ILC ~~staging~~
(specific for Higgs and top)

ILC 250

(focusing on Higgs physics)

Junping Tian (U' of Tokyo)

Annual ILC detector meeting, Mar. 30-31, 2017 @ KEK

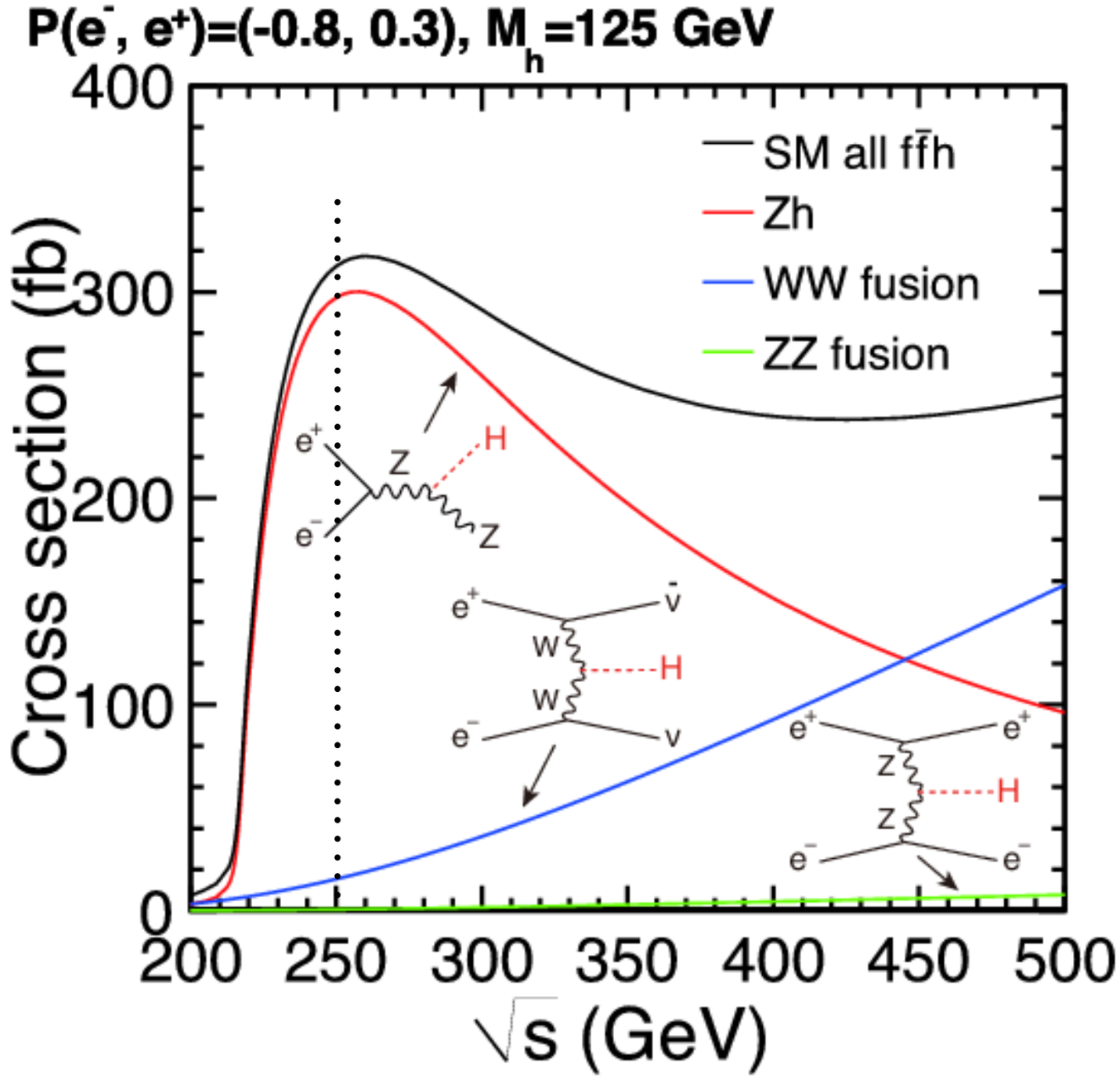
for useful discussions, many thanks to
K.Fujii, D.Jeans, S.Komamiya, J.List, M.Peskin

try to provide some inputs to a physics case for a 250 GeV ILC

- highlights after initial run at 250 GeV ($\int Ldt \sim 500$ fb^{-1})
- projections at the end of 250 GeV run ($\int Ldt \sim 2000$ fb^{-1})
- what can be learned: next energy scale, BSM fingerprinting
- possible improvement & homework

(exact $\int Ldt$ to be defined later by LCC Physics WG & ILC Parameter Group)

introduction (&summary): there is a physics case at $\sqrt{s}$ = 250 GeV



see detailed physics in Fujii san's talk

- highlights after initial run

$\sqrt{s}$ = 250 GeV

$\int Ldt \sim 500\ fb^{-1}$

highlight 1: absolute Higgs couplings

ILC initial: $\delta g_{HZZ} = 0.75\%$

$$\Lambda > \sqrt{\frac{1\%}{\delta g_{HZZ}}} 1.74\mathrm{TeV}$$

- model-independent measurement —> qualitative improvement w.r.t. coupling measurement @ LHC

- important to know absolute value of Higgs couplings —> Higgs branching ratios, or ratios of couplings, can remain unchanged in BSM models, e.g. some composite models

- with ~0.75% precision on HZZ coupling, composite scale $\Lambda > 2$ TeV can be probed (cf talk by N.Craig @ LCWS16)

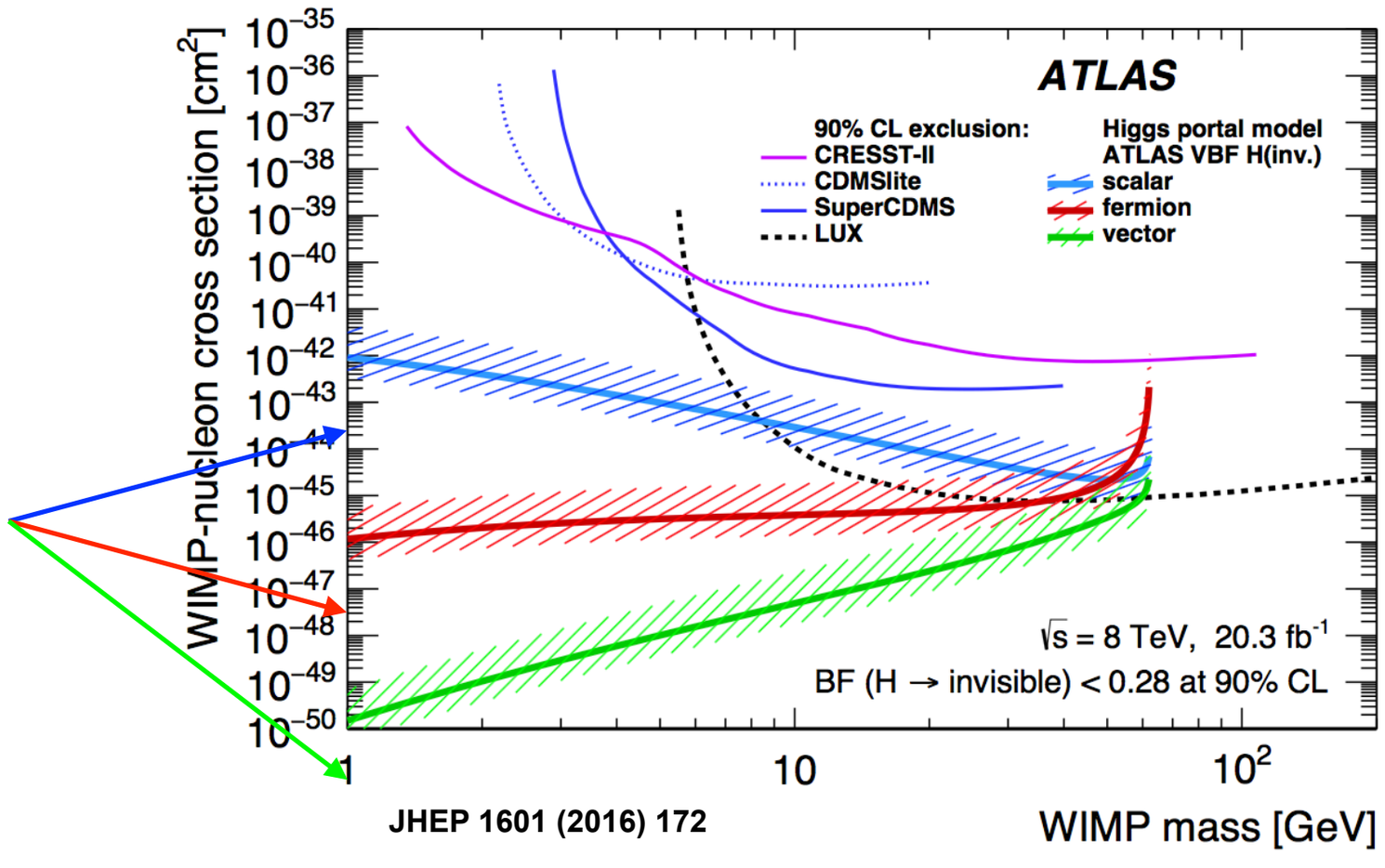
- together with κ_Z/κ_γ @ LHC —> ~1% precision on $H\gamma\gamma$ coupling

highlight 2: Higgs to invisible decay

ILC initial: BR(H—>inv.) < 0.59% (95% CL)

