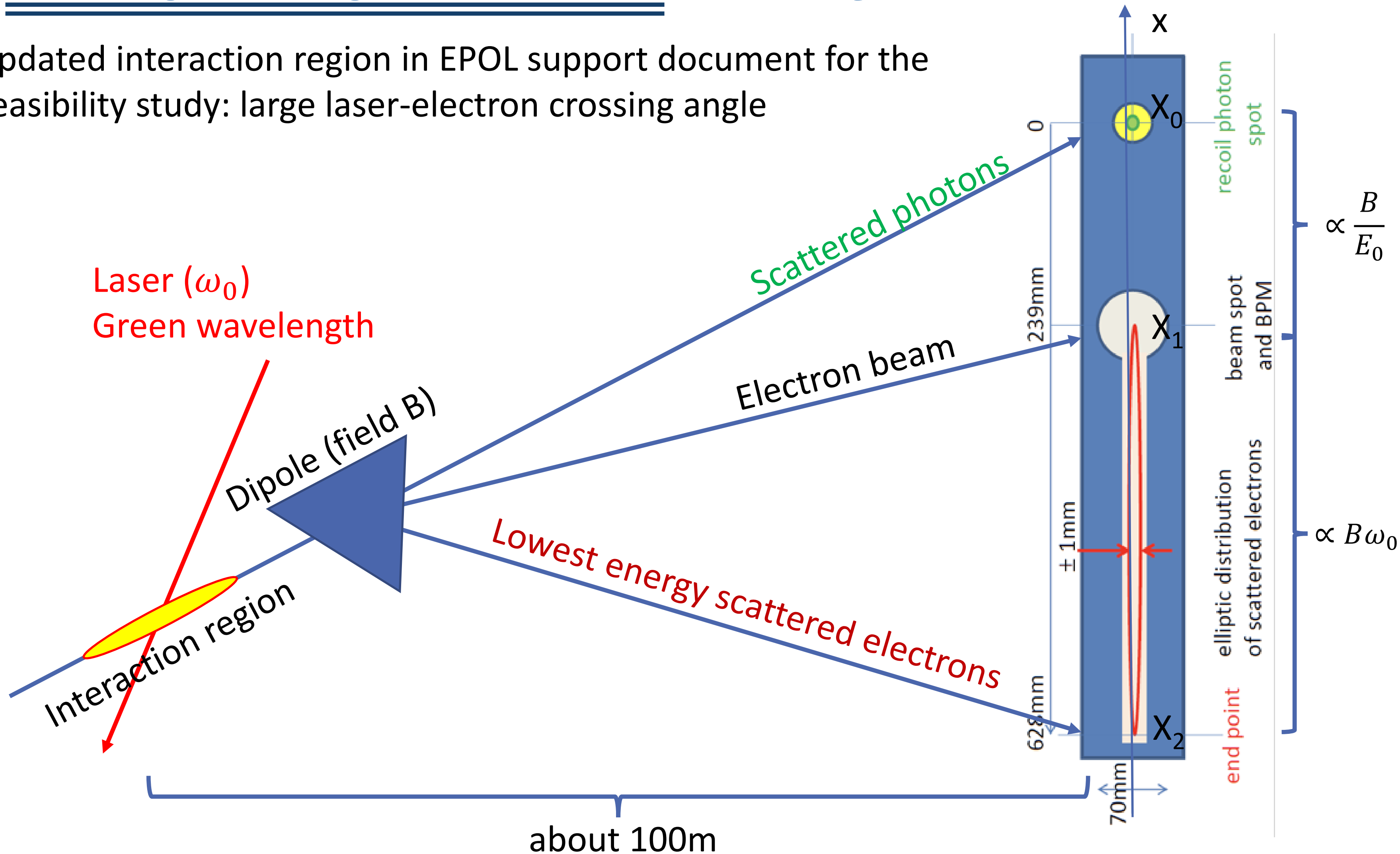
Compton polarimeters and fit procedures

TAMAZIRT juba (IJCLab Orsay)

Updated

Compton polarimeter layout

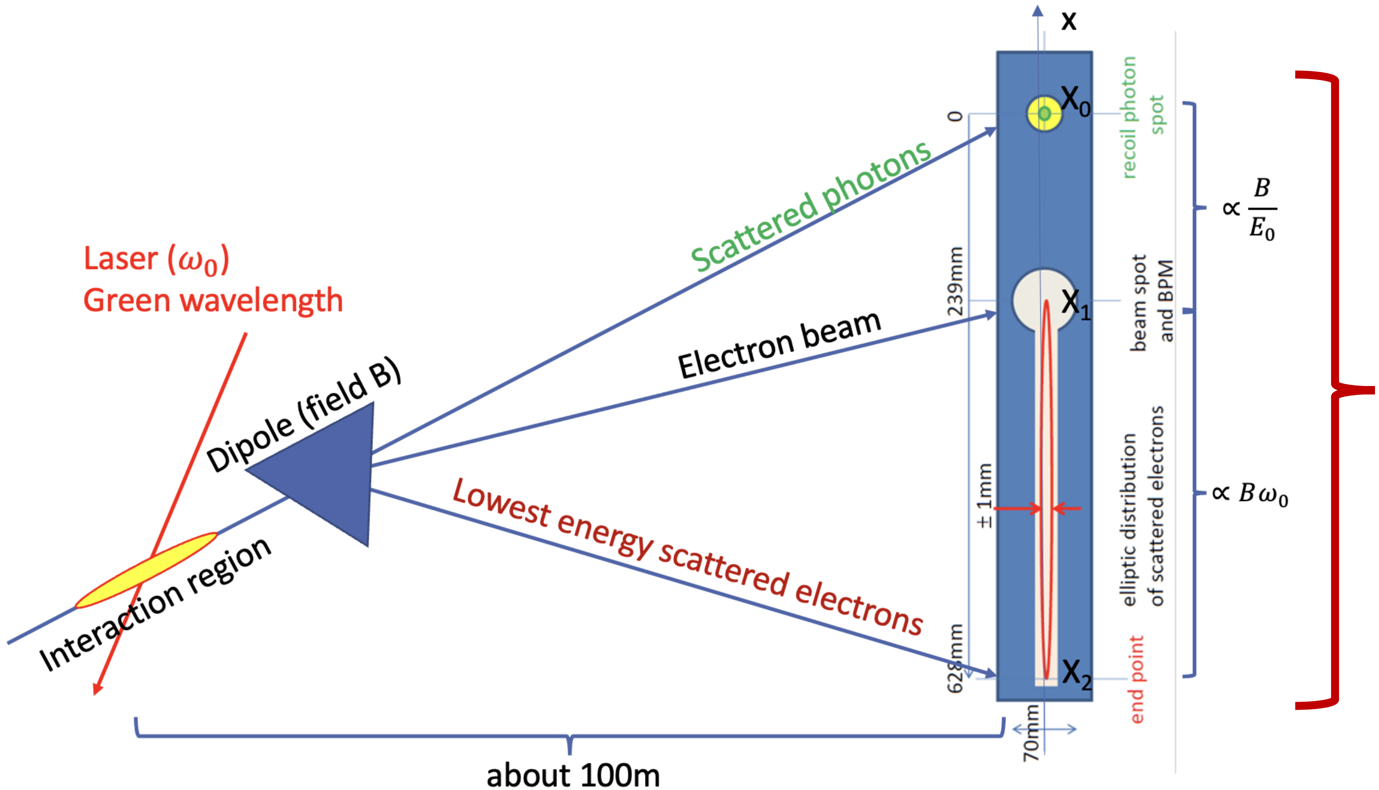
Updated interaction region in EPOL support document for the Feasibility study: large laser-electron crossing angle



New concept (N. Yu Muchnoi) to measure all polarization parameters → 3D polarimeter

Blondel et al., arXiv:1909.12245; Muchnoi, INST 17 P10014 (2022)

Reminder of key goals



Direct measurement of beam energy from geometry of scattered particles in observation plane

1. Center of mass energy calibration using resonant depolarization on pilot bunches
2. Relative and relatively fast monitoring of beam energy from geometry in the measurement plane → useful when pilots cannot be polarized ?
3. Control systematic uncertainty ($<10^{-4}$) on colliding bunch polarization at detector's IPs by providing upper limit on e- beam polarization paramters at Compton IP

Differential cross-section

Besides realistic detector and system design and validation, accurate parameter extraction is needed

Electrons are located on an ellipsoidal surface which parameterization can be transformed into a unit disk over which the expression of the differential cross section is more convenient

Muchnoi, INST 17 P10014 (2022)

$$\frac{1}{r_e^2}\frac{d\sigma_0}{dxdy}\bigg|_\pm = \frac{1+(1+u_\pm)^2-(1+u_\pm)(1-\Delta_\pm^2)}{2(1+u_\pm)^3\sqrt{1-x^2-y^2}},$$

$$\frac{1}{r_e^2}\frac{d\sigma_{\xi_1}}{dxdy}\bigg|_\pm = \xi_1\frac{\delta_\pm^2-y^2}{2(1+u_\pm)^2\sqrt{1-x^2-y^2}},$$

$$\frac{1}{r_e^2}\frac{d\sigma_{\xi_2}}{dxdy}\bigg|_\pm = \xi_2\frac{-\delta_\pm y}{(1+u_\pm)^2\sqrt{1-x^2-y^2}},$$

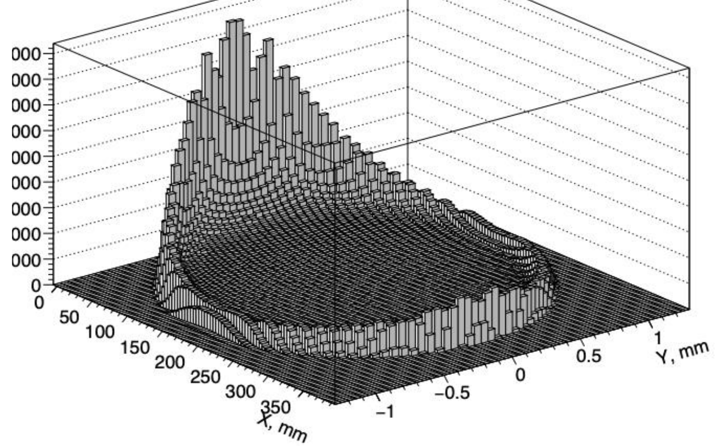
$$\frac{1}{r_e^2}\frac{d\sigma_x}{dxdy}\bigg|_\pm = \xi_3\zeta_x\frac{-u_\pm\delta_\pm}{2(1+u_\pm)^3\sqrt{1-x^2-y^2}},$$

$$\frac{1}{r_e^2}\frac{d\sigma_y}{dxdy}\bigg|_\pm = \xi_3\zeta_y\frac{u_\pm y}{2(1+u_\pm)^3\sqrt{1-x^2-y^2}},$$

$$\frac{1}{r_e^2}\frac{d\sigma_z}{dxdy}\bigg|_\pm = \xi_3\zeta_z\frac{-u_\pm(u_\pm+2)\Delta_\pm}{2(1+u_\pm)^3\sqrt{1-x^2-y^2}}.$$

NB: $1/\sqrt{1-x^2-y^2}$ gets very large on circle limits

Example electron distribution



$u_\pm$, $\Delta_\pm$ and $\delta_\pm$ are functions of (x, y)

$\delta_\pm$ is a vanishingly small quantity

$\zeta_{x,y,z}$ are the e-beam polarization parameters

$\xi_{1,2,3}$ are the laser Stokes (polarization) parameters

NB: $\xi_3 = \pm 1 \Leftrightarrow$ left/right circular polarization

Improved

Further simplification

$\pm$ sign correspond to two energy solutions possible to reach a given position on detector
Observation is averaged over this un-observed quantity
Detailed analysis shows that further simplification is possible exploiting the structure of the $u_{\pm}$, $\Delta_{\pm}$ and $\delta_{\pm}$ functions and averaging over the two solutions

$$\frac{1}{r_e^2}\frac{d\sigma_0}{dxdy} = \frac{1+(1+u)^2-(1+u)(1-\Delta^2)}{(1+u)^3\sqrt{1-x^2-y^2}} + A^2\frac{6\kappa^2+12(1+u)(1+\kappa)-(1+u)^2(8+(4-\kappa)\kappa)}{4(1+u)^5}\sqrt{1-x^2-y^2}$$

$$\frac{1}{r_e^2}\frac{d\sigma_{\xi_1}}{dxdy} = \frac{-y^2+A^2x^2}{(1+u)^2\sqrt{1-x^2-y^2}} + \left(\frac{B^2}{(1+u)^2}+A^2\frac{8Bx\kappa(1+u)-3y^2\kappa^2}{4(1+u)^4}\right)\sqrt{1-x^2-y^2}$$

$$\frac{1}{r_e^2}\frac{d\sigma_{\xi_2}}{dxdy} = \frac{2Ayx}{(1+u)^2\sqrt{1-x^2-y^2}} + A^2\frac{By\kappa}{(1+u)^3}\sqrt{1-x^2-y^2}$$

$$\frac{1}{r_e^2}\frac{d\sigma_{\xi_3\zeta_x}}{dxdy} = \frac{Axu}{(1+u)^3\sqrt{1-x^2-y^2}} + A\frac{(2u-1)B\kappa}{2(1+u)^4}\sqrt{1-x^2-y^2}$$

$$\frac{1}{r_e^2}\frac{d\sigma_{\xi_3\zeta_y}}{dxdy} = \frac{yu}{(1+u)^3\sqrt{1-x^2-y^2}} - A^2\frac{3y\kappa^2(1-u)}{4(1+u)^5}\sqrt{1-x^2-y^2}$$

$$\frac{1}{r_e^2}\frac{d\sigma_{\xi_3\zeta_z}}{dxdy} = -\frac{u(2+u)\Delta}{(1+u)^3\sqrt{1-x^2-y^2}} + A^2\frac{\kappa(-6(2+\kappa)+6(1+u)+(1+u)^2(2+\kappa)}{4(1+u)^5}\sqrt{1-x^2-y^2}$$

With

A=$\frac{1}{\sqrt{1+\gamma^2\theta^2{}_0}}$ B=$\frac{\gamma\theta_0}{\sqrt{1+\gamma^2\theta^2{}_0}}$

$\theta_0 = \frac{\int B_\perp dl}{mc/e}$ is the maximum bend

The terms in green are neglected in the simmulation !!

