# Testing anomalous $H-W$ couplings and Higgs self-couplings via double and triple Higgs production at $e^+e^-$colliders

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# Introduction

In the SM, the Higgs boson is part of an electroweak doublet. Gauge symmetry leads to some relations among its couplings:

$$V_{HHH}^{SM} = \mathrm{v} V_{HHHH}^{SM}$$

$$V_{HWW}^{SM} = \mathrm{v} V_{HHWW}^{SM}$$

Deviations from this relations could point to new physics!

**EFTs are a useful tool to probe such BSM effects. In this work we will employ the Effective Chiral Lagrangian (EChL) and study its signals in $e^+e^-$ colliders.**

# The EChL

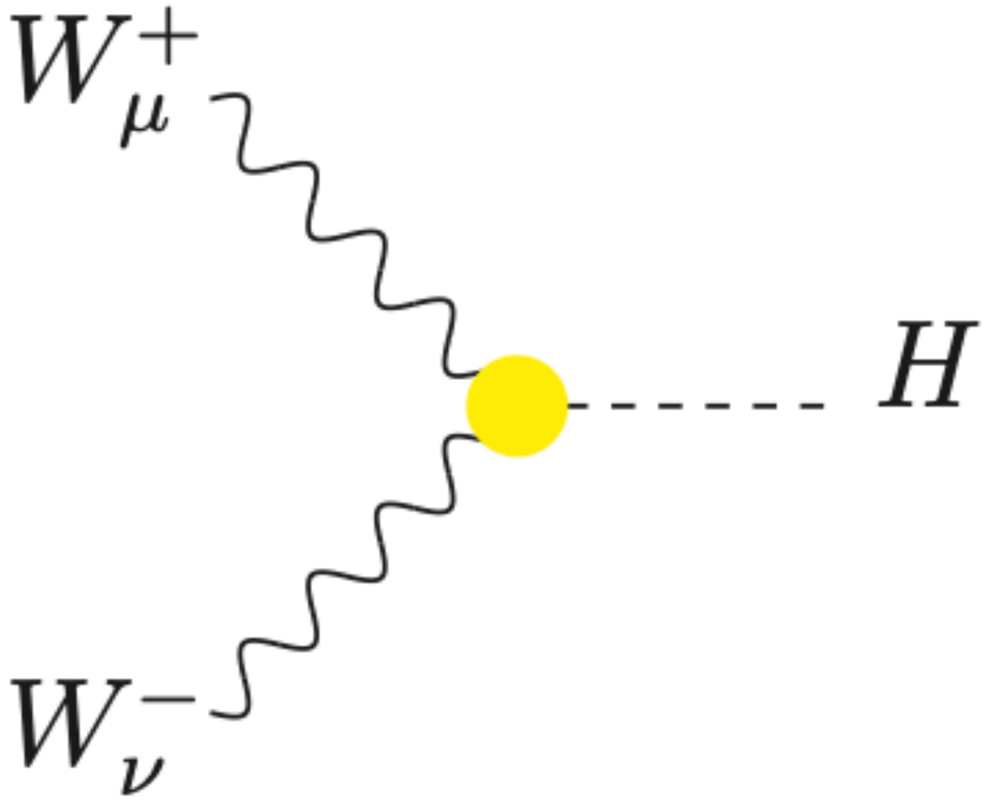
- The Higgs boson, $H$, is introduced as a singlet, being no longer part of a doublet.
- Thus, its triple and quartic couplings (to itself and to gauge bosons) are no longer correlated.
- The electroweak Goldstone bosons are placed in an exponential representation , $U = \exp\left(\frac{i\vec{\omega}\vec{\tau}}{v}\right)$

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

Anomalous Higgs couplings: parametrize possible BSM effects.

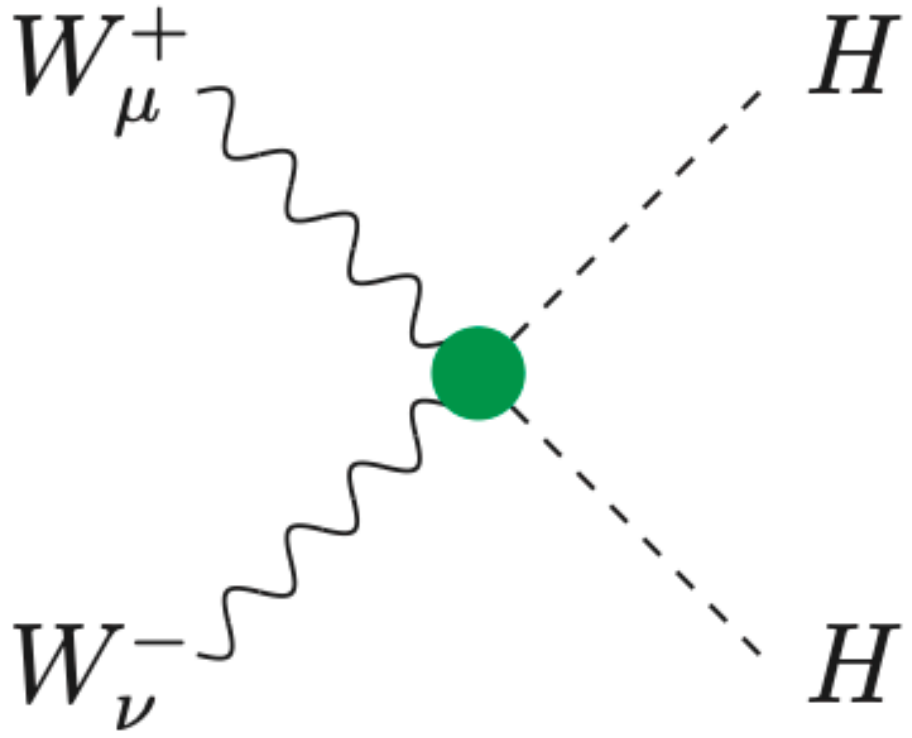
In the SM, $a = b = \kappa_3 = \kappa_4 = 1$, and the correlations are recovered.

# The EChL



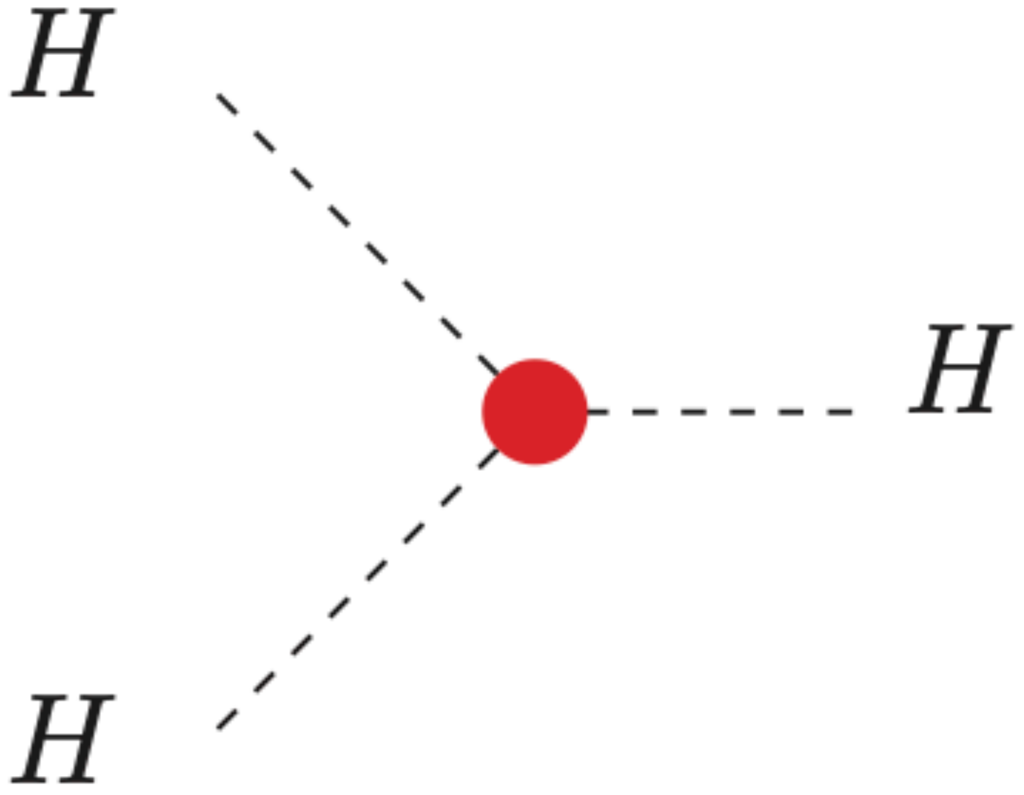

$$V_{WWH} = iagm_W g_{\mu\nu}$$

$$a^{\text{exp}} \in [0.97, 1.13]^{[1]}$$



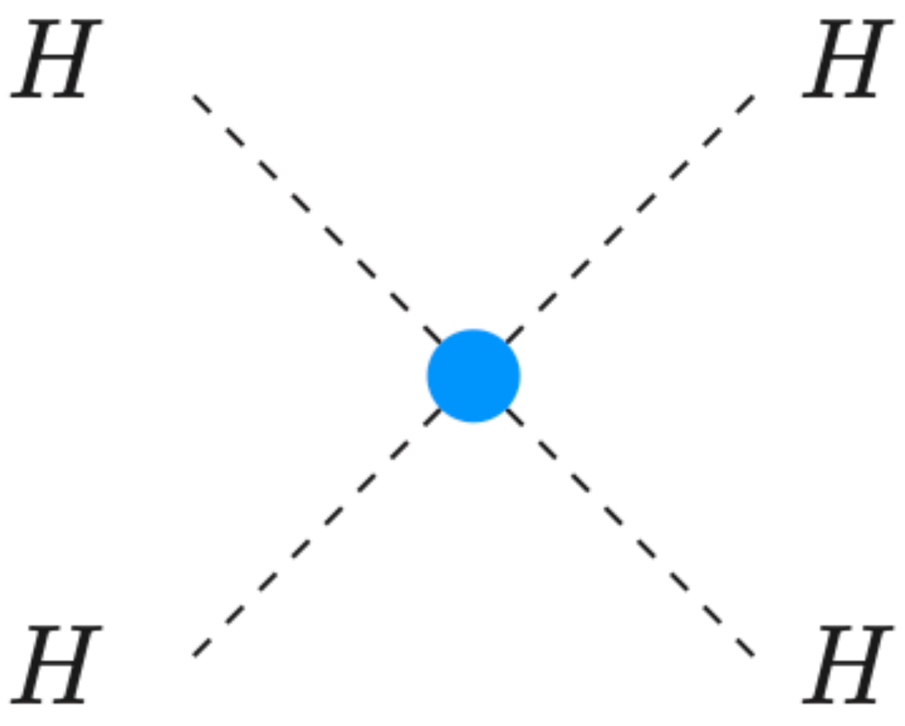

$$V_{WWHH} = \frac{ibg^2}{2} g_{\mu\nu}$$

$$b^{\text{exp}} \in [-0.76, 2.90]^{[2]}$$




$$V_{HHH} = -i\kappa_3 6\lambda v$$

$$\kappa_3^{\text{exp}} \in [-2.3, 10.3]^{[3]}$$




$$V_{HHHH} = -i\kappa_4 6\lambda$$

$$\kappa_4^{\text{exp}} \in (-\infty, \infty)$$

[1]ATLAS, Phys. Rev. D **101** (2020) [1909.02845]

[2]ATLAS, JHEP **07** (2020) [2001.05178]

[3]ATLAS-CONF-2019-049

# Analysis strategy

We will study the sensitivity to BSM Higgs couplings in TeV-scale $e^+e^-$ colliders, as they provide cleaner signals.

