

PSI

Higgs-Pair Production via Gluon Fusion: 2-Loop Top-Yukawa- and Light-Quark- Induced Electroweak Corrections and Beyond

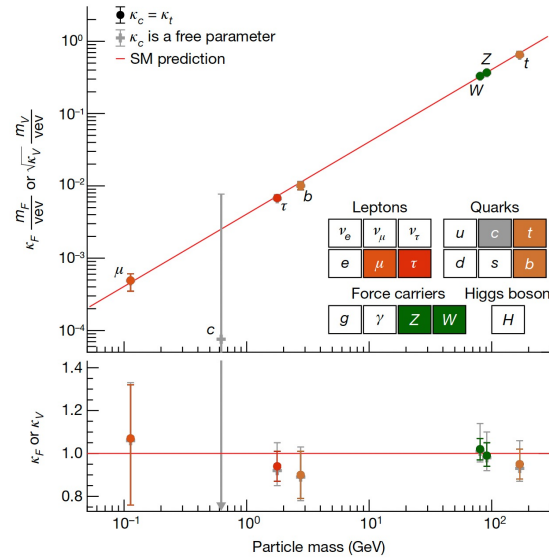
- Jamie Chang
- In collaboration with A. Bhattacharya, L. Biermann, F. Campanario, S. Carlotti, J. Mazzitelli, M. Mühlleitner, J. Ronca and M. Spira [[JHEP.07.\(2026\)0571](#)]

What is already known?



Is this the SM Higgs?

[ATLAS, Nature 607, pages 52-59 (2022)]

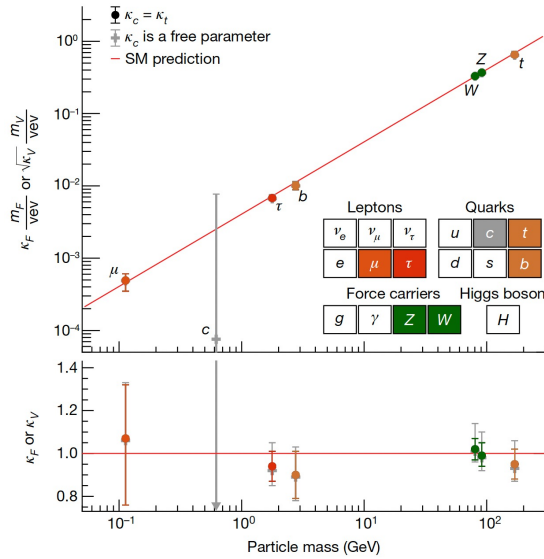


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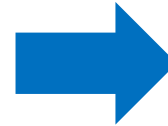


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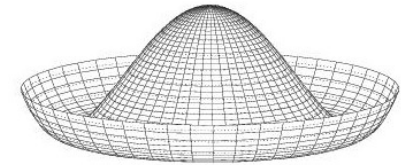
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Yukawa & gauge couplings ☺



Higgs self-interactions?: $\lambda_{HHH}, \lambda_{HHHH}$

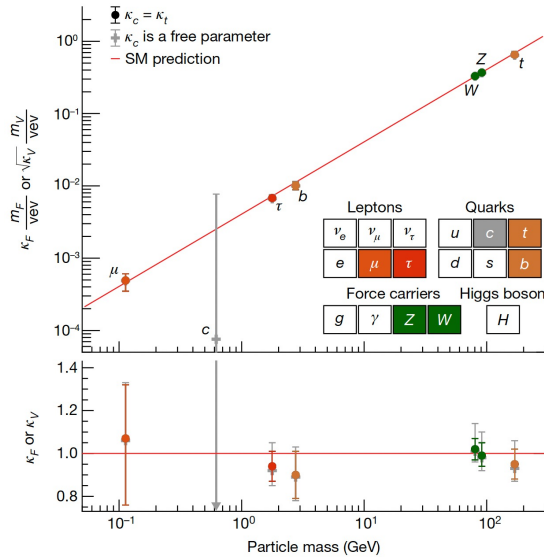


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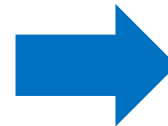


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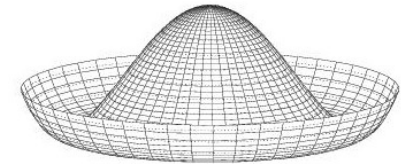
Yukawa & gauge couplings ☺



Higgs self-interactions?: $\lambda_{HHHH}, \lambda_{HHHHH}$

Measurable at (HL-)LHC

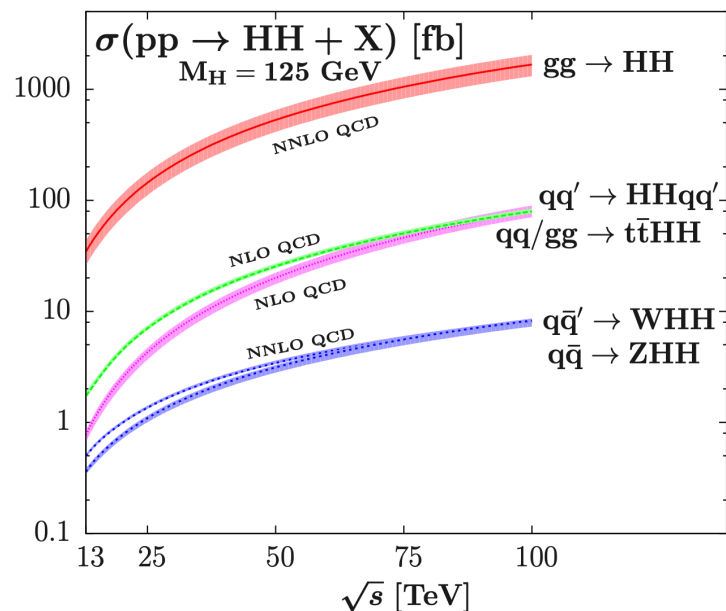
Direct search via multiple-Higgs (>2) production – **goal for a future collider**



Why this process in particular?



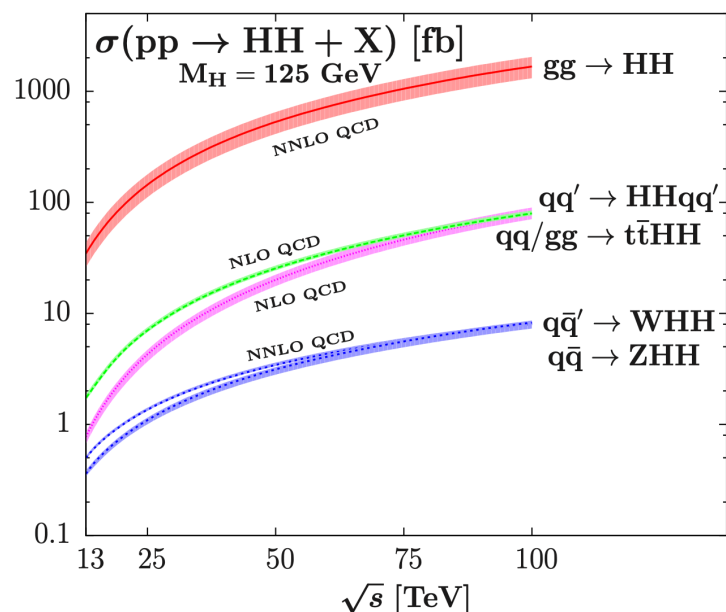
[Baglio et al. Rep. Prog. Phys. 79 (2016) 116201]



