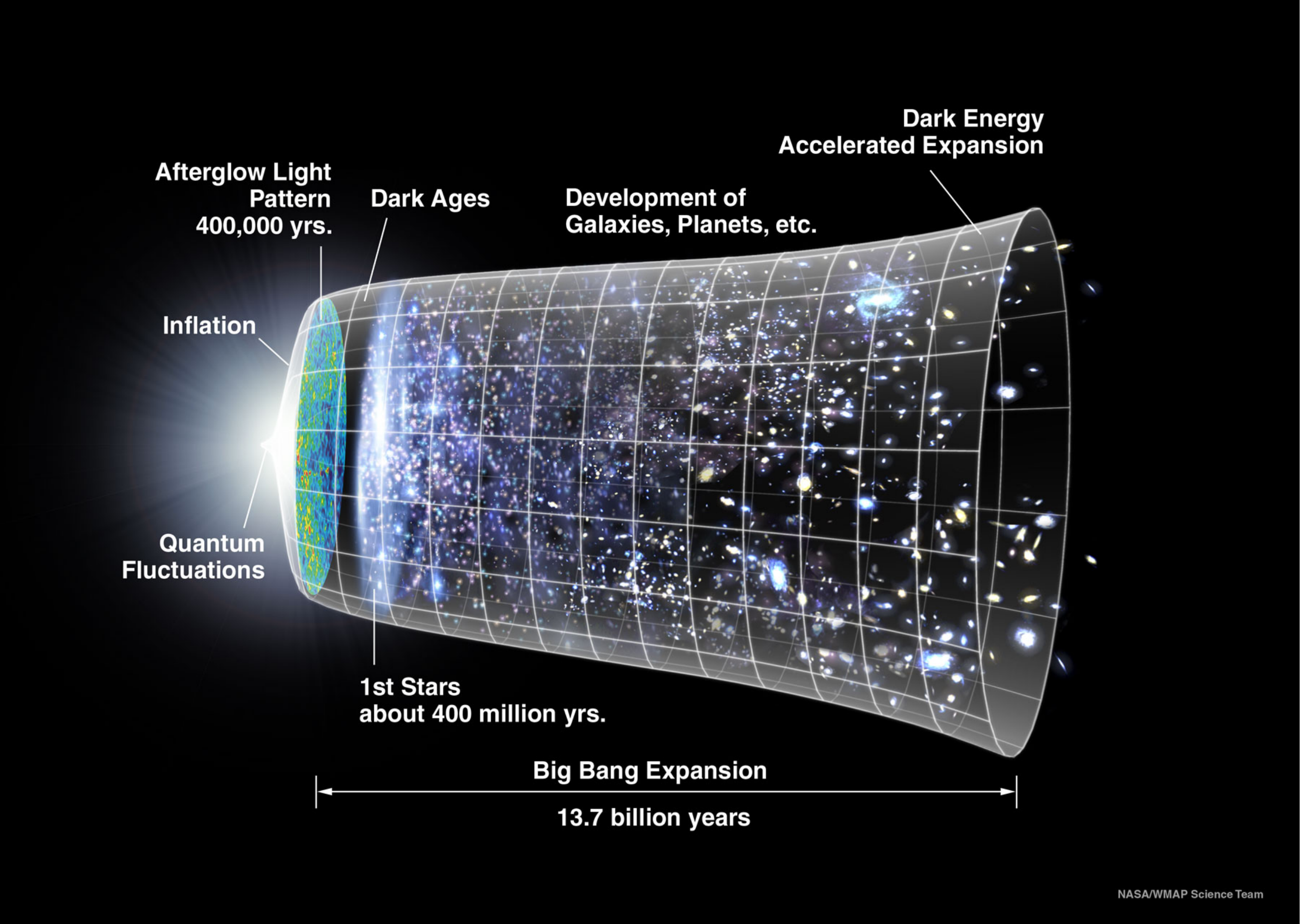
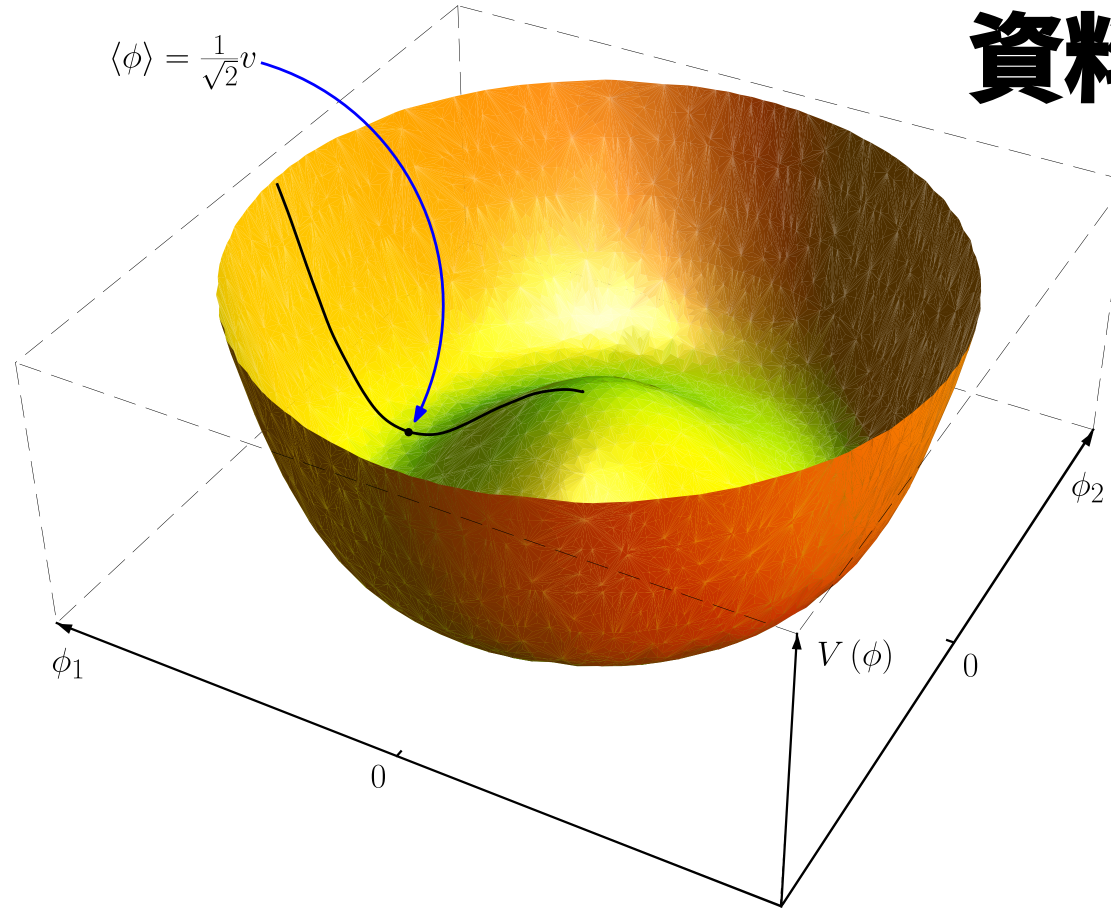
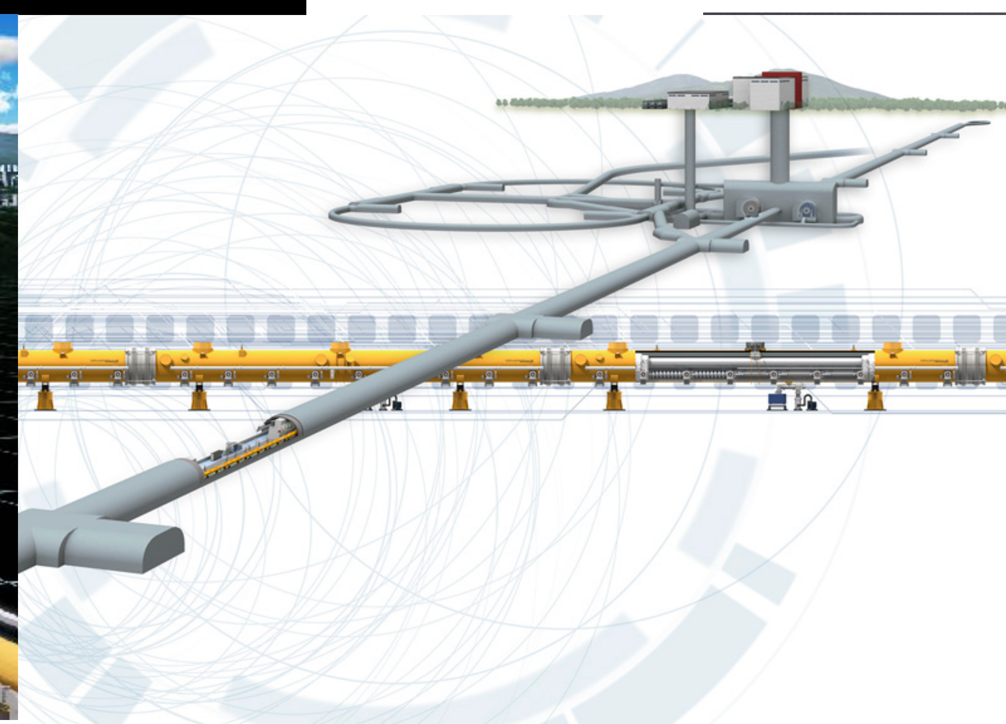
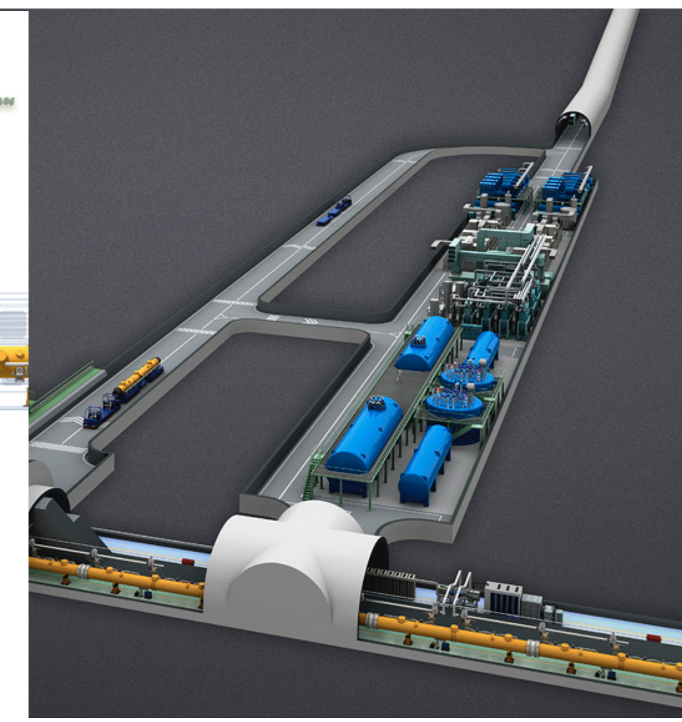
資料2









