Exploring correlations between HEFT Higgs couplings κ_V and κ_{2V} via HH production at e^+e^- colliders

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For more references, see Eur.Phys.J.C 84 (2024) 5, 503, in collaboration with D. Domenech, M. J. Herrero and R. A. Morales.

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Motivation

Since discovery of Higgs particle in 2012 → big effort in exploring its properties.

Test of **BSM** Higgs physics at colliders: **Anomalous Higgs couplings** → $\boldsymbol{\kappa}$**-modifiers**.

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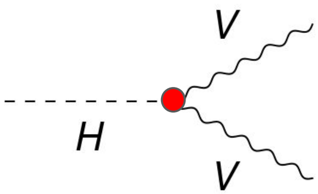
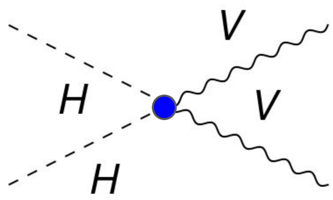
We focus in the **bosonic sector**, in particular the effective interactions of the Higgs to electroweak (EW) bosons, ***HVV*** and ***HHVV*** ($V = W, Z$):

$$\kappa_V = \frac{g_{HVV}}{g^{SM}_{HVV}}$$



$$\kappa_{2V} = \frac{g_{HHVV}}{g^{SM}_{HHVV}}$$



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* ATLAS PRD 101, 012002 (2020)
* ATLAS CONF-2024-006

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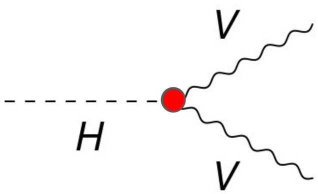

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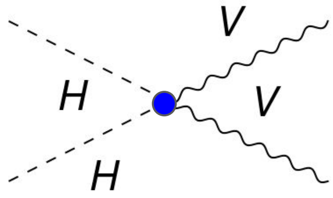

95% CL constraints from **ATLAS**: $\kappa_V \in (0.97, 1.13)$ * $\kappa_{2V} \in (0.57, 1.48)$ *

Effective Field Theories

Proper way to study anomalous couplings → **Effective Field Theories**.

Most popular ones:

- **Standard Model Effective Field Theory** (**SMEFT**)
- **Higgs Effective Field Theory** (**HEFT**, also called **Electroweak Chiral Lagrangian**, EChL)

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Here, we choose the **HEFT**, since the effective couplings of our interest are given by the leading order (**LO**) Wilson coefficients ***a*** and ***b***, which are **independent** and identifiable with the κ-modifiers:

$$a = \kappa_V \qquad b = \kappa_{2V}$$

The HEFT

➔ In contrast to the SM and the **SMEFT**, ***H*** is introduced as a **singlet**, while the **Goldstone Bosons** (GBs) are introduced in a non-linear representation:

$$U = \exp\left(i\frac{\omega_i \tau_i}{v}\right) \Rightarrow \begin{cases} \omega_i \rightarrow \text{GBs (i = 1, 2, 3)} \\ \tau_i \rightarrow \text{Pauli matrices} \end{cases}$$

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- Inspired in the **QCD Chiral Lagrangian**, follows the formalism of **Chiral Perturbation Theory** (**ChPT**): the effective operators are classified by their **chiral dimension** → The boson masses and the derivatives of ***U*** count as dimension 1.

Relevant HEFT terms at LO

LO-HEFT Lagrangian:

Chiral dimension 2

$$\mathcal{L}_{\rm LO}^{\rm HEFT} = \frac{v^2}{4}\left(1 + 2a\frac{H}{v} + b\frac{H^2}{v^2}\right)\mathrm{Tr}[D_\mu U^\dagger D^\mu U] + \frac{1}{2}\partial_\mu H \partial^\mu H - V(H)$$
$$- \frac{1}{2g^2}\mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] - \frac{1}{2g'^2}\mathrm{Tr}[\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}] + \mathcal{L}_{GF} + \mathcal{L}_{FP}$$

- **Potential:** $V(H) = \frac{1}{2}m_H^2 H^2 + \kappa_3 \lambda v H^3 + \kappa_4 \frac{\lambda}{4} H^4$ **(Here, $\kappa_{3,4}$ = 1)**

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In this work, we are only interested in the coefficients ***a*** and ***b***, and **correlations** between deviations from their **SM** values: ***Δa*** = ***1*** − ***a*** and ***Δb*** = ***1*** − ***b***.

Correlations between Δa and Δb in concrete NP models

Once a particular underlying **UV** theory is assumed to generate the low-energy theory, the **Wilson coefficients** from the **EFT** can be derived by a matching procedure at low energies. Thus, we can get different **correlation hypothesis** between Δa and Δb:

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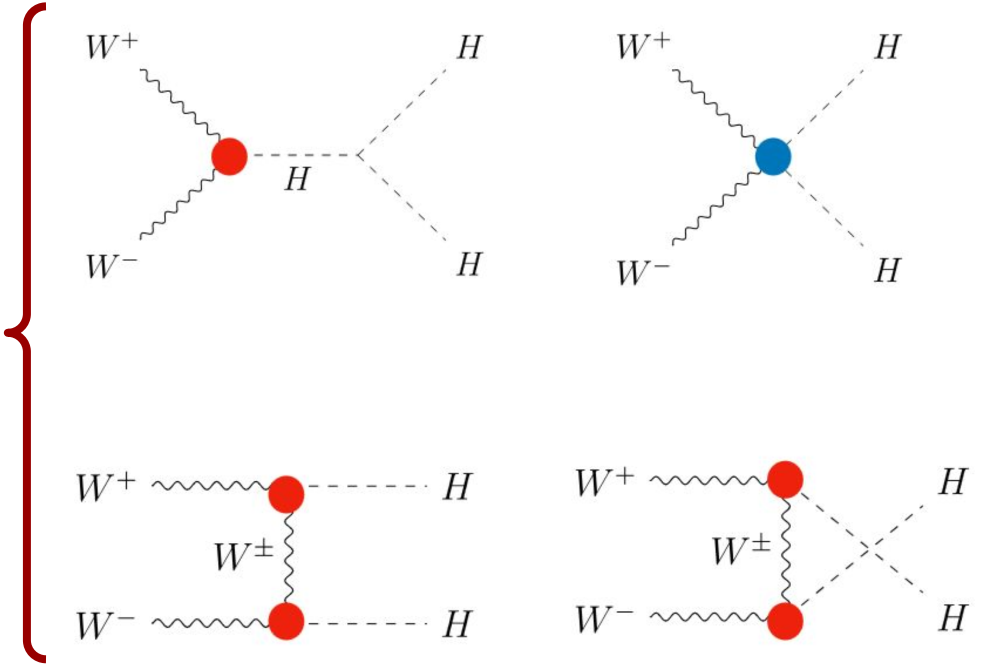
- ➔ **2HDM*** → $-2\,\Delta a = \Delta b$. [Arco '23]

* In the decoupling limit and within the region close to the alignment condition: $\cos(\alpha - \beta) \ll 1$

Double Higgs Production via WBF

Sensitive process to ***a*** and ***b*** → Double Higgs Production via *WW* Vector Boson Fusion (**WBF**).

4 diagrams contribute to the amplitude:



The amplitude of the process is gauge invariant → we choose the **Unitary Gauge** (no internal GBs).

$WW \rightarrow HH$ channel amplitudes at high energies

At high energies ($\sqrt{s} \gg m_H, m_W$), the dominant contribution comes from W_L.