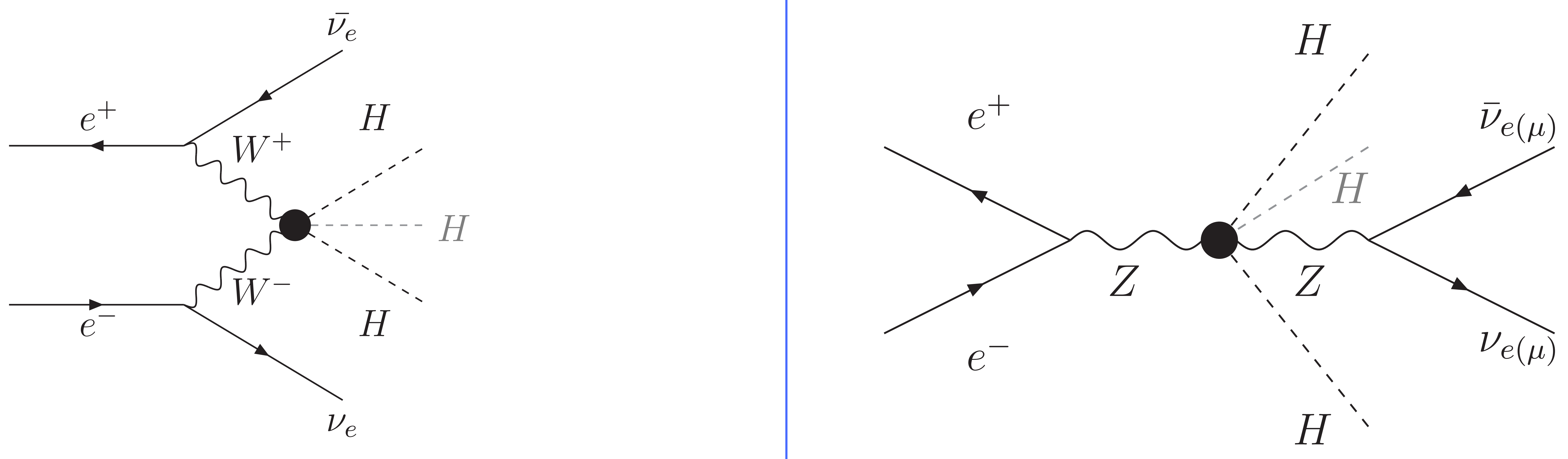
The process $e^+e^- \to HH(H)\nu_e\bar{\nu}_e$ is dominated by $WW$ scattering and, thus, particularly sensitive to anomalous Higgs couplings.

The problem will be factorized in two parts: the effects of $a$ and $b$ in $HH$ production and those of $\kappa_3$ and $\kappa_4$ in $HHH$ production.

Cross sections at the subprocess level will be computed via FeynArts and FormCalc, whereas MadGraph5 will be employed for those at the collider level.

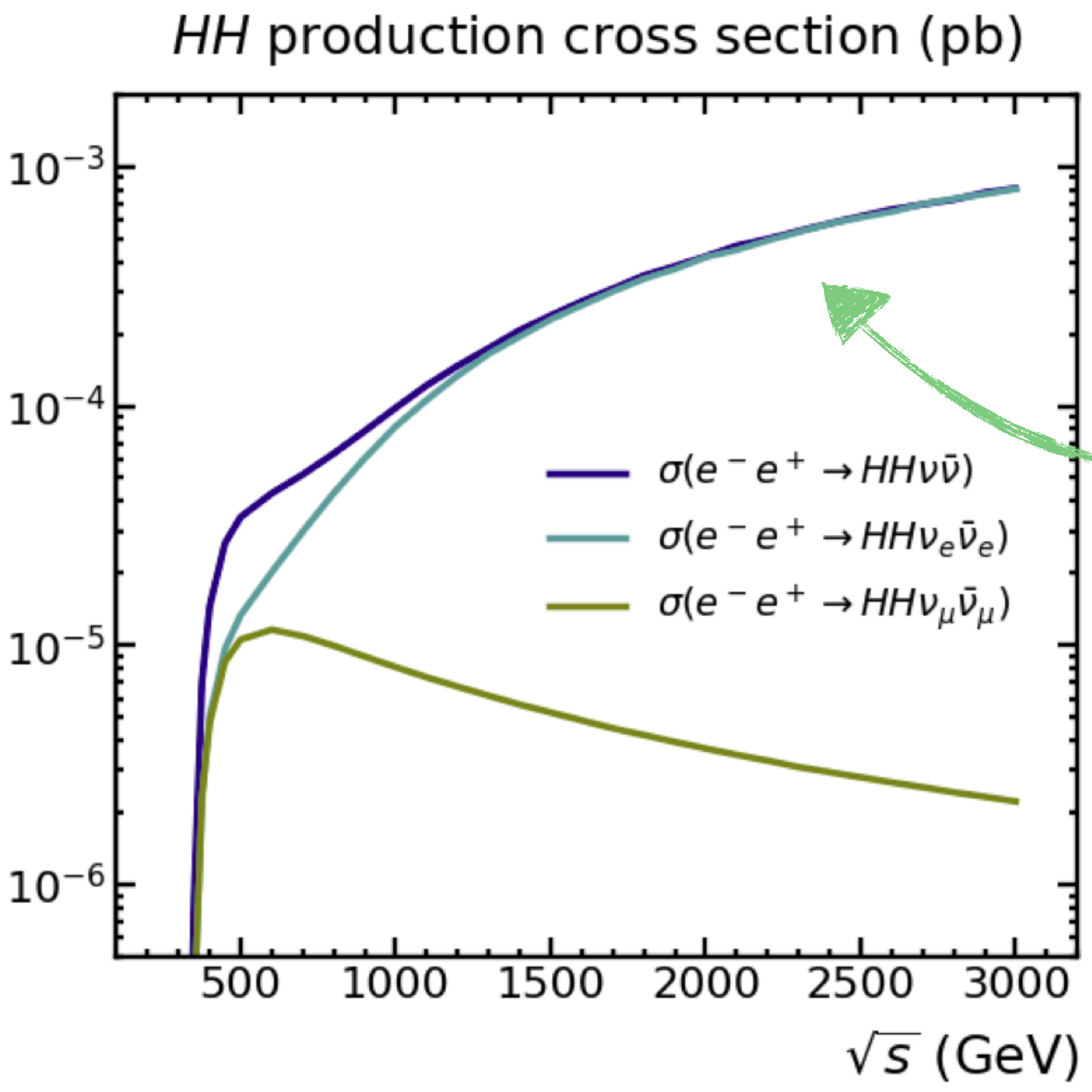
# The role of $WW$ scattering

Multi-Higgs production at $e^+e^-$ colliders may be mediated by VBS or by $Z$ bosons produced in $s$-channel.

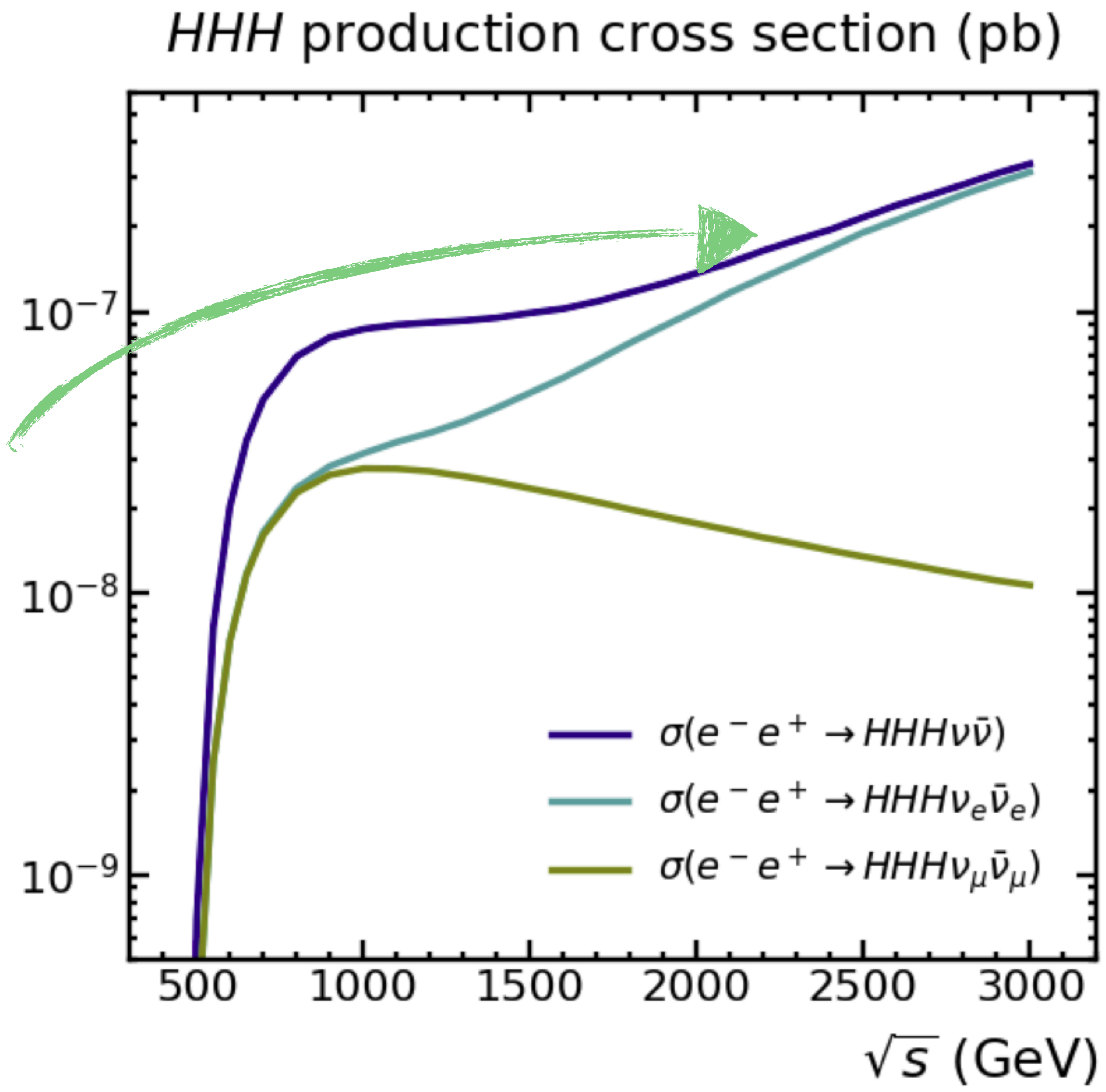



Identifying the dominant subprocesses is key to studying the sensitivity to the anomalous couplings.

