delta} (1 + \delta_1 + \Delta_{HHH})$$

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Relevant Diagrams

How many diagrams need to be considered?

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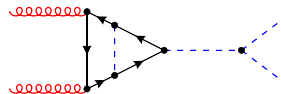
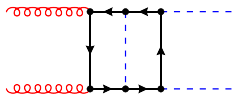
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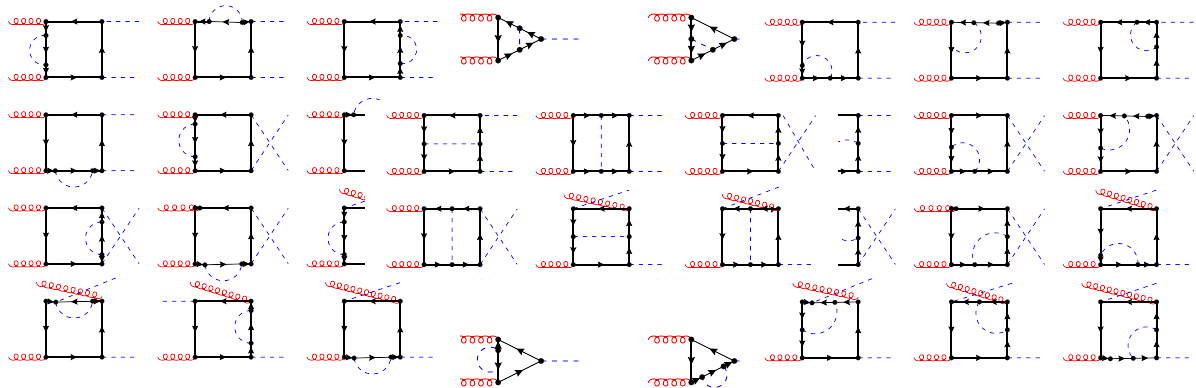
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- Identify all the Feynman diagrams that contribute to the process for the considered correction

Workflow

- Identify all the Feynman diagrams that contribute to the process for the considered correction
- Apply Feynman parametrization to all the diagrams

$$\frac{1}{a_1^{\alpha_1} a_2^{\alpha_2} \dots a_n^{\alpha_n}} = \frac{\Gamma(\alpha_1 + \dots + \alpha_n)}{\Gamma(\alpha_1) \dots \Gamma(\alpha_n)} \int_0^1 dx_1 \dots \int_0^{1-x_1-\dots-x_{n-2}} dx_{n-1} \frac{(1-x_1-\dots-x_{n-1})^{\alpha_1-1} x_1^{\alpha_2-1} \dots x_{n-1}^{\alpha_n-1}}{(a_1(1-x_1-\dots-x_{n-1}) + a_2 x_1 + \dots a_n x_{n-1})^{\sum \alpha_i}}$$

→ up to $(n-1)$ -dimensional integral

Workflow

- Identify all the Feynman diagrams that contribute to the process for the considered correction
- Apply Feynman parametrization to all the diagrams
- Small mass regulator for the internal particles + endpoint subtraction $\rightarrow$ isolate the UV singularities

$$m^2 \rightarrow m^2 (1 - i\bar{\epsilon})$$

$$\int_0^1 dx \frac{f(x)}{(1-x)^{1-\epsilon}} = \frac{f(1)}{\epsilon} + \int_0^1 dx \frac{f(x) - f(1)}{1-x} + \mathcal{O}(\epsilon)$$

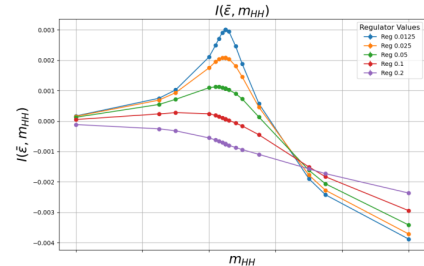
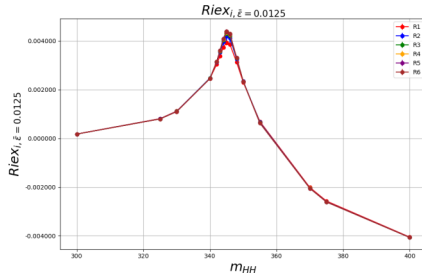
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- Instability? → Integration by parts

$$\int_0^1 dx \frac{f(x)}{(a+bx)^3} = \frac{f(0)}{2a^2b} - \frac{f(1)}{2b(a+b)^2} + \int_0^1 \frac{dx}{2b} \frac{f'(x)}{(a+bx)^2}$$

