Higgs Trilinear coupling at Linear Colliders

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Linear Collider Workshop 2018

10/25/2018

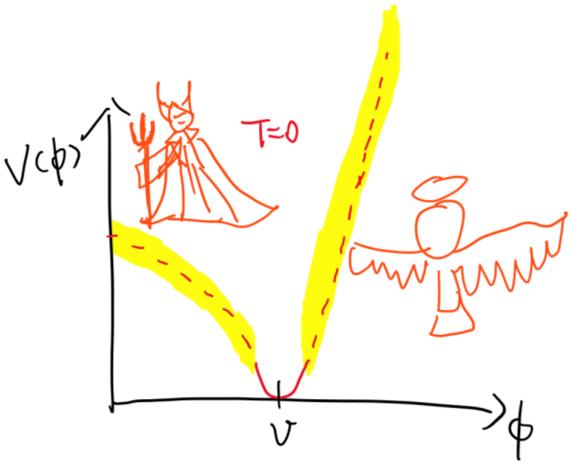
mainly based upon [1711.03978]
S. Di Vita, G. Durieux, C. Grojean, J. Gu, **ZL**, G. Panico, M. Riembau, T. Vantalon
and contributions to various reports

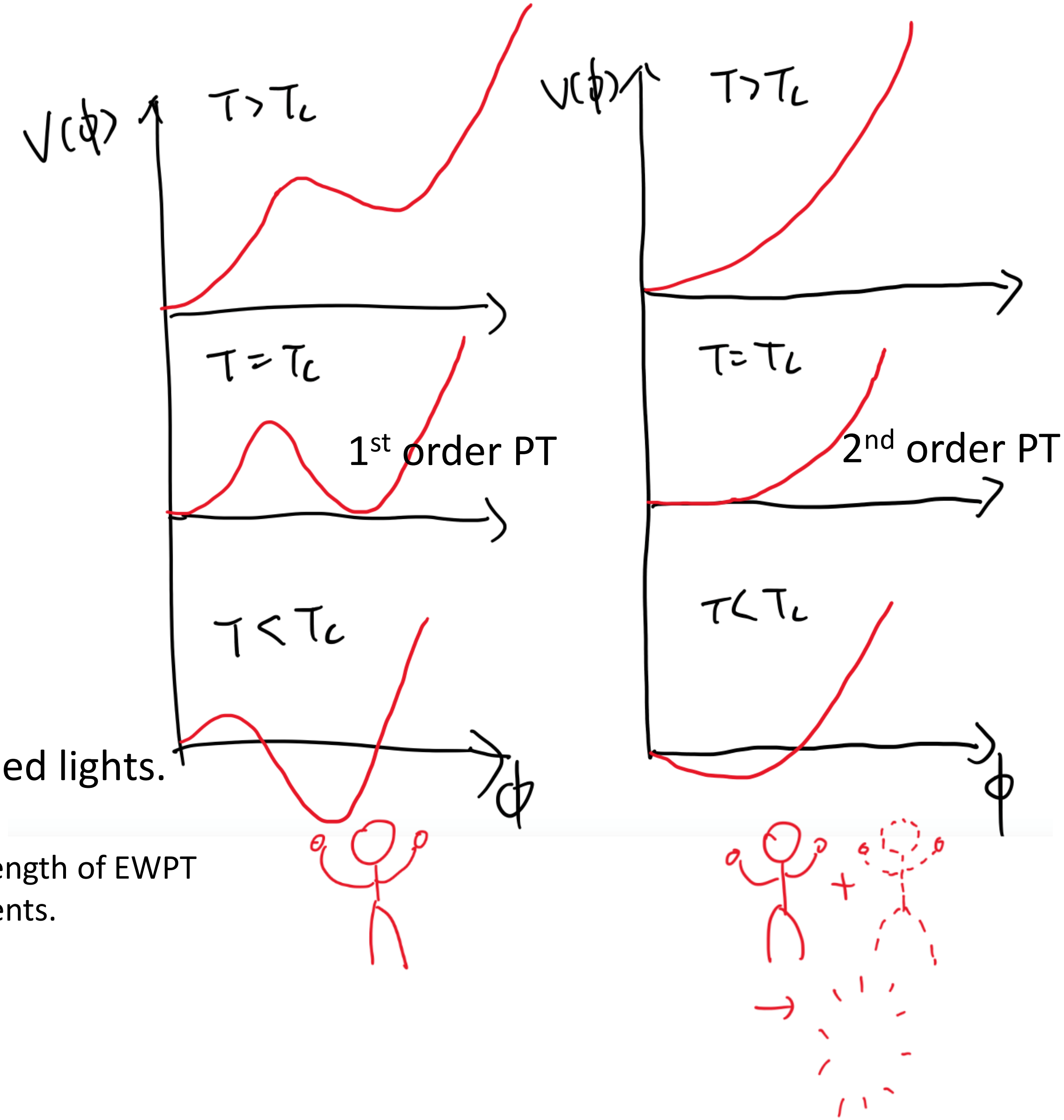
Outline

Motivation and probes for Higgs trilinear at linear colliders:

- Double Higgs observables
- Singlet Higgs observables
- EFT global fit
- **Results and implications:**
  - **Are we limited by knowledge on other operators entering the 2H process?**
  - **Are we limited by knowledge on other operators entering the 1H process?**
  - **How complimentary are the HL-LHC and LCs with different energy runs?**

Higgs Precision and Electroweak Phase-Transition





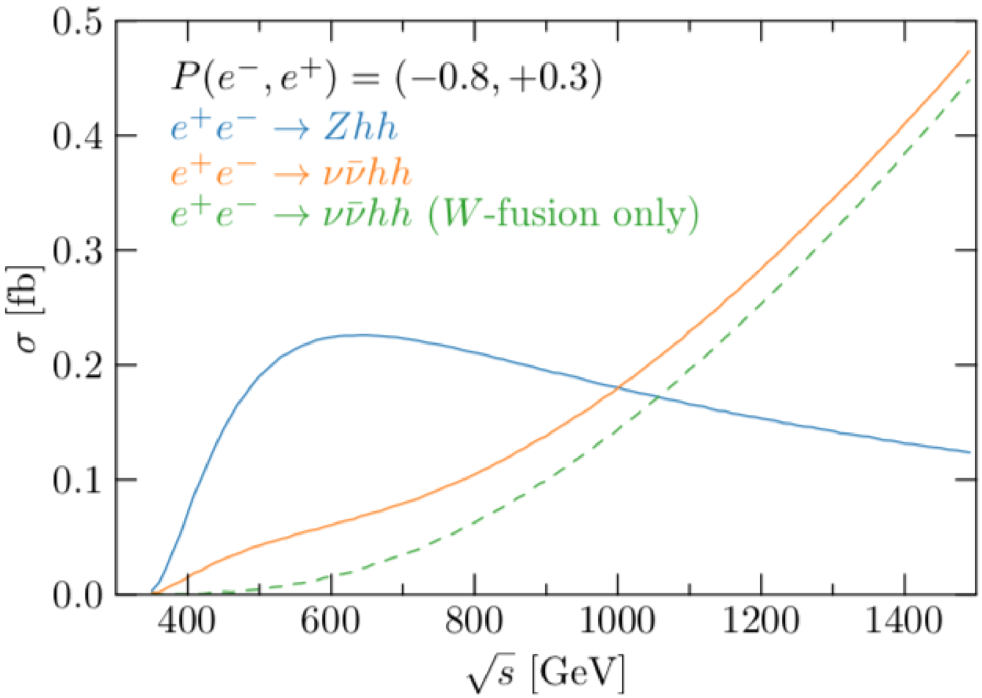
How does the potential look like?

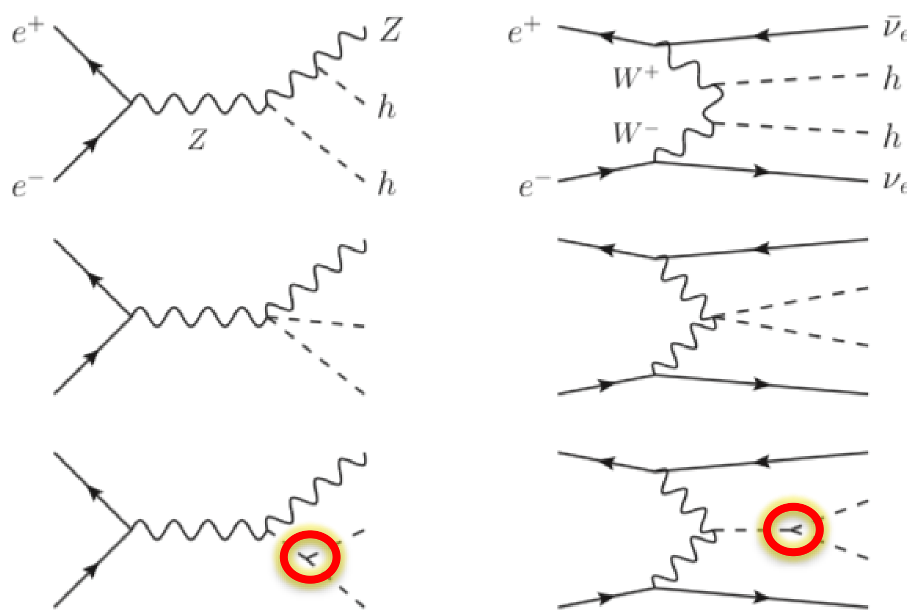
Is EWPT strong enough?

Higgs self-couplings determinations shed lights.

Both the self-coupling determination and the strength of EWPT convolutes with other Higgs property measurements.

Finding probes: 2H processes

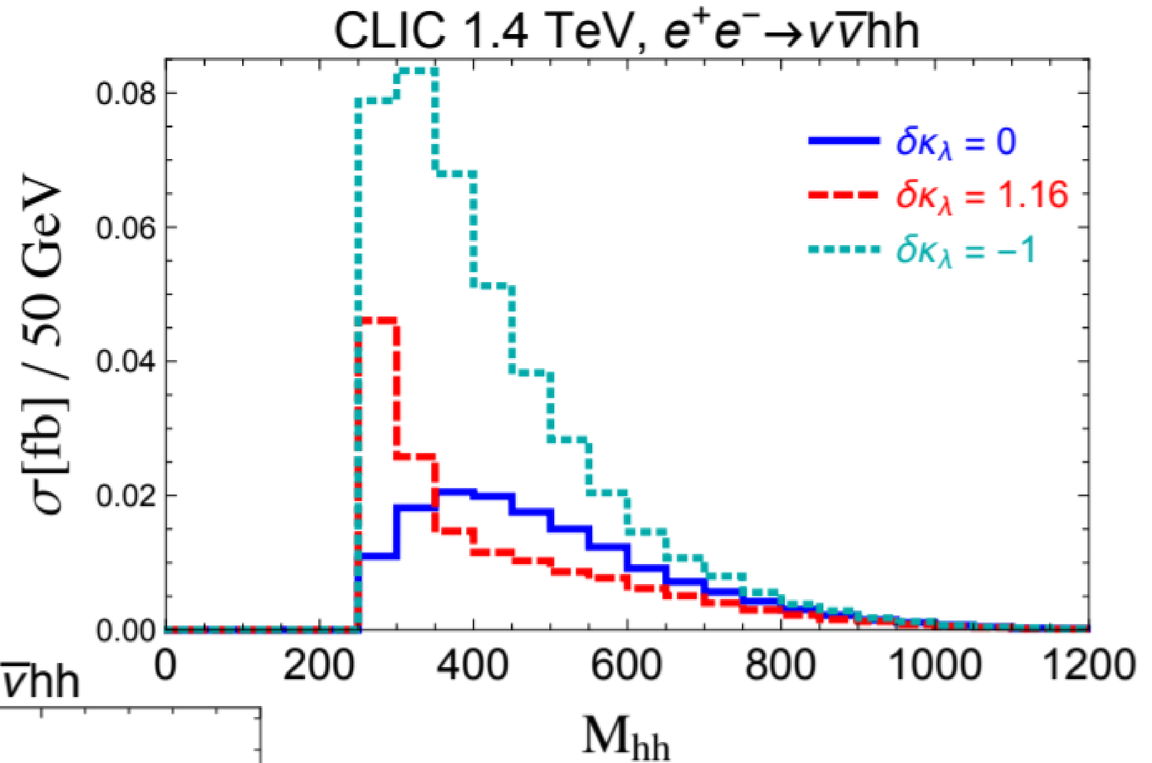


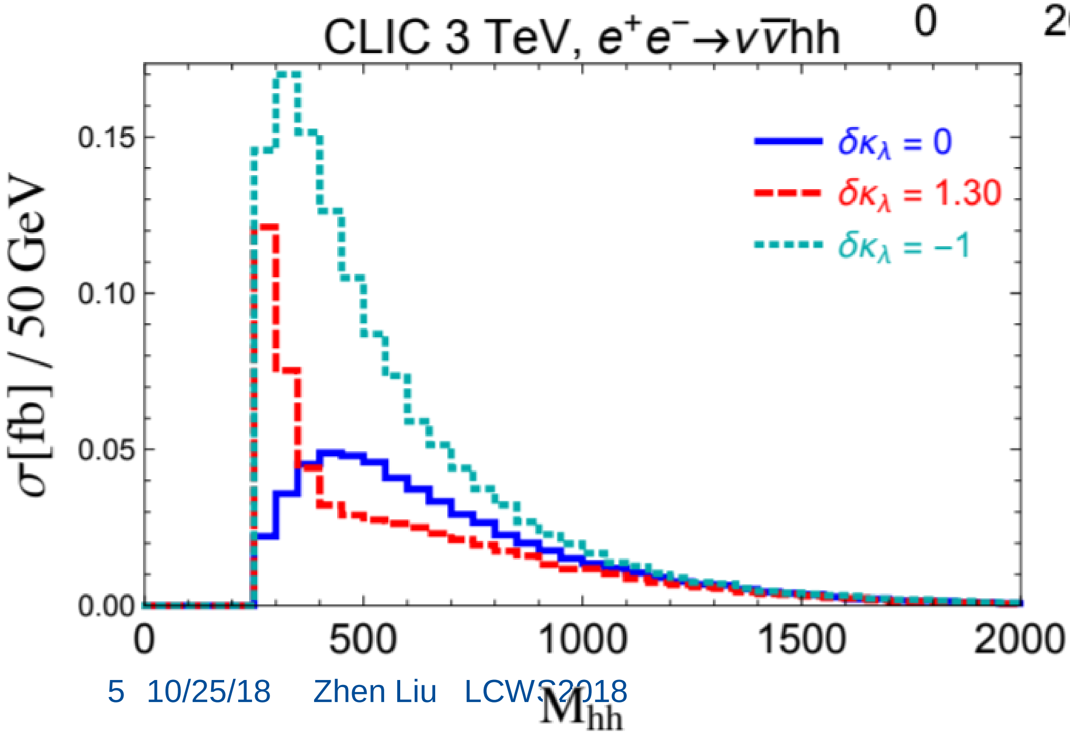


- ``direct'' tree-level dependence on the Higgs trilinear;
- Many other 2H processes not originated from Higgs trilinear
  ➔Need to evaluate the impact of trilinear extraction in a EFT framework

