Physics Motivation for Future Colliders

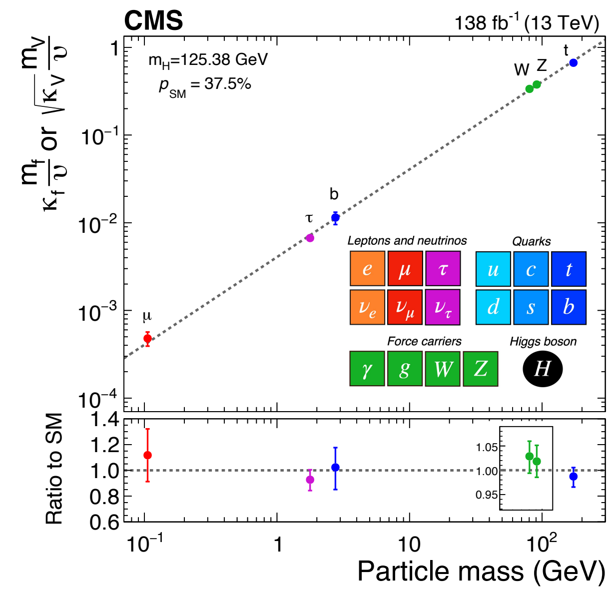
S. Dawson, BNL

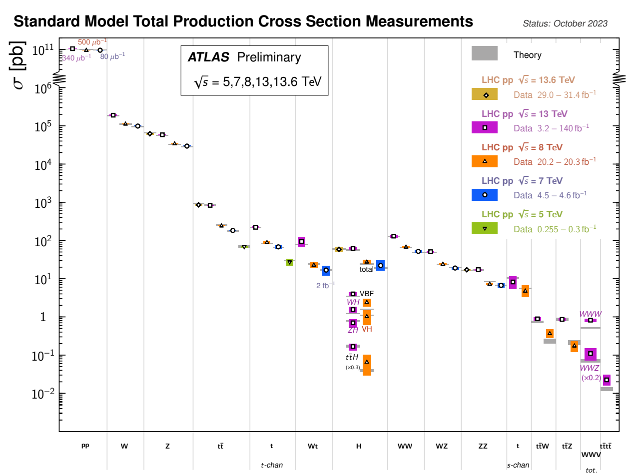
LHCP Conference, Northeastern University

June 4, 2024

Where are we?

- What are the big questions of particle physics?
- What do we expect to learn before the next collider?
- Some possible futures





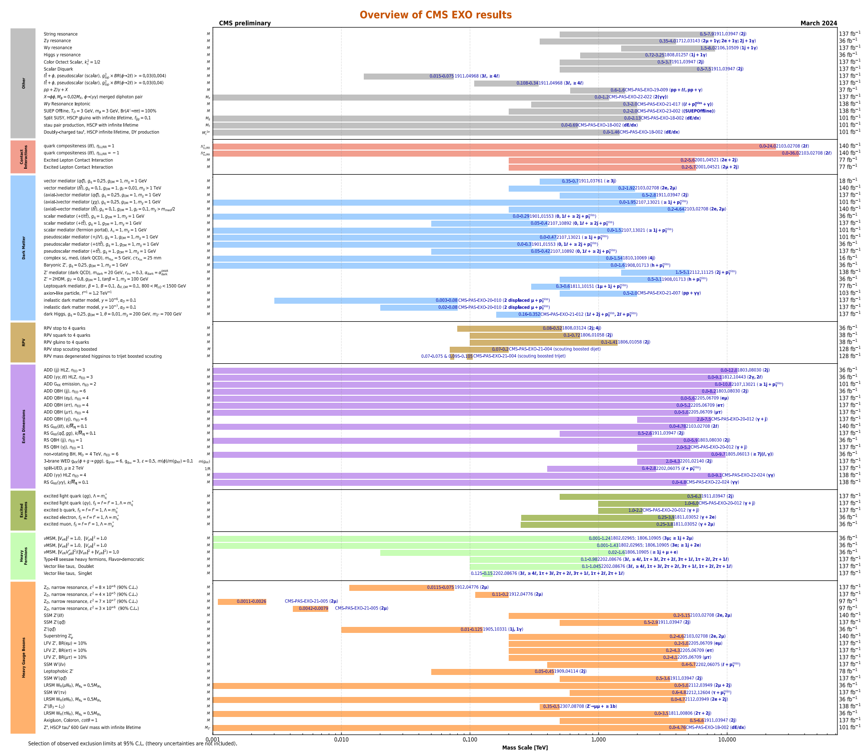
THE STANDARD MODEL WORKS!

And it works over many orders of magnitude

New physics is probably at the >1 TeV Scale

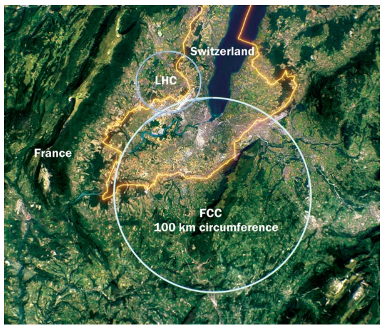
or…. It could be very weakly coupled…..