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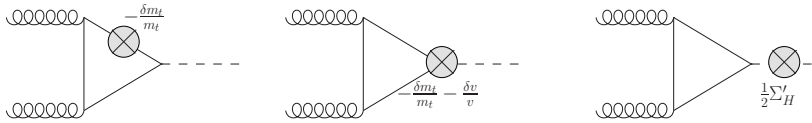
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 - Instability? $\rightarrow$ Integration by parts
 - Richardson extrapolation to do the narrow-width limit $\bar{\epsilon} \rightarrow 0$
- ... and if is it not enough? $\rightarrow$ choice of a new parametrization

Triangle Counterterms



$$\delta Z_H = \frac{1}{2} \Sigma'_H(Q^2) = 6x_t [(4m_t^2 - Q^2) B'_0(Q^2, m_t, m_t) - B_0(Q^2, m_t, m_t)]$$

$$\frac{\delta v}{v} = \frac{1}{2} \frac{\delta m_W^2}{m_W^2} = \frac{1}{2} \frac{\Sigma_W(0)}{m_W^2} = \frac{T_1}{vm_H^2} + x_t [B_0(0, m_t, m_b) + 2B_0(0, m_t, m_t) + m_t^2 B'_0(0, m_t, m_b)]$$

$$\frac{\delta m_t}{m_t} = \frac{\Sigma(m_t)}{m_t} = \frac{T_1}{vm_H^2} - x_t \left\{ \left(2 - \frac{m_H^2}{2m_t^2} \right) B_0(p, m_t, m_H) + \frac{m_t^2 + m_b^2}{2m_t^2} B_0(p, m_b, 0) + \frac{A_0(m_H) - 2A_0(m_t) - A_0(m_b)}{2m_t^2} \right\} \Big|_{p^2=m_t^2}$$

where $x_t = \frac{G_F m_t^2}{8\sqrt{2}\pi^2}$, $T_1 = -12x_t v A_0(m_t)$

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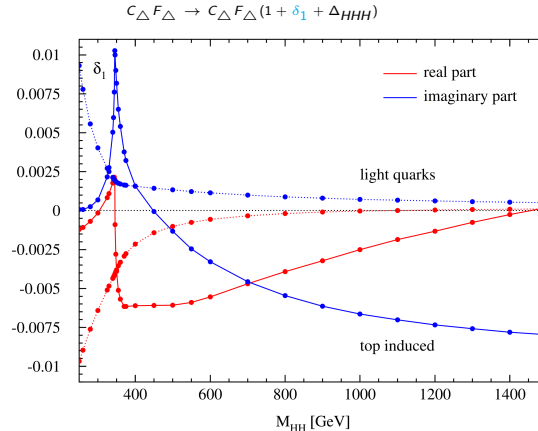
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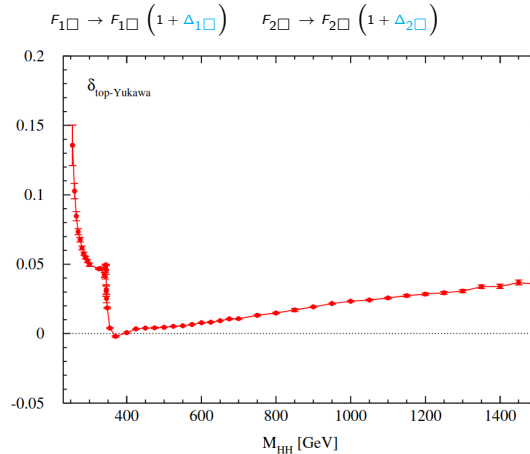
Triangle-like Corrections

- Top-Yukawa-induced corrections to $\mathcal{M}$ as a function of the invariant Higgs-pair mass M_{HH}
- Solid lines: top-Yukawa-induced corrections
- Dashed lines: light quark loops contributions
- Large contribution around $t\bar{t}$ threshold



