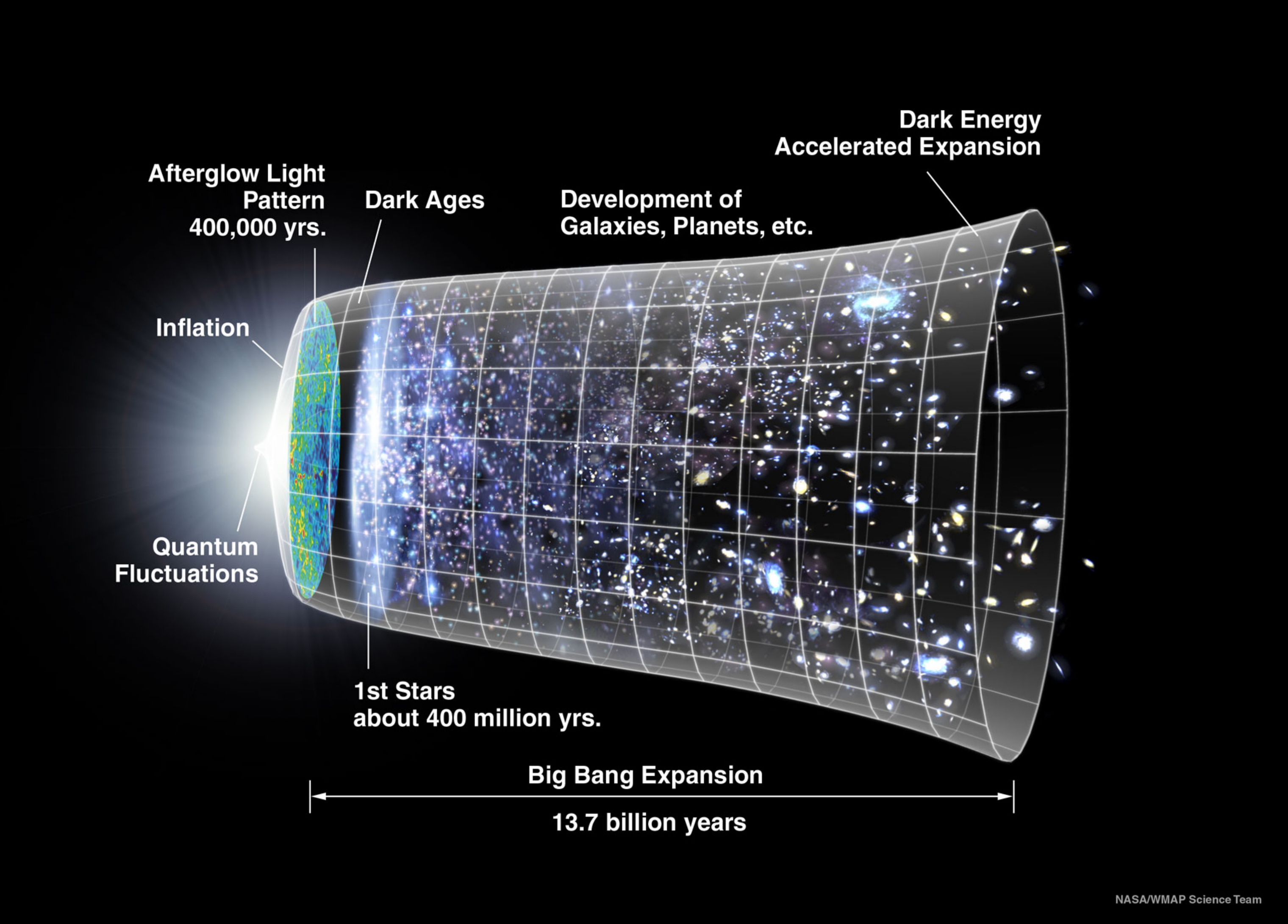
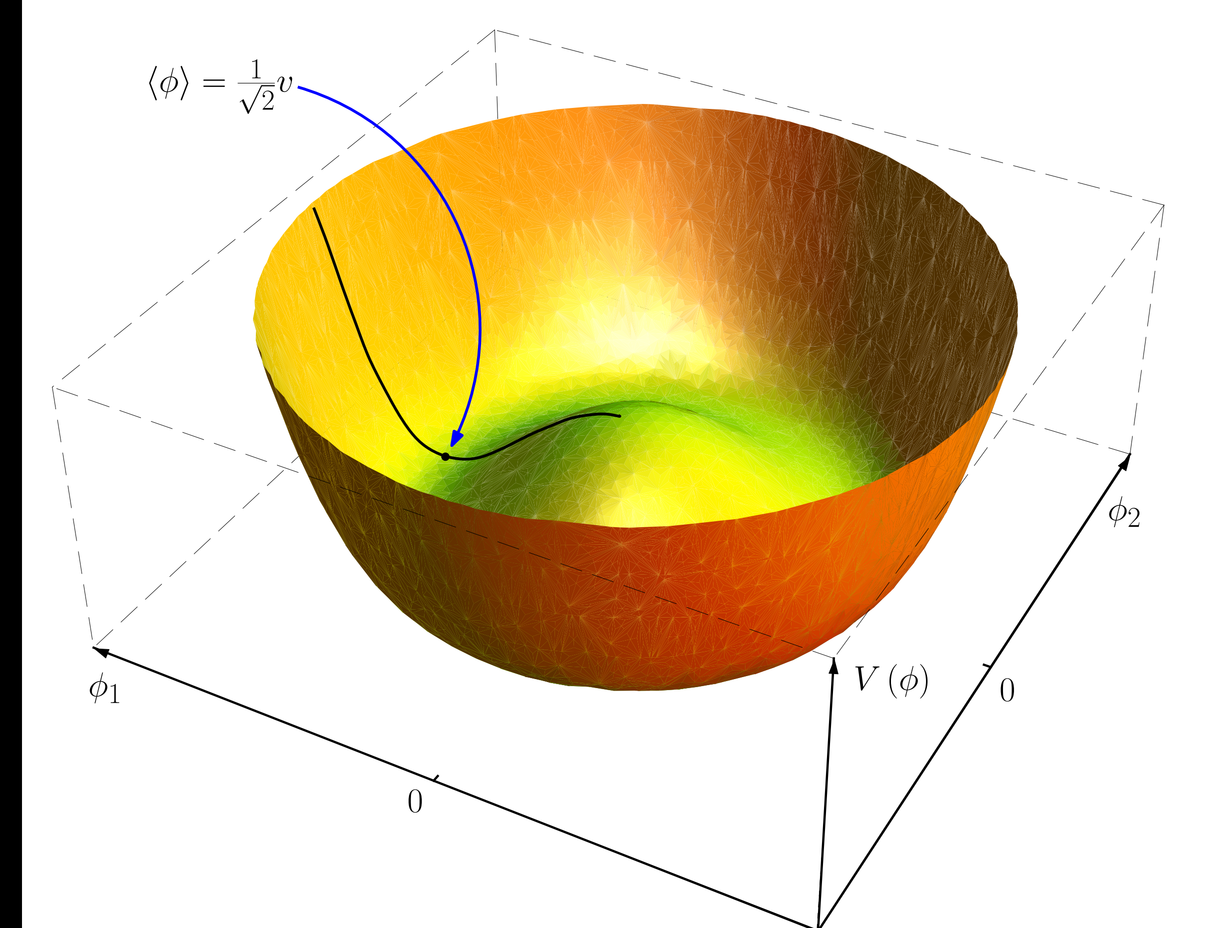




LCWS2021

INTERNATIONAL WORKSHOP ON FUTURE LINEAR COLLIDERS

Linear Collider physics

Georg Weiglein, DESY

03 / 2021

Outline

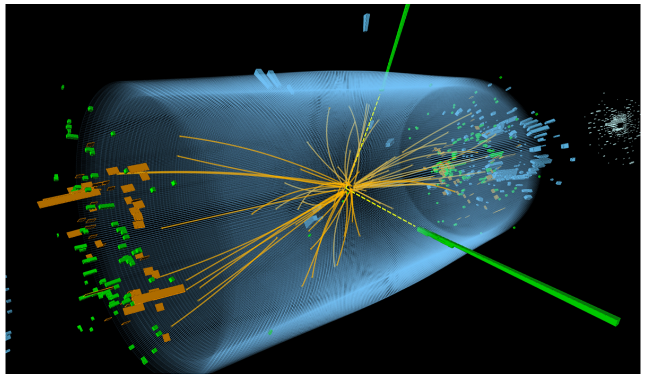
- Introduction and present status
- The Higgs signal at 125 GeV
- Information from searches for additional Higgses
- BSM, electroweak, top and flavour physics
- Conclusions

Introduction and present status

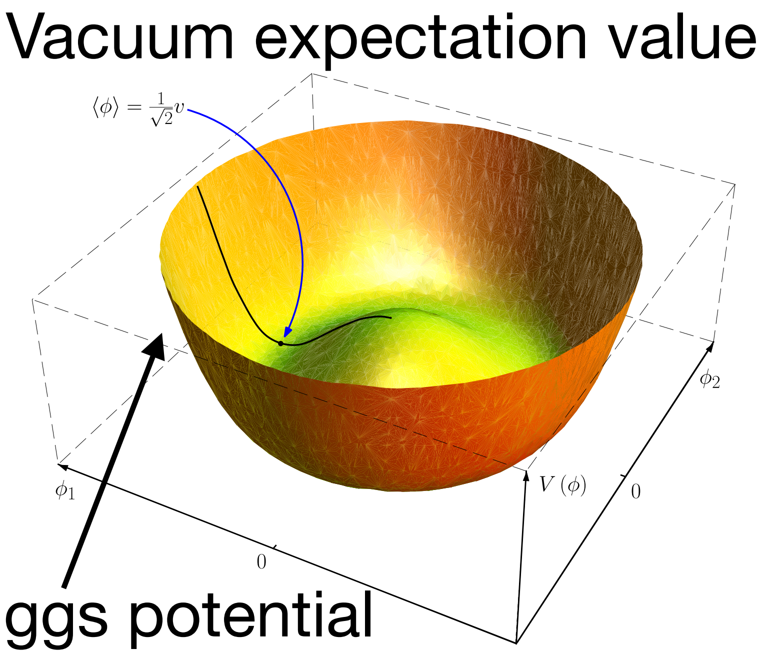
The Higgs-boson discovery at the LHC in 2012 has established a non-trivial structure of the vacuum, i.e. of the lowest-energy state in our universe. The origin of mass of elementary particles is related to this structure: mass arises from the interaction with the Higgs field.

The vacuum structure is caused by the Higgs field through the Higgs potential. We lack a deeper understanding of this!

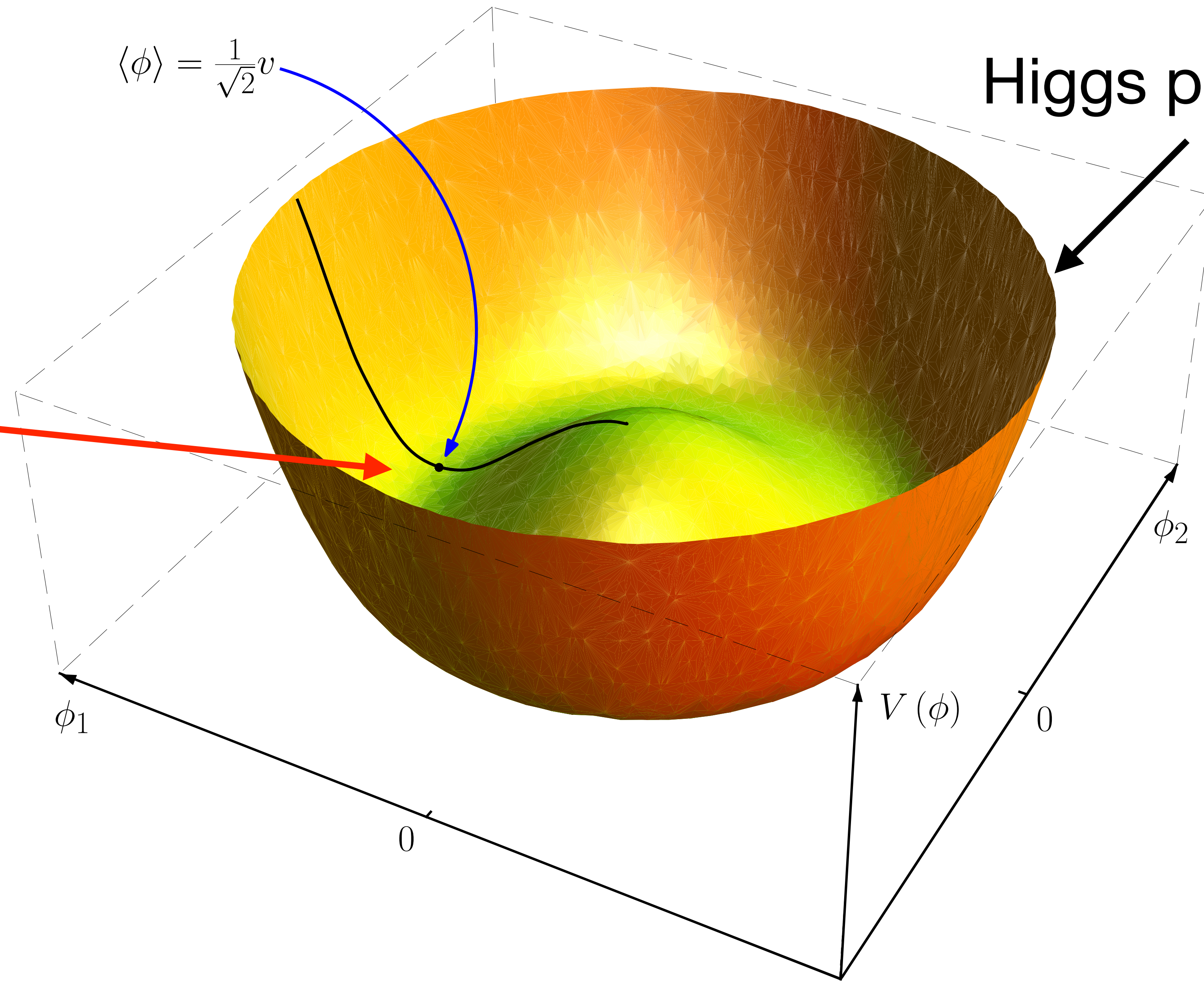
We do not know where the Higgs potential that causes the structure of the vacuum actually comes from and which form of the potential is realised in nature. Experimental input is needed to clarify this!



Nobel Prize 2013



The Brout-Englert-Higgs (BEH) mechanism and the structure of the vacuum



v: vacuum expectation value; fundamental property of the vacuum state

BEH mechanism, spontaneous symmetry breaking: vacuum state does not obey the underlying symmetry principle (gauge invariance)

BEH mechanism ⇔ non-trivial structure of the vacuum

Higgs physics: present understanding

The Standard Model of particle physics uses a ``minimal" form of the Higgs potential with a single Higgs boson that is an elementary particle.

The LHC results on the discovered Higgs boson within the current uncertainties are compatible with the predictions of the Standard Model, but also with a wide variety of other possibilities, corresponding to very different underlying physics.

Thus, we have discovered a new particle, but we do not know yet the physics that is associated with it. We have a description of the known particles and their interactions, but we do not know the underlying dynamics.

This is similar to the case of superconductivity, where first a phenomenological description was obtained (Ginzburg-Landau theory). The actual understanding was achieved with the microscopic BCS theory.

The puzzle of the Higgs mass

The mass of the discovered new particle, $M_{\text{H}} \approx 125$ GeV, is similar to v and to the masses of the W and Z bosons and the top quark. We call this the weak scale, M_{weak}.

The scale of gravity, M_{Planck}, is 17 orders of magnitude larger than the weak scale, i.e. $M_{\text{Planck}} \approx 100000000000000000\ M_{\text{weak}}$

This causes a problem, since via quantum effects the Higgs mass should be affected by such huge contributions.

How can the Higgs mass be as small as 125 GeV?

All other elementary particle masses are ``protected" by known symmetries. But what protects the Higgs mass?

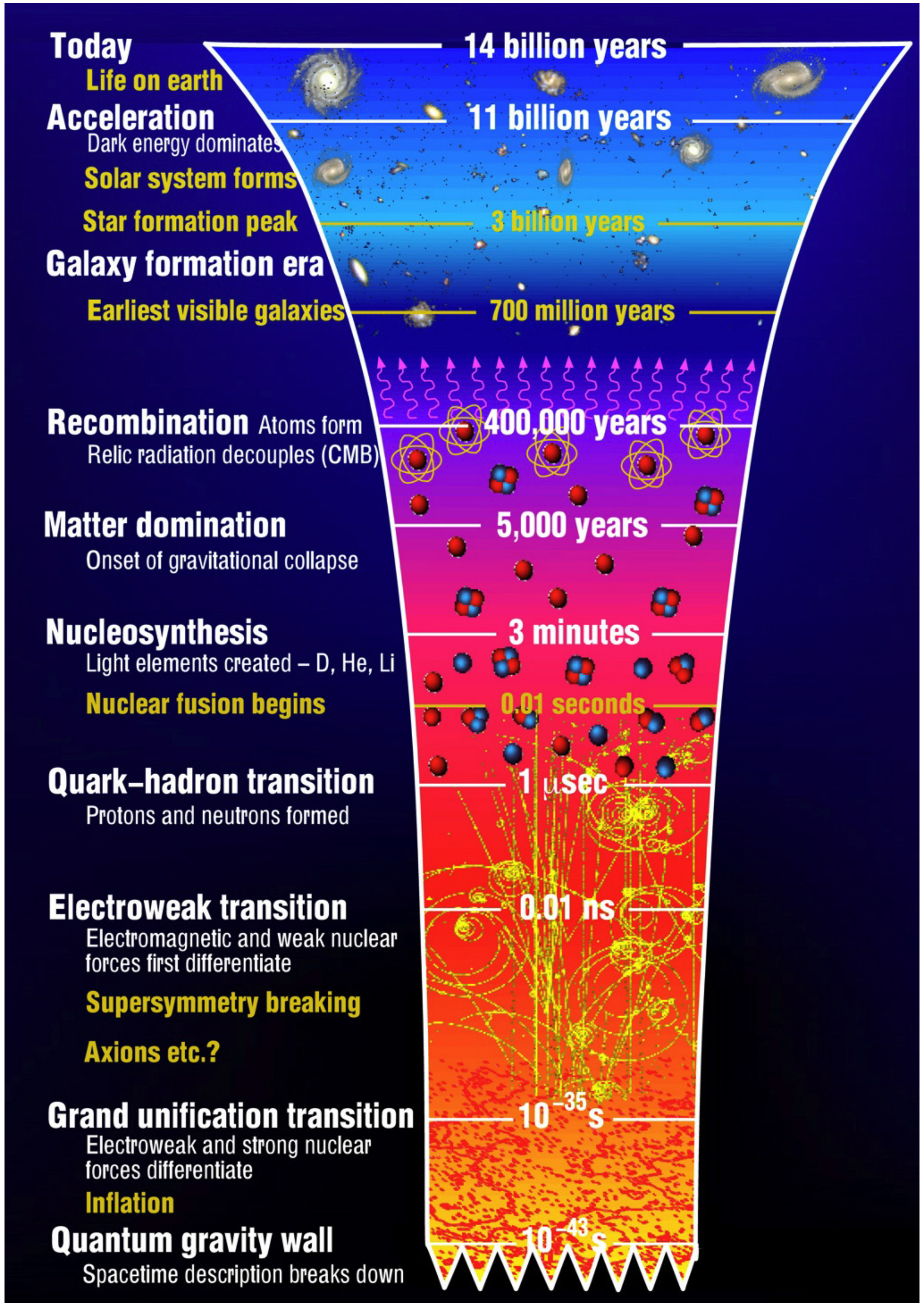
How can a Higgs boson be as light as 125 GeV?

Identifying the physics associated with the Higgs boson will have profound implications. Possible outcomes could be:

- Additional Higgs bosons $\longleftrightarrow$ a new space-time symmetry, more than 100 years after Einstein?
- Substructure of the Higgs boson $\longleftrightarrow$ a new interaction of nature (a ``fifth force")?
- Properties of the Higgs sector $\longleftrightarrow$ evidence for additional dimensions of space?
- Higgs and dark energy $\longleftrightarrow$ could our universe be just one of many parallel universes?

Study of Higgs physics provides information about the "electroweak phase transition" in the early universe

History of the universe:



← Now: 14 billion years after the Big Bang

Particle colliders produce energy densities as they existed just after the Big Bang

⇒ Information about the early universe

← 0.0000000001 s after the Big Bang

Particle 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

Composite Higgs

Approaches to address the question how a scalar particle can be light, $M \sim 125$ GeV:

- SUSY: elementary scalars related via SUSY to elementary fermionic superpartners, which naturally have a small mass (weakly broken chiral symmetries)

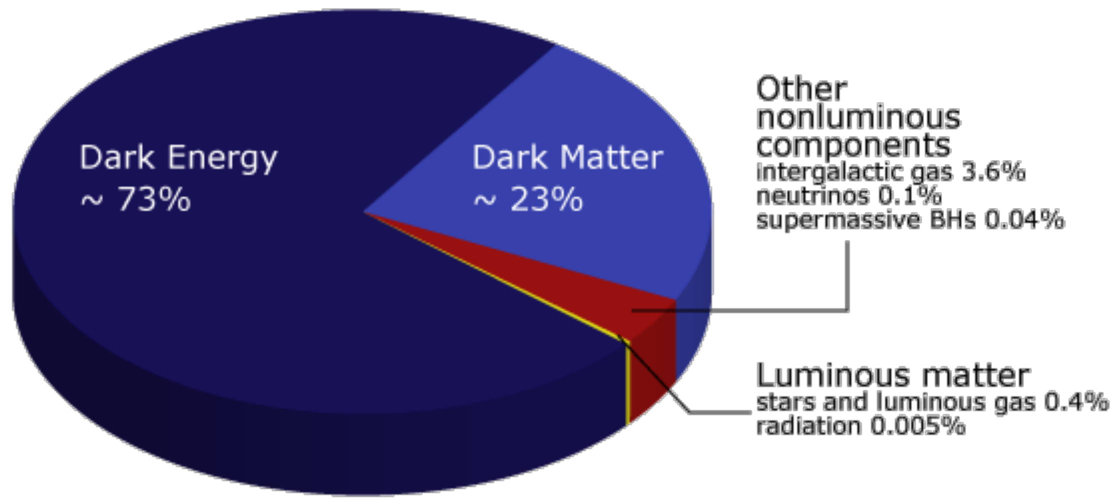
- Spontaneous breaking of a continuous global symmetry:
  ⇒ massless Goldstone boson

  Explicit breaking of global symmetry
  ⇒ pseudo-Goldstone boson (PGB)

  Mass of the PGB is proportional to the strength of the symmetry breaking

Many more questions to answer

- Nature of the ``dark sector” of the universe (accounts for 96% of it)?



- Origin of the matter/anti-matter imbalance in the universe?
- Origin of the observed patterns of flavour (quarks, neutrino physics)?
- How is gravity related to the quantum world? Quantum structure of space-time? Are there more than three dimensions of space?
- Unification of the fundamental interactions of nature?
- …

Possible relations of the Higgs and the dark sector

We know that dark matter interacts at most very weakly with the known ordinary matter. The Higgs boson(s) may provide us access to the dark sector of the universe. At present we do not know what 96% of the universe is made of!