- Dominant production mechanism at hadron colliders

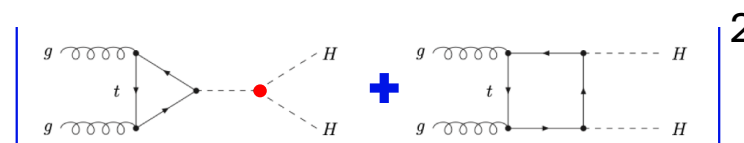
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- Dominant production mechanism at hadron colliders

Destructive interference of triangles + boxes



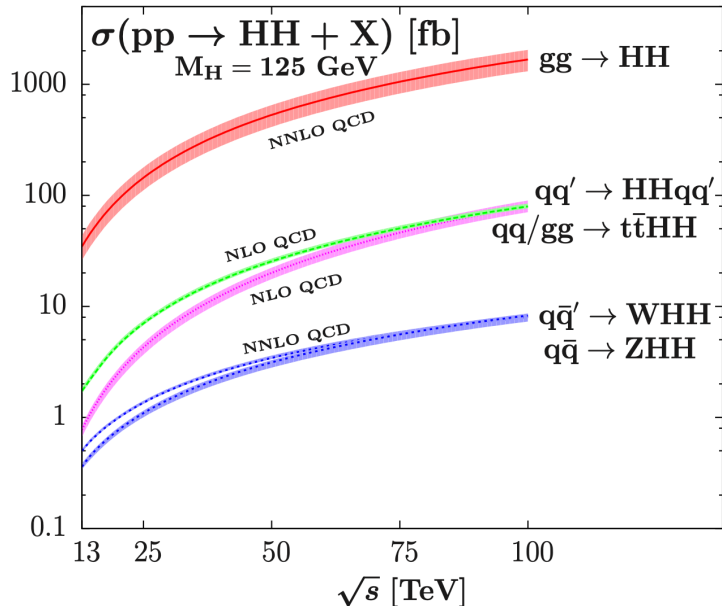
$$\frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}.$$

Valid for $\kappa_\lambda \approx 1$

Why this process in particular?

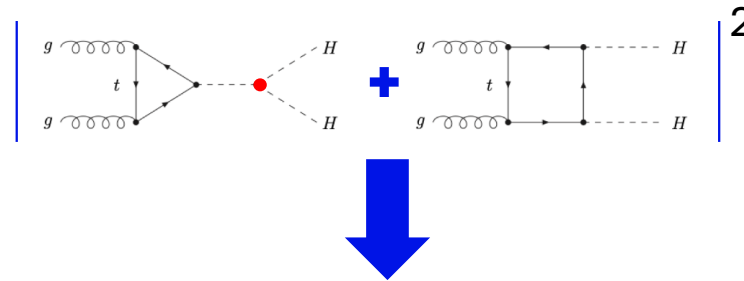


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- Dominant production mechanism at hadron colliders

Destructive interference of triangles + boxes



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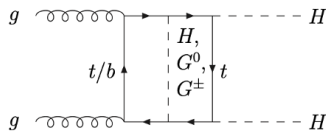
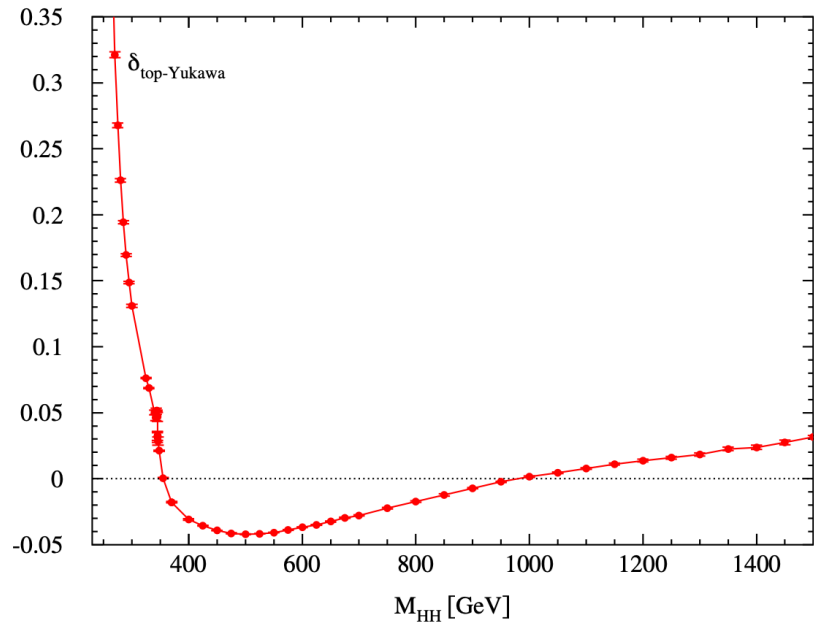
- Typical hierarchy : LO ~ NLO QCD > **NLO EW**
- HL-LHC aims for ~O(30%) precision of κ_λ
- Need computation of NLO EW contributions!

Top-Yukawa and Light-Quark Results



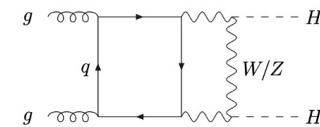
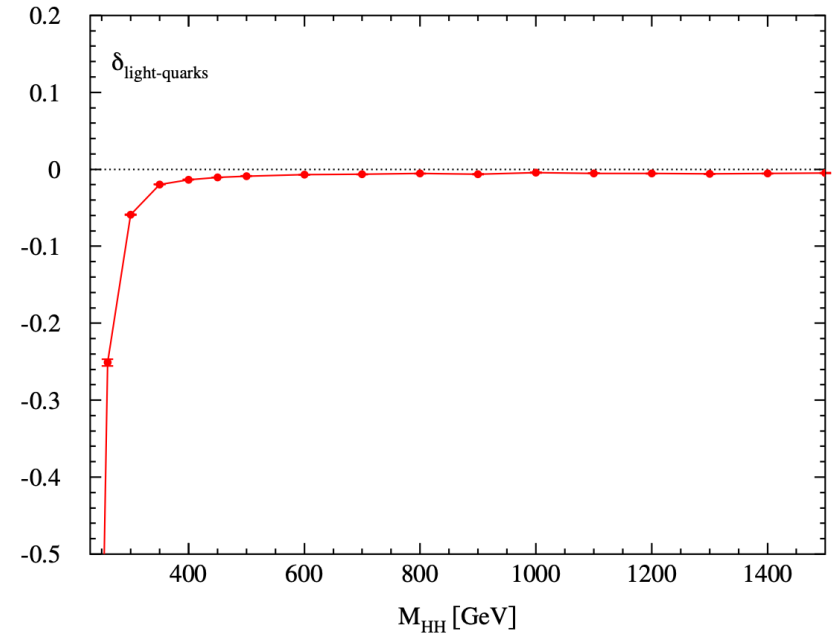
[JHEP 07 (2026) 057]

Top-Yukawa: -1.9% correction to σ_{tot}



δ 's = rel. corr. to differential x.s.