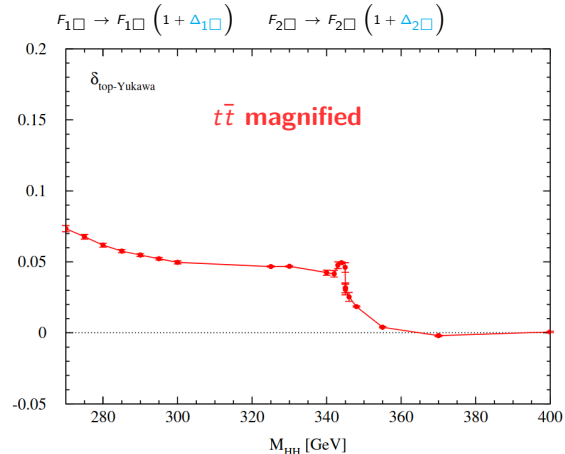
Box-like Corrections

- Top-Yukawa-induced corrections to σ as a function of the invariant Higgs-pair mass M_{HH}
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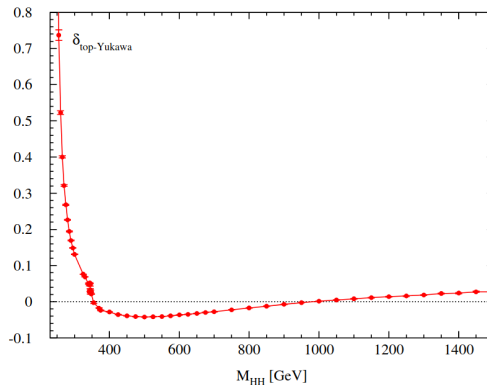
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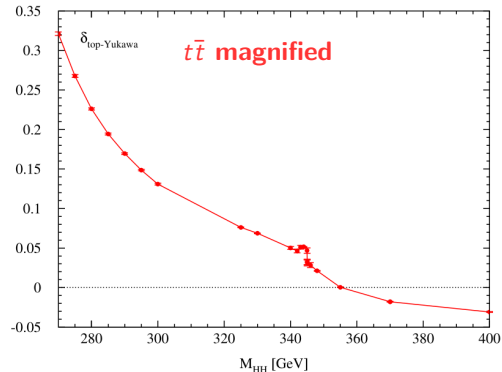
Full Top-Yukawa-Induced Corrections

- Full Top-Yukawa-induced corrections to σ as a function of the invariant Higgs-pair mass M_{HH} , normalized to σ_{LO}
- Large contributions around the $t\bar{t}$ threshold and below (Δ_{HHH})



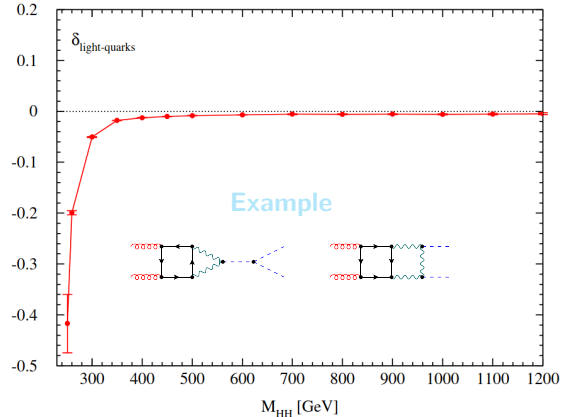
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Light Quark Corrections

- Light quark loops corrections to σ as a function of the invariant Higgs-pair mass M_{HH} , normalized to σ_{LO}
- Sizeable contributions below $M_{HH} = 400$ GeV
- Negligible contributions at high energies



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- Agreement with Bonetti et al. [[2503.16620](#)]

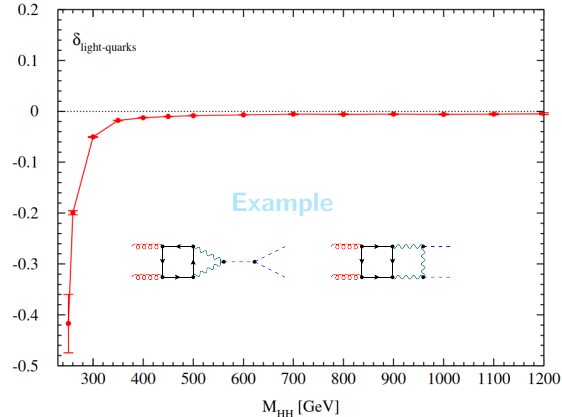


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1. $gg \rightarrow HH$ NLO Overview
2. Computational Strategy
3. Results
4. Summary and Conclusions

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Thank You for your Attention!