Physics potential of the ILC at 250 GeV

Georg Weiglein, DESY

Tokyo, 02 / 2018

Outline

1. Introduction: the ILC at 250 GeV is a ``Higgs factory”

2. Physics programme of the ILC at 250 GeV: brief overview

3. How does the physics programme of the ILC at 250 GeV compare with the one up to 500 GeV?

4. Conclusions

Appendix

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

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

Concept of the talk:

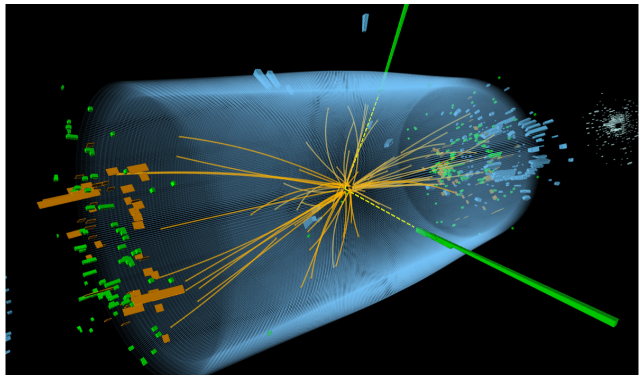
Sections 2 and 3 start with a summary that avoids as much as possible technical details and specific jargon. More details are given on the following slides. Appendix A addresses the relevance of Higgs physics in a wider context, while Appendix B contains further details on Section 2.

