Appendix

A. What is Higgs physics about and why are we interested in it?

The ILC at 250 GeV is a ``Higgs factory", i.e. a facility with a great potential for doing Higgs physics.

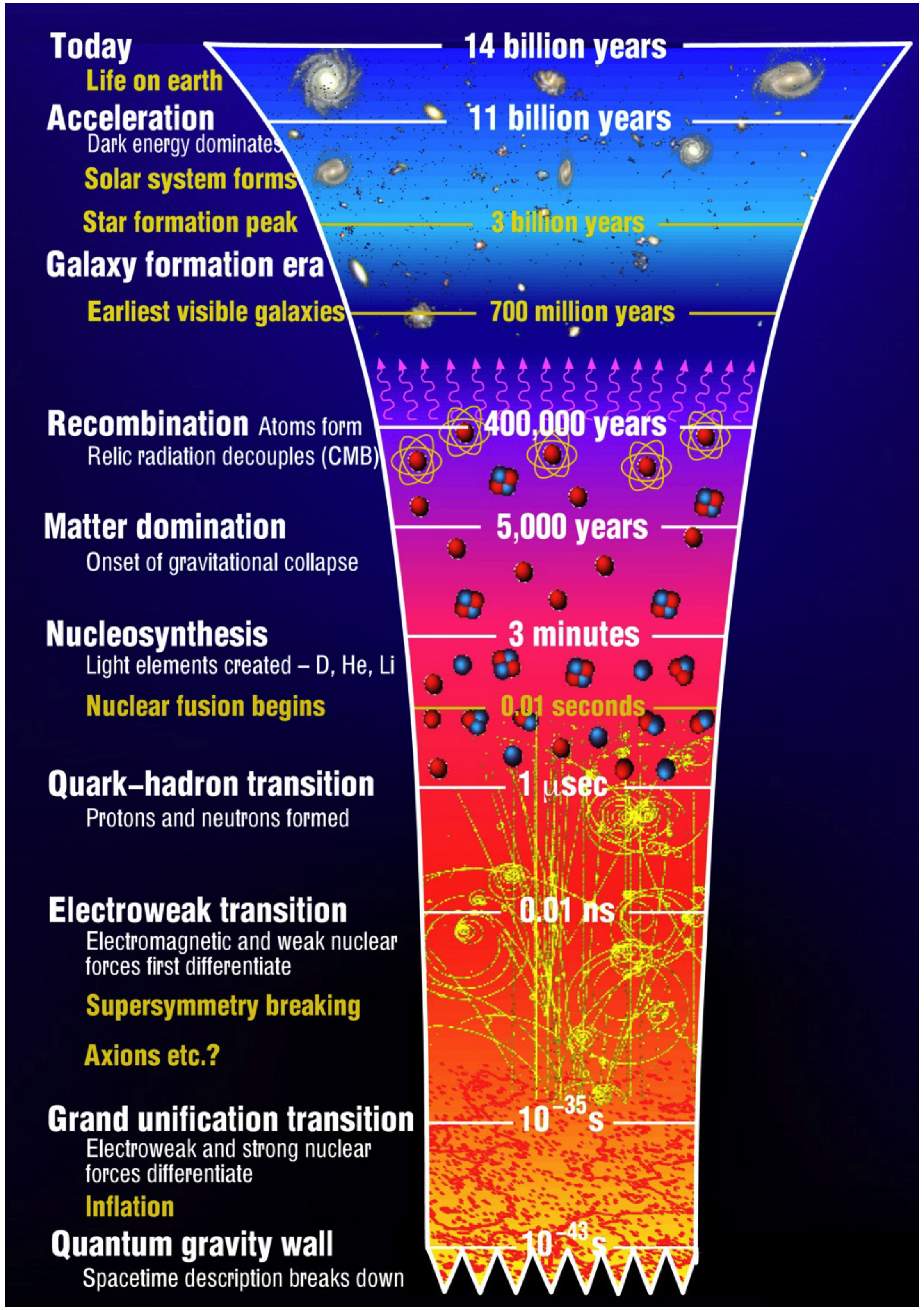
Why is this important?

- The ``electroweak phase transition" in the early Universe
- The origin of mass of elementary particles
- Relation to the imbalance between matter and antimatter in the Universe?
- Connection to the ``dark sector" of the Universe?

Study of Higgs physics provides information about the “electroweak phase transition” in the early Universe

History of the Universe:

Particle colliders produce energy densities as they existed just after the Big Bang
⇒ Information about the early Universe



← Now: 14 billion years after the Big Bang

← 0.0000000001 s after the Big Bang

The origin of mass of elementary particles

The successful description of the known interactions (= forces) of nature arises from fundamental symmetries that we call ``gauge symmetries”.

It was realised already several decades ago that masses of elementary particles seem to violate those fundamental symmetries.

This led to the idea that the interactions respect the fundamental symmetries but not the state of lowest energy, which is called the vacuum.

Such a situation is called ``spontaneous symmetry breaking” and sounds very complicated.

But it frequently happens in nature and is much simpler than it sounds.

An example of spontaneous symmetry breaking

The standing pencil is in a state which is symmetric with respect to rotations along its axis.

But this is not the state of lowest energy. The pencil will fall over into a particular direction. This breaks the symmetry.

We believe that the same as for the pencil also happened in the early Universe when it cooled down after the Big Bang.

Nature had to choose one particular state of lowest energy, the ``vacuum” state, that breaks the gauge symmetry.

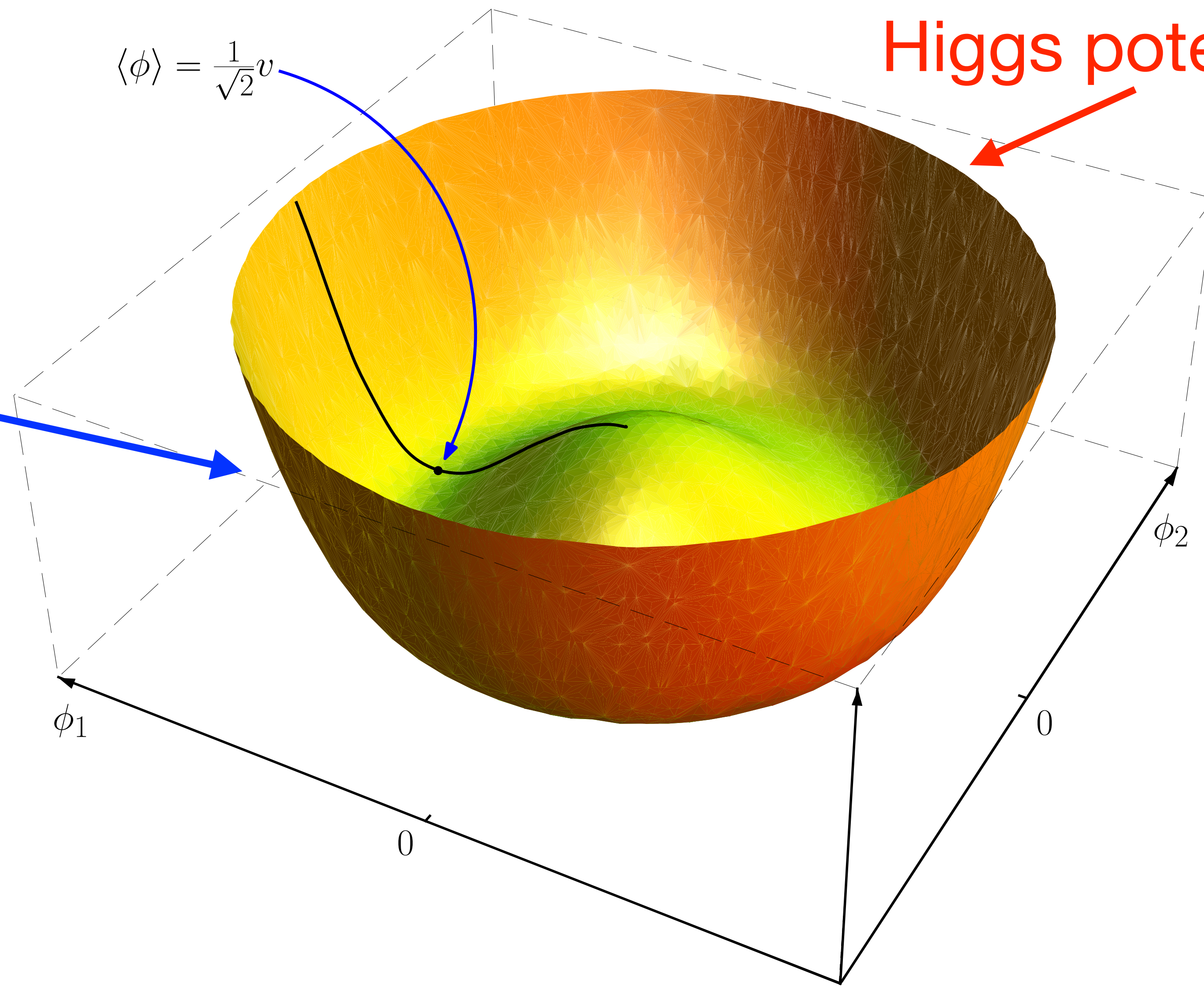
The Higgs-boson field was postulated by Brout, Englert and Higgs in 1964 in order to enable such a spontaneous symmetry breaking.

The vacuum state of the Universe arises from the ``Higgs potential” formed by the Higgs field.

The Higgs discovery confirms this idea

The vacuum has a non-trivial structure arising from a ``Higgs potential”

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



Higgs potential

Prediction: the mass of every elementary particle is proportional to the fundamental constant v and to the coupling of the Higgs boson to this particle.

The puzzle of the Higgs mass

The mass of the discovered new particle, $M_\mathrm{H} \approx 125$ 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. $M_\mathrm{Planck} \approx 100000000000000000\ M_\mathrm{weak}$

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?

