Physics Case: Highlights and Future Perspectives

Nathaniel Craig
University of California, Santa Barbara

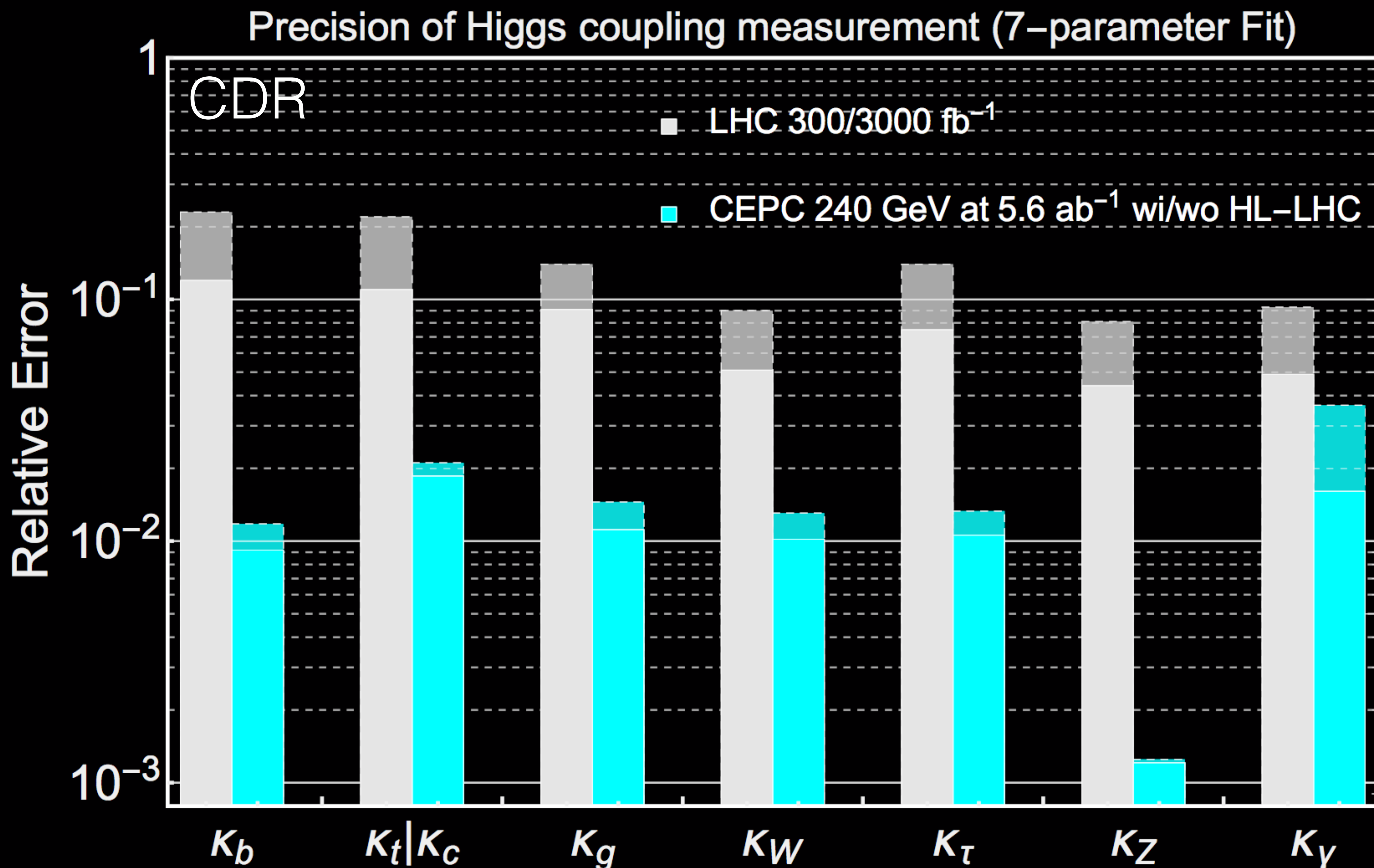
2019 International Workshop on the CEPC, Beijing, 20.11.19

Strengthening the Case

- We have had O(7) years to develop the physics case for the CEPC.
- It’s an excellent physics case, and one for which all involved should justifiably be proud.
- Now is the time to build on initial projections with detailed analysis and innovation.
- Account for developments such as HL-LHC projections, aspire to highest level of ambition.

Apologies in advance for incompleteness of highlights

Higgs Couplings



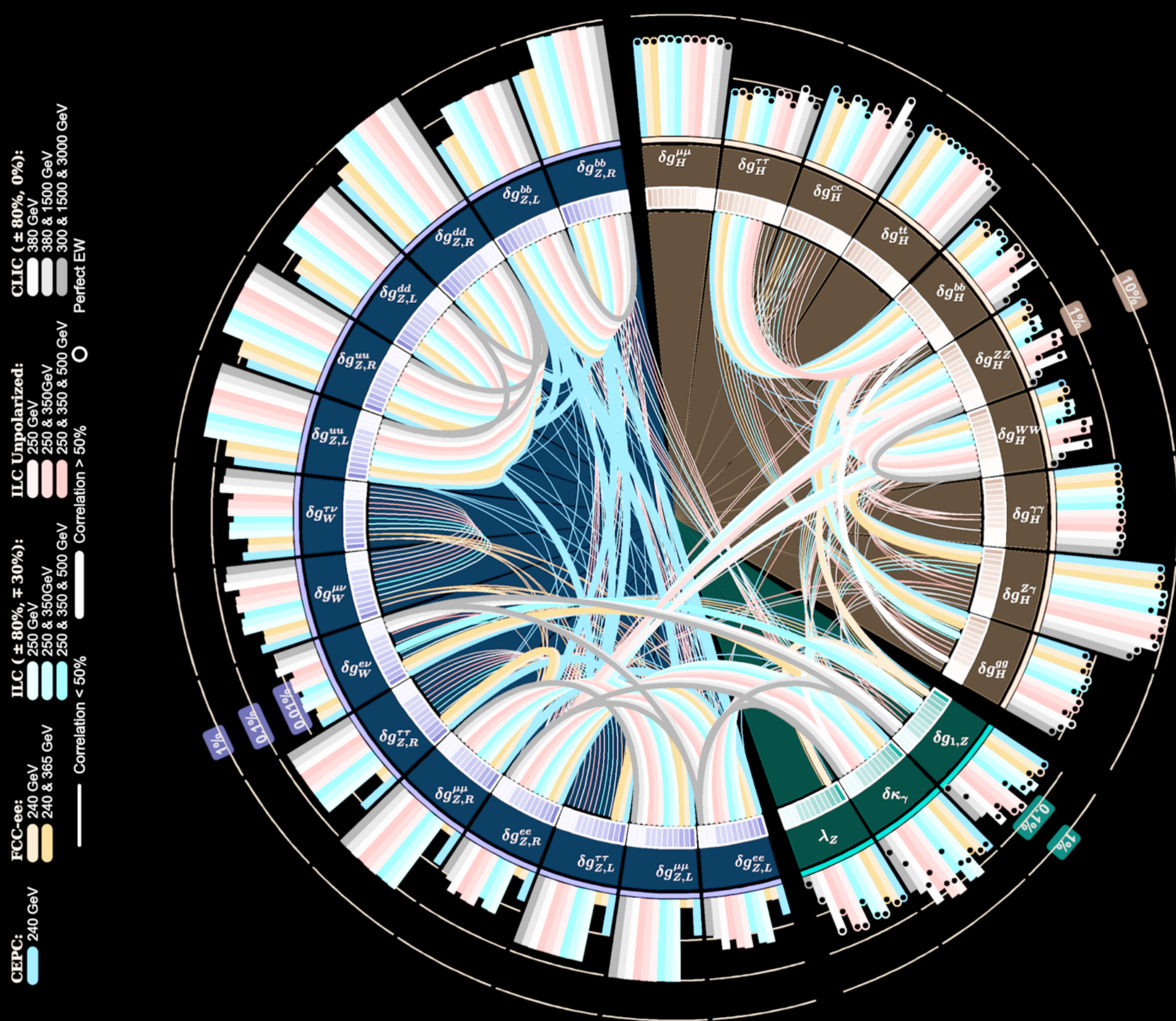
CEPC Higgs coupling projections are dynamic

(240GeV,5.6ab^{-1})	CDR, (2018)	Current: 2019.11	Reports in this workshop
$\sigma(ZH)$	**0.50%**		
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{bb})$	**0.27%**		Yu Bai
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{cc})$	**3.3%**		
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{gg})$	**1.3%**		
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{WW})$	**1.0%**		
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{ZZ})$	**5.1%**		Ryuta Kiuchi
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \tau\tau)$	**0.8%**		Dan Yu
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \gamma\gamma)$	**6.8%**	**5.4%**	Fangyi Guo
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mu\mu)$	**17%**	**12%**	
$\sigma(\mathrm{vv}H) * \mathrm{Br}(\mathrm{H} \to \mathrm{bb})$	**3.0%**		Hao Liang
$\mathrm{Br}_{\mathrm{upper}}(\mathrm{H} \to \mathrm{inv.})$	**0.41%**	**0.2%**	Ryuta Kiuchi
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to Z\gamma)$	**16%**		
Width	**2.8%**		

from Kaili Zhang's talk

Higgs Without Higgs

[J. de Blas, G. Durieux, C. Grojean, J. Gu, A. Paul, 1907.04311]



from Jorge de Blas' talk

Theory Precision

$e^+e^- \to ZH$:

$\delta\sigma_{HZ}^{\text{exp}} \sim 0.4\%$

full one-loop available, corrections of 5-10%

rough estimate: $\delta\sigma_{HZ}^{\text{theo}} \sim 1\%$ from missing two-loop corrections

Two-loop corrections for $2 \to 2$ can in principle be done . . .
$\mathcal{O}(\alpha_t\alpha_s)$ corrections: 1.3% [*Y. Gong, Z. Li, X. Xu, L. Yang '16*]

$\Rightarrow$ theory uncertainties sufficiently small
$\Rightarrow$ full two-loop for $2 \to 2$ should be done!

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

small contribution . . .

Partial two-loop calculation (with closed fermion loops)
can in principle be done . . .

from Sven Heinemeyer's talk

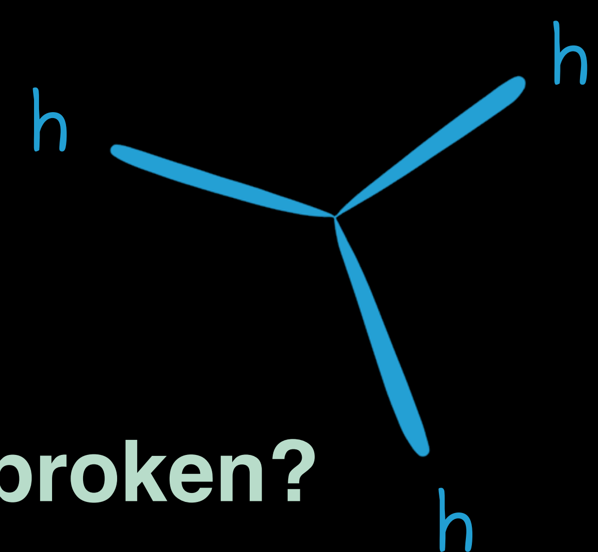
see also talk by Roberto Mondini
& plenary by Alessandro Vicini

Building on Discovery

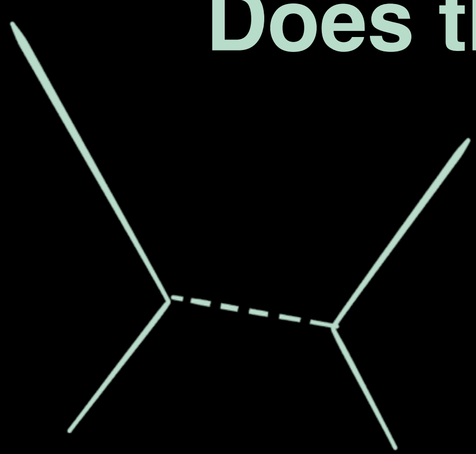
What can we learn from this precision?

Answer **major conceptual questions**:

Is the Higgs elementary, or composite?



Does the Higgs interact with itself?



Why is electroweak symmetry broken?

