Probing New Physics with Precision Higgs Measurements

CEPC Workshop
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What next in High Energy Physics?

- There are strong motivations for the BSM physics at the weak scale

Hierarchy Problem

Dark Matter

- In many cases BSM states may interact with the Higgs

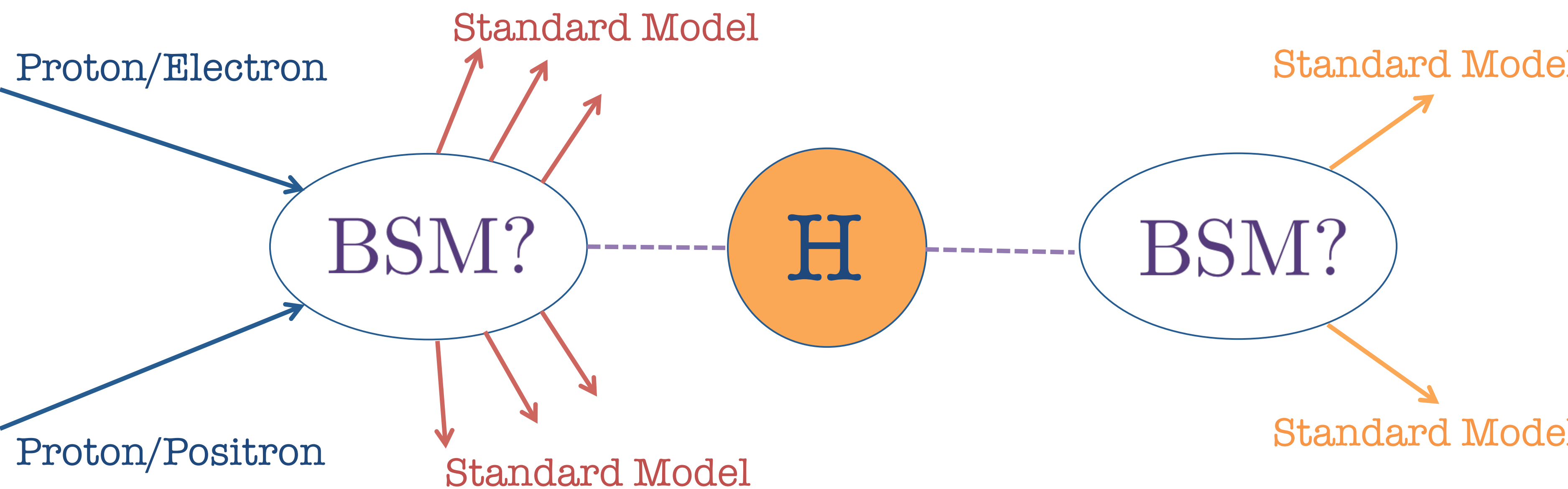
Top Partners

Higgs Portal

- However, directly observing new states may be difficult due to mass/couplings/decays….

What next in High Energy Physics?

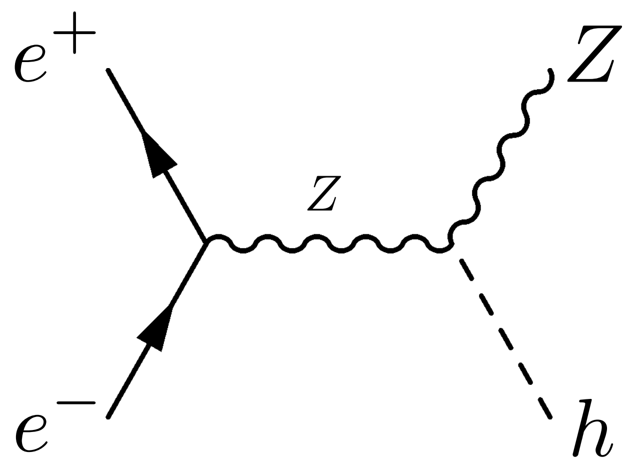
- Can search for indirect effects of BSM by measuring SM processes to high precision



- The greater the precision, the greater the <u>discovery potential</u>.

A Dream Measurement

- An e^+e^- collider is the surgeon's scalpel of particle physics.
- Dominant Higgs production at lower energies is associated production:

