European Strategy for Particle Physics Update 2018 - 2020

European Strategy Update

Strategy Workshop Particle Physics, May 2018

Electron-positron colliders

Georg Weiglein, DESY

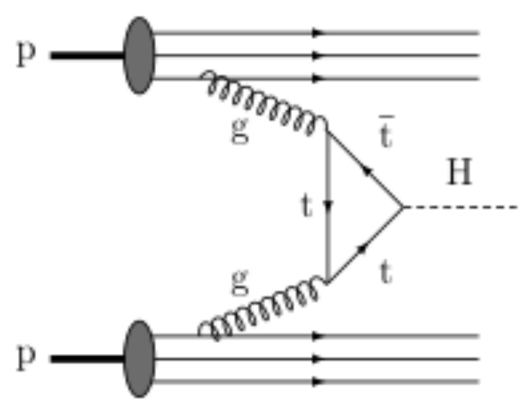
Bonn, 05 / 2018

Introduction

Hadron and e^+e^- colliders

[P. Roloff '18]

Hadron colliders:

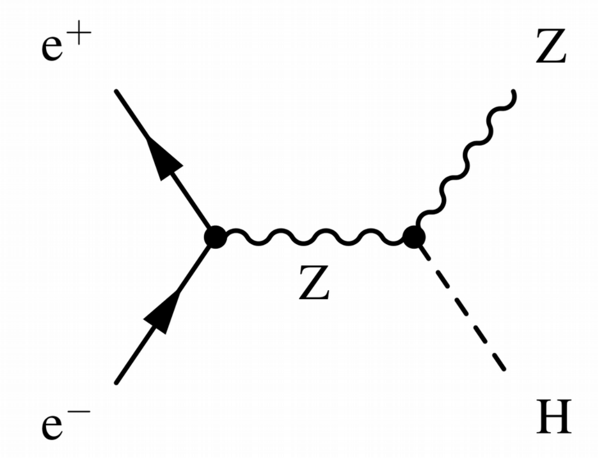


- **The proton is a compound object**
→ Initial state unknown
→ Limits achievable precision

- **High-energy circular colliders possible**

- **High rates of QCD backgrounds**
→ Complex triggers
→ High levels of radiation

e^+e^- colliders:



- **e^+e^- are pointlike**
→ Initial state well-defined ($\sqrt{s}$, polarisation)
→ High-precision measurements

- **High energies ($\sqrt{s}$ > 350 GeV) require linear colliders**

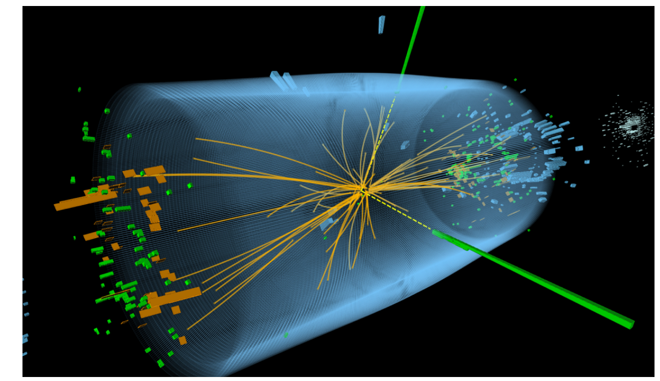
- **Clean experimental environment**
→ Less / no need for triggers
→ Lower radiation levels

Complementary information

Long success story of interplay of hadron and lepton colliders

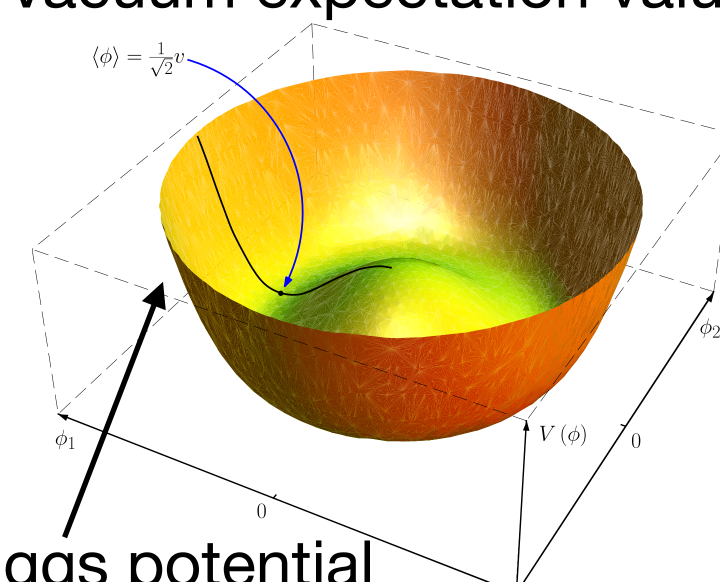
The origin of mass of elementary particles: present status (in a nutshell)

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?
- …

Higgs coupling determination at the LHC

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

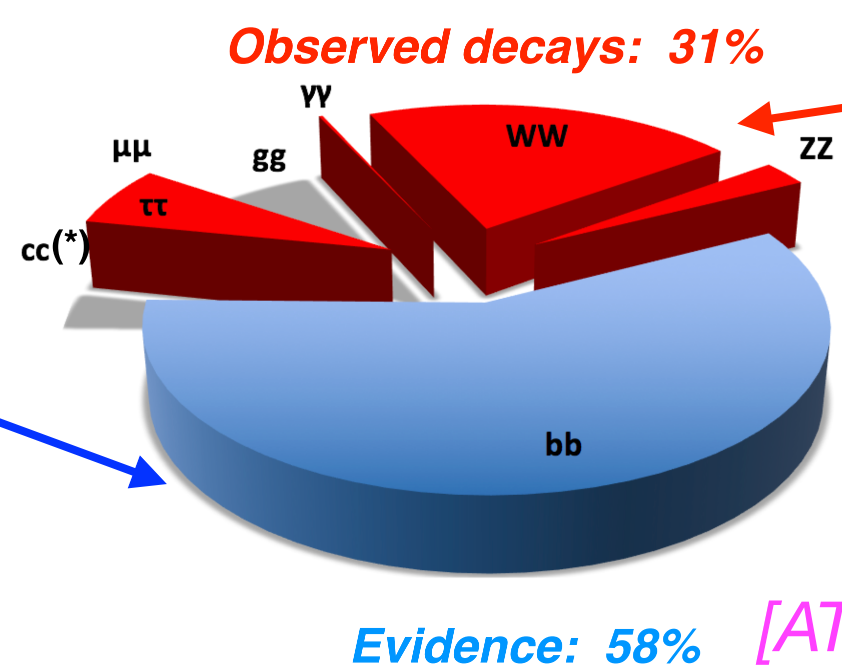
(Production) x (decay) at the LHC yields combinations of Higgs couplings ($\Gamma_{\mathrm{prod,\,decay}} \sim g^2_{\mathrm{prod,\,decay}}$):

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

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

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, $\boldsymbol{\tau\tau}$, $\gamma\gamma$

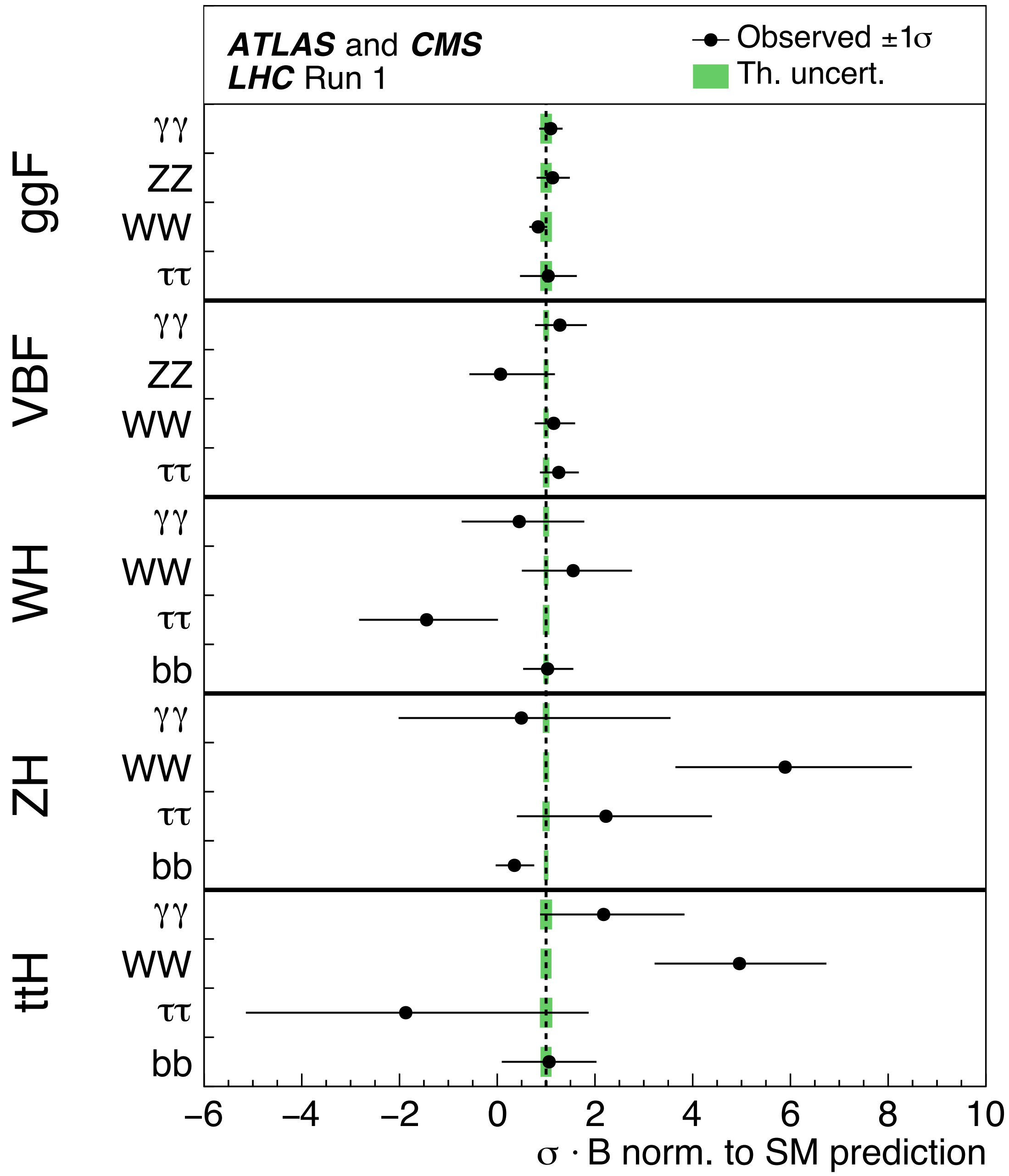
Evidences:
ATLAS: 3.6 σ, CMS: 3.8 σ

[ATLAS, CMS Collaborations ’17]

Signal strengths from LHC Run 1: ATLAS + CMS

Signal strength:

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



[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

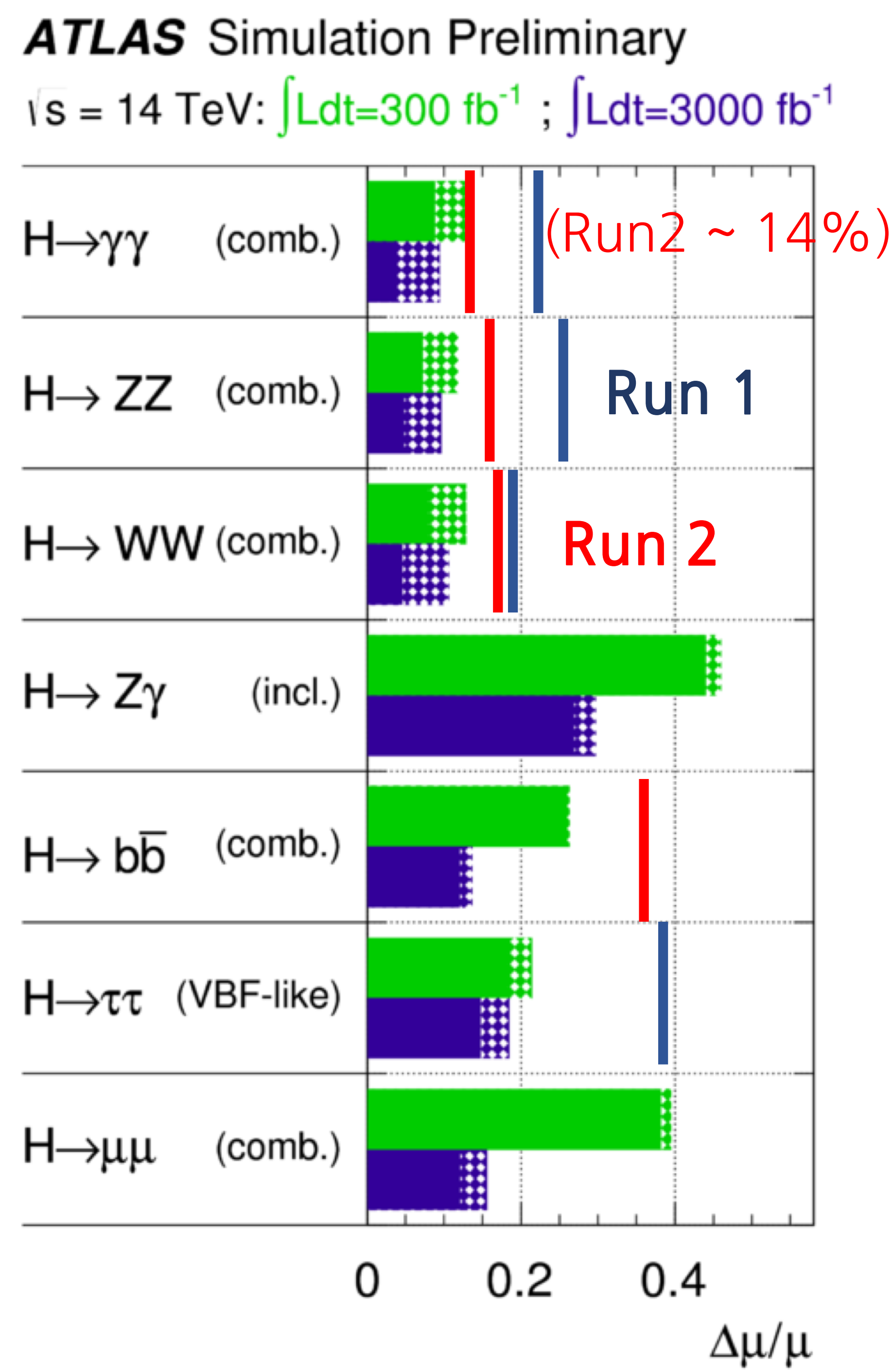
Expected improvements of Higgs signal strengths

[T.J. Kim '18]

Higgs signal strength

- $H \to \gamma\gamma$ and $H \to ZZ$
  - Run1 analysis strategy with expected performance at 140 pileup events
  - Precision : a few% level, 9% including theory uncertainty
- For VH, $H \to b\bar{b}$ 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

ATL-PHYS-PUB-2014-016



The quest for identifying the underlying physics

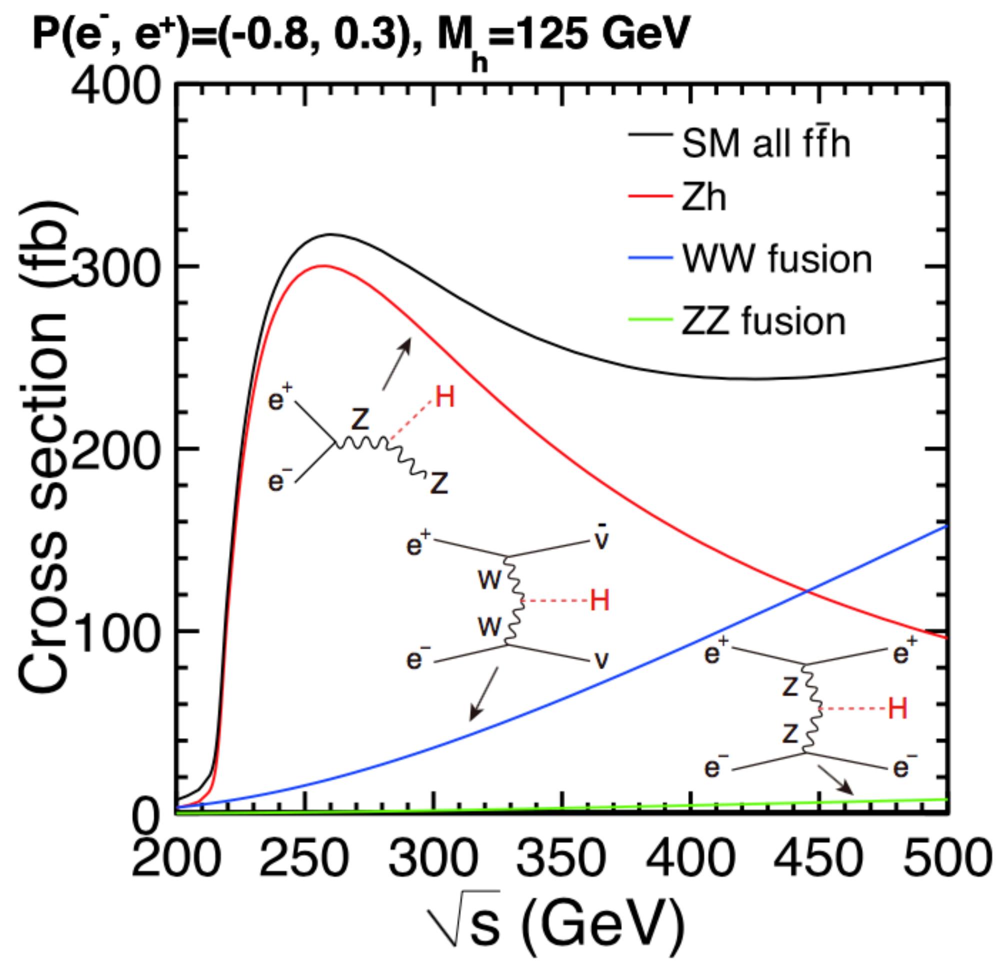
In many BSM models one expects only % level deviations from the SM couplings for BSM particles in the TeV range. Example of 2HDM-type model:

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

⇒ Need very high precision for the couplings

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

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



With this channel it is possible to detect the Higgs boson independently from the way it decays: ``recoil method”

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

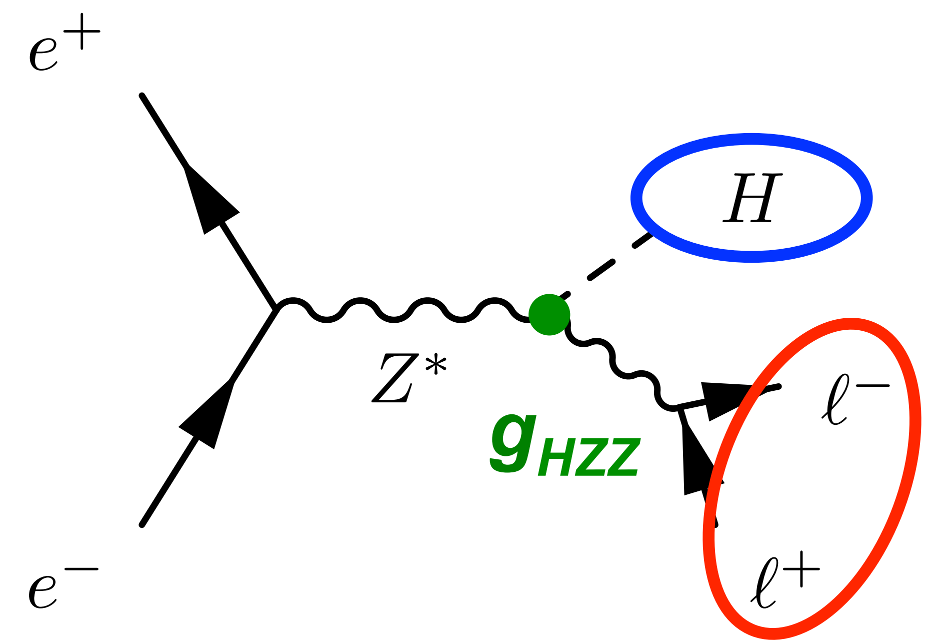
"Golden channel": $e^+e^- \to ZH, Z \to e^+e^-, \mu^+\mu^-$

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

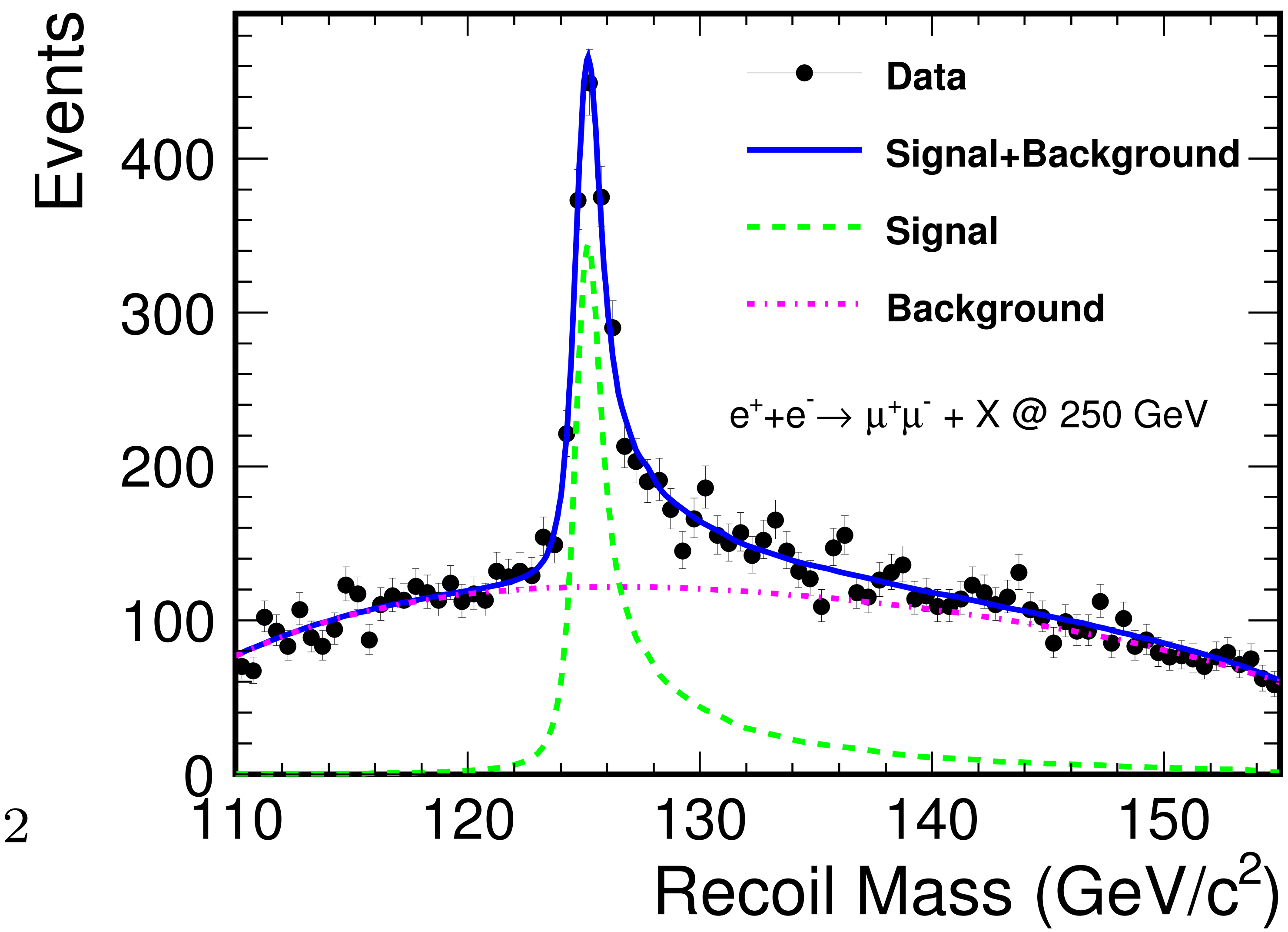
Reconstruct **$Z \to l^+l^-$**

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!

