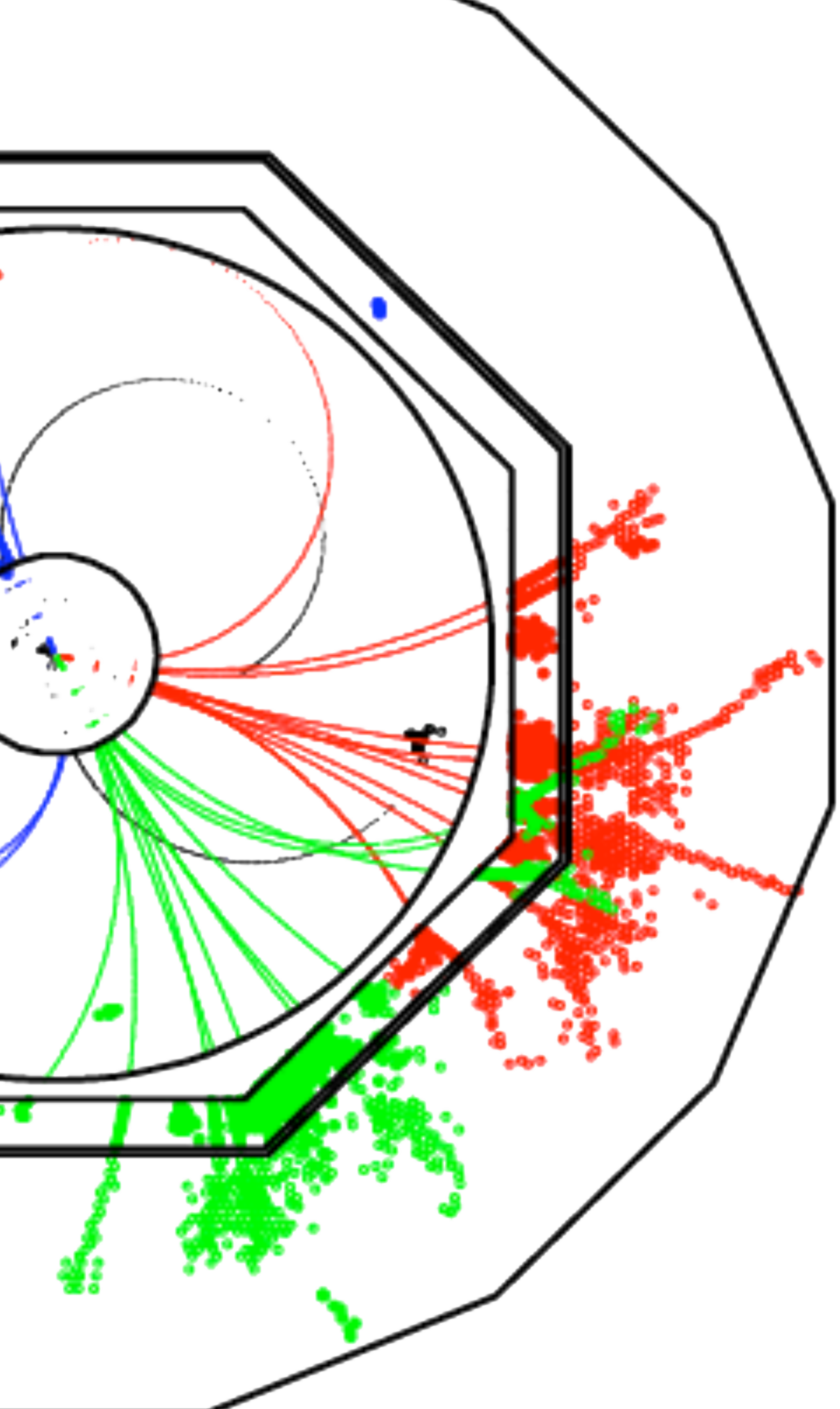

Physics at the ILC

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STATUS OF PARTICLE PHYSICS

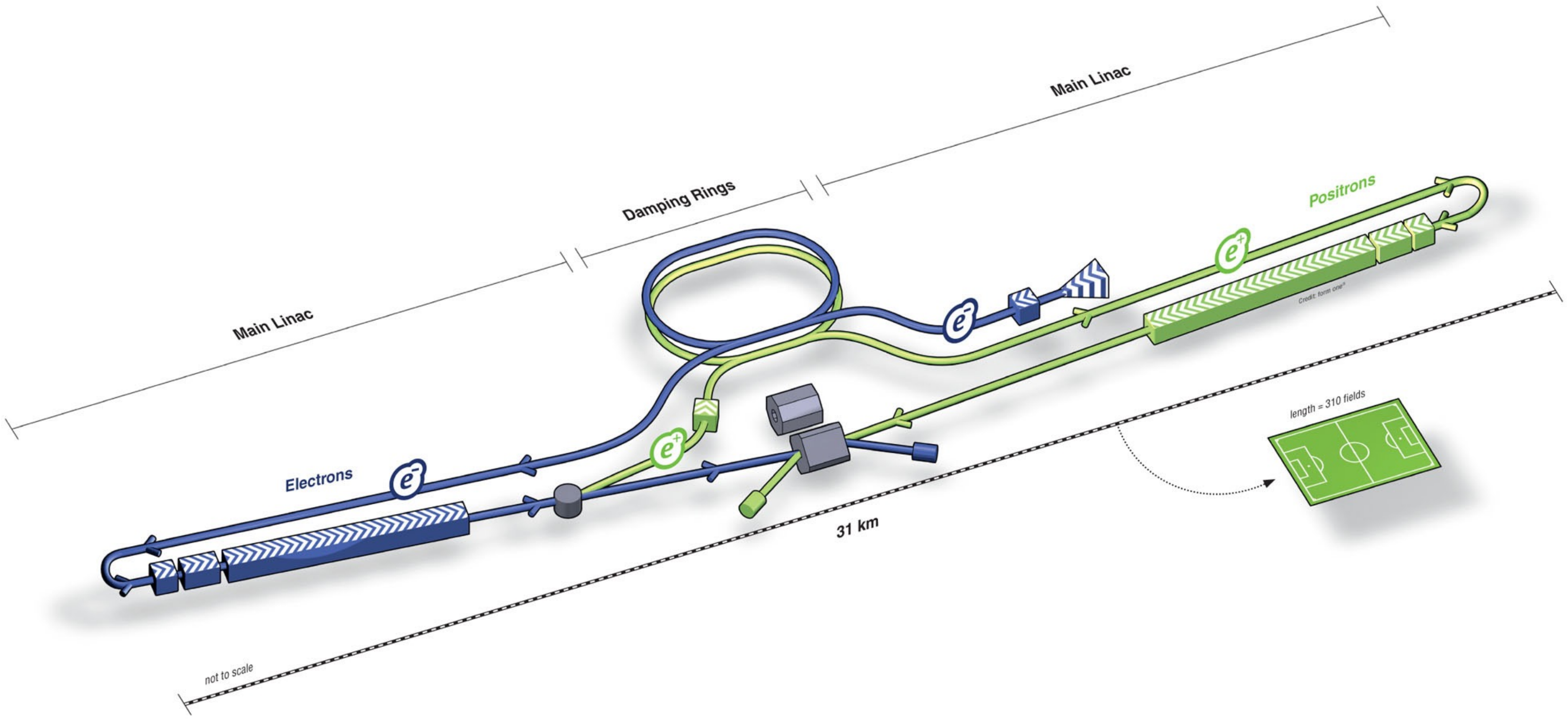
- Standard model has been highly successful
- Higgs found in 2012
- However, still many open questions
- Validity of the SM is limited
- At what energy does it break down?
- No evidence yet for New Physics
- Not clear at which energy scale to expect new physics

NEXT STEPS

- Precision measurements of electroweak processes could provide answers to the open questions
  - precision measurements of the Higgs properties in order to understand electroweak symmetry breaking and the nature of the Higgs potential
  - precision measurements of top quark properties are a window for new physics
  - precision measurements of other electroweak processes to look for deviations from the Standard Model predictions (e.g. W and Z)
- Direct searches for New Physics at higher energy scales, new regions of phase space (e.g. direct production of new particles)
- An electron-positron collider is ideally suited for precision measurements
- Most mature proposal: International Linear Collider (ILC)