Possible explanations:

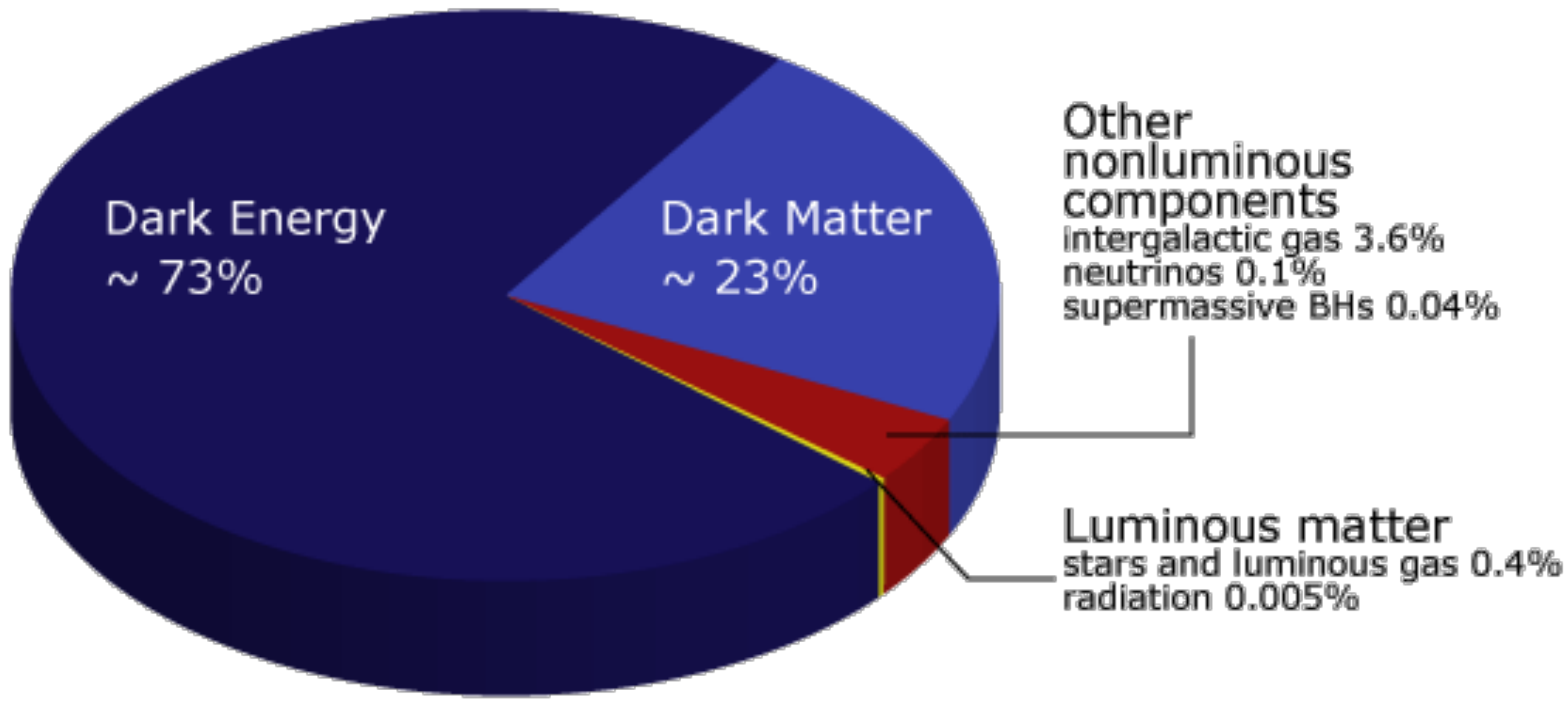
- A new symmetry of nature $\longrightarrow$ Supersymmetry?
- A new fundamental interaction of nature $\longrightarrow$ composite Higgs?
- Extra dimensions of space $\longrightarrow$ impact on gravity at small scales?
- Multiverses $\longrightarrow$ anthropic principle?

What do we need to know?

- In order to understand the underlying physics of the Higgs boson we need to determine its properties as precisely as possible.
- This refers in particular to the couplings of the Higgs boson to other particles, which are at the foundation of our ideas about the origin of mass of elementary particles.
- These measurements can reveal whether the Higgs boson is an elementary particle or whether it has a substructure of more fundamental particles. The latter possibility would resemble the ``Cooper pairs" of the case of superconductivity.
- They also provide information on whether there is just a single Higgs or whether there are further Higgs bosons.
- They may also reveal the origin of the imbalance between matter and anti-matter in the Universe and tell us about the relation between the electroweak phase transition and the phase of inflation in the early Universe.

The Higgs boson: a portal to the ``dark sector" of the Universe?

We don't know what the ``dark sector" of the Universe (dark matter and dark energy) is made of, which accounts for 96% of the Universe.



Dark matter interacts at most very weakly with the known ordinary matter. The Higgs boson(s) can act as a ``mediator" between the visible and the dark sector.
Higgs decays into dark matter particles would give rise to an ``invisible" decay mode (``missing energy" signature).

B. More details on the physics programme of the ILC at 250 GeV

Comparison:

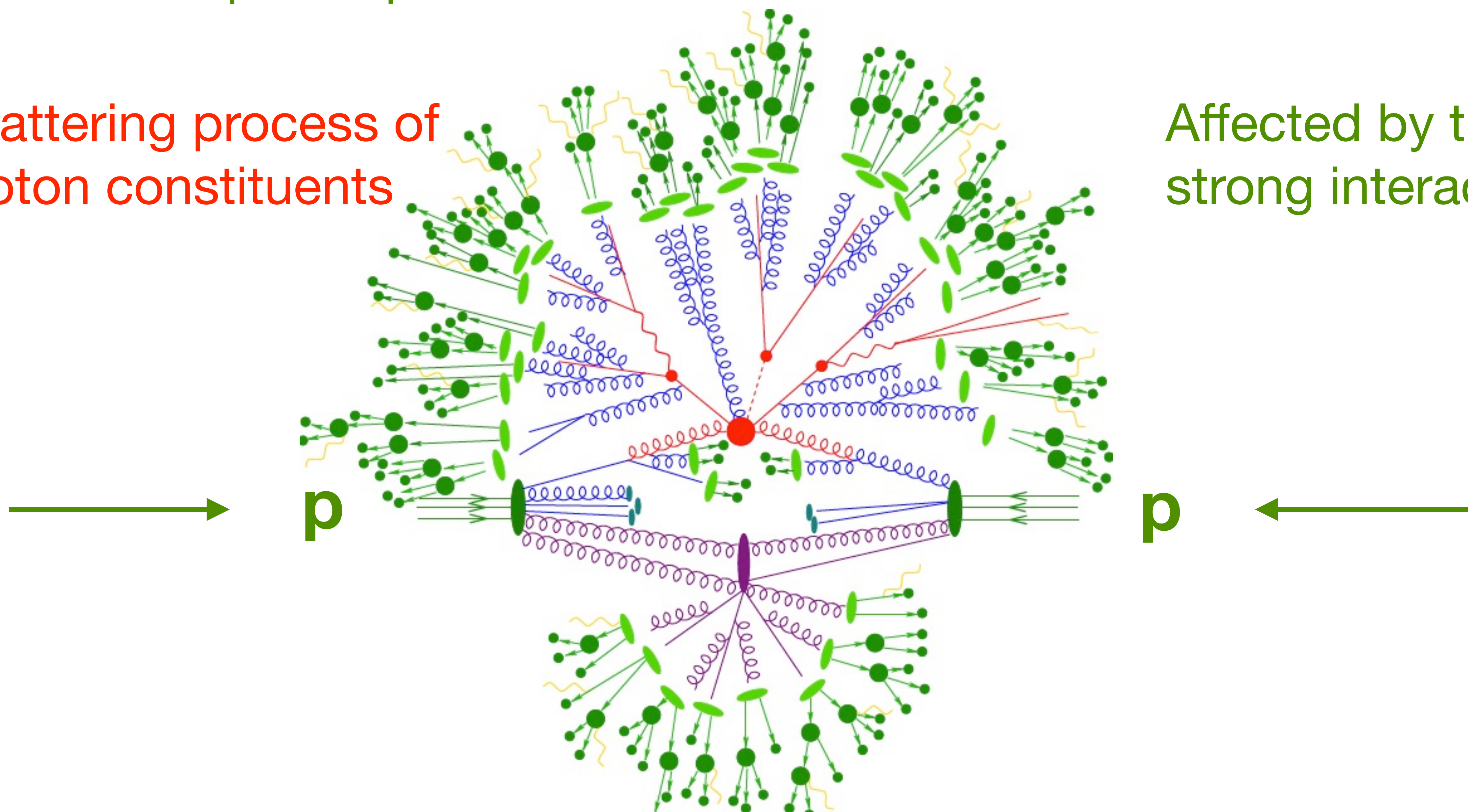
Experimental environments of the LHC (proton-proton scattering) and the ILC (electron-positron scattering)

LHC: proton-proton (pp) scattering

Proton: composite particle

Scattering process of proton constituents

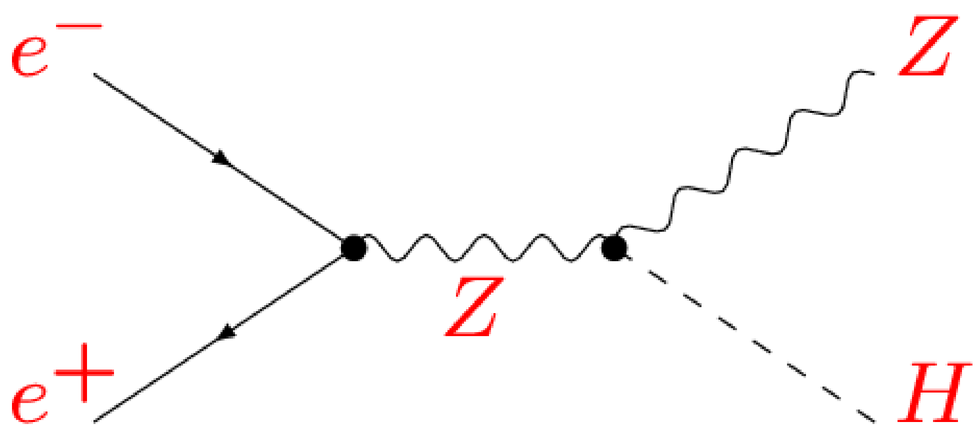
Affected by the strong interaction



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")

