FUTURE CIRCULAR COLLIDER
Innovation Study

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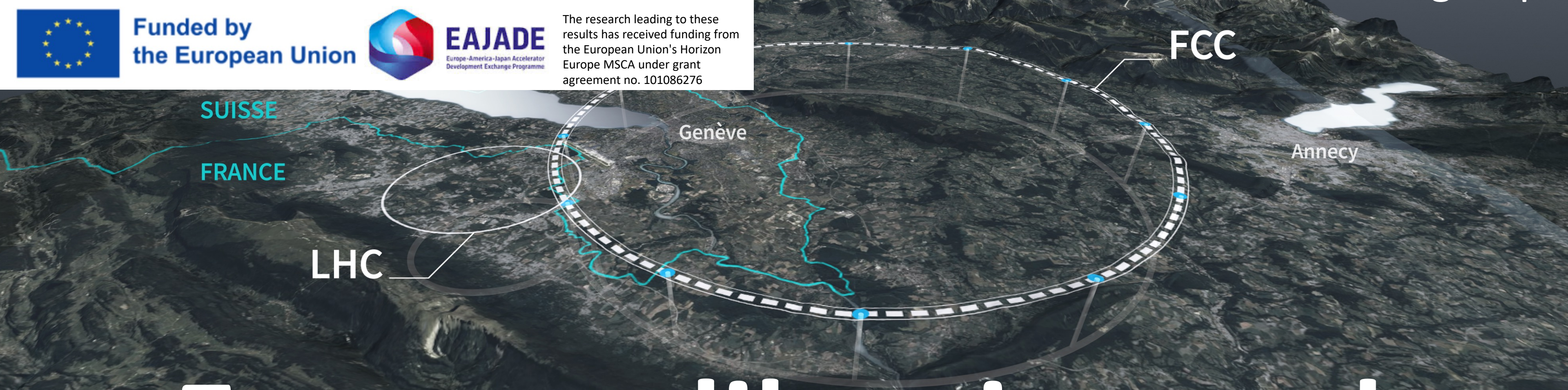
Aurélien MARTENS

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

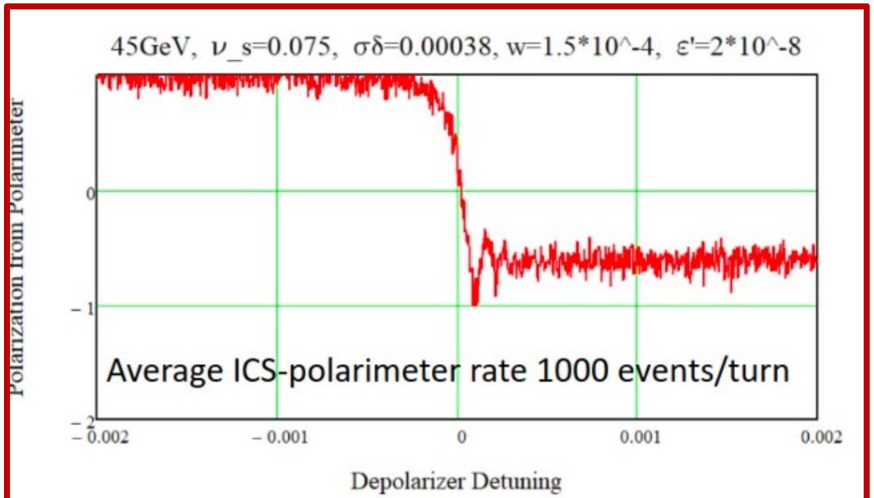
Extreme precision on the electroweak bosons masses and widths at the core of FCCee physics program

Table 24: Current projected $\sqrt{s}$-related uncertainties on selected electroweak observables.

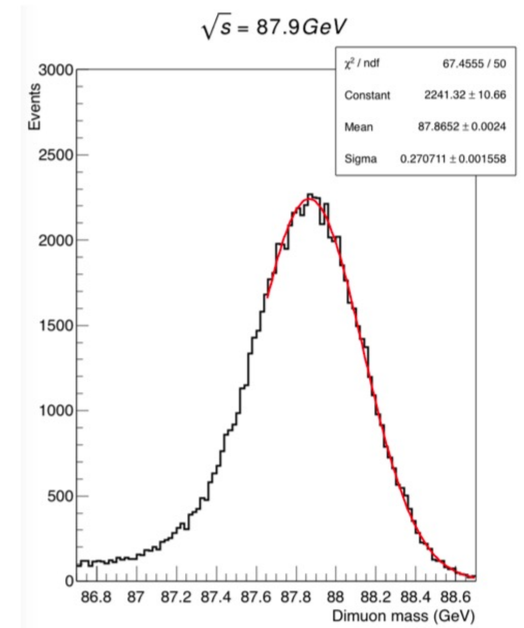
Uncertainty	Observable m_Z (keV)	Γ_Z (keV)	$\sin^2\theta_W^{\text{eff}}$ ($\times10^{-6}$)	$\frac{\Delta\alpha_{\text{QED}}(m_Z^2)}{\alpha_{\text{QED}}(m_Z^2)}$ ($\times10^{-5}$)	m_W (keV)
Absolute	100	2.5	–	0.1	150
Point-to-point	14	11	1.2	0.5	50
Sample size	1	1	0.1	–	3
Energy spread	–	5	–	0.1	–
Total $\sqrt{s}$-related	101	12	1.2	0.5	158
FCC-ee statistical	4	4	1.2	3.9	180

