Future perspectives

Georg Weiglein, DESY

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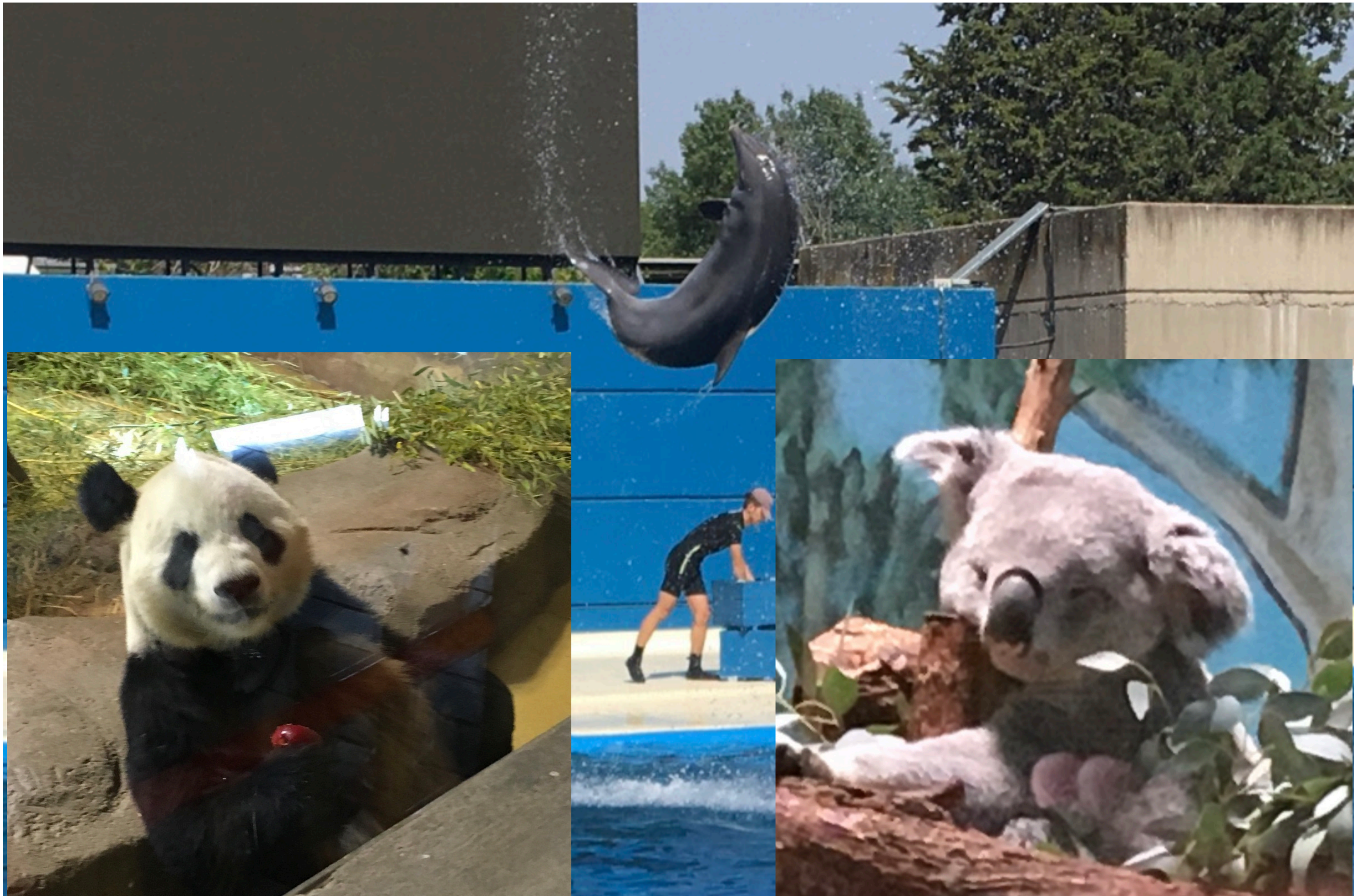
- Tough job …

- A view from the zoo (of Madrid)

Future perspectives: like this?



Future perspectives: or rather like that?

Key questions of the workshop

[see Ivanka's talk on Tuesday]

AN ATTEMPT TO ANSWER THE QUESTIONS*

- **To what extent are the linear and circular e+e- colliders complementary?**
- **To what extent are they synergistic with the HL- LHC?**
- **How might the results from the HL-LHC affect the opportunities with these other future machines?**
- **Is there a need for more than one future collider?**

Outline

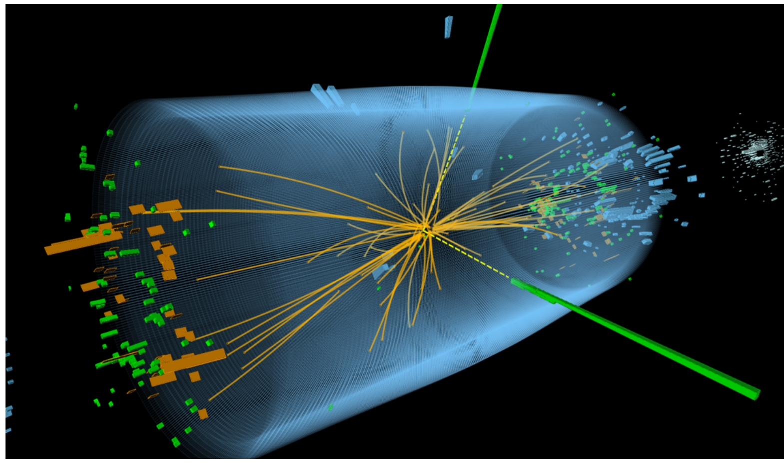
- Introduction: present status

- How to make progress? Precision physics + searches

- Towards a European / global strategy: outcome of the Granada Open Symposium (my interpretation)

Introduction: present status

Experimental situation (in a nutshell):



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

- No further clear sign of new physics so far

Goals:

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

Present status seen from the outside

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

We did not do well in communicating the actual implications of the Higgs discovery, with 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!

Higgs discovery was the beginning of a story rather than the end of one!

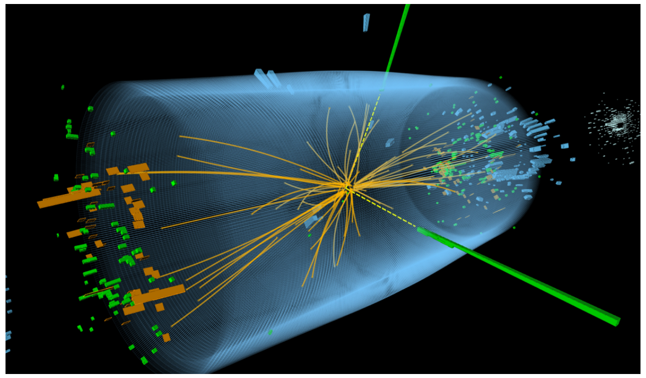
Future strategy

- Our future strategy needs to be very convincing and has to be communicated very well

- *``We want to have machine XYZ because we deserve it"* will not be sufficient in this context!

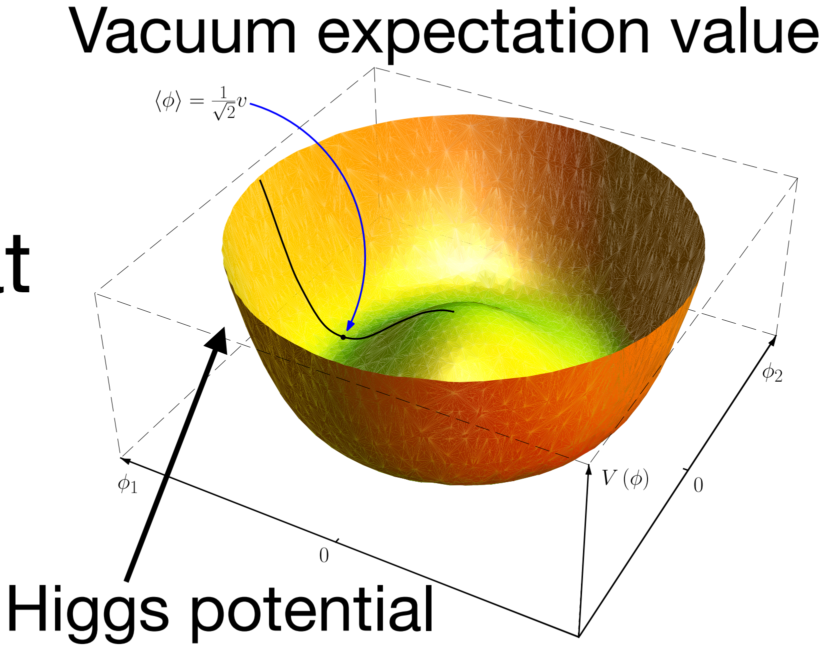
Implications of the Higgs discovery

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.



Nobel Prize 2013

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!

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 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).

How is the Higgs mass protected from physics at high scales (new space-time symmetry, new interaction of nature, extra dimensions of space, parallel universes, …)?

⟶ Exploration of the detected Higgs signal provides access

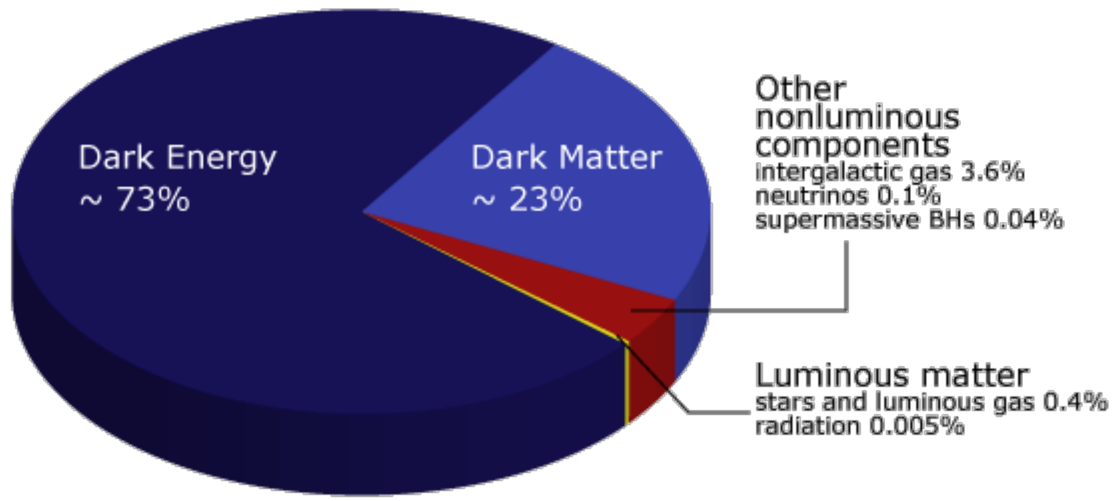
Needed in Higgs physics: high-precision measurements + searches

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, … . This will enable us to address the questions:

- Elementary particle or substructure of more fundamental particles (latter possibility would resemble the ``Cooper pairs" of the case of superconductivity)?
- Single Higgs or further Higgs bosons?
- BSM physics connected to the Higgs sector (Higgs portal, …)?
- Connection to imbalance between matter and anti-matter in the universe? Additional sources of CP violation in the Higgs sector?
- Relation between the electroweak phase transition and the phase of inflation in the early universe?
- …

Many more questions to answer

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

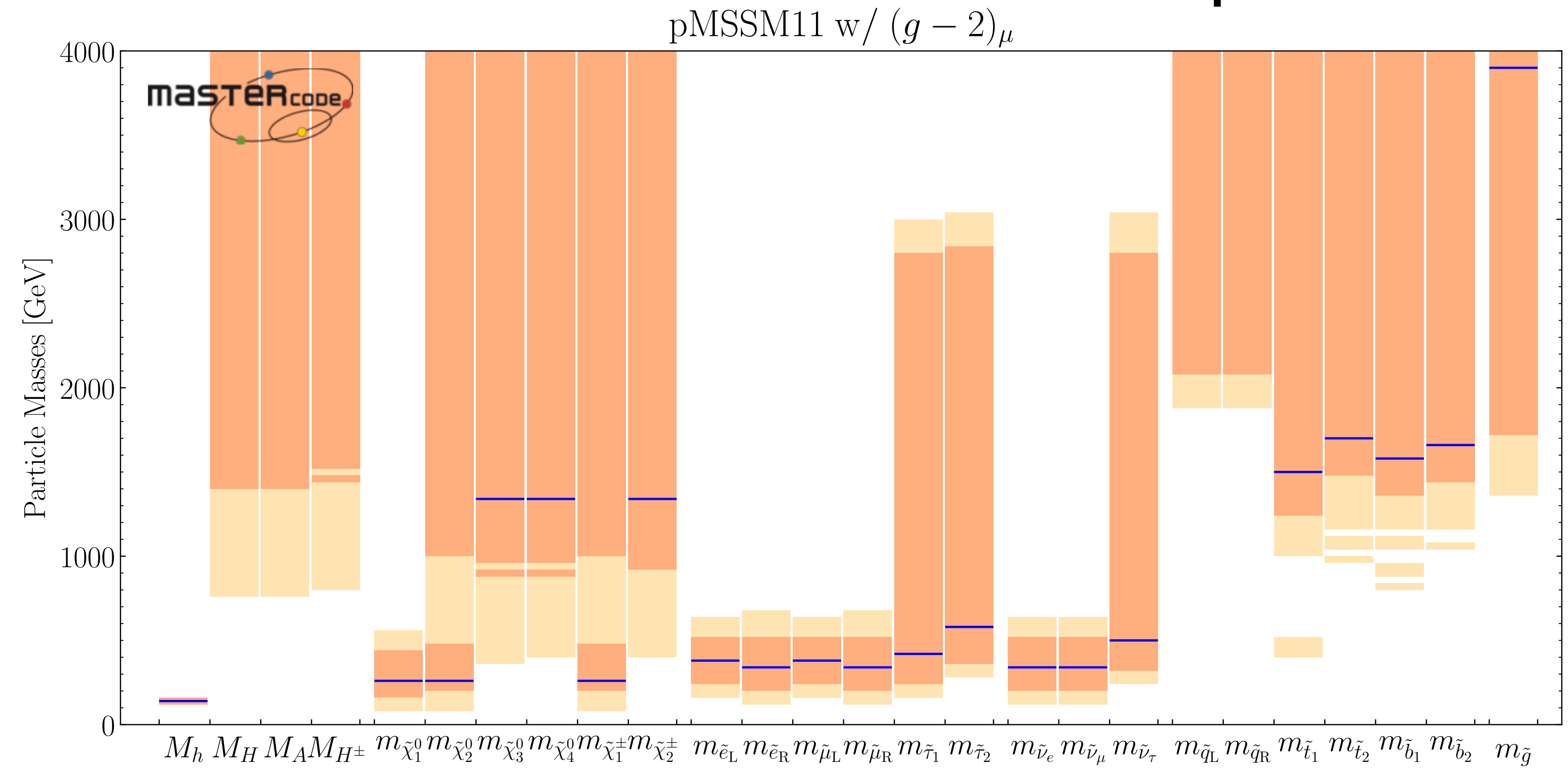


- Origin of the matter/anti-matter imbalance in the universe?
- Origin of the observed patterns of flavour (quarks, neutrino physics)?
- How is gravity related to the quantum world? Quantum structure of space-time? Are there more than three dimensions of space?
- Unification of the fundamental interactions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