Higgs decays into dark matter particles would give rise to a ``missing energy” signature corresponding to an ``invisible” decay mode

The Higgs boson(s) could also act as a ``mediator” between the visible and the dark sector

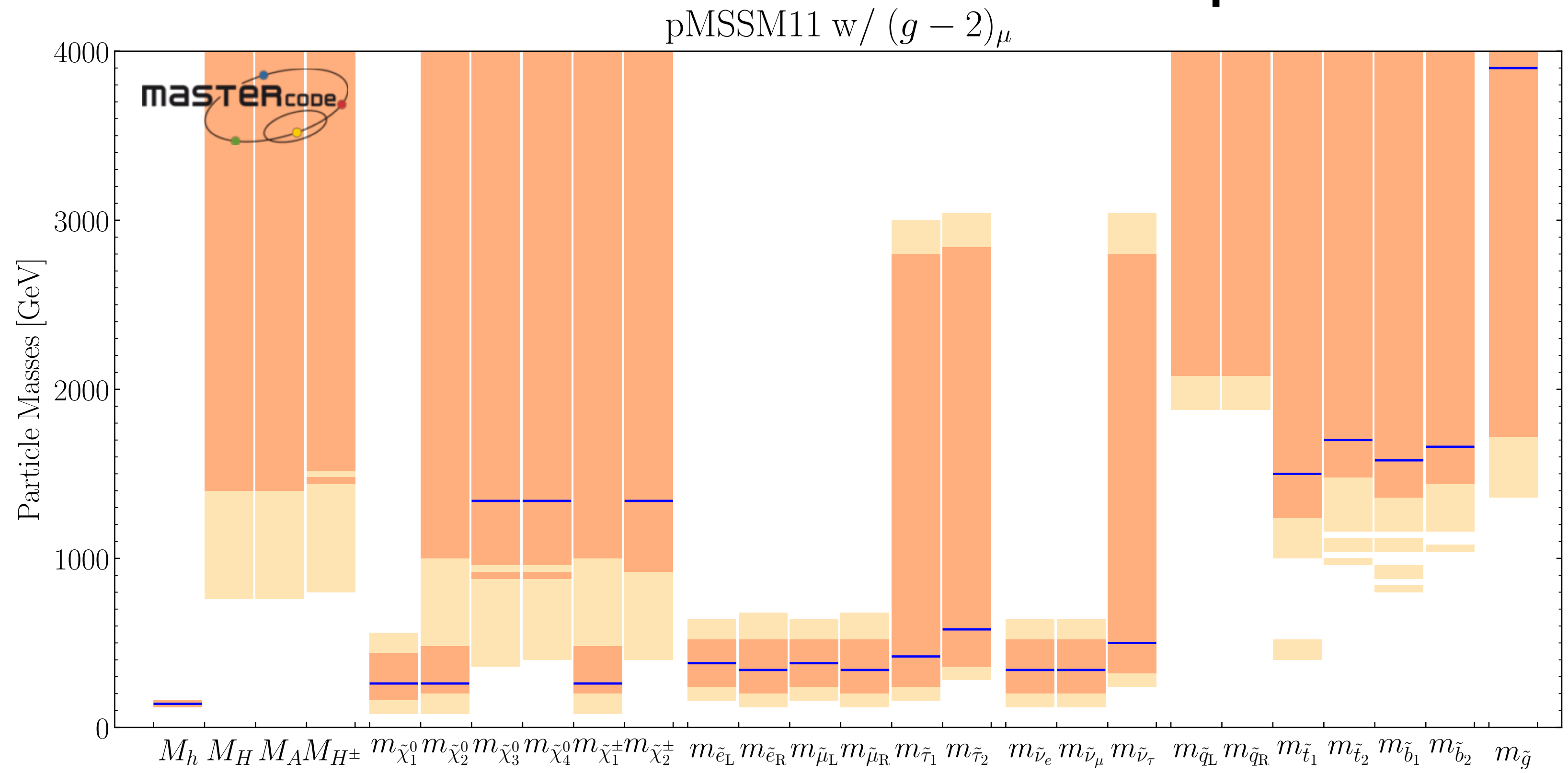
The Higgs sector could furthermore be crucial for explaining the imbalance between matter and anti-matter in the universe

Precision measurements of the Higgs decays, the Higgs couplings and the CP properties of the Higgs boson(s) have the potential to shed light on the dark sector!

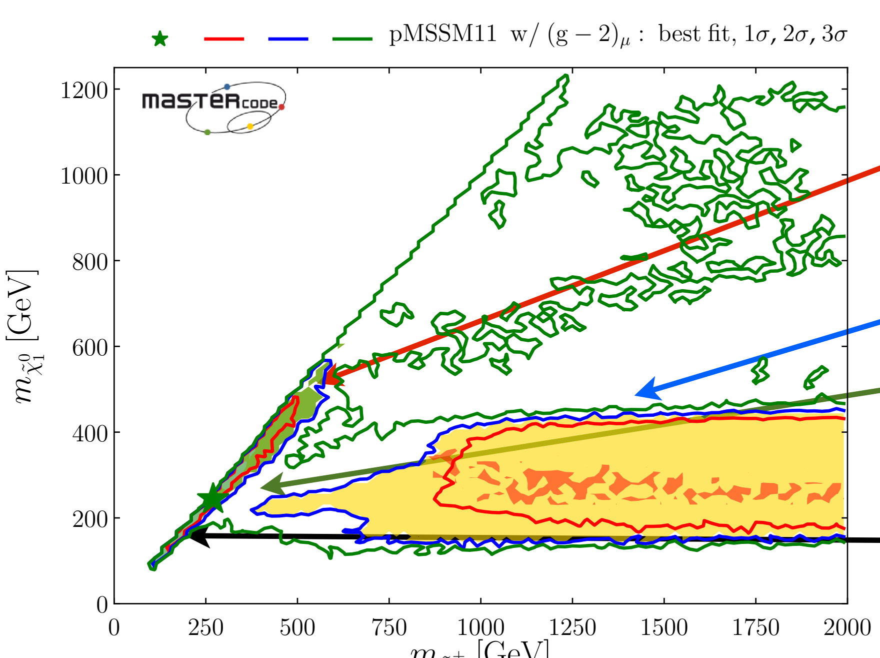
Where are the new particles?
Example: global SUSY fit

[E. Bagnaschi et al ’18, 19]

MasterCode: Global fit in the MSSM with 11 parameters



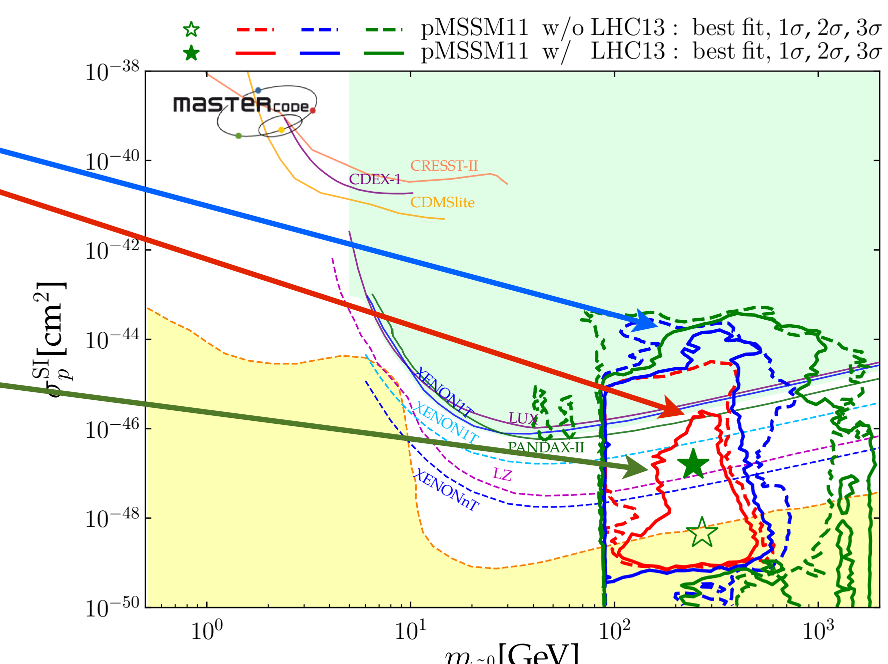
Best fit region and implications for collider and dark matter searches:



68% / 95%
C.L. contours

Best fit points

Compressed
spectrum



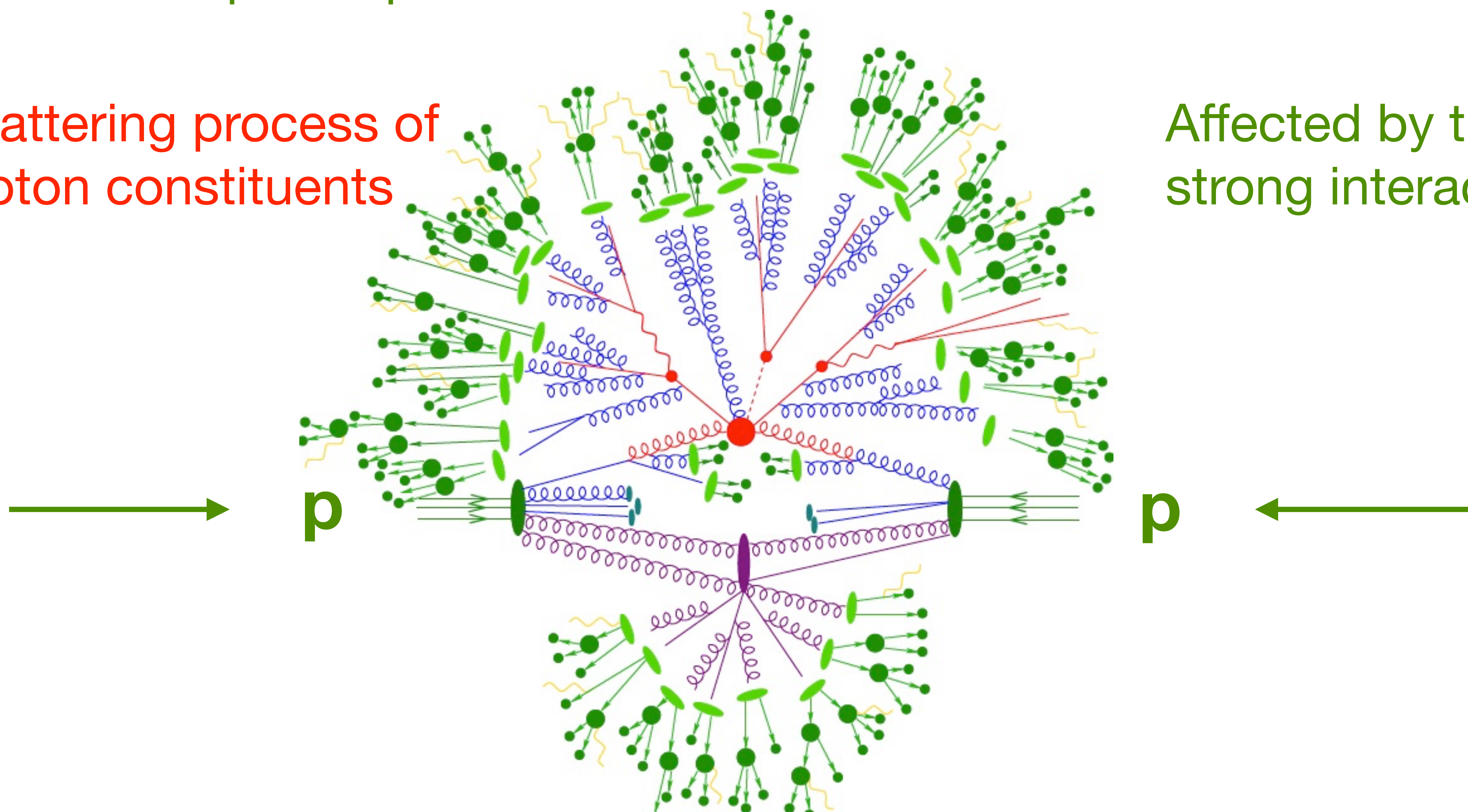
⇒ Dark matter constraint and $(g\text{-}2)_\mu$ favour light ew particles, compressed spectra

LHC: proton-proton (pp) scattering

Proton: composite particle

Scattering process of proton constituents

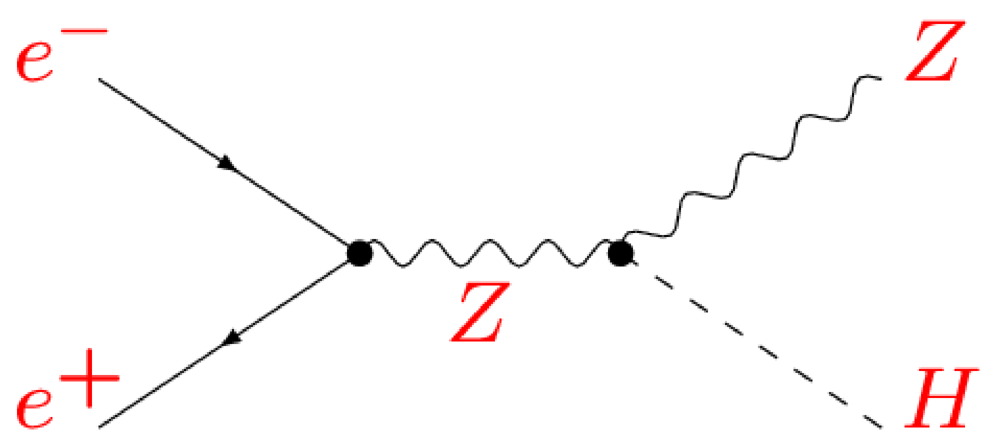
Affected by the strong interaction



Protons can be accelerated to high energies
Very large backgrounds from effects of the strong interaction
Low signal-to-background ratios (`search for needle in haystack")

LC: electron-positron (e^-e^+) scattering

Electron, positron: elementary particles, not affected by strong interaction



Clean experimental environment:

Well-defined initial state, complete knowledge of energy and momentum of the collision process

Tuneable energy, polarisation of the electron and positron beams

Very small backgrounds

High-precision physics

Hadron colliders (LHC) and lepton colliders (LC) provide complementary information, both needed for the understanding of nature; long success story of interplay of hadron and lepton colliders

Impact of beam polarisation at a LC

Beam polarisation is crucial for investigating observables like left-right asymmetries, which have a high sensitivity for discriminating between different realisations of the underlying physics and for the determination of chiral quantum numbers.

The polarisation of both the electron and the positron beams yields four distinct sets of observables instead of only two observables for the case where only the electron beam is polarised.

	e^-	e^+		
σ_{RR}	$\Rightarrow$	$\Leftarrow$	$\frac{1+P_{e^-}}{2} \cdot \frac{1+P_{e^+}}{2}$	$J_z = 0$
σ_{LL}	$\Leftarrow$	$\Rightarrow$	$\frac{1-P_{e^-}}{2} \cdot \frac{1-P_{e^+}}{2}$	
σ_{RL}	$\Rightarrow$	$\Rightarrow$	$\frac{1+P_{e^-}}{2} \cdot \frac{1-P_{e^+}}{2}$	$J_z = 1$
σ_{LR}	$\Leftarrow$	$\Leftarrow$	$\frac{1-P_{e^-}}{2} \cdot \frac{1+P_{e^+}}{2}$	

Most important reactions can be studied with opposite-sign polarisation, but the two like-sign polarisation configurations provide additional information that can be unique.

$\Rightarrow$ Enhancement of effective luminosity and sensitivity to rare processes

LC with polarisation of both beams

- Efficient enhancement of the investigated signal and reduction of the backgrounds
- Control of systematic uncertainties
- Transverse beam polarisation can only be exploited if both beams are polarised. Certain observables can only be accessed with transverse beam polarisation.
- Background determination and discrimination of signal and backgrounds in dark matter searches
- High sensitivity to the chirality and tensor structure of the produced particles

Sensitivity to BSM effects

- Searches for physics beyond the Standard Model (BSM): light / heavy new states
  The options proposed in models that are currently discussed span many orders of magnitude from extremely light (e.g. axion-like particles: WISPs, …) to very heavy

- High-precision tests: high sensitivity to deviations from the SM
  SM vs. other explicit models
  Effective field theory (EFT) analyses: new physics is assumed to be heavy

The Higgs 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 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

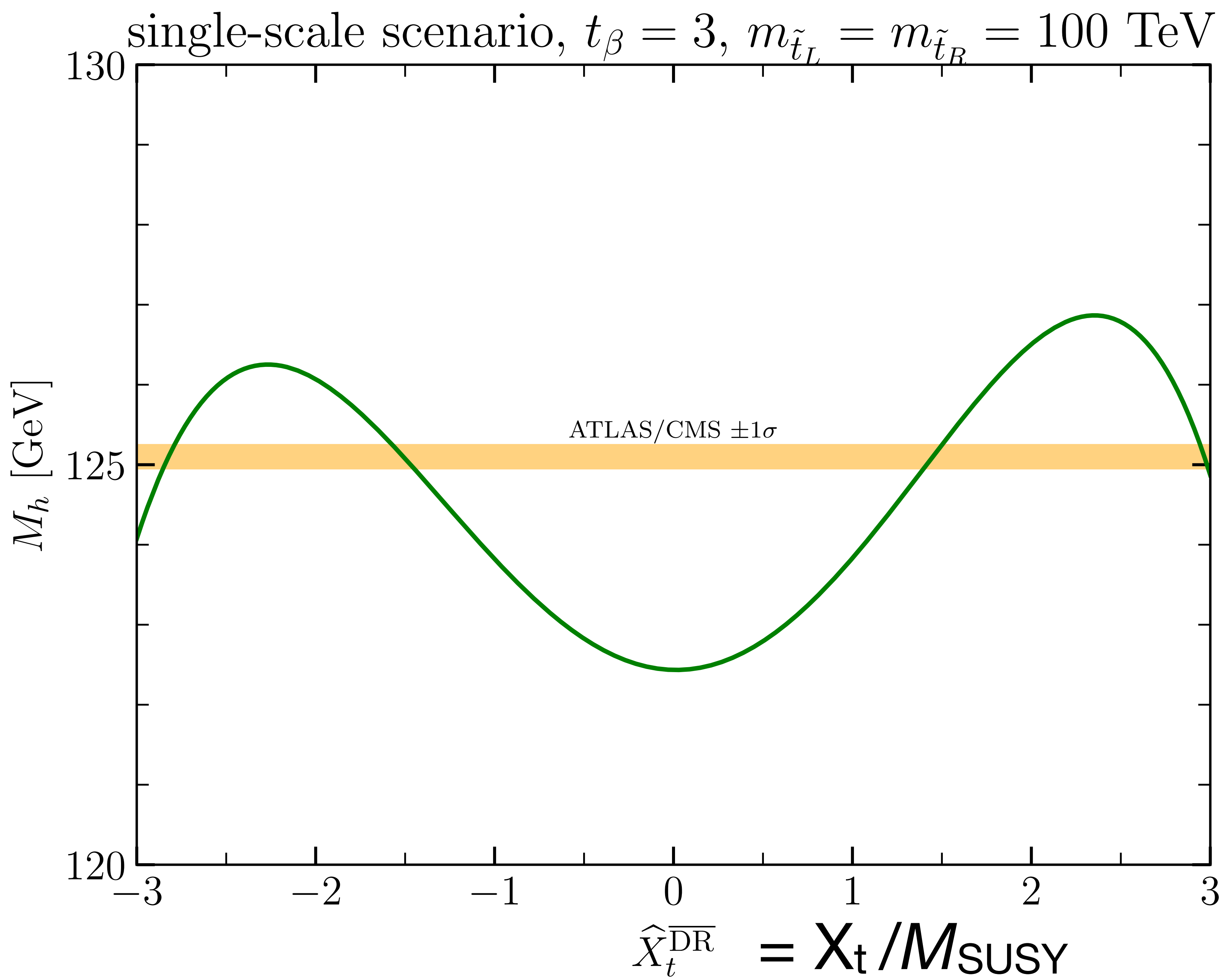
BR($H \to ZZ^*$), BR($H \to WW^*$): highly sensitive to precise numerical value of M_H

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

Higgs mass prediction vs. experimental result

Example: M_h prediction for heavy SUSY (M_{SUSY} = 100 TeV)



$= X_t / M_{SUSY}$

[H. Bahl, J. Braathen, G. W. '21]

X_t : mixing in the scalar top sector

⇒ High-precision measurement of the Higgs mass puts important constraints on BSM physics even if new physics scale is very high!

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

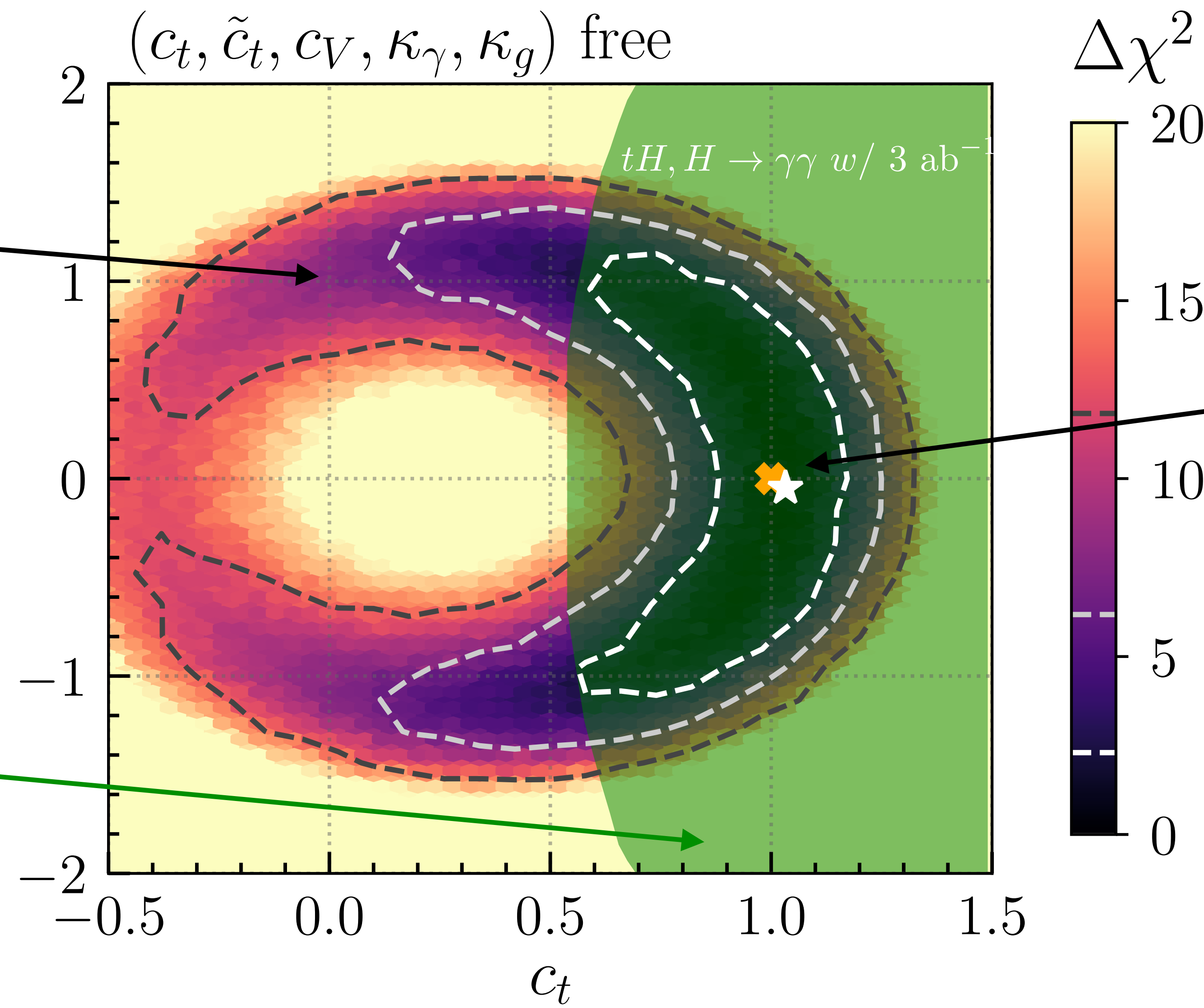
CP structure of the top Yukawa coupling: current constraints and HL-LHC prospects

[H. Bahl et al. '20]

Global fit to LHC inclusive and differential signal rates

$$\mathcal{L}_{\text{yuk}} = -\frac{y_t^{\text{SM}}}{\sqrt{2}}\bar{t}\left(c_t + i\gamma_5\tilde{c}_t\right)tH$$

current constraints



SM value

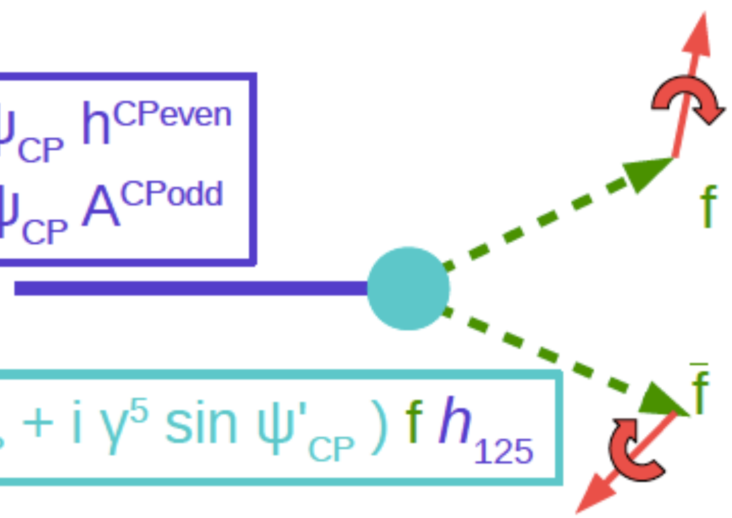
impact of measurement of *tH* production at the HL-LHC

⇒ Only mild constraints on the CP structure at LHC and HL-LHC

Determination of Higgs CP properties at the LC

Higgs CP properties at the LC: h $\longrightarrow$ $\boldsymbol{\tau\tau}$ channel

$$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$$

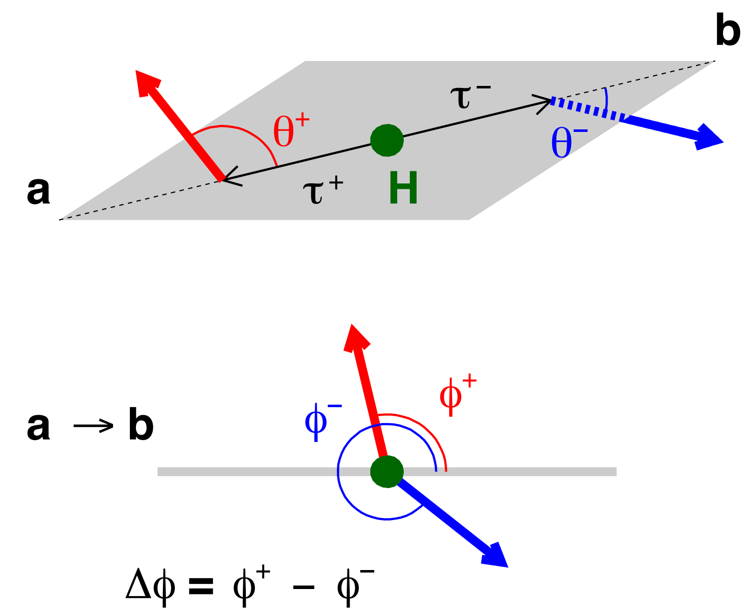


$$g\,\bar{f}\,(\cos\psi'_{CP} + i\,\gamma^5 \sin\psi'_{CP})\,f\,h_{125}$$

h is a spin 0 state:

$|f\,\bar{f}\rangle = |\uparrow\downarrow\rangle + e^{2i\psi}\,|\downarrow\uparrow\rangle$

[ψ = 0 CP even,
$\pi/2$ CP odd]



$\Rightarrow$ Precise determination of the CP phase

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

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

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

- $\varkappa$ framework: ``interim” framework designed for early LHC analyses, 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

ϰ, EFT framework and specific models

- ϰ 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 in general physically not meaningful
  Higher-order contributions need to be properly incorporated
  An EFT analysis is not ``model-independent”!

