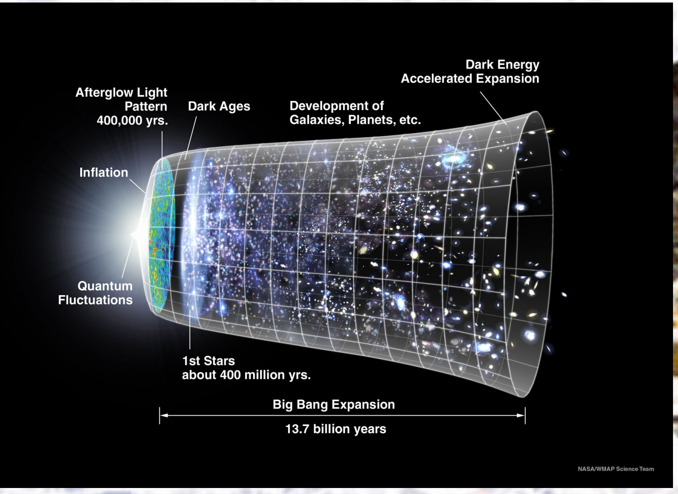
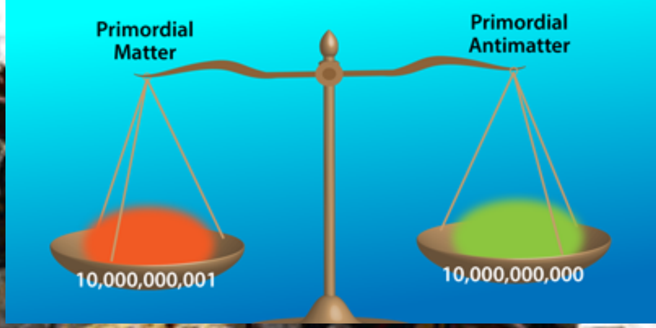
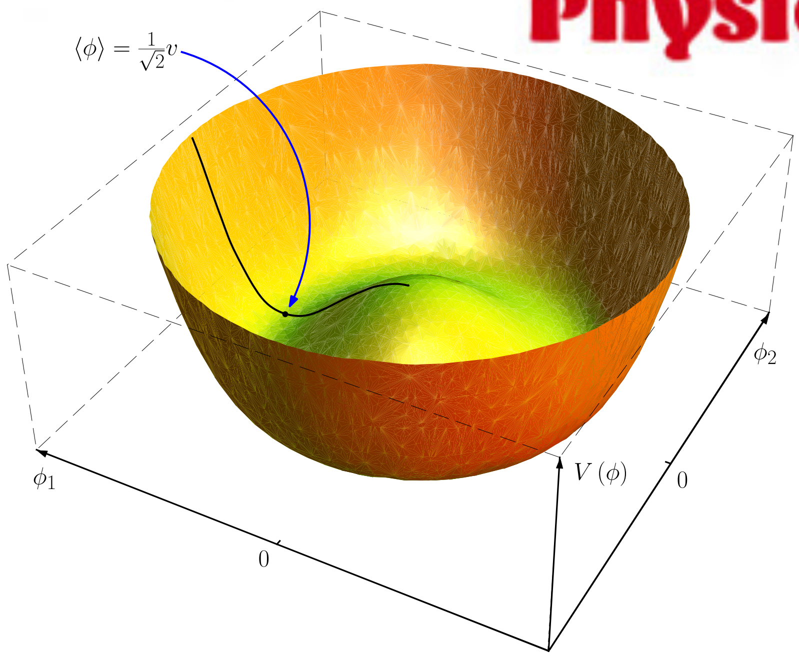
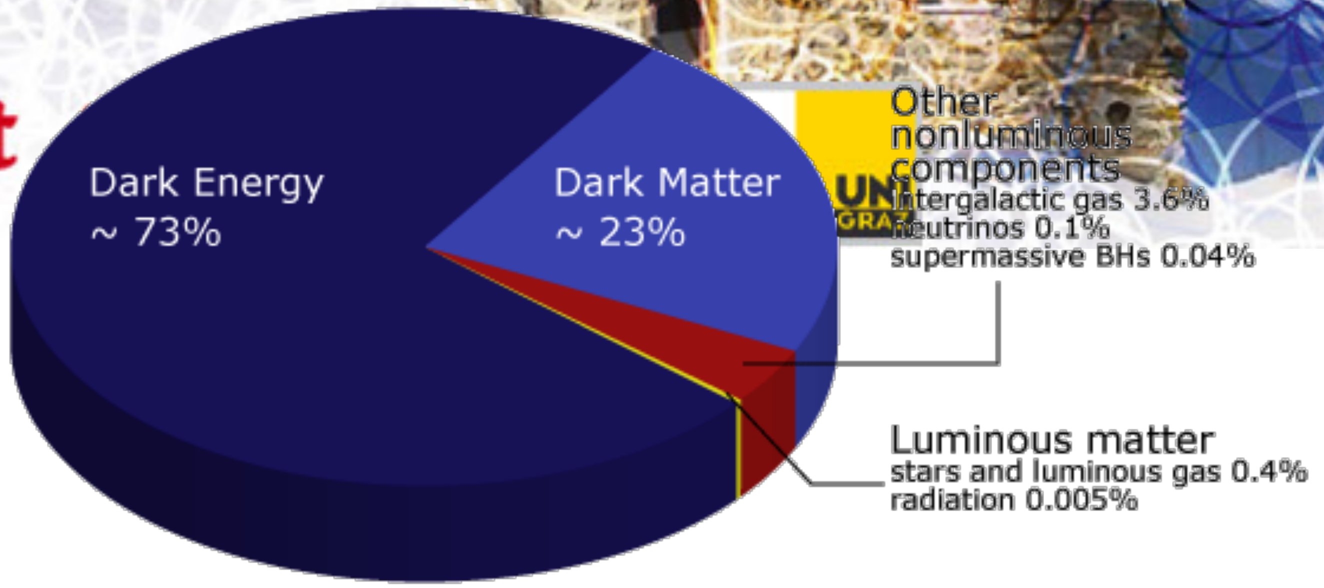




Alps 2018

an Alpine LHC Physics Summit





Open Questions after the HL-LHC

Georg Weiglein, DESY

Obergurgl, 04 / 2018

This is not meant to be a summary talk …

… and I will only mention a small fraction of the many nice talks that we heard during this week.

In fact, all the talks that were given at the workshop fit into the context of the topic that the organisers asked me to talk about, so I should have actually mentioned them all. Please accept my apologies if your nice talk is not explicitly mentioned below!

What will be the open questions after the HL-LHC?

Not an easy question to answer …
Would need a crystal ball, divine inspiration, …

Outline

1. What are the open questions now?

2. What can we expect from the HL-LHC and from the other experiments that will take place within the next two decades?

3. What may be the open questions in about 20 years from now?

4. How could we answer the open questions?

5. Conclusions

1. What are the open questions now?

Personal view, not a comprehensive list

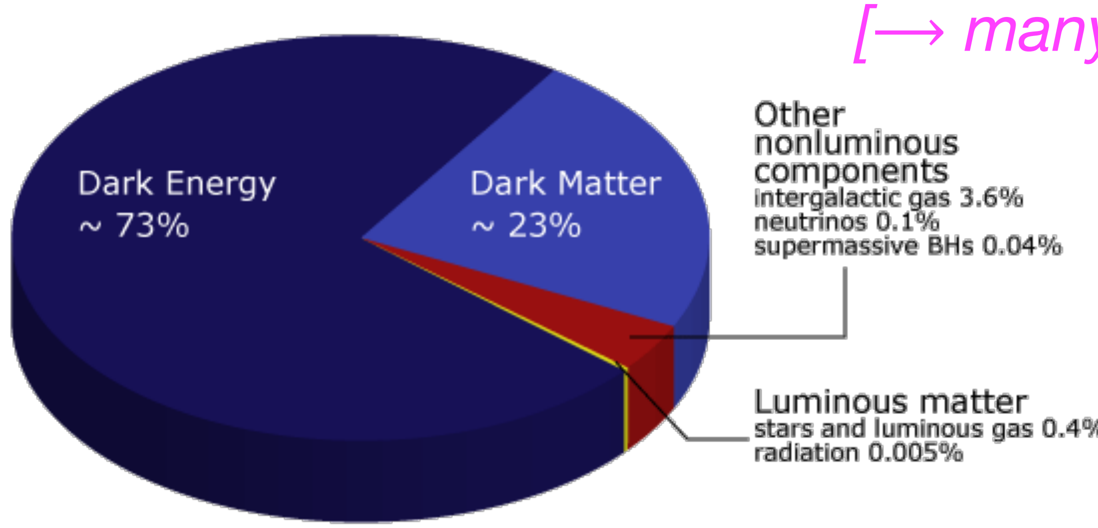
- Mechanism of electroweak symmetry breaking: origin of mass of elementary particles and its relation to the structure of the vacuum? How is the Higgs mass protected from physics at high scales?
  $\longrightarrow$ Exploration of the detected Higgs signal provides access

  [$\longrightarrow$ many talks at this workshop]

- How did the electroweak phase transition in the early universe work?

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

  [$\longrightarrow$ many talks at this workshop]



- Origin of the matter/anti-matter imbalance in the universe?

What are the open questions now?

Personal view, not a comprehensive list

- Origin of the observed patterns of flavour?

  [⟶ see talks by F. Deppisch, P. Krizan, A. Signer, U. Nierste, A. Crivellin, …]

- How is gravity related to the quantum world? Quantum structure of space-time? This workshop: Gravitational atoms? Black hole bomb?

  [⟶ see talk by M. Baryakhtar]

- Are there more than three dimensions of space?

- Unification of the fundamental interactions of nature?

  [⟶ see talks by W. Porod, D. Litim, …]

- Origin of the inflationary phase in the early universe?

- Origin of the highest-energy particles in the universe?

- This workshop: What is precisely meant by ``the Standard Model”: ``old” ``or” new SM?

  [⟶ see talks by F. Deppisch, A. Signer, …]

Higgs physics and the origin of mass of elementary particles

Nowadays one often reads sentences like

``In 2012 the Higgs boson has been found, and the Standard Model of particle physics is now complete.”

Higgs physics and the origin of mass of elementary particles

Nowadays one often reads sentences like

``In 2012 the Higgs boson has been found, and the Standard Model of particle physics is now complete."

This would imply that we know for sure that there is only a single one!

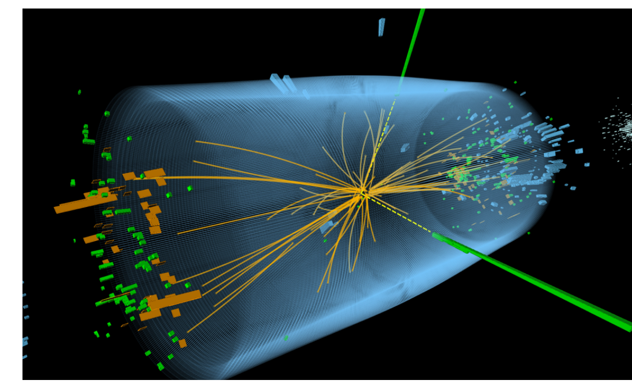
This would imply that we know for sure that the discovered particle is fundamental and not composite and that it has ***exactly*** the properties of the Higgs predicted by the SM!

None of the above is true!
We should be careful in choosing our language in order not to pre-empt a large part of the work that we intend to do in our field during the next decades!

Higgs physics and the origin of mass of elementary particles

Here is my version for how one could phrase the issue:

The Higgs-boson discovery at the LHC in 2012 was a major scientific breakthrough that has started a new era in our understanding of the fundamental laws of nature.

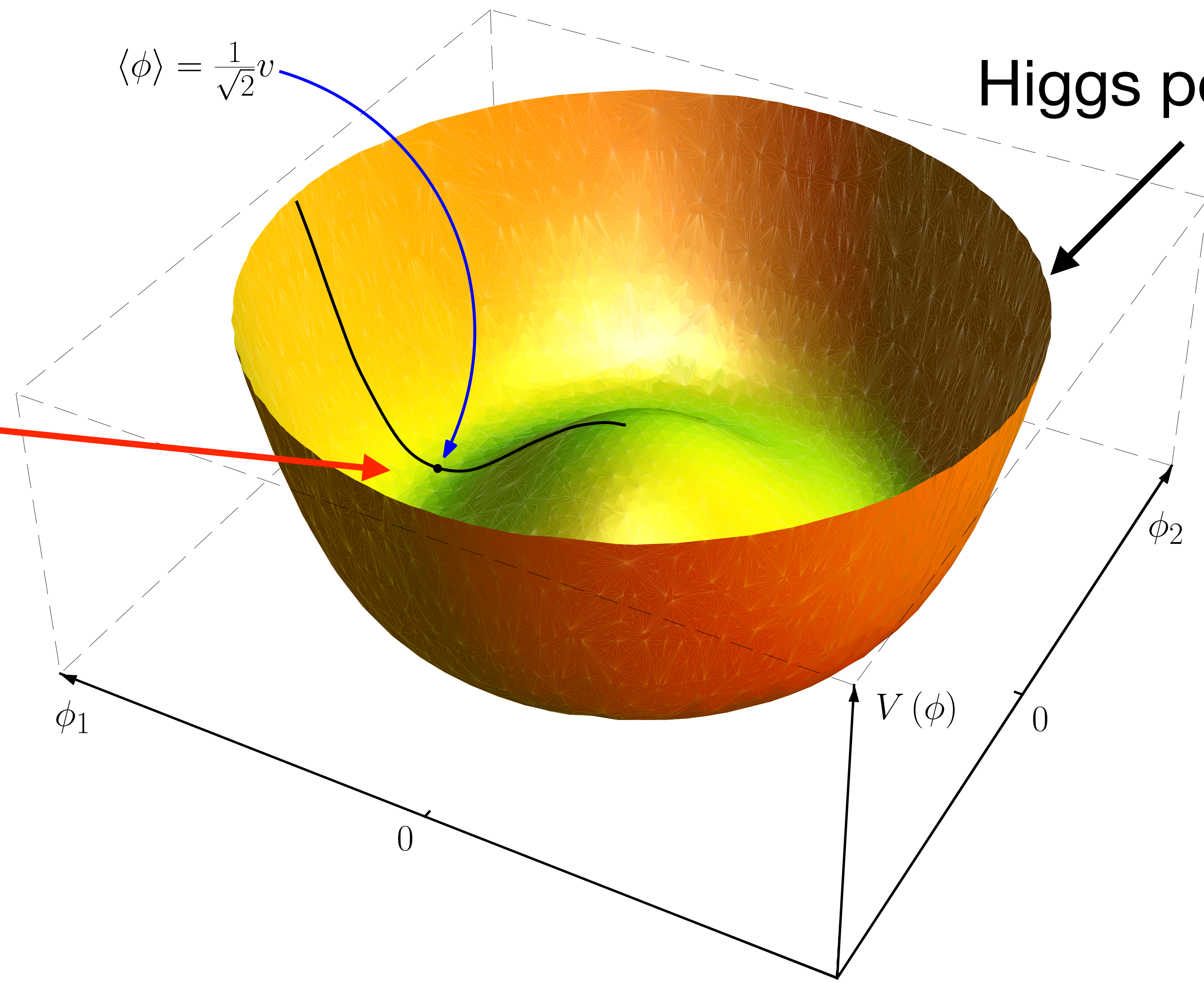


The discovery establishes a non-trivial structure of the vacuum, i.e. of the lowest-energy state in our universe. The origin of mass of elementary particles is related to this structure: mass arises from the interaction with the Higgs field.

Nobel Prize 2013

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

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

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

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 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.

We have a phenomenological description of the known particles and their interactions, but we do not know the underlying dynamics. This is similar to the development of the understanding of superconductivity (phenomenological description: Ginzburg-Landau theory; actual understanding: microscopic BCS theory).

Related issue:
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 ⟷ a new space-time symmetry, more than 100 years after Einstein?

- Substructure of the Higgs boson ⟷ a new interaction of nature (a ``fifth force")?

- Properties of the Higgs sector ⟷ evidence for additional dimensions of space?

- Higgs and dark energy ⟷ could our Universe be just one of many parallel Universes?

Needed in Higgs physics: high-precision measurements + searches

[⟶ many talks at this workshop]

- In order to understand the underlying physics of the Higgs boson we need to determine its properties as precisely as possible: couplings, CP-properties, mass, …
- Elementary particle or substructure of more fundamental particles (latter possibility would resemble the ``Cooper pairs" of the case of superconductivity)? [⟶ see talks by F. Goertz, A. Pomarol, …]
- Single Higgs or further Higgs bosons? [⟶ see talks by R. Santos, …]
- BSM physics connected to the Higgs sector (Higgs portal, …)?
- Connection to imbalance between matter and anti-matter in the universe?
- Relation between the electroweak phase transition and the phase of inflation in the early universe?
- …

More generally: how to get access to BSM effects?

[⟶ many talks at this workshop]

- BSM searches: light / heavy new states
  The options discussed at this workshop span many orders of magnitude from extremely light to very heavy

- High-precision tests: high sensitivity to deviations from the SM
  SM vs. other explicit models (chosen with or without divine inspiration)
  EFT analyses (new physics assumed to be heavy)

2. What will be learn until the end of the HL-LHC?

Significant improvements of the measurements carried out at the LHC so far and high sensitivity of the searches
[⟶ see talks by Tae Jeong Kim, Hideyuki Oide, …]

How far will we get?

Higgs coupling determination at the LHC

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

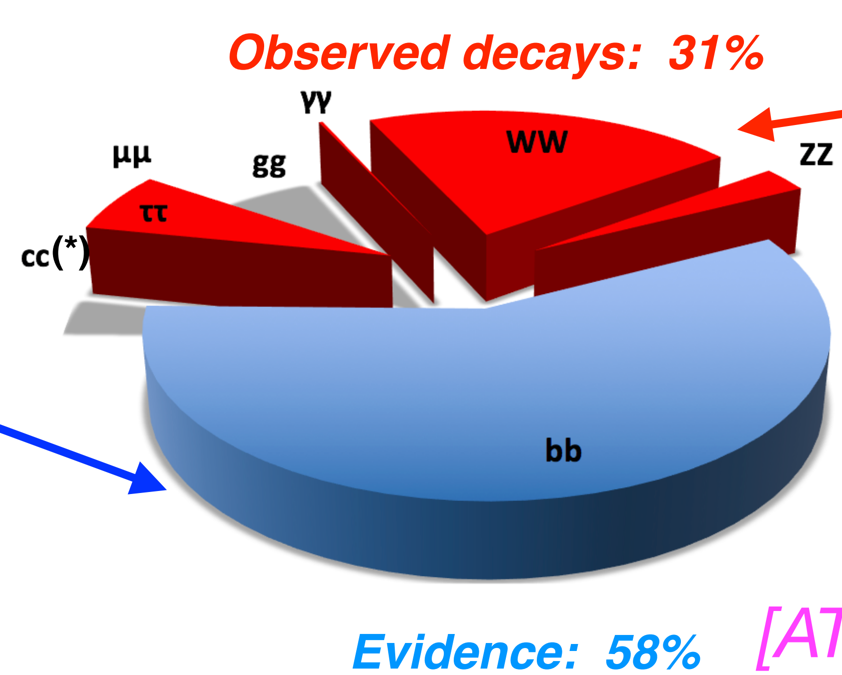
(Production) x (decay) at the LHC yields combinations of Higgs couplings ($\Gamma_{\text{prod, decay}} \sim g^2_{\text{prod, decay}}$):

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

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 established yet at the 5 σ level



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

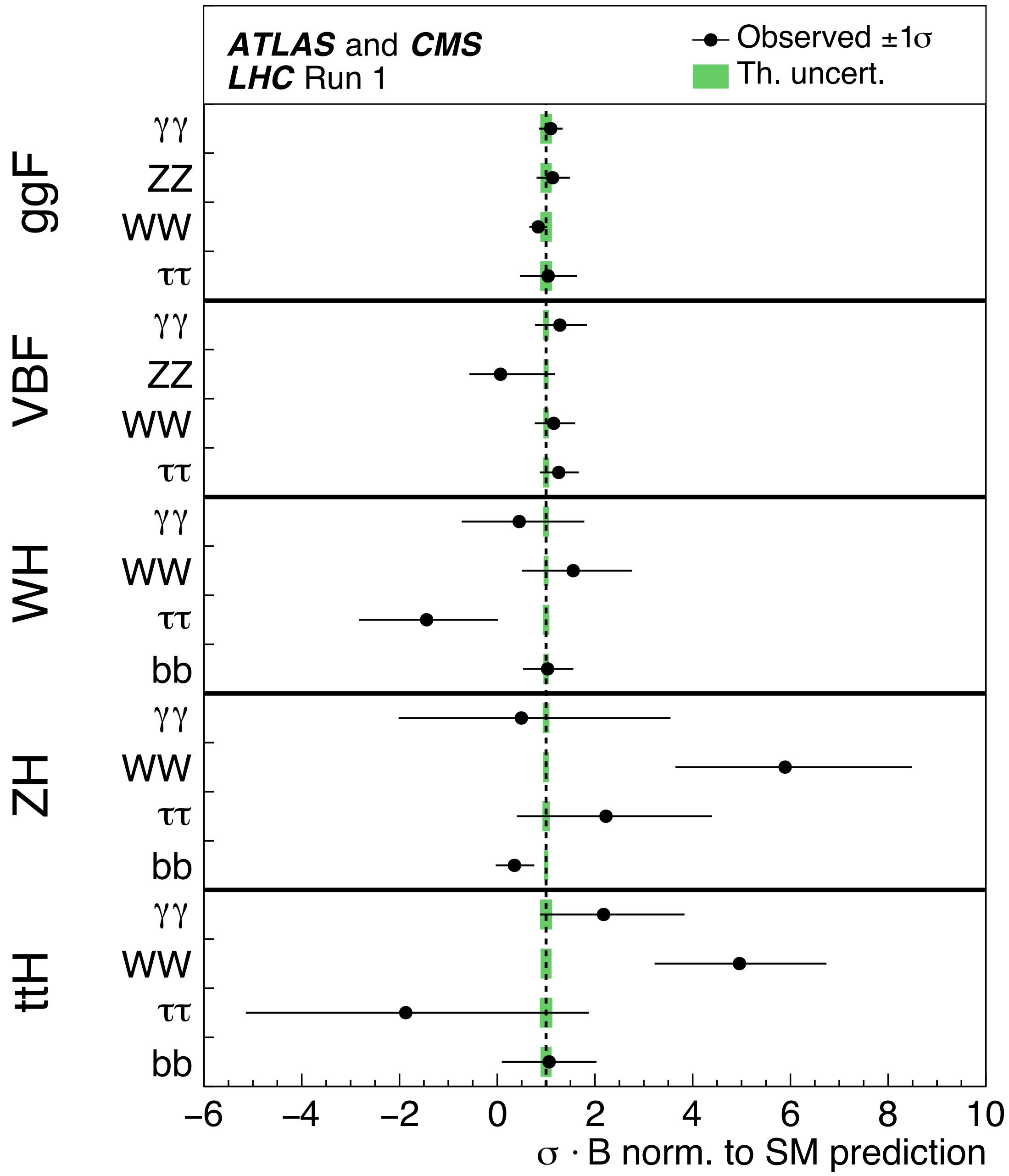
Evidences: ATLAS: 3.6 σ, CMS: 3.8 σ

[ATLAS, CMS Collaborations ’17]