Light-Quark: -1.5% correction to σ_{tot}

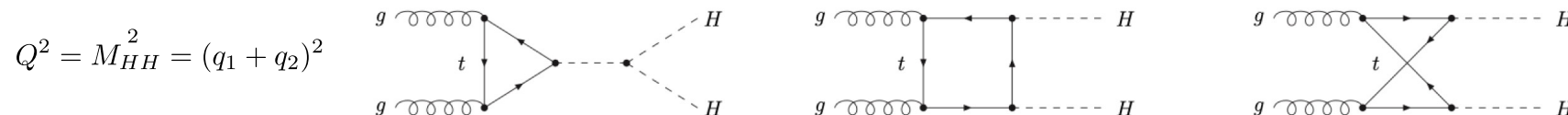


In agreement with HTL analysis of [Mühleitner et al. JHEP 10 (2022) 185]

In agreement with [Bonetti et al. JHEP 07 (2025) 024]

Computational details

Returning to the problem at hand



- **Leading order** takes form:

$$\mathcal{M}(gg \rightarrow HH) = -i \frac{G_F \alpha_s(\mu_R) Q^2}{2\sqrt{2}\pi} \mathcal{A}^{\mu\nu} \epsilon_{1\mu} \epsilon_{2\nu} \delta_{ab}$$

- Amplitude decomposition into **two** orthogonal spin structures

$$\mathcal{A}^{\mu\nu} = \underbrace{(C_\Delta F_\Delta + F_\square)}_{F_1} T_1^{\mu\nu} + \underbrace{G_\square}_{F_2} T_2^{\mu\nu}$$

- At **NLO**: EW corrections **IR** and **collinear** finite:

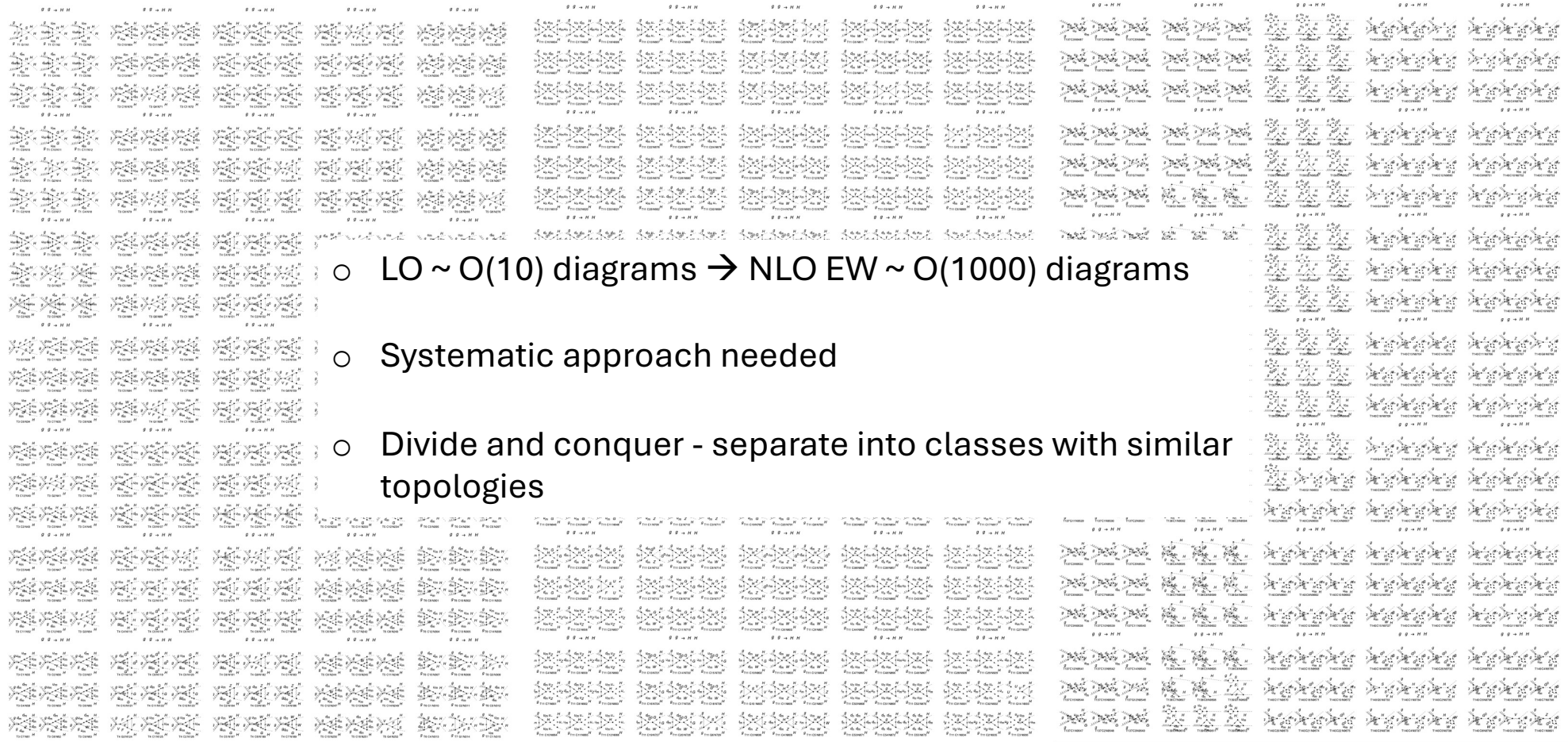
$$F_\Delta \rightarrow F_\Delta(1 + \Delta_\Delta), \quad F_\square \rightarrow F_\square(1 + \Delta_\square), \quad G_\square \rightarrow G_\square(1 + \Delta_G)$$



$$\frac{d\sigma_{NLO}}{dQ^2} = \frac{d\sigma_{LO}}{dQ^2} (1 + \delta)$$

Relative NLO/LO correction

Okay, okay – some planning involved here!

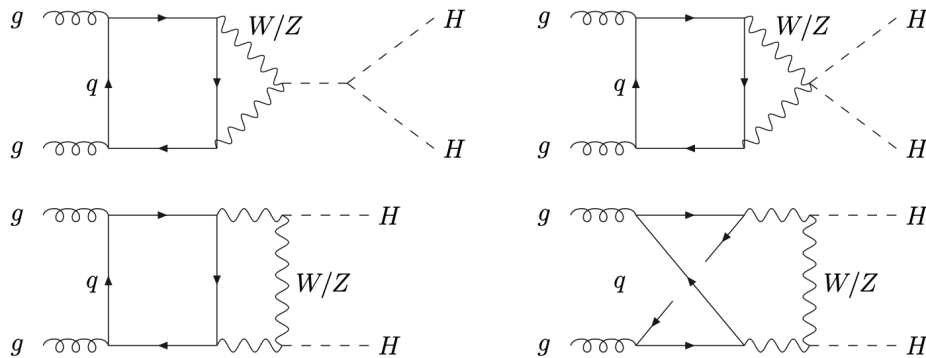


- LO ~ O(10) diagrams → NLO EW ~ O(1000) diagrams
- Systematic approach needed
- Divide and conquer - separate into classes with similar topologies

⋮

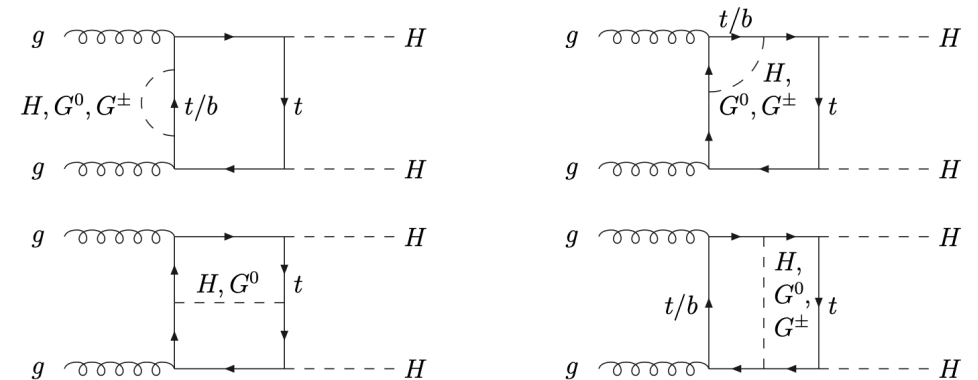
First steps : Light-quark and top-Yukawa induced corrections

