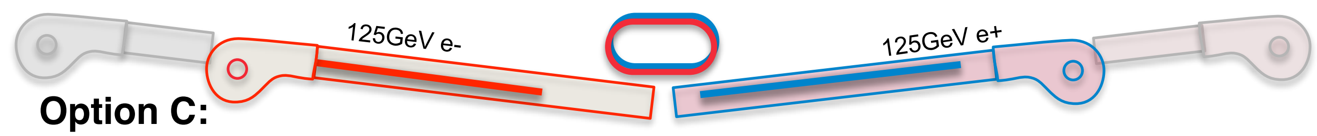
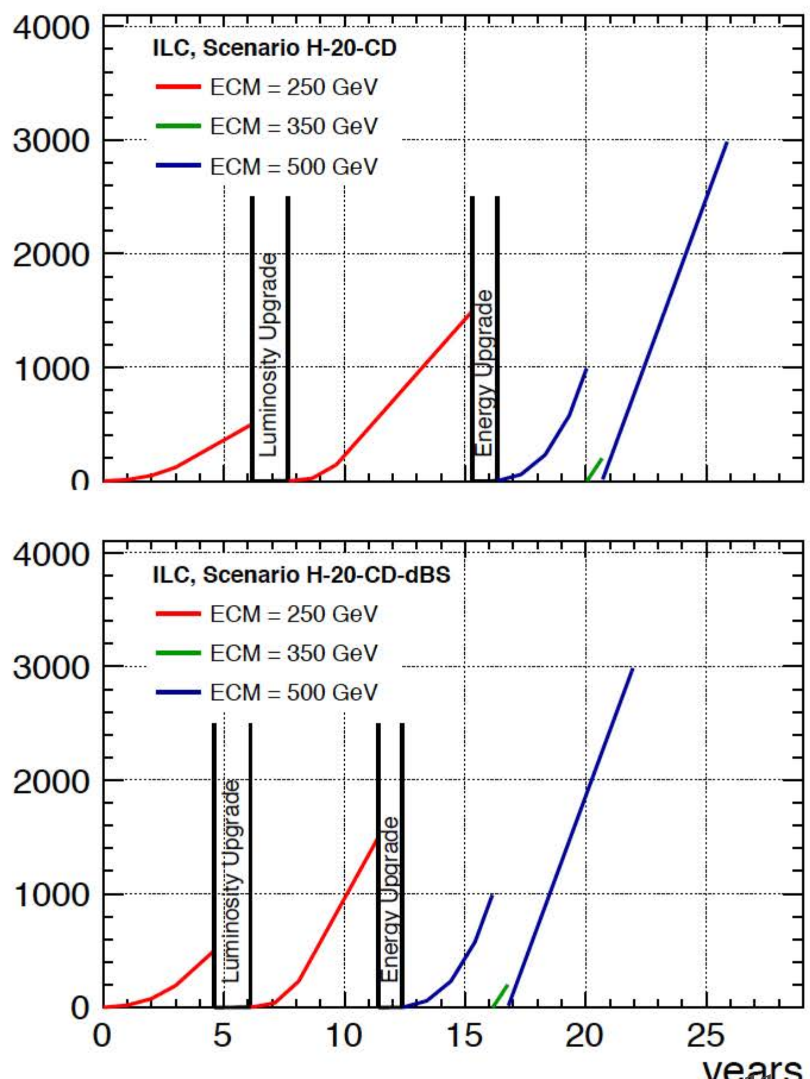
Physics Case for ILC250

Staging from 250 GeV

LCC ILC parameters WG

new scenarios: H-20-CD (-δ_{BS})





lumi upgrade after $\int L dt \sim 500\ \mathrm{fb}^{-1}$ (double bunches)

energy upgrade after $\int L dt \sim 2\ \mathrm{ab}^{-1}$ at 250 GeV in ~15 (11)y

ILC500 starts with x2 bunches directly

save ~4y with δ_{BS}

based on J. Tian, AWLC 2017

Staging from 250 GeV

What happens if we don't have 500 GeV data?

So far LHC Run II saw no clear signal of physics beyond the Standard Model.

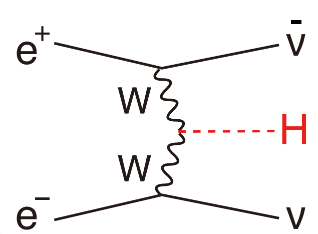
→***No new particle in the ILC's range or it is in the LHC's blind spot.***

→***Importance of precision Higgs measurements enhanced.***

1st stage as a Higgs factory

Potential drawback:
Γ_h determination

$$\Gamma_h = \frac{\Gamma(h \to WW^*)}{BR(h \to WW^*)}$$



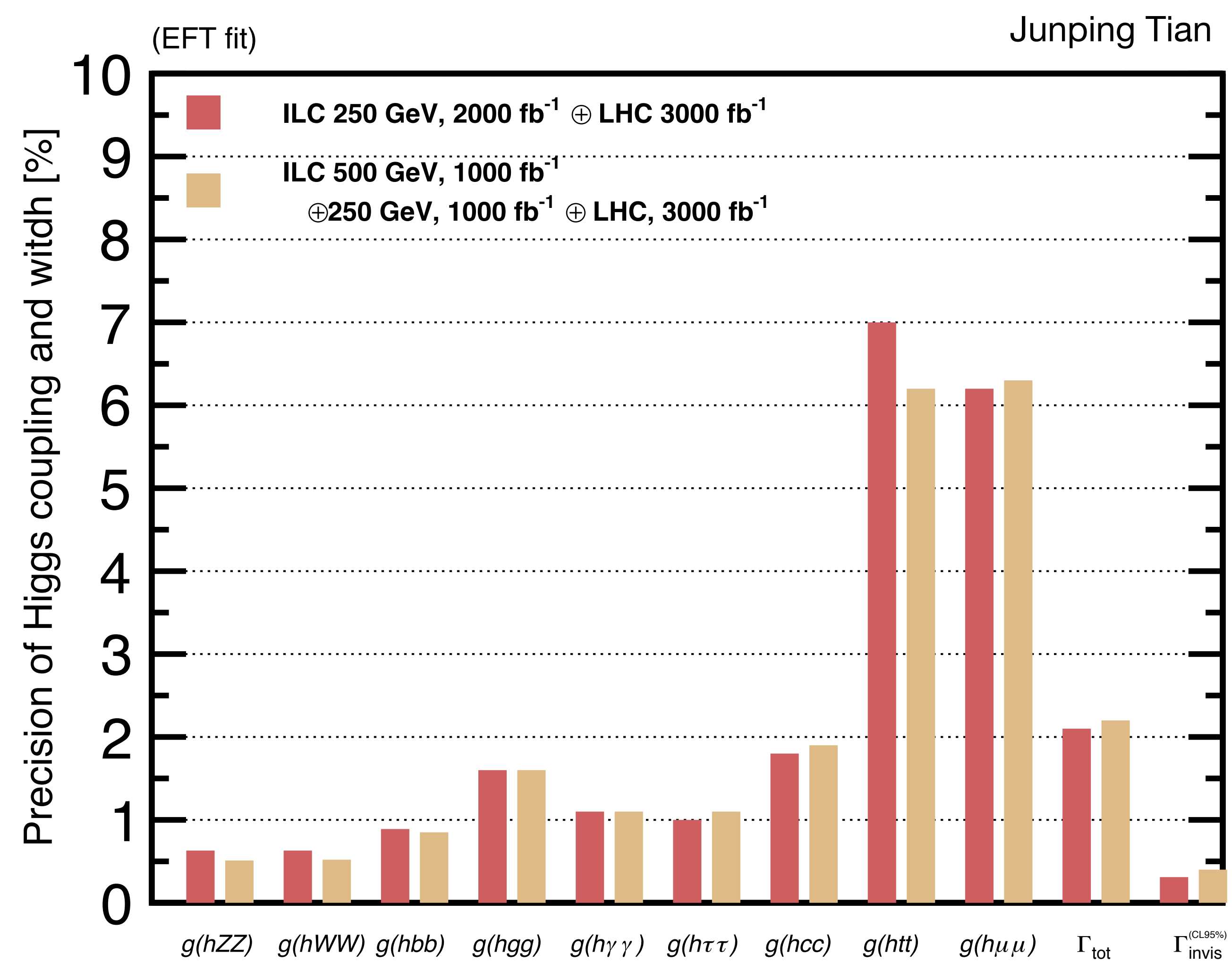
$$\Gamma(h \to WW^*) \propto \sigma(\nu\bar{\nu}h)$$