ILC - Machine

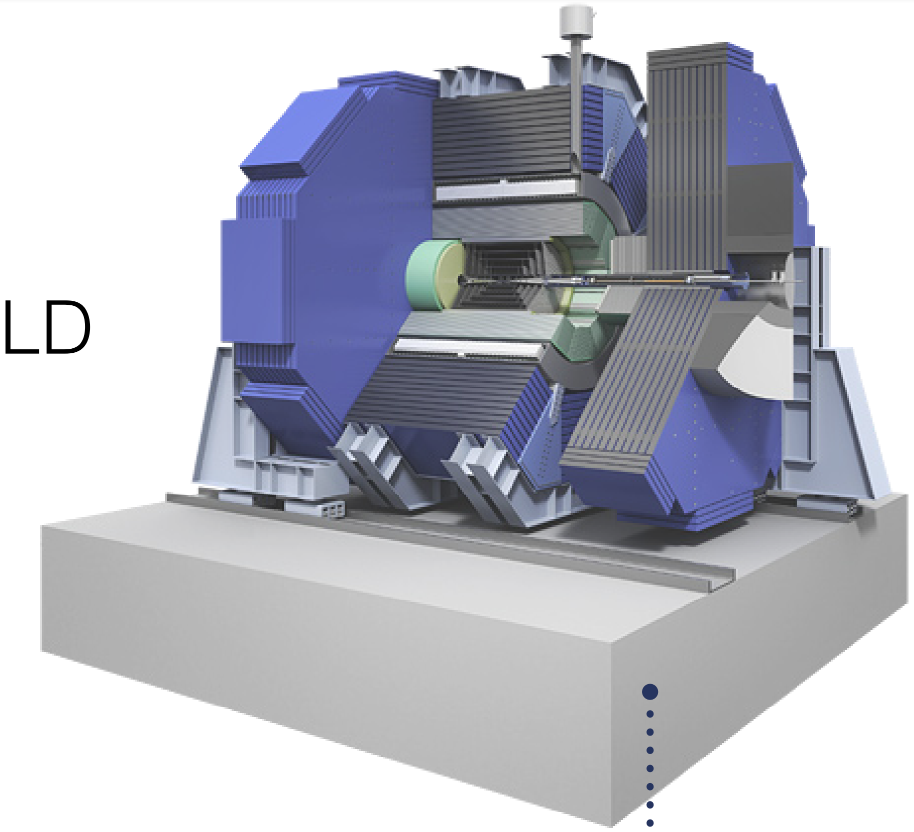
E_{cm}	91 - 500 GeV (1 TeV)
Luminosity	2×10^{34} $cm^{-2}s^{-1}$ (baseline at 500 GeV) x2 luminosity upgrade
Acc. gradient	31.5 MV/m
beam size	474 nm
Polarisation	e^- >80%, e^+ ~30%
Length	~ 31 km (~50 km)



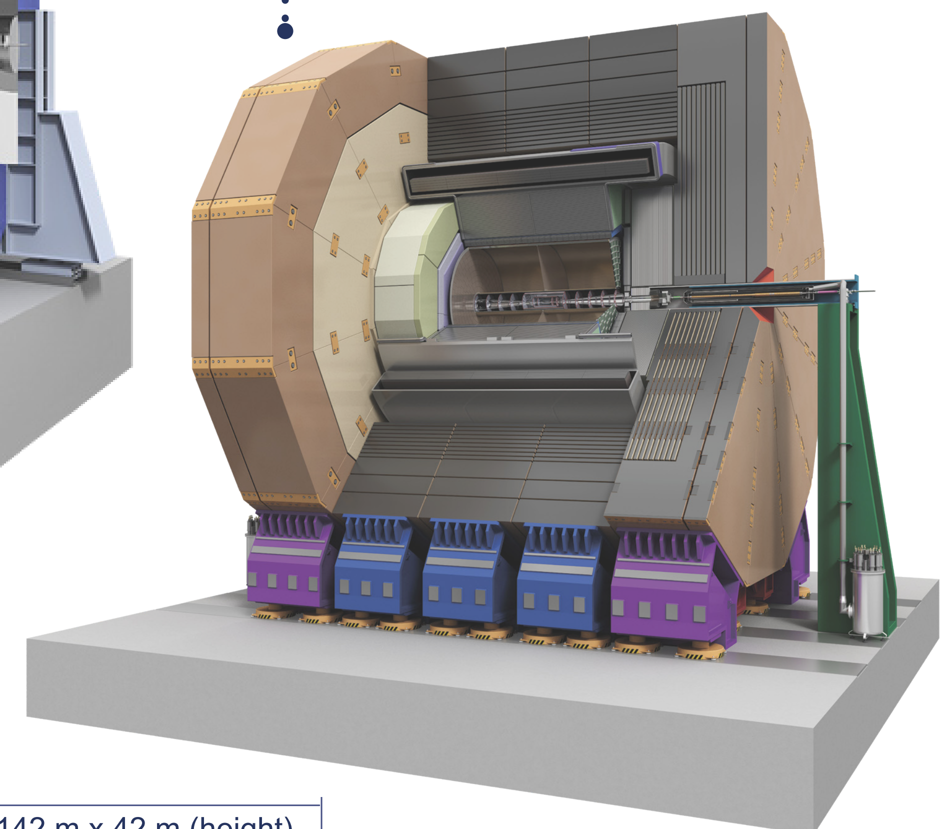
- Superconducting RF acceleration structures
- Staged operation, design energy **500 GeV**, possibility to upgrade to 1 TeV
- Two detectors share one interaction point (push-pull configuration)
- Technical Design Report (**TDR**) published in 2013
- Mature technology: being used in the construction of **XFEL** at DESY
- Japan is considering to host the ILC: North of Sendai (Kitakami)

ILC – Detectors

- Two detectors with complementary technology: SiD and ILD
- Detailed Baseline Design 2013
- Design optimisation ongoing



SiD (Silicon Detector)

