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Heavy Quarks and Leptons
Virginia Tech 5/27/16

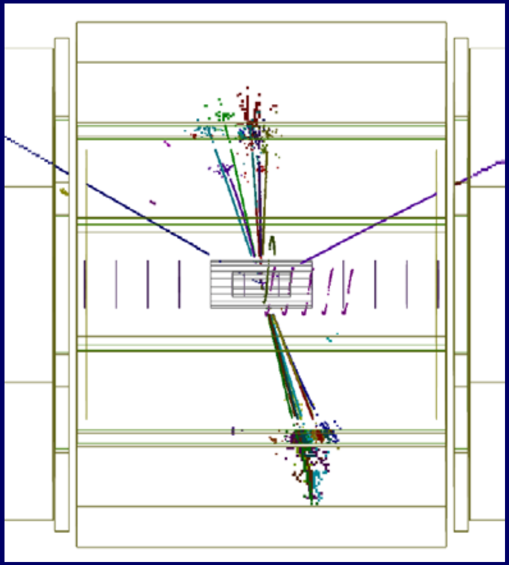
The International Linear Collider

A 250 – 500 GeV e^+e^- collider, upgradeable to 1 TeV (and running at the Z pole and WW threshold), offers significant opportunity to extend our understanding of EW symmetry breaking and physics beyond the SM.

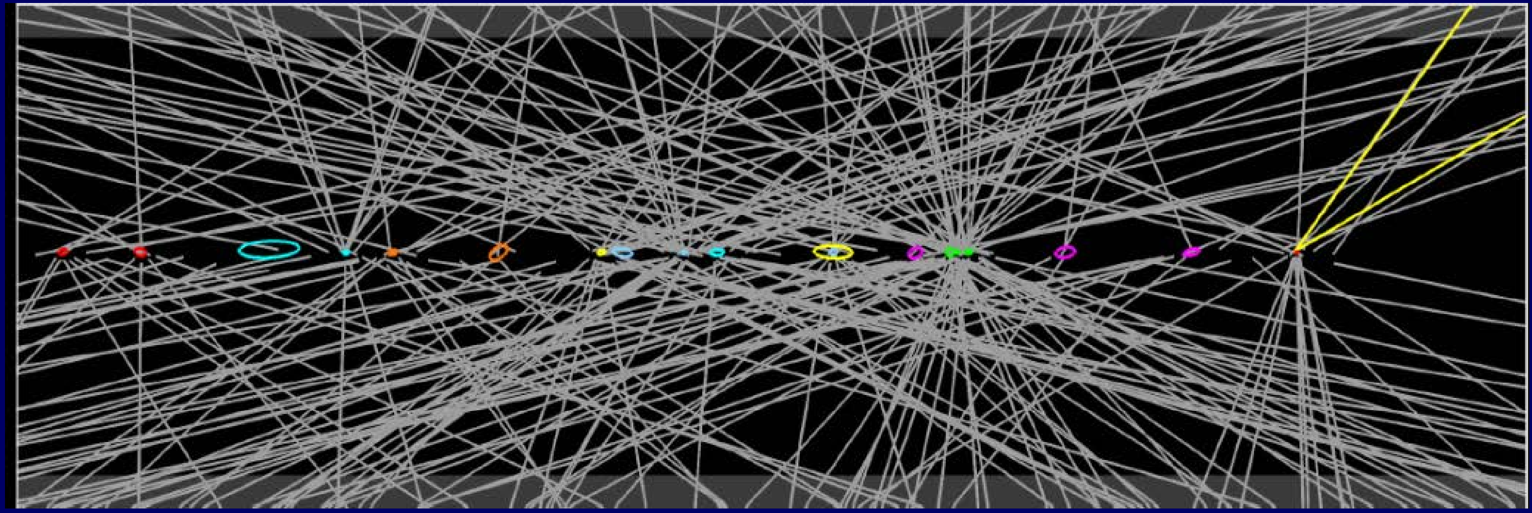
Why Lepton Colliders?

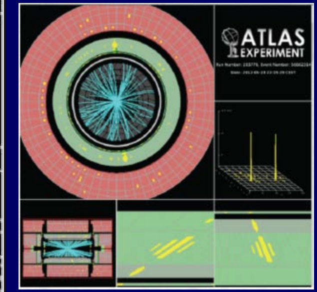
Compared to hadron colliders, the events are "clean" – one observes just the hard process, without extra particles produced by spectators in the primary collision, and without pileup from additional collisions during the bunch crossing.

