Status and Prospects of e+e- Linear Collider Projects

Sabine Riemann, DESY

Matter to the Deepest, Ustron, 15 Sept 2015

LCWS 2013, Tokyo

LINEAR COLLIDER COLLABORATION

HELMHOLTZ GEMEINSCHAFT

DESY

Outline

- Future e+e- collider projects
- Topics from physics programme
- Towards the realization of the International Linear Collider project
- Summary

Future e+e- linear collider projects

International Linear Collider ILC

E_{cm}: 250GeV – 500GeV, 1TeV, 91GeV
L ≈ $2\times10^{34}cm^{-2}s^{-1}$ (~few $100fb^{-1}$/year)
Beam polarization:

e- beam P = 80-90%
e+ beam P = 30% baseline; 60% upgrade

→ Stat. uncertainty ~ $10^{-3}\ldots10^{-2}$

- Superconducting cavities
- Gradient 31 – 40MV/m, → length 31 km
- Power consumption
  - ≤200MW (≤500GeV)
  - 300MW (1TeV)
- **technology at hand**, prototype=European XFEL
- ILC realization in Japan??

Compact Linear Collider CLIC

E_{cm}: 350GeV – 3TeV
L ≈ $2\times10^{34}cm^{-2}s^{-1}$ (~few $100fb^{-1}$/year)
Beam polarization:

e- beam P = 80-90%
e+ beam unpolarized; pol upgrade if required

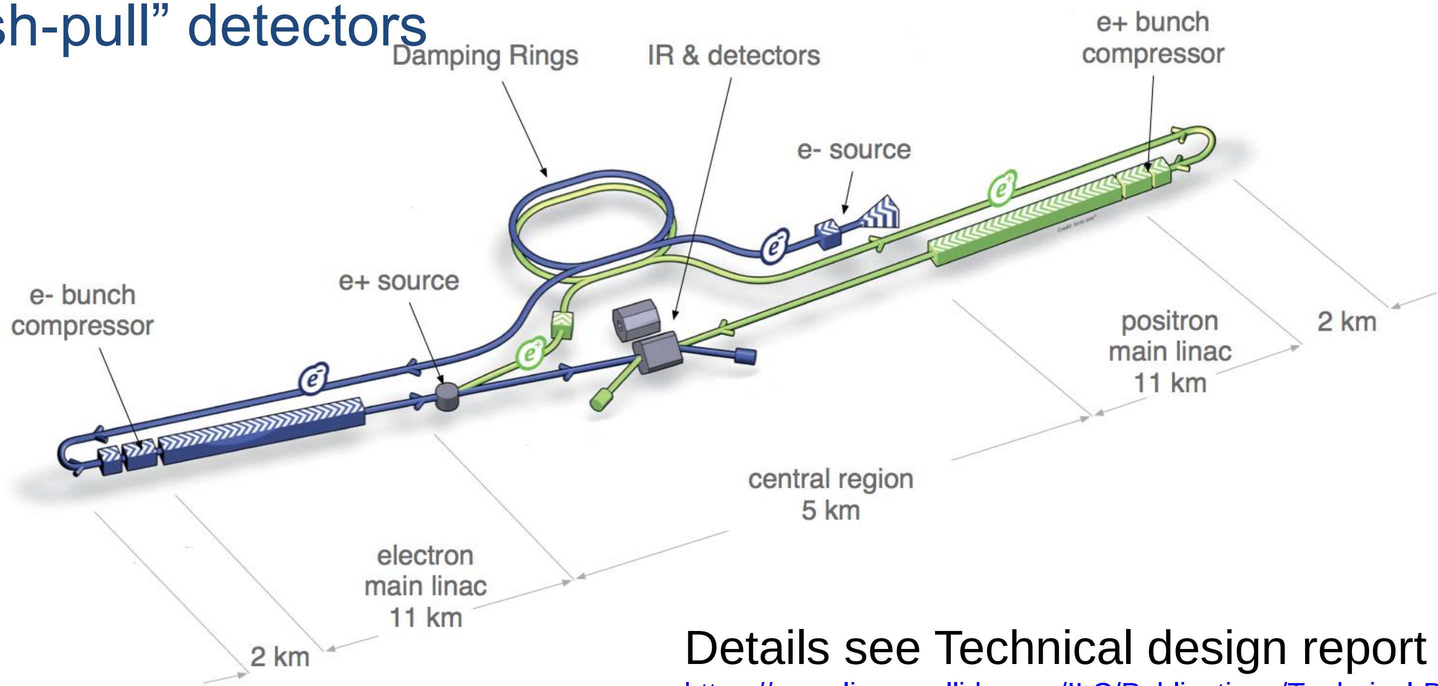
→ Stat. uncertainty ~ $10^{-3}\ldots10^{-2}$

- Two-beam acceleration, normal conducting accelerating structures
- Gradient 100MV/m, → length 40-50km
- Power consumption ≤580MW (3TeV)
- technology under development

Linear collider Collaboration (LCC) brings together ILC and CLIC to advance the global R&D work for accelerators and detectors and physics studies

Layout of the ILC

- E_{cm} adjustable from ~250 – 500 GeV (upgradeable to 1TeV):
- Polarized electron source P > 80%
- (Polarized) positron source (P > 30%)
- Two damping rings
- Main linacs: 16 000 superconducting cavities (Nb), 2000 cryomodules, total length 31km
- 2 “push-pull” detectors



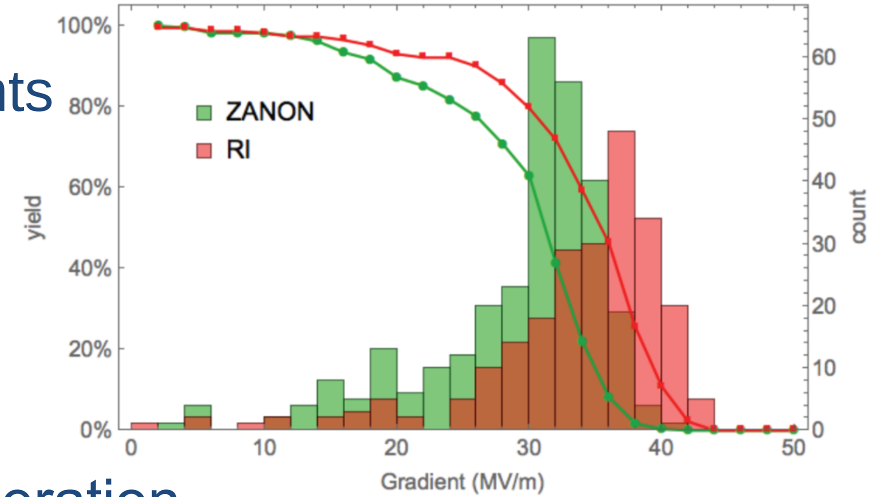
Details see Technical design report (TDR)
https://www.linearcollider.org/ILC/Publications/Technical-Design-Report

ILC specification

High energy

- Acceleration gradient achievements (European XFEL):
  - average gradient: 31.5 MV/m
  - 35 MV/m for individual cavities

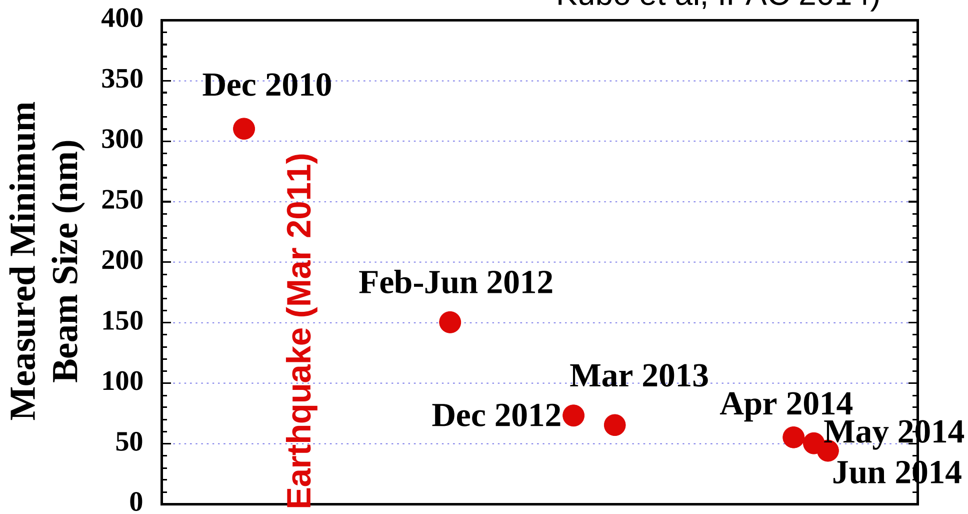
N. Walker et al, LLC-PAC meeting, 13.4. 2015)



