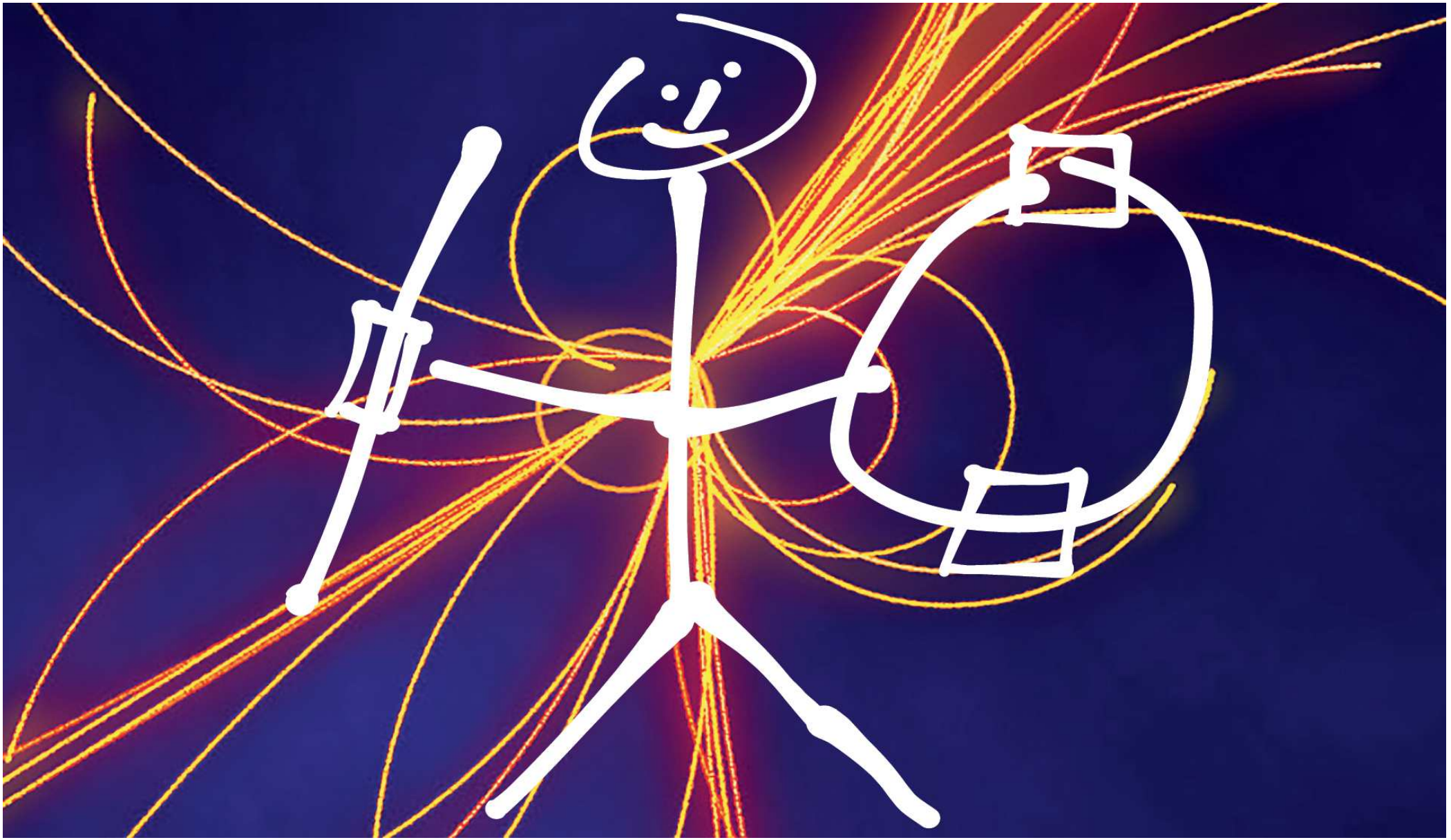


ECFA focus topic: HSelf (Higgs Self-Coupings)

Sven Heinemeyer, IFT (CSIC, Madrid)

Tokyo, 07/2024

Focus team:

Junping Tian (leader)

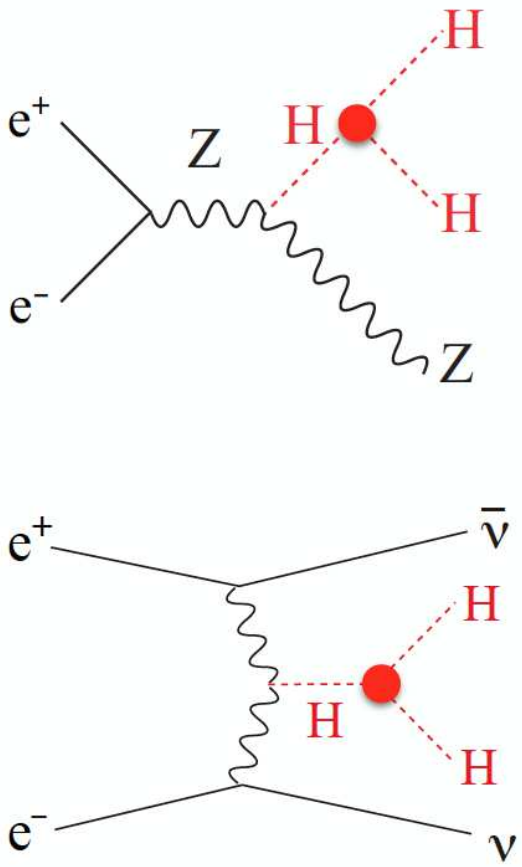
Gauthier Durieux, Jose Goncalo, S.H., Michael Peskin,

Philipp Roloff, Roberto Salerno

The simple THC case:

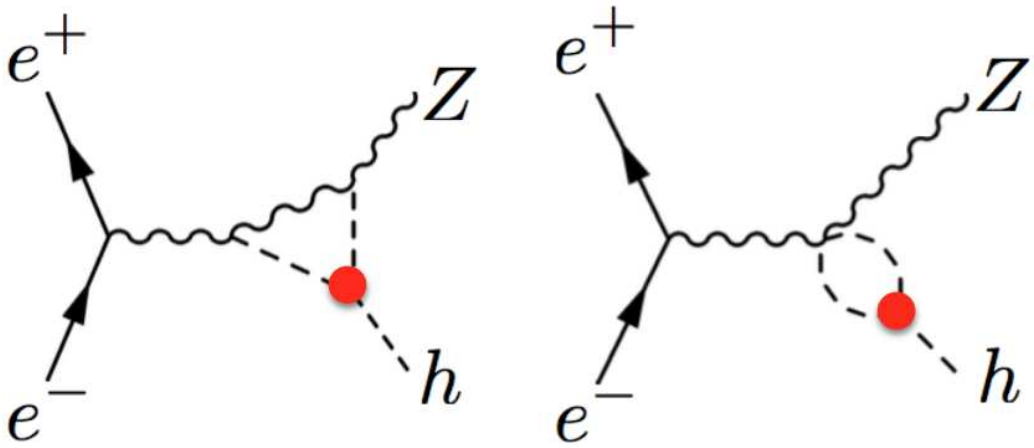
[*taken from J. Tian*]