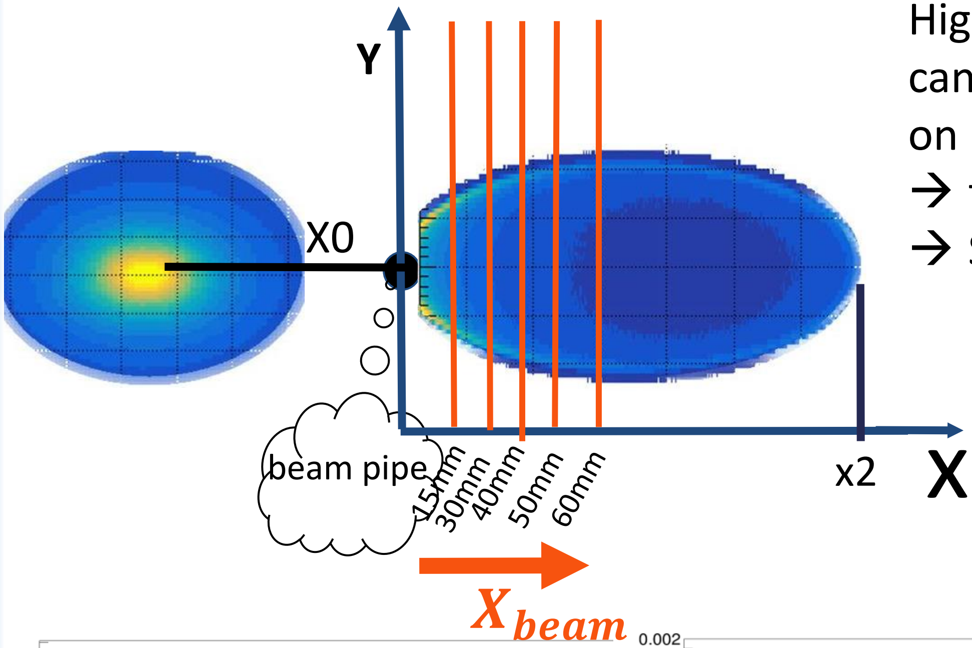
(red box) Small terms but kept in the simulation

Detector integration

Study at Z^0 pole

Toy: 100 experiments of 1min data taking

Updated

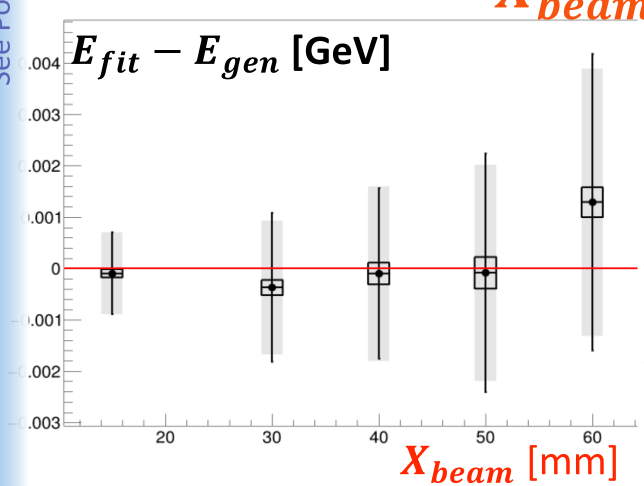


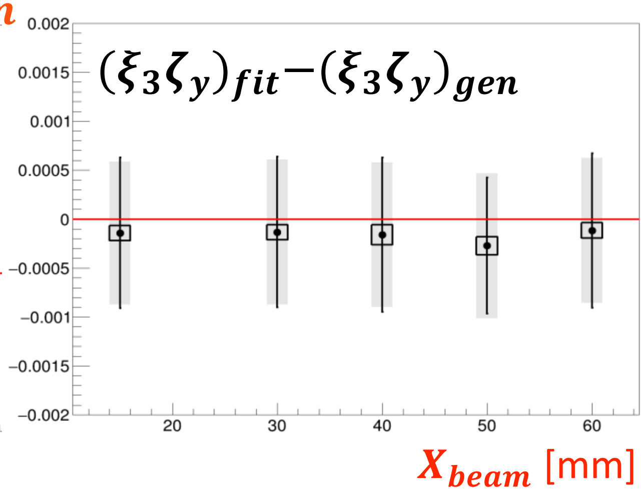
High-energy end of the scattered electron cannot be measured (spatially superimposes on main beam…)

→ finite cut-off for detector integration

→ Study impact on parameter extraction

- average and standard deviation of fit central values
- Statistical uncertainty of average of fit central values
- average of single fit uncertainties





Polarization parameters not affected

Expected growth of uncertainty on direct energy extraction (x2.5 from 15 to 60mm)

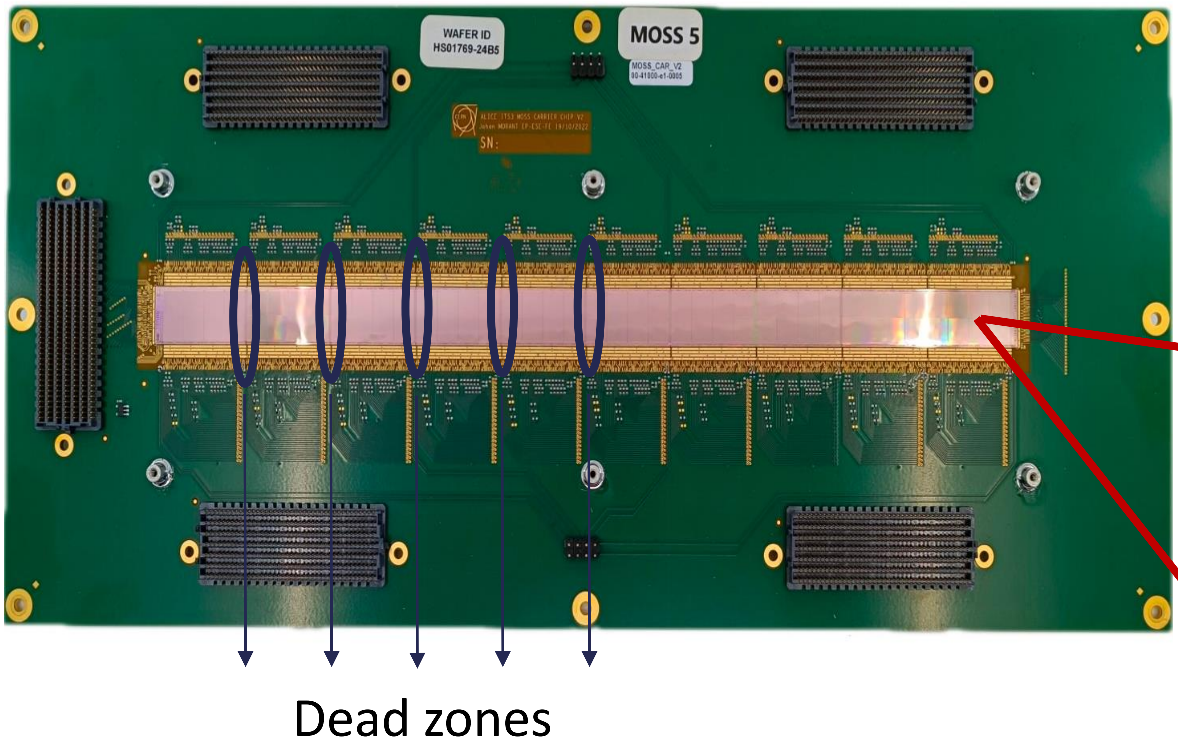
Choose 40mm as baseline

See Poster at FCC Physics Week, Jan. 2025

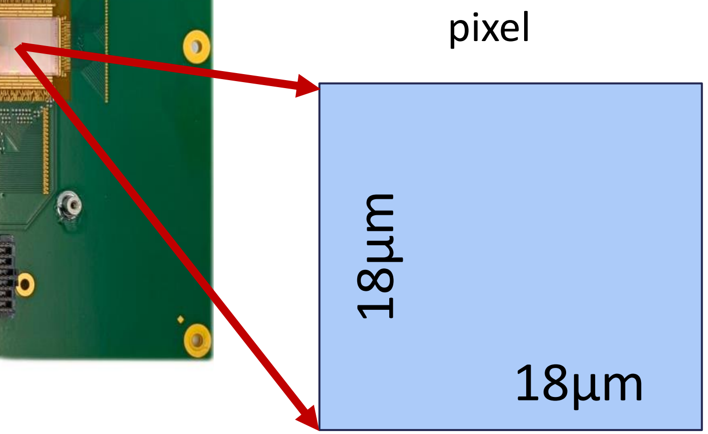
New baseline scenario

Simulations with a realistic geometry

Already available design that may fulfill the needs → ALICE MOSS prototype sensor
NB: just one of the possibilities, for illustration purposes



pixellisation:
nX=21020 horizontal pixels
nY=320 vertical pixels



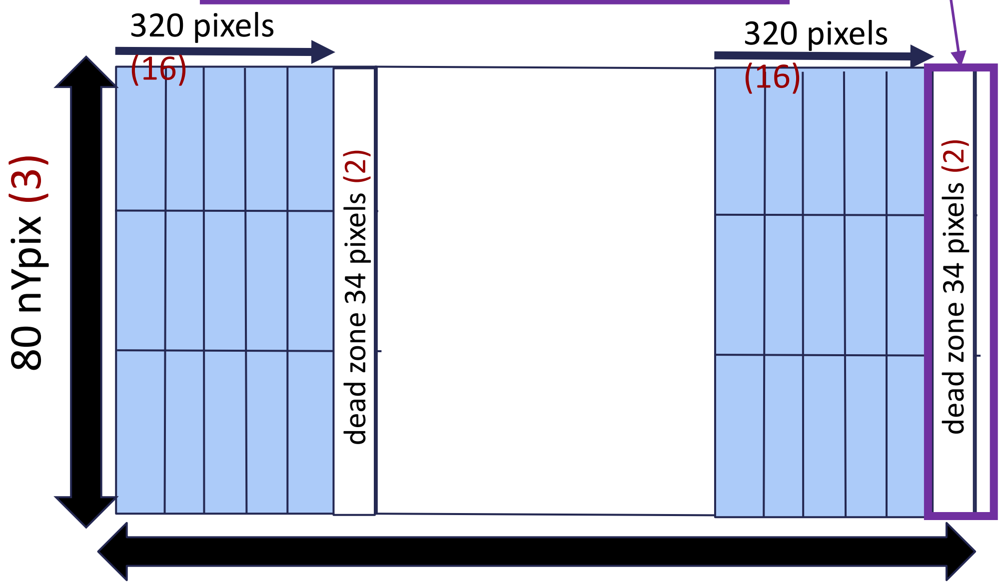
→ Simulation updated to account for dead columns, and possible rebinning in X and Y directions
→ Effective beam size on detector of 500µm in horizontal direction
→ Merge pixels in horizontal size to spare computation time w/o significant loss of precision

Simulation implementation

Rebinning applied at fit level to save simulation time

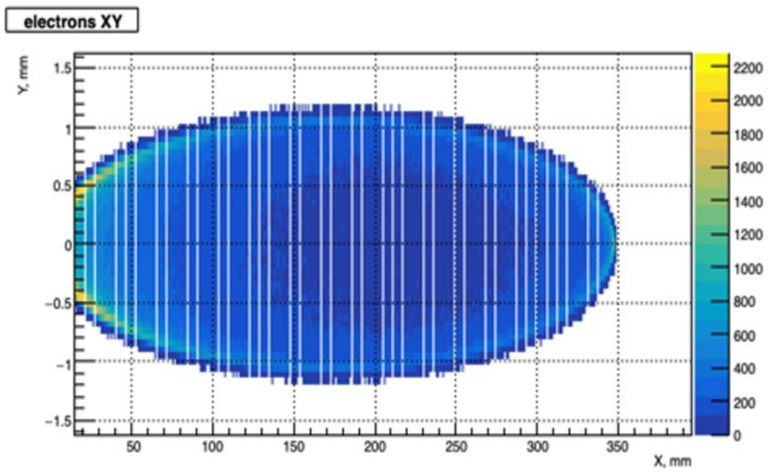
Rebinning on x axis by $R_x = 16$
Rebinning on y axis by $R_y = 3$

Configurable as option before fit



1320 nXpix with
60 dead zones

Typical simulation output



warning! 5 rows of dead pixels instead of 2 for better visualisation

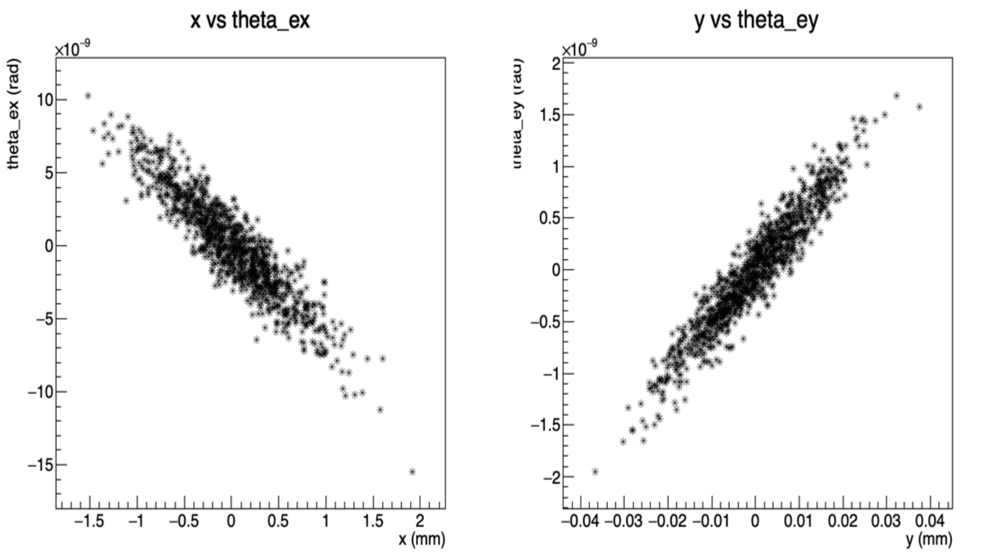
Example for $R_x = 16$, $R_y = 1$: pixels of 288x18 μm^2
NB: initial simulations were 250x38 μm^2

Improved

Phase space correlations

Beam phase space correlation not implemented initially in Nickolai’s software

Electron sampling according to the electron beam size



Example result

$$x_e = \sqrt{2u_x\epsilon_x\beta_x}\cos\phi_x + \eta_x\delta$$

$$y_e = \sqrt{2u_y\epsilon_y\beta_y}\cos\phi_y + \eta_y\delta$$

$$x'_e = -\sqrt{2u_x\frac{\epsilon_x}{\beta_x}}\left(\alpha_x\cos\phi_x + \sin\phi_x\right) + \eta'_x\delta$$

$$y'_e = -\sqrt{2u_y\frac{\epsilon_y}{\beta_y}}\left(\alpha_y\cos\phi_y + \sin\phi_y\right) + \eta'_y\delta$$

$u_{x,y}$, $\phi_{x,y}$ and δ are random numbers

$\alpha_{x,y}$ and $\beta_{x,y}$ are Courant-Snyder parameters

$\eta_{x,y}$ and $\eta'_{x,y}$ are dispersion functions

See Charlet et al. JINST 18 (2023) P10014 for instance

Improved

Luminosity and crossing-angle

- Simulation was using a fixed number of events instead a computation of expected number of scatters from luminosity and total cross-section

$$\mathcal{L} = \frac{f_{\text{rep}} N_l N_e}{2\pi\sigma_x\sigma_y\sqrt{1 + \frac{\sigma_z^2}{\sigma_x^2}\tan^2\frac{\theta}{2}}}. \qquad \sigma_{x,y,z} = \sqrt{\sigma_{e,x,y,z}^2 + \sigma_{l,x,y,z}^2}$$

Laser-electron beam crossing angle

- Simulation now also includes accounting of crossing angle → significantly modifies some approximations used in initial software, as photon energy in e- rest frame $\kappa = 2(1 + \beta\cos\theta)\frac{E_0\hbar\omega_0}{mc^2}$

E_0 initial electron energy; $\hbar\omega_0$ intial photon energy; β Lorentz factor

- Extraction of beam energy from horizontal photon and electron spots position gets modified too:

θ_0 bending angle

$$E_{beam} = \frac{mc^2}{2\hbar\omega_0(1 + \beta\cos\theta)}\frac{X_2 - X_1}{X_1 - X_0}\left(1 - \frac{2 + \frac{X_2 - X_1}{X_1 - X_0}}{(2\gamma\theta_0)^2}\right)$$

