FCCee Optics Design Meeting

FCCee: Luminosity tuning and optimization

With inputs from F. Zimmermann, J.P. Salvesen, J. Keintzel, C. Carli

Vaibhavi Gawas
CERN and University of Geneva

Outline

- Introduction
- Luminosity measurement
- Beamstrahlung signals
- Beam tolerances
- GUINEA-PIG
- Preliminary results

Work Plan: Luminosity optimization and tuning

- **Luminometer signal:**
- Single Bremsstrahlung based fast luminosity monitors?

- **Beamstrahlung monitor signals**: Dependence on IP position, closed-orbit angle, beam sizes

    - If possible- information from **silicon vertex detector signals**

Combine this information for luminosity tuning and optimization

Machine-Learning based recipe to calculate beam-parameters and tune knobs??

SuperKEKB- Large Angle Beamstrahlung Monitor, neural network based techniques: measuring 32 independent values with different optical properties (32 Photomultipliers)

Supervised learning based model for **magnetic error correction at LHC**

Luminosity determination in machines

LEP	● 16 small tungsten-silicon calorimeters ● Rate of small angle Bhabha scattering events ● Luminosity and beam angular divergence: fast monitor based on the single bremsstrahlung process
SuperKEKB	● Detecting photons from radiative Bhabha scattering ● Specific luminosity from ZDLM luminosity monitor ● Instant total luminosity by ECL monitor
SLC	● Small angle monitor (SAM) for measuring Bhabha scattering (with Mark-II detector)
LHC	● Van Der Meer method (using vertical beam steering)

Luminosity $10^{34}cm^{-2}s^{-1}$	Z	W	ZH	$t\bar{t}$
	140	20	5.0	1.4

Beamstrahlung signals

- Transverse sizes of e+ and e- beam:
  Analysis of beamstrahlung energy patterns
  SLC
- IP beam-beam steering:
  Angular shift in in centre of beamstrahlung distribution (in gamma region)
- Luminosity, beam size variation: SLC
  Visible(light) beamstrahlung at fixed angle
- Moments of beam distribution: CESR studies
  From polarization data of beamstrahlung
- Passive monitoring of position and size of beam:
  Beamstrahlung polarization and spectra
  EIC studies
- Beam length and collision timing:
  Beamstrahlung time profile SuperKEKB
- Relative height of beams, relative vertical offsets:
  Polarization observables (ratios)
  SuperKEKB
- Information about IP geometry:
  Angular scans

Tolerances

IP Spot size related tolerances
(aberrations that increase the IP spot size)

Vertical waist shift

- Horizontally displaced sextupole
- Displaced upstream quadrupoles

$$y^* \rightarrow y^* + Ly'^*$$

Vertical dispersion

- Displaced quadrupole or change in its strength
- Rolls of bending magnets or quadrupoles
- Vertical displacement of sextupoles

$$y^* \rightarrow y^* + D_y \delta_i$$

Skew coupling

- Rolls of quadrupole magnets
- Vertical displacement of sextupoles
- Trajectory offset causing vertical orbit offset in sextupoles

$$y^* \rightarrow y^* + ax^*$$
$$y^* \rightarrow y^* + bx'^*$$

Tolerances

Waist shift

$$y^* \rightarrow y^* + Ly'^*$$

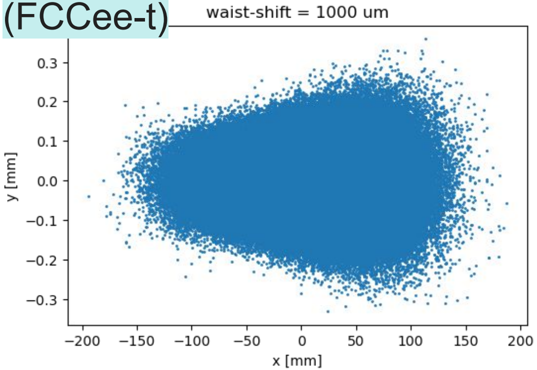
Vertical dispersion

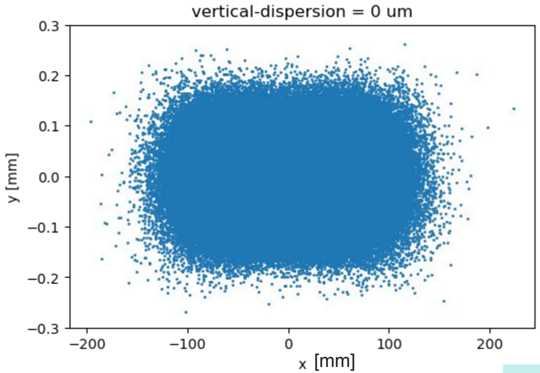
$$y^* \rightarrow y^* + D_y\delta_i$$

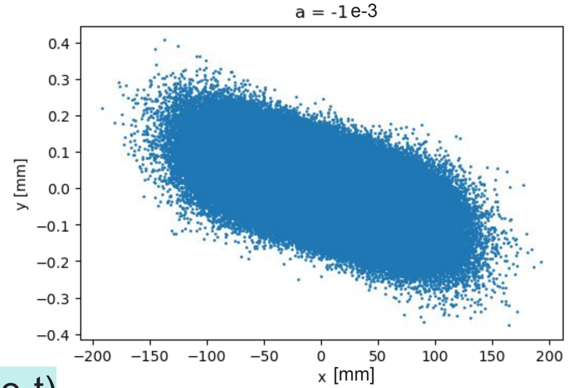
Skew coupling

$$y^* \rightarrow y^* + ax^*$$

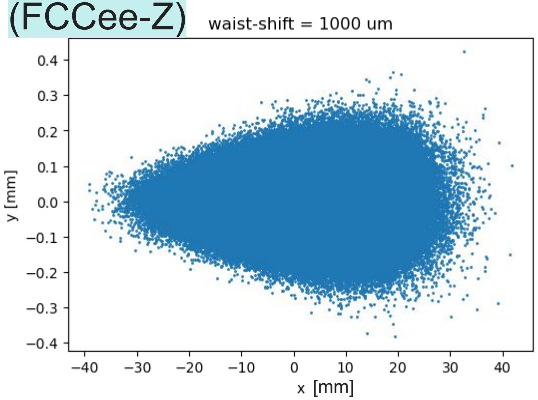
(FCCee-t)

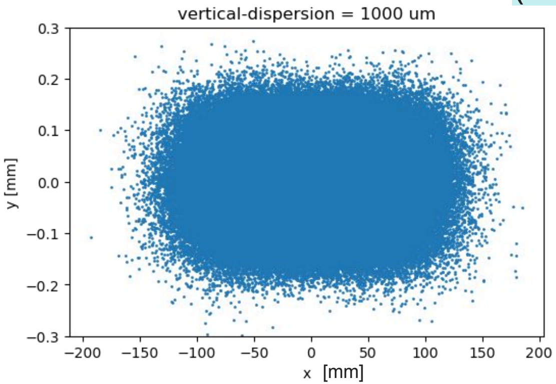




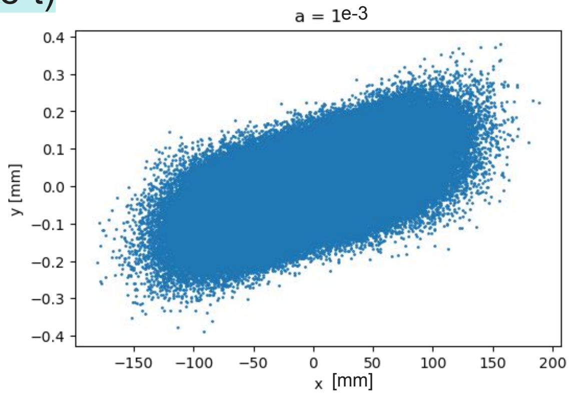


(FCCee-Z)





