Detector R&D for ILC Compton Polarimeters

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HELMHOLTZ | ASSOCIATION

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UHH Universität Hamburg
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DESY.

Introduction

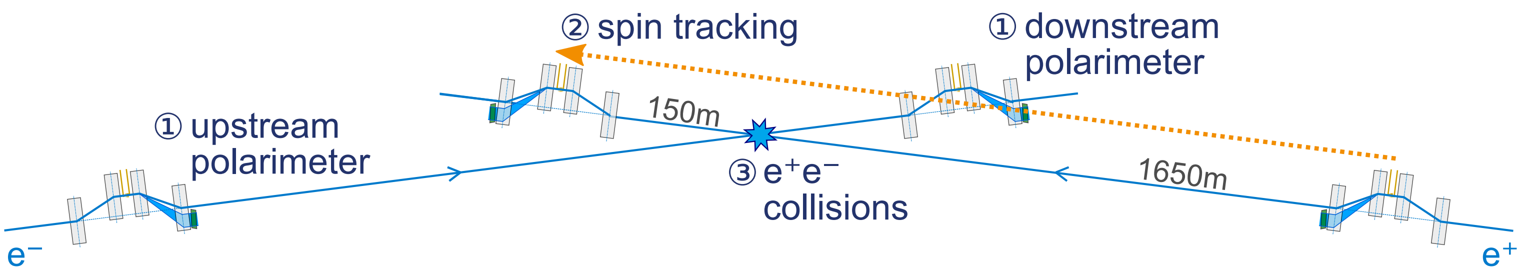
Compton Polarimeters

Detector R&D

Conclusions

Polarimetry concept.

Goal for ILC polarimetry: per-mille level precision on luminosity weighted average polarisation at the IP, $\langle P_z \rangle_{IP} = \frac{\int P_z(t)\mathcal{L}(t)dt}{\int \mathcal{L}(t)dt}$



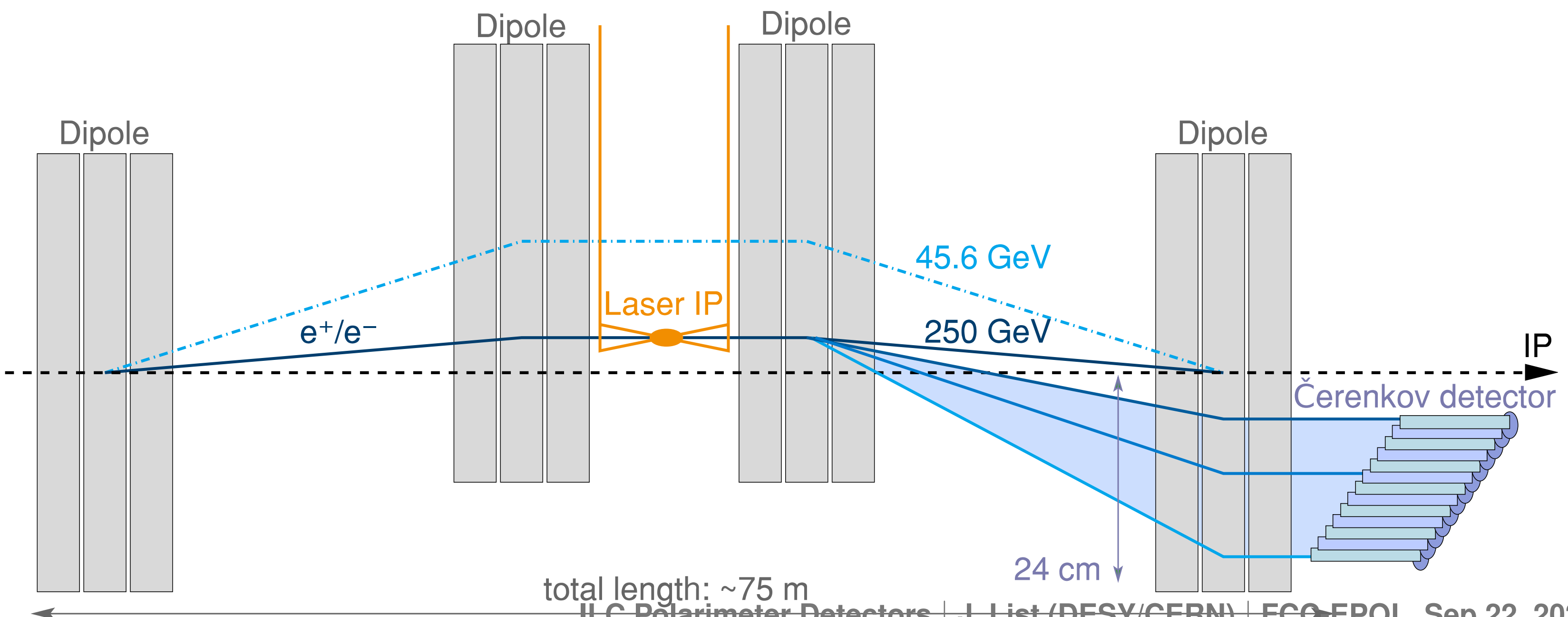
① Compton polarimeter measurements upstream and downstream of the e^+e^- interaction point

② Spin tracking to relate these measurements to the polarization at the e^+e^- interaction point

③ Long-term average determined from e^+e^- collision data as absolute scale calibration

Upstream Polarimeter.

- fast measurement: $\mathcal{O}(10^3)$ Compton scatterings/bunch
- Energy spectrum of scattered e^+/e^- depends on product of longitudinal lepton ($\mathcal{P}$) and circular laser (λ) polarisations
- Magnetic chicane: energy distibution $\to$ (horizontal) position distribution
- Measure number of e^+/e^- per detector channel
- Transverse polarisation: need vertical position as well



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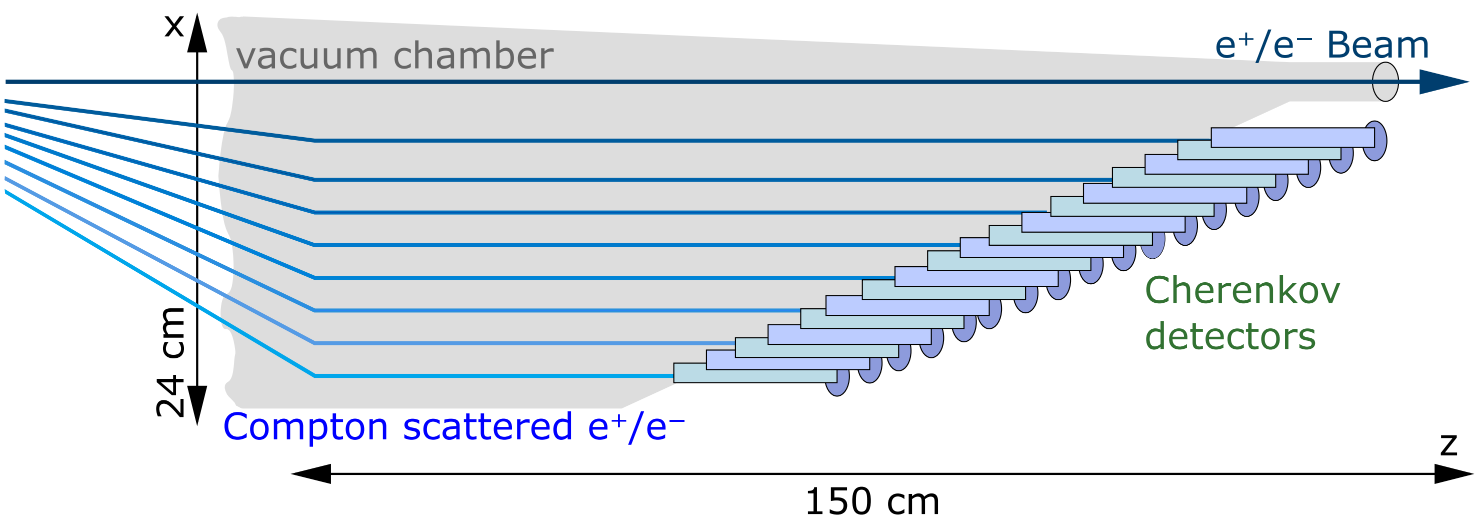
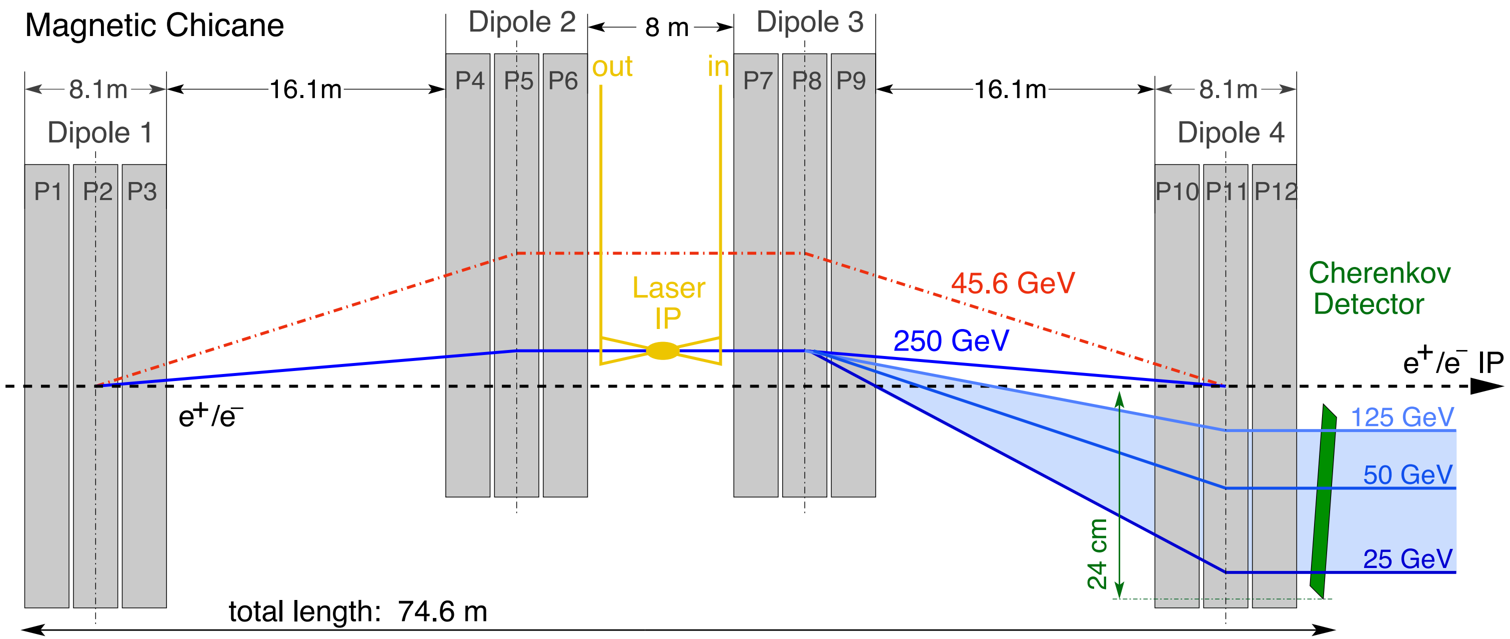


Design of the Upstream Polarimeter Chicane.

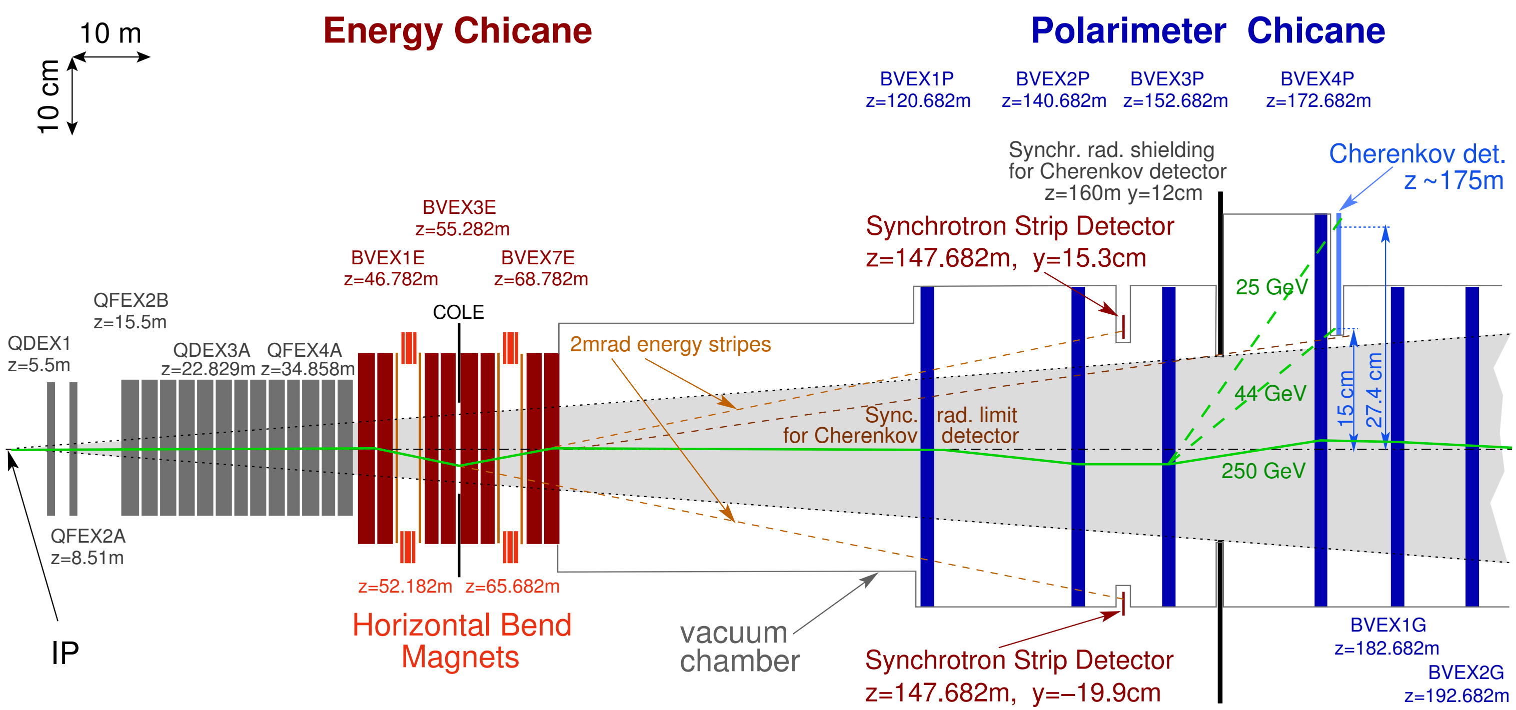
Why a 4-Dipole-Chicane?

