

Status of beam polarisation measurements at the ILC

LCWS14, Belgrade

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for the DESY FLC



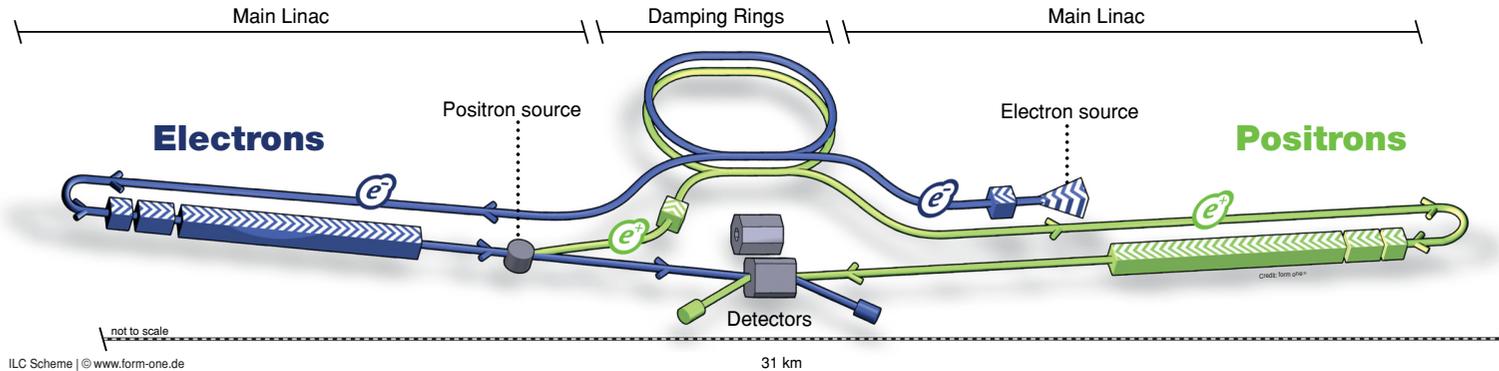
October 7, 2014



- 1 Polarimetry at the International Linear Collider
- 2 Spin Tracking
- 3 Conclusions and Future Plans

Polarimetry at the International Linear Collider.

International Linear Collider (ILC).



- Planned e^+e^- linear collider (length ≈ 30 km)
- Energy up to $\sqrt{s} = 500$ GeV , potential upgrade to 1 TeV
- Use of polarised beams $P(e^-) \approx \pm 80 - 90\%$, $P(e^+) \gtrsim \pm 30 - 60\%$

Polarisation.

Longitudinal polarisation $P_z = \frac{N_R - N_L}{N_R + N_L}$ ($\mathcal{P} \equiv P_z$ thereafter)

with $N_{R,L}$: number of right-/left-handed particles in bunch

- ▶ Important quantity for physics: **luminosity weighted average polarisation at the IP** (accessible from e^\pm collision data)
- ▶ SM & BSM: left- and right handed particles couple differently
 - ▶ polarised cross-sections carry **qualitatively** new information
 - ▶ beam polarisation can suppress background / enhance signal

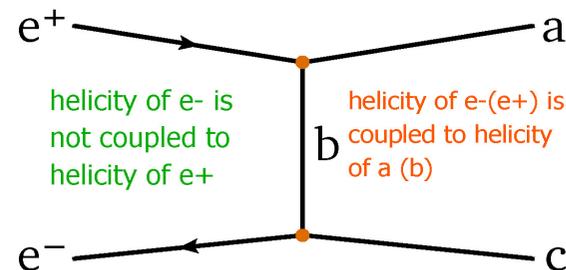
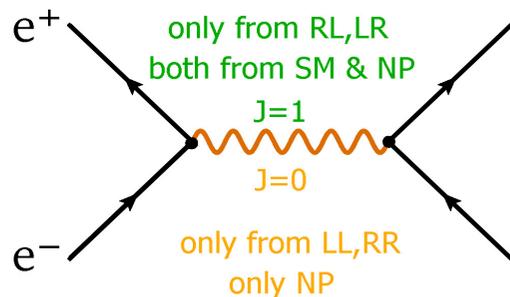
	e^-	e^+	h_{e^-}	h_{e^+}	cross section
$J=1$			-1	+1	σ_{LR}
$J=1$			+1	-1	σ_{RL}
$J=0$			+1	+1	σ_{RR}
$J=0$			-1	-1	σ_{LL}

[LC-REP-2013-017]

Benefits of polarised beams.

\mathcal{P} is the key for the success of the ILC physics programme:

- e^\pm LC : **Annihilation** (s-channel) & **Scattering** (t & u- channels)
- **Annihilation** : helicities of e^\pm correlated by the \vec{s} of the exchanged particle
 - enhanced rates and bkgr suppression for $e_L^\pm e_R^\mp$ (SM) or $e_R^\pm e_L^\pm$ (BSM)
- **Scattering** : helicities of e^\pm can be related to properties of (new) particles
 - access to quantum numbers & chiral couplings
- polarisation asymmetry observable for E/W precision measurements



polarisation for Physics : Examples.

A "simple" case example i.e. Higgs physics:

- scaling of production cross-sections with polarisation

Configuration ($\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$)	scaling factor	
	$e^-e^+ \rightarrow HZ$	$e^-e^+ \rightarrow H\nu\bar{\nu}$
(+80 %, -60 %)	1.26	0.08
(-80 %, +60 %)	1.70	2.88

[hep/1406.4313]

- effect of Higgs couplings to c, b, g (numbers based on $m_H = 120$ GeV)

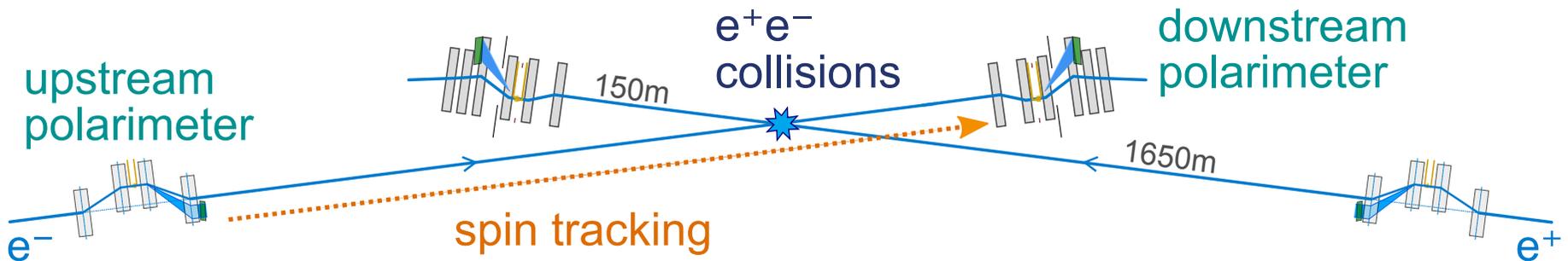
$\Delta(\sigma * \text{BR}) / (\sigma * \text{BR})$	$\sqrt{s} = 250$ GeV	$\sqrt{s} = 350$ GeV
$\mathcal{P}(-80\%, +30\%)$	250 fb^{-1}	350 fb^{-1}
$H \rightarrow bb$	1.0%	1.0% ($\times 10$ vs HL-LHC)
$H \rightarrow cc$	6.9%	6.2% (unique for LC)
$H \rightarrow gg$	8.5%	7.3% (unique for LC)

[EPJC(2013) 73]

- ..but also important for determination of Higgs width (crucial for absolute BR's, model discrimination etc)

Polarimetry at the ILC.

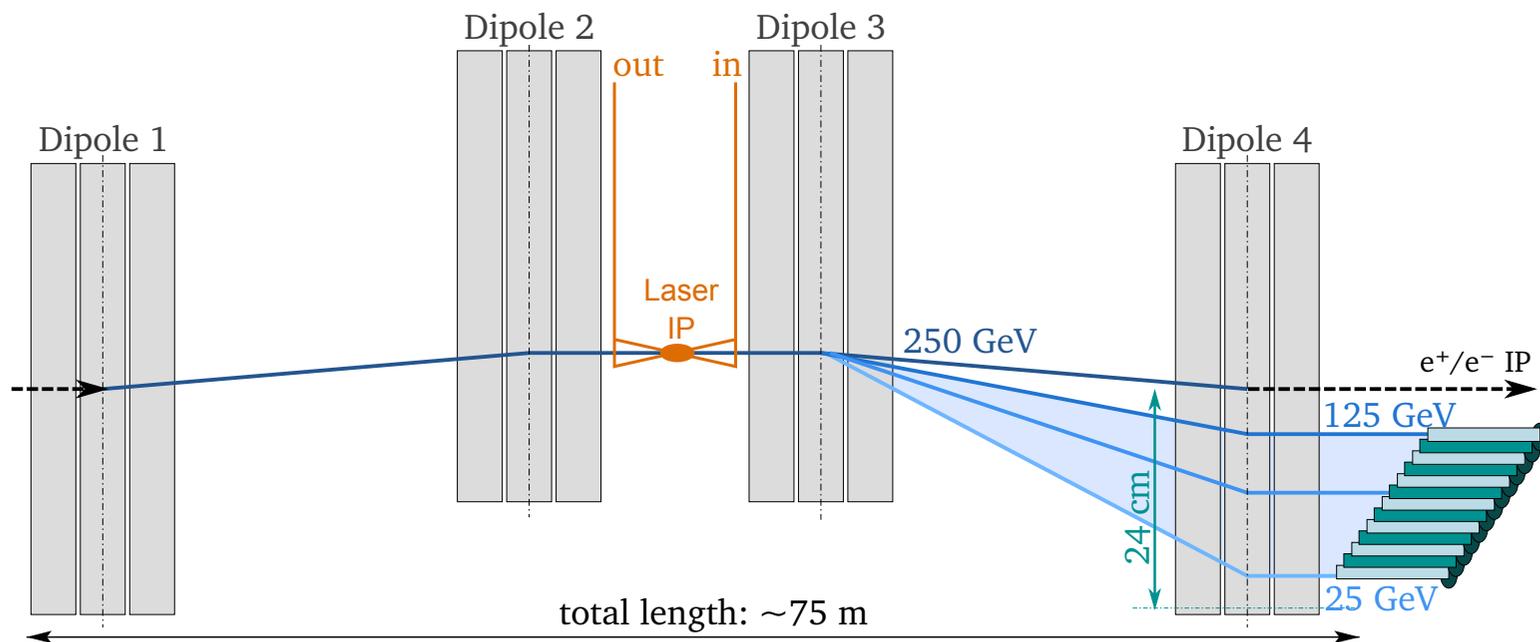
ILC polarimetry: per mille level precision by combining



- Compton polarimeters measurement
 - ▶ Upstream (UP): Capable of excellent time resolution
 - ▶ Downstream (DP) : Give access to collision effects
- Spin tracking studies to relate these measurements to the polarisation at the e^+e^- interaction point
- Long-term average determined from e^+e^- collision data as absolute scale calibration

Compton polarimeters (Upstream).

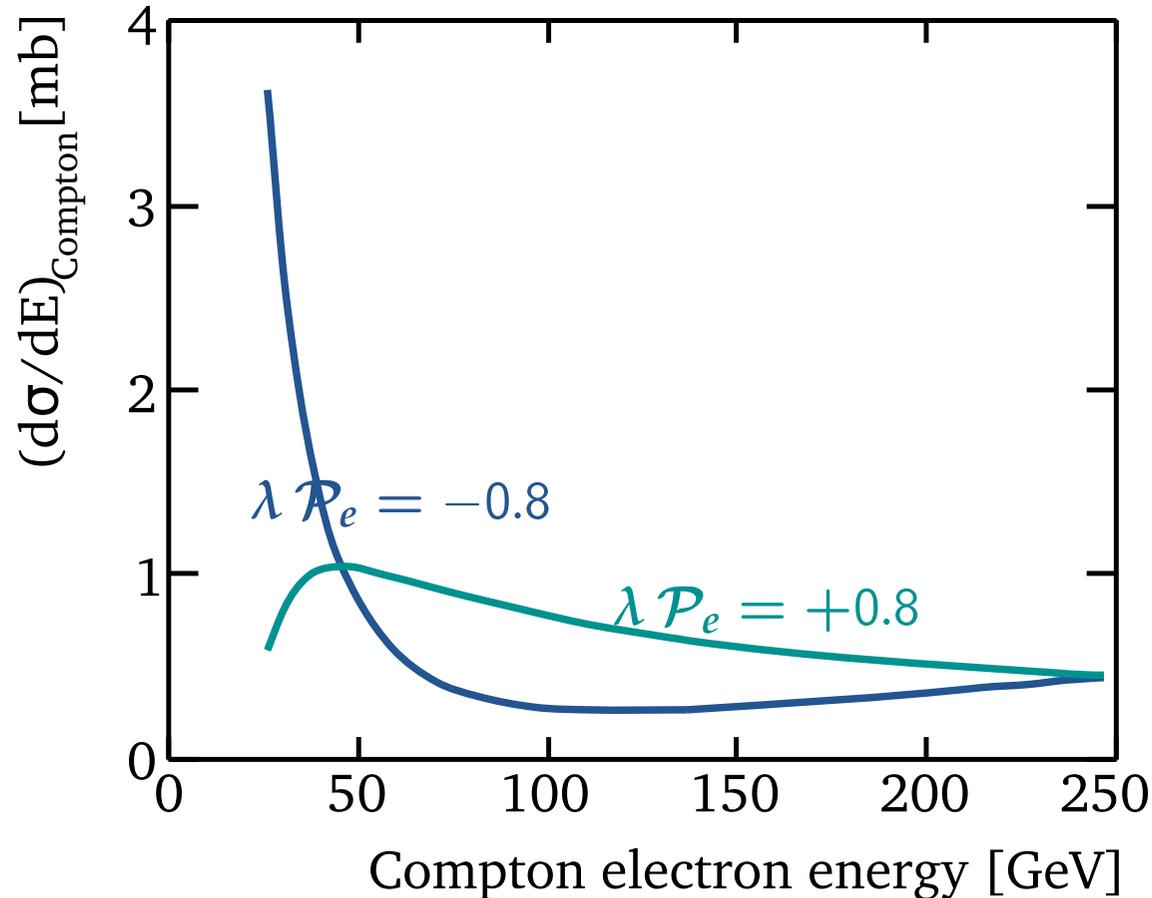
- $\mathcal{O}(10^3)$ e^\pm undergo Compton scattering / bunch
 - Energy spectrum of scattered e^\pm depends on polarisation
 - Magnetic chicane: energy distribution \rightarrow spacial distribution
- \Rightarrow Measure number of e^+/e^- per detector channel



[JINST 4(2009), 10015]

Measurement principle.