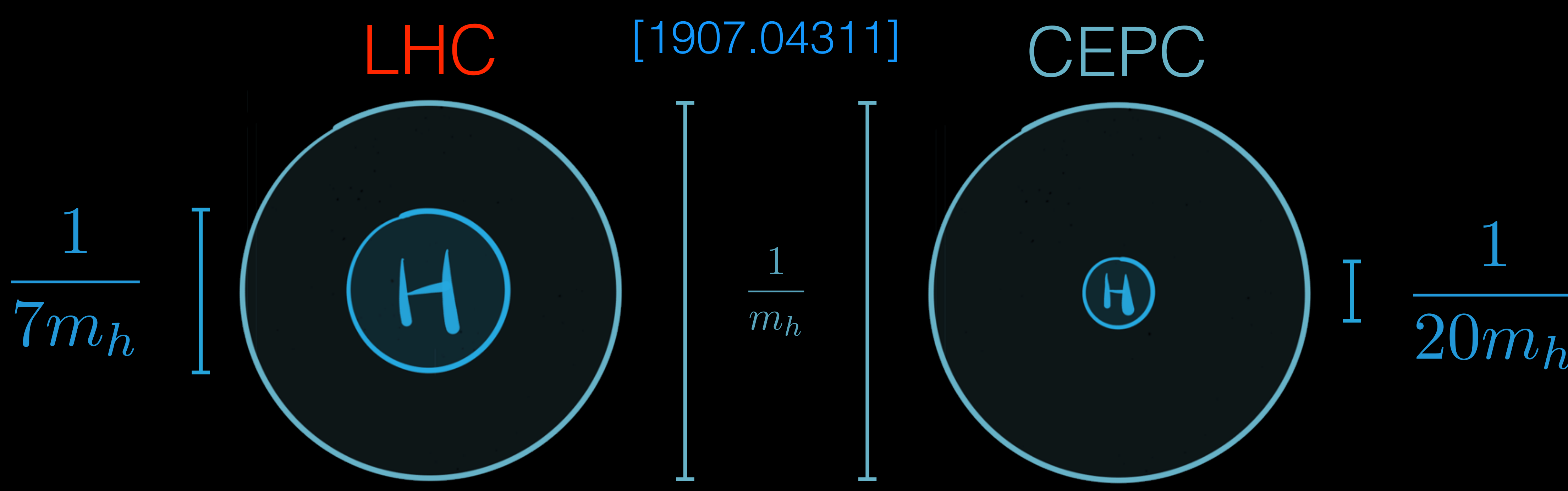
How is electroweak symmetry broken?

An Elementary Scalar

Is the Higgs elementary or composite?

Beginning to probe the size of the Higgs at the LHC,
but expect LHC will only probe π-like compositeness

More precisely: bound "size" corrections, e.g. $\mathcal{O}_H = \frac{1}{2\Lambda^2}\left(\partial_\mu |H|^2\right)^2$



CEPC will probe size of the Higgs well beyond this, providing strong evidence that the Higgs is elementary. *If not, an abundance of new physics awaits.*

Higgs Form Factor

LHC bound perhaps optimistic / sensitive to framework:
O_H cannot be measured in any ratios.
CEPC advantages also clear in models (see talk by Shufang Su)

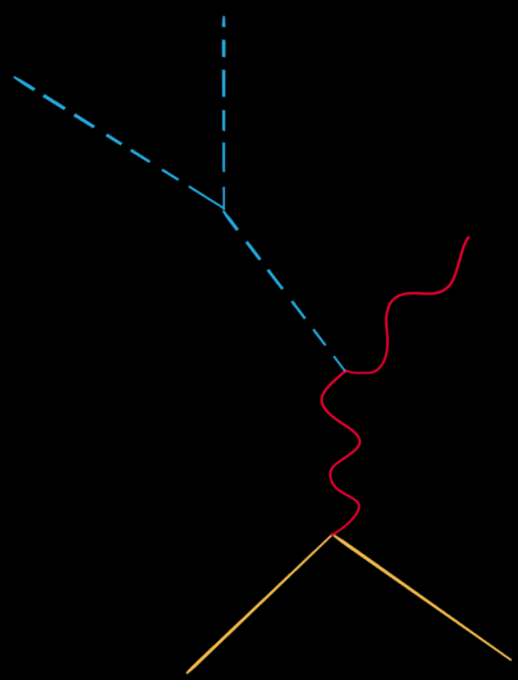
Looking further: suppose a "size" correction seen @ HL-LHC or CEPC. Next goal: Higgs form factor as a function of p^2

In EFT language this requires going to dimension 8, e.g. operators of the form

$$\frac{c}{\Lambda^4}|H|^2(\partial_\mu|H|^2)^2 \qquad \frac{c}{\Lambda^4}(DH^\dagger DH)^2$$

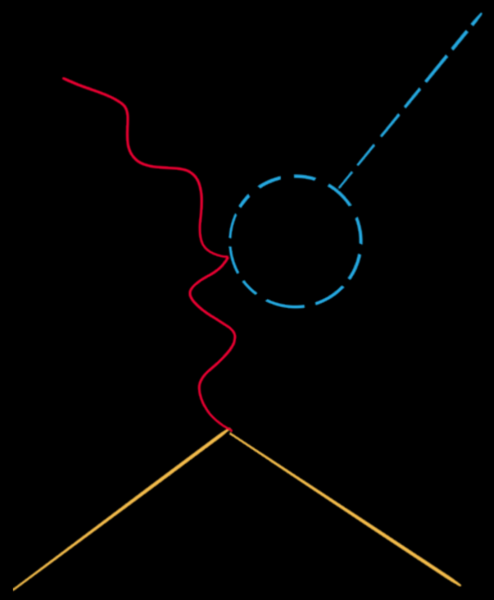
Although down by v^2/Λ^2, potentially within reach of CEPC precision esp. if suppression is by small *c*. ***Energy would help.***

A Self-Interacting Particle



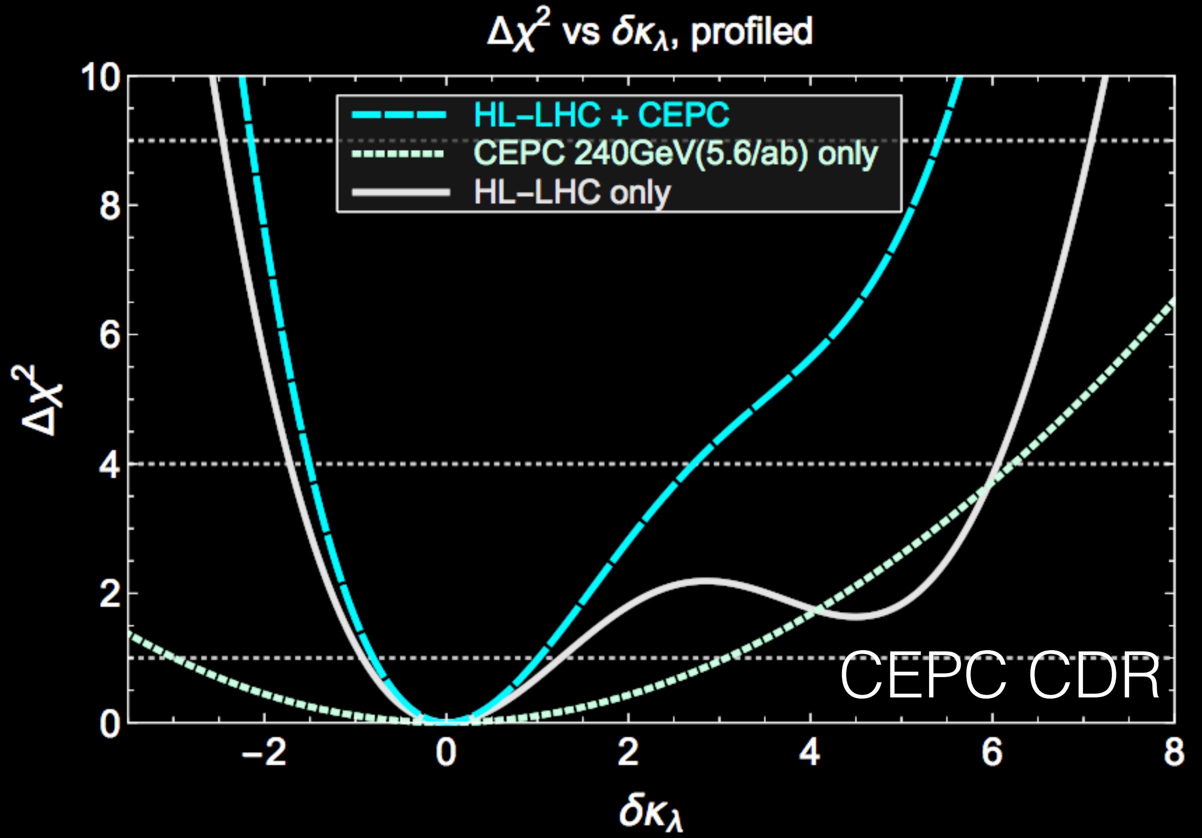
Classically test Higgs self-coupling via Higgs pair production.

Quantum mechanically test Higgs self-coupling via virtual corrections [McCullough 1312.3322]

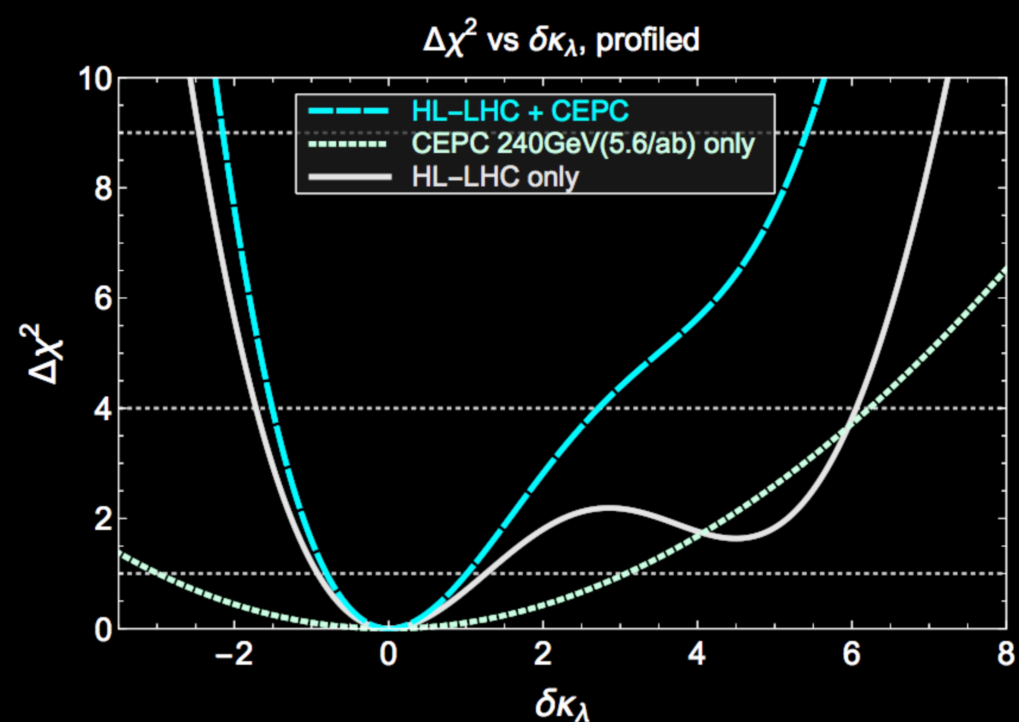


CEPC: measure Higgs self-interactions at ~35% level

Powerful measurement of self-coupling even allowing *many* modifications of Higgs properties in, conjunction w/ LHC data