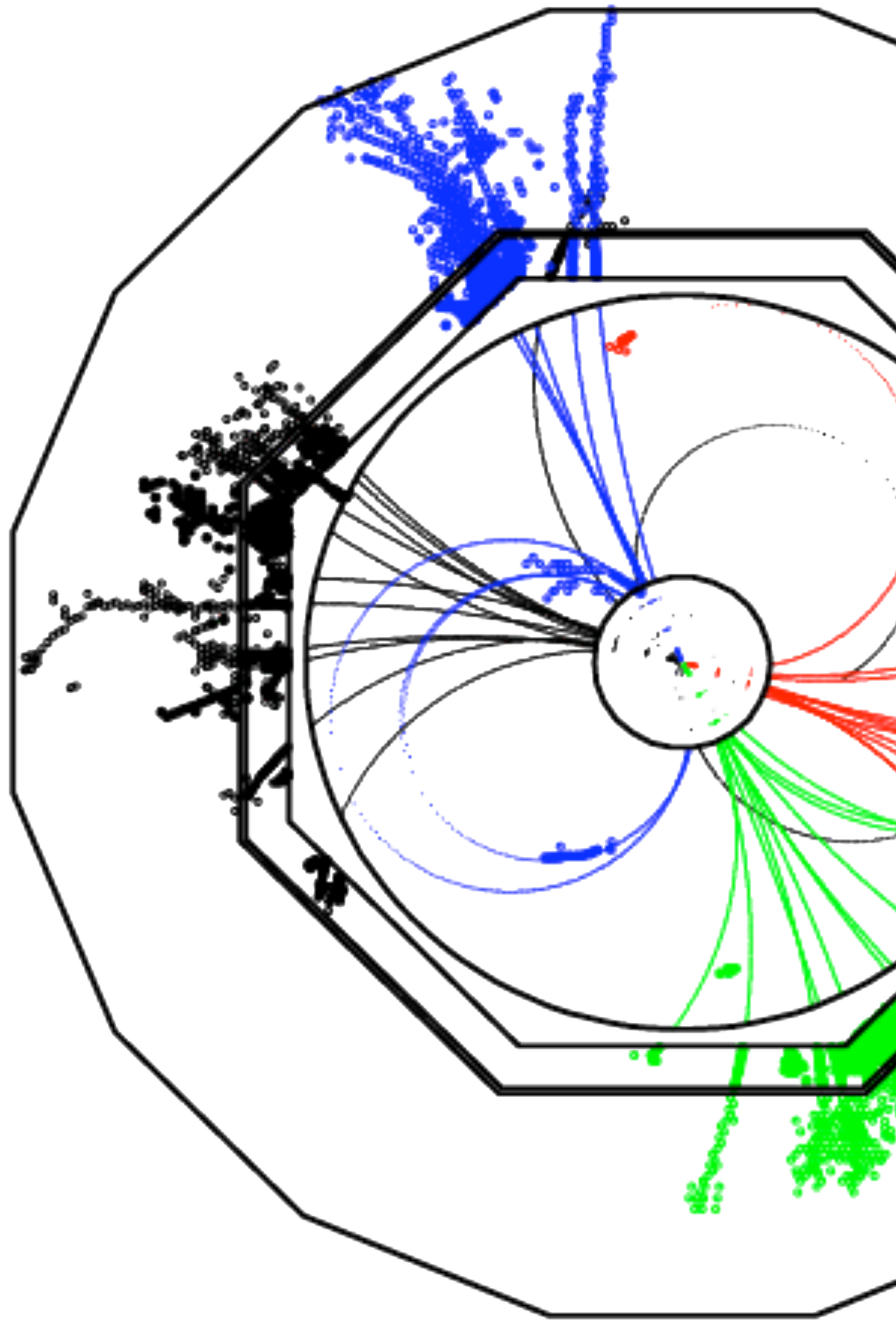


ILD (International Large Detector)

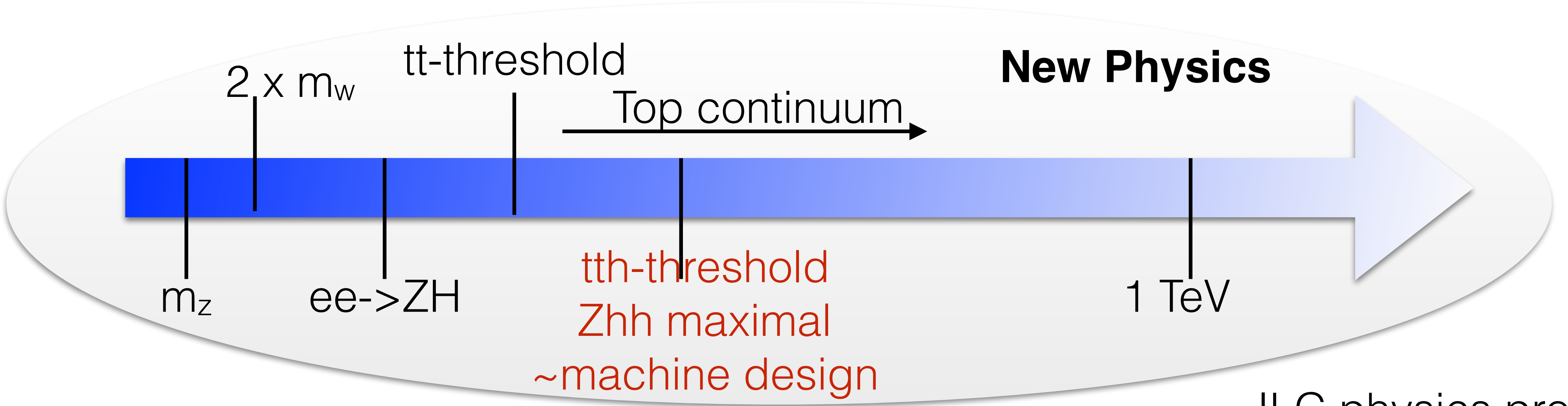
Experimental hall	Hall size	25 m x 142 m x 42 m (height)
	The ILD detector in detail	
	Height	~ 16 m
	Length	~ 14 m
	Weight	~ 14,000 tonnes
	Superconducting solenoid	3.5 teslas
	Vertex detector spatial resolution	3 µm
	Central tracker (TPC) spatial resolution	< 100 µm (220 layers)
Detectors	The SiD detector in detail	
	Height	~ 14 m
	Length	~ 11 m
	Weight	~ 10,100 tonnes
	Superconducting solenoid	5 teslas
	Vertex detector spatial resolution	< 5 µm
	Central semiconductor tracker spatial resolution	8 µm (5 layers)

Detector requirements

- Precision measurements require:
  - excellent track momentum reconstruction
  - secondary vertex reconstruction
    (b/c tagging)
  - high energy resolution (Jet energy resolution)
  - hermetic (missing energy)
- Final state will consist of many jets
  - Jet energy resolution
    dE/dx < 0.3/Sqrt(E[GeV])
    needs Particle flow (PFA) detectors:
    highly granular calorimeters,
    high separation power for nearby tracks