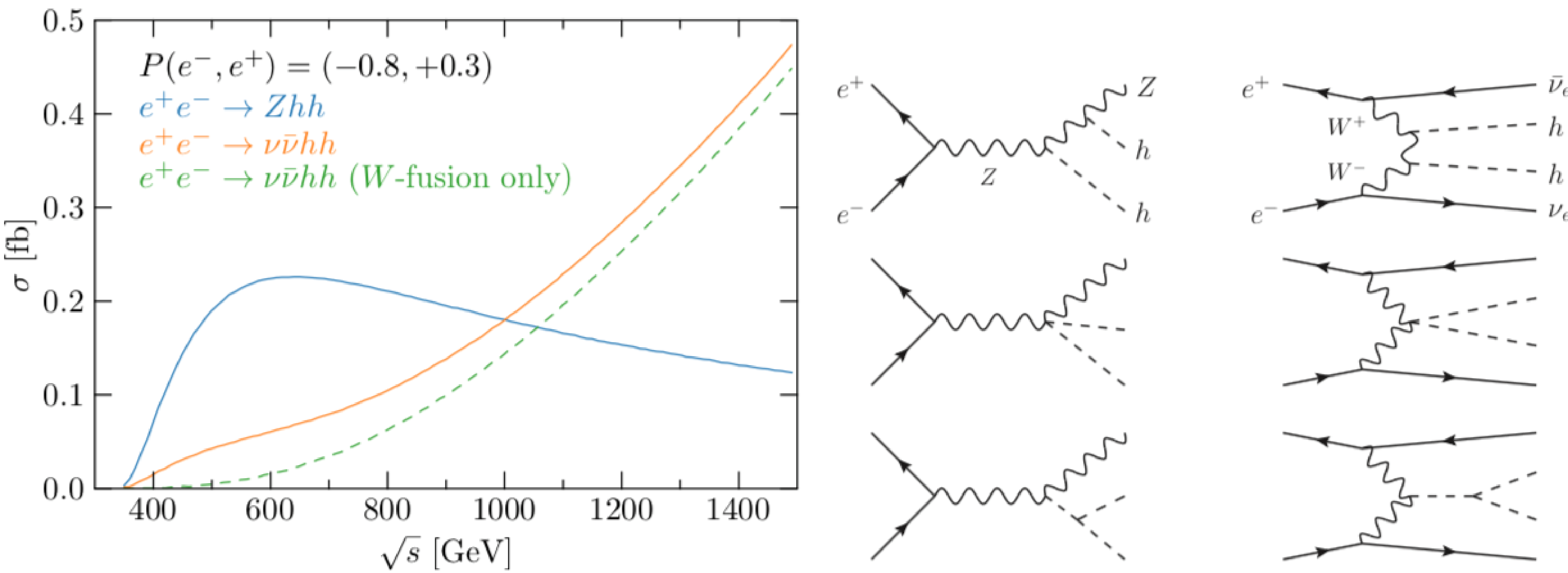
More observables in 2h

Differential observables help resolve interplays between different diagrams.



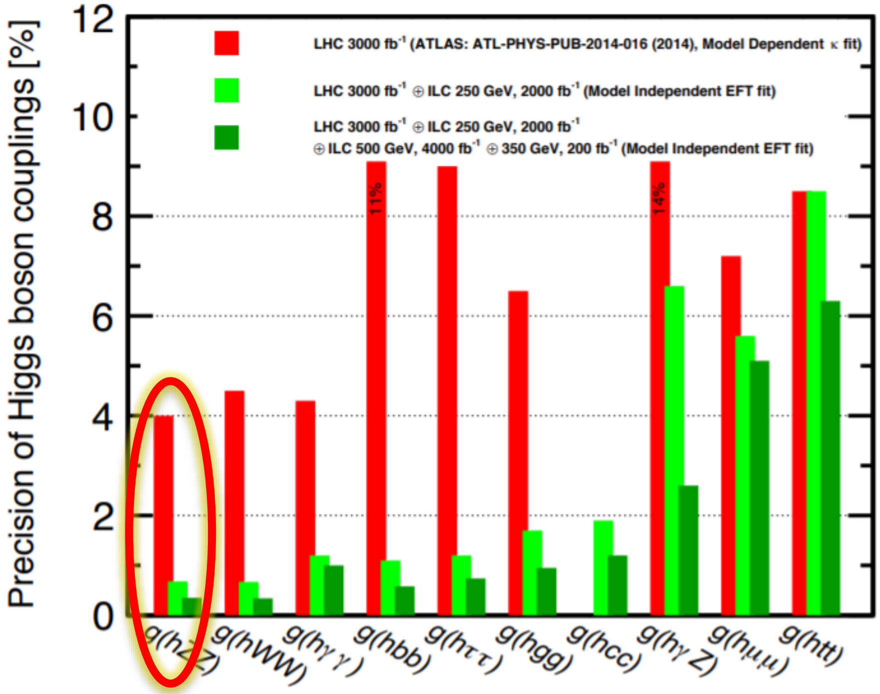


Finding probes: 2H processes



- Tree-level probes for the Higgs self-couplings are *NOT* kinematically accessible at their baseline running (250 GeV for ILC and 350 GeV for CLIC), we need to think about alternative probes.
- Help understanding the staging and complementarity between different running energies.

Finding probes for Higgs trilinear at Linear Colliders



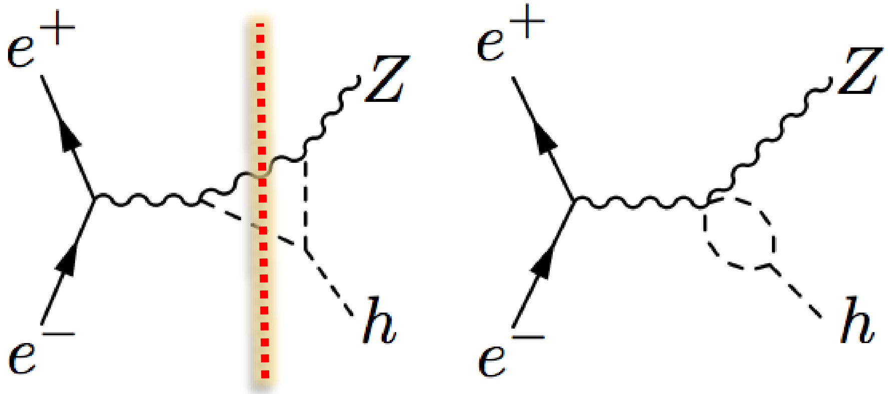
LCC Physics WG, arXiv: 1710.07621

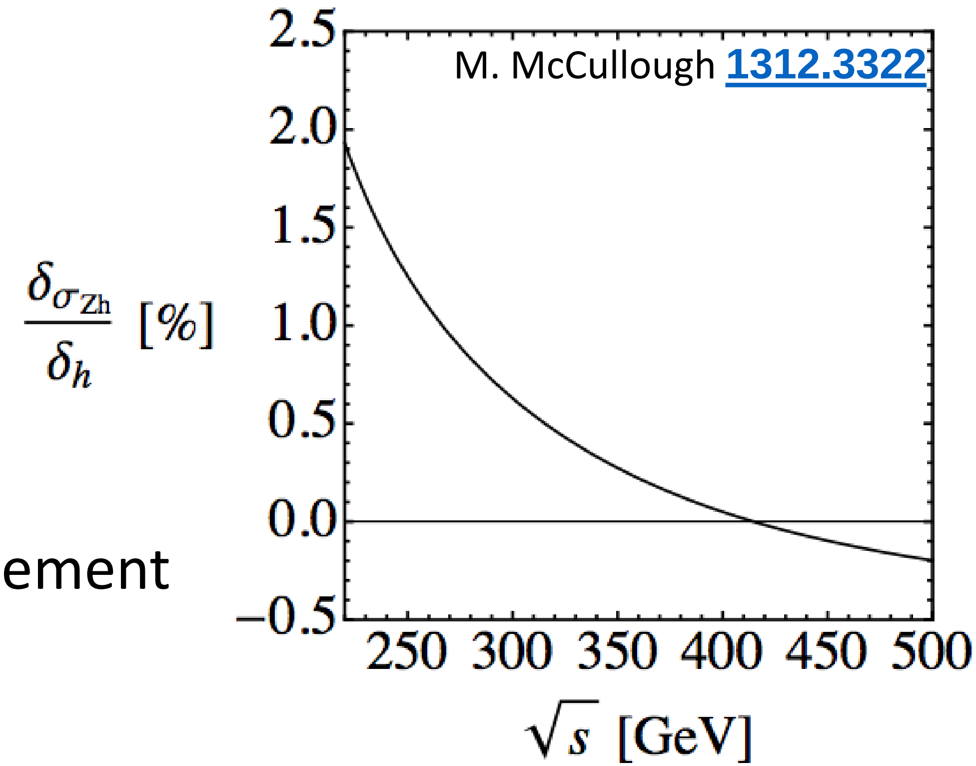
$e^+e^- \to ZH$, the best determined process without dependence on the exclusive decay of the Higgs boson

Use precision to gain knowledge (directly) accessible at higher energy.

*here I choose the fit result on hZZ coupling in κ-framework instead the direct measurement, just to visualize the precision.

Constraints from $e^+e^- \to ZH$





A natural/free threshold enhancement helps enhancing the sensitivity;

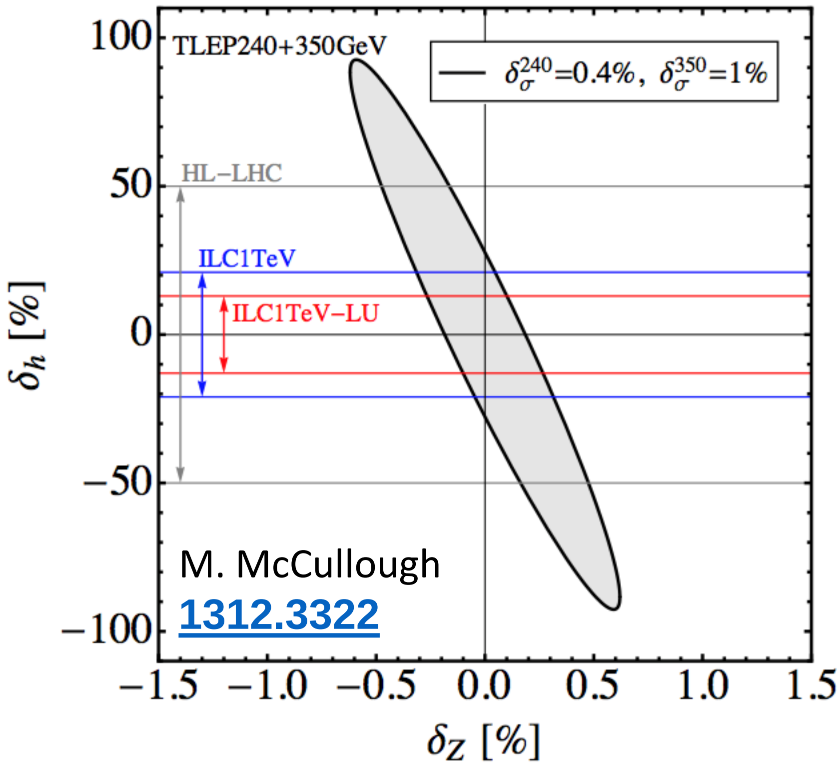
O(30%) precision achievable, at 5 ab^-1 for an unpolarized e+e- machine, with some assumptions that we will break down in the next few slides;

Constraints from $e^+e^- \to ZH$: discussion

Hard to achieve single O_6 operator from UV point of view;

To gain knowledge about the O_6 in presence of other operators one needs to include more observables;

Constraints from $e^+e^- \to ZH$: discussion



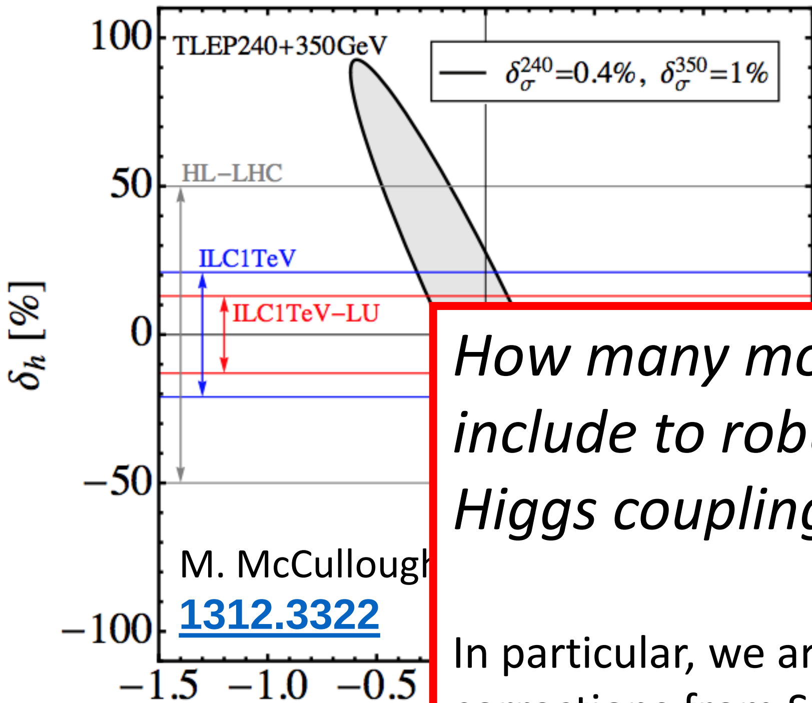
Hard to achieve single O_6 operator from UV point of view;

To gain knowledge about the O_6 in presence of other operators one needs to include more observables;

Taking the simplest extension of the SM:
SM+1 singlet O_H and O_6 are simultaneously generated, can be translated into δ_h and δ_Z here;*
One can use the $e^+e^- \to ZH$ cross section at different center of mass energy to constrain the Higgs trilinear coupling.

*for more detailed discussion using fuller set of observables, see next talk by S. Su, on work J. Gu, H. Li, ZL, S. Su, W. Su 1709.06103;

Constraints from $e^+e^- \to ZH$: discussion



Hard to achieve single O_6 operator from UV point of view;

To gain knowledge about the O_6 … operators … more

How many more do we need to include to robustly extract trilinear Higgs couplings from this process?