Small @ 250GeV

Solution: ***EFT***
that relates hZZ and hWW couplings

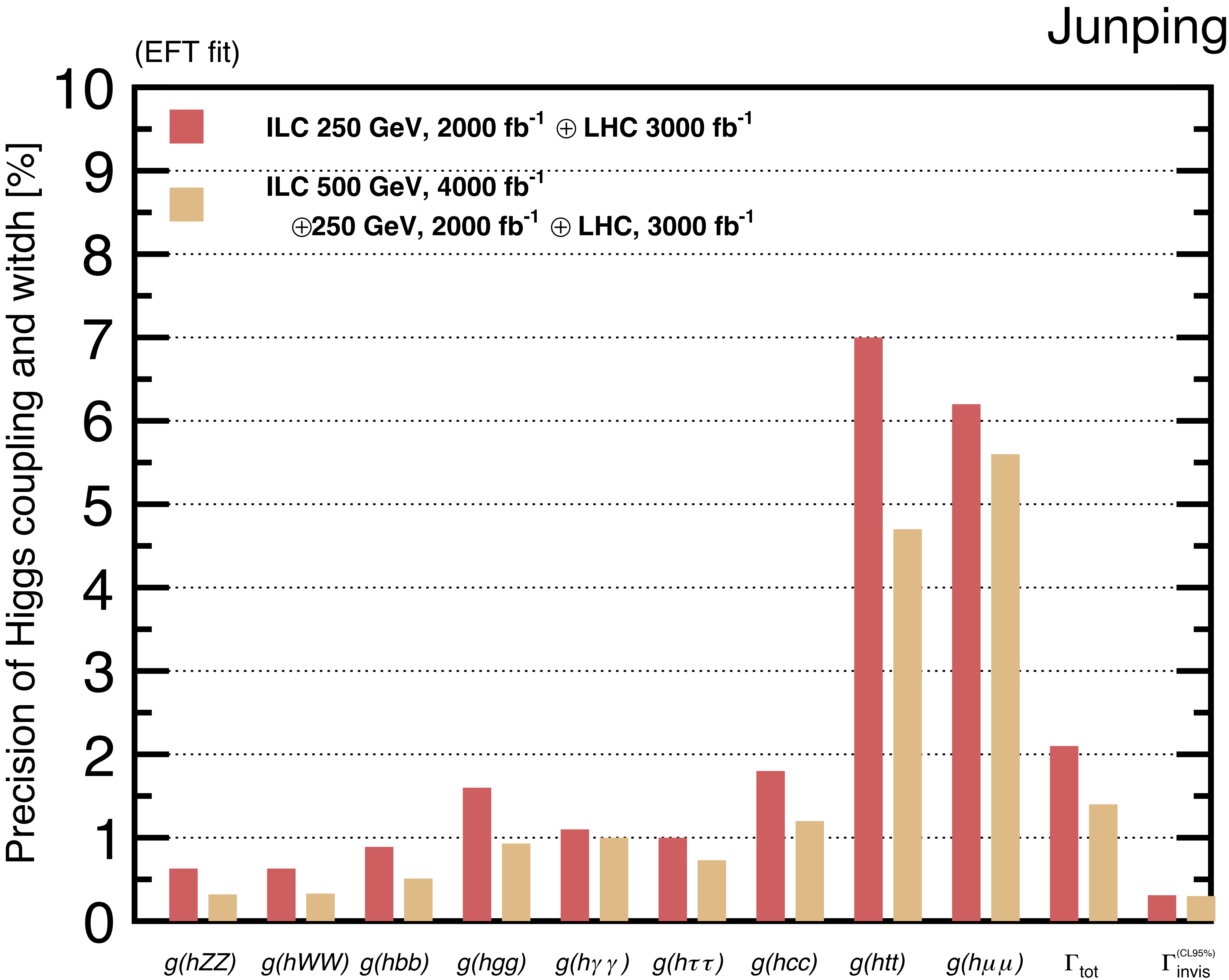
Many EFT coefficients will have to be constrained by various SM processes that involve EW gauge bosons.
→possible at ILC250.

arXiv: 1708.08912



For the same integrated luminosity, the 250 GeV ILC performs equally well.

Beam polarization provides enough redundancy to test the validity of the EFT in case there is a light new particle


Junping
(EFT fit)
ILC 250 GeV, 2000 fb-1 ⊕ LHC 3000 fb-1
ILC 500 GeV, 4000 fb-1
⊕250 GeV, 2000 fb-1 ⊕ LHC, 3000 fb-1
Precision of Higgs coupling and witdh [%]
0
1
2
3
4
5
6
7
8
9
10
g(hZZ)
g(hWW)
g(hbb)
g(hgg)
g(hγγ)
g(hττ)
g(hcc)
g(htt)
g(hμμ)
Γtot
Γinvis (CL95%)

H20 Scenario

arXiv: 1506.05992

arXiv: 1506.07830

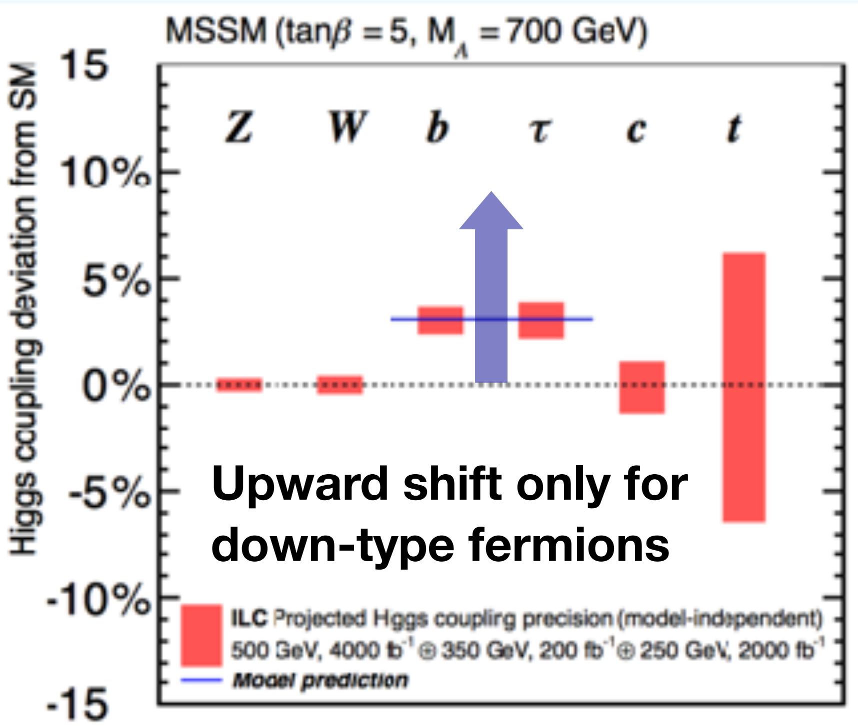
ILC 250+500 LumiUP

Which way to go?

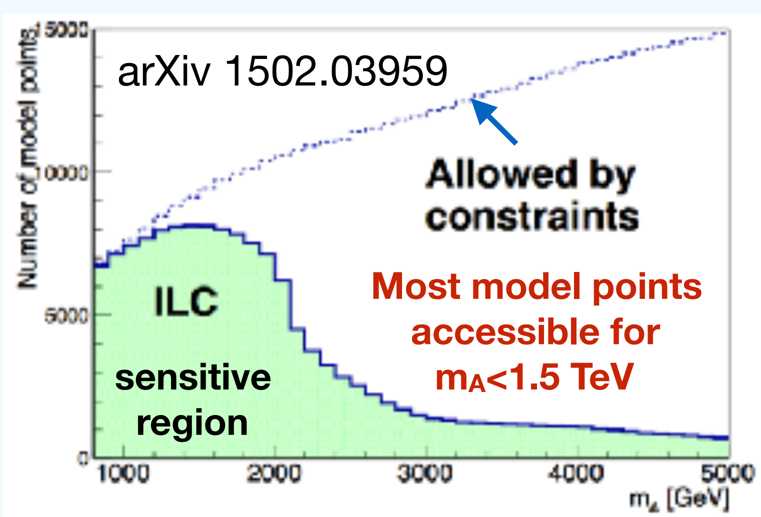
Fingerprinting models with Precision Higgs Measurements

Supersymmetry

(MSSM)

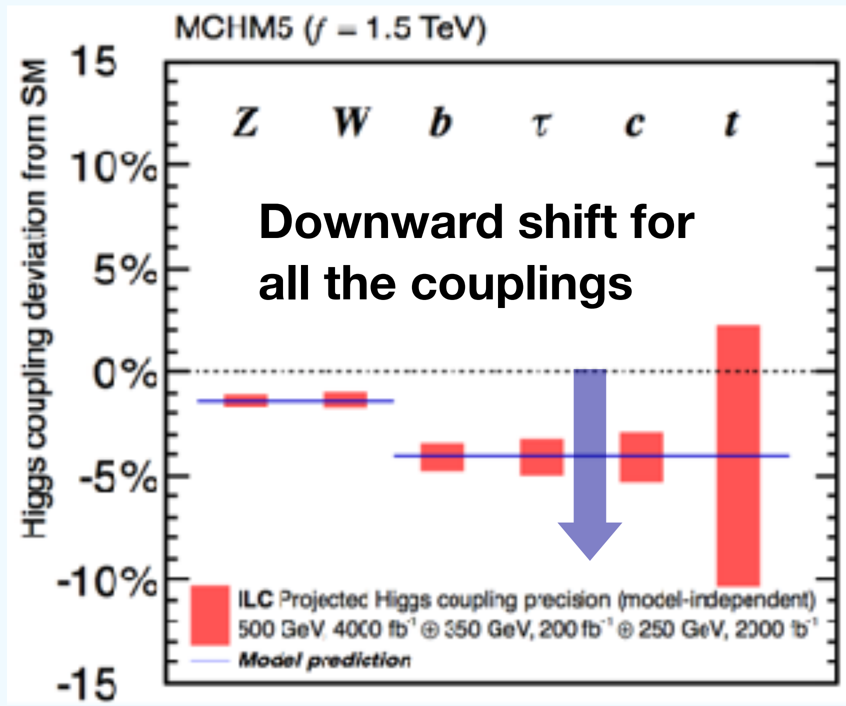


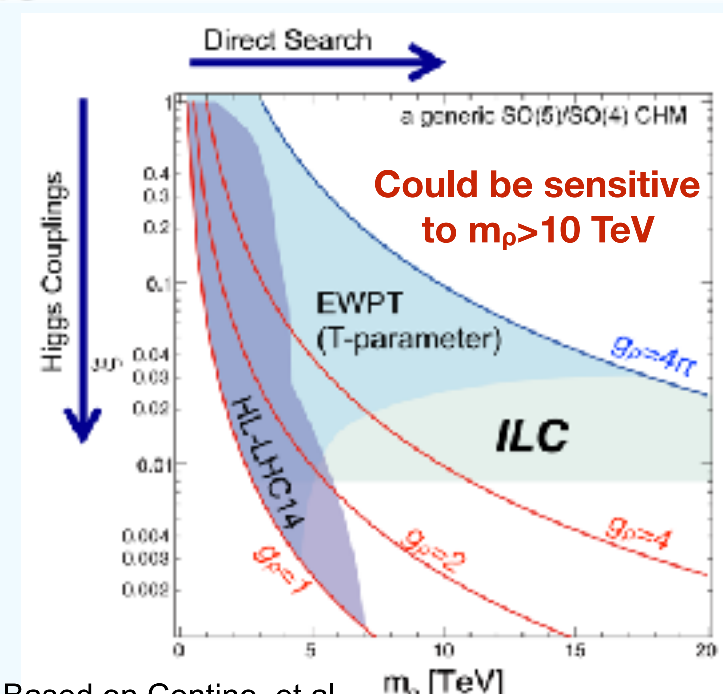
MSSM Model Scan



Composite Higgs

(MCHM5)

