DPG Hamburg 2016

The International Linear Collider

Background Simulations & Optimizing the Final Focus Region

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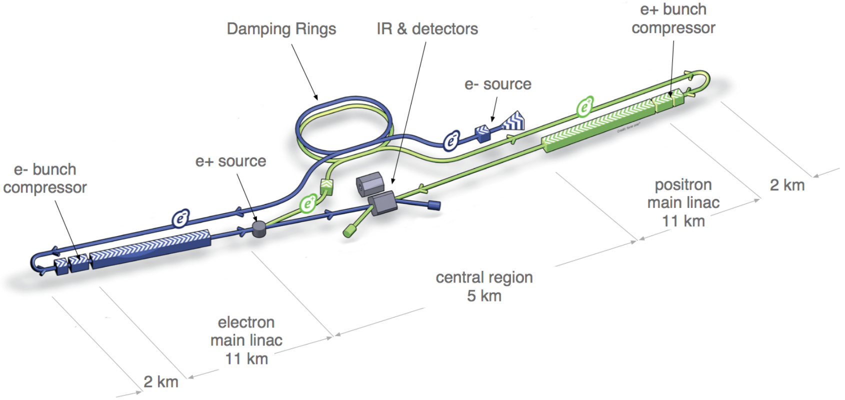
The layout of the ILC

e^+e^- linear collider:

- 30 km long
- adjustable center-of-mass energy
- polarized beams



The site of the ILC - The Kitakami mountains

The ILC is under consideration by the Japanese government!

The two detectors - SiD and ILD

The ILC has only one interaction point (IP)!
The two detectors can be swapped in the so-called **push-pull-system**.

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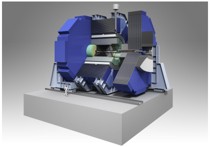
The two detectors can be swapped in the so-called **push-pull-system**.

SiD - Silicon Detector

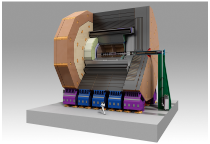
- Height: ∼14 m, length: ∼11 m
- Weight: ∼10 100 t
- Supercond. solenoid field: 5 T
- Full silicon tracker



→ SiD is a compact detector, designed for Particle Flow.

ILD - International Large Detector

- Height: ∼16 m, length: ∼14 m
- Weight: ∼14 000 t
- Supercond. solenoid field: 3.5 T
- TPC



The physics motivation of the ILC - Summary

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PRECISION MEASUREMENTS:

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PRECISION MEASUREMENTS:

- The initial particle energy is precisely known. There are no PDFs, as the initial particles are elementary.
- Due to the high energy resolution, peaks are now measurable that weren't measurable before. Particles with small mass difference are distinguishable.
- c-tagging is possible because of small distance between IP and the detectors (nano-sized beam)

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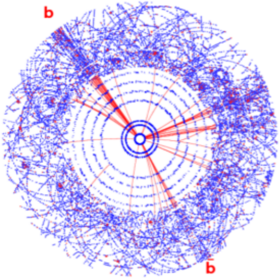
MODEL INDEPENDENT:

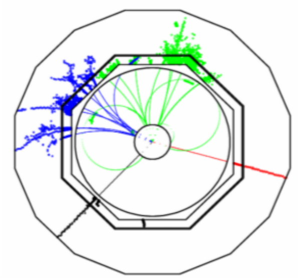
- The reactions will be measured and reconstructed in completeness. No theoretical assumptions have to be taken into account.
- New physics and BSM physics, which are not measurable at the LHC, are accessible.

Comparison between ILC and LHC event displays

The LHC $\mathrm{pp} \rightarrow \mathrm{H} + X$



The ILC $\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{HZ}$



Background simulation & Final-Focus optimization

THE MOTIVATION FOR MY PH.D

The ILC will be a high luminosity particle accelerator with extraordinary precision.

The high precision depends on the cleanliness, the high luminosity on the capability to focus the beam to nanometer size.

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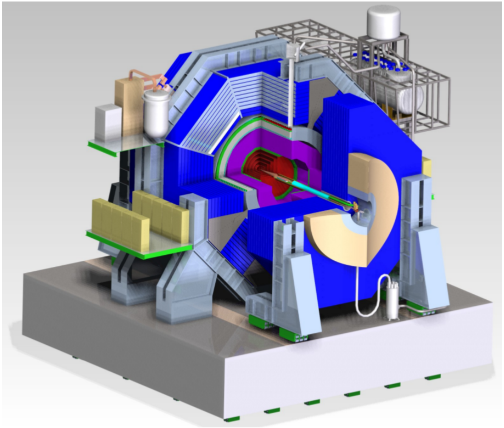
The high precision depends on the cleanliness, the high luminosity on the capability to focus the beam to nanometer size.