Required accuracy of ~1ppm

Resonant depolarization



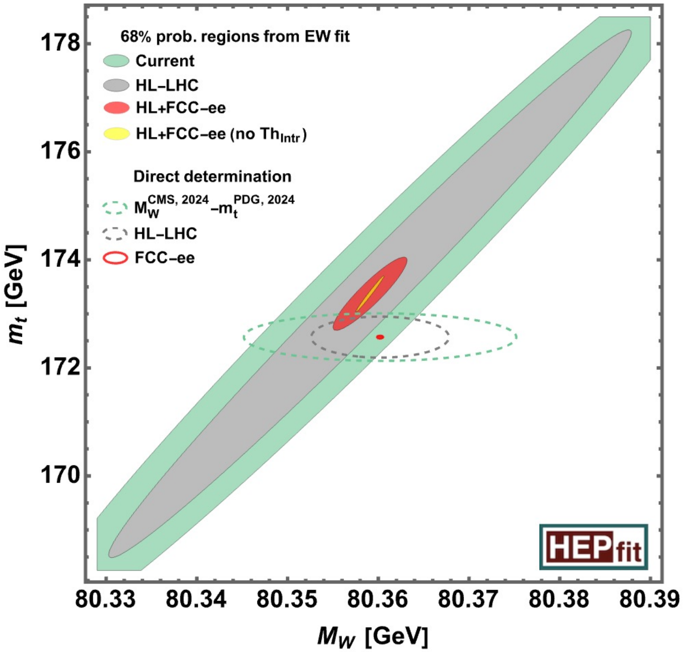
Muon pairs

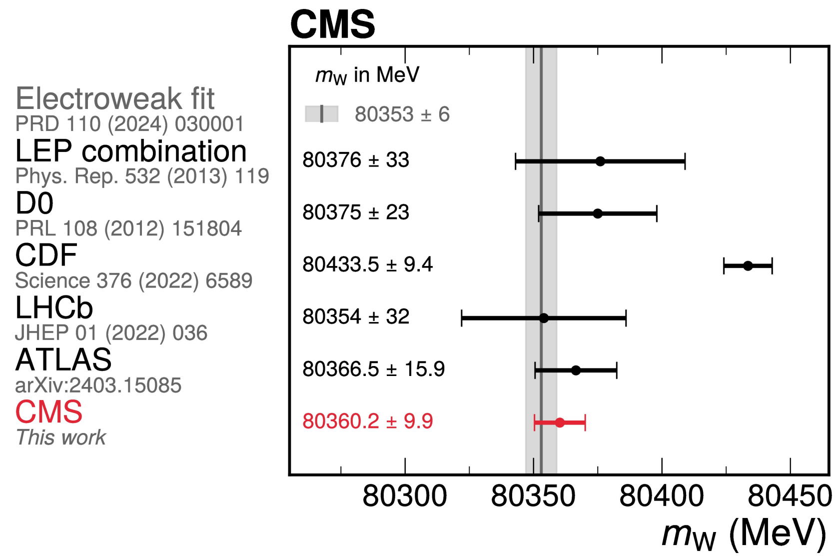


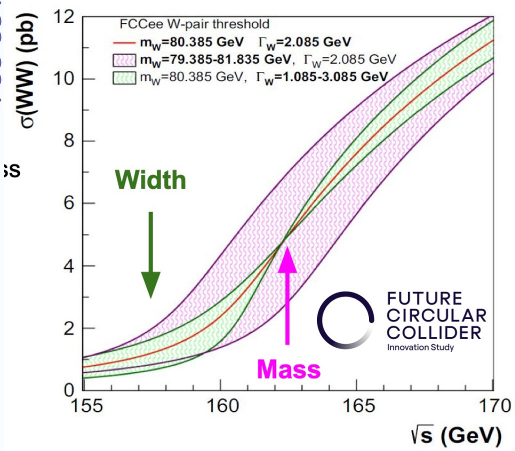
Wise admixture of precise detector data and 24/7 operable measurement of depolarization

FCC-ee Feasibility Report vol. 1, arxiv:2505.00272

Measurement of m_W







https://hepfit.roma1.infn.it/;
CMS Collaboration, arXiv:2412.13872v1
FCC-ee Feasibility Report vol. 1, arXiv:2505.00272

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

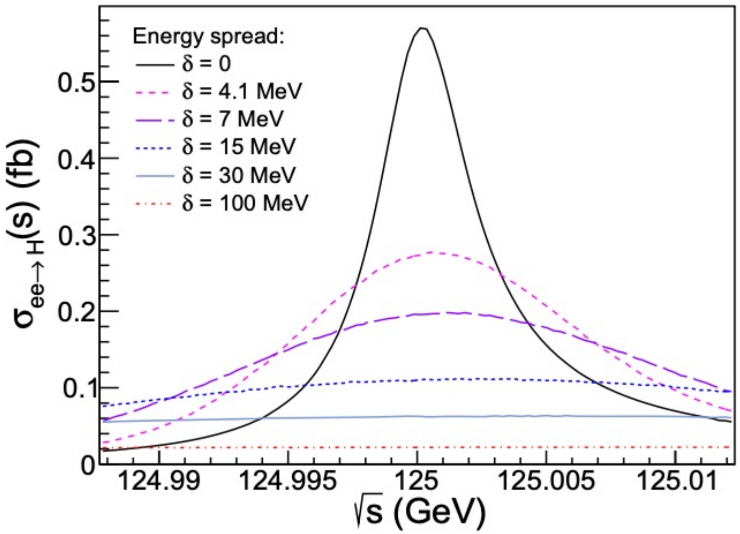
Expected accuracies:

$$m_W \pm 0.18\ (stat) \pm 0.16\ (syst)\ [\text{MeV}]$$
$$\Gamma_W \pm 0.27\ (stat) \pm 0.20\ (syst)\ [\text{MeV}]$$

Energy monochromatization at H pole

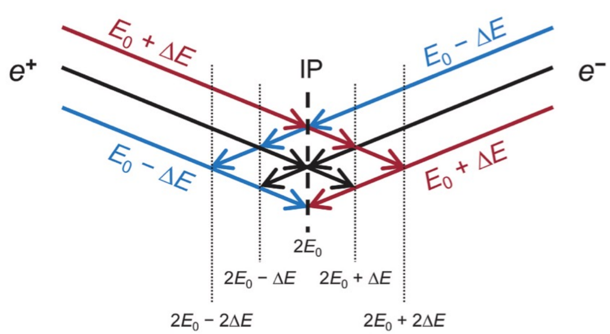
High luminosity provides unique opportunity to constrain electron Yukawa
with resonant s-channel Higgs production at FCC-ee

D'Enterria, Eur. Phys. J. Plus (2022) 137:201 ; Z. Zhang, NIM A 1073 (2025) 170268
FCC-ee Feasibility Report vol. 1, arxiv:2505.00272

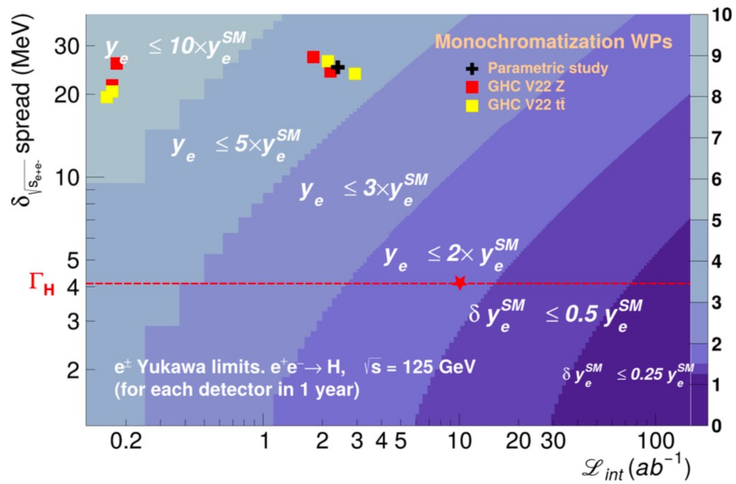


$$\sigma_w = \frac{\sqrt{2}E_b\sigma_\delta}{\lambda} \qquad L = \frac{L_0}{\lambda}$$