- Compton spectrum position at detector independent of E_{beam} if B-field constant
- price to pay: Compton IP moves laterally with E_{beam}



The Downstream Polarimeter .

- 6-magnet chicane kicks Compton signal out of synchrotron fan
- more background ⇒ higher laser intensity for enough signal
- TDR design assumes laser can only fire at one bunch / train
  revisit – based on laser technology from 20 years ago!



Measurement Precision.

ILC Goal: total uncertainty $\delta P / P \approx 0.25\,\%$ for $|P| \simeq 80\%$

source of uncertainty	$\delta P / P$	
	SLC achieved	ILC goals
laser polarisation	0.1%	0.1%
analyzing power	0.4%	0.15% – 0.2%
detector linearity	0.2%	0.1%
electronic noise and beam jitter	0.2%	0.05%
Total	0.5%	0.25%

- laser: precision non-trivial $\Rightarrow$ exploit synergies with other polarimeters and experiments (e.g. LUXE))
- analysing power: prediction of count rate asymmetry per detector channel $\Rightarrow$ knowledge of beam parameters, design of chicane, beam-detector alignment, backgrounds
- detector linearity, electronic noise: $\Rightarrow$ detector design & calibration
- beam jitter: much smaller at ILC due to luminosity requirements

Complementarity of Up- and Downstream.

Upstream Polarimeter

- 1.8 km upstream of IP
- rather clean environment
- begnin beam cond.
- samples every bunch
- stat. error 1% after few μs
- reference for control of collision effects

Downstream Polarimeter

- 140 m downstream of IP
- high backgrounds
- distrupted beam
- samples one bunch / train
- stat. error 1% after $\simeq$ 1 min
- access to depolarisation in collision

Combination

- without collisions: spin transport in Beam Delivery System and Extraction Line
- with collisions: depolarisation at IP
- **cross check each other!**

  [c.f. “Spin Dance” Exp., Phys. Rev. ST Accel. Beams **7** 042802 (2004)]

Introduction

Compton Polarimeters

Detector R&D

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Detector Requirements.

Magnetic Chicane...

- transforms energy spectrum into spatial distribution
- behind chicane: $\sim$ 20 cm wide
- detect Compton electrons over this area

Detector requirements:

- Total ionising dose up to 100 Mrad / year
- read out signals of 1000-2000 Compton electrons (25-250 GeV) every bunch crossing
- either very linear response or “counting“ electrons
- alignment to $\sim$ 100 µm and $\sim$ 1 mrad
- suppression of background from low energetic particles

Detector Options.

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

Detector Options.

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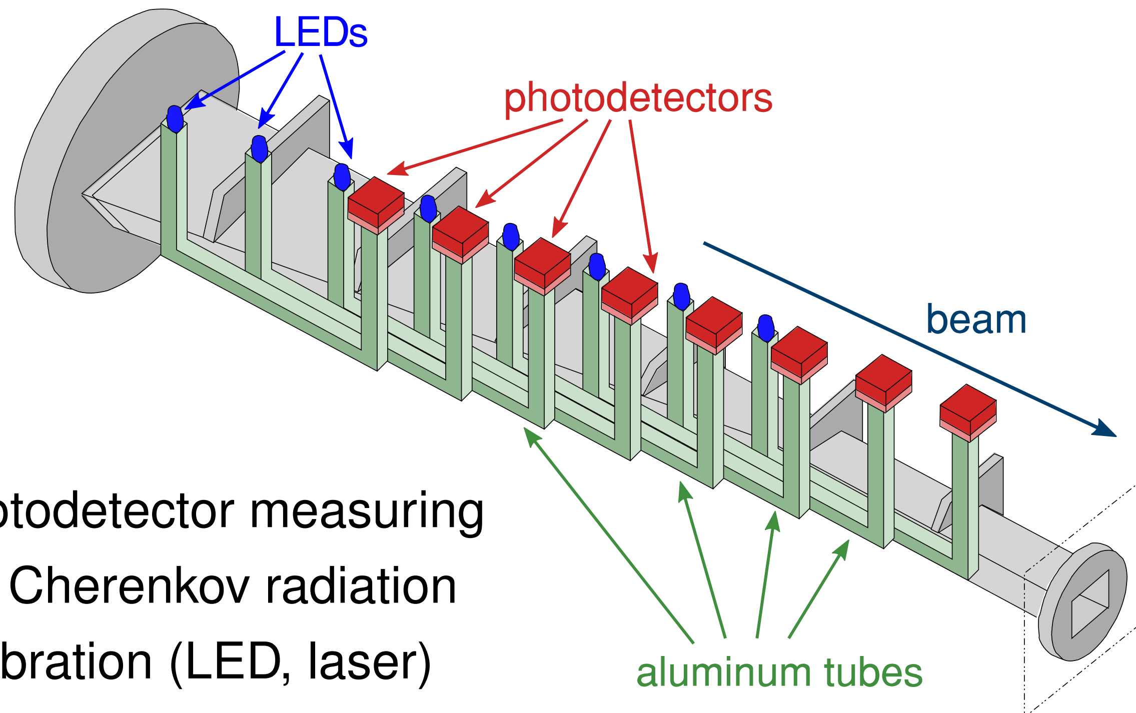
Take home message:

- detector performance required to meet overall error budget has been achieved in prototypes
  - analysing power (i.e. asymmetry at $\mathcal{P} = 1$): 0.2 %
    $\Rightarrow$ e.g. alignment
  - detector linearity: 0.1 % $\Rightarrow$ photodetector calibration
- some details on the next slides...

Gas Cherenkov detector.



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

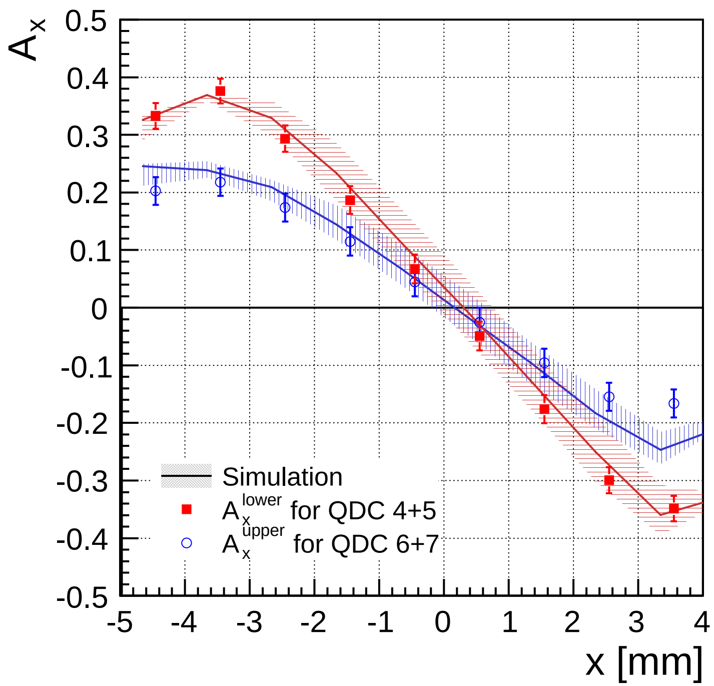
Alignment: locate Compton edge in the spectrometer
Segmented photodetectors: Tilt alignments via asymmetries

2-channel prototype tested at ELSA [JINST 7, P01019 (2012)]
$\Rightarrow$ tilt alignment of 0.1°, nearly fulfils alignment requirements

Gas Cherenkov detector: Alignment.

If the detector is tilted

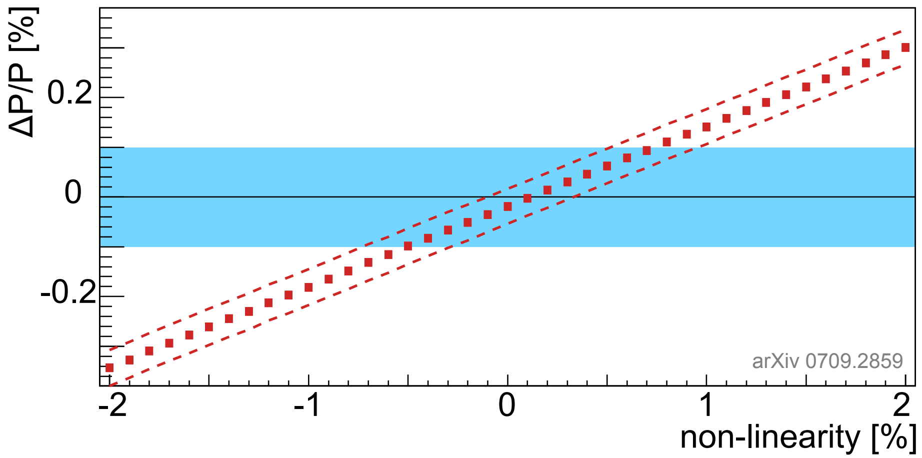
- beam path through the detector varies $\Rightarrow$ different light path
- different light pattern on the photocathode
  $\Rightarrow$ alignment via spatial assymetries possible:



$\Rightarrow$ Reached a tilt alignment of 0.1°. [JINST 7, P01019 (2012)]

Calibration of detector non-linearity.

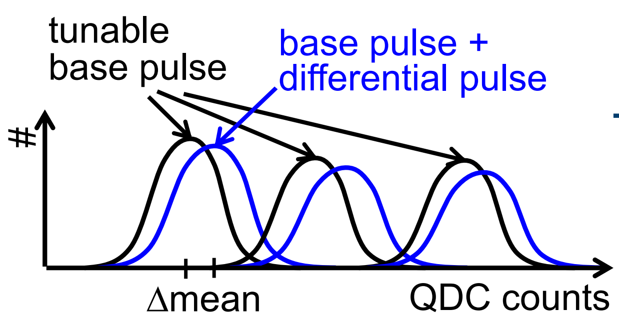
Goal: contribution to overall uncertainty $< 0.1\,\%$

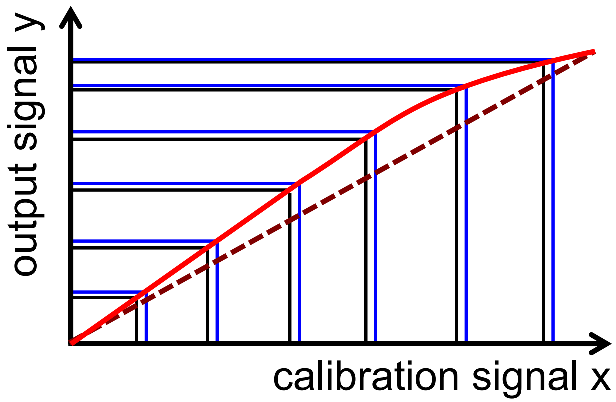


PMTs have to be calibrated to non-linearity $< 0.5\,\%$.

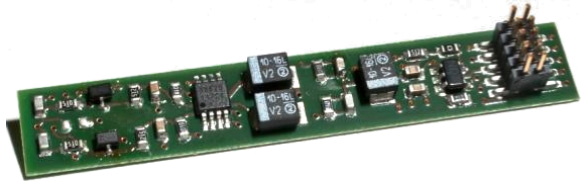
$\mathcal{P} \propto \frac{N^+ - N^-}{N^+ + N^-}$: no absolute calibration needed.

$\rightarrow$ Differential calibration method using two LEDs:



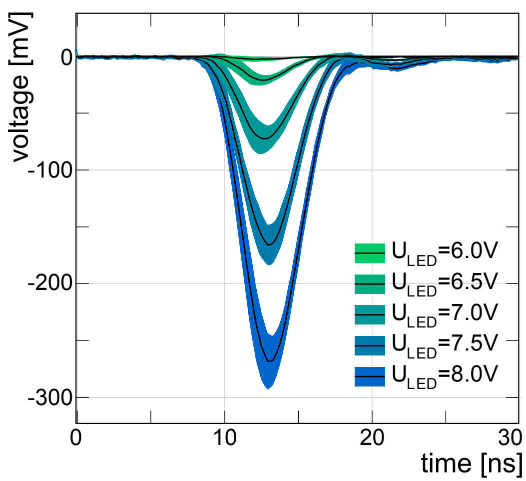


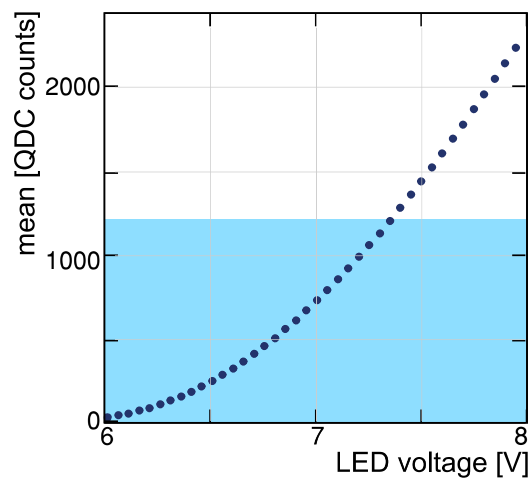
Calibration source requirements.