[Domenech '22]

$$\mathcal{A}^L_C = b\frac{g^2}{4m_W^2}s + \mathcal{O}(s^0)$$

$$\mathcal{A}^L_S = 0 + \mathcal{O}(s^0)$$

$$\mathcal{A}^L_T = a^2\frac{g^2}{8m_W^2}(\cos\theta - 1)s + \mathcal{O}(s^0)$$

$$\mathcal{A}^L_U = -a^2\frac{g^2}{8m_W^2}(\cos\theta + 1)s + \mathcal{O}(s^0)$$

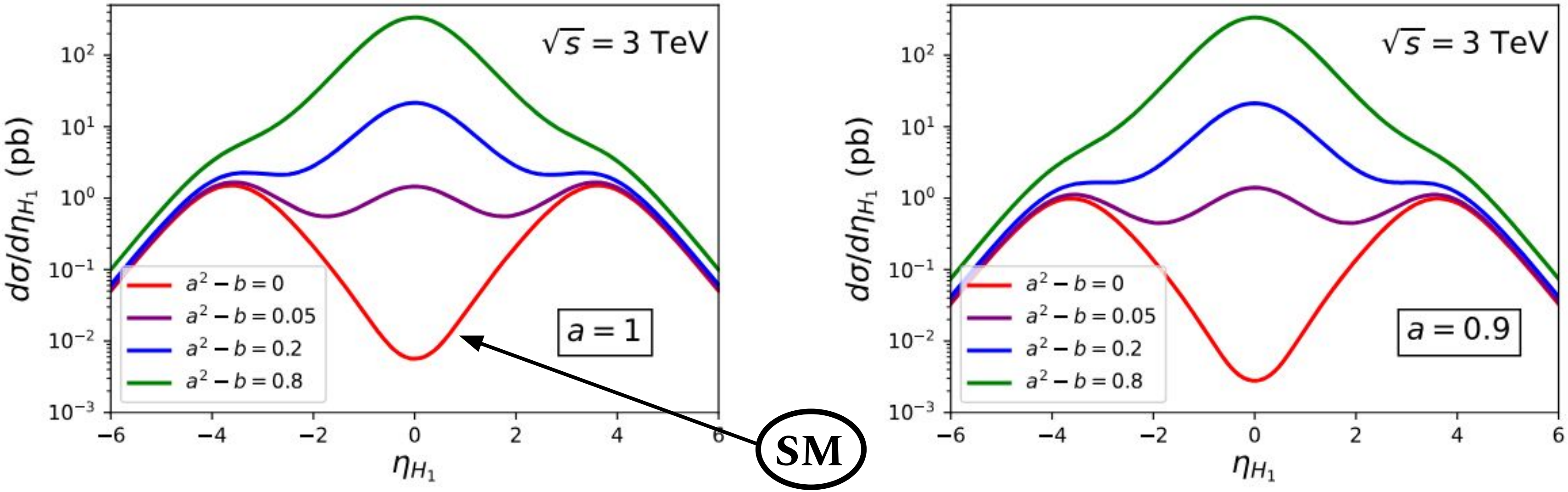
$$\Rightarrow$$

$$\mathcal{A} = (b - a^2)\frac{g^2}{4m_W^2}s + \mathcal{O}(s^0)$$

Pseudorapidity

$$\eta_H = -\log(\tan(\theta/2))$$

Pseudorapidity distributions of *WW* → *HH*



- ➔ **BSM** distributions present a central maximum when $a^2 - b$ differs from ***0***.
- ➔ Expect to have phenomenological consequences in the full process.

HH production in e^+e^- colliders

- **Complete process** that contains $WW \to HH$ in a collider.
- Already studied at the **LHC** → limited sensitivity to ***b*** (hadron collider).
- Alternative: ***e^+e^-* colliders**. Here, we consider:
  - **International Linear Collider** (ILC) at 500 GeV and 1 TeV.
  - **Compact Linear Collider** (CLIC) at 3 TeV.
- Simulation with **MadGraph** (MG5) to compute the cross section.

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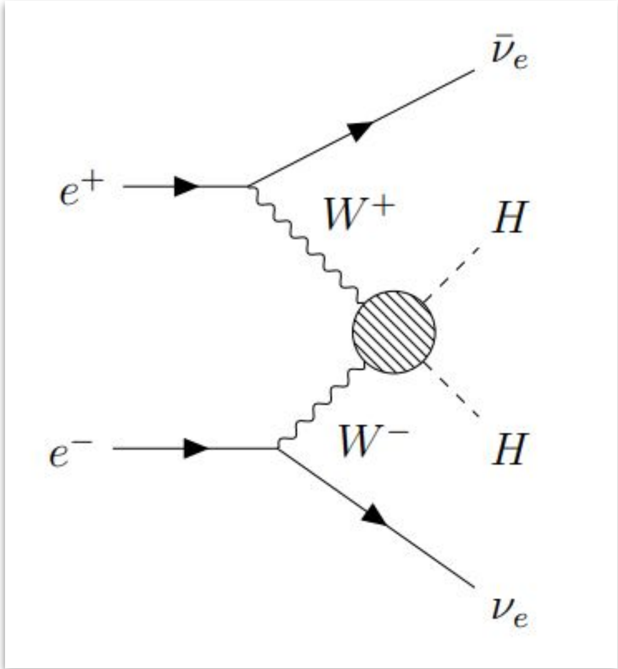
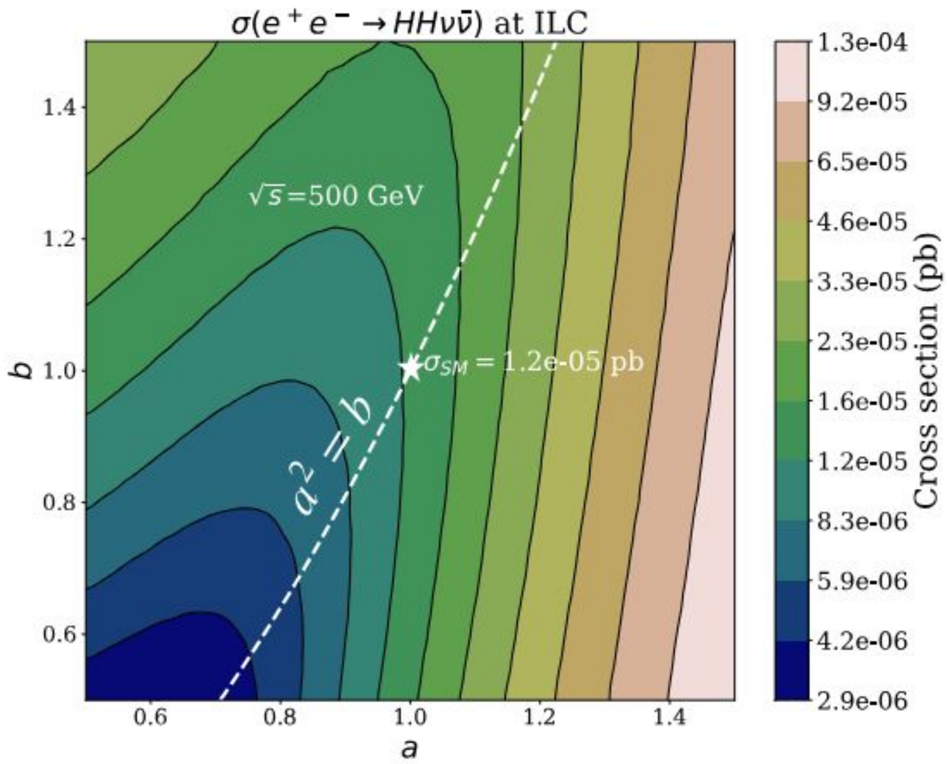
- Process of interest: $e^+e^- \rightarrow HH\nu_e\bar{\nu}_e$



Sensitivity to HEFT LO parameters *a* and *b*



- ➔ Bounds on ***a*** and ***b*** → Ensure **perturbative unitarity**.
- ➔ Higher collider energy → higher sensitivity to ***a*** and **b**.
- ➔ Minimum of the xsection close to $a^2 = b$ → **2** $\Delta a = \Delta b$