Signal strengths from LHC Run 1: ATLAS + CMS

Signal strength:

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



[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 are still rather large, will be improved at HL-LHC

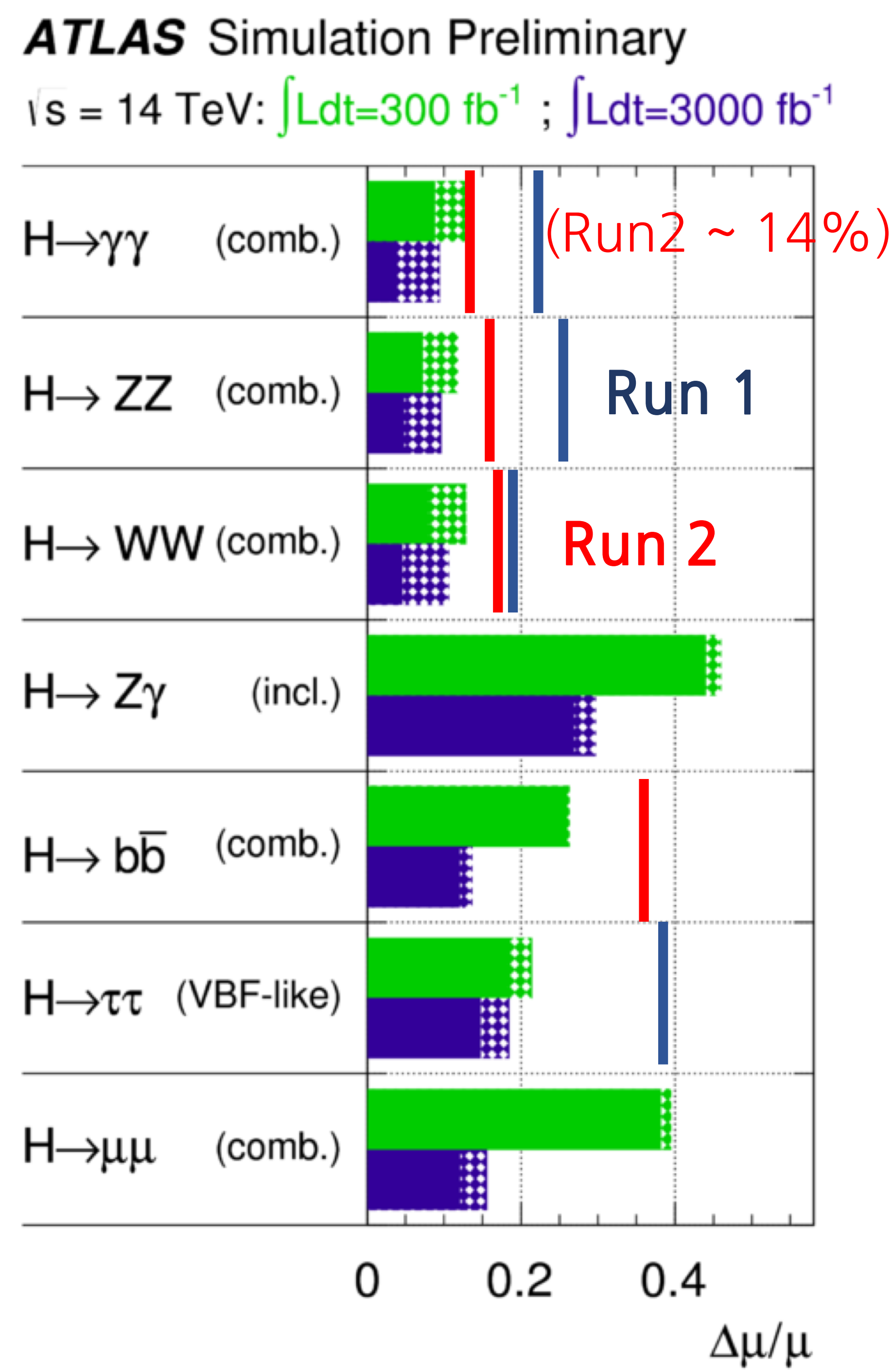
Expected improvements of Higgs signal strengths

[⟶ see talk by Tae Jeong Kim]

ATL-PHYS-PUB-2014-016

Higgs signal strength

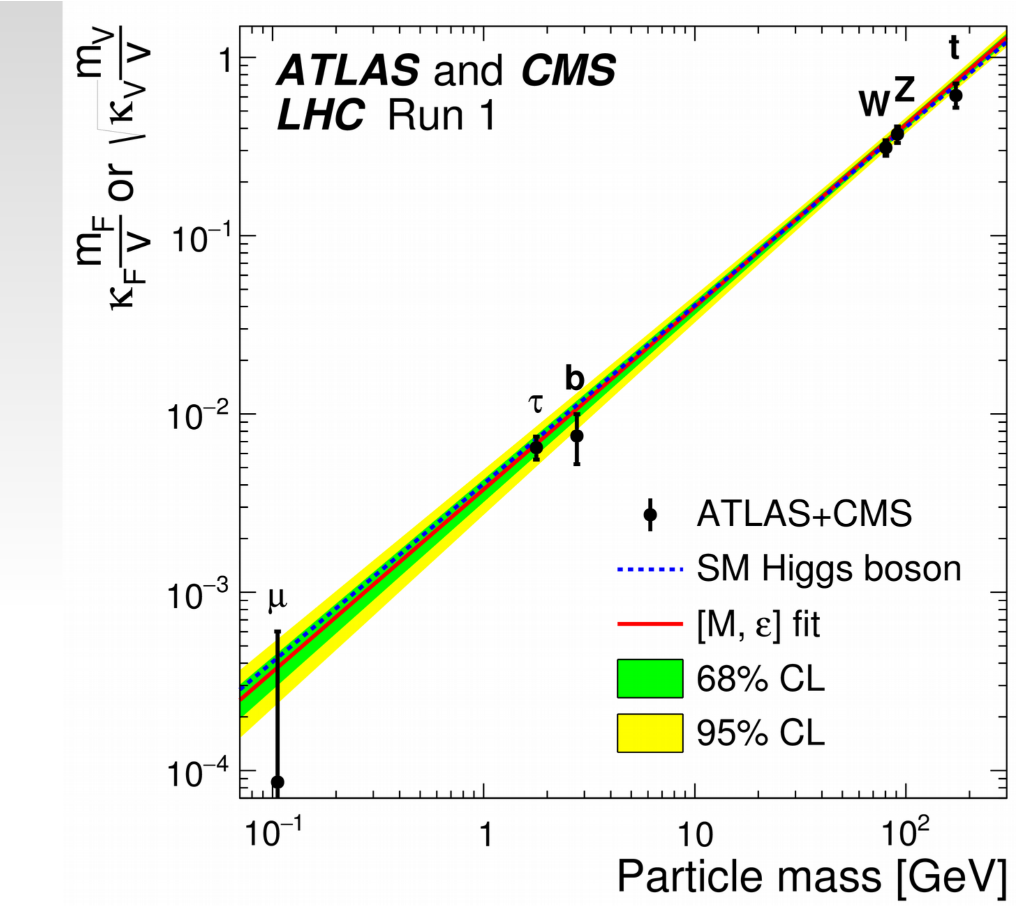
- $\mathrm{H} \to \gamma\gamma$ and $\mathrm{H} \to \mathrm{ZZ}$
  - Run1 analysis strategy with expected performance at 140 pileup events
  - Precision : a few% level, 9% including theory uncertainty
- For VH, $\mathrm{H} \to b\bar{b}$ and $t\bar{t}H$
  - 10-20% uncertainty
  - Signal modeling (QCD scale)
  - $t\bar{t}b\bar{b}$ modeling in $t\bar{t}H(b\bar{b})$
- Statistical uncertainty better with a factor of ~9 with 3000 fb^{-1}
- Reduced theory uncertainty is needed
  - QCD scale, PDF, α_S

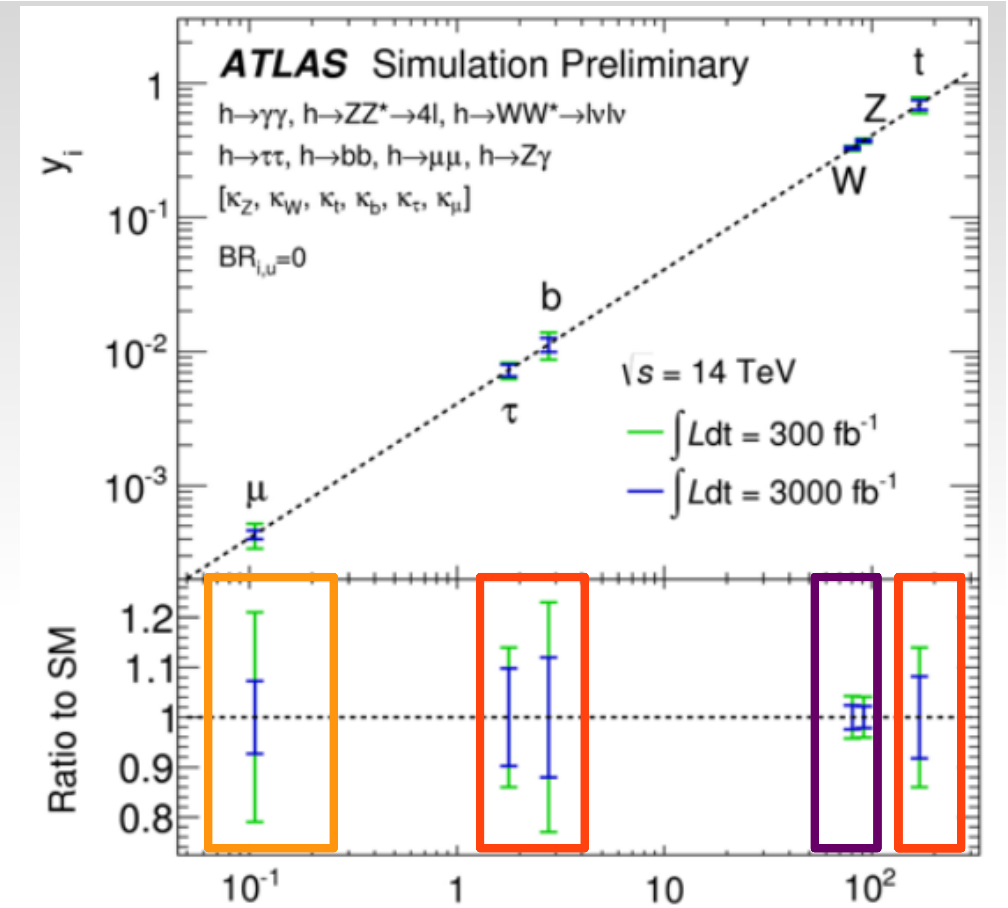


Higgs couplings at the HL-LHC

Significant improvement of precision compared to present situation; access to rare processes, e.g. Hμμ coupling

[M. Gouzevitch, LCWS2017]





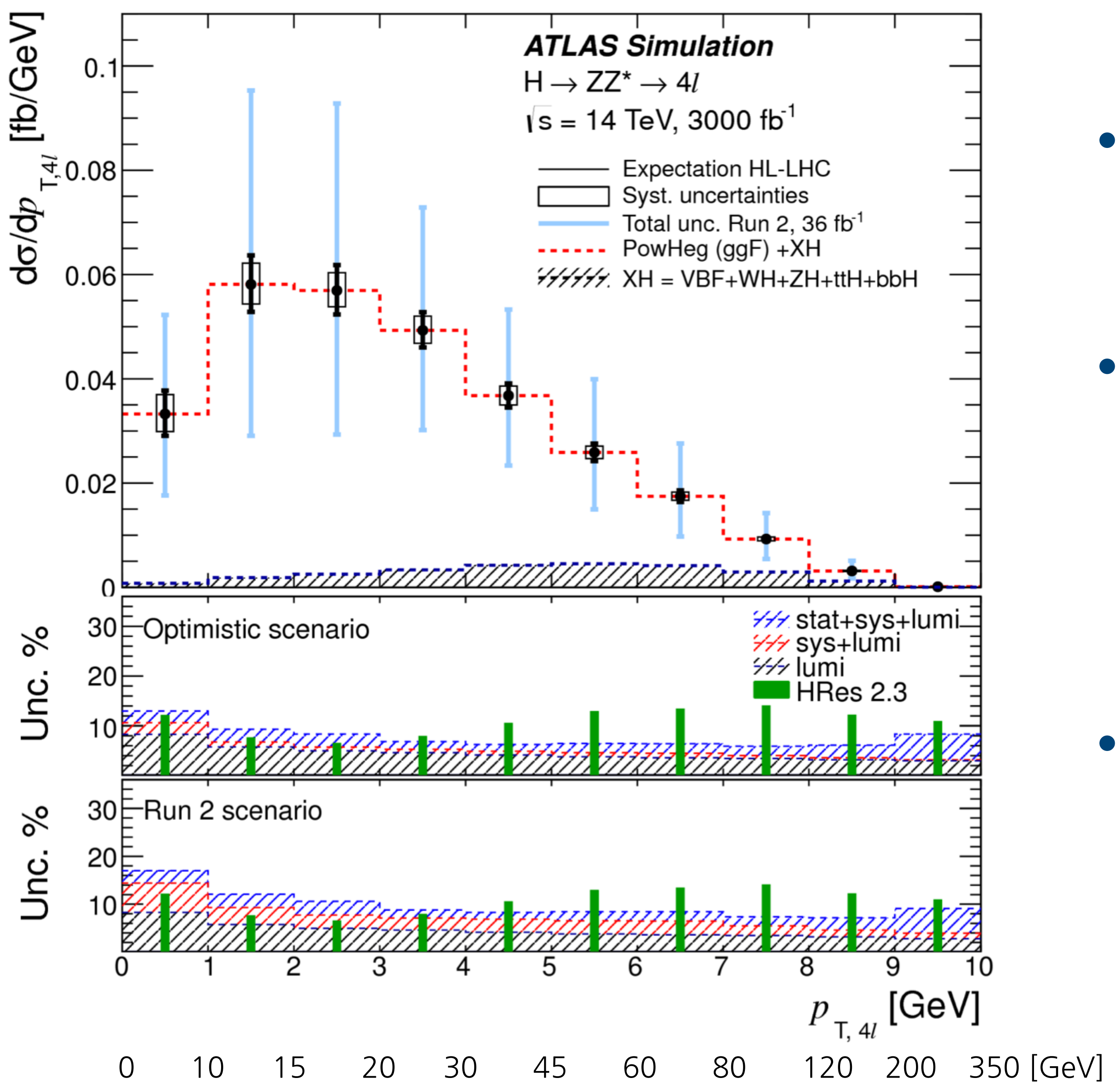
- Assuming no new physics in Γ_{tot}. $(\sigma \cdot \mathrm{BR})(x \to \mathrm{H} \to ff) = \frac{\sigma_x \cdot \Gamma_{ff}}{\Gamma_{tot}}$
- W/Z sector and 3rd generation: most of the improvement comes from Phase I. Phase II limited by systematics (experimental and theory).
- 2nd generation (μ): Phase II opens the gate (Carlo R. would be happy).

Improvements in Higgs differential cross sections

[⟶ see talk by Tae Jeong Kim]

ATLAS TDR-026

- Sensitivity to physics beyond the SM.
- Probes perturbative QCD calculations



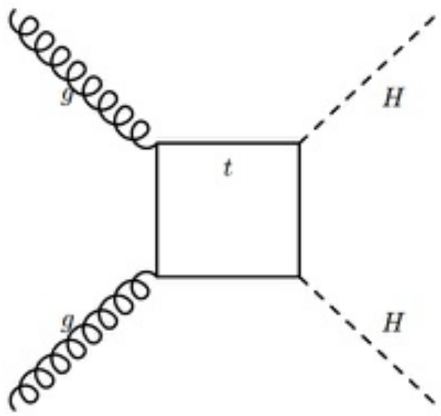
- In Run2 scenario, the uncertainty is between 8-17%
- In optimistic scenario where the experimental uncertainties are reduced by a factor of 2, the uncertainty is between 6-14%.
- This improves the current result by more than factor of 6.

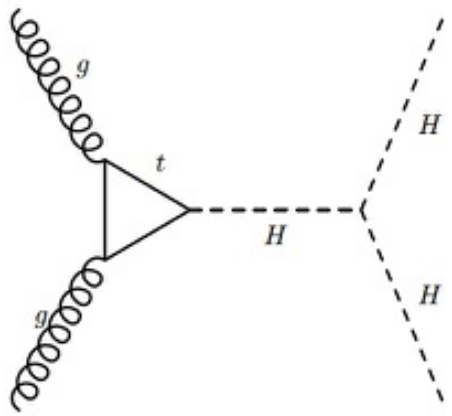
The "holy grail": Higgs self-coupling

[⟶ see talk by Tae Jeong Kim]

DiHiggs production

- Interfere destructively
  - SM HH ggF production : 39.51 fb at 14 TeV
  - 120K HH events with 3000 fb^{-1}





Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	4.1×10^4
$b\bar{b} + W^+W^-$	25%	3.1×10^4
$b\bar{b} + \tau^+\tau^-$	7.4%	9.0×10^3
$W^+W^- + \tau^+\tau^-$	5.4%	6.6×10^3
$ZZ + b\bar{b}$	3.1%	3.8×10^3
$ZZ + W^+W^-$	1.2%	1.4×10^3
$\gamma\gamma + b\bar{b}$	0.3%	3.3×10^2
$\gamma\gamma + \gamma\gamma$	0.0010%	1

Main SM backgrounds are $t\bar{t}$, Z+jets for most of channels or photon+jets (misidentified as photon) for $\gamma\gamma$ final states

The “holy grail”: Higgs self-coupling

[⟶ see talk by Tae Jeong Kim]

ATL-PHYS-PUB-2017-001

DiHiggs production ($HH \to b\bar{b}\gamma\gamma$)

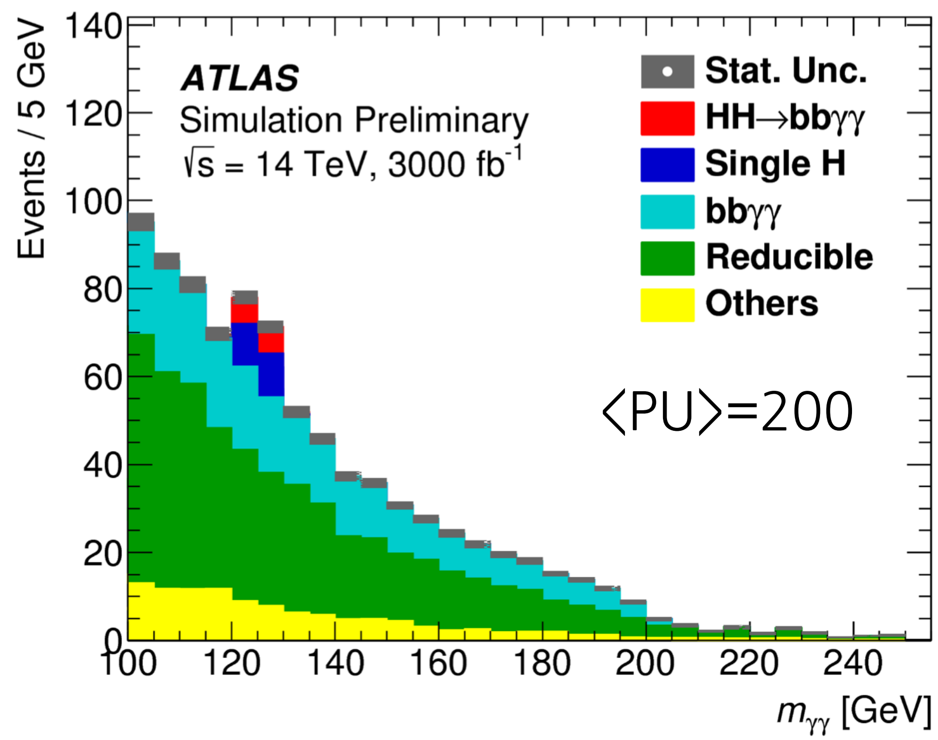
- Clear mass peak from $\gamma\gamma$ even though very low branching ratio (0.28%)
- Photon ID and b-tagging are essential
- Main background from single Higgs and non-resonant $b\bar{b}\gamma\gamma$