$\sqrt{s} \gtrsim 500$ GeV



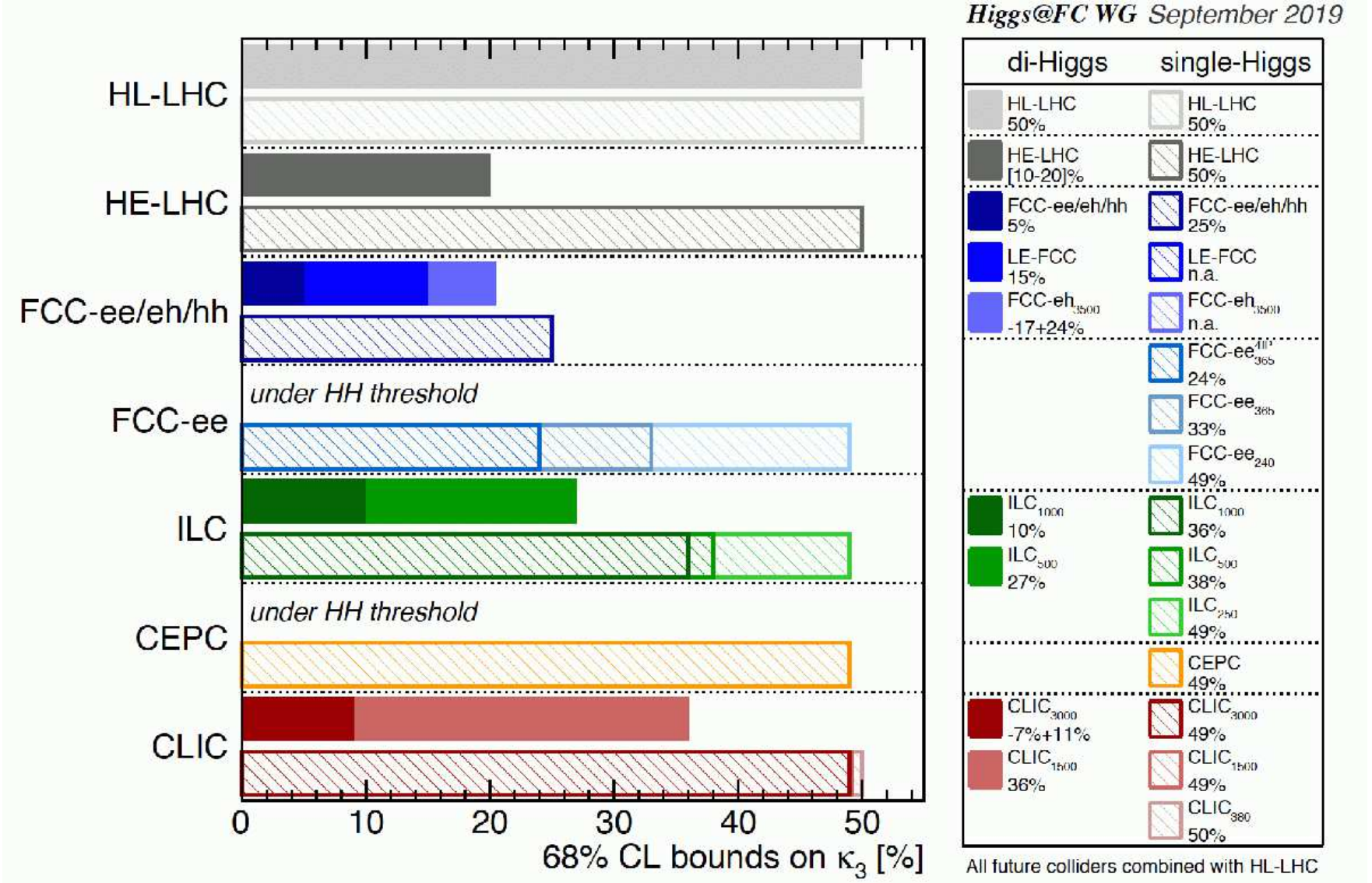
$\sigma_{HH} \sim O(0.1)$ fb

$\sqrt{s} \gtrsim 240$–250 GeV



$\delta\sigma_{ZH} \sim O(1\%)$

SM triple Higgs coupling: comparison of all colliders:



⇒ Many remaining open questions!

$\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}$

Open question I/II:

Analysis focuses on $\kappa_\lambda \equiv 1$ (SM case)

