Particle physics at the high energy frontier with the next electron-positron collider

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@ IPAC2019

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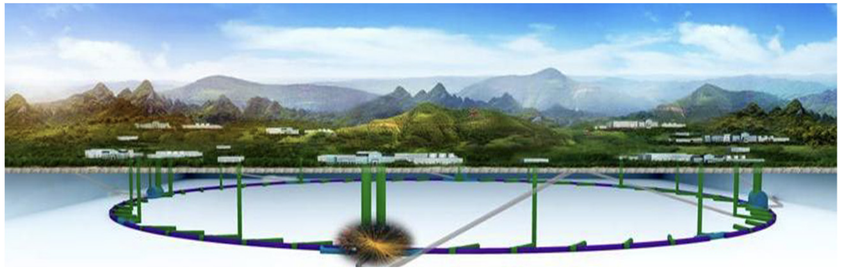
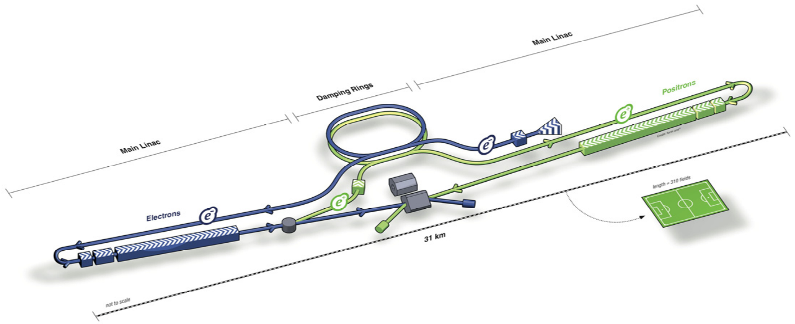
Proposed next generation machines

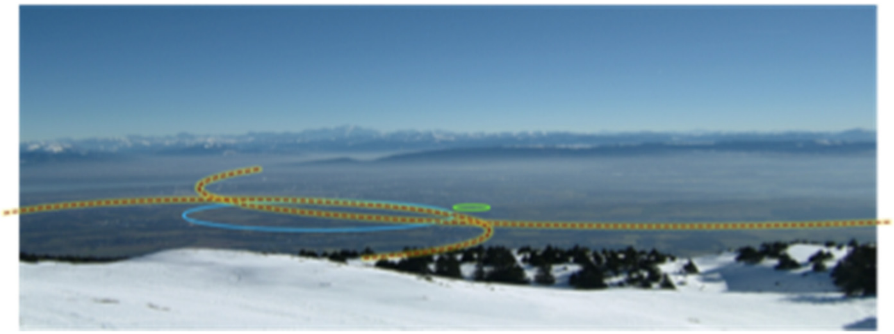


Circular electron positron collider : 2030



International Linear Collider 250: 2032

Compact Linear Collider 350: 2035



Future Circular Collider -ee: 2043

Consensus among HEP community

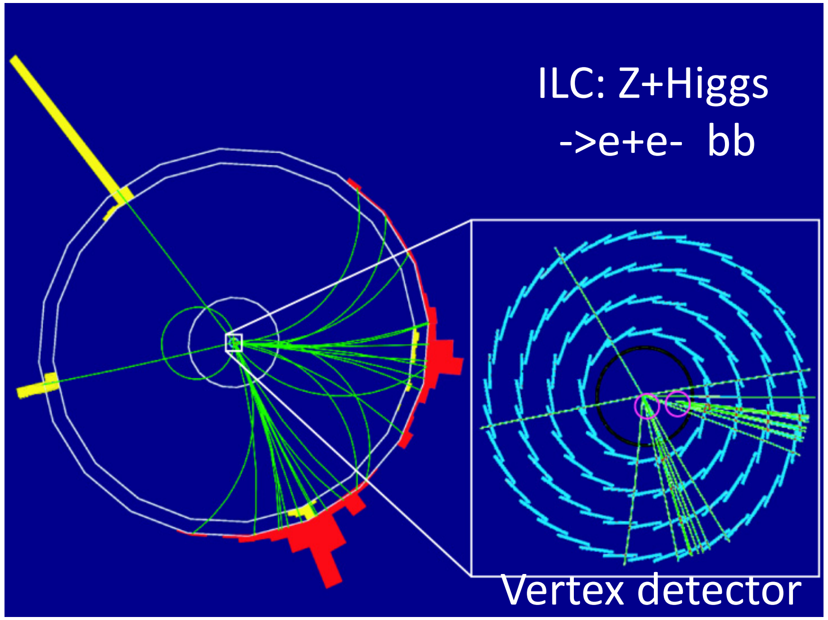
- Next machine concurrent with (or beyond) High Luminosity LHC is an electron-positron collider Higgs factory.

- Higgs factory is a vehicle or tool to discover physics beyond the standard model.

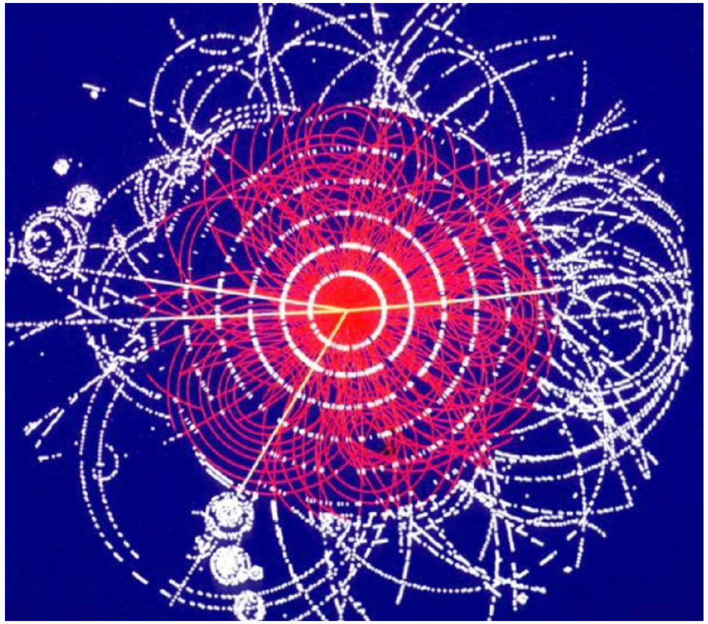
- We need one regardless of its form/shape: Linear or Circular.

Why lepton colliders ?

- Two elementary particles (e^+e^- or mu^+mu^-) collide with electromagnetic or weak interactions
  - No underlying/QCD event background
  - Signal can be clearly seen without hadronic noises
  - Helicity (or LR) selector can be employed to separate diagrams



