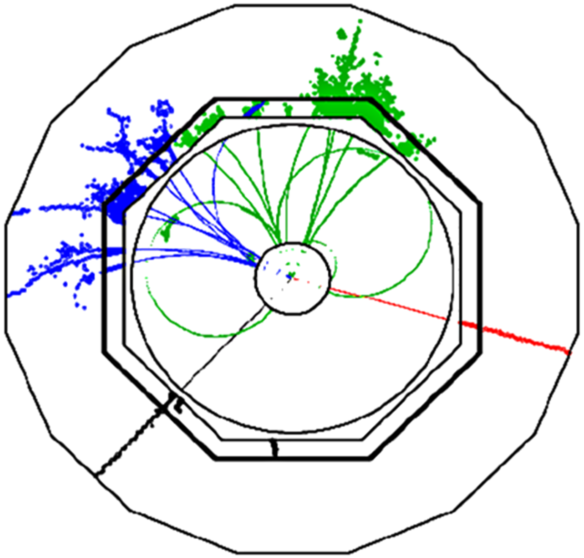
Beam Polarisation at the ILC: Physics Case and Realisation.

Annika Vauth

SPIN 2014, Beijing

Introduction: the ILC.

Motivation for a linear lepton collider.



$e^+e^- \rightarrow HZ$

Electron positron colliders

- pointlike particles
- well defined initial state
- precision machines
- discovery potential

Advantage of linear collider

- no energy loss due to synchrotron radiation
- extendable (length $\rightarrow$ energy)

ILC history.

Since early 90s different LC studies

TESLA (SCRF)

NLC/JLC (normal conducting)

2004 technology decision: SCRF

2004 ILC Global Design Effort founded

2007 ILC Reference Design Report

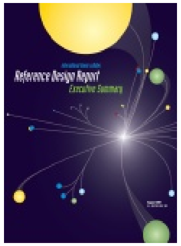
2009 LOI for detector concepts

2012/13 ILC Technical Design Report

since 2012/13: Linear Collider Collaboration

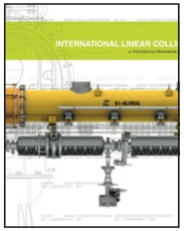
- ILC: Higgs/Top factory
  possible realisation in Japan
- CLIC: multi-TeV, on longer timescale
  (next energy frontier project in Europe?)

2007



2009

2011



2013

ILC in Japan.

Japanese HEP community put the ILC high on their roadmap

Japanese government is interested to host ILC in Japan:

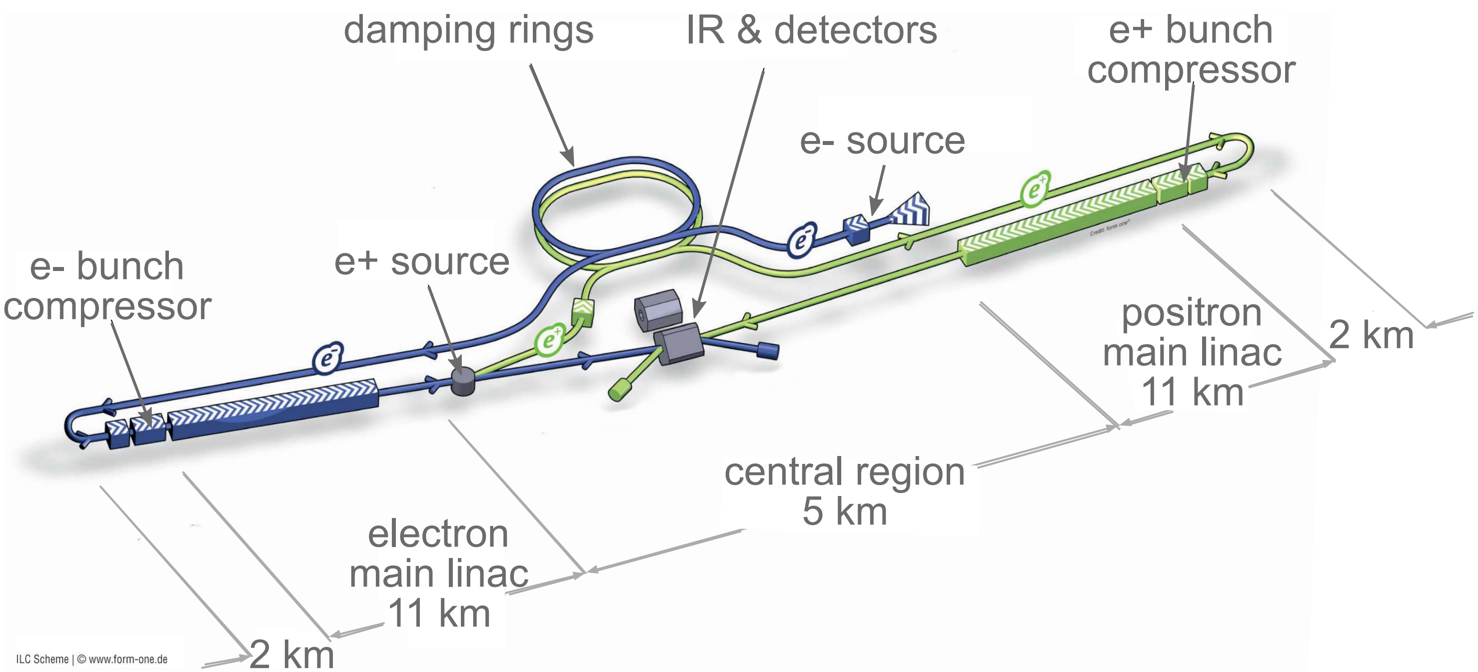
- Support for ILC in Japanese parliament (Diet) is multi-partisan
- government has started international initiative
- MEXT has assigned 50 MJPY project money to ILC

2010: two candidate sites (Sefuri and Kitakami)

August 2013: Kitakami site chosen

ILC overview.

- Planned e^+e^- collider (length $\approx 30\,\text{km}$)
- Energy up to $\sqrt{s} = 500\,\text{GeV}$, potential upgrade to 1 TeV
- Technology: superconducting RF-cavities



[ILC TDR vol. 1, 2013]

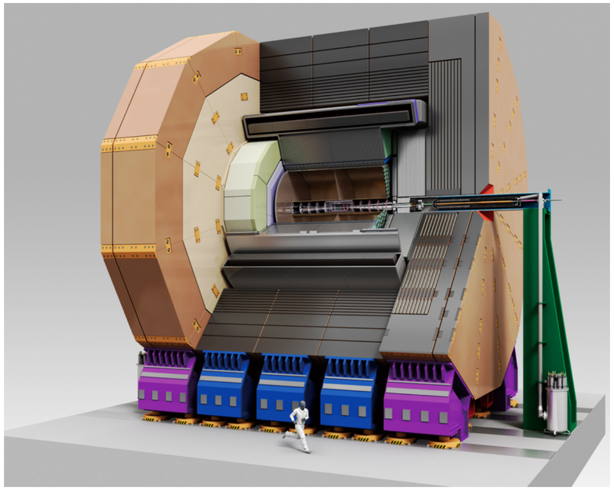
Detectors for physics measurements.

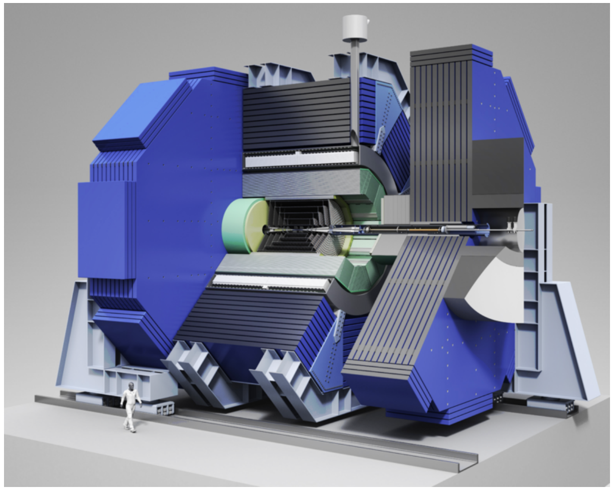
Two detector concepts: ILD and SiD

Use push-pull system at interaction region

Both detectors use particle flow algorithm:

- measure each particle type in the most appropriate subdetector (charged particles → tracker, photons → ECAL, neutral hadrons → HCAL)
- low material budget for the vertex detector and tracker
- high granularity calorimeters



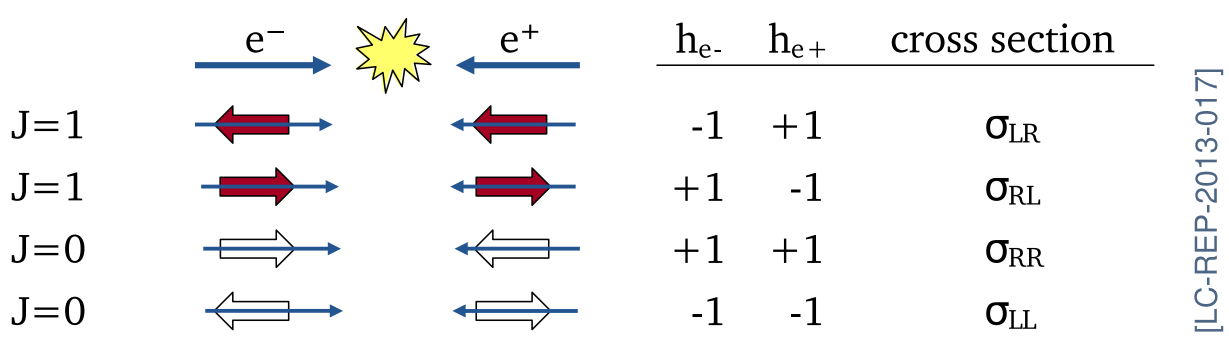


[linearcollider.org]

Physics case for beam polarisation.

Precision physics at ILC.

- Cleanliness calculability
- Tune-able center-of-mass energy
- Polarised beams: $P(e^+) \gtrsim 30\%$, $P(e^-) \approx 80\%$
  - polarisation asymmetry as observable
  - enhanced rates and background suppression for $e^-_L e^+_R$ (Standard Model) or $e^-_R e^+_L$ (new physics searches)
  - access to chirality of new particles



ILC physics program.

Polarisation benefits for major physics studies:

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'
	$e^+e^- \to tth$	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

[ILC TDR vol. 2, 2013]

polarisation asymmetry as observable

SM: $e^+_R e^-_L$ enhance rates / suppress BG

opposite polarisations enhance luminosity

NP: $e^+_L e^-_R$ enhance rates / suppress BG

Top electroweak coupling.

