Introduction to BSM/Higgs Joint Session

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Electroweak Symmetry Breaking
Mystery of something in the vacuum

- The EW symmetry forbids masses of gauge bosons and matter fermions. In order to break it without breaking that of the Lagrangian, we need ***"something" condensed in the vacuum which carries weak charge:*** $\langle 0 \,|\, I_3, Y \,|\, 0 \rangle \neq 0 \quad \langle 0 \,|\, I_3 + Y \,|\, 0 \rangle = 0$

  → ***We are living in a weakly charged vacuum!***

- The discovery of H(125) provided evidence that it is an excitation of (at least part of) this "something" in the vacuum and hence the correctness of this idea of the vacuum breaking the EW symmetry.

- In the SM, ***a single complex doublet scalar field*** is responsible for both gauge boson and matter fermion masses. The SM EWSB sector is the simplest, but other than that there is no reason for it. ***The EWSB sector might be more complex.***

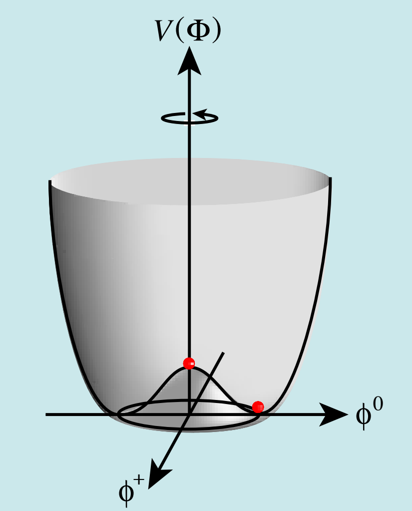
  → We need to know ***the multiplet structure*** of the EWSB sector.

- Moreover, the SM does not explain ***why the Higgs field developed a vacuum expectation value.***

  - ***In other words the SM does not answer the question:***

Why $\mu^2 < 0$?

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



Why $\mu^2 < 0$?

We need to go *B*eyond the *SM* to answer this question.

The Big Branch Point

- Concerning ***the dynamics behind the EWSB***.

  Is it ***weakly interacting or strongly interacting?***

  = Is the H(125) ***elementary or composite?***

- ***SUSY***, which gives ***a raison d'être for a fundamental scalar fields***, is the most attractive scenario for the 1st branch, where EW symmetry is broken radiatively.
  → ***The EWSB sector is weakly interacting.***
  → ***H(125) is elementary*** and embedded in an ***extended multiplet structure*** (there must be ***at least 2 Higgs doublets***).

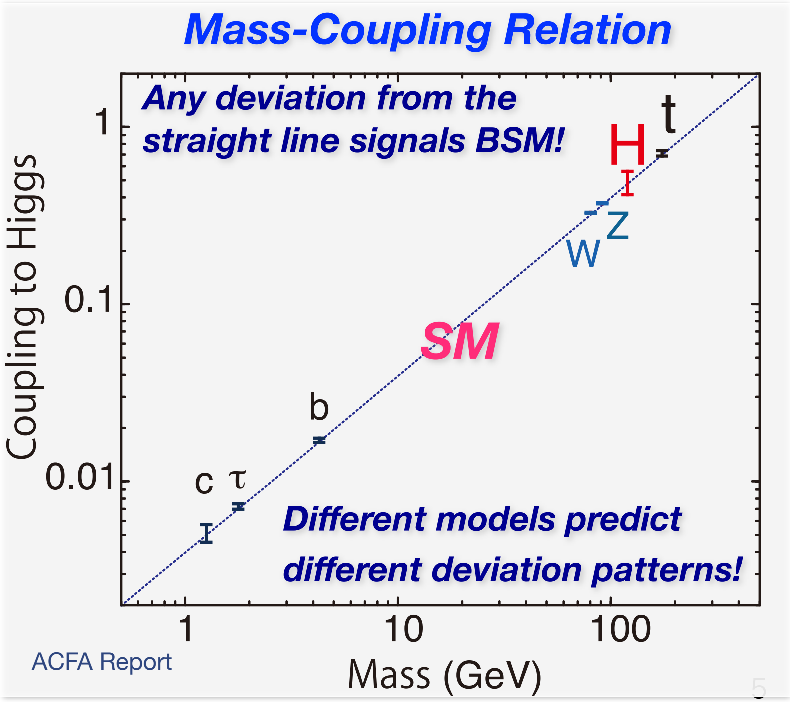
- ***Composite Higgs Models,*** the 2nd branch, where a new QCD-like strong interaction makes a vacuum condensate.
  → ***The EWSB sector is strongly interacting***.
  → ***H(125) is composite.***

Elementary or Composite?

