FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

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on behalf of FCC-ee FS EPOL group

Energy calibration and monochromatization at the e^+e^- Future Circular Collider

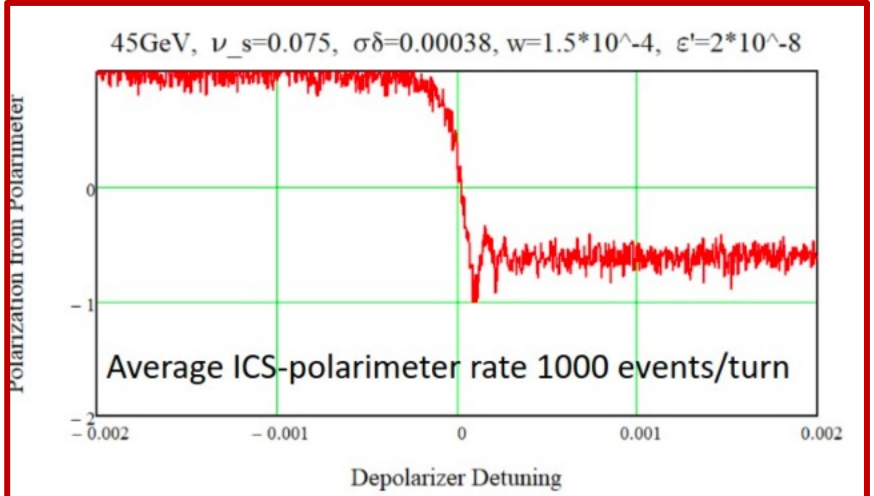
Energy calibration – near and at Z-pole

Extreme precision on the electroweak bosons masses and widths at the core of FCCee physics program

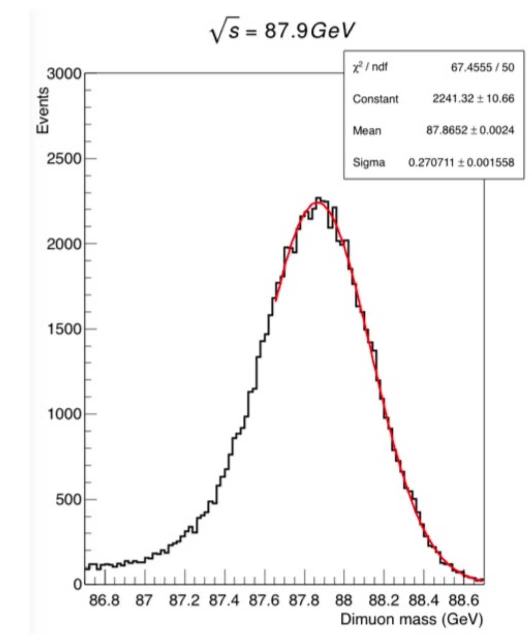
Observable	statistics	$\Delta\sqrt{s}_{\text{abs}}$ 100 keV	$\Delta\sqrt{s}_{\text{syst-ptp}}$ **40 keV**	calib. stats. $200\,\text{keV}/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ $85 \pm \mathbf{0.05}$ MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_W^{\text{eff}} \times 10^6$ from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

Required accuracy of ~1ppm

Resonant depolarization



Muon pairs

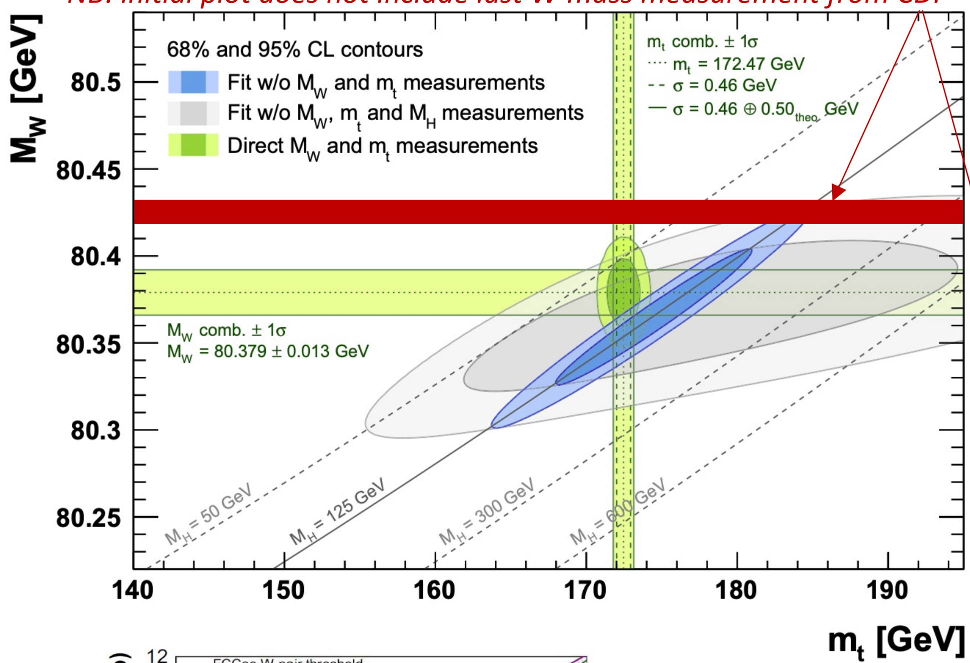


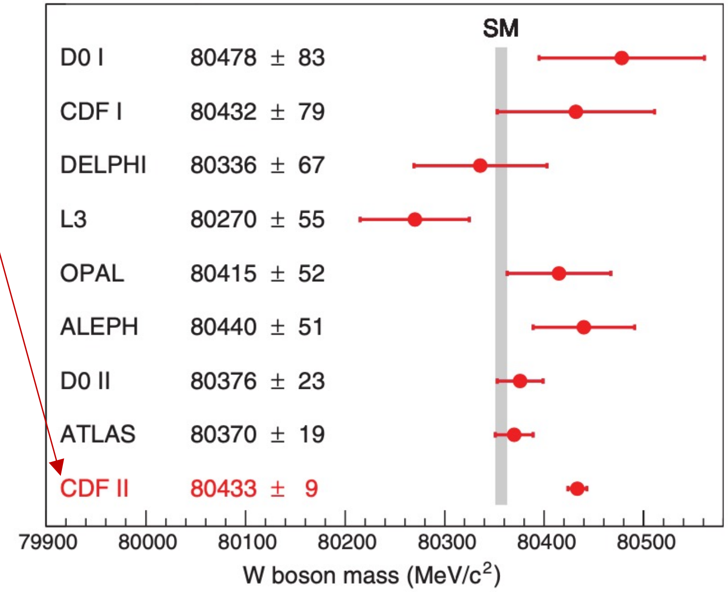
Wise admixture of precise detector data and 24/7 operable measurement of depolarization