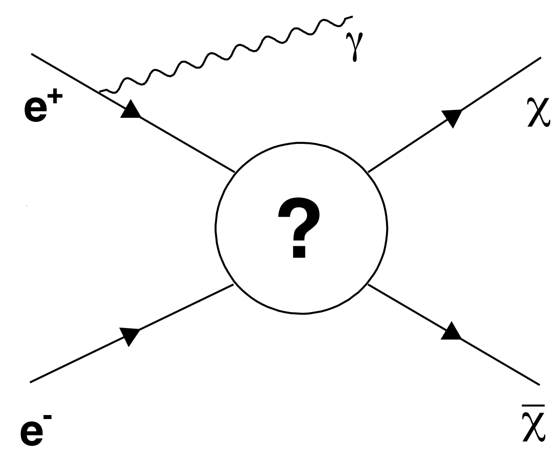
⇒ Large quantitative + qualitative improvements over HL-LHC

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

- 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



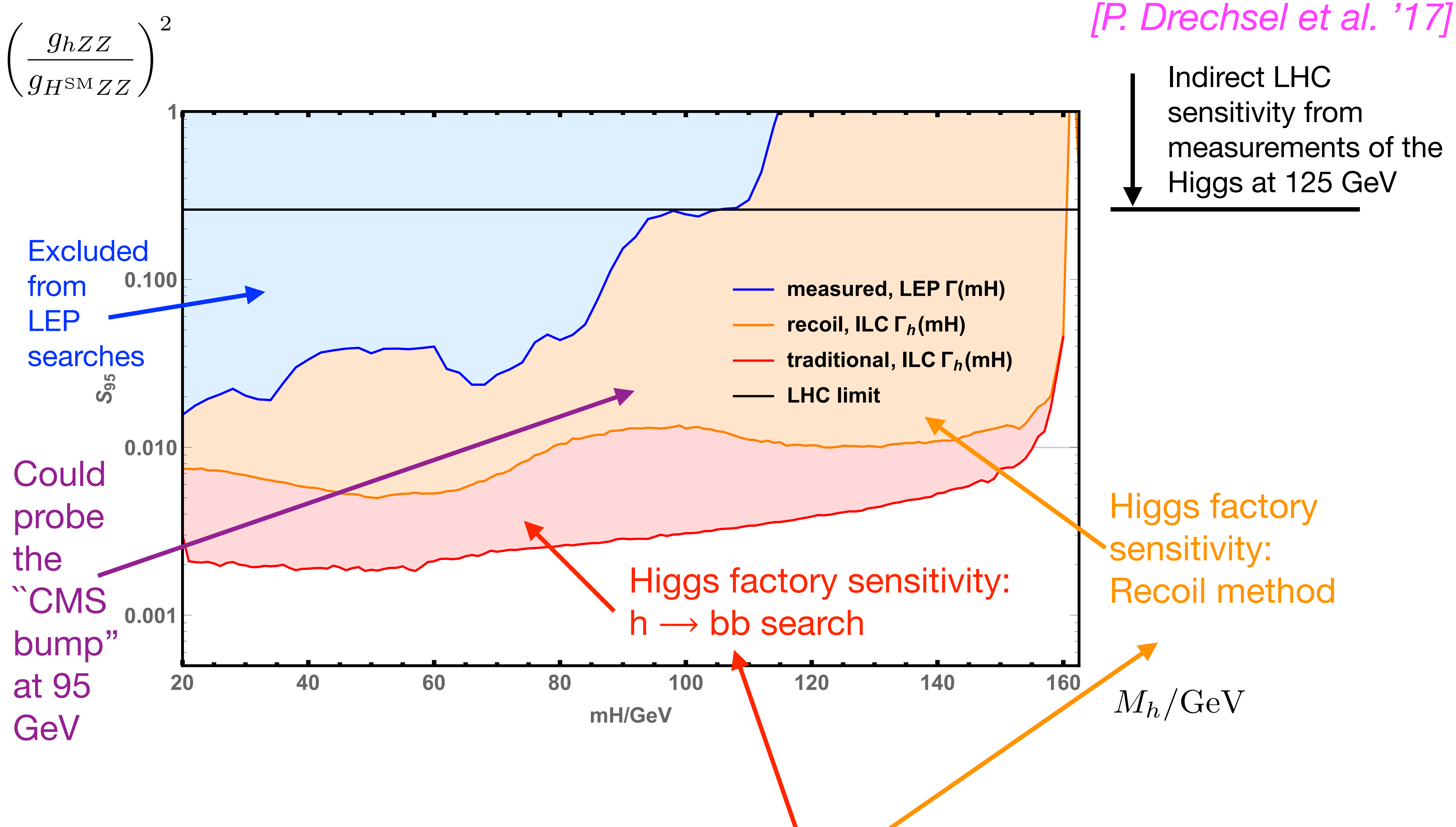
yields complementary sensitivity to the LHC and to direct detection experiments

- 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 at 250 GeV with 500 fb^{-1} to a new light Higgs

[P. Drechsel et al. '17]



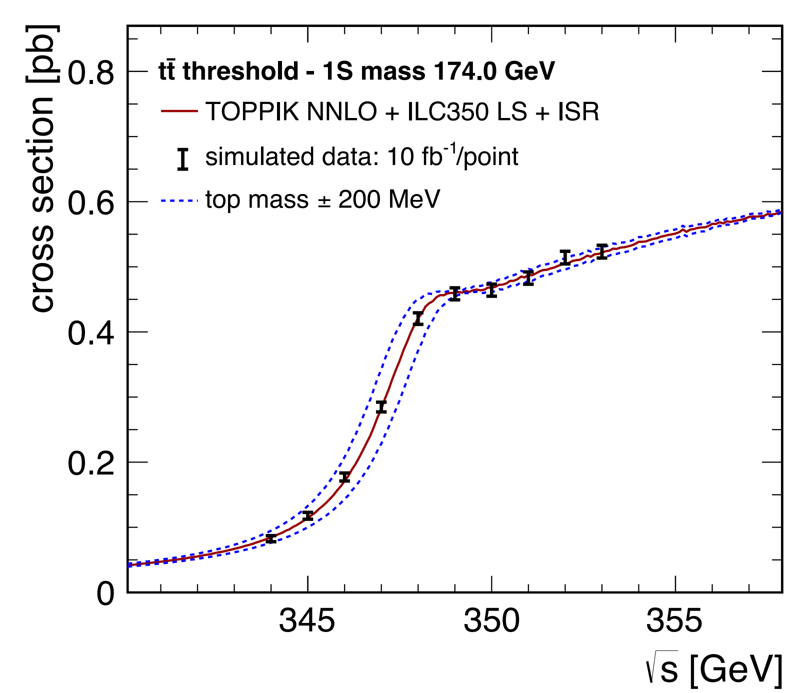
⇒ Higgs factory at 250 GeV will explore a large untested region!

Top-quark mass measurement at the top threshold

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

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

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



Top couplings: sensitivity to new physics

[P. Roloff '18]

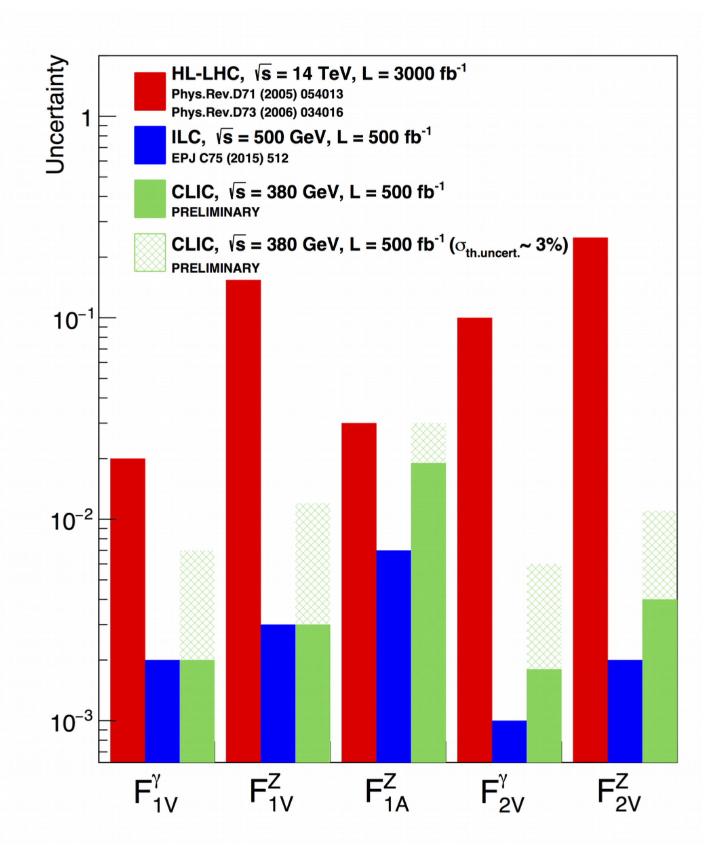
Top electroweak couplings

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

arXiv:hep-ph/0601112

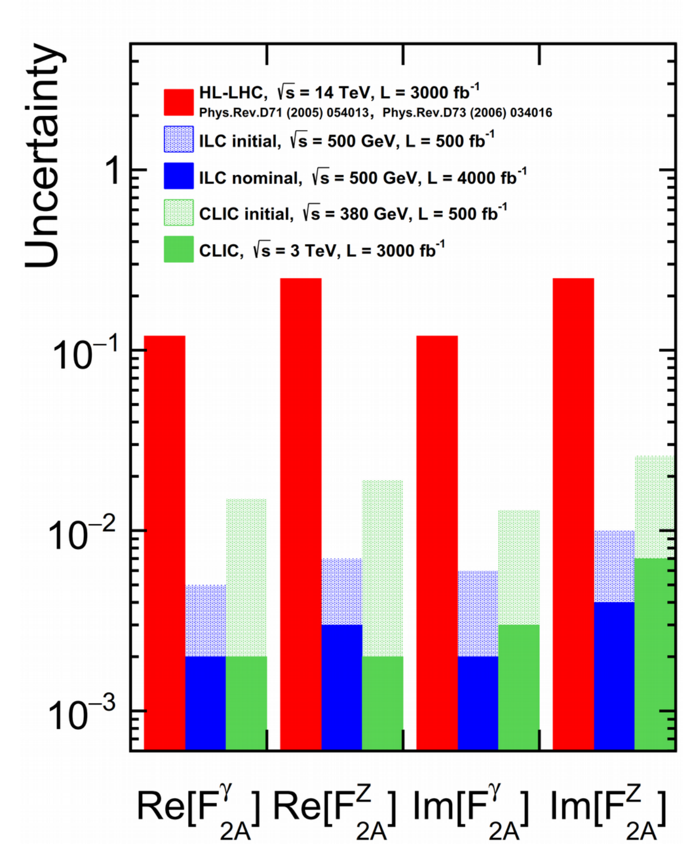
CP conserving **CPV**

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



CERN-2016-004

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

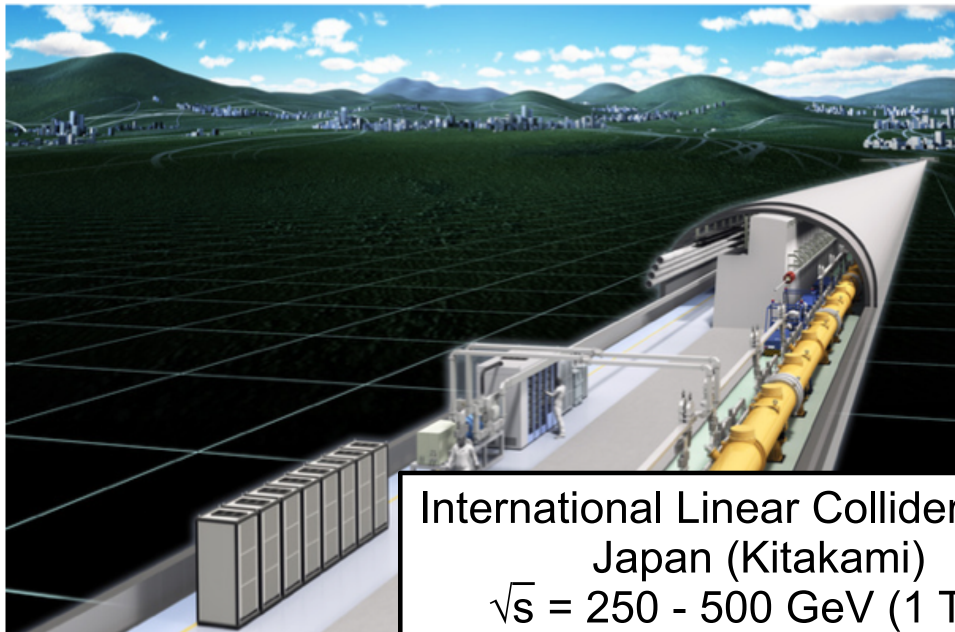


Eur. Phys. J. C 78, 155 (2018)

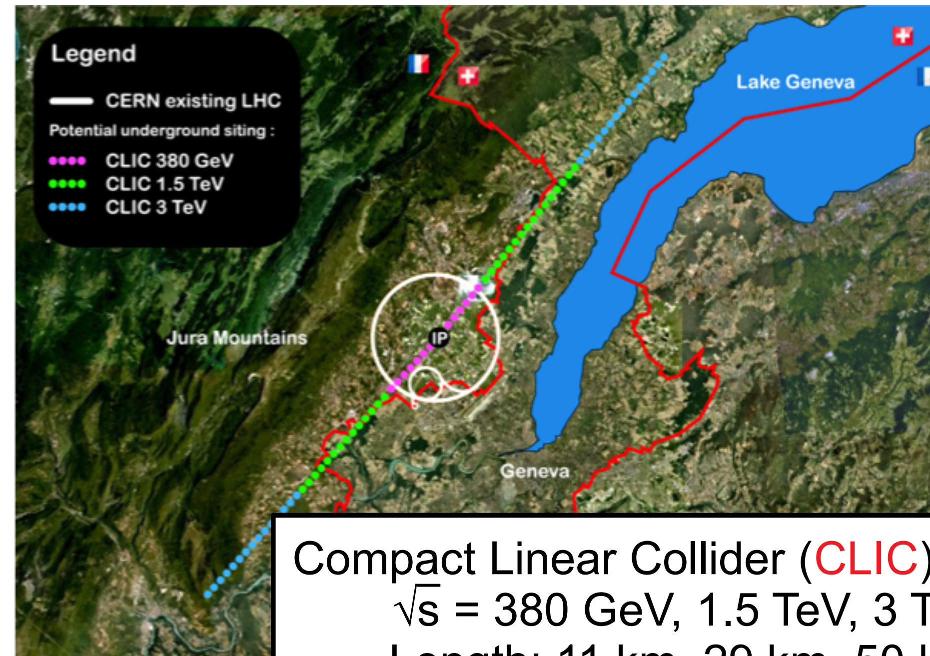
e+e- collider projects: Higgs factory + possibly higher energies

- Linear colliders: ILC, CLIC

[P. Roloff '18]

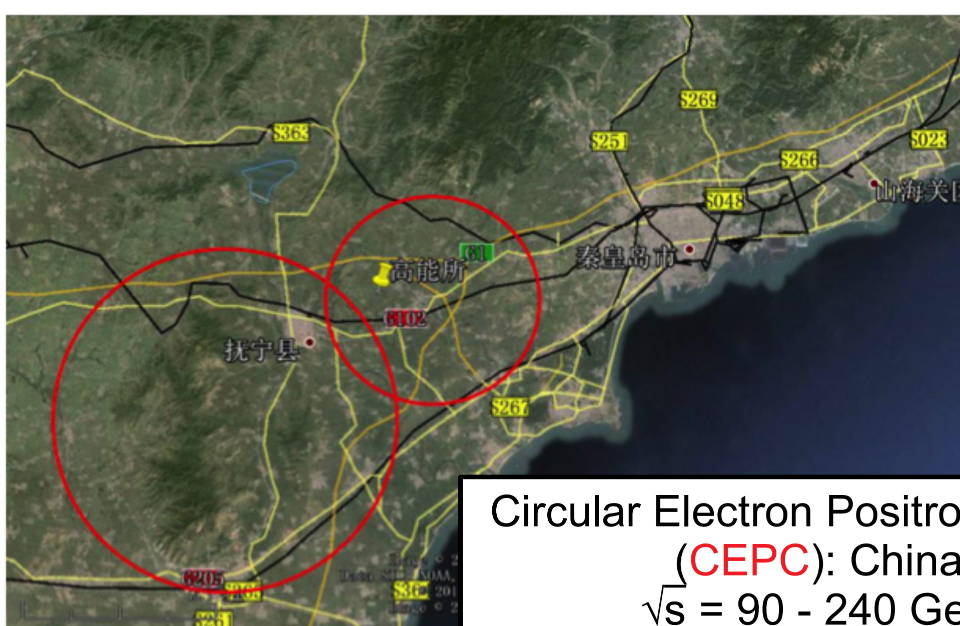


International Linear Collider (ILC): Japan (Kitakami)
$\sqrt{s}$ = 250 - 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)



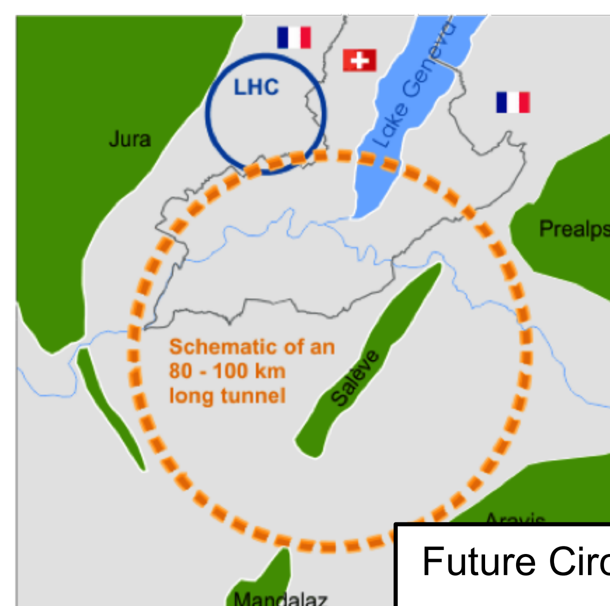
Compact Linear Collider (CLIC): CERN
$\sqrt{s}$ = 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km, 50 km

- Circular colliders: CEPC, FCC-ee



Circular Electron Positron Collider (CEPC): China
$\sqrt{s}$ = 90 - 240 GeV
Circumference: 100 km

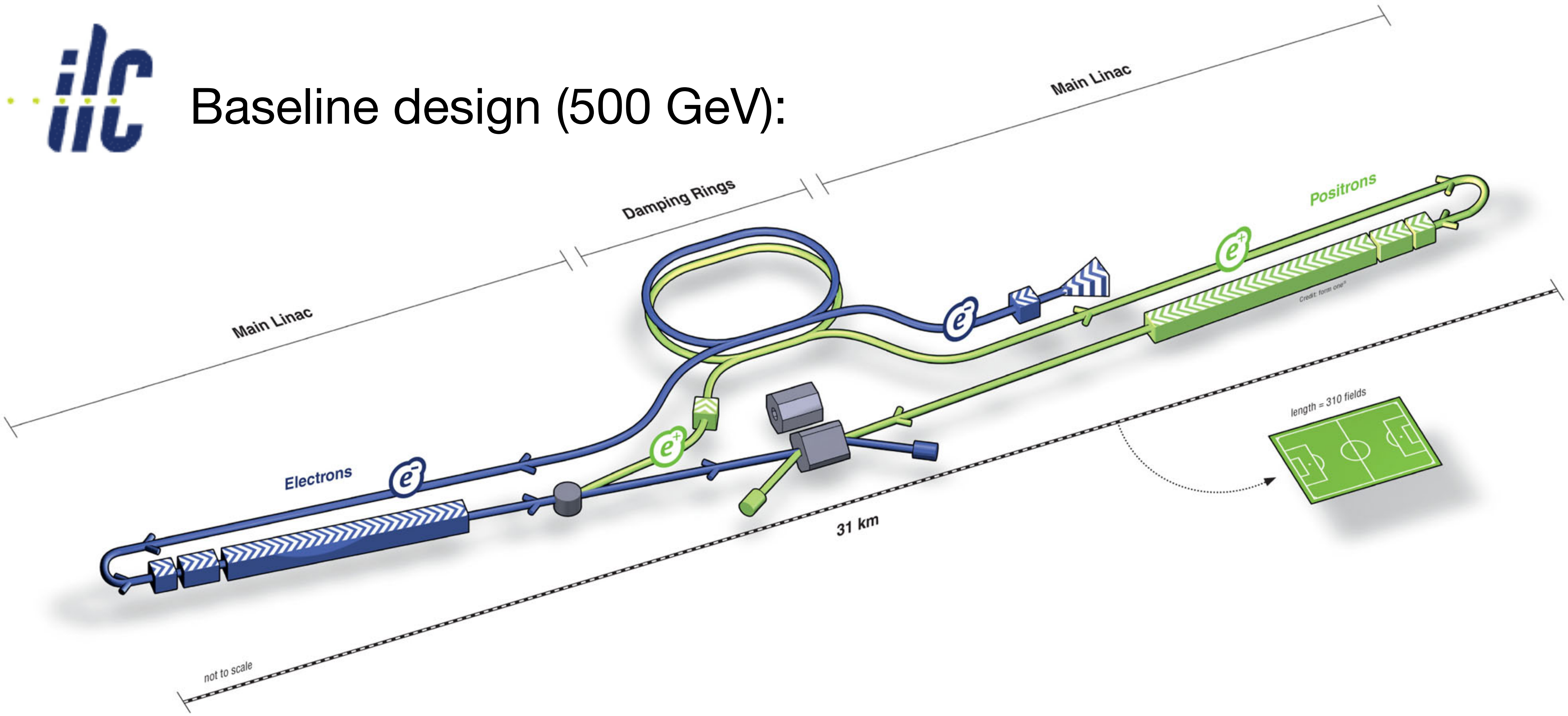
s, Ge



Future Circular Collider (FCC-ee): CERN
$\sqrt{s}$ = 90 - 350 GeV
Circumference: 97.75 km

International Linear Collider (ILC)

Baseline design (500 GeV):



CM energy 90-1000 GeV, 500 GeV baseline in TDR
Superconducting cavities; electron and positron polarisation
Proof of key technology: European XFEL at DESY successfully constructed and put into operation

Technical Design Report (TDR) + DBD for Detectors: 2013

Recent developments w.r.t. the physics TDR

The International Linear Collider Machine Staging Report 2017

Addendum to the International Linear Collider Technical Design Report published in 2013

Linear Collider Collaboration / October, 2017

Editors:Lyn Evans and Shinichiro Michizono

Abstract (arXiv)

The Technical Design Report (TDR) of the ILC mainly concentrates on a baseline machine of 500 GeV centre-of-mass with detailed cost and manpower estimates consistent with this option. However, the discovery of a Higgs Boson with a mass of 125 GeV opens up the possibility of reducing cost by starting at a centre-of-mass energy of 250 GeV with the possibility of future upgrades to 500 GeV or even 1 TeV should the physics case for such an upgrade be compelling. The rest of this paper outlines the options for the design of a 250 GeV "Higgs factory".

Recent developments w.r.t. the physics TDR

[J. Brau '18]

The LCC Physics Working Group put out three papers in the past year:

"The Potential of the ILC for Discovering New Particles", arXiv:1702.05333.

"Physics Case for the 250 GeV Stage of the International Linear Collider", arXiv:1707621.

"The Role of Positron Polarization for the Initial 250 GeV stage of the ILC", arXiv:1801.02840.

In addition, members of the group from DESY, SLAC, KEK, Tokyo, and Seoul National U. produced two major physics research papers on precision Higgs physics, arXiv:1708.08912 and arXiv:1708.09079. These will soon appear in Phys. Rev. D.

ILC staging

[S. Michizono '18]

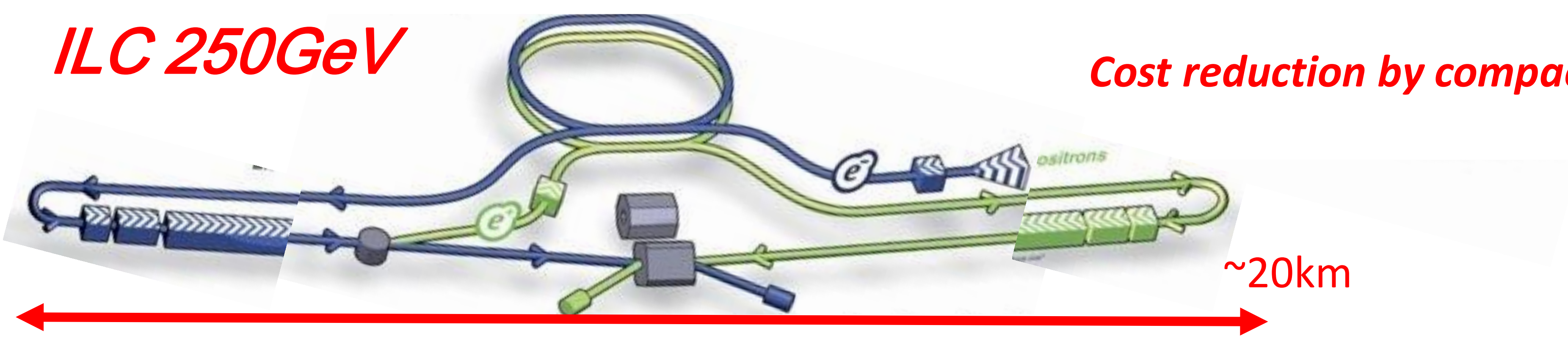
Staging

ILC 500GeV

~31km

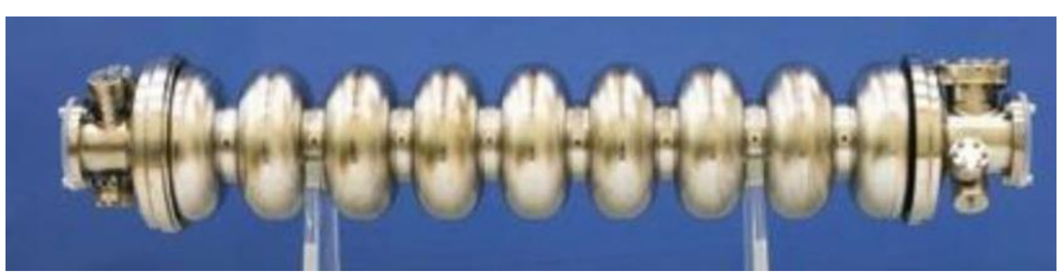
ILC 250GeV

Cost reduction by compact ILC



~20km

US-Japan cost reduction R&D

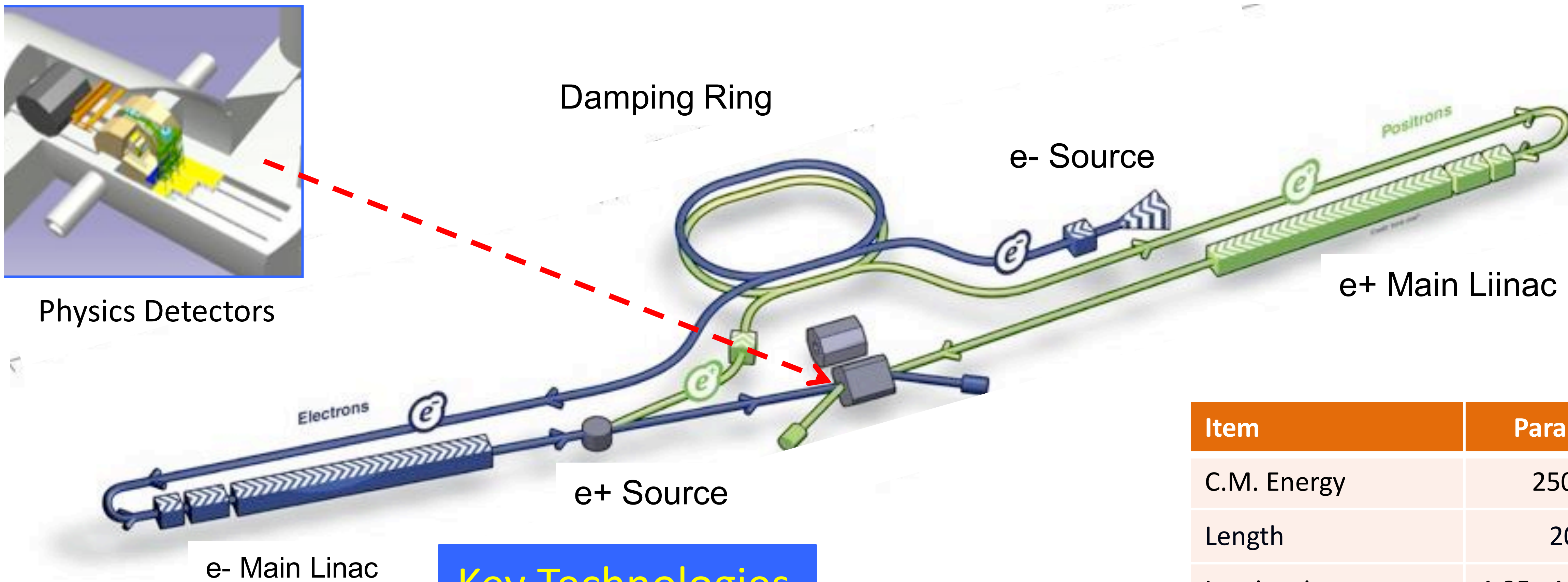


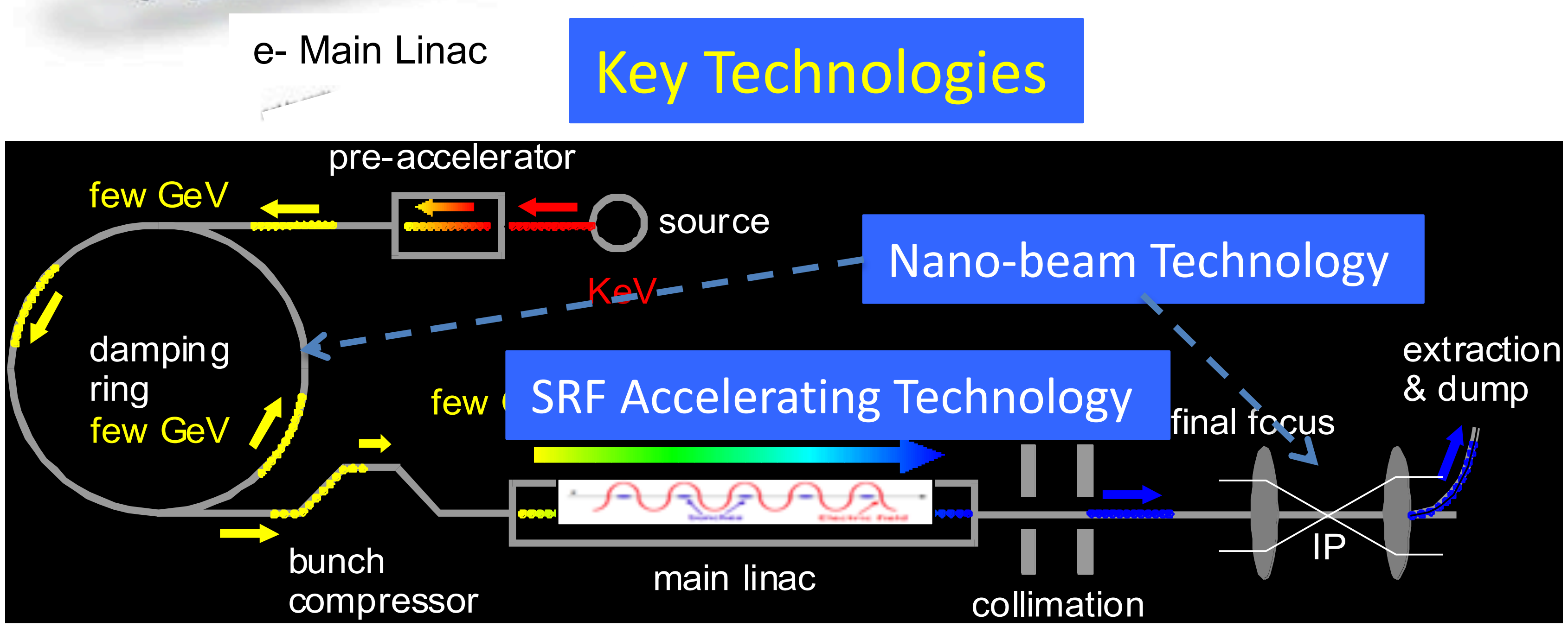
Cost reduction by technological innovation