ILC - Physics program

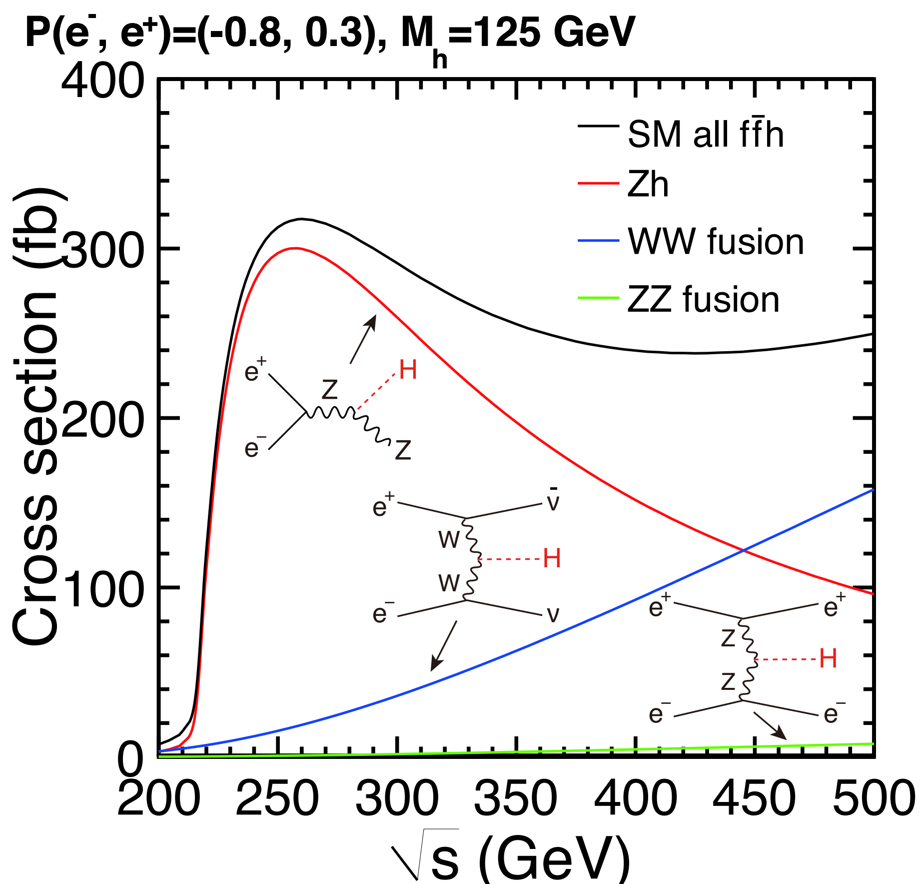


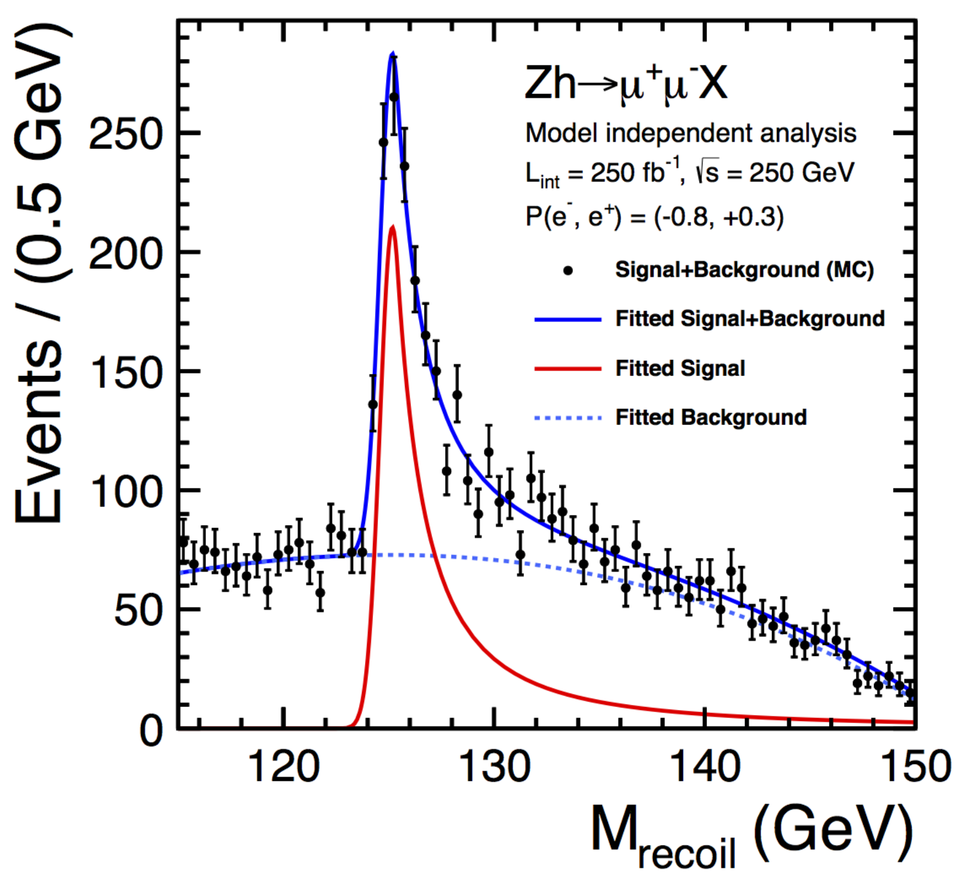
ILC physics program:
arXiv:1506.05992

- e^+e^- collider offers a well defined initial state, absence of strong interaction background, controlled and calculable electroweak background
- High precision tests of the Standard Model over a wide energy range to detect the onset of New Physics
- Main focus on Higgs and top quark, W and Z
- Machine settings can be “tailored” for specific processes: E_{cm} and beam polarisation (enhance cross section, remove background)

HIGGS PHYSICS

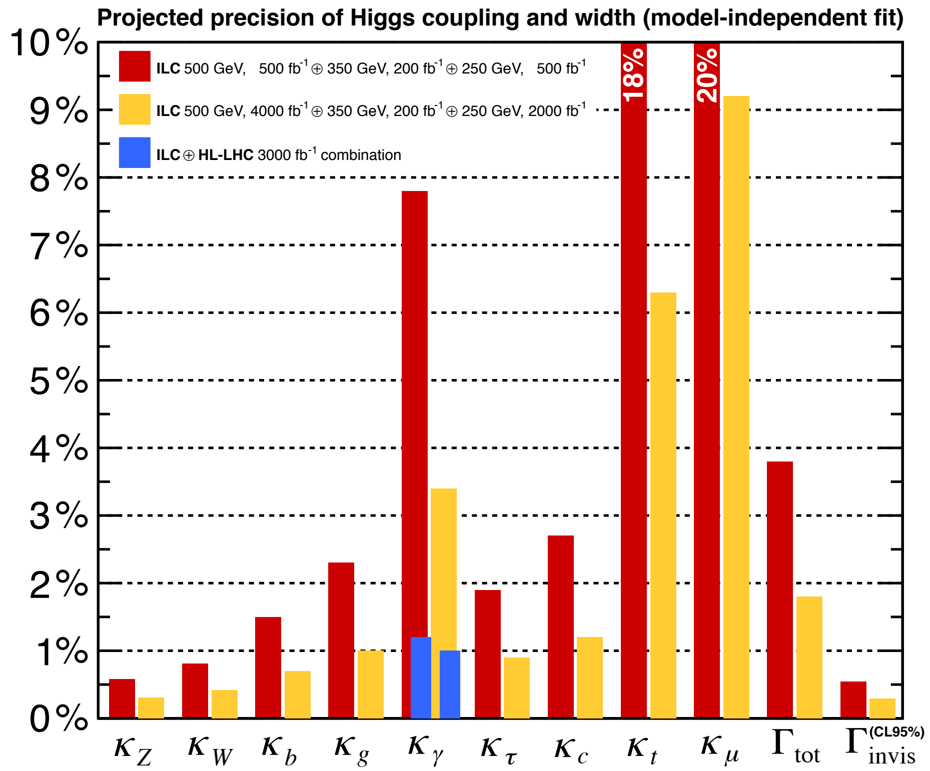
- Precision Higgs physics can provide crucial information on the electroweak symmetry breaking mechanism
- 3 major Higgs production channels; at 250 GeV "higgsstrahlung" (e^+e^- -> Zh) dominant
- Measure all major Higgs decay channels individually, including h->cc, gg, (very difficult at the LHC)
- **Model independent** measurement of Higgs properties possible via recoil mass by looking only at the Z decay
    - total Higgs width, absolute normalisation of Higgs couplings
    - Higgs mass to better than 30 MeV via Z-> $\mu^+\mu^-$



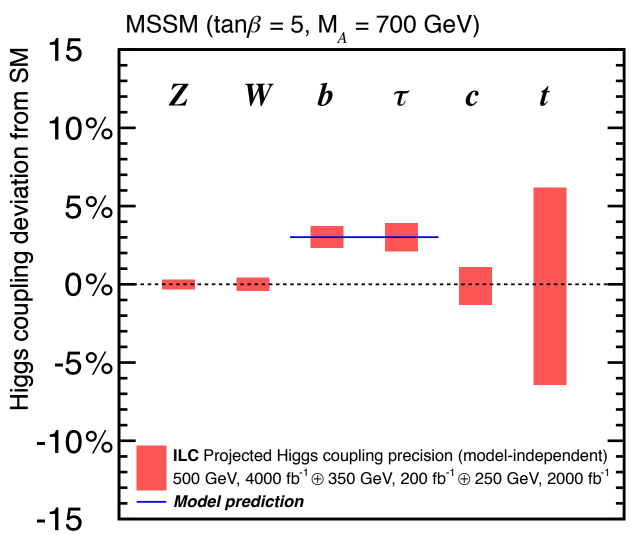


Higgs physics

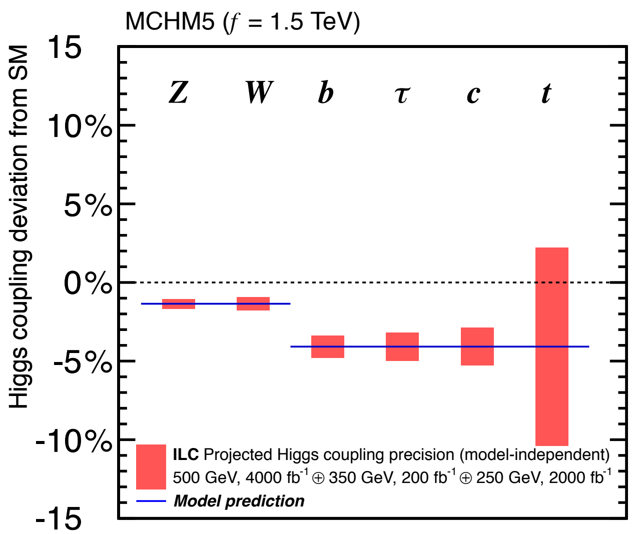
- Measure coupling to fermions and bosons through the individual Higgs decay channels (model independent)
- 500 GeV: Coupling to top (from e^+e^- ->t tbar h) and Higgs self coupling (from e^+e^- -> Zhh)
- Deviations from the SM prediction point to New Physics and the nature of the Higgs boson (compositeness)
- Deviations in general expected to be small ~5%