⇒ Both the ϰ 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

Higgs coupling determination at the LHC

Problem: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Production $\times$ decay at the LHC yields combinations of Higgs couplings ($\Gamma_{\text{prod, decay}} \sim g^2_{\text{prod, decay}}$):

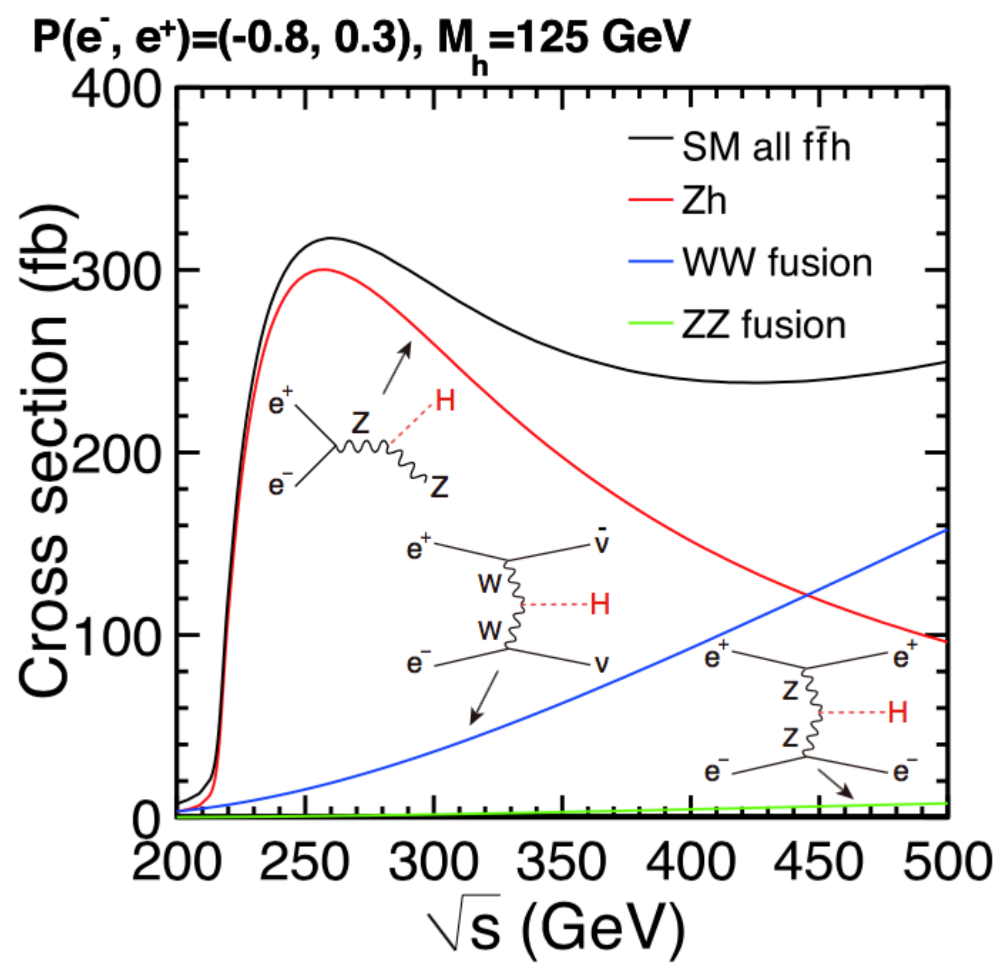
$$\sigma(H) \times \text{BR}(H \to a + b) \sim \frac{\Gamma_{\text{prod}}\Gamma_{\text{decay}}}{\Gamma_{\text{tot}}},$$

Total Higgs width cannot be determined without further assumptions

$\Rightarrow$ LHC can directly determine only ratios of couplings, e.g. $g^2_{H\tau\tau}/g^2_{HWW}$

Qualitative new feature at an e^+e^- Higgs factory

``Golden channel”, $e^+e^- \longrightarrow ZH$, can best be exploited at 250 GeV



With this channel it is possible to detect the Higgs boson independently from the way it decays: ``recoil method”
This leads to absolute and model-independent measurements of the Higgs production process and of the Higgs decay branching ratios

e⁺e⁻ Higgs factories: recoil method

[B. Heinemann '19]

Higgs width and/or untagged decays

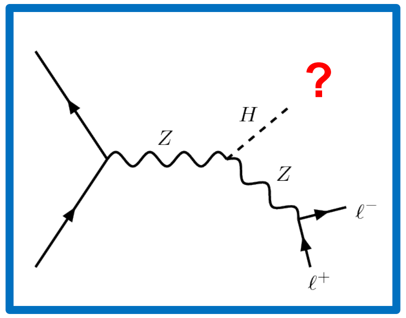
Unique feature of lepton-lepton colliders:

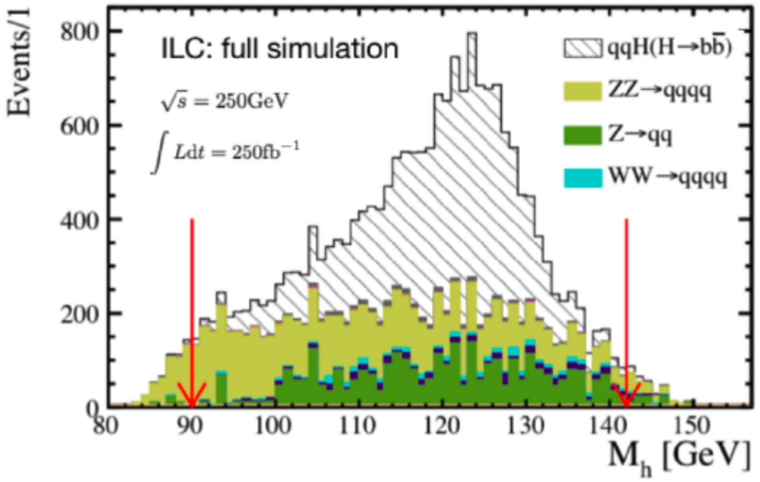
- **Detecting the Higgs boson without seeing decay: "recoil method"**
- **Measure ZH cross section with high precision without assumptions on decay**
- **Often interpreted as quasi-direct measurement of width**

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

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

$\boxed{\text{=> Will probe width with 1-2\% precision}}$





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	$\sigma(ZH, \nu\bar{\nu}H)$, BR$(H \to Z, b\bar{b}, WW)$ [90]	1.8
$\mathrm{FCC\text{-}ee}_{240}$	2.7	κ-framework [1]	1.9
$\mathrm{FCC\text{-}ee}_{365}$	1.3	κ-framework [1]	1.2

arXiv:1905.03764

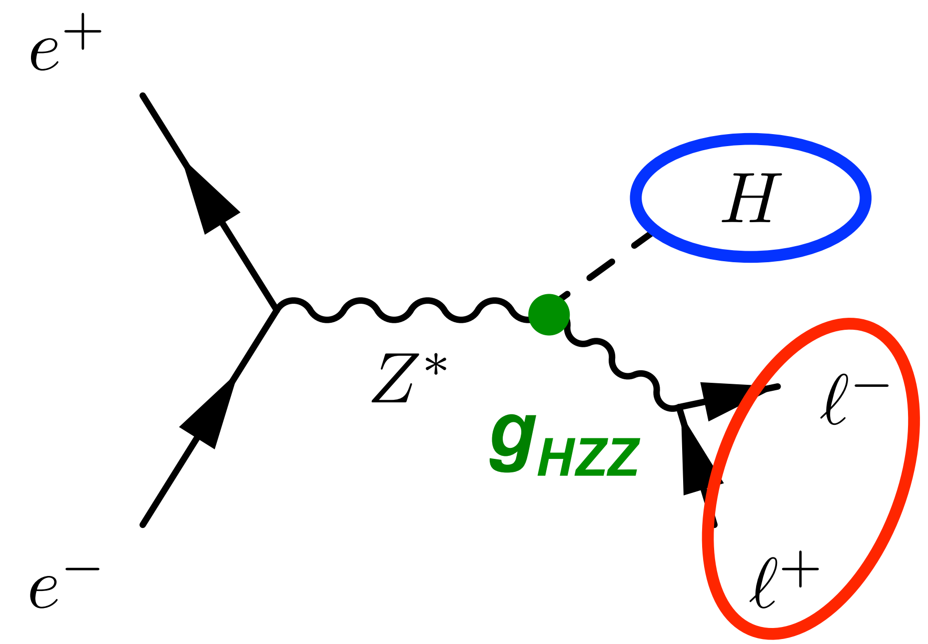
"Golden channel": $e^+e^- \to ZH, Z \to e^+e^-, \mu^+\mu^-$

Recoil method: detecting the Higgs boson without using its decay!

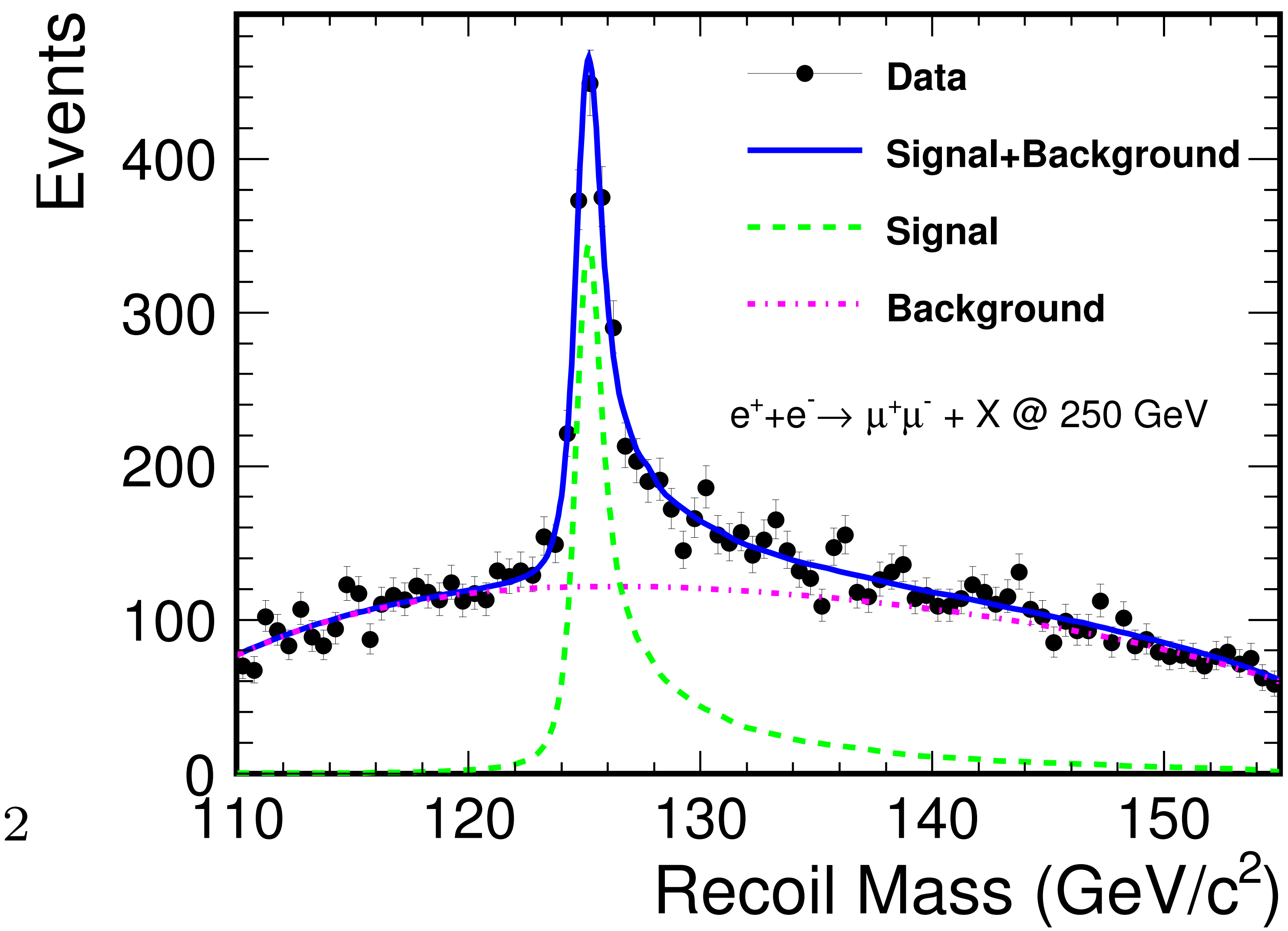
Reconstruct **$Z \to l^+l^-$**

independent of Higgs decay

sensitive to invisible Higgs decays



$$m^2_{\rm recoil} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$



Since the Z ⟶ l^+l^- decay branching fraction is known from the e^+e^- collider LEP, this method yields an absolute measurement of the ZH cross section and the Higgs branching ratios! 1% level reachable!

⇒ Large quantitative + qualitative improvements over HL-LHC

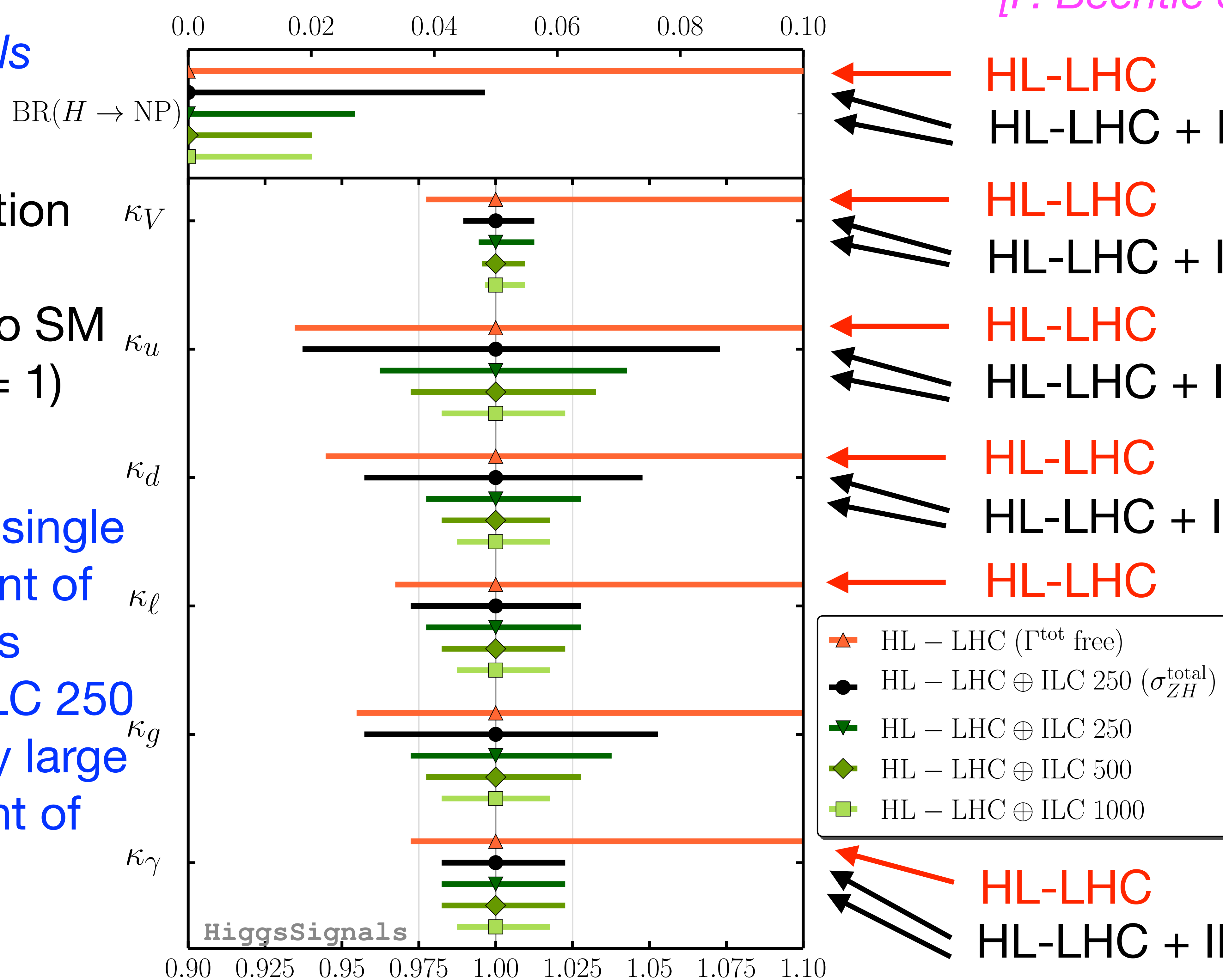
Projections for HL-LHC and ILC, no additional theory assumptions (ILC 250: only 250 fb^{-1})

[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!



HL-LHC
HL-LHC + ILC 250

HL-LHC
HL-LHC + ILC 250

HL-LHC
HL-LHC + ILC 250

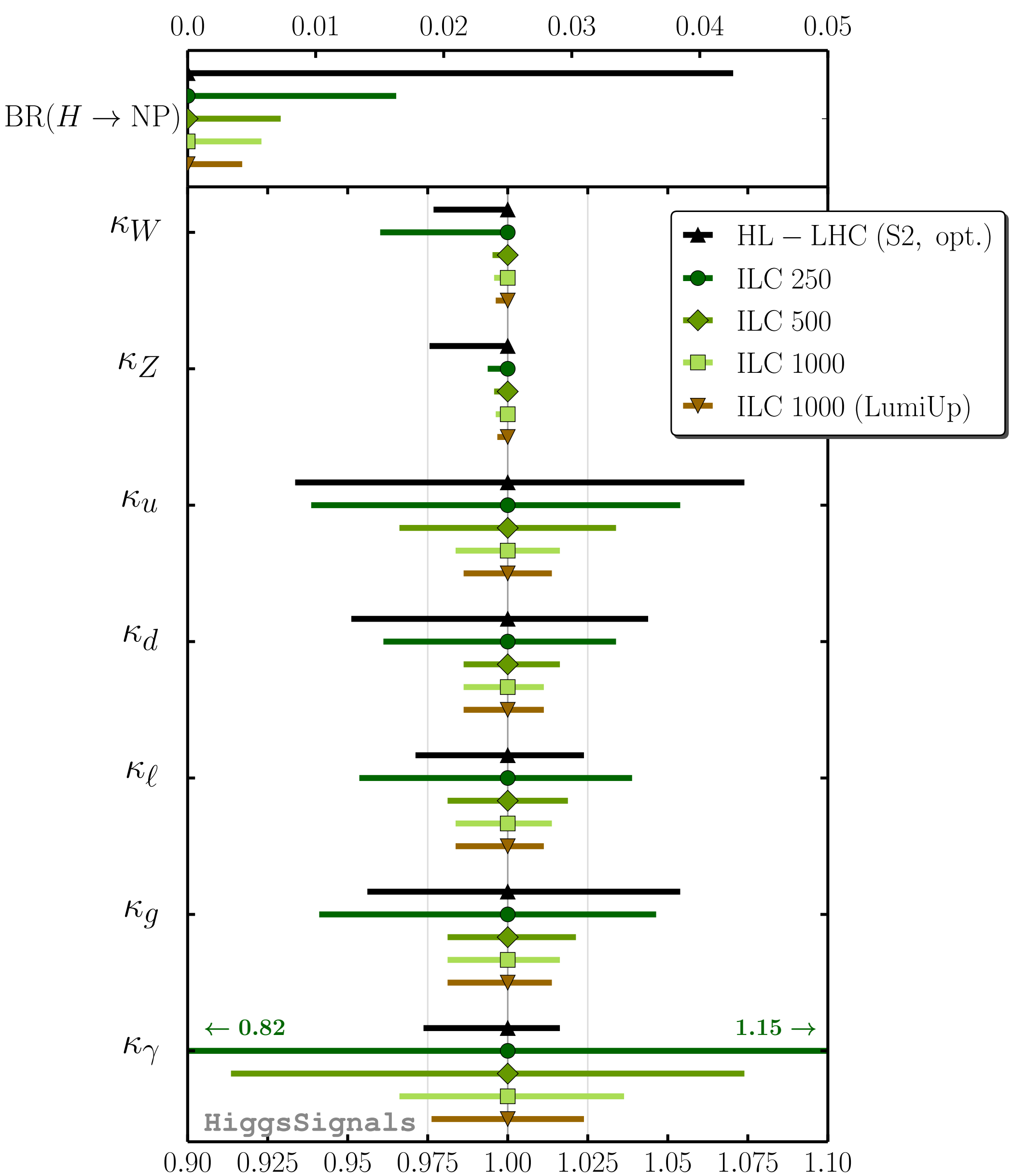
HL-LHC
HL-LHC + ILC 250

HL-LHC

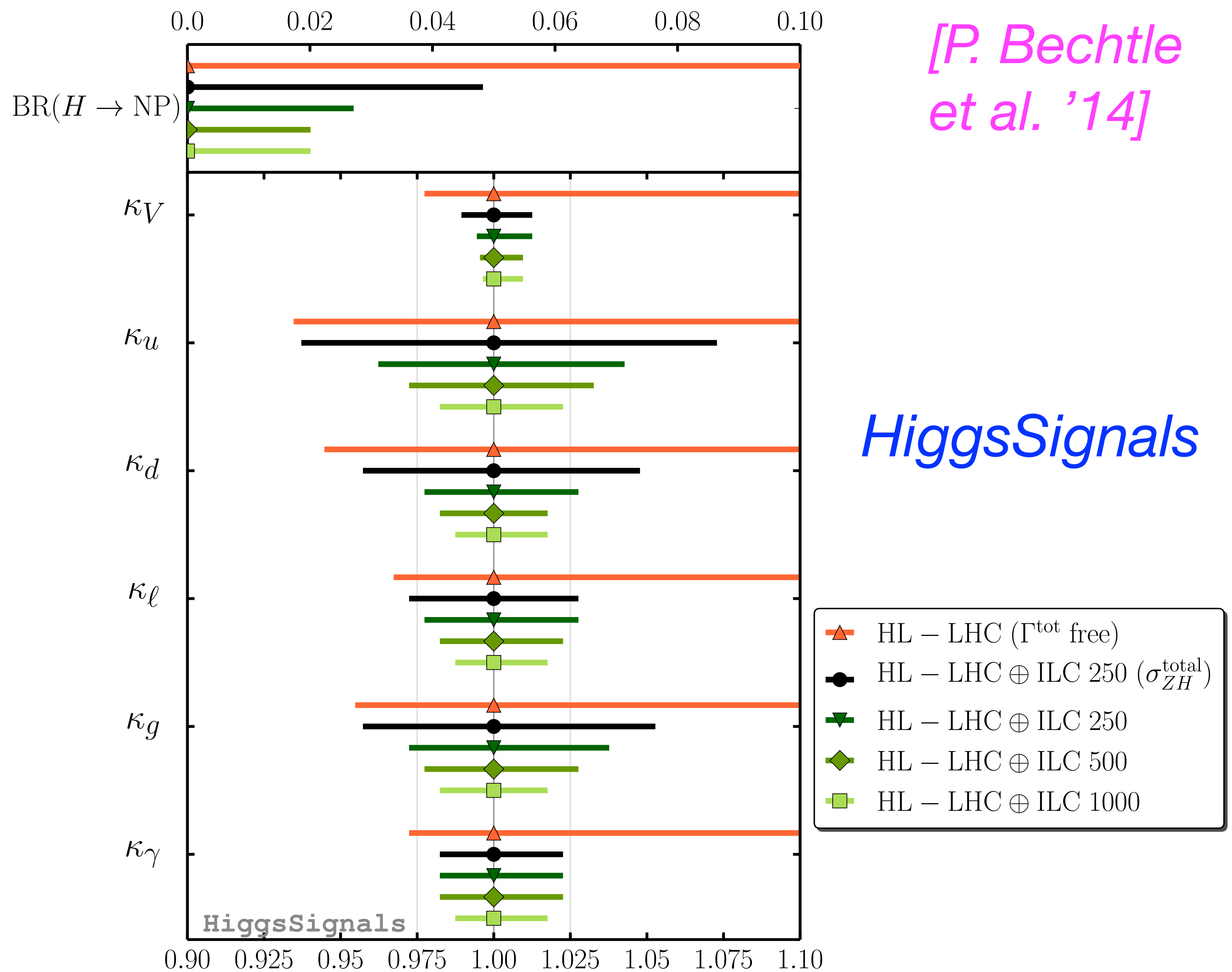
HL-LHC
HL-LHC + ILC 250

Prospects for Higgs-coupling determinations at HL-LHC and ILC: with and without theory assumption on $\varkappa_V$