$e^+e^- \rightarrow Z(\mu\mu)H(bb)$ at ILC



$gg \rightarrow H(\gamma\gamma)$ (+ X) at LHC

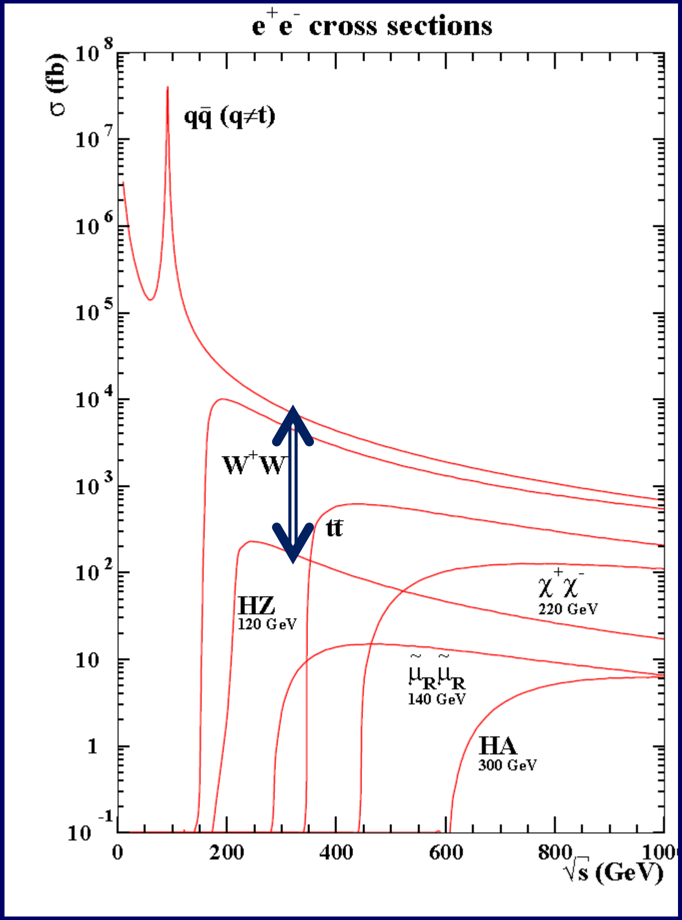


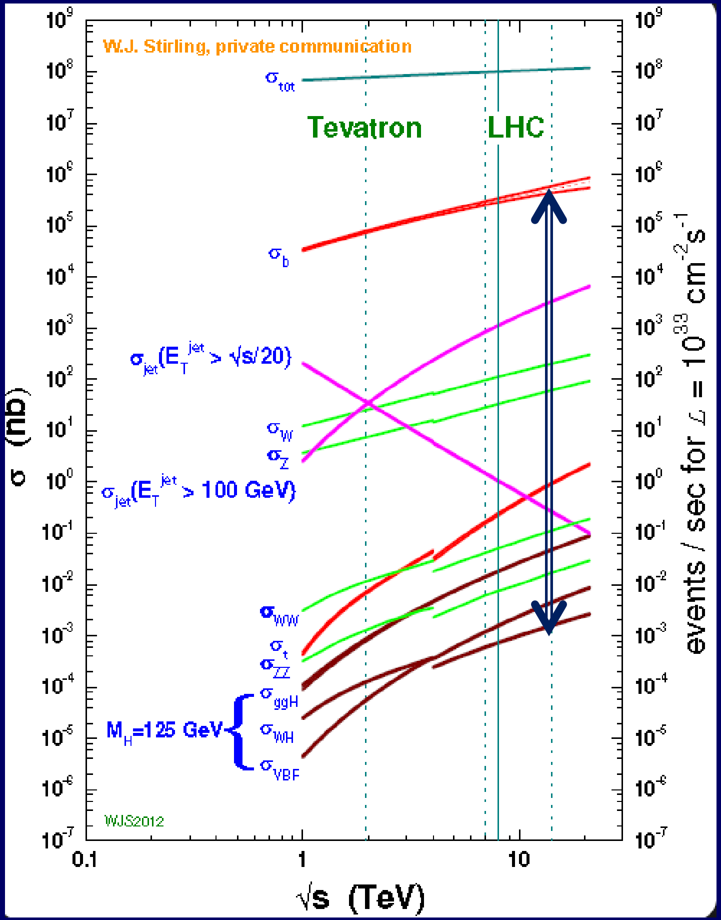


Why Lepton Colliders?

Interesting processes are a large fraction of the total rate. Various signal cross sections are similar. Backgrounds are typically not a big problem. No trigger is required.

ILC: $e^+e^- \to HZ$ is 1% of $e^+e^- \to q\bar{q}$





Backgrounds for hadron production are huge. Multi-level triggers must be used and calibrated.

LHC: $pp \to H\,W/Z$ is 10^{-9} of $pp \to b\bar{b}$

Why Lepton Colliders?

- The partonic collision energy in e^+e^- is nearly a δ-function at $2E_{bm}$ rather than a convolution over PDFs.

- The virtual γ/Z intermediate state tells us that the final state quantum numbers are $J^{PC} = 1^{--}$.

- e^+ and e^- can be polarized (in ILC, $\mathcal{P}(e^-)=\pm 80\%$ and $\mathcal{P}(e^+)=\pm 30\%$). Since at high energies, right- and left-handed fermions are distinct particles, one can enhance signal processes or suppress backgrounds by the choice of beam polarization.

- Cross sections in e^+e^- can be calculated to $\mathcal{O}(0.1\%)$ accuracy; unlike in QCD, higher order terms are small. This means that the sensitivity to new physics at high mass scales is enhanced.

Lepton and hadron colliders have complementary roles. For example

- Hadrons containing heavy quarks (b, c, t) discovered at hadron colliders but their precision properties were explored at e^+e^- colliders

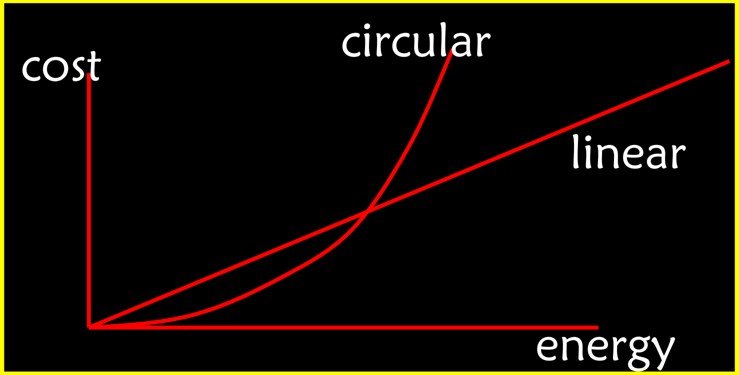
- We inferred the presence of the Higgs boson from precision e^+e^- colliders but discovered it at a hadron collider

Circular vs. Linear Lepton Colliders

Synchrotron radiation grows rapidly with E

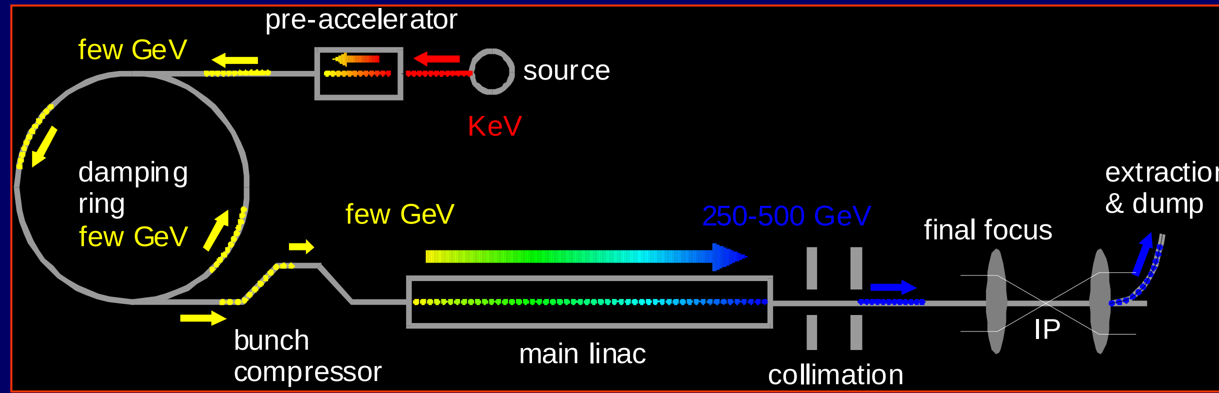
$\Delta E/\text{turn} \sim (E/m)^4/R$ (synchrotron radiation)

e.g. LEP2: $\Delta E = 3.4$ GeV/turn $\rightarrow P_{loss} \sim 20$ MW)

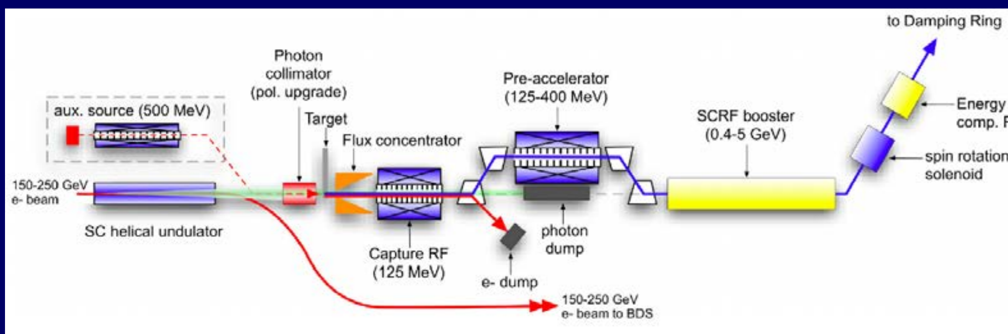


- New high gradient Superconducting RF allows going beyond LEP – e.g. in 350 GeV circular FCC/TLEP collider with 81 km circumference, each particle loses 9.3 GeV per turn that has to be made up with ~100 MW of RF.
- In a Linear Collider, go to long, single-pass linacs to reach desired energy. Collide the beams just once (but electrons are cheap!). But the full energy has to be made on one traverse of the machine rather than in multiple passes, so need more RF in the LC and RF is expensive. (The tunnel length in a 350 GeV circular machine is 2xlonger than for same energy linear machine.)
- The beamstrahlung losses (radiation in the field of the other beam) are similar for circular and linear e^+e^- machines. But in the circular machines, the lower energy electrons fail to stay in orbit, so the beam lifetime is ~1 minute and a second full energy accelerator is needed to top-up the beams continuously.
- $\mathcal{L}$ falls with E_{cm} in circular collider; grows with E_{cm} in linear collider.
- A circular muon storage ring is immune to synchrotron radiation. ($m_\mu \sim 200 m_e$)