Supersymmetry

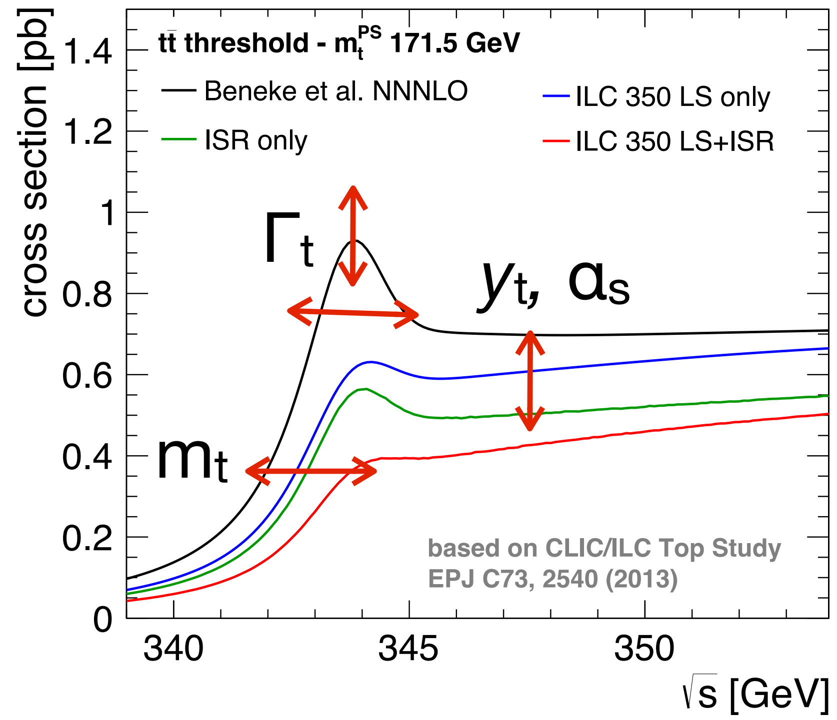


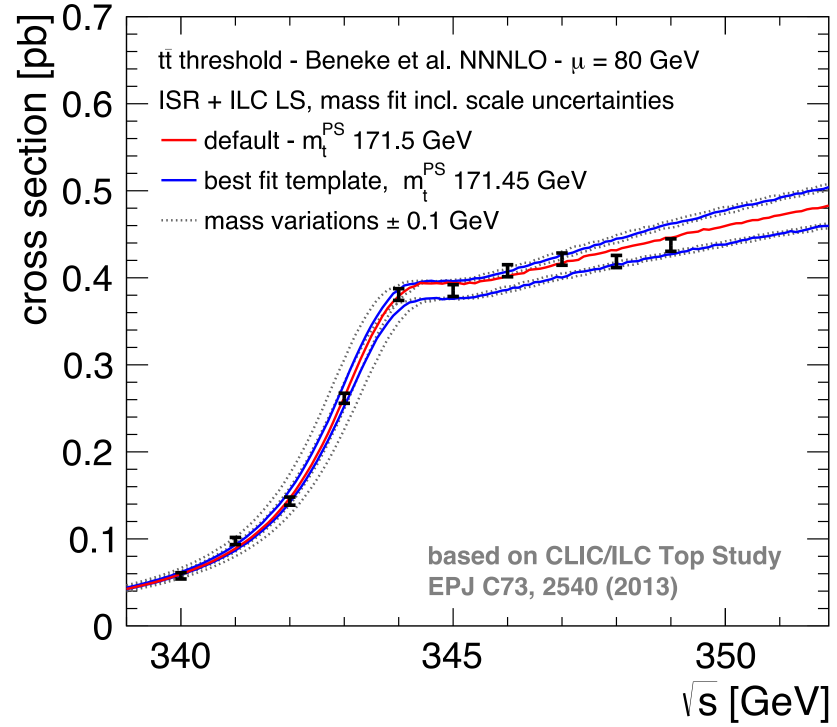
Composite Higgs



Top physics

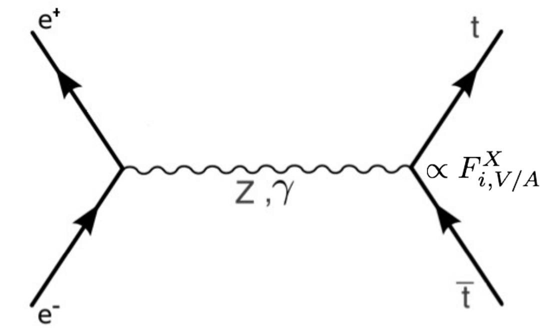
- The top quark plays a key role in electroweak symmetry breaking, top mass is an important Standard Model parameter
- Not measured before in e^+e^- colliders
- Pair production threshold around 350 GeV allows precise and theoretically clean measurement of the top mass
  - Cross section around the threshold is affected by top quark properties and QCD (mass, width, Yukawa coupling and α_s)
  - Final precision on mass, < 100 MeV expected, most likely dominated by theoretical uncertainties
  - Experimental uncertainties (beam energy, luminosity, luminosity spectrum, event selection, impurities) < 50 MeV
  - Statistical uncertainties < 20 MeV (100 fb-1)
  - theory uncertainties from NNNLO QCD (M. Beneke et al. 2015) scale variations ~50 MeV

