Testing BSM Higgs couplings to Ws via VBF-HH at colliders

CPAN-IMFP Meeting 2-6 Oct 2023

Daniel Domenech Moya
(IFT - Universidad Autónoma de Madrid)

In collaboration with María José Herrero (IFT - UAM), Roberto Morales (IFLP, CONICET)

Summary

- The WW → HH process and its relevance at colliders

  1807.09736, *Nucl.Phys.B* 945 (2019) 114687, Arganda, García-García, Herrero

  2011.13195, EPJC 81 (2021)3, 260, González-López, Herrero, Martínez-Suárez

  2208.05452, Phys. Rev. D 106 (2022) 115027, Domenech, Herrero, Morales, Ramos

- The EFT approach to study BSM Higgs couplings: the HEFT

  2208.05452, Phys. Rev. D 106 (2022) 115027, Domenech, Herrero, Morales, Ramos

  2307.15693, Arco, Domenech, Herrero, Morales. To appear in PRD 2023

- How to test Higgs couplings via Vector Boson Fusion at colliders:

  - e^+e^- colliders

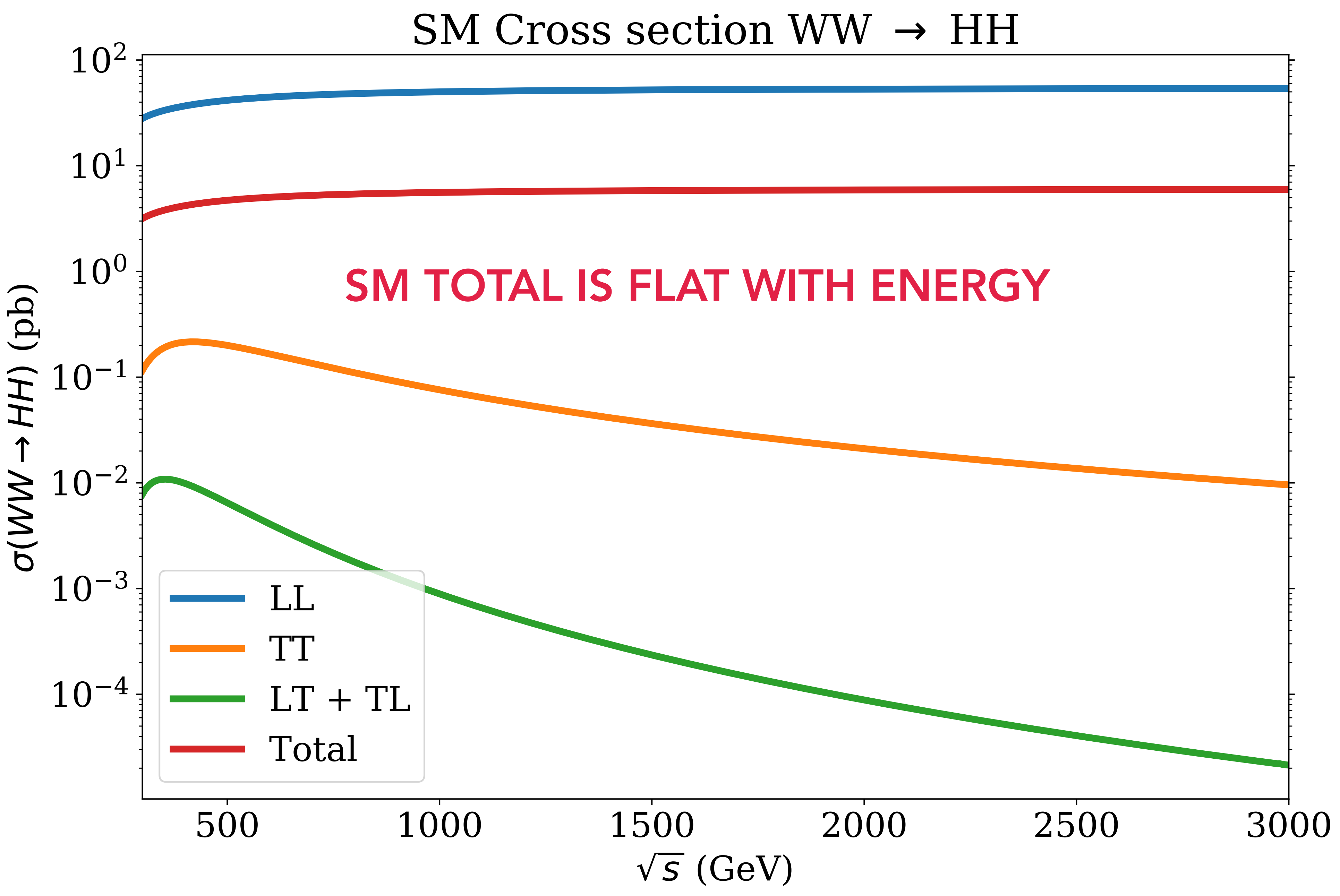
    2208.05452, Phys. Rev. D 106 (2022) 115027, Domenech, Herrero, Morales, Ramos

    + Work in progress, Dávila, Domenech, Herrero, Morales

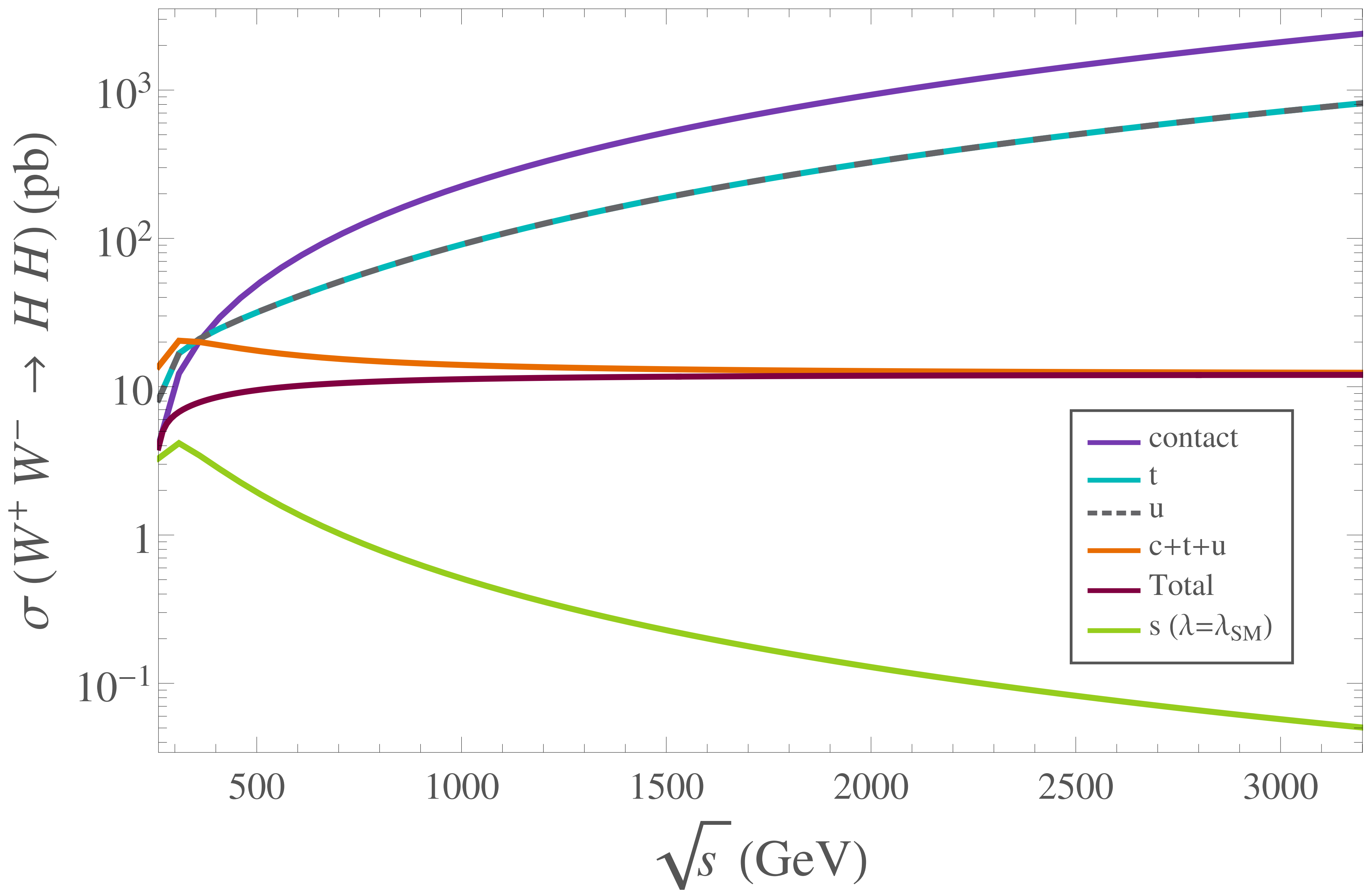
  - The LHC

    Work in progress, Domenech, Herrero, Morales

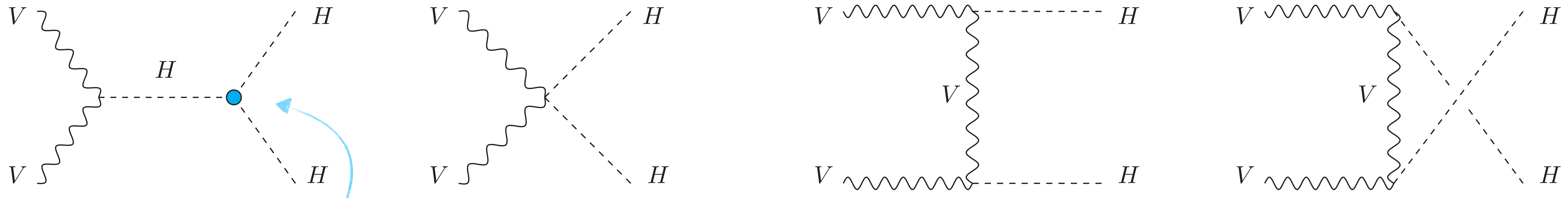
The relevance of WW → HH in the SM



Very subtle cancellations at TeV among channels



Diagrams in unitary gauge



Equivalence Theorem: OK at TeV

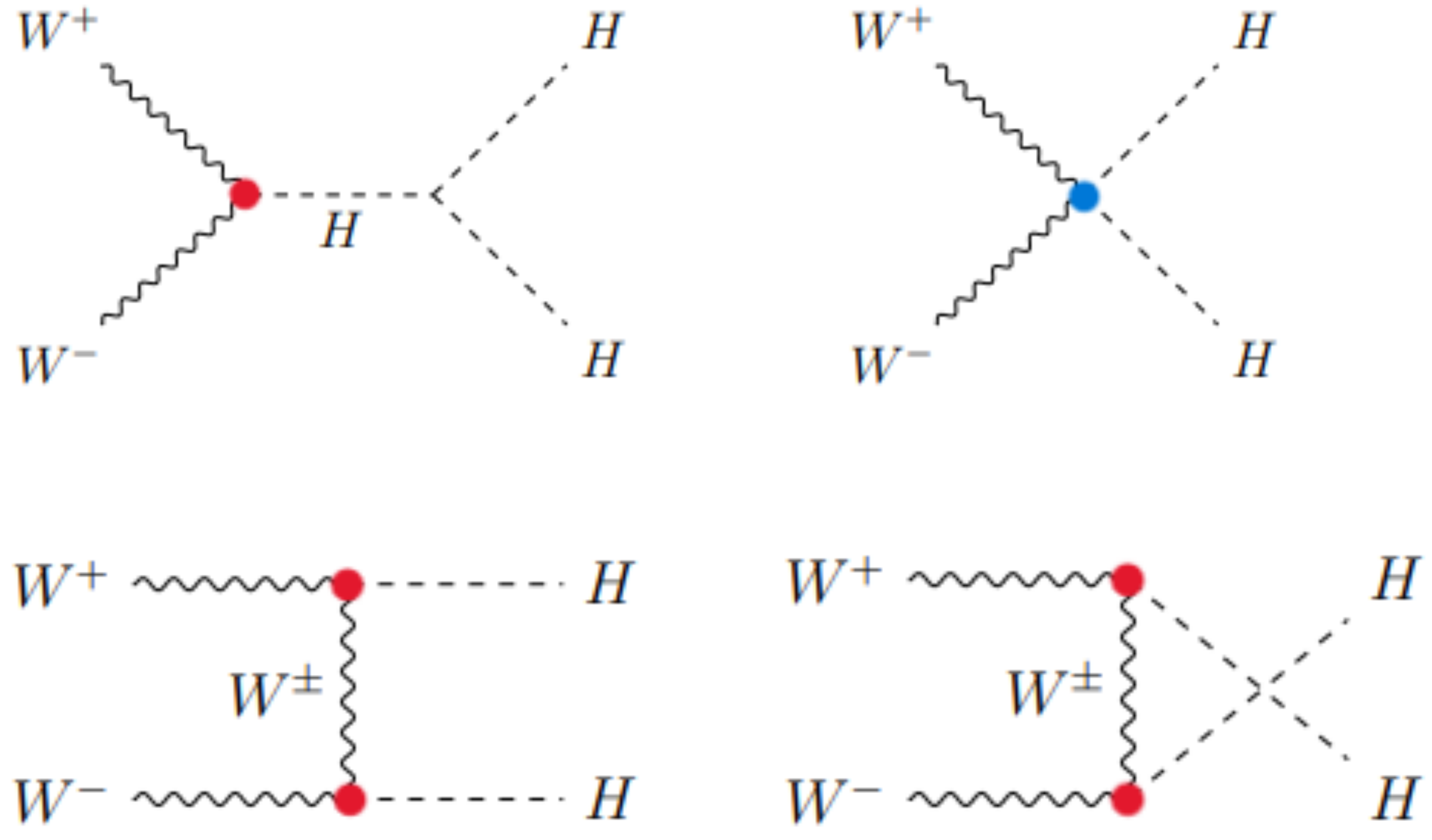
$$|\mathbf{T}(\mathbf{W_L^+W_L^-} \to \mathbf{HH})| \simeq |\mathbf{T}(\phi^+\phi^- \to \mathbf{HH})|$$