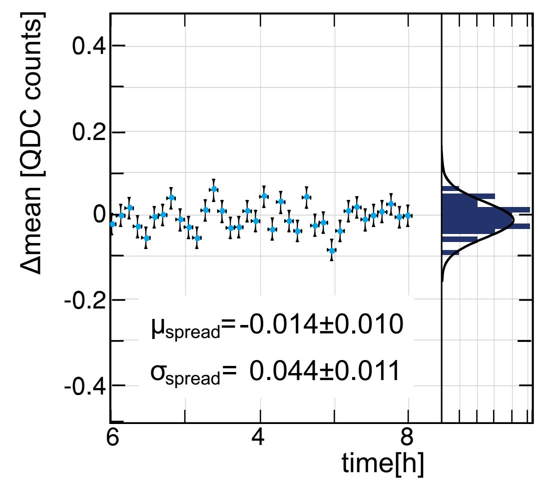


Requirements on the LED driver:

- wave length in UV range ($\lambda = 405\,$nm)
- applicable in detector design $\rightarrow$ small
- short light pulses ($< 10\,$ns)
- coverage of the whole dynamic range of the expected signal
- reproducable and stable light pulses

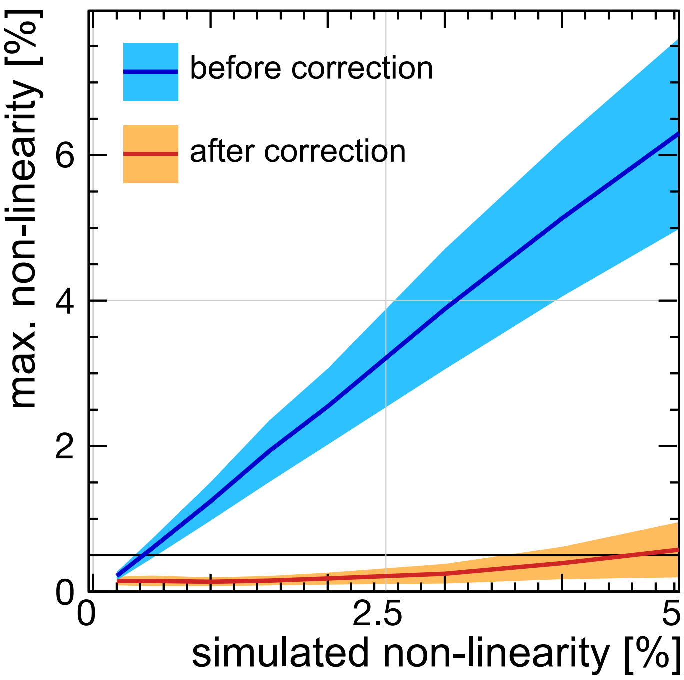






Test of non-linearity correction.

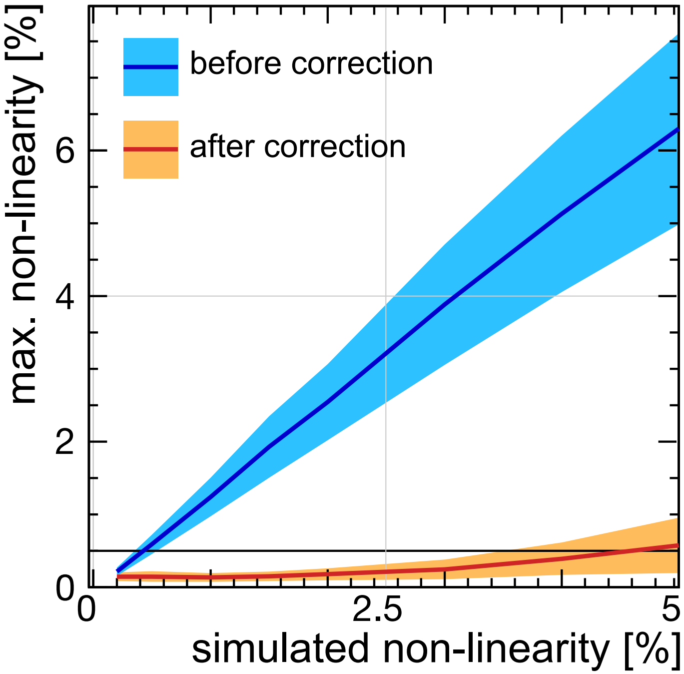
Simulations: Corrections of non-linearities up to 4 % possible.

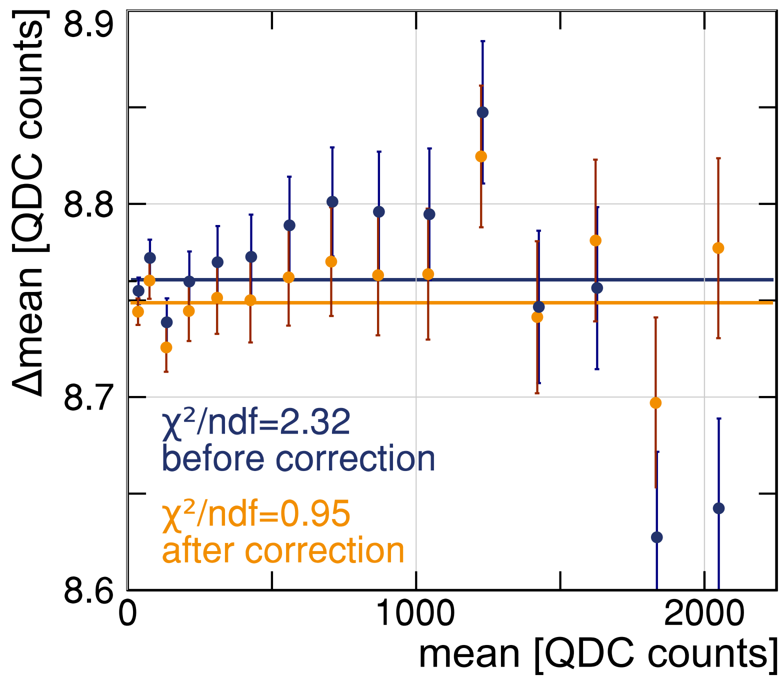


Test of non-linearity correction.

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

Applied method to on of the photodetectors used in testbeam:



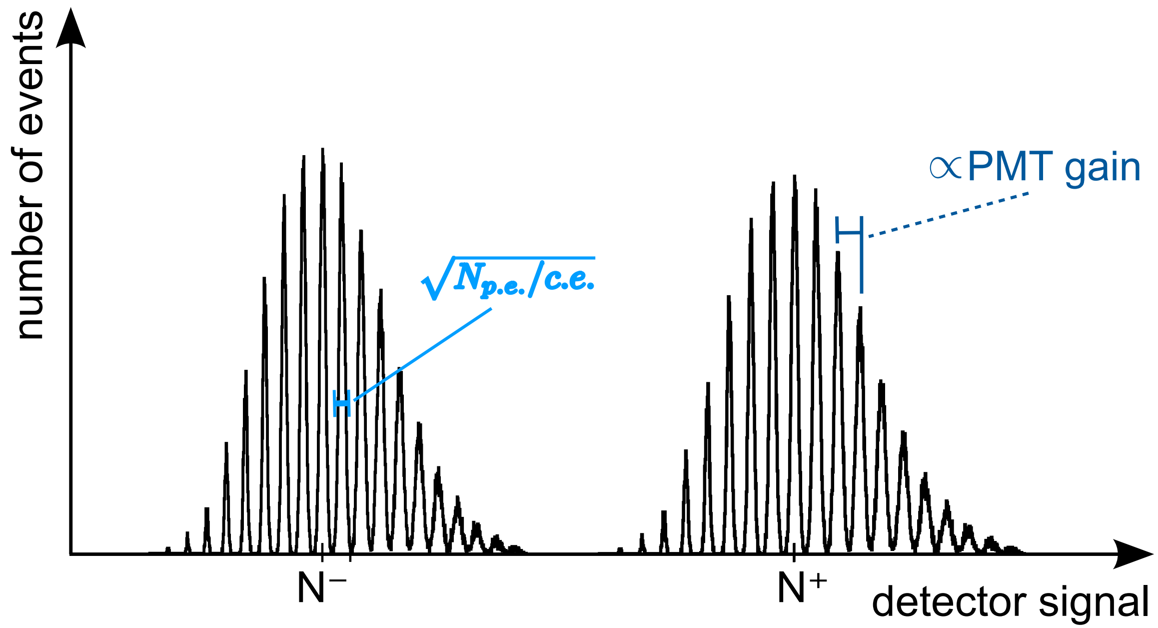


⇒ Reached non-linearity $< 0.2\,\%$ in the expected dynamic range, in single polarimeter channels even smaller.

Quartz Cherenkov detector - idea.

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

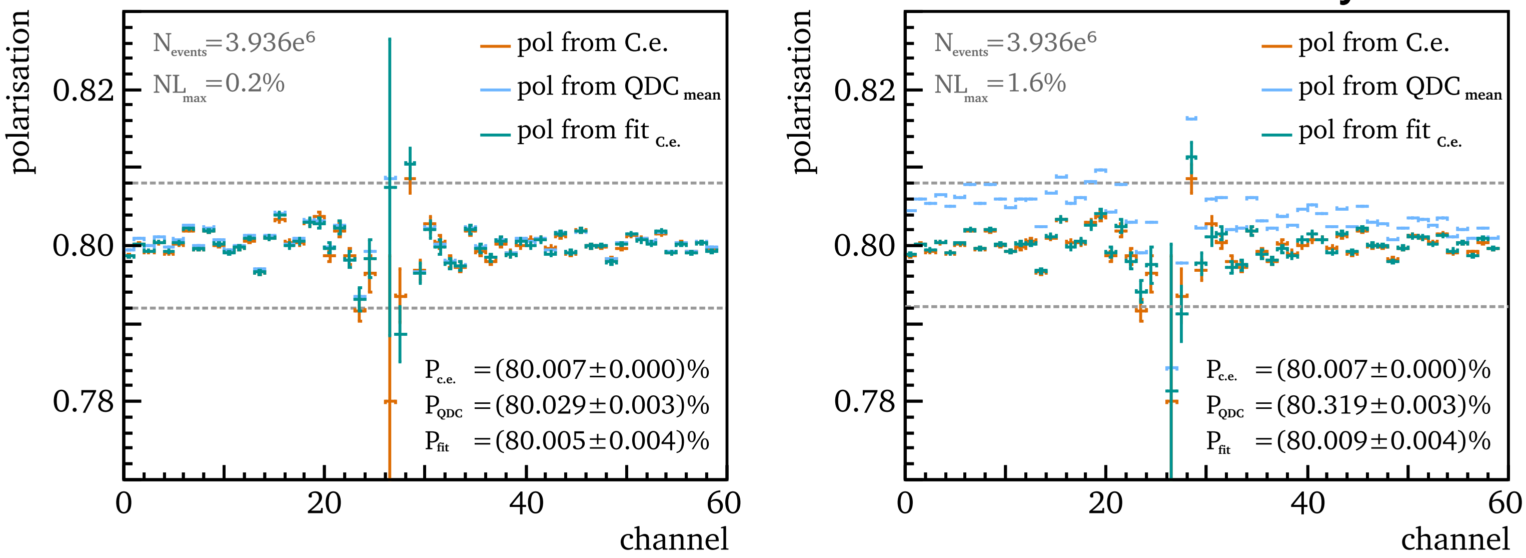


Quartz Cherenkov detector - simulation.

Compare asymmetry from

- true Compton electrons
- QCD mean (no peaks resolved)
- peak counting

without and with non-linearity:

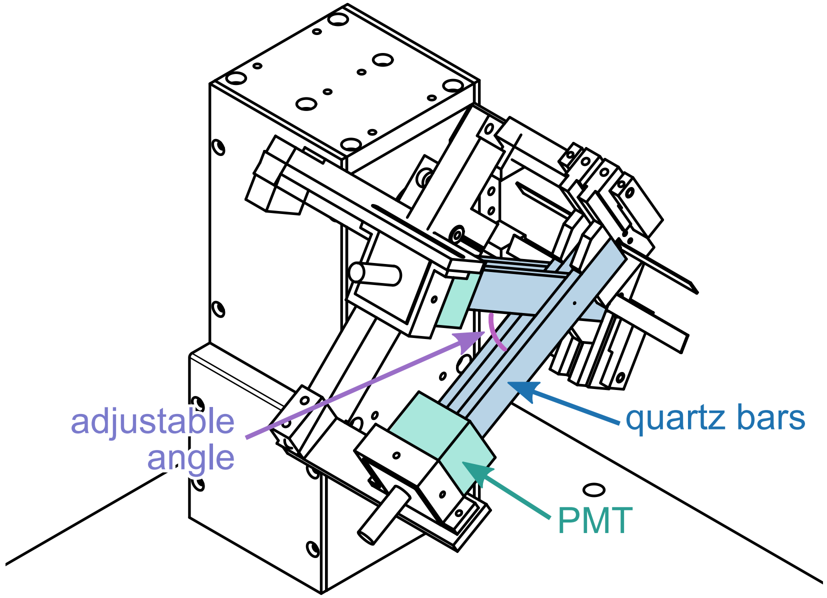


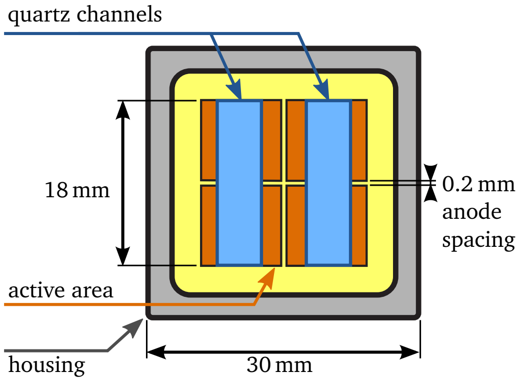
Peak-counting asymmetry robust against non-linearities!