In order to minimize the effect of the background on the detectors and the measurements, the different background sources need to be modeled in great detail,
also with respect to a possible optimization of the Final-Focus layout.

SiD detector



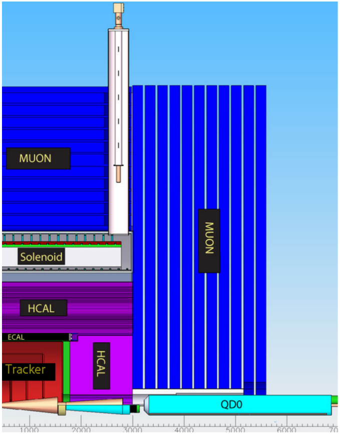
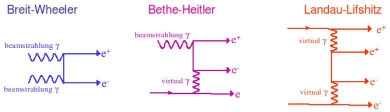


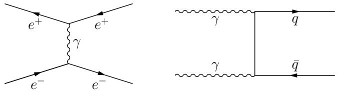
Figure 1 : SiD detector model: Vertex detector (red), ECAL (green), HCAL (pink), Muon system (blue)

Background sources

The main sources of background:

- Pair background
- Bhabha scattering
- $\gamma\gamma \rightarrow$ hadrons
- Neutrons from the beam dumps
- Background from Final-Focus system (beam halo collimators, muon spoilers)





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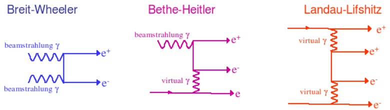
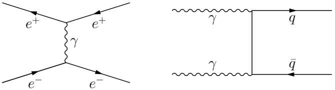




⇒So, if the ILC is supposed to see such clean signals, the question is:

With all these background sources, how many background events do the detectors get?

Pair background

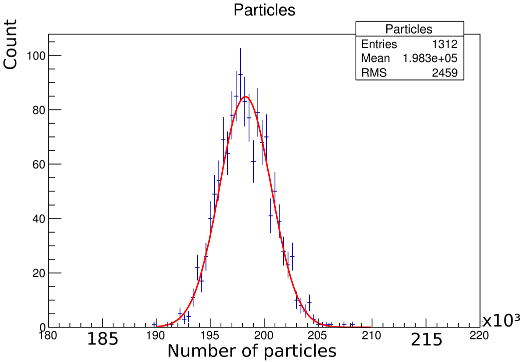
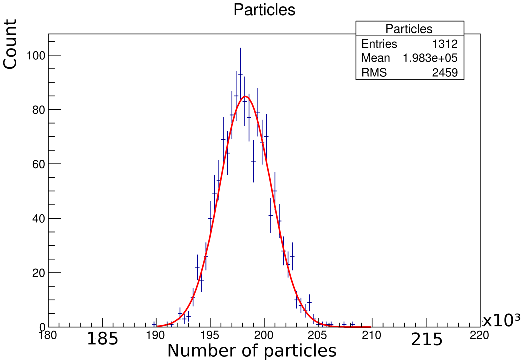


Figure 2 : Distribution of number of pair background particles per bunch crossing hitting the detector.

Per bunch, there are about 200 000 pair background particles, in the whole detector.

Pair background



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In comparison:
$e^+e^- \to ZH \to 4$ jets: ~ 80 final state particles

Hits in the SiD - EcalEndcaps

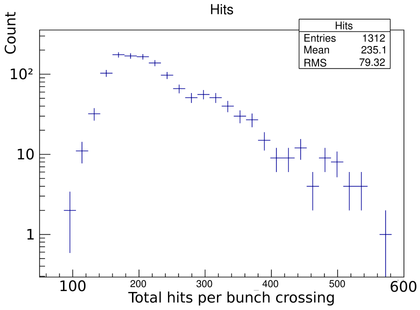


Figure 3 : Hits of pair background particles from a full train in the EcalEndcaps