Assumed: $\kappa_V \leq 1$



No theory assumption:



[P. Bechtle et al. '14]

HiggsSignals

⇒ HL-LHC result crucially relies on theory assumption on $\varkappa_V$

The quest for identifying the underlying physics

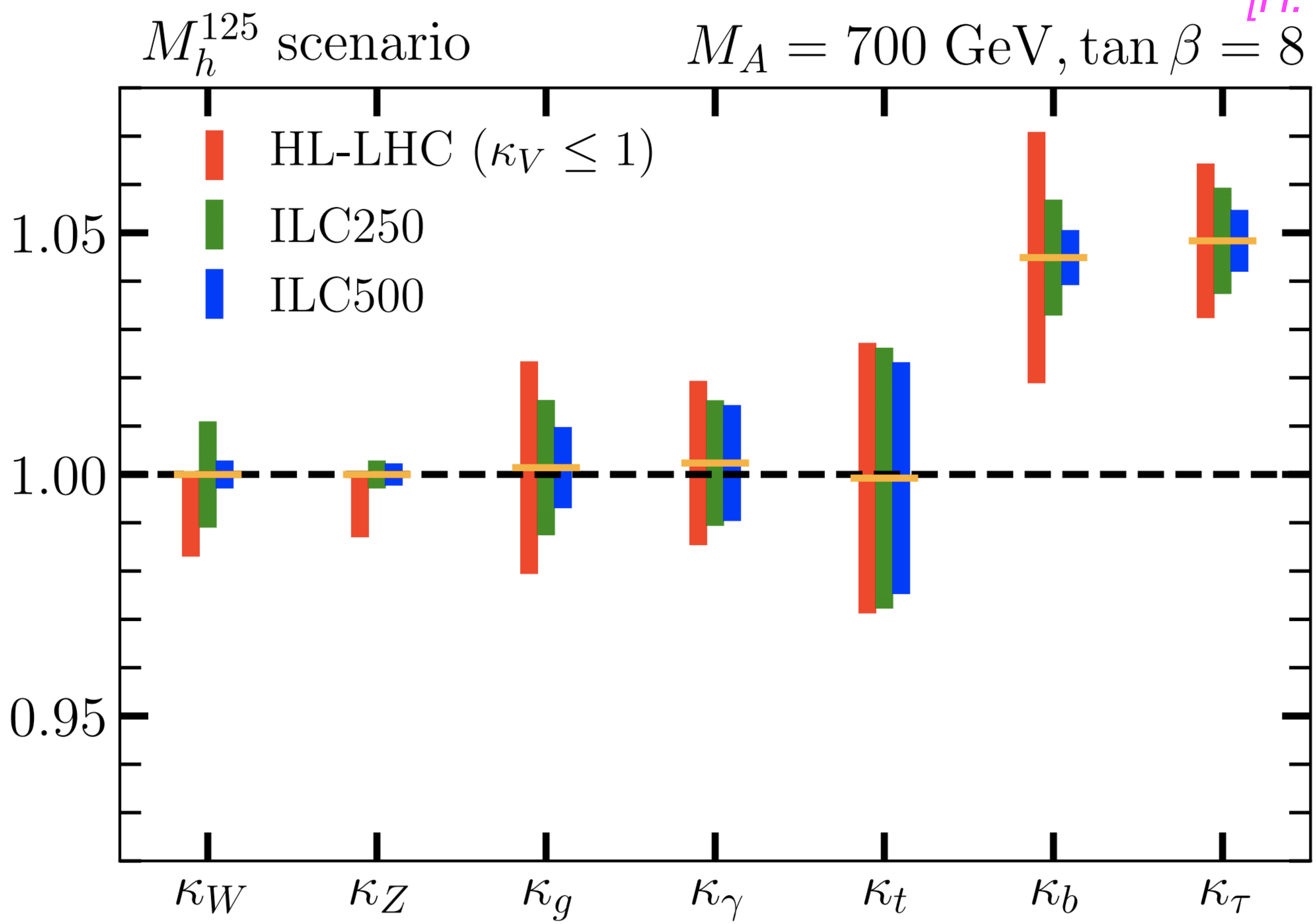
In many BSM models one expects only % level deviations from the SM couplings for BSM particles in the TeV range. For example, a 2HDM-type model in the decoupling limit roughly yields:

$$\begin{aligned}
\frac{g_{hVV}}{g_{h_{\rm SM}VV}} &\simeq 1 - 0.3\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^4 \\
\frac{g_{htt}}{g_{h_{\rm SM}tt}} = \frac{g_{hcc}}{g_{h_{\rm SM}cc}} &\simeq 1 - 1.7\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2 \\
\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} &\simeq 1 + 40\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2 .
\end{aligned}$$

⇒ Need very high precision for the couplings

Example: heavy SUSY scenario

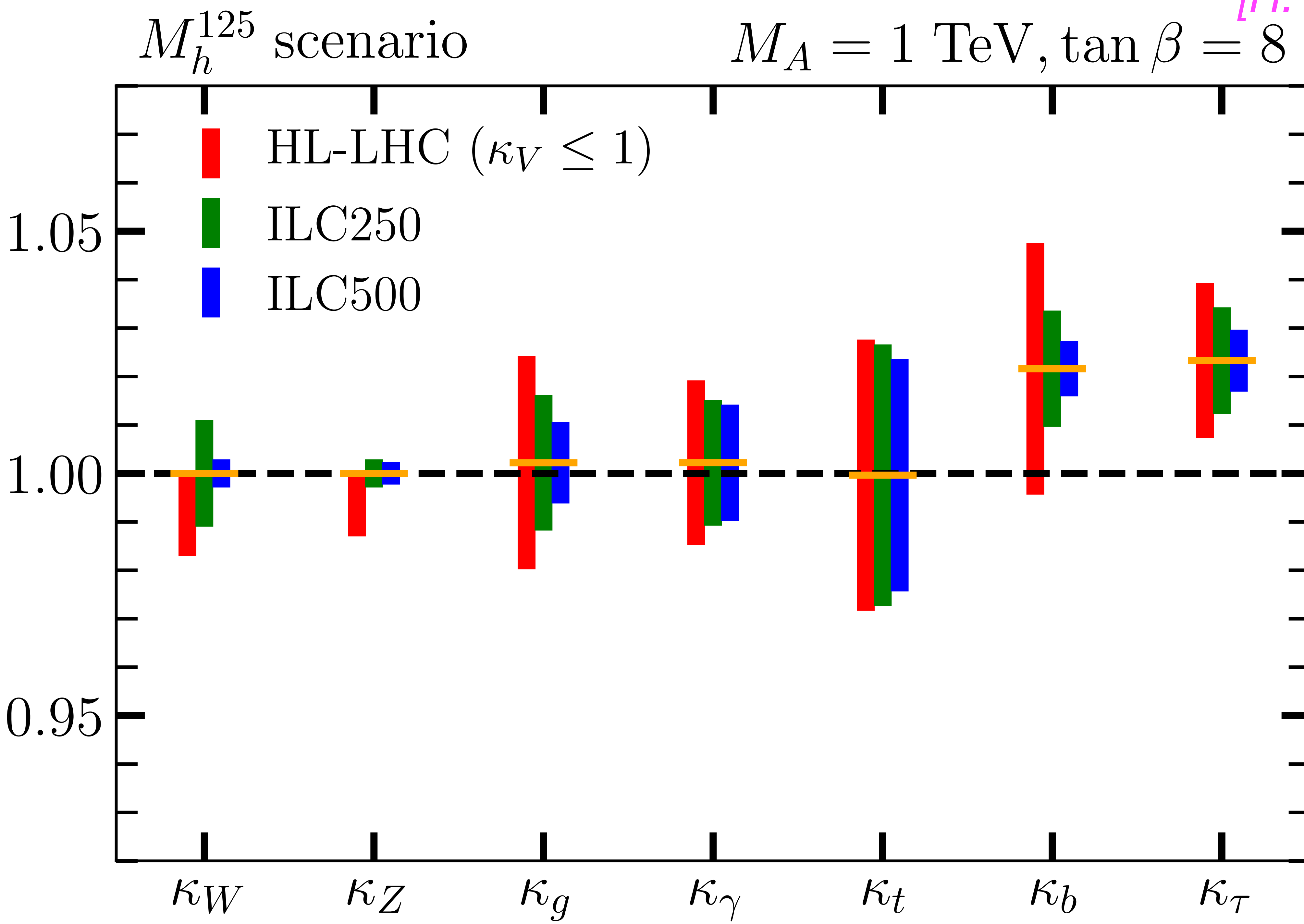
[H. Bahl et al. '20]



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

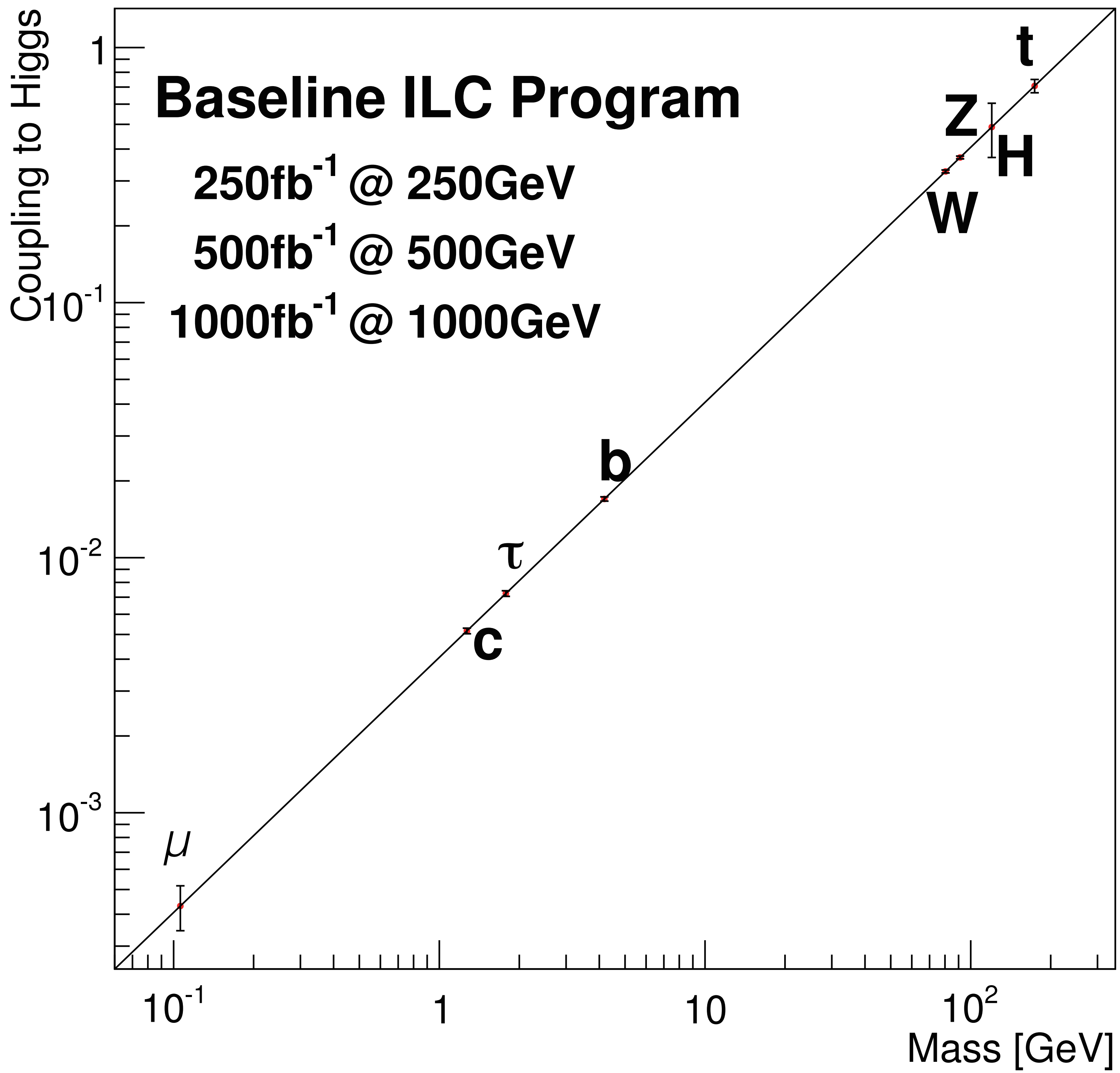
Example: heavy SUSY scenario

[H. Bahl et al. ’20]



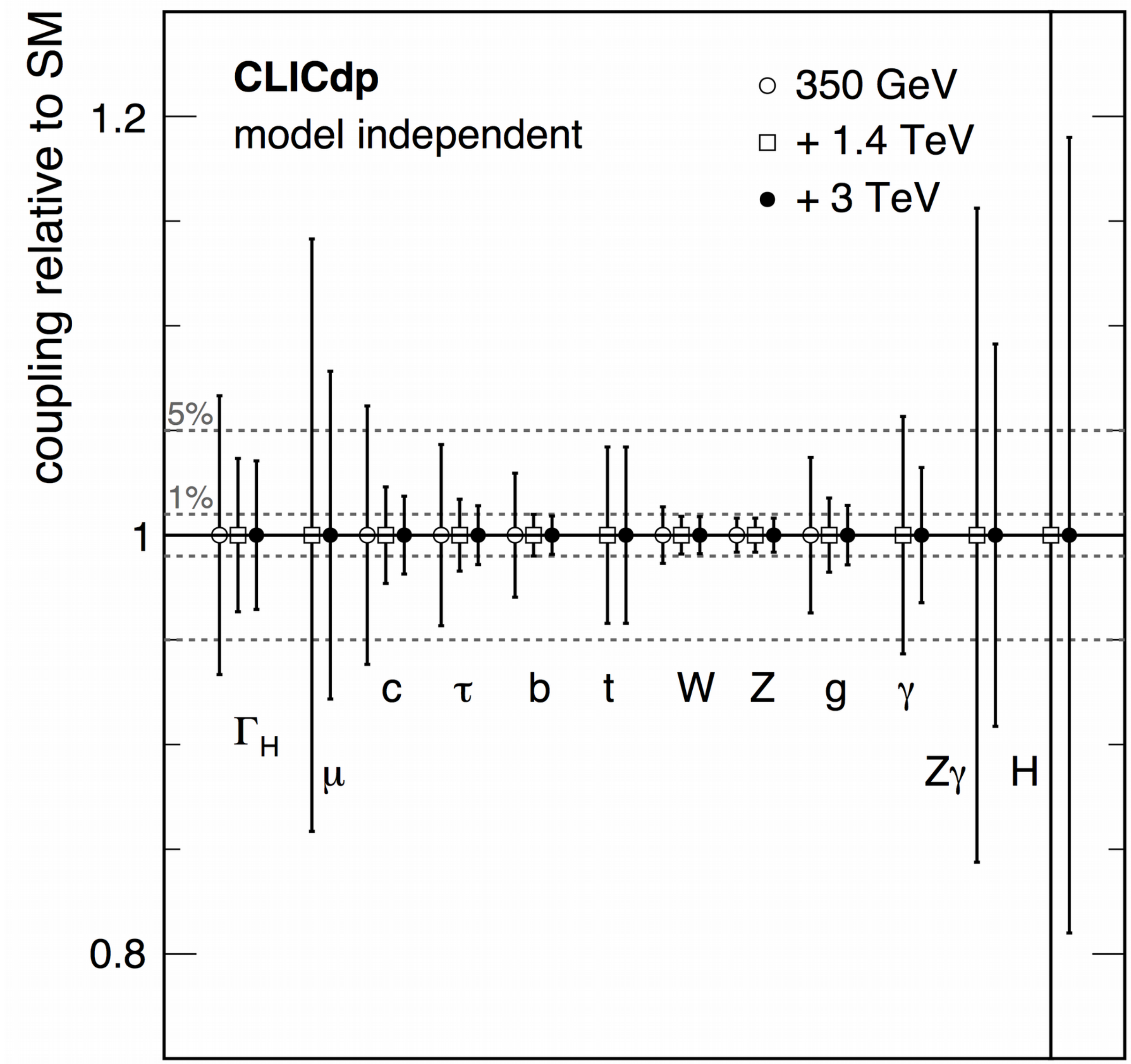
⇒ Precision at 1% level provides large sensitivity for discriminating between different realisations of underlying physics

Coupling determination at the ILC



Higgs coupling accuracies at CLIC

[P. Roloff ’18]



Fully model-independent analysis only possible at lepton colliders

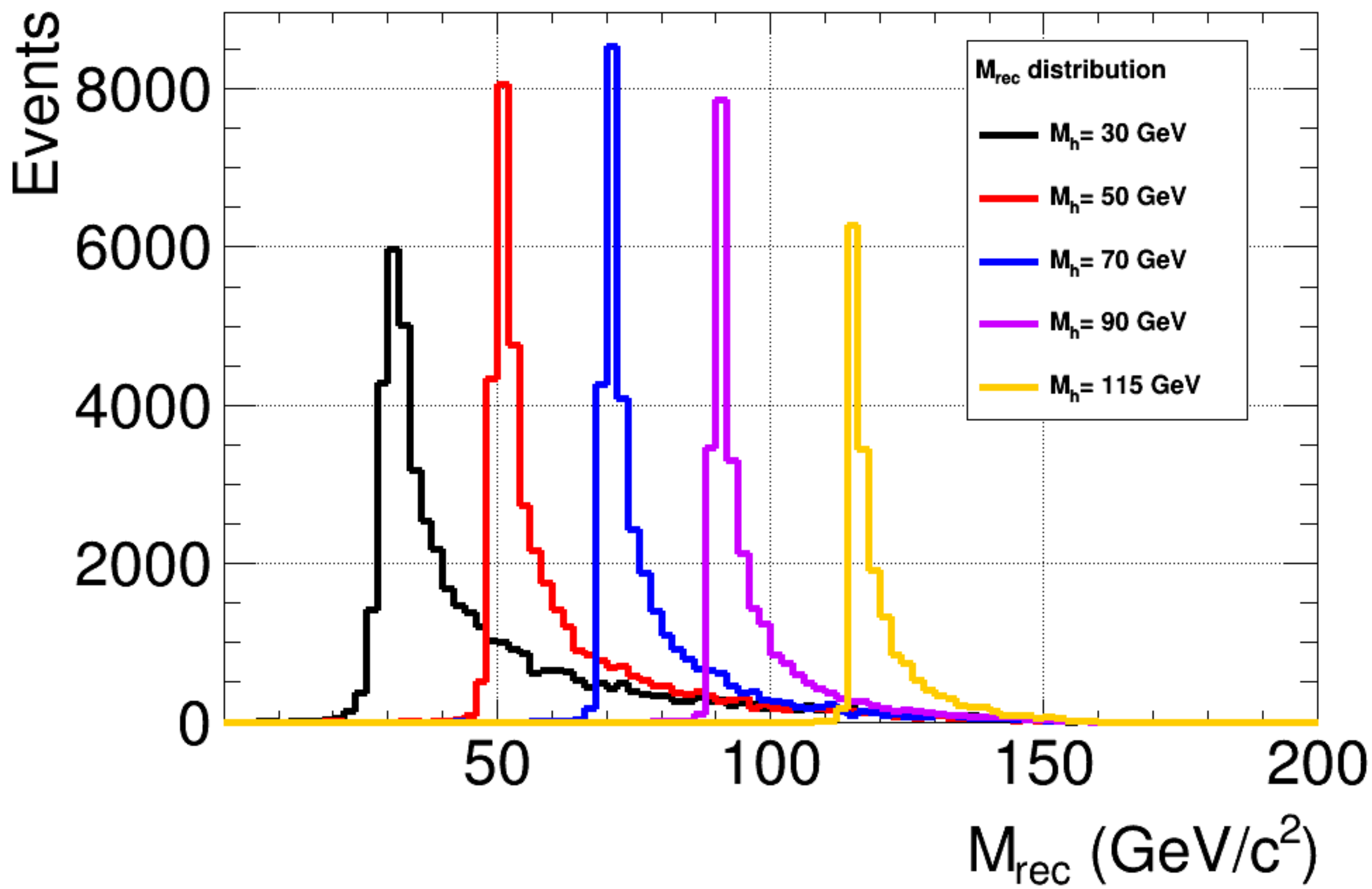
NB: All projections are based on benchmark studies using full detector simulations

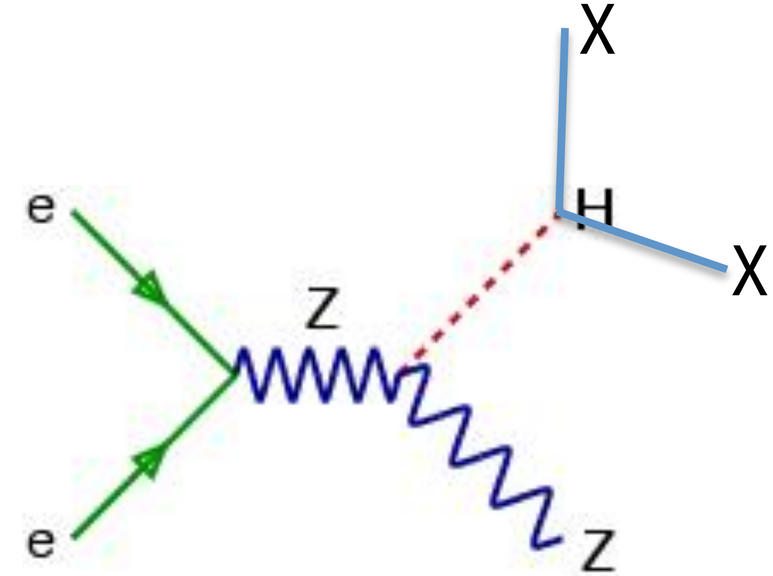

Eur. Phys. J. C (2017) 77:475
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

Higgs physics at the CLIC electron–positron linear collider

Eur. Phys. J. C 77, 475 (2017)

Invisible decays





⇒ Unique sensitivity at an e^+e^- Higgs factory!

Discovery potential of ILC 250 for invisible decays and decays that are ``undetectable” at the LHC

Direct search for H → invisible at ILC 250 has sensitivity down to branching ratios 0.3%

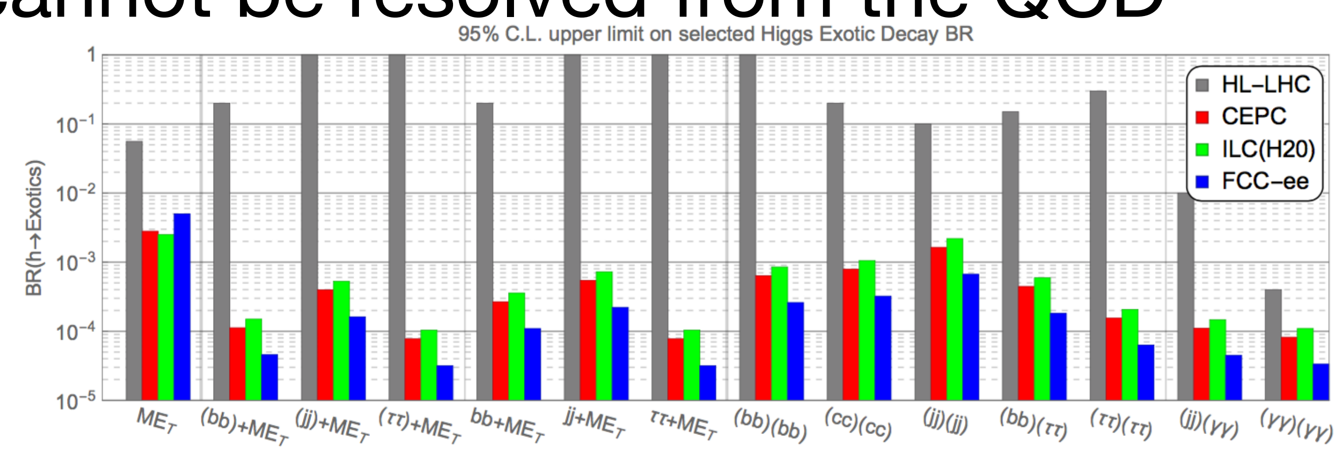
If there are dark matter particles with a mass below half of the Higgs mass, then the Higgs decay into a pair of those particles will give rise to an invisible decay mode

⇒ Discovery potential for dark matter and other new physics

Complementary sensitivity via high-precision measurements of the Higgs couplings: the presence of an invisible decay mode leads to a simultaneous suppression of all other branching ratios!