1. Introduction: the ILC at 250 GeV is a ``Higgs factory"

- The ILC running at 250 GeV will be a ``Higgs factory"
- 250 GeV is the ideal energy to mass-produce the recently discovered Higgs boson together with the Z boson
- The large number of produced Higgs bosons (~500 000) will allow the determination of the Higgs properties with high precision
- This will lead to an enormous progress in the understanding of the fundamental laws of nature and of the evolution of our Universe
- The Higgs boson may provide access to the dark matter of the Universe
- The ILC at 250 GeV also has a discovery potential for dark matter and other new particles

The Higgs boson and the origin of mass of elementary particles

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.



Nobel Prize 2013

The discovery establishes a non-trivial structure of the vacuum, i.e. of the lowest-energy state in our Universe. This structure is caused by the Higgs field (``Higgs potential”).

The origin of mass of elementary particles is related to the structure of the vacuum: mass arises from the interaction with the Higgs field.

Studying the properties of the discovered particle allows us to explore the foundation upon which the Universe has been shaped during its phase transition and from which it continues to evolve.

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. Experiments are 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.

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

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

Present understanding: Historical comparison with superconductivity

Discovered 1911 *Nobel Prize 1913* (Kamerlingh Onnes)

Ginzburg-Landau theory, 1950: phenomenological theory of superconductivity, successful description of macroscopic properties *Nobel Prize 2003* (Abrikosov, Ginzburg)

Bardeen-Cooper-Schrieffer (BCS) theory, 1957: microscopic theory of the underlying physics in terms of ``Cooper pairs" of two electrons, explains macroscopic parameters *Nobel Prize 1972*

Our current understanding of the origin of mass of elementary particles is at the level of the Ginzburg-Landau theory of superconductivity. We are lacking an understanding of the underlying physics at the level of the BCS theory. Achieving this understanding would be a huge progress in the quest to reveal the fundamental laws of nature.

Implications of Higgs physics

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?

2. Physics programme of the ILC at 250 GeV: brief overview

The quest to identify the origin of mass of elementary particles is among the most important challenges of modern science. A Higgs factory is an ideal facility to address this.

The ``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.

This leads to absolute and model-independent measurements of the Higgs production process and of the Higgs decay branching ratios.

These measurements will be crucial for discovering the physics that is responsible for generating the masses of elementary particles.

The ILC at 250 GeV furthermore has a large discovery potential for new particles and new physics.

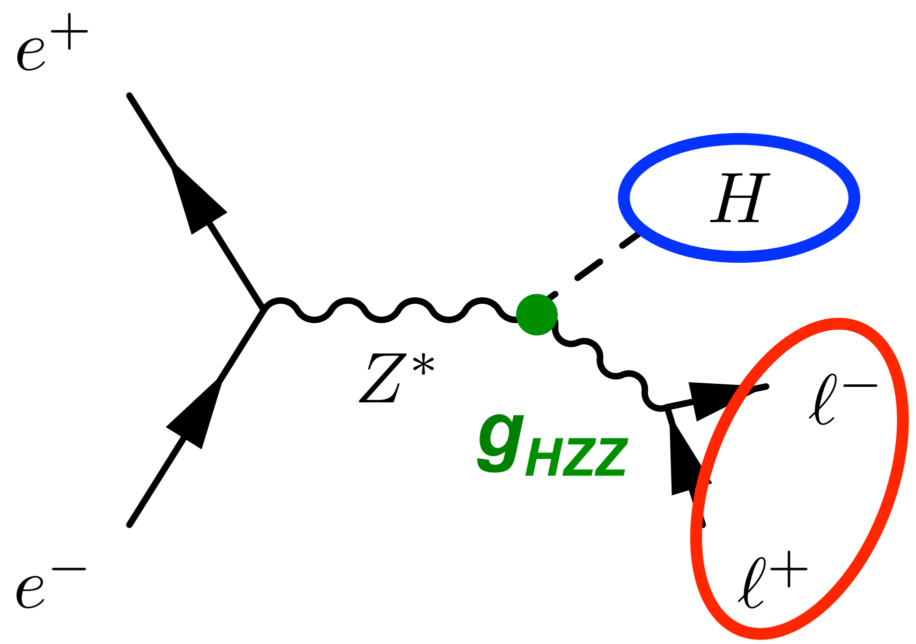
"Golden channel" at the ILC: $e^+e^- \to ZH, Z \to e^+e^-, \mu^+\mu^-$