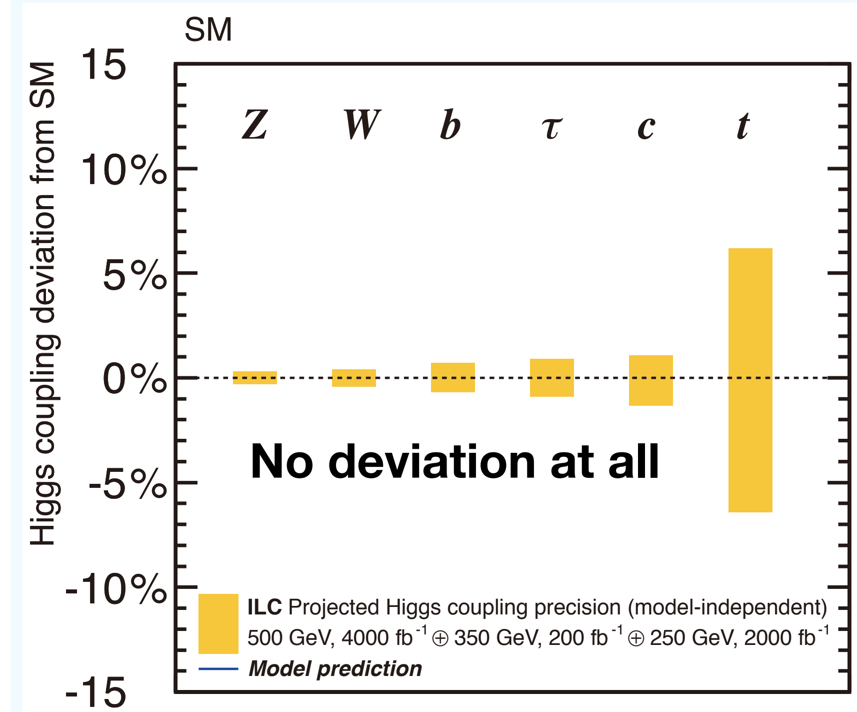




Based on Contino, et al, JHEP 1402 (2014) 006

Multi-verse?

(Standard Model)



Complementary to direct searches at LHC: Depending on parameters, ILC's sensitivity goes well beyond that of LHC!

arXiv: 1708.08912

DESY 17-120
KEK Preprint 2017–22
SLAC–PUB–17129
August, 2017

Improved Formalism for Precision Higgs Coupling Fits

Tim Barklow[a], Keisuke Fujii[b], Sunghoon Jung[ac], Robert Karl[d], Jenny List[d], Tomohisa Ogawa[b], Michael E. Peskin[a], and Junping Tian[e]

[a] *SLAC, Stanford University, Menlo Park, CA 94025, USA*
[b] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, JAPAN*
[c] *Dept. of Physics and Astronomy, Seoul National Univ., Seoul 08826, KOREA*
[d] *DESY, Notkestrasse 85, 22607 Hamburg, GERMANY*
[e] *ICEPP, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, 113-0033, JAPAN*

Sensitivity of EFT Analysis

to sample new physics scenarios

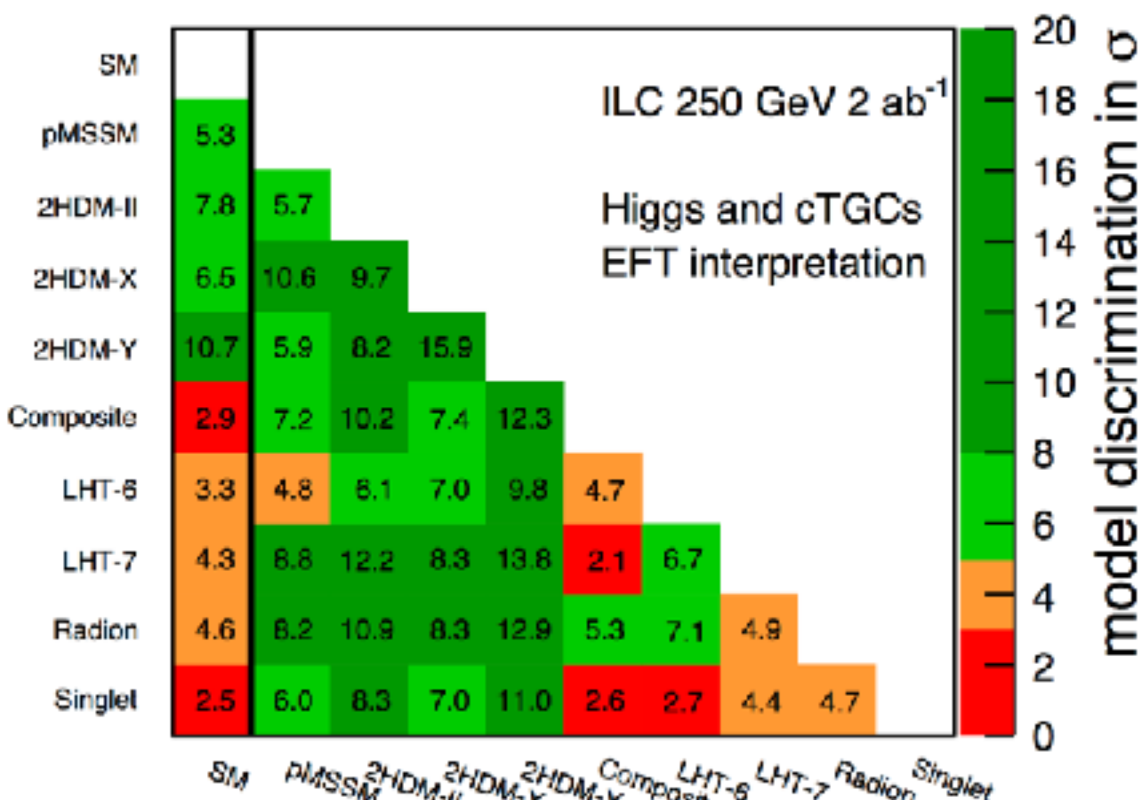
arXiv: 1708.08912

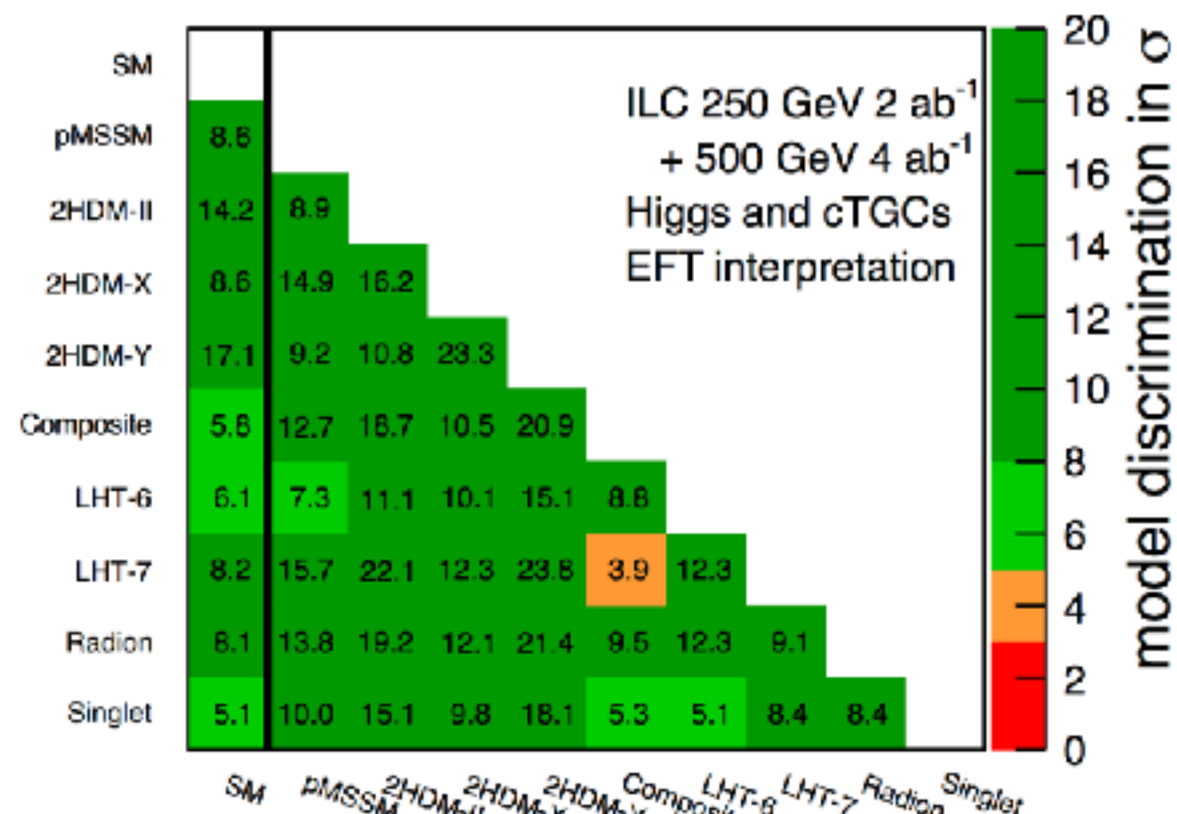
9 sample models and expected deviations (%)