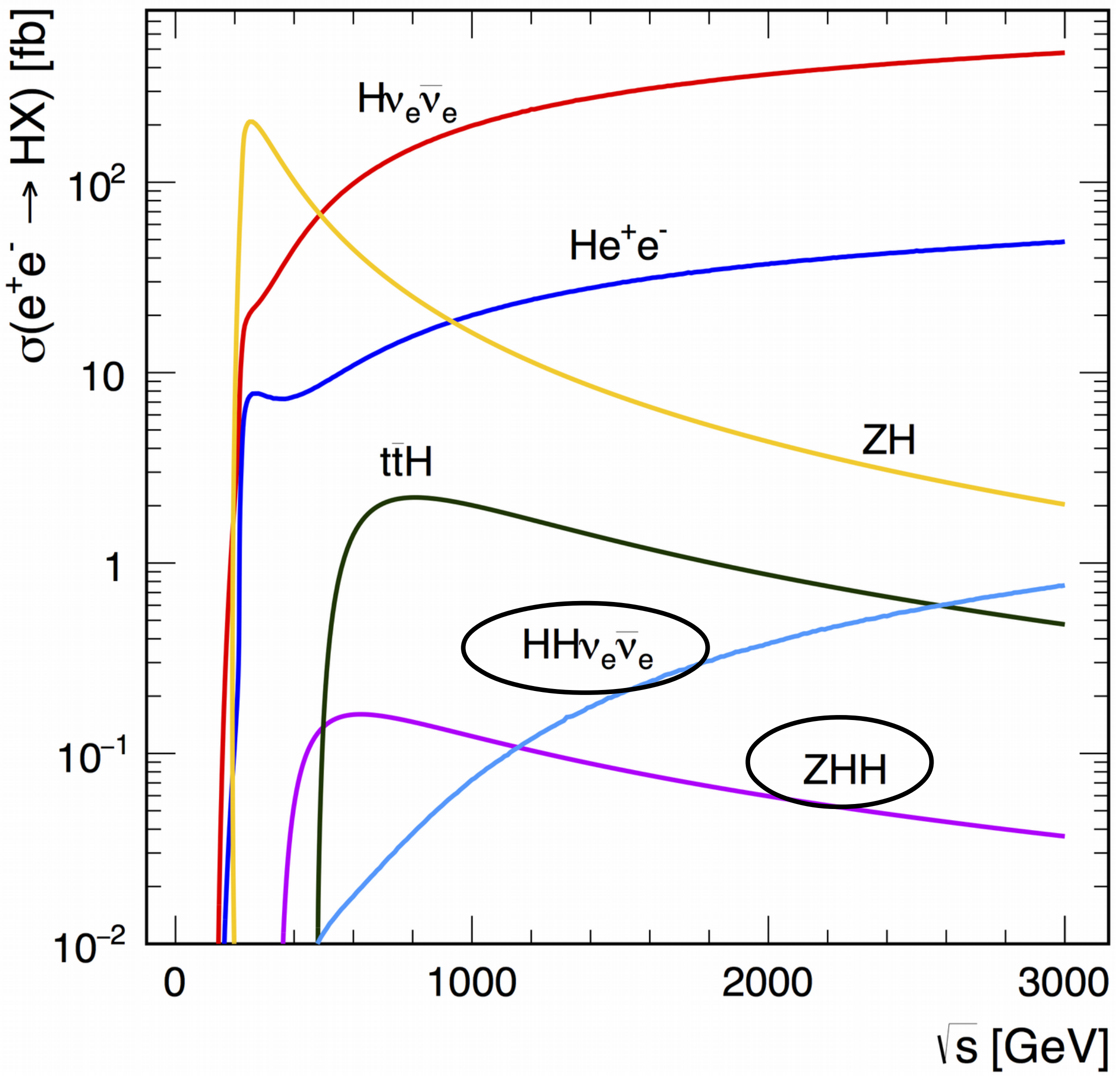
Also sensitivity at the %-level to decays that are ``undetectable” at the LHC: decay products that cannot be resolved from the QCD background (non-b jets, gg, …)

``Exotic” decay modes: large improvements over HL-LHC
[Z. Liu, L.T. Wang, H. Zhang ’17]



Higgs pair production and trilinear Higgs coupling

[P. Roloff '18]

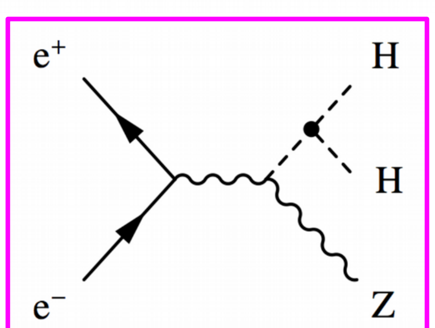


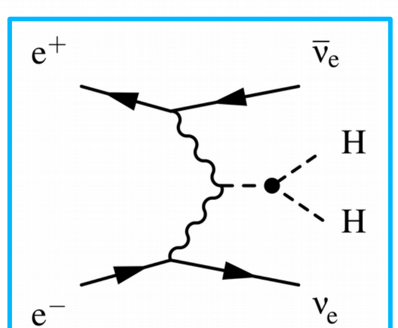
$e^+e^- \to$ ZHH:
- Cross section maximum ≈ 600 GeV, but very small number of events ($\sigma \leq 0.2$ fb)

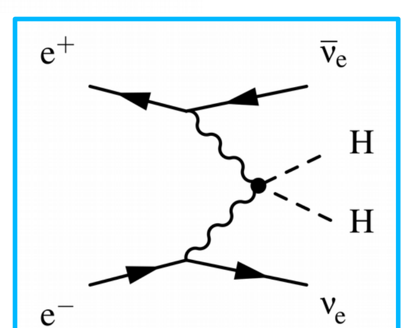
$e^+e^- \to HH\nu_e\bar{\nu}_e$:
- Allows simultaneous extraction of triple Higgs coupling, λ, and quartic HHWW coupling
- Benefits from high-energy operation

Projected precisions:
- $\Delta(\lambda) = 16\%$ for CLIC from total cross section assuming 3 ab^{-1} at 3 TeV
(→ $\Delta(\lambda) \approx 10\%$ from differential distributions)

Eur. Phys. J. C 77, 475 (2017)







Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $\quad -15\,\%^b$
NMSSM	$-25\,\%$

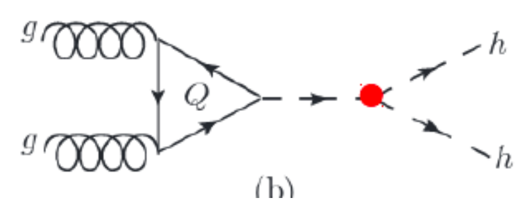
Phys. Rev. D 88, 055024 (2013)

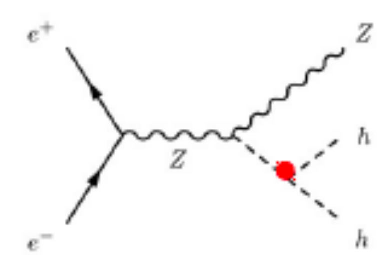
Higgs self coupling λ

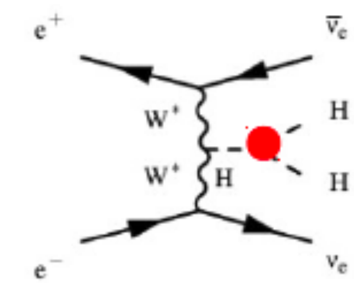
Sensitivity of different processes crucially depends on the actual value of λ

[B. Heinemann '19]

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

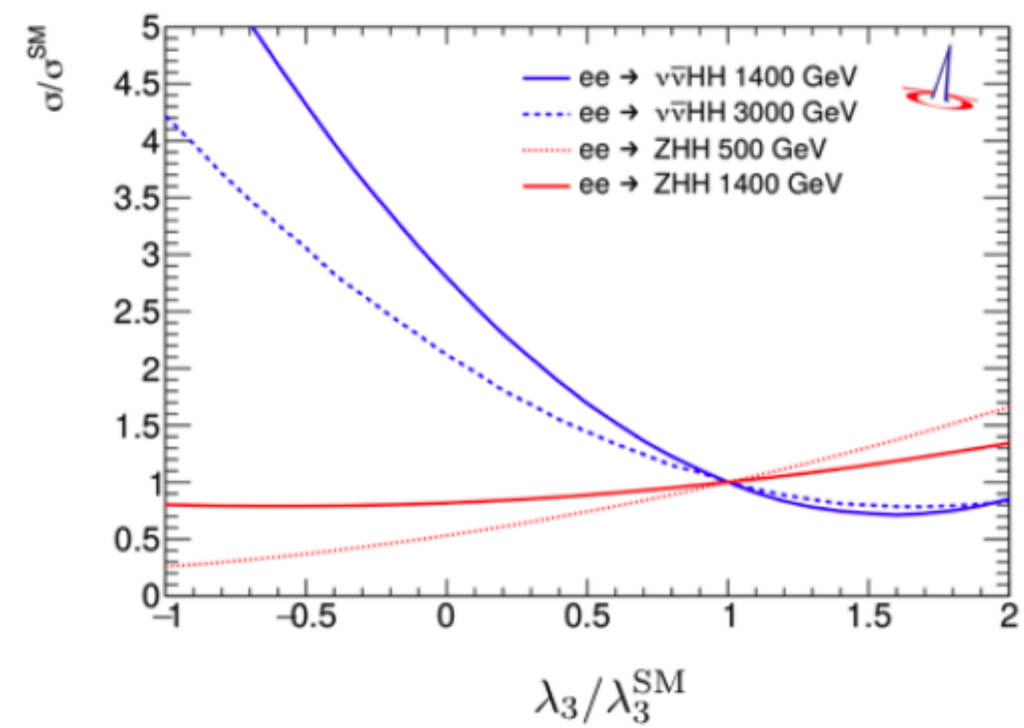


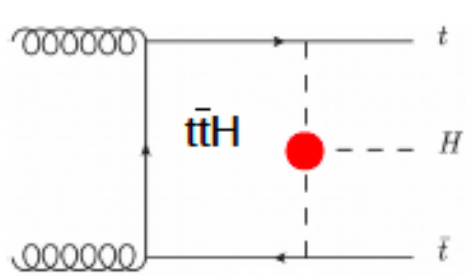




Di-Higgs processes at lepton colliders
- **ZHH or VBF production complementary**

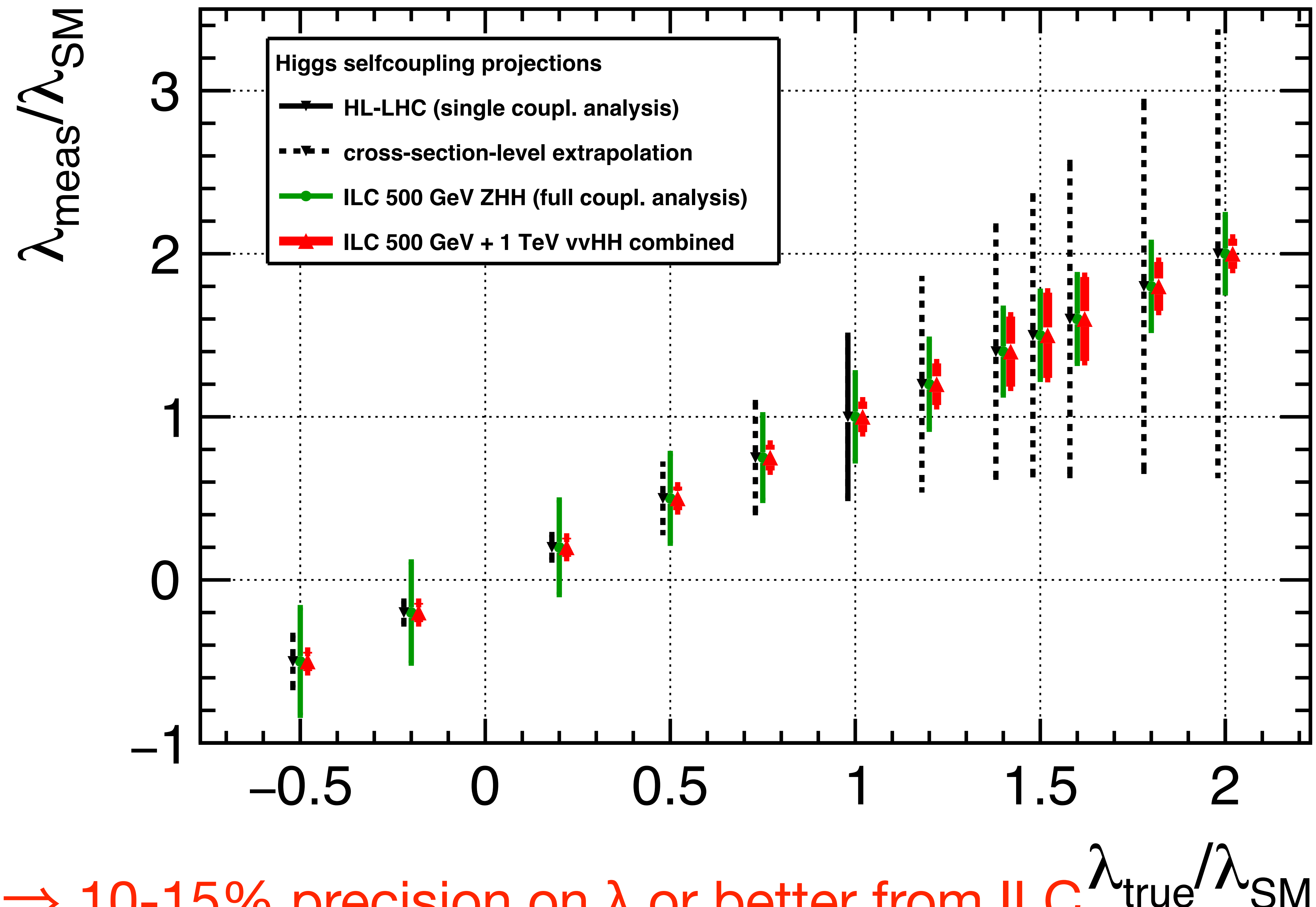
Single-Higgs production sensitive through loop effects, e.g. for $\kappa_\lambda = 2$:
- **Hadron colliders: ~3%**
- **Lepton colliders: ~1%**





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

[J. List et al. '21]



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

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

$\Rightarrow$ 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

Search for additional Higgs bosons

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

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

$\Rightarrow$ •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

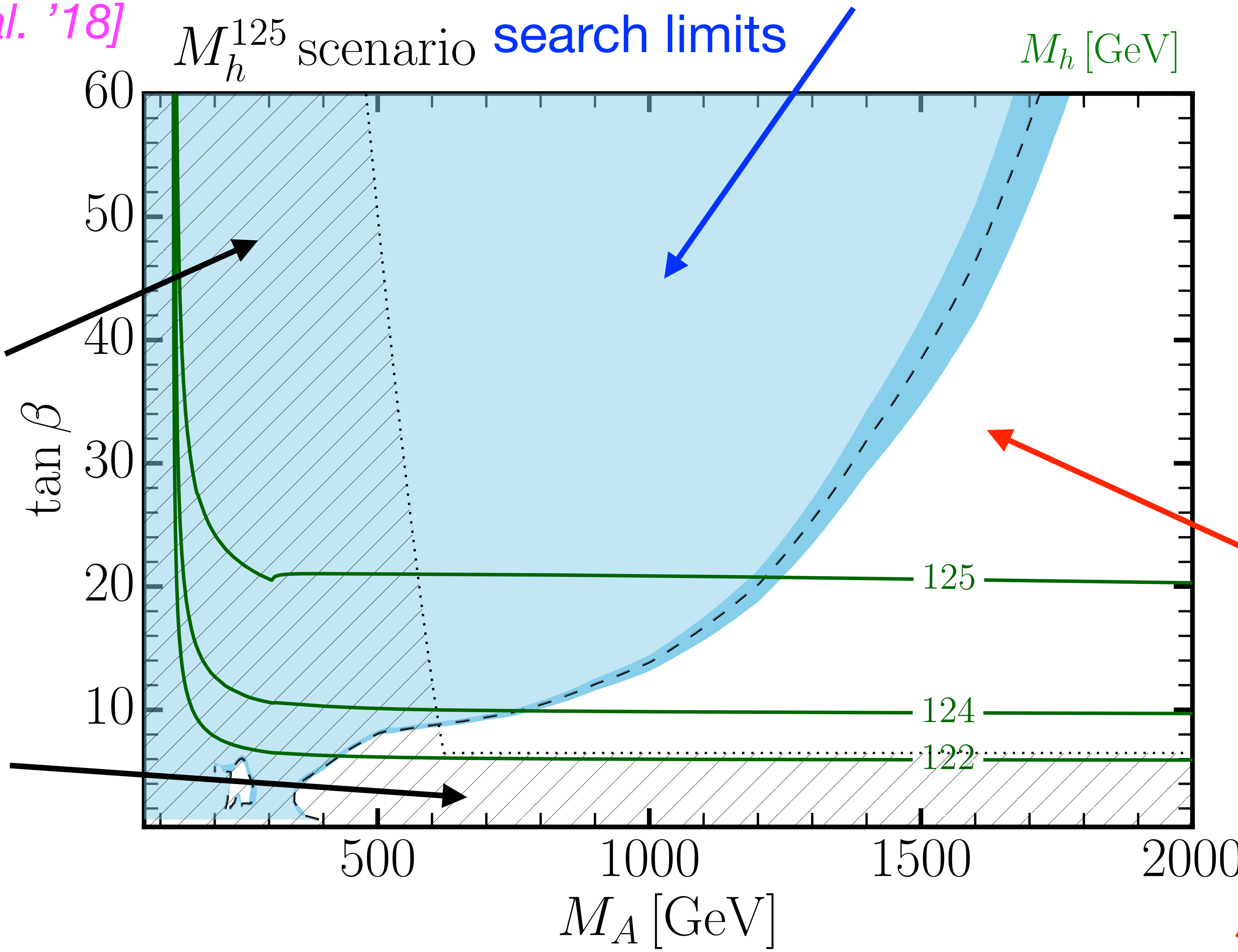
• Searches for additional Higgs bosons need to test compatibility with the observed signal at 125 GeV!

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

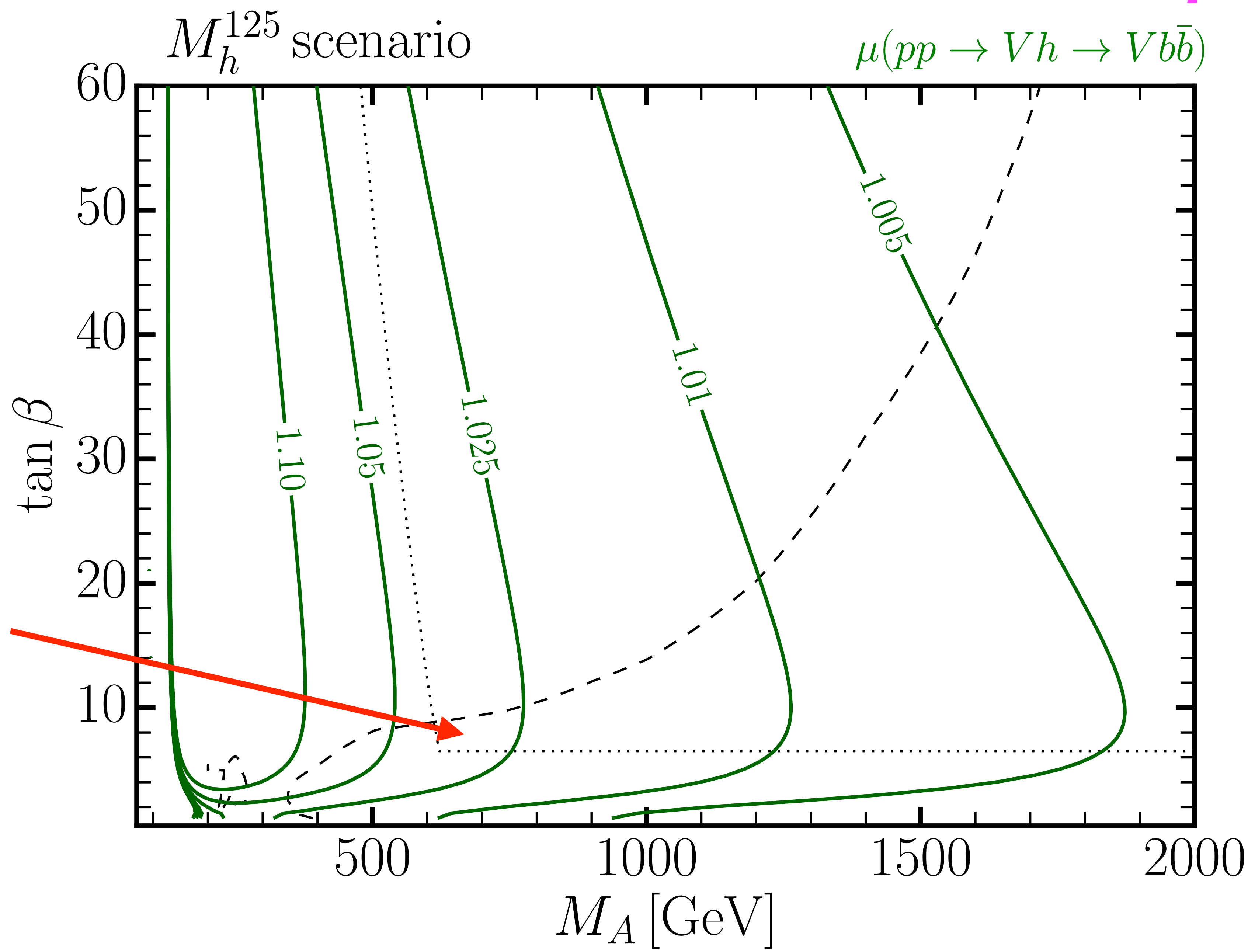


HiggsSignals: area is not compatible with the properties of the detected Higgs signal

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]



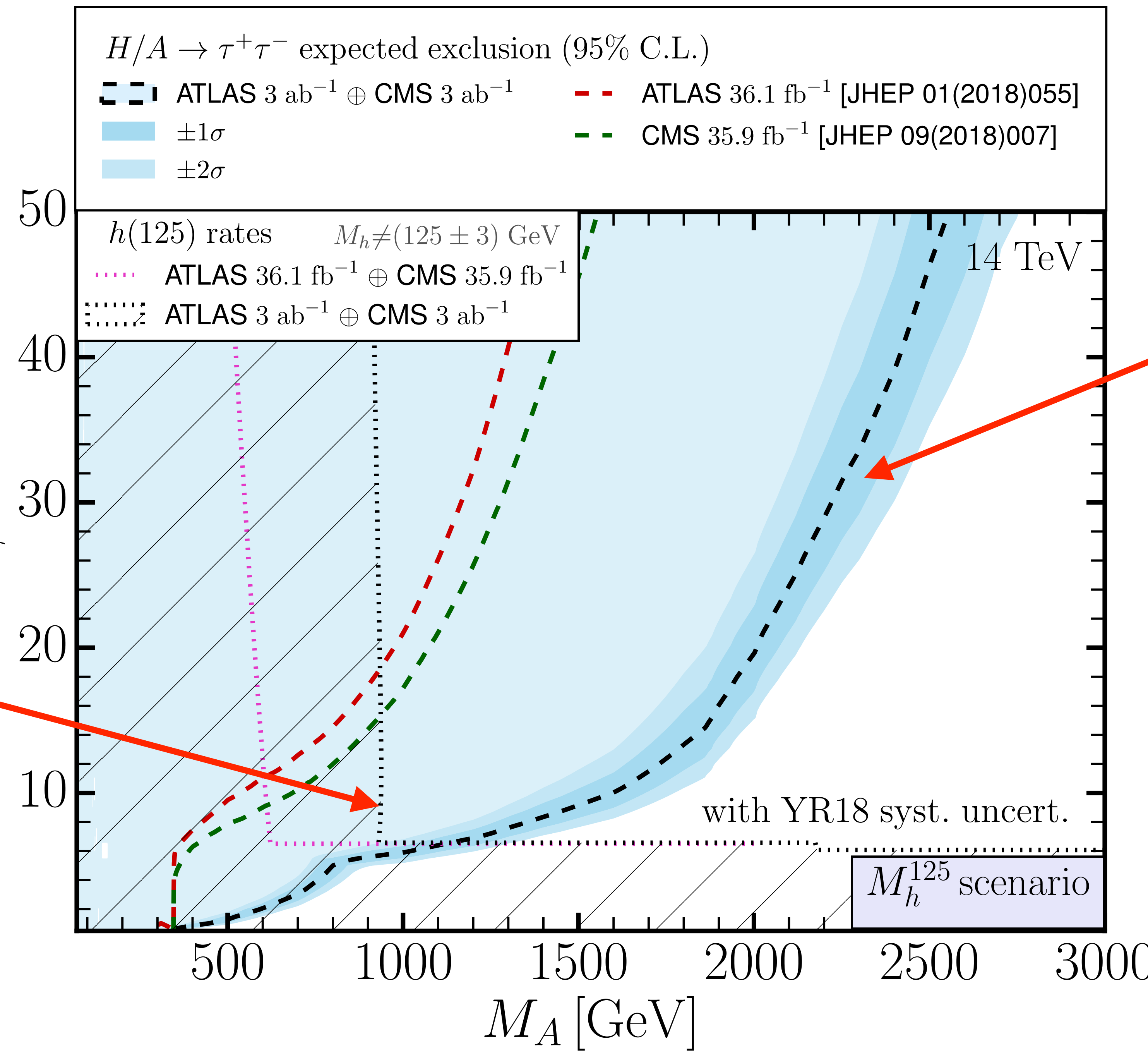
Maximal deviation below 5%

⇒ 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. '20]