- a very powerful test for Higgs portal model —> could be more sensitive than other direct DM search experiments
- initial sensitivity is already more than one order of magnitude higher than expectation after HL-LHC

ILC initial
x50 lower



highlight 3: Higgs CP mixing

- find CP-violating source in Higgs sector —> baryongenesis
- essential to understand structures of all Higgs couplings

through H—>$\tau^+\tau^-$ $L_{Hff} = -\frac{m_f}{v} H\bar{f}(\cos\Phi_{CP} + i\gamma^5 \sin\Phi_{CP})f$

ILC initial: $\Delta\Phi_{CP} \sim 7.6^\circ$

D.Jeans @ LCWS16

through HZZ/HWW $L_{HVV} = 2C_V M_V^2(\frac{1}{v} + \frac{a}{\Lambda})HV_\mu V^\mu + C_V\frac{b}{\Lambda}HV_{\mu\nu}V^{\mu\nu} + C_V\frac{\tilde{b}}{\Lambda}HV_{\mu\nu}\tilde{V}_{\mu\nu}$

(CP-odd)

ILC initial: $\Delta\tilde{b} \sim 0.01$ (for Λ=246GeV)

T.Ogawa @ LCWS16

highlight 4: Higgs mass and total width

ILC initial: $\Delta m_H \sim 30$MeV, $\delta\Gamma_H \sim 8.8\%$

- Δm_H is one source of systematic errors for H—>WW*/ZZ* partial width calculation: 30MeV uncertainty would yield 0.2% error for HWW/HZZ coupling determination (arXiv:1404.0319)

- model-independent determination of Higgs total width —> one direct probe for existence of new large decay modes

highlight 5: Higgs decays to bb/cc/gg

ILC initial: $\delta BR_b \sim 1\%$

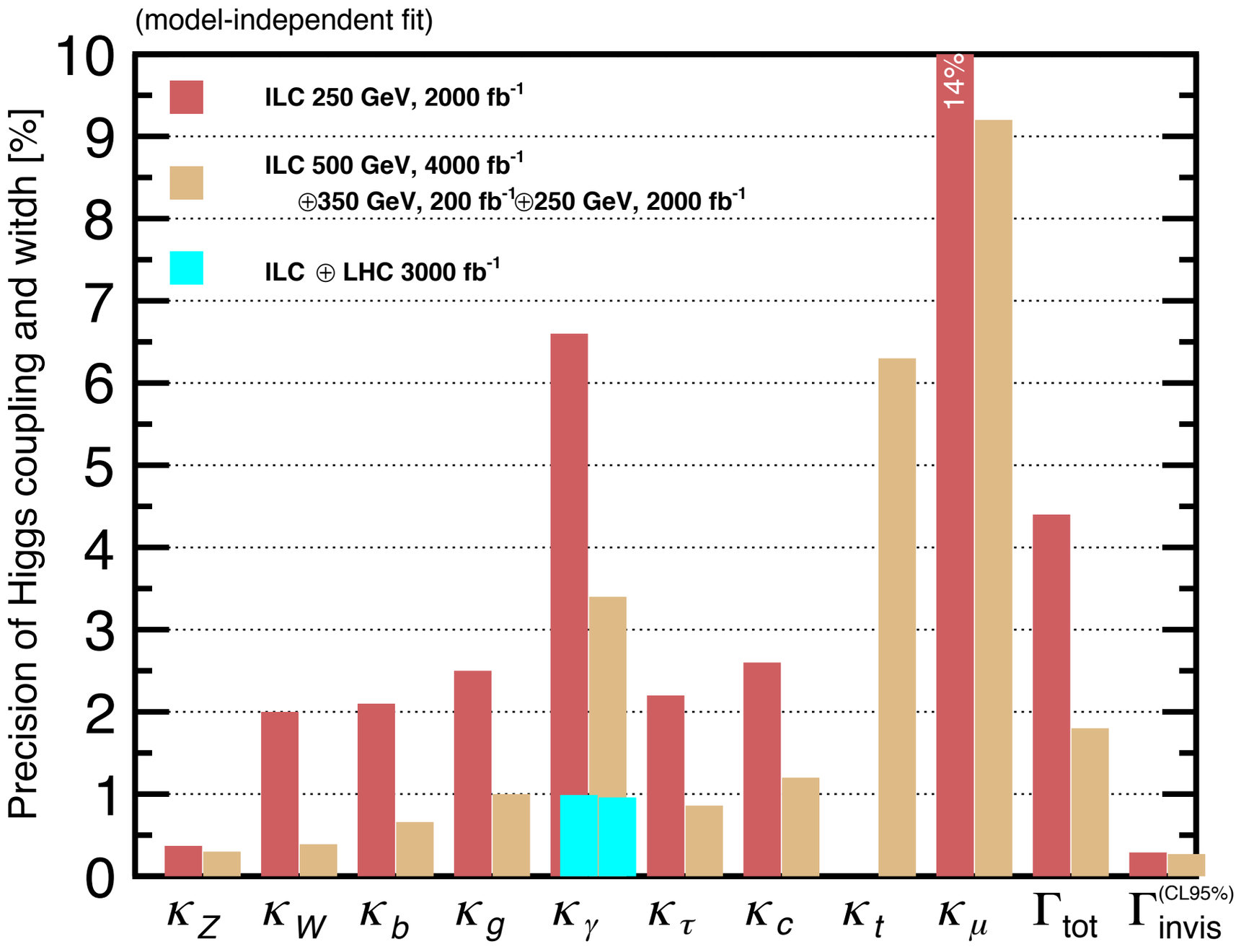
- precise measurement of BR(H—>bb), largest decay mode
- first direct measurement of Hcc coupling ~ 5%
- first direct measurement of Hgg coupling ~5%

- highlights after full run

$\sqrt{s}$ = 250 GeV

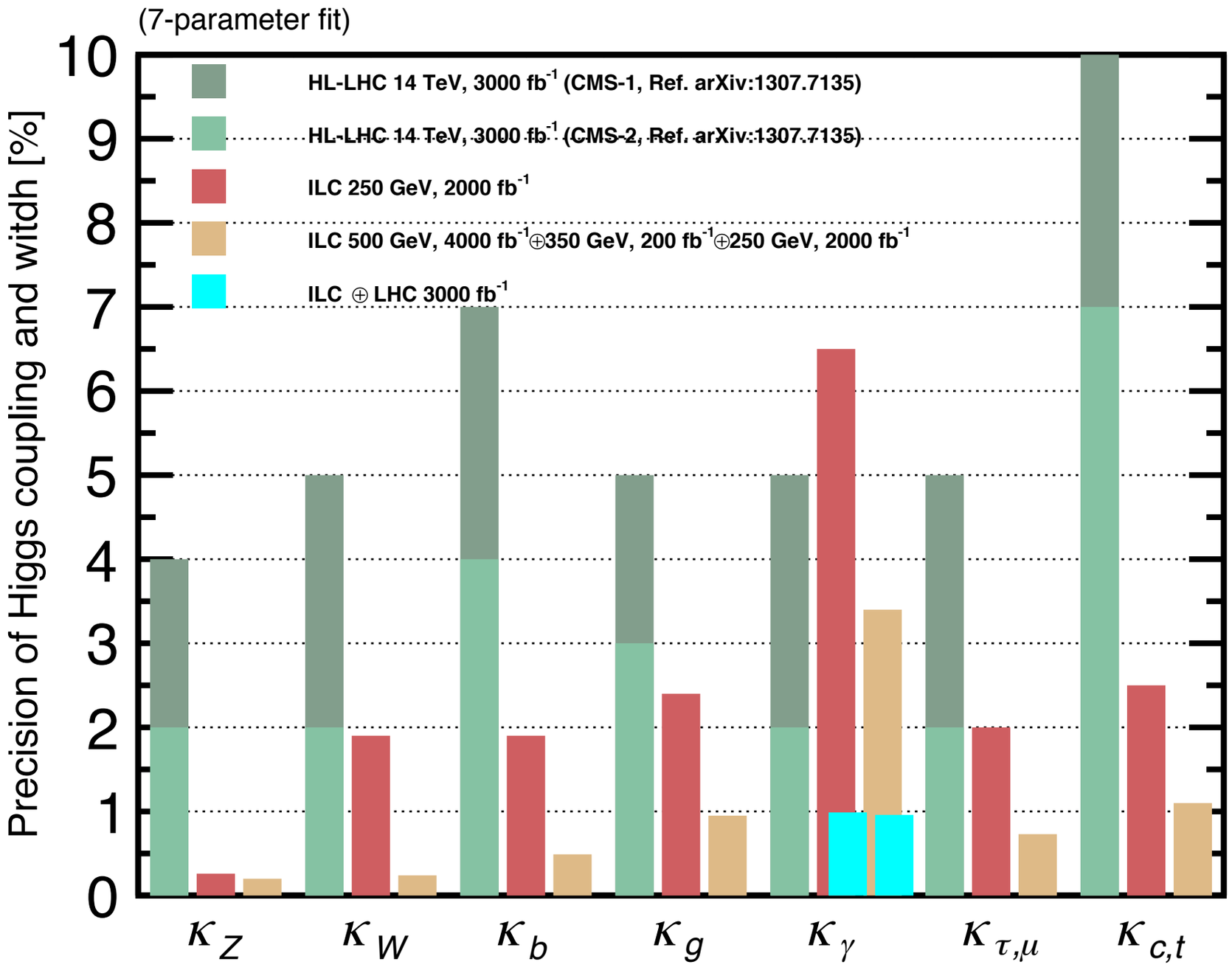
$\int Ldt \sim 2000\ fb^{-1}$

precision of coupling and width (model-independent fit)