(FCCee-t)



GUINEA PIG

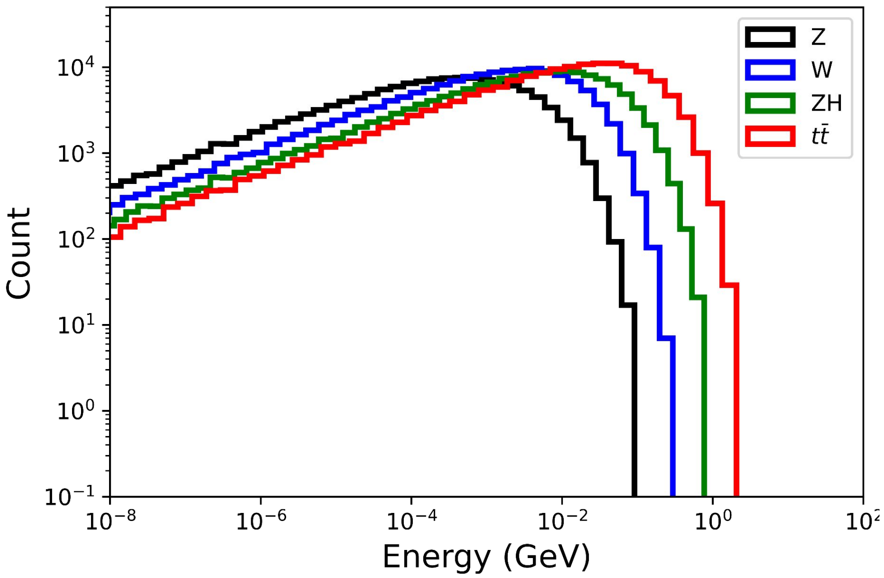
Generator of Unwanted Interactions for Numerical Experiment Analysis: Program Interfaced to GEANT

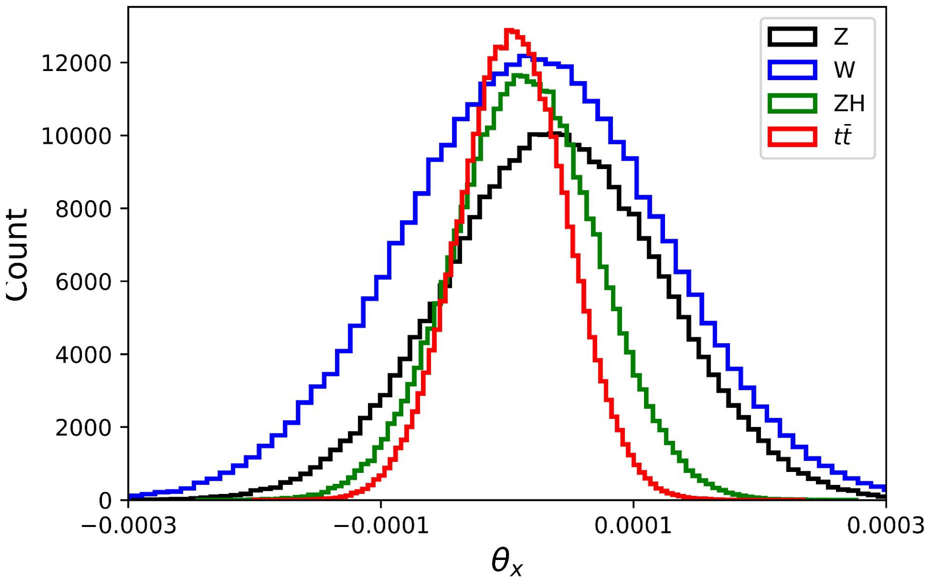
- Implements full beam dynamics for particle generation, Beamstrahlung, interaction effects on luminosity and background, generates radiative Bhabhas
- Both classical and quantum description of beamstrahlung can be used
- Simulation code also includes pinch effect, pair creation, hadronic background calculations
- Accepts input files of electron and positron beams with crab-waist transform

Preliminary results

Beamstrahlung flux at four working points of FCCee

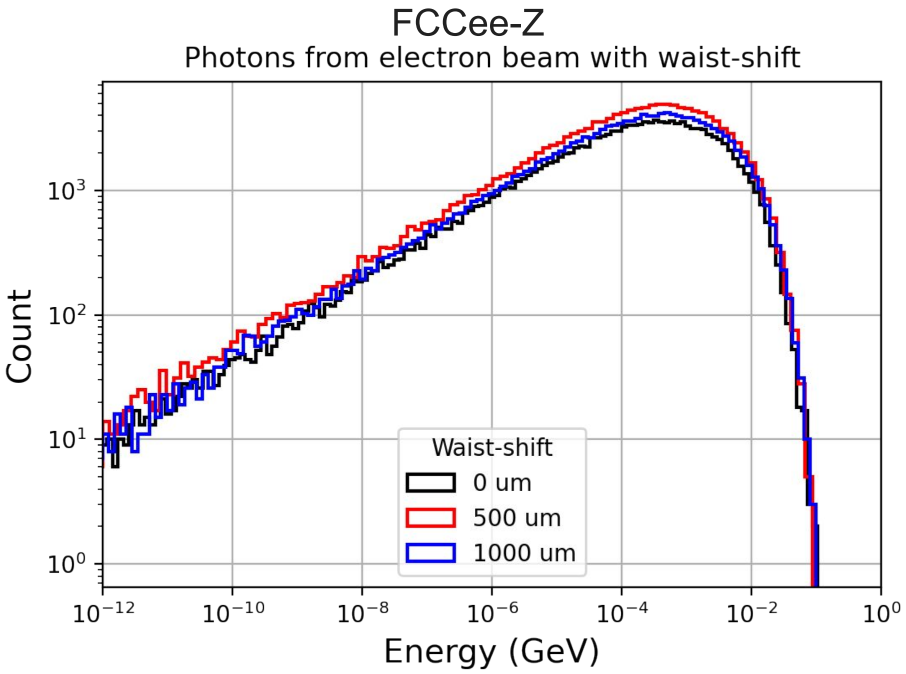
45.6 GeV, 80.0 GeV, 120.0 GeV, 182.5 GeV

