Theory opportunities at future colliders

Anke Biekötter - JGU Mainz

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

Unterstützt von / Supported by

Alexander von Humboldt Stiftung / Foundation

Future Colliders for Early-Career Researchers - CERN - 27 September 2023

Theory wishlist

- Dark matter candidate
- Explanation of flavor hierarchy
- Explanation of matter-antimatter asymmetry
- Solution to strong CP problem (axion)
- Explanation of fine-tuning problems

Theory wishlist

- Dark matter candidate
- Explanation of flavor hierarchy
- Explanation of matter-antimatter asymmetry
- Solution to strong CP problem (axion)
- Explanation of fine-tuning problems

More modest expectations

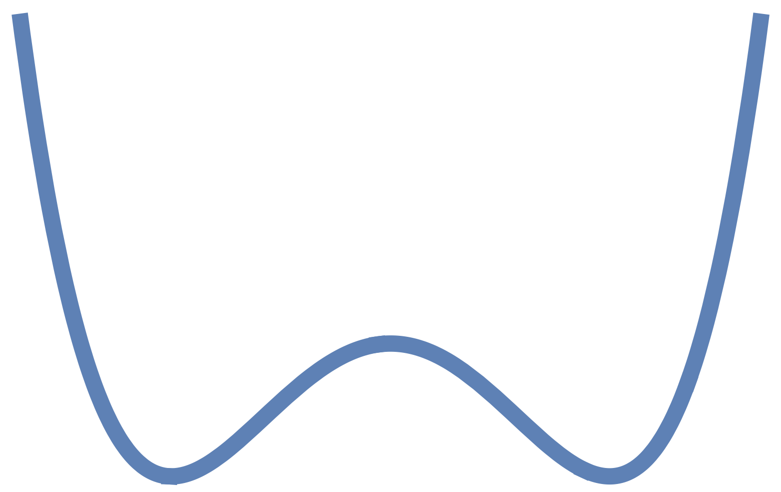
"No-lose theorem" - guaranteed deliverables

Unbiased exploration potential

Focus on EW+Higgs

Higgs physics

What we know



$$V = -\mu^2 \, |\phi|^2 + \lambda \, |\phi|^4$$

Higgs physics

What we actually know

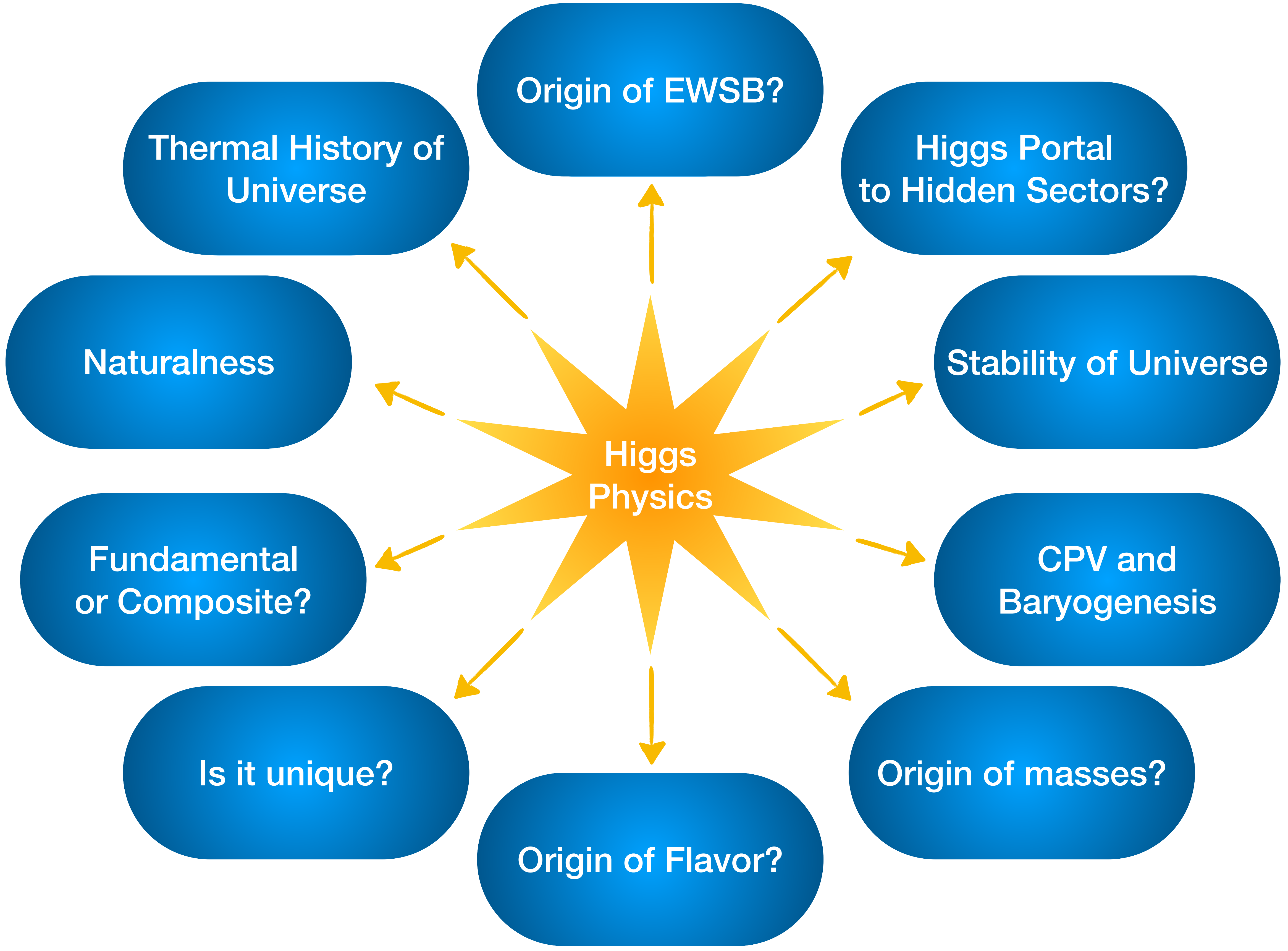
$$V = -\mu^2 \, |\phi|^2 + \lambda \, |\phi|^4$$

Higgs physics

What we actually know

$$V = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

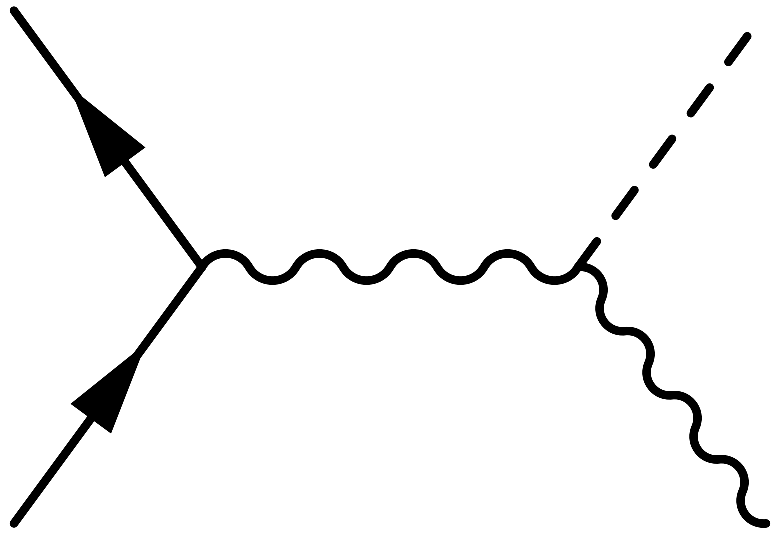
Good reasons to believe that the Higgs is related to BSM physics

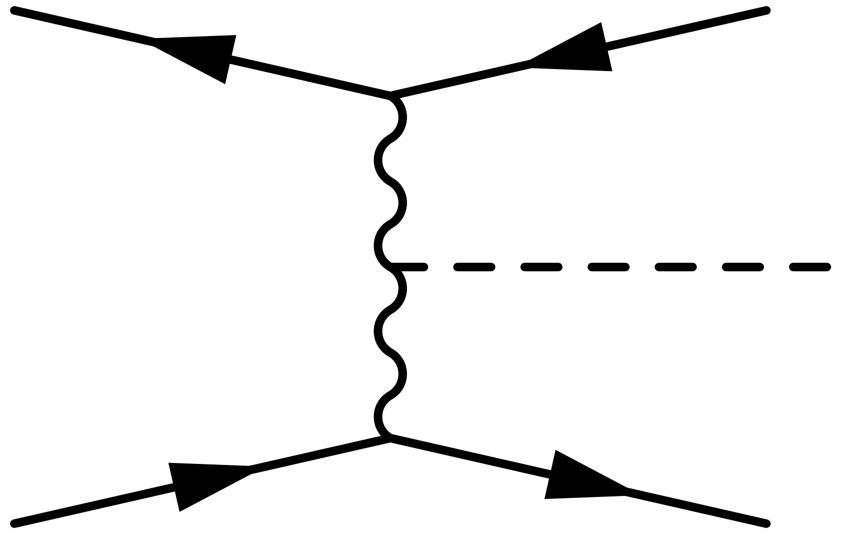


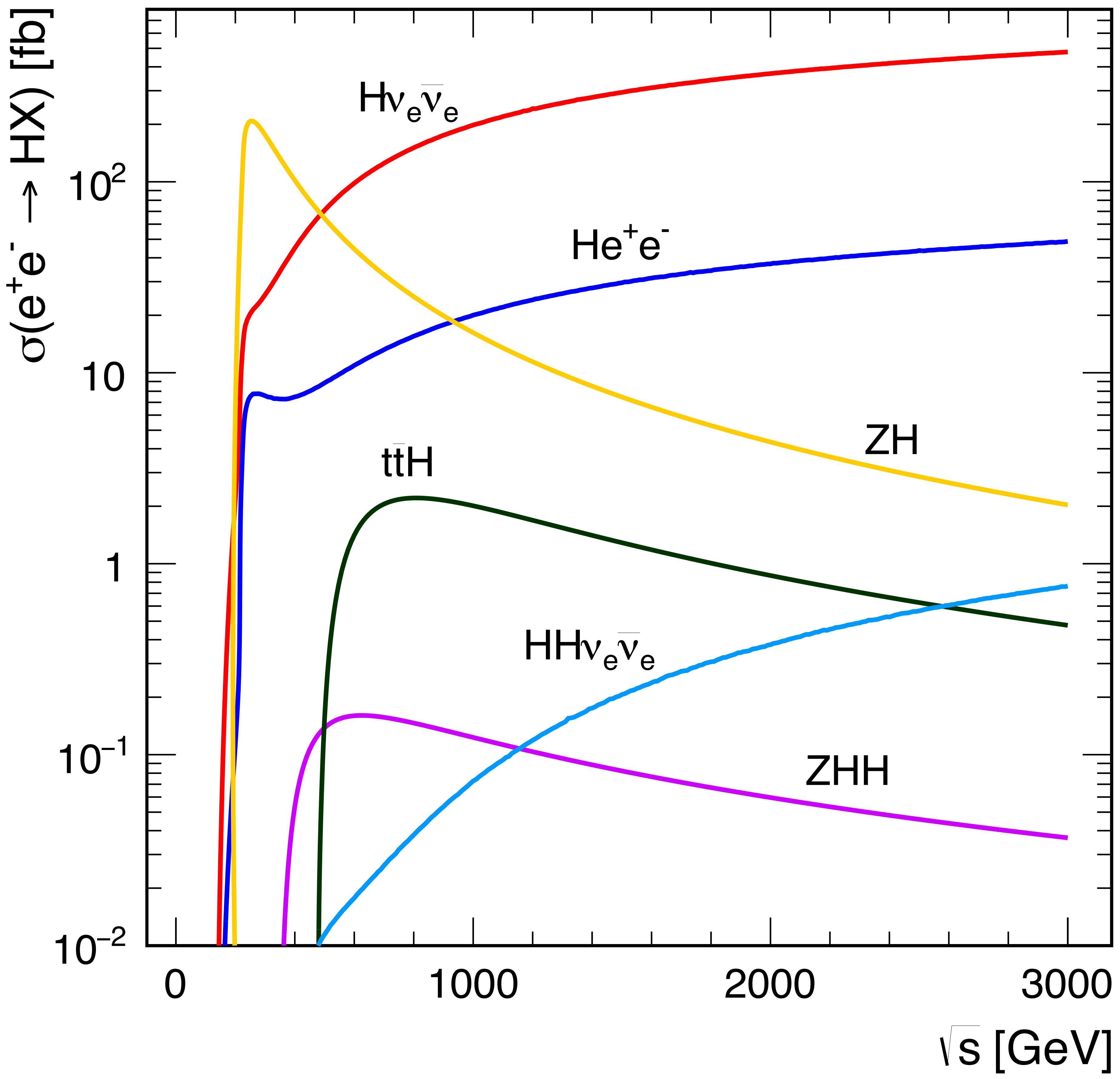
[Dawson et al. (2209.07510)]

Higgs physics at e+e- colliders

[CLIC (1608.07537)]