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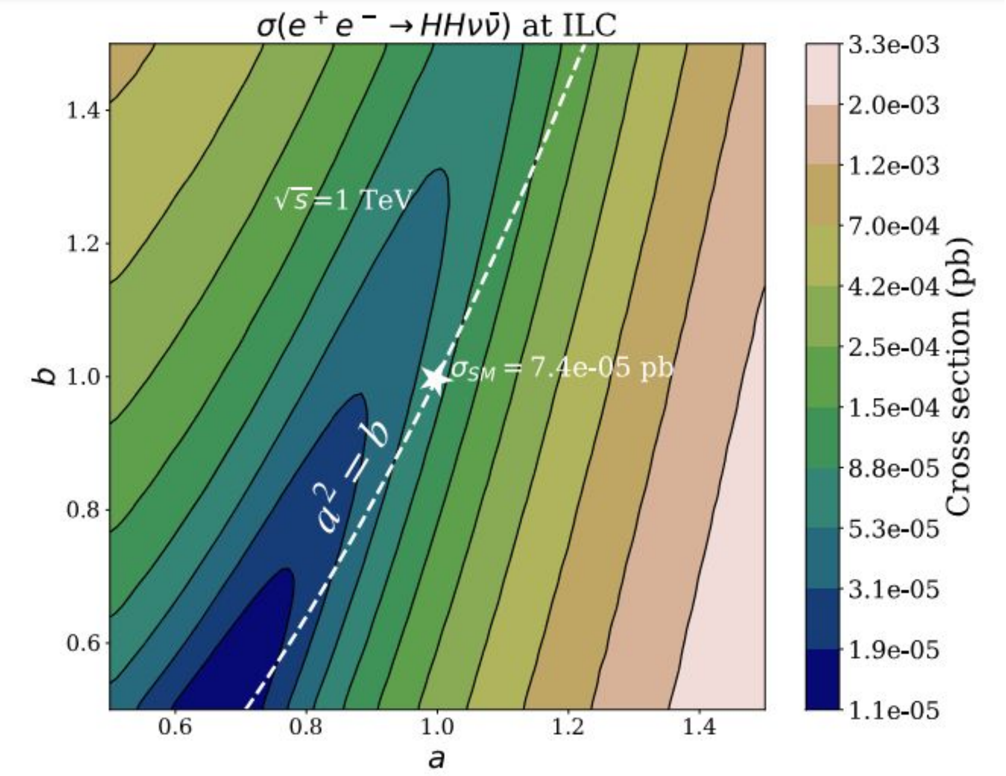

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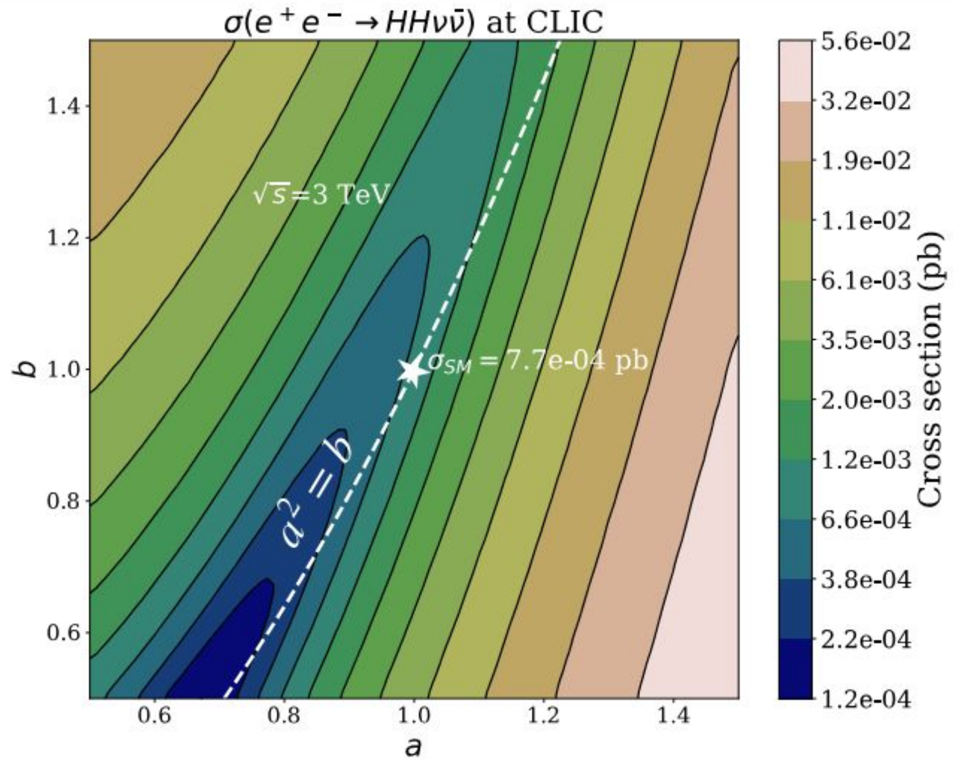

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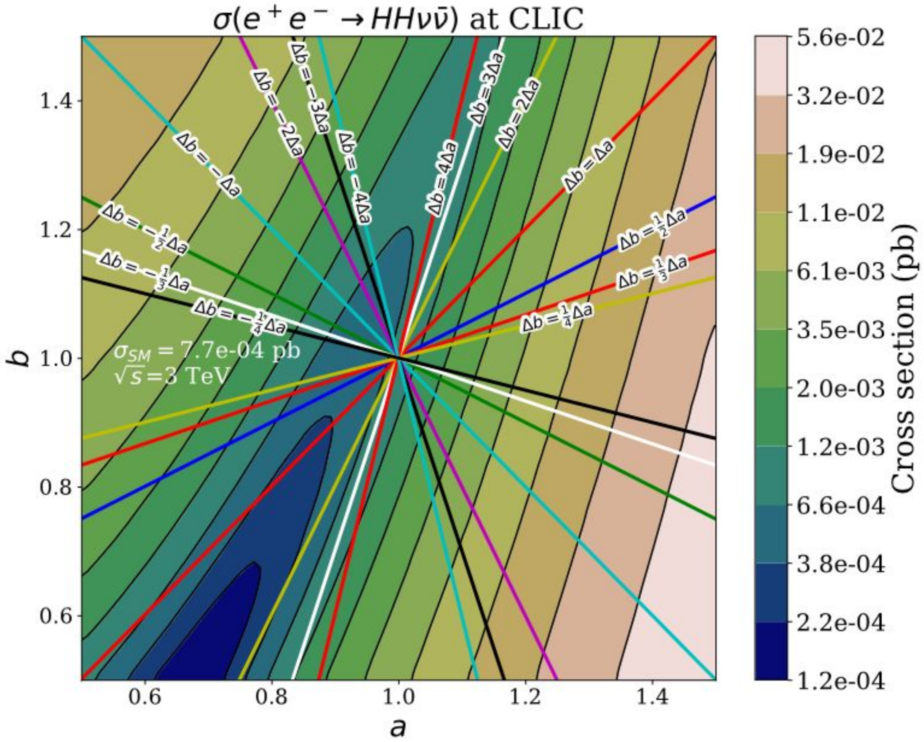

- ➔ Higher cross sections are reached if the correlation between Δa and Δb follows a path approximately 'perpendicular' to the line $a^2 = b$.
- ➔ From now on, focus on **3 TeV**.

Phenomenological consequences of correlations between HEFT LO parameters

➔ How do different correlations between **Δa** and **Δb** affect **kinematic variables**?

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➔ We computed the differential cross section of the process with respect to:

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- The pseudorapidity of one of the final H.
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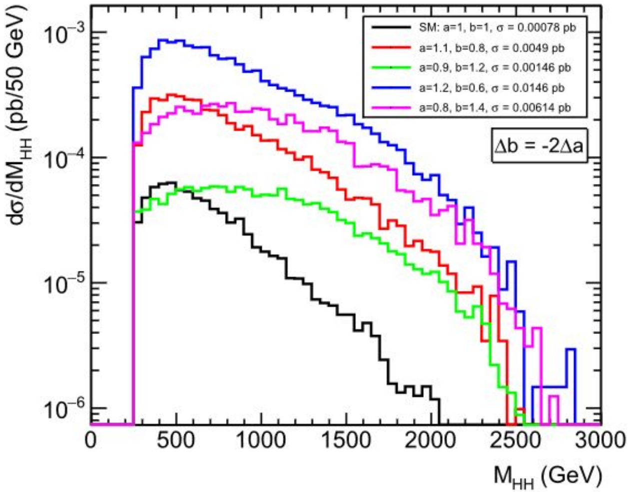
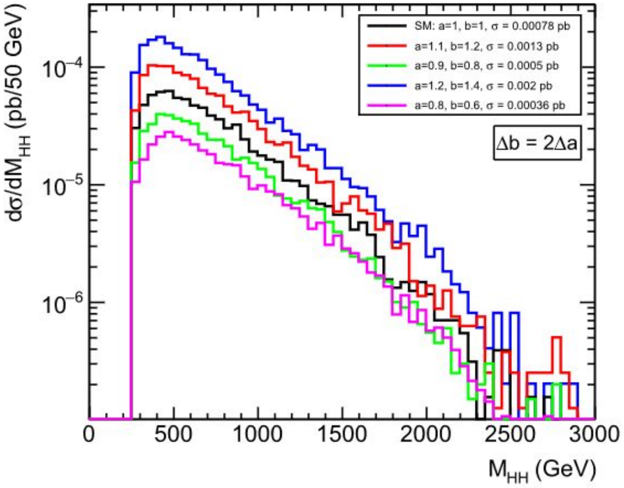
➔ A **linear correlation** between Δa and Δb is assumed: $\Delta b = C\,\Delta a$.