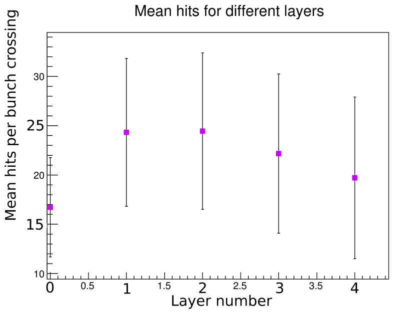
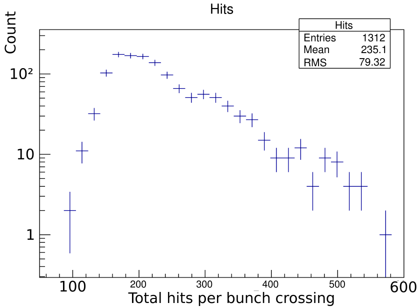


Figure 4 : Comparison of the MEAN number of hits in the first 5 layers of the EcalEndcaps.

In the EcalEndcaps only, there are about 200 hits per bunch crossing.

The mean number of hits per layer is between 15 and 25 hits, per full bunch crossing!

Hits in the SiD - EcalEndcaps



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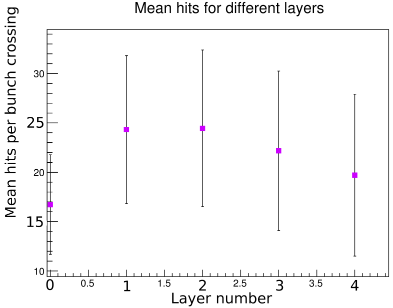

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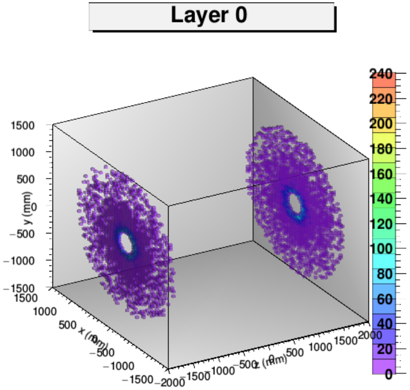
In comparison:

$e^+e^- \rightarrow ZH \rightarrow 4$ jets: $\sim$ 2100 hits in the EcalEndcaps Go to event display

3D hit map animation of the EcalEndcaps



Most of the hits are around the beam pipe → Ring of fire

Pair background origins

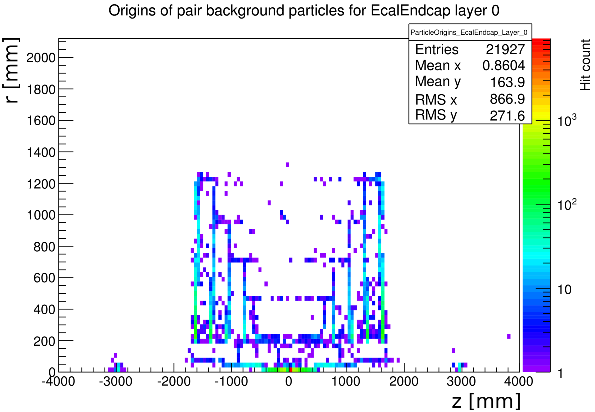
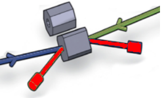


Figure 5 : 2D map of the origins of the pair background particles that hit the EcalEndcap layer 0.

Most of the background particles are coming from the IP as expected. But there are a lot of particles backscattering from the tracker layers and the BeamCal.

FLUKA simulation of the ILC Beam Dump



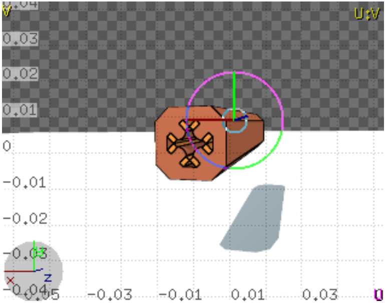


Figure 6 : FLUKA simulation model of one of the ILC lattice quadrupoles.

- The beam is dumped into a water tank after collision.
- Neutrons are emitted that radiate the surroundings.
- Neutrons fly back towards the detectors.