Correction to account for scattered electrons at high energy

- Now also update saving of fit results to analyse fit correlation

Input parameter table

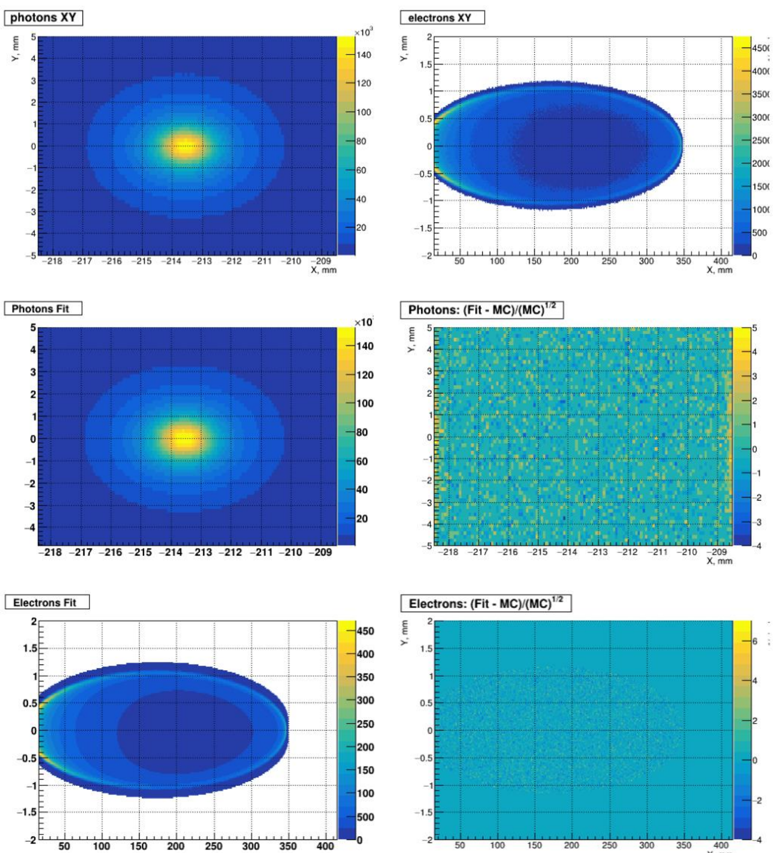
Input parameter	Value
Dx (horizontal dispersion)	28.6572 mm
Dy (vertical dispersion)	0.0000 mm
Dpx (horizontal angular dispersion)	-0.0021
Dpy (vertical angular dispersion)	0.0000
εx (emmitance on x)	0.0007 mm*rad
εy (emmitance on y)	$19*10^{-7}$ mm*rad
βx (beta function on x)	392.6665 m
βy (beta function on y)	62.06445 m
Ax (alpha function on x)	2.3819
Ay (alpha function on y)	-3.1232
Δ (Energy spread)	10^{-3}
θo (Bending angle)	0.0021 rad

Typically obtained in 30s for a single bunch

Typical result – fit of Distributions

Based on measurement of scattered particles transverse distributions (pixelized detectors)

$$\frac{d\sigma}{dud\varphi} = \frac{d\sigma_0}{dud\varphi} + \xi_1 \frac{d\sigma_1}{dud\varphi} + \xi_2 \frac{d\sigma_2}{dud\varphi} + \xi_3 \left(\zeta_x \frac{d\sigma_x}{dud\varphi} + \zeta_y \frac{d\sigma_y}{dud\varphi} + \zeta_z \frac{d\sigma_z}{dud\varphi} \right)$$



Monte-Carlo Parameters:
Laser λ_0 = 0.532 um
Electron E_0 = 45.600 GeV
Electron $\gamma = 89.237 \times 10^3$
Compton κ = 1.628
Bend: $\gamma\theta_0$ = 190.441
(ξ_1, ξ_2, ξ_3) = (0.000, 0.000, 1.000)
$(\zeta_x, \zeta_y, \zeta_z)$ = (0.100, 0.250, 0.100)

Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Photons fit: t = 319 s (CPU 267 s)
χ^2/NDF = 7820.4/7190 | Prob = 0.0000
$X_0 = -213.539 \pm 0.001$
$\xi_1 = 0.001 \pm 0.001$
$\xi_2 = -0.000 \pm 0.000$
$\xi_3\zeta_x = 0.096 \pm 0.002$
$\xi_3\zeta_y = 0.249 \pm 0.002$
$\xi_3\zeta_z = 0.101 \pm 0.001$
$\sigma_x = 250.574 \pm 1.022$
$\sigma_y = 30.401 \pm 6.268$

Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Electrons fit: t = 12172 s (CPU 12172 s)
χ^2/NDF = 216987.3/216179 | Prob = 0.1096
$X_1 = -0.014 \pm 0.002$
$X_2 = 347.634 \pm 0.001$
$\xi_1 = -0.001 \pm 0.001$
$\xi_2 = 0.000 \pm 0.000$
$\xi_3\zeta_x = 0.100 \pm 0.000$
$\xi_3\zeta_y = 0.250 \pm 0.001$
$\xi_3\zeta_z = 0.102 \pm 0.000$
$\sigma_x = 315.241 \pm 1.208$
$\sigma_y = 26.430 \pm 0.009$
$E_{beam} = 45.604 \pm 0.001$

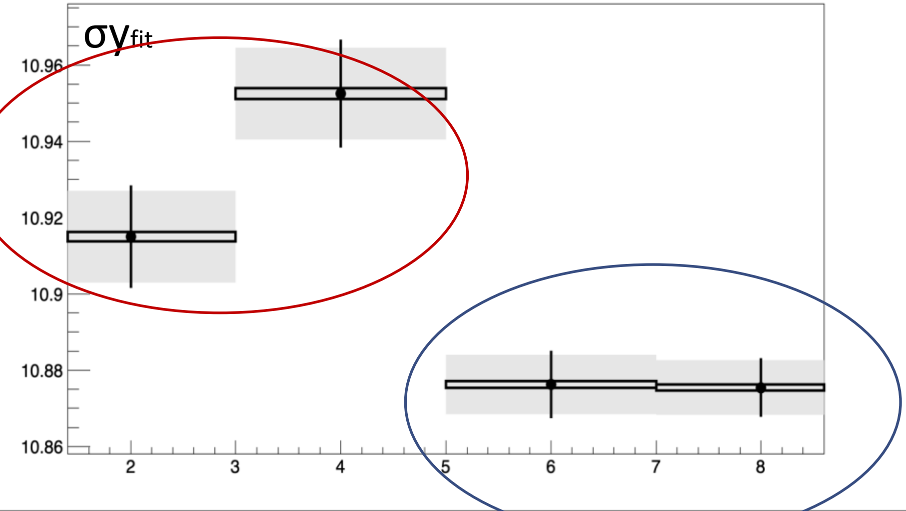
All components extracted with ~0.001 precision in few seconds

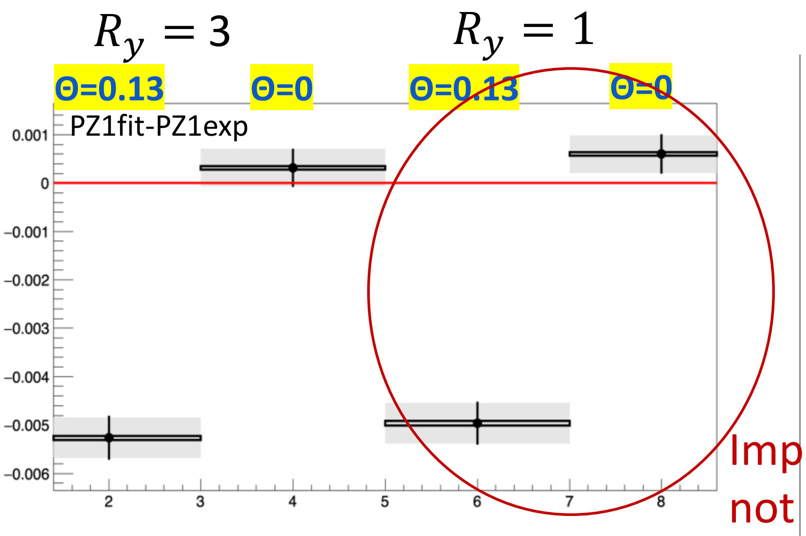
Beam energy may be extracted too! → redundancy with RDP

Blondel et al., arXiv:1909.12245; Muchnoi, INST 17 P10014 (2022)

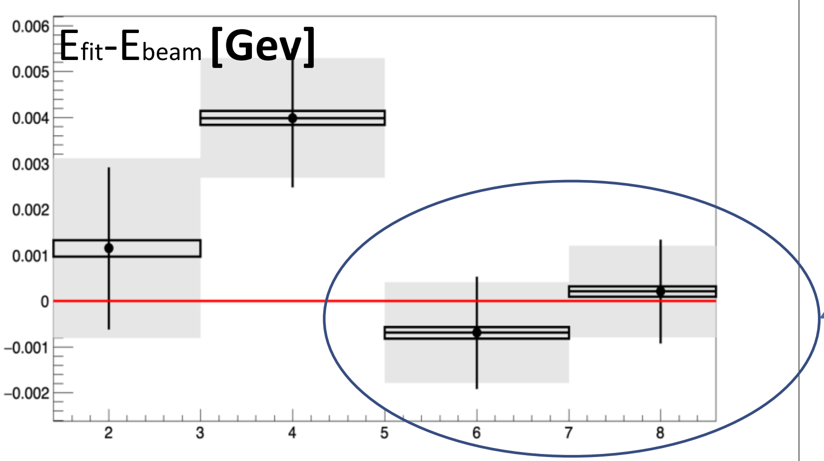
Some results

Unexpected behavior but $\sigma_y \ll$ pixel size





Impact of crossing angle not understood at this stage



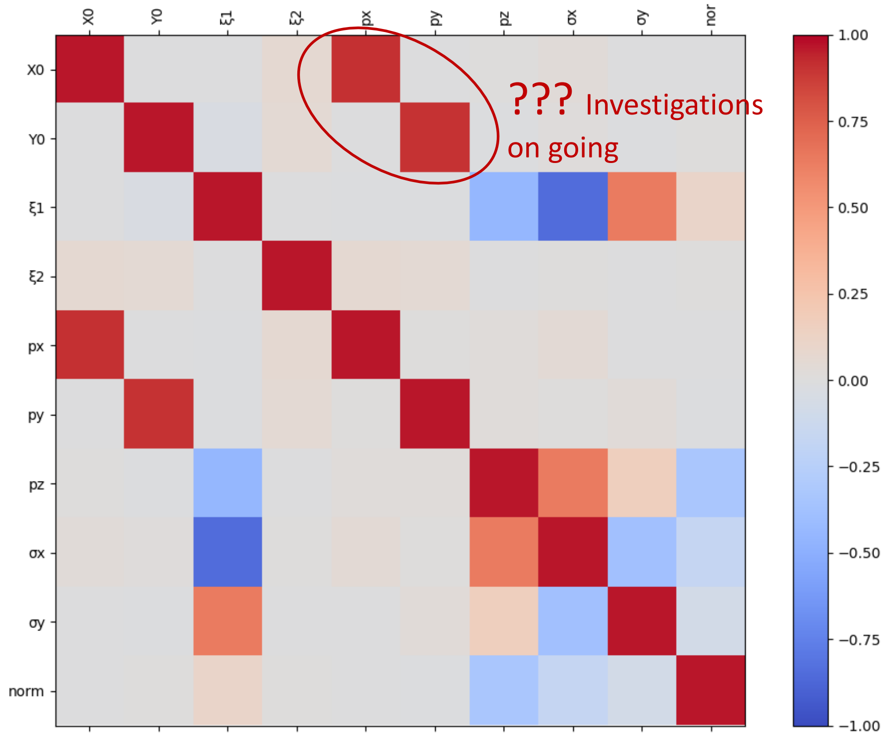
Much better behavior

Prefer 18um vertical pixel size (Ry=1) otherwise too large wrt effective vertical beam size on detector.

Residual effect of crossing angle on ellipse position and polarization still to understand

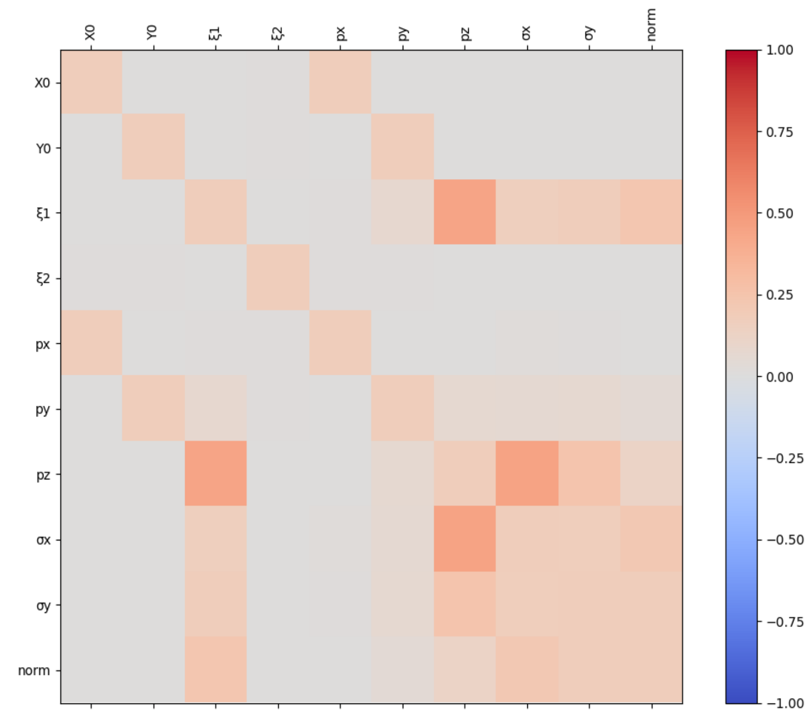
Fit correlation matrix (photons)

Average of correlation coefficients over 100 exps.



Rx=16
Ry= 1
Crossing angle $\theta_{in} = 0.139\ rad$
$5\mathrm{x}10^7$ events (60 seconds of data aqcuisition)

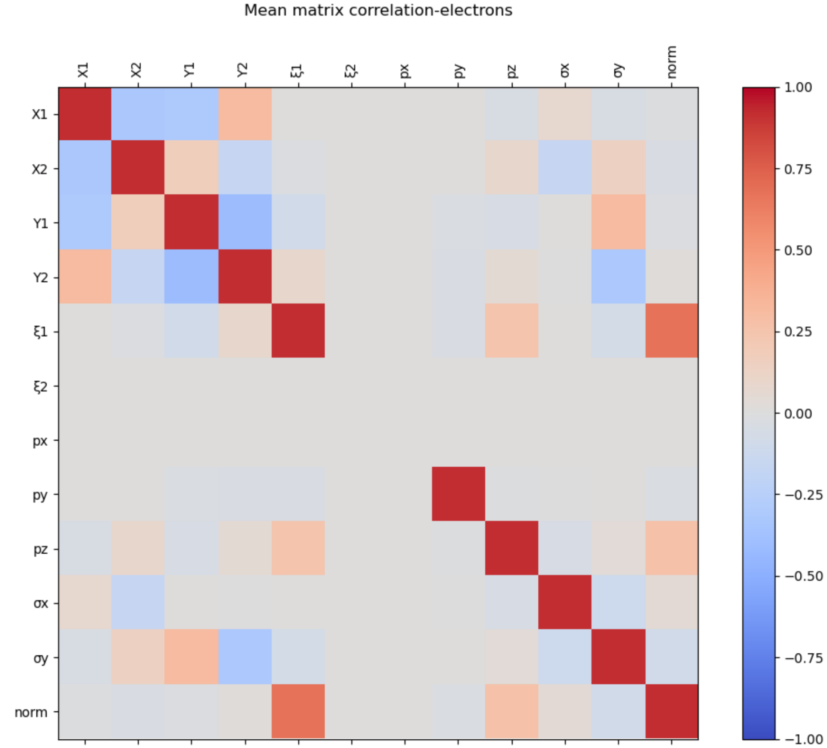
Standard deviation



- **Correlations of ξ_1 and beam sizes $\sigma_{x,y}$ and longitudinal polarization as they all affect scattered photon spatial distribution**
- **Longitudinal polarization affects total cross-section and thus normalization**

Fit correlation matrix (electrons)

Average of correlation coefficients over 100 exps.



