3D Compton polarimeter

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On behalf of FCC-ee FS EPOL group
https://indico.cern.ch/category/8678/

Introduction: Physics requirements

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

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 depolarization

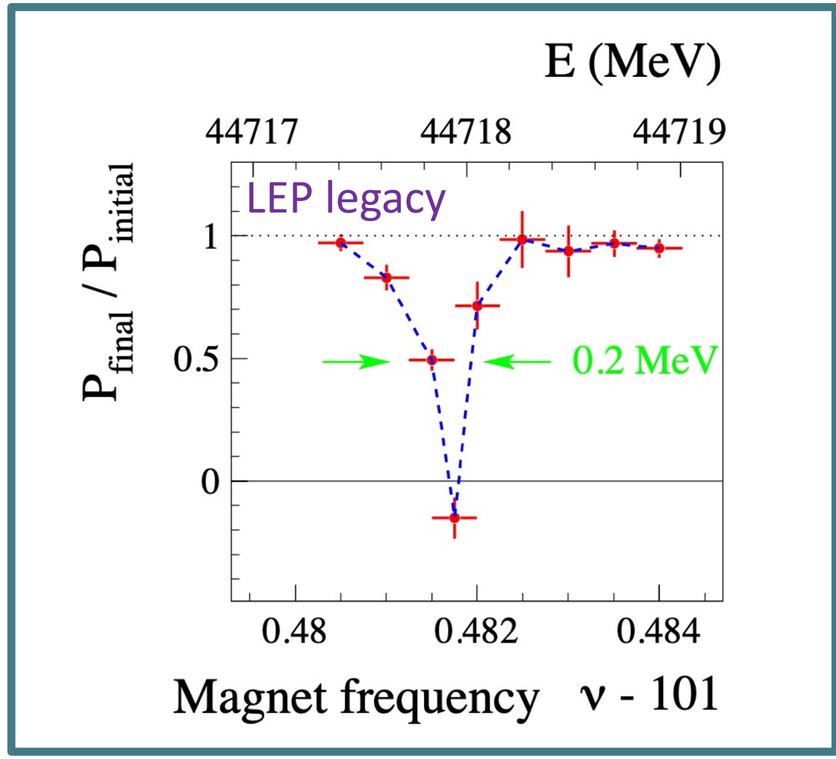
Resonant depolarization

Scan spin precession frequency with magnetic kicker

Detect beam depolarization at resonance

beam energy spread too large for colliding beams (smeared spin resonances)

Use pilot bunches instead



24/7 operable Compton polarimeter for pilot bunches

Assman et al., Eur. Phys. J. C 6, 187−223 (1999), Blondel et al., arXiv:1909.12245; Baier & Khoze, Sov. J. Nucl. Phys. \textbf{9}, 238-240 (1969)

Precision experiments and Pz

Precision EW physics is sensitive to longitudinal polarization (Pz)

few 10^{-5} accuracy on EW asymmetries require that Pz is known at 10^{-5} level !