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [33]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [35]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [35]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [35]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [37]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [38]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [39]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [40]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [41]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

All new particles outside the projected reach of the HL-LHC

Discrimination power in σs





What we might lose

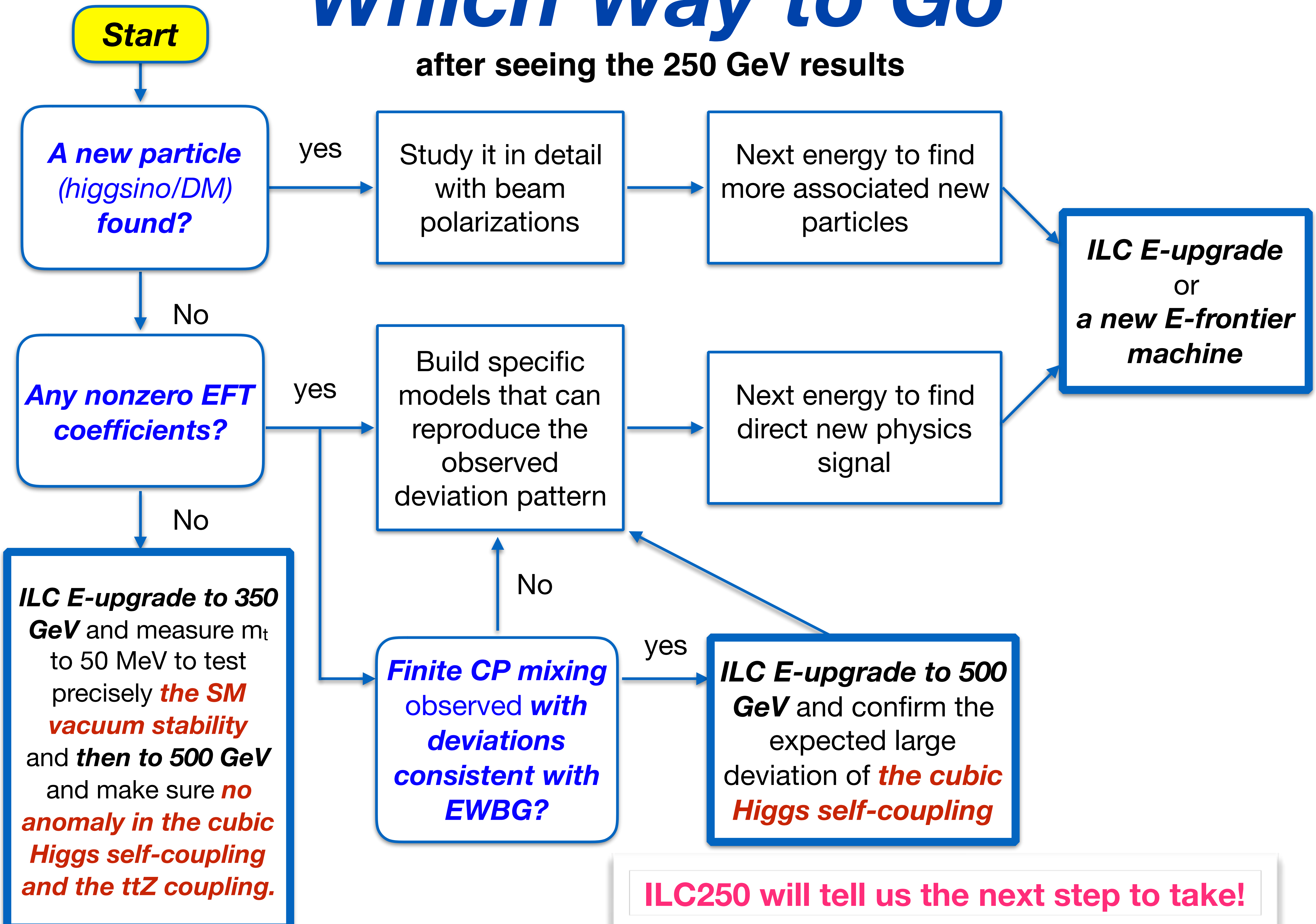
by staying at 250 GeV for long time

Challenging Tasks for ILC250	Issues	Possible Solutions/Measures
Higgs cubic self-coupling	A new interaction at the heart of EWSB, important in its own right. Large enhancement expected for models of EWBG. ***500 GeV needed for $e^+e^- \to ZHH$.***	Models of EWBG often predicts ***shifts in other Higgs couplings***, too. ***Synergy with HL-LHC, SuperKEKB, GW.***
Precision top mass	A parameter of SM, important in its own right. O(50) MeV desirable for vacuum stability test. ***Theoretically cleanest measurement requires ttbar threshold scan at around 350 GeV.***	***Direct top reconstruction at LHC with possible future theoretical progress*** to relate MC mass to pole mass (~200-300 MeV?).
Anomalous Top Couplings	Being heaviest in SM, top couples to new physics that caused EWSB. ***Needs at least 350 GeV, the best sensitivity expected at around 500 GeV.***	Most models of EWSB often predicts ***shifts in various Higgs couplings*** as well. ***Use the b-quark ($e^+e^- \to$ bbbar) as another 3rd generation quark.***
Top Yukawa coupling	6 (3)% at 500 (550) GeV, ***not available at 250 GeV.***	***Synergy with HL-LHC (~7%).***
New Particles	***Direct search limited by $m_X < E_{cm}/2$.***	Natural SUSY prefers ***light higgsinos.*** Indirect search through oblique correction may reach ~200GeV ***($e^+e^- \to$ ffbar)***. DM searches by ***$h \to$ invisible. Exotic higgs decays. Synergy with HL-LHC.***

My Personal View

Which Way to Go

after seeing the 250 GeV results



ILC250 will tell us the next step to take!

Summary

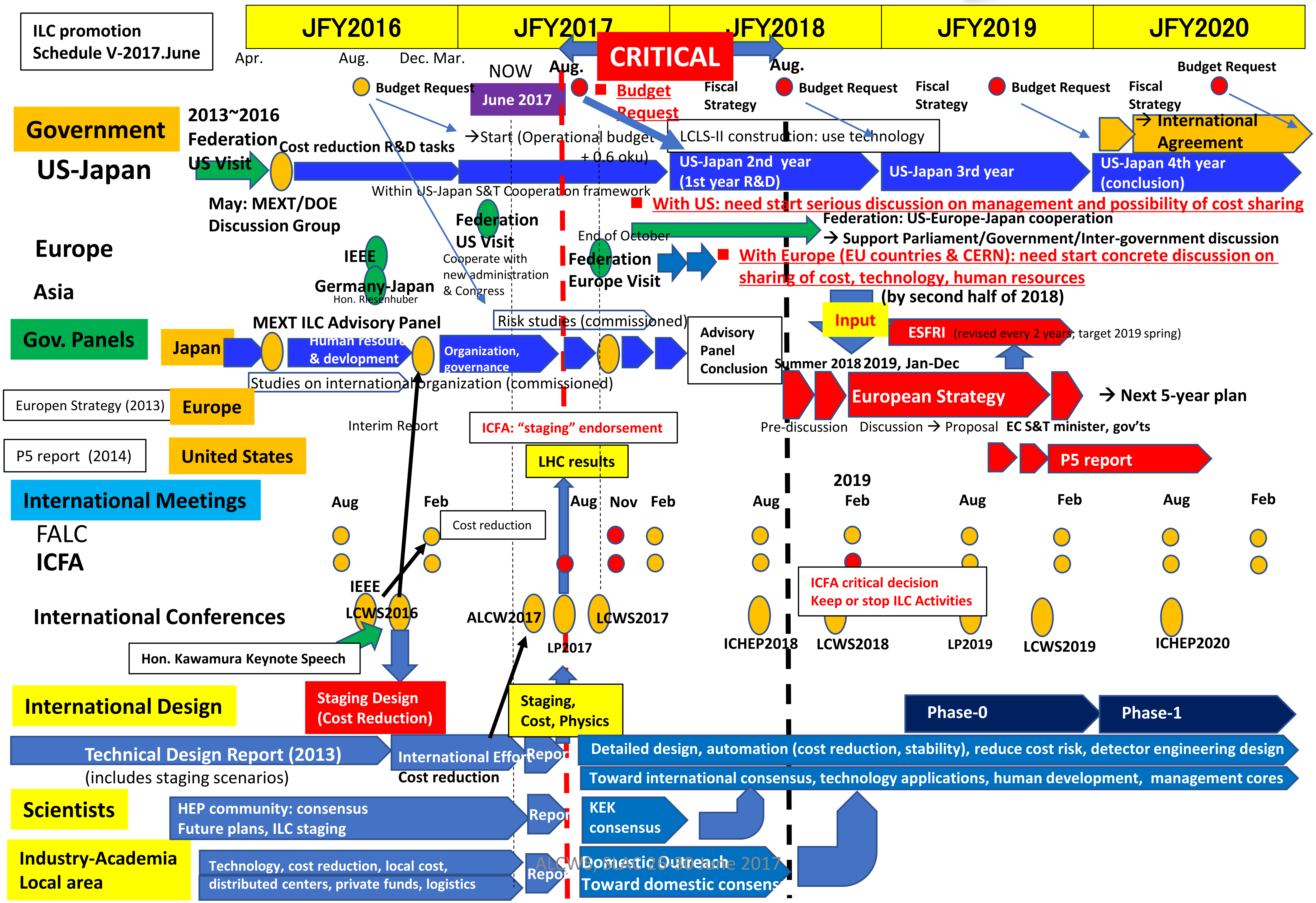
- The primary goal for the next decades is ***to uncover the secret of the EW symmetry breaking.*** ***Why $\mu^2 < 0$?*** To answer this question we need to go beyond the SM.
- There is a big fork ahead of us. We have a very powerful probe: the ***H(125) itself***. Different models predict different deviation patterns in various Higgs couplings. ***ILC will measure these couplings with unprecedented precision.***
- This will open up a window to BSM and ***fingerprint BSM models***, otherwise it will set the energy scale for energy upgrade or the next machine.
- The ILC, too, is an energy frontier machine. It will enter ***uncharted waters of e^+e^- collisions*** and search for new particles, covering the blind spots of the LHC.
- In this way, ***ILC will pave the way towards the moment of creation.***
- ***MEXT is seriously investigating various issues to be solved to host the ILC in Japan.***
- ***MEXT-DOE joint discussion group*** started and is meeting regularly.
- ***US-Japan joint effort on cost reduction*** is on-going.
- There are important ***political interactions happening also in Europe and Asia.***
- Serious discussions on ***staging from 250 GeV*** is on-going.
- ***2017-2018 will be a very important time for the ILC.***

Stay Tuned!