# The role of $WW$ scattering

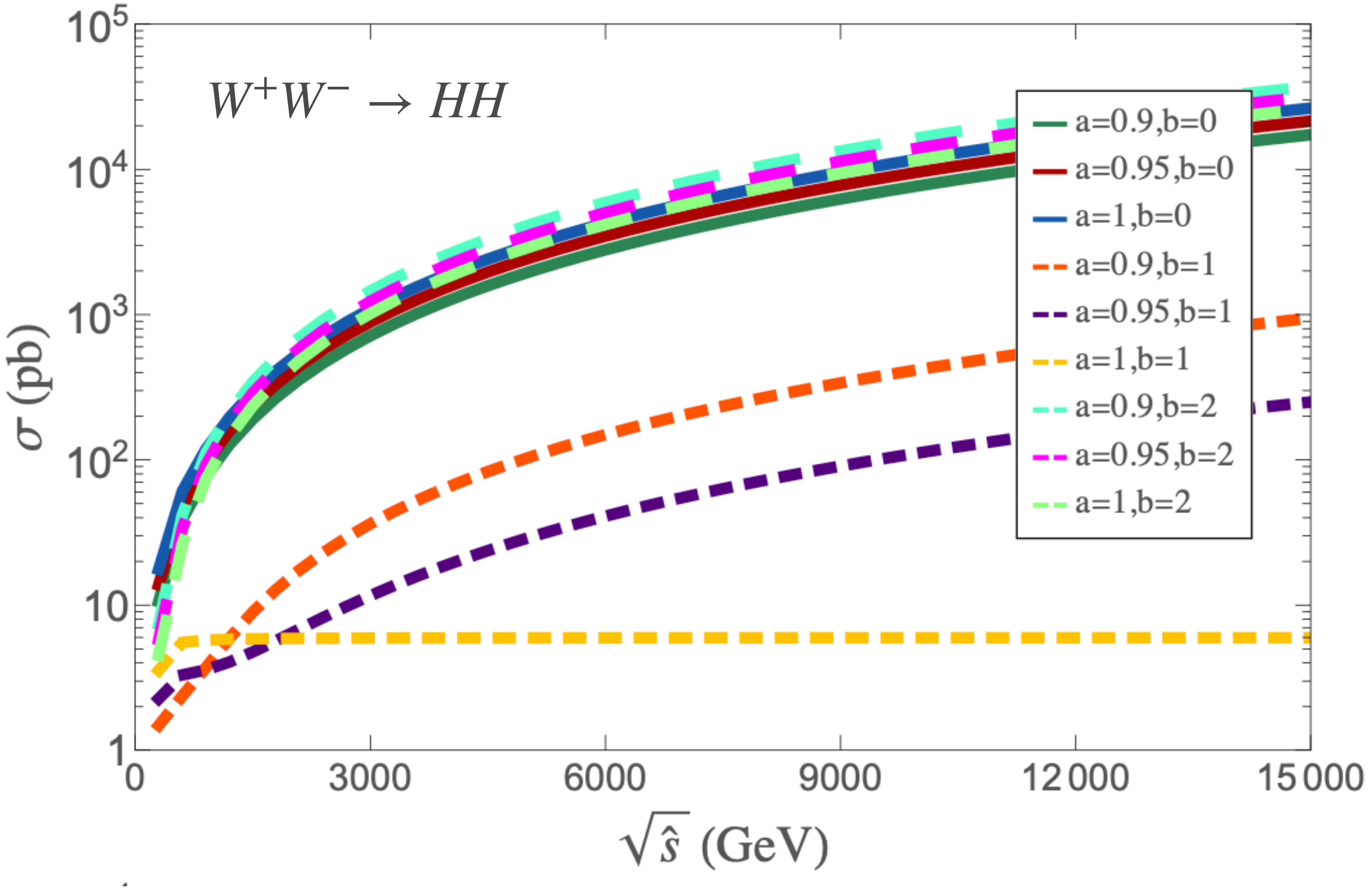




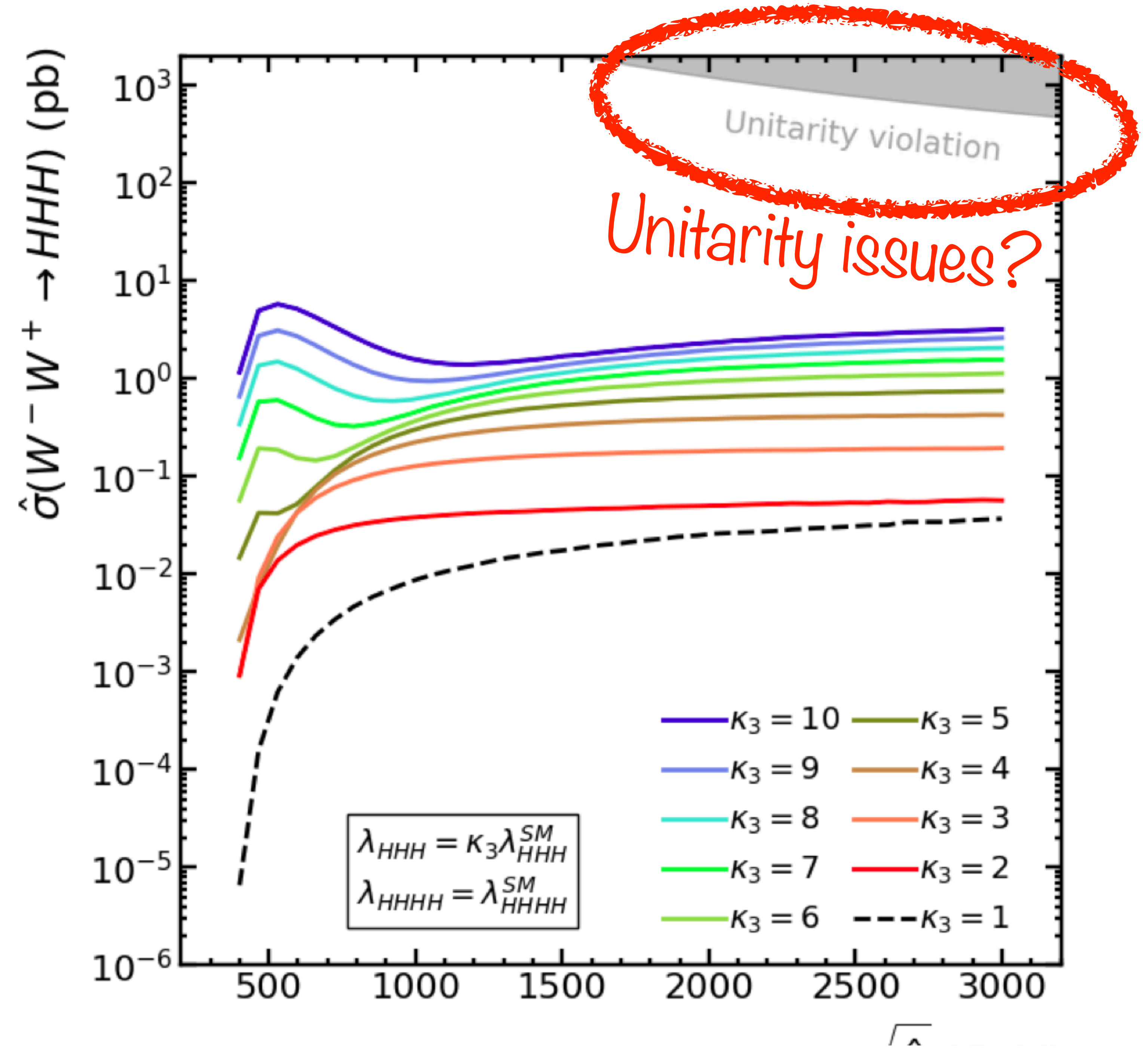


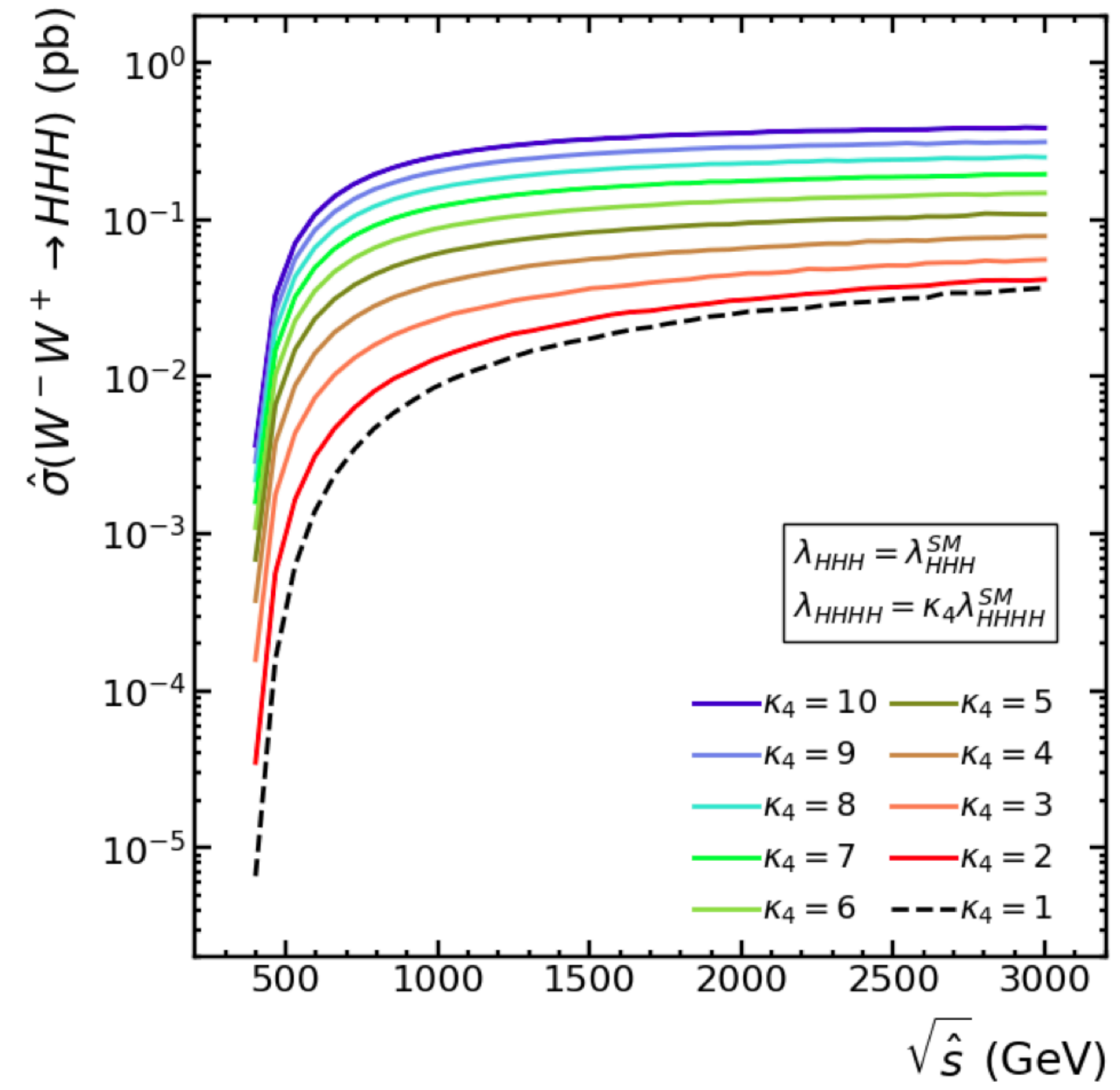

This is only a theoretical exercise! Neutrino flavors cannot be measured at colliders.