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

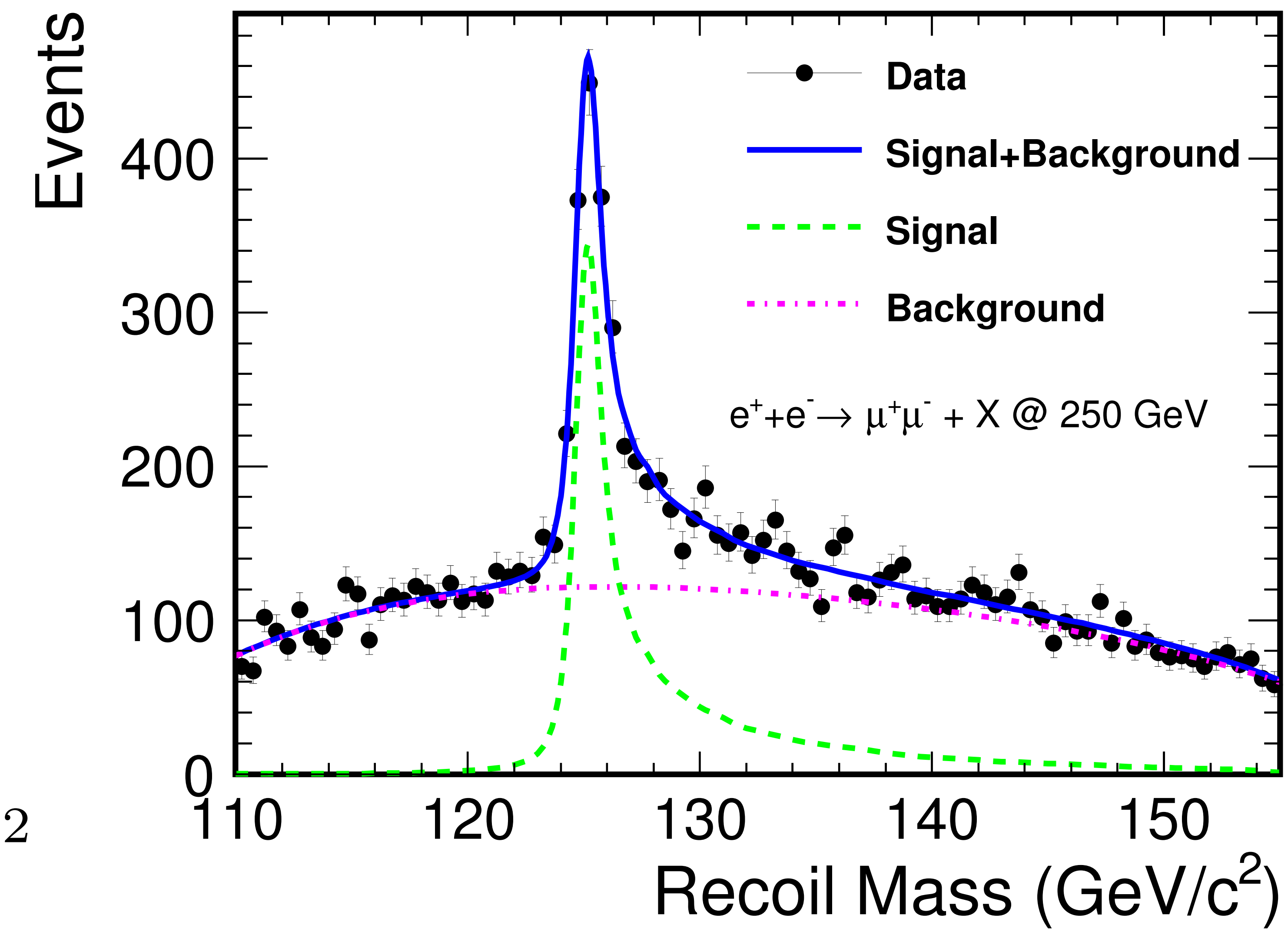
Reconstruct $Z \to l^+l^-$

independent of Higgs decay

sensitive to invisible Higgs decays



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



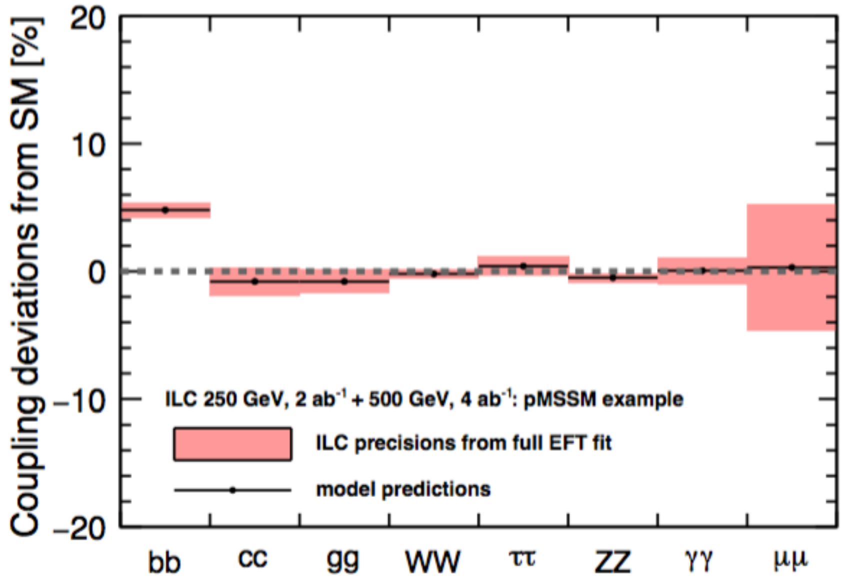
Since the Z ⟶ l^+l^- decay branching fraction is known from the e^+e^- collider LEP, this method yields an absolute measurement of the ZH cross section and the Higgs branching ratios! 1% level reachable!

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

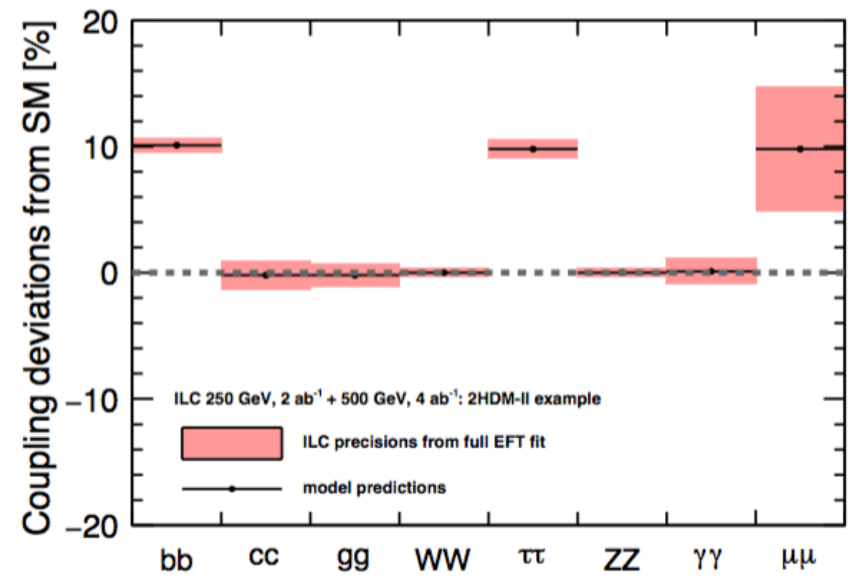
Coupling deviations for different models vs. ILC precision

[T. Barklow et al. ’17]