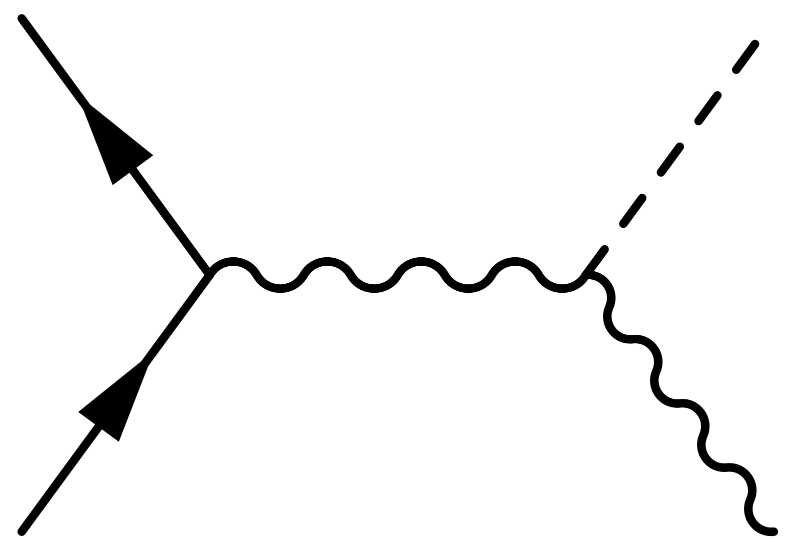


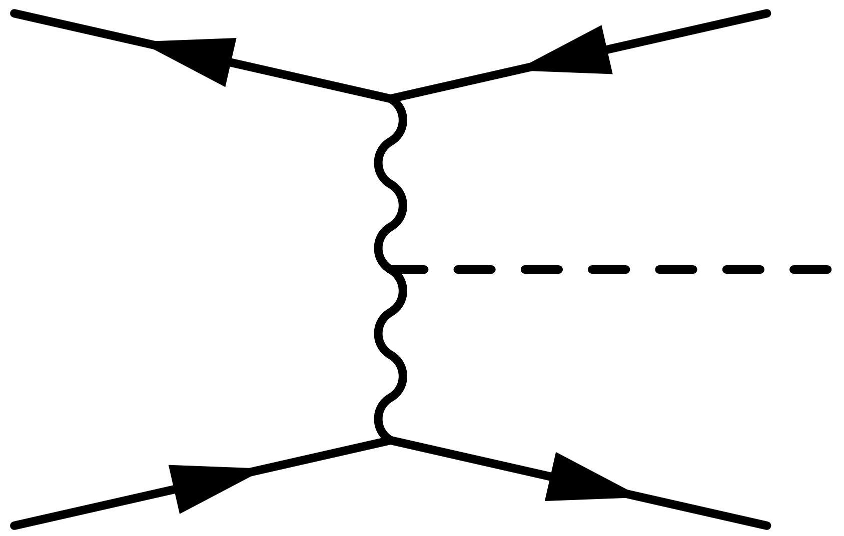


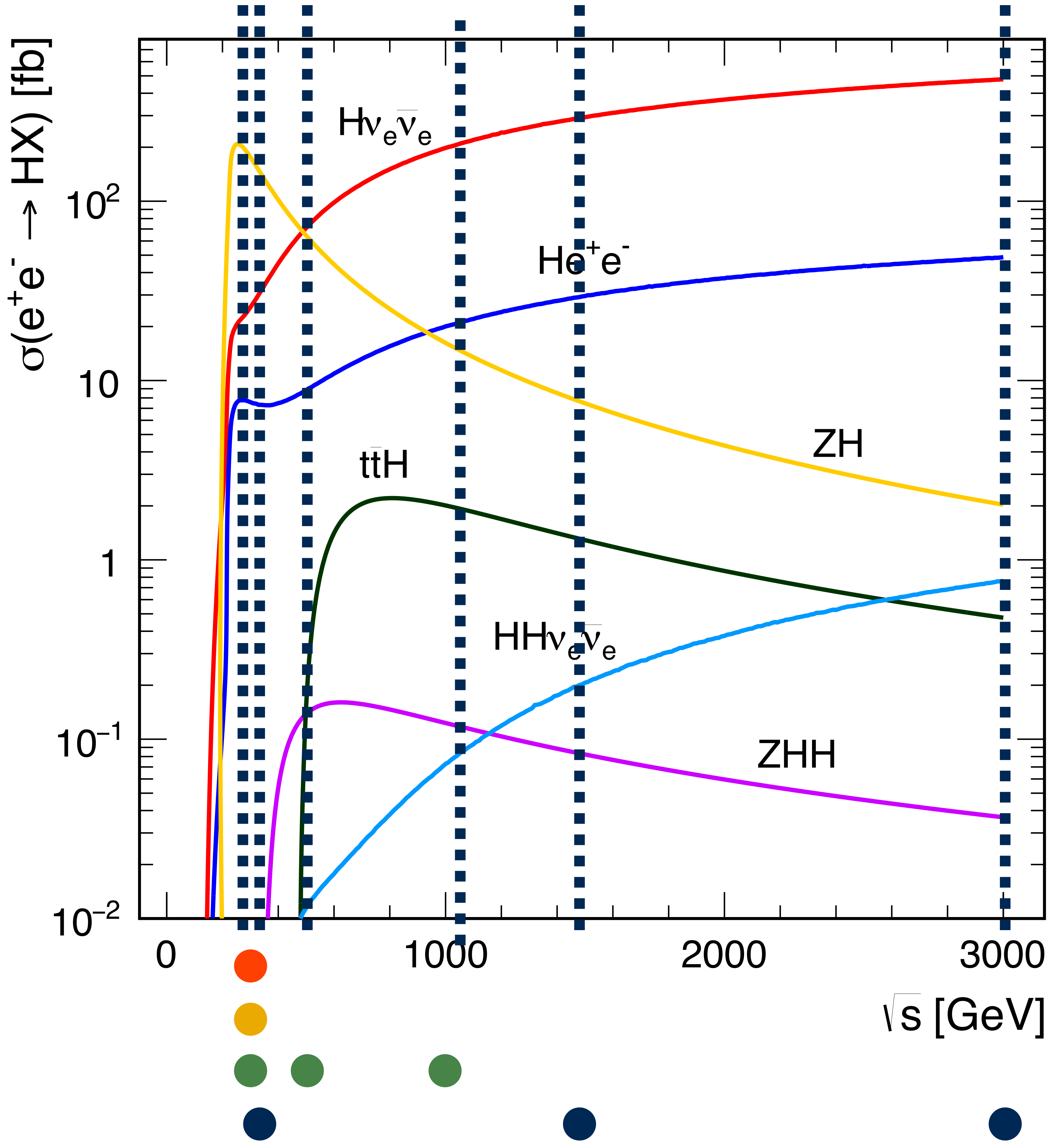
- CEPC
- FCC
- ilc
- CLIC

Higgs physics at e+e- colliders

[CLIC (1608.07537)]



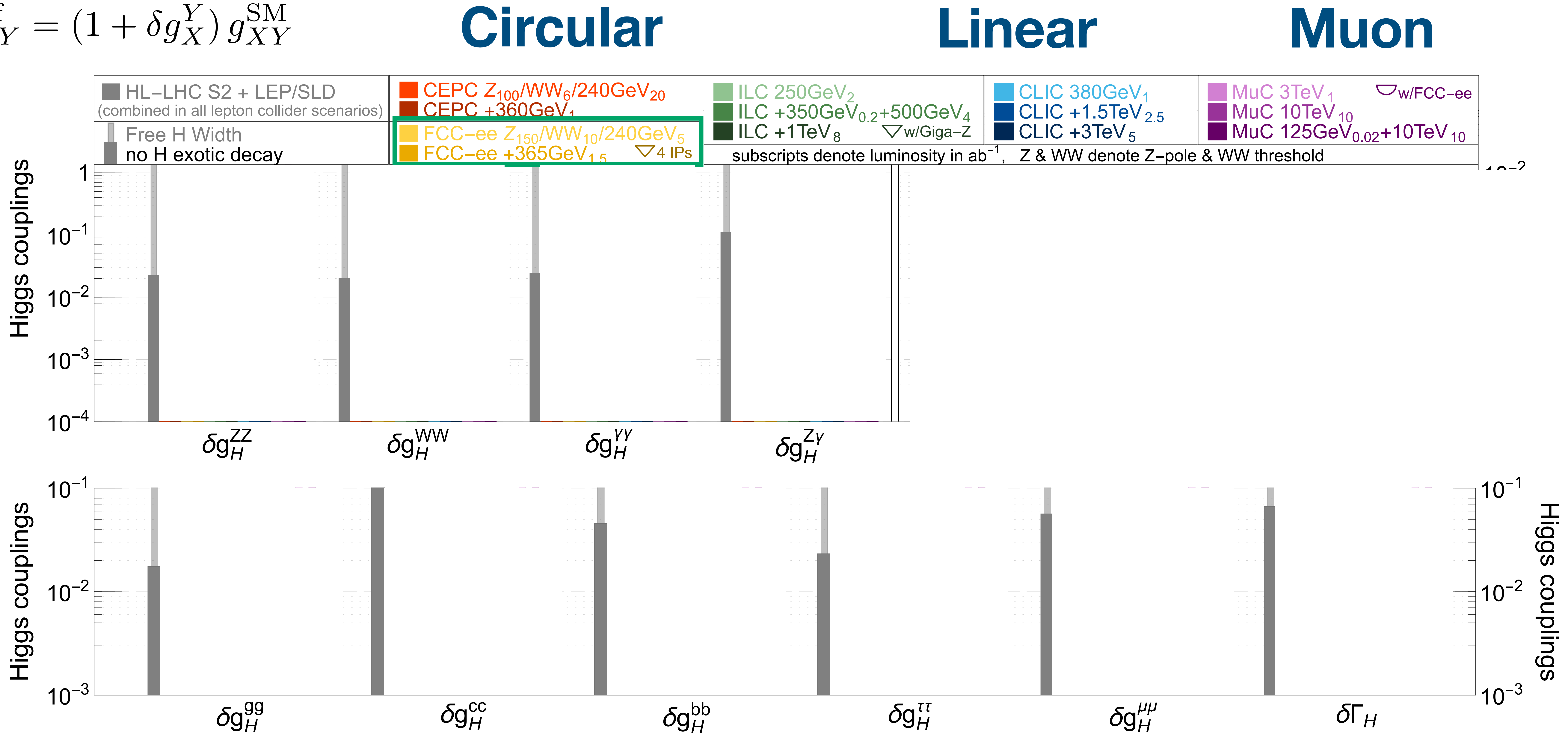




Precision: Higgs

[de Blas et al. (1907.04311)]
[de Blas et al. (2206.08326)]

$$g_{XY}^{\text{eff}} = (1 + \delta g_X^Y)\, g_{XY}^{\text{SM}}$$



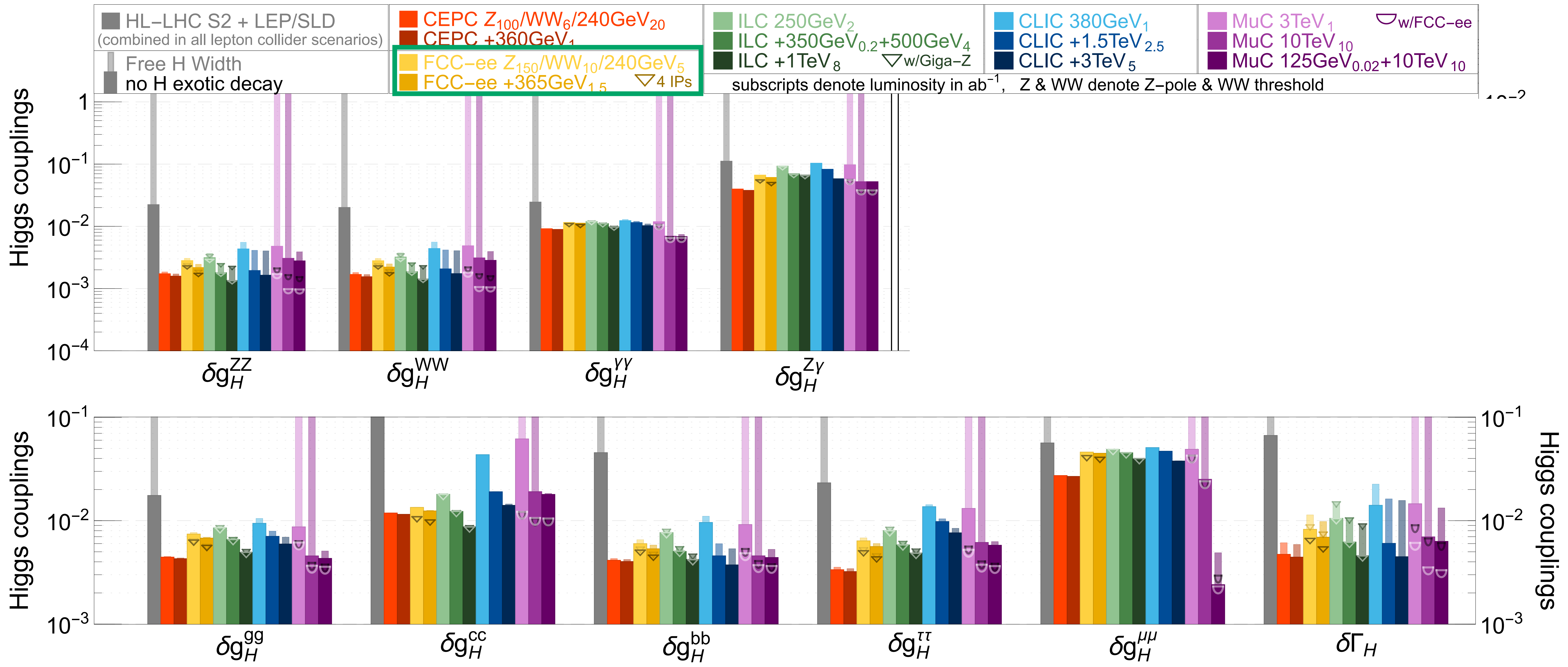
Higgs width -> sensitivity to exotic decays