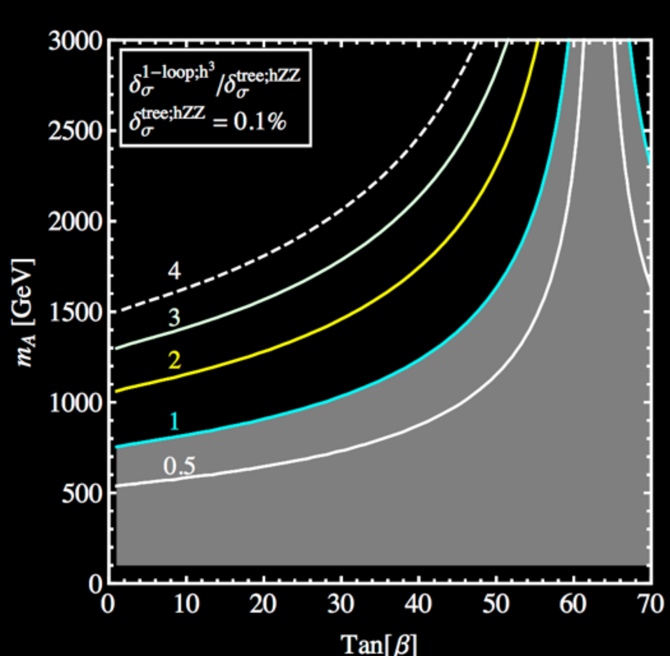
A Self-Interacting Particle



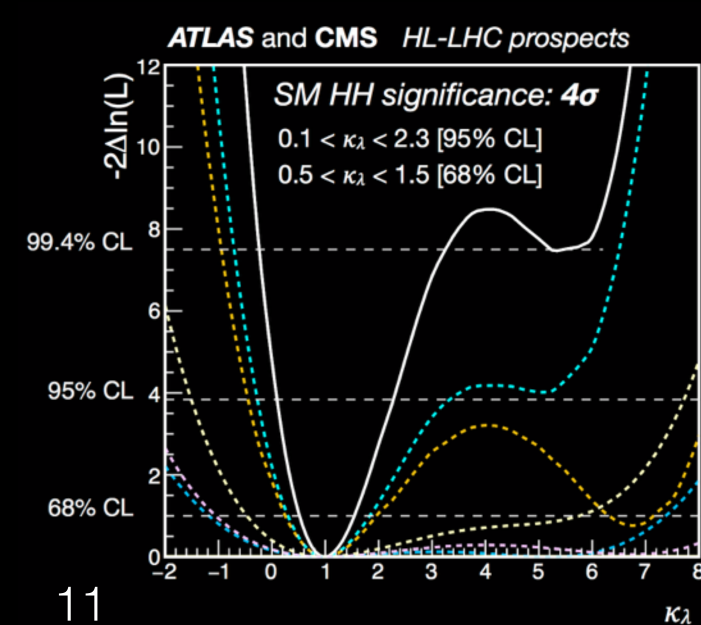
The profiled constraint from CEPC is modest and adds little to HL-LHC for $\delta\kappa_\lambda < 0$ (most relevant for showing self-interaction)

Energy would help.

Also: profiling over ~12 params is, in some sense, overly conservative



There are NP scenarios where $\delta\kappa_\lambda$ is the leading effect.



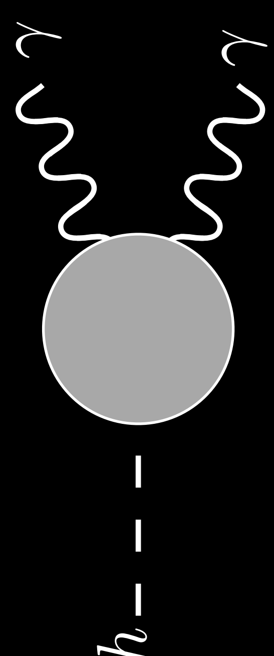
HL-LHC ability to exclude $\kappa_\lambda=0$ at 2σ relies on $\delta\kappa_\lambda$-only scenario

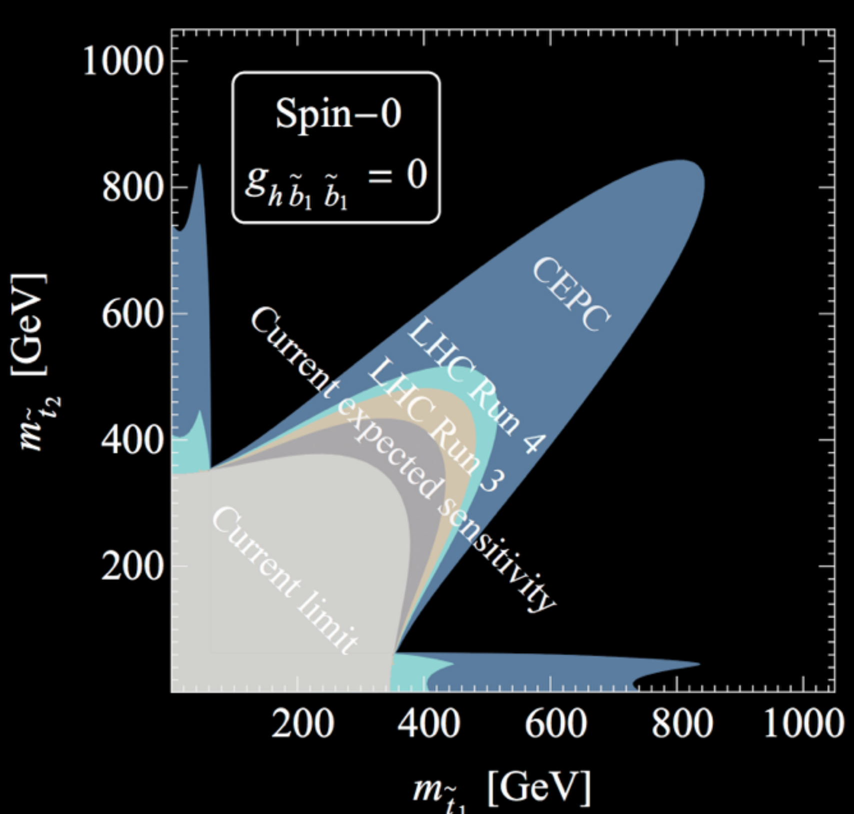
Why is electroweak symmetry broken?

Pressing questions: Why $|m_H^2| \ll \Lambda^2$? Why $m_H^2 < 0$?

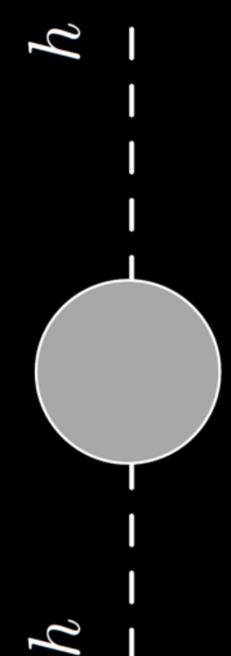
Whatever new physics enters to answer these questions must couple to Higgs, probed above weak scale by CEPC.

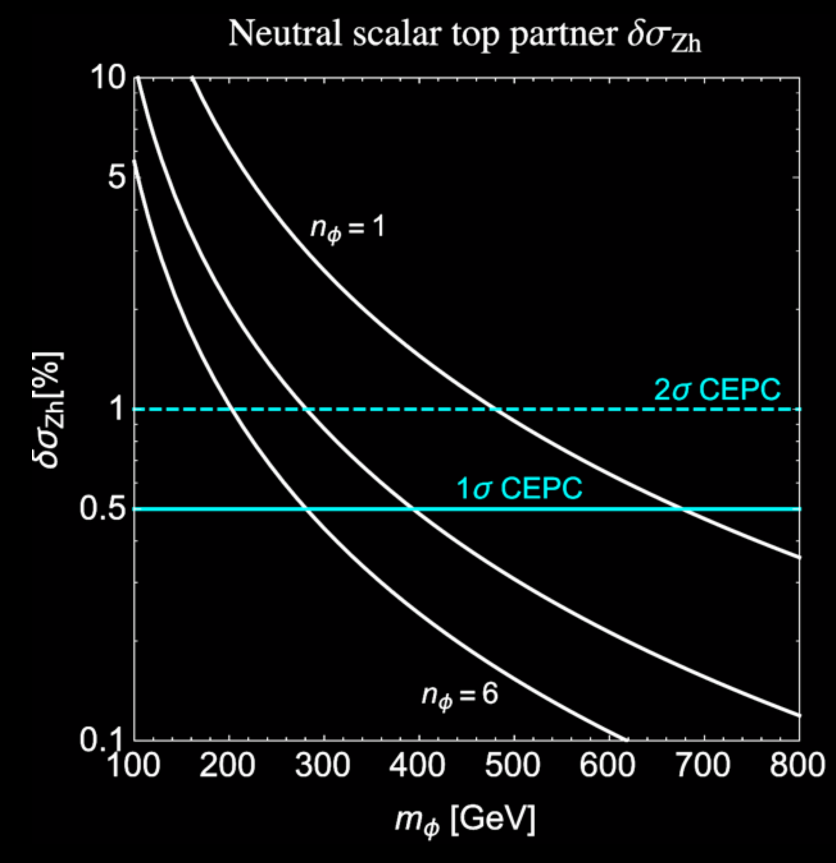
Loop corrections to loop couplings: Dependent on quantum #'s