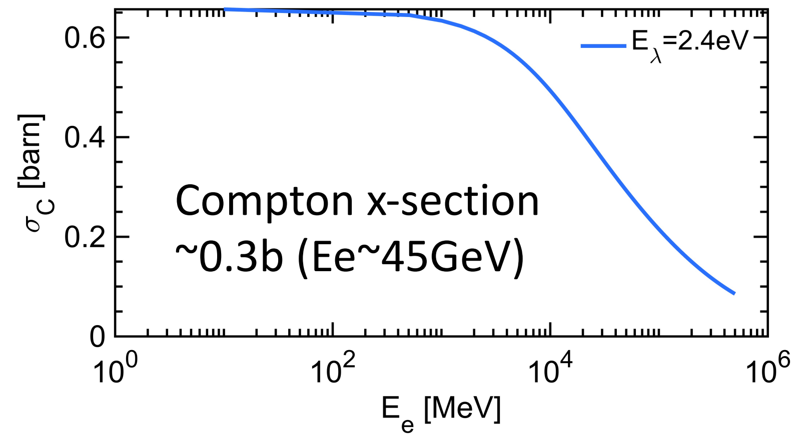
↓

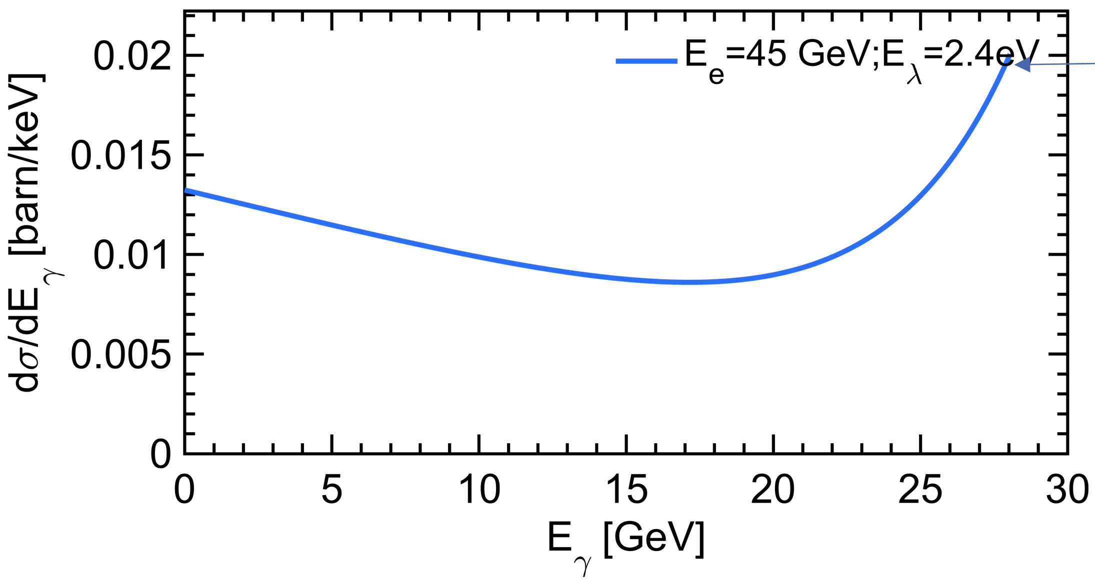
High precision polarimetry in all directions AND accurate spin propagation desired for colliding bunches too

Can the same polarimeter be used for both colliding (accurate P measurement) and pilots bunches (accurate E measurement from P) ?

The Compton process

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





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.)

Compton polarimeter layout

Blondel et al., arXiv:1909.12245

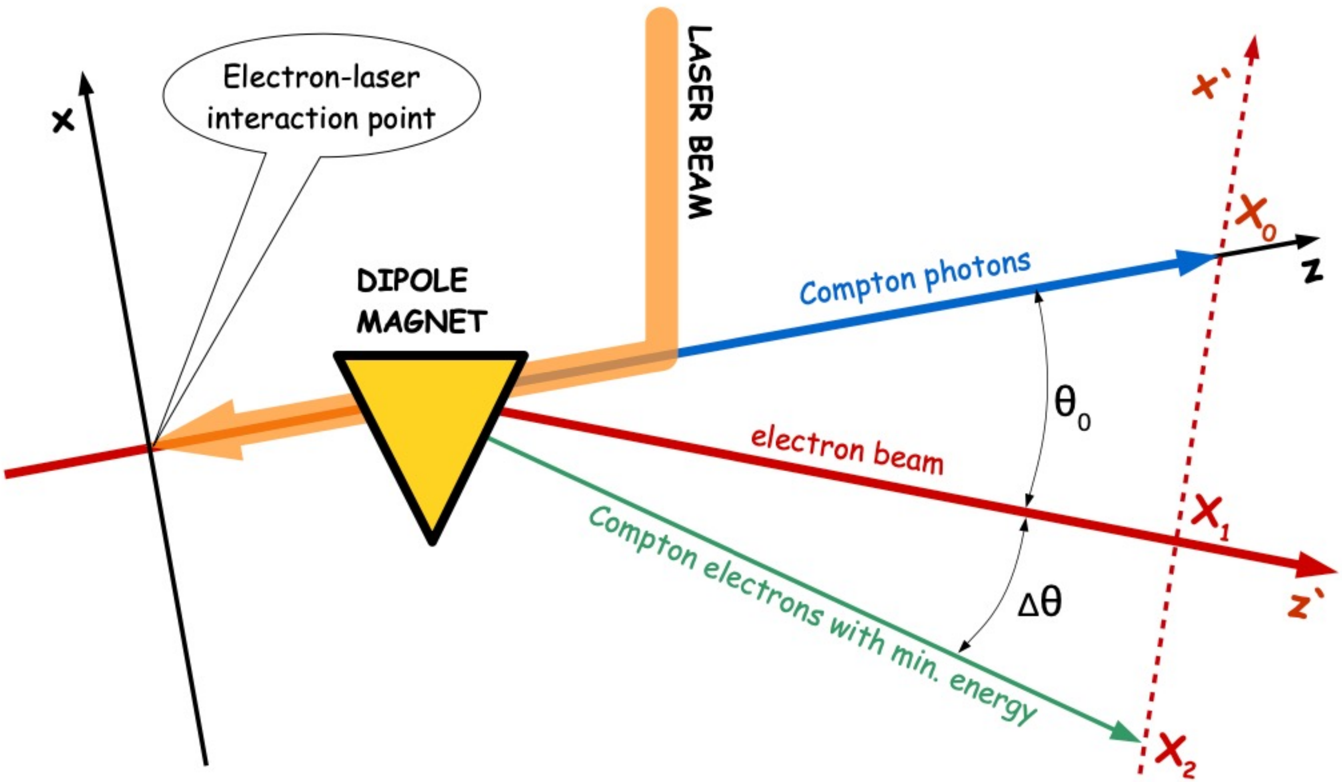


Figure 25. Regular layout of ICS experiments realization.