Requirement of FOEWPT may yield $\kappa_\lambda \sim 2$

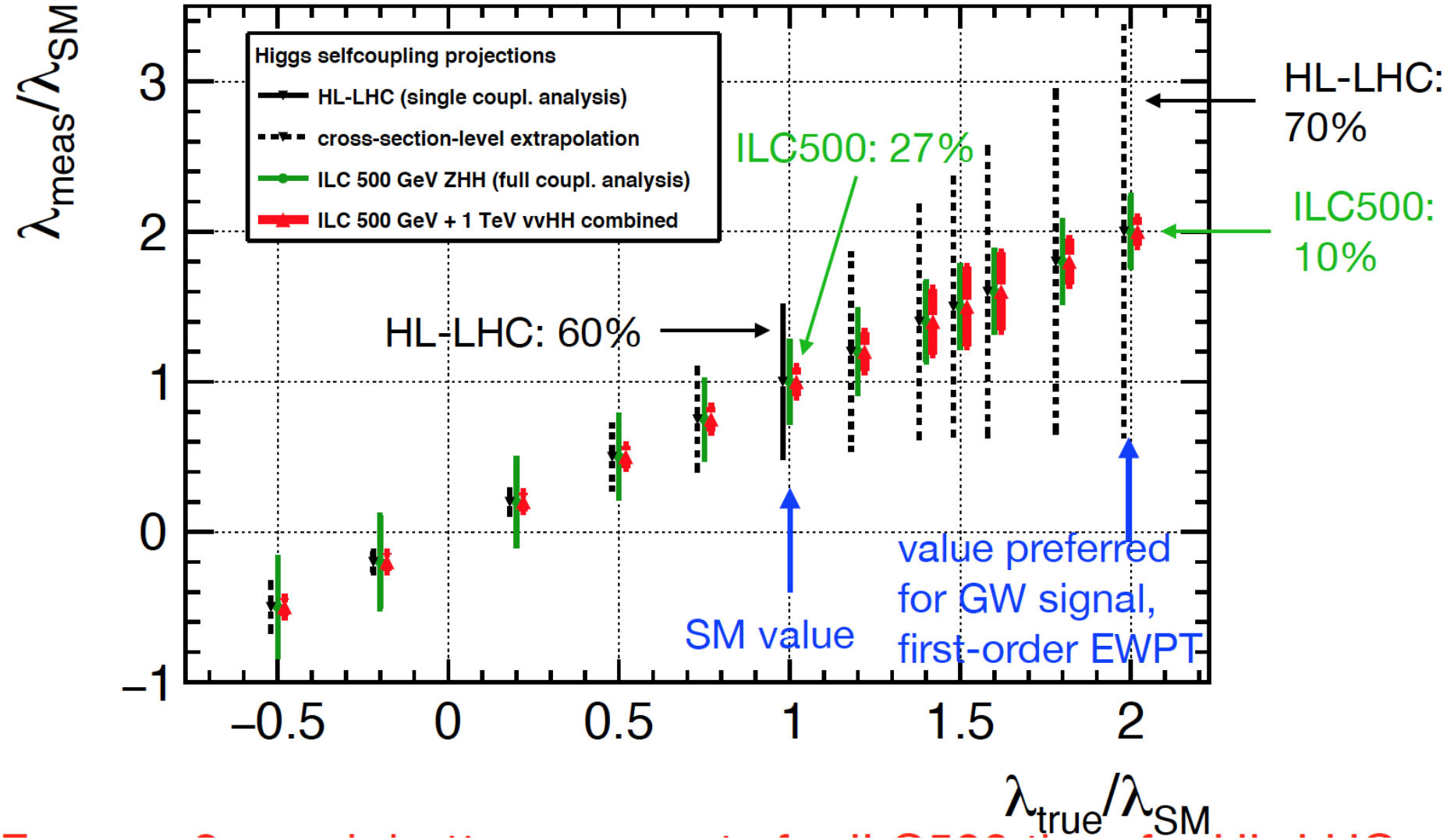
Q: How do the experimental precisions change for $\kappa_\lambda \neq 1$?

$\Rightarrow$ single Higgs EFT update needed

Q: What are the possible ranges of κ_λ?

Measurement of κ_λ selfcoupling at HL-LHC/ILC:

[J. List et al. '21]



⇒ over most of the parameter space ILC is clearly superior to HL-LHC

⇒ consolidated update needed

Open question I/II:

Analysis focuses on $\kappa_\lambda \equiv 1$ (SM case)

Requirement of FOEWPT may yield $\kappa_\lambda \sim 2$

Q: How do the experimental precisions change for $\kappa_\lambda \neq 1$?

$\Rightarrow$ single Higgs EFT update needed

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Open question I/II:

Analysis focuses on $\kappa_\lambda \equiv 1$ (SM case)

Requirement of FOEWPT may yield $\kappa_\lambda \sim 2$

Q: How do the experimental precisions change for $\kappa_\lambda \neq 1$?

$\Rightarrow$ single Higgs EFT update needed

Q: What are the possible ranges of κ_λ?

Open question III/IV:

Analysis assumes that only one Higgs boson exists (SM case)

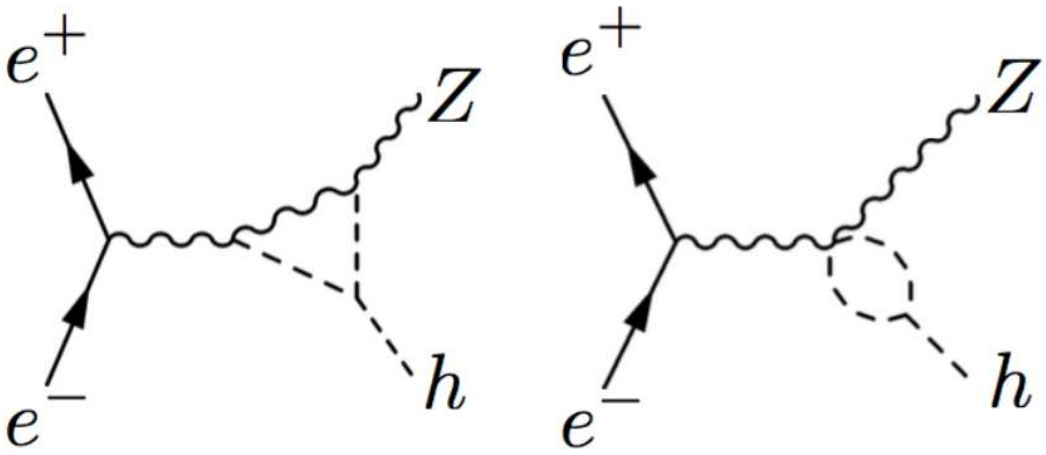
Requirement of FOEWPT easily results in additional Higgs bosons

Q: Impact of additional Higgs boson on κ_λ determination?

Q: Determination of BSM THCs?

Open question V:

[*taken from J. Tian*]



[McCullough, '13]

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- if only δh is deviated —> δh ~ 28% [ILC as example]
- if both δz and δh deviated —> δh ~ 90%
- δσ could receive contributions from many other sources

Q: Can degeneracies be lifted by new observables ($\rightarrow$ ZHang)?

Q: Impact of inclusion of other loop effects (top)?

More open quesions for single Higgs:

[*Focus Topic Document '24*]

Q: can we clarify the importance of each input measurement for the κ_λ determination in the global fit?

Q: updates from experimental analyses about single-Higgs observables?

Q: single-Higgs contribution at $\sqrt{s} \gtrsim 500$ GeV should be combined with double-Higgs determination of κ_λ

More open quesions for double Higgs:

Q: would energy slightly above 500 GeV help in the analysis? (more boosted jets etc.?)

Q: can we do simulations with distributions for large κ_λ?

Q: can we do simulations with distributions incl. BSM THCs?

Q: improvement by machine learning, e.g. for b-tagging?

Problem: we have an accelerated time-line??

- community input for the ESPPU to be submitted by 03/25

- a first version of our report should be completed by (mid) December
  comments etc. can be included, but updates for the results will be difficult

- effective deadline: third ECFA Higgs factories workshop
  in Paris (10/24)
  $\Rightarrow$ new results should be presented there
  $\Rightarrow$ drafts of the written summaries should be available

Studies can (of course) continue afterwards and can be published indepedently.

