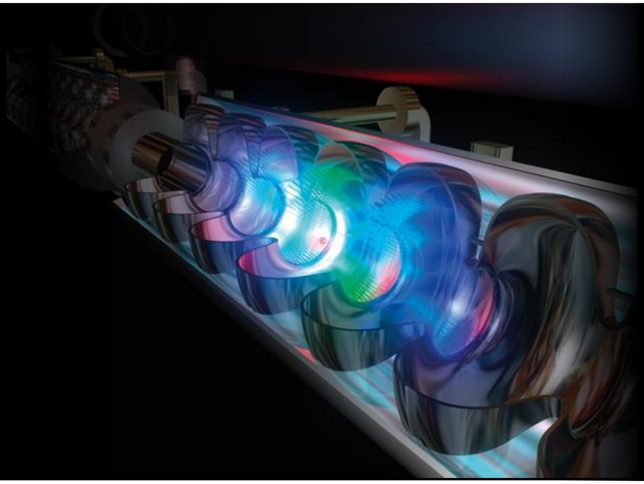
Polarisation and Beam Energy Measurement at a Linear e^+e^- Collider.

Plans and Prospects at the ILC.



Benedikt Vormwald
INSTR 2014
Novosibirsk, 24.02.2014-01.03.2014

Outline

- Introduction
- Beam polarisation measurement
- Beam energy measurement
- Conclusions

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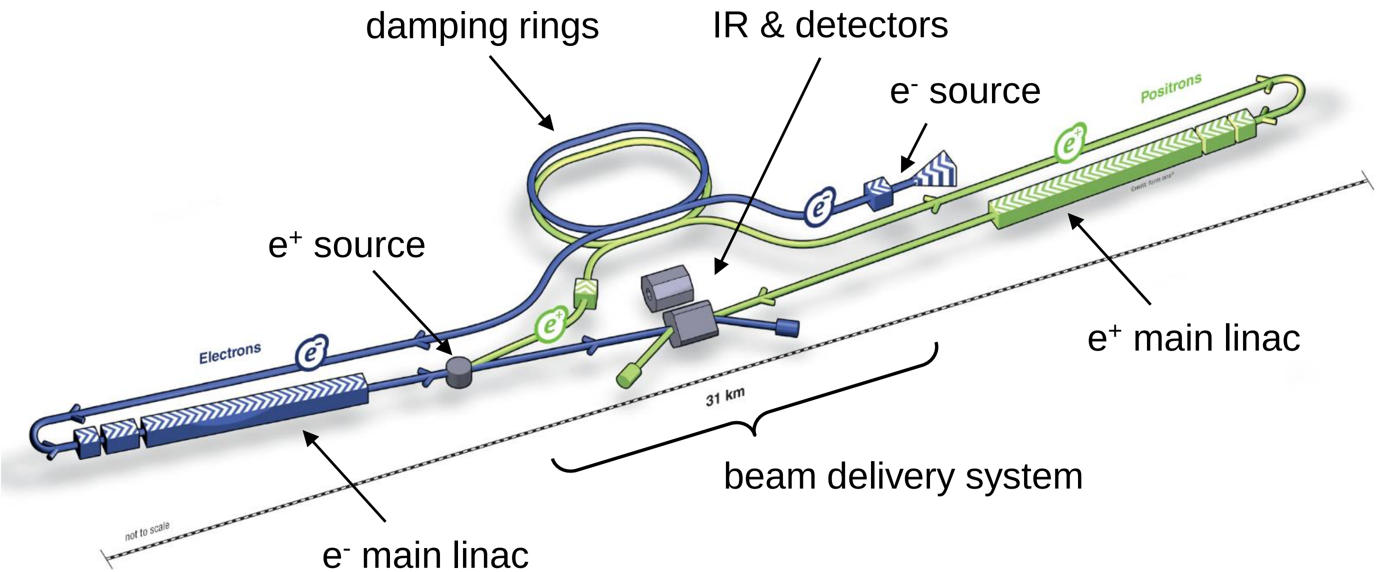
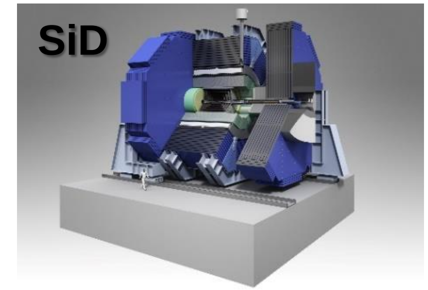
The International Linear Collider





- 31 km long, future linear lepton collider at the energy frontier
- Technical Design Report published on 12th June 2013
- centre-of-mass energy $\sqrt{s}$ =500GeV (upgrade to 1TeV)
- polarised lepton beams ($P(e^+) \geq 30\%$, $P(e^-) \geq 80\%$)

$$P_Z \equiv P = \frac{N_R - N_L}{N_R + N_L}$$

Physics Motivation

Collision of elementary particles offers the possibility to do high precision physics

→ well defined initial state

Particle helicity

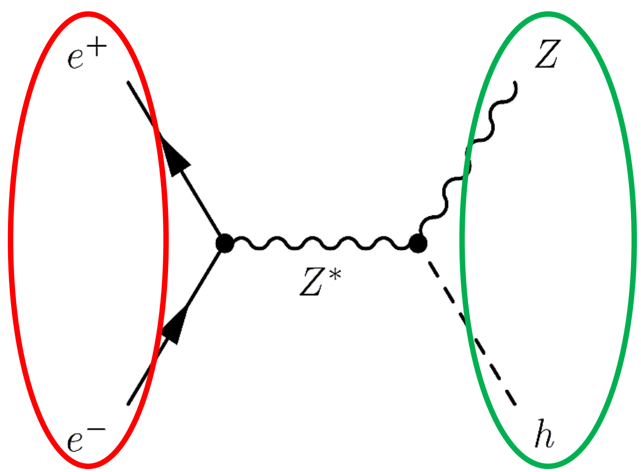
- electroweak production (V-A theory) → spin dependent
- beam polarisation can enhance and supress processes
- beam polarisation gives new observables (A_{LR})

Centre-of-mass energy

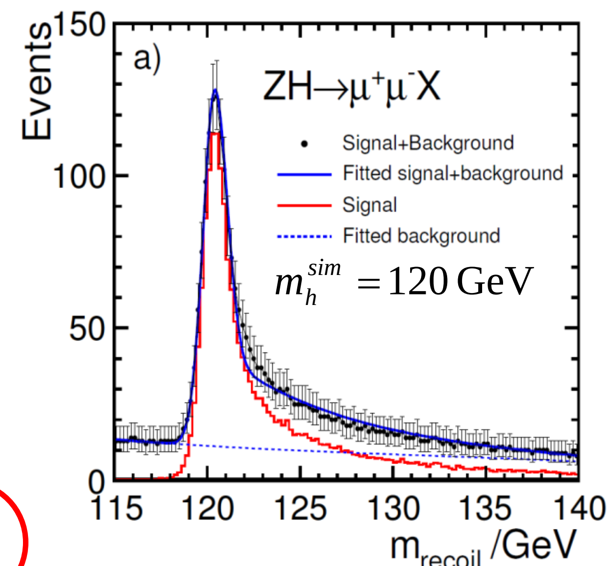
- cross sections are energy dependent
- kinematic constraints can improve resolution (kinematic fitting)

excellent detectors for the final state

excellent beam line instrumentation for the initial state

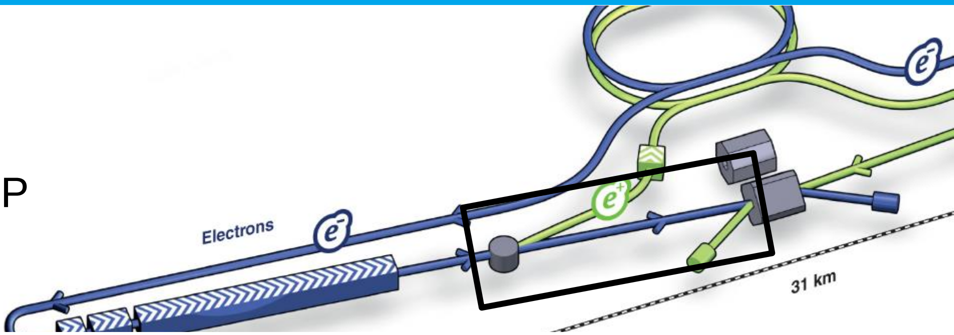


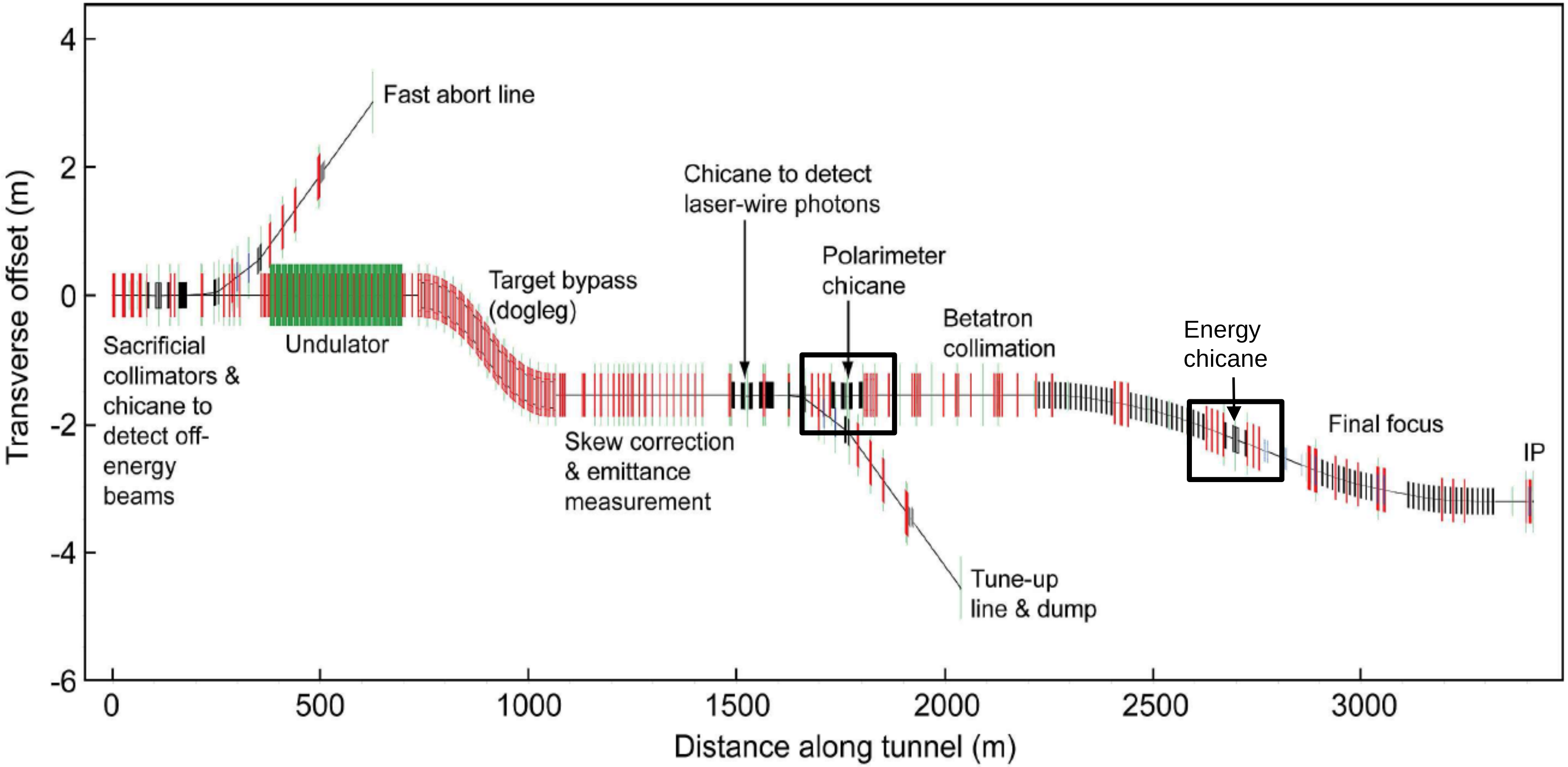
$$m_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$$