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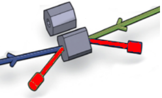

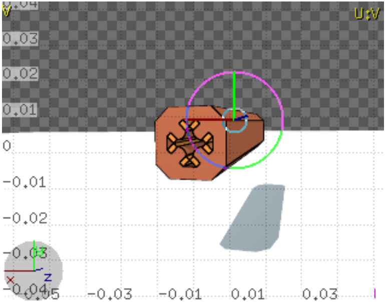

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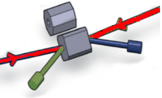
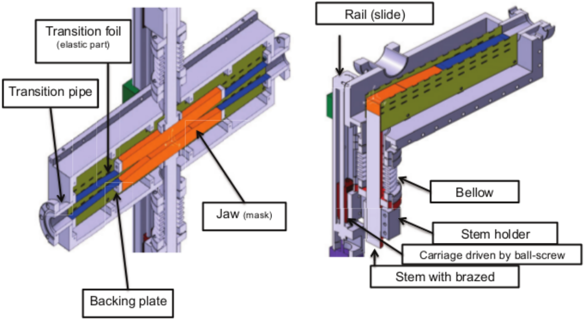
Simulation

Pluging the real extraction line lattice into FLUKA
Realistic simulation of the interaction between the neutrons,the lattice and the detectors.

Beam Halo collimators





By driving collimator blocks into the beam:

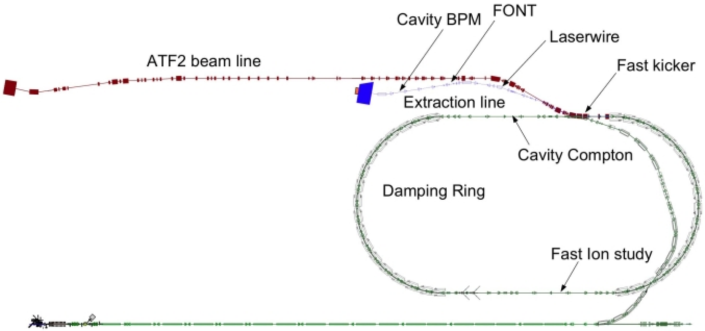
- The beam halo is cut off.
- New background is produced.

Beam time at ATF2 in March

I will be joining ATF2 in March, thanks to the E-JADE program (www.e-jade.eu).

ATF2 is the ILC Final-Focus test bench at KEK in Japan, where the March beam time is dedicated to:

- Installing a new beam halo collimator
- Measuring the beam size and the beam halo
- Studies of the generated background with Cherenkov detectors



Thanks!

どうもありがとうございます。

References

- T. Behnke, et al. *The International Linear Collider - Technical Design Report*, 2013.
- *LHC - Design Report*, http://ab-div.web.cern.ch/ab-div/Publications/LHC-DesignReport.html
- ATLAS-CONF-2010-027. *Characterization of Interaction-Point Beam Parameters Using the pp Event-Vertex Distribution Reconstructed in the ATLAS Detector at the LHC*, 2010. http://cds.cern.ch/record/1277659/files/ATLAS-CONF-2010-027.pdf
- M. Peskin. *Physics Motivation for the ILC*, 2012. http://www.fnal.gov/directorate/ILCPAC/2012Dec/Physics-ILCPAC2012-Peskin.pdf

References

- Klute, Markus, Rémi Lafaye, Tilman Plehn, Michael Rauch, and Dirk Zerwas. *Measuring Higgs Couplings at a Linear Collider* EPL (Europhysics Letters) 101, no. 5 (March 1, 2013): 51001. http://dx.doi.org/10.1209/0295-5075/101/51001
- Mark Thomson. *Physics and Detectors at the ILC*, 2013. https://www.royalholloway.ac.uk/physics/documents/pdf/events/particlephysicsseminars/13-14markthomson23oct2013.pdf
- Kuroda et al. *A plan of KEK-ATF Final Focus Test Beam Line (ATF2)* . http://icfa-nanobeam.web.cern.ch/icfa-nanobeam/paper/urakawa_ATF2-2.pdf

Additional Material

Why linear?