Concrete example: theory advances in the 2HDM: [taken from F. Arco '24]

Parameter scan in the 2HDM (all types):

[F. Arco, S.H., M. Mühlleitner - PRELIMINARY]

Type	$\kappa_\lambda^{(0)}$	$\kappa_\lambda^{(1)}$	$\lambda_{hhH}^{(0)}$	$\lambda_{hhH}^{(1)}$
I	[-0.2, 1.2]	[0.2, 6.8]	[-1.6, 1.5]	[-2.1, 1.9]
II	[0.6, 1.0]	[0.7, 5.6]	[-1.5, 1.6]	[-1.7, 2.0]
LS	[0.5, 1.0]	[0.6, 5.6]	[-1.7, 1.7]	[-2.0, 2.1]
FL	[0.7, 1.0]	[0.8, 5.6]	[-1.6, 1.3]	[-1.9, 1.5]

- Scan of the parameter space
- Applied ***constraints*** to the 2HDM
  - EWPO
  - Tree-level unitarity + potential stability
  - BSM Higgs boson searches
  - Properties of the SM-like Higgs boson
    - *Close to the alignment!*
  - Flavor Observables

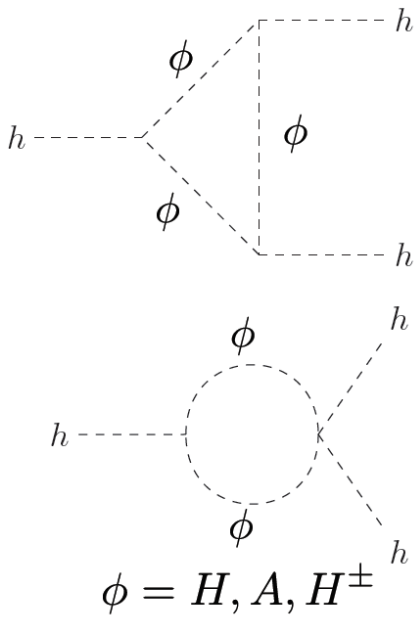
[ScannerS + HiggsTools + HDECAY]

Concrete example: 2HDM:

[taken from F. Arco '24]

Parameter scan in the 2HDM (all types):

[F. Arco, S.H., M. Mühlleitner - PRELIMINARY]



$\phi = H, A, H^{\pm}$

Type	$\kappa_\lambda^{(0)}$	$\kappa_\lambda^{(1)}$	$\lambda_{hhH}^{(0)}$	$\lambda_{hhH}^{(1)}$
I	[-0.2, 1.2]	[0.2, 6.8]	[-1.6, 1.5]	[-2.1, 1.9]
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FL	[0.7, 1.0]	[0.8, 5.6]	[-1.6, 1.3]	[-1.9, 1.5]

(results from the effective potential)

- Very large corrections are possible! $\lambda_{hhh}^{(1)} >> \lambda_{hhh}^{(0)}$
- h couplings to heavy Higgs bosons can be large ($\lambda_{h\phi\phi} \sim 15$)
  - Even at the ***alignment limit*** !!!

(In the SM, top-loops are ~ -8%)

⇒ effect of the extended BSM Higgs sector!

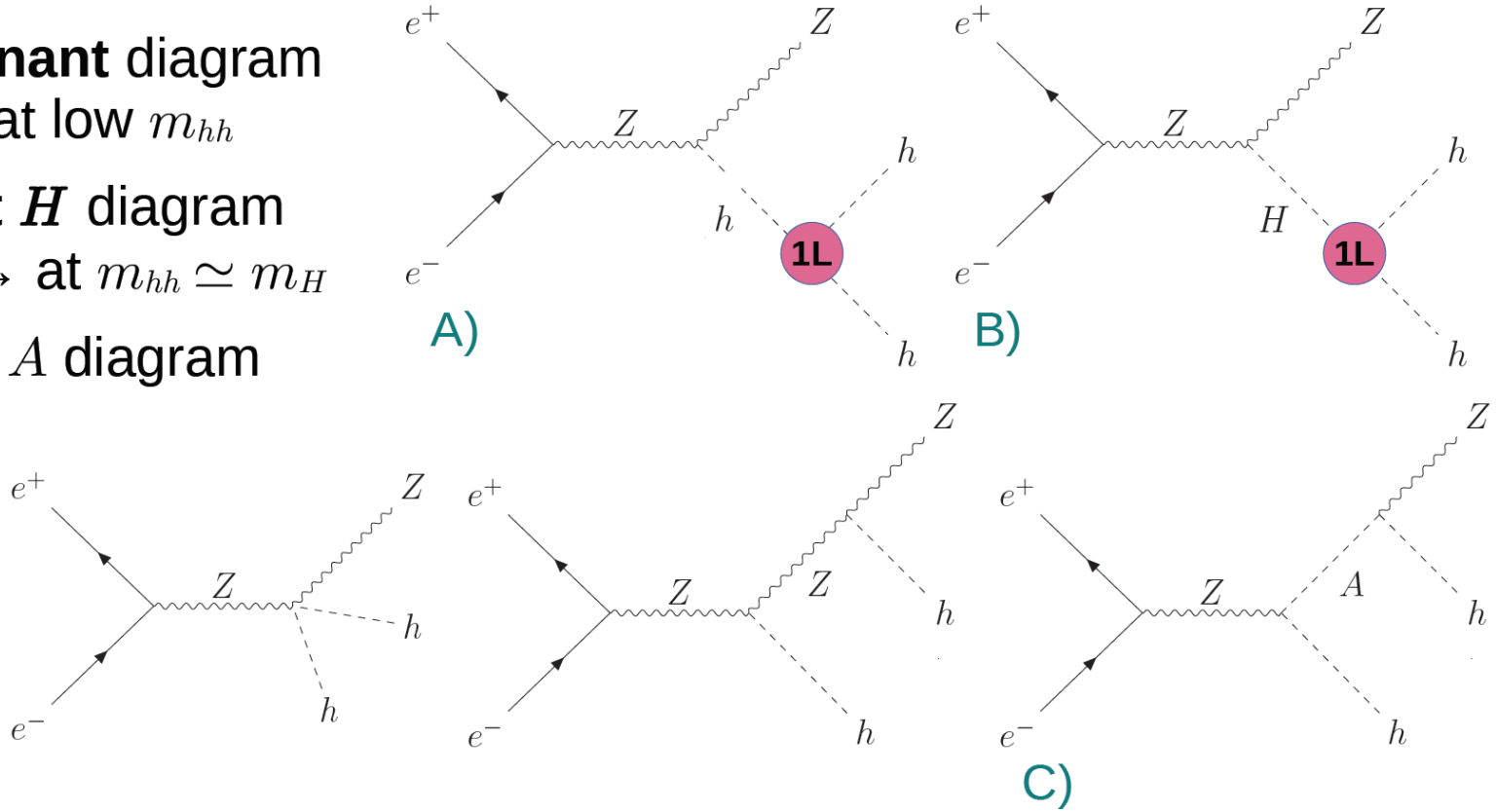
[F. Arco, S.H., M. Mühlleitner - PRELIMINARY]