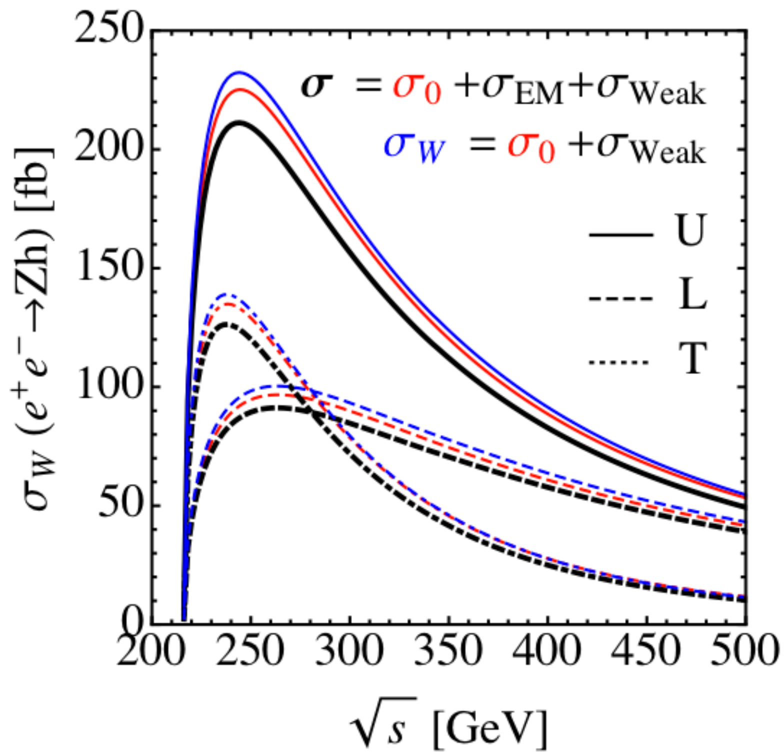


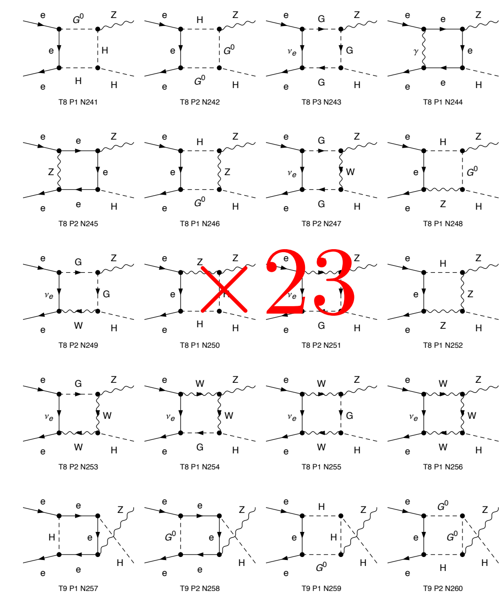
- Can measure Z-recoils alone
  - Total cross section measurement independent of Higgs decays!

A Dream Measurement

- At CEPC could measure this cross section with accuracy of 0.5%. What does this mean?

SM 1-loop electroweak corrections to cross section are around 3%





- Probe quantum regime of Higgs:
  - Can probe new physics near weak scale with perturbative Higgs couplings!

Outline

- I want to focus on what we can learn about the quantum Higgs world. Tree-level modifications due to e.g. extended scalar sectors, have been well studied already.

- New particle benchmarks
  - Vector-like leptons
  - Higgs Portal

- Modified Higgs interactions
  - Higgs self-coupling

- Conclusions

Probing New Particles

- BSM States considered:
  - Uncolored
  - Coupled to Higgs
  - Possibly electroweak-charged
- This leaves two main observables:

$$\delta_{2\sigma}\left(\mathrm{BR}_{h\to\gamma\gamma}\right) \approx 5\% \qquad \delta_{2\sigma}\left(\sigma_{e^+e^-\to hZ}\right) \approx 1\%$$

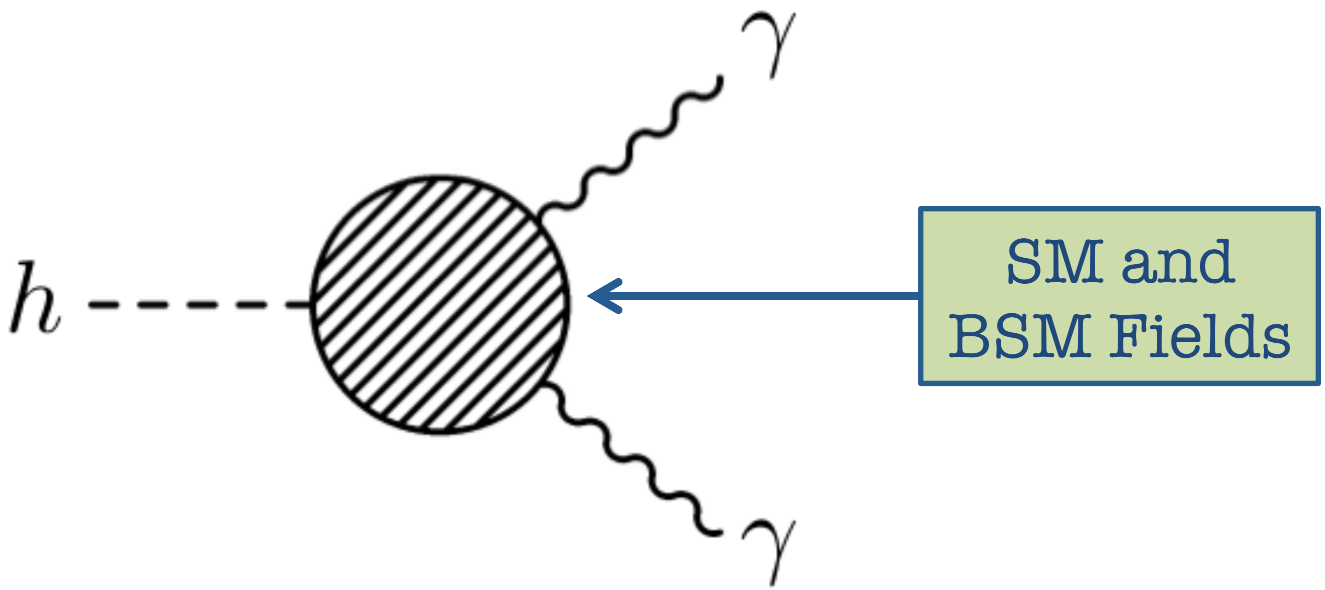
Higgs-Diphoton

Higgs production

- CEPC+LHC sensitivity.