In particular, we are extracting loop-level corrections from SM corrections on a tree-level process; any in precise determination of other BSM contributions could spoil this.

Taking the simplest …
SM+1 singlet O_H and O_6 are simultaneously generated, can be translated into δ_h and δ_Z here;*
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more operators

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EFT is a nice framework to address this issue:

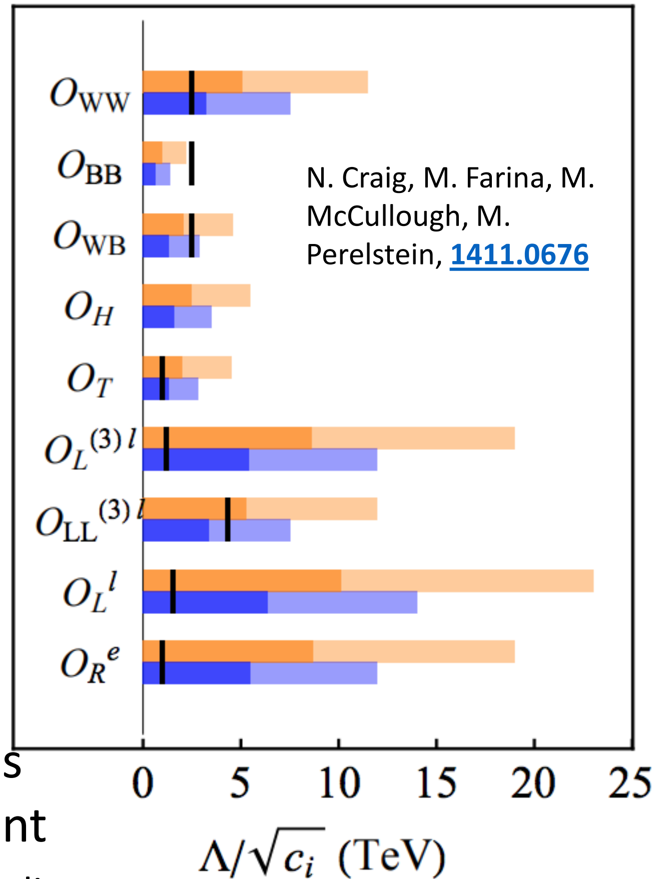
a) ``model blind'';

b) Can relate different measurements at different scales and observables, allowing a more consistent/transparent treatment beyond Higgs observables; (see M. Trott's talk earlier in the Higgs session)

more operators

How many more do we need to include to robustly extract trilinear Higgs couplings from this process?

$$\mathcal{O}_{WW} = g^2|H|^2 W^a_{\mu\nu}W^{a,\mu\nu}$$
$$\mathcal{O}_{BB} = g'^2|H|^2 B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{H} = \frac{1}{2}(\partial_\mu |H|^2)^2$$
$$\mathcal{O}_{T} = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$$
$$\mathcal{O}_{L}^{(3)\ell} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$$
$$\mathcal{O}_{LL}^{(3)\ell} = (\bar{L}_L \gamma_\mu \sigma^a L_L)(\bar{L}_L \gamma^\mu \sigma^a L_L)$$
$$\mathcal{O}_{L}^{\ell} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$$
$$\mathcal{O}_{R}^{e} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$$



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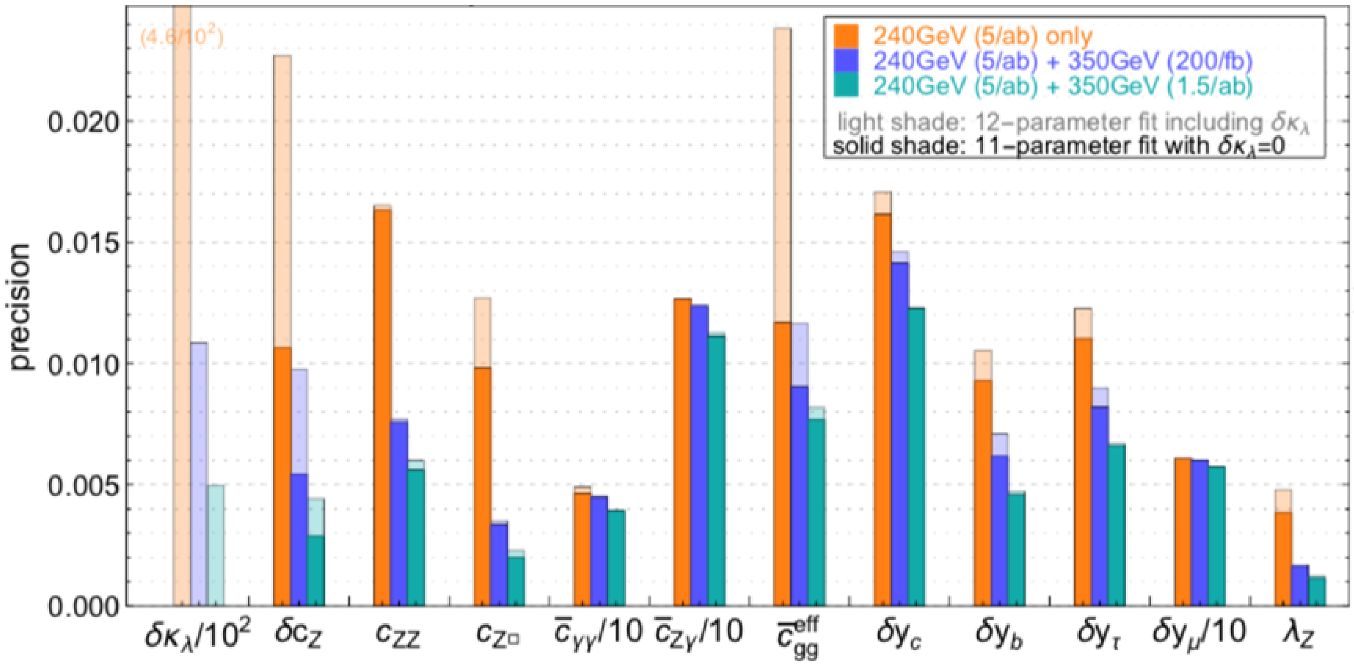
b) Can relate different measurements at different scales and observables, allowing a more consistent/transparent treatment beyond Higgs observables; (see M. Trott's talk earlier in the Higgs session)

9 tree-level CP even dimension-6 operators contributing at linear level;
<u>and more if we include some of the SM input parameter uncertainties;</u>

Angular asymmetries help probe these operators, see N. Craig, J. Gu, ZL, K. Wang, **1512.06877**

more operators

Higgs fit *without* trilinear, see Durieux, Grojean, Gu, Wang, 1704.02333 , with trilinear + more observables,+ZL et al, 1711.03978

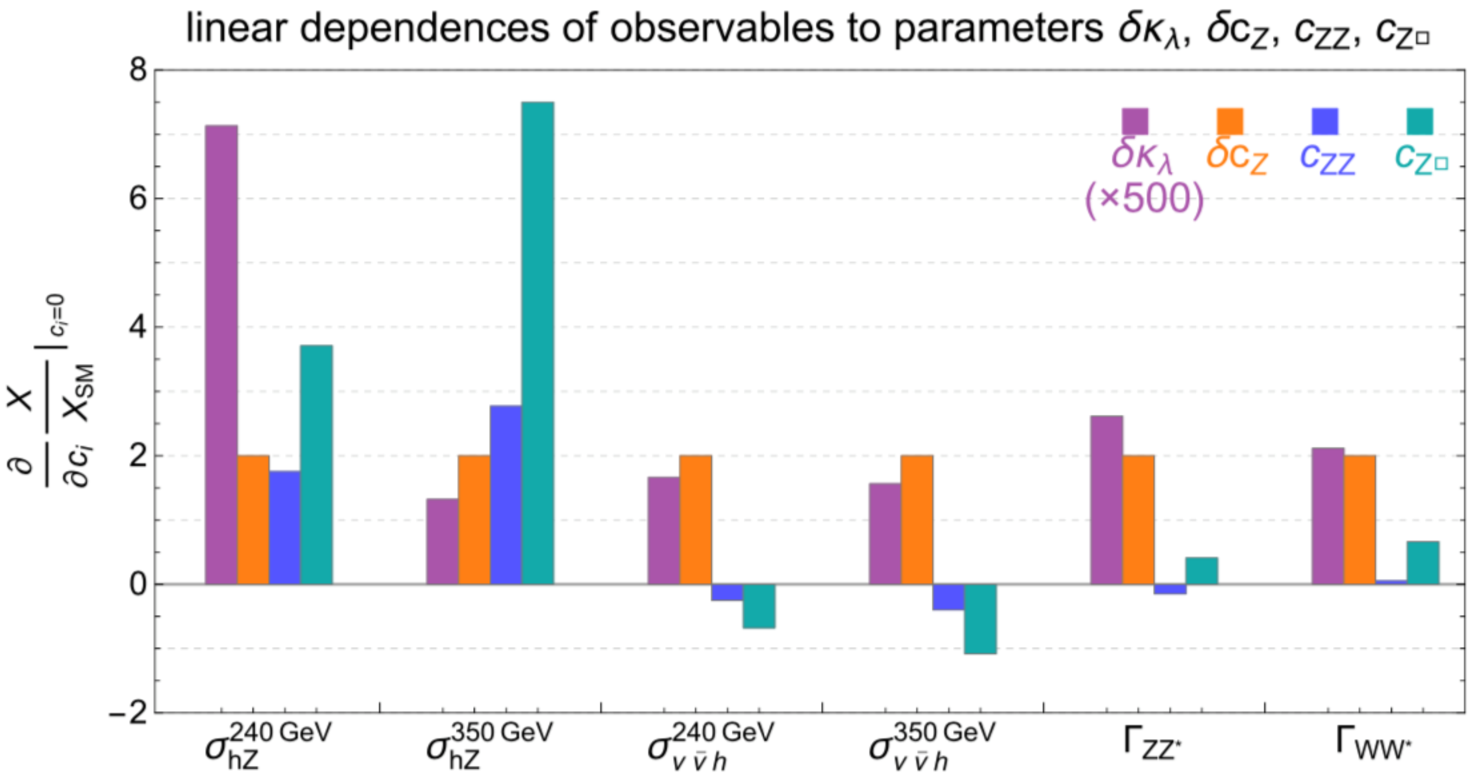


- The impact of adding the new d.o.f. of Higgs trilinear modifications is quite sizable;
- Strong correlations between the trilinear modification and the parameter (hZZ shifting); already seen in the simplest example for the singlet extension;
- Sizable reduction in other ``coupled'' coefficients;

C_1	ZZ	WW	$\gamma\gamma$	gg	$f\bar{f}$
on-shell h decay	0.0083	0.0073	0.0049	0.0066	0

C_1 linear dependence on trilinear modifications
G. Degrassi, P. Giardino, F. Maltoni, D. Pagani, 1607.04251

More observables (that are sensitive to Higgs trilinear)



New probes:

Cross sections at different c.o.m. energies, 240 GeV & 350 GeV ;

Different production processes, ZH & WW-fusion;

Decay processes, WW^* and ZZ^*;

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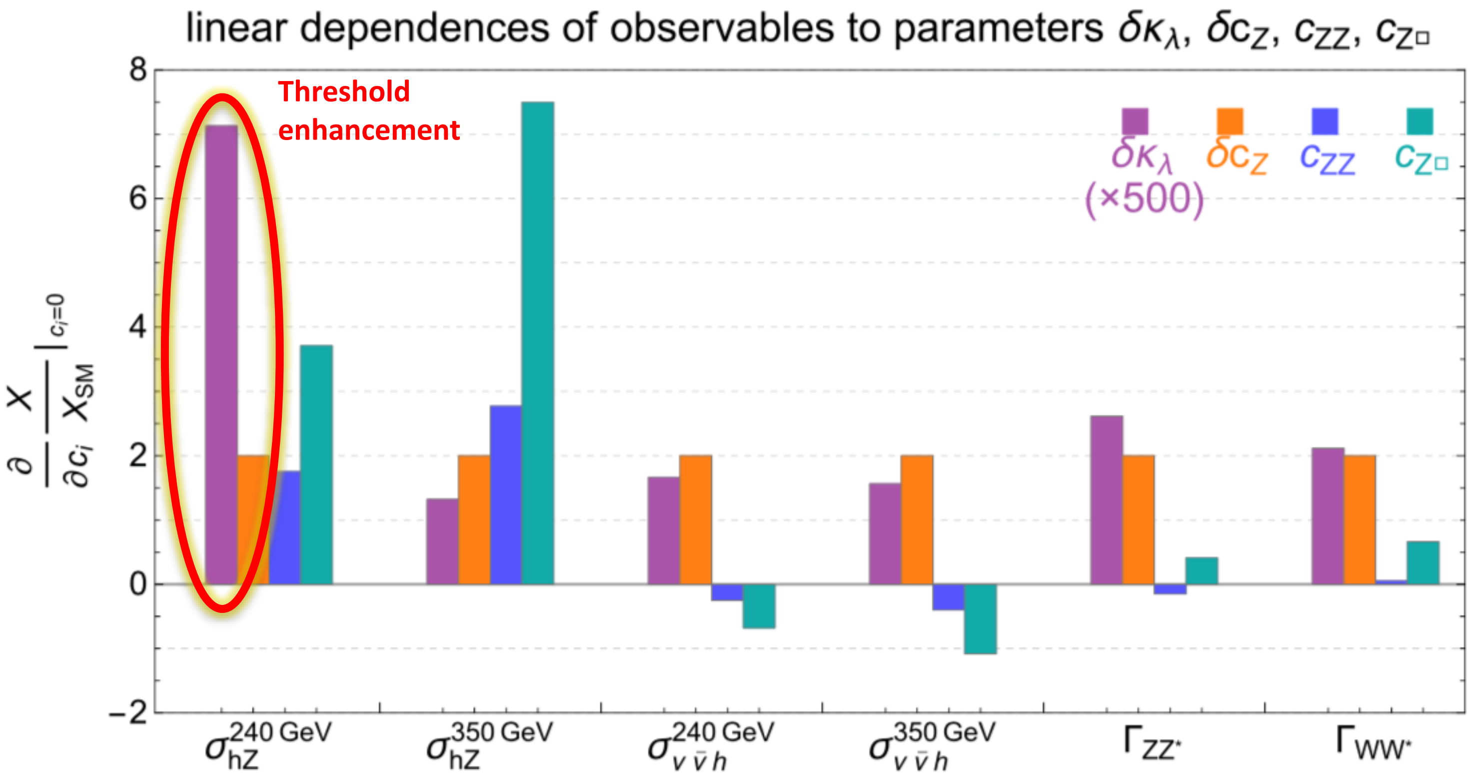