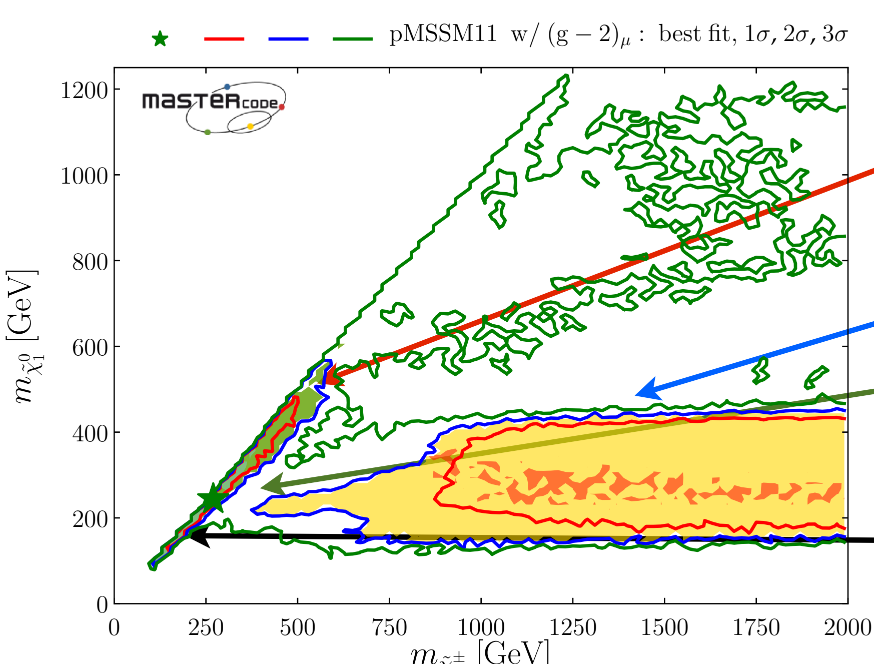
Where are the new particles?
Example: global SUSY fit

[E. Bagnaschi et al '18, 19]

MasterCode: Global fit in the MSSM with 11 parameters



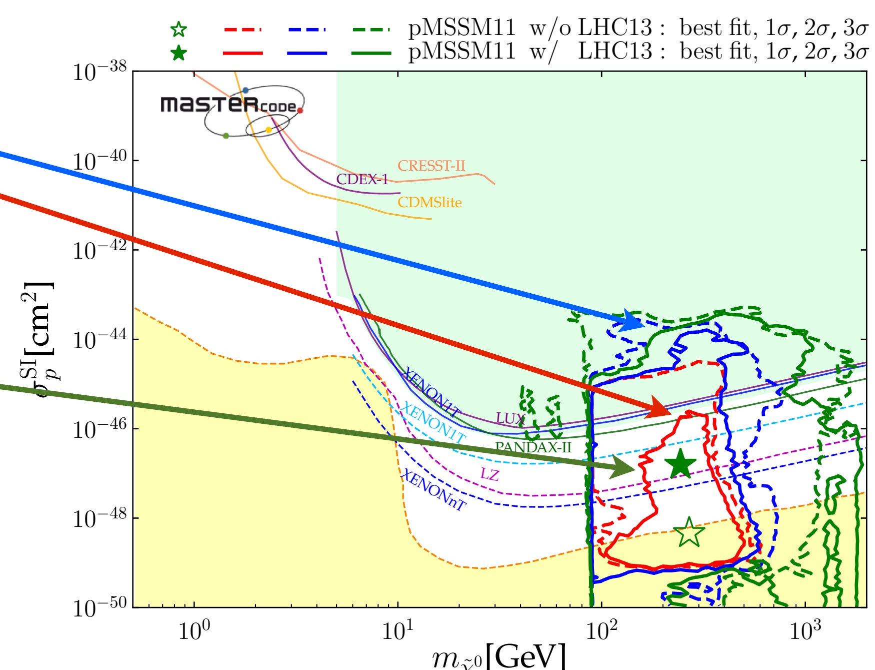
Best fit region and implications for collider and dark matter searches:



68% / 95%
C.L. contours

Best fit points

Compressed
spectrum



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

How to make progress? Precision physics + searches

- Electroweak symmetry breaking: information from the Higgs signal (h125) and from searches for additional Higgs bosons, longitudinal gauge boson scattering, search for new resonances, EWPOs, …

- Dark sector: search for dark matter particles, mediators, …

- Flavour physics: precision measurements, rare processes, …

- CP violation: new particle searches, EDMs, precision measurements, …

- …

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

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

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

CP properties

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

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

General structure of HVV coupling (from Lorentz invariance):

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

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

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

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

CP properties

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

Hypothesis of a pure CP-odd state is experimentally disfavoured

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

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

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

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 ($\Gamma_{\text{prod, decay}} \sim g^2_{\text{prod, decay}}$):

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

Total Higgs width cannot be determined without further assumptions

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

The quest for identifying the underlying physics

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

[see Shinya's talk yesterday]

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

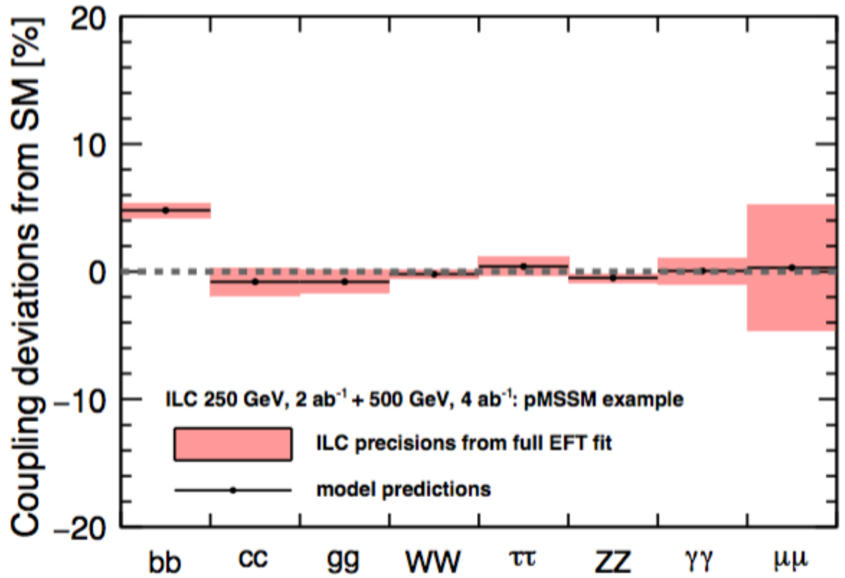
$$\frac{g_{htt}}{g_{h_{\mathrm{SM}}tt}} = \frac{g_{hcc}}{g_{h_{\mathrm{SM}}cc}} \simeq 1 - 1.7\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2$$

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

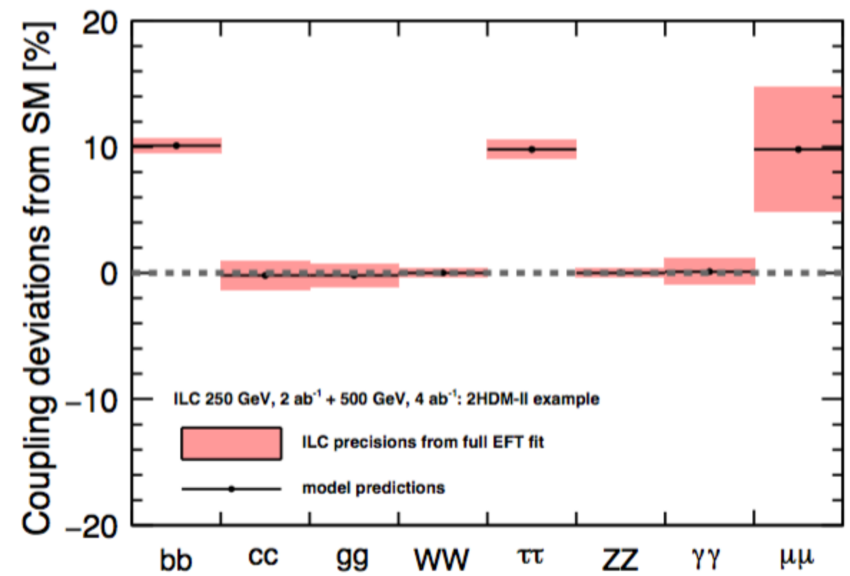
⇒ Need very high precision for the couplings

Coupling deviations for different models vs. future precision (example: ILC)

heavy SUSY

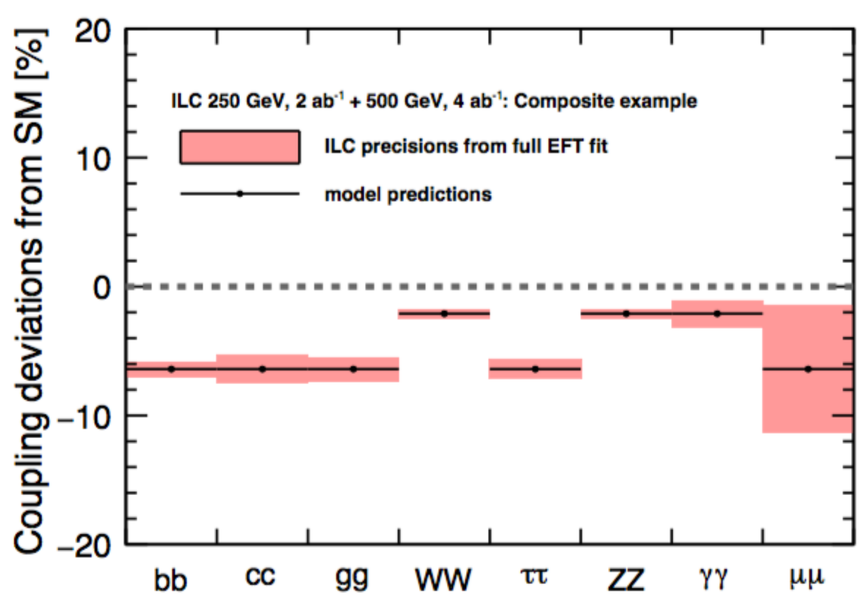


2 Higgs doublet

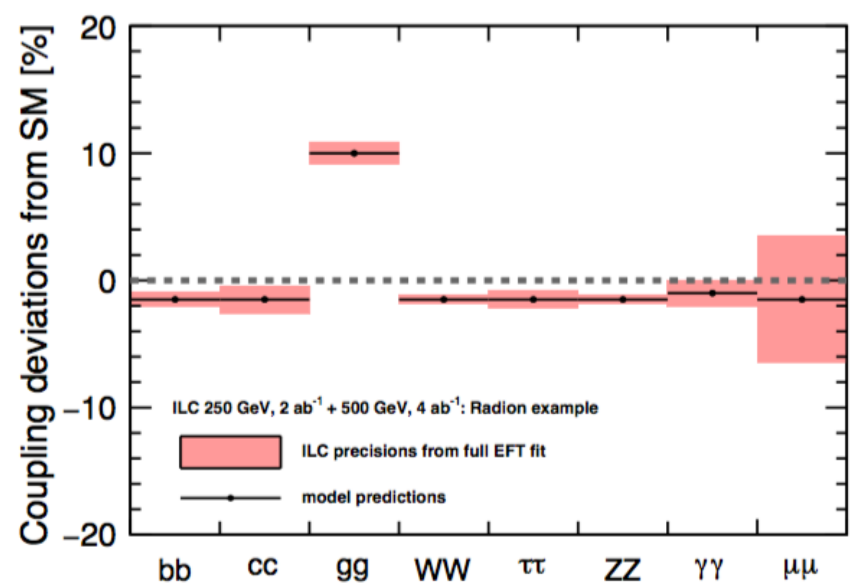


[T. Barklow et al. ’17]

composite Higgs



Higgs-Radion mixing



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

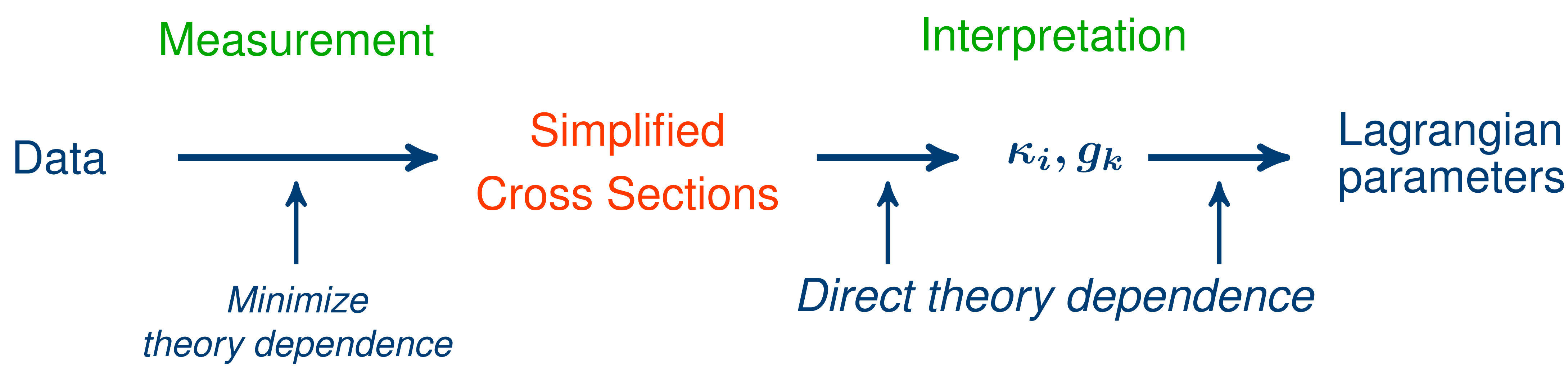
⇒ Precision at 1% level provides large sensitivity for discriminating between different realisations of underlying physics

Signal strengths, STXS, ϰ framework and beyond

Interface between experiment and theory:

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

- Simplified template cross sections (STXS):



- Fiducial cross sections, pseudo observables, …

Signal strengths, STXS, $\varkappa$ framework and beyond

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

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

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

- Specific models

Higgs couplings: ϰ and EFT framework

- 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 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

Comparison of the capabilities of future colliders

[see Maria's talk on Monday]