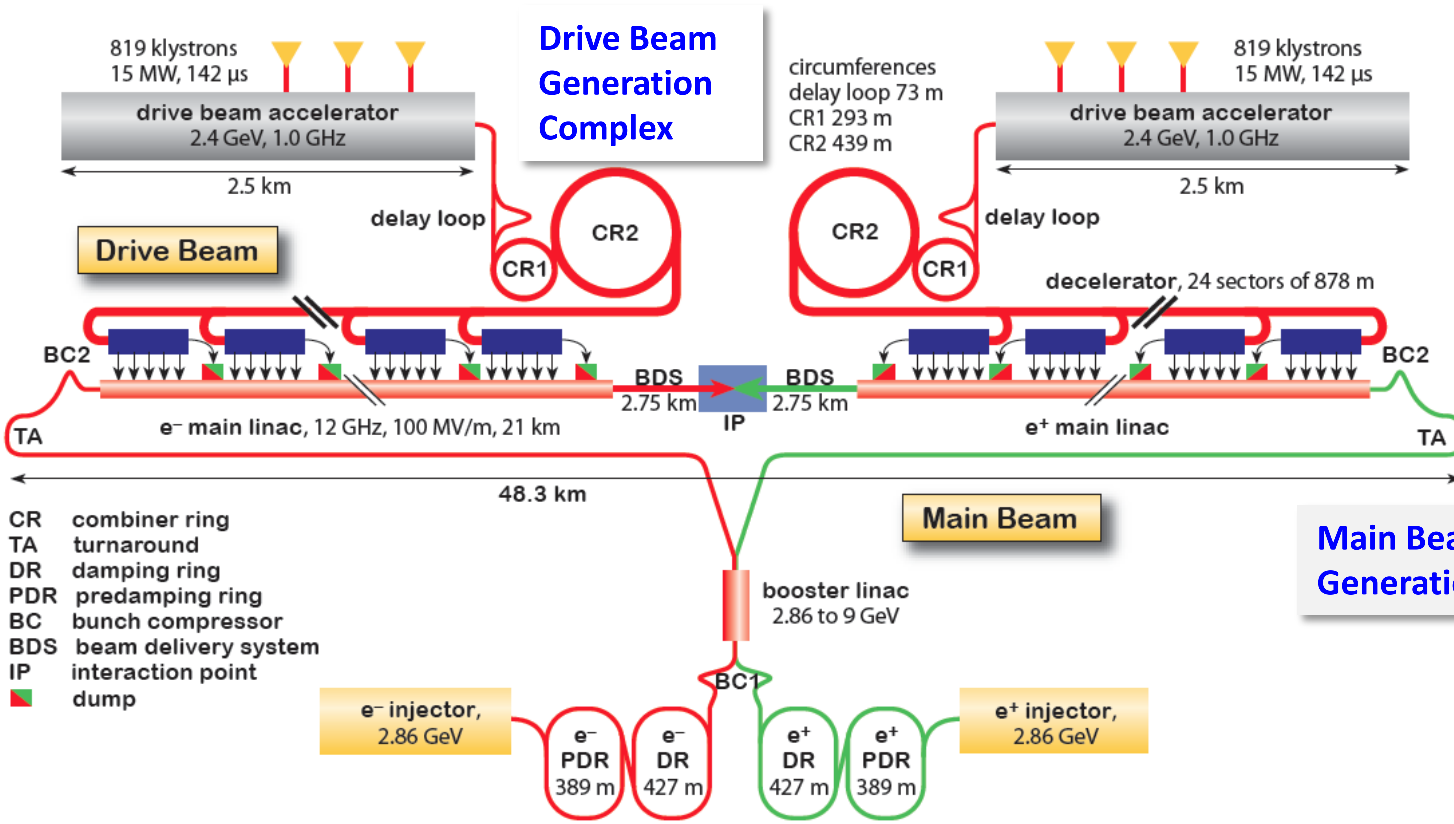
High luminosity

- Linear collider ⇔ 'one-way' acceleration
- High luminosity achieved with small beams; $L \sim 1/(\sigma_x \sigma_x)$
  - Beam cross section at ILC collisions (TDR):
    - σ_x = 470nm;
    - σ_y = 7nm
  - Achieved at ATF2 test area:
    - σ = 44nm (Goal σ = 37nm, corresponds to ~6nm at ILC)

Kubo et al, IPAC 2014)



CLIC layout (3 TeV)

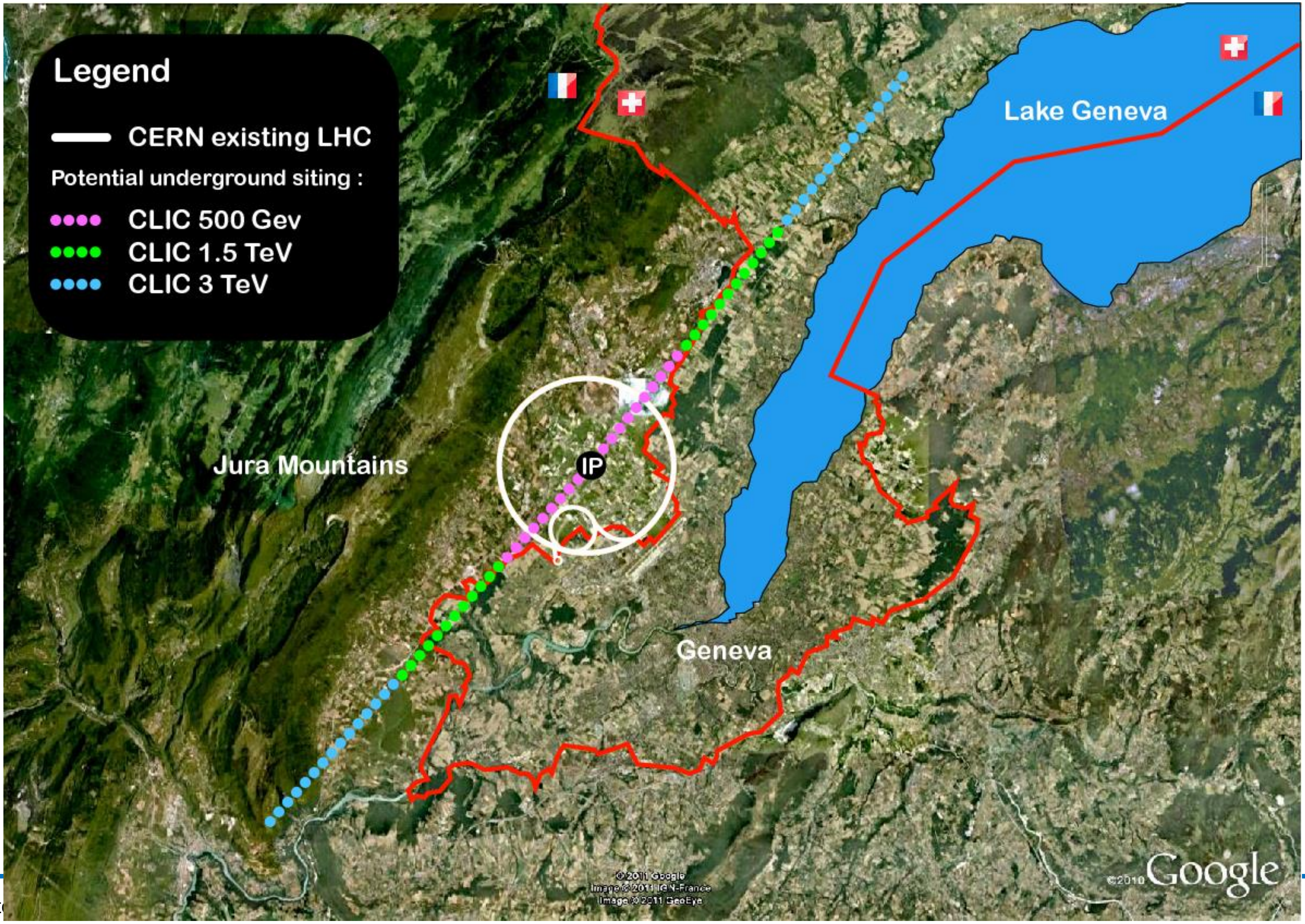


Main Beam
Generation Complex

CLIC is a possible LHC successor at CERN

- 2013-18 Development Phase
  - Project Plan (⇔ LHC results); R&D for accelerator and detectors are ongoing
- 2018-19 Decisions about next project(s) at the Energy Frontier

CLIC site

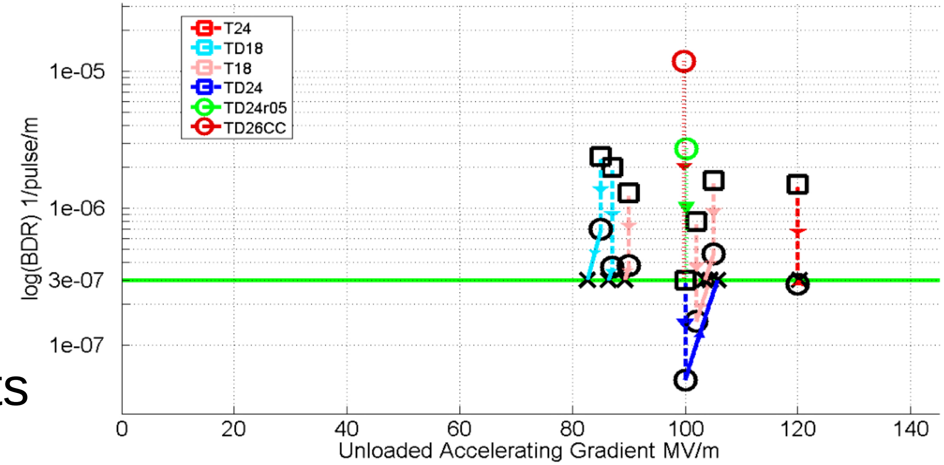


Legend
CERN existing LHC
Potential underground siting :
CLIC 500 Gev
CLIC 1.5 TeV
CLIC 3 TeV
Lake Geneva
Jura Mountains
IP
Geneva
©2011 Google
Image © 2011 IGN-France
Image © 2011 GeoEye
©2010 Google

CLIC status

- ‘rebaselining’ of machine parameters (cost, power consumption, energy stages as needed for Higgs and top measurements) is now being completed

- Demonstrated:
  - accelerating structure can reach a gradient of **105 MV/m** at a pulse length of 240ns and a low breakdown rate (BDR) in separate high-power tests



- complete 2m CLIC module has been installed CLIC Test Facility (CTF3) and is under test

- rapidly increasing interest in the CLIC technology, e.g. for use in linacs for Free Electron Lasers

Physics at high-energy e^+e^- linear colliders

Each future e+e- collider needs its own strong physics case

- So far: discovery of a SM-like Higgs boson coupled with the absence of other phenomena .
  - Are these 'new' phenomena to be found at higher energies, or have they escaped detection because of very small couplings?
- What would a LC add to the LHC results?
  - Precision , model-independence of analyses
  - Discovery

Does the expected physics goal justify costs and effort?