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Crossing angle $\theta_{in} = 0.139\ rad$
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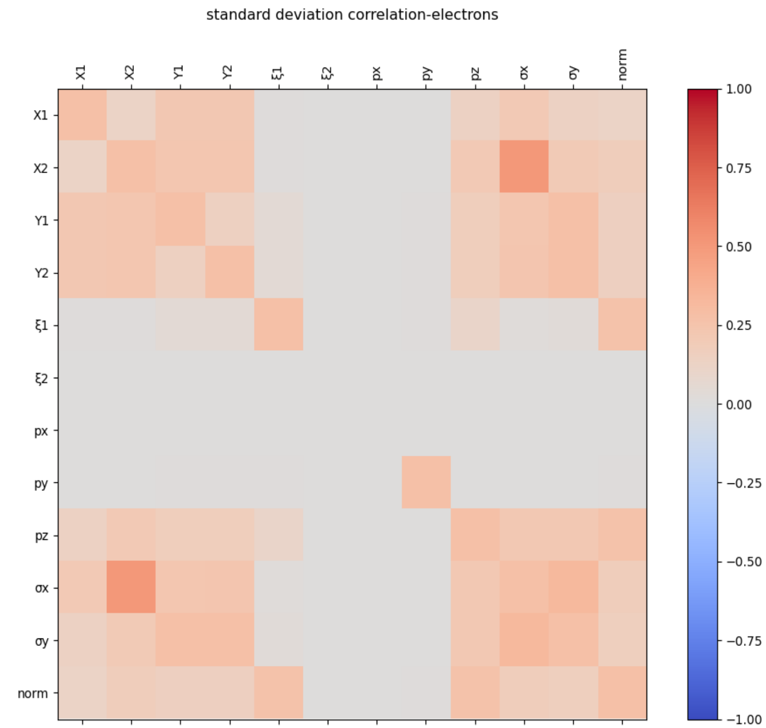


- **Ellipse parameters correlated with beam sizes**
- **Correlations of ξ_1 and longitudinal polarization**
- **Longitudinal polarization affects total cross-section and thus normalization**

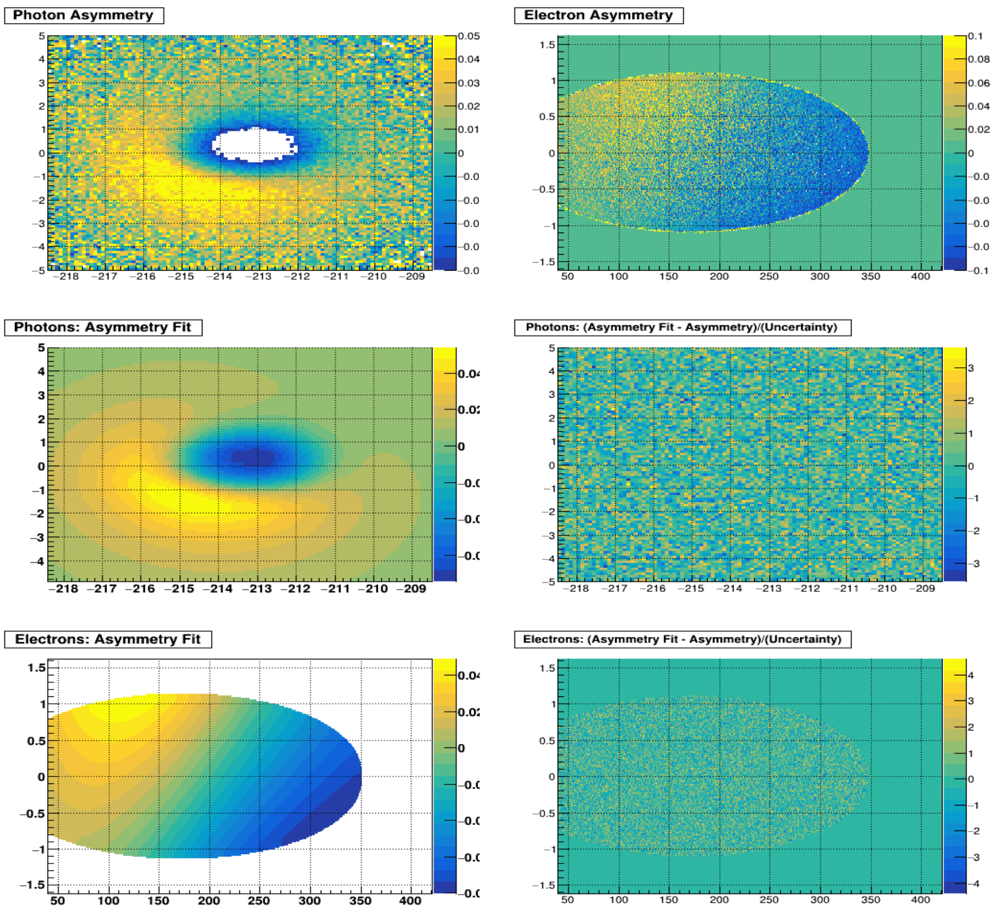
Next step: simultaneous fit of electrons and photons

Asymmetry

$$\frac{\frac{d\sigma^+}{du\,d\varphi} - \frac{d\sigma^-}{du\,d\varphi}}{\frac{d\sigma^+}{du\,d\varphi} + \frac{d\sigma^-}{du\,d\varphi}} = \frac{\left(\zeta_x \frac{d\sigma_x}{du\,d\varphi} + \zeta_y \frac{d\sigma_y}{du\,d\varphi} + \zeta_z \frac{d\sigma_z}{du\,d\varphi}\right)}{\frac{d\sigma_0}{du\,d\varphi} + \xi_1 \cancel{\frac{d\sigma_1}{du\,d\varphi}} + \xi_2 \cancel{\frac{d\sigma_2}{du\,d\varphi}}}$$

for $\pm\xi_3$

Asymmetry induced by laser helicity flip improves robustness against systematic uncertainties in transverse polarization extraction.



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Laser λ_0 = 0.532 um
Electron E_0 = 45.600 GeV
Electron γ = 89.237×10^3
Compton κ = 1.620
Bend: $\gamma\theta_0$ = 190.441
(ξ_1, ξ_2, ξ_3) = (0.000, 0.000, 1.000)
$(\zeta_x, \zeta_y, \zeta_z)$ = (0.100, 0.100, 0.100)

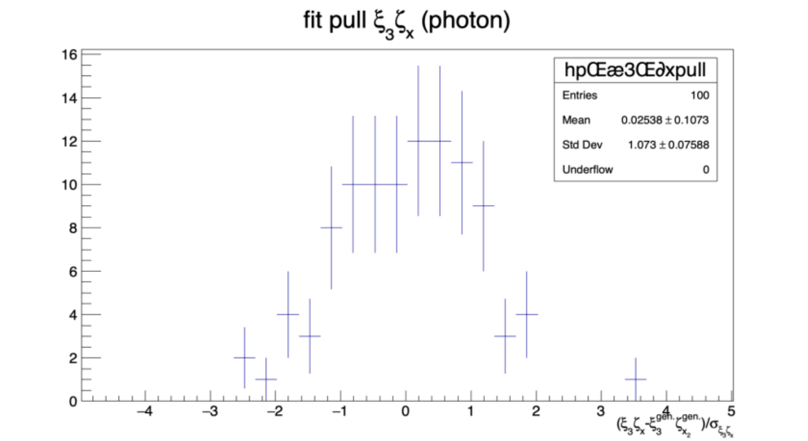
Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Photons fit: t = 273 s (CPU 273 s)
χ^2/NDF = 9994.0/10000 | Prob = 0.5150
X_0 = -213.537 ± 0.007
ξ_1 = 0.000 ± 0.000
ξ_2 = 0.000 ± 0.000
$\xi_3\zeta_x$ = 0.099 ± 0.001
$\xi_3\zeta_y$ = 0.101 ± 0.001
$\xi_3\zeta_z$ = 0.100 ± 0.000
σ_x = 569.382 ± 0.000
σ_y = 10.859 ± 0.000

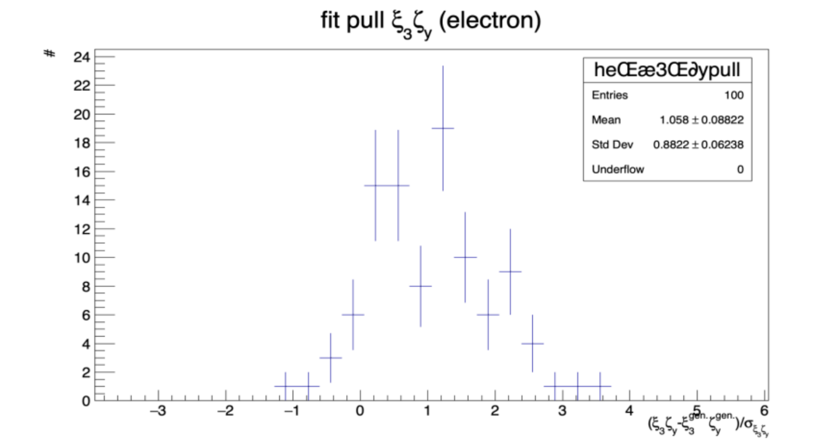
Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Electrons fit: t = 1342 s (CPU 1340 s)
χ^2/NDF = 111036.6/110208 | Prob = 0.0390
X_1 = -0.005 ± 0.000
X_2 = 345.937 ± 0.000
ξ_1 = 0.000 ± 0.000
ξ_2 = 0.000 ± 0.000
$\xi_3\zeta_x$ = 0.100 ± 0.000
$\xi_3\zeta_y$ = 0.102 ± 0.001
$\xi_3\zeta_z$ = 0.100 ± 0.000
σ_x = 681.652 ± 0.000
σ_y = 10.859 ± 0.000
E_{beam} = 45.601 ± 0.001

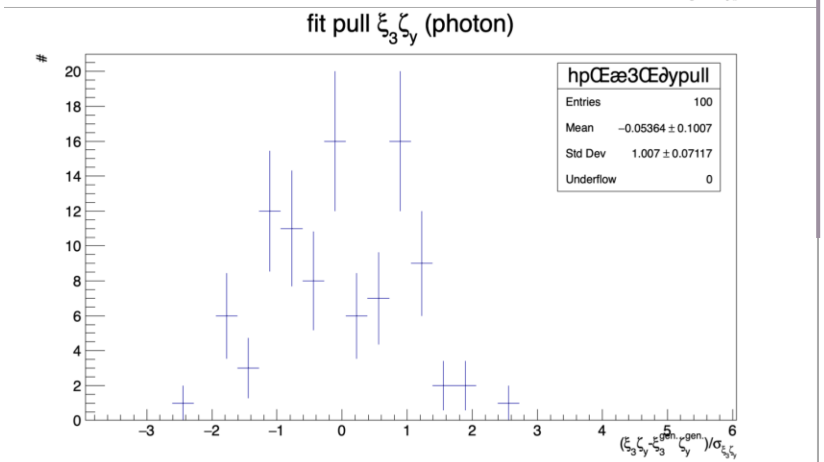
Reproductible and well known laser helicity flip is required

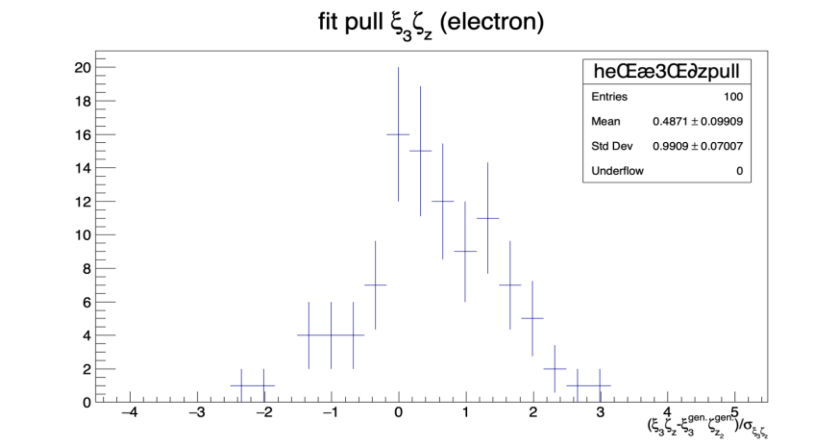
Asymmetry

$$\frac{\frac{d\sigma^+}{dud\varphi}-\frac{d\sigma^-}{dud\varphi}}{\frac{d\sigma^+}{dud\varphi}+\frac{d\sigma^-}{dud\varphi}}=\frac{\left(\zeta_x\frac{d\sigma_x}{dud\varphi}+\zeta_y\frac{d\sigma_y}{dud\varphi}+\zeta_z\frac{d\sigma_z}{dud\varphi}\right)}{\frac{d\sigma_0}{dud\varphi}+\xi_1\cancel{\frac{d\sigma_1}{dud\varphi}}+\xi_2\cancel{\frac{d\sigma_2}{dud\varphi}}}$$









- The position and spatial resolution parameters are fixed, as the fit is found to be largely insensitive to their variation.
- No bias at the 10^-4 level except for **ζ**_y (7x10^-4) to be investigated.
- Next step evaluate how uncertainties in these fixed parameters might affect the systematic errors

NB: systematics related to fixed parameters to be looked at.