Blondel et al., arXiv:1909.12245

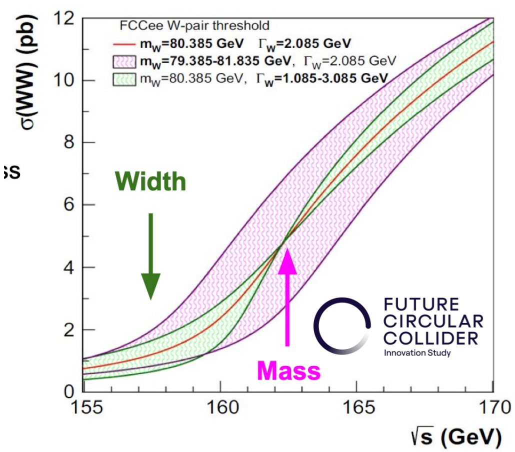
The m_W question

NB: initial plot does not include last W-mass measurement from CDF





Gfitter group, Eur. Phys. J. C (2018) 78:675;
CDF Collaboration et al., Science 376, 170–176 (2022)
Blondel et al., arXiv:1909.12245



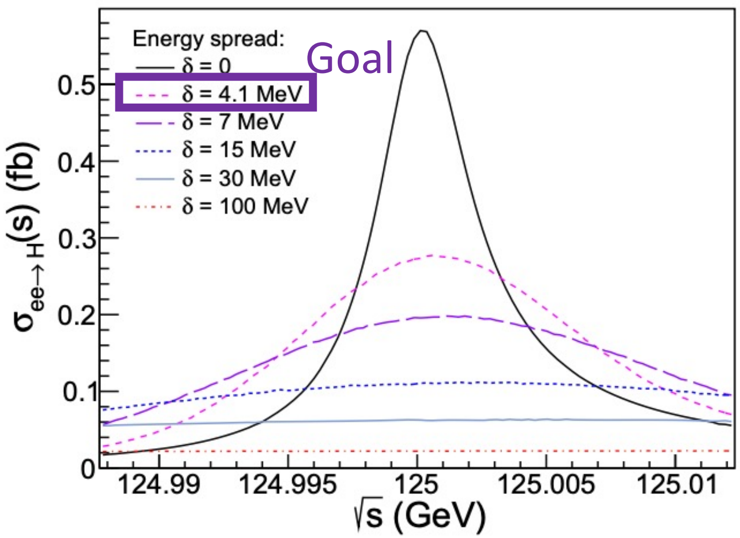
FCC-ee energy calibration is key for a high precision measurement of W mass and width

Expected accuracies:
$$m_W \pm 0.25\ (stat) \pm 0.3\ (syst)$$
$$\Gamma_W \pm 1.2\ (stat) \pm 0.3\ (syst)$$

Energy monochromatization at H pole

High luminosity provides unique opportunity to constrain electron Yukawa
with resonant s-channel Higgs production at FCC-ee

D'Enterria, Eur. Phys. J. Plus (2022) 137:201
Faus-Golfe, Eur. Phys. J. Plus (2022) 137:31; Faus-Golfe, FCC Week 2024 report



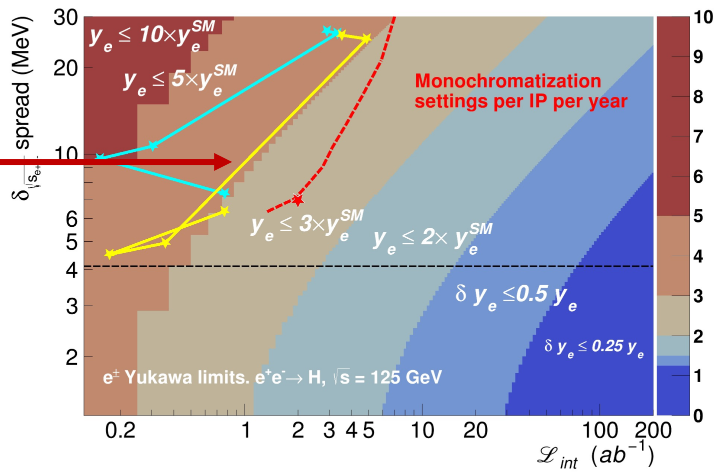
$$\sigma_w = \frac{\sqrt{2}E_b\sigma_\delta}{\lambda} \qquad L = \frac{L_0}{\lambda}$$

$$\lambda = \left(1 + \sigma_\delta^2\left(\frac{D_x^{*2}}{\sigma_{x\beta}^{*2}} + \frac{D_y^{*2}}{\sigma_{y\beta}^{*2}}\right)\right)^{1/2}$$

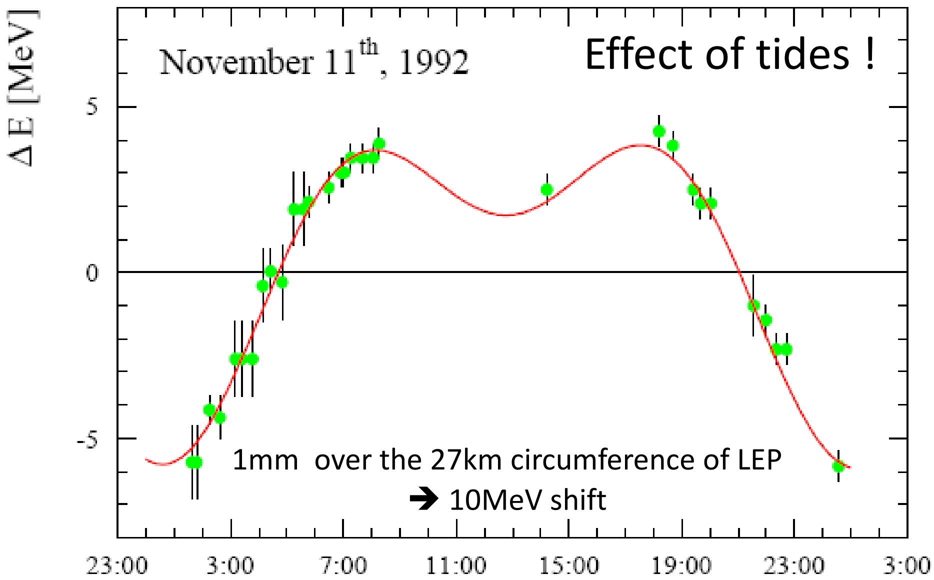
Trade luminosity for monochromaticity

Current status of implementation
(before lattice re-optimisation)