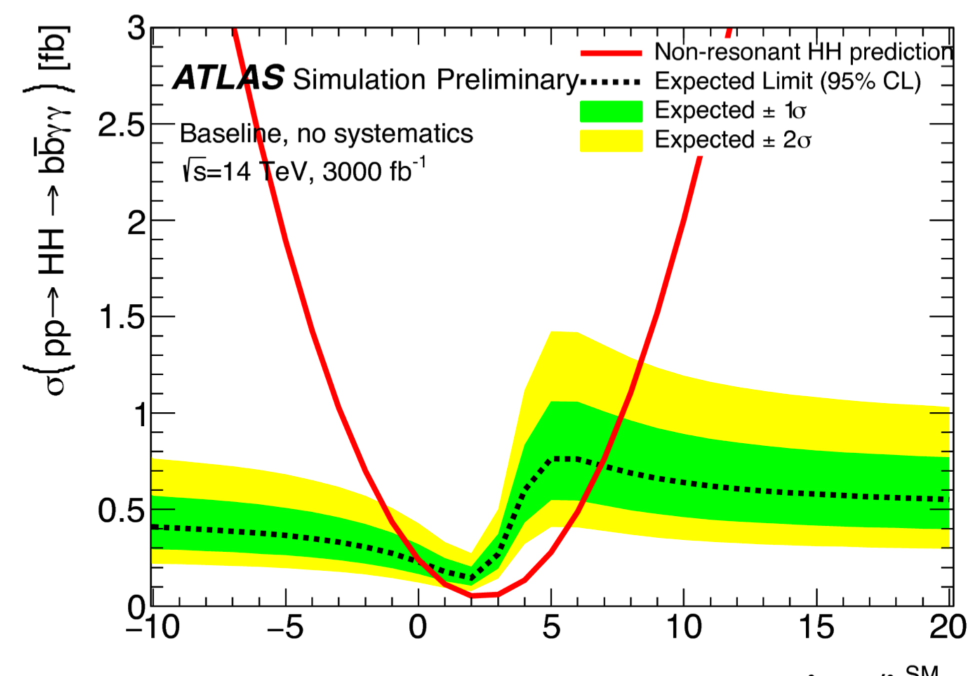
Sig. $\frac{S}{\sqrt{B}} = 1.05\,\sigma$

Higgs boson self-coupling

$$-0.8 < \frac{\lambda}{\lambda_{SM}} < 7.7$$

(not including syst. uncertainty)





Updated for Pixel TDR

⇒ Very difficult

Higgs 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

Higgs 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 → ZZ^* → 4 l, etc. because of the smallness of a_3

Hypothesis of a pure CP-odd state is experimentally disfavoured

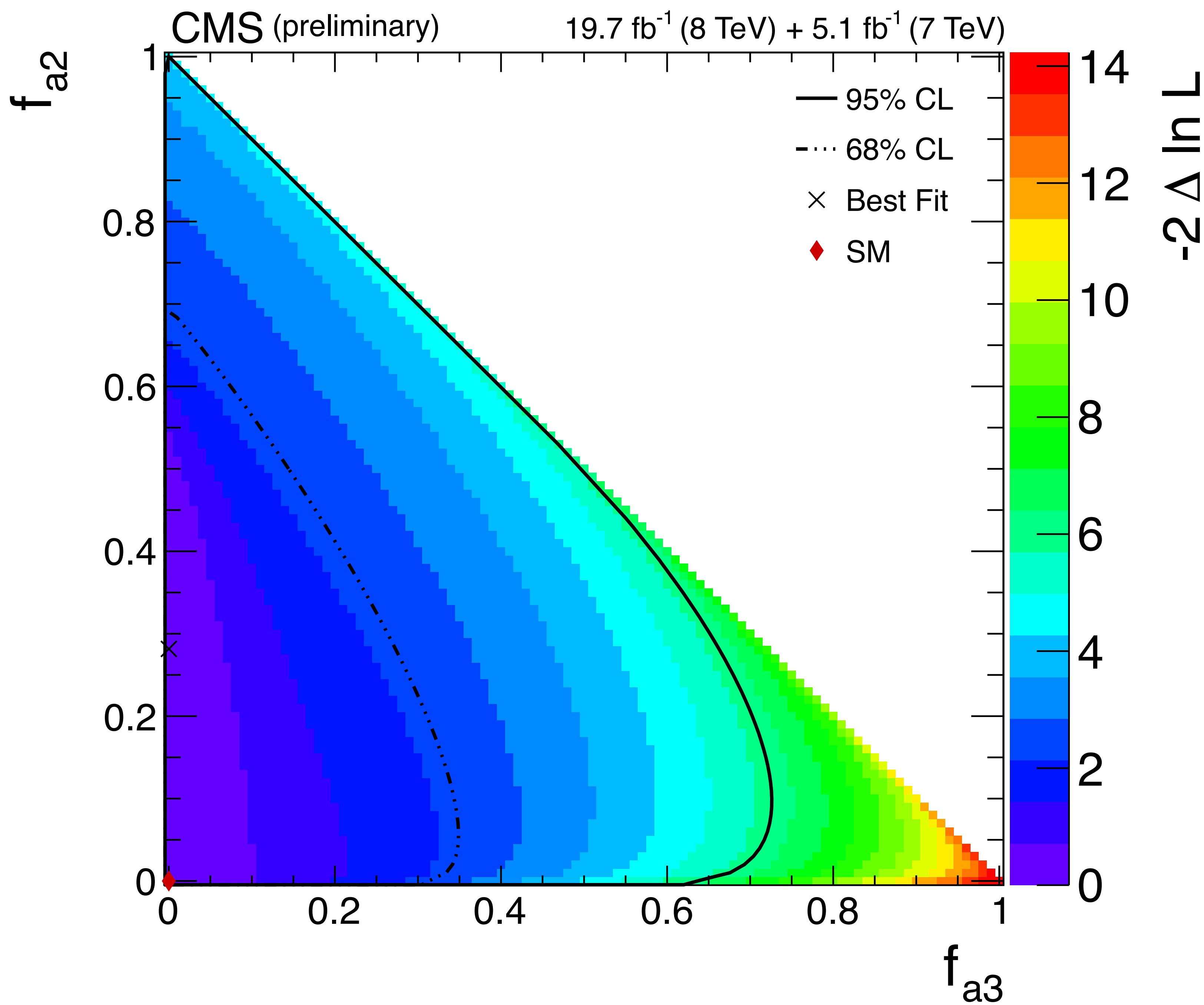
However, there are only very weak bounds so far on an admixture of CP-even and CP-odd components

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

Experimental analyses beyond the hypotheses of pure CP-even / CP-odd states

[CMS Collaboration '14]

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3}$$



Experimental analyses beyond the hypotheses of pure CP-even / CP-odd states

Loop suppression of a_3 in many BSM models

$\Rightarrow$ Even a rather large CP-admixture would result in only a very small effect in f_{a3}!

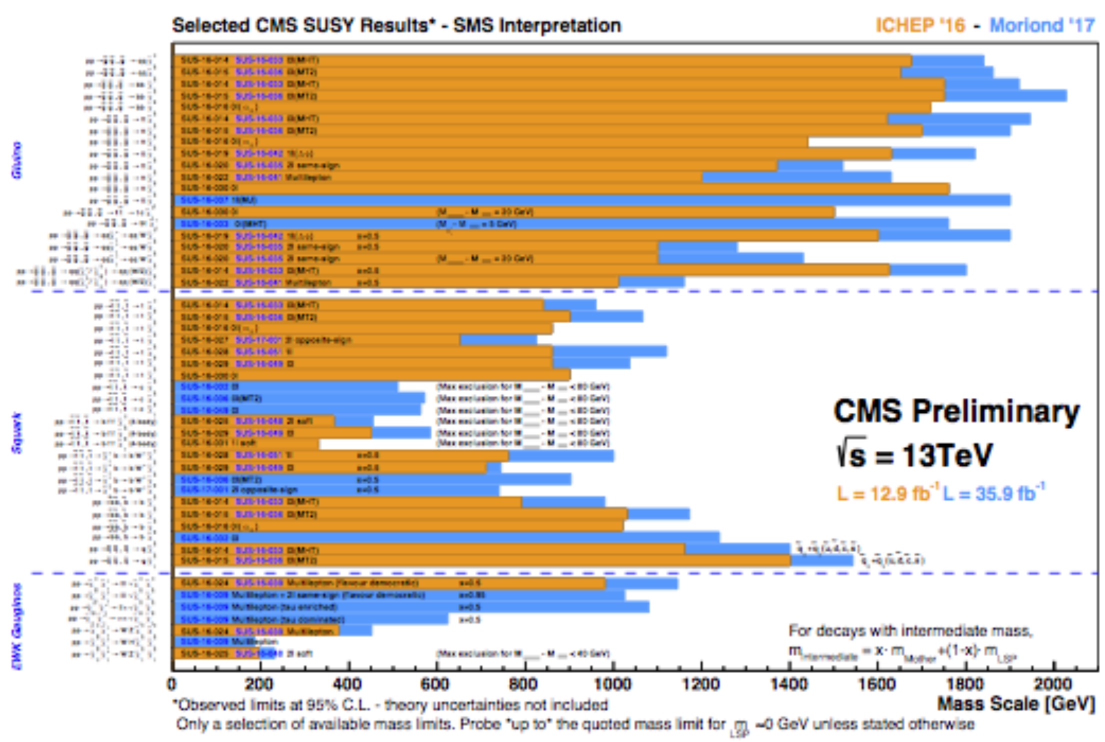
$\Rightarrow$ Extremely high precision in f_{a3} needed to probe possible deviations from the SM

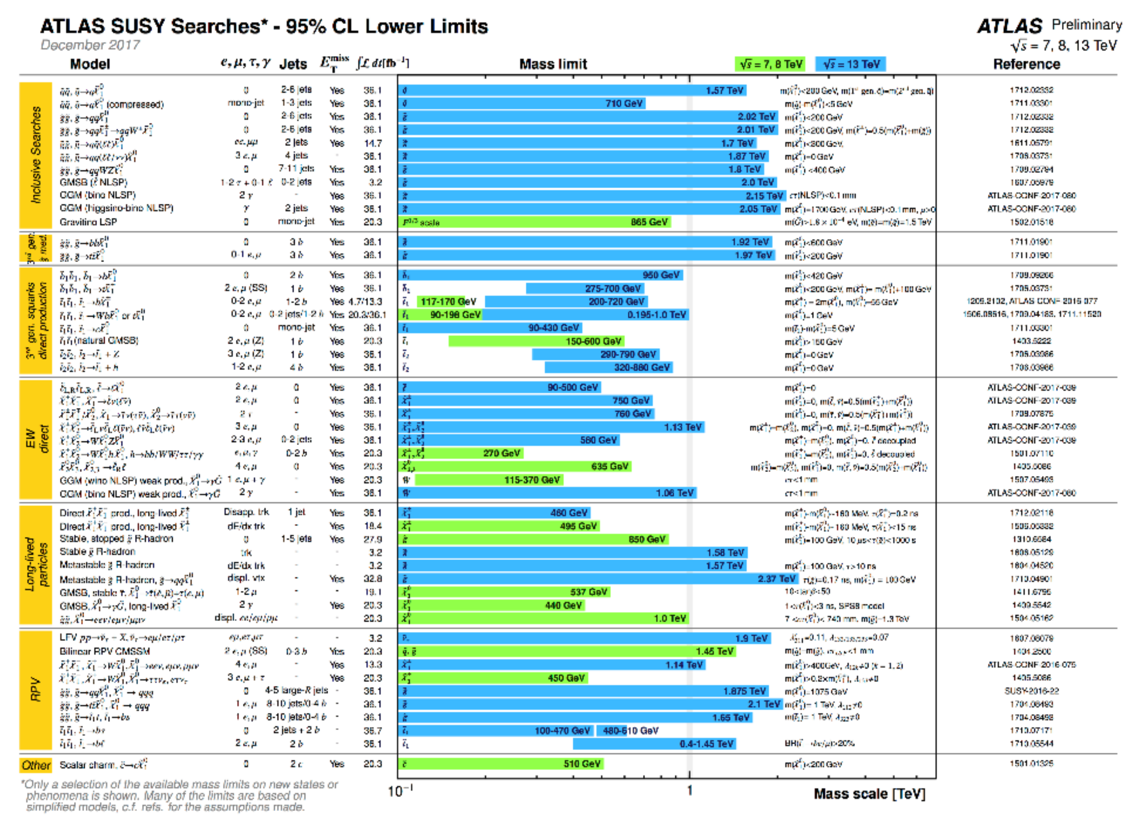
The Snowmass report sets as a target that should be achieved for f_{a3} an accuracy of better than 10^{-5}!

LHC searches for new particles

[⟶ see talks by A. Spiezia. H. Oide, …]

Example: current SUSY limits





Summary for **SuSy searches** at ATLAS and CMS (**caveat** - limits based on simplified models with many signal model assumptions):

- **squarks** mass < 1.5 TeV
- **gluinos** mass < 2 TeV
- third generation **b/t squark** mass < 1 TeV
- **chargino/neutralino** < 0.5 TeV

There is much more to explore in the next 20 years

[⟶ many talks at this workshop]

- Flavour physics at the LHC and Belle II: what will be the fate of the currently observed anomalies in the flavour sector? Will a clear pattern of deviations from the SM be established?

- Electroweak precision measurements at the LHC and other experiments, rare processes: M_W, g_μ-2, edms, …

- Dark matter searches: LHC, Belle II, direct detection experiments, indirect detection experiments, searches for axions and axion-like particles, …

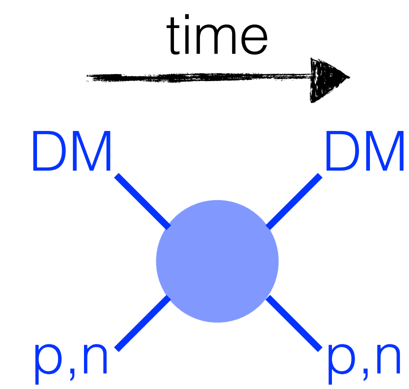
- Astrophysical observations, gravitational wave detection

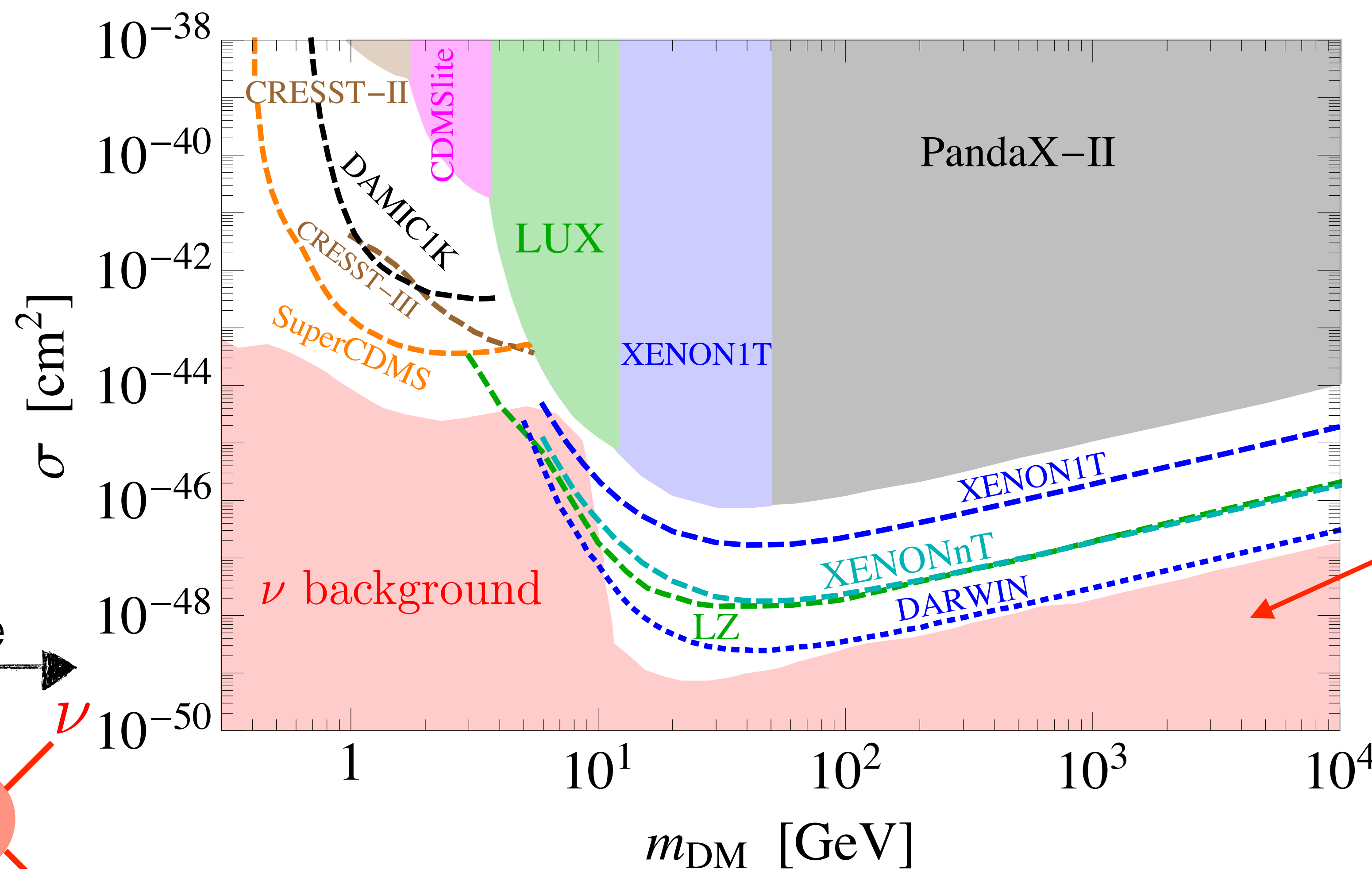
- …

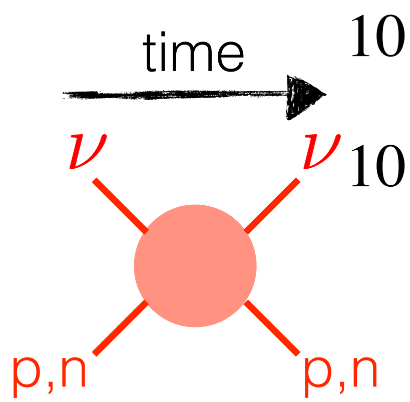
Prospects for dark matter searches

Direct Detection

[J. Ruderman '18]







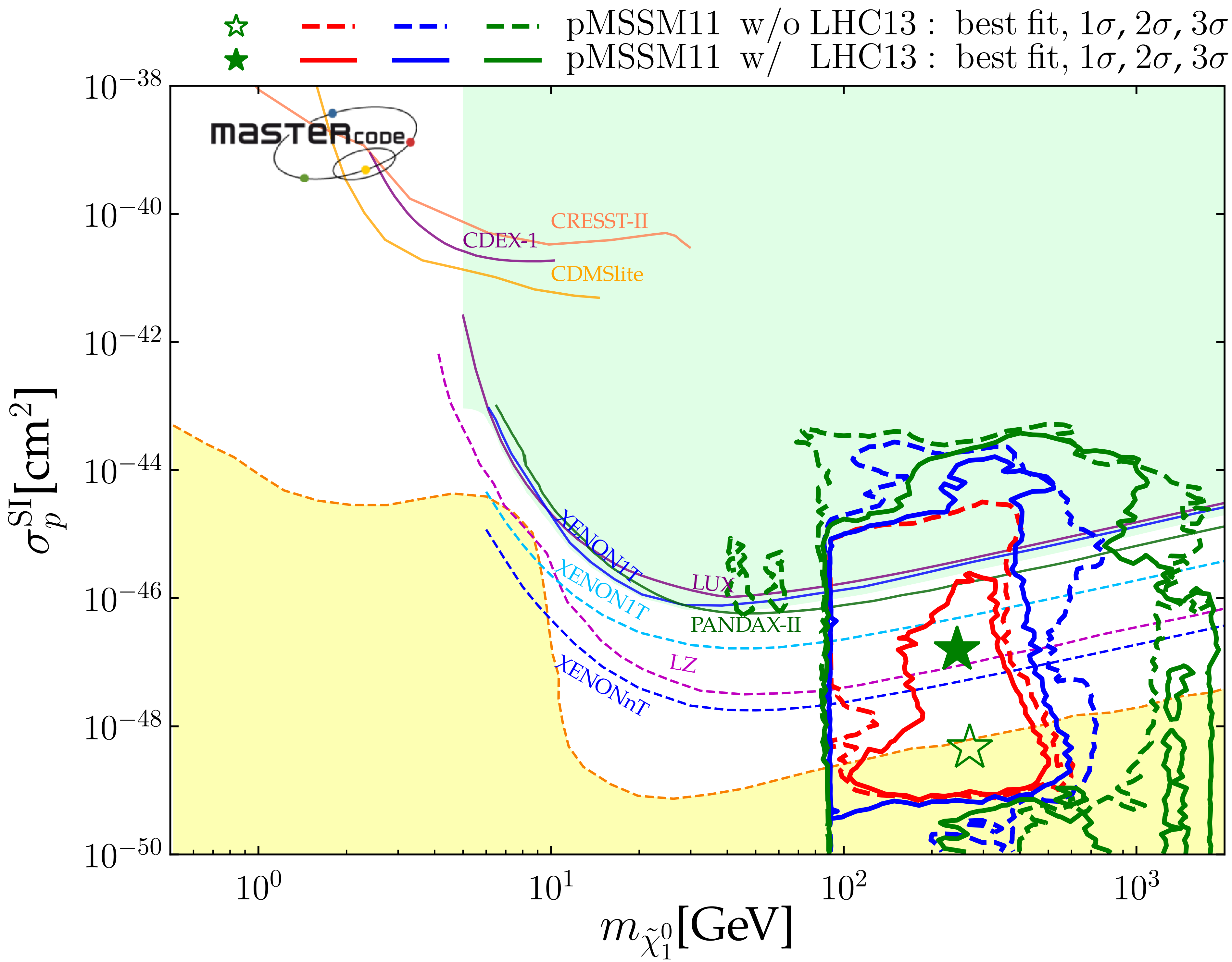
How to probe the ``neutrino floor"?

[⟶ see talk by Antonia Di Crescenzo]

- SuperCDMS Collaboration, Phys. Rev. D **95**, 082002 (2017)
- DAMIC1K, US Cosmic Visions, arXiv:**1707.04591** (2017)
- CRESST Collaboration, arXiv:**1503.08065** (2015)
- XENON Collaboration, JCAP **1604**, 027 (2016)
- DARWIN Collaboration, JCAP **1611**, 017 (2017)
- LUX-ZEPLIN Collaboration, TDR, arXiv:**1703.09144** (2017)

Present direct detection bounds and expected future sensitivities vs. preferred MSSM region

[E. Bagnaschi et al. ’17]



3. What may be the open questions in about 20 years from now?

To what extent will we have answered the open questions that we have now?
Which additional questions will have emerged?