Redundancy: measure both electrons and photons

Compton cross-section

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

Berestskii & Lfshitz QED textbook

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

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

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

Electron beam polarization independent

Electron beam polarization dependent

⚠ But small opening angle of scattered particles:

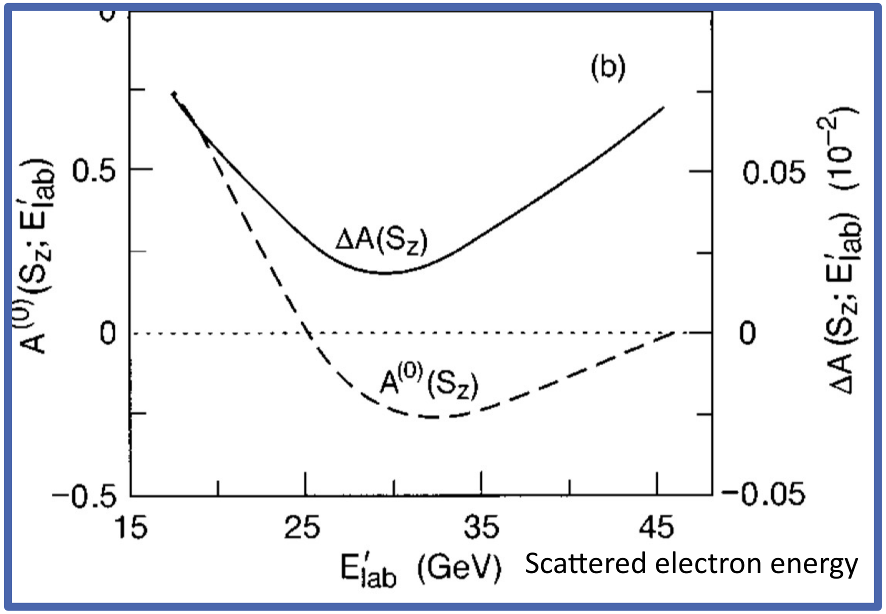
- Electrons → spectrometer
- Photons → difficult to measure asymmetric distribution of a narrow spot → long lever arm needed