Phen. cons. of correlations between HEFT LO parameters: Invariant *HH* Mass

$e^+e^- \to HH\nu_e\bar{\nu}_e$ at $\sqrt{s} = 3\,\mathrm{TeV}$





C = - 2 ← **2HDM**

C = 2

- ➔ In general, going BSM distorts the distributions **elevating the tails** at high M_{HH}.
- ➔ Exception: ***C*** = 2 → close to $\boldsymbol{a}^2$ = $\boldsymbol{b}$.

Phen. cons. of correlations between HEFT LO parameters: Pseudorapidity

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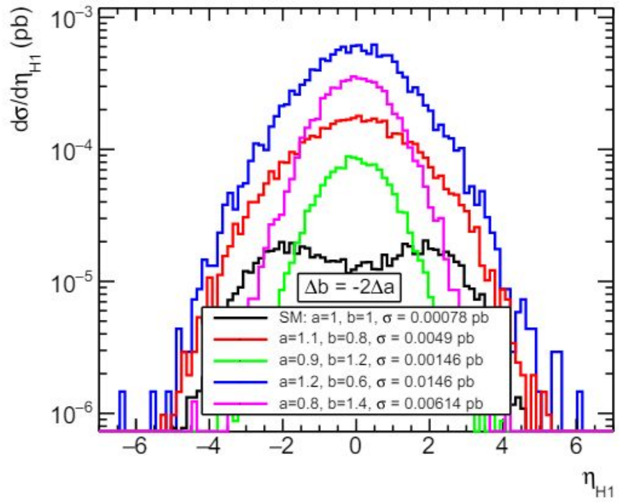

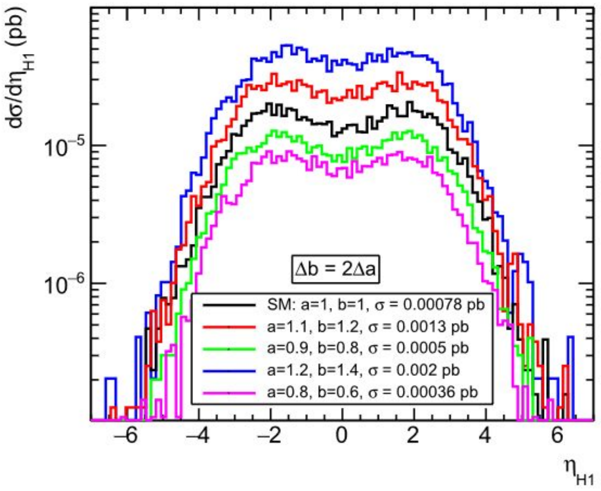

C = - 2 ← **2HDM**

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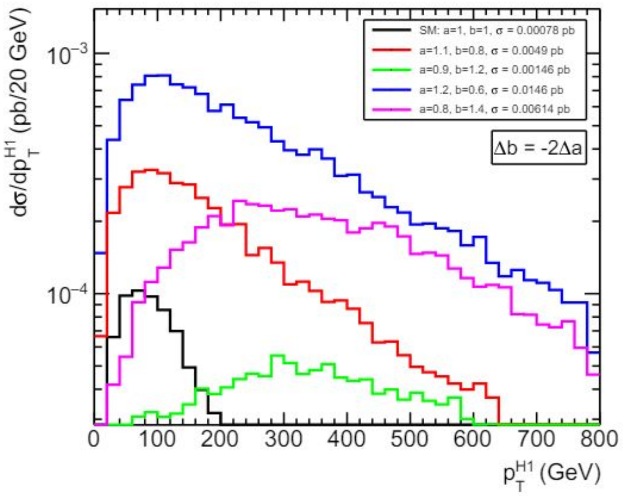
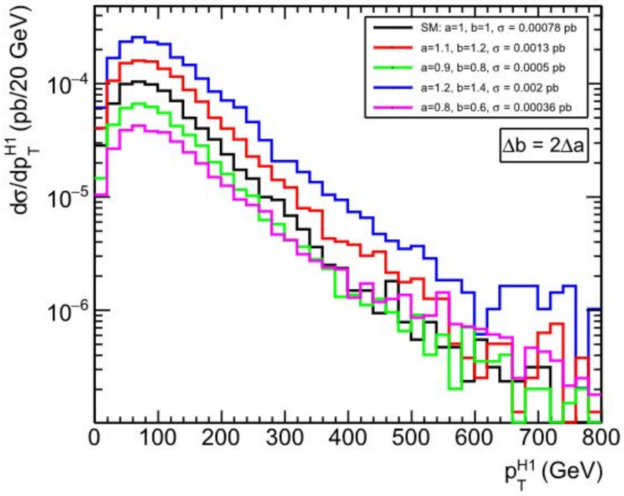
➔ Peak at $\eta_H = 0$ in contrast to SM → **high transversality.**

Phen. cons. of correlations between HEFT LO parameters: Transverse Momentum

$e^+e^- \to HH\nu_e\bar{\nu}_e$ at $\sqrt{s} = 3\,\mathrm{TeV}$





➔ The **tail at large p_T** is higher for most BSM distributions.

C = - 2 ← **2HDM**

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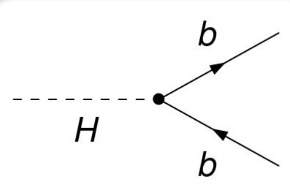
Accessibility to *a* and *b* in e^+e^- colliders

- ➔ Higgs bosons are **unstable** → dominant decay channel: $H \to b\bar{b}$ ➡



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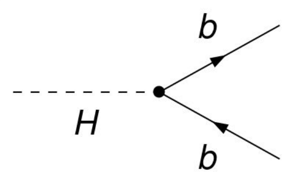

- ➔ **Full process**: $e^+e^- \to HH\nu_e\bar{\nu}_e \to b\bar{b}b\bar{b}\nu_e\bar{\nu}_e$
- ➔ The b-jets are defined at parton level and some energy will be **missing** through the neutrinos.
- ➔ Minimal detection cuts: $p_T^b > 20$ GeV, $|\eta^b| < 2$, $\Delta R_{bb} > 0.4$, $\not{E}_T > 20$ GeV [Gonzalez-Lopez '20], [Abramowicz '16]
- ➔ *b*-tagging efficiency factor $\varepsilon_b = 0.8$. [Contino '13]
- ➔ Expected luminosity for CLIC: 5 ab^{-1}.

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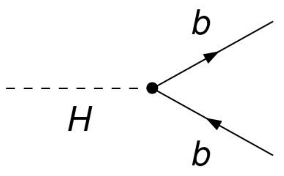

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➔ **Background** not taken into account → additional cuts on M_{bb}.