ILC: 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

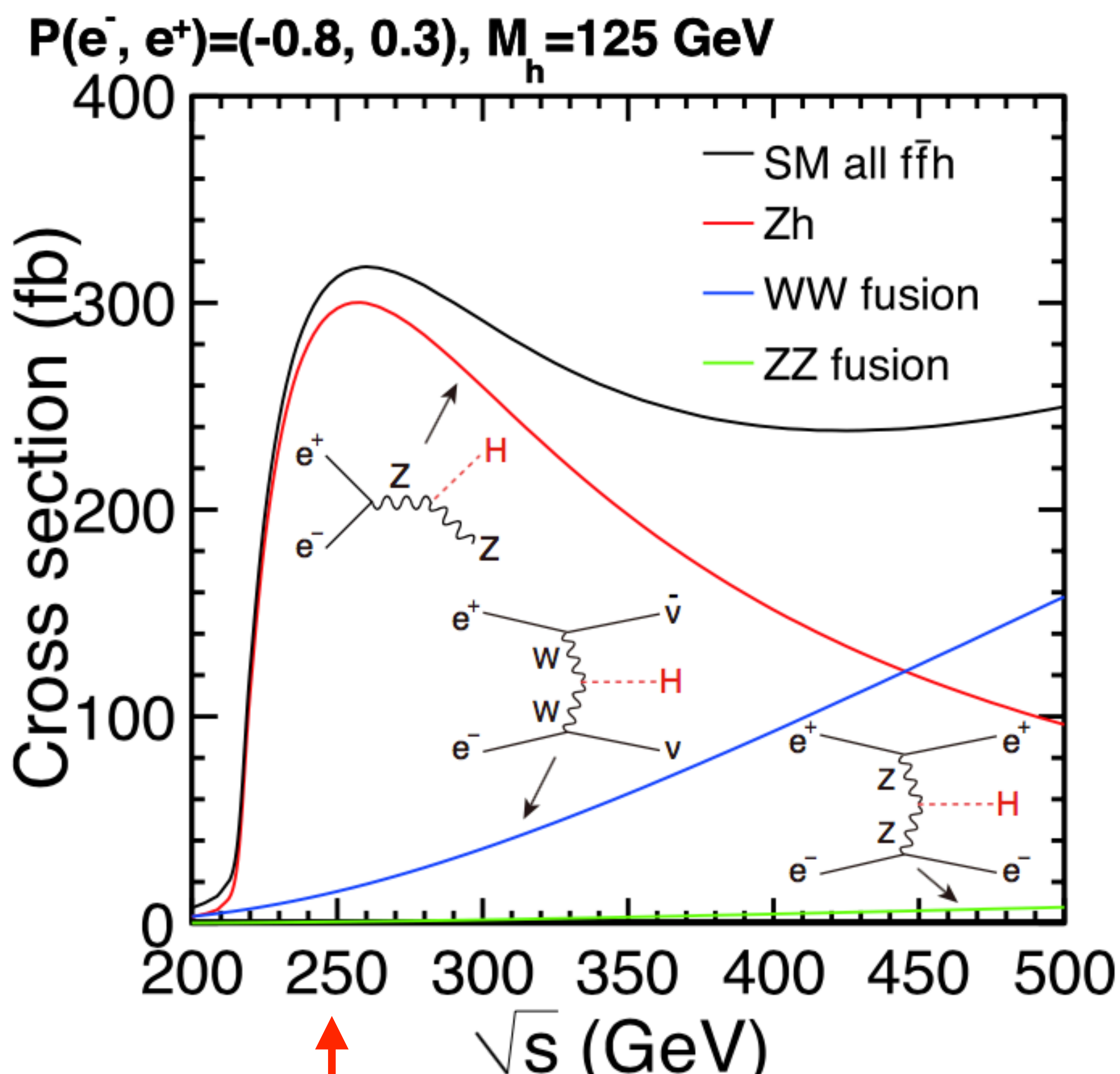
High-precision physics

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

250 GeV is the energy at which the largest number of Higgs and Z bosons will be produced

Higgs production cross section as function of the ILC collision energy:

The number of produced Higgs bosons is obtained from the cross section times the luminosity



~500 000 produced Higgs bosons for a luminosity of 2 ab^{-1}

ILC at 250 GeV is a “Higgs factory”

Impact of beam polarisation at ILC 250

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 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

ILC 250 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

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: 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

Coupling determination: comparison with the LHC

Problem at the LHC: no absolute measurement of the production cross sections (no recoil method)

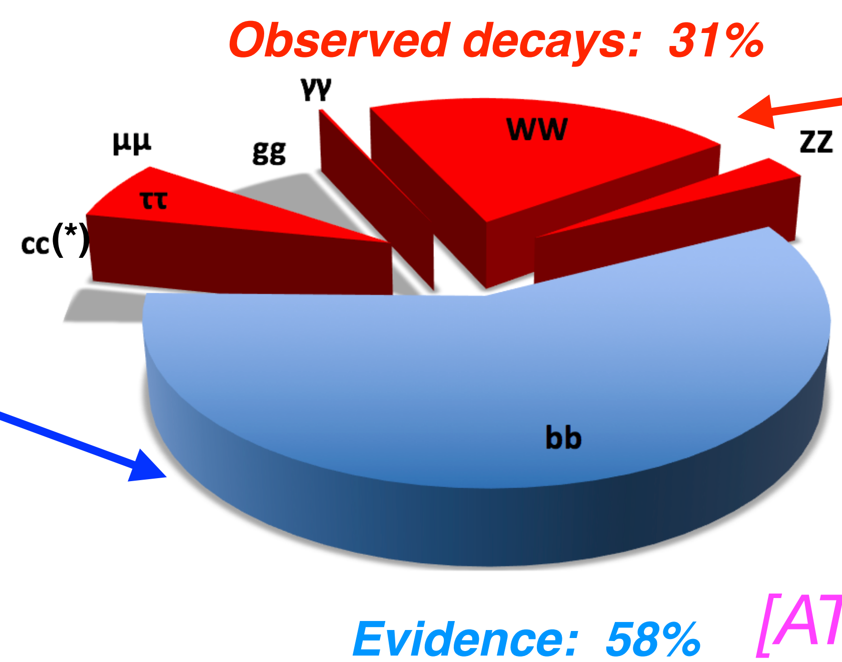
(Production) x (decay) at the LHC yields combinations of Higgs couplings ($\Gamma_{\mathrm{prod,\,decay}} \sim g^2_{\mathrm{prod,\,decay}}$):

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

The total Higgs width cannot be determined without further assumptions at the LHC

Current status at LHC:

Even the dominant decay of a SM-like Higgs into bb is not firmly established yet



Observed decays: WW, ZZ, $\tau\tau$, $\gamma\gamma$

Evidences:
ATLAS: 3.6 σ, CMS: 3.8 σ

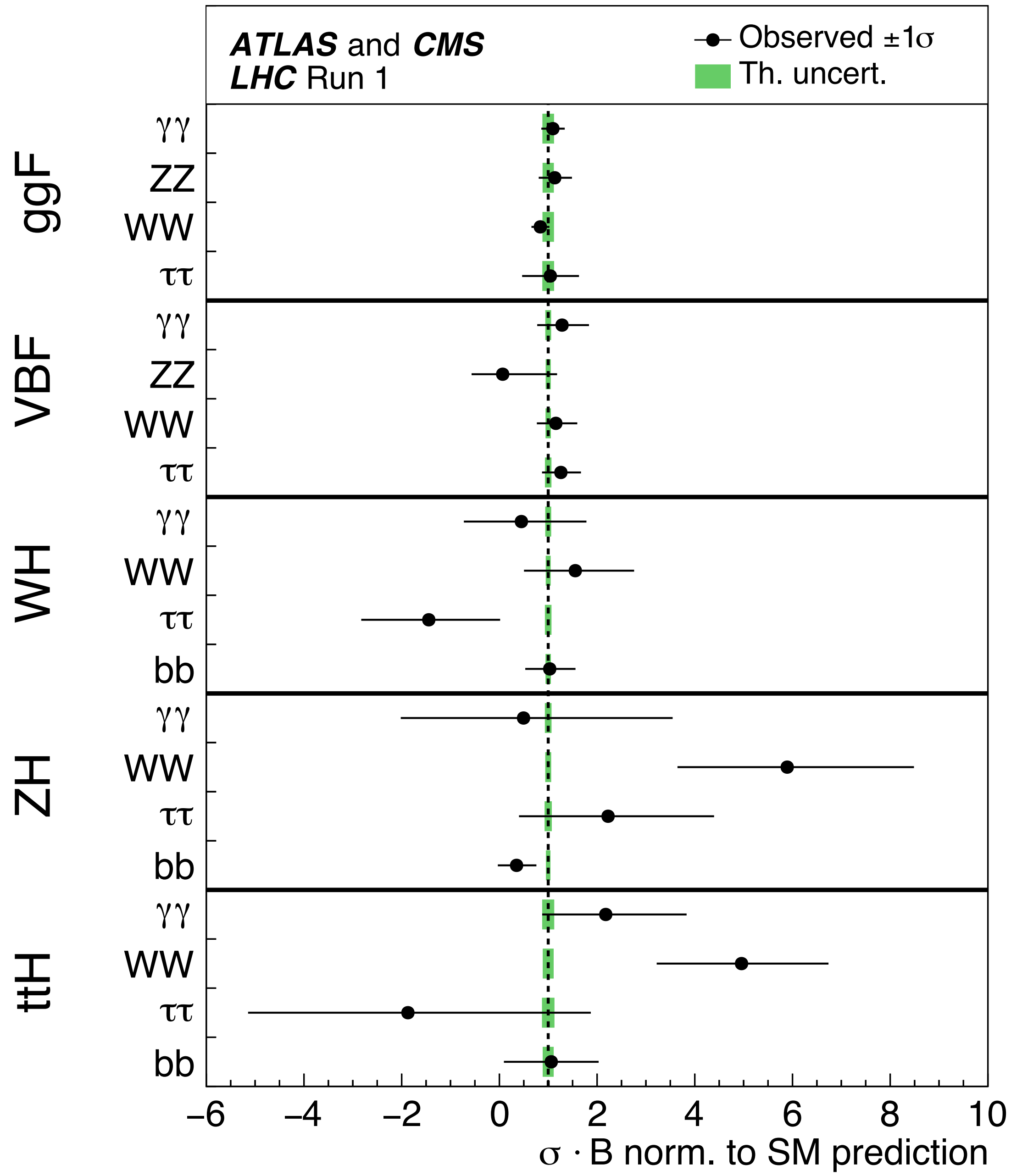
[ATLAS, CMS Collaborations '17]

Signal strengths from LHC Run 1: ATLAS + CMS

Signal strength:

$$\mu = \frac{\sigma \times Br}{(\sigma \times Br)_{SM}}$$

Indicates deviations from the SM predictions



[ATLAS and CMS Collaborations '16, Run 1 combination]

Note: the scale extends from -600% to +1000%!