Top quark production at ILC through electroweak processes

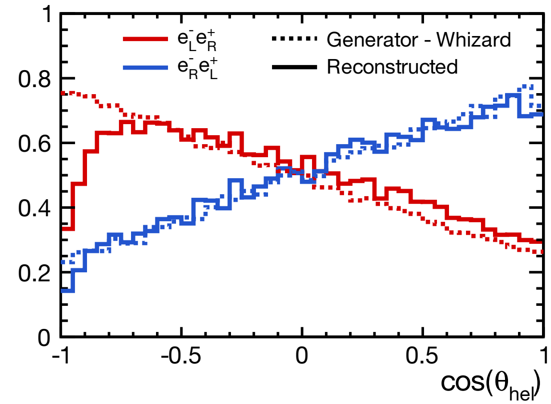
no competing QCD production

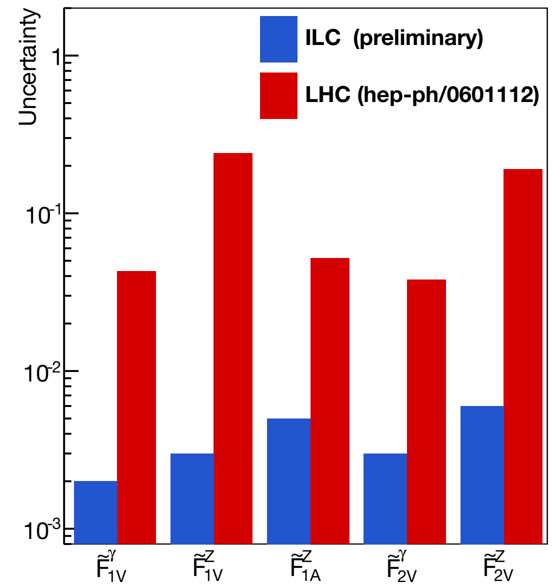
→ small theoretical errors

Polarised beams allow to test chiral structure at ttX vertex

- cross sections
- forward-backward asymmetry
- helicity angle distribution

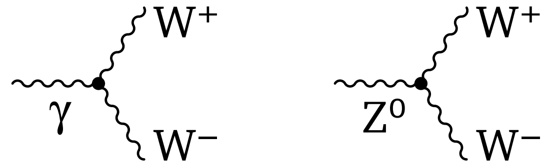
→ precision on form factors
sensitive to new physics





[LC-REP-2013-007]

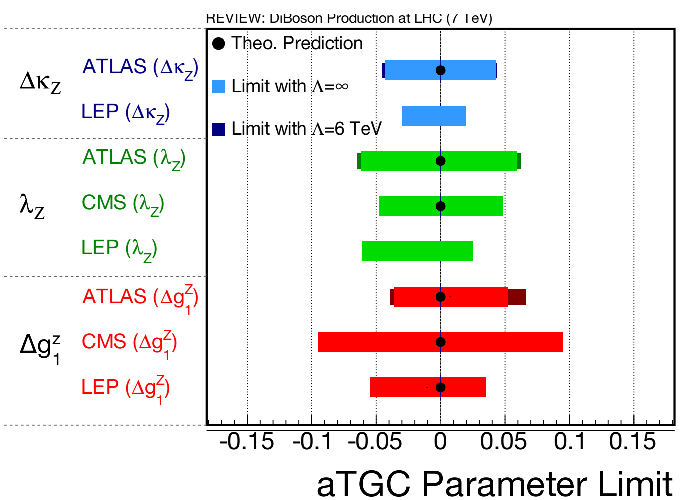
Trilinear gauge boson couplings (TGC).



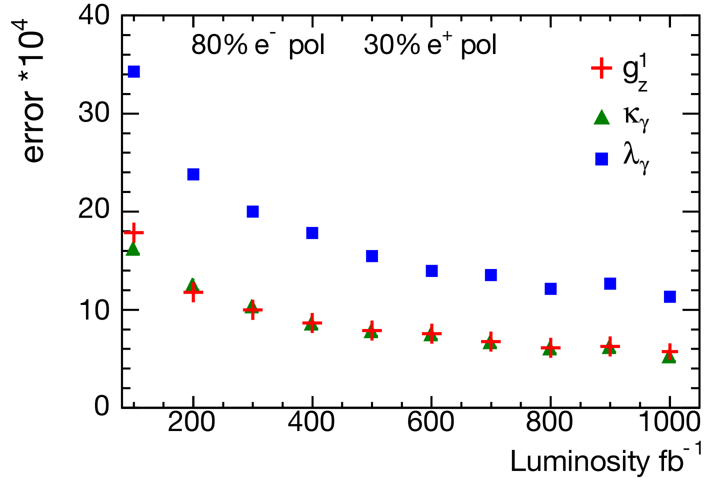
Current experimental status
on charged TGCs in WW production:
few percent precision from single parameter fits (LEP & LHC)

Study of *WWZ* and $WW\gamma$ at ILC:

Beam polarisation increases sensitivity to deviations from the standard model & allows to disentangle couplings
$\rightarrow$ resolutions of few 10^{-4} in simultaneous fit



[hep-ex/1406.7731]

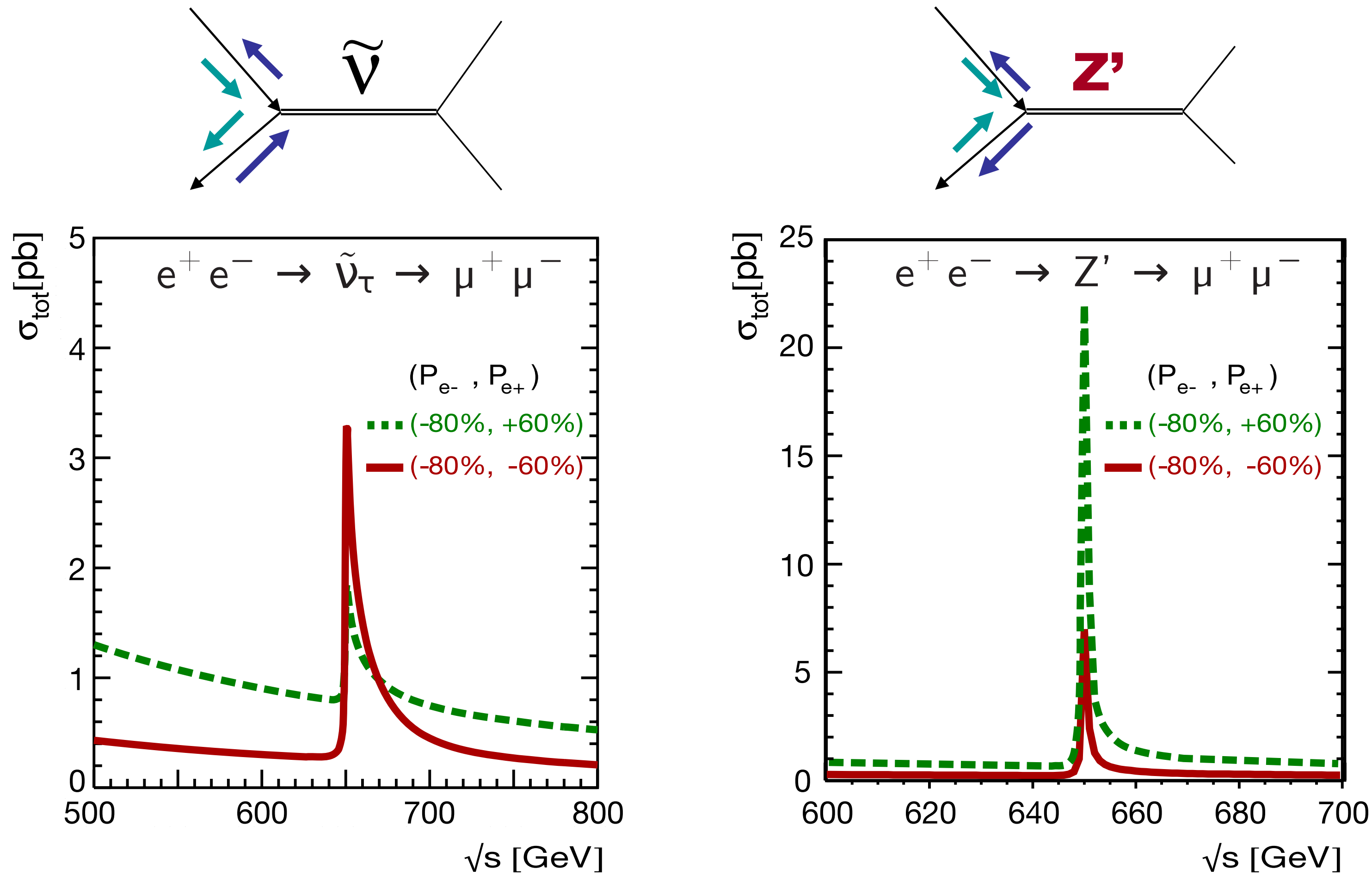


[LC-DET-2009-003]

Model distinction.

Polarisation can improve distinction between physics models.

Example: R-parity violating SUSY (spin 0) or Z' (spin 1)?



[hep-ph/0509099]

Precision observables.

What if nothing beyond the standard model is found?

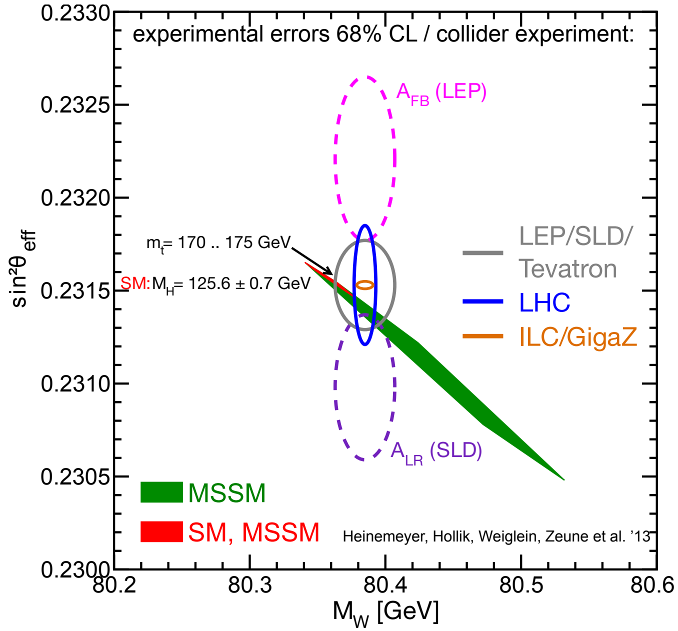
$\sin^2\theta_{\text{eff}}$ can be crucial quantity to reveal effects of new physics

LEP:
$\sin^2\theta_{\text{eff}}(A^{\text{b}}_{\text{FB}}) = 0.23221 \pm 0.00029$

SLC:
$\sin^2\theta_{\text{eff}}(A_{\text{LR}}) = 0.23098 \pm 0.00026$

World average:
$\sin^2\theta_{\text{eff}} = 0.23153 \pm 0.00016$

Goal ILC "GigaZ" ($\sqrt{91\text{ GeV}}$):
$\Delta\sin^2\theta = 1.3 \cdot 10^{-5}$



[hep-ph/1310.6708]

Precision measurement via left-right cross-section asymmetry

$$A_{LR} = \sqrt{\frac{(\sigma_{RR} + \sigma_{RL} - \sigma_{LR} - \sigma_{LL})(-\sigma_{RR} + \sigma_{RL} - \sigma_{LR} + \sigma_{LL})}{(\sigma_{RR} + \sigma_{RL} + \sigma_{LR} + \sigma_{LL})(-\sigma_{RR} + \sigma_{RL} + \sigma_{LR} - \sigma_{LL})}}$$

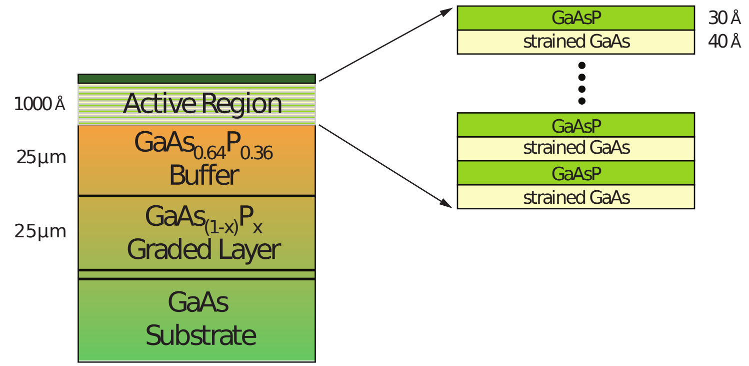
Realisation at the ILC.