# BSM effects at subprocess level




Anomalous couplings induce a large cross section enhancement



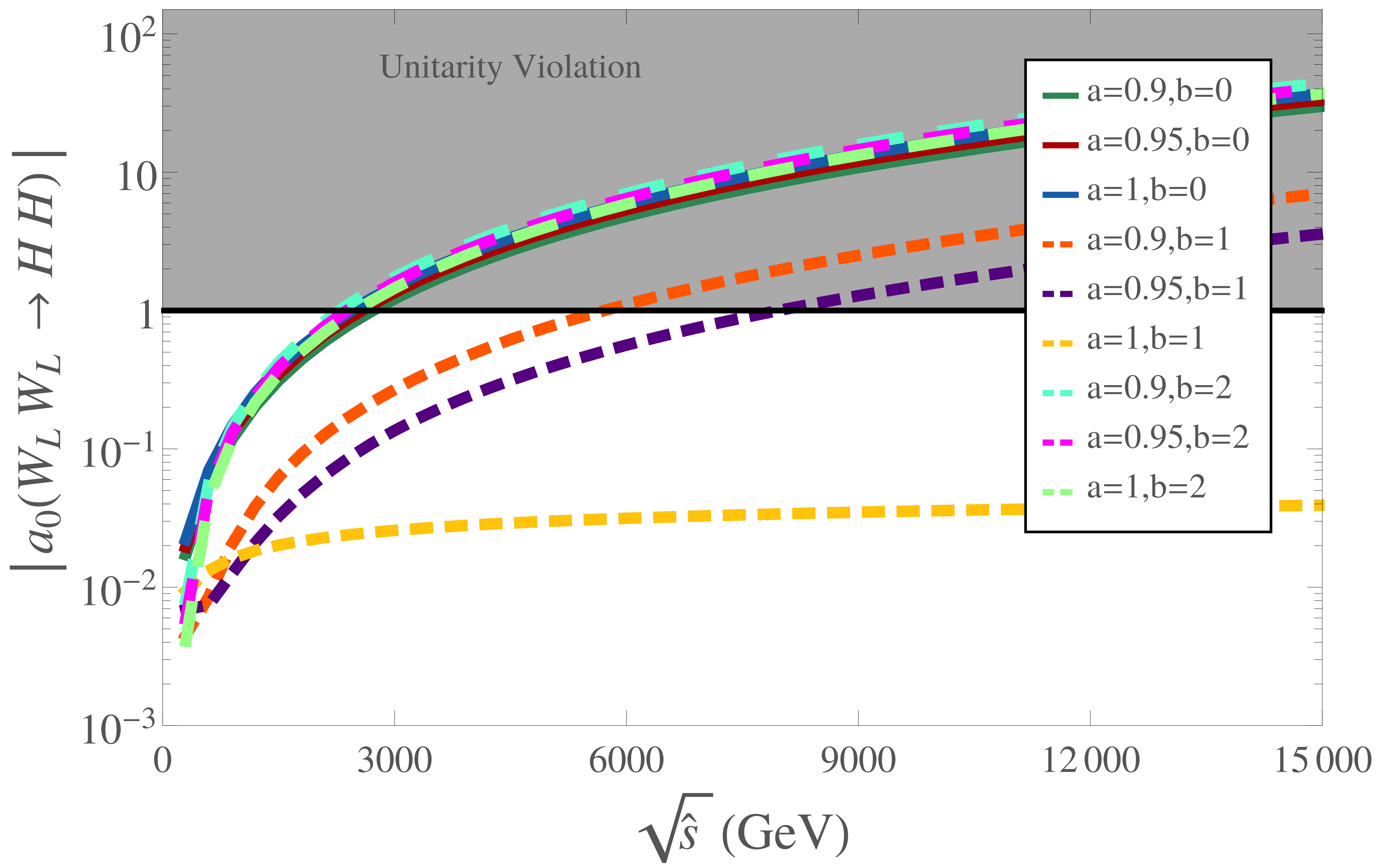
# Unitarity issues?

- ✓ Triple Higgs production cross sections are small enough to keep unitarity even for large anomalous couplings.

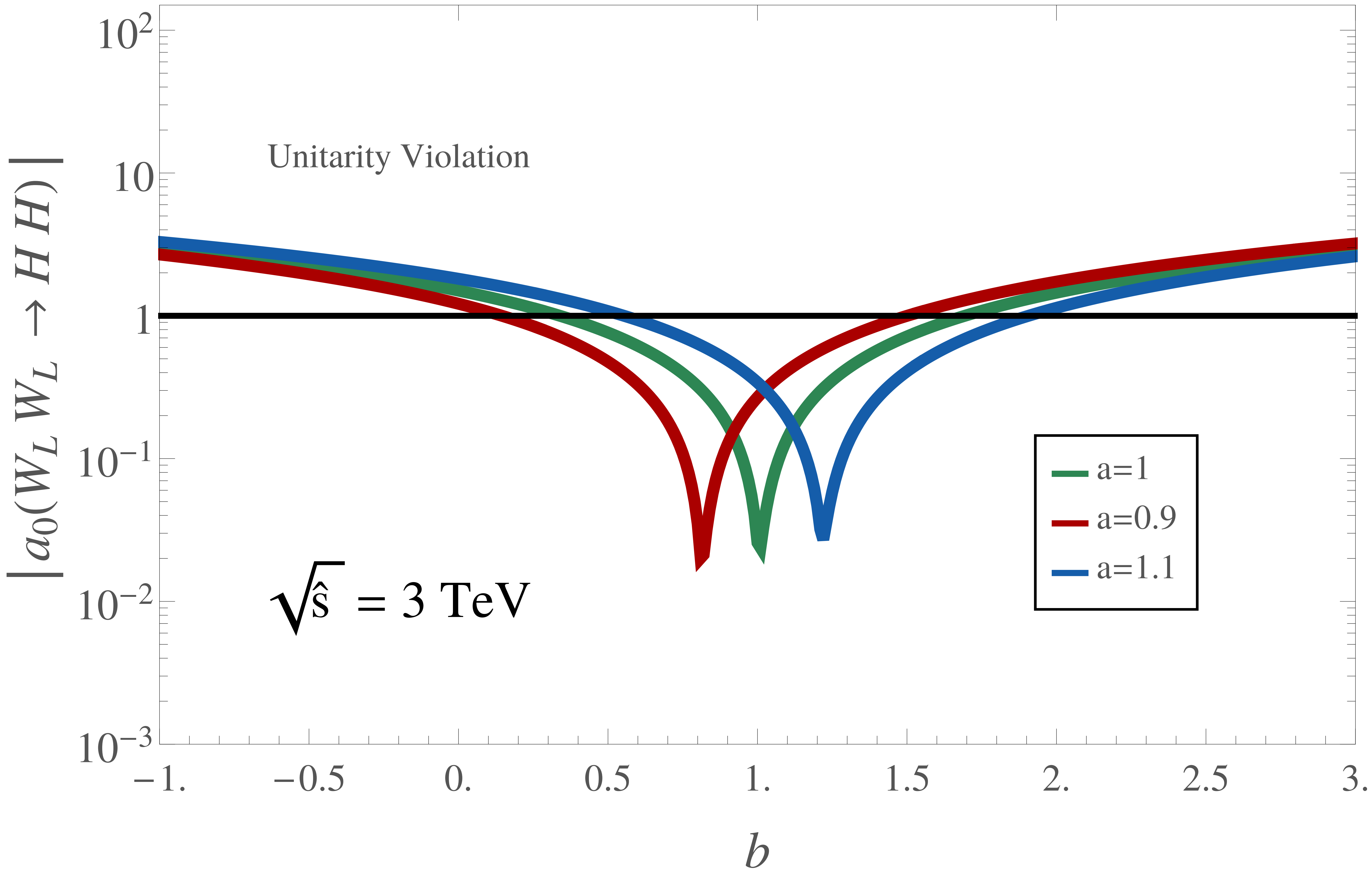
- ? Also the case for double Higgs production?

# Unitarity issues?

- Double Higgs cross sections grow beyond unitarity for large $a$ and/or $b$. Some limits can be inferred.



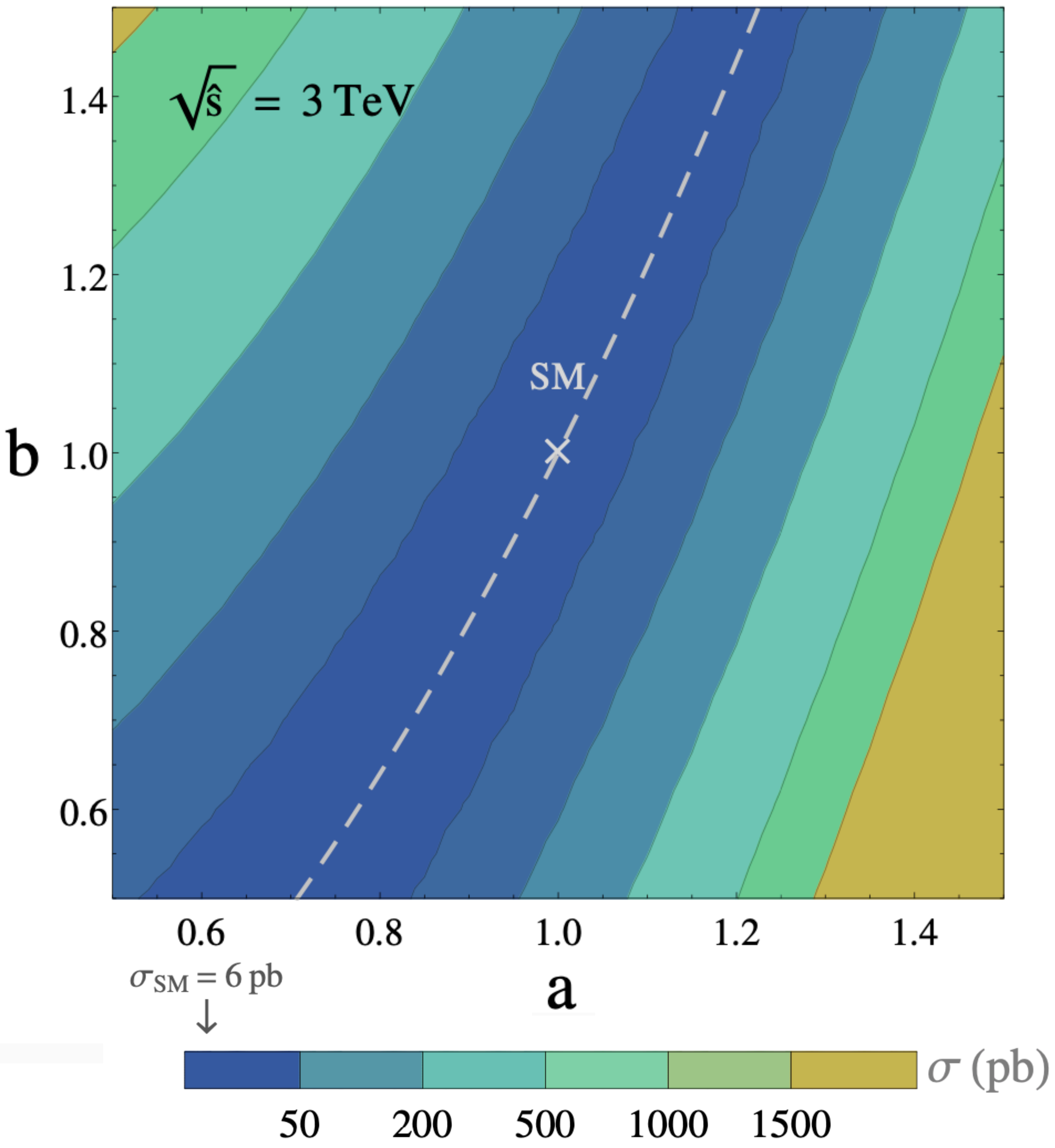
# Unitarity issues?