Innovation of Nb (superconducting) material process: decrease in material cost
Innovative surface process for high efficiency cavity (N-infusion): decrease in number of cavities

ILC250: parameters

[S. Michizono '18]





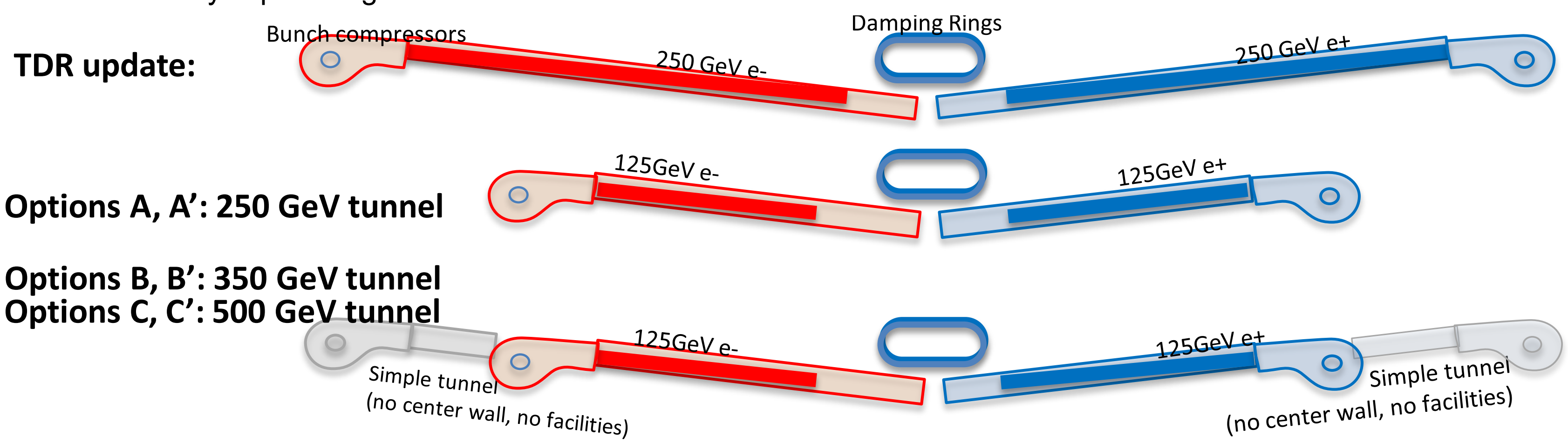
Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10 ^{10}

Cost (ILCU) comparison: ILC250 (options) vs. ILC500

[S. Michizono '18]

All options include possible cost reductions when the following R&D efforts succeed (as Options A', B', and C').

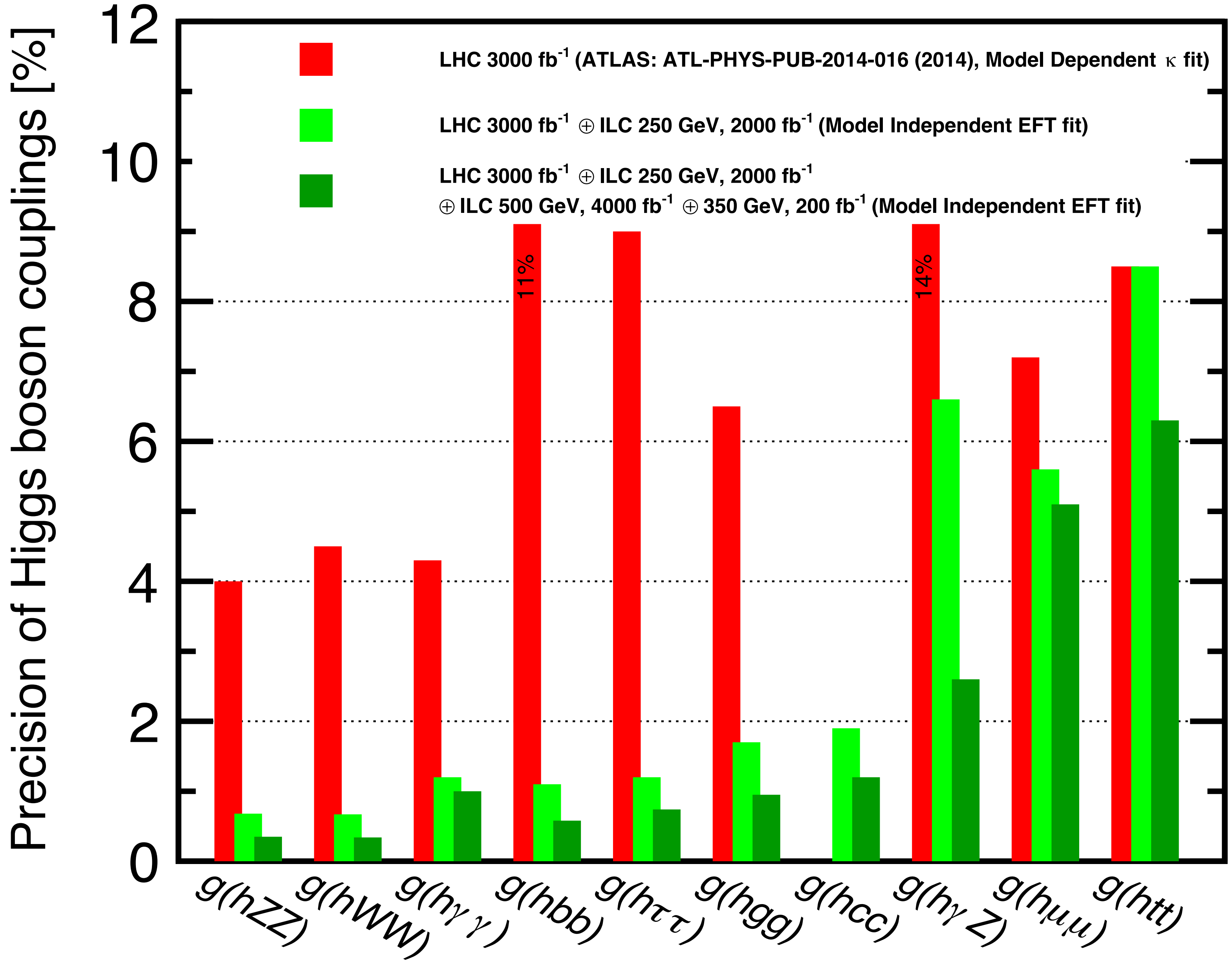
- Further improvement of niobium materials (processing for sheet fabrication and piping)
- Higher efficiency in superconducting radiofrequency (SCRF) cavity fabrication to ensure a high gradient and high Q (N-infusion)
- Improved input coupler
- Successful electrolytic polishing



	e+/e- collision [GeV]	Tunnel Space for [GeV]	Value Total (MILCU)	Reduction [%]
TDR	250/250	500	7,980	0
TDR update	250/250	500	7,950	-0.4
Option A	125/125	250	5,260	-34
Option B	125/125	350	5,350	-33
Option C	125/125	500	5,470	-31.5
Option A'	125/125	250	4,780	-40
Option B'	125/125	350	4,870	-39
Option C'	125/125	500	4,990	-37.5

Projections for HL-LHC, ILC 250 and ILC 500

[LCC Physics Working Group '17]



HL-LHC

HL-LHC⊕ILC 250

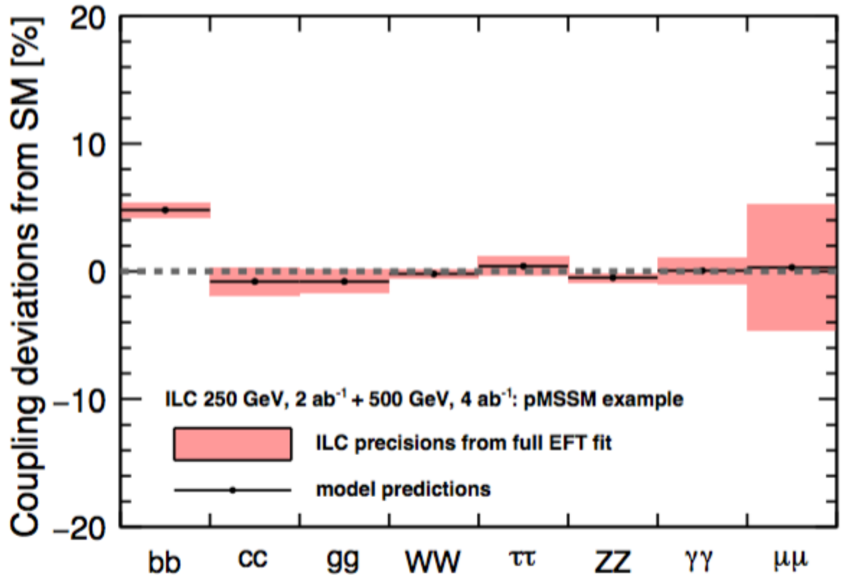
HL-LHC⊕ILC 250 ⊕ILC 500

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

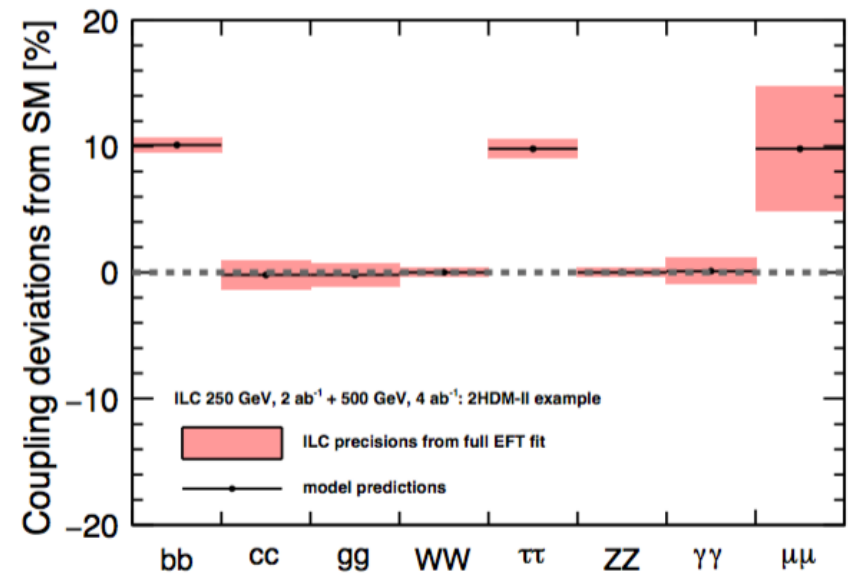
Precision at the 1% level reachable for many couplings

Coupling deviations for different models vs. ILC precision

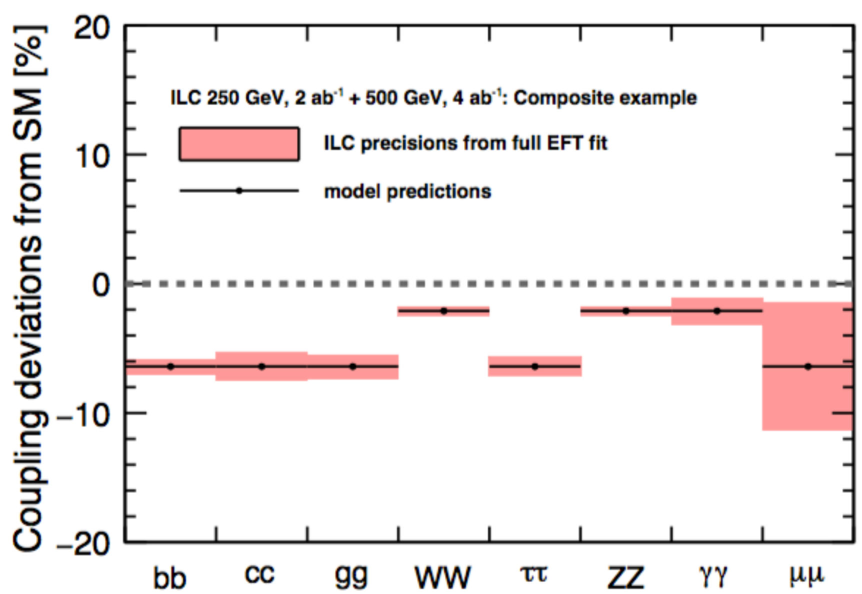
heavy SUSY



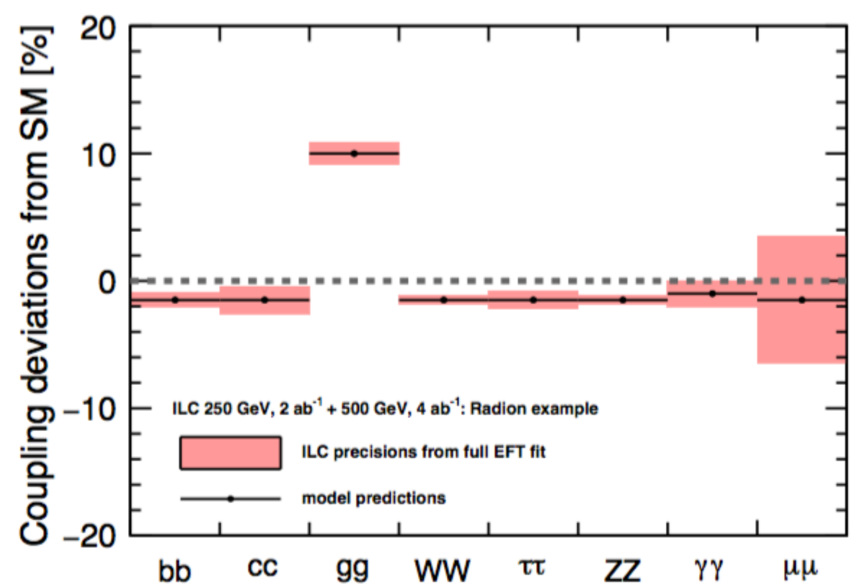
2 Higgs doublet



composite Higgs



Higgs-Radion mixing



[T. Barklow et al. '17]

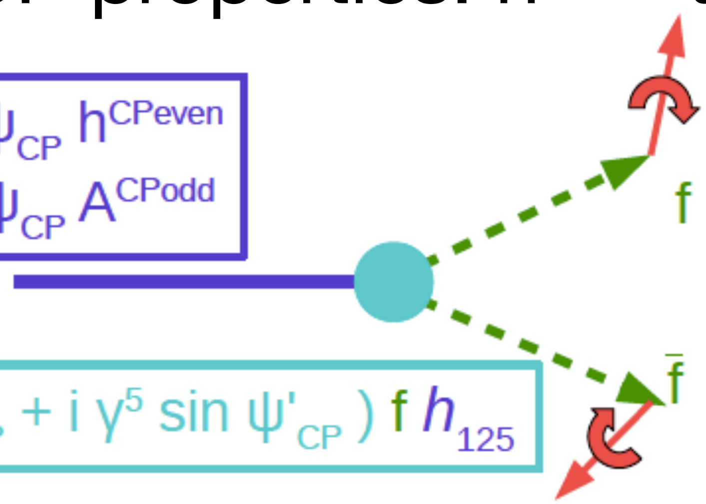
Note:
the displayed models are outside of the reach of the HL-LHC!

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

Higgs CP properties and Higgs self-coupling

- Higgs CP properties: $h \longrightarrow \boldsymbol{\tau\tau}$ channel

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

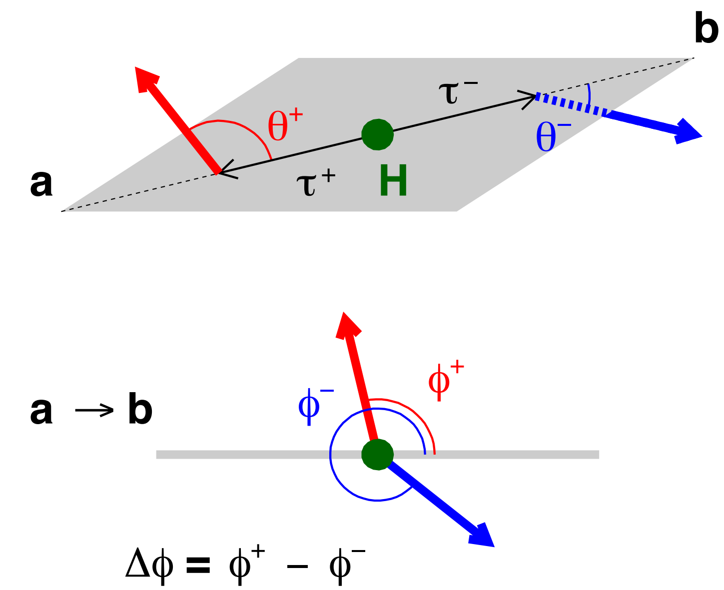


$g\,\bar{f}\,(\cos\psi'_{CP} + i\,\gamma^5 \sin\psi'_{CP})\,f\,h_{125}$

h is a spin 0 state:

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

[ψ = 0 CP even,
$\pi/2$ CP odd]



⇒ Precise determination of CP phase

- Higgs self-coupling at ILC500 and ILC1000:
    - ILC500, ZHH, full simulation: observation of HH with ~8σ, extraction of λ_{SM} with 27% accuracy for 4 ab^{-1}
    - ILC1000, 4 ab^{-1}: 10% accuracy on λ_{SM}

Developments at the political level

[T. Nakada '17]

Recent development in 2017

- A new statement from the Japanese Association for High Energy Physicists:
  "To conclude, in light of the recent outcomes of LHC Run 2, JAHEP proposes to promptly construct ILC as a Higgs factory with the center-of-mass energy of 250 GeV in Japan."
- Cost evaluation of a 250 GeV machine by the Linear Collider Collaboration gives a reduction of up to ~40% compared to the TDR cost for the 500 GeV machine.

ICFA statement on ILC250 (Ottawa, Nov. 2017)

ICFA Statement on the ILC Operating at 250 GeV as a Higgs Boson Factory

The discovery of a Higgs boson in 2012 at the Large Hadron Collider (LHC) at CERN is one of the most significant recent breakthroughs in science and marks a major step forward in fundamental physics. Precision studies of the Higgs boson will further deepen our understanding of the most fundamental laws of matter and its interactions.

The International Linear Collider (ILC) operating at 250 GeV center-of-mass energy will provide excellent science from precision studies of the Higgs boson. Therefore, ICFA considers the ILC a key science project complementary to the LHC and its upgrade.

ICFA welcomes the efforts by the Linear Collider Collaboration on cost reductions for the ILC, which indicate that up to 40% cost reduction relative to the 2013 Technical Design Report (500 GeV ILC) is possible for a 250 GeV collider.

ICFA emphasizes the extendibility of the ILC to higher energies and notes that there is large discovery potential with important additional measurements accessible at energies beyond 250 GeV.

ICFA thus supports the conclusions of the Linear Collider Board (LCB) in their report presented at this meeting and very strongly encourages Japan to realize the ILC in a timely fashion as a Higgs boson factory with a center-of-mass energy of 250 GeV as an international project[1], led by Japanese initiative.

[1] In the LCB report the European XFEL and FAIR are mentioned as recent examples for international projects.

ILC Advisory Panel at the Japanese MEXT Ministry

[M. Yamauchi '18]

- Following the LCB/ICFA statement on ILC250 in November 2017, we officially proposed it to the MEXT, and the proposal was discussed at the ILC Advisory Panel meeting in December.
- …
- Main concern given by the panel member:
  - The Panel had previously understood that the ILC in Japan would be a global project, globally led and globally financed such as ITER, whereas the ICFA Statement suggests that the project is Japanese-led with majority contribution coming from Japan. There is a substantial change in the nature of the project.
  - Tatsuya explained how Germany took lead in XFEL and how the Japanese 250 GeV ILC scenario could be seen in a similar manner.
- …
- The panel agreed to re-start physics and TDR working groups to evaluate physics potential, cost and technical issues of the new ILC250 proposal.
- It is expected that the conclusion of the Advisory Panel will be given in summer 2018 after hearing conclusions of the working groups, and the outcome will be sent to the Science Council of Japan for the final evaluation of the project.

Revisit of ILC-PIP in view of ICFA statement on ILC250

[M. Yamauchi '18]

Governance

ILC-PIP recommends a treaty-based international organization, or otherwise, an organization based on an intergovernmental agreement. The document describes the roles of Council and DG and their relationship, voting structure in Council, Personnel Policy, etc.

=>The legal status of the ILC lab should be included in the proposal from the Japanese government, and eventually determined by intergovernmental negotiations. On the other hand, the basic idea of these governance policies seems to remain appropriate in any legal status. For example, European XFEL and FIAR projects have a similar principle for governance based on intergovernmental conventions although their legal status is a limited liability company in Germany.

Funding Models

In the ILC-PIP, the host contribution is estimated to be approximately 50% based on the cost-sharing principle that the cost for the civil construction and other infrastructure is the responsibility of the host country, while the accelerator construction should be shared appropriately.

=>The host contribution for the 250GeV machine is approximately 60% based on the same principle.

European Action Plan

Report in preparation outlining Europe’s possible contribution during preparation and construction phase of the ILC in Japan, involvement of CERN management and CERN Council

[S. Stapnes ’17]

Preparation Phase 2019-22: Key activities in Europe

This period needs to be initiated by a positive statement from the Japanese government about hosting the ILC, followed by a European strategy update that ranks European participation in the ILC as a high-priority item. The preparation phase focuses on preparation for construction and agreement on the definition of deliverables and their allocation to regions.

- The European groups will concentrate on preparation for their deliverables, including European industry.
- Europe and European scientists, as part of an international project team, will also participate in the overall finalization of the design, while in parallel contributing to the work of setting up the overall structure and governance of the ILC project and of the associated laboratory.

Key activities in Europe	More details
SCRF activities	
	Cavity fabrication and preparation, Power Couplers, Automation of assembly, E-XFEL -> ILC
High efficiency klystron R&D	
Cryogenics system	LHC system similar in size to ILC
Accelerator Domain Issues	
	Positron source, Damping Rings, Beam Delivery Systems, Low emittance beam transport, Beam dumps, Positron source
Detector and Physics	
	Design optimization, MDI, Technical prototypes, TDRs, physics studies
Documentation system	Experience from E-XFEL
“Regional” Design office	Naturally at CERN, linking to other European National Labs

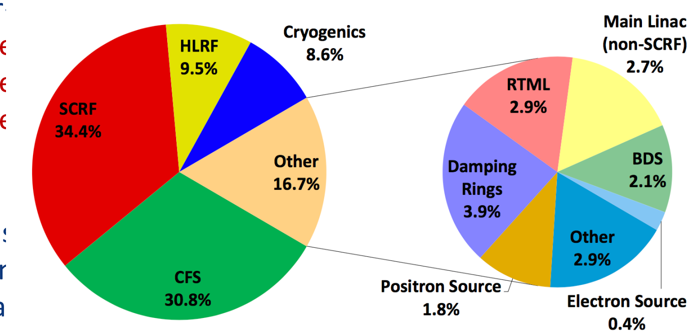
A European ILC project in the preparation phase 2019-22:

- Resources needed estimated to ~25 MCHF/year (material) and 60 FTE/year (personnel), ramping up from 2019
- Move towards more engineering personnel
- The organisational model above is used for existing studies at CERN, e.g. CLIC/HE-LHC/FCC

Construction phase 2023 and beyond

The construction phase will start after the ILC laboratory has been established and inter governmental agreements are in place. At the current stage, only the existing capabilities of the European groups relevant for this phase can be described.