Basic limitations of lepton synchrotons:

- Energy loss due to synchrotron radiation: $\sim E^4/R$
- Cost $\sim$ quadratically with energy
  (B. Richter 1980)

$$P_S = \frac{e^2 c}{6\pi\epsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

$$\Delta E = \frac{e}{3\epsilon_0 (m_0 c^2)^4} \frac{E^4}{R}$$

Therefore a linear collider:

- Not limited by synchrotron radiation
- Cost $\sim$ linear with energy

The beam parameters of the ILC compared to LHC

		Baseline 500	Lumi Upgrade	TeV Upgrade	LHC 25ns
E_{CM}	[GeV]	500	500	1000	14 000
n_b		1312	2625	2450	2808
Δt_b	[ns]	554	366	366	25
N		2.0×10^{10}	2.0×10^{10}	1.74×10^{10}	11.5×10^{10}
q_b	[nC]	3.2	3.2	2.7	18.4
σ_x^*	[nm]	474	474	481	16 700
σ_y^*	[nm]	5.9	5.9	2.8	16 700
σ_z	[mm]	0.3	0.3	0.25	0.755
L	[$cm^{-2}\,s^{-1}$]	1.8×10^{34}	3.6×10^{34}	3.6×10^{34}	1.0×10^{34}

ILC baseline parameters

Centre-of-mass energy	E_{CM}	GeV	200	230	250	350	500
Luminosity pulse repetition rate		Hz	5	5	5	5	5
Positron production mode			10 Hz	10 Hz	10 Hz	nom.	nom.
Estimated AC power	P_{AC}	MW	114	119	122	121	163
Bunch population	N	$\times 10^{10}$	2	2	2	2	2
Number of bunches	n_b		1312	1312	1312	1312	1312
Linac bunch interval	Δt_b	ns	554	554	554	554	554
RMS bunch length	σ_z	μm	300	300	300	300	300
Normalized horizontal emittance at IP	$\gamma\epsilon_x$	μm	10	10	10	10	10
Normalized vertical emittance at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
Horizontal beta function at IP	β_x^*	mm	16	14	13	16	11
Vertical beta function at IP	β_y^*	mm	0.34	0.38	0.41	0.34	0.48
RMS horizontal beam size at IP	σ_x^*	nm	904	789	729	684	474
RMS vertical beam size at IP	σ_y^*	nm	7.8	7.7	7.7	5.9	5.9
Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6
Fractional RMS energy loss to beamstrahlung	δ_{BS}	%	0.65	0.83	0.97	1.9	4.5
Luminosity	L	$\times 10^{34}$ cm^{-2} s^{-1}	0.56	0.67	0.75	1.0	1.8
Fraction of L in top 1% E_{CM}	$L_{0.01}$	%	91	89	87	77	58
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30
Electron relative energy spread at IP	$\Delta p/p$	%	0.20	0.19	0.19	0.16	0.13
Positron relative energy spread at IP	$\Delta p/p$	%	0.19	0.17	0.15	0.10	0.07

ILC parameters for the different upgrade stages

Centre-of-mass energy	E_{CM}	GeV	Baseline 500	1st Stage 250	L Upgrade 500	TeV Upgrade A 1000	TeV Upgrade B 1000
Collision rate	f_{rep}	Hz	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	5	10	5	4	4
Number of bunches	n_b		1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	366	366	366
Pulse current	I_{beam}	mA	5.79	5.8	8.75	7.6	7.6
Average total beam power	P_{beam}	MW	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	μm	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	11.0	13.0	11.0	22.6	11.0
IP vertical beta function (no TF)	β_y^*	mm	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	474	729	474	481	335
IP RMS veritcal beam size (no TF)	σ_y^*	nm	5.9	7.7	5.9	2.8	2.7
Luminosity (inc. waist shift)	L	$\times 10^{34}$ cm^{-2}s^{-1}	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	344.1	46.5	344.1	1338.0	3441.0

The physics motivation of the ILC

Cleanliness - Democracy - Calculability - Detail

- Small background
- Small detector occupancy
- Smaller energy range
- No out-of-time pileup or underlying events

- Elementary coupling e of γ the same for all quarks & leptons
- e^+e^- annihilation produces pairs of all species, SM & exotics, at similar rates
- No triggers

- Pointlike elementary particles in initial state
- Coupling only to EW interactions
- No sys. uncert. due to PDF uncertainties and QCD corrections

- Reconstruction of complete events
- Quark & lepton momenta determined by kinematic fits
- Study of spin-dependence of production & decay process

The physics motivation of the ILC - Higgs factory

- Higgs factory
  Fraction of the total cross section for Higgs production:
  In pp: 10^{-9}, in e^+e^-: $10^{-2} \approx 1\%$
- Each individual Higgs coupling will be measured to a percent accuracy, and the global width of the Higgs can be measured directly: LHC experiments have to make a global fit to all Higgs signals (plus using theoretical assumptions of the width), in order to get the Higgs couplings $\rightarrow$ can never be as precise as at the ILC