How can ILC answer this question?

- If ***SUSY (elementary),***
  → ***(At least) 2 Higgs doublets***
    → ***Search*** for
      - extra Higgs bosons: ***H, A, H±***
      - uncolored SUSY particles: ***EWkinos, sleptons***
    → ***Look for specific deviation pattern*** in
      - ***various Higgs couplings***
      - gauge boson properties

- If ***Composite,***
    → ***Look for specific deviation pattern*** in
      - ***various Higgs couplings***
      - ***Top (ttZ) couplings***



Our Mission = Bottom-up Model-Independent Reconstruction of the EWSB Sector

through Precision Higgs Measurements

- **Multiplet structure :**
  - Additional singlet? (ϕ + S) + …?
  - Additional doublet? (ϕ + ϕ') + …?
  - Additional triplet? (ϕ + Δ) + …?
- **Underlying dynamics :**
  - ***Why $\mu^2 < 0$?***
  - Weakly interacting or strongly interacting?
    = ***elementary or composite ?***
- **Relations to other questions of HEP :**
  - ϕ + S → (B-L) gauge, **DM**, …
  - ϕ + ϕ' → Type I : m_ν from small vev, …
    → Type II: **SUSY**, DM, …
    → Type X: m_ν (rad.seesaw), …
  - ϕ + Δ → m_ν (Type II seesaw), …
  - $\lambda > \lambda_{SM}$ → **EW baryogenesis** ?
  - $\lambda \downarrow 0$ → inflation ?

→ There are many possibilities!

Different models predict different deviation patterns --> Fingerprinting!

Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

Mixing with singlet

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \frac{g_{hff}}{g_{h_{SM}ff}} = \cos\theta \simeq 1 - \frac{\delta^2}{2}$$

Composite Higgs

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\%(1\ \mathrm{TeV}/f)^2$$

$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \mathrm{TeV}/f)^2 & \text{(MCHM4)} \\ 1 - 9\%(1\ \mathrm{TeV}/f)^2 & \text{(MCHM5)} \end{cases}$$

SUSY

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

Expected deviations are small, typically a few % → ***We need a sub-% precision!***

Our mission is to understand

Multiplet Structure & Dynamics

of the EWSB sector,

and their relation to

***Other Big Questions* of High Energy Physics:**

DM, baryogenesis, …

→ *Bottom up Reconstruction of*

BSM Lagrangian

Our strategy is to fully exploit

LHC-LC Synergies

in

direct searches/studies of

***New Particles*,**

and

Precision measurements of

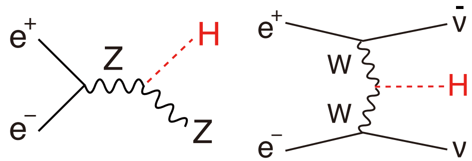
H(125) Properties (coupling)