Conclusion & prospects

- **Now the software allows for more realistic simulation and accounting of phase space correlations,**

  actual luminostiy and laser-electron beams crossing angle

- **Studies related to pixel size to be performed again with these parameters**
- **Small vertical pixel size seem essential, 18um looks good at this stage**
- **Impact of laser-electron crossing angle to be understood. Large bias on longitudinal polarization not explained.**

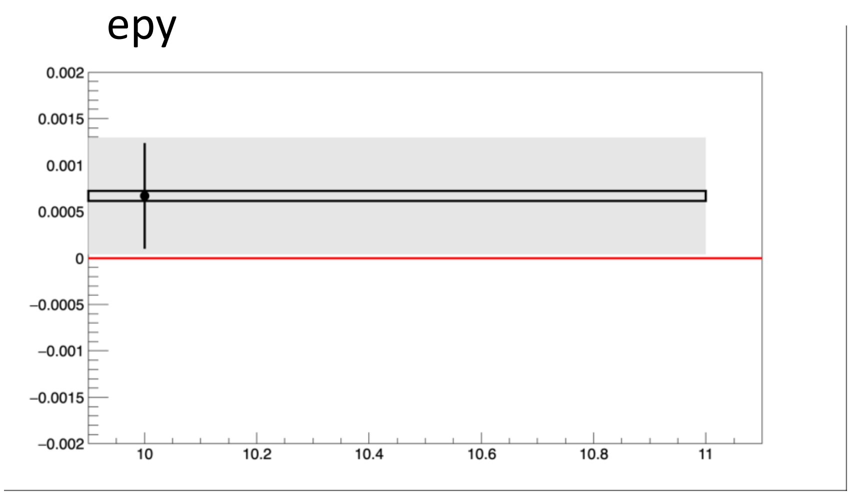
Prospects and ongoing steps:

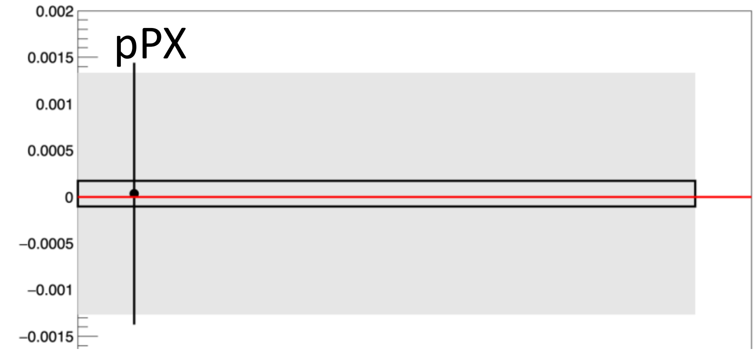
- Some previous analyses should be revisited using small vertical pixel size.
- possibly perform a simultaneous fit of electrons and photons to improve parameter extraction
- On longer term start to end simulation of the Compton interaction up to detection and parameter extraction

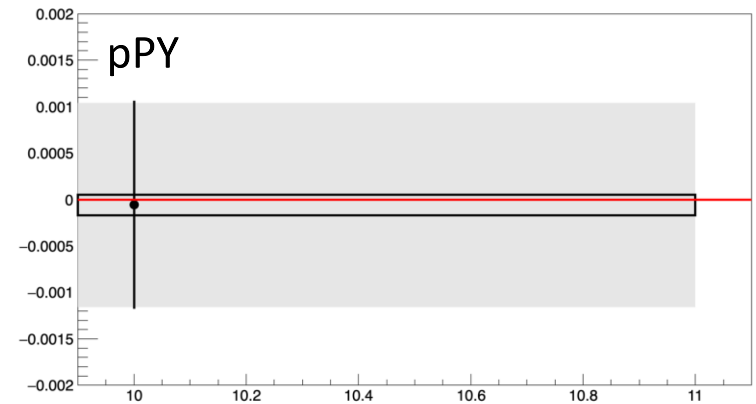
THANK YOU FOR YOUR ATTENTION

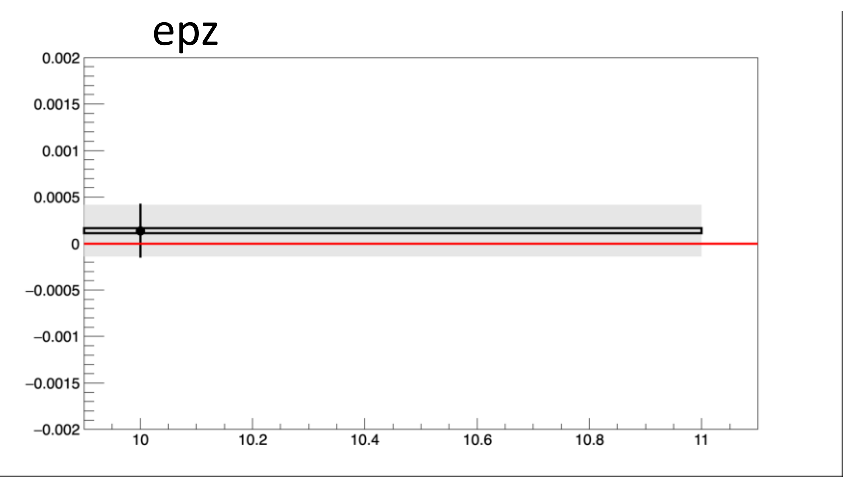
backup

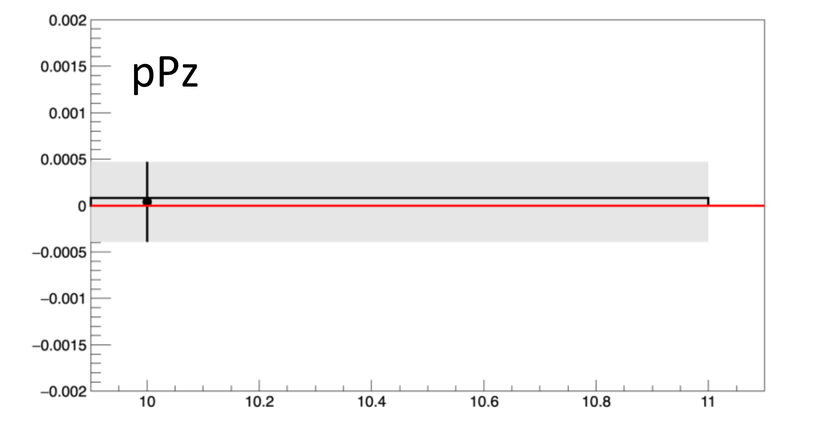
Asymmetry scan



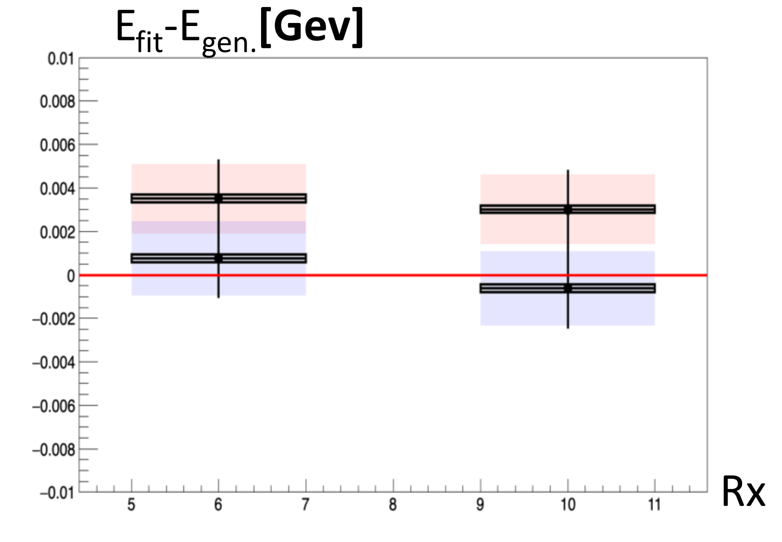




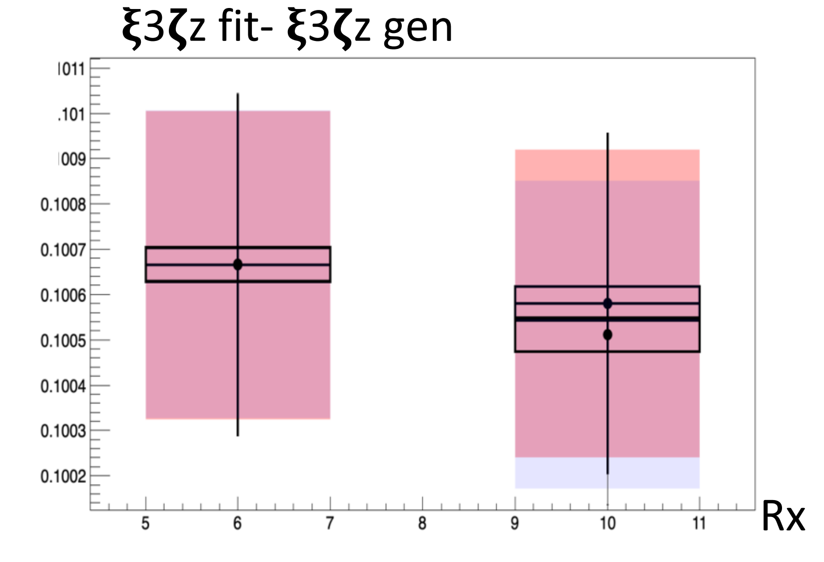


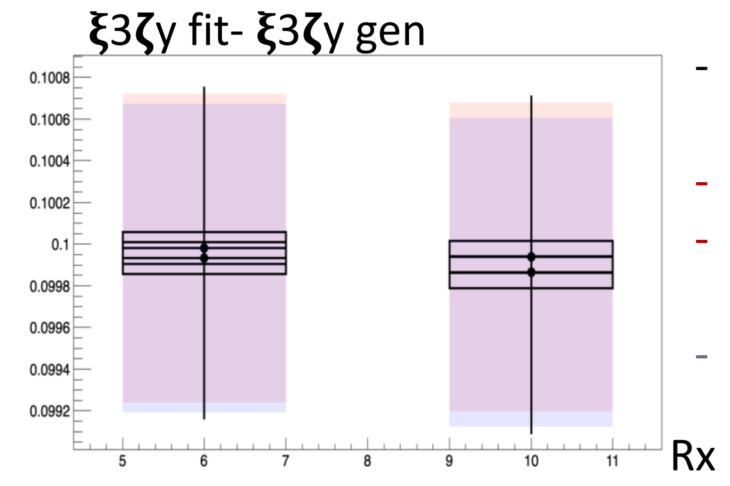


Simulation on Monolithic pixel sensor



R_y=2
Ry=3

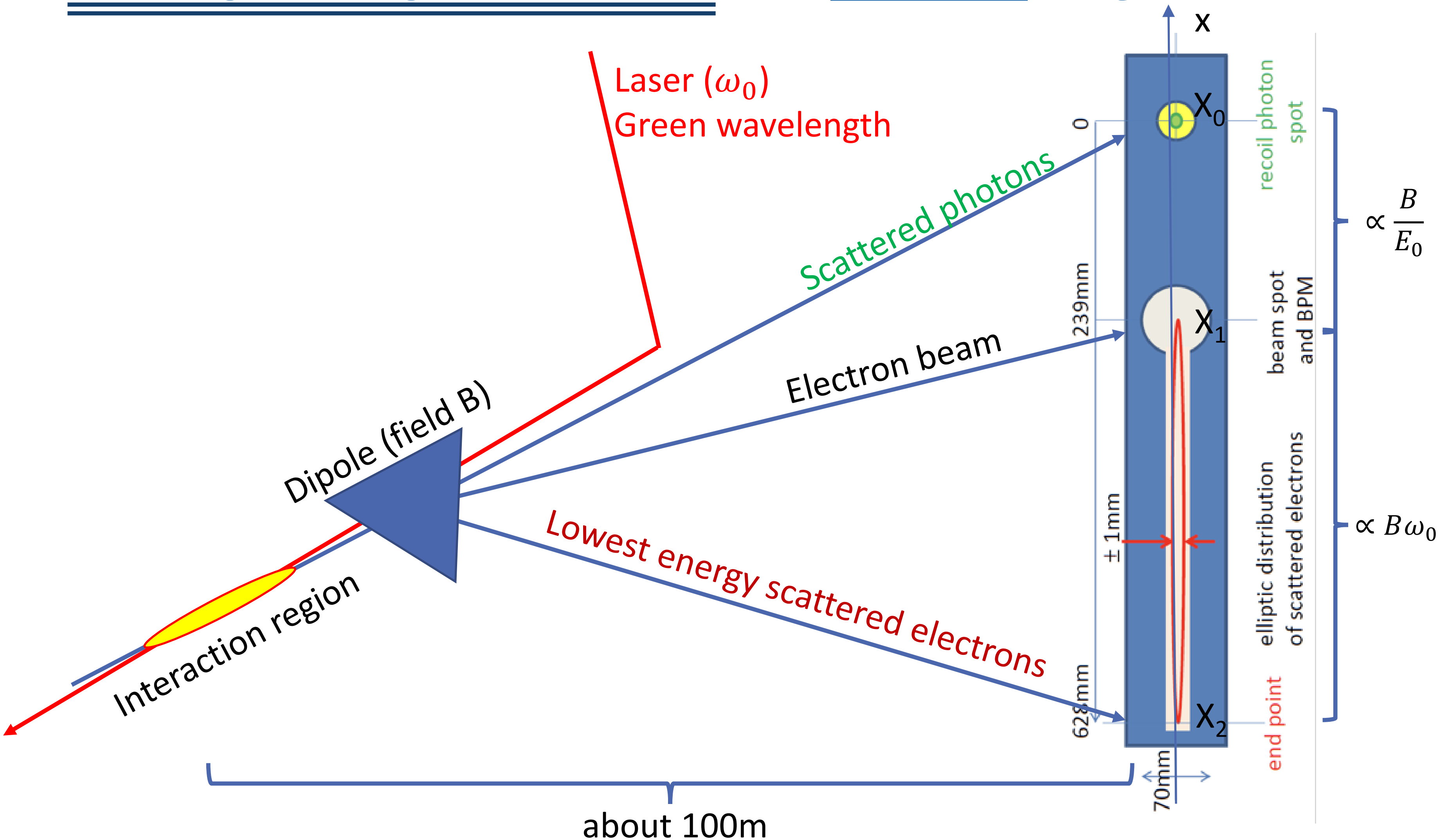




- Beam energy extraction (ellipse coordinates) is significantly affected by the pixel size (few per-mil level)
- Interesting correlation with vertical pixel size ! (why ?)
- Significant effect on longitudinal polarization too (why situation improves when pixel area increases ?)
- Much smaller impact on vertical polarization (small fraction of per-mille)

Compton polarimeter initial layout

Blondel et al., arXiv:1909.12245; Muchnoi, INST 17 P10014 (2022)



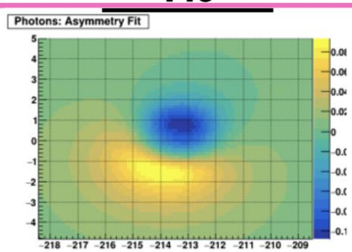
New concept (N. Yu Muchnoi) to measure all polarization parameters → 3D polarimeter

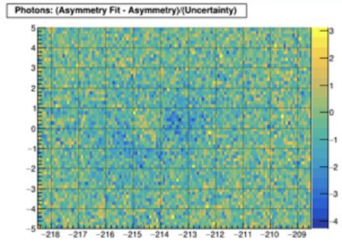
$$\frac{\frac{d\sigma^+}{dud\varphi}-\frac{d\sigma^-}{dud\varphi}}{\frac{d\sigma^+}{dud\varphi}+\frac{d\sigma^-}{dud\varphi}} = \frac{\left(\zeta_x \frac{d\sigma_x}{dud\varphi}+\zeta_y\frac{d\sigma_y}{dud\varphi}+\zeta_z\frac{d\sigma_z}{dud\varphi}\right)}{\frac{d\sigma_0}{dud\varphi}+\xi_1\frac{d\sigma_1}{dud\varphi}+\xi_2\frac{d\sigma_2}{dud\varphi}}$$

Asymmetry fit (preliminary)

Fit | **Residuals** | **Results**

Asymmetry



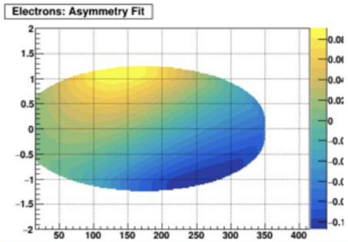


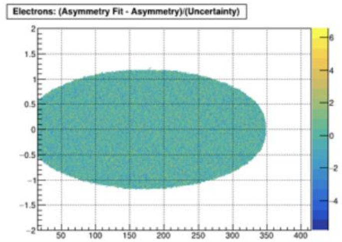
Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Photons fit: t = 374 s (CPU 227 s)
χ^2/NDF = 9171.3/7200 | Prob = 0.0000
X_0 = -213.496 ± 0.003
ξ_1 = 0.000 ± 0.000
ξ_2 = 0.000 ± 0.000
$\xi_3\zeta_x$ = 0.092 ± 0.001
$\xi_3\zeta_y$ = 0.250 ± 0.001
$\xi_3\zeta_z$ = 0.099 ± 0.000
σ_x = 217.255 ± 4.659
σ_y = 26.431 ± 0.000