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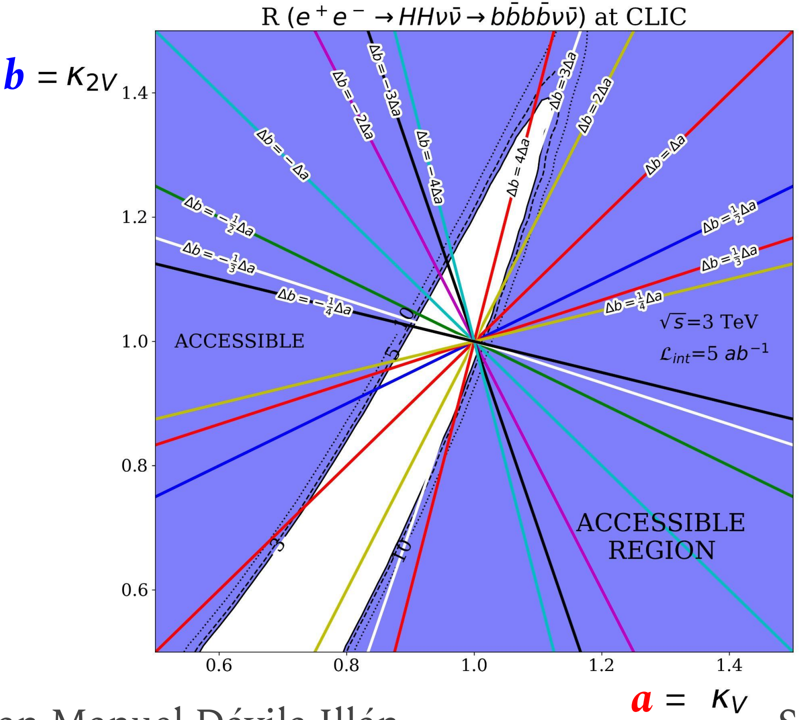


$$R = \frac{N_{BSM} - N_{SM}}{\sqrt{N_{SM}}}$$

➔ ***R*** quantifies the sensitivity to departures from the SM.

➔ **Colored region** → accessible region for ***R*** > **3**.

Conclusions

- ➔ In the region close to $a^2 = b$ it is very **difficult to test** both a and b, but correlation hypothesis for Δa versus Δb that point in a '**perpendicular**' direction to the $a^2 = b$ line will reach **higher sensitivities** for small deviations with respect to the SM.

- ➔ In general, BSM predictions show a **high-transversality behaviour** of the final Higgs bosons in comparison with the SM.

- ➔ Most of the correlations $\Delta b = C\ \Delta a$ will be **testable** at **CLIC** (and potentially at **ILC**). One **exception**: $C = 2$, which is the closest to the line $a^2 = b$.

- ➔ Access to these correlations will provide **interesting information** on the UV theory.

Thank you for your attention!!

BACKUP

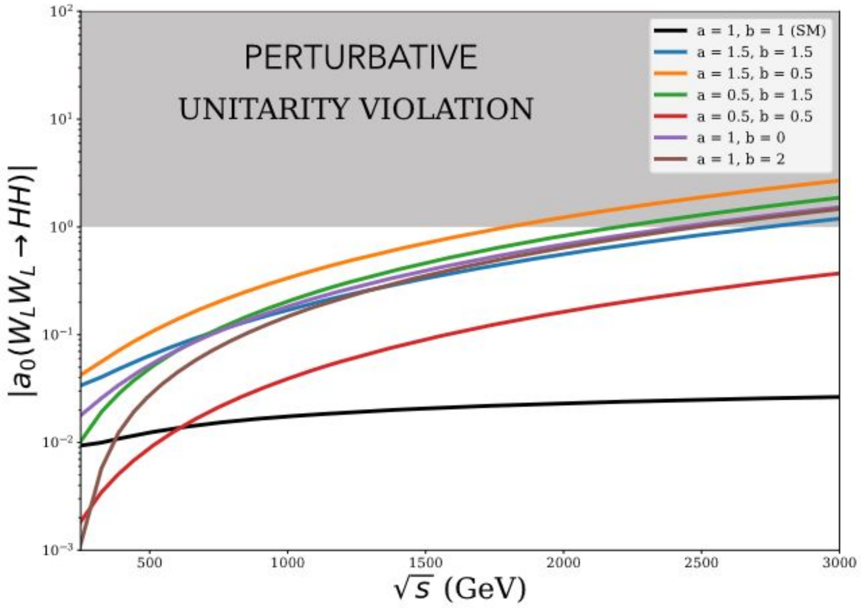
The HEFT

- **Covariant Derivative:** $D_\mu U = \partial_\mu U + i\hat{W}_\mu U - iU\hat{B}_\mu$

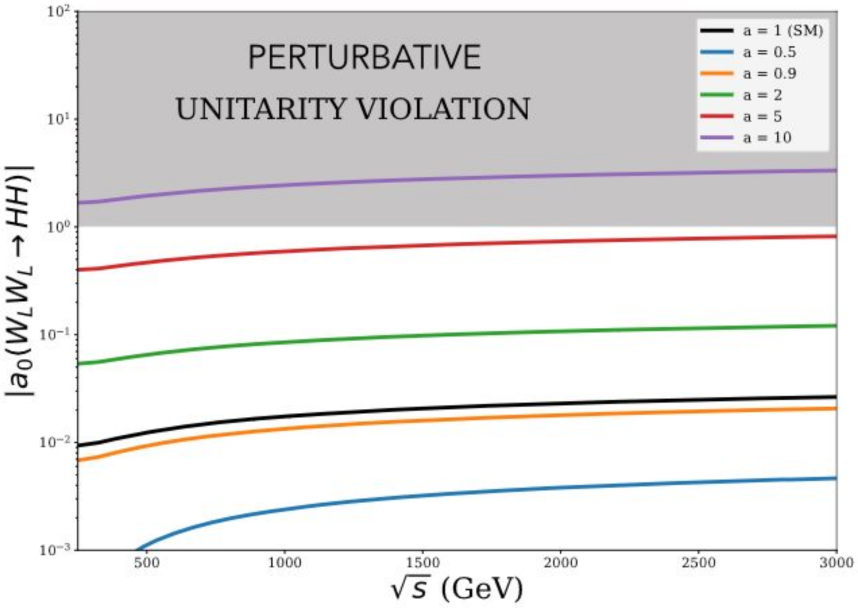
- **EW gauge fields:** $\hat{W}_\mu = \frac{g}{2} W^i_\mu \tau^i \qquad \hat{B}_\mu = \frac{g'}{2} B_\mu \tau^3$

