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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Future perspectives

Georg Weiglein, DESY

DESY, 11 / 2019

Outline

- Present status

- The signal at 125 GeV

- Information from searches for additional Higgses

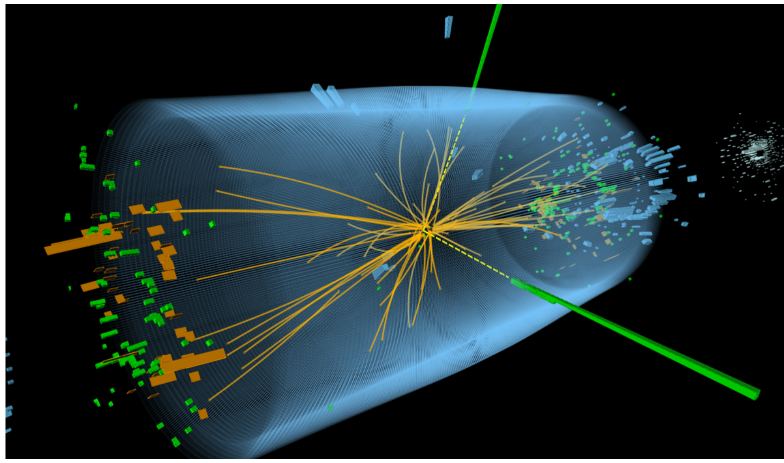
- Outcome of the Granada Open Symposium (my interpretation) and recent developments

- Conclusions (personal view)

Present status

Experimental situation (in a nutshell):

- Higgs signal at 125 GeV (h125): the discovered particle looks SM-like so far



- No further clear sign of new physics so far

Goals:

Use the information from the properties of the detected Higgs signal, from searches for new particles, from electroweak precision observables, flavour physics, cosmological and astrophysical observations (dark matter, gravitational waves, etc.) to explore the mechanism of electroweak symmetry breaking and to discriminate between models

Higgs physics: goals

- Identify the underlying dynamics of electroweak symmetry breaking; so far only phenomenological description (similar to Ginzburg-Landau theory of superconductivity)

- Determine the structure of the Higgs potential

- Discriminate between:
  — single doublet and extended Higgs sector (new symmetry?)
  — fundamental scalar and compositeness (new interaction?)

- Find out what protects the Higgs mass from physics at high scales

- Unravel the connection to dark matter, to the imbalance between matter and anti-matter in the universe, and to the phase of inflation in the early universe

Present status seen from the outside

Misconception from people outside of our field: the Standard Model of particle physics is now complete after the Higgs discovery; nothing exciting to expect from this field anymore

We need to make it clear that the Higgs discovery was the beginning of an exciting story rather than the end of one!

We need to be aware of the above criticism in the context of the update of our strategy for particle physics:

- Our future strategy needs to be very convincing and has to be communicated very well
- *``We want to have machine XYZ because we deserve it"*
  will not be sufficient in this context!

The signal at 125 GeV (h125)

- Mass

- Spin and CP properties

- Couplings, partial widths, total width, branching ratios, production cross sections (total and differential), information from off-shell contributions, interference effects, …

Higgs couplings: towards high precision

- A coupling is not a physical observable: if one talks about measuring Higgs couplings at the % level or better, one needs to precisely define what is actually meant by those couplings!

- For the determination of an appropriate coupling parameter at this level of accuracy the incorporation of strong and electroweak loop corrections is inevitable. This is in general not possible in a strictly model-independent way!

- For comparisons of present and future facilities it is crucial to clearly spell out under which assumptions these comparisons are done

The quest for identifying the underlying physics

In many BSM models one expects only % level deviations from the SM couplings for BSM particles in the TeV range. Example of 2HDM-type model in decoupling limit:

$$\frac{g_{hVV}}{g_{h_{\mathrm{SM}}VV}} \simeq 1 - 0.3\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^4$$

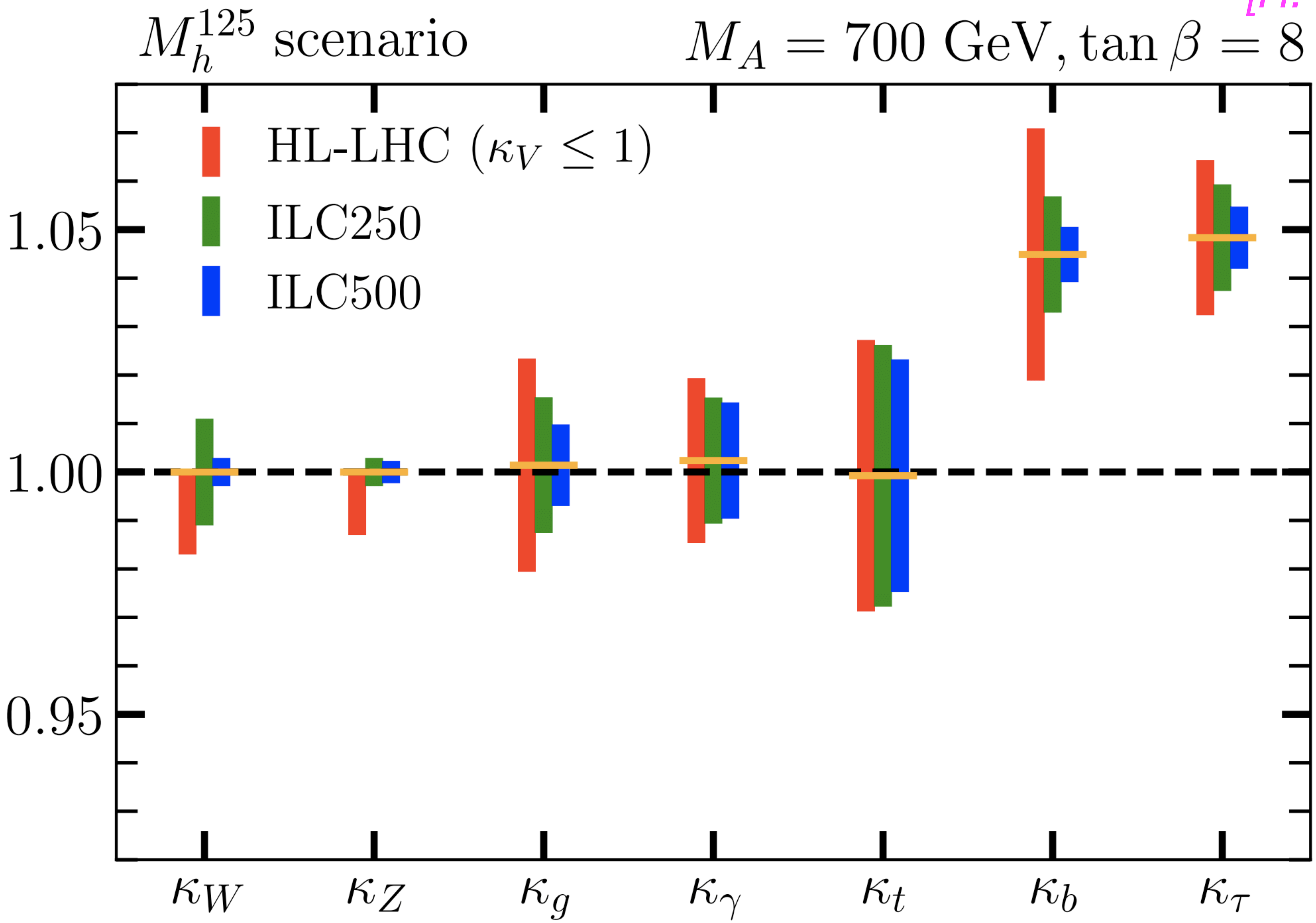
$$\frac{g_{htt}}{g_{h_{\mathrm{SM}}tt}} = \frac{g_{hcc}}{g_{h_{\mathrm{SM}}cc}} \simeq 1 - 1.7\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2$$

$$\frac{g_{hbb}}{g_{h_{\mathrm{SM}}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\mathrm{SM}}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2 .$$

⇒ Need very high precision for the couplings

Example: heavy SUSY scenario

[H. Bahl et al. '19]



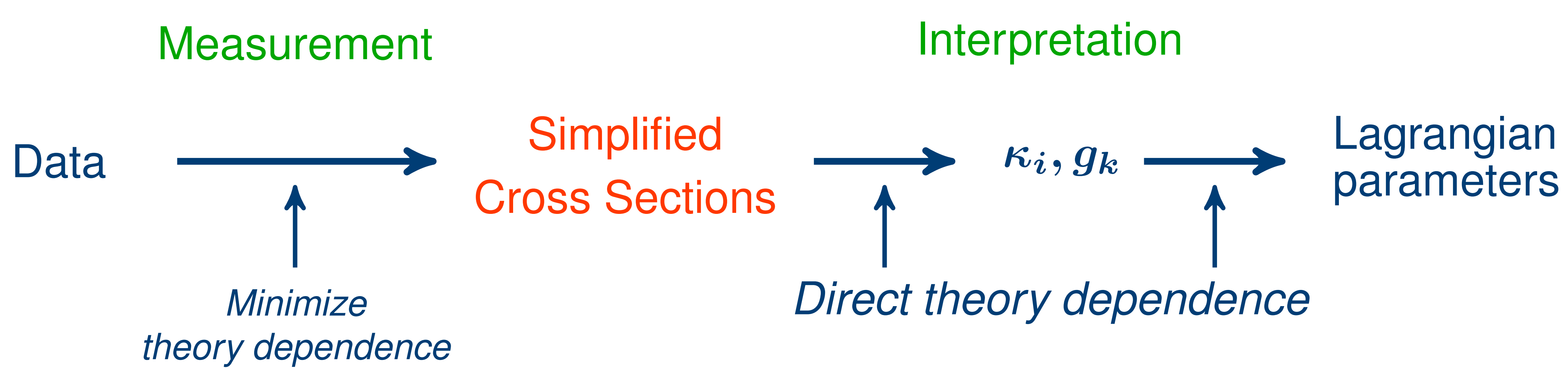
⇒ Precision at 1% level provides large sensitivity for discriminating between different realisations of underlying physics

Signal strengths, STXS, ϰ framework and beyond

Interface between experiment and theory:

- Signal strengths: clear interpretation, but involve extrapolations to total cross sections, etc. and are affected if predictions for the SM cross sections change

- Simplified template cross sections (STXS):



- Fiducial cross sections, pseudo observables, …

Interpretation: $\varkappa$, EFT frameworks and specific models

Interpretation of the experimental results in terms of Higgs coupling properties:

- $\varkappa$ framework: ``interim” framework used so far, deviations from the SM parametrised by ``scale factors” $\varkappa_i$ (SM $\varkappa_i = 1$), involve various theoretical assumptions (signal corresponds to only one state, no overlapping resonances, zero width approximation, no change in tensor structure of the couplings, only overall strength, implies assumption that the observed state is a CP-even scalar)

- EFT framework: assumes that new physics appears only at a scale $\Lambda \gg M_h, M_t, \ldots$

- Specific models: Clear interpretation of the impact of constraints and the viable parameter space, light new physics can be probed