$\chi2$/NDF = 9171.3/7200

Photons

Preliminary
More investigations ongoing



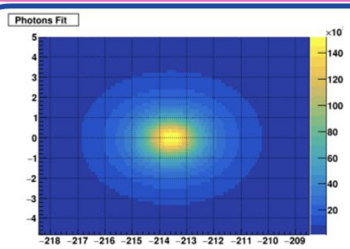


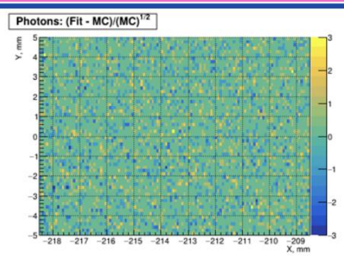
Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Electrons fit: t = 1464 s (CPU 1250 s)
χ^2/NDF = 220825.7/217297 | Prob = 0.0000
X_1 = -0.012 ± 0.000
X_2 = 347.634 ± 0.000
ξ_1 = 0.000 ± 0.000
ξ_2 = 0.000 ± 0.000
$\xi_3\zeta_x$ = 0.100 ± 0.000
$\xi_3\zeta_y$ = 0.250 ± 0.001
$\xi_3\zeta_z$ = 0.098 ± 0.000
σ_x = 315.000 ± 0.000
σ_y = 26.431 ± 0.000
E_{beam} = 45.613 ± 0.001

$\chi2$/NDF = 220825.7/217297

Electrons

Distribution

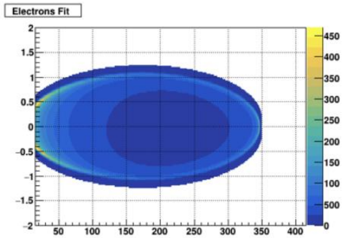


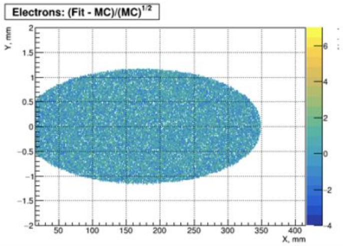


Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Photons fit: t = 338 s (CPU 338 s)
χ^2/NDF = 7274.1/7190 | Prob = 0.2406
X_0 = -213.538 ± 0.001
ξ_1 = 0.000 ± 0.001
ξ_2 = 0.000 ± 0.000
$\xi_3\zeta_x$ = 0.101 ± 0.002
$\xi_3\zeta_y$ = 0.248 ± 0.002
$\xi_3\zeta_z$ = 0.099 ± 0.001
σ_x = 255.354 ± 1.020
σ_y = 34.820 ± 5.791

$\chi2$/NDF = 7274.1/7190

Photons





Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Electrons fit: t = 21199 s (CPU 21196 s)
χ^2/NDF = 215915.1/216089 | Prob = 0.6040
X_1 = -0.011 ± 0.002
X_2 = 347.631 ± 0.001
ξ_1 = -0.000 ± 0.001
ξ_2 = 0.000 ± 0.000
$\xi_3\zeta_x$ = 0.100 ± 0.000
$\xi_3\zeta_y$ = 0.250 ± 0.001
$\xi_3\zeta_z$ = 0.101 ± 0.000
σ_x = 316.905 ± 1.217
σ_y = 26.435 ± 0.009
E_{beam} = 45.603 ± 0.001

$\chi2$/NDF = 215915.1/216089

Electrons

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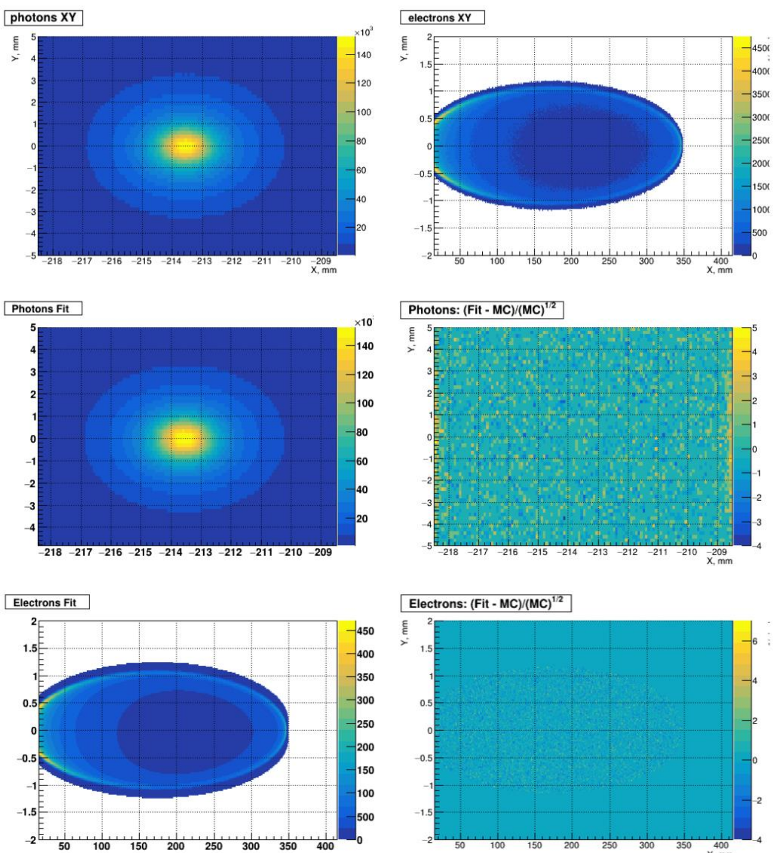
Narvaez, EPOL meeting

Typically obtained in 30s for a single bunch

Typical result – fit of Asymetry

Based on measurement of scattered particles transverse distributions (pixelized detectors)

$$\frac{d\sigma}{du d\varphi} = \frac{d\sigma_0}{du d\varphi} + \xi_1 \frac{d\sigma_1}{du d\varphi} + \xi_2 \frac{d\sigma_2}{du d\varphi} + \xi_3 \left(\zeta_x \frac{d\sigma_x}{du d\varphi} + \zeta_y \frac{d\sigma_y}{du d\varphi} + \zeta_z \frac{d\sigma_z}{du d\varphi} \right)$$



Monte-Carlo Parameters:
Laser λ_0 = 0.532 um
Electron E_0 = 45.600 GeV
Electron $\gamma = 89.237\times10^3$
Compton κ = 1.628
Bend: $\gamma\theta_0$ = 190.441
(ξ_1, ξ_2, ξ_3) = (0.000, 0.000, 1.000)
$(\zeta_x, \zeta_y, \zeta_z)$ = (0.100, 0.250, 0.100)

Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Photons fit: t = 319 s (CPU 267 s)
χ^2/NDF = 7820.4/7190 | Prob = 0.0000
$X_0 = -213.539 \pm 0.001$
$\xi_1 = 0.001 \pm 0.001$
$\xi_2 = -0.000 \pm 0.000$
$\xi_3\zeta_x = 0.096 \pm 0.002$
$\xi_3\zeta_y = 0.249 \pm 0.002$
$\xi_3\zeta_z = 0.101 \pm 0.001$
$\sigma_x = 250.574 \pm 1.022$
$\sigma_y = 30.401 \pm 6.268$

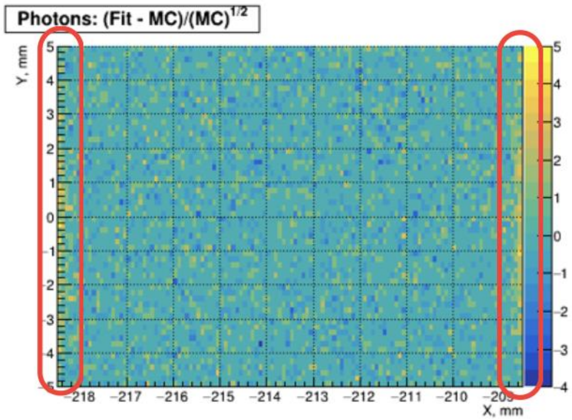
Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Electrons fit: t = 12172 s (CPU 12172 s)
χ^2/NDF = 216987.3/216179 | Prob = 0.1096
$X_1 = -0.014 \pm 0.002$
$X_2 = 347.634 \pm 0.001$
$\xi_1 = -0.001 \pm 0.001$
$\xi_2 = 0.000 \pm 0.000$
$\xi_3\zeta_x = 0.100 \pm 0.000$
$\xi_3\zeta_y = 0.250 \pm 0.001$
$\xi_3\zeta_z = 0.102 \pm 0.000$
$\sigma_x = 315.241 \pm 1.208$
$\sigma_y = 26.430 \pm 0.009$
$E_{beam} = 45.604 \pm 0.001$

All components extracted with ~0.001 precision in few seconds

Beam energy may be extracted too! → redundancy with RDP

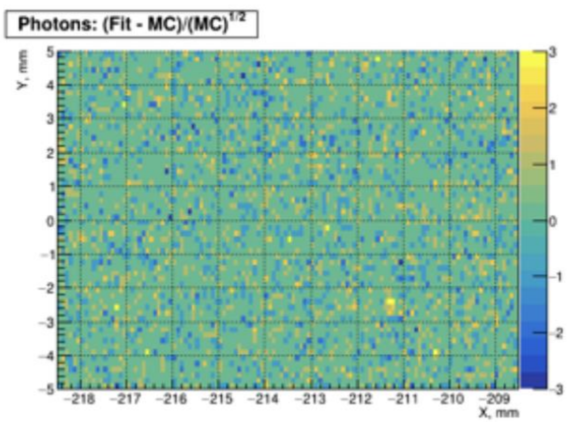
Blondel et al., arXiv:1909.12245; Muchnoi, INST 17 P10014 (2022)

Fit refinements



Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Photons fit: t = 278 s (CPU 278 s)
χ^2/NDF = 7820.4/7190, Prob = 0.0000
X_0 = -213.539 $\pm$ 0.001
ξ_1 = 0.001 $\pm$ 0.001
ξ_2 = -0.000 $\pm$ 0.000
$\xi_3\zeta_x$ = 0.096 $\pm$ 0.002
$\xi_3\zeta_y$ = 0.249 $\pm$ 0.002
$\xi_3\zeta_z$ = 0.101 $\pm$ 0.001
σ_x = 250.574 $\pm$ 1.022
σ_y = 30.401 $\pm$ 6.268

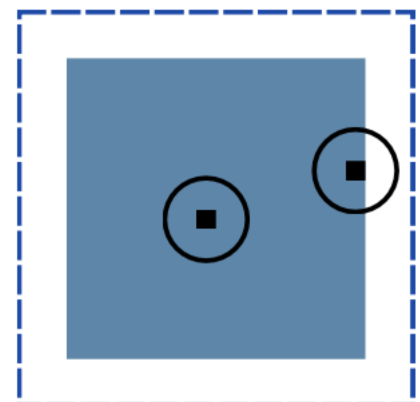
χ2/NDF = 7820.4/7190



Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Photons fit: t = 464 s (CPU 463 s)
χ^2/NDF = 6981.9/7190, Prob = 0.9596
X_0 = -213.539 $\pm$ 0.001
ξ_1 = 0.001 $\pm$ 0.001
ξ_2 = -0.000 $\pm$ 0.000
$\xi_3\zeta_x$ = 0.099 $\pm$ 0.002
$\xi_3\zeta_y$ = 0.247 $\pm$ 0.002
$\xi_3\zeta_z$ = 0.099 $\pm$ 0.001
σ_x = 254.946 $\pm$ 1.022
σ_y = 41.104 $\pm$ 4.908

χ2/NDF = 6981.9/7190

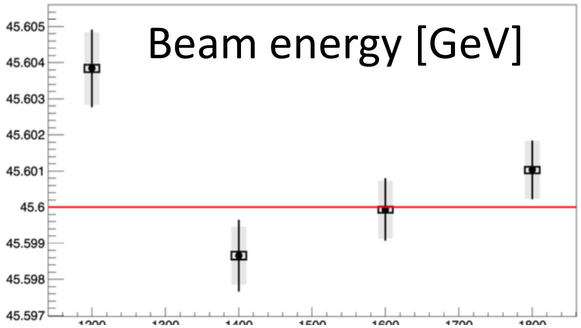
Convolution



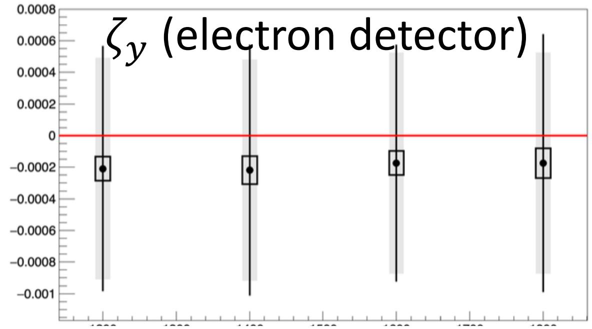
Extend calculation over extended range beyond sensitive area see also J. Tamazirt poster

Updated toy study

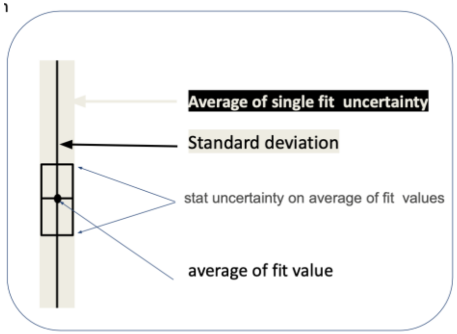
A toy MonteCarlo procedure is applied (100 experiments, 10^8 events each

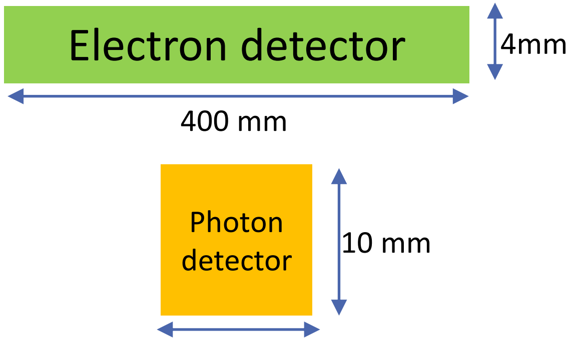


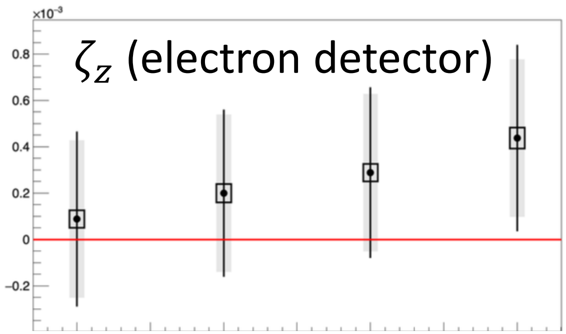
X: 1200 1400 1600 1800
Y: 40 60 80 100
Npixels for electrons