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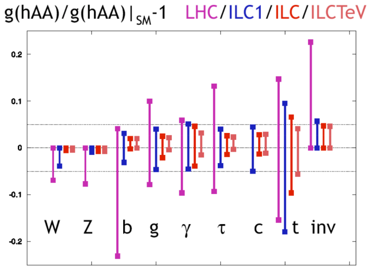
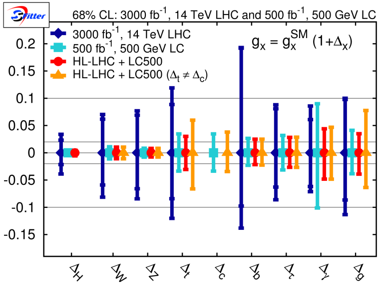
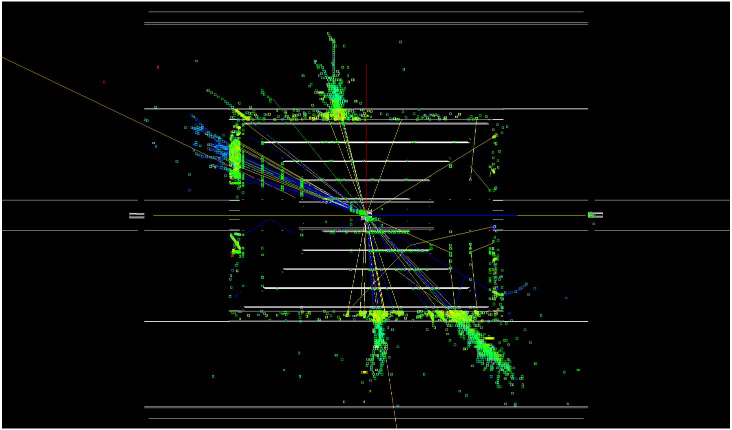




$e^+e^- \to ZH \to 4$ jets in the SiD detector



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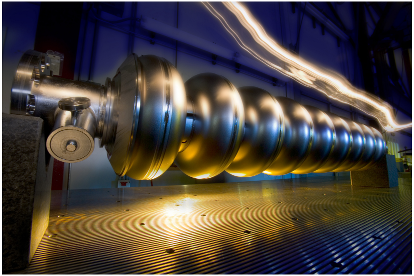
Basic accelerating structure

The main accelerating structures are the two 11km long LINACs.

- 9-cell superconducting RF cavities operating at 1.3 GHz
- Accelerating gradient of $>$30 MV/m
- Electrons and positrons accelerated in RF standing waves in the cavities

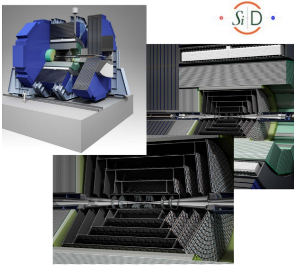


The cavities are also developed, built and tested at DESY.

SiD detector

SiD has a very convincing design:

- compact and robust
- full silicon vertex detector and tracker
  Vertex detector:
  - $<5\,\mu m$ resolution
  - Momentum resolution $\sim$ 2-5 $\times 10^{-5}$ GeV^{-1}
  - $\sim 0.1\,\%$ X_0 per layer
  - Single bunch timing resolution
  - $\cos(\theta)\approx 0.984$
- highly granular calorimetry optimized for Particle Flow (ECAL: radiation length $= 26\ X_0$, EM energy resolution $= 0.17/\sqrt{E} \bigoplus 1\%$)



Simulation tools

The background is first modeled in different simulation tools:

- GuineaPig (Generator of background events from beam-beam interactions)
- BDSIM (Geant4 based extension toolkit for beam line simulations)
- FLUKA (Fully integrated particle physics MonteCarlo simulation package)

The background events are then simulated in a full detector simulation with a Geant4 toolkit.

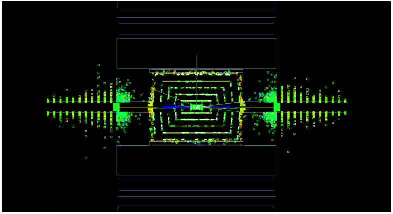


Figure 7 : The inner detector part of SiD. WIRED4 event display of the pair background of one bunch crossing.

