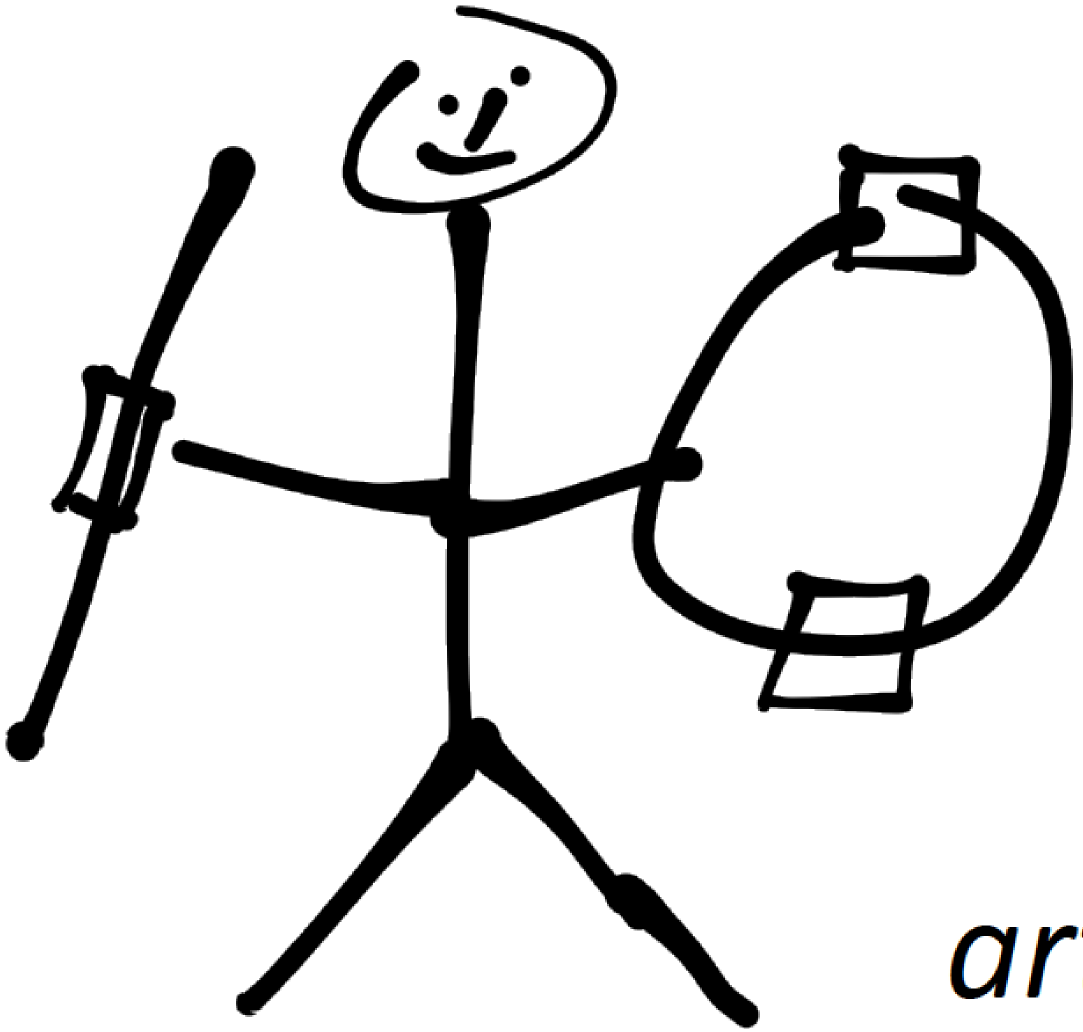


artwork by F. Simon

Opportunities for BSM and Higgs Physics
at Future Lepton Colliders

Sven Heinemeyer, IFT (CSIC, Madrid)

virtual, 07/2021

1. SM Higgs

2. BSM Higgs

3. Other BSM physics

Recommendation of the ESPPU:

(European Strategy for Particle Physics Update)

> The next large facility after the (HL-)LHC
> for particle physics should be an e^+e^- collider.

- to study the Higgs at $\sim$ 125 GeV
- top/EW physics
- BSM searches
- ...

$\Rightarrow$ This new e^+e^- collider will come after,
or in the end phase of the HL-LHC

$\Rightarrow$ physics potential of the new e^+e^- collider must be viewed
in the context of HL-LHC results

$\Rightarrow$ often e^+e^- expectations are shown in comparison to HL-LHC

Overview of current at possible future collider experiments:

LHC (Large Hadron Collider): running

pp collisions at 13(14) TeV

HL-LHC final high-luminosity phase: approved

HE-LHC new magnets $\Rightarrow$ 27 TeV (possible?)

ILC (International Linear Collider) decision 2021/22 in Japan

e^+e^- collisions at 250 GeV (final stage 1000 GeV)

CLIC (Compact LInear Collider)

e^+e^- collisions at 380 GeV (final stage 3000 GeV)

FCC-ee (Future Circular Collider e^+e^-)

e^+e^- collisions up to 350 GeV

CEPC (Chinese e^-e^+ Collider)

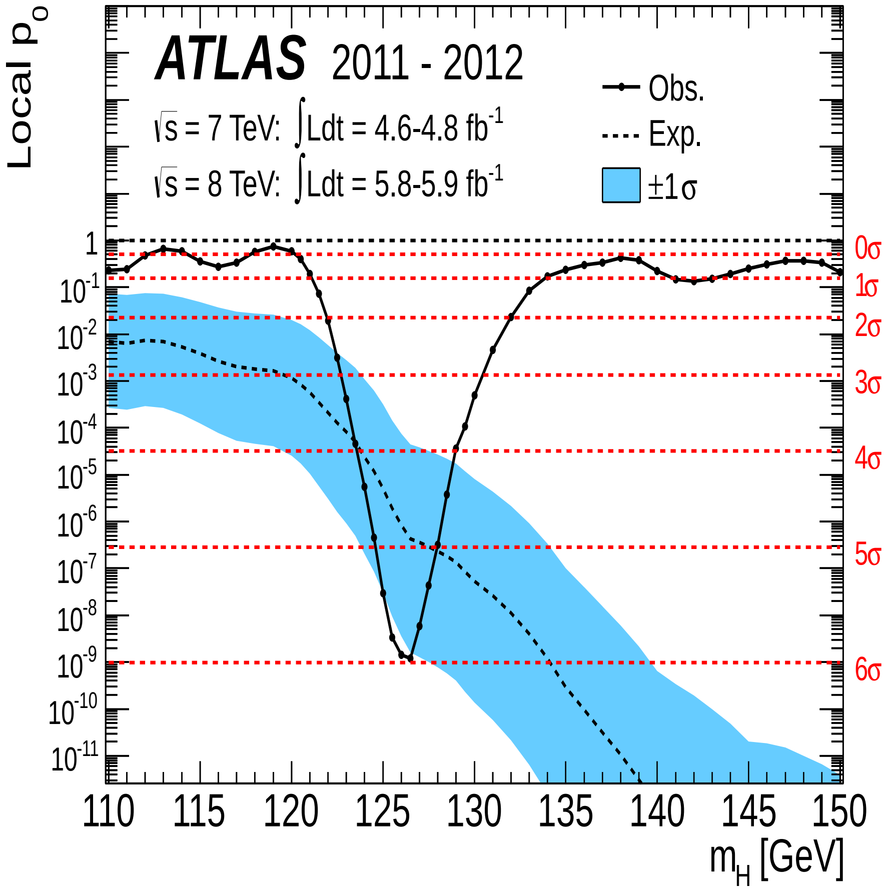
e^+e^- collisions up to 250 GeV

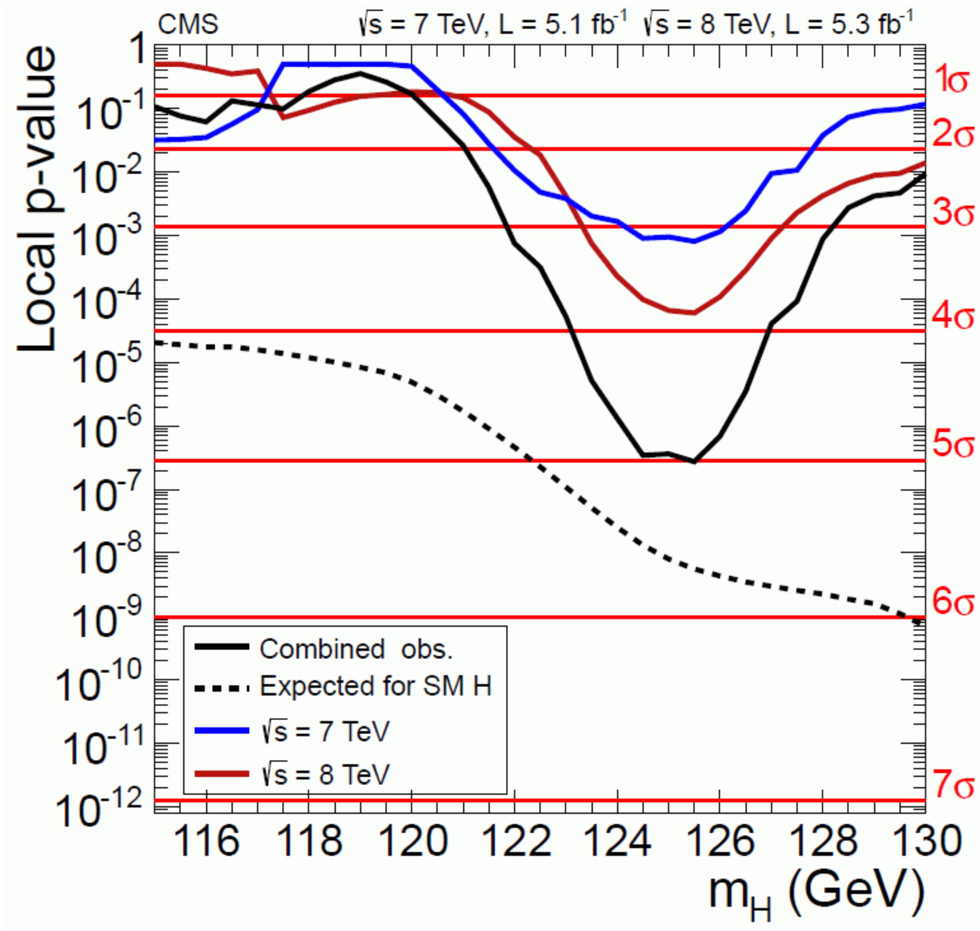
FCC-hh (Future Circular Collider had-had)

pp collisions at 100 TeV (possible?)

Fact I: The physics world changed on 04.07.2012:

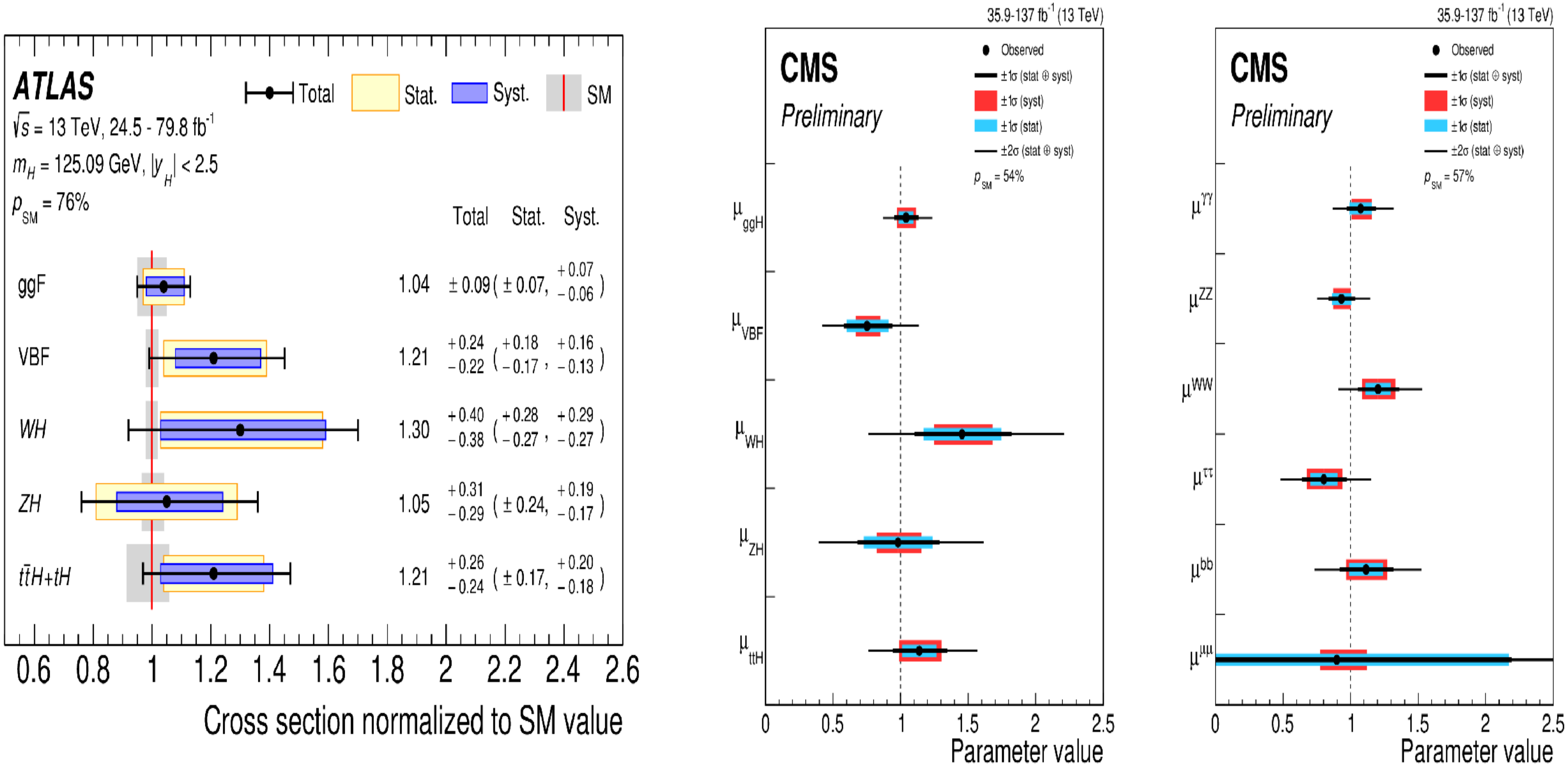
We have a discovery!





Fact I: The physics world changed on 04.07.2012:

We have an SM-like discovery!



Fact II:

The SM cannot be the ultimate theory!

Some sub-facts:

1. gravity is not included
2. the hierarchy problem
3. no unification of the three forces
4. Dark Matter is not included
5. Baryon Asymmetry of the Universe cannot be explained
6. neutrino masses are not included
7. anomalous magnetic moment of the muon shows a $\sim 4\,\sigma$ discrepancy

Fact I & II:

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

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Q': Which model?

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We have a discovery!

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Q': Which model?

A1: check changed properties of the h_{125}

A2: check for additional Higgs bosons
A2': check for additional Higgs bosons above and below 125 GeV

The main questions:

- What are the couplings of this particle to other known elementary particles? Is its coupling to each particle proportional to that particles mass, as required by the BEH mechanism?

- What are the mass, total width, spin and $\mathcal{CP}$ properties of this particle? Are there additional sources of $\mathcal{CP}$ violation in the Higgs sector?

- What is the value of the particles self-coupling? Is this consistent with the expectation from the symmetry-breaking potential?

- Is this particle a single, fundamental scalar as in the SM, or is it part of a larger structure? Is it part of a model with additional scalar singlets/doublets/ldots?
  Or, could it be a composite state, bound by new interactions?

- Does this particle couple to new particles with no other couplings to the SM ("Higgs portal")? Is the particle mixed with new scalars of exotic origin, for example, the radion of extra-dimensional models?

Models with extended Higgs sectors:

1. SM with addional Higgs singlet
2. Two Higgs Doublet Model (THDM): type I, II, III, IV
3. Minimal Supersymmetric Standard Model (MSSM)
4. MSSM with one extra singlet (NMSSM)
5. MSSM with more extra singlets
6. SM/MSSM with Higgs triplets
7. ...

⇒ BSM models without extended Higgs sectors still have changed Higgs properties (quantum corrections!)

⇒ SM + vector-like fermions, Higgs portal, Higgs-radion mixing, ...

Extended Higgs sectors

Compatibility with the experimental results requires:

- A SM-like Higgs at ~ 125 GeV
- Properties of the other Higgs bosons (masses, couplings,. . .) have to be such that they are in agreement with the present bounds

Prediction for the mass of the SM-like Higgs vs. exp. result:

- Important constraints on parameter space of the model
- Limited by remaining theoretical uncertainties
- Very accurate Higgs-mass predictions needed

The "sum rule":

In a large variety of models with extended Higgs sectors the squared couplings to gauge bosons fulfill a ``sum rule":

$$\sum_i g^2_{H_i VV} = \left(g^{\rm SM}_{HVV}\right)^2$$

⇒ •The SM coupling strength is ``shared" between the Higgses of an extended Higgs sector, $\varkappa_V \leqq 1$

•The more SM-like the couplings of the state at 125 GeV turn out to be, the more suppressed are the couplings of the other Higgses to gauge bosons; heavy Higgses usually have a much smaller width than a SM-like Higgs of the same mass

• Searches for additional Higgs bosons need to test compatibility with the observed signal at 125 GeV!

[*Taken from G. Weiglein '18*]

Which model should we focus on?

Which model should we focus on? ⇒ experimental data as guidance!

Which model should we focus on? $\Rightarrow$ experimental data as guidance!

Some "recent" measurements:

- top quark mass
- Higgs boson mass
- Higgs boson "couplings"
- Dark Matter (properties)

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Simple SUSY models predicted correctly:

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Which model should we focus on? ⇒ experimental data as guidance!

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- top quark mass
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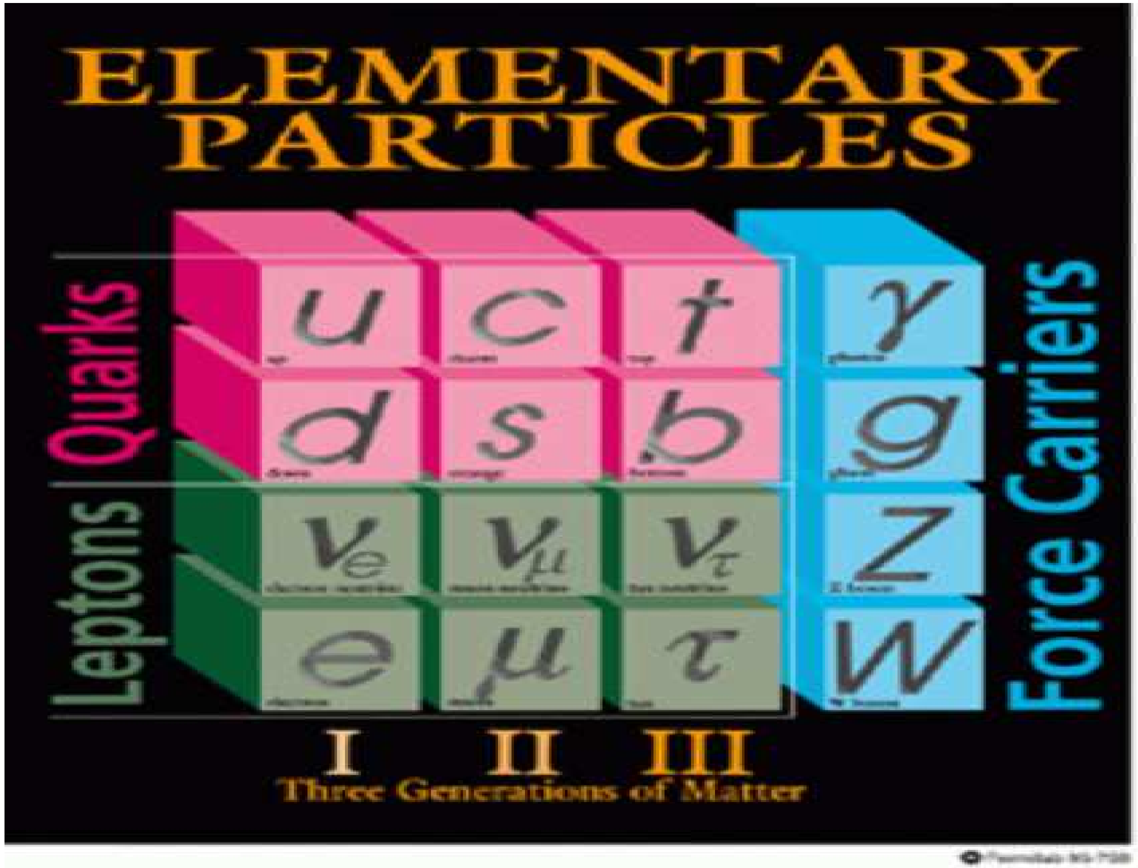
Simple SUSY models predicted correctly:

- top quark mass
- Higgs boson mass
- Higgs boson "couplings"
- Dark Matter (properties)

⇒ **good motivation to look at SUSY! :-)**

But we also look at other models (2HDM, N2HDM, . . .)

Current status of knowledge: the Standard Model (SM)



$\Rightarrow$ all particles experimentally seen (as of 2011)

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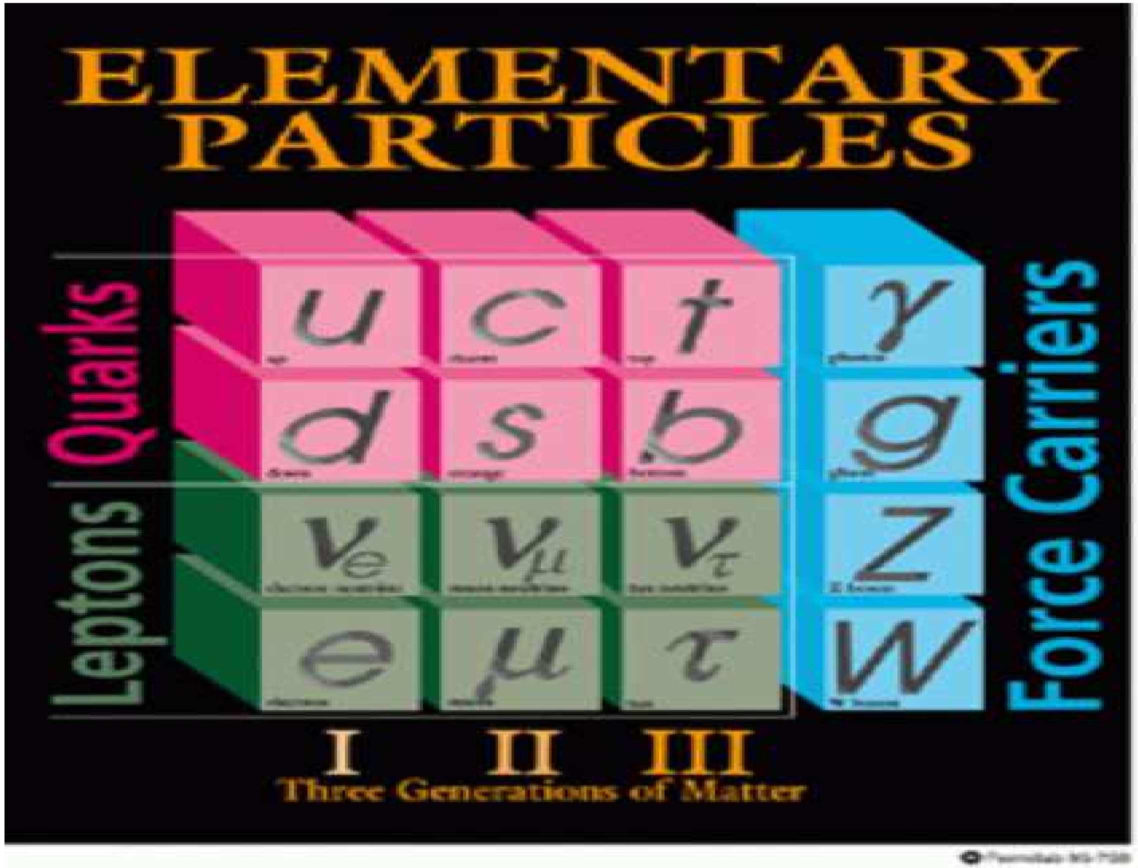


⇒ all particles experimentally seen (as of 2011)

⇒ but it predicts massless gauge bosons . . .

Problem:

Gauge fields Z, W^+, W^- are massive

explicite mass terms in the Lagrangian $\Leftrightarrow$ breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

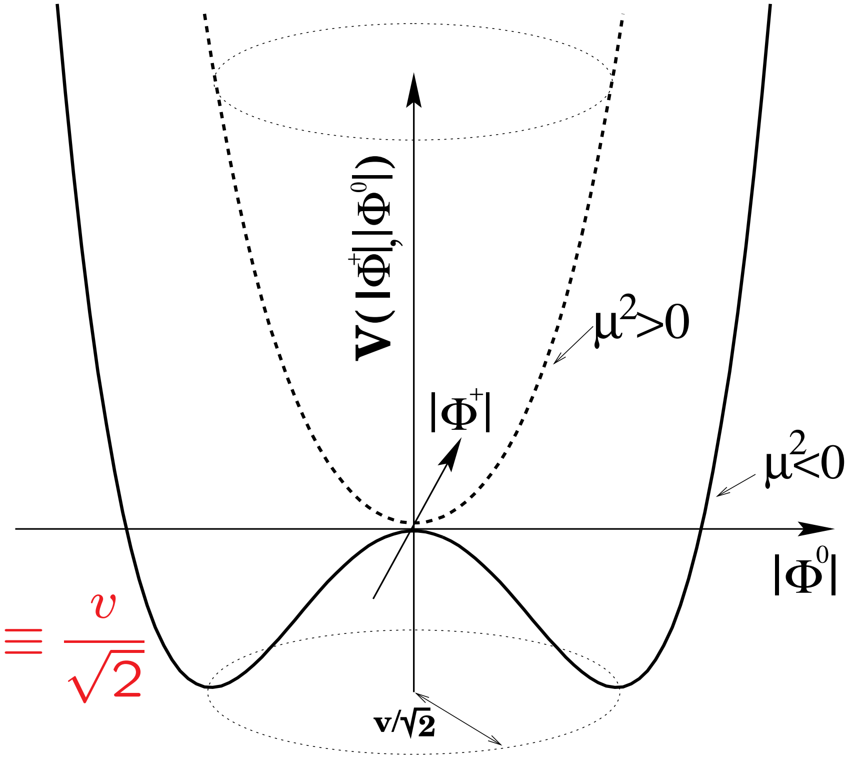
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle\Phi_0\rangle| = \sqrt{\frac{-\mu^2}{2\,\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \text{(unitary gauge)}$$

H: elementary scalar field, Higgs boson

Lagrange density:

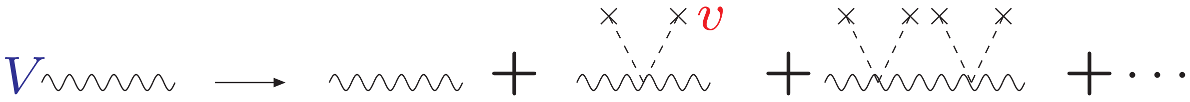
$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = \quad & (D_\mu \Phi)^\dagger (D^\mu \Phi) \\ & - g_d \bar{Q}_L \Phi d_R - g_u \bar{Q}_L \Phi_c u_R \\ & - V(\Phi) \end{aligned}$$

with

$$\begin{aligned} iD_\mu &= i\partial_\mu - g_2 \vec{I}\vec{W}_\mu - g_1 Y B_\mu \\ \Phi_c &= i\sigma_2 \Phi^* \qquad\qquad Q_L \sim \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \ \Phi \sim \begin{pmatrix} 0 \\ v \end{pmatrix}, \ \Phi_c \sim \begin{pmatrix} v \\ 0 \end{pmatrix} \end{aligned}$$

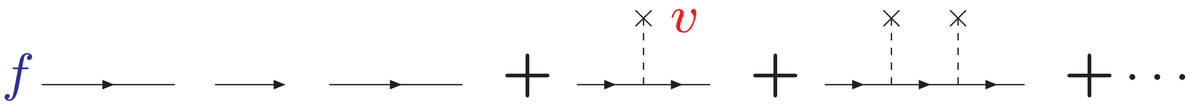
Gauge invariant coupling to gauge fields
$\Rightarrow$ mass terms for gauge bosons and fermions

1.) $VV\Phi\Phi$ coupling:



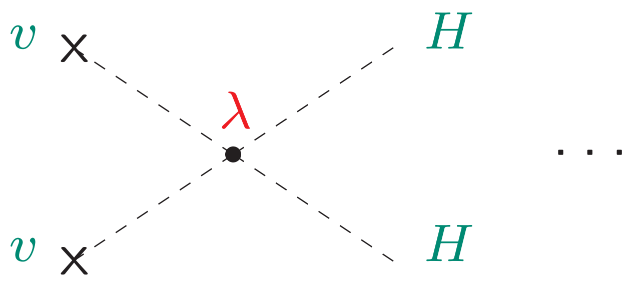
$$\frac{1}{q^2} \to \frac{1}{q^2} + \sum_j \frac{1}{q^2}\left[\left(\frac{gv}{\sqrt{2}}\right)^2 \frac{1}{q^2}\right]^j = \frac{1}{q^2 - M^2} \; : \; M^2 = g^2\frac{v^2}{2} \qquad \Rightarrow M \propto g$$

2.) fermion mass terms: Yukawa couplings:



$$\frac{1}{\not{q}} \to \frac{1}{\not{q}} + \sum_j \frac{1}{\not{q}}\left[\frac{g_f v}{\sqrt{2}} \frac{1}{\not{q}}\right]^j = \frac{1}{\not{q} - m_f} \; : \; m_f = g_f\frac{v}{\sqrt{2}} \qquad \Rightarrow m_f \propto g_f$$

3.) mass of the Higgs boson: self coupling



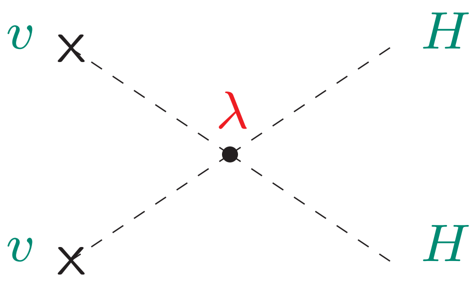
$$\lambda = M_H^2/v^2$$

$M_H = v\sqrt{\lambda}$ free parameter

$\rightarrow$ last unknown (now measured) parameter of the SM

3.) mass of the Higgs boson: self coupling

$$\lambda = M_H^2/v^2$$



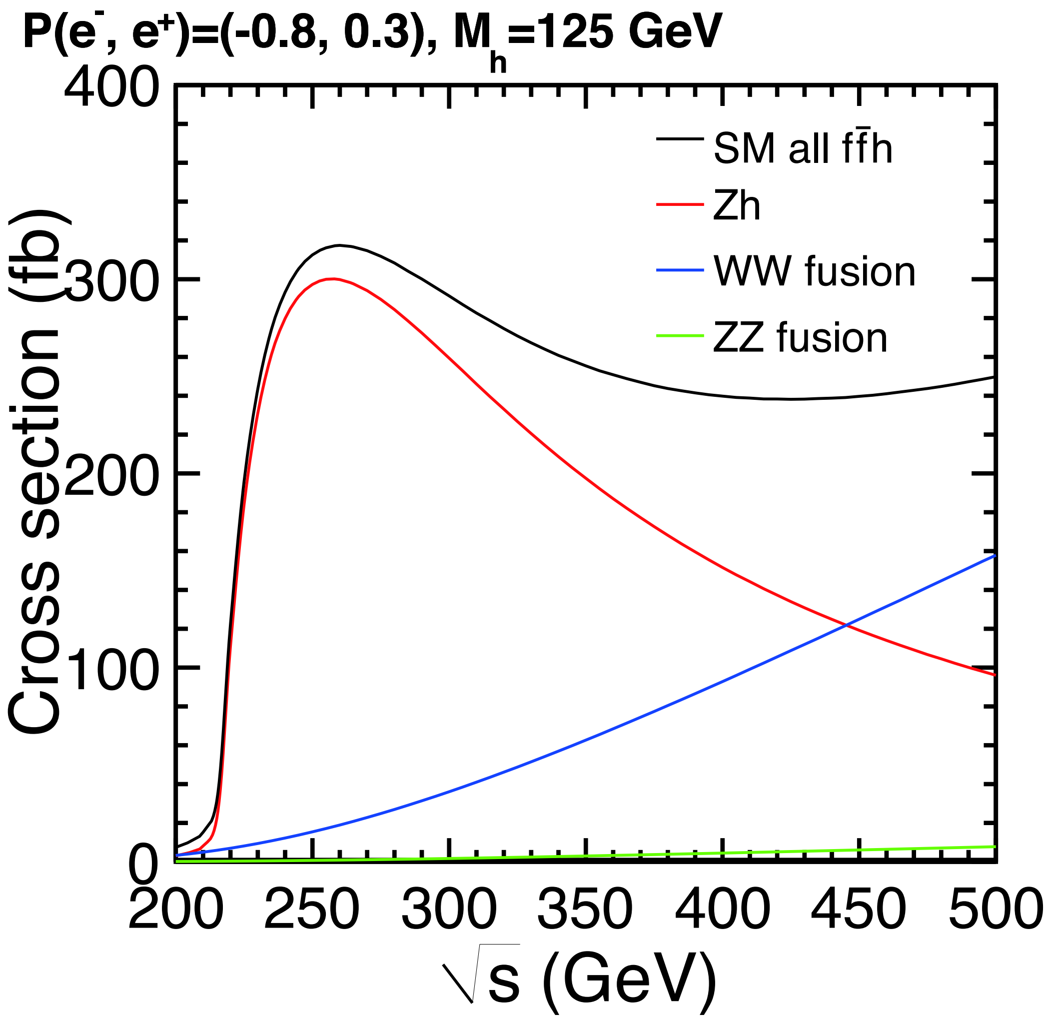
. . .

$M_H = v\sqrt{\lambda}$ free parameter

→ last unknown (now measured) parameter of the SM

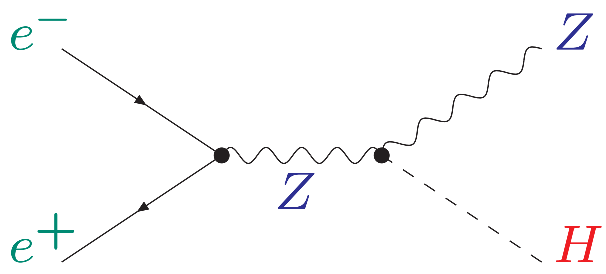
⇒ establish Higgs mechanism ≡ find the Higgs ⊕ measure its couplings

Higgs production cross sections at e^+e^- colliders:



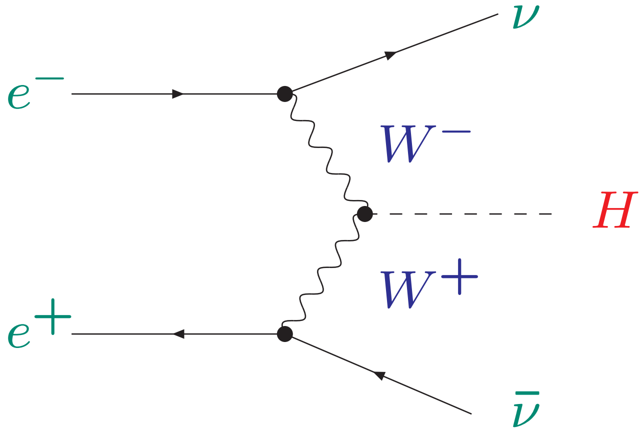
Higgs-strahlung:

$e^+e^- \to Z^* \to ZH$



weak boson fusion (WBF):

$e + e- \to \nu\bar{\nu}H$



$\sqrt{s} \sim$ 250 GeV, Higgs-strahlung dominated

Higgs coupling measurements at e^+e^- colliders

Initial measurement: $\sigma \times$ BR

recoil method: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

⇒ measurement of the Higgs production cross section

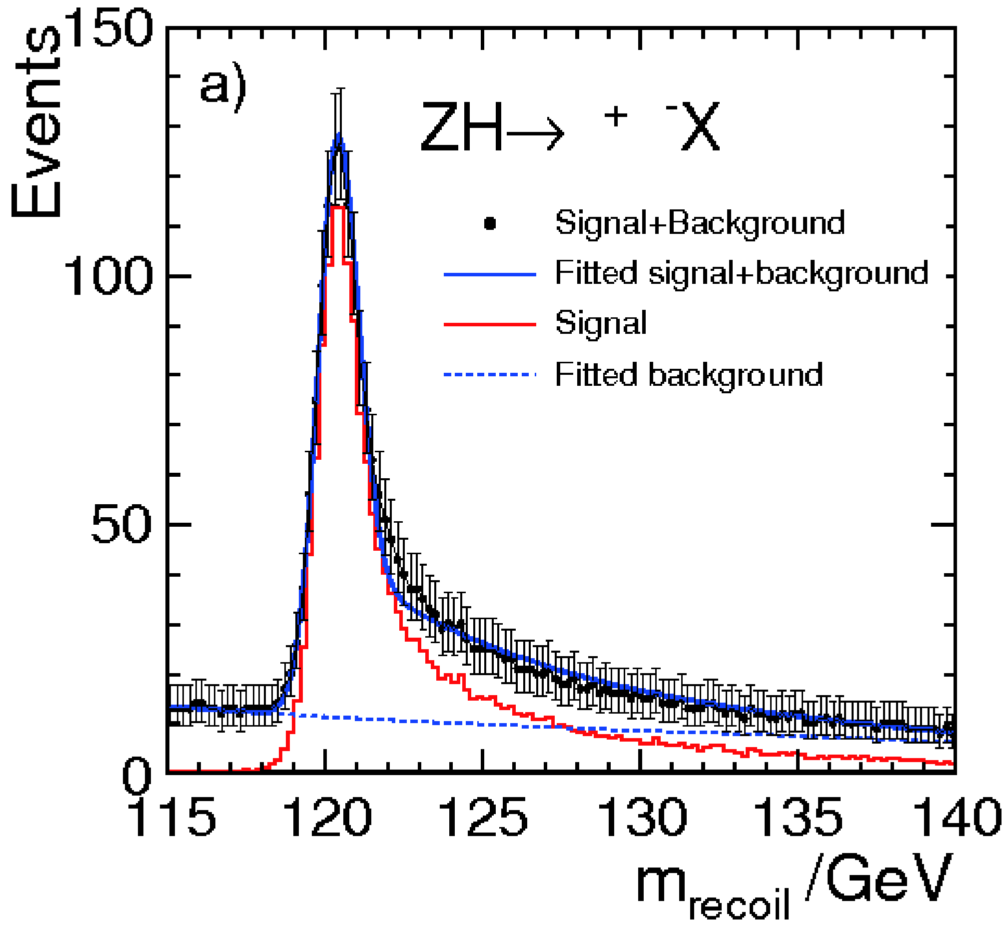
⇒ NO additional theoretical assumptions needed for absolute determination of partial widths (in contrast to LHC measurements!)

⇒ indirect measurement of total width

⇒ direct extraction of partial widths (couplings)

⇒ search for deviations from the SM
⇒ distinction between different models

Z-recoil method: $e^+e^- \to ZH \to \mu^+\mu^- X$



⇒ crucial for a model independent coupling measurement! $\delta M_H^{\rm exp} \lesssim 0.05$ GeV

Required precision for M_H?

– M_H is fundamental parameter
  $\Rightarrow$ high precision measurement on its own right

– M_H is input parameter for Higgs physics:

$$\delta M_H = 0.2\ \text{GeV} \quad \Rightarrow \quad \frac{\delta\text{BR}(H \to ZZ^*)}{\text{BR}(H \to ZZ^*)} \sim 2.5\%$$

$$\frac{\delta\text{BR}(H \to WW^*)}{\text{BR}(H \to WW^*)} \sim 2.2\%$$

$\Rightarrow \delta M_H \lesssim 0.02$ GeV desirable

Higgs observables: Higgs couplings

LHC always measures $\sigma \times$ BR

$\Rightarrow$ Total width $\Gamma_{H,\text{tot}}$ cannot be measured without further theory assumptions.

LHCHWG recommendation: Higgs coupling strength scale factors: κ_i

Assumptions for κ-framework:

1. Signal corresponds to only one state, no overlapping signal etc.
2. Zero-width approximation
3. Only modification of coupling strength (absolute values of couplings) but not of tensore structure wrt. to SM
4. Use state-of-the-art predictions in the SM and rescale the predictions with "leading order inspired" scale factors κ_i ($\kappa_i = 1$ corresponds to the SM case)

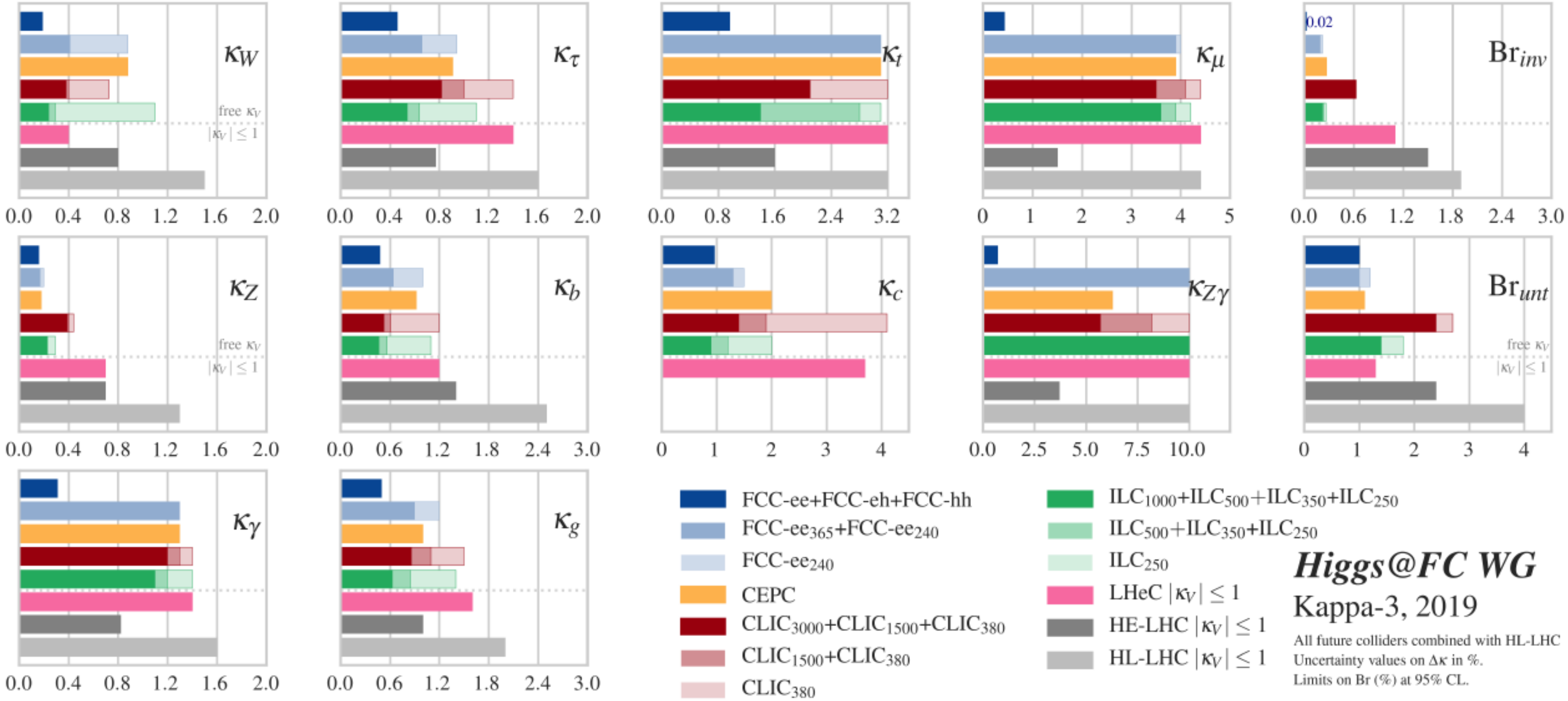
– no additional theory assumptions on your model:

$\Rightarrow$ Determination of ratios of scaling factors, e.g. $\kappa_i \kappa_j / \kappa_H$

– additional theory assumptions (on $\Gamma_{H,\text{tot}}$ or $\kappa_{W,Z}$ or $H \to$ NP)

$\Rightarrow$ Determination of κ_i (evaluated to NLO QCD accuracy)

Future expectations for κ (kappa-3 framework)



$\Rightarrow$ very roughly similar results

$\Rightarrow$ FCC-hh/-he/-ee appears better

$\Rightarrow$ FCC-hh uses different theory assumptions, uncertainties $\lesssim 1\%$

$\Rightarrow$ also remember different time scales!

Intrinsic uncertainties for decay widths: [arXiv:1905.03764]

"ILC/CEPC/FCC-ee" = expected precision on g^2_{Hxx} (incl. HL-LHC meas.)