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

QED corrections

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

QED corrections<0.001 @ 45 GeV

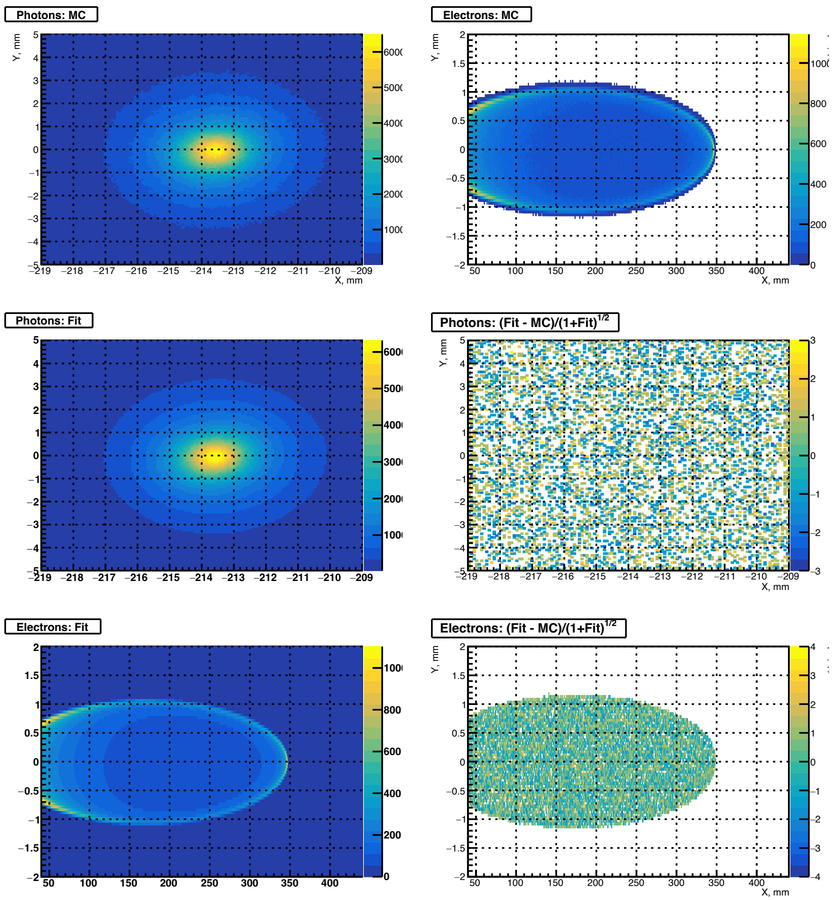


Need to be eventually included in simulations…

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) in a few seconds for pilots

Transverse distributions

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



Monte-Carlo Parameters:
Electron E_0 = 45.600 GeV
Laser λ_0 = 0.532 um
Electron $\gamma = 89.240\times10^3$
Compton κ = 1.628
Bend: $\gamma\theta_0$ = 190.441
(ξ_1, ξ_2, ξ_3) = (0.100, 0.100, 0.990)
$(\zeta_x, \zeta_y, \zeta_z)$ = (0.200, 0.200, 0.200)

All components extracted with ~0.001 precision in few seconds

Intel(R) Core(TM) i3-6100U CPU @ 2.30GHz
