Compton polarimetry for SuperKEKB upgrade

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Introduction

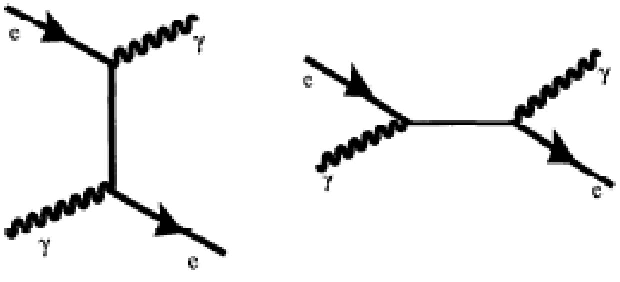
White report drafting:

- A draft document for the polarimeter is ready, attached to the indico page, please comment.
- An overleaf version is available upon request
- Baseline location of polarimeter needs to be decided to progress further
- Assumes so far that longitudinal polarization will be measured

Content of today's presentation:

- Investigations related to the detection system for photons
- Short summary about the physics process
- Summary of what needs to be done (assuming at this stage a longitudinal e-beam polarization)
- Detection system for photons ?
- Progress on a dedicated MC and fitter (for offline extraction)

Compton cross-section



$$x = \frac{2E_0\omega_0}{m^2}(1+\cos\theta_0) \qquad y = \frac{E_\gamma}{E_0}$$

The Compton cross-section averaged over scattered particles spins:

Differential cross-section

Transverse laser polarisation: nuisance parameter to minimize and keep under control

Transverse electron beam polarisation: intervenes as an asymmetry in the transverse plane

$$\frac{d\sigma}{dy\,d\varphi_{obs}}(x,y) = \frac{d\sigma_0}{dy}(x,y) + \frac{d\sigma_\perp}{dy}(x,y)\cos\big(2(\varphi_{obs}-\varphi_{las})\big)\boxed{\mathcal{P}_\perp^{las}} + \frac{d\sigma_\parallel}{dy}(x,y)\mathcal{P}_C^{las}\Big(\boxed{P_T f_T(x,y)\cos(\varphi_{obs}-\varphi_{elec})} + P_L f_L(x,y)\Big)$$

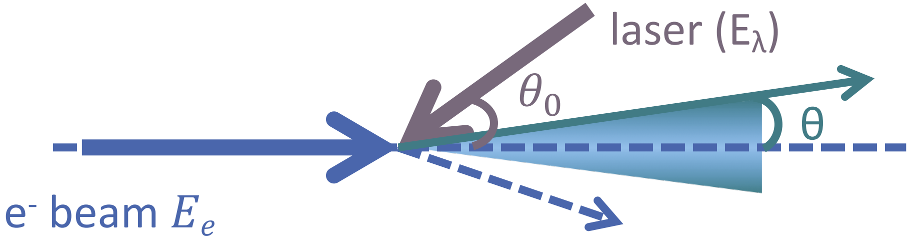
Electron beam polarization independent

Electron beam polarization dependent

⚠ Assume in the following:

- purely circular laser polarization $\mathcal{P}_C^{las}$: transverse polarization of laser will be a systematic uncertainty or a constrained parameter in the fit
- I also assume for the sensitivities studies performed here that $\mathcal{P}_C^{las}$=1 (or -1)
- I postpone quantitative studies related to imperfect laser polarization to a later stage

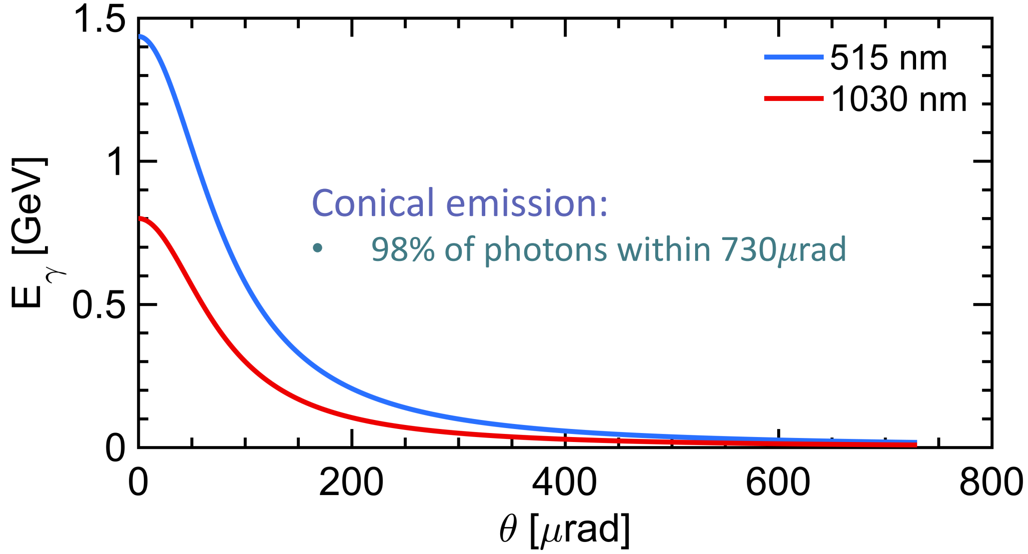
A first look at the unpolarized term



- Initial electron energy (7 GeV)
- Initial photon energy (1.2eV at 1030nm)
- Crossing angle of beams
- Emitted photon energy

Landau-Lifshitz QED book paragaphs 86 and 87

energy vs emission angle correlation



Conical emission:

- 98% of photons within 730μrad

⚠ Remember:

- Photons (electrons too) are scatterred in the forward direction, in a narrow cone around the electron beam axis
- I further implicitely assume that detection of photons require to clear a line of sight of about L=30m

Detection of photons: requirements

Energy of photons (~1GeV) in a narrow cone

Distinguish each bunch at 250MHz (4ns)

Two interesting regimes:

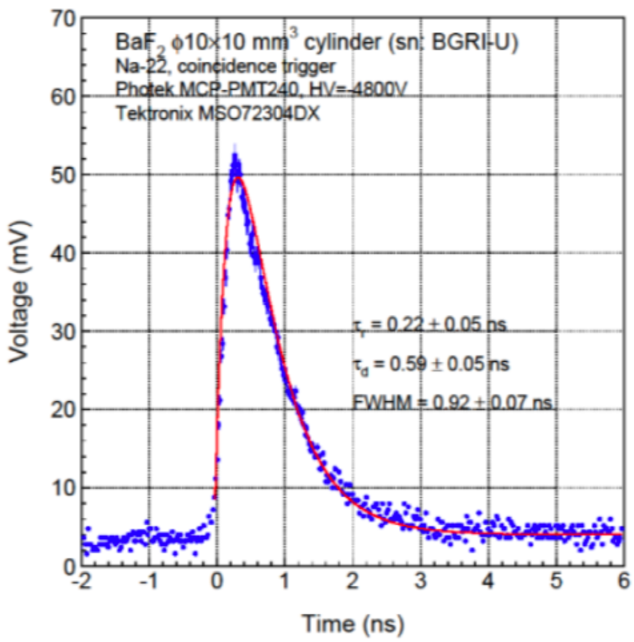
- Low scattering rate: $(\sim 1/\mathrm{bunch})$
  - ☺ Data-driven, online calibration and linearity control can be considered (edges of 1, 2, 3 photons)
  - 😐 Signal only radiation dose in detector O(1MGy/year) (1GeV@250MHz)
  - ☹ Very good knowledge (spectrum shape) of backgrounds is necessary (data driven)
- High scattering rate: $(\sim 10 - 100/\mathrm{bunch})$
  - ☹ Sensitive to threshold calibration, detector linearity
  - ☹ Very large radiation dose O(10MGy/year) or larger
  - ☺ Background free (background energy deposition below thresholds)
  - ☹ Asymmetry less pronounced (integrated over spectrum)