Precision Measurements of Higgs Couplings

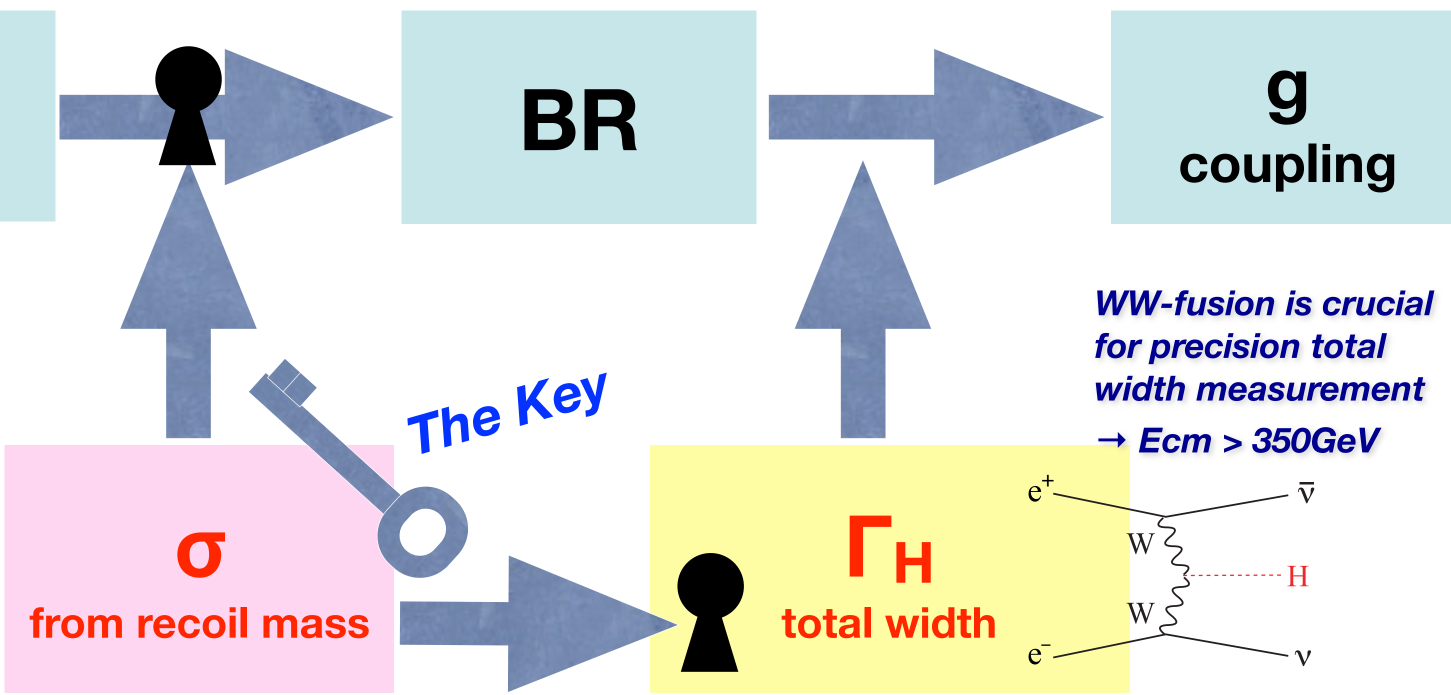
Key Point

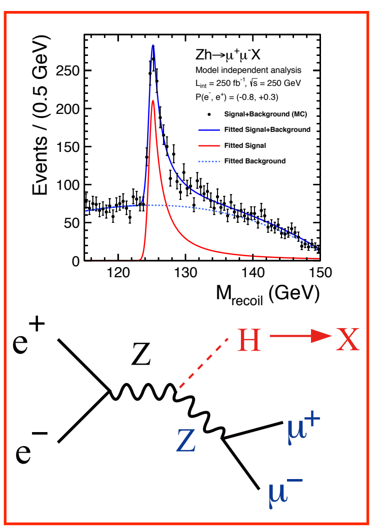
At LHC all the measurements are σ×BR measurements.

At ILC all but the σ measurement using recoil mass technique is σ×BR measurements.



$$g_{HAA}^2 \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$





Z→qq is also usable/promising (c.f. Tim's talk).

Independent Higgs Measurements

Hypothetical HL-ILC

250 GeV: 250 fb^{-1}	250 GeV: 1150 fb^{-1}
500 GeV: 500 fb^{-1}	500 GeV: 1600 fb^{-1}
1 TeV: 1000 fb^{-1}	1 TeV: 2500 fb^{-1}

(M_H = 125 GeV)

Ecm	250 GeV		500 GeV		1 TeV
luminosity · fb	250		500		1000
polarization (e-,e+)	(-0.8, +0.3)		(-0.8, +0.3)		(-0.8, +0.2)
process	ZH	vvH(fusion)	ZH	vvH(fusion)	vvH(fusion)
cross section	1.2%	-	1.7%	-	
	σ·Br	σ·Br	σ·Br	σ·Br	σ·Br
H-->bb	0.56%	4.9%	1%	0.37%	0.3%
H-->cc	3.9%		7.2%	3.5%	2%
H-->gg	3.3%		6%	2.3%	1.4%
H-->WW*	3%		5.1%	1.3%	1%
H-->ττ	2%		3%	5%	2%
H-->ZZ*	8.4%		14%	4.6%	2.6%
H-->γγ	16%		19%	13%	5.4%
H-->μμ	46.6%	-	-	-	20%