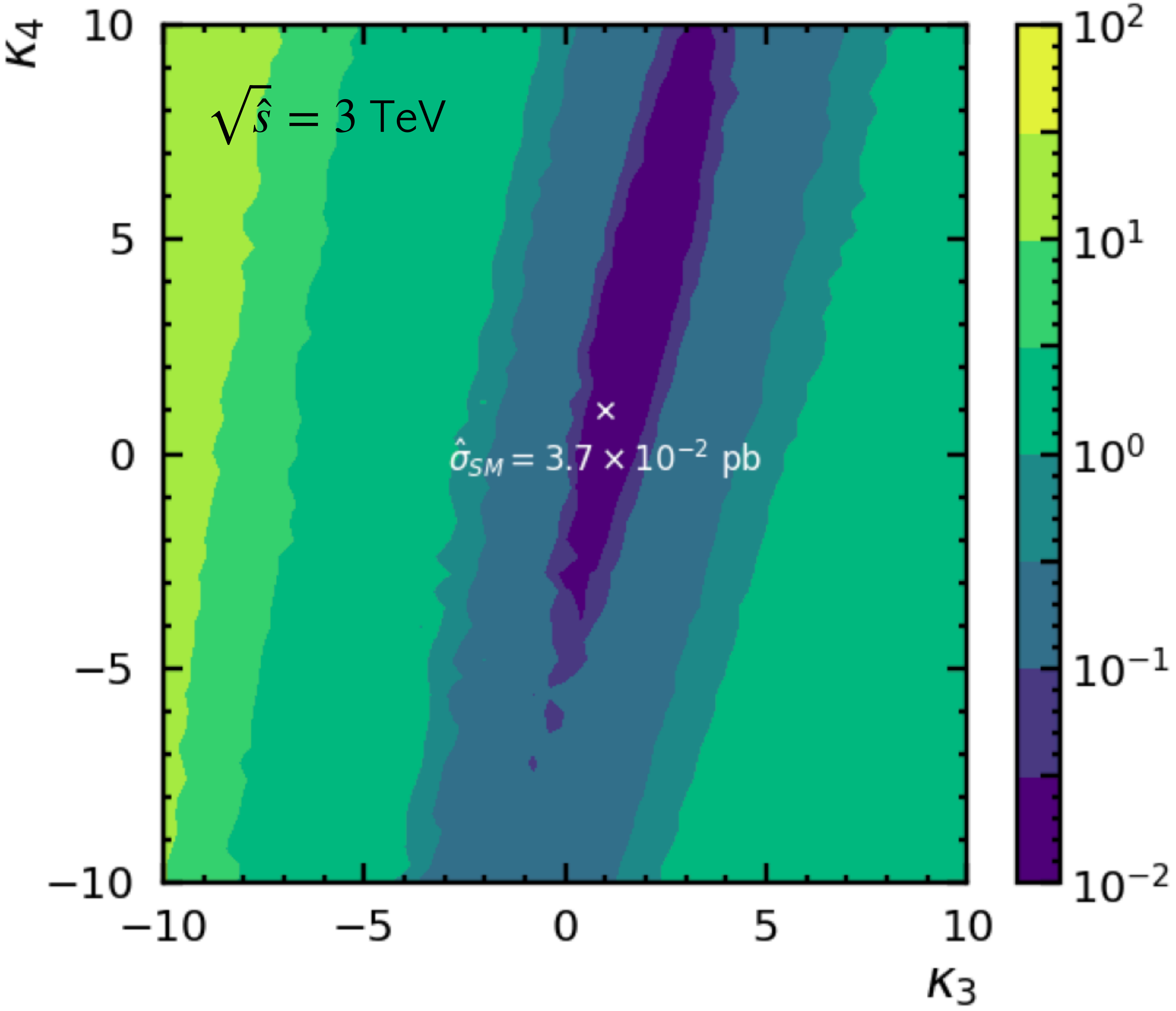

We will stay within the range $b \in [0.5, 1.5]$. Experimental constraints on $a$ are stronger than any that could be derived from unitarity.