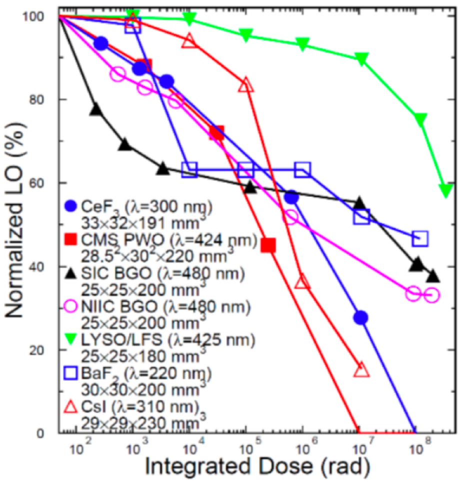
Concentrate on this strategy

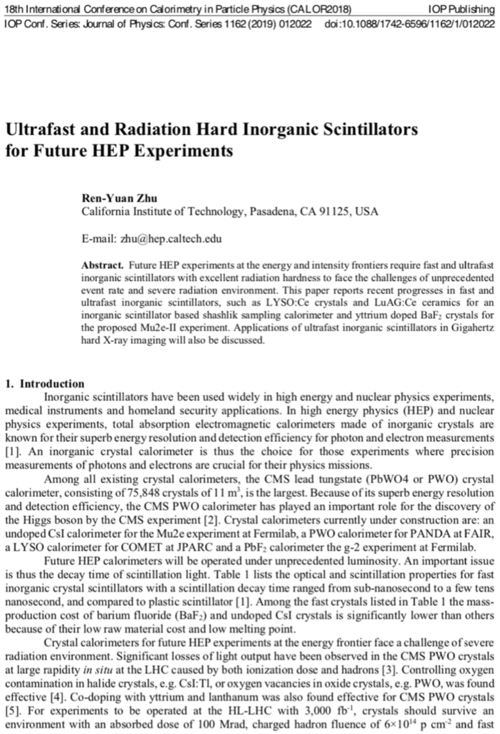
Basic idea of detector

Basic elements

- a VERY FAST radhard scintillating crystal → BaF2
  - Need to filter out the slow component → UV optical filters
  - Interesting: Y doping reduces the slow component, but R&D stage
- a PMT with low transit time dispersion → commercially available (hamamatsu for instance)
- Associated electronics
- Next step: validate detection scheme



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Ultrafast and Radiation Hard Inorganic Scintillators for Future HEP Experiments

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Abstract. Future HEP experiments at the energy and intensity frontiers require fast and ultrafast inorganic scintillators with excellent radiation hardness to face the challenges of unprecedented event rate and severe radiation environment. This paper reports recent progresses in fast and ultrafast inorganic scintillators, such as LYSO:Ce crystals and LuAG:Ce ceramics for an inorganic scintillator based shashlik sampling calorimeter and yttrium doped BaF_2 crystals for the proposed Mu2e-II experiment. Applications of ultrafast inorganic scintillators in Gigahertz hard X-ray imaging will also be discussed.

1. Introduction

Inorganic scintillators have been used widely in high energy and nuclear physics experiments, medical instruments and homeland security applications. In high energy physics (HEP) and nuclear physics experiments, total absorption electromagnetic calorimeters made of inorganic crystals are known for their superb energy resolution and detection efficiency for photon and electron measurements [1]. An inorganic crystal calorimeter is thus the choice for those experiments where precision measurements of photons and electrons are crucial for their physics missions.

Among all existing crystal calorimeters, the CMS lead tungstate (PbWO4 or PWO) crystal calorimeter, consisting of 75,848 crystals of 11 m^3, is the largest. Because of its superb energy resolution and detection efficiency, the CMS PWO calorimeter has played an important role for the discovery of the Higgs boson by the CMS experiment [2]. Crystal calorimeters currently under construction are: an undoped CsI calorimeter for the Mu2e experiment at Fermilab, a PWO calorimeter for PANDA at FAIR, a LYSO calorimeter for COMET at JPARC and a PbF_2 calorimeter the g-2 experiment at Fermilab.

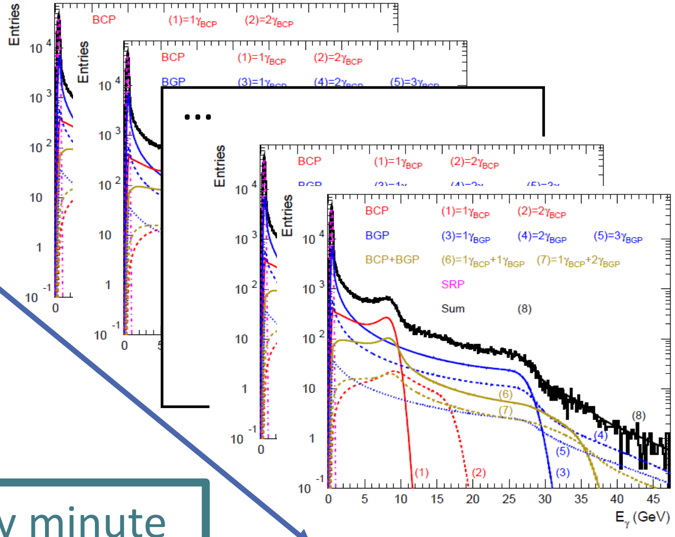
Future HEP calorimeters will be operated under unprecedented luminosity. An important issue is thus the decay time of scintillation light. Table 1 lists the optical and scintillation properties for fast inorganic crystal scintillators with a scintillation decay time ranged from sub-nanosecond to a few tens nanosecond, and compared to plastic scintillator [1]. Among the fast crystals listed in Table 1 the mass-production cost of barium fluoride (BaF_2) and undoped CsI crystals is significantly lower than others because of their low raw material cost and low melting point.