- Physics program (main topics)
  - Higgs boson
  - W, Z boson physics
  - Top quark
  - Beyond the Standard Model

Details see also in: ILC Technical Report, CLIC Conceptual Design Report, TESLA TDR, Snowmass study 2013, Fuji et al., arXiv:1506.05992, Barklow et al., arXiv:1506.07830, and reference therein

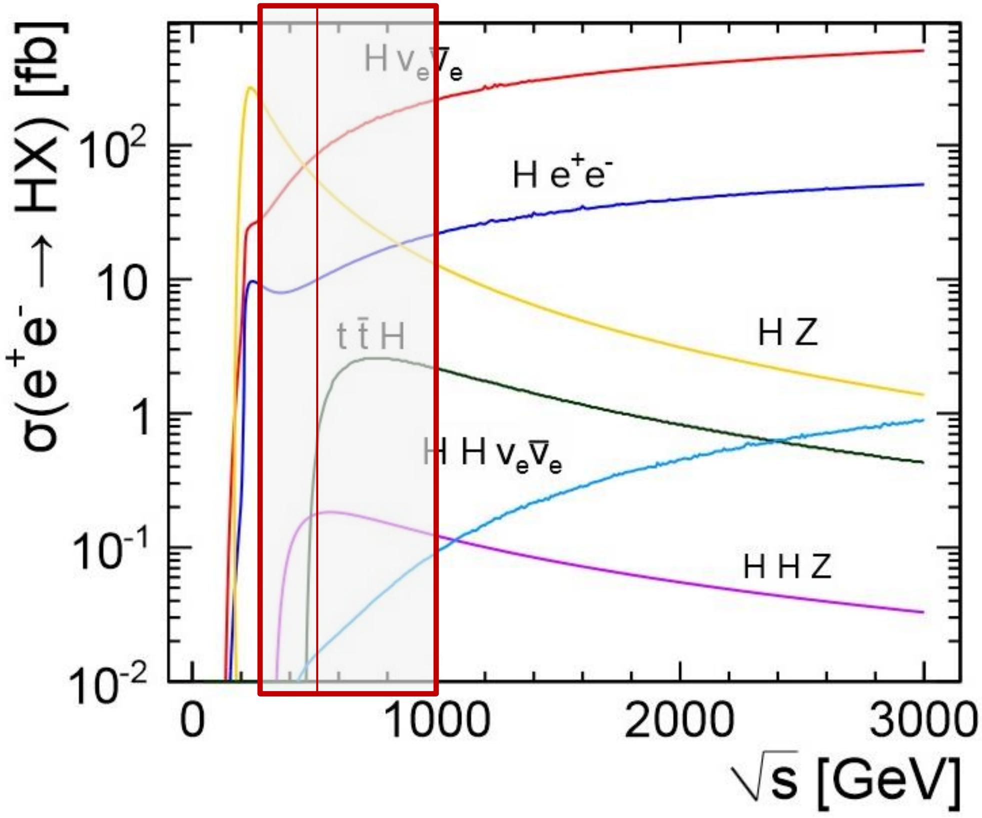
Key physics explorations at high-energy e+e- colliders

Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings
	$e^+e^- \to WW$	precision W couplings
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top
	$e^+e^- \to Zhh$	Higgs self-coupling
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry

e+e- LC: Higgs factory

Higgs within achievable accuracy at LHC: SM-like

- Could be the only SM Higgs
- Could be a SUSY Higgs (one has to be close to a SM-like one)
- Could be a composite state

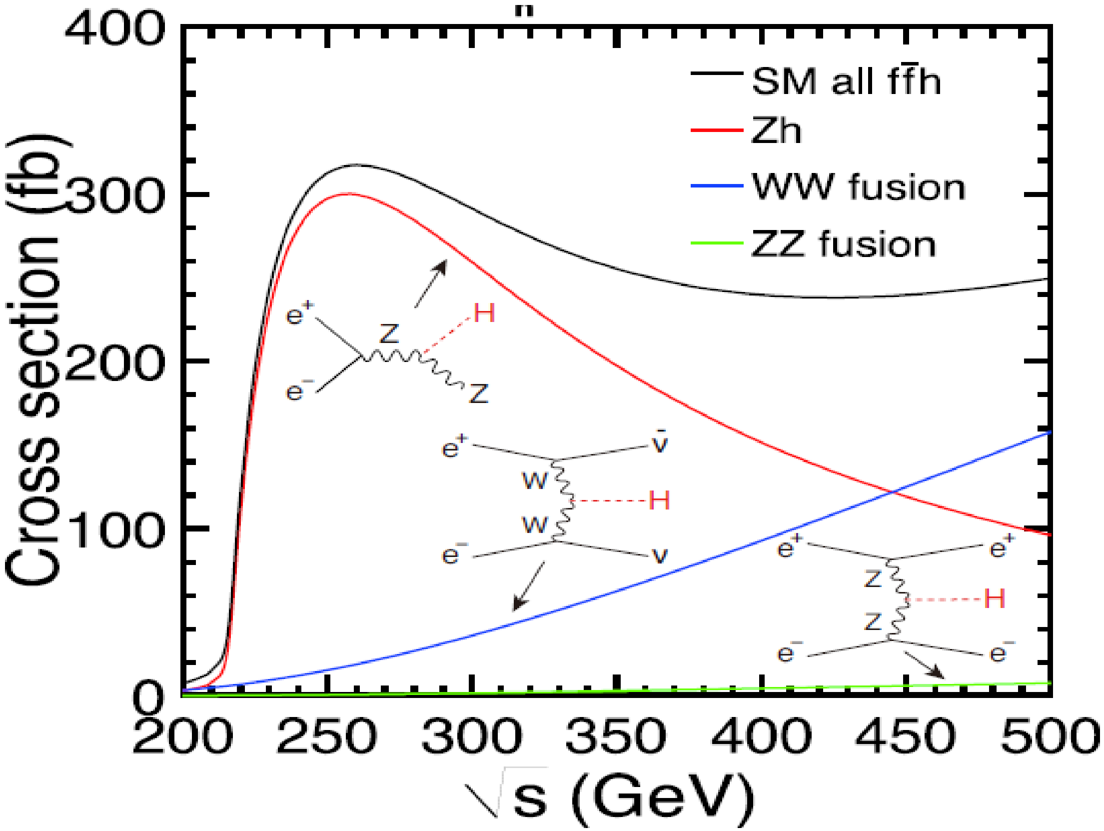


P(e+,e-) = (0,0)

e+e- ILC: Higgs factory

Higgs within achievable accuracy at LHC: SM-like

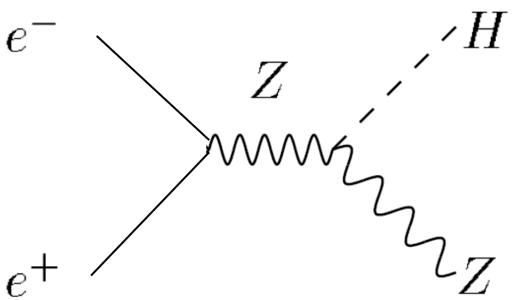
- Could be the only SM Higgs
- Could be a SUSY Higgs (one has to be close to a SM-like one)
- Could be a composite state



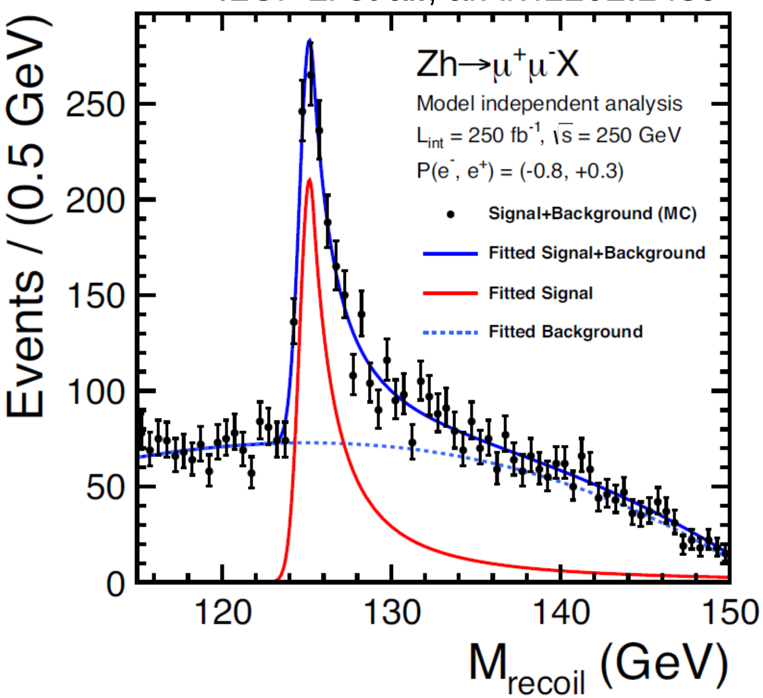
P(e+,e-) = (-80%,+30%)

Higgsstrahlung: Coupling to the Z boson

arXiv:1506.05992



ILC: Li et al., arXiv:1202.1439



e+e- → ZH

- Reconstruct Z in lepton and quark channels
- Higgs becomes visible in the mass spectrum recoiling against the Z boson

$$M^2_{recoil} = \left(p_{e+e-} - p_Z\right)^2$$

→ Higgs mass and coupling:

(without reconstructing H)

Peak position ⇔ H mass, $\Delta m_h < 30$ MeV

Peak height ⇔ $\sigma_{HZZ} \sim g_{HZZ}^2$

→ Model-independent measurement of HZZ coupling

$\Delta g_{HZZ}/g_{HZZ} \approx 0.6\%$ (ILC 500)

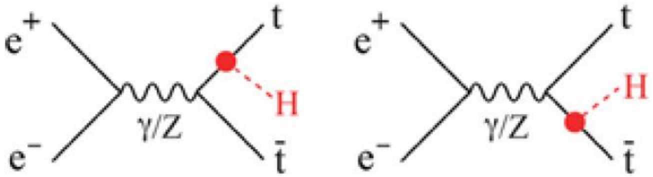
$\approx 0.3\%$ (ILC500 high L)