(back to this later)

comparison (synergy) with LHC



anomalous HZZ/HWW couplings

Fujii, Ogawa, Tian (paper in preparation)

$$\mathcal{L} = \frac{1}{2}(\frac{2m_Z^2(1+a)}{v})hZ_\mu Z^\mu + \frac{1}{2}(\frac{b}{\Lambda})hZ_{\mu\nu}Z^{\mu\nu} + \frac{1}{2}(\frac{\tilde{b}}{\Lambda})hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$$

(SM-like) (CP-even) (CP-odd)

observables: σ_{Zh} $\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_Z}$ $\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_f}$ $\frac{\mathrm{d}\sigma}{\mathrm{d}\phi_f}$

full simulation results (2 ab-1 @ 250 GeV):

$$\Delta a = 0.027 \qquad \frac{\Delta b}{\Lambda} = \frac{0.039}{\mathrm{TeV}} \qquad \frac{\Delta \tilde{b}}{\Lambda} = \frac{0.016}{\mathrm{TeV}}$$

physics implication: if b(b~) is O(1) in certain BSM, sensitivity to Λ ~ 10 (30) TeV

anomalous WWZ/WWγ couplings

$$\Delta\mathcal{L}_{TGC} = ig_V\{g_{1V}V^\mu(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m^2_W}W^{-\rho}_\mu W^+_{\rho\nu}V^{\mu\nu}\}$$

V = Z, γ

physics implication: provide strong constraints on Dimension-6 operators

$$\frac{g^3 c_{3W}}{m^2_W}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \qquad \frac{4gg' c_{WB}}{m^2_W}\Phi^\dagger t^a \Phi W^a_{\mu\nu}B^{\mu\nu} \qquad \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)$$

simulation results now exist for ILC 500/1000 GeV (TDR)

http://bib-pubdb1.desy.de/record/94888/
http://inspirehep.net/record/1467642/

for ILC 250, we expect x5-10 better than at LEP2

(—>contact T.Barklow for numbers)

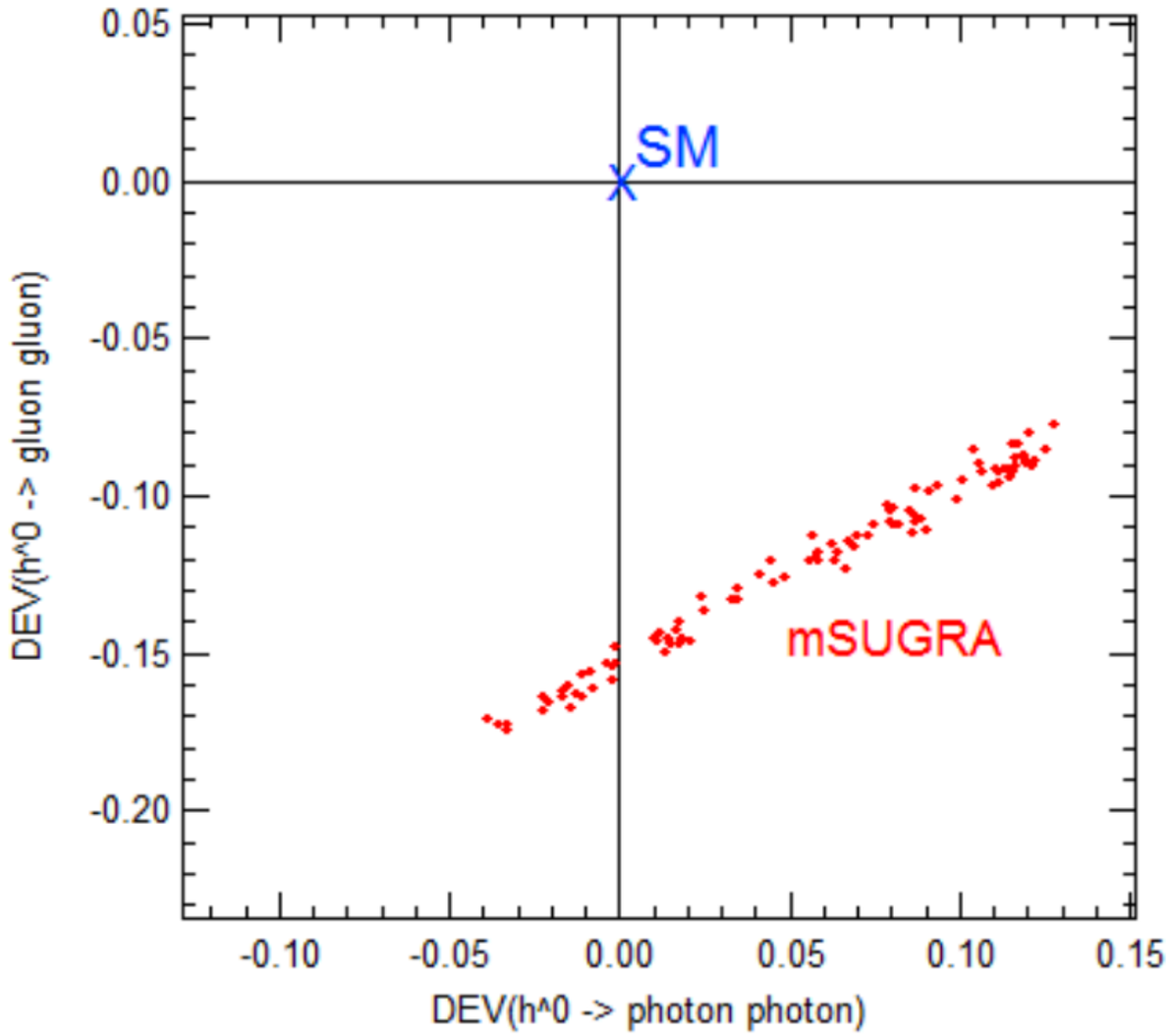
Higgs rare decays

modes	physics implication	Δg/g @ ILC
H—>γγ	sensitive to new heavy particles, typically O(10%) deviations	~1% (+LHC)
H—>γZ		5% (preliminary)
(H—>gg)		~2%
H—>μμ	one useful point to test $y_f \propto m_f$; test mass generation mechanism for 2nd & 3rd gen. leptons (κ_μ/κ_τ), and for 2nd lepton & quark (κ_μ/κ_c)	~13% (5%?)
H—>invisible	test Higgs portal dark matter model	BR<0.31% (95% C.L.)

Hγγ/Hgg in mSUGRA

https://agenda.linearcollider.org/event/7509/contributions/38405/attachments/31189/46846/HidakaILCWS2017_02_04.pdf

Hidaka, et al.



Scatter plot in DEV(h^0 -> photon photon) - DEV(h^0 -> gluon gluon) plane

**** The deviation of the width ratio GAMMA(h^0 -> photon photon) / GAMMA(h^0 -> gluon gluon) from the SM value is large and roughly +20% nearly independently of the basic parameters of the mSUGRA*** $\{\tan\beta, m_0, m_{1/2}, A_0\}$ ***in the scanned parameter ranges!***