The exciting physics at an e^+e^- collider is likely to be precision physics



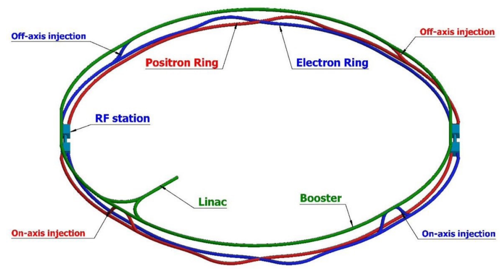
1 TeV

Many proposals for e⁺e⁻ Colliders



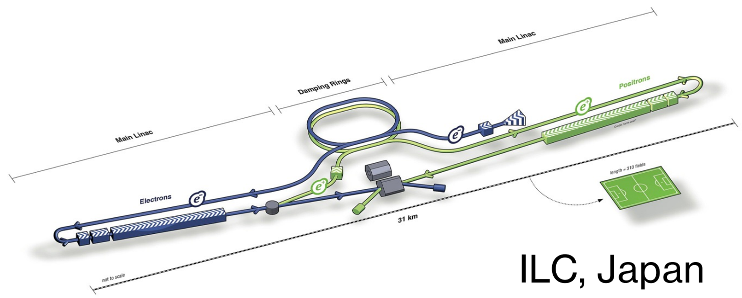
FCC-ee, CERN

$\sqrt{s} = M_Z \rightarrow 2M_W \rightarrow 240\ GeV \rightarrow 2M_t$



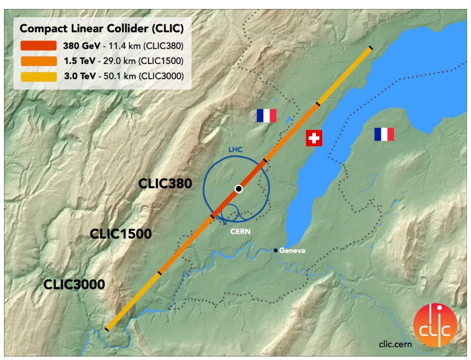
CEPC, China

$\sqrt{s} = M_Z \rightarrow 2M_W \rightarrow 240\ GeV$



ILC, Japan

$\sqrt{s} = 250\ GeV \rightarrow 500\ GeV \rightarrow 1\ TeV$

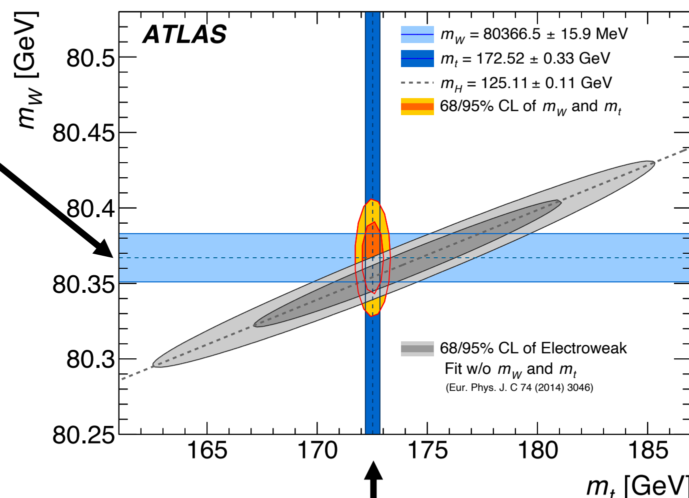


CLIC, CERN

$\sqrt{s} = 380\ GeV \rightarrow 1.5\ TeV \rightarrow 3\ TeV$

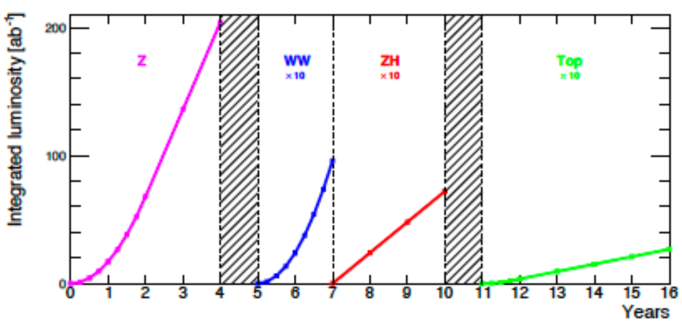
The SM works at the Quantum Level

Running e^+e^- at $2M_W$ will take
$\delta M_W = \pm 15\ MeV \rightarrow \pm .4\ MeV$



Running e^+e^- at the Z resonance will make this narrower (quantum corrections to Z observables depend on M_H)