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

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

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

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

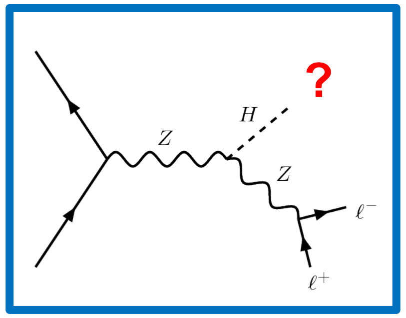
e^+e^- Higgs factories: recoil method

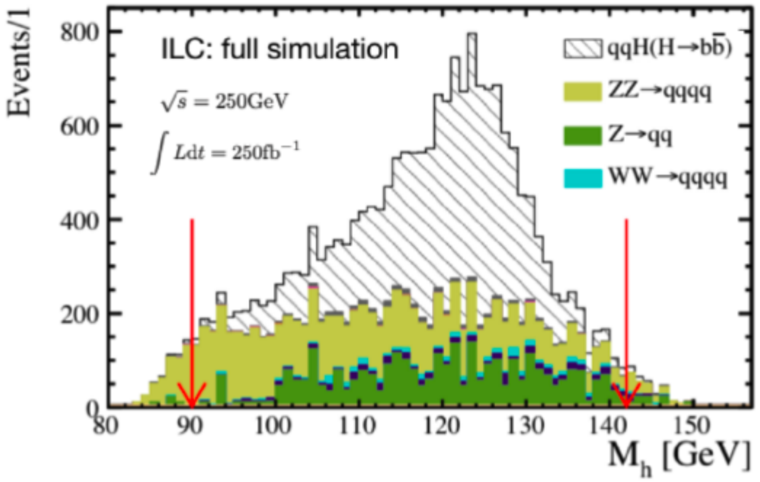
[B. Heinemann '19]

Higgs width and/or untagged decays

Unique feature of lepton-lepton colliders:

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





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

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

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

arXiv:1905.03764

=> Will probe width with 1-2% precision

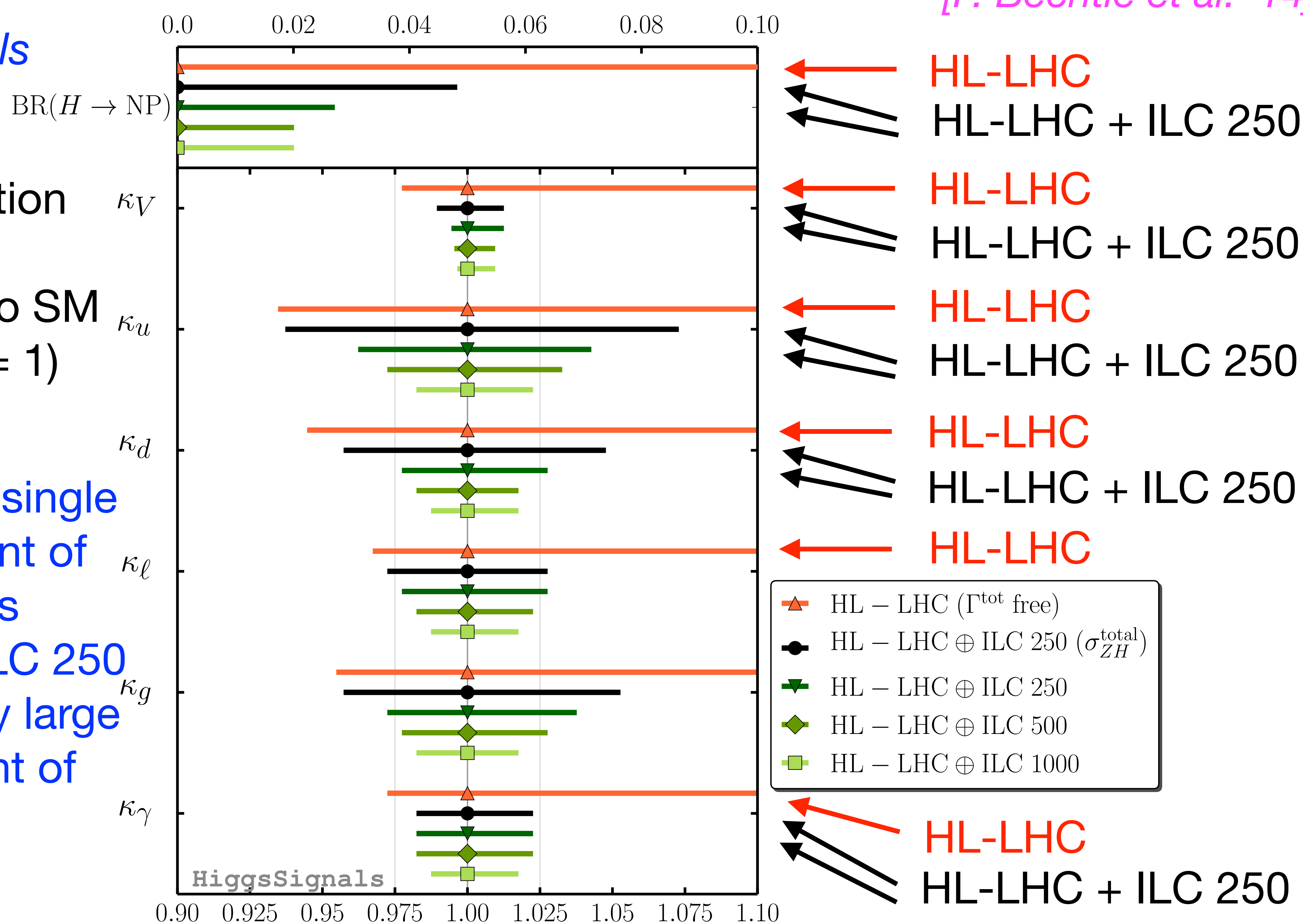
Projections for HL-LHC and ILC, no additional theory assumptions (ILC 250: only 250 fb^{-1})

[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!

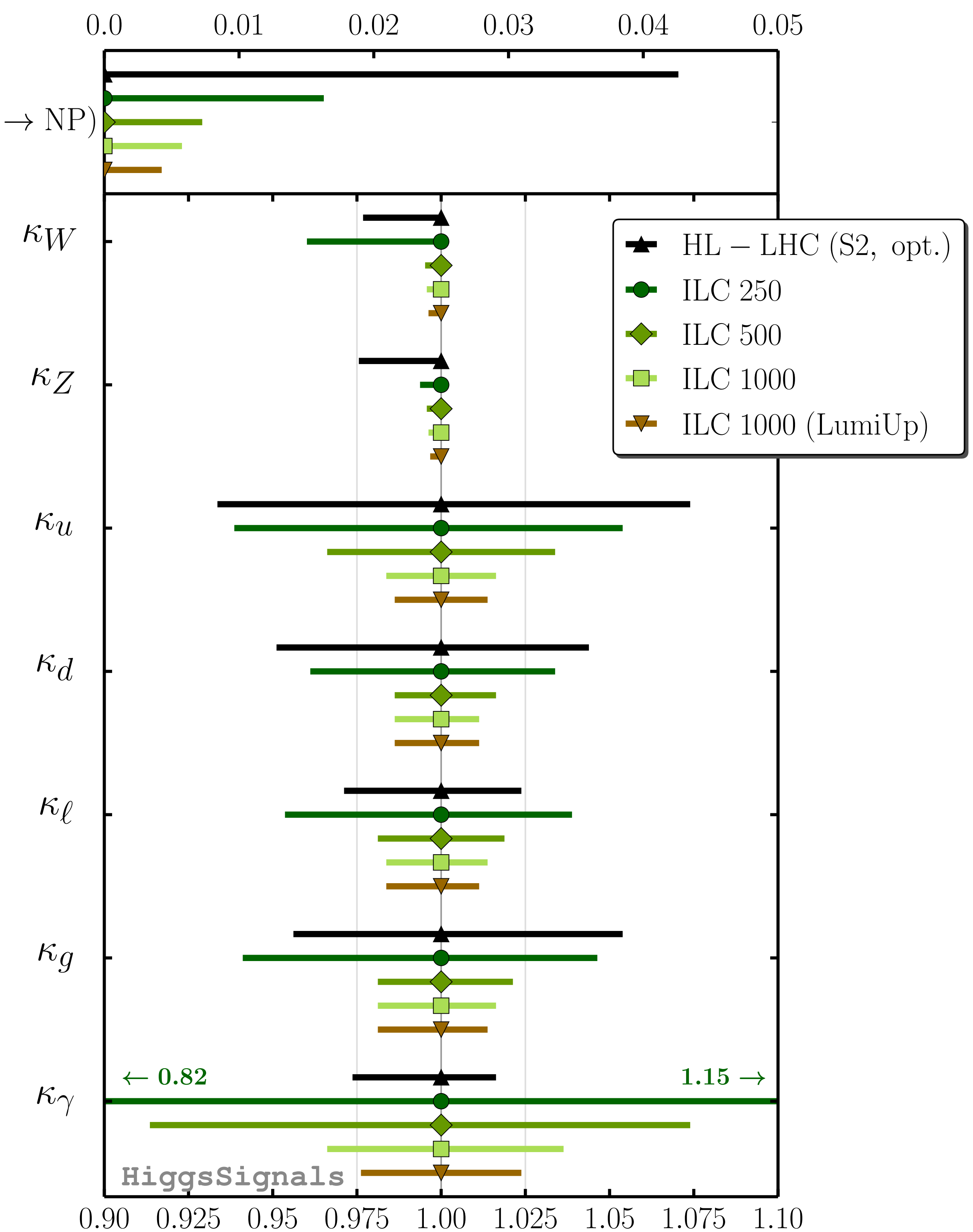


Prospects for Higgs-coupling determinations at HL-LHC and ILC: with theory assumption on $\varkappa_V$

[P. Bechtle et al. ’14]

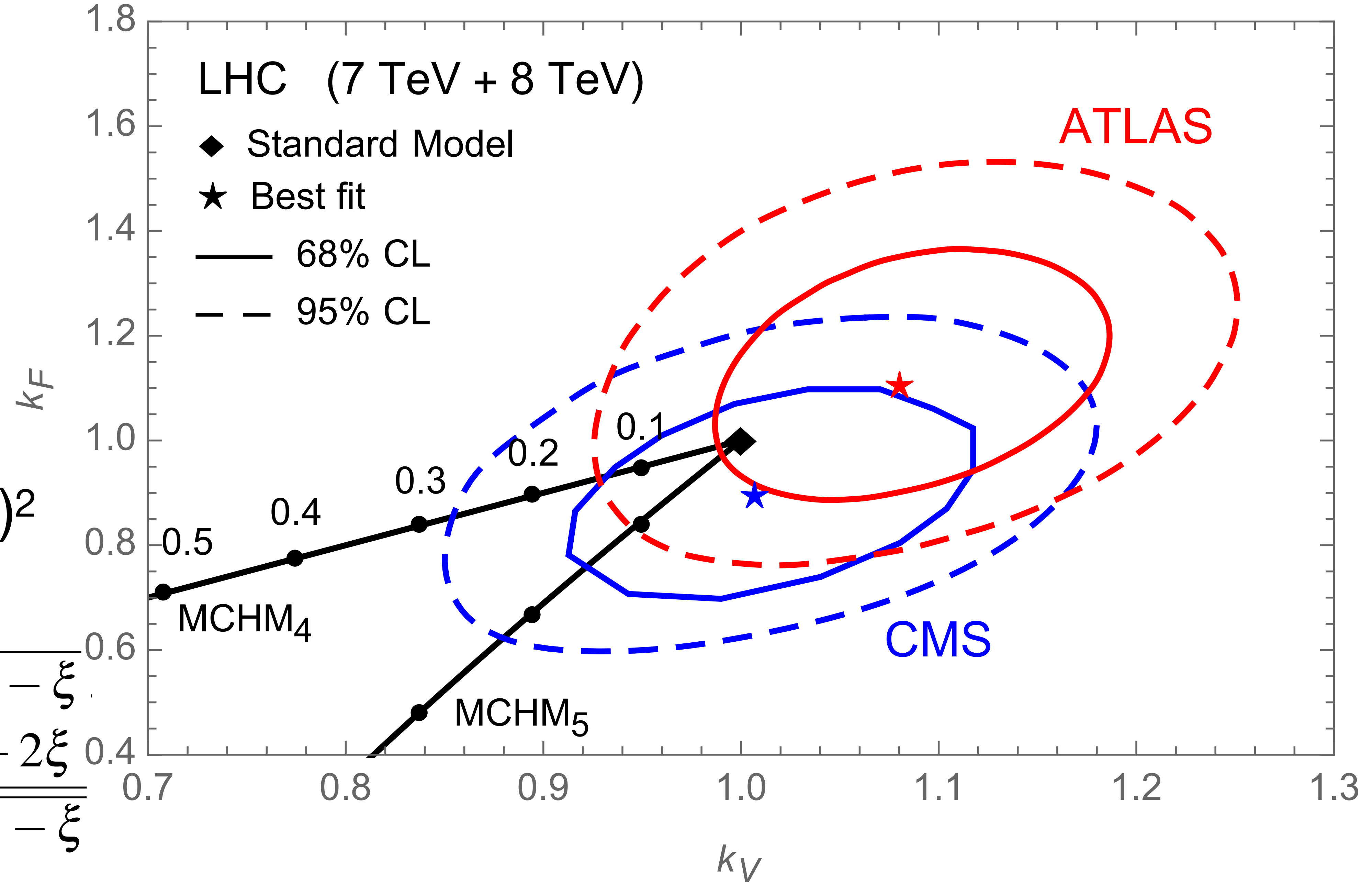
HiggsSignals

Assumed: $\kappa_V \leq 1$



Coupling modifications in composite Higgs models

[A. Wulzer '15]



$\xi = (v/f)^2$

$$\kappa_F^4 = \sqrt{1-\xi}$$

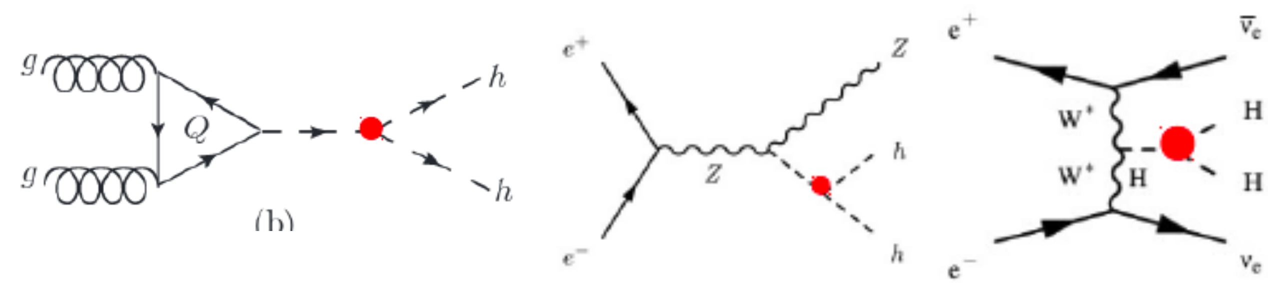
$$\kappa_F^5 = \frac{1-2\xi}{\sqrt{1-\xi}}$$