Measurements of cross sections times branching rations normalised to the prediction of the Standard Model

Uncertainties in most channels are large

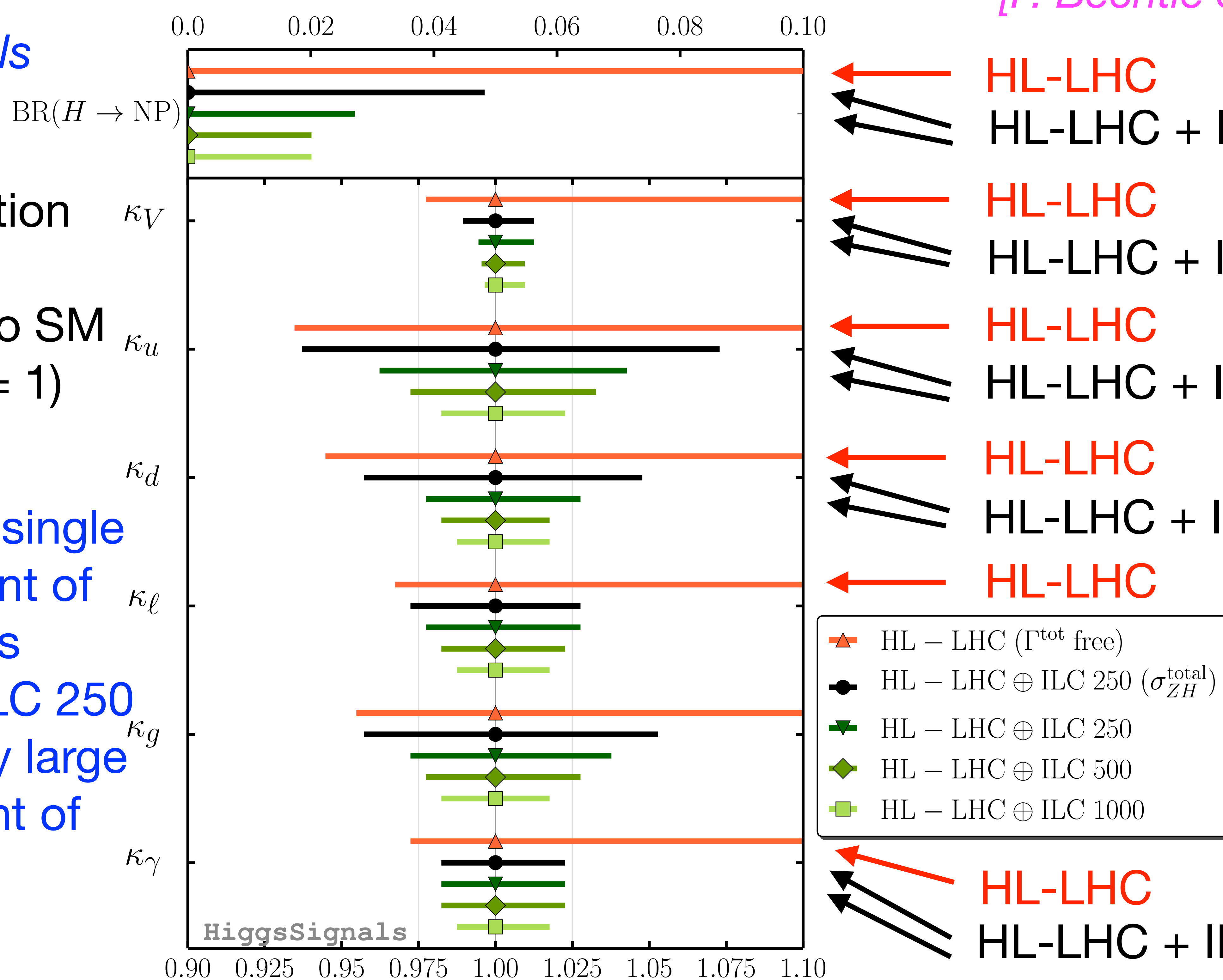
Projections for HL-LHC and ILC, no additional theory assumptions (ILC 250: only 250 fb^{-1})

[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

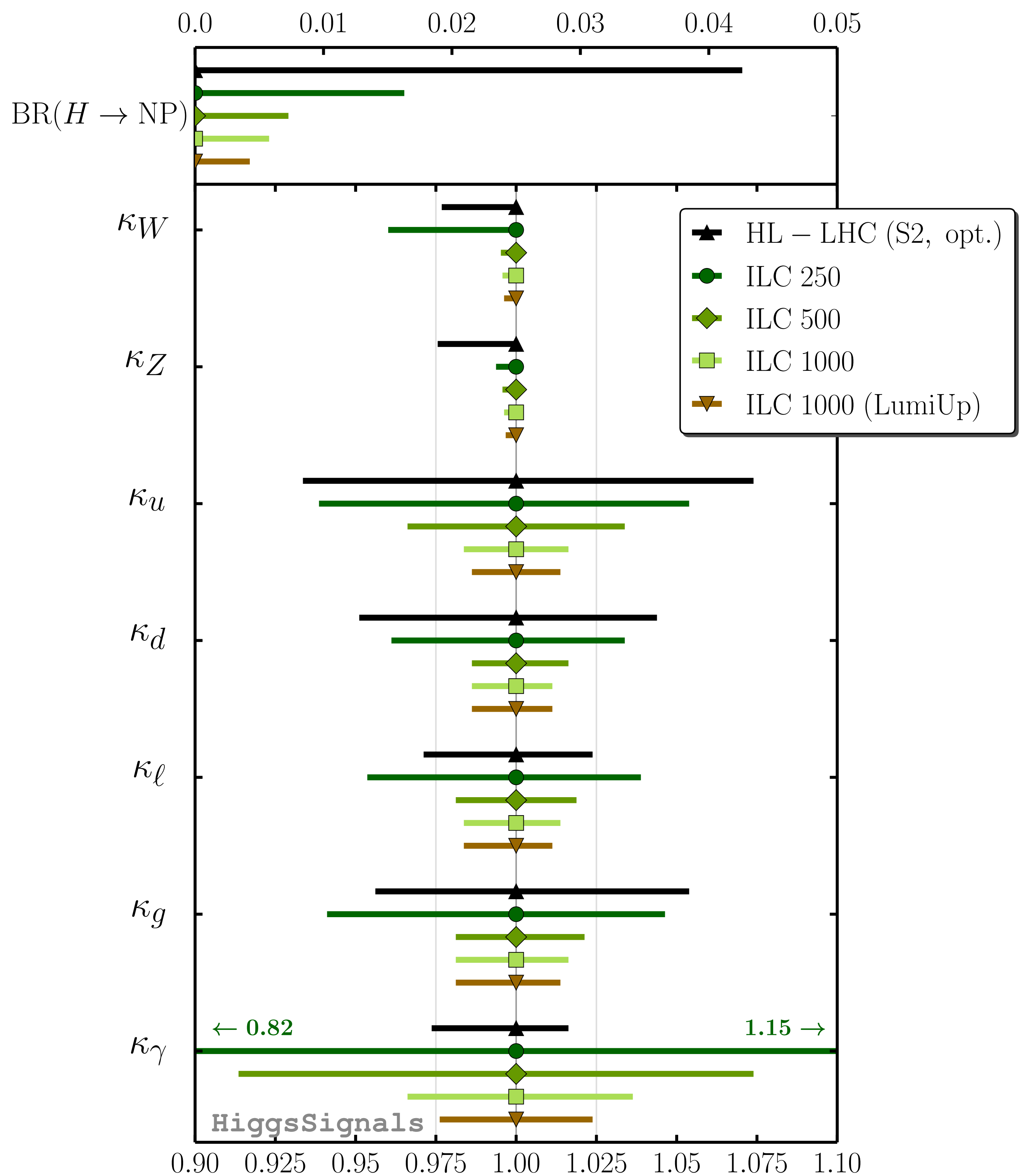
HL-LHC
HL-LHC + ILC 250

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

[P. Bechtle et al. '14]