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BACKUP

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Projectors

Matrix element can be written as:

$$M^{\mu\nu} = F_1 T_1^{\mu\nu} + F_2 T_2^{\mu\nu}$$

The Form factors can be obtained via the projectors

$$P_i^{\mu\nu} T_{j,\mu\nu} = \delta_{ij}$$

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

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

with $p_T = \sqrt{\frac{tu - m_H^4}{s}}$

Integration by parts

$$\int_0^1 dx \frac{f(x)}{N^3(x)} \stackrel{1'IBP}{=} -\frac{1}{2b} \frac{f(x)}{N^2(x)} \Big|_0^1 + \frac{1}{2b} \int_0^1 dx \frac{f'(x)}{N^2(x)} \stackrel{2'IBP}{=} \frac{1}{2b} \left[-\frac{f(x)}{N^2(x)} \Big|_0^1 + \frac{1}{b} \left(\frac{f'(x)}{N(x)} \Big|_0^1 + \int_0^1 dx \frac{f''(x)}{N^2(x)} \right) \right]$$

Richardson Extrapolation

Improve accuracy by combining approximations with different step sizes.

- 1 Compute the approximation S_h for step size h .
- 2 Compute the approximation S_{2h} for step size $2h$.
- 3 Extrapolated solution:

$$S_{\text{extr}} = \frac{2S_h - S_{2h}}{1}$$

- 4 First four polynomials of Richardson extrapolation:

$$S_h = p_0 + p_1 h + p_2 h^2 + p_3 h^3 + \dots$$

$$S_{2h} = p_0 + p_1(2h) + p_2(2h)^2 + p_3(2h)^3 + \dots$$

- 5 Applying Richardson's method, we obtain:

$$S_{\text{extr}} = \frac{2(p_0 + p_1 h + p_2 h^2 + p_3 h^3) - (p_0 + p_1(2h) + p_2(2h)^2 + p_3(2h)^3)}{1}$$

Useful relations for loop integrals

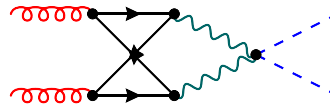
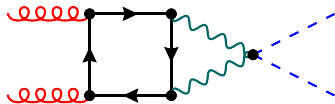
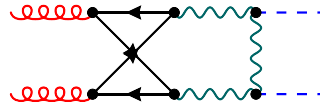
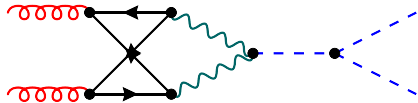
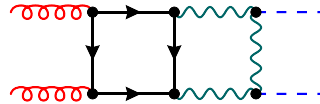
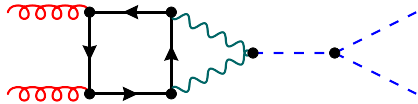
$$\int \frac{d^D k}{(2\pi)^D} \frac{1}{(k^2 - M^2 + i\epsilon)^N} = i \frac{(-1)^N}{(4\pi)^{(\frac{D}{2})}} \frac{\Gamma(N - \frac{D}{2})}{\Gamma(N)} \frac{1}{(M^2 - i\epsilon)^{(N - \frac{D}{2})}}$$

$$\int \frac{d^D k}{(2\pi)^D} \frac{k^2}{(k^2 - M^2 + i\epsilon)^N} = i \frac{1}{2} \frac{(-1)^{N-1}}{(4\pi)^{(\frac{D}{2})}} \frac{\Gamma(N - 1 - \frac{D}{2})}{\Gamma(N)} \frac{1}{(M^2 - i\epsilon)^{(N-1 - \frac{D}{2})}}$$

$$\int \frac{d^D k}{(2\pi)^D} \frac{k_\mu k_\nu}{(k^2 - M^2 + i\epsilon)^N} = i \frac{1}{2} \frac{(-1)^{N-1}}{(4\pi)^{(\frac{D}{2})}} \frac{\Gamma(N - 1 - \frac{D}{2})}{\Gamma(N)} \frac{g_{\mu\nu}}{(M^2 - i\epsilon)^{(N-1 - \frac{D}{2})}}$$