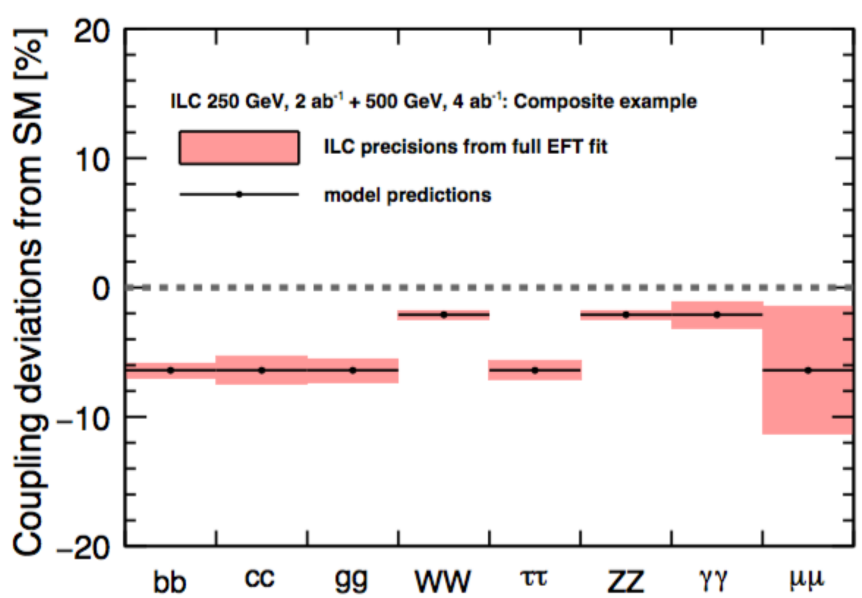
heavy SUSY



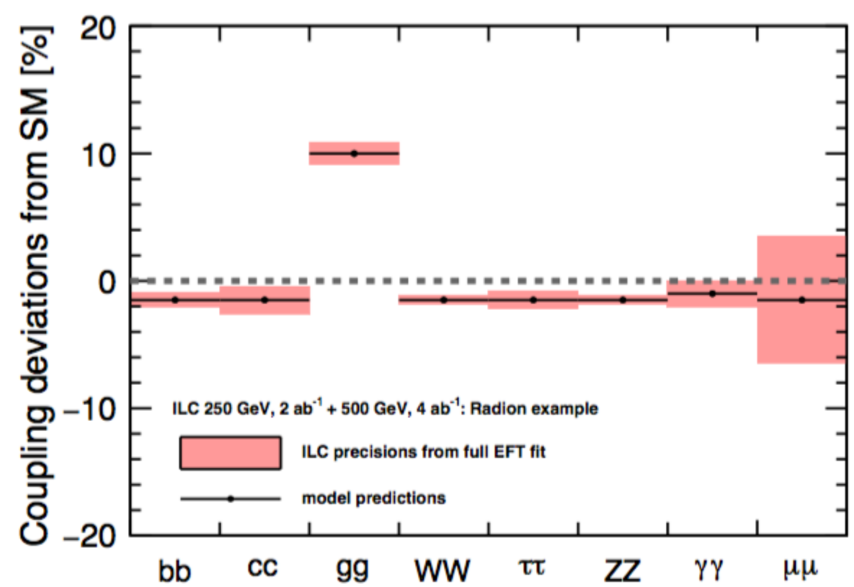
2 Higgs doublet



composite Higgs



Higgs-Radion mixing



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

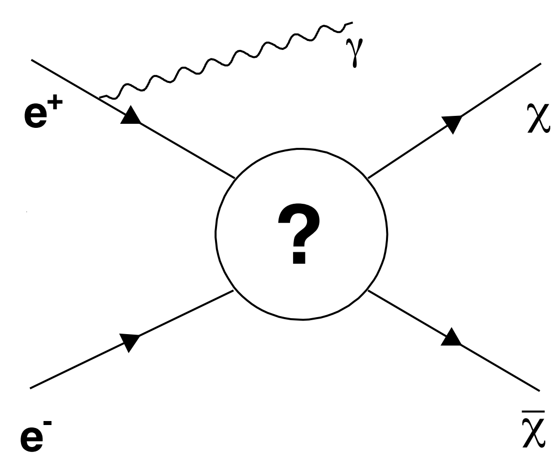
⇒ ILC precision at 1% level provides large sensitivity for discriminating between different realisations of underlying physics

Discovery potential of ILC 250 for the production of new particles

- Higgs decays to dark matter and other new particles: ILC 250 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