Electron source.

Requirements: 1312 bunches of $3 \cdot 10^{10}$ electrons at 5 Hz
with polarisation >80 %

Polarisation, charge & lifetime already reached at SLC in the past

photocathodes with GaAs/GaAsP
strain-compensated superlattice
at least 85% polarisation,
quantum efficiency typically >0.4%



[ILC TDR vol. 3.2, 2013]

Primary challenges at ILC:

- long bunch train → laser system developement
- high RF-power on the normal-conducting pre-accelerator

both demonstrated in R&D prototypes

Positron source.

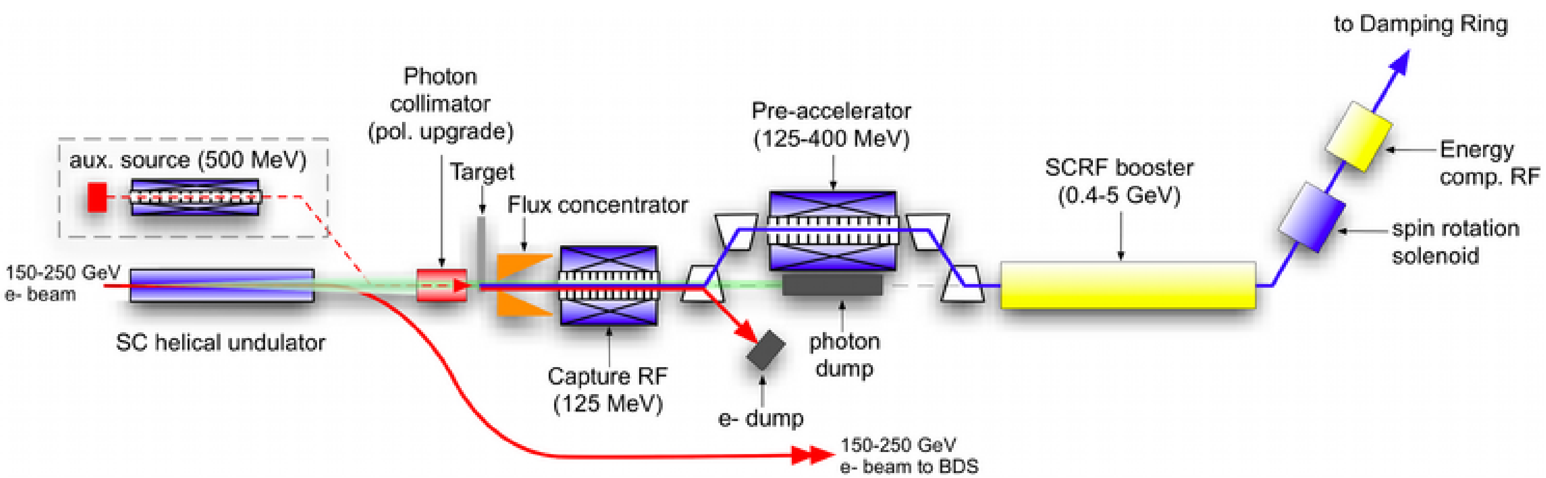
Electromagnetic showers to generate positrons:
multi-MeV photon beam onto thin metal target

alternative: e^- driven source ("300 Hz scheme"), but no polarisation

Options for generation of the photons:

- Compton backscattering
- Helical undulator - generates circularly polarised photons, which in turn generate longitudinally polarised positrons

  147 m long undulator, space reserved for upgrade

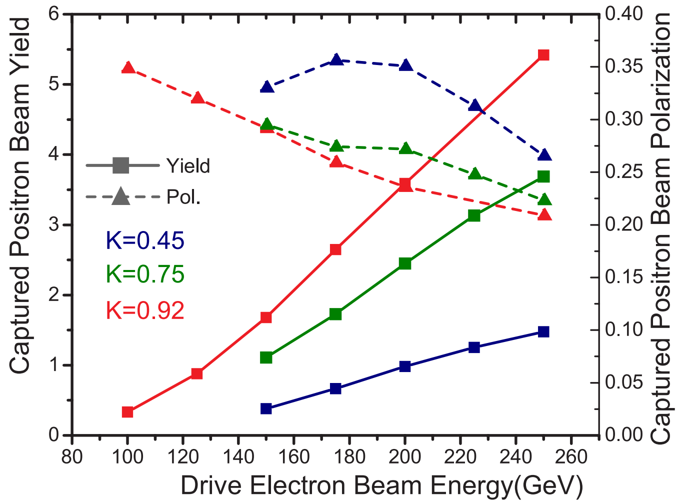


[ILC TDR vol. 1, 2013]

Positron source (2).

Positron yield

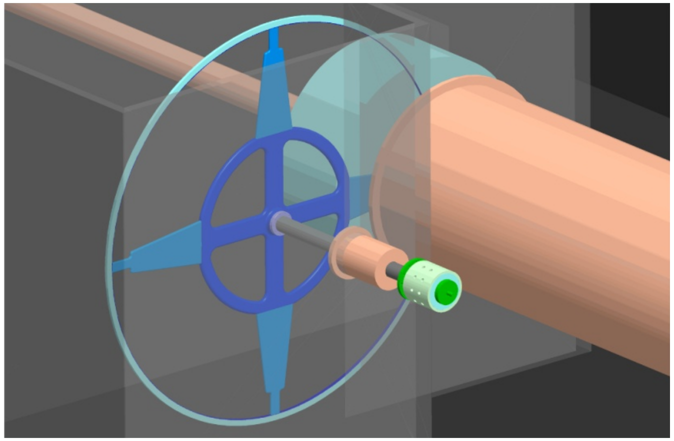
- requirement $Y = 1.5\, e^+ / e^-$
- polarisation and yield strongly coupled to e^- beam energy
- below 150 GeV: "10 Hz scheme" with dedicated drive beam
  (tuning of undulator and collimator parameters - possible to go to 120 GeV without this)



[ILC TDR vol. 3.2, 2013]

Polarisation upgrade

- nominal design $\sim 30\,\%$ e^+ pol
- for 60 %: 73.5 m longer undulator & photon beam collimation



[ILC TDR vol. 3,2, 2013]

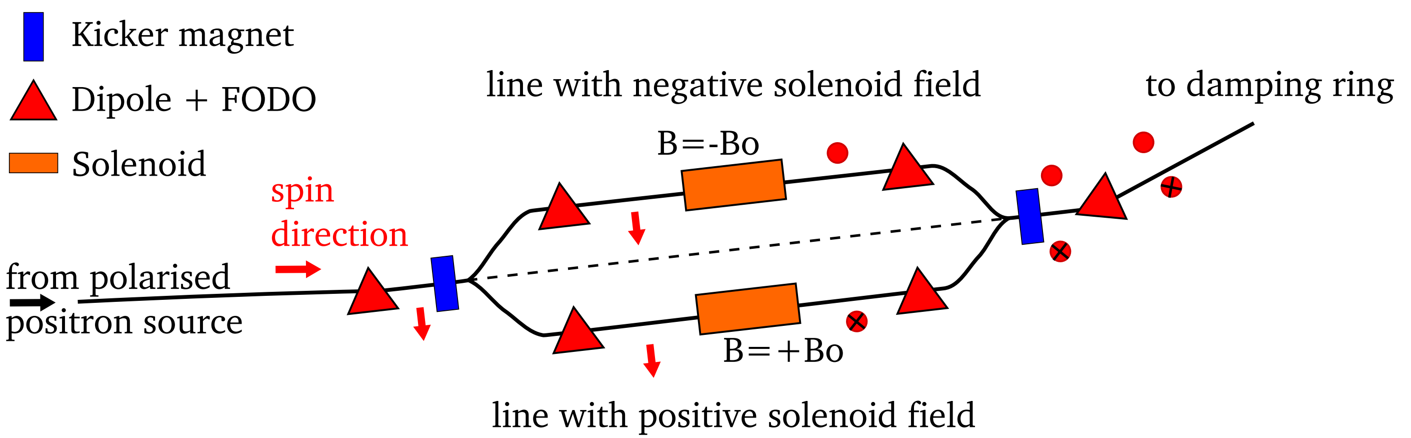
R&D work remains (e.g. target design, photon collimator)

Spin rotators.

Spin rotators before / after damping rings to preserve polarisation

Fest helicity reversal → cancellation of time-dependent effects

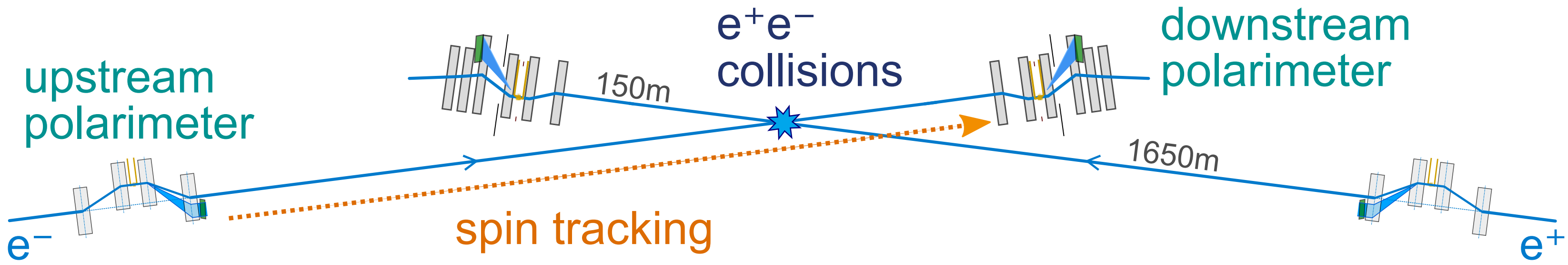
- Electron polarisation: switch at source by changing laser polarity
- Positron polarisation:
  - depends on direction of undulator windings
  - helicity reversal: use spin flipper near the damping ring
  - beam is kicked into one of two parallel transport lines



[LC-REP-2013-016]

Polarimetry concept.