LHC Higgs

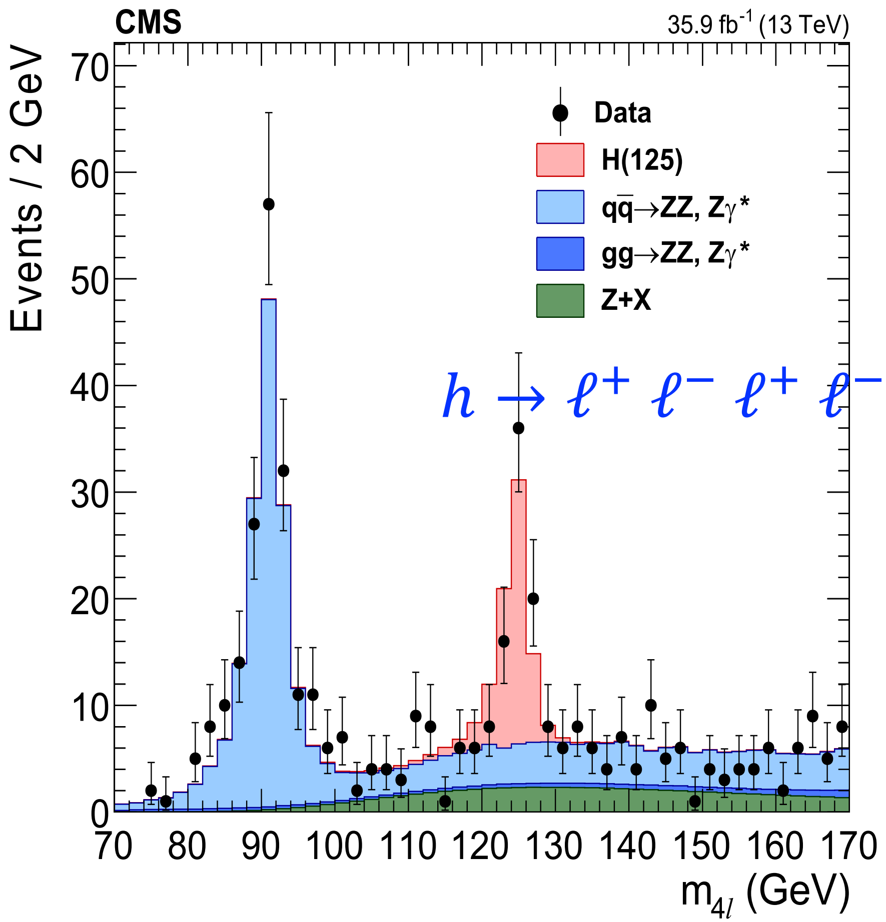


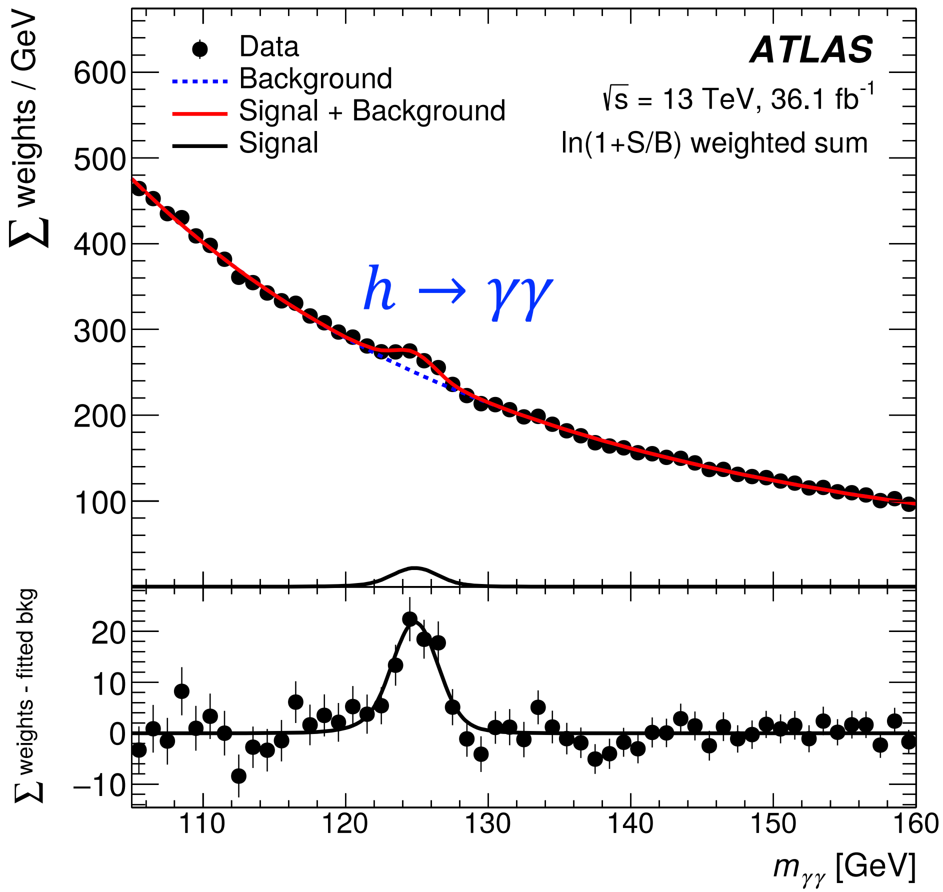
Caveat 1: Lepton colliders are not background free. Beamstrahlung present in e^+e^- linear colliders, but can be contained.

Caveat 2: Hadron collider physicists are quickly learning how to handle noise with advanced detector technology.

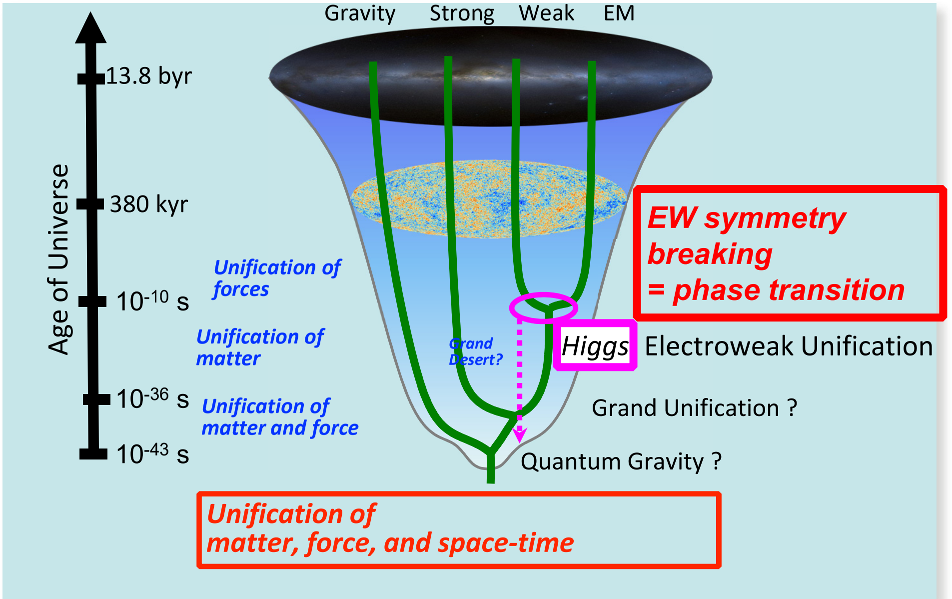
Why precision Higgs physics ?

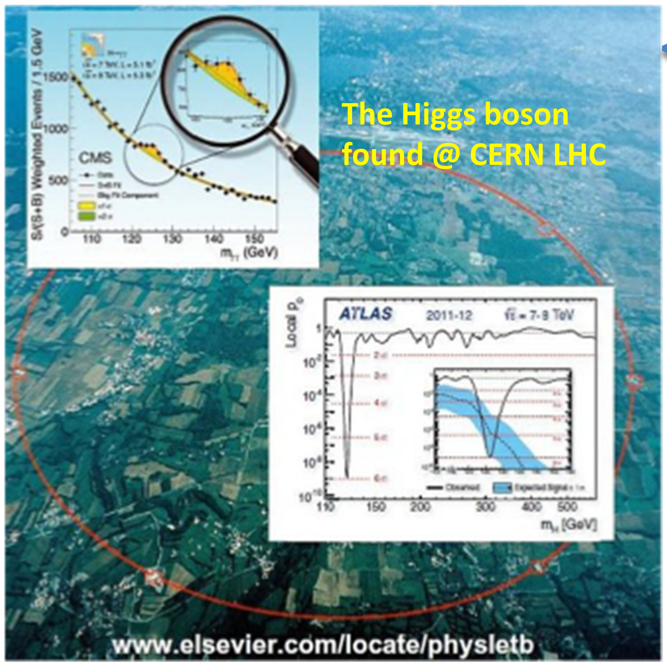
Discovery of Higgs boson at LHC





$$m_h = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})\ \text{GeV}$$





Standard Model (SM)
=Summary of Our Current Understanding

Gauge Symmetry = SU(3)xSU(2)xU(1)

Matter Fields = Quarks & Leptons (3 Gen.)

1995 Top discovery @ FNAL Tevatron
→3 generations of matter fields completed

Force Fields = Gauge Fields (γ,W/Z, g)

1983 W/Z discovery @ CERN SPPS
→ Gauge bosons for the 3 forces found

Symmetry Breaking Field = **Higgs Field (H)**

→ **2012 found @ LHC**: SM completed

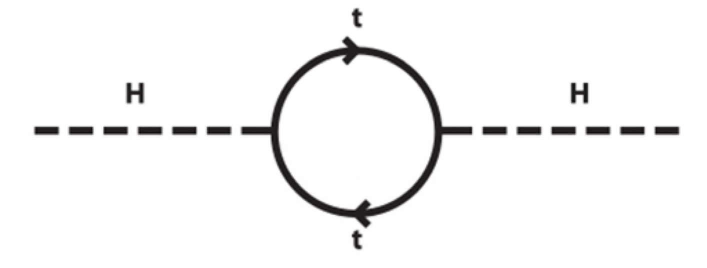
Beyond the SM

The SM has been extremely successful.

→ Yet, there remain a lot of mysteries (Dark Matter, Baryon Number Asymmetry, Neutrino Mass/Mixing, Dark Energy, ..)

→ Theoretical problems: Hierarchy problem, Origin of EW symmetry breaking, …

- Is the Higgs mass natural or fine tuned? The Higgs mass is receives quantum corrections proportional to highest energy scale.