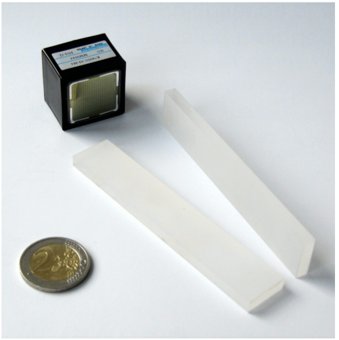
Quartz Cherenkov detector - prototype.

4-channel prototype operated at DESY II testbeam in 2014

- channels: quartz bars (5 mm x 18 mm x 100 mm)
- reasonable agreement with simulations (angular dependence, etc.)

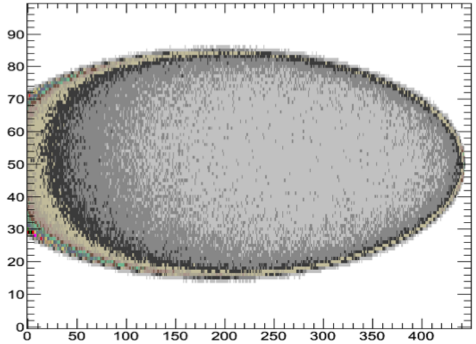


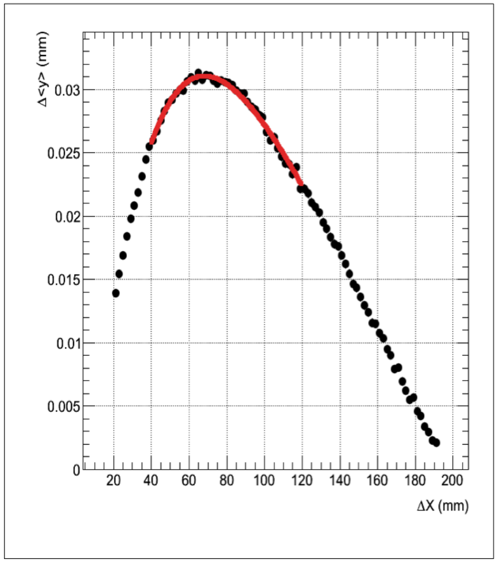




Transverse Polarisation.

- requires to measure also vertical position, width of spectrum $\sim$ mm $\Rightarrow$ Si pixel detector
- pioneered by G. Alexander, I. Ben Mordechai [https://inspirehep.net/literature/1475547]
- detailed simulation study incl. assessment of systematic uncertainties $\Rightarrow \delta P_Y / P_Y = 0.2\%$ achievable
- dominated by y position (assume 25 μm) and tilt around z (0.1°)





Conclusions.

- precision target for ILC Compton polarimeters $\delta P/P = 0.25\%$ on longitudinal polarisation at Compton IP
- requires detector linearity and analyzing power to be understood 2-3 times better than at SLC polarimeter
- Cherenkov detectors as baseline due to simplicity and robustness
- for detectors, translates to
  - alignment to $\sim$ 100 µm and $\sim$ 1 mrad
  - linearity $\leq$ 0.5%
- two detector concepts incl. calibration system have been succesfully prototyped
- requirements have been met in testbeam
- work ready to resume after project decision

More Details.

- E&P workshop Zeuthen 2008

  http://indico.desy.de/conferenceDisplay.py?confId=585

- its Executive Summary

  arXiv:0903.2959 [physics.acc-ph]

- downstream polarimeter 6-magnet chicane

  http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-12425.pdf

- publication on beam energy and polarisation measurements

  JINST **4** (2009) P10015, arXiv:0904.0122 [physics.ins-det]

- publications on polarimeter detector R&D:

  JINST **7** (2012) P01019, arXiv:1011.6314 [physics.ins-det]

  JINST **10** (2015) 05, P05014, arXiv:1502.06955 [physics.ins-det]

  JINST **11** (2016) 01, P01014 , arXiv:1509.03178 [physics.ins-det]

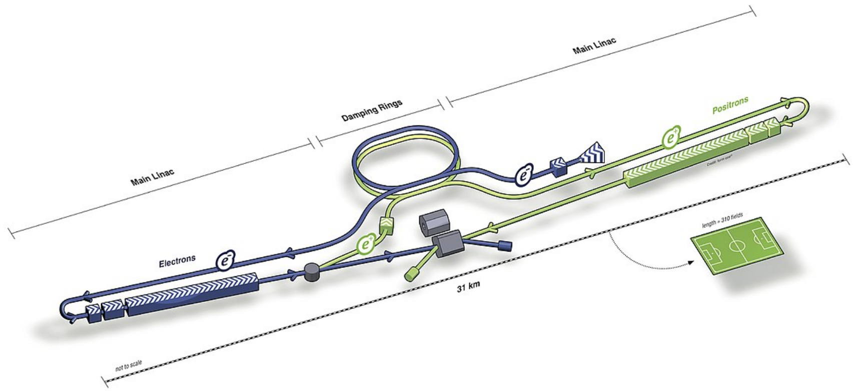
- publication on BDS spin tracking

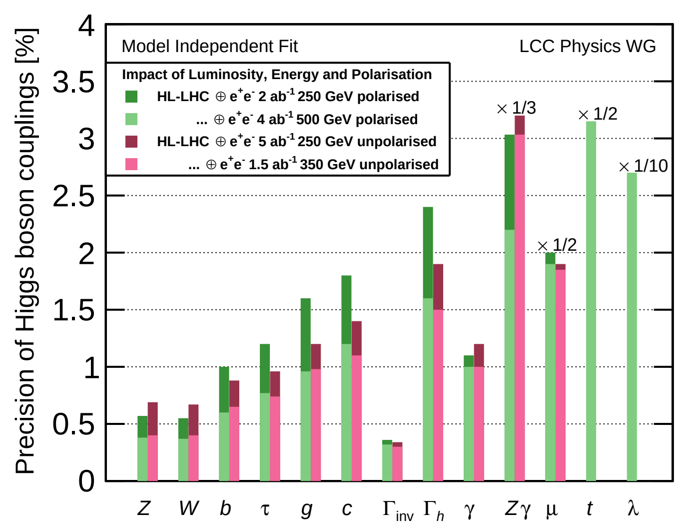
  JINST **9** (2014) P07003, arXiv:1405.2156 [physics.acc-ph]

Backup Slides .

The International Linear Collider.

- e^+e^- “Higgs factory” with $\sqrt{s} = 250$ GeV, upgradable to up to 1 TeV
- *both* beams polarised: $|P(e^-)| = 80\%$, $|P(e^+)| = 30\%...60\%$
- integral part of physics programme, for Higgs and beyond, c.f. https://arxiv.org/abs/1801.02840.
- construction under political consideration in Japan



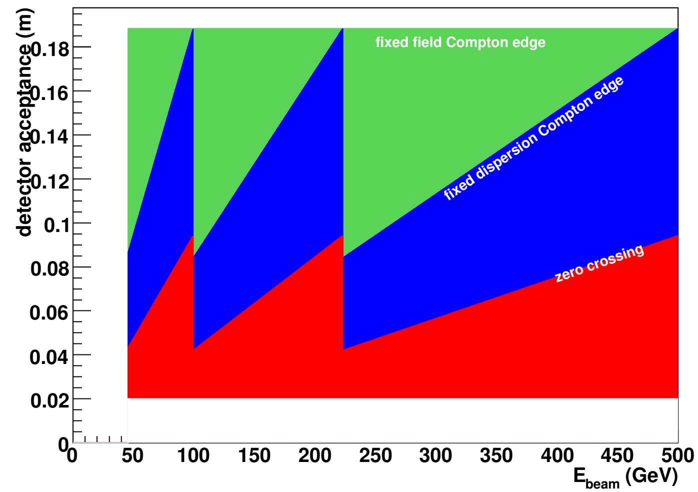


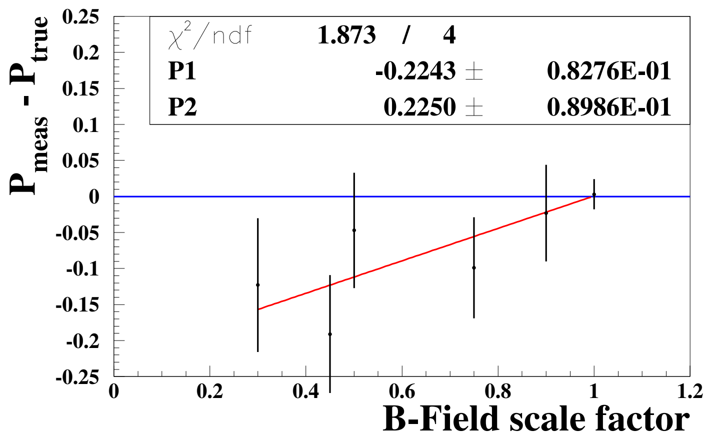
Scaled vs Fixed Field Operation.

Effects of scaled field on measurement:

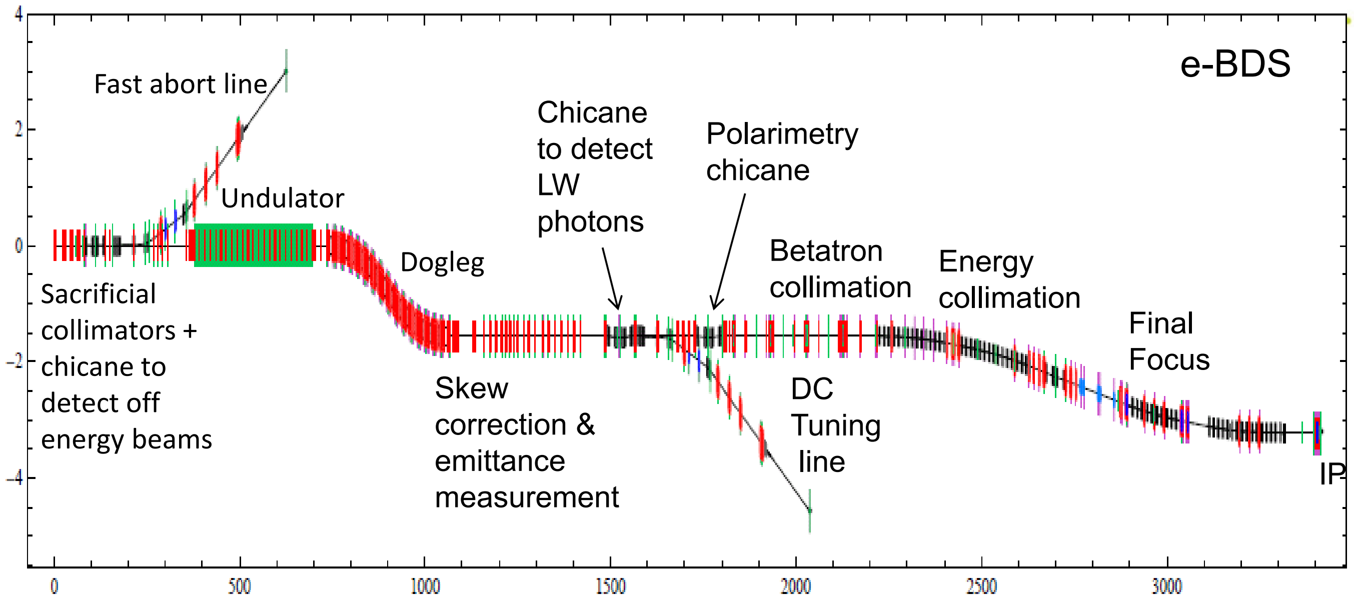
- acceptance: varies with E_{beam} $\Rightarrow$ inhomogeneous quality of polarisation measurement
- alignment: via Compton edge position w.r.t. main beam $\Rightarrow$ effect on $\delta\mathcal{P}/\mathcal{P}$ doubles
- systematic deviations for large scale factors

not compatible with extreme precision requirements c.f. ILC-NOTE-2008-047





The Upstream Polarimeter in SB2009-Nov10 lattice.