ILC polarimetry: per mille level precision by combining

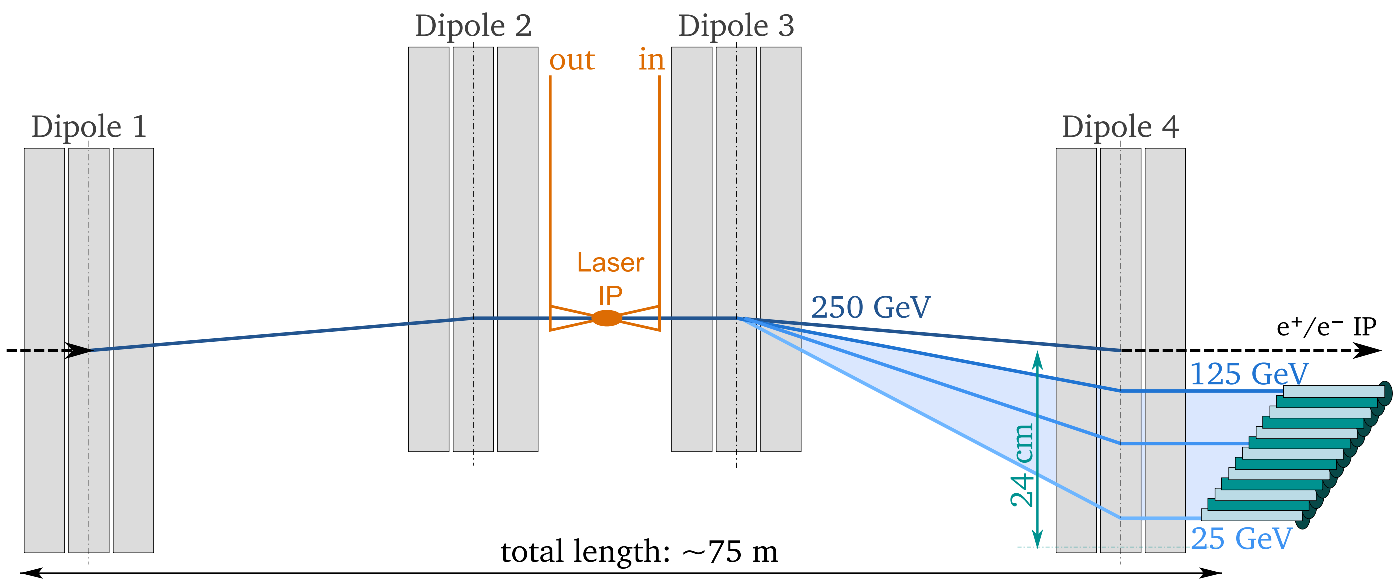


- Compton polarimeter measurements upstream and downstream of the e^+e^- interaction point
- Spin tracking studies to relate these measurements to the polarization at the e^+e^- interaction point
- Long-term average determined from e^+e^- collision data as absolute scale calibration

Compton polarimeters.

- $\mathcal{O}(10^3)$ Compton scatterings/bunch
- Energy spectrum of scattered e^+/e^- depends on polarisation
- Magnetic chicane: energy distribution $\rightarrow$ position distribution
- Measure number of e^+/e^- per detector channel

Upstream polarimeter:

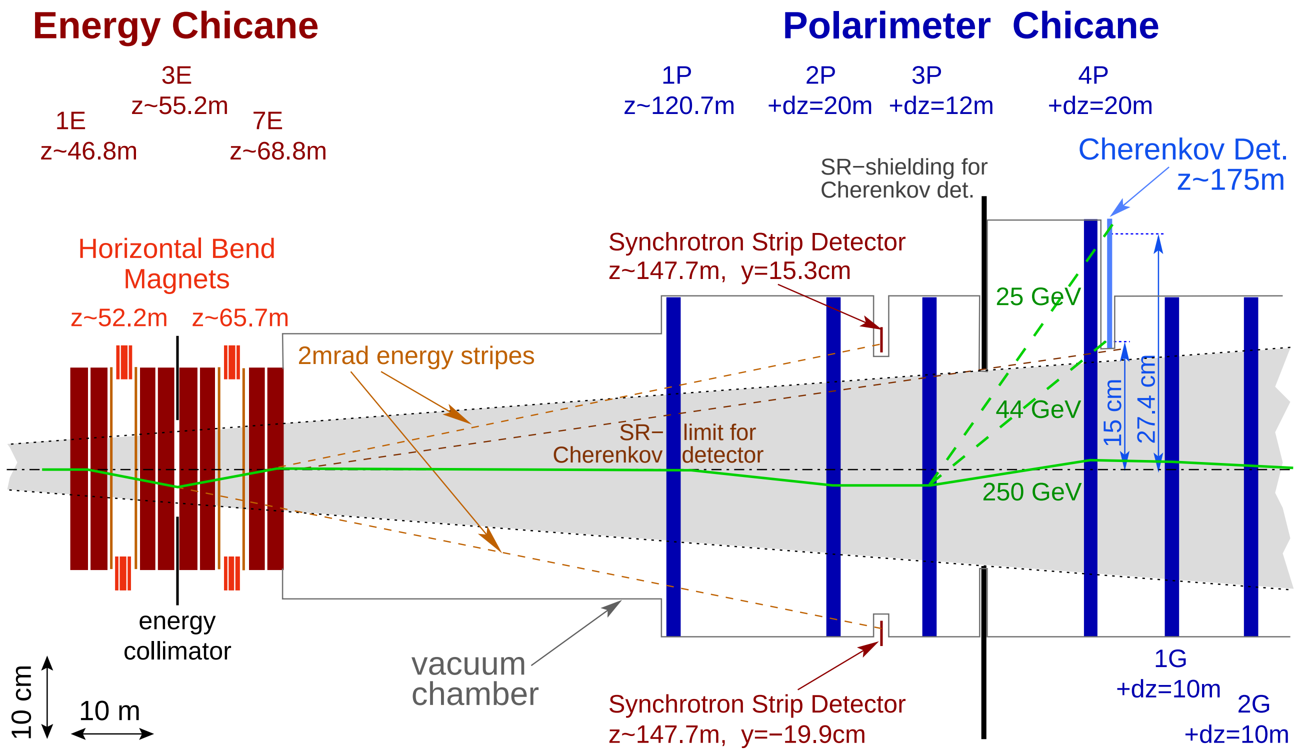


[JINST **4**(2009), 10015]

Compton polarimeters (2).

Downstream Polarimeter

- located at secondary focus
- 6-magnet chicane kicks Compton $e^{\pm}$ out of synchrotron fan



[JINST **4**(2009), 10015]

Polarimeter detectors.

Simple, robust, fast: Cherenkov detectors

- Cherenkov light emission proportional to number of electrons
- independent of electron energy (once relativistic)
- successfully used in best polarimeter sofar at SLC
- gas or quartz option for Cherenkov medium

Goal: total uncertainty $\Delta P / P \approx 0.25\,\%$, of which

- laser: 0.1 %
- analysing power (i.e. asymmetry at $\mathcal{P} = 1$): 0.2 %
- detector linearity: 0.1 %

Cross-calibration of Polarimeters.

Polarimeter locations 1650 m before and 150 m after the IP

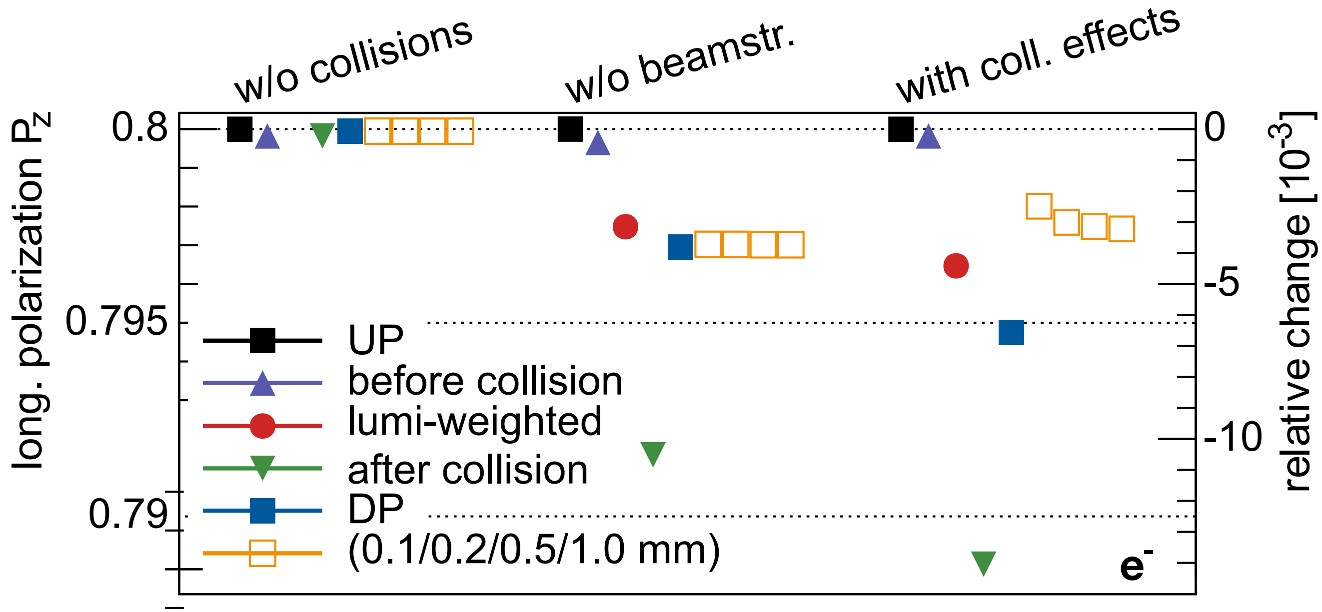
Spin tracking studies to understand spin transport in-between

Without collisions: cross-calibration of polarimeters

	effect on $P[10^{-3}]$
Beam and detector alignment at polarimeters ($\Delta\theta_{bunch} = 50$ mrad, $\Delta\theta_{pol} = 25$ mrad)	0.72
Beam parameter variations (10 % in emittances)	0.03
Bunch rotation to compensate crossing angle	< 0.01
Longitudinal precession in detector magnets	0.01
Emission of synchrotron radiation	0.005
random misalignments (10 µm)	0.35
Total	0.80

JINST 9 (2014) P07003

Collision Effects.



- beamstrahlung (energy loss, radiative depolarisation): difference downstream measurement vs. $\langle P \rangle_{IP}$ increases
- energy loss limits refocusing of the beam: laser spot at the polarimeter affects measurement

Polarisation Average from Collision Data.