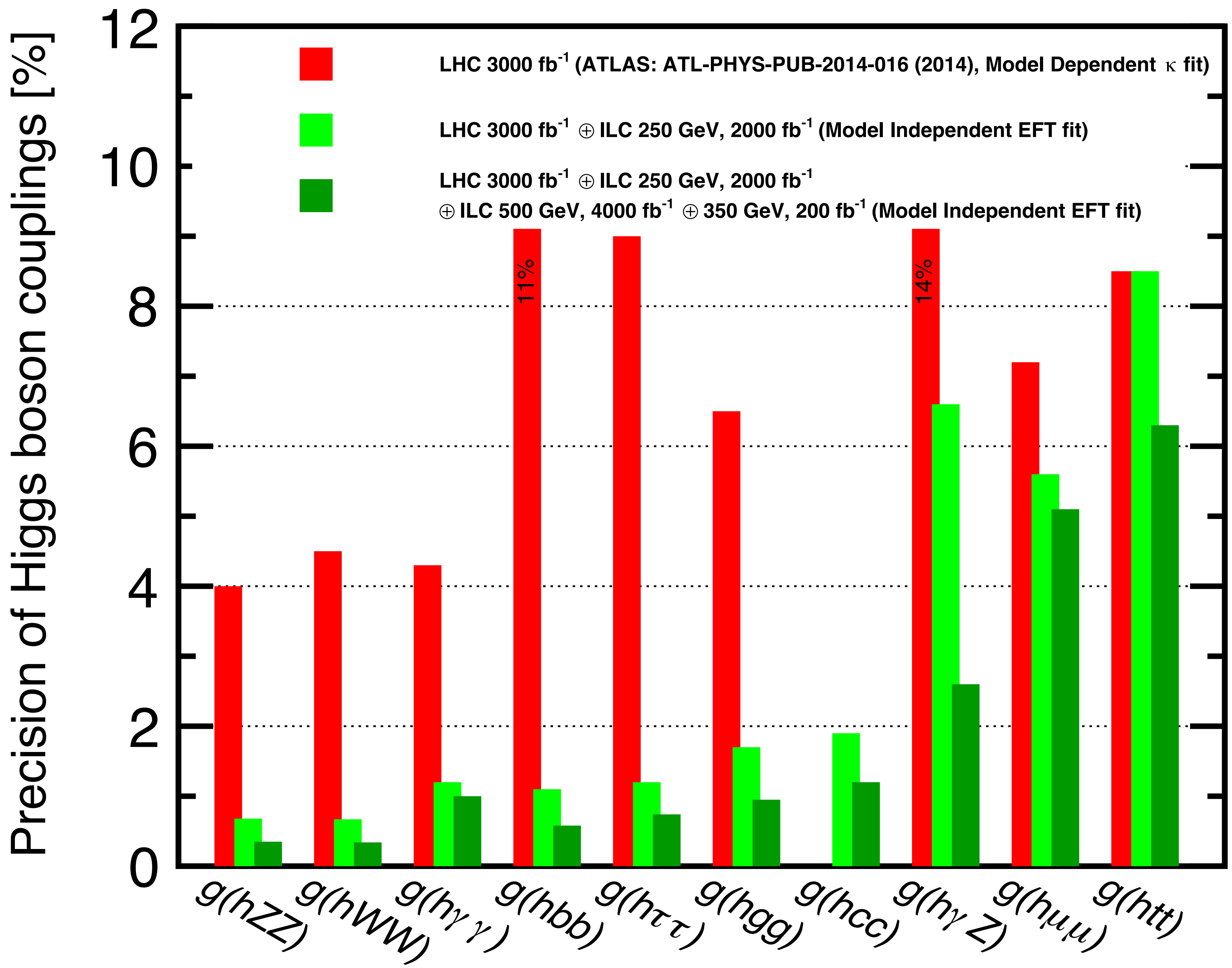
HiggsSignals

Assumed: $\kappa_V \leq 1$



Projections for HL-LHC, ILC 250 and ILC 500

[LCC Physics Working Group ’17]



HL-LHC

HL-LHC⊕ILC 250

HL-LHC⊕ILC 250 ⊕ILC 500

ILC 250: large quantitative + qualitative improvements over HL-LHC

Precision at the 1% level reachable for many couplings

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

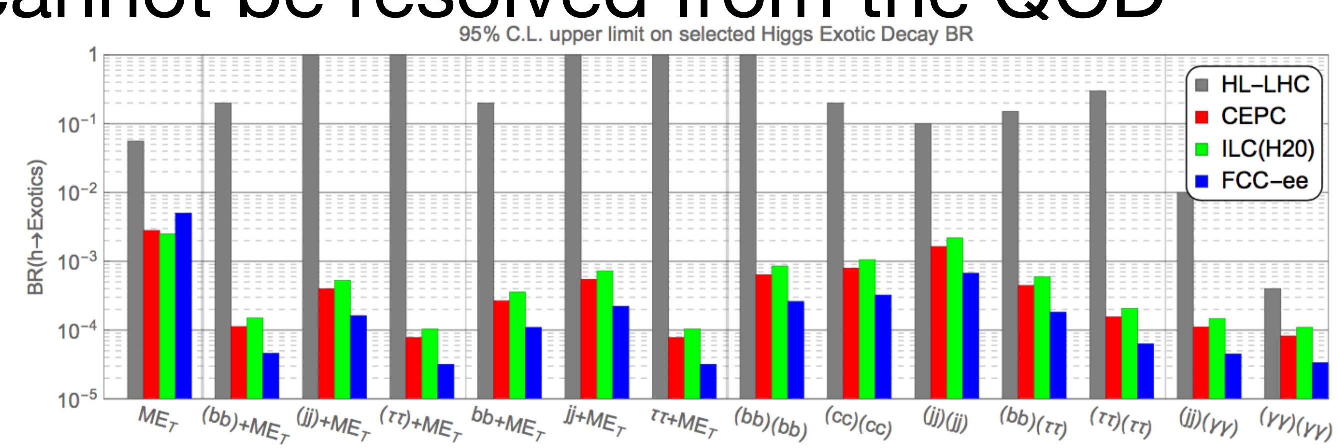
⇒ Discovery potential for dark matter and other new physics

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

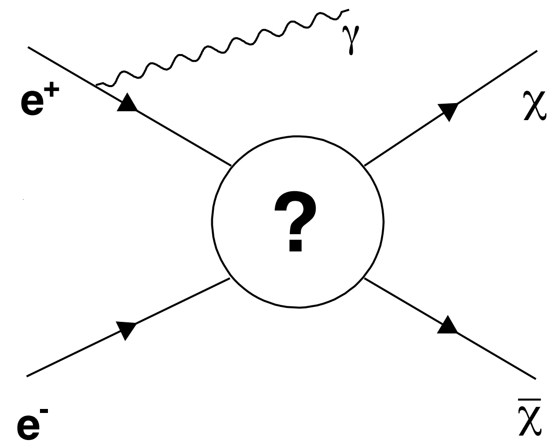
[Z. Liu, L.T. Wang, H. Zhang ’17]



Discovery potential of ILC 250 to the production of new particles

Example: dark matter

+ Higgs as mediator



yields complementary sensitivity to the LHC and to direct detection experiments

Example: one or more additional light Higgs boson(s)

In a large variety of models with extended Higgs sectors the squared couplings to gauge bosons add up to the coupling of the SM Higgs, i.e. the SM coupling strength is ``shared" between the Higgses of an extended Higgs sector (this ensures the correct high-energy behaviour of longitudinal gauge boson scattering). SM-like couplings of the state at 125 GeV imply suppressed couplings of the other Higgses to gauge bosons. The searches carried out so far at LEP, the Tevatron and the LHC hardly constrain additional light Higgs bosons with suppressed couplings to gauge bosons.

⇒ Large discovery potential for ILC 250!

Further examples of the physics programme of the ILC at 250 GeV

CP properties of the Higgs boson:

While the LHC measurements excluded the hypothesis that the detected Higgs boson is a pure CP-odd state, the limits on the possibility that it could be a mixture of CP-even and CP-odd components are very weak.
The ILC measurements could reveal the presence of CP-violation in the Higgs sector, which would have important implications for our understanding of the imbalance between matter and anti-matter in the Universe.

Electroweak physics:

Precision measurements of WW production and 2-fermion production are very sensitive probes of possible effects of new physics.

Backup

The quest for identifying the underlying physics

In general 2HDM-type models one expects % level deviations from the SM couplings for BSM particles in the TeV range, e.g.

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

⇒ Need very high precision for the couplings

Total Higgs width: recent analyses from CMS and ATLAS

- Exploit different dependence of on-peak and off-peak contributions on the total width in Higgs decays to $ZZ^{(*)}$

- CMS quote an upper bound of $\Gamma/\Gamma_{\mathrm{SM}} < 5.4$ at 95% C.L., where 8.0 was expected, ATLAS: $\Gamma/\Gamma_{\mathrm{SM}} < 5.7$ at 95% C.L., 8.5 expect.

  [CMS Collaboration '14] *[ATLAS Collaboration '14]*

- Problem: equality of on-shell and far off-shell couplings assumed; relation can be severely affected by new physics contributions, in particular via threshold effects (note: effects of this kind may be needed to give rise to a Higgs-boson width that differs from the SM one by the currently probed amount)

  [C. Englert, M. Spannowsky '14]

$\Rightarrow$ SM consistency test rather than model-independent bound

Destructive interference between Higgs- and gauge-boson contributions (unitarity cancellations) $\Rightarrow$ difficult to reach $\Gamma/\Gamma_{\mathrm{SM}} \approx 1$ even for high statistics

LC: constraints on the Higgs width via off-shell effects

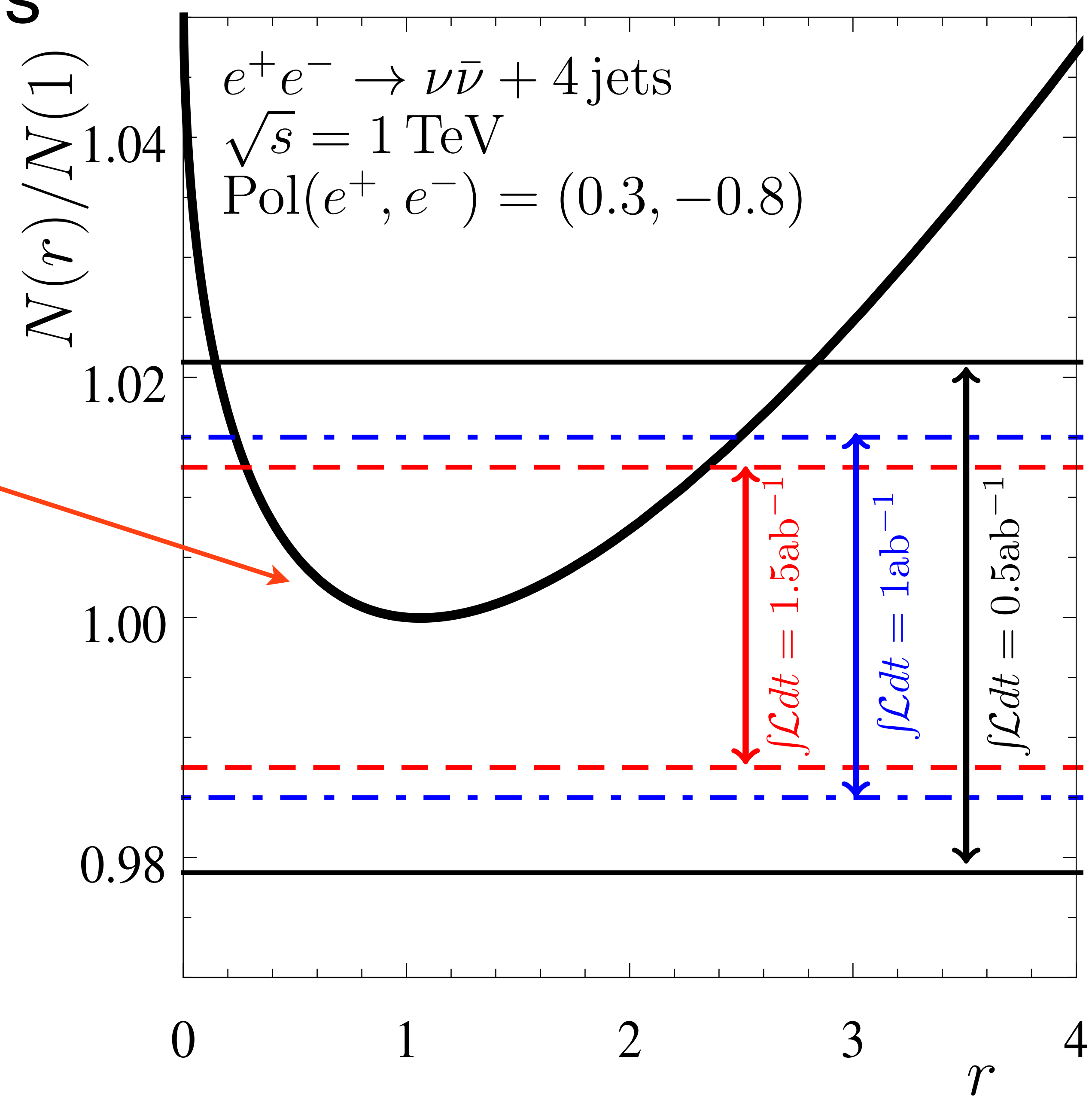
[S. Liebler et al. '15]

Same theoretical assumptions as in LHC analyses

Large negative signal - background interference
(reason: unitarity cancellations)

$$N(r) = N_0(1 + R_1\sqrt{r} + R_2 r)$$

$r = \Gamma/\Gamma_{\text{SM}}$



⇒ Limited sensitivity even with high integrated luminosity

Qualitative behaviour at the LHC is the same!