Further improvements expected



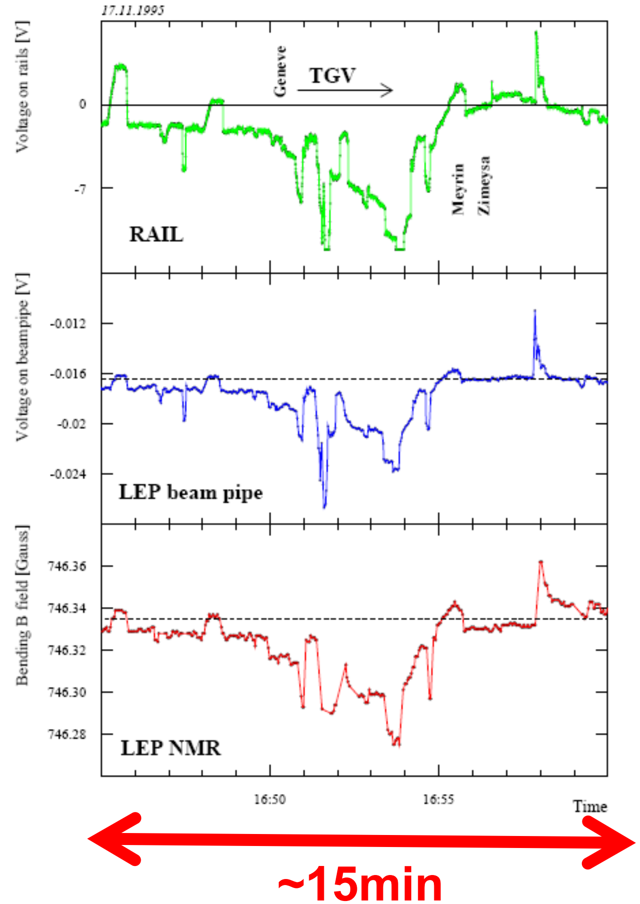
Beam energy model – LEP legacy



A detailed model accounting for tides, parasitic currents, thermal effects in bending magnets,…

FCCee: Recurrent real-time (15min spacing) measurements of beam energy using pilot bunches backed up with instrumentation of few dipoles in ring

Leakage currents !
→ Change fields !
→ Change circumference



Assman et al., Eur. Phys. J. C 6, 187–223 (1999), Assman et al., Eur. Phys. J. C 39, 253–292 (2005)

Resonant depolarization

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)

Q_x … horizontal tune
Q_y … vertical tune
Q_s … synchrotron tune
m_i, k … integer
a … gyromagnetic moment
γ … relativistic gamma

Resonance condition:

$$\underbrace{a\gamma}_{\text{Spin tune for ideal machine}} + \underbrace{m_x Q_x + m_y Q_y}_{\text{Transverse planes}} + \underbrace{m_s Q_s}_{\text{Longitudinal plane}} = k$$