Effects from THCs at $e^+e^- \to hhZ$

A) **Non-resonant** diagram with $\kappa_\lambda \to$ at low m_{hh}

B) **Resonant** H diagram with $\lambda_{hhH} \to$ at $m_{hh} \simeq m_H$

C) Resonant A diagram (no THC)



[F. Arco, S.H., M. Mühlleitner - PRELIMINARY]

In the alignment limit ($c_{\beta-\alpha}=0$)

A) **Non-resonant** diagram
wit… h

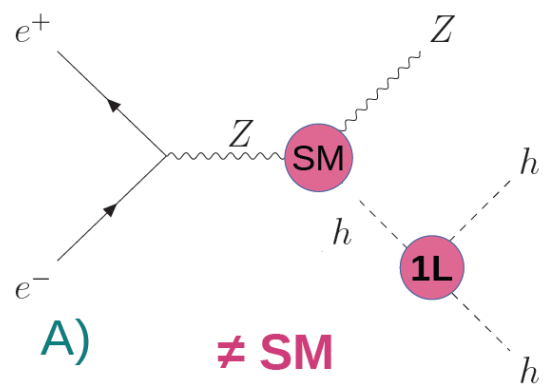
B) **R**… …am
wit… $\simeq m_H$

C) R…m
(no THC)

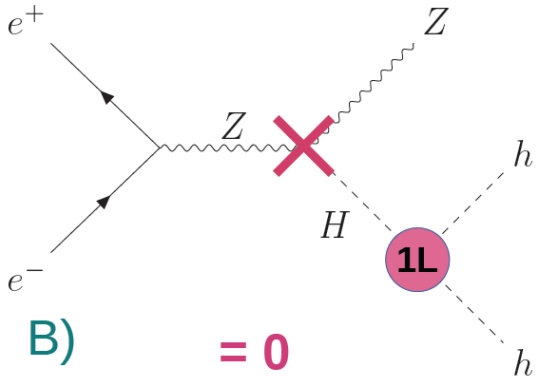
Only BSM effects in $\kappa_\lambda^{(1)}$

$\kappa_\lambda^{(0)} = 1,$

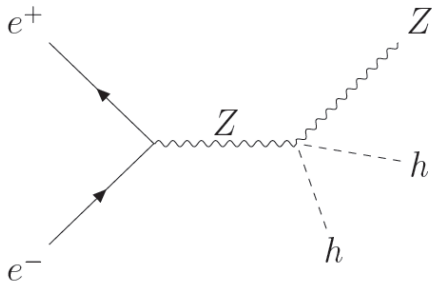
$\lambda_{hhH}^{(0)} = 0$



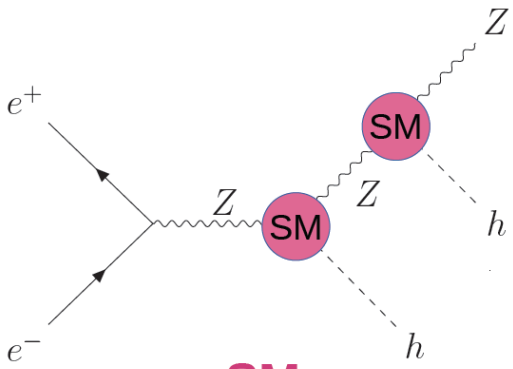
A) ≠ SM



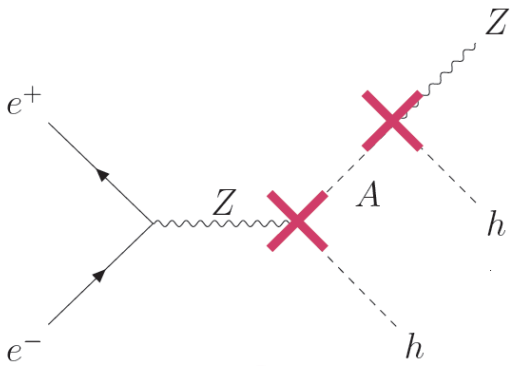
B) = 0



= SM



= SM



C) = 0

[F. Arco, S.H., M. Mühlleitner - PRELIMINARY]