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

Interpretation of the signal in extended Higgs sectors: signal interpreted as next-to-lightest state H

Extended Higgs sector where the second-lightest (or higher) Higgs has SM-like couplings to gauge bosons

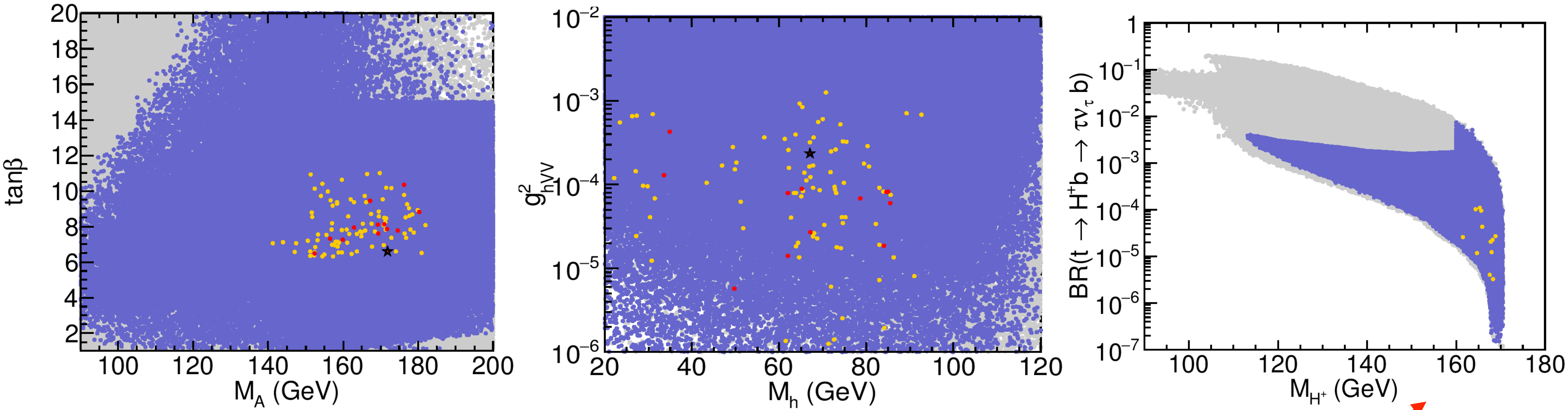
⇒ Lightest neutral Higgs with heavily suppressed couplings to gauge bosons, may have a mass below the LEP limit of 114.4 GeV for a SM-like Higgs (in agreement with LEP bounds)

Possible realisations: 2HDM, MSSM, NMSSM, ...

A light neutral Higgs in the mass range of about 60-100 GeV (above the threshold for the decay of the state at 125 GeV into hh) is a generic feature of this kind of scenario. The search for Higgses in this mass range has only recently been started at the LHC. Such a state could copiously be produced in SUSY cascades.

Global fit in the MSSM, h125 as heavy MSSM Higgs

[P. Bechtle et al. '16]

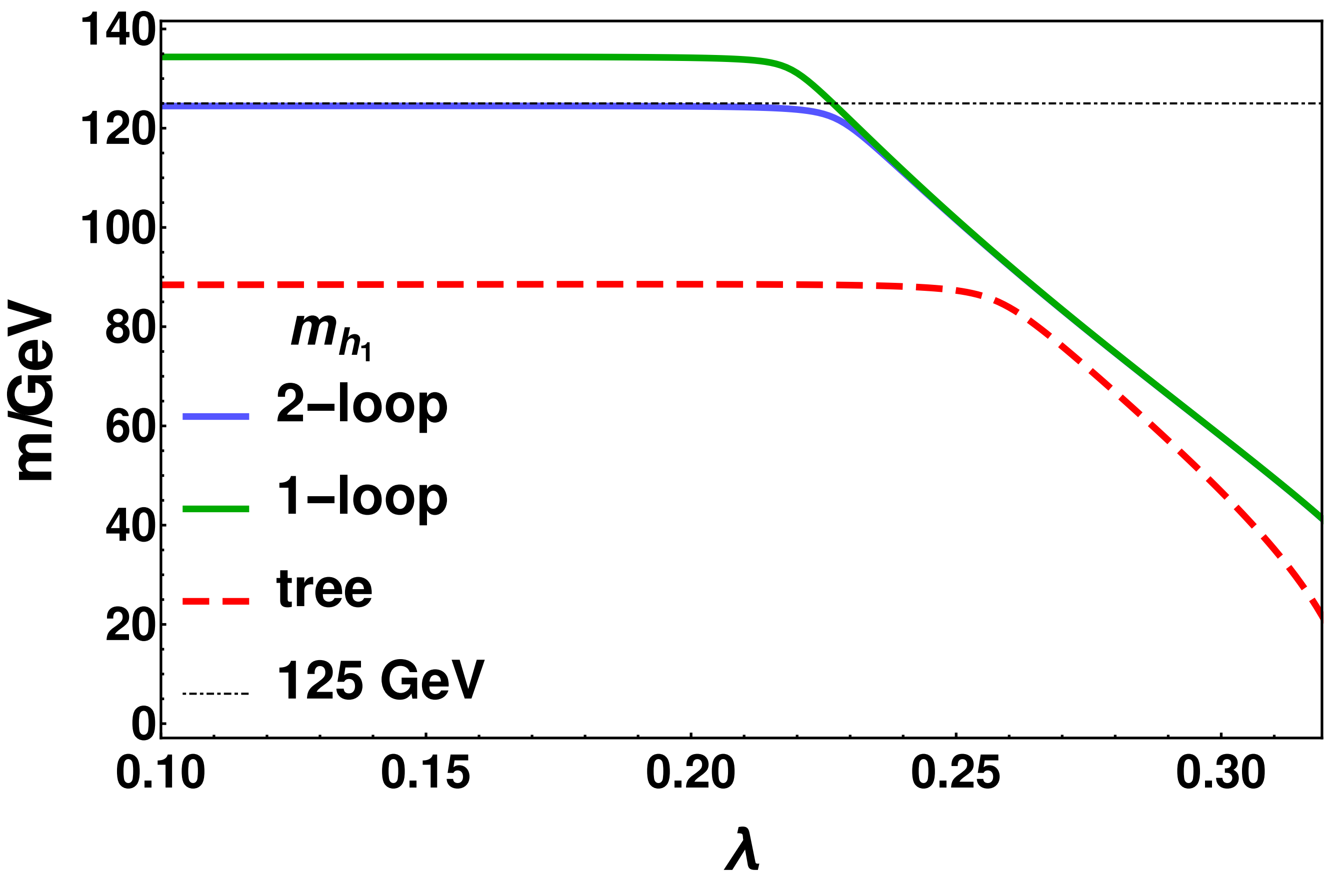


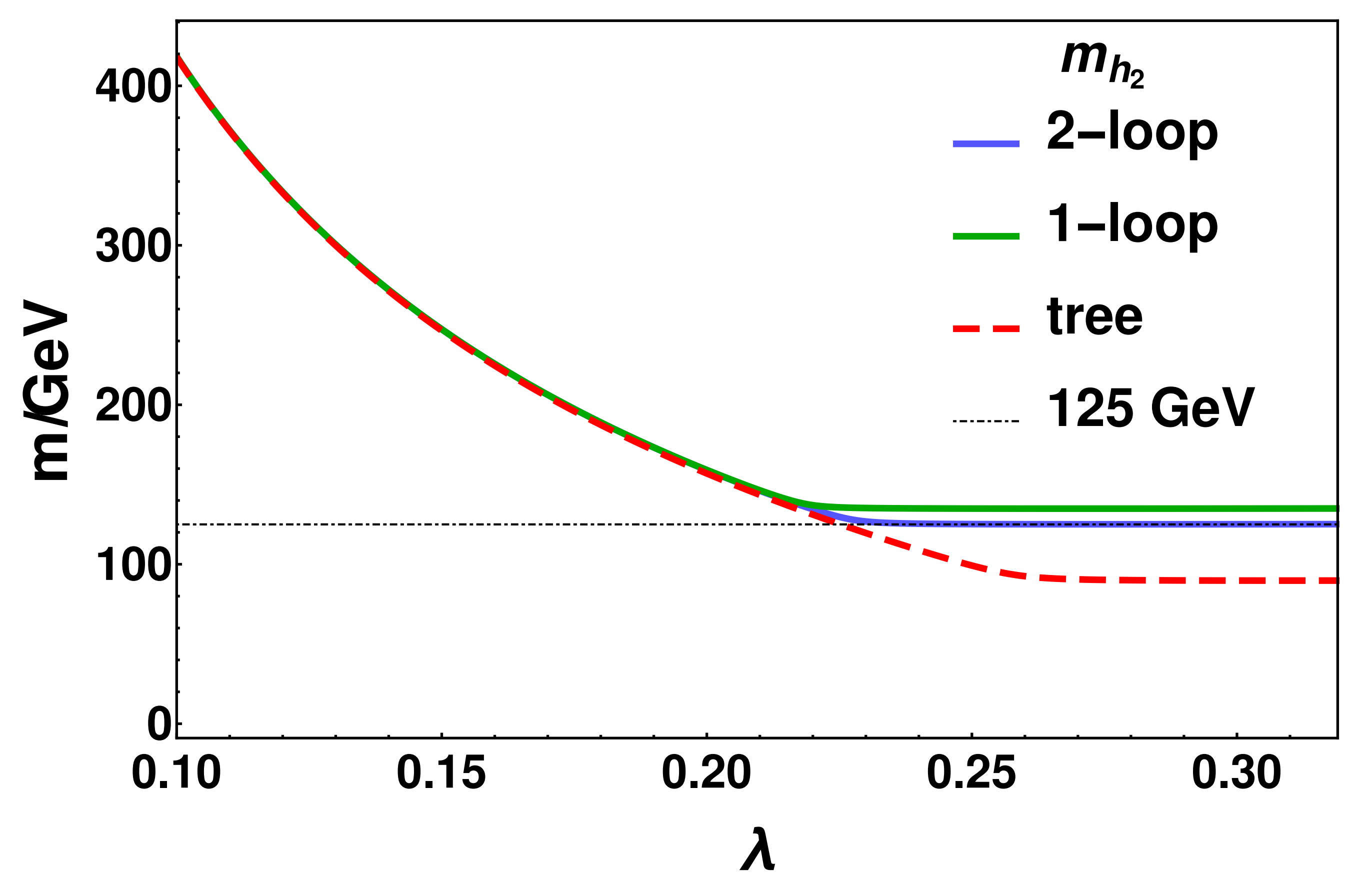
⇒Very light Higgs h is compatible with the experimental results
Tight constraints in the MSSM from charged Higgs searches