Running e^+e^- at $\sqrt{s}$=365 GeV will take
$\delta m_t = \pm .5\ GeV \rightarrow \pm .017 GeV$



FCC-ee baseline

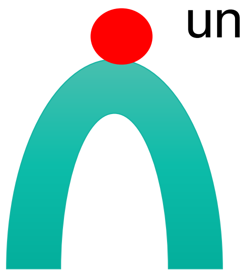
e^+e^- colliders take test of quantum effects to new level

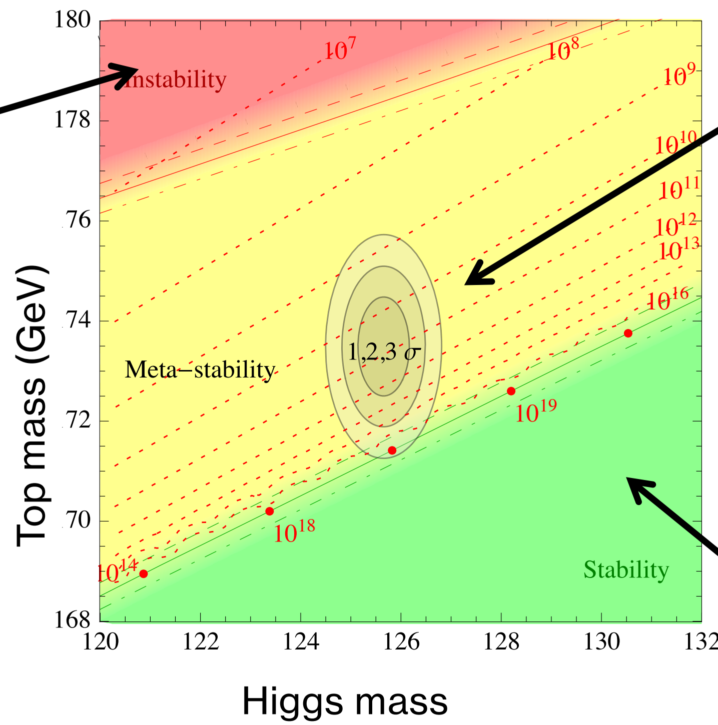
ATLAS, 2403.15085

Precision masses point to the fate of the Universe

- *Assuming no new physics!*

Unstable universe





Our world

Stable universe

Whether or not the Higgs potential is unstable depends sensitively on precision measurements of M_t

1307.3536

Why new physics? We've all seen the list

- What is dark matter? What is dark energy?
- Why is the top quark so much heavier than the W boson?
- Why is the weak force so much weaker than the strong force?
- Where does CP violation come from?
- What is the source of the matter-antimatter asymmetry in the universe?
- What is the shape of the Higgs potential?
- What about neutrino masses?

We have the SM, but…

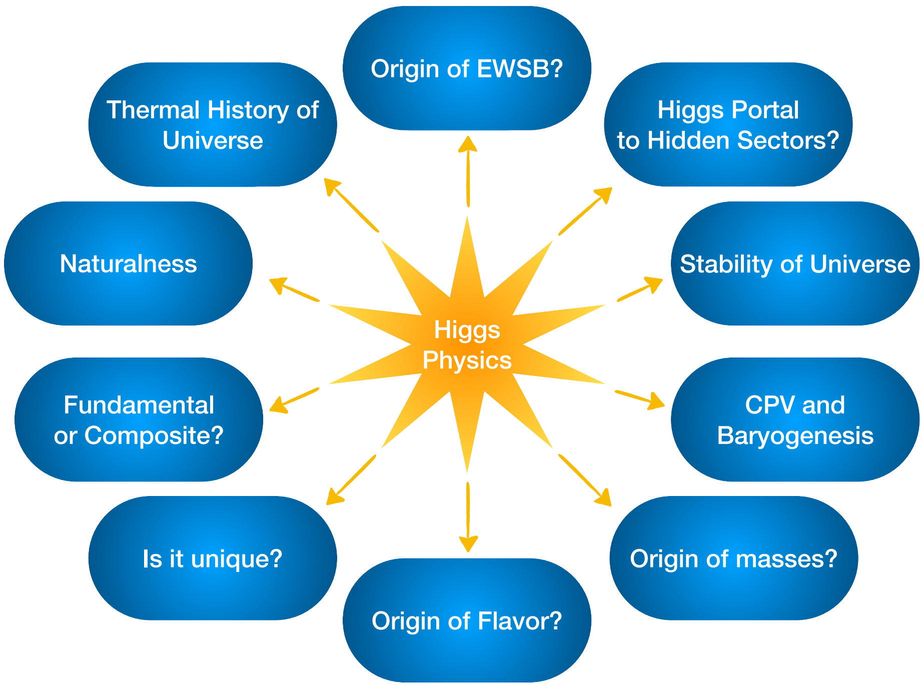
The SM doesn't answer any of these questions