Partial width	QCD	electroweak	total	future	ILC/CEPC/FCC-ee
$H \to WW \to$ 4f	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	$\lesssim 0.4\%$	0.6/1.9/0.8%
$H \to ZZ \to$ 4f	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	$\lesssim 0.3\%$	0.4/0.4/0.3%
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$	$\sim 1\%$	1.7/2.2/1.8%
$H \to \gamma\gamma$	$< 0.1\%$	$< 1\%$	$<1\%$	$< 1\%$	2.4/2.4/2.4%
$H \to Z\gamma$	$\lesssim 0.1\%$	$\sim 5\%$	$\sim 5\%$	$\sim 1\%$	22/13/20%
$H \to b\bar{b}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	$\sim 0.2\%$	1.2/1.8/1.3%
$H \to c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	$\sim 0.2\%$	2.4/4.0/2.6%
$H \to \tau^+\tau^-$	–	$< 0.3\%$	$< 0.3\%$	$< 0.1\%$	1.3/1.9/1.3%
$H \to \mu^+\mu^-$	–	$< 0.3\%$	$< 0.3\%$	$< 0.1\%$	7.8/7.8/7.8%
$\Gamma_{\rm tot}$				$\sim 0.3\%$	1.1/1.8/1.2%

$\Rightarrow$ non-negligible for $H \to WW/ZZ \to$ 4f

Future parametric uncertainties for decay widths:

decay	fut. intr.	fut. para. m_q	para. α_s	para. M_H	ILC/CEPC/FCC-ee
$H \to WW$	$\lesssim 0.4\%$	–	–	$\sim 0.1\%$	0.6/1.9/0.8%
$H \to ZZ$	$\lesssim 0.3\%$	–	–	$\sim 0.1\%$	0.4/0.4/0.3%
$H \to gg$	$\sim 1\%$		0.5%	–	1.7/2.2/1.8%
$H \to \gamma\gamma$	$< 1\%$	–	–	–	2.4/2.4/2.4%
$H \to Z\gamma$	$\sim 1\%$	–	–	$\sim 0.1\%$	22/13/20%
$H \to b\bar{b}$	$\sim 0.2\%$	$\sim 0.6\%$	$< 0.1\%$	–	1.3/1.8/1.3%
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	–	2.4/4.0/2.6%
$H \to \tau^+\tau^-$	$< 0.1\%$	–	–	–	1.3/1.0/1.3%
$H \to \mu^+\mu^-$	$< 0.1\%$	–	–	–	7.8/7.8/7.8%
Γ_{tot}	$\sim 0.3\%$	$\sim 0.4\%$	$< 0.1\%$	$< 0.1\%$	1.1/1.8/1.2%

Γ_{tot} applies "to all" (partial cancelations . . .)
$\Rightarrow$ possible impact particular on ZZ, WW

One word of caution:

The above numbers have all been obtained assuming the SM as calculational framework.

The SM constitutes the model in which highest theoretical precision for the predictions of Higgs observables can be obtained.

We know that BSM physics must exist! (DM, gravity, . . .)

As soon as BSM physics will be discovered, an evaluation of the Higgs predictions in any preferred BSM model will be necessary.

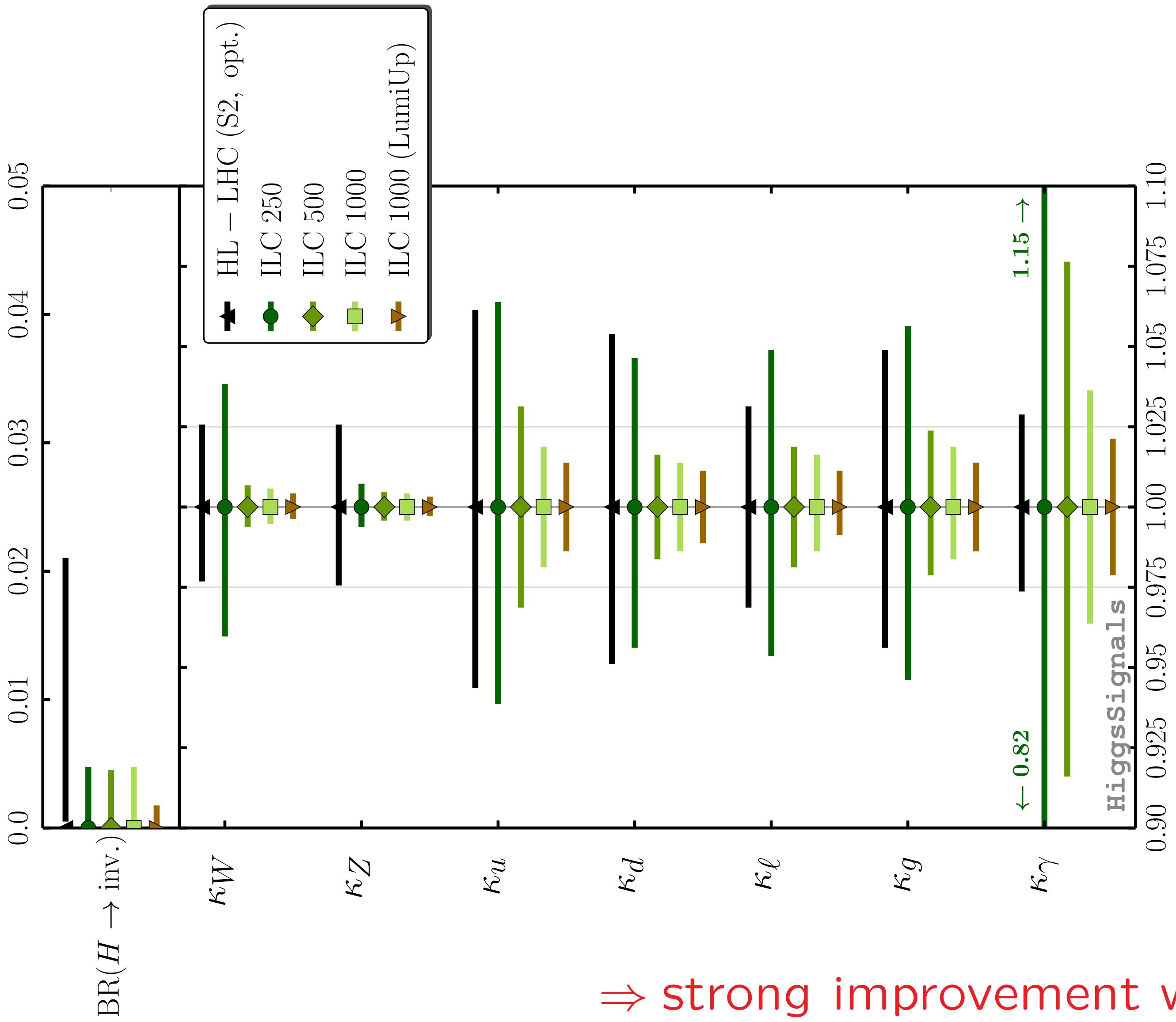
The corresponding theory uncertainties, both intrinsic and parametric, can then be larger (as known for the MSSM).

A dedicated theory effort (beyond the SM) would be needed in this case.

HL-LHC vs. ILC in the most general κ framework:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

assumption: BR($H \to$ NP) = BR($H \to$ inv.)



⇒ strong improvement with the ILC

HL-LHC vs. ILC in the most general κ framework:

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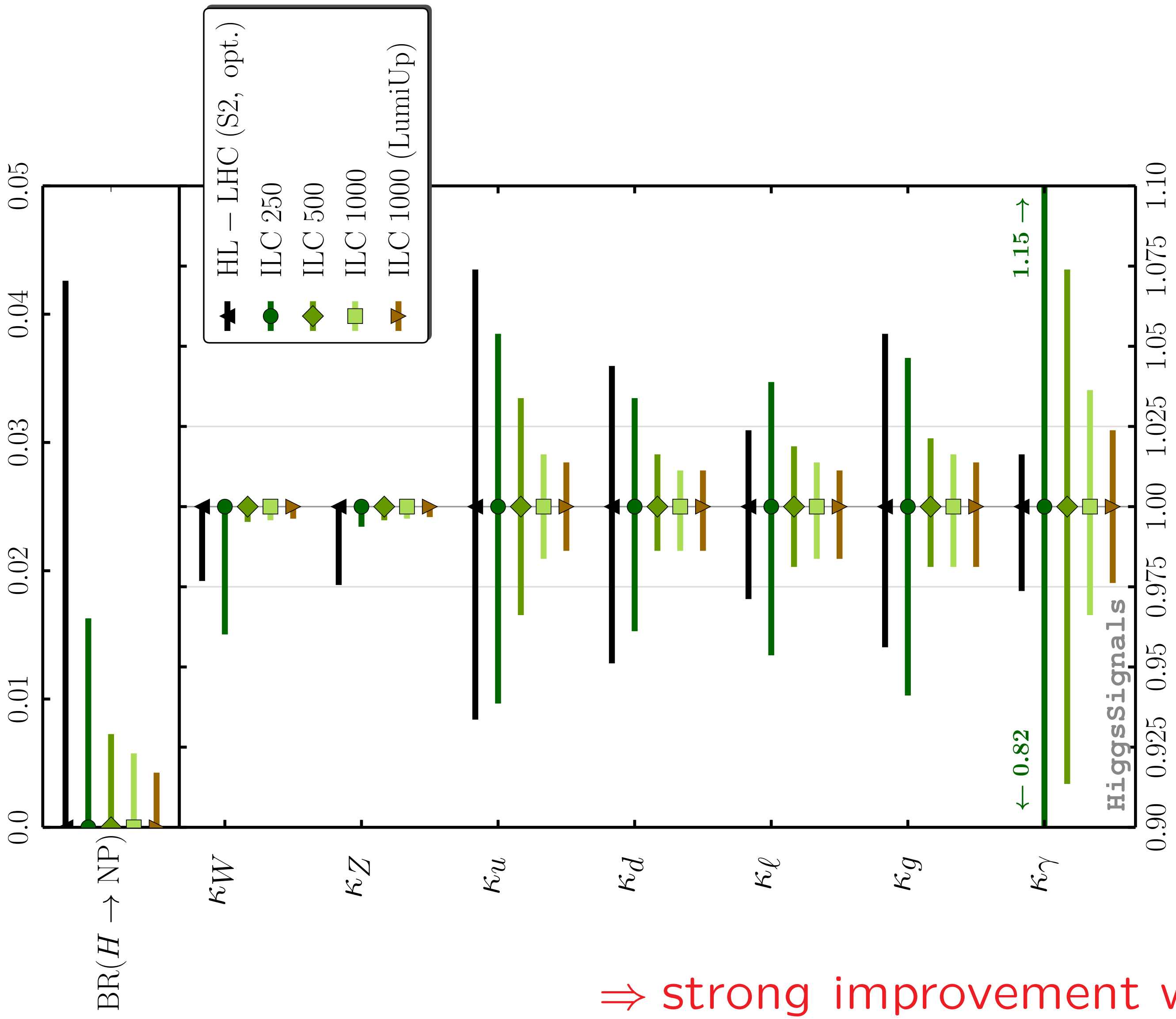
assumption: $\kappa_V \leq 1$



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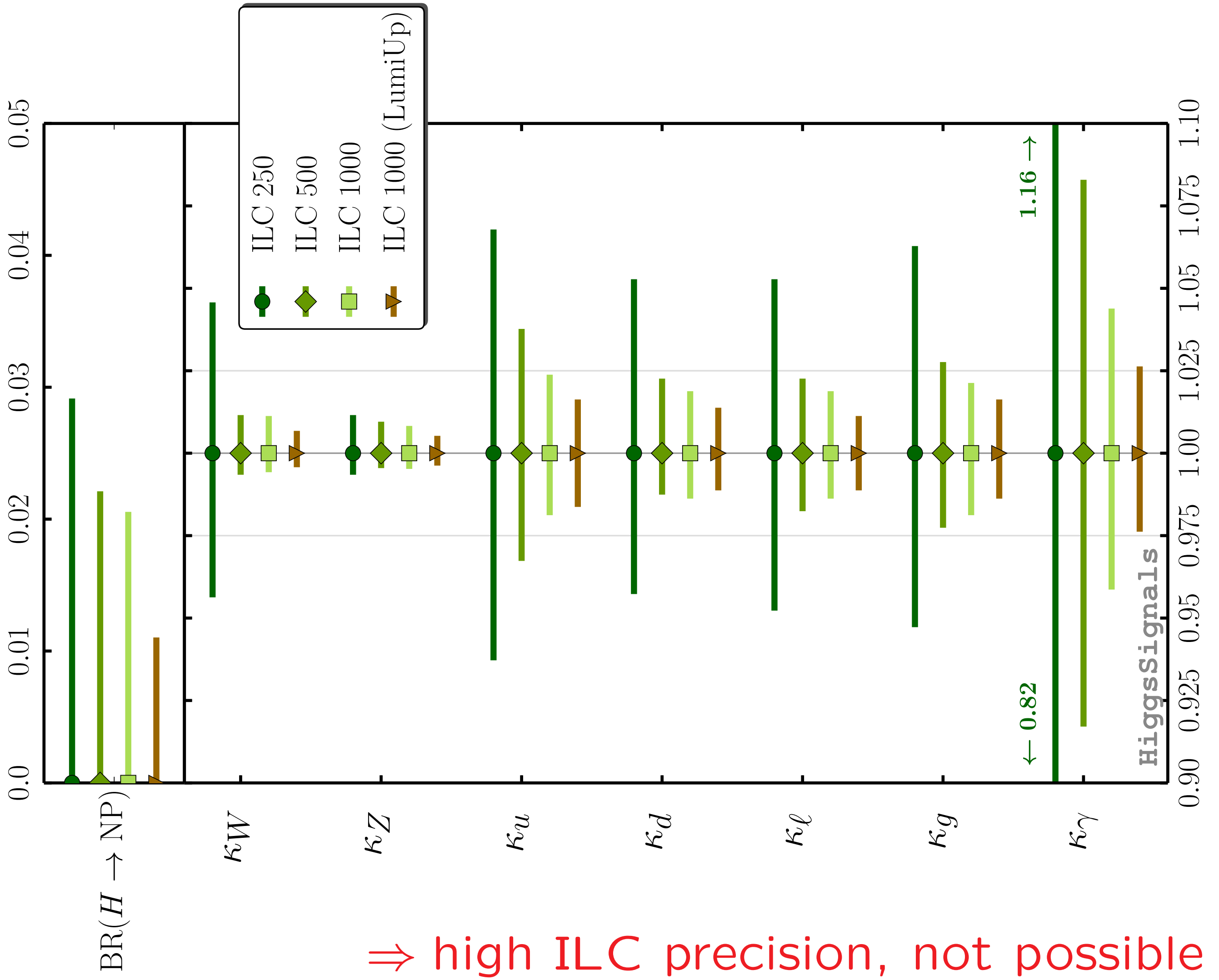
no theory assumptions, full fit



⇒ high ILC precision, not possible at the LHC

HL-LHC vs. ILC in the most general κ framework:

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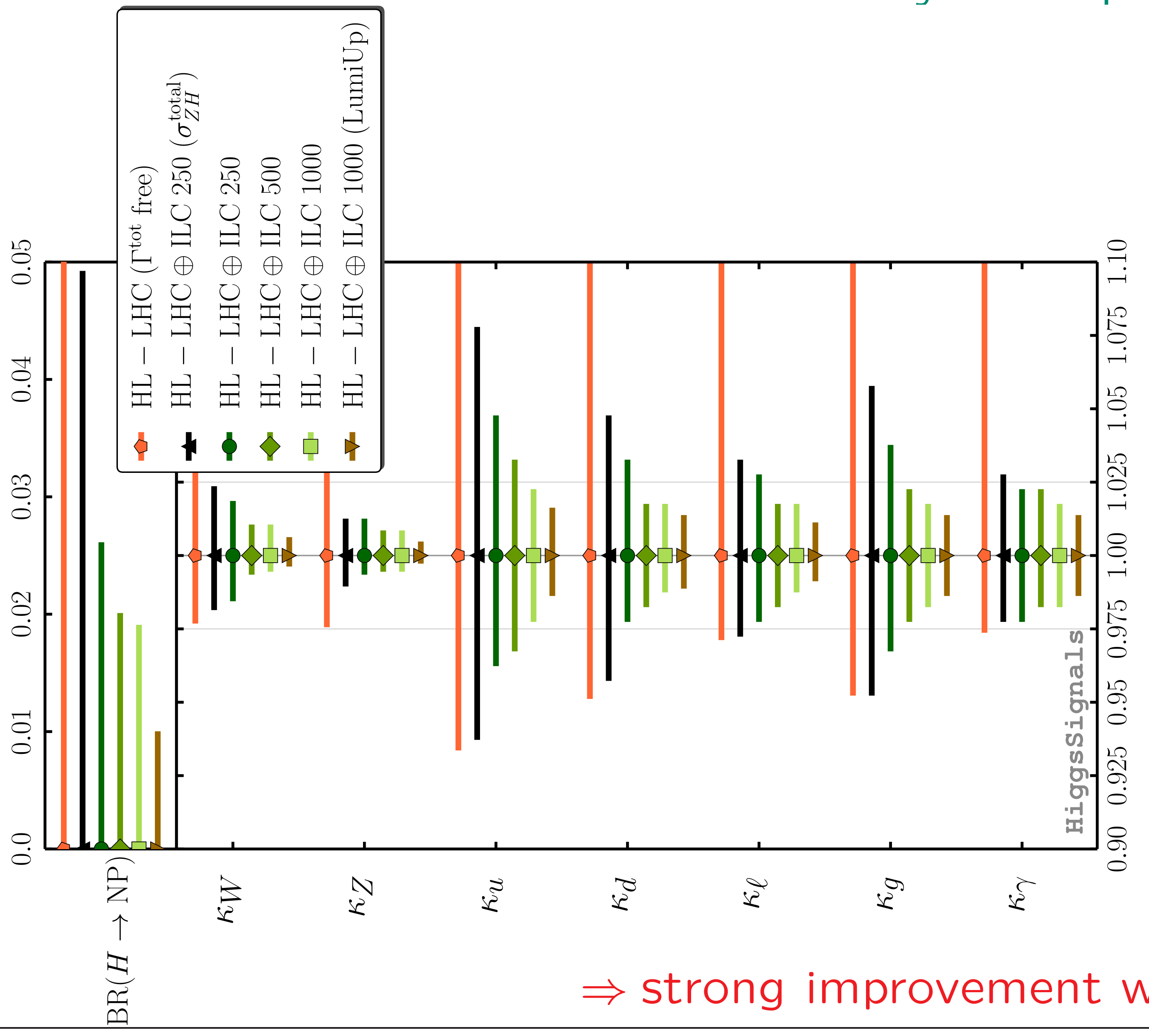


⇒ strong improvement with the ILC

What if nature is more complicated than κ's?

Assumptions for κ-framework:

1. Signal corresponds to only one state, no overlapping signal etc.

2. Zero-width approximation

3. Only modification of coupling strength (absolute values of couplings) but not of tensore structure wrt. to SM

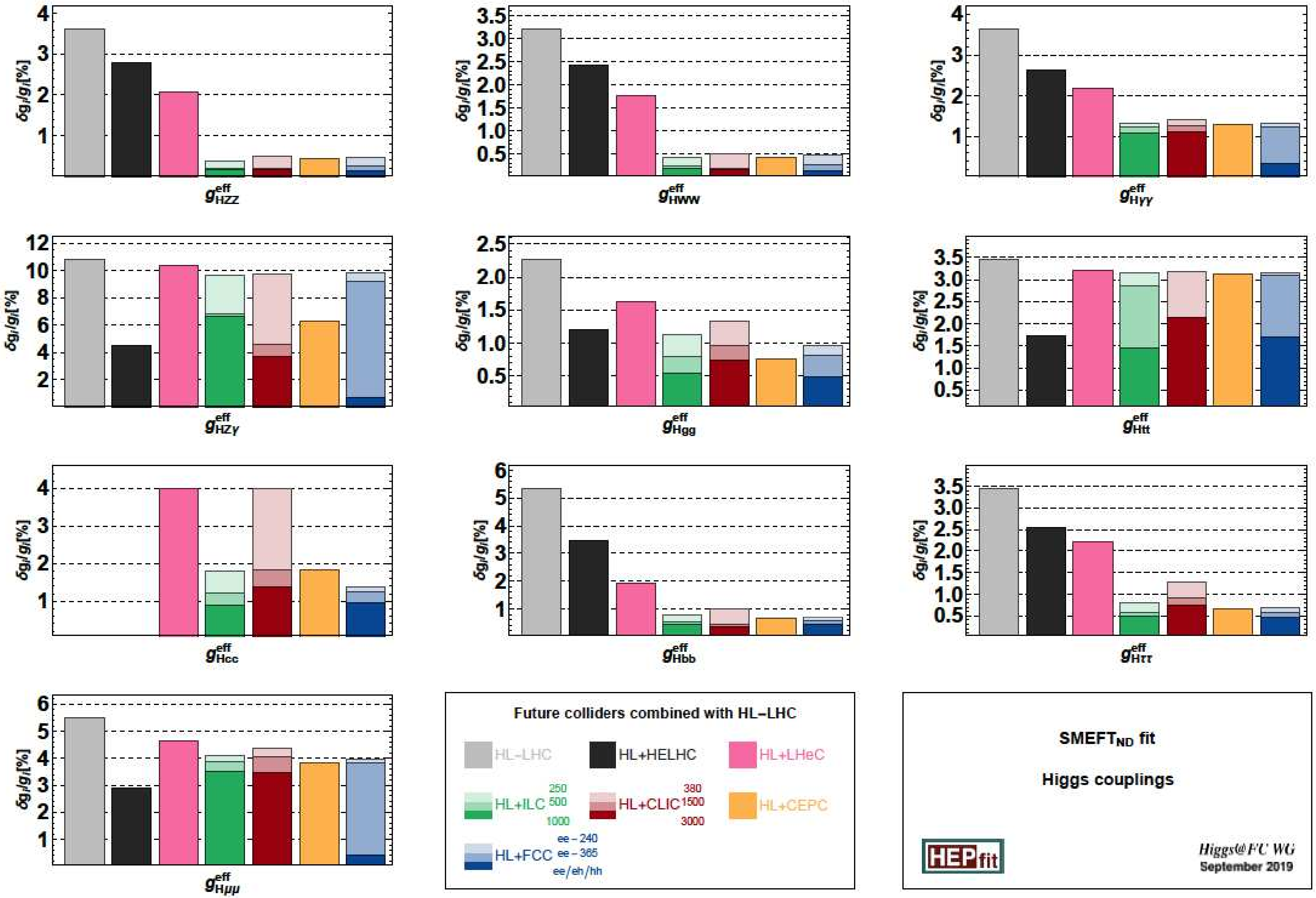
4. Use state-of-the-art predictions in the SM and rescale the predictions with "leading order inspired" scale factors κ_i ($\kappa_i = 1$ corresponds to the SM case)

Broader class of models covered: EFT

– no light new states
– non-SM-like coupling structures
– UV-complete model: consistent higher-order calculations possible

Note: also EFT does NOT cover all models
⇒ investigate in addition "realistic" models!

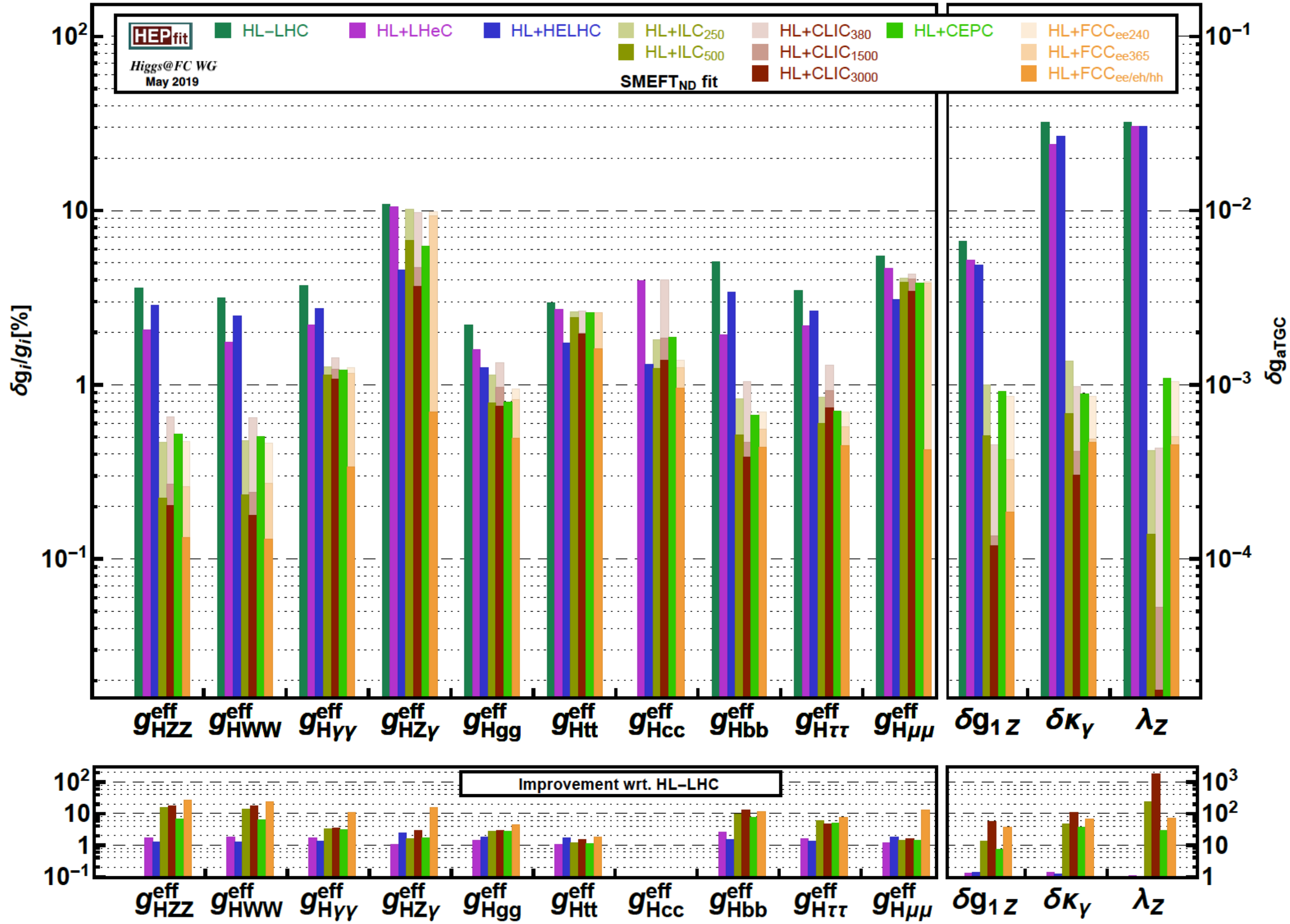
Future expections for Higgs couplings in SMEFT (I)



⇒ clear improvement with e^+e^- colliders!

⇒ similar performance (polarization vs. luminosity)

Future expections for Higgs couplings in SMEFT (II)



⇒ clear improvement with e^+e^- colliders!

⇒ similar performance (polarization vs. luminosity)

Most challenging: λ_{hhh} measurements

Possibilities for λ_{hhh} measurements:

1. measurement of di-Higgs production
   $\rightarrow$ (HL-)LHC, FCC-hh, ILC500, CLIC

2. single Higgs production in an EFT
   $\rightarrow$ (HL-)LHC, FCC-hh, ILC, CLIC, FCC-ee, CEPC

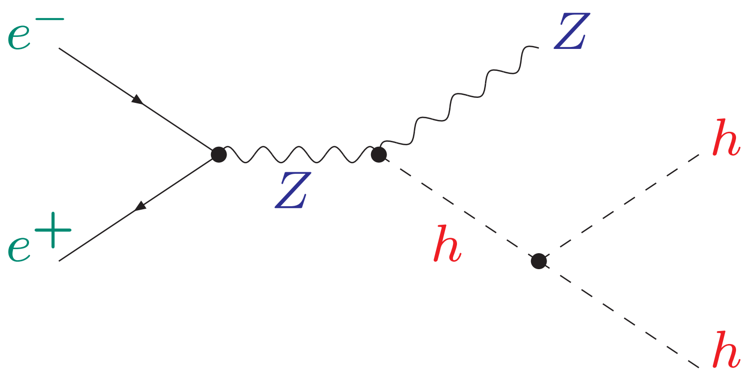
3. EWPO measurements in an EFT
   $\rightarrow$ ILC (GigaZ, radiative return), FCC-ee (TeraZ), CEPC

$\Rightarrow$ focus on (1), (2)

Direct λ_{hhh} at e^+e^- colliders:

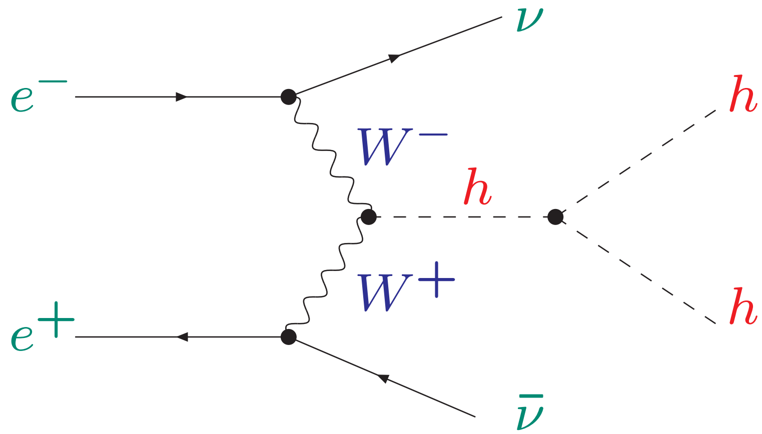
Higgs-strahlung:

$e^+e^- \to Z^* \to Zhh$

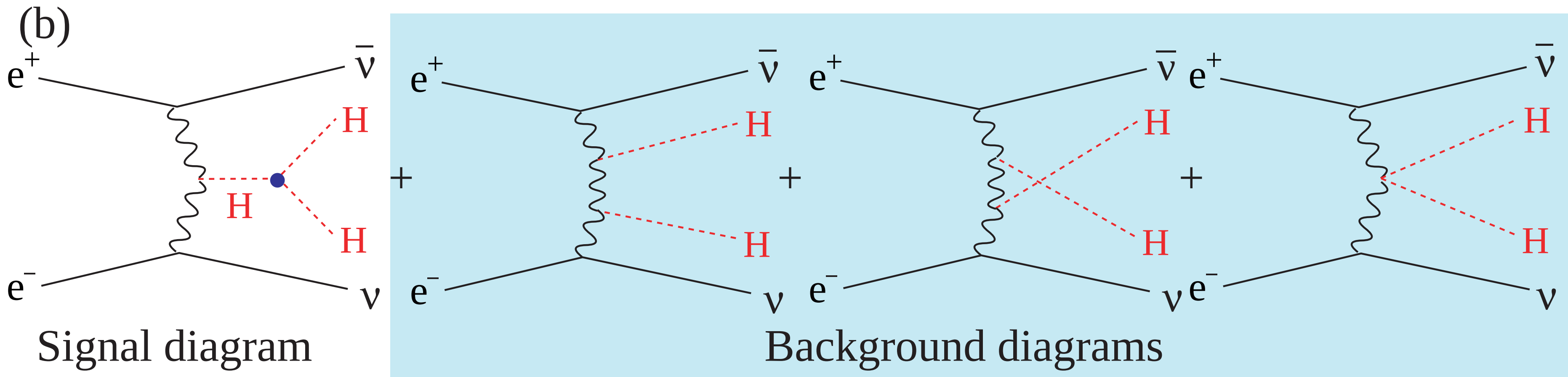


weak boson fusion (WBF):

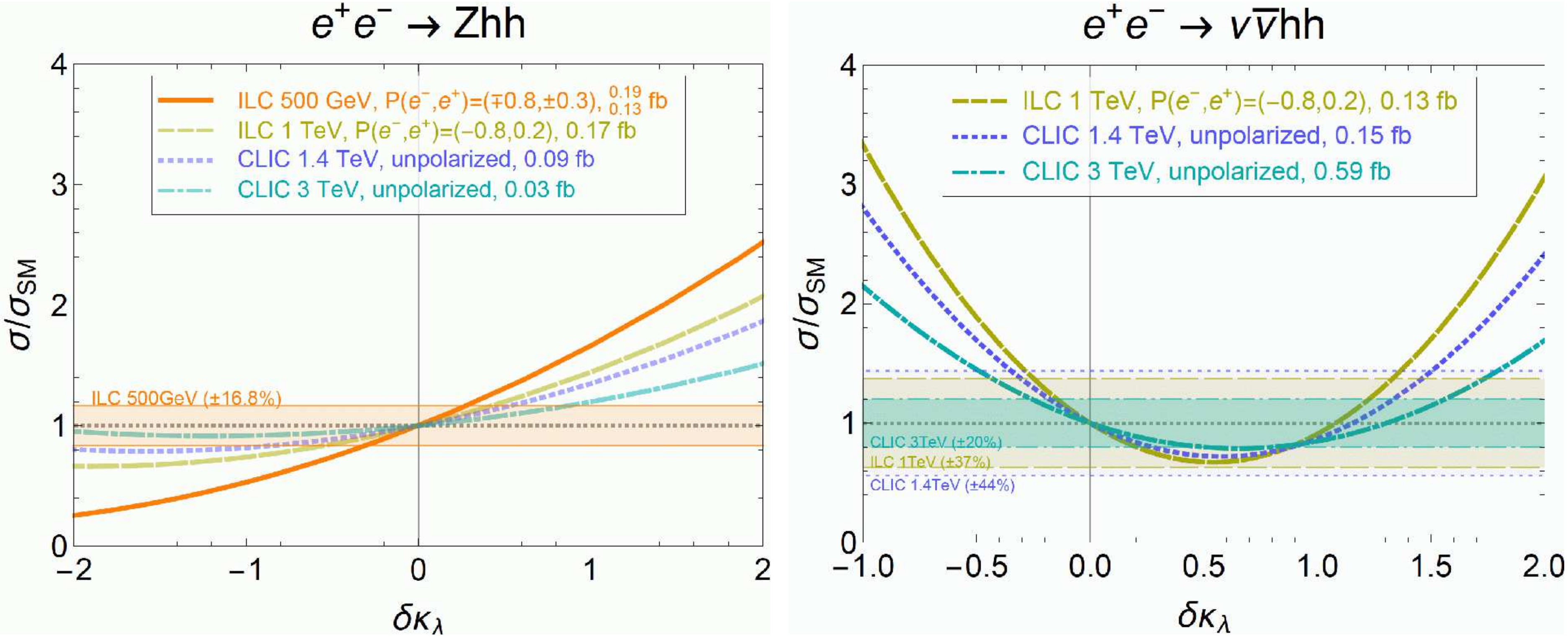
$e+e- \to \nu\bar{\nu}hh$



Signal and background interference:

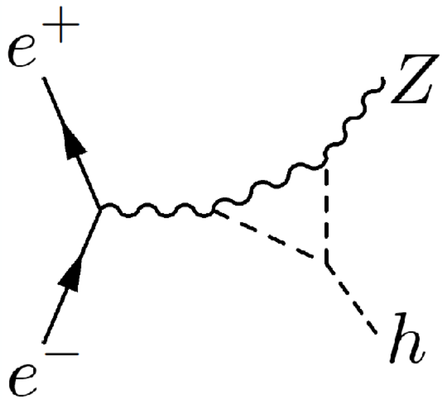


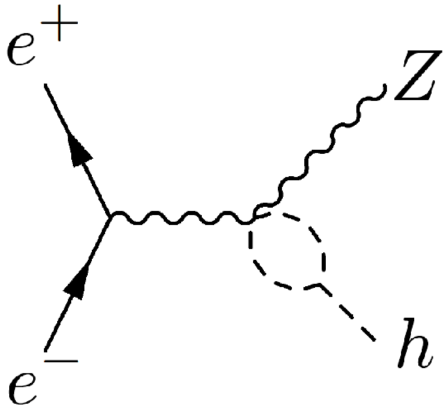
Di-Higgs production at ILC/CLIC:

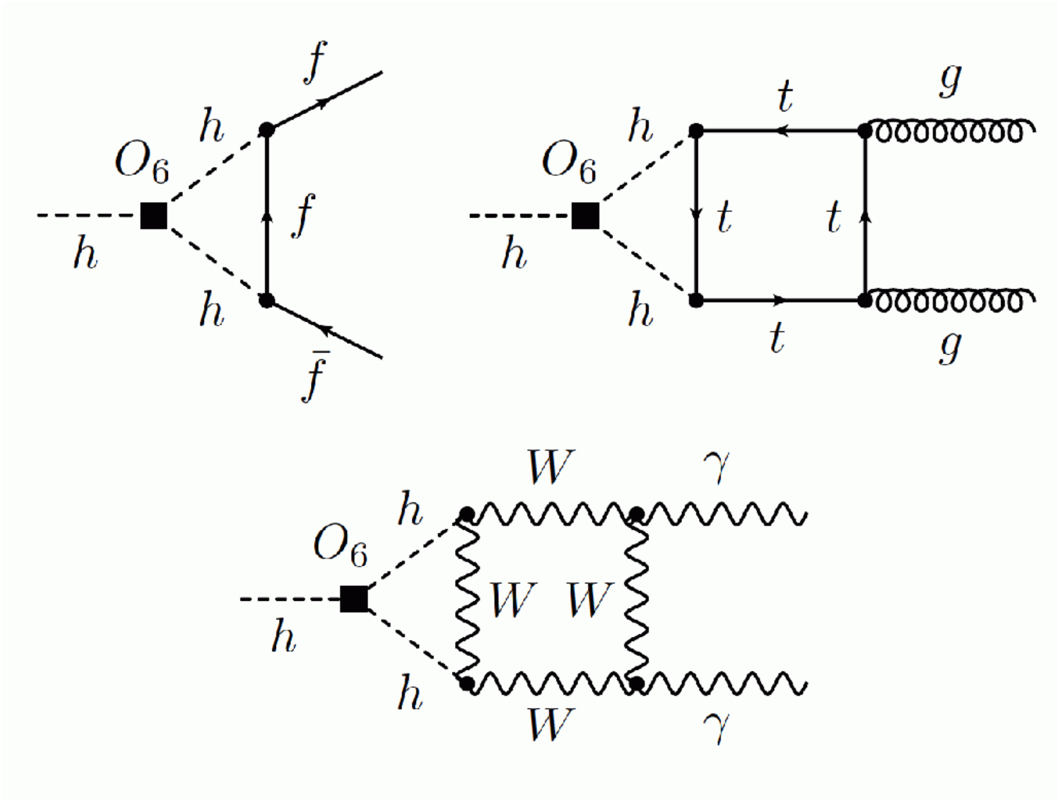


$\Rightarrow$ strong and different dependence on κ_λ

Single-Higgs production:

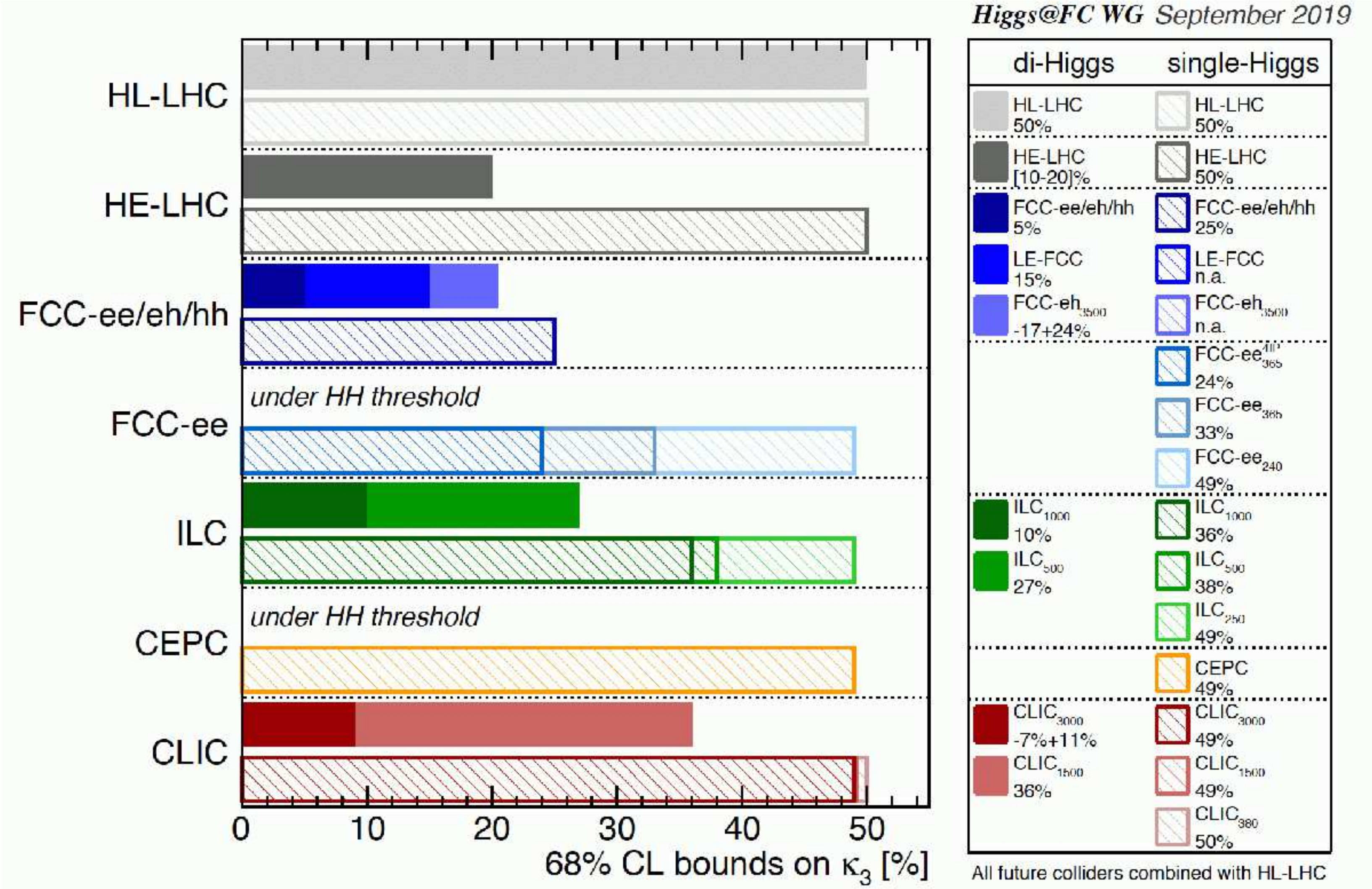






EFT analysis performed only for $\kappa_\lambda = 1$

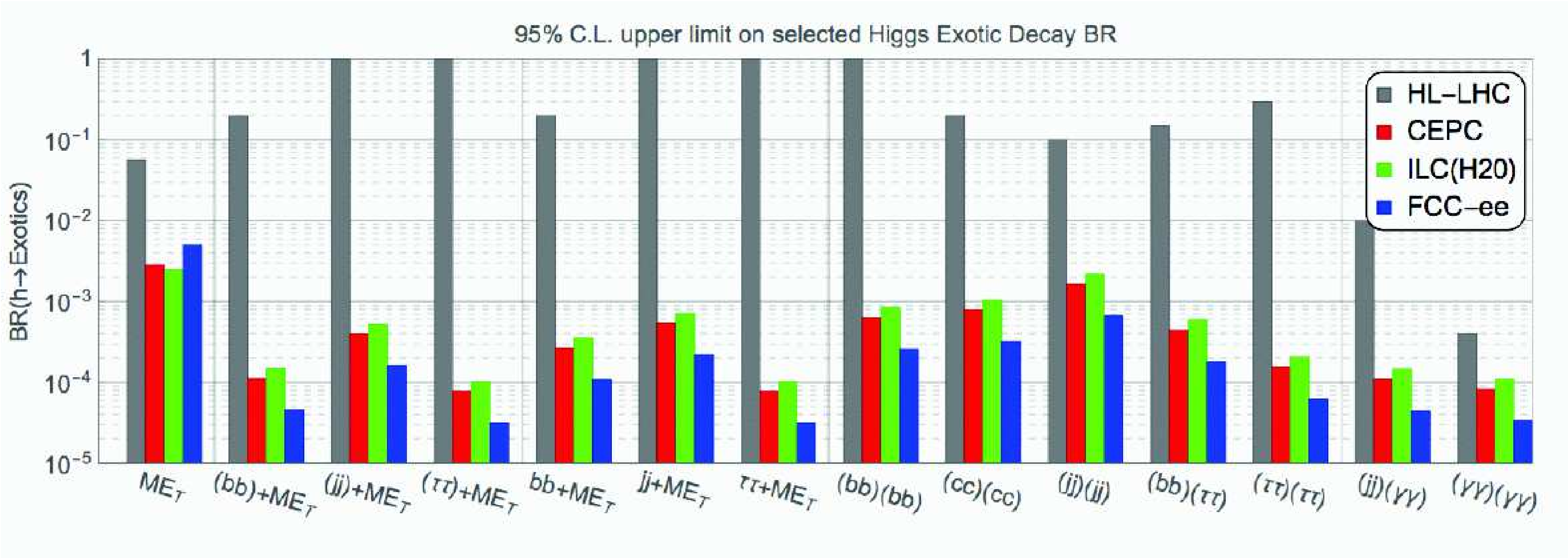
Comparison of all colliders:



Analysis/comparison performed only for $\kappa_\lambda = 1$

Exotic Higgs decays:

[*Z. Liu, L.-T. Wang, H. Zhang '17*]



⇒ strong improvement at e^+e^- colliders

⇒ sensitivity to BSM physics?!

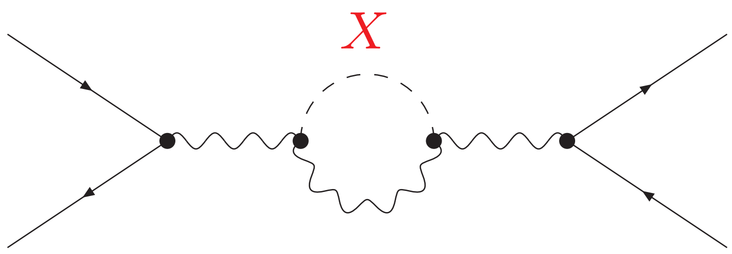
Higgs consistency tests via EWPO:

Comparison of observables with theory:

Precision data:		Theory:
$M_W, \sin^2\theta_{\rm eff}, a_\mu,\ M_h$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. X



$\Downarrow$

SM: limits on M_H,   BSM: limits on M_X

Very high accuracy of measurements and theoretical predictions needed

$\Rightarrow$ models "ready" so far: SM, MSSM, "pure multi-Higgs" models (?)