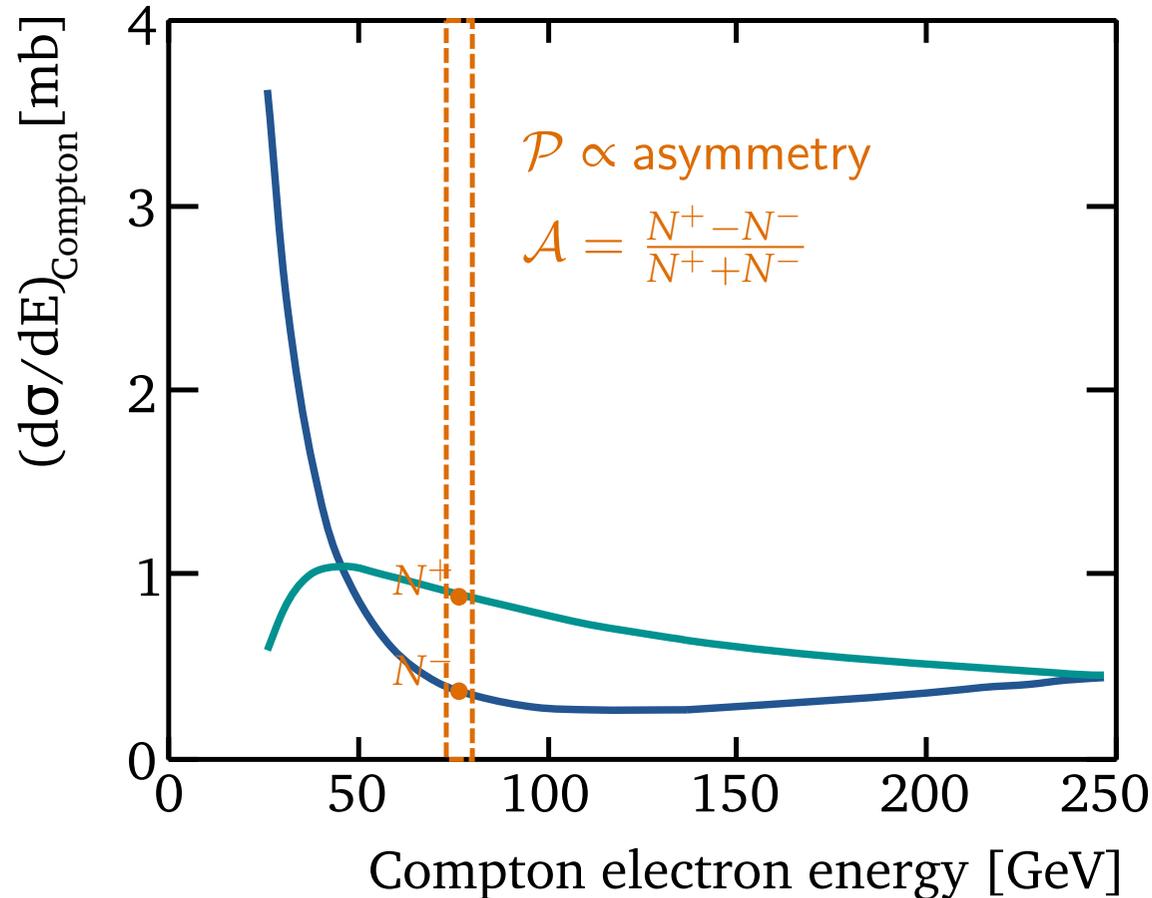
Energy of Compton electrons depends on $\lambda \cdot \mathcal{P}$



λ : Circular polarisation of γ \mathcal{P} : Longitudinal polarisation of e^-

Measurement principle.

Compton rate asymmetry is proportional to the beam polarisation:



λ : Circular polarisation of γ \mathcal{P} : Longitudinal polarisation of e^-

Detector requirements.

Detection of Compton electrons:

- ~ 1000 Compton e^- every bunch crossing (25-250 GeV)
- very linear response or “counting” electrons
- alignment to $\sim 100 \mu\text{m}$ and $\sim 1 \text{ mrad}$
- suppression of background from low energetic particles
- readout rates \mathcal{O} (MHz)

Simple, robust, fast: [Cherenkov detectors](#)

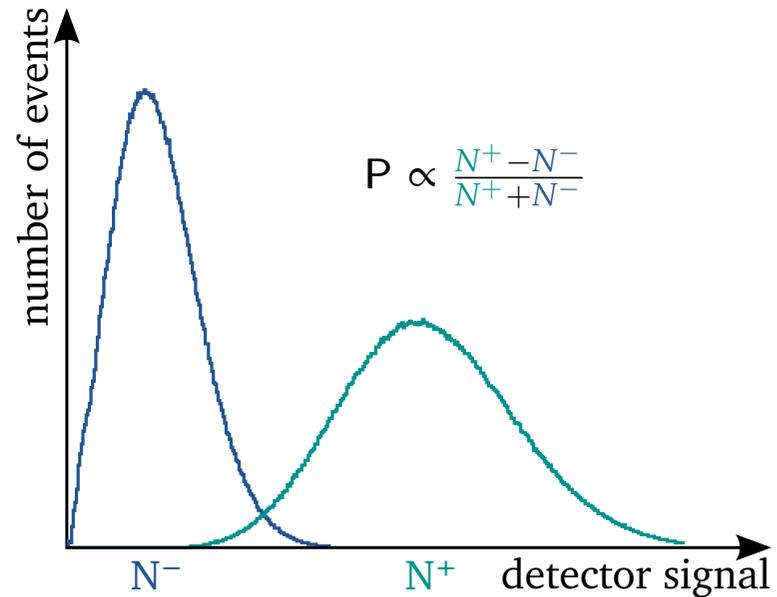
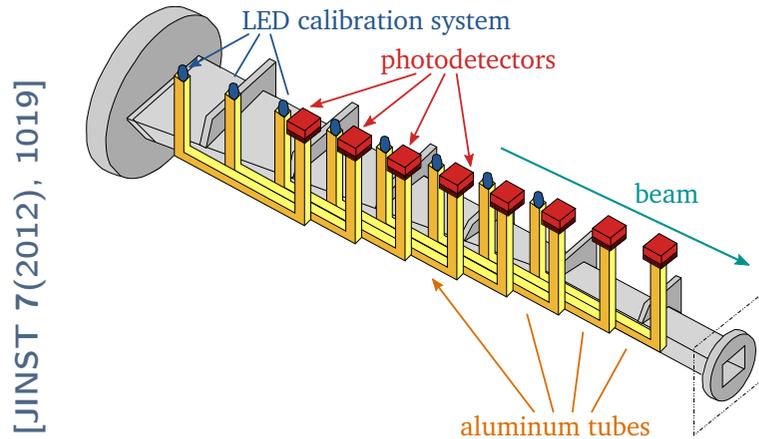
- successfully used in best polarimeter so far at SLC
- light emission proportional to number of electrons ($n > 1$)
- independent of electron energy (once relativistic)
- filled with gas (i.e. perfluorobutane) as Cherenkov medium
- radiation hard

Detector options.

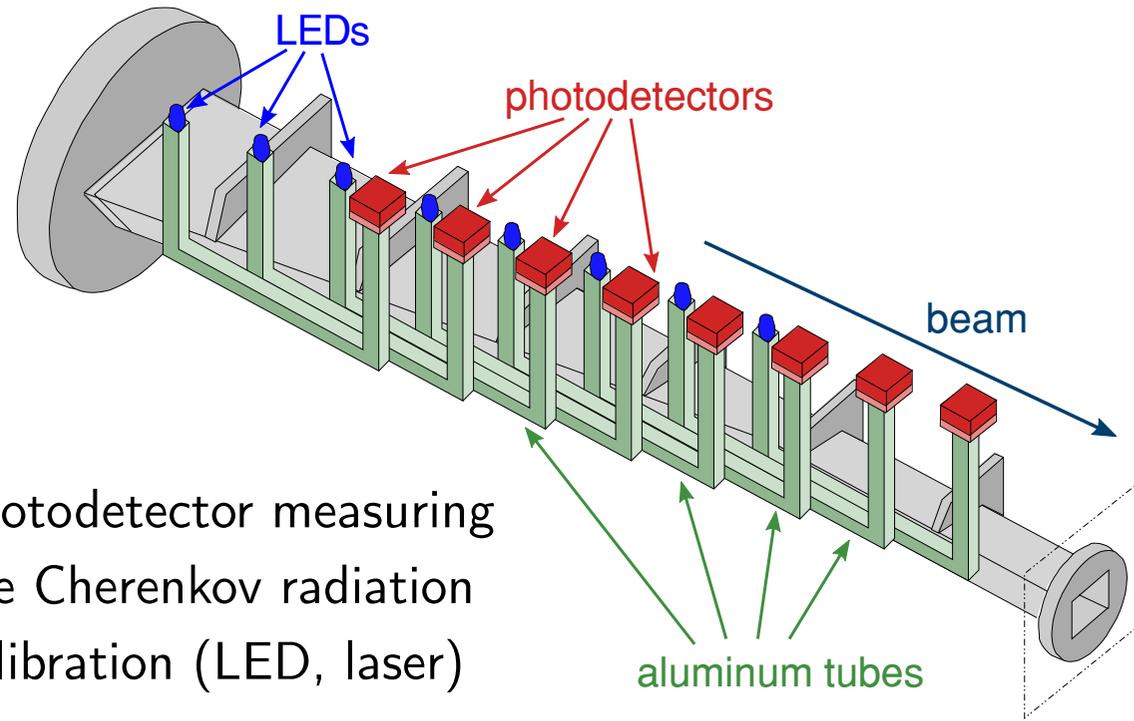
Goal: $\Delta\mathcal{P}/\mathcal{P} \approx 0.25\%$ (total) with :

- laser: 0.1% (already achieved at SLC)
- detector alignment : 0.15 - 0.2 %
- detector linearity: 0.1 %

Gas Cherenkov detector :



Gas Cherenkov detector.



- **hind U-leg:** photodetector measuring the Cherenkov radiation
- **front U-leg:** calibration (LED, laser)

Alignment: locate Compton edge in the spectrometer

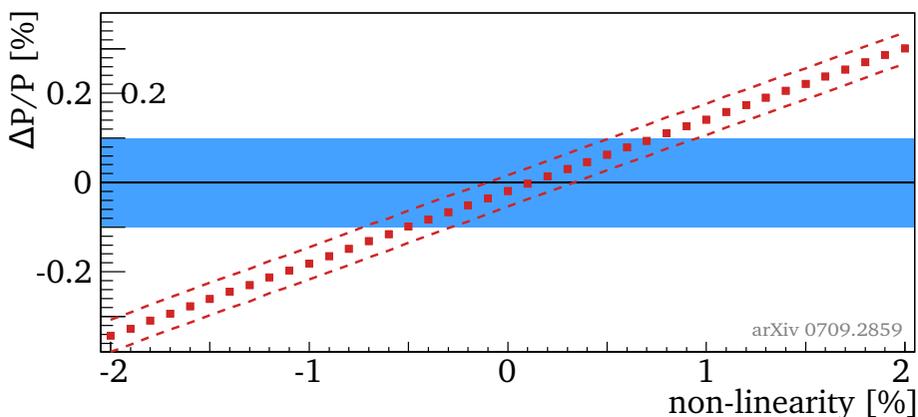
Segmented photodetectors: Tilt alignments via asymmetries

2-channel prototype tested at ELSA [JINST 7, P01019 (2012)]

⇒ tilt alignment of 1 mrad, nearly fulfils alignment requirements

Calibration of detector non-linearity.

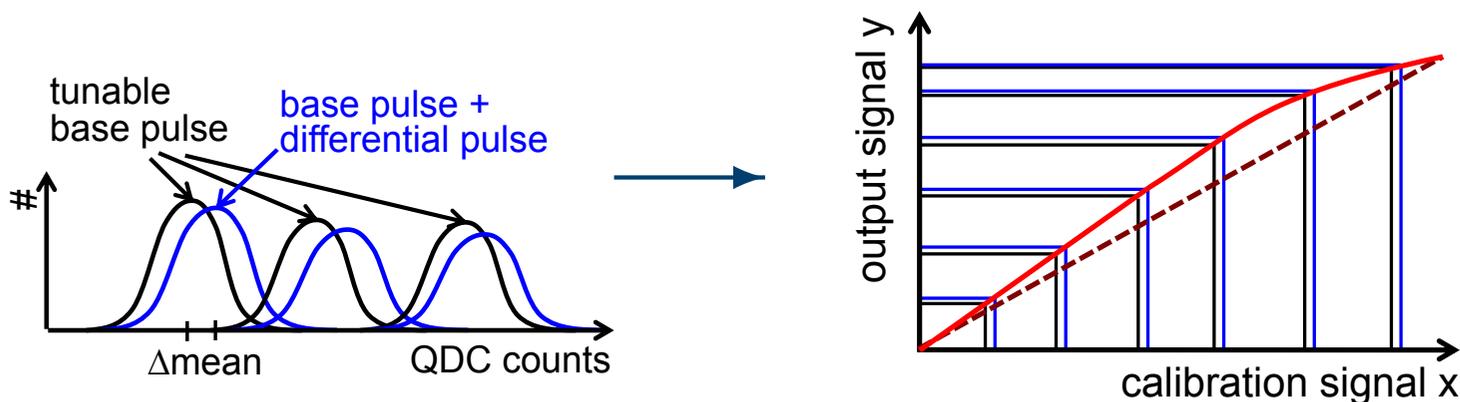
Goal: contribution to overall uncertainty $< 0.1\%$



PMTs have to be calibrated to non-linearity $< 0.5\%$.