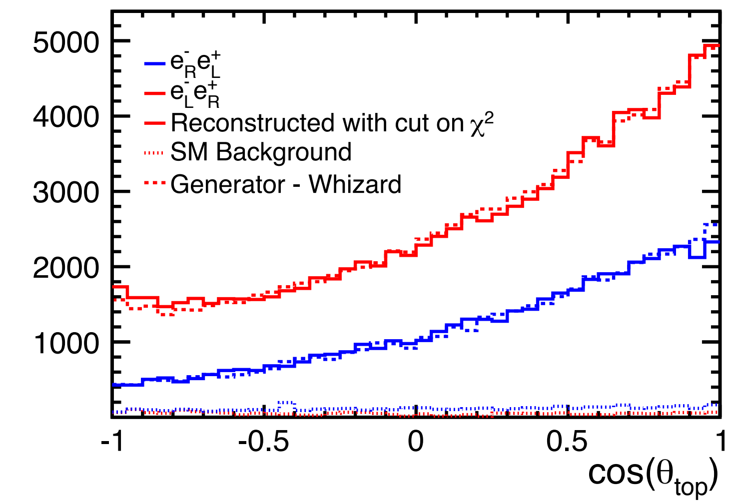


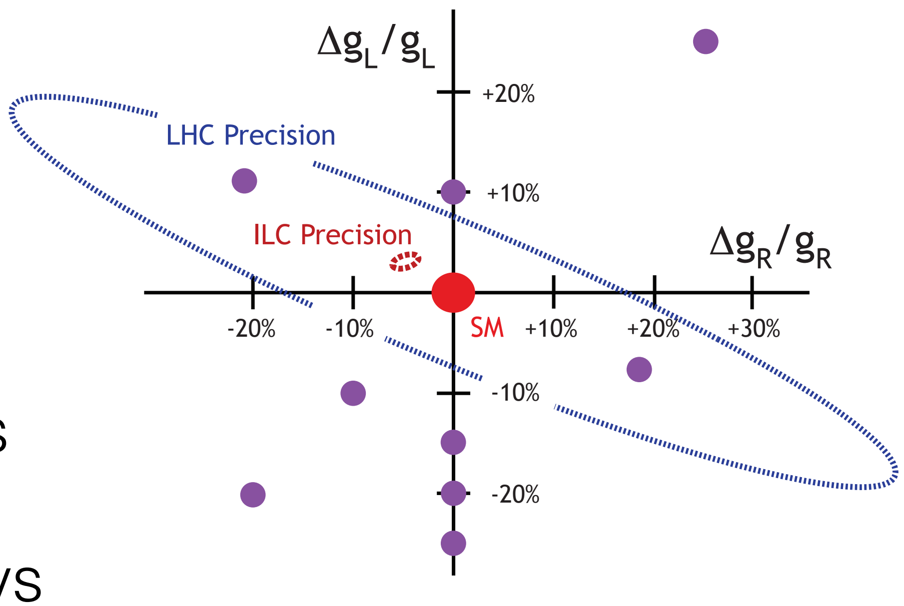


Top physics

- Top quark production and decay at 500 GeV
  Electroweak production dominant, no QCD background
- Detailed measurement of weak and electromagnetic couplings
  - Weak couplings depend on polarisation
  - Coupling to W and Z for each polarisation state accessible
  - Total production cross section, forward-backward asymmetry and helicity angle for 2 polarisations fully constrain top quark couplings
    Precisions <2% can be achieved
  - New Physics predicts changes in these couplings
- Exotic top quark decay modes, such as FCNC decays





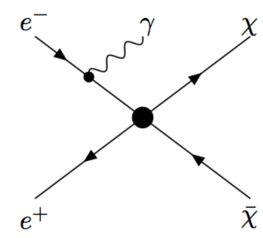


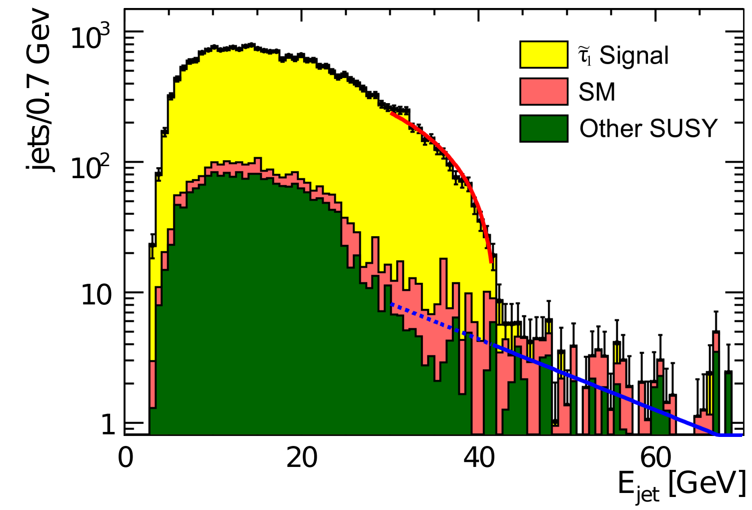
BSM PHYSICS

- Indirect searches via precision measurements of Standard Model processes
  - e.g. Higgs and Top physics
- Direct searches for new particles up to ~E_{cm}/2 for almost any type of particle (extend into regions not covered by LHC)
  - Beam polarisation suppresses Standard Model background
  - E_{cm} can be tuned to production threshold, energy scan provides accurate mass and quantum numbers
  - Pair production rate at different polarisations provides quantum numbers under electroweak interactions

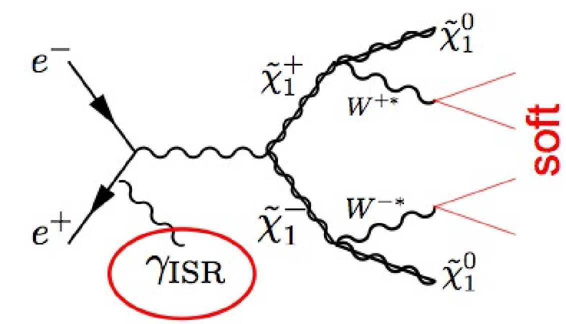
BSM PHYSICS

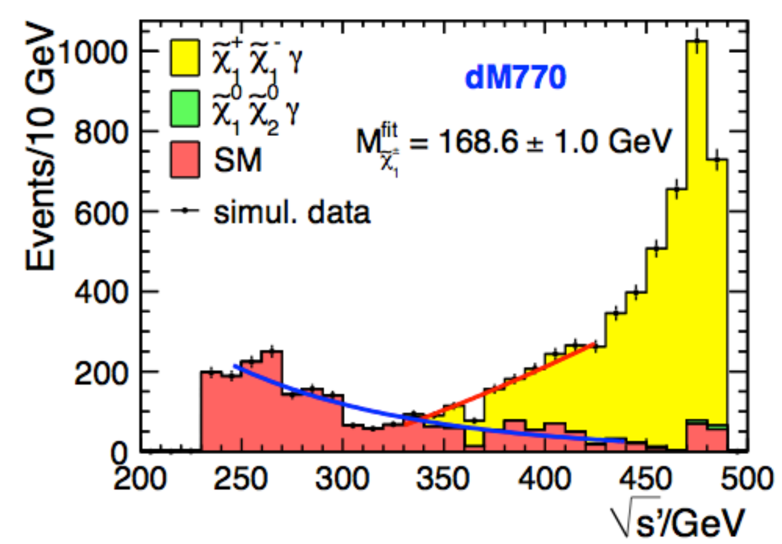
- Dark matter searches
  - Coannihilation of charged and neutral DM particles, requires a small mass difference < 20 GeV, produces soft decay particles
  - Initial state radiation recoiling against invisible particles





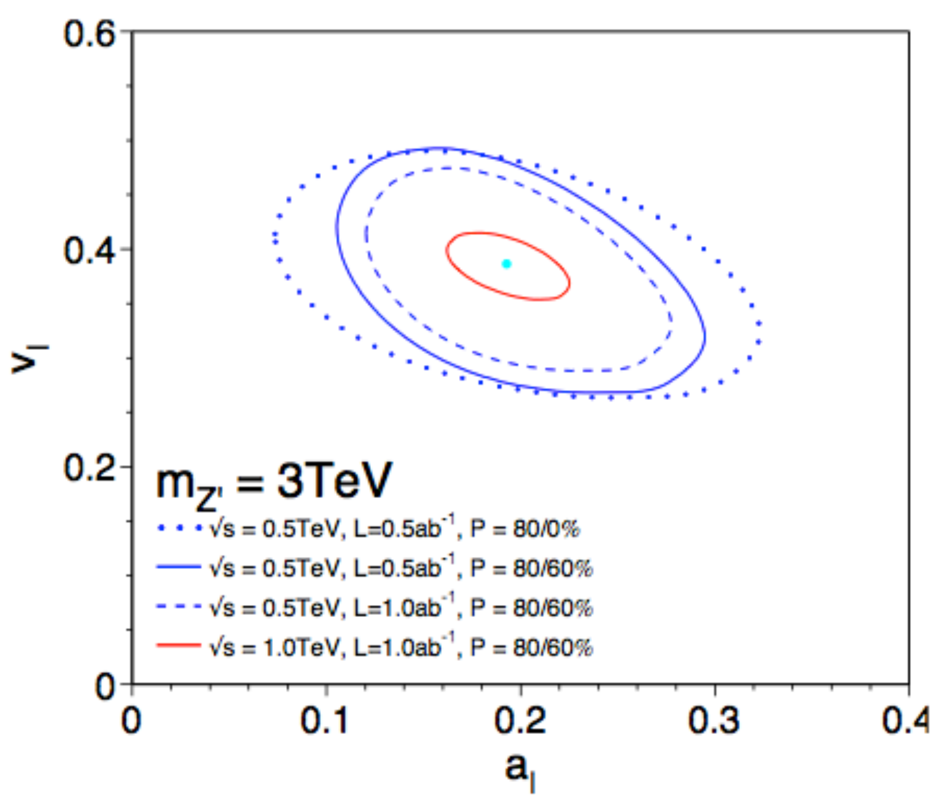
- Supersymmetric Higgs partners: light Higgsinos
  - Naturalness requires relatively light almost degenerate Higgsinos
  - Small mass difference ~ 10 GeV between charged and neutral Higgsinos (if susy partners of W and Z are heavy)
  - Recoil against initial state radiation photon, soft decay products determine mass difference
  - Polarisation gives access to quantum numbers
- Additional Higgs bosons