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



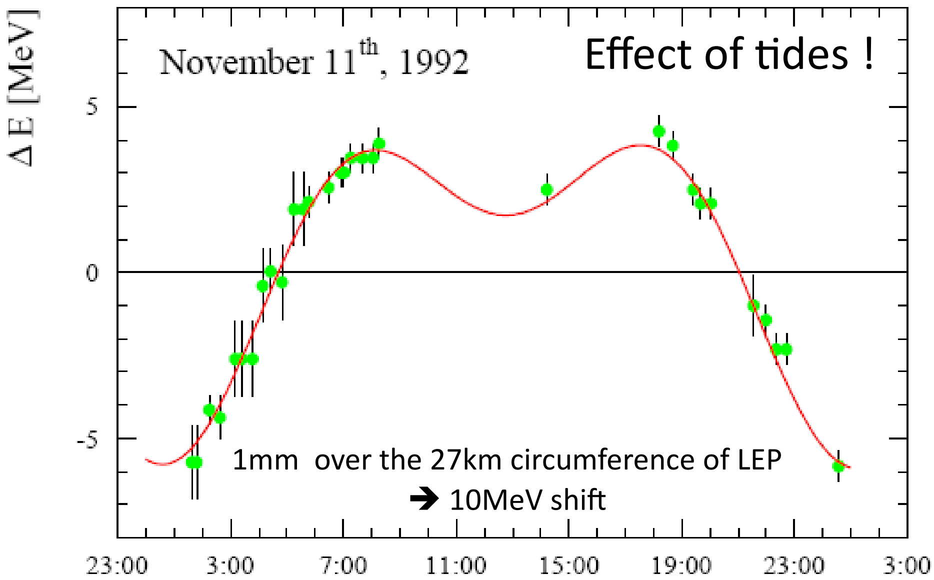
Trade luminosity for monochromaticity



Realistic schemes studied, further improvements expected

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

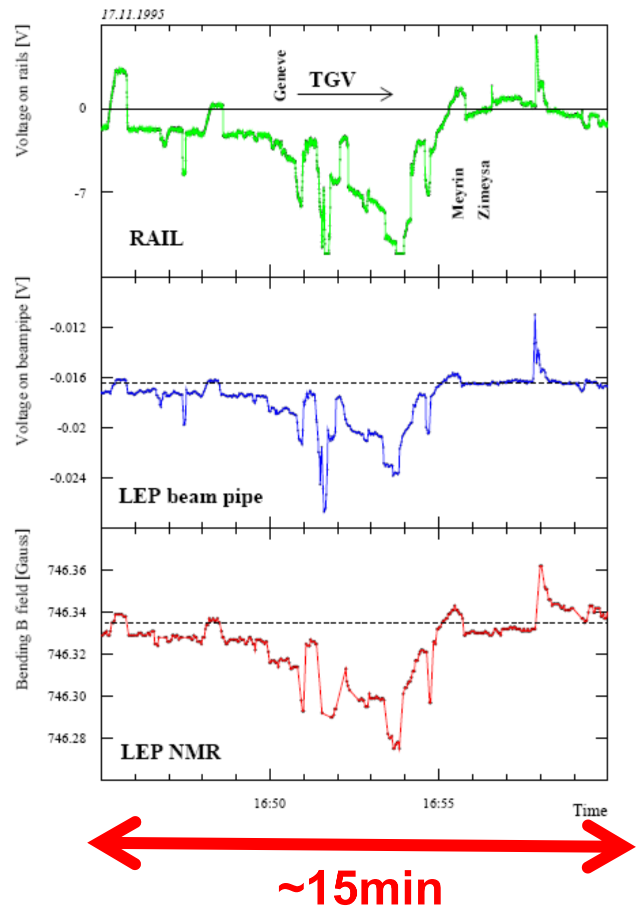
LEP lessons – beam energy variation with time



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

FCC-ee: 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

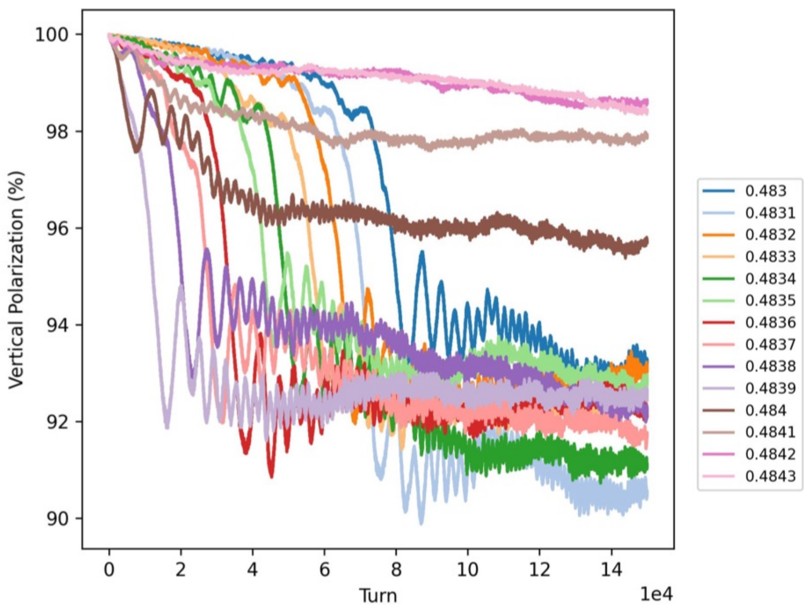


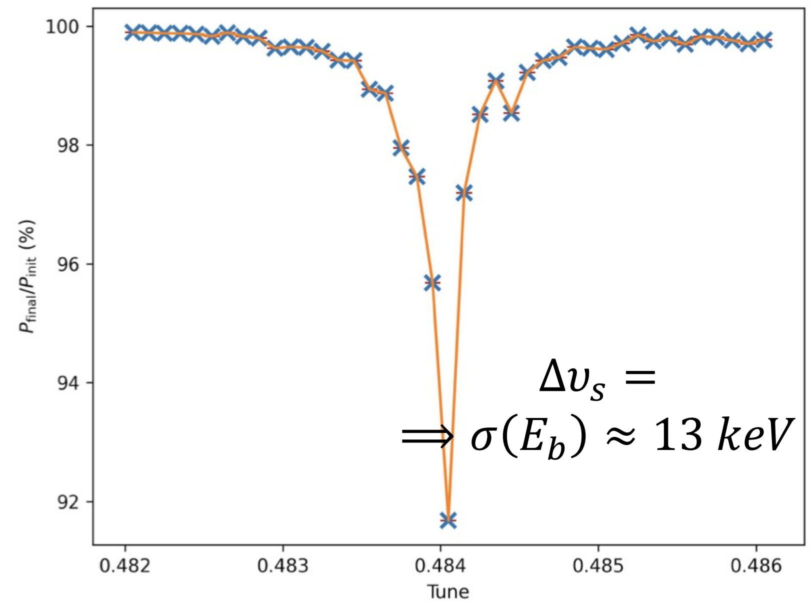
Resonant depolarization – First simulations at FCC-ee

Resonance condition (flat lattice, perfectly aligned):

$$\upsilon_s = \frac{g-2}{2}\langle E_b \rangle \approx \frac{\langle E_b \rangle\ [GeV]}{0.44}$$ Equally-spaced in energy

Scan spin precession frequency with kicker → Detect beam depolarization at resonance