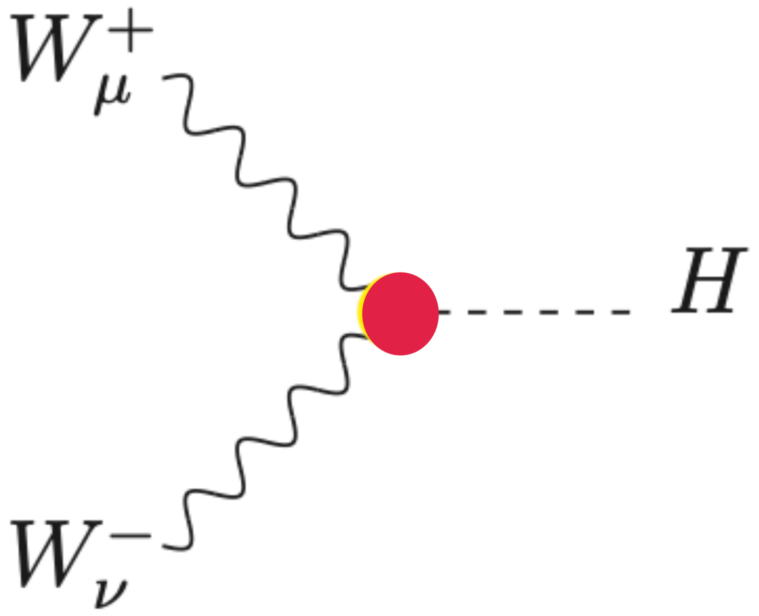
Clear LL dominance explaining the flat behavior with energy : LL >TT >LT+TL

Access to $\lambda_{SM} = \dfrac{m_H^2}{2v^2}$

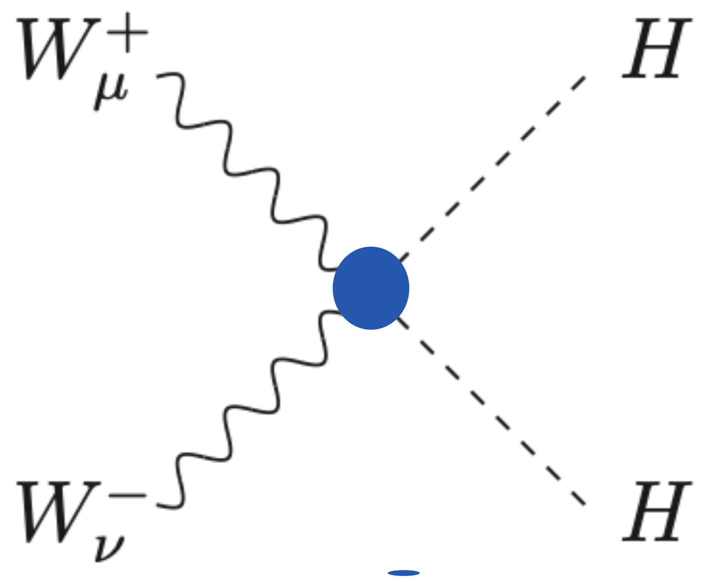
WW ⟶ HH in BSM

Diagrams in unitary gauge:
like in most simulations with MG5





$$V_{WWH} = i\kappa_V g m_W g_{\mu\nu}$$



$$V_{WWHH} = \frac{i\kappa_{2V} g^2}{2} g_{\mu\nu}$$

BSM parameterizations must preserve Gauge Invariance in the Lagrangian

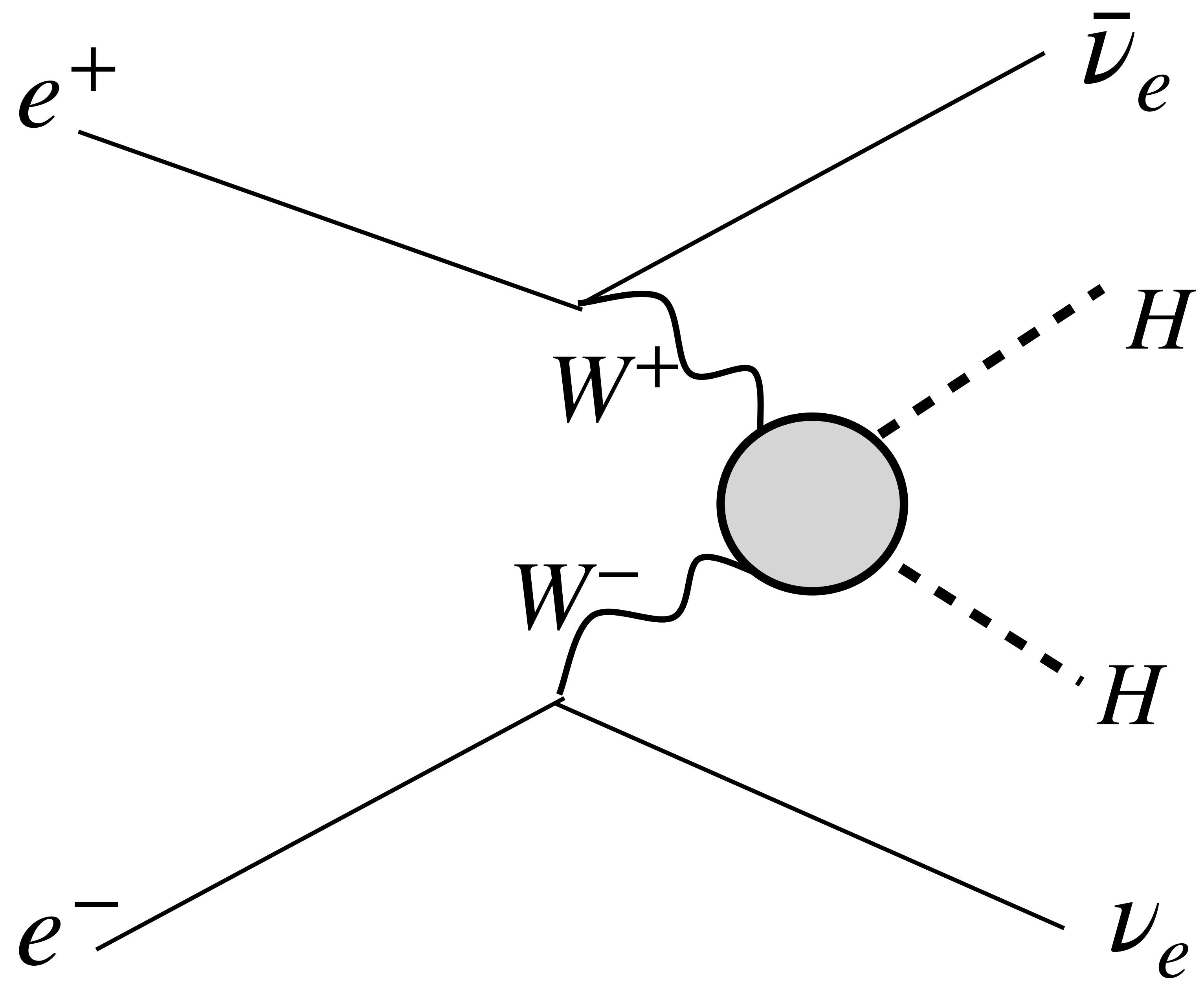
Example: HEFT $\kappa_V = a\,;\ \kappa_{2V} = b$

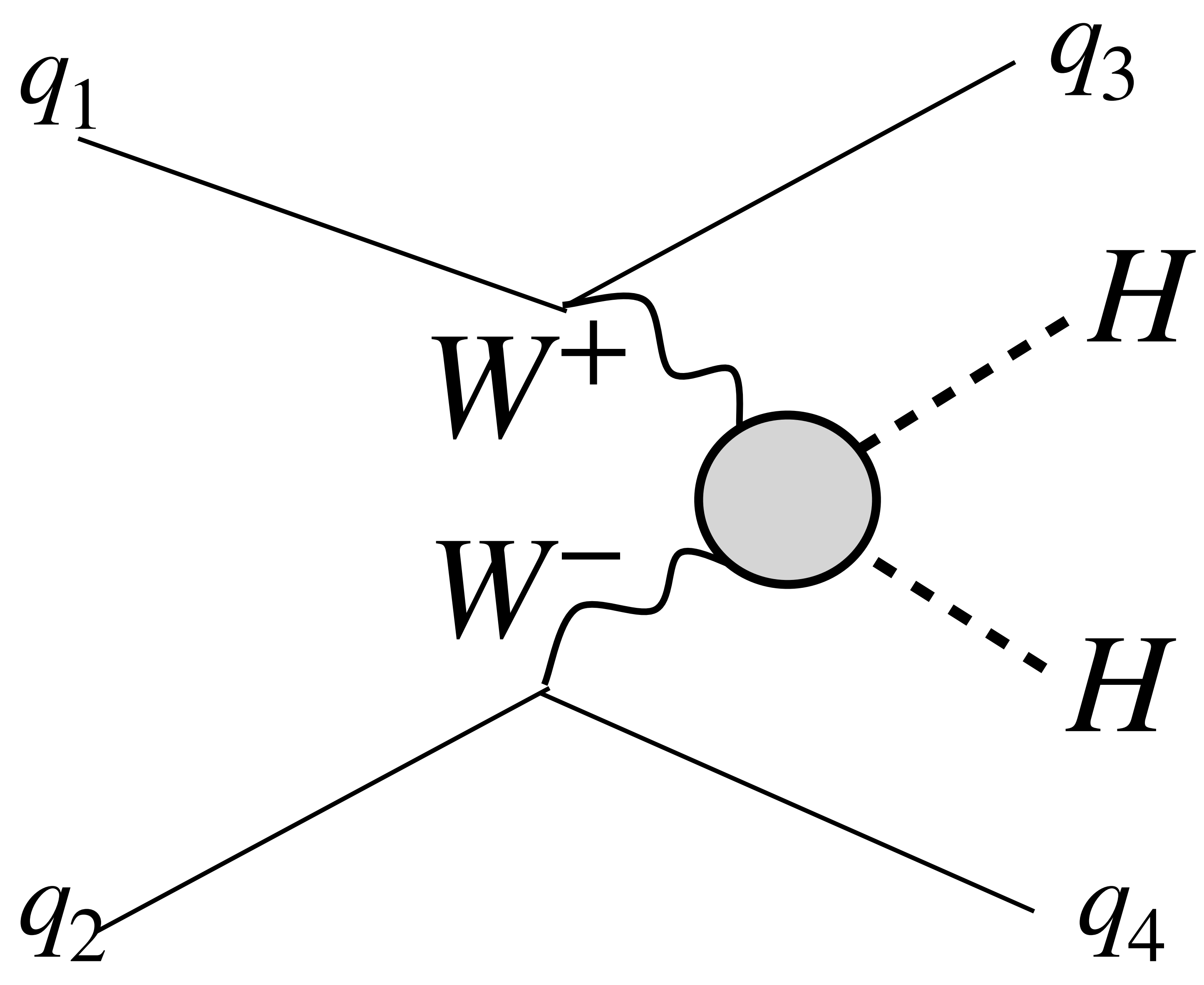
SM-VBF predictions recovered for $\kappa_{2V} = \kappa_V = 1$

BSM-VBF means : $\Delta\kappa_{2V} \neq 0\,;\ \Delta\kappa_V \neq 0$
with $\kappa_{2V} = 1 - \Delta\kappa_{2V}\,;\ \kappa_V = 1 - \Delta\kappa_V$

WW → HH at colliders (SM and BSM)

WW→HH takes place as a subprocess at both the LHC and e^+e^- colliders (ILC, CLIC)





- **Cleaner**
- **Lower backgrounds**
- **No data yet (still a project)**

- **More difficult signals (separate WBF from ggF)**
- **Higher backgrounds**
- **Significant data (mainly HL-LHC)**

Higgs Effective Field Theory (HEFT)

(Also called Electroweak Chiral Lagrangian)

$$\mathscr{L}^{\rm LO}_{\rm EChL} = \frac{v^2}{4}\left[1 + 2a\left(\frac{H}{v}\right) + b\left(\frac{H}{v}\right)^2 + \dots\right] {\rm Tr}\left[D_\mu U^\dagger D^\mu U\right] - \kappa_3 \lambda v H^3 - \frac{1}{4}\kappa_4 \lambda H^4$$

Ch. dim. 2

a, b, κ_3, κ_4 **: Couplings parameterising the BSM effects**

$a = b = \kappa_3 = \kappa_4 = 1 \Rightarrow$ **SM case**

$$0.97 < a^{exp}_{[1]} < 1.13 \qquad -0.6 < b^{exp}_{[2]} < 2.8 \qquad -0.4 < \kappa_3{}^{exp}_{[3]} < 6.3$$