The Beam Delivery System

- instrumentation for emittance measurement
- **polarimeter** 1700m upstream the IP
- **energy spectrometer** 700m upstream the IP
- final focus of the beam to nm scale

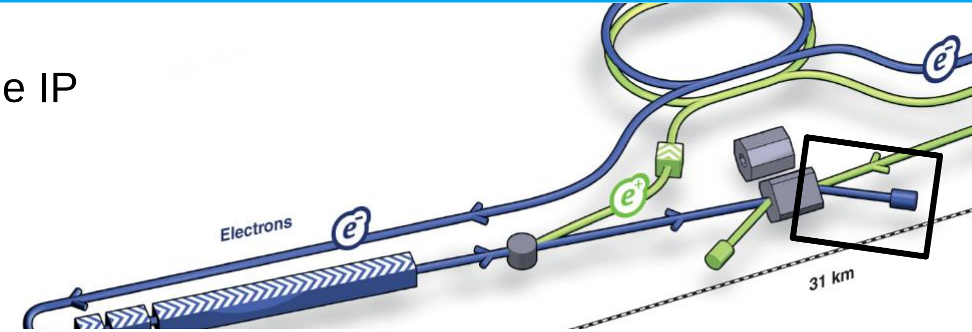


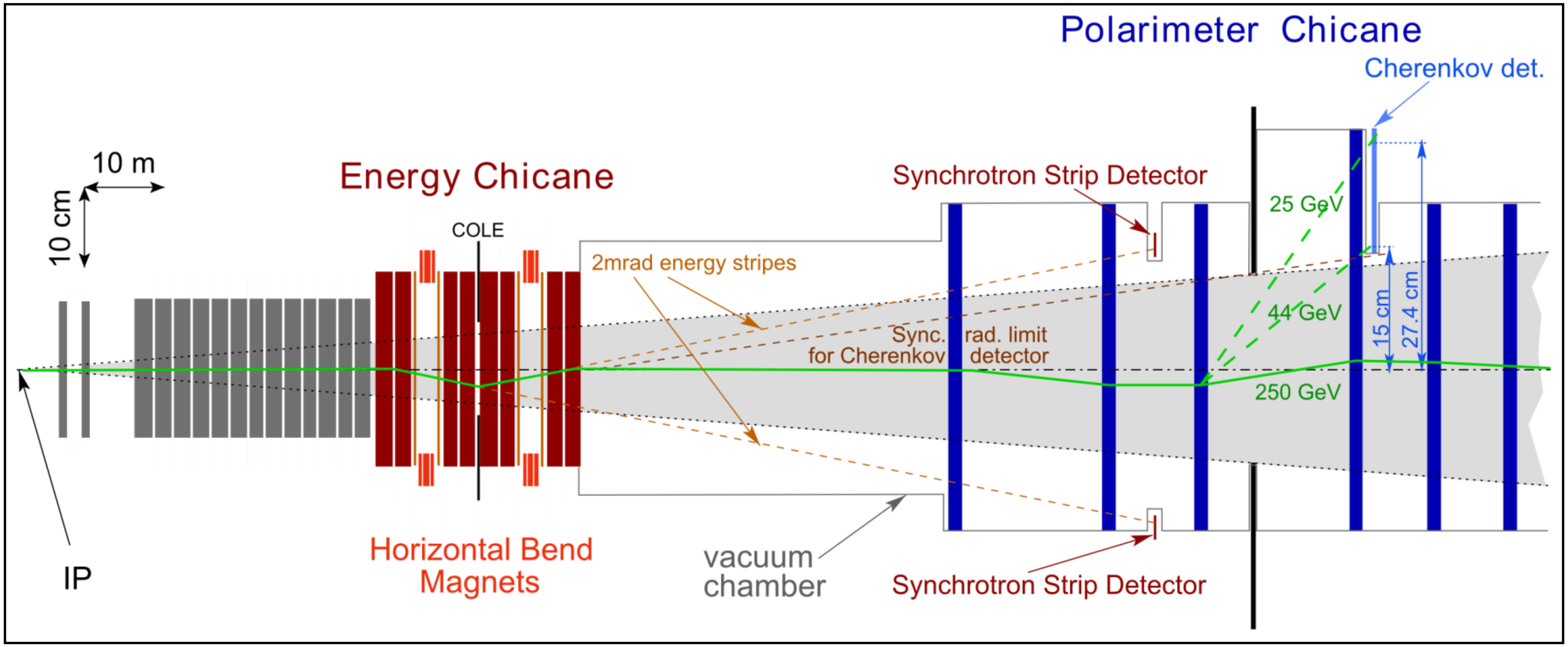


The Extraction Line

- **energy spectrometer** 55m downstream the IP
- secondary focus in extraction line
- **polarimeter** 150m downstream the IP

→ measure **collision effects**
→ **cross check** when no collision





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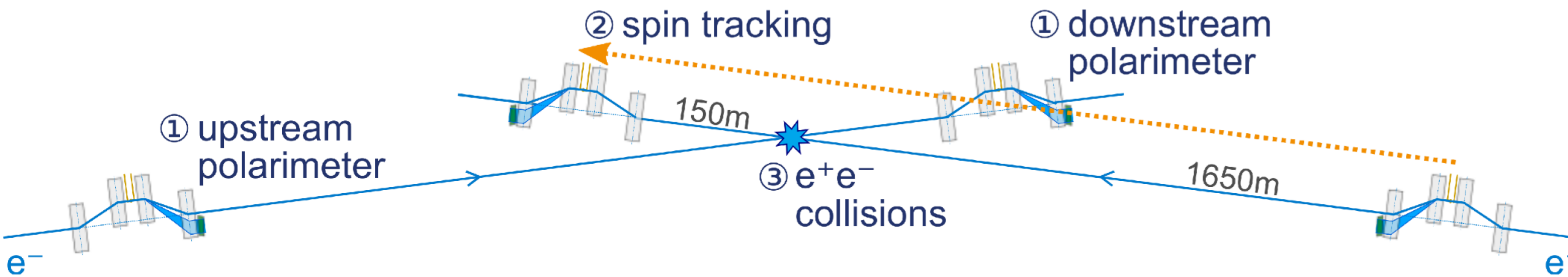
Polarimetry Concept for the ILC



① **Polarimeters** for direct beam polarisation measurements

→ making use of spin dependent scattering process

→ Compton scattering (non-invasive)

② **Spin tracking** along the beam delivery system in order to relate measurements to the interaction point

→ simulation of spin precession in the BDS (T-BMT)

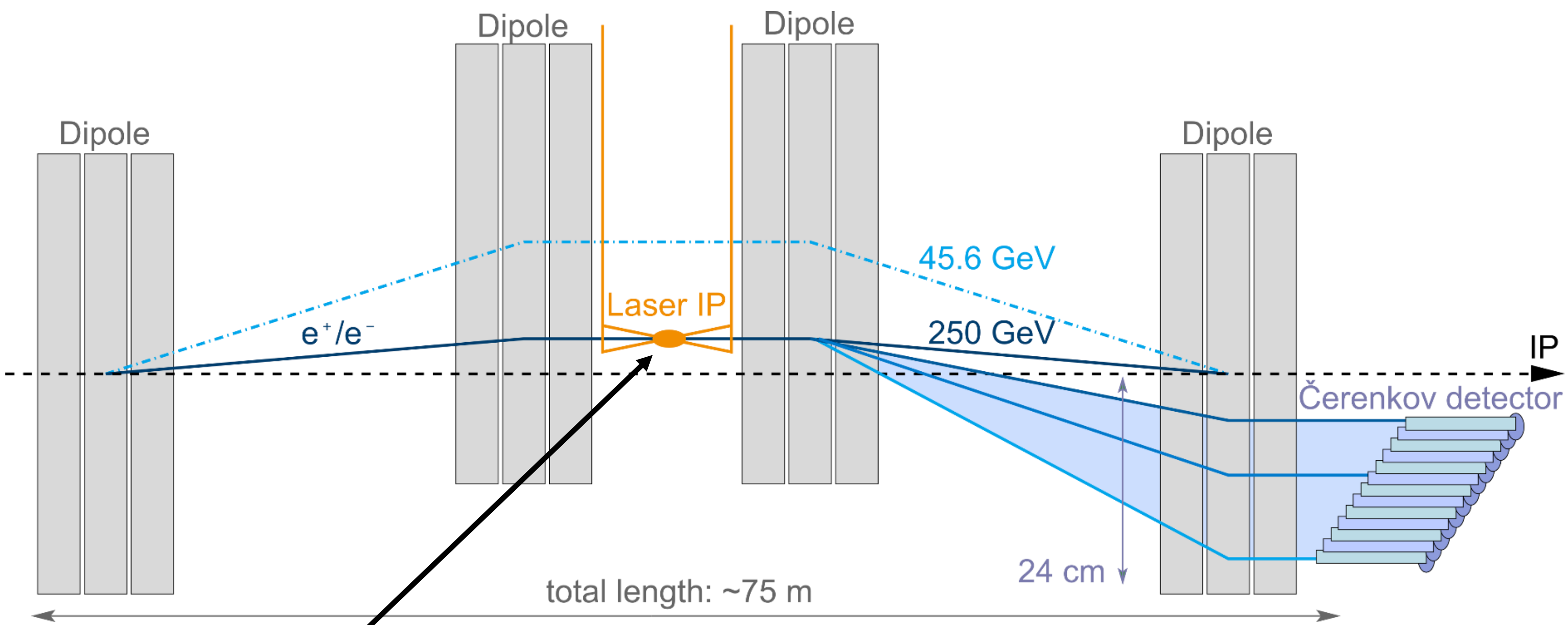
→ depolarising effects in collision

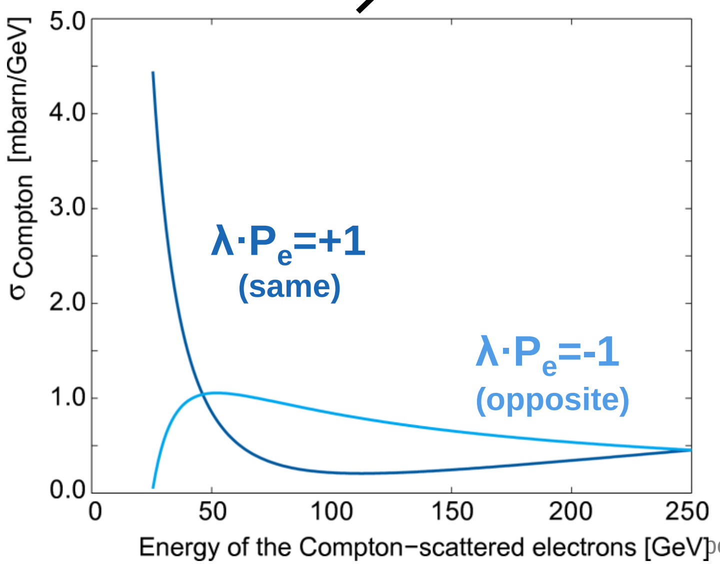
③ **e^+e^- annihilation data** for long-term polarisation measurement