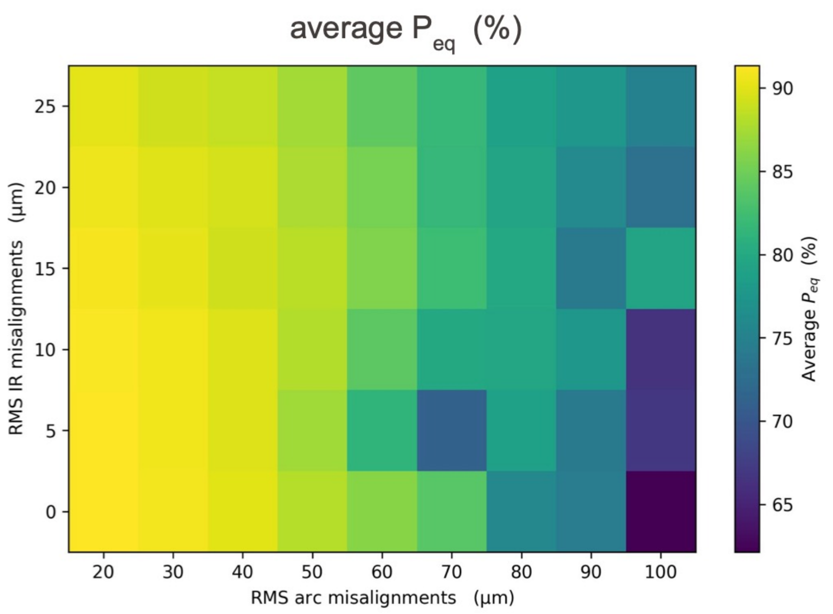


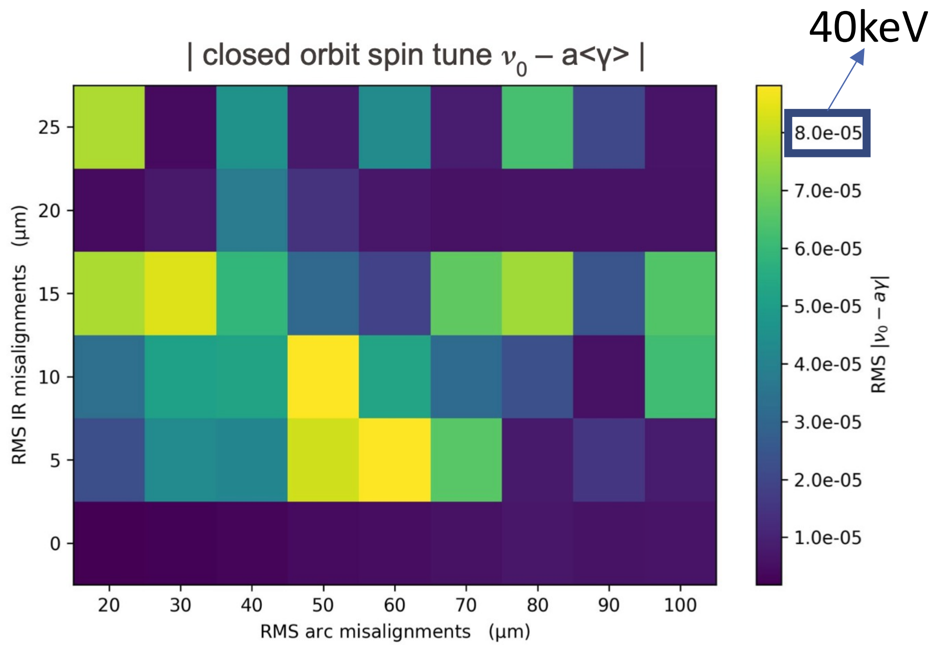
Converts a well calibrated frequency scan in RF element into an accurate energy measurement !

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) ; Y. Wu FCC Week report

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 increased
Variance of polarization increased and average decreased

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

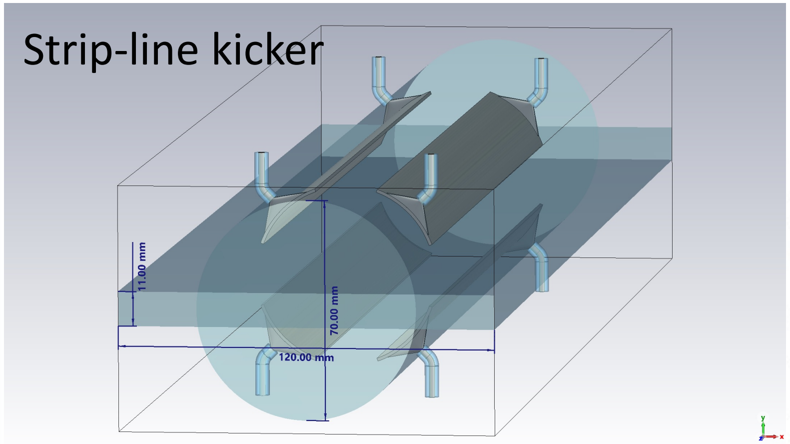
Polarization can be preserved at high degree in presence of misalignments