$\varkappa$, EFT framework and specific models

- $\varkappa$ framework: various theoretical assumptions, see above

- EFT framework: an EFT represents certain classes of models, but there are different assumptions on the form of the EFT (SMEFT vs. non-SM Higgs sector, assumption that there are no light new particles), on the flavour structure and on further symmetries
  Note:
  Need to be careful about the range of validity, dim-6 vs. dim-8 operators, etc.
  It is crucial to use a complete basis of operators, results for an incomplete basis are physically not meaningful
  Higher-order contributions need to be properly incorporated
  An EFT analysis is not model-independent

$\Rightarrow$ Both the $\varkappa$ and the EFT framework contain various assumptions
Analyses using EFTs and specific models are complementary

Comparison of the capabilities of future colliders

In comparisons of future facilities with the HL-LHC in terms of the $\varkappa$ and EFT frameworks the capabilities of the future facilities for testing the assumptions made in those frameworks are not included by construction

This means that only a part of the actual improvements is visible in the comparisons

In view of this fact, it would be useful to avoid even further assumptions, such as $\varkappa_V < 1$ for the $\varkappa$ framework

Big qualitative improvement from an e^+e^- Higgs factory: absolute measurement of the HZ cross section, absolute measurements of the Higgs branching ratios, nearly model-independent determination of the total Higgs width

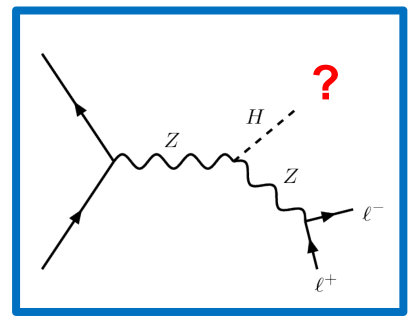
e^+e^- Higgs factories: recoil method

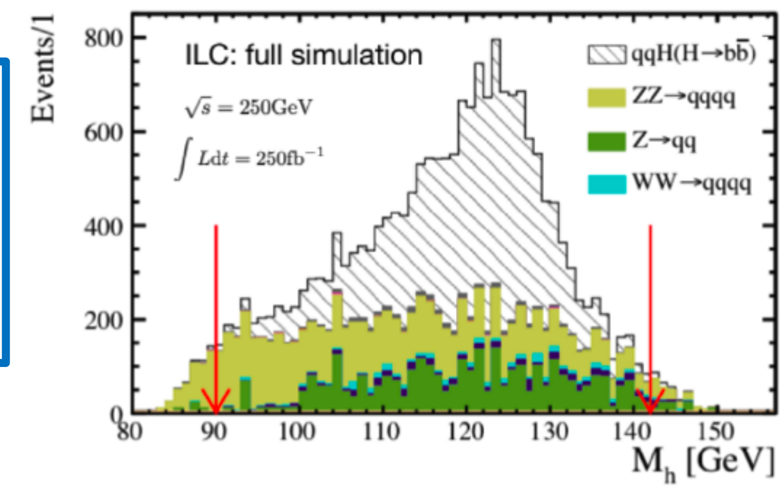
[B. Heinemann '19]

Higgs width and/or untagged decays

Unique feature of lepton-lepton colliders:

- **Detecting the Higgs boson without seeing decay: "recoil method"**
- **Measure ZH cross section with high precision without assumptions on decay**
- **Often interpreted as quasi-direct measurement of width**





$$\frac{\sigma(e^+e^- \to ZH)}{\mathrm{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$$

In kappa-framework: $$\Gamma_H = \frac{\Gamma_H^{\mathrm{SM}} \cdot \kappa_H^2}{1-(BR_{inv}+BR_{unt})}$$

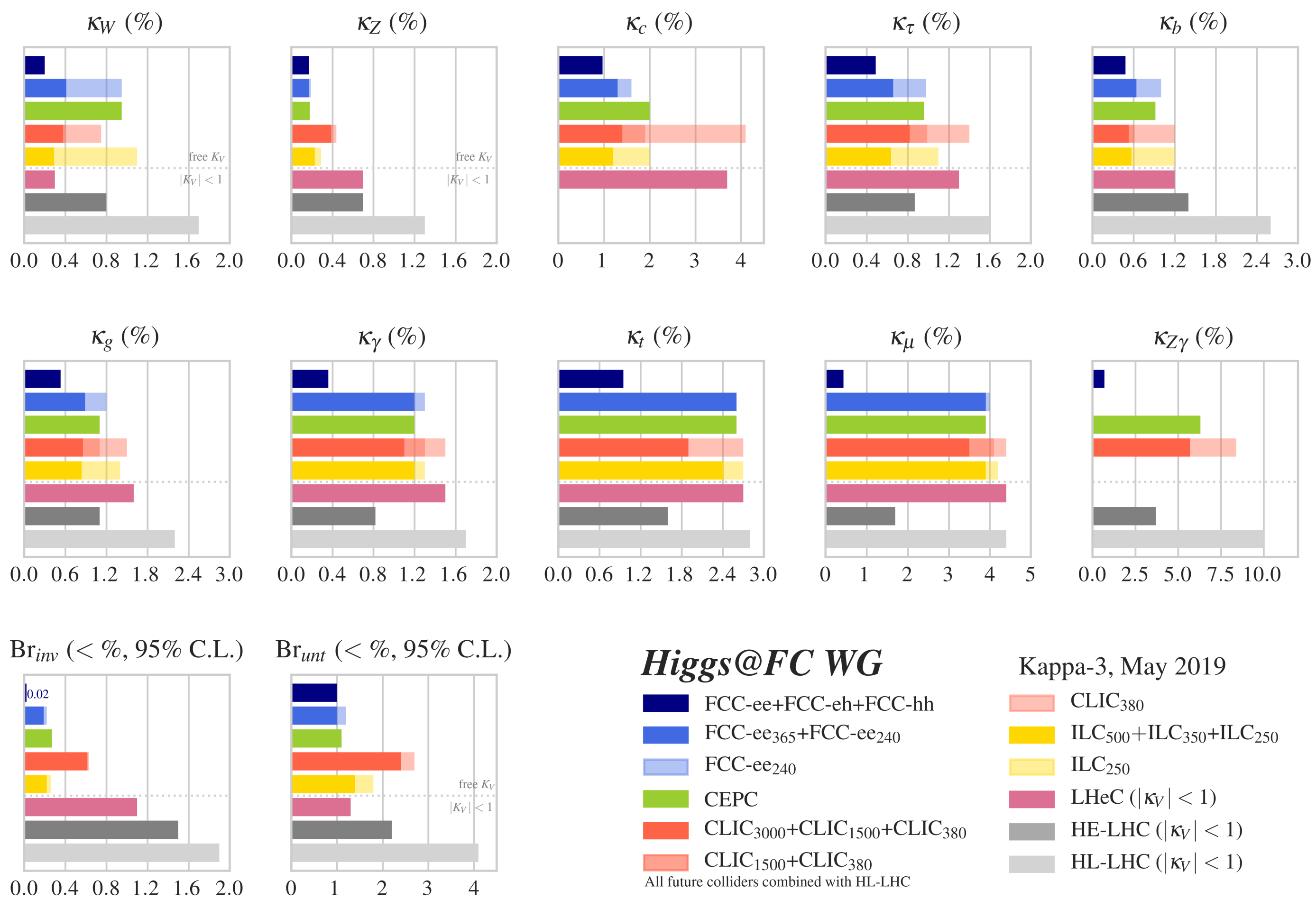
=> Will probe width with 1-2% precision

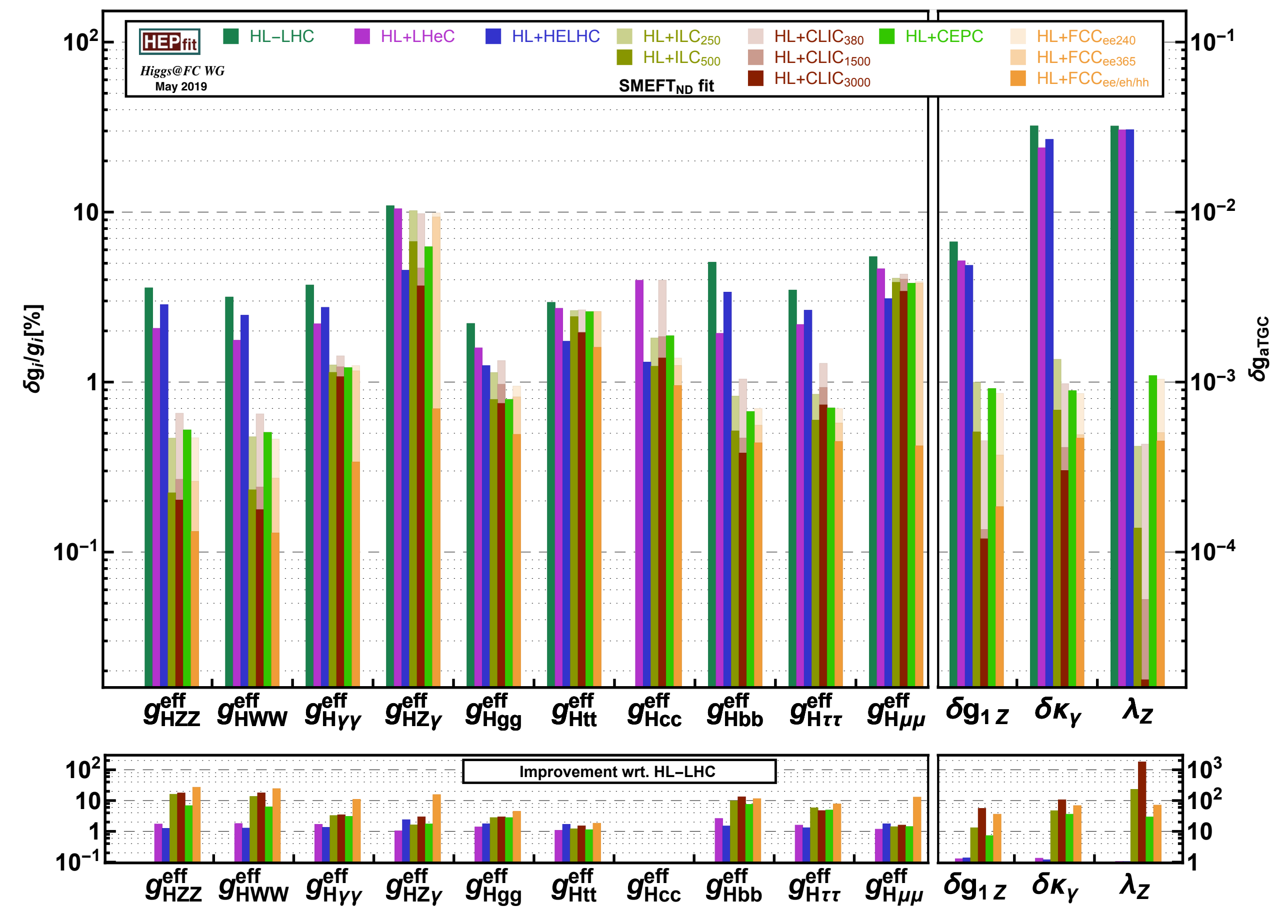
Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
CLIC_{350}	4.7	κ-framework [85]	2.6
CLIC_{1500}	2.6	κ-framework [85]	1.7
CLIC_{3000}	2.5	κ-framework [85]	1.6
CEPC	3.1	$\sigma(ZH, \nu\bar{\nu}H)$, $\mathrm{BR}(H \to Z, b\bar{b}, WW)$ [90]	1.8
FCC-ee_{240}	2.7	κ-framework [1]	1.9
FCC-ee_{365}	1.3	κ-framework [1]	1.2

arXiv:1905.03764

Comparison plots for the strategy update

[J. de Blas et al. ’19]





Plots of this kind are dangerous since people from outside of our field may use them to claim that the improvement from any future facility compared to the HL-LHC is unimpressive!