Loop corrections to tree couplings: Independent of quantum #'s

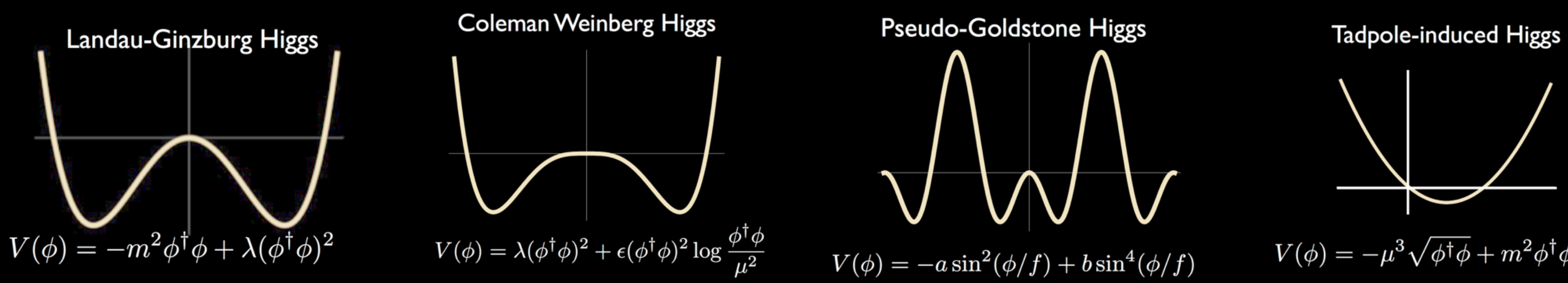


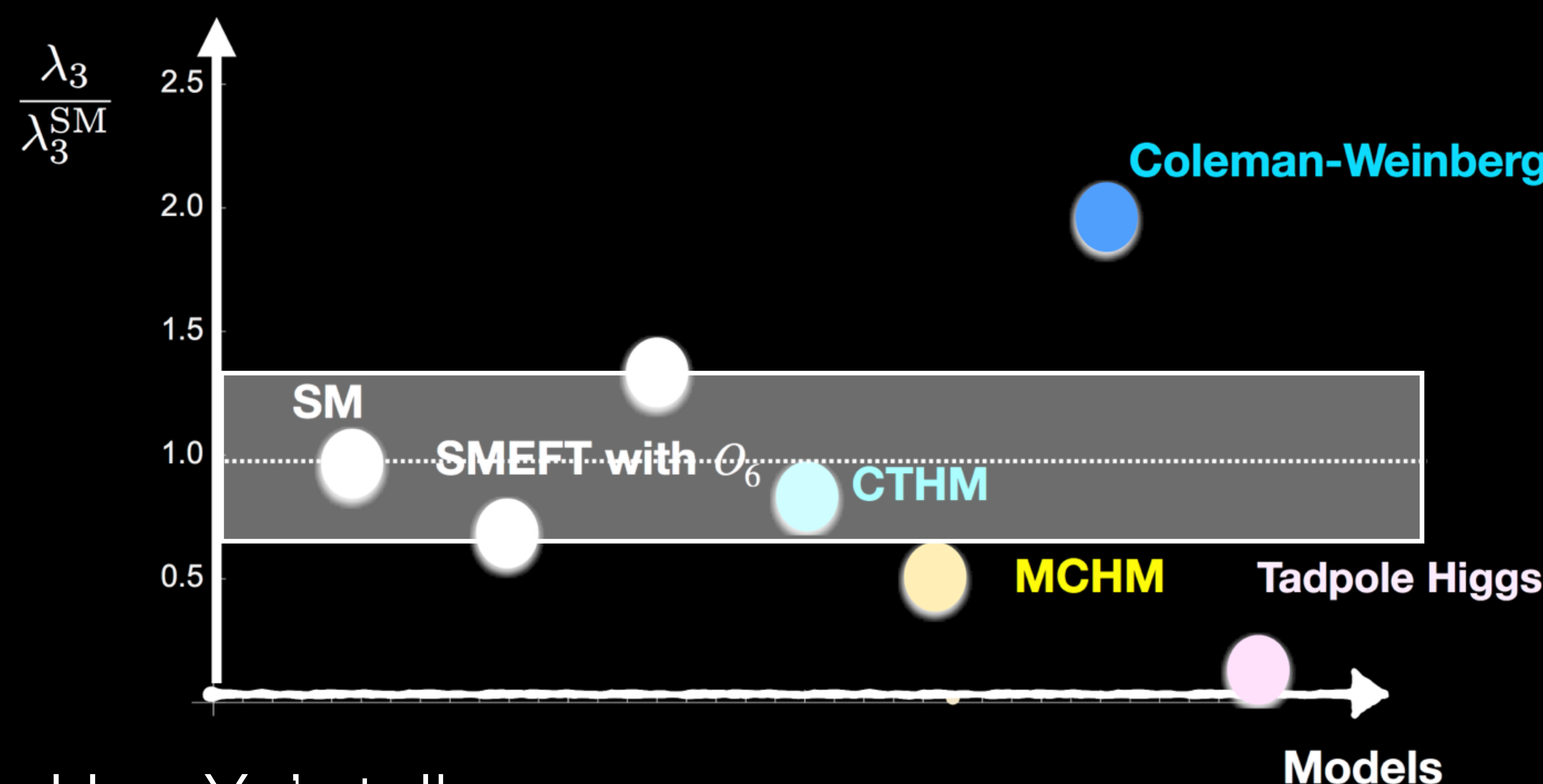


see talk by Wei Su

How is electroweak symmetry broken?

Higgs self-coupling begins probing potential globally

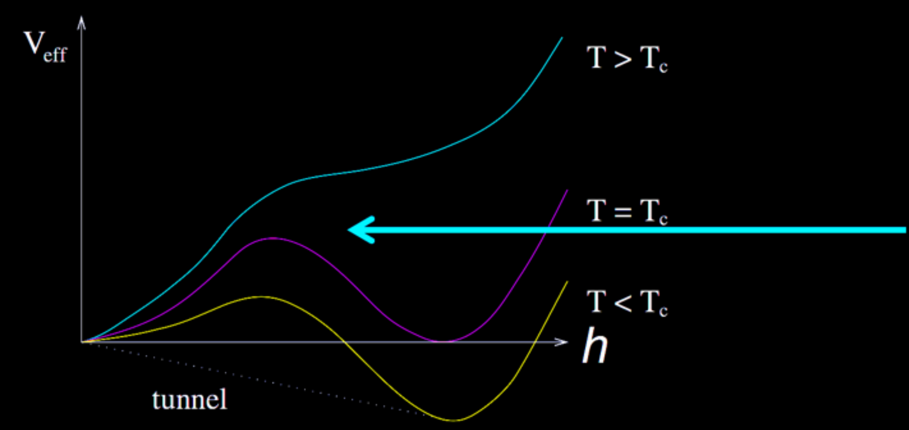




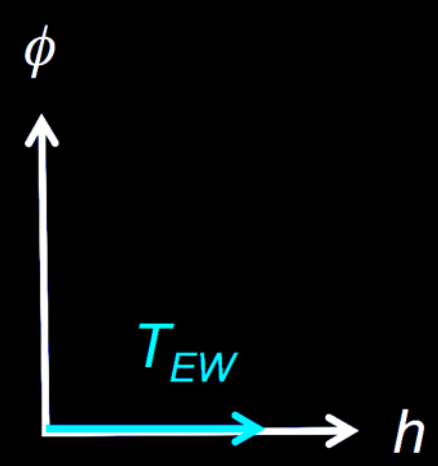
from Jiang-Hao Yu's talk

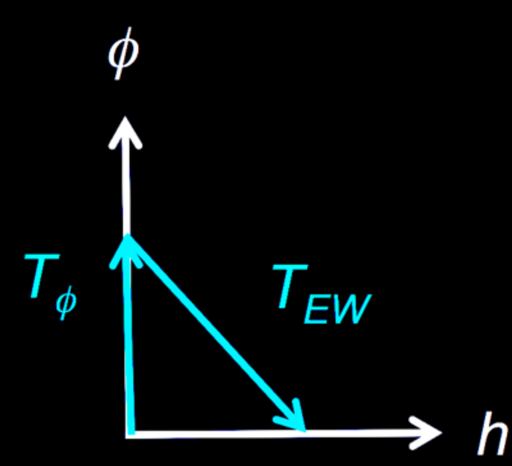
How is electroweak symmetry broken?

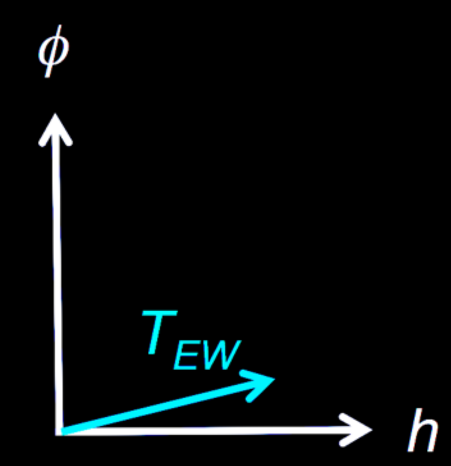
First Order EWPT from BSM Physics



Generate finite-T barrier







$a_2\, H^2\phi^2$: $T > 0$
loop effect

$a_2\, H^2\phi^2$: $T = 0$
tree-level effect

$a_1\, H^2\phi$: $T = 0$
tree-level effect

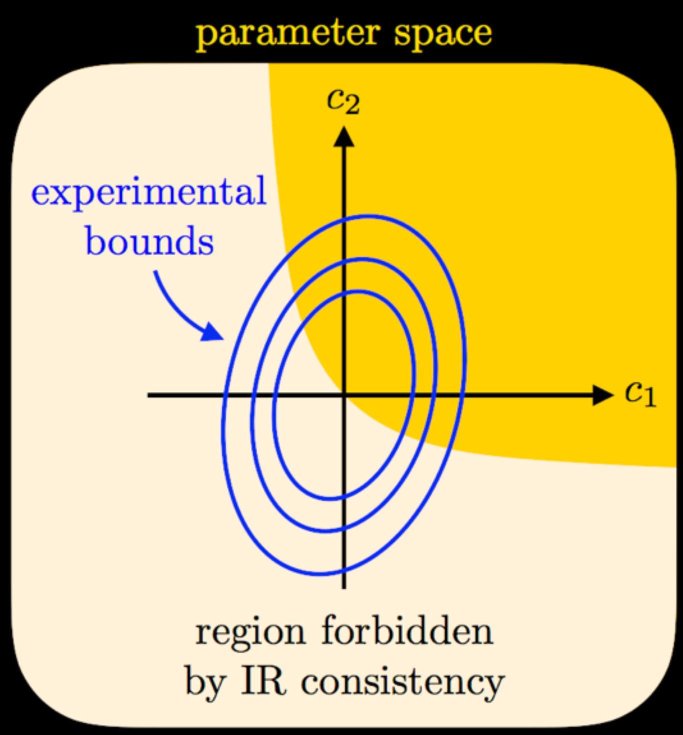
from Michael Ramsey-Musolf's talk
see also talk by Zhen Liu

Higgs precision a powerful probe

Thinking Positively

Causality, unitarity, and analyticity constrain EFT corrections to SM

Potentially significant impact on interpretation of expt. results



[G. Remmen, N. Rodd, 1908.09845]

d=6: UV-sensitive positivity bounds, sum rules

d=8: UV-insensitive positivity bounds

For example…

d=6: If Higgs is elementary or goldstone & UV completion lacks triplet scalars: $\frac{c_H}{2\Lambda^2}\left(\partial_\mu |H|^2\right)^2$ $\quad c_H > 0$

d=8: universal bound $\frac{c_2}{\Lambda^4}(D_\mu H^\dagger D_\nu H)(D^\mu H^\dagger D^\nu H)$ $\quad c_2 > 0$

Thinking Positively

Naive expectation: dim-8 operator effects subleading
Reality: often leading effect due to non-interference thms
(or unusual UV physics, see N. Arkani-Hamed's talk)

Thus far: primarily applied to aQGCs @ LHC
[C. Zhang, S-Y. Zhou, 1808.00010]

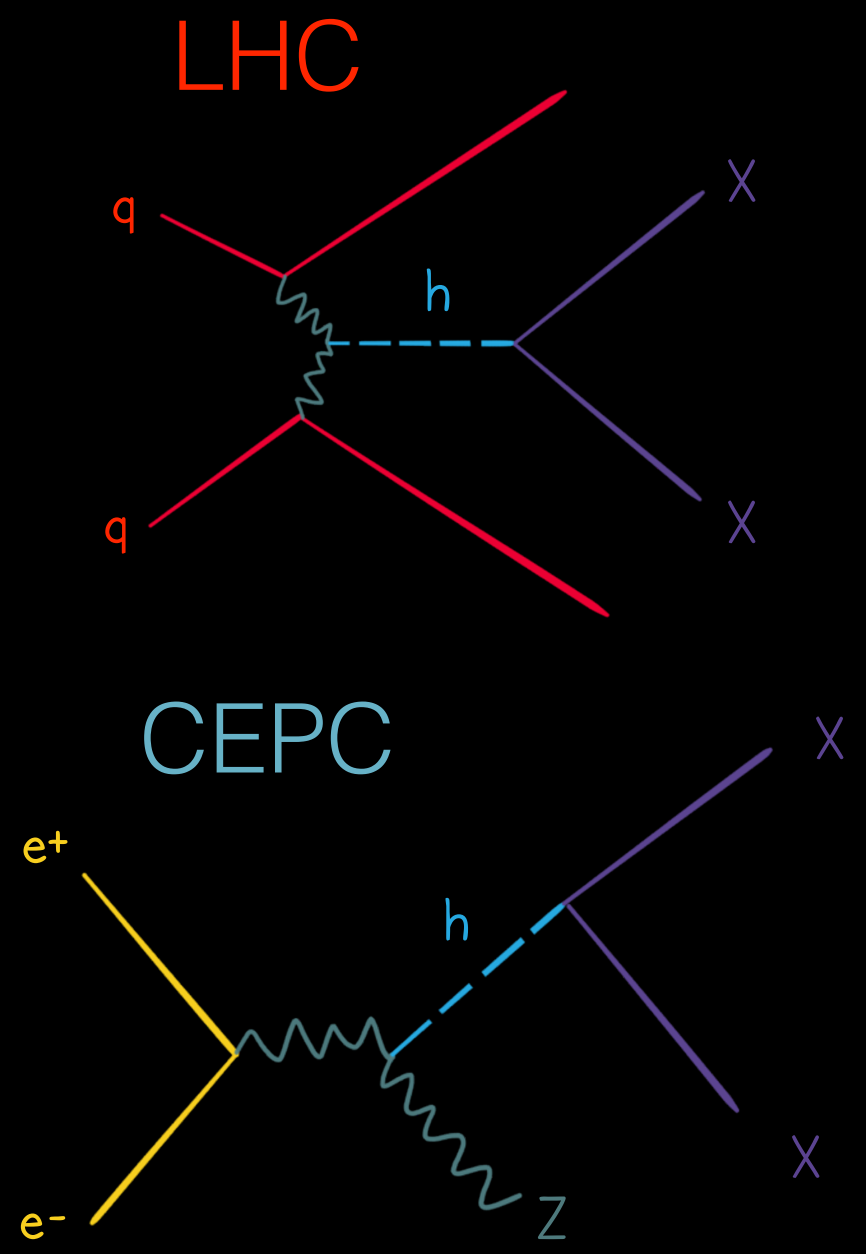
Not yet understood: when could dim-8 operators provide leading effects at CEPC? Prospects for constraints?

If yes, CEPC can test positivity bounds, therefore testing bedrock principles of QFT: analyticity, causality, unitarity.