Sensitivity from HL-LHC signal measurements



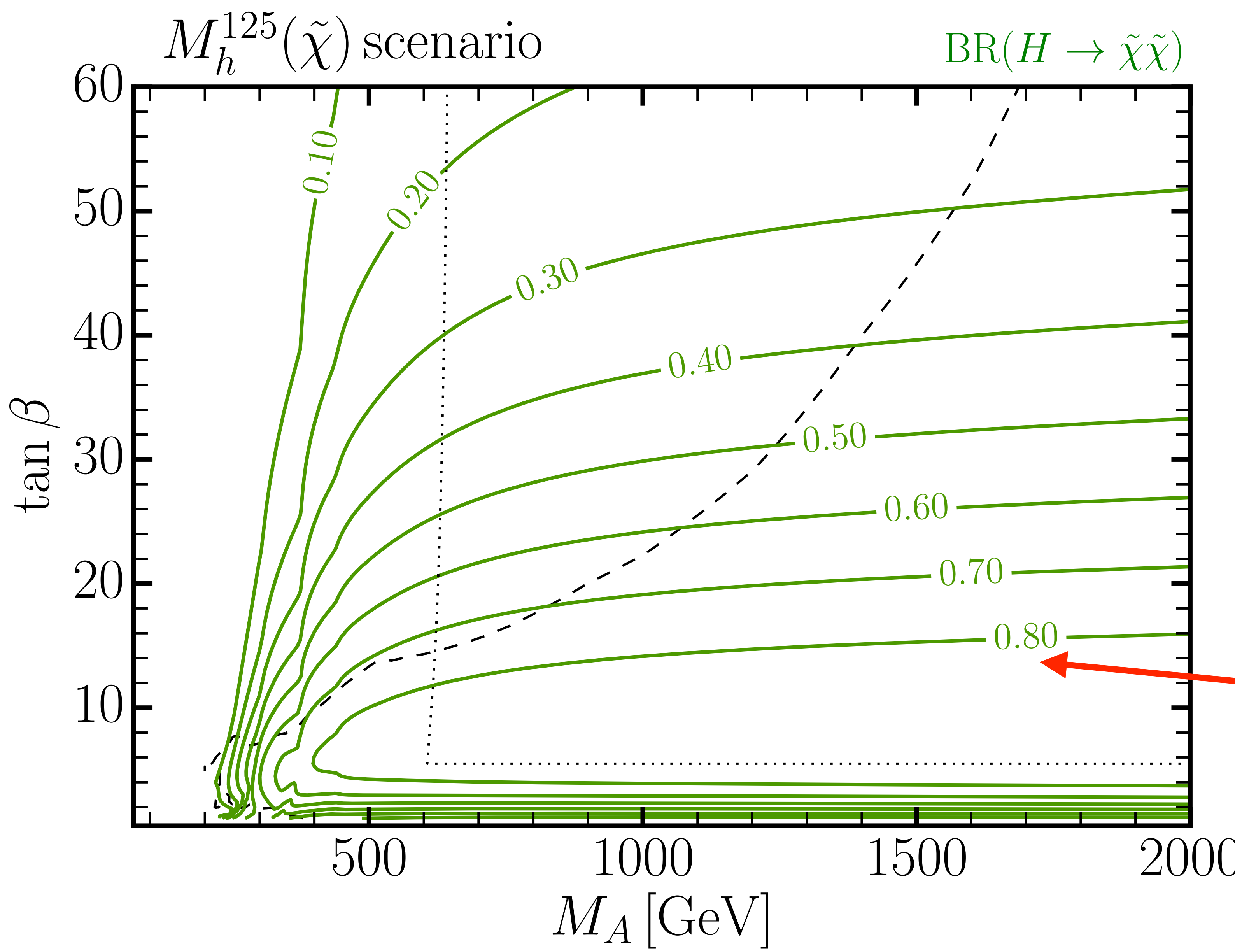
Projected exclusion region for H, A searchs

⇒ 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]

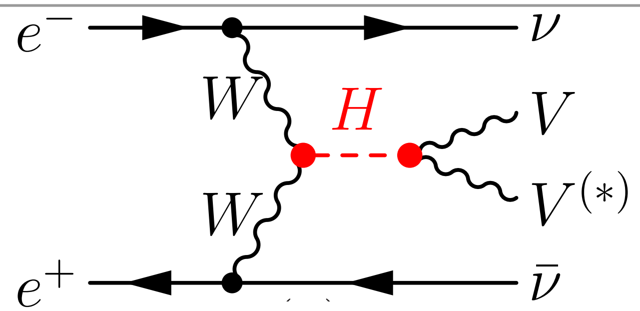
Decays of heavy Higgs bosons *H, A* into charginos and neutralinos:



Branching ratios of more than 80% possible!

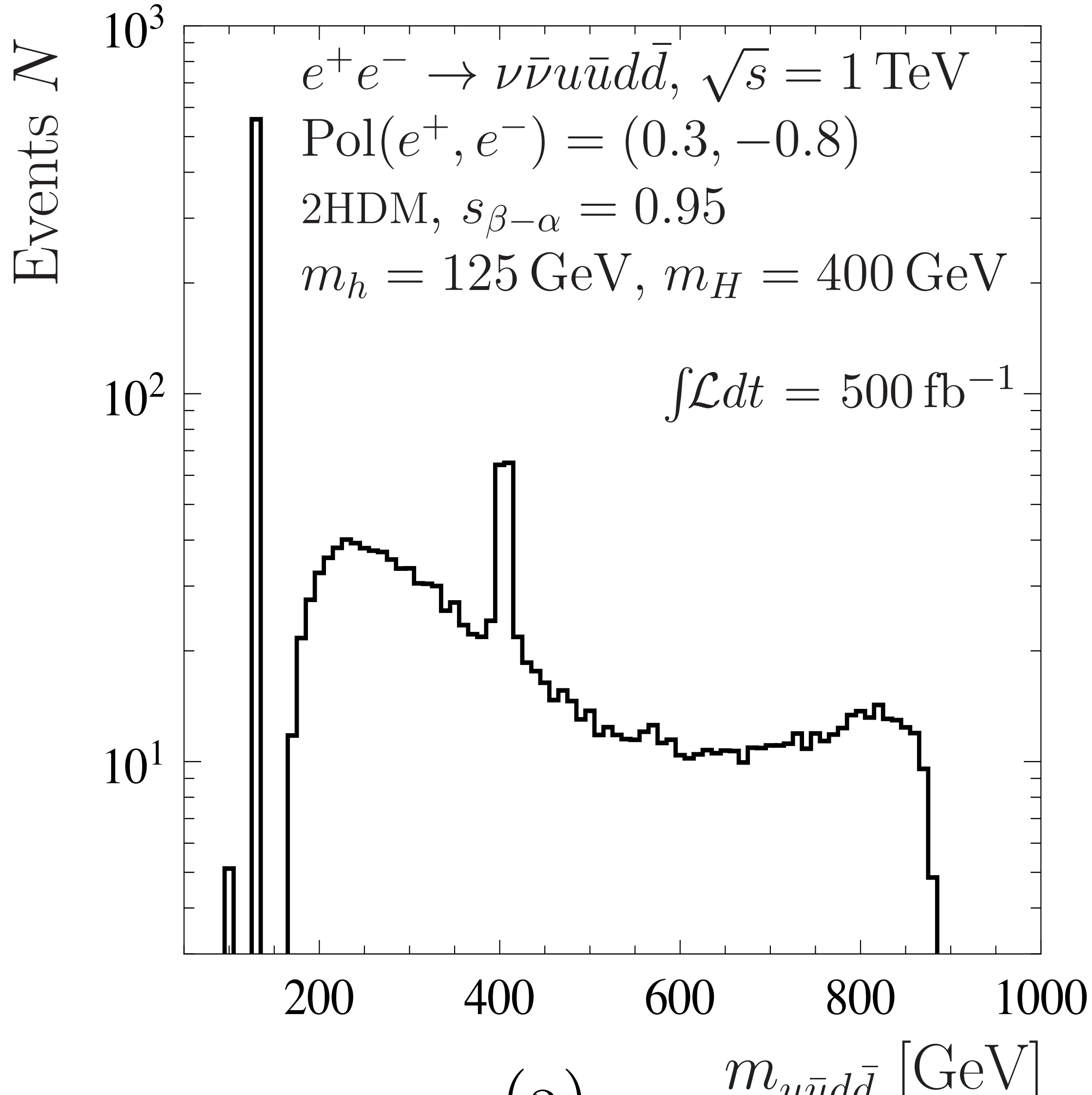
⇒ Dedicated searches for heavy Higgs decays into SUSY particles could probe the ``LHC wedge” region

LC sensitivity to the small signal of an additional heavy Higgs boson in a Two-Higgs-Doublet model (2HDM)

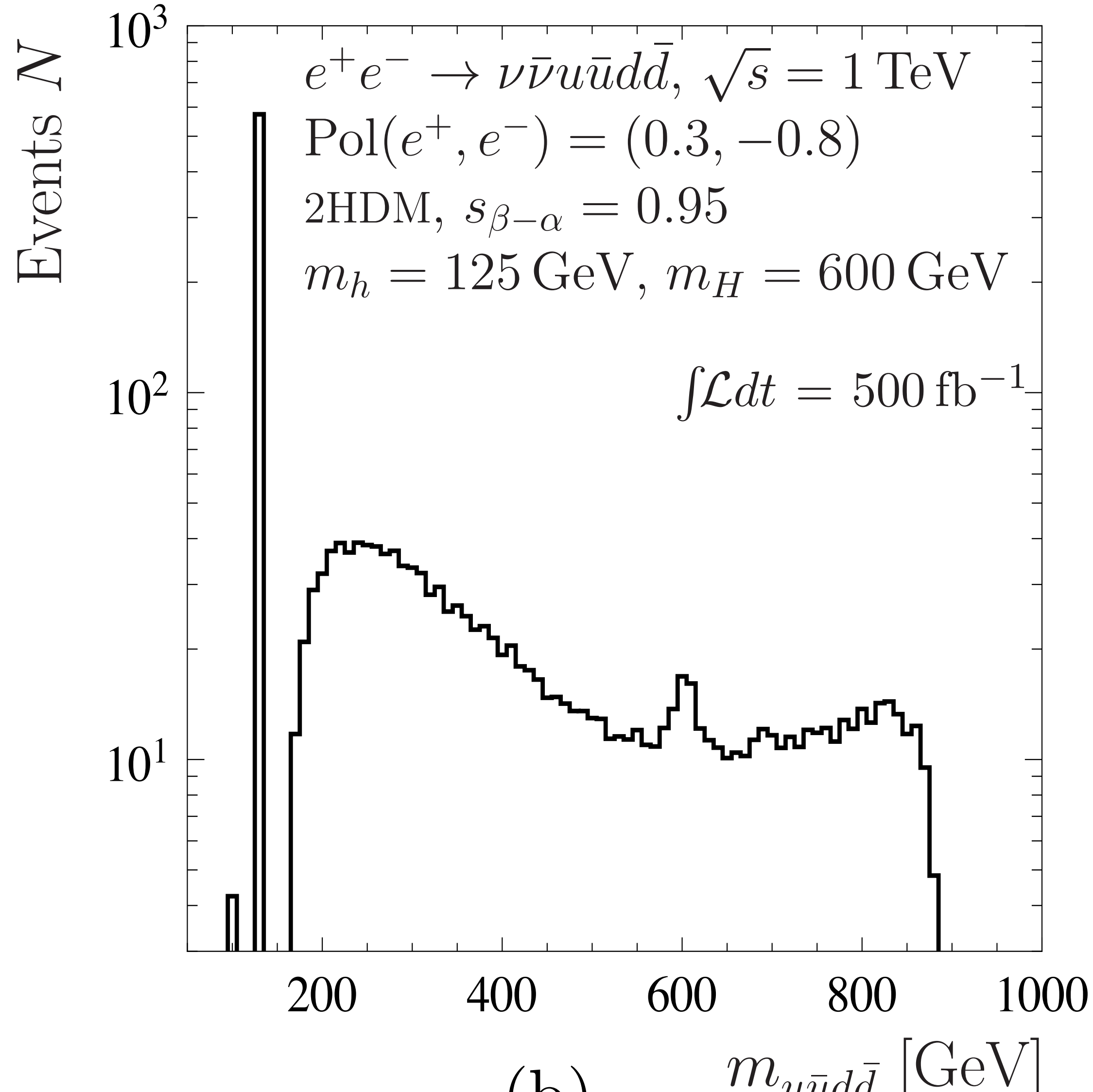


[S. Liebler et al. ’15]

$$g_{\mathrm{hVV}} = \sin(\beta-\alpha)\, g^{\mathrm{SM}}_{\mathrm{HVV}}, \quad g_{\mathrm{HVV}} = \cos(\beta-\alpha)\, g^{\mathrm{SM}}_{\mathrm{HVV}}, \quad V = W^{\pm}, Z$$



(a)

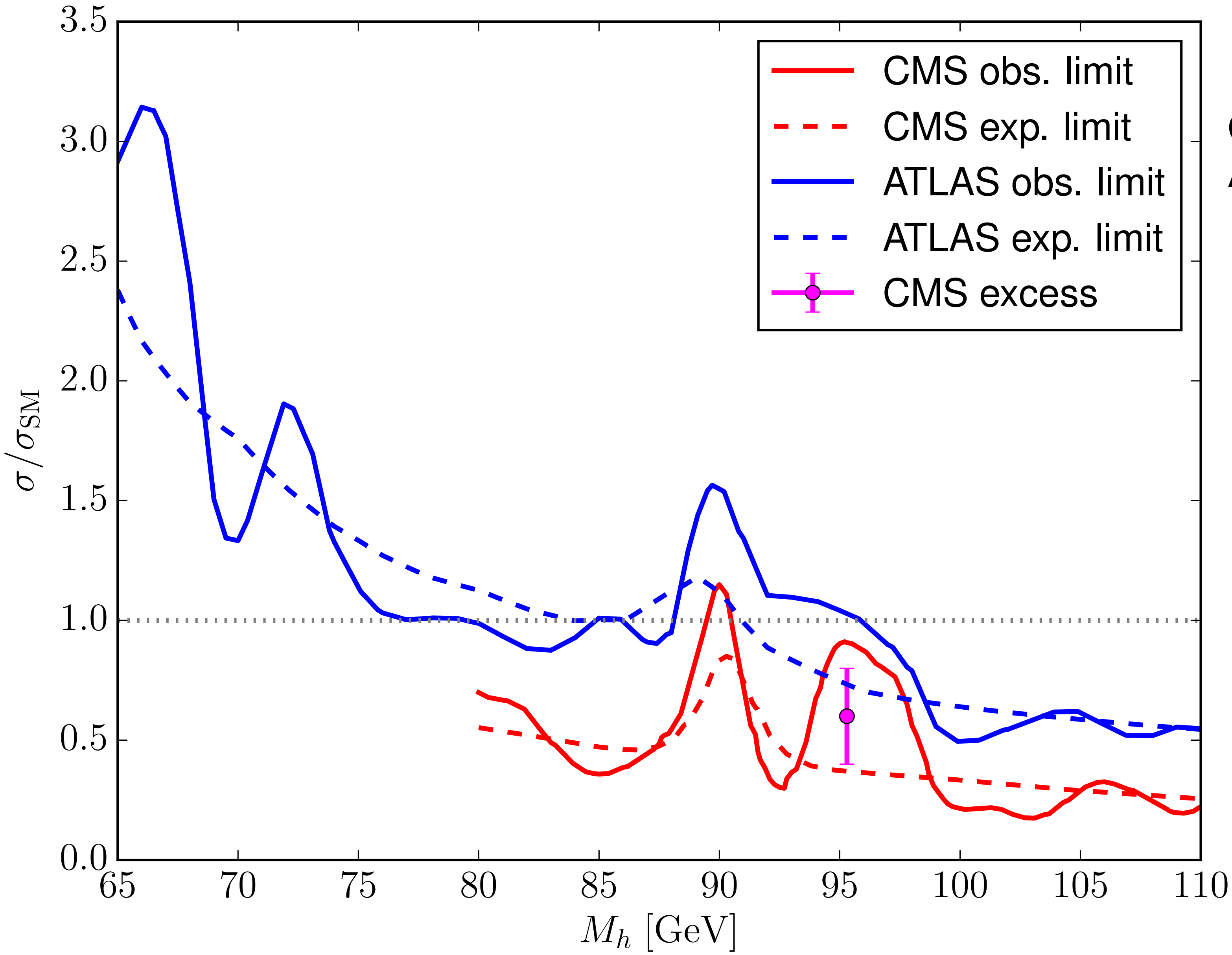


(b)

$\Rightarrow$ ILC: Potential sensitivity beyond the kinematic reach of Higgs pair production

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

[T. Stefaniak '18]

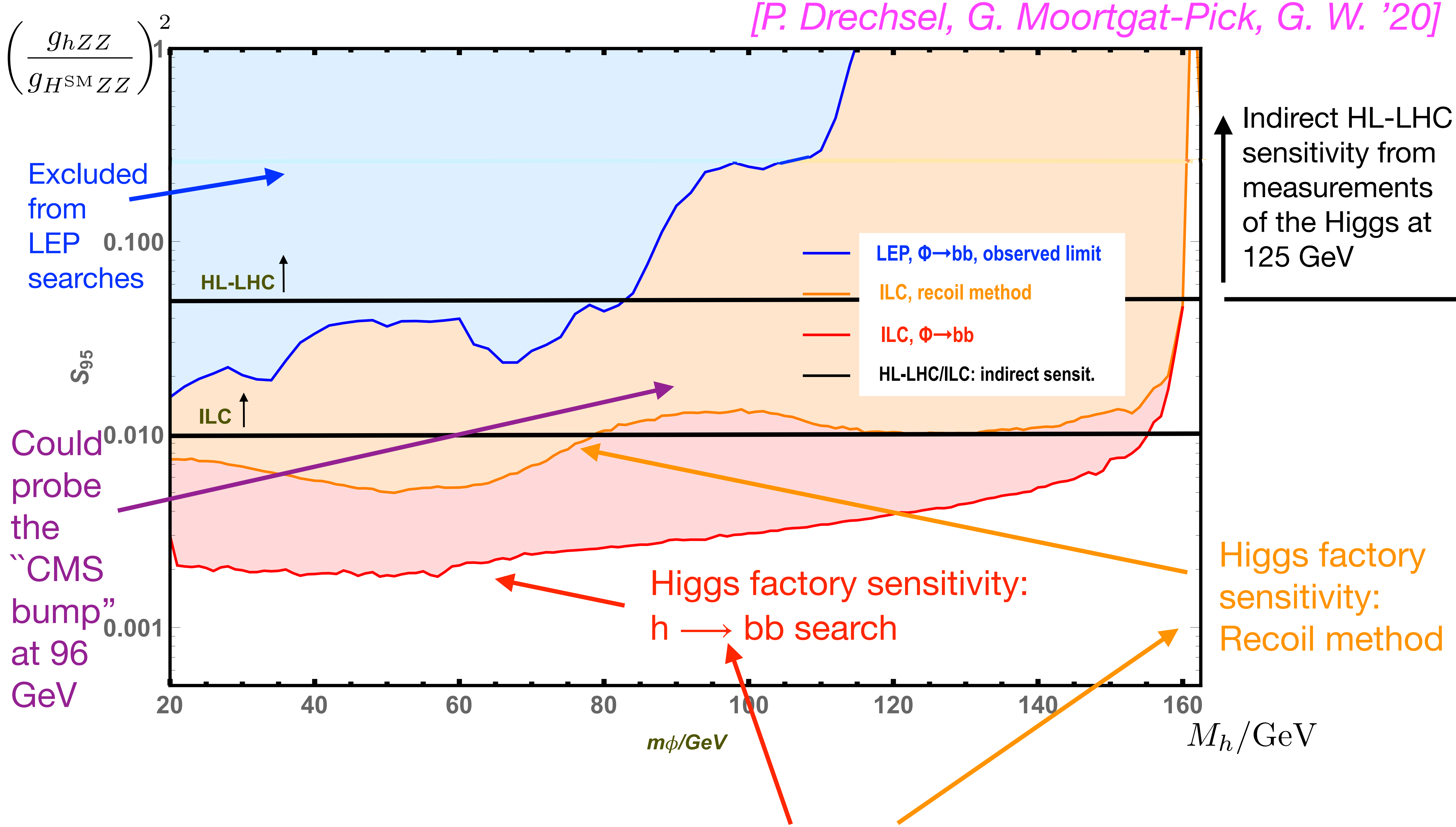


CMS-PAS-HIG 17-013,
ATLAS-CONF-2018-025

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

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

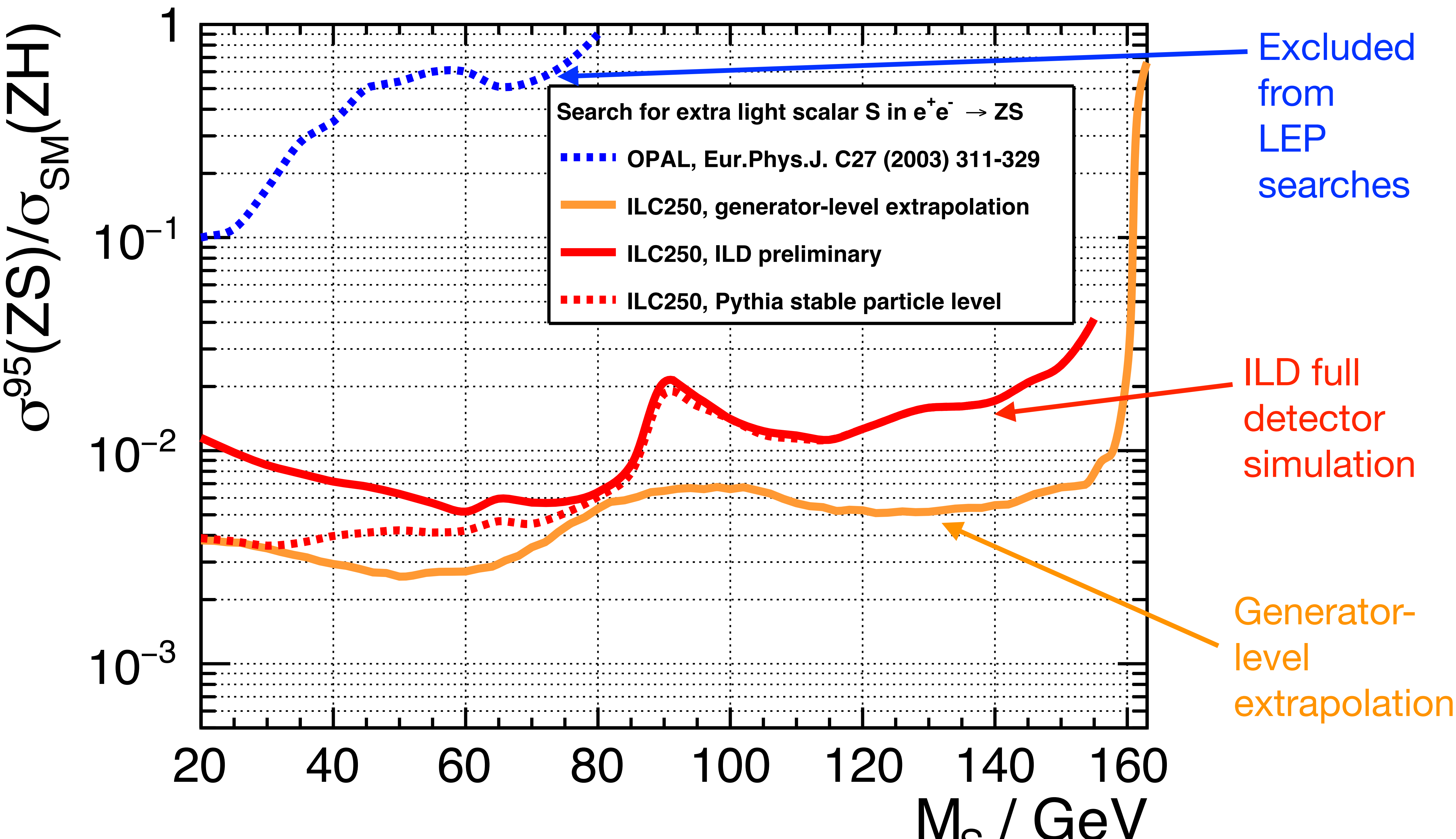
[P. Drechsel, G. Moortgat-Pick, G. W. '20]



⇒ 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. '20] [Y. Wang, J. List, M. Berggren '19]



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

BSM, electroweak, top and flavour physics

BSM physics:

- Searches + precision physics: what is the sensitivity for finding manifestations of new physics?
- Characterisation of new physics: once we have found something new, how well can we determine its properties and find out what it actually is?