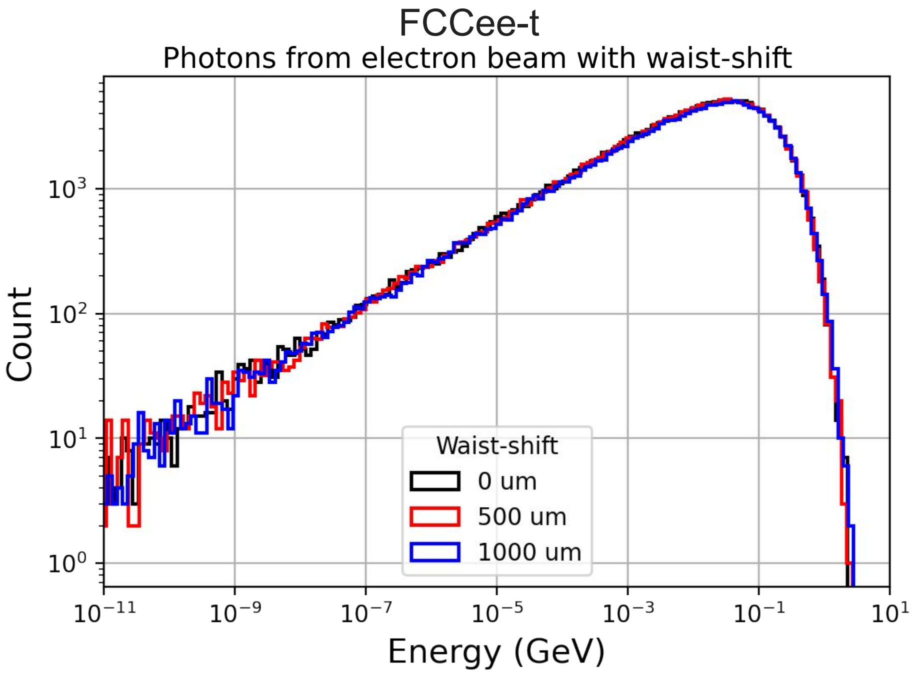




Energy distribution

Waist shifts in electron beam



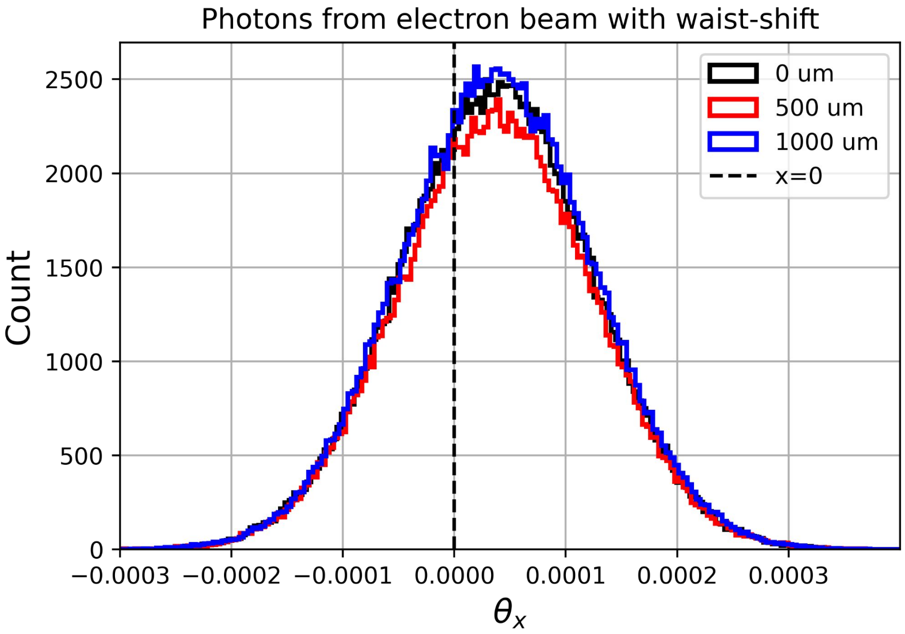


$$y^* \rightarrow y^* + Ly'^*$$

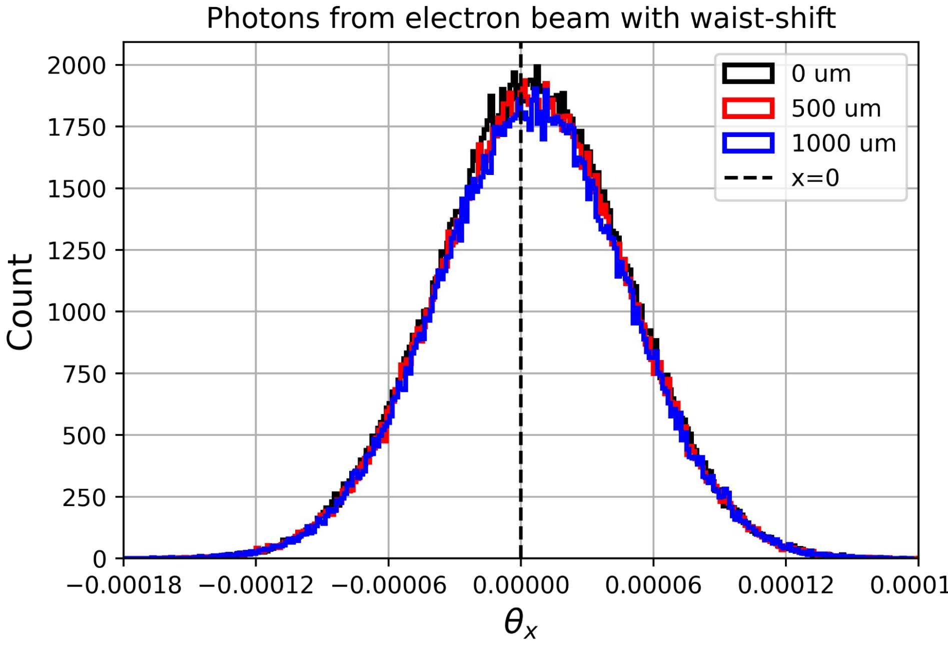
Angular distribution

Waist shifts in electron beam

FCCee-Z



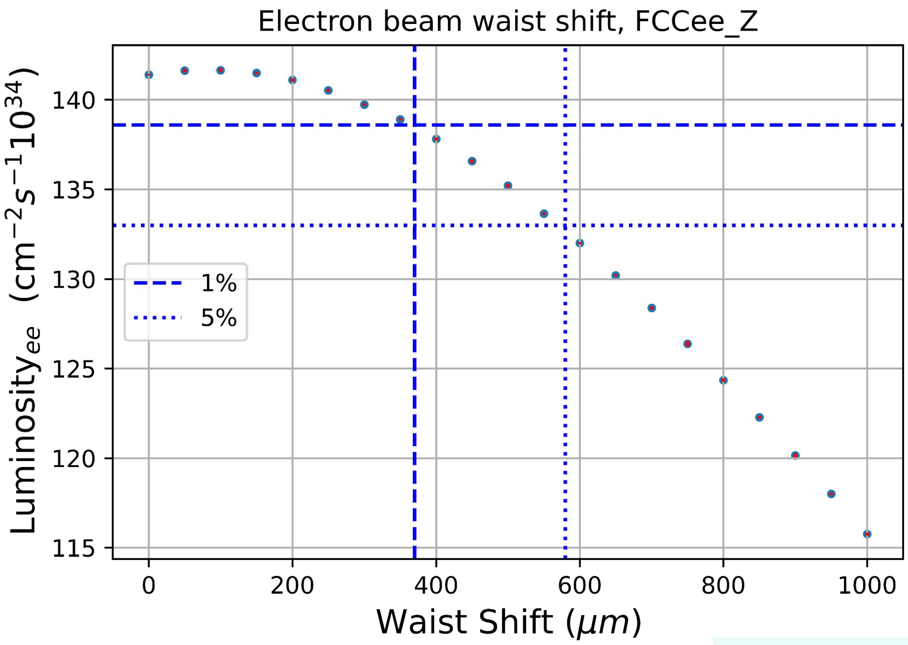
FCCee-t

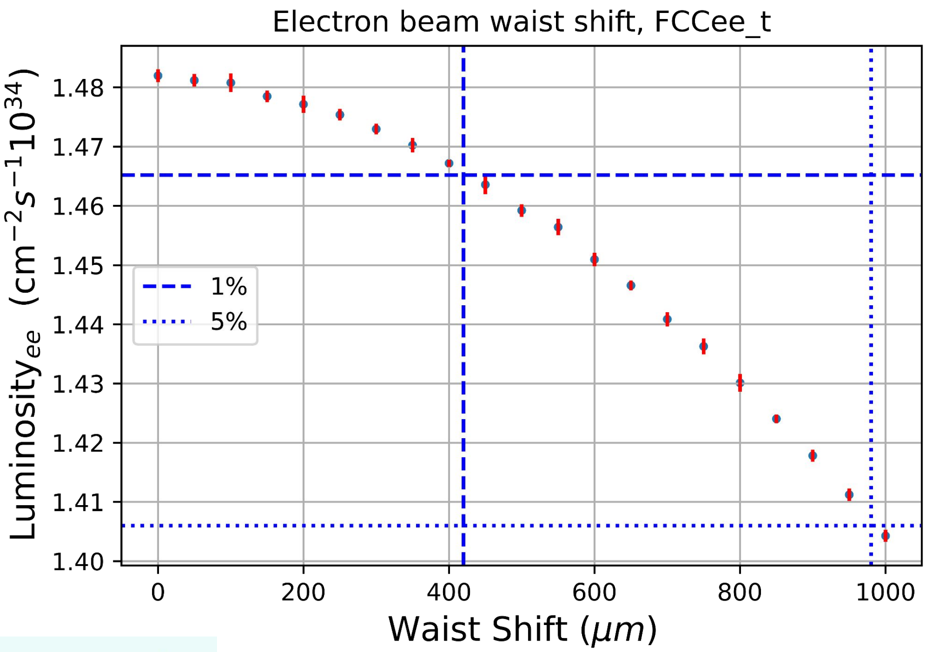


$$y^* \rightarrow y^* + Ly'^*$$

Luminosity Measurements

Waist shifts in electron beam

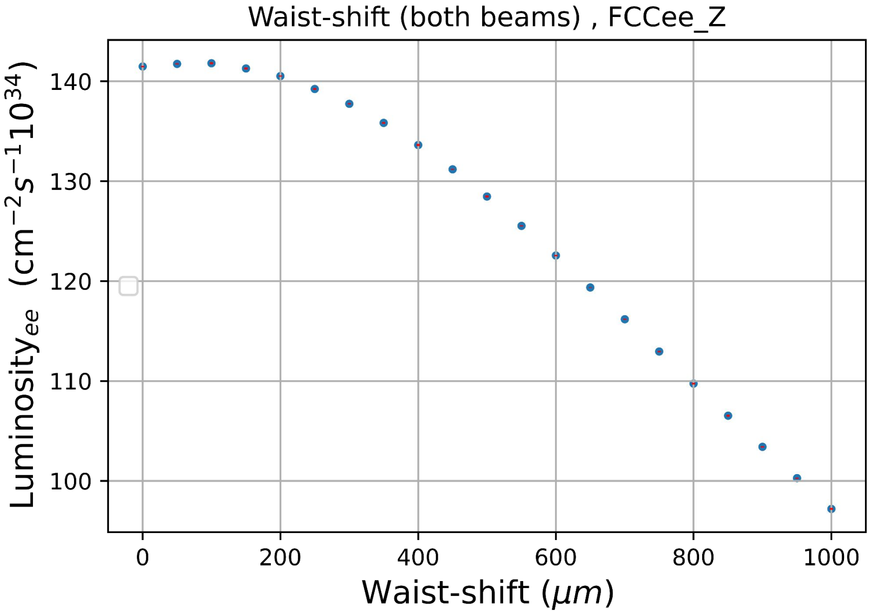


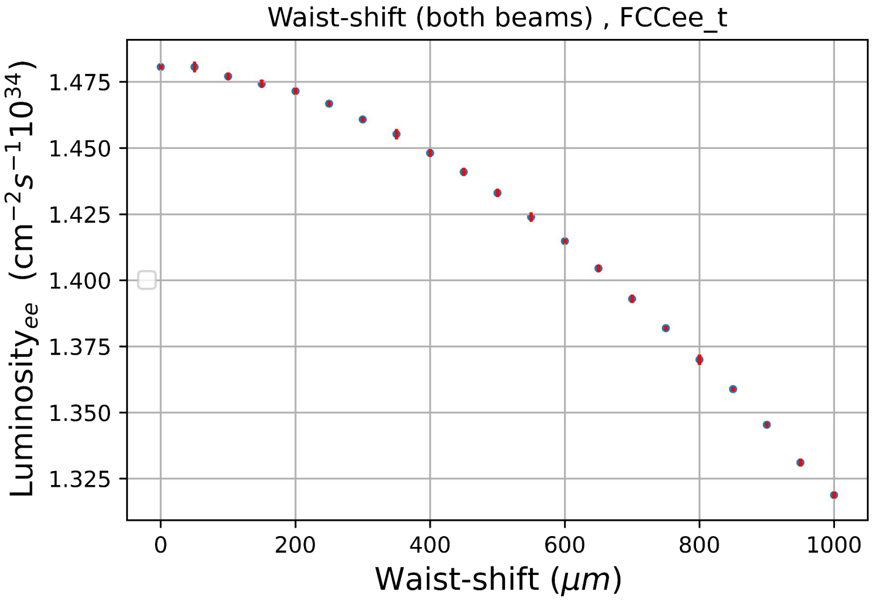


$$y^* \to y^* + Ly'^*$$

Luminosity Measurements

Waist shifts in both beam