Precision: Higgs

[de Blas et al. (1907.04311)]
[de Blas et al. (2206.08326)]

$$g_{XY}^{\text{eff}} = (1 + \delta g_X^Y)\, g_{XY}^{\text{SM}}$$

Circular
Linear
Muon



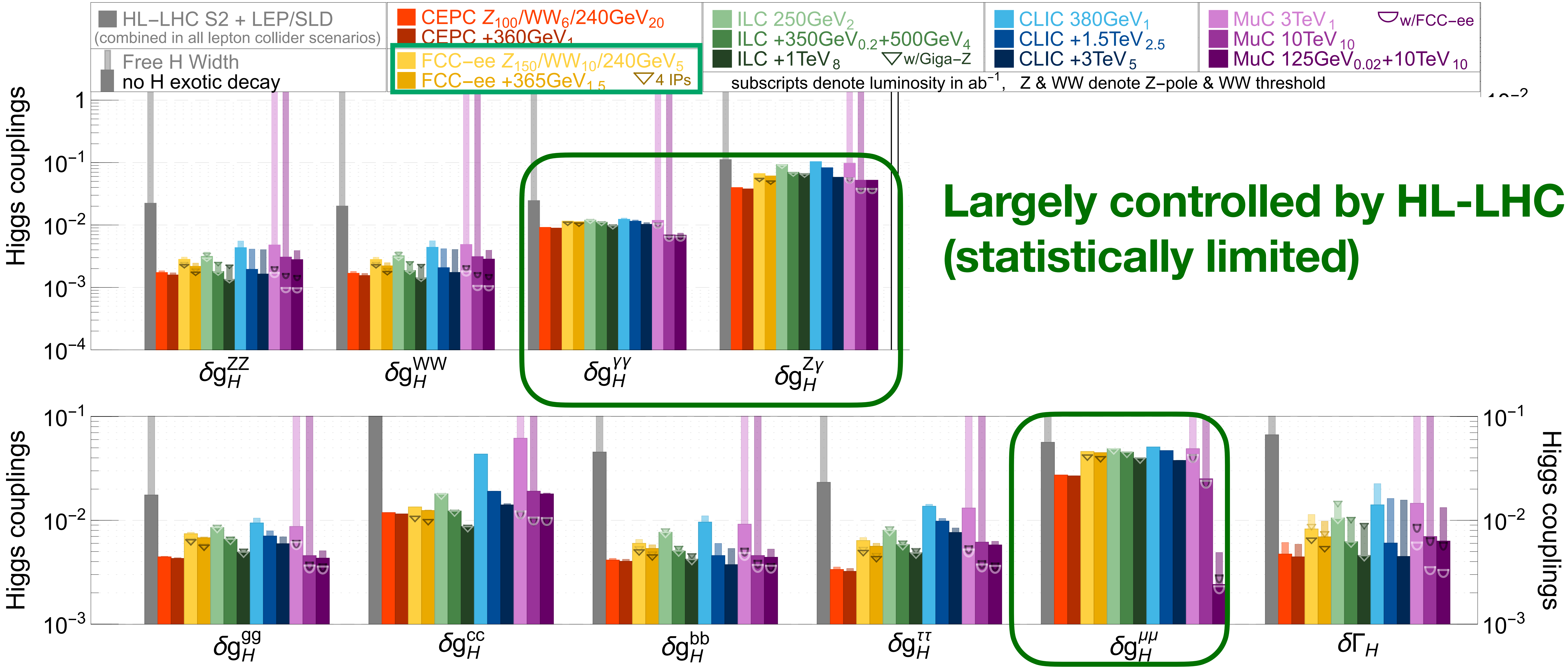
Higgs width -> sensitivity to exotic decays

Precision: Higgs

[de Blas et al. (1907.04311)]
[de Blas et al. (2206.08326)]

$$g_{XY}^{\text{eff}} = (1 + \delta g_X^Y)\, g_{XY}^{\text{SM}}$$

Circular **Linear** **Muon**



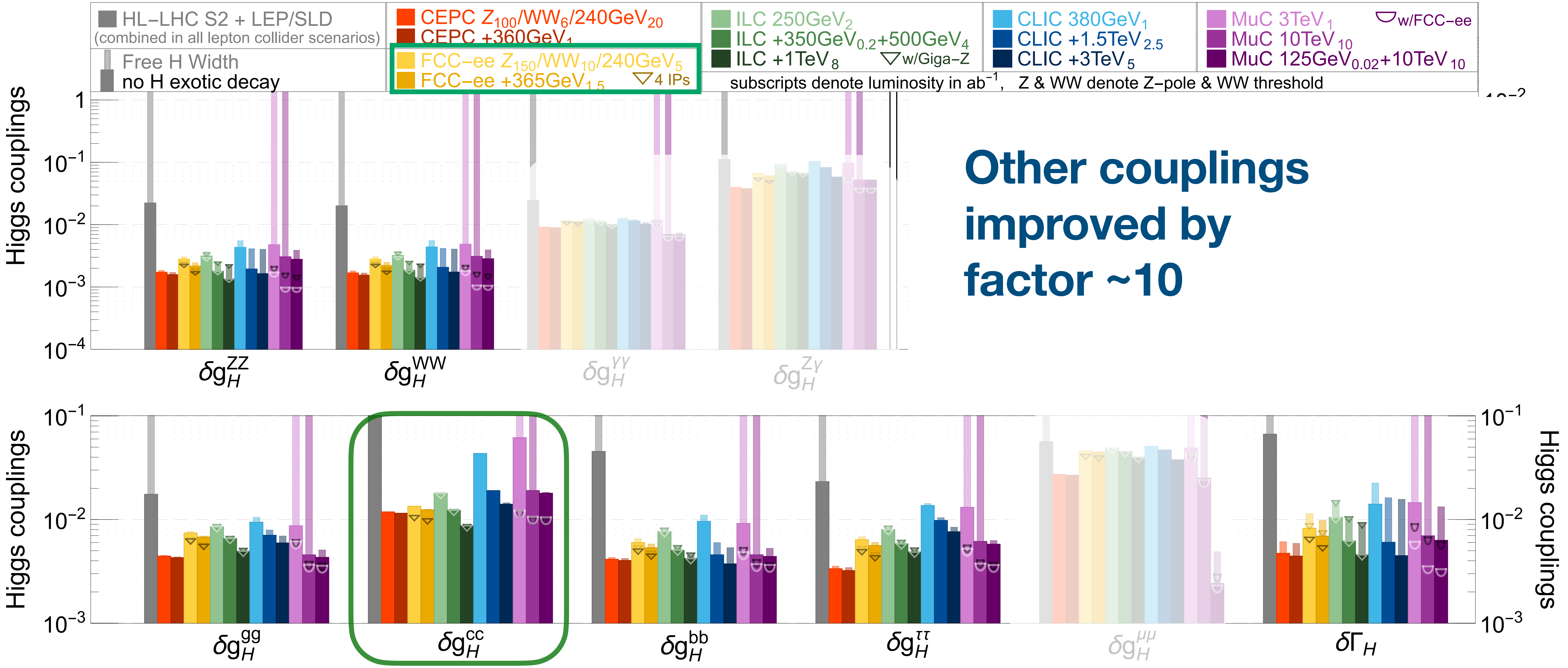
Largely controlled by HL-LHC (statistically limited)

Higgs width -> sensitivity to exotic decays

Precision: Higgs

[de Blas et al. (1907.04311)]
[de Blas et al. (2206.08326)]

$$g_{XY}^{\text{eff}} = (1 + \delta g_X^Y)\, g_{XY}^{\text{SM}}$$



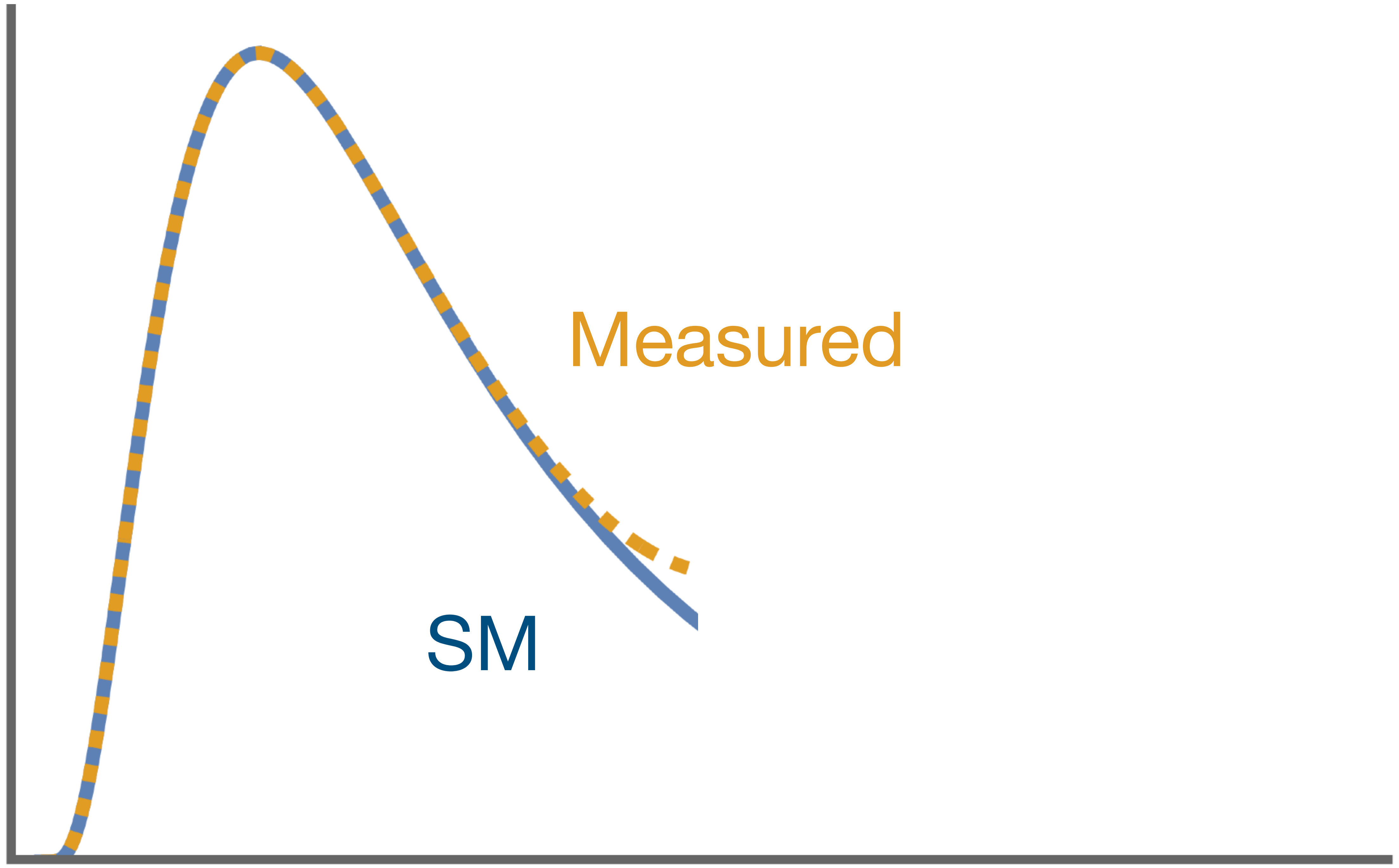
Other couplings improved by factor ~10

Access to 2nd gen quarks

Higgs width -> sensitivity to exotic decays

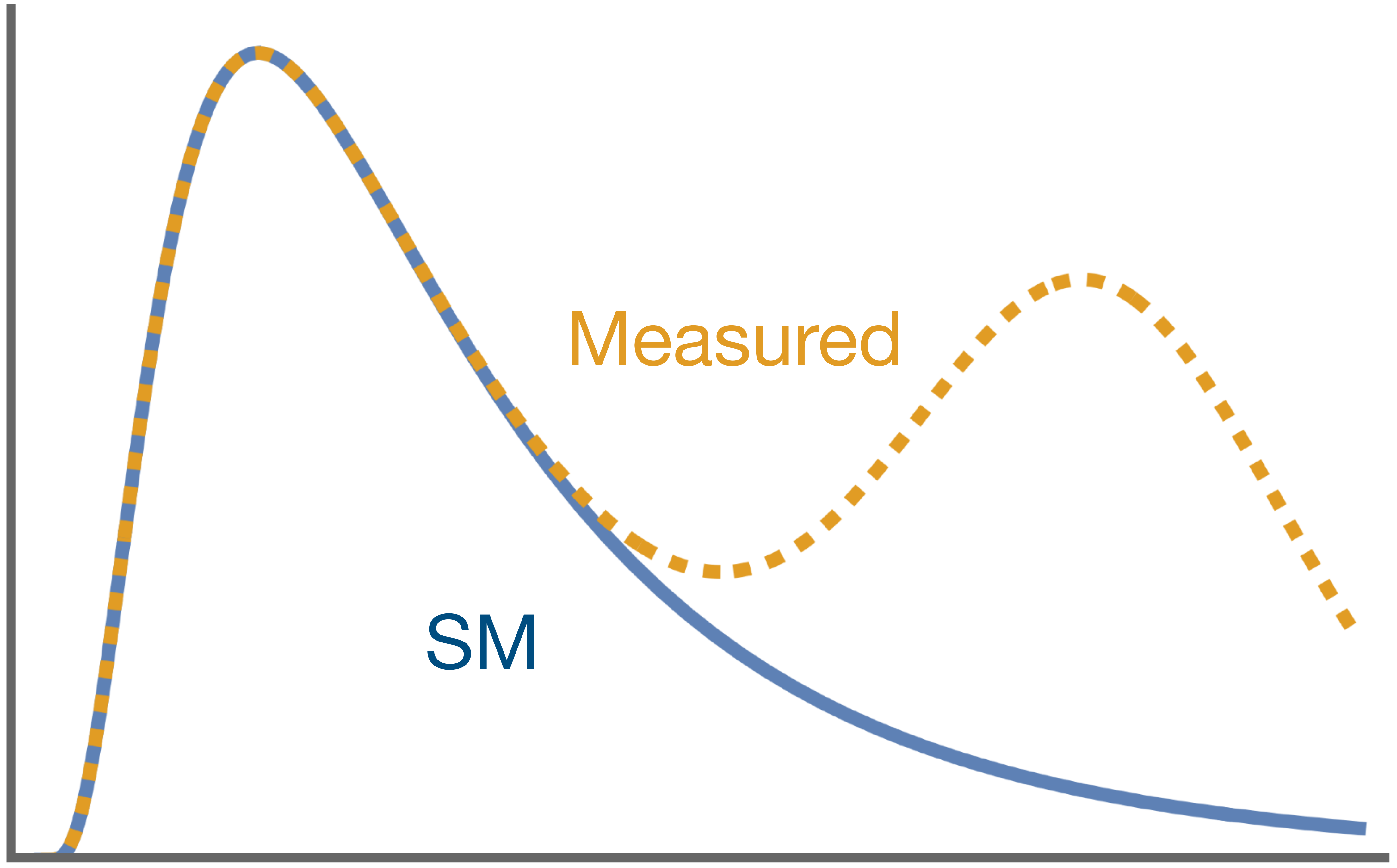
Precision → Exploration

Deviations from SM predictions at low energies could be an indirect hint of new physics at higher energy scales