⇒ Higgs coupling measurements constrain symmetry breaking scale f

Higgs self coupling λ

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

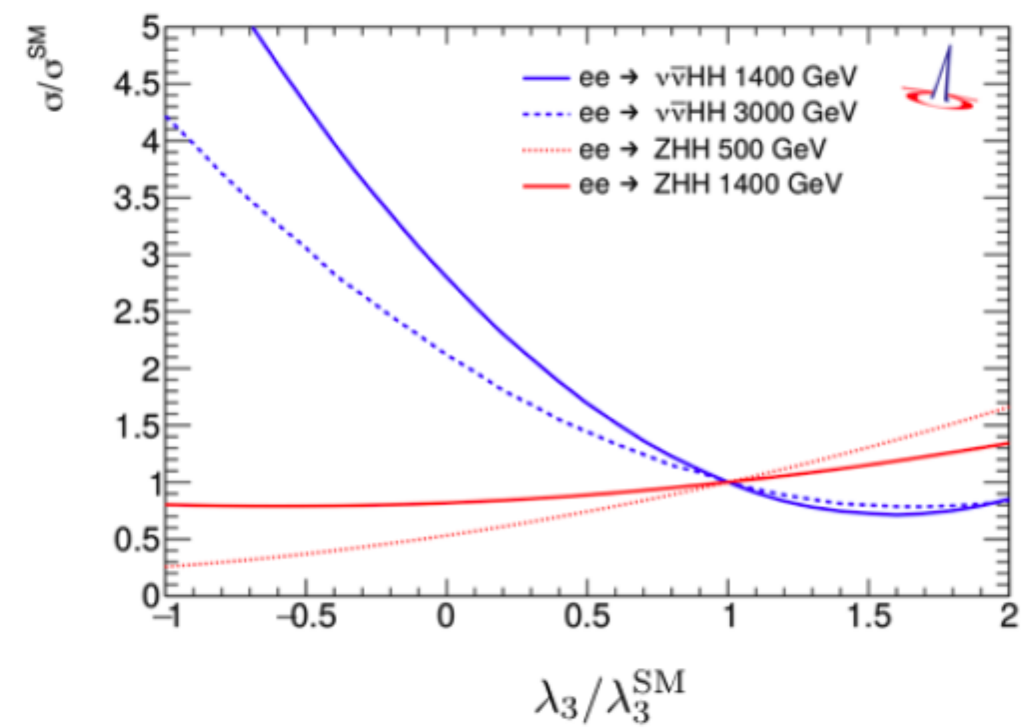
[B. Heinemann ’19]

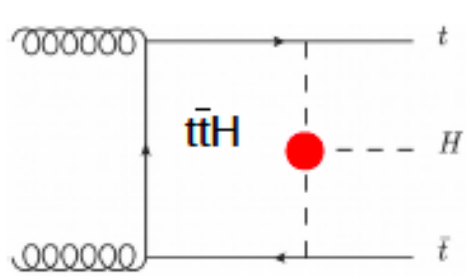


Di-Higgs processes at hadron colliders:
- $\sigma(HH) \approx 0.01 \times \sigma(H)$
- **Important to use differential measurements**

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%**





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!

Interpretation of the projections for future facilities

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

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

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

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

Sceptics: "Enormous challenge! Conceptual progress difficult to extrapolate."

Requirements from theory for future facilities

[B. Heinemann '19]

Theoretical Uncertainties: production

Production at hadron colliders

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

Requires e.g.

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

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

Information from searches for additional Higgses

For compatibility of extended Higgs sectors with exp. results:

- A SM-like Higgs at ~125 GeV

- Properties of the other Higgs bosons (masses, couplings, …) have to be such that they are in agreement with the present bounds

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

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

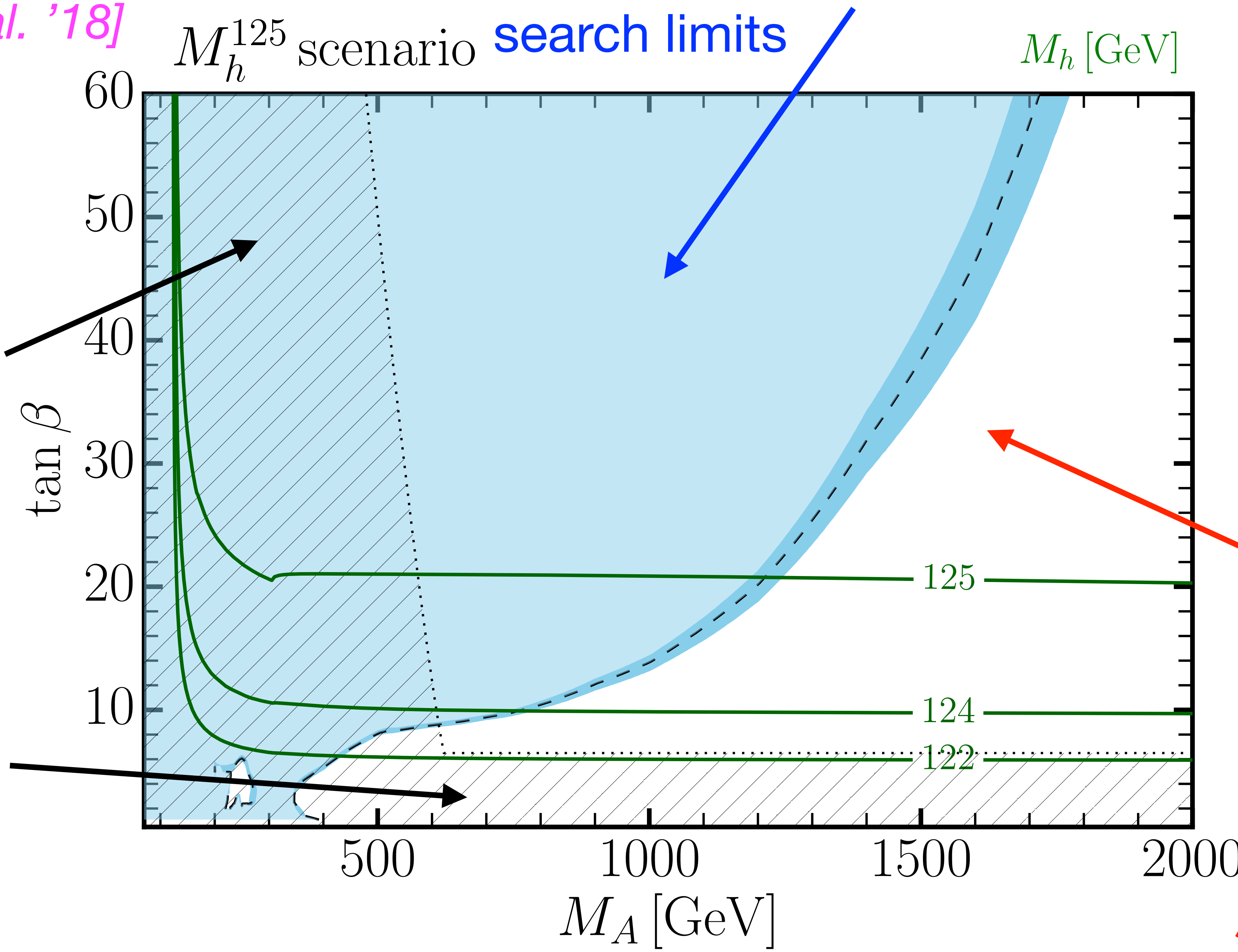
Information from Higgs signal + Higgs searches

MSSM example: recent M_h^{125} benchmark scenario

HiggsBounds: area excluded by Higgs search limits

[H. Bahl et al. '18]

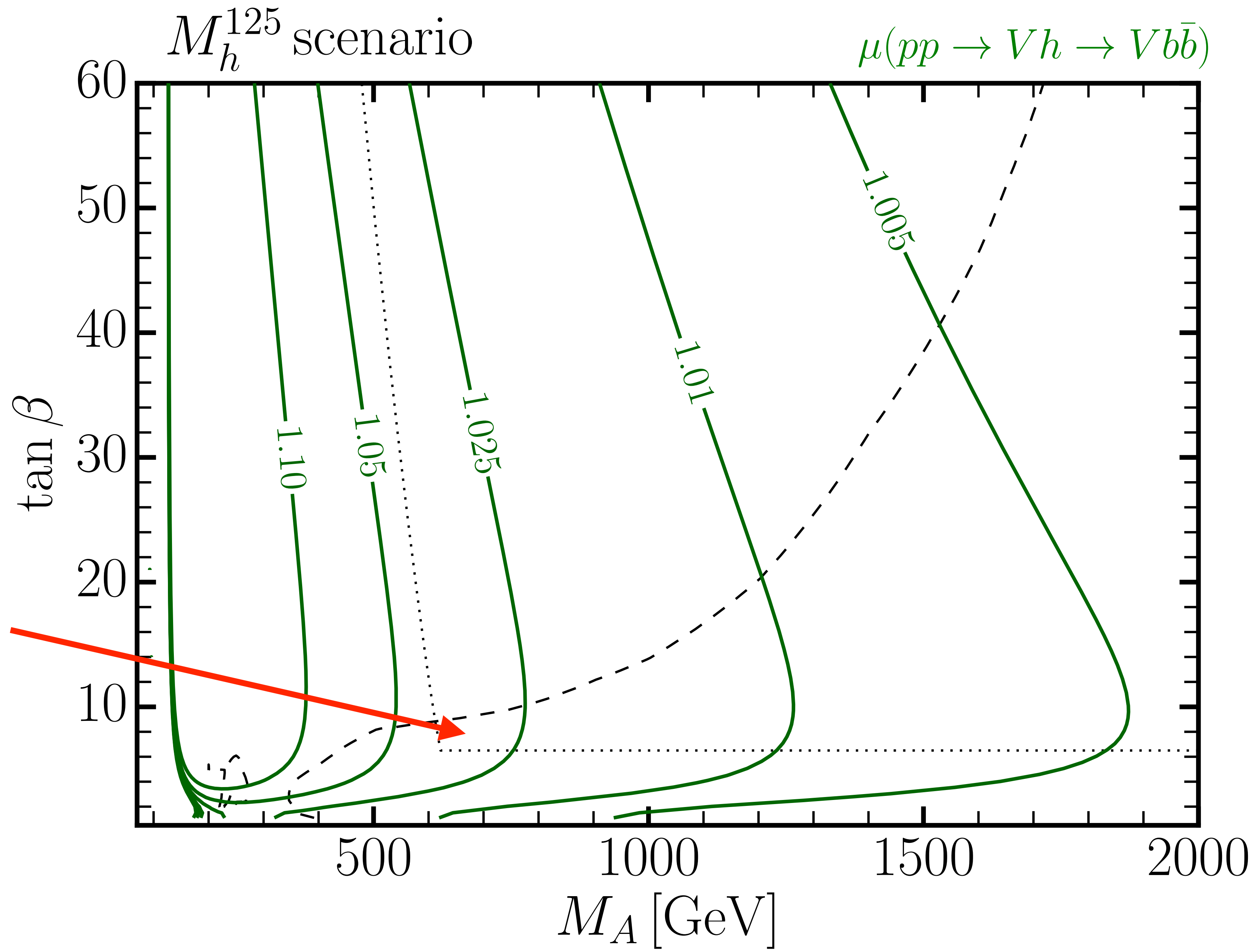
HiggsSignals: area is not compatible with the properties of the detected Higgs signal



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]

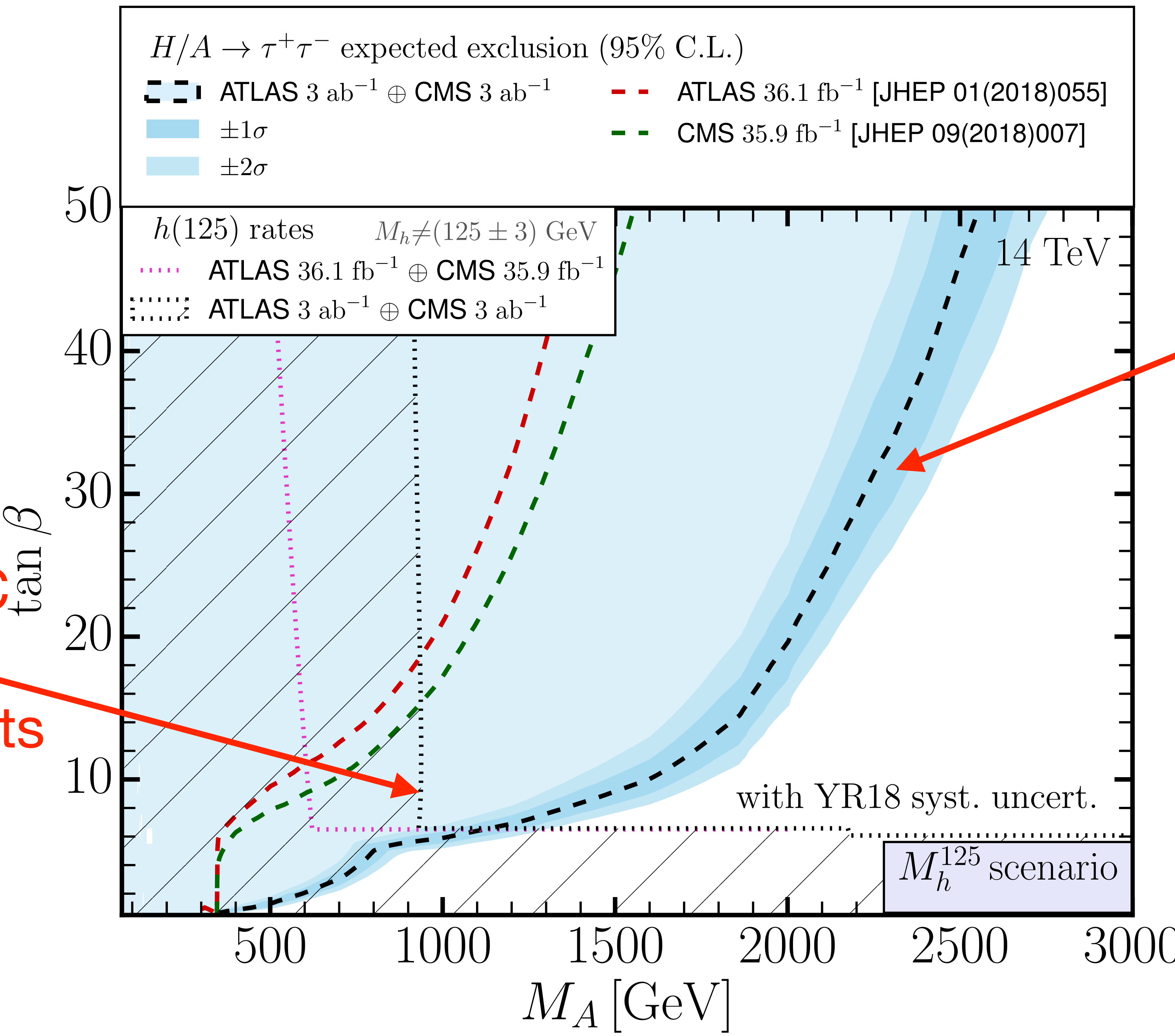


Maximal deviation below 5%

⇒ 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. '19]