- Operator ordering in terms of chiral dimension → Powers of momentum in the operator
- GBs are in a non-linear representation $U = exp(-i\phi^i\tau_i/v)$
- H is a singlet → Uncorrelated Higgs couplings

In contrast to the doublet Φ used in the SM and SMEFT

$$\mathscr{L}^{\rm NLO}_{\rm EChL} = \dots + \eta (1/v^2)\, \partial^\mu H \partial^\nu H {\rm Tr}\left[(D_\mu U^+)(D_\nu U)\right] + \delta (1/v^2)\, \partial^\mu H \partial_\mu H {\rm Tr}\left[(D^\nu U^+)(D_\nu U)\right] + \dots$$

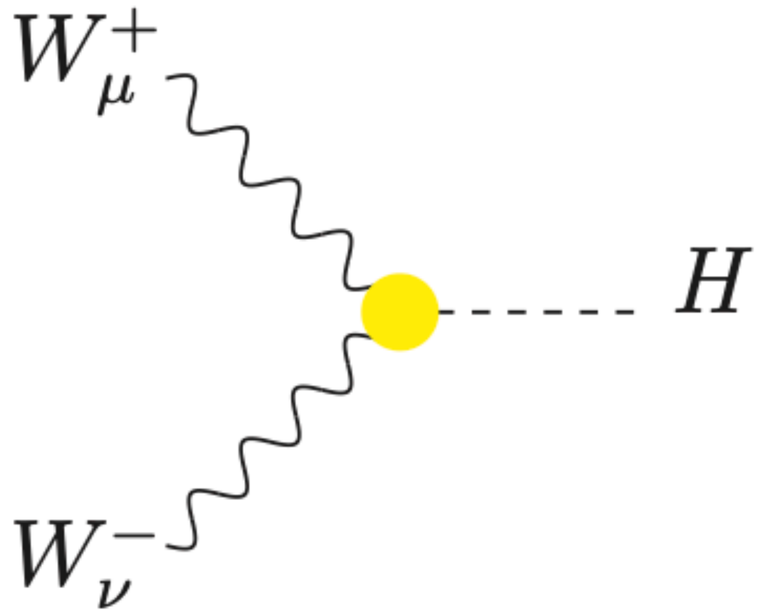
η, δ **: Relevant NLO couplings**

$\eta = \delta = 0 \Rightarrow$ **SM case**

Ch. dim. 4

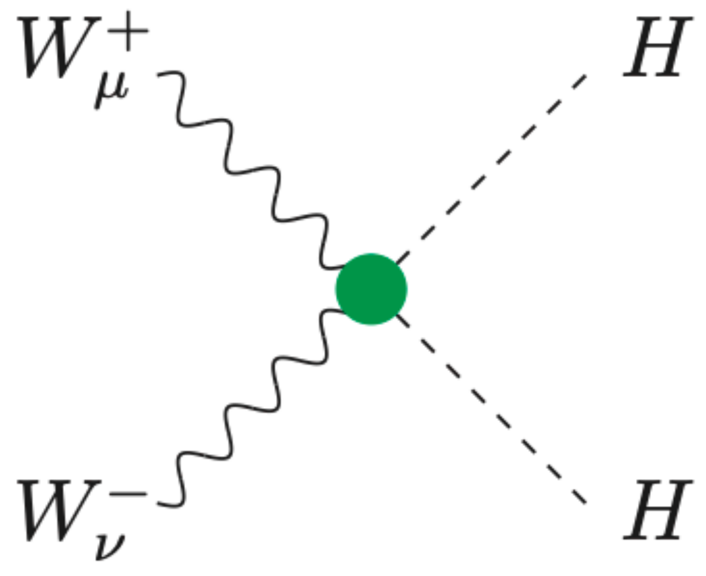
[1] ATLAS, PRD 101 (2020) 1909.02845 [2] CMS, PLB 842 (2023) 137531 [3] ATLAS, PLB 843 (2023) 137745

Effective couplings of H with EW gauge bosons in HEFT



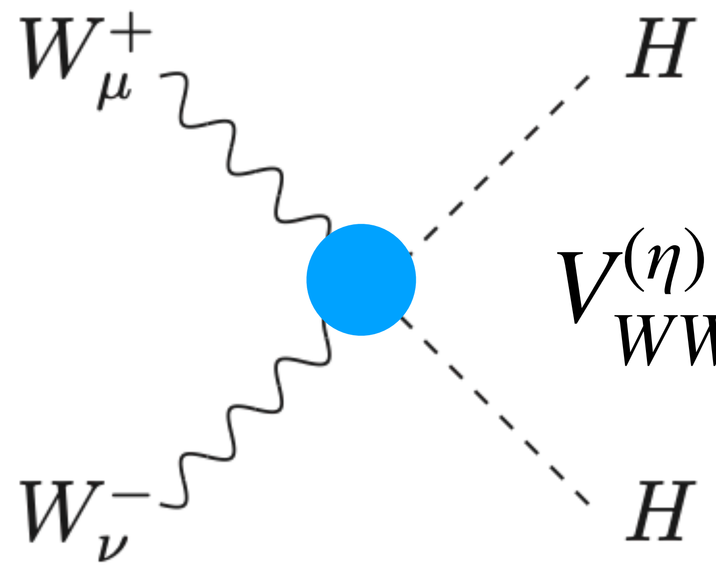
$a = \kappa_V$

$$V^{(\mathrm{LO})}_{WWH} = iagm_W g_{\mu\nu}$$



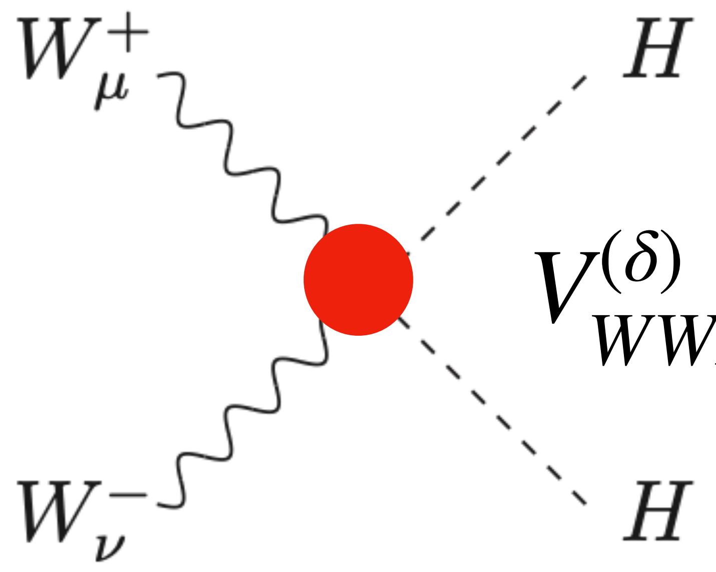
$b = \kappa_{2V}$

$$V^{(\mathrm{LO})}_{WWHH} = \frac{ibg^2}{2} g_{\mu\nu}$$



η

$$V^{(\eta)}_{WWHH} = -i\frac{g^2}{v}\eta\left[p^\mu_{H_1}p^\nu_{H_2} + p^\nu_{H_1}p^\mu_{H_2}\right]$$



δ

$$V^{(\delta)}_{WWHH} = -2i\frac{g^2}{v}\delta\left[p_{H_1}\cdot p_{H_2}\right]$$

η and δ grow stronger with energy (chiral ordering), and affect the (dominant) LL modes

→ **At high energies, η and δ dominate both a and b and other NLO coefficients**

RESULTS

All the following predicted rates are generated with MadGraph 5 @NLO at LO
Parton level simulations

2208.05452, Phys. Rev. D 106 (2022) 115027, Domenech, Herrero, Morales, Ramos

2307.15693, Arco, Domenech, Herrero, Morales. To appear in Phys. Rev. D 2023

+ preliminar results from Dávila, Domenech, Herrero, Morales (e^+e^-)

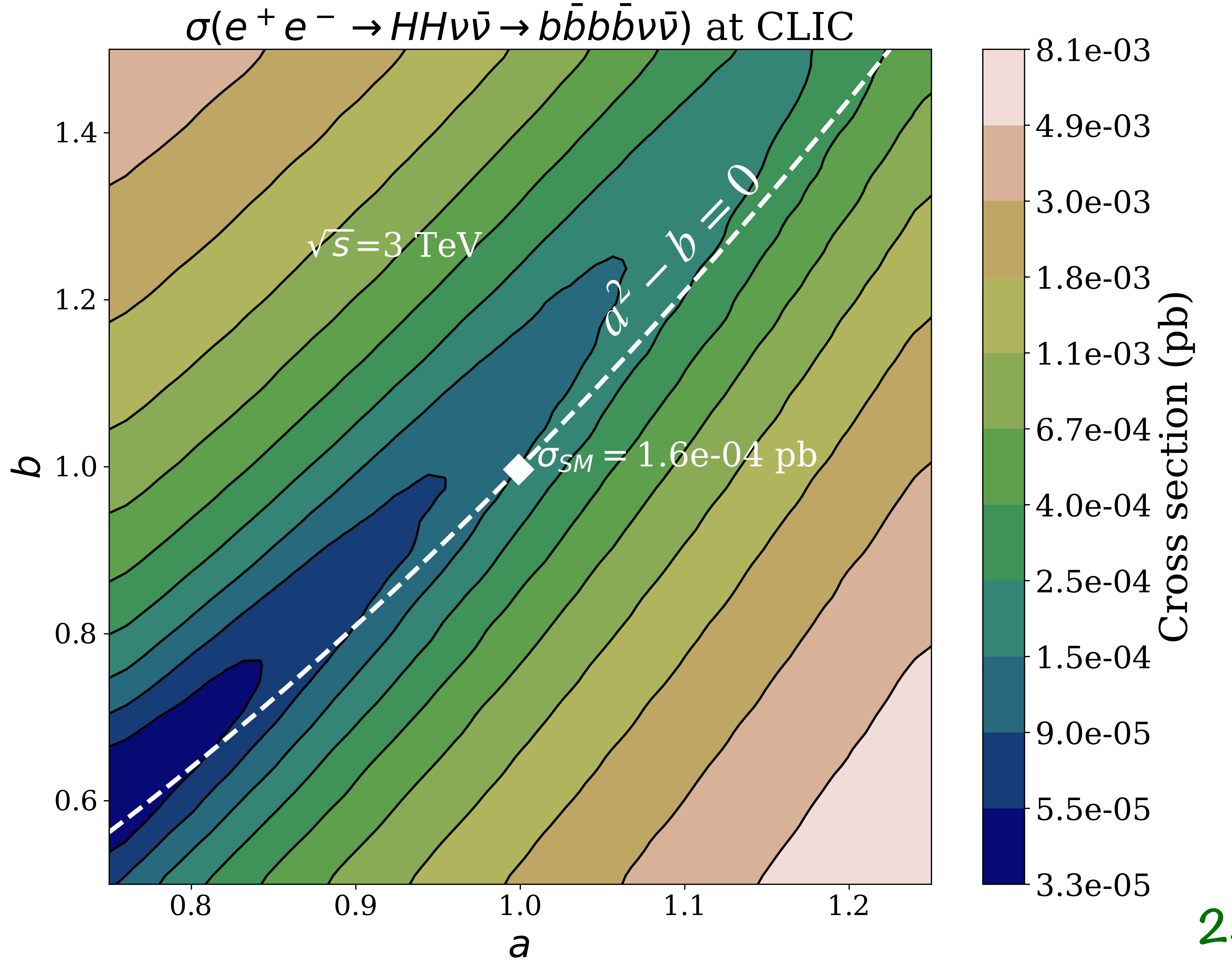
+ preliminar results from Domenech, Herrero, Morales (LHC)

Results in e^+e^- colliders: a and b

CLIC 3 TeV **Also studied ILC at 500 GeV and 1 TeV**

Predicted signal cross section

(Similar results expected for qq→HHqq)



Signal with greater statistics: e+ e- → HH$\nu\bar{\nu}$ → $b\bar{b}b\bar{b}\nu\bar{\nu}$