a

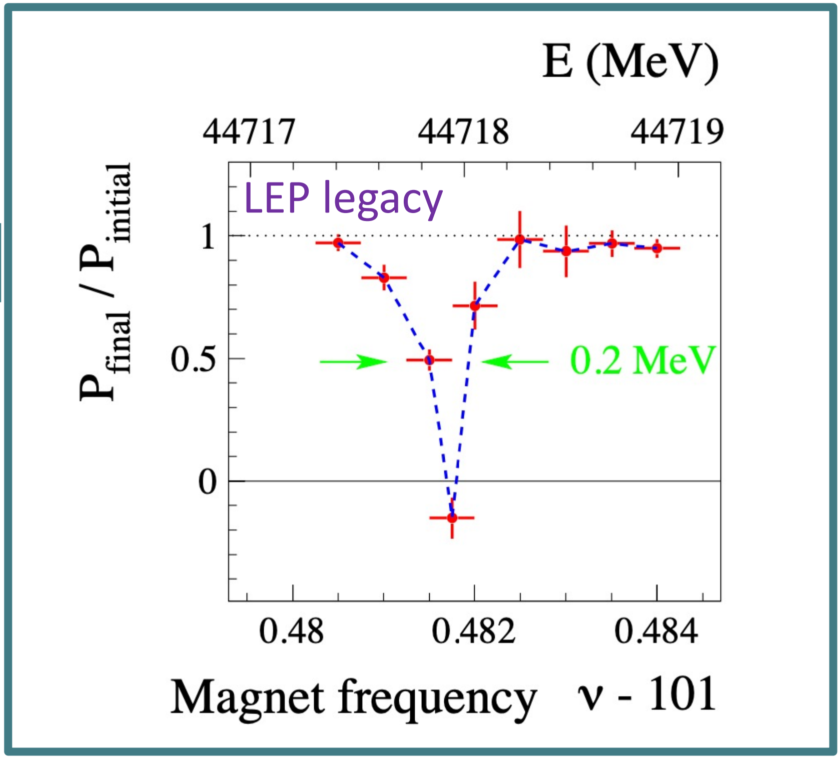
Y. Wu: indico.cern.ch/event/1119730/

Equally-spaced in energy

Scan spin precession frequency with magnetic kicker

↓

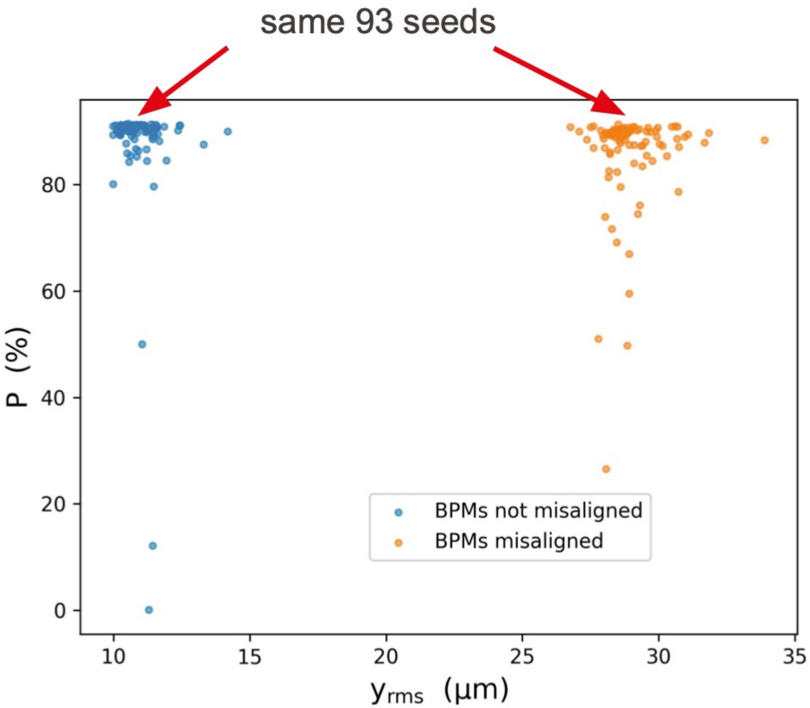
Detect beam depolarization at resonance



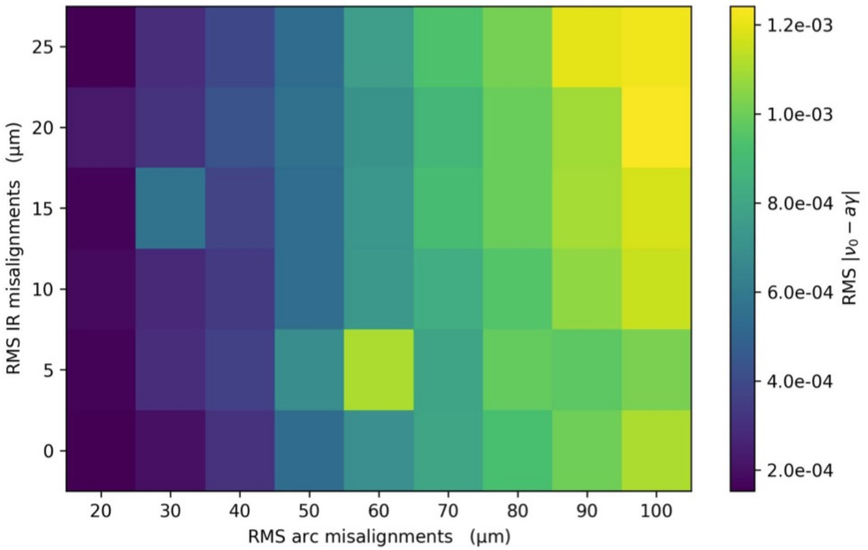
Converts a well calibrated frequency scan in RF element into an accurate energy measurement !

Depolarization sources

Many sources: Stochastic process of quantum emission, Energy dependance of $\hat{n}_0$, misalignments, beam-beam effects at the collision points,...



RMS residual orbit much increased
Variance of polarization increased



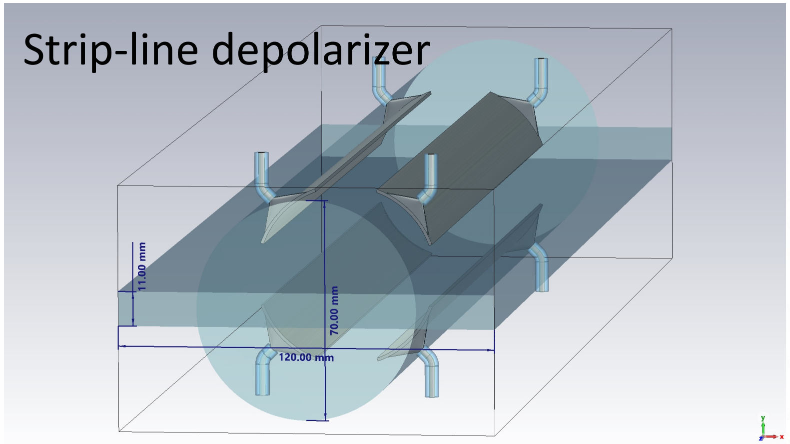
Spin tune shift studied for arc and IR misalignements
Also BPM error and scaling

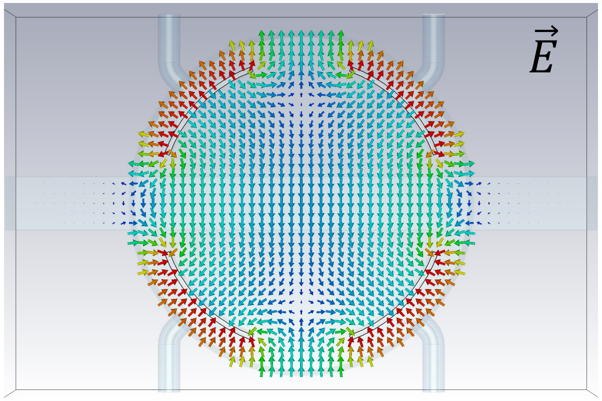
Polarization can be preserved at high degree in presence of misalignments

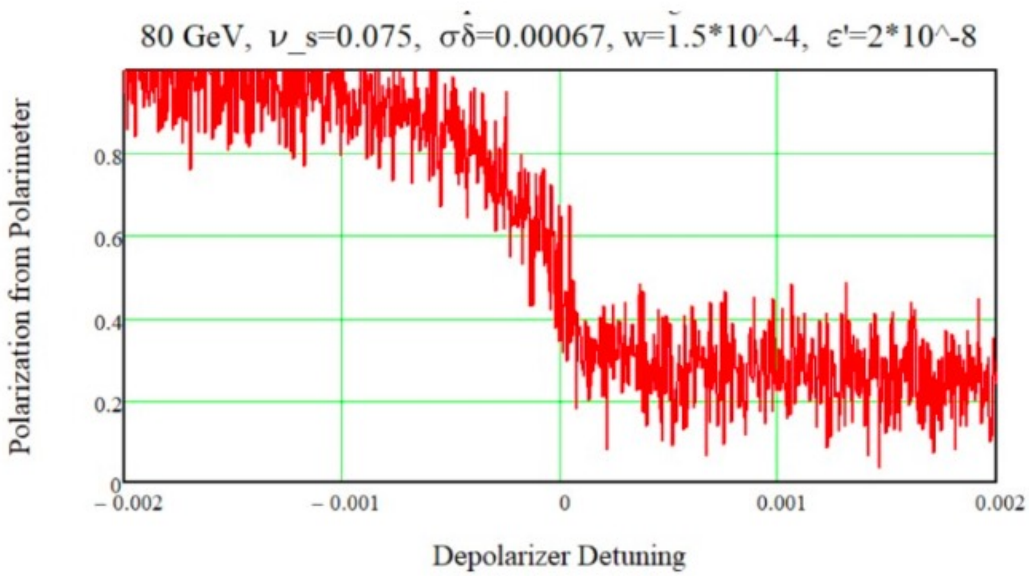
Measurement strategy at FCC-ee

1. Inject hundreds of pilot bunches in ring.
2. Switch on wigglers to reach 10% polarization in ~2h
3. Switch off wigglers
4. Inject colliding bunches and operate collider
5. Depolarize a pilot bunch every ~15min to follow energy changes