Crystal calorimeters for future HEP experiments at the energy frontier face a challenge of severe radiation environment. Significant losses of light output have been observed in the CMS PWO crystals at large rapidity *in situ* at the LHC caused by both ionization dose and hadrons [3]. Controlling oxygen contamination in halide crystals, e.g. CsI:Tl, or oxygen vacancies in oxide crystals, e.g. PWO, was found effective [4]. Co-doping with yttrium and lanthanum was also found effective for CMS PWO crystals [5]. For experiments to be operated at the HL-LHC with 3,000 fb^{-1}, crystals should survive an environment with an absorbed dose of 100 Mrad, charged hadron fluence of 6×10^{14} p cm^{-2} and fast

Basic idea of detector

Basic elements

- a VERY FAST radhard scintillating crystal → BaF2, the only solution ?
  - ☹ Need to filter out the slow component → UV optical filters
  - ☺ Interesting: Y doping reduces the slow component, but R&D stage
- a PMT with low transit time dispersion → commercially available (hamamatsu for instance)
- Associated electronics
- Next step: validate detection scheme



2500 bunches → 2500 histograms
About 1000 bins each (or less ?)
12 bits dynamics ?

30Mb (3.75MB) to transfer every minute

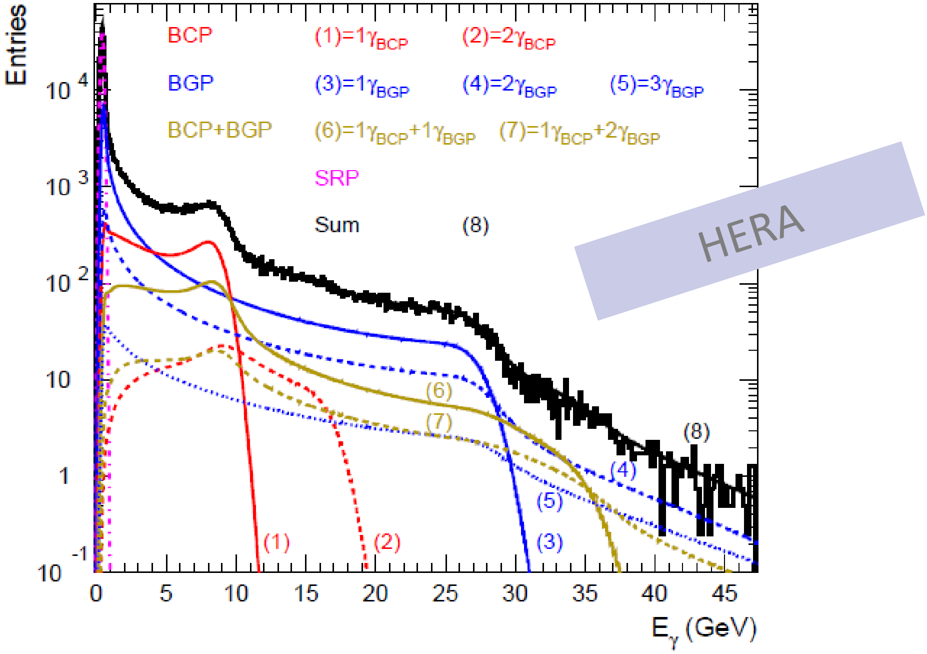
Two options

- Embarked ADC and data processing in the accelerator bay w/transfer link to storage, requires clock (laser also needs it) and bunch identification
- Deported electronics 'à la' lumi with diamonds sensors ? (expensive high BW cables)

Polarization extraction

Offline: fitter

- Not immediate but can be very precise
- Account for every detail of the experiment → I start by implementing this step by step



Online: fast approximate/biased extraction

- To be investigated based on HERA work by C. Pascaud et al. (Orsay group)

Offline fitter: ingredients

Ideally (time consuming, can be part of a PhD project):

- One should probably use a dedicated generator (CAIN most probably)
- Account for every detail of the detection system with a Geant4 reconstruction

However the most important aspects of the simulation are relatively simple to implement in a quick Monte Carlo :

- Compton cross-section (polarization effects included)
- Detector energy resolution
- Finite detector size
- Smearing from the finite electron beam emittance and dispersion (depends on baseline location)
- Data filled in histograms

All these effects can also be fit in a simple binned chi2 (or ML) with ROOT6 and MINUIT2 library

- To start with: I only fit a scale factor and Pz.
- I numerically integrate the Compton cross-section over the detector size and bin width accounting for
  - detector energy resolution
  - horizontal point spread due to finite e-beam sizes
  - Miscalibration (if any)
- I assume that the detector has nominally a square cross-section (despite it may be simpler to implement a cylindrical detector in the end)

I first go through a sanity check that everything goes fine when I assume one and only photon is scaterred per bunch crossing.

This is obviously work in progress !

Detector/e-beam parameters

Detector energy resolution

$$\frac{\sigma_E}{E} = \sqrt{\frac{A^2}{E[GeV]} + B^2 + \frac{C^2}{E^2[GeV^2]}}$$

A=10% (conservative ?); B=1% (optimistic ?); C=pile-up, electronics, 0 for now on

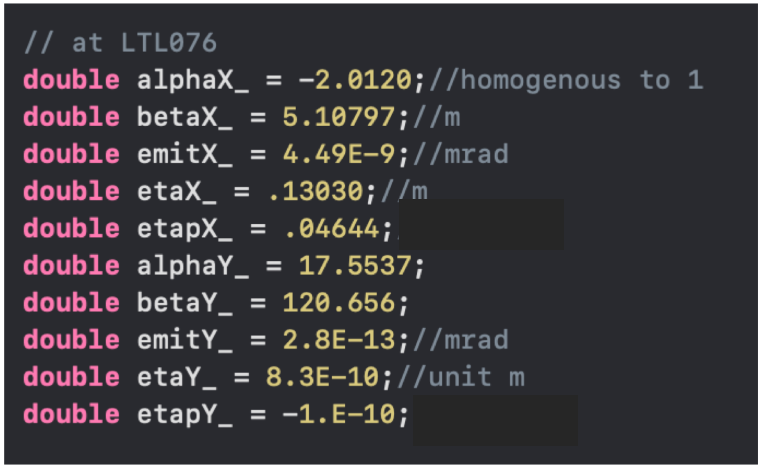
Finite detector size

- Detector assumed to be placed at L=30m from Compton IP
- Square section of 25x25 mm^2

Electron beam parameters

- Taken at LTL076 (numbers to consolidate)
- Relative energy spread 6.3e-4

$$\begin{aligned}
x_1 &= \sqrt{2\epsilon_x u_1 \beta_{x1}} \cos\varphi_1 + \eta_x \varepsilon_1 \\
x_1' &= \sqrt{2\epsilon_x u_1 / \beta_{x1}} (-\alpha_{x1} \cos\varphi_1 - \sin\varphi_1) + \eta_x' \varepsilon_1 \\
y_1 &= \sqrt{2\epsilon_y u_2 \beta_{y1}} \cos\varphi_2 + \eta_y \varepsilon_1 \\
y_1' &= \sqrt{2\epsilon_y u_2 / \beta_{y1}} (-\alpha_{y1} \cos\varphi_2 - \sin\varphi_2) + \eta_y' \varepsilon_1
\end{aligned}$$



```
// at LTL076
double alphaX_ = -2.0120;//homogenous to 1
double betaX_ = 5.10797;//m
double emitX_ = 4.49E-9;//mrad
double etaX_ = .13030;//m
double etapX_ = .04644;[redacted]
double alphaY_ = 17.5537;
double betaY_ = 120.656;
double emitY_ = 2.8E-13;//mrad
double etaY_ = 8.3E-10;//unit m
double etapY_ = -1.E-10;[redacted]
```