The ILC machine



Electron source: polarized laser on GaAs cathode gives >80% e⁻ polarization

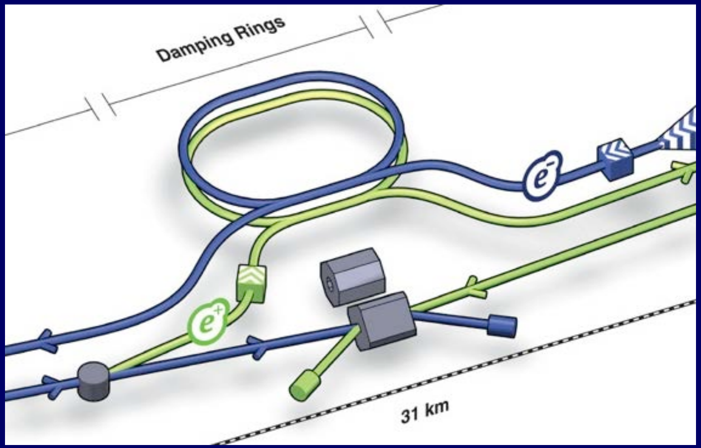


Positron source: Pass e⁻ beam at 150 GeV through helical undulator; polarized γ's on target make e⁺ with 30% polarization. Collect the e⁺ and send to Damping Ring. The e⁻ pass on to IR.

Damping Rings: To get the final 6 nm beam heights at IR, reduce the large emittance of e⁺ and e⁻ beams by $\mathcal{O}(10^5)$ in 5 GeV DRs using wigglers to radiate γ's. Recover longitudinal momentum with RF acceleration.

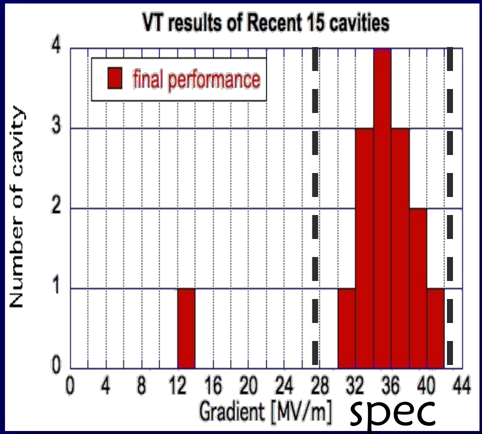
The 1312 beam bunches (554 ns apart) occupy ~200 km, so fold the bunches into Δt=6 ns in 3.2 km circumference DRs. Kick the bunches back out with fast rise time magnet to restore desired bunch structure.

Special mitigation strategies needed to reduce electron cloud in e⁺ DR.



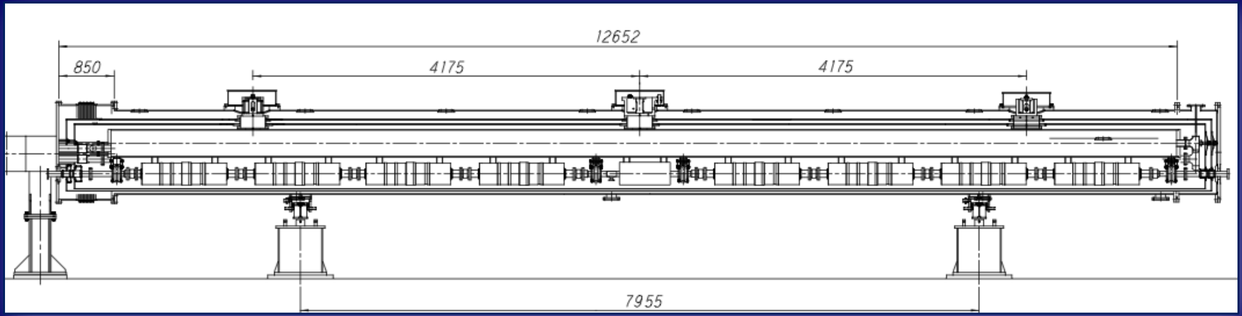
The ILC machine – main linac

7400 superconducting 9 cell pure Nb RF cavities (1m long) in each linac to provide acceleration to 250 GeV, at frequency =1.3 GHz (L-band). Require 35 MV/m in vertical test (31.5 MV/m average as installed in linac).



→ Cavities meet specs

Assemble 9 cavities (or 8 + quadrupole) in cryomodule

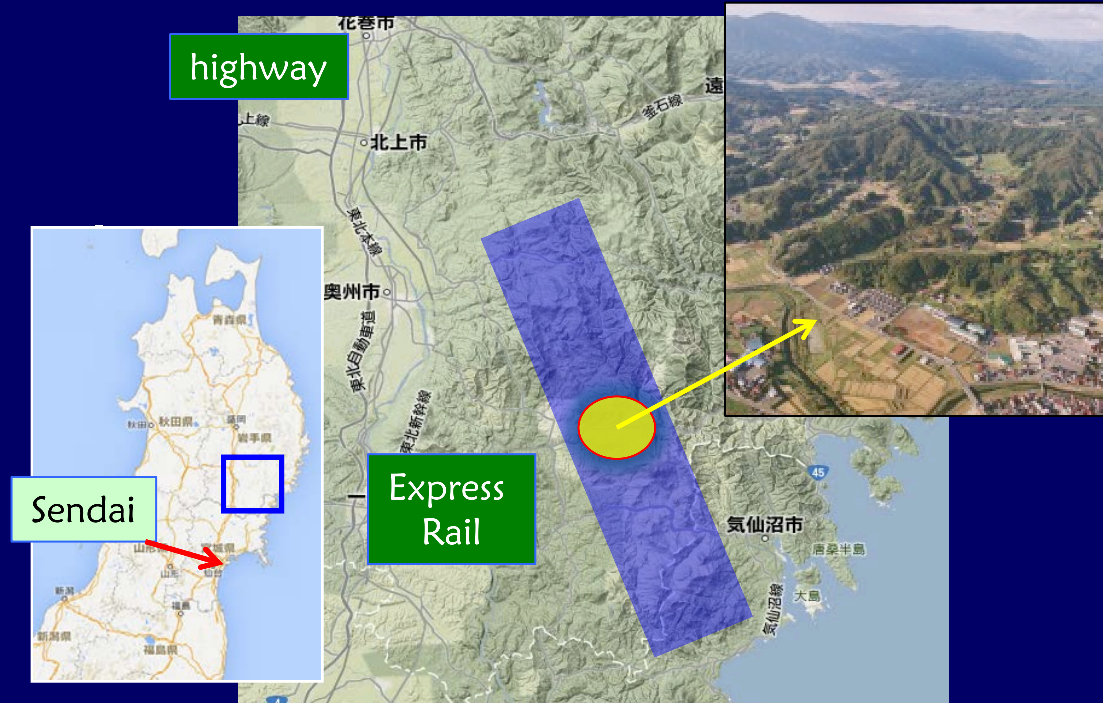


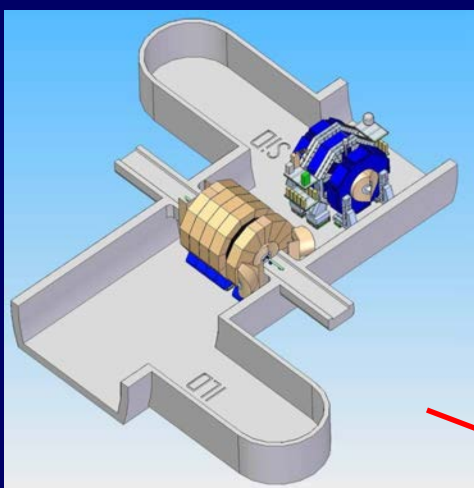
Test strings of cryomodules now in KEK and FNAL.