→ Blondel-scheme: determine P from all possible beam helicity combinations

→ WW production (total cross section, differential cross sections depend on P)

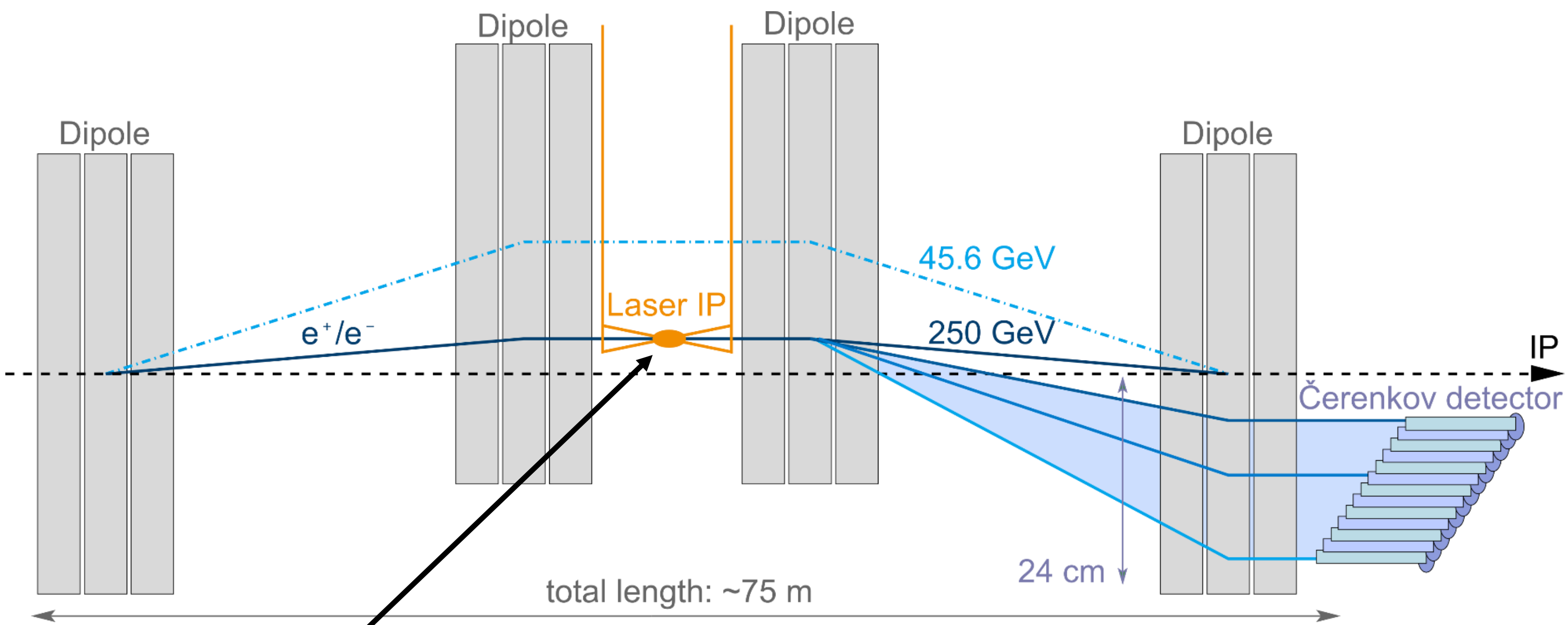
Polarisation Measurement

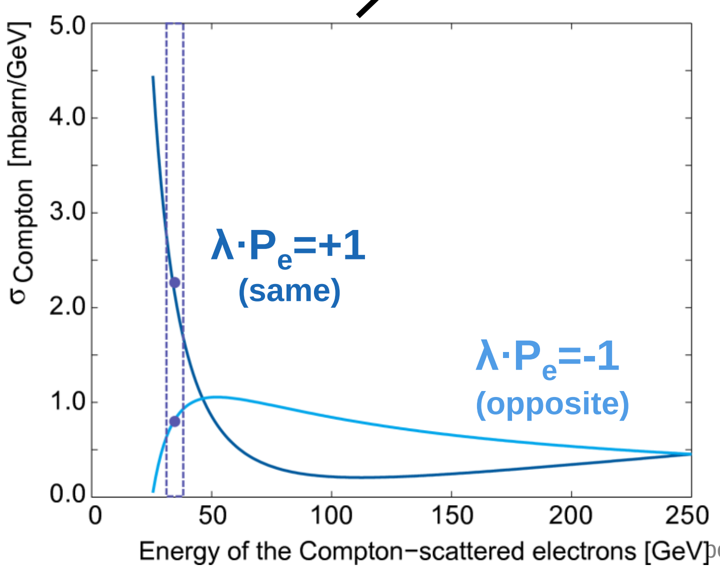


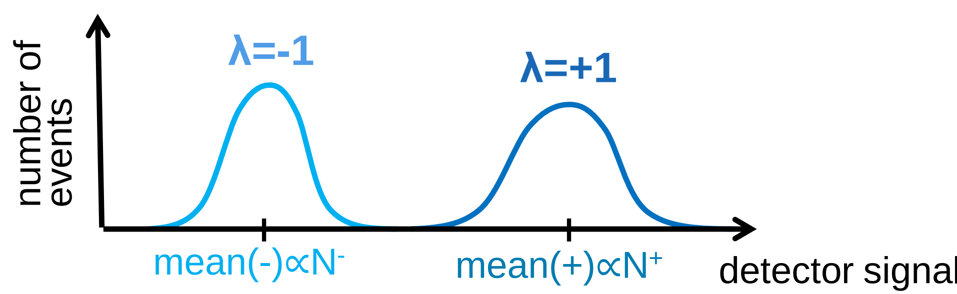


- $O(10^3)$ Compton scatterings/bunch
- energy spectrum of scattered e^+/e^- depends on beam and laser polarisation
- magnetic chicane acts as energy analyser
- measure number of scattered e^+/e^- per detector channel for both laser helicities

Polarisation Measurement







per energy interval = detector channel:

$$P = \frac{1}{A} \frac{N^+ - N^-}{N^+ + N^-}$$

Polarisation Measurement

Precision Goal

$$\Delta P / P \approx 0.25\%$$

laser helicity
overall contribution to
ΔP/P less than **0.1%**

→ **in situ monitoring**

knowledge of analysing power
overall contribution to
ΔP/P less than **0.2%**

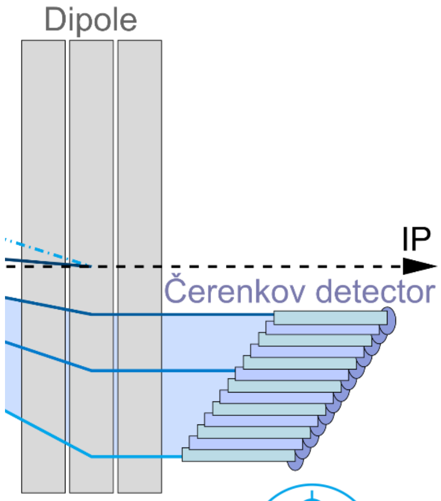
→ **in situ beam-detector alignment**

detector nonlinearity
overall contribution to
ΔP/P less than **0.1%**

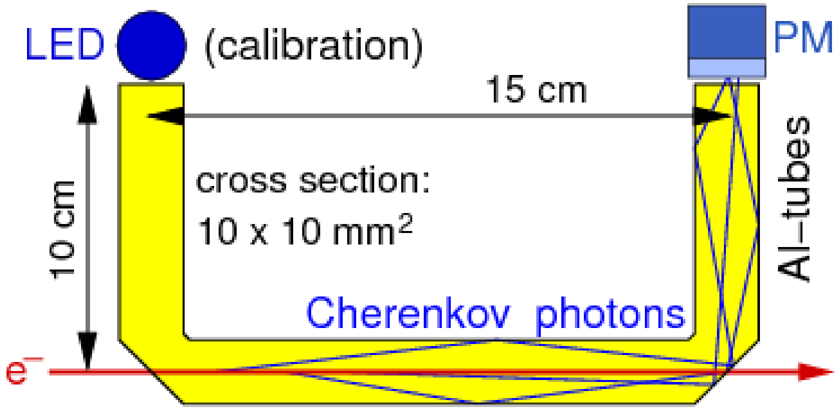
→ **detector DNL**

Detector Requirements

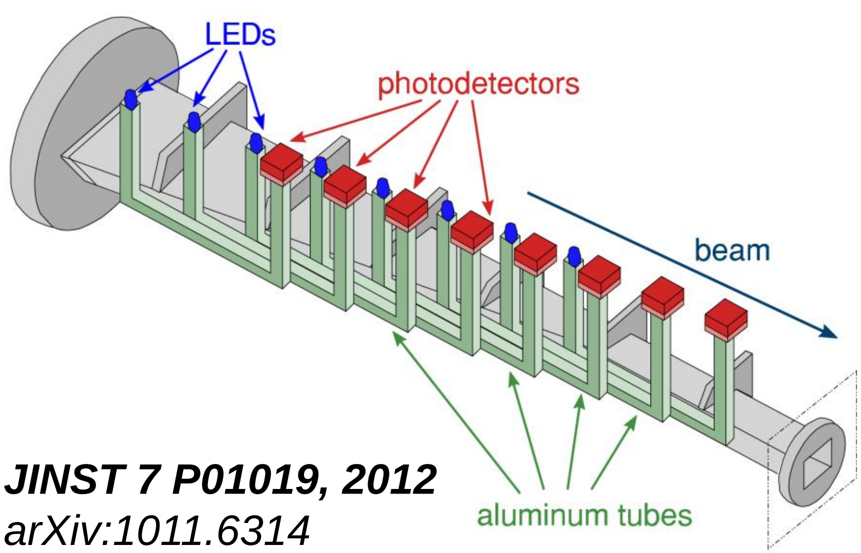
- covering ~20cm next to the beam pipe ≙ 25GeV-125GeV
- total ionising dose up to 100 Mrad/year
- read-out signals of 1000-2000 Compton-scattered e^+/e^- **every** bunch crossing (1.3 MHz)
- either very linear response or “counting” of e^+/e^-
- alignment to ~100µm and ~1mrad
- suppression of background from low-energetic particles

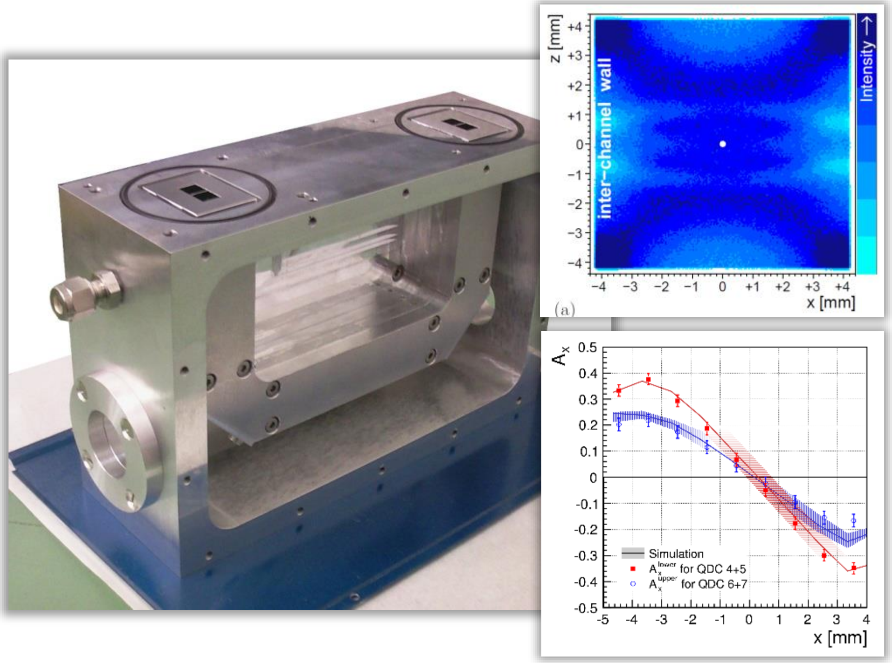


Gas Cherenkov Detector Prototype



- gas-filled U-shaped tube (C_4F_{10} → n = 1,0014)
- improved design compared to SLC polarimeter
- front leg: PM calibration system
- hind leg: channel readout with segmented PMs
- 2-channel prototype tested in testbeam