$W_L W_L \to HH$ for $\sqrt{s} \gg m_W, m_H$ has

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

Close to the σ minimum

$\Delta b = 2\Delta a$

Minimal detection cuts

$p_T^b > 20$ GeV $|\eta^b| < 2$

$\Delta R_{bb} > 0.4$ $\not{E}_T > 20$ GeV

b-tagging efficiency of 80%

Sensitive to correlation hypothesis

$\Delta b|_{2HDM} \simeq -2\Delta a|_{2HDM}$ $c_{\beta-\alpha} << 1$

$\Delta b|_{SMEFT} = 4\Delta a|_{SMEFT}$

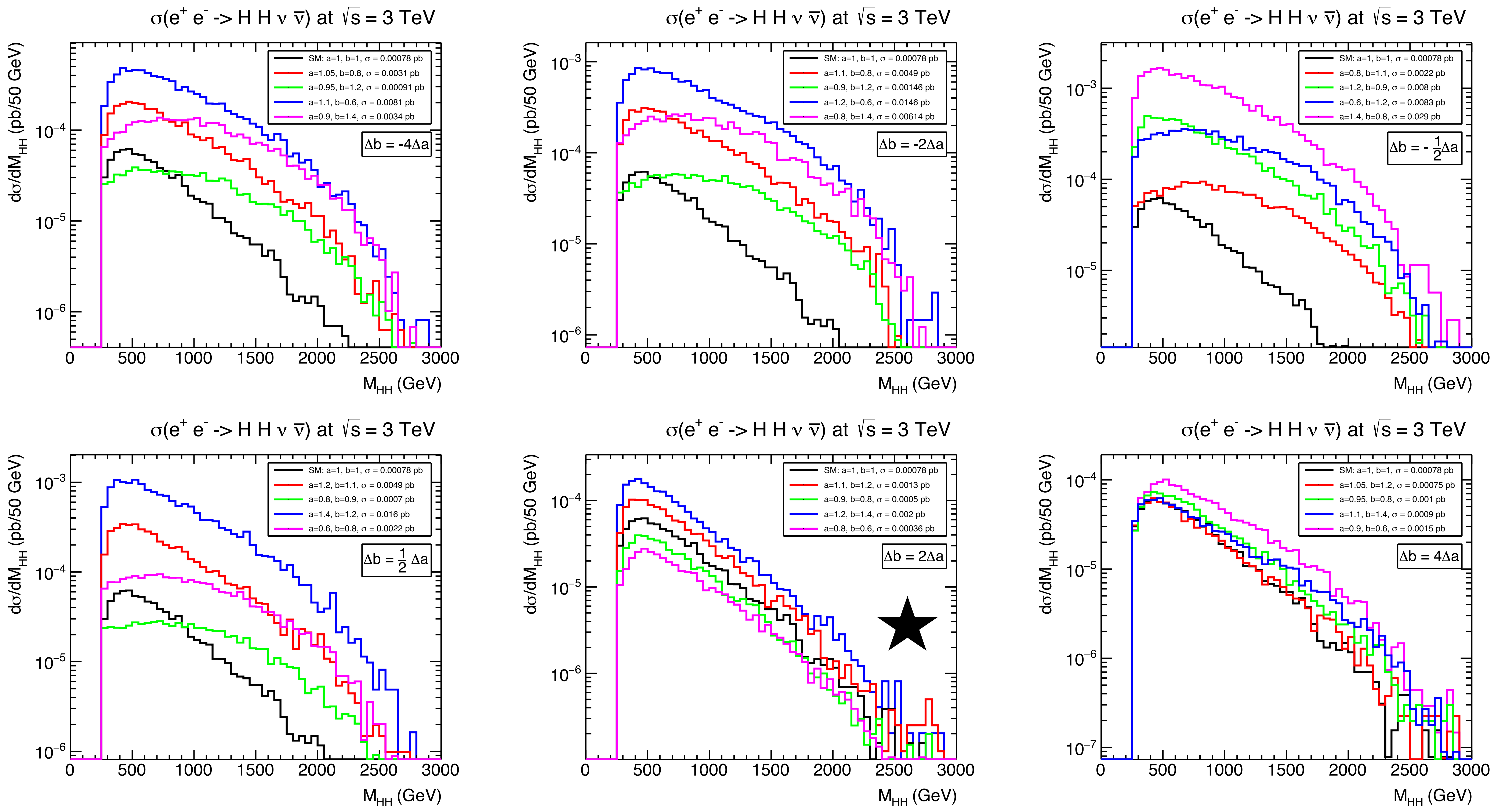
2307.15693, Arco, Domenech, Herrero, Morales. To appear in PRD 2023

Preliminar, Dávila, Domenech, Herrero, Morales

2208.05452, Phys. Rev. D 106 (2022) 115027, Domenech, Herrero, Morales, Ramos

In general going BSM with $\kappa_{2V} \neq 1$; $\kappa_V \neq 1$ distorts the dist. in M_{HH} producing bumps, Except close to $\kappa_{2V} = \kappa_V^2$ ★

Example: $e^+e^- \to HH\nu\bar{\nu}$



Close to

$\kappa_{2V} = \kappa_V^2$

$\Delta\kappa_{2V} = 2\Delta\kappa_V$

$(\Delta b = 2\Delta a)$

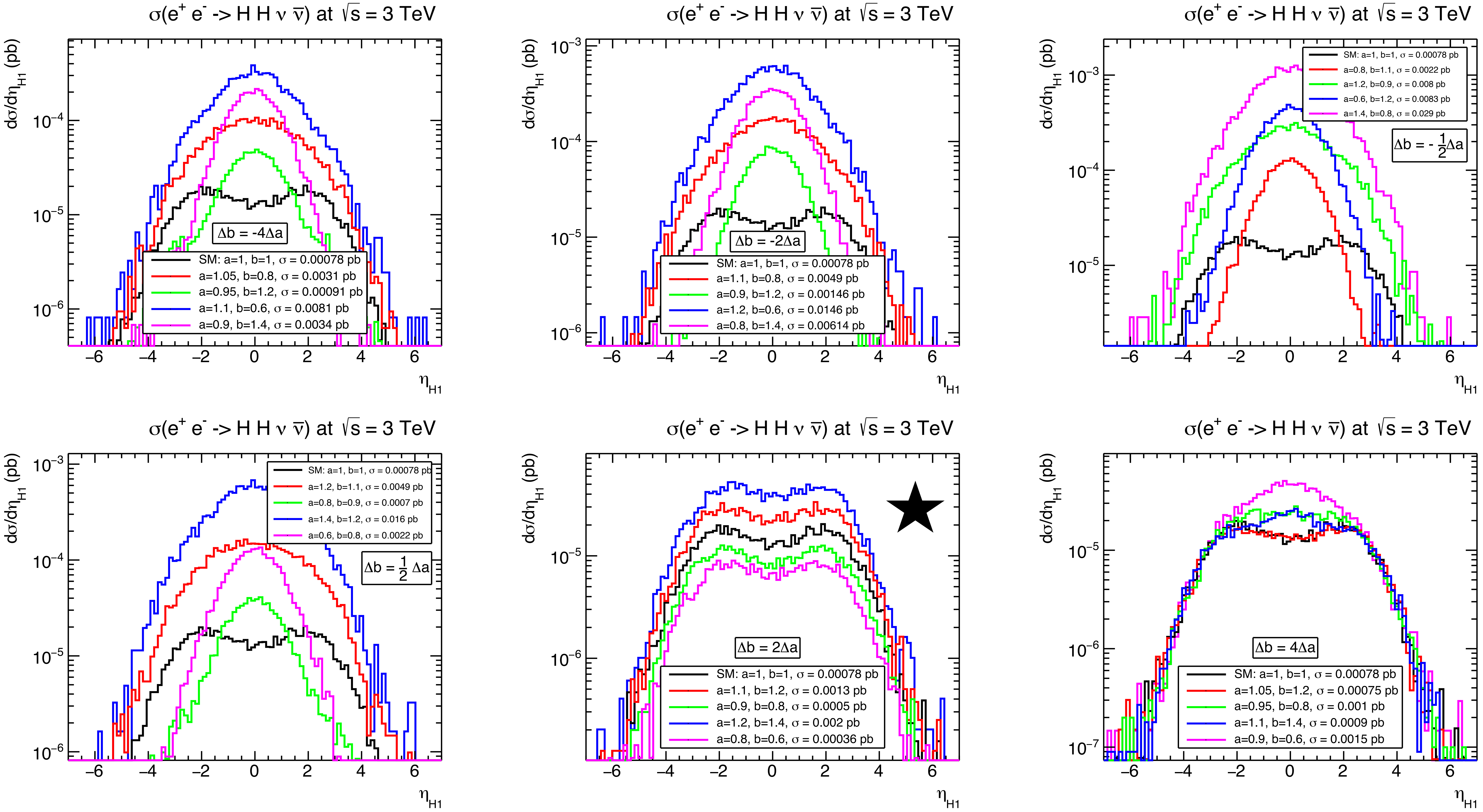
Similar results expected for $q_1q_2 \to HHq_3q_4$ (WBF at LHC)
(Work in progress)

Preliminar, Dávila, Domenech, Herrero, Morales

In general going BSM with $\kappa_{2V} \neq 1$; $\kappa_V \neq 1$ distorts the dist. in η_H producing peaks at $\eta_H = 0$

Except close to $\kappa_{2V} = \kappa_V^2$ ★

Example: $e^+e^- \to HH\nu\bar{\nu}$



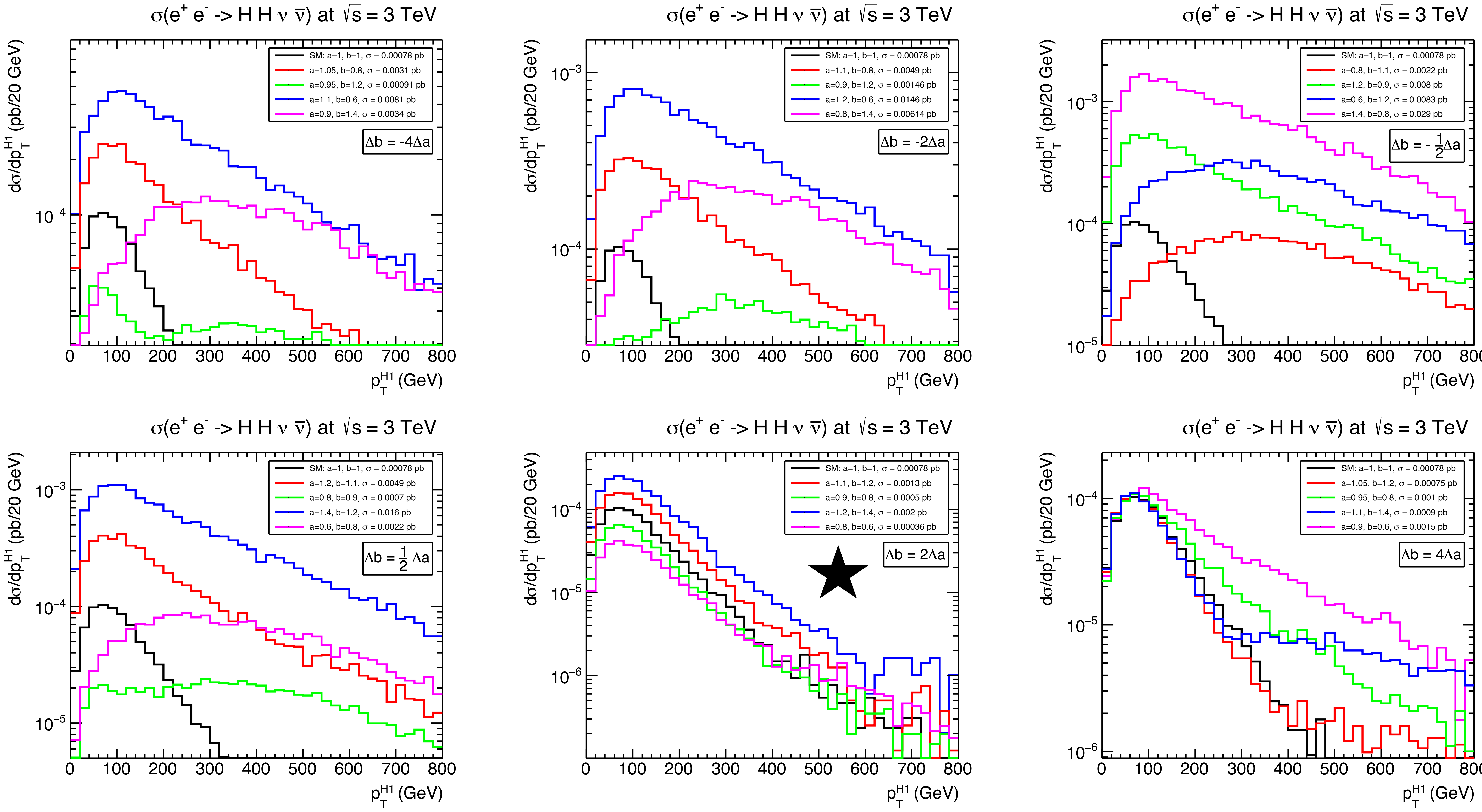
Similar results expected for $q_1q_2 \to HHq_3q_4$ (WBF at LHC)
(Work in progress)

Preliminar, Dávila, Domenech, Herrero, Morales

In general going BSM with $\kappa_{2V} \neq 1$; $\kappa_V \neq 1$ distorts the dist. in p_T^H elevating the tails at large p_T^H

Except close to $\kappa_{2V} = \kappa_V^2$ ★

Example: $e^+e^- \to HH\nu\bar{\nu}$



Similar results expected for $q_1q_2 \to HHq_3q_4$ (WBF at LHC)

(Work in progress)