Model-independent Global Fit for Couplings

33 σxBR measurements (Y_i) and σ_{ZH} ($Y_{34,35}$)

$$\chi^2 = \sum_{i=1}^{35} \left(\frac{Y_i - Y_i'}{\Delta Y_i} \right)^2$$

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0} \qquad (A_i = Z, W, t)$$

$$(i = 1, \cdots, 33) \qquad (B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay})$$

$$F_i = S_i\, G_i$$

$$G_i = \left(\frac{\Gamma_i}{g_i^2} \right)$$

$$S_i = \left(\frac{\sigma_{ZH}}{g^2_{HZZ}} \right), \left(\frac{\sigma_{\nu\bar{\nu}H}}{g^2_{HWW}} \right), \text{ or } \left(\frac{\sigma_{t\bar{t}H}}{g^2_{Htt}} \right)$$

10 free parameters:

$$g_{HZZ},\ g_{HWW},\ g_{Hbb},\ g_{Hcc},\ g_{Hgg},\ g_{H\tau\tau},\ g_{H\gamma\gamma},\ g_{H\mu\mu},\ g_{Htt},\ \Gamma_0$$

- It is the recoil mass measurement that is the key to unlock the door to this completely model-independent analysis!
- Cross section calculations (S_i) do not involve QCD ISR.
- Partial width calculations (G_i) do not need quark mass as input.

We are confident that the total theory errors for S_i and G_i will be at the 0.1% level at the time of LC running.

Systematic Errors

	Baseline	LumUp
luminosity	0.1%	0.05%
polarization	0.1%	0.05%
b-tag efficiency	0.3%	0.15%

arXiv: 1310.0763

Model-independent Global Fit for Couplings

Luminosity Upgraded LC

250 GeV: 250 fb^{-1} 500 GeV: 500 fb^{-1} 1 TeV: 1000 fb^{-1}	250 GeV: 1150 fb^{-1} 500 GeV: 1600 fb^{-1} 1 TeV: 2500 fb^{-1}

(M_H = 125 GeV)

P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV

P(e-,e+)=(-0.8,+0.2) @ 1 TeV

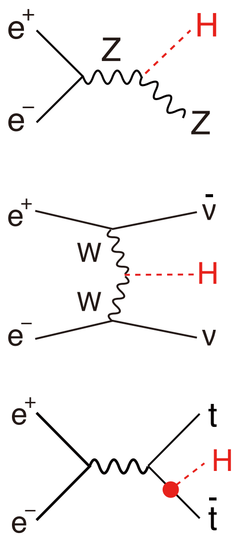
coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	0.6%	0.5%	0.5%
HWW	2.3%	0.6%	0.6%
Hbb	2.5%	0.8%	0.7%
Hcc	3.2%	1.5%	1%
Hgg	3%	1.2%	0.93%
Hττ	2.7%	1.2%	0.9%
Hγγ	8.2%	4.5%	2.4%
Hμμ	42%	42%	10%
Γ	5.4%	2.5%	2.3%
Htt	-	7.8%	1.9%