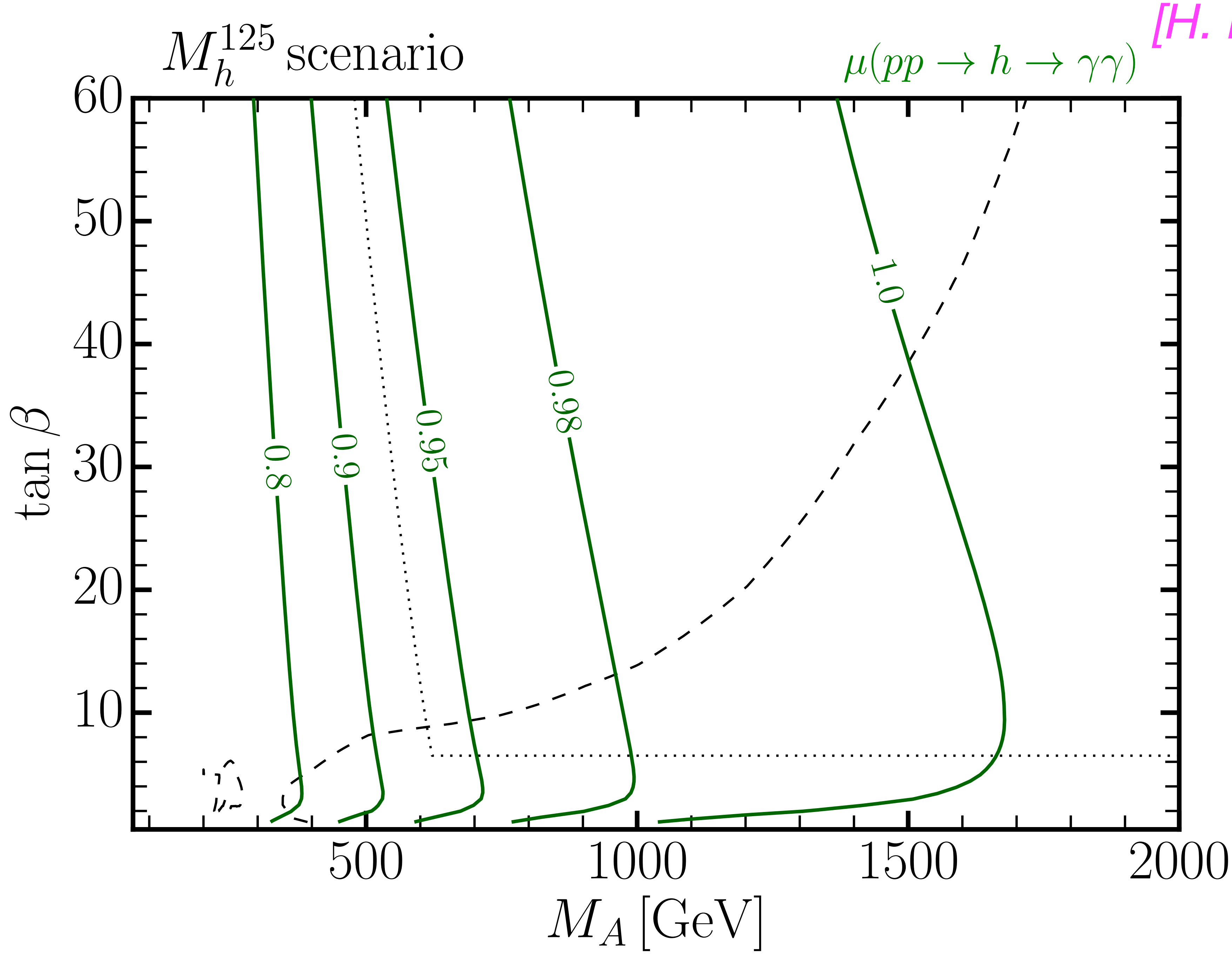
Sensitivity from HL-LHC signal measurements

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

Deviations of signal rates into $\gamma\gamma$

[H. Bahl et al. '18]

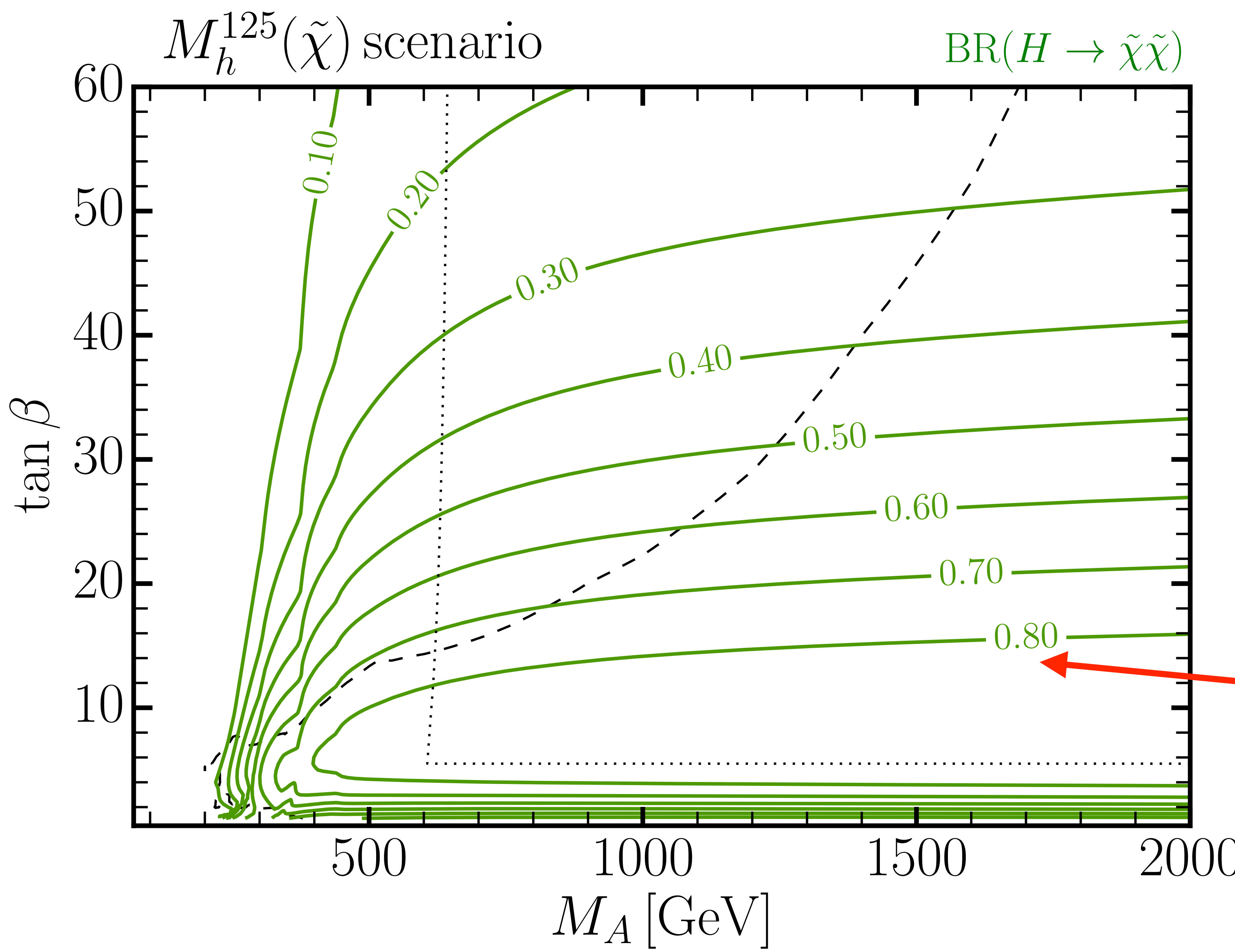


⇒ Indirect sensitivity to the hbb coupling via the total Higgs width

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:

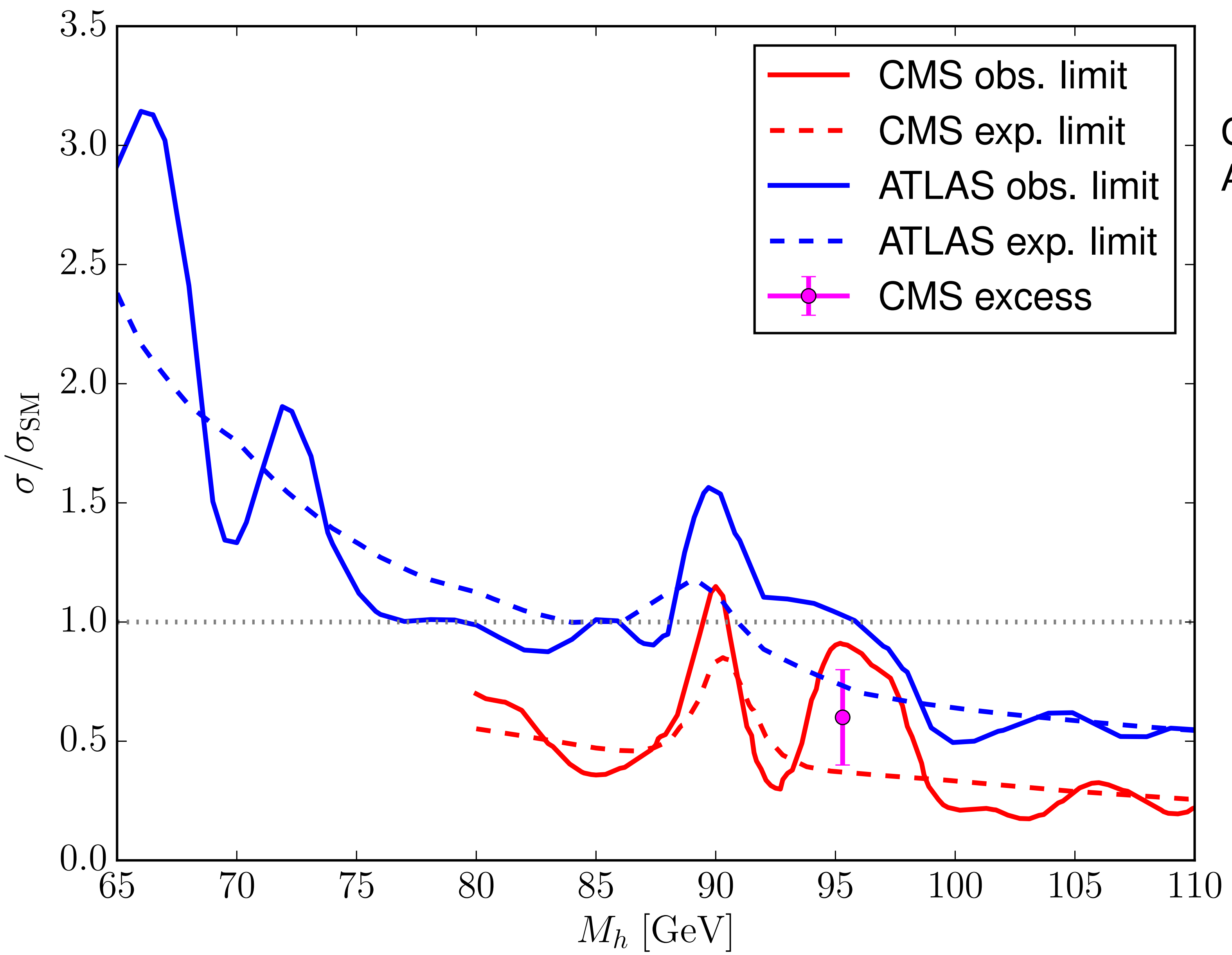


Branching ratios of more than 80% possible!

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

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

[T. Stefaniak '18]



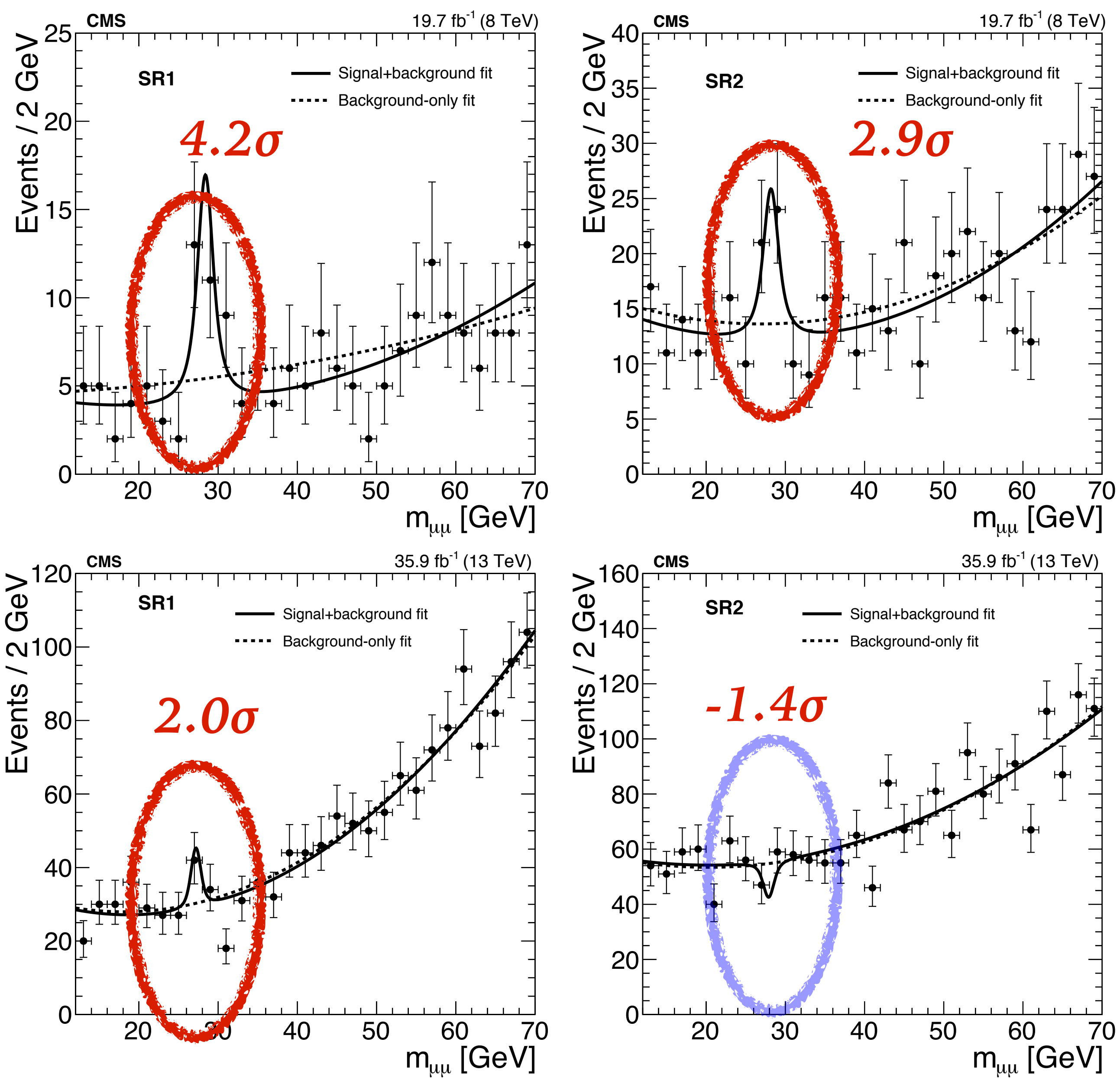
CMS-PAS-HIG 17-013,
ATLAS-CONF-2018-025

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

Could there be something even more exotic?