The discussions in the context of the European strategy update mainly focussed on a comparison of the limits that can be achieved with the different facilities

EWPO, top physics, flavour physics

- Complements Higgs physics and direct searches in probing the underlying physics
- High sensitivity to quantum effects of new physics
- Indirect reach up to high scales
- Patterns of deviations from the SM can point to particular classes of BSM models and provide information about the possible scale of new physics

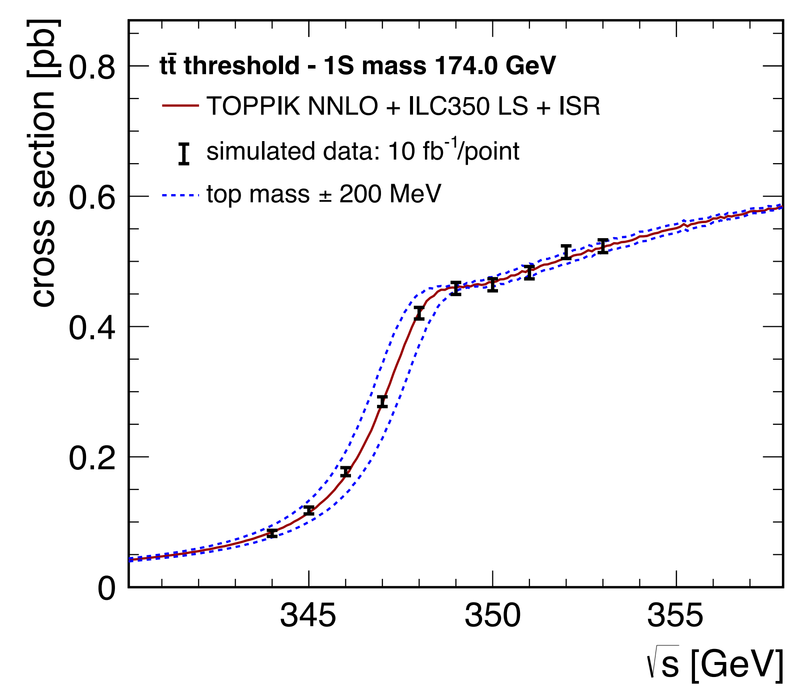
$\Rightarrow$ Improved precision from LC and results from dedicated experiments (low-energy experiments, flavour factories, etc.) will provide important information

Top-quark mass measurement at the top threshold

The top-quark mass is a crucial input parameter entering comparisons between experiment and theory either directly or via quantum effects.

At the LHC top quarks are produced with high statistics. The measurement of the top-quark mass, however, is affected by a rather large systematic uncertainty in relating the measured quantity (which is a ``Monte Carlo mass”) to a theoretically well-defined top-quark mass. Large efforts are currently made at the LHC with the goal to improve on this situation.

At an e^+e^- collider a ``threshold mass” will be measured with an unprecedented precision of about 50 MeV. It is theoretically well-defined and can be translated into the top-quark mass value used in theoretical predictions at the same level of accuracy.



Top couplings: sensitivity to new physics

[P. Roloff '18]

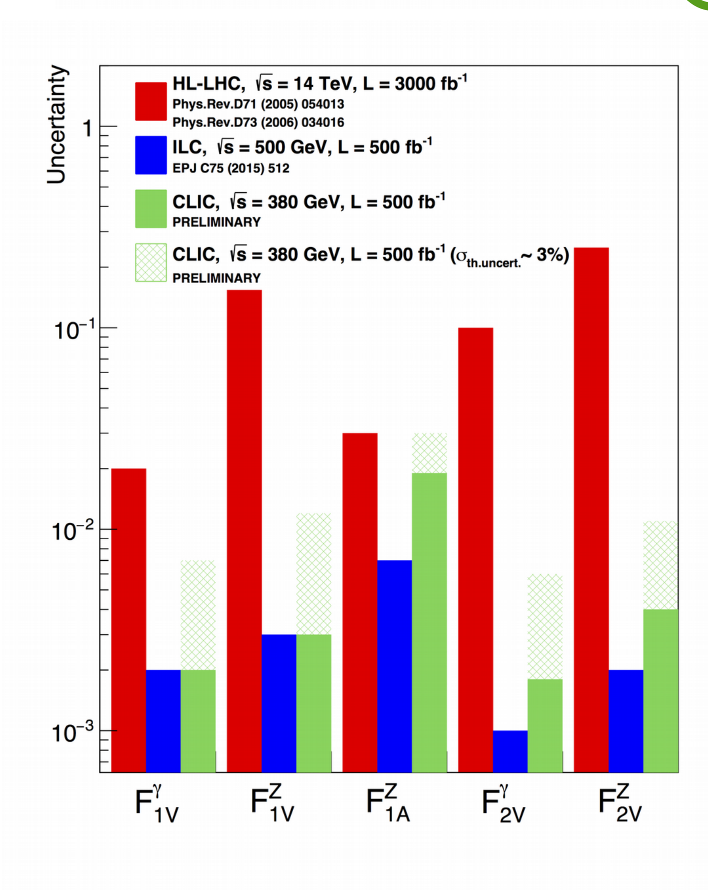
Top electroweak couplings

- Top quark pairs are produced via Z/γ* in electron-positron collisions
- The general form of the coupling can be described as:

arXiv:hep-ph/0601112

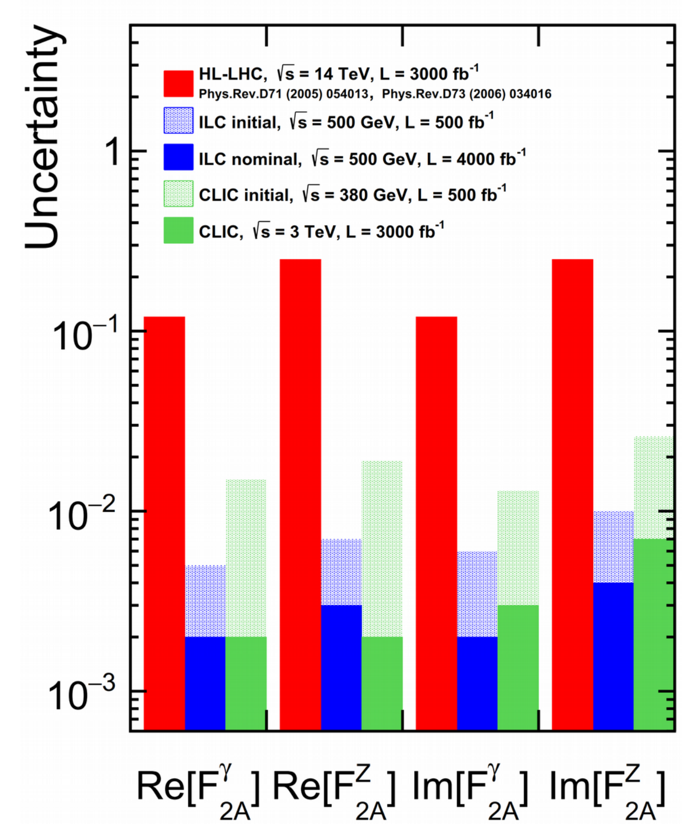
CP conserving — CPV

$$\Gamma_\mu^{ttV}(k^2,\, q,\, \bar{q}) = -ie\left\{\gamma_\mu\ \left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}\ (q+\bar{q})^\nu\ \left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$



CERN-2016-004

- New physics would modify the $t\bar{t}V$ vertex
- CLIC typically 1-2 orders of magnitude better than HL-LHC

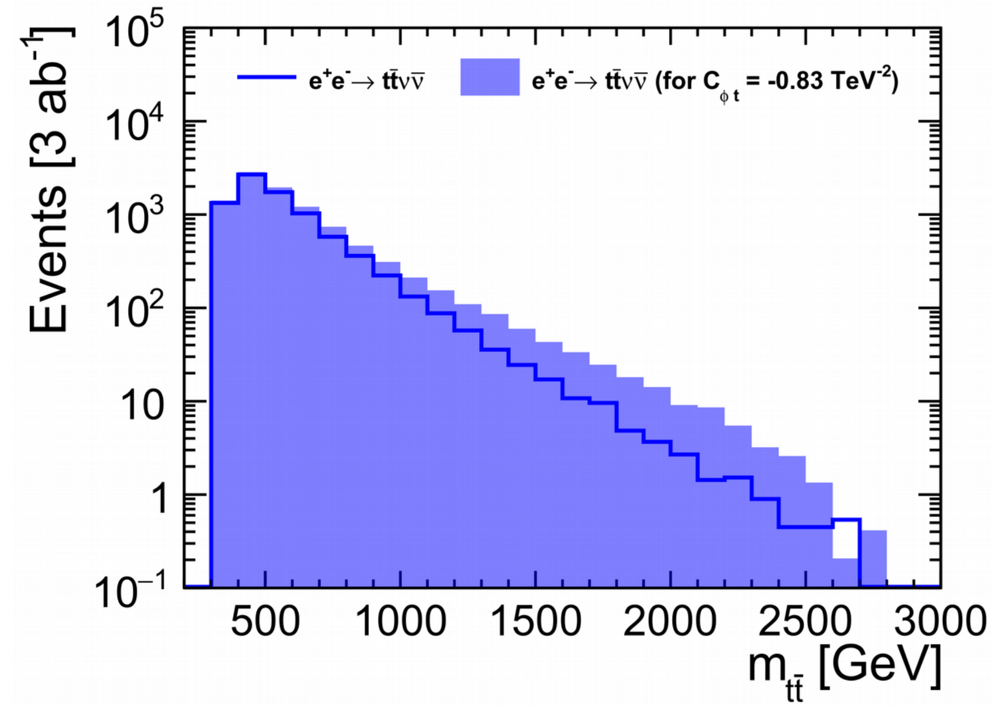


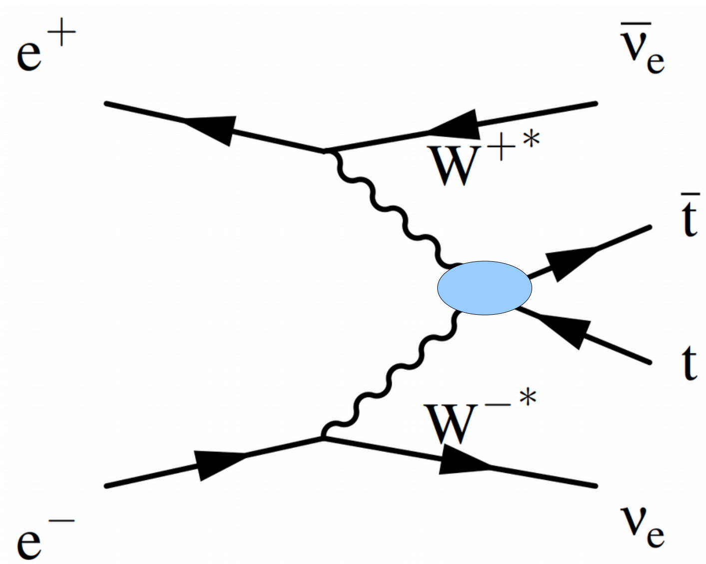
Eur. Phys. J. C 78, 155 (2018)

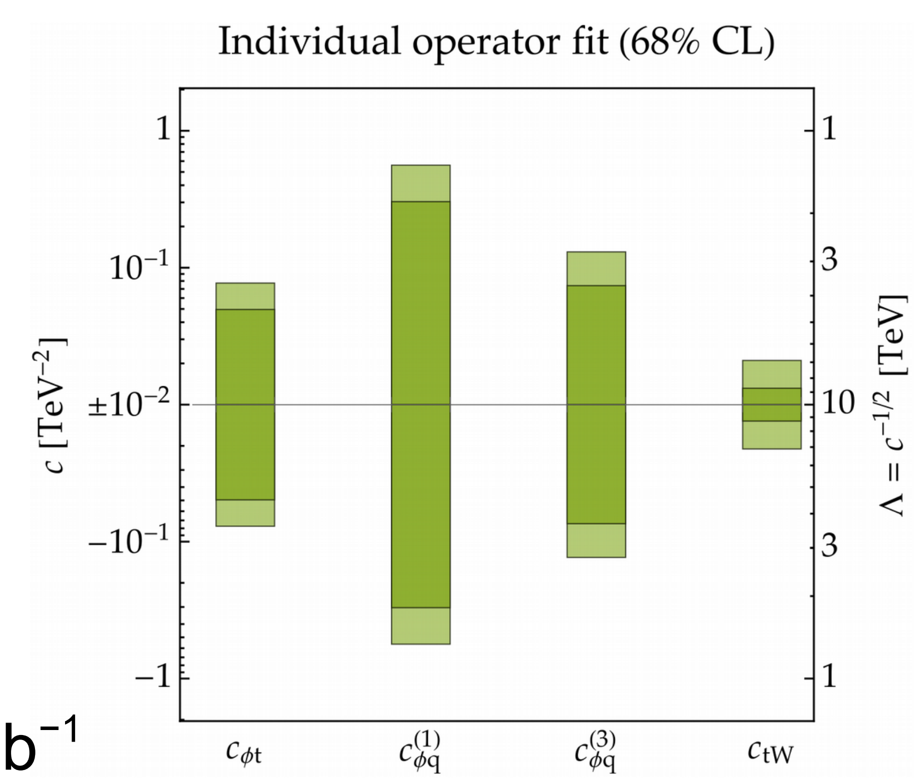
Higher energies (CLIC): weak boson fusion processes

[P. Roloff '18]

- Generator-level study and EFT interpretation
- Contributions of considered operators grow quadratically with energy
- Potential high-energy probe of the top Yukawa coupling





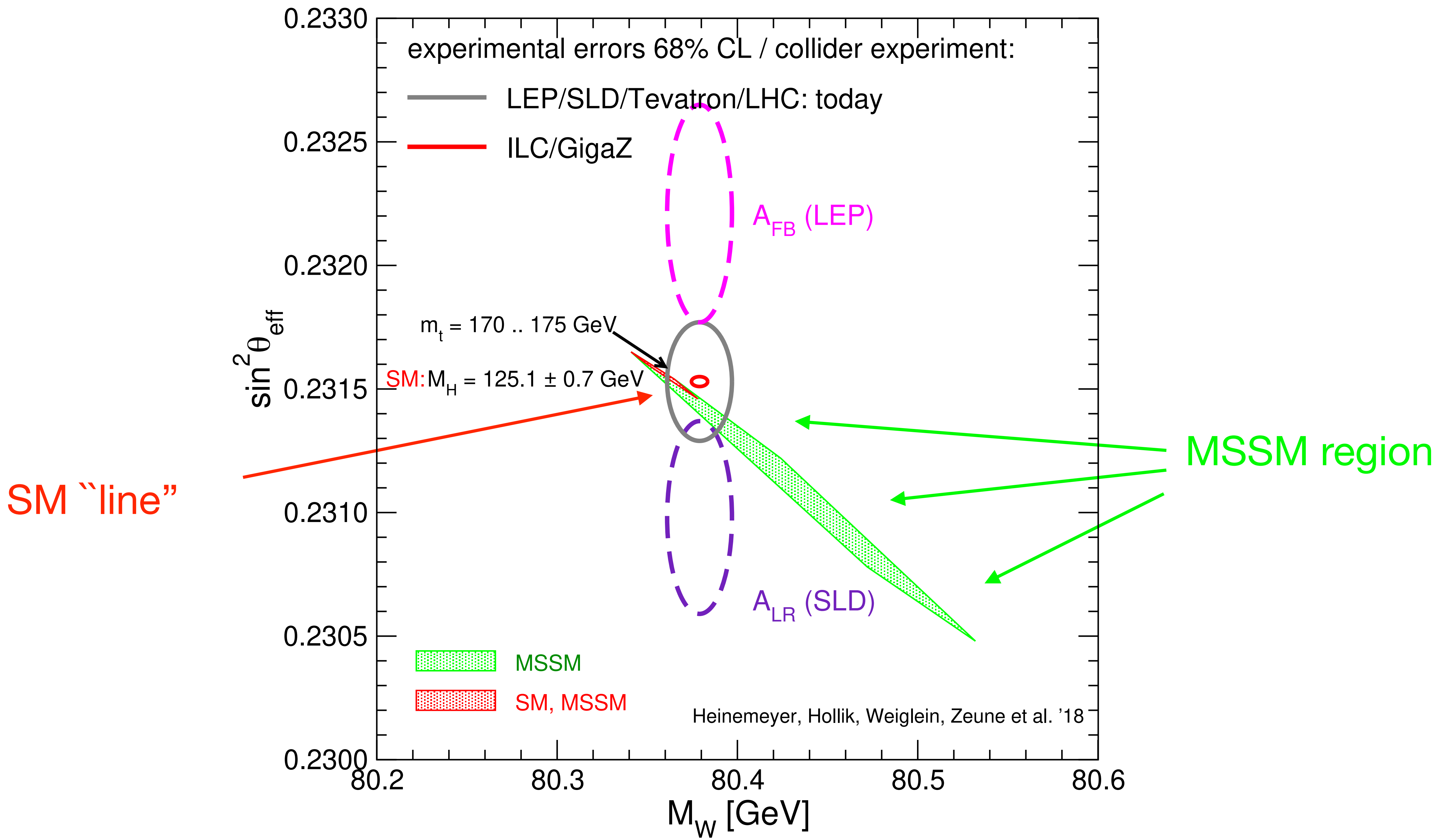


Grojean, You, Wulzer, Zhang

$\sqrt{s}$ = 3 TeV, L = 3 ab^{-1}

Electroweak precision physics: Prediction for M_W and $\sin^2\theta_{eff}$ in SM and MSSM vs. exp. accuracies

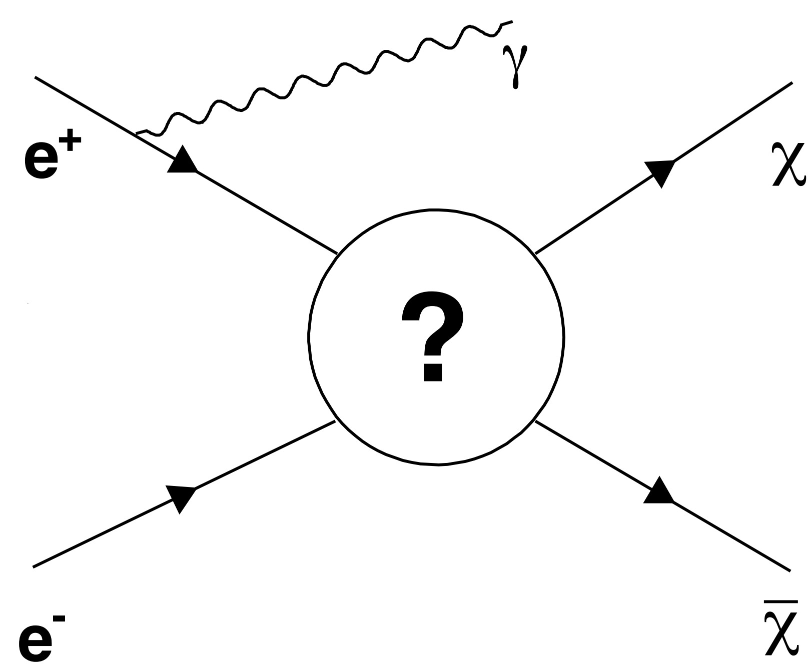
[S. Heinemeyer, W. Hollik, G. W., L. Zeune '18]



⇒ M_W and $\sin^2\theta_{eff}$ have high sensitivity for model discrimination

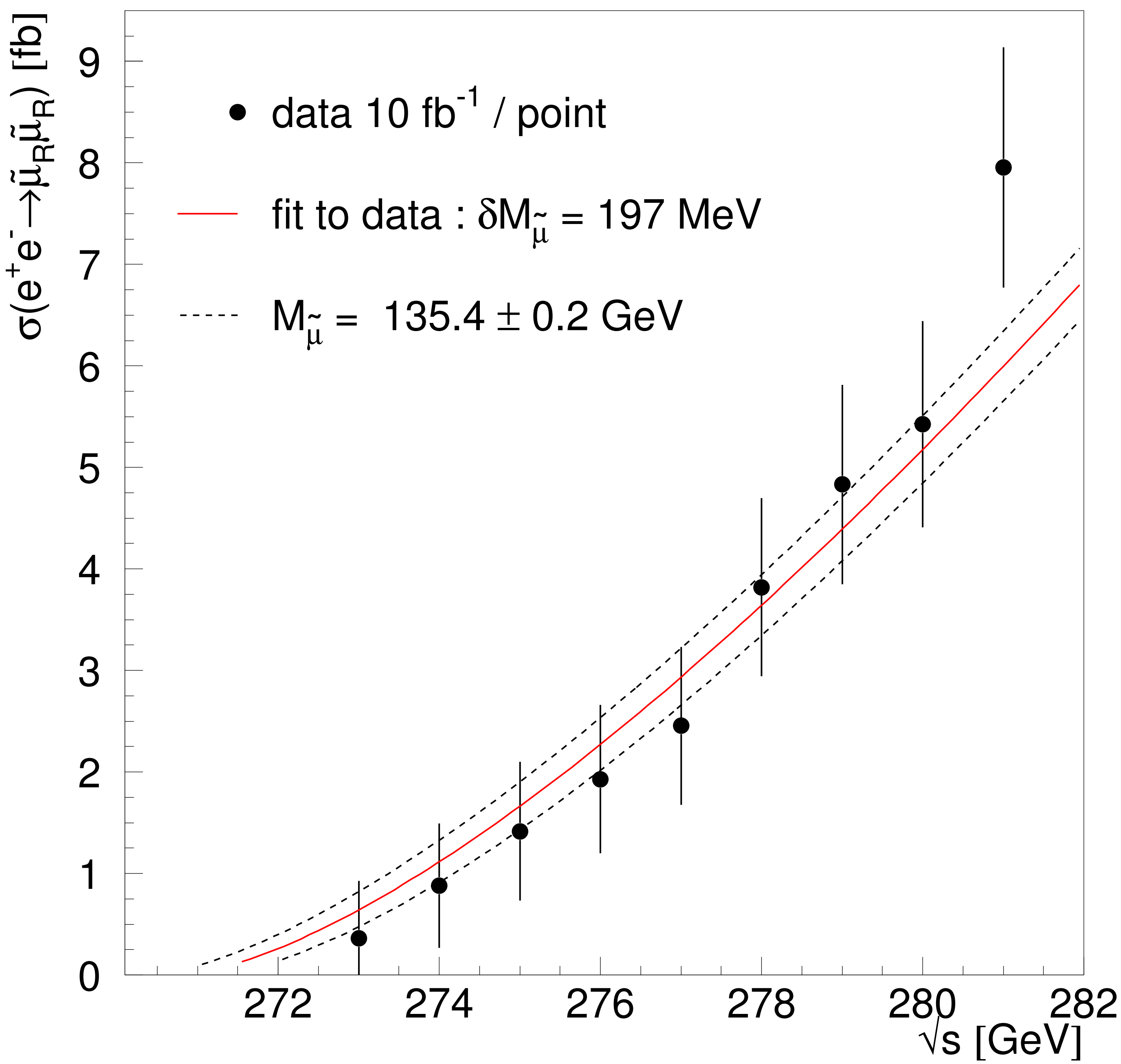
LC physics programme beyond 250 GeV

Searches for new particles:
A LC with 500 GeV or more will have an improved sensitivity in particular in the searches for dark matter and new weakly interacting particles, which is complementary to the sensitivity of the HL-LHC.



Electroweak physics:
The higher collider energy increases the sensitivity to effects from new physics (see the example above).