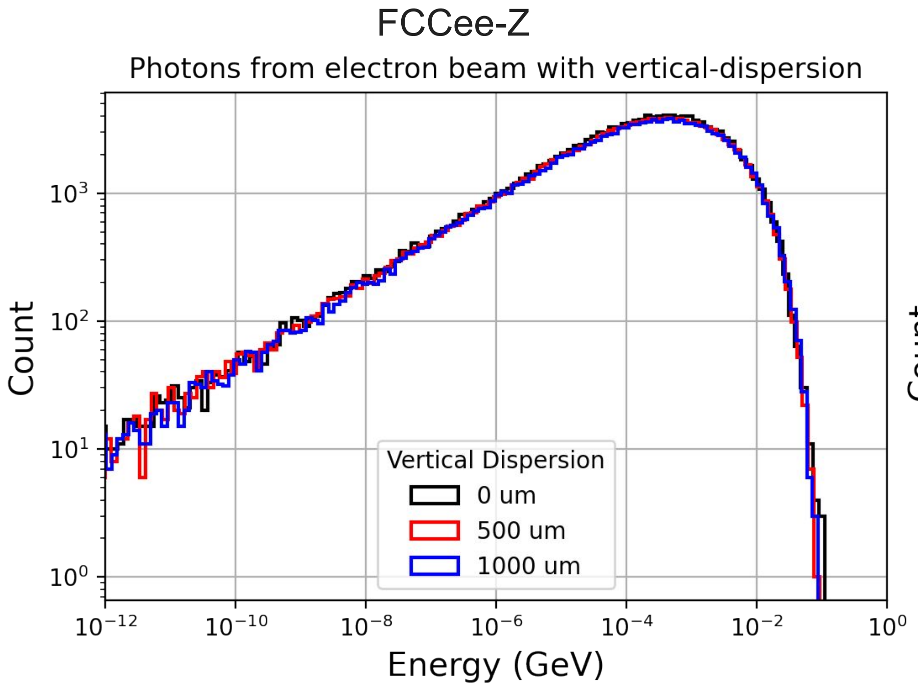


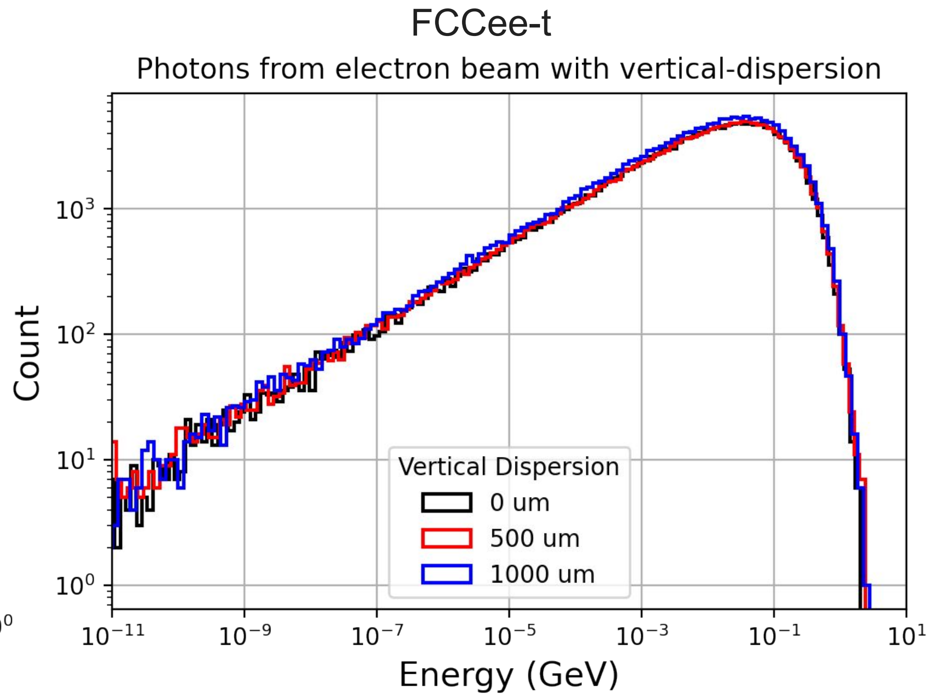


$$y^* \rightarrow y^* + D_y \delta_i$$

Energy distribution

Vertical dispersion in electron beam



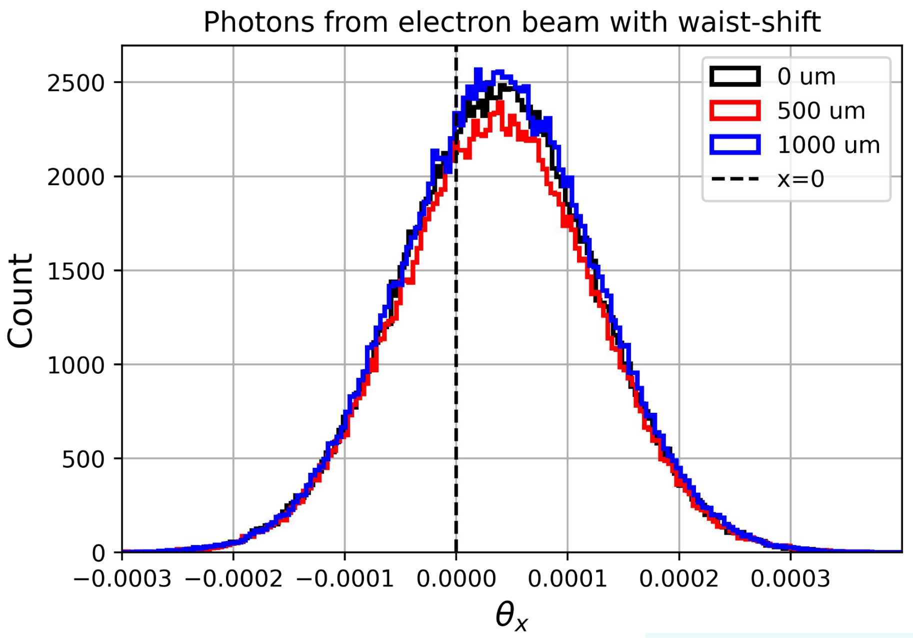


$$y^* \to y^* + D_y \delta_i$$

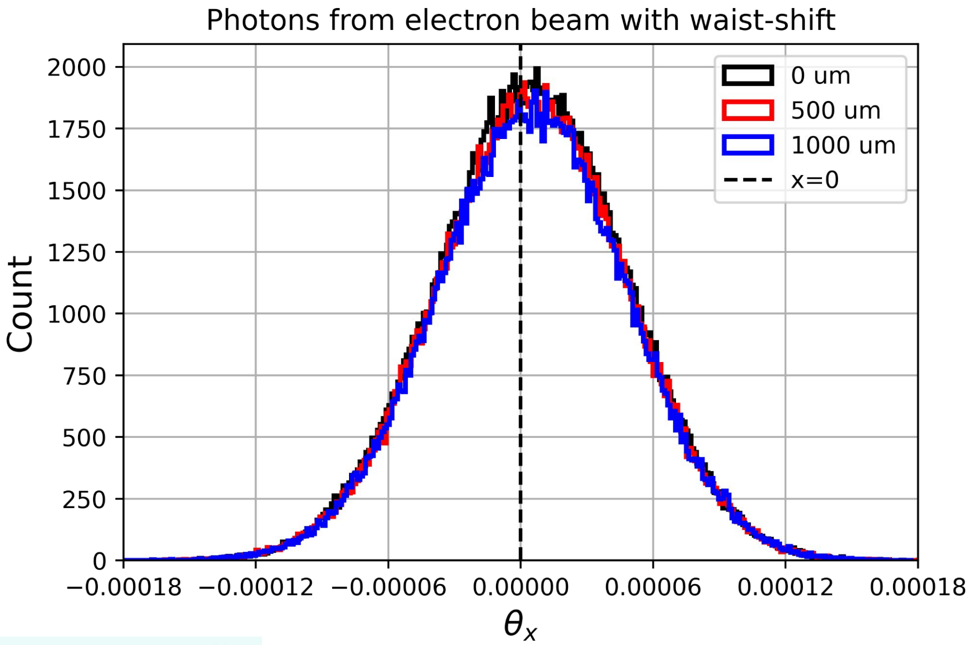
Energy distribution

Vertical dispersion in electron beam

FCCee-Z



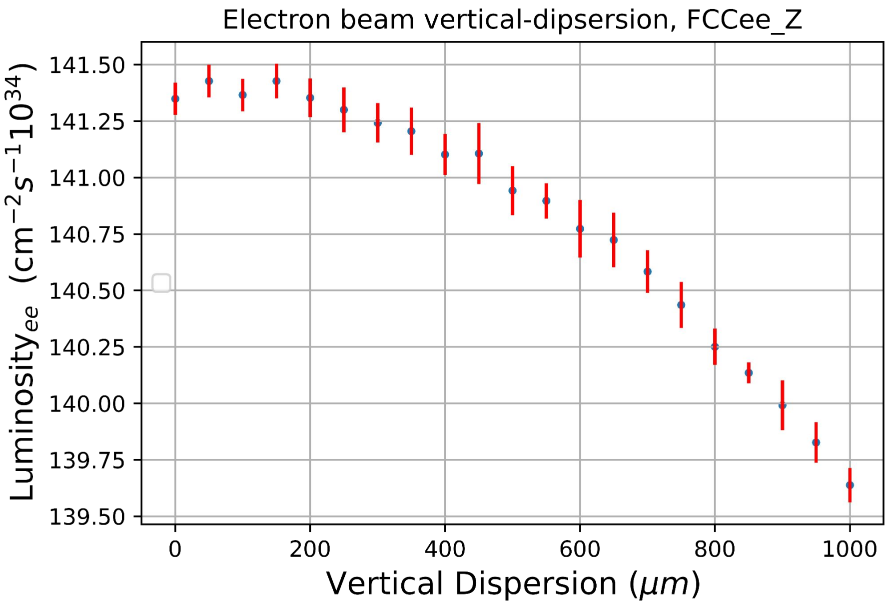
FCCee-t

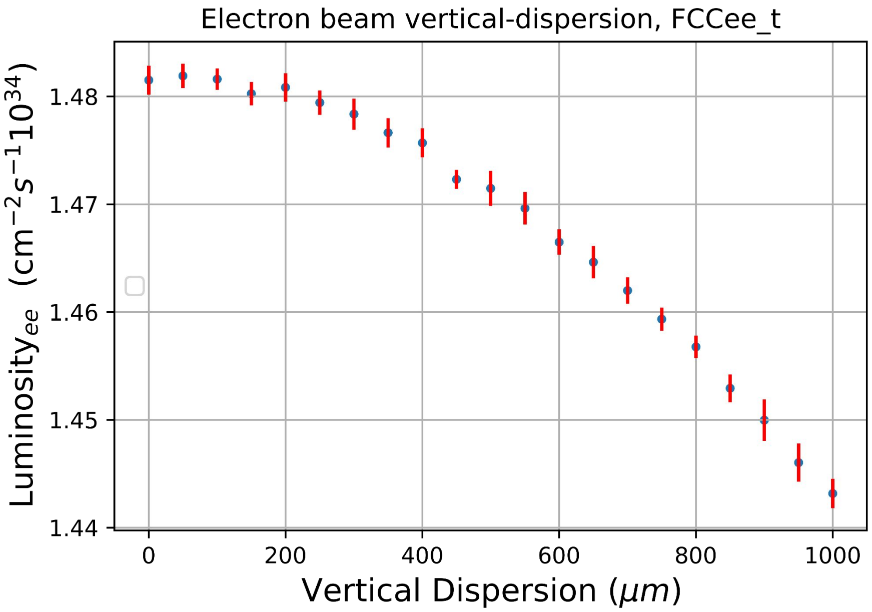


$$y^* \rightarrow y^* + D_y \delta_i$$

Luminosity Measurements

Vertical dispersion in electron beam

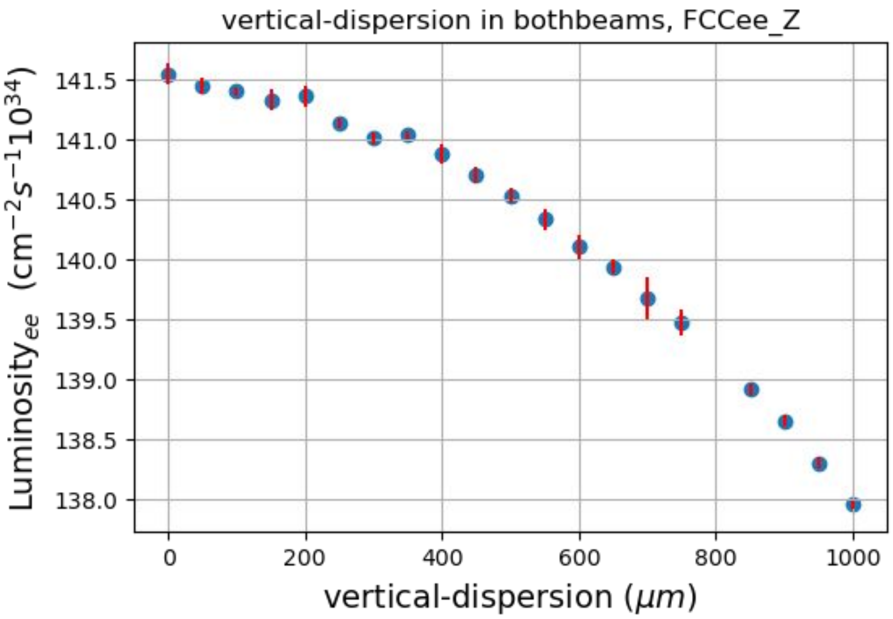