Photons fit: t = 75 s (CPU 74 s)
χ^2/NDF = 16476.5/16374 I Prob = 0.2846
X_0 = -213.543 ± 0.002 mm
ξ_1 = 0.107 ± 0.002
ξ_2 = 0.100 ± 0.001
$\xi_3\zeta_x$ = 0.184 ± 0.007
$\xi_3\zeta_y$ = 0.188 ± 0.006
$\xi_3\zeta_z$ = 0.202 ± 0.002
σ_x = 235.0 ± 4.0 um
σ_y = 49.27 ± 9.64 um

Beam energy may be extracted too! → redundancy

Intel(R) Core(TM) i3-6100U CPU @ 2.30GHz
Electrons fit: t = 1193 s (CPU 1260 s)
χ^2/NDF = 48942.0/49849 I Prob = 0.9981
X_1 = -000.025 ± 0.015 mm
X_2 = 0347.562 ± 0.003 mm
ξ_1 = 0.102 ± 0.001
$\xi_3\zeta_y$ = 0.195 ± 0.002
$\xi_3\zeta_z$ = 0.196 ± 0.001
σ_x = 274.3 ± 3.3 μm
σ_y = 28.31 ± 0.03 μm
E_{beam} = 45.5984 ± 0.0051 GeV.

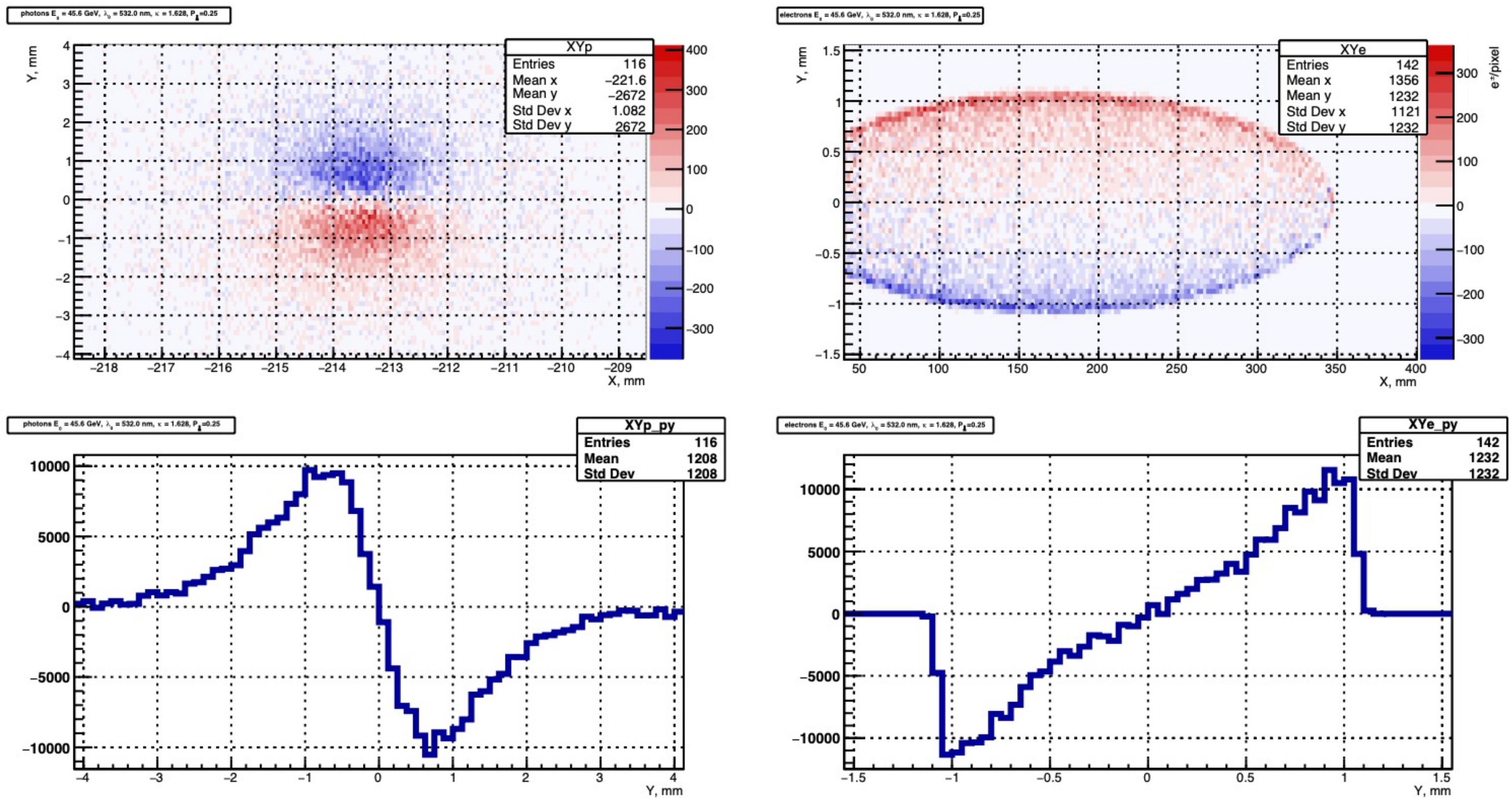
Realistic detector specifications to be drawn