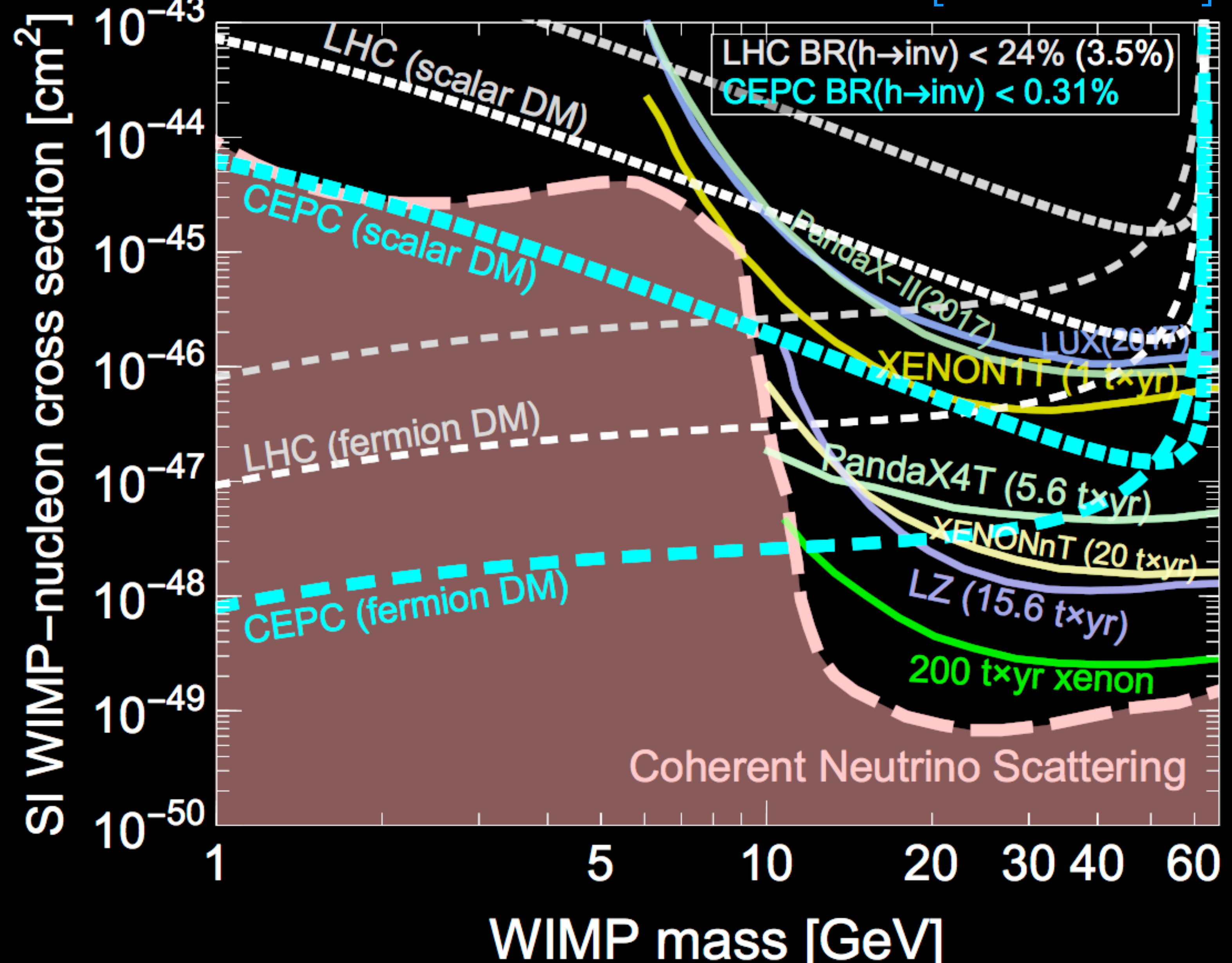
More broadly: 0.1% level precision of CEPC puts dim-8 operators within reach even if subleading, warranting further study.

Dark Matter & Higgs

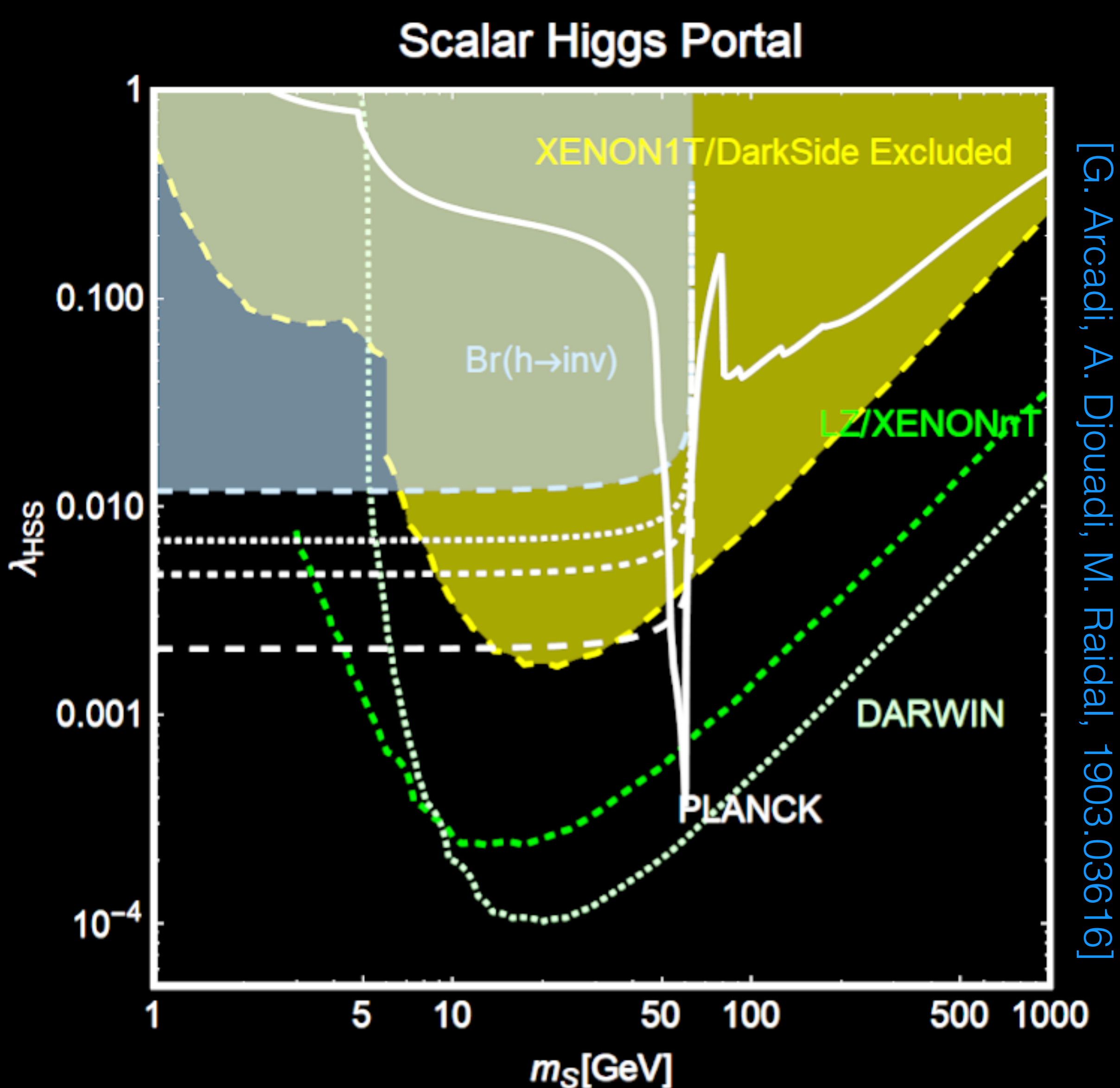
An example: dark matter interacting via the Higgs

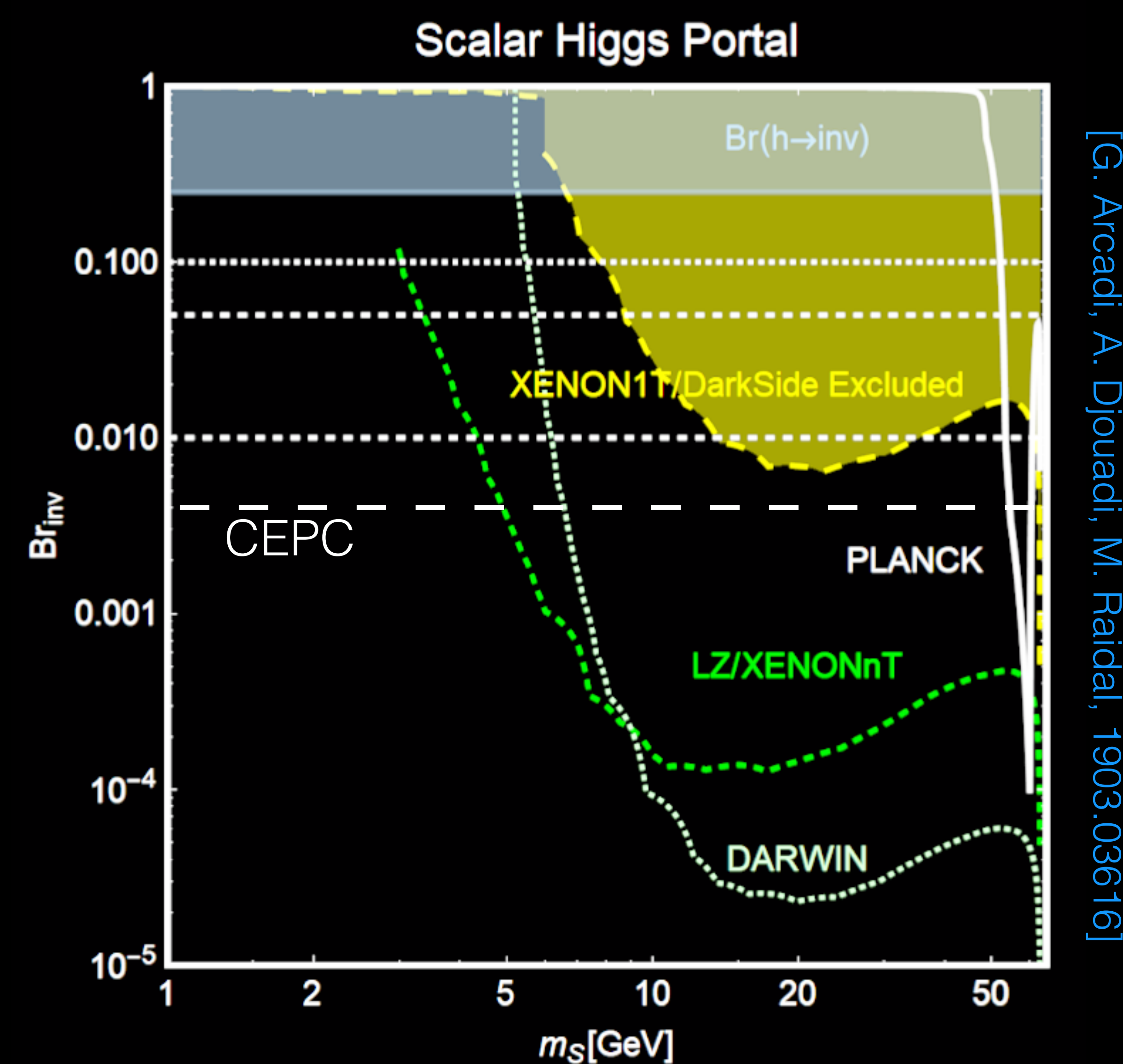


[CEPC CDR]