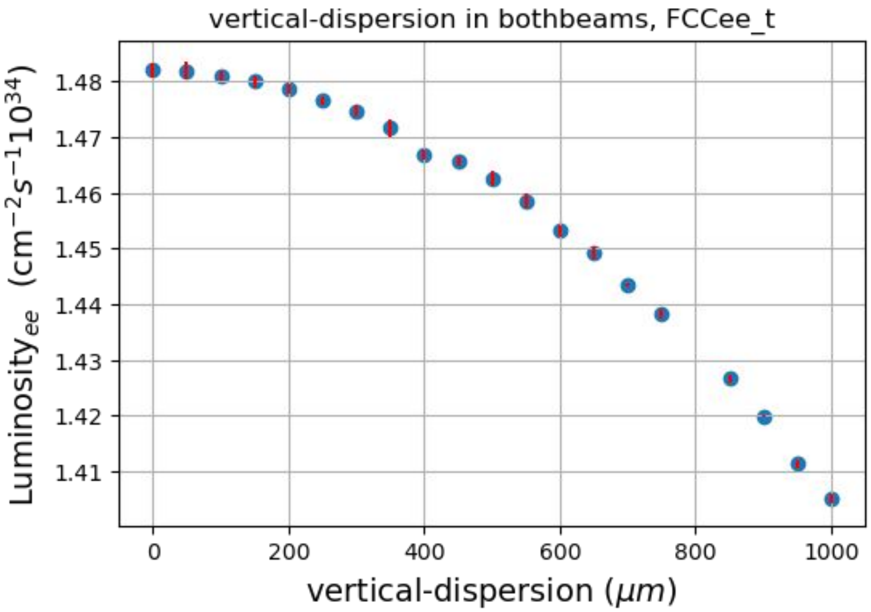


$$y^* \rightarrow y^* + D_y \delta_i$$

Luminosity Measurements

Vertical dispersion in both beams

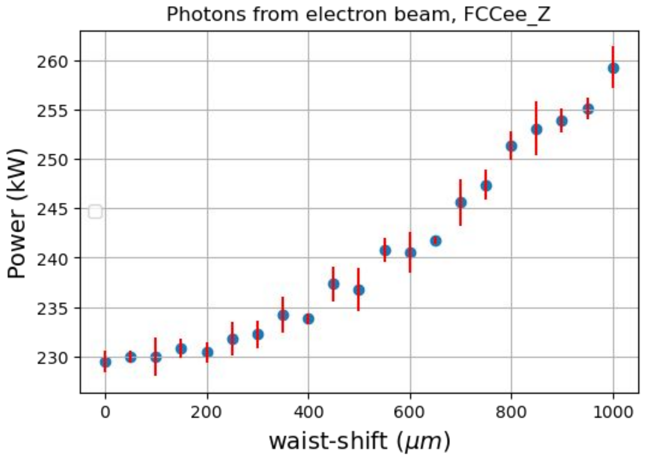




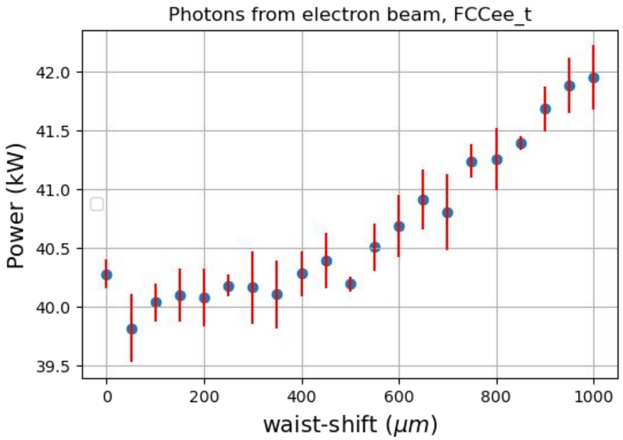
$$y^* \rightarrow y^* + D_y \delta_i$$

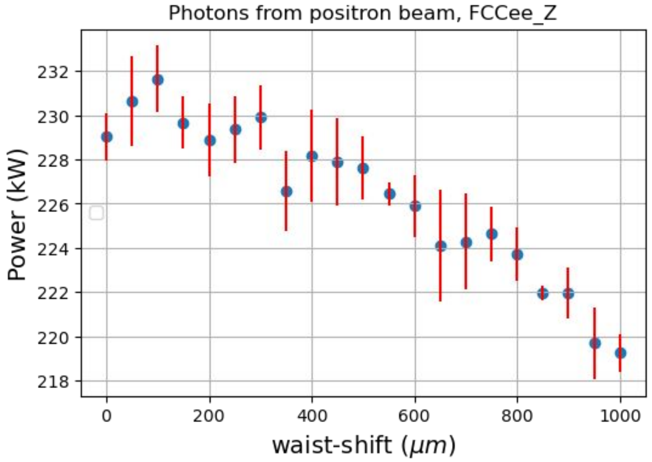
Power Measurements

Waist shift in electron beam only

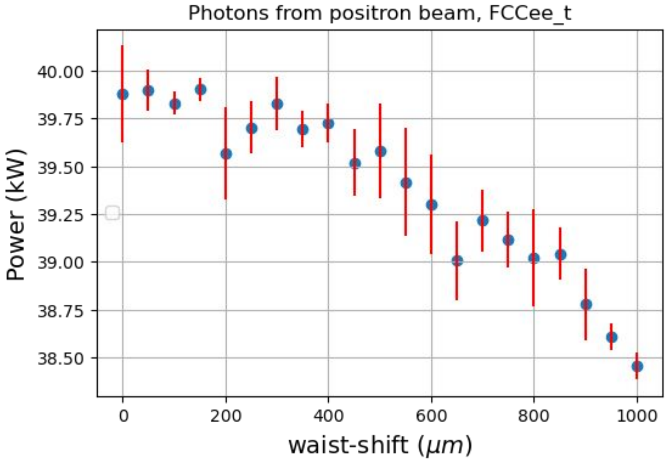


Electron beam power



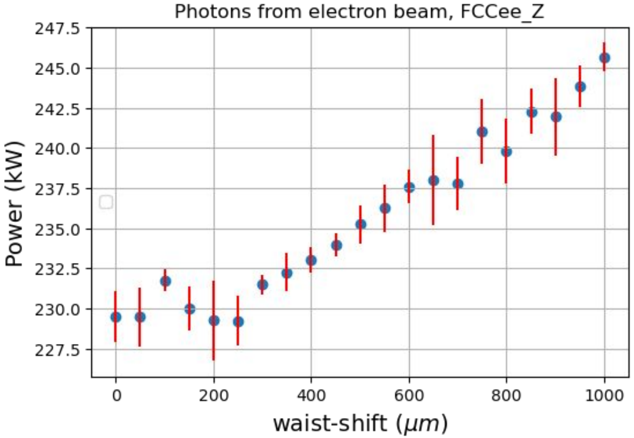


Positron beam power

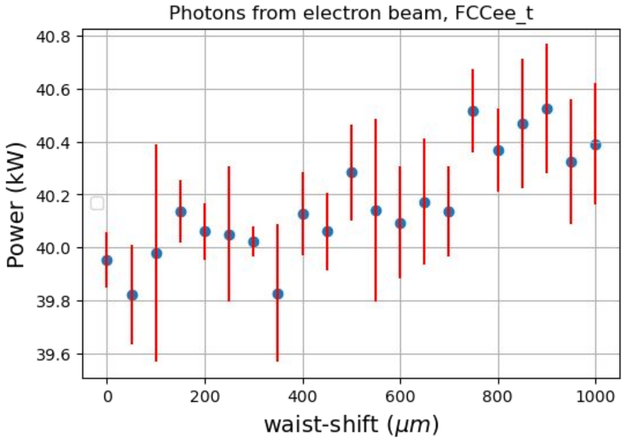


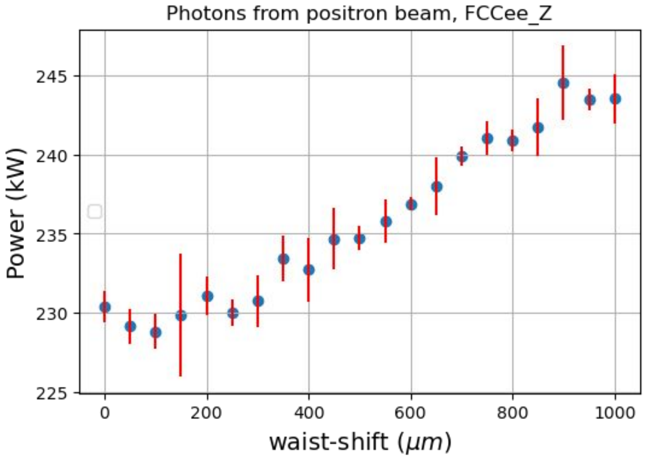
Power Measurements

Waist shift both beams