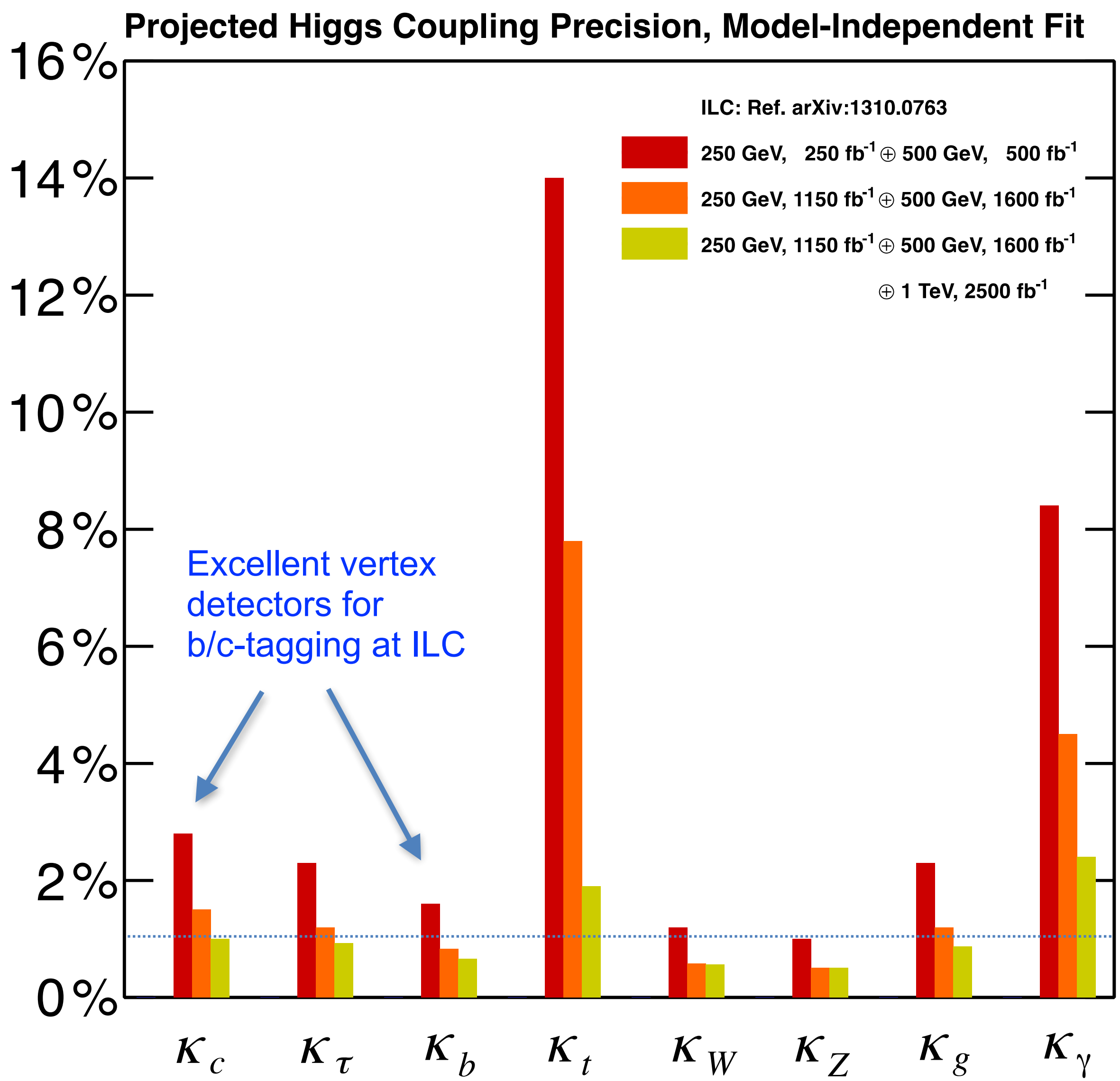
HHH	-	46%(*)	13%(*)

) With H->WW (preliminary), if we include expected improvements in jet clustering, it would become 10%!

Higgs Couplings

Model-independent coupling determination, impossible at LHC



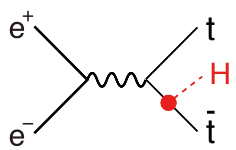


All of major Higgs decay modes accessible at ILC!