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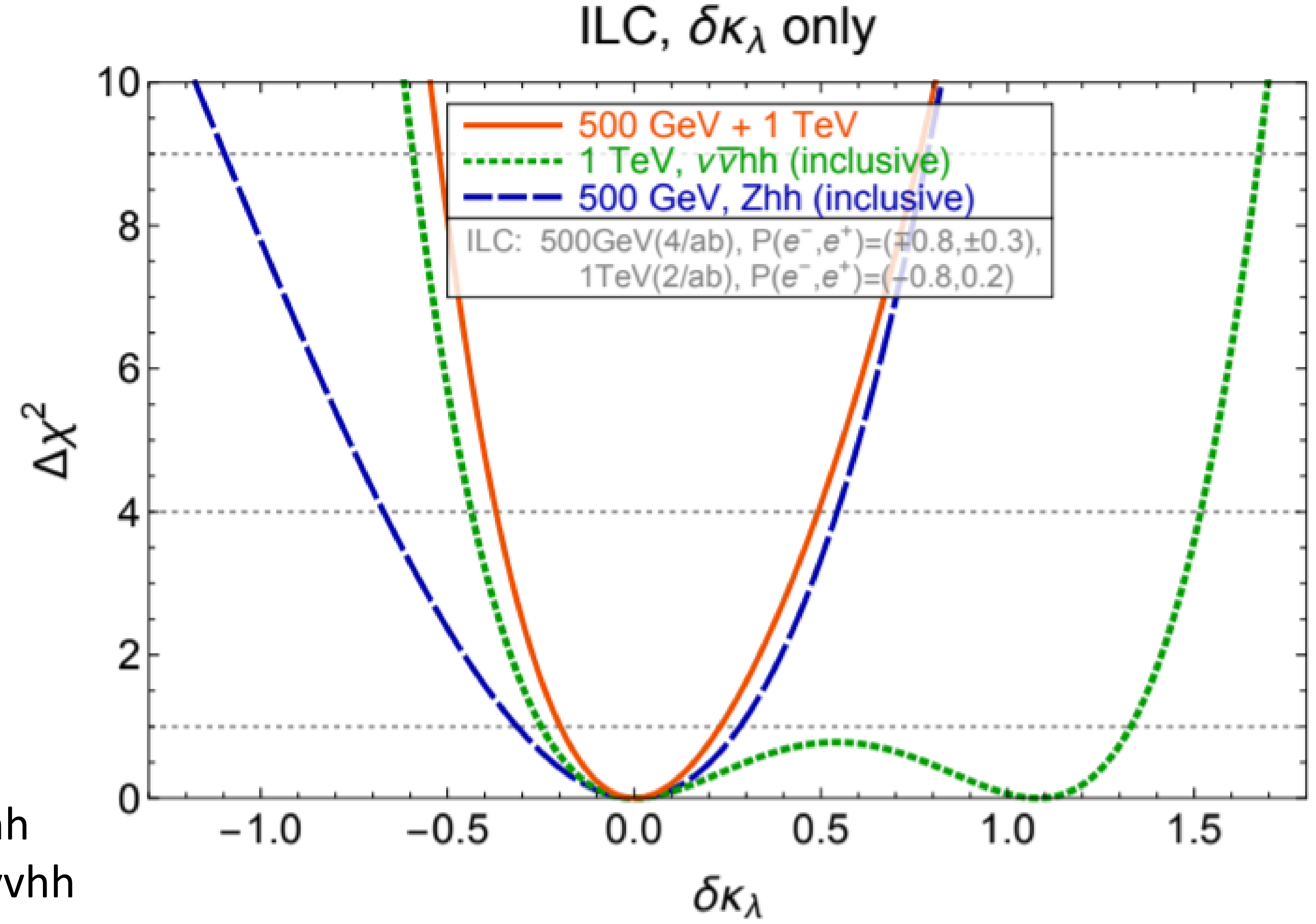
Results and implications

- ILC results
- CLIC results

- Are we limited by knowledge on other operators entering the 2H process?
- Are we limited by knowledge on other operators entering the 1H process?
- How complimentary are the HL-LHC and LCs with different energy runs?

ILC Results (one parameter fit)



ILC 500 GeV Zhh

ILC 1000 GeV vvhh

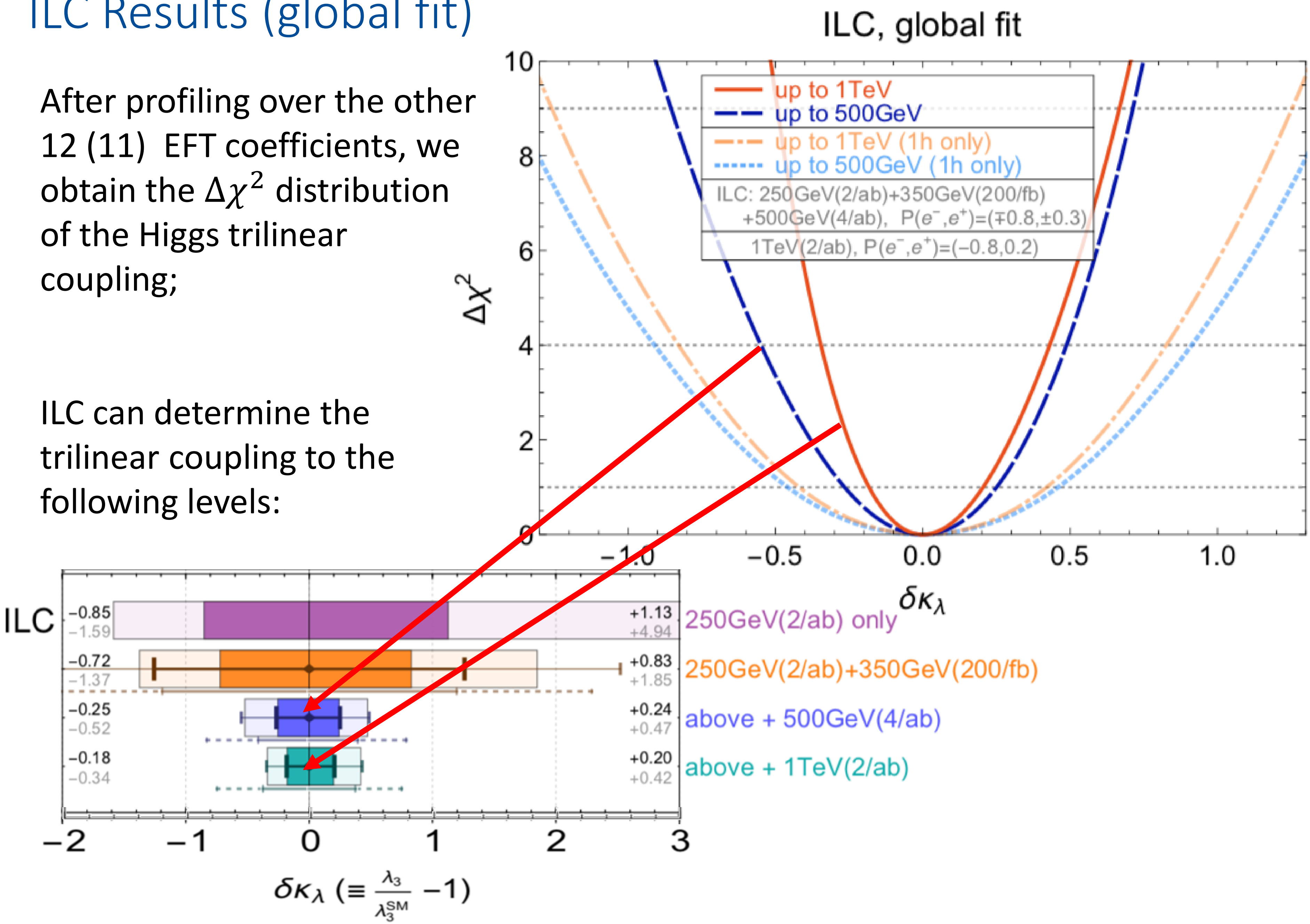
ILC 500 GeV + 1000 GeV

Zhh and vvhh complementary in removing second minimum from vvhh searches

ILC Results (global fit)

After profiling over the other 12 (11) EFT coefficients, we obtain the $\Delta\chi^2$ distribution of the Higgs trilinear coupling;

ILC can determine the trilinear coupling to the following levels:



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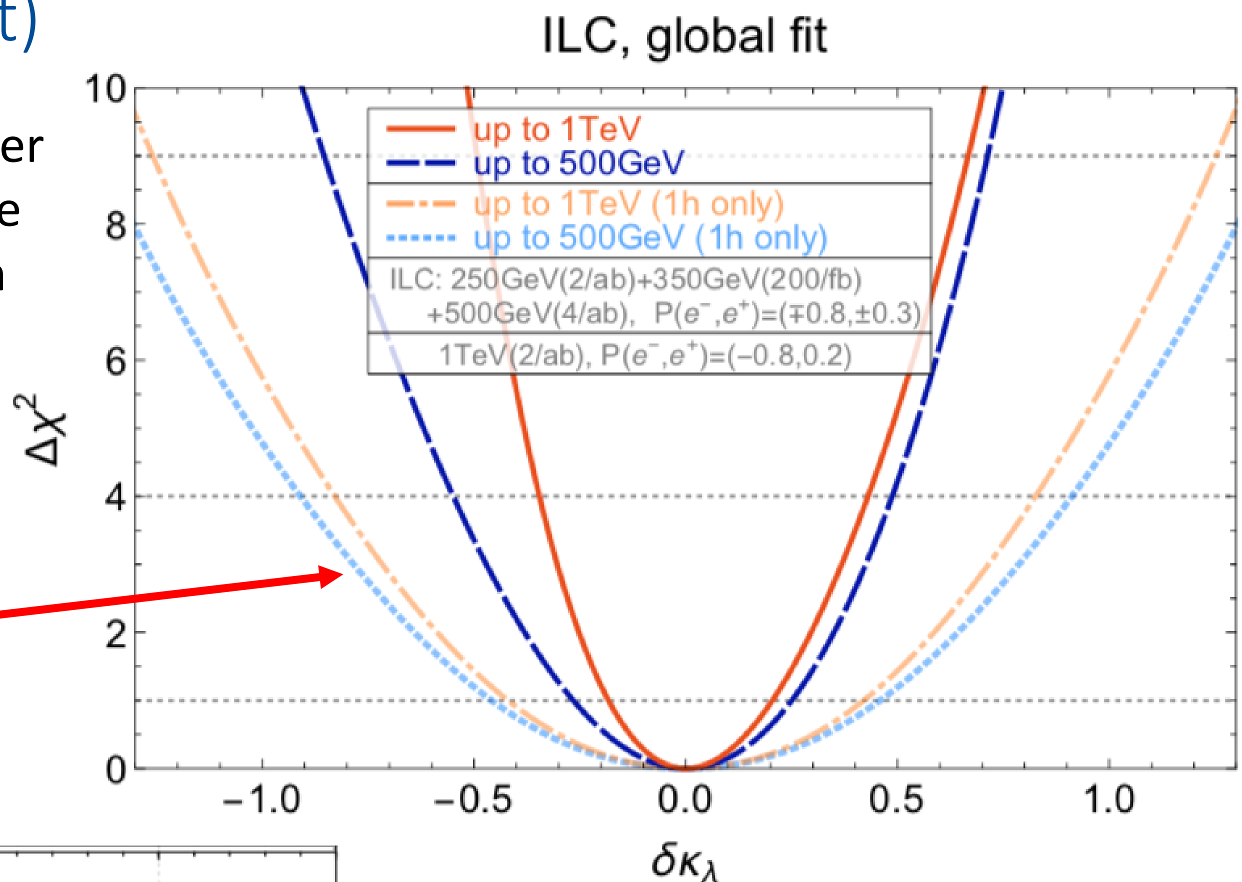
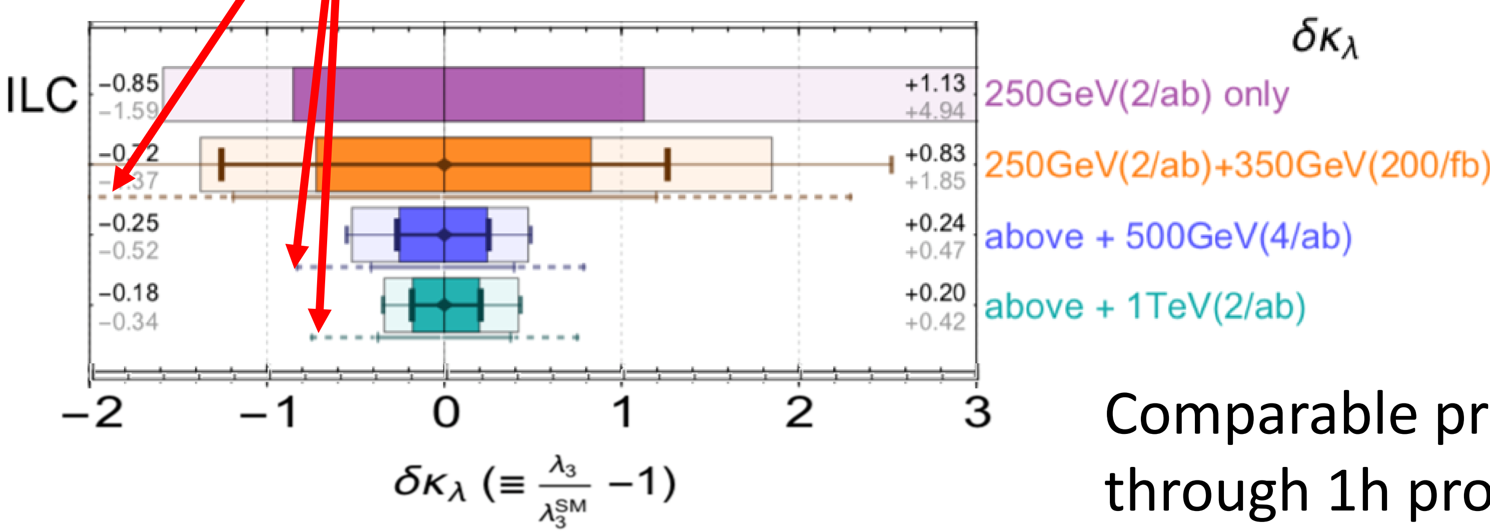
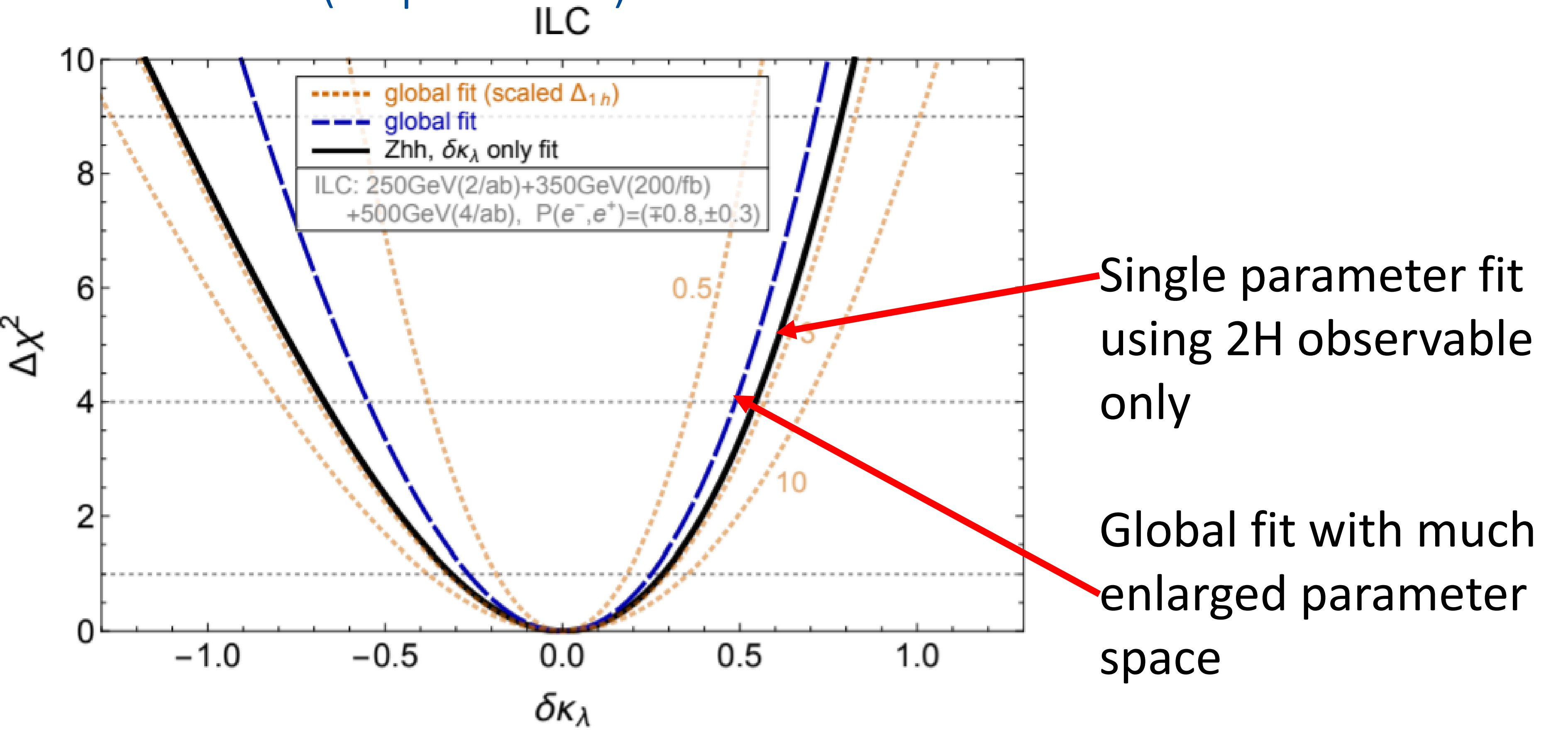