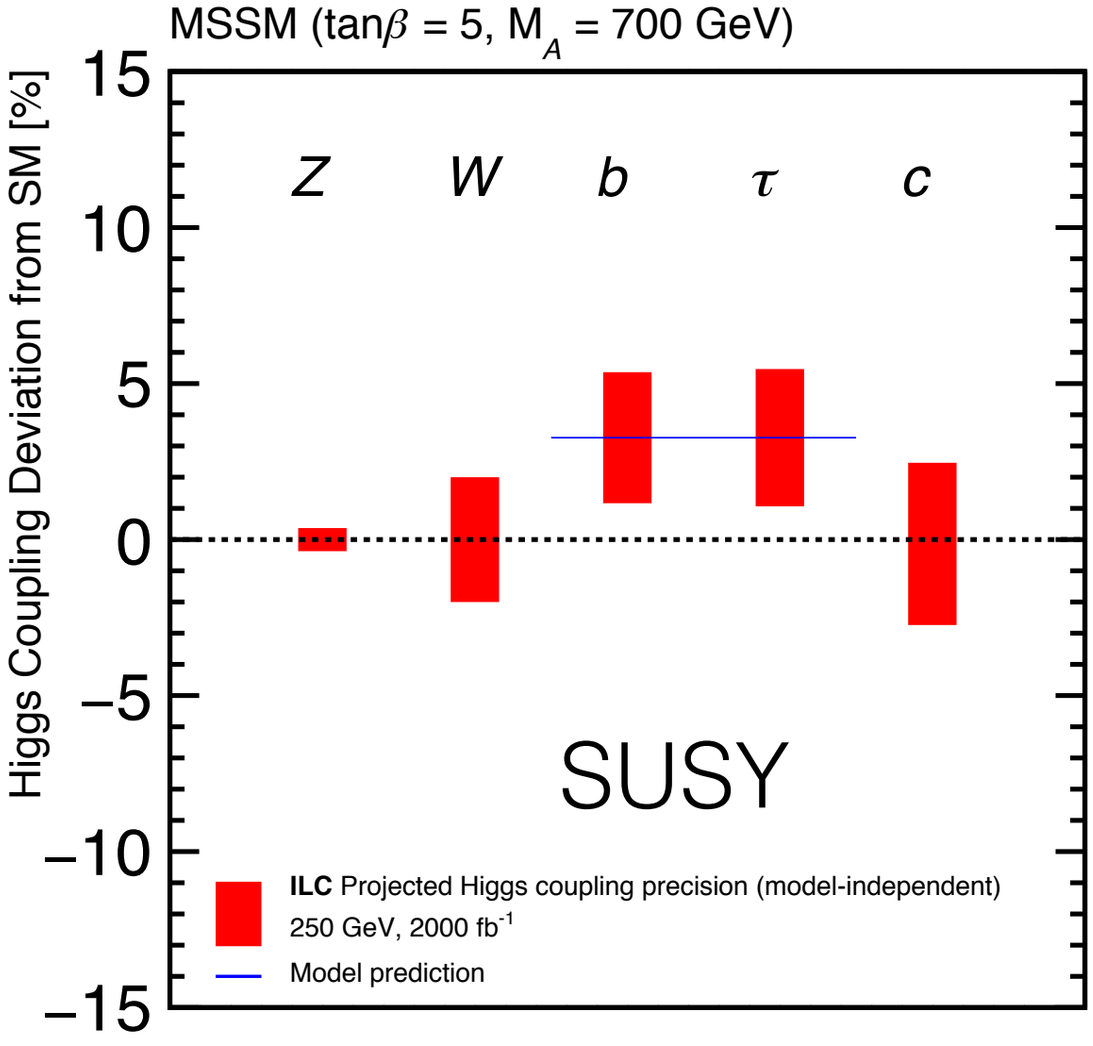
- potential to discover next energy scale & to fingerprint models

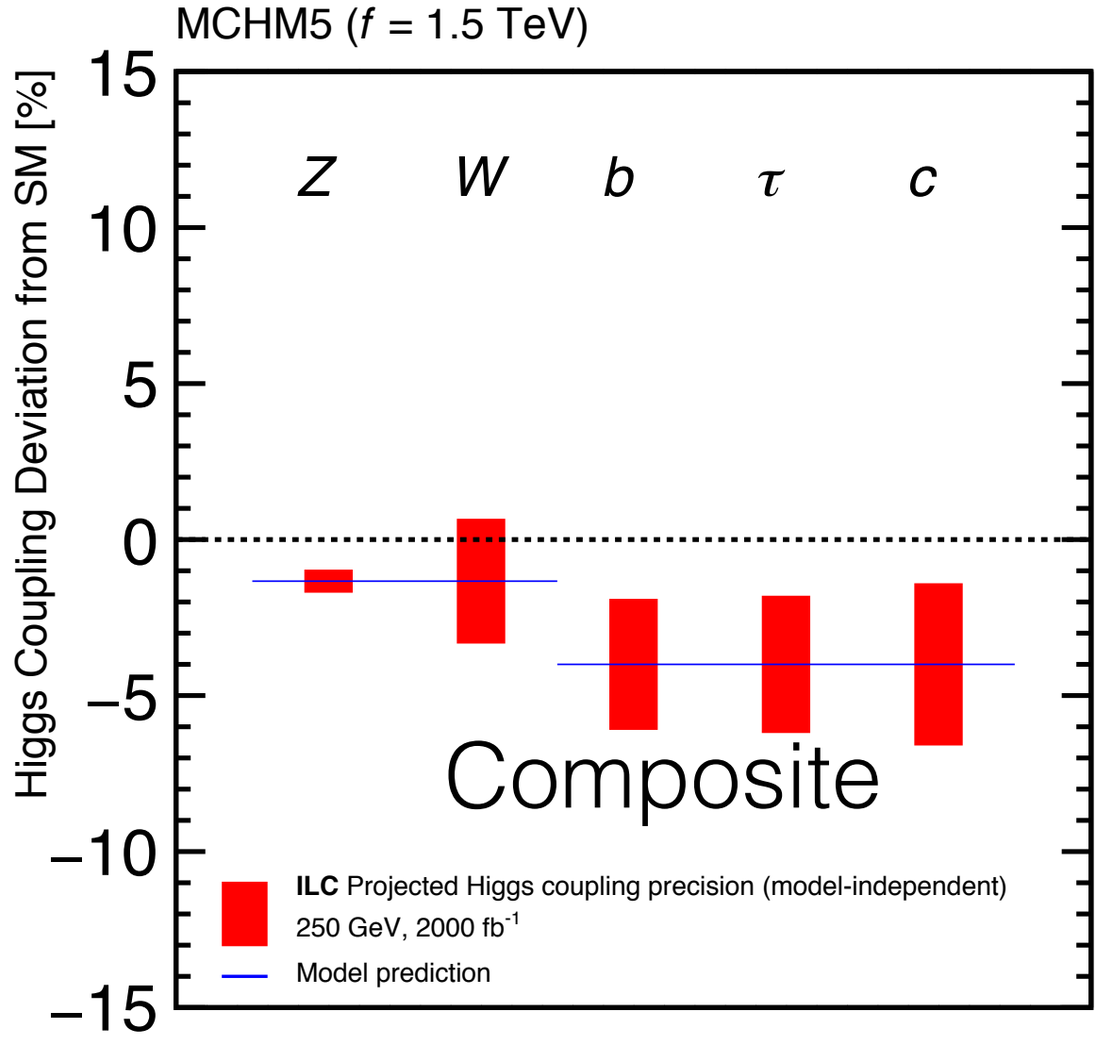
$\sqrt{s}$ = 250 GeV

$\int Ldt \sim 2000\ fb^{-1}$

deviations pattern for Higgs couplings

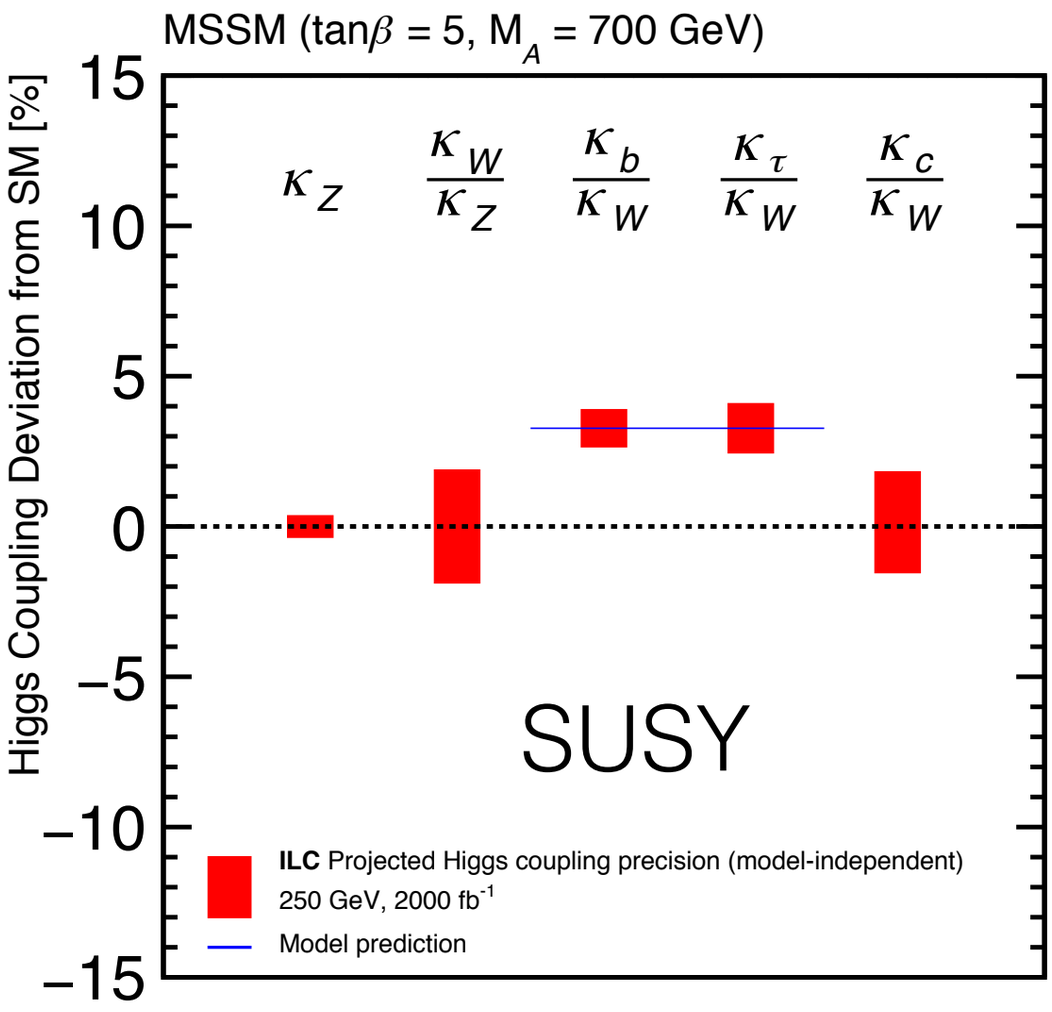
(use absolute couplings)