``Rumsfeld's Matrix of Particle Physics": *[J. Ruderman, FCC Week 2018]*

I. **known knowns** Standard Model	**II.** **known unknowns** "known" new physics ex) dark matter, baryogenesis, inflation, quantum gravity, …
IV. **unknown knowns** new physics modifies known physics	**III.** **unknown unknowns** surprises

How much will we know about BSM physics?

- We will for sure be able to rule out many scenarios / parameter regions that are currently viable
- The improved precision of Higgs measurements together with reduced theoretical uncertainties will play an important role in this context

But will we have firm direct or indirect evidence for physics beyond the SM?

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.

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

⇒ Need very high precision for the couplings

4. How could we answer the open questions?

- Higgs factory: 250 GeV + possibly higher energies
  ILC, CEPC, FCC-ee

[⟶ see talks by J. List, M. Petric, R. Poeschl, …]

- ee linear colliders at higher energies
  ILC500, ILC1000, CLIC380, …, CLIC3000

- ep colliders
  LHeC, FCC-ep

[⟶ see talk by R. Poeschl]

- pp colliders
  HE-LHC, FCC-hh, SPPC

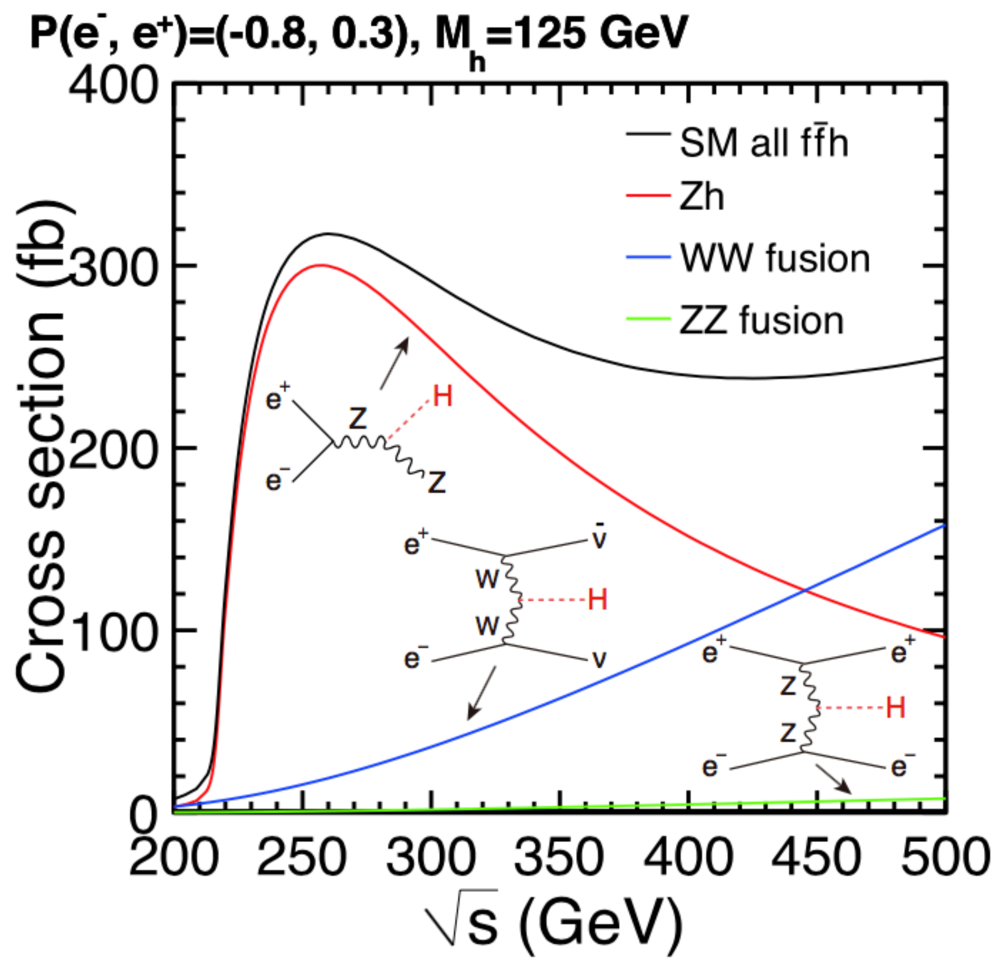
- …

- \+ other experiments at lower energies

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

[⟶ see talks by J. List, M. Petric, R. Poeschl]

``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

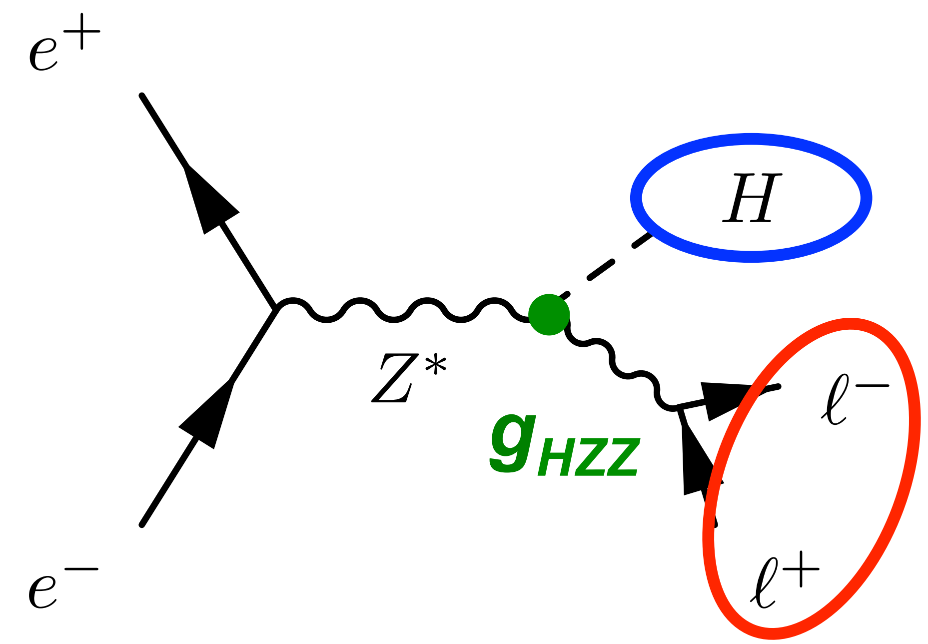
"Golden channel": $e^+e^- \to ZH, Z \to e^+e^-, \mu^+\mu^-$

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

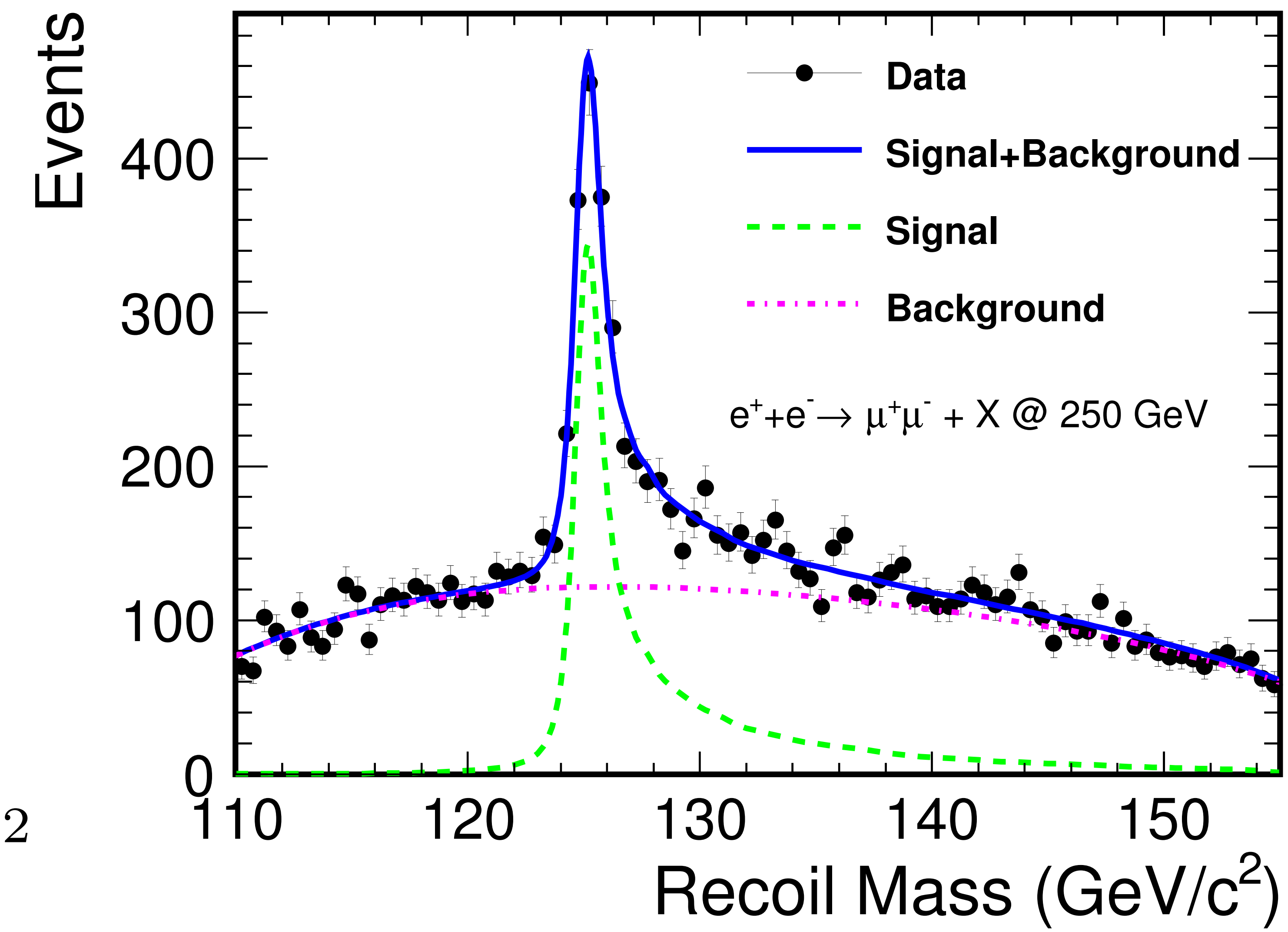
Reconstruct **$Z \to l^+l^-$**

independent of Higgs decay

sensitive to invisible Higgs decays



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



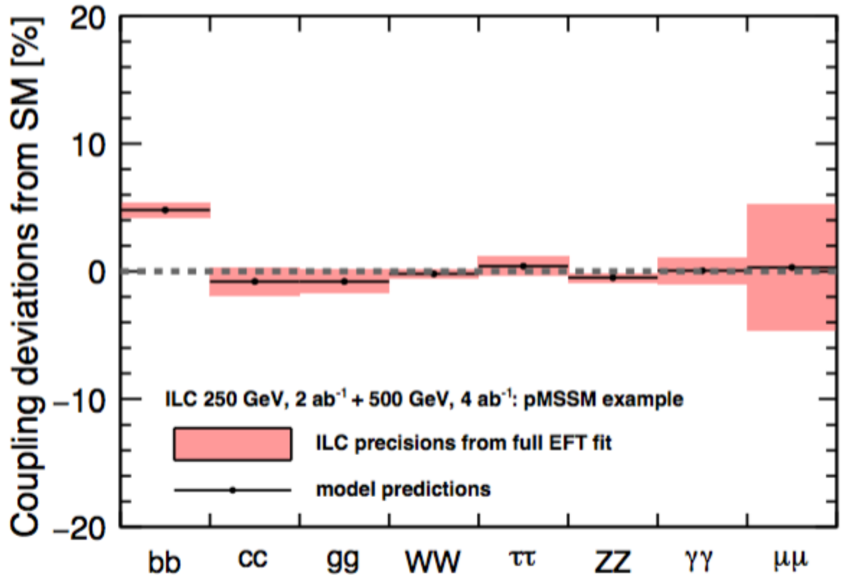
Since the Z ⟶ l^+l^- decay branching fraction is known from the e^+e^- collider LEP, this method yields an absolute measurement of the ZH cross section and the Higgs branching ratios! 1% level reachable!

⇒ Large quantitative + qualitative improvements over HL-LHC

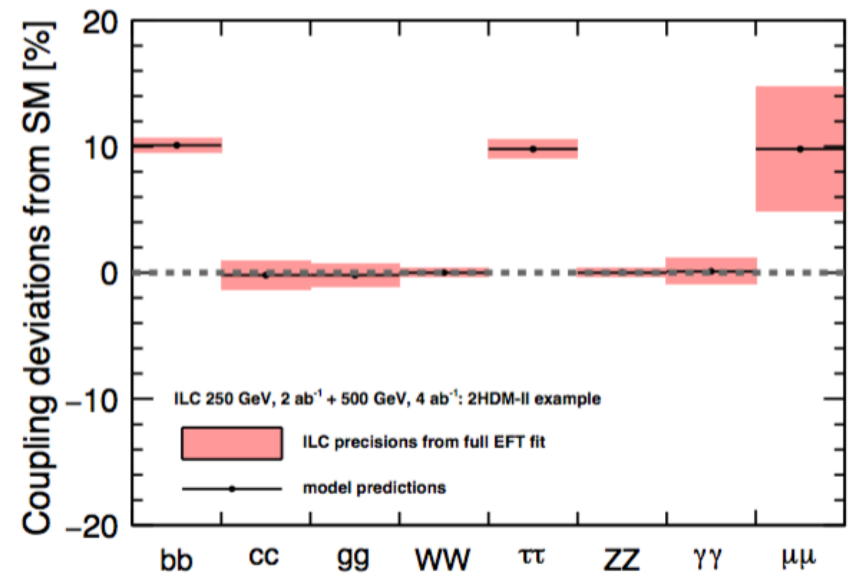
Coupling deviations for different models vs. ILC precision

[⟶ see talk by J. List]

heavy SUSY

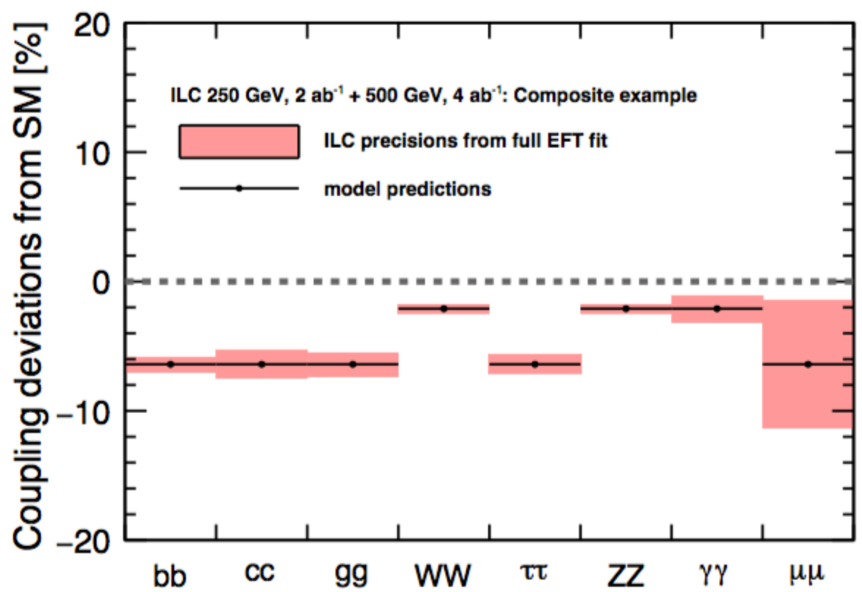


2 Higgs doublet

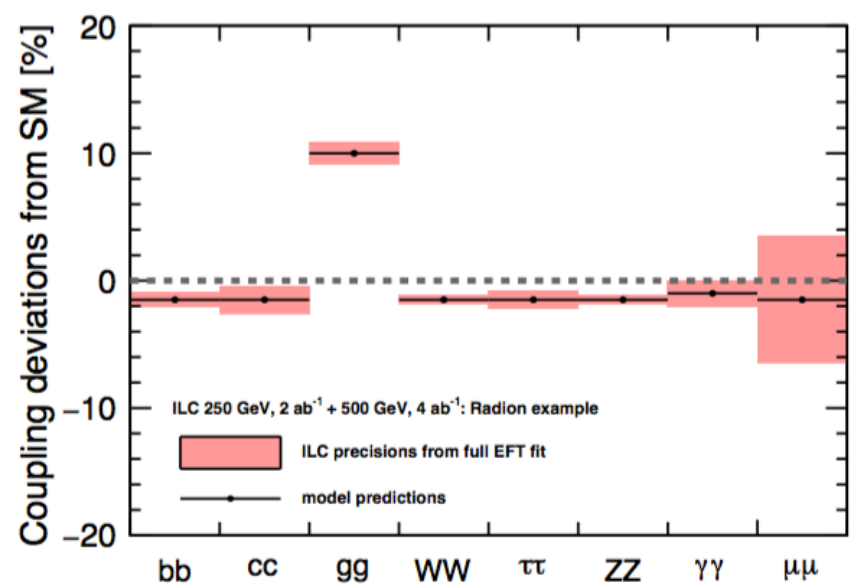


[T. Barklow et al. '17]

composite Higgs



Higgs-Radion mixing



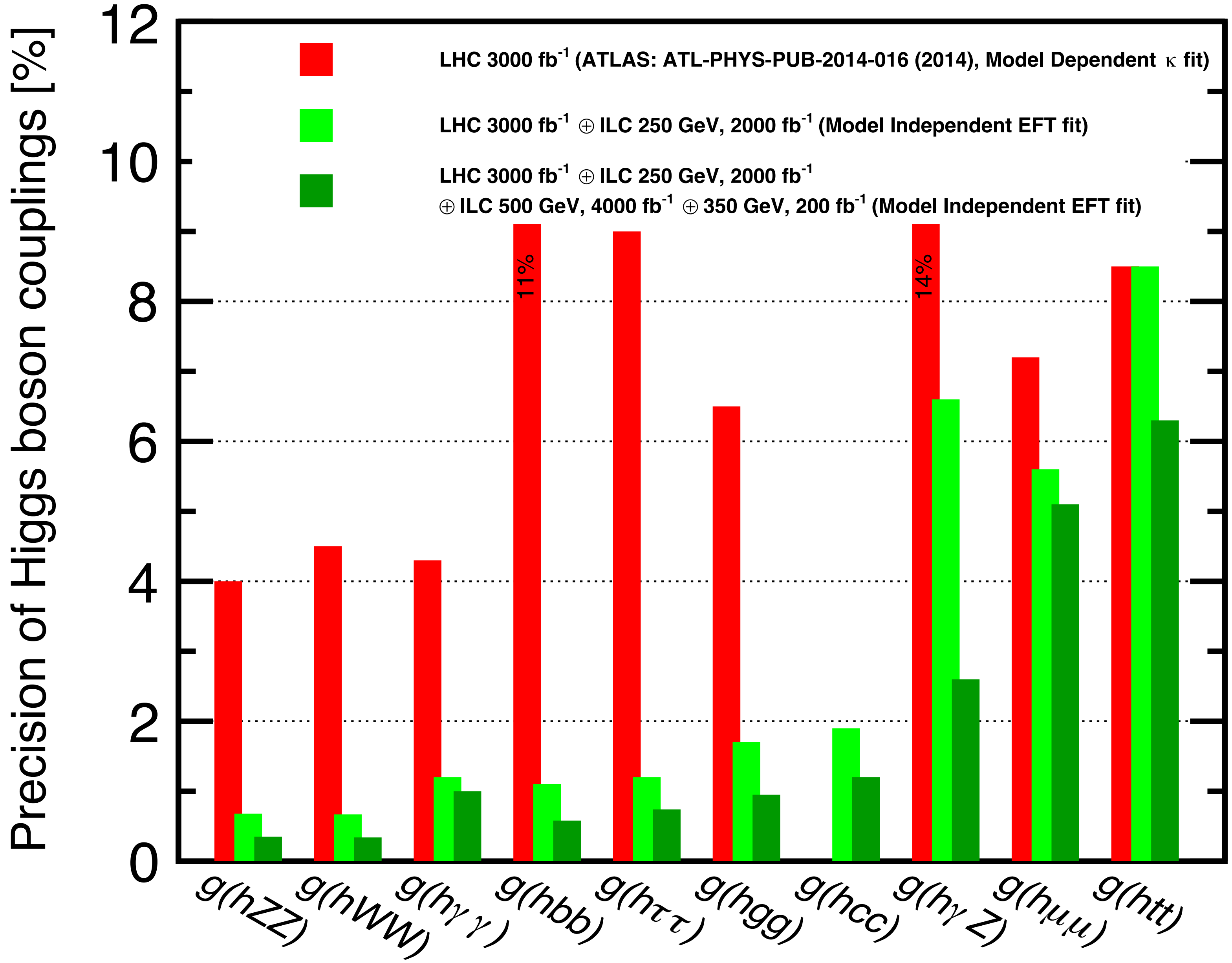
Note:
the displayed models are outside of the reach of the HL-LHC!