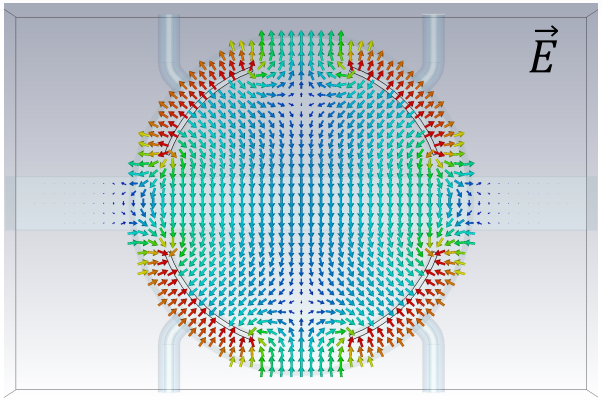
Y. Wu, FCC Week 2025 report

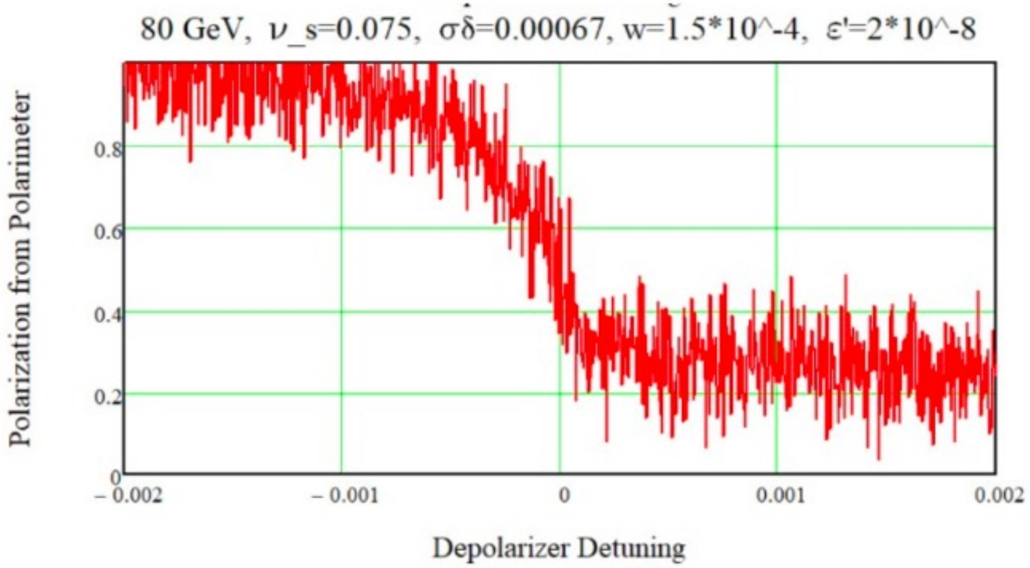
Measurement strategy at FCC-ee

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 being studied







Example of depolarisation exercise at 80 GeV

Höfle, FCC Week 2025 report; Heron, FCC Week 2024 report

Berestskii & Lfshitz QED textbook

Compton polarimetry

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

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

Electron beam polarization independent *Electron beam polarization dependent*

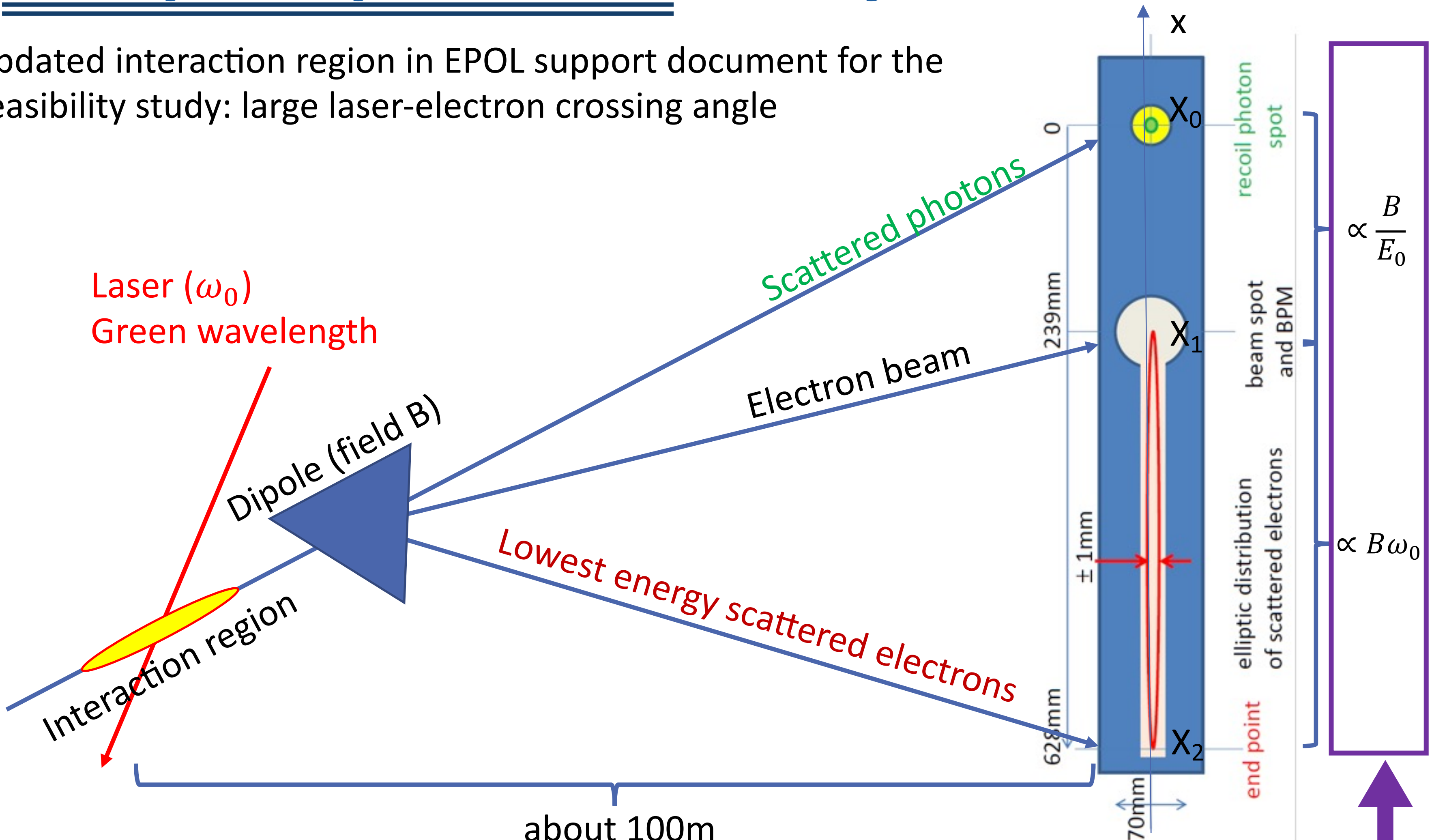
⚠ But small opening angle of scattered particles:

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

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

Compton polarimeter layout

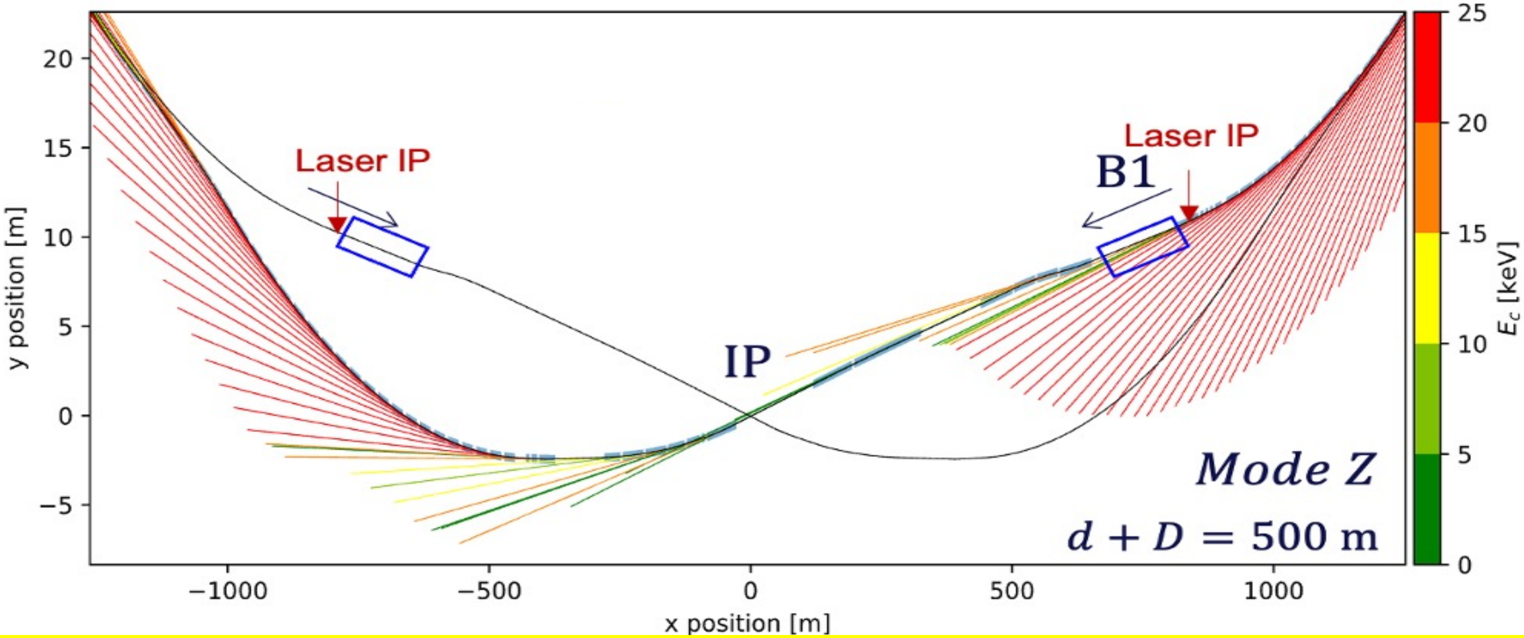
Updated interaction region in EPOL support document for the Feasibility study: large laser-electron crossing angle