} Alternative: Injection of pre-polarized pilots (applies to steps 1–3)







Example of depolarisation exercise at 80 GeV

Höfle, FCC Week 2024 report; Heron, FCC Week 2024 report

Compton polarimetry

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

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

Electron beam polarization independent | *Electron beam polarization dependent*

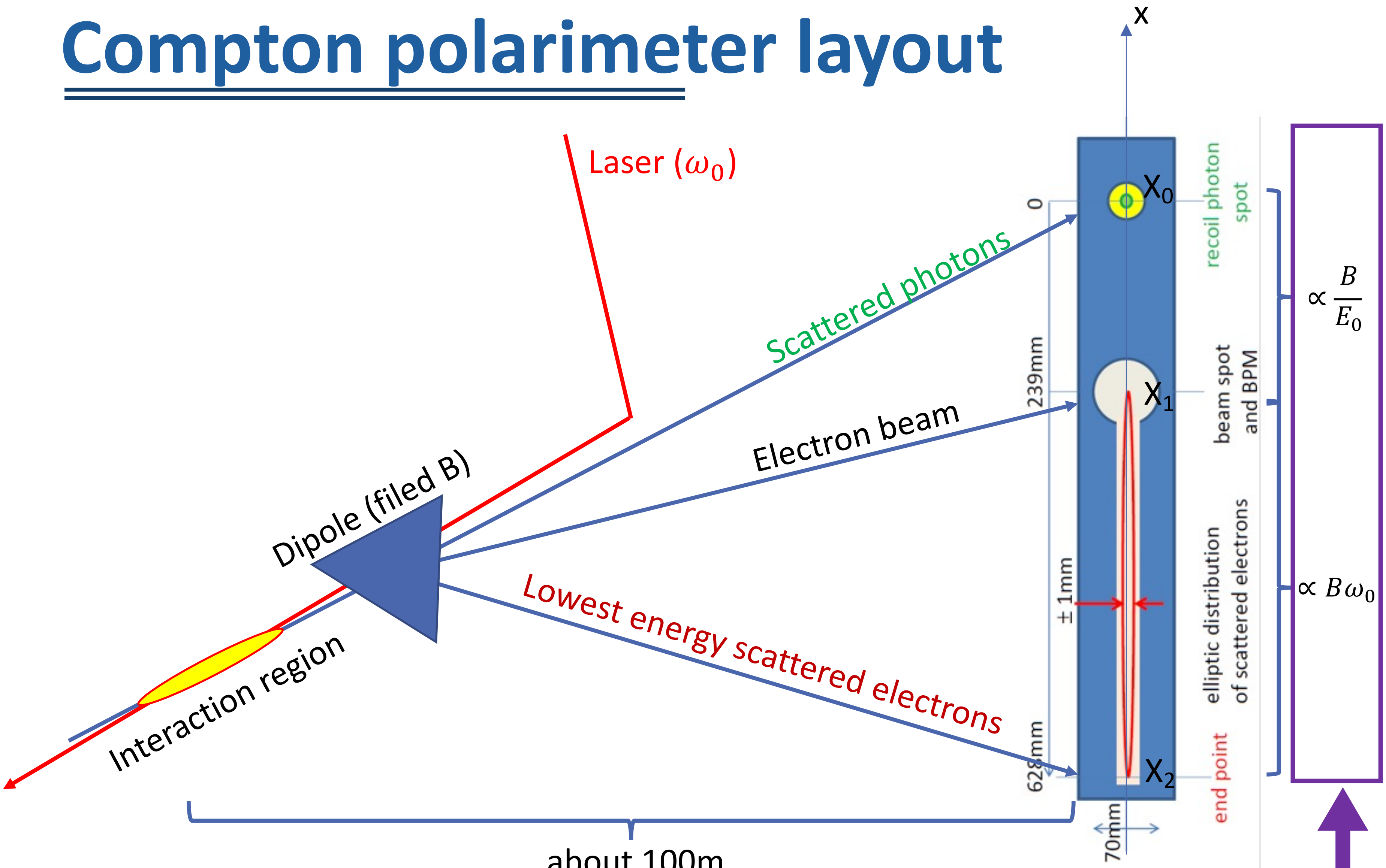
⚠ But small opening angle of scattered particles:

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

Precise Laser polarization control and monitoring required !
→ R&D study needed

Compton polarimeter layout

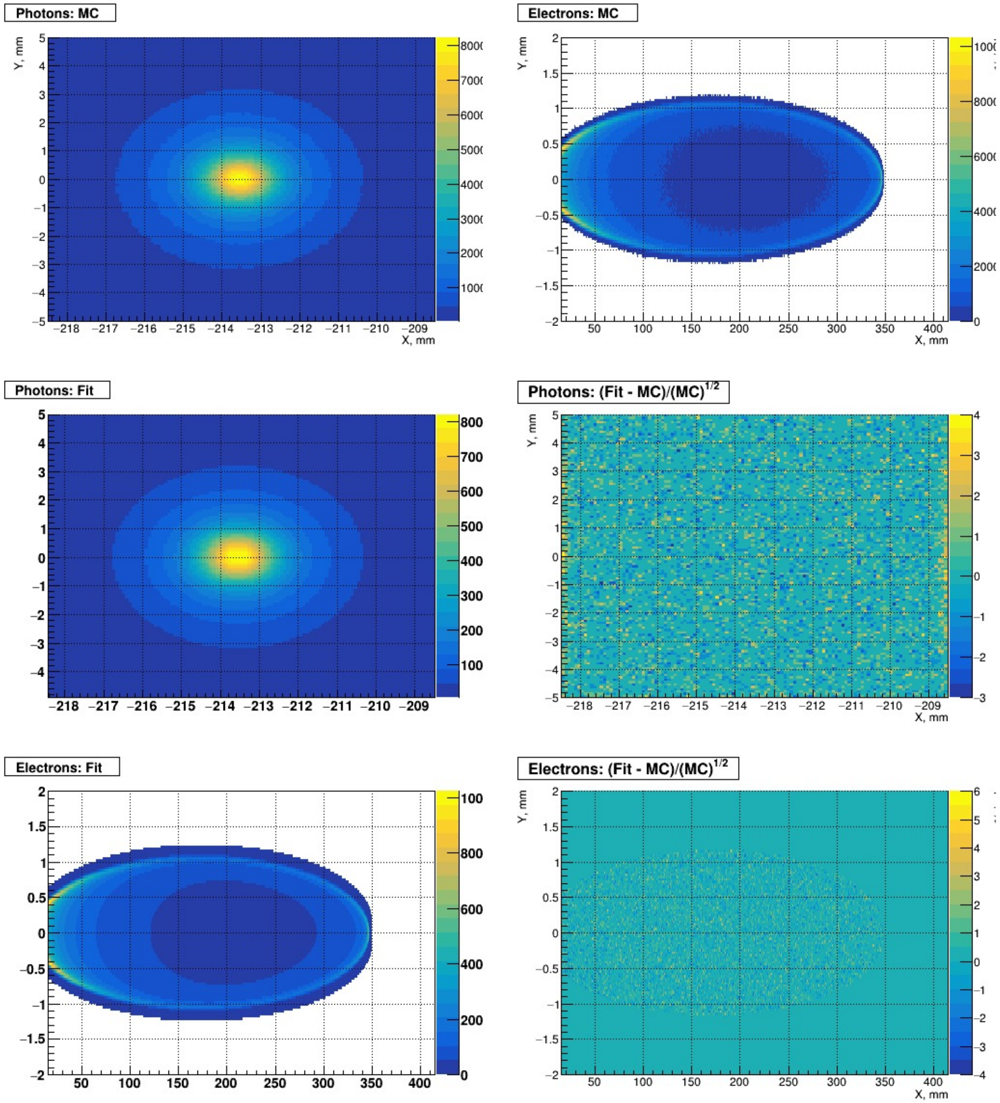
Blondel et al., arXiv:1909.12245; Muchnoi, INST 17 P10014 (2022)