The NMSSM: two Higgs doublets and a singlet

Mass of the lightest and next-to-lightest Higgs in the NMSSM:
NMSSM version of *FeynHiggs*

[P. Drechsel et al. '16]





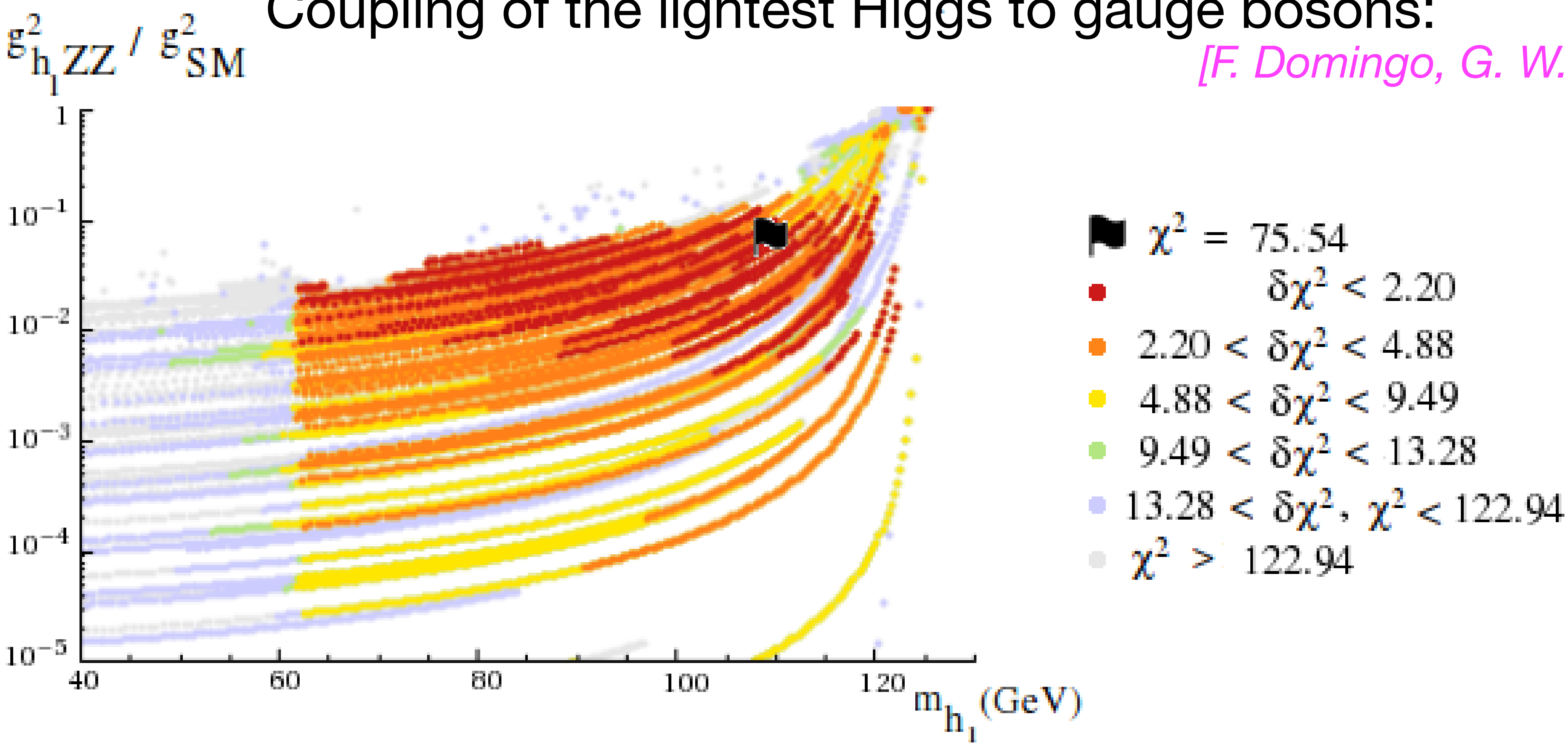
⇒ Variation of λ leads to cross-over behaviour between doublet-like and singlet-like state

⇒ The case where the signal at 125 GeV is not the lightest Higgs arises generically in the NMSSM

Example: NMSSM with a light Higgs singlet

Coupling of the lightest Higgs to gauge bosons:

[F. Domingo, G. W. '15]



⇒ SM-like Higgs at 125 GeV + singlet-like Higgs at lower mass

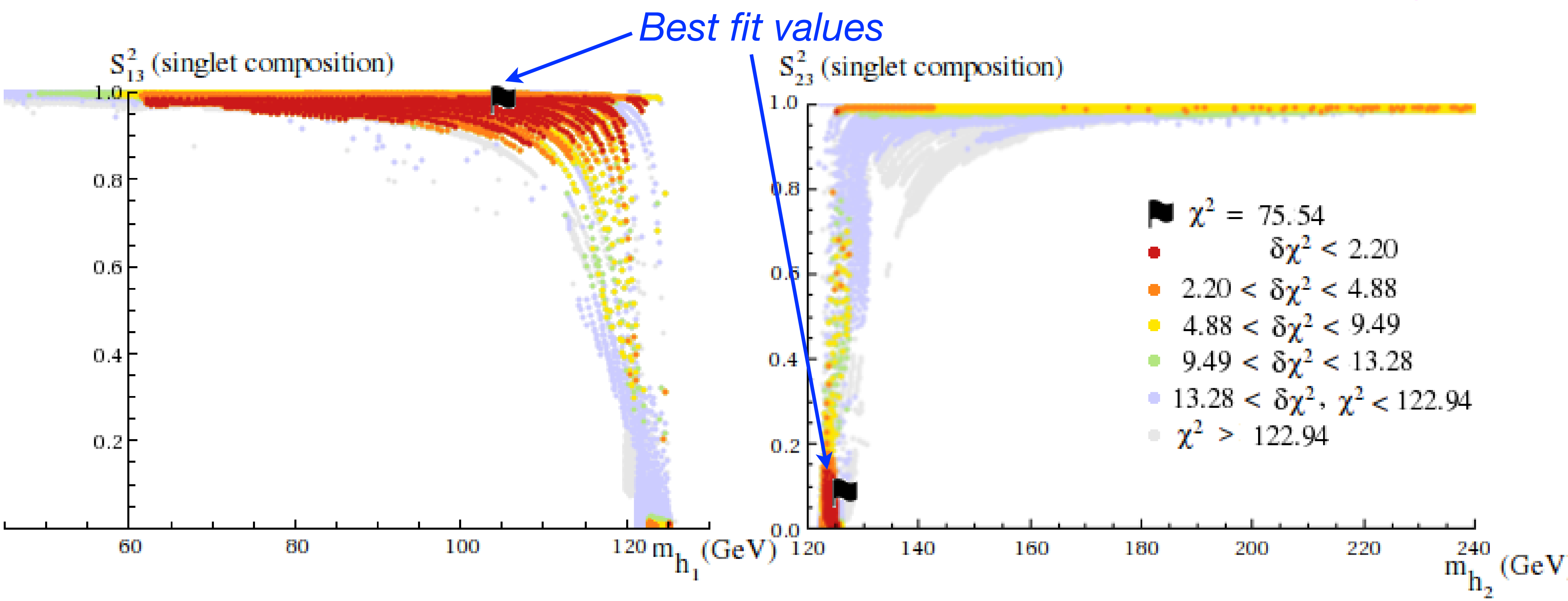
The case where the signal at 125 GeV is not the lightest Higgs arises generically if the Higgs singlet is light

⇒ Strong suppression of the coupling to gauge bosons

NMSSM interpretation of the observed signal

Extended Higgs sector where h(125) is not the lightest state:
NMSSM with a SM-like Higgs at 125 GeV + a light singlet