Probing New Particles

- Diphoton decay diagrams:

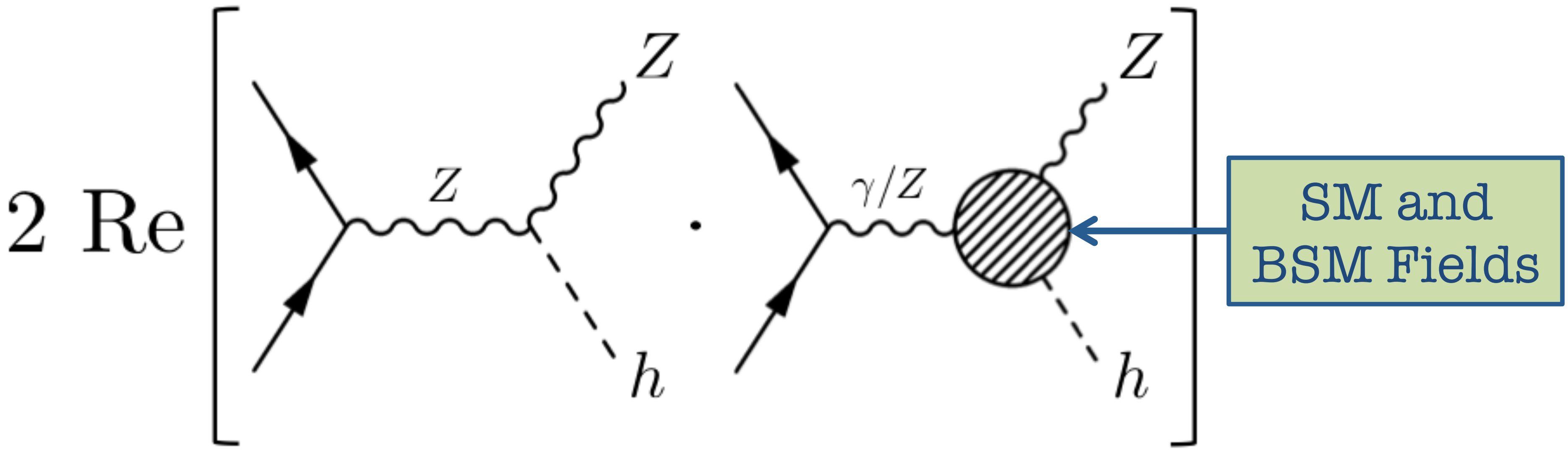


$$\delta_{2\sigma}\left(\mathrm{BR}_{h\to\gamma\gamma}\right) \approx 5\%$$

Higgs-Diphoton

Probing New Particles

- Associated production diagrams:



$$\delta_{2\sigma}\left(\sigma_{e^+e^-\to hZ}\right) \approx 1\%$$

Higgs production

Englert, MM. 2013

Vector-Like Fermions

- Vector-like fourth generation leptons

$$-\mathcal{L} \supset m_\ell \bar{\ell}'_L \ell''_R + m_e \bar{e}''_L e'_R + m_\nu \bar{\nu}''_L \nu'_R + \text{h.c.}$$
$$+ Y'_c(\bar{\ell}'_L H) e'_R + Y'_n(\bar{\ell}'_L i\sigma^2 H^\dagger)\nu'_R + Y''_c(\bar{\ell}''_R H) e''_L + Y''_n(\bar{\ell}''_R i\sigma^2 H^\dagger)\nu''_L + \text{h.c.}$$

- Simplify via:
  - Common "vector-like" mass: $m_\ell = m_e = m_\nu = m_V$
  - Common "chiral" mass:

$$Y'_c v_h/\sqrt{2} = Y''_c v_h/\sqrt{2} = m_{Ch}$$
$$Y'_n v_h/\sqrt{2} = Y''_n v_h/\sqrt{2} = m_{Ch} + \Delta_\nu$$

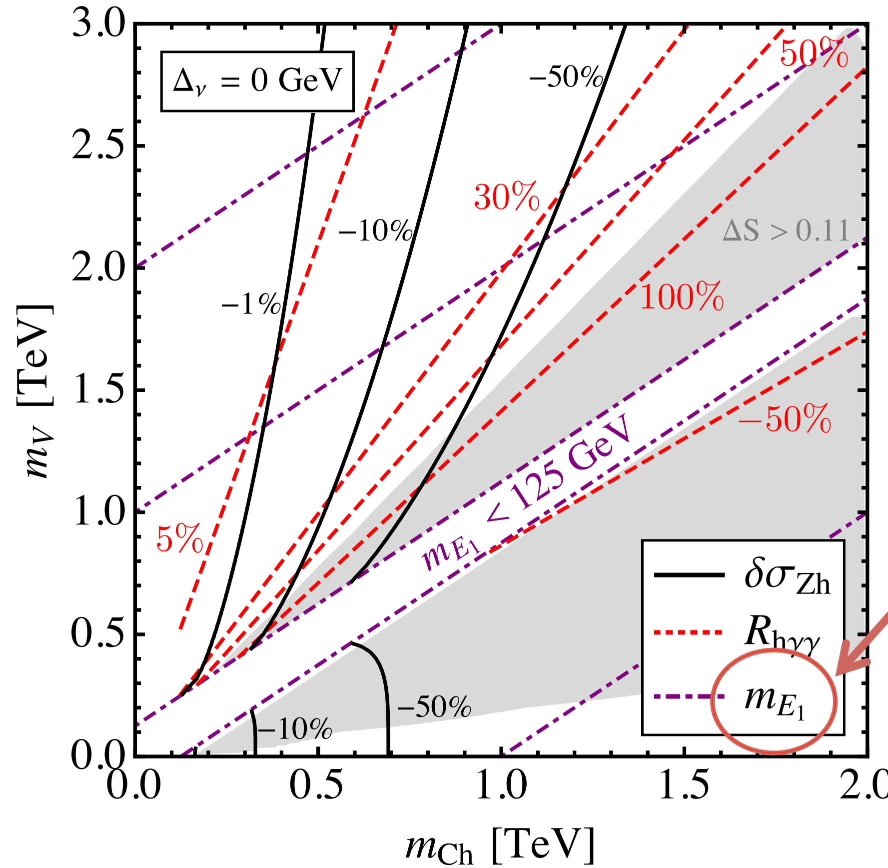
  - EW precision important

Violates Custodial

Englert, MM. 2013

Results: Vector-Like Leptons

- Superimpose EW Precision constraints:



Lightest charged fermion mass

Mini-Summary

- A) If Higgs is coupled to new electroweak states then precision Higgs measurements can probe large swathes of parameter space.