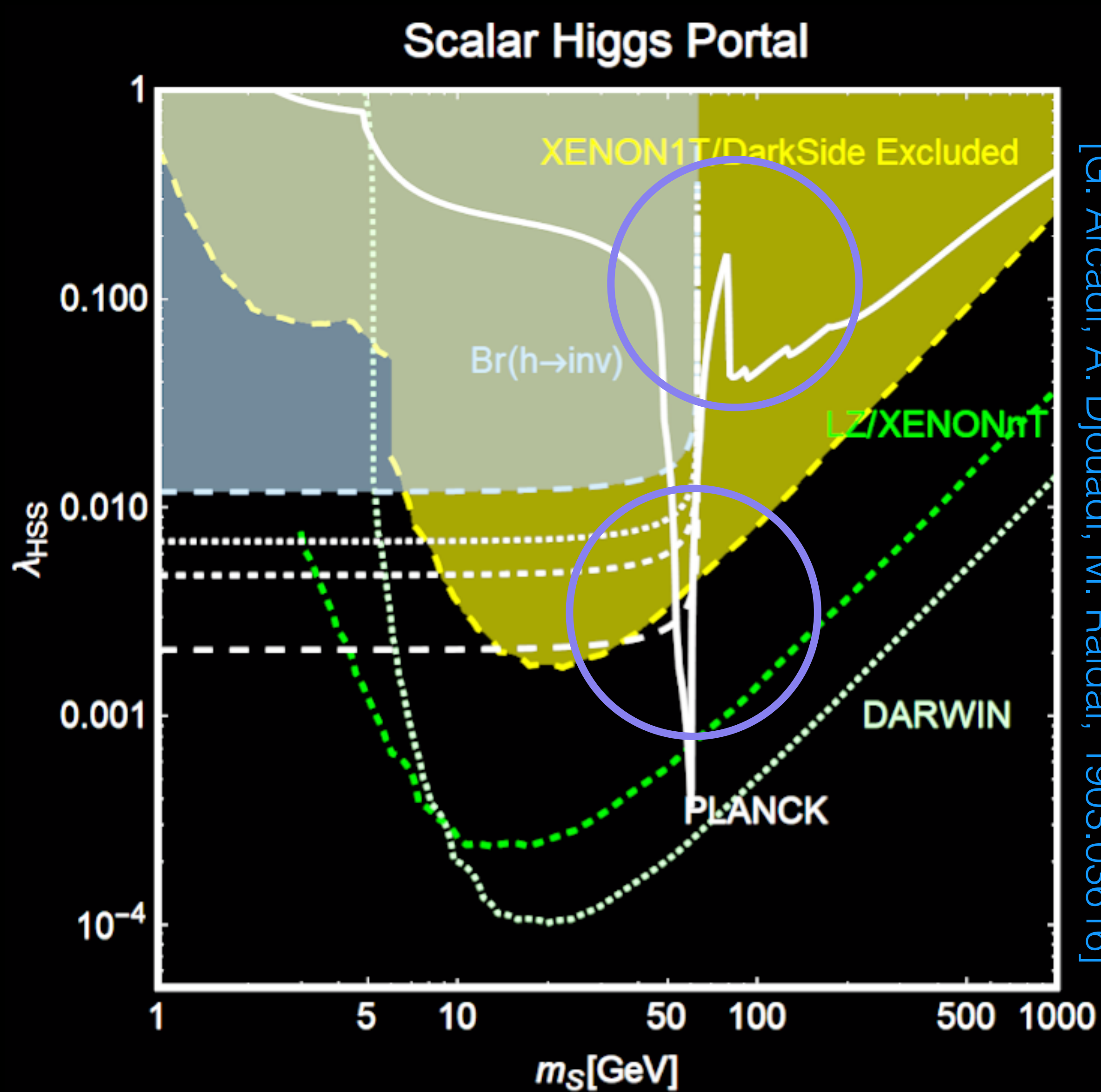
Dark Matter & Higgs





Impressive CEPC constraints from invisible Higgs not necessarily relevant to thermal relic dark matter. If not, relic abundance and Higgs coupling no longer correlated.

DM Above Threshold



[G. Arcadi, A. Djouadi, M. Raidal, 1903.03616]

CEPC relevance to thermal dark matter sharpest at resonance, $m_{DM} \sim m_h/2$

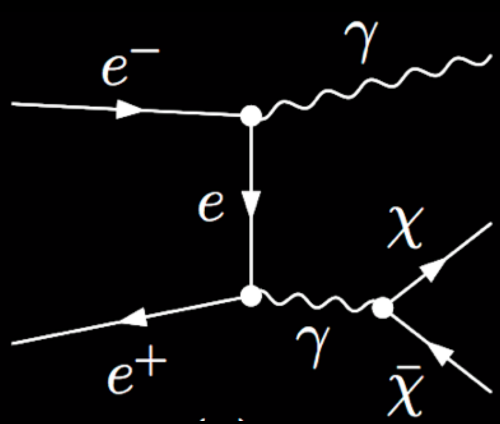
Current analysis in NWA; although $\Gamma/m_h \sim 3 \times 10^{-5}$ makes off-shell contributions a minor correction to NWA analysis, may be decisive in covering thermal relic (similar care in relic calc).

Energy would help.

Even more relevant to scenarios with direct detection blind spots, e.g. pseudo-Dirac dark matter

Millicharged DM

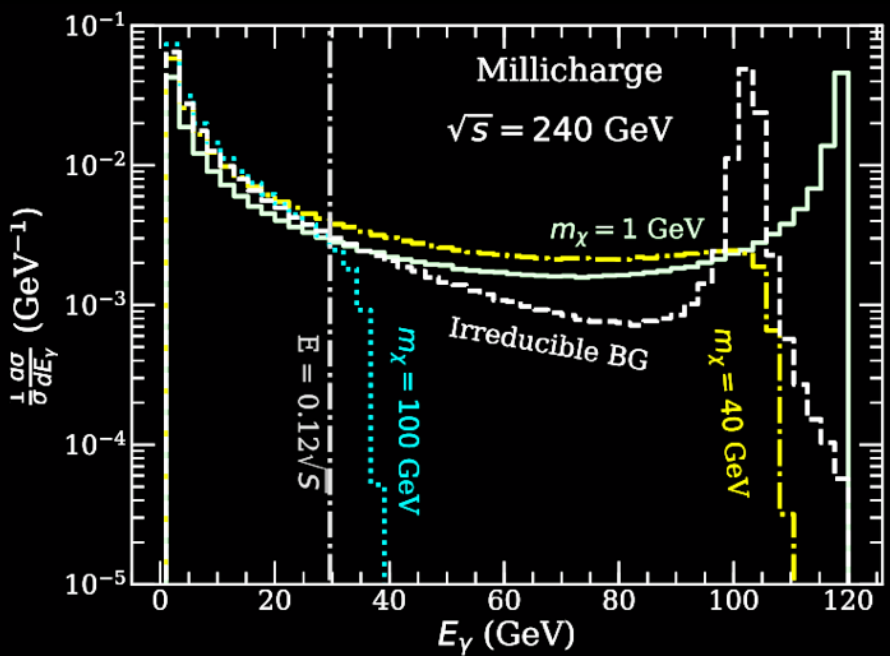
Millicharged DM from kinetic mixing: search in γ + MET

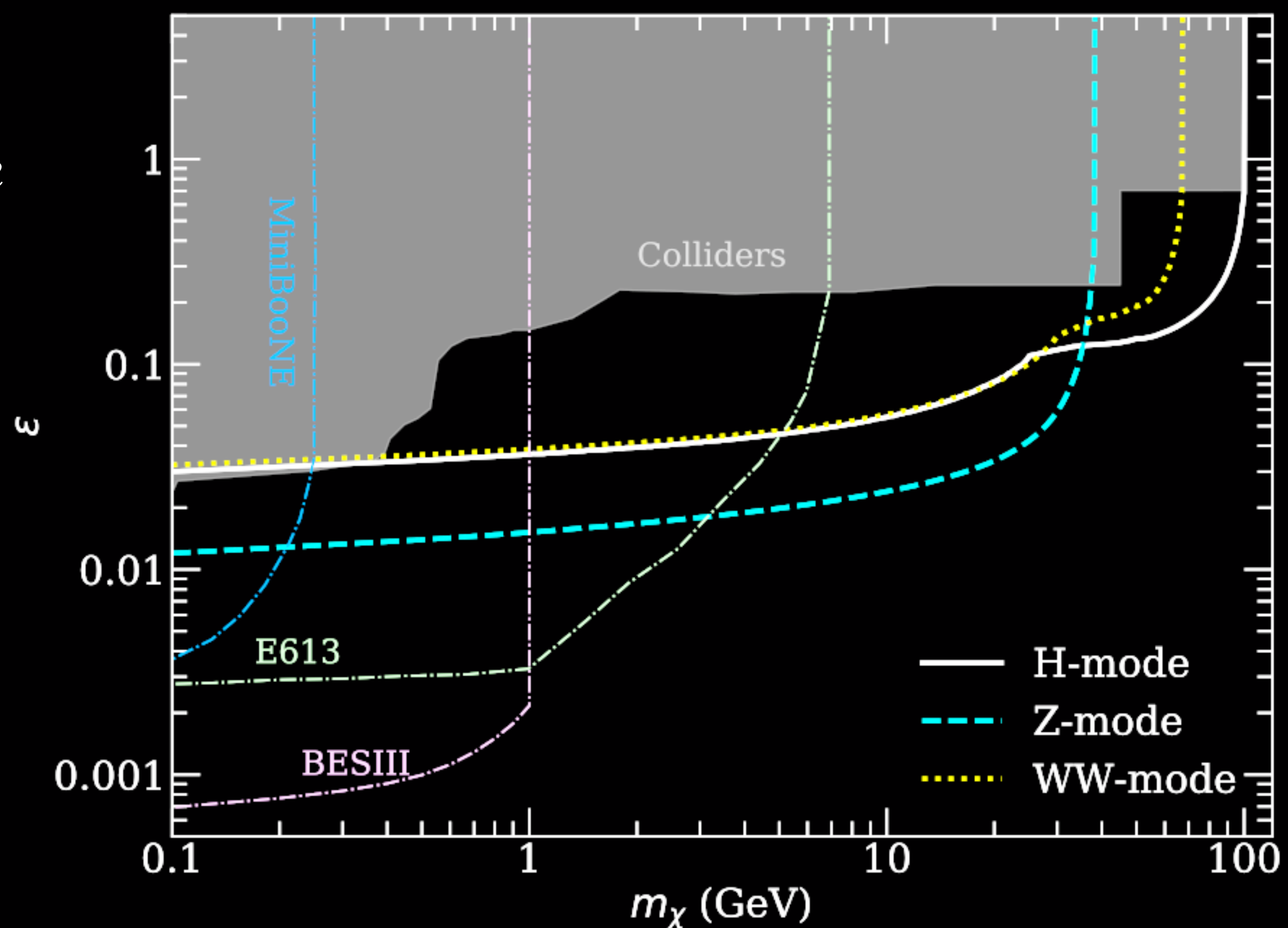


DM χ

$$Q_{em} = \varepsilon e$$

[Z. Liu, Y-H. Xu, Y. Zhang 1903.12114]