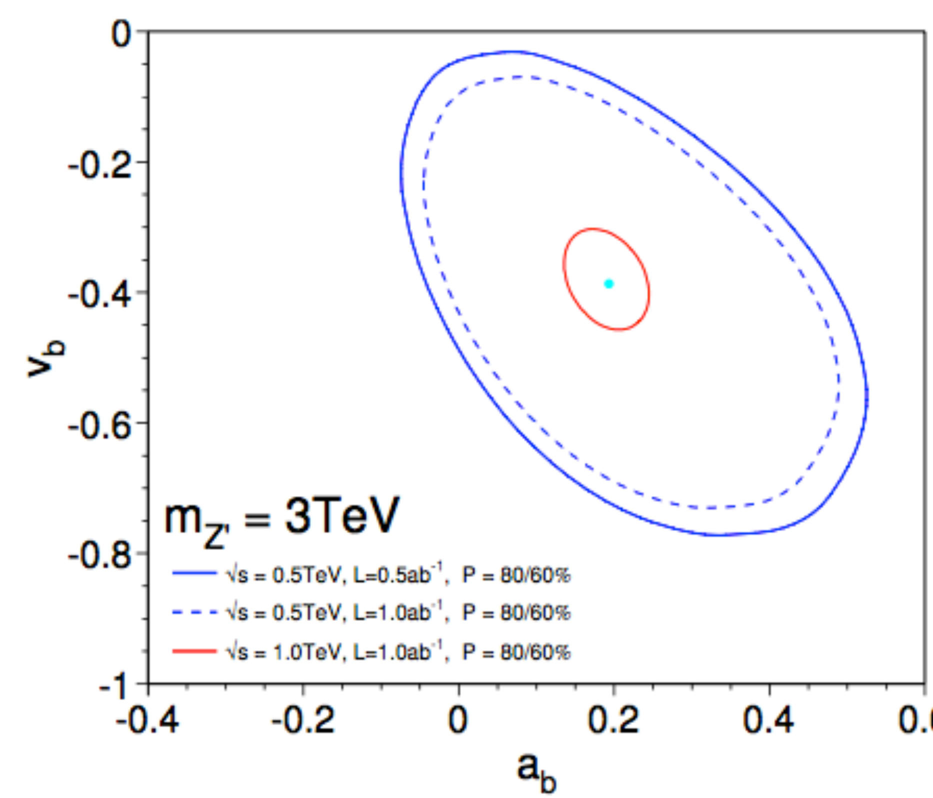




BSM PHYSICS

- Two-fermion processes allow search for new gauge bosons, e.g Z’
- Z’ will perturb Standard Model cross sections
  - If found at LHC, ILC can measure all its couplings
- Quark and lepton compositeness

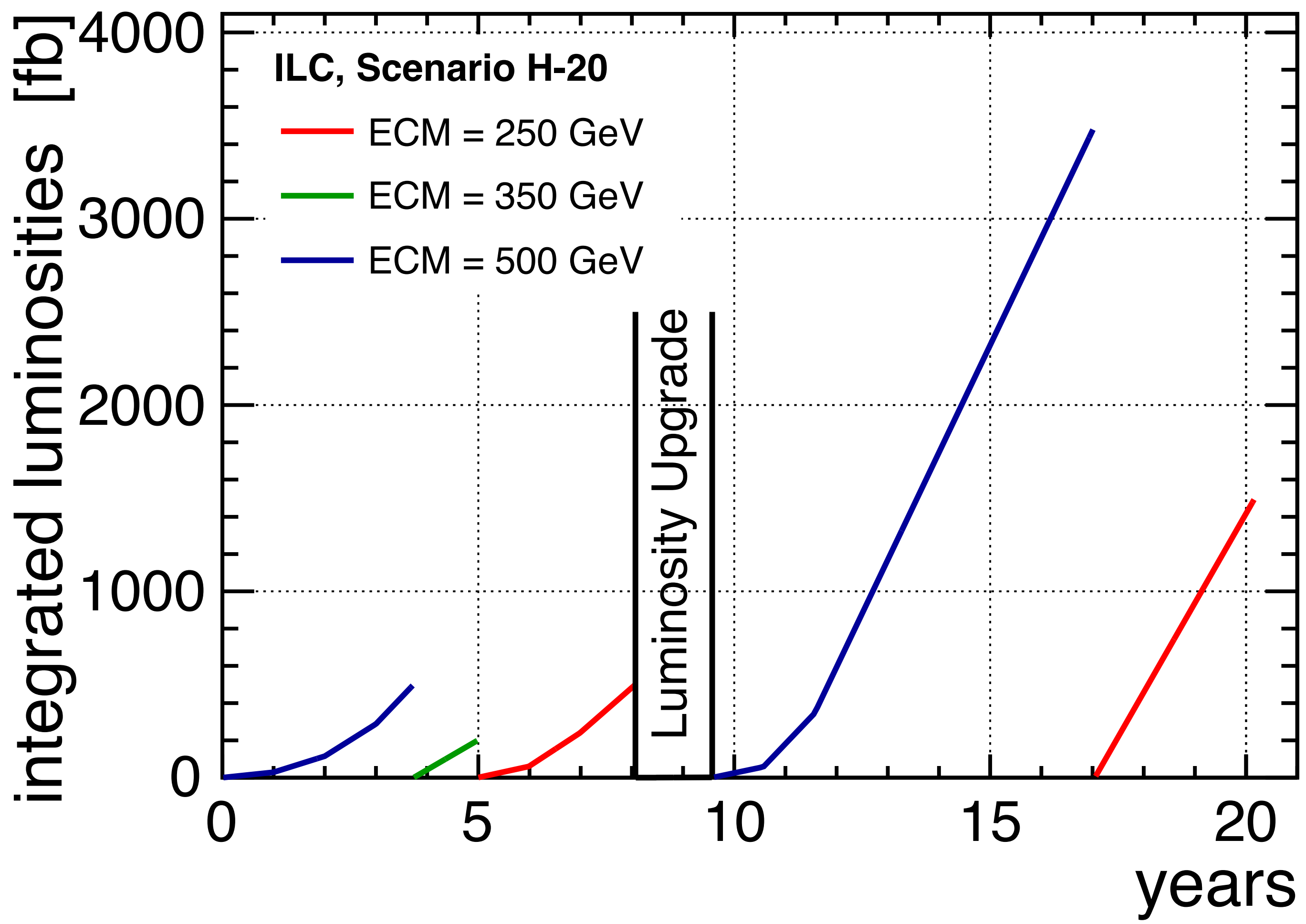




ILC running scenario

- Standard running scenario **H20** assuming 20 years of operation
- The actual running scenario will depend on physics outcomes from LHC and ILC
- Guarantees the fully independent profiling of the Higgs boson

Integrated Luminosities [fb]



	$\sqrt{s}$ [GeV]	$\int \mathscr{L} dt$ [fb^{-1}]	L_{peak} [fb^{-1}/a]
Physics run	500	500	288
Physics run	350	200	160
Physics run	250	500	240
Shutdown			
Physics run	500	3500	576
Physics run	250	1500	480