1h observables only



Comparable precision gained through 1h processes

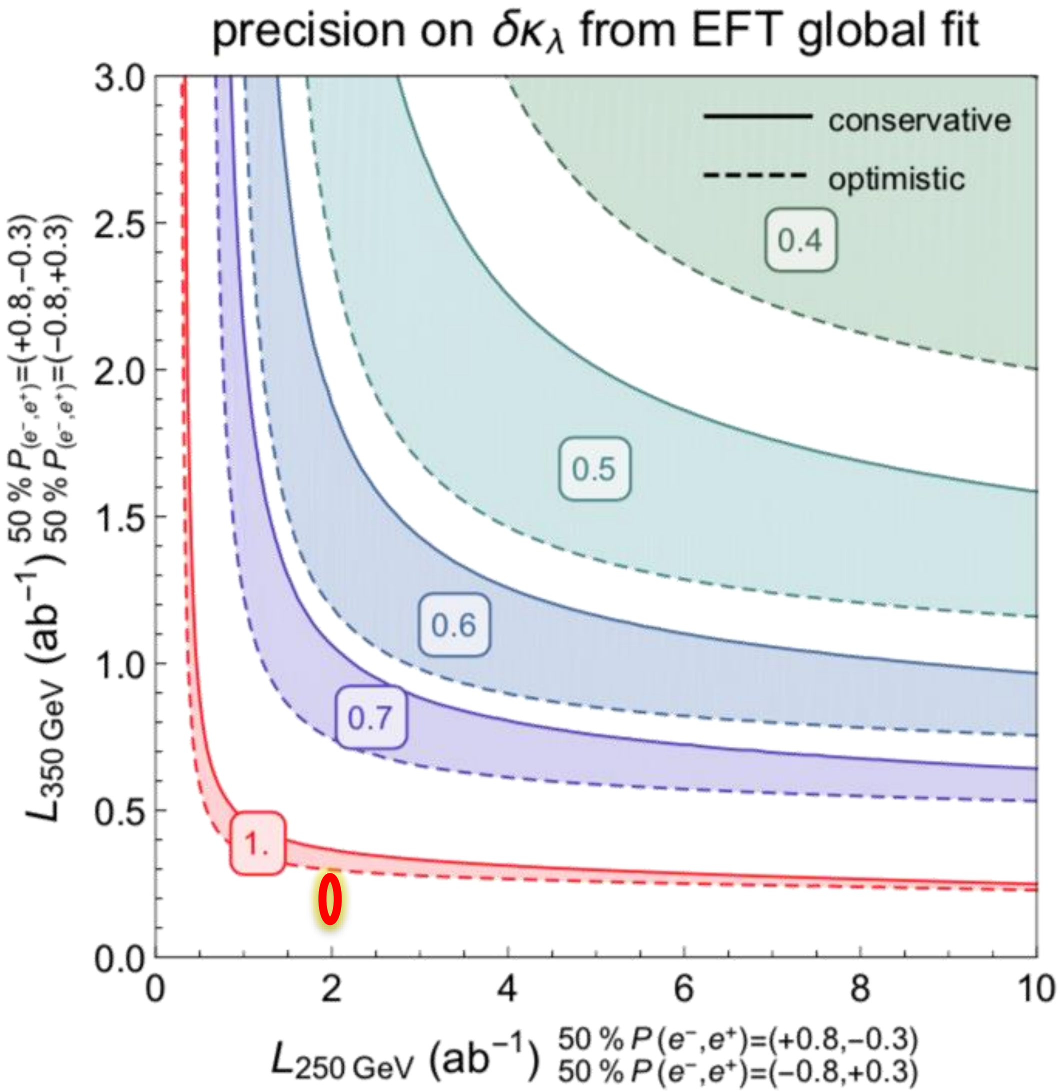
ILC Results (implication)



Clearly, the ILC 500 GeV trilinear extrapolation:

- Not limited by Higgs coupling uncertainties;
- 1H trilinear observable even improves the sensitivity;
- If Higgs properties worsen by a factor of 3, start limiting the trilinear extrapolation;
- improving 1h will continue to improve the trilinear extrapolation (other precision Higgs machines help!)

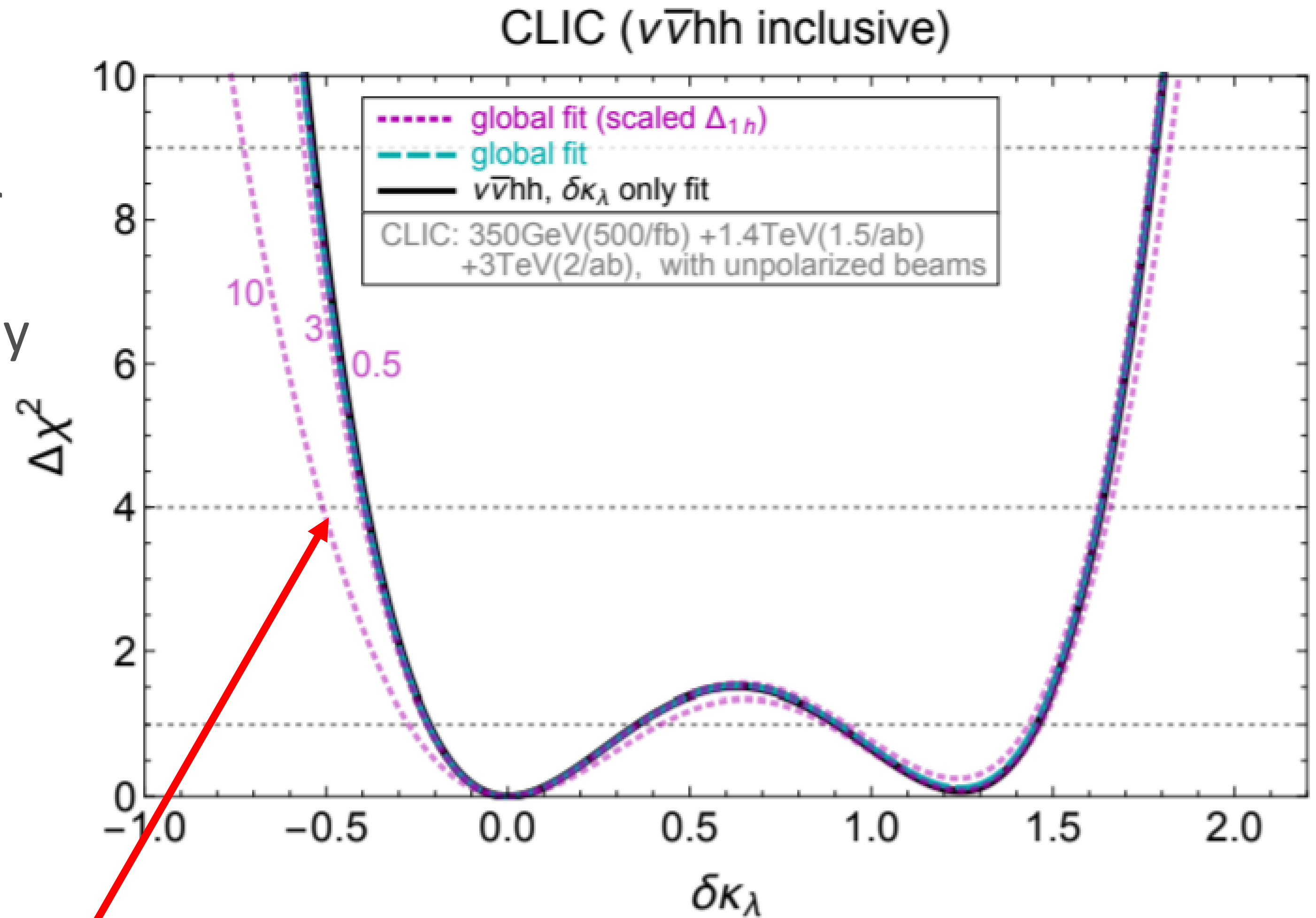
ILC Results: 240 GeV and 350 GeV interplay (1h)



- Optimization of relative size of data sets (run scenarios) remain interesting practice;
- Result depend on physics goals; need to be chosen carefully.
- Maybe we can consider some other running scenarios? Trilinear would be a nice measure as it requires balanced information about Higgs and EW.

CLIC results

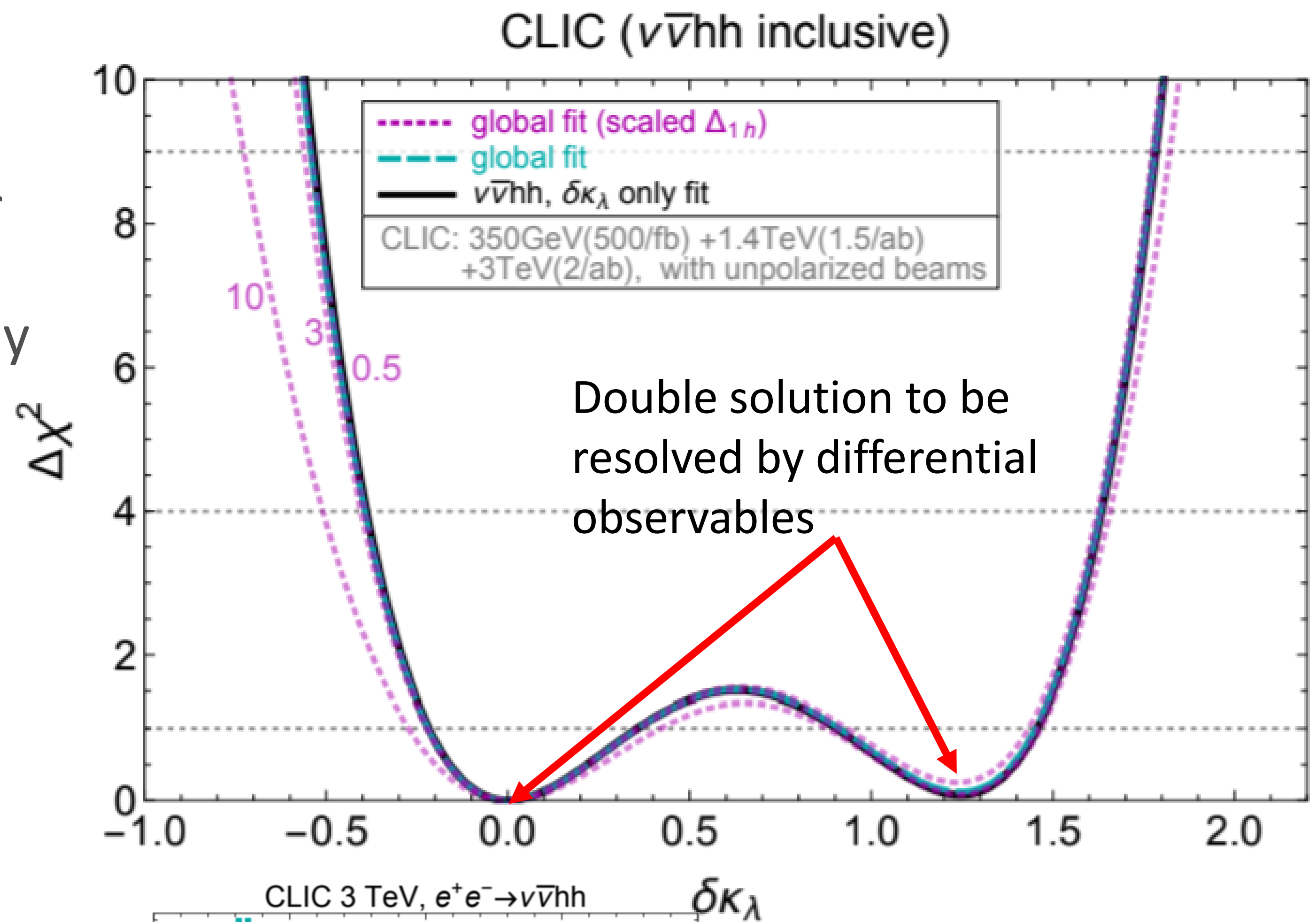
Single parameter fit and global fit doesn't diff visibly so only show global here.