σ_x = 170um, $\sigma_{x'}$ = 73urad

σ_y = 5um, $\sigma_{y'}$ = 1urad

Induces a (gaussian) point spread function at the detector plane:

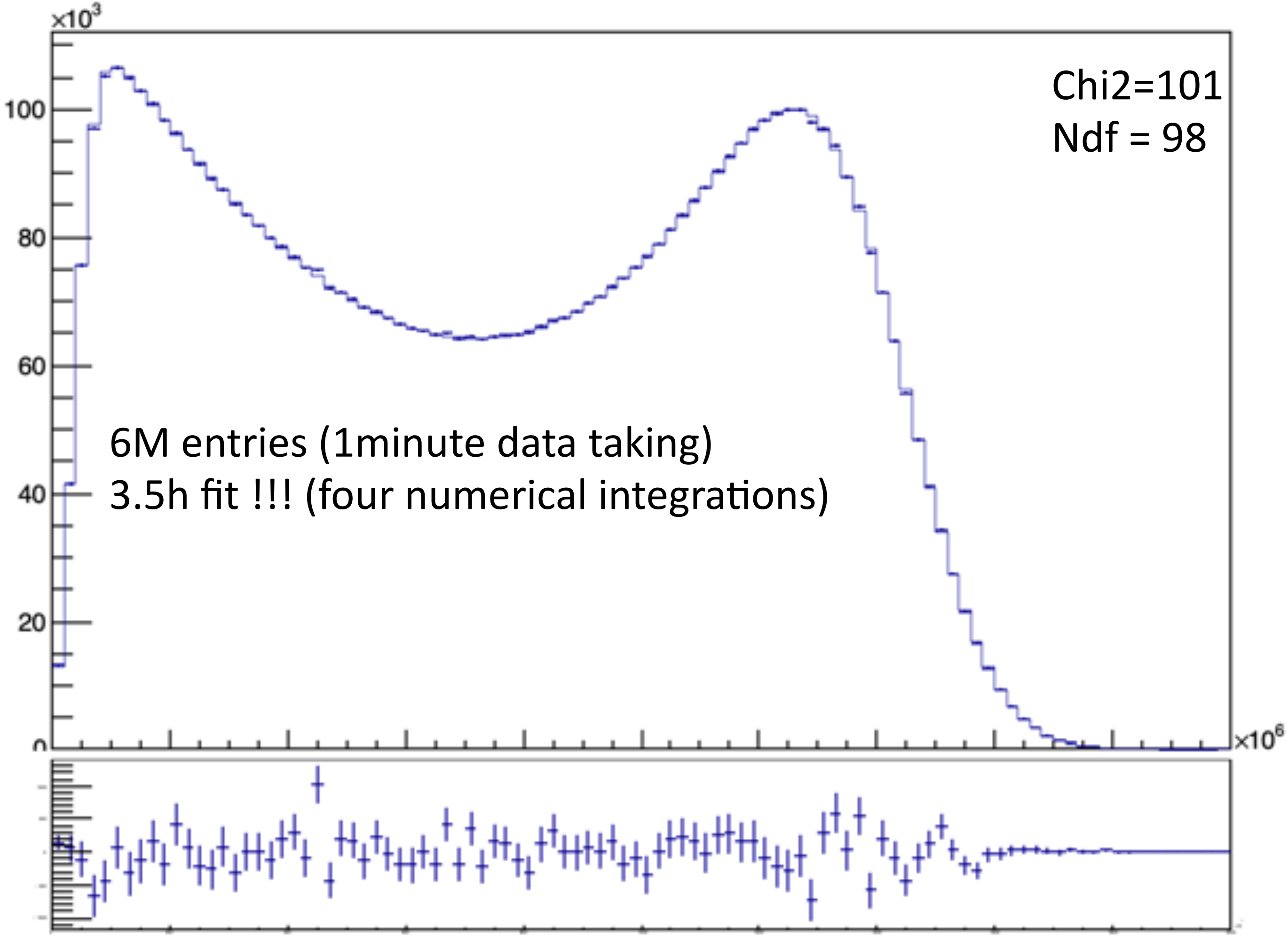
$$\sigma_D^2 = \sigma_x^2 + L^2 \sigma_{x'}^2$$

- Similarly in y

See for instance CAIN user manual, for the generation of e-beam parameters

Result

Perfectly aligned, calibrated, known average beam energy, known e-beam phase-space parameters

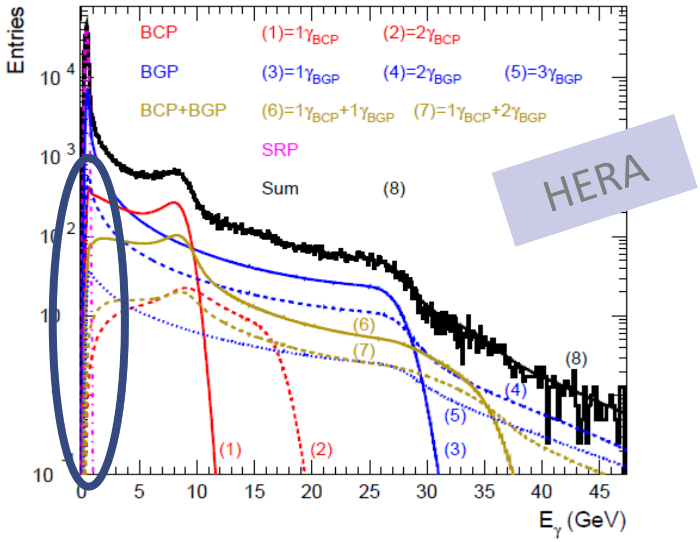


Chi2=101
Ndf = 98

6M entries (1minute data taking)
3.5h fit !!! (four numerical integrations)

But…

The fit is time consuming but actually too accurate for the situation we may face in data:

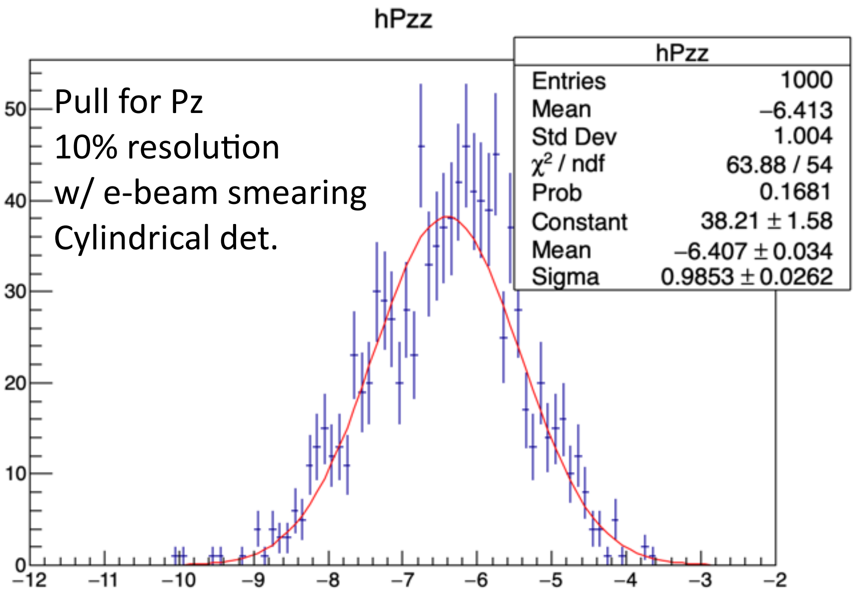


Beam gas + synchrotron radiation peak may be the dominant contributions at low energies