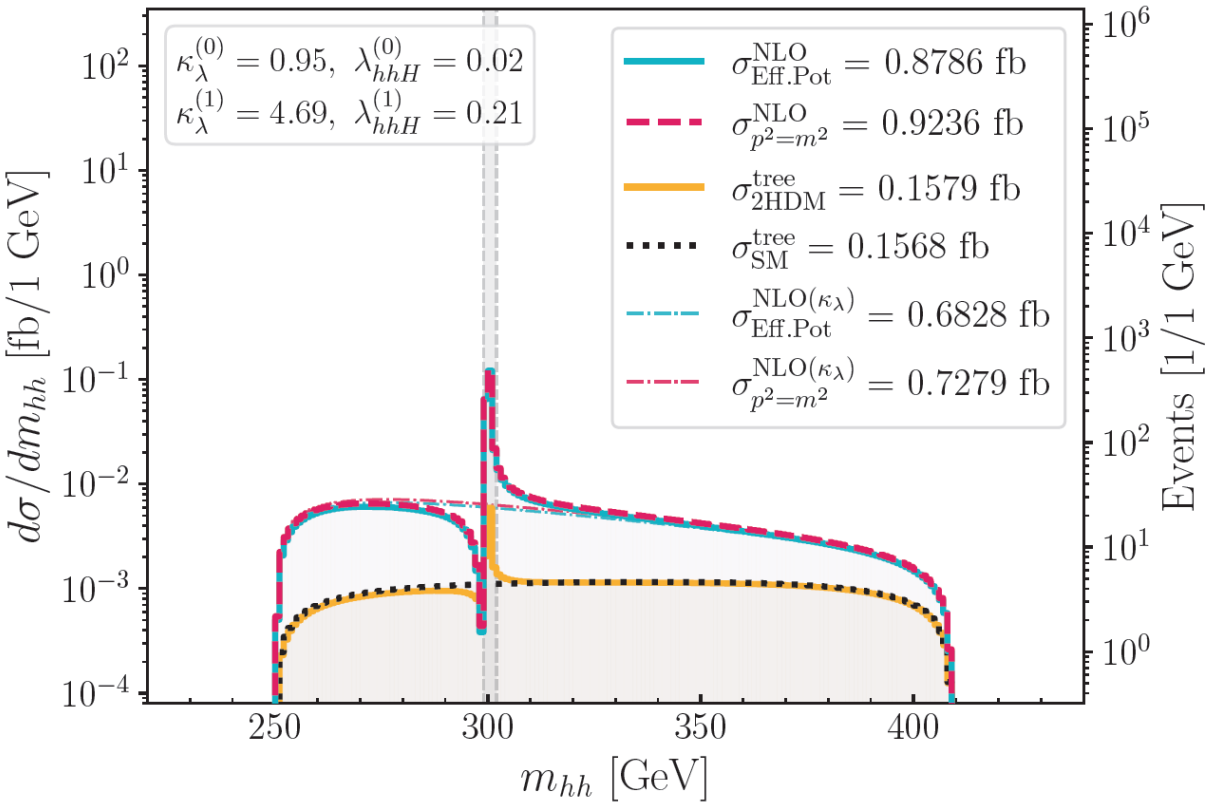
Large 1L λ_{hhH} @ILC500GeV

Karlsruhe Institute of Technology

BPlahhH-1, type I

$$m_H = \bar{m} = 300 \text{ GeV},$$
$$m_A = m_{H^\pm} = 650 \text{ GeV},$$
$$\tan\beta = 12,\ \cos(\beta-\alpha) = 0.12$$

- Large effect from $\kappa_\lambda^{(1)}$
- For this point $\lambda_{hhH}^{(0)} \ll \lambda_{hhH}^{(1)}$
  $\Rightarrow$ the H resonance is more prominent



$\Rightarrow$ individual effects of $\lambda_{hhh}^{(1)}$ and $\lambda_{hhH}^{(1)}$ $\Rightarrow$ extraction possible? $\Rightarrow$ WIP

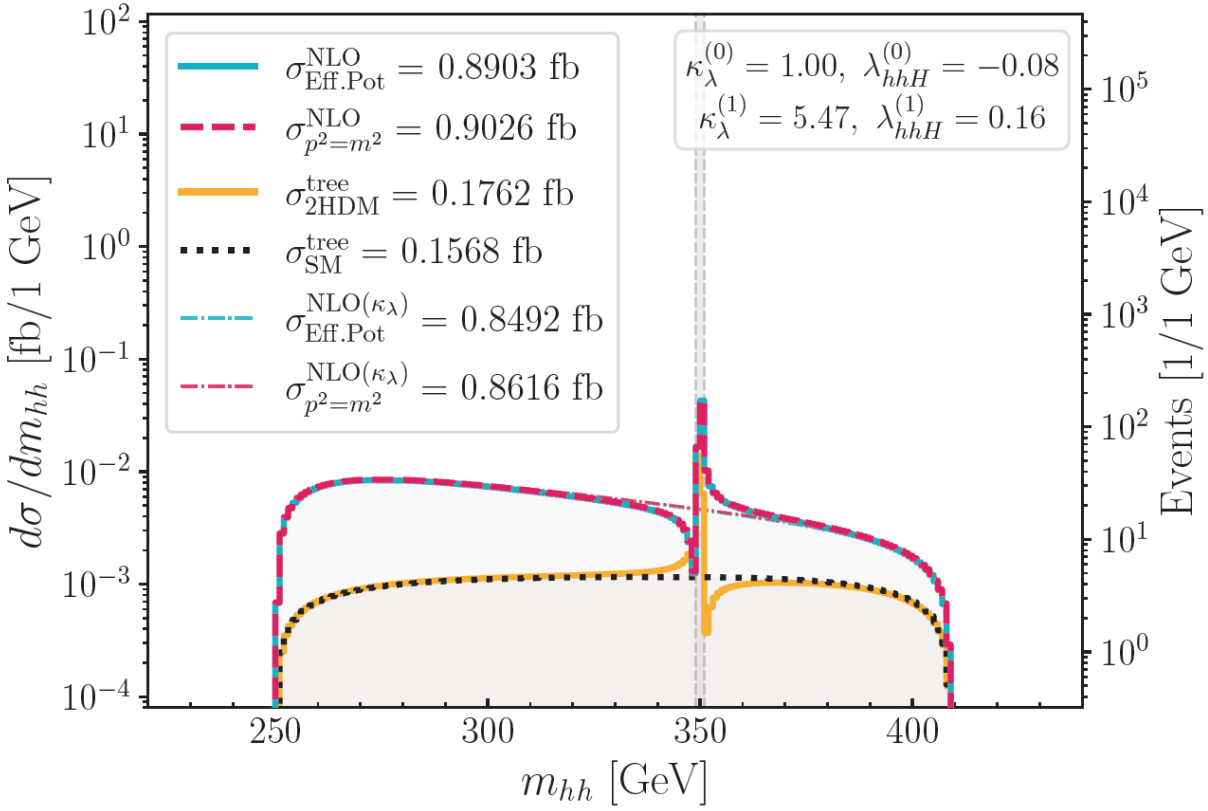
[F. Arco, S.H., M. Mühlleitner - PRELIMINARY]

1L λ_{hhH} with different sign @ILC500

Karlsruhe Institute of Technology

$$\text{BPsign, type I}$$
$$m_H = \bar{m} = 350 \text{ GeV},$$
$$m_A = m_{H^\pm} = 650 \text{ GeV},$$
$$\tan\beta = 20,\ \cos(\beta-\alpha) = 0.1$$