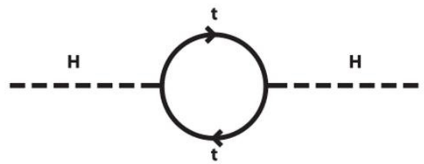


$$\delta m_h^2 = \frac{3m_t^2}{2\pi^2 v^2}\Lambda^2$$

Λ could be Planck Energy $\sim 10^{19}$ GeV

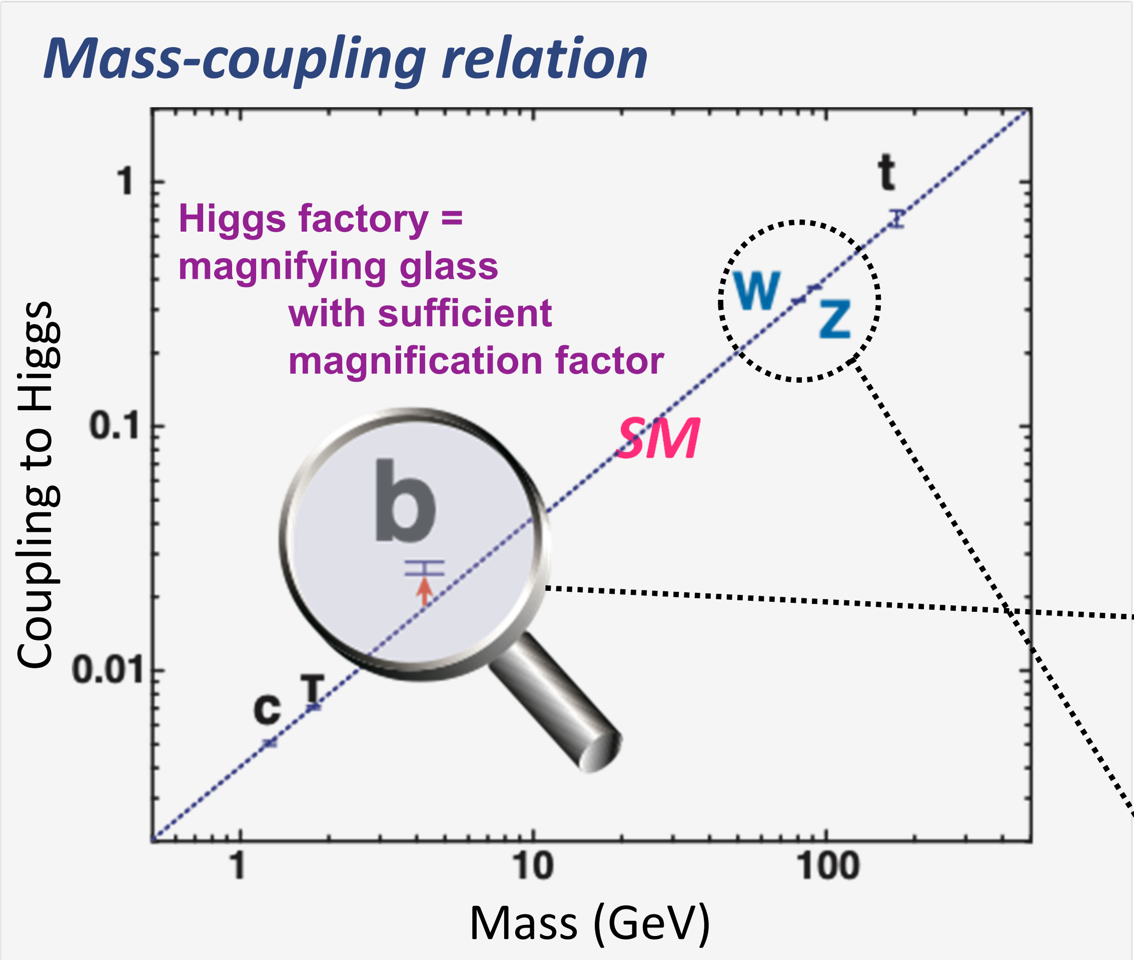
- What prevents m_h from blowing up?
  - There must be New Physics around the corner (a few TeV).

- New fermion-boson symmetry: SUSY



- New strong interactions:
  - Technicolor
  - Composite Higgs
- Extra Dimensions

Mass-coupling relation



The size of the deviation depends on the new physics scale (Λ)!

Decoupling Theorem:
Λ↑ → SM

example 1: **Minimal SUSY**
(MSSM : tanβ=5, radiative correction factor ≈ 1)

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

heavy Higgs mass

example 2: **Minimal Composite Higgs Model**

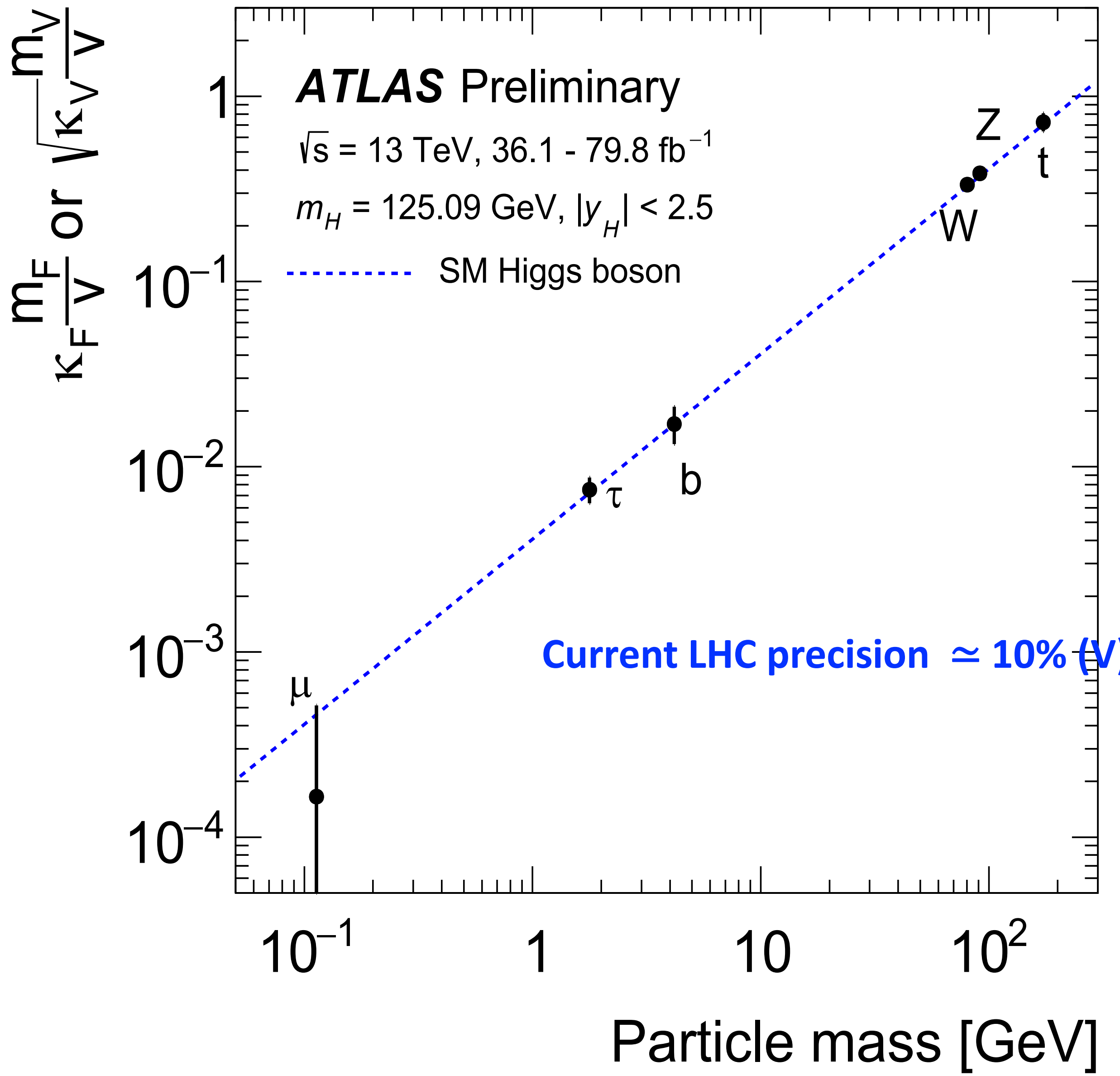
$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 8.3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

$V=W/Z$ composite scale

New physics at 1 TeV → **deviation is at most ~10%**

We ***need 1%-level precision***.

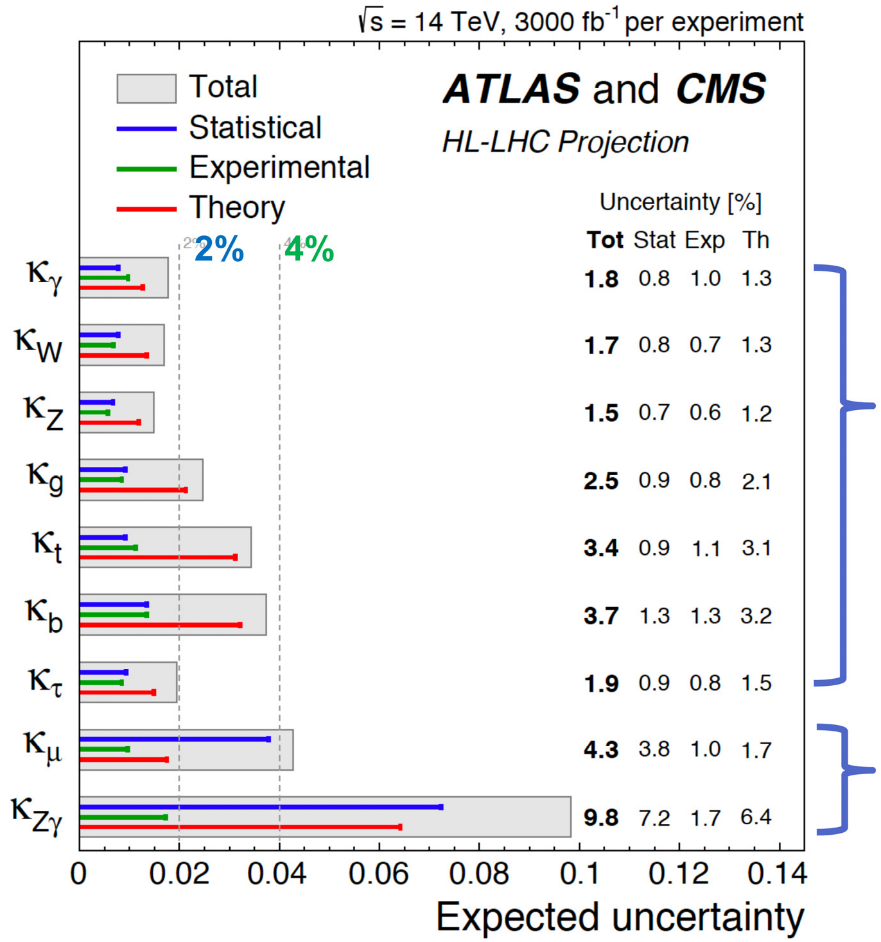
Coupling to SM Higgs ∝ m_F, m_V



Current LHC precision ≃ 10% (V) , 15-25% (F)