Preliminar, Dávila, Domenech, Herrero, Morales

Accessibility to LO-HEFT $(a,b) = (\kappa_V, \kappa_{2V})$ at e^+e^-

No realistic background considered

Accessibility parameter

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

$N_{BSM} \equiv$ **Events for a, b $\neq$1**

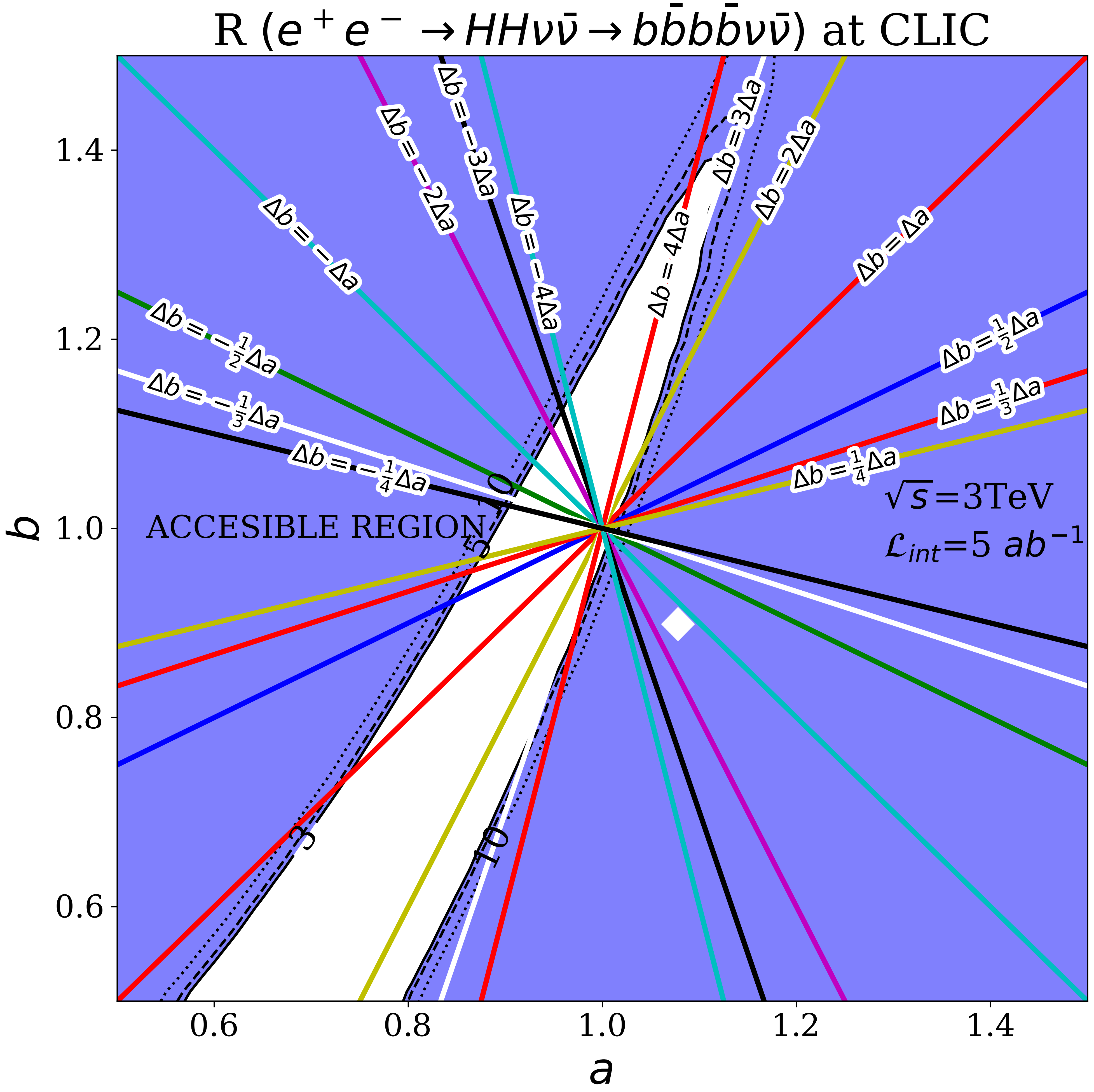
$N_{SM} \equiv$ **Events for a, b =1**

Purple region ($R > 3$) $\equiv$ accesible region

Also considered $R > 5$ and $R > 10$

CLIC is the best collider to access a and b and their correlations

Accesible region



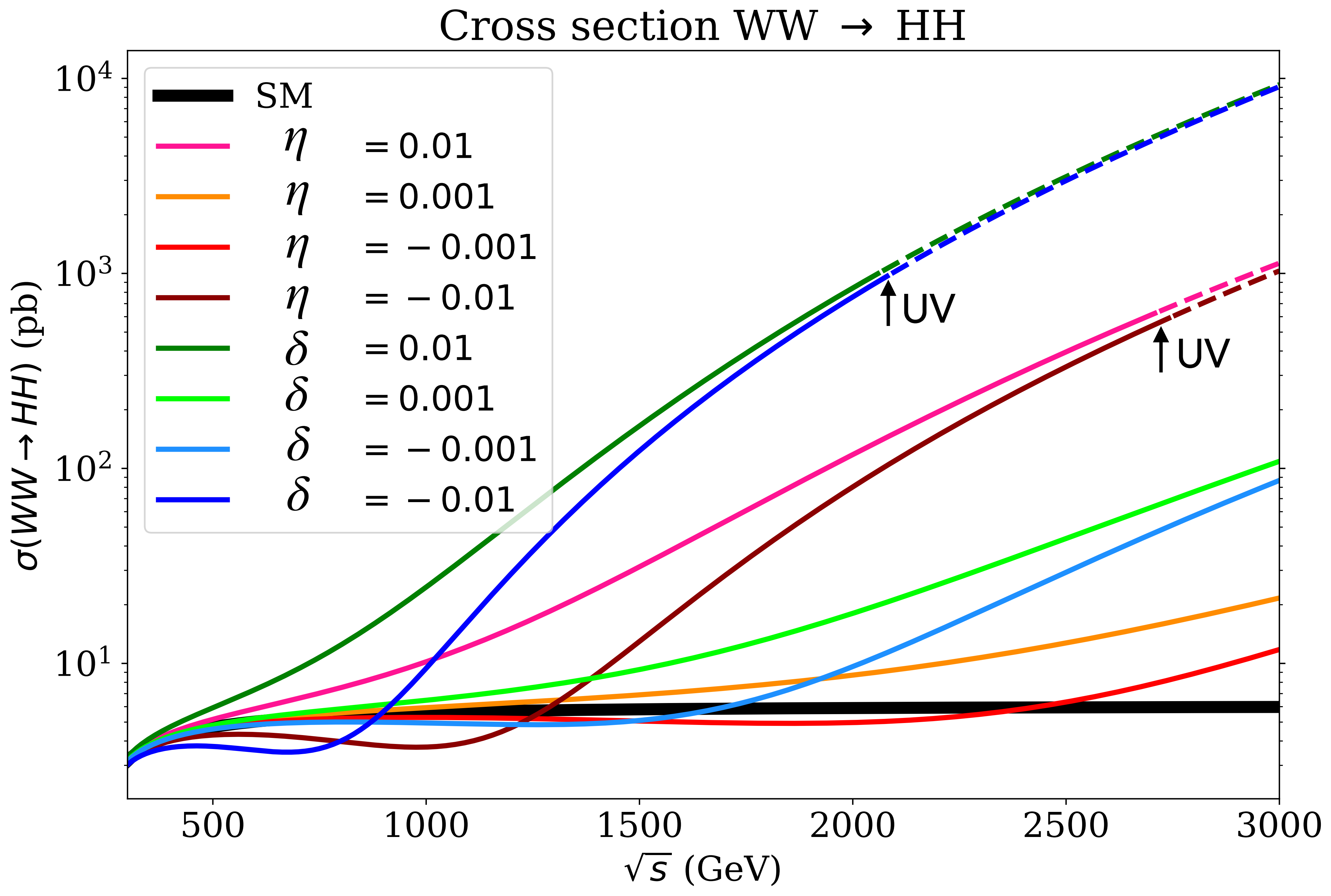
Some correlations are less accesible, such as $\Delta b = 2\Delta a$,

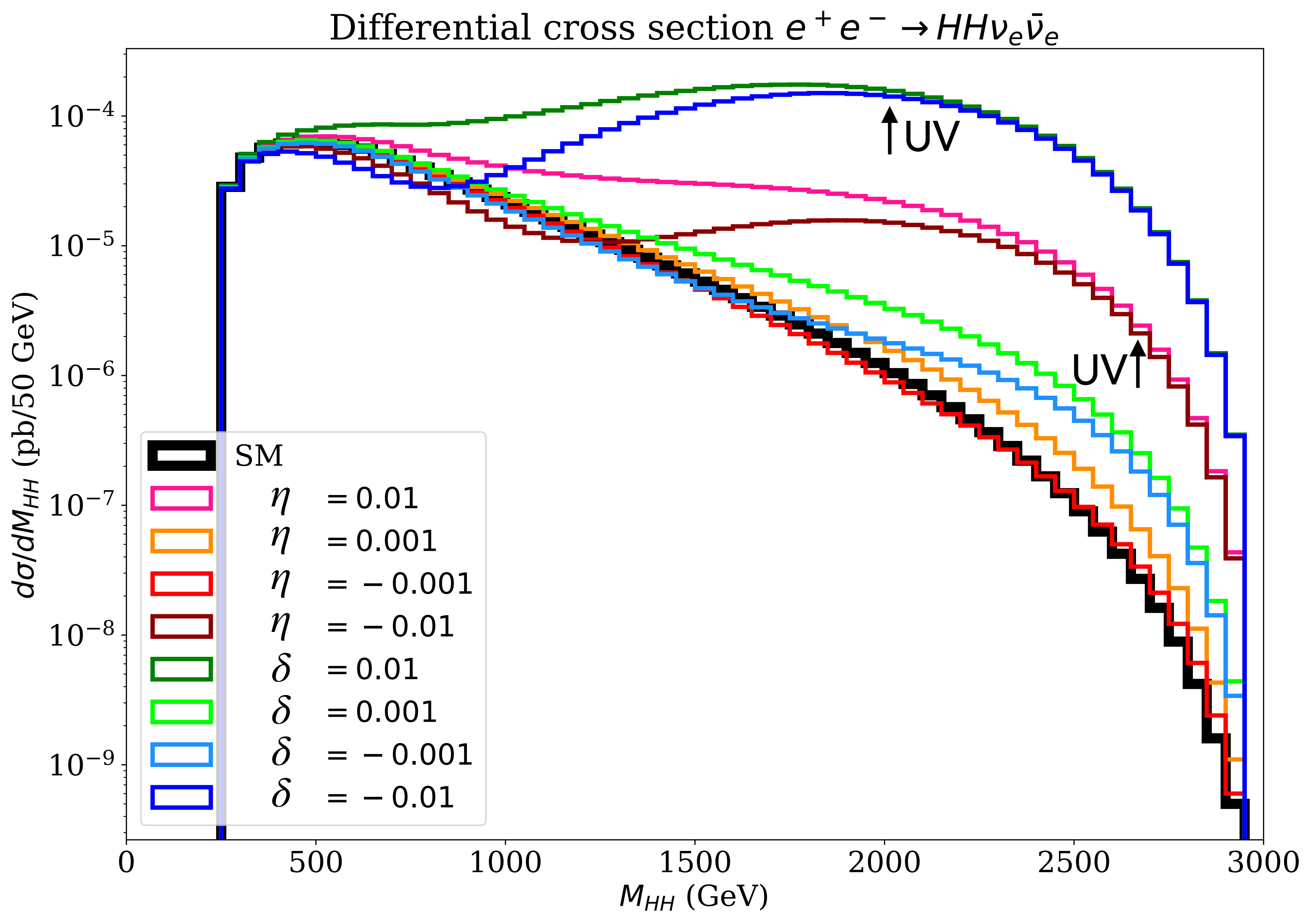
And others are more. e.g. in the UL quadrant, $\Delta b = -\frac{1}{2}\Delta a$ is the best

Testability of UV theories varies

Preliminar, Dávila, Domenech, Herrero, Morales

Enhancement effects of NLO-HEFT (η, δ) at e^+e^-





Notice the fast growth with energy of NLO, $A \sim \mathcal{O}(s^2)$; to be compared with LO, $A \sim \mathcal{O}(s)$

Enhancement in $WW \to HH$ at large $\sqrt{s}$ $\Rightarrow$ enhancement in $e^+e^- \to HH\bar{\nu}_e\nu_e$ at large invariant mass M_{HH}

The dashed lines correspond to the unitarity violation region

2208.05452, Phys. Rev. D 106 (2022) 115027, Domenech, Herrero, Morales, Ramos

Accessibility to NLO-HEFT (η, δ) at e^+e^-

Minimal detection cuts

$p_T^b > 20$ GeV $|\eta^b| < 2$

$\Delta R_{bb} > 0.4$ $\not{E}_T > 20$ GeV

b-tagging efficiency of 80%

Signal with greater statistics: e+ e- → HH$\nu\bar{\nu}$ → $b\bar{b}b\bar{b}\nu\bar{\nu}$