Precision observables in the SM and BSM

M_W, $\sin^2\theta_{\text{eff}}$, M_h, $(g-2)_\mu$, b physics, . . .

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

$\Updownarrow$

loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[*A. Sirlin '80*] , [*W. Marciano, A. Sirlin '80*]

$$\Delta r_{1-\text{loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\text{rem}}(M_H)$$

$\Delta\alpha$	$\frac{c_W^2}{s_W^2}\Delta\rho$	$\Delta r_{\text{rem}}(M_H)$
$\sim \log\frac{M_Z}{m_f}$	$\sim m_t^2$	$\log(M_H/M_W)$
$\sim 6\%$	$\sim 3.3\%$	$\sim 1\%$

Precision observables in the SM and BSM

M_W, $\sin^2\theta_{\rm eff}$, M_h, $(g-2)_\mu$, b physics, . . .

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1 + \Delta r)$$

$\Updownarrow$

loop corrections

B) Effective mixing angle:

$$\sin^2\theta_{\rm eff} = \frac{1}{4\,|Q_f|}\left(1 - \frac{{\rm Re}\,g_V^f}{{\rm Re}\,g_A^f}\right)$$

Higher order contributions:

$$g_V^f \to g_V^f + \Delta g_V^f, \quad g_A^f \to g_A^f + \Delta g_A^f$$

Comparison of SM prediction of M_W with direct measurements:

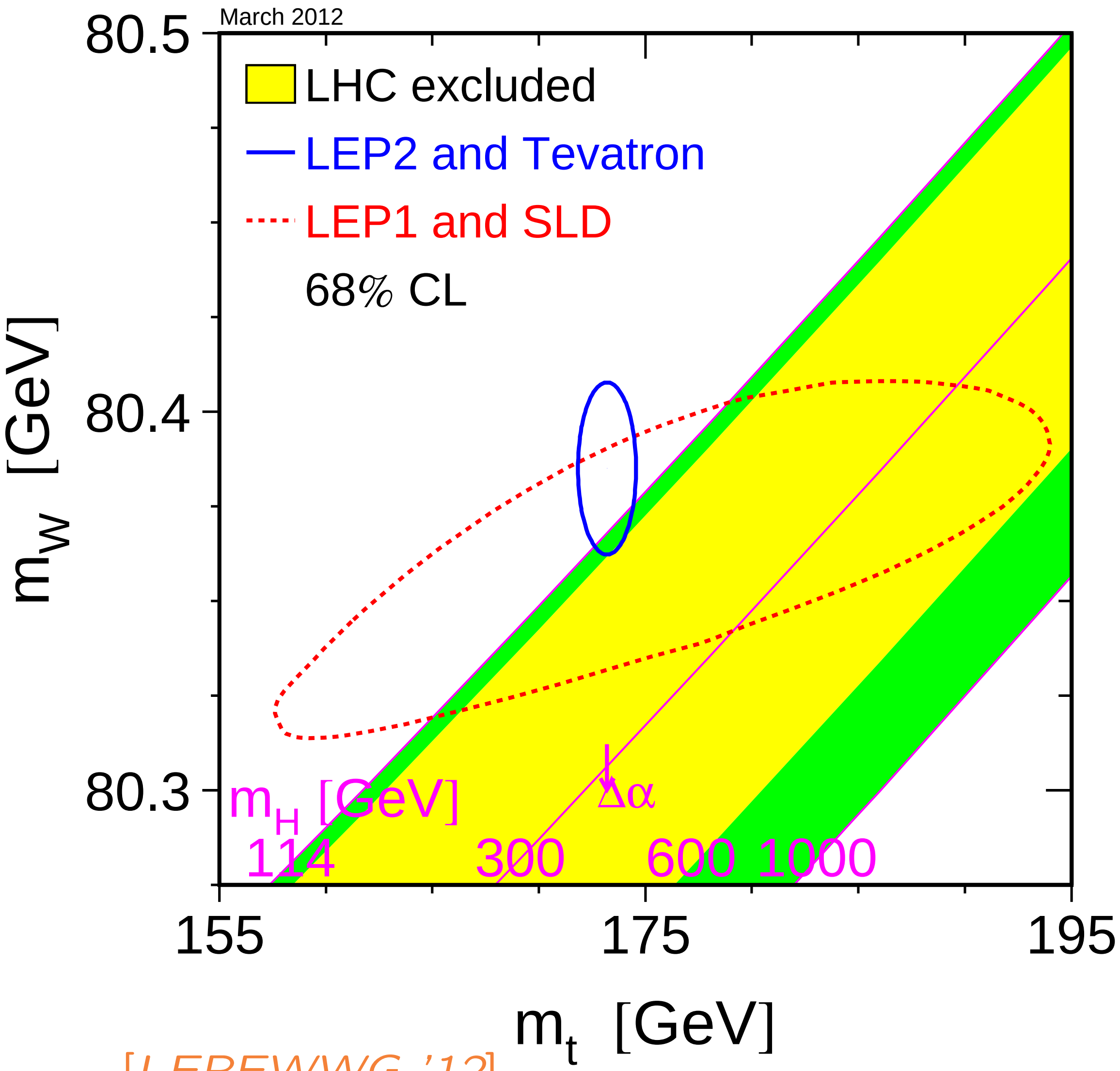
$$\Delta r = -\frac{11 g_2^2}{96\,\pi^2}\frac{s_W^2}{c_W^2}\log\left(\frac{M_H}{M_W}\right)$$

general for EWPO:

$$\Delta \sim g_2^2\left[\log\left(\frac{M_H}{M_W}\right) + g_2^2\frac{M_H^2}{M_W^2}\right]$$

leading term: $\log(M_H)$

first term $\sim M_H^2$ with g_2^4

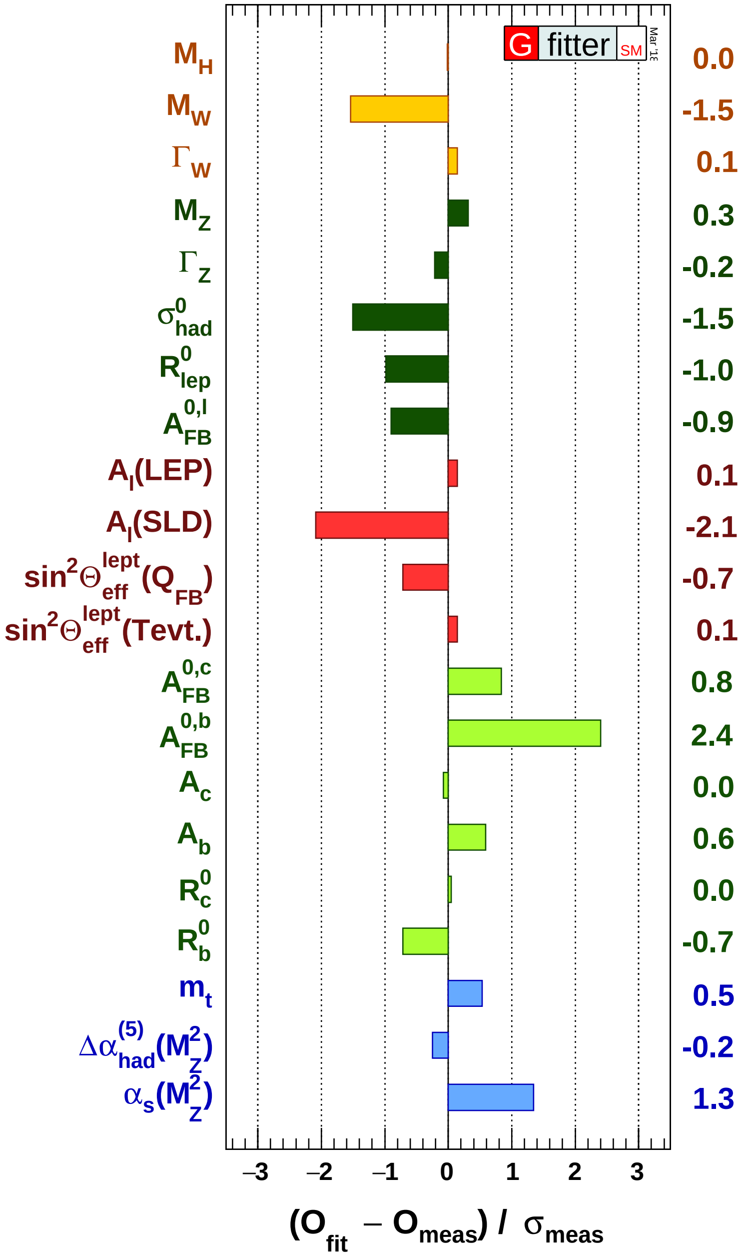


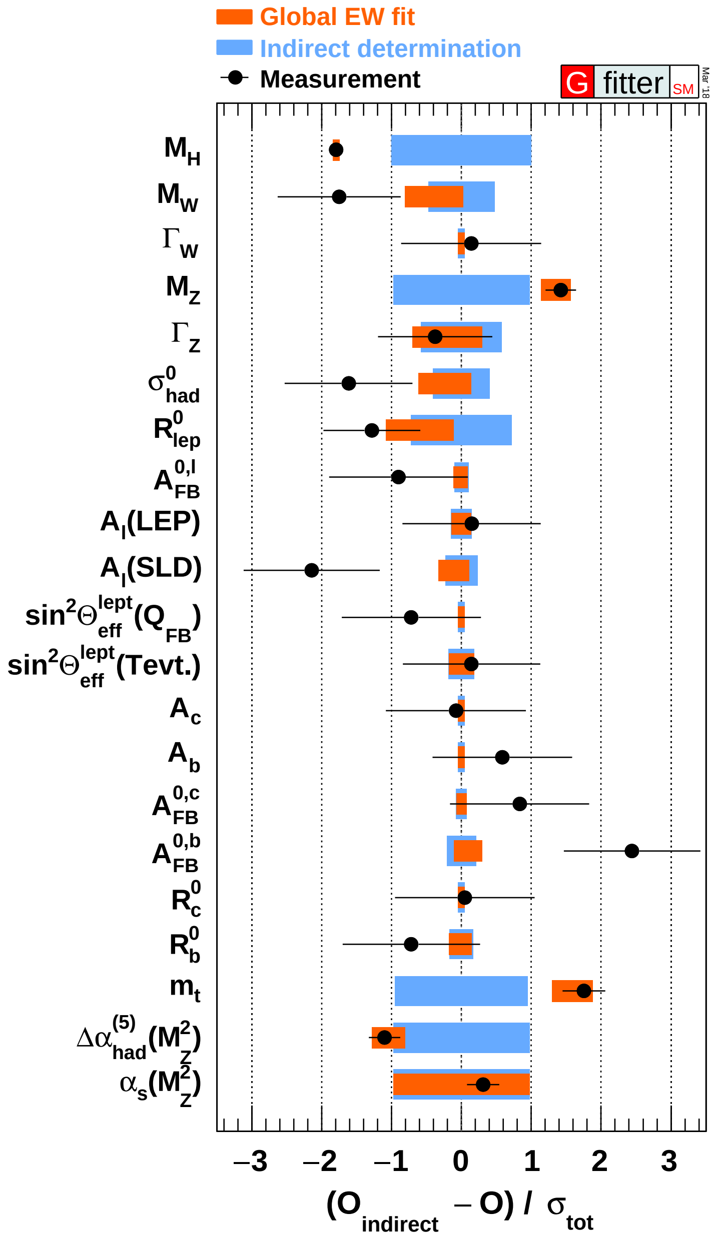
[LEPEWWG '12]

⇒ light Higgs boson preferred

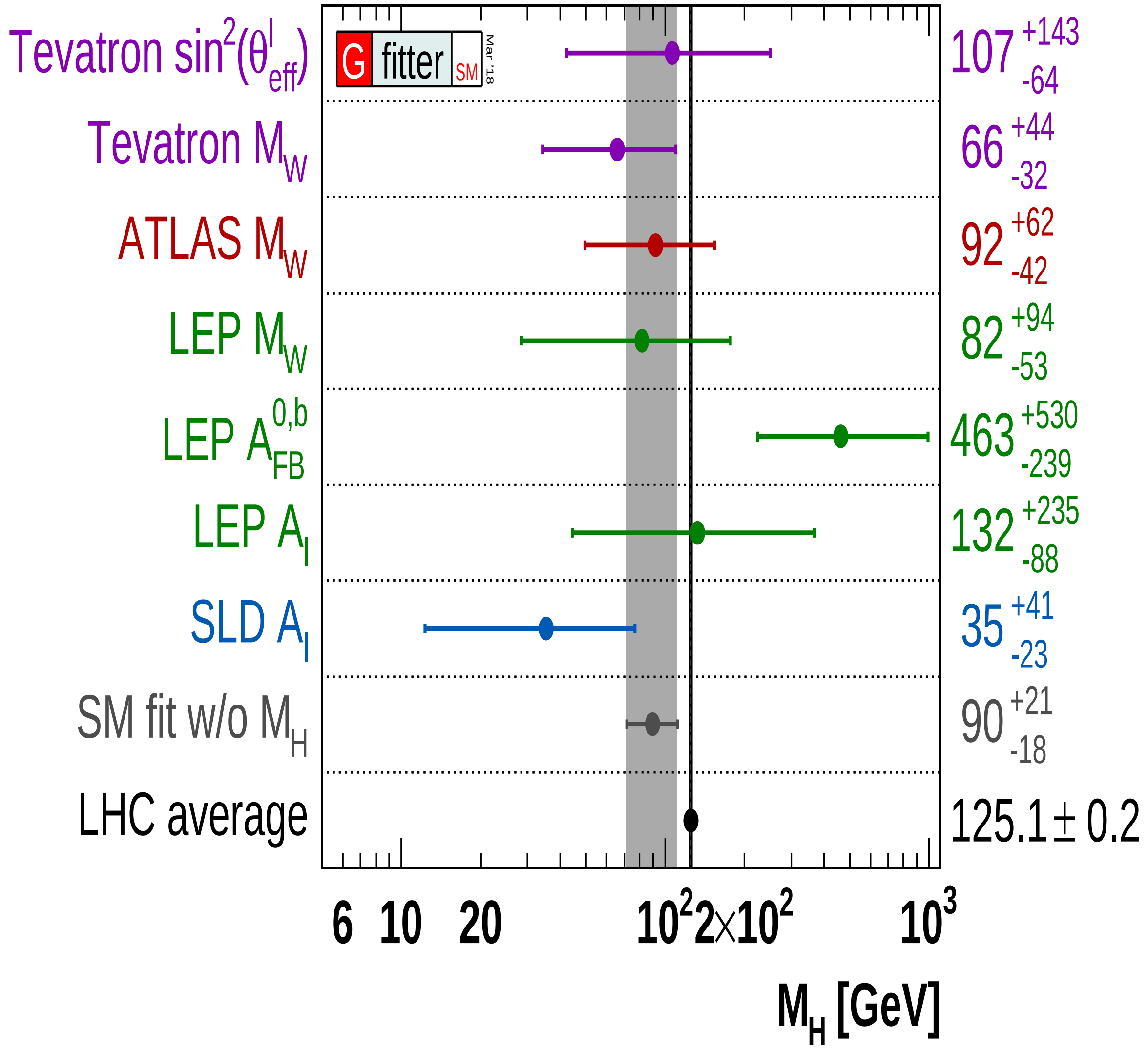
Overview about all EWPO:

[GFitter '18]





Results for M_H from other EWPO:



light Higgs preferred by:
M_W, $A^l_{\rm LR}$ (SLD)

heavier Higgs preferred by:
$A^b_{\rm FB}$ (LEP)
$\Rightarrow$ keeps SM alive

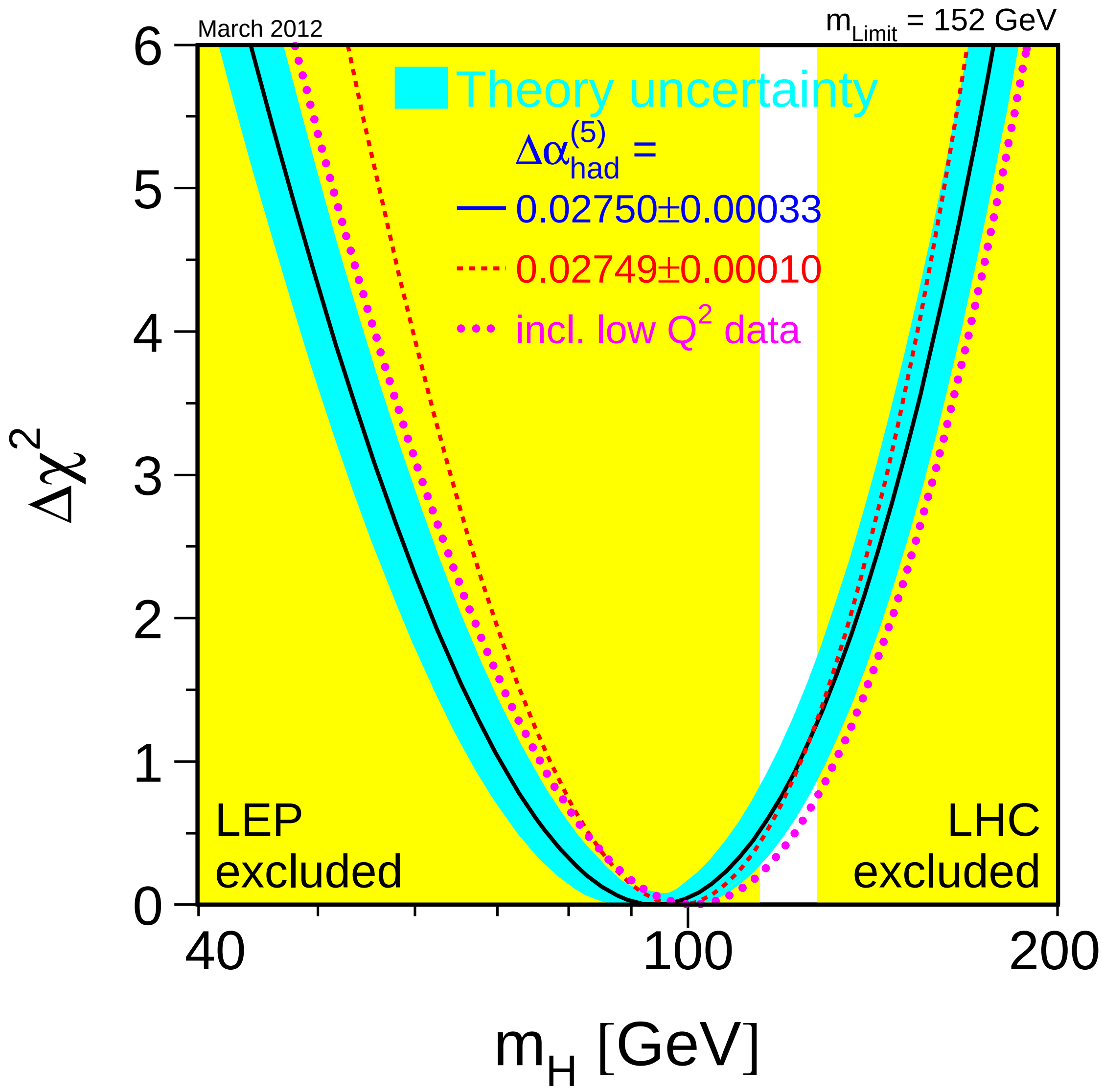
$\Rightarrow$ light Higgs boson preferred *[GFitter '18]*

Global fit to all SM data:

[*LEPEWWG '12*]

$\Rightarrow M_H = 94^{+29}_{-24}$ GeV

$M_H < 152$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

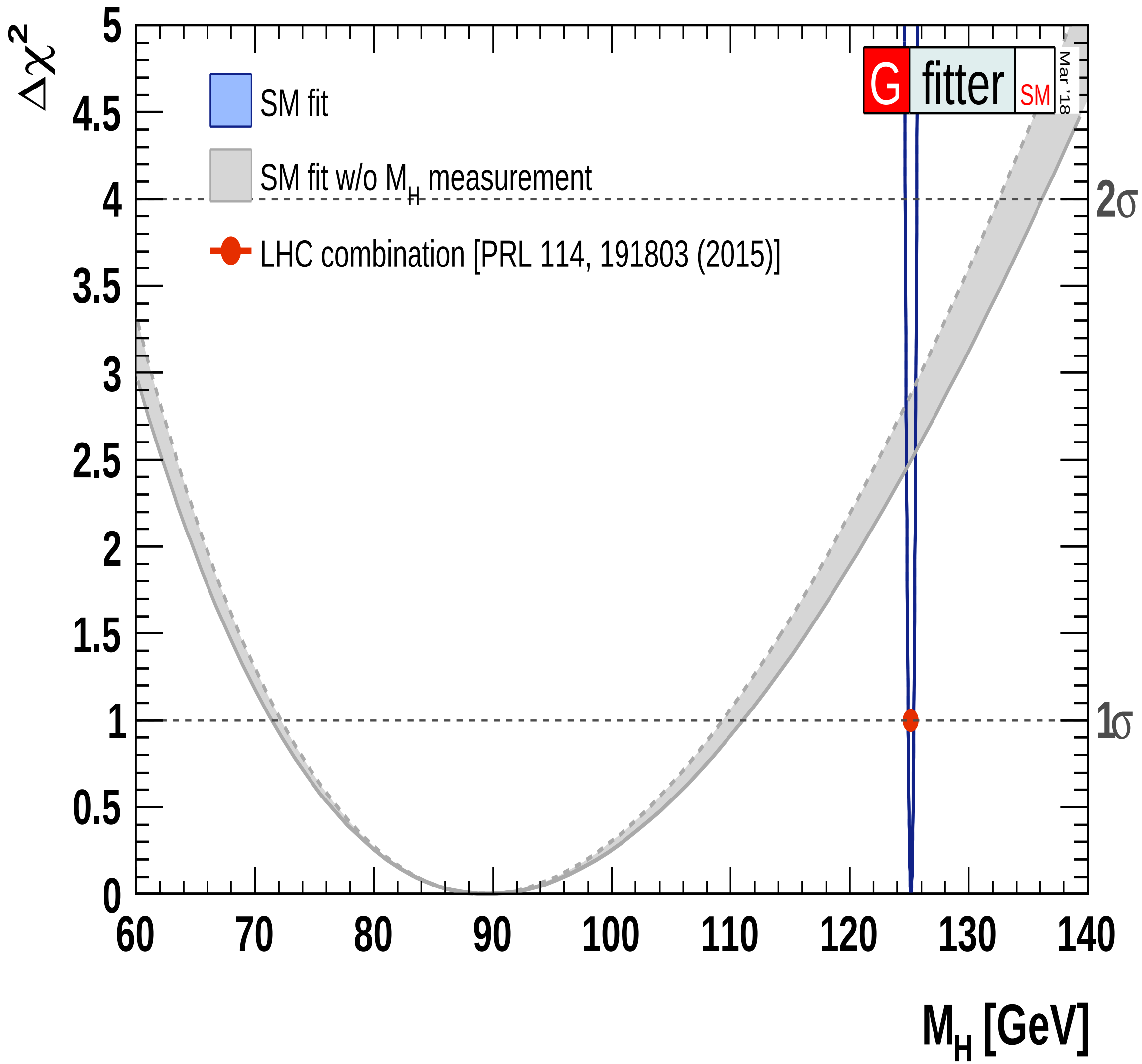
$\Rightarrow$ no confirmation of
Higgs mechanism

$\Rightarrow$ Prediction before discovery: in the SM: $M_H \lesssim 160$ GeV

Latest global fit to all SM data:
[*GFitter '18*]

$\Rightarrow M_H = 90^{+21}_{-18}$ GeV

"agreement" at $1.8\,\sigma$



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

$\Rightarrow$ slightly rising "tension" over the last years . . .

Improvements with the ILC/FCC-ee:

Experimental errors of the precision observables:

	today	Tev./LHC	ILC/GigaZ	FCC-ee/TeraZ
$\delta \sin^2\theta_{\text{eff}} (\times 10^5)$	15	15	1.3	0.6
δM_W [MeV]	12	$\lesssim 12$	2-3	0.5
δm_t [GeV]	0.6	$\lesssim 0.5$	0.05	0.05

M_W: from direct reconstruction and threshold scan

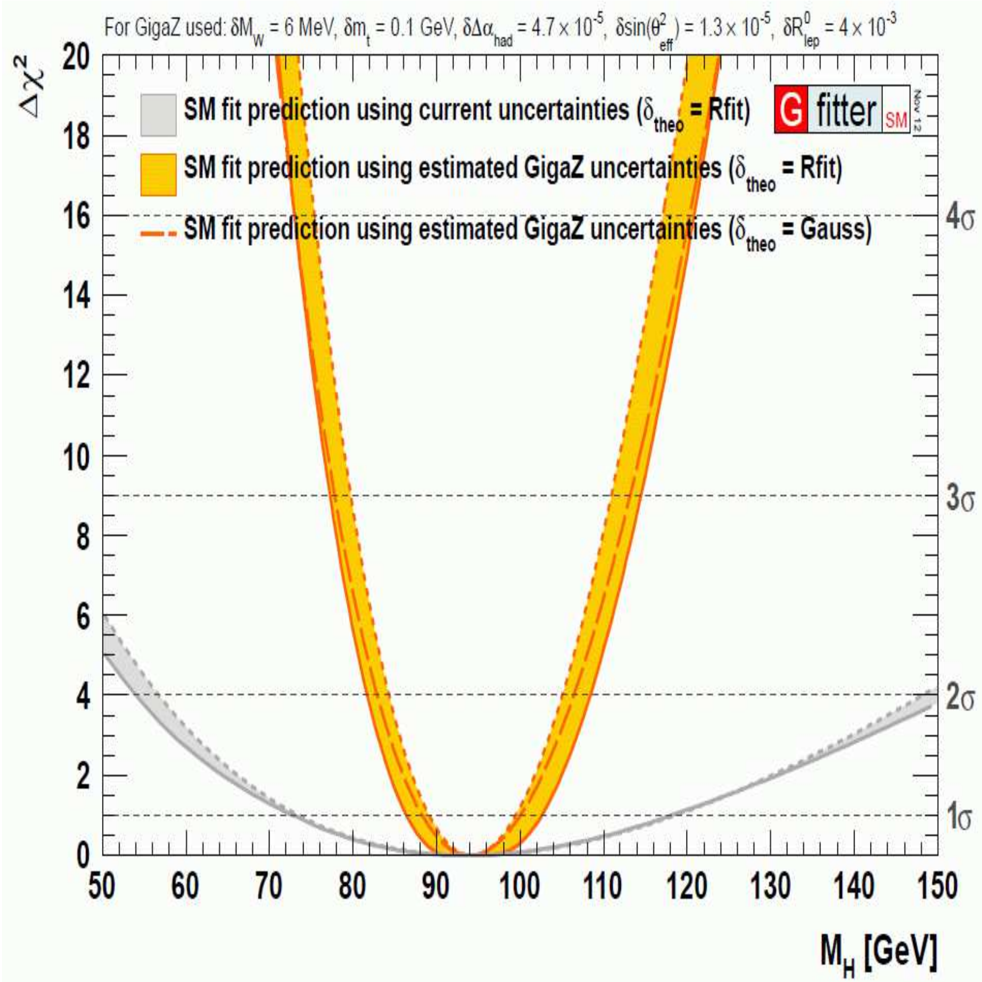
$\sin^2\theta_{\text{eff}}$: 1/2 year TeraZ/GigaZ run (GigaZ: polarization important)

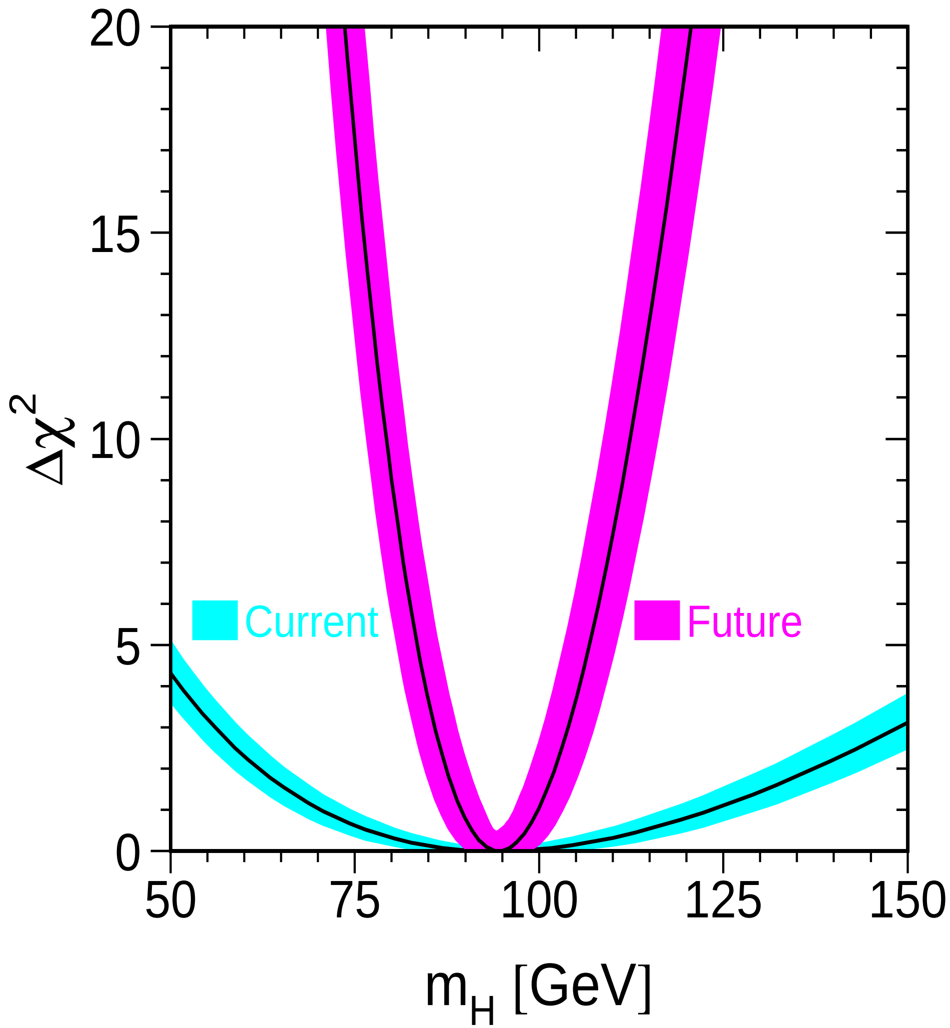
α_s : Improvement from GigaZ/TeraZ run

$\Rightarrow$ no theory uncertainties included $\Rightarrow$ lecture by A. Freitas

Most precise M_H test with the ILC:

[GFitter '13] [LEPEWWG '13]





$\Rightarrow \delta M_H^{\text{ind}} \lesssim 6$ GeV

$\Rightarrow$ extremely sensitive test of SM (and BSM) possible

BSM Higgs sectors at future e^+e^- colliders

Remember (I):

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

Q: Does the BSM physics have any (relevant) impact on the Higgs?
Q': Which model?

A1: check changed properties of the h_{125}

A2: check for additional Higgs bosons
A2': check for additional Higgs bosons above and below 125 GeV

Remember (II):

Models with extended Higgs sectors:

1. SM with addional Higgs singlet
2. Two Higgs Doublet Model (THDM): type I, II, III, IV
3. Minimal Supersymmetric Standard Model (MSSM)
4. MSSM with one extra singlet (NMSSM)
5. MSSM with more extra singlets
6. SM/MSSM with Higgs triplets
7. . . .

⇒ BSM models without extended Higgs sectors still have changed Higgs properties (quantum corrections!)

⇒ SM + vector-like fermions, Higgs portal, Higgs-radion mixing, . . .

Remember (III):

Which model should we focus on? ⇒ experimental data as guidance!

Some "recent" measurements:

– top quark mass
– Higgs boson mass
– Higgs boson "couplings"
– Dark Matter (properties)

Simple SUSY models predicted correctly:

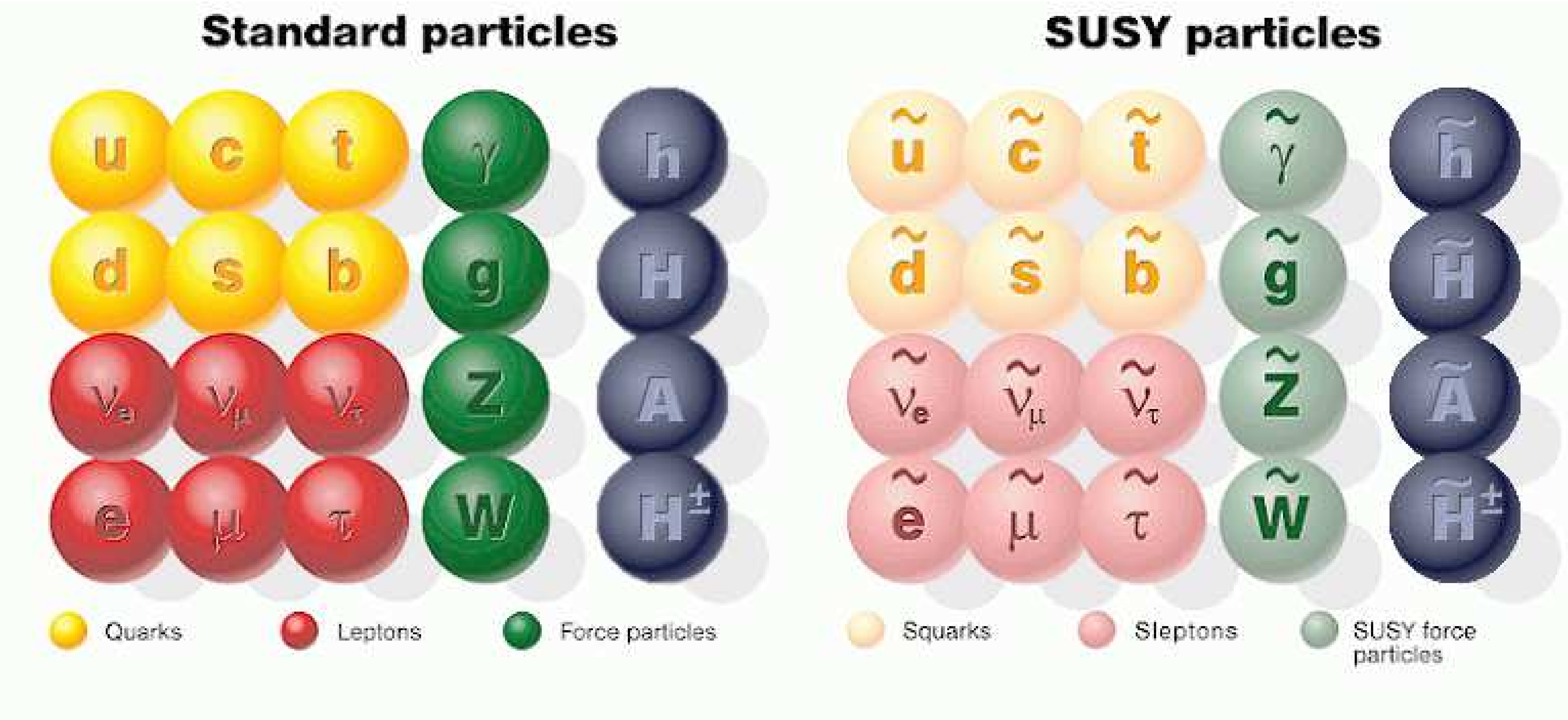
– top quark mass
– Higgs boson mass
– Higgs boson "couplings"
– Dark Matter (properties)

⇒ good motivation to look at SUSY! :-)

But we also look at other models (2HDM, N2HDM, . . .)

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature
has so many free parameters! ⇒ GUT based models?!

The MSSM Higgs sector:

Comparison with SM case:

$$\mathcal{L}_{\text{SM}} = \underbrace{m_d \bar{Q}_L \Phi d_R}_{\text{d-quark mass}} + \underbrace{m_u \bar{Q}_L \Phi_c u_R}_{\text{u-quark mass}}$$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \Phi_c = i\sigma_2 \Phi^*, \quad \Phi \to \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \Phi_c \to \begin{pmatrix} v \\ 0 \end{pmatrix}$$

In SUSY: term $\bar{Q}_L \Phi^*$ not allowed

Superpotential is holomorphic function of chiral superfields, i.e. depends only on φ_i, not on φ_i^*

No soft SUSY-breaking terms allowed for chiral fermions

$\Rightarrow$ $H_d (\equiv H_1)$ and $H_u (\equiv H_2)$ needed to give masses to down- and up-type fermions

Furthermore: two doublets also needed for cancellation of anomalies, quadratic divergences

The MSSM Higgs sector:

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}(H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$ Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

Tree-level result for m_h, m_H:

$$m^2_{H,h} = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right]$$

$\Rightarrow$ $m_h \leq M_Z$ at tree level

$\Rightarrow$ Light Higgs boson h required in SUSY

Measurement of m_h, Higgs couplings

$\Rightarrow$ test of the theory (more directly than in SM)

Scalar top ($\tilde{t}$) sector of the MSSM

Stop mass matrices

$$\mathbf{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

with

$$X_t = A_t - \mu / \tan\beta$$

$\Rightarrow$ mixing important in stop sector!

Simplifying abbreviation:

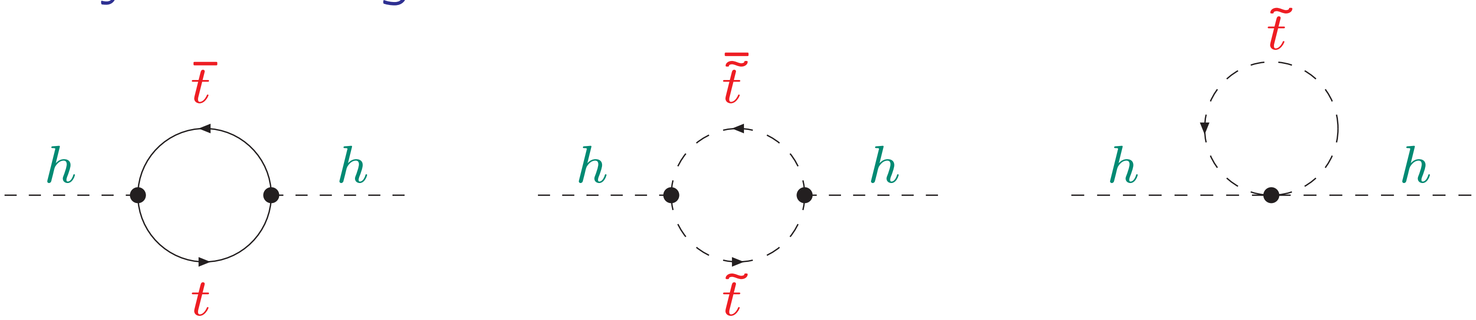
$$M_{\text{SUSY}} = M_S := M_{\tilde{t}_L} = M_{\tilde{t}_R}$$

Problem of the MSSM:

$$m_h \leq M_Z \text{ at tree level}$$

$\Rightarrow$ Quantum corrections come to rescue!

1-Loop: Feynman diagrams:



Dominant 1-loop corrections: $\Delta M_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

size of the corrections: $\mathcal{O}$(50 GeV)

$\Rightarrow M_h \sim 125$ GeV reached for $m_{\tilde{t}} \gtrsim 1.5$ TeV

Upper bound on M_h in the MSSM:

"Unconstrained MSSM":

M_A, $\tan\beta$, 5 parameters in $\tilde{t}$–$\tilde{b}$ sector, μ, $m_{\tilde{g}}$, M_2

$$M_h \lesssim 135 \text{ GeV}$$

for $m_t = 173.2 \pm 0.9\,\text{GeV}$ and $m_{\tilde{t}} \lesssim 2$ TeV

(including theoretical uncertainties from unknown higher orders)

$\Rightarrow$ in agreement with all LHC Higgs measurements and stop searches

Obtained with:

FeynHiggs

www.feynhiggs.de

[*H. Bahl, T. Hahn, S.H., W. Hollik, S. Passehr, H. Rzehak, G. Weiglein '98 – '21*]

$\rightarrow$ all Higgs masses, couplings, BRs, XSs (easy to link, easy to use :-)

Upper bound on M_h in the MSSM:

"Unconstrained MSSM":

M_A, $\tan\beta$, 5 parameters in $\tilde{t}$–$\tilde{b}$ sector, μ, $m_{\tilde{g}}$, M_2

$M_h \lesssim 135$ GeV   Note : $125 < 135$!

for $m_t = 173.2 \pm 0.9\,\text{GeV}$ and $m_{\tilde{t}} \lesssim 2$ TeV

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2 Higgs Doublet Model without SUSY restrictions:

The 2HDM

Two Higgs Doublet Model CP conserving

The potential:

$$V = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$

Considerations:

- ⋆ CP conserving $\longrightarrow$ all parameters are real
- ⋆ $\mathbb{Z}_2$ symmetry to avoid FCNC $\longrightarrow$ softly broken by m_{12}^2 **Very important!**
- ⋆ Four types of Yukawa structure (we will focus on type I and II)

7 free parameters + 5 physical states: h, H, A, H^+ and H^-

(A: CP odd; h, H: CP even)

Extension of Z_2 symmetry to fermions $\Rightarrow$ 4 types

Possible choice for free parameters:

Free parameters of the 2HDM

- ⋆ Physical masses: m_h, m_H, m_A and $m_{H^\pm}$
  - ⋆ We set $m_h = 125$ GeV
  - ⋆ The rest Higgs bosons are assumed to be heavier
- ⋆ $\tan(\beta) := v_2/v_1$: Ratio of the Higgs doublets vevs
- ⋆ $\cos(\beta - \alpha)$: α diagonalizes the neutral CP even states h and H
  - ⋆ If $\cos(\beta - \alpha) \to 0$ the SM Higgs couplings to gauge bosons are recovered $\Longrightarrow$ *Alignment limit*
  - ⋆ Alignment limit $\neq$ SM, we can have hH^+H^-, ZHA or $H^+u\bar{d}$ interactions even if $\cos(\beta - \alpha) = 0$
- ⋆ Soft $\mathbb{Z}_2$ breaking parameter m_{12}^2
  - ⋆ It only enters in the scalar sector

Alignment limit: $\cos(\beta - \alpha) \to 0$

Higgs-boson couplings in the 2HDM

$$\mathcal{L} = -\sum_{f=u,d,l} \frac{m_f}{v}\left[\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H + i\xi_A^f \bar{f}\gamma_5 f A\right]$$
$$+ \sum_{h_i=h,H,A}\left[g M_W \xi_{h_i}^W W_\mu W^\mu h_i + \frac{1}{2} g M_Z \xi_{h_i}^Z Z_\mu Z^\mu h_i\right],$$

	I	II	III/Y/Flipped	IV/X/Lepton-Specific
u-quarks	Φ_2	Φ_2	Φ_2	Φ_2
d-quarks	Φ_2	Φ_1	Φ_1	Φ_2
leptons	Φ_2	Φ_1	Φ_2	Φ_1

Table 1: Couplings to fermions for the four 2HDM types.

	I	II	III/Y/Flipped	IV/X/Lepton-Specific
ξ_h^u	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$
ξ_h^d	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$
ξ_h^l	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta$
ξ_H^u	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$
ξ_H^d	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta$	$c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$
ξ_H^l	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta$
ξ_A^u	$-\cot\beta$	$-\cot\beta$	$-\cot\beta$	$-\cot\beta$
ξ_A^d	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$
ξ_A^l	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$

Table 2: Couplings to fermions for the four 2HDM types.

Required precision for Higgs couplings?

MSSM example:

$$\kappa_V \approx 1 - 0.5\% \left(\frac{400\text{ GeV}}{M_A}\right)^4$$

$$\kappa_t = \kappa_c \approx 1 - \mathcal{O}(10\%) \left(\frac{400\text{ GeV}}{M_A}\right)^2 \cot^2\beta$$

$$\kappa_b = \kappa_\tau \approx 1 + \mathcal{O}(10\%) \left(\frac{400\text{ GeV}}{M_A}\right)^2$$

Composite Higgs example:

$$\kappa_V \approx 1 - 3\% \left(\frac{1\text{ TeV}}{f}\right)^2$$

$$\kappa_F \approx 1 - (3-9)\% \left(\frac{1\text{ TeV}}{f}\right)^2$$

⇒ couplings to bosons in the per mille range

⇒ couplings to fermions in the per cent range

⇒ theory/experimental match?

Let us assume that we do see a deviation

What do we learn from that?
How do we learn something from that?

⇒ We have to compare the observed deviation with predicted deviations

⇒ Preferrably with the predicted deviations in a concrete models
(A comparison with an EFT result subsequently requires the mapping to concrete models anyway . . .)