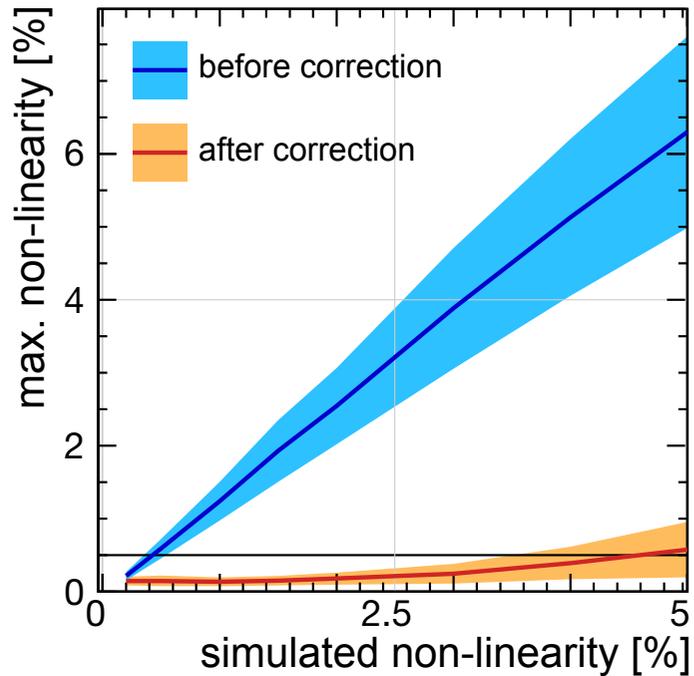
$\mathcal{P} \propto \frac{N^+ - N^-}{N^+ + N^-}$: no absolute calibration needed.

→ Differential calibration method using two LEDs:



Test of non-linearity correction.

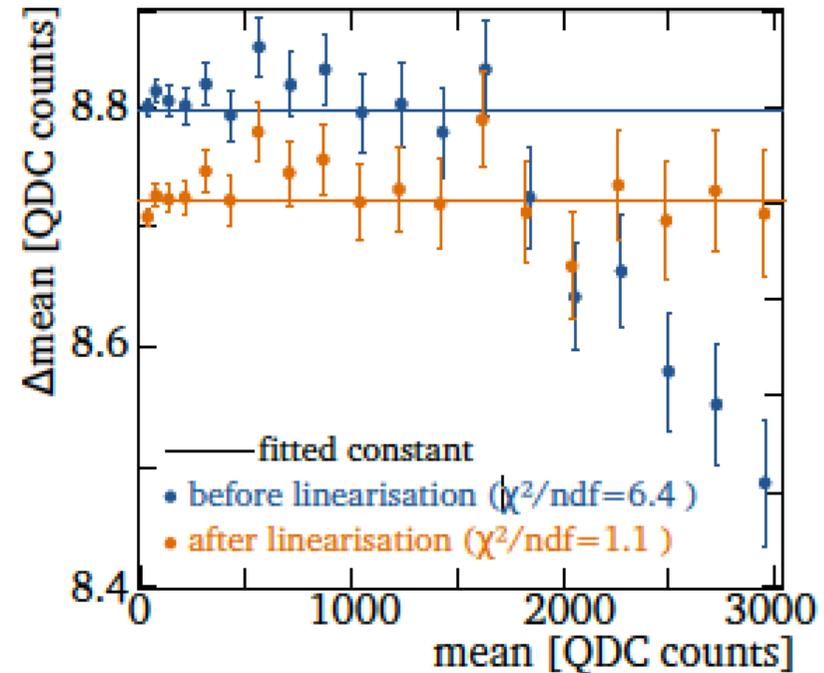
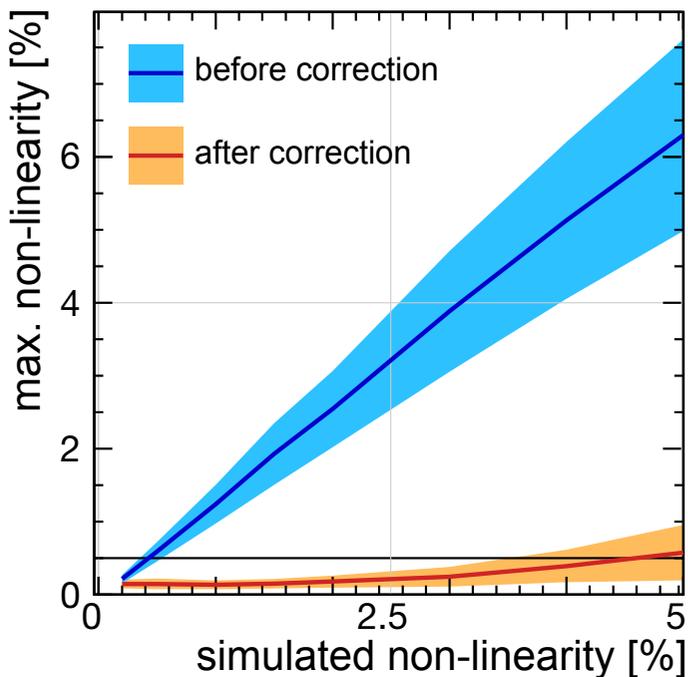
Simulations: Corrections of non-linearities up to 4% possible.



Test of non-linearity correction.

Simulations: Corrections of non-linearities up to 4% possible.

Applied method to one of the photodetectors used in the test-beam:



⇒ Reached non-linearity $< 0.2\%$ in the expected dynamic range, in single polarimeter channels even smaller.

Detector options - Quartz.

Goal: $\Delta\mathcal{P}/\mathcal{P} \approx 0.25\%$ (total) with :

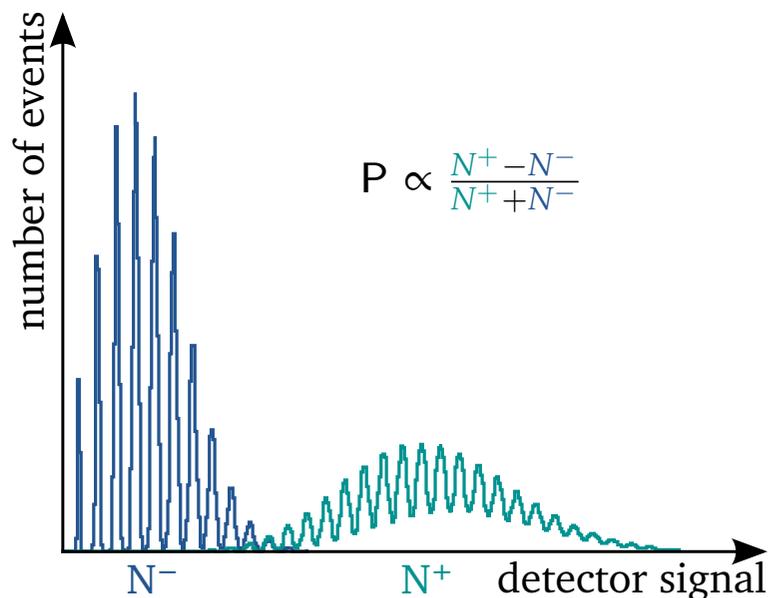
- laser: 0.1% (already achieved at SLC)
- detector alignment : 0.15 - 0.2 %
- detector linearity: 0.1 %

Alternative detector concept:

Quartz Cherenkov detector :

less Compton e^- per channel,
more detected photons/ C.e.

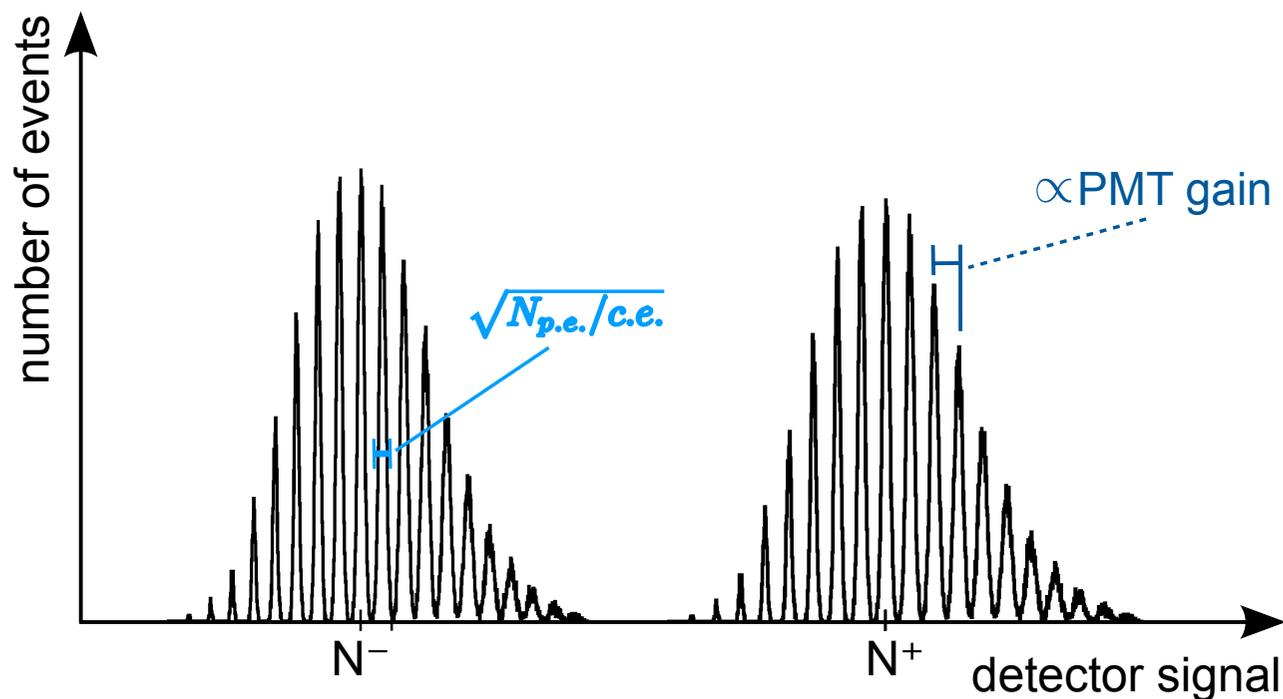
→ better resolution on peaks



Quartz Cherenkov detector.

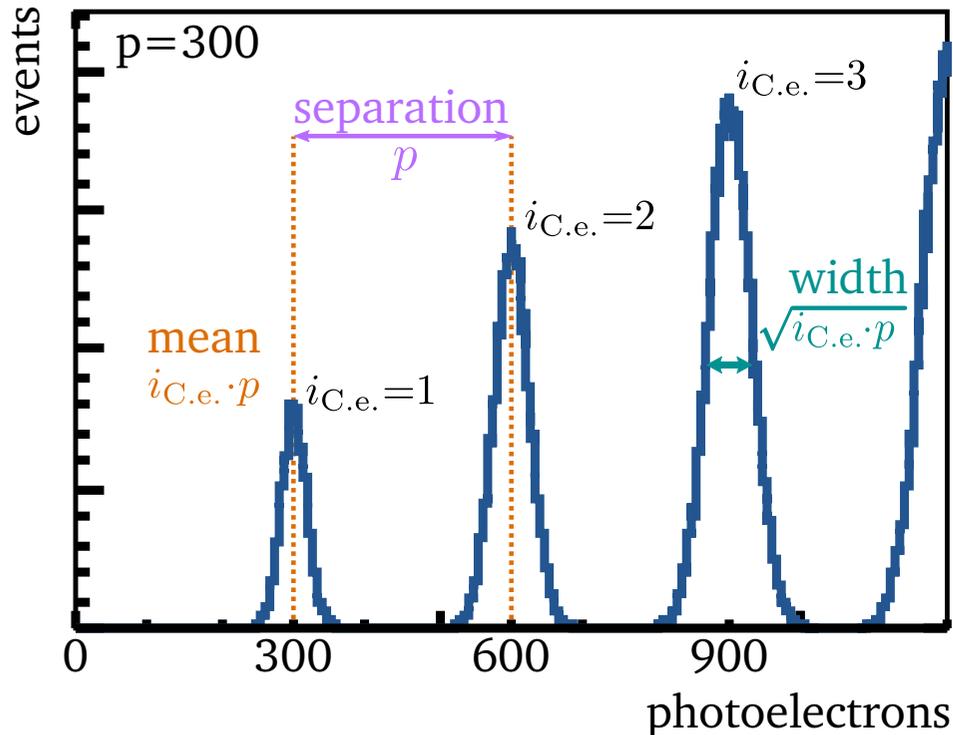
Alternative detector concept: quartz detector

- Higher refractive index \rightarrow higher photon yield
- For enough photons per Compton e^- :
 \rightarrow calibrate gain directly from the data



4-channel prototype operated at DESY II testbeam in 2013 year.

Why quartz?



required detected photons
per Compton electron

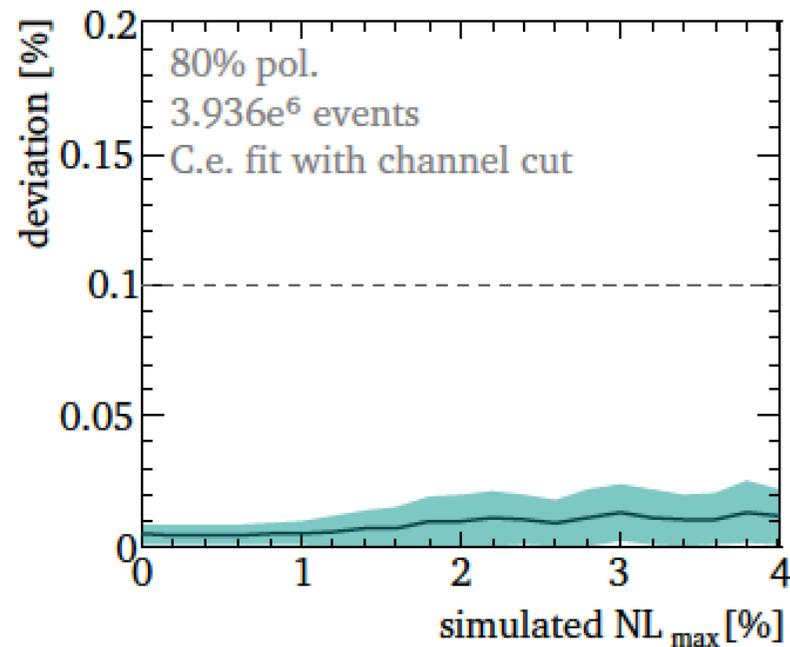
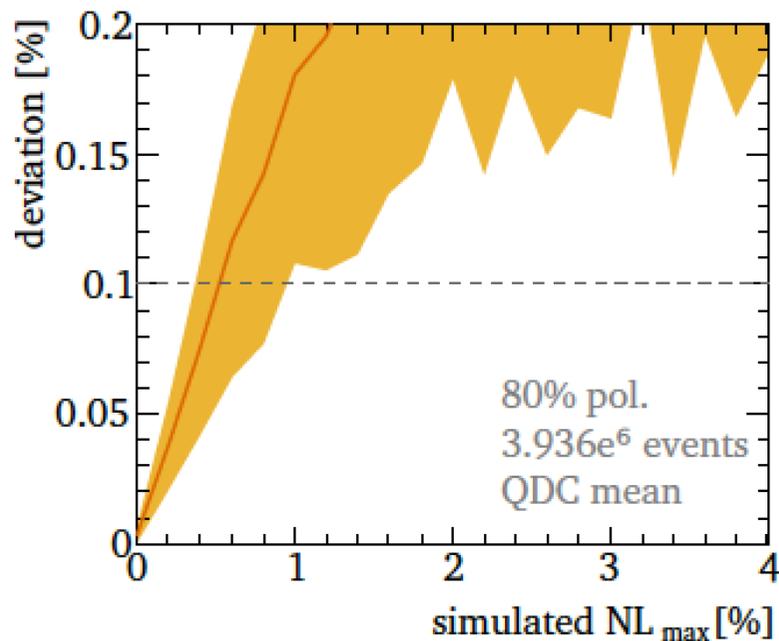
$$p > \frac{N_{C.e.}}{\frac{1}{2.35^2} - (N_{C.e.} \cdot \frac{\Delta g}{g} / Q)^2}$$

- less Compton electrons $N_{C.e.}$: smaller channels
- higher light yield p : quartz as Cherenkov material
 - ▶ refractive index $n \approx 1.45$ (for comparison: $n(C_4F_{10}) = 1.0014$)
 - ▶ Cherenkov angle $\theta_c \approx 46^\circ$
 - ▶ Cherenkov threshold $E_{thr} \lesssim 1 \text{ MeV}$

Test of non-linearity correction for PMTs.