As mentioned above, the detailed contributions will have to be defined during the preparation phase and formalized by inter-governmental agreements. Some contributions from Europe are imperative for the project - most prominently superconducting RF modules.



So premature to plan in detail, however some comments can be made:

- Focus on technical items for ILC (not CE and infrastructure)
- E-XFEL ~7% of a 250 GeV ILC – and more than 10% of the cryo-modules needed
- Detector construction expected to follow LHC detector model
- Spending significantly above the levels mentioned on previous page only by ~2025-26

Any guidance from Japan on contributions would allow us to make firmer European Planning for this period

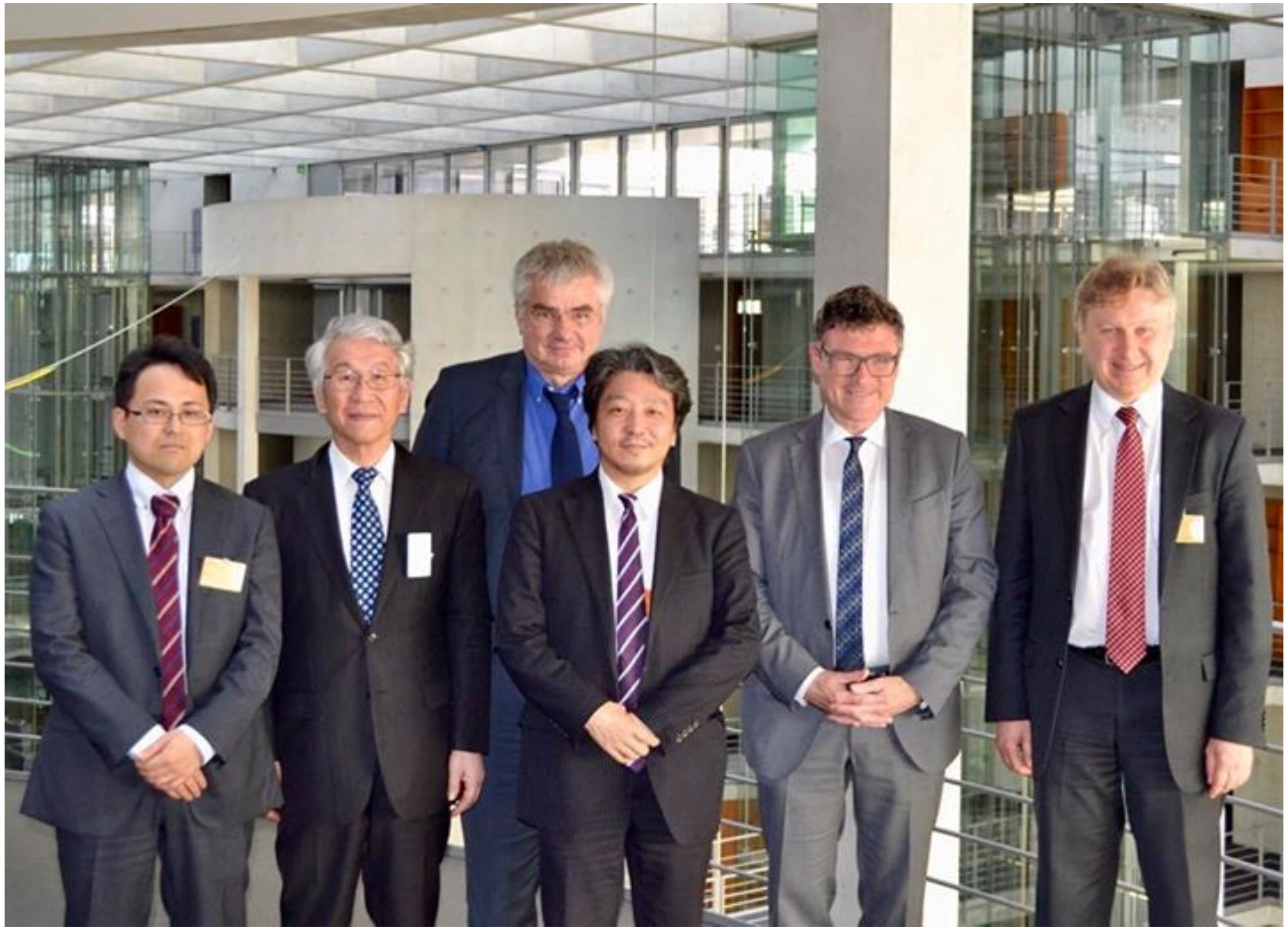
Summary

Resources needed – in Europe - are quite modest until ~2025-26, construction spending then picks up

From the web page of S. Kaufmann, MdB

Aktueller Beitrag

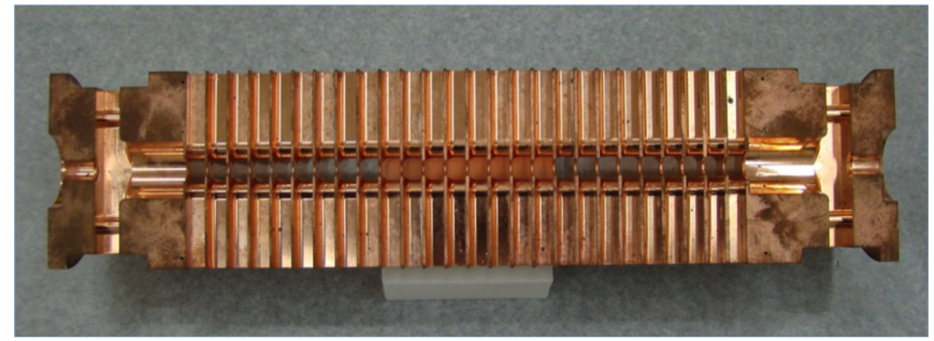
Aktuelles
26.04.2018

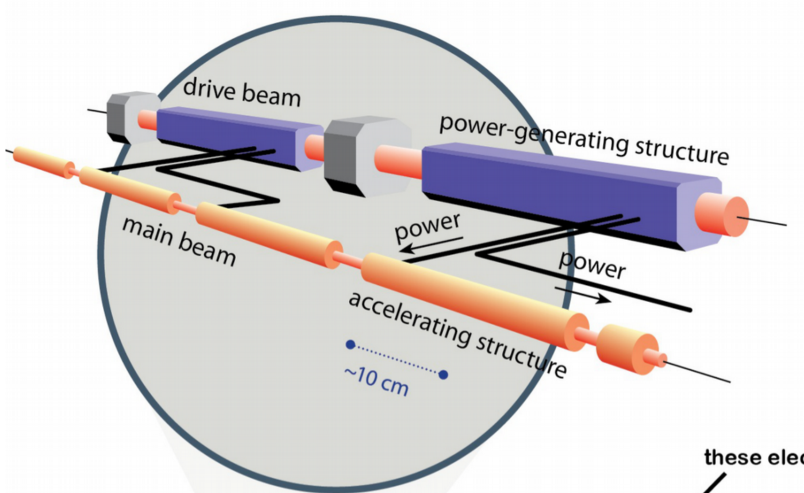


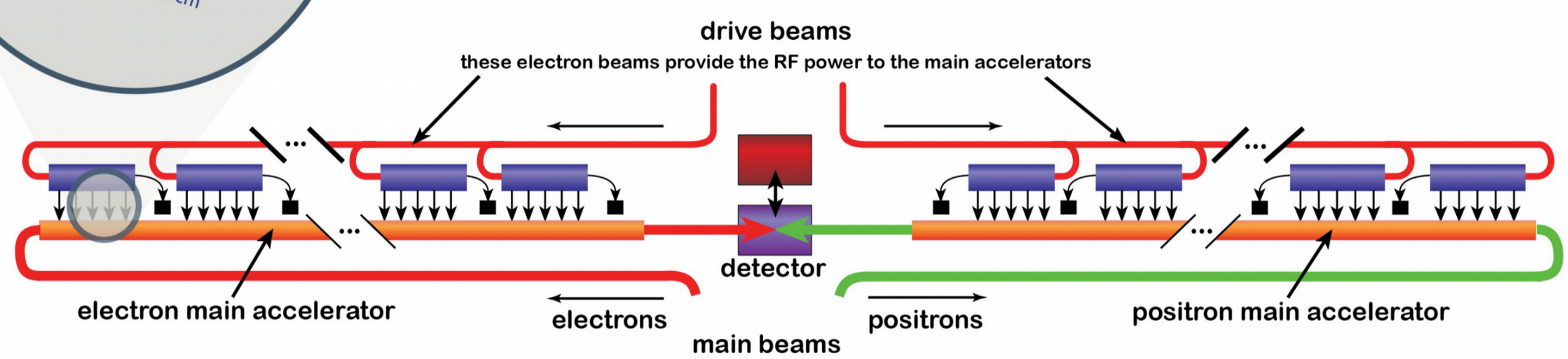
Auch diese Berlin-Woche ist stark durch die internationale Forschungszusammenarbeit geprägt: Zum Bau des neuen Linearbeschleunigers „International Linear Collider (ILC)“ in Iwate/Japan durfte ich eine japanische Delegation in Berlin empfangen. Der hochmoderne Forschungsverbundstandort ermöglicht die Untersuchung von Elementarteilchen in bisher nicht dagewesener Genauigkeit. Mit Unterstützung der EU könnten auch europäische Forscher an dieser innovativen und wirklich wichtigen Grundlagenforschung teilhaben. Das Projekt hat meine Unterstützung und ich werde mich weiterhin für eine Beteiligung der EU einsetzen.

Compact Linear Collider (CLIC)

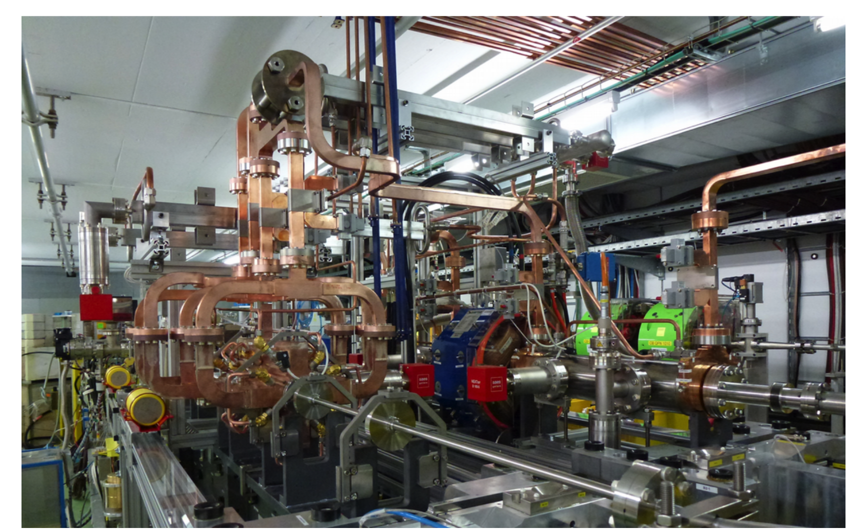
[P. Roloff '18]







Compact Linear Collider (CLIC):
- Based on 2-beam acceleration scheme
- Gradient: 100 MV/m
- Energy: 380 GeV - 3 TeV (in several stages)
- $P(e^{-}) = \pm 80\%$



Conceptual Design Report (CDR): 2012
Updated Staging Baseline: 2016

CLIC CDR: energy staging

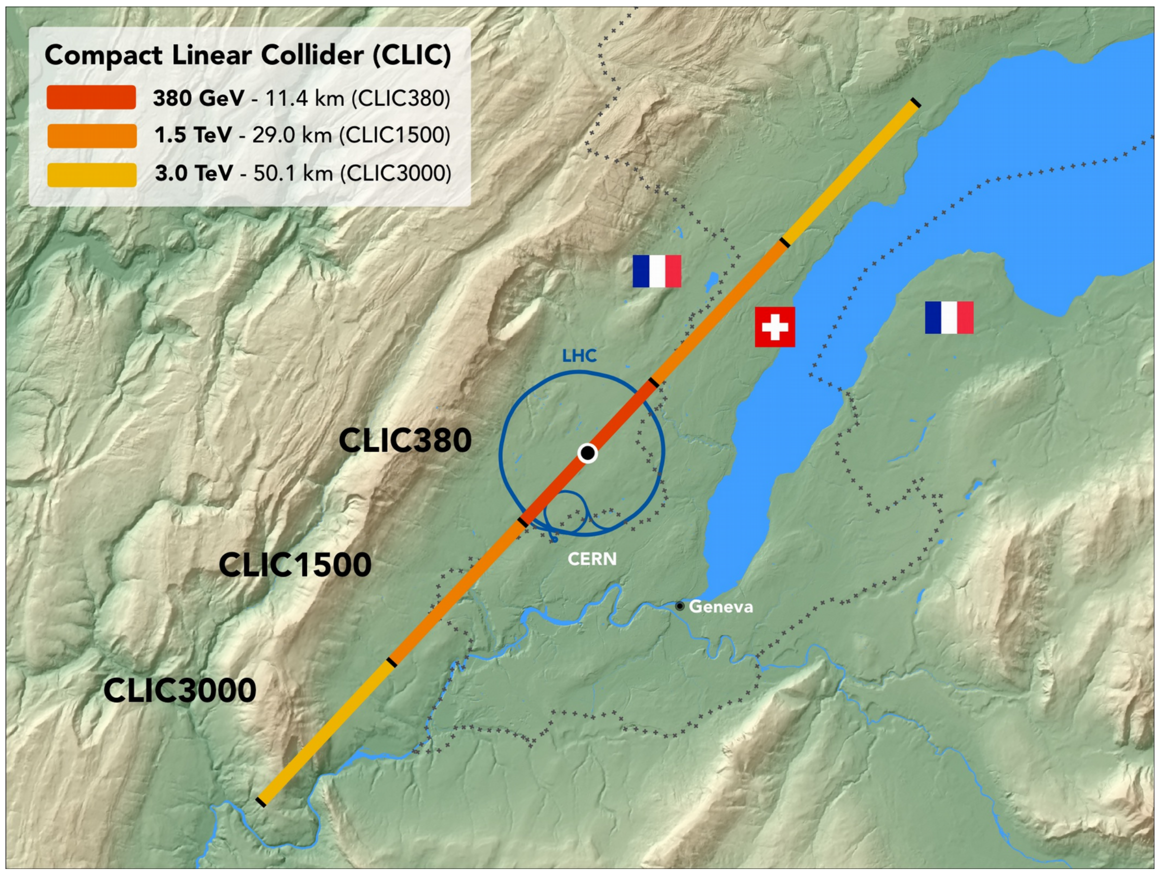
[P. Burrows '16]

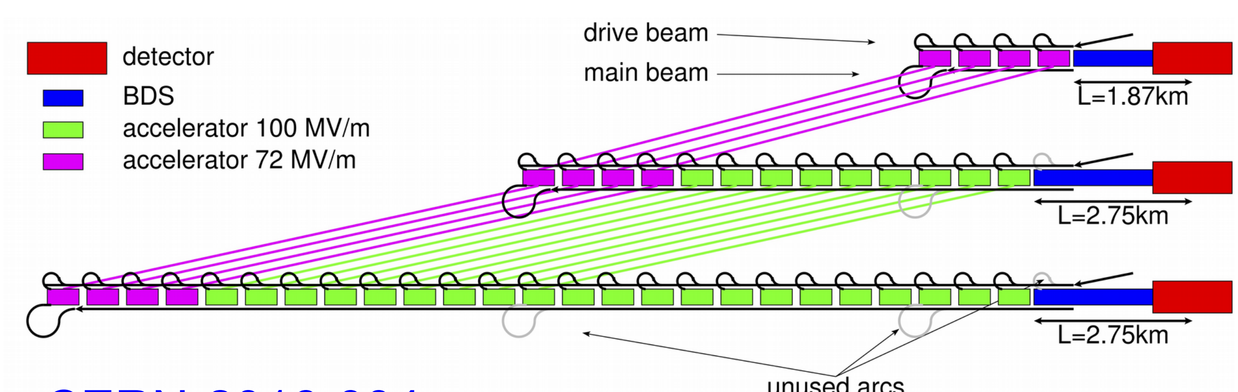
Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	µm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589

Updated staging baseline for CLIC

[P. Roloff '18]

CLIC staged implementation





CERN-2016-004

CLIC would be implemented in several energy stages

Baseline scenario:

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380 350	500 100
2	1500	1500
3	3000	3000

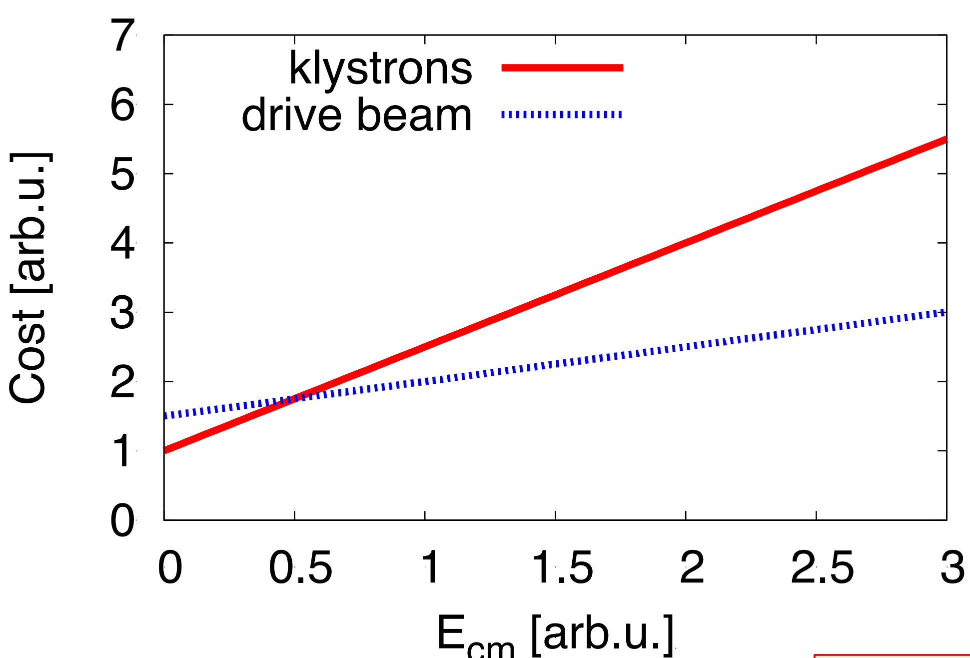
→ The strategy can be adapted to possible LHC discoveries at 13/14 TeV!

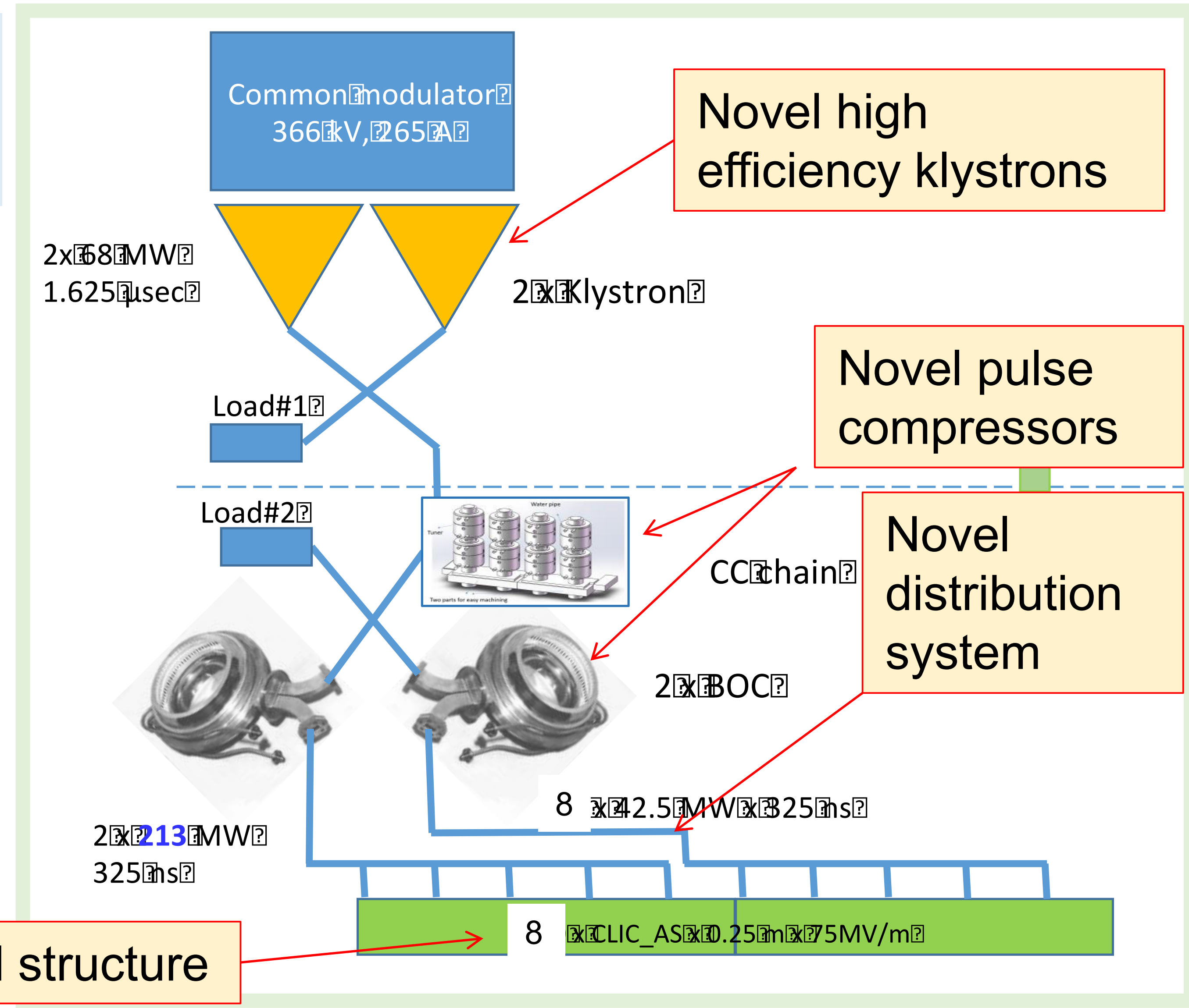
CLIC380: Klystron-based alternative

[D. Schulte '18]

Klystron-based Alternative

Develop klystron-based alternative
Expect comparable cost for first energy stage
But increases faster for high energies





Optimised structure

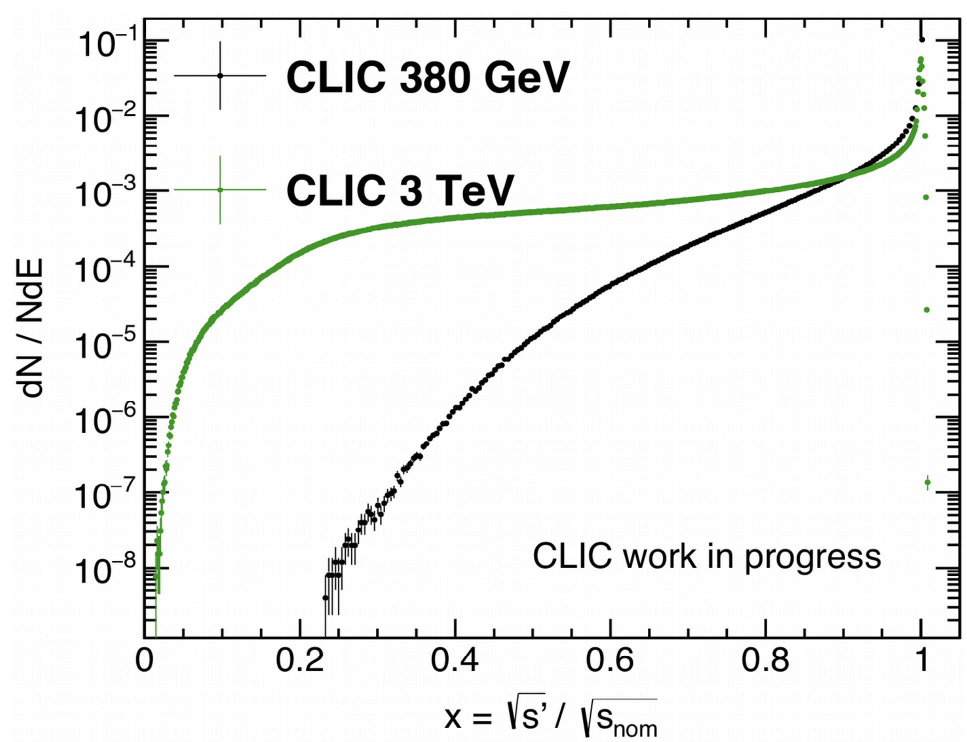
Beamstrahlung and luminosity spectra

[P. Roloff '18]

CLIC luminosity spectra

- Beamstrahlung causes energy loss at the interaction point
- Physics processes studied well above the production threshold benefit from the full spectrum
- The luminosity can be measured using large-angle Bhabha scattering events ($e^+e^- \rightarrow e^+e^-$)