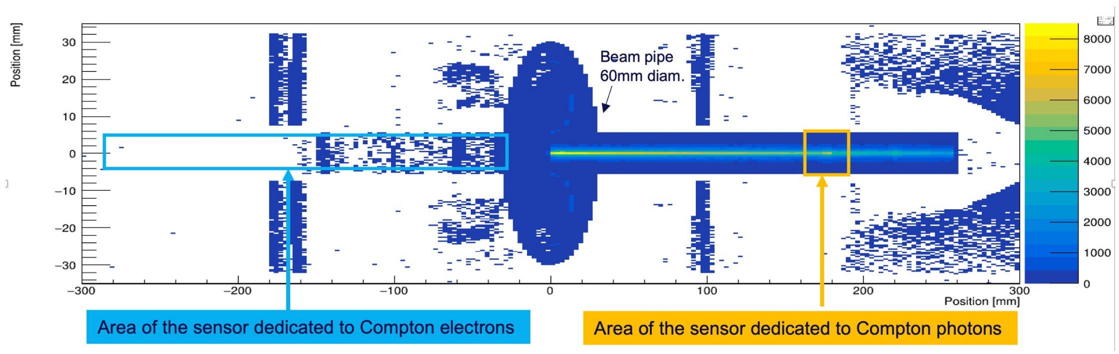
New concept to measure all polarization parameters → 3D polarimeter
Direct energy measurement as a bonus