The DESY XFEL and SLAC LCLS-II now under construction are driving the industrialization of the cavities/cryomodules

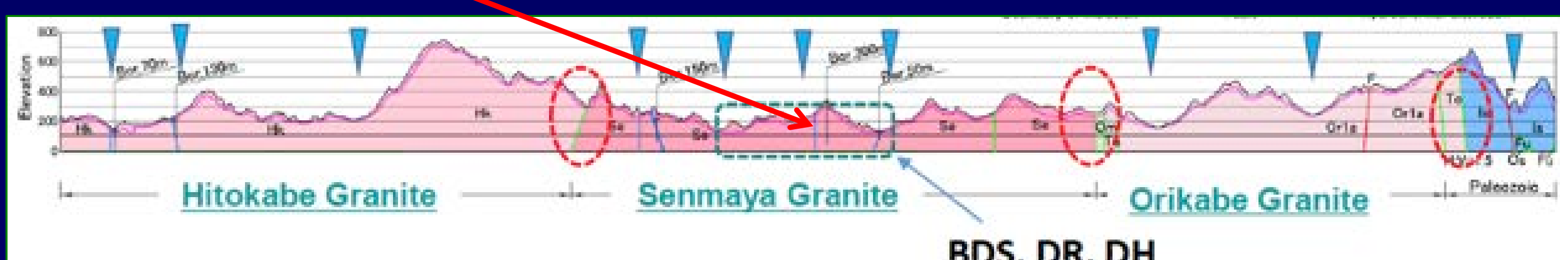
The ILC site

Work now underway to make the design specific to the planned site in northern Japan. Some simplifications made (2 → 1 tunnel, allow for LHC style vertical access, increase tunnel length by 10% for energy overhead).





Collision hall allows for two detectors – one on beam and other in garage. Push/pull the detectors every ~month



ILC Machine – high level parameters

Initial ILC: $\sqrt{s}$ = 250 – 500 GeV
Later can extend to 1000 GeV (lengthen tunnel, new higher gradient RF) and if desired, go down to $\sqrt{s} = M_Z$ and $2M_W$.

Run scenario: Initial set **500 fb^{-1} @ 500 GeV**, **200 fb^{-1} @ 350 GeV** and **500 fb^{-1} @ 250 GeV**, followed by luminosity upgrade and runs **3500**, **1500** fb $^{-1}$

About 20 years for full program including the initial learning curve and the luminosity upgrade.

Centre-of-mass energy	E_{CM}	GeV	500
Luminosity pulse repetition rate		Hz	5
Positron production mode			nom.
Estimated AC power	P_{AC}	MW	163
Bunch population	N	$\times 10^{10}$	2
Number of bunches	n_b		1312
Linac bunch interval	Δt_b	ns	554
RMS bunch length	σ_z	μm	300
Normalized horizontal emittance at IP	$\gamma\epsilon_x$	μm	10
Normalized vertical emittance at IP	$\gamma\epsilon_y$	nm	35
Horizontal beta function at IP	β^*_x	mm	11
Vertical beta function at IP	β^*_y	mm	0.48
RMS horizontal beam size at IP	σ^*_x	nm	474
RMS vertical beam size at IP	σ^*_y	nm	5.9
Vertical disruption parameter	D_y		24.6
Fractional RMS energy loss to beamstrahlung	δ_{BS}	%	4.5
Luminosity	L	$\times 10^{34}$	1.8
Fraction of L in top 1% E_{CM}	$L_{0.01}$	%	58
Electron polarisation	P_-	%	80
Positron polarisation	P_+	%	30
Electron relative energy spread at IP	$\Delta p/p$	%	0.13
Positron relative energy spread at IP	$\Delta p/p$	%	0.07

Cost is well understood, but high –

$7.8B (FY2013) for materials and supplies (no contingency, escalation) ,

13,000 person-years of labor at collaborating institutions.

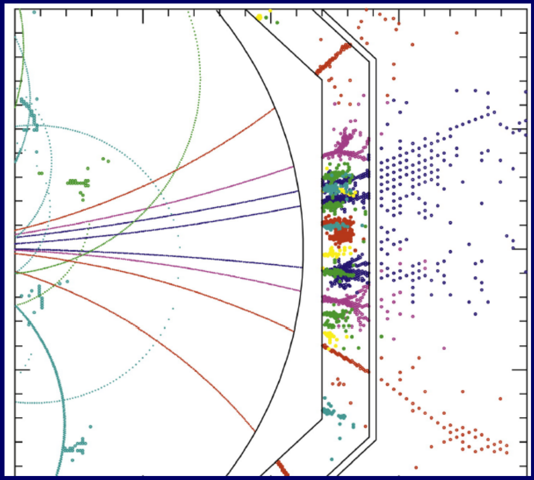
Thus, broad international collaboration is essential.

ILC Detectors

Primary design goals

1. Hermetic coverage for calorimetry ($\theta > 2.6^o$) and tracking($\theta > 8^o$)

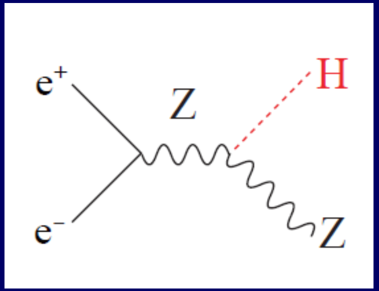
2. Jet energy resolution good enough to distinguish $W \rightarrow qq'$ and $Z \rightarrow qq$.



Particle Flow method: Build calorimetry with very fine transverse and longitudinal segmentation, small X_o & Moliere radius, so as to distinguish showers due to different particles. Ignore calorimeter clusters associated with charged particles and instead use the more precise track momentum. Calorimeter is used for γs and neutral hadrons.
Need jet $\delta E/E \sim 3\text{–}4\%$

This dictates that calorimeters are inside the solenoid magnet coil.

3. Track momentum resolution: $\delta p_T/p_T^2 = 5 \times 10^{-5}\ \mathrm{GeV}^{-1}$ (at high momentum). For example measure recoil Higgs mass in ZH production with $Z \rightarrow \mu\mu$. (Can measure H decaying to invisible particles.)