Precision → Exploration

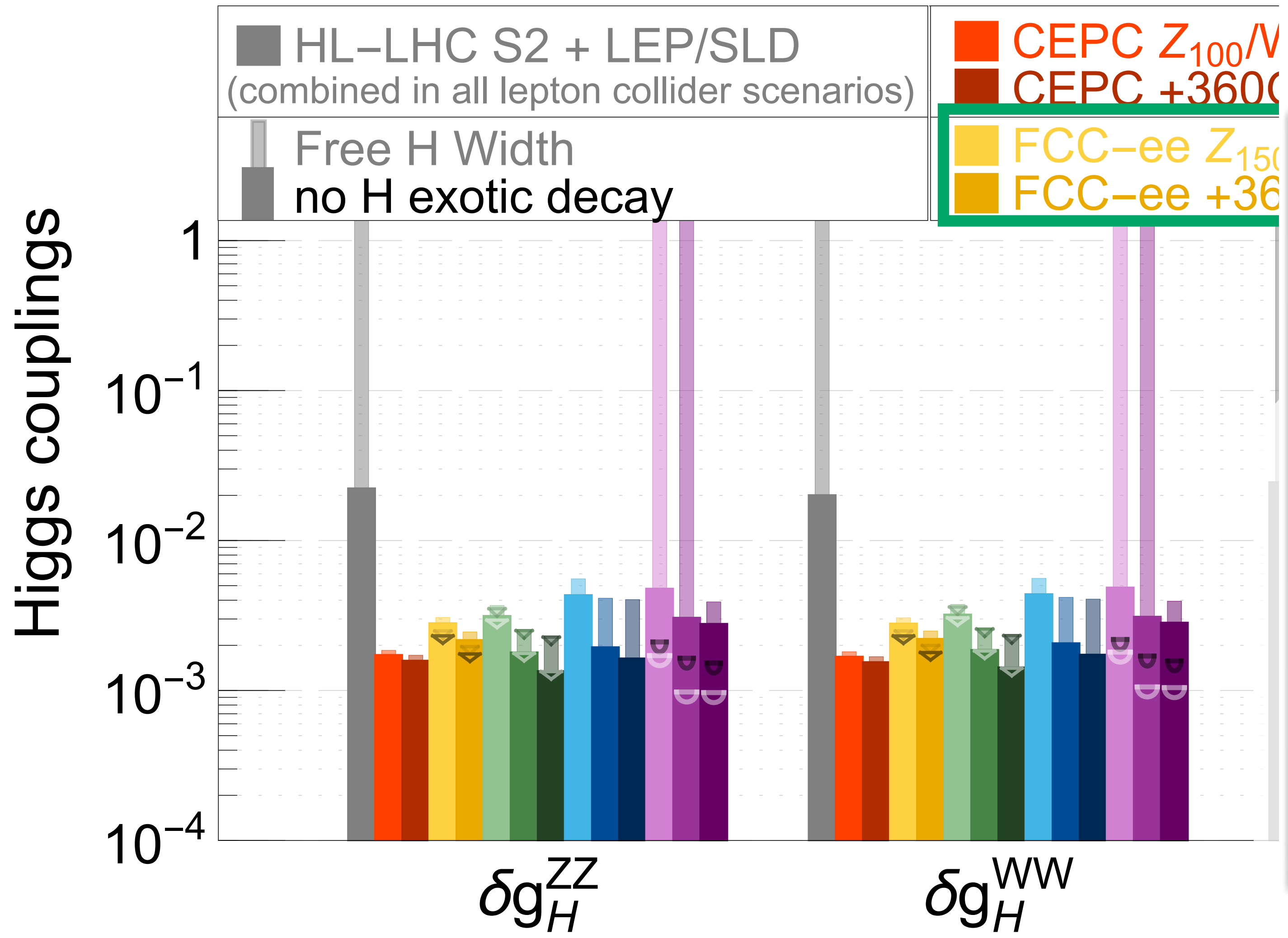
Deviations from SM predictions at low energies could be an indirect hint of new physics at higher energy scales



Precision: Higgs

[de Blas et al. (1907.04311)]
[de Blas et al. (2206.08326)]

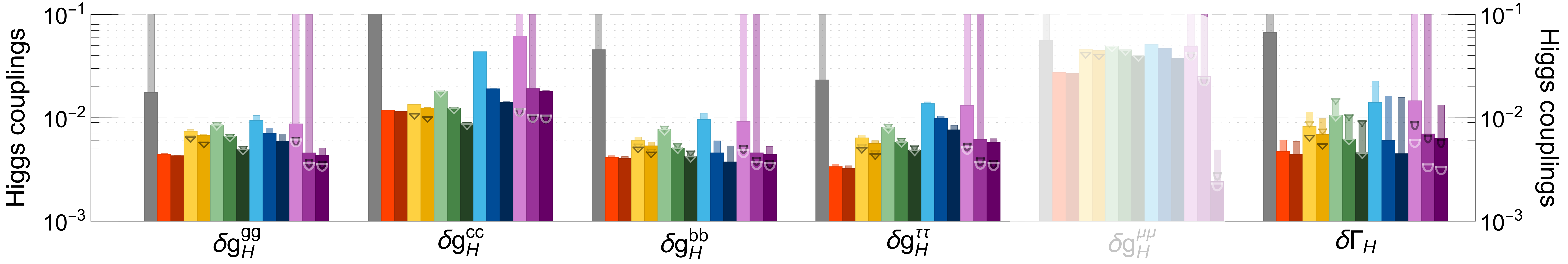
$$g_{XY}^{\text{eff}} = (1 + \delta g_X^Y)\, g_{XY}^{\text{SM}}$$



(Sub)percent level accuracy needed to test BSM scenarios

[Dawson et al. (1310.8361)]

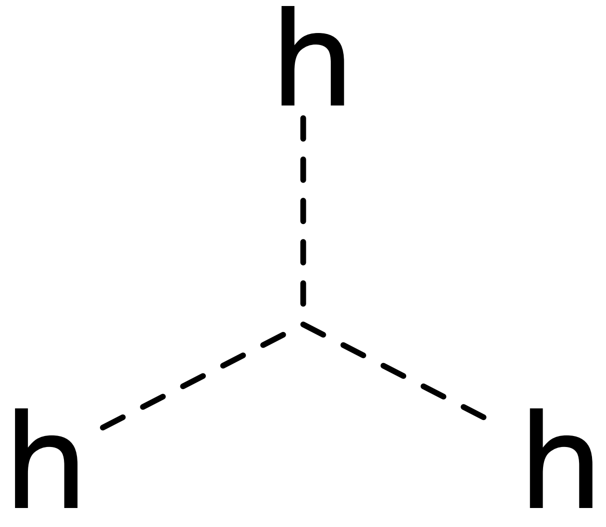
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$



Access to 2nd gen quarks

Higgs width -> sensitivity to exotic decays

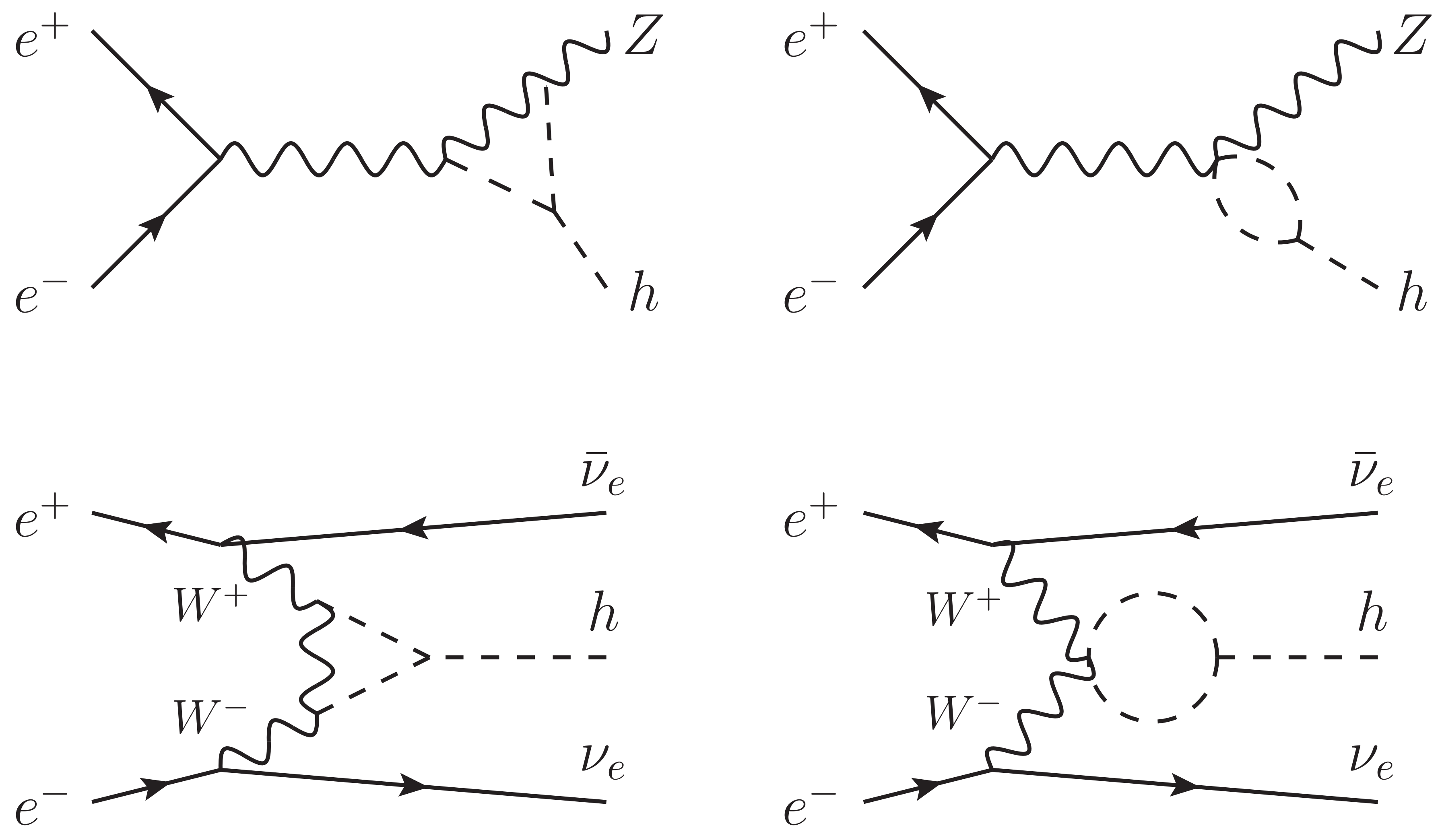
Higgs self-coupling

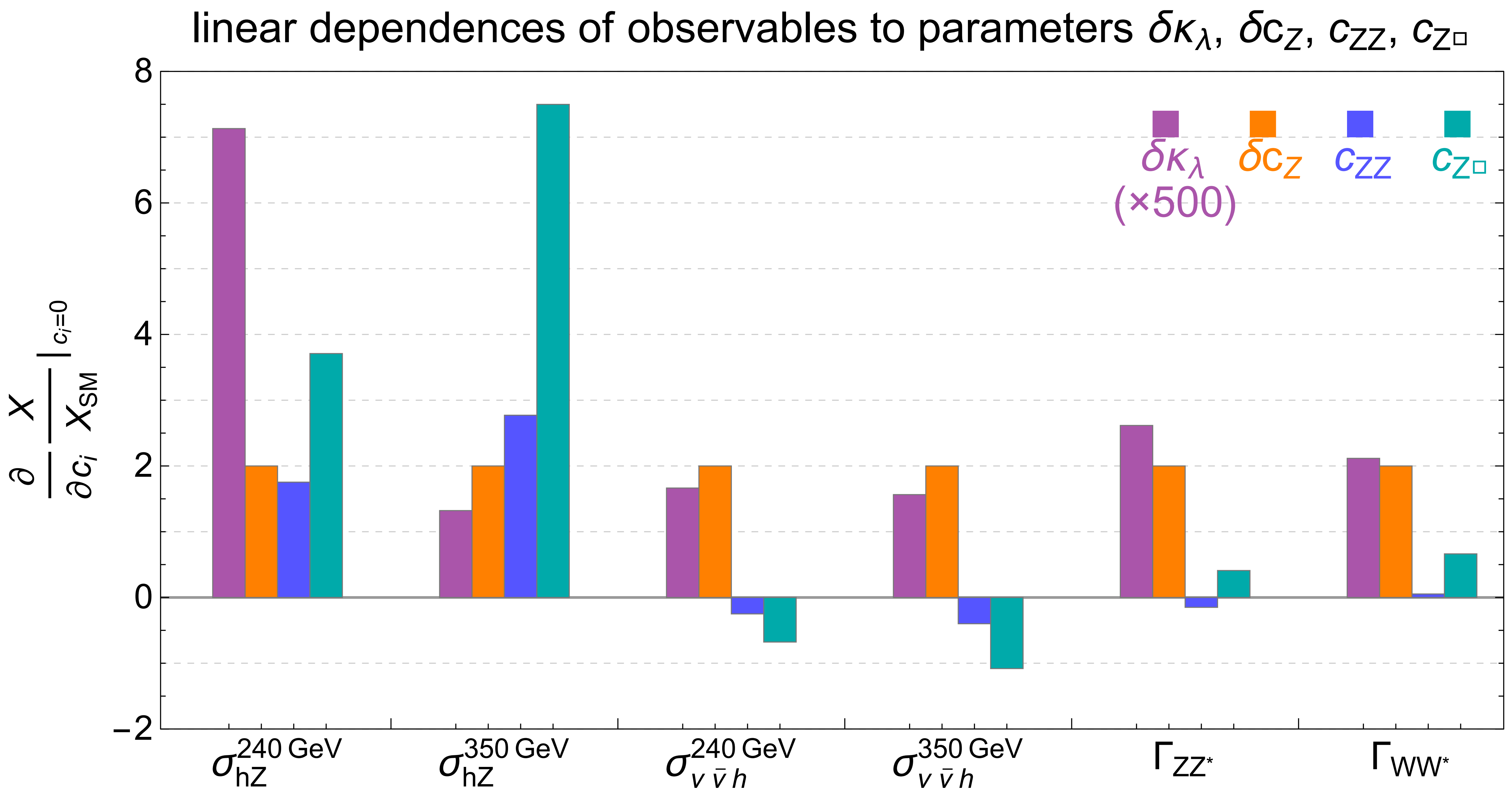


[McCullough (1312.3322)]
[Di Vita et al. (1711.03978)]