Non-linearities in [0-4 %] with a step of 0.2% : 100 different random non-linearity transfer functions → generate the spectrum

Deviation of the \mathcal{P}_{QDC} (mean of the QDC spectra) vs $\mathcal{P}_{C.e.}$ (from the prim. C.e) (left)



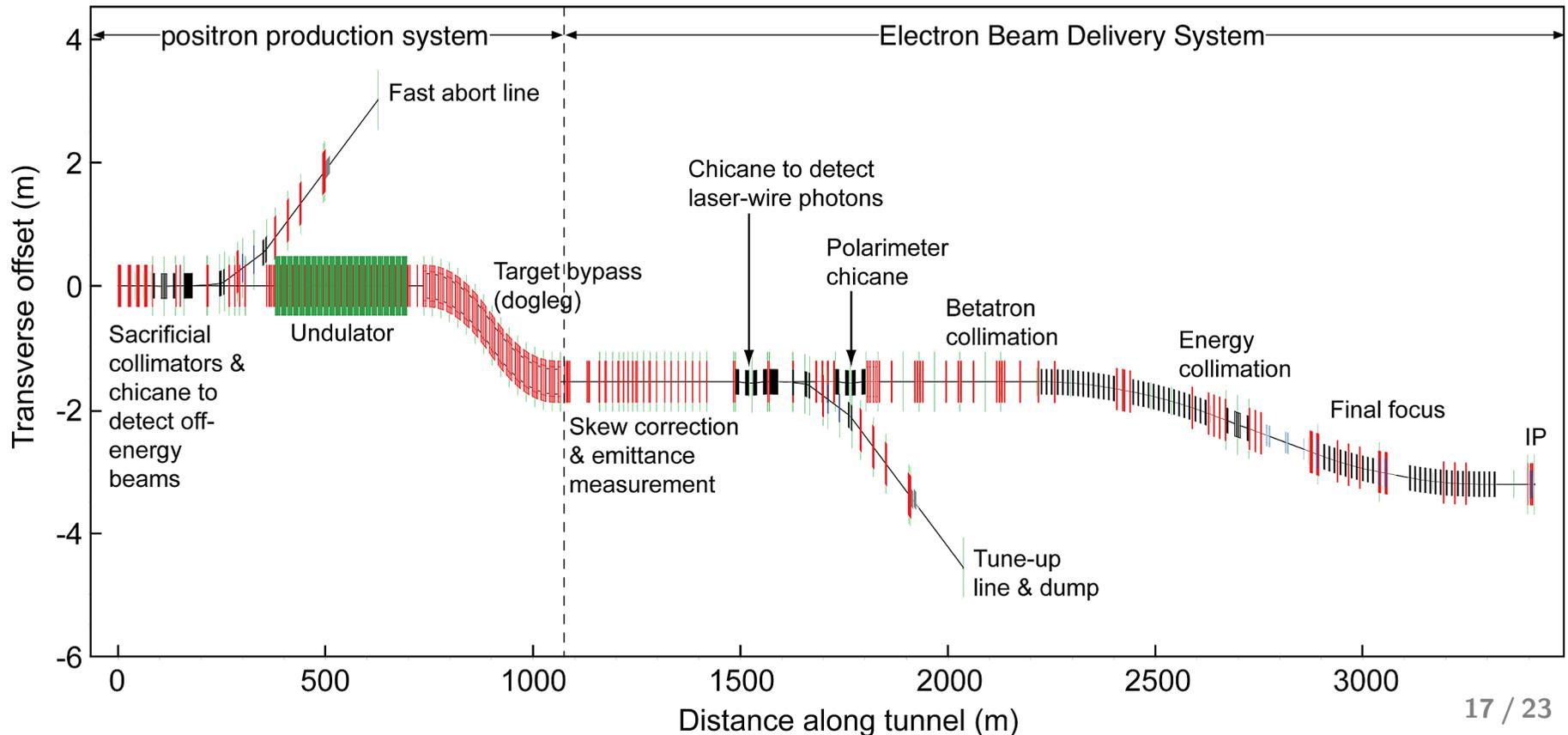
Use only channels whose polarisations $\mathcal{P}_{fit,i}$ agree within $1\% \pm P_{fit}$ with the \mathcal{P} from all channels (right).

Spin Tracking.

Spin Tracking along the BDS.

The Beam Delivery System in the TDR

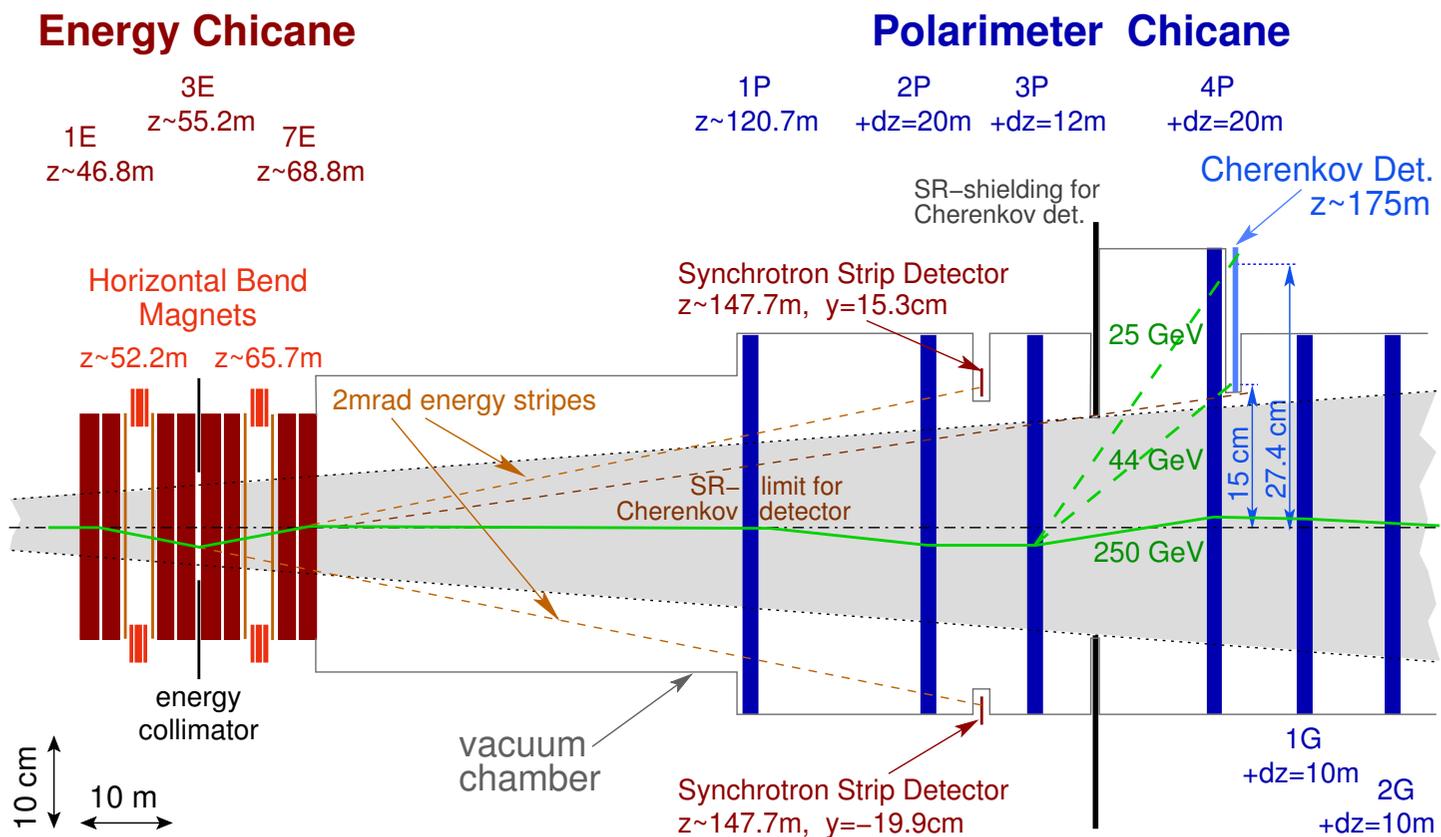
- hosts beam diagnostics, skew correction, energy collimation, final focus system
- aims to minimise emittance growth
- behind the tune-up dump extraction line



Extraction Line.

Downstream Polarimeter

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



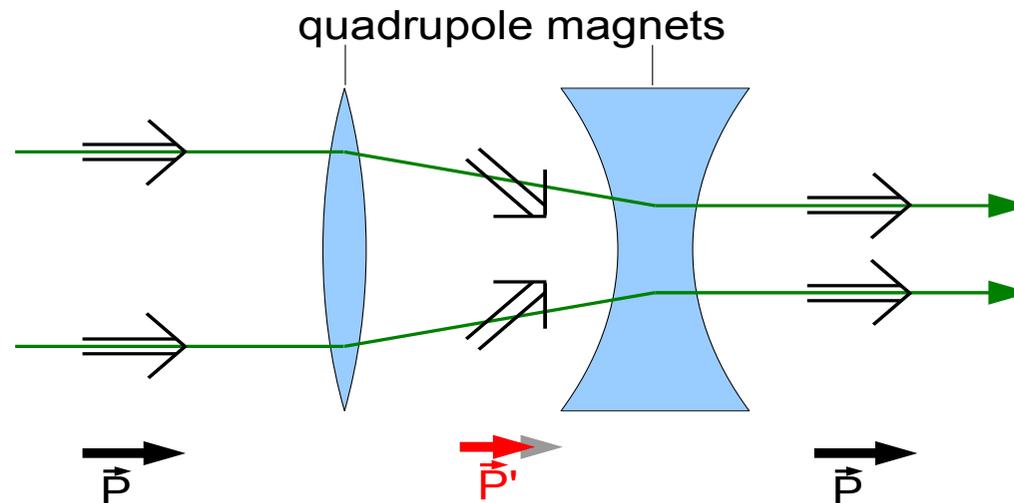
Spin transport & spin fan-out.

The spins are subject to :

- spin precession in E/M fields
 - energy loss due to synchrotron radiation
- spin-flips i.e. emission of γ s (can be neglected)

Spin fan-out :

- in cases of non uniform spin-precession i.e. inhomogeneous \vec{B}
- beam energy spread



in this example $|\vec{P}'| < |\vec{P}|$ after crossing the 1st quad

Cross-calibration of Polarimeters.

Without Collisions (based on TDR lattice):
predict polarisation at DP location from UP measurements ($\sqrt{s} = 250$ GeV)

	$\delta P_z / P_z [10^{-3}]$
Beam and polarisation alignment at polarimeters assuming ($\Delta\theta_{bunch} = 50 \mu\text{rad}$, $\Delta\theta_{pol} = 25 \text{mrad}$)	0.72
Random misalignments ($10 \mu\text{m} / \mu\text{rad}$ with beam orbit correction)	0.35
Variation in beam parameters (10% in the emittances)	0.03
Longitudinal precession in detector magnets	0.01
Bunch rotation to compensate the beam crossing angle	< 0.01
Emission of synchrotron rad.	0.005
Total	0.80

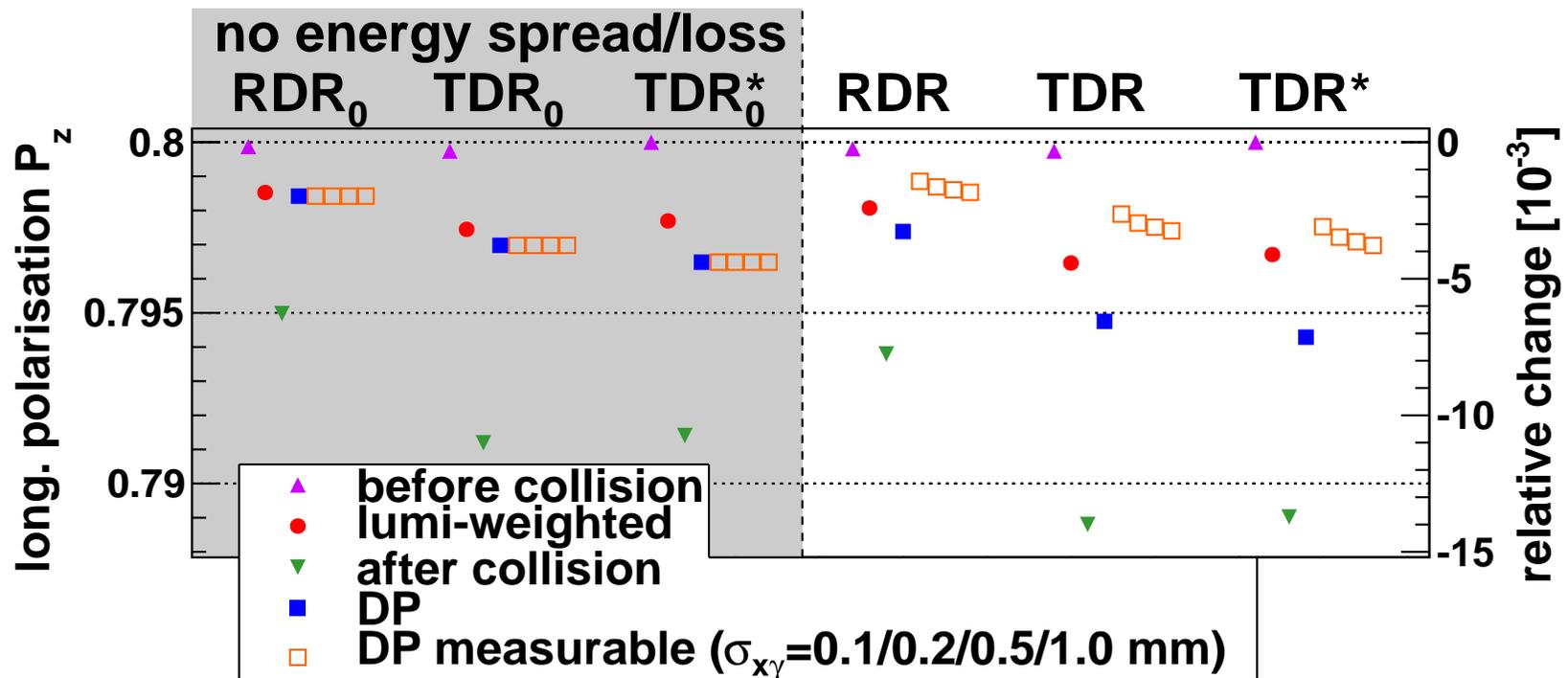
JINST 9 (2014) P07003

Need to understand :

- deviations due to instrumental effects
- deviations due to spin transportation effects
- disentangle those

Collision Effects.