⇒ Needed: sufficiently precise predictions in BSM model
close to ready: MSSM, NMSSM
(I am not aware of uncertainty estimates in other models)

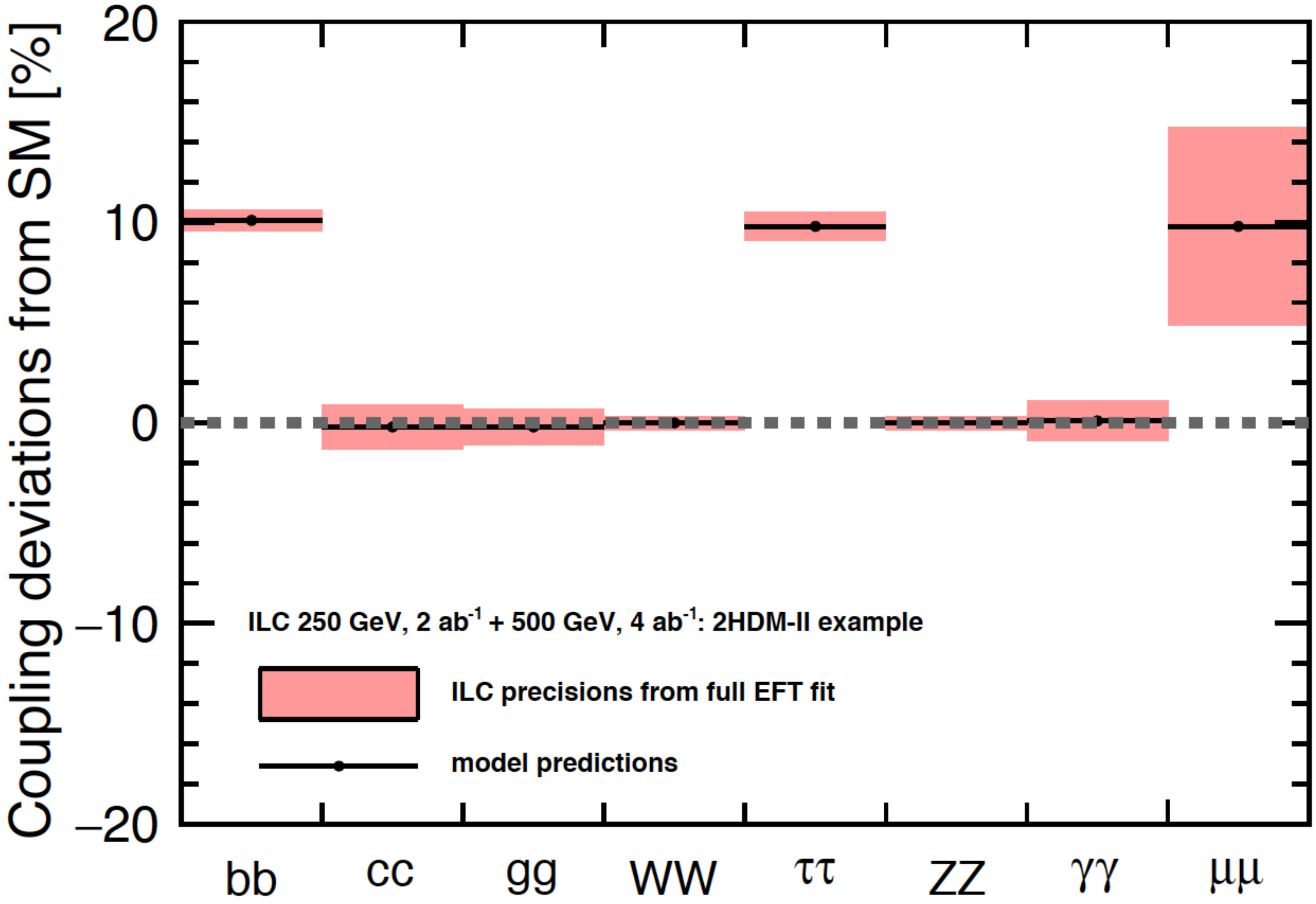
⇒ in the following:

model prediction (w/o TH unc.) ⇔ e^+e^- precision

⇒ “Wäscheleinen-Plots” (concrete: ILC500 – FCC-ee similar!)

Wäscheleine I: e^+e^- precision vs. 2HDM type II prediction:

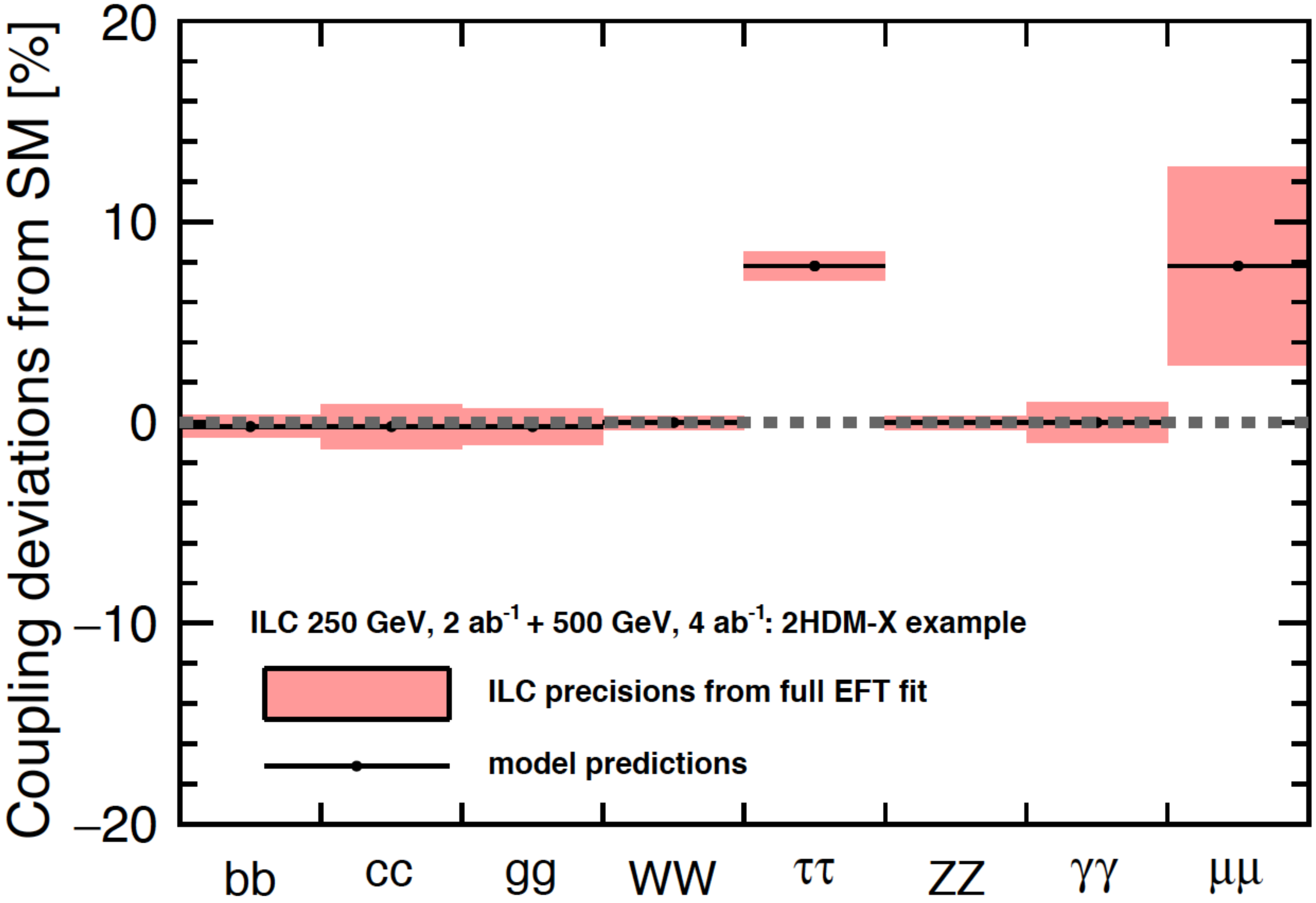
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for 2HDM type II?!

Wäscheleine II: e^+e^- precision vs. 2HDM type X prediction:

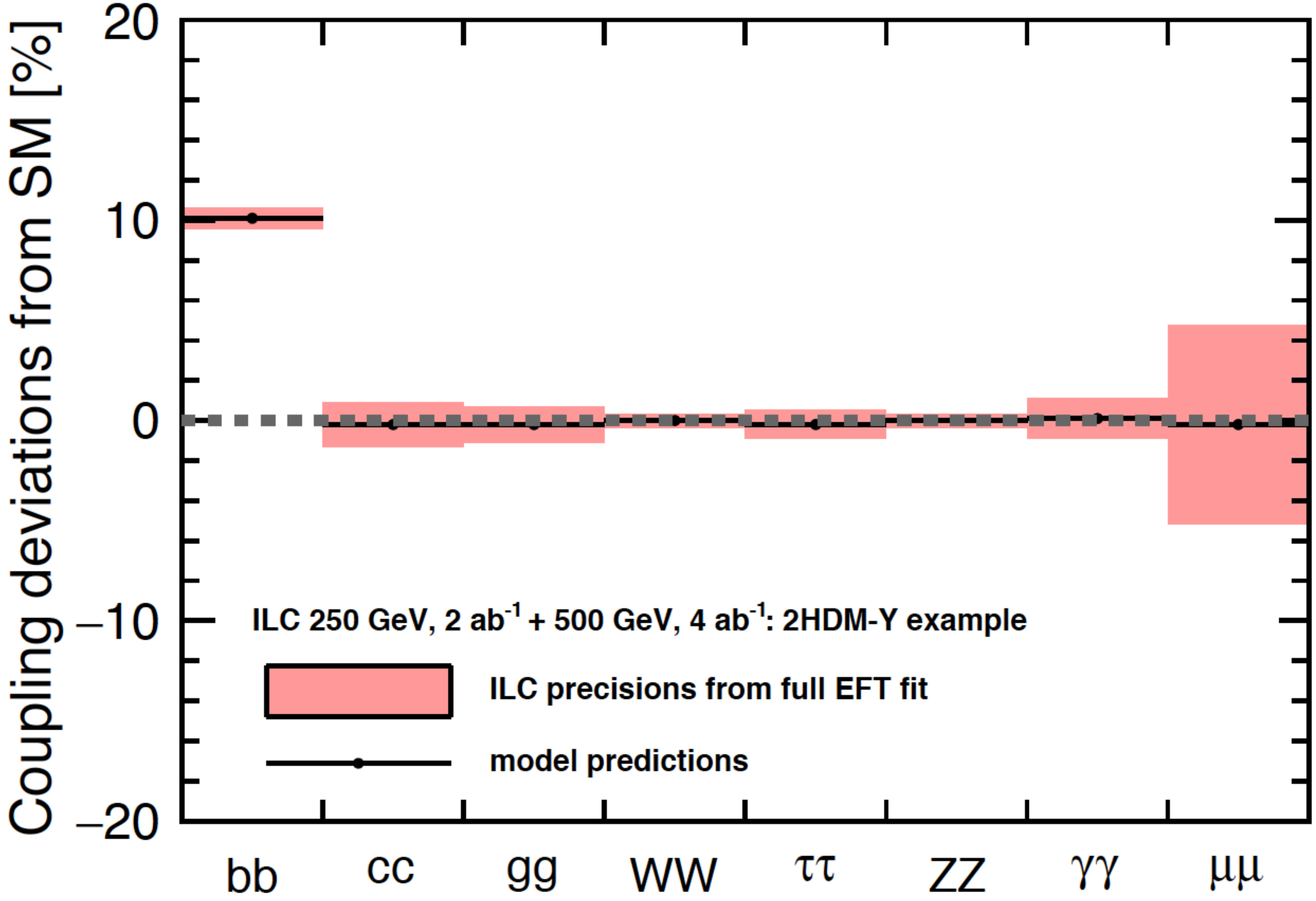
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for 2HDM type X?!

Wäscheleine III: e^+e^- precision vs. 2HDM type Y prediction:

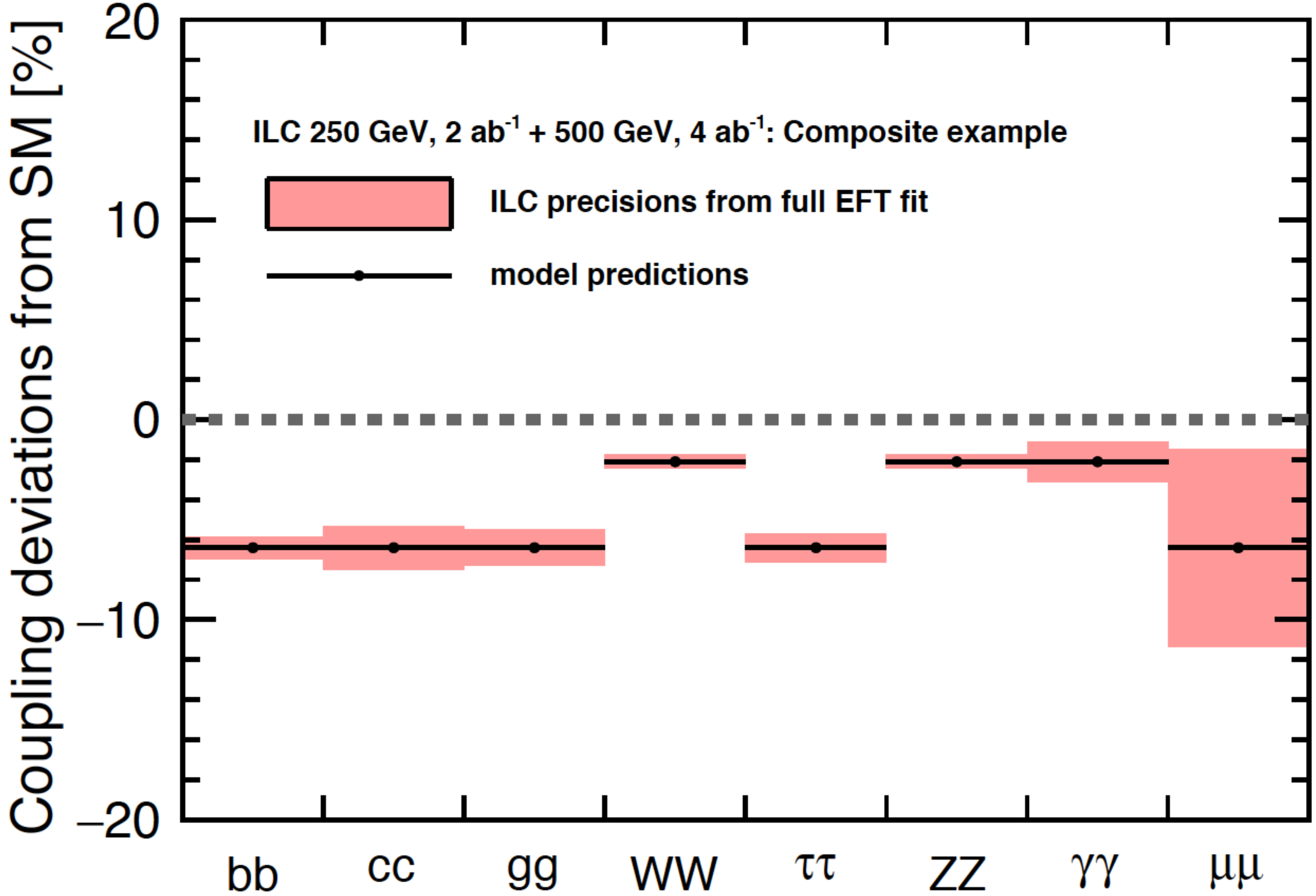
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for 2HDM type Y?!

Wäscheleine IV: e^+e^- precision vs. Composite Higgs prediction:

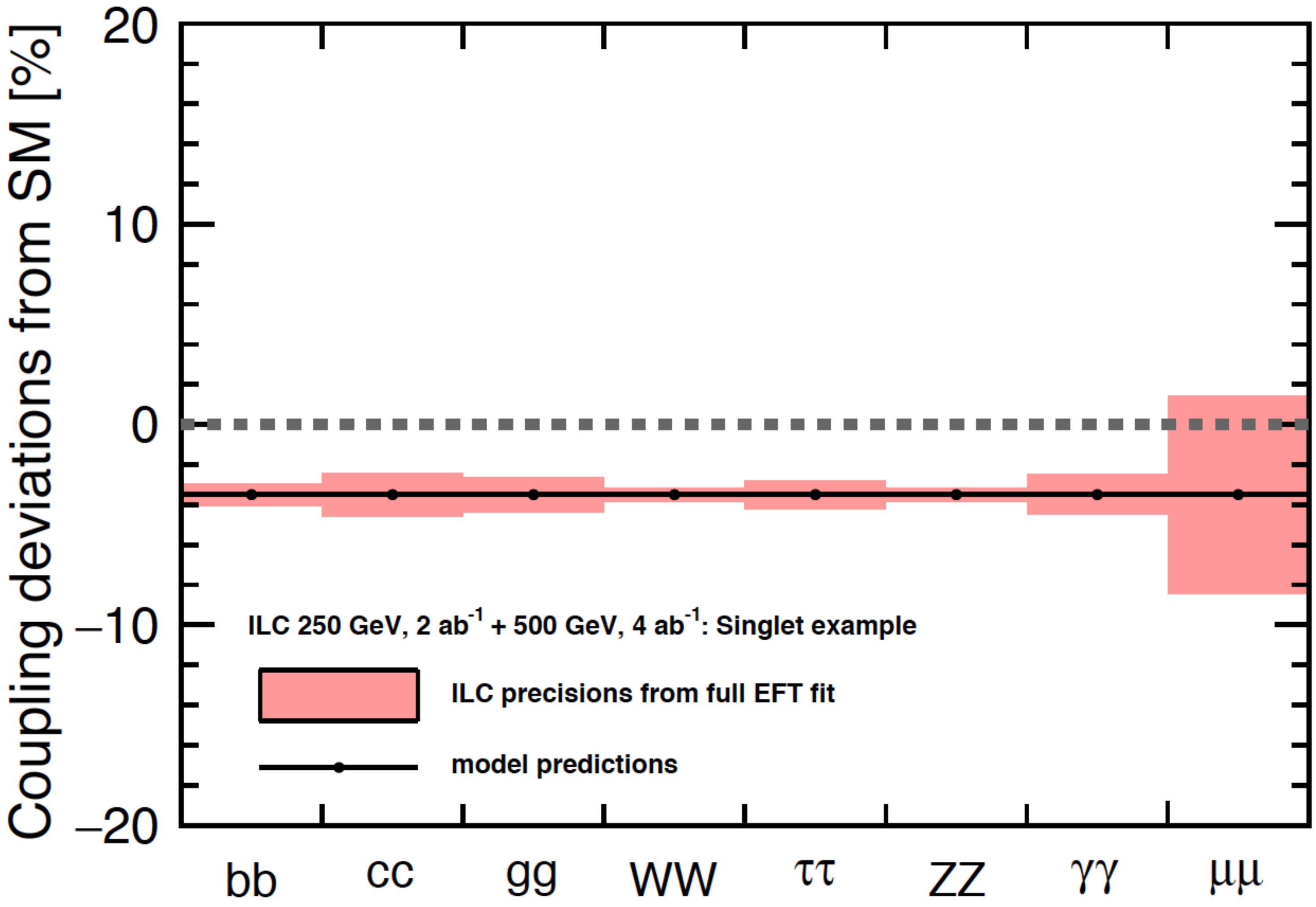
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for Composite Higgs?!

Wäscheleine V: e^+e^- precision vs. HxSM prediction:

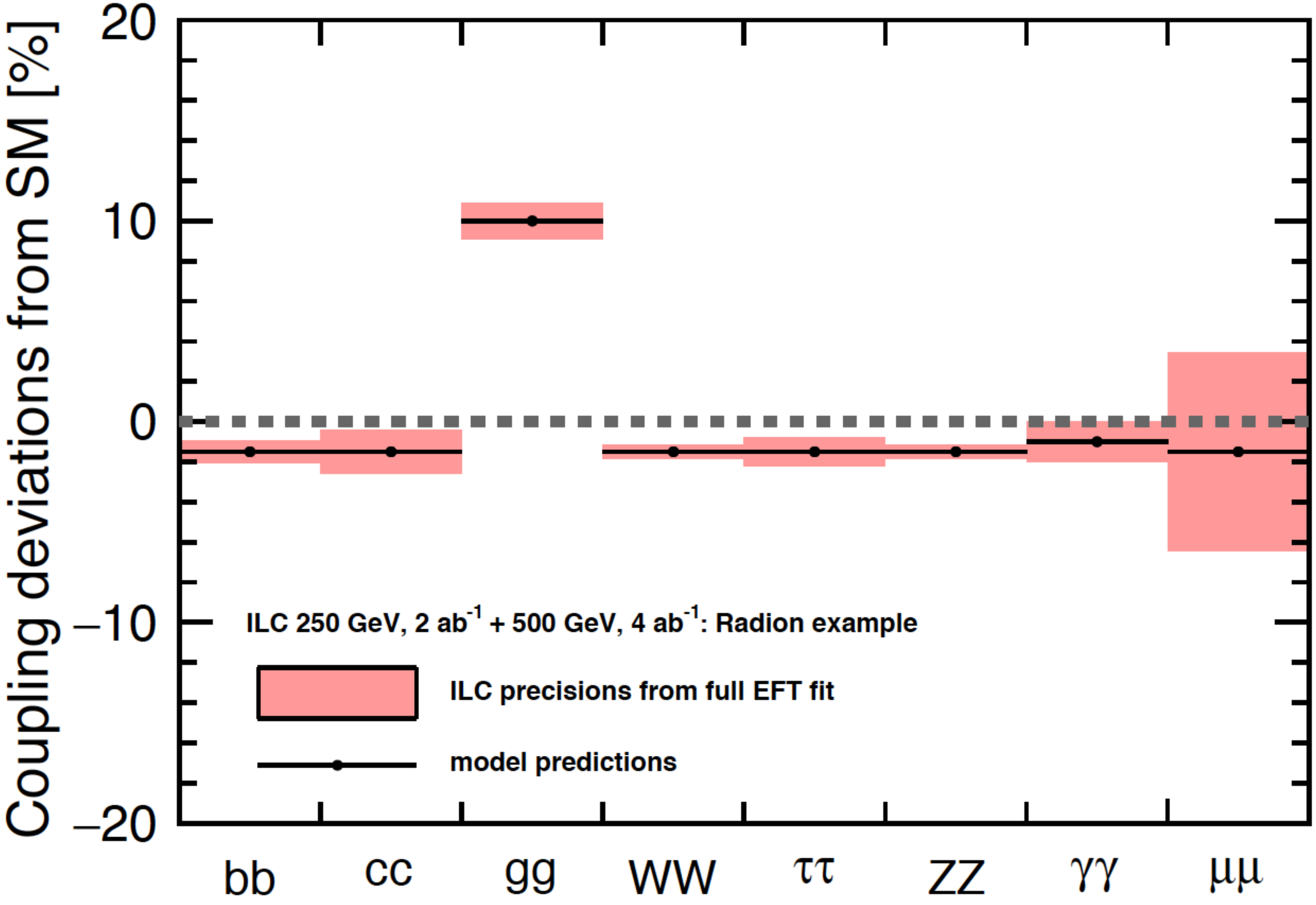
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for HxSM?!

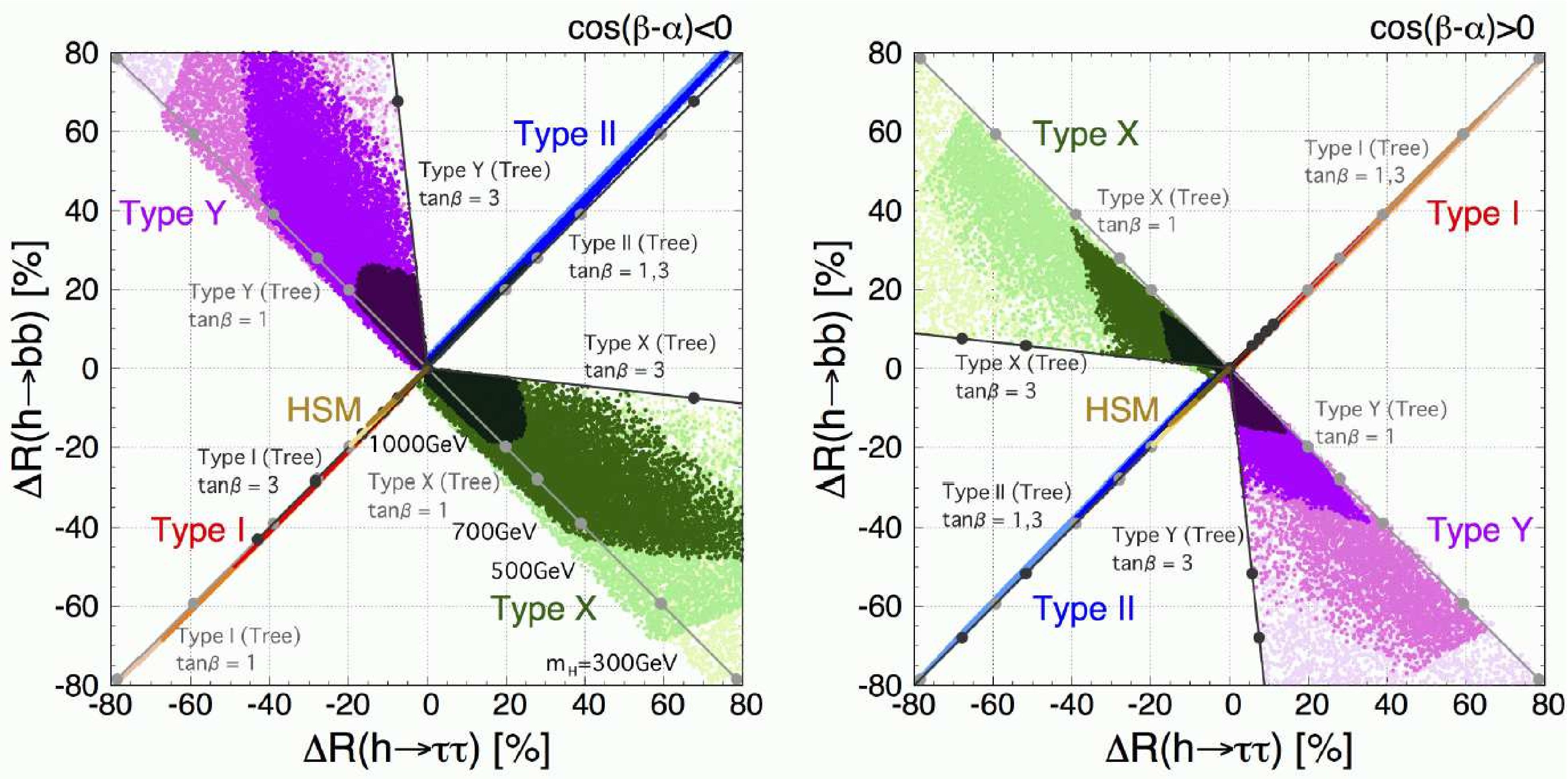
Wäscheleine VI: e^+e^- precision vs. Higgs-Radion prediction:

[*T. Barklow et al., '17*]



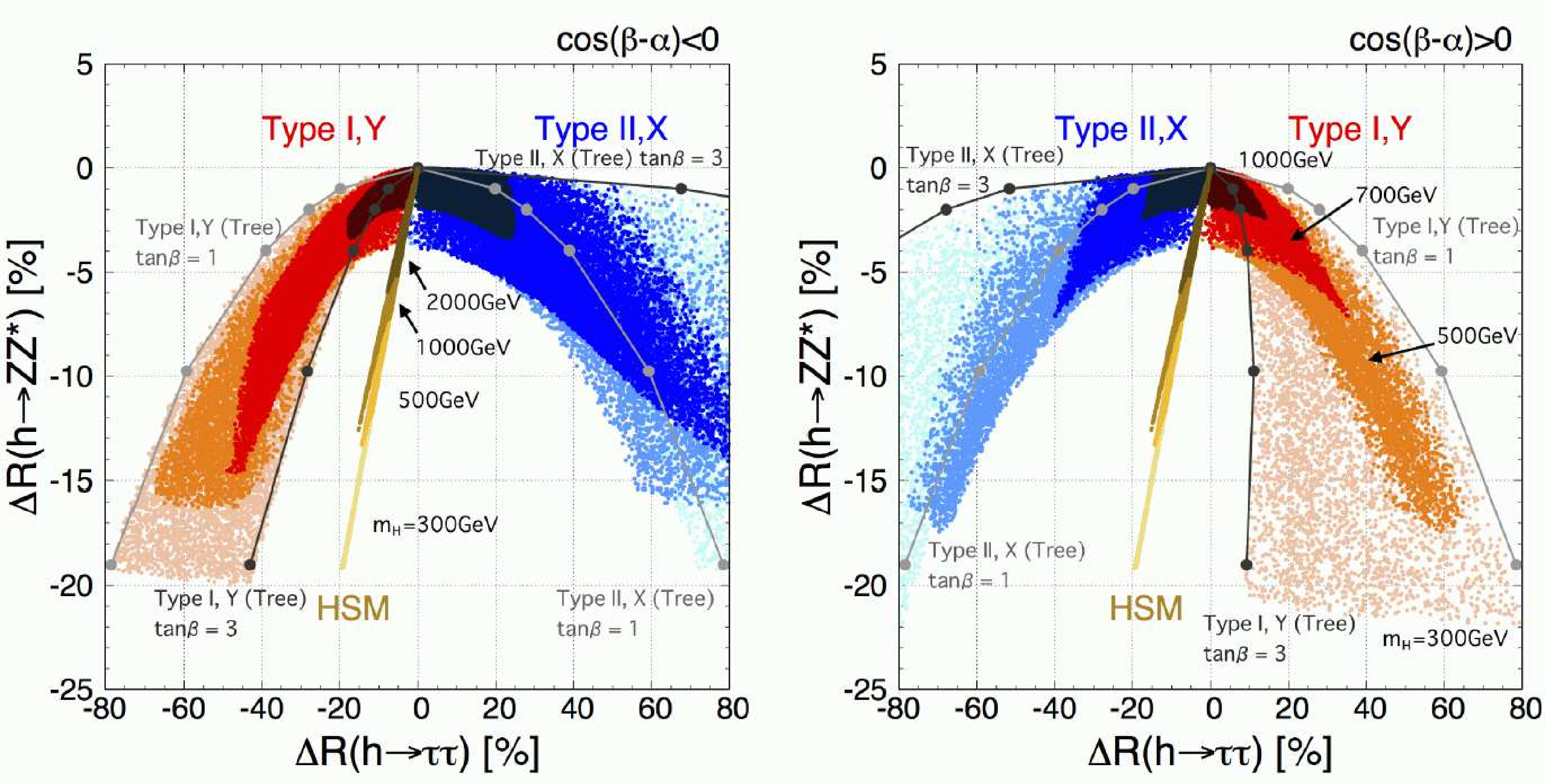
⇒ clear pattern, distinctive for Higgs Radion?!

2HDM example (I): [S. Kanemura et al. '18]



⇒ LC precision has a great potential to discriminate the models!

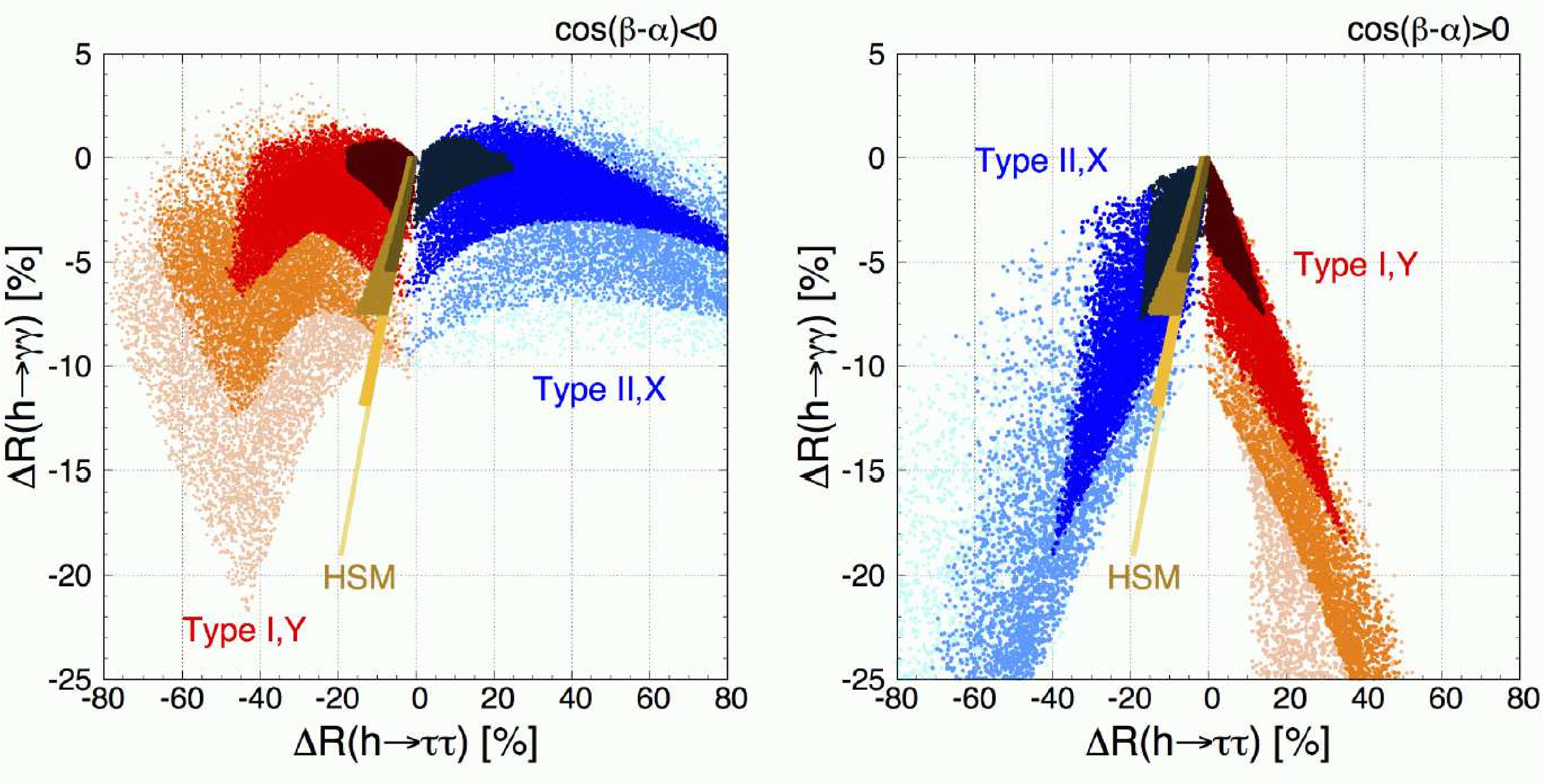
 [*S. Kanemura et al. '18*]



⇒ LC precision has a great potential to discriminate the models!

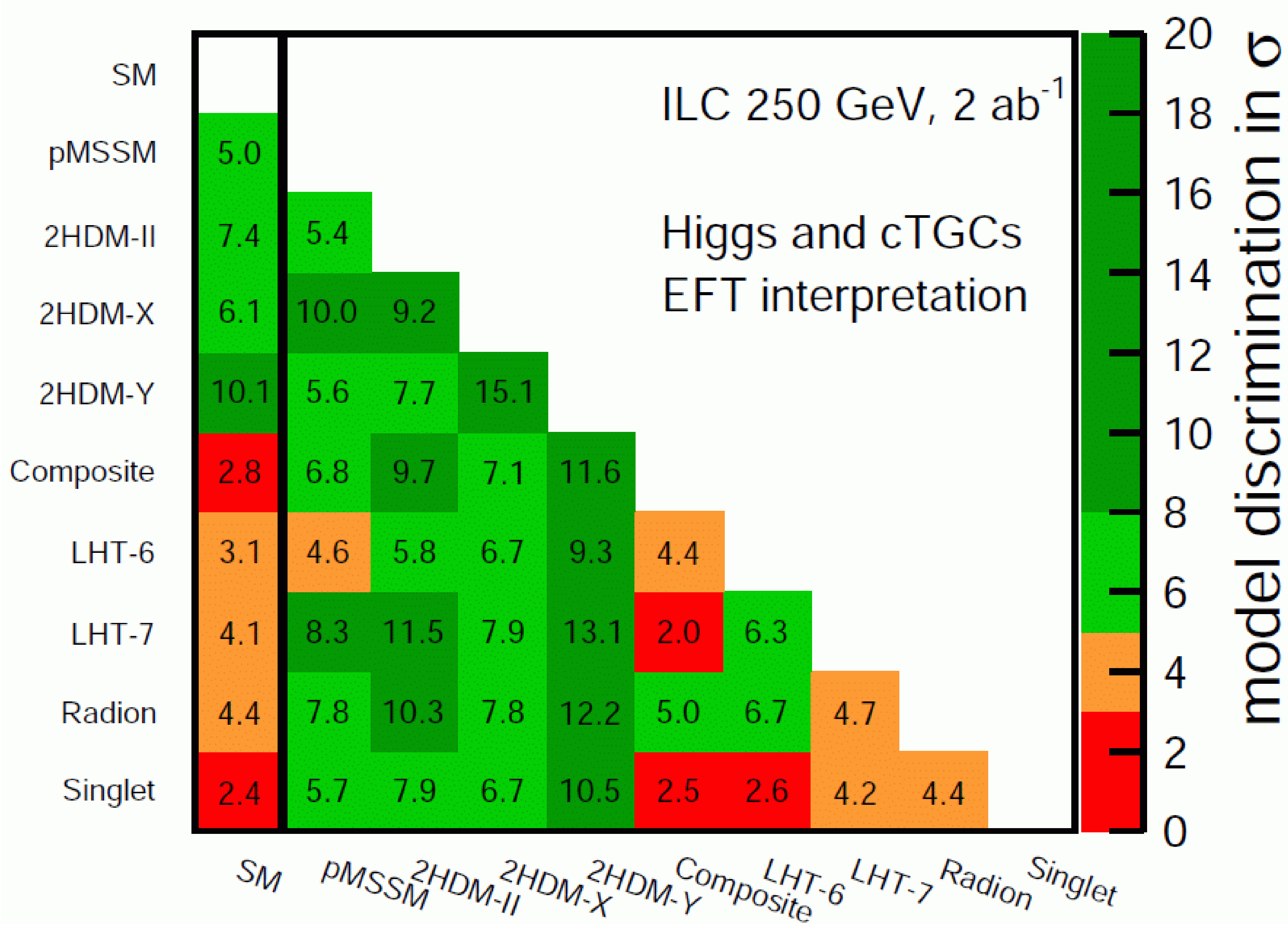
2HDM example (III):

[*S. Kanemura et al. '18*]



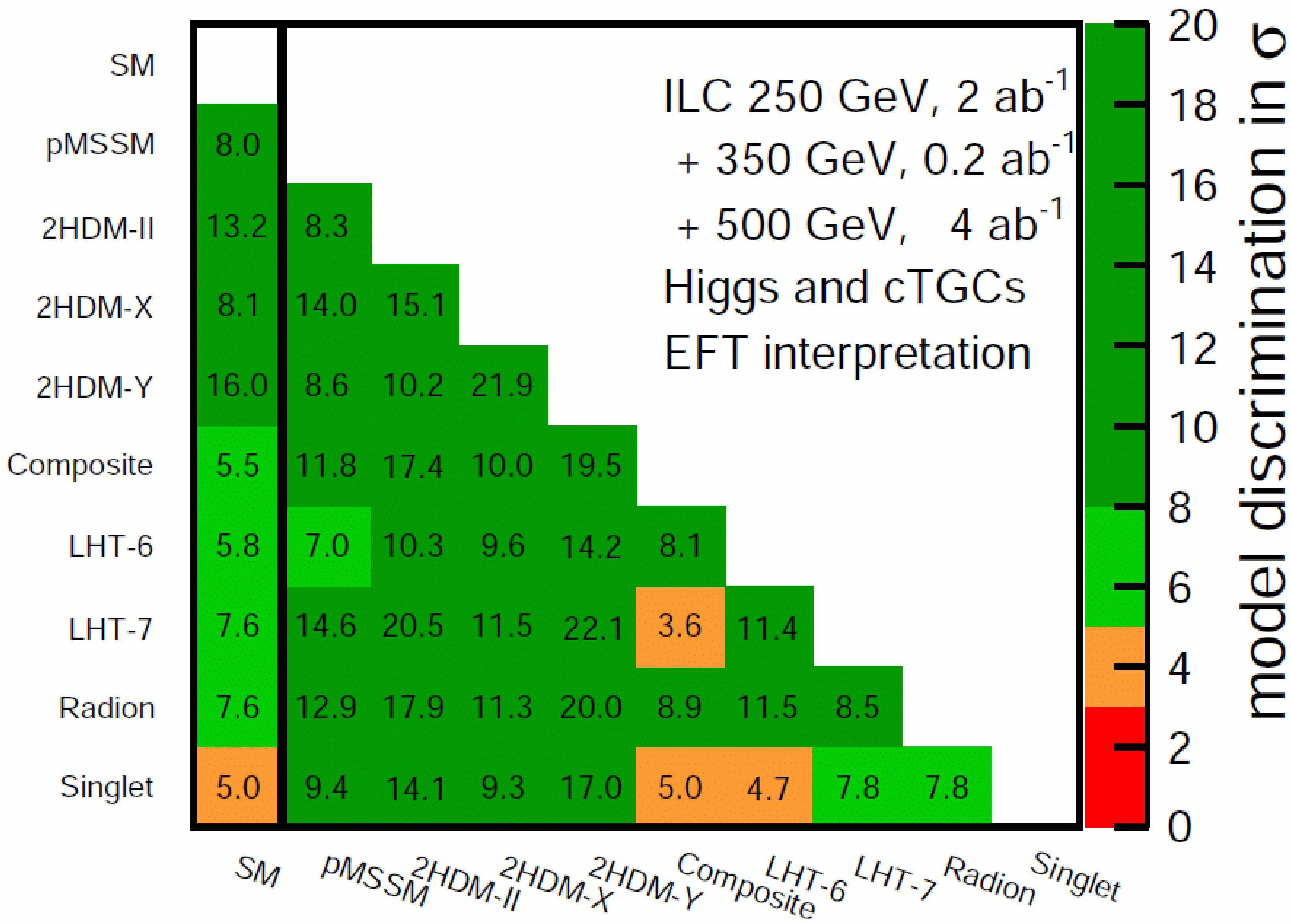
⇒ LC precision has a great potential to discriminate the models!

Model discrimination at ILC250: [*K. Fujii et al. '17*]



	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion
pMSSM	5.0								
2HDM-II	7.4	5.4							
2HDM-X	6.1	10.0	9.2						
2HDM-Y	10.1	5.6	7.7	15.1					
Composite	2.8	6.8	9.7	7.1	11.6				
LHT-6	3.1	4.6	5.8	6.7	9.3	4.4			
LHT-7	4.1	8.3	11.5	7.9	13.1	2.0	6.3		
Radion	4.4	7.8	10.3	7.8	12.2	5.0	6.7	4.7	
Singlet	2.4	5.7	7.9	6.7	10.5	2.5	2.6	4.2	4.4

Model discrimination at ILC500: [*K. Fujii et al. '17*]



Compare future colliders:

⇒ focus on Higgs searches and measurements

HL-LHC:

– will improve direct search limits
– will improve rate measurements (production × decay)
systematic/theory uncertainties: S2 scenario

[*M. Cepeda et al. '19 – YR18*]

ILC: (similar for FCC-ee/CEPC/CLIC)

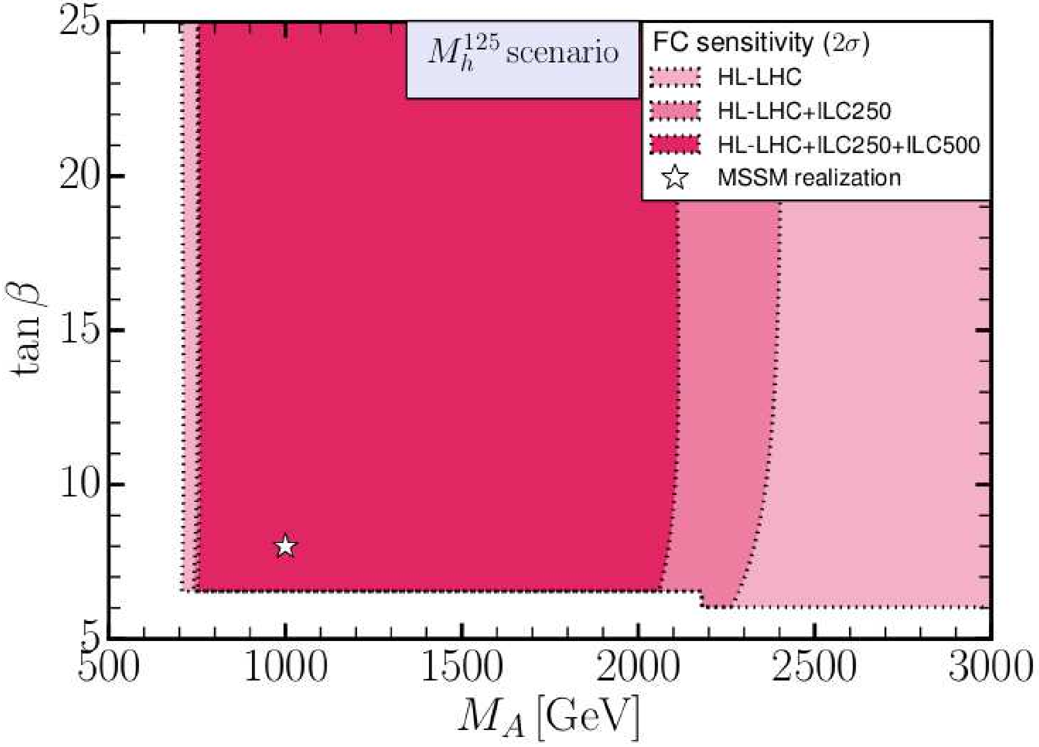
– will improve rate measurements (no theory assumptions!)
  – $250\,\text{fb}^{-1}$ at ILC250 $\oplus$ $500\,\text{fb}^{-1}$ at ILC500
  – polarization: $P(e^-, e^+) = (-80\%, +30\%)$

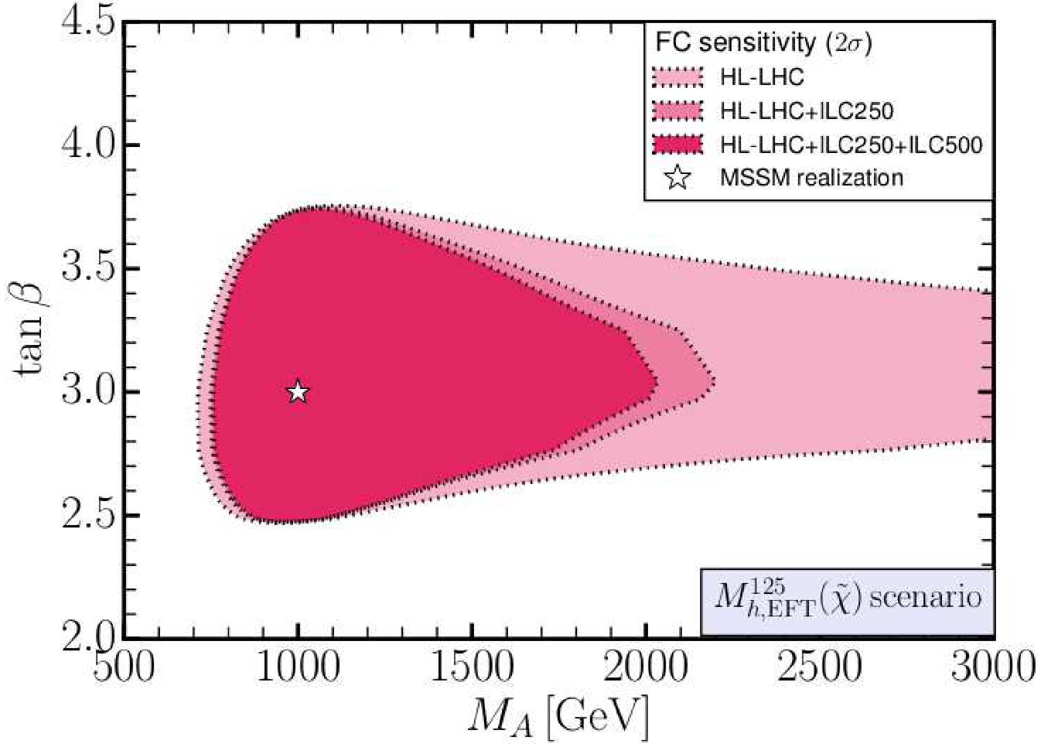
[*T. Barklow et al. '17, '19*]

Relevance of ILC measurements:

[H. Bahl et al., '20]

– Assume a realization of an MSSM point: $M_A = 1$ TeV, $\tan\beta = 7\,/\,3$
– What limits can be set from rate/coupling measurements?