# BSM effects at subprocess level

$W^+W^- \to HH$

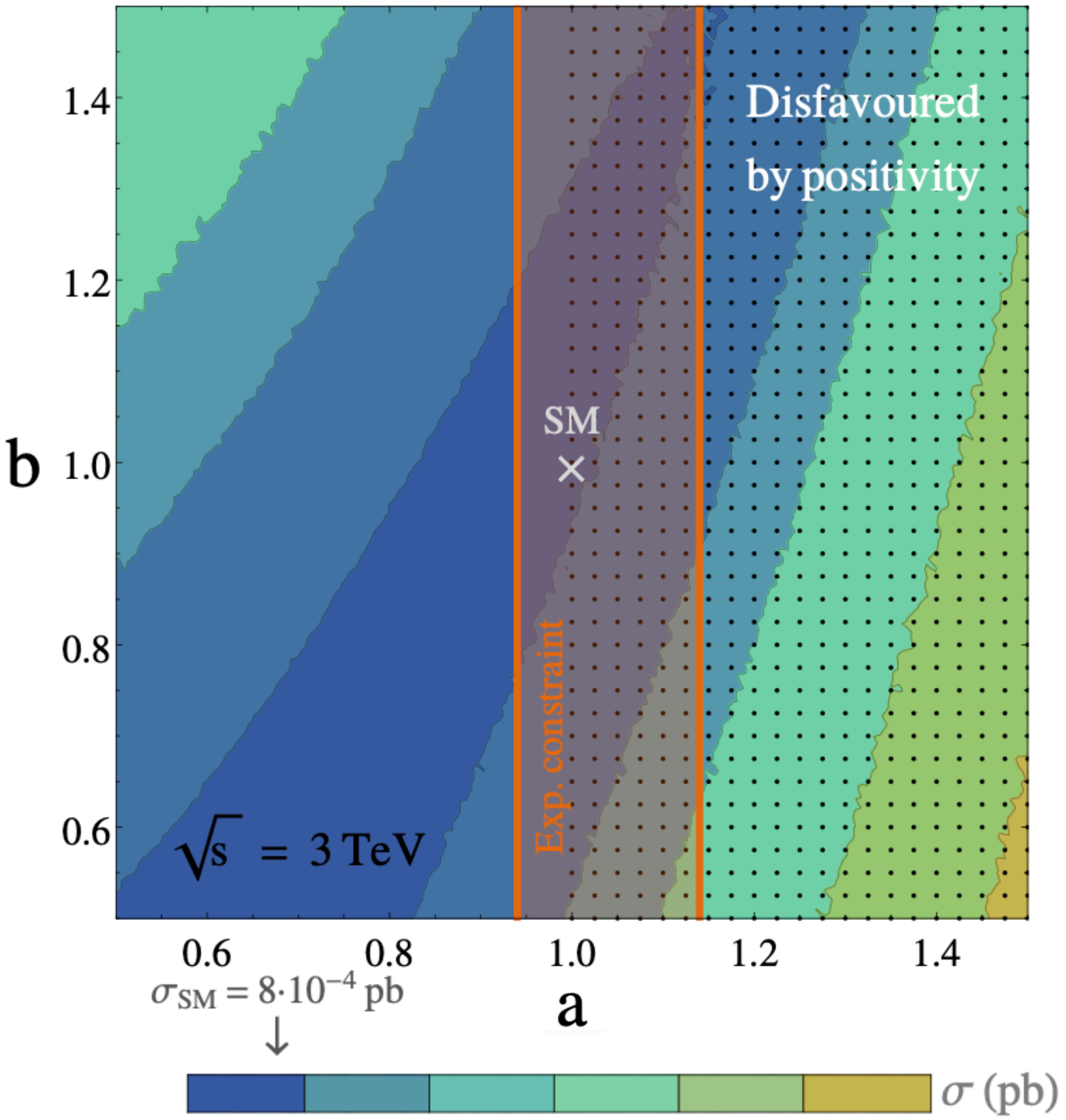



$W^+W^- \to HHH$

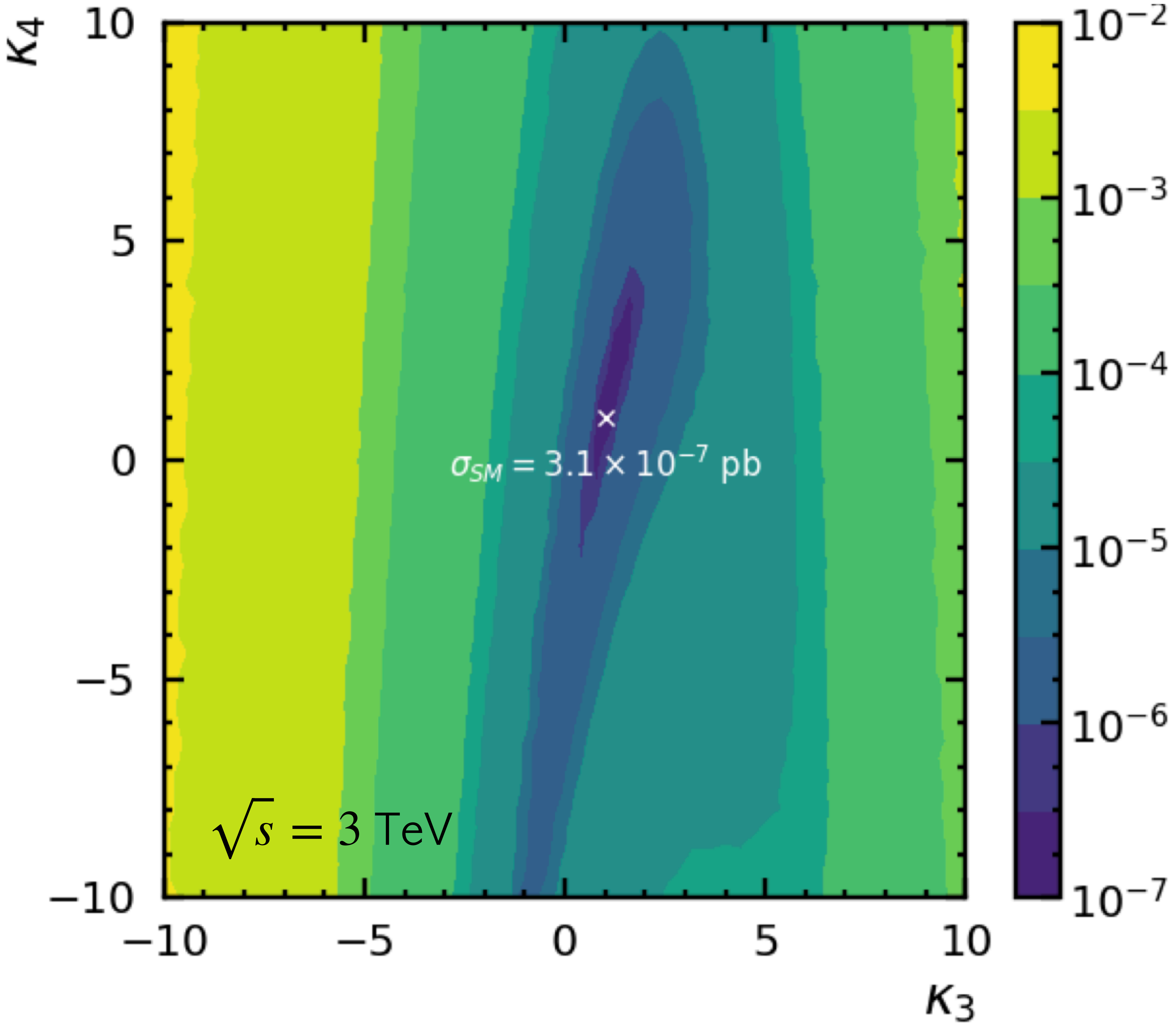


# BSM effects at collider level

$e^+e^- \to HH\bar{\nu}_e\nu_e$




$e^+e^- \to HHH\bar{\nu}_e\nu_e$



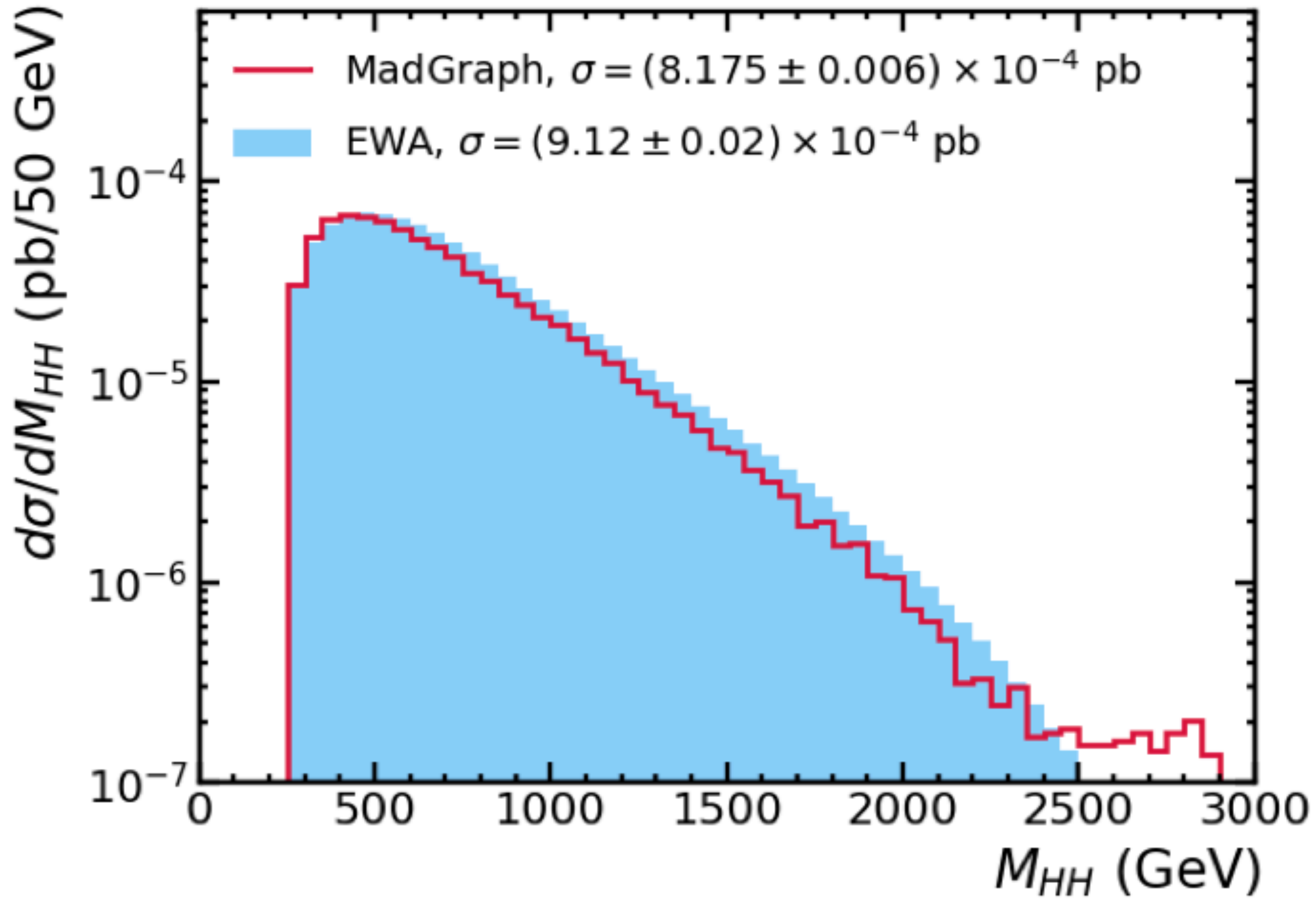

The behavior of the subprocess is inherited due to WWS dominance

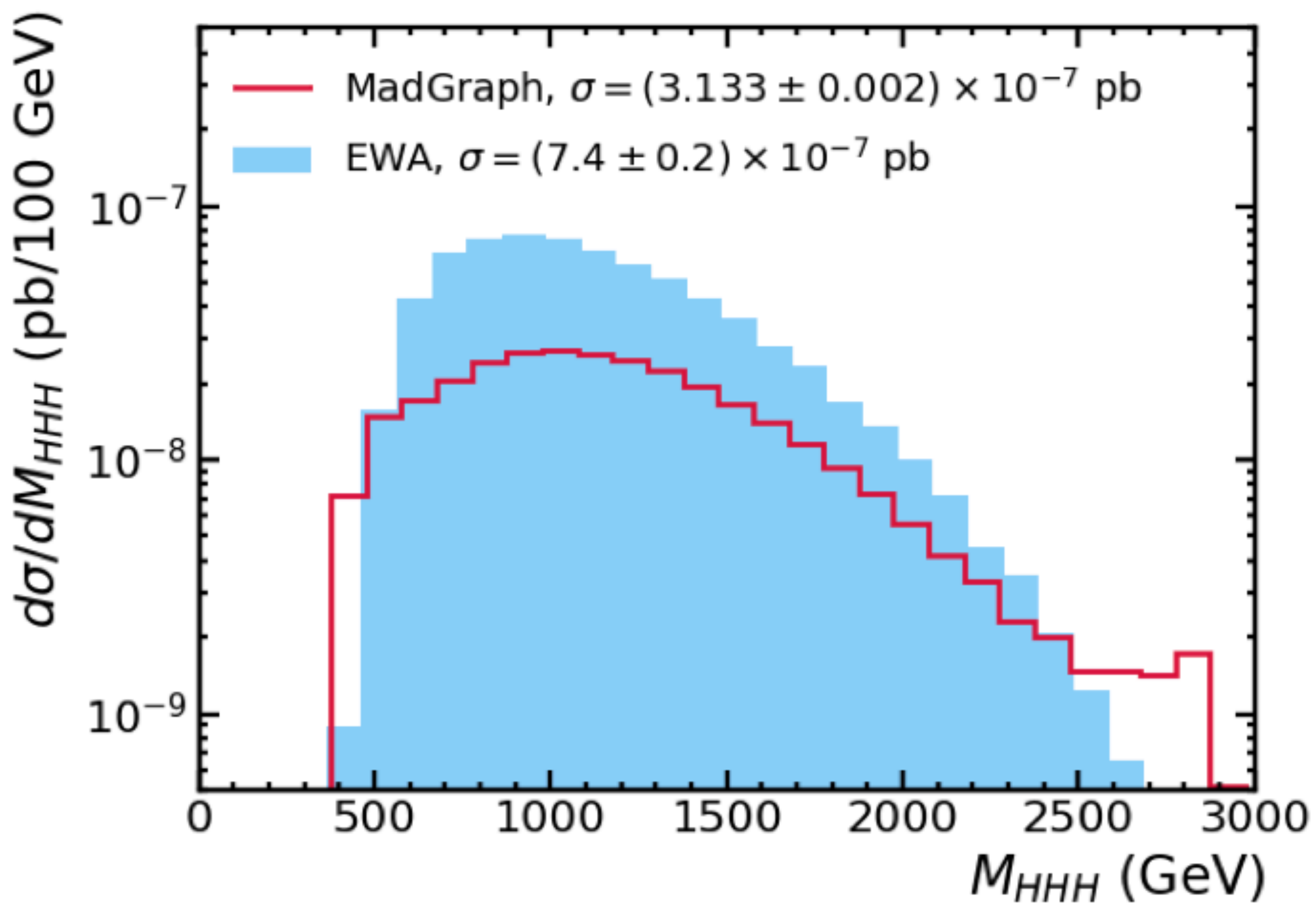
# The effective $W$ approximation

$W$'s are treated as partons inside electrons. Their "PDFs" allow to compute full cross sections from subprocess.[4]

[4]S. Dawson, Nucl. Phys. B **249** (1985)

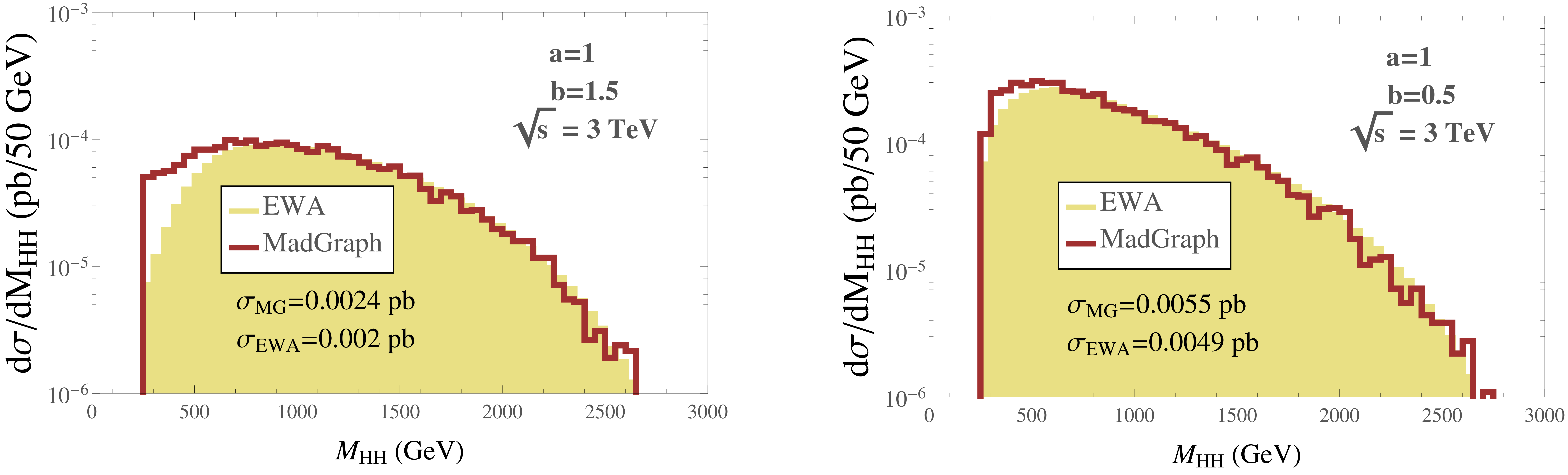
$$\sigma(e^+e^- \to HH\nu\bar{\nu}) = \int dx_1 \int dx_2 f(x_1) f(x_2) \hat{\sigma}(W^+W^- \to HH)$$




Good approximation for HH, not so good for HHH

# The effective $W$ approximation




Even better approach for BSM!