- Without beamstrahlung: extraction line optics retrieves $\langle P \rangle_{IP}$ at downstream polarimeter (if spin fan-out is dominant effect)
- With increasing beamstrahlung (energy loss!): difference to $\langle P \rangle_{IP}$ increases to few permille
- Effect doubles from RDR \rightarrow TDR parameters



Conclusions and Future Plans.

Conclusions.

Physics case for ILC well justified!

Required $\%_0$ -level precision on lumi-weighted average polarisation at IP combined with :

- scale calibration from e^+e^- collision data
- upstream (time resolution) and downstream (collision effects) polarimeters
 - **combined**: cross-check, lumi-weighted polarisation @ IP
- spin tracking studies and understanding of collision effects

Compton Polarimeters:

- detector alignment & linearity crucial for $\delta P/P = 0.25\%$
- R&D well underway
- cross-calibration without collisions: $\sim 0.1\%$ from alignment

Next Steps.

Detectors RD:

- Plans for a pixel-based detector

Luminosity-weighted average polarisation:

- collision effects with TDR beam parameters and lattice
- how to combine polarimeter measurements, luminosity measurement and collision data ?

Polarisation from collision data :

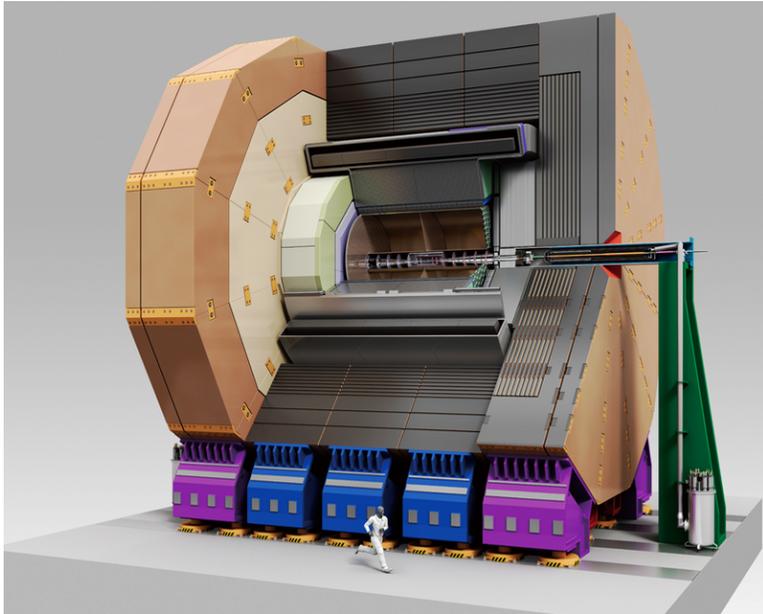
- for example extract \mathcal{P} from W^+W^-
- systematic evaluation of various approaches & combination ?
 - studies on systematics, correlations etc

Realisation:

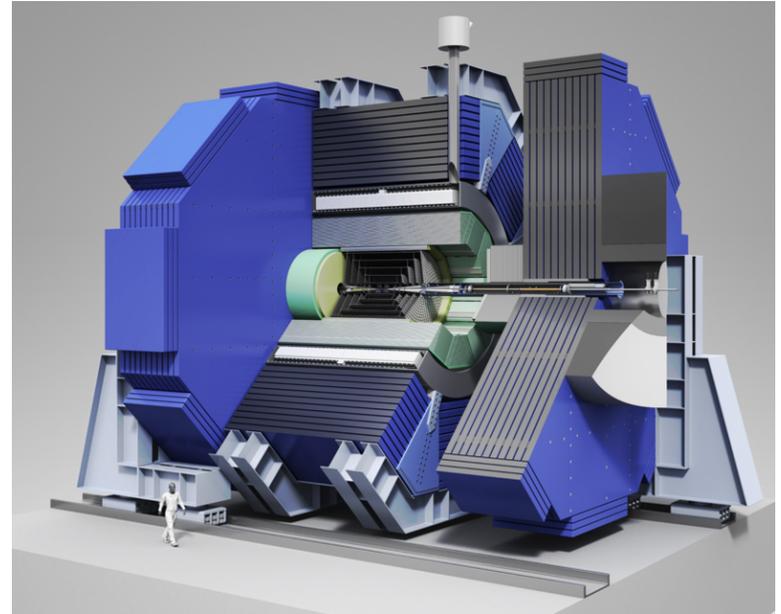
- site specific misalignments, ground motion etc and embed them in more realistic simulation
- revisit laser systems (site specific, new laser technologies...)
- design chicane magnets and vacuum chamber
- detectors: from prototypes → full-scale, DAQ, calibration ...

Backup Slides.

ILC detectors.

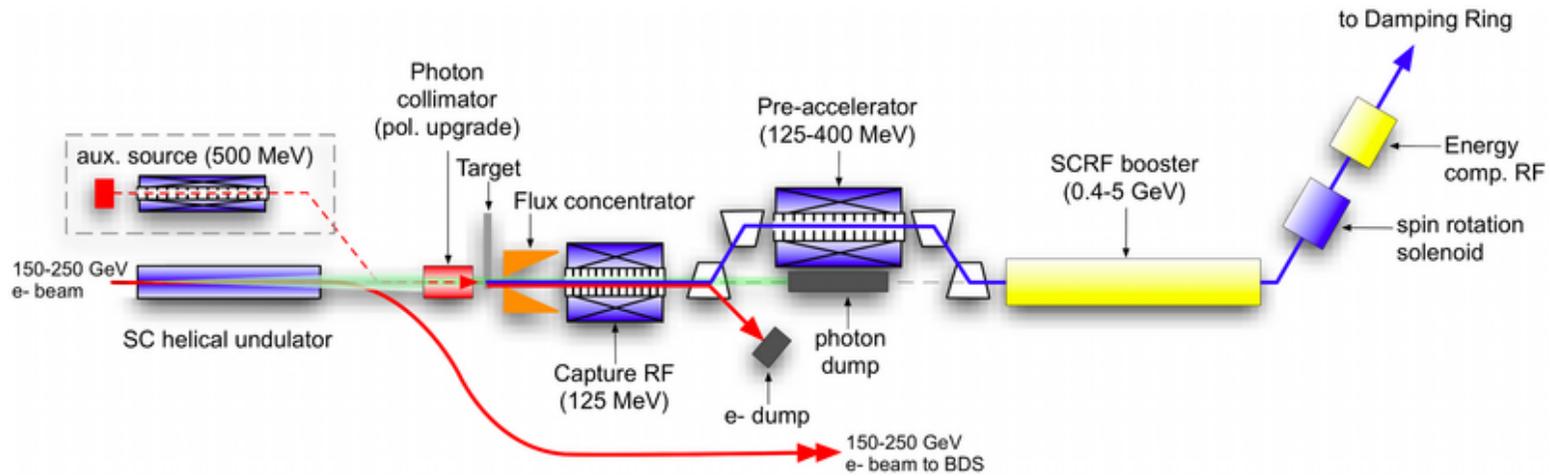


ILD



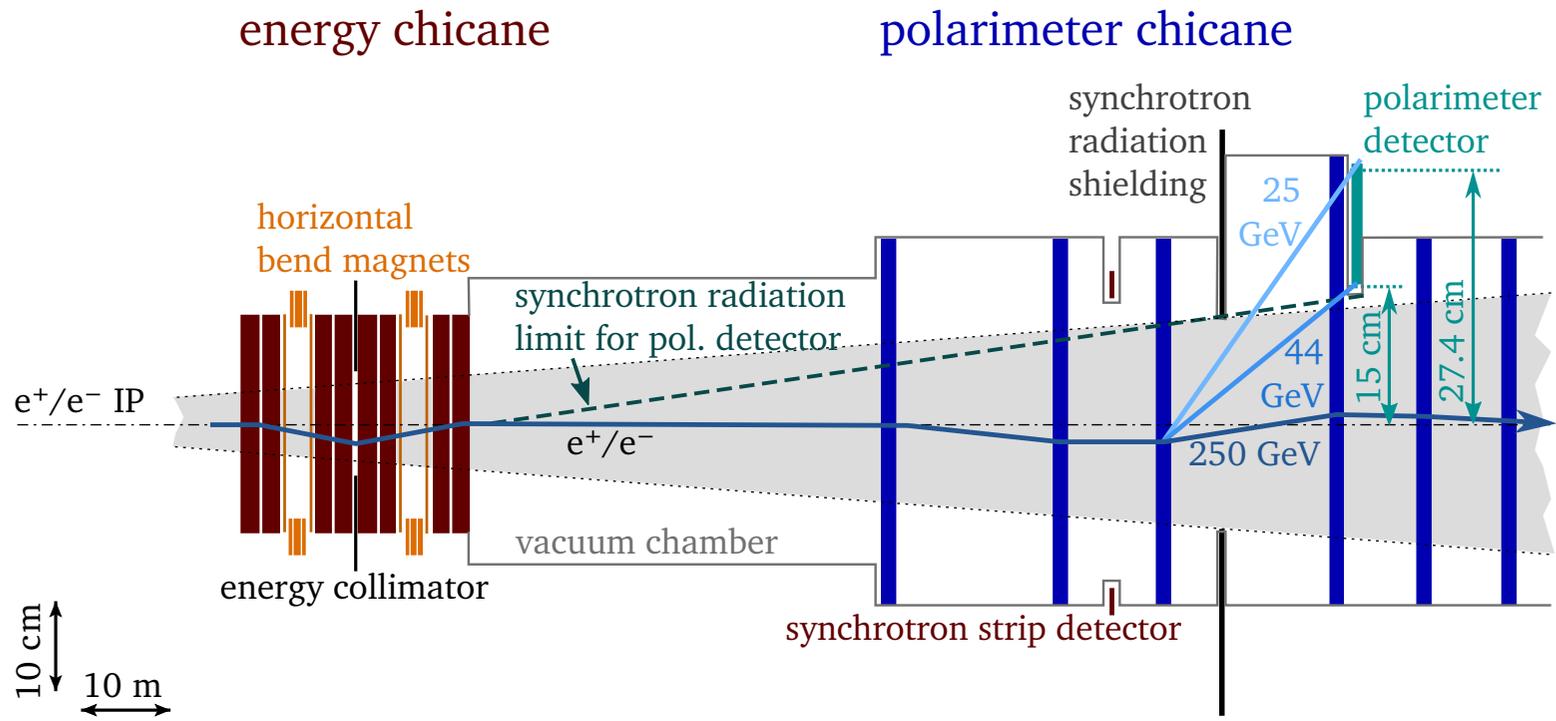
SiD

ILC positron source.



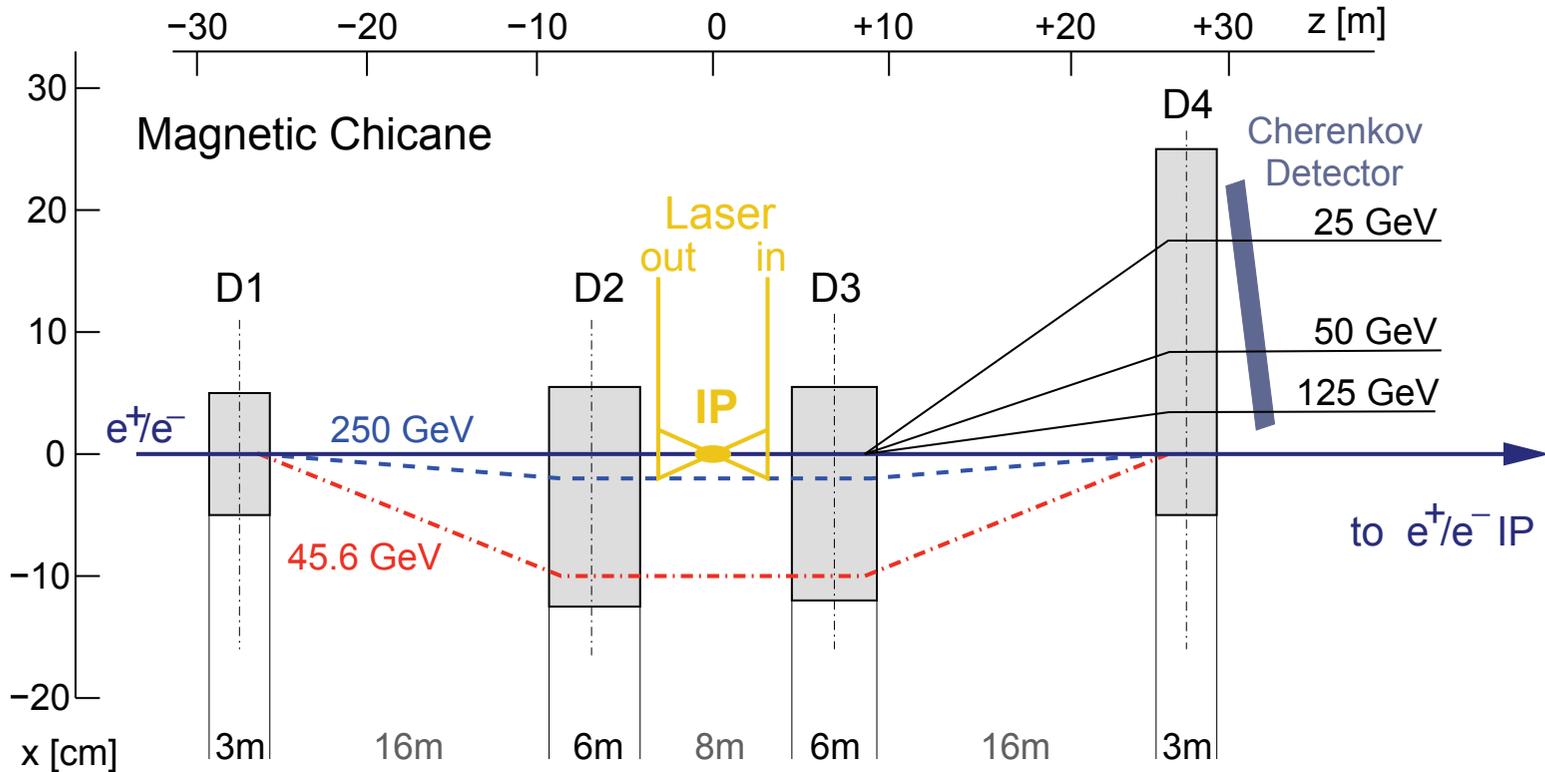
[ILC TDR vol. 1, 2013]

Downstream polarimeter.