Backup

AWLC2017 @ SLAC, June 26-30, 2017

Lyn Evans, June 29



Kitakami Site

北上サイト

研究者による検討結果：主に技術的観点

国際設計チーム
北上サイトでの国際詳細設計を進行

Satoru Yamashita @ JPS 2017 fall

Local Support

Tohoku tourism ad seen on Tokyo Metro

OUTREACH and SUPPORTS by LOCAL AREA

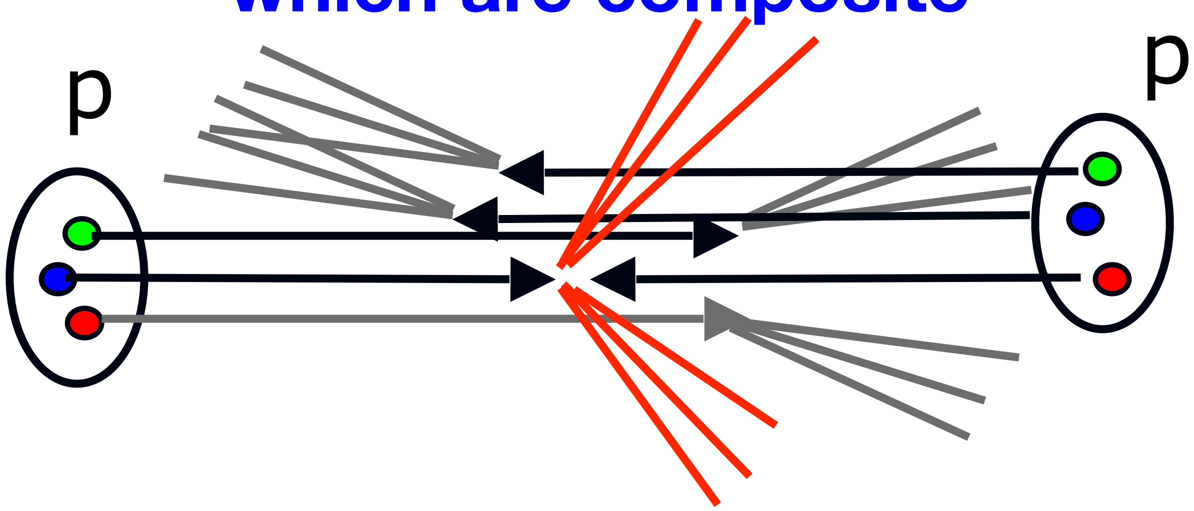
Oshu City

Ichinoseki Station

Morioka

3 Powerful Tools

LHC: Collision of protons which are composite

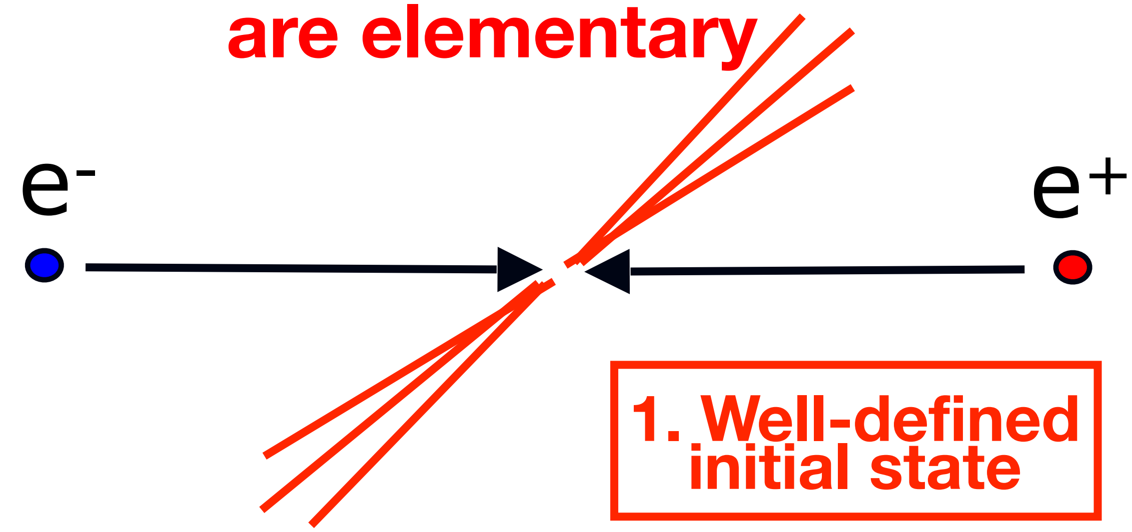


Ecm 7-14 TeV

Pileup

Initial state not very well defined

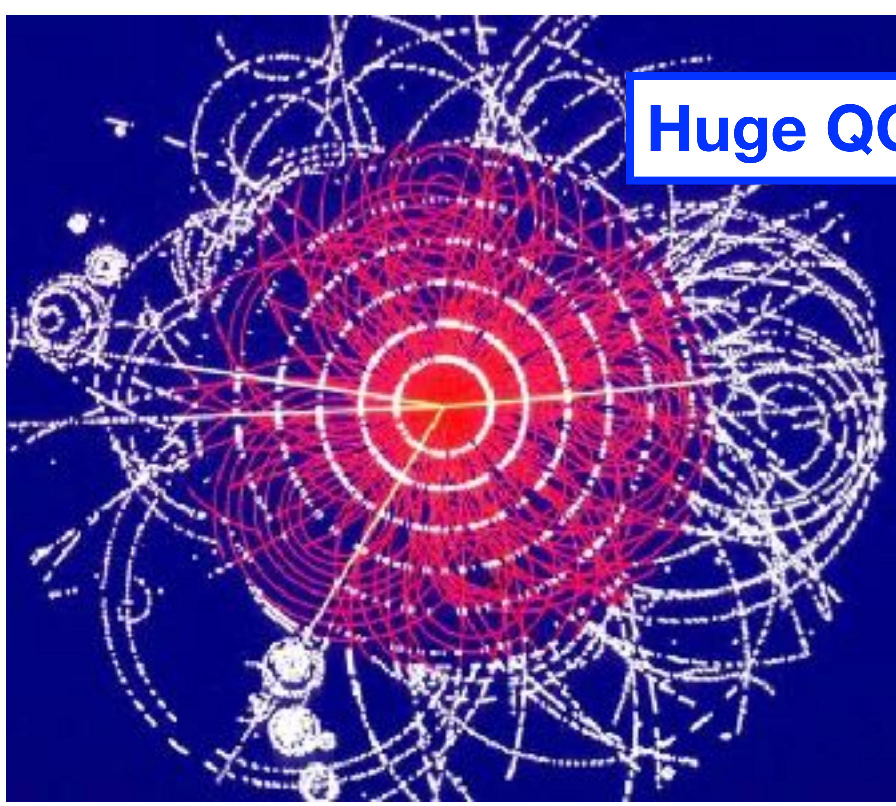
ILC: Collision of e^+e^- which are elementary