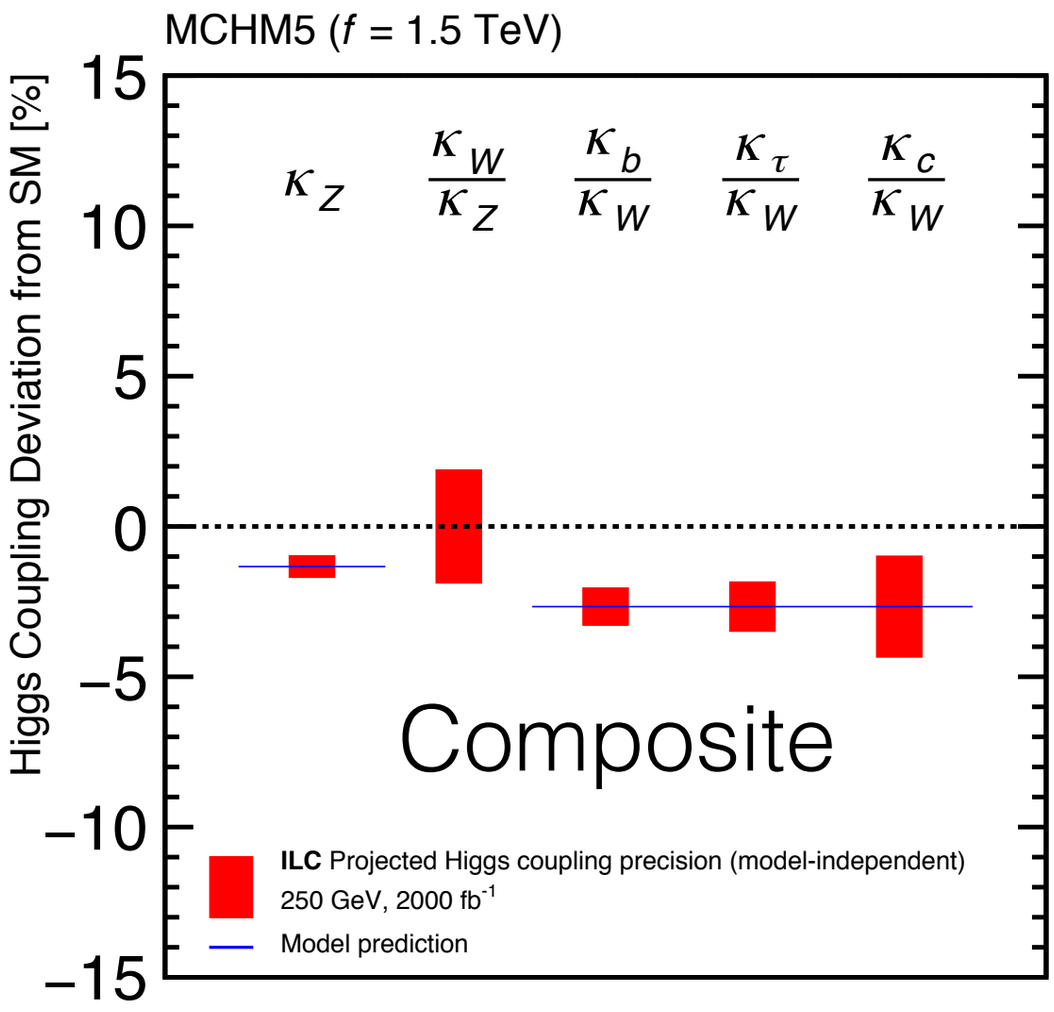




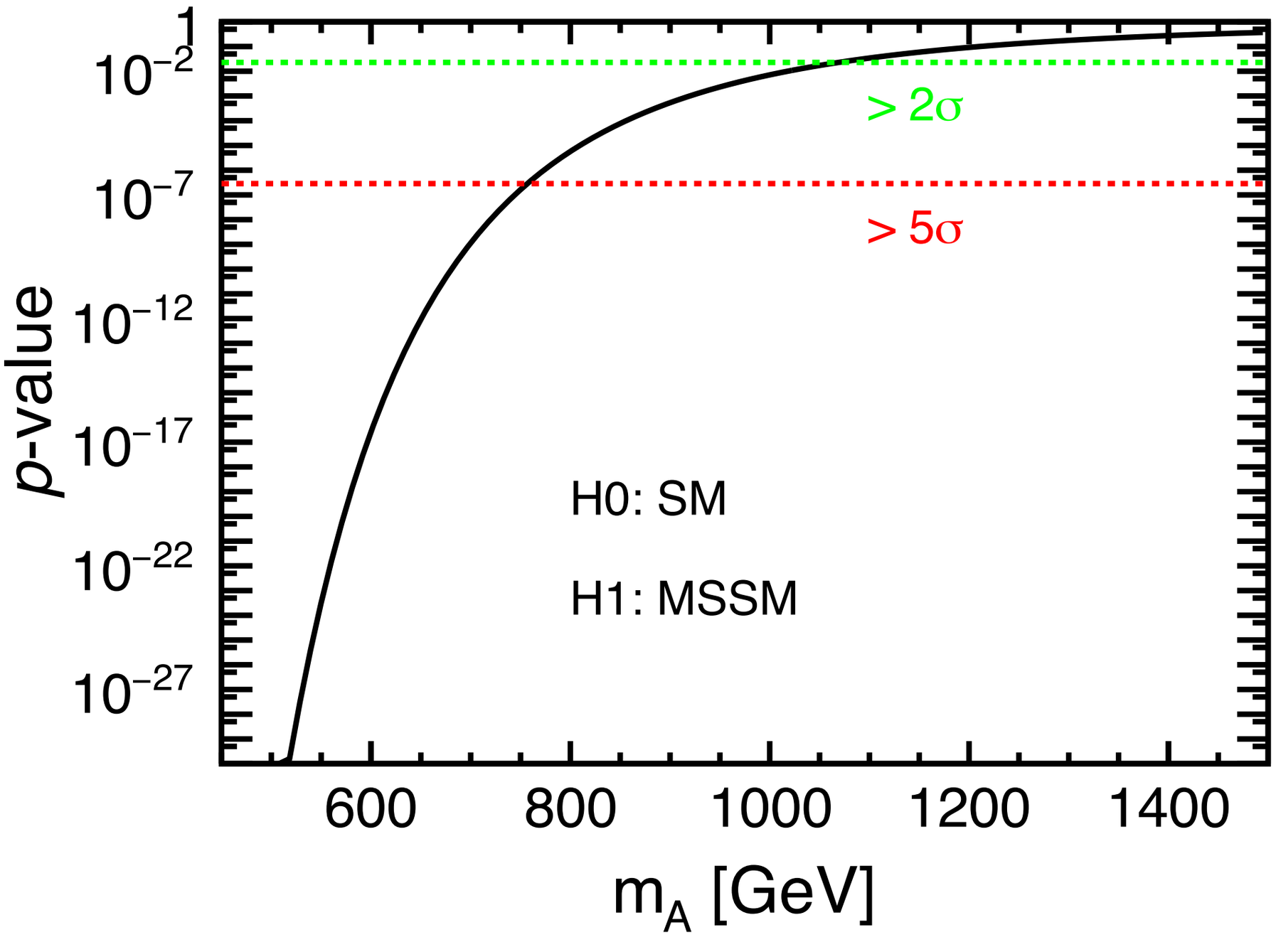
deviations pattern for Higgs couplings

(use absolute coupling & ratio of couplings)