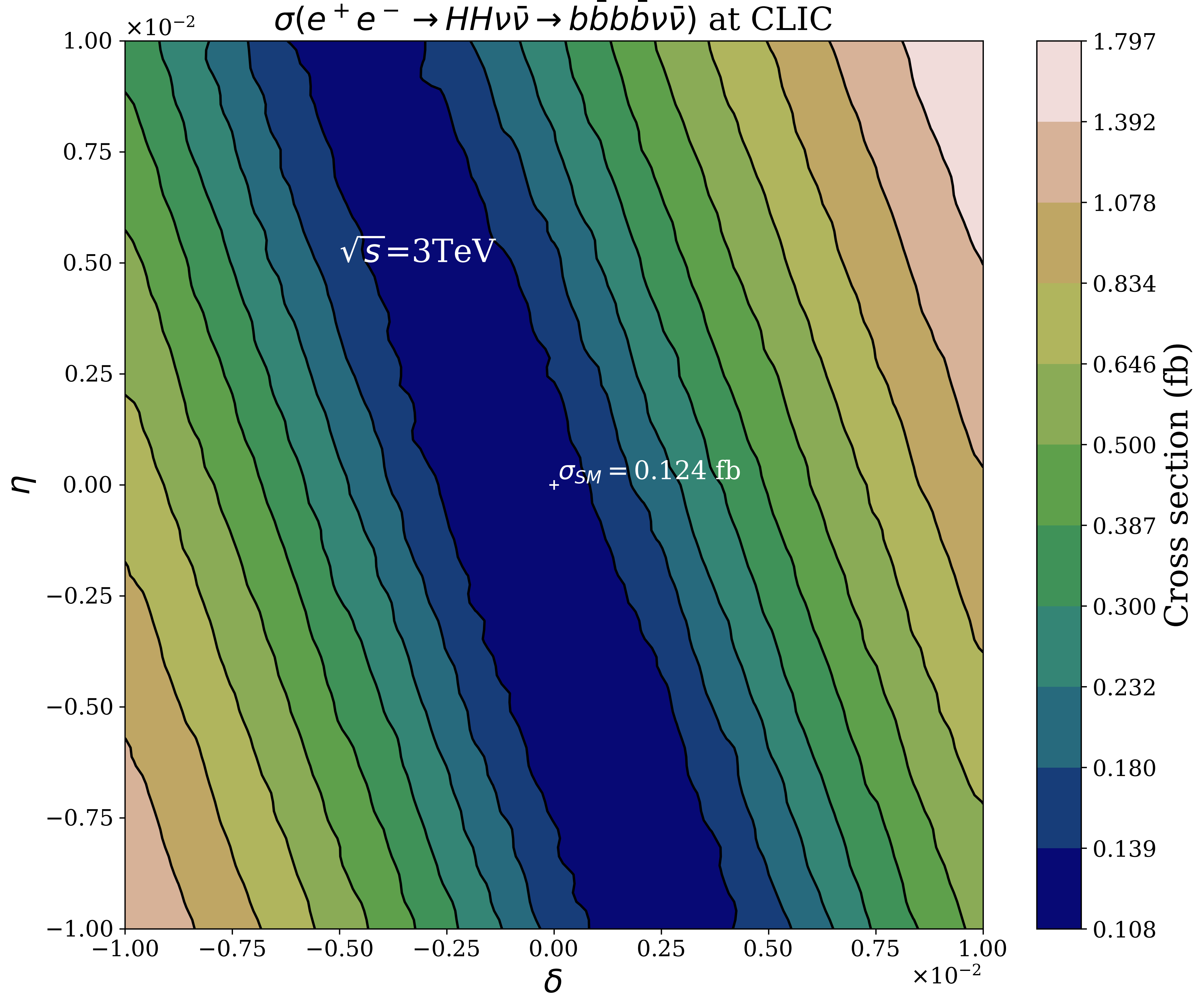
As expected, more accessibility in CLIC

(BSM cross section departs from the SM with energy)

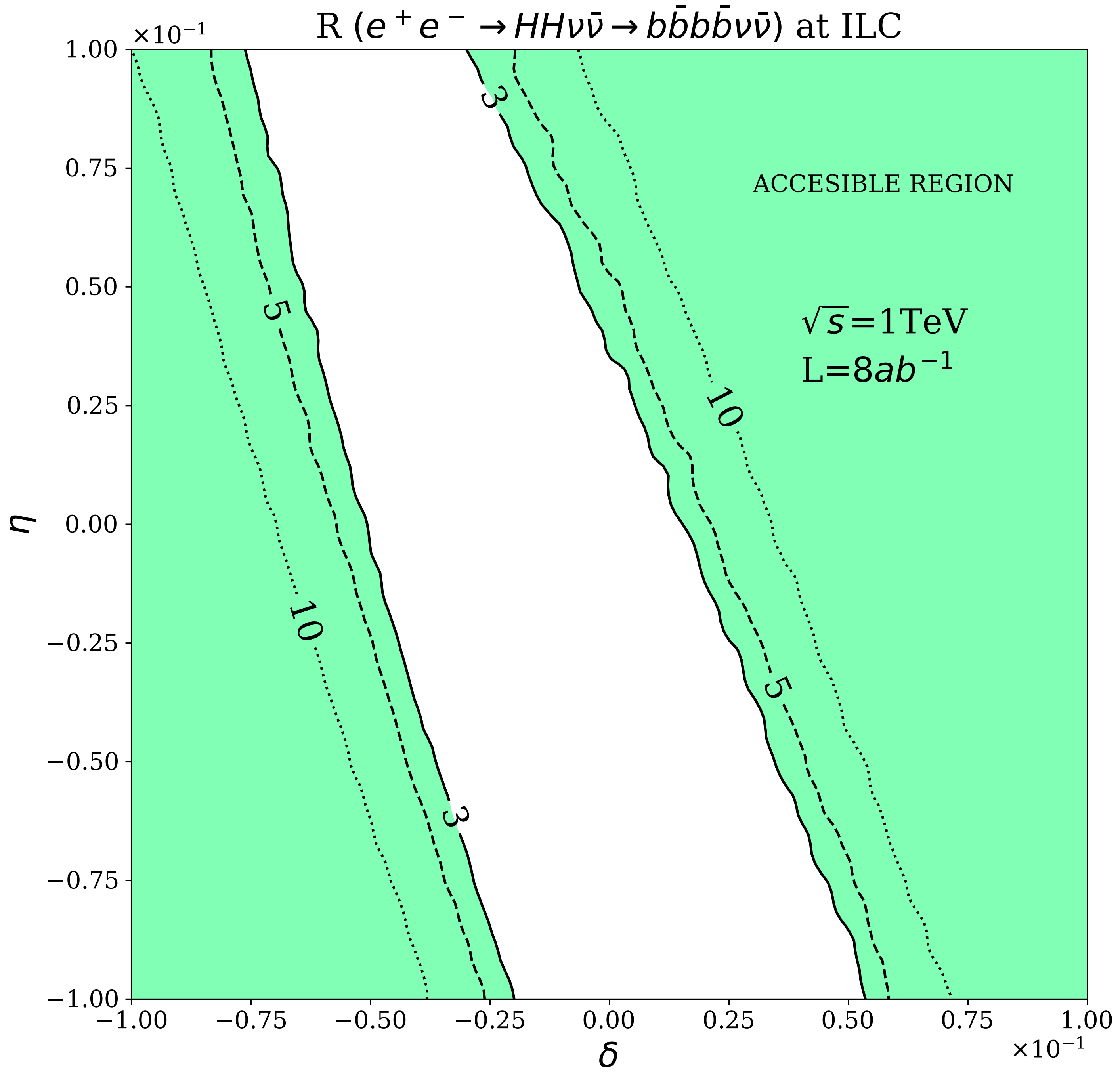
Accessibility parameter

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

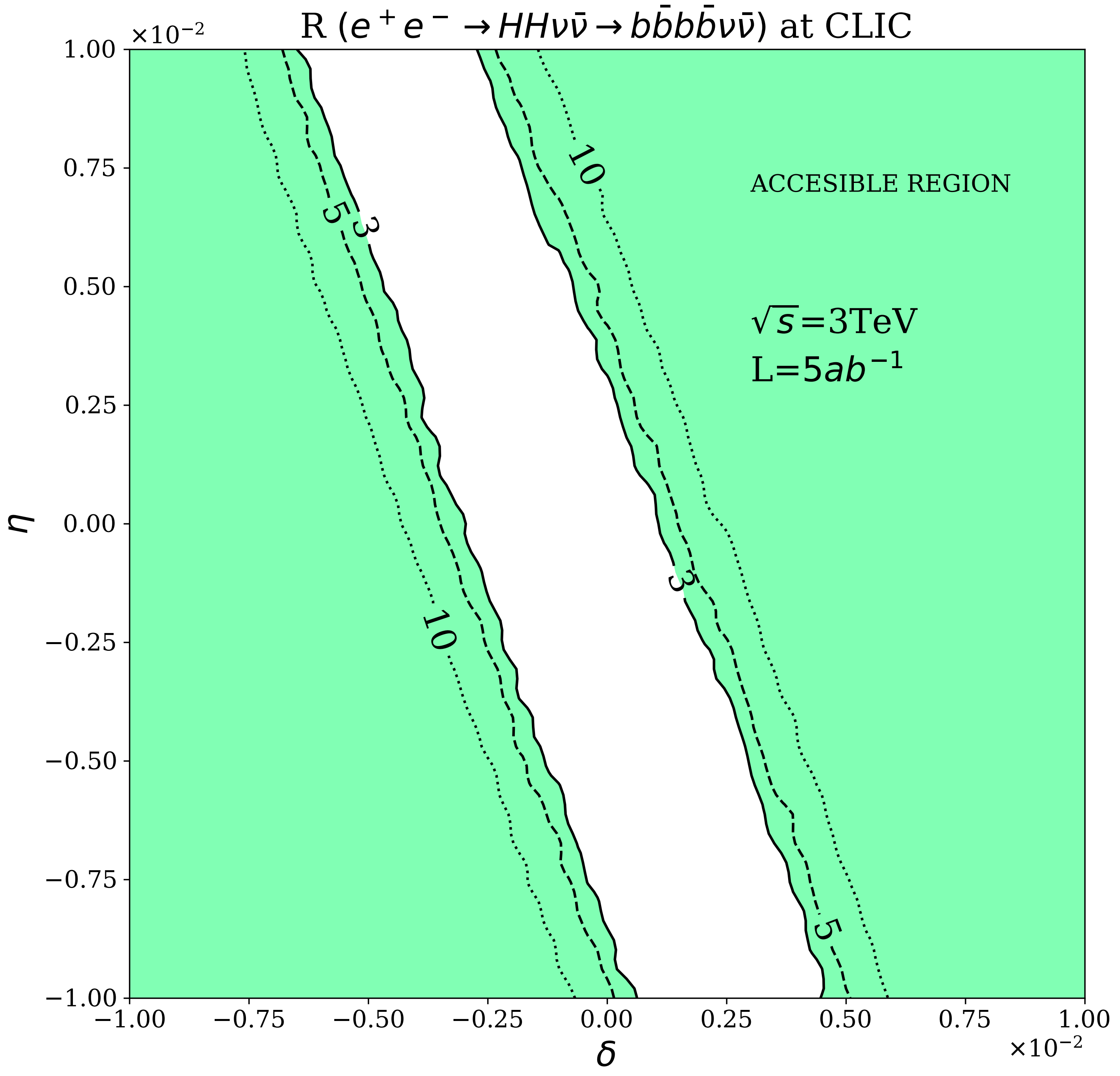
Accesible region: R > 3



ILC



CLIC



2208.05452, Phys. Rev. D 106 (2022) 115027, Domenech, Herrero, Morales, Ramos

Accessibility to NLO-HEFT (η, δ) at LHC

All events generated with MadGraph 5: signal and background (Pdf set NN23LO1)

At the LHC, the background acquires a strong relevance

Signal of choice is qq → HH jj → $\gamma\gamma$ bb jj

Two relevant backgrounds

ZH Background: qq → ZH jj → $\gamma\gamma$ bb jj

QCD-EW Background: A($\gamma\gamma$ bb jj) ~$\mathcal{O}(\alpha_s^2\alpha)$

Several cuts to discriminate the signal:

VBF cuts

$2 < |\eta_j| < 5$

$\eta_{j_1} \cdot \eta_{j_2} < 0$

$M_{jj} > 500$ GeV

$\Delta\eta_{jj} > 4$

Higgs selection cuts

$M_{\gamma\gamma} \in [120, 130]$ GeV

$M_{bb} \in [120, 130]$ GeV

Basic detection cuts

$\eta_b < 2.5$

$\eta_\gamma < 2.5$

$\Delta R_{jj} > 0.4$ $\quad \Delta R_{\gamma j} > 0.4$

$\Delta R_{\gamma\gamma} > 0.4$ $\quad \Delta R_{\gamma b} > 0.4$

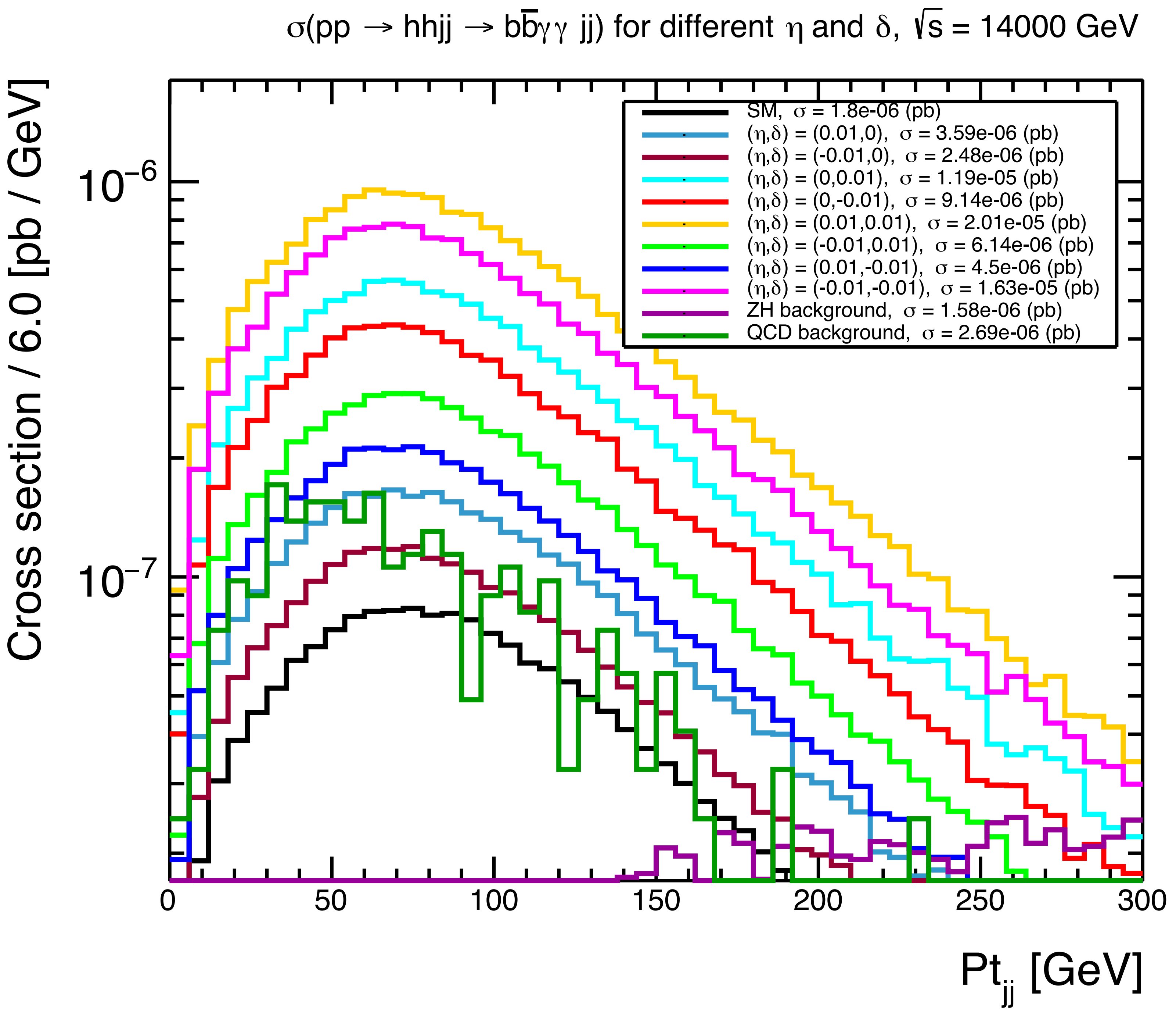
$\Delta R_{bj} > 0.4$ $\quad \Delta R_{bb} > 0.2$

$p_T^j > 20$ GeV $\quad p_T^b > 25$ GeV $\quad p_T^\gamma > 30$ GeV

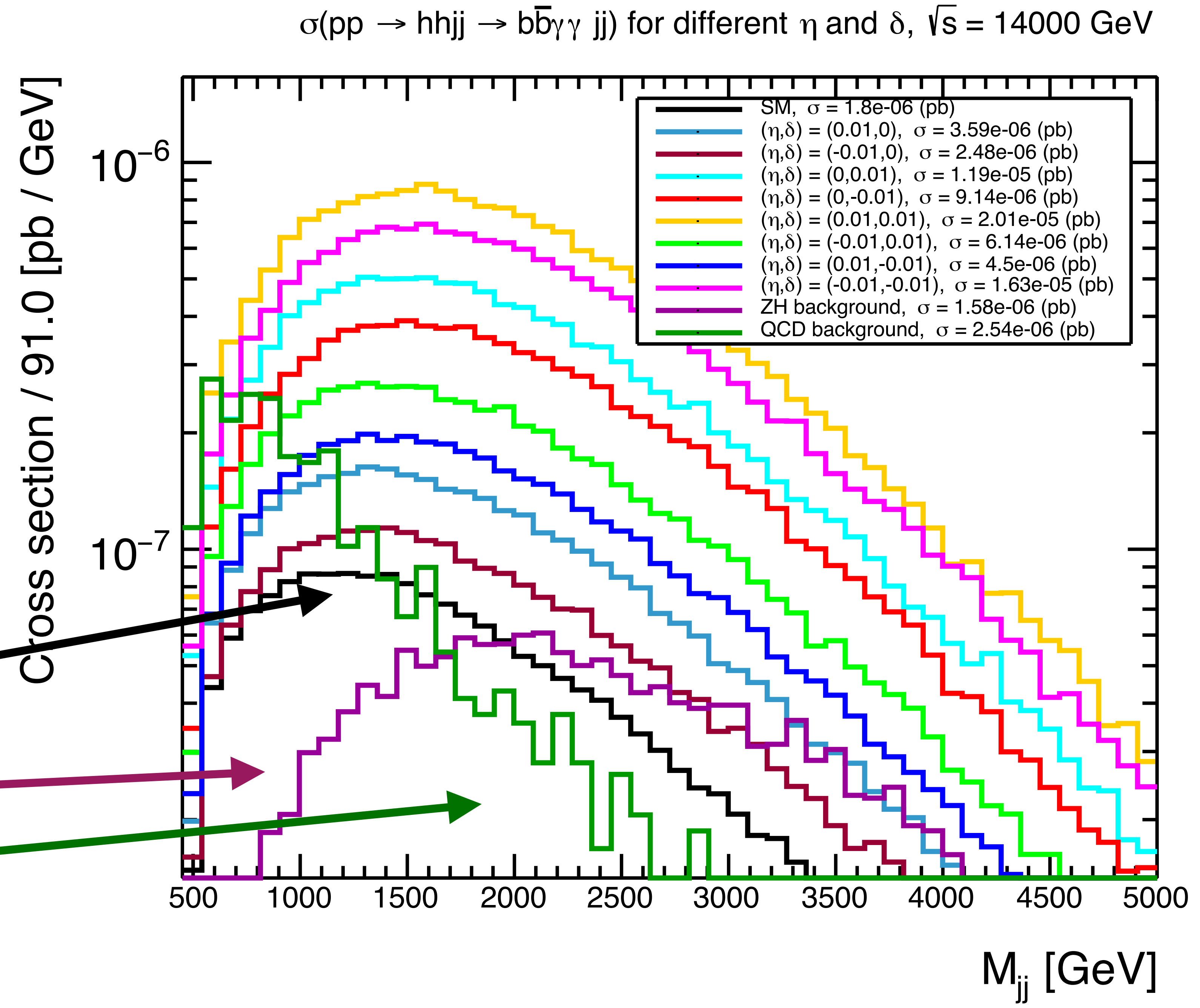
(Work in progress, Domenech, Herrero, Morales)