$$V = -\mu^2 \, |\phi|^2 + \lambda \, |\phi|^4$$

From single-Higgs

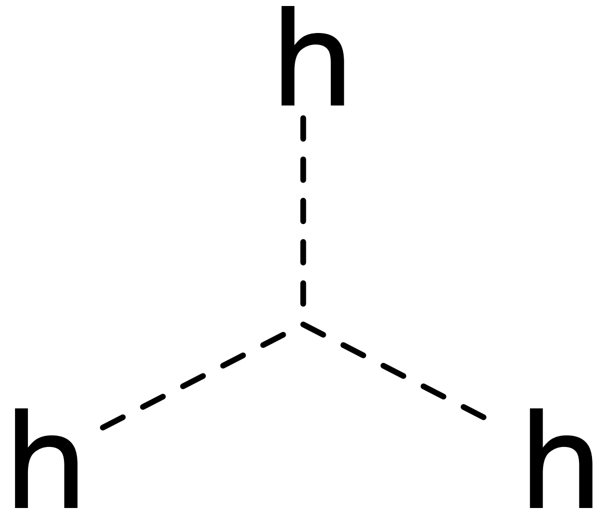




Two runs needed for good sensitivity to κ_λ

CEPC FCC

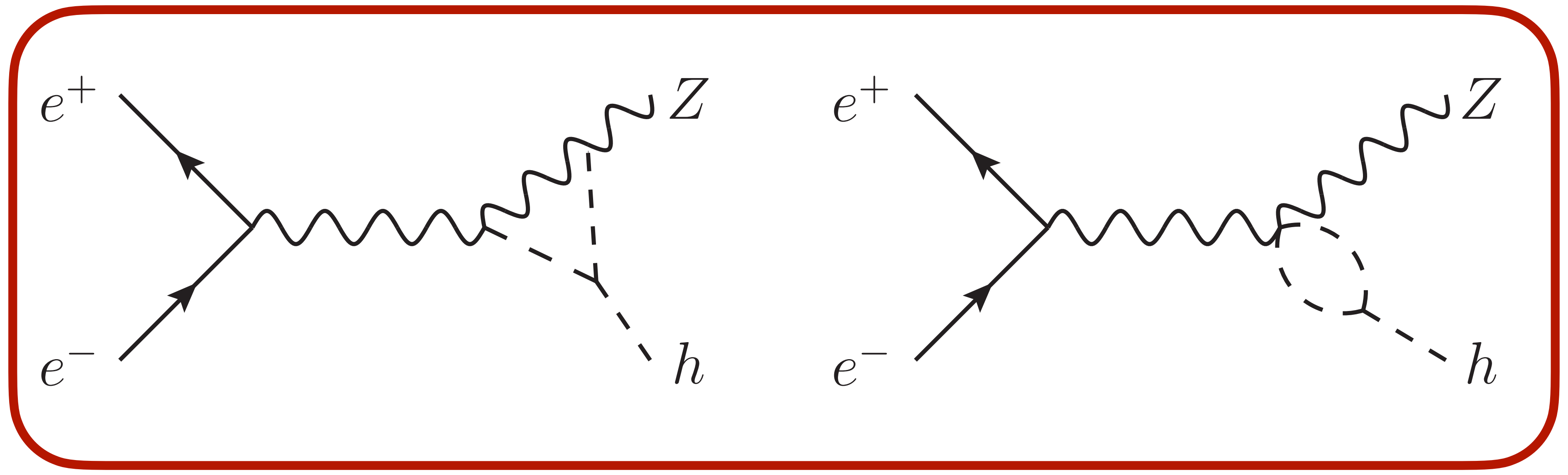
Higgs self-coupling

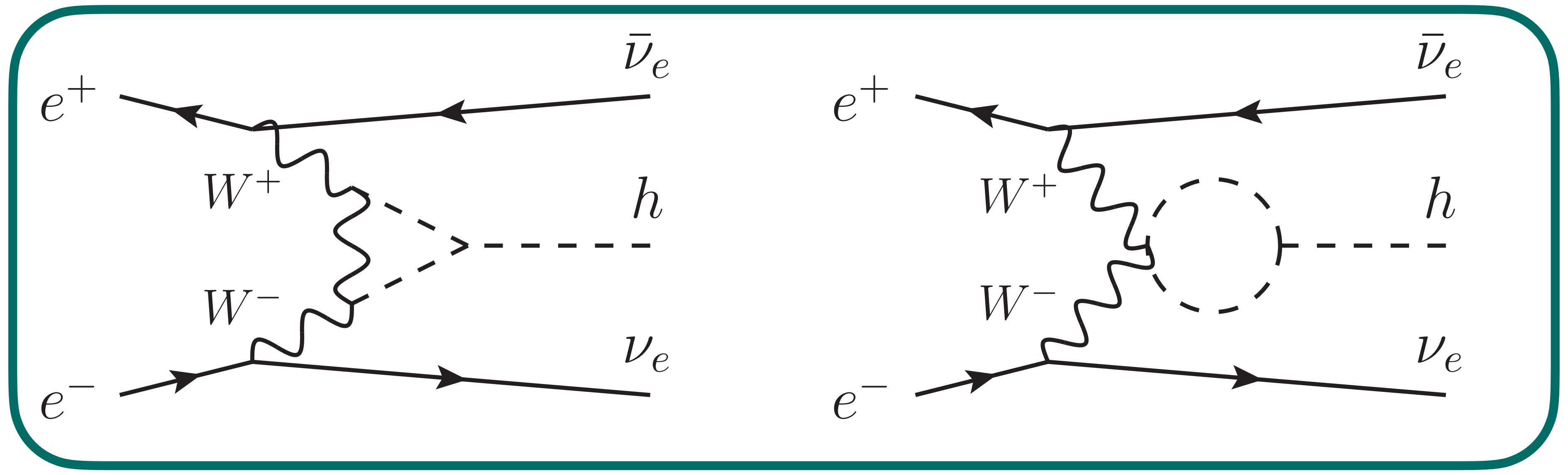


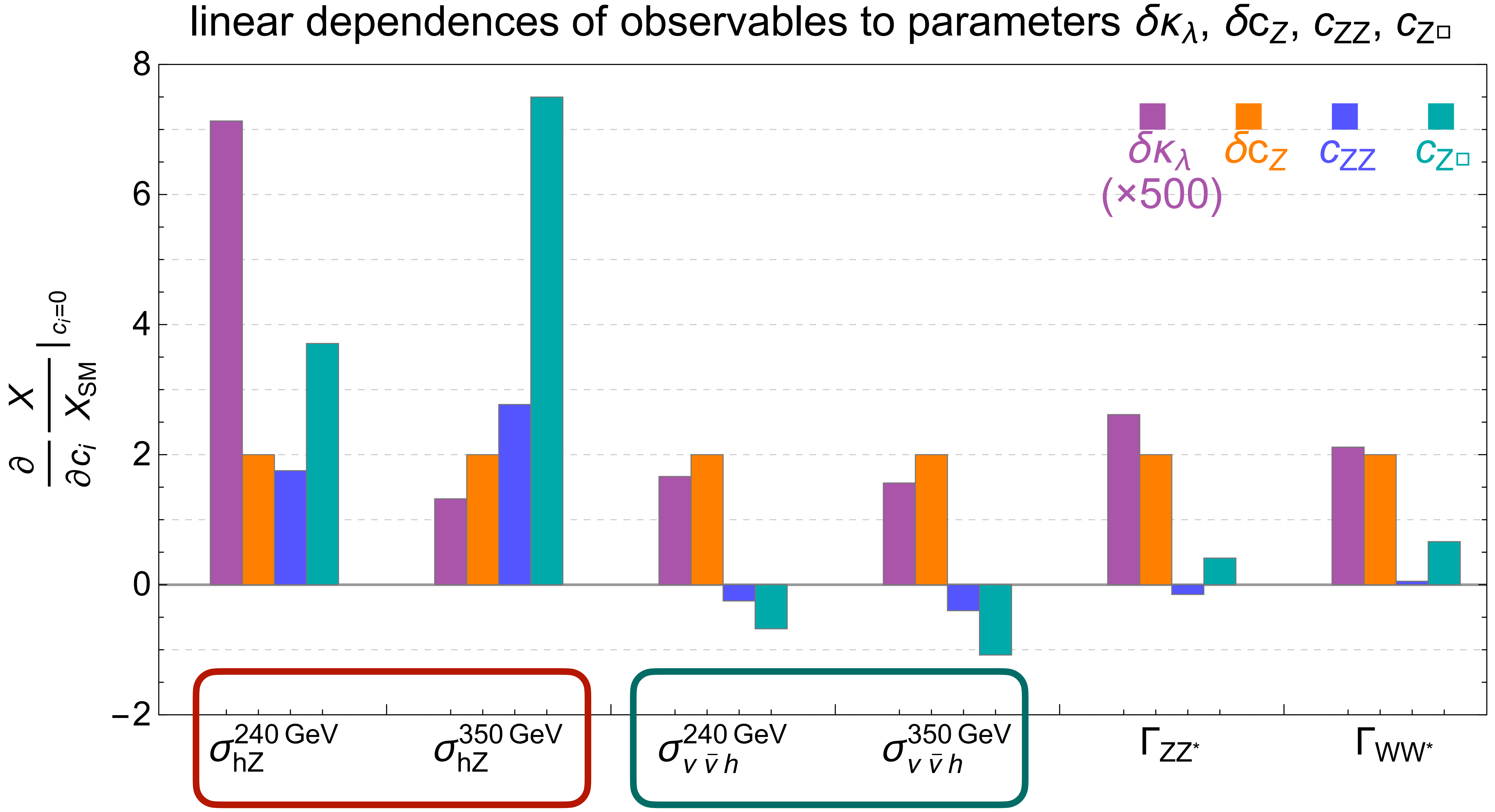
[McCullough (1312.3322)]
[Di Vita et al. (1711.03978)]