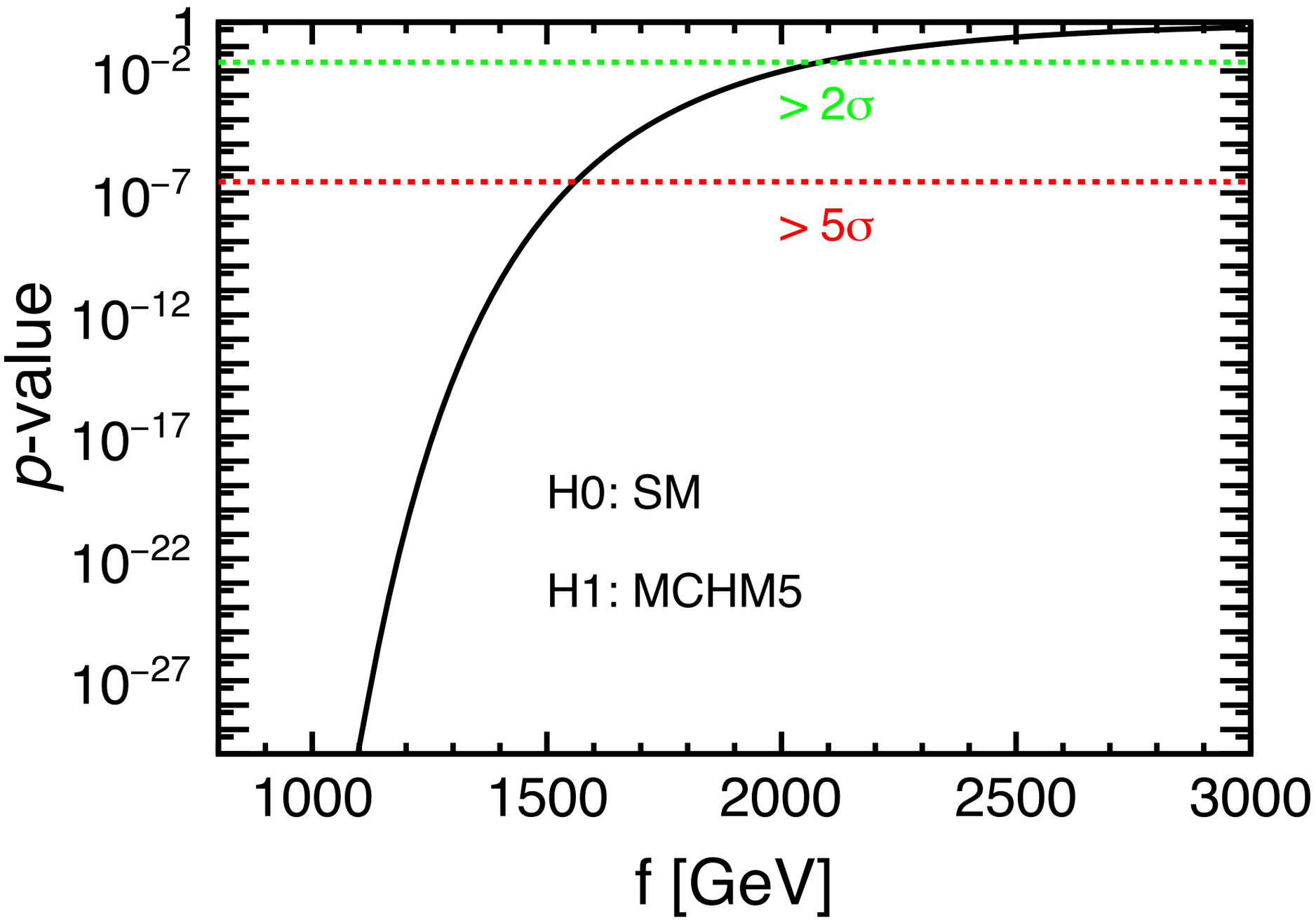


combined significance: MSSM .vs. SM

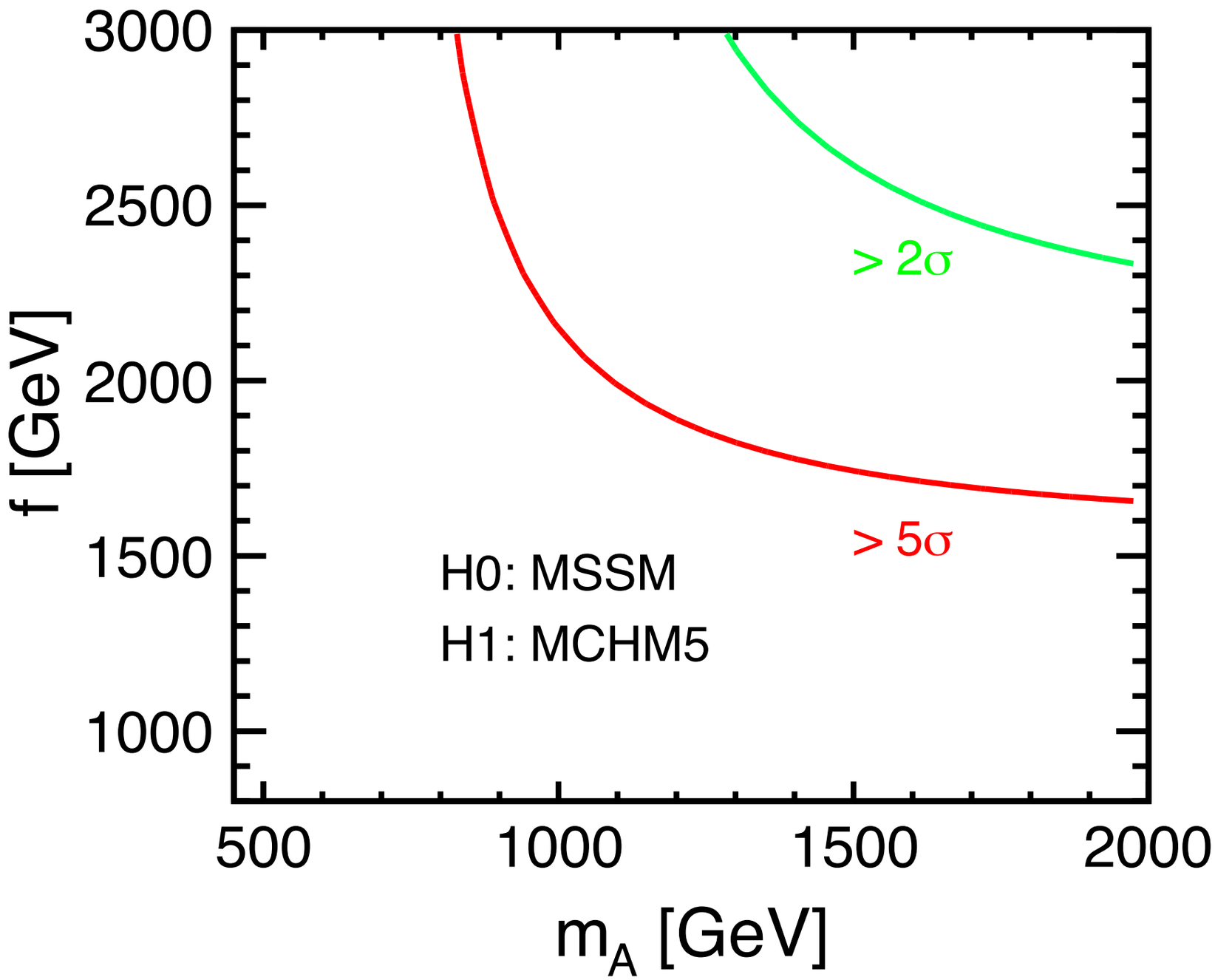


(tanβ=5)

combined significance: MCHM5 .vs. SM



combined significance: MCHM5 .vs. MSSM



(tanβ=5)

- possible improvements & homework

Higgs total width

(standard method at e+e-; model independent)

$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

—>Br(H->ZZ*) very small

$$\Gamma_H = \frac{\Gamma_{HWW}}{\mathrm{Br}(H \to WW^*)} \propto \frac{g^2_{HWW}}{\mathrm{Br}(H \to WW^*)}$$

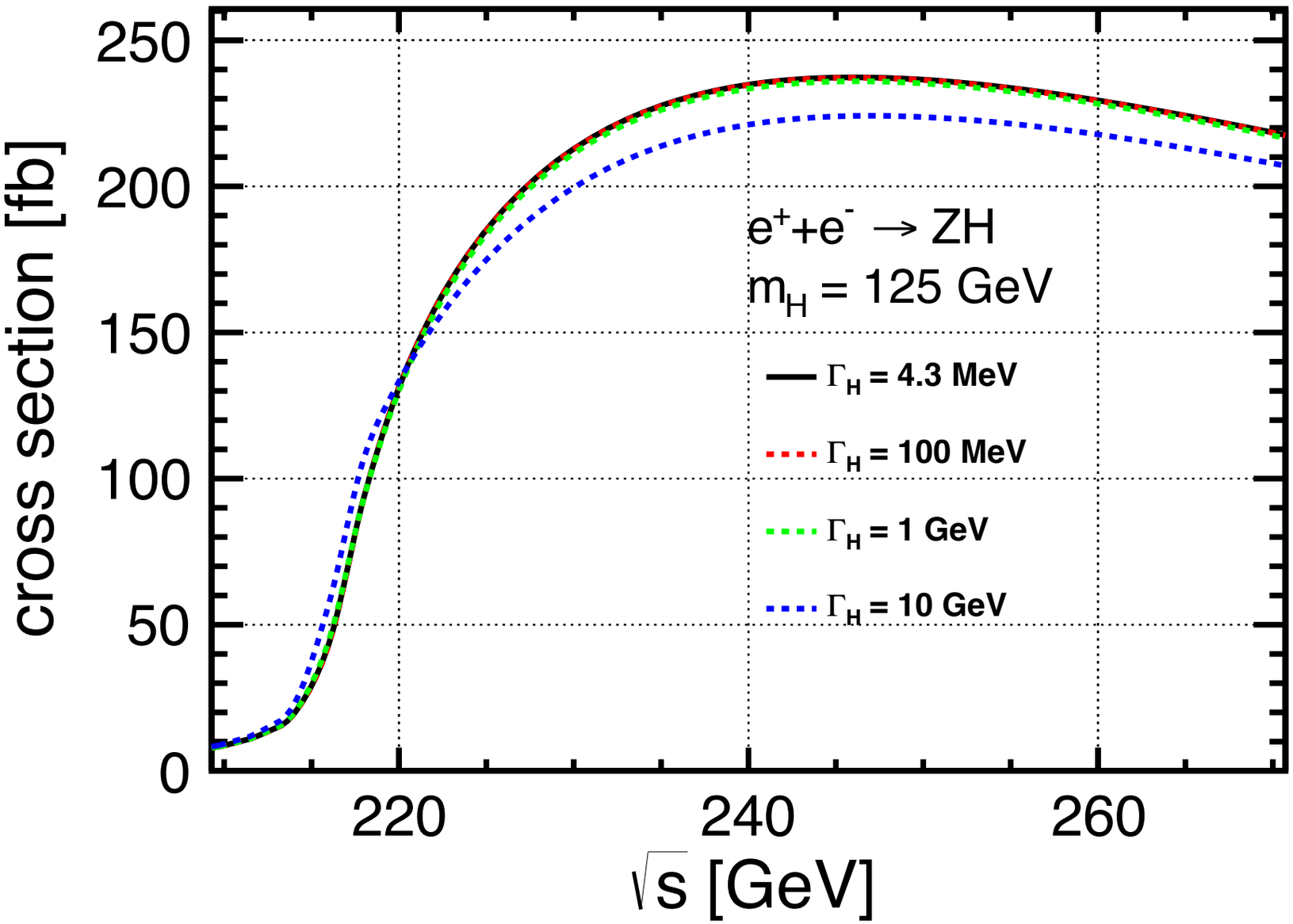
—> better option

κ_W is determined using WW-fusion $\nu_e\nu_e H$, which is at 250 GeV statistically limited