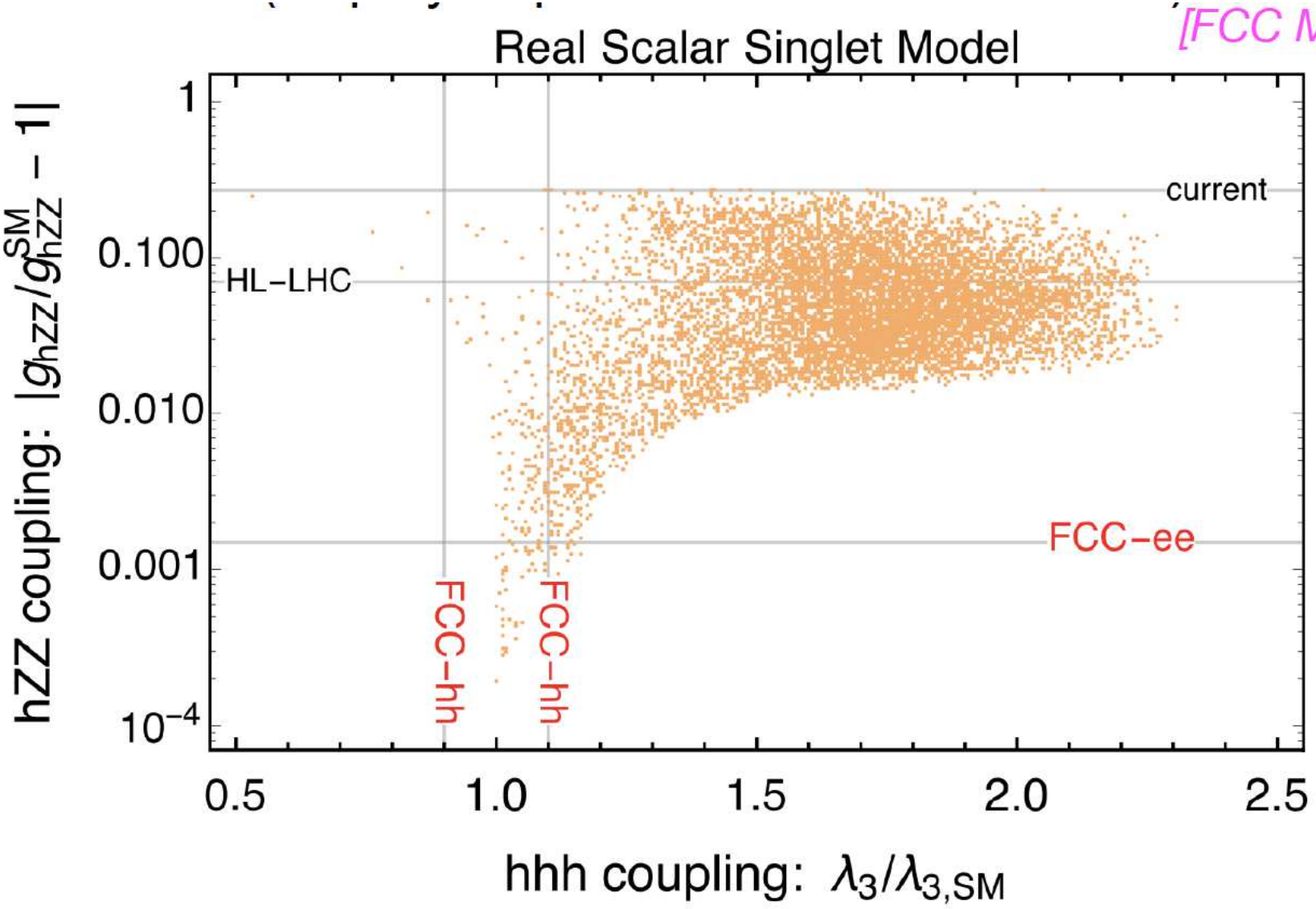
- In this point:
  $$\text{sign}\left(\lambda^{(1)}_{hhH}\right) \neq \text{sign}\left(\lambda^{(0)}_{hhH}\right)$$
- $\Rightarrow$ changes the dip-peak structure of the resonance !
- Large effect from $\kappa^{(1)}_\lambda$



$\Rightarrow$ individual effects of $\lambda^{(1)}_{hhh}$ and $\lambda^{(1)}_{hhH}$ $\Rightarrow$ extraction possible? $\Rightarrow$ WIP