Hit maps of the inner most EcalEndcap layer

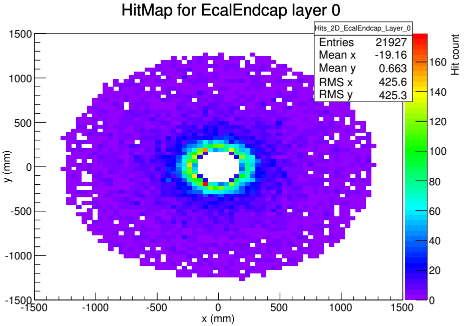


Figure 8 : 2D hit map of the hits from a full pair background train in the EcalEndcap layer 0.

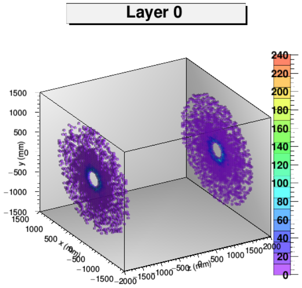


Figure 9 : 3D hit map of the hits from a full pair background train in the EcalEndcap layer 0.

Most of the hits are around the beam pipe → Ring of fire

Absolute time of hits in the EcalEndcaps

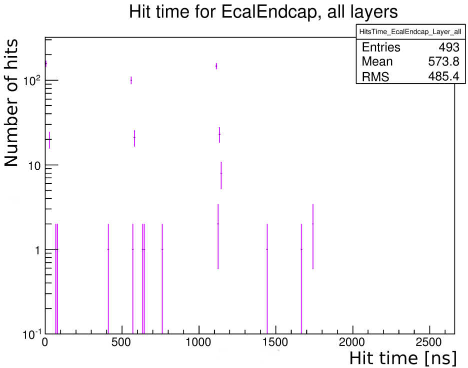


Figure 10 : Number of particles arriving at the EcalEndcaps as a function of the absolute time.

The pair background particles don't arrive all at the same time.
The second smaller peak of particles are backscatter particles.

Absolute time of hits in the EcalEndcaps

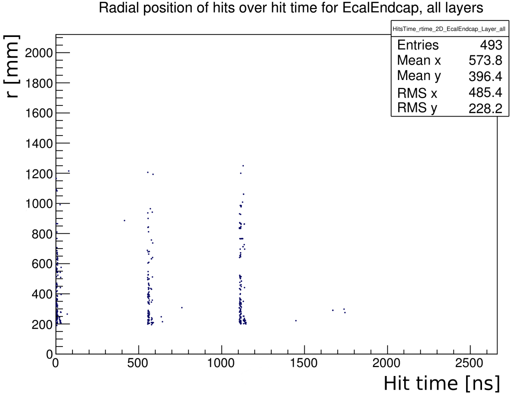


Figure 10 : The radial position of the particles arriving at the EcalEndcaps.

The pair background particles don't arrive all at the same time.
The second smaller peak of particles are backscatter particles.

Energy deposition of hits in SiD-EcalEndcaps

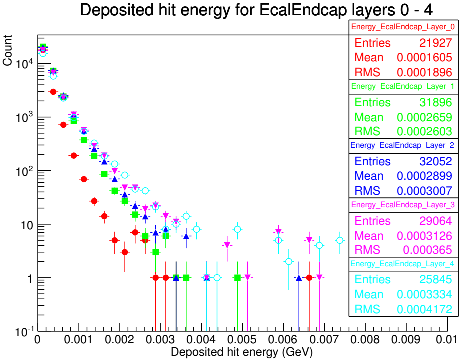


Figure 11 : Energy distribution of the hits in the first five layers of the SiD EcalEndcaps

The distributions reach up to about 8 MeV.

The Final-Focus system

The Final-Focus (FF) uses:

- Strong compact superconducting quadrupoles to focus the beam at the IP (single collision point with a 14 mrad beam-crossing angle)
- Sextupoles providing local chromaticity correction
- Two superconducting octupole doublets, which use nonlinear focusing to reduce the amplitude of beam-halo particles while leaving the beam core untouched $\rightarrow$ permitting larger collimation amplitude
- Collimators and spoilers to prevent the beam halo and background particles from entering the detectors

Accelerator Test Facility 2

ATF2

- Extension of the Accelerator Test Facility (ATF) at KEK in Japan
- Test bench for the Final-Focus system of the ILC $\rightarrow$ very close to the ILC 500
- Achieving 42 nm beam size (goal: 39 nm)