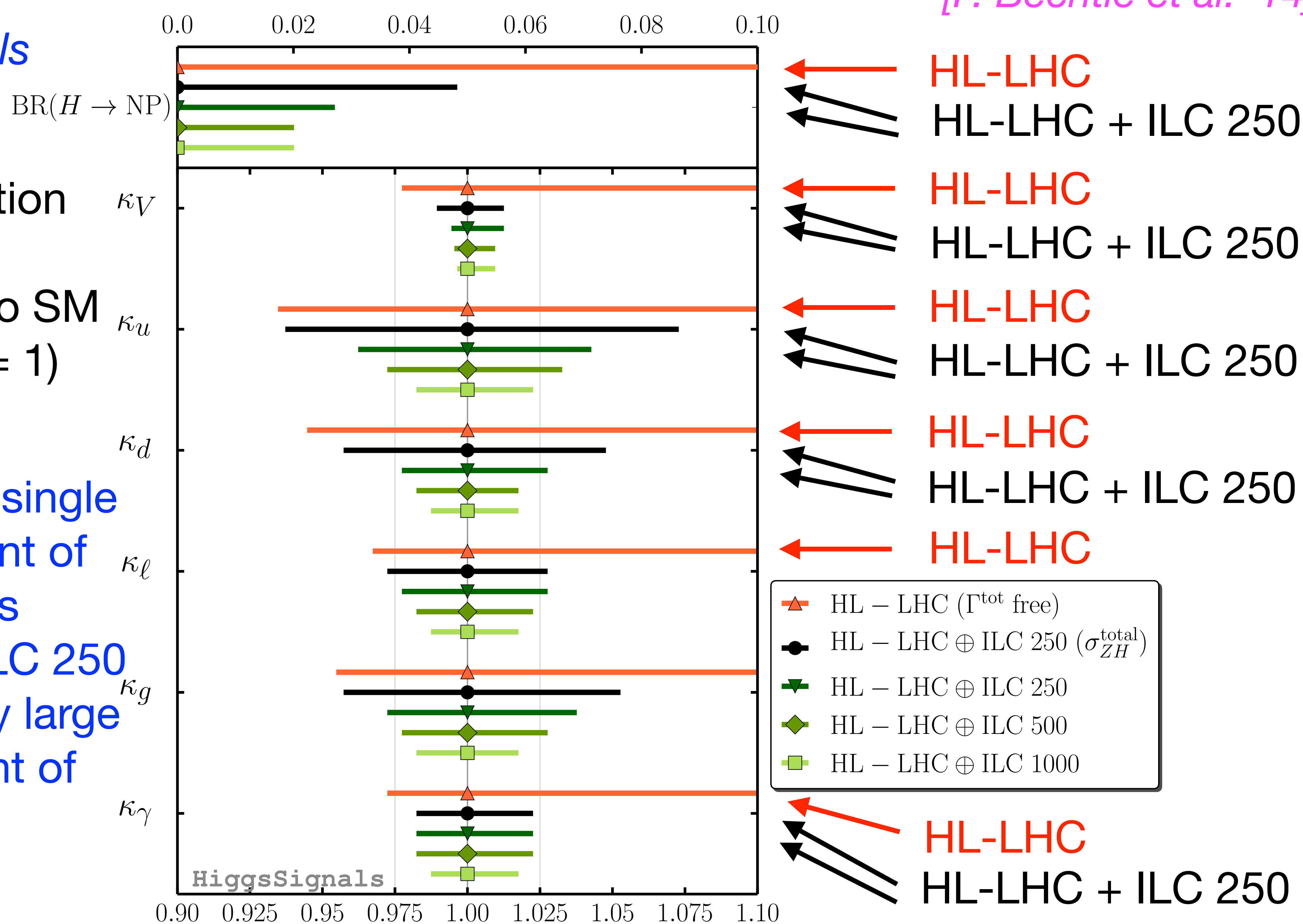
Projections for HL-LHC and ILC, no additional theory assumptions (ILC 250: only 250 fb^{-1})

[P. Bechtle et al. '14]

HiggsSignals

$\varkappa_i$: modification of coupling compared to SM value ($\varkappa_i^{SM} = 1$)

⇒ Already the single measurement of the HZ cross section at ILC 250 yields a very large improvement of the LHC accuracies!



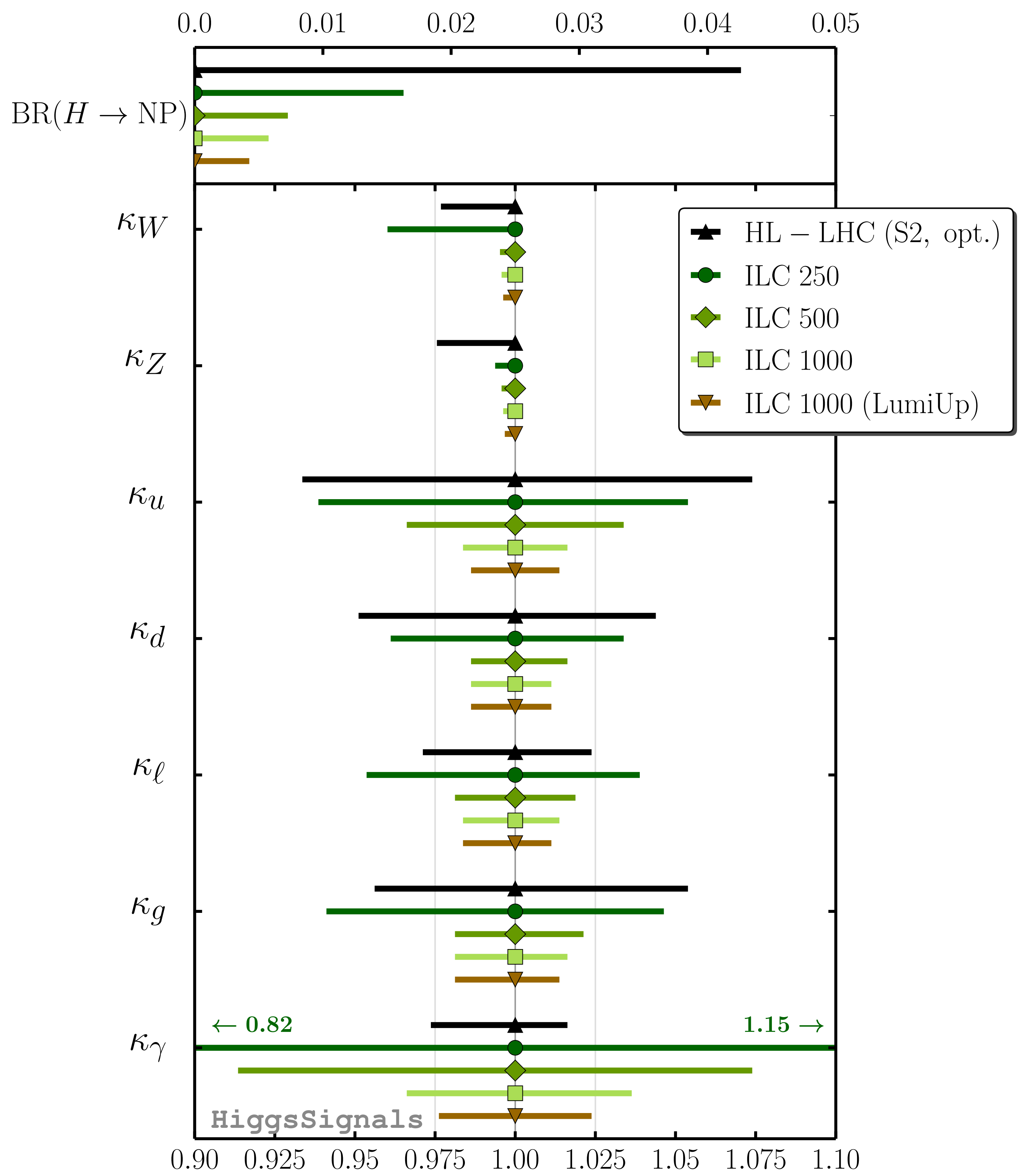
Prospects for Higgs-coupling determinations at HL-LHC and ILC: with theory assumption on κ_V

[P. Bechtle et al. '14]

HiggsSignals

Assumed:

$\kappa_V \leq 1$



Higgs self coupling λ

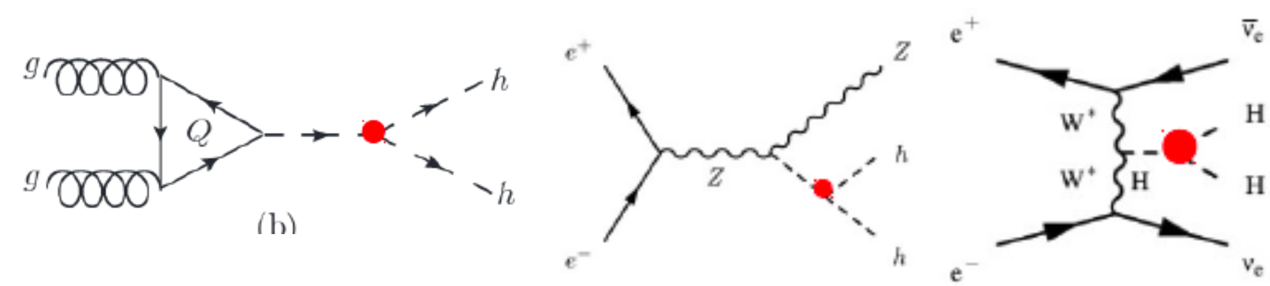
Sensitivity of different processes crucially depends on the actual value of λ