Open questions: detector spatial resolution, longitudinal sampling, rates, combined fits, laser polarization flips,…

Blondel et al., arXiv:1909.12245

Laser helicity asymmetries

Blondel et al., arXiv:1909.12245



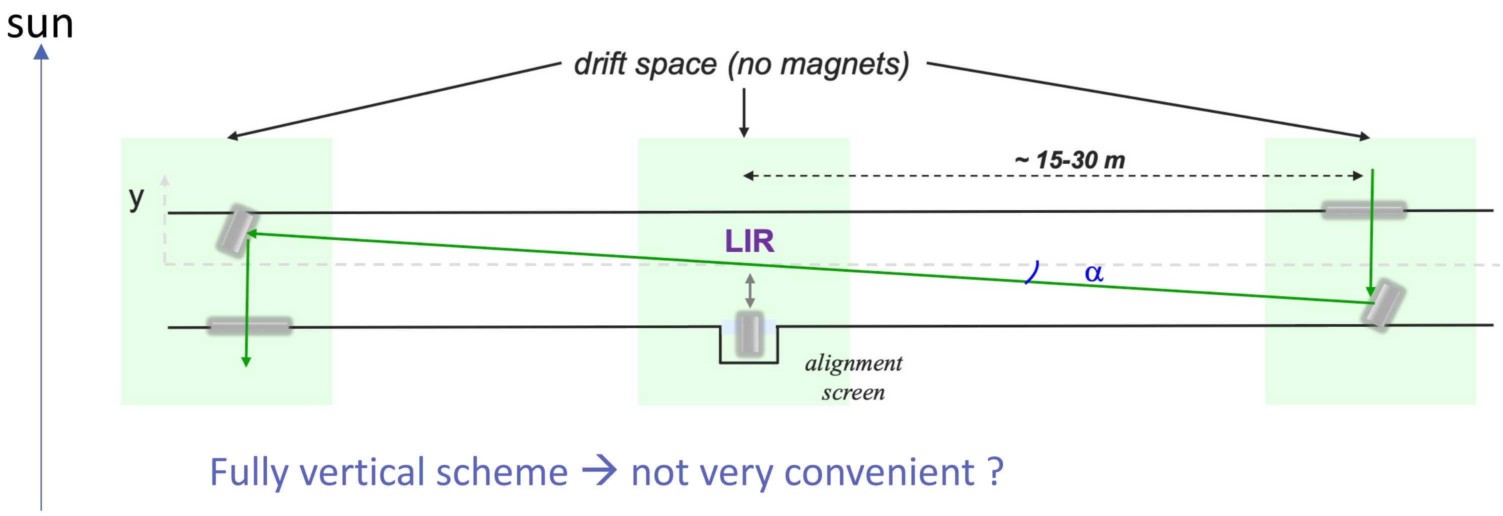
Reproductible and well known laser helicity flip is required