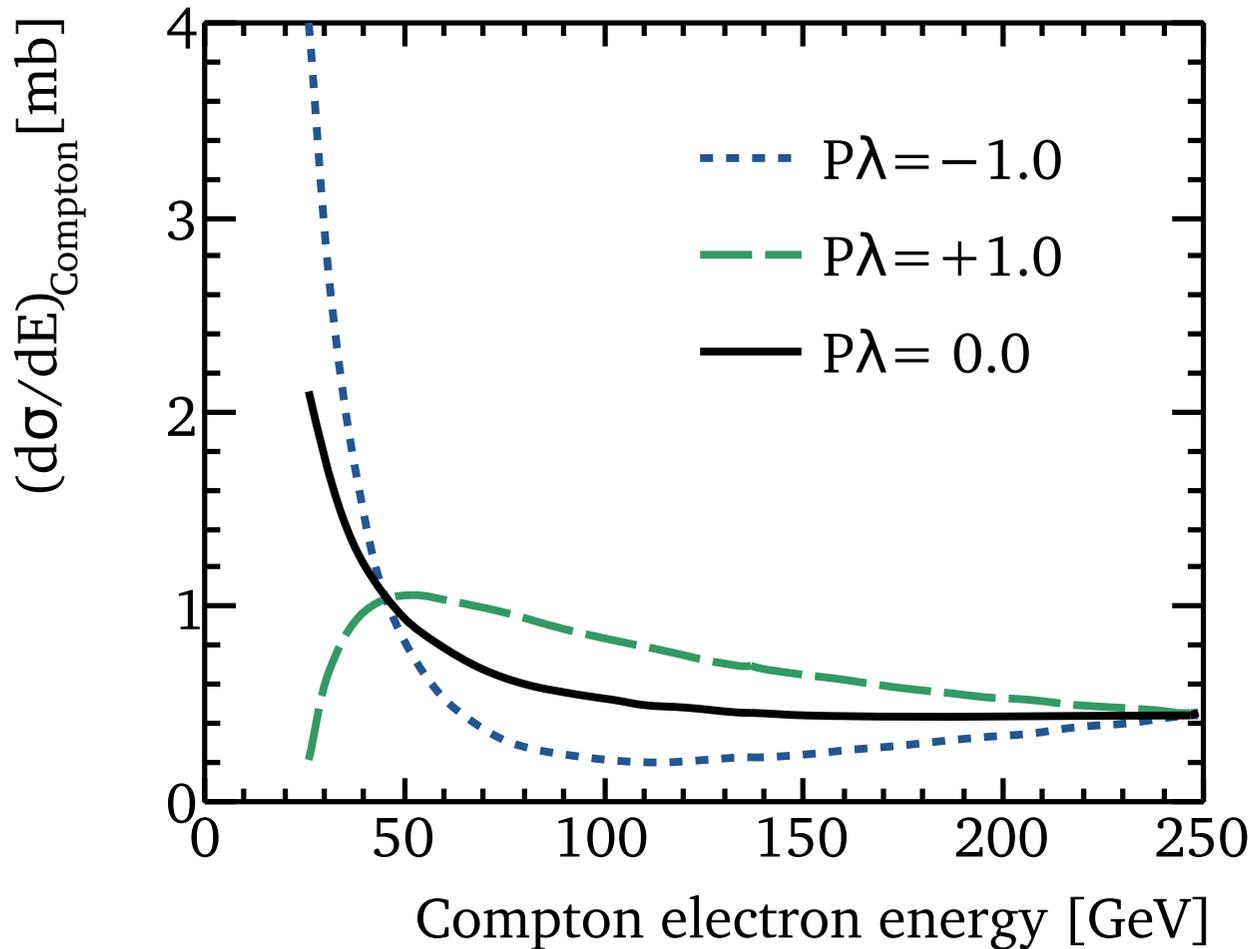
[JINST 4(2009), 10015]

Upstream polarimeter.



Compton cross-subsection.

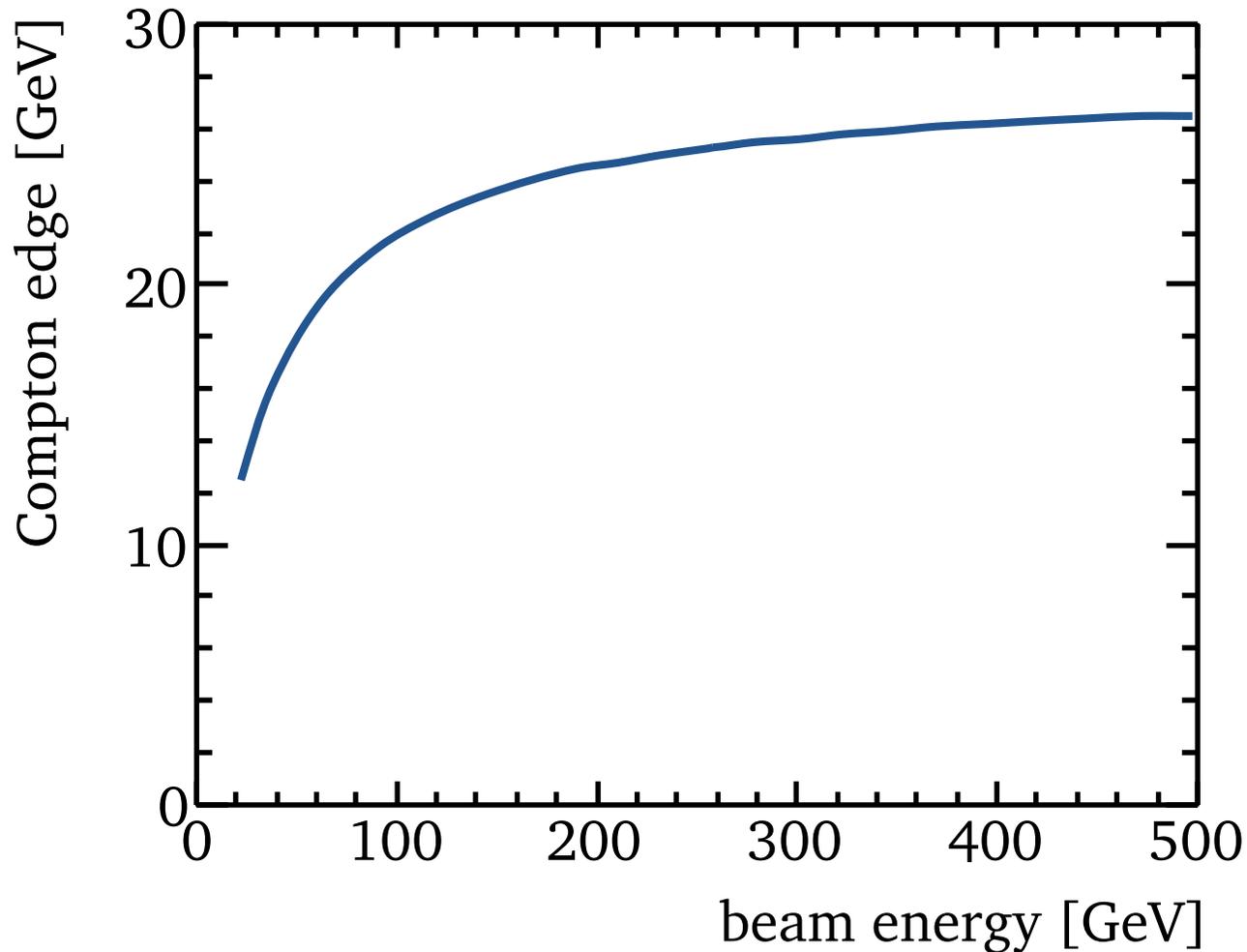
$$\left(\frac{d\sigma}{dy}\right)_{\text{Compton}} = \left(\frac{d\sigma}{dy}\right)_{\text{unpol}} + \frac{2\pi r_0}{x} \cdot \lambda \mathcal{P} \cdot rx(1-2r)(2-y)$$



$$x = \frac{4E_0\omega_0}{m^2} \cos^2(\theta_0/2), \quad y = 1 - \frac{E}{E_0}, \quad r = \frac{y}{x(1-y)}, \quad \left(\frac{d\sigma}{dy}\right)_{\text{unpol}} = \frac{2\pi r_0}{x} \left[\frac{1}{1-y} + 1 - y - 4r(1-r) \right]$$

Compton edge.

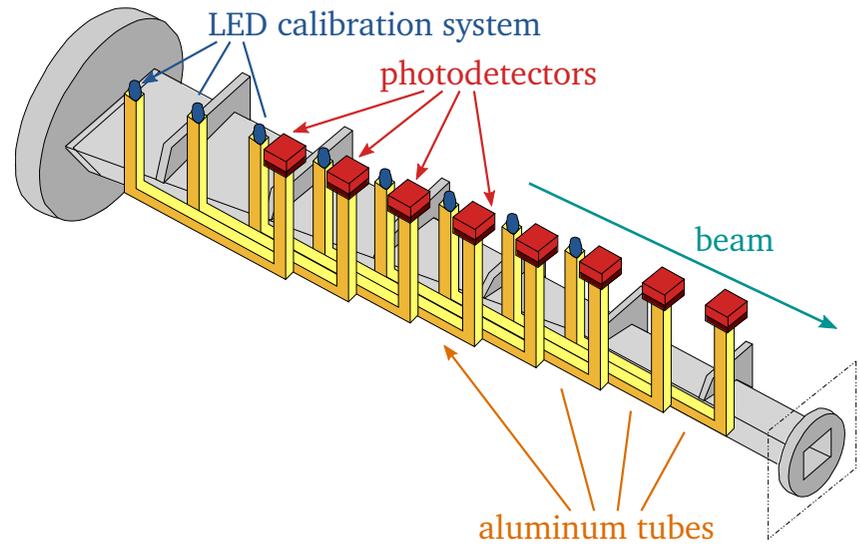
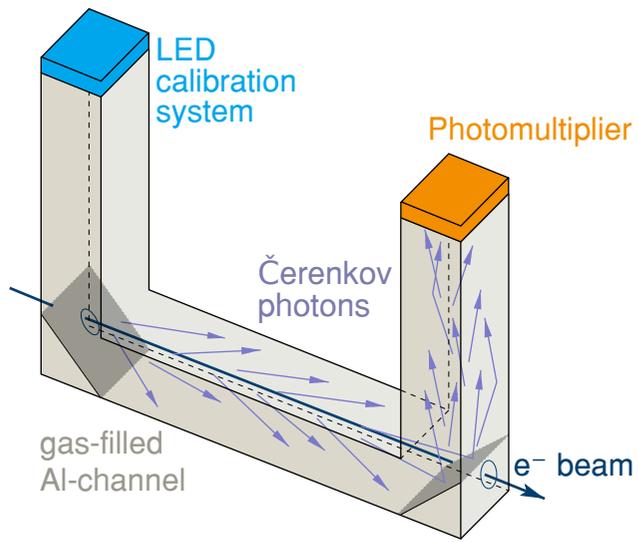
Compton edge position nearly independent of beam energy



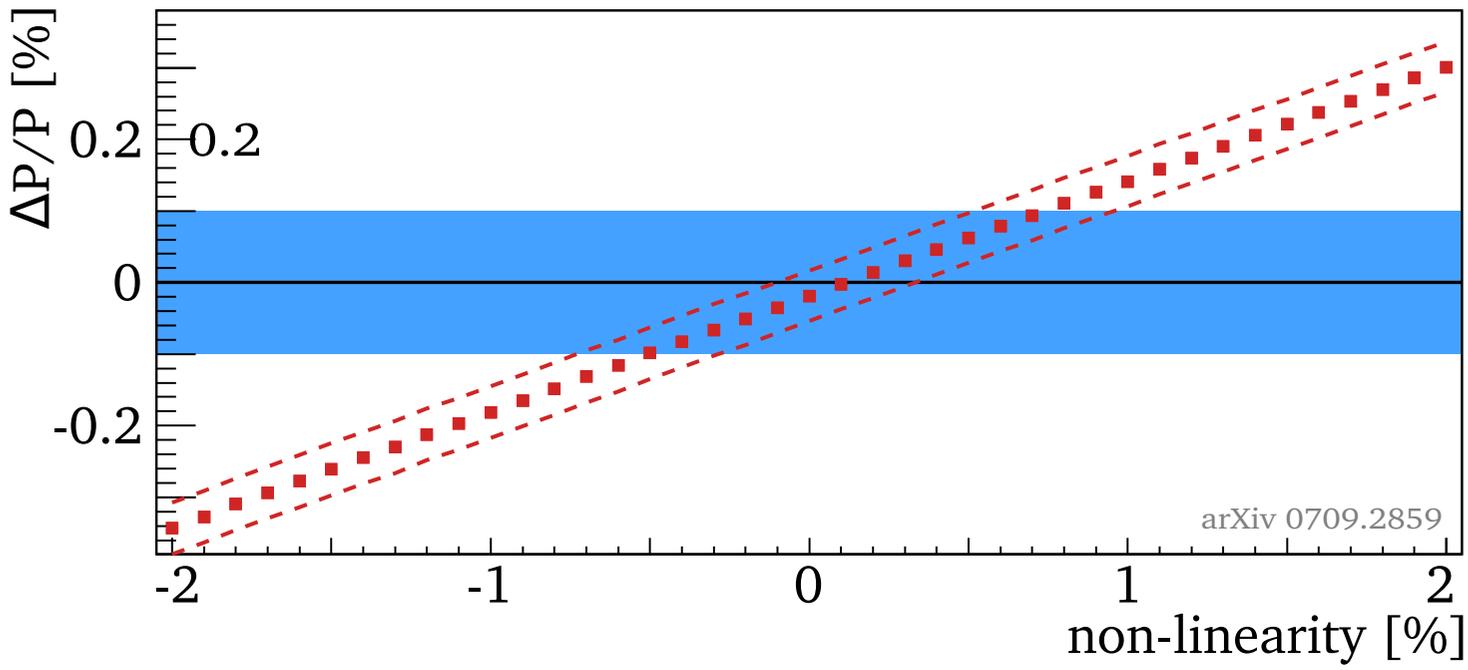
$$E_{\min} = \frac{x}{1 + 4x \frac{\omega_0}{m^2}}$$

$$\text{with } x = \frac{4E_0\omega_0}{m^2} \cos^2(\theta_0/2)$$

Gas detector concept.