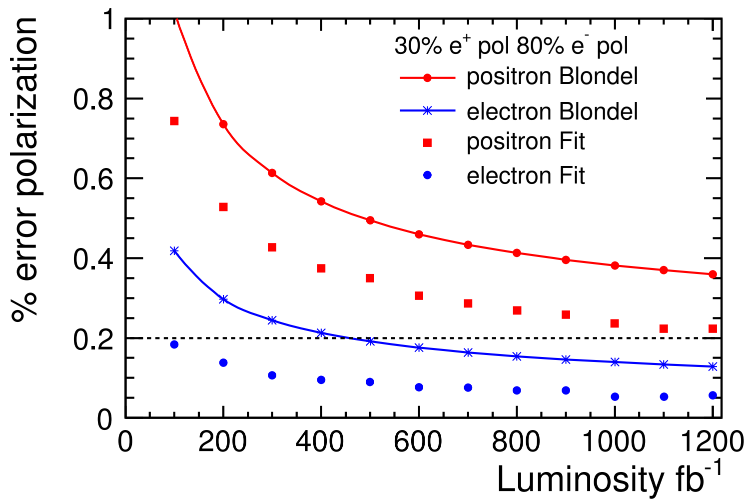
Direct extraction from collision data:
any abundant, well-known, polarisation dependent process

$$\langle | P_{e^\pm} | \rangle_{IP} = \sqrt{\frac{(\sigma_{-+} + \sigma_{+-} - \sigma_{--} - \sigma_{++})(\pm\sigma_{-+} \mp \sigma_{+-} + \sigma_{--} - \sigma_{++})}{(\sigma_{-+} + \sigma_{+-} + \sigma_{--} + \sigma_{++})(\pm\sigma_{-+} \mp \sigma_{+-} - \sigma_{--} + \sigma_{++})}}$$

(assumes $P_+(e^-) = -P_-(e^-)$ and $P_+(e^+) = -P_-(e^+)$)

Methods studied so far

- total cross-sections:
  WW at 500 GeV and 1 TeV
- single-differential cross-sections:
  WW at 500 GeV and 1 TeV
- double-differential cross-sections:
  WW at 1 TeV

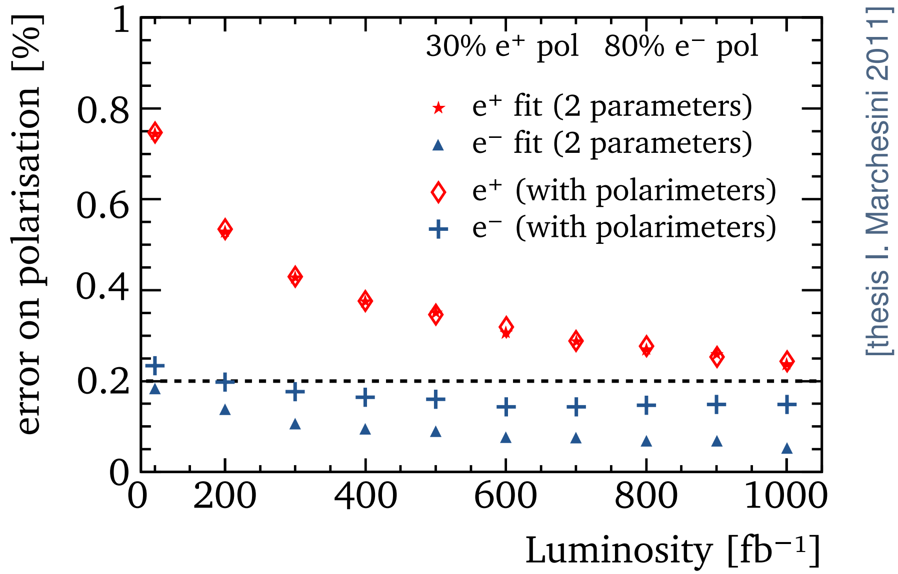


[LC-DET-2009-003]

Impact of Polarimeter Precision.

What happens if $P_+(e^-) \neq -P_-(e^-)$ and $P_+(e^+) \neq -P_-(e^+)$?

- let all P vary independently $\Rightarrow$ $\delta P/P$ in *percent* regime
- better: difference to $\pm\delta P/P|_{pol} = 0.25\%$ with polarimeters
- limits ultimate precision on $P(e^-)$!



$\rightarrow$ need polarimetry at permille-level and fast helicity reversal

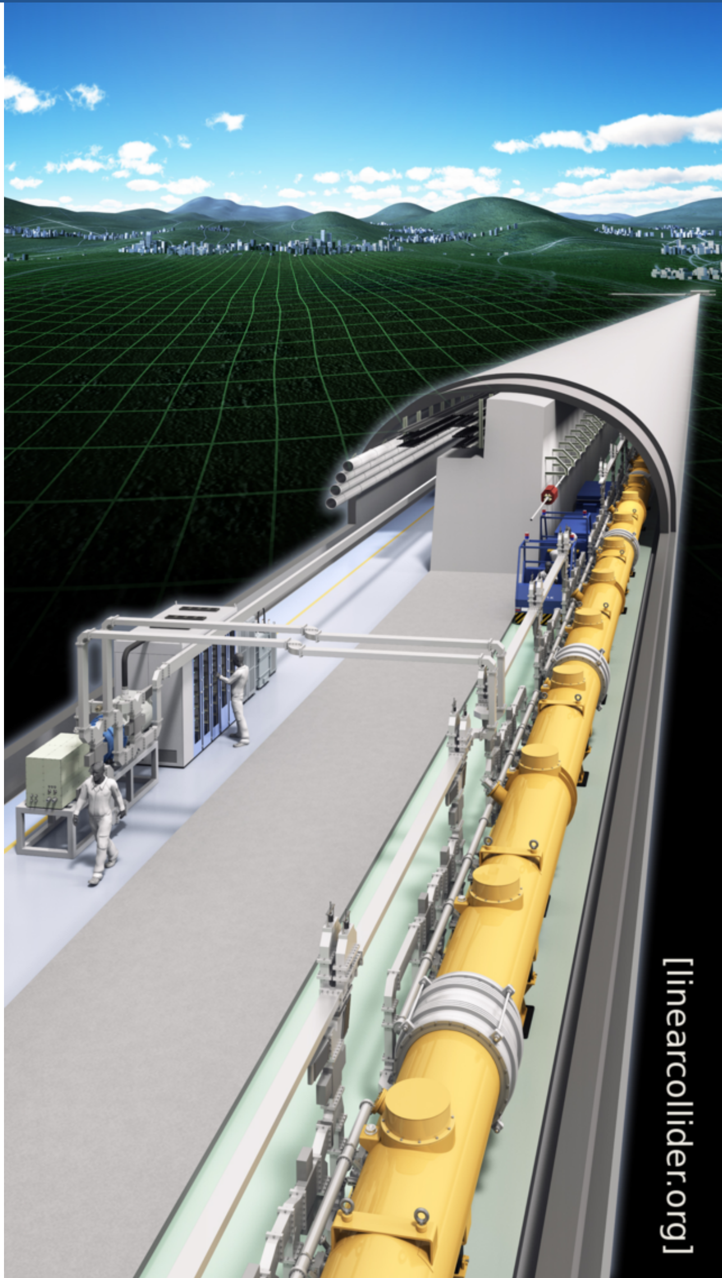
Conclusion.

Conclusion.

- Beam polarisation is a key ingredient for ILC physics studies
- Polarised electron and positron sources

  more R&D on e^+ source necessary, no show-stoppers
- Permille-level polarimetry from a combination of
  - up- and downstream polarimeters
  - spin tracking, collision effects
  - scale calibration from e^+e^- data
- Site for ILC selected, government negotiations ongoing

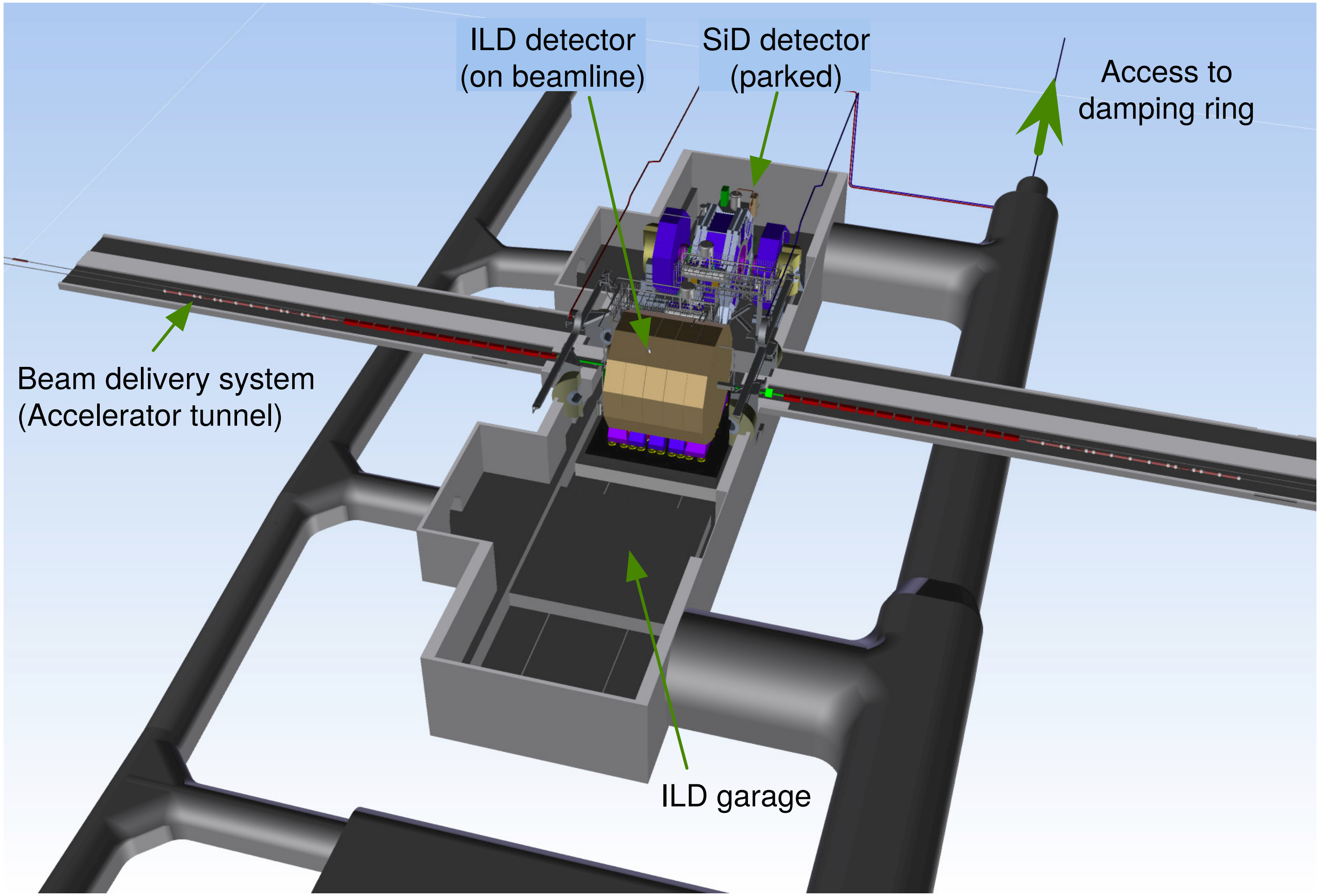
$\Rightarrow$ **Exciting times ahead!**



[linearcollider.org]