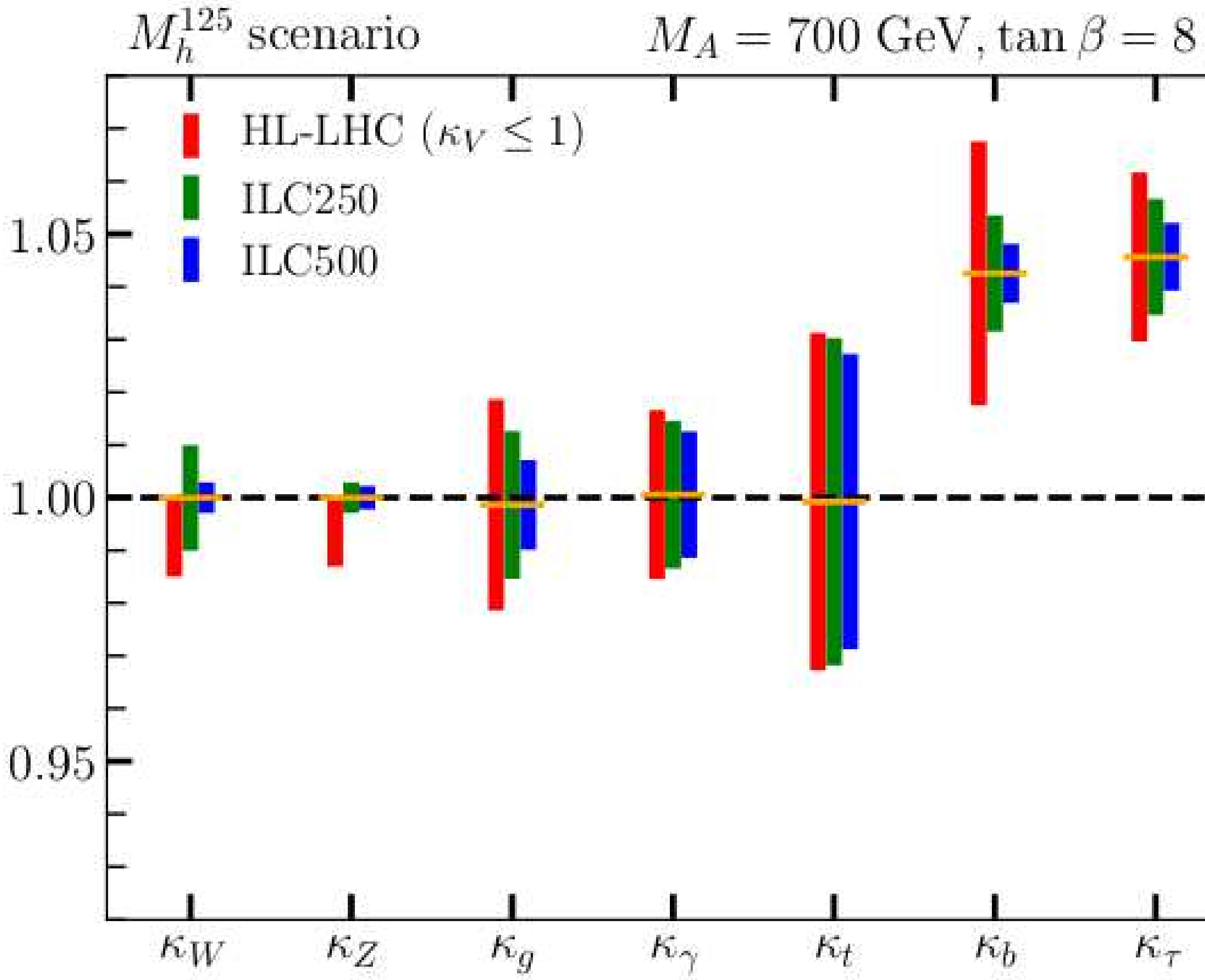


⇒ only ILC measurements give upper limit on M_A

⇒ limits on $\tan\beta$ only for small(er) $\tan\beta$

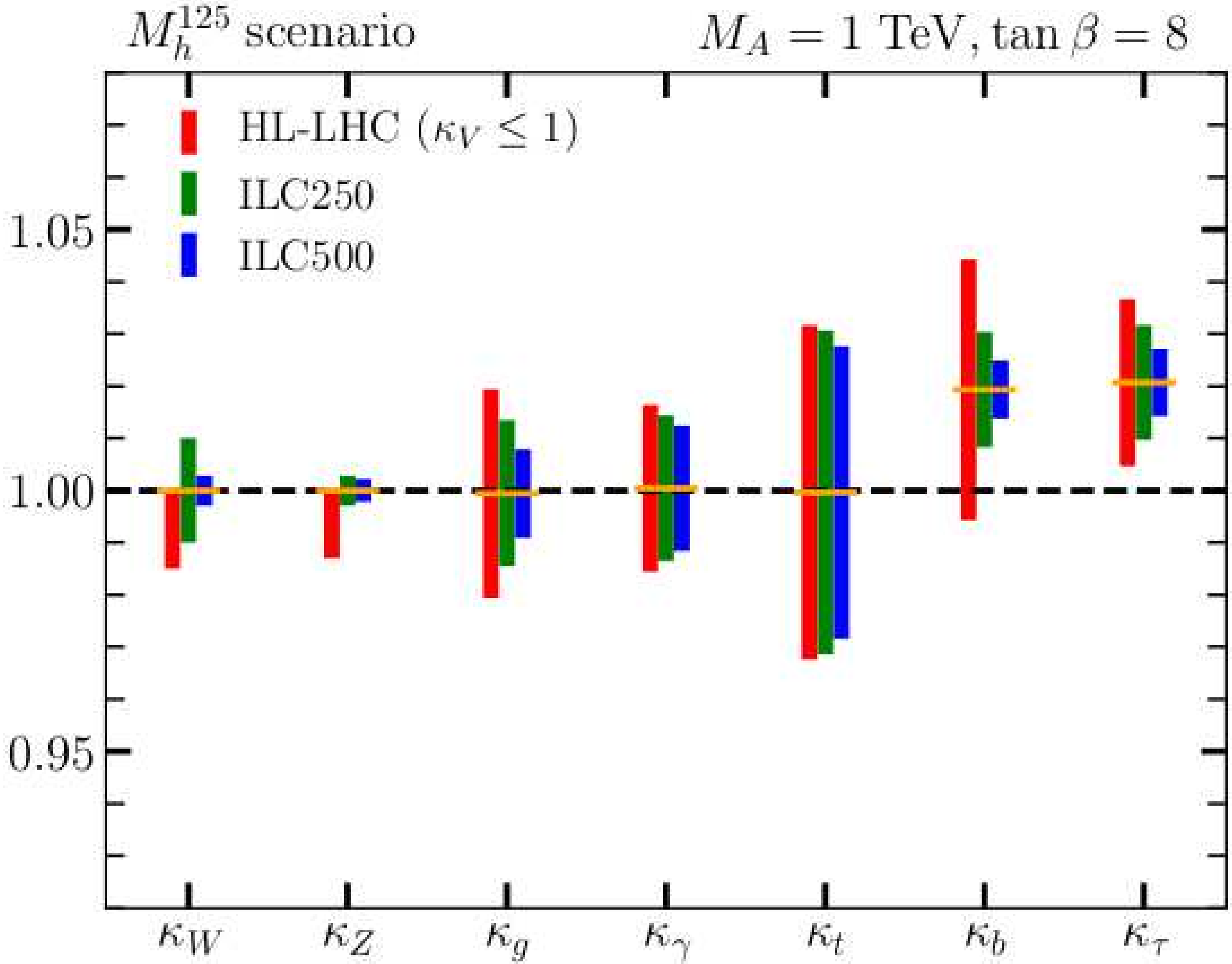
MSSM Wäscheleine I: e^+e^- precision vs. M_h^{125} ($M_A = 700$ GeV, $\tan\beta = 8$)

[*H. Bahl et al. '20*]



MSSM Wäscheleine II: e^+e^- precision vs. M_h^{125} ($M_A = 1000$ GeV, $\tan\beta = 8$)

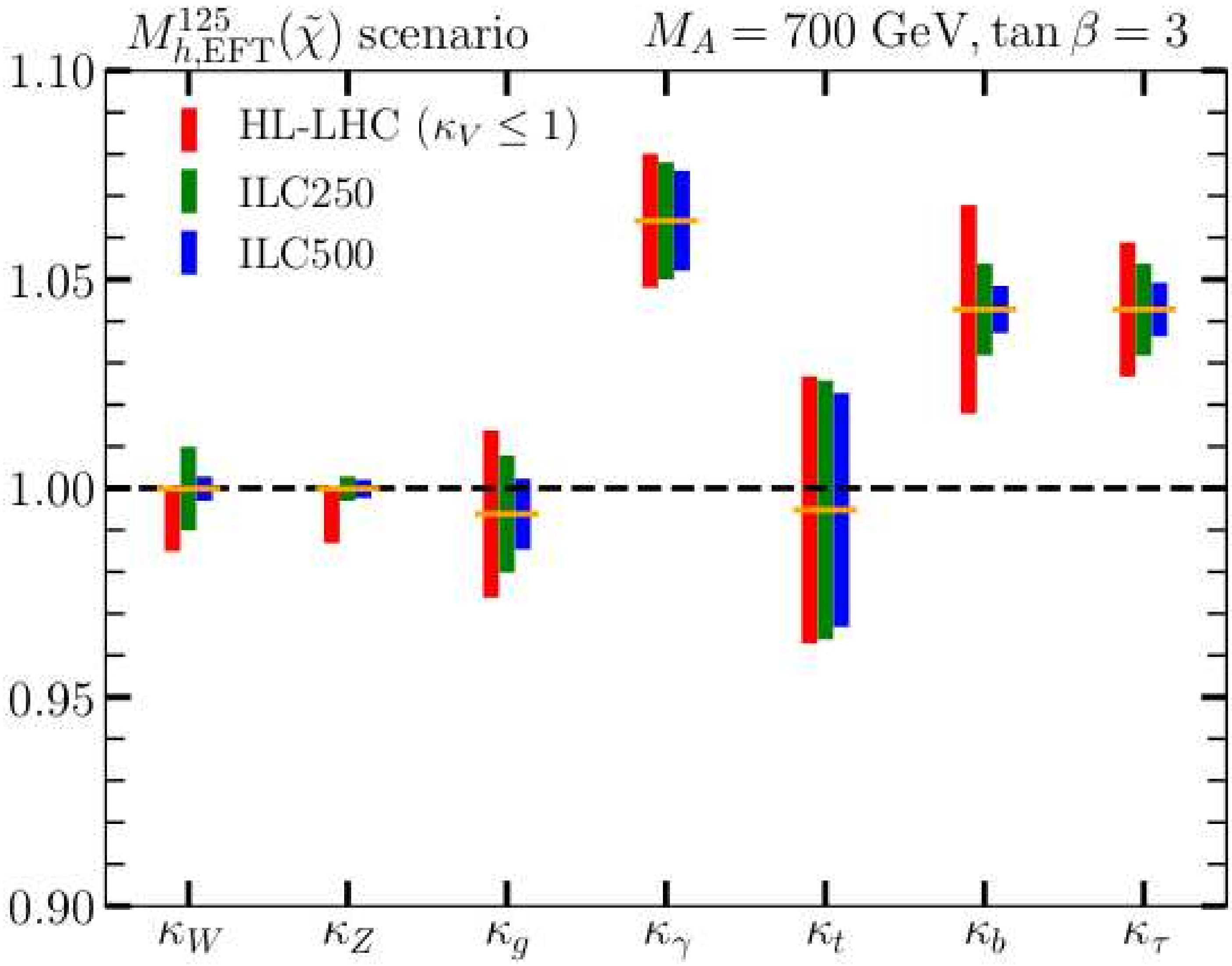
[*H. Bahl et al. '20*]



$\Rightarrow$ only e^+e^- measurements allows to set upper limit on M_A

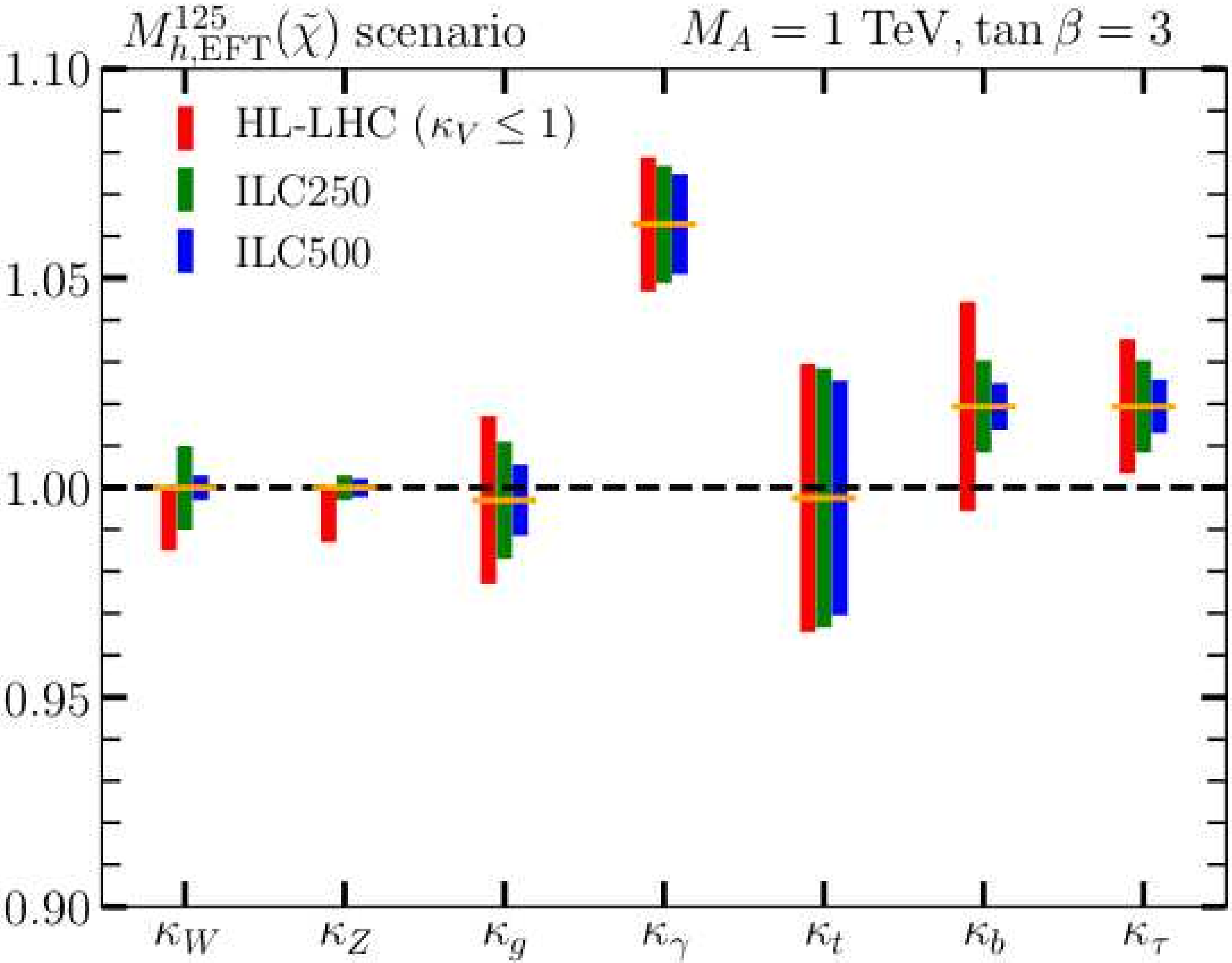
MSSM Wäscheleine III: e^+e^- vs. $M_h^{125,\text{EFT}}(\tilde{\chi})$ ($M_A = 700$ GeV, $\tan\beta = 3$)

[*H. Bahl et al. '20*]



MSSM Wäscheleine IV: e^+e^- vs. $M_h^{125,\mathrm{EFT}}(\tilde{\chi})$ ($M_A = 1000$ GeV, $\tan\beta = 3$)

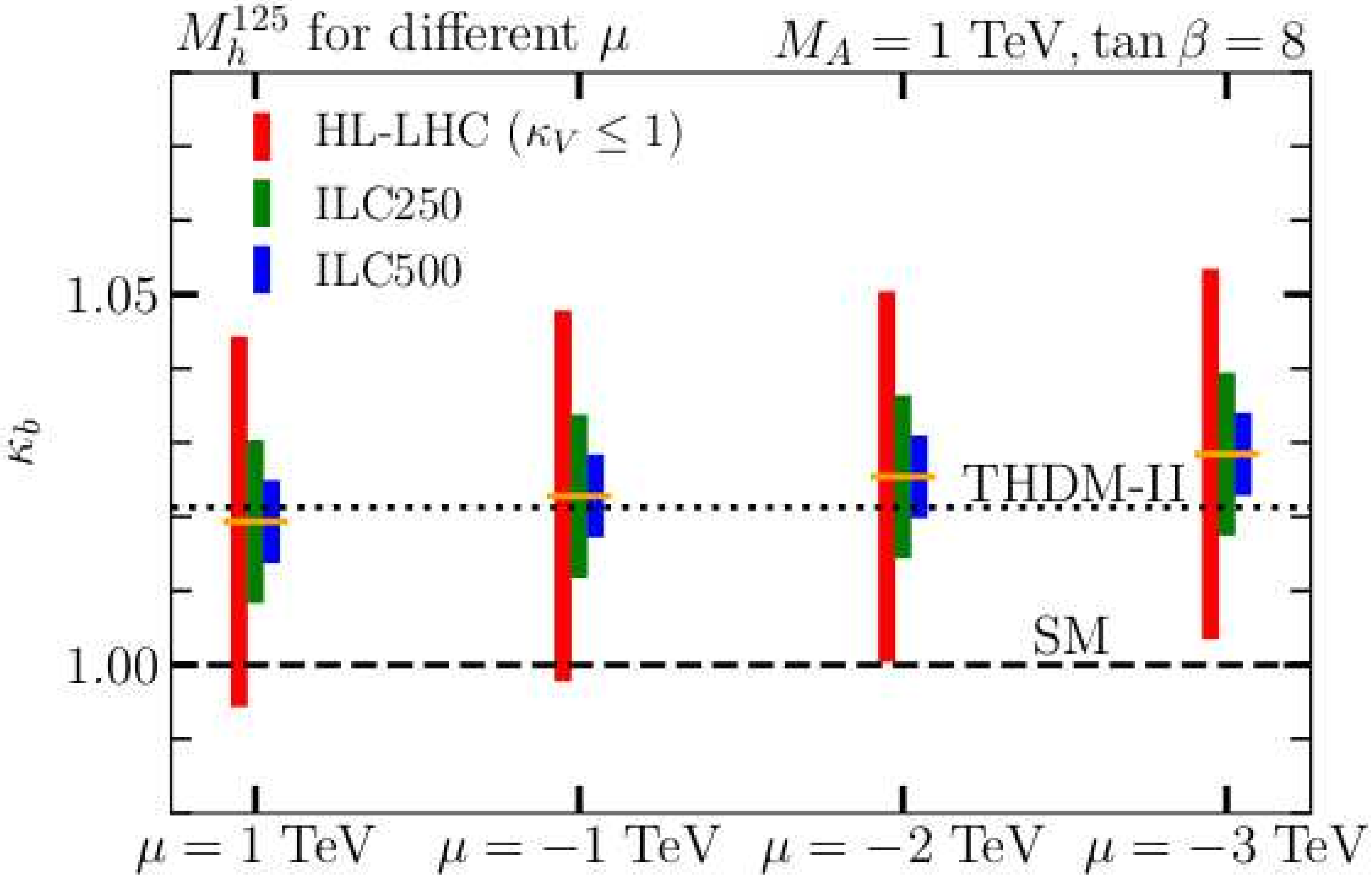
[*H. Bahl et al. '20*]



⇒ only e^+e^- measurements allows to set upper limit on M_A

MSSM Wäscheleine V: e^+e^- vs. M_h^{125} ($M_A = 1000$ GeV, $\tan\beta = 8$)

[*H. Bahl et al. '20*]

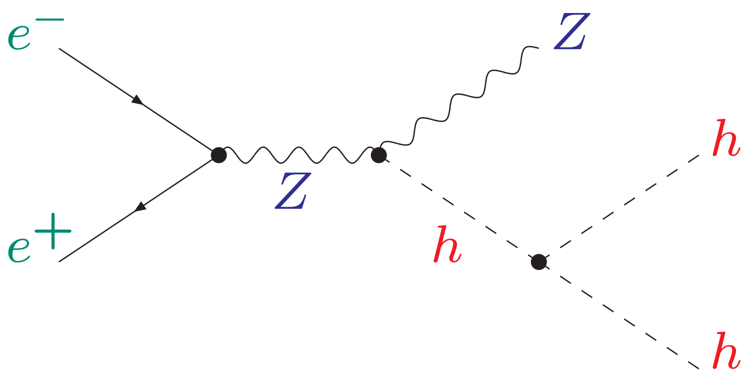


⇒ MSSM vs. 2HDM: very challenging!

Measurement of $\lambda_{hhh}^{\text{BSM}}$ at e^+e^- colliders: $\lambda_{hhh}^{\text{BSM}} \neq \lambda_{hhh}^{\text{SM}}$ possible!

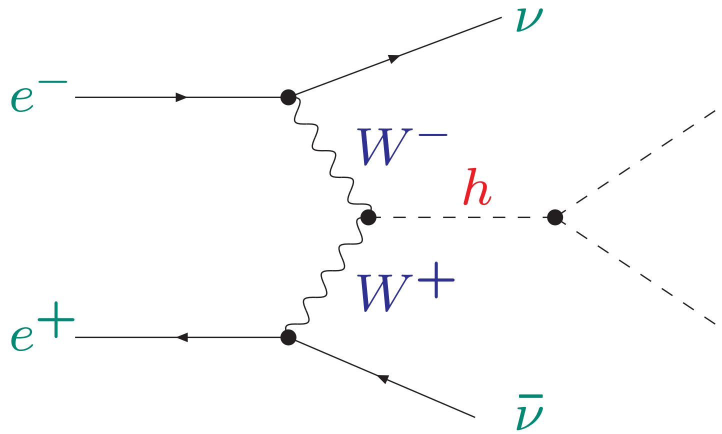
Higgs-strahlung:

$e^+e^- \to Z^* \to Zhh$

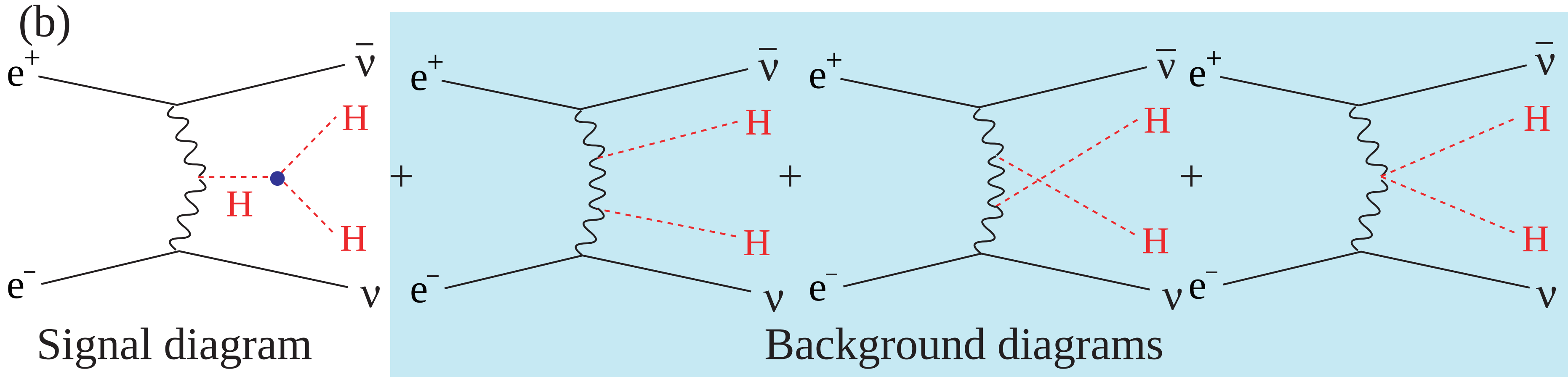


weak boson fusion (WBF):

$e+e- \to \nu\bar{\nu}hh$



Signal and background interference:



Desired precision in λ?

$\Rightarrow$ highly model dependent

Examples: [*R. Gupta, H. Rzehak, J. Wells '13*]

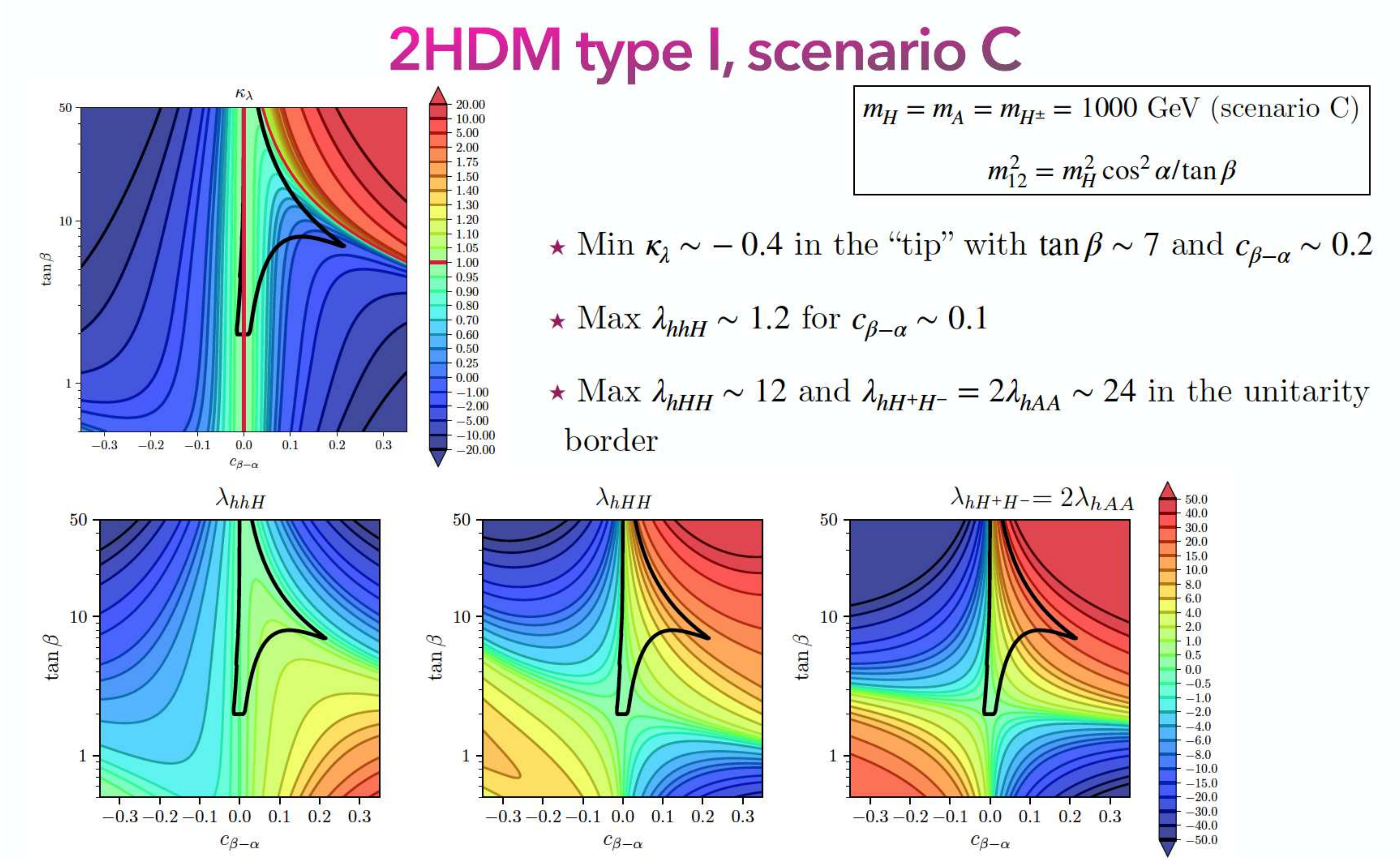
- Higgs singlet extension: $(\Delta\lambda/\lambda)^{\text{max}} \sim -18\%$
- Composite Higgs models: $(\Delta\lambda/\lambda)^{\text{max}} \sim +20\%$
- MSSM: $(\Delta\lambda/\lambda)^{\text{max}} \lesssim -15\%$
- NMSSM: $(\Delta\lambda/\lambda)^{\text{max}} \lesssim -25\%$
- 2HDM: NEW: detailed analysis [*F. Arco, S.H., M. Herrero '20*]

For any BSM (Higgs) analysis: the constraints:

$\rightarrow$ applied to every point analyzed/scanned/...

- Tree-level perturbativity
- Stability: potential is bounded from below
- Higgs searches at LEP, Tevatron, LHC $\Rightarrow$ HiggsBounds (2HDMC)
- SM-like Higgs properties $\Rightarrow$ HiggsSignals (2HDMC)
- Flavor physics (mainly BR($B_s \to X_s \gamma$), ΔM_{B_s}) $\Rightarrow$ SuperIso
- Electroweak precision data (S, T and U) $\Rightarrow$ 2HDMC

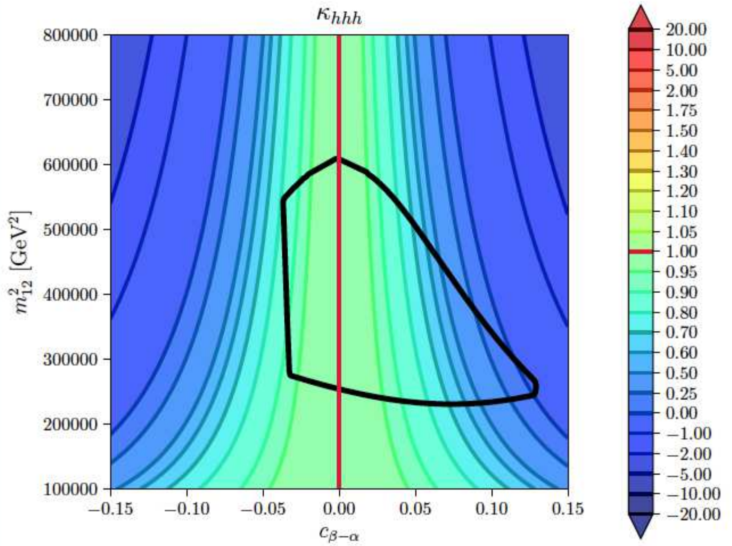
Example I: 2HDM type I: results



$\Rightarrow$ large deviations for κ_λ $\quad$ $\Rightarrow$ large values for BSM λ's

Example II: 2HDM type II: results

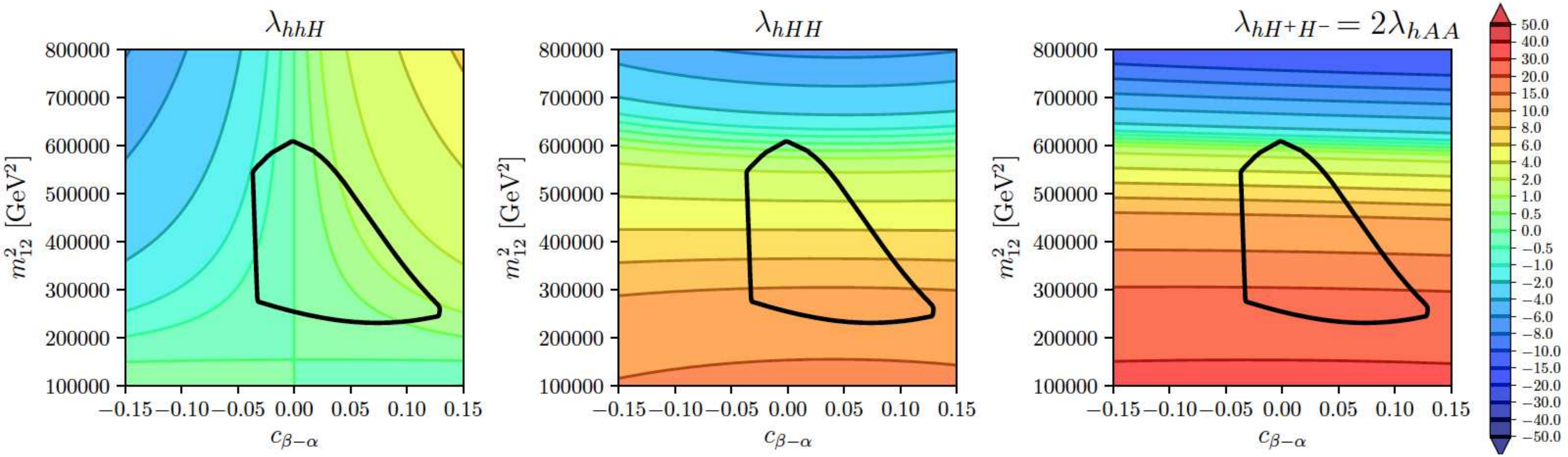
2HDM type II, scenario C



$m_H = m_A = m_{H^\pm} = 1100$ GeV (scenario C)

$\tan\beta = 0.9$

- ⋆ Min $\kappa_\lambda \sim -1.0$ for max $c_{\beta-\alpha} \sim 0.13$
- ⋆ Allowed $\lambda_{hhH} \in [-1,\ 1.4]$
- ⋆ Max $\lambda_{hHH} \sim 12$ and $\lambda_{hH^+H^-} = 2\lambda_{hAA} \sim 24$ for min $m_{12}^2 \sim 2 \times 10^5$ GeV^2



⇒ large deviations for κ_λ ⇒ large values for BSM λ's

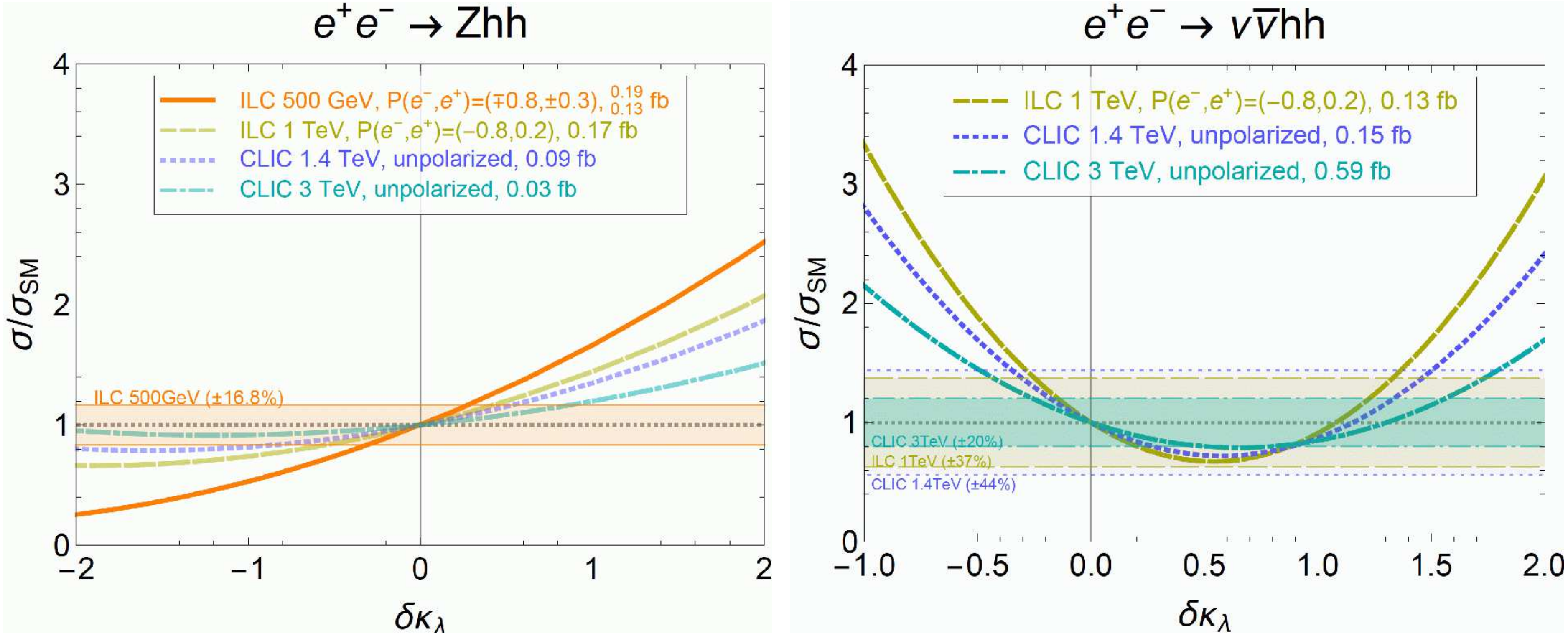
Final allowed ranges

Type I	Type II	
$\kappa_\lambda \in [-0.5,\ 1.5]$	$\kappa_\lambda \in [0.0,\ 1.0]$	→ Far from the alignment limit and playing with m_{12}^2
$\lambda_{hhH} \in [-1.4,\ 1.5]$	$\lambda_{hhH} \in [-1.6,\ 1.8]$	→ For $c_{\beta-\alpha} \sim \pm 0.05$
$\lambda_{hHH} \in [0,\ 15]$	$\lambda_{hHH} \in [0,\ 15]$	} Large masses and nearly independent of $c_{\beta-\alpha}$ and scenario A or B
$\lambda_{hAA} \in [0,\ 16]$	$\lambda_{hAA} \in [0,\ 16]$	
$\lambda_{hH^+H^-} \in [0,\ 32]$	$\lambda_{hH^+H^-} \in [0,\ 32]$	

✨ Interesting points are shown in our paper [arXiv:2005.10576] ✨

Di-Higgs production at ILC/CLIC:

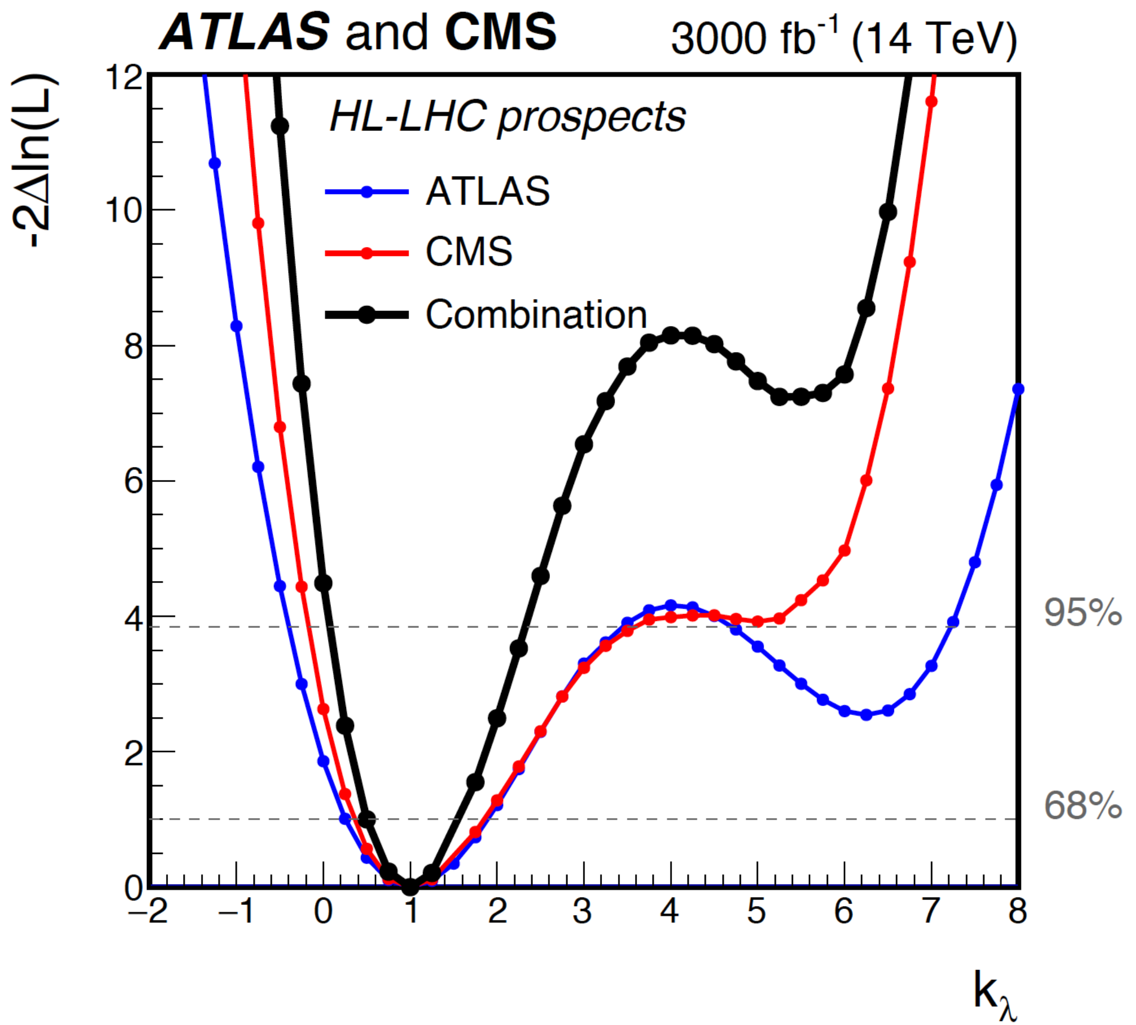
$[\kappa_\lambda = -0.5 \ldots +1.5]$



⇒ strong and different dependence on κ_λ

⇒ not all $\kappa_\lambda = 1 + \delta\kappa_\lambda$ range covered (but one can imagine . . .)