$\delta\Gamma_H$	500 fb-1	2000 fb-1
model independent	8.8%	4.4%

Higgs total width

(use σ_{ZH} Line-shape at threshold; proposed by J.Tanaka)



(challenging)

Higgs total width: new method

Fujii, Tian

if we assume custodial symmetry holds in BSM as well,

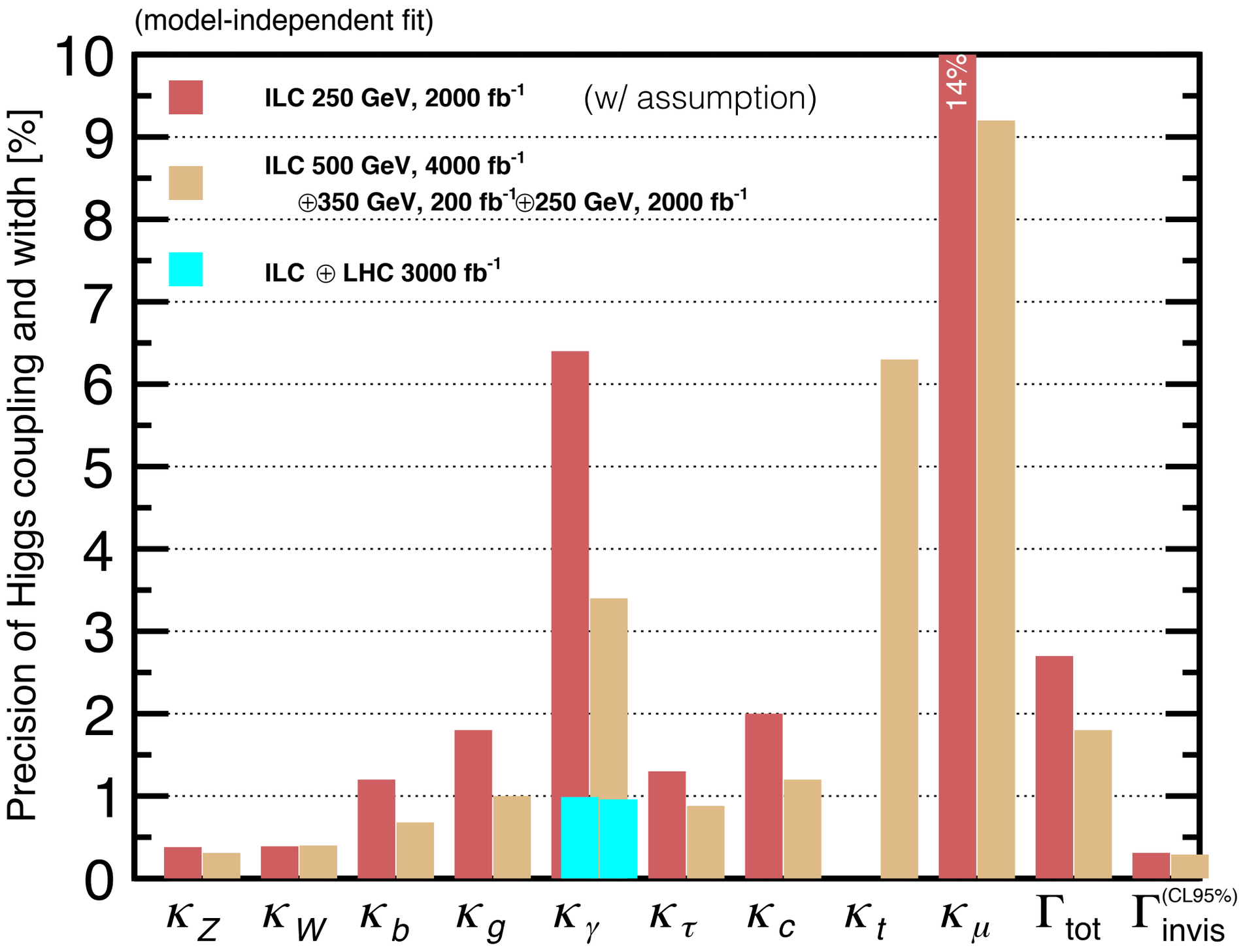
$\kappa_W / \kappa_Z = 1$,

then we can relax the requirement of $\nu_e\nu_e H$ measurement

$\delta\Gamma_H$	500 fb-1	2000 fb-1
model independent	8.8%	4.4%
$k_W/k_Z = 1$ holds up to 0.5%	5.5%	2.9%

Higgs total width: new method

Fujii, Tian



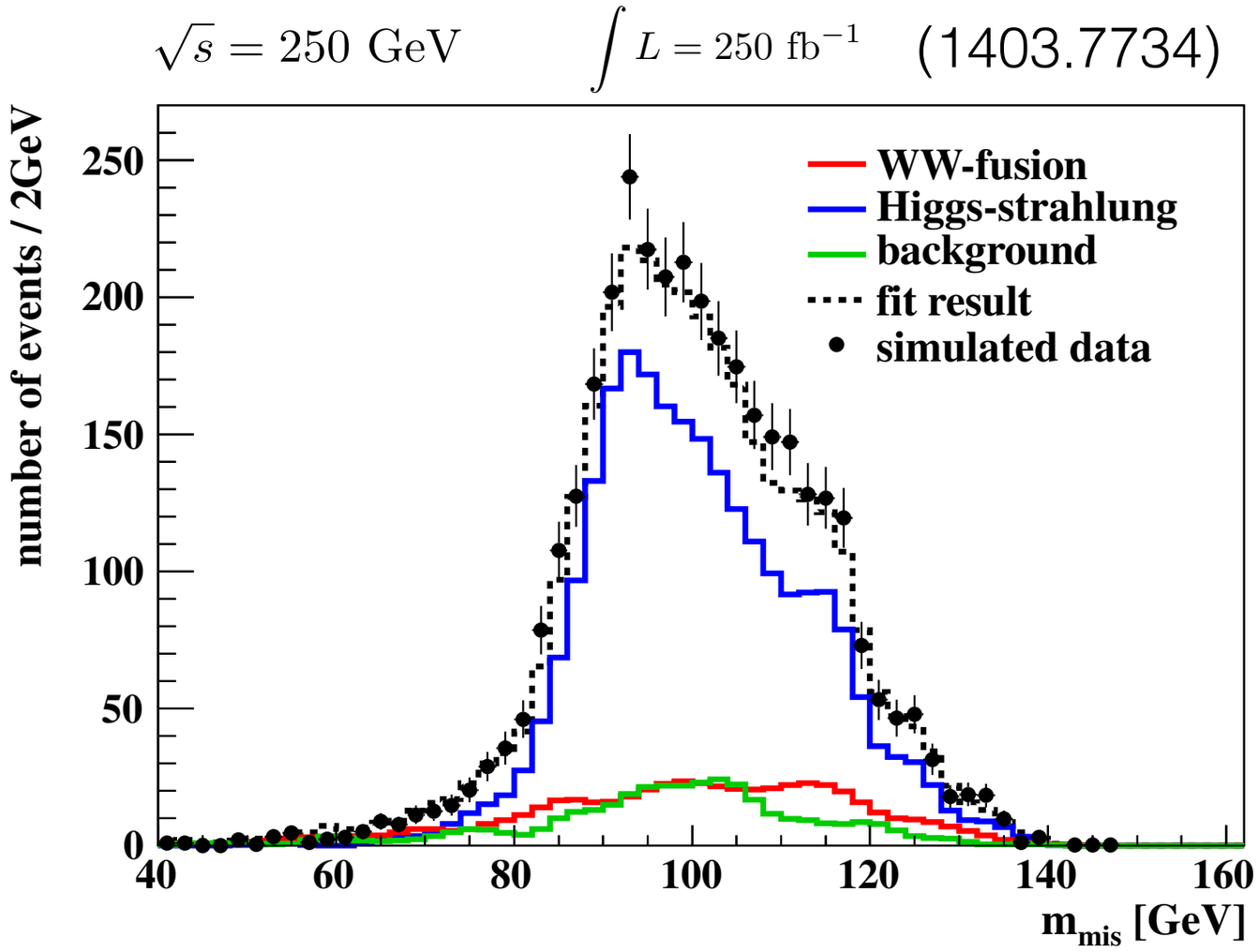
a formal proof: relation between κ_W and κ_Z

benefit from recent EFT analysis for ZHH done by Barlow, Fujii, Jung, Peskin, Tian —> paper ongoing