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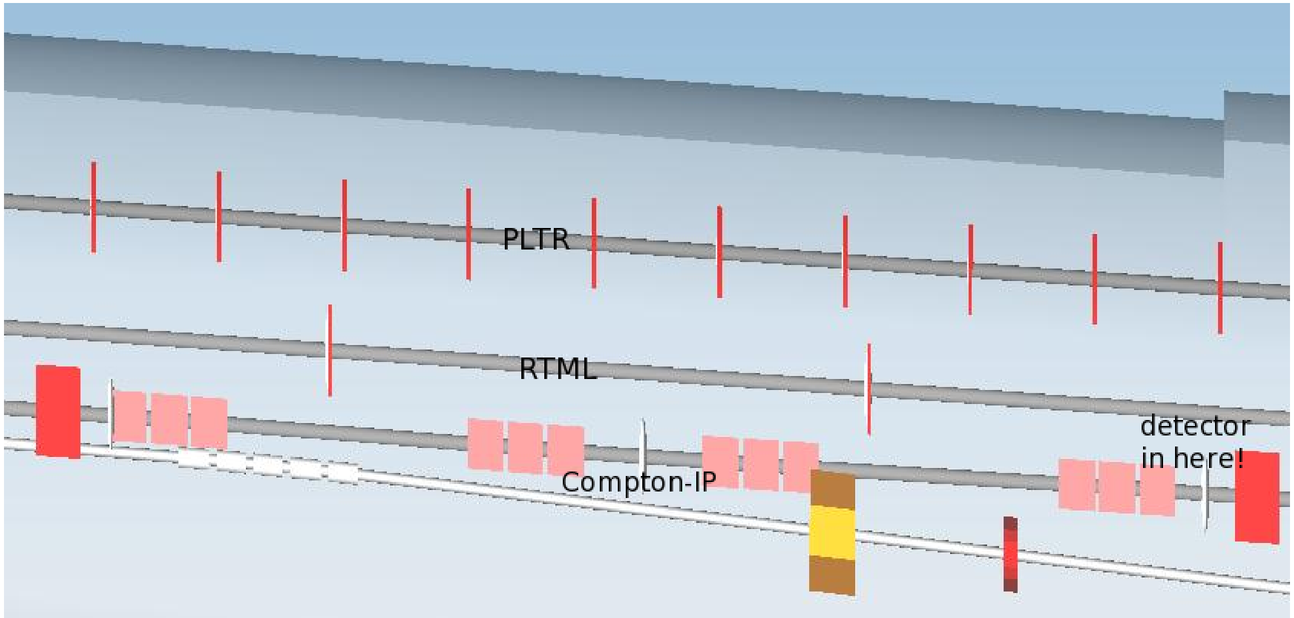

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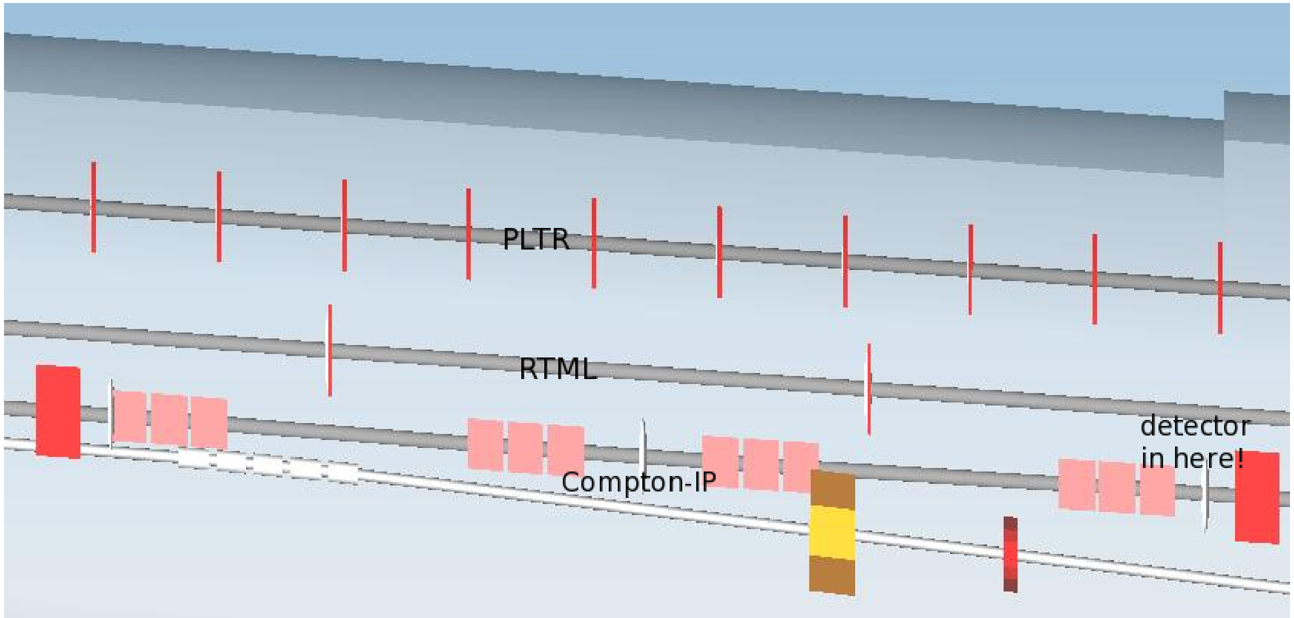


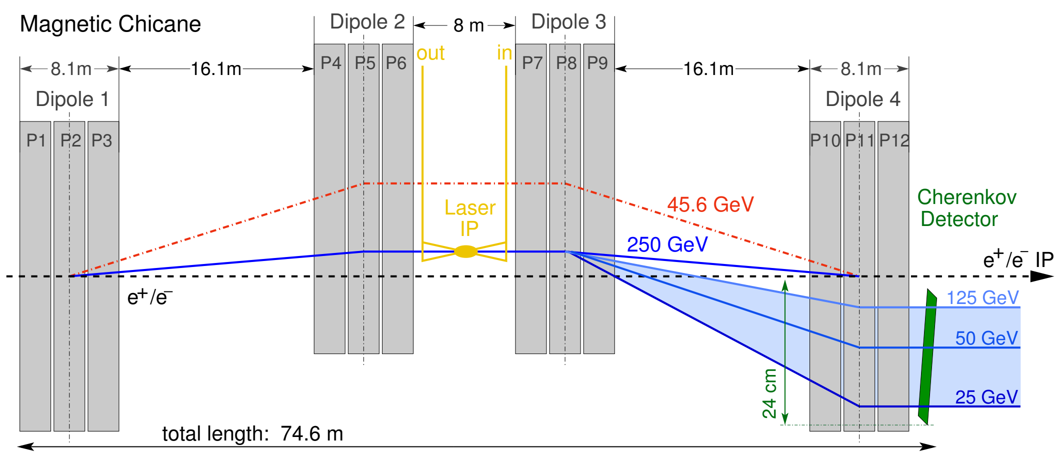
- distance Compton-IP to dump line ca 30 cm at 250 GeV
- down to ca 20 cm at lowest energies - enough?

[c.f. Baseline Technical Review Workshop 2011]

Vacuum Chamber in Chicane Region.

need special beam pipe through out whole chicane

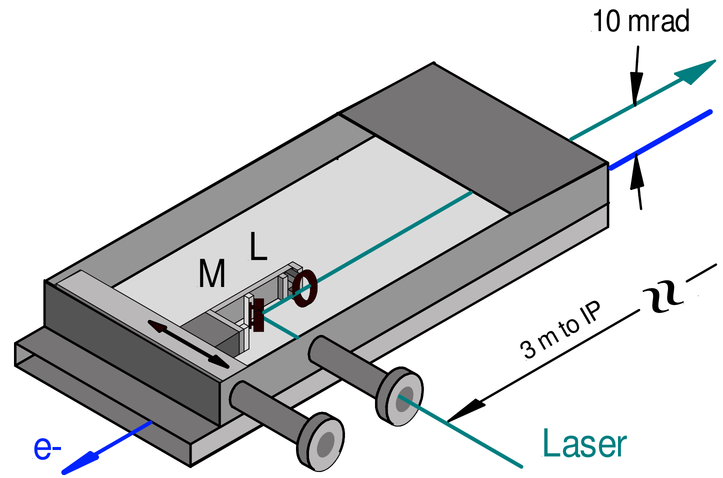
- to allow for varying bending angle
- to guide laser in and out
- to let fan of Compton scattered electrons pass
- to extract Compton fan to detector



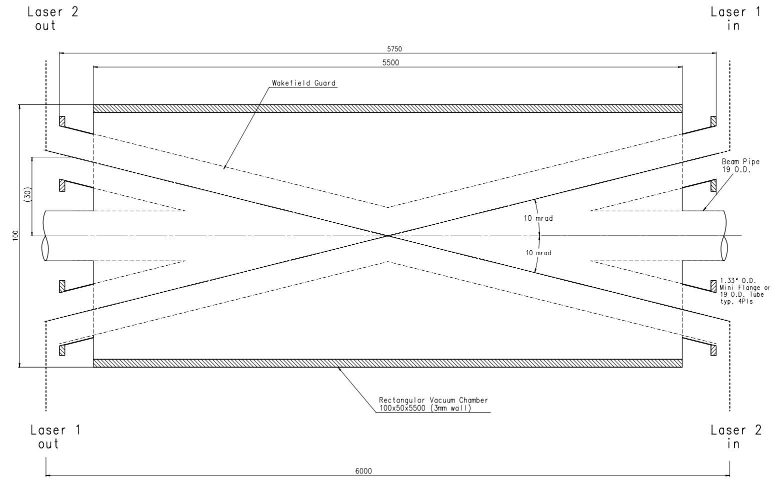
Attention: deflection of chicane the otherway round as on previous page!

Vacuum Chamber: Laser in / out.

- Laser enters chicane *horizontally* (far side from tune-up dump line!)
- final mirror / lens movable to adjust to e^- beam
- had been designed to some extent for TESLA (!) by N. Meyners, P. Schüler

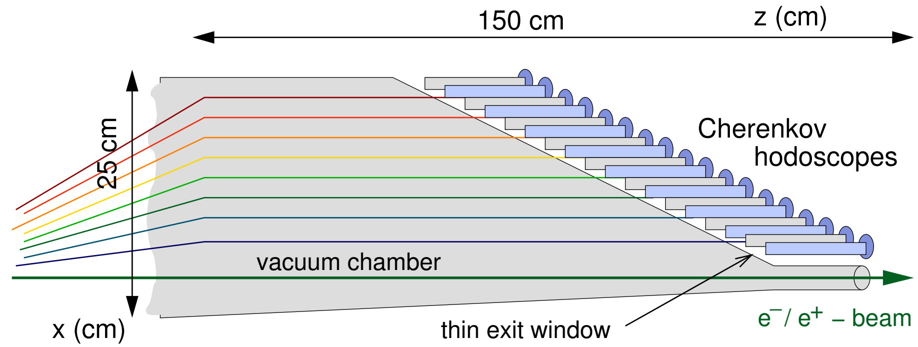


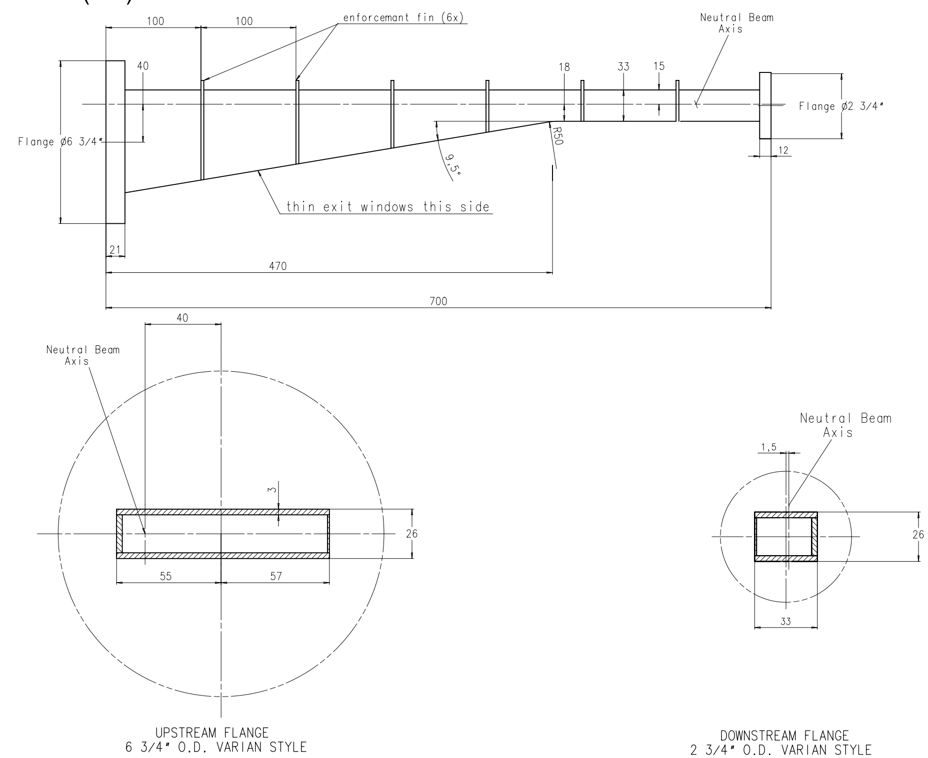
Movable Laser Beam



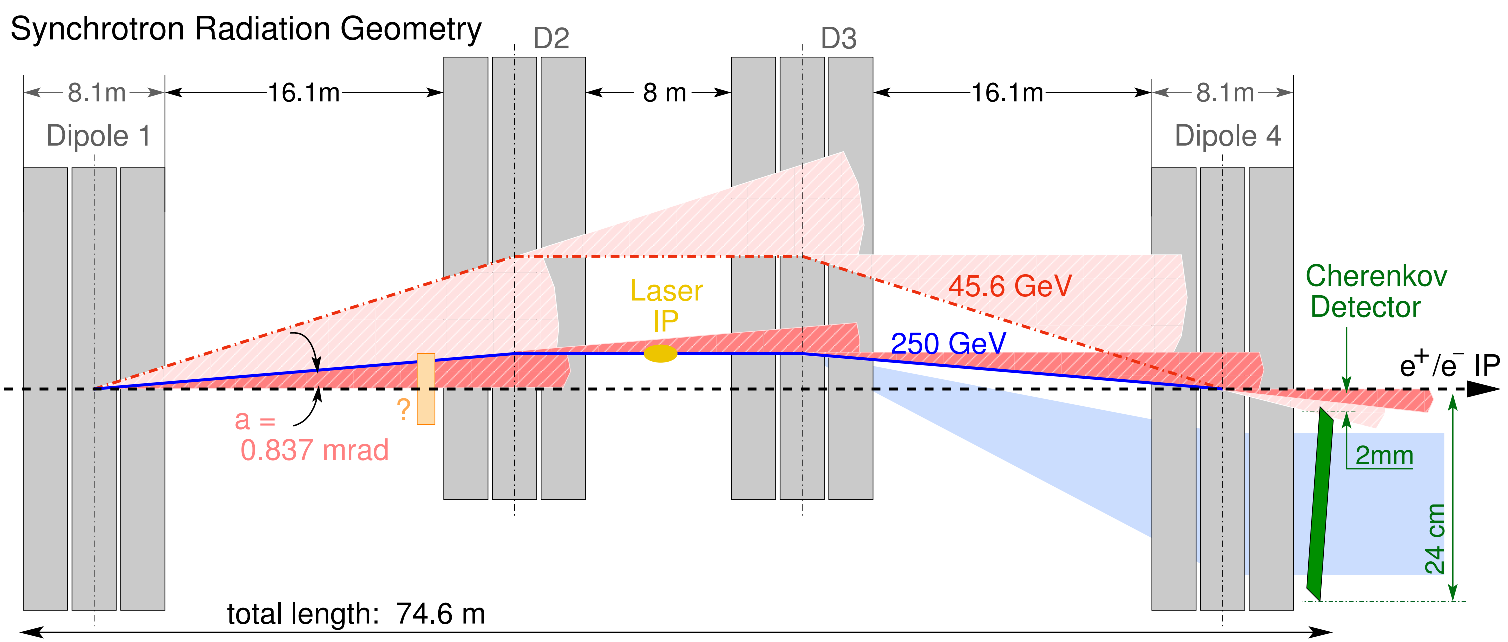
Vacuum Chamber: Compton fan exit.