Example: scalar muon production at the ILC



⇒ Determination of mass and spin of the new particle

Direct searches for new particles at CLIC

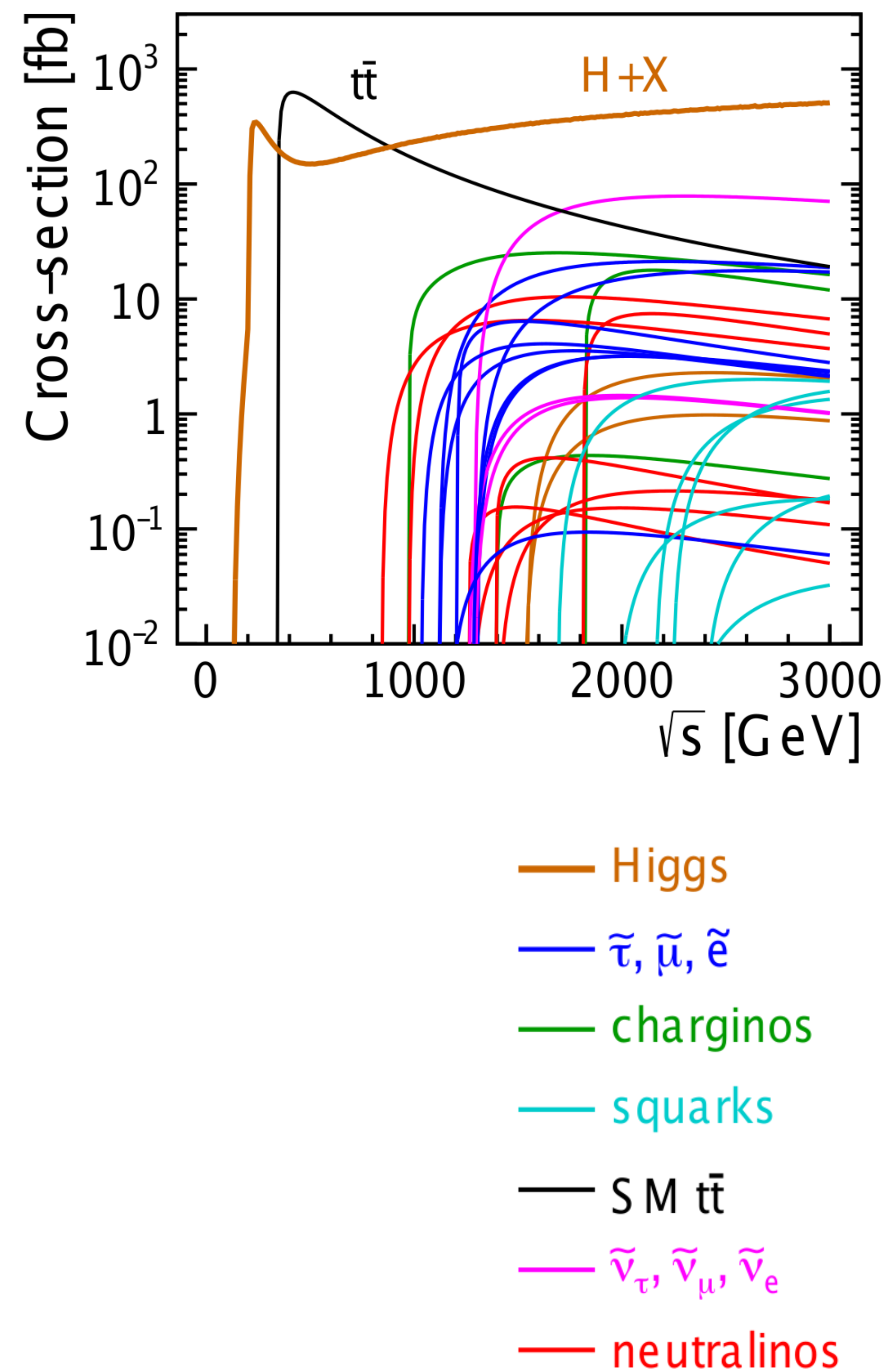
[P. Roloff '18]

- Direct observation of new particles coupling to γ*/Z/W
→ precision measurement of new particle masses and couplings

- The sensitivity often extends up to the kinematic limit (e.g. $M \leq \sqrt{s}\,/\,2$ for pair production)

- Very rare processes accessible due to low backgrounds (no QCD)
→ CLIC especially suitable for electroweak states

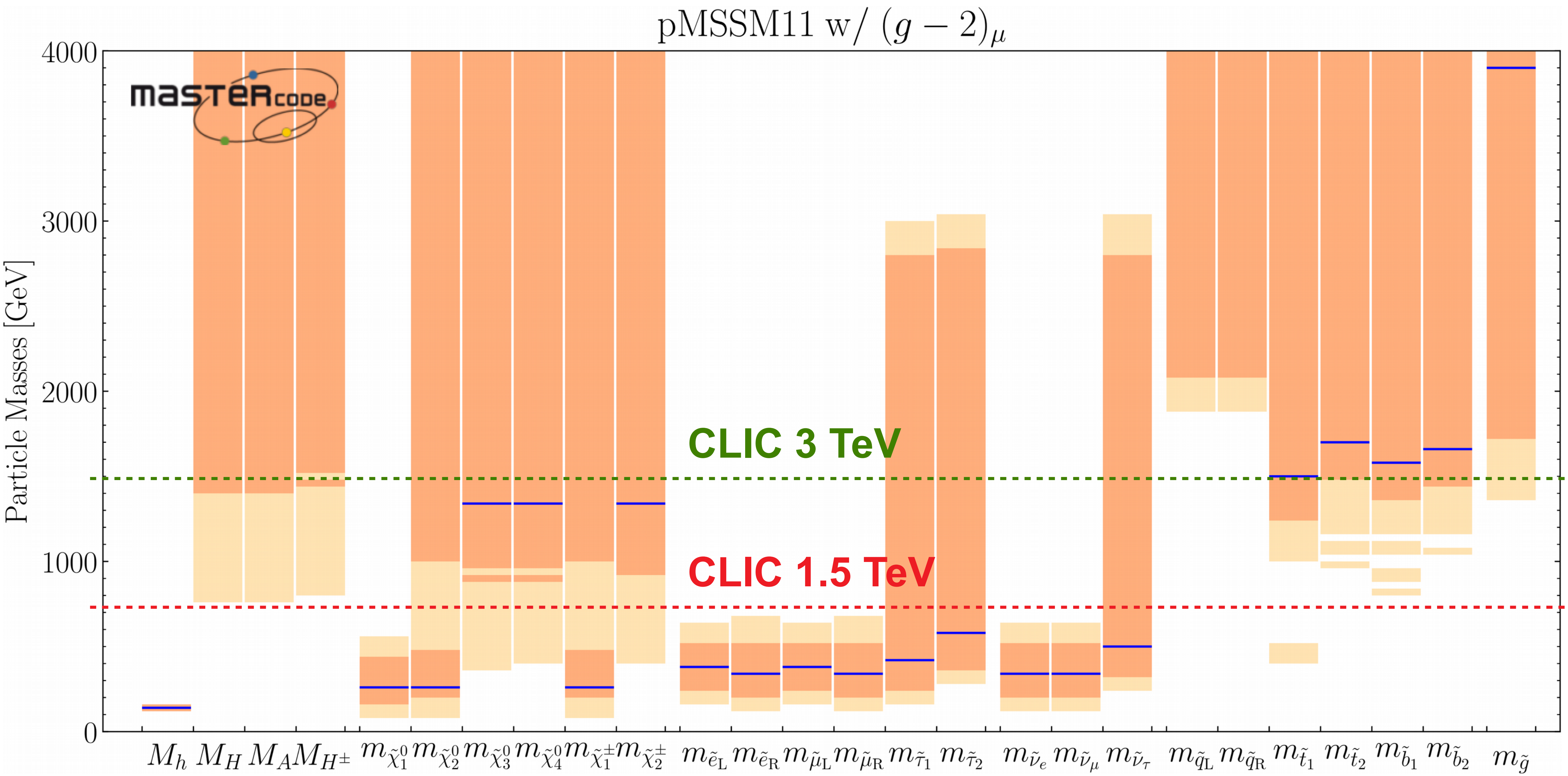
- Polarised electron beam and threshold scans might be useful to constrain the underlying theory



Comparison with SUSY fit

[P. Roloff '18]

Example: Phenomenological MSSM with 11 parameters



arXiv:1710.11091

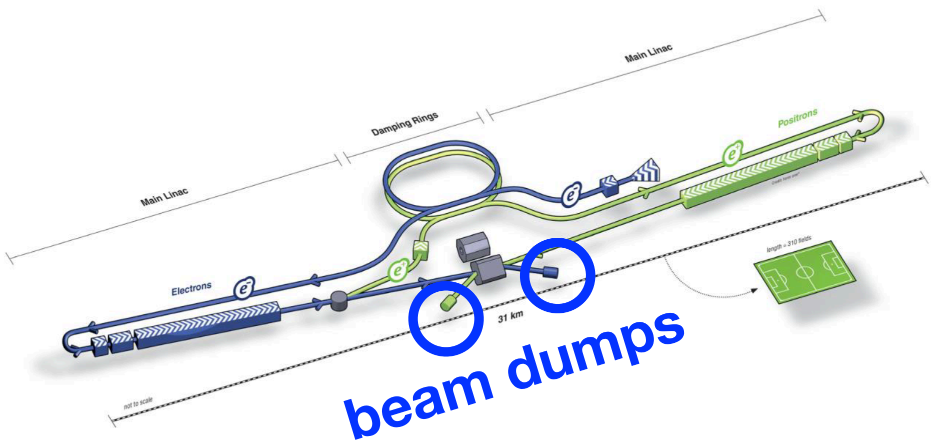
Further experimental opportunities at a LC facility

- Beam dump experiments
- Fixed-target experiments
- Detectors near the interaction point
- …

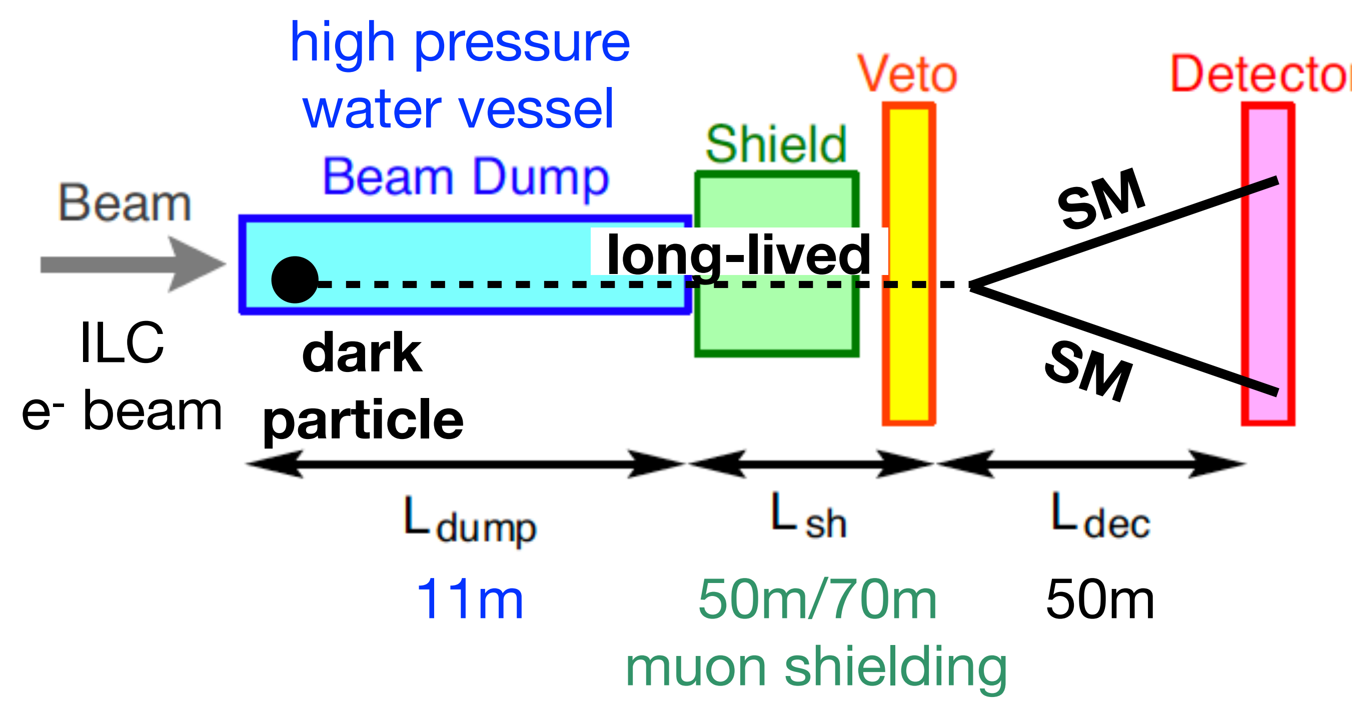
Beam dump experiments at a Linear Collider

[S. Gori '20]

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)

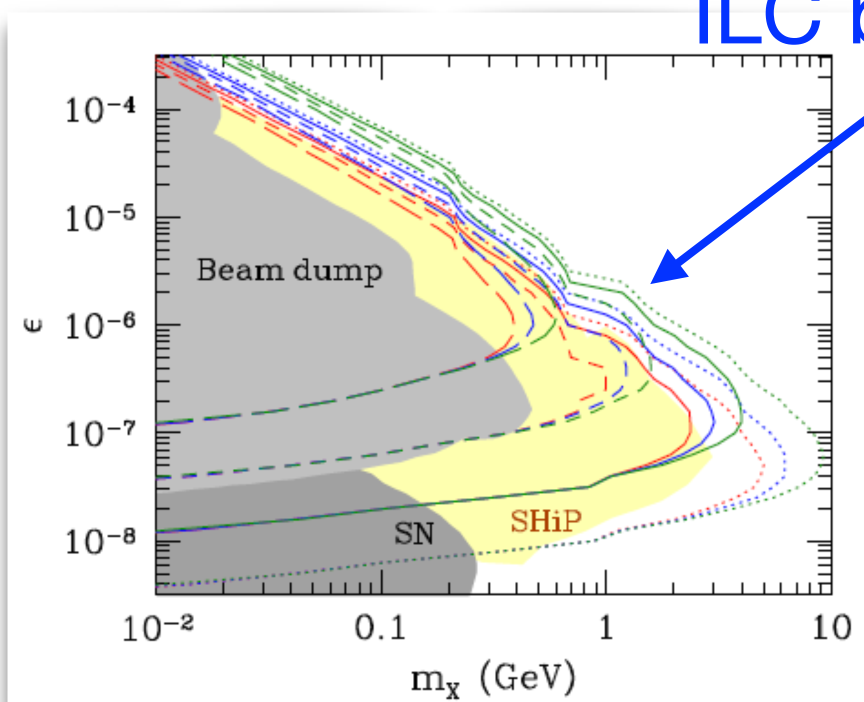
- **Very high luminosities**: ~$4*10^{21}$ electrons on target (EOT)/year compared to
- E137 @ SLAC: ~$2*10^{20}$ EOT
- HPS @ JLAB: ~10^{18} EOT

Dark photon searches via beam dump experiments

[S. Gori '20]

Complementarity with other experiments

ILC beam dump

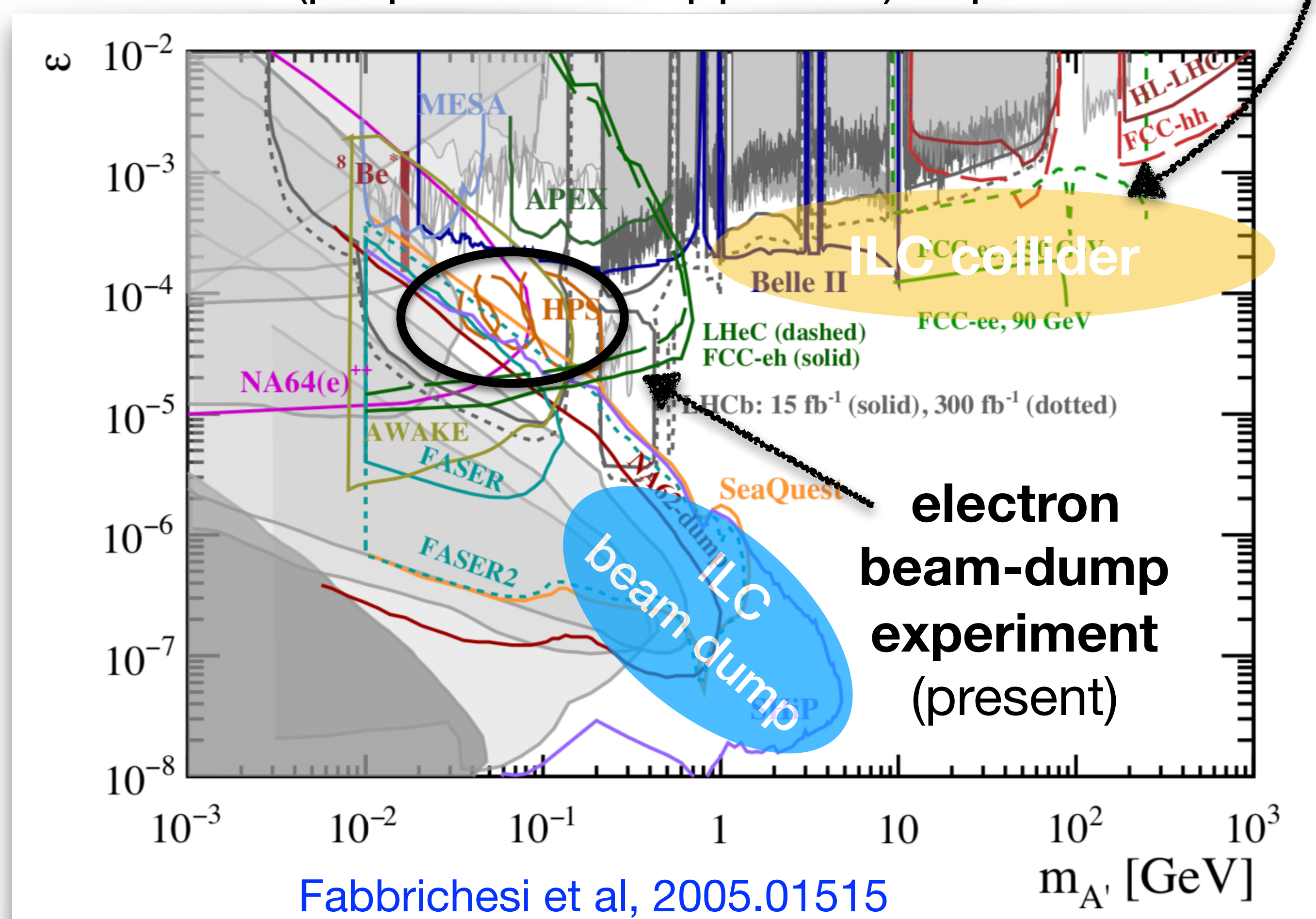


Kanemura et al.,1507.02809

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

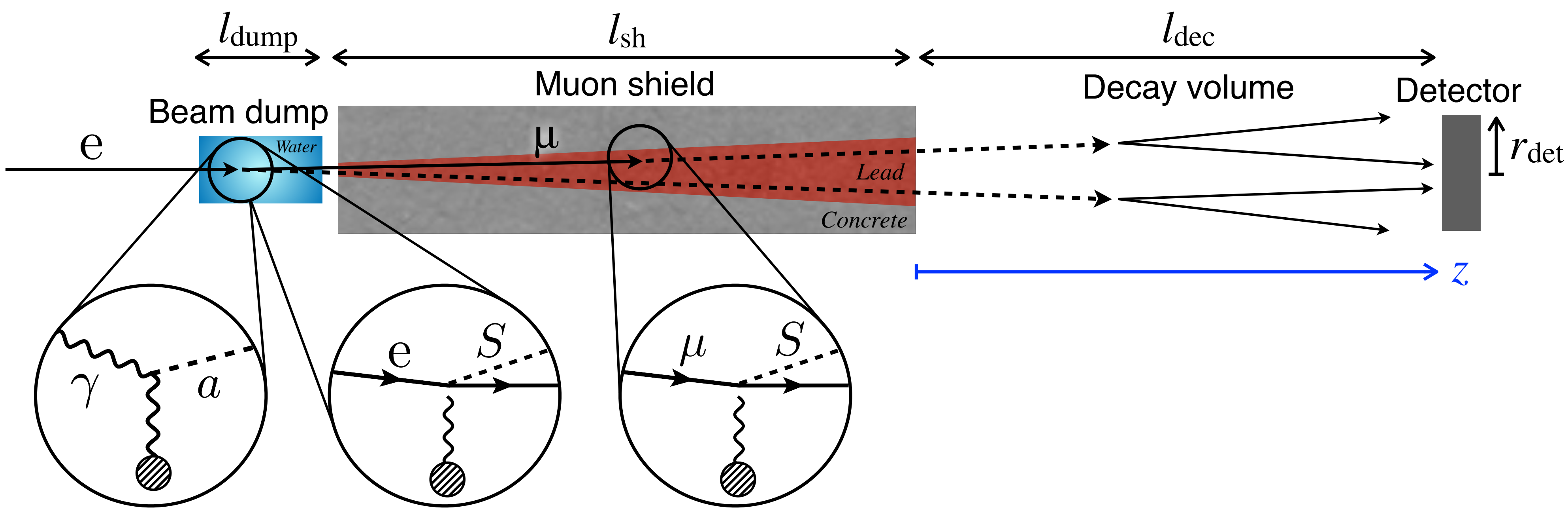
Few references:

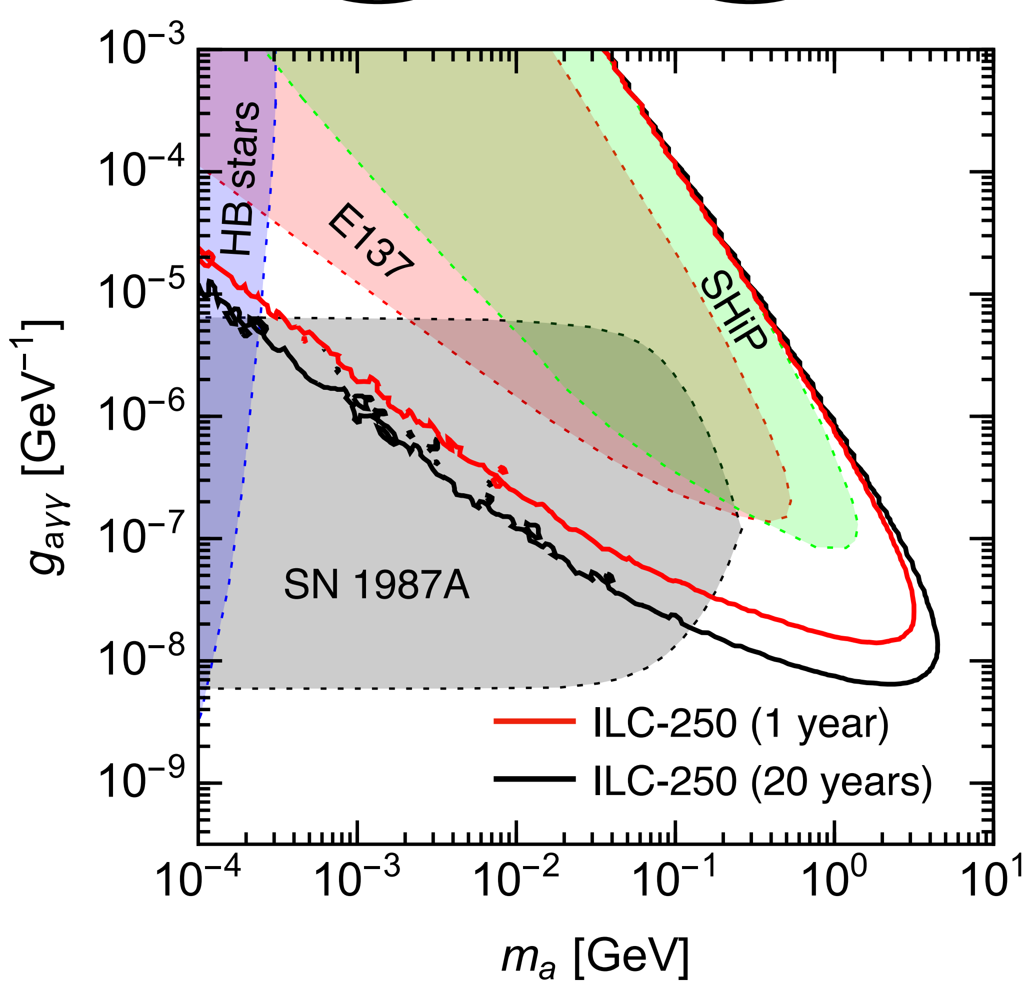
- SeaQuest: Berlin, SG, Schuster, Toro, 1804.00661
- FCC: Karliner et al., 1503.07209
- SHiP: Alekhin et al., 1504.04855
- FASER: Feng et al., 1708.09389

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

Search for axion-like particles with LC beam dump

[Y. Sakaki, D. Ueda '20]





⇒ Large improvements over other beam dump experiments in the small coupling region

Conclusions

The discovery of a Higgs boson has provided us with a window to the mechanism of electroweak symmetry breaking and the structure of the vacuum.

An e^+e^- Higgs factory is ideally suited for exploring the detected signal with the highest precision and it will provide a very high sensitivity to direct and indirect effects of new physics.

An e^+e^- collider, including its programme at higher c.m. energies of direct and indirect searches for new states, has a great physics potential and will be crucial for addressing the most profound questions of our field.

Backup

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