1. Well-defined initial state

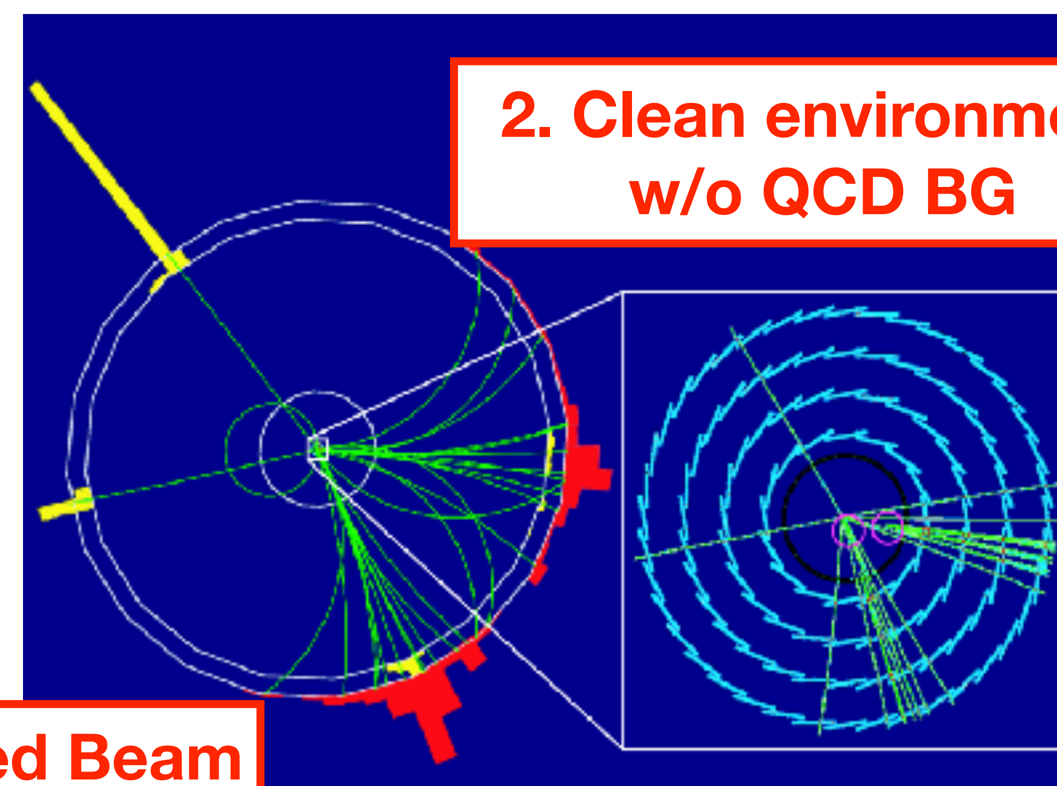
Ecm 0.25-1 TeV

Lab. frame = CM frame



Huge QCD BG

proton is composite ⇒ events are complicated but **maximum reachable energy is high!**



2. Clean environment w/o QCD BG

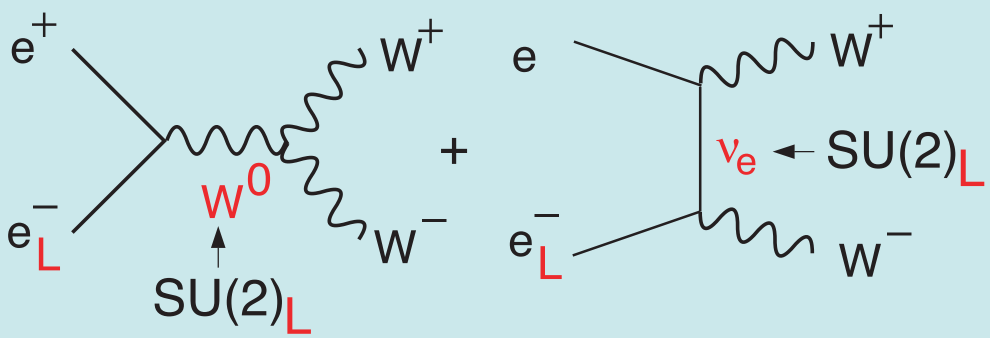
3. Polarized Beam

clean and and able to detect everything produced!

Power of Beam Polarization

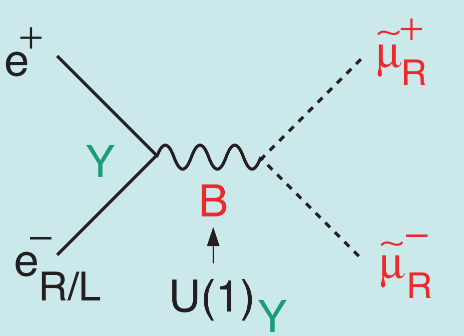
BG Suppression

W^+W^- *(Largest SM BG in SUSY searches)*



In the symmetry limit, $\sigma_{WW} \to 0$ for e_R^- !

Right-handed Smuon Pair

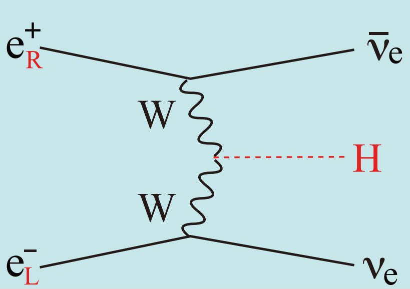


$$\begin{cases} Y_L = -1/2 : e_L^- \\ Y_R = -1 \quad : e_R^- \end{cases}$$

In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

Signal Enhancement

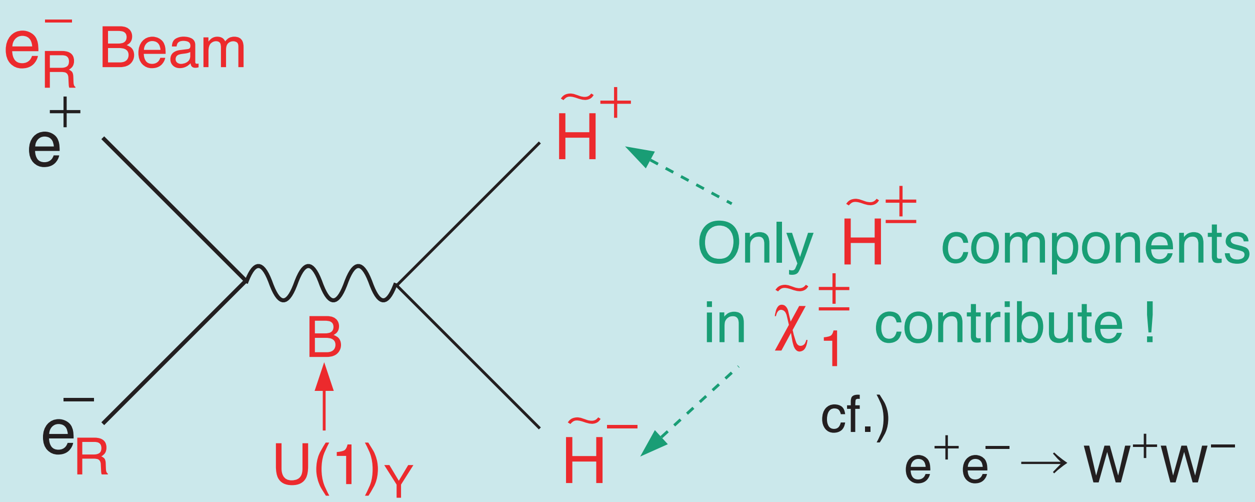
WW-fusion Higgs Prod.



	ILC
Pol (e-)	-0.8
Pol (e+)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=2.34

Decomposition

Chargino Pair

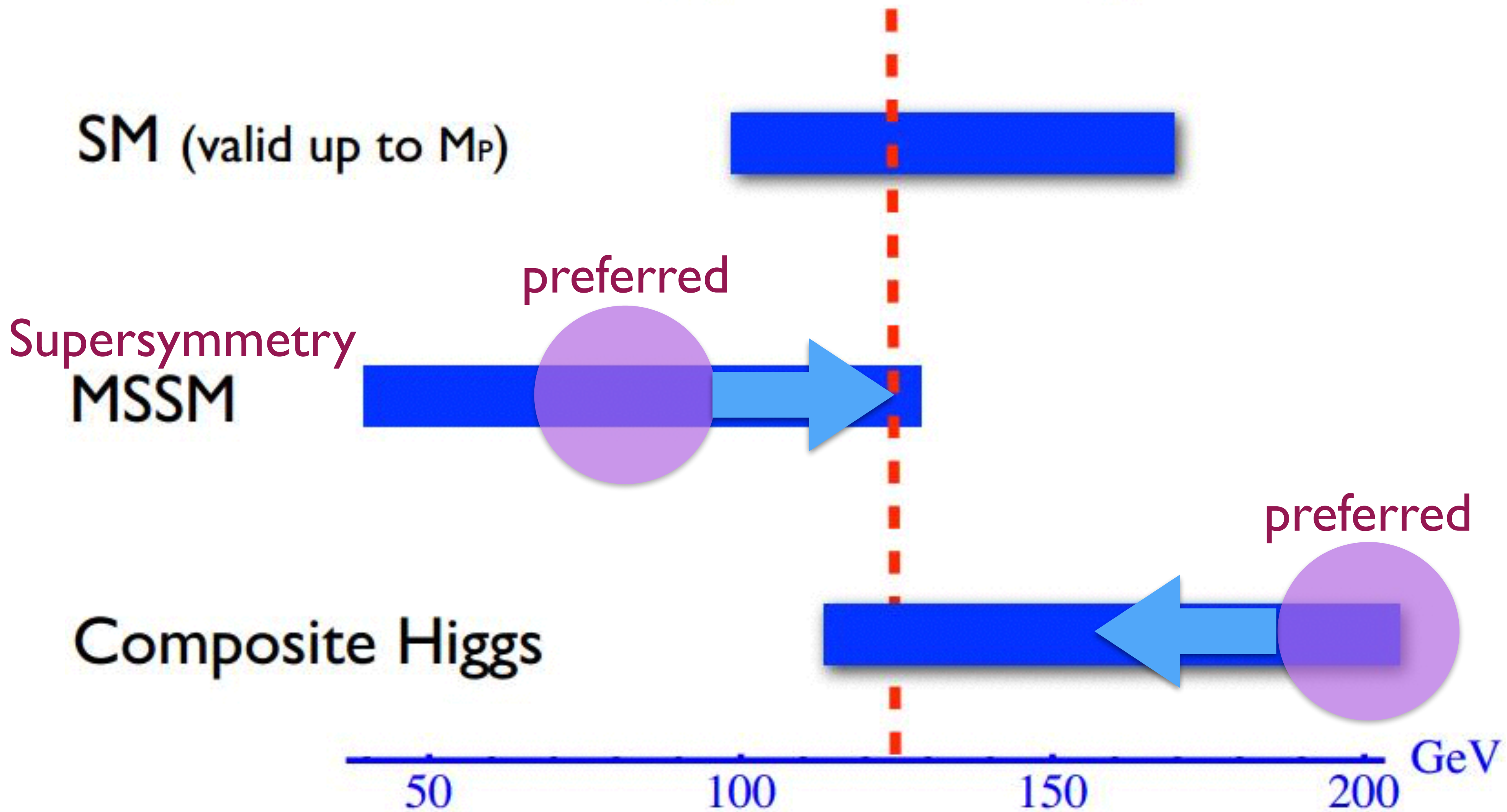


$$\tilde{\chi}_1^\pm = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$$

$$\bullet = \langle \tilde{H}^\pm | \tilde{\chi}_1^\pm \rangle$$

Precision Higgs Analysis with EFT

Higgs mass range



Hyung Do Kim

By A Pomarol

arXiv: 1708.08912

DESY 17-120
KEK Preprint 2017–22
SLAC–PUB–17129
August, 2017

Improved Formalism for Precision Higgs Coupling Fits

Tim Barklow[a], Keisuke Fujii[b], Sunghoon Jung[ac], Robert Karl[d], Jenny List[d], Tomohisa Ogawa[b], Michael E. Peskin[a], and Junping Tian[e]