100 times more statistics @ Hi-Lum LHC

Coupling Measurement at HL-LHC

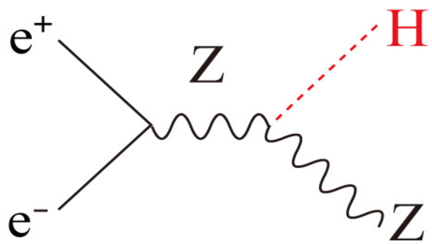


Combination of ATLAS and CMS extrapolation from Run2 analysis
* Expected uncertainty on κ-framework (coupling modifiers)

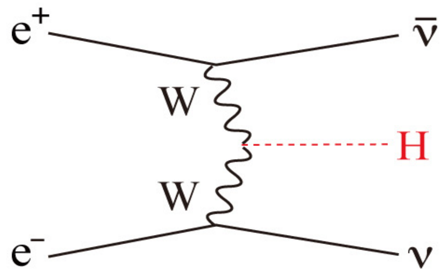
Dominant coupling modifier parameters can be measured **2-4%** level (limited by theoretical systematic)

Statistically limited

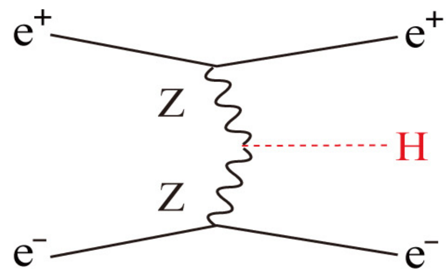
Higgs production at e^+e^- colliders



Higgs-strahlung



WW fusion



ZZ fusion

$$\sigma(e^+e^- \to ZH) = \frac{G_F^2 m_Z^4}{96\pi s}\left\{(-1+4\sin^2\theta_W)^2+1\right\}\lambda^{1/2}\frac{\lambda+12m_Z^2/s}{(1-m_Z^2/s)^2}$$

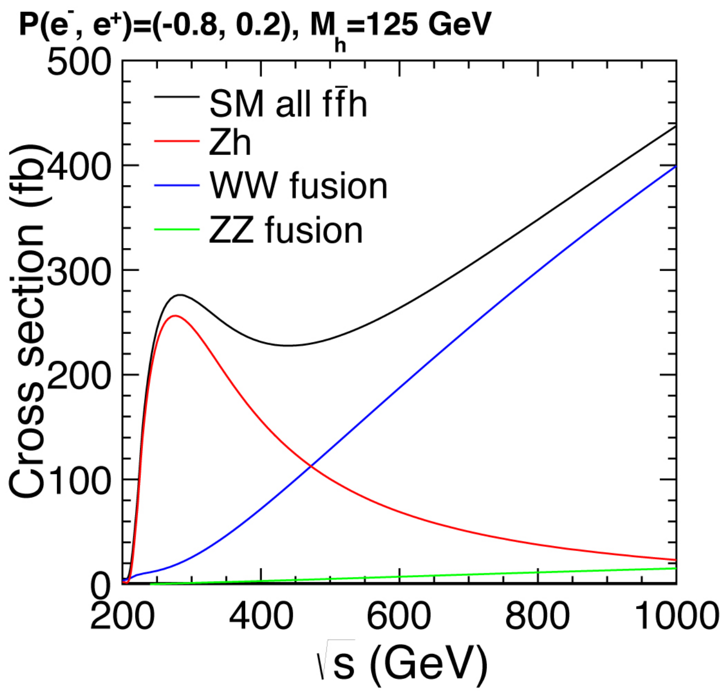
$$\lambda = (1-(m_H+m_Z)^2/s)(1-(m_H-m_Z)^2/s)$$

$$\sigma(e^+e^- \to \bar{\nu}_e\nu_e H) \approx \frac{G_F^3 m_W^4}{4\sqrt{2}\pi^3}\left[\left(1+\frac{m_H^2}{s}\right)\ln\frac{s}{m_H^2} - 2\left(1-\frac{m_H^2}{s}\right)\right]$$

$$\to \frac{G_F^3 m_W^4}{4\sqrt{2}\pi^3}\ln\frac{s}{m_H^2} \quad \text{(t-channel log rise)}$$

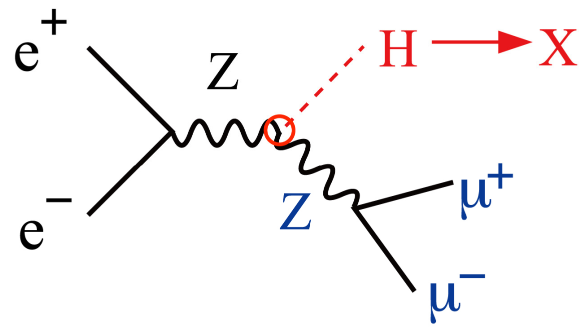
$$\sigma(ZZ\ \text{fusion}) \approx \sigma(WW\ \text{fusion}) \times 16\cos^4\theta_W$$

$$\approx \sigma(WW\ \text{fusion}) \times \frac{1}{9.5}$$



Cross section to *Zh* peaks at 250 GeV.
~0.5 million higgs for 2 ab^{-1}

Precision Higgs mass and BR measurements at ILC250

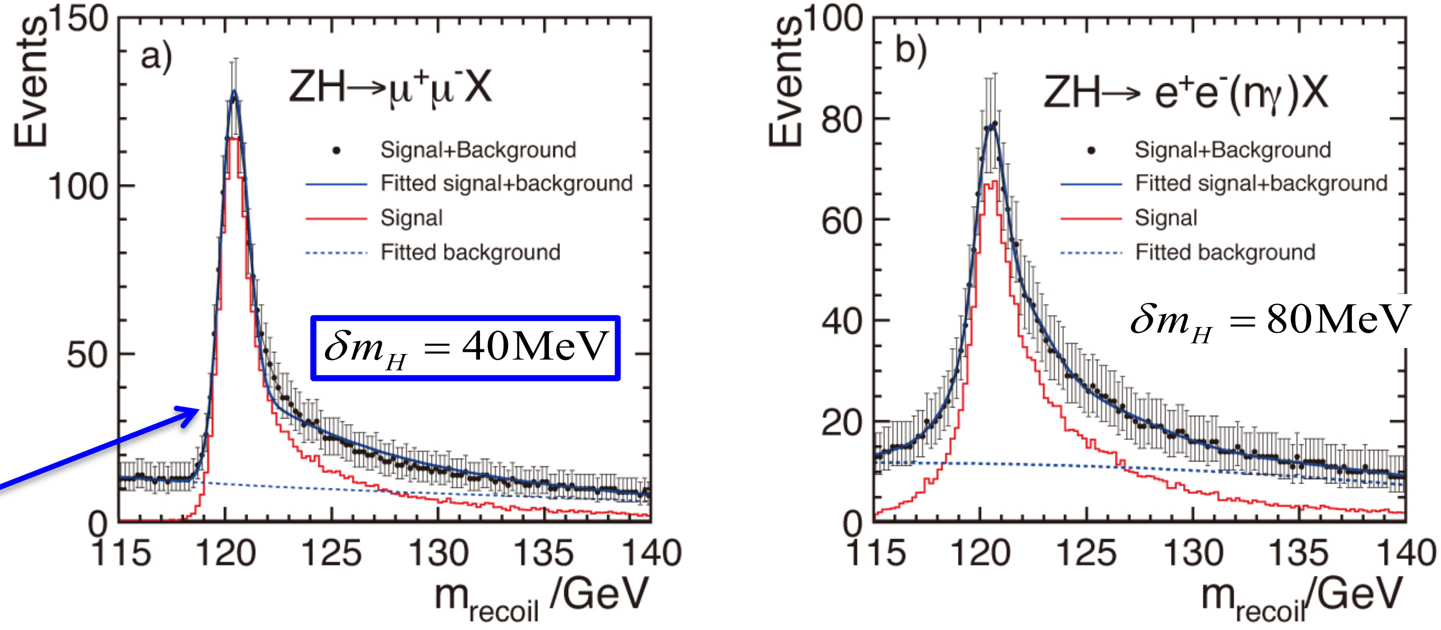


Recoil mass recosntruction technique

$$m_{\mathrm{recoil}}^2 = \left(\sqrt{s} - E_{\ell^+} - E_{\ell^-}\right)^2 - \left|\mathbf{p}_{\ell^+} + \mathbf{p}_{\ell^-}\right|^2$$

Independent of X

Figure 2.8
Higgs recoil mass distribution in the Higgs-strahlung process $e^+e^- \to Zh$, with (a) $Z \to \mu^+\mu^-$ and (b) $Z \to e^+e^-(n\gamma)$. The results are shown for $P(e^+, e^-) = (+30\%, -80\%)$ beam polarization.