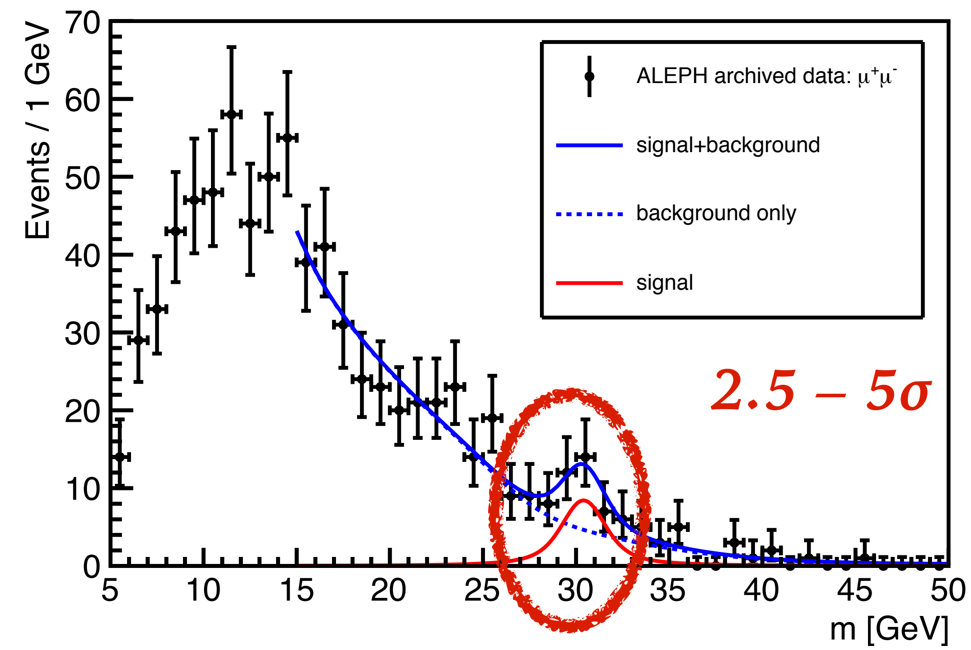
[G. Salam '19]

CMS pp → b j $\mu^+\mu^-$ + X



https://arxiv.org/abs/1808.01890

ALEPH e^+e^- → b b $\mu^+\mu^-$ + X



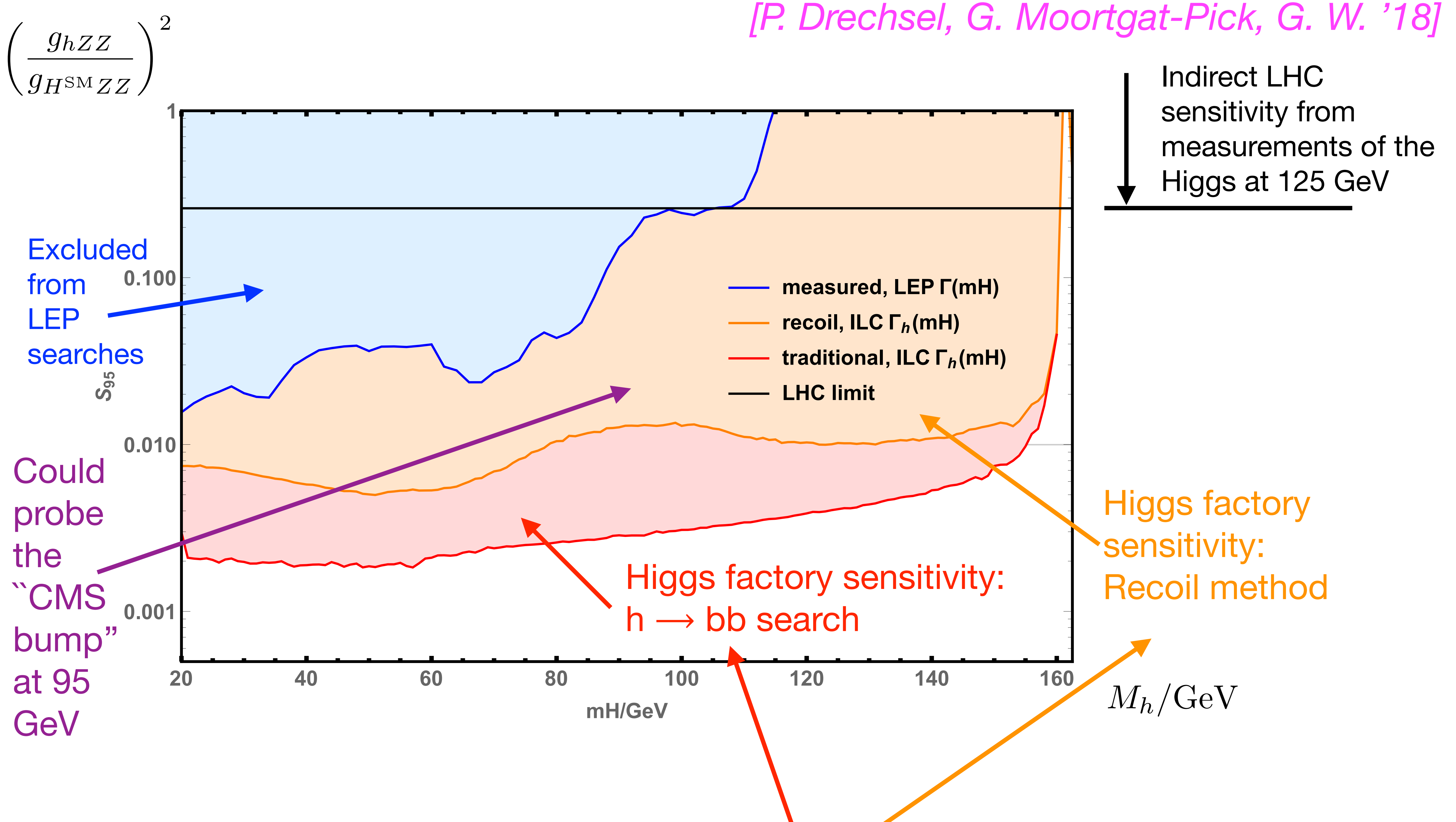
https://arxiv.org/abs/1610.06536

and various non-collider anomalies

- DAMA
- Miniboone & LSND
- $g_\mu - 2$
- ^{8}Be 16.7 MeV e^+e^- peak

Sensitivity of an e^+e^- collider at 250 GeV with 500 fb^{-1} to a new light Higgs (simple-minded projection)

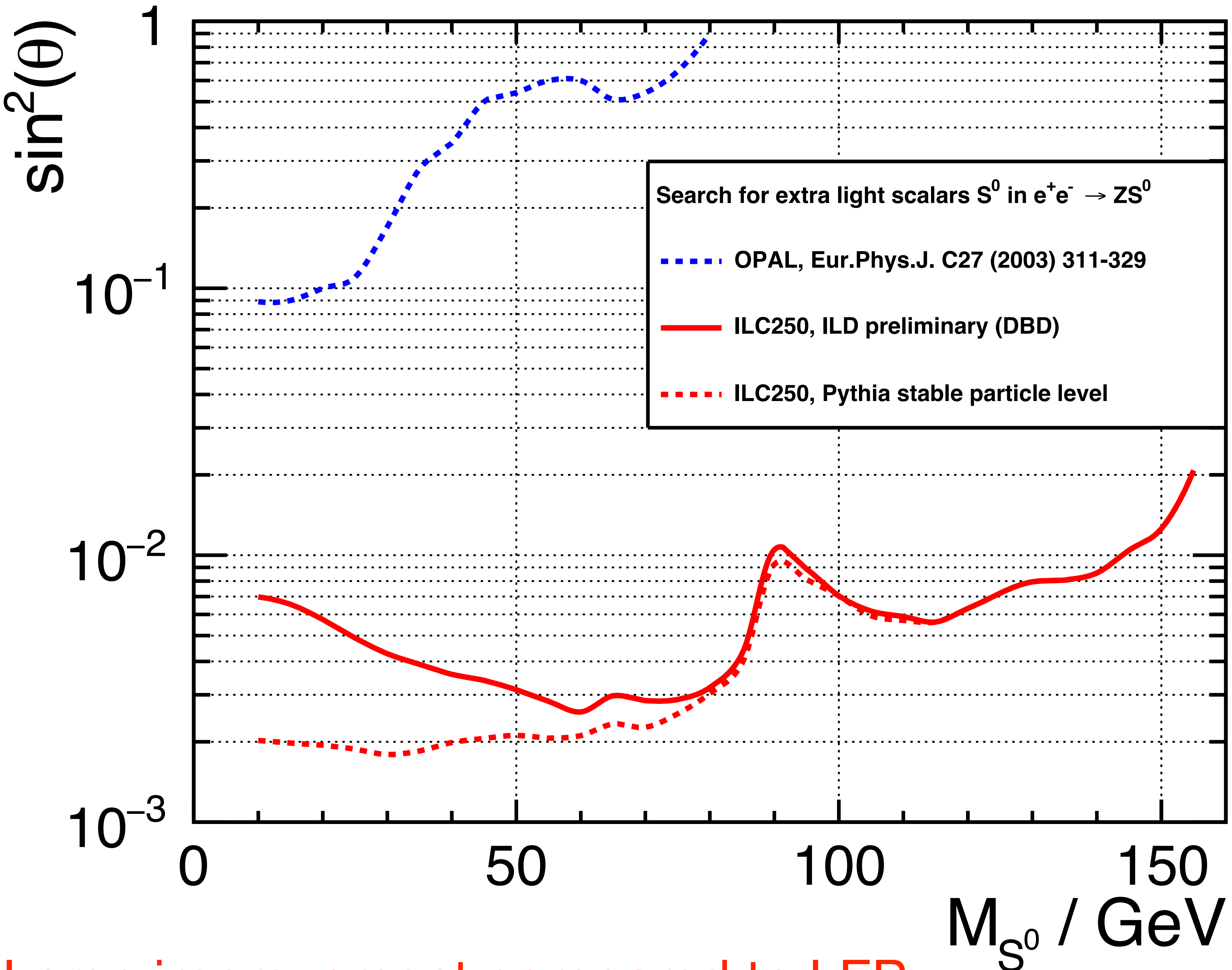
[P. Drechsel, G. Moortgat-Pick, G. W. '18]



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

Recoil method: ILC study with full detector simulation

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



⇒ Large improvement compared to LEP

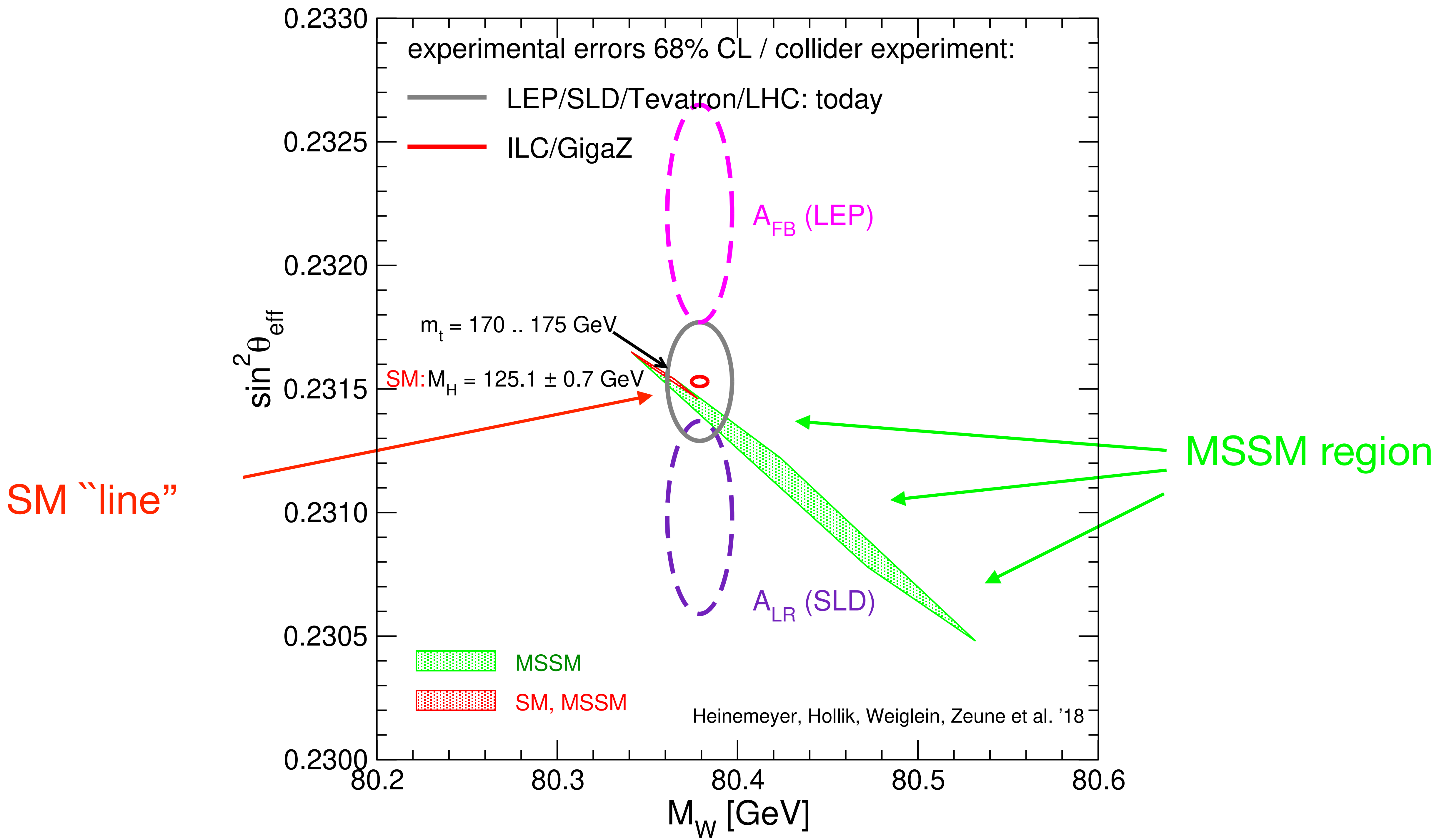
EWPO, top physics, flavour physics

- 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 possible scale of new physics