Top-quark Yukawa coupling

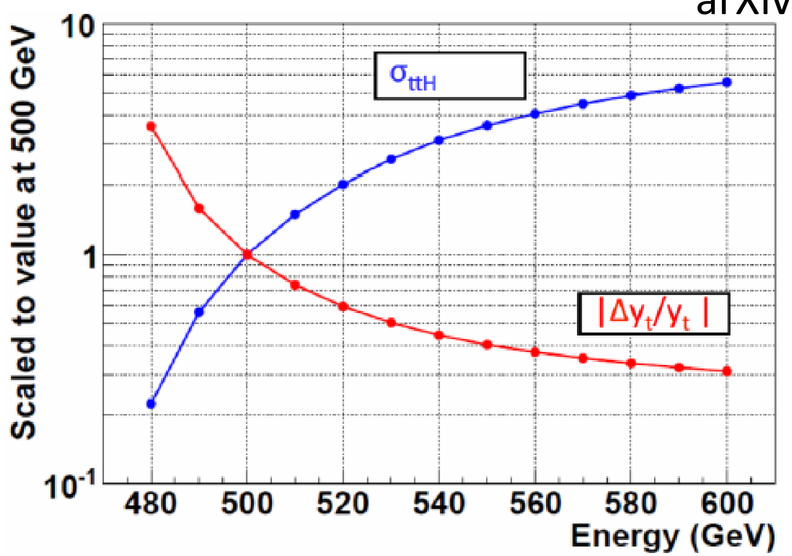
- Strongest coupling to Higgs boson
- g_{Htt} is sensitive to unexpected effects
- Should be measured model-independent

$e^+e^- \rightarrow Htt$

$H \rightarrow bb$



arXiv:1506.07830, Duerig EPS2015



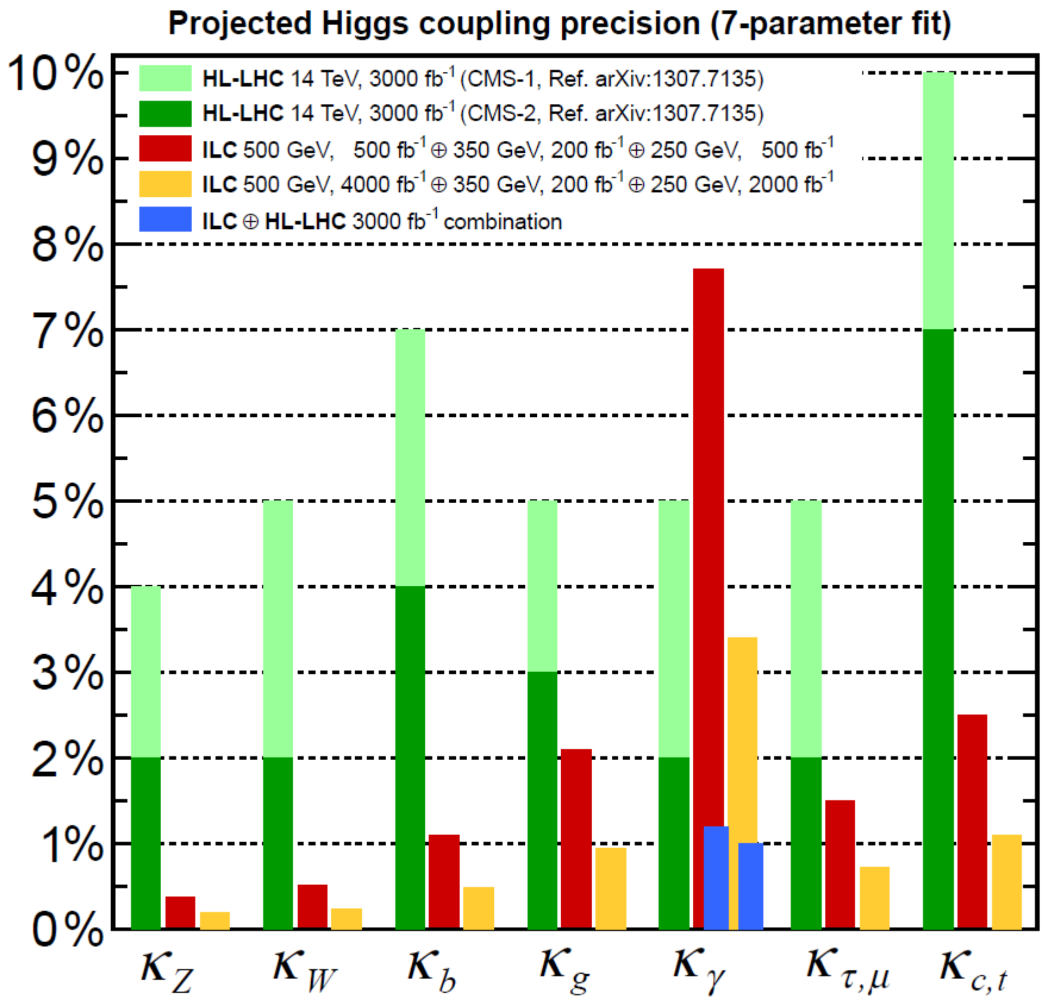
σ_{tt} and relative precision of top Yukawa coupling

$\Delta g_{Htt}/g_{Htt}$	ILC 500 GeV	ILC 500GeV, Lumi upgrade
500GeV	18%	6.3%
550GeV	~9%	~3%

Increase √s by 10% → precision improves by factor 2 for same integrated luminosity

Precision of Higgs boson coupling

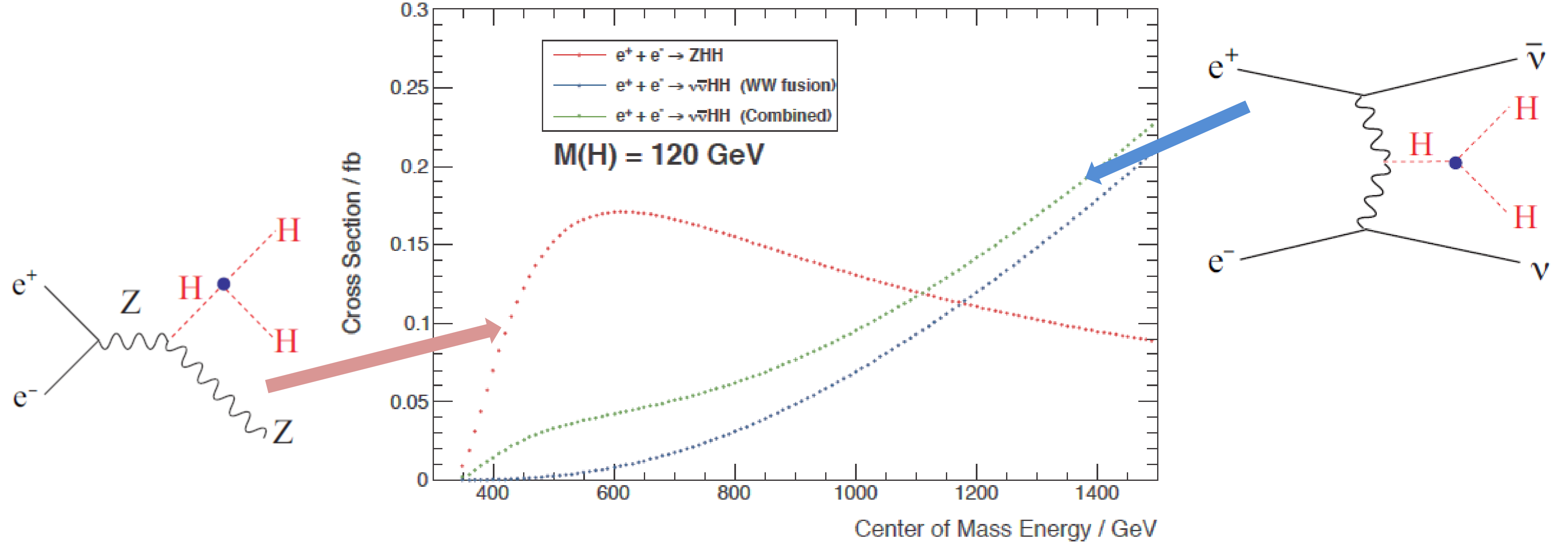
arXiv:1506.05992



Shown is the relative precision; $\kappa_A = \frac{g_{A\bar{A}h}}{g^{SM}_{A\bar{A}h}}$

Trilinear Higgs coupling

arXiv:1506.05992



- Higgs self coupling is important for establishing Higgs mechanism
- Also at LC very challenging due to small rates ~0.2fb and huge background
- Full ILC data set (500GeV) → precision of 27% can be achieved
  - This would already be more than 3σ evidence for the existence of the Higgs self-coupling at the Standard Model value
- Upgrade to 1TeV: ~16% for 2000fb^{-1} and 10% for 5000fb^{-1}

Top quark

The top quark mass is a basic input parameter for the Standard Model.