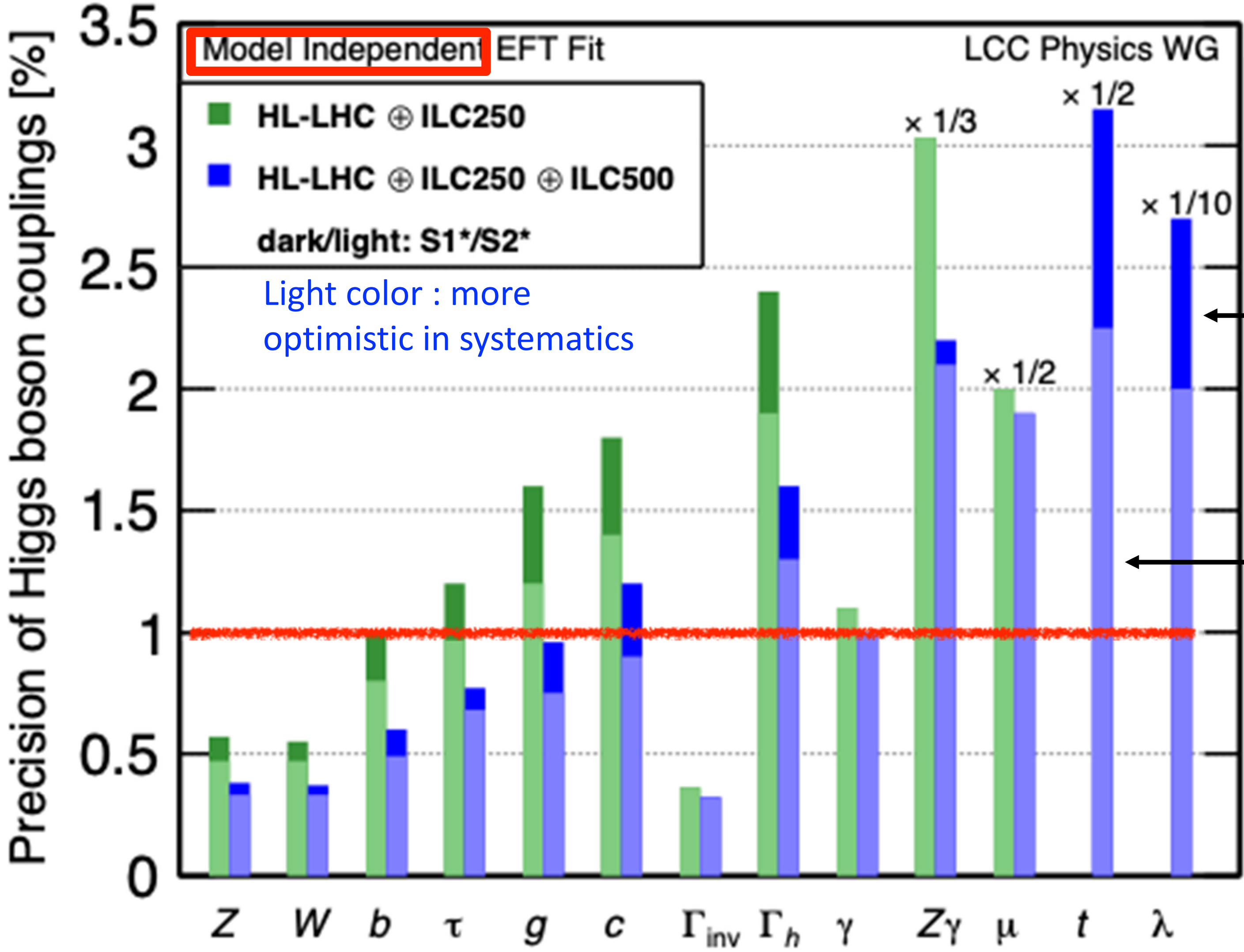


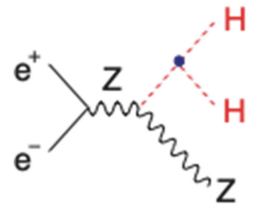
dominated by beam energy spread

$\Gamma_H \approx 4\mathrm{MeV}$ (SM)

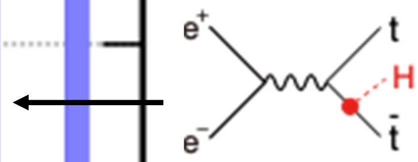
- Inclusive ZH cross section measurement: $\Delta\sigma_{ZH} / \sigma_{ZH} \approx 2.5\%$
- Branching ratios by identifying X
- Both measurements are absolute, model-independent.

arXiv: 1901.09829



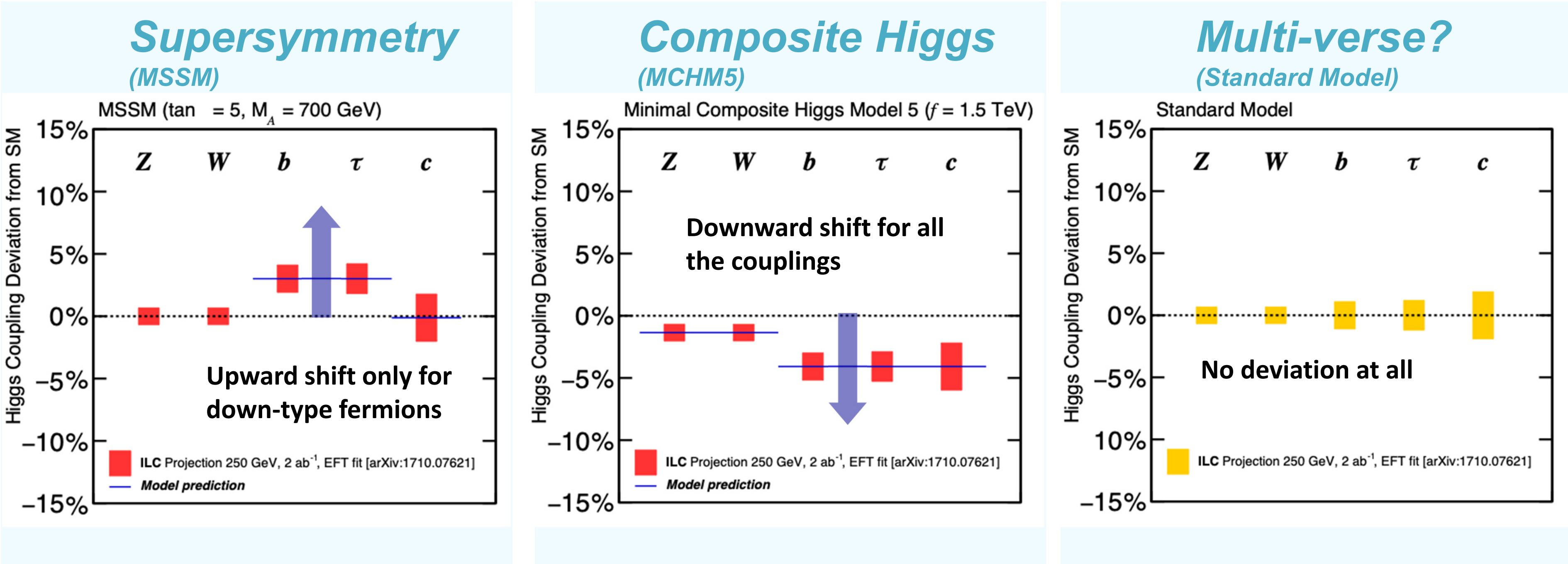


Self-coupling
Not accessible at 250 GeV.
Can reach 26% at 500 GeV.



Top Yukawa
Not accessible at 250 GeV.
Can reach 3% at 550 GeV.

ILC allows model-independent fit to extract all the major Higgs couplings !



Different models predict different deviation patterns

→ ***Deviation pattern tells us which way to go.***

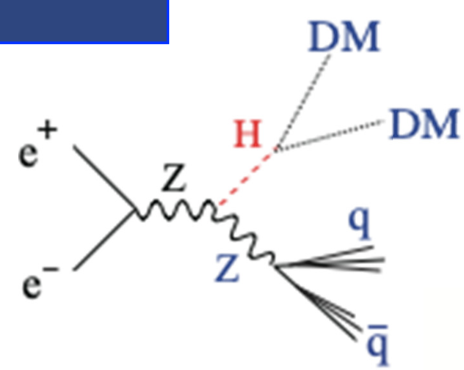
Higgs factory offers discovery reach for new physics up to ~2-3 TeV.