$$V = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

From single-Higgs

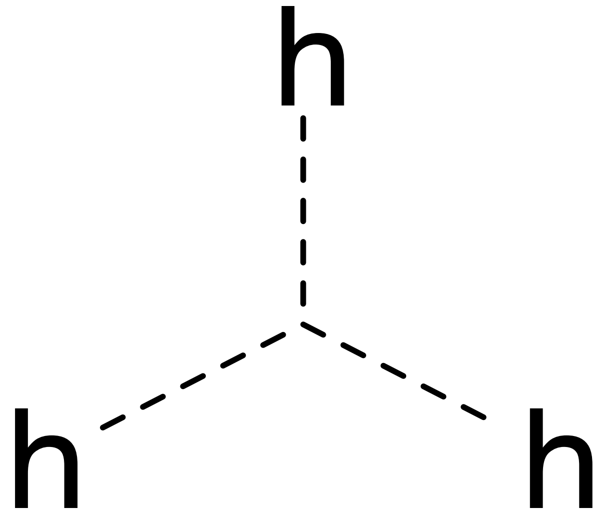






Two runs needed for good sensitivity to κ_λ

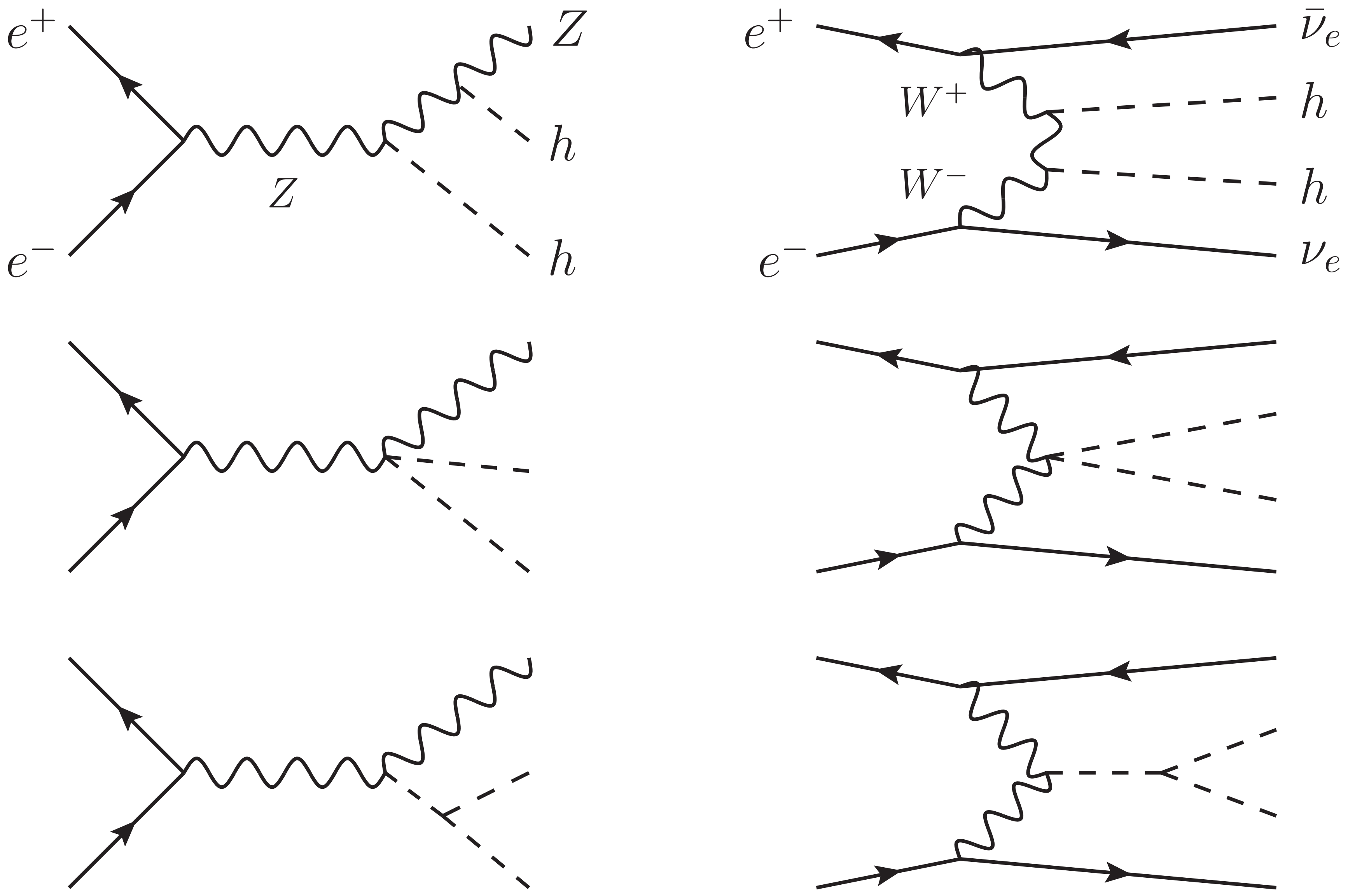
Higgs self-coupling II

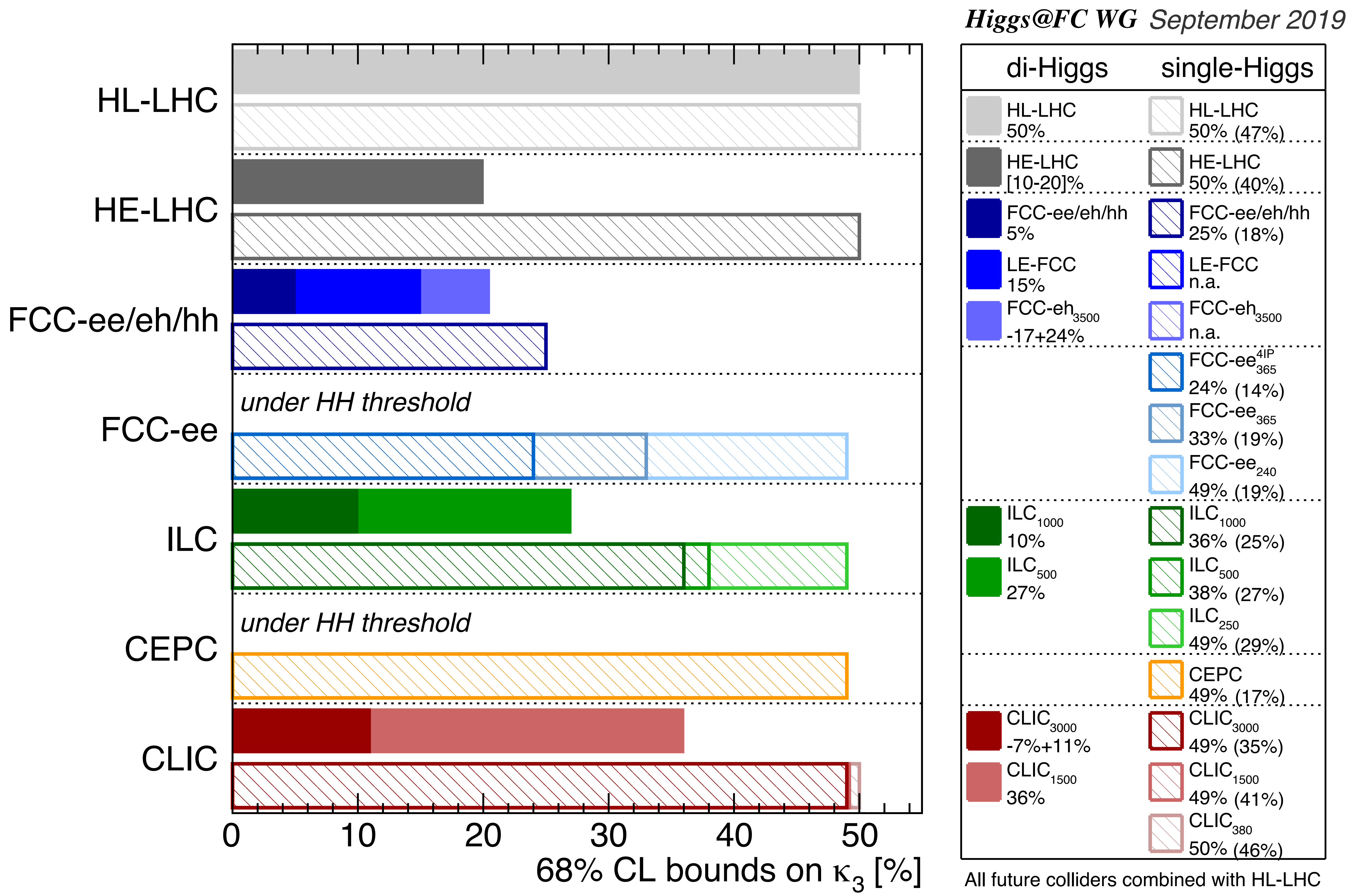


[McCullough (1312.3322)]
[Di Vita et al. (1711.03978)]
[Mangano et al. (2004.03505)]
[AB et al. (1811.08401)]

$$V = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

From di-Higgs



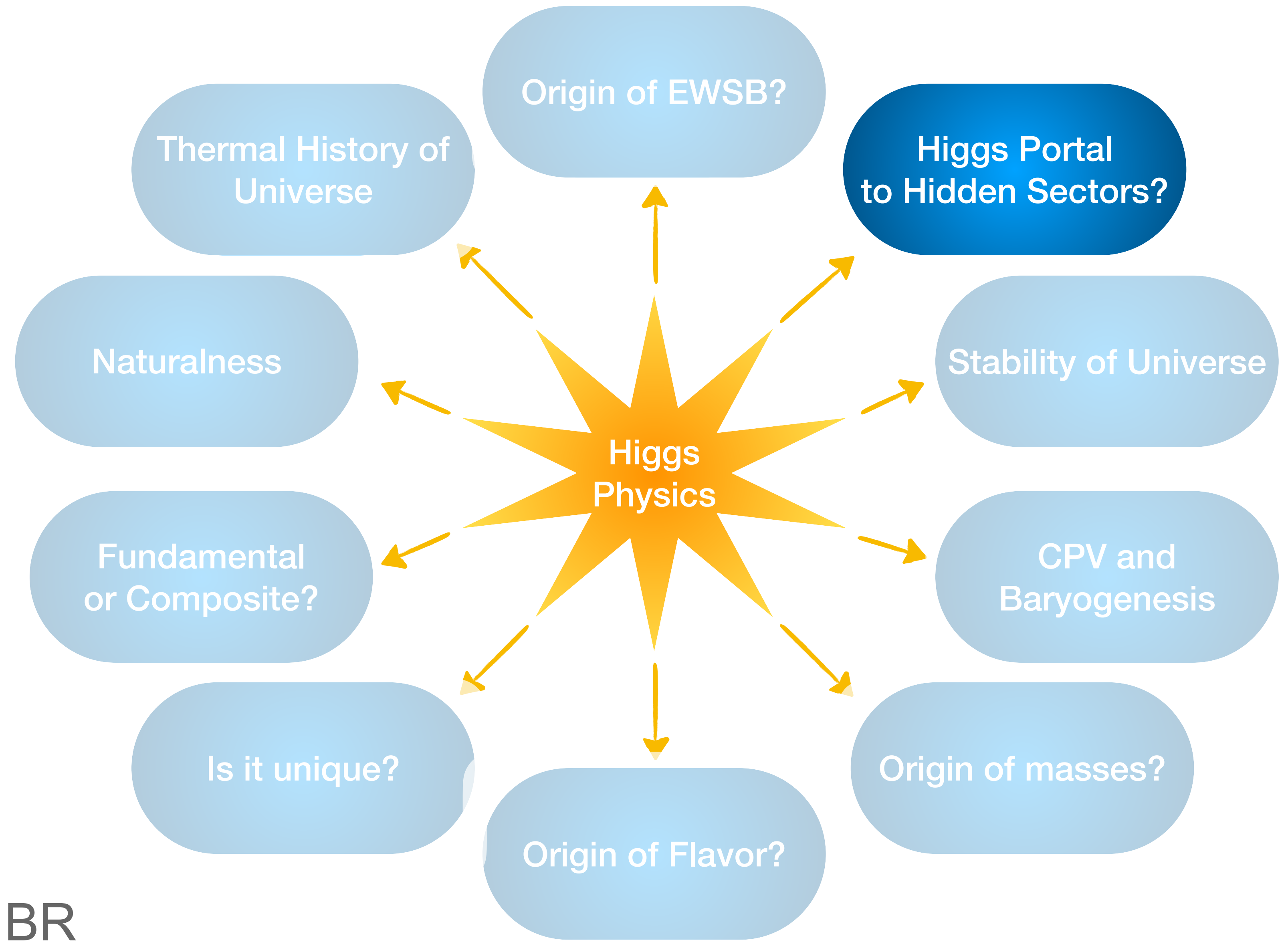


Possible for NP to first show up in Higgs self-coupling

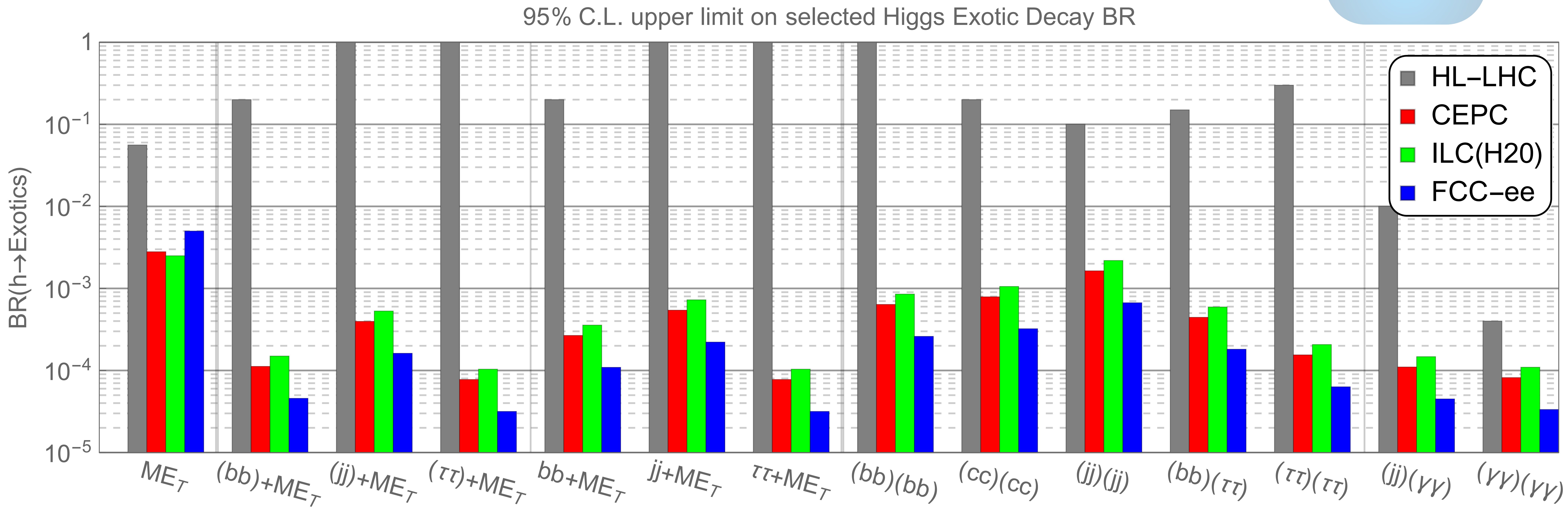
[Durieux et al. (2209.00666)]

(One-parameter fit)

Exploration: Higgs - exotics

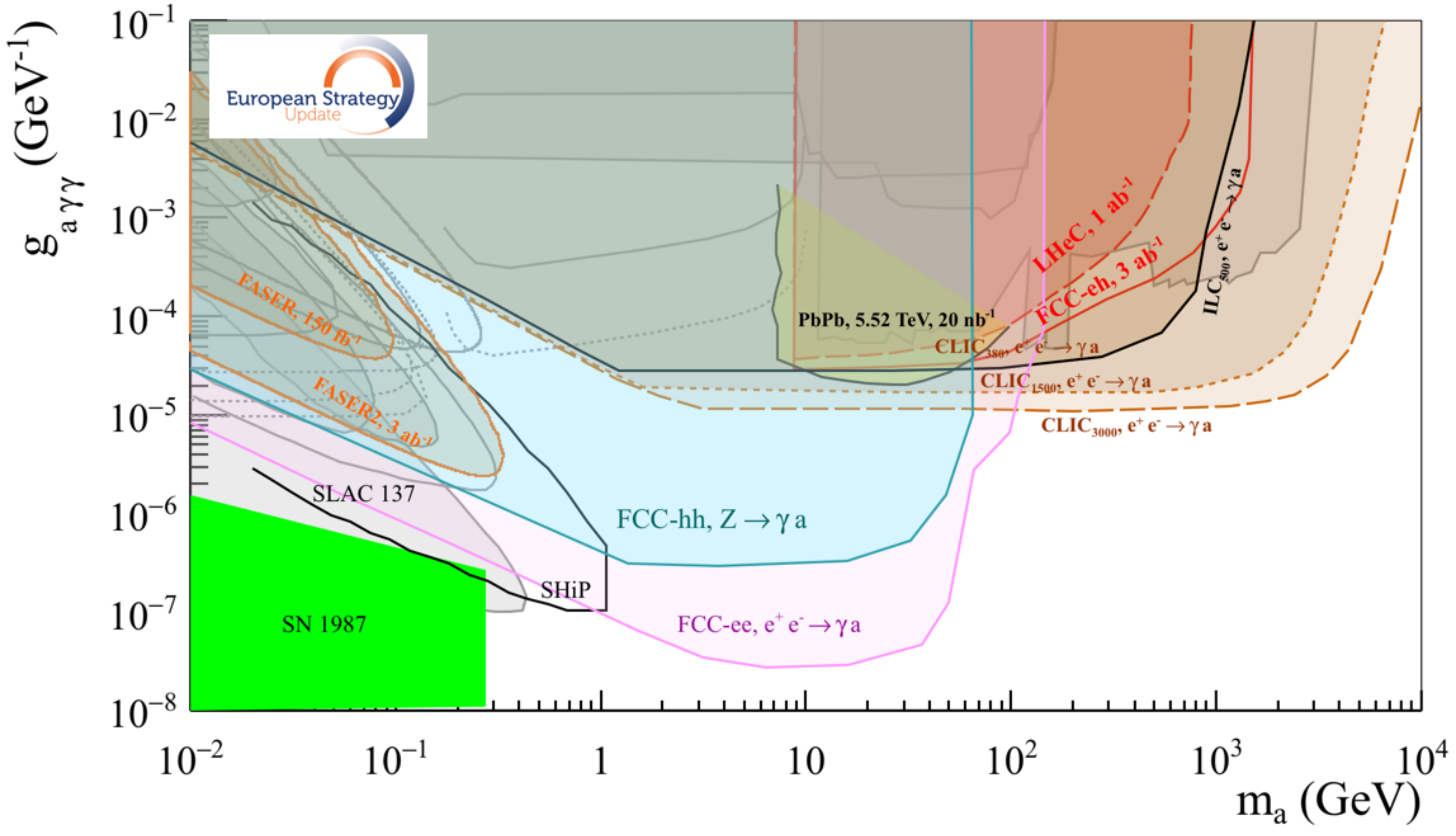


[Liu, Wang, Zhang (1612.09284)]