Maybe not so important to accurately fit the low energy part

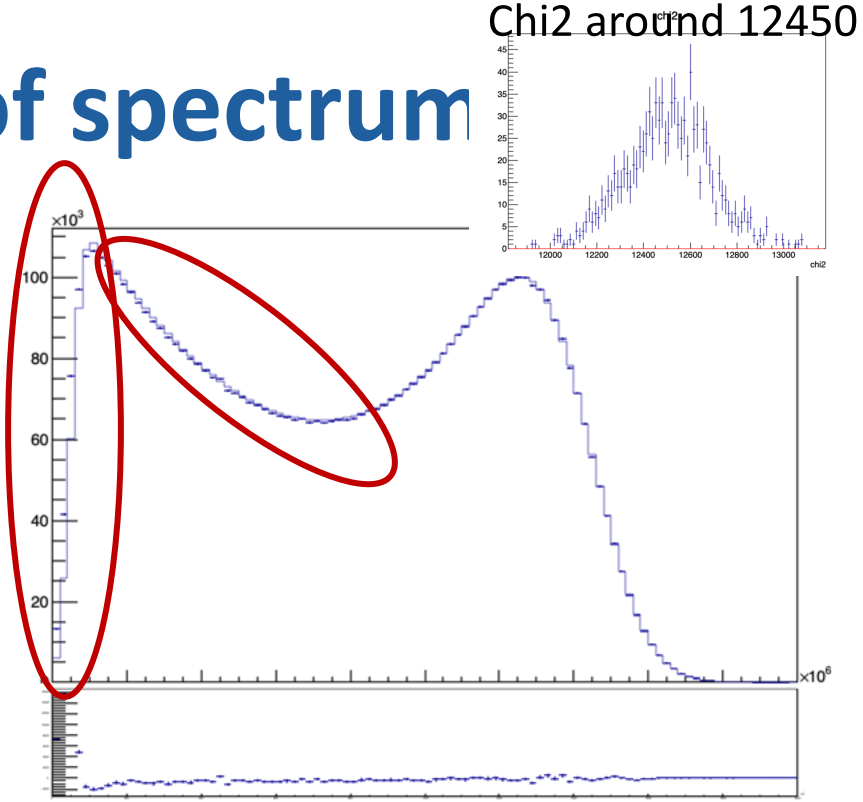
I will now try to look at ‘degraded’ fitters to investigate several effects, keeping in mind that we are able to revert to an accurate fit of MC data (and that maybe a cylindrical geometry is maybe more appropriate)

Lower energy part of spectrum



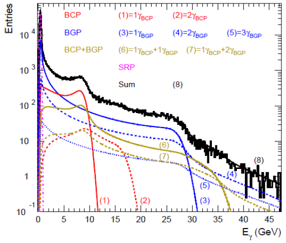
Pull for Pz
10% resolution
w/ e-beam smearing
Cylindrical det.

Chi2 around 12450

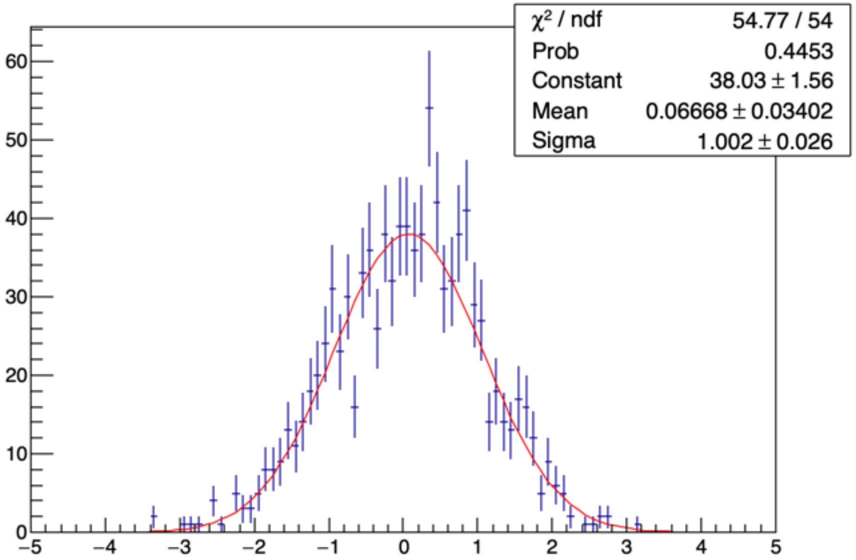


The (deliberately) wrong assumption about detector geometry mainly biases low energy contibution that is likely to be dominated by backgrounds and will not provide sensitivity.

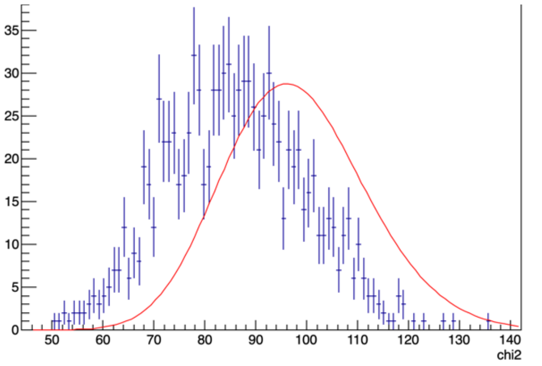
→ Need a full model with realistic backgrounds