Laser injection

Some constraints

- Small crossing angles are preferred (cross-section, beam jitters) few mrad typically
- Vertical crossing angle is preferred (space and synchrotron in horizontal plane)
- beam impedance
- beam induced currents in metallic parts
- mechanical stability
- ease of maintenance works

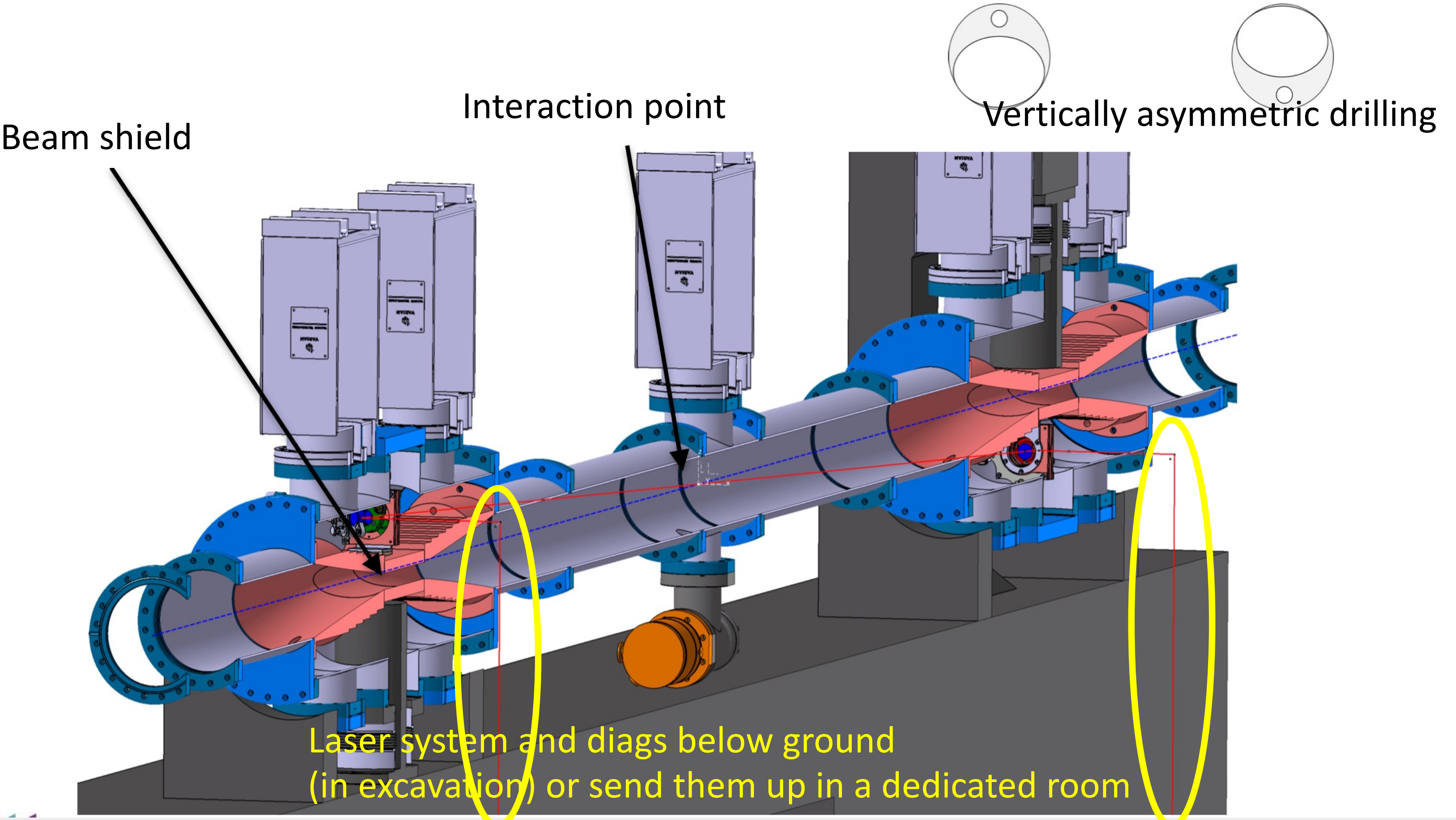
Blondel et al., arXiv:1909.12245



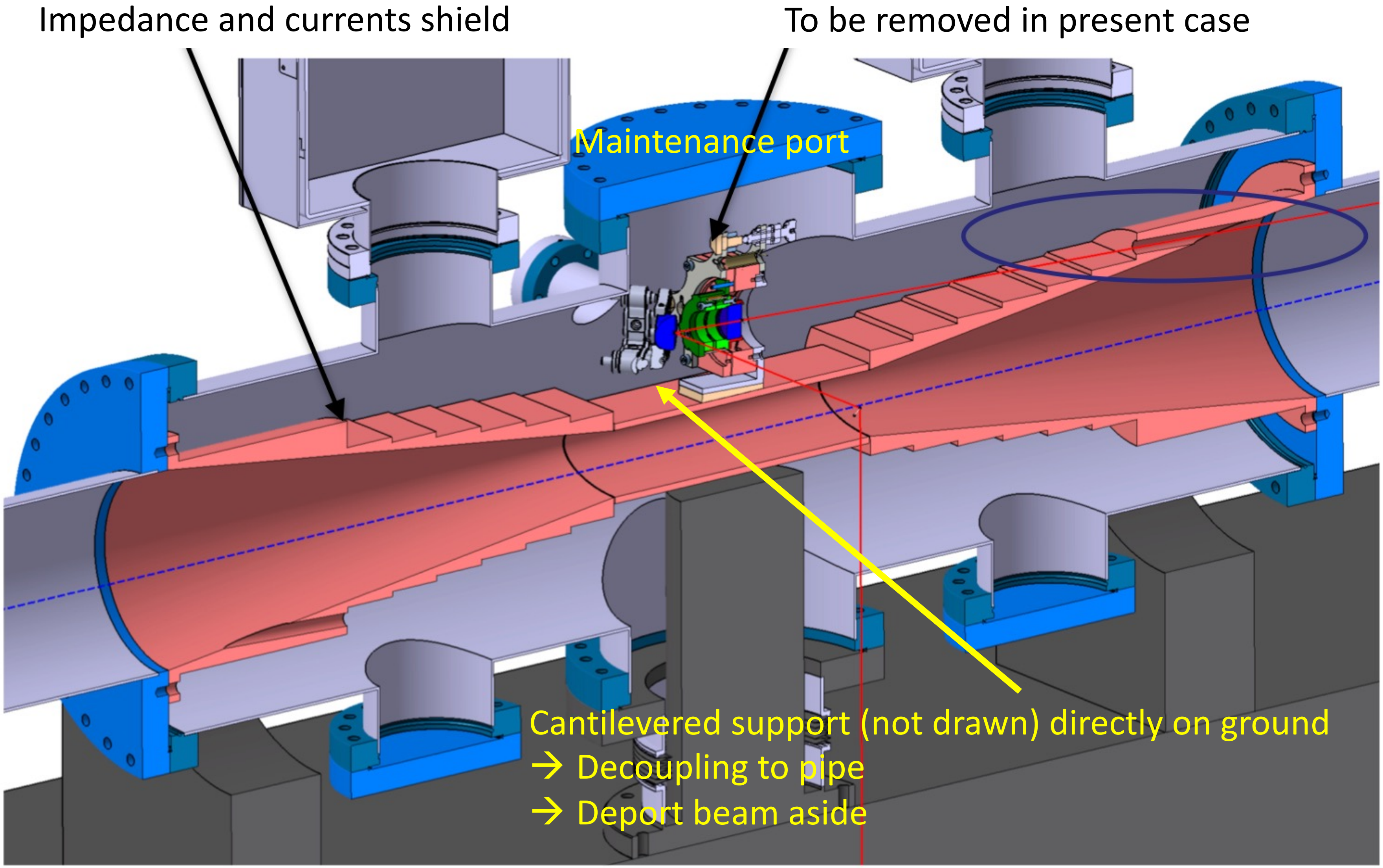
Fully vertical scheme → not very convenient ?

Laser injection: some inspiration

Gamma Factory SPS proof of principle optical cavity mechanical design could be adapted ?