- B) Even though diphoton modifications are leading-order, and cross section modifications are NLO both are complementary, comparable, probes.

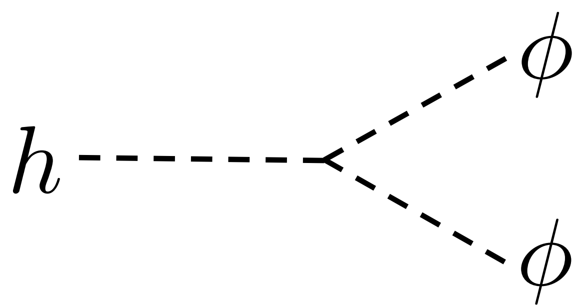
- C) For CEPC need to think beyond Higgs-Diphoton paradigm for e.g. charged states if we are to fully exploit the measurements.

Hidden New Physics

- Imagine Higgs Portal to gauge-neutral scalar

$$\mathcal{L} = c_\phi |H|^2 \phi^2$$

- If $m_\phi < m_h/2$ then we may have invisible Higgs decays:

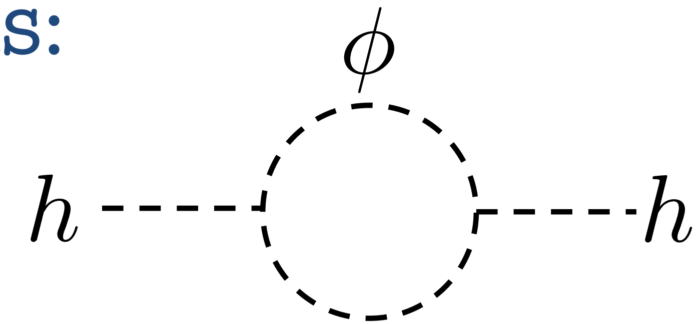


- However, if $m_\phi > m_h/2$, which is very plausible, then no invisible decays, no modified diphoton rate!
- What can we do in this very difficult situation?

E, M. 2013.
C, E, M. 2013

Physical Effects at NLO

- Staring at this:

$$\delta Z_h =$$ 

- Is it physical? Integrating out generates:

Loop factor

$$\mathcal{L}_{eff} = \frac{c_H}{m_\phi^2}\left(\frac{1}{2}\partial_\mu |H|^2 \partial^\mu |H|^2\right) + \ldots$$

- In EW breaking vacuum this feeds into all Higgs couplings.

(Not-so) Hidden New Physics

- Thus, due to extremely high precision measurements, in this very challenging scenario an e^+e^- collider offers the possibility of discovering the indirect effects of hidden particles.

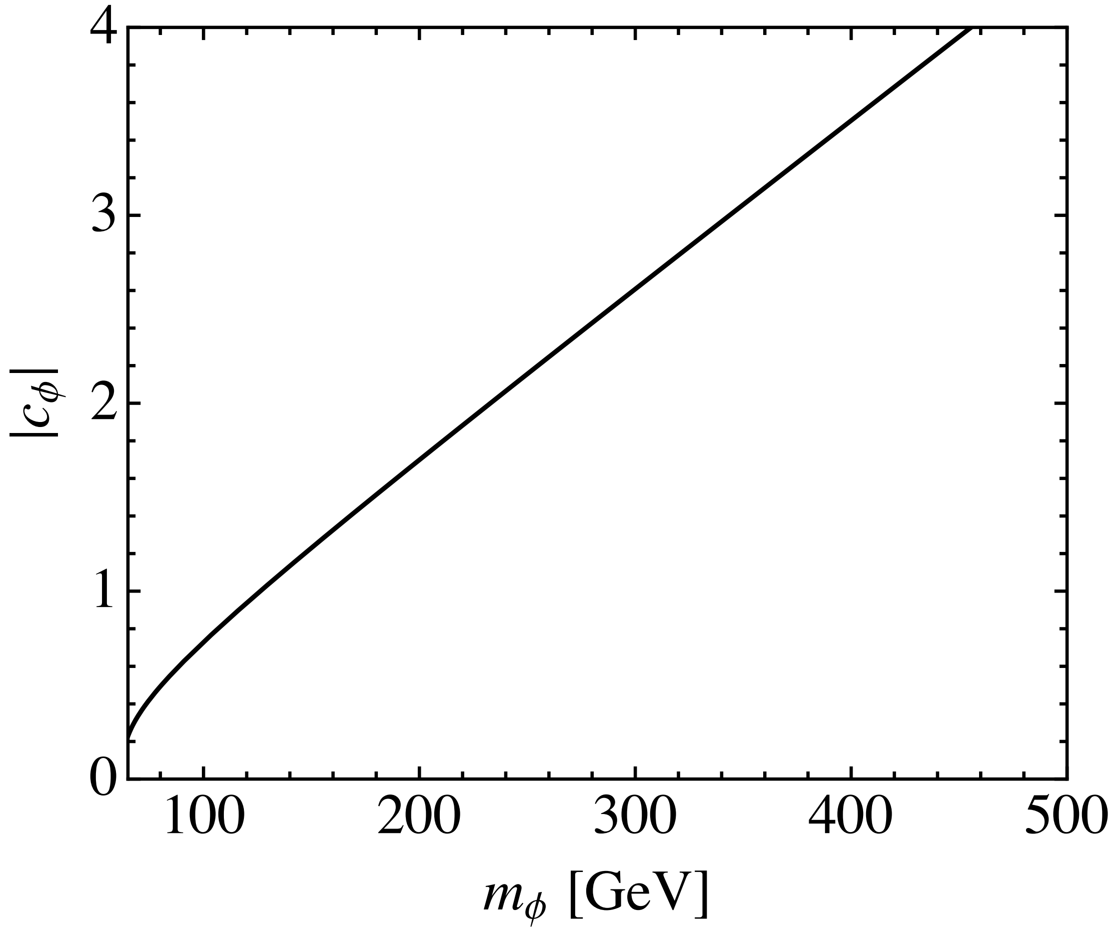
- Cross section at CEPC modified by:

$$\delta\sigma_{Zh} = \frac{|c_\phi|^2}{8\pi^2}\frac{v^2}{m_h^2}\left(1 + \frac{1}{4\sqrt{\tau_\phi(\tau_\phi - 1)}}\log\left[\frac{1 - 2\tau_\phi - 2\sqrt{\tau_\phi(\tau_\phi - 1)}}{1 - 2\tau_\phi + 2\sqrt{\tau_\phi(\tau_\phi - 1)}}\right]\right)$$

where $\tau_\phi = m_h^2/4m_\phi^2$ and $\delta\sigma_{Zh} = (\sigma_{Zh} - \sigma_{Zh}^{\text{SM}})/\sigma_{Zh}^{\text{SM}}$

(Not-so) Hidden New Physics

- The 2σ reach for CEPC is:



That you could indirectly probe completely neutral scalars which interact with the Higgs at the CEPC is extraordinary.

Mini-Summary

- Even if the only new states at the weak scale are gauge neutral scalars coupled to the Higgs, CEPC would offer an indirect test.

Comment

- All of the probes discussed here are indirect. Can be used to set limits on scenarios under assumption that no other contributions cancel.
- If a deviation were observed, underlying cause would remain unclear. Other higher energy measurements would be required to fully determine the nature of underlying new physics.
- Indirect probes are a tried and tested concept in HEP. Think of LEP, flavor, etc.

Modified Higgs Interactions: Self Coupling

- Why is it important?
  - White Whale of phenomenologists…
  - It is there, so we should try to measure it.
  - Known Higgs mass means it is predicted in SM. Important test of EW breaking.
  - Probe of SM scalar potential, with implications for many aspects of phsyics, including lifetime of Universe!

Measuring the Self-Coupling Directly

- At LHC (Requires $E_{CM} > 2\ m_h$):

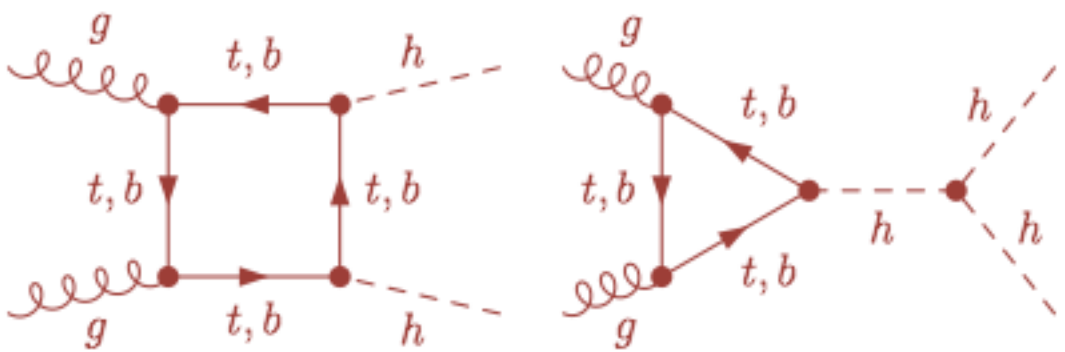


Figure from Dolan, Englert, Spannowsky

- At ILC (Requires $E_{CM} > 2\ m_h + m_Z$):