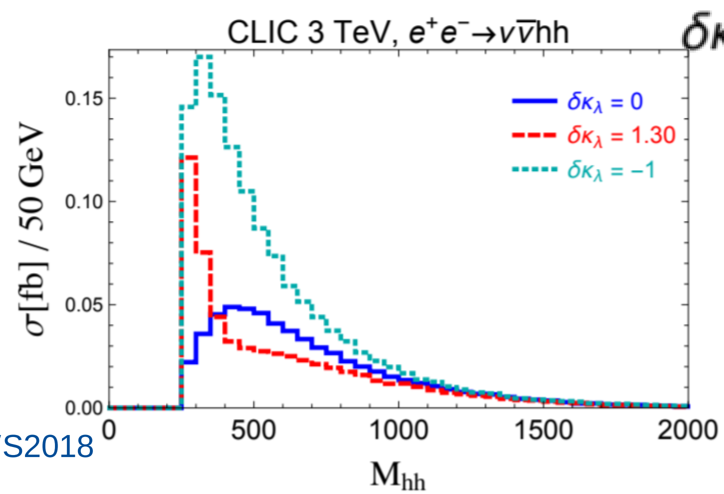
Varying 1H inputs between 0.5~3 do not change the result much: implying at CLIC 1H is not yet sensitive to trilinear but good enough to not affect the trilinear extrapolation from 2H processes

CLIC results

Single parameter fit and global fit doesn't diff visibly so only show global here.

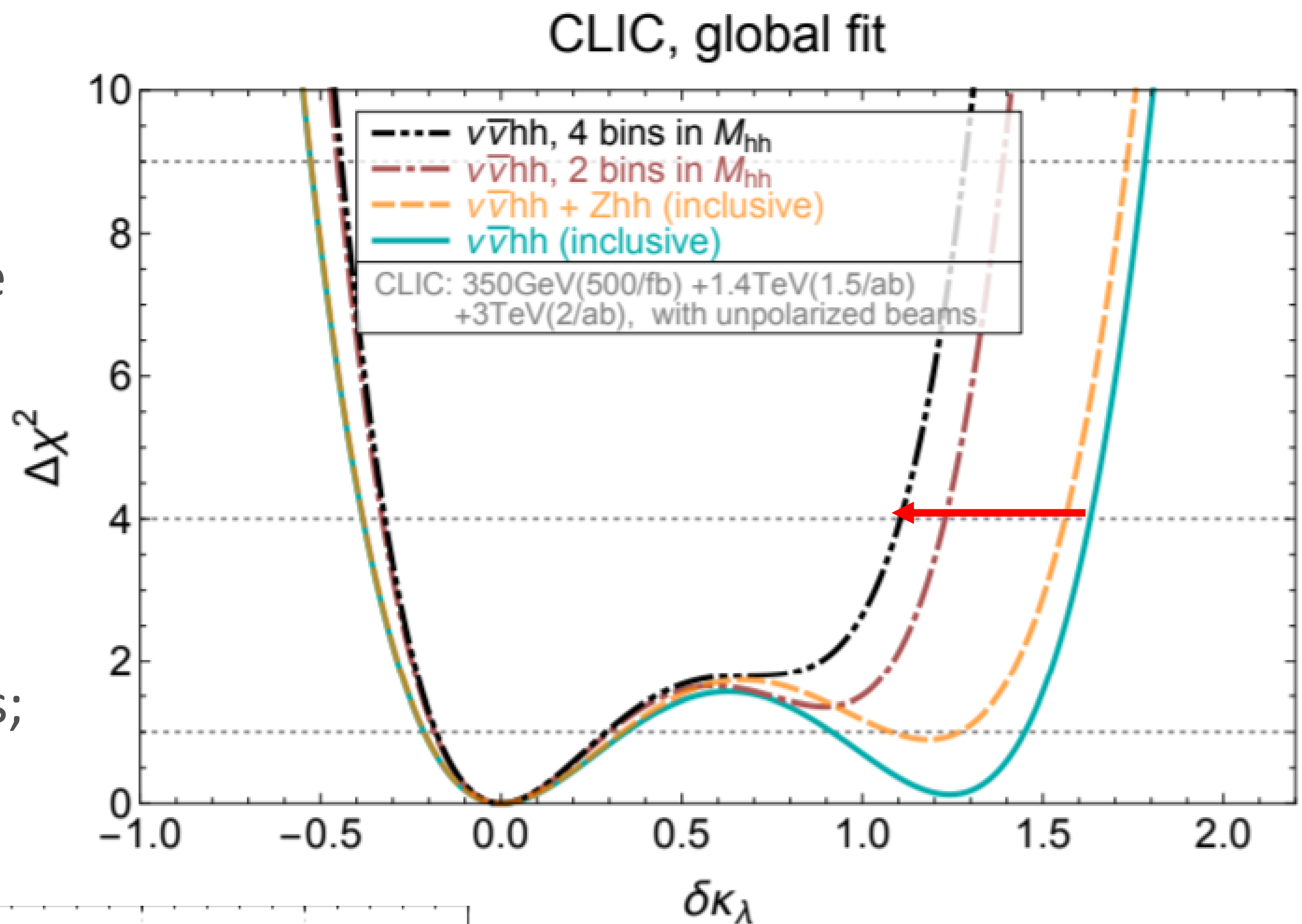


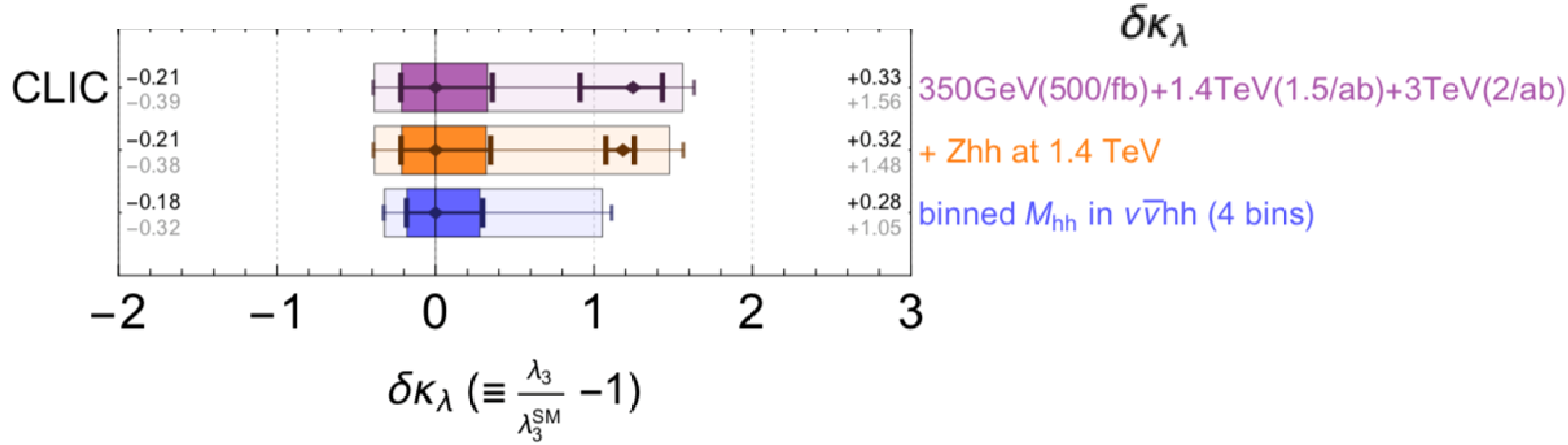
Double solution to be resolved by differential observables



CLIC results

- 1H not good enough to derive trilinear limits, but also not limiting;
- More modes helps;
- Differential helps;

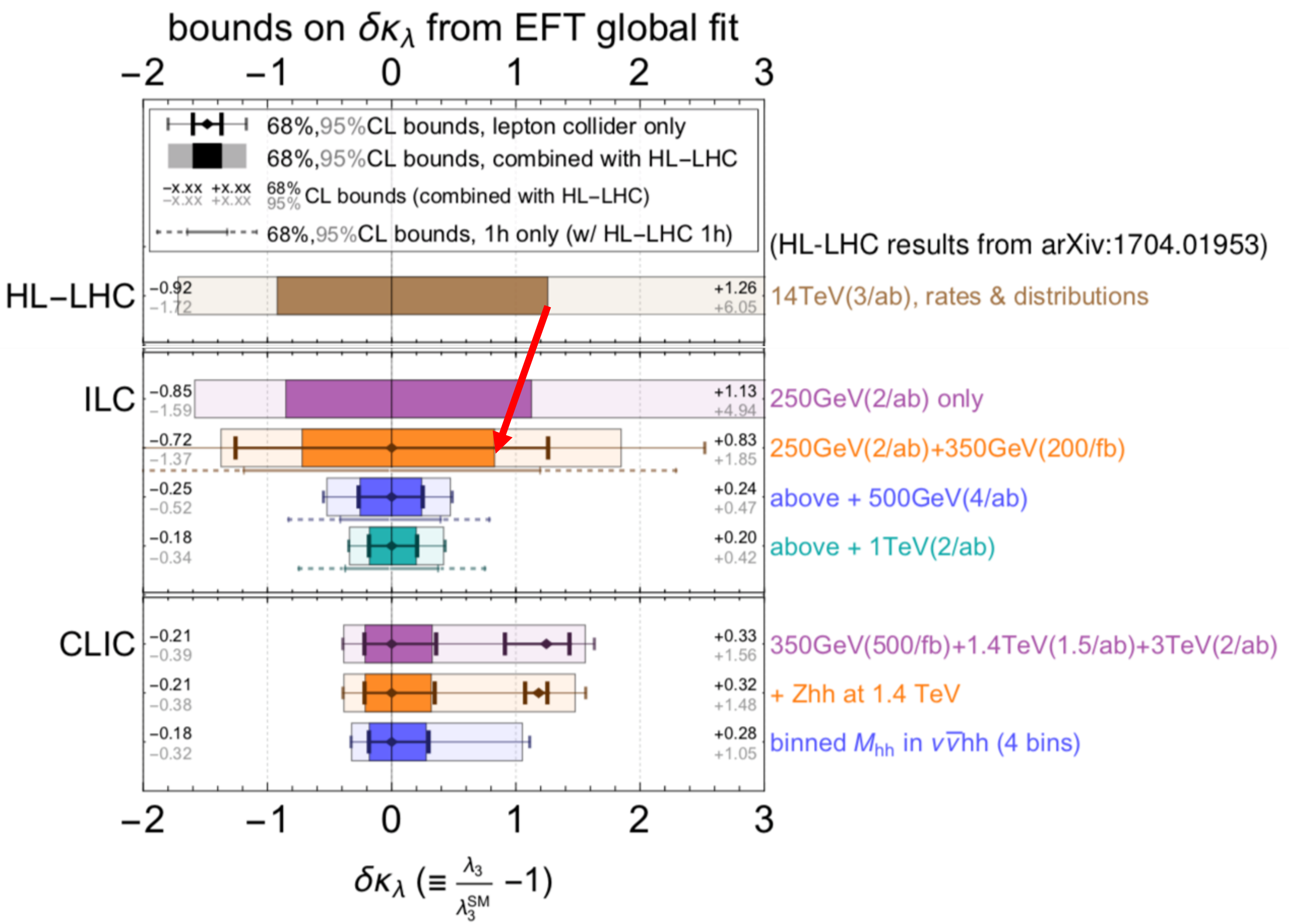




Results: complementarities

Higgs precision enhances LHC trilinear extrapolation;

HL-LHC also enhances LC trilinear determinations.



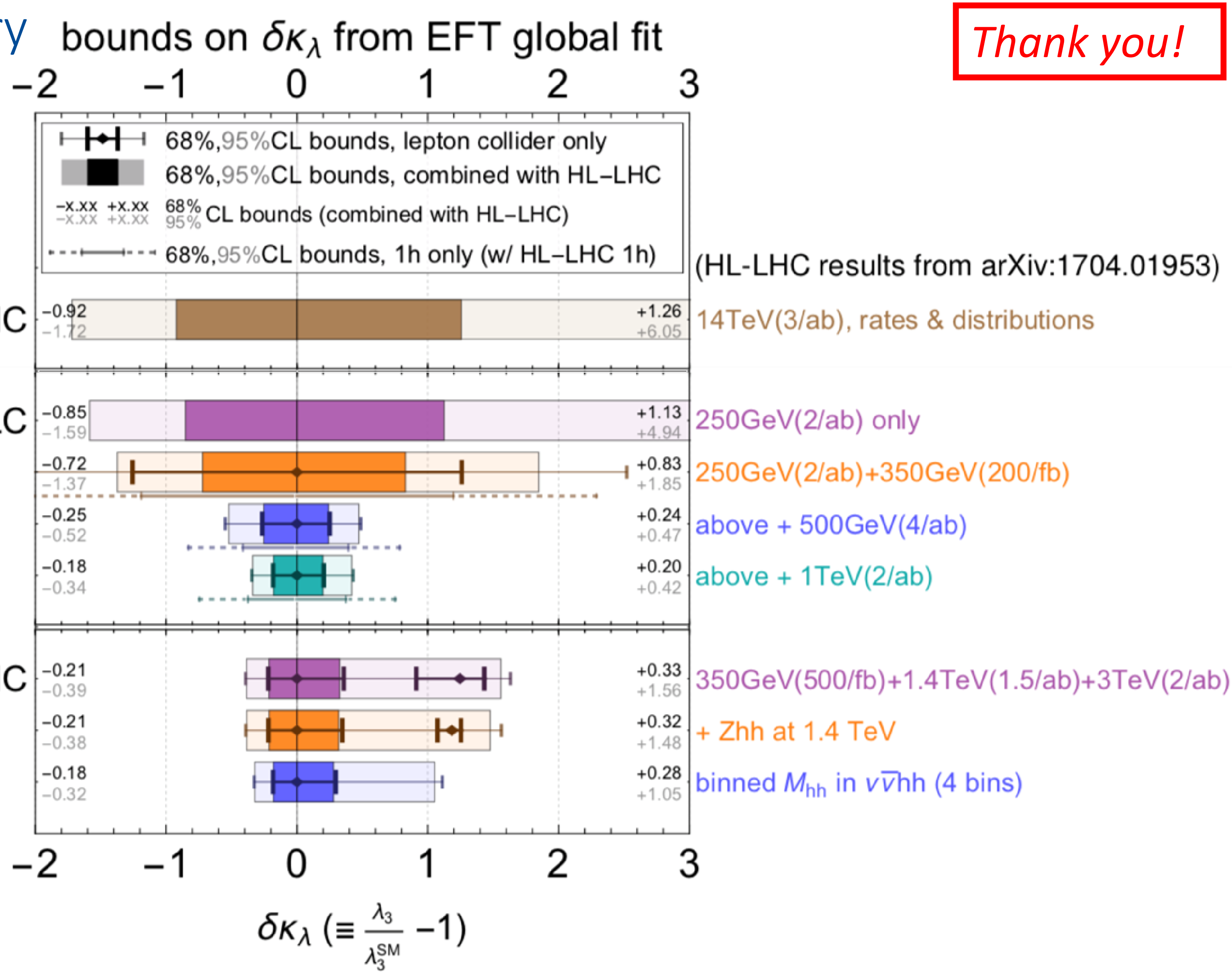
Summary

- Higgs self-couplings are the keys to reveal nature of EWPT and EWBG;
- LCs could use precision Higgs measures to constrain Higgs trilinear couplings in a robust way in the general EFT framework; we setup the framework and include more observables;
- The observable set and operator set can be further expanded for a fuller treatment, so far we dropped a few of them constrained by EWPO;*
- Interplay between Higgs precision and EWPO, 240 GeV and 350 GeV, LCs and other future collider programs, can be studied in this framework and provide useful information; <u>This direction needs support from simulation groups for various channels and programs;</u>
- Independent probes are always useful, even if we can achieve 5% precision at FCC-hh;