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Light quark diagrams



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Cross section

The cross section can be decomposed as follows

$$d\sigma = d\sigma_{LO} + d\sigma_{virt}$$

$$d\sigma_{virt} \sim Re \left[(C_{\Delta} F_{1\Delta}^{LO} + F_{1\Box}^{LO})^* (C_{\Delta} F_{1\Delta} + F_{1\Box}) + F_{2\Box}^{LO*} F_{2\Box} \right]$$

$$\delta_{top-yukawa-\Delta} \sim Re \left| (C_{\Delta} F_{1\Delta}^{LO})^* C_{\Delta} F_{1\Delta}^{LO} \right|$$

$$\delta_{top-Yukawa} \sim Re \left| \left[(C_{\Delta} F_{1\Delta}^{LO} + F_{1\Box}^{LO})^* (C_{\Delta} F_{1\Delta} + F_{1\Box}) + F_{2\Box}^{LO*} F_{2\Box} \right] \right| - \delta_{top-yukawa-\Delta}$$

Heavy Top-Quark Limit (HTL)

In the HTL, the top-Yukawa-induced electroweak corrections to the effective Hgg and $HHgg$ couplings can be obtained as

$$\mathcal{L}_{eff} = C_1 \frac{\alpha_s}{12\pi} G^{a\mu\nu} G_{\mu\nu}^a \log \left(1 + C_2 \frac{H}{v} \right)$$

where $G_{\mu\nu}^a$ denotes the gluonic field-strength tensor, $C_1 = 1 - 3x_t + O(x_t^2)$, and $C_2 = 1 + \frac{7}{2}x_t + O(x_t^2)$. C_1 and C_2 yield the explicit effective Hgg and $HHgg$ couplings,

$$\mathcal{L}_{eff} = C_1 \frac{\alpha_s}{12\pi} G^{a\mu\nu} G_{\mu\nu}^a \log \left[\left(1 + \delta_1 \right) \frac{H}{v} + \left(1 + \eta_1 \right) \frac{H^2}{2v^2} + O(H^3) \right]$$

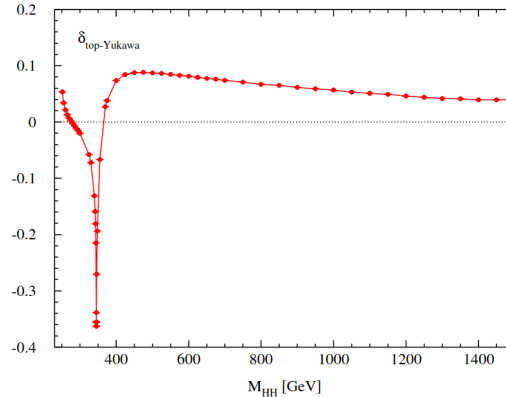
where

$$\delta_1 = \frac{x_t}{2} + O(x_t^2)$$

$$\eta_1 = 4x_t + O(x_t^2)$$

Counterterms Corrections

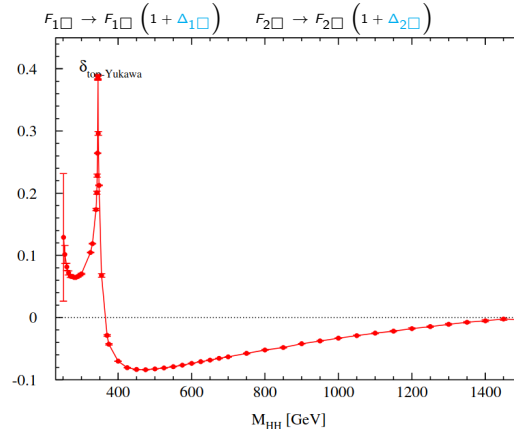
- Counterterms corrections to σ as a function of the invariant Higgs-pair mass M_{HH}
- Large contributions around the $t\bar{t}$ threshold
- Few percent corrections at the high energy tail



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Box-like Corrections

- Pure two loops Top-Yukawa-induced corrections to σ as a function of the invariant Higgs-pair mass M_{HH}
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