# Final results

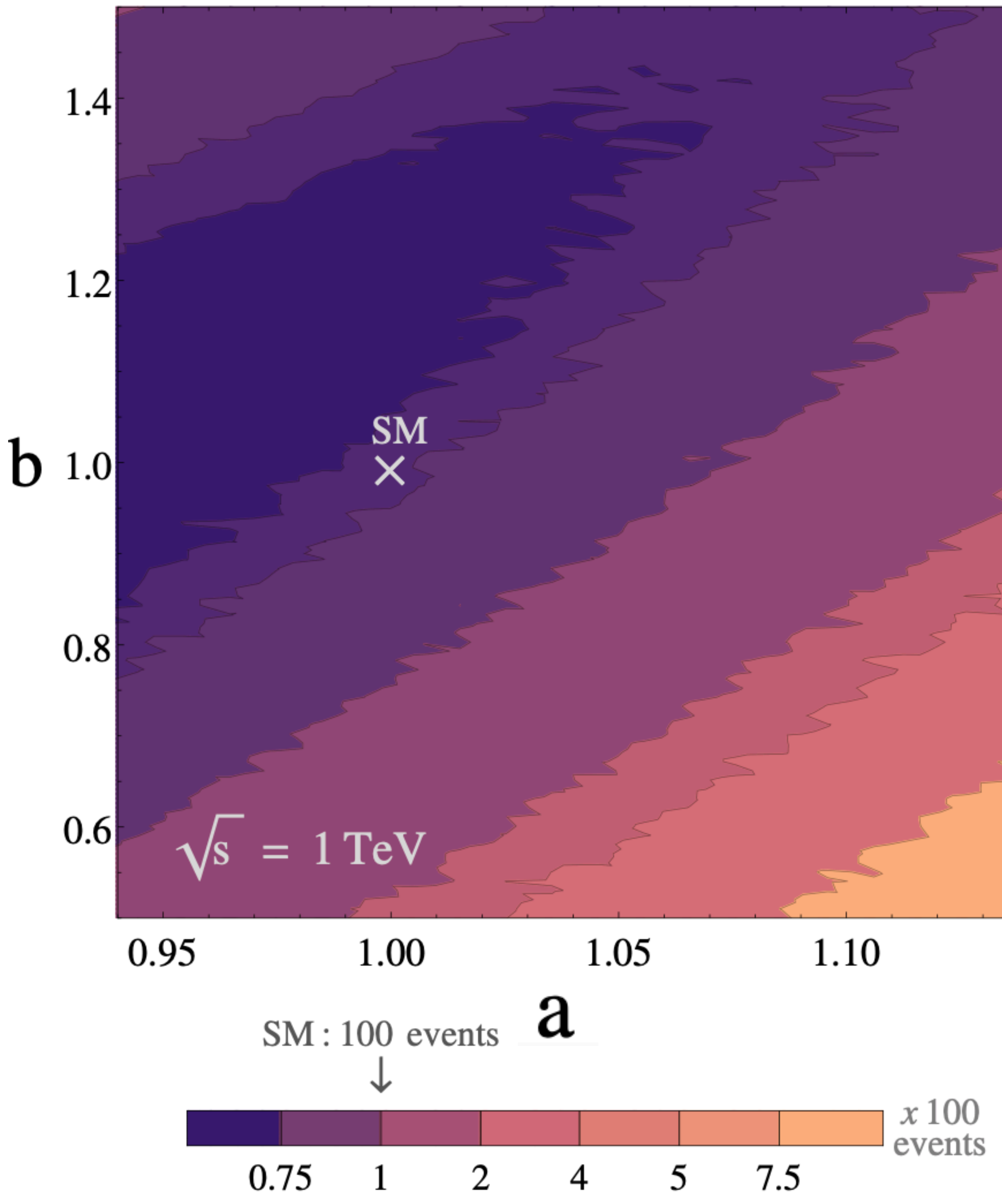
We choose the main Higgs decay channel, $H \to b\bar{b}$. The final states will consist of $b$-jets and missing energy.

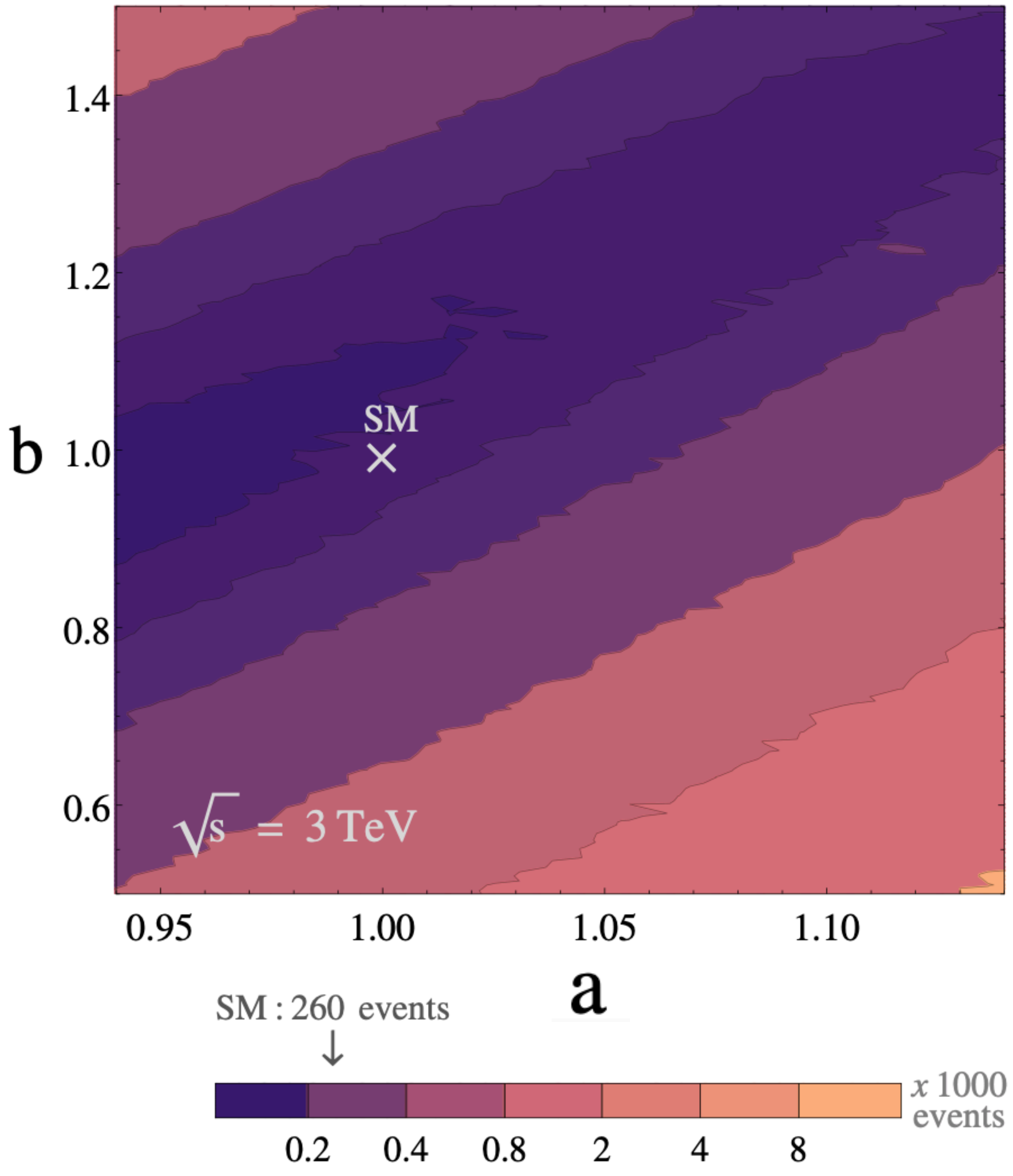
No background simulations are performed. Proper cuts and the presence of neutrinos may reduce backgrounds to negligible levels.

We will focus on the ILC (1 TeV, 8 $ab^{-1}$) and CLIC (3 TeV, 5 $ab^{-1}$).