JINST 7 P01019, 2012
arXiv:1011.6314

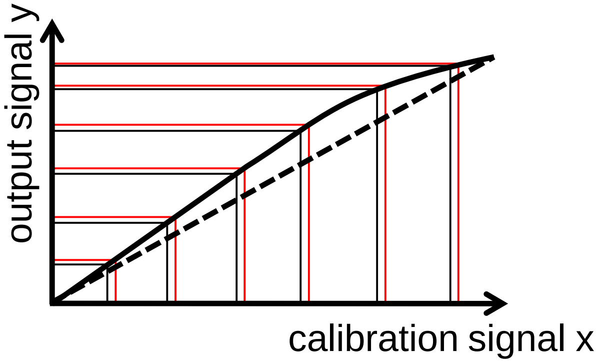
→ **nearly reached alignment requirements**

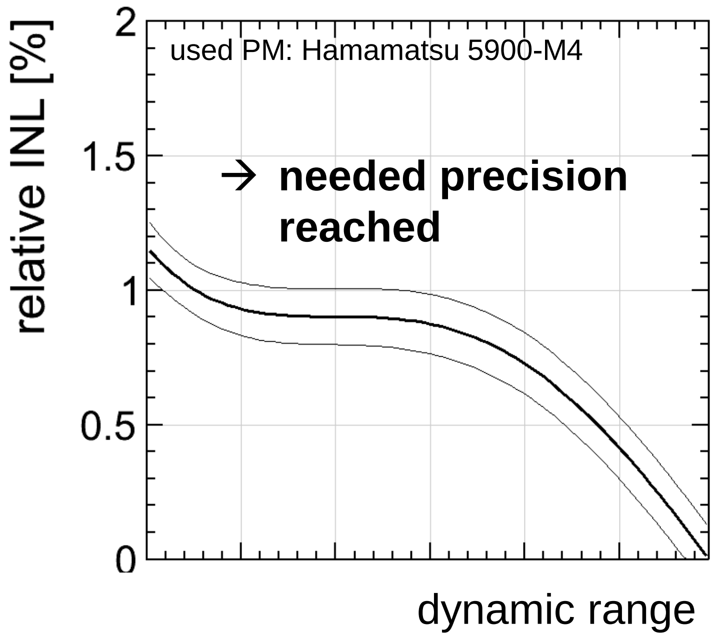
Differential Photomultiplier Calibration

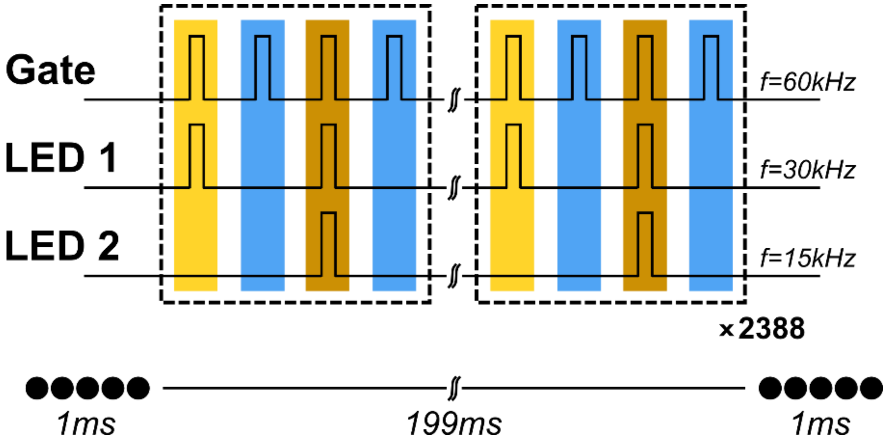
requirement: detector nonlinearity < 0.5% → **calibration**

$$P = \frac{1}{A}\frac{N^+ - N^-}{N^+ + N^-}$$

→ no absolute calibration, **but "only"** linear response
→ differential nonlinearity measurement with 2 light pulses
→ dedicated LED system fulfils requirements







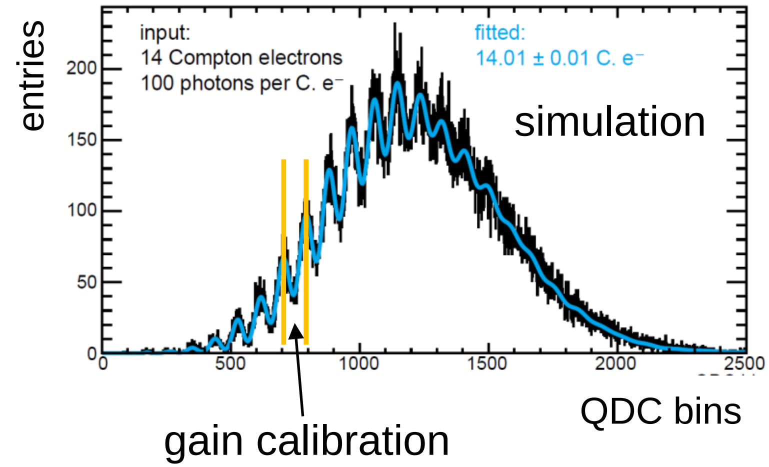
→ **ILC bunch structure allows for online nonlinearity monitoring (~5h)**

Quartz Cherenkov Detector Prototype

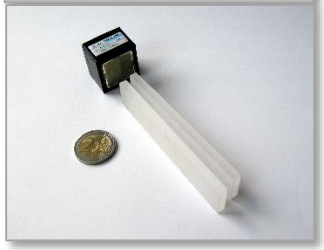
Alternative: Quartz as Cherenkov Material

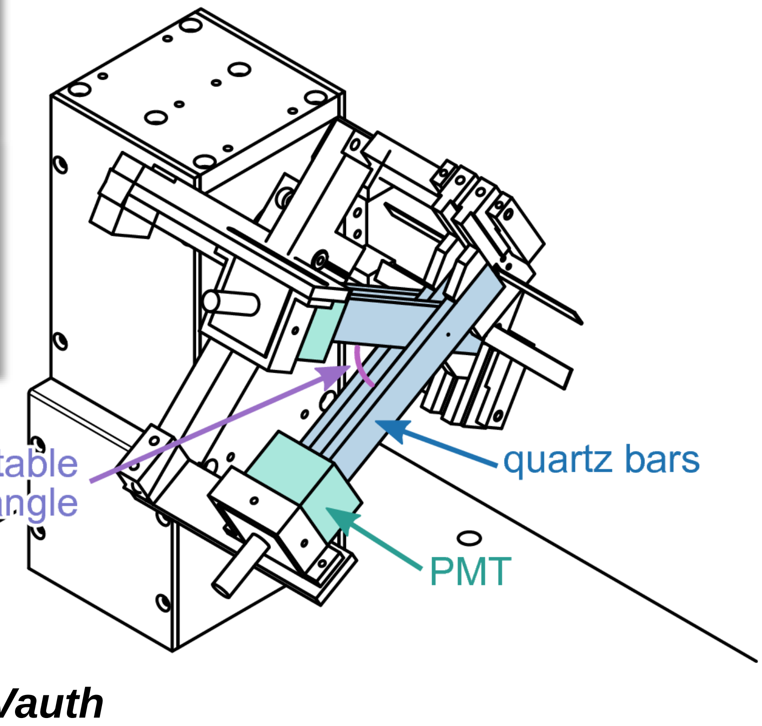
- higher refractive index → higher photon yield
- for enough photons per Compton e^-
  resolve singe Compton e^- multiplicities

→ **self-calibrating detector**



$n \approx 1.45$
$\theta_C \approx 46°$
$E_{thr} \approx 0.9$ MeV





Annika Vauth

Prototype Build and Testing

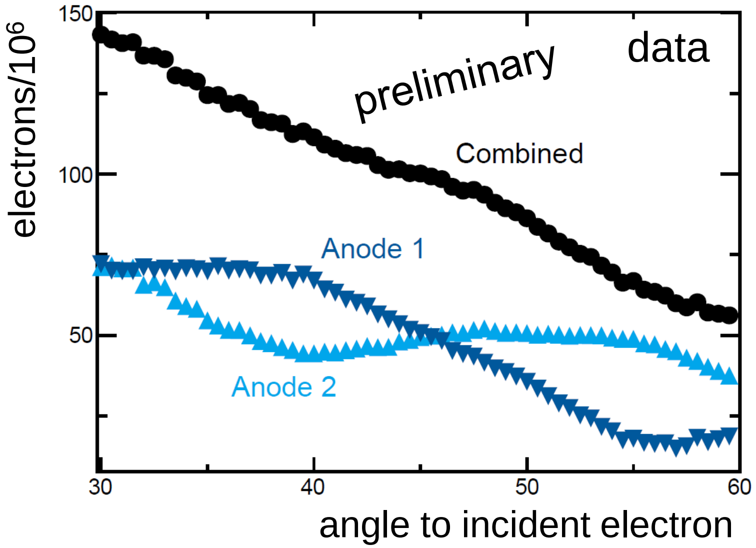
- quartz bars: 5mm x 18mm x 100mm
- adjustable incident angle of e^-
- multianode PM readout
- 4-channel prototype tested in DESY II testbeam (2013)

Quartz Cherenkov Detector Prototype

Alternative: Quartz as Cherenkov Material

- higher refractive index → higher photon yield
- for enough photons per Compton e⁻:
  resolve singe Compton e⁻ multiplicities

→ **self-calibrating detector**



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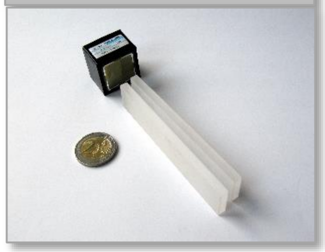

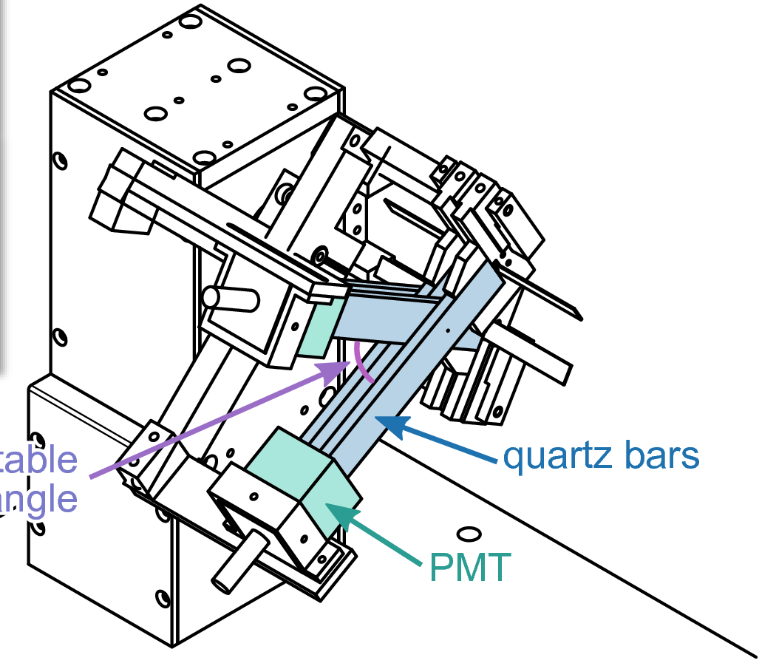

Prototype Build and Testing

- quartz bars: 5mmx18mmx100mm
- adjustable incident angle of e⁻
- multianode PM readout
- 4-channel prototype tested in DESY II testbeam (2013)