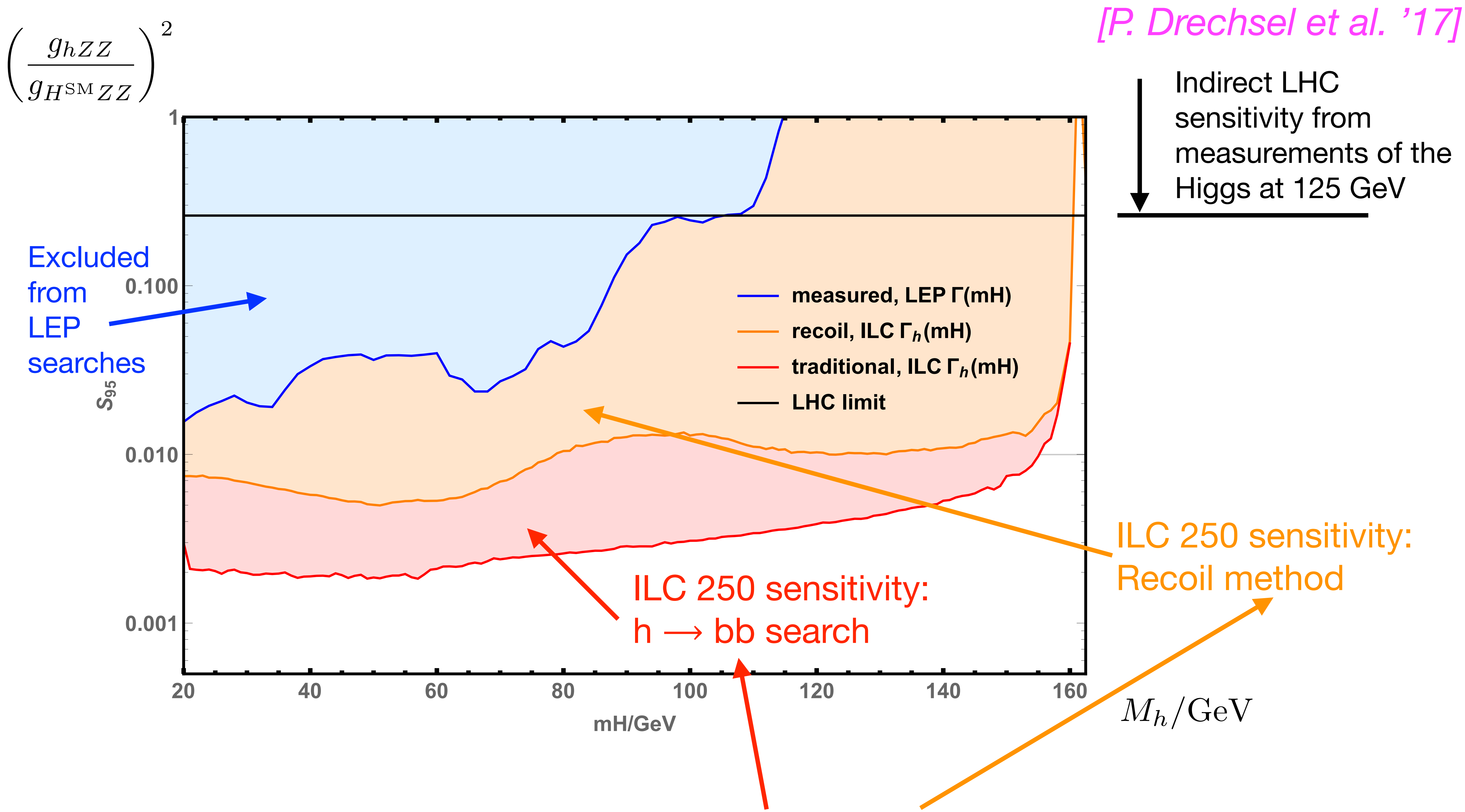


yields complementary sensitivity to the LHC and to direct detection experiments

- 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 for ILC 250!

Sensitivity of ILC 250 with 500 fb^{-1} to a new light Higgs



⇒ ILC 250 will explore a large untested region!

3. How does the physics programme of the ILC at 250 GeV compare with the one up to 500 GeV?

The core of the physics programme of the ILC with energies up to 500 GeV can be carried out at the 250 GeV energy stage.

The results from the ILC running at 250 GeV will be crucial for a possible programme at higher energies!

Higgs physics:

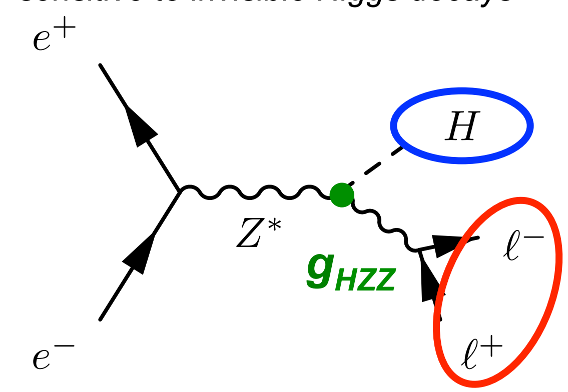
ILC 500 yields quantitative improvements of the determination of the Higgs couplings.

At ILC 500 the weak boson fusion channel, where the Higgs is produced together with two neutrinos (missing energy), can be exploited as additional Higgs production channel. This leads in particular to an improved determination of the total Higgs width.

Standard method at the ILC for the determination of the total Higgs width

ILC: absolute measurements of the cross section and Higgs branching ratios

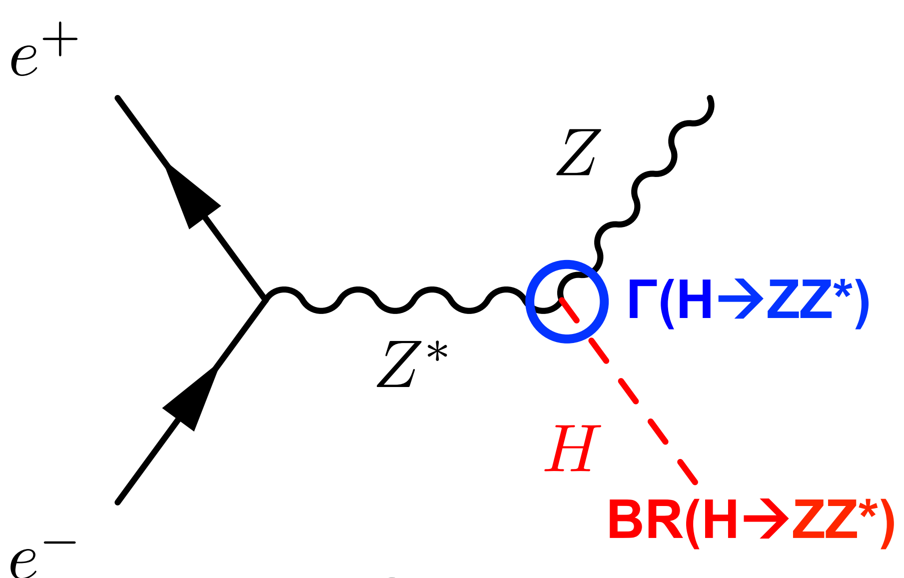
Reconstruct Z→l⁺l⁻
independent of Higgs decay
sensitive to invisible Higgs decays



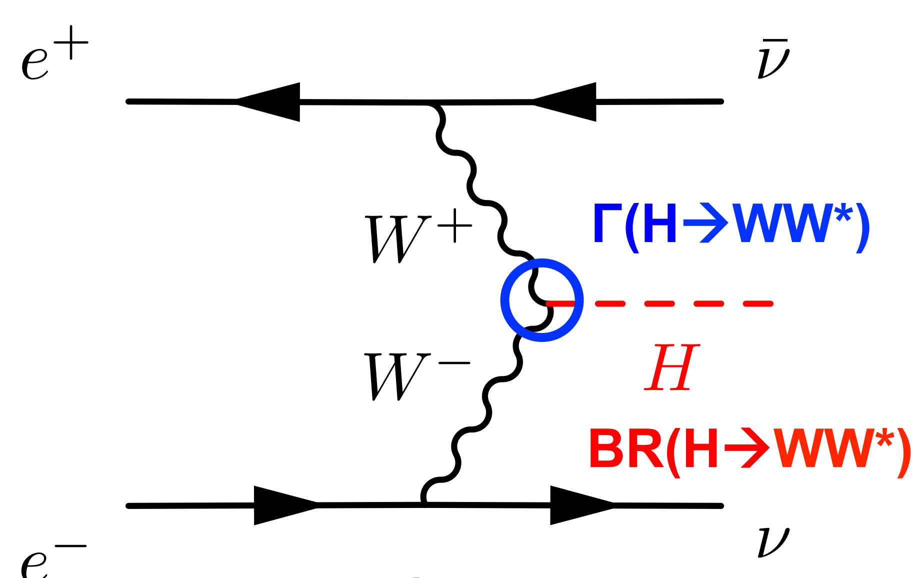
$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