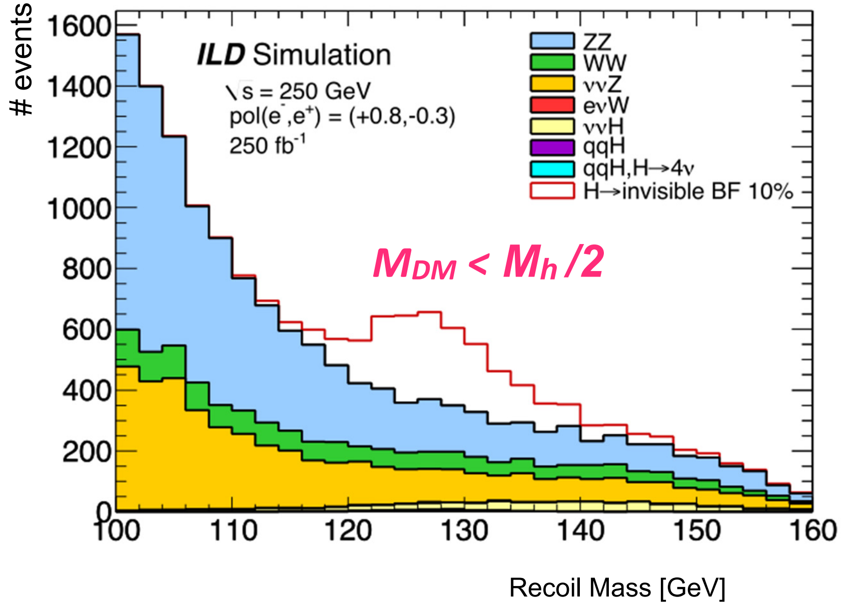
WIMP Dark Matter Search @ Higgs Factory

Weakly Interacting Massive Particle

1. Higgs Invisible Decay

Effective when the Dark Matter particle interacts with the Higgs boson





$M_{DM} < M_h/2$

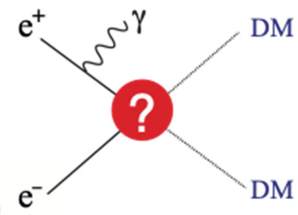
Possible to access BR_{inv} to 0.3%!

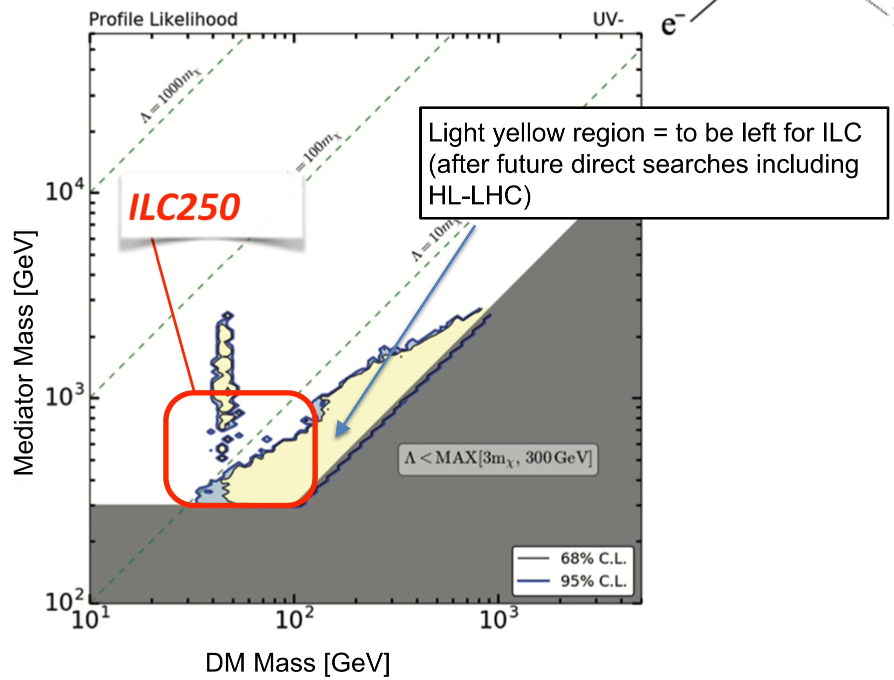
O(10) more sensitive than HL-LHC

2. Mono-photon Search

Sensitive to various types of Dark Matter particles

Effective in particular for DM particles which couple mostly to EW gauge bosons and leptons and hence difficult to find at the LHC.





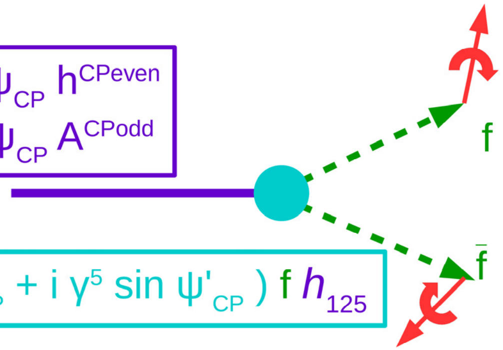
Significant chunk of region remains for ILC250!

CP Violation in Higgs sector ?

- We know CKM mechanism for CPV in the quark sector is not enough to explain the matter dominance over anti-matter in the Universe. There must be unknow source(s) for CPV beyond the Standard Model.

CP affects correlations between polarisation of *h* daughters

$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$



$g\,\bar{f}\,(\cos\psi'_{CP} + i\,\gamma^5 \sin\psi'_{CP})\, f\, h_{125}$

h is a spin 0 state:

$|f\,\bar{f}\rangle = |\uparrow\downarrow\rangle + e^{2i\psi}\,|\downarrow\uparrow\rangle$

[ψ = 0 CP even,
π/2 CP odd]

To reconstruct spins of *h* daughters, they must be unstable

kinematics of of *h* grand-daughters →
polarisation of *h* daughters →
CP of *higgs* and couplings

$h \rightarrow \tau^+\tau^-$
is most promising.

Down to $\psi_{CP} \sim 4$ (ILC) to 10 degrees (FCC-ee) can be probed.
If non-zero, a major Discovery!

Linear vs Circular

- ✓ ***Beam polarization***
- ✓ ***Luminosity***

Role of e^+ e- longitudinal polarizations in LC

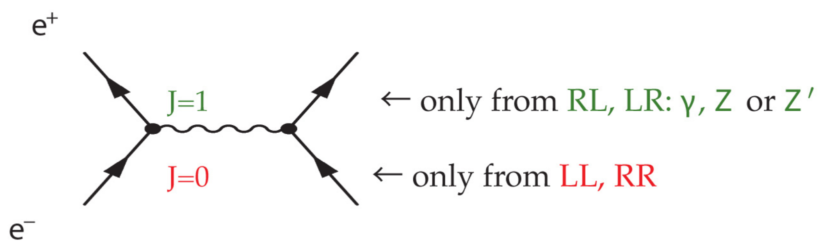
- Cross sections can be expressed, in terms of the longitudinal polarization of the beams, as: *(helicity amplitude formalism)*

$$\sigma_{P_-P_+} = \frac{1}{4}\left[(1+P_-)(1+P_+)\sigma_{\mathrm{RR}} + (1-P_-)(1-P_+)\sigma_{\mathrm{LL}} + (1+P_-)(1-P_+)\sigma_{\mathrm{RL}} + (1-P_-)(1+P_+)\sigma_{\mathrm{LR}}\right]$$

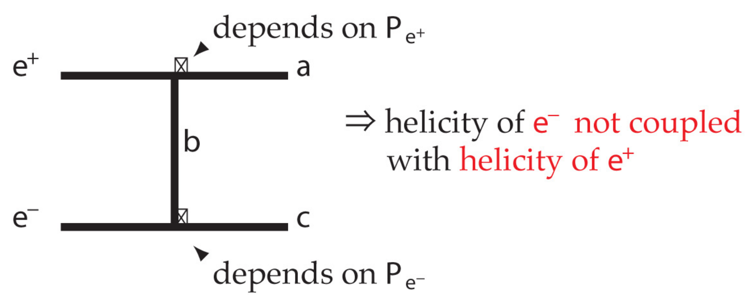
	e^-	e^+		
σ_{RR}	⇒	⇐	$\frac{1+P_{e^-}}{2}\cdot\frac{1+P_{e^+}}{2}$	$J_z = 0$
σ_{LL}	⇐	⇒	$\frac{1-P_{e^-}}{2}\cdot\frac{1-P_{e^+}}{2}$	
σ_{RL}	⇒	⇒	$\frac{1+P_{e^-}}{2}\cdot\frac{1-P_{e^+}}{2}$	$J_z = 1$
σ_{LR}	⇐	⇐	$\frac{1-P_{e^-}}{2}\cdot\frac{1+P_{e^+}}{2}$	