- need tapered exit window to avoid wake fields
- again estimate from TESLA: $\simeq 10^\circ$ is fine (opinions?)
- need $\simeq$ 1.5 m for detector array, make it 2 m for shielding, accessability,...
- fine with SB2009-Nov10 lattice



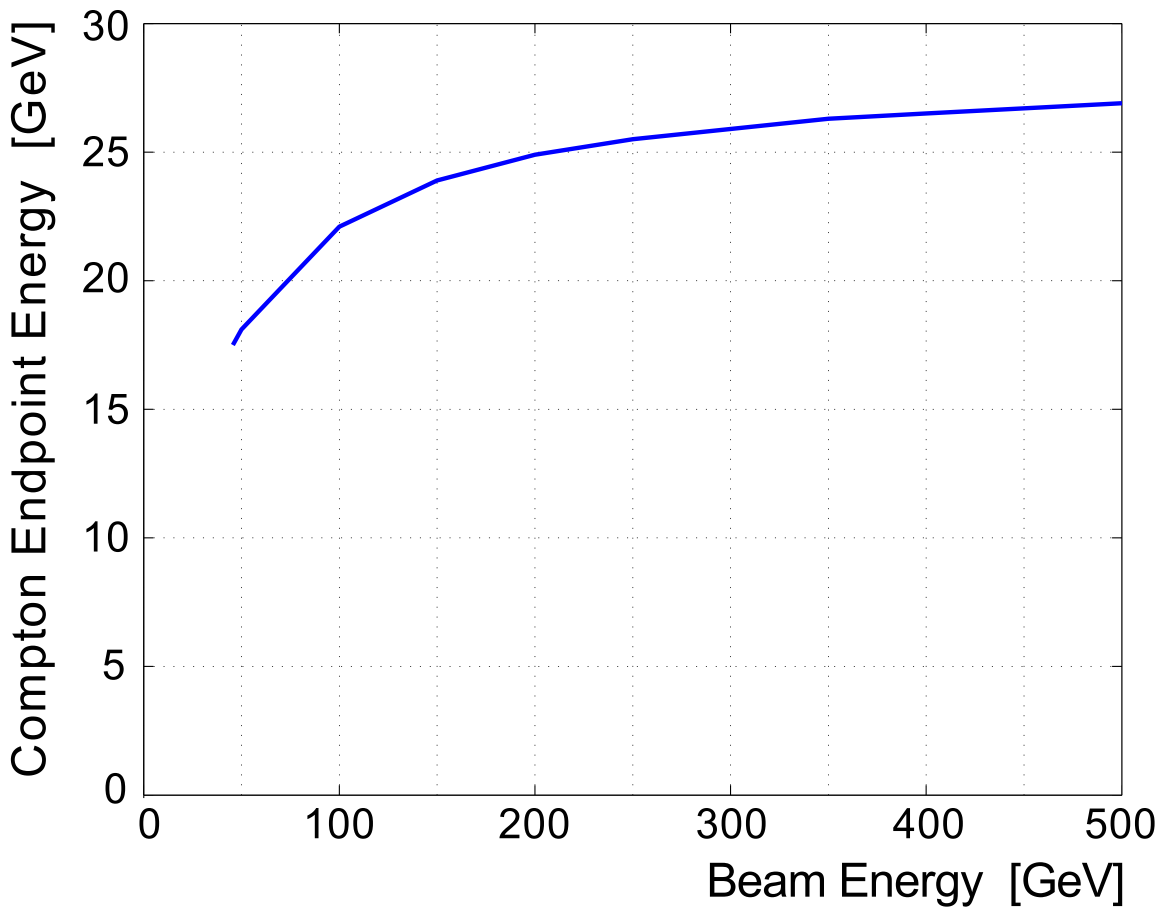


Synchrotron Radiation.



Compton edge.

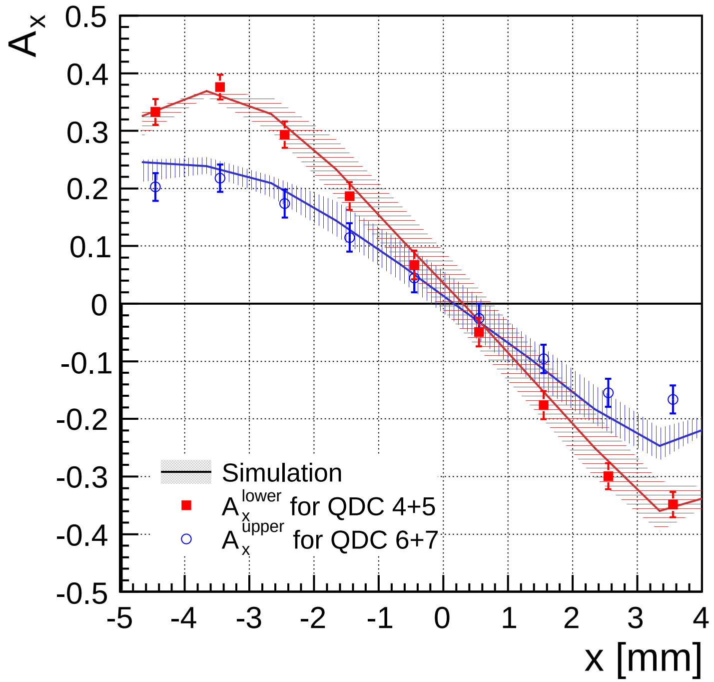
Compton edge position nearly independent of beam energy



Gas Cherenkov detector: Alignment.

If the detector is tilted

- beam path through the detector varies $\Rightarrow$ different light path
- different light pattern on the photocathode
  $\Rightarrow$ alignment via spatial assymetries possible:

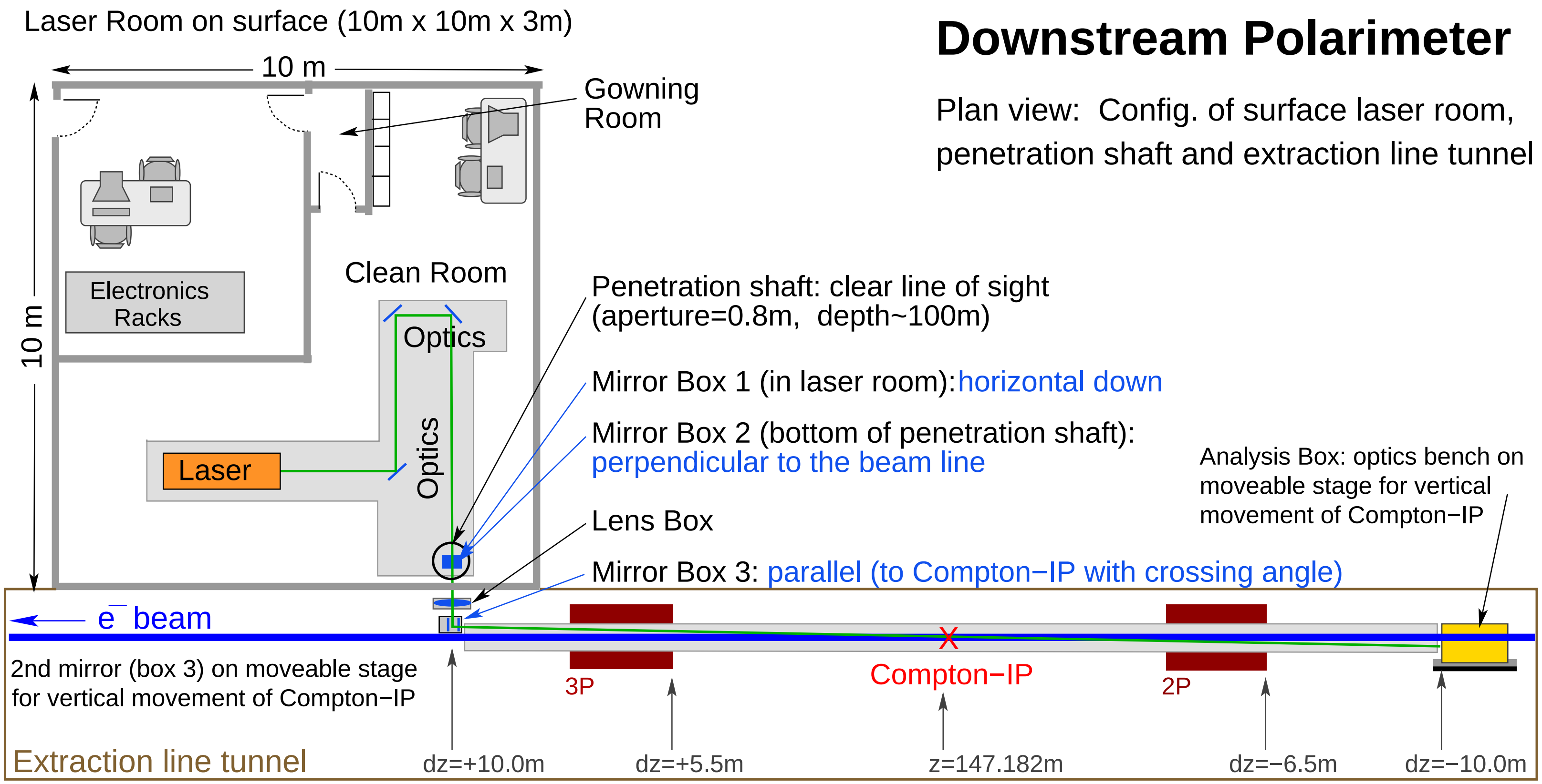


$\Rightarrow$ Reached a tilt alignment of 0.1°. [JINST 7, P01019 (2012)]

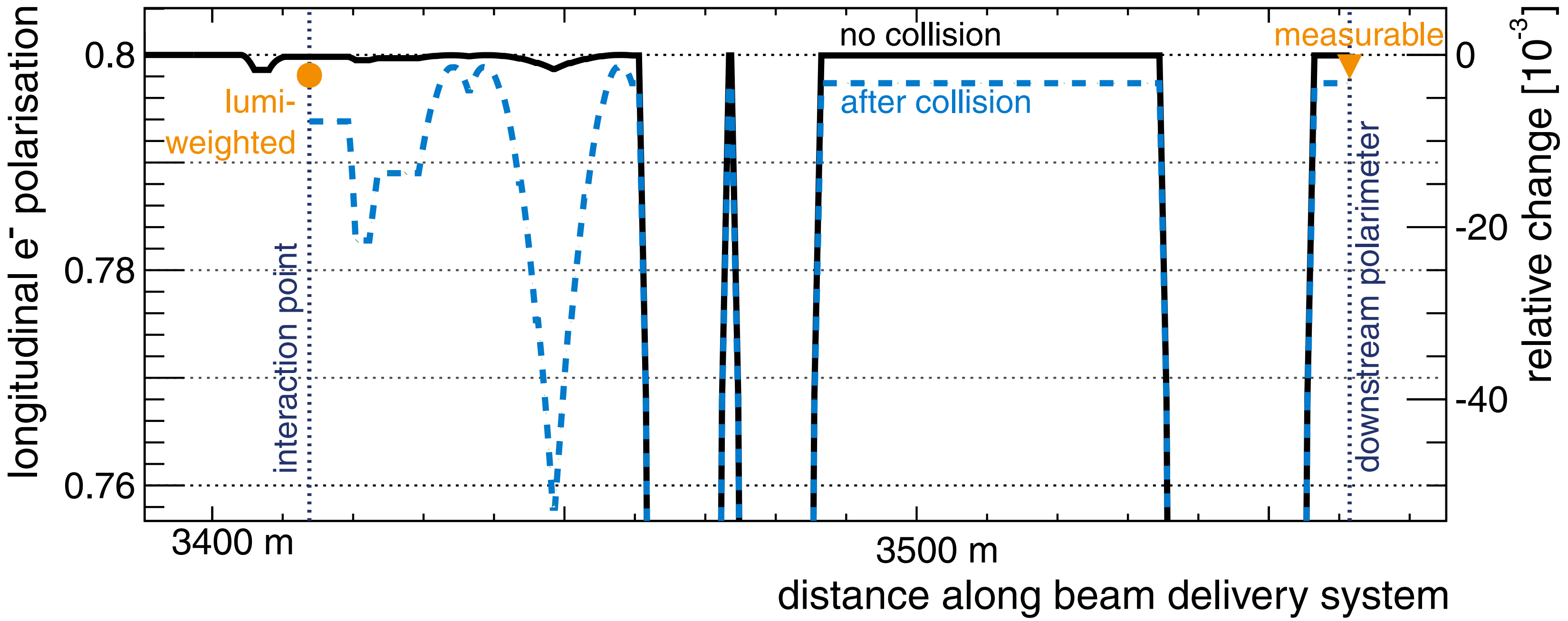
Laser Room.