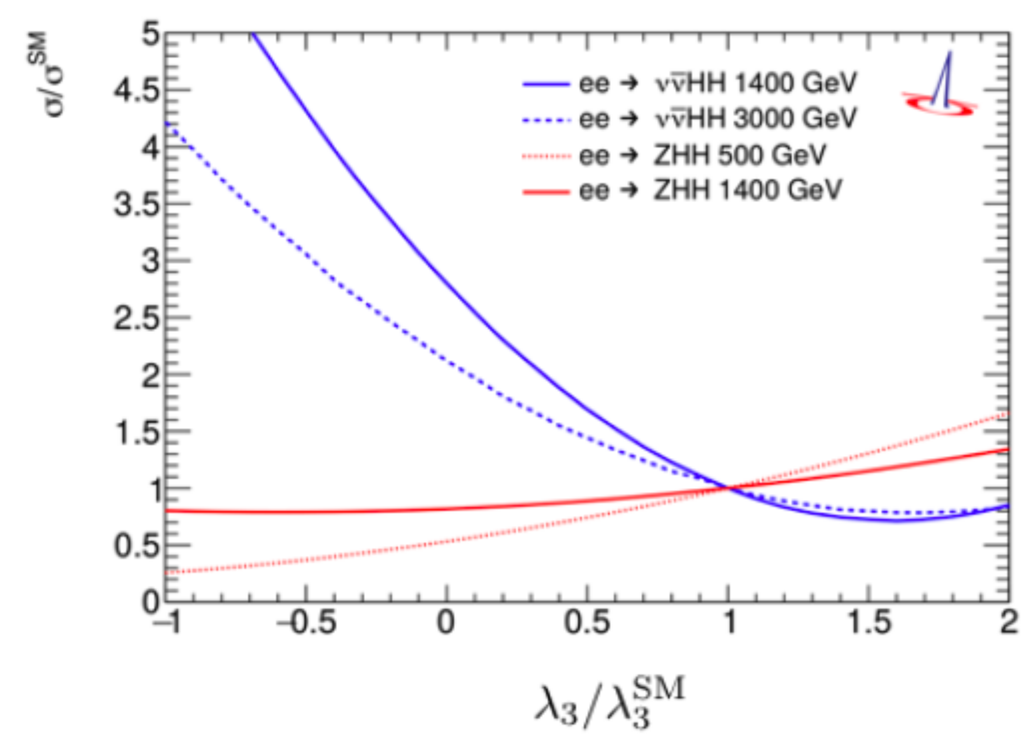
[B. Heinemann '19]

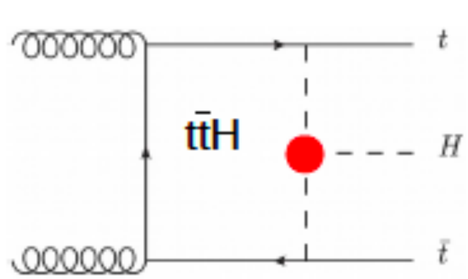
Di-Higgs processes at hadron colliders:
- $\sigma(HH) \approx 0.01 \times \sigma(H)$
- Important to use differential measurements

Di-Higgs processes at lepton colliders
- ZHH or VBF production complementary

Single-Higgs production sensitive through loop effects, e.g. for $\kappa_\lambda = 2$:
- Hadron colliders: ~3%
- Lepton colliders: ~1%





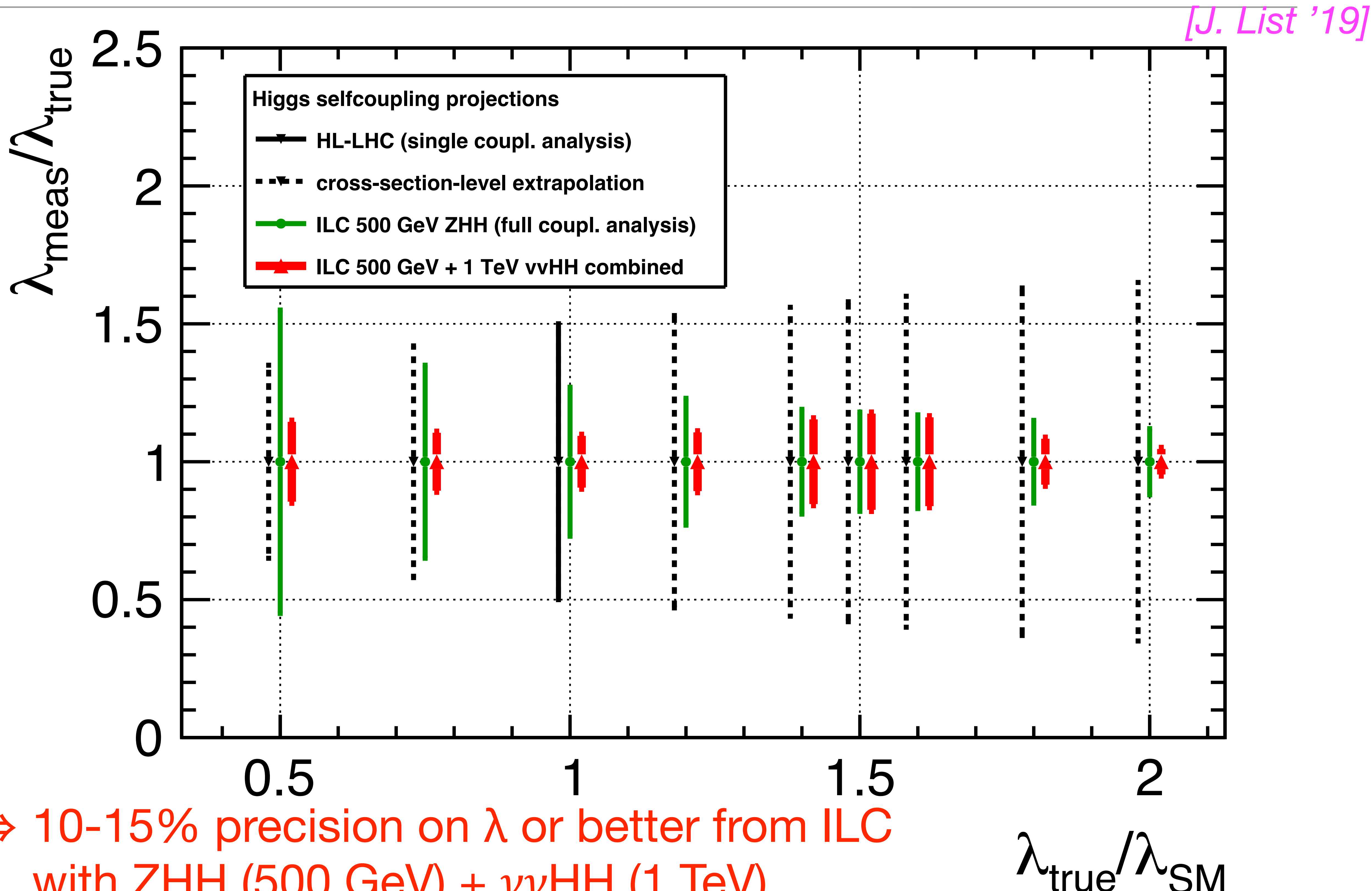


Recent discussion regarding Higgs self-coupling

Does one really need an e^+e^- Linear Collider with at least 500 GeV to precisely measure the Higgs self-coupling?

- The projections for the HL-LHC have significantly improved recently. Isn't that enough?
- Isn't it sufficient to use the information on single Higgs production from an e^+e^- collider (possibly circular) at lower energies?
- What about FCC-hh?

Higgs self-coupling sensitivity: ILC vs. HL-LHC



⇒ 10-15% precision on λ or better from ILC
with ZHH (500 GeV) + $\nu\nu$HH (1 TeV)

Single-Higgs processes: λ enters at loop level

[E. Petit '19]

How to measure deviations of λ_3

- The Higgs self-coupling can be assessed using di-Higgs production and single-Higgs production
- The sensitivity of the various future colliders can be obtained using four different methods:

	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
global	**2. di-H, glob.** • Use of σ(HH) • deformation of κλ + of the single-H couplings (a) do not consider the effects at higher order of κλ to single H production and decays (b) these higher order effects are included	**4. single-H, glob.** • single Higgs processes at higher order • deformation of κλ + of the single Higgs couplings

Note: it is highly artificial to assume that there is a large shift in λ, but no change anywhere else!

Single-Higgs processes: λ enters at loop level

[B. Heinemann ’19]

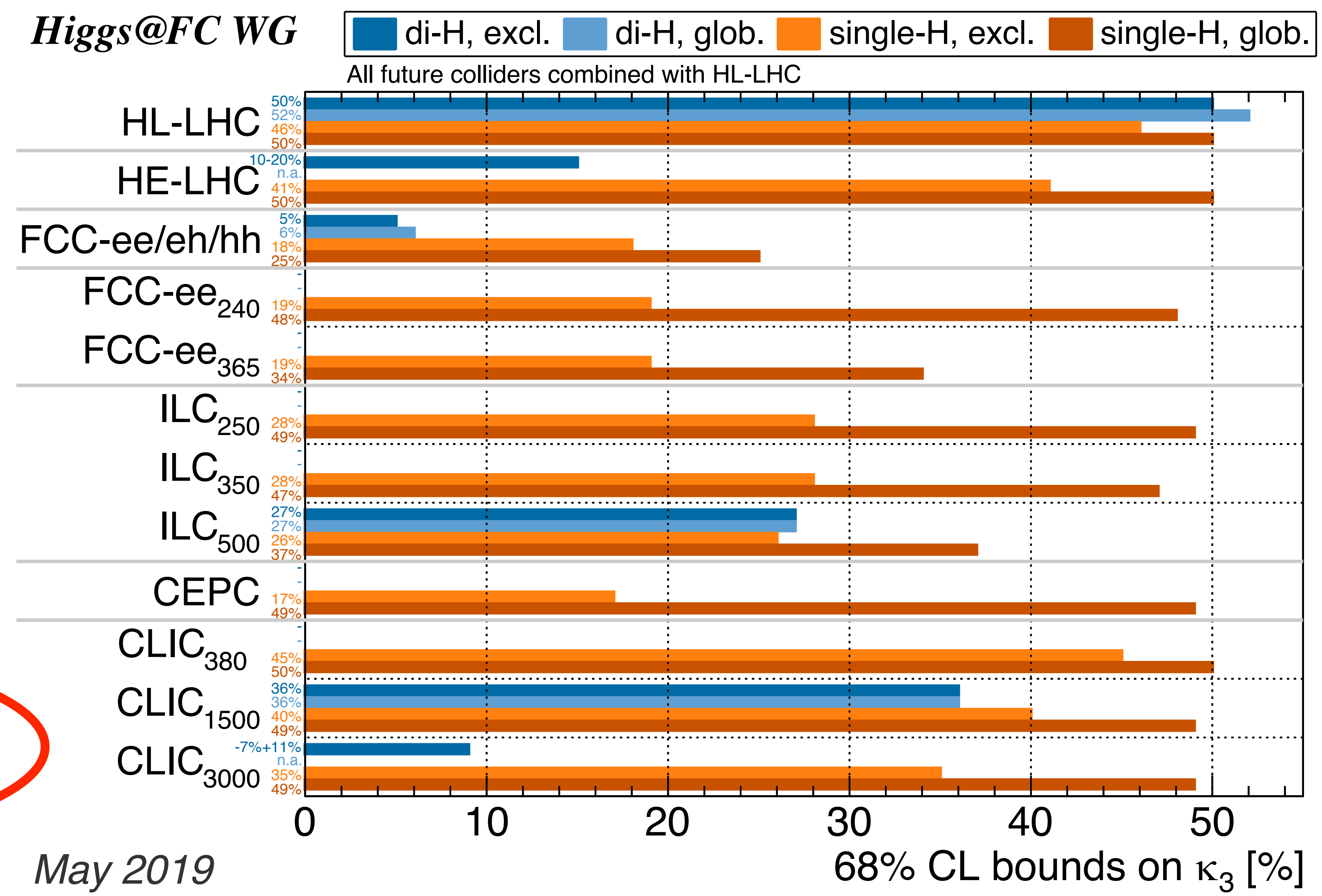
Sensitivity to λ: via single-H and di-H production

Di-Higgs:

- **HL-LHC: ~50% or better?**
- **Improved by HE-LHC (~15%), ILC_{500} (~27%), $CLIC_{1500}$ (~36%)**
- **Precisely by $CLIC_{3000}$ (~9%), FCC-hh (~5%),**
- **Robust w.r.t other operators**

Single-Higgs:

- **Global analysis: FCC-ee365 and ILC500 sensitive to ~35% when combined with HL-LHC**
  - **~21% if FCC-ee has 4 detectors**
- **Exclusive analysis: too sensitive to other new physics to draw conclusion**



Interpretation of the projections for future facilities

- Report by Higgs@FC Group: charge was to use the inputs as provided by the projects, no scrutinisation of optimism vs. realism and of the level of sophistication of the inputs
- HL-LHC projections are to a large extent systematics-limited; they crucially depend on the level of improvement of the theory uncertainties that can be reached
- This is also a reason for the fact that the Higgs coupling projections for HE-LHC show only relatively small improvements over HL-LHC
- FCC-hh projections, in particular when taken separately, depend on the assumption of a drastic reduction of theory uncertainties
- FCC-ee requires very significant conceptual progress on theory side

ILC and FCC-ee have great potential for high-precision Z, WW, and Higgs physics

Can theory provide the necessary precision? *[S. Dittmaier '19]*

$\hookrightarrow$ Optimists: “Yes. No show-stoppers seen, great progress can be anticipated.”