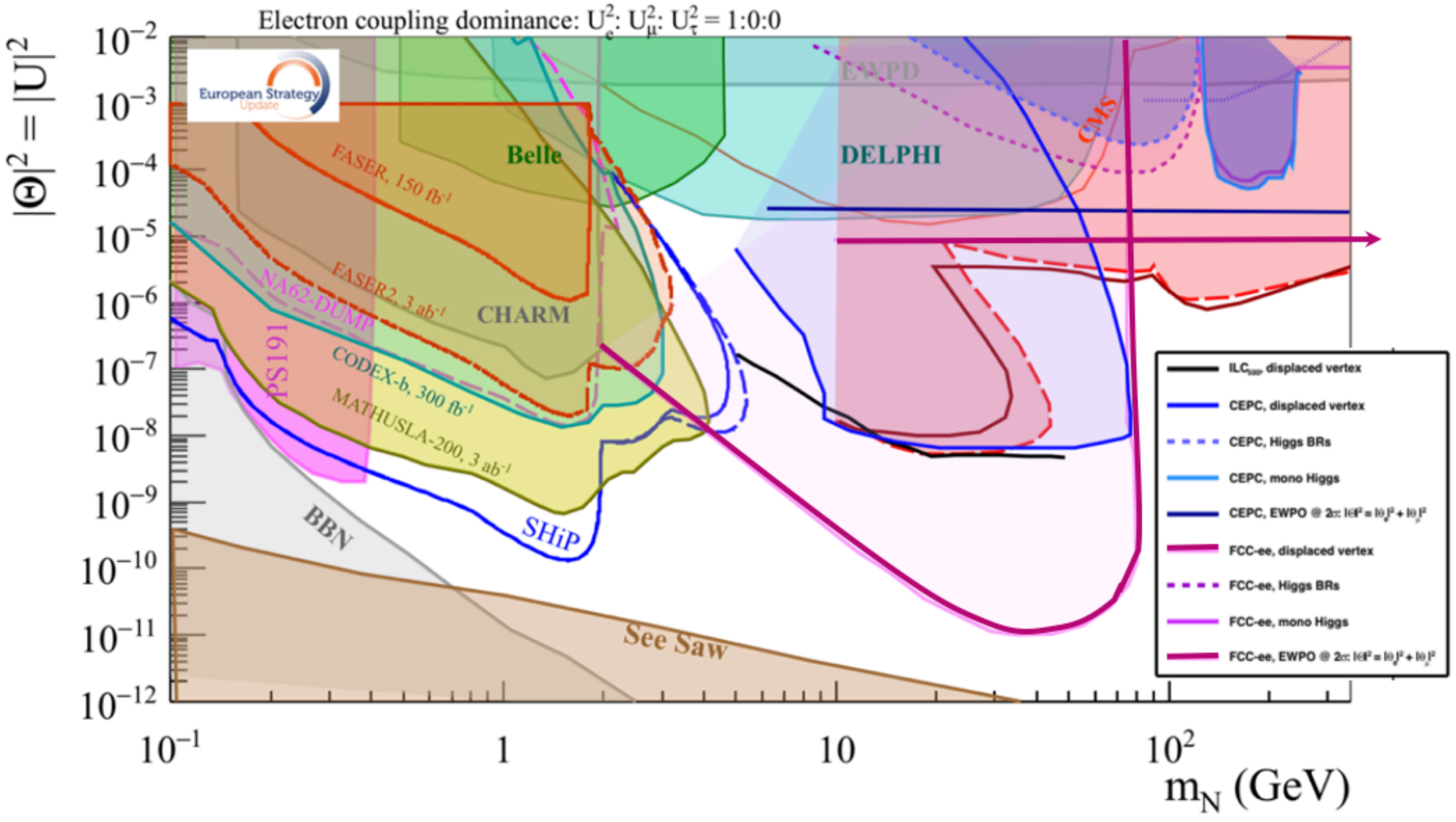


More BSM exploration potential

[Bernardi et al. (2203.06520)]



Axion-like particles



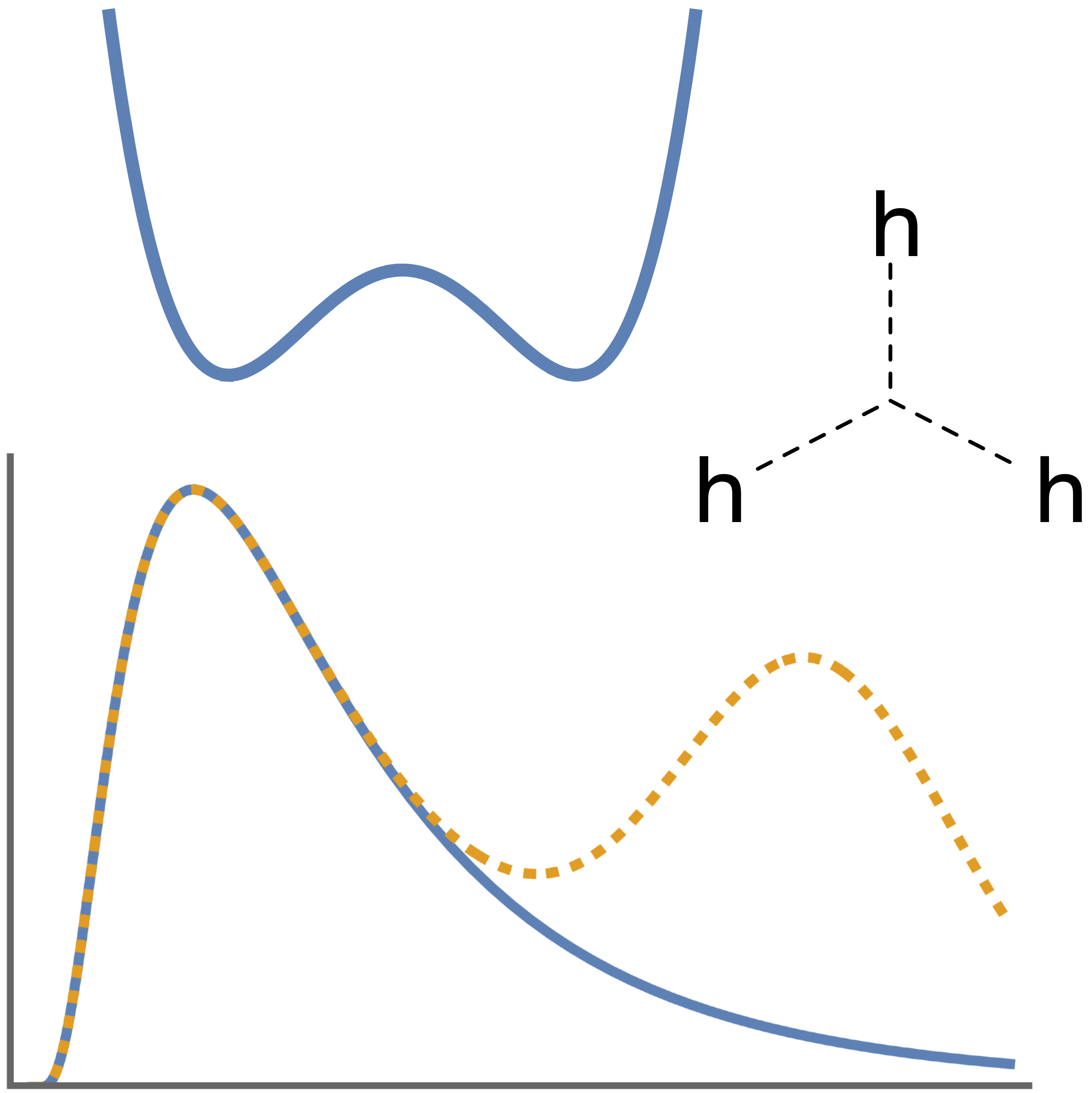
Heavy neutral leptons

Summary

Exciting times ahead if a future collider is built!

- Guaranteed deliverables:
  - Precision measurements
  - Higgs self-coupling

- Potential direct discoveries

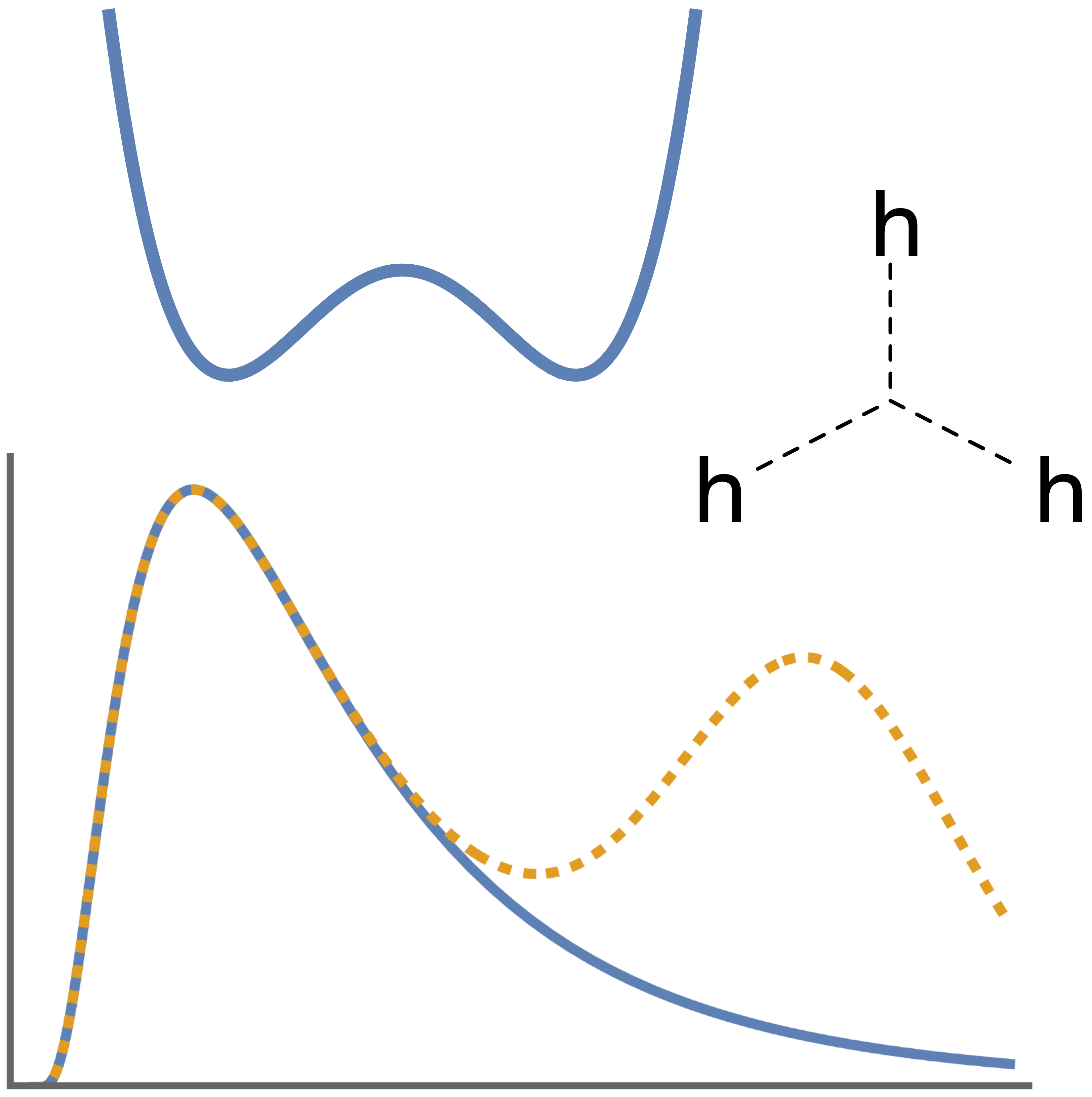


Summary

Exciting times ahead if a future collider is built!

- Guaranteed deliverables:
  - Precision measurements
  - Higgs self-coupling

- Potential direct discoveries



Thank you for your attention!

Backup

References

- HL-LHC [Cepeda et al. (1902.00134)]
- ILC [Adachi et al. (2203.07622)]
- CLIC [Robson, Rologg (1812.01644)]
- FCC [Bernardi et al. (2203.06520)]
- CEPC [Cheng et al. (2205.08553)]
- MuC [Forslund, Meade (2203.09425)], [de Blas, Gu, Liu (2203.04324)]

- Lepton colliders [de Blas et al. (1907.04311)]
- Global SMEFT fits at future colliders [de Blas et al. (2206.08326)]
- HE-LHC [AB et al. (1811.08401)]
- HepFit [de Blas et al. (1910.14012)]