Downstream Polarimeter

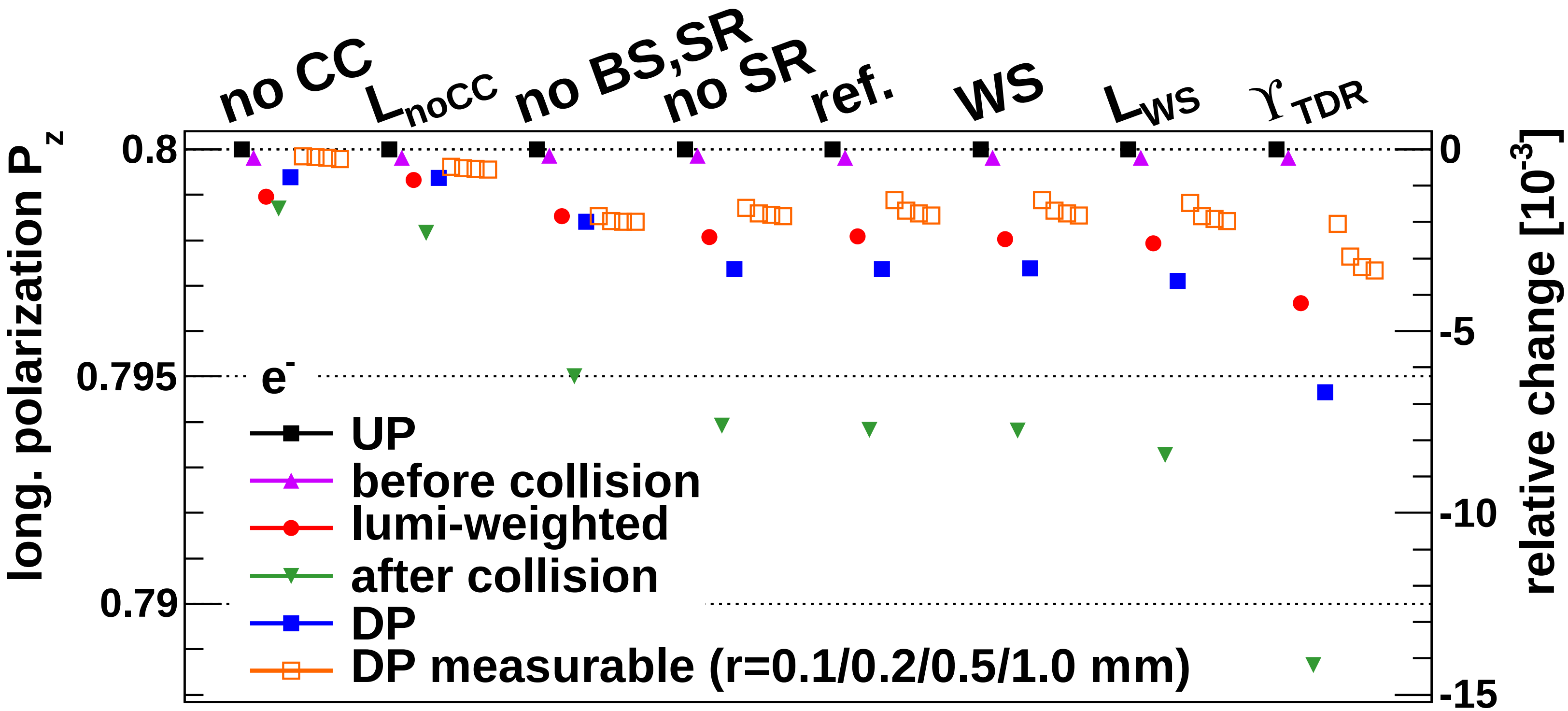
Plan view: Config. of surface laser room, penetration shaft and extraction line tunnel



Spin transport.

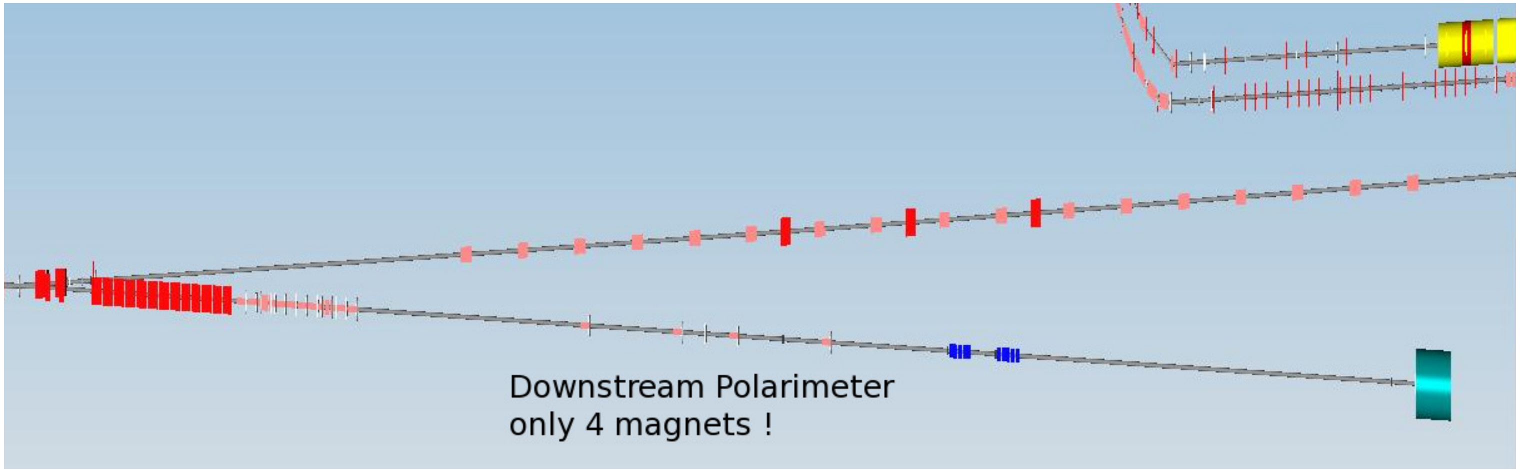


Spin tracking (more).



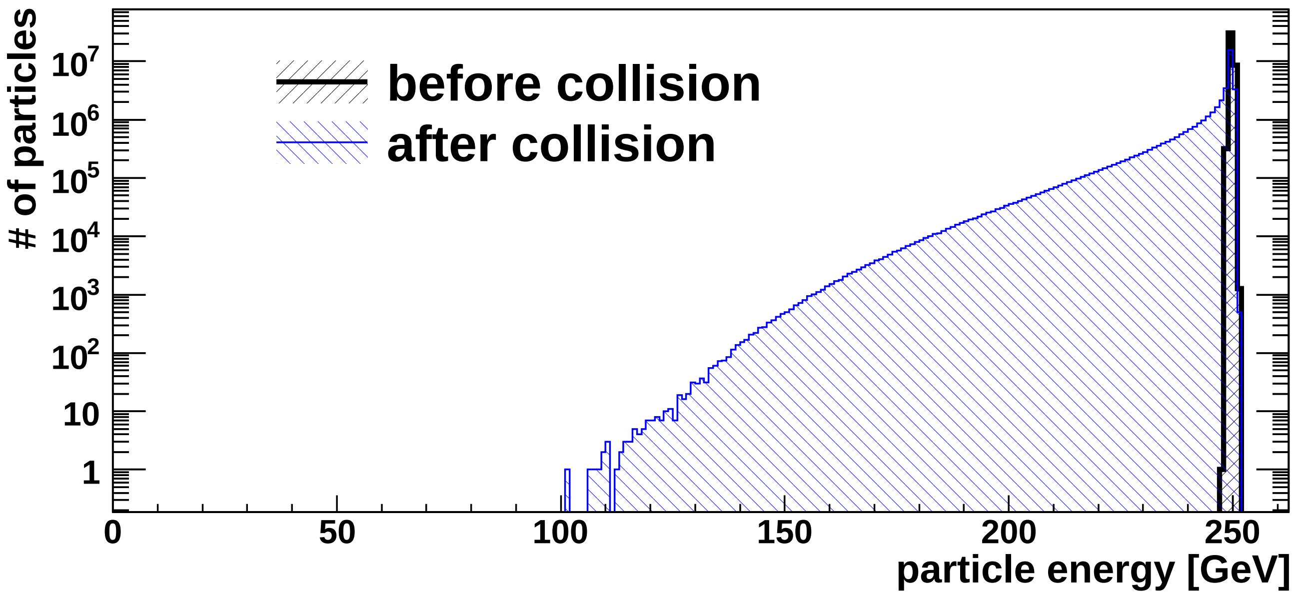
Downstream Polarimeter in SB2009-Nov10 lattice.

- still 4-magnet chicane - should be upgraded to 6-magnet design as propsed in SLAC-PUB-12425
- necessary due to push-pull related changes to the extraction SC quadrupoles
- at the same time gives better shielding of magnets due to additional collimators
- even more impact due to worse spent beam in low power configuration....



Beam Energy Spectrum with Collisions.

GuineaPig++, RDR nominal, $\sqrt{s} = 500\,\text{GeV}$

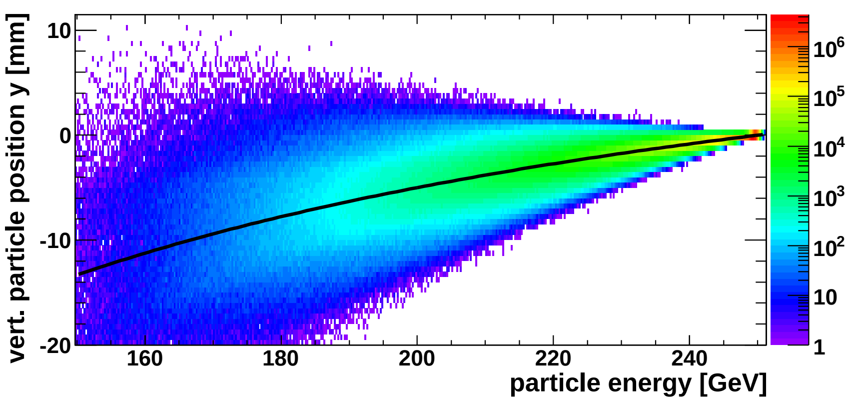


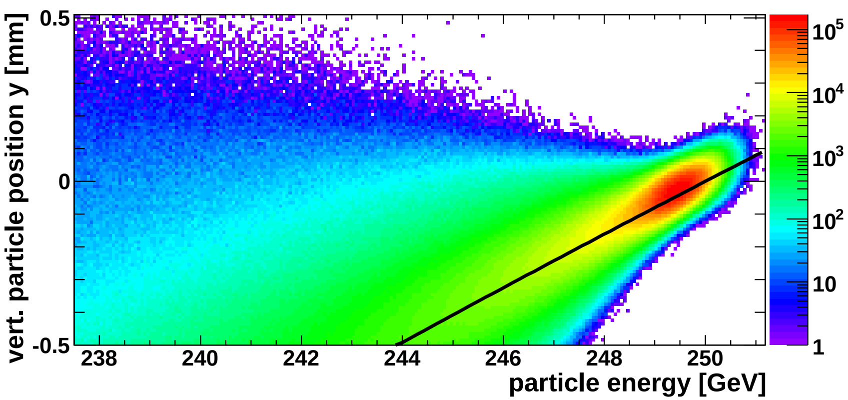
How will this influence the measurement at the downstream polarimeter?

y vs *E* at DP IP.