Sceptics: “Enormous challenge! Conceptual progress difficult to extrapolate.”

Requirements from theory for future facilities

[B. Heinemann '19]

Theoretical Uncertainties: production

Production at hadron colliders

- **For HL-LHC uncertainties expected to be improved by factor 2 w.r.t. current**
- **HE-LHC: another factor of 2**
- **FCC-hh: well below 1%**

Requires e.g.

- **Improved PDFs**
- **Higher precision calculations**
- **Improved non-perturbative aspects**
- **…**

Note: this is related to the fact that FCC-hh is assumed to be realised only far in the future!

Can one trust the projections for FCC-hh?

- Note: essentially all FCC-hh numbers that were provided as input for the Granada symposium assume the whole sequence of FCC-ee, FCC-eh, FCC-hh

- The numbers crucially rely on very optimistic estimates for future theoretical uncertainties and on the capabilities of detectors, for which we don’t know yet how to build them

Granada Open Symposium: Higgs / electroweak

[B. Heinemann '19]

of "largely" improved H couplings (EFT)

		Factor ≥2	Factor ≥5	Factor ≥10	Years from T_0
Initial run	CLIC380	9	6	4	**7**
	FCC-ee240	10	8	3	**9**
	CEPC	10	8	3	**10**
	ILC250	10	7	3	**11**
2nd/3rd Run ee	FCC-ee365	10	8	6	**15**
	CLIC1500	10	7	7	**17**
hh	HE-LHC	1	0	0	**20**
2nd/3rd Run ee	ILC500	10	8	6	**22**
	CLIC3000	11	7	7	**28**
ee,eh & hh	FCC-ee/eh/hh	12	11	10	**>50**

13 quantities in total

NB: number of seconds/year differs: ILC 1.6×10^7, FCC-ee & CLIC: 1.2×10^7, CEPC: 1.3×10^7

Information from searches for additional Higgses

For compatibility of extended Higgs sectors with exp. results:

- 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

⇒ Additional Higgs bosons may well be lighter than the SM-like Higgs (h125)

If h125 is the lightest state of an extended Higgs sector, a typical feature is that the other states are nearly mass-degenerate and show ``decoupling” behaviour

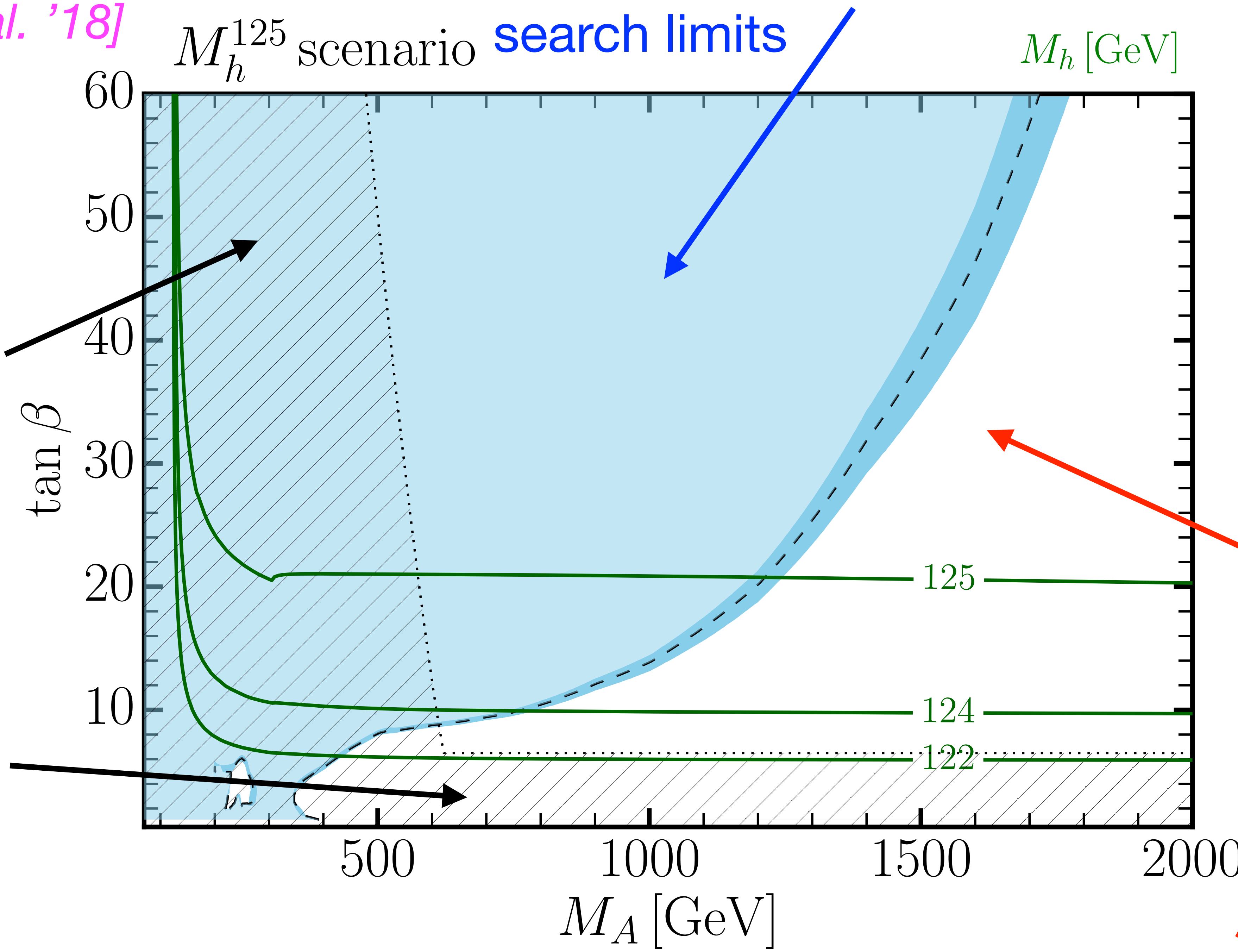
Information from Higgs signal + Higgs searches

MSSM example: recent M_h^{125} benchmark scenario

[H. Bahl et al. '18]

HiggsBounds: area excluded by Higgs search limits

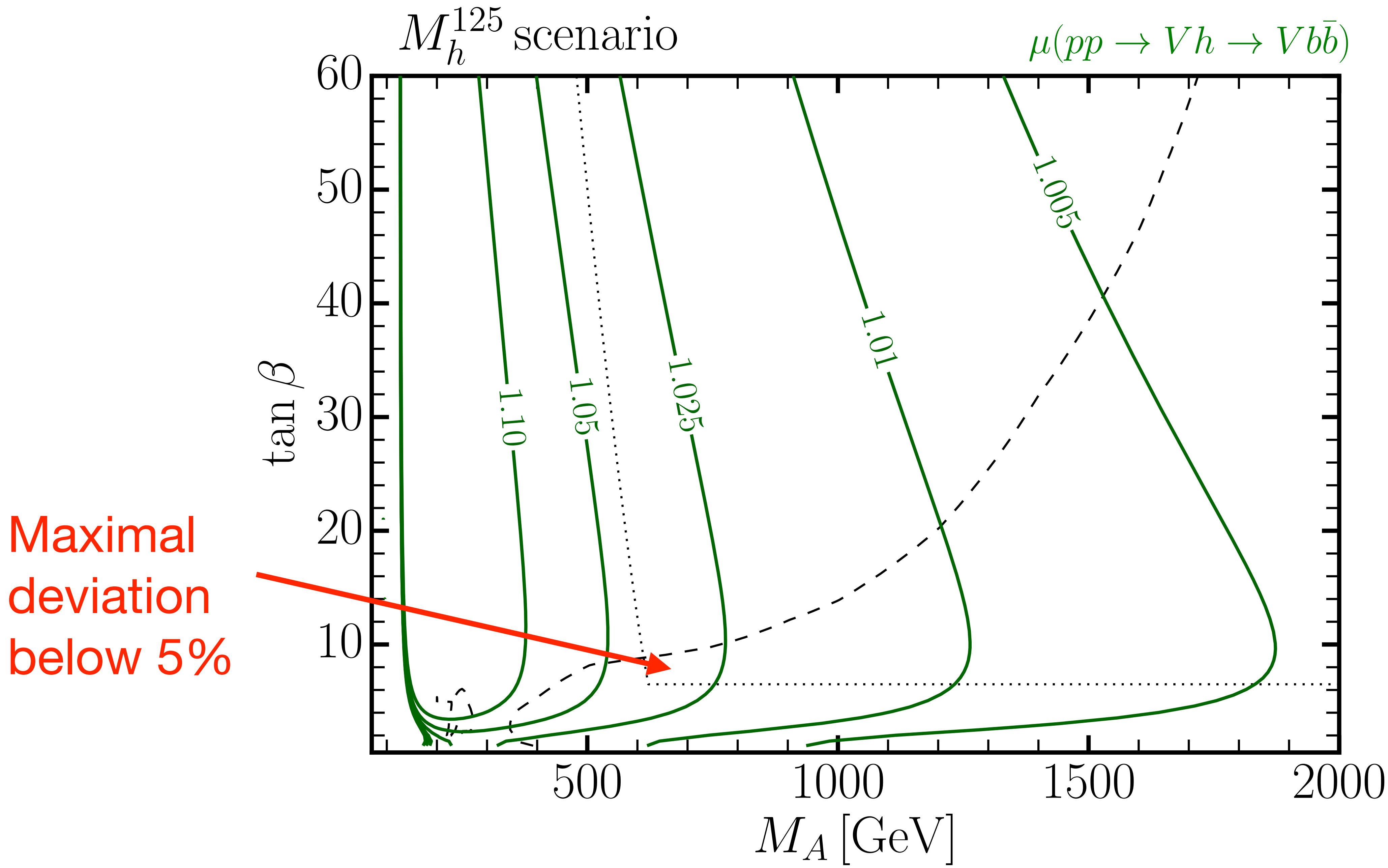
HiggsSignals: area is not compatible with the properties of the detected Higgs signal