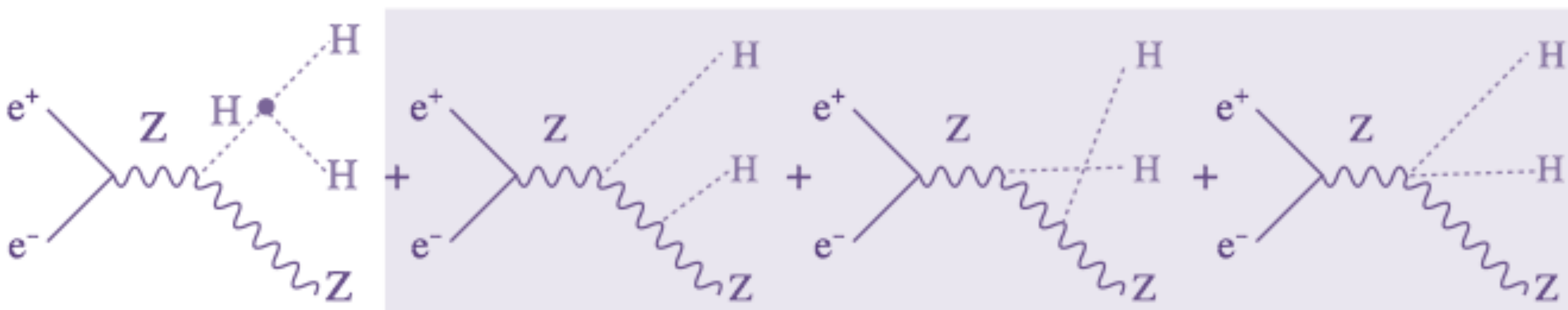
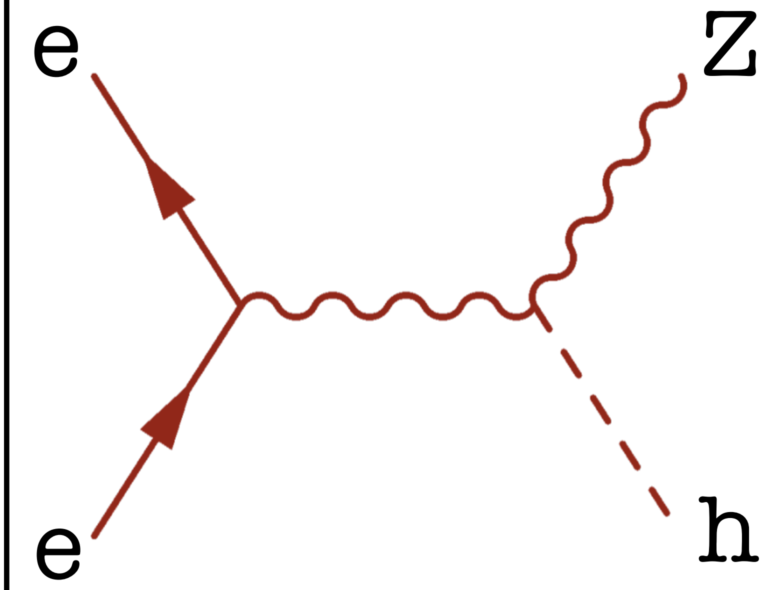


Figure from J. Tian, K. Fujii

What if $E_{CM} < 2\,m_h + m_Z$?

- At 240 GeV:

$$\sigma_{Zh} = \left| \quad \right|^2$$

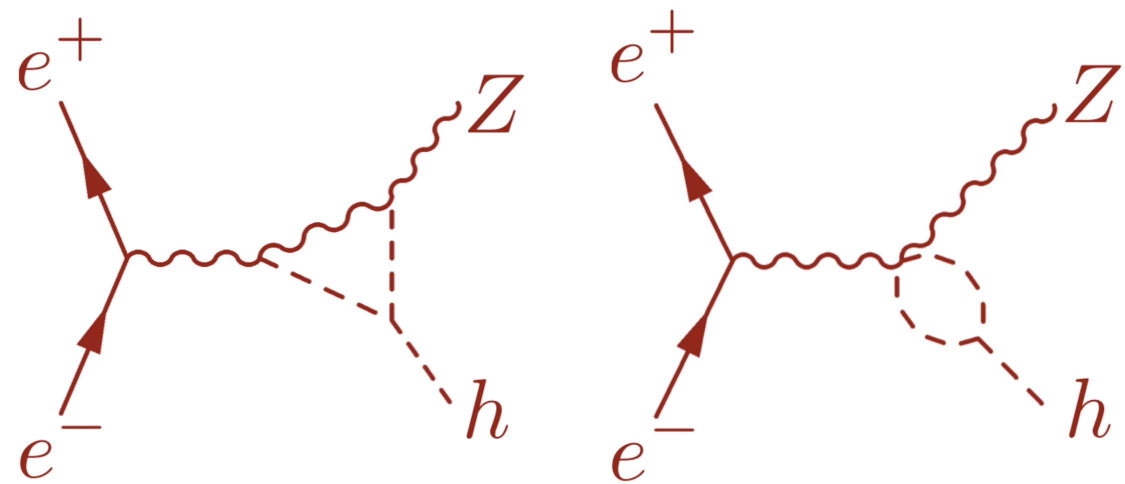


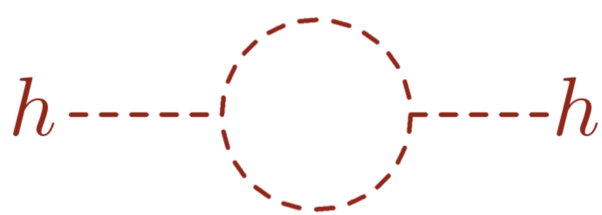
- But what if we have a modified self-coupling?

- We would never know from CEPC?

Self-Coupling Indirectly at NLO

- At NLO modified coupling enters in the following loops:



- And also: 

Self-Coupling at NLO

- Result: $\delta_\sigma^{240} = \frac{\sigma_{\delta_{h\neq 0}}}{\sigma_{\delta_{h=0}}} - 1 = 1.4 \times \delta_h\%$
- At CEPC sensitive to:
$$\delta_{2\sigma}^{Zh} \approx 1\%$$
- Thus a modified self-coupling of:
$$\delta_{2\sigma}^{h^3} \approx 71\%$$
- ... would generate a 2σ deviation in the cross section measurement!

Self-Coupling at NLO

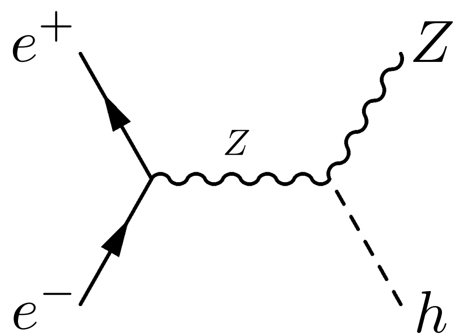
- In most realistic BSM scenarios not just self-coupling modified and if rescaled couplings, really measure:

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- Can't "fingerprint" modified self-coupling from a single cross section deviation.
  - For similar examples of tree vs loop see many LEP papers (available on request).
- However, for constraint to be invalidated would require unnatural cancellation between different contributions.