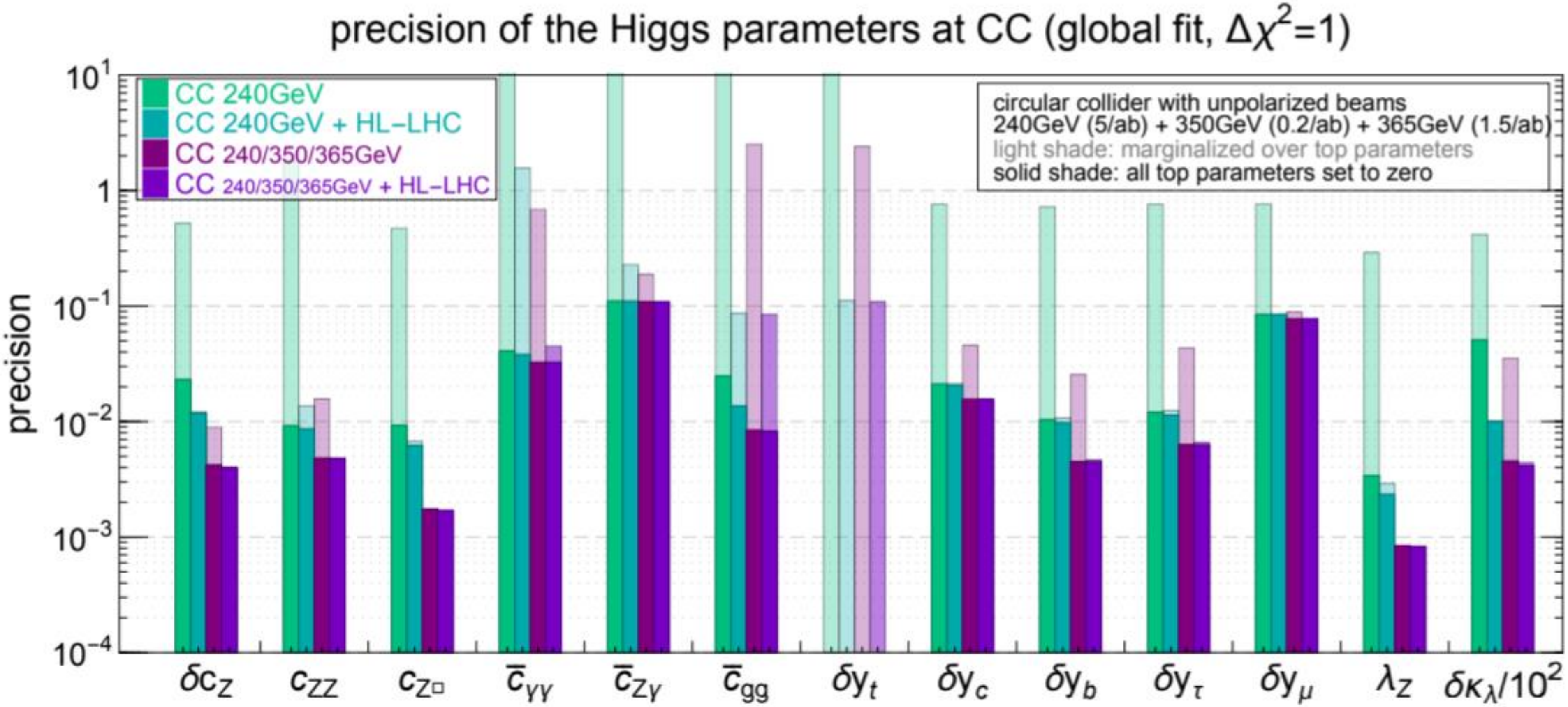
*Studies by Peskin et al (1708.09079), and Lian-Tao Wang et al (1711.04046), indicate a larger EFT set analysis will not affect the trilinear determination, consistent with our treatment;

Summary

Thank you!



Backup



Durieux, Gu, Vryonidou, Zhang, 1809.03520

Fuller consideration: input uncertainties

$$[\langle(\delta\sigma)^2\rangle]^{1/2} = 2.4\%$$

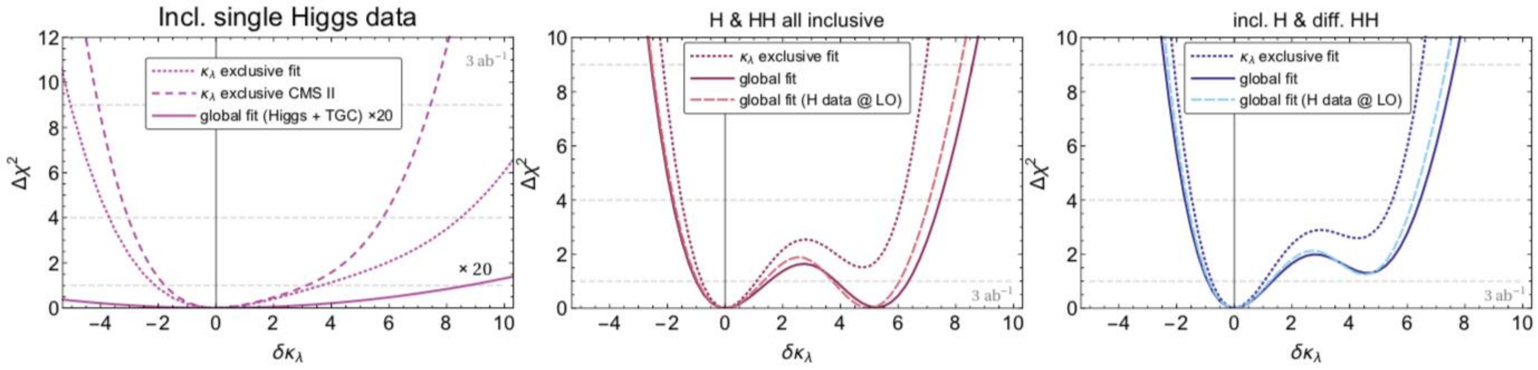
A	$[< A^2 >]^{1/2}$	A	$[< A^2 >]^{1/2}$
c_H	0.65	$(c_{HL} + c'_{HL})$	0.014
$(8c_{WW})$	0.039	c_{HE}	0.009
$(-4.15c_H + 15.1(8c_{WW}))$	2.8	$62.1(c_{HL} + c'_{HL}) - 53.5c_{HE}$	0.85

$$\begin{aligned}\sigma/(SM) = 1 &+ 1.15\delta g_L + 0.85\delta g_R + 1.40\eta_Z + 1.02\eta_{ZZ} + 18.6\zeta_Z + 2.0\zeta_{AZ} \\ &+0.56\eta_h - 1.58\theta_h + 62.1(c_{HL} + c'_{HL}) - 53.5c_{HE} \\ &-3.9\delta m_h + 3.5\delta m_Z \ .\end{aligned}$$

- A global fit with 12+1 parameters!
- Triple Higgs coupling

$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}, \quad \delta\kappa_\lambda \equiv \kappa_\lambda - 1 = c_6 - \frac{3}{2}c_H, \quad \text{with } \mathcal{L} \supset -\frac{c_6\lambda}{v^2}(H^\dagger H)^3$$

- HL-LHC: [arXiv:1704.01953] Di Vita, Grojean, Panico, Riembau, Vantalon
  - Single Higgs measurements alone could not constrain $\delta\kappa_\lambda$ well under a global framework.
  - Other parameters contributing to the double-Higgs process can be well constrained by single Higgs measurements.
  - Differential observables in HH process helps resolve the 2nd minimum.



- HL-LHC: $\kappa_\lambda \in [-0.8, 7.7]$ at 95% CL from Atlas projection for the $b\bar{b}\gamma\gamma$ channel, ATL-PHYS-PUB-2017-001
- 100 TeV collider (from the CERN Yellow Report [arXiv:1606.09408])

process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

Table 26: Expected precision (at 68% CL) on the SM cross section and 68% CL interval on the Higgs trilinear and quartic self-couplings (in SM units). All the numbers are obtained for an integrated luminosity of 30 ab^{-1} and do not take into account possible systematic errors.

- We work in the Higgs basis (LHCHXSWG-INT-2015-001, A. Falkowski) with the following 12 parameters,

$$\delta c_Z\,,\quad c_{ZZ}\,,\quad c_{Z\Box}\,,\quad c_{\gamma\gamma}\,,\quad c_{Z\gamma}\,,\quad c_{gg}\,,\quad \delta y_t\,,\quad \delta y_c\,,\quad \delta y_b\,,\quad \delta y_\tau\,,\quad \delta y_\mu\,,\quad \lambda_Z\,.$$

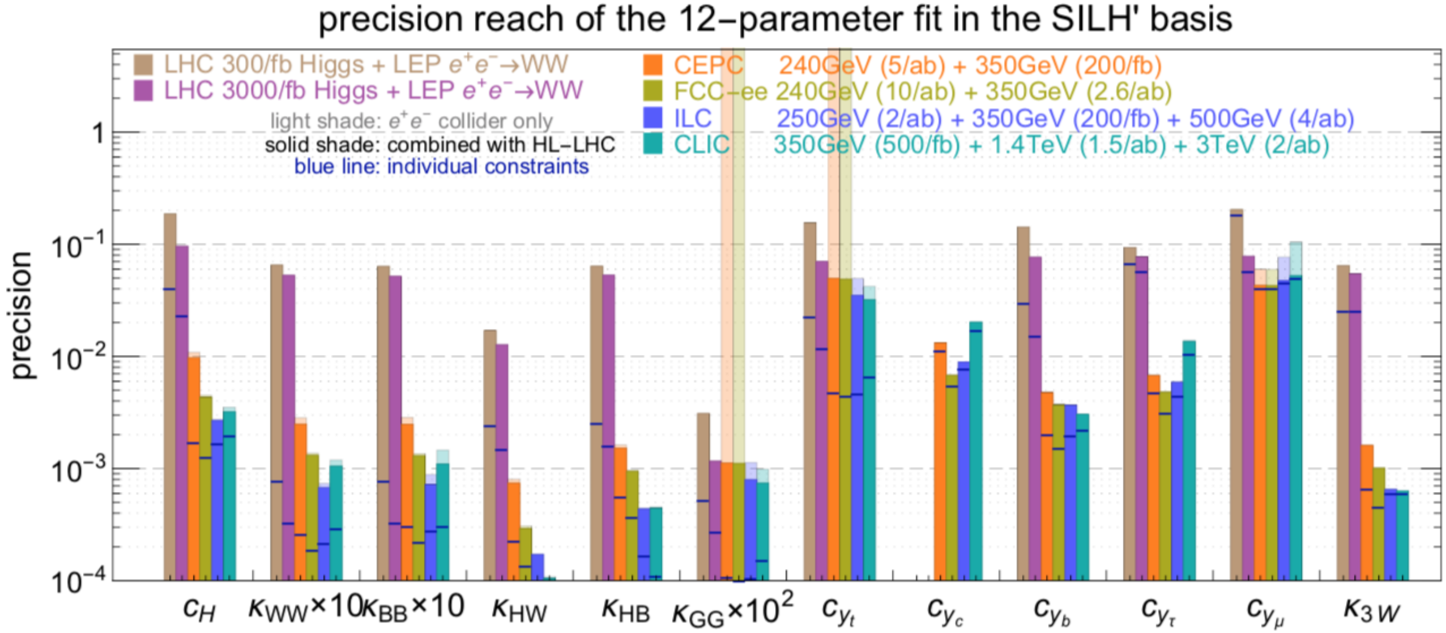
- The Higgs basis is defined in the broken electroweak phase.
  - $\delta c_Z \leftrightarrow hZ^\mu Z_\mu, \quad c_{ZZ} \leftrightarrow hZ^{\mu\nu}Z_{\mu\nu}, \quad c_{Z\Box} \leftrightarrow hZ_\mu\partial_\nu Z^{\mu\nu}.$

- Couplings of h to W are written in terms of couplings of h to Z and γ.

- 3 aTGC parameters ($\delta g_{1,Z}$, $\delta\kappa_\gamma$, λ_Z), 2 written in terms of Higgs parameters.