⇒Determination of the total Higgs width

$$\Gamma_H = \Gamma(H \to XX)/\text{BR}(H \to XX)$$



ILC 250



ILC 350

⇒Increased precision of total width determination at 350 GeV

ILC physics programme beyond 250 GeV

Further Higgs physics:

The ttH production channel at ILC 500 (or ILC 550) will provide a direct measurement of the ttH coupling with higher precision than at the HL-LHC.

At ILC 500 also processes with two Higgs bosons in the final state will be accessible. They will allow a measurement of the Higgs self-coupling HHH, which is important for determining the Higgs potential.

Top physics:

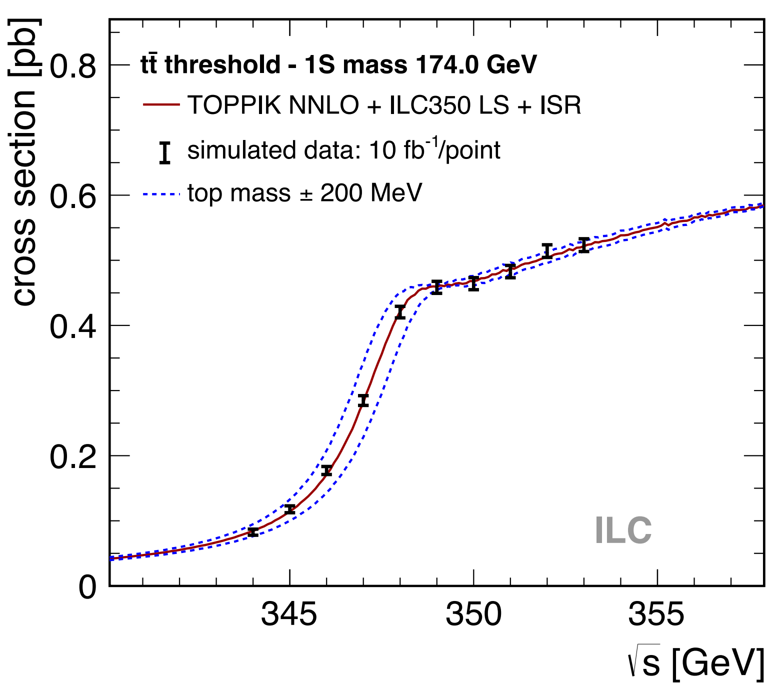
At ILC 350 the measurement of the top-quark mass will significantly be improved both quantitatively and qualitatively compared to the HL-LHC. The top physics programme at ILC energies up to 500 GeV will have a large potential for revealing effects of new physics.

Top-quark mass measurement at the ILC

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.

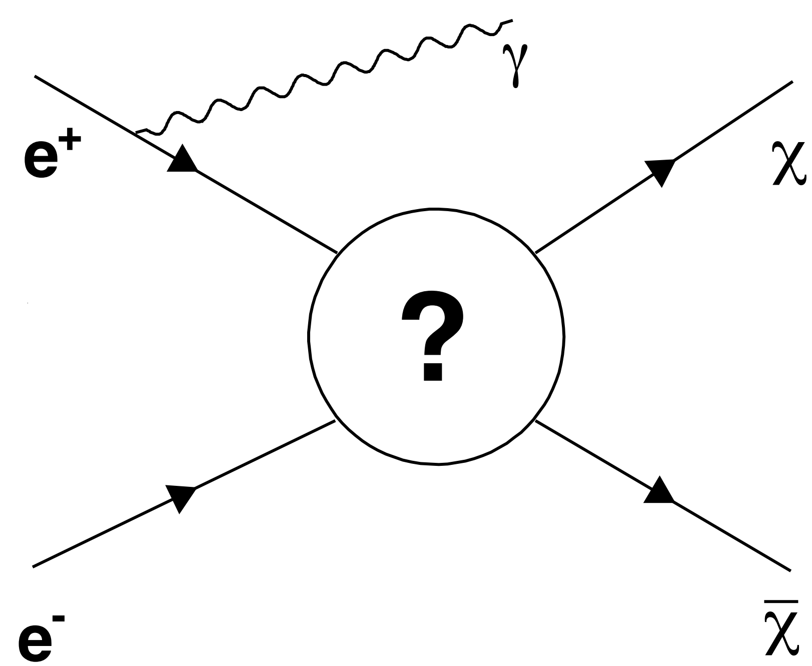
At the ILC a ``threshold mass" will be measured with an unprecedented precision of about 50 MeV. It is theoretically well-defined and can be translated into the top-quark mass value used in theoretical predictions at the same level of accuracy.



ILC physics programme beyond 250 GeV

Searches for new particles:

ILC 500 will have an improved sensitivity in particular in the searches for dark matter and new weakly interacting particles, which is complementary to the sensitivity of the HL-LHC.



Electroweak physics:

The higher collider energy of ILC 500 will increase the sensitivity to effects from new physics.

How should one interpret this table in this context?

[J. Brau '17]

ILC Physics Goals	500 GeV	350 GeV	250 GeV
• precision Higgs couplings	✔	✔	✔
• **g**HWW and overall normalization of Higgs couplings	✔	✔	
• search for invisible and exotic Higgs decay modes	✔	✔	✔
• Higgs couplings to top	✔		
• Higgs self-coupling	✔		
• search for extended Higgs states	✔		
• precision electroweak couplings of the top quark	✔		
• precision **W** couplings	✔	✔	
• precision search for **Z**′	✔		
• search for supersymmetry	✔		
• search for Dark Matter	✔		
• top quark mass from threshold scan		✔	
• precision Higgs mass			✔

How should one interpret this table in this context?