Together, the LHC and future colliders can yield new insights

I will focus on e^+e^- colliders

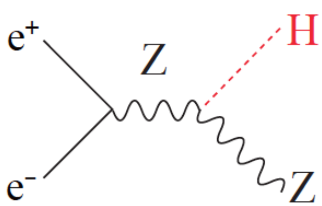
New physics is needed, but we don't know where

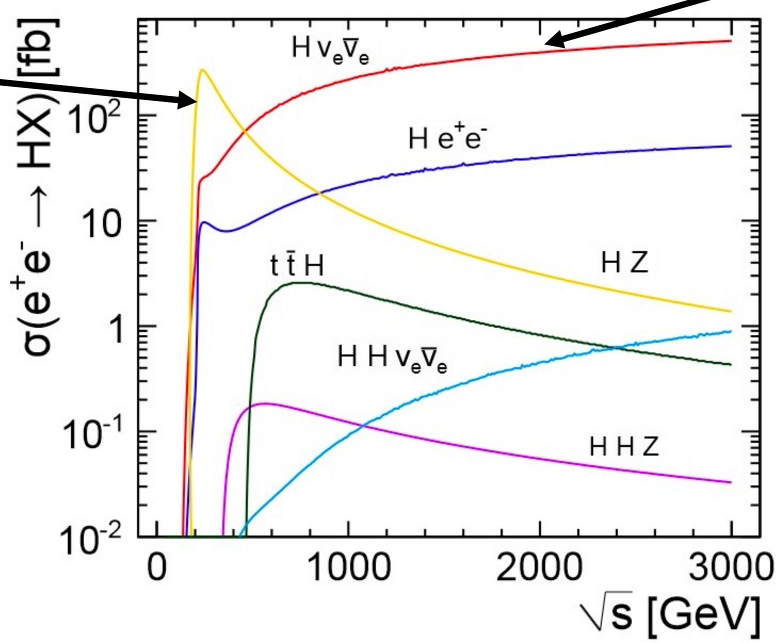
The Higgs is central to our understanding

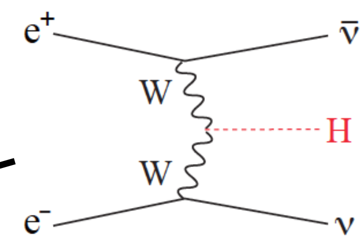


HL-LHC and future colliders are complementary probes of these questions

e^+e^- colliders are Higgs factories







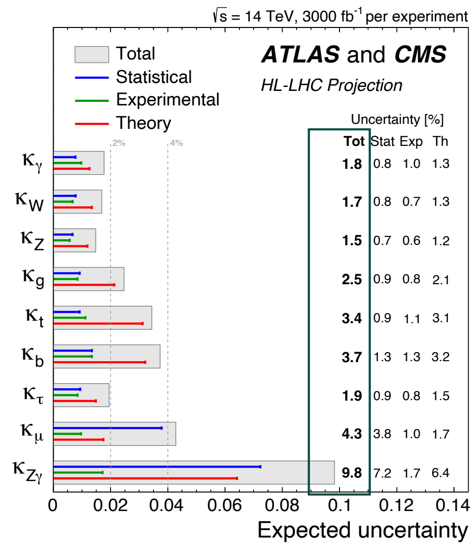
FCC-ee:

- ***A million Higgs particles***
- Baseline with 4 interaction points
- 240 GeV / 7.2 ab^{-1} and

  365 GeV/ 3 ab^{-1}

We already know a lot about the Higgs

- *The Higgs couplings are close to SM predictions*
- High Luminosity LHC will push Higgs coupling limits to 2-4%, restricting many possibilities for new physics



Target for e^+e^- collider Higgs precision must be O(1%)

2203.13923

Precision Measurements of Higgs Couplings

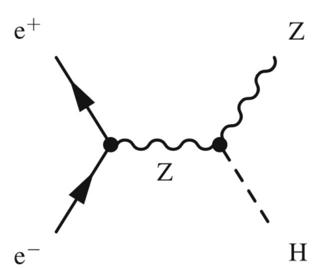
- Is there a target precision?
- Compute deviations in Standard Model Effective Field Theory (SMEFT)
- Consistent expansion that can be systematically improved
- Power is that Higgs couplings are related to other processes (WW production, top quark production, Z pole measurements)
- Generically, deviations from SM are of

$$\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right) \sim 1.6\% \left(\frac{2\ TeV}{\Lambda}\right)^2$$

- VERY MODEL DEPENDENT!!! (and a moving target....)

Model independent Higgs measurements

- Model independent Higgs couplings and Higgs width at e^+e^- colliders
- Total Higgs width is window into light new physics. Perhaps H-> dark matter?