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

Implementation



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

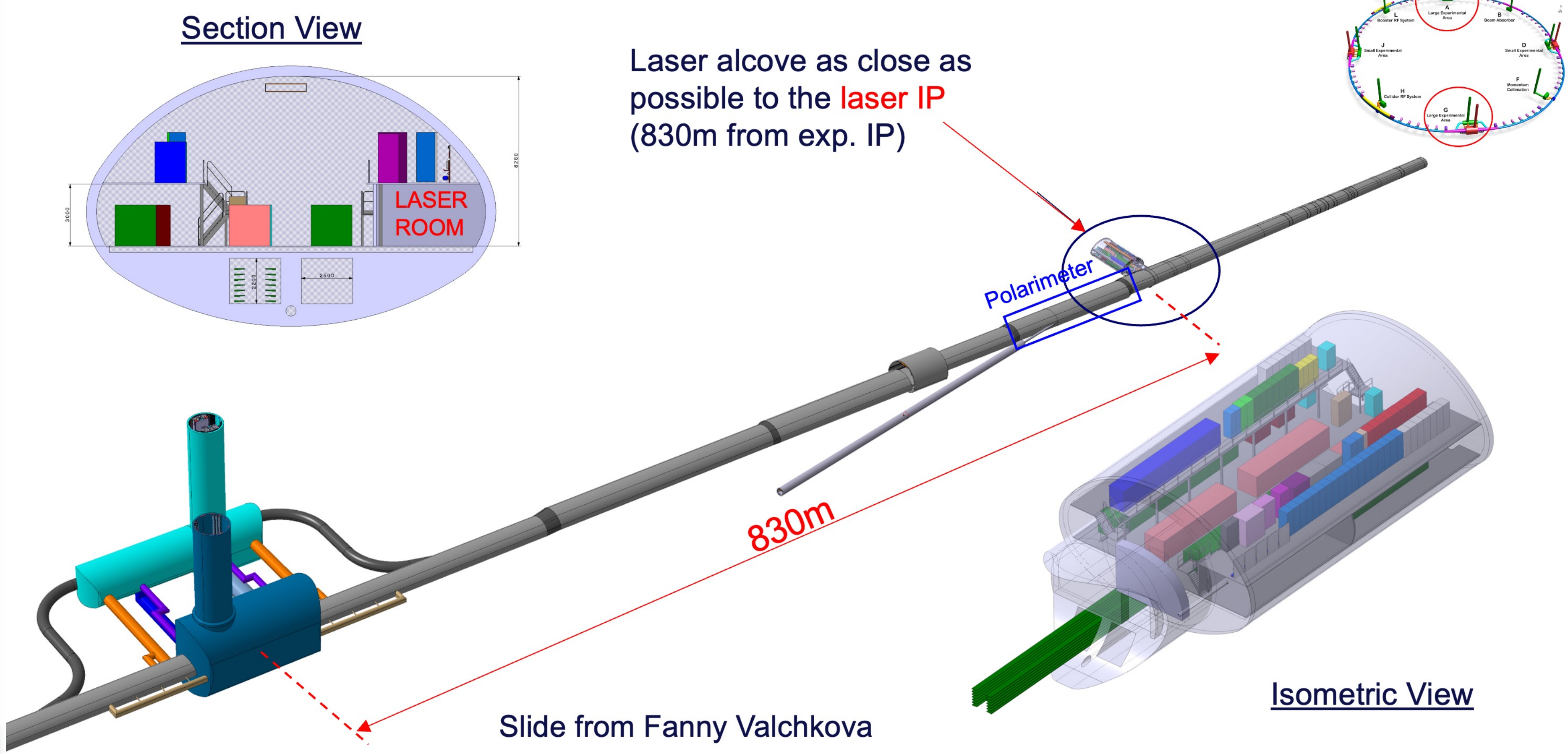


Evaluation of backgrounds (SR, Brem,…) in the Compton polarimeter has started

Kieffer, FCC Week 2024 report

Integration

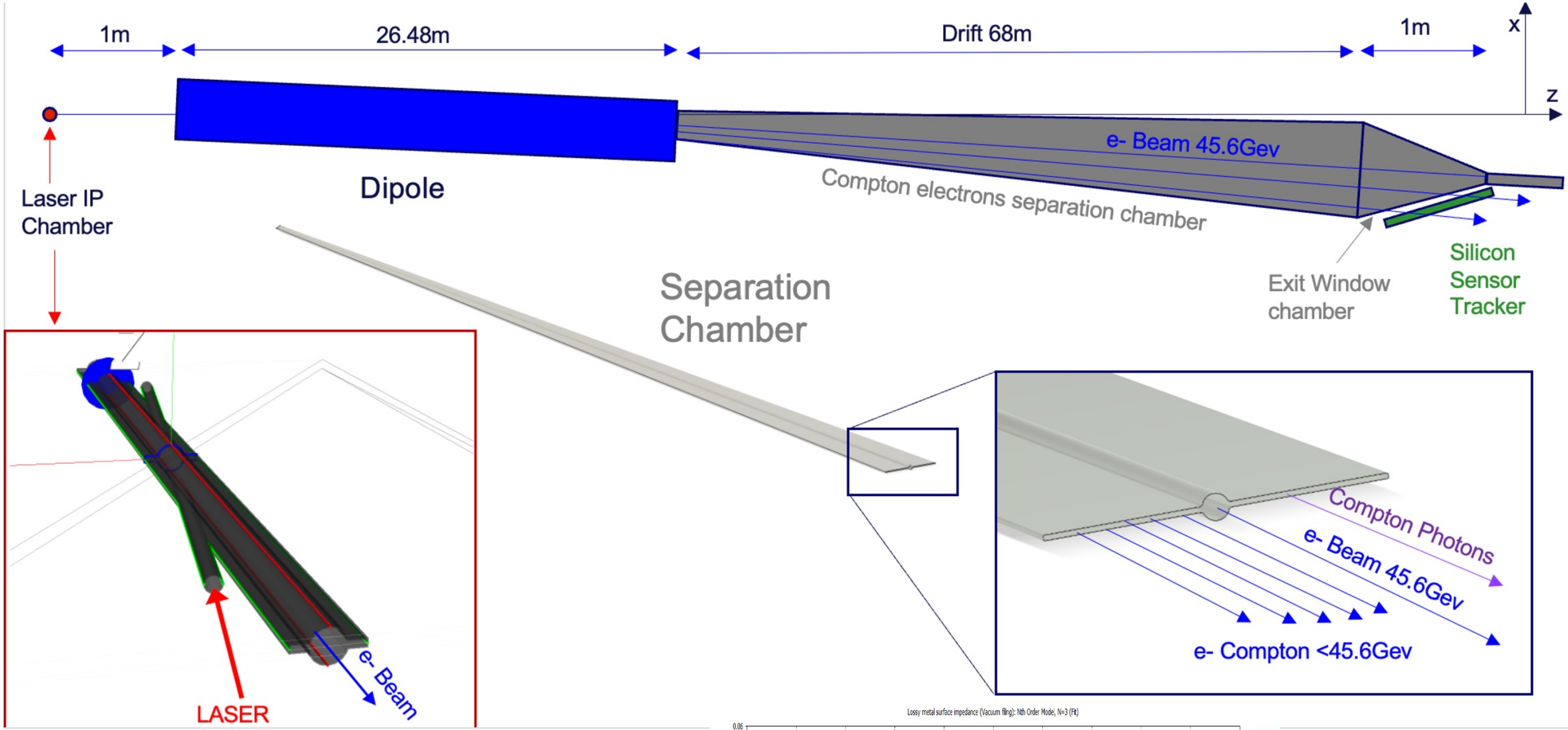
FCC-ee Underground Structure Big Alcove point A



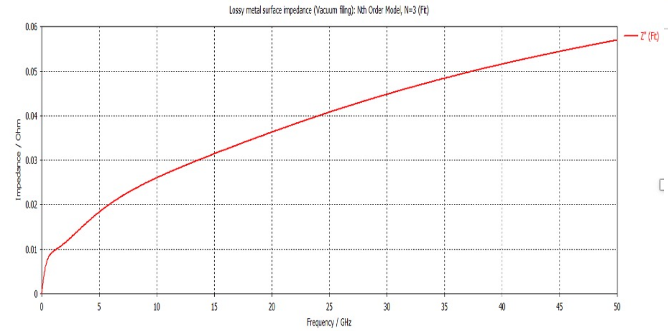
Slide from Fanny Valchkova

Kieffer, FCC Week 2025 report

Towards integration

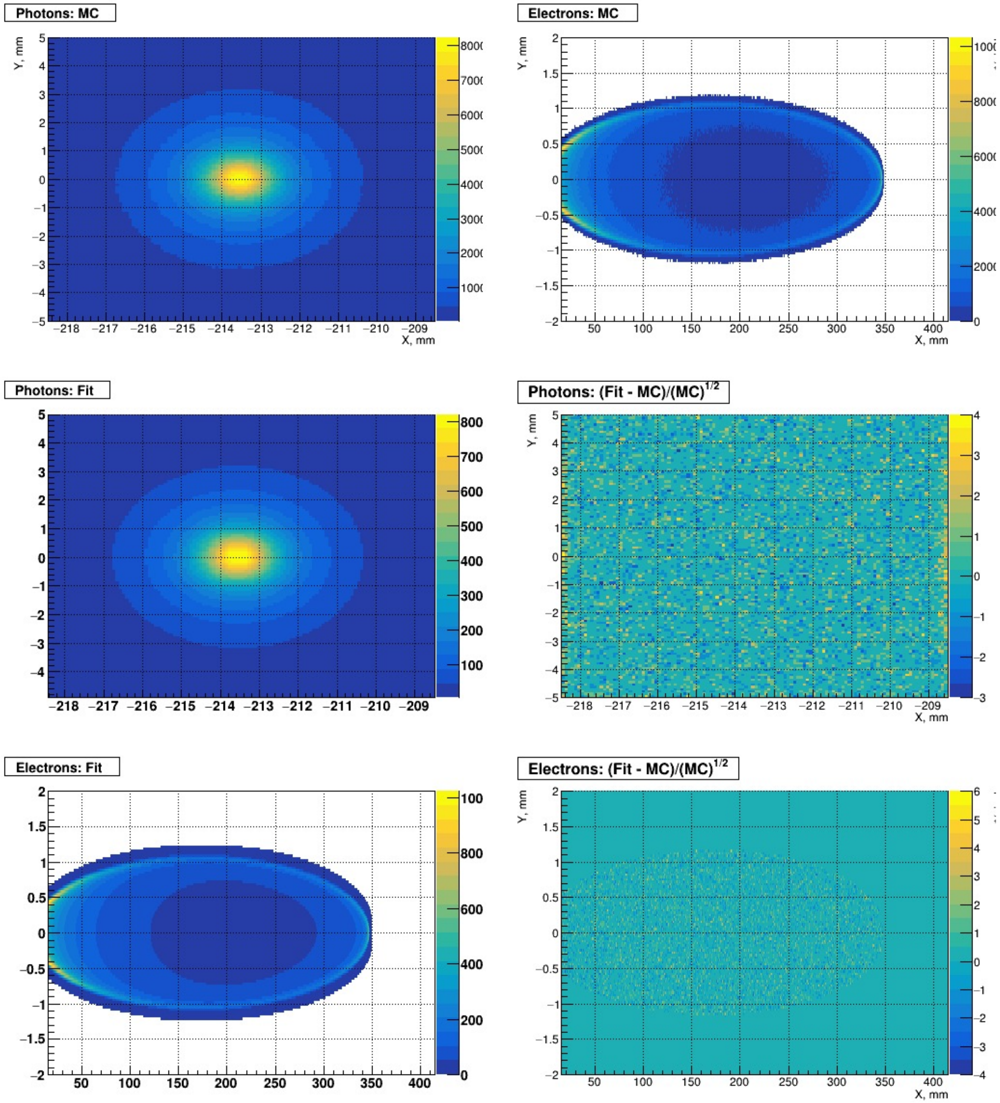


90° tapering validated for impedance



Kieffer, FCC Week 2024 report

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 ± 0.001 mm
ξ_1 = 0.001 ± 0.001
ξ_2 = -0.000 ± 0.000
$\xi_3\zeta_x$ = -0.001 ± 0.002
$\xi_3\zeta_y$ = 0.002 ± 0.002
$\xi_3\zeta_z$ = 0.001 ± 0.001
σ_x = 252.0 ± 0.9 µm
σ_y = 27.15 ± 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 ± 0.002 mm
X_2 = 347.632 ± 0.001 mm
ξ_1 = -0.000 ± 0.001
ξ_2 = 0.000 ± 0.000
$\xi_3\zeta_x$ = 0.000 ± 0.000
$\xi_3\zeta_y$ = -0.000 ± 0.001
$\xi_3\zeta_z$ = 0.001 ± 0.000
σ_x = 314.0 ± 1.2 µm
σ_y = 26.49 ± 0.01 µm
E_{beam} = 45.6008 ± 0.0008 GeV.