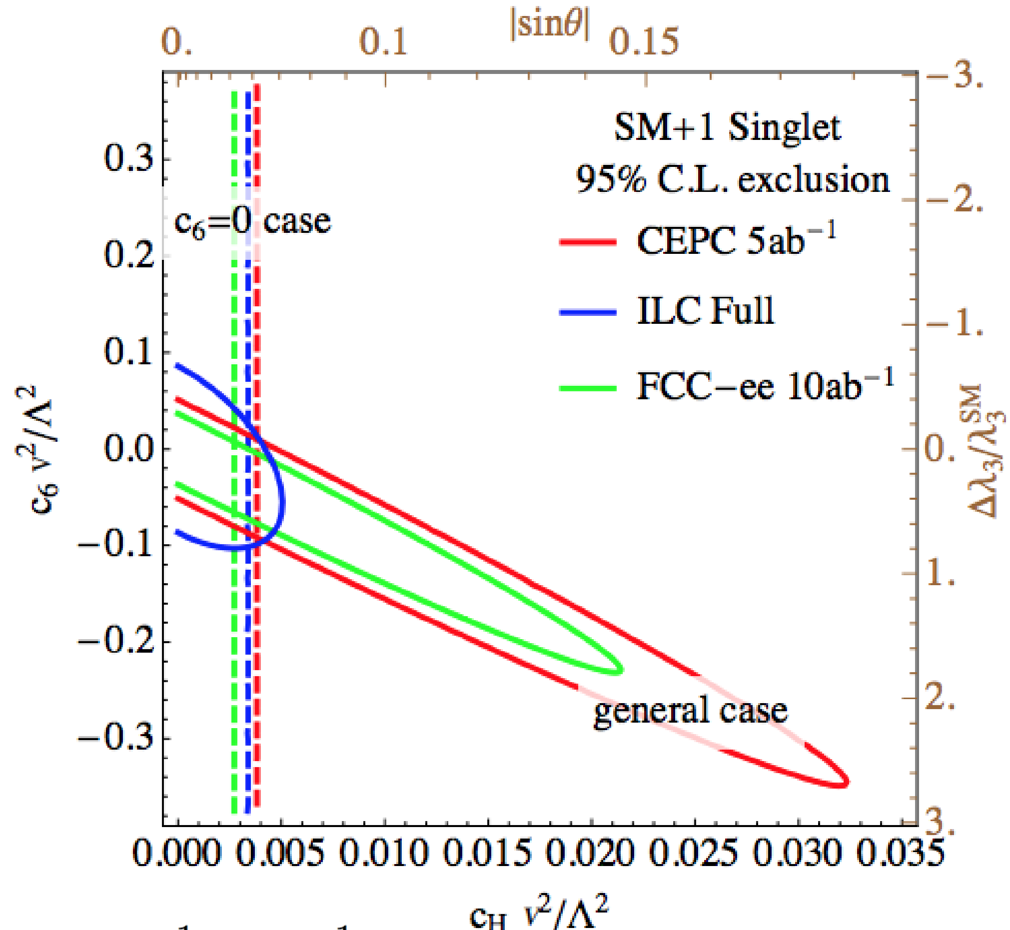
- It can be easily mapped to the following basis with D6 operators.

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2\rvert)^2$	$\mathcal{O}_{GG} = g_s^2\lvert H\rvert^2 G^A_{\mu\nu}G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2\lvert H\rvert^2 W^a_{\mu\nu}W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u\lvert H\rvert^2\bar{Q}_L\tilde{H}u_R$
$\mathcal{O}_{BB} = g'^2\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d\lvert H\rvert^2\bar{Q}_L H d_R$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e\lvert H\rvert^2\bar{L}_L H e_R$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!}g\epsilon_{abc}W^{a\,\nu}_{\mu}W^b_{\nu\rho}W^{c\,\rho\mu}$



- Results in the SILH'(-like) basis ($\mathcal{O}_{W,\,B} \to \mathcal{O}_{WW,\,WB}$)

$$\mathcal{L}_{\rm D6} = \frac{c_H}{v^2}\mathcal{O}_H + \frac{\kappa_{WW}}{m_W^2}\mathcal{O}_{WW} + \frac{\kappa_{BB}}{m_W^2}\mathcal{O}_{BB} + \frac{\kappa_{HW}}{m_W^2}\mathcal{O}_{HW} + \frac{\kappa_{HB}}{m_W^2}\mathcal{O}_{HB}$$
$$+ \frac{\kappa_{GG}}{m_W^2}\mathcal{O}_{GG} + \frac{\kappa_{3W}}{m_W^2}\mathcal{O}_{3W} + \sum_{f=t,c,b,\tau,\mu}\frac{c_{y_f}}{v^2}\mathcal{O}_{y_f}\,.$$



$$\Delta\mathcal{L}_{\text{eff,1-loop}} = \frac{1}{2(4\pi)^2}\frac{1}{m^2}\left[-\frac{1}{12}(P_\mu U)^2 - \frac{1}{6}U^3\right] = \frac{1}{(4\pi)^2}\frac{1}{m^2}\left(\frac{k^2}{12}\mathcal{O}_H - \frac{k^3}{12}\mathcal{O}_6\right).$$

Murayama et al, 1412.1837

$$\Delta\mathcal{L}_{\text{eff,tree}} = -A\left|H\right|^2\Phi_c + \frac{1}{2}\Phi_c\left(-\partial^2 - m^2 - k\left|H\right|^2\right)\Phi_c - \frac{1}{3!}\mu\Phi_c^3 - \frac{1}{4!}\lambda_\Phi\Phi_c^4 \approx \frac{1}{2m^2}A^2\left|H\right|^4 + \frac{A^2}{m^4}\mathcal{O}_H + \left(-\frac{kA^2}{2m^4} + \frac{1}{3!}\frac{\mu A^3}{m^6}\right)\mathcal{O}_6.$$

$$\Delta\mathcal{L} = \frac{1}{2}\left(\partial_\mu\Phi\right)^2 - \frac{1}{2}m^2\Phi^2 - A\left|H\right|^2\Phi - \frac{1}{2}k\left|H\right|^2\Phi^2 - \frac{1}{3!}\mu\Phi^3 - \frac{1}{4!}\lambda_\Phi\Phi^4.$$

	CEPC				FCC-ee			
	[240 GeV, 5 ab^{-1}]		[350 GeV, 200 fb^{-1}]		[240 GeV, 10 ab^{-1}]		[350 GeV, 2.6 ab^{-1}]	
production	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ	0.50%	-	2.4%	-	0.40%	-	0.67%	-
	$\sigma \times \mathrm{BR}$				$\sigma \times \mathrm{BR}$			
$h \to b\bar{b}$	0.21%$^\bigstar$	0.39%$^\diamond$	2.0%	2.6%	0.20%	0.28%$^\diamond$	0.54%	0.71%
$h \to c\bar{c}$	2.5%	-	15%	26%	1.2%	-	4.1%	7.1%
$h \to gg$	1.2%	-	11%	17%	1.4%	-	3.1%	4.7%
$h \to \tau\tau$	1.0%	-	5.3%	37%	0.7%	-	1.5%	10%
$h \to WW^*$	1.0%	-	10%	9.8%	0.9%	-	2.8%	2.7%
$h \to ZZ^*$	4.3%	-	33%	33%	3.1%	-	9.2%	9.3%
$h \to \gamma\gamma$	9.0%	-	51%	77%	3.0%	-	14%	21%
$h \to \mu\mu$	12%	-	115%	275%	13%	-	32%	76%
$h \to Z\gamma$	25%	-	144%	-	18%	-	40%	-

Table: For $e^+e^- \to \nu\bar{\nu}h$, the precisions marked with a diamond $\diamond$ are normalized to the cross section of the inclusive channel which includes both the WW fusion and $e^+e^- \to hZ, Z \to \nu\bar{\nu}$, while the unmarked ones include WW fusion only.

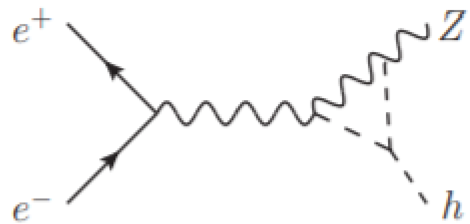
ILC

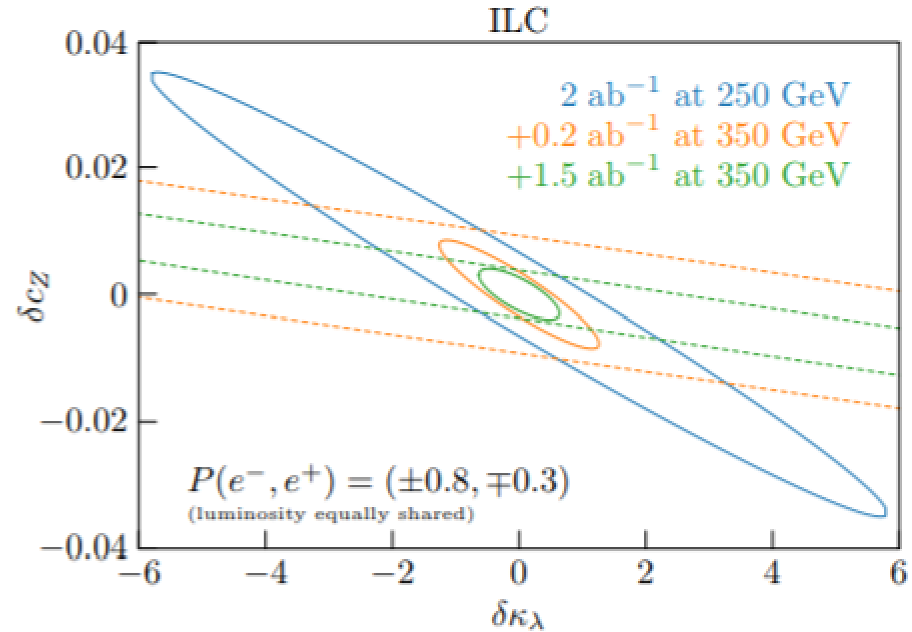
	[250 GeV, 2 ab^{-1}]		[350 GeV, 200 fb^{-1}]		[500 GeV, 4 ab^{-1}]			[1 TeV, 1 ab^{-1}]		[1 TeV, 2.5 ab^{-1}]	
production	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}h$	$t\bar{t}h$
σ	0.71%	-	2.1%	-	1.1%	-	-	-	-	-	-
	$\sigma \times \mathrm{BR}$										
$h \to b\bar{b}$	0.42%	3.7%	1.7%	1.7%	0.64%	0.25%	9.9%	0.5%	6.0%	0.3%	3.8%
$h \to c\bar{c}$	2.9%	-	13%	17%	4.6%	2.2%	-	3.1%	-	2.0%	-
$h \to gg$	2.5%	-	9.4%	11%	3.9%	1.4%	-	2.3%	-	1.4%	-
$h \to \tau\tau$	1.1%	-	4.5%	24%	1.9%	3.2%	-	1.6%	-	1.0%	-
$h \to WW^*$	2.3%	-	8.7%	6.4%	3.3%	0.85%	-	3.1%	-	2.0%	-
$h \to ZZ^*$	6.7%	-	28%	22%	8.8%	2.9%	-	4.1%	-	2.6%	-
$h \to \gamma\gamma$	12%	-	44%	50%	12%	6.7%	-	8.5%	-	5.4%	-
$h \to \mu\mu$	25%	-	98%	180%	31%	25%	-	31%	-	20%	-
$h \to Z\gamma$	34%	-	145%	-	49%	-	-	-	-	-	-

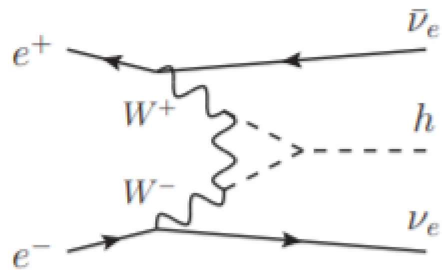
CLIC

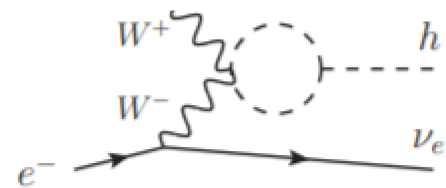
	[350 GeV, 500 fb^{-1}]		[1.4 TeV, 1.5 ab^{-1}]		[3 TeV, 2 ab^{-1}]
production	Zh	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}h$
σ	1.6%	-	-	-	-
	$\sigma \times \mathrm{BR}$				
$h \to b\bar{b}$	0.84%	1.9%	0.4%	8.4%	0.3%
$h \to c\bar{c}$	10.3%	14.3%	6.1%	-	6.9%
$h \to gg$	4.5%	5.7%	5.0%	-	4.3%
$h \to \tau\tau$	6.2%	-	4.2%	-	4.4%
$h \to WW^*$	5.1%	-	1.0%	-	0.7%
$h \to ZZ^*$	-	-	5.6%	-	3.9%
$h \to \gamma\gamma$	-	-	15%	-	10%
$h \to \mu\mu$	-	-	38%	-	25%
$h \to Z\gamma$	-	-	42%	-	30%

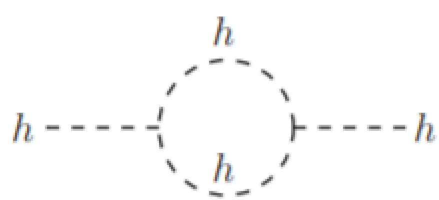
Table: We also include the estimations for $\sigma(hZ) \times \mathrm{BR}(h \to b\bar{b})$ at high energies in [arXiv:1701.04804] (Ellis et al.), which are 3.3% (6.8%) at 1.4 TeV (3 TeV). For simplicity, the measurements of ZZ fusion ($e^+e^- \to e^+e^-h$) are not included in our analysis.


e^+
e^-
Z
h


ILC
2 ab^{-1} at 250 GeV
+0.2 ab^{-1} at 350 GeV
+1.5 ab^{-1} at 350 GeV
$P(e^-, e^+) = (\pm 0.8, \mp 0.3)$
(luminosity equally shared)
δc_Z
$\delta \kappa_\lambda$
0.04
0.02
0
−0.02
−0.04
−6
−4
−2
0
2
4
6

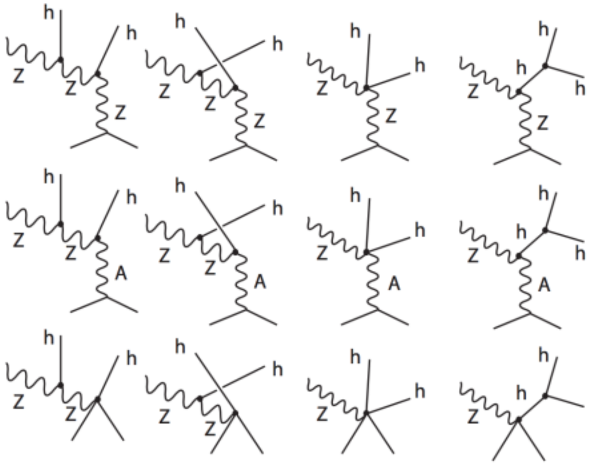

e^+
$\bar{\nu}_e$
W^+
h
W^-
ν_e
e^-


W^+
h
W^-
ν_e
e^-


h
h
h
h

10 d=6 operators

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



The 10 HEFT ops consist of:
(1) at least one Higgs or EW gauge,
(2) only Higgs, EW gauge and electrons

HEFT 9 Sunghoon Jung (SNU)