Final Conclusions

A measurement of the total Higgs production cross section at the CEPC with accuracy of



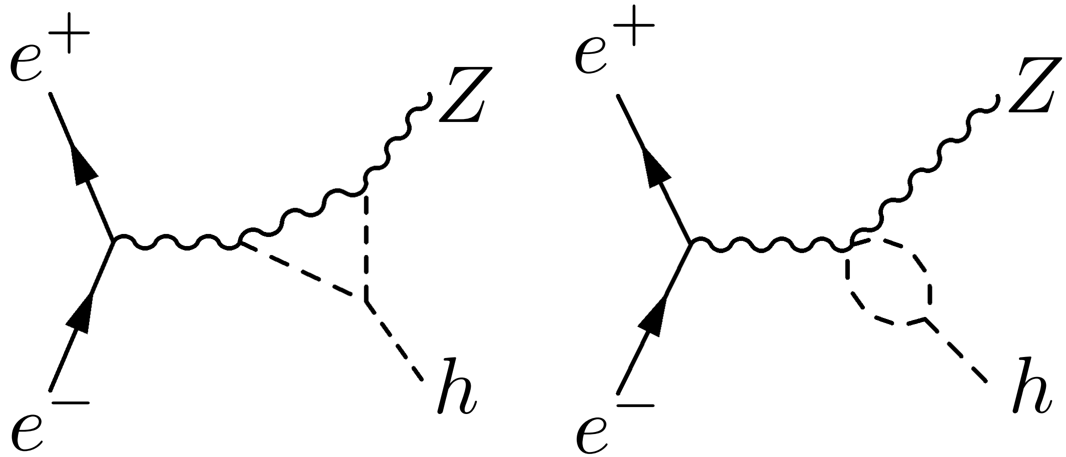
$$\delta_{2\sigma}\left(\sigma_{e^+e^-\to hZ}\right) \approx 1\%$$

Would be a tremendous human achievement.

Staying mindful of the dangers of over-interpreting a single measurement, it is clear that this measurement could shed light on key questions in fundamental physics.

Conclusions

The CEPC would thoroughly explore the quantum Higgs world, e.g.



This would open exciting new avenues for investigation. I have only managed to cover:

- New particles interacting with the Higgs entering at one loop.
- Modified Higgs self-coupling entering at one loop.

Englert, MM. 2013

Inert Higgs Doublet

- "Inert" Higgs doublet model

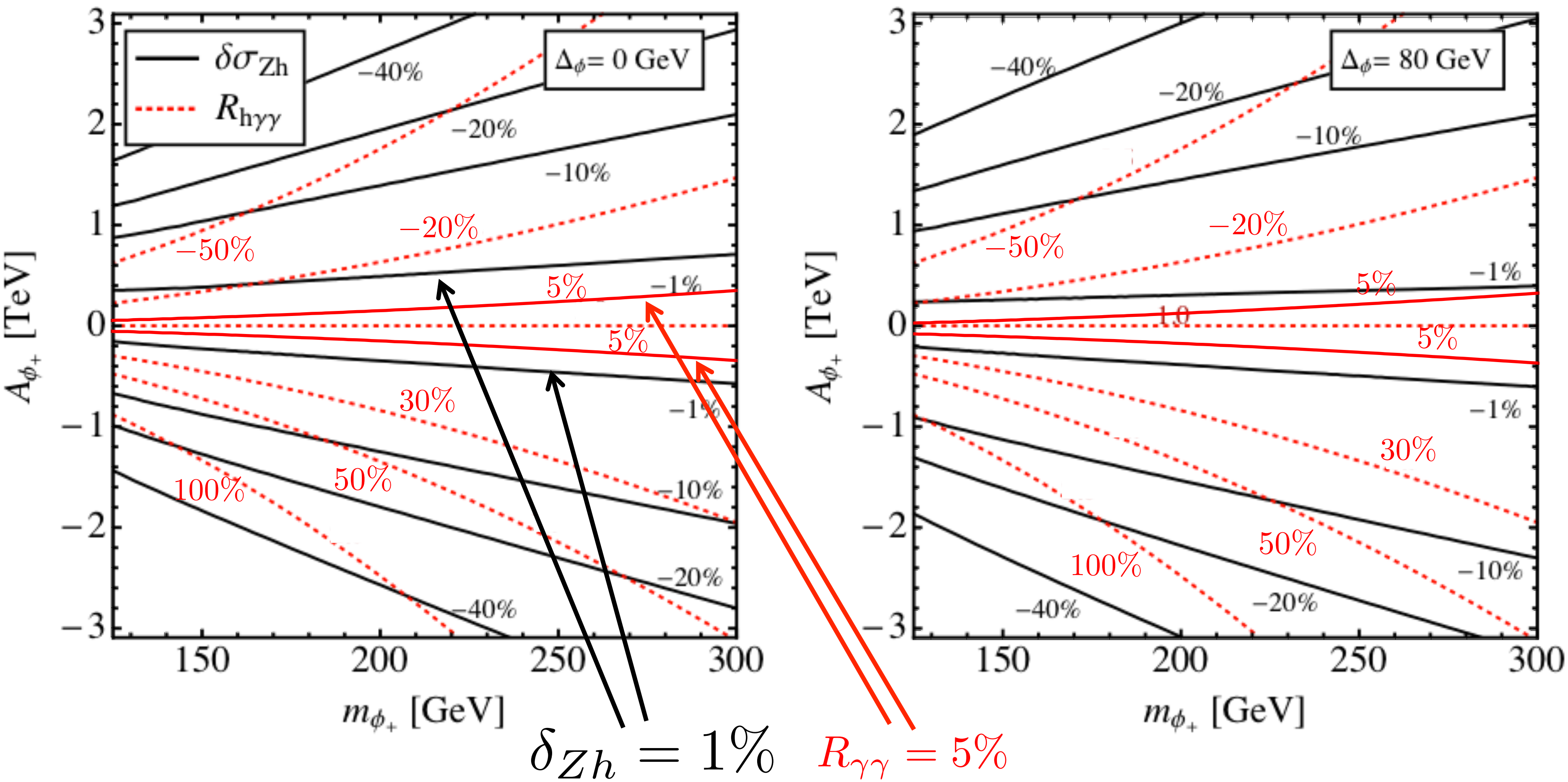
$$V \supset m_\phi^2 |\phi|^2 + \lambda |H|^2 |\phi|^2 + \lambda' |H \cdot \phi^\dagger|^2$$