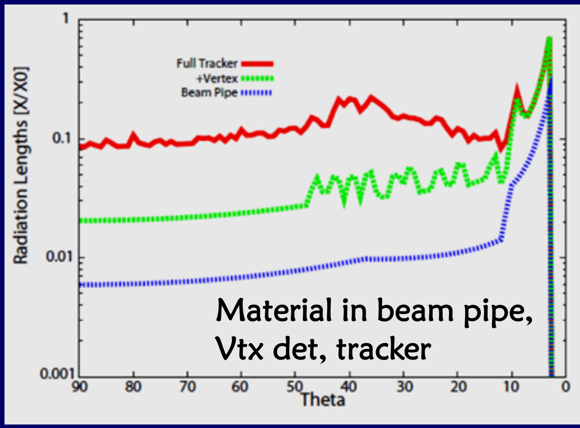


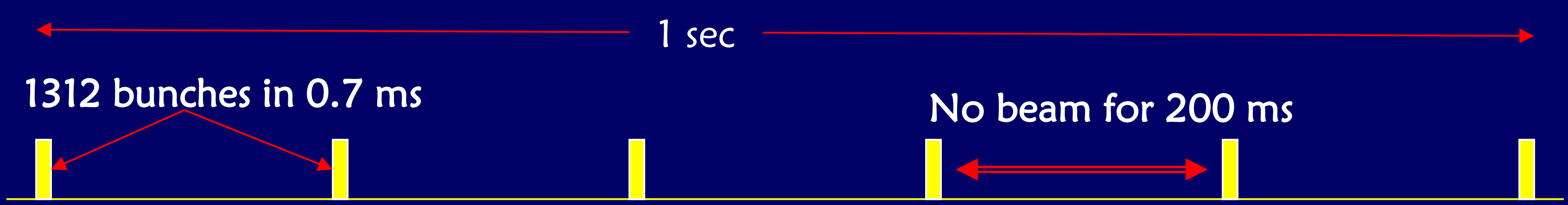
ILC Detectors

Primary design goals, cont'd:

4. Vertex detectors: Precise determination of separated vertices for b, c, τ identification. For example measurements of Higgs BRs to each particle species.
   $\delta d = 5\mu m + 10\ \mu m/p(GeV)\ \sin^{3/2}\theta$

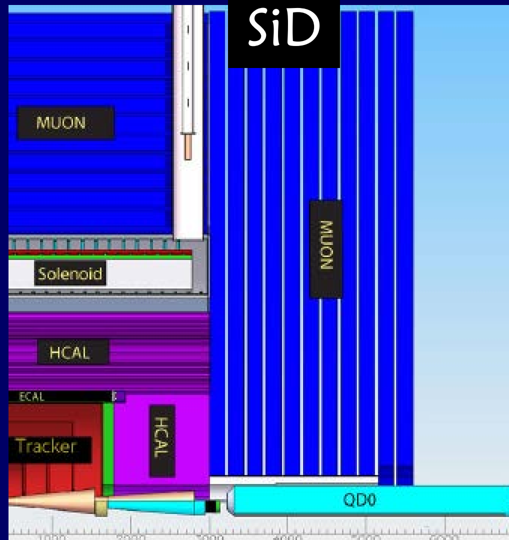
5. Minimize dead material in supports, cooling, cables etc. The ILC beam structure and low event rate permits reading out the full bunch train information at 5 Hz. During the quiet time between trains, lower the front end electronics voltages to reduce heat load (power pulsing). Provide a time stamp in individual detectors to specify which bunch within the train the information comes from.

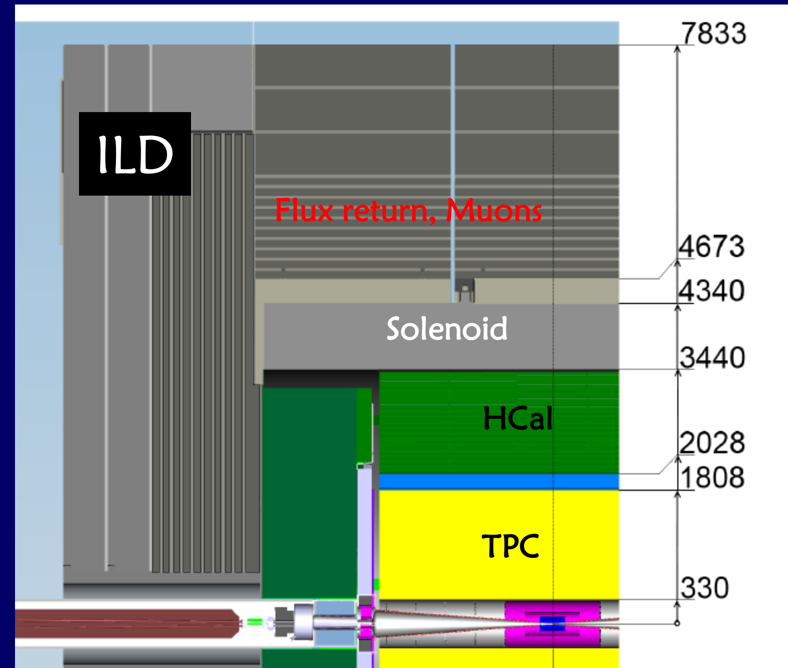




ILD and SiD Detectors

604.2 cm

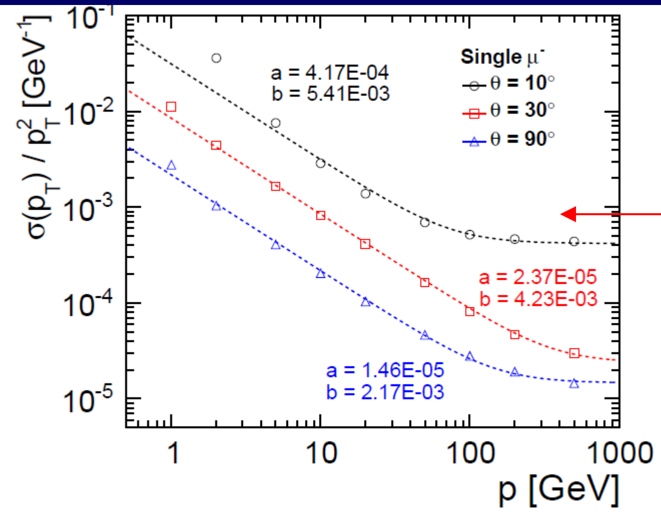




SiD	(* = similar choice)	ILD
* Si pixel vertex (CMOS, DEPFET, CCD, MAPS hybrid pixels, 3D, etc.)		
Si Strip: 5 barrel/4 disk	Tracking	TPC + auxiliary Si strips
W abs, Si pads	EM CAL	Scintillator/W (Si/W)
Fe/RPC digital readout	Had CAL	Fe/scint analog (RPC)
* Forward CALs (lumi meas) –Si, GaAs or CVD diamond sensors		
* Muons Scintillator strips/RPC		
5 T, 6.2 m dia	Solenoid (outside CAL)	3.5 T, 6.9 m dia

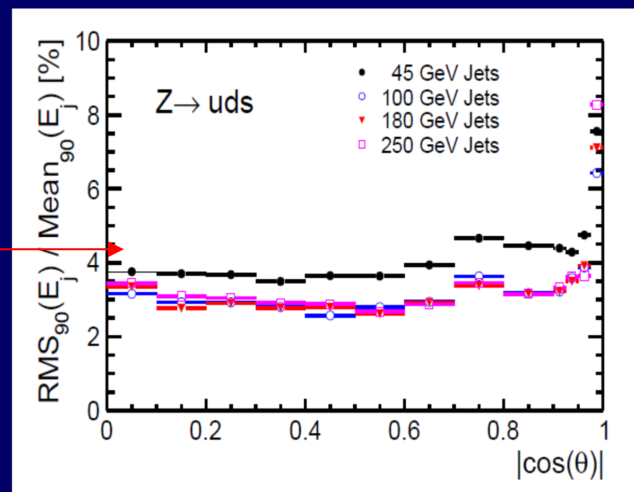
Detector performance

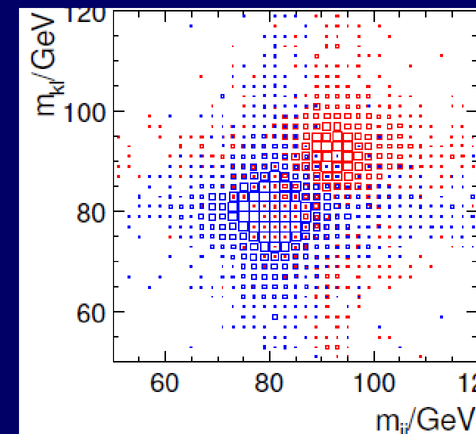
Full simulations (GEANT4) with all supports, cable plants, cooling, electronics. Simulations checked against test beam data.