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

Projections for HL-LHC, ILC 250 and ILC 500

[⟶ see talk by J. List]

[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

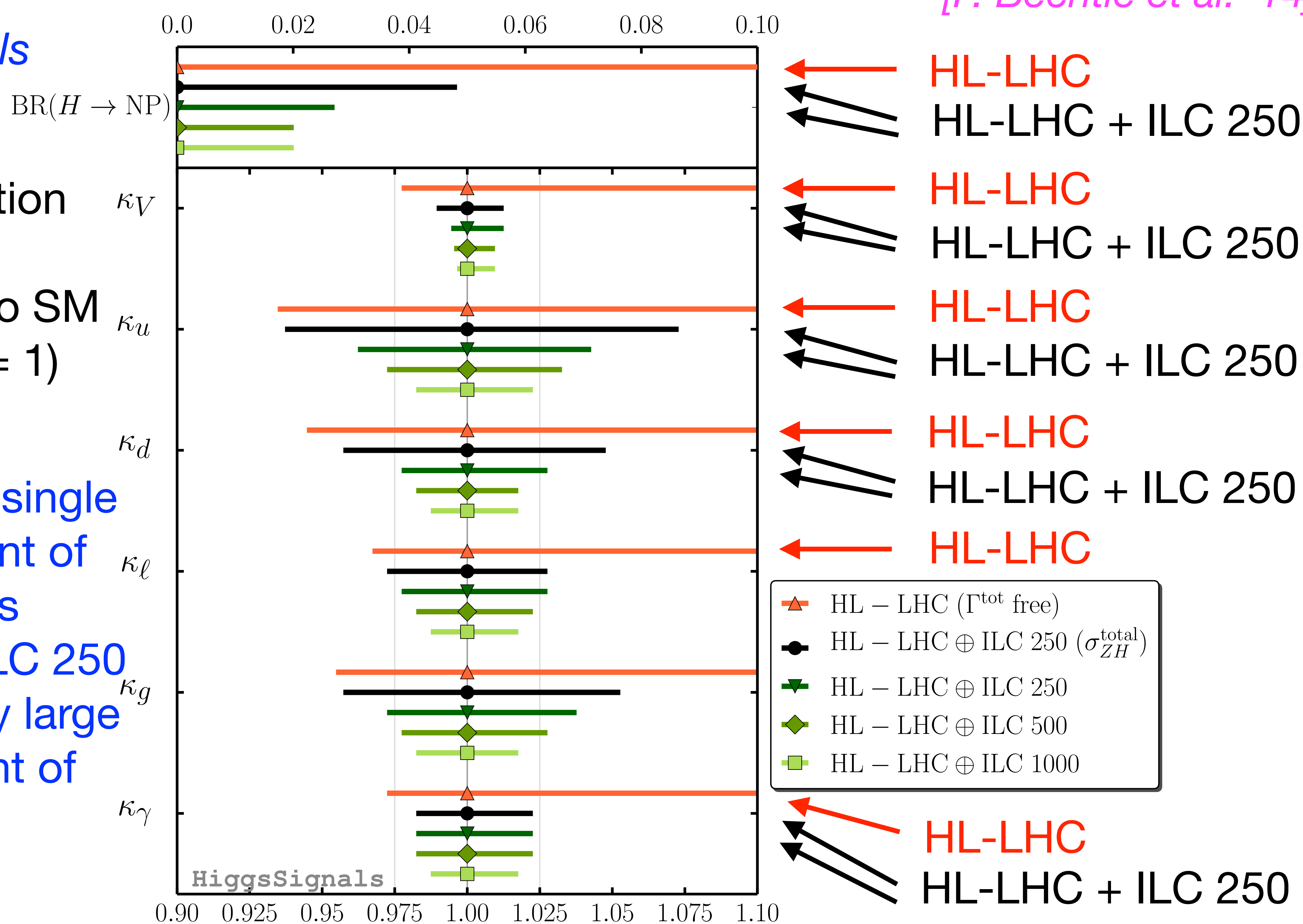
Projections for HL-LHC and ILC, no additional theory assumptions (ILC 250: only 250 fb^{-1})

[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!

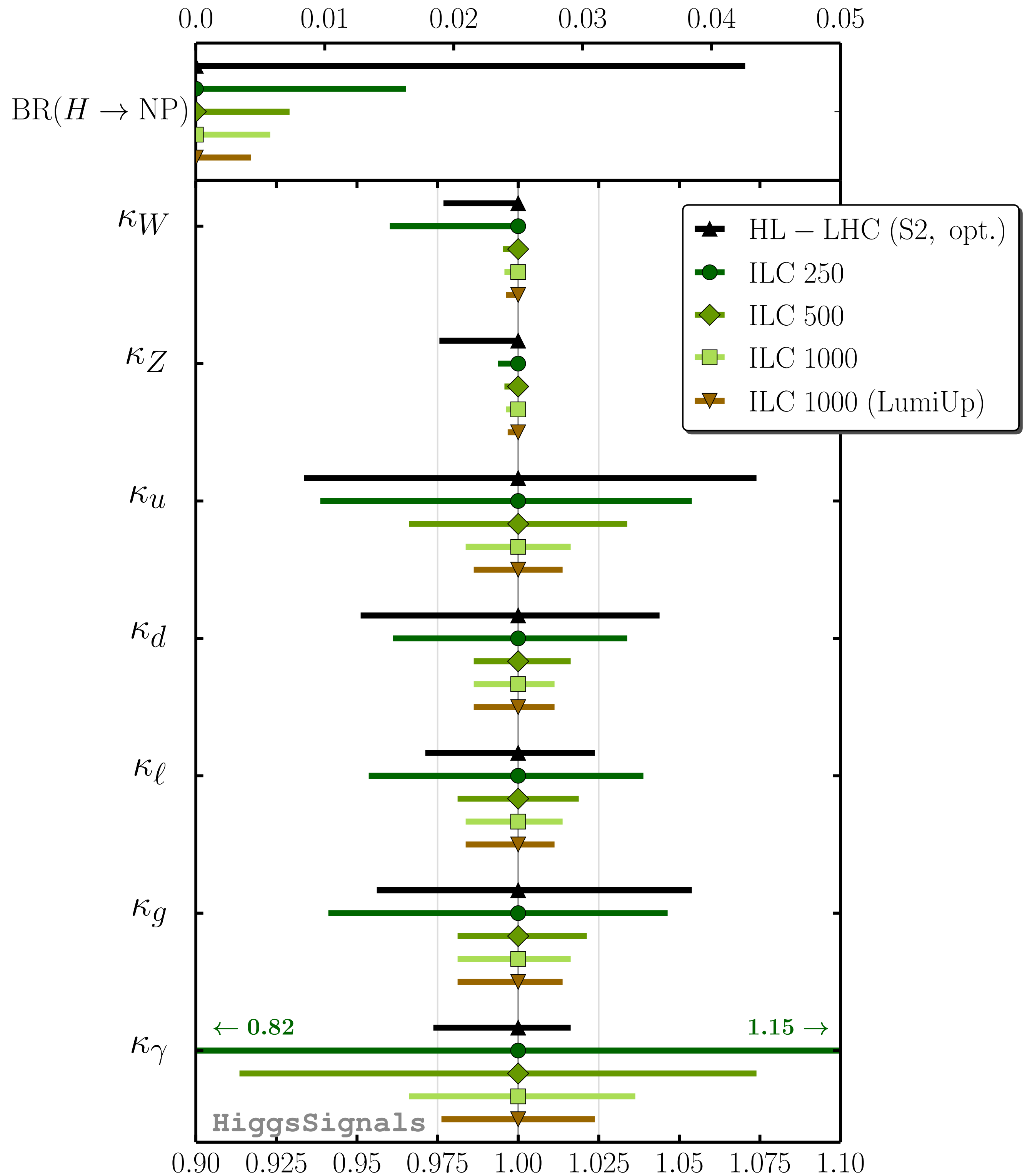


Prospects for Higgs-coupling determinations at HL-LHC and ILC: with theory assumption on κ_V

[P. Bechtle et al. ’14]

HiggsSignals

Assumed: $\kappa_V \leq 1$



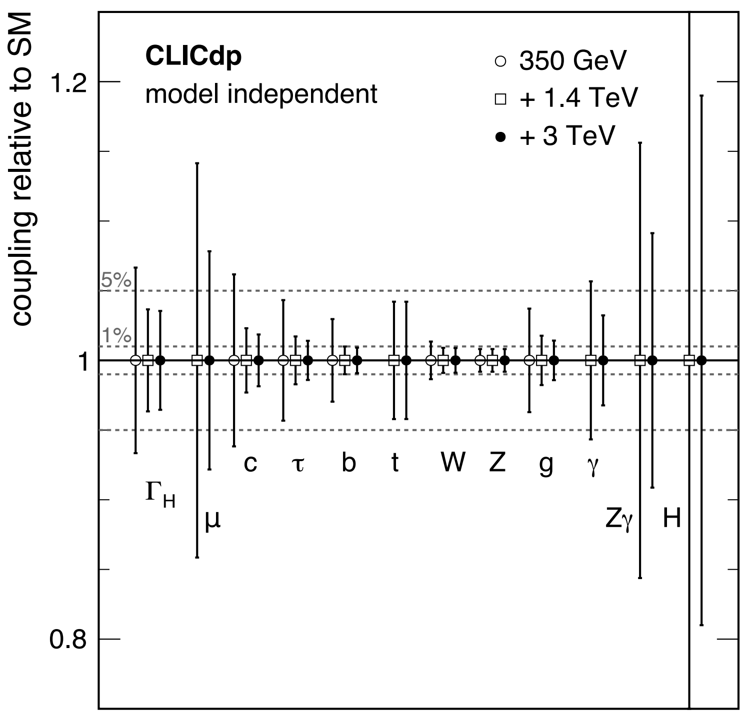
Higgs physics at CLIC

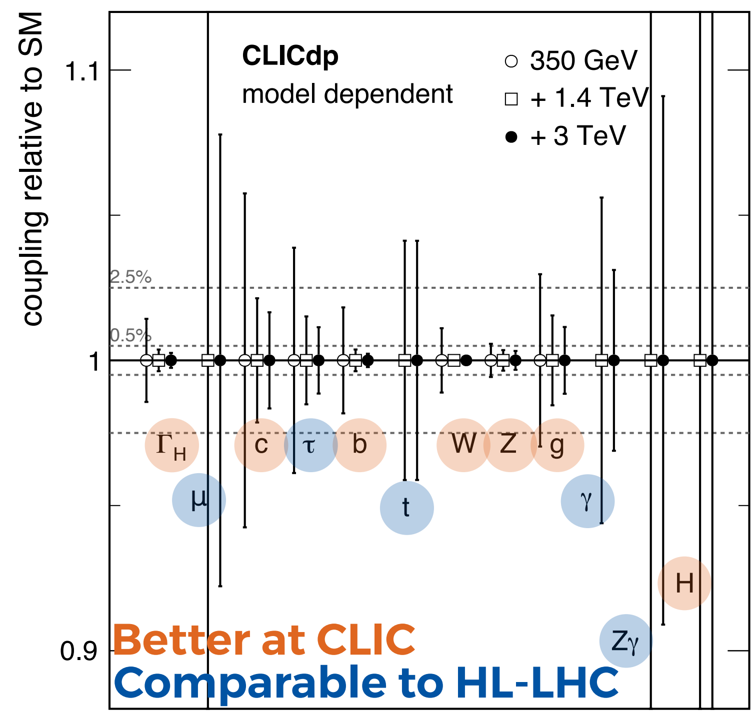
[⟶ see talk by M. Petric]

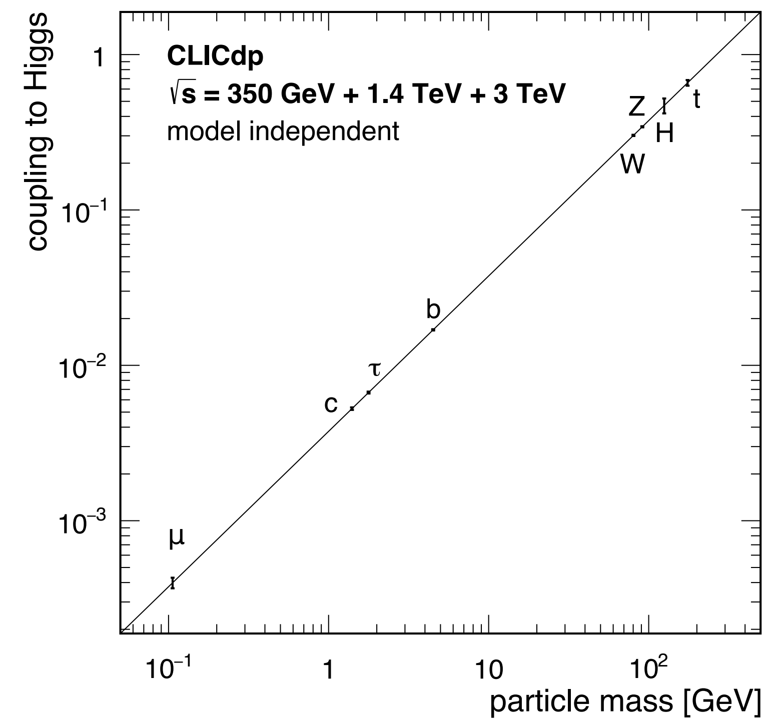
Higgs Measurements Summary

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

Lepton collider allows to measure Higgs properties with high precision







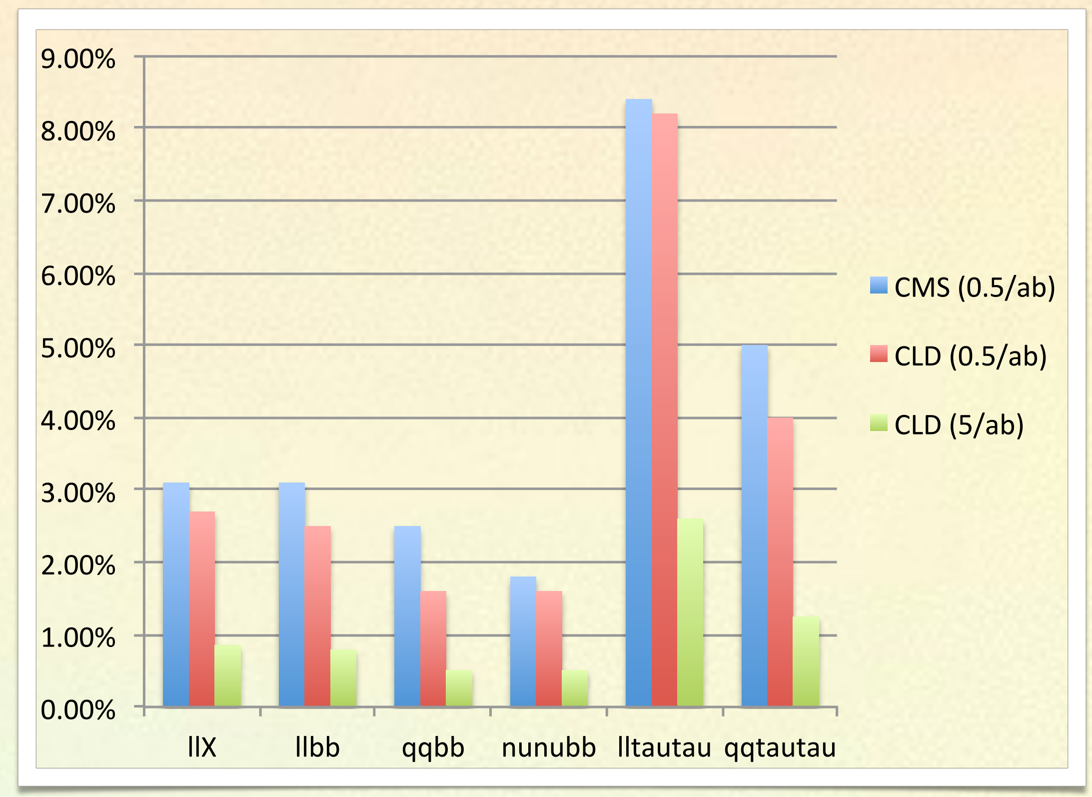
- Model independent extraction only at lepton colliders due to model independent measurement of g_{HZZ}
- Many couplings measured with ~ 1% precision
- Higgs width extracted with 5-3.5% precision
- Model dependent fits can achieve precision below 1%

Higgs physics at FCC-ee

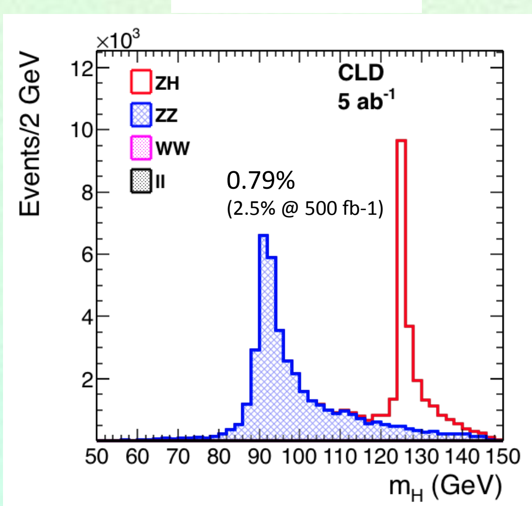
[P. Azzi, FCC Week 2018]

HIGGS

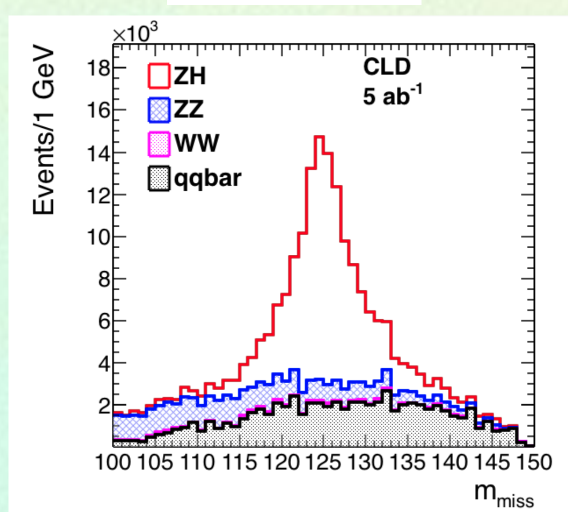
- **Ultimate precision on Higgs couplings below 1% (and measurement of the total width) a milestone of the FCC physics program.**
- **Model independent determination of the total Higgs decay width**
- New estimates of Higgs coupling precision made with custom simulation (PAPAS)
  - CLD performs 10-35% better compared to results with CMS simulation
  - now ready to study variation in detector design cost/performance



$\mathrm{ZH} \rightarrow \ell\ell bb$



$\mathrm{ZH} \rightarrow qqbb$



Patrizia Azzi (INFN/PD) FCC-Week Amsterdam 2018 13

Higgs self-coupling at ILC and CLIC

[⟶ see talks by J. List, M. Petric]

Dissertation C.Dürig, Uni Hamburg, 2016

- **e^+e^- at 500 GeV, ZHH, full simulation:**
    1. Observation of HH with ~8σ ✔
    2. extract $\lambda|_{SM}$ with 27% uncertainty
    3. recent demonstration that parametric uncertainties from other couplings well under control with full ILC Higgs program

arXiv:1708.09079

$\lambda_{HHH}/\lambda^{SM}_{HHH}$

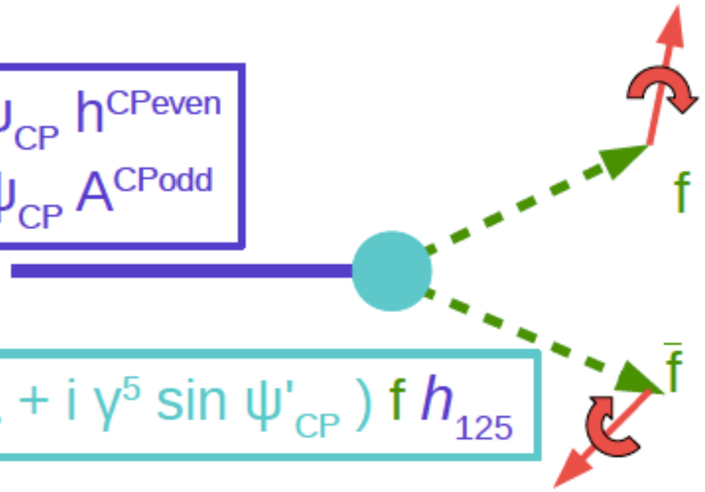
- **e^+e^- at > 500 GeV, vvHH, full simulation:**
    - 1 TeV, 4ab^{-1}: $\delta\lambda/\lambda\ |_{SM}$ = 10%
    - 1.4 TeV, 1.5ab^{-1}: $\delta\lambda/\lambda\ |_{SM}$ = 40%
    - + 3 TeV, 3ab^{-1}: $\delta\lambda/\lambda\ |_{SM}$ = 16%
    - upcoming improvement: exploit differential distributions at 3 TeV: expect ~ 10%

Eur.Phys.J. C77 (2017) no.7, 475

Higgs CP properties at ILC: h ⟶ $\boldsymbol{\tau\tau}$ channel

[⟶ see talk by J. List]

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

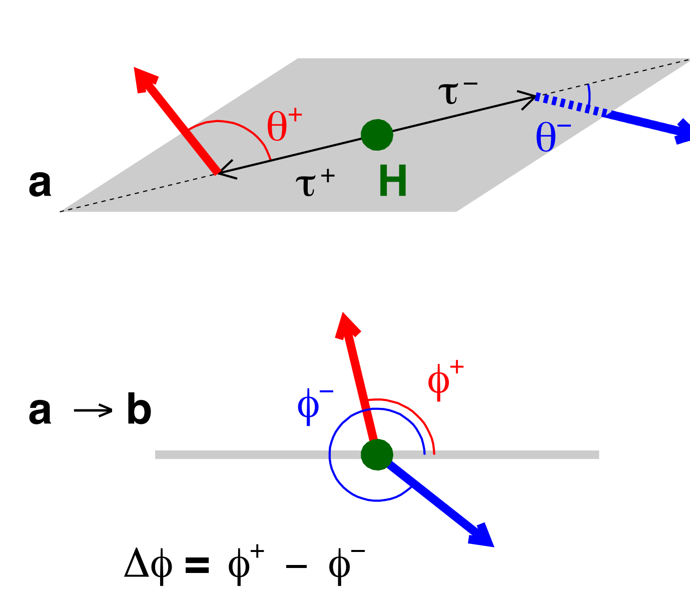


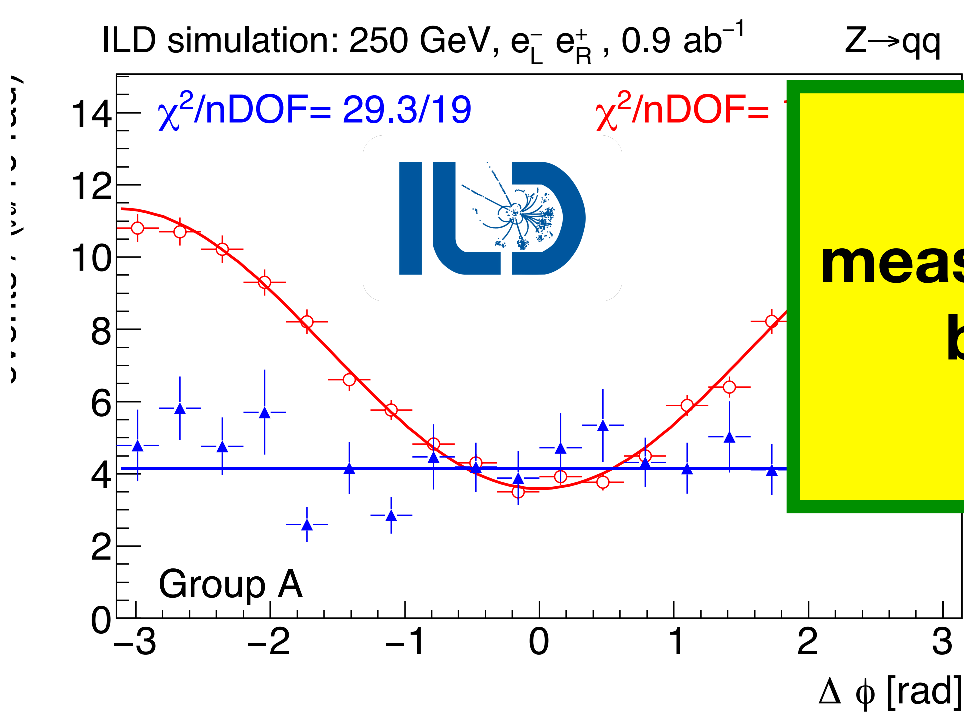
$g\, \bar{f}\, (\cos\psi'_{CP} + i\, \gamma^5 \sin\psi'_{CP})\, f\, h_{125}$