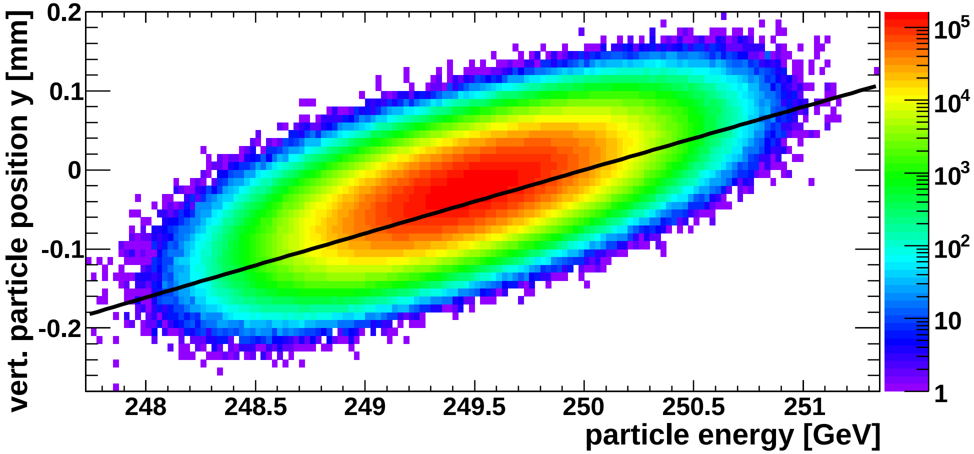
Particle Tracking through SB2009-Nov10 lattice (M.Beckmann)

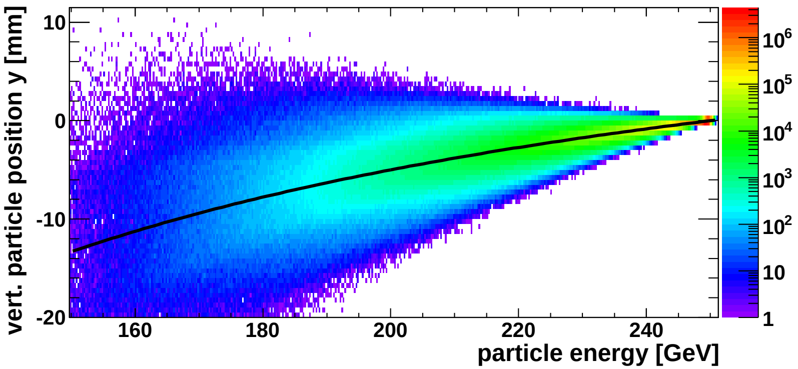
- vertical extension of spent beam at DP IP $\mathcal{O}$(cm)
- "core" size still $\simeq 0.5\,\text{mm}$
- sizable correlation of energy and position
- which part will the laser sample?
- expect dependence of measured polarisation on laser spot size and laser-beam alignment

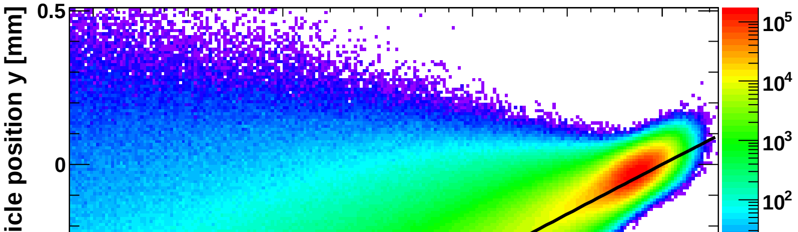




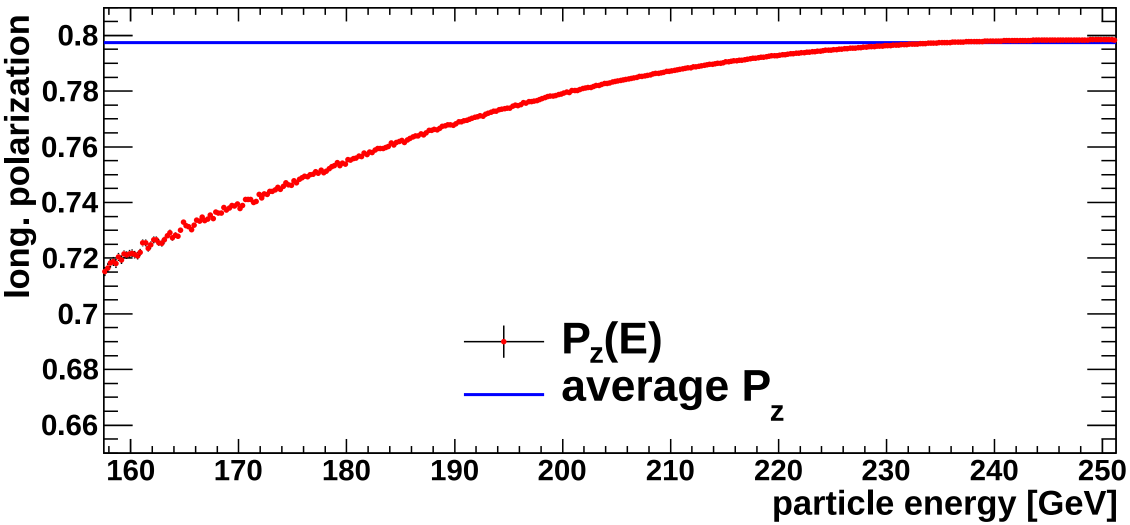
Downstream Polarimeter: *y* vs *E*.

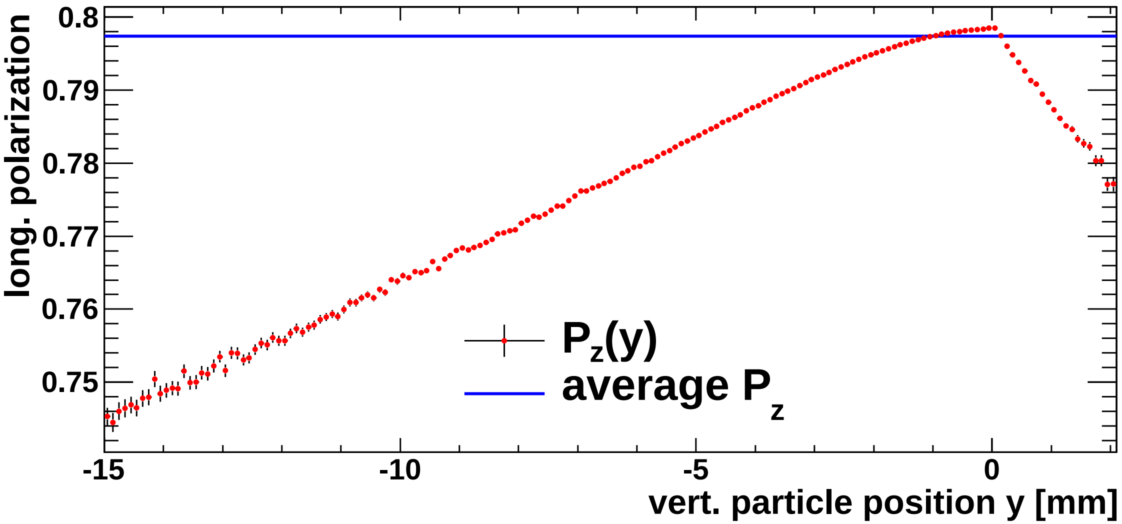




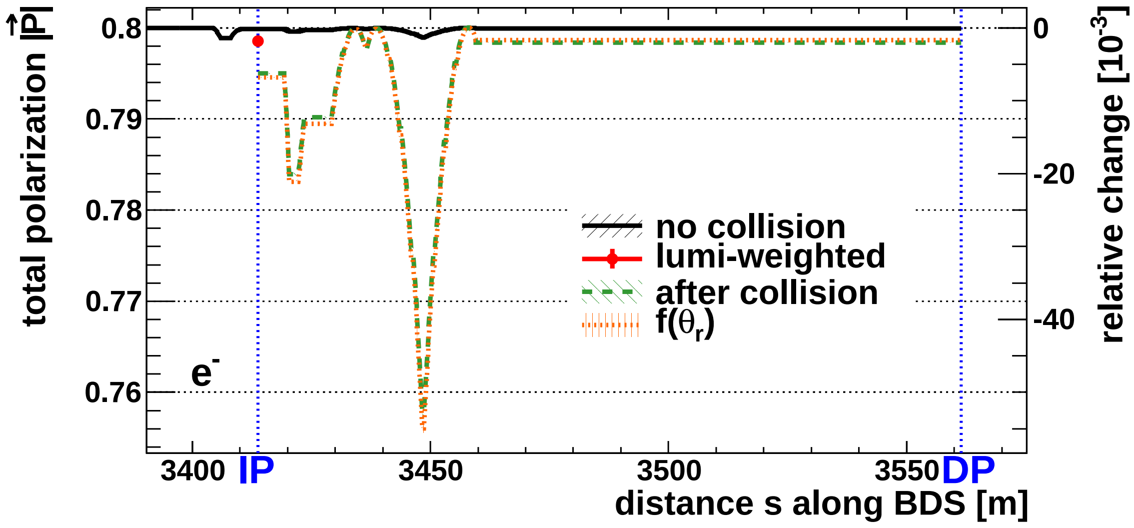


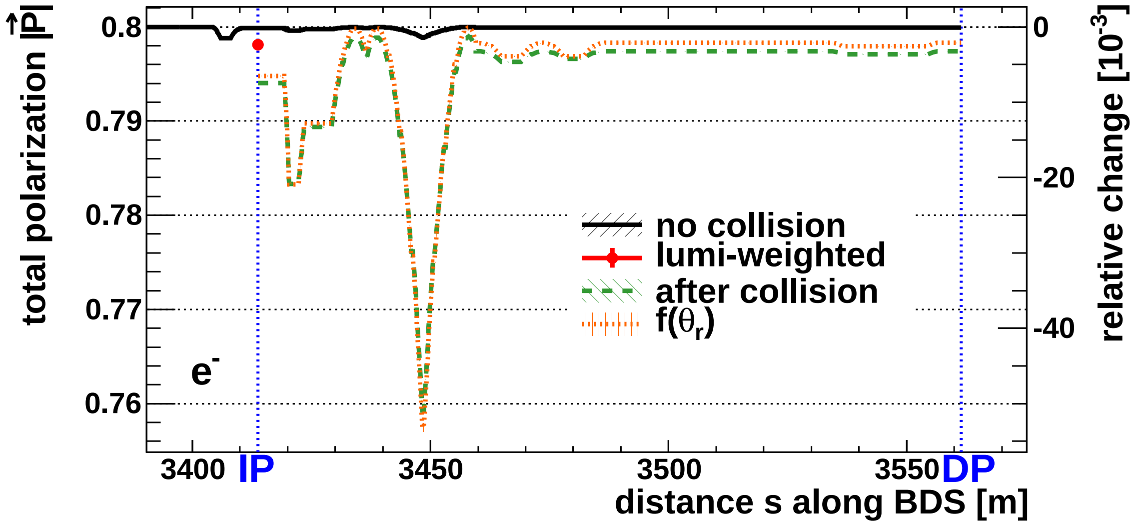
Downstream Polarimeter: P_Z vs E, P_Z vs y.





Total Polarisation IP → DP.





Polarisation for Physics.

Longitudinal polarisation $P_z = \frac{N_R - N_L}{N_R + N_L}$
with $N_{R,L}$: number of right-/left-handed particles in bunch

- SM & BSM: left- and righthanded particles couple differently
  - polarised cross-sections are important observables carrying qualitatively new information!
  - beam polarisation can suppress background / enhance signal
- wanted for physics: luminosity weighted average polarisation at the IP, $\langle P_z \rangle_{IP} = \frac{\int P_z(t)\mathcal{L}(t)dt}{\int \mathcal{L}(t)dt}$
- Note: most physics studies sofar assume this average is known exactly and independently for e^- and e^+ beam.

$P \equiv P_z$ in the following.

Polarised Cross-sections.

$$\sigma_{P_{e^-} P_{e^+}} = \frac{1}{4} \quad \{ \quad (1 + P_{e^-})(1 + P_{e^+})\sigma_{RR} + (1 - P_{e^-})(1 - P_{e^+})\sigma_{LL}$$
$$+ \quad (1 + P_{e^-})(1 - P_{e^+})\sigma_{RL} + (1 - P_{e^-})(1 + P_{e^+})\sigma_{LR}\}$$

processes with s-channel Z/γ exchange only:

- $\sigma_{RR} = \sigma_{LL} = 0$
- $4\sigma_{P_{e^-} P_{e^+}} = (1 - P_{e^-} P_{e^+})(\sigma_{LR} + \sigma_{RL})[1 - P^-_{\text{eff}} A_{LR}]$
- with $P^-_{\text{eff}} = 1 - \frac{P_{e^-} - P_{e^+}}{1 - P_{e^-} P_{e^+}}$ and $A_{LR} = \frac{\sigma_{LR} - \sigma_{RL}}{\sigma_{LR} + \sigma_{RL}}$

general case:

- $\sigma_{RR} \neq \sigma_{LL} \neq 0$
- $4\sigma_{P_{e^-} P_{e^+}} = (1 + P_{e^-} P_{e^+})(\sigma_{LL} + \sigma_{RR})[1 + P^+_{\text{eff}} A_{LLRR}]$ + above
- with $P^+_{\text{eff}} = 1 + \frac{P_{e^-} + P_{e^+}}{1 + P_{e^-} P_{e^+}}$ and $A_{LLRR} = \frac{\sigma_{LL} - \sigma_{RR}}{\sigma_{LL} + \sigma_{RR}}$

Polarisation Averages.

Absolute cross-section measurements require:

- $\langle P_{e^\pm} \rangle_{IP} = \frac{\int P_{e^\pm}(t)\mathcal{L}(t)dt}{\int \mathcal{L}(t)dt}$
- $\langle P_{e^-} P_{e^+} \rangle_{IP} = \frac{\int P_{e^-}(t)P_{e^+}(t)\mathcal{L}(t)dt}{\int \mathcal{L}(t)dt}$
- correlations between lumi and polarisation?!

Direct extraction from collision data

- any abundant, well-known, polarisation dependent process:
- $\langle | \ P_{e^\pm} \ | \rangle_{IP} = \sqrt{\frac{(\sigma_{-+}+\sigma_{+-}-\sigma_{--}-\sigma_{++})(\pm\sigma_{-+}\mp\sigma_{+-}+\sigma_{--}-\sigma_{++})}{(\sigma_{-+}+\sigma_{+-}+\sigma_{--}+\sigma_{++})(\pm\sigma_{-+}\mp\sigma_{+-}-\sigma_{--}+\sigma_{++})}}$
- σ_{+-} is total cross-section for $P(e^-, e^+) = (+x\%, -y\%)$, etc.
- assumes $P_+(e^-) = -P_-(e^-)$ and $P_+(e^+) = -P_-(e^+)$

Correction to modified Blondel scheme.

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