Perturbative Unitarity Violation

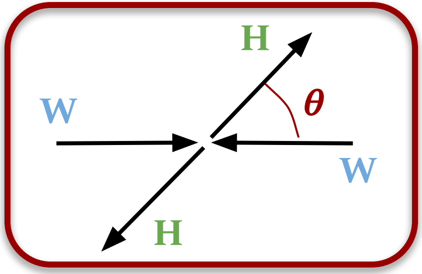
$a^2 \neq b$

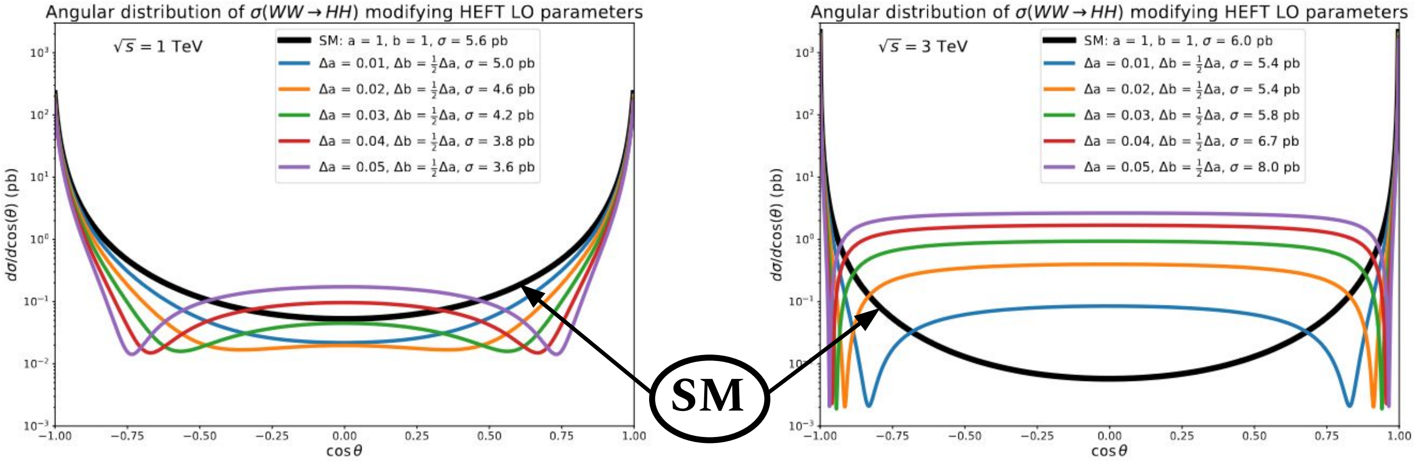


$a^2 = b$



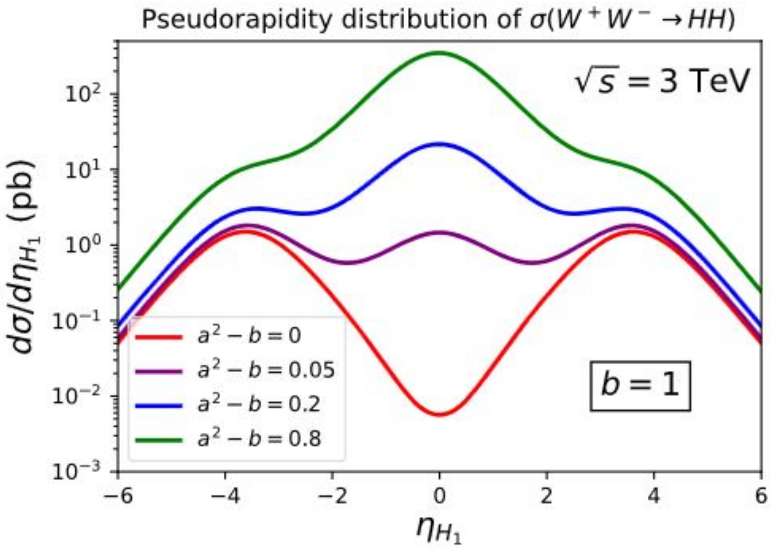
Angular distributions of $WW \to HH$ (Ex. $\Delta b = \Delta a/2$)

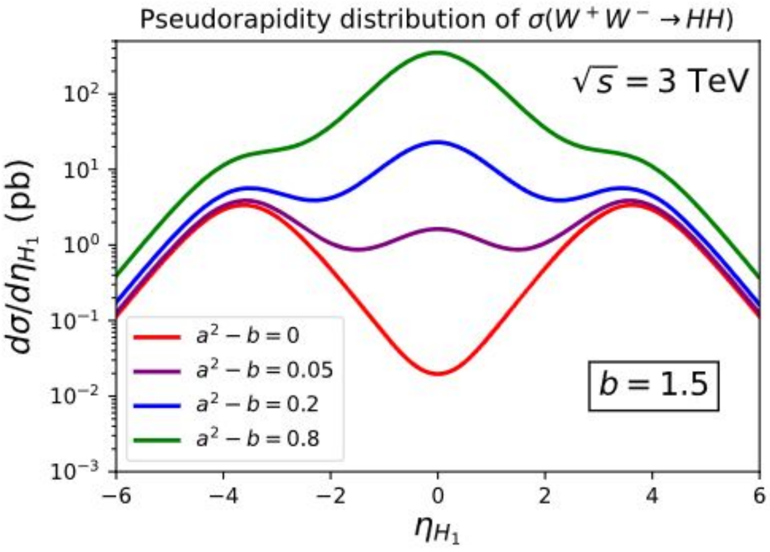




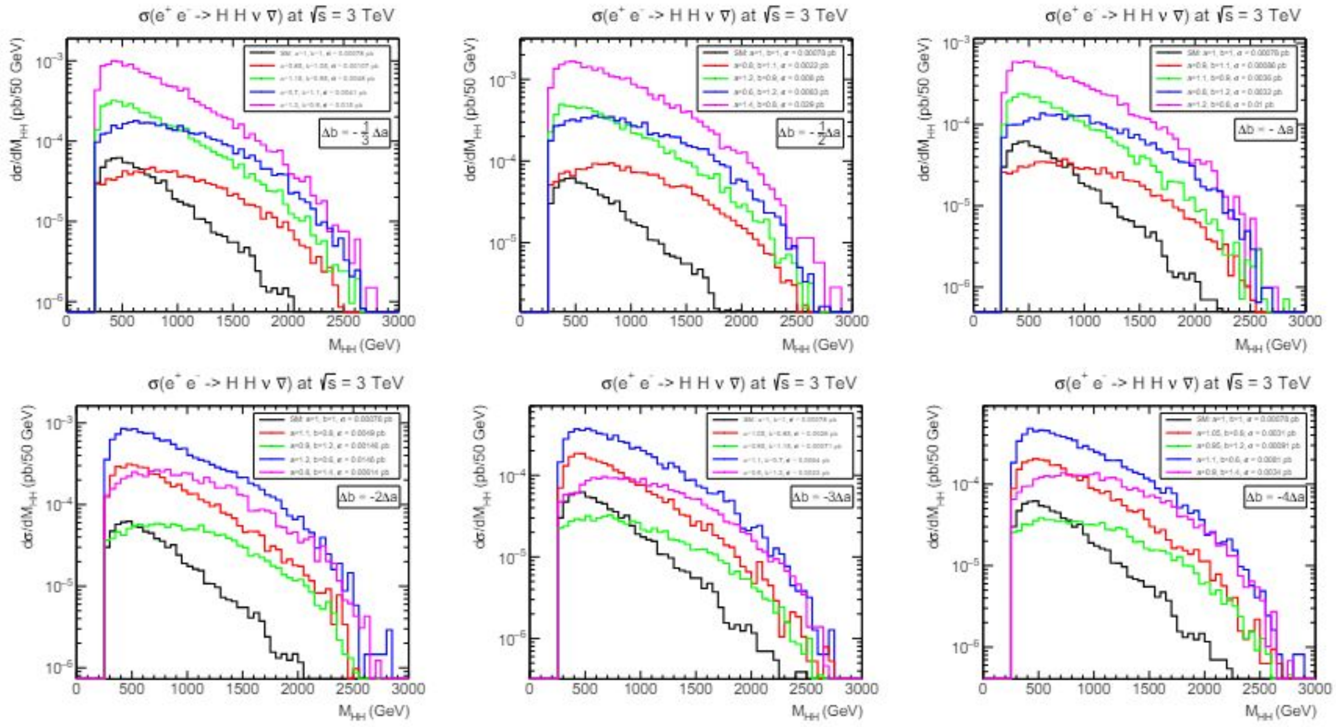
- At high energies, the **BSM** angular distributions present 2 minima and a plateau .
- Larger value of Δa and Δb → higher plateau.
- Linked to a dependence in the factor $(a^2 - b)$ in the amplitude.