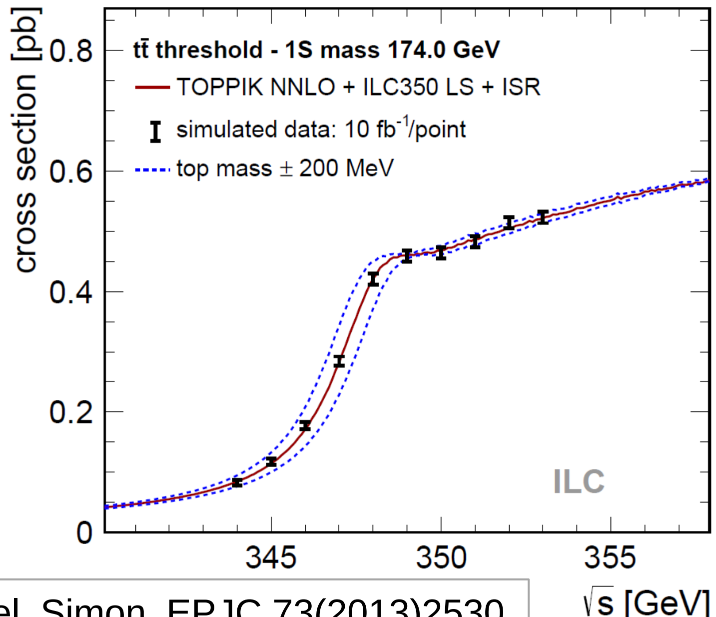
- For example, Δm_t = 600MeV corresponds to Δm_W = 5MeV for the prediction of m_W
- At the ILC, we expect to measure m_W to a few MeV ⬄ sensitivity to loop corrections from a variety of new particles

So far, top quark has been directly studied at hadron colliders

<u>ILC: ttbar threshold scan</u>

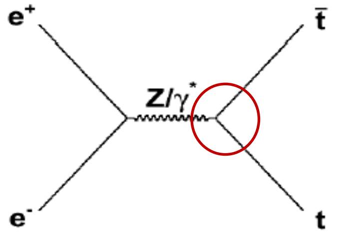
- The real part of the pole corresponding to the 1S bound state can be extracted from threshold measurements
- This mass parameter can be determined to about 50 MeV
  The accuracy is limited by the precision of the theoretical prediction of the threshold shape
- Expect for the 200 fb^{-1} data at ~350 GeV: (Barklow et al, arXiv:1506.07830)

  statistical errors (3-parameter fit)
  - 17 MeV for m_t,
  - 26 MeV for Γ_t



Seidel, Simon, EPJC 73(2013)2530

Electromagn. and weak top quark coupling

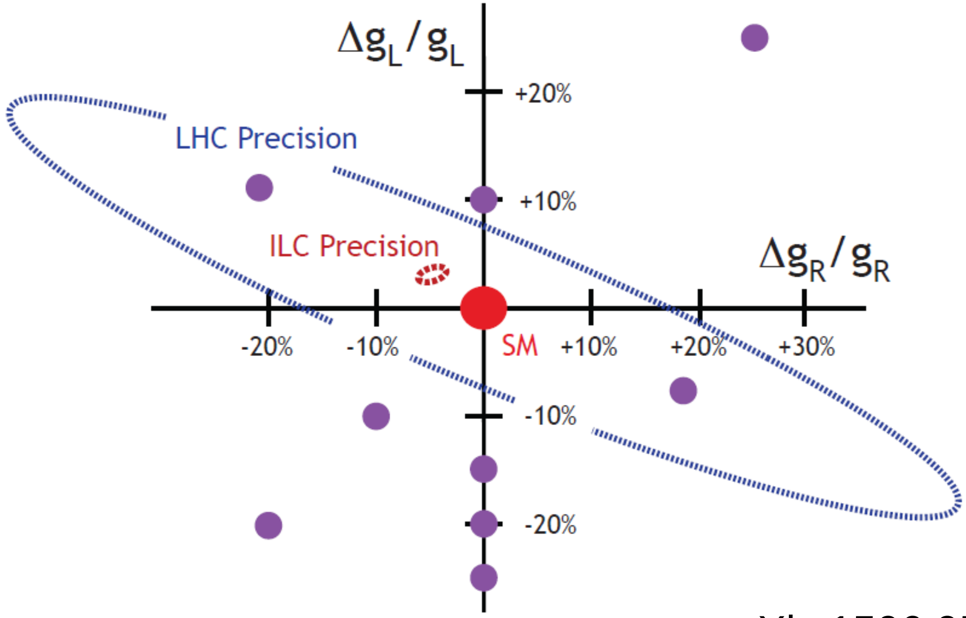


- Polarized e- and e+ beam, measure forward-backward asymmetry for 2 beam polarizations

→ measurement of left- and right-handed top coupling to γ and Z

Top coupling is sensitive to new physics:

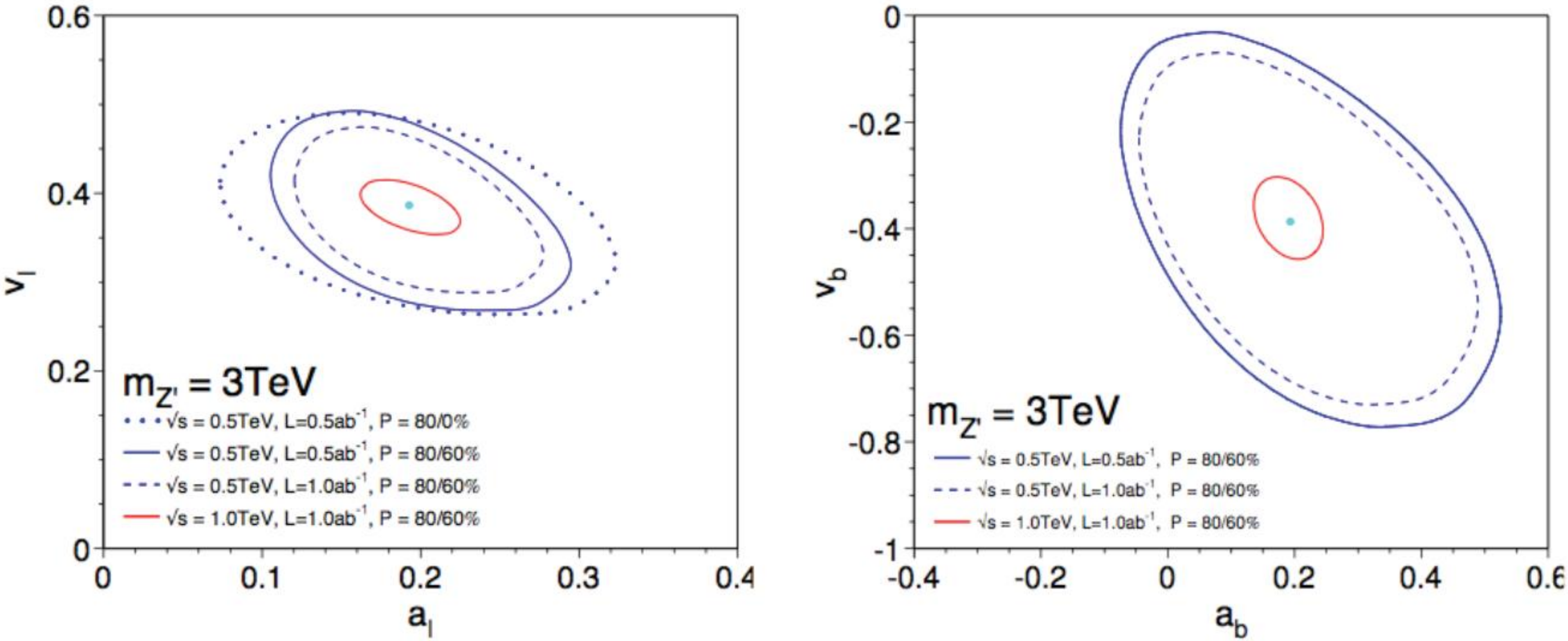
Comparison of g_L, g_R (SM) with composite Higgs models



arXiv:1506.05992

Physics beyond the SM

- Precision measurements allow indirect search for new phenomena, even beyond the LHC reach
- Deviations from SM → interpretation and disentangling of new physics models



Z’ vector and axial vector couplings to leptons and b quarks from fermion-pair production (χ model reproduced in a model-pendent fit)

Towards the ‘realization’ of the International Linear Collider project

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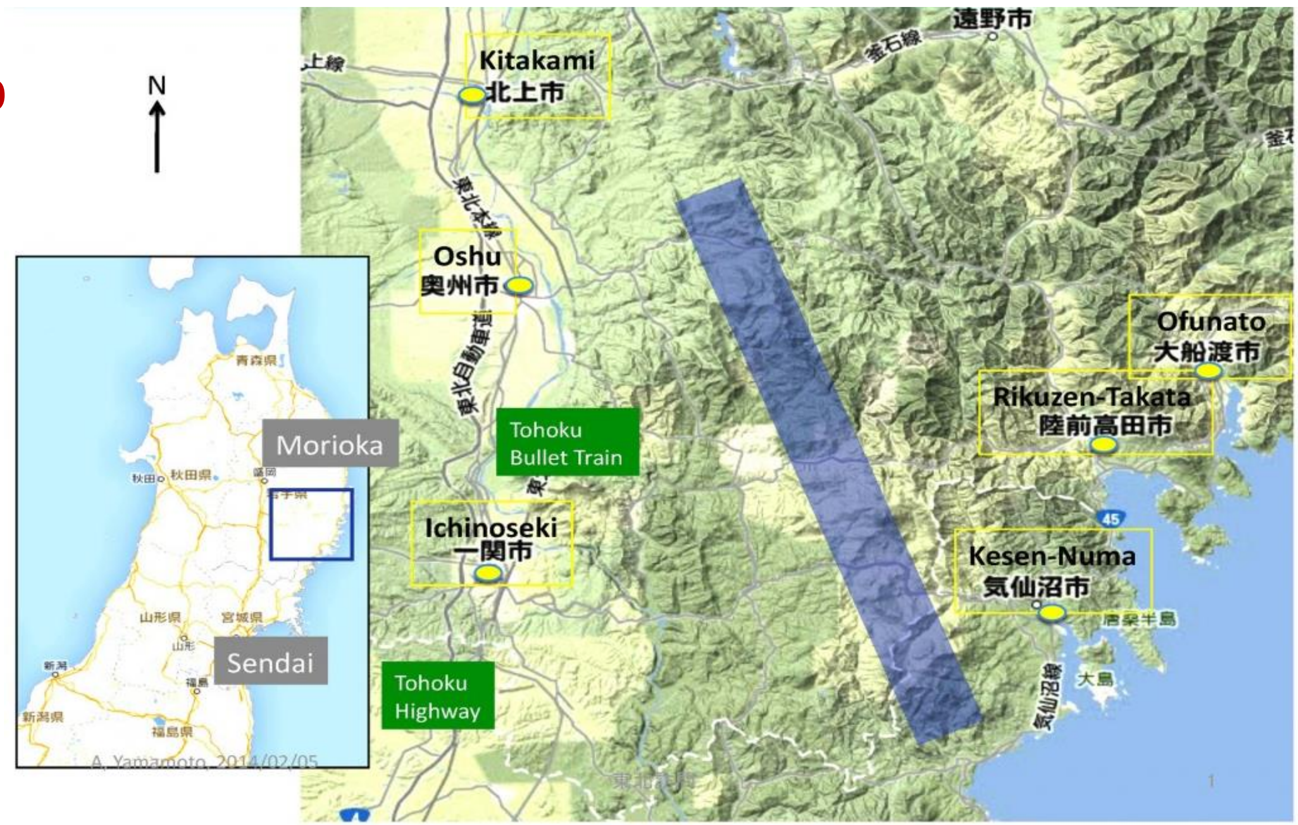
ILC candidate site: Kitakami, Japan

The ILC is basically ready for construction; the scientific community in Asia, the Americas and Europe feature it on their strategies for future facilities

- within the next few years governments will have to decide whether to go ahead and build the ILC or not.
- Japan shows great interest to host the ILC:



Interims Report of the ILC Advisory Panel

MEXT (Ministry of education, culture, sports, science and technology, Japan) established an expert committee of scientists from different areas (ILC Advisory Panel) to review:

- Physics case
- Validation of the Technical Design
- The costs
- International Collaboration
- Social effects of the ILC Project, economic effects, industrial spin-off
- Can Japan do it?