1. Light-quark topologies



$$q \in \{u, d, c, s, b\}$$

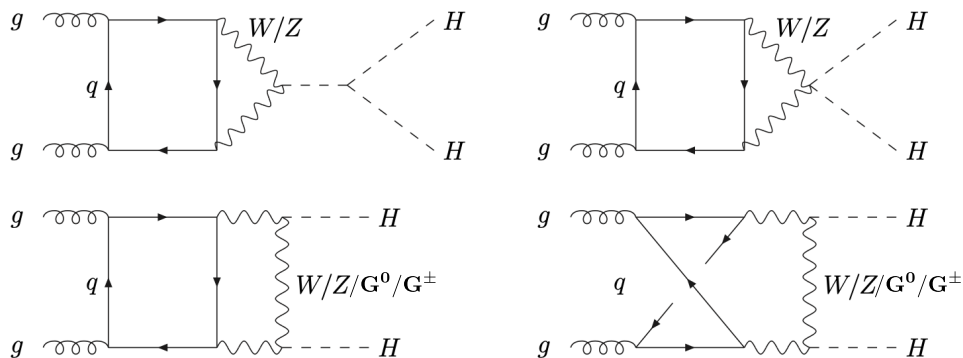
2. Top-Yukawa (box) topologies



First steps : Light-quark and top-Yukawa induced corrections

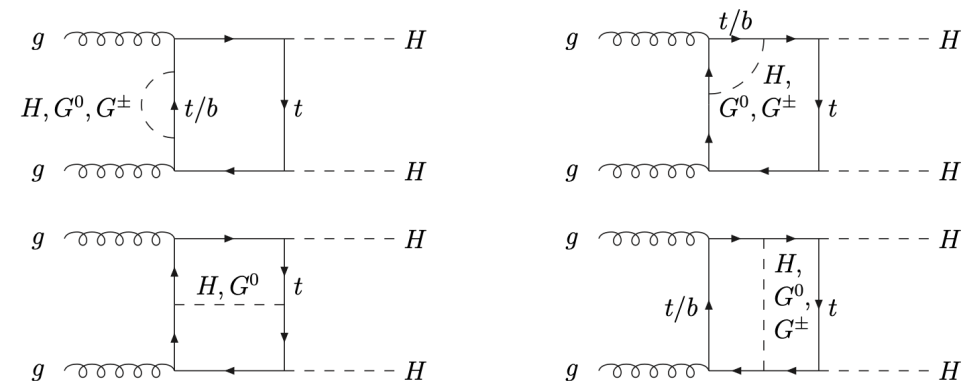


1. Light-quark topologies



Feynman gauge: $\frac{-ig^{\mu\nu}}{p^2 - M_V^2}$

2. Top-Yukawa (box) topologies



Gaugeless limit: $M_{G^0} = M_{G^\pm} = 0$

[Brignole et al. Nucl.Phys.B 631 (2002) 195-218]

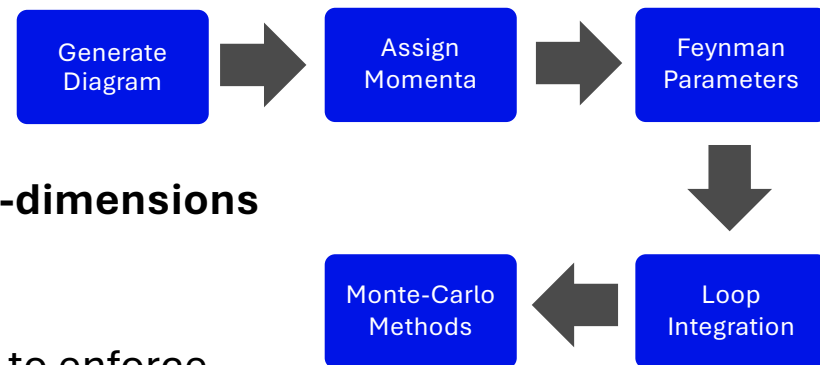
[Espinosa et al. Nucl.Phys.B 586 (2000) 3-38]

Workflow



Workflow Overview

- Numerical method
 - Many mass scales
 - Feynman parameters + phase space ~ **7-dimensions**
- Fully symbolic
 - **Working diagram-by-diagram**: no need to enforce ratio of masses to simplify calculation
 - **No tensor reduction** or reduction to master integrals
 - Instead, project onto F_1 / F_2
- MC integrations
 - Main challenges come from **stabilising integrands**

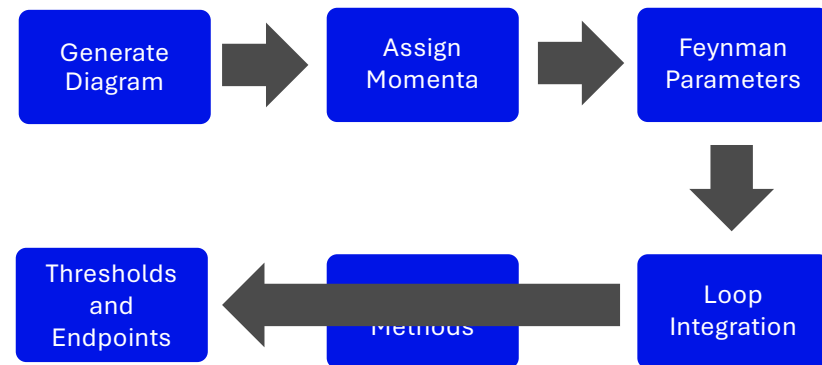


Workflow



Stability problems → Employ some tactics!

1. End-point singularities



$$\begin{aligned}
 I(x, y, z) &= \int_0^1 d\vec{x} \frac{1}{y^{1+\epsilon}} \frac{f(\vec{x})}{R^{3+2\epsilon}(\vec{x})} \\
 &= \underbrace{\int_0^1 d\vec{x} \frac{1}{y^{1+\epsilon}} \left\{ \frac{f(\vec{x})}{R^{3+2\epsilon}(\vec{x})} - \frac{f(\vec{x}; y=0)}{R^{3+2\epsilon}(\vec{x}; y=0)} \right\}}_{\text{Regular in } y} + \underbrace{\left(\int_0^1 dy \frac{1}{y^{1+\epsilon}} \right)}_{\frac{-1}{\epsilon}} \underbrace{\int_0^1 dx dz \frac{f(\vec{x}; y=0)}{R^{3+2\epsilon}(\vec{x}; y=0)}}_{\text{Regular in } y}
 \end{aligned}$$

Extract hidden pole structure
Increase stability of numerical integration

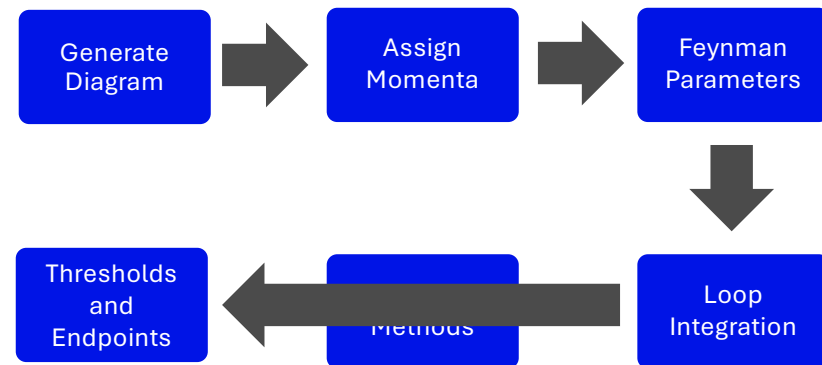
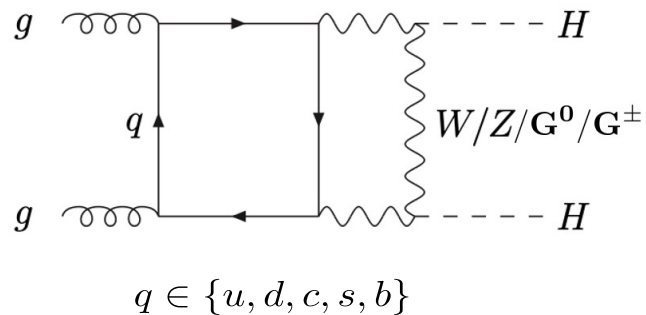
Workflow