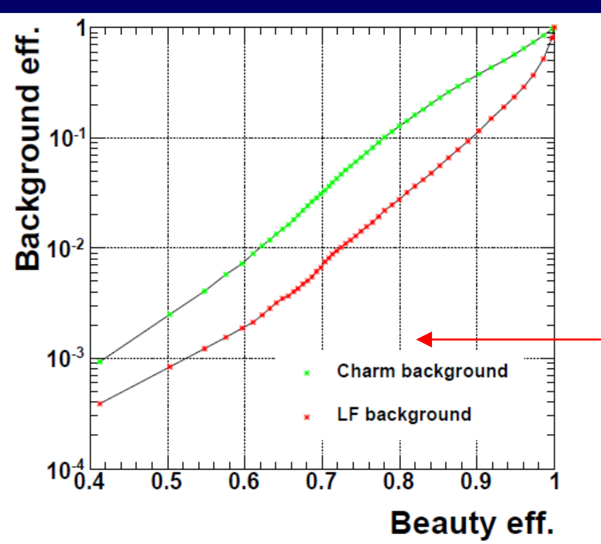
SiD tracking resolution

ILD jet energy resolution





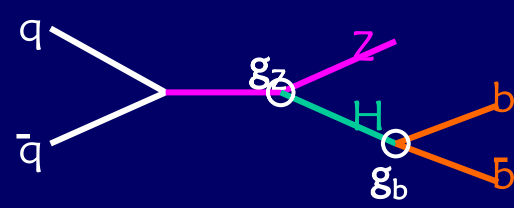
ILD: 4 jet WW vs. ZZ final states separated

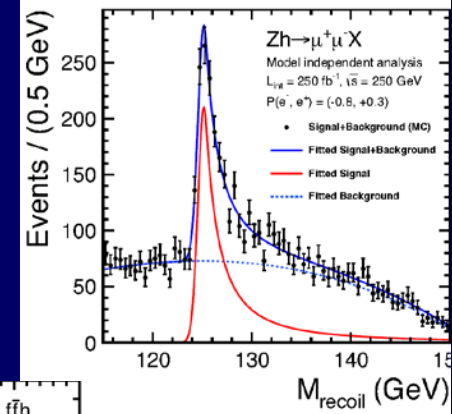


SiD flavor tagging efficiency for $Z \to bb$ vs. cc and light quark backgrounds

Both detectors meet/exceed specifications

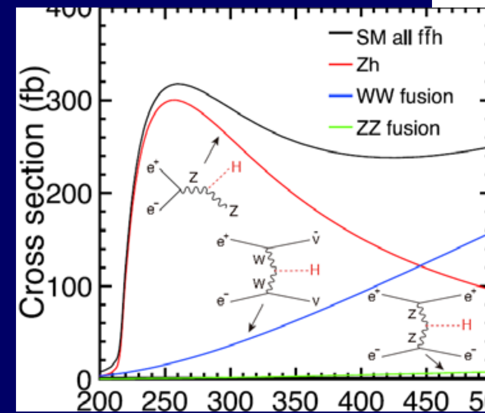
Physics program – Higgs



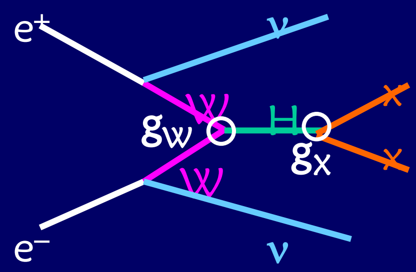


ILC Higgs production:

For √s < 250, 350 GeV, ee → ZH dominates. Can measure the Z precisely, so 'see' all decay modes of the recoiling Higgs, including invisible modes, and measure their BRs.



At 500 GeV, WW fusion of Higgs dominates.



For Higgs produced in collisions of AA and decay to BB, measured σxBR is $\sim g_A^2\,(g_B^2/\Gamma_{tot}) \sim$ BR(H→AA) x BR(H→BB) x Γ_{tot} where Γ_{tot} is the total Higgs width (~4 MeV).

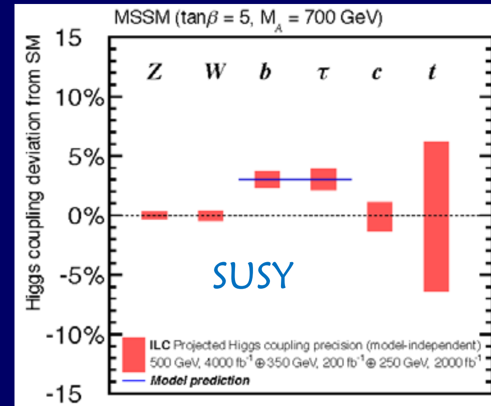
At LHC, cannot measure Γ_{tot} (cannot see all decay modes and mass resolution not good enough to resolve width directly).

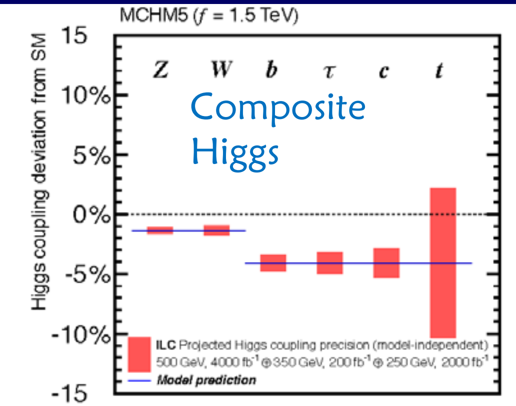
At ILC, measure σxBR(XX) in WW fusion with decay to XX. Know the BR(WW) and BR(XX) from recoil Higgs in ZH production and thus measure Γ_{tot} .

Thus can measure all Higgs couplings, g_X at ILC

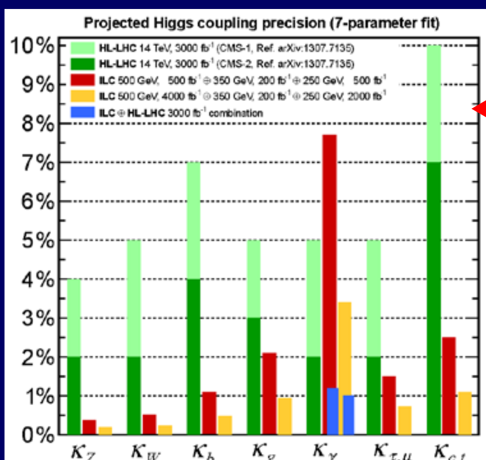
Physics program – Higgs

New physics alters the couplings from their SM values. The patterns of changes from SM differ for different New Physics models.