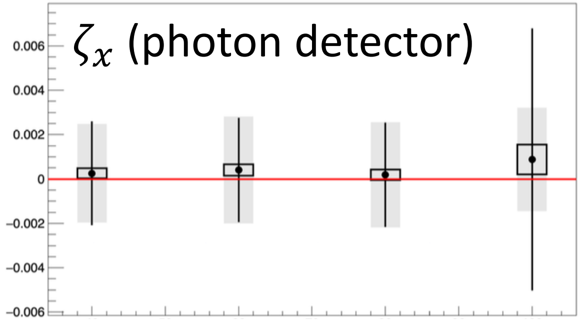
X: 1200 1400 1600 1800
Y: 40 60 80 100







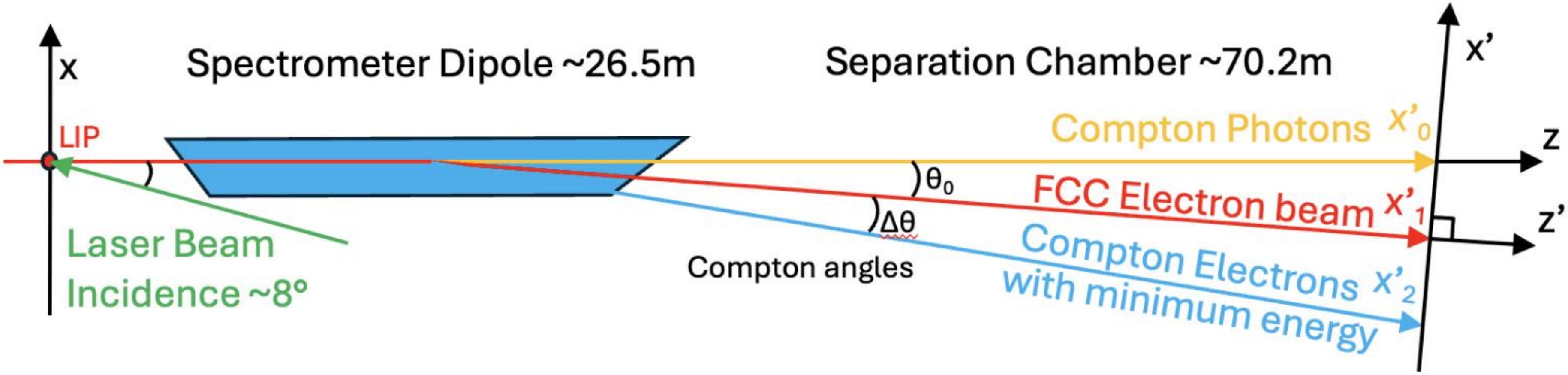
X: 1200 1400 1600 1800
Y: 40 60 80 100
Npixels for electron detector



X: 40 60 80 100
Y: 40 60 80 100
Npixels for photon detector

Residual biases (1-5 10^{-4}) under investigation
Combined fit to be investigated

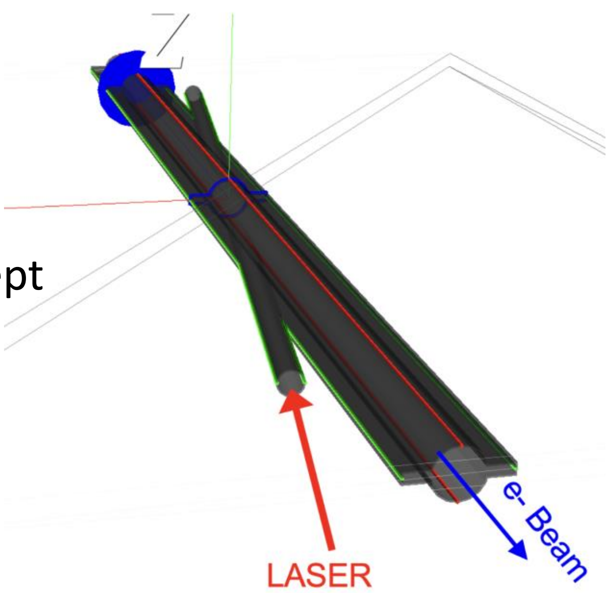
Impact on integration



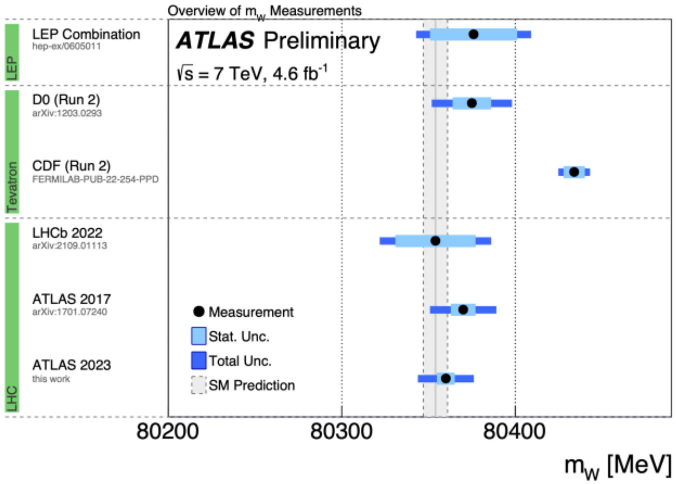
Laser does not travel through dipole → easier integration (Q-switch would)

Vacuum chamber concept adapted from SuperKEKB concept

Validated for impedance budget



Physics requirements



Observable	statistics	$\Delta\sqrt{s}_{\mathrm{abs}}$ 100 keV	$\Delta\sqrt{s}_{\mathrm{syst-ptp}}$ **40 keV**	calib. stats. $200\,\mathrm{keV}/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ $85 \pm \mathbf{0.05}$ MeV
$\mathrm{m_Z}$ (keV)	4	100	**28**	1	–
Γ_{Z} (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}} \times 10^6$ from $A_{\mathrm{FB}}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{\mathrm{QED}}(\mathrm{m_Z^2})}{\alpha_{\mathrm{QED}}(\mathrm{m_Z^2})} \times 10^5$	3	0.1	**0.9**	–	**0.1**

Required accuracy of <1ppm

Blondel et al., arXiv:1909.12245

High reproductibility of measurements for various sqrt(s) is critically needed

Extract as much information as possible from physics experiments themselves (crossing angle, luminosity, sqrt(s) spread)

Beam-based measurements in real time, including beams energy with resonant depolarization

24/7 operable measurement of (de-)polarization

Integration

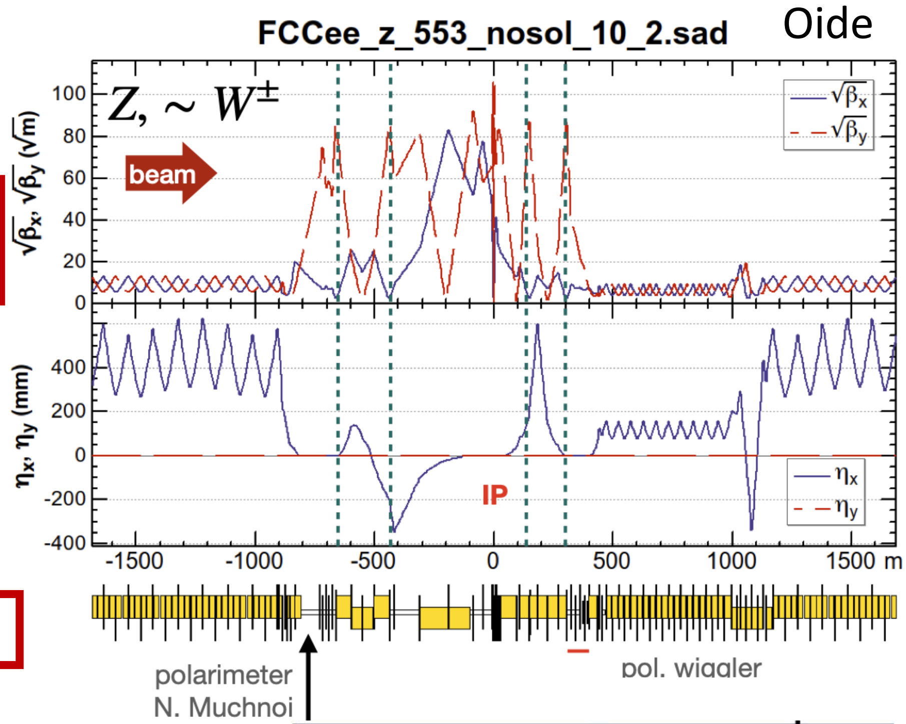
Oide, https://indico.cern.ch/event/1237189

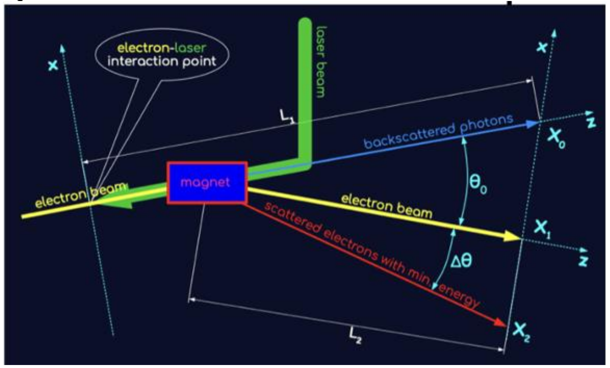
Polarimeter integrated close to experiments IP
1/beam (baseline)

e-beam size at Compton IP :
~500µm (horizontal)

Robust laser technology is available nowadays

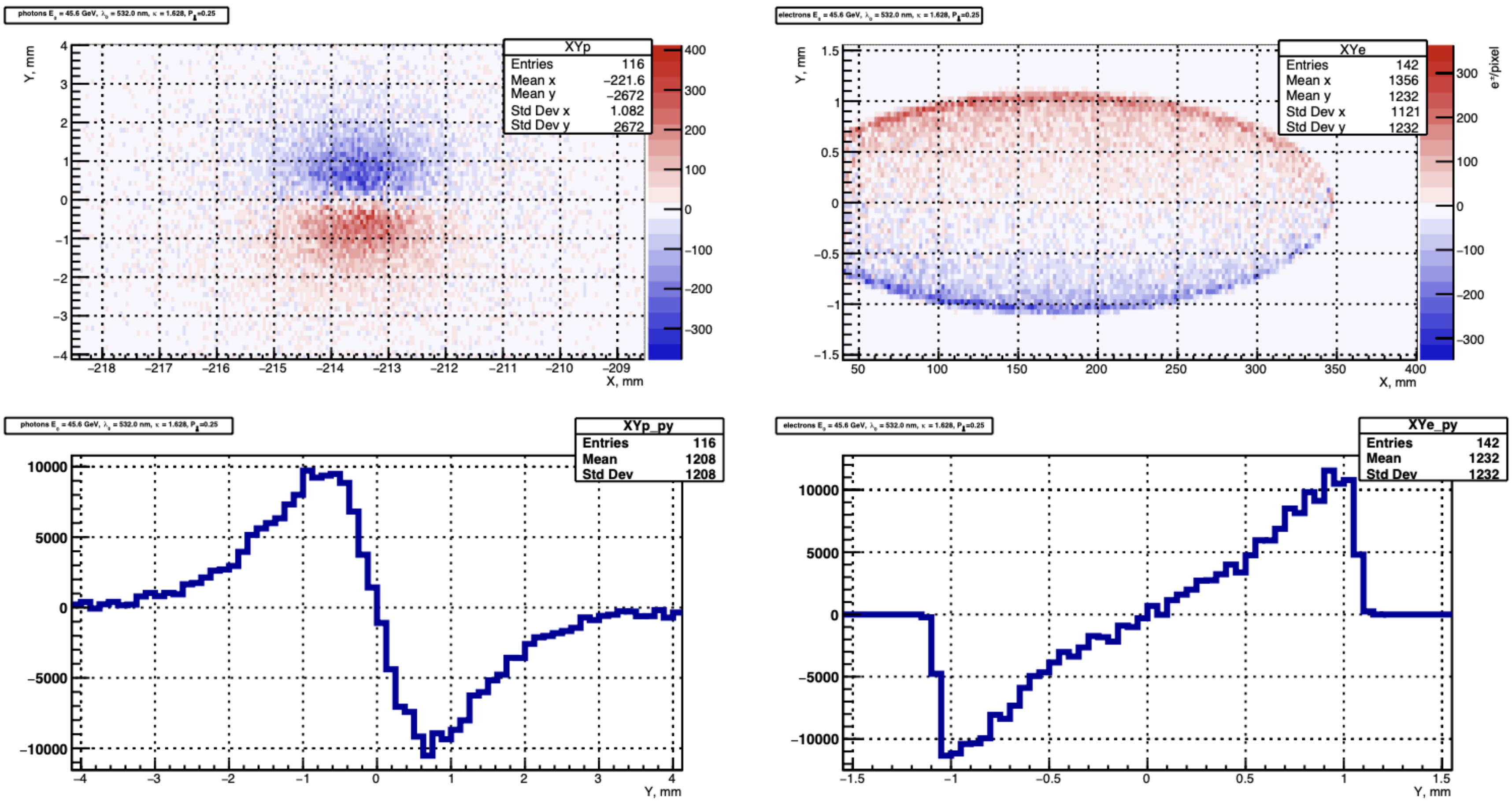
Demanding operational constraints
→ laser room in the parallel technical gallery
→ 24/7 access to the laser system and related electronics





Laser helicity asymmetries

Blondel et al., arXiv:1909.12245

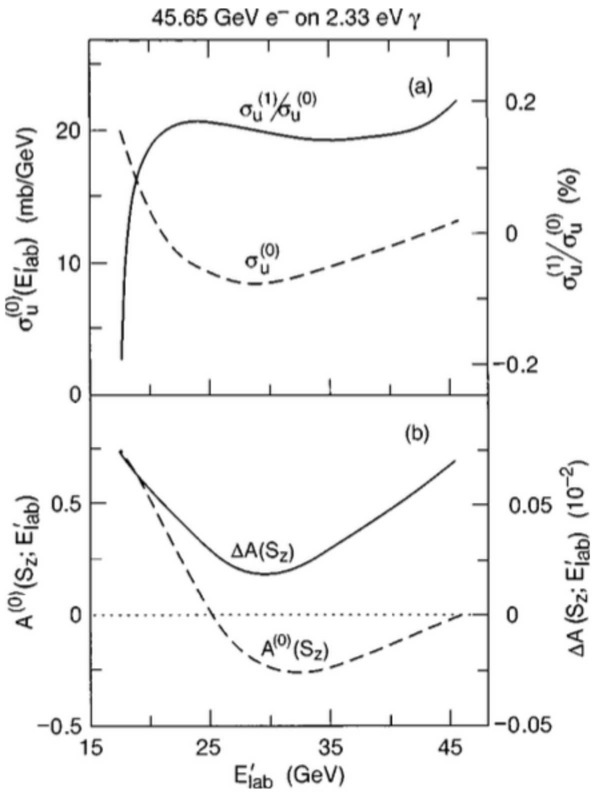


Reproductible and well known laser helicity flip is required

QED corrections

Denner & Dittmaier Nucl. Phys. B 540 (1999) 58, Swartz Phys. Rev. D 58 014010 (1998), Veltman Phys. Rev. D 40 2810 (1989), Veltman Phys. Rev D 42 1856E (1990); A. Martens et al 2023 JINST 18 P10001

Studied in details at SLD



PHYSICAL REVIEW D, VOLUME 58, 014010

Complete order-α^3 calculation of the cross section for polarized Compton scattering

Morris L. Swartz
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
(Received 24 November 1997; published 28 May 1998)

The construction of a computer code to calculate the cross sections for the spin-polarized processes $e^-\gamma \rightarrow e^-\gamma, e^-\gamma\gamma, e^-e^+e^-$ to order α^3 is described. The code calculates cross sections for circularly polarized initial-state photons and arbitrarily polarized initial-state electrons. The application of the code to the SLD Compton polarimeter indicates that the order-α^3 corrections produce a fractional shift in the SLC polarization scale of -0.1% which is too small and of the wrong sign to account for the discrepancy in the Z-pole asymmetries measured by the SLD Collaboration and the CERN LEP Collaborations.
[S0556-2821(98)03413-4]

Measurement of transverse polarization at FCCee :

photons $\frac{\delta P}{P} \approx 1\times10^{-3}$ (0.5×10^{-3}) at 45 (80) GeV

electrons $\frac{\delta P}{P} \approx 4\times10^{-3}$ (10×10^{-3}) at 45 (80) GeV

Measurement of longitudinal polarization at FCCee :

$\frac{\delta P}{P} \approx 1\times10^{-3}$ at 45 GeV

If and only if laser helicity asymmetries are measured

Magnetic field tolerancing

Many potential sources of 'bending angle' uncertainties (for instance genuine inhomogeneities of B-field, short-/long-term fluctuations of currents, temperatures, alignments)

Over the useful aperture of the magnet: $\frac{\sigma(\int B_y dl)}{\int B_y dl} \ll 2 \times 10^{-4}$

Fringe fields also may affect performance of polarimeter

$$\int B_x dl \ll \frac{\sigma_y \gamma}{L_2} \frac{mc}{q} \approx 1.1 \times 10^{-4} \text{ T.m and}$$

$$\int B_z dl \ll \frac{\sigma_y \gamma}{L_2 \kappa \theta_0} \frac{mc}{q} \approx 3.2 \times 10^{-2} \text{ T.m.}$$

Nominal vertical field for reference:

$$\int B_y dl = \theta_0 \gamma \frac{mc}{q} \approx 0.3 \text{ T.m.}$$

By product: angular alignment

$$\delta_B \ll \frac{\sigma_y \gamma}{L_2 \int B_y dl} \frac{mc}{q} \approx 370 \ \mu\text{rad.}$$

NB: Requirements not met → not a show-stopper but detailed studies required

Physics requirements cont'd

Wilkinson at EPOL workshop https://indico.cern.ch/event/1181966

Importance of longitudinal polarisation measurement

Any residual longitudinal-polarisation will bias cross sections & forward-backward asymmetries (indeed, high longitudinal polarisation is actually useful, but we assume we are not in that regime – rather longitudinal polarisation is a nuisance).