Final report is expected for spring 2016; an interim report of the scientific case was published in August 2015.

No ILC scientists belong to this panel.

S. Komamiya explained the Interims Report at LP2015 and at http://newsline.linearcollider.org/2015/09/03/the-summary-report-explained/

Recommendations + comments/homework

1. Huge investments must be weighted based on the scientific merit of the project
   - Clear vision on the discovery potential of new particles as well as that of precision measurements of the Higgs boson and the top quark has to be shown

Discovery is not guaranteed but the clear vision of the potential will be better pointed out

2. Specifications of the ILC Physics case are based also on the LHC results expected until end of 2017.
   - So it is necessary to monitor and examine the LHC results.
   - It is also necessary to clarify how to solve technical issues and how to mitigate cost risk
   - LHC results will be monitored
   - Recent ILC Progress Report answers most technical items http://slac.stanford.edu/pubs/slacreports/reports21/slac-r-1056.pdf,
   - MEXT is contacting governments during the LHC 13TeV run

3. It is important to have general understanding on the project by the public and science communities

PR will be reinforced; discussions with scientists of other fields have been undertaken

Timeline for the ILC project

S. Komamiya at LP2015

- 2013: Technical Design Report (accelerator, physics, detector)
- Official investigation and review of the ILC project by MEXT (ongoing)
- Contacts and discussion between to governments have been started
- 'green sign' from Japanese government → Negotiation of sharing
- International agreement, approval

Time estimate to construct and operate the ILC

Year 1-2 preparation, continue high-tech R&D

3-6 preparation of the ILC construction (with real budget)

7-15 construction

-12 start installation

-13 start of accelerator test (step-by-step)

16 Beam commissioning

17 Start physics run

25 Luminosity upgrade

TBD energy upgrade to ~1TeV

Summary

- e+e- linear colliders at the energy frontier are under study since long times
- Strong physics case for a e+e- linear collider exists
- The discovery of the Higgs boson and the necessity to understand this particle has sharpened the case for a new e+e- machine
- Linear colliders have the advantage of energy flexibility
- Projects: ILC and CLIC
- For the ILC a design exists that is ready to build
- Japan has expressed interest in hosting the ILC, Kitakami has been selected as candidate site
- The political process has started
- The next 2 years will be decisive…..

Backup

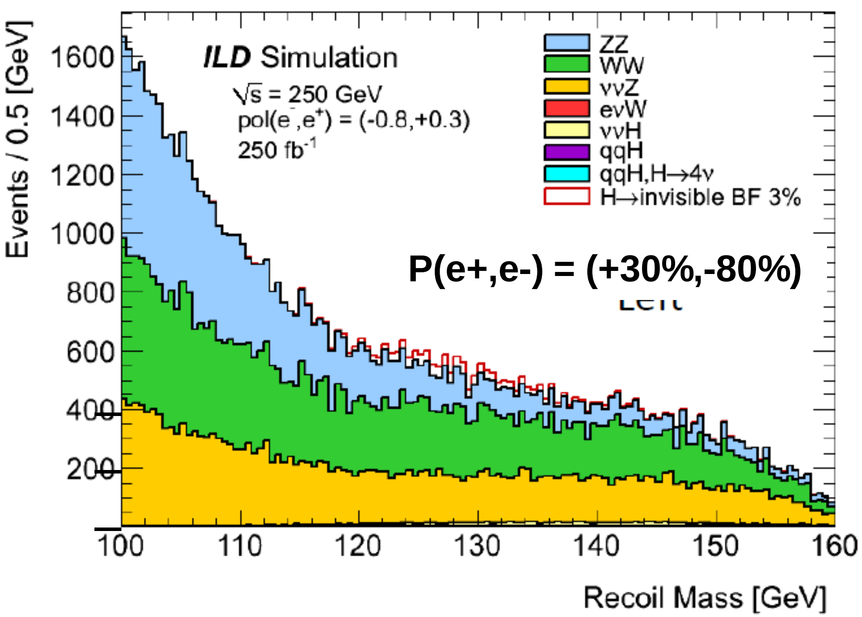
Invisible Higgs decay

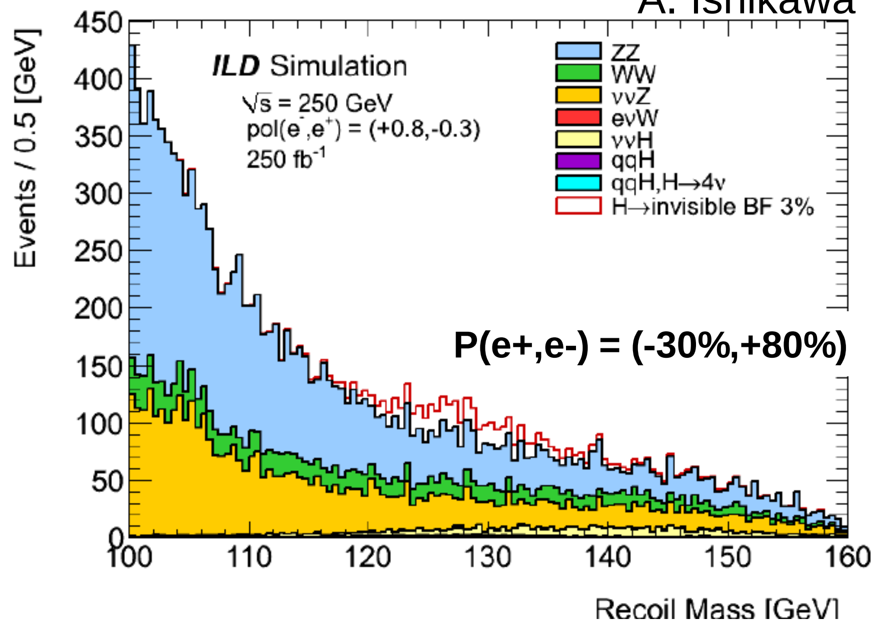
arXiv:1506.05992

Invisible Higgs decay in the SM, H → ZZ* → 4ν, has small branching fraction ~0.1%

- sizable invisible Higgs decay is a new physics signal (dark matter candidates)
- search for invisible H decays using a recoil mass technique ⇔ model independent way!
  - Invisible Higgs width can be measured at ILC with ~1% accuracy
  - invisible H decay with Br(H→invisible) ~ 3% can clearly be seen
- LHC: limit for invisible H decay is O(10%).