New concept to measure all polarization parameters → 3D polarimeter

Direct energy measurement as a bonus

Typical fit result – 1.5min data taking



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)
$(\zeta_x, \zeta_y, \zeta_z)$ = (0.000, 0.000, 0.000)

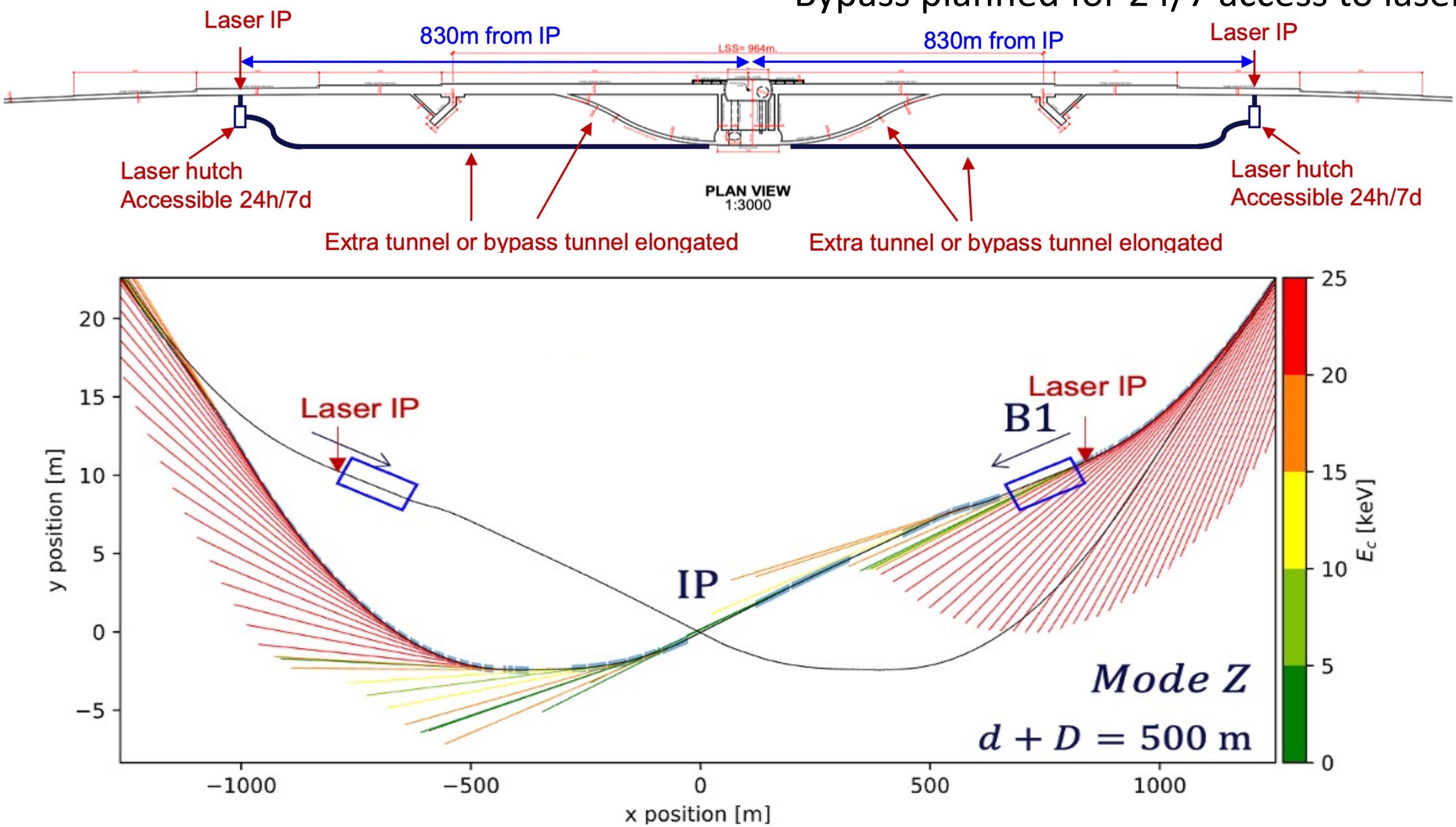
Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Photons fit: t = 1154 s (CPU 1153 s)
χ^2/NDF = 15150.8/14390 | Prob = 0.0000
X_0 = -213.538 $\pm$ 0.001 mm
ξ_1 = 0.001 $\pm$ 0.001
ξ_2 = -0.000 $\pm$ 0.000
$\xi_3\zeta_x$ = -0.001 $\pm$ 0.002
$\xi_3\zeta_y$ = 0.002 $\pm$ 0.002
$\xi_3\zeta_z$ = 0.001 $\pm$ 0.001
σ_x = 252.0 $\pm$ 0.9 μm
σ_y = 27.15 $\pm$ 6.16 μm

Intel(R) Xeon(R) CPU E5-2650 v4 @ 2.20GHz
Electrons fit: t = 22781 s (CPU 22748 s)
χ^2/NDF = 96668.3/96933 | Prob = 0.7258
X_1 = -0.0043 $\pm$ 0.002 mm
X_2 = 347.632 $\pm$ 0.001 mm
ξ_1 = -0.000 $\pm$ 0.001
ξ_2 = 0.000 $\pm$ 0.000
$\xi_3\zeta_x$ = 0.000 $\pm$ 0.000
$\xi_3\zeta_y$ = -0.000 $\pm$ 0.001
$\xi_3\zeta_z$ = 0.001 $\pm$ 0.000
σ_x = 314.0 $\pm$ 1.2 μm
σ_y = 26.49 $\pm$ 0.01 μm
E_{beam} = 45.6008 $\pm$ 0.0008 GeV.