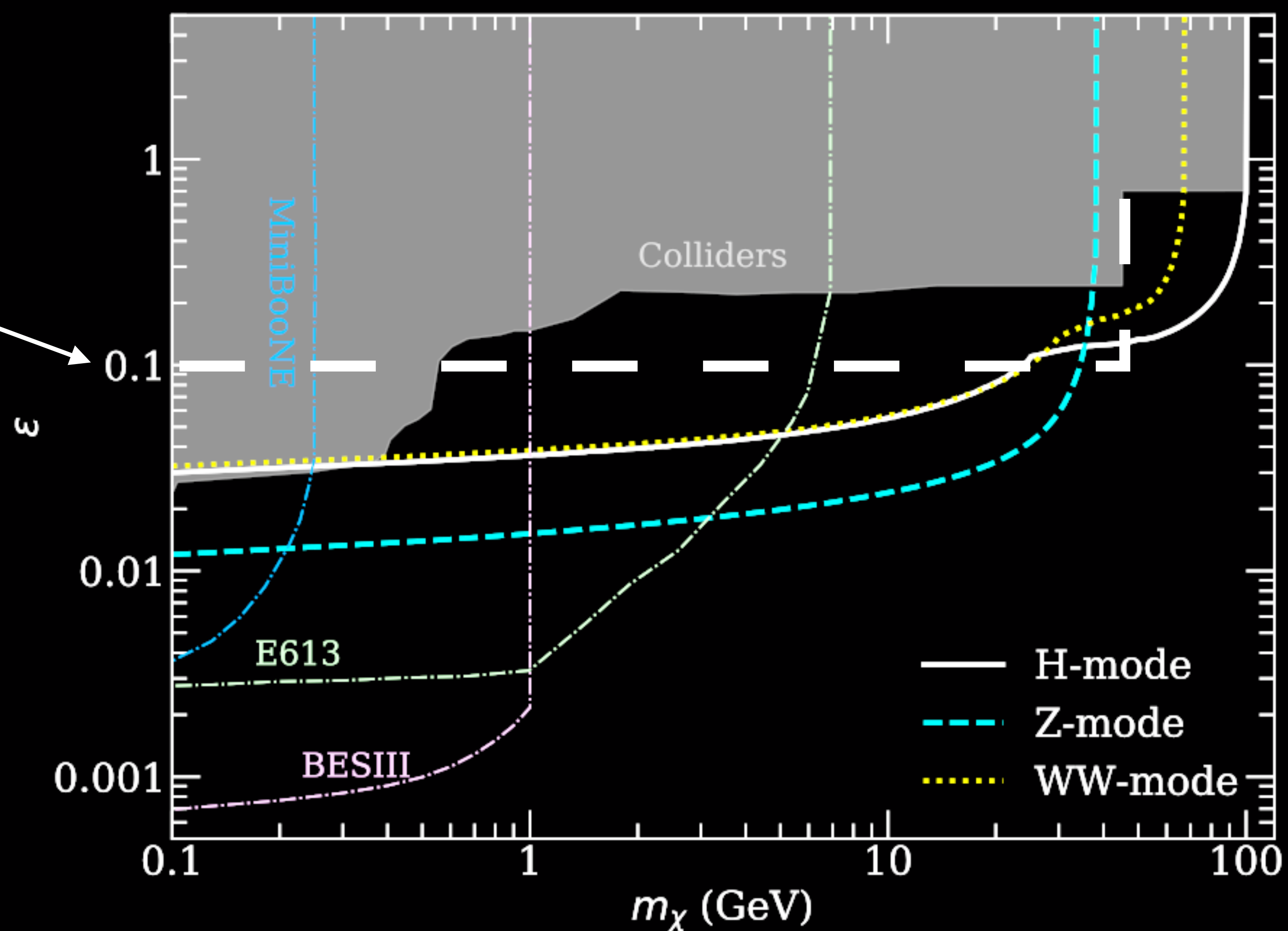




Improving coverage at LHC requires e.g. MilliQan

Dark Matter & Z

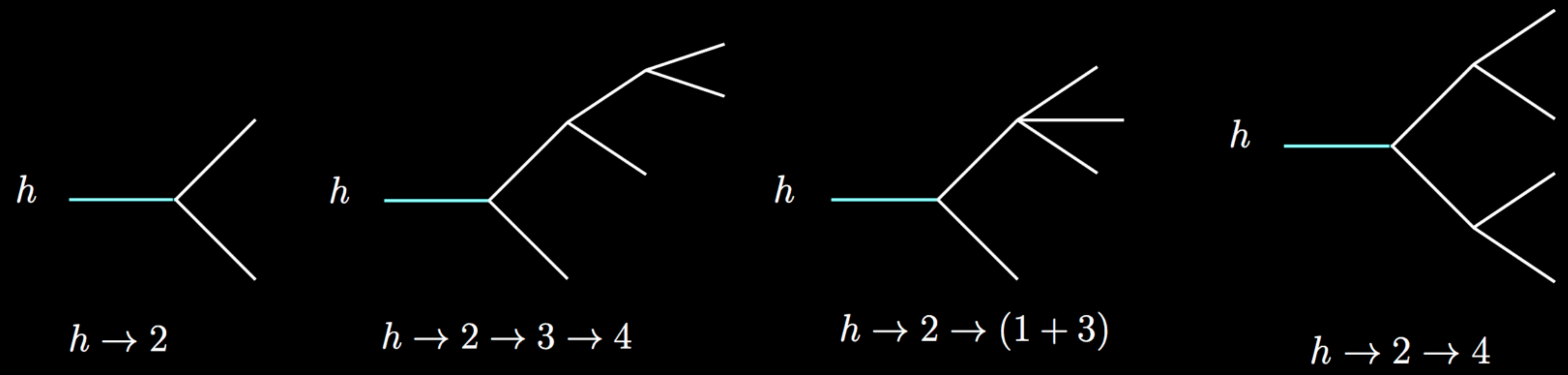
Indirect bound from improved Z width measurement @ CEPC

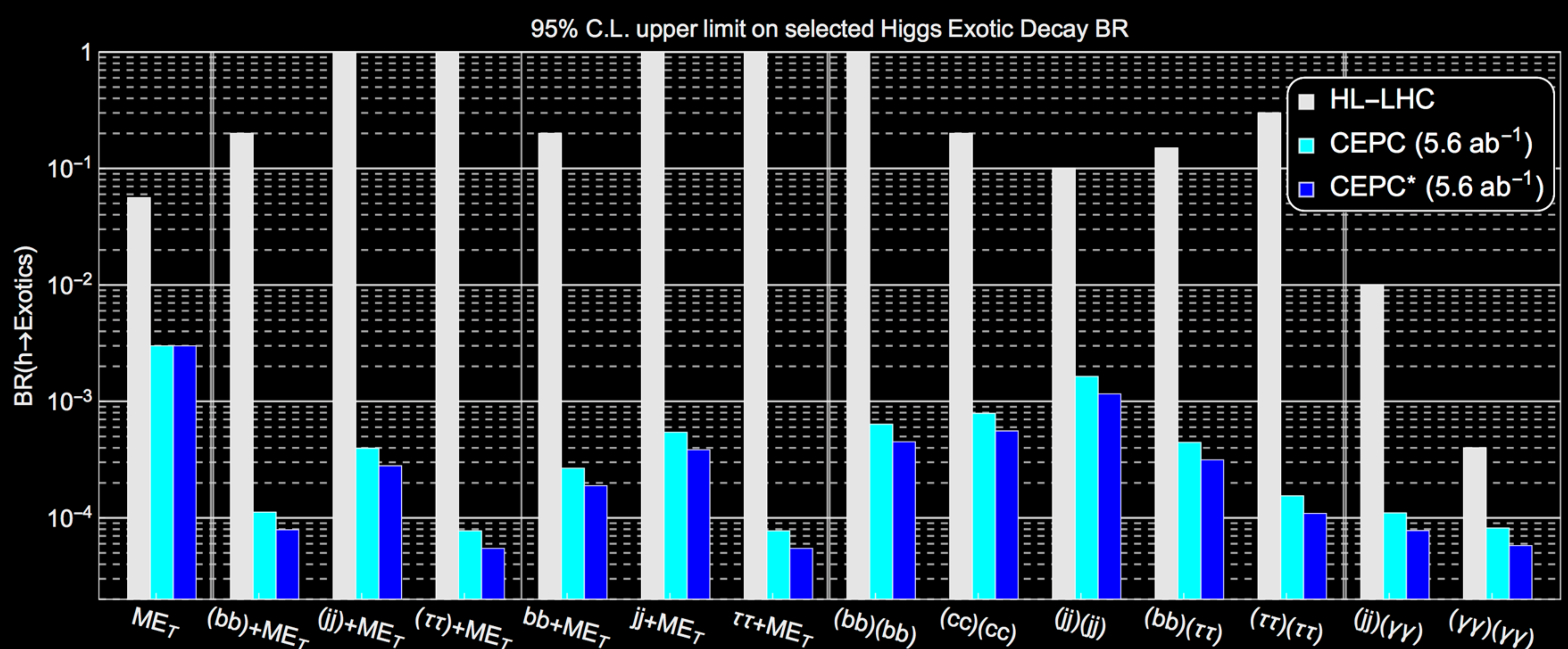


Further improvements likely possible…

see talks by Zuowei Liu, Zhijun Liang

Dark Sectors & Higgs





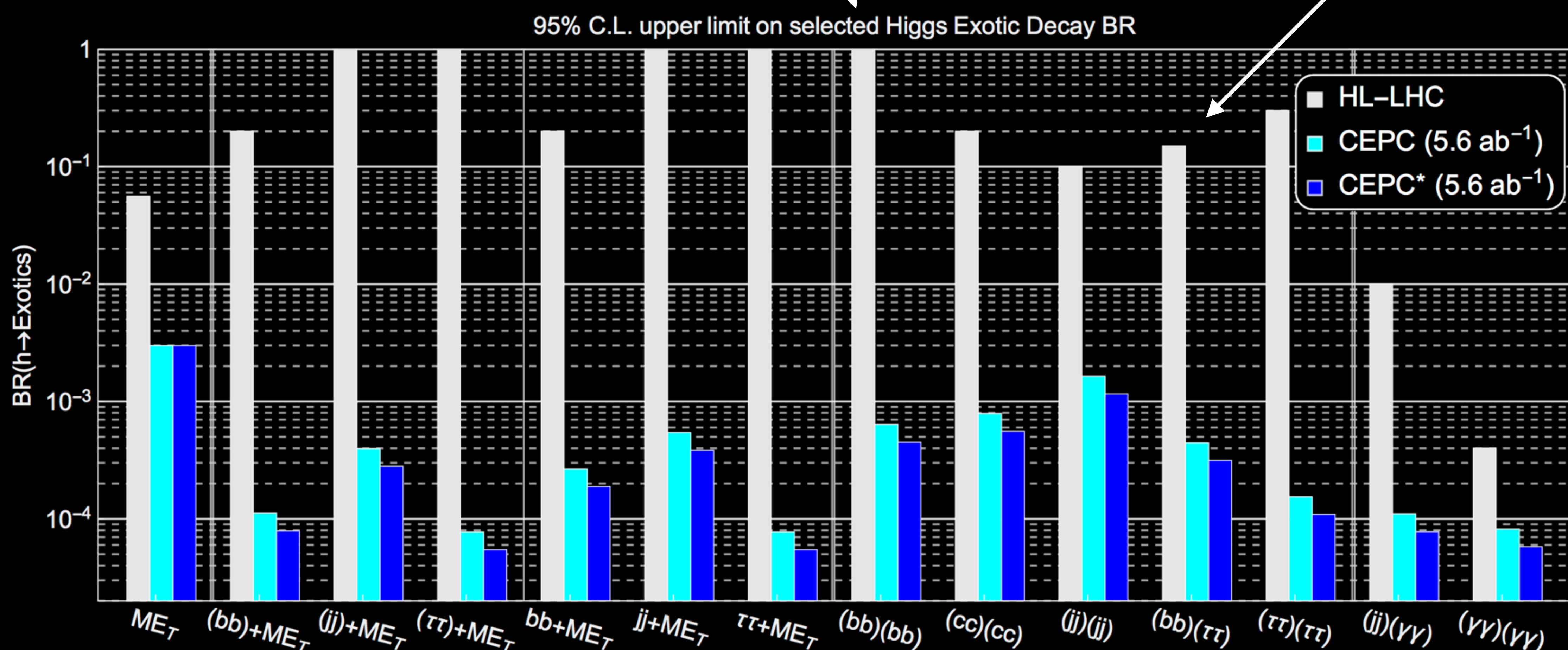
[CEPC CDR, from Z. Liu, L-T. Wang, H. Zhang, 1612.09284]