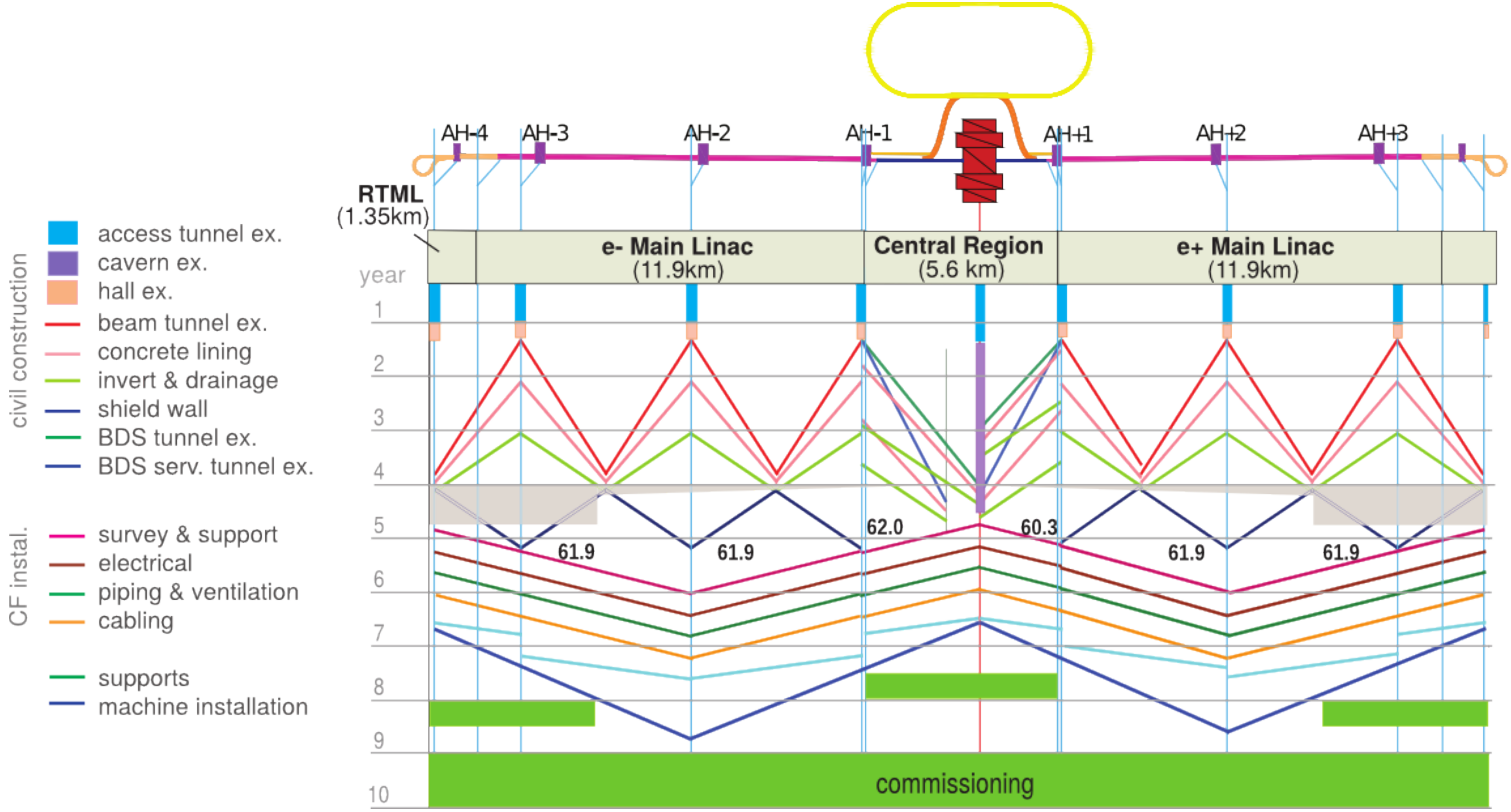
Backup Slides.

Push-Pull concept.



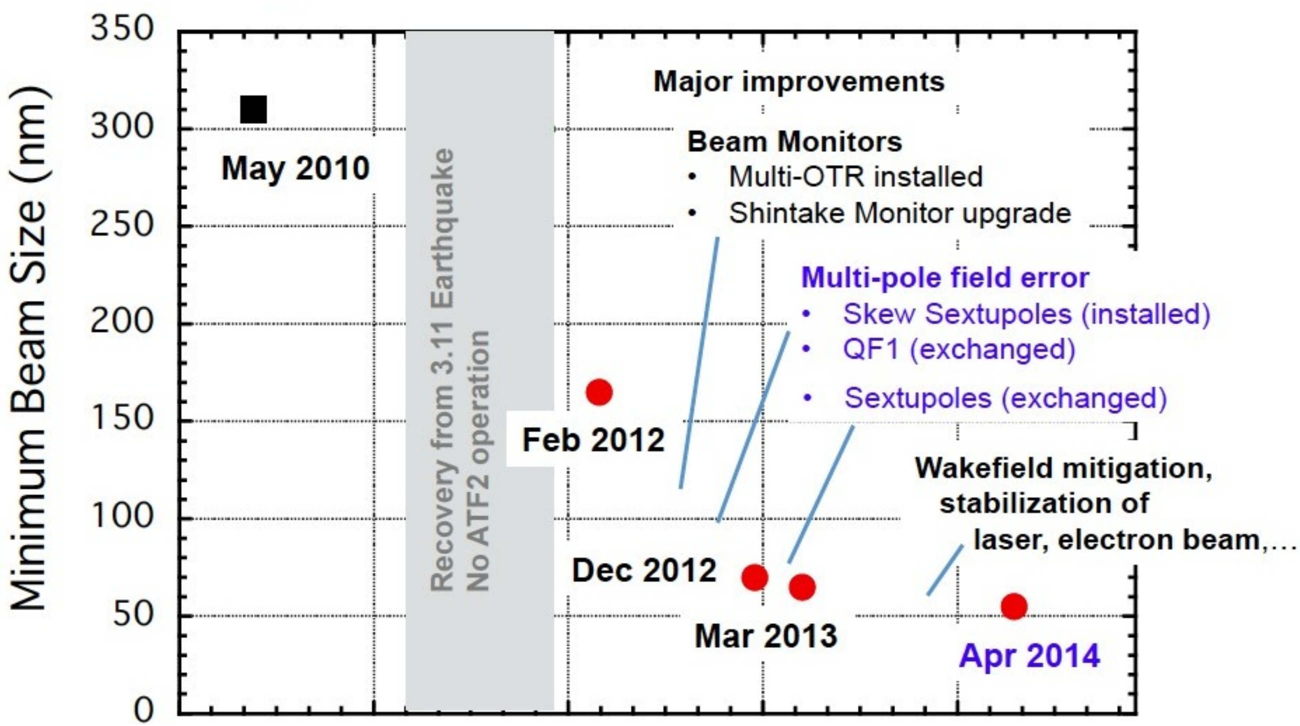
[ILC TDR vol. 1, 2013]

Possible construction schedule.



[ILC TDR vol. 1, 2013]

Beam size.



[AFT2]

44 nm reached in July 2014
(different beam energy
$\rightarrow$ 37 nm at ATF will correspond to $<$ 5 nm at ILC)

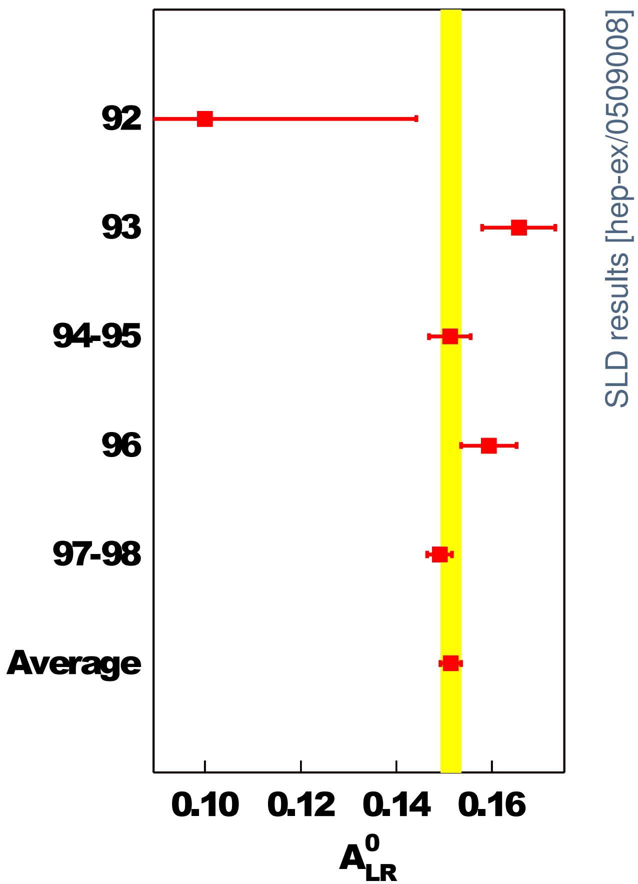
Sin Theta.

Connection between A_{LR} and $\sin^2\theta_{\rm eff}$:

$$A_{LR} = \frac{1}{\langle \mathcal{P}_{\rm eff} \rangle} \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{2 v_e a_e}{v_e^2 + a_c^2}$$

$$\frac{v_e}{a_e} = 1 - 4\sin^2\theta_{\rm eff}$$

$$\mathcal{P}_{\rm eff} = \frac{\mathcal{P}_{e^+} + \mathcal{P}_{e^-}}{1 + \mathcal{P}_{e^+}\mathcal{P}_{e^-}}$$



With positron polarisation:

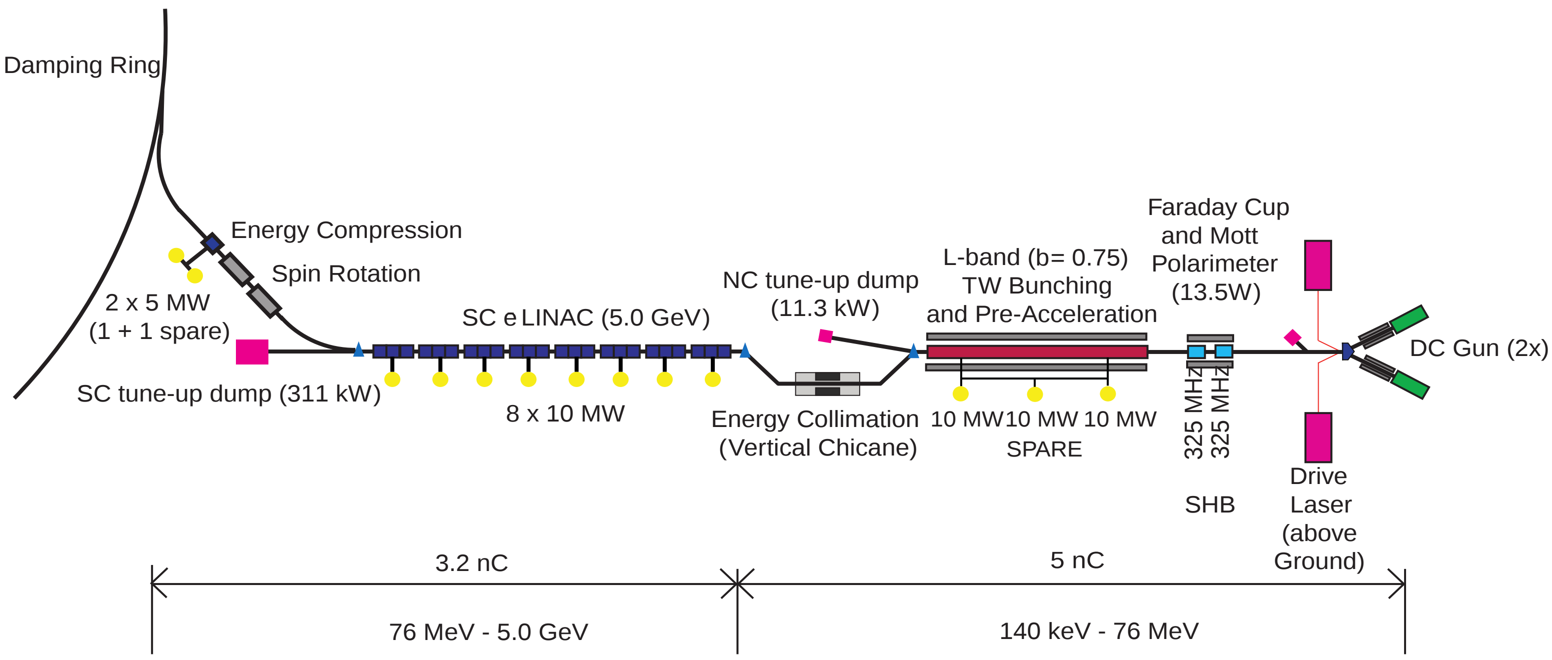
$$A_{LR} = \sqrt{\frac{(\sigma_{RR} + \sigma_{RL} - \sigma_{LR} - \sigma_{LL})(-\sigma_{RR} + \sigma_{RL} - \sigma_{LR} + \sigma_{LL})}{(\sigma_{RR} + \sigma_{RL} + \sigma_{LR} + \sigma_{LL})(-\sigma_{RR} + \sigma_{RL} + \sigma_{LR} - \sigma_{LL})}}$$

Electron source parameters.