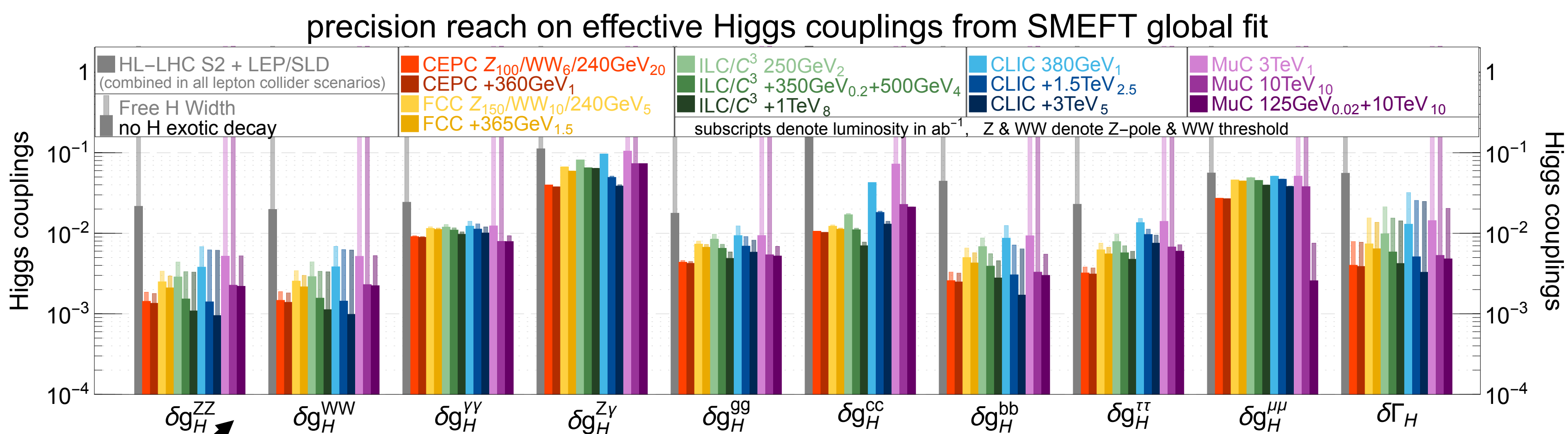


- Measure recoil mass from $Z \rightarrow l^+l^-$ to get σ_{ZH} and absolute measurement of g_{HZZ}
- Exclusive Higgs decays to xx give g_{Hxx}

$$\sigma_{HZ}\frac{\Gamma(H\rightarrow ZZ)}{\Gamma_H} \sim \frac{g^4_{HZZ}}{\Gamma_H}$$

*For the purists among you, all of this can be done in a SMEFT framework

Significant advances in precision



Order of magnitude improvement in hWW/hZZ couplings at future machines

Off-shell@HL-LHC, $\delta\Gamma_H$~17%
Recoil@full FCC-ee, $\delta\Gamma_H$~1%

Solid: no BSM decays
Light: width floats (invisible/BSM allowed)

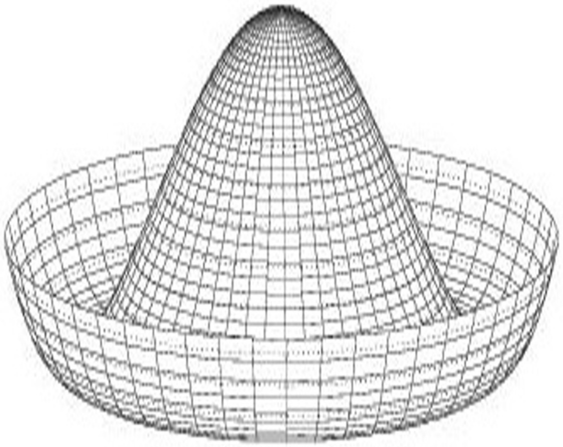
2209.08078

Order of magnitude improvement in unconstrained Γ_H at future machines

Why do we care about Higgs couplings?

- We know almost nothing about the Higgs potential!
- Higgs potential has 2 free parameters, μ^2, λ

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$



- Trade μ^2, λ for v=246 GeV, M_H^2

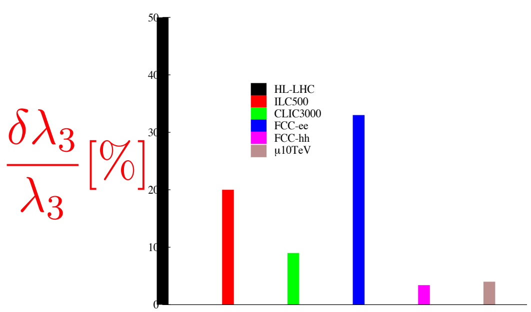
$$V \to \frac{M_H^2}{2} H^2 + \lambda_3 v H^3 + \lambda_4 H^4 \qquad \lambda_3 = \frac{M_H^2}{2v^2}$$

  - λ_3 and λ_4 NOT FREE PARAMETERS
  - Can we measure these couplings at a future collider?