- Use beam polarization as a Feynman diagram selector

s-channel



t-channel



Role of e^+ e- longitudinal polarizations in LC

- Electroweak weak interaction is Left-Right asymmetric.
  - W couples only to Left-handed particles and Right-handed antiparticles.
  - Z couples stronger to Left-handed particles (Right-handed antiparticles) than Right-handed particles (Left-handed antiparticles).

$$\frac{\sigma_{P_{e^+}P_{e^-}}}{\sigma_0} = (1 - P_{e^+}P_{e^-})(1 - A_{LR}P_{\rm eff})$$

$$P_{\rm eff} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^+}P_{e^-}}; \quad A_{LR} = \frac{\sigma_{LR} - \sigma_{RL}}{\sigma_{LR} + \sigma_{RL}}$$

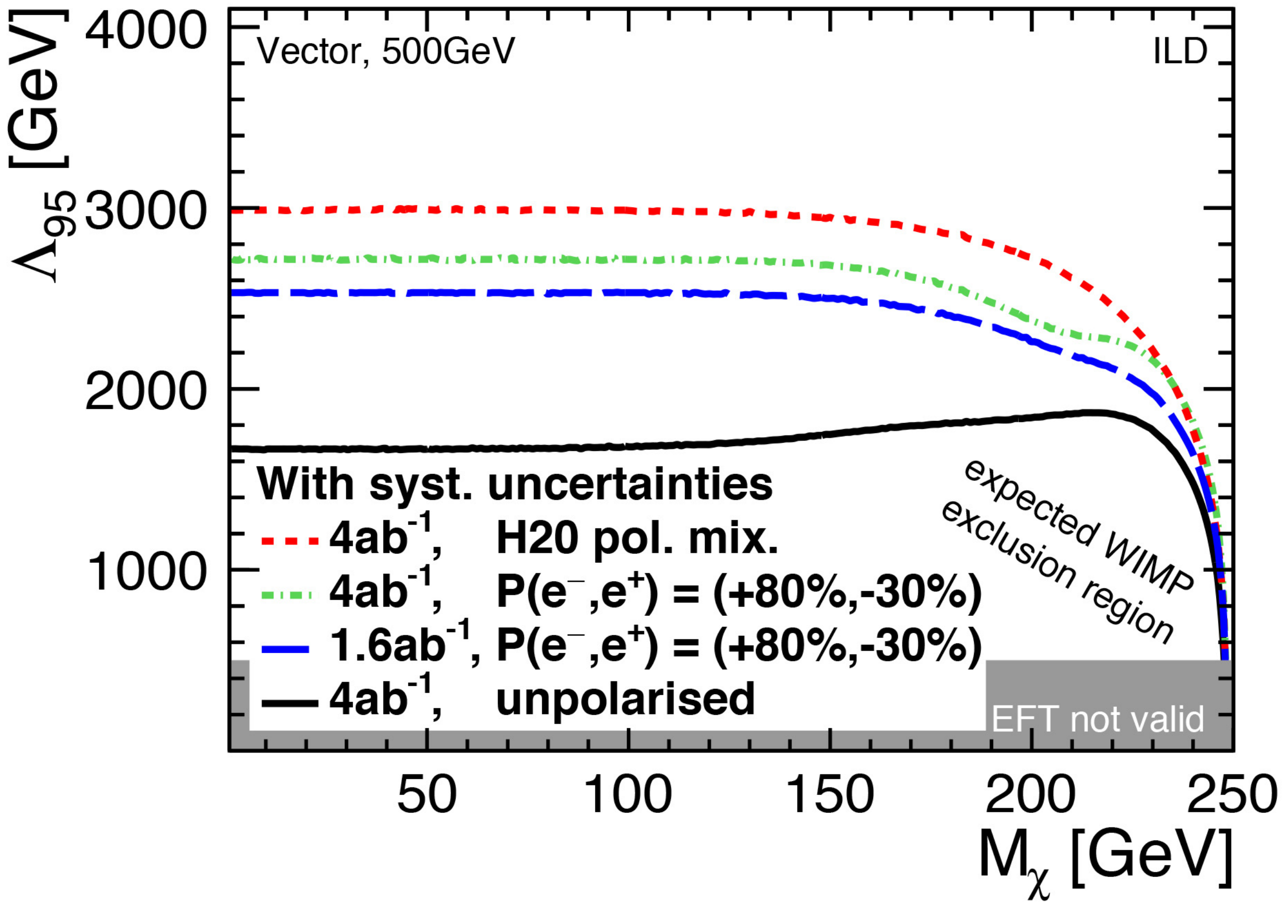
$A_{LR} = 0.151$ for $e^+e^- \rightarrow Zh$

P_{e^-}	0	-0.8	-0.8
P_{e^+}	0	0	+0.3
$P_{\rm eff}$	0	-0.8	-0.89
$\sigma_{P_{e^+}P_{e^-}}/\sigma_0$	1	1.12	1.446

enhancement

Role of e^+ e- longitudinal polarizations in LC

- Background suppression: Running with (P_{e-}=+0.8,P_{e+}=-0.3) suppresses e^+e^- to W^+W^-, which is the dominant background to dark matter search in the mono-photon mode: e^+e^- to γ + DM + DM.

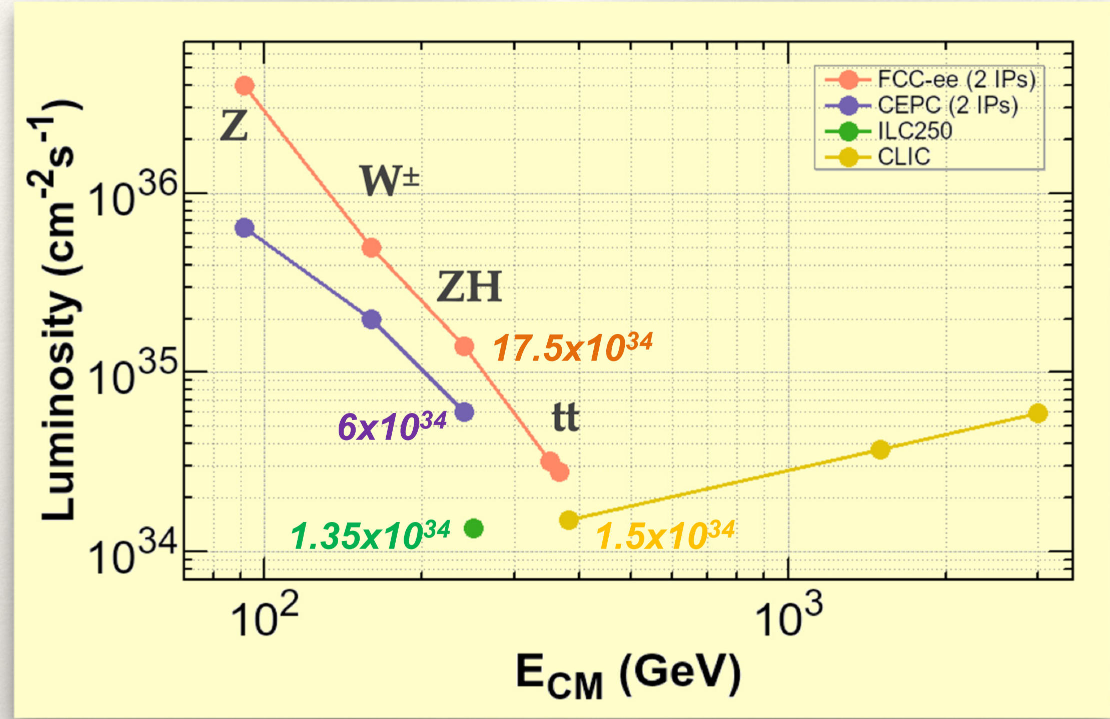


K. Oide(KEK)

Future e+e- colliders (CEPC, FCC-ee, CLIC)

Future Circular Collider, The Lepton Collider (FCC-ee) V1.5 (2018-12-17)