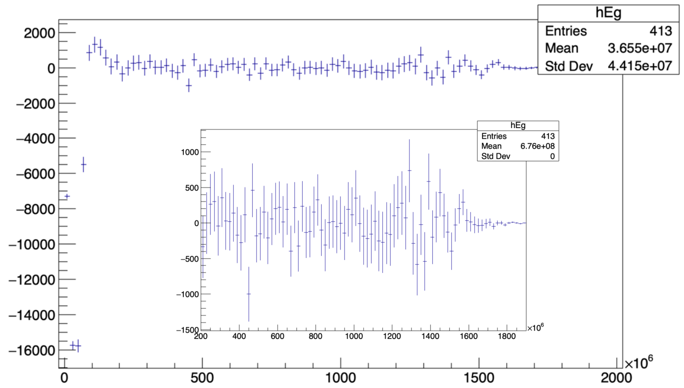
Removing the first 10 bins from fit

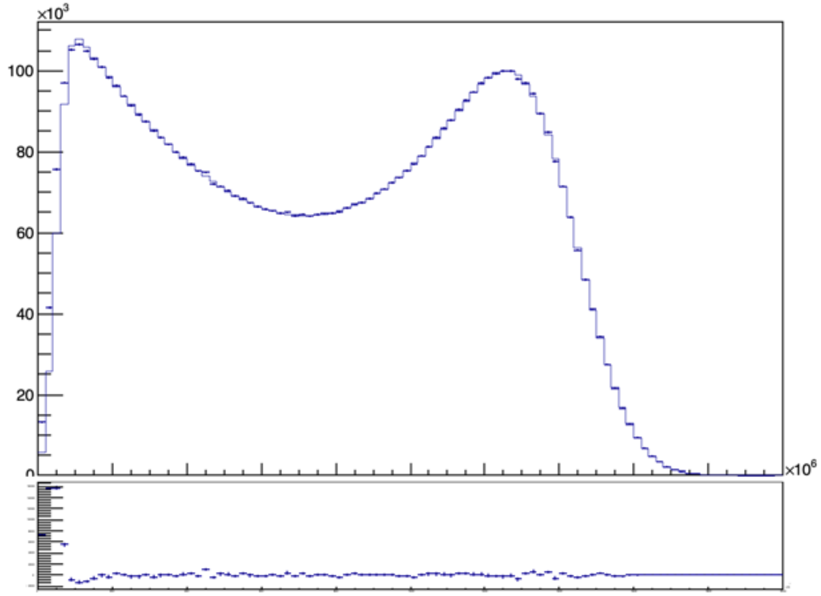


Chi2 good (10 removed bins)



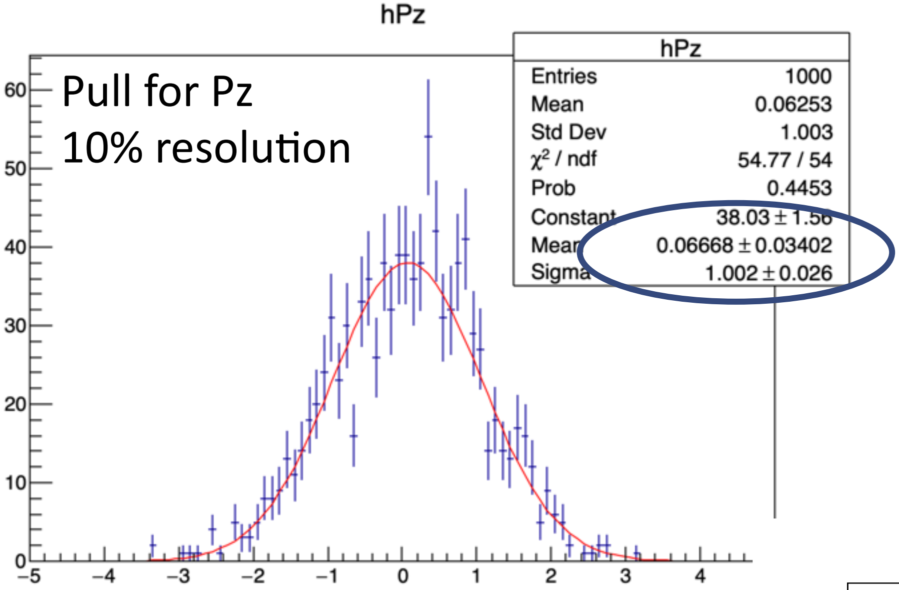
Fit-MC

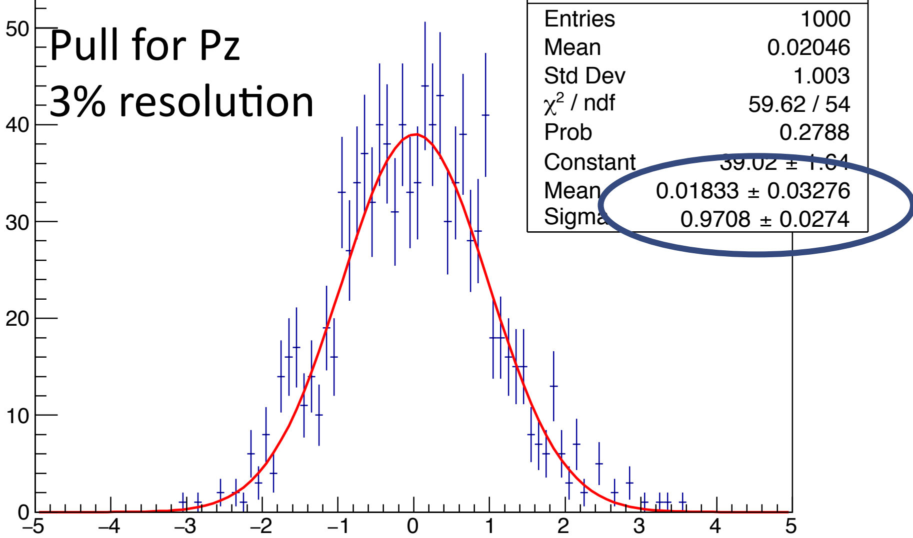




Confirms that the detector geometry and beam spreads do not impact longitudinal polarization extraction on the largest (and most senstive part) of the spectrum