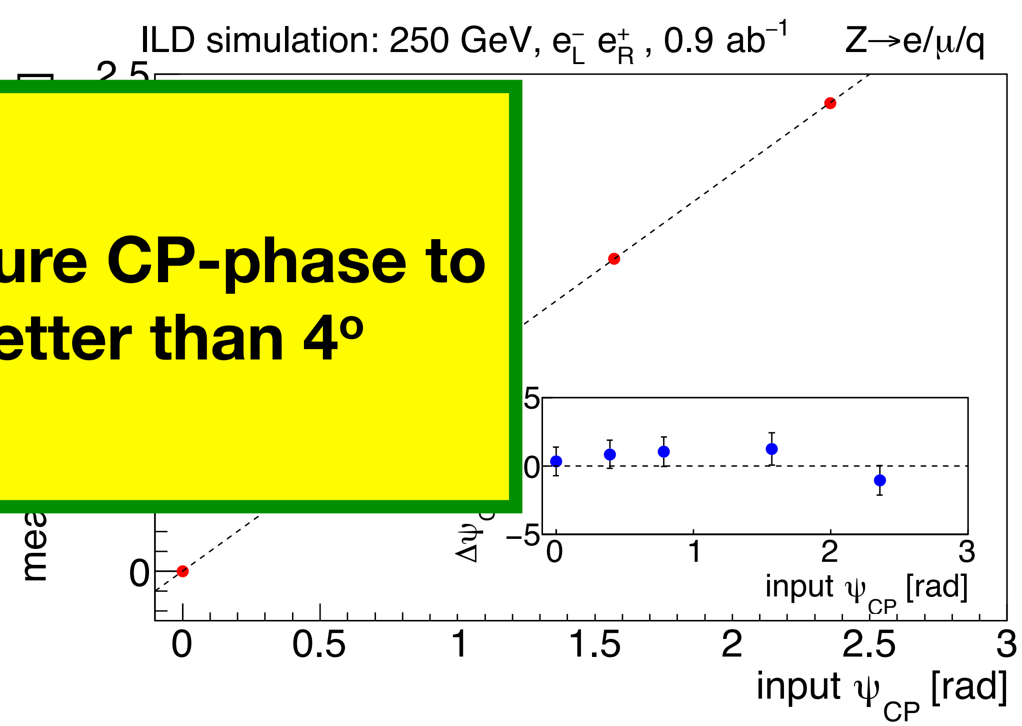
h is a spin 0 state:

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

[ψ = 0 CP even, $\pi/2$ CP odd]







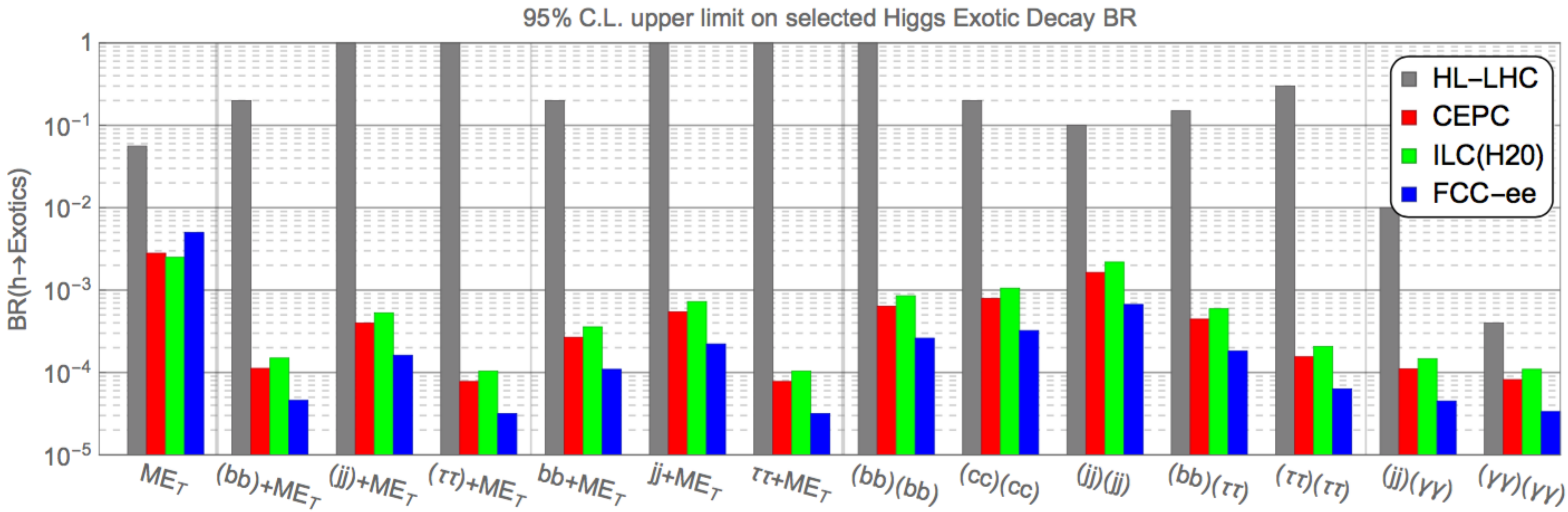
measure CP-phase to better than 4°

arxiv:1804.01241

based on NIM A810 (2016) 51-58

Exotic Higgs decays: HL-LHC and e^+e^- Higgs factories

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



⇒ Large improvements over HL-LHC

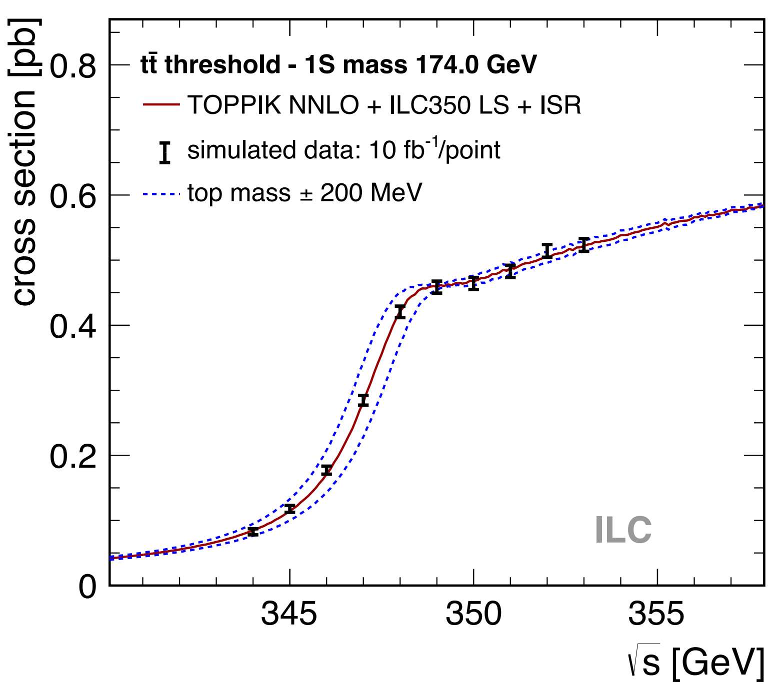
Top-quark mass measurement at ILC / CLIC

[⟶ see talks by J. List, M. Petric]

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 the ILC / CLIC 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.

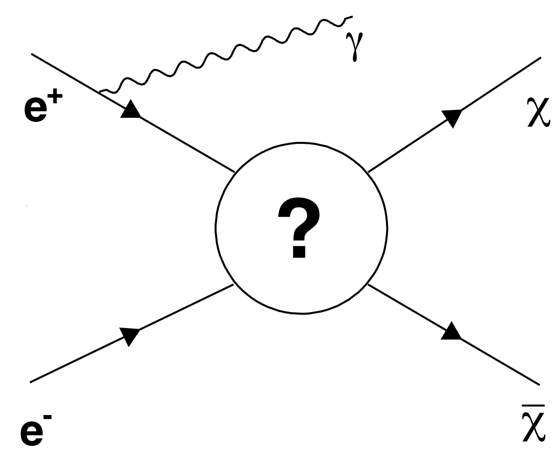


Discovery potential of an e^+e^- Higgs factory for the production of new particles

- Higgs decays to dark matter and other new particles: Higgs factory has sensitivity down to branching ratios of ~0.3% for decays into dark matter (invisible decays); complementary information from precision measurements of the other branching ratios.

- Dark matter production

  + Higgs as mediator



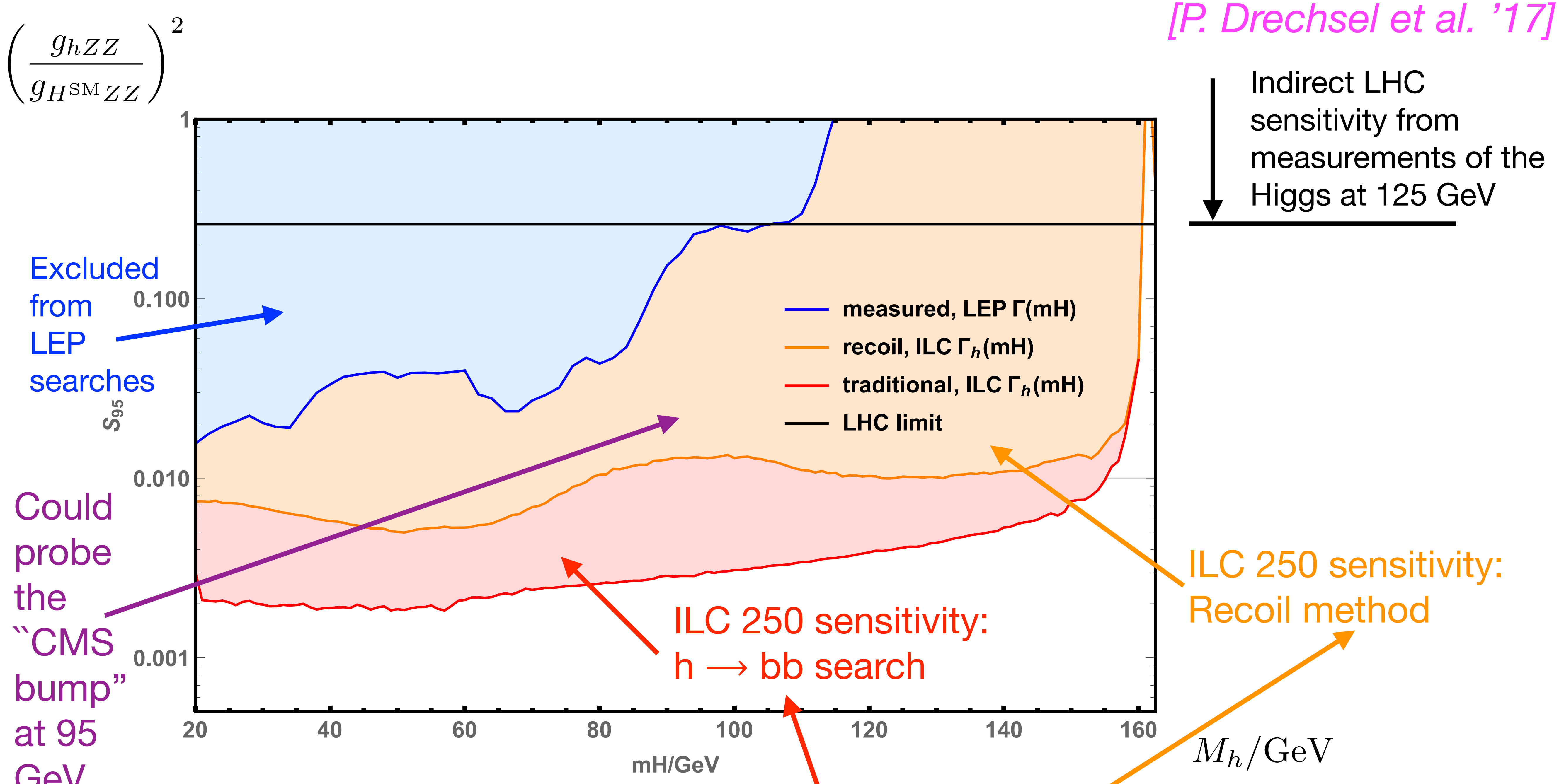
yields complementary sensitivity to the LHC and to direct detection experiments

- Production of additional light Higgs boson(s): Higgs at 125 GeV with SM-like couplings + additional Higgs states with strongly suppressed couplings to gauge bosons (squared couplings of all Higgs bosons add up to SM value). Hardly constrained from searches at LEP, the Tevatron and the LHC.

⇒ Large discovery potential!

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

[P. Drechsel et al. '17]



[⟶ see talk by Anne-Marie Magnan]

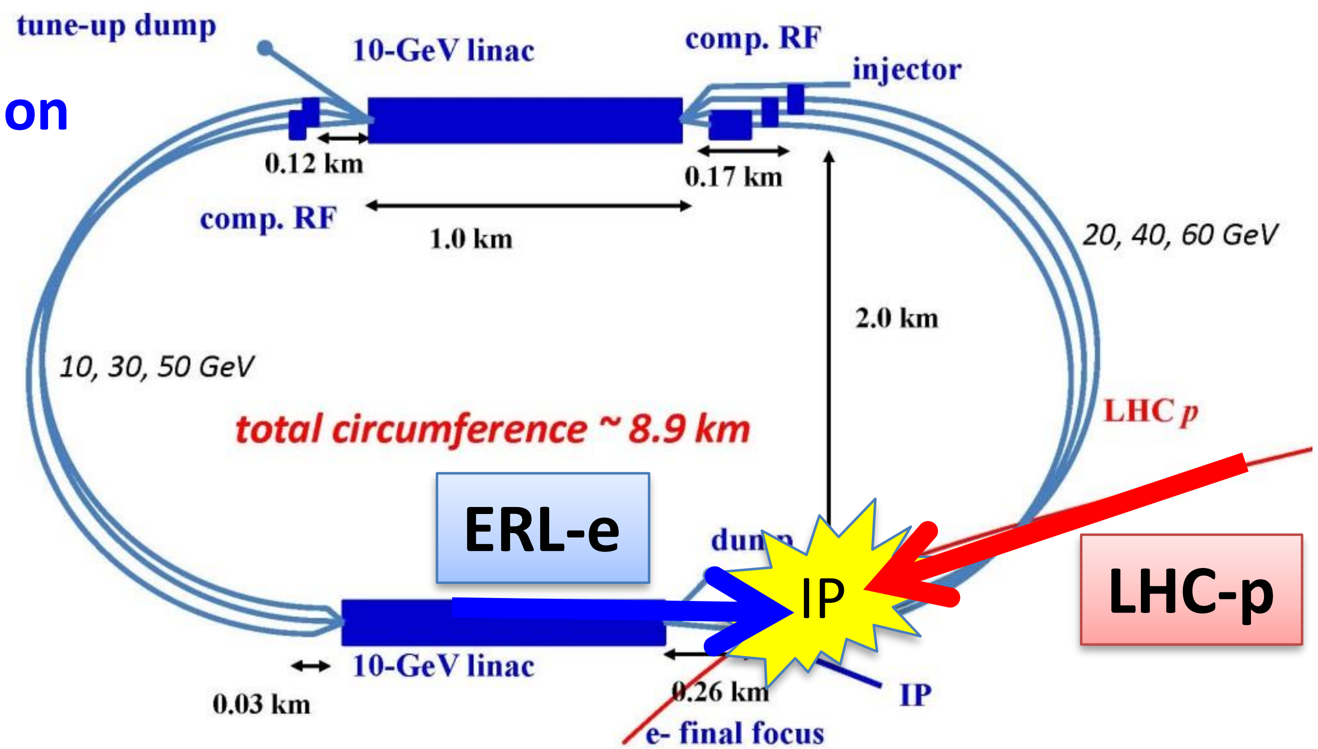
⇒ ILC 250 will explore a large untested region!

LHeC: LHC proton beam + energy-recovery linac

[U. Klein, FCC Week 2018]

- **Two Electron LINACs + 3 return arcs: using energy recovery in same structure: 'green' technology with power consumption < 100 MW : nominal E_e = 60 GeV**
- **Beam dump: no radioactive waste!**
- **high electron polarisation of 80-90%**
- **Installation decoupled from LHC operation**

Concurrent ep and HL-LHC operation!
Same idea holds for HE-LHC and FCC-hh



- **ep Lumi 10^{34} cm s^{-2} s^{-1} ****
- **100 fb^{-1} per year, e.g. ~2030-2040 (HL-LHC)**
- **L= 1000 fb^{-1} total collected in 10 years**
- **eA luminosity estimates ~ 10^{33} cm s^{-2} s^{-1} eA**

** based on existing HL-LHC proposal

Detector Design
for HL+HE+FCC ep
Peter Kostka et al.
→ installation in 2 years,
e.g. during LS4

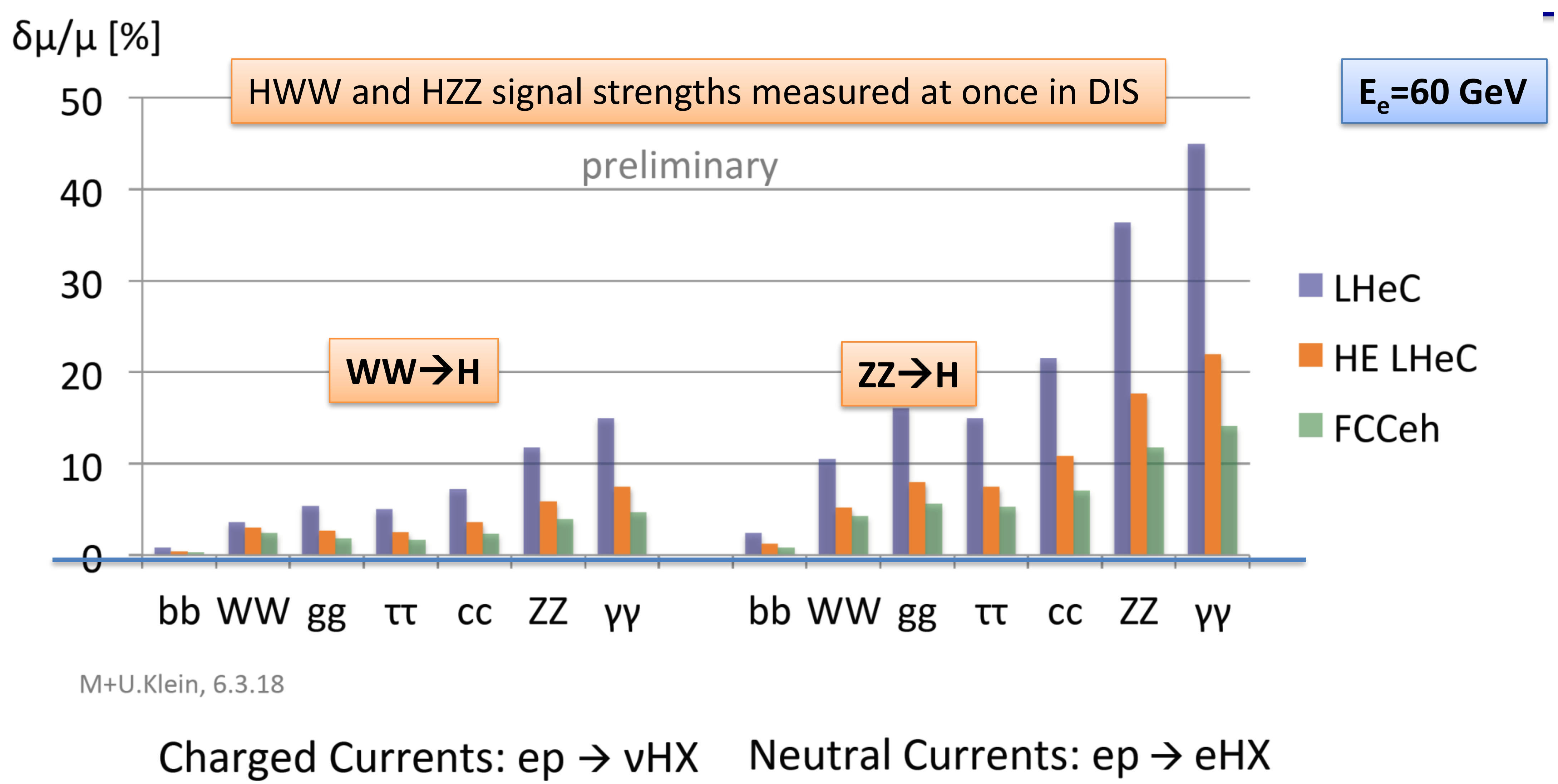
LHeC CDR: arXiv:1206.2913 and updates at LheC/FCC-eh WS@CERN, 9/17

Higgs physics at LHeC and beyond

[U. Klein, FCC Week 2018]

Uta & Max Klein, Contribution to HL/HE Workshop, 4.4.2018, preliminary

Signal Strengths @ LHeC - HE-LHeC - FCCeh



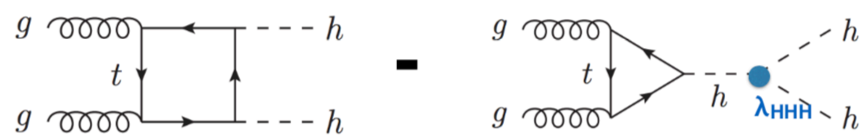
→NC and CC DIS together over-constrain Higgs couplings in a combined fit.