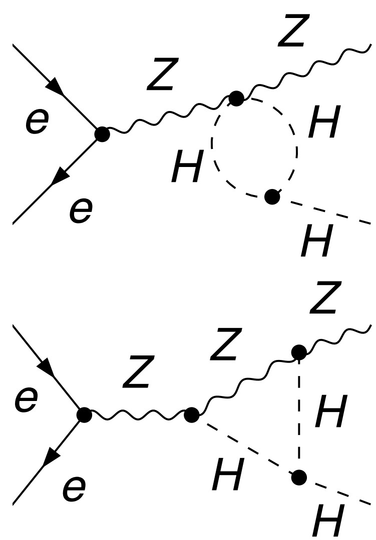
Does EWSB really work like this??

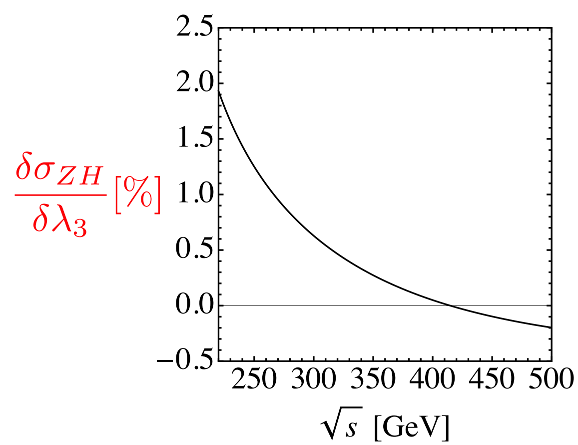
Quantum corrections as tool for discovery

- Contributions from operators that first arise at one-loop give window to multiple new interactions beyond tree level fits
- Current LHC indirect sensitivity compatible with direct measurement from HH production at LHC



Snowmass Higgs, arXiv:2209.07510



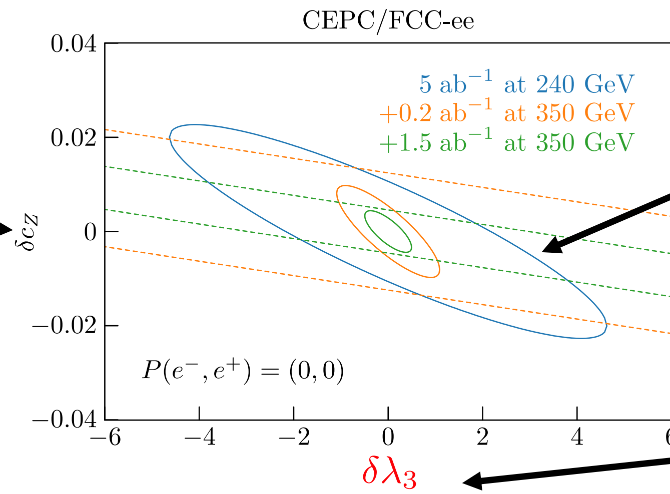


McCullough,arXiv:1312.3322

Correlations: Tri-linear HHH vs modifications to ZHH coupling

- There are many correlated effects and cancellations

Modification of ZZH coupling. Stringent limits from Higgs decays (Note scale)



√s=240 GeV with 5 ab^{-1}

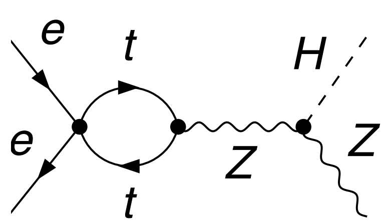
Modification of Higgs trilinear coupling

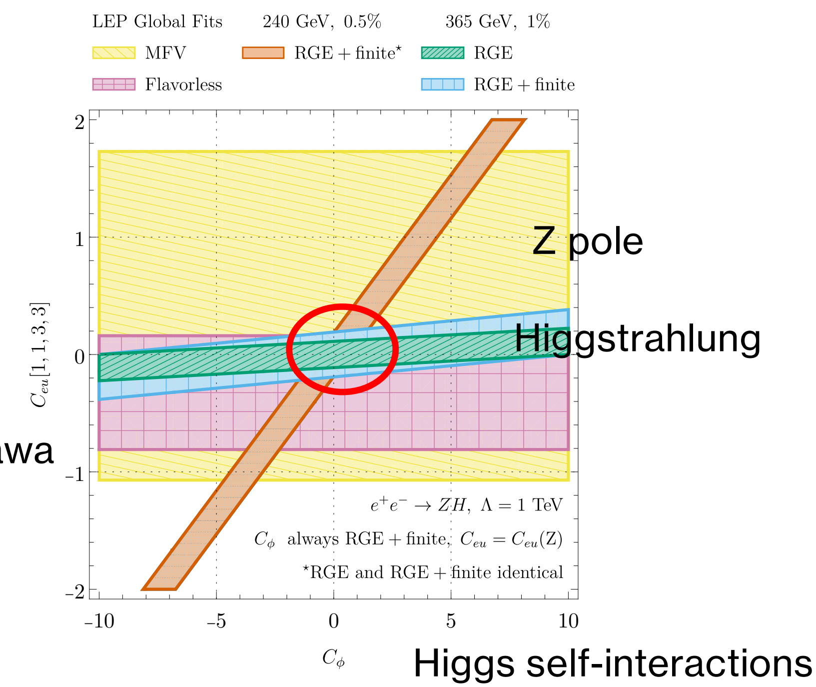
In any given BSM scenario, it is likely that there is more new physics than just modification of Higgs potential