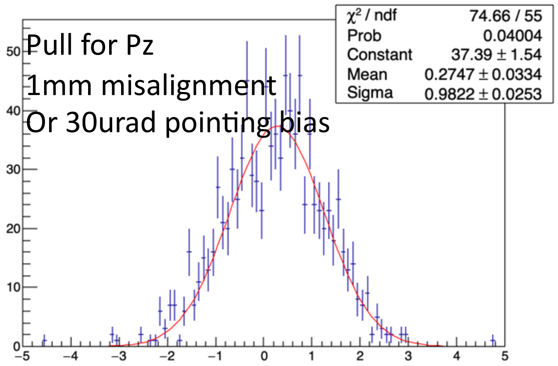
Effect of detector energy resolution

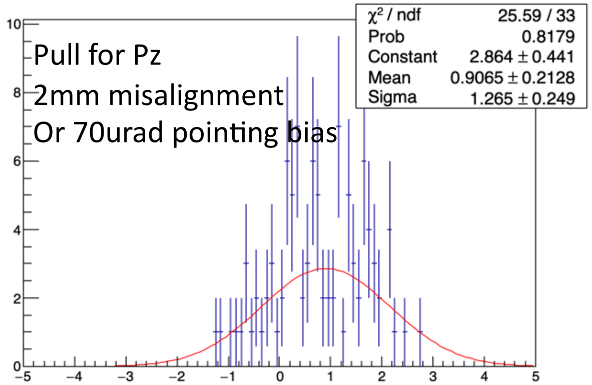


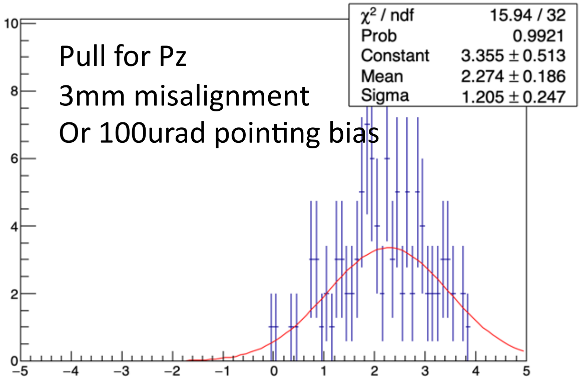


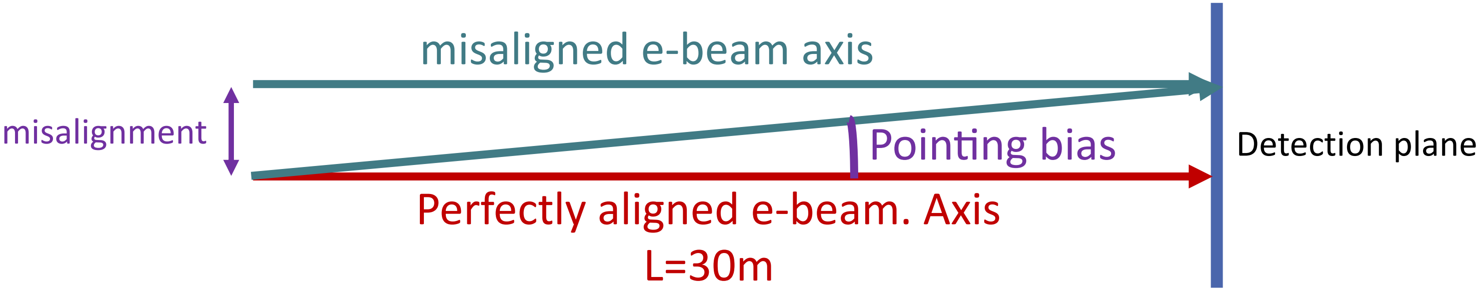
Misalignements

Repeat the previous fit but with various misalignments, or angular pointing biases









misaligned e-beam axis

misalignment

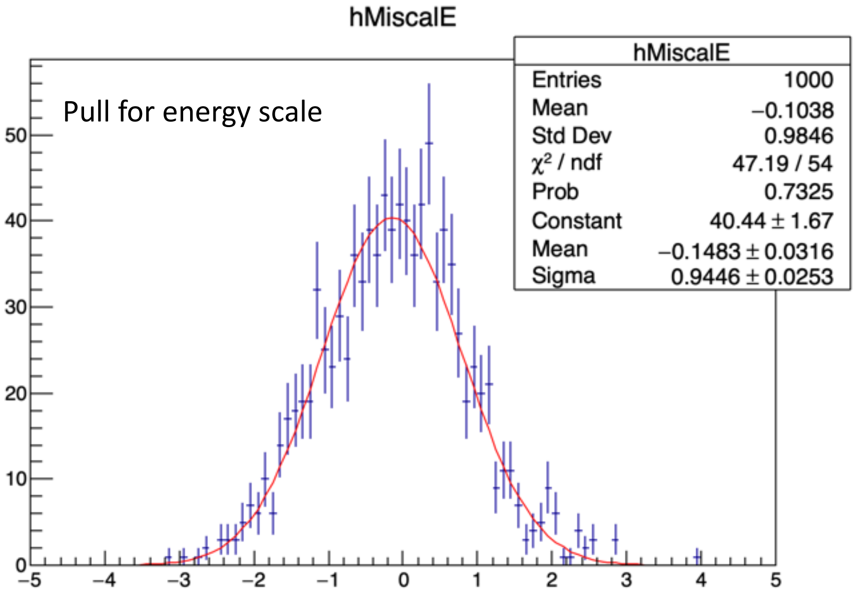
Pointing bias

Detection plane

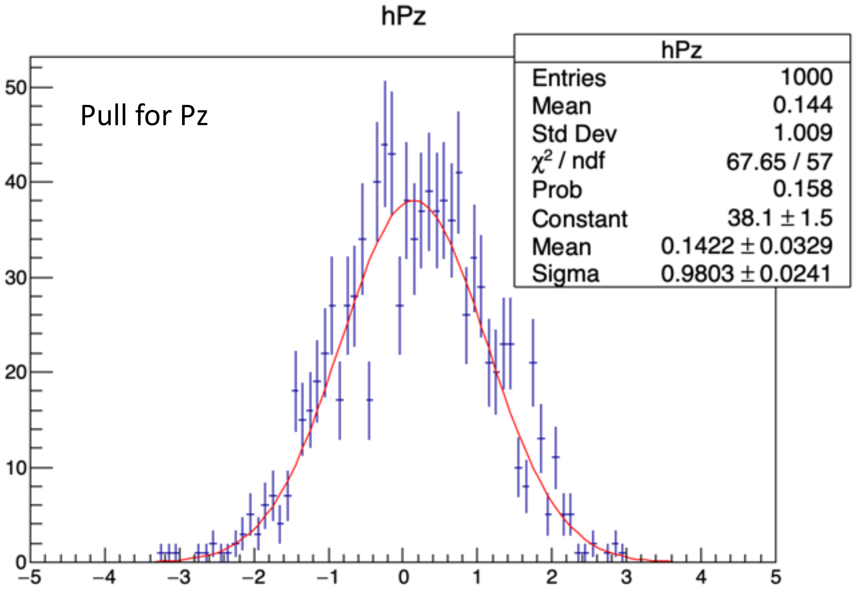
Perfectly aligned e-beam. Axis
L=30m

Need to ensure the beam points towards the center of the detector within 1mm to avoid biasing the polarization more than 0.001

Miscalibration (10% on scale)



hMiscalE	
Entries	1000
Mean	−0.1038
Std Dev	0.9846
χ^2 / ndf	47.19 / 54
Prob	0.7325
Constant	40.44 ± 1.67
Mean	−0.1483 ± 0.0316
Sigma	0.9446 ± 0.0253