[a] *SLAC, Stanford University, Menlo Park, CA 94025, USA*
[b] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, JAPAN*
[c] *Dept. of Physics and Astronomy, Seoul National Univ., Seoul 08826, KOREA*
[d] *DESY, Notkestrasse 85, 22607 Hamburg, GERMANY*
[e] *ICEPP, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, 113-0033, JAPAN*

EFT Lagrangian Before EW Symmetry Breaking

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}$$

$$\begin{aligned}\Delta\mathcal{L} = &\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\ &+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\ &+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\ &+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L) \\ &+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .\end{aligned}$$

Manifestly SU(2)xU(1) gauge invariant
∵ BSM must be SU(2)xU(1) symmetric

10 parameters of which C_6 only affects Higgs self-coupling analysis.
5 parameters to account for Higgs coupling to b, c, τ, μ, g.
\+ **2** parameters to account for invisible and exotic Higgs decays.
\+ **4** parameters to account for the shifts of g, g’, v, and λ

EFT Lagrangian After EW Symmetry Breaking

$$\Delta\mathcal{L}_h = -\eta_h\lambda_0 v_0 h^3 + \frac{\theta_h}{v_0}h\partial_\mu h\partial^\mu h + \eta_Z\frac{m_Z^2}{v_0}Z_\mu Z^\mu h + \frac{1}{2}\eta_{2Z}\frac{m_Z^2}{v_0^2}Z_\mu Z^\mu h^2$$
$$+\eta_W\frac{2m_W^2}{v_0}W_\mu^+W^{-\mu}h + \eta_{2W}\frac{m_W^2}{v_0^2}W_\mu^+W^{-\mu}h^2$$
$$+\frac{1}{2}\left(\zeta_Z\frac{h}{v_0} + \frac{1}{2}\zeta_{2Z}\frac{h^2}{v_0^2}\right)\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} + \left(\zeta_W\frac{h}{v_0} + \frac{1}{2}\zeta_{2W}\frac{h^2}{v_0^2}\right)\hat{W}_{\mu\nu}^+\hat{W}^{-\mu\nu}$$
$$+\frac{1}{2}\left(\zeta_A\frac{h}{v_0} + \frac{1}{2}\zeta_{2A}\frac{h^2}{v_0^2}\right)\hat{A}_{\mu\nu}\hat{A}^{\mu\nu} + \left(\zeta_{AZ}\frac{h}{v_0} + \zeta_{2AZ}\frac{h^2}{v_0^2}\right)\hat{A}_{\mu\nu}\hat{Z}^{\mu\nu}\ .$$

Coefficients, η's, ζ's, θ_h are given in terms of C's and hence interrelated, for instance

$$\eta_W = -\frac{1}{2}c_H$$
$$\eta_Z = -\frac{1}{2}c_H - \boxed{c_T}$$

Custodial SU(2) Symmetry

which come to our rescue in Γ_h determination at 250GeV where the WW-fusion cross section is small.

The details of the EFT formalism is described in

KEK Preprint 2017–23
SLAC–PUB–17130
August, 2017

Model-Independent Determination of the Triple Higgs Coupling at e^+e^- Colliders

TIM BARKLOW[a], KEISUKE FUJII[b], SUNGHOON JUNG[ac],
MICHAEL E. PESKIN[a], AND JUNPING TIAN[d]

[a] *SLAC, Stanford University, Menlo Park, CA 94025, USA*
[b] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, JAPAN*
[c] *Dept. of Physics and Astronomy, Seoul National Univ., Seoul 08826, KOREA*
[d] *ICEPP, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, 113-0033, JAPAN*

Recently appeared in arXiv: 1708.09079

There are many coefficients to decide. But remember that *W_L and Z_L are NGBs from the Higgs sector*.

We can use all kinds of SM processes involving *W* and *Z* to constrain them!

→ *Global Higgs+EWPO+TGC fit*

All the SM processes suddenly become equally important!

Higgs

- **$e^+e^- \to H\gamma$**
- **$H \to Z\gamma$**
- **…**

Precision EW

- **TGC**
- **$e^+e^- \to Z\gamma$ (A_{LR}), $\gamma\gamma$, …**
- **…**

At ILC 250, we will have enough redundancy (#observables > #unknown) to test the validity of EFT.

If we see inconsistency, it suggests $\Lambda_{BSM} \sim E_{cm}$. We then expect to see significant deviations from the SM, or to find some new particle. In this case, we forget about EFT and try to build specific models to explain the observed deviation pattern and/or the new particle and test these specific models.

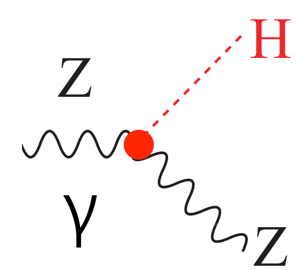
For new particle searches, we will work on particular models anyway.

J.Tian

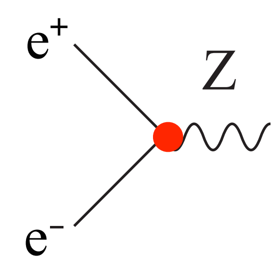
comments on beam polarizations

- not changed: important for systematics control, nature of new particle (once found), e.g. Higgsino, WIMPs
- new roles in EFT

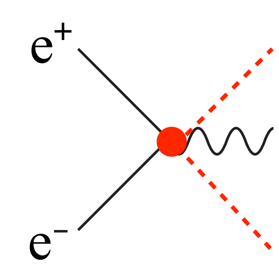
-> separate hZZ and hγZ couplings



-> improve A_{LR} in Z-e-e coupling

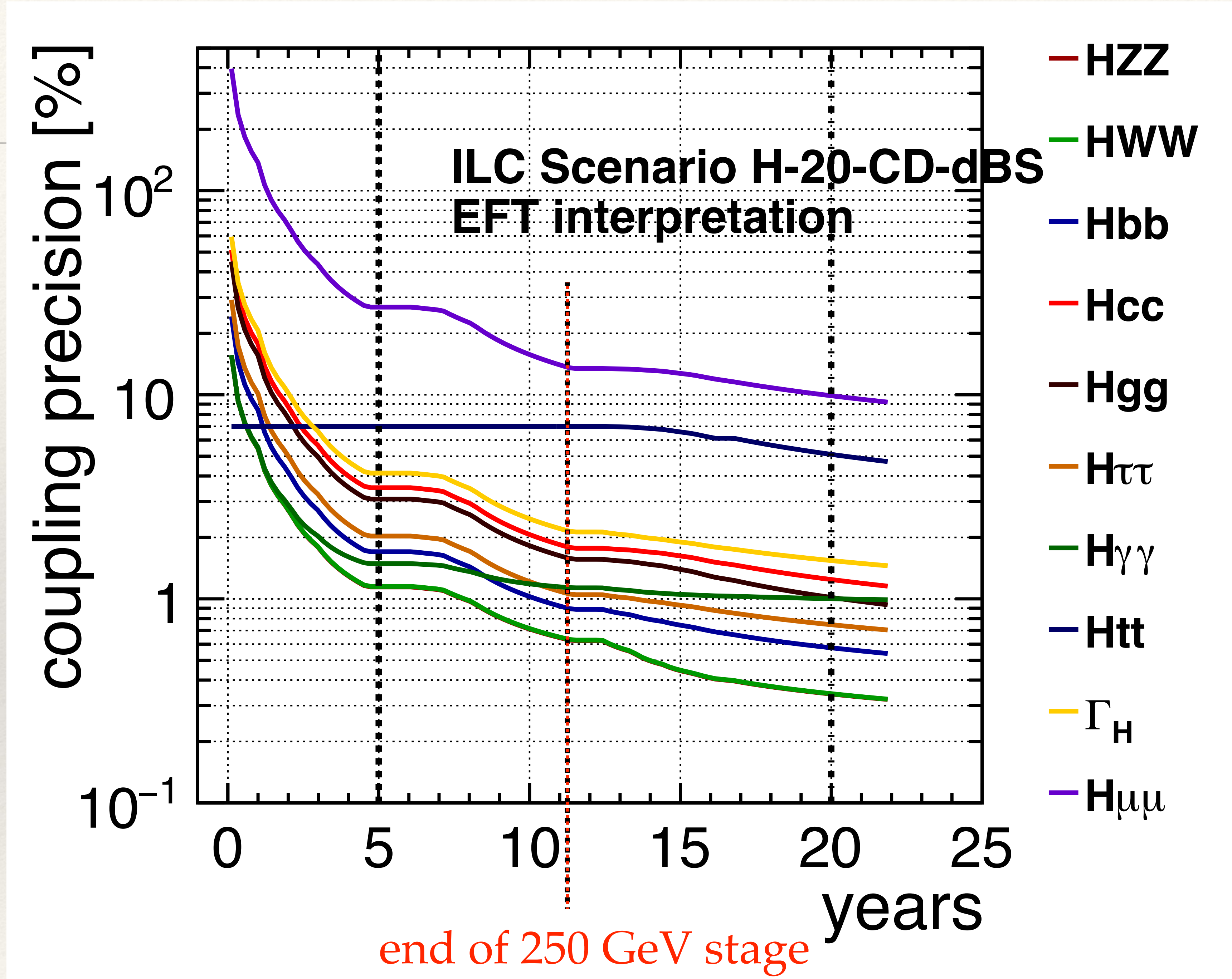


important to constrain contact interaction



34

Polarization is one of the most important tools that provide redundancy in EFT analysis!