Dark Sectors & Higgs

Most of the HL-LHC projections from 2013, very conservative, many w/ 300/fb

LHC limit already BR < 50% w/ 36/fb

LHC limit at BR < 4%, CMS HL-LHC projection BR < 0.4%

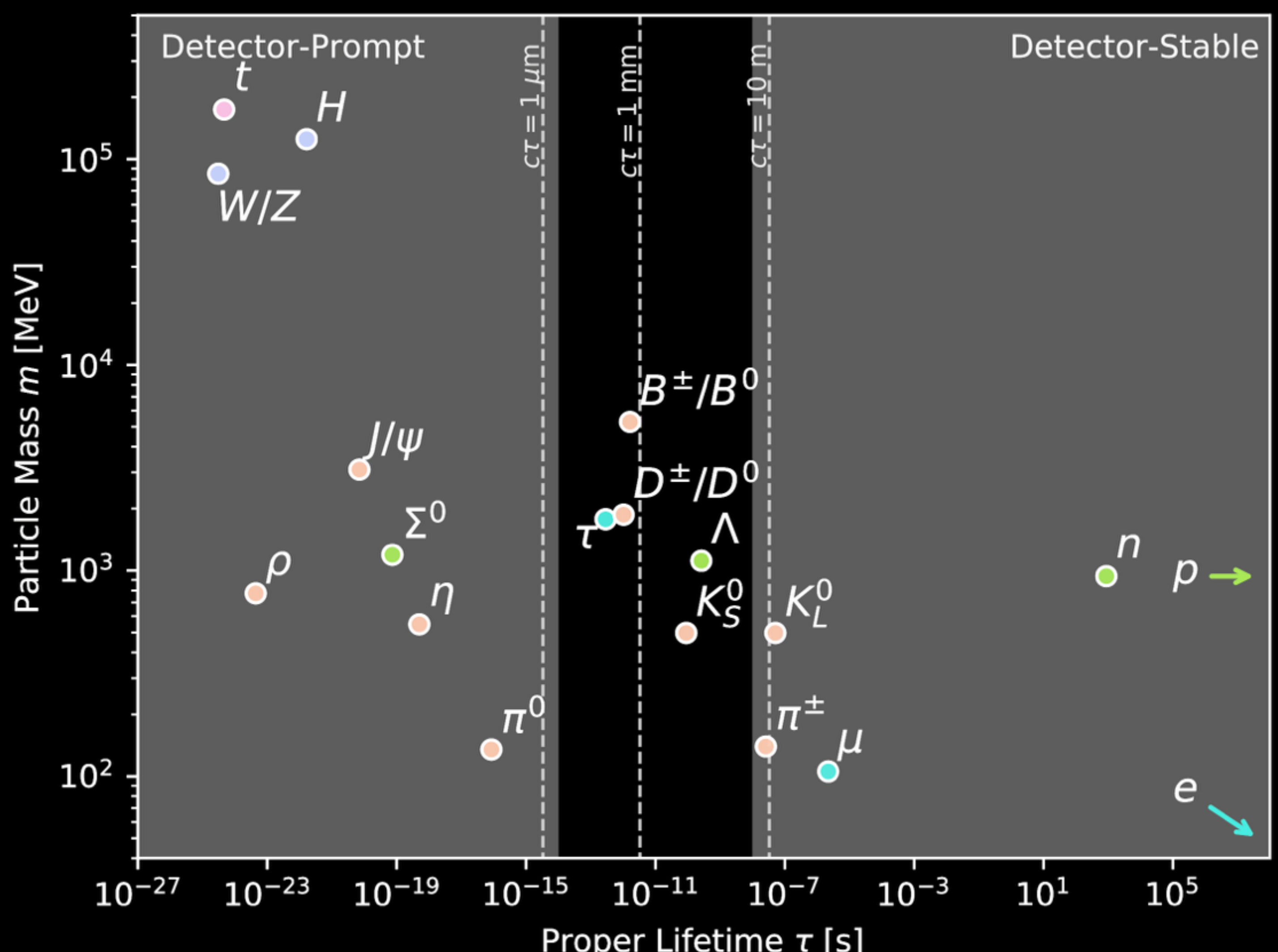


HL-LHC still unlikely to get below the % level in most channels; still impressive improvement at CEPC, time for greater ambition.

Dark Sectors & Higgs

Dark sector decays to SM can have macroscopic decay lengths
→ long-lived particles (LLPs)

[Lee, Ohm, Soffer, Yu 1810.12602]

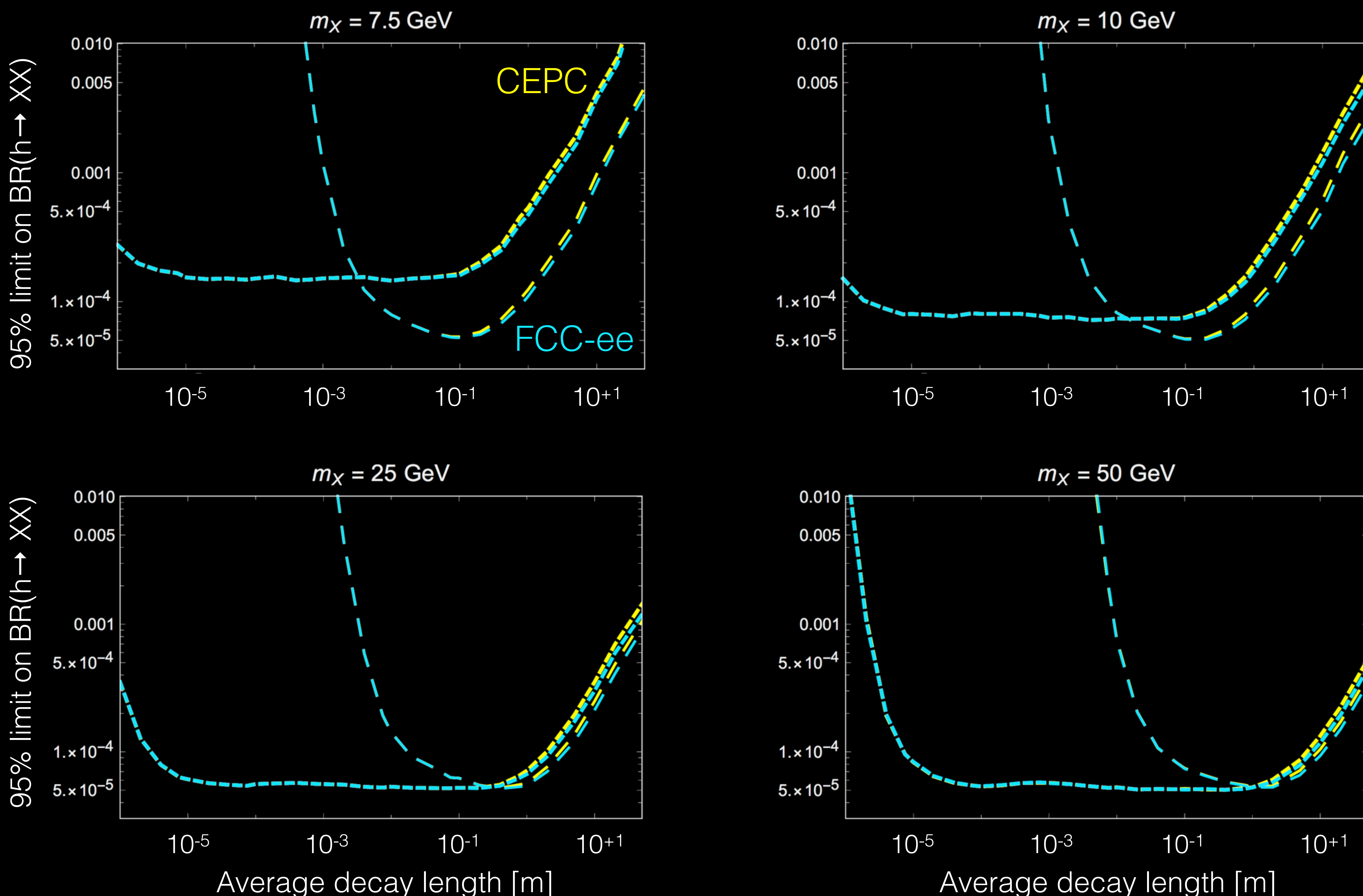


Easily realized in dark sectors coupling via Higgs

LHC sensitivity largely trigger-limited

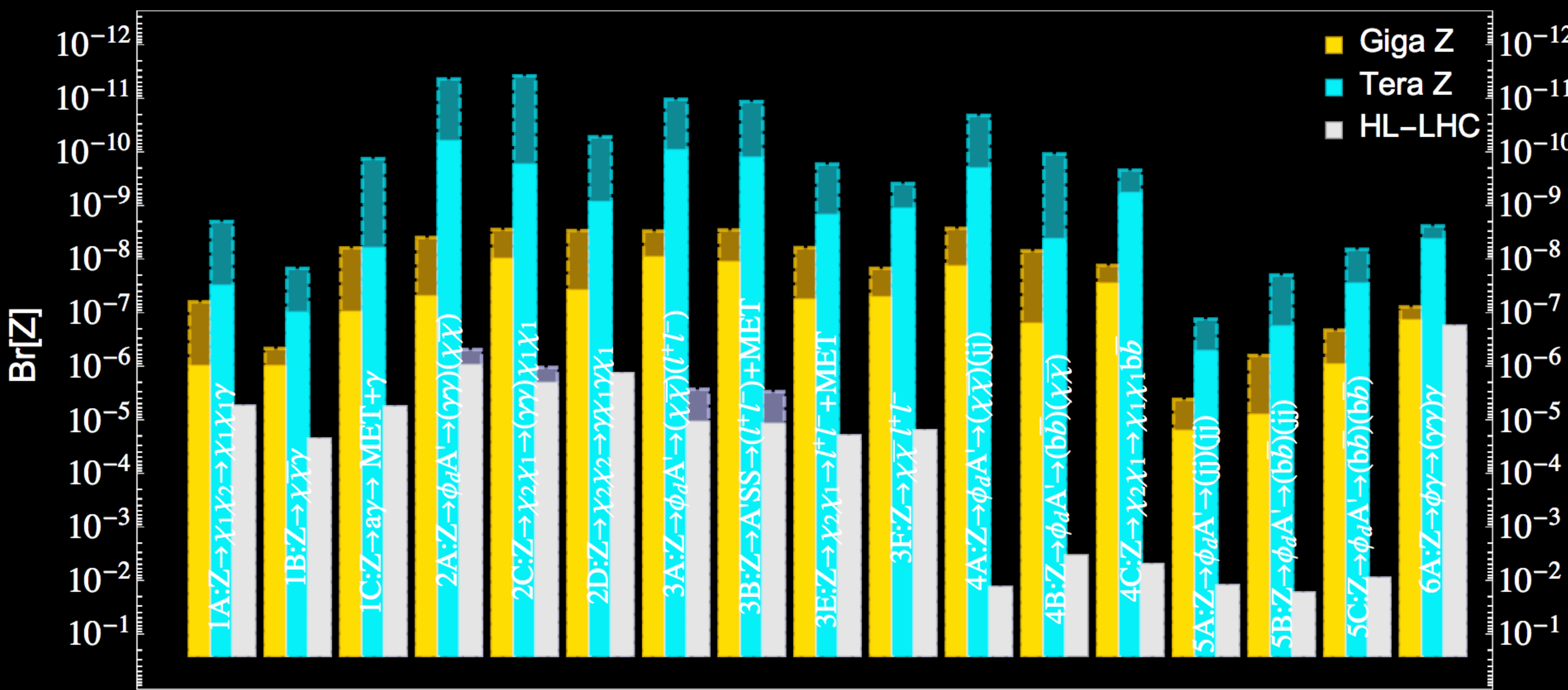
Sensitivity of CEPC & other lepton colliders relatively unexplored

[S. Alipour-fard, NC, M. Jiang, S. Koren, 1812.05588]



Competitive w/ LHC, likely stronger at low LLP mass, detailed study required

Dark Sectors & Z



LHC limited by large QCD and QCD-induced backgrounds, though some improvement in HL-LHC reach possible.

[CEPC CDR, from J. Liu, L-T. Wang, X-P. Wang, W. Xue 1712.07237]

Flavor

Particle	@ Tera-Z	@ Belle II		@ LHCb
***b* hadrons**				
B^+	2×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B^0	2×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B_s	7×10^{9}	3×10^{8}	$(5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S))$	8×10^{12}
b baryons	3×10^{9}			1×10^{13}
Λ_b	3×10^{9}			1×10^{13}

vs Belle II: b baryons, Λ_b, 100x B_s
vs LHCb: low bkg→neutrals (γ, π_0,…)

Unique sensitivity to processes unavailable at LHCb or Belle II: flavor-violating Z decays*, lepton universality in Z decays*, rare $b \to s\tau\tau$ decays, rare $b \to s\nu\nu$ decays, B_c decays*, semi-tauonic $b \to c\tau\nu$ decays, τ decays, FCNC single top.

*Progress relative to CDR, see e.g. talks by Sebastien Descotes-Genon, Soeren Prell, Lorenzo Calibbi. *Other estimates based on scaling, detailed studies required.*

Conclusions

- The physics case for CEPC is robust and compelling; time for great ambition now that details are converging.
- Big questions: fundamental identity of Higgs, origin & nature of EWSB, identity of dark matter, existence of dark sectors, origin of flavor
- Benchmark analyses continually evolving, new directions beckon: **Higgs form factor**, **tests of QFT** (dimension-8 operators & positivity), **dark matter** (Higgs portal @ threshold; millicharge), **dark sectors** (prompt & long-lived exotic decays), **flavor**…
- …and this is only the beginning.

Thank you!