Pseudorapidity distributions of $WW \to HH$

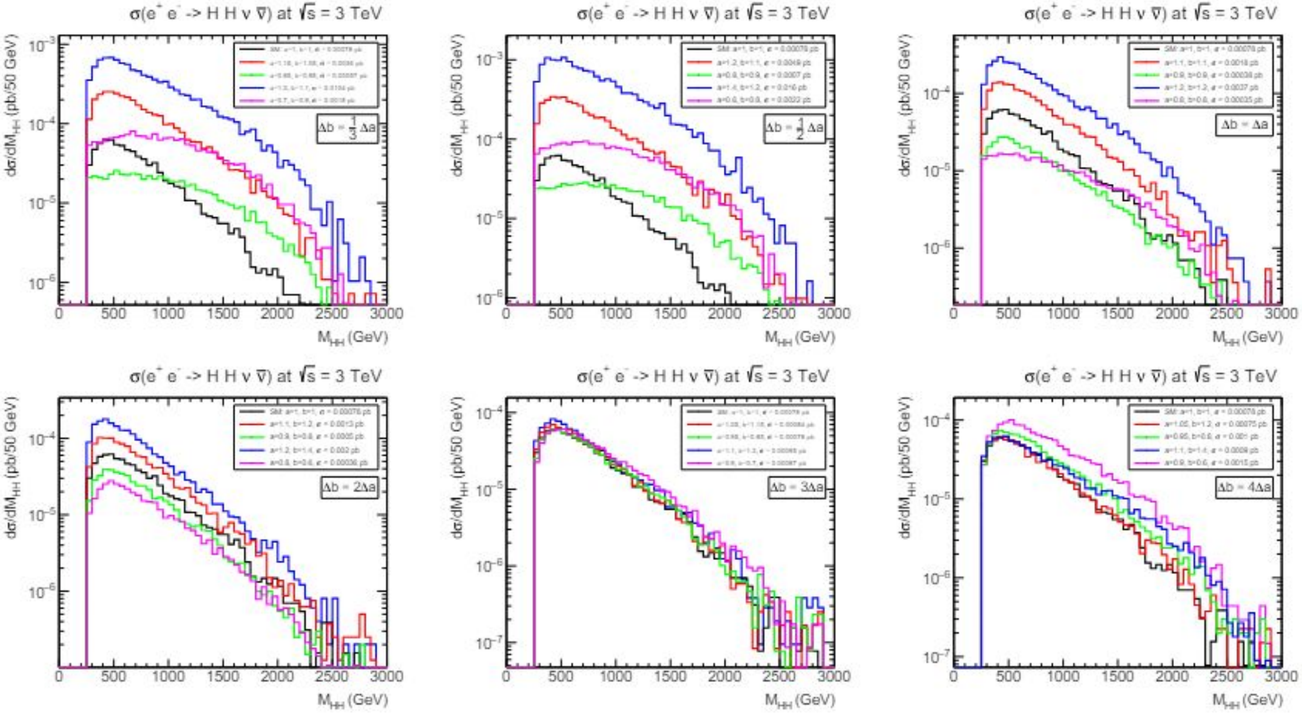




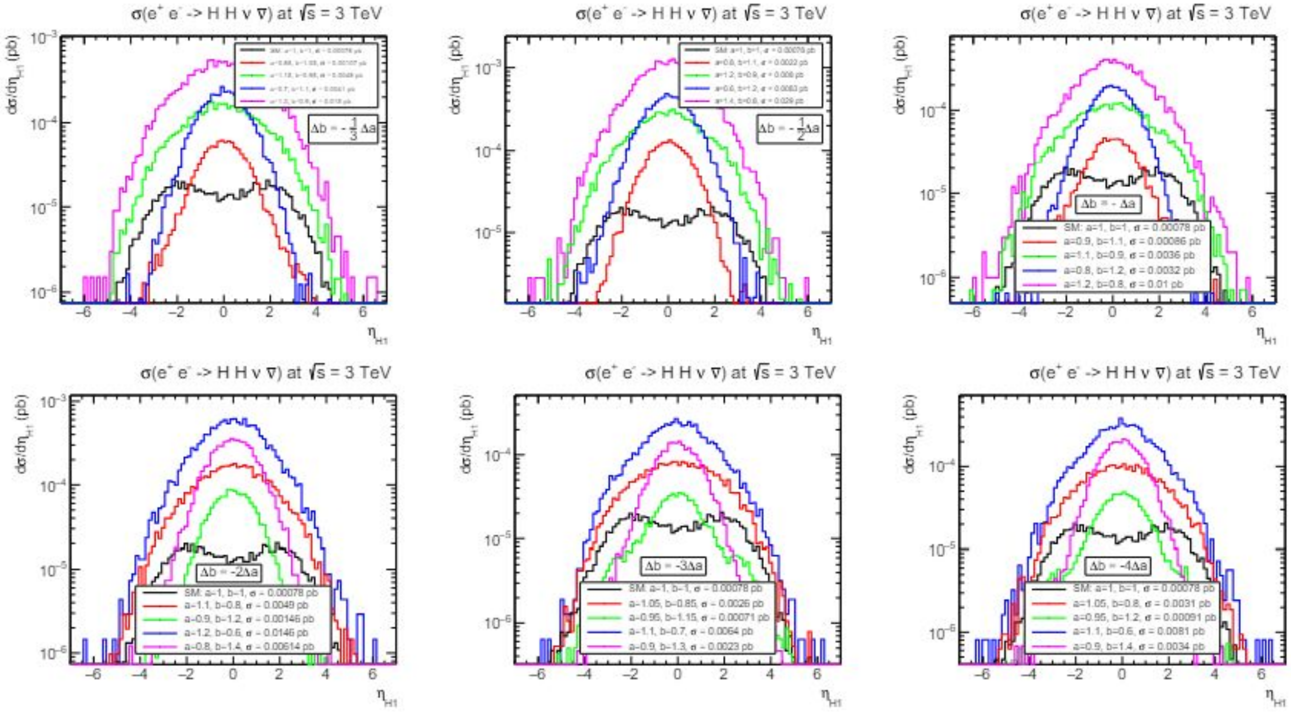
Phen. cons. of correlations between HEFT LO parameters: Invariant *HH* Mass



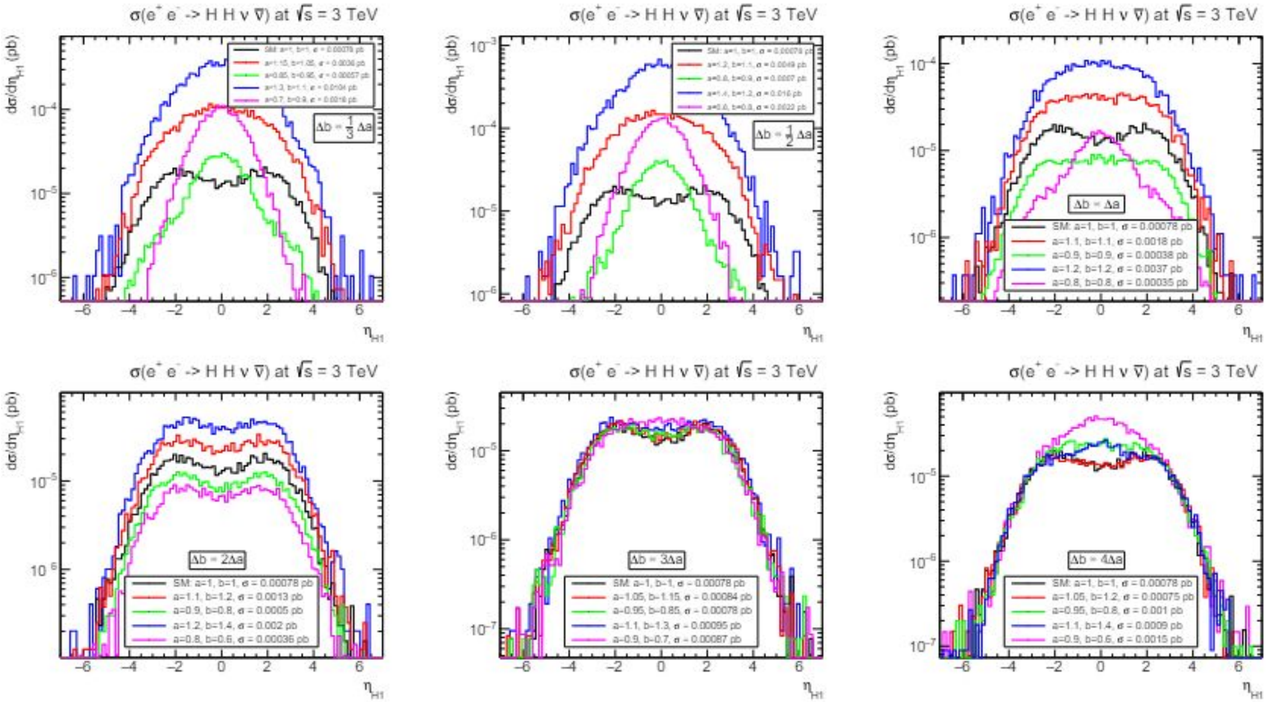
Phen. cons. of correlations between HEFT LO parameters: Invariant *HH* Mass