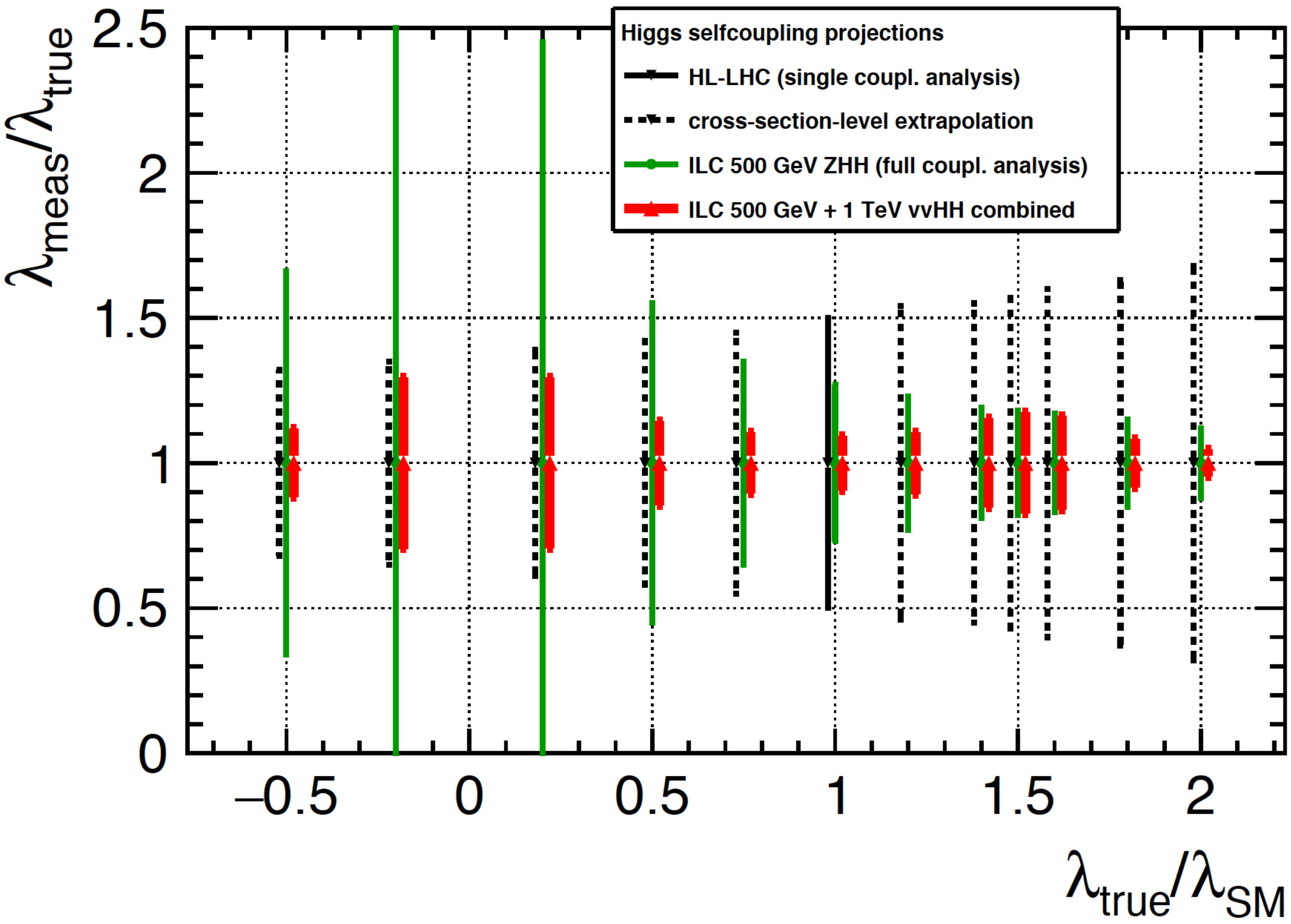
Results for HL-LHC: $[\kappa_\lambda = -0.5 \ldots +1.5]$



$\Rightarrow$ only evaluated for $\kappa_\lambda = 1$

Measurement of κ_λ selfcoupling at ILC/HL-LHC: $[\kappa_\lambda = -0.5 \ldots +1.5]$

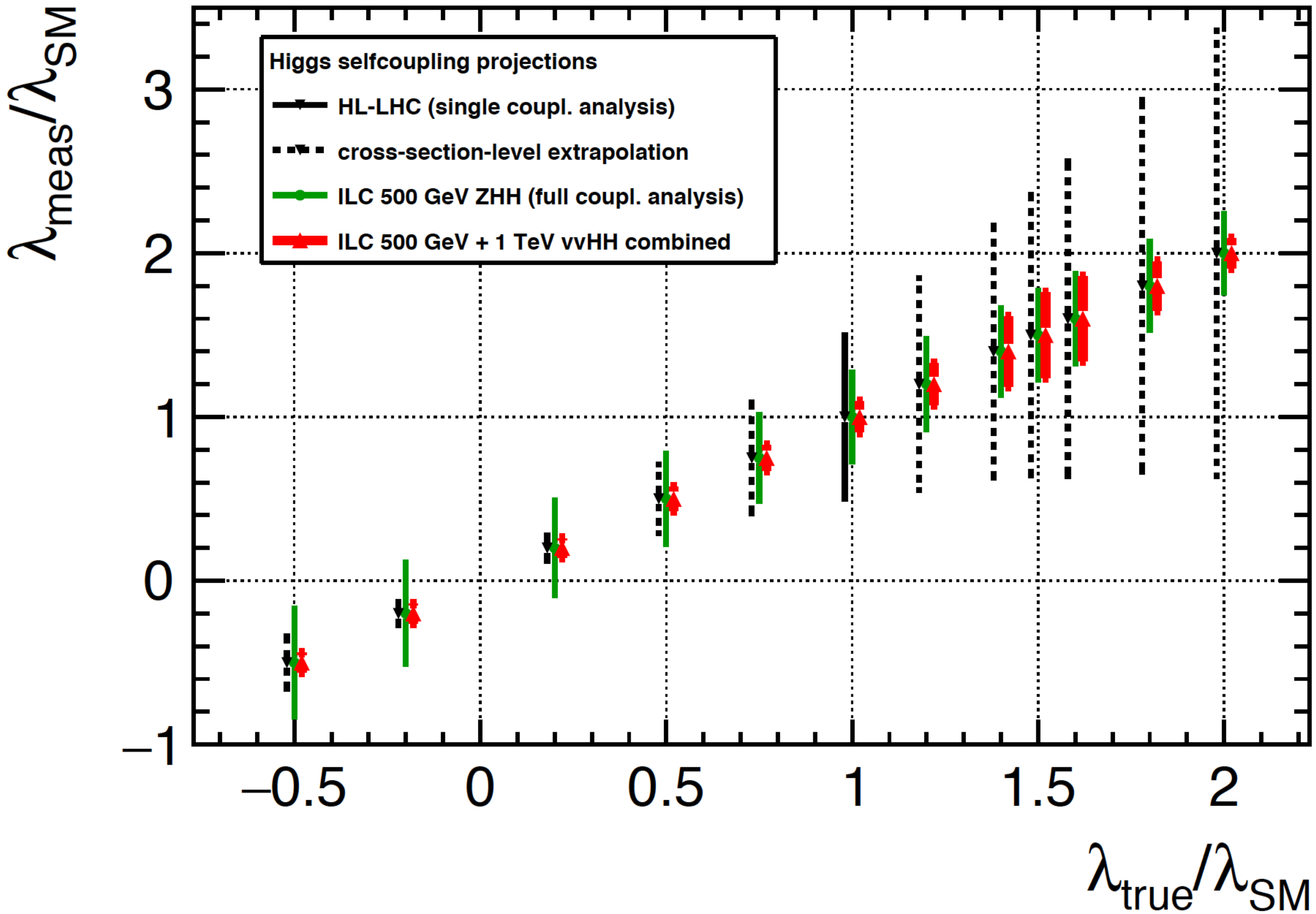
[J. List et al. – PRELIMINARY]



$\Rightarrow$ over most of the parameter space ILC is clearly superior to HL-LHC

Measurement of κ_λ selfcoupling at ILC/HL-LHC: $[\kappa_\lambda = -0.5 \ldots + 1.5]$

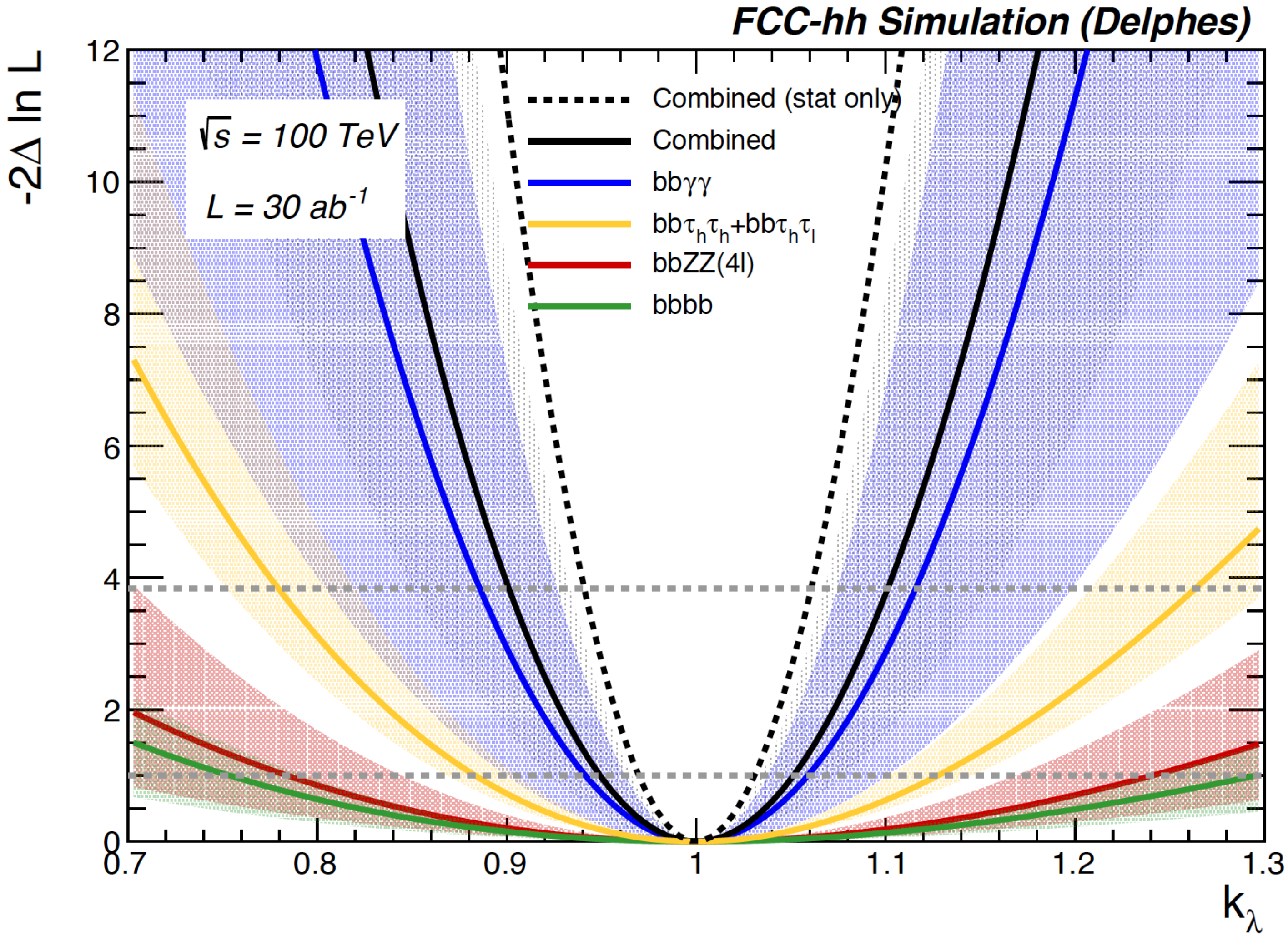
[J. List et al. – PRELIMINARY]



$\Rightarrow$ over most of the parameter space ILC is clearly superior to HL-LHC

Measurement of κ_λ at the FCC-hh:

[*Mangano, Ortona, Selvaggi '20*]

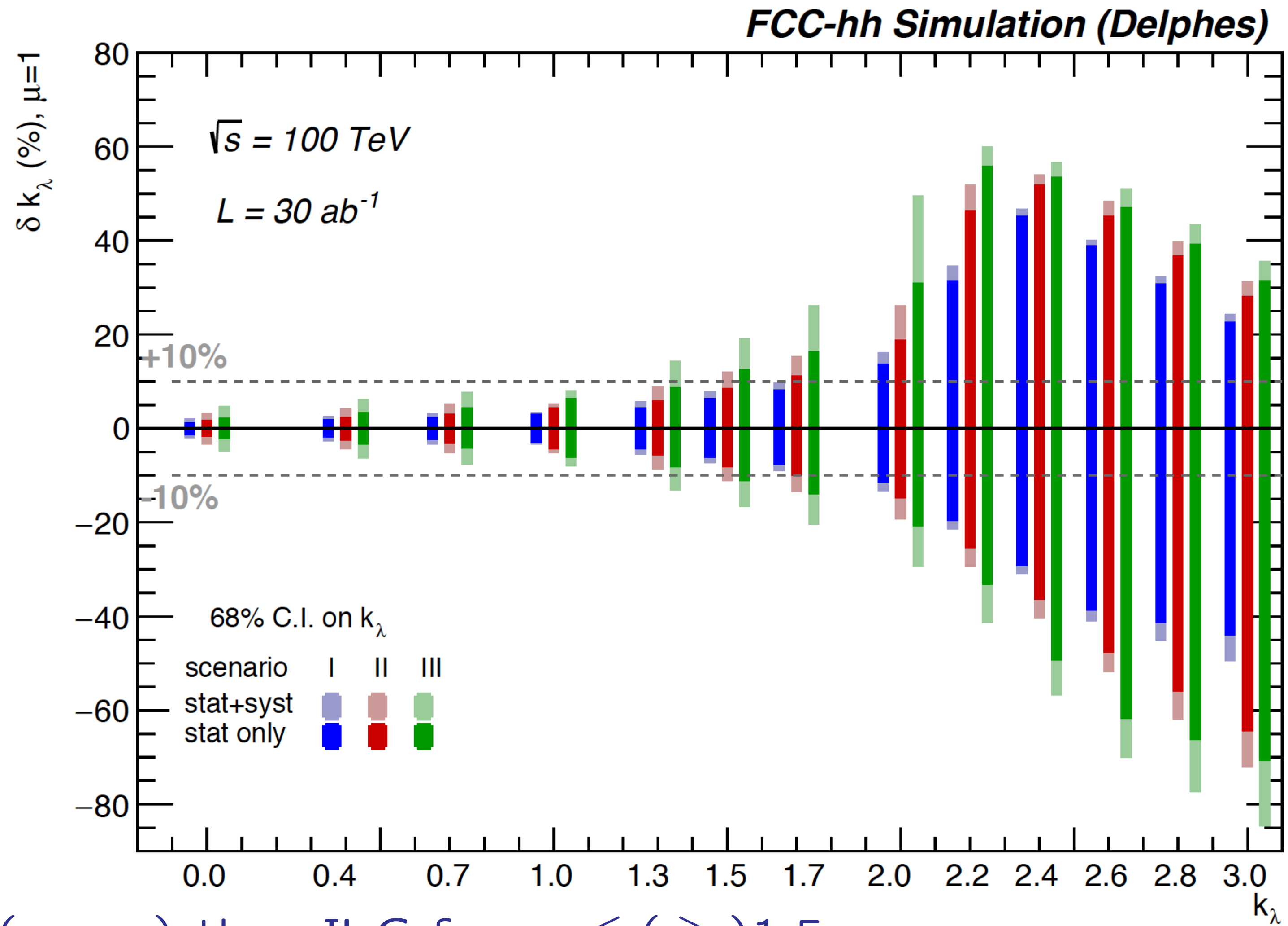


⇒ result only for $\kappa_\lambda = 1$

⇒ pile-up neglected . . .

Measurement of κ_λ at the FCC-hh: $[\kappa_\lambda = -0.5 \ldots + 1.5]$

[*Mangano, Ortona, Selvaggi '20*]

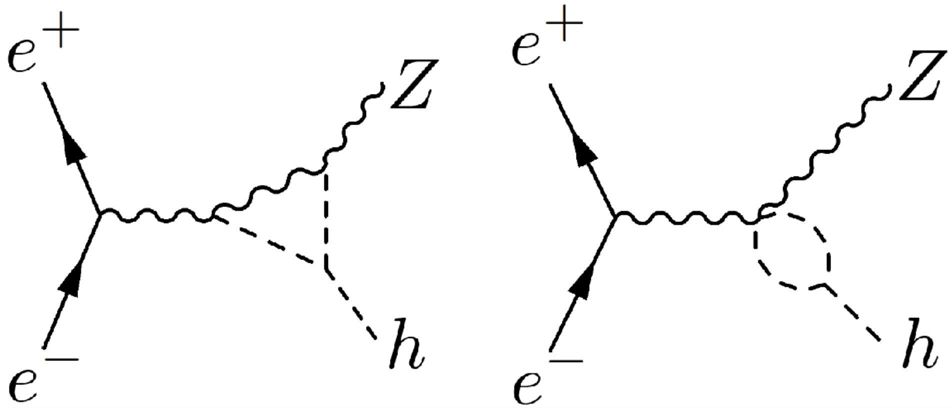


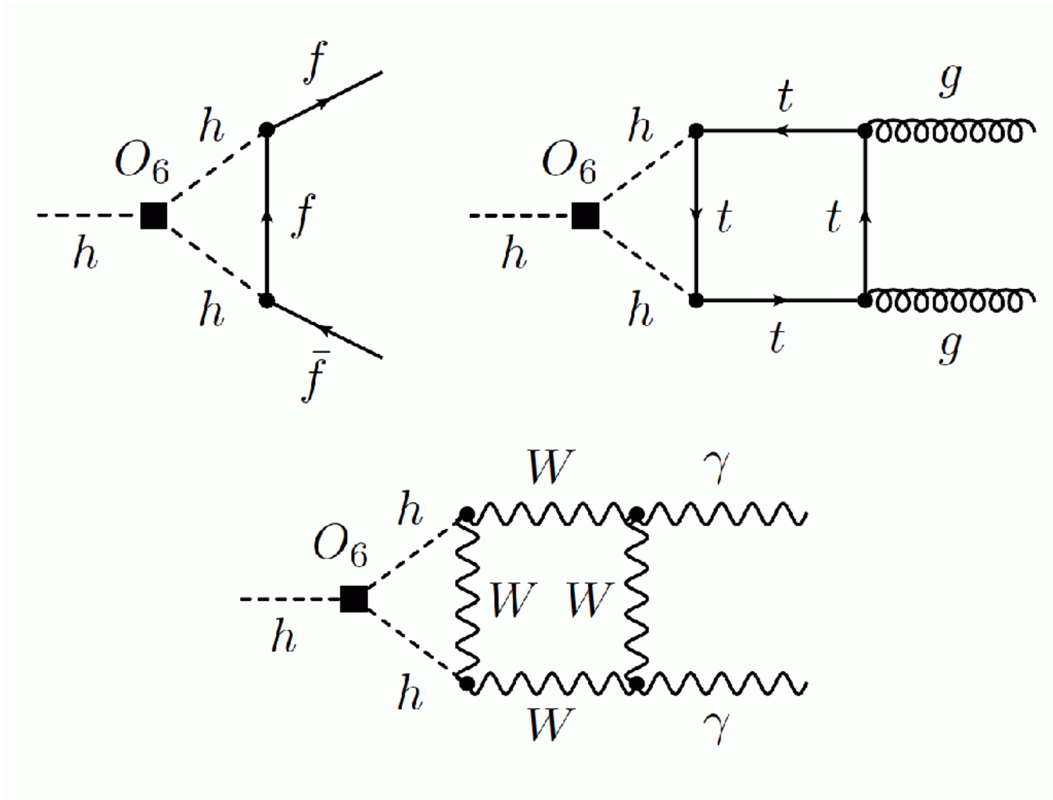
⇒ better (worse) than ILC for $\kappa_\lambda \lesssim (\gtrsim) 1.5$

⇒ no results for $\kappa_\lambda \leq 0$

⇒ pile-up neglected . . .

<u>Single-Higgs production:</u> $[\kappa_\lambda = -0.5 \ldots + 1.5]$

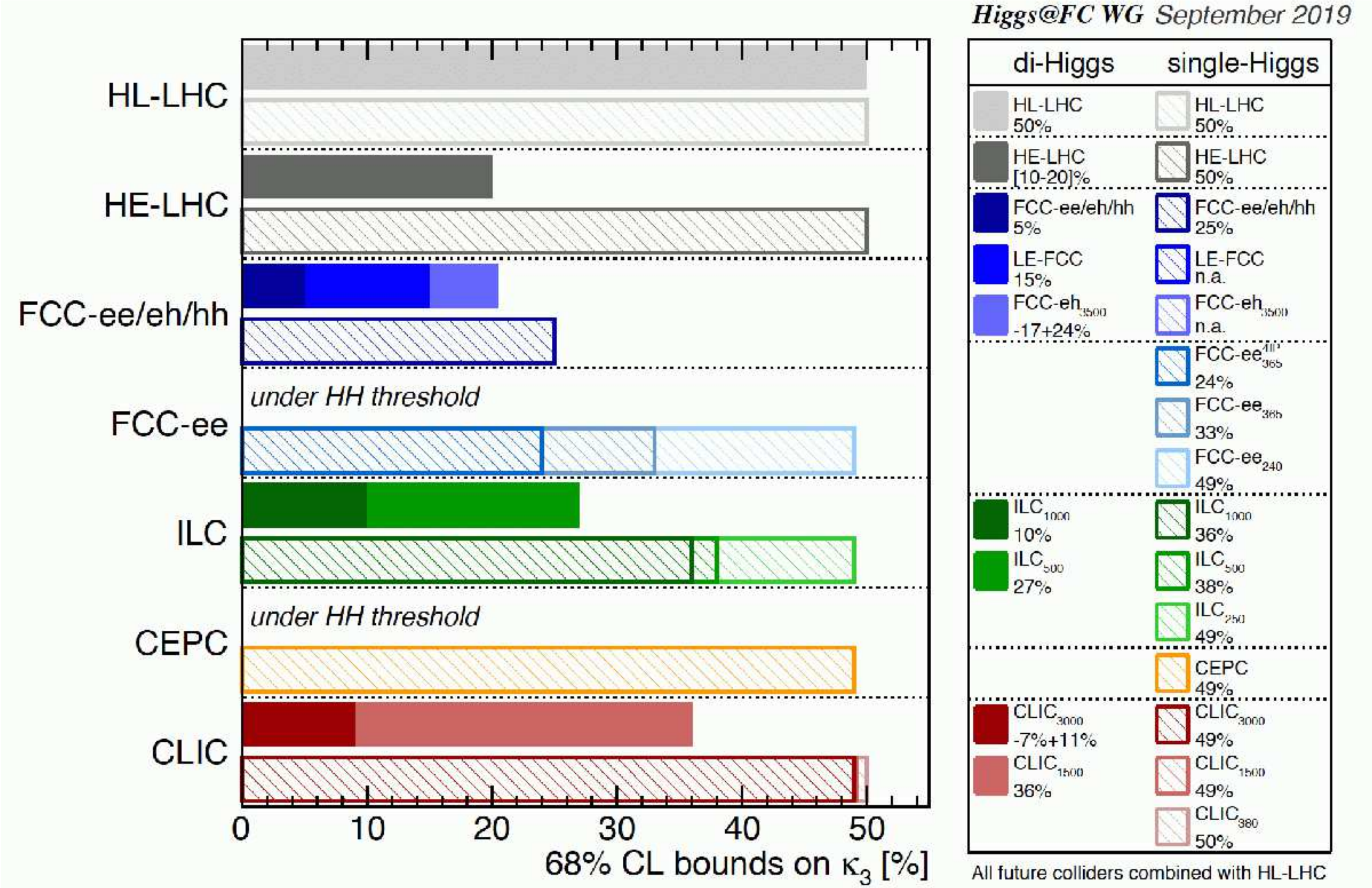




EFT analysis performed only for $\kappa_\lambda = 1$

$\Rightarrow$ CEPC/FCC-ee prospects unclear!

Comparison of all colliders: $[\kappa_\lambda = -0.5 \ldots +1.5]$



Analysis/comparison performed only for $\kappa_\lambda = 1$

$\Rightarrow$ CEPC/FCC-ee prospects unclear!

Remeber again:

Conclusion: It cannot be “the SM Higgs”!

Q: Does the BSM physics have any (relevant) impact on the Higgs?
Q’: Which model?

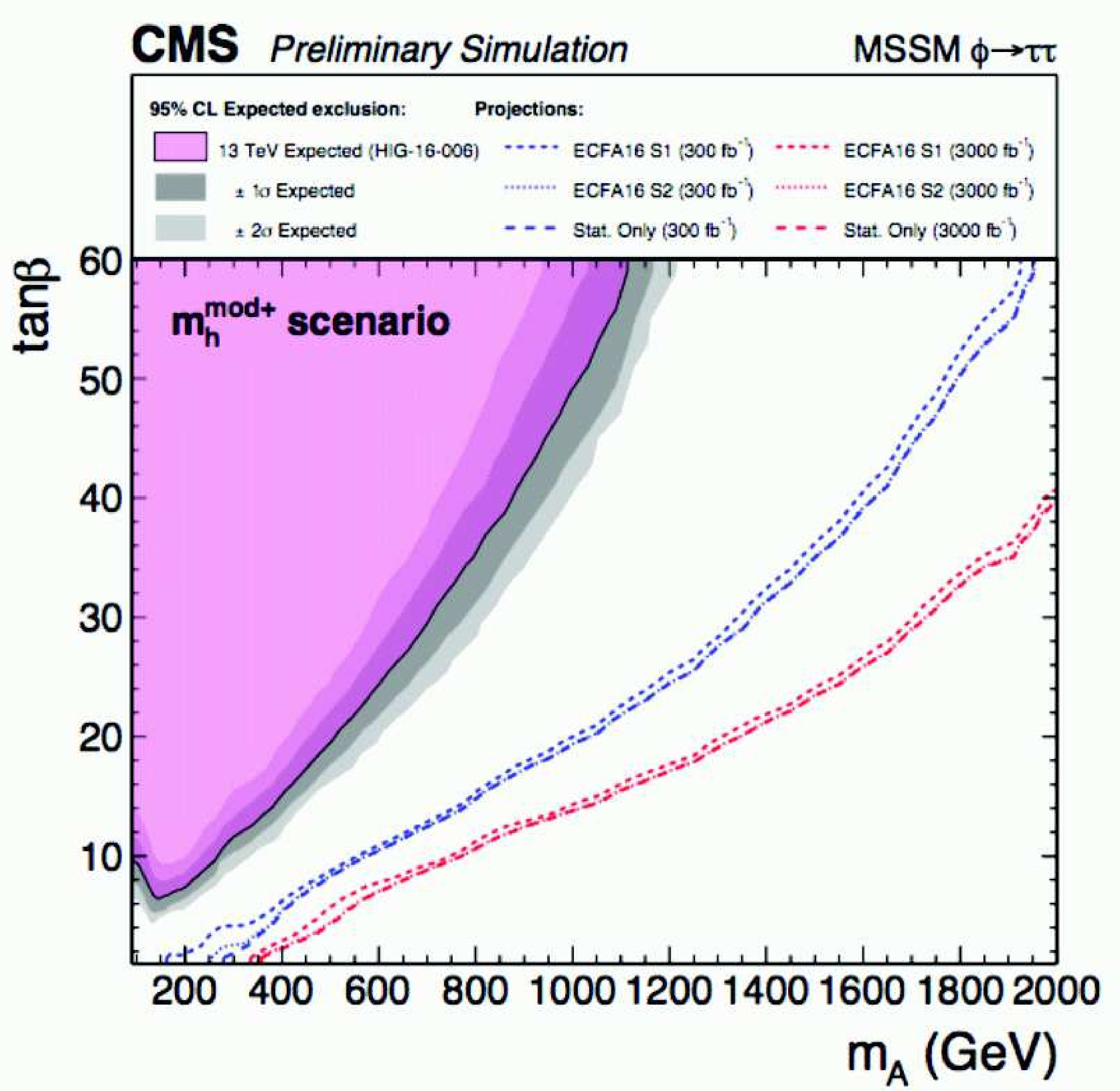
A1: check changed properties of the h_{125}

A2: check for additional Higgs bosons
A2’: check for additional Higgs bosons above and below 125 GeV

Searches above 125 GeV: depend stongly on available $\sqrt{s}$
$\Rightarrow$ only ILC/CLIC can go to high(er) energies

Searches below 125 GeV: possible at all proposed colliders
First stage: ILC/FCC-ee/CEPC: $\sqrt{s} \sim 250$ GeV
CLIC: $\sqrt{s} \sim 380$ GeV

BSM Higgs Bosons above 125 GeV

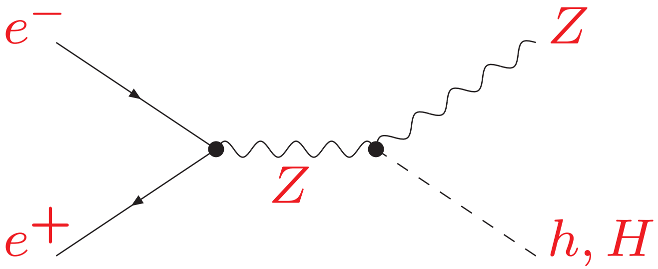


⇒ strong (HL-)LHC limits

Sum rule in the MSSM with h SM-like: $\sin(\beta-\alpha)\approx 1$, $\cos(\beta-\alpha)\approx 0$

Search for neutral SUSY Higgs bosons:

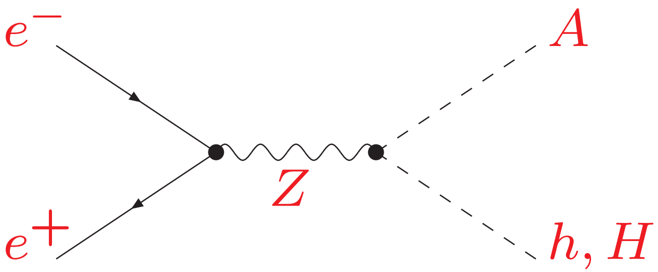
$e^+e^- \to Zh, ZH$



$\sigma_{hZ} \approx \sin^2(\beta-\alpha_{\text{eff}})\sigma^{\text{SM}}_{hZ}$

$\sigma_{HZ} \approx \cos^2(\beta-\alpha_{\text{eff}})\sigma^{\text{SM}}_{hZ}$

$e^+e^- \to Ah, AH$

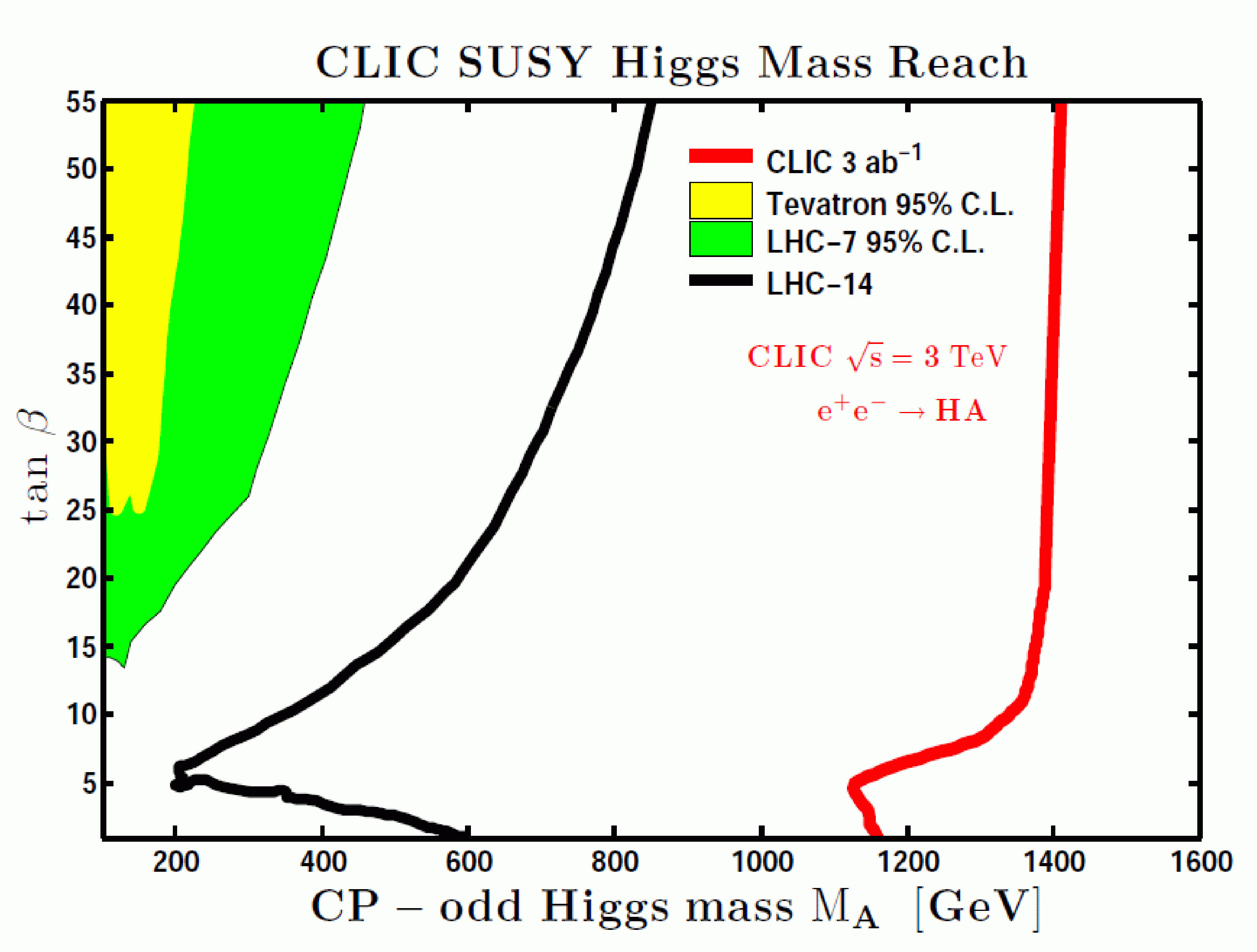


$\sigma_{hA} \propto \cos^2(\beta-\alpha_{\text{eff}})\sigma^{\text{SM}}_{hZ}$

$\sigma_{HA} \propto \sin^2(\beta-\alpha_{\text{eff}})\sigma^{\text{SM}}_{hZ}$

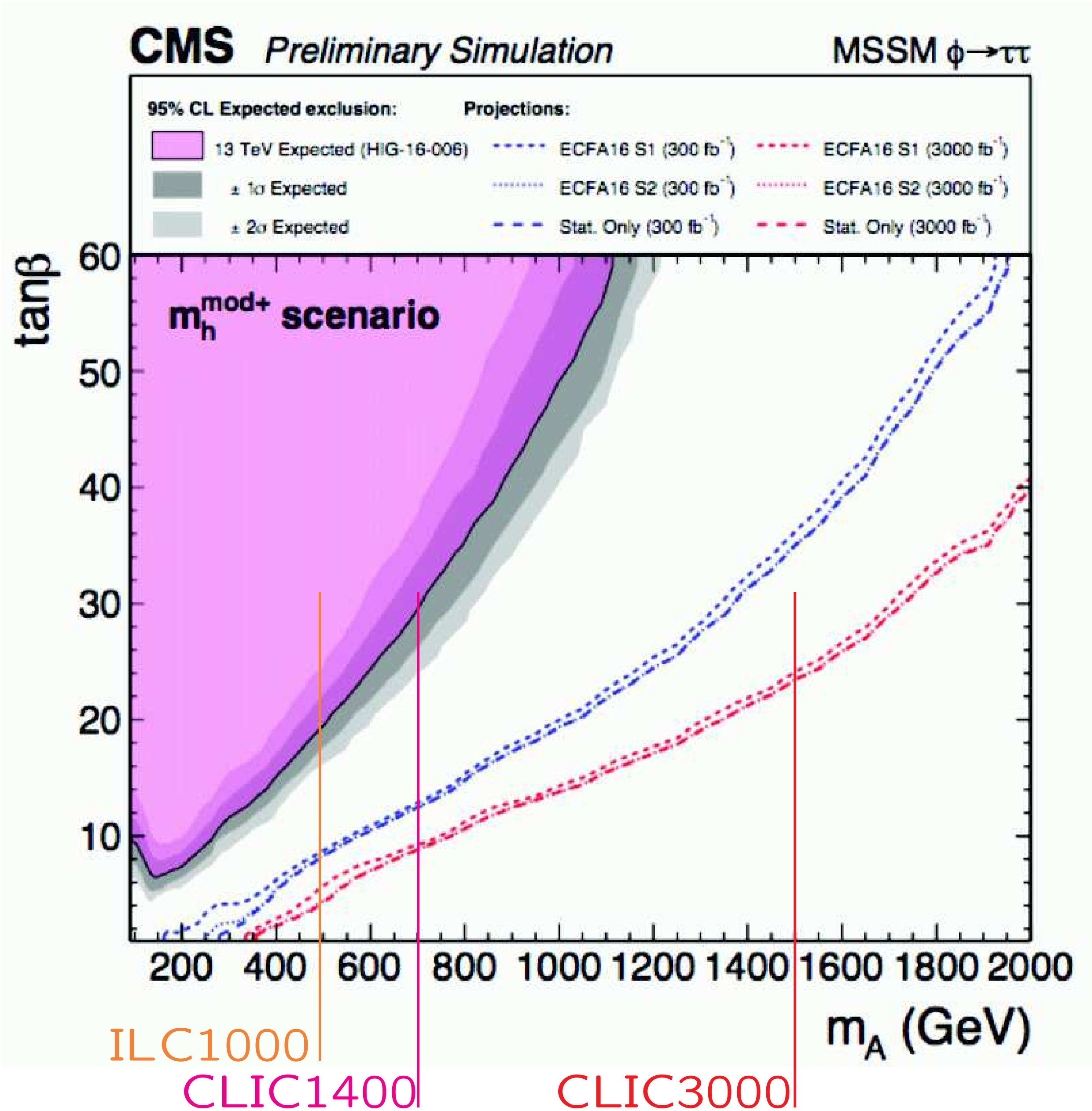
$\Rightarrow$ only pair production of heavy Higgs bosons! reach: $M_A \lesssim \sqrt{s}/2$

CLIC reach: [L. Linssen et al. '12]

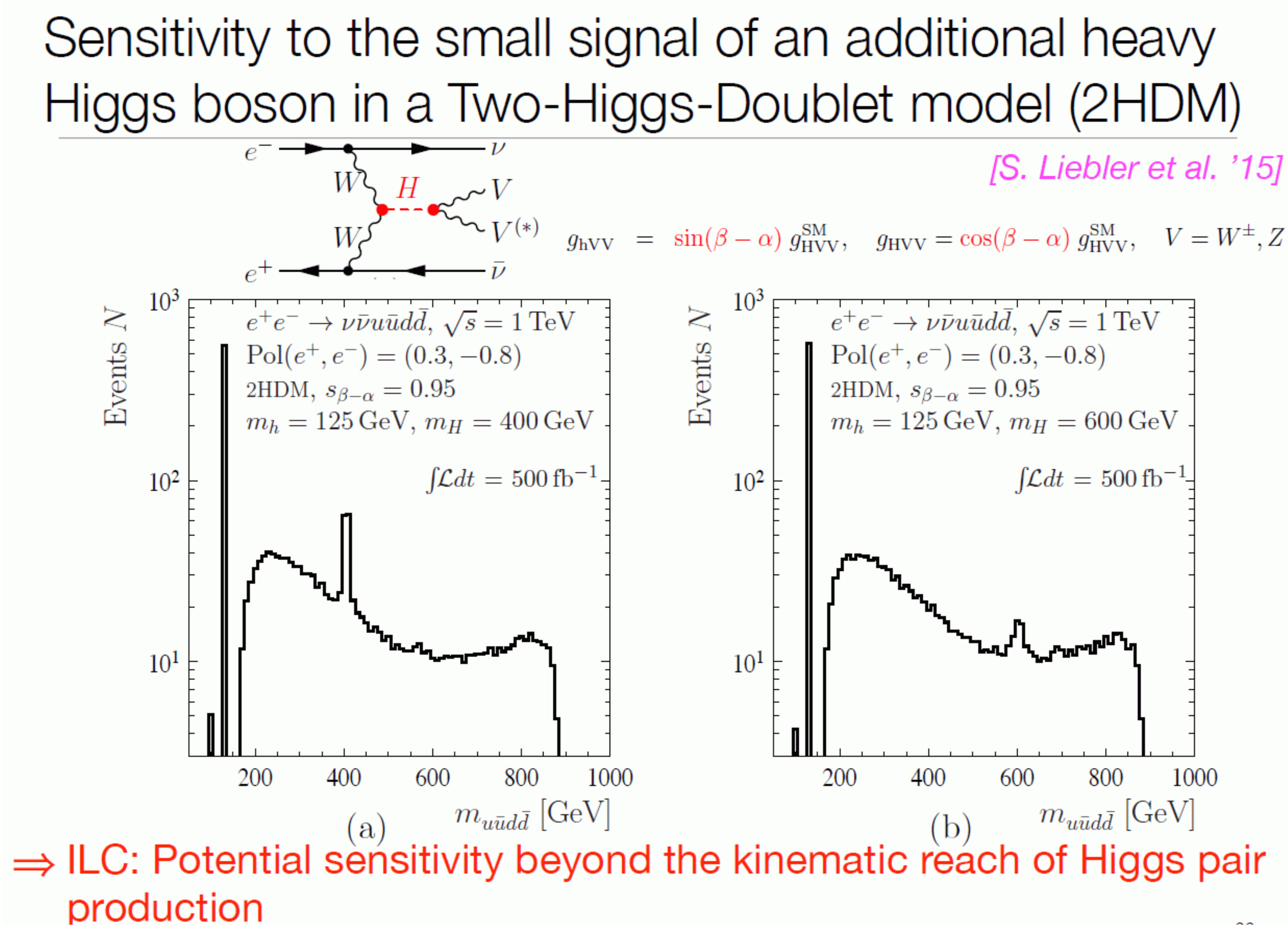


⇒ close to kinematic limit

"Simple" LC reach in the MSSM (neglecting $t\bar{t}$ final states)



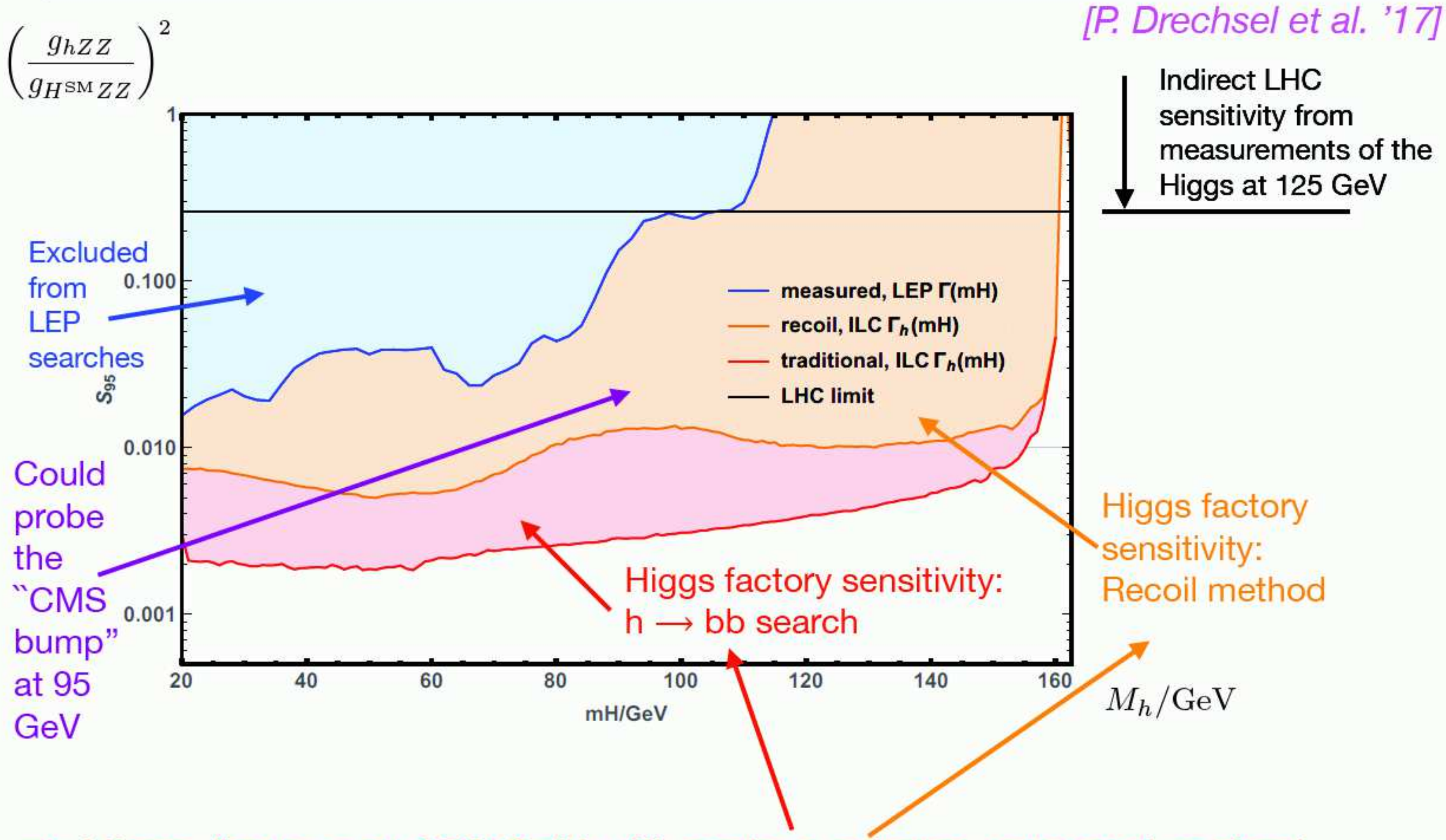
⇒ unique opportunities!