- Trade these parameters for more intuitive set:
  - Charged scalar mass: m_{ϕ_+}
  - Charged scalar trilinear coupling to Higgs: A_{ϕ_+}
  - Charged-neutral mass-splitting: Δ_ϕ

- Where we define $\Delta_\phi = m_{\phi_0} - m_{\phi_+}$
  - Think precision electroweak...

Englert, MM. 2013

Results: Inert Doublet

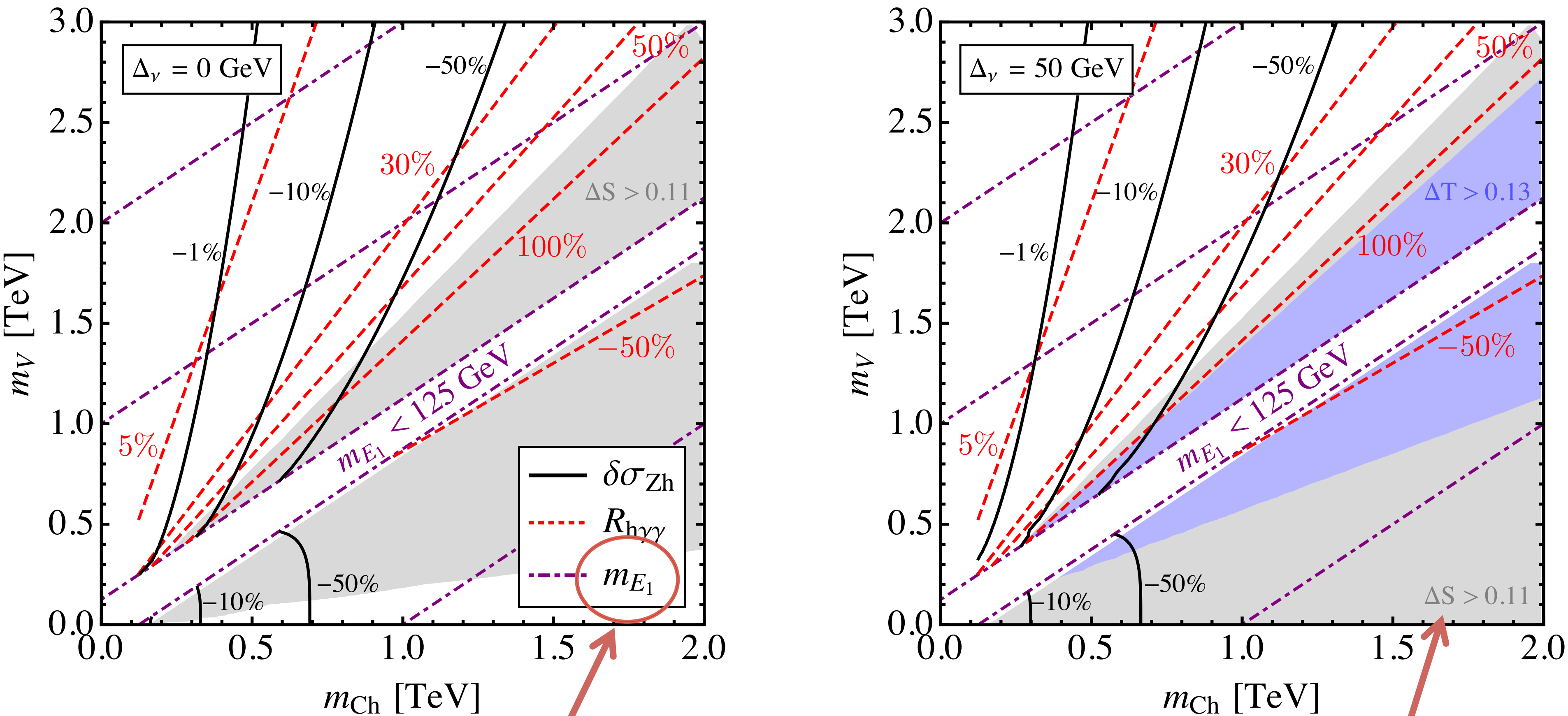


- As expected, corrections to associated production are observable!

Englert, MM. 2013

Results: Vector-Like Leptons

- Superimpose EW Precision constraints:



Lightest charged fermion mass

S measures: $|n_{\psi_L} - n_{\psi_R}|$

More on self-coupling

- A specific example….