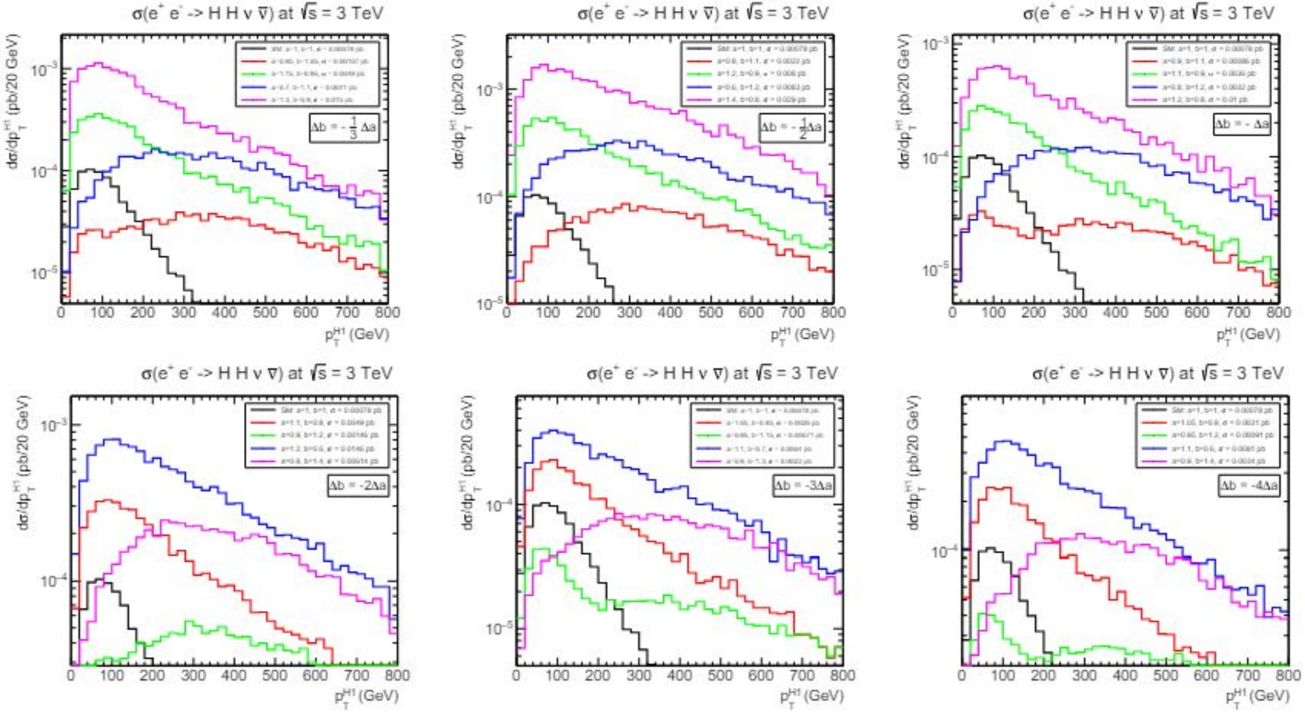
Phen. cons. of correlations between HEFT LO parameters: Pseudorapidity



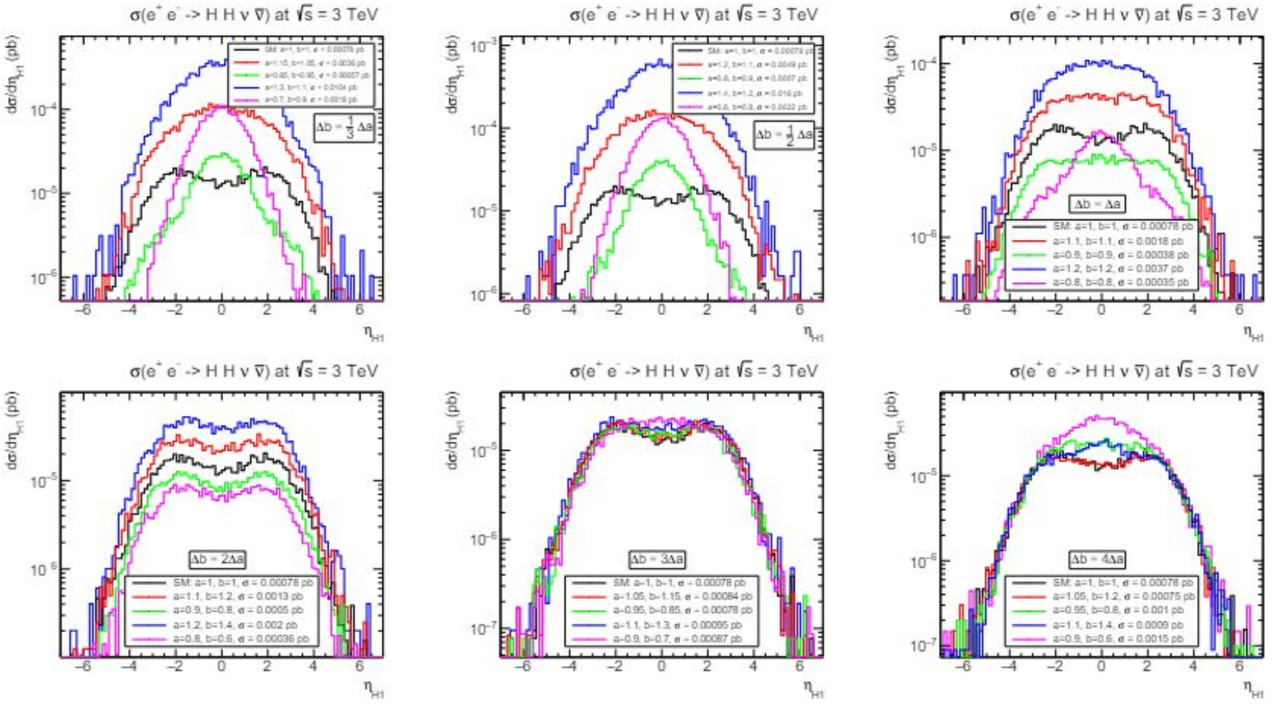
Phen. cons. of correlations between HEFT LO parameters: Pseudorapidity



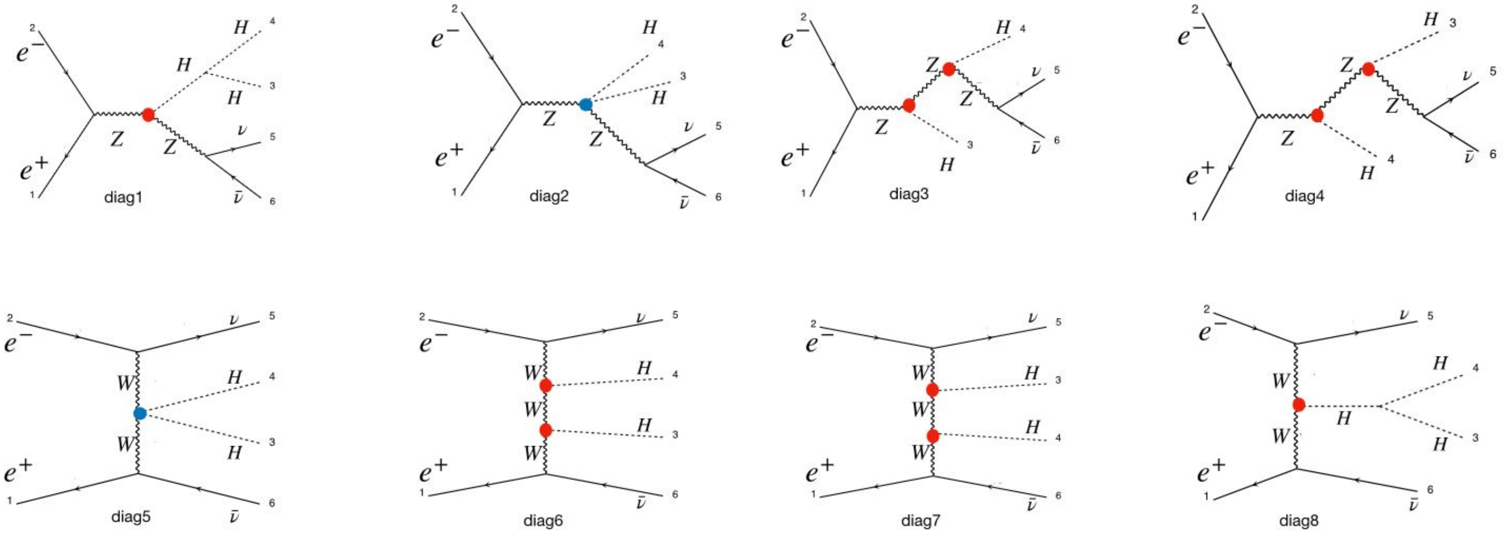
Phen. cons. of correlations between HEFT LO parameters: Transverse Momentum



Phen. cons. of correlations between HEFT LO parameters: Transverse Momentum



Feynman diagrams contributing to the full process



- Generated by MG5 in the unitary gauge.
- The mass of the electron is neglected.