VBF jets topology at LHC: BSM with NLO-HEFT (η, δ) versus SM

We consider conservative values in $[-0.01, 0.01]$ for both η and δ



The M_{jj} cut removes the stronger region from the QCD-EW background

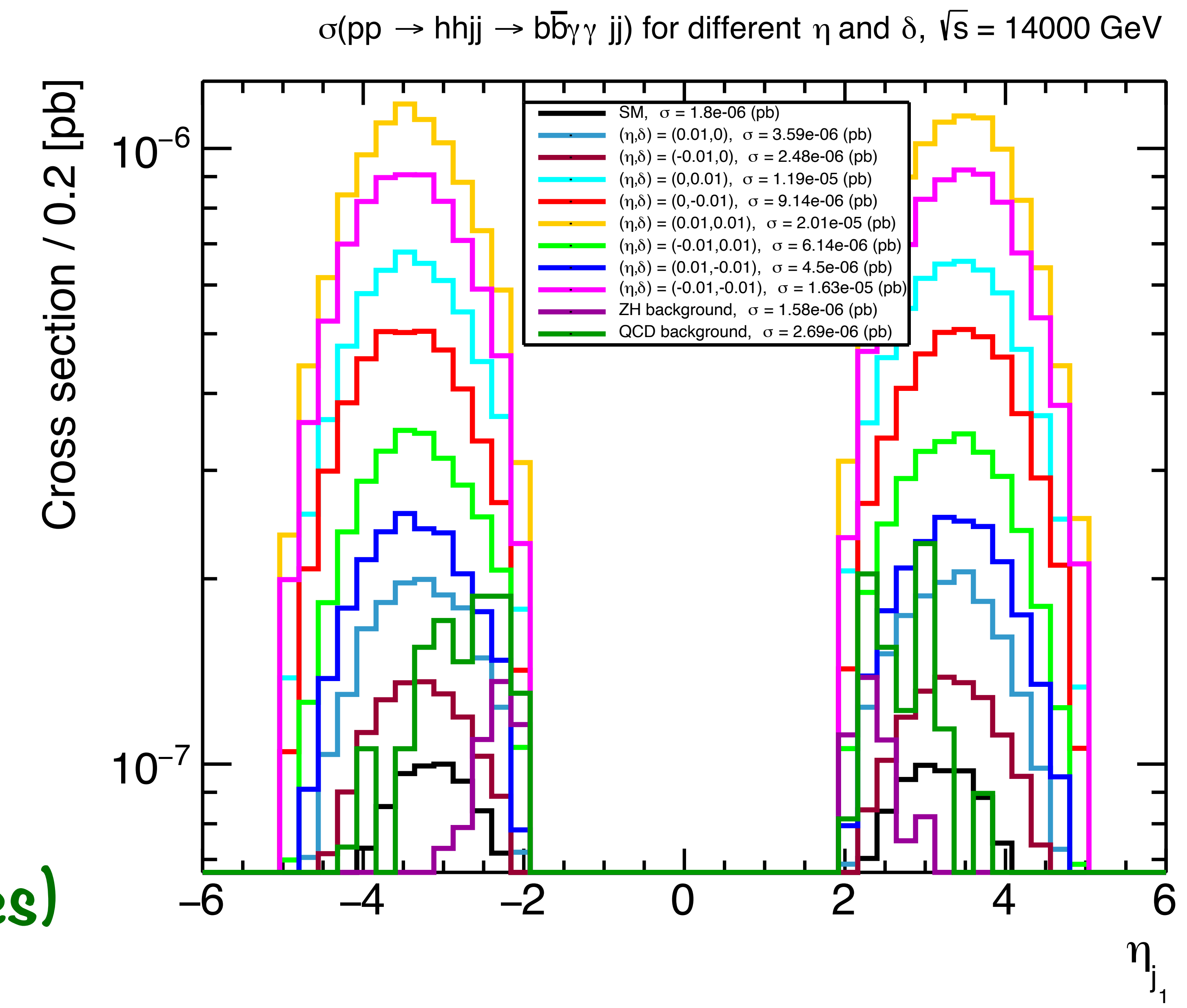


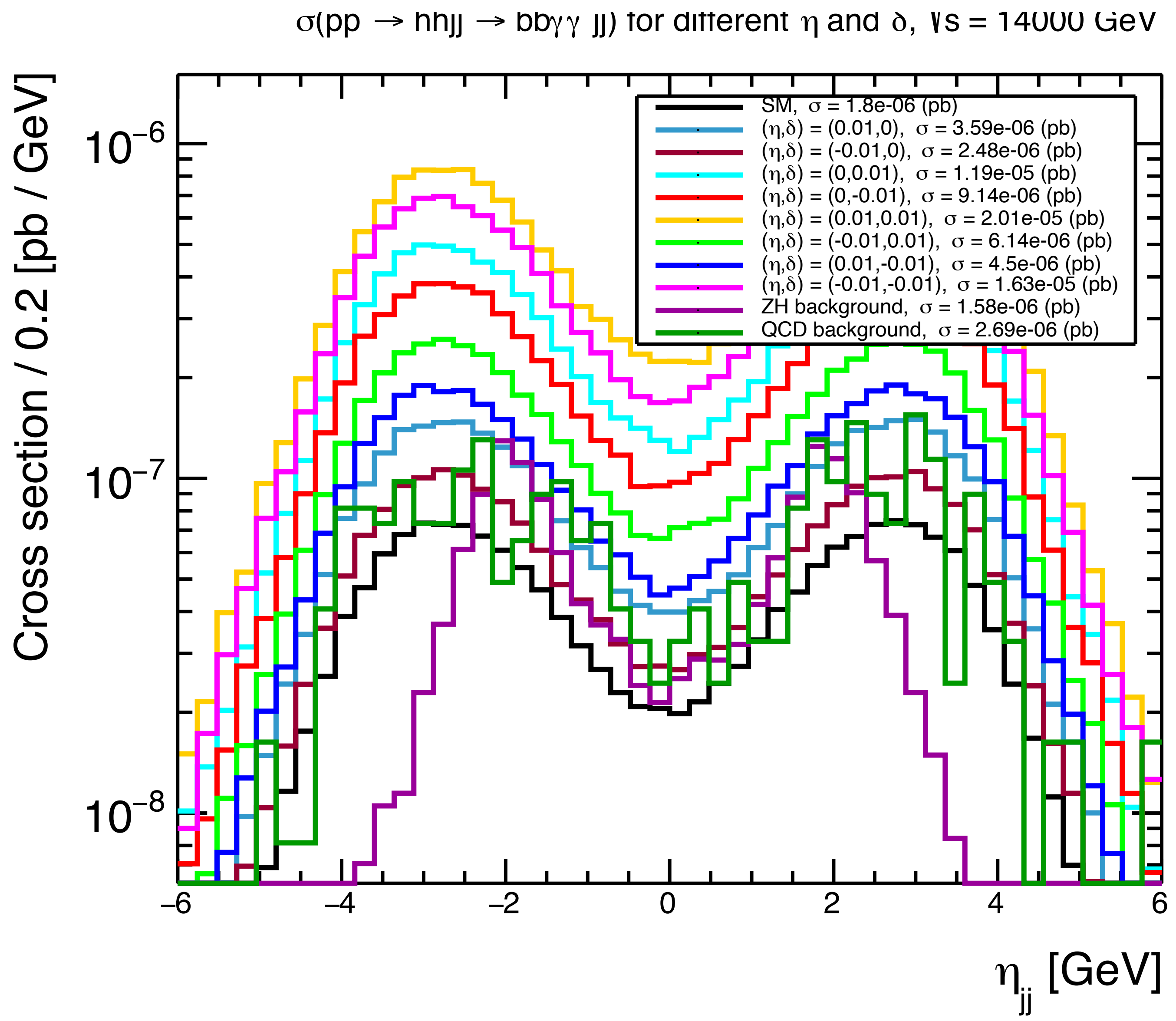
WBF SM

ZH bkg

QCD-EW bkg

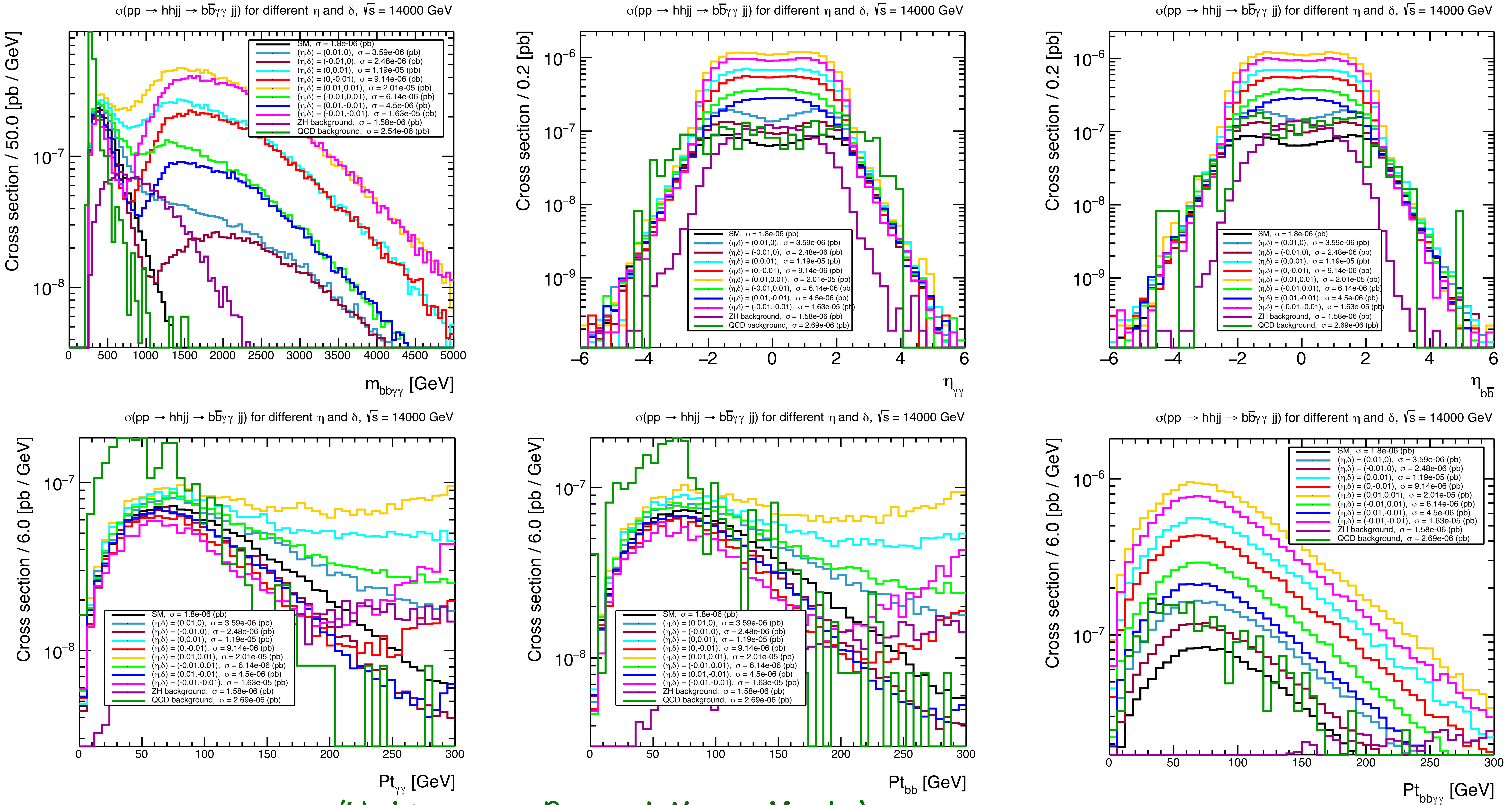
The η_j cuts remove the stronger region from both backgrounds





(Work in progress, Domenech, Herrero, Morales)

$\gamma\gamma b\bar{b}$ topology from HH decays at LHC: BSM with NLO-HEFT (η, δ) versus SM



(Work in progress, Domenech, Herrero, Morales)

Optimising detection cuts to access (η, δ) at HL-LHC

Example of refining cuts → **Provide good accessibility to most of the considered signals**

$p_{T_{\gamma_1}} > 60$ GeV $\quad p_{T_{b_1}} > 60$ GeV

$M_{bb\gamma\gamma} > 400$ GeV

$M_{jj} > 700$ GeV

Number of detected qq → HH jj → $\gamma\gamma$ bb jj events

η \ δ	-0.01	0	0.01
-0.01	50.8	6.2	17.8
0	27.7	4.0 (SM)	36.2
0.01	12.7	9.6	62.6

Events for backgrounds

ZH	4.9
QCD-EW	1.6

We assume 14 TeV and L = 3 ab^{-1}

Most BSM signals have an expected number of events much greater than the backgrounds, being potentially accesible

(Work in progress, Domenech, Herrero, Morales)

Conclusions

- Studying the WBF process provides access to BSM Higgs couplings

- Possible correlations among effective couplings give information about UV theories in addition to the couplings themselves

- There is good accessibility to BSM Higgs couplings to W bosons in both future e^+e^-colliders and the HL-LHC

Thanks for your attention

Relevance of testing correlations among effective couplings

- Each UV theory predicts the values of the effective couplings:
- In HEFT, this means predicting values for $a, b, \kappa_3, \kappa_4, \eta, \delta, \ldots$

- UV theories also predict possible correlations among the eff. couplings
- Specific observables (such as WBF) are sensitive to certain correlations

e.g. WW ➔ HH is sensitive to $\kappa_V^2 - \kappa_{2V}$

- Therefore, testing sensitivity to this correlation is also testing the UV theory

Predictions of the HEFT coefficients from particular settings

Amplitude matching: identify mathematical structures within the scattering amplitudes at low energies, up to a certain order in Λ_{UV}.

Amplitudes are directly related to observables. $T(WW \to HH)_{HEFT} = T(WW \to HH)_{UV}$ at $\sqrt{s} \ll \Lambda_{UV}$

Example: 2HDM

$\Delta a \equiv 1 - a \quad \Delta b \equiv 1 - b$

SM-like

Heavy masses

Input parameters: v, m_H, $m_{H_{heavy}}$, $m_{H^\pm}$, m_A, $c_{\beta-\alpha}$, t_β, m_{12}

SMEFT matching

Results in the heavy masses expansion $m_{heavy} \gg m_H, m_W, m_Z$, v, . . .

$$\Delta a|_{SMEFT} = -\frac{1}{4}\frac{v^2}{\Lambda^2}\delta_{\phi D} \quad \Delta b|_{SMEFT} = -\frac{v^2}{\Lambda^2}\delta_{\phi D}$$

$$a|_{2HDM} = s_{\beta-\alpha} \quad b|_{2HDM} = 1 + c^2_{\beta-\alpha}\left[1 - 2c^2_{\beta-\alpha} + 2c_{\beta-\alpha}s_{\beta-\alpha}\cot(2\beta)\right]$$

Also correlated! $\Delta b|_{SMEFT} = 4\Delta a|_{SMEFT}$

Notice the non-decoupling effects

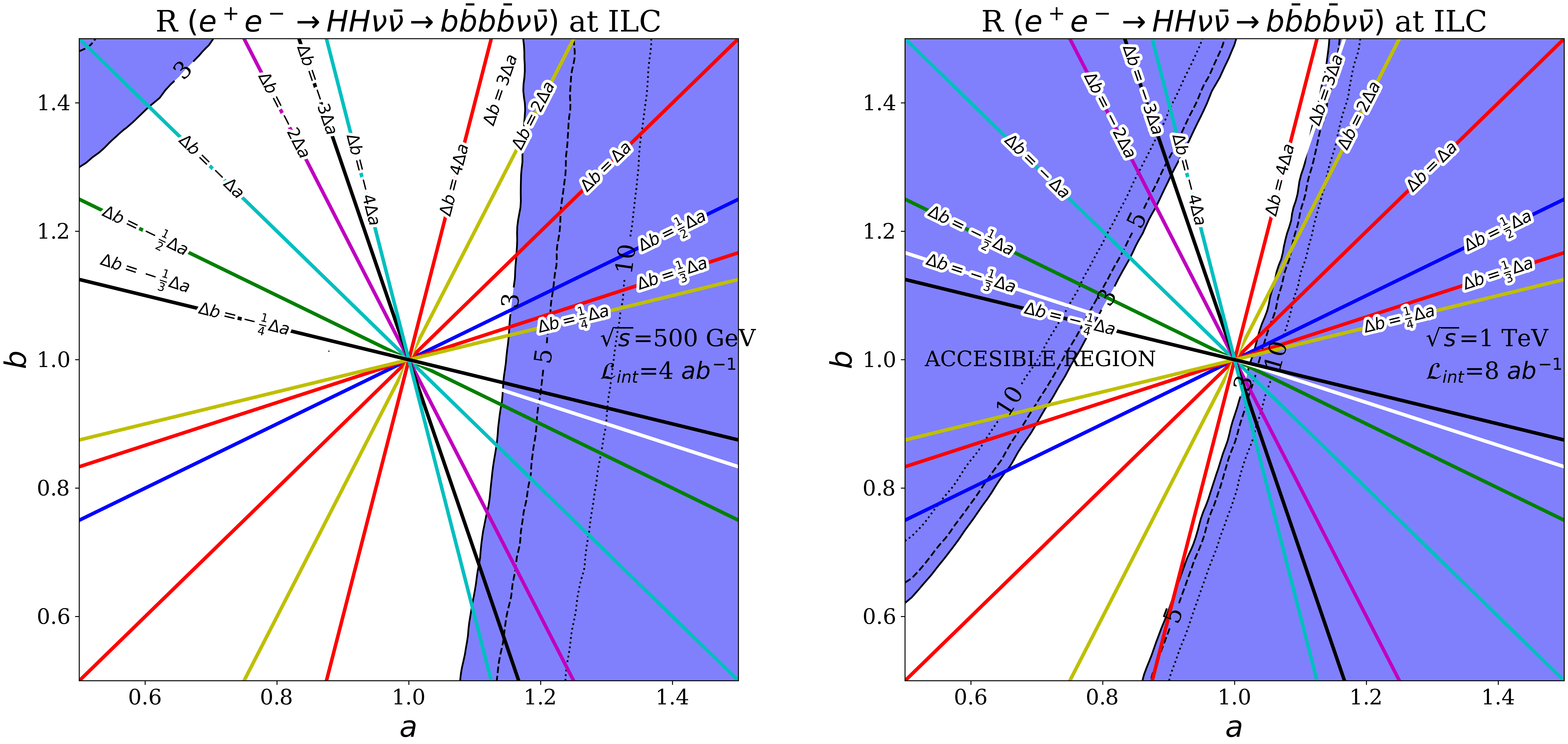
$\Delta b|_{2HDM} \simeq -2\Delta a|_{2HDM}$

Correlated for $c_{\beta-\alpha}$ << 1

Correlations among coefficients give information about possible UV theories!

$$\eta = \frac{v^4}{4\Lambda^4}\left[a^{(1)}_{\phi^4} + a^{(2)}_{\phi^4}\right] \qquad \delta = \frac{v^4}{4\Lambda^4}a^{(3)}_{\phi^4}$$

2307.15693, Arco, Domenech, Herrero, Morales. To appear in Phys. Rev. D 2023
2208.05452, Phys. Rev. D 106 (2022) 115027, Domenech, Herrero, Morales, Ramos



R $(e^+e^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu})$ at ILC
$\sqrt{s}$=500 GeV
$\mathcal{L}_{int}$=4 ab^{-1}
R $(e^+e^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu})$ at ILC
$\sqrt{s}$=1 TeV
$\mathcal{L}_{int}$=8 ab^{-1}
ACCESIBLE REGION
$\Delta b = 4\Delta a$
$\Delta b = 3\Delta a$
$\Delta b = 2\Delta a$
$\Delta b = \Delta a$
$\Delta b = \frac{1}{2}\Delta a$
$\Delta b = \frac{1}{3}\Delta a$
$\Delta b = \frac{1}{4}\Delta a$
$\Delta b = -4\Delta a$
$\Delta b = -3\Delta a$
$\Delta b = -2\Delta a$
$\Delta b = -\Delta a$
$\Delta b = -\frac{1}{2}\Delta a$
$\Delta b = -\frac{1}{3}\Delta a$
$\Delta b = -\frac{1}{4}\Delta a$
3
5
10
a
b