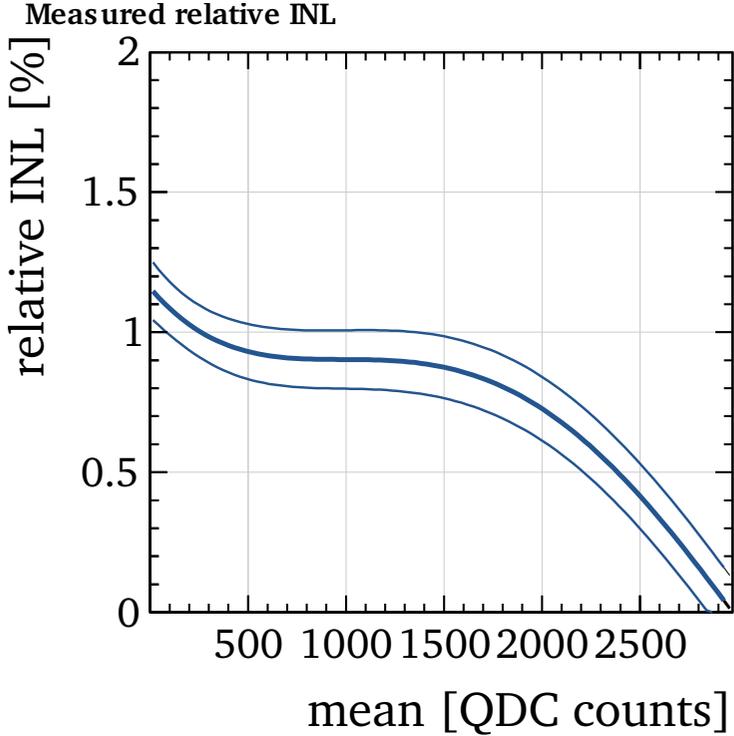


PD NL effect.

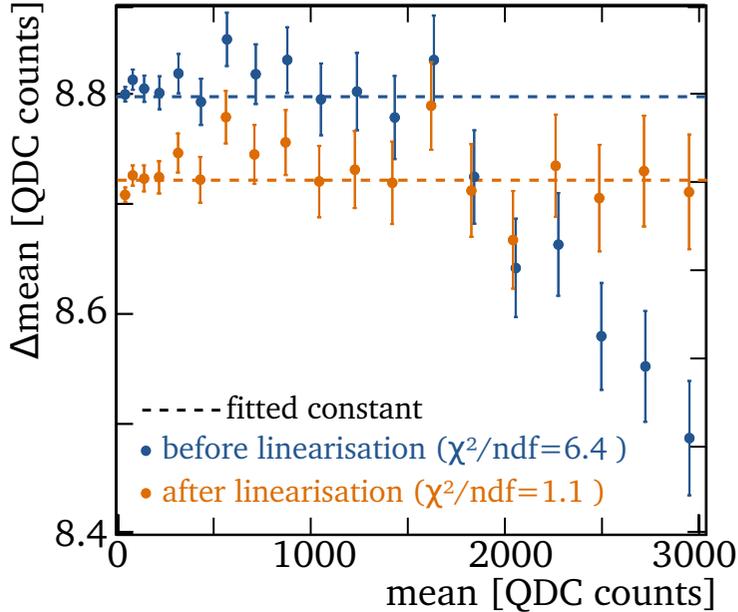


[arXiv:0709.2859]

PD NL meas.



[thesis B. Vormwald 2014]



[thesis B. Vormwald 2014]

ALR.

SM precision measurement: $\sin^2 \theta_{\text{eff}}$

via left-right asymmetry $A_{LR} = \frac{1}{\langle P \rangle} \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$

Measurement with smallest systematic uncertainty so far by SLD:

Uncertainty	$\delta A_{LR}/A_{LR}$ [%]	$\delta A_{LR}^0/A_{LR}^0$ [%]
Total polarimeter uncertainty	0.50	
Chromaticity and IP corrections	0.15	
Correction terms	0.07	
A_{LR} systematic uncertainty		0.52
electroweak interference correction		0.39
A_{LR}^0 systematic uncertainty		0.64

[hep-ex/0509008]

Systematic uncertainties on A_{LR} measurement (SLC 1997/98)

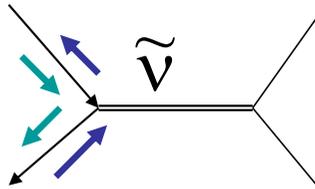
Model distinction.



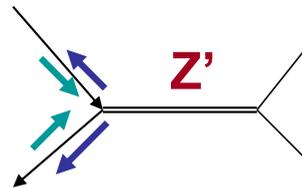
Model distinction with polarized beams

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

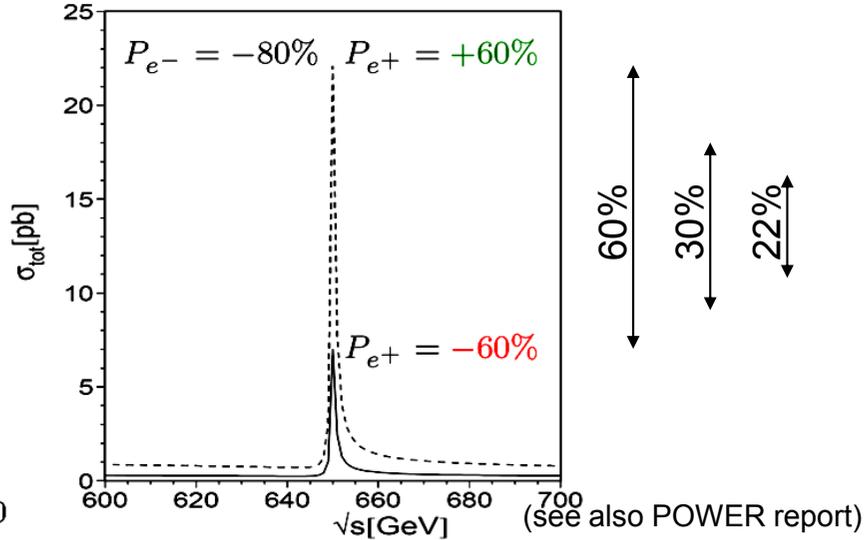
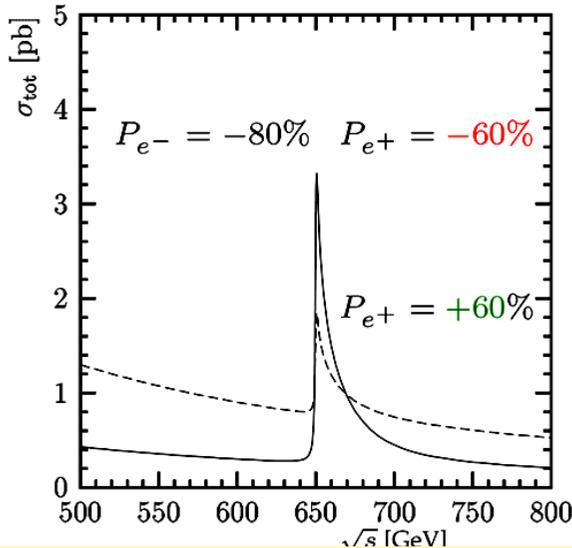
- angular distribution
- helicities of initial e^+ and e^-



$$e^+e^- \rightarrow \tilde{\nu}_\tau \rightarrow \mu^+\mu^-$$

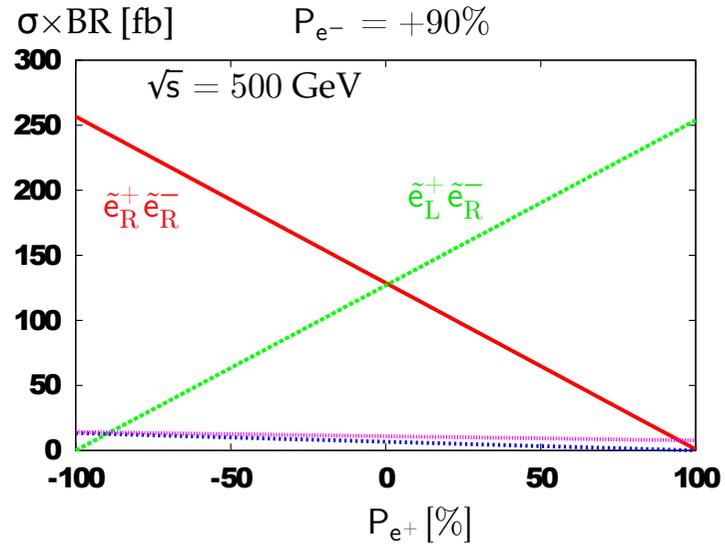
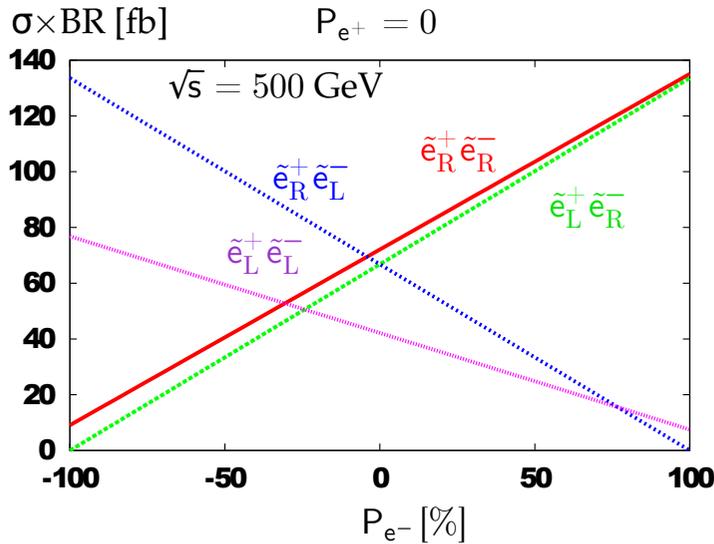


$$e^+e^- \rightarrow Z' \rightarrow \mu^+\mu^-$$



e^+ polarisation improves substantially distinction between physics models – even below new resonances!

Selectrons.



[hep-ph/0507011]

cross

sections of selectron pair production $\tilde{e}_L^+ \tilde{e}_R^-$:
separation possibility with different polarisations

Blondel scheme.

Blondel scheme:

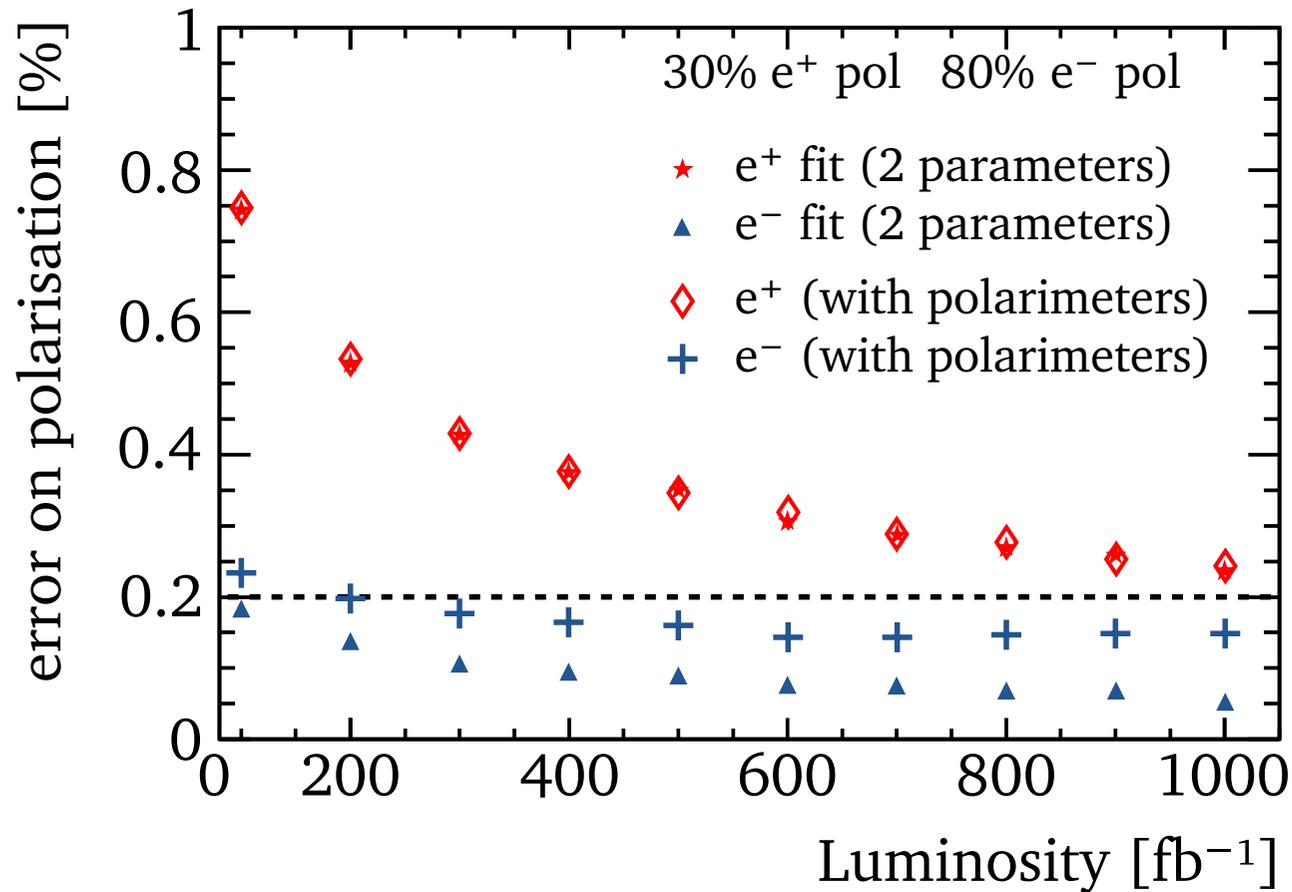
$$\langle | P_{e^\pm} | \rangle_{IP} = \sqrt{\frac{(\sigma_{+-} + \sigma_{-+} - \sigma_{--} - \sigma_{++})(\mp\sigma_{-+} \pm \sigma_{+-} + \sigma_{--} - \sigma_{++})}{(\sigma_{-+} + \sigma_{+-} + \sigma_{--} + \sigma_{++})(\mp\sigma_{-+} \mp\sigma_{+-} - \sigma_{--} + \sigma_{++})}}$$

included assumption:

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

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

Polarimeter impact on collision data.