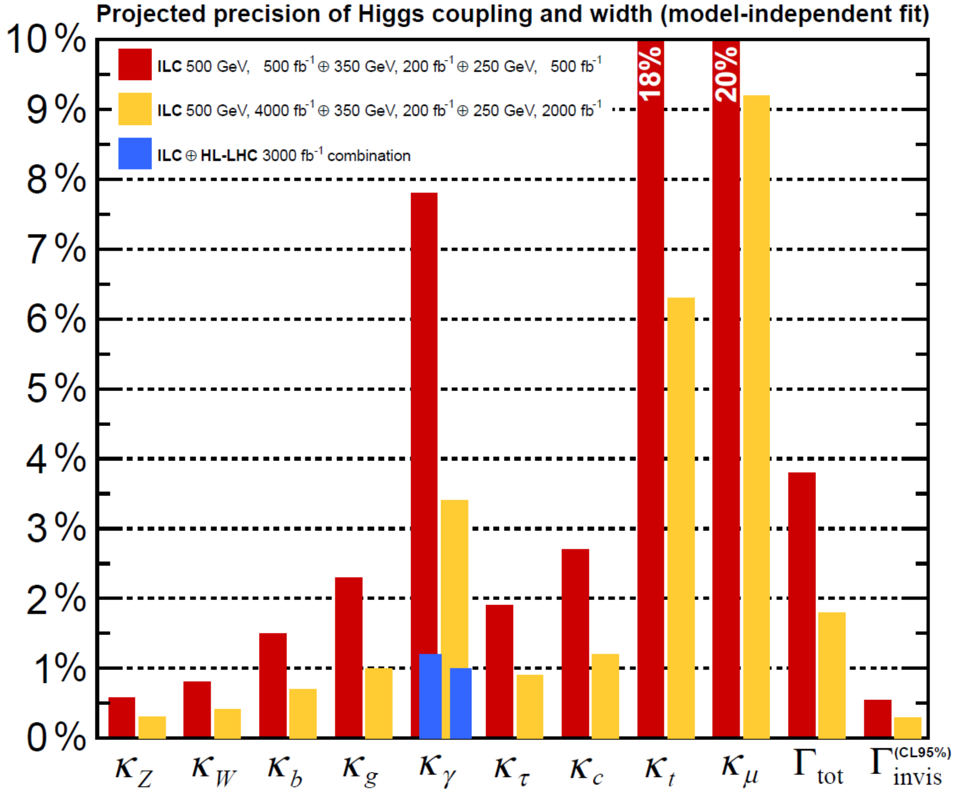
A. Ishikawa

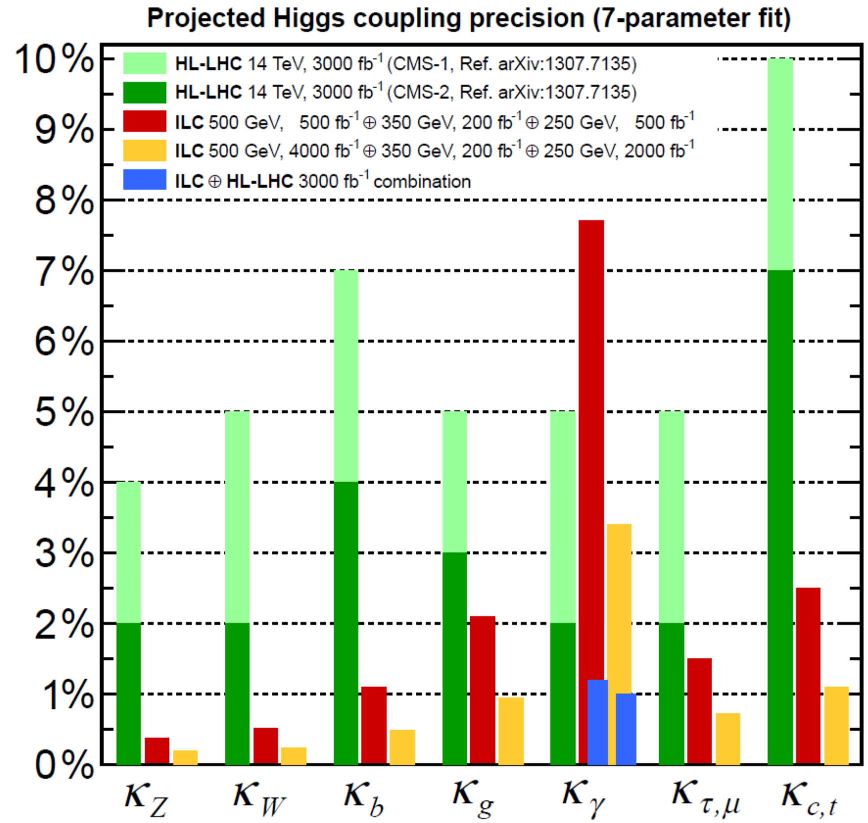




Precision of Higgs boson coupling

arXiv:1506.05992

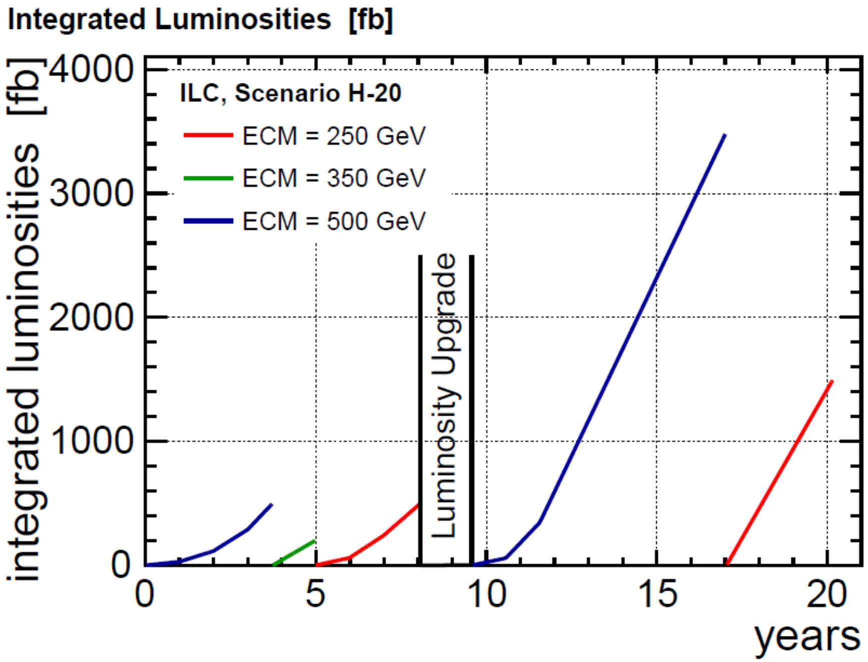




Shown is the relative precision; $\kappa_A = \frac{g_{A\bar{A}h}}{g^{SM}_{A\bar{A}h}}$

Possible running scenario with ILC

- Running time based on 20 years physics data, lumi upgrade included after 8 (10) years
- •Specific lumi fraction on √s=250, 350 and 500 GeV



- Most popular 'H-20': 6200 fb-1 (2032, >2040 HL-ILC, until 2052)

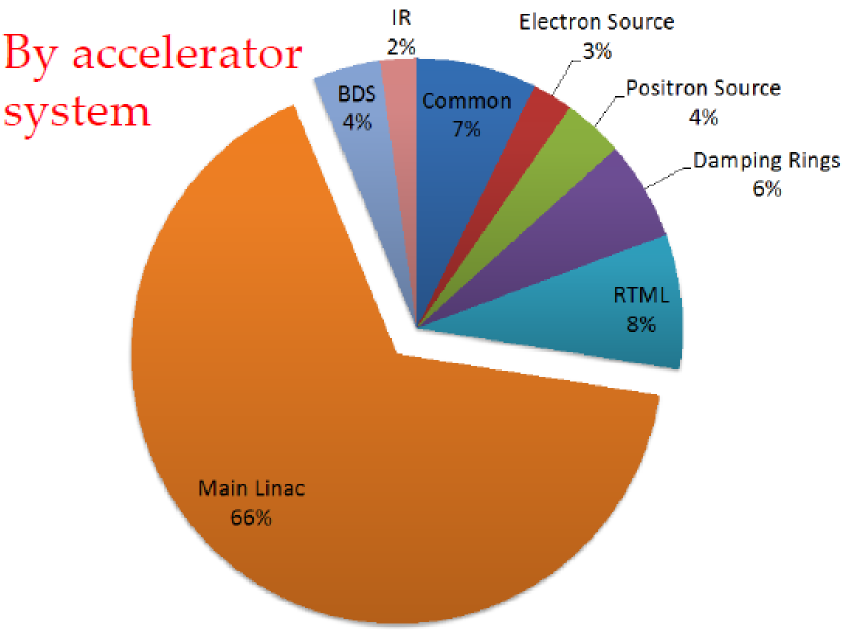
- Prospects LHC:
  - 300 fb-1 in 2023
  - HL-LHC: 3000 fb-1 in 2037 (start HL-LHC: 2027)

ILC costs

Accelerator

http://www.linearcollider.org/pdf/ILC%20TDR%20value%20estimate_final.pdf

- Costs for the construction of the ILC (500GeV):
  7.8 billion ILCU
  + 23 million person hours
  (≈13,000person years)



- The variance among estimates for sites in Europe, Americas, As is about 2%.

Detectors (ILD, SiD)

http://edmsdirect.desy.de/edmsdirect/file.jsp?edmsid=D00000001021135&fileClass=native