Allowed region, can be reduced with improved precision of M_h prediction

Which deviations are still possible in the allowed region? Example: signal rates into bb

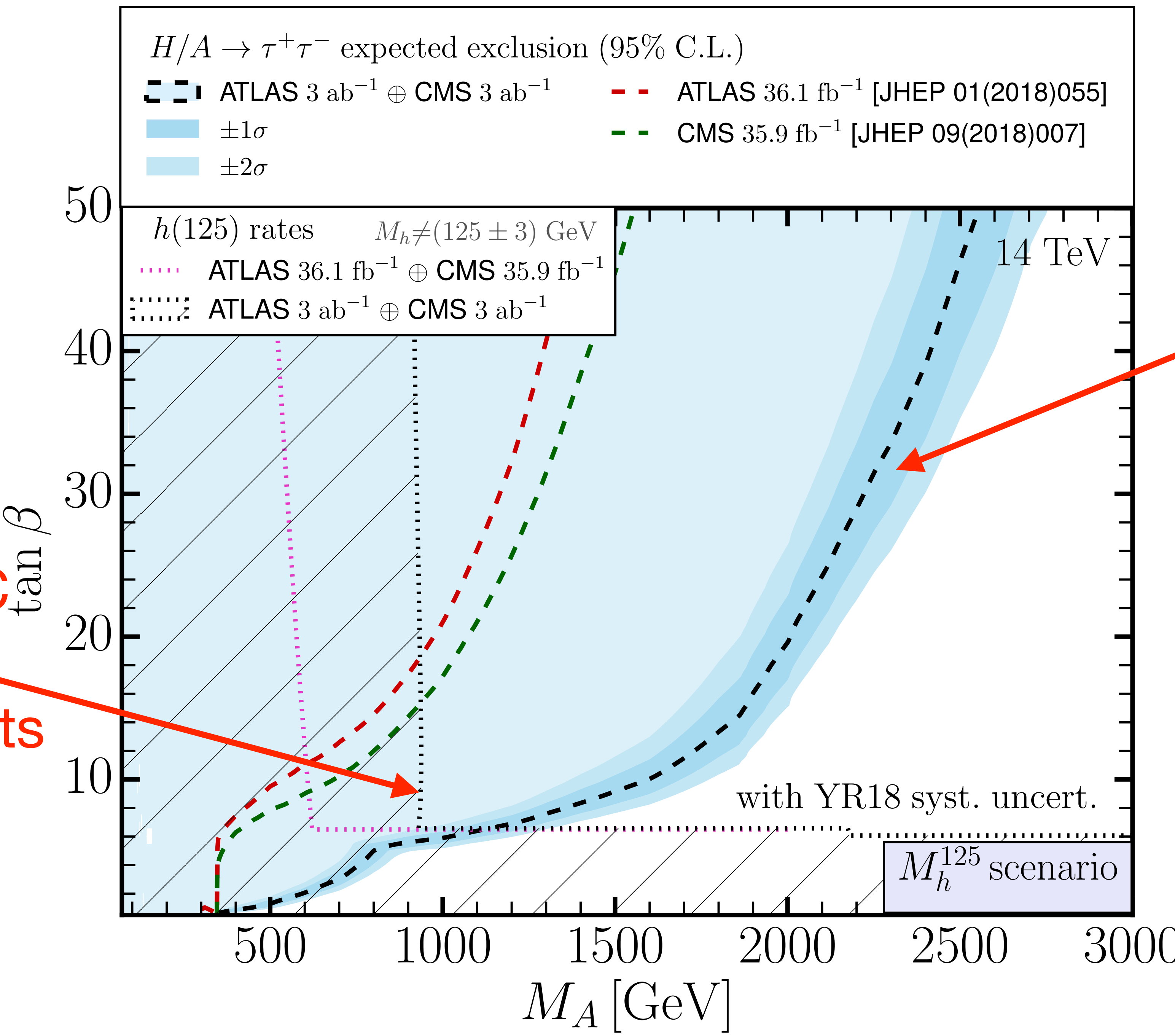
[H. Bahl et al. '18]



⇒ Sensitivity for discrimination between SM and BSM requires precision at % level or better!

HL-LHC projections: search for heavy Higgses + improved precision of h125 signal measurements

[H. Bahl et al. ’19]



Projected exclusion region for H, A searchs

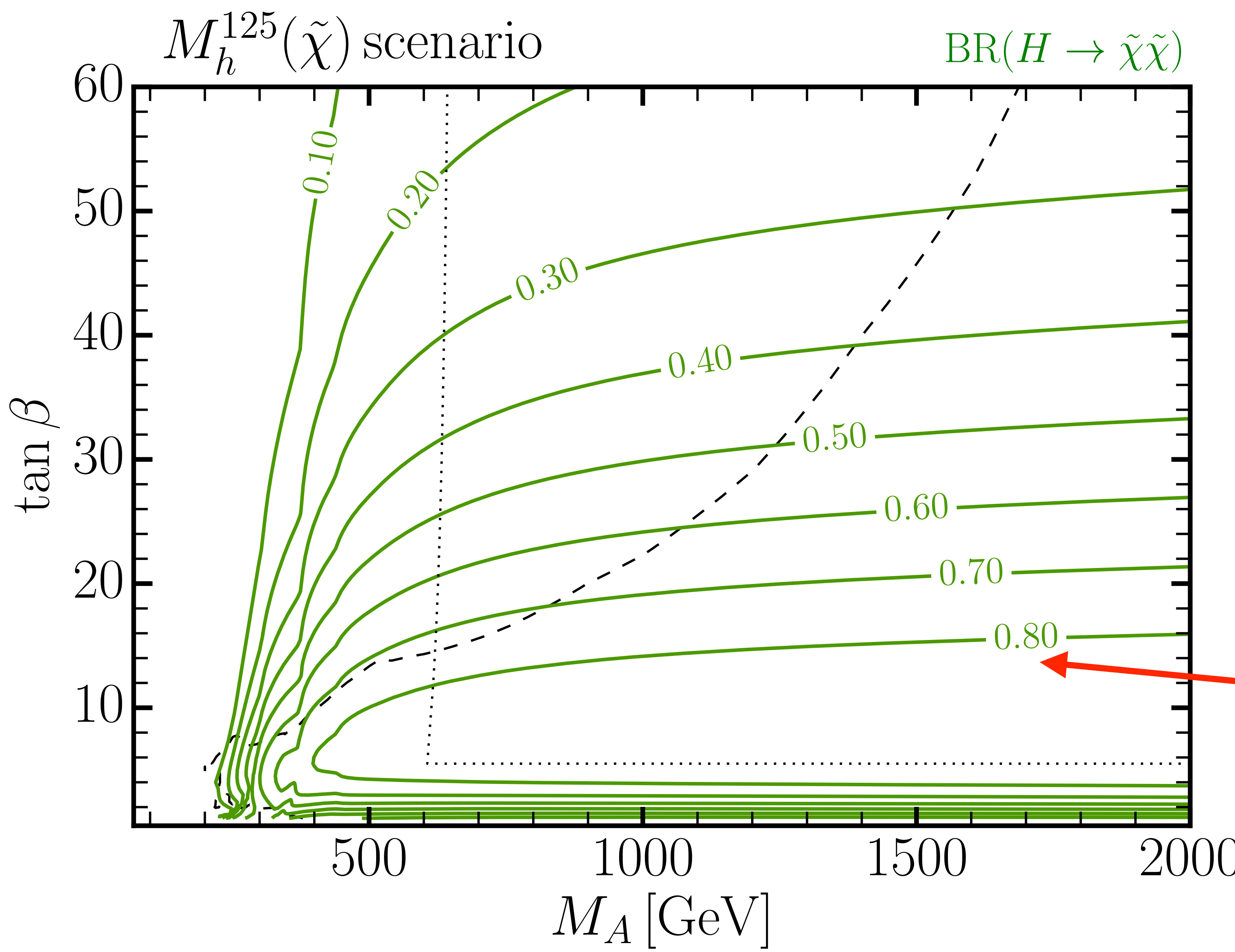
Sensitivity from HL-LHC signal measurements

⇒ Much higher precision of h125 signal measurements needed than at HL-LHC in order to probe unexcluded region

Non-standard decays of heavy Higgses, e.g. $H \to \tilde{\chi}\tilde{\chi}$

[H. Bahl et al. '18]

Decays of heavy Higgs bosons *H, A* into charginos and neutralinos:

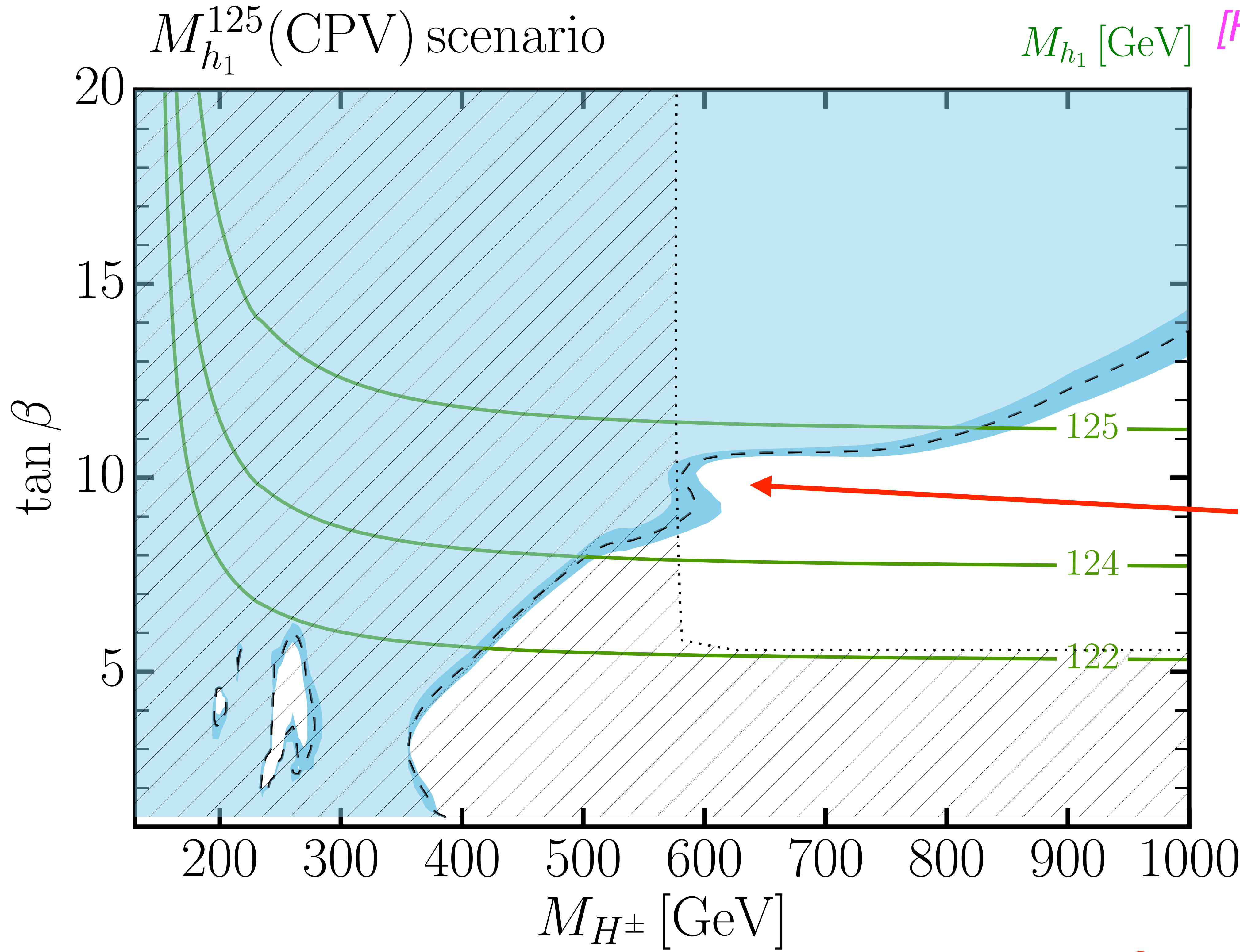


Branching ratios of more than 80% possible!