[*Taken from G. Weiglein '18*]

BSM Higgs Bosons below 125 GeV

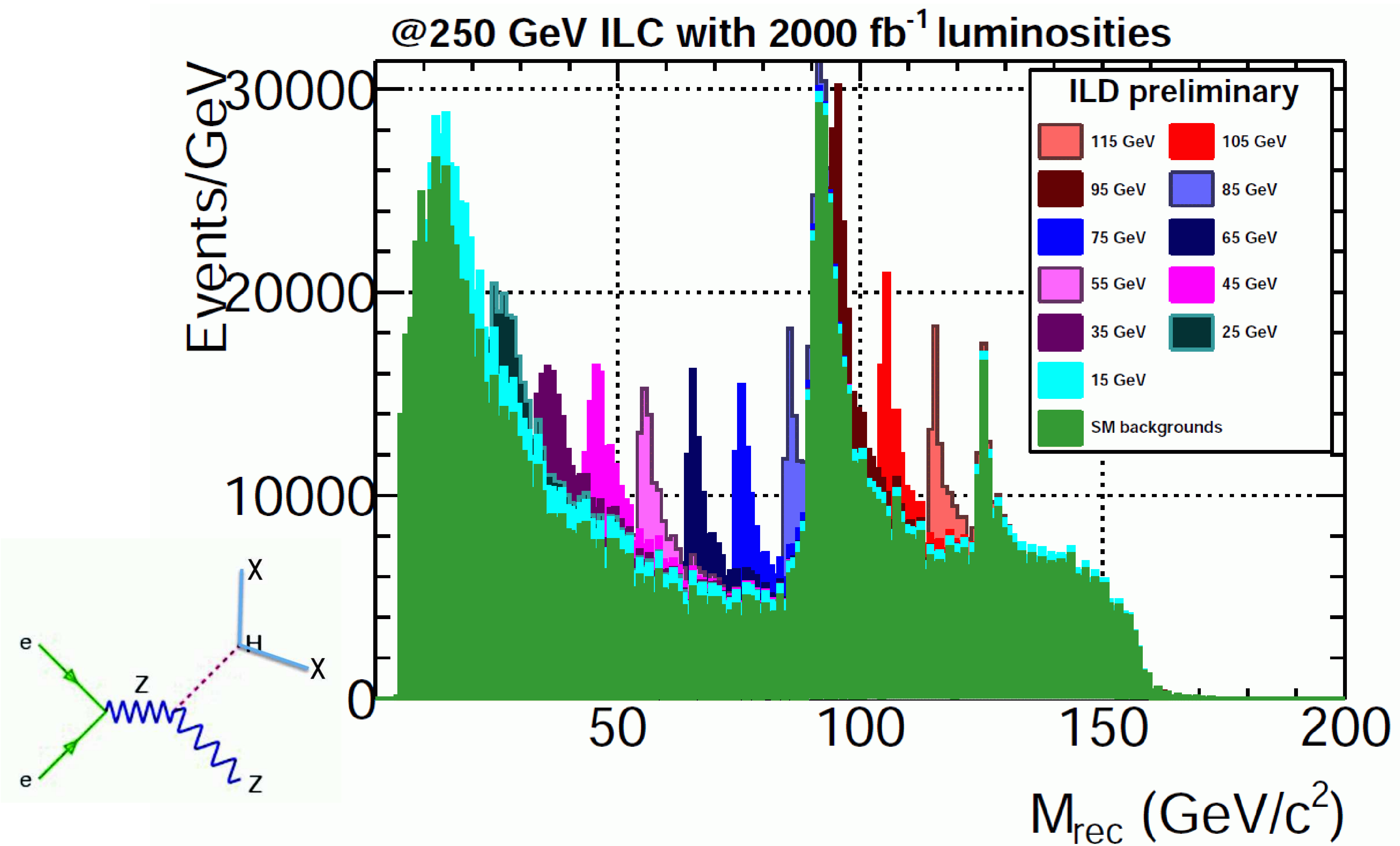
Example for discovery potential for new light states:
Sensitivity at 250 GeV with 500 fb^{-1} to a new light Higgs



⇒ Higgs factory at 250 GeV will explore a large untested region!

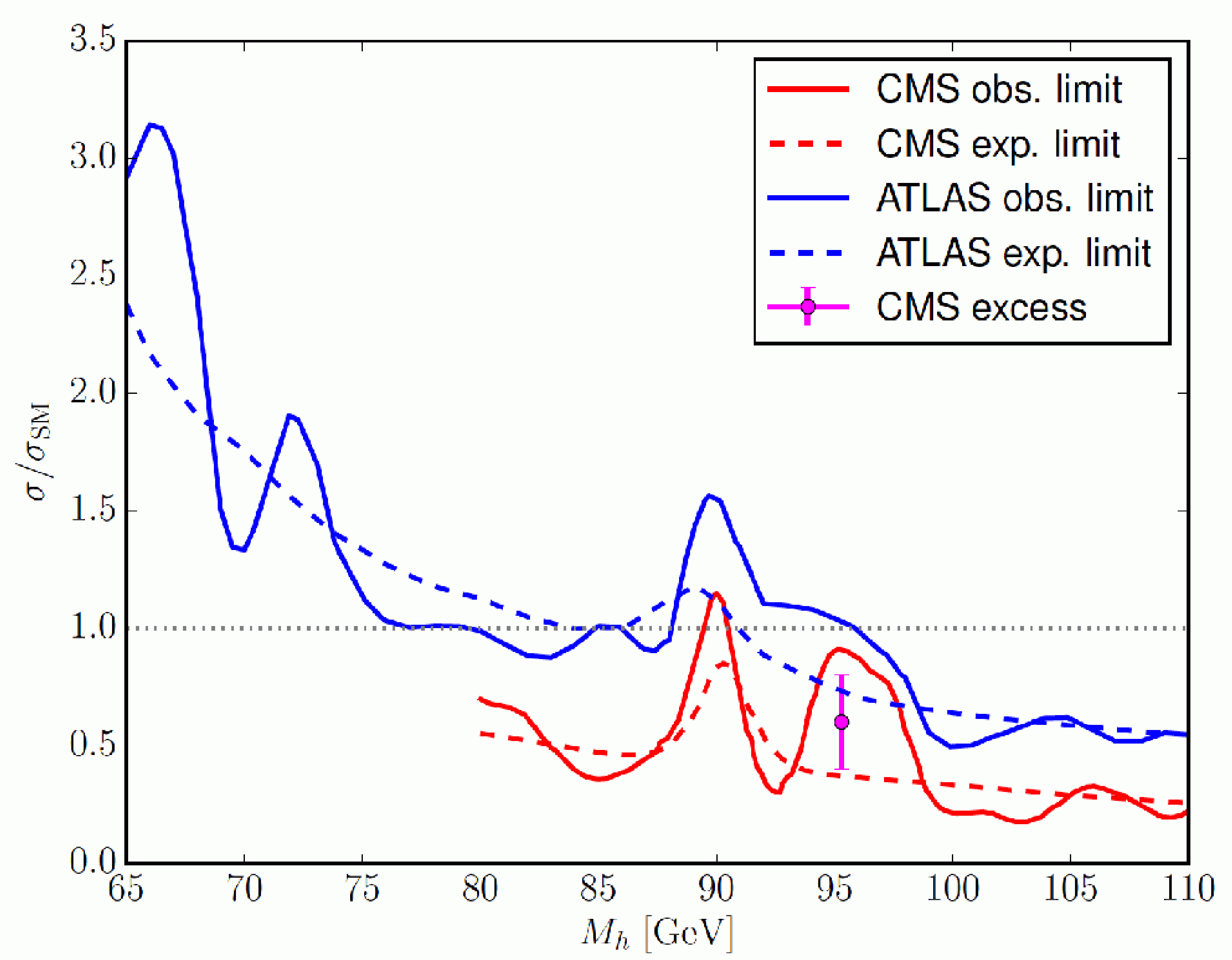
[*Taken from G. Weiglein '18*]

Search for invisibly decaying light Higgses via recoil method: [*Y. Wang et al. '18*]



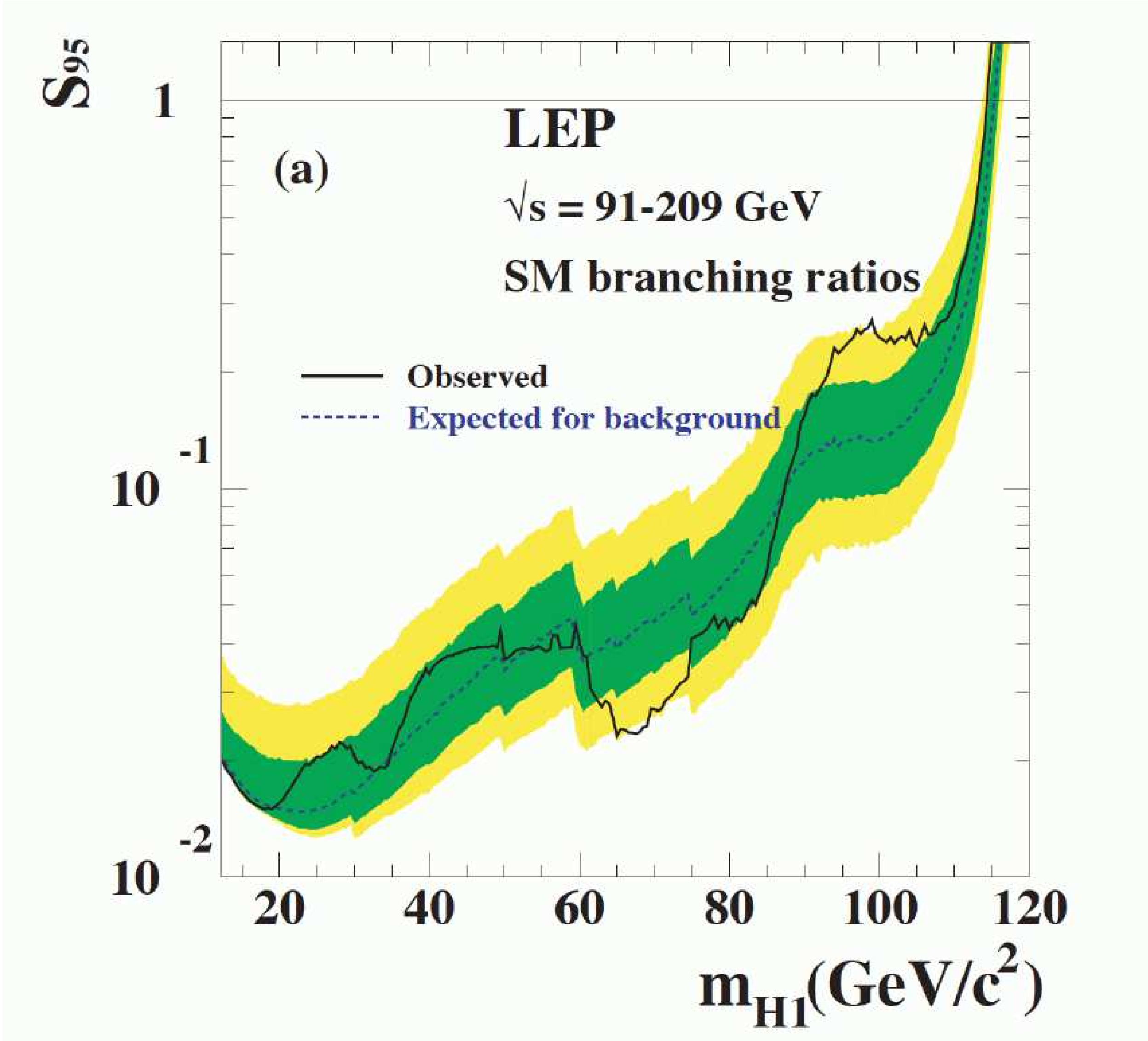
Search for $pp \to \phi \to \gamma\gamma$ with $m_\phi \leq 125$ GeV

[*CMS '17, ATLAS '18, S.H., T. Stefaniak '18*] $\mu_{\text{CMS}} = 0.6 \pm 0.2$



$\Rightarrow$ if there is something, it would look exactly like this!

Remember the LEP excess?



$$\mu_{\text{LEP}}(98\text{ GeV}) = \left[\sigma(e^+e^- \to Zh_1) \times \text{BR}(h_1 \to b\bar{b})\right]_{\text{exp/SM}} = 0.117 \pm 0.057$$

Investigation in BSM Higgs models: **N2HDM**

[*T. Biekötter, M. Chakraborti, S.H. '19*]

Fields:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \Phi_S = v_S + \rho_S$$

Physical states: h_1, h_2, h_3 ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged)

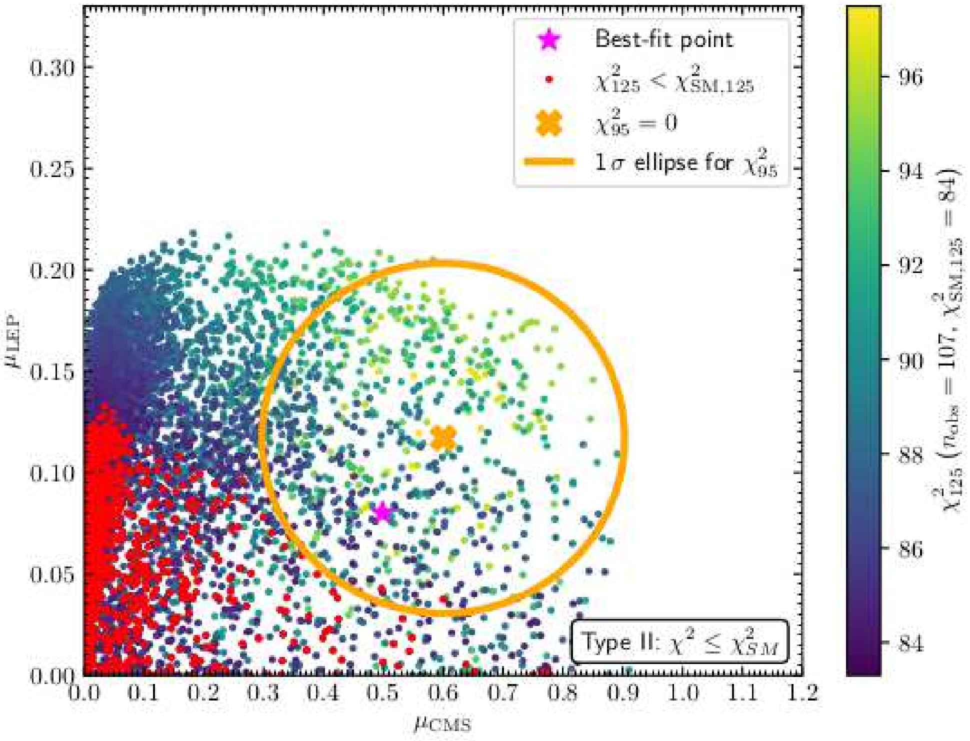
	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
type III (lepton-specific)	Φ_2	Φ_2	Φ_1
type IV (flipped)	Φ_2	Φ_1	Φ_2

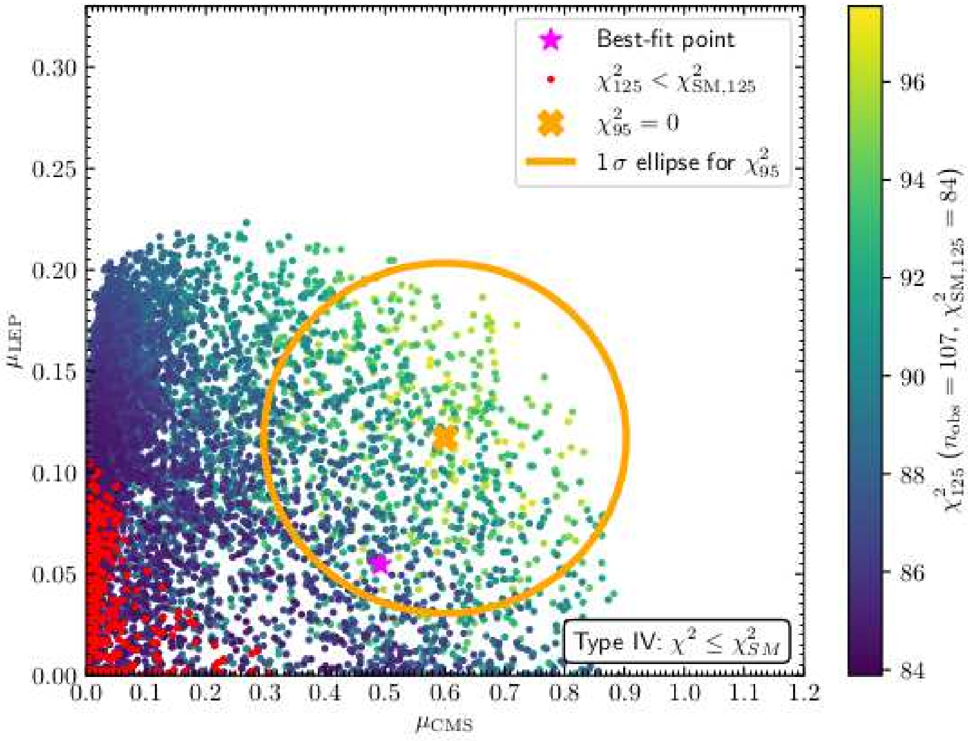
$\Rightarrow$ exactly as in 2HDM

Fitting the excesses:

[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]

type I: NO   type II: BEST   type III: NO   type IV: OK   ⇒ SUSY?



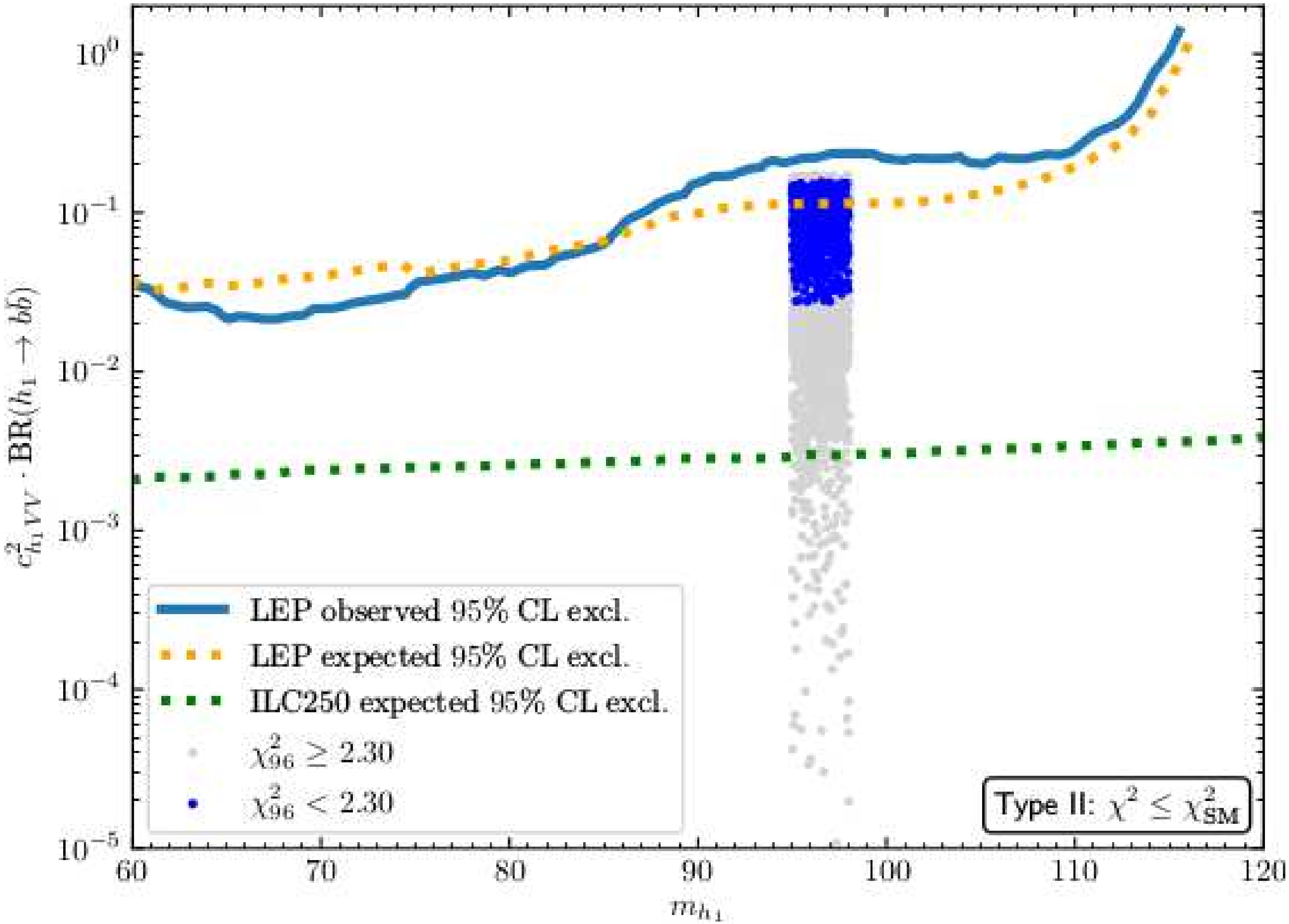


⇒ excesses well fitted, with good χ^2_{125}

red points have $\chi^2_{125} < \chi^2_{\mathrm{SM},125}$

ILC production of the light scalar in the N2HDM type II:

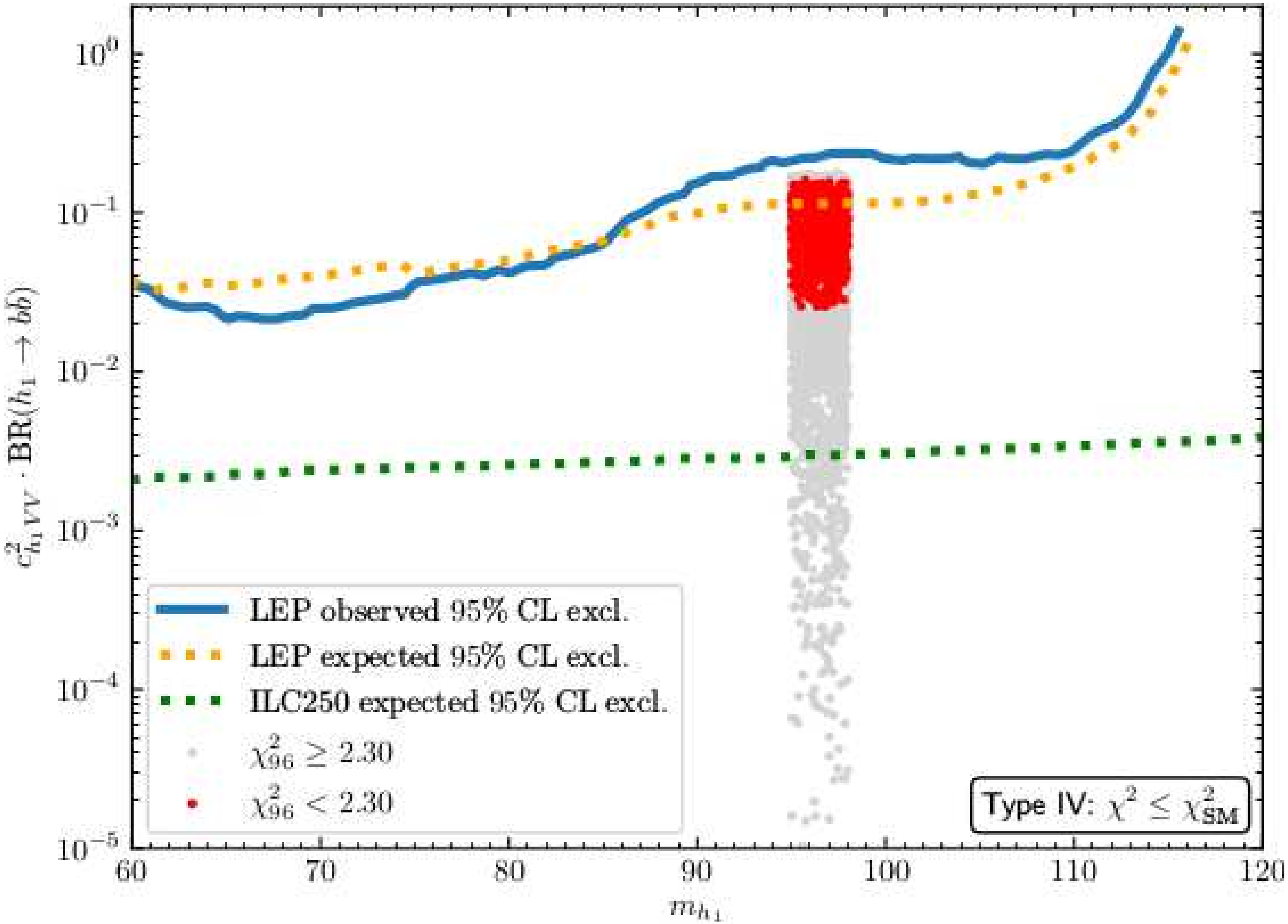
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



⇒ new state easily in the reach of the ILC ⇒ coupling measurements

ILC production of the light scalar in the N2HDM type IV:

[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



$\Rightarrow$ new state easily in the reach of the ILC $\Rightarrow$ coupling measurements

What can we learn from future measurements?

- LHC h_{125} coupling measurements
- HL-LHC h_{125} coupling measurements $\Leftarrow$ focus
- ILC h_{125} coupling measurements $\Leftarrow$ focus

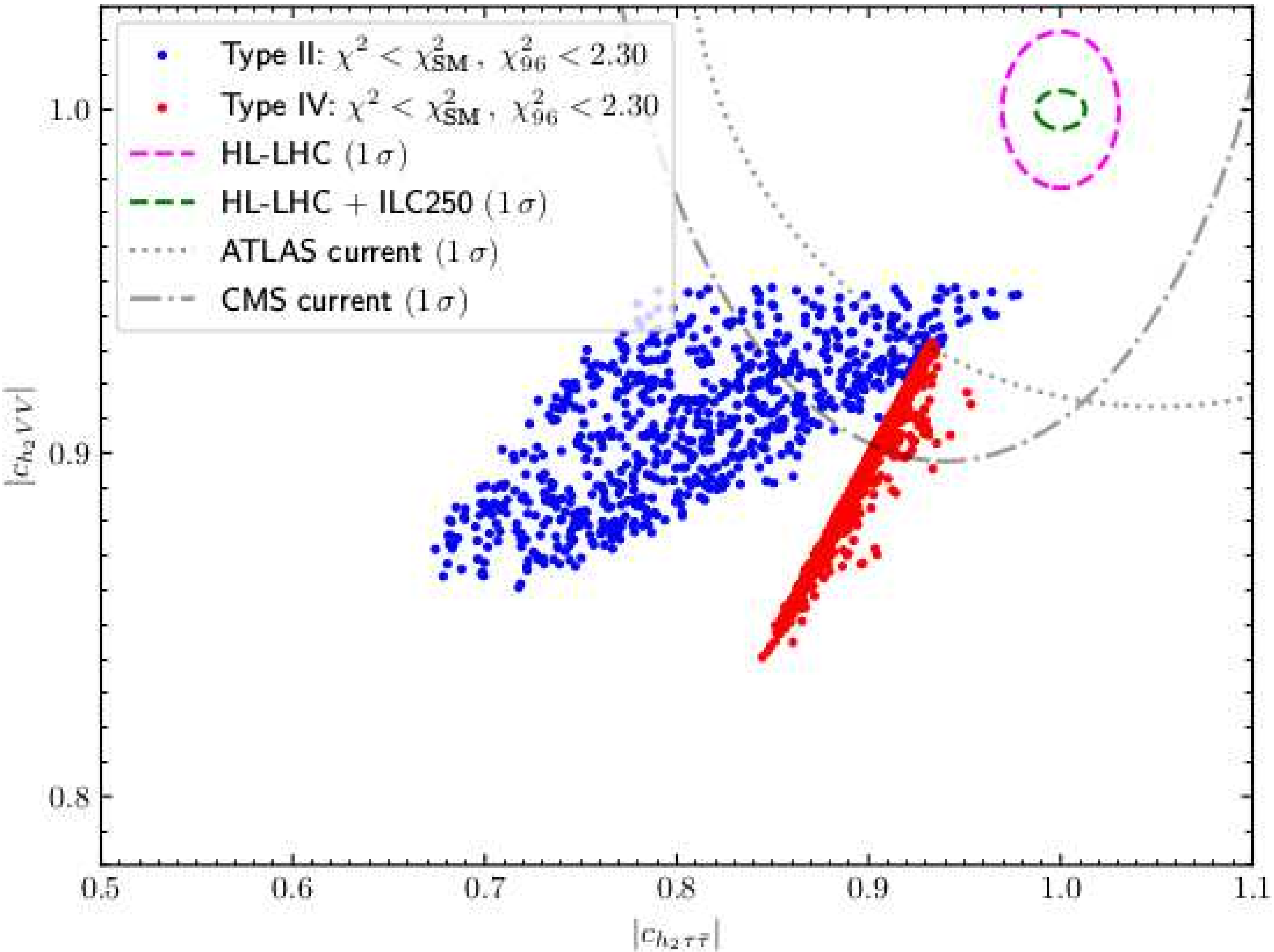
- direct production of ϕ_{96} at the LHC
- direct production of ϕ_{96} at the HL-LHC
- direct production of ϕ_{96} at the ILC $\Leftarrow$ focus
- ILC ϕ_{96} coupling measurements $\Leftarrow$ focus

- production of other BSM Higgs bosons at the LHC/HL-LHC/ILC/...

ILC = ILC (or other e^+e^- collider)

Future measurements: ⇒ HL-LHC/ILC Higgs coupling measurements

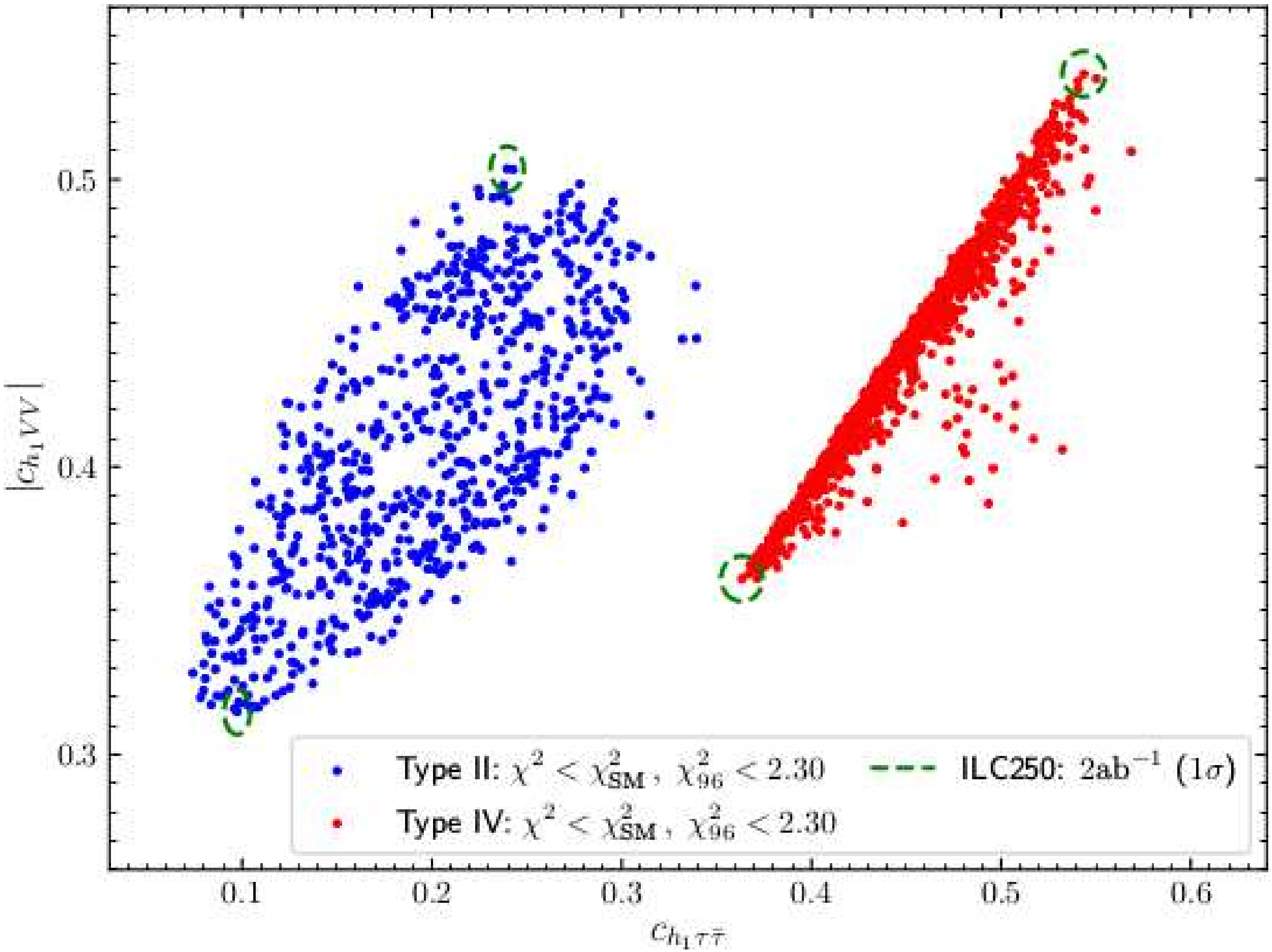
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



⇒ type II and IV show strong deviations from SM

⇒ N2HDM can always be distinguished from SM!

N2HDM: $\tau\tau$ vs. WW/ZZ: [T. Biekötter, S.H., G. Weiglein – PRELIMINARY]



⇒ model distinction possible via coupling measurements

BSM Particle searches at e^+e^- colliders

Indirect evidence (deviations from SM expectations) is nice . . .
But we want to see new particles! :-)

pp colliders:
– higher energy
– high reach for colored particles
– problems in “difficult” regions (e.g. compressed spectra)

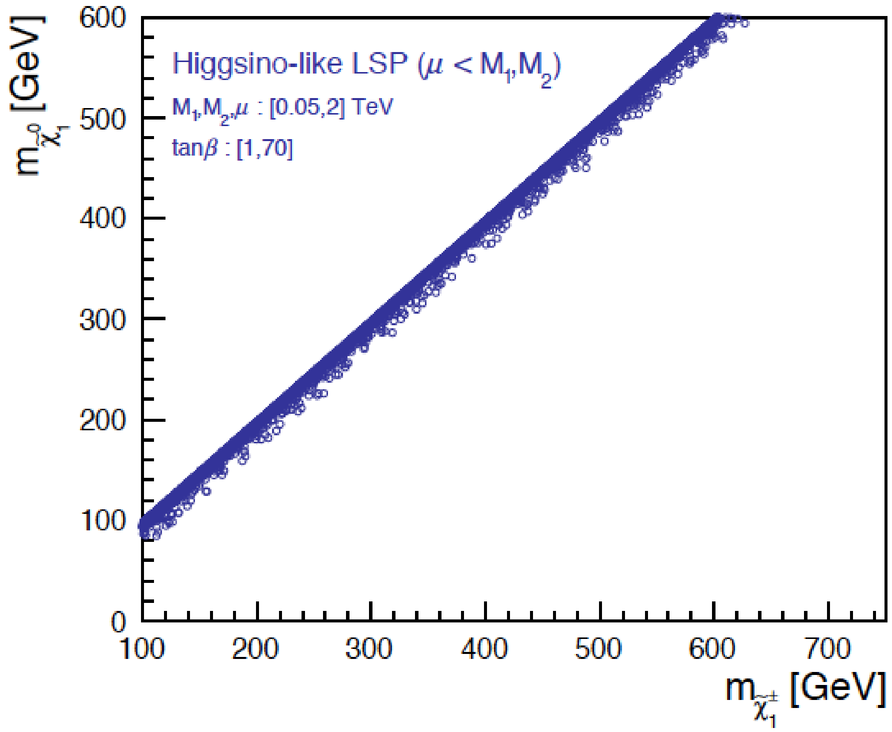
e^+e^- colliders:
– lower energy
– “easier” reach for uncolored particles
– “difficult” regions better covered (e.g. compressed spectra)

Problem: we do not have a mass scale prediction

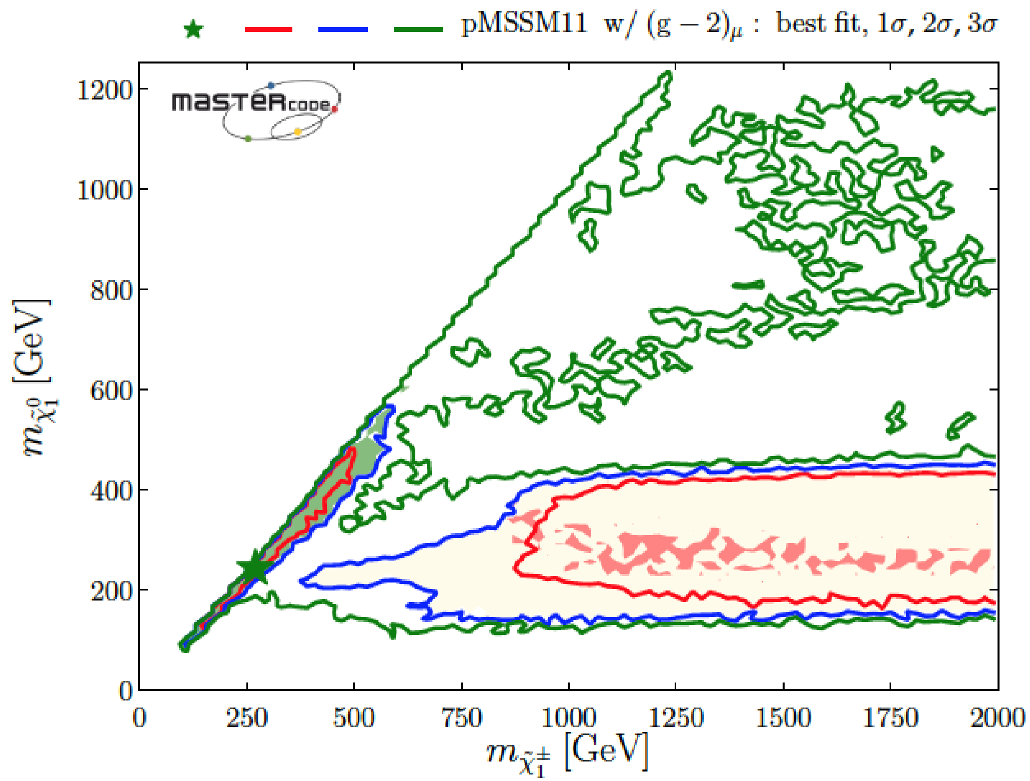
Or do we?

How relevant are compressed spectra?

Natural SUSY: low μ



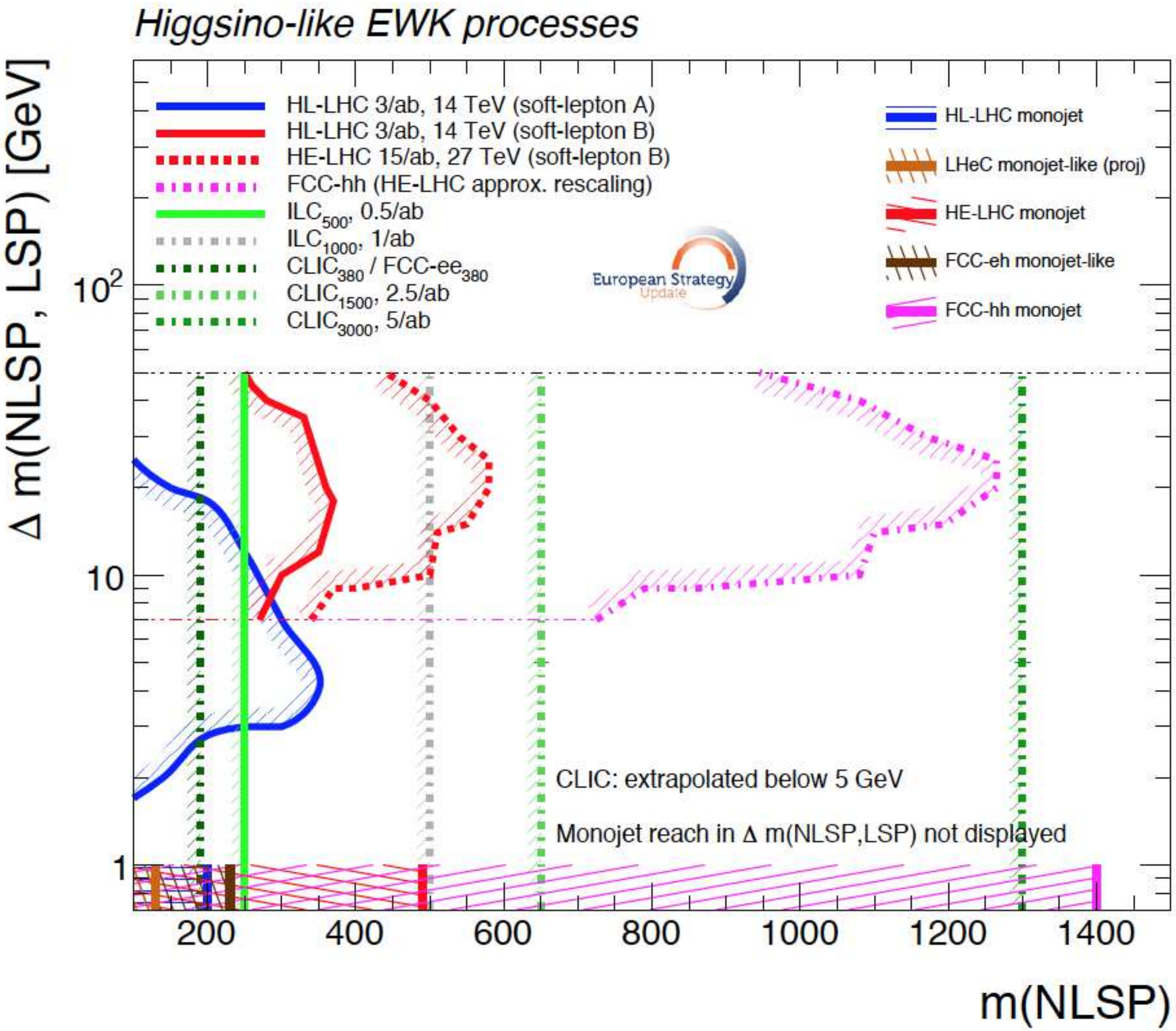
Global pMSSM11 fit



⇒ two well motivated and independent scenarios

⇒ both favor independently compressed spectra ⇒ DM connection

Future reach for compressed spectra



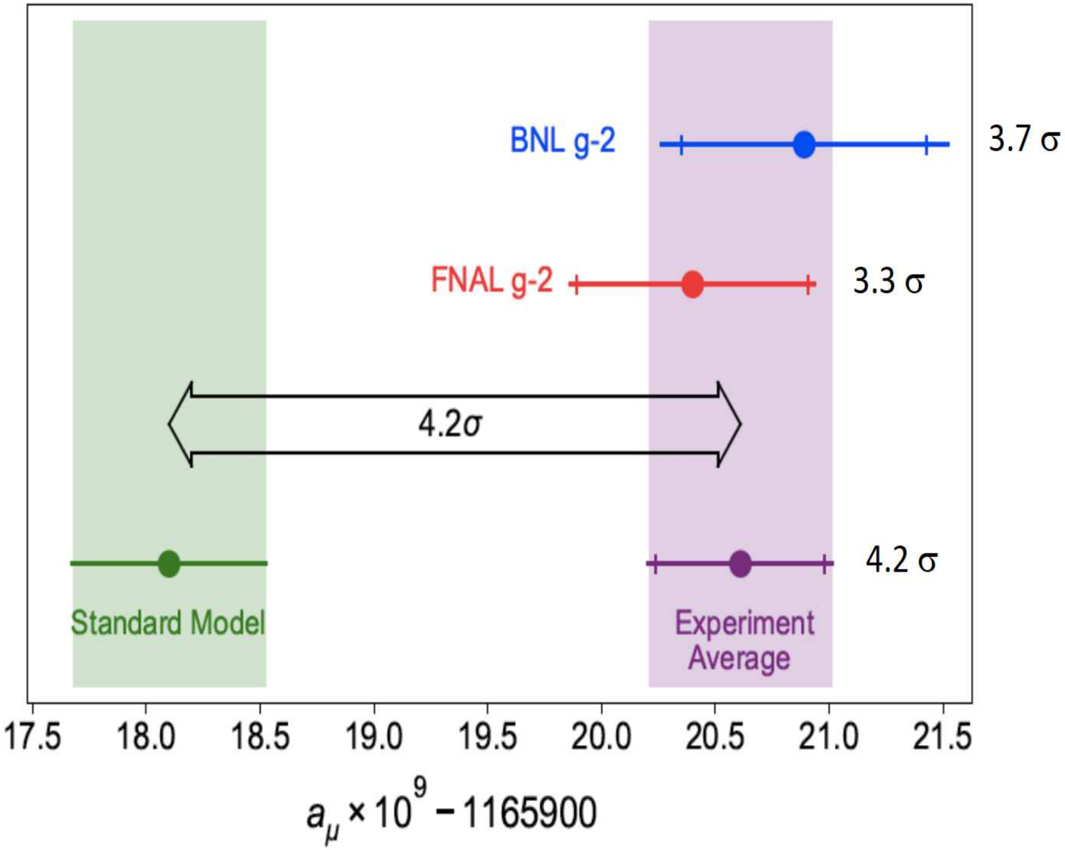
⇒ clear complementarity between pp and e^+e^-

⇒ e^+e^- much more "robust"!

Prediction for a BSM mass scale?