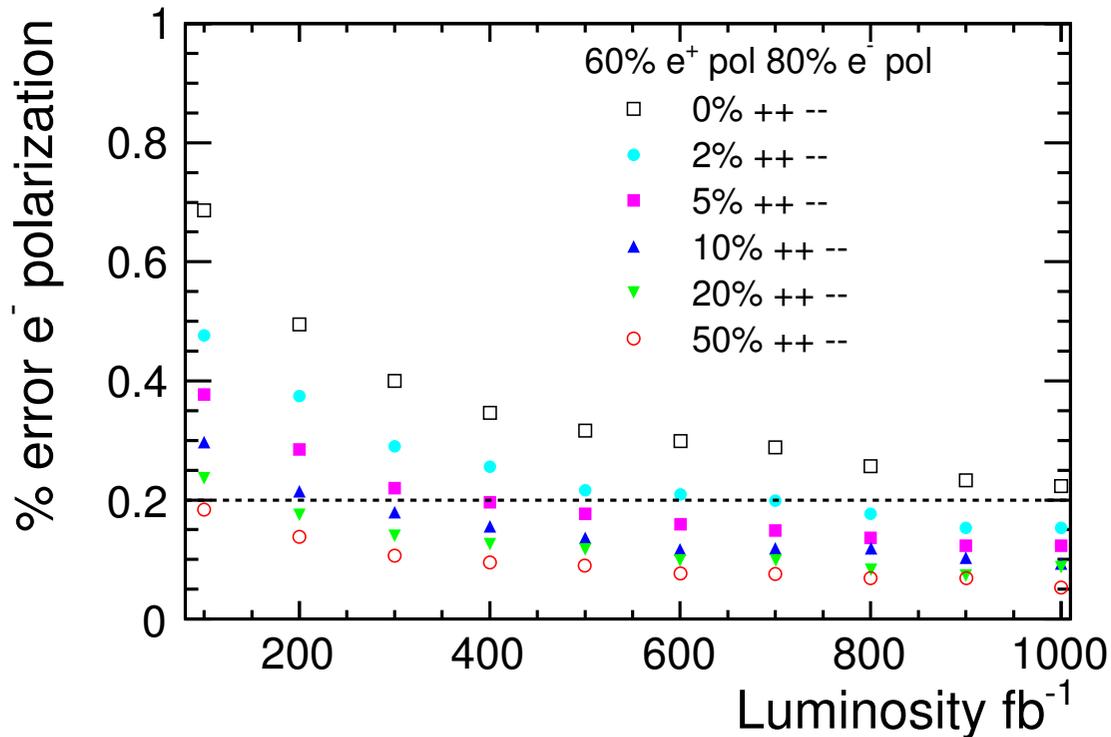
[thesis I. Marchesini 2011]

Precision achievable for the determination of the beam polarisation from the angular fit method with and without taking into account an 0.25 % polarimeter uncertainty.

Luminosity Sharing.

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

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



[thesis I. Marchesini 2011]

Cherenkov effect.

Intensity: Frank-Tamm eq.: $dE = \frac{\mu(\omega)q^2}{4\pi} \omega \left(1 - \frac{c^2}{n^2 v^2(\omega)}\right) dx d\omega$

Cherenkov angle: $\cos \theta_c = \frac{1}{n\beta}$

Cherenkov threshold: $E_{thr} = \gamma_{thr} mc^2$, $\gamma_{thr} = \frac{1}{\sqrt{1 - \frac{1}{n^2}}}$

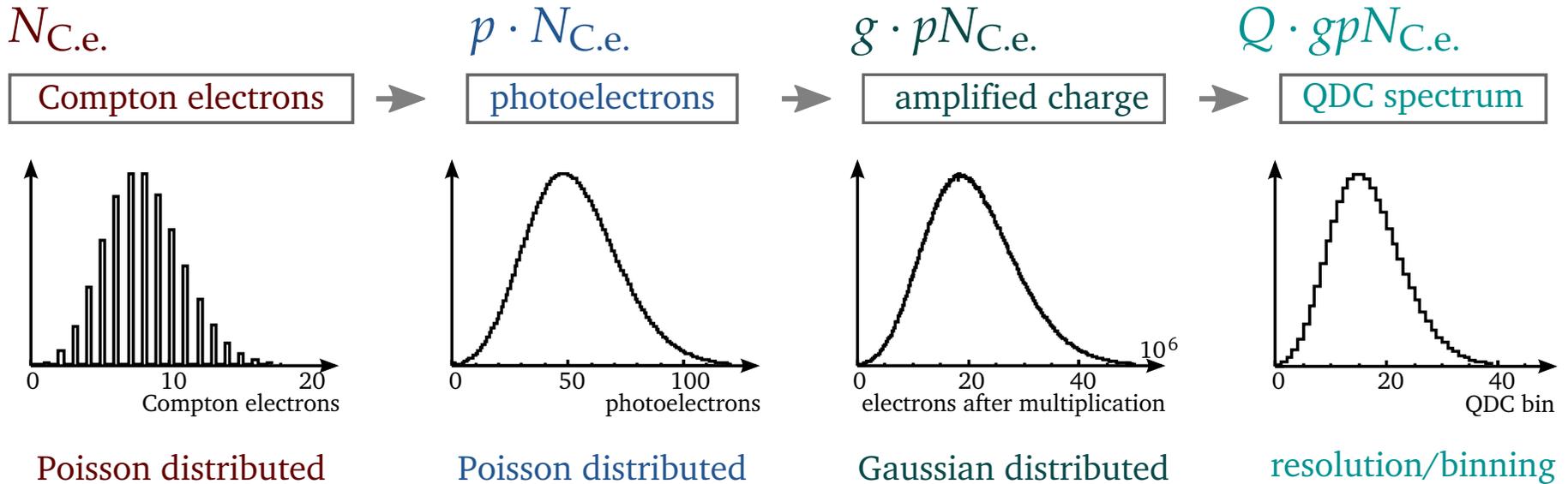
Properties of **fused silica** (for e^+ / e^-):

- at 210 nm: $n_q = 1.53836 \Rightarrow \theta_c = 49.5^\circ$, $E_{thr} = 0.67$ MeV
- at 800 nm: $n_q = 1.45332 \Rightarrow \theta_c = 46.5^\circ$, $E_{thr} = 0.71$ MeV

Properties of **C₄F₁₀** (for e^+ / e^-):

- at 210 nm: $n_q = 1.00146 \Rightarrow \theta_c = 4.4^\circ$, $E_{thr} = 9.47$ MeV
- at 650 nm: $n_q = 1.00131 \Rightarrow \theta_c = 4.1^\circ$, $E_{thr} = 9.99$ MeV

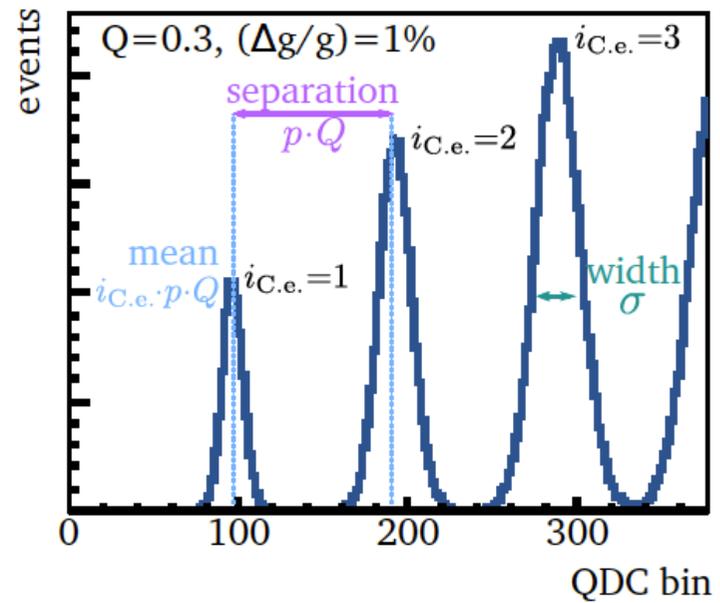
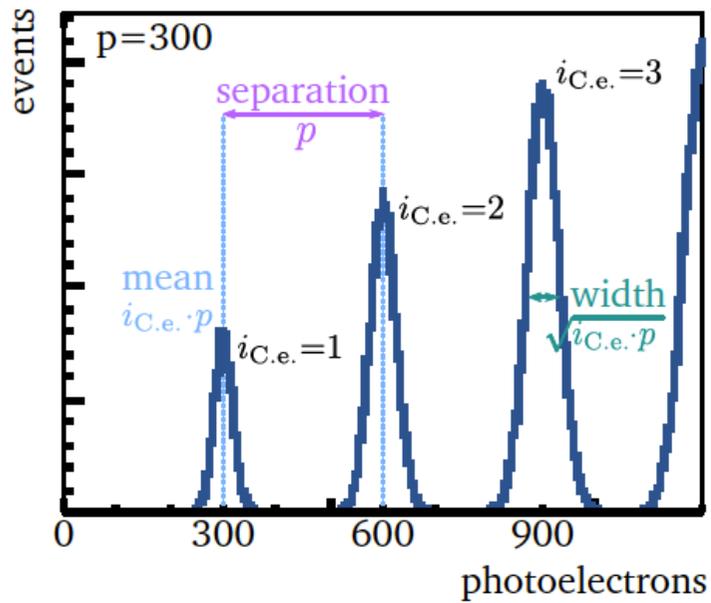
SPR requirements.



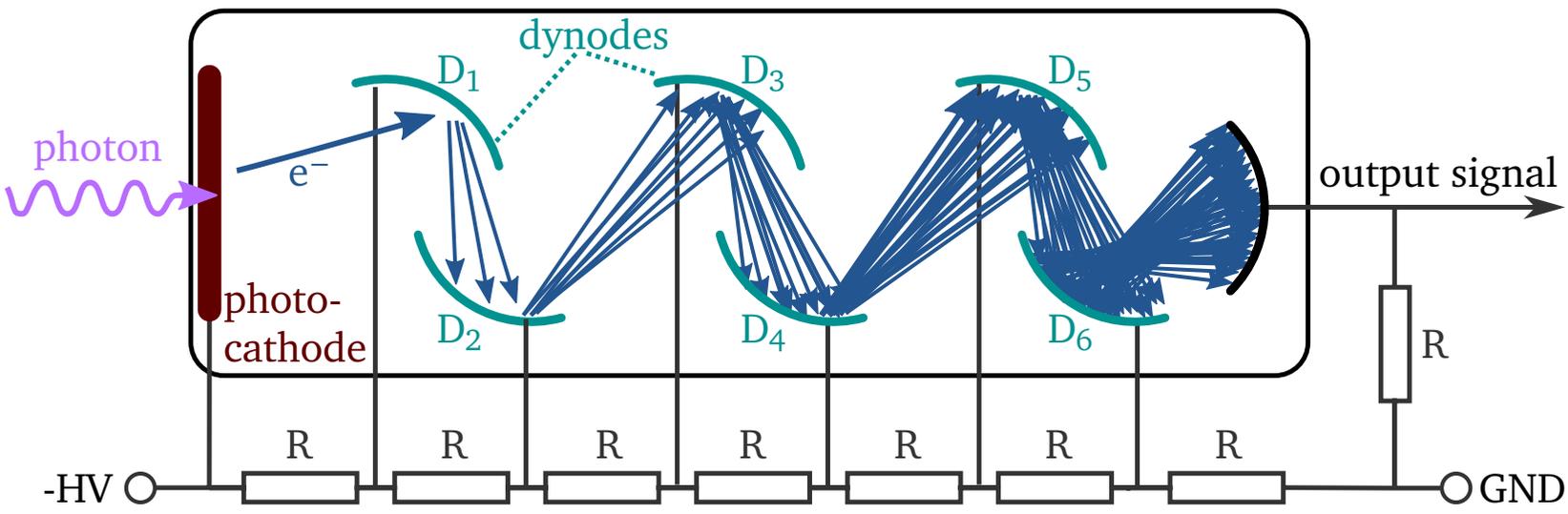
require:
$$p > \frac{N_{C.e.}}{\frac{1}{2.35^2} - (N_{C.e.} \cdot \frac{\Delta g}{g} / Q)^2}$$

- a) less Compton electrons: smaller channels
- b) large number of detected photons per Compton electron:
material with high light yield → quartz as Cherenkov material

Quartz detector.



PMT.



Simulated samples for the beam-beam collision effect studies.

Sample name	Description
RDR	Beam parameters according to RDR, but with the energy spread according to the TDR
TDR	Beam parameters according to the TDR
TDR*	Like TDR, but with a different initial spin config : all macro particle polarisation vectors are aligned along the z -axis at the IP, instead of being fanned out according to the focussing of the beam
RDR_0, TDR_0, RDR_0^*	Like above, but all particles with fixed energy $E = 250$ GeV (no energy spread, no synchrotron radiation or bremsstrahlung)