[J. Brau '17]

ILC Physics Goals	500 GeV	350 GeV	250 GeV
• precision Higgs couplings	✔	✔	✔
• **g**HWW and overall normalization of Higgs couplings	✔	✔	
• search for invisible and exotic Higgs decay modes	✔	✔	✔
• Higgs couplings to top	✔		
• Higgs self-coupling	✔		
• search for extended Higgs states	✔		
• precision electroweak couplings of the top quark	✔		
• precision **W** couplings	✔	✔	
• precision search for Z'	✔		
• search for supersymmetry	✔		
• search for Dark Matter	✔		
• top quark mass from threshold scan		✔	
• precision Higgs mass			✔

A quote from J. Brau: ``The number of ticks on that table by no means can be used as a measure of the significance of the program at each energy!"

Some comments on the interpretation of the table

- A summary in form of such a table is necessarily over-simplified.

- There would be many other possibilities for how to group the physics topics in the rows of the table and for which rows to put.

- The table does not provide information about the relative weights of the different ticks.

- For those reasons it would not be appropriate to do a simple counting of ticks.

- Even sticking to the format of the table and to the way it is organised, according to my assessment the ILC running at 250 GeV does tick most of the boxes that have been left empty in the table, either on its own or in combination with the LHC.

How should one interpret this table in this context?

[J. Brau ’17]

ILC Physics Goals	500 GeV	350 GeV	250 GeV	
• precision Higgs couplings	✔	✔	✔ ✅	Core is specific to ILC 250!
• **g**HWW and overall normalization of Higgs couplings	✔	✔	✅	ILC 250 ⊕ LHC
• search for invisible and exotic Higgs decay modes	✔	✔	✔	
• Higgs couplings to top	✔		✅	LHC
• Higgs self-coupling	✔		(✅)	LHC
• search for extended Higgs states	✔		✅	ILC 250 ⊕ LHC
• precision electroweak couplings of the top quark	✔		✅	LHC
• precision **W** couplings	✔	✔	✅	ILC 250 ⊕ LHC
• precision search for **Z**′	✔		✅	ILC 250 ⊕ LHC
• search for supersymmetry	✔		✅	ILC 250 ⊕ LHC
• search for Dark Matter	✔		✅	ILC 250 ⊕ LHC
• top quark mass from threshold scan		✔		
• precision Higgs mass			✔	

• precision Higgs couplings	✔	✔	✔	✅ Core is specific to ILC 250!

- The Higgs precision measurements are the core of the physics programme of the ILC.

- What appears as a single tick in the table is in fact a very rich programme, which gives this tick a very large weight.

- The capabilities of the ILC running at 250 GeV are unique for those measurements.

• gHWW and overall normalization of Higgs couplings	✔	✔	✅

ILC 250 ⊕ LHC

- The HWW coupling is accessible at ILC 250 via the Higgs decay into WW.

- The determination of the total width, which is needed to extract couplings from branching ratios, can be done at 250 GeV using the ZH cross section and BR(H $\longrightarrow$ ZZ). The accuracy of this determination is limited by the statistics of BR(H $\longrightarrow$ ZZ).

- This accuracy can be improved by inserting the ZH cross section measurements into the LHC analyses and using the resulting BR(H $\longrightarrow$ ZZ) from the LHC. Another way of improving it is to make use of BR(H $\longrightarrow$ WW) via the measurement of the ratio of the two branching ratios or via the application of an effective Lagrangian formalism respecting gauge invariance and custodial symmetry.

• Higgs couplings to top	✔		✅	LHC
• Higgs self-coupling	✔		(✅)	LHC

- Higgs couplings to the top quark will be accessible at the LHC, making use of the input from the ILC

- Higgs self-coupling: limited information from the LHC making use of its total accumulated luminosity

⇒ Important synergies: ILC 250 ⊕ LHC

• search for extended Higgs states	✔		✅	ILC 250 ⊕ LHC
• search for supersymmetry	✔		✅	ILC 250 ⊕ LHC
• search for Dark Matter	✔		✅	ILC 250 ⊕ LHC

- See slides 11, 12 above for examples that tick the boxes

- The ILC running at 250 GeV will have a large discovery potential for light new particles compared to the e^+e^- collider LEP2 (higher energy, much higher luminosity, polarised beams, much better detectors) and to the hadron colliders Tevatron and LHC (much better signal-to-background rates, much better sensitivity for signals with small cross sections and for new states with compressed spectra).

• precision electroweak couplings of the top quark	✔		✅
• precision **W** couplings	✔	✔	✅
• precision search for **Z**′	✔		✅

ILC 250 ⊕ LHC will have significant sensitivity

4. Conclusions

The physics case of the ILC at 250 GeV is extremely strong.

The physics programme at 250 GeV with polarised beams will tremendously advance the understanding of the fundamental laws of nature and complement the measurements at the LHC. The interplay of the results from the LHC and the ILC will allow one to go far beyond the results that could be achieved at each of the two machines individually.

A timely realisation of the ILC at 250 GeV will be crucial for exploiting those synergies.

I fully support the statements of ICFA ``*… will provide excellent science from precision studies of the Higgs boson … a key science project complementary to the LHC and its upgrade*" and the Japanese HEP community ``*a compelling physics case for constructing an ILC at 250 GeV centre of mass energy as a Higgs factory*".

The extendibility of the ILC to reach higher energies is a uniquely important advantage compared to circular machines. The results from ILC 250 will shape a possible programme at higher energies.

Preparations for the update of the European Strategy for Particle Physics: Germany

KET
Komitee für Elementarteilchenphysik

Conclusions of the

KET Workshop on Future e^+e^- Colliders[a]

Max-Planck-Institut für Physik Munich, May 2-3, 2016

2. The ILC meets all the requirements discussed at this workshop.[ii] It is currently the only project in a mature technical state. Therefore this project, as proposed by the international community and discussed to be hosted in Japan, should be realised with urgency. As the result of this workshop, this project receives our strongest support.[iii]