→ **first testbeam results look promising**

Annika Vauth

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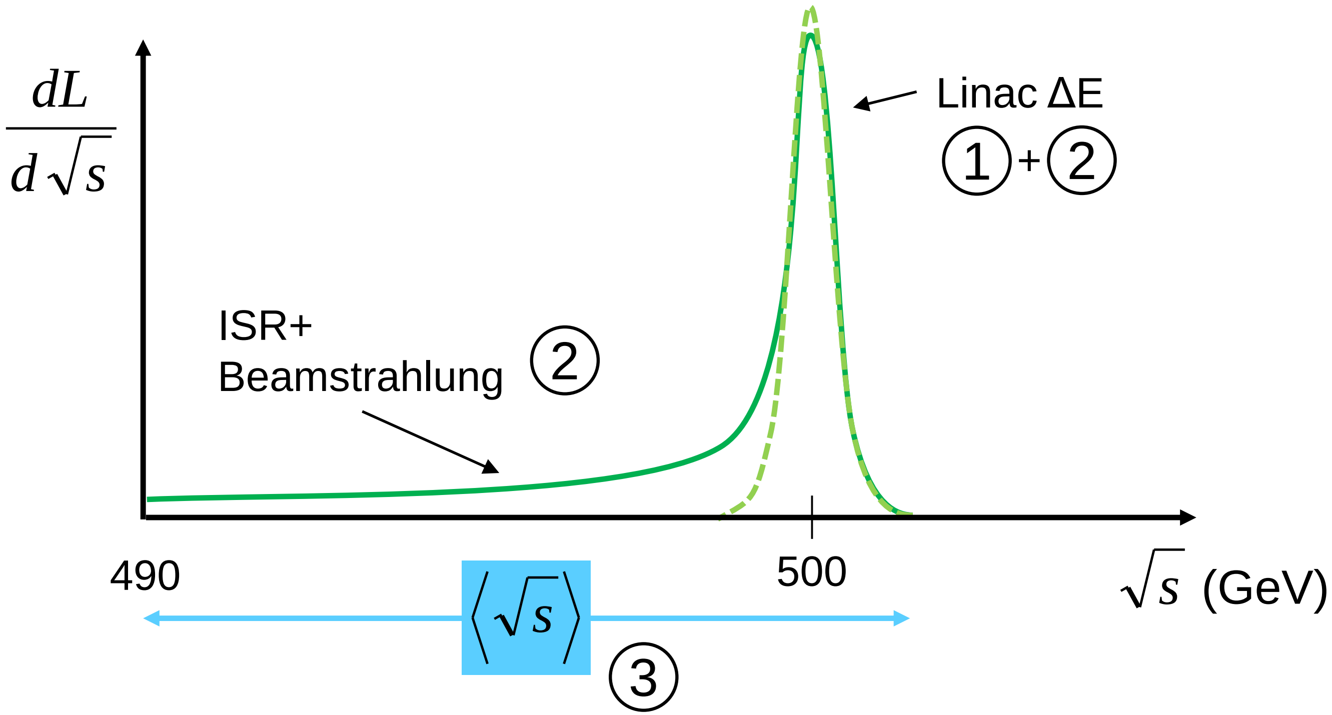
Energy Measurements Concept for the ILC



① **Upstream Energy Spectrometer** for direct beam energy measurement

→ non-invasive energy measurement before collision

② **Downstream Energy Spectrometer** for direct beam energy measurement

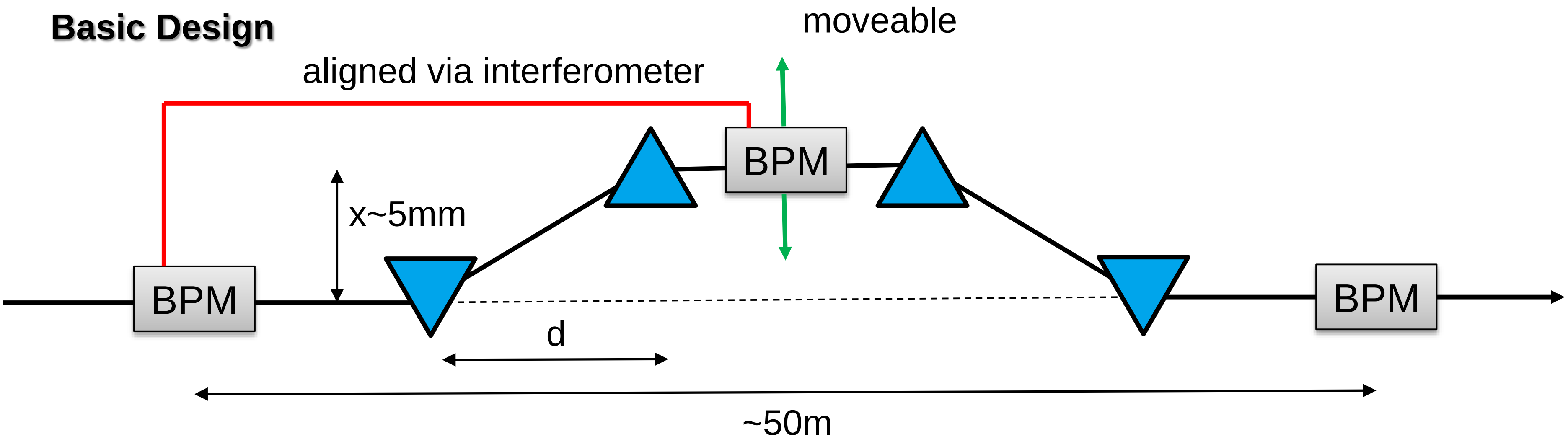
→ downstream measurement sensitive to beamstrahlung losses after collision

③ **e^+e^- collision data** for long-term energy calibration

→ radiative Z return ($e^+e^- \rightarrow \mu\mu\gamma$), acolinear Bhabha events, …

Beam Energy Measurement – BPM Energy Spectrometer

Basic Design



- ILC baseline **upstream** energy spectrometer
- design inspired by LEP2 energy spectrometer → single dipole (ΔE/E=0.017%)
- small inclination of beam in cavity BPM favourable
- displacement of beam in chicane by 5mm → minimise emittance growth
- vertical offset proportional to energy

$$E = qc\frac{d}{x}\int \vec{B}\cdot\mathrm{d}\,\vec{s}$$

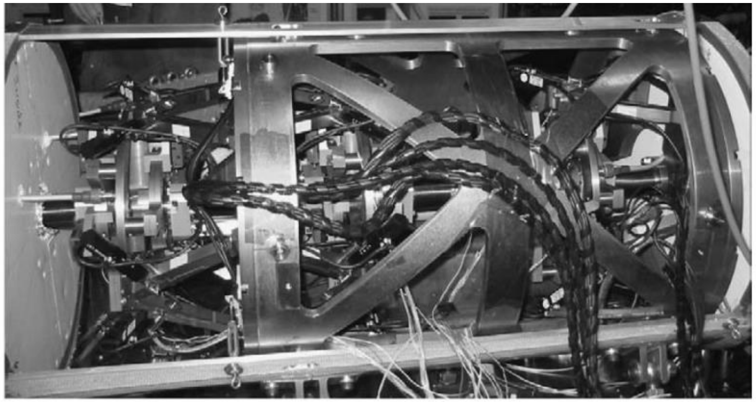
Precision Goal $\Delta E / E \approx O(0.01\%)$ → resolution better than 500nm

Status of the BPM Energy Spectrometer

Nanometer Precision BPMs

- cavity BPM capable to reach nm precision
- nanoBPM tested in ATF extraction line (KEK)
- achieved BPM resolution:
  position: 15.6nm
  tilt: 2.1µrad

NIM A 578 (2007) 1-22



ILC-like Energy Chicane Test Setup

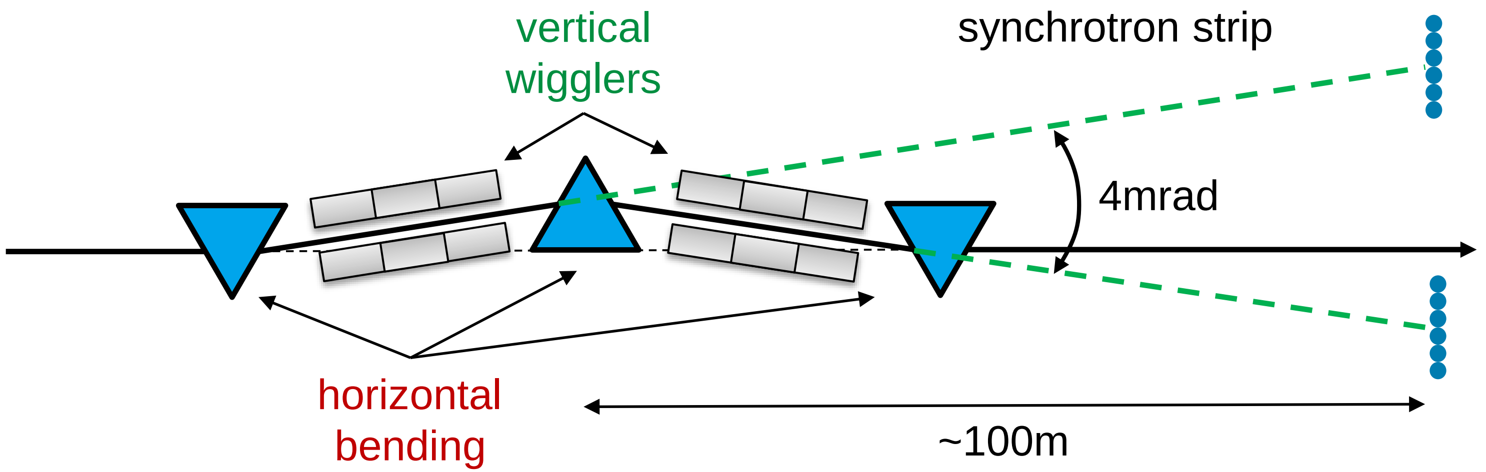
- test setup in ESA at SLAC
- ILC like beam conditions at ESA
- operated at dispersion of 5mm
- stability over one hour on *O*(µm)
- achieved resolution: 0.8µm in x/ 1.2µm in y
  → ΔE/E=0.05%

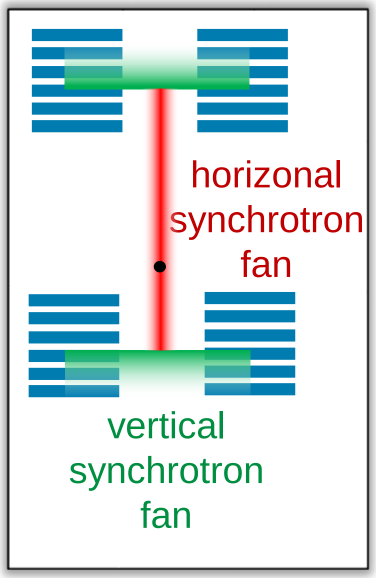
NIM A 592 (2008) 201-217
JINST 6 P02002, 2011

parameter	SLAC ESA	ILC500
rep. rate	10Hz	5Hz
energy	28.5GeV	250GeV
bunch charge	$1.6 \cdot 10^{10}$	$2.0 \cdot 10^{10}$
bunch length	500µm	300µm
energy spread	0.15%	0.15%