500 GeV already excellent except for K_t and K_γ

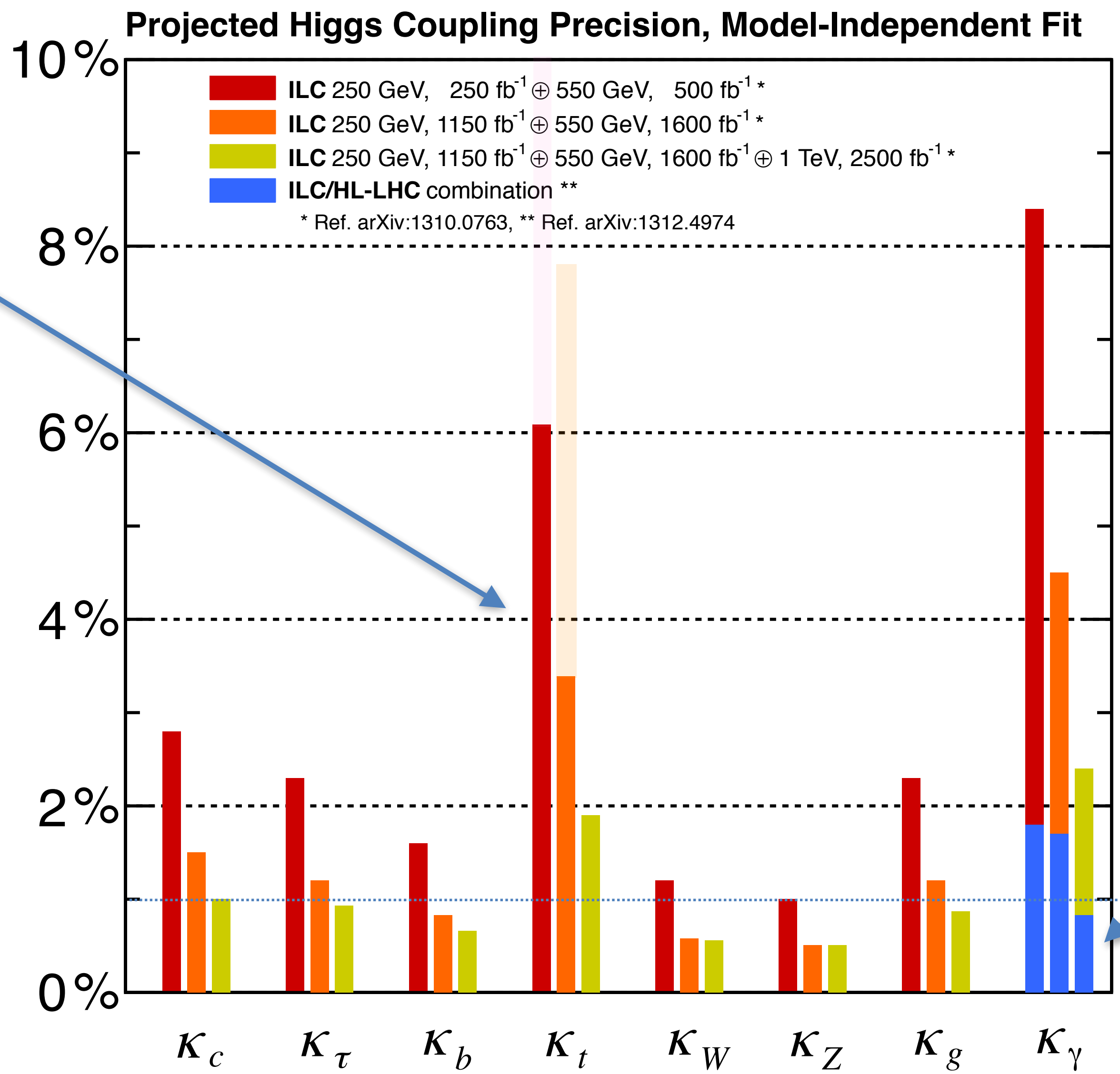
Higgs Couplings

Model-independent coupling determination, impossible at LHC



Top Yukawa improves by going to 550 GeV

Near threshold → a factor of 4 enhancement of σ_{tth} by going from 500GeV to 550 GeV



LHC can precisely measure

$BR(h\to\gamma\gamma) / BR(h\to ZZ^*) = (K_\gamma / K_Z)^2$

ILC can precisely measure K_Z

Better hγγ with LHC/ILC synergy

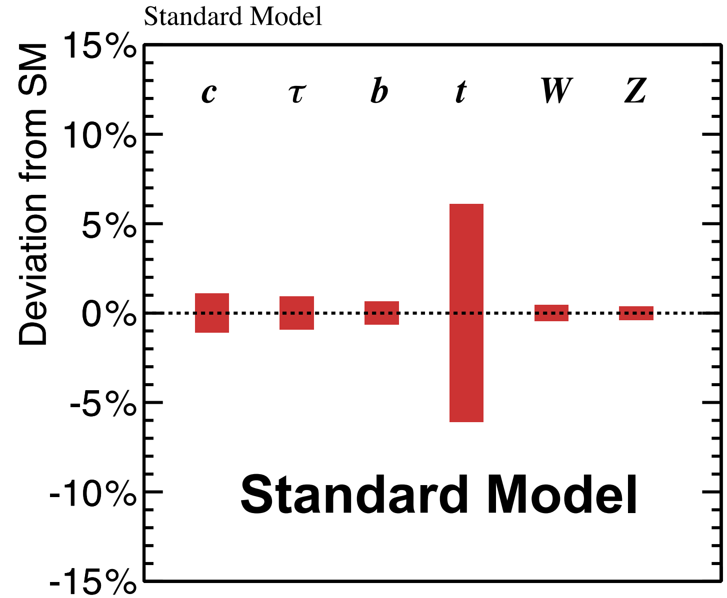
~1% or better precision for most couplings!