2. Virtual Thresholds

Singularities occur when **Virtual Thresholds** are reached

e.g. $Q^2 \geq 0, 4M_V^2, \dots$



Analytic continuation of propagator masses:

$$M_V^2 \rightarrow M_V^2(1 - i\chi)$$

Then, send χ close to zero $\sim$ approx. true value of integral

Workflow



2. Virtual Thresholds

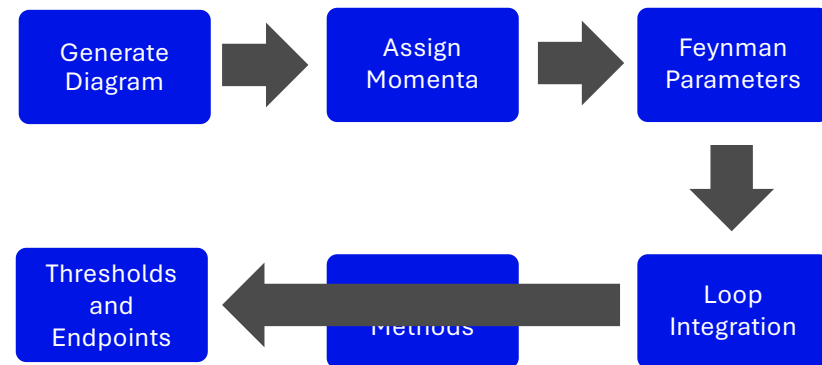
$$F_{1/2} \sim \int_0^1 d\vec{x} J(\vec{x}) \frac{f(\vec{x})}{R^{\color{red}3}}$$

Lessen **severity** of these singularities via **integration by parts** (IBPs)

$$\text{e.g. } \int_0^1 dx \frac{f(x)}{(a+bx)^{\color{red}3}} = \frac{f(0)}{2ba^{\color{green}2}} - \frac{f(1)}{2b(a+b)^{\color{green}2}} + \int_0^1 dx \frac{f'(x)}{2b(a+bx)^{\color{green}2}}$$



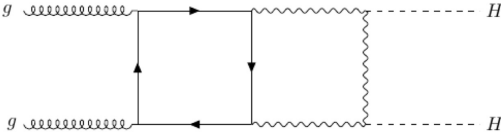
Trade off: Increase size of form factor



Workflow

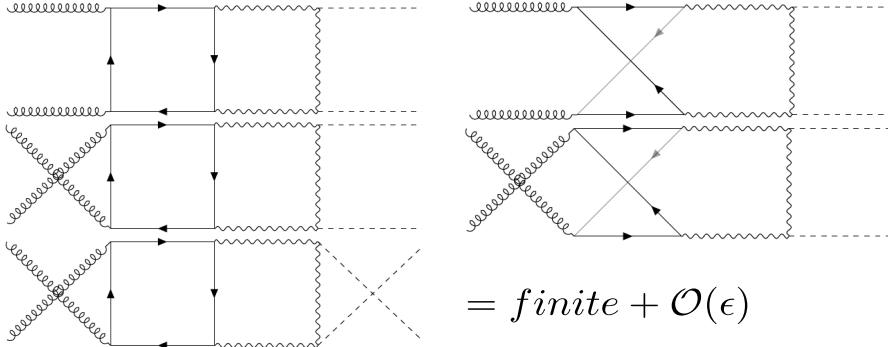


Sanity Check:

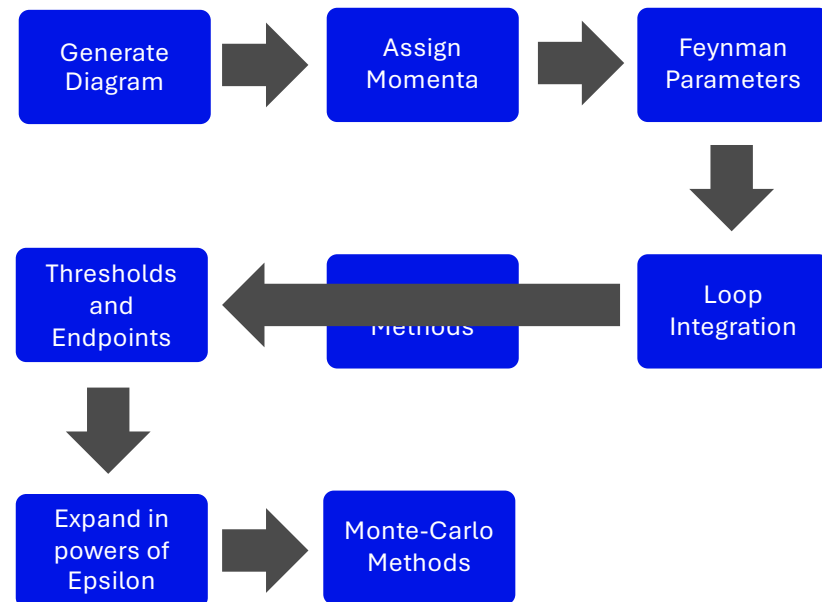


$$= \frac{finite}{\epsilon} + finite + \mathcal{O}(\epsilon)$$

Then, the sum:



$$= finite + \mathcal{O}(\epsilon)$$

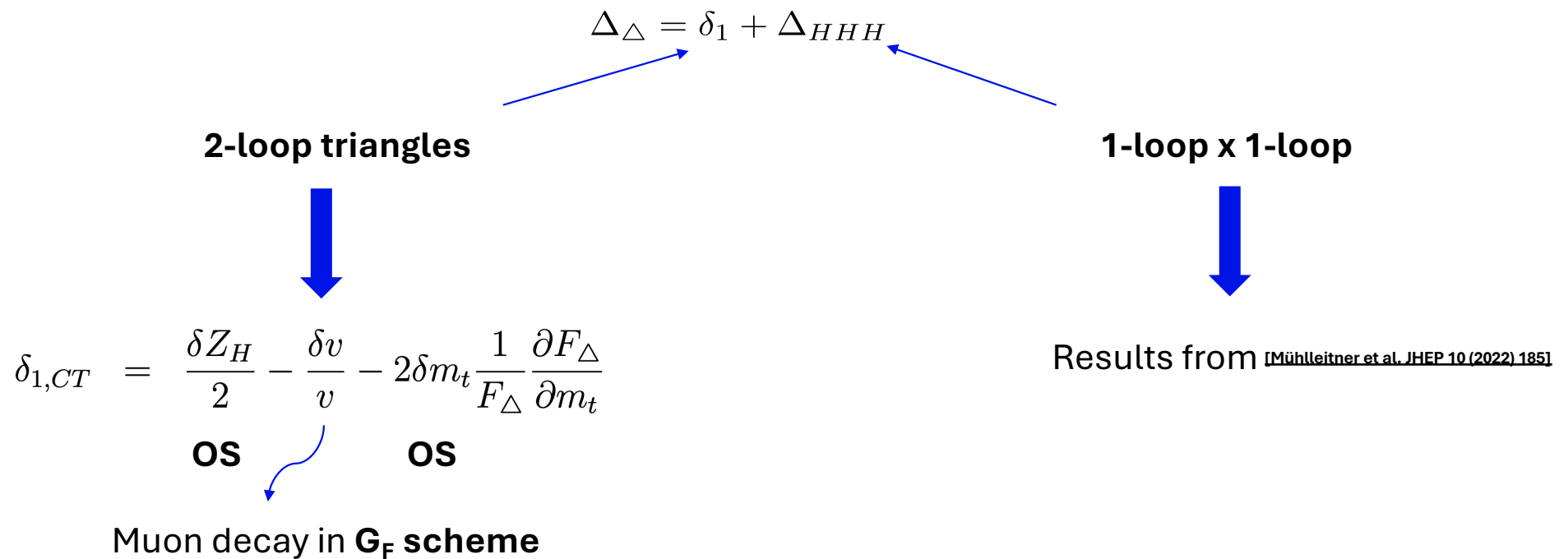


As expected, no renormalisation required for the light-quark loops ✓
 No (hidden) singularities missed!