Beam Energy Measurement – Synchrotron Strip Detector

Basic Design





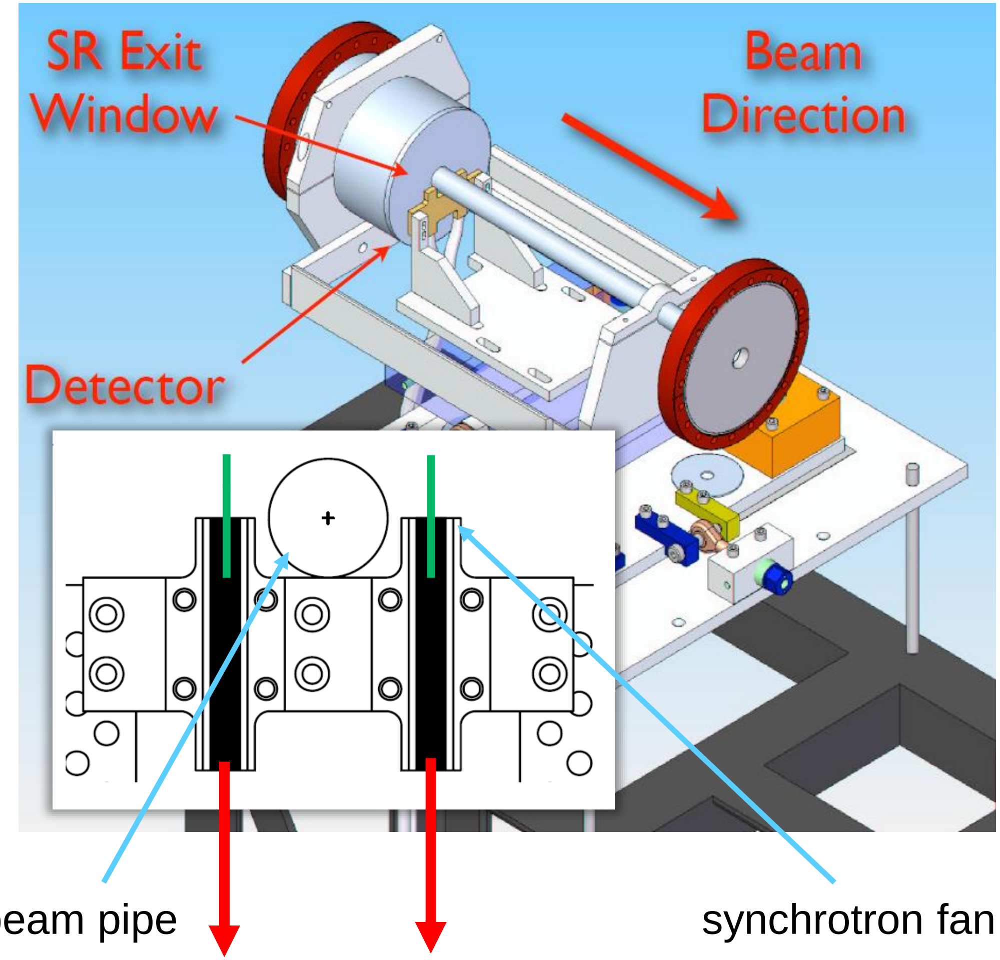
- ILC baseline **downstream** energy spectrometer
- design inspired by SLC WISRD → ΔE/E=0.02%
- quartz fibres (100µm) producing Cherenkov light
- readout via photomultipliers
- synchrotron radiation distributed over a few fibres due to beam energy spread
  → sensitive to energy spread/ width

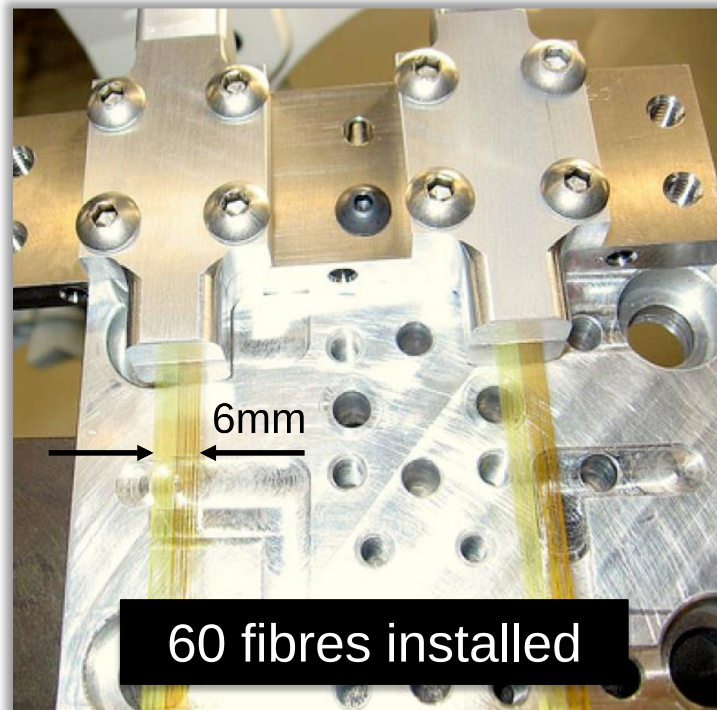
Precision Goal

$$\Delta E / E \approx O(0.01\%)$$

→ precision of fibre positioning: 20µm

Status of Synchrotron Strip Detector





- prototype tested in ESA at SLAC
- ILC-like setup
- 64x140µm(100µm active) UV fibres
- spaced on 200µm pitch

→ **no show-stopper in sight**

Eric Torrence

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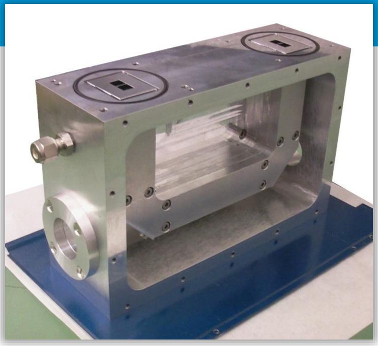
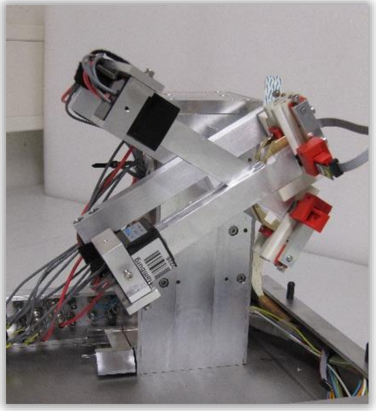
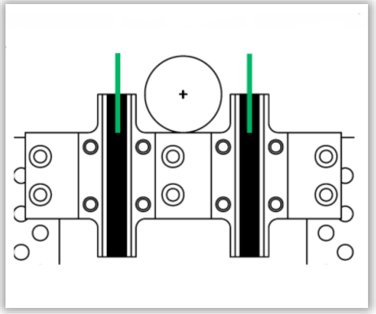
Conclusions







- **High precision physics** needs also **excellent beam instrumentation**
- Polarimeter: two possible **Cherenkov detector concepts** (gas, quartz)
- Energy spectrometer: two **independent spectrometer concepts**
- Polarisation and energy measurement **concepts** at the ILC **in a good shape**
- **Precision goals reachable**

Backup slides

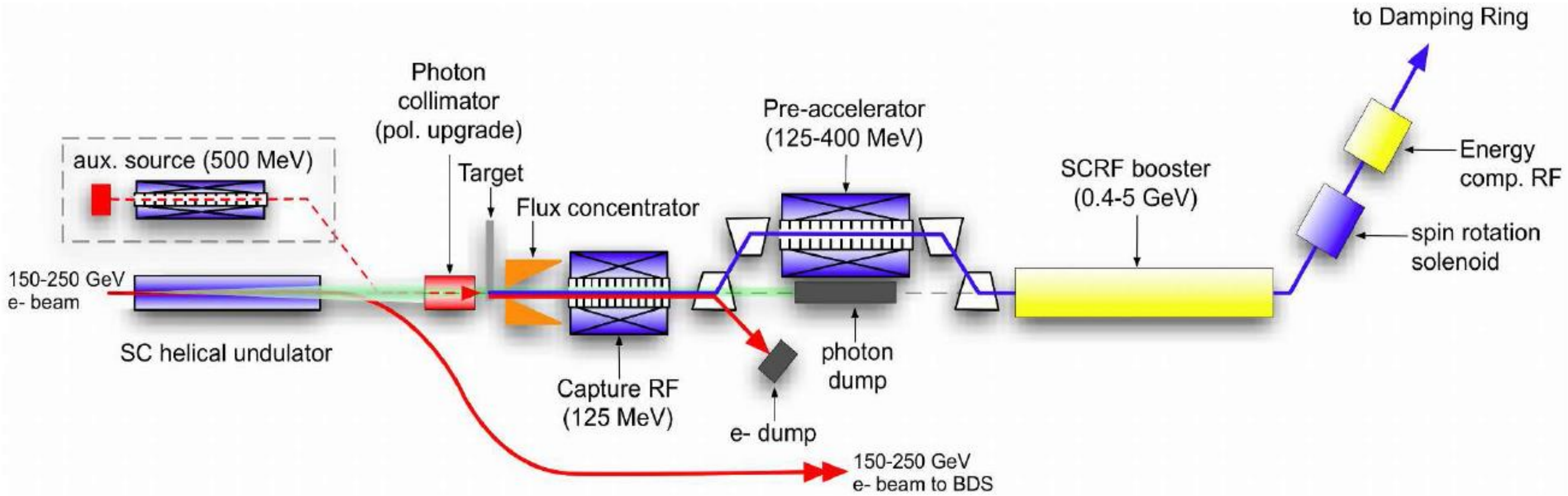
The International Linear Collider – Beam Parameters

Center-of-mass energy	E_{cm}	GeV	250	500	1000
Number of bunches per train	N_b		1312	1312	2450
Bunch population	N	$\times 10^{10}$	2.00	2.00	1.74
Average total beam power	P_{beam}	MW	5.9	10.5	27.2
Estimated AC power	P_{AC}	MW	122	163	300
RMS bunch length	σ_z	μm	300	300	250
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.124	0.083
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.070	0.043
Horizontal emittance	$\gamma\epsilon_x$	μm	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35
IP horizontal beta function	β_x	mm	13.0	11.0	22.6
IP vertical beta function	β_y	mm	0.41	0.48	0.25
IP RMS horizontal bunch size	σ_x	nm	729.5	474.0	481.0
IP RMS vertical bunch size	σ_y	nm	7.7	5.9	2.8
Luminosity	$\mathcal{L}$	$\times 10^{34}$cm^{-2}s^{-1}	0.75	1.8	3.6
Average energy loss	δ_{BS}	%	0.97	4.5	5.6

- high luminosity needs strongly focused beams
- beam strahlung limits focussing → flat beam
- however: after collision disrupted bunches