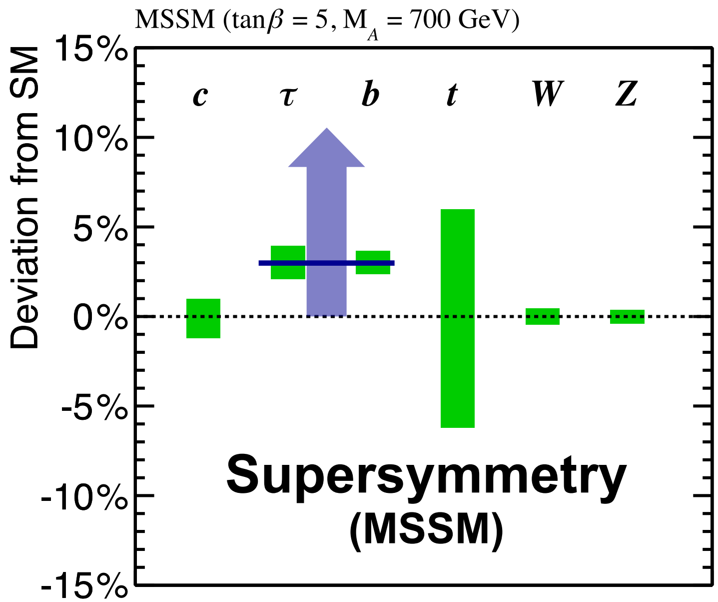
Impact of BSM on Higgs Sector

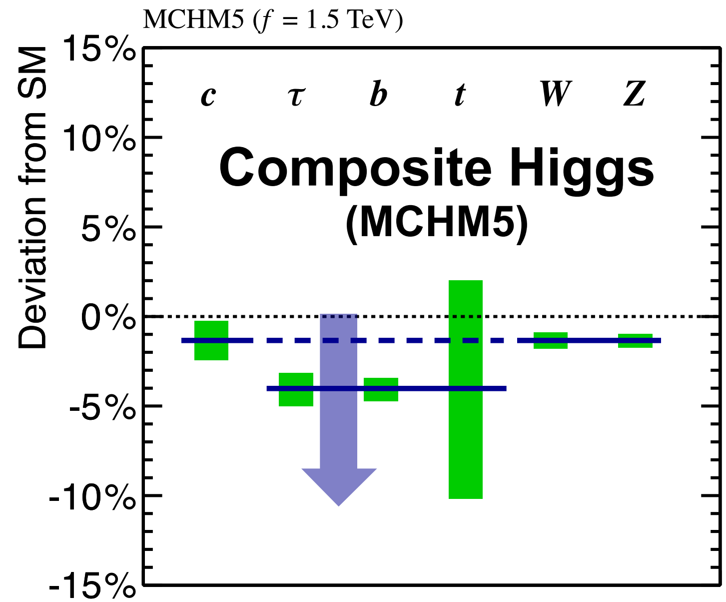
Elementary or Composite?

Deviations in Higgs couplings are a signature of BSM theories. **The deviation pattern is often specific to the model.** Precision Higgs coupling measurements at the ILC at the 1%-level enable us to discriminate the different models.