Parameter	Symbol	Value	Units
Electrons per bunch (at gun exit)	N_-	3×10^{10}	Number
Electrons per bunch (at DR injection)	N_-	2×10^{10}	Number
Number of bunches	n_b	1312	Number
Bunch repetition rate	f_b	1.8	MHz
Bunch train repetition rate	f_{rep}	5 (10)	Hz
FW Bunch length at source	Δt	1	ns
Peak current in bunch at source	I_{avg}	3.2	A
Energy stability	σ_E/E	<5	% rms
Polarization	P_e	80 (min)	%
Photocathode Quantum Ef ciency	QE	0.5	%
Drive laser wavelength	λ	790±20 (tunable)	nm
Single bunch laser energy	u_b	5	μJ

[ILC TDR vol. 3.2, 2013]

Electron source system.



[ILC TDR vol. 3.2, 2013]

Positron source parameters.

Parameter	Symbol	Value	Units
Positrons per bunch at IP	n_b	2×10^{10}	number
Bunches per pulse	N_b	1312	number
Pulse Repetition Rate	f_{rep}	5	Hz
Positron Energy (DR injection)	E_0	5	GeV
DR Dynamic Aperture	$\gamma(A_x + A_y)$	<0.07	m rad
DR Energy Acceptance	Δ	0.75	%
DR Longitudinal Acceptance	A_l	3.4 x 37.5	cm-MeV
Electron Drive Beam Energy†	E_e	150/175/250	GeV
Undulator Period	λ	1.15	cm
Undulator Strength‡	K	0.92/0.75/0.45	-
Undulator Type	-	Helical	-
Undulator Length	L_u	147	m
Photon Energy (1^{st} harm cutof)	E_{c10}	10.1/16.2/42.8	MeV
Photon Beam Power	P_γ	63.1/54.7/41.7	kW
Target Material	-	Ti-6%Al-4%V	-
Target Thickness	L_t	0.4 / 1.4	r.l. / cm
Target Absorption	-	7	%
Incident Spot Size on Target	σ_i	1.4/1.2/0.8	mm, rms
Positron Polarisation	P	31/30/29	%

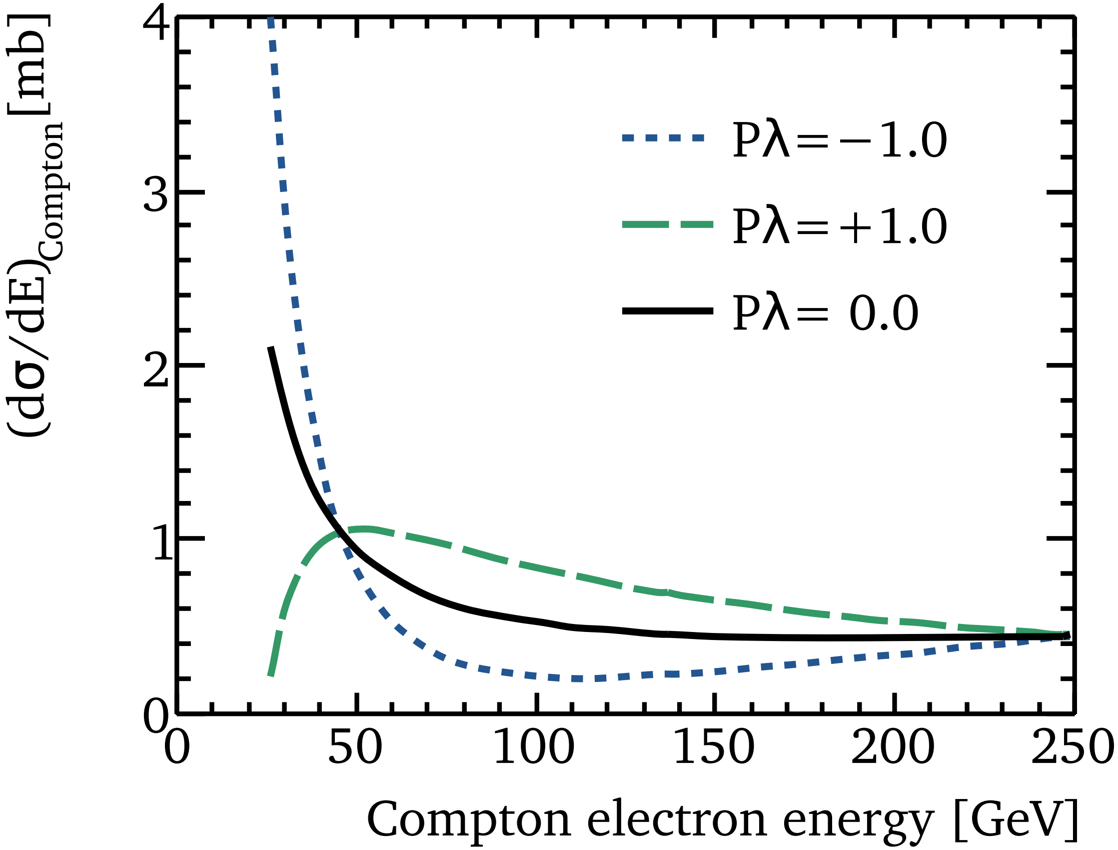
† For centre-of-mass energy below 300 GeV, the machine operates in 10 Hz mode where a 5 Hz 150 GeV beam with parameters as shown in the table is a dedicated drive beam positron source.

‡ K is lowered for beam energies above 150 GeV to bring the polarisation back to 30 % without adding a photon collimator before the target.

[ILC TDR vol. 3.2, 2013]

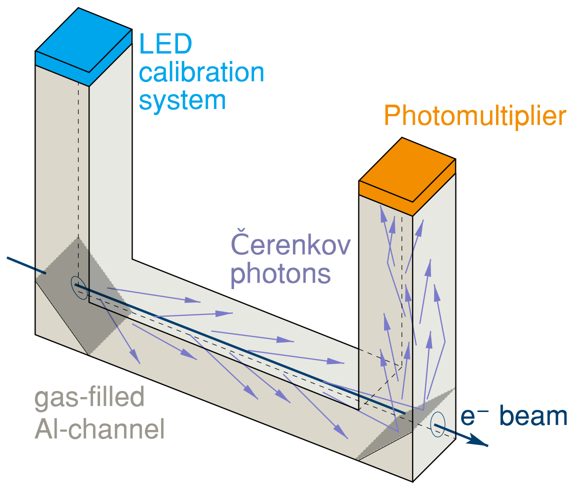
Compton cross-subsection.

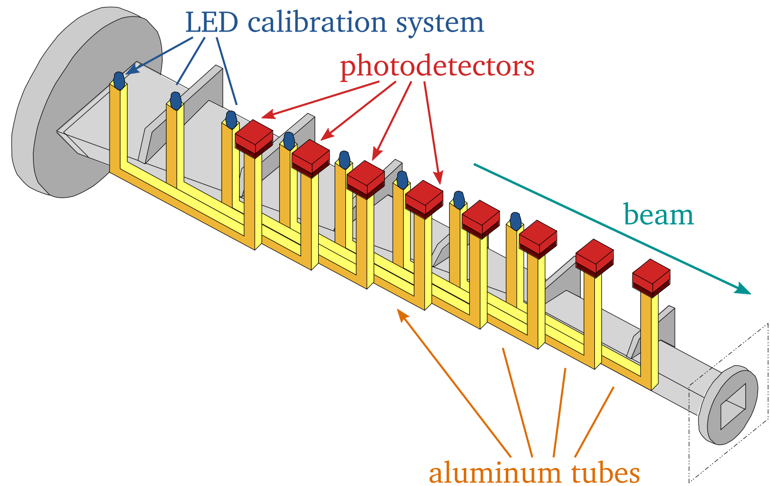
$$\left(\frac{d\sigma}{dy}\right)_{\text{Compton}} = \left(\frac{d\sigma}{dy}\right)_{\text{unpol}} + \frac{2\pi r_o}{x} \cdot \lambda\mathcal{P} \cdot rx(1-2r)(2-y)$$



$$x = \frac{4E_0\omega_0}{m^2}\cos^2(\theta_0/2), \quad y = 1 - \frac{E}{E_0}, \quad r = \frac{y}{x(1-y)}, \quad \left(\frac{d\sigma}{dy}\right)_{\text{unpol}} = \frac{2\pi r_o}{x}\left[\frac{1}{1-y} + 1 - y - 4r(1-r)\right]$$

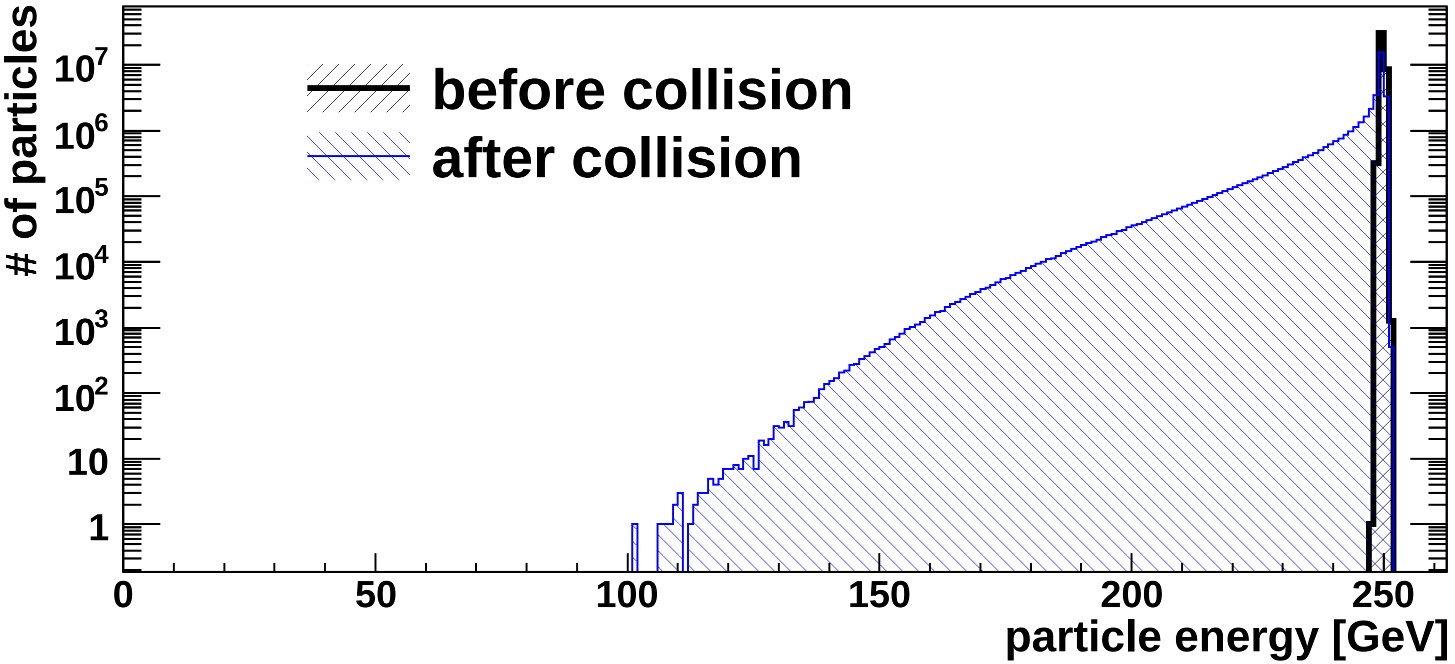
Polarimetry - gas detector concept.