Consider forward-backward asymmetry of $b\bar{b}$ at Z pole: $A^b_{\rm FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b$

where in the SM $\mathcal{A}_e \approx 0.15, \ \mathcal{A}_b \approx 0.95 \Longrightarrow A^b_{\rm FB} \approx 0.11$

Now, if there is longitudinal polarisation, asymmetry becomes: $(A^b_{\rm FB})' = \frac{3}{4}\mathcal{A}'_e\mathcal{A}_b$

where $\mathcal{A}'_e = -\left(\frac{\mathcal{A}_e - P}{1 - \mathcal{A}_e P}\right)$ with $P = \frac{(P_z)_{e^-} - (P_z)_{e^+}}{1 - (P_z)_{e^-}(P_z)_{e^+}}$

and $(P_z)_{e^\pm}$ the longitudinal polarisation of the $e^\pm$.

21/9/22 EPOL requirements at FCC-ee Guy Wilkinson 17

Importance of longitudinal polarisation measurement

Any residual longitudinal-polarisation will bias cross sections & forward-backward asymmetries (indeed, high longitudinal polarisation is actually useful, but we assume we are not in that regime – rather longitudinal polarisation is a nuisance).

So, if $(P_z)_{e^-} = (P_z)_{e^+}$ (no reason to be so) = 10^{-5} (ballpark guess)

$$P = 2 \times 10^{-5} \quad \Longrightarrow \quad \frac{(A^b_{FB})' - A^b_{FB}}{A^b_{FB}} = 1.3 \times 10^{-4}$$

Statistical uncertainty on $A^b_{\rm FB}$ around 2 x 10^{-5} (relative), and QCD uncertainty which will probably be larger. Still, to be safe we would want to control P_Z to < 10^{-5}.

How is this to be done ? Measurements must be made on colliding bunches, where scattering rates are lower. Can we sample all bunches ? Will it prove necessary to depolarise the physics bunches ? If so, we will still need to monitor residual effects. And what are the systematics on an absolute measurement ?

Note also, that calculations required to transport the measurement of 3-vector at polarimeter to P_Z value at the interaction points. How can this be cross checked ?

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High accuracy longitudinal polarization measurement is needed
→ Naturally small at IPs but with what accuracy ?
→ Measure it !

Berestskii & Lfshitz QED textbook

Compton cross-section

Fig. 1. Tree diagrams for $e^-\gamma \to e^-\gamma$

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

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

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

Electron beam polarization independent

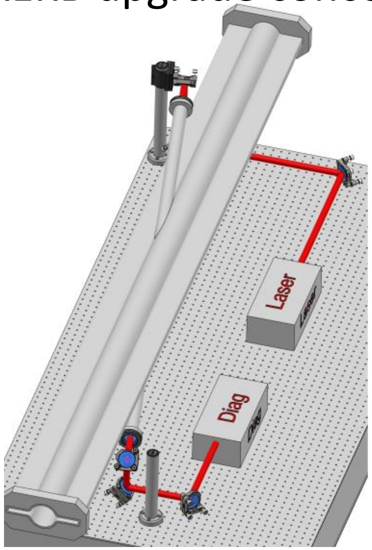
Electron beam polarization dependent

⚠ But small opening angle of scattered particles:

- Electrons → spectrometer
- Photons → difficult to measure asymmetric distribution of a narrow spot → long lever arm needed

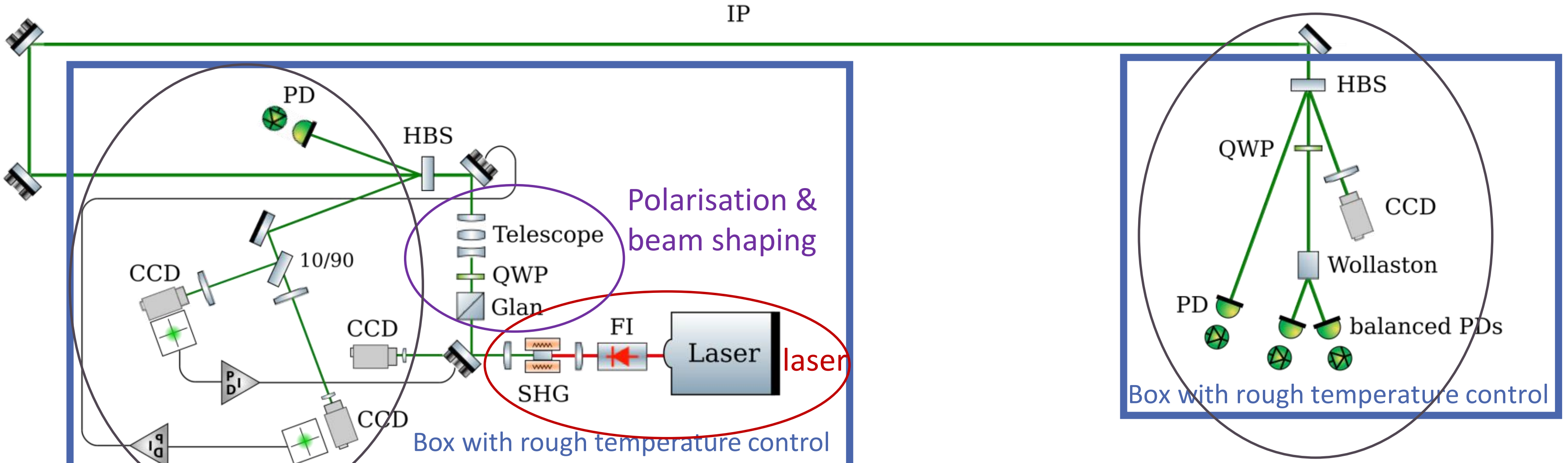
Laser integration

SuperKEKB upgrade concept



Some constraints

- Small crossing angles are preferred (cross-section, beam jitters) few mrad typically
- Beams crossing plane neither horizontal nor vertical
- beam impedance
- beam induced currents in metallic parts ← avoid
- mechanical stability
- ease of maintenance works



Position, pointing control and monitoring
Polarisation independent intensity monitoring
Optical spectrum monitoring possible

Polarisation monitoring
Duplicated at injection
Add Position and pointing monitoring
R&D needed to reach required perf.

24/7 operable laser system, with full monitoring, remote control

Some laser systems

Nikolai's baseline (Q-switch Nd-YAG)

Versatile Yb system

Laser param.	1 pilot	1 pilot v2	All colliding bunches (at Z)
Repetition rate	3 kHz	3 kHz	30 kHz
Pulse energy	1 mJ	1 mJ	10x0.05mJ
Pulse duration	3 ns	30 ps (**)	30 ps
Average power	3 W	3 W	15 W (***)
Scattering rate	$3x10^5$/s (*)	$3x10^5$/s (****)	$4x10^7$/s (****)
Scattering rate per bunch	$3x10^5$/s (*)	$3x10^5$/s	$4x10^5$/s

adaptable

Same oscillator may be used but two different amplification schemes

(*) crossing angle ~ 2mrad

(**) related to optical bandwidth ← constrains resolution of 'direct' energy measurement from polarimeter

(***) Can be increased to typically ~100W (nowadays) but requires operational validation

(****) not limited by Piwinski contribution → can be several degrees without affecting rate

Scattering rates

Laser-beam single pulse energy

Compton cross-section

Electron bunch charge
(25nC for colliding bunches,
1.5nC for pilots)

Geometrical factor

Photon rate $n = \sigma_C \frac{\mathcal{E}}{E_\lambda} \frac{Q}{q} \frac{\mathcal{F}}{2\pi\sigma_y\sigma_x}$

- $\mathcal{F}^{-1} = \sqrt{1 + \left(\frac{\sigma_z}{\sigma_x} \tan\frac{\theta_0}{2}\right)^2}$
- $\theta_0 \sim 2mrad$

Transverse beam sizes:

- $\sigma_{x,y,z} = \sqrt{\sigma^2_{x,y,z,laser} + \sigma^2_{x,y,z,e-}}$
- $\sigma_{x,laser} = \sigma_{y,laser}$=1000µm
- $\sigma_{x,e-}$ = 500µm, $\sigma_{y,e-}$=10µm, $\sigma_{z,e-} \sim$10mm

Laser photon energy
(2.4eV for 0.5µm wavelengths)

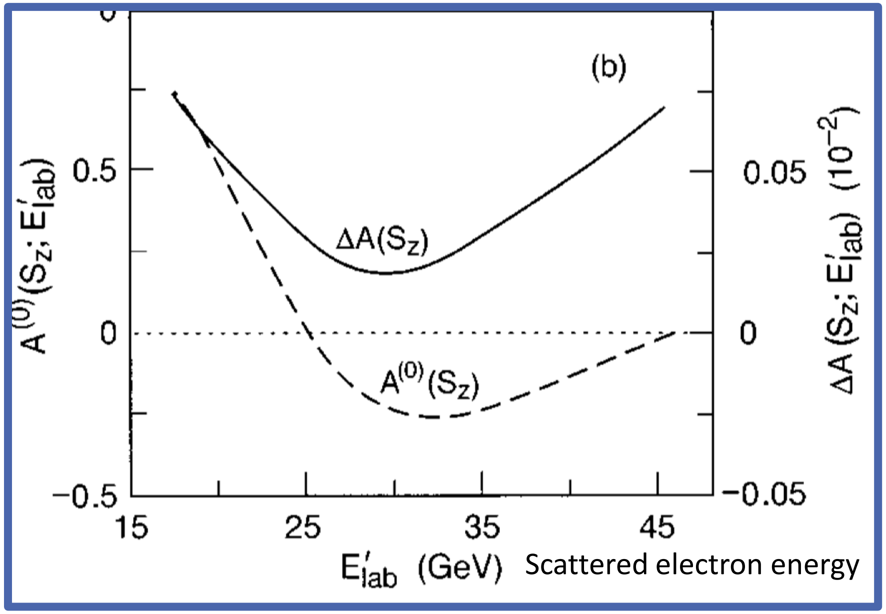
Involved processes $e\gamma \to e\gamma$, $e\gamma \to eee$, $e\gamma \to e\gamma\gamma$

QED corrections

Denner & Dittmaier Nucl. Phys. B 540 (1999) 58, Swartz Phys. Rev. D 58 014010 (1998), Veltman Ophys. Rev. D 40 2810 (1989), Veltman Phys. Rev D 42 1856E (1990)

$$\frac{d\sigma}{dE'}(E') \cong \frac{d\sigma_0}{dE'}(1+\delta)\left[1+\mathcal{P}_z\mathcal{P}_{C,las}(A+\Delta A)\right]$$

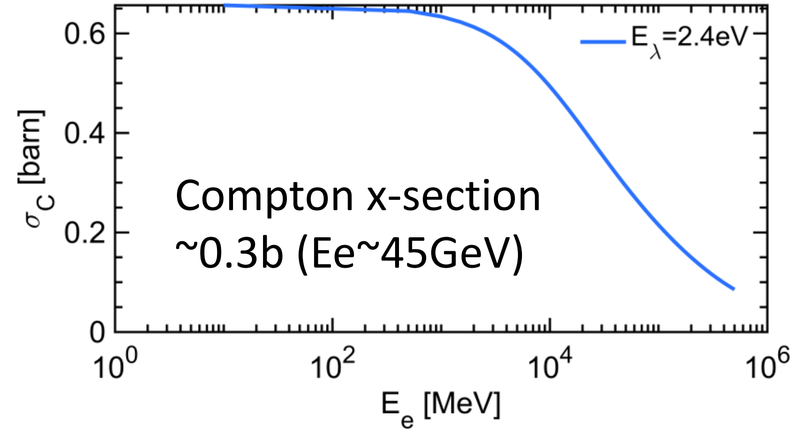
QED corrections<0.001 @ 45 GeV

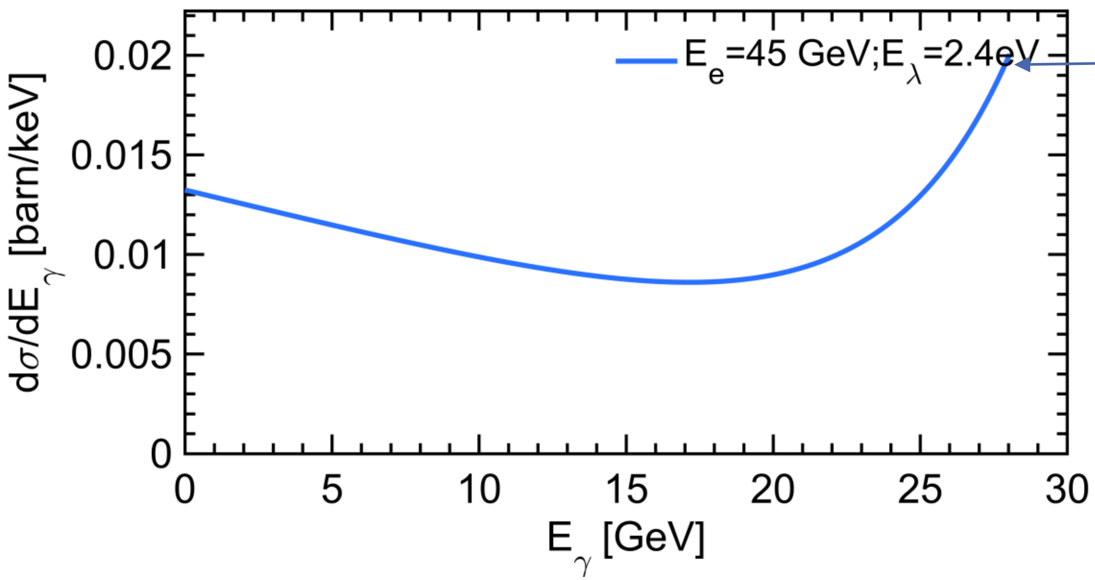


Need to be eventually included in simulations…

The Compton process

Fig. 1. Tree diagrams for $e^- \gamma \rightarrow e^- \gamma$





Kinematic edge

Klein O. and Nishina Y., Z. Phys. 52(1929) 853; Ginzburg I. et al., Nucl. Instr. Methods in Phys. Research 219 (1984) 5, V. B. Berestetskii, E. M. Lifshitz, L. P. Pitaevskii (1982). Quantum Electrodynamics. Vol. 4 (2nd ed.)