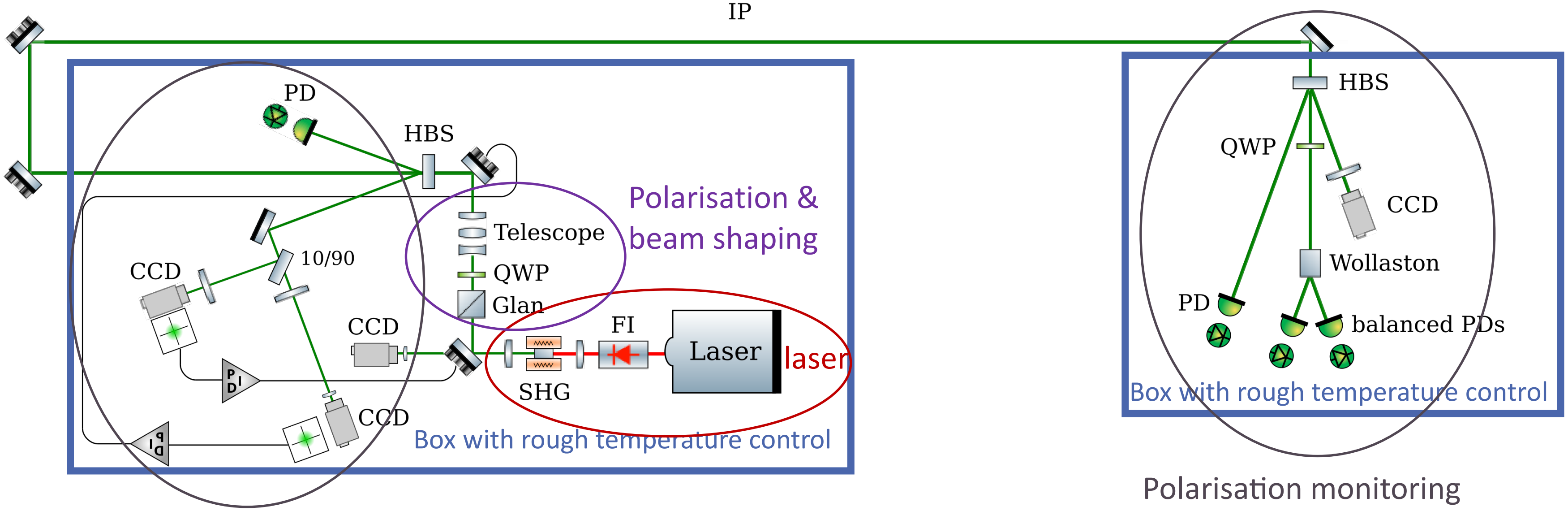


Laser injection: some inspiration



Schematic layout of laser system

Rough design based on past experience, similar to other polarimeters



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

Polarisation monitoring
Duplicated at injection
Add Position and pointing monitoring

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

Some comments

- usual scheme for polarization control and monitoring rely on DC measurements
- actual figures for beam size are constrained by integration related issues (inputs needed)
- Laser polarization flipping rate ?

R&D path: photo-elastic modulators allow to measure polarization with FFT or lock-in detection techniques (synergy with SuperKEKB upgrade)

S. Barneljee, M. Roney et al., Upgrading SuperKEKB with a Polarized Electron Beam

Scattered photon rate

Laser-beam single pulse energy

Compton cross-section

pilots

Electron bunch charge (25nC or 6nC)

Geometrical factor

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

<u>*Photon rate*</u> $n = \sigma_C \frac{\mathcal{E}}{E_\lambda} \frac{Q}{q} \frac{\mathcal{F}}{4\pi\sigma_y\sigma_x}$

Transverse beam sizes:

- $\sigma_{x,y,z} = \sqrt{\sigma^2_{x,y,z,laser} + \sigma^2_{x,y,z,e-}}$
- $\sigma_{x,laser} = \sigma_{y,laser}$=300µm
- $\sigma_{x,e-}$ = 200µm, $\sigma_{y,e-}$=25µm, $\sigma_{z,e-} \sim 10$mm

Laser photon energy
(2.4eV for 0.5µm wavelengths)

Some possible laser systems

Nikolai's baseline

Laser param.	1 pilot	1 pilot v2	All colliding bunches (at Z)
Repetition rate	3 kHz	3 kHz	50 MHz
Pulse energy	1 mJ	1 mJ	100 nJ
Pulse duration	5 ns	5 ps (**)	5 ps (**)
Average power	3 W	3 W (***)	5 W (***)
Scattering rate	4×10^5/s (*)	2×10^6/s (****)	2×10^6/s (****)
Scattering rate per bunch	4×10^5/s (*)	2×10^6/s	1.7×10^2/s

Same oscillator may be used but two different amplification schemes

(*) Large piwinski contribution, nearly scales as crossing angle, very dependent on laser beam size (was 2×10^6/s in ref. paper)
(**) Short pulse duration → broader laser spectrum, energy measurement from threshold more difficult
(***) Can be increased to typically ~100W (nowadays) but requires operational validation, management of thermal effects…
(****) not limited by Piwinski contribution → significantly increases when decreasing laser beam size

Conclusion

High precision beams energy calibration

High precision beams polarimetry

24/7 operable Compton polarimeter for pilot and colliding bunches

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

Seems technically achievable with present day technology

Statistical precision compatible with physics requirements

Design being prepared within FCC-FS

A lot of work ahead still (laser design and polarimeter detector design and performance)