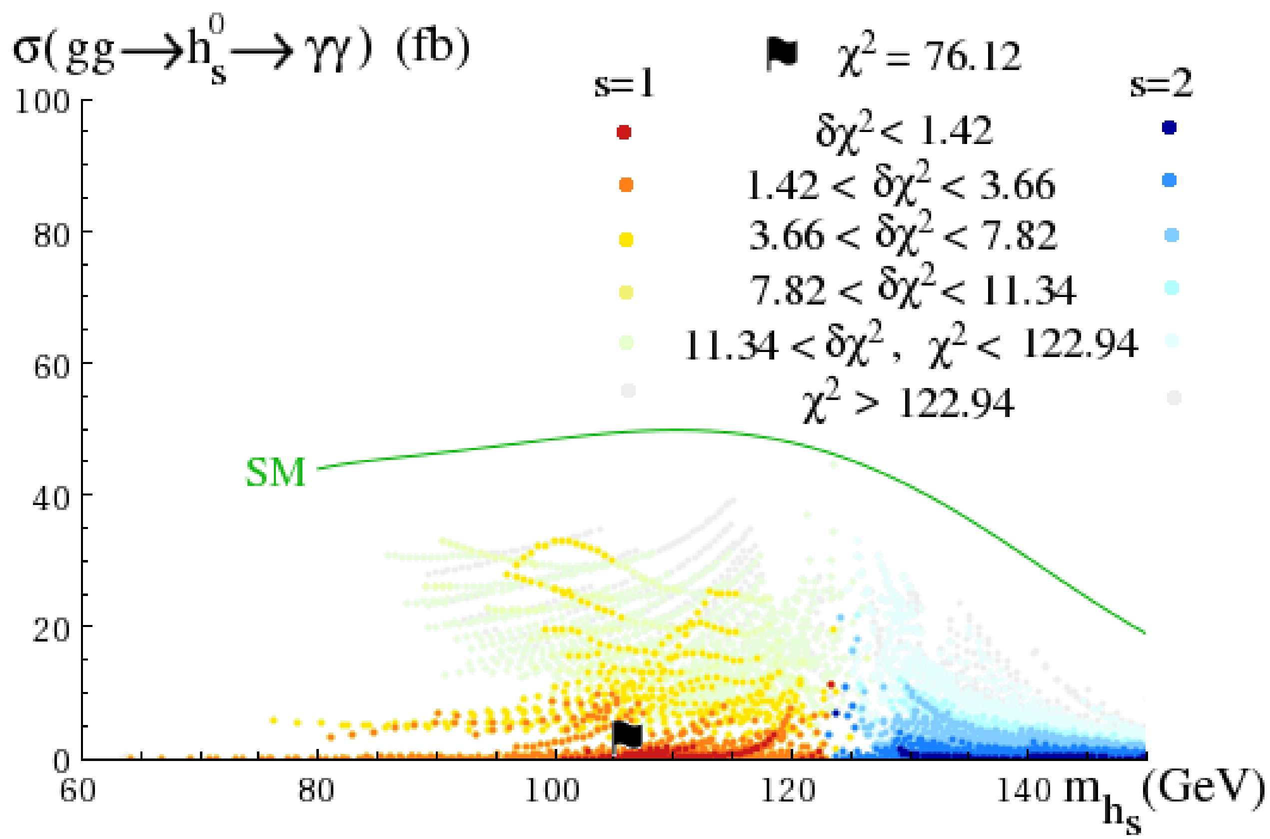
[F. Domingo, G. W. '15]

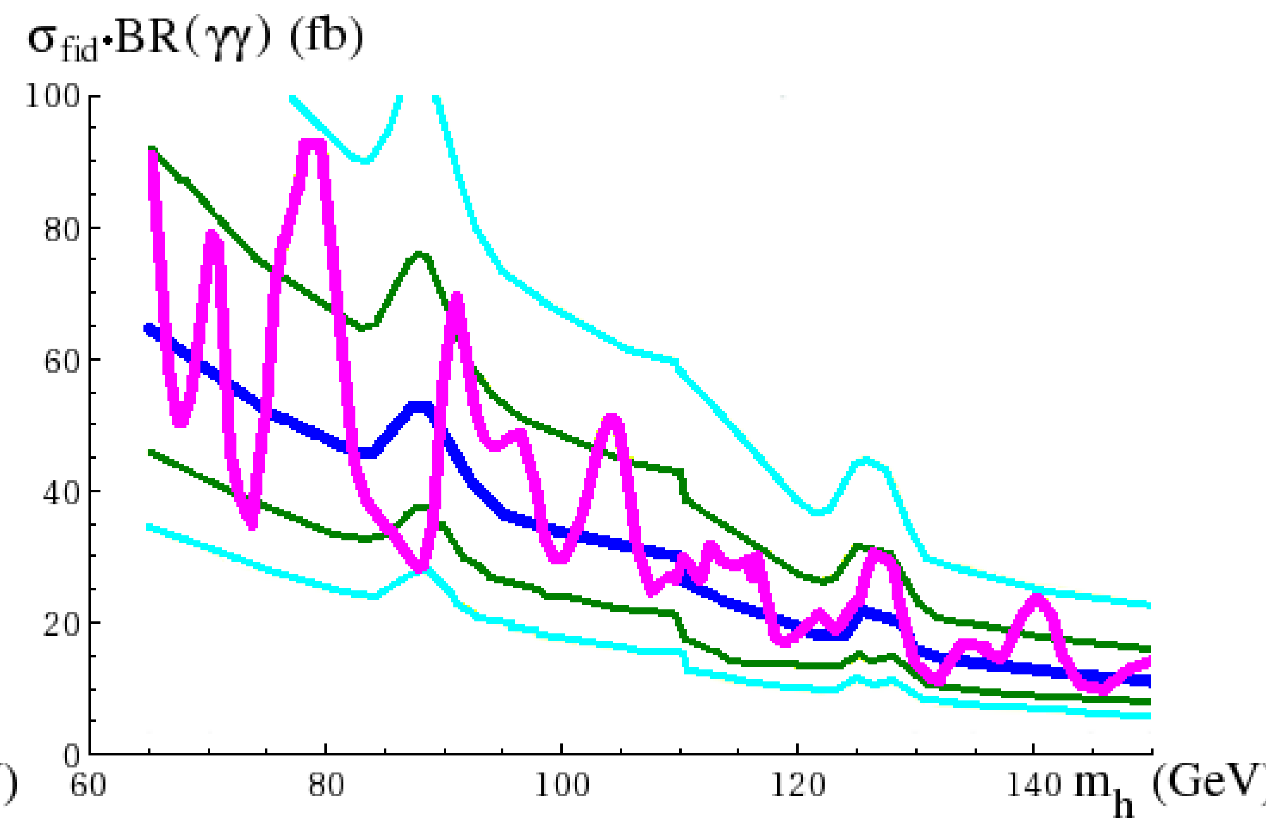


$\Rightarrow$ Additional light Higgs with suppressed couplings to gauge bosons, in agreement with all existing constraints

Light NMSSM Higgs: comparison of gg $\to h_1 \to \gamma\gamma$ with the SM case and the ATLAS limit on fiducial σ

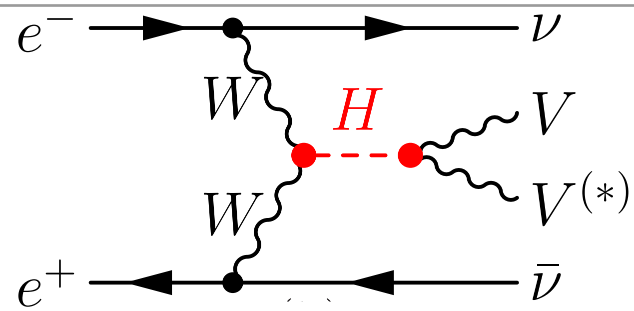
[F. Domingo, G. W. '15]





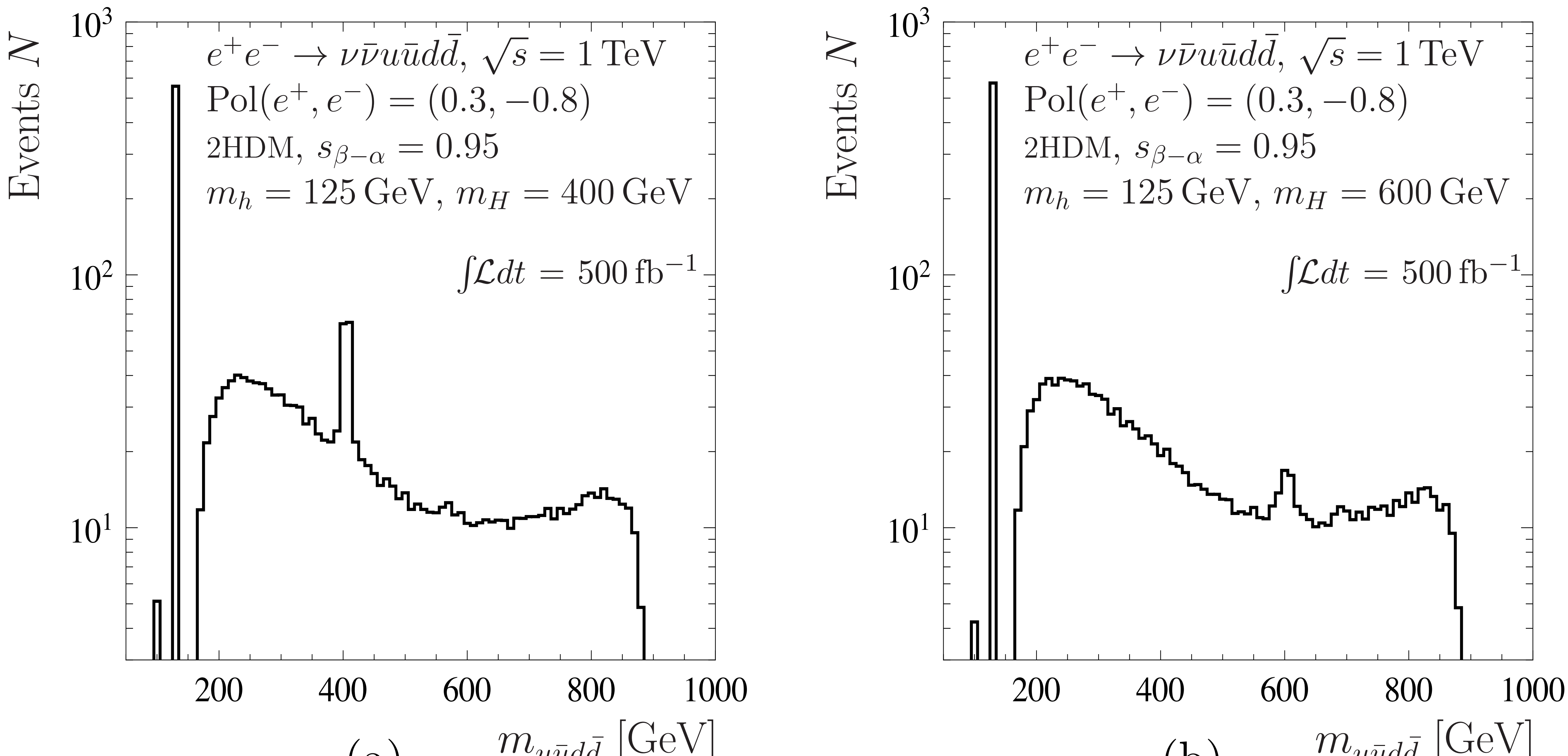
⇒ Limit starts to probe the NMSSM parameter space
But: best fit region is far below the present sensitivity

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



[S. Liebler et al. '15]

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



(a) (b)

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