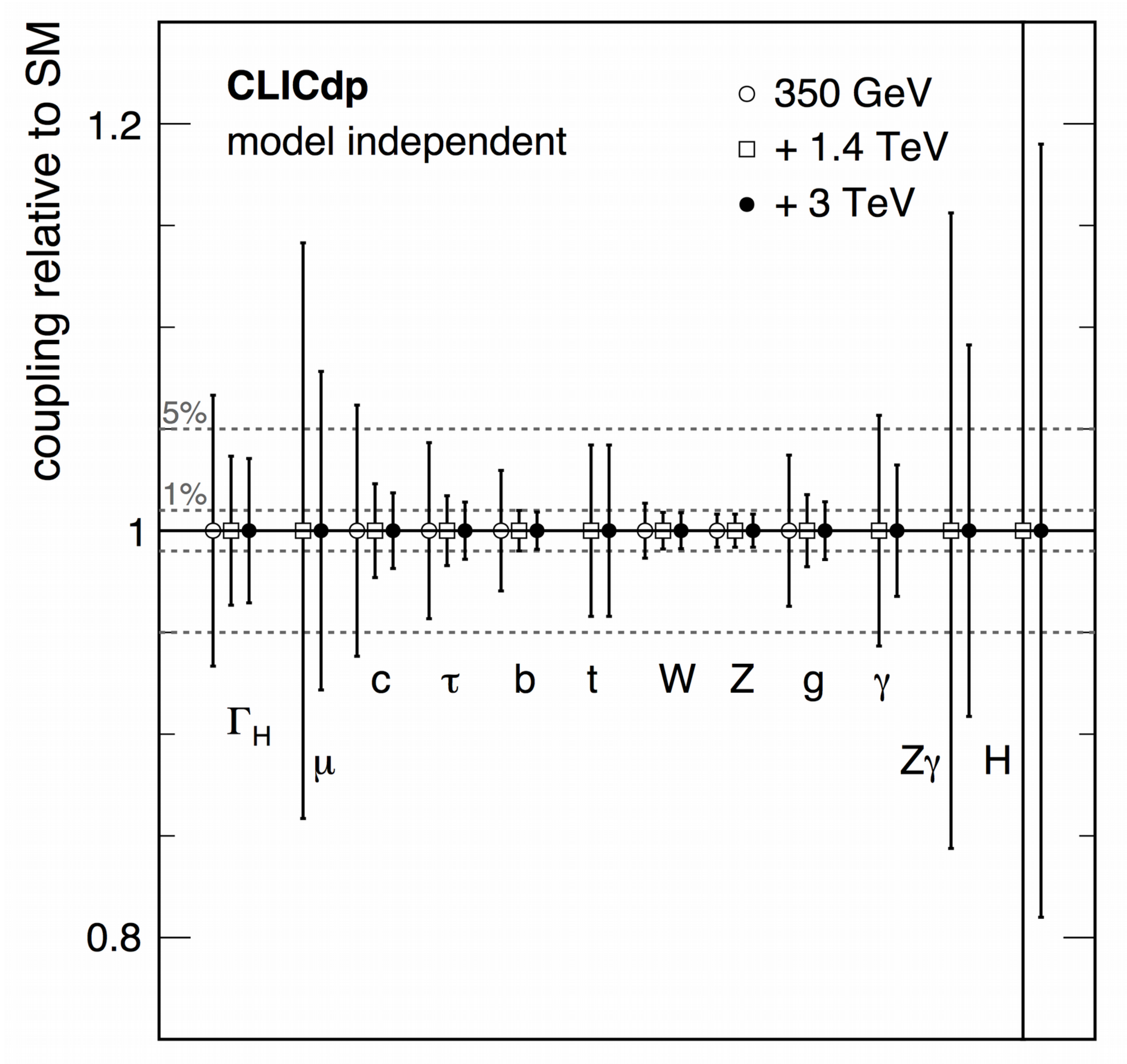
Eur. Phys. J. C 74, 2833 (2014)



Fraction $\sqrt{s'}/\sqrt{s}$	380 GeV	3 TeV
> 0.99	63%	36%
> 0.9	91%	57%
> 0.8	98%	69%
> 0.7	99.5%	77%
> 0.5	≈100%	89%

Higgs coupling accuracies at CLIC

[P. Roloff ’18]



Fully model-independent analysis only possible at lepton colliders

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


Eur. Phys. J. C (2017) 77:475
DOI 10.1140/epjc/s10052-017-4968-5
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

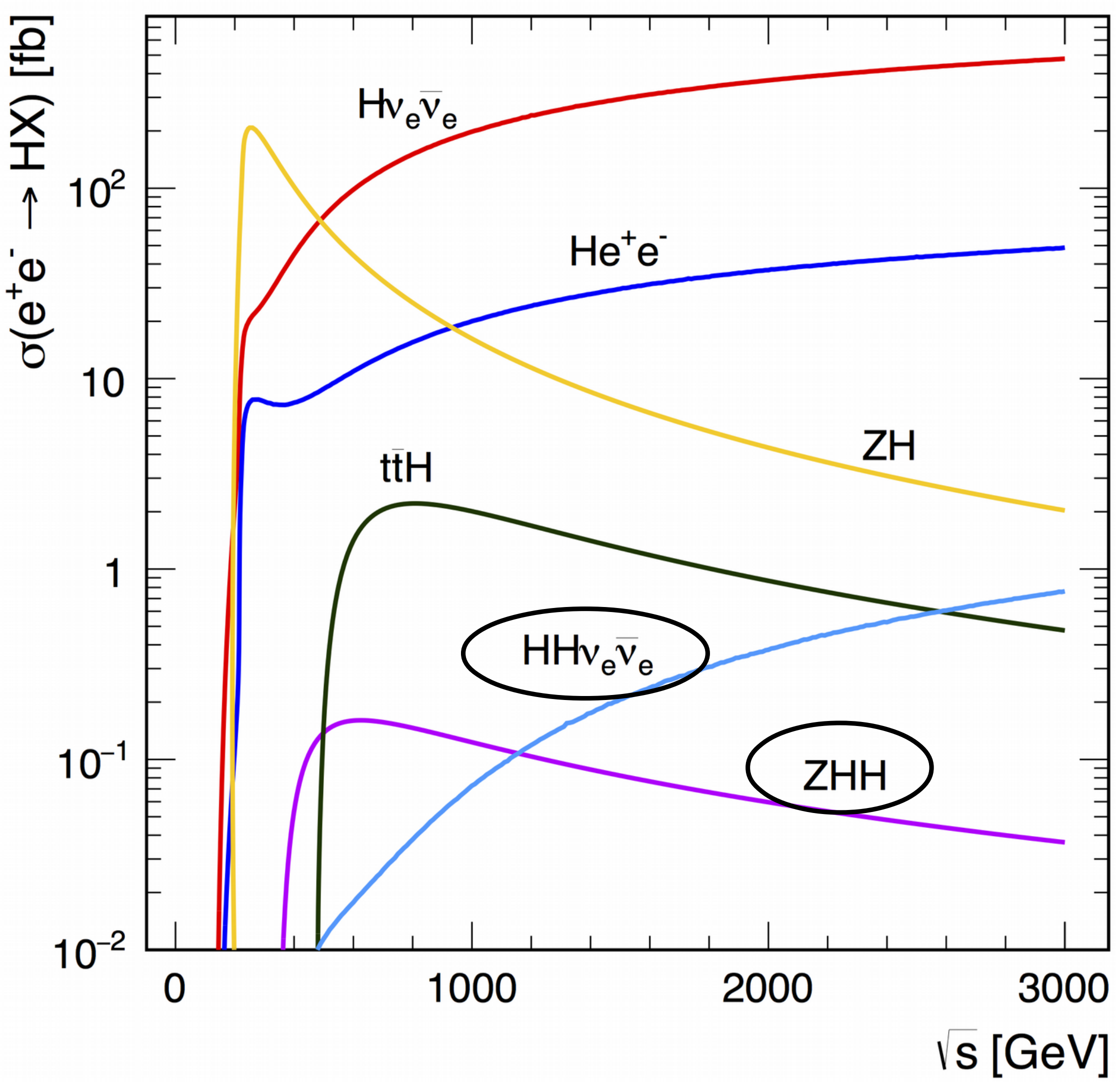
Higgs physics at the CLIC electron–positron linear collider

H. Abramowicz[1], A. Abusleme[2], K. Afanaciev[3], N. Alipour Tehrani[4], C. Balázs[5], Y. Benhammou[1], M. Benoit[6], B. Bilki[7], J.-J. Blaising[8], M. J. Boland[9], M. Boronat[10], O. Borysov[1], I. Božović-Jelisavčić[11], M. Buckland[12], S. Bugiel[13], P. N. Burrows[14], T. K. Charles[5], W. Daniluk[15], D. Dannheim[4], R. Dasgupta[13], M. Demarteau[7], M. A. Díaz Gutierrez[2], G. Eigen[16], K. Elsener[4], U. Felzmann[9], M. Firlej[13], E. Firu[17], T. Fiutowski[13], J. Fuster[10], M. Gabriel[18], F. Gaede[4,19], I. García[10], V. Ghenescu[17], J. Goldstein[20], S. Green[21], C. Grefe[4,b,d], M. Hauschild[4], …

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

Higgs pair production and trilinear Higgs coupling

[P. Roloff '18]

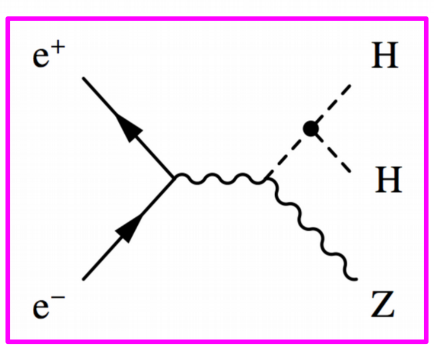


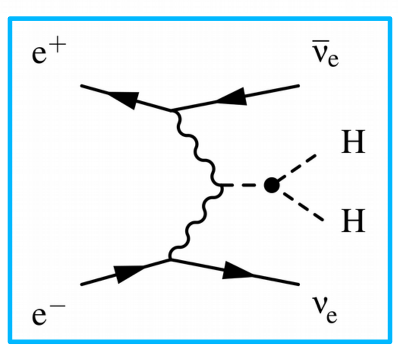
$e^+e^- \to$ ZHH:
• Cross section maximum ≈ 600 GeV, but very small number of events ($\sigma \leq 0.2$ fb)

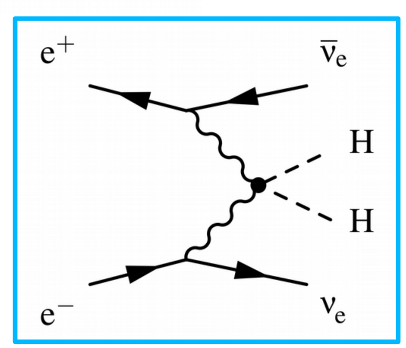
$e^+e^- \to HH\nu_e\bar{\nu}_e$:
• Allows simultaneous extraction of triple Higgs coupling, λ, and quartic HHWW coupling
• Benefits from high-energy operation

Projected precisions:
• Δ(λ) = 16% for CLIC from total cross section assuming 3 ab^{-1} at 3 TeV
(→ Δ(λ) ≈ 10% from differential distributions)

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







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

Phys. Rev. D 88, 055024 (2013)

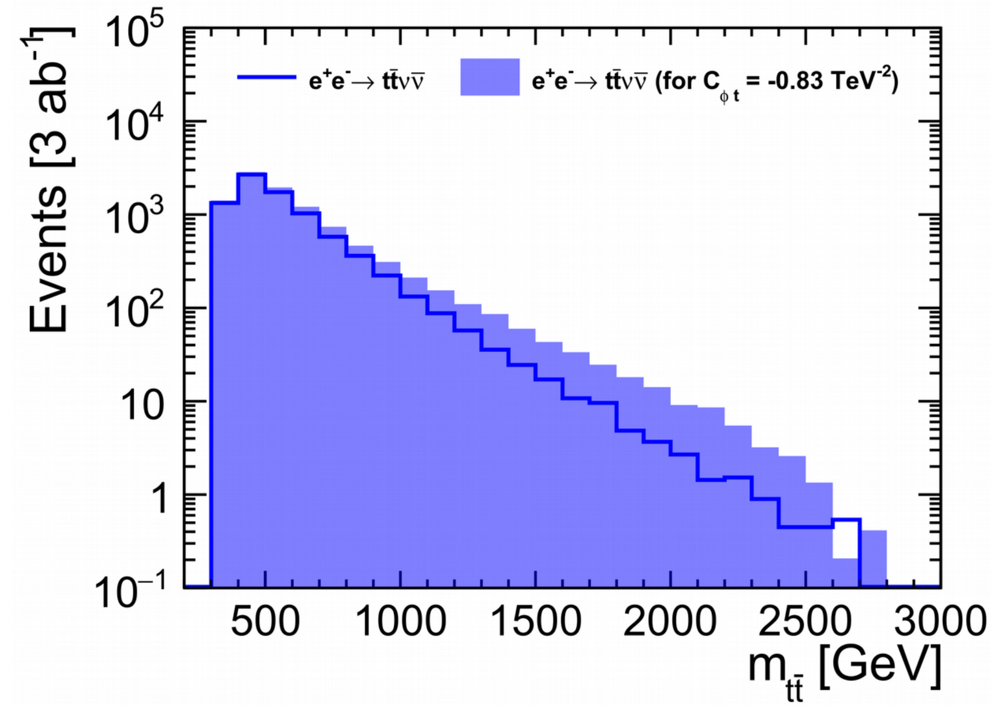
Weak boson fusion processes

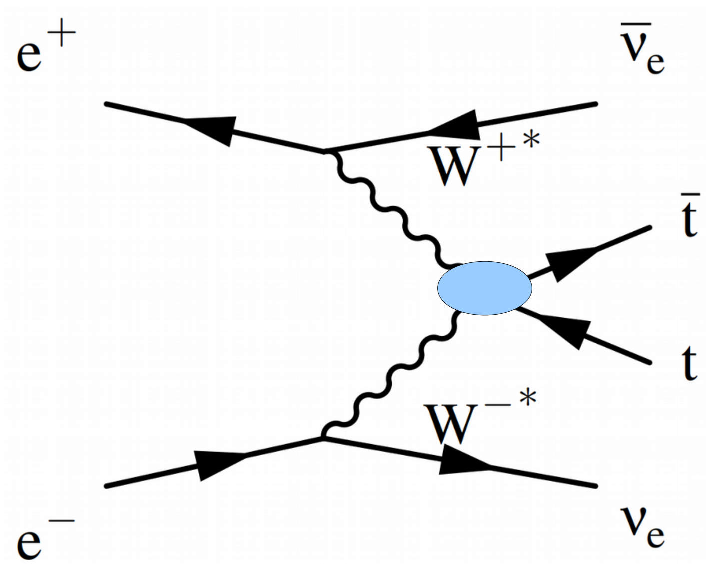
[P. Roloff ’18]

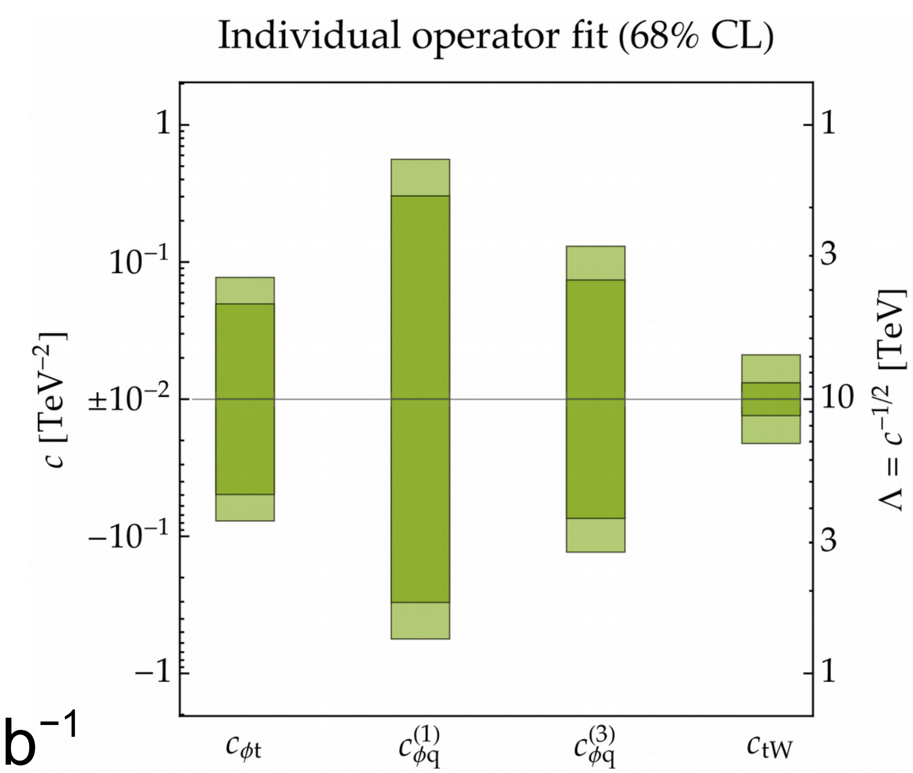
- Generator-level study and EFT interpretation

- Contributions of considered operators grow quadratically with energy

- Potential high-energy probe of the top Yukawa coupling







Grojean, You, Wulzer, Zhang

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

Direct searches for new particles

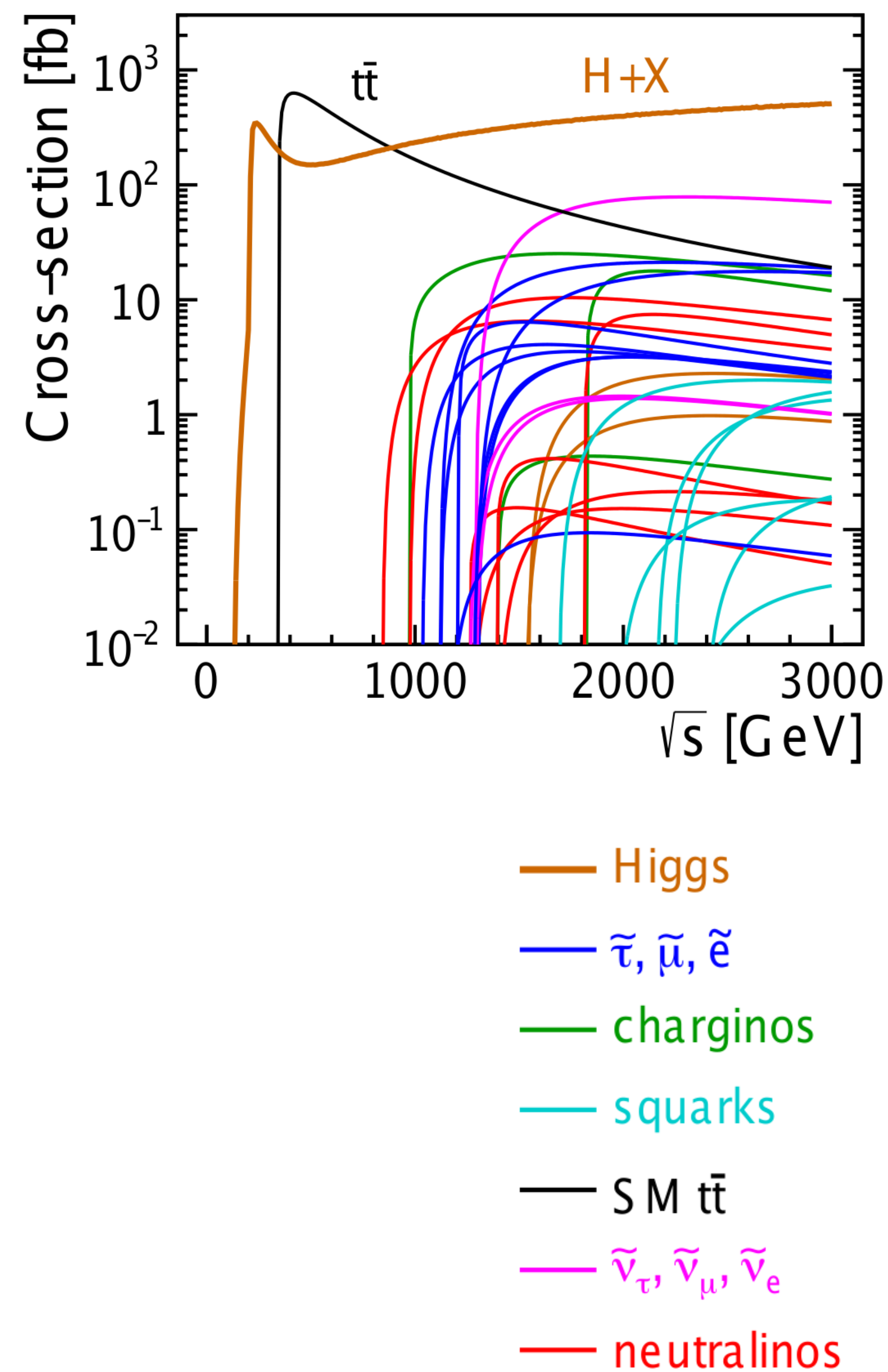
[P. Roloff '18]

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

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

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

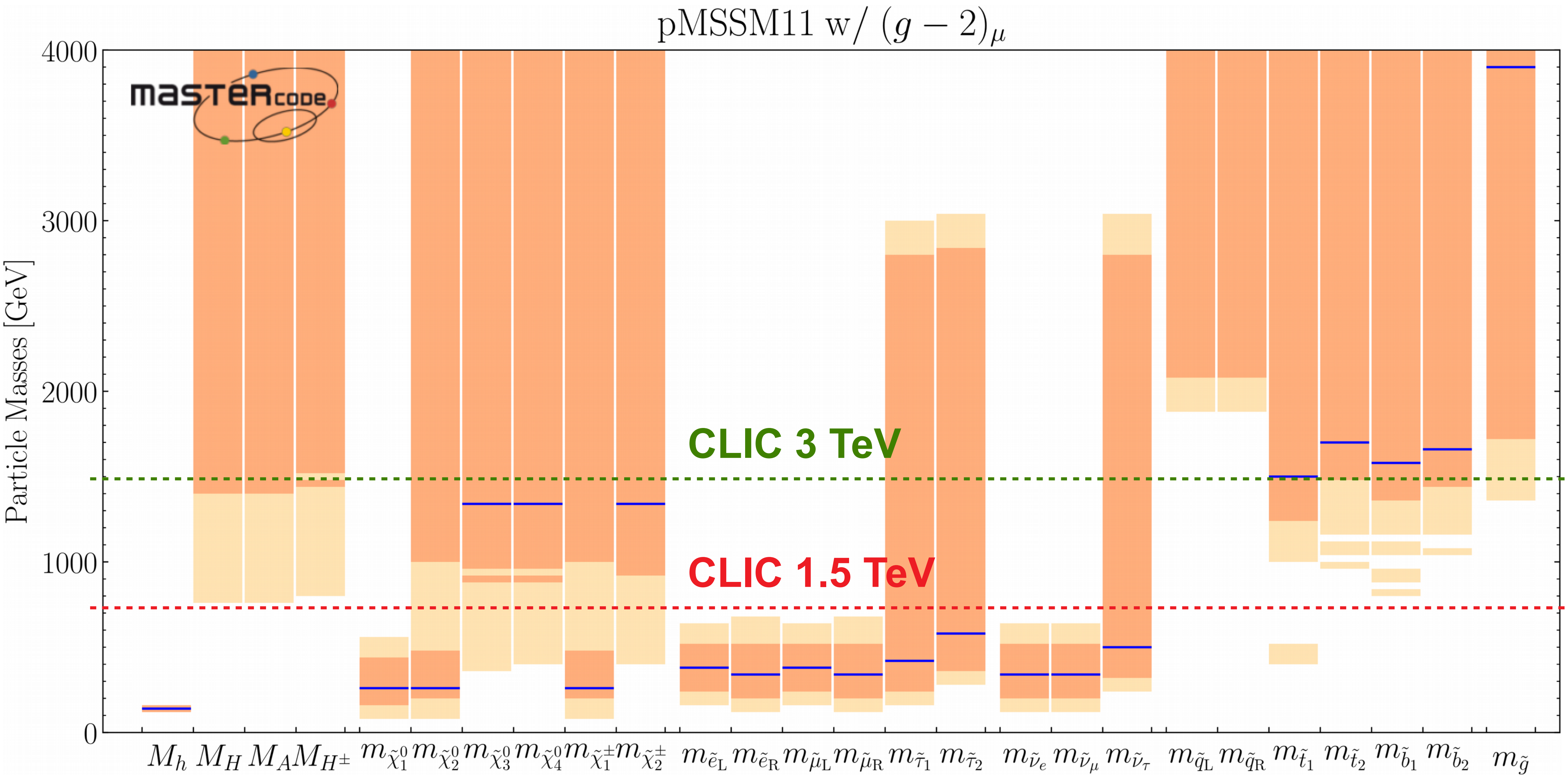
- Polarised electron beam and threshold scans might be useful to constrain the underlying theory



Comparison with SUSY fit

[P. Roloff '18]

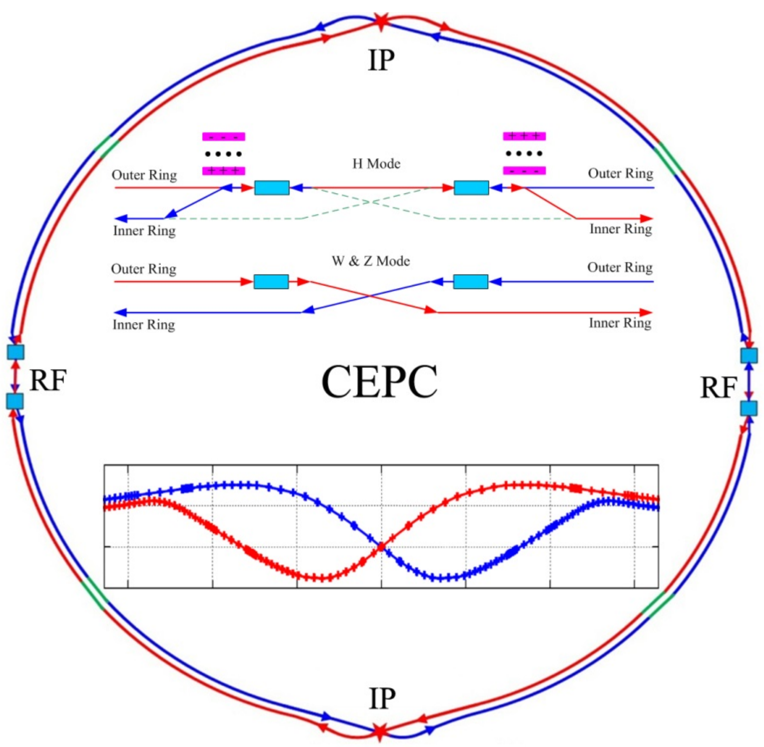
Example: Phenomenological MSSM with 11 parameters



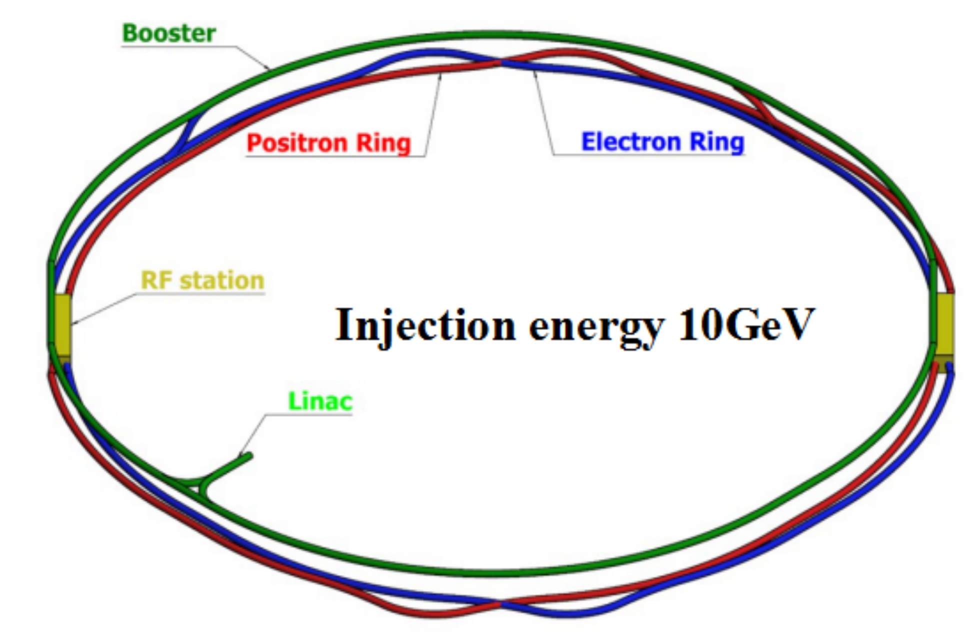
arXiv:1710.11091

Circular Electron Positron Collider (CEPC)