$\Rightarrow$ Improved precision from future facilities and / or dedicated experiments (low-energy experiments, flavour factories, etc.) will provide important information

Prediction for M_W and $\sin^2\theta_{eff}$ in the SM and the MSSM vs. experimental accuracies

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

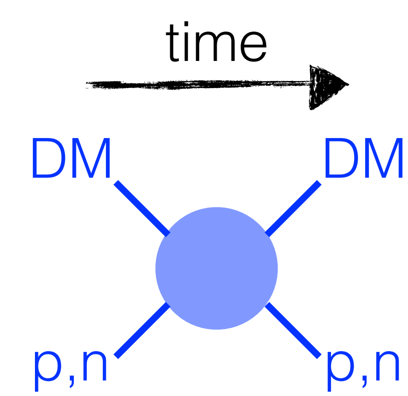


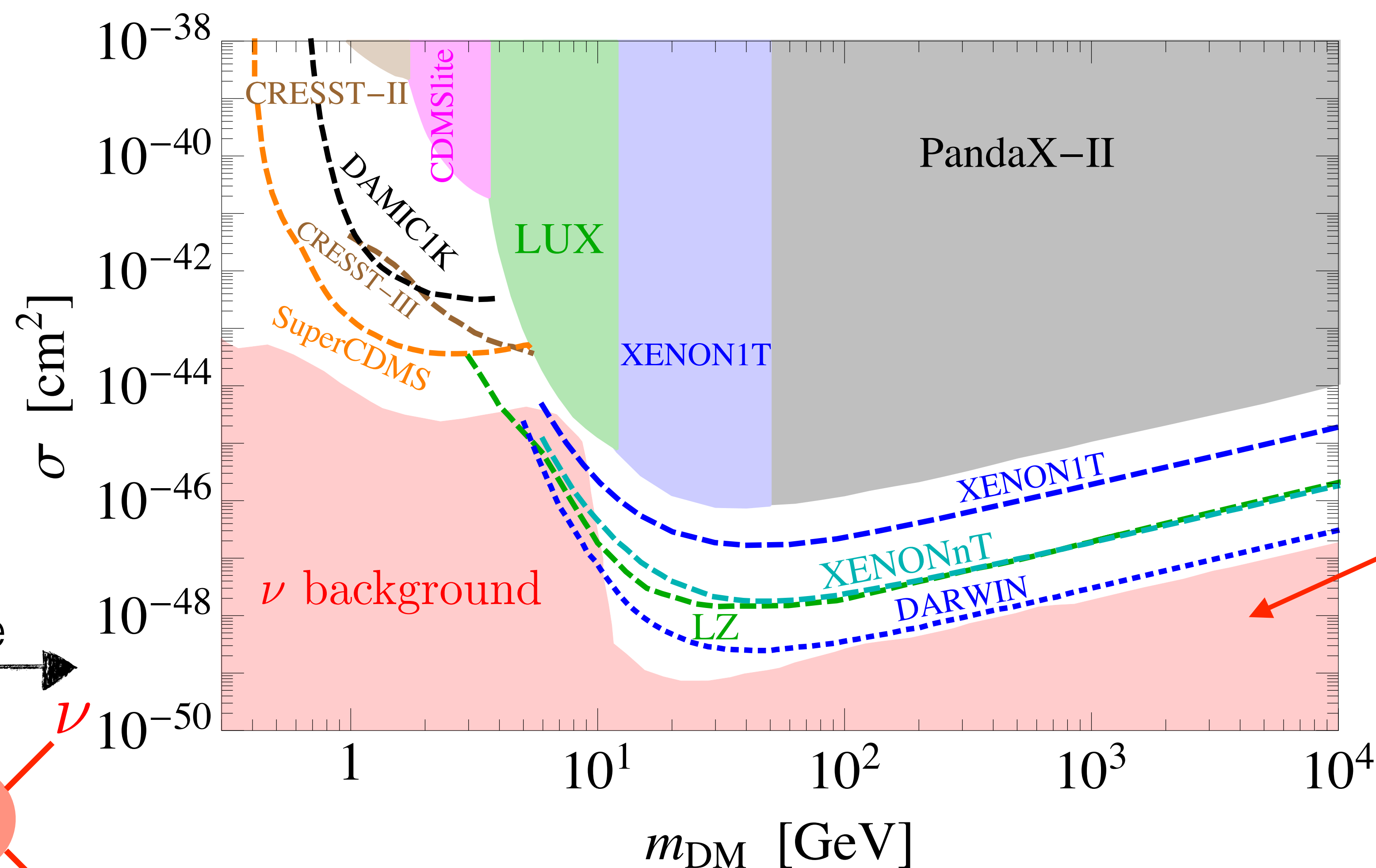
⇒ M_W and $\sin^2\theta_{eff}$ have high sensitivity for model discrimination

Prospects for dark matter searches

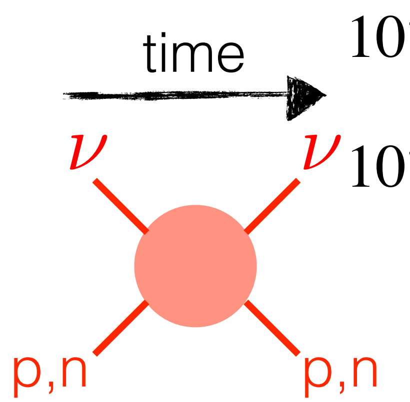
[J. Ruderman '18]

Direct Detection





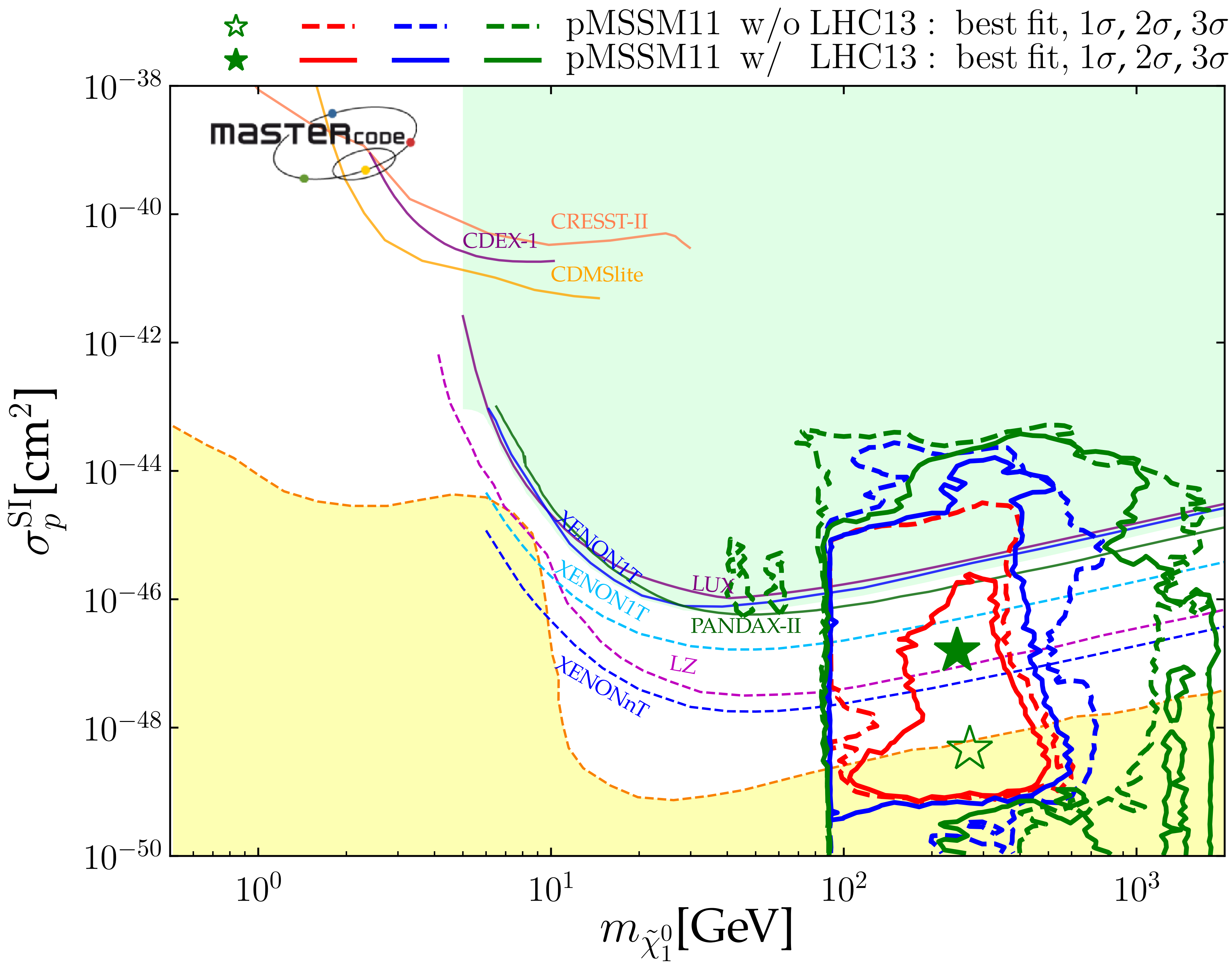
How to probe the "neutrino floor"?



- 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)

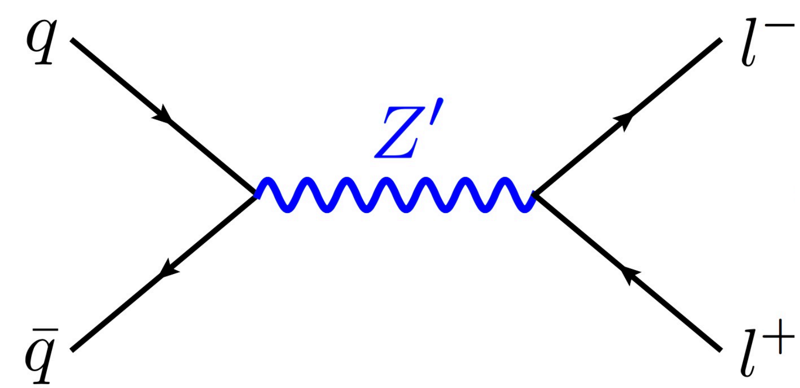
Present direct detection bounds and expected future sensitivities vs. preferred MSSM region

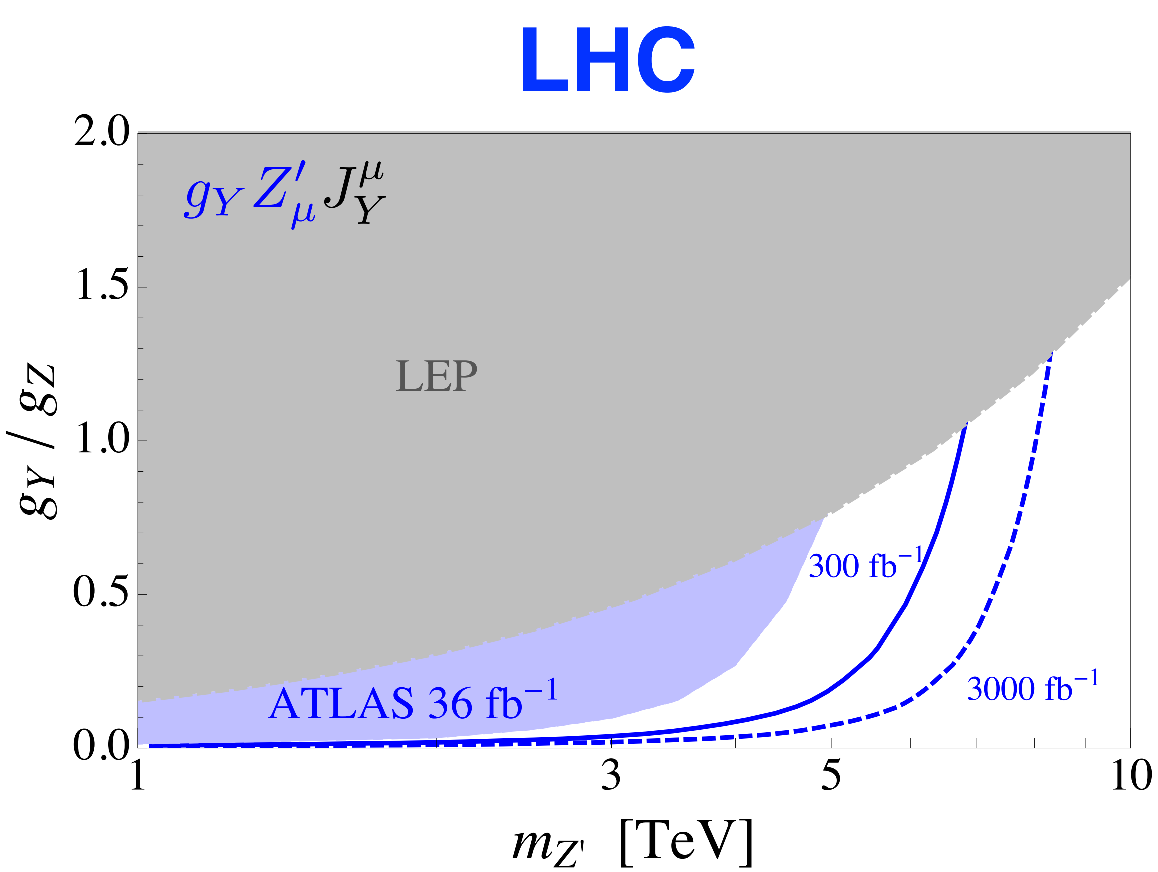
[E. Bagnaschi et al. ’17]