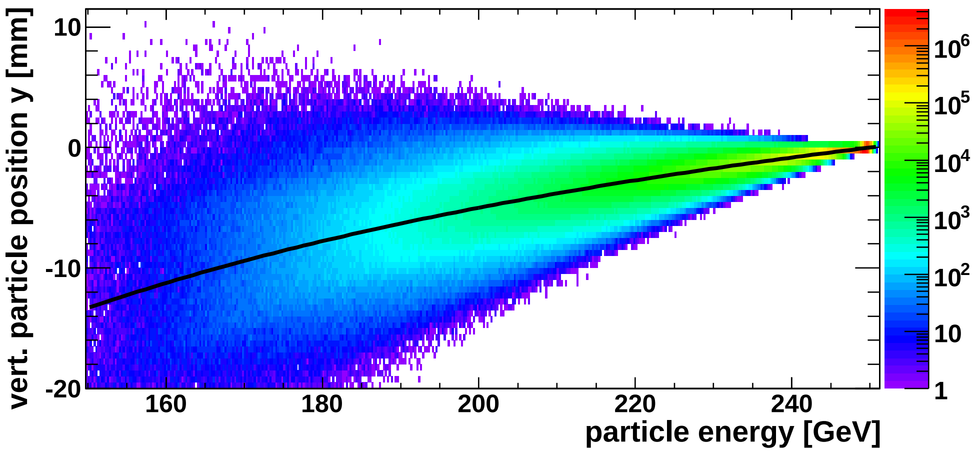


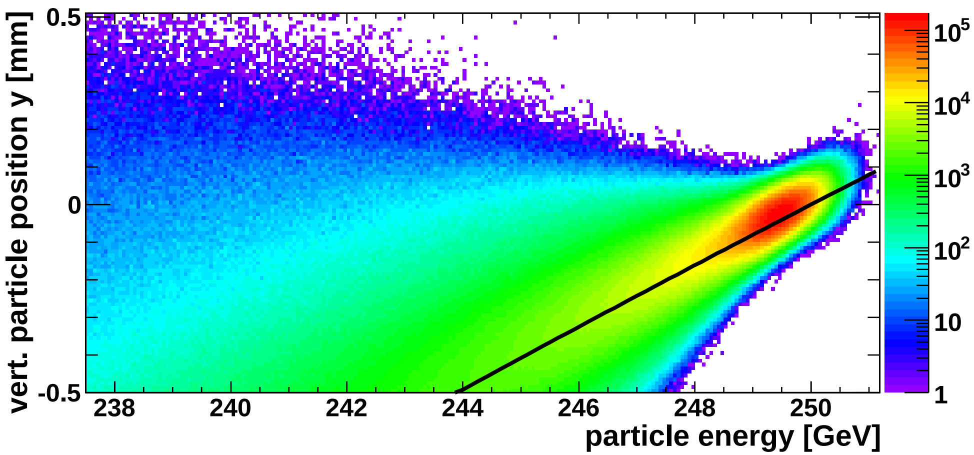
[arXiv:1011.6314]

Beam Energy Spectrum After Collision.



Downstream Polarimeter: y vs E.





Blondel scheme.

Blondel scheme:

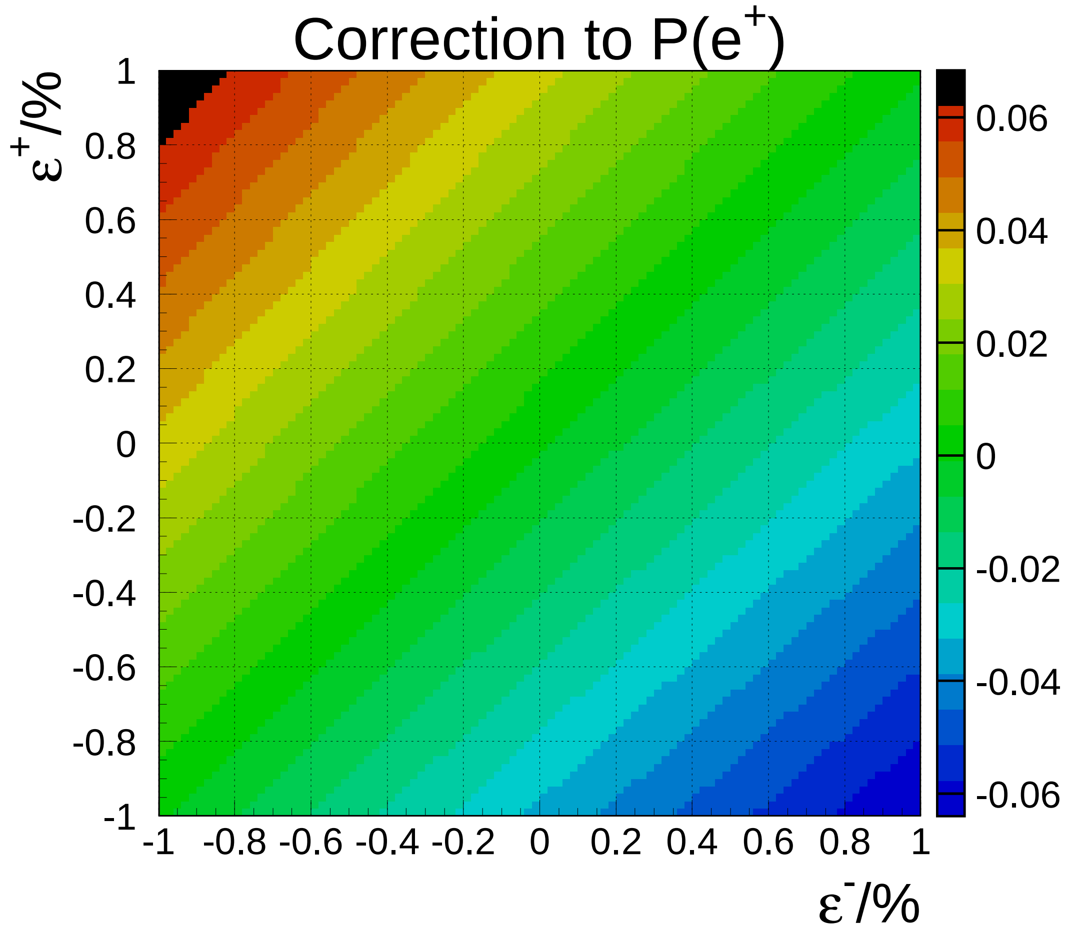
$$\langle | \mathcal{P}_{e^\pm} | \rangle_{IP} = \sqrt{\frac{(\sigma_{+-} + \sigma_{-+} - \sigma_{--} - \sigma_{++})(\mp\sigma_{-+} \pm \sigma_{+-} + \sigma_{--} - \sigma_{++})}{(\sigma_{-+} + \sigma_{+-} + \sigma_{--} + \sigma_{++})(\mp\sigma_{-+} \mp \sigma_{+-} - \sigma_{--} + \sigma_{++})}}$$

included assumption:
$\mathcal{P}_+(e^-) = -\mathcal{P}_-(e^-)$ and $\mathcal{P}_+(e^+) = -\mathcal{P}_-(e^+)$

If not: assume $| \mathcal{P} |$ equal up to $2\epsilon^\pm$
measure $\epsilon^\pm$ with polarimeters.

Correction to modified Blondel scheme.

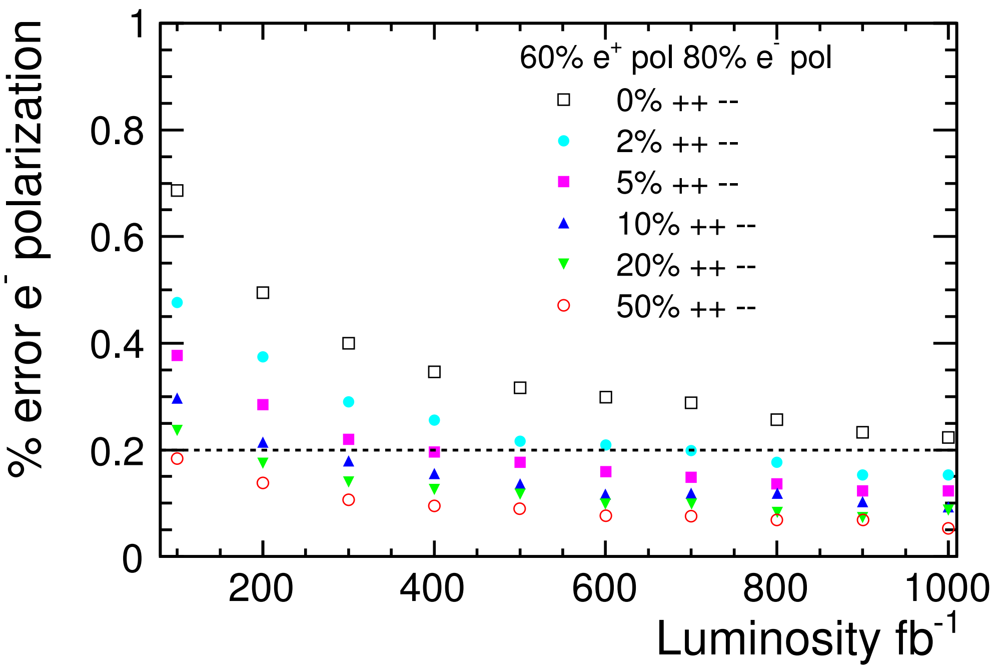
$$P_+(e^\pm) = P^\pm + \epsilon^\pm \text{ and } P_-(e^\pm) = P^\pm - \epsilon^\pm$$



Luminosity Sharing.

How much running time needed for $++$ and $--$?

- like-sign combinations less interesting for SM phyics
- 10% to 20% like-sign lumi rather close to optimum (50%)
- even 2% halfs already total lumi needed for 0.2% precision



[thesis I. Marchesini 2011]