Tunnel length: 100 km; planned to run at 240 GeV, 160 GeV, 91 GeV

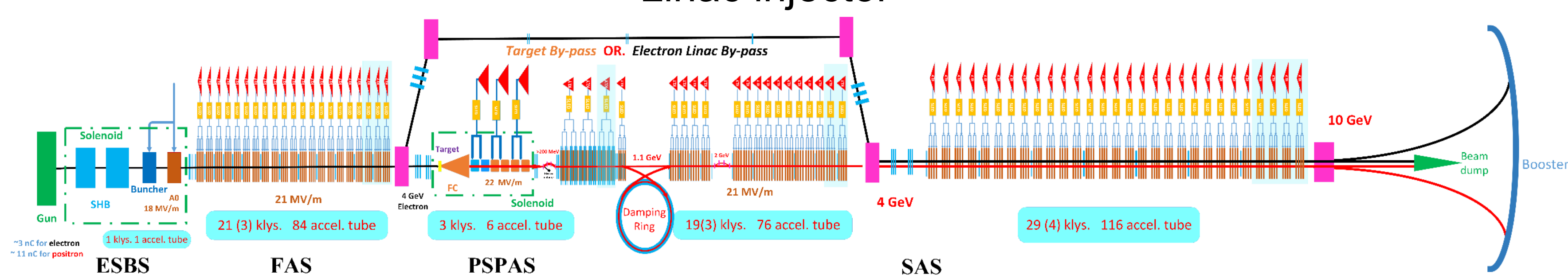


Collider ring



Booster ring

Linac injector



Conceptual Design Report (CDR): planned to be released this summer
Technical Design Report (TDR): preparation will start next year

Main parameters of CEPC double ring

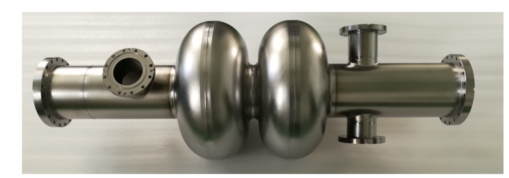
[Y. Wang ’18]

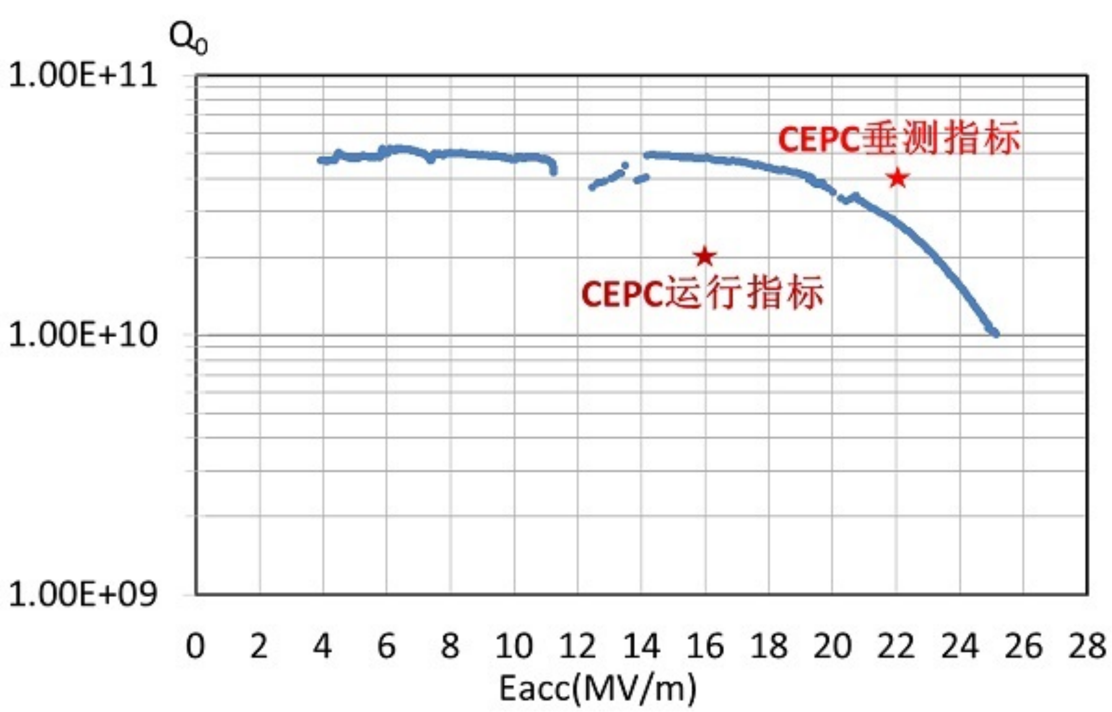
	Higgs	*W*	*Z (3T)*	*Z (2T)*
Number of IPs				2
Beam energy (GeV)	120	80	45.5	
Circumference (km)				100
Synchrotron radiation loss/turn (GeV)	1.73	0.34		36
Crossing angle at IP (mrad)		16.5Ã—2		
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	242 (0.68ms)	1524 (0.21ms)	12000 (25ns+10%gap)	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	30	30	16.5	
Bending radius (km)		10.7		
Momentum compact (10^{-5})		1.11		
b function at IP b_x* / b_y* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance e_x/e_y (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP s_x/s_y (mm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters x_x/x_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz)Â (harmonic)		650 (216816)		
Natural bunch length s_z (mm)	2.72	2.98	2.42	
Bunch length s_z (mm)	3.26	5.9	8.5	
Betatron tune n_x/n_y		363.10 / 365.22		
Synchrotron tune n_s	65	0.0395		28
HOM power/cavity (2 cell) (kw)	0.54	0.75	1.94	
Natural energy spread (%)	0.1	66		38
Energy acceptance requirement (%)	1.35	0.4	0.23	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.29	0.35	0.55	
Lifetime _simulation (min)	100			
Lifetime (hour)	0.67	1.4	4.0	2.1
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP *L* ($10^{34}cm^{-2}s^{-1}$)	2.93	10.1	16.6	32.1

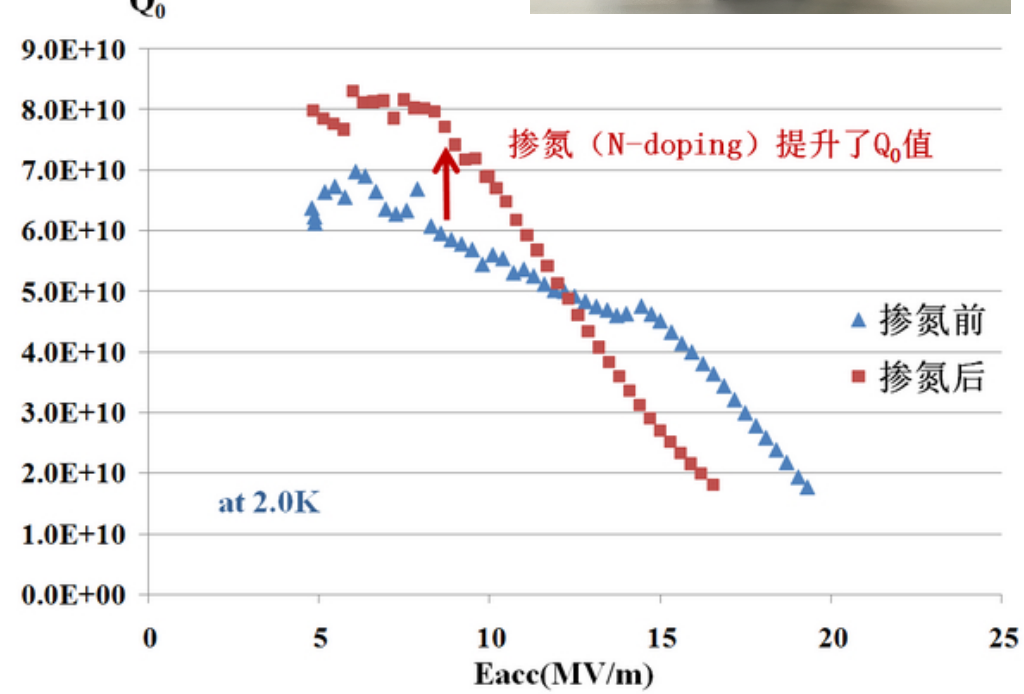
Current R&D results

[Y. Wang ’18]

- A CEPC 650MHz 1-cell cavity completed the vertical test.
- A CEPC 650MHz 2-cell cavity completed, to be test soon
- EP facility is under construction(ADS funding and others), ready this summer
- Two CEPC 650MHz 1-cell cavities tried N-doping, Q_0 increase is seen.







Possible schedule (ideal)

[Y. Wang '18]

CEPC Schedule (ideal)

design issues
R&D items
preCDR

design, funding
R&D program
Intl. collaboration
site study

seek approval, site decision
construction during 14th 5-year plan
commissioning

Physics programme of CEPC-SppC

[Y. Wang '16]

- **Electron-positron collider(90, 250 GeV)**
  - **Higgs Factory（10^6 Higgs）：**
    - **Precision study of Higgs(m_H, J^{PC}, couplings)，Similar & complementary to ILC**
    - **Looking for hints of new physics**
  - **Z & W factory（10^{10} Z^0）：**
    - **precision test of SM**
    - **Rare decays ?**
  - **Flavor factory: b, c, τ and QCD studies**
- **Proton-proton collider(~100 TeV)**
  - **Directly search for new physics beyond SM**
  - **Precision test of SM**
    - **e.g., h^3 & h^4 couplings**

Summary slide of CEPC talk at 2016 workshop

[Y. Wang ’16]

- CEPC is the first Chinese effort for a Science project at such a scale ➔ Challenges every where.
- Tremendous progresses up to now, but a long way to go
- Given the importance of Higgs, we hope that at least one of them, FCC-ee, ILC, or CEPC, can be realized.

We fully support a global effort, even if it is not built in China

International collaboration

[Y. Wang '18]

- **Limited international participation for the CDR**
  - **Not in any roadmap**
  - **No funding support**
- **Hopefully it will be included in the roadmap of Europe, Japan and the US**
- **The international advisory board worked very well**
  - **A lot of suggestions**
- **MOUs have been signed with many institutions**
- **Welcome recommendation/suggestions**

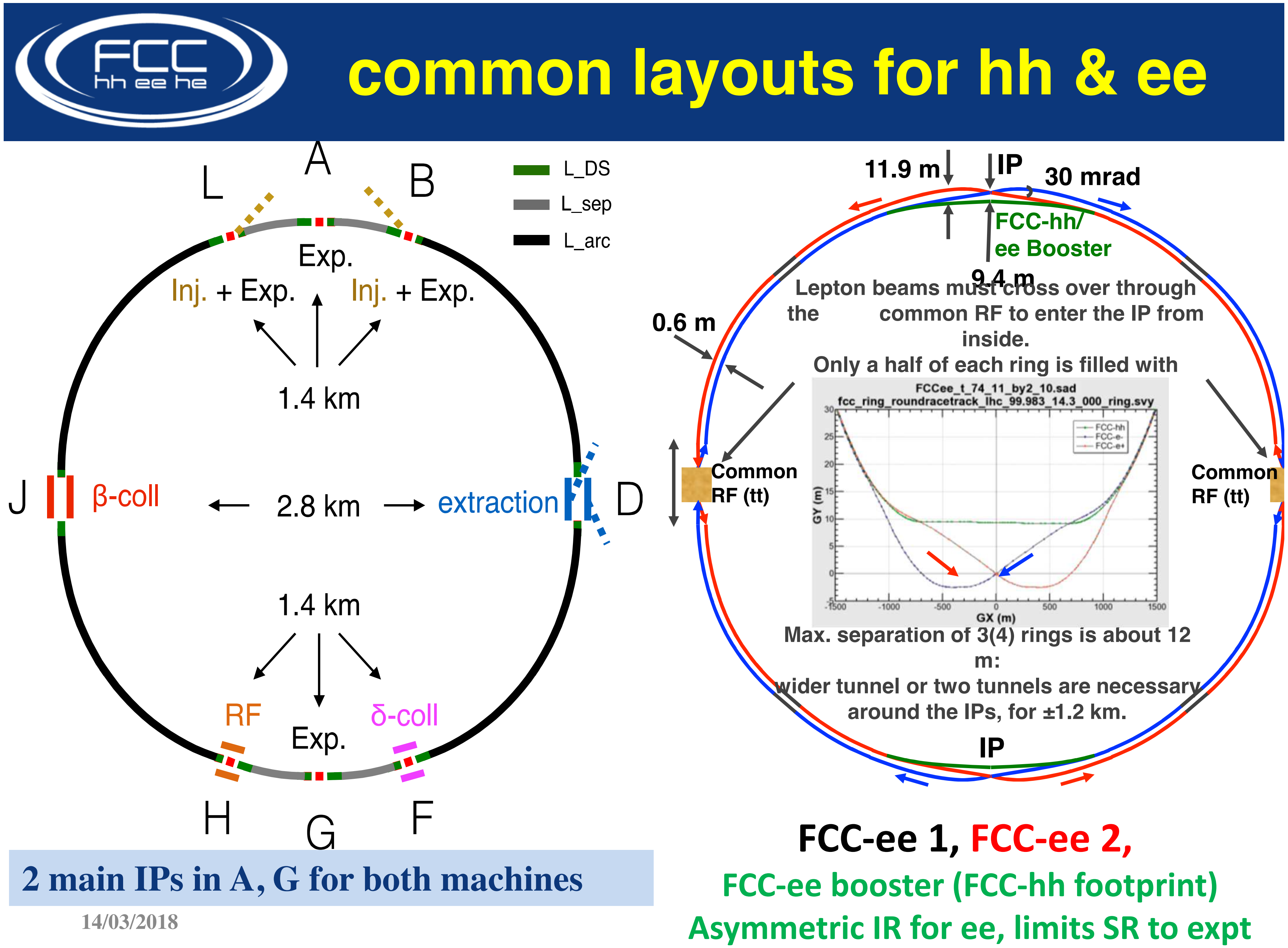
Latest political developments

[Y. Wang '18]

- Science & Technology is strongly supported by this government ➔ also a "requirement" to local governments (difference seen at Beijing & Shanghai since 2016)
- Not difficult to find local support for the site
- State Council announced in March "Implementation method to support China-initiated large international science projects and plans"
  - Science of Matter, Evolution of the Universe, life science, earth, energy, …
  - Goal:
    - up to 2020, 3-5 preparatory projects; 1-2 construction projects
    - up to 2035, 6-10 preparatory projects; ? construction projects
  - Possible competitors: ~ 50 ideas collected, Fusion reactor, space program, brain program, Investigation of the Qinghai Tibet Plateau, CEPC, …
- We are working with the MOST to be included in the roadmap planning, project selection, etc.

FCC-ee: Future Circular Collider Study

[A. Blondel '18]



Conceptual Design Report (CDR): in preparation

Fcc-ee: parameters

[A. Blondel ’18]

Recent FCC-ee parameter list

	Z	W	H	tt
Circumference [km]	97.750			
Bending radius [km]	10.747			
Beam energy [GeV]	45.6	80	120	175
Beam current [mA]	1390	147	29	6.4
Bunches / beam	18800	2000	375	45
Bunch spacing [ns]	15	150	455	6000
Bunch population [10^{11}]	1.5	1.5	1.6	2.9
Horizontal emittance ε [nm]	0.267	0.26	0.61	1.33, 2.03
Vertical emittance ε [pm]	1.0	1.0	1.2	2.66, 3.1
Momentum comp. [10^{-6}]	14.79	7.31	7.31	7.31
Arc sextupole families	208	292	292	292
Betatron function at IP				
- Horizontal β^* [m]	0.15	0.20	0.5	1
- Vertical β^* [mm]	0.8	1	1.2	2
Horizontal beam size at IP σ^* [μm]	6.3	7.2	17	45
Vertical beam size at IP σ^* [nm]	28	32	38	79
Free length to IP l^* [m]	2.2			
Solenoid field at IP [T]	2			
Full crossing angle at IP [mrad]	30			
Energy spread [%]				
- Synchrotron radiation	0.038	0.066	0.10	0.145
- Total (including BS)	0.130	0.153	0.14	0.194
Bunch length [mm]				
- Synchrotron radiation	3.5	3.27	3.1	2.4
- Total	11.2	7.65	4.4	3.3
Energy loss / turn [GeV]	0.0356	0.34	1.71	7.7
SR power / beam [MW]	50			
Total RF voltage [GV]	0.10	0.44	2.0	9.5
RF frequency [MHz]	400			
Longitudinal damping time [turns]	1281	235	70	23
Energy acceptance RF / DA [%]	1.9,	1.9,	2.4,	5.3, 2.5 (2.0)
Synchrotron tune Q_s	-0.025	-0.023	-0.036	-0.069
Polarization time τ_p [min]	15040	905	119	18
Interaction region length L_i [mm]	0.42	1.00	1.45	1.85
Hourglass factor $H(L_i)$	0.95	0.95	0.87	0.85
Luminosity/IP for 2IPs [10^{34} cm^{-2}s^{-1}]	215	31.0	7.9	**1.9**
Beam-beam parameter				
- Horizontal	0.004	0.007	0.033	0.092
- Vertical	0.134	0.126	0.141	0.150
Beam lifetime rad Bhabha, BS [min]	72	54	42	47, 70 (12)

14/03/2018

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FCC-ee: new run plan

[P. Azzi ’18]

Working point	Z, years 1-2	Z, later	WW	HZ	tt threshold	365 GeV
Lumi/IP (10^{34} cm^{-2}s^{-1})	100	200	31	7.5	0.85	1.5
Lumi/year (2 IP)	26 ab^{-1}	52 ab^{-1}	8.1 ab^{-1}	1.95 ab^{-1}	0.22 ab^{-1}	0.39 ab^{-1}
Physics goal	150		10	5	0.2	1.5
Run time (year)	2	2	1	3	1	4

Operation assumptions (10% safety margin)

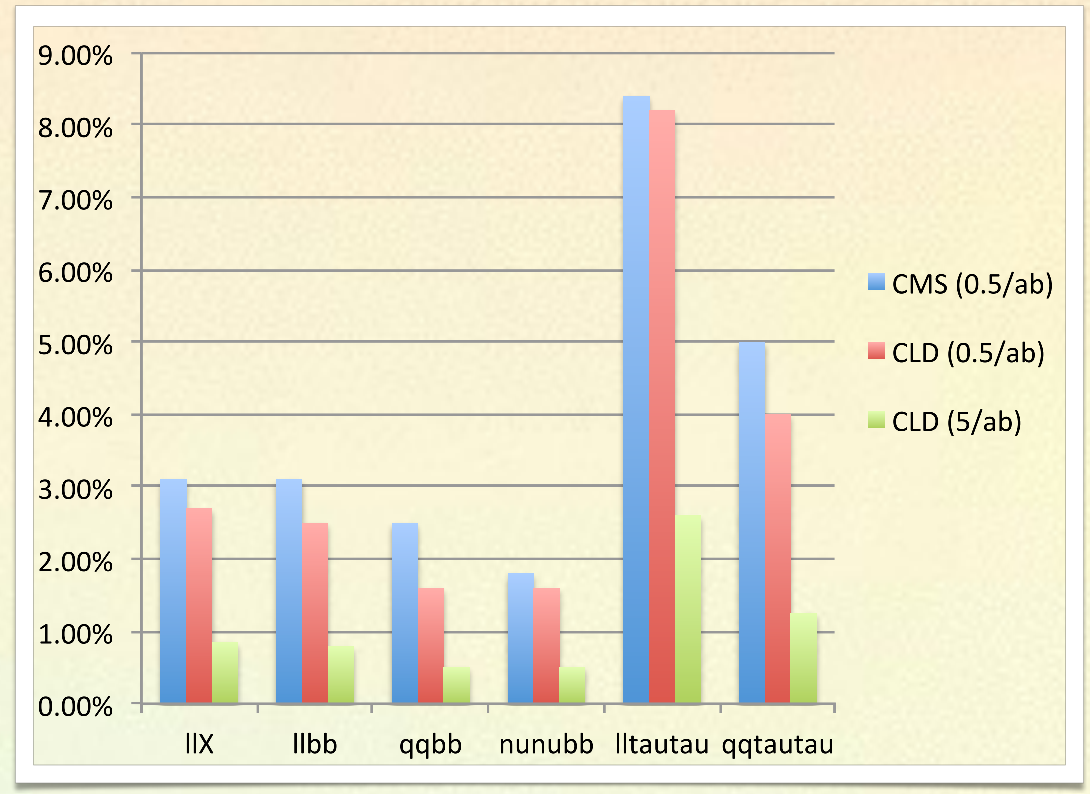
- 200 physics days/year
- Hubner factor ~0.75 (lower than KEKB top-up injection that reached >80%)
- half the design luminosity in the first year of Z and top operation
- machine upgrades during Winter shutdown (3m/y)
- Longer shutdown to install the 196 RF

Higgs physics at FCC-ee

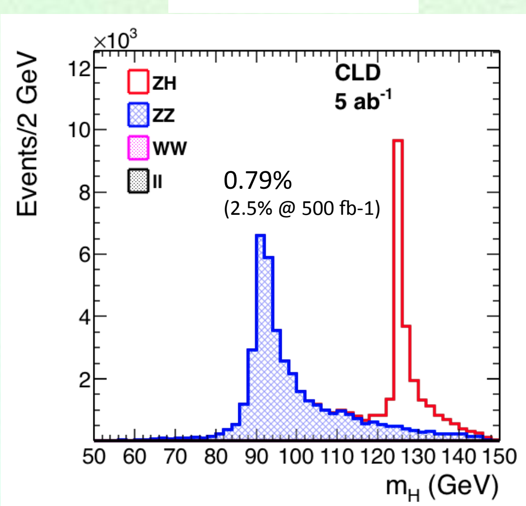
[P. Azzi '18]

HIGGS

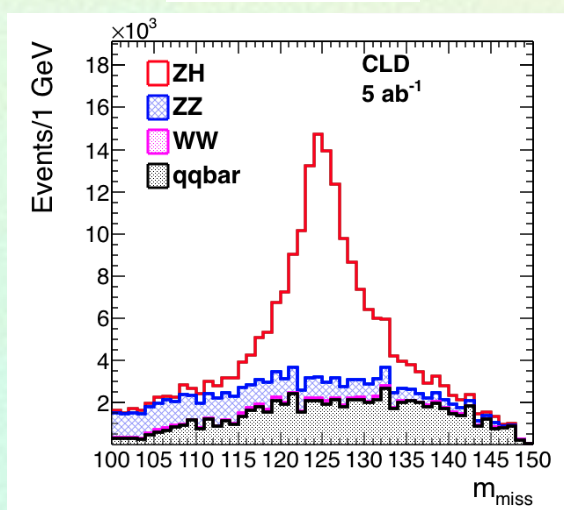
- **Ultimate precision on Higgs couplings below 1% (and measurement of the total width) a milestone of the FCC physics program.**
- **Model independent determination of the total Higgs decay width**
- New estimates of Higgs coupling precision made with custom simulation (PAPAS)
  - CLD performs 10-35%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



$ZH \to \ell\ell bb$



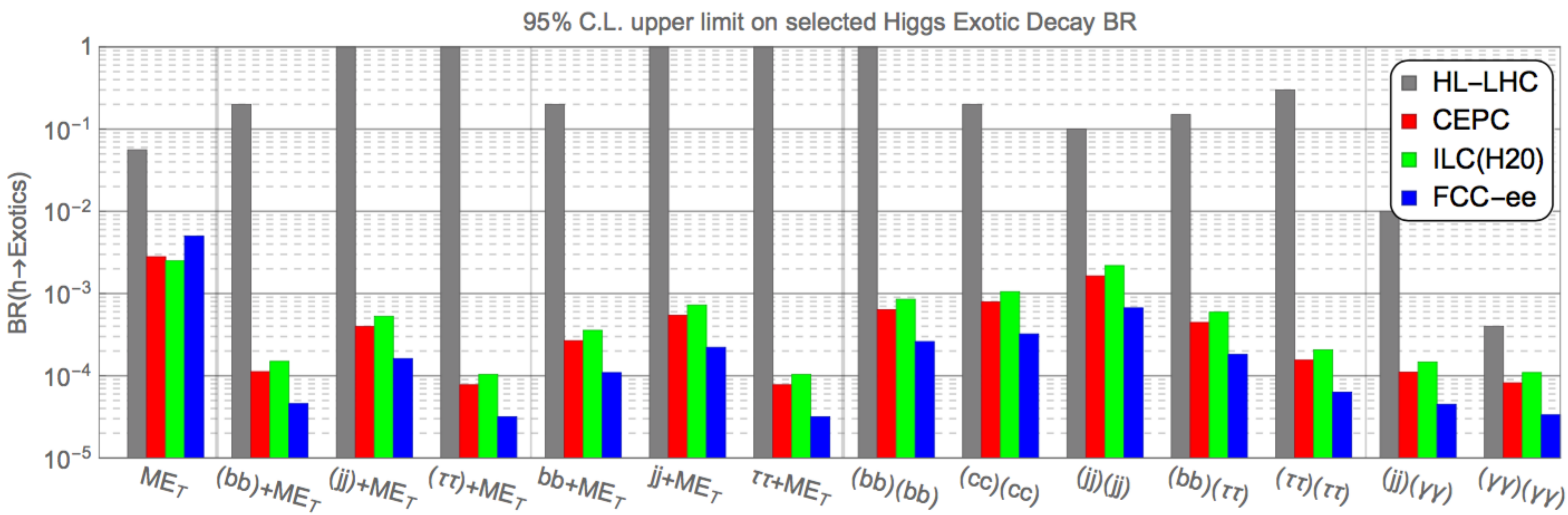
$ZH \to qqbb$



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

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

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



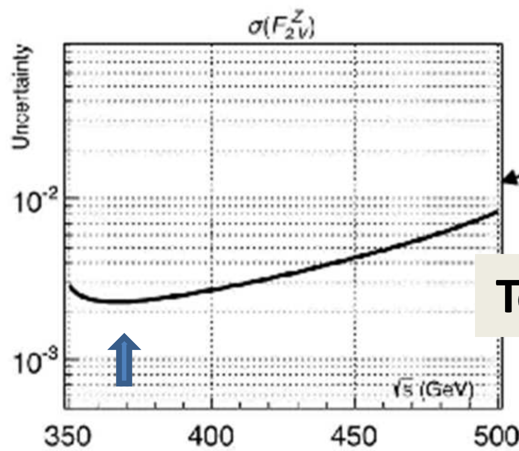
⇒ Large improvements over HL-LHC

Top physics at FCC-ee

[A. Blondel '18]

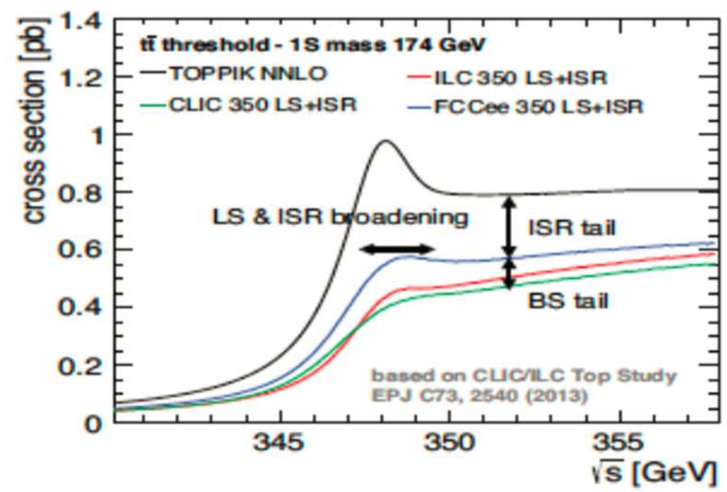
Top physics

Determination of top-quark EW couplings via measurement of top-quark polarization.
In semileptonic decays, fit to lepton momentum vs scattering angle



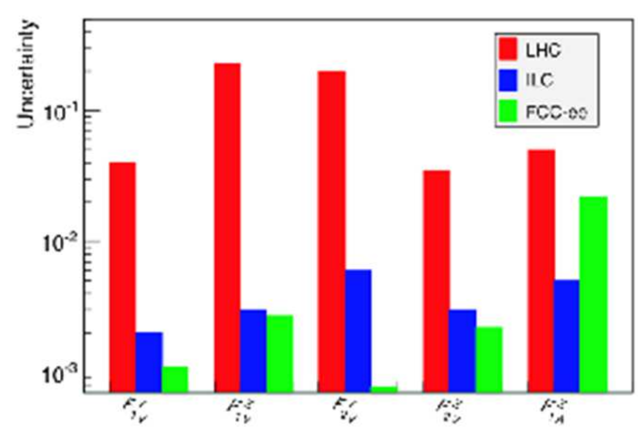
Typically best sensitivity just above production threshold

Top beam energy is 185 GeV



Top mas can be measured to O(10 MeV)
Beam energy calibration from WW, γZ, ZZ
Reduce th. errors due α_S meast @FCC-ee

Patrick Janot
arXiv:1503.01325v2



Also:
CKM measurements
FCNC decays down to 10^{-6}
All luminosity can be used!

beam polarization is not necessary here.