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

Implementation

Bypass planned for 24/7 access to laser room

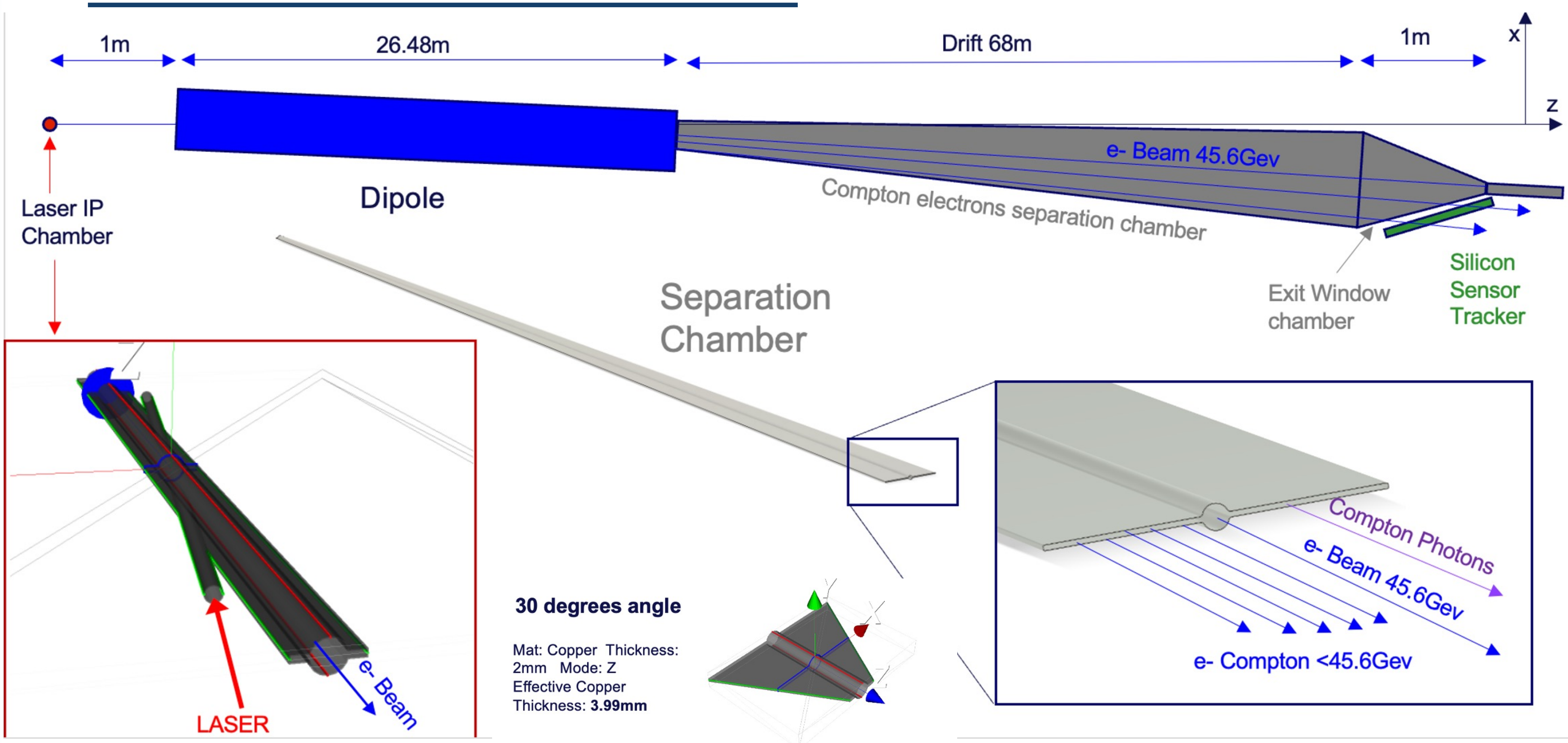


Integration close to IP, also allows to constrain polarization at IP for colliding bunches

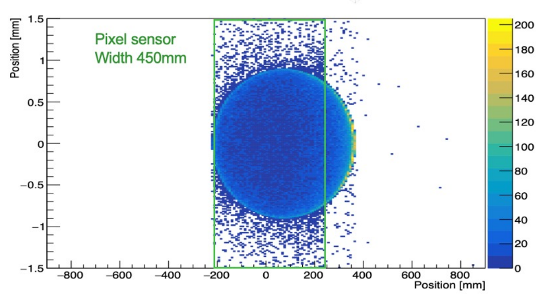
Evaluation of backgrounds (SR, Brem,…) in the Compton polarimeter has started