1711.03978

$e^+e^- \to$ ZH is window to many new interactions

- Complete 1-loop SMEFT calculation of $e^+e^- \to$ ZH
- Sensitivity to many possible operators that do not contribute at tree level
- How do future constraints compare with existing information?





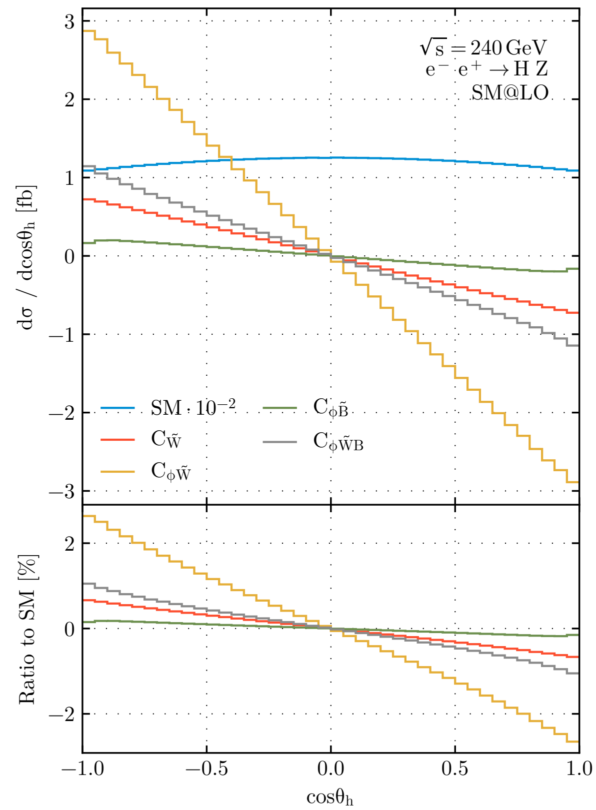
Power of measurement at 2 different energies

Asteriadis, Dawson, Giardino, and Szafron, arXiv:2024xxxx

There is sensitivity to much new physics beyond HHH coupling

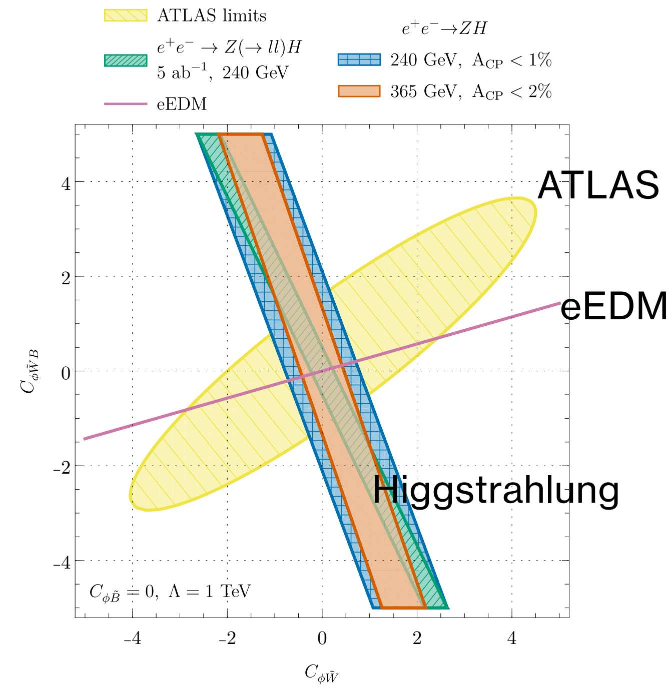
- Higgstrahlung at e^+e^- colliders is sensitive to many new interactions that are not well understood at the present time
- CP violation in the gauge sector
- At tree level, CP violating dimension-6 operators do not interfere with SM contribution from $e^+e^- \rightarrow ZH$
- At one-loop, there are further contributions from imaginary part of loop integrals

$$O_{\tilde{W}} = \epsilon_{abc} \tilde{W}_{\mu}^{a\nu} W_{\nu}^{b\rho} W_{\rho}^{c,\mu}$$
$$O_{\phi\tilde{W}} = \tilde{W}_{\mu\nu}^{a} W^{\mu\nu b} (\phi^\dagger \phi)$$
$$O_{\phi\tilde{B}} = \tilde{B}_{\mu\nu} B^{\mu\nu} (\phi^\dagger \phi)$$
$$O_{\phi\tilde{W}B} = \tilde{W}_{\mu\nu}^{a} B^{\mu\nu} (\phi^\dagger \sigma^a \phi)$$