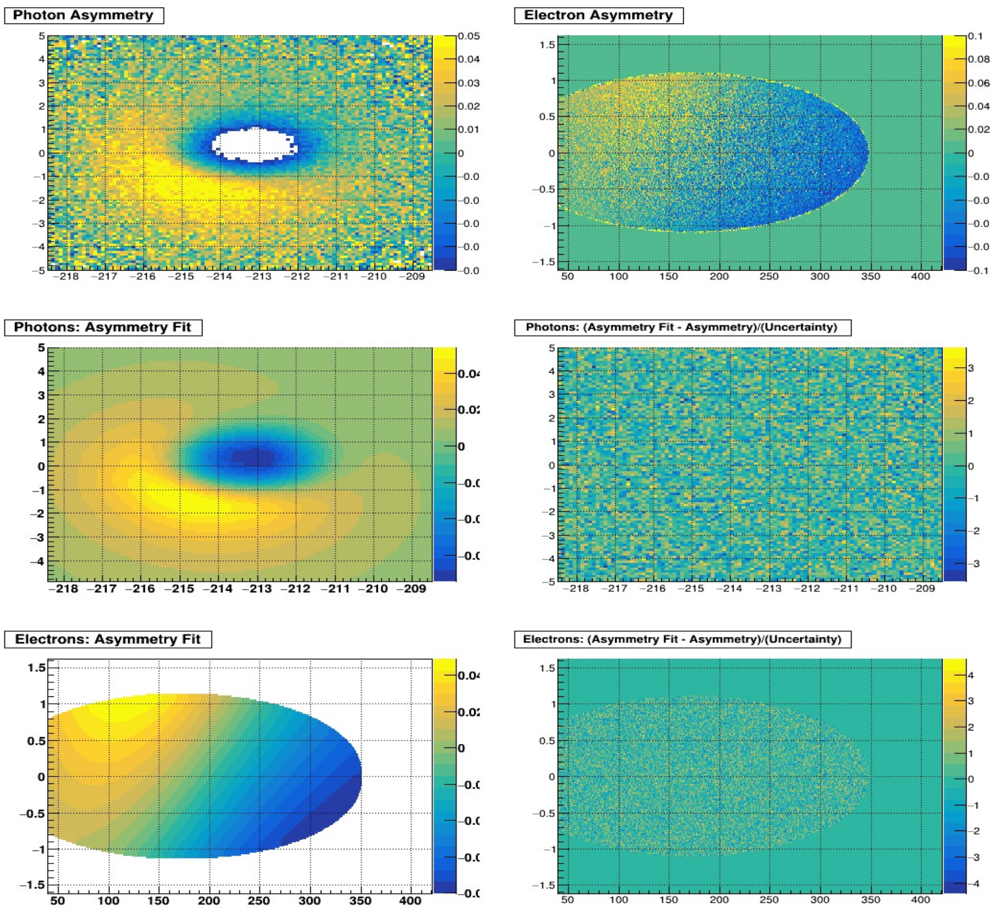
Blondel et al., arXiv:1909.12245; Muchnoi, JINST 17 P10014 (2022)

Asymmetry

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

for $\pm\xi_3$

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



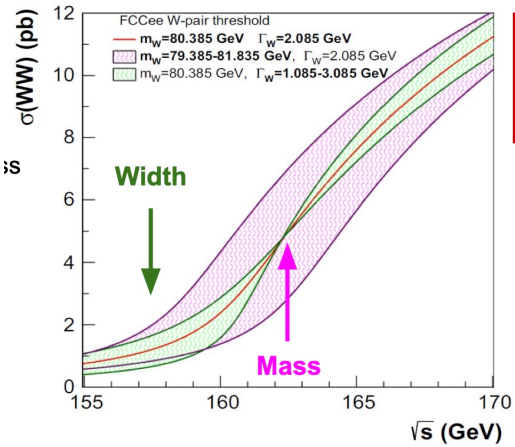
Monte-Carlo Parameters:
Laser λ_0 = 0.532 um
Electron E_0 = 45.600 GeV
Electron $\gamma = 89.237\times10^3$
Compton κ = 1.620
Bend: $\gamma\theta_0$ = 190.441
(ξ_1, ξ_2, ξ_3) = (0.000, 0.000, 1.000)
$(\zeta_x, \zeta_y, \zeta_z)$ = (0.100, 0.100, 0.100)

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

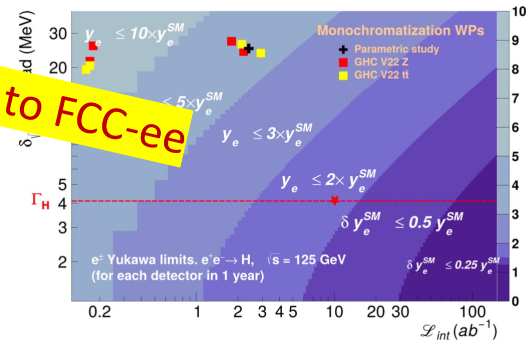
Conclusion & prospects



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

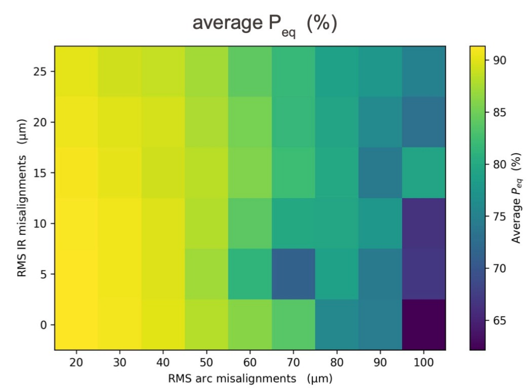
Unique to FCC-ee

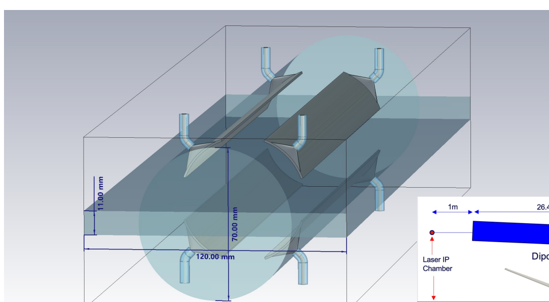


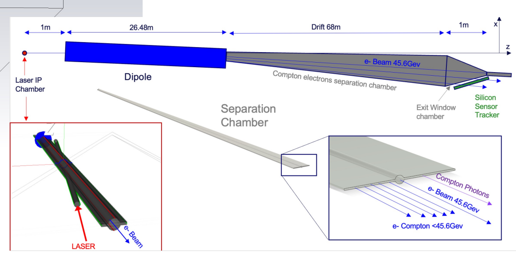
Much progress in all areas during feasibility study

100keV (abs.) / 20 keV (ptp) accuracy of $\sqrt{s}$ calibration (or better)

Reduced energy spread with monochromatization







No showstopper found at this stage

Huge task still ahead