Di-Higgs production at FCC-hh

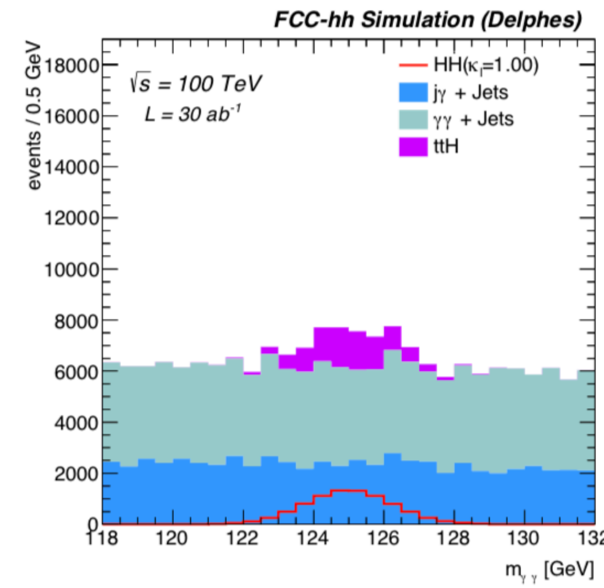
[M. Selvaggi, FCC Week 2018]

Di-Higgs

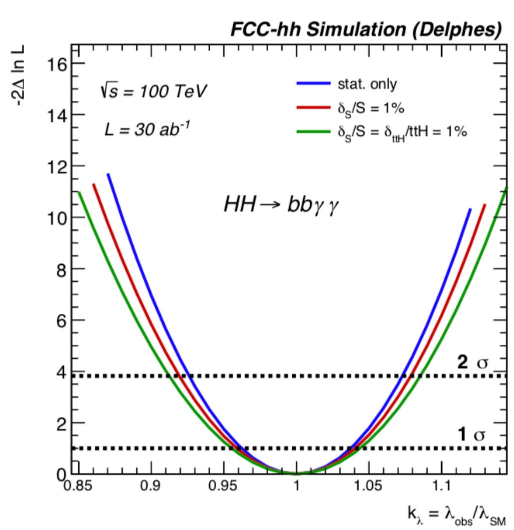
gluon fusion:



$\sigma(100\ \text{TeV}) / \sigma(14\ \text{TeV}) \approx 40$

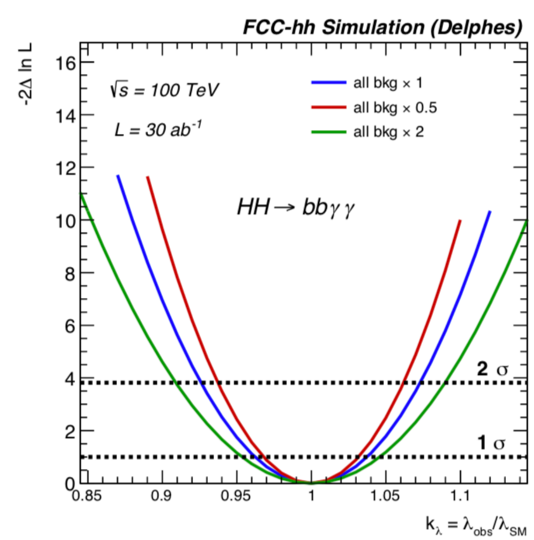


assuming QCD can be measured from sidebands



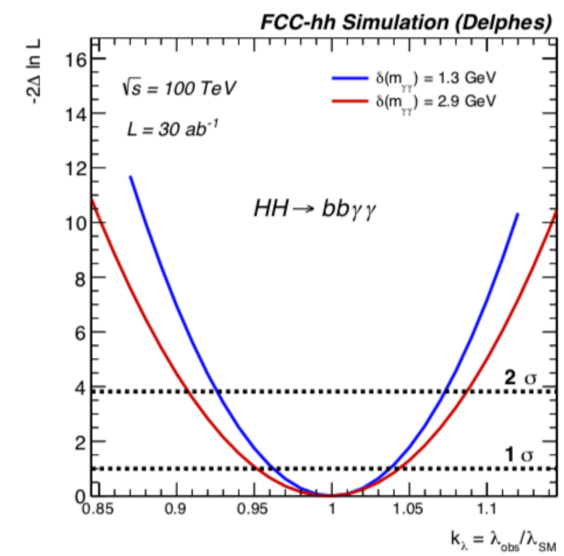
nominal background yields:

$\delta\kappa_\lambda(\text{stat}) \approx 3.5\ \%$
$\delta\kappa_\lambda(\text{stat + syst}) \approx 4.5\ \%$
$\delta r(\text{stat}) \approx 2.5\ \%$
$\delta r(\text{stat + syst}) \approx 3\ \%$



varying (0.5x-2x) background yields:

$\delta\kappa_\lambda(\text{stat}) \approx 3 - 5\ \%$
$\delta r(\text{stat}) \approx 2 - 3\%$

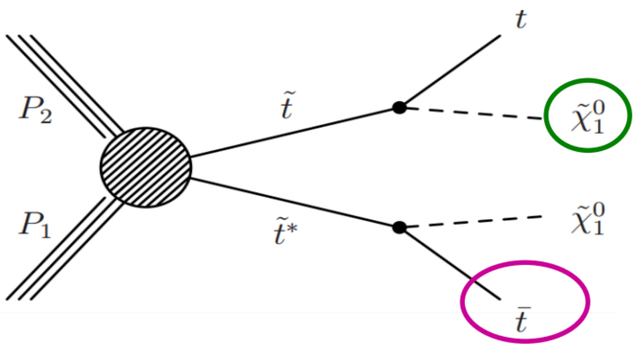


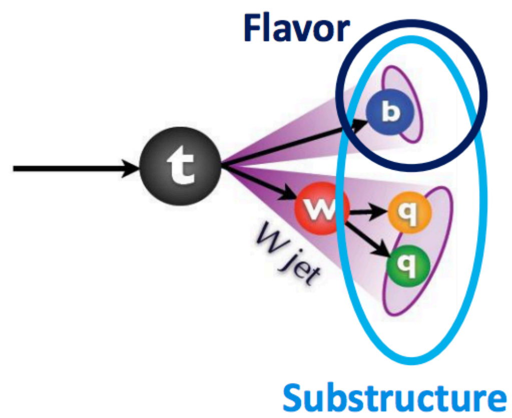
$m(\gamma\gamma)$ resolution

Giacomo Ortona

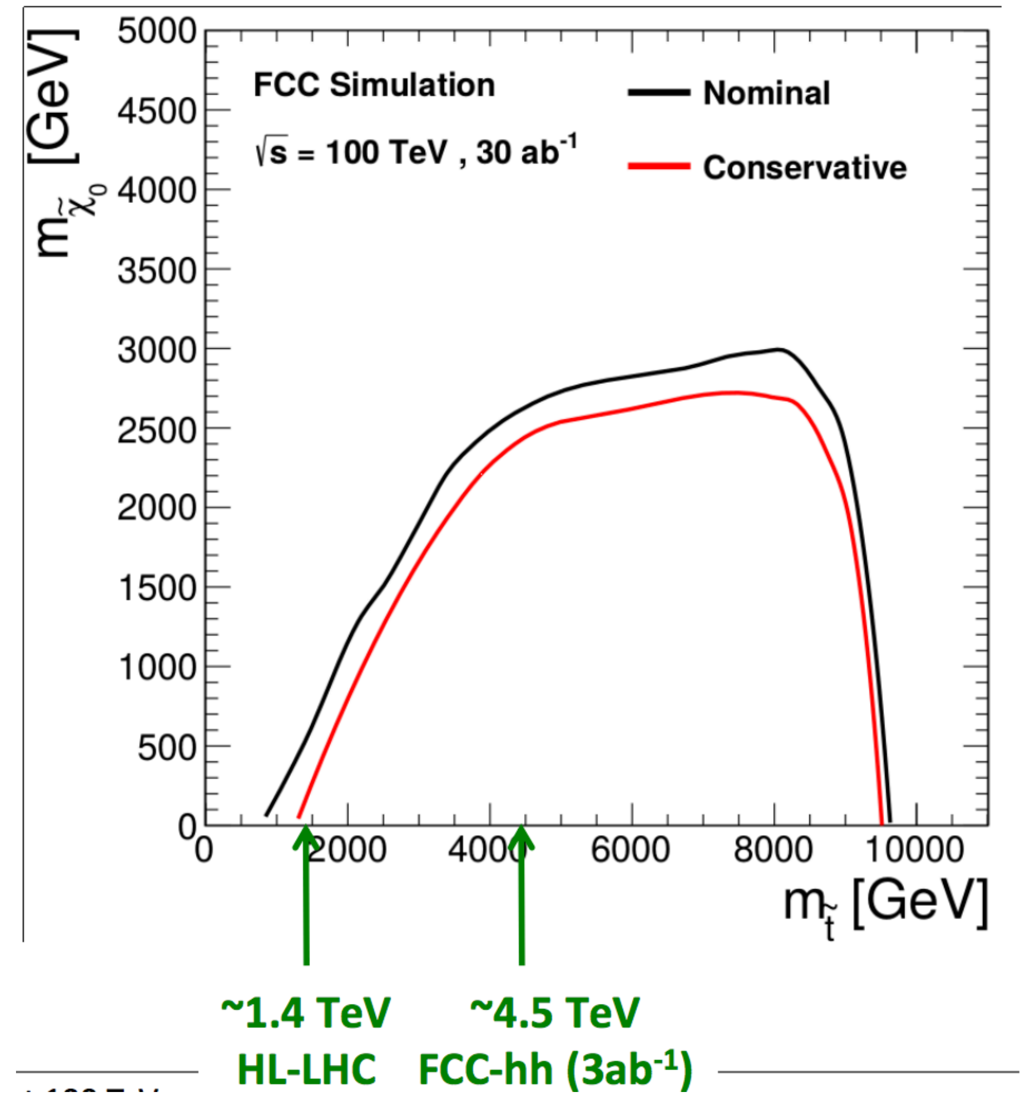
Search for new particles, example: stops (SUSY)

[M. Selvaggi, FCC Week 2018]





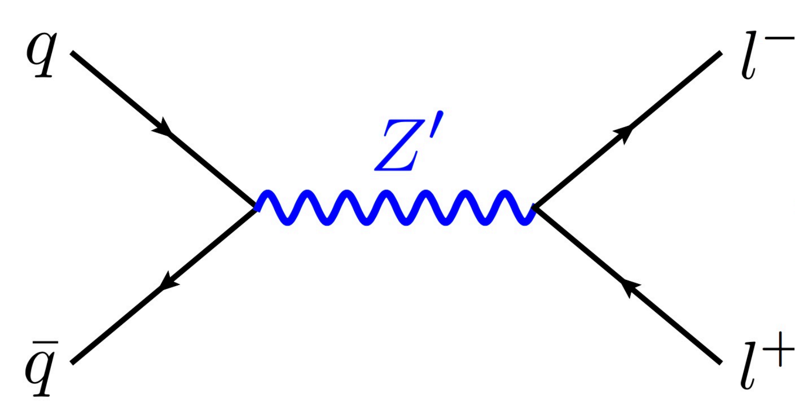
Discovery potential (5σ)

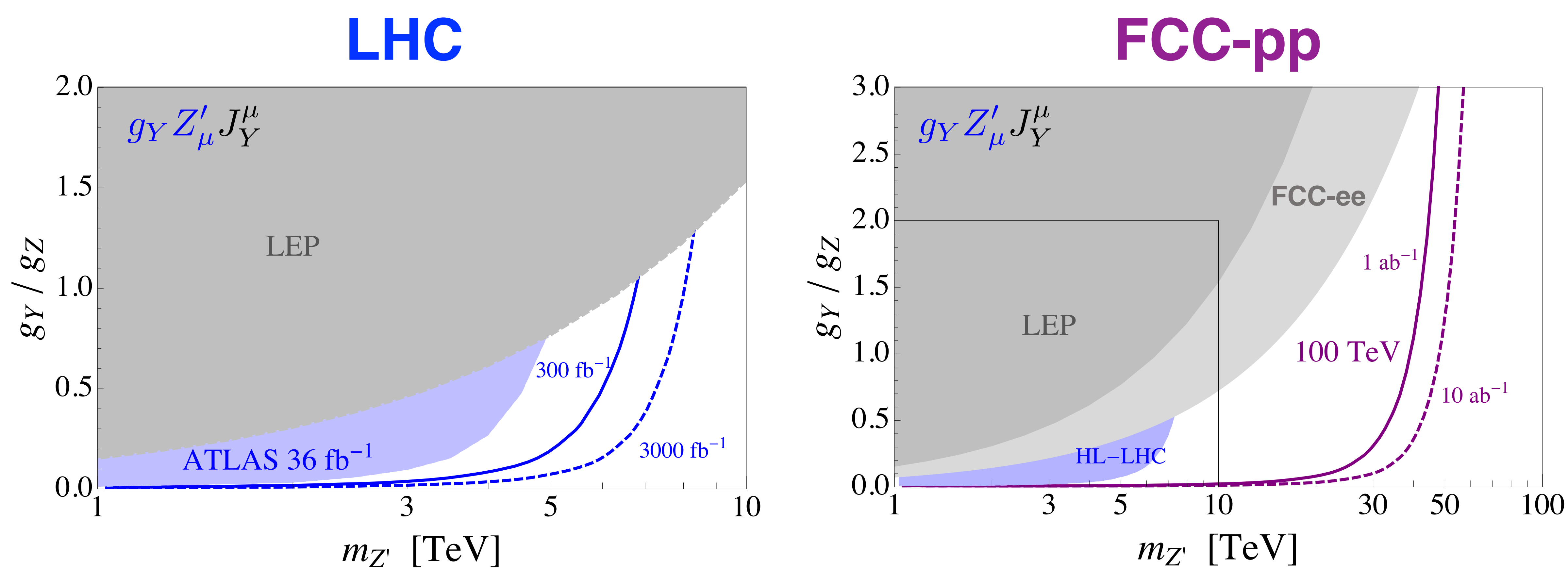


⇒ Large discovery potential
for heavy new particles

Sensitivity to new force carrier

[J. Ruderman, FCC Week 2018]





- LEP: Falkowski, Gonzalez-Alonso, Mimouni, JHEP **1708**, 123 (2017)
- LHC: ATLAS Collaboration, JHEP **1710**, 182 (2017)
- FCC-pp: Thamm, Torre, Wulzer, JHEP **1507**, 100 (2015)

5. Conclusions

It is likely that many of the open questions that we have now will not be fully answered by the end of the HL-LHC, and there will for sure also be new open questions.

An e^+e^- Higgs factory could play a crucial role in addressing some of those questions. Such a facility could be ready in time to directly follow on from the HL-LHC and even have some overlap with it.

The results from a Higgs factory could have a large impact on shaping the physics programme of a future hadron machine at the energy-frontier as well as of a possible upgrade of an e^+e^- facility to higher energies.

Can the physics potential of LHeC compete with the one of a dedicated Higgs factory?

The HE-LHC, FCC-hh and SPPC have a large discovery potential for new physics. We need guidance on what is the right energy.

Many thanks to the organisers for making this great workshop possible!

I think all of you will agree with me that we very much enjoyed the physics, the mountains and the nice atmosphere at the University Centre Obergurgl!

Thank you very much to both the organisers and the team of UZ Obergurgl for taking care of us so well!

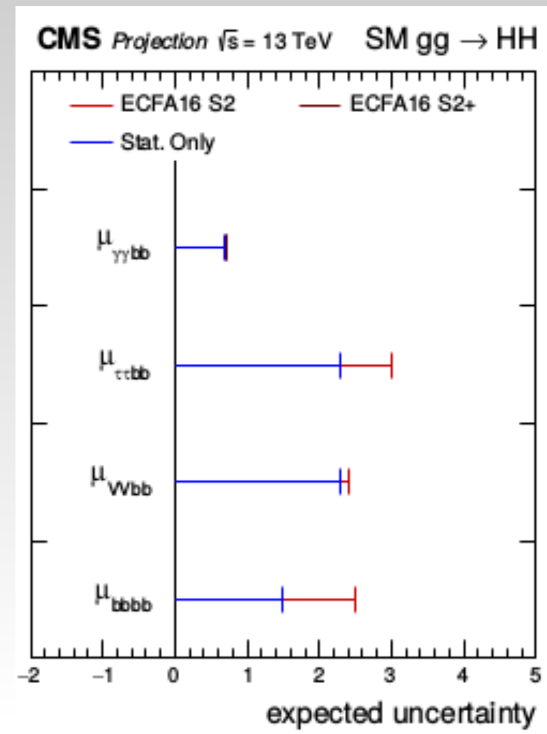
Backup

HH production and Higgs self-coupling at HL-LHC

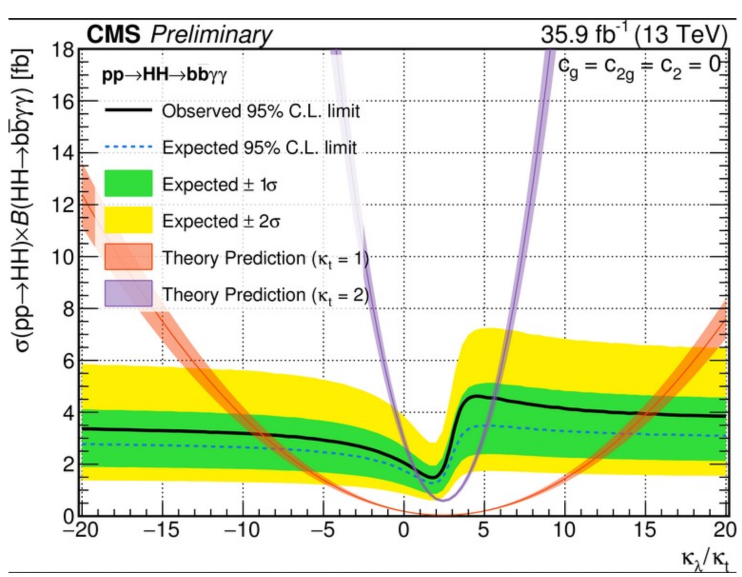
[M. Gouzevitch, LCWS2017]

2.9) HH projections

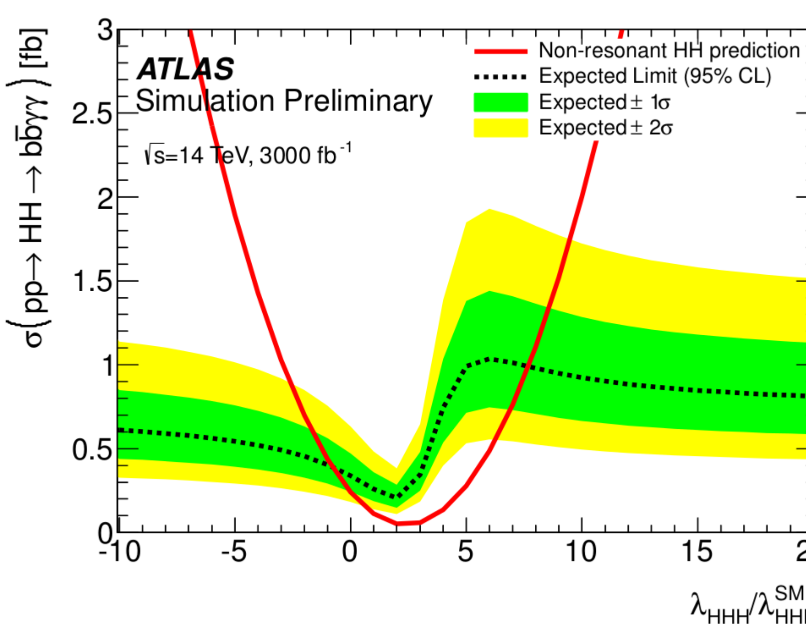
- All sensitive channels includes H → bb final state to maximize the branching fraction.
- The most sensitive channel appears to be HH → 2b2γ.
- The other channels shows a similar sensitivity. In particular HH → 4b is expected to have a similar sensitivity to HH →ττbb when optimized.
  → In ATLAS this is the most sensitive channels.
- The possibility of "evidence" of HH can be reached combining all channels in CMS and ATLAS.