Renormalisation Rundown: Top-Yukawa



○ Triangles:



Renormalisation Rundown: Top-Yukawa



- **Triangles:**

$$\Delta_{\triangle} = \delta_1 + \Delta_{HHH}$$

- **2-loop boxes:**

$$\begin{array}{lcl} \Delta_{\square,CT} = \delta Z_H - 2\frac{\delta v}{v} - 2\delta m_t \frac{1}{F_{\square}} \frac{\partial F_{\square}}{\partial m_t} & \longrightarrow & F_{\square} \\ \Delta_{G,CT} = \delta Z_H - 2\frac{\delta v}{v} - 2\delta m_t \frac{1}{G_{\square}} \frac{\partial G_{\square}}{\partial m_t} & \longrightarrow & G_{\square} \end{array}$$

Tadpole Renormalisation Schemes



[Denner Fortschr. Phys. 41 (1993) 307–420]

[Fleischer, Jegerlehner, PRD 23 (1981) 2001]

Tadpole Schemes	Parameter-renormalised (PR)	Fleischer-Jegerlehner (FJ)
Origin of δt	Renormalisation of tadpole parameter t in Higgs potential	Shift of Higgs field
Tadpole diagrams?	Cancel against δt ; dropped everywhere	Kept explicitly in all 2-point functions and 3-point bosonic vertices
Consequences to counterterms	Mass CTs gauge dependent	Gauge independent
Physical result	Gauge independent	Gauge independent

$$T^H = \text{---}^H \text{---} \bigcirc t$$

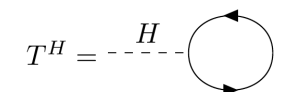
Requirement: $T^H + \delta t = 0$

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$$T^H = \text{---}^H\text{---} \bigcirc^t$$

Requirement: $T^H + \delta t = 0$

FJ in practice:

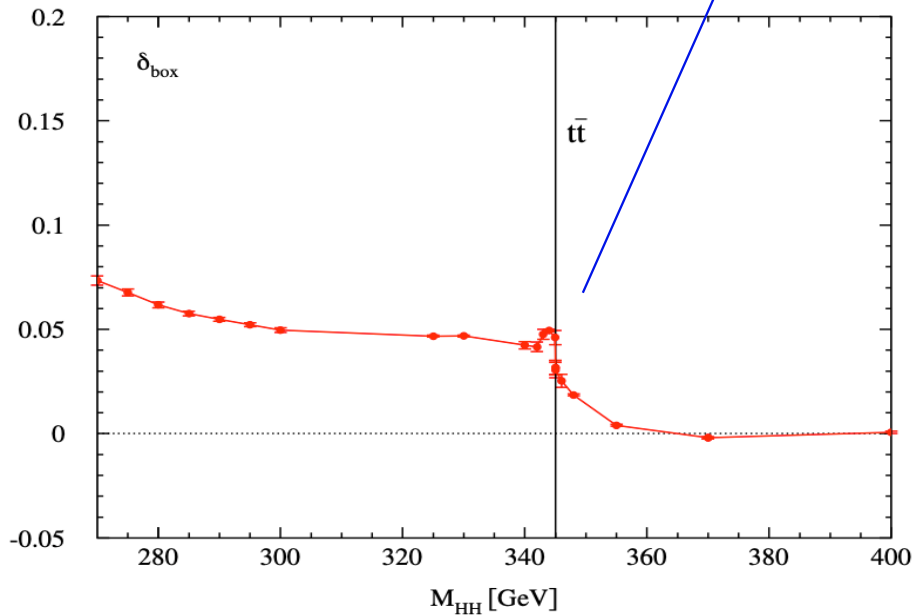
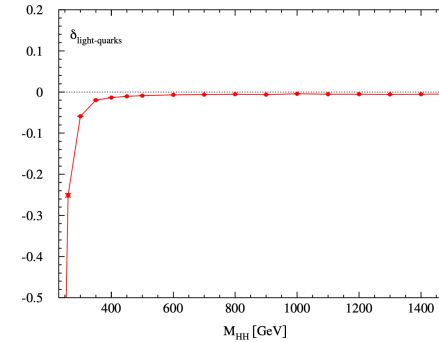
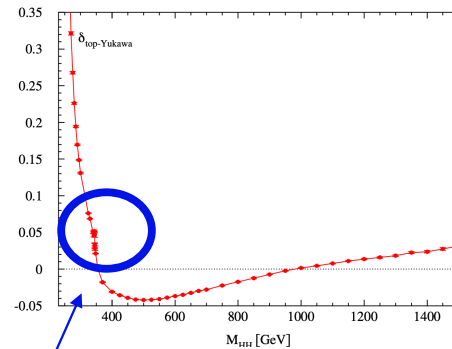
$$v \rightarrow v + \Delta v, \quad \Delta v = -\frac{\delta t}{m_H^2} = \frac{T^H}{m_H^2}$$

$$\Rightarrow \frac{\delta m_t}{m_t}, \frac{\delta v}{v} \supset \frac{T^H}{vm_H^2}$$

**Renormalized amplitude identical in FJ and PR schemes:
tadpole-dependent counterterm pieces cancel ✓**

Looping back...

$$\delta_{top-Yukawa} = \delta_{triangle} + \delta_{HHH} + \delta_{box}$$



Bin-free: resolves individual points, not finite width-histograms

- **Detailed structure** of virtual thresholds
- **Cross check: Shoulder-like** shape indicative of **p-wave** $t\bar{t}$ threshold – in agreement with single Higgs production ✓
- Dominant contributions from F_1
- **Finite slope** in large M_{HH}

Full NLO Electroweak Calculation

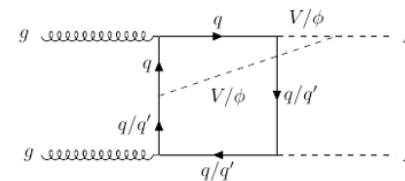


1. Heavy-quark loops

- i. Top/bottom loops with non-zero quark masses

2. Triple and Quartic gauge interactions

- i. New topology types

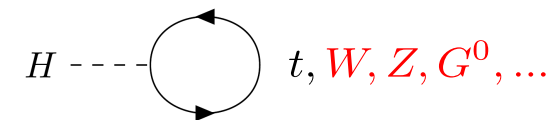


3. Massive gauge boson extension of top-Yukawa corrections

- i. Gaugeless limit  Full EW theory

4. Renormalisation

- i. More mass scales, counterterms and tadpoles
- ii. Use both FJ and PR tadpole schemes as cross check