→ beam energy and polarisation measurement before and after IP differ

ILC Positron Source



Challenges of Downstream Polarimetry

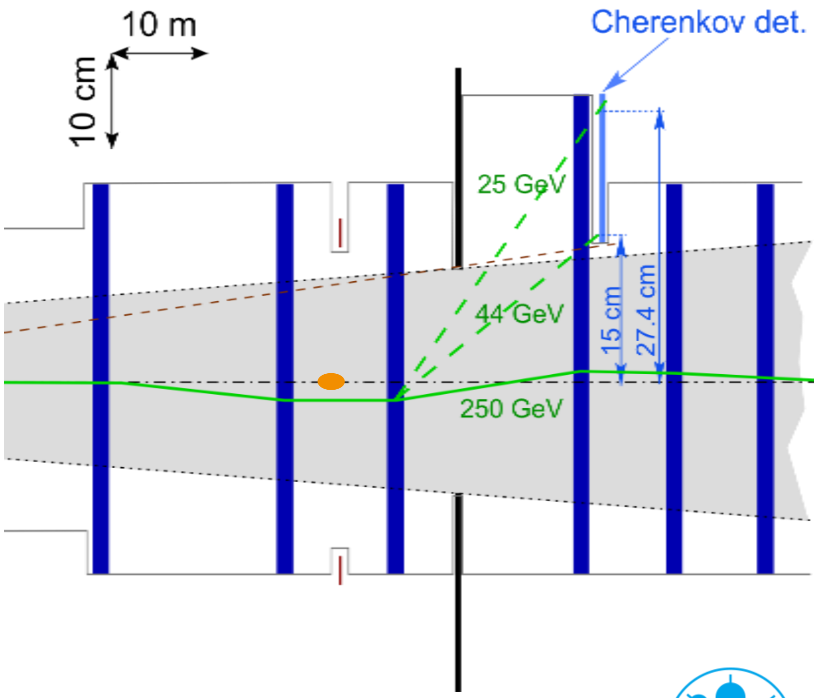
Downstream polarimeter necessary in order to measure beam **depolarisation in collision**

Laser System

- highly disrupted bunch → e+/e- density smaller
- compensation by larger laser power (100mJ)
- impossible to probe all O(1000) bunches per train → three shots per train

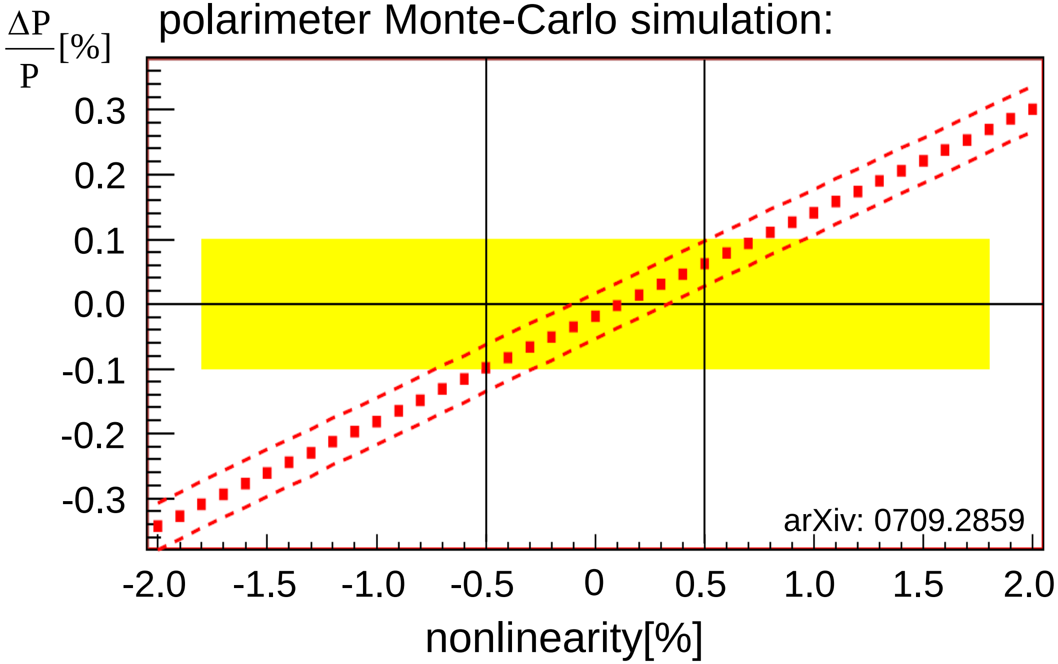
Magnetic Chicane Design

- downstream polarimeter IP at secondary focus
- downstream the IP large backgrounds → blind area for polarimeters
- special 6-dipole-chicane
  dipole 3 stronger than dipoles 1+2
- larger fraction of Compton fan outside the blind area



Error Budget: Nonlinearity of Gas-Cherenkov Detector

polarimeter Monte-Carlo simulation:



→ nonlinearity of detector has to be less than 0.5%

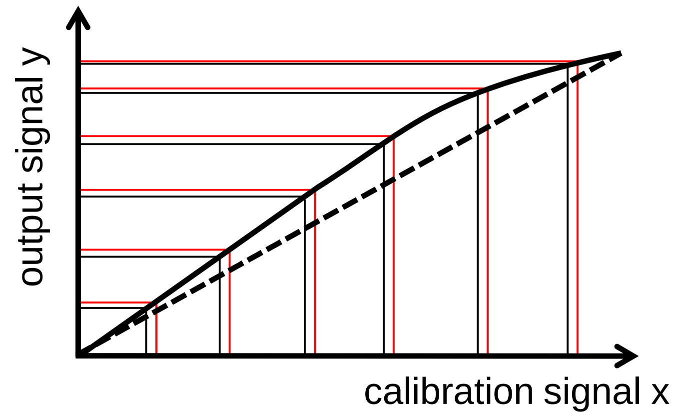
→ calibration of detectors/PMTs neccessary

Principle of Differential Nonlinearity Measurement

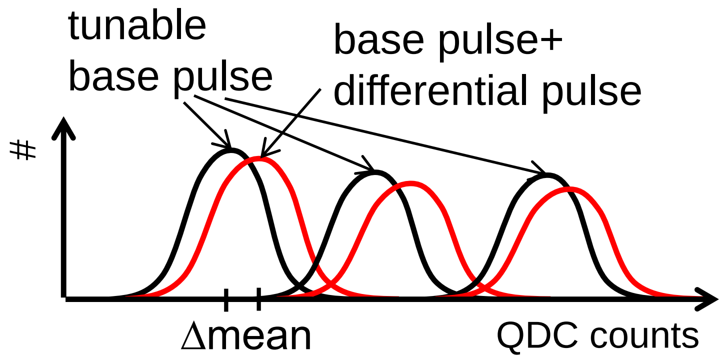
Measurement of number of Compton electrons for two helicity configurations of the laser in one detector channel (=energy interval):

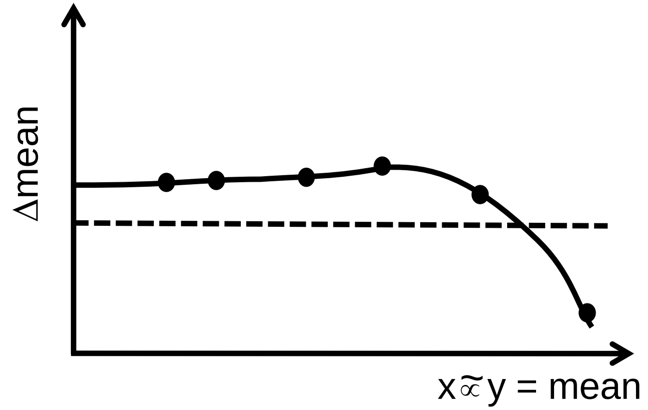
$$P(e) \propto \mathrm{A} = \frac{N^+ - N^-}{N^+ + N^-}$$

differential nonlinearity (DNL)