# Sensitivity to $a$ and $b$

$e^+e^- \to 4b + E_T^{\mathrm{mis}}$



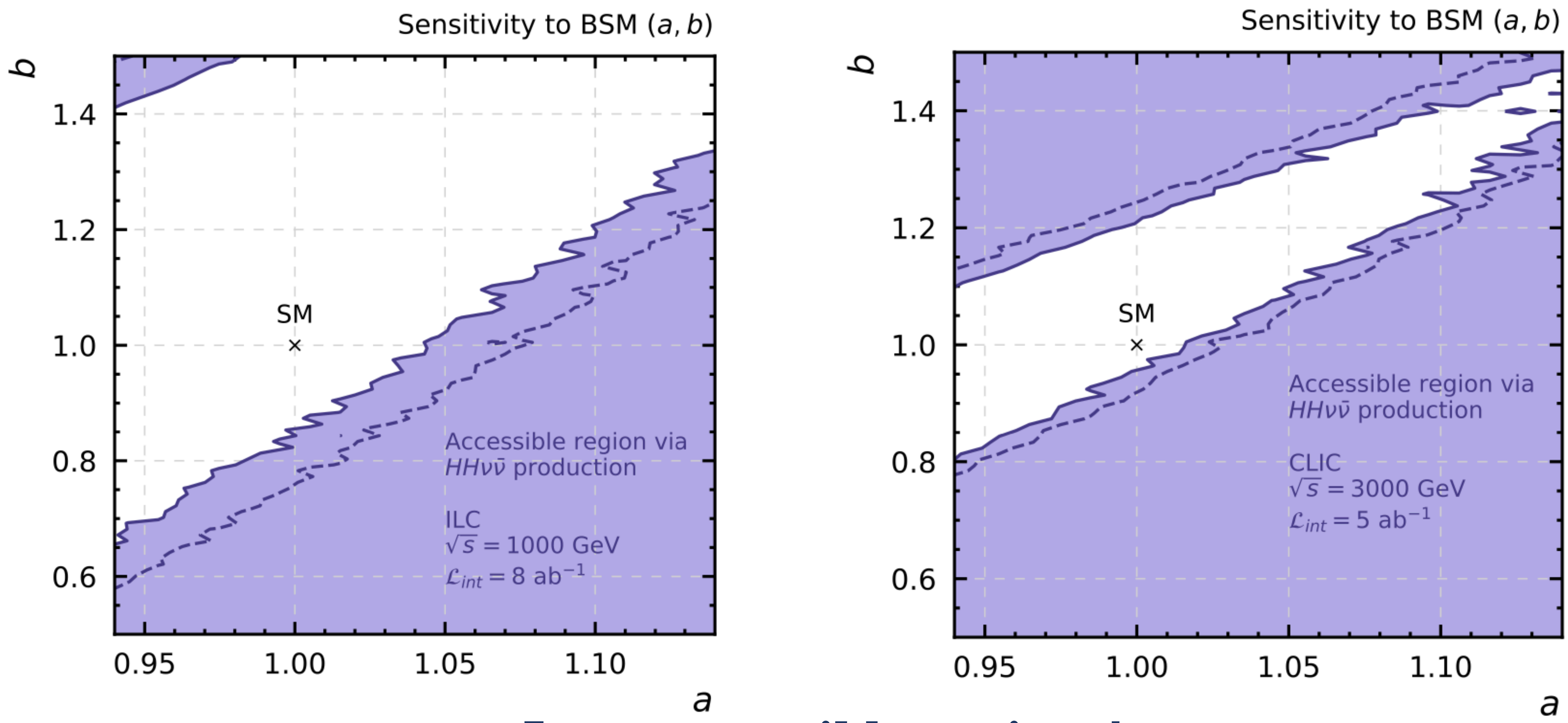

- ✓ $p_T^j > 20$ GeV
- ✓ $|\eta^j| < 2$
- ✓ $\Delta R_{jj} > 0.4$
- ✓ $E_T^{\mathrm{mis}} > 20$ GeV

+

Factor of $\varepsilon^4$, where $\varepsilon = 0.8$ is the $b$-tagging efficiency.

# Sensitivity to $a$ and $b$

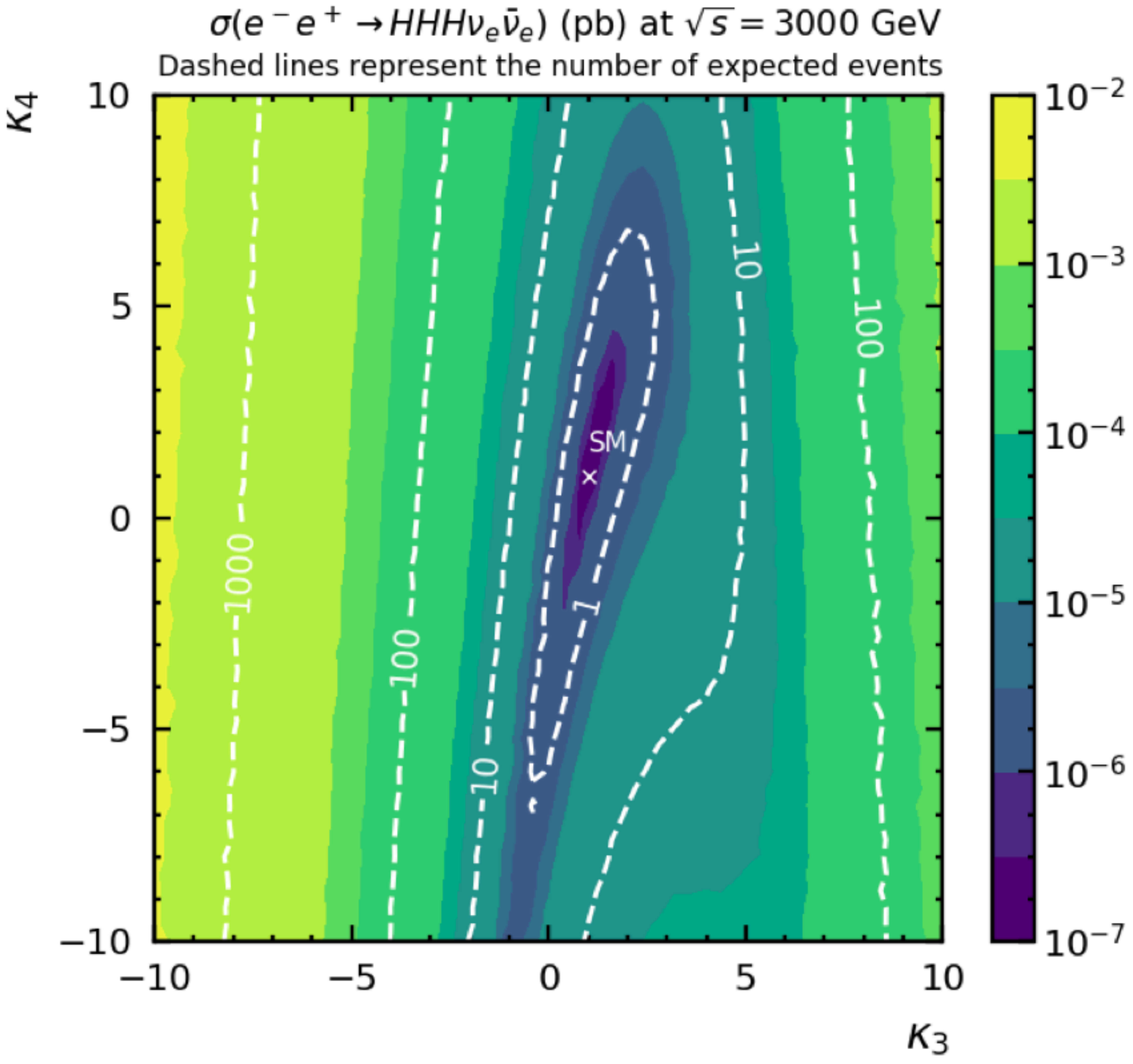
Solid (dashed) lines bound regions with $R < 5\,(10)$, with $R = (N_{\rm BSM} - N_{\rm SM})/\sqrt{N_{\rm SM}}$.




**Large accesible regions!**

# Sensitivity to $\kappa_3$ and $\kappa_4$

$e^+e^- \to 6b + E_T^{\text{mis}}$

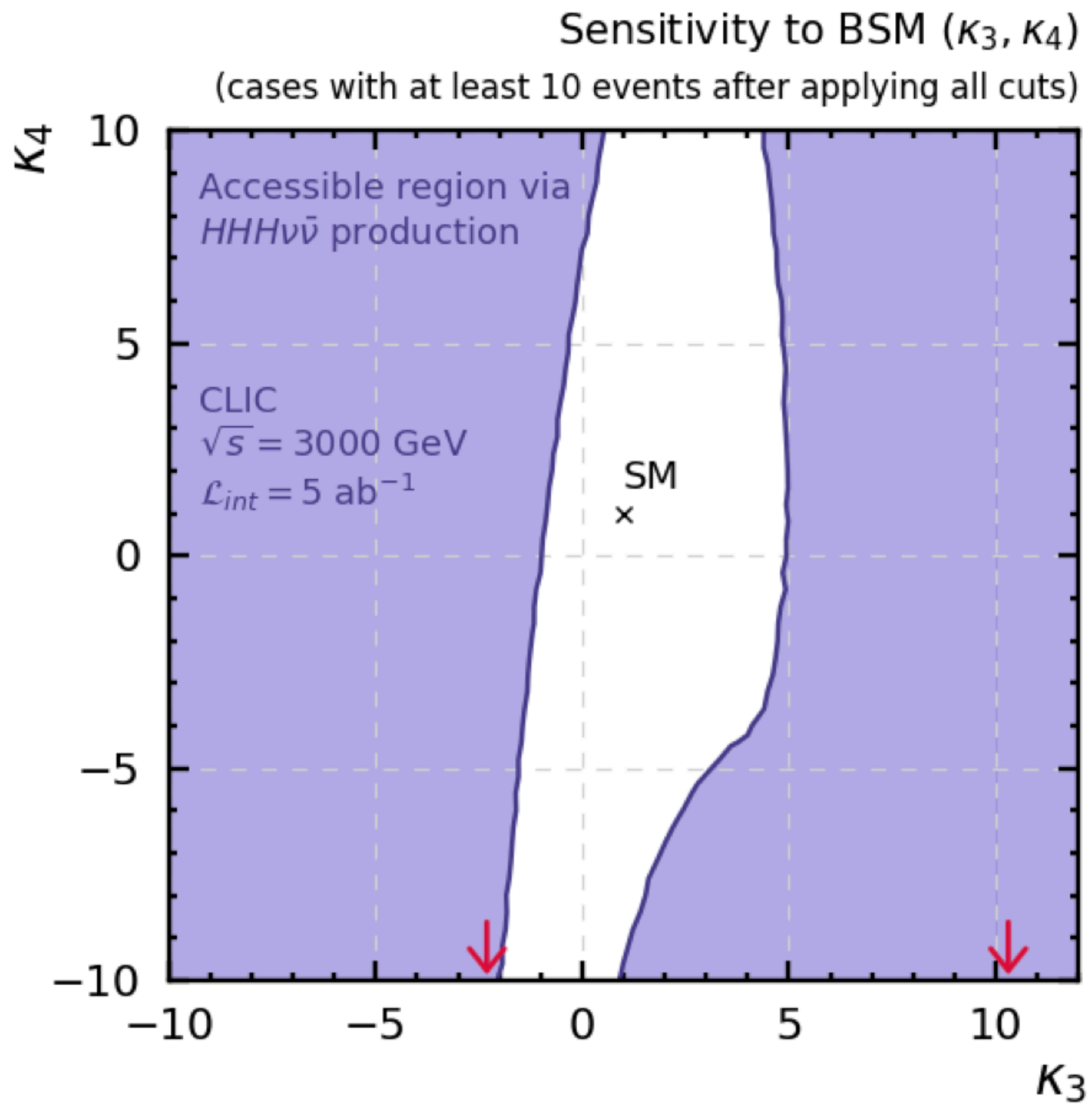



- ✓ $p_T^j > 20$ GeV
- ✓ $N_j \geq 6$
- ✓ $|\eta^j| < 2.72$
- ✓ $E_T^{\text{mis}} > 20$ GeV

Requiring at least 5 $b$-tagged jets: $\varepsilon_5 = 6 \times \varepsilon^5/5 + \varepsilon^6$

# Sensitivity to $\kappa_3$ and $\kappa_4$

10 events required for accessibility




**Very interesting sensitivity to the quartic Higgs-coupling!**

# Summary

- ✓ BSM physics could lead to deviations in Higgs couplings to W's and to itself.
- ✓ The EChL is an EFT which encodes these effects in the anomalous couplings.
- ✓ $e^+e^-$ colliders show promising prospects to improve sensitivity to anomalous couplings.
- ✓ Interestingly, CLIC could access to the Higgs quartic coupling, so far untested experimentally.

thank you!