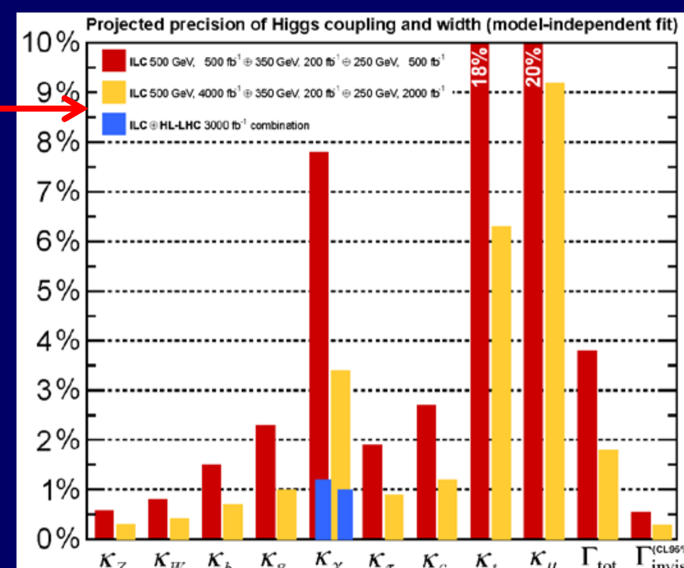


The differences between SM and new physics for allowed model parameter values is a few %, so one desires precision at the <1% level.



<u>**Assume**</u> Γ_{tot} is SM value and no unseen decays so as to compare LHC (green) and ILC (red/yellow). Blue bars require combined LHC and ILC.

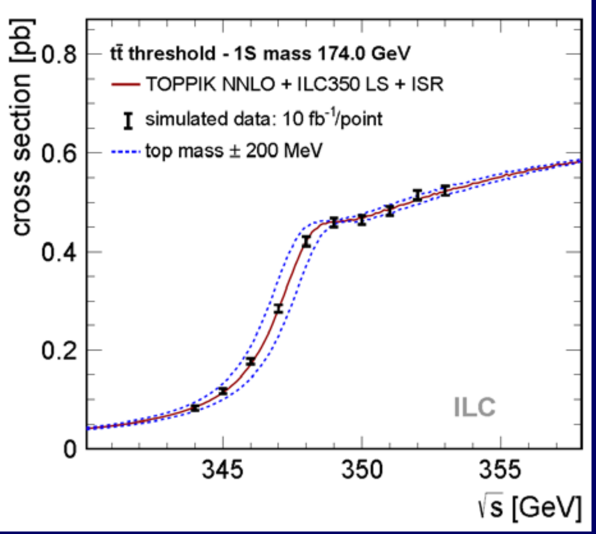
No model assumptions for ILC measurements.



Running at 550 instead of 500 GeV would halve $\delta\kappa_t$

Measure Higgs self coupling to 27% at 500 GeV; to 16% at 1 TeV.

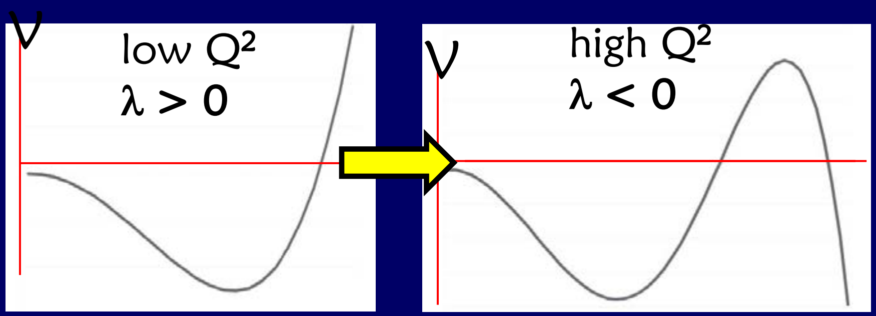
Physics program – top quark



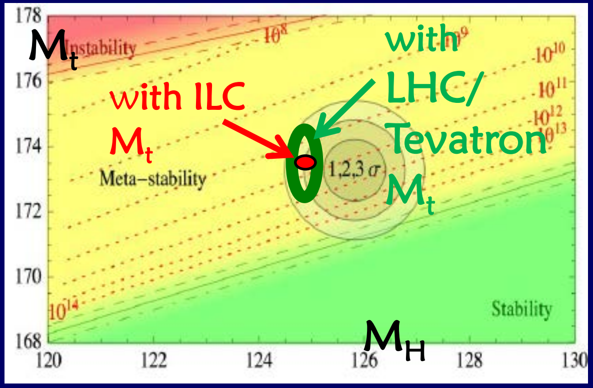
The top quark is unique among QCD objects in that it decays before the non-perturbative effects of hadronization occur. Thus it is an ideal laboratory for studies of QCD free of such effects.

ILC threshold scan measures the '1S' pole mass, which is well defined theoretically and can be converted to the $\overline{\mathrm{MS}}$ mass. (At hadron colliders, measure the MC mass whose theoretical meaning is uncertain at the level of ~1 GeV)

δm_t = 17 MeV (but NNNLO theory uncertainty ~50 MeV) $\delta\Gamma_t$=26 MeV



Current values of m_t and M_H make the running quartic term in the Higgs potential negative at large Q^2, thus producing a new minimum in potential and a metastable universe.

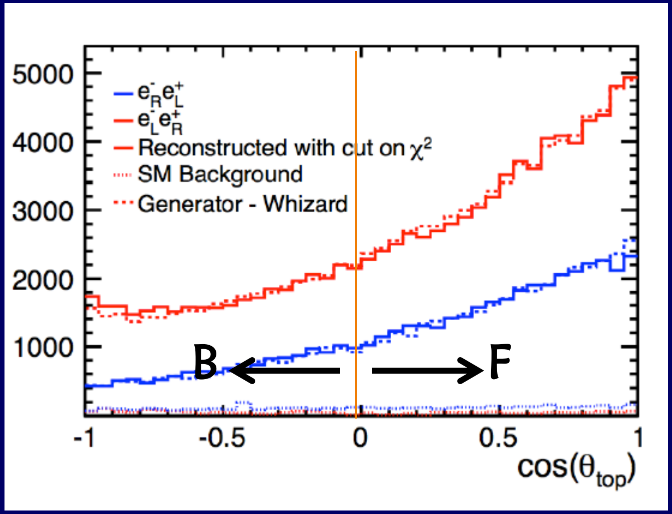


A precision top mass would give an interesting take on the instability of the SM universe (but leave the question of why we live in a universe so close to instability?)

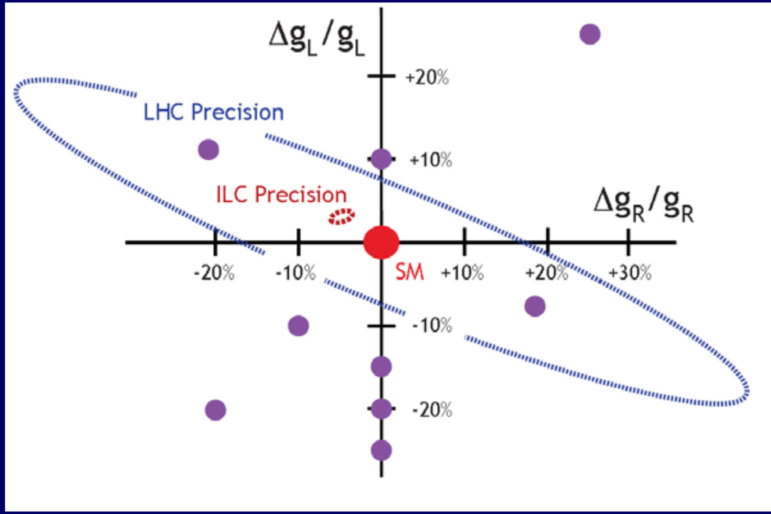
Physics program – top quark

The *s*-channel production of $t\bar{t}$ pairs by γ and Z interfere differently for left and right polarizations of incoming e^+ and e^-, producing F-B and polarization asymmetries.