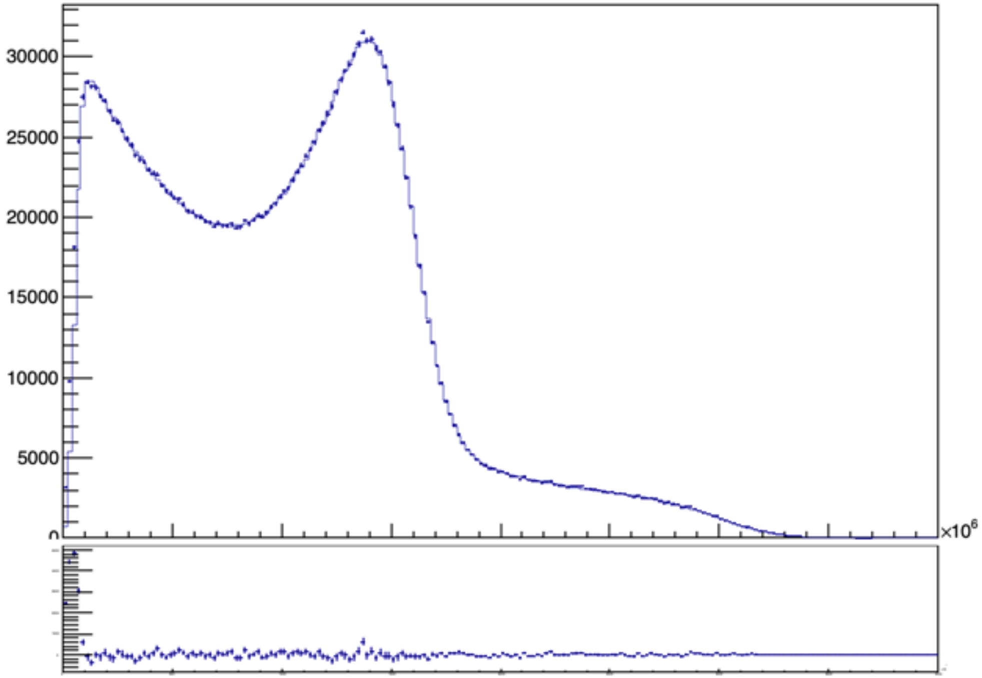


hPz	
Entries	1000
Mean	0.144
Std Dev	1.009
χ^2 / ndf	67.65 / 57
Prob	0.158
Constant	38.1 ± 1.5
Mean	0.1422 ± 0.0329
Sigma	0.9803 ± 0.0241

Ongoing improvements

Extraction of polarization:

- Upgraded the fit to perform with LUT filled on demand 6s → 0.15s/fit
  - Performs well
  - O(2500) estimates in a minute may be done that way on a relatively powerful PC
- Multi-photon contributions included (so far only 2 photon)
- Statistical precision in a minute with a 5W 515nm laser → 0.9% for every bunch.
- Next steps
  - Re-estimate systematic uncertainties
  - alignment procedure
  - Backgrounds
  - E-beam jitters ?



Next steps

Waiting for comments on White Report

Continue progressing on extraction of polarization:

R&D:

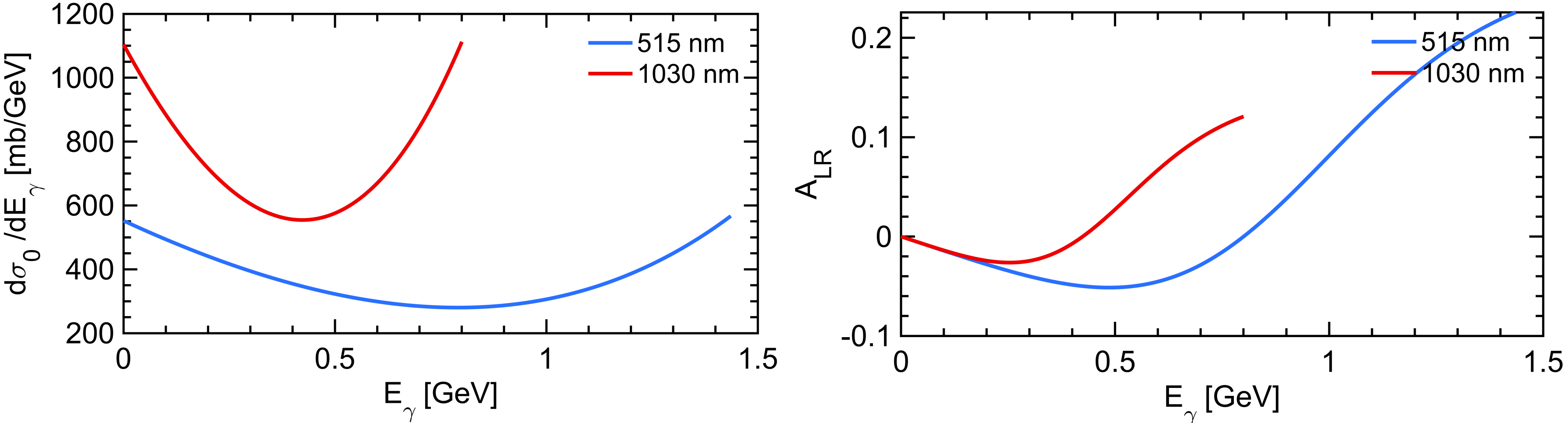
- Test the concept of a BaF2 detector
- Costing exercice for the laser system

A slightly more detailed look

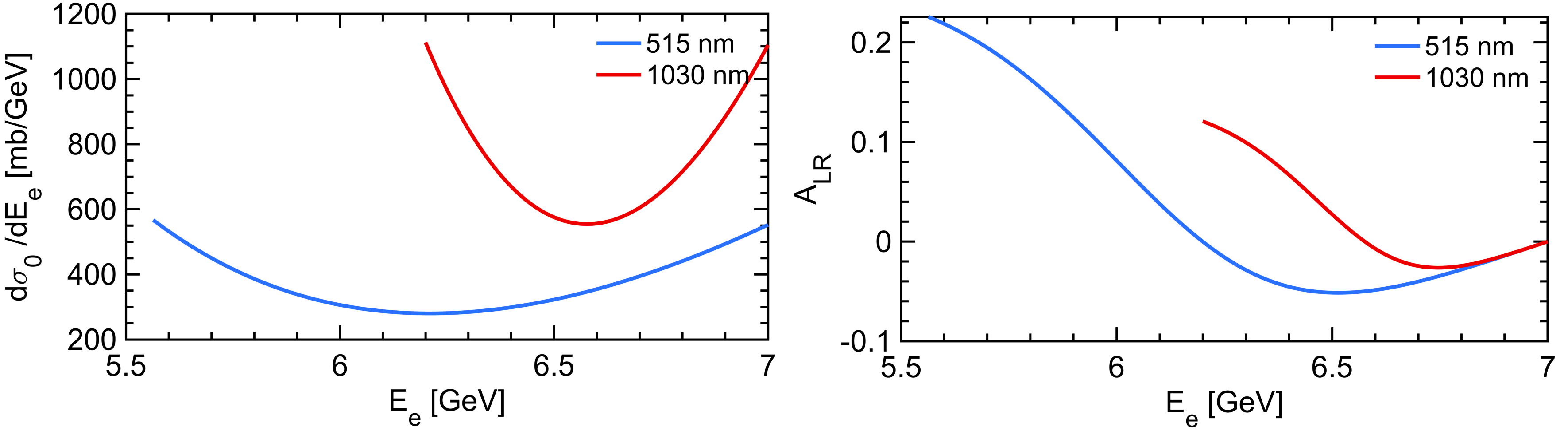
$$\frac{d\sigma}{dy}(x,y) \cong \frac{d\sigma_0}{dy}(1 + P_L A_{LR})$$

Landau-Lifshitz QED book paragraphs 86 and 87

Polarization dependent term generates a left-right asymmetry function of E_γ



that reflects also as a function of the energy of the emitted electron



Green light provides higher sensitivity