⇒ Dedicated searches for heavy Higgs decays into SUSY particles could probe the ``LHC wedge" region

CPV benchmark scenario

[H. Bahl et al. '18]

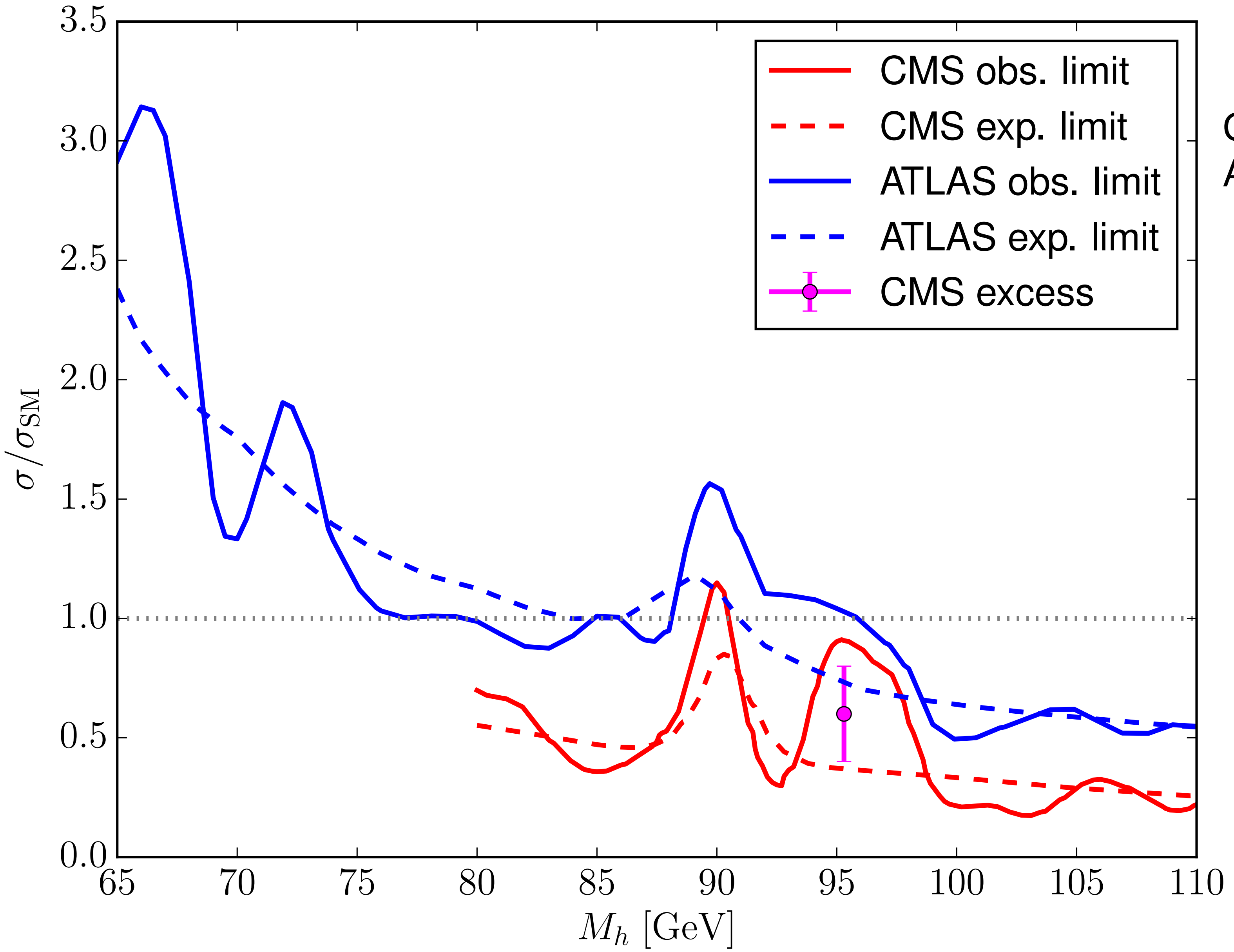


Destructive interference weakens the search limit

⇒ Exp. analyses should take into account possible CPV effects

Additional Higgs bosons could also be light: CMS excess in $h \longrightarrow \gamma\gamma$ search vs. ATLAS limit

[T. Stefaniak '18]



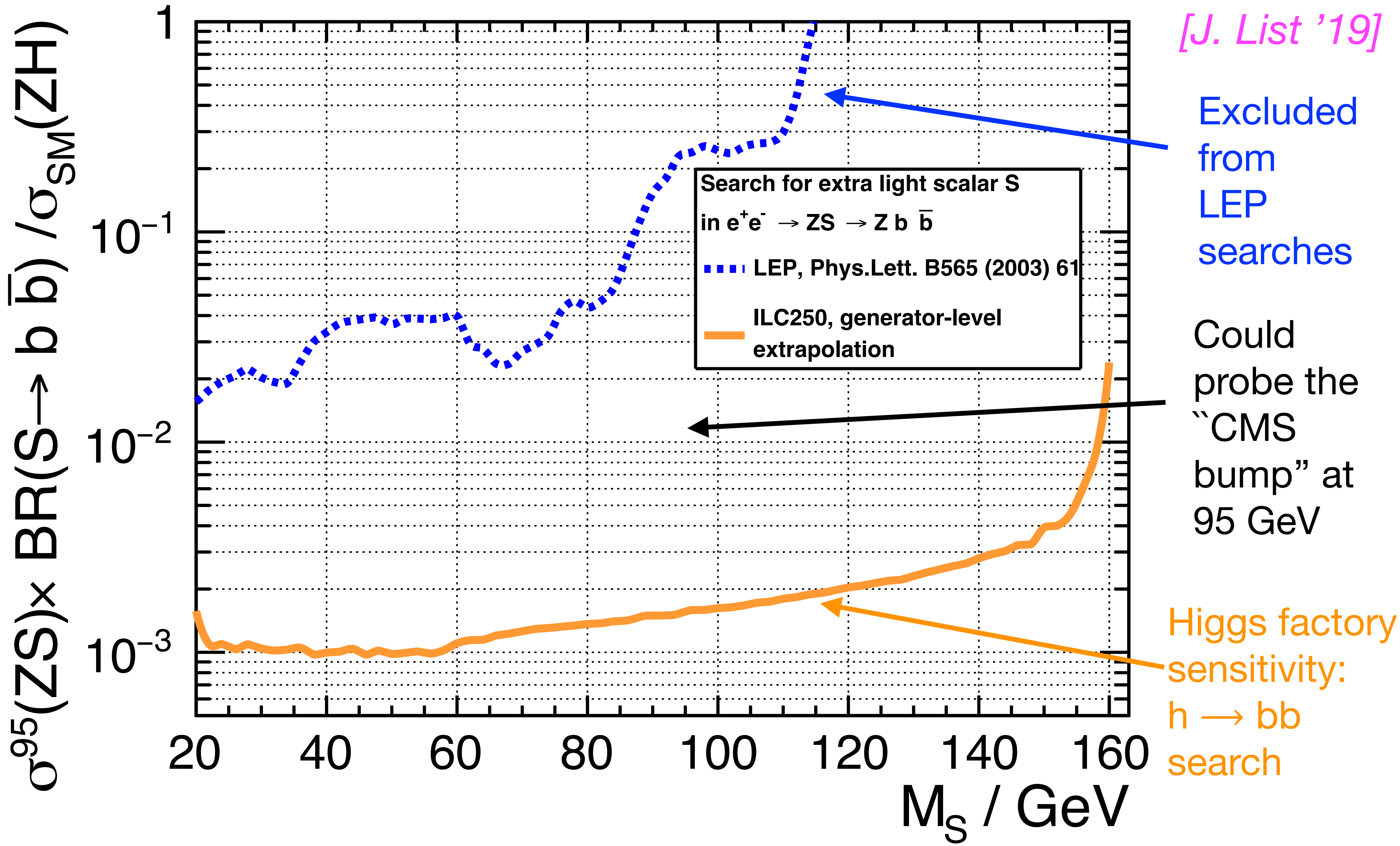
CMS-PAS-HIG 17-013,
ATLAS-CONF-2018-025

$\Rightarrow$ It is crucial to search for light additional Higgs bosons at the LHC and future facilities!