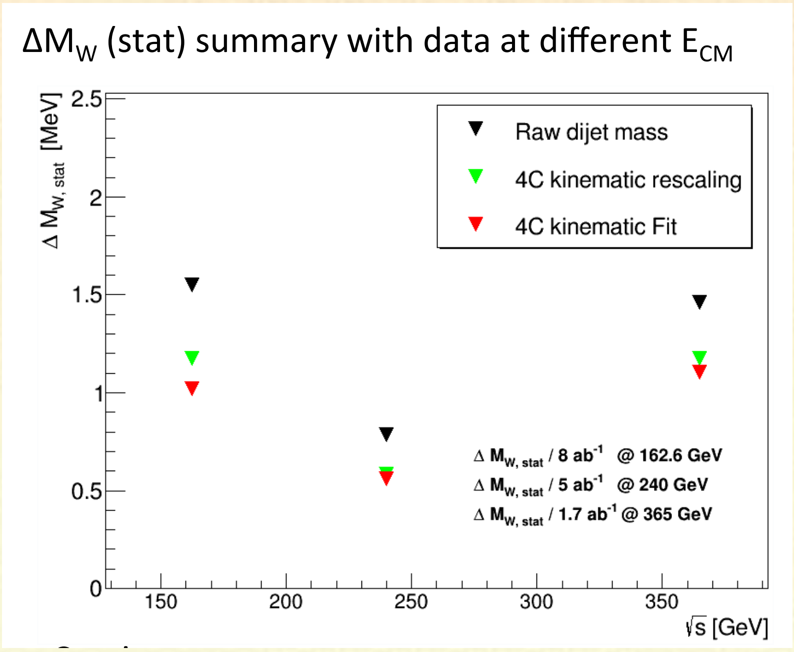
3/14/2018

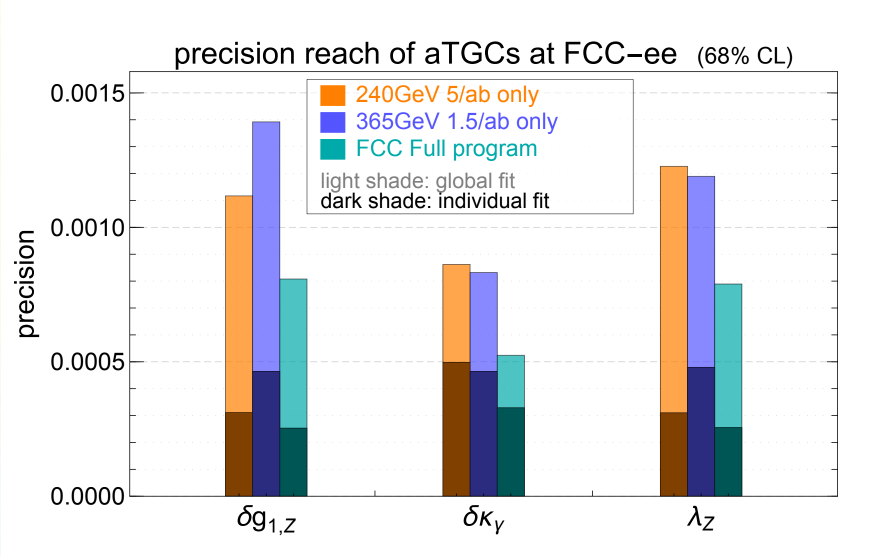
Electroweak physics at FCC-ee

[P. Azzi ’18]

EWK

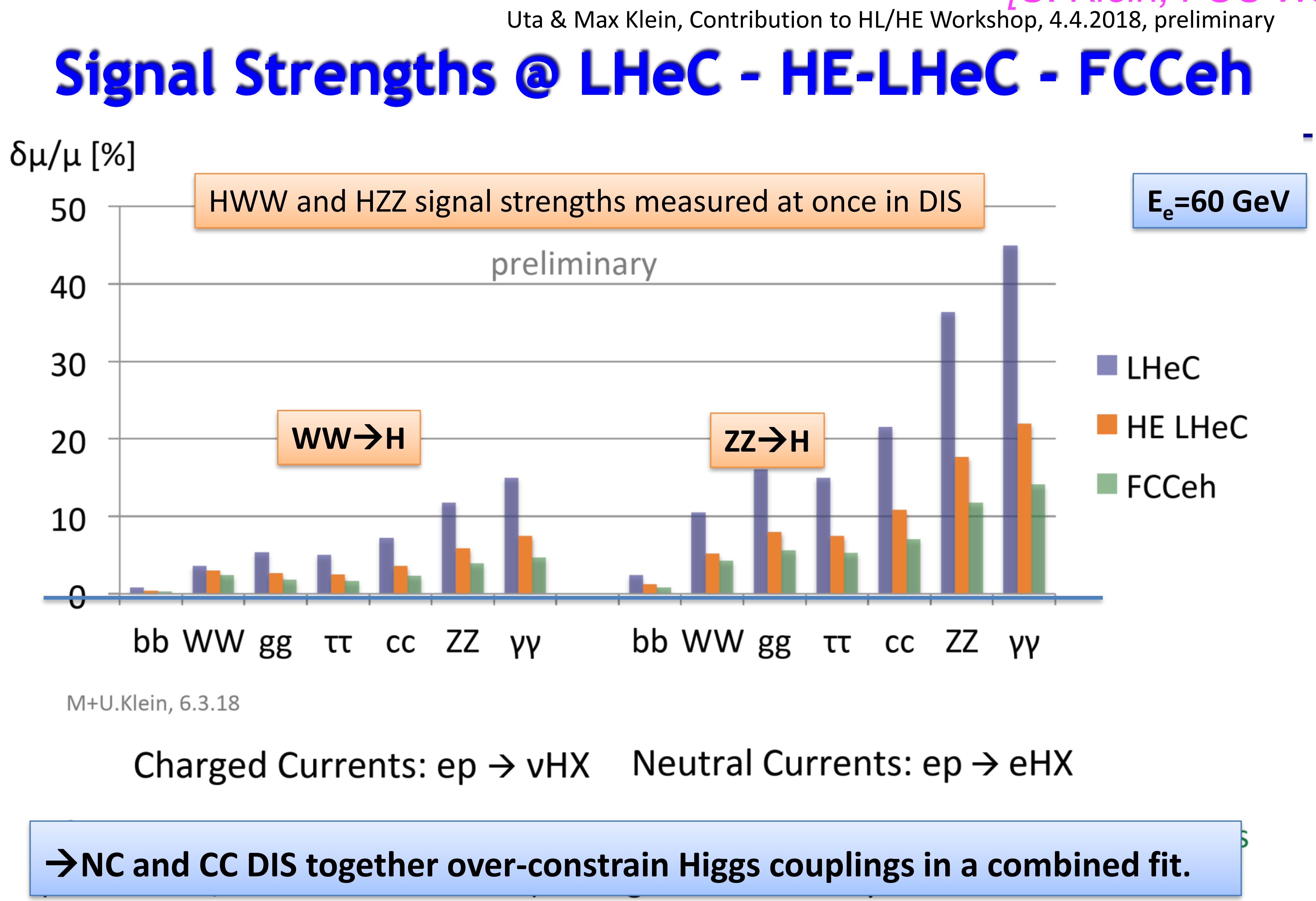
- Integrated luminosity goals for Z and W physics
  - 150 ab^{-1} around the Z pole (~ 25 ab–1 at 88 and 94 GeV, 100 ab–1 at 91 GeV)
  - 10 ab^{-1} around the WW threshold (161 GeV with ±few GeV scan)
  - runs at 240 and at 350-365 GeV very important for WW physics as well
- **FCC-ee program will bring improvement of 1 to 2 orders of magnitude in precision of EWPO**
- New at this collaboration meeting:
  - Direct M(W) reconstruction in the 4-jet channel to be used above the WW threshold region. ΔM(W)=0.5MeV (stat) with 5ab^{-1} at $\sqrt{s}$=240 GeV
  - Study of TGC (leptonic mode only) shows a precision achievable of $O(10^{-3})$!





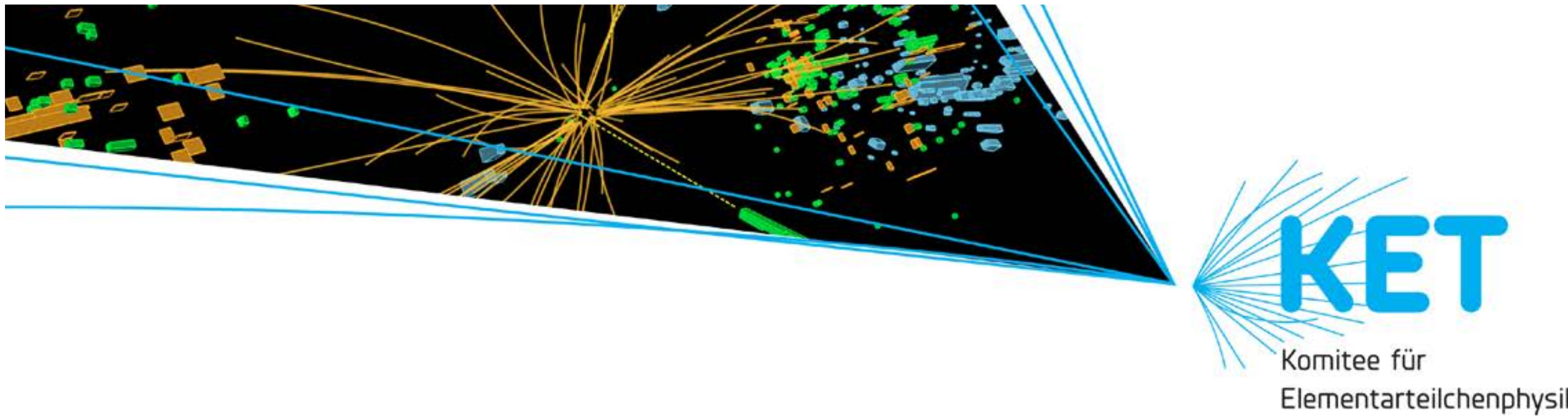
Higgs physics at LHeC and beyond (see next talk)

[U. Klein, FCC Week 2018]



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

Summary statement from the previous workshop



Conclusions of the

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

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

1. The physics case for a future e^+e^- collider, covering energies from M_Z up to the TeV regime, is regarded to be very strong, justifying (and in fact requiring) the timely construction and operation of such a machine.[i]

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]

3. FCC-ee, as a possible first stage of FCC-hh, and CEPC could well cover the low-energy part of the e^+e^- physics case, and would thus be complementary to the ILC.[iv]

4. CLIC has the potential to reach significantly higher energies than the ILC. CLIC R&D should be continued until a decision on future CERN projects, based on further LHC results and in the context of the 2019/2020 European Strategy, will be made.

[i] Main topics are ultra-high precision tests of the electroweak Standard Model and of Quantum-Chromodynamics (QCD), precision Higgs Physics (mass, width, couplings, self coupling) and precision top-quark physics, which are all well defined and not based on speculation. Apart from these "guaranteed" advancements of our knowledge, precision tests also carry a huge potential towards physics Beyond the Standard Model (BSM), especially through the effects of radiative corrections with sensitivities beyond the TeV region. At high energies these projects are sensitive to the direct observation of physics BSM, complementary to and extending the reach of searches performed at the LHC.

Summary statement from the previous workshop

[ii] The basic requirements and features of e^+e^- circular and linear collider projects have been extensively discussed at this workshop, and are summarized, in a simplistic scheme, in the following table:

Topic	CEPC	FCC-ee	ILC	CLIC
Higgs Mass, couplings	+	+	+	+
Higgs self-coupling	-	-	+	+
Top physics	-	+	+	+
ew- precision parameters	+	+	+	-
BSM (direct searches)	-	-	+	+
Flexibility to new high mass signal	-	-	-	+
Maturity of project	-	-	+	-
Start by/before 2035	+	-	+	-

[iii] Technological maturity is reached in general, proven by successful industrial mass production and implementation in the European XFEL, which can be considered as a large scale technological prototype of the ILC. The design provides the possibility of beam polarisation, which is an essential ingredient for precision physics results. The project is under political consideration in Japan. There exist superior detector designs and respective R&D.

[iv] Circular colliders are especially advantageous for efficient measurements with highest statistics at the "low-energy" (M_Z and below) side of the targeted energy spectrum. This "Tera-Z" operation allows to reduce the uncertainties of electroweak parameters substantially, which are an important ingredient for theoretical predictions at high energies. The efficiency of the linear collider projects at M_Z and below is limited and requires substantial effort. This opens the possibility of efficient task- and cost-sharing between circular and linear colliders, if regional considerations and possibilities lead to the realization of more than one project.

Conclusions

While the physics programme of the HL-LHC will bring important progress on the exploration of the detected Higgs boson, the quest for revealing the underlying physics of electroweak symmetry breaking will most likely remain to be of utmost importance also after the end of the HL-LHC.

An e^+e^- Higgs factory would be ideally suited to address this issue. 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.

Conclusions

The main conclusions of the KET Workshop on Future e^+e^- Colliders in May 2016 remain valid in the light of the developments of the last two years.

The most striking news are:

- ILC250 has been officially proposed to the Japanese ministry. Physics studies, ICFA statement, significant progress at the political level
- CLIC380: Updated Staging Baseline
- CEPC: progress towards the CDR, international review foreseen for the next months
- FCC-ee: CDR in preparation

Backup

ILC political developments: prospects until end of 2018

[T. Nakada '18]

Issues by the end of 2018

- "Clear" statement from the Japanese government by the end of 2018 needed for:
  - Input for the European Strategy discussion in 2019
  - Support for ILC related activities to continue
- Informal contacts at all levels between Japan and other countries, which have started early this year, have to continue and extended
- Governments of partner countries have to be informed about their technological and industrial opportunities by the scientific community, European Action Plan, (European) National Laboratory Group, …

ILC political developments: prospects until end of 2018

[T. Nakada ’18]

- What should be included in the government statement to be understood as “clear”:
  for example…
  1. Wish to host the ILC in Japan as an international project
  2. Indication of a level of contribution from Japan:
     - e.g. all the civil engineering cost plus an appropriate contribution to the accelerator,

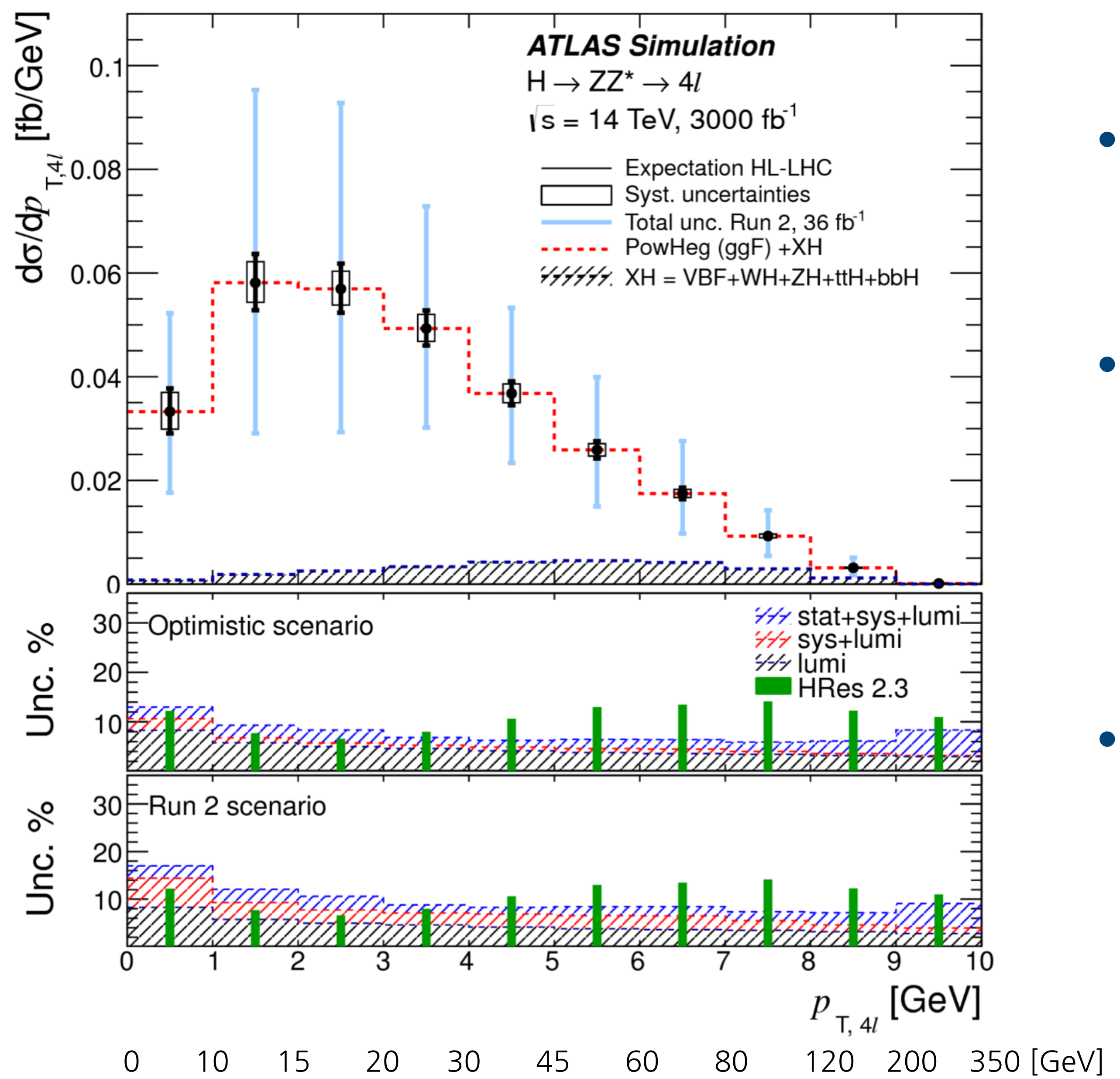
     something more or less explicit?
  3. Wish to start negotiation to form the international project
- Who would be the appropriate body to make the statement?
  – At a MEXT level or even beyond?
- Global profiling could be done by (or together with) ICFA

Improvements in Higgs differential cross sections

[T.J. Kim '18]

ATLAS TDR-026

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

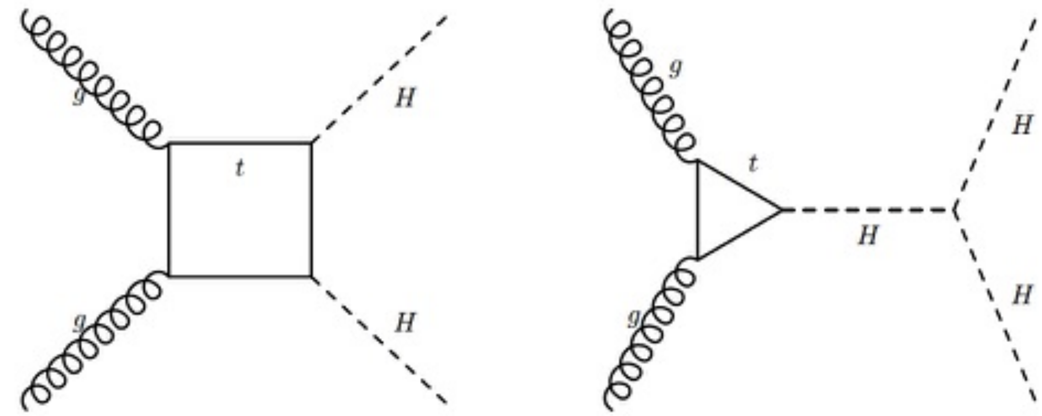


- In Run2 scenario, the uncertainty is between 8-17%
- In optimistic scenario where the experimental uncertainties are reduced by a factor of 2, the uncertainty is between 6-14%.
- This improves the current result by more than factor of 6.

The "holy grail": Higgs self-coupling

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

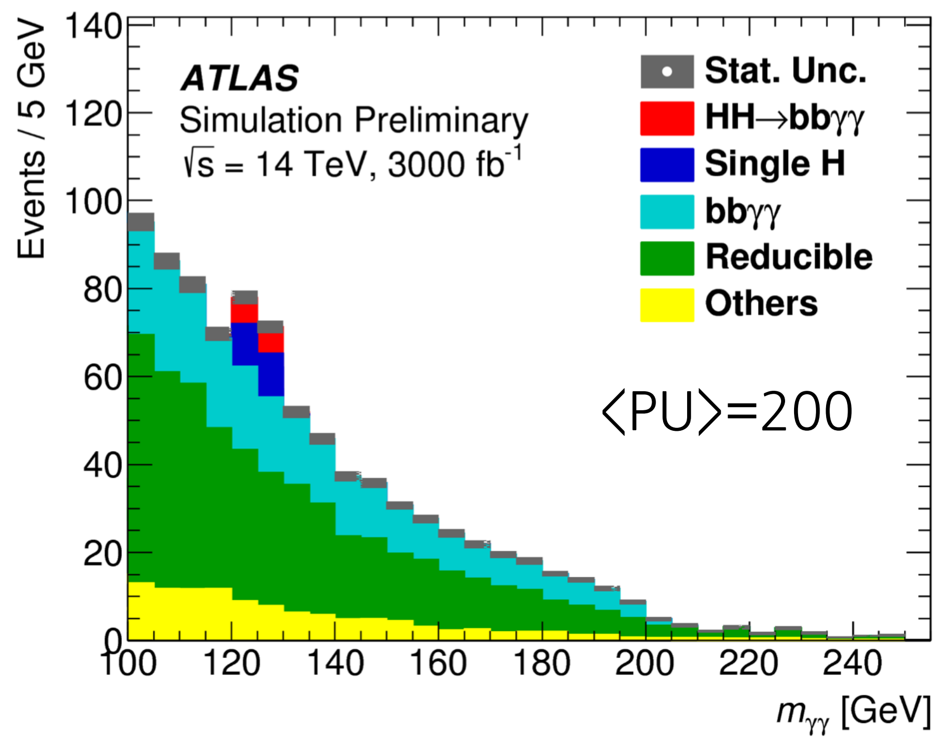
The "holy grail": Higgs self-coupling

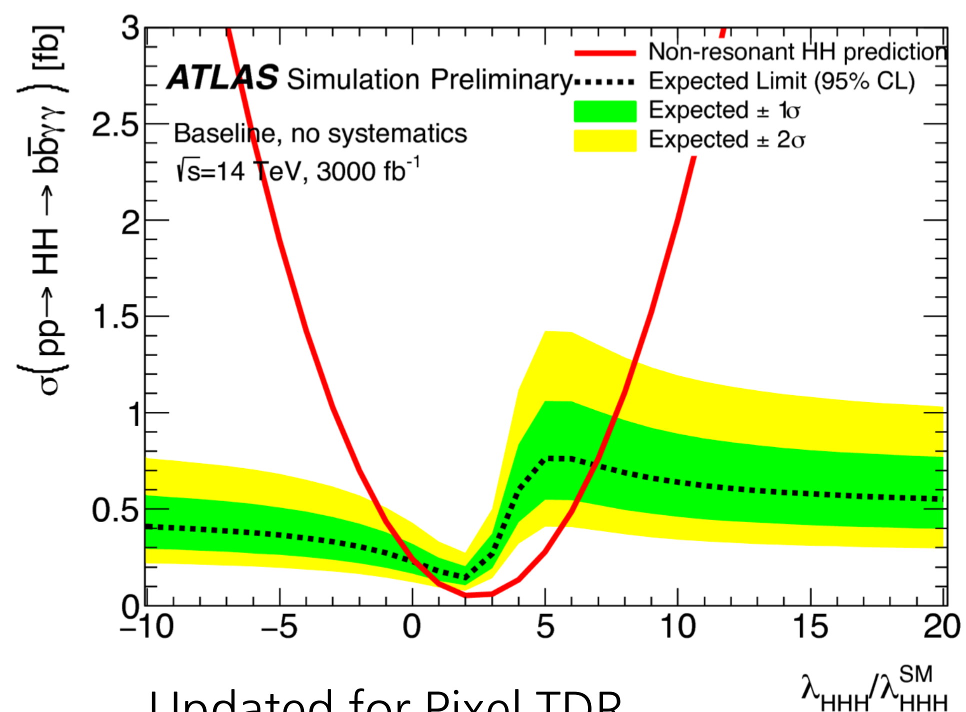
ATL-PHYS-PUB-2017-001

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 $H \to ZZ^* \to 4\,l$, etc. because of the smallness of a_3