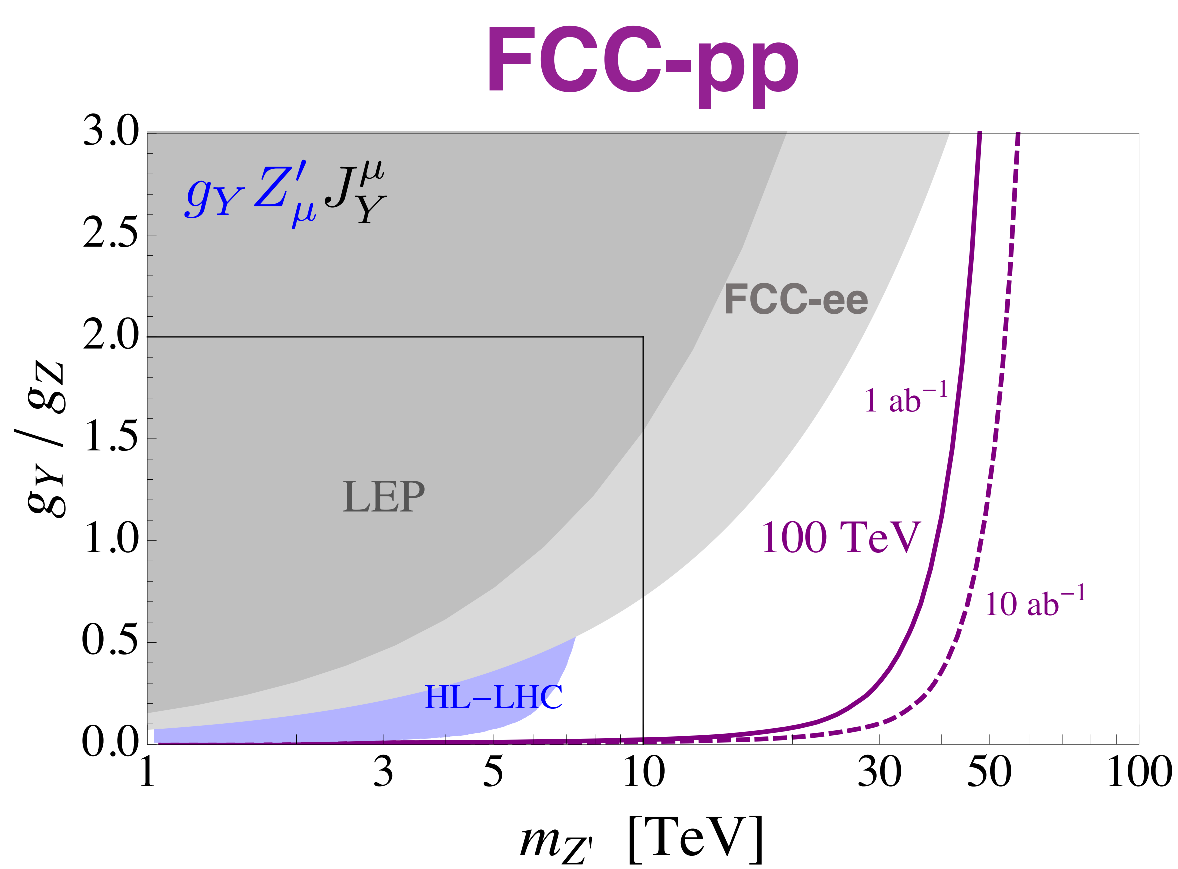


Sensitivity to new force carrier

[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)

Towards a European / global strategy: outcome of the Granada Open Symposium (my interpretation)

Higgs / electroweak

Answers to Big Questions

[B. Heinemann '19]

1. **How well can the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?**
   - Current colliders: ~1-3% for 3rd gen fermions and gauge bosons, 4% to μ, 50% to itself
   - Future colliders: factors of ~2-10 better (!) + $\kappa_c \sim 2\%$ + model-independent $\sigma(ZH)$
2. **How do precision electroweak observables inform us about the Higgs boson properties and/or BSM physics?**
   - Important to make sure precision H measurements (δg_Z) not limited by these
   - Themselves probe new physics in interesting and complementary way
3. **What progress is needed in theoretical developments in QCD and EWK to fully capitalize on the experimental data?**
   - A lot of progress needed! Plan exists but lots of work/people needed!!
   - In some cases, new ideas are needed => and unclear when/if new ideas come
4. **What is the best path towards measuring the Higgs potential?**
   - Di-Higgs and single Higgs production are sensitive to derivative $d^3V/d^3\phi$ near minimum
   - Seems conceivable to determine it with sufficient precision to test 1st order EWΦT

Higgs / electroweak

[B. Heinemann '19]

of "largely" improved H couplings (EFT)

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

13 quantities in total

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

Higgs / electroweak

[B. Heinemann '19]

1. **Measuring H coupling at the level of few% or better very interesting!!**
   - **Naturalness vs simplicity tested: complementary to LHC direct searches**
   - **Many important questions are related to Higgs boson**
2. **Significant advances in theory needed to exploit data from all (!) colliders**
3. **HL-LHC probes many H couplings to few % level**
   - **Absolute values model dependent, ratios of couplings model-independent**
4. **All ee colliders achieve major (and comparable) improvements in their first stage already in probing Higgs sector compared to HL-LHC:**
   - **At least half of couplings get improved by factor 5 or more**
   - **W/Z effective couplings and $BR(H \rightarrow invisible)$ even probed to ~3x10^{-3}**
   - **Model-independent total cross section measurement => access to width, untagged BR**
   - **Clean environment to study H if/when anomalies are seen to understand underlying physics**
5. **Higher energy stages of ee and hadron colliders important**
   - **Excellent sensitivity to high-scale physics, e.g. CLIC3000 and FCC-hh**
   - **FCC-hh/eh improves rare Higgs couplings by large factor compared to FCC-ee**
6. **Electroweak precision measurements important for Higgs programme and NP tests**
   - **Oblique parameters**
     - Circular colliders have naturally an extensive programme on EWPO at Z-pole (also Γ_Z)
     - CLIC at high energy and FCC-hh excellent reach
   - **Precision top and W programme** important for EFT analysis and theor. Uncertainties
     - Top requires $\sqrt{s} \geq 350$ GeV
   - **Tera-Z programme** at FCC-ee (and potentially CEPC) impressive
     - Giga-Z programme at ILC (incl. polarisation) not part of baseline plan => needs follow-up
7. **Higgs self-coupling sensitivity interesting for electroweak phase transition:**
   - **di-Higgs process probes κ_λ to 50% at HL-LHC => Improvements from HE-LHC (~15%), ILC$_{500}$ (~27%), CLIC$_{3000}$ (~9%), FCC-hh (~5%)**
   - **Single Higgs production also sensitive through loop effects**
8. **A few other interesting submissions for non-collider/low-energy measurements:**
   - **Not covered here but will include in briefing book**

Beyond the Standard Model (at colliders)

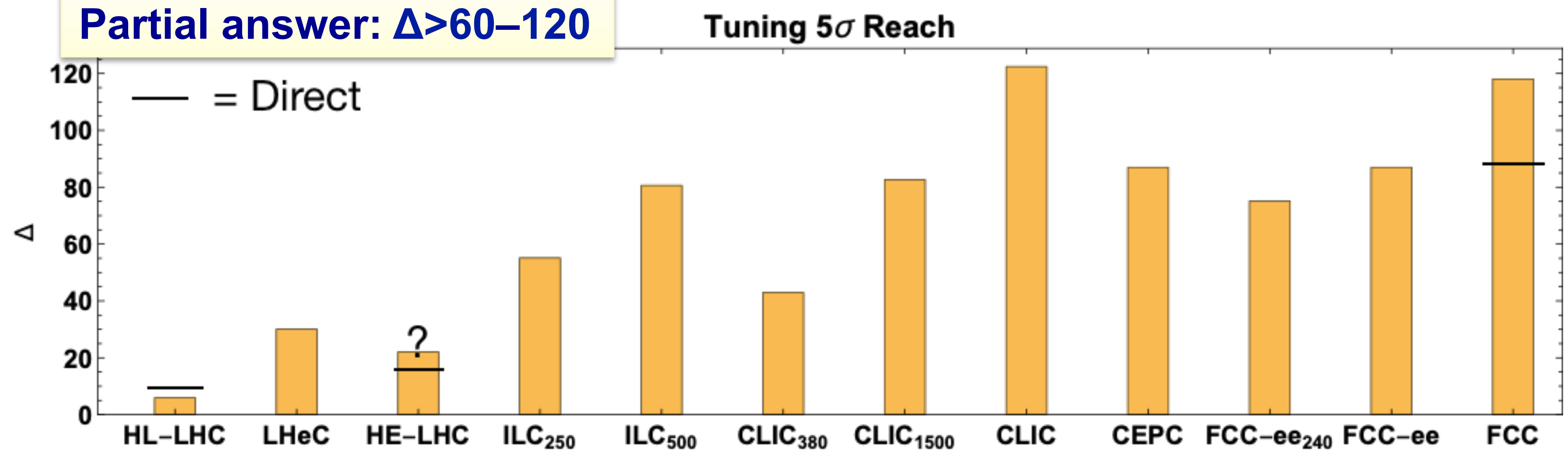
[P. Sphicas '19]

The four big questions for BSM (@colliders):

- **To what extent can we tell whether the Higgs is fundamental or composite?**
- **Are there new interactions or new particles around or above the electroweak scale?**
- **What cases of thermal relic WIMPs are still unprobed and can be fully covered by future collider searches?**
- **To what extent can current or future accelerators probe feebly interacting sectors?**

$$\Delta > \left(\frac{M_{\mathrm{T.P.}}}{500\,\mathrm{GeV}}\right)^2 > \frac{1}{\xi} \qquad \frac{c_\phi}{\Lambda^2} = \frac{g_*^2}{m_*^2} = \frac{\xi}{v^2} \Rightarrow \frac{1}{\xi} = \frac{1}{v^2}\left(\frac{c_\phi}{\Lambda^2}\right)^{-1}$$

Partial answer: Δ>60–120



Perspective from the Americas

[see JoAnne's talk on Wednesday] [Y.-K. Kim '19]

Next Collider Options

ILC

Statement by American Linear Collider Committee (US+Canada)

ALCC stance vis-a-vis discussions concerning the International Linear Collider in the context of the European Strategy for Particle Physics (2020) ALCC, March 27, 2019

The Americas Linear Collider Committee supports the ICFA position confirming the international consensus that *"the highest priority for the next global machine is a 'Higgs Factory' capable of precision studies of the Higgs boson."* We remain convinced that the ILC best meets all of the requirements needed to probe detailed properties of the Higgs boson. The ILC has the potential for a future upgrade in energy, can sustain beam polarizations that increase its ability to do precision measurements, and is the most technically mature proposal for an electron-positron collider now available.

The recent statement by MEXT in Japan stated that further consideration by the Science Council of Japan and intergovernmental discussions are necessary before Japan would be in a position to make a bid to host the ILC. Unfortunately, this does not fit naturally into the timetable for finalizing the European Strategy recommendation. On the other hand, it appears that high-level interactions between the U.S. DOE and the Japanese principals, government and DIET, continue to be positive. We understand that the DOE remains interested in discussing with senior Japanese officials about ILC and the possibility of hosting it in Japan.

The ALCC is supportive of any electron-positron project that can distinguish the Standard Model from new physics models through precision measurements of the Higgs production and decay couplings. However, given the strengths of the ILC noted above and the recent progress in obtaining support for it within Japan, we urge that the European Strategy group support the completion of the process underway in Japan to decide on a bid to host the ILC.

CLIC

- CLIC and normal conducting high-gradient activities
- O(200) signatories for CDR
- Detector design and R&D
- Ongoing studies on physics potential

FCC-ee, ep, pp

- Deep expertise in accelerator technologies including high field magnets and SCRF
- O(500) engaged; O(100) co-authored European Strategy Documents
- Ongoing studies on physics potential and detector design
- Long and productive cooperation on joint projects in US and at CERN

CEPC

- Pre-CDR & CDR on arXiv with international contributions
- O(100) participated
- Detector design and R&D

Perspective from the Americas

[Y.-K. Kim '19]

Conclusions: Towards 2020 ESG

- Support of Americas' current plan
  - Importance of current high-priority projects such as HL-LHC, DUNE, …
- Beyond mid-2020's
  - Scientific drivers of the current plans are still valid
  - More capable facilities and broader programs
  - R&D of enabling technologies for future (accelerator, detector and computing)
- Support of facilities and activities outside of Europe
  - DUNE/LBNF, SNOLAB, CMB-S4, EIC, ….
  - A statement in the ESG document plays a significant role for success of facilities outside of Europe that serves the European / worldwide community
- The American community
  - will continue with its strong partnership with Europe
  - would like to see positive steps toward a new collider: an e+e- collider might be the first one to be realized: O(1000) American community

[Y.-K. Kim ’19]

Closing Remarks

The worldwide particle physics community can together address
the full breadth of the field's most urgent scientific questions
with
each major player hosting a unique world-class facility at home
and partnering in high-priority facilities hosted elsewhere.

Perspective from Asia

[G. Taylor '19]

ILC/CepC Advantage for Europe

- **Allows concentration on proton, high energy future**
  - ***CERN essential for the energy frontier.***
  - ***Proton and high-field magnet expertise***
  - ***The ONLY laboratory capable of attempting very difficult projects, thus should be setting a "high bar"***
- **CERN infrastructure in protons beams outlays the fear of a second 100km tunnel.**
  - ***Possible to see a new proton collider at CERN by mid-2040s (not mid 2060s, but also not 100TeV)***

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

Geoffrey Taylor "Perspective on the European Strategy from Asia", EPPSU2019, Granada 39

European Strategy Update

Perspective from Asia

[G. Taylor '19]

The Needs of Particle Physics

- **A e+e- collider higgs factory ASAP**
  - ***and, yes, in time, t-tbar, ttH, HH, ..***
- **A new energy frontier facility following HL-LHC**
  - ***even without a specific physics driver, as yet***
  - ***pp, ion-ion and ep all possible***
- **An active field, with multiple activities in parallel:**
  - ***particle physics data taking and analysis***
  - ***accelerator physics, including μμ colliders and plasma acc'n***
  - ***detector development***
  - ***advanced computing techniques***

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Perspective from Asia

[G. Taylor '19]

Asian (and personal) View

- **Diversity is Critical to thrive in all environments, including HEP.**
  - ***Big and small facilities/experiments, at various stages of development and operation***
- **Push for e+e- colliders, both Linear and Circular, as soon as possible.**
  - ***Linear Collider: ILC***
    - **1 Collision point**
  - ***Circular Collider: CepC***
    - **2 Collision points**
- **Push for FCC tunnel to be ready at completion of HL-LHC**
  - ***Stage the energy frontier with best option magnets available for early 2040's***
  - ***?? Default: ~8T LHC magnets optimised for price***
    - **Minimum energy: >50TeV**
    - **Magnet upgrade foreseen.**
  - ***ep and ion-ion options available***
  - ***4 collision points***
  - ***Upgrade path to higher energy after 20 years operation?***

See A. Yamamoto, S. Rossi, V. Shiltzev talks this symposium

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European Strategy Update

Outcome of the Open Symposium (my interpretation)

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

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

  Some arguments:

  [K. Jakobs, G. Taylor, …]

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

Outcome of the Open Symposium (my interpretation)

- Our field would not survive the long gap between FCC-ee and FCC-hh

  [L. Evans, …]

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

Implications (my interpretation)

- We should not take it for granted that there will be another big collider project, neither at CERN nor elsewhere
- Some people seem to think that the next big CERN project should be the ET
- What we put forward as the outcome of this strategy process has to be very convincing for other scientists, the general public and politicians. Otherwise the future of our field is at risk.
- We need a coherent world-wide programme (see statements by the other areas) and, as a crucial part of it, a forefront collider project at CERN