Sensitivity of an e^+e^- collider at 250 GeV with 2 ab^{-1} to a new light Higgs (generator-level extrapolation)

[P. Drechsel, G. Moortgat-Pick, G. W. '18]

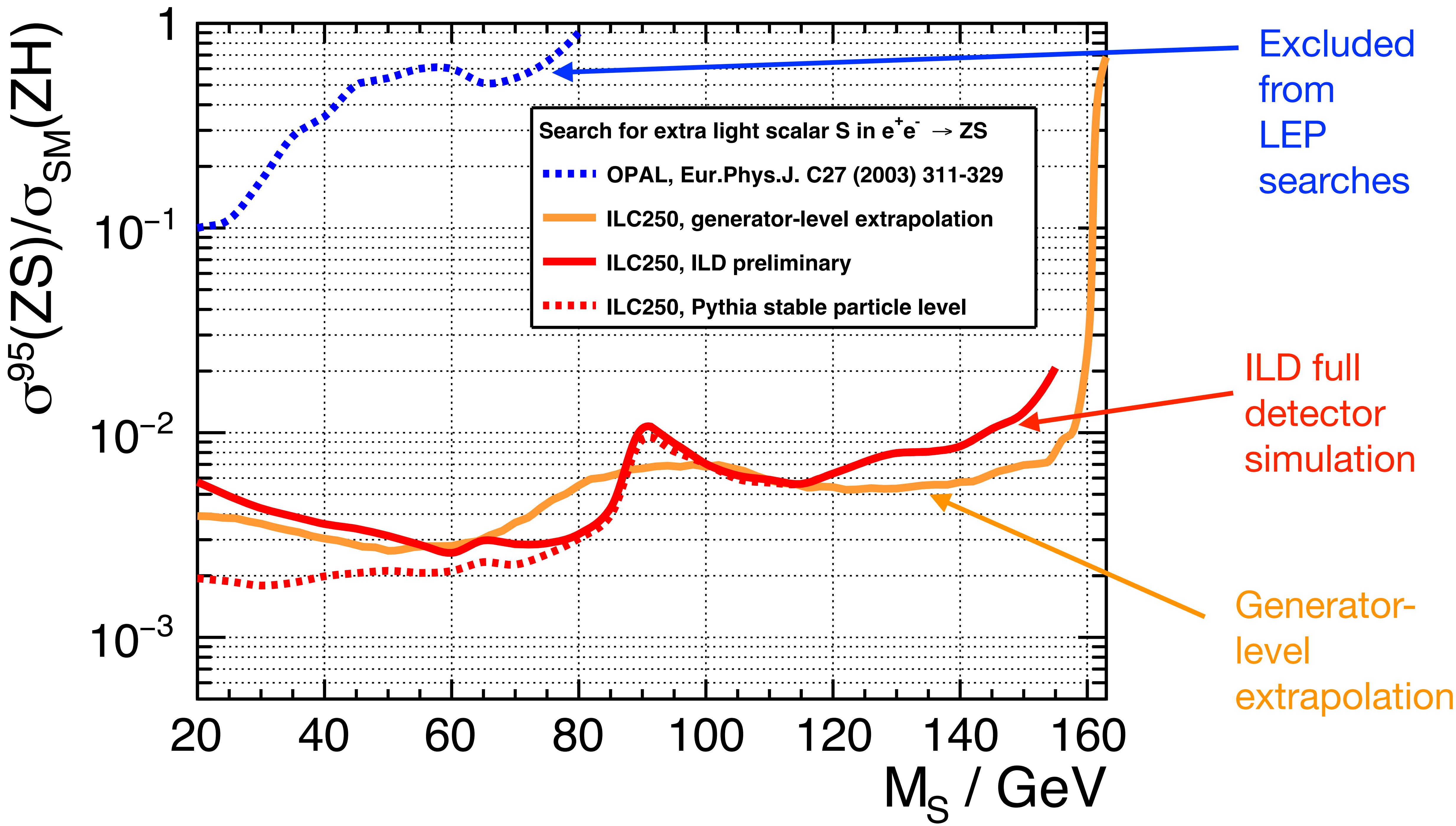
[J. List '19]



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

e^+e^- collider at 250 GeV with 2 ab^{-1}, recoil method: generator-level extrapol. + ILD full detector simulation

[P. Drechsel, G. Moortgat-Pick, G. W. '18] [Y. Wang, J. List, M. Berggren '19]



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

Outcome of the Open Symposium (my interpretation)

- Strong preference for an e^+e^- Higgs factory as the next big project; location and shape to be determined (but: importance of extendibility to about 500 GeV was emphasised)

- The full package of FCC-ee, FCC-eh and FCC-hh looks well in the comparison tables, but this has to be weighted against a timescale of more than 70 years and enormous costs. There was strong opposition against this sequence of projects.

  Some arguments:

  [K. Jakobs, G. Taylor, …]

  - Go for a higher-energy proton machine directly
    Do not spend another 30 years on development of 16T magnets, which at the end might turn out to be unaffordable
    Rather use existing magnet technology, cost-optimised; could reach about 50 TeV with 100 km tunnel

Outcome of the Open Symposium (my interpretation)

- Our field would not survive the long gap between FCC-ee and FCC-hh *[L. Evans, …]*

- An e^+e^- Higgs factory could provide crucial guidance for the future hadron machine. However, this does not work if one has to decide about the size of a circular tunnel as the first step.

Request from the ESG for further national input

CERN/ESG/05 1

Towards an update of the European Strategy for Particle Physics

With a view to update the European Strategy for Particle Physics, the Briefing Book compiled by the Physics Preparatory Group (PPG), based on the submitted inputs and the discussions during the Open Symposium in Granada, provides a summary of the present landscape in the field. It summarises the scientific aspirations, opportunities, as well as technical challenges. Revolving around future major colliders in Europe, at this stage, five scenarios are defined to initiate the discussions within the European Strategy Group (ESG).

	2020-2040		2040-2060 1st gen technology	2060-2080 2nd gen technology
CLIC-all	HL-LHC		**CLIC380-1500**	CLIC3000 / other tech
CLIC-FCC	HL-LHC		**CLIC380**	FCC-h/e/A (Adv HF magnets) / other tech
FCC-all	HL-LHC		**FCC-ee (90-365)**	FCC-h/e/A (Adv HF magnets) / other tech
LE-to-HE-FCC-h/e/A	HL-LHC		**LE-FCC-h/e/A (low-field magnets)**	FCC-h/e/A (Adv HF magnets) / other tech
LHeC-FCC-h/e/A	HL-LHC	**+ LHeC**	**LHeC**	FCC-h/e/A (Adv HF magnets) / other tech

All elements related to the CLIC and FCC proposals are discussed in their respective CDRs. As examples, the last two scenarios assume that an e^+e^- collider is built outside Europe. The LE-to-HE-FCC-h/e/A scenario moves from initially lower-field magnets in the window of 6-10T (e.g. adiabatically) to higher-field magnets, potentially HTS magnets. In the LHeC+FCC-h/e/A scenario, the time gap between the end of HL-LHC and the realisation of FCC-h/e/A with high-field magnets is used for the LHeC programme, potentially even starting in parallel with the HL-LHC. (Note that the indicative timelines in the table above do not necessarily match exactly the ones presented in Figure 1, attached for convenience at the end of the document, which were extracted from the submitted inputs.)

Response from KET (German Committee for Particle Phys.)

The German particle physics community has provided input to the ESPPU process in its document "Statement by the German Particle Physics Community as Input to the Update of the European Strategy for Particle Physics" submitted in December 2018. This statement is the consensus result of a two-year long series of community workshops.

The key statements[2] addressing present and future large colliders and to CERN formulated in the German input document are:

The physics potential of the experiments at the LHC and its upgrade, the HL-LHC, as well as at SuperKEKB must be fully exploited.

An electron-positron collider, upgradeable to a centre-of-mass energy of at least 500 GeV, should be realised, with the highest priority, as the next international high-energy project.

We strongly support the Japanese initiative to realise, as an international project in Japan, the ILC as a "Higgs-Factory" with an initial centre-of-mass energy of about 250 GeV.

Continuation of the development of accelerator and detector technologies and studies for a next-generation hadron collider, at the highest possible centre-of-mass energies beyond the LHC, should be pursued with high priority.

CERN must maintain its leading role in particle physics, and further develop its potential. This requires the continued close collaboration with national laboratories, institutions and universities.

In response to the ESG request to provide additional input on the scenarios for CERN-based large colliders we further expand on these consensus statements:

Response from KET (German Committee for Particle Phys.)

We reaffirm CERNs leading role in particle physics. A long-term perspective for the laboratory is vital for the development of our field.

The successful realization of the HL-LHC and the full exploitation of its physics potential should be the highest priority for the mid-term future.

As next international high-energy project, we consider an electron-positron collider as highest priority of our field. Maximum complementarity with measurements at hadron colliders would require the collider to be upgradable to center-of-mass energies of at least 500 GeV to allow direct measurements of the Higgs self-couplings and to provide a high sensitivity to BSM physics.

Currently, different design options for the next electron-positron collider are being discussed; one of these machines should be built. The decision for one of these projects and its realisation should happen in a globally coordinated context and as an international effort. Europe, with CERN as the European laboratory for particle physics, should play a leading role in both the decision making process and the realisation of the next electron-positron collider project.

We emphasise the vital role of CERN for Particle Physics in Europe and world-wide and believe that CERN should prepare to host the next hadron collider at the high-energy frontier.

Europe through CERN and the national laboratories and institutes should pursue the development of advanced accelerator and detector technologies with high priority.

A note on political circumstances

This talk is meant to be about science, not politics. Nevertheless, on the next two slides I will try to fold in also the aspect of what might actually be politically doable. This is of course just my personal view:

We cannot sell a new big project of our field with arguments like

- The biggest and most long-term project is the best for CERN since it secures its future for a long time
- We want to have the FCC-ee because it provides us a justification to build a 100 km long tunnel and it gives us time to develop high-field magnets for FCC-hh

The case for the project that we put forward has to be rock-solid in its own right!

A note on political circumstances

I do not think that such a case can be made for FCC-ee: if we request a 100 km long tunnel for a 350 GeV e^+e^- machine, people will tell us that this is not justified since we could get essentially the same physics with just a 10 km long tunnel!

Bottom line (personal view): if we want to go for FCC, we should go for FCC-hh directly!

Conclusions (personal view)

- We should not take it for granted that there will be another big collider project, neither at CERN nor elsewhere

- Some people seem to think that the next big CERN project should be the ET

- What we put forward as the outcome of this strategy process has to be very convincing for other scientists, the general public and politicians. Otherwise the future of our field is at risk.

- We need a coherent world-wide programme (see statements by the other areas at the Granada Open Symposium) and, as a crucial part of it, a forefront collider project at CERN

Backup

Higgs mass measurement: the need for high precision

Measuring the mass of the discovered signal with high precision is of interest in its own right

But a high-precision measurement has also direct implications for probing Higgs physics

M_H (H = h125): crucial input parameter for Higgs physics

BR($H \to ZZ^*$), BR($H \to WW^*$): highly sensitive to precise numerical value of M_H

A change in M_H of 0.2 GeV shifts BR($H \to ZZ^*$) by 2.5%!

$\Rightarrow$ Need high-precision determination of M_H to exploit the sensitivity of BR($H \to ZZ^*$), ... to test BSM physics

CP properties

$\mathcal{CP}$ properties: more difficult than spin, observed state can be any admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components

Observables mainly used for investigaton of $\mathcal{CP}$-properties ($H \to ZZ^*, WW^*$ and H production in weak boson fusion) involve HVV coupling

General structure of HVV coupling (from Lorentz invariance):

$$a_1(q_1, q_2) g^{\mu\nu} + a_2(q_1, q_2) \left[(q_1 q_2)\, g^{\mu\nu} - q_1^\mu q_2^\nu \right] + a_3(q_1, q_2) \epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

SM, pure $\mathcal{CP}$-even state: $a_1 = 1, a_2 = 0, a_3 = 0$,

Pure $\mathcal{CP}$-odd state: $a_1 = 0, a_2 = 0, a_3 = 1$

However: in many models (example: SUSY, 2HDM, ...) a_3 is loop-induced and heavily suppressed

CP properties

⇒ Observables involving the *HVV* coupling provide only limited sensitivity to effects of a CP-odd component, even a rather large CP-admixture would not lead to detectable effects in the angular distributions of $H \to ZZ^* \to 4\,l$, etc. because of the smallness of a_3

Hypothesis of a pure CP-odd state is experimentally disfavoured

However, there are only very weak bounds so far on an admixture of CP-even and CP-odd components

Channels involving only Higgs couplings to fermions could provide much higher sensitivity