Full NLO EW corrections to complement existing NLO QCD corrections

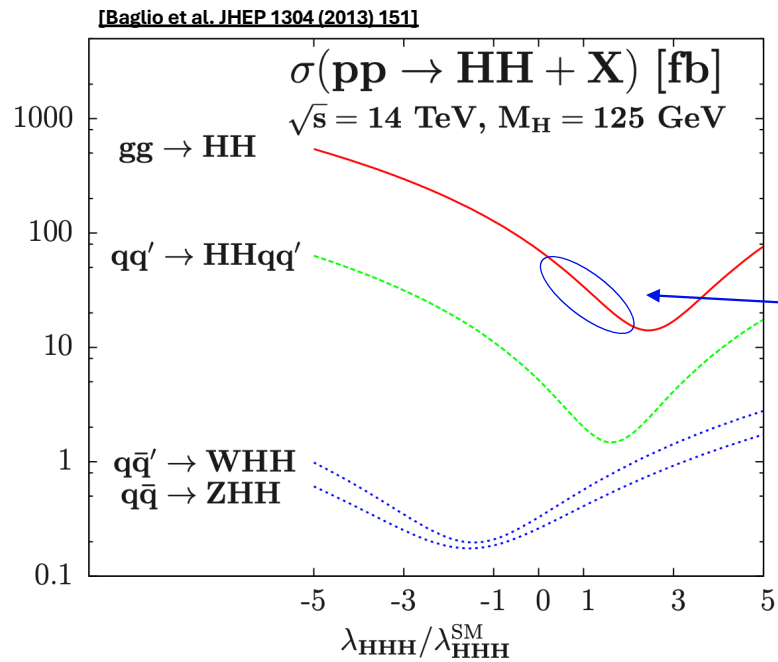
Conclusion



- **Trilinear coupling** λ_{HHH} is the primary target: HL-LHC aims for $\sim O(30\%)$ precision for κ_λ — requiring improved theory uncertainties
- **Light-quark (-1.5%)** and **top-Yukawa (-1.9%)** corrections computed and contribute at the percent level — non-negligible at HL-LHC precision targets
- **Goal:** Compute the remaining 2-loop EW contributions
- With QCD corrections complete, full EW corrections would provide a pathway to develop this method into a **community tool** for cutting-edge loop calculations

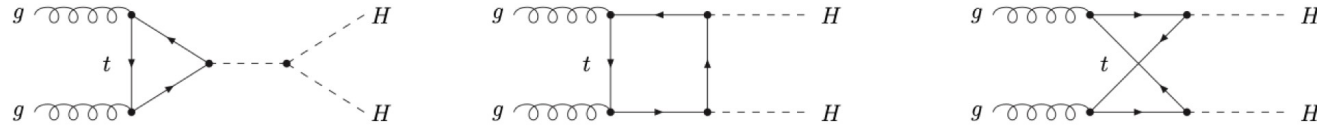
Backup slides

How does this help?



$$\frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}.$$

Further decomposition



- Spin tensors:

$$T_1^{\mu\nu} = g^{\mu\nu} - \frac{q_1^\nu q_2^\mu}{q_1 \cdot q_2}$$

$$T_2^{\mu\nu} = g^{\mu\nu} + \frac{M_H^2 q_1^\nu q_2^\mu}{p_T^2 q_1 \cdot q_2} - 2 \frac{q_2 \cdot p_1 q_1^\nu p_1^\mu}{p_T^2 q_1 \cdot q_2} - 2 \frac{q_1 \cdot p_1 p_1^\nu q_2^\mu}{p_T^2 q_1 \cdot q_2} + 2 \frac{p_1^\nu p_1^\mu}{p_T^2}$$

p_T transverse momentum of each final state Higgs

- Projectors cast in D dimensions

$$P_1^{\mu\nu} = \frac{(1 - \epsilon)T_1^{\mu\nu} + \epsilon T_2^{\mu\nu}}{2(1 - 2\epsilon)} \quad P_2^{\mu\nu} = \frac{\epsilon T_1^{\mu\nu} + (1 - \epsilon)T_2^{\mu\nu}}{2(1 - 2\epsilon)}$$

$$\delta = 2\Re \frac{\int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} \left[(C_\Delta F_\Delta + F_\square)^* (C_\Delta F_\Delta \Delta_\Delta + F_\square \Delta_\square) + |G_\square|^2 \Delta_G \right]}{\int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} \left[|C_\Delta F_\Delta + F_\square|^2 + |G_\square|^2 \right]}$$

First steps : Light-quark and top-Yukawa induced corrections

Gaugeless limit:

[Brignole et al. Nucl.Phys.B 631 (2002) 195-218]

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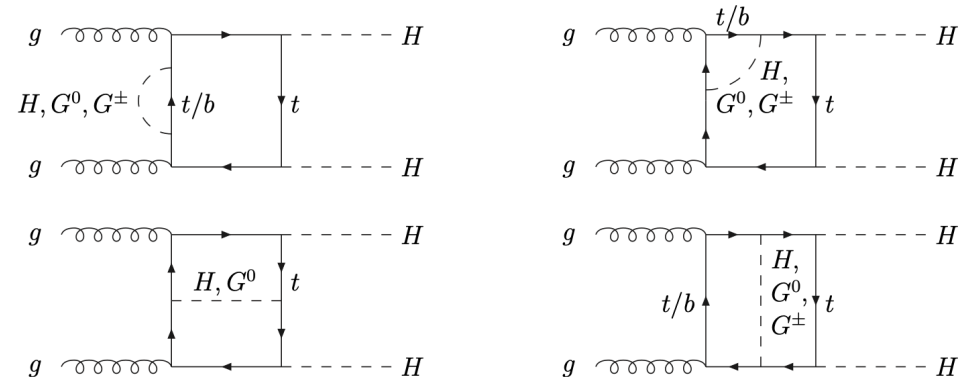
$$\mathcal{L} = -\frac{1}{4}G^{a\mu\nu}G_{\mu\nu}^a + \bar{t}i\not{D}t + \bar{b}i\not{D}b + |\partial_\mu\phi|^2 - V(\phi) - g_t\bar{Q}_L\phi^c t_R - g_b\bar{Q}_L\phi b_R + h.c$$

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



$M_{G^0} = M_{G^\pm} = 0$

2. Top-Yukawa box topologies



Stabilising the MC Integration: Richardson Extrapolation

Feynman integrals are now **regulator dependent**:

$$I(\chi) = I(0) + \mathcal{O}(\chi)$$

Generate iterative function defined as:

$$R_n(\chi, t) = \frac{t^n R_{n-1}(\chi) - R_{n-1}(t\chi)}{t^n - 1} = I(0) + \mathcal{O}(\chi^{n+1})$$