CEPC CDR



2 interaction Points

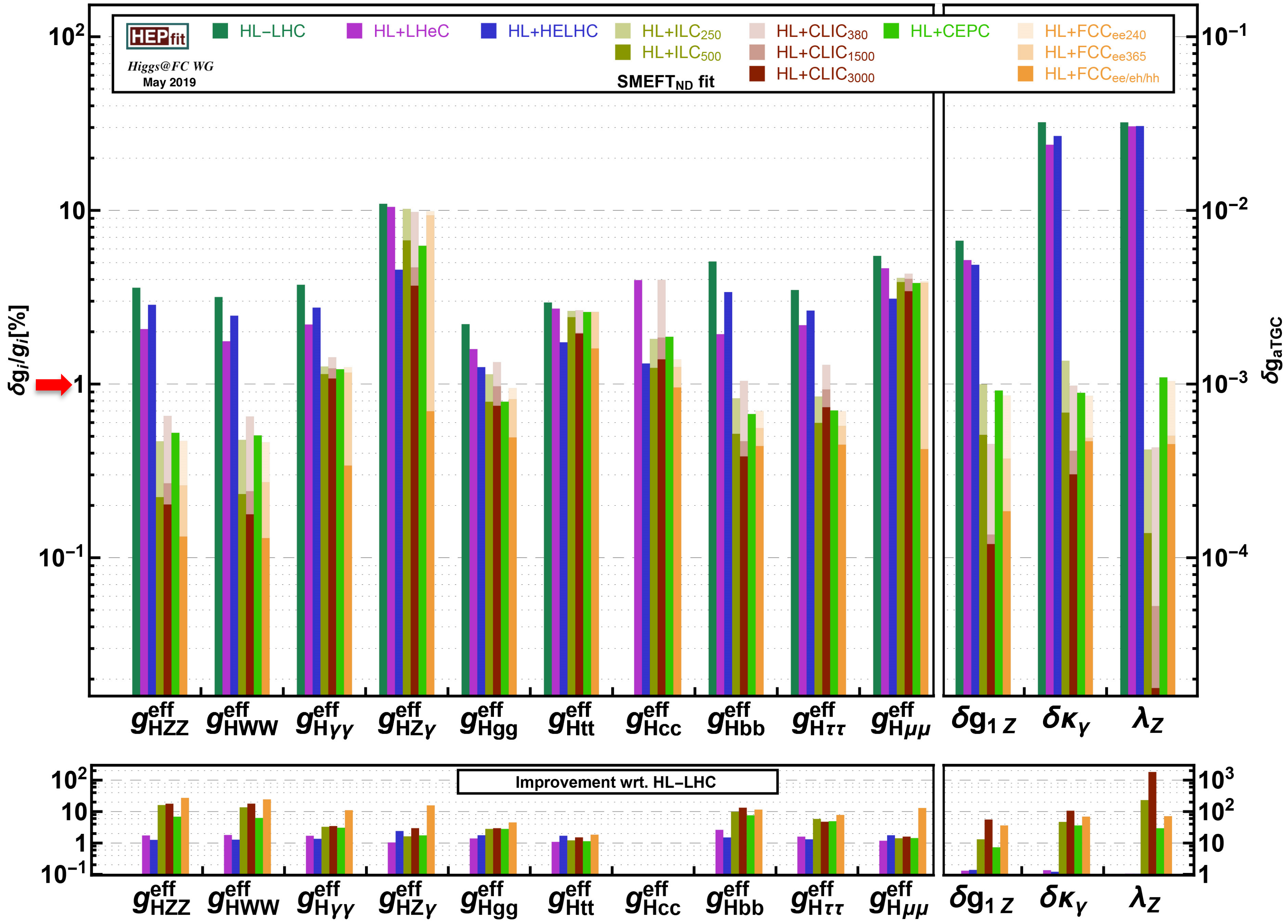
UPDATED BASELINE FOR A STAGED COMPACT LINEAR COLLIDER, CERN–2016–004

http://newsline.linearcollider.org/2018/04/05/the-ilc-at-250-gev-an-overview-of-options/

- Circular colliders have advantage in luminosity up to 400 GeV CM. At Z, they have 2-3 orders higher luminosity than LCs.
- The steep falls in the luminosity of circular colliders are due to constraints to keep the synchrotron radiation power constant over energies.
- Beyond 400 GeV, LCs take over, and there is no chance for circular e+e- machines (for 100 km circumference & 50 MW/beam).
- More exotic energies, such as the s-channel Higgs production, may be possible at circular colliders.

Sensitivity to Higgs couplings

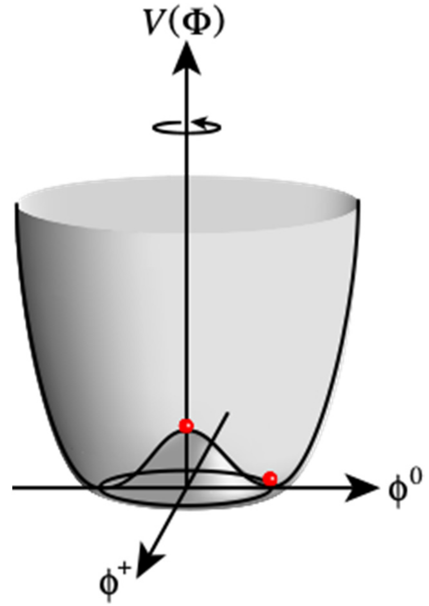
arXiv:1905.03764



The Standard Model Higgs potential

Higgs scalar potential: $V = -|\mu|^2 \Phi^+\Phi + \lambda(\Phi^+\Phi)^2$

A minimum away from zero field value causes (spontaneous) electroweak symmetry breaking



$$v^2 = \frac{|\mu|^2}{\lambda} = \frac{1}{\sqrt{2}G_F} = (246\ \mathrm{GeV})^2$$

$$\frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}} = \frac{1}{2v^2} \qquad m_H^2 = 2\lambda v^2 = 2|\mu|^2$$

m_h=125 GeV by ATLAS & CMS

$$|\mu|^2 = \frac{m_h^2}{2} \approx \frac{(125\ \mathrm{GeV})^2}{2} \approx (89\ \mathrm{GeV})^2$$

$$\lambda = \frac{|\mu|^2}{v^2} = \frac{m_h^2}{2v^2} \approx \frac{(125\ \mathrm{GeV})^2}{2(246\ \mathrm{GeV})^2} \approx 0.13$$ Weak coupling !

Higgs potential beyond the Standard Model

arXiv:1810.09037

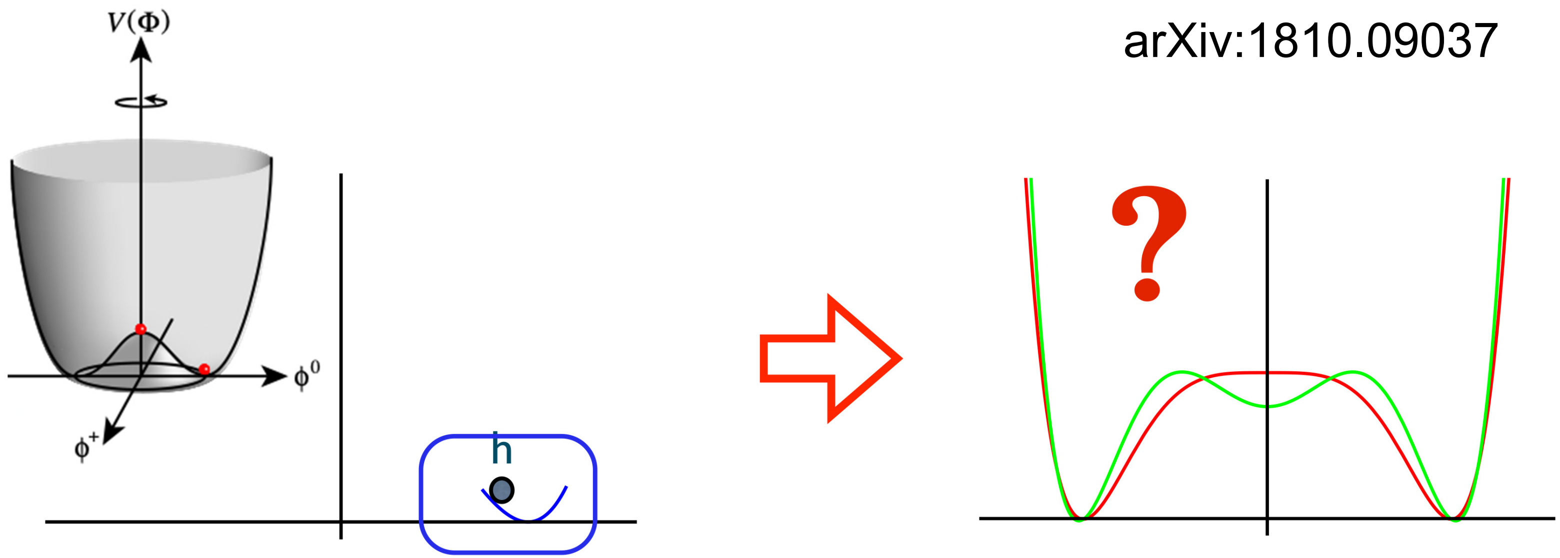


Fig. 32. A schematic drawing illustrating the question of the nature of the electroweak phase transition. Left: Our current knowledge of the Higgs potential. Right: Based on our current knowledge, we could not distinguish the SM Mexican Hat potential from an alternative one with more wiggles.

The study requires the measurement of the triple Higgs coupling and, therefore, a Higgs factory with CMS energy greater than 500 GeV.

Conclusions

- Potentials of precision Higgs measurements:
  - Higgs couplings to the SM particles will be measured to 1% or better accuracy(model-independent). Discovery reach will be 2-3 TeV (model-dependent).
  - WIMP Dark Matter will be searched for ($DM<M_H/2$).
  - CP Violation in the Higgs sector will be probed.

- So, We, HEP community, do have consensus:
  - Next machine concurrently running with (or beyond) High Luminosity LHC is an electron-positron collider Higgs factory.
  - We need one regardless of its form/shape; Linear or Circular. Either way, it will be a Discovery Accelerator.