double pulse method

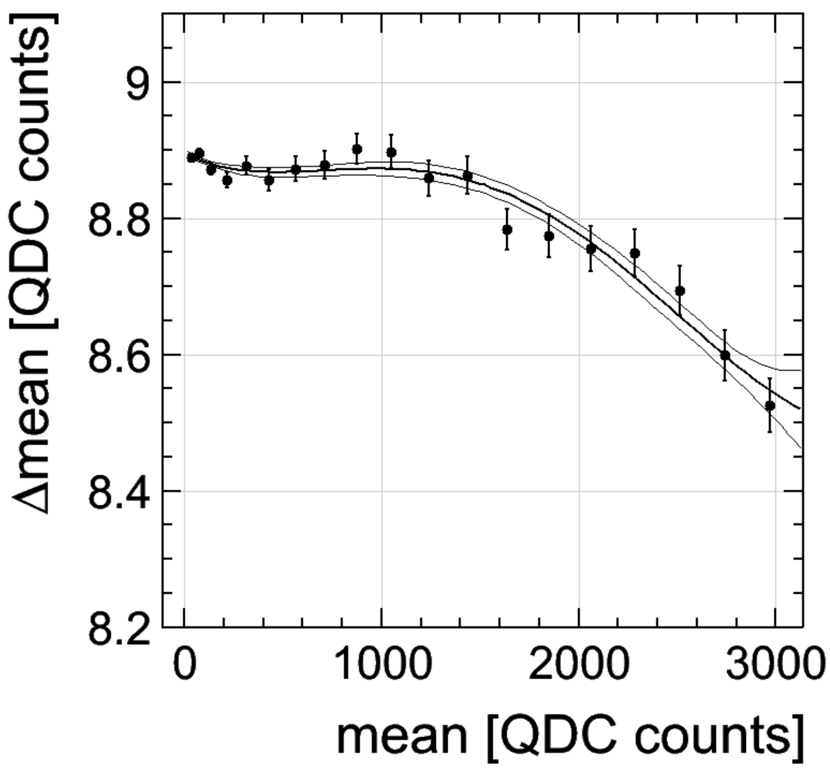




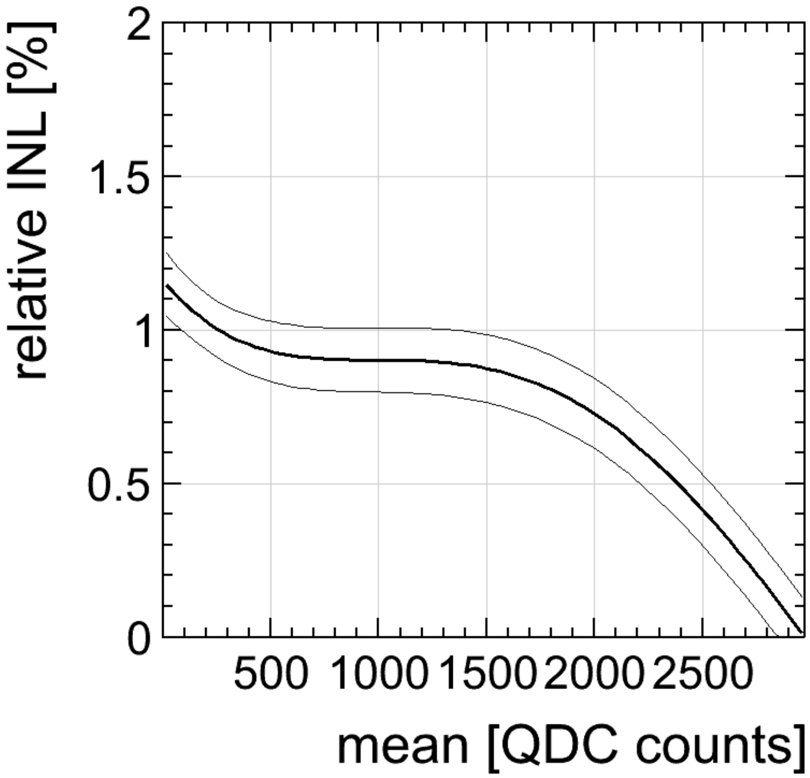
DNL Measurement

Hamamatsu 5900-M4 PMT 2x2
→ *PMT used in gas-prototype*

Default configuration



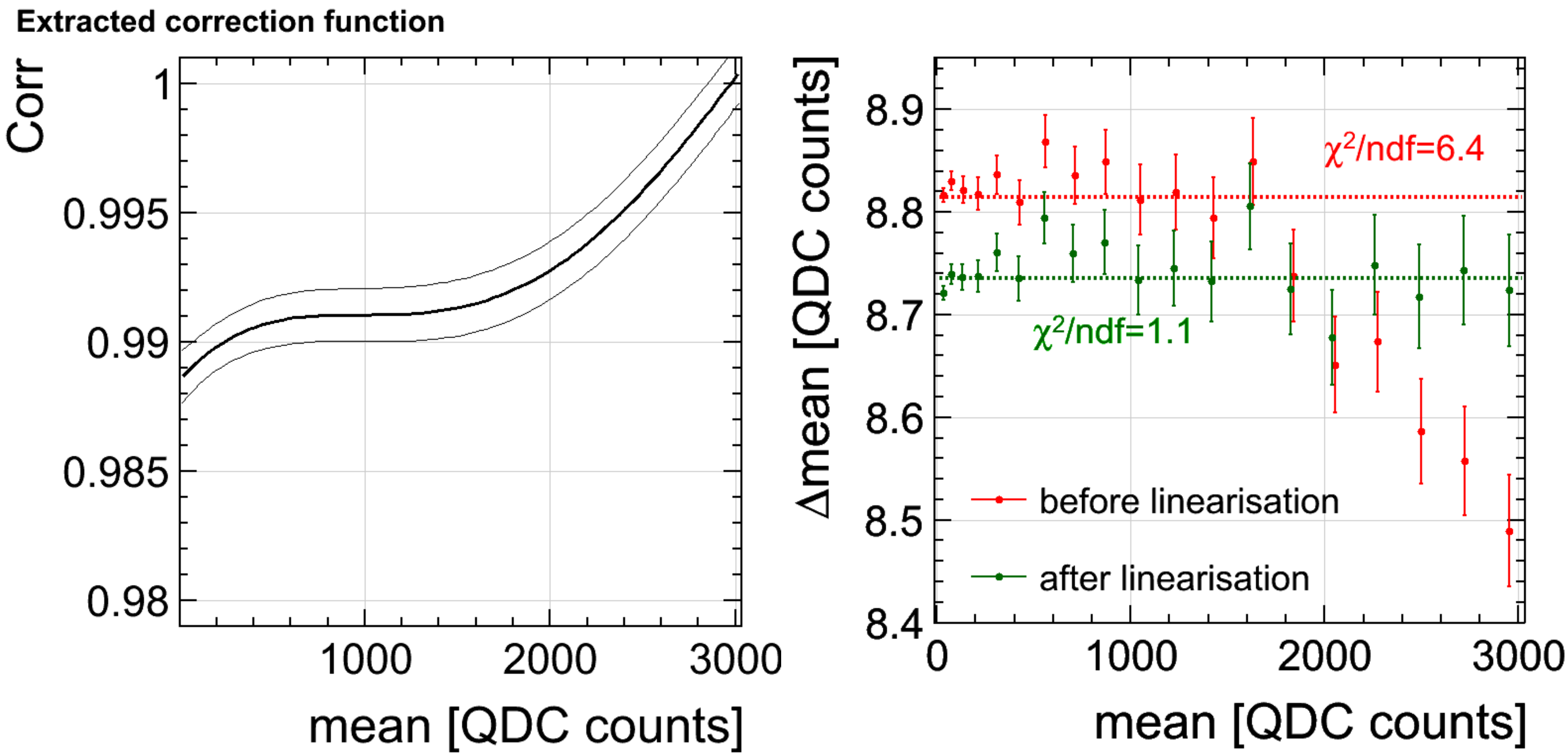
Measured relative INL



→ **already very linear in the low intensity regime**

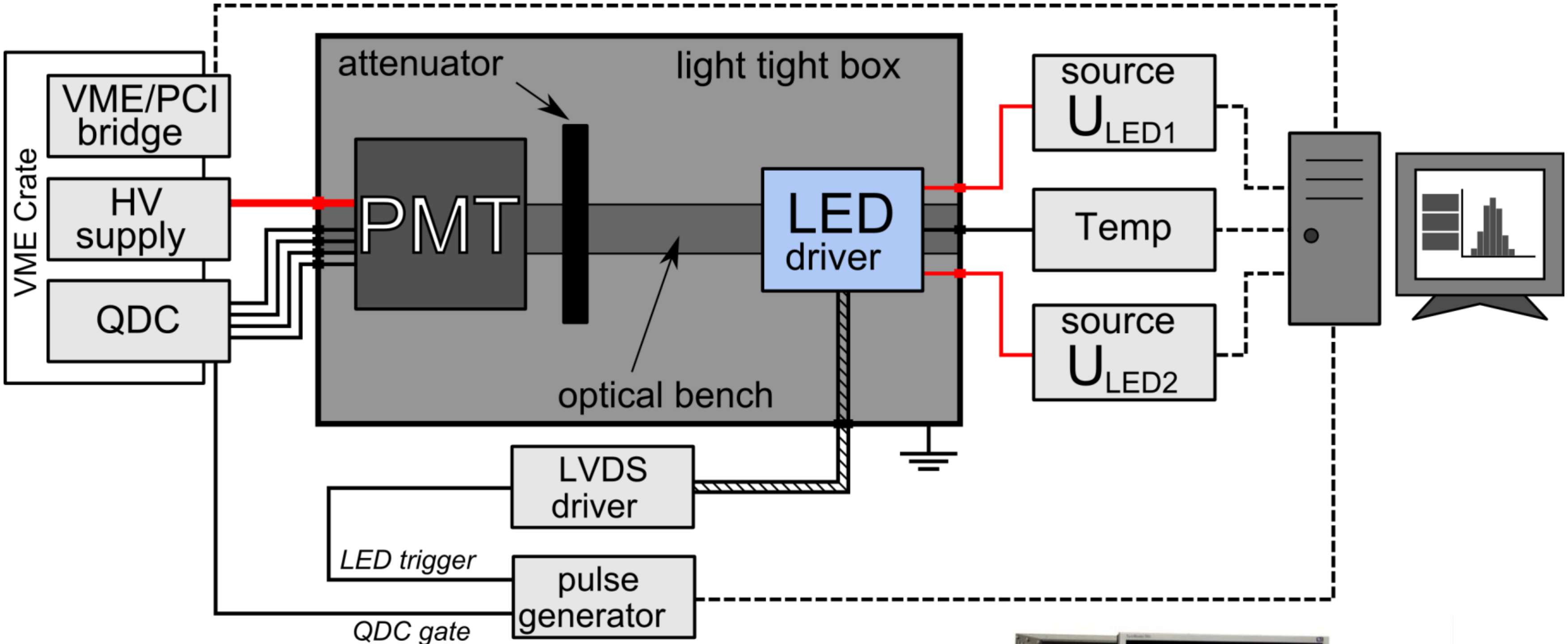
DNL Measurement (Correction)

- correction extracted from statistically independent data set A
- applied to data set B

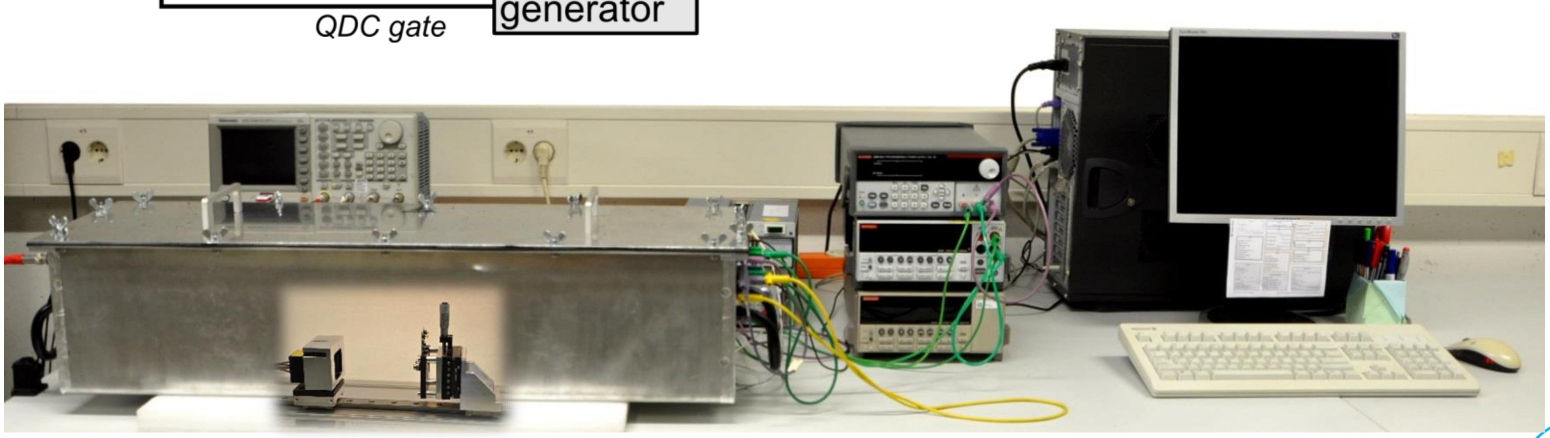


→ **correction linearises dataset B**

Test Setup

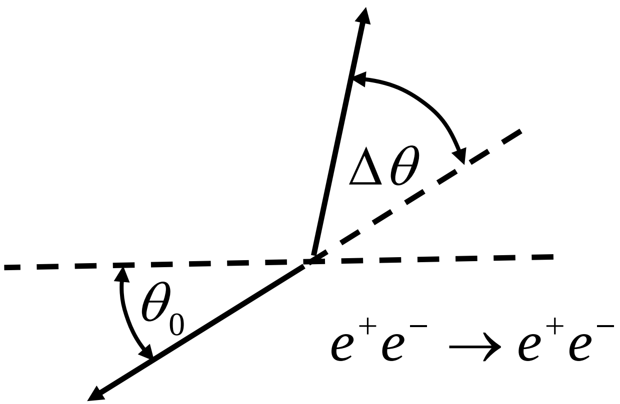


VME Crate
VME/PCI bridge
HV supply
QDC
attenuator
light tight box
PMT
LED driver
optical bench
source U_{LED1}
Temp
source U_{LED2}
LVDS driver
LED trigger
pulse generator
QDC gate



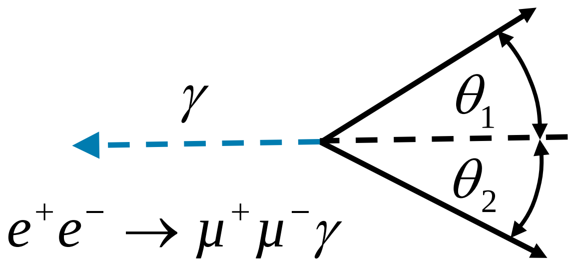
Beam Energy from Collision Data

Acolinear Bhabhas



$$\frac{\sqrt{s'}}{\sqrt{s}} = 1 - \frac{\Delta\theta}{2\sin\theta_0}$$

Radiative Z return



$$\frac{s'}{s} = \frac{\sin\theta_1 + \sin\theta_2 - |\sin(\theta_1+\theta_2)|}{\sin\theta_1 + \sin\theta_2 + |\sin(\theta_1+\theta_2)|}$$

→needs excellent tracking
→$\Delta\theta = 10^{-4}$