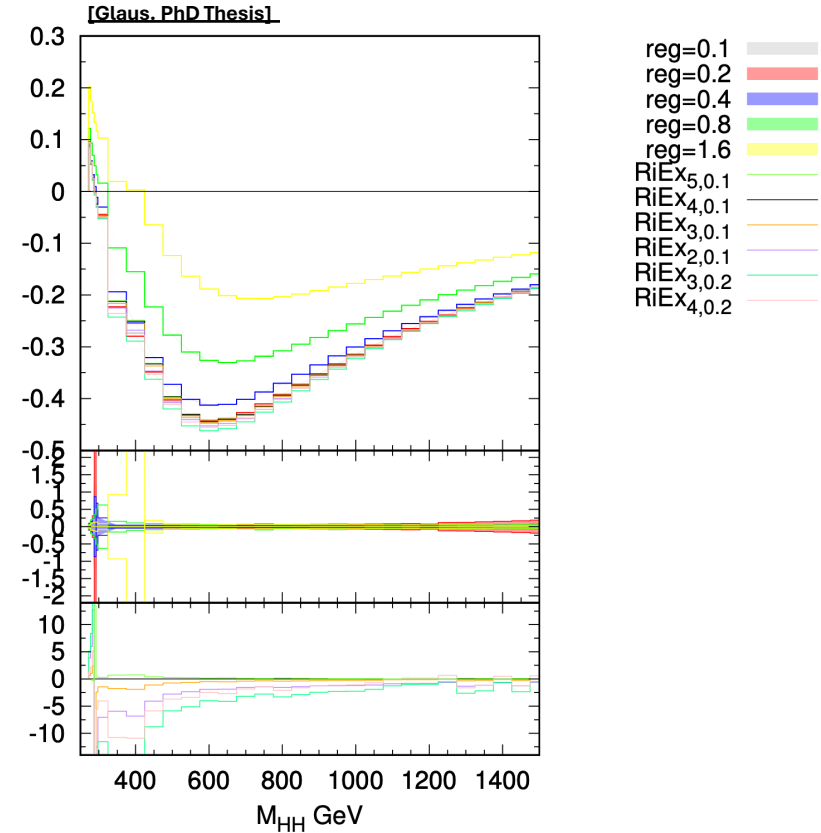
$$R_1(\chi, t) = \frac{tI(\chi) - I(t\chi)}{t - 1} = I(0) + \mathcal{O}(\chi^2)$$



$$R_1(\chi, 2) = 2I(\chi) - I(2\chi) = I(0) + \mathcal{O}(\chi^2)$$

$$R_2(\chi, 2) = \frac{1}{3} [8I(\chi) - 6I(2\chi) + I(4\chi)] = I(0) + \mathcal{O}(\chi^3)$$

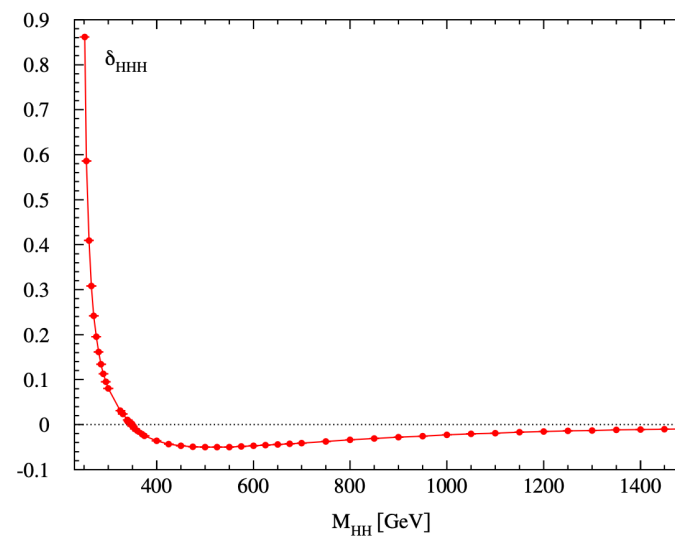
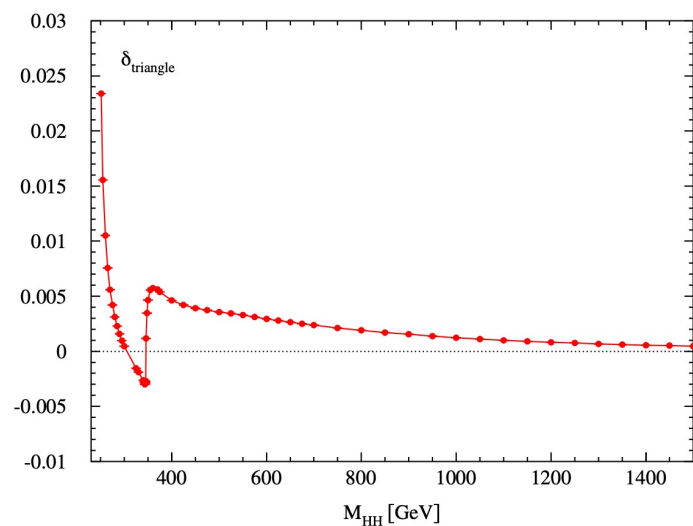
⋮



Top-Yukawa contribution decomposition



$$\delta = \delta_{top-Yukawa} + \delta_{light-quarks}$$
$$\delta_{top-Yukawa} = \delta_{triangle} + \delta_{HHH} + \delta_{box}$$



Renormalisation details – Top Yukawa



Tadpoles:

$$\frac{T_1}{v} = -12 x_t A_0(m_t).$$

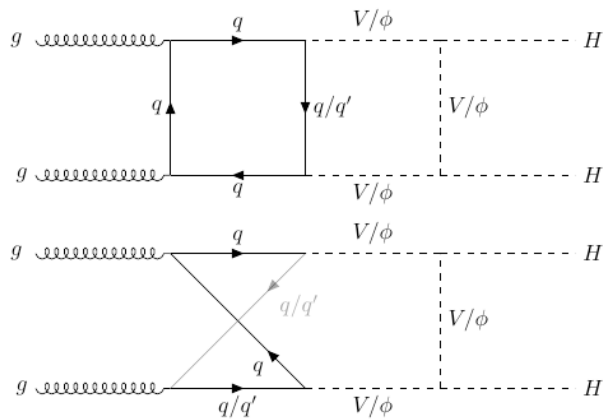
Counterterms:

$$\begin{aligned} \delta_{1,CT} &= \frac{\delta Z_H}{2} - \frac{\delta v}{v} - 2\delta m_t \frac{1}{F_\Delta} \frac{\partial F_\Delta}{\partial m_t} \\ \delta Z_H = \Sigma'_H(Q^2) &= 6 x_t \{ (4m_t^2 - Q^2) B'_0(Q^2; m_t, m_t) - B_0(Q^2; m_t, m_t) \} \\ \frac{\delta v}{v} = \frac{1}{2} \frac{\Sigma_W(0)}{M_W^2} &= \frac{T_1}{v M_H^2} + x_t \{ B_0(0; m_t, m_b) + 2B_0(0; m_t, m_t) + m_t^2 B'_0(0; m_t, m_b) \} \\ \frac{\delta m_t}{m_t} = \frac{\Sigma(m_t)}{m_t} &= \frac{T_1}{v M_H^2} - x_t \left\{ \left(2 - \frac{M_H^2}{2m_t^2} \right) B_0(p; m_t, M_H) + \frac{m_t^2 + m_b^2}{2m_t^2} B_0(p; m_b, 0) \right. \\ &\quad \left. + \frac{A_0(M_H) - 2A_0(m_t) - A_0(m_b)}{2m_t^2} \Big|_{p^2=m_t^2} \right\} \end{aligned}$$

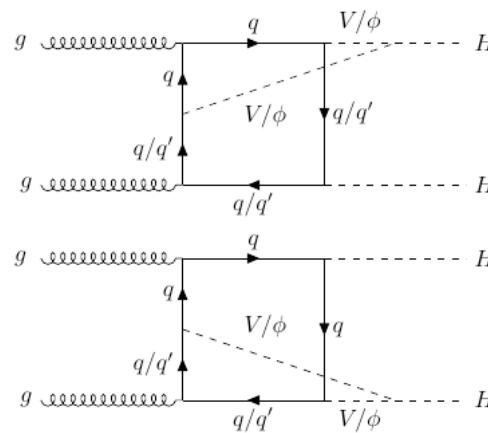
Full NLO Electroweak Calculation



1. Heavy-quark loops



2. Triple gauge interactions



3. Quartic gauge interactions