coupling precision [%]
10^2
10
1
10^{-1}
0
5
10
15
20
25
years
ILC Scenario H-20-CD-dBS
EFT interpretation
HZZ
HWW
Hbb
Hcc
Hgg
Hττ
Hγγ
Htt
Γ_H
Hμμ
end of 250 GeV stage

Kappa vs EFT

arXiv: 1708.08912

	full 250 GeV EFT fit	initial ILC [3]	full ILC [3]	full ILC EFT fit
$g(hb\bar{b})$	1.04	1.5	0.7	0.55
$g(hc\bar{c})$	1.79	2.7	1.2	1.09
$g(hgg)$	1.60	2.3	1.0	0.89
$g(hWW)$	0.65	0.81	0.42	0.34
$g(h\tau\tau)$	1.16	1.9	0.9	0.71
$g(hZZ)$	0.66	0.58	0.31	0.34
$g(h\mu\mu)$	5.53	20	9.2	4.95
Γ_h	2.38	3.8	1.8	1.50

Table 2: Projected relative errors for Higgs boson couplings and other Higgs observables, in %, from the EFT fits in this paper, compared to the results of Higgs couplings fits shown in Table 1 of [3]. The first column gives the result of the fit described in Section 4, with 2 ab^{-1} of data at 250 GeV. The fourth column gives the results of Section 6, adding 4 ab^{-1} at 500 GeV. The total data samples assumed in the third and fourth columns are the same.

ILC250 vs Others

arXiv: 1708.08912

	2 ab^{-1} w. pol.	2 ab^{-1} 350 GeV	5 ab^{-1} no pol.	+ 1.5 ab^{-1} at 350 GeV	full ILC 250+500 GeV
$g(hb\bar{b})$	1.04	1.08	0.98	0.66	0.55
$g(hc\bar{c})$	1.79	2.27	1.42	1.15	1.09
$g(hgg)$	1.60	1.65	1.31	0.99	0.89
$g(hWW)$	0.65	0.56	0.80	0.42	0.34
$g(h\tau\tau)$	1.16	1.35	1.06	0.75	0.71
$g(hZZ)$	0.66	0.57	0.80	0.42	0.34
$g(h\gamma\gamma)$	1.20	1.15	1.26	1.04	1.01
$g(h\mu\mu)$	5.53	5.71	5.10	4.87	4.95
$g(hbb)/g(hWW)$	0.82	0.90	0.58	0.51	0.43
$g(hWW)/g(hZZ)$	0.07	0.06	0.07	0.06	0.05
Γ_h	2.38	2.50	2.11	1.49	1.50
$\sigma(e^+e^- \to Zh)$	0.70	0.77	0.50	0.22	0.61
$BR(h \to inv)$	0.30	0.56	0.30	0.27	0.28
$BR(h \to other)$	1.50	1.63	1.09	0.94	1.15

Table 3: Projected relative errors for Higgs boson couplings and other Higgs observables, in %, comparing the full EFT fit described in Section 4 to other possible e^+e^- collider scenarios. The second column shows a fit with 2 ab^{-1}, with 80% electron and zero positron polarization, and with a higher energy of 350 GeV. The third and fourth columns show scenarios with no polarization but higher intergrated luminosity, 5 ab^{-1} at 250 GeV in the third column and 5 ab^{-1} at 250 GeV plus 1.5 ab^{-1} at 350 GeV in the fourth column. The fifth column gives the result of the fit described in Section 6 including data from 250 and 500 GeV. The notation is as in Table 1.

Beam Polarizations

arXiv: 1708.08912

	no pol.	80%/0%	80%/30%
$g(hb\bar{b})$	1.33	1.13	1.04
$g(hc\bar{c})$	2.09	1.97	1.79
$g(hgg)$	1.90	1.77	1.60
$g(hWW)$	0.98	0.68	0.65
$g(h\tau\tau)$	1.45	1.27	1.16
$g(hZZ)$	0.97	0.69	0.66
$g(h\gamma\gamma)$	1.38	1.22	1.20
$g(h\mu\mu)$	5.67	5.64	5.53
$g(hb\bar{b})/g(hWW)$	0.91	0.91	0.82
$g(hWW)/g(hZZ)$	0.07	0.07	0.07
Γ_h	2.93	2.60	2.38
$\sigma(e^+e^- \to Zh)$	0.78	0.78	0.70
$BR(h \to inv)$	0.36	0.33	0.30
$BR(h \to other)$	1.68	1.67	1.50

Table 4: Projected relative errors for Higgs boson couplings and other Higgs observables with 2 ab^{-1} of data at 250 GeV, comparing the cases of zero polarization, 80% e^- polarization and zero positron polarization, and 80% e^- polarization and 30% positron polarization. In each case, the running is equally divided into two samples with opposite beam polarization orientation.

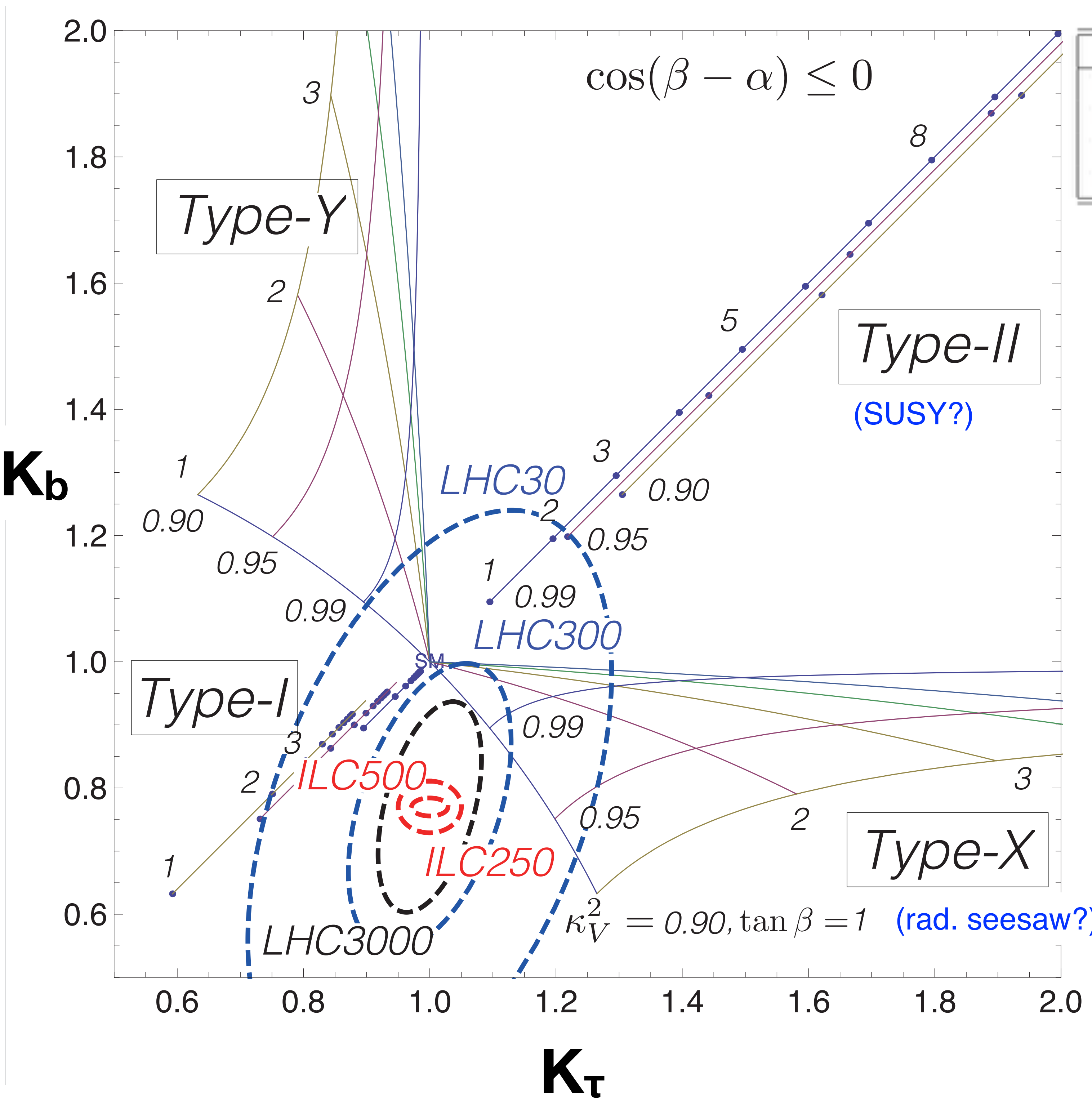
Beam polarization essentially doubles the number of independent observables and provides enough redundancy to test the validity of the EFT in case there is a light new particle!

Sensitivity of Precision Measurements to New Physics Scale

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: ***ΔK_V^2 = 1-K_V^2 = 0.01*** *we will be able to* ***discriminate the 4 models!***

Model-dependent
7-parameter fit
ILC: Baseline lumi.

ILC TDR

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

Kanemura et al (arXiv: 1406.3294)