Hypothesis of a pure CP-odd state is experimentally disfavoured

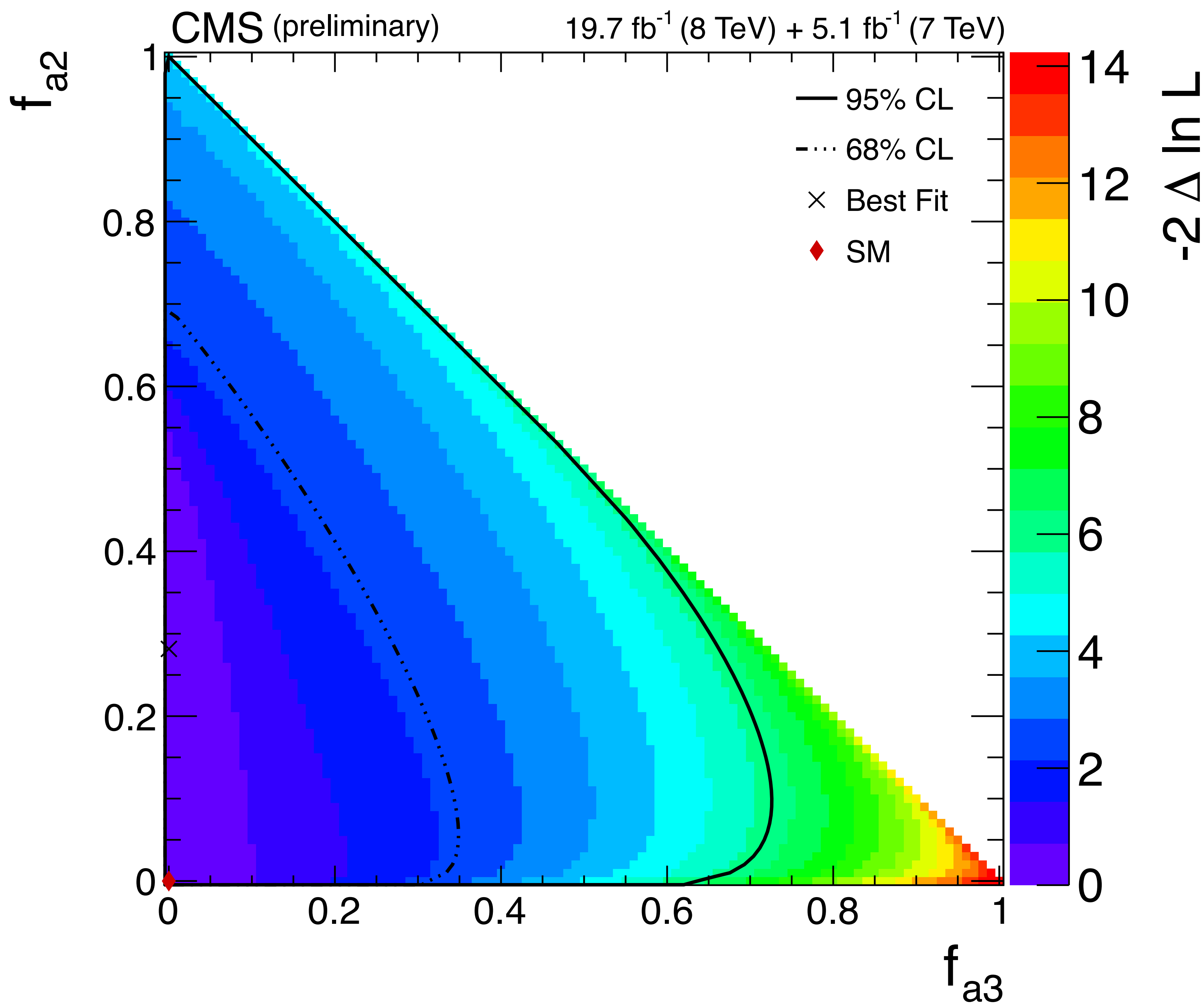
However, there are only very weak bounds so far on an admixture of CP-even and CP-odd components

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

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

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

⇒ 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}!

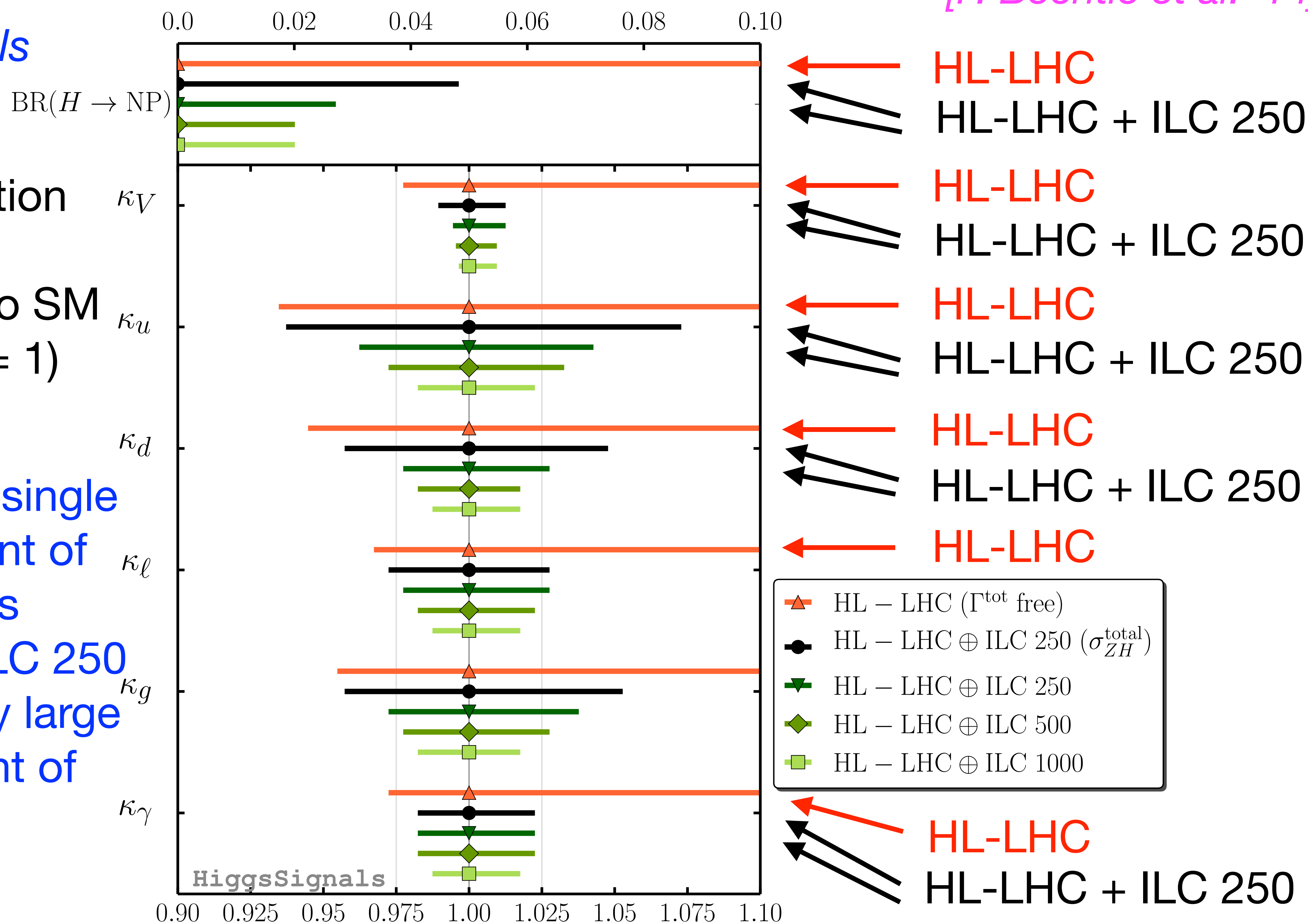
Projections for HL-LHC and ILC, no additional theory assumptions (ILC 250: only 250 fb^{-1})

[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!

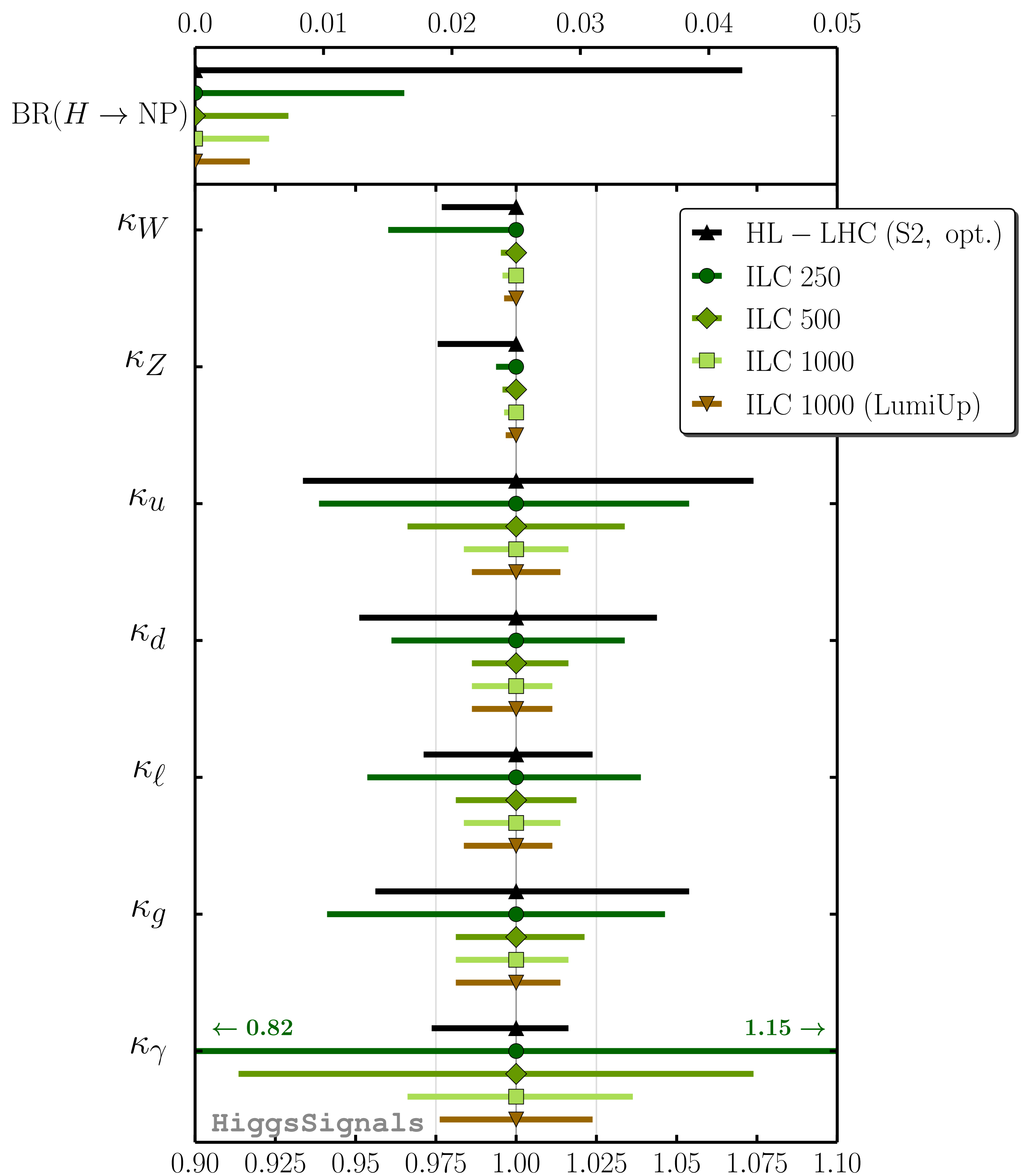


Prospects for Higgs-coupling determinations at HL-LHC and ILC: with theory assumption on $\varkappa_V$

[P. Bechtle et al. '14]

HiggsSignals

Assumed: $\kappa_V \leq 1$



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

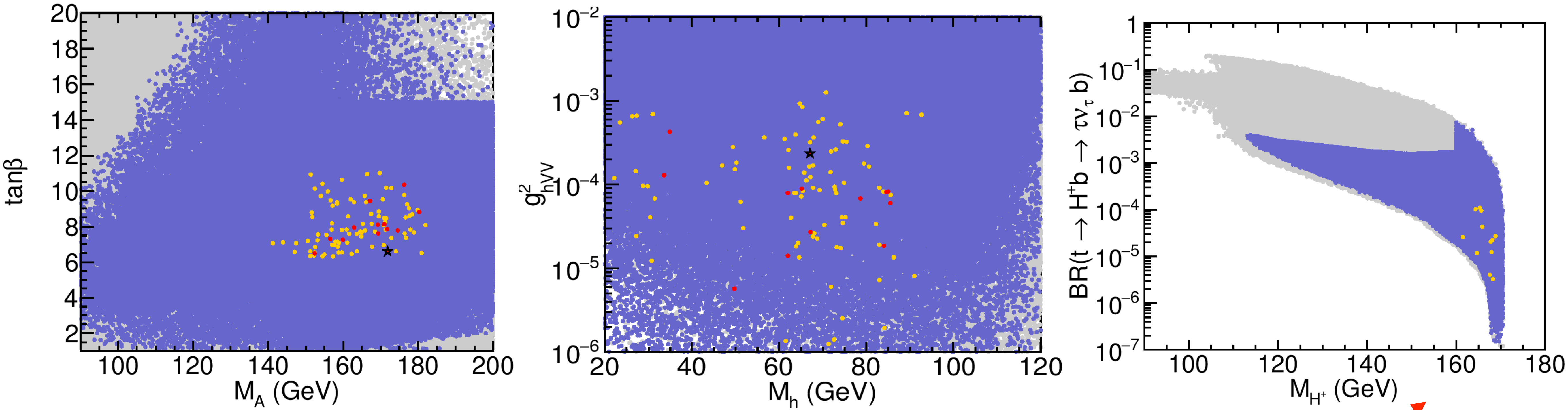
⇒ Lightest neutral Higgs with heavily suppressed couplings to gauge bosons, may have a mass below the LEP limit of 114.4 GeV for a SM-like Higgs (in agreement with LEP bounds)

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]

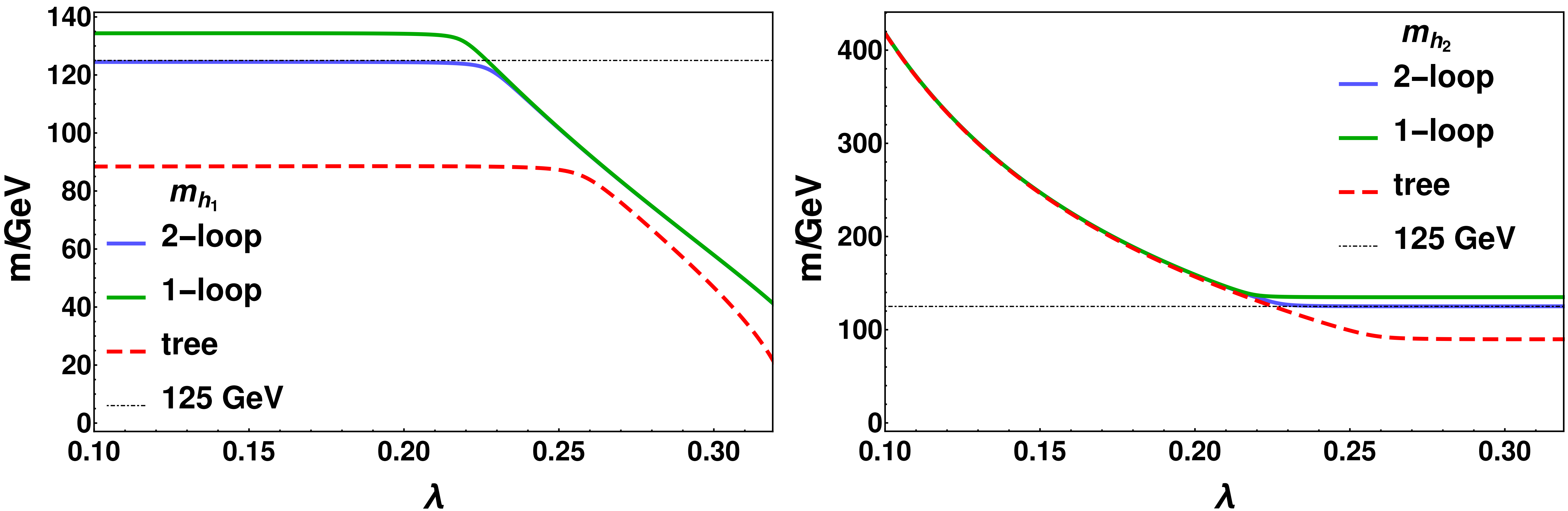


⇒Very light Higgs h is compatible with the experimental results
Tight constraints in the MSSM from charged Higgs searches

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]



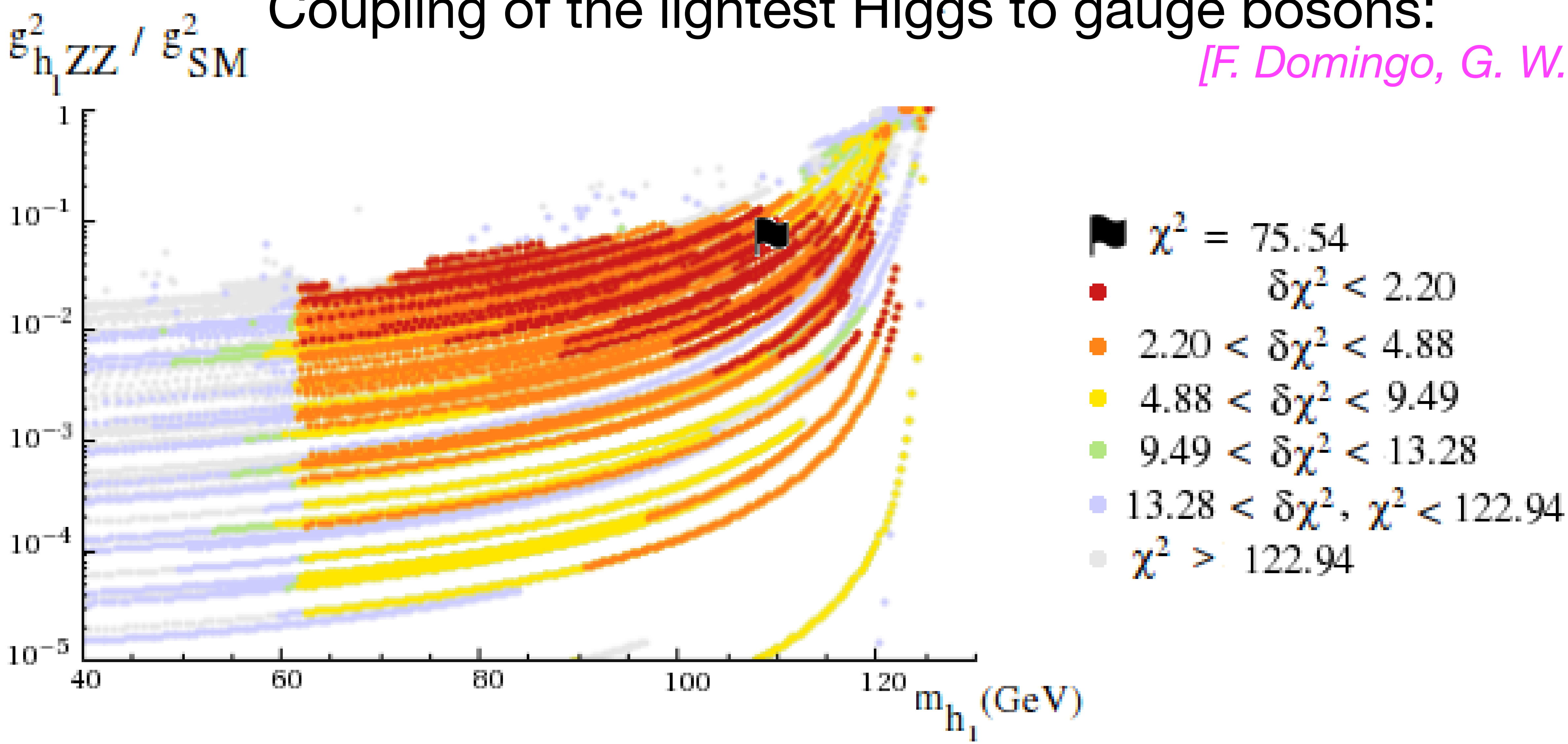
⇒ Variation of λ leads to cross-over behaviour between doublet-like and singlet-like state

⇒ 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

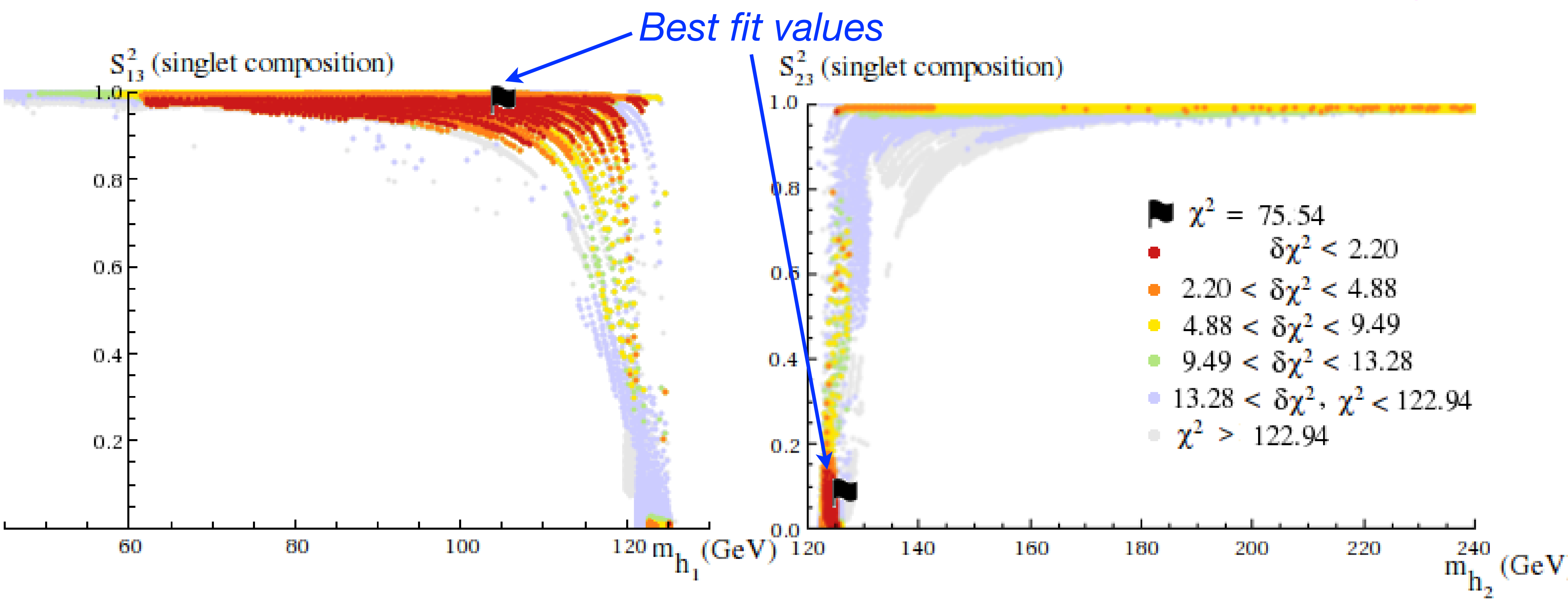
The case where the signal at 125 GeV is not the lightest Higgs arises generically if the Higgs singlet is light

⇒ 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

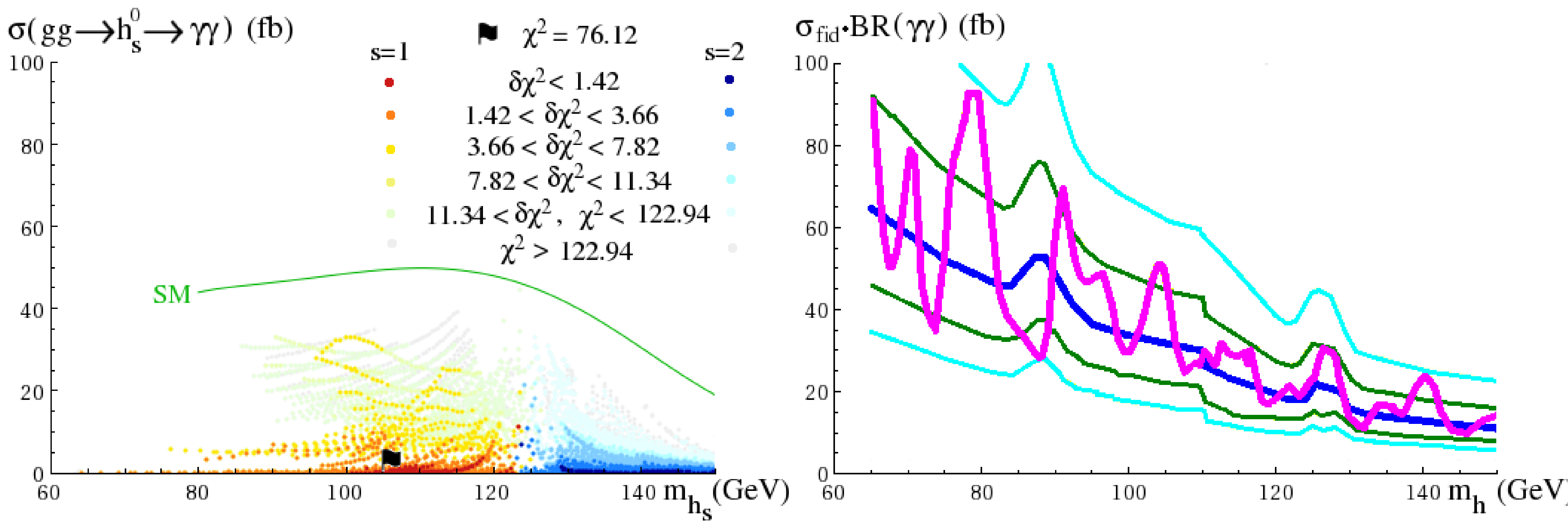
[F. Domingo, G. W. '15]



⇒ 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