- 315 - 440 billion ILCU +1.3 million person-hours for each detector

Necessary steps and time line for the ILC project

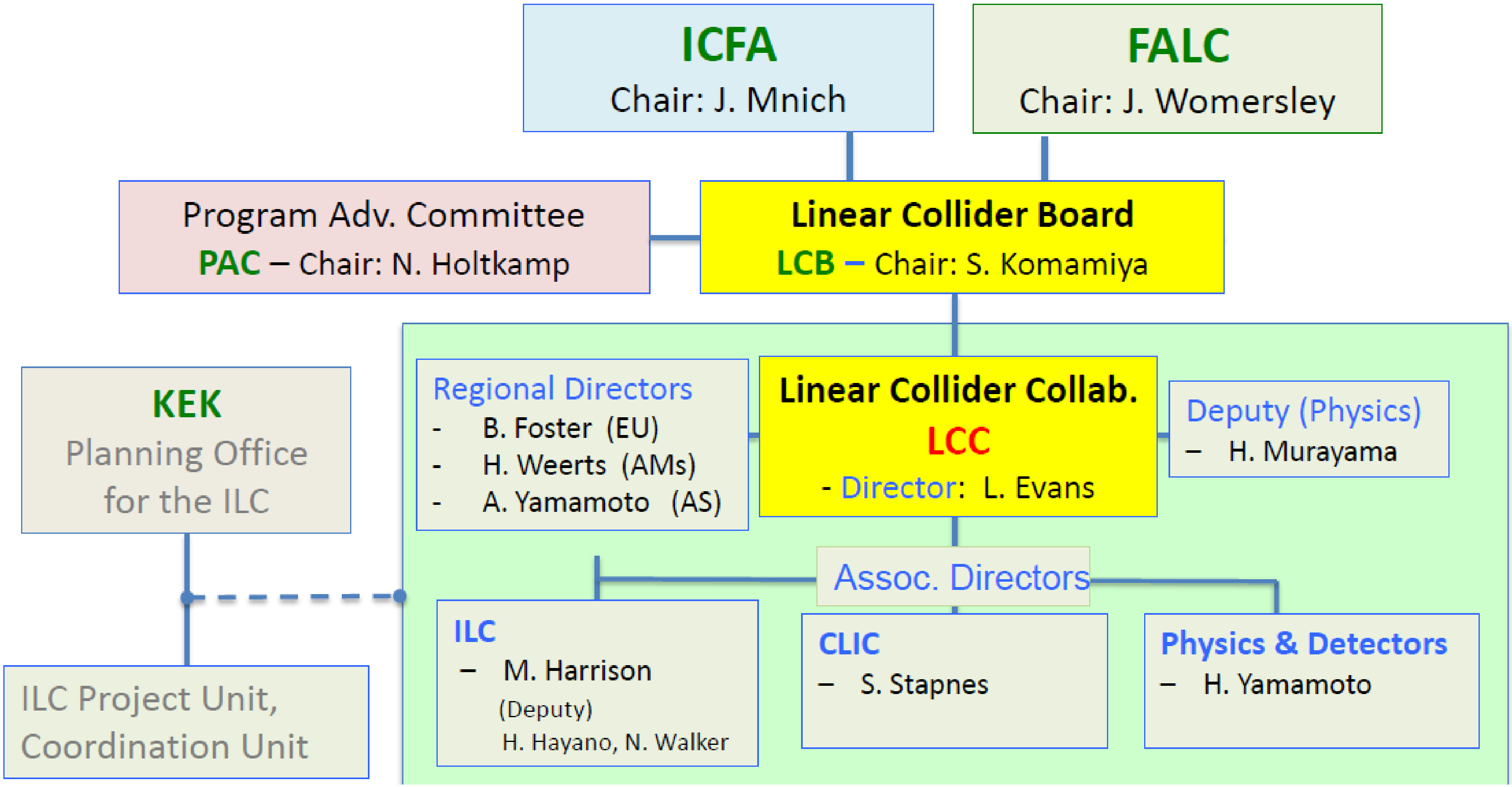
S. Komamiya at LP2015

Necessary steps

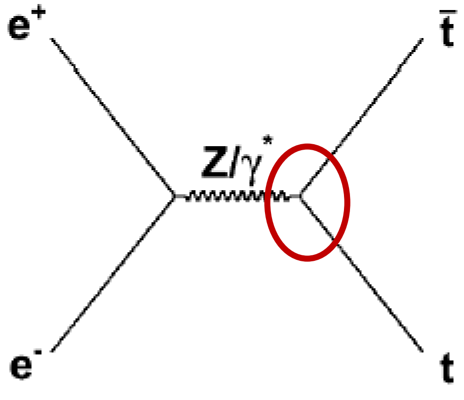
1. Technology Choice (2003)
2. R&D and design of the machine/detectors by the international team
   ⇒ Technical Design Report (2013)
3. Official investigation and reviews of the ILC project by MEXT (now)
4. Government-to-government discussion has been started (now)
5. Green sign from the Japanese government ⇒ negotiation of the sharing
6. International agreement ⇒ International approval

years	
1-2	Preparation period Continuation of high-tech R&D
3-6	Preparation for the ILC construction (with real budget)
7-15	Construction
12-	Start Installation
13-	Start of step-by-step accelerator test
16-	Beam Commissioning
~17-	Physics Run (500 GeV, 350 GeV, 250 GeV)
~25-	Luminosity upgrade (500 GeV, 250 GeV)
TBD	Energy upgrade (~ 1TeV)

Linear Collider Organization



Top-Quark coupling: ttX



- Idea (Amjad et al.,arXiv:1307.8102):
  - use polarized beams
  - Discriminate top coupling to Z and γ
- ttX vertex :

$$\Gamma_\mu^{t\bar{t}X} = ie\left[\gamma_\mu\left(\tilde{F}_{1V}^X + \gamma_5\tilde{F}_{1A}^X\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\tilde{F}_{2V}^X + \gamma_5\tilde{F}_{2A}^X\right)\right]$$

Form factors and their SM values (Born level):

$$\tilde{F}_{1V}^X = -\left(F_{1V}^X + F_{2V}^X\right) \qquad \tilde{F}_{2V}^X = F_{2V}^X$$

$$F_{1V}^\gamma = -\frac{2}{3} \qquad F_{1V}^Z = -\frac{1}{4s_W c_W}\left(1-\frac{8}{3}s_W^2\right) \qquad F_{2V}^\gamma = Q_t\frac{(g\text{-}2)}{2} \qquad F_{2V}^Z$$

$$\tilde{F}_{1A}^X = -F_{1A}^X \qquad \tilde{F}_{2A}^X = -iF_{2A}^X$$

$$F_{1A}^\gamma = 0 \qquad F_{1A}^Z = \frac{1}{4s_w c_w} \qquad F_{2A}^X \propto d_A^X$$

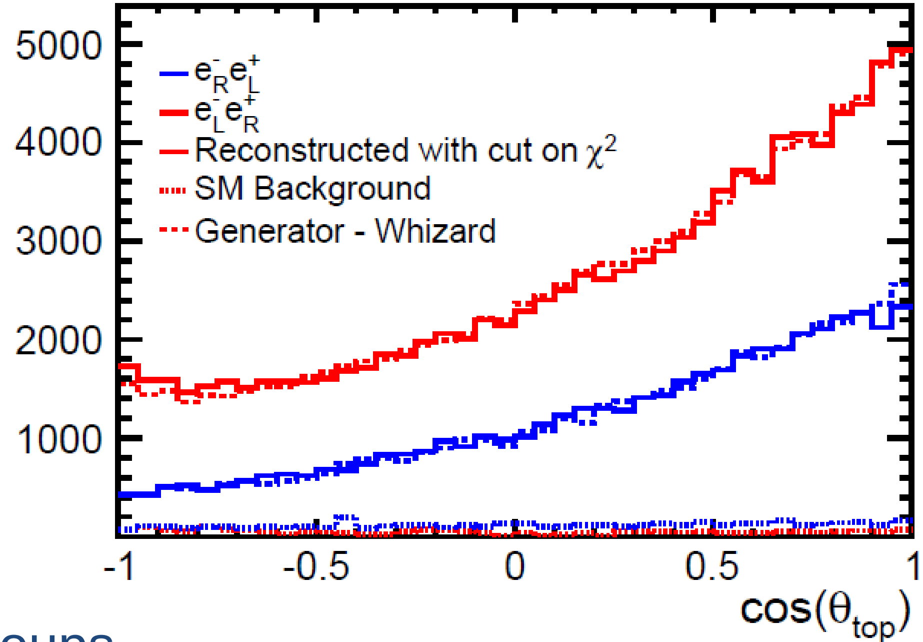
d = dipole moment;
F_{2A} violates CP

Top-quark coupling

- Polarized cross section for tt production

  (polar angle of top from decay products in the hadronic decay branch)

arXiv:1307.8102

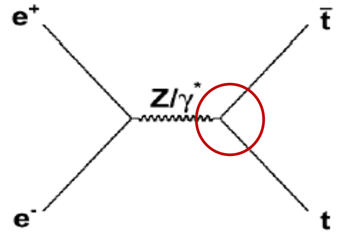


- measure forward-backward asymmetry for 2 beam polarizations
- Extract form factors in groups assuming SM for remaining groups
- Polarization is decisive to distinguish top coupling to Z and γ
- sign of form factors is fixed by γZ interference

Achieved in this study: relative uncertainty of ttX coupling ≤1%

Electroweak top quark coupling

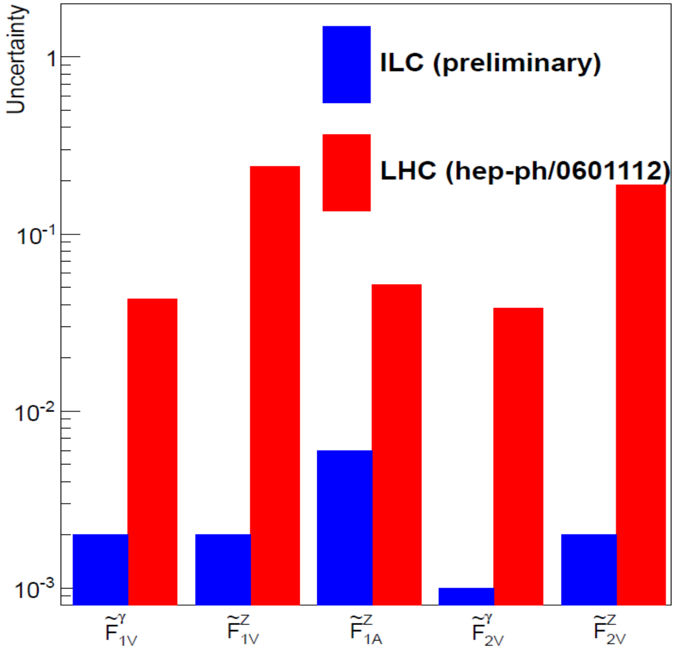
- Polarized e- and e+ beam → measurement of left- and right-handed top coupling to γ and Z

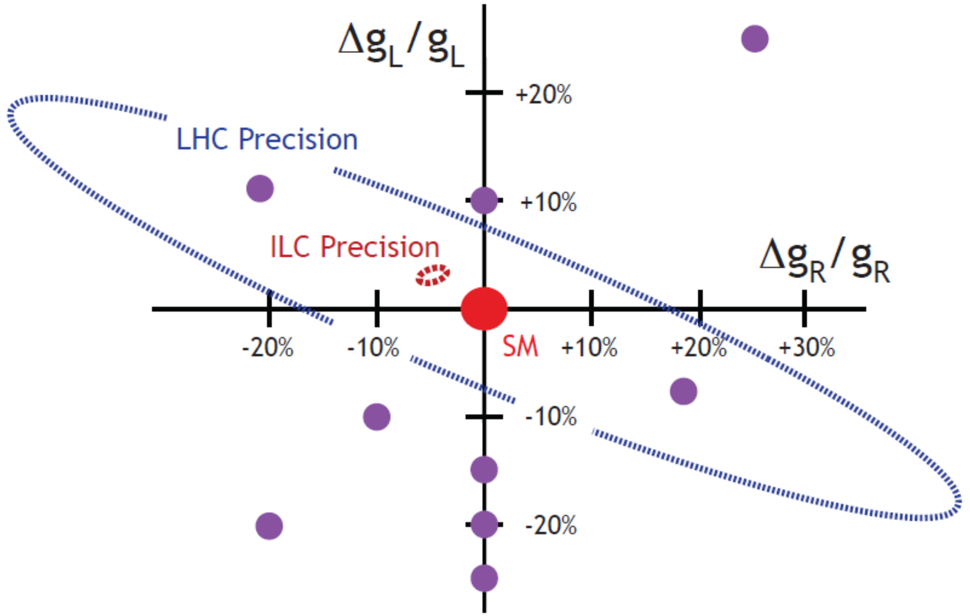


Top coupling is sensitive to new physics:

Comparison of g_L,g_R (SM) with composite Higgs models

arXiv:1307.8102





Statistical precision on CP conserving form factors expected at LHC (3000fb^{-1}) and ILC (500fb^{-1}, Pe-=±0.8, Pe+= ±0.3)

arXiv:1506.05992