ILC running scenarios:
arXiv: 1506.07830

Conclusion

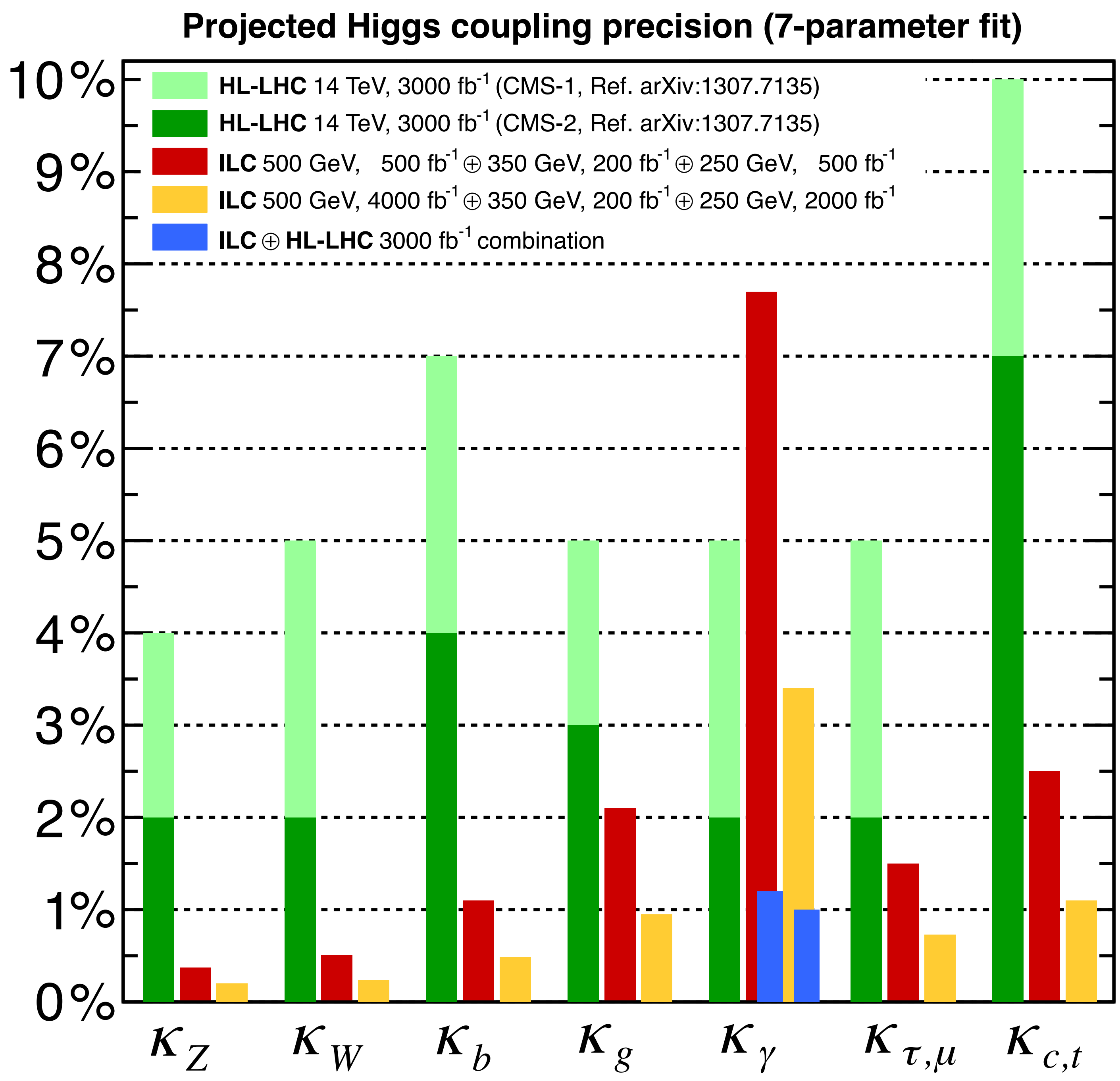
- The ILC is an ideal machine for **precision electroweak measurements**
  - Precision studies of Higgs and top quark allow to find new particles and interactions and answers to the nature of electroweak symmetry breaking
- The ILC is a **discovery** machine
  - Direct search for new particles in regions that are inaccessible for LHC
- **Mature technology** - ILC is ready to be constructed
- Japan is considering to host the ILC
  - Strong local support and also in government bodies
  - Political decision to be made in the coming years
  - Meetings between Japanese and American and European delegates ongoing and MEXT project review report underway

Thank you for your attention!

- TDR:
  http://www.linearcollider.org/ILC/physics-detectors/Detectors/Detailed-Baseline-Design

- Reference documents:
  ILC physics case arXiv:1506.05992
  ILC running scenarios arXiv:1506.07830

MODEL DEPENDENT COUPLINGS



ILC PROJECTED ACCURACIES

Topic	Parameter	Initial Phase	Full Data Set	units	ref.
Higgs	m_h	25	15	MeV	[15]
	$g(hZZ)$	0.58	0.31	%	[2]
	$g(hWW)$	0.81	0.42	%	[2]
	$g(hb\bar{b})$	1.5	0.7	%	[2]
	$g(hgg)$	2.3	1.0	%	[2]
	$g(h\gamma\gamma)$	7.8	3.4	%	[2]
		1.2	1.0	%, w. LHC results	[17]
	$g(h\tau\tau)$	1.9	0.9	%	[2]
	$g(hc\bar{c})$	2.7	1.2	%	[2]
	$g(ht\bar{t})$	18	6.3	%, direct	[2]
		20	20	%, $t\bar{t}$ threshold	[34]
	$g(h\mu\mu)$	20	9.2	%	[2]
	$g(hhh)$	77	27	%	[2]
	Γ_{tot}	3.8	1.8	%	[2]
	Γ_{invis}	0.54	0.29	%, 95% conf. limit	[2]
Top	m_t	50	50	MeV (m_t(1S))	[33]
	Γ_t	60	60	MeV	[34]
	g_L^γ	0.8	0.6	%	[42]
	g_R^γ	0.8	0.6	%	[42]
	g_L^Z	1.0	0.6	%	[42]
	g_R^Z	2.5	1.0	%	[42]
	F_2^γ	0.001	0.001	absolute	[42]
	F_2^Z	0.002	0.002	absolute	[42]
W	m_W	2.8	2.4	MeV	[62]
	g_1^Z	8.5×10^{-4}	6×10^{-4}	absolute	[63]
	κ_γ	9.2×10^{-4}	7×10^{-4}	absolute	[63]
	λ_γ	7×10^{-4}	2.5×10^{-4}	absolute	[63]
Dark Matter	EFT Λ: D5	2.3	3.0	TeV, 90% conf. limit	[61]
	EFT Λ: D8	2.2	2.8	TeV, 90% conf. limit	[61]

Table 1: Projected accuracies of measurements of Standard Model parameters at the two stages of the ILC program proposed in the report of the ILC Parameters Joint Working Group [7]. This program has an initial phase with 500 fb^{-1} at 500 GeV, 200 fb^{-1} at 350 GeV, and 500 fb^{-1} at 250 GeV, and a luminosity-upgraded phase with an additional 3500 fb^{-1} at 500 GeV and 1500 fb^{-1} at 250 GeV. Initial state polarizations are taken according to the prescriptions of [7]. Uncertainties are listed as 1σ errors (except where indicated), computed cumulatively at each stage of the program. These estimated errors include both statistical uncertainties and theoretical and experimental systematic uncertainties. Except where indicated, errors in percent (%) are fractional uncertainties relative to the Standard Model values. More specific information for the sets of measurements is given in the text. For each measurement, a reference describing the technique is given.

Topic	Parameter	Initial Phase	Full Data Set	
Higgs	$g(hZZ)$	0.37	0.2	%
	$g(hWW)$	0.51	0.24	%
	$g(hb\bar{b})$	1.1	0.49	%
	$g(hgg)$	2.1	0.95	%
	$g(h\gamma\gamma)$	7.7	3.4	%
	$g(h\tau\tau), g(\mu\mu)$	1.5	0.73	%
	$g(hc\bar{c}), g(ht\bar{t})$	2.5	1.1	%
	Γ_{tot}	1.8	0.96	%

Table 2: Projected accuracies of measurements of Higgs boson couplings at the two stages of the ILC program, from the model-dependent fit used in the Snowmass 2013 study [18]. The analysis is as described in [2]. The ILC run plan assumed is the same as in Table 1.