The anomalous magnetic moment of the muon: $a_\mu \equiv (g-2)_\mu/2$

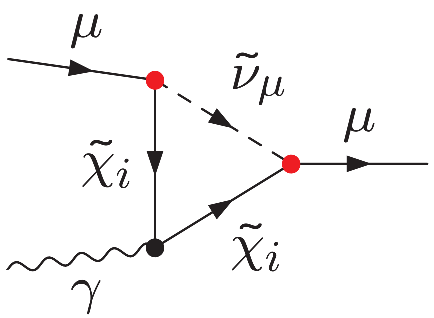
Overview about the current experimental and SM (theory) result:

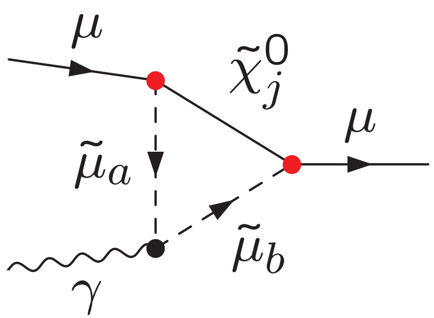


$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (25.1 \pm 5.9) \times 10^{-10} \quad : 4.2\,\sigma$$

SUSY can easily explain the deviation in a_μ:

Feynman diagrams for MSSM 1L corrections:





– Diagrams with chargino/sneutrino exchange

– Diagrams with neutralino/smuon exchange

Enhancement factor as compared to SM:

$$\mu - \tilde{\chi}_i^{\pm} - \tilde{\nu}_\mu \quad : \quad \sim m_\mu \tan\beta$$
$$\mu - \tilde{\chi}_j^{0} - \tilde{\mu}_a \quad : \quad \sim m_\mu \tan\beta$$

SM, EW 1L: $\frac{\alpha}{\pi}\frac{m_\mu^2}{M_W^2}$

MSSM, 1L: $\frac{\alpha}{\pi}\frac{m_\mu^2}{M_{\text{SUSY}}^2} \times \tan\beta$

The general idea:

[*M. Chakraborti, S.H., I. Saha '20, '21*]

- scan the relevant EW SUSY parameter space
- impose all relevant experimental constraints:
  - $(g-2)_\mu$
  - Dark Matter relic density
  - Dark Matter direct detection
  - LHC searches for EW particles
- Dark Matter relic density requires a mechanism to reduce the density in the early universe
  - bino/wino DM with chargino co-annihilation
  - bino/wino DM with slepton co-annihilation
  - higgsino DM
  - wino DM
- obtain lower and upper limits on the various EW particle masses
- evaluate the prospects for future searches

$(g-2)_\mu$ constraint: GM2Calc

$$\text{old: } \Delta a_\mu^{\text{old}} = (28.0 \pm 7.4) \times 10^{-10}$$
$$\text{new: } \Delta a_\mu^{\text{new}} = (25.1 \pm 5.9) \times 10^{-10}$$

$\Rightarrow$ some results for $\Delta a_\mu^{\text{new}} (\equiv \Delta a_\mu)$, some results only available for $\Delta a_\mu^{\text{old}}$

LHC searches: for EW particles: CheckMate (recasting)

Dark Matter relic density: MicrOmegas

$$\Omega_{\text{CDM}} h^2 = 0.120 \pm 0.001$$
$$\text{or} \quad \Omega_{\text{CDM}} h^2 \leq 0.122$$

(as taken from [*Planck '18*])

Dark Matter direct detection: MicrOmegas

limit on spin independent scattering cross section (Xenon1T)

[*Xenon collab. '18*]

Possible scenarios:

A) bino/wino DM with chargino co-annihilation

relic DM density 100% fulfilled

$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 600(650) GeV for new (and old) $(g-2)_\mu$

B/C) bino DM with slepton co-annihilation

relic DM density 100% fulfilled

$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 550(600) GeV for new (and old) $(g-2)_\mu$

D) higgsino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$

relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim 1$ TeV)

$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 500 GeV

E) wino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim M_2$

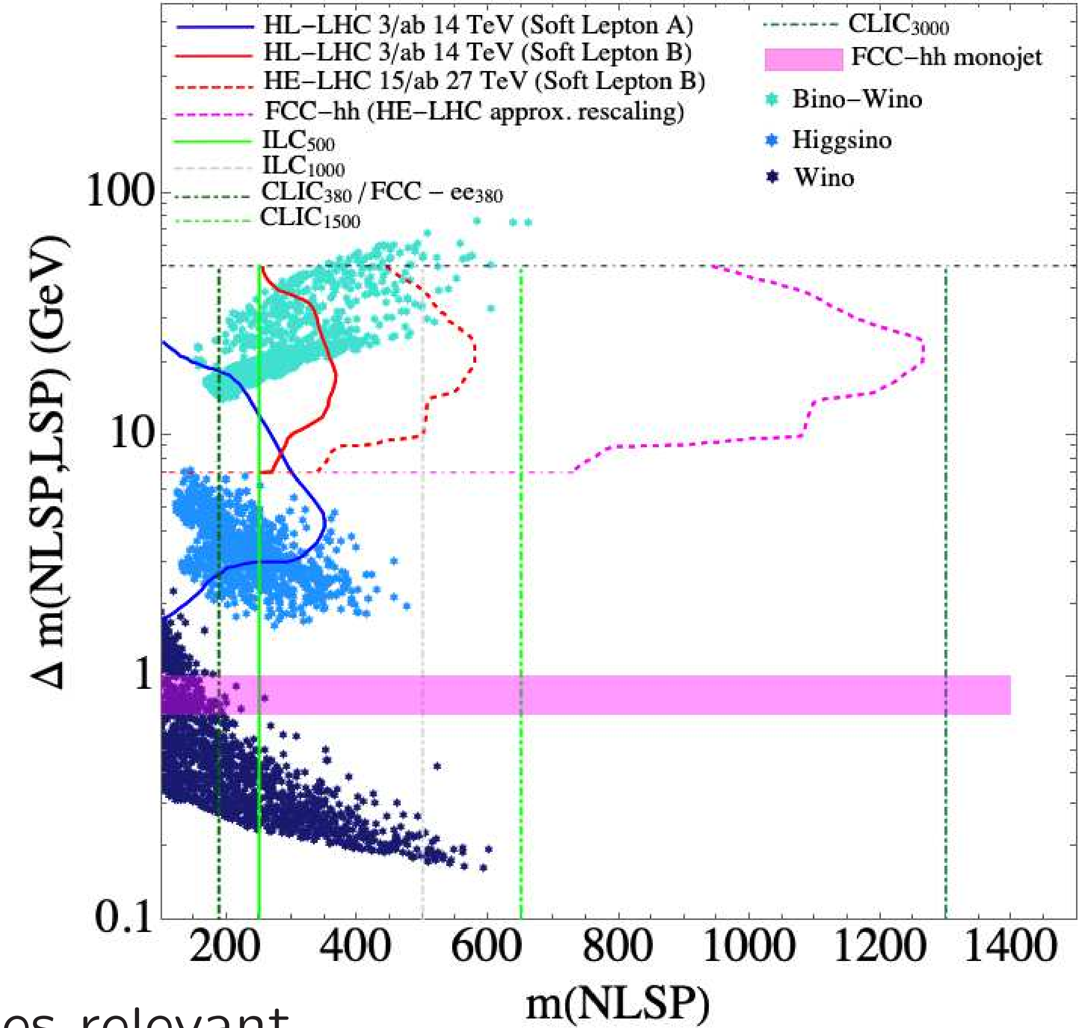
relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim 3$ TeV)

$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 600 GeV

$\Rightarrow$ predictions for future (e^+e^-) colliders?!

Compressed spectra at current and future colliders

Higgsino, wino and bino/wino DM:



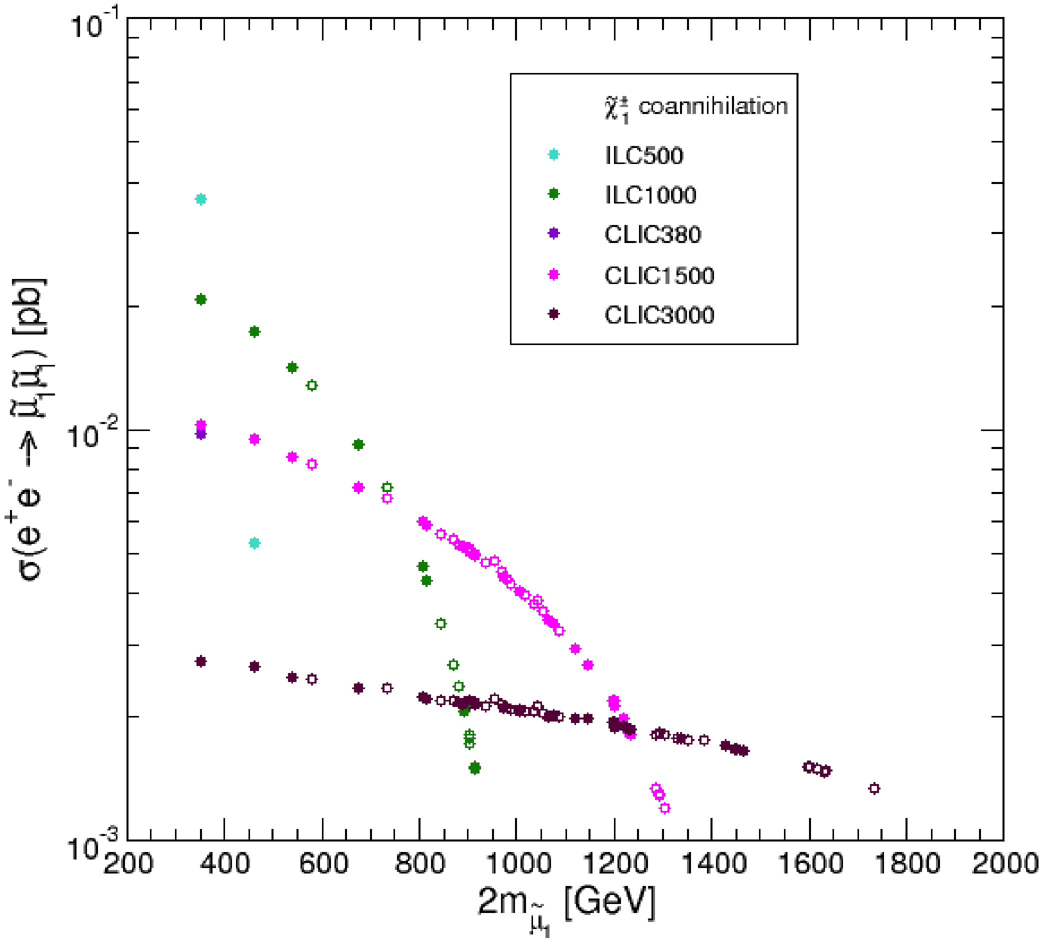
– current searches relevant

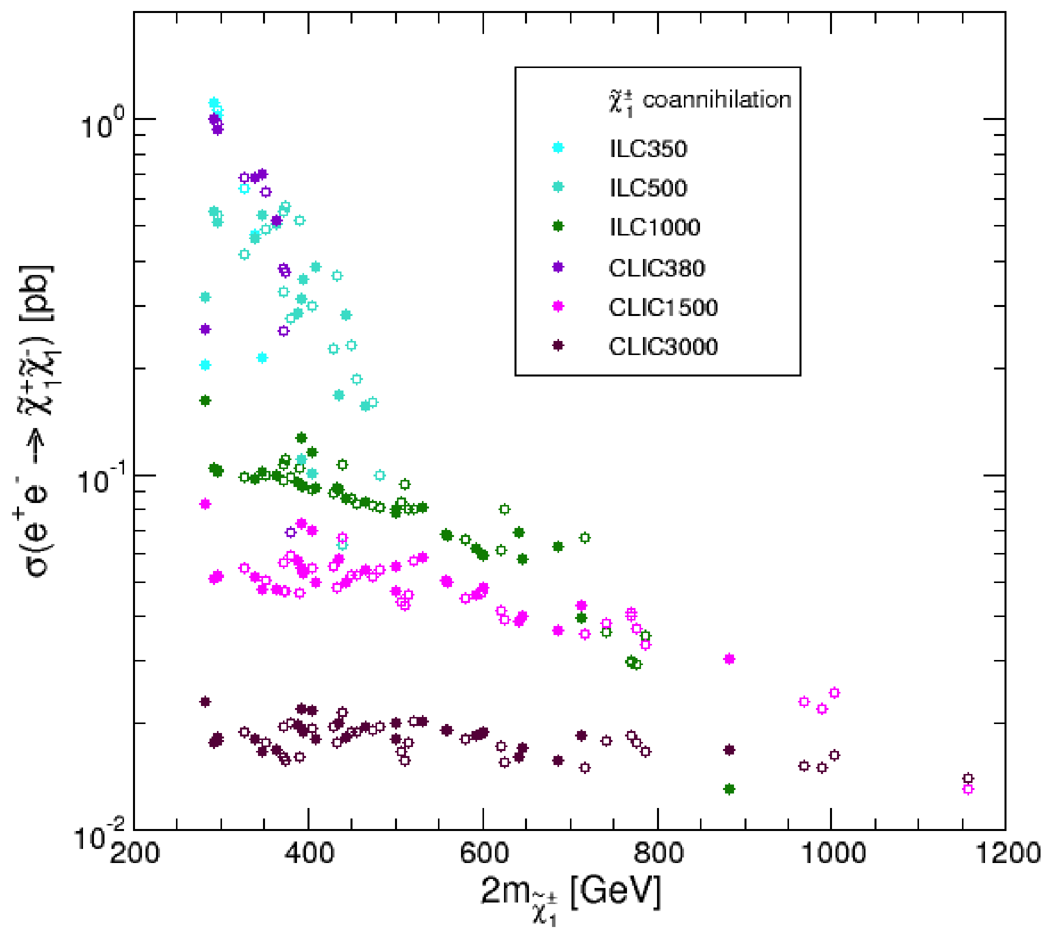
– HL-LHC searches can cover some part of the parameter space

– ILC/CLIC needed to cover these scenario

Direct production at e^+e^- colliders (ILC/CLIC)

wino/bino DM with chargino co-ann. (open/full: "old" $(g-2)_\mu$)



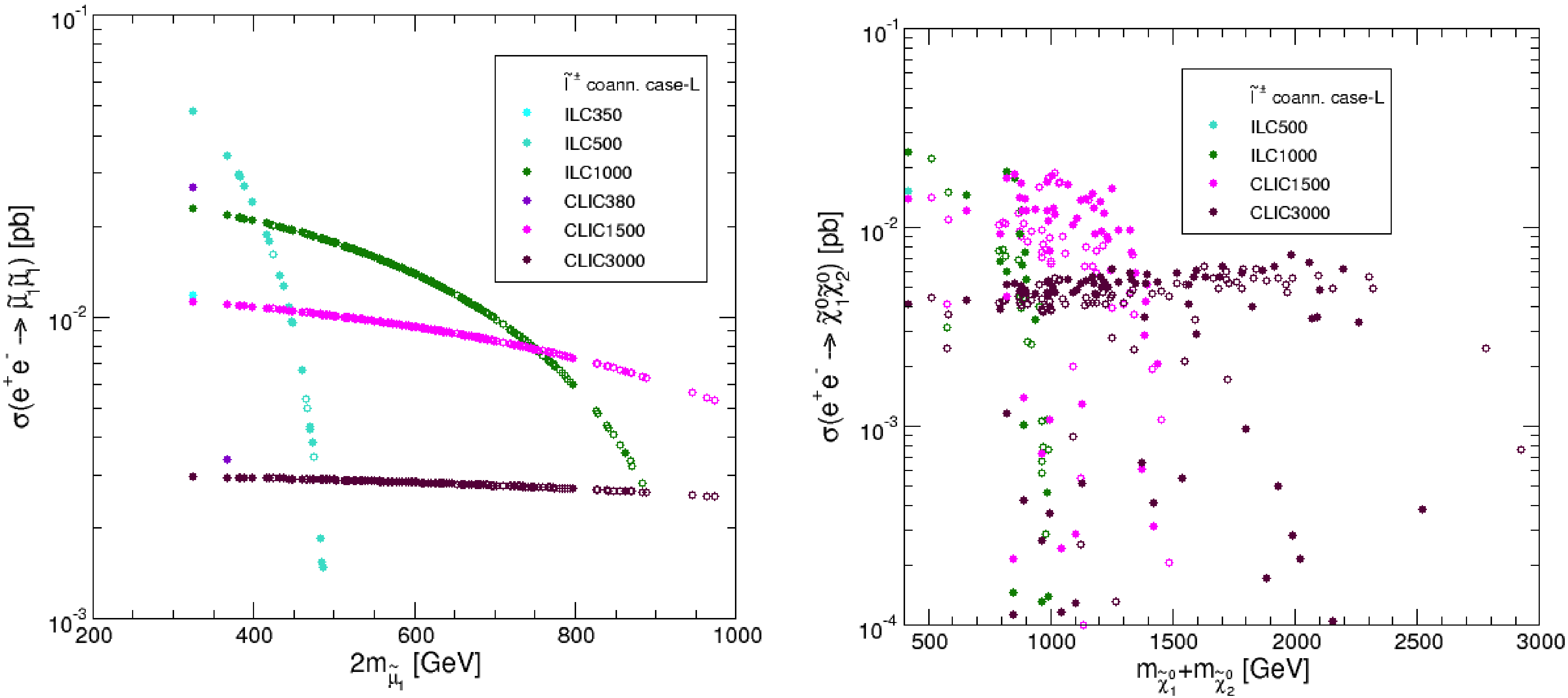


⇒ ILC has good prospects (particularly for $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$)

⇒ CLIC can cover evertything

Direct production at e^+e^- colliders (ILC/CLIC)

bino DM with slepton co-ann. (open/full: "old" $(g-2)_\mu$)

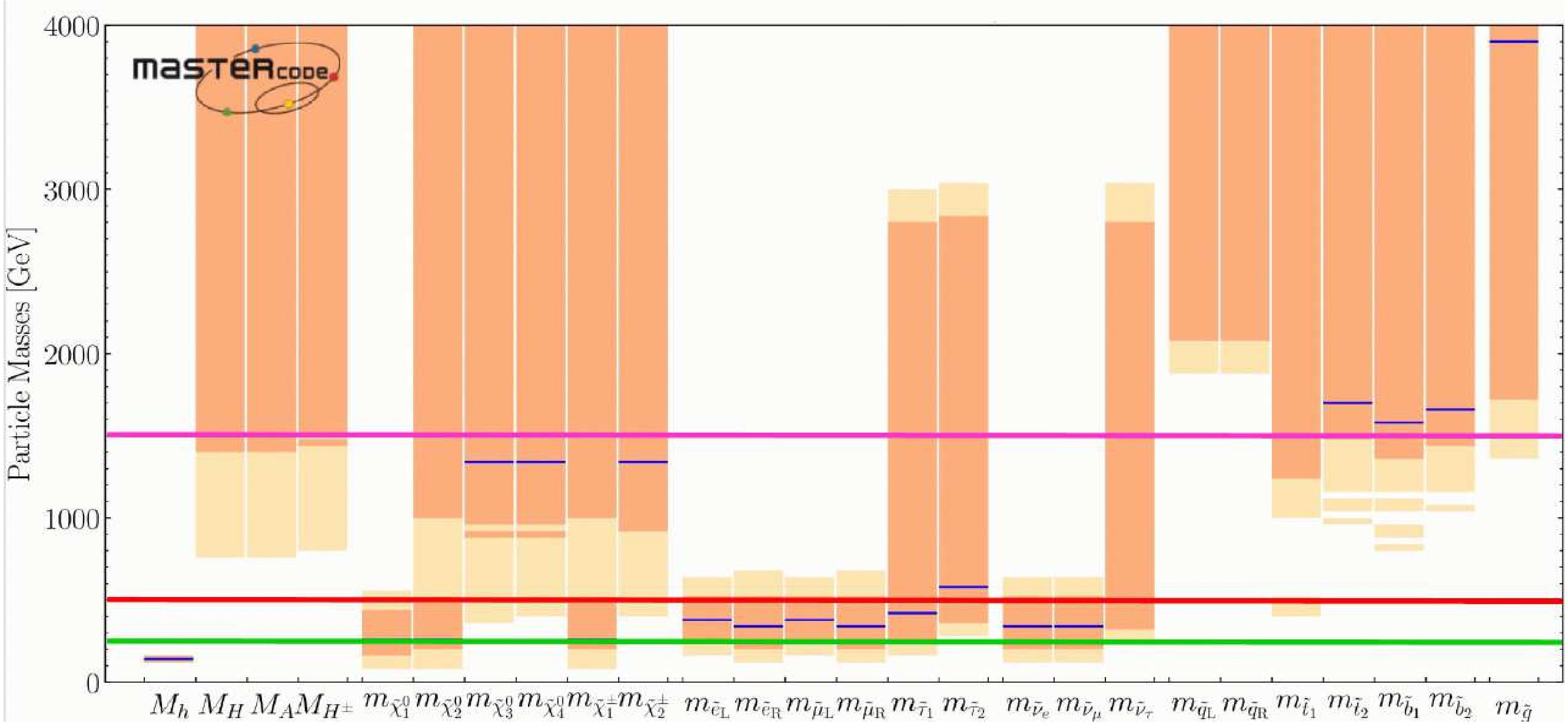


⇒ ILC can nearly covers full smuon channel (but not $\tilde{\chi}_1^0\tilde{\chi}_2^0$)

⇒ CLIC can cover evertything

pMSSM11: prospects for ILC and CLIC

[2017]



ILC: $\sqrt{s} = 500$ GeV $\Rightarrow$ some particles might be in reach

ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ precision analysis of EW particle and DM easy!

CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ precision analysis of EW particles and DM easy!

Further opportunities at a LC facility

1. Beam dump experimenta

2. Fixed target experiments

3. Detectors far from the interaction points

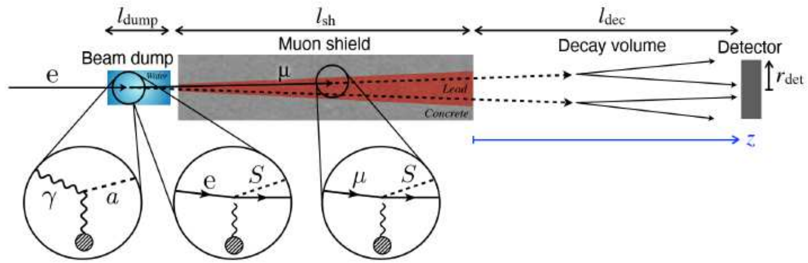
4. . . .

$\Rightarrow$ new, recent ideas

Use of ILC Beam for Fixed Target Experiment

There are many possible experiments using the ILC beam other than the colliding experiment

- Experiments using the main dump
  - ✓ Observe particles created in the main beam dump
  - ✓ Dark photon, dark lepton, ALP (axion-like particle), Higgs-portal particles, ……
  - ✓ Positron main dump
    - Positron annihilation with atomic electrons
  - ✓ Parasitic with the main collision experiment



- Experiments using Extracted beam
  - ✓ Extract the strong ILC beam somewhere for e.g., strong QED experiment
    - This is perhaps difficult (the beam is too strong to ontercept)
  - ✓ Or, create and extract a weak beam
    - Low bunch intensity but many (>> 1312) bunches
    - Ideally, CW
    - Missing energy experiment to search for dark photons
    - Lots of accelerator issues such as beam creation, to avoid damping in DR, control of very weak beam, etc.

By Kaoru Yokoya on Tuesday 10PM (Europe)
"N1: Dark Sector, Fixed-Target and Beam Dump Experiments"

- Far detector
  - ✓ Long-lived particles may be produced at the IP
  - ✓ They may be detected by a detector behind 50-200m shield (natural rocks)
  - ✓ Need to construct a cavern (near the main beamline, or along the access tunnel)

We would be happy to discuss the further possibilities of the ILC accelerator.

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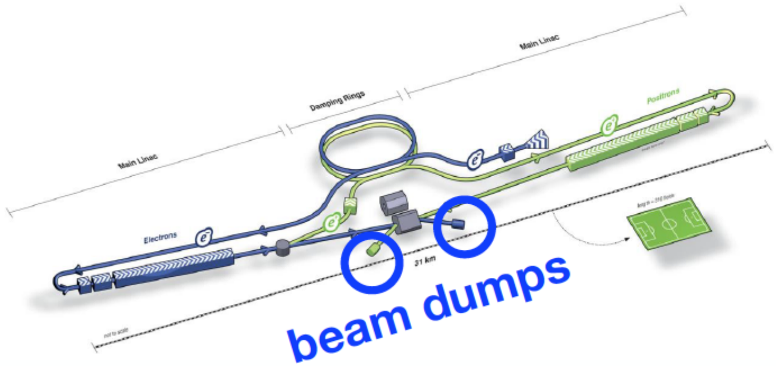
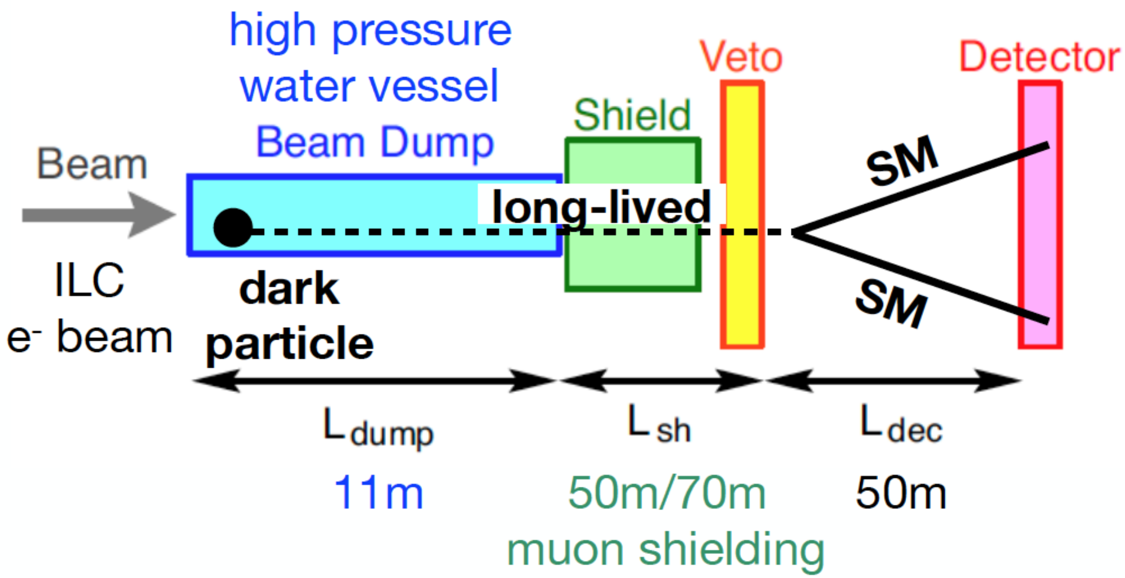
[S. Michizono '21]

ILC beam-dump setup



Kanemura, Moroi, Tanabe, 1507.02809



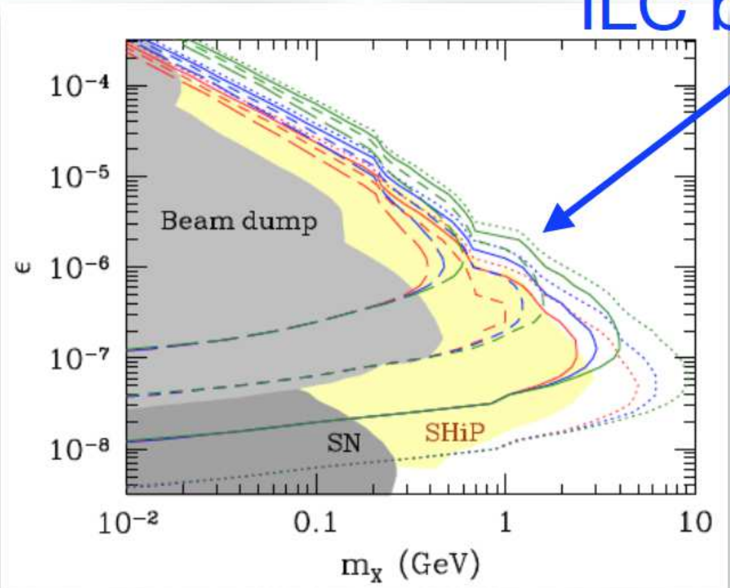
- Much **larger energy:** 125 GeV, 250 GeV, 500 GeV, 1.5 TeV electron beams compared to past/present e^- beam dump experiments:
  - E137 @ SLAC: ~20 GeV electron beam (past)
  - HPS @ JLAB: ~ (1-6) GeV electron beam (present)

- **Very high luminosities**: ~$4*10^{21}$ electrons on target (EOT)/year compared to
  - E137 @ SLAC: ~$2*10^{20}$ EOT
  - HPS @ JLAB: ~10^{18} EOT

[*S. Gori '20*]

Complementarity with other experiments

ILC beam dump

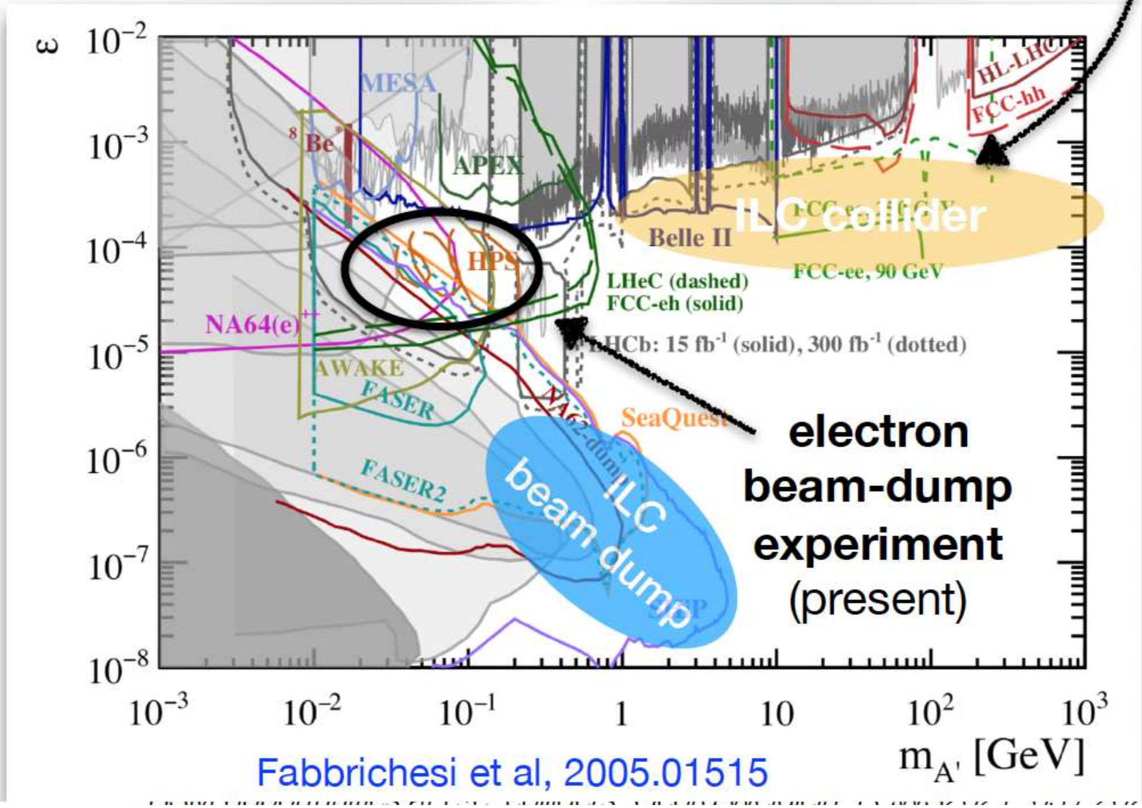


Kanemura et al.,1507.02809

Additional opportunities for the ILC here!

$e^+e^- \to A' \gamma \to \gamma\, l^+ l^-$ (prompt dark photon)

Future (proposed and approved) experiments



Fabbrichesi et al, 2005.01515

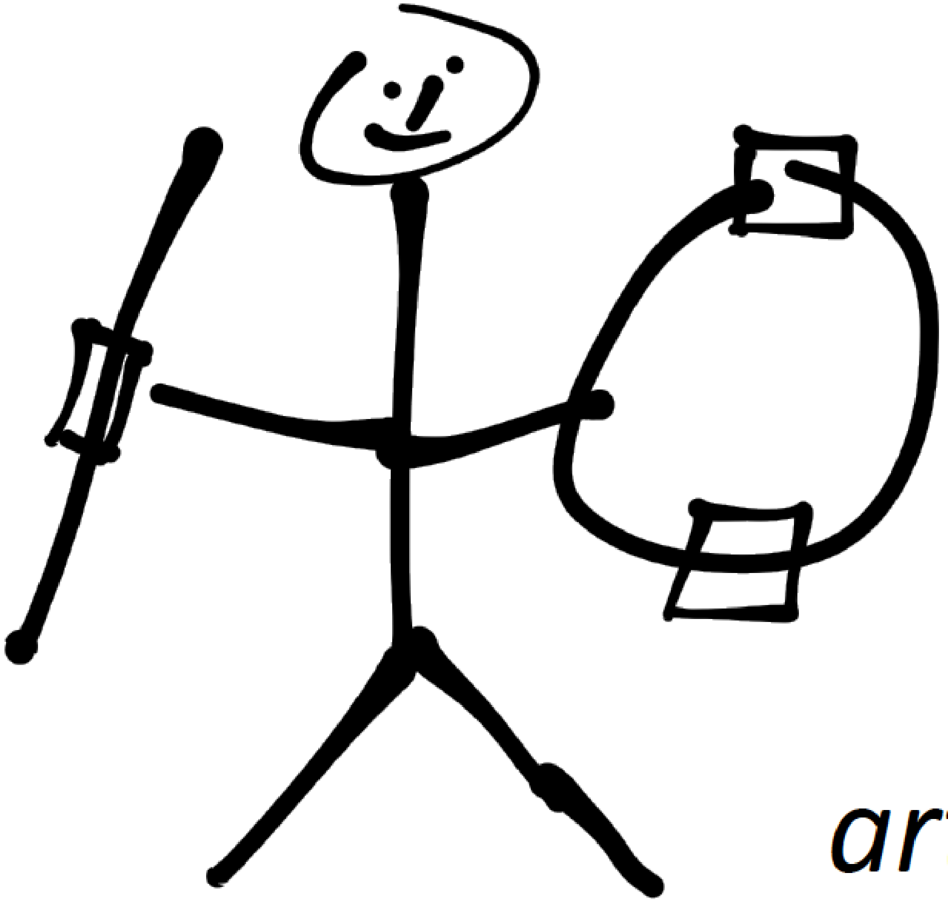
Few references:

- SeaQuest: Berlin, SG, Schuster, Toro, 1804.00661
- FCC: Karliner et al., 1503.07209
- SHiP: Alekhin et al., 1504.04855
- FASER: Feng et al., 1708.09389

+ Proposal for the Belle II experiment: Gazelle (Evans et al.)

[S. Gori '20]

Conclusion: Let's build "it"! :-)



artwork by F. Simon


Further Questions?

SUSY realizations

What about SUSY??

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$\Rightarrow$ type II fits best, type II is needed for SUSY $\Rightarrow$ no surprize! ;-)

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⇒ models with an additional singlet??

- NMSSM
- $\mu\nu$SSM
- ...

SUSY realizations

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⇒ models with an additional singlet??

- NMSSM
- $\mu\nu$SSM
- ...

Q: Can the models fit the excesses despite the additional SUSY constraints on the Higgs sector **???**

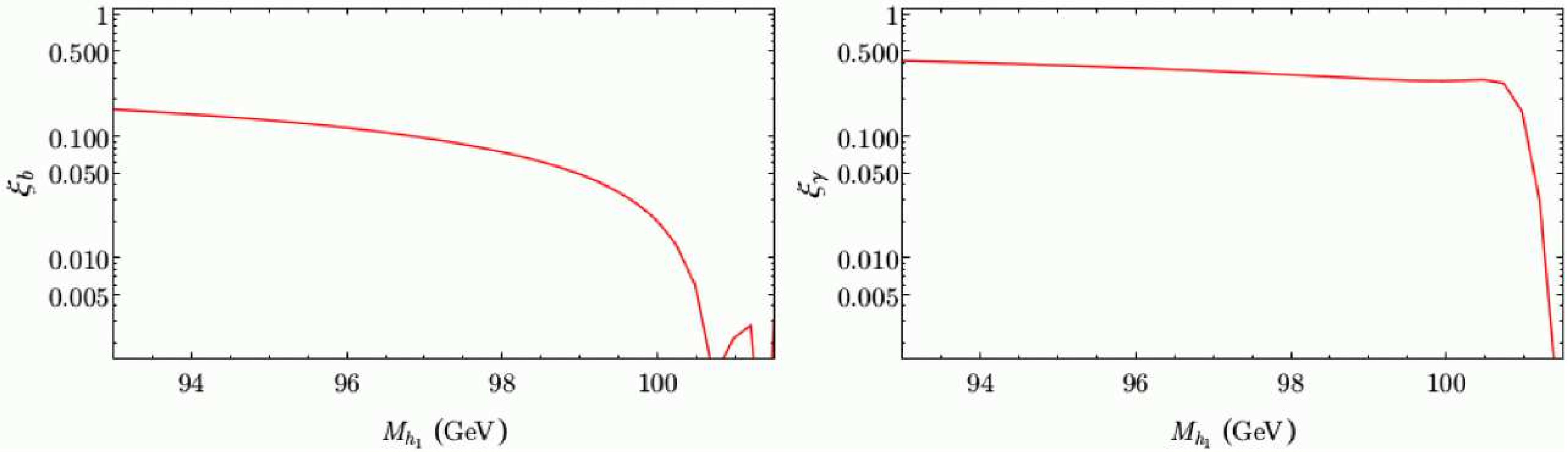
What about the NMSSM? [F. Domingo, S.H., S. Passehr, G. Weiglein '18]

Parameters:

$\lambda = 0.6$, $\kappa = 0.035$, $\tan\beta = 2$, $\mu_{\rm eff} = (397 + 15x)$ GeV, $M_{H^\pm} = 1$ TeV, $A_\kappa = -325$ GeV, $M_{\rm SUSY} = 1$ TeV, $A_t = A_b = 0$

$$\xi_b \equiv \frac{\Gamma[h_1 \to ZZ] \cdot {\rm BR}[h_1 \to b\bar{b}]}{\Gamma[H_{\rm SM}(M_{h_1}) \to ZZ] \cdot {\rm BR}[H_{\rm SM}(M_{h_1}) \to b\bar{b}]} \sim \frac{\sigma[e^+e^- \to Z(h_1 \to b\bar{b})]}{\sigma[e^+e^- \to Z(H_{\rm SM}(M_{h_1}) \to b\bar{b})]}$$

$$\xi_\gamma \equiv \frac{\Gamma[h_1 \to gg] \cdot {\rm BR}[h_1 \to \gamma\gamma]}{\Gamma[H_{\rm SM}(M_{h_1}) \to gg] \cdot {\rm BR}[H_{\rm SM}(M_{h_1}) \to \gamma\gamma]} \sim \frac{\sigma[gg \to h_1 \to \gamma\gamma]}{\sigma[gg \to H_{\rm SM}(M_{h_1}) \to \gamma\gamma]}\,.$$



⇒ both excesses can be fitted simultaneously (at $1 - 1.5\,\sigma$)!

What about the $\mu\nu$SSM?

$\mu\nu$SSM: [*D. Lopez-Fogliani, C. Muñoz '06*]

$\mu\nu$SSM: NMSSM + well motivated RPV (in simple terms)

$\Rightarrow$ EW scale seesaw to reproduce the neutrino data

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Can the $\mu\nu$SSM explain the two excesses?

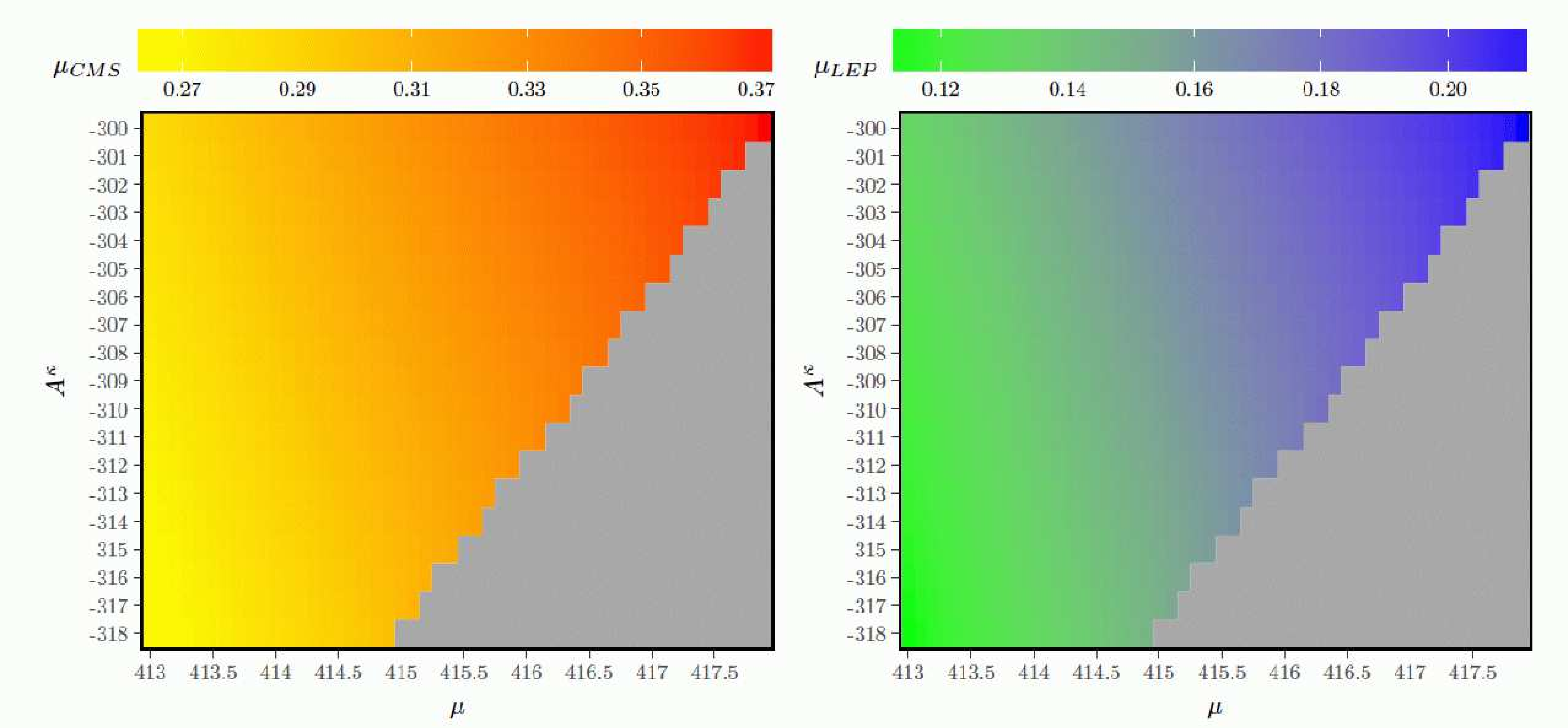
[*T. Biekötter, S.H., C. Muñoz '17*]

v_{iL}	Y_i^ν	A_i^ν	$\tan\beta$	μ	λ	A^λ	κ	A^κ	M_1
$\sqrt{2}\cdot 10^{-5}$	10^{-7}	-1000	2	$[413;418]$	0.6	956.035	0.035	$[-300;-318]$	100

M_2	M_3	$m^2_{\tilde{Q}_{iL}}$	$m^2_{\tilde{u}_{iR}}$	$m^2_{\tilde{d}_{iR}}$	A_1^u	$A_{2,3}^{u,d}$	$(m^2_{\tilde{e}})_{ii}$	A_{33}^e	$A_{11,22}^e$
200	1500	800^2	800^2	800^2	0	0	800^2	0	0

Can the $\mu\nu$SSM explain the two excesses?

[*T. Biekötter, S.H., C. Muñoz '17*]

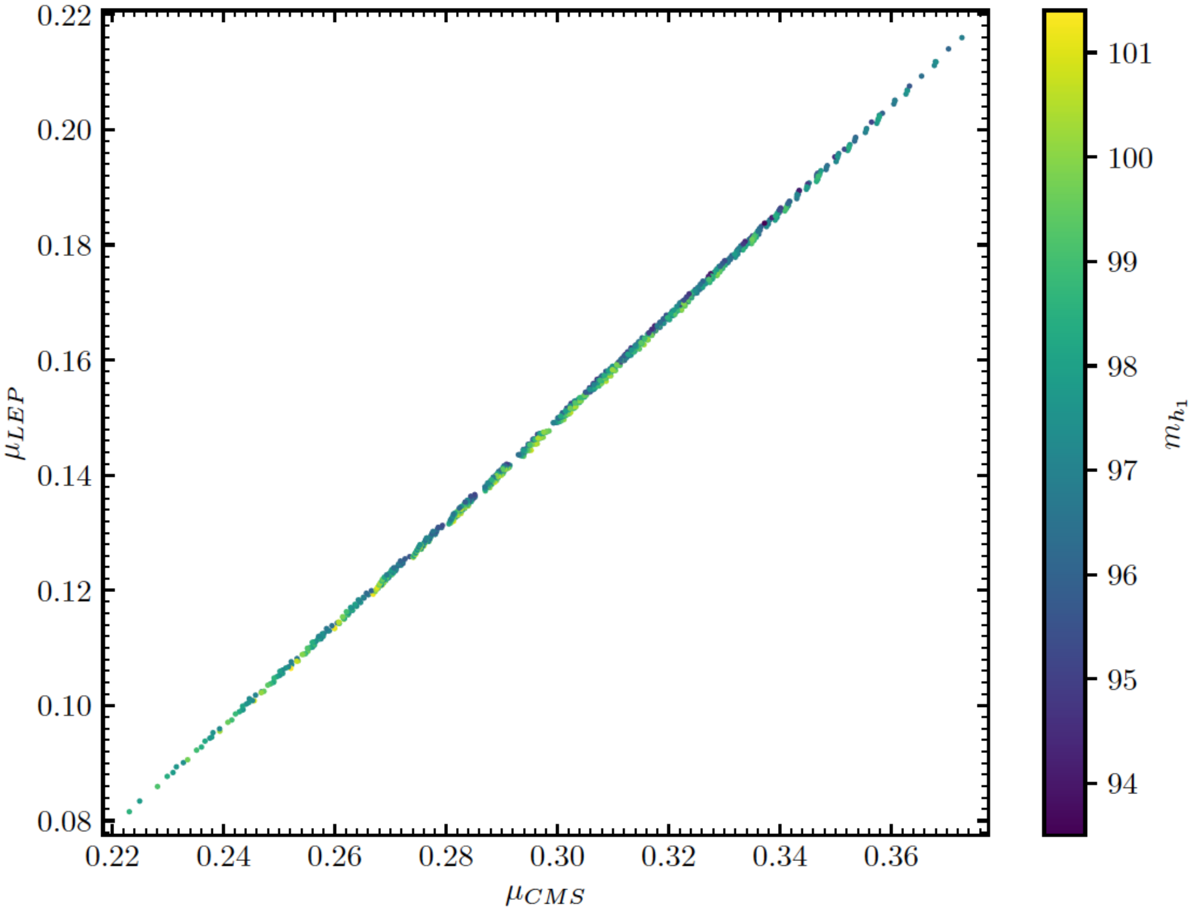


⇒ YES, WE CAN! :-)

at the $1 - 1.5\,\sigma$ level

Why can SUSY explain the excesses only at $1 - 1.5\,\sigma$?

[*T. Biekötter, S.H., C. Muñoz '19*]



⇒ SUSY enforces strong correlation!

⇒ note: ATLAS limits and CMS "observation"
will likely result in a lower μ_{LHC}!