Lumi 1920 fb^{-1}, sqrt(s) = 250 GeV
Lumi 2670 fb^{-1}, sqrt(s) = 500 GeV



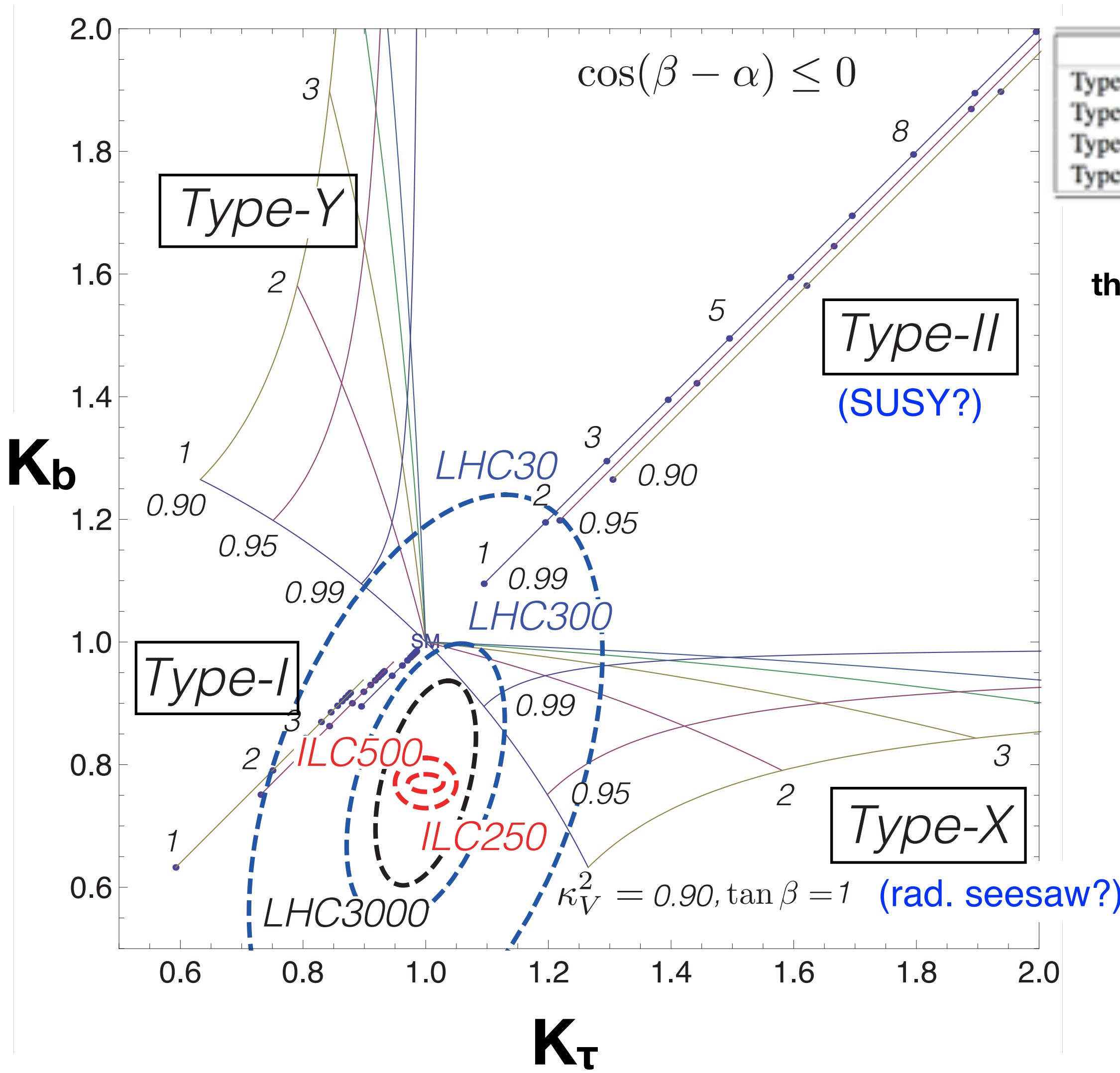




Fingerprinting

2HDM

Multiplet Structure



	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	+	−	−	−	−	+
Type II (SUSY)	+	−	−	+	+	+
Type X (Lepton-specific)	+	−	−	−	+	+
Type Y (Flipped)	+	−	−	+	−	+

4 Possible Z_2 Charge Assignments that forbids tree-level Higgs-induced FCNC

$K_V^2 = \sin(\beta-\alpha)^2 = 1 \Leftrightarrow$ SM

Given a deviation of the Higgs to Z coupling: ***$\Delta K_V^2 = 1 - K_V^2 = 0.01$*** *we will be able to* ***discriminate the 4 models!***

TDR ILC

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

We need to refine strategies for *Fingerprinting* and *Extraction of Model Parameters*

We need information about

The BSM Mass Scale

But what about higher order corrections?

- **Cross sections,**
- **BRs,**
- **couplings**

What about systematics?

- theoretical,
- parametric,
- experimental

How to further improve precisions?

- ***By improving analysis method:***
  - **fully use hadronic Z decays for recoil mass (issue: dependence on Higgs decay mode)**
  - **identify exotic Higgs decays (incl. invisible one separately) and use Σ BR = 1 constraint. (cf. Michael Peskin's analysis)**
- ***By optimizing running scenarios:***
  - **How much luminosities at what energies and in which order?**
  - **When do we do energy/luminosity upgrades?**