CP violation at future e^+e^- colliders

- CP violation in the gauge sector is strongly limited by eEDMs
  - eEDM depends on multiple parameters
- Also limits from angular observables at LHC from H-> 4 lepton
- e^+e^- helps to further understand CP violation in the gauge sector

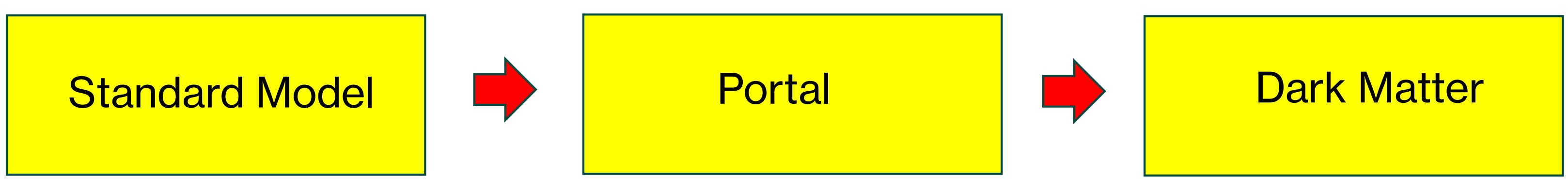


eEDM, LHC, $e+e^-$ probes of CP violation are complementary

Asteriadis, Dawson, Giardino, and Szafron, arXiv:2024xxxx

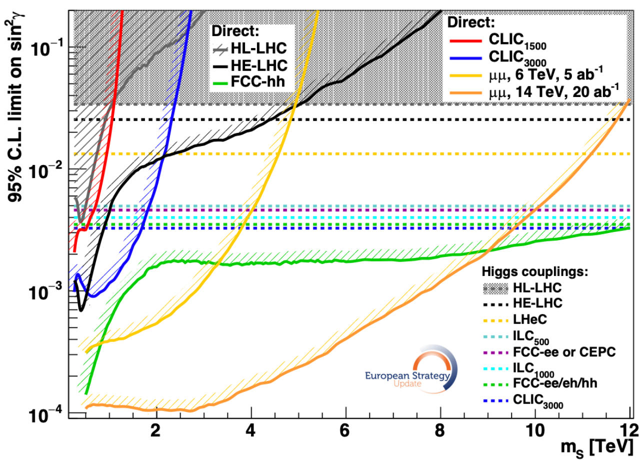
More Scalars?

- More scalars can help stabilize the Higgs potential
- More scalars can help to understand fermion masses
- Attractive scenario has dark matter connecting to the SM through a scalar portal
- More scalars can provide a strong first order EW phase transition and provide new sources of CP violation
- Future colliders sensitively probe these scenarios

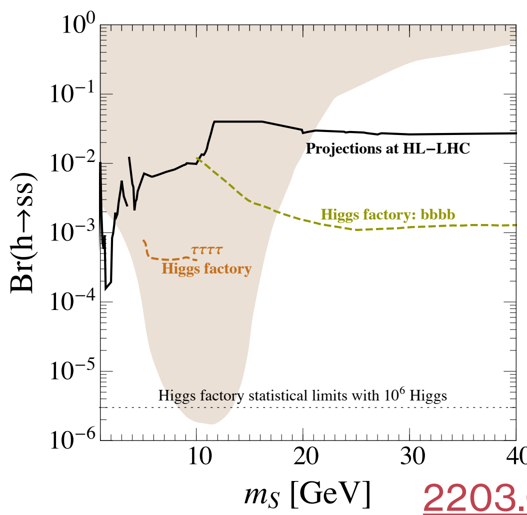


Scalar Singlet extensions

- Many variations: Z_2 symmetry, no Z_2 symmetry, complex singlet
- Complementarity between direct searches and precision Higgs measurements
- Information about EW phase transition in non-Z_2 symmetric example



ESG report, 1910.11775



2203.08206

Light scalar allows EWPT in region probed by HL-LHC and future e^+e^- colliders

Conclusions

- Much more physics than discussed here!!!!
- e^+e^- colliders are discovery machines
  - Precision Higgs measurements beyond HL-LHC
  - Test quantum consistency of SM through precision Z pole measurements
  - Probe Z boson exotic decays (dark sector)
  - Is the Higgs boson composite?
  - Probe models explaining stability of the universe
  - Further our understanding of EWSB
  - Look for axion-like particles in new regimes
  - Look for feebly interacting/long-lived particles
  - .....

Z/Higgs/top factory in clean environment

Theory effort needed to match experimental projections