Measurements: g_{hZZ} vs. λ_{hhh}

⇒ Analysis in the RxSM

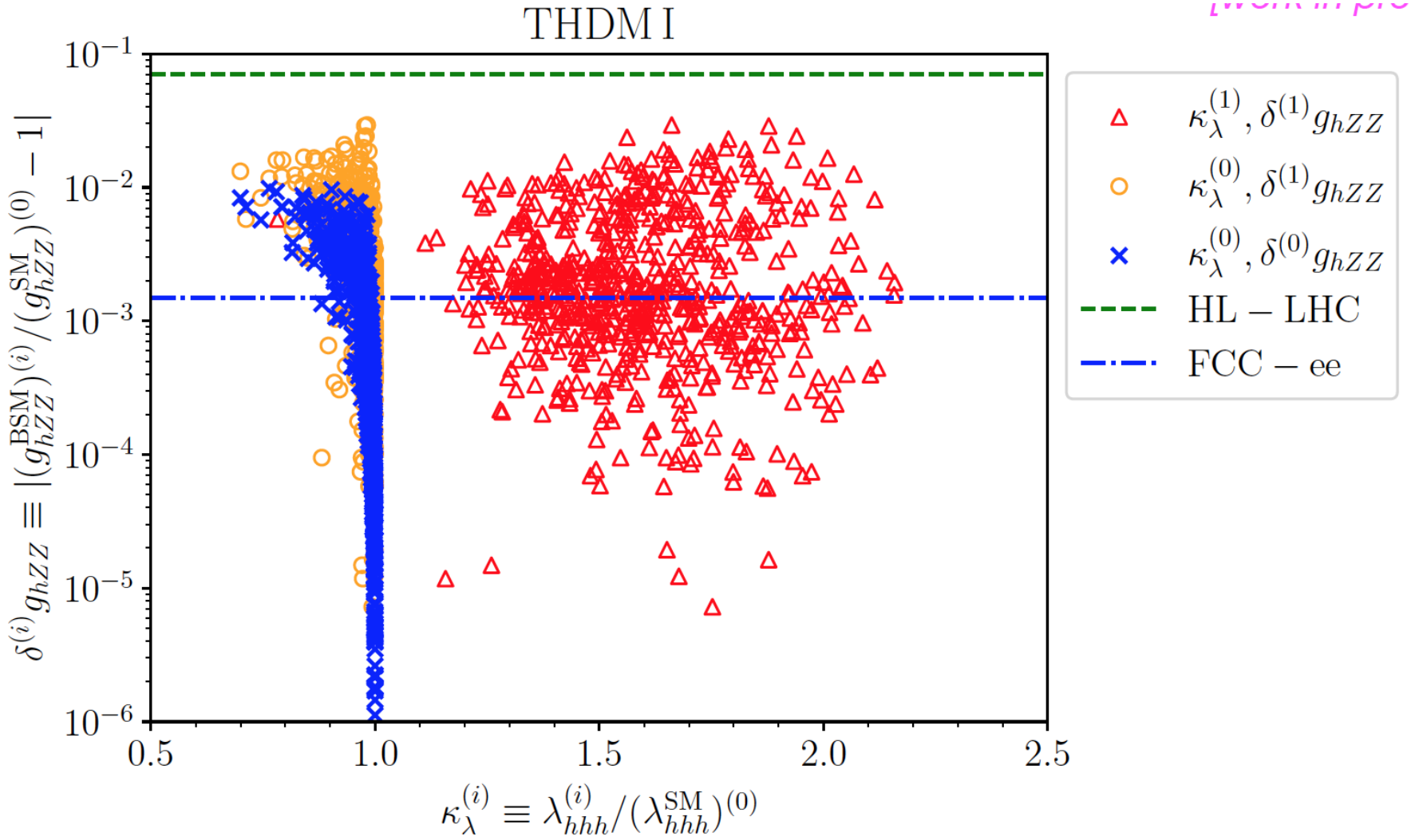


no deviation in g_{hZZ} ⇒ no deviation in λ_{hhh} **???**

Measurements: g_{hZZ} vs. λ_{hhh}: incl. loop corrections

$\Rightarrow$ Analysis in the 2HDM: points with SFOEWPT

[H. Bahl, J. Braathen, M. Gabelmann, S.H., K. Radchenko, A. Verduras, G. Weiglein - PRELIMINARY]

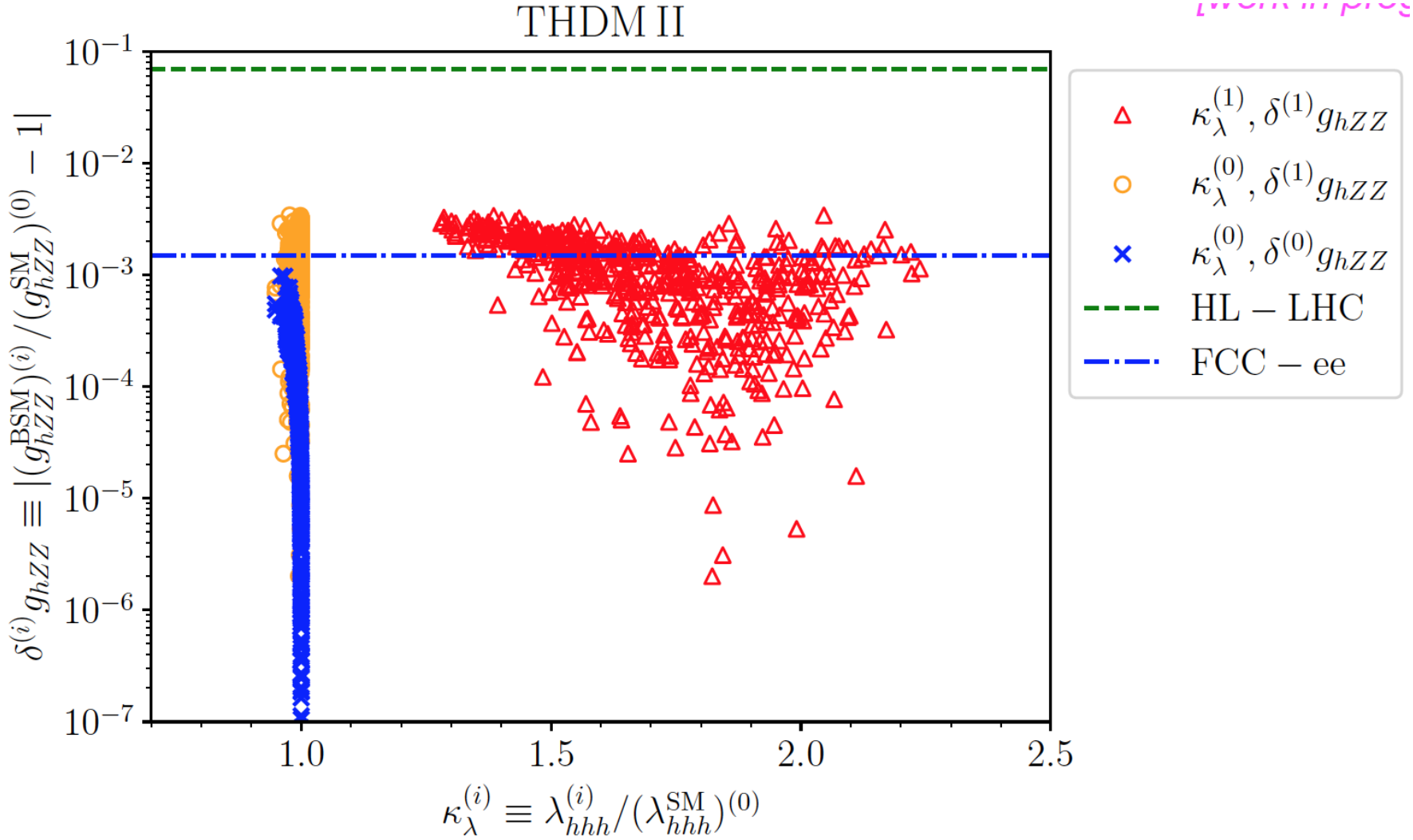


no deviation in g_{hZZ} $\Rightarrow$ very large values of λ_{hhh} possible

Measurements: g_{hZZ} vs. λ_{hhh}: incl. loop corrections

$\Rightarrow$ Analysis in the 2HDM: points with SFOEWPT

[H. Bahl, J. Braathen, M. Gabelmann, S.H., K. Radchenko, A. Verduras, G. Weiglein - PRELIMINARY]



no deviation in g_{hZZ} $\Rightarrow$ very large values of λ_{hhh} possible

Conclusions for Focus Topic 3: HSelf

Open question I/II:

So far analysis focuses on $\kappa_\lambda \equiv 1$ (SM case)

Q: What are the possible ranges of κ_λ?

– new theory calculations under way
– new tool development under way
– no deviation in $g_{hZZ} \Rightarrow$ large values of λ_{hhh} possible (WIP)

Open question III/IV:

So far analysis assumes that only one Higgs boson exists (SM case)

Q: Impact of additional Higgs boson on κ_λ determination?

– large loop corrections to λ_{hhh}, λ_{hhH}, ...
– new tool development under way
– analysis on effects on $\sigma(e^+e^- \to Zhh)$, m_{hh} under way

Q: Determination of BSM THCs?

– analysis on effects on $\sigma(e^+e^- \to Zhh)$, m_{hh} under way

New experimental analyses crucially needed! Partially under way!


Further Questions?