Kieffer, FCC Week 2024 report

Towards integration



Kieffer, FCC Week 2024 report

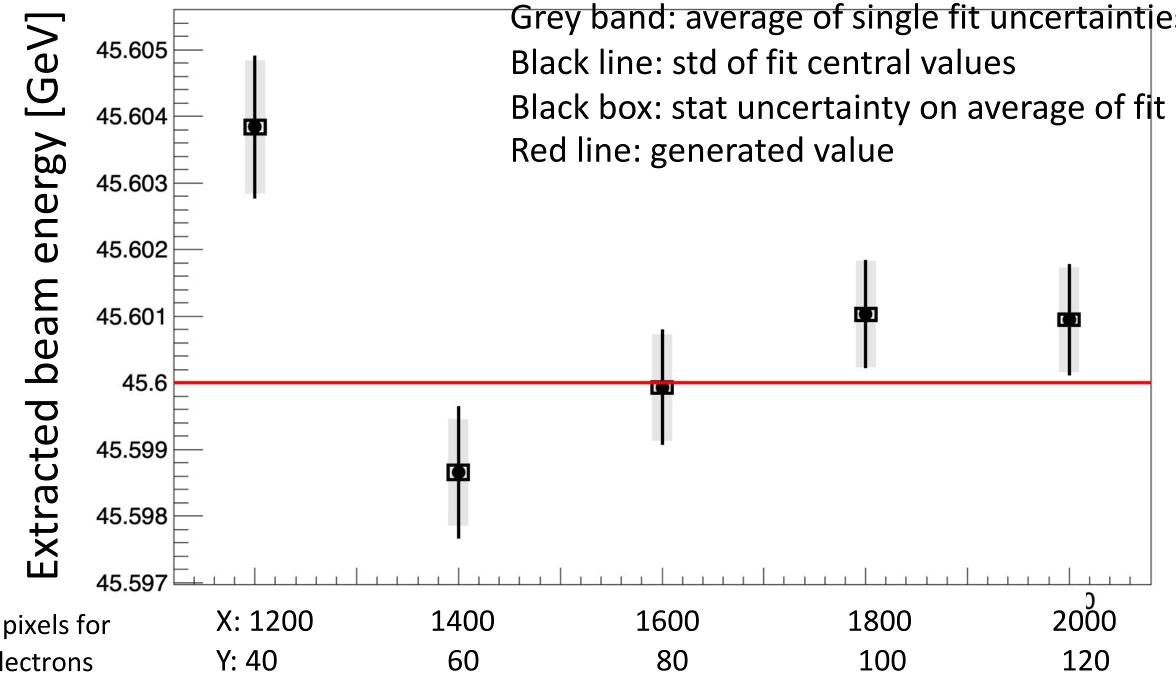


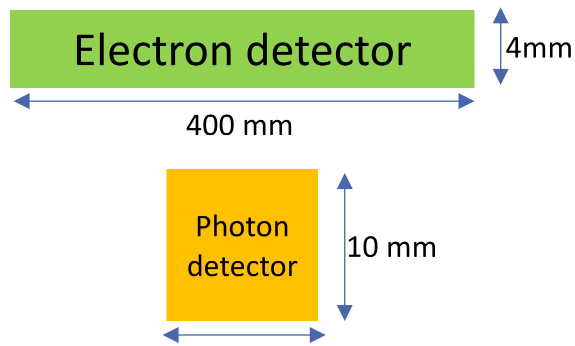
Evaluation of tapering need for impedance and impact on parameter estimation on-going

Preliminary performance studies (E_b)

toy MonteCarlo procedure in place (100 experiments, 10^8 events each)

$$E_b = \frac{(mc^2)^2}{4h\nu_0}\frac{X_2 - X_1}{X_1 - X_0}$$



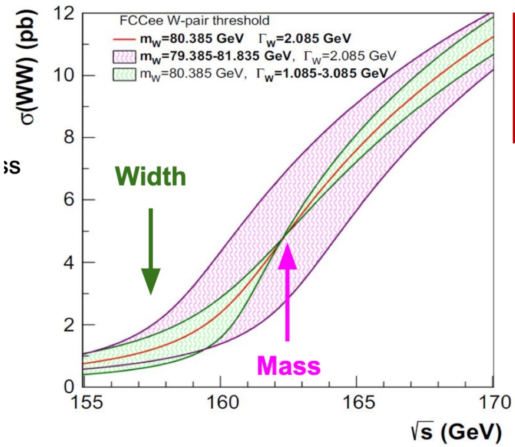


Polarization parameters show <0.1% bias

Fit bias on the extraction of the scattered particle disitributions at µm level
→ Related tight alignement constraints, impact of tapering, backgrounds to be evaluated

Martens, 7th FCC Physics Workshop 2024 report

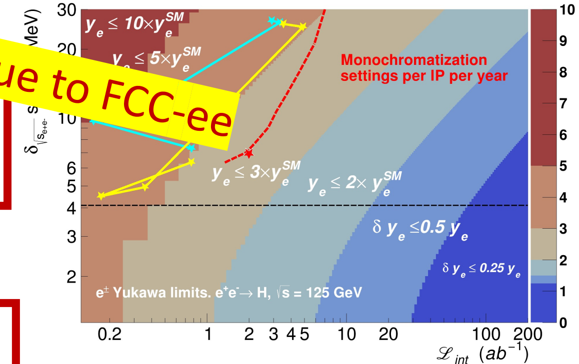
Conclusion & prospects



Extreme precision on the electroweak bosons masses and widths at the core of FCCee physics program

electron-Yukawa coupling via resonant $e^+e^- \rightarrow H$ production

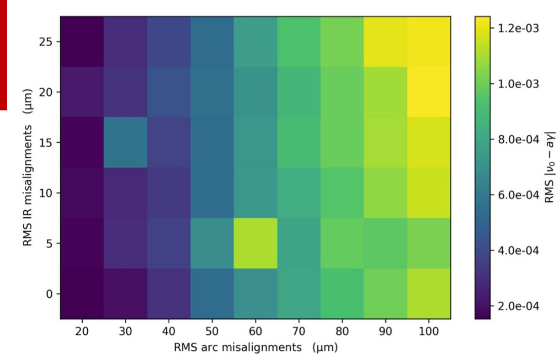
Unique to FCC-ee

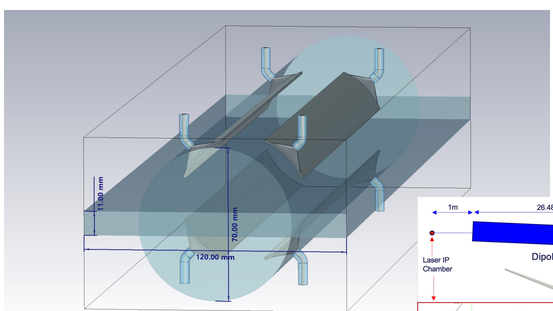


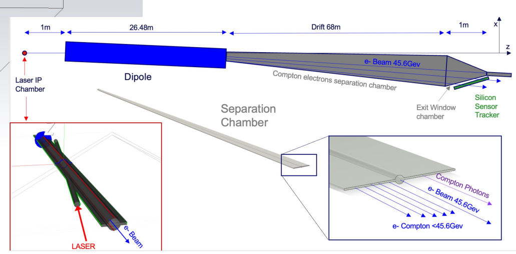
Much progress in all areas towards confirmation of feasibility

100keV accuracy of calibration on $\sqrt{s}$

Few MeV energy spread with monochromatization







No showstopper found at this stage

Huge task still ahead