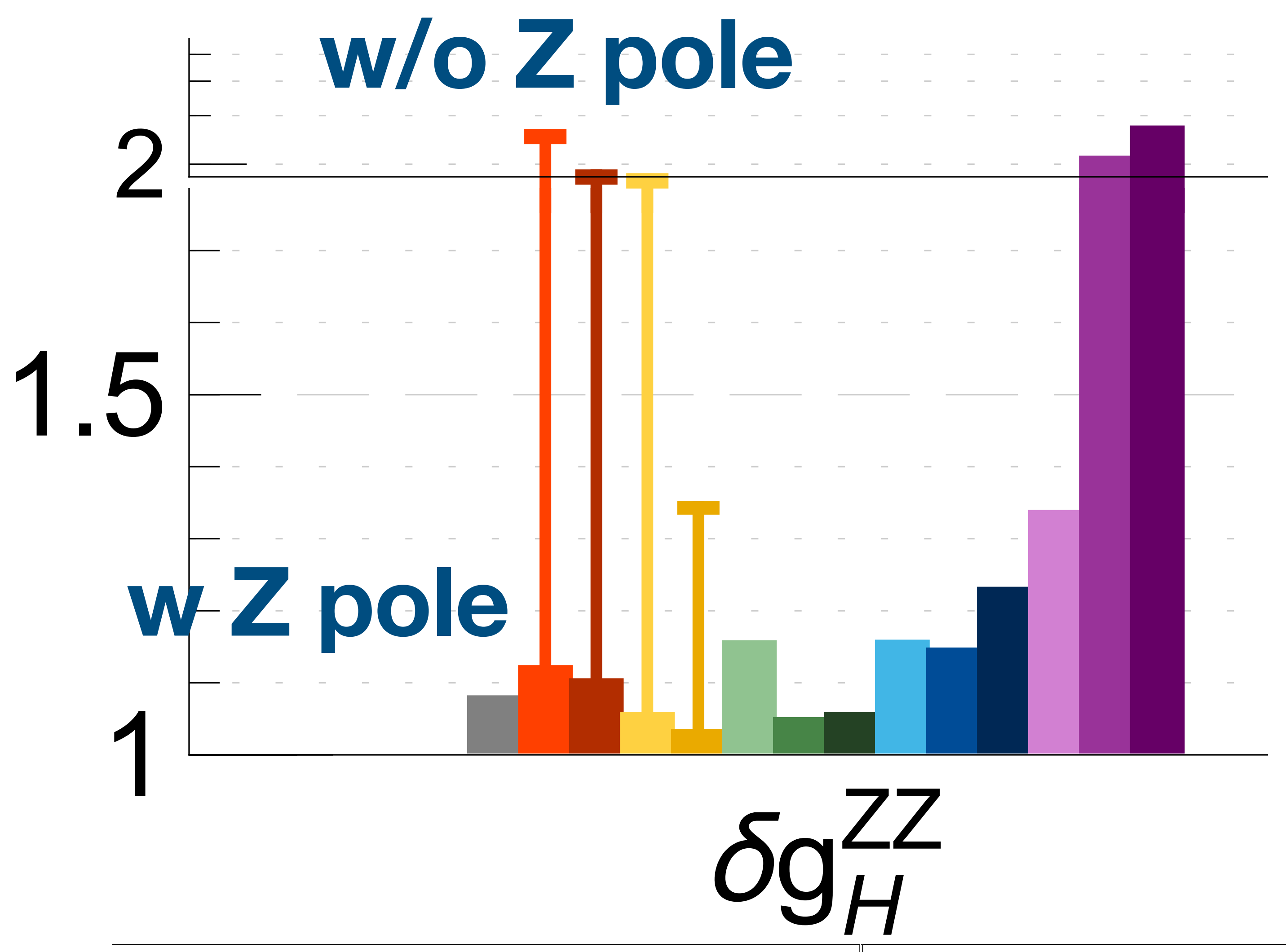
Higgs couplings fits: ESU2020 → Snowmass

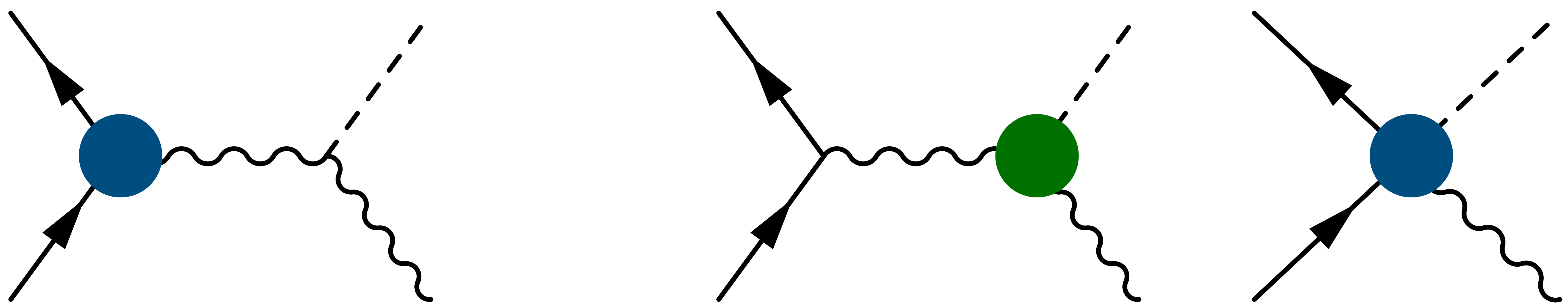
- **Snowmass:** Summary of collider scenarios considered in the SMEFT studies

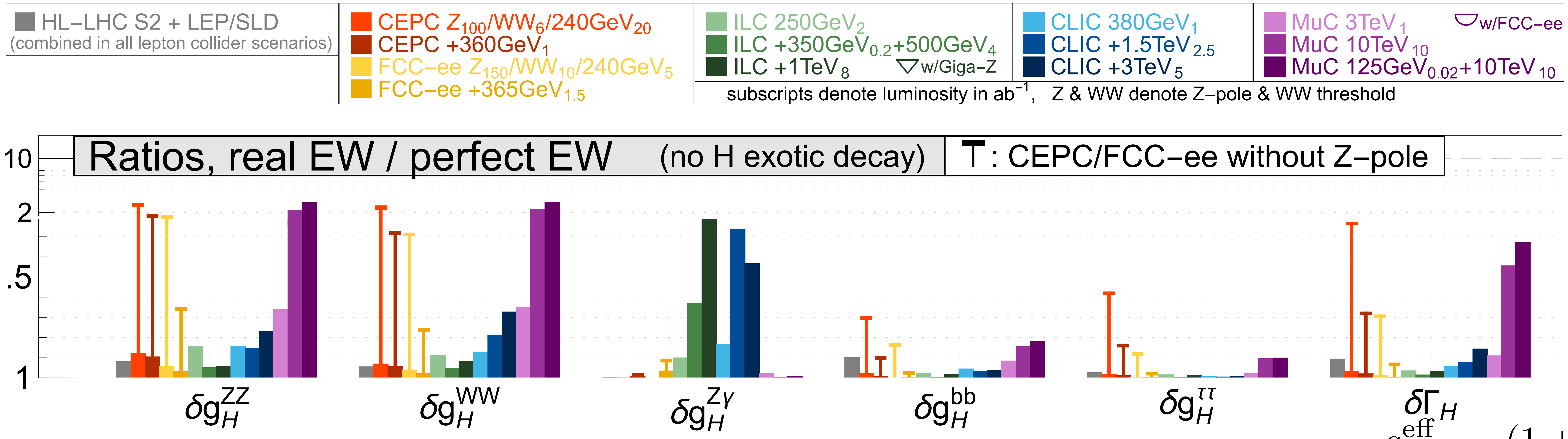
Machine	Pol. (e^-, e^+)	Energy	Luminosity
HL-LHC	Unpolarised	14 TeV	3 ab^{-1}
ILC	$(\mp 80\%, \pm 30\%)$	250 GeV	2 ab^{-1}
		350 GeV	0.2 ab^{-1}
		500 GeV	4 ab^{-1}
	$(\mp 80\%, \pm 20\%)$	1 TeV	8 ab^{-1}
CLIC	$(\pm 80\%, 0\%)$	380 GeV	1 ab^{-1}
		1.5 TeV	2.5 ab^{-1}
		3 TeV	5 ab^{-1}
FCC-*ee*	Unpolarised	Z-pole	150 ab^{-1}
		$2m_W$	10 ab^{-1}
		240 GeV	5 ab^{-1}
		350 GeV	0.2 ab^{-1}
		365 GeV	1.5 ab^{-1}
CEPC	Unpolarised	Z-pole	100 ab^{-1}
		$2m_W$	6 ab^{-1}
		240 GeV	20 ab^{-1}
		350 GeV	0.2 ab^{-1}
		360 GeV	1 ab^{-1}
MuC	Unpolarised	125 GeV	0.02 ab^{-1}
		3 TeV	3 ab^{-1}
		10 TeV	10 ab^{-1}

Higgs - EW interplay

[de Blas et al. (1907.04311)]
[de Blas et al. (2206.08326)]





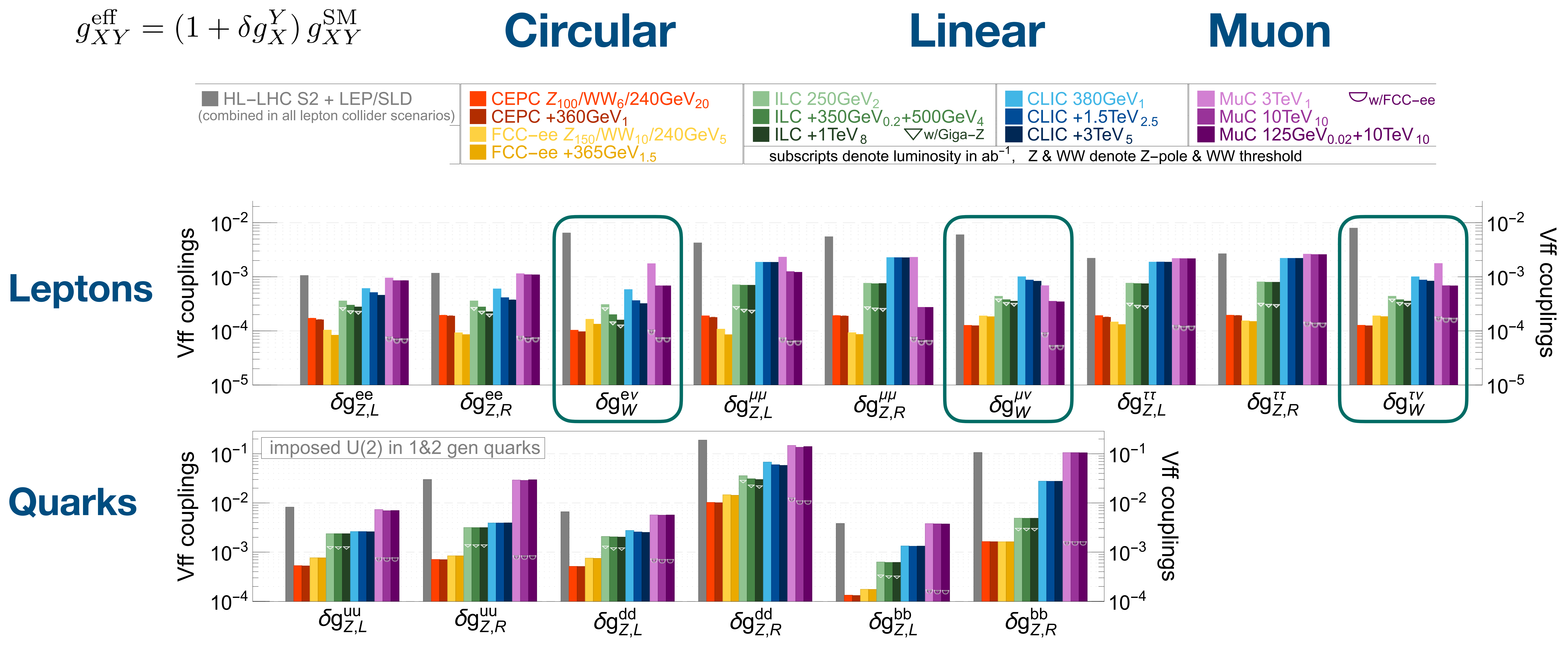


$$g_{XY}^{\text{eff}} = \left(1 + \delta g_X^Y\right) g_{XY}^{\text{SM}}$$

[de Blas et al. (2206.08326)]

Precision: Electroweak

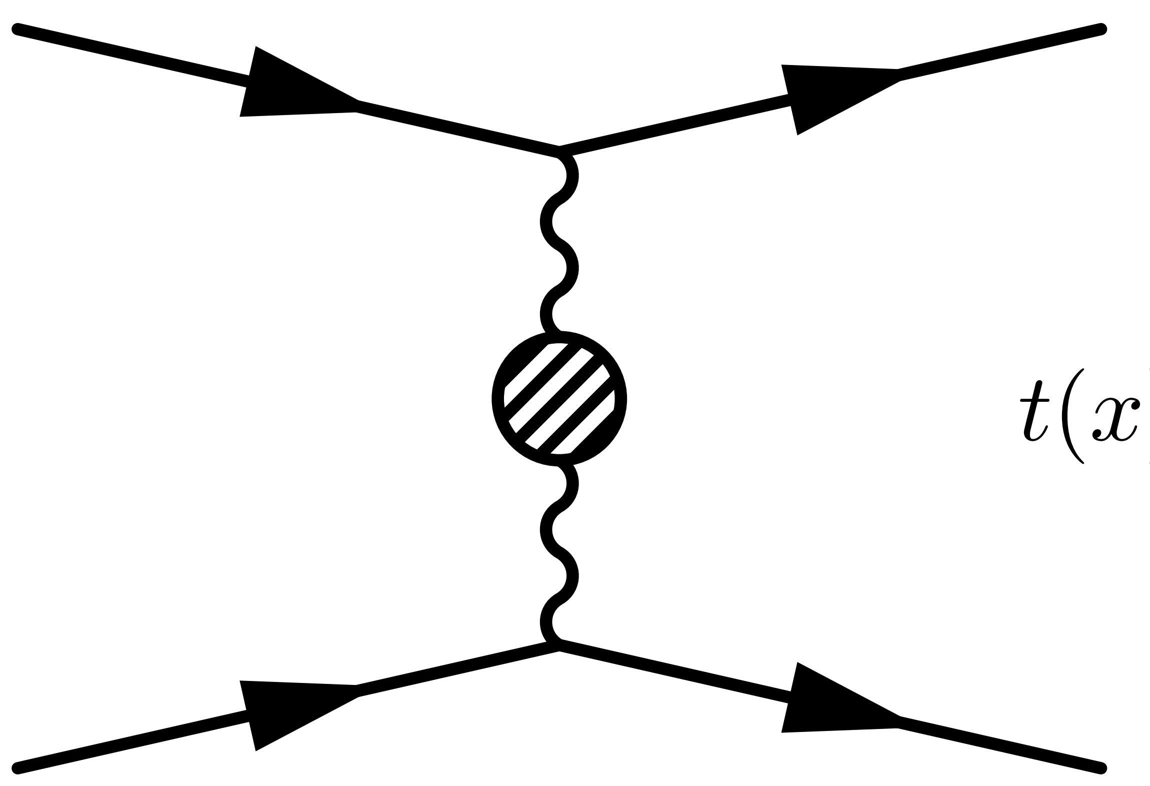
$$g_{XY}^{\text{eff}} = (1 + \delta g_X^Y)\, g_{XY}^{\text{SM}}$$



MUonE experiment @ CERN

$$a_\mu^{\rm HLO} = \frac{\alpha_0}{\pi}\int_0^1 {\rm d}x\,(1-x)\,\Delta\alpha_{\rm had}[t(x)]$$

$\mu\, e \to \mu\, e$



$$t(x) = \frac{x^2\, m_\mu^2}{x-1} < 0$$

Will shed light on muon g-2 anomaly

[Matteuzzi et al. (MUonE)]