CMS Run I



ATLAS HL-LHC



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

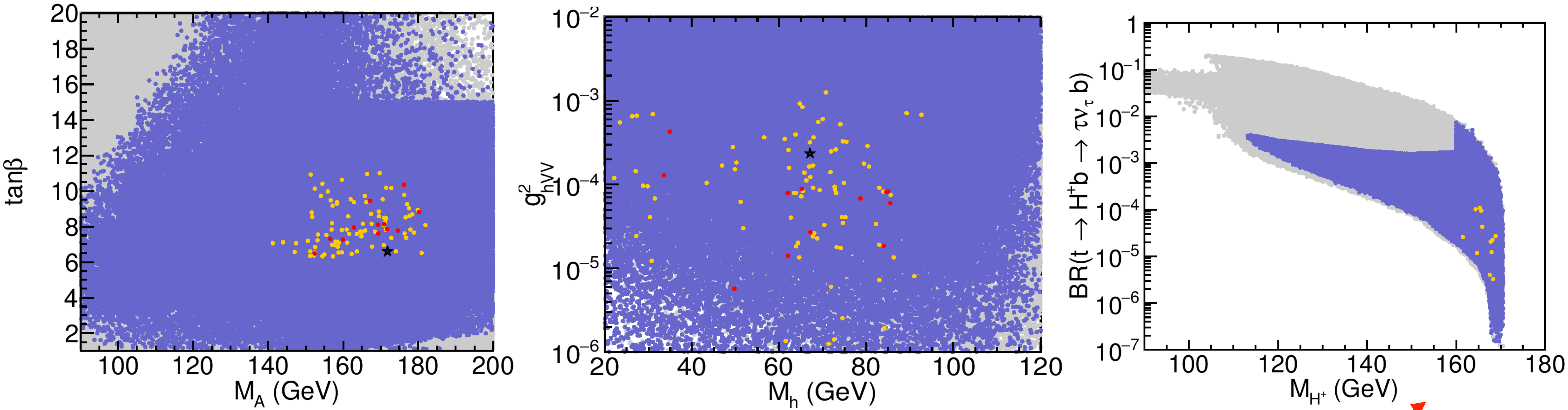
⇒ Lightest neutral Higgs with heavily suppressed couplings to gauge bosons, may have a mass below the LEP limit of 114.4 GeV for a SM-like Higgs (in agreement with LEP bounds)

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]

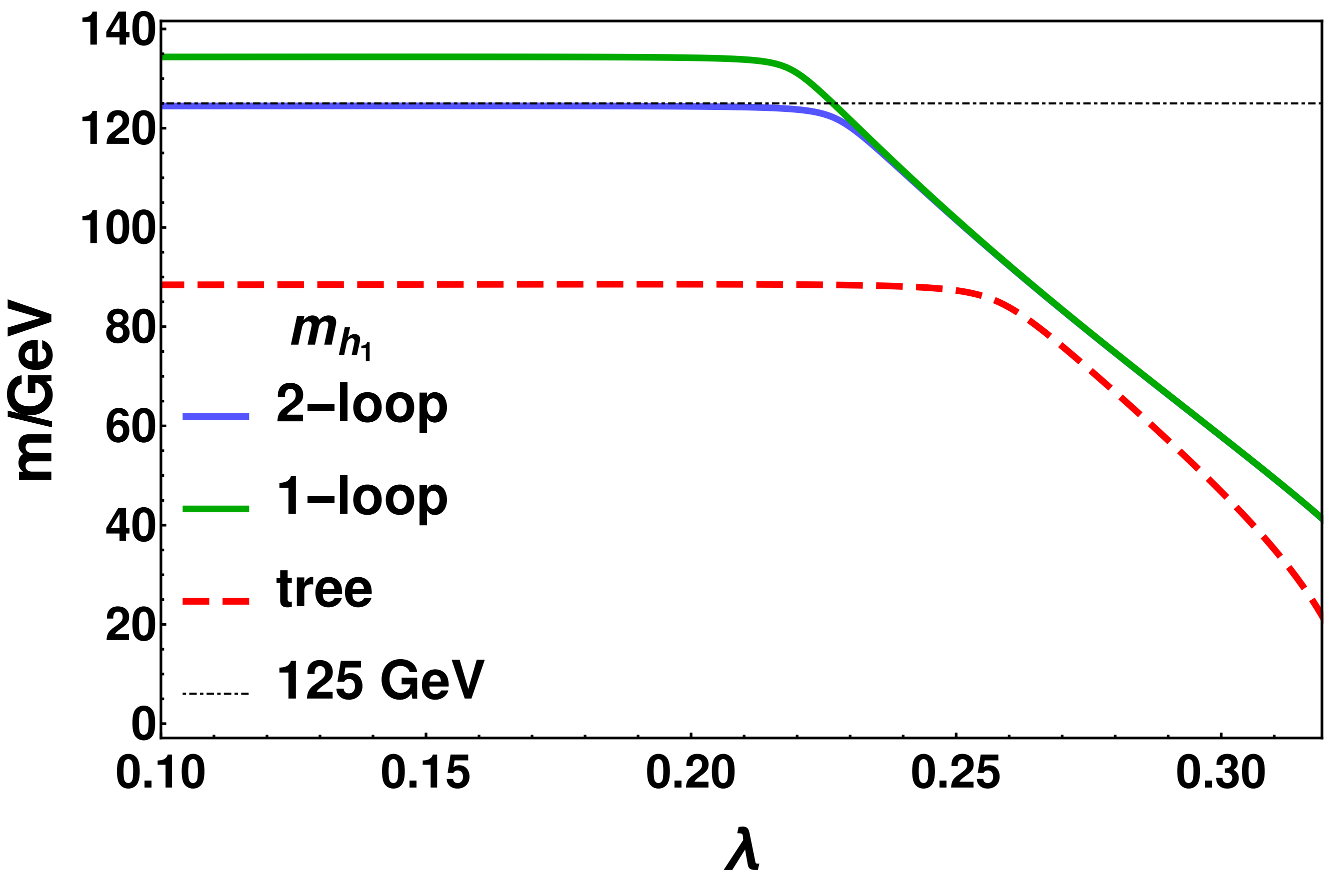


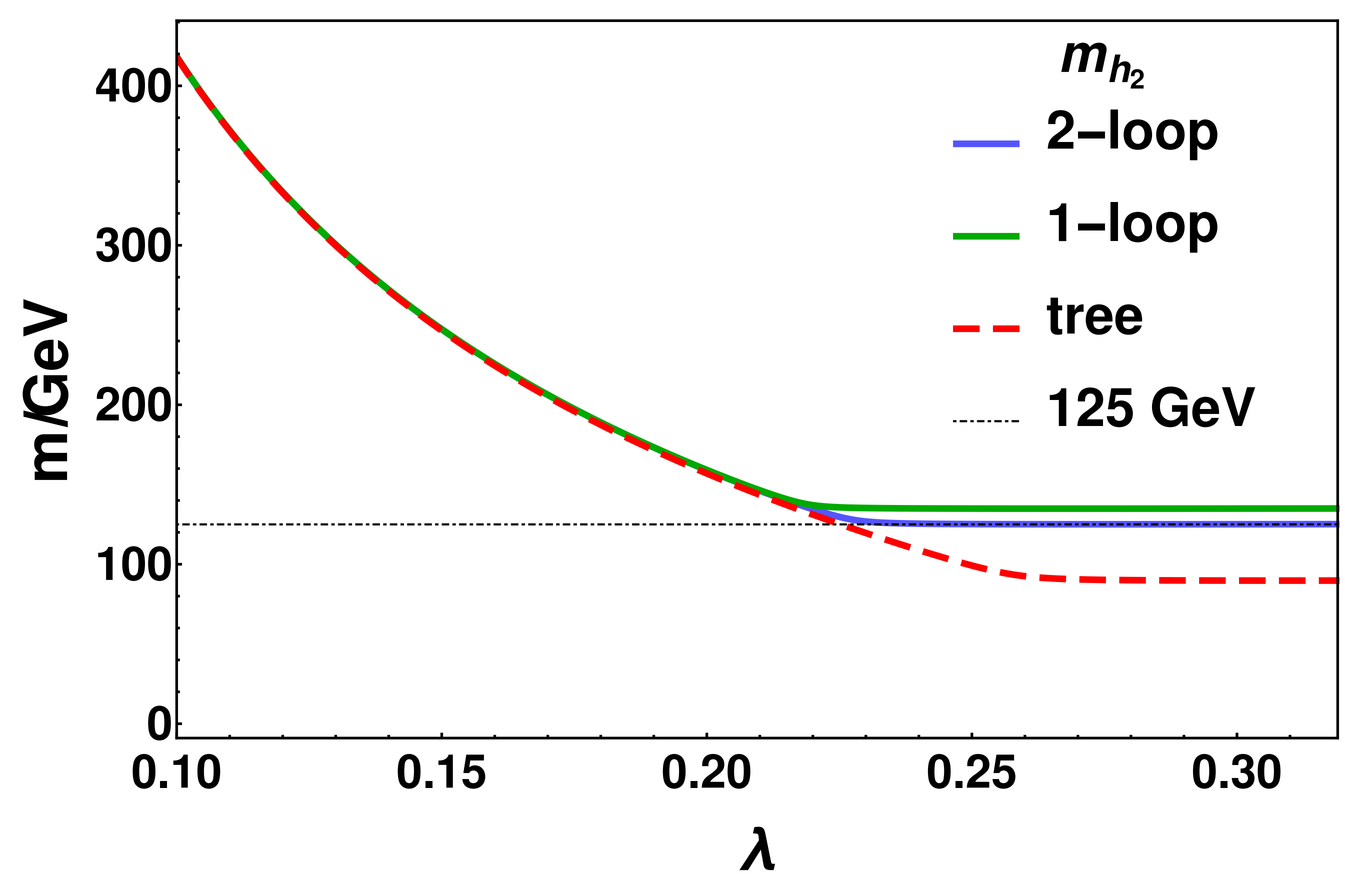
⇒Very light Higgs h is compatible with the experimental results
Tight constraints in the MSSM from charged Higgs searches

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]





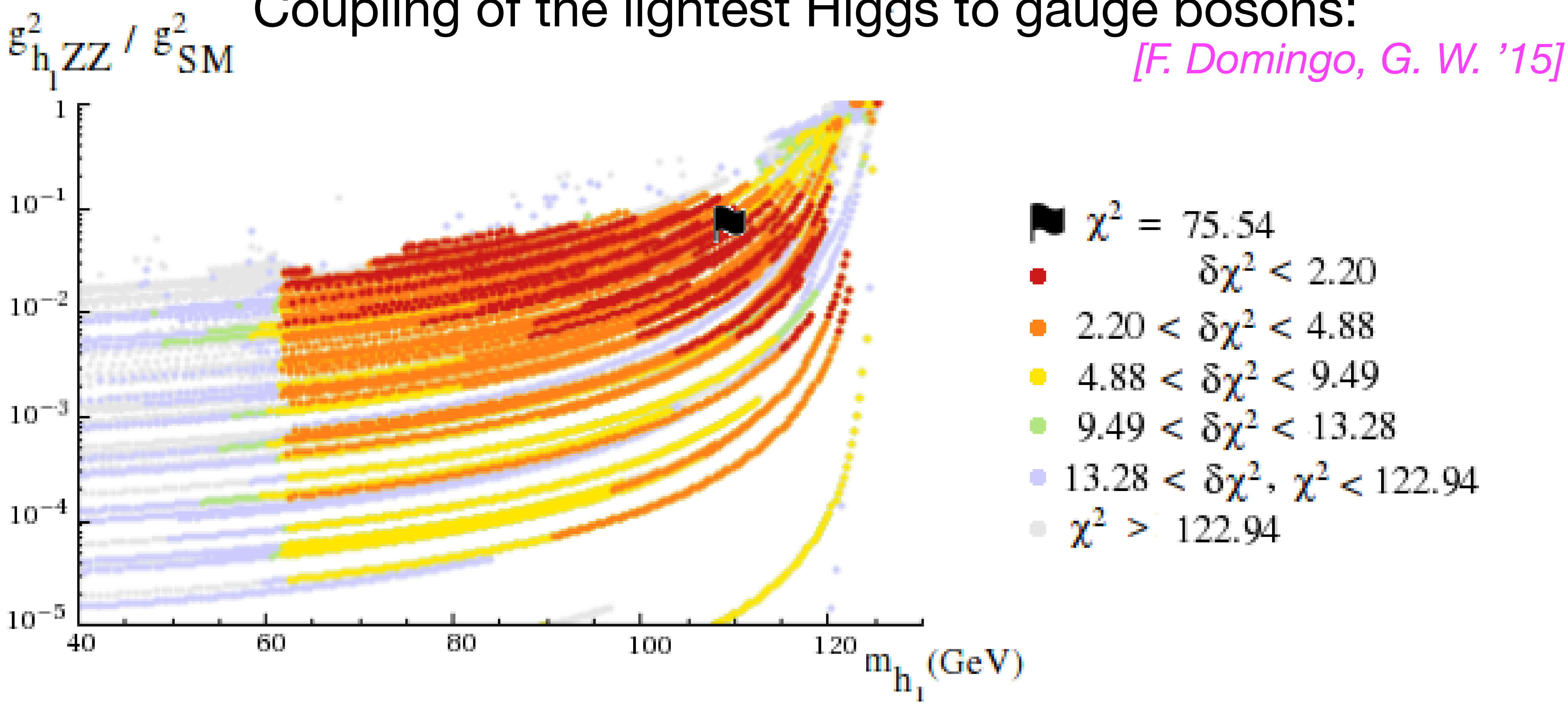
⇒ Variation of λ leads to cross-over behaviour between doublet-like and singlet-like state

⇒ 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

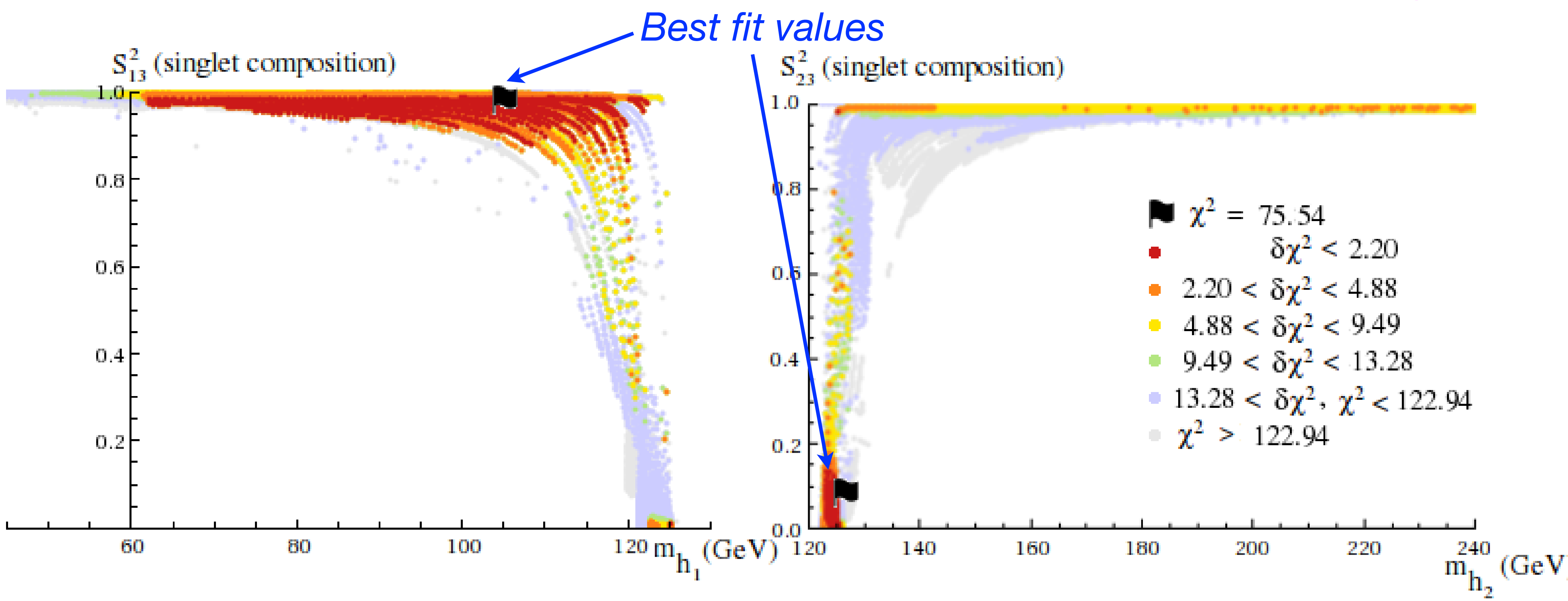
The case where the signal at 125 GeV is not the lightest Higgs arises generically if the Higgs singlet is light

⇒ 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

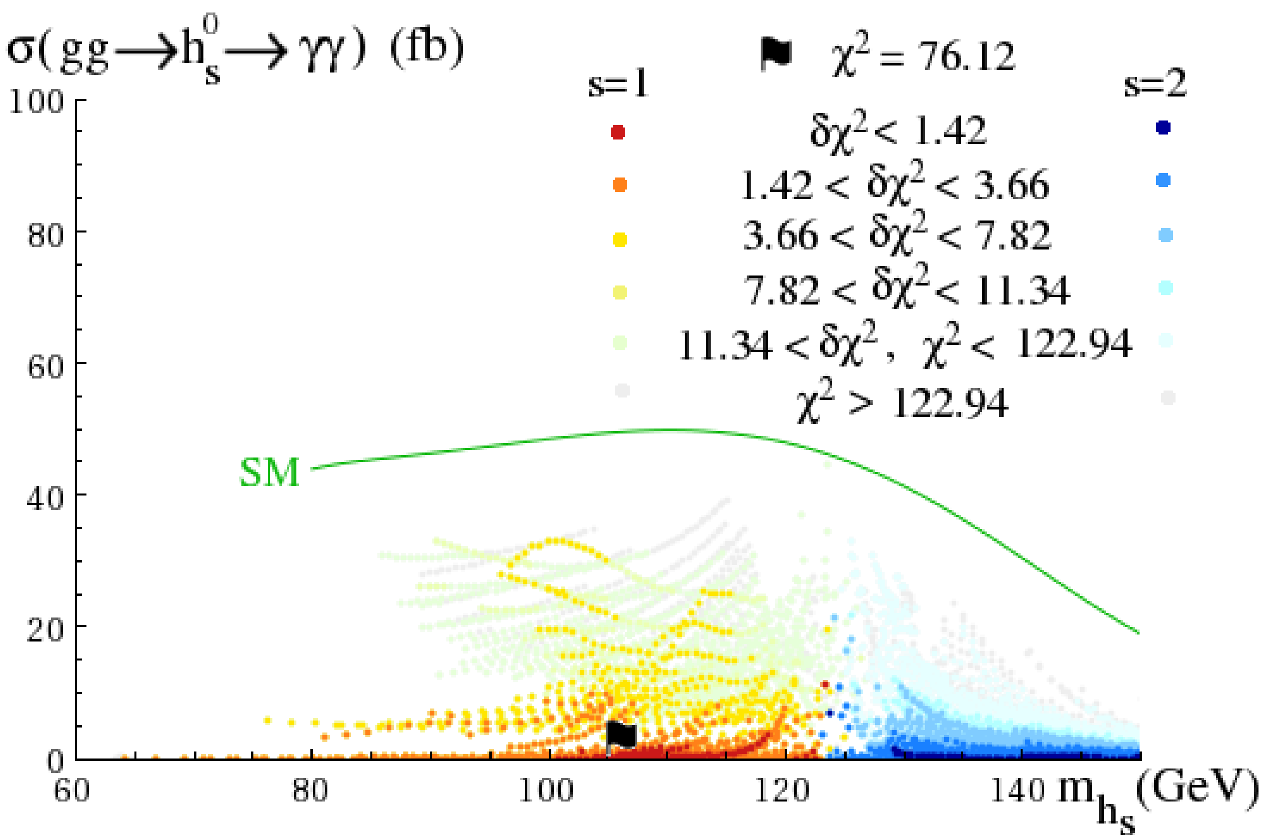
[F. Domingo, G. W. '15]

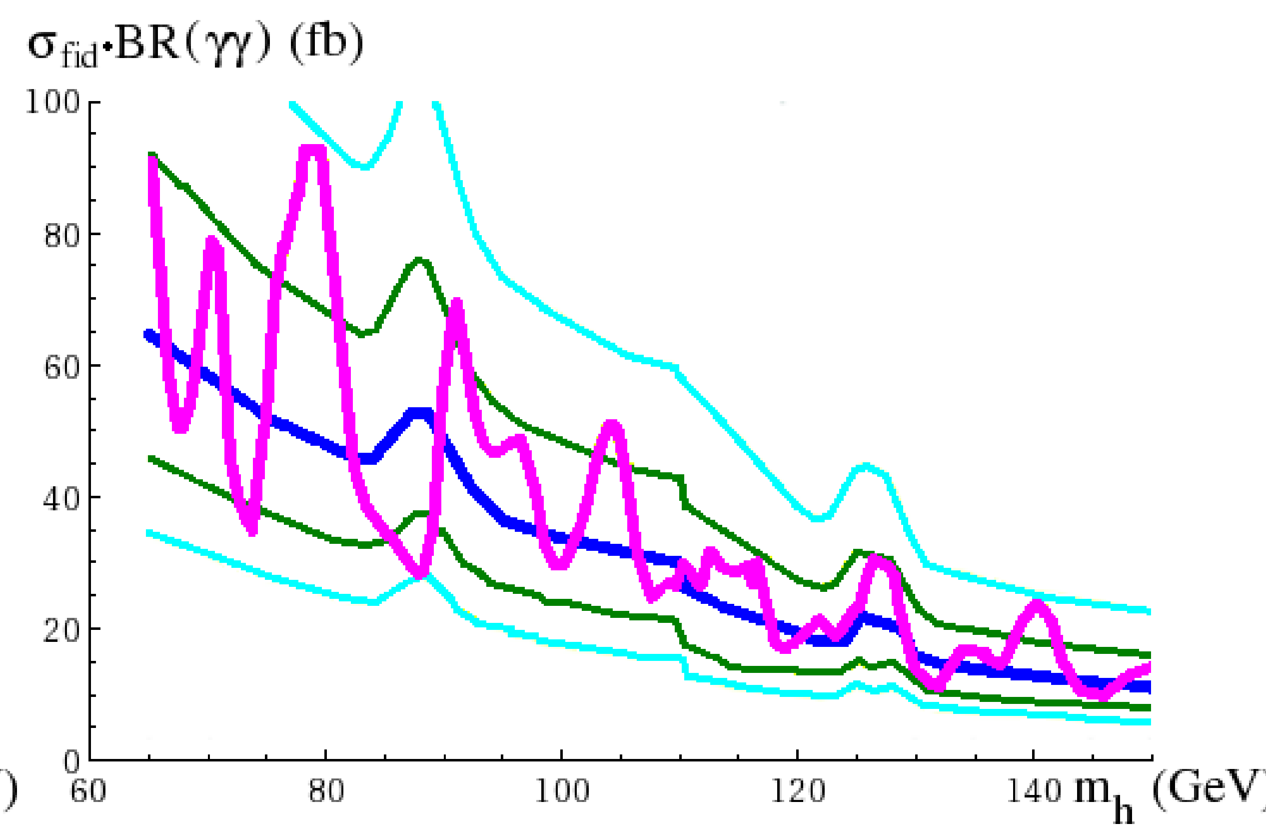


⇒ Additional light Higgs with suppressed couplings to gauge bosons, in agreement with all existing constraints

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