$$\Delta\mathcal{L}_h = -\eta_h\lambda_0 v_0 h^3 + \frac{\theta_h}{v_0} h\partial_\mu h\partial^\mu h + \eta_Z \frac{m_Z^2}{v_0} Z_\mu Z^\mu h + \frac{1}{2}\eta_{2Z}\frac{m_Z^2}{v_0^2} Z_\mu Z^\mu h^2$$
$$+\eta_W \frac{2m_W^2}{v_0} W_\mu^+ W^{-\mu} h + \eta_{2W}\frac{m_W^2}{v_0^2} W_\mu^+ W^{-\mu} h^2$$
$$+\frac{1}{2}\left(\zeta_Z\frac{h}{v_0} + \frac{1}{2}\zeta_{2Z}\frac{h^2}{v_0^2}\right)\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} + \left(\zeta_W\frac{h}{v_0} + \frac{1}{2}\zeta_{2W}\frac{h^2}{v_0^2}\right)\hat{W}^+_{\mu\nu}\hat{W}^{-\mu\nu}$$
$$+\frac{1}{2}\left(\zeta_A\frac{h}{v_0} + \frac{1}{2}\zeta_{2A}\frac{h^2}{v_0^2}\right)\hat{A}_{\mu\nu}\hat{A}^{\mu\nu} + \left(\zeta_{AZ}\frac{h}{v_0} + \zeta_{2AZ}\frac{h^2}{v_0^2}\right)\hat{A}_{\mu\nu}\hat{Z}^{\mu\nu}\ . \qquad (18)$$

a model-independent proof is promising —> stay tuned

measurement for WW-fusion $\nu_e\nu_e H$



$\sigma_{\nu e\nu e H}$ ~ 14 fb —> 2000 signal vvbb events

can we do better than 10%?

new idea is being tried out —> stay tuned

measurement for BR(H—>WW*)

in the DBD, with nominal 250 fb-1

precision for σ_{ZH} x BR(H—>WW*): 6.4%

which was too conservative

only small fraction of signal (~40%) was used

benefit from recent analysis from M.Pandurovic done for 500 GeV full hadronic mode, which is significantly better than previously used modes
—> stay tuned

measurements for Higgs exotic decays

experimentally large variety of decay final states have already been covered by SM decay modes

e.g. H—>2j, H—>2l, H—>γZ—>γ+2j/γ+mis./γ+2l, H—>ZZ*—>2l+2j/2j+mis./2l+mis/invisible

H—>WW*—>XXXXXX

one example studied: BR(H—>ZZ*—>2l+2j) = 0.24% which is demonstrated to be discoverable

generally, sensitive to BR(H—>exotic) < 1%

homework: theory inputs

other homework

many EW measurements: m_W, $\sin^2\theta$, aTGC, Z', etc.

e+e- —> 2f (see next talk by Jackie)

synergy with other experiments (m_t, λ_{hhh}, y_t, etc.)

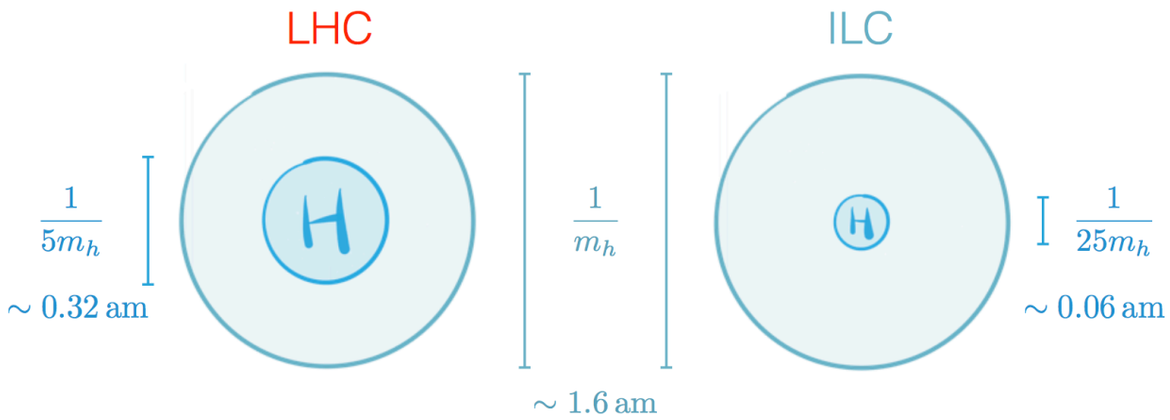
backup

additional publication / notes / reference talks

- leptonic recoil: J.Yan, S.Watanuki, et. al, arXiv:1604.07524, arXiv:1601.06481; H.Li, et. al, arXiv:1202.1439
- hadroni recoil: M.Thomson, arxiv:1509.02853; T.Tomita @ LCWS14; A.Miyamoto, arxiv: 1311.2248
- H—>invisible: A.Ishikawa @ LCWS14; J.Tian@ALCW15
- H->WW/ZZ: J.Tian et. al, LC-REP-2013-022, arxiv:1403.7734
- H->bb/cc/gg: H.Ono, et. al, Euro. Phys. J. C73, 2343; LC-REP-2013-005; F.Mueller @ ILD soft/ana meeting
- H->ττ: S. Kawada, et. al, LC-REP-2013-001, arXiv: 1509.01885;
- H->γγ/μμ: C.Calancha, LC-REP-2013-006
- top-Yukawa: R.Yonamine, et. al, Phys.Rev.D84:014033,2011; T. Price, et. al, Eur. Phys. J. C (2015) 75:309
- Higgs self-coupling: J.Tian, LC-Rep-2013-003; M.Kurata, LC-Rep-2014-025; C.Duerig @ ALCW15
- W mass by single W: K.Tsuchimoto @ ALCW15, note in preparation

elementary or composite

N.Craig @ LCWS16



What I really meant: Higgs has zero size in the SM. Its "size" comes from the scale of higher-dimensional operators in the Higgs EFT.

How strongly can we bound the operator

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$

Appears in Lagrangian as $\mathcal{L} \supset \frac{c_H}{\Lambda^2}\mathcal{O}_H$ and after EWSB $H \to v + \frac{1}{\sqrt{2}}h$

$$\frac{c_H}{\Lambda^2}\cdot\frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \to \left(\frac{2c_H v^2}{\Lambda^2}\right)\cdot\frac{1}{2}(\partial_\mu h)^2$$

Correction to Higgs wavefunction in broken phase

Canonically normalizing $h \to \left(1 - c_H v^2/\Lambda^2\right) h$

shifts all Higgs couplings uniformly, e.g.

$$\frac{m_Z^2}{v} h Z_\mu Z^\mu \to \frac{m_Z^2}{v}\left(1 - c_H v^2/\Lambda^2\right) h Z_\mu Z^\mu$$

$$\Lambda > \sqrt{\frac{1\%}{\delta\kappa_Z}}\,1.74\text{TeV}$$

ILC 250 GeV: $\delta\kappa_Z \sim 0.37\%$

$\Lambda > 2.86$ TeV

expected Higgs precisions @ ILC 250 GeV

(assume custodial symmetry; others as same as arXiv:1506.05992 / 1506.07830)

coupling Δg/g	500 fb-1	1000 fb-1	2000 fb-1
HZZ	0.75%	0.53%	0.38%
HWW	0.90%	0.72%	0.61%
Hbb	2.5%	1.8%	1.3%
Hcc	3.9%	2.8%	2%
Hgg	3.6%	2.5%	1.8%
Hττ	2.7%	1.9%	1.4%
Hγγ	13% (1%)*	9.0% (1%)*	6.4% (1%)*
HγZ	10%	7%	5%
Hμμ	27%	19%	13%
Γ_H	5.5%	3.9%	2.9%
BR(H->inv.) (95% CL)	0.59%	0.43%	0.31%
Htt	-	-	-
HHH	-	-	-

()*: + κ_γ/κ_Z @ HL-LHC

expected Higgs precisions @ ILC 250 GeV

(model independent fit; sys. errors included; c.f. arXiv:1506.05992 / 1506.07830)

coupling $\Delta g/g$	500 fb-1	1000 fb-1	2000 fb-1
HZZ	0.75%	0.53%	0.38%
HWW	3.9%	2.8%	2%
Hbb	4.2%	3%	2.1%
Hcc	5.2%	3.7%	2.6%
Hgg	4.9%	3.5%	2.5%
Hττ	4.4%	3.1%	2.2%
Hγγ	13% (1%)*	9.3% (1%)*	6.6% (1%)*
HγZ	10%	7%	5%
Hμμ	27%	19%	14%
Γ_H	8.8%	6.2%	4.4%
BR(H->inv.) (95% CL)	0.59%	0.43%	0.31%
Htt	-	-	-
HHH	-	-	-

()*: + κ_γ/κ_Z @ HL-LHC

input precisions (ILC 250 GeV)

(model independent fit; sys. errors included; c.f. arXiv:1506.05992 / 1506.07830)

absolute couplings

$\Delta g/g$	2000 fb-1
κ_Z	0.38%
κ_W	2.0%
κ_b	2.1%
κ_τ	2.2%
κ_c	2.6%

ratio of couplings

$\Delta g/g$	2000 fb-1
κ_Z	0.38%
κ_W/κ_Z	1.9%
κ_b/κ_W	0.64%
κ_τ/κ_W	0.84%
κ_c/κ_W	1.7%