Studying the production of $t\bar{t}$ with different beam polarizations allows the determination of the couplings of the Z (and γ) to the distinct L and R top quarks. Deviations of these couplings from the SM values are different for different new physics models. The LHC resolution is comparable to the size of these deviations. The ILC resolution is much smaller than the deviations.



Angular distributions of the top quark for different beam polarizations.

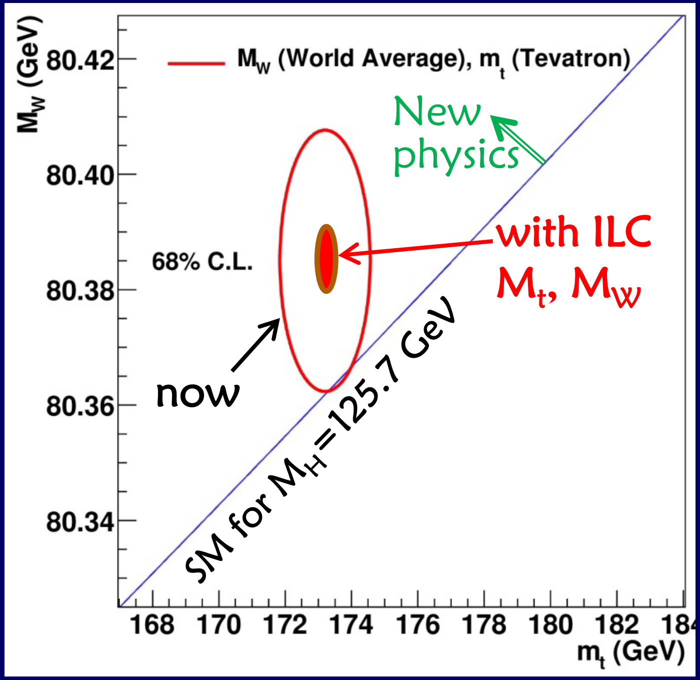


Fractional L and R top –Z couplings with expected error ellipses for LHC and ILC. The purple dots are predictions of different NP models.

Physics program – top, W and Higgs

The masses of the Higgs boson, top quark and W boson masses are inextricably connected. Their relationship is a bellwether test of the SM.

- Running the ILC at the WW pair threshold should enable the W mass measurement to 4x better than the current world average.
- At the ILC, measure top quark mass 5x better than current world average <u>and we will know what this mass means theoretically</u>.



ILC top and W measurements shown at the current central values. Lack of intersection of top–W ellipse with Higgs mass line would unambiguously signal New Physics.

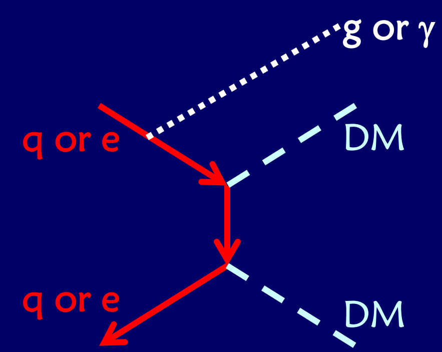
Physics program – new physics

We think of the LHC as the discovery machine for new heavy particles, but ILC will surpass it in many sectors. ILC can sense departures in $e^+e^- \rightarrow ff$ that are sensitive to new very massive states. Advantages for ILC new physics studies include:

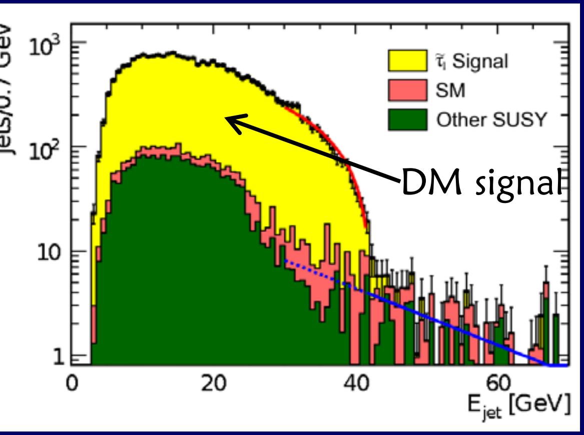
- Particles without strong interactions are better produced in lepton colliders (e.g. Supersymmetry gauginos, higgsinos, sleptons).
- Smaller backgrounds to new physics (and calculable) than LHC.
- Study with both L and R handed beam particles, thus improving the sensitivity of many searches and help in fixing backgrounds.
- ILC can do a threshold scan to obtain high precision mass and quantum number measurements.

Physics program – new physics

Dark Matter may be sensed through radiation of gluons from initial state quarks (LHC), or photons from initial state electrons (ILC). Similar processes for nearly invisible particles (e.g. Higgsinos) .



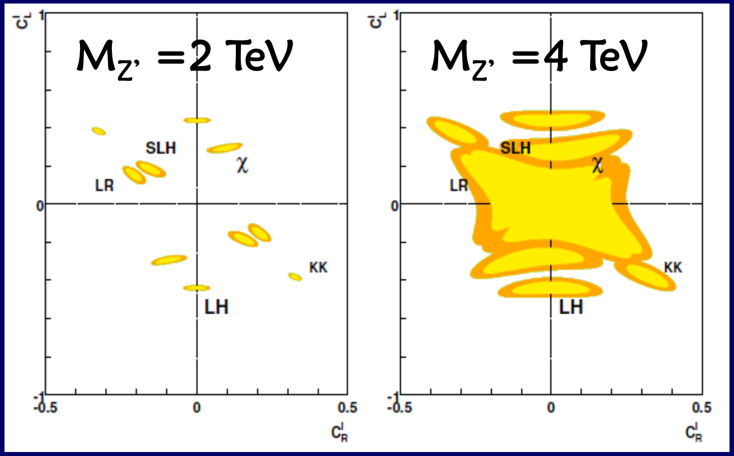
At LHC, these radiative processes have large backgrounds and are typically swamped.



At ILC, no trigger needed, so soft radiated photons can be seen, and backgrounds are small. If DM particle is close in mass to a charged particle C, the low energy decay pion in $C \rightarrow DM\ \pi$ can also be seen leading to reconstruction of the DM.

Hadronic decay product energy of τ in events of $\tilde{\tau}\tilde{\tau}$ production with $\tilde{\tau} \rightarrow \tilde{\chi}\tau$ ($M_{\tau} - M_{\chi} \sim 10$ GeV)

ILC (500 GeV) measurements of L- and R-handed couplings for $Z' \rightarrow f\bar{f}$ can tell us what kind of Z' is being produced. (Factor of 1.5 – 2 more reach than LHC)



We long for discovery of new physics at LHC! The ILC can then tell us what it is.

In summary

- e^+e^- and hadron colliders have traditionally provided complementary information
- The Higgs discovery raises important questions for which ILC is needed
- New information from the Intensity Frontier and Cosmic frontier will pose further questions (e.g. Majorana neutrinos, observation of dark matter in scattering from nuclei or annihilation in the sun)
- A e^+e^- collider need not be as high in $\sqrt{s}$ as LHC to compete, but higher energy than can be reached in circular e^+e^- machine is needed (top mass and couplings, searches for new phenomena, Higgs self couplings …)
- Possibilities for drive beam RF (CLIC), very large circular e^+e^- machines in China or CERN, muon colliders exist but none is yet technically ready to be built.
- The existence of a solid technical design, detectors that can achieve the physics goals, and a nation that is interested in hosting is a powerful argument for ILC.
- Strong support in strategy documents from all regions for ILC in Japan.