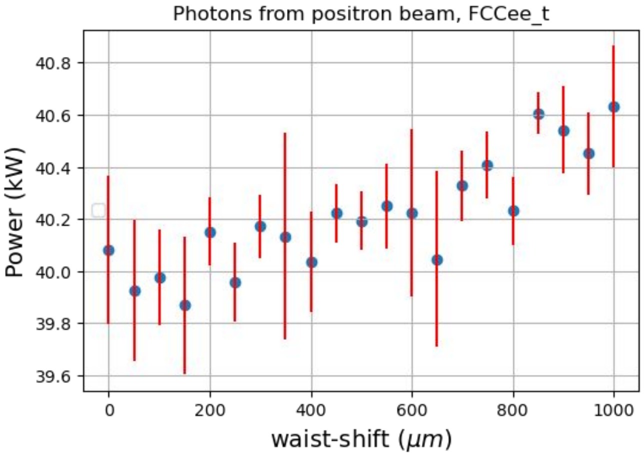


Electron beam power



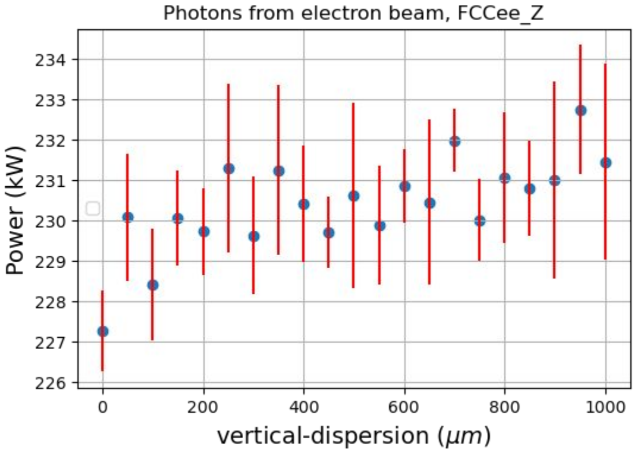


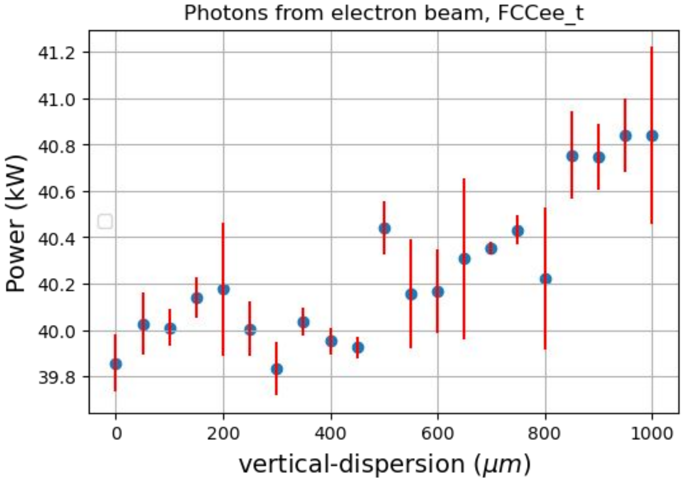
Positron beam power



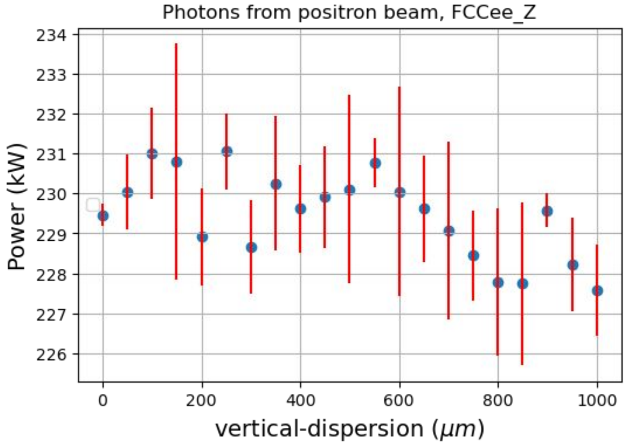
Power Measurements

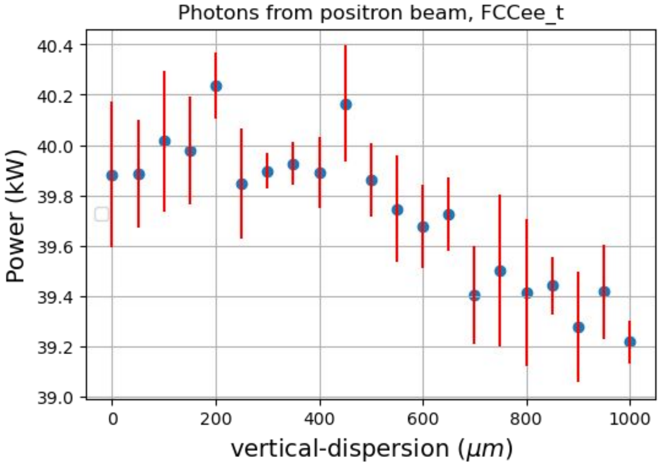
Vertical dispersion in electron beam only





Electron beam power





Positron beam power

Summary

- Luminometer and tuning knobs: Implied alignment or Beam stability tolerance
- Beamstrahlung monitor signals: Dependence
- on IP position, closed-orbit angle, beam sizes
- If possible: information from silicon vertex detector signals

The overall recipe for luminosity tuning

Combine this information for Luminosity tuning and optimization

Starting with Beamstrahlung signals

Simulations

- Guinea Pig: Generate effects of skew-coupling, other offsets on BS spectrum, power output, and luminosity
- Additional beam-generation code to set-up switches that are unavailable in GP.

Further Goals

- Effects of multiple tolerances applied together
- BBBREM for radiative Bhabhas
- BHLUMI/other MCs? for Bhabha electrons
- Combining signals in a ML framework

Thank you all!

Acknowledgements

Frank Zimmermann, Jack Salvesen, Jacqueline Keintzel, Christian Carli,
Kevin Andre, Manuela Boscolo

References

- Study of Electromagnetic and Hadronic Background in the Interaction Region of the TESLA Collider https://cds.cern.ch/record/331845?ln=en
- Characterization of the beamstrahlung radiation at the future high-energy circular collider https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.26.111002
- Beam Spot Size Measurement Using Beamstrahlung Signals at the SLC Interaction Point https://accelconf.web.cern.ch/p91/PDF/PAC1991_1207.PDF
- Beam-beam deflection as a beam tuning tool at the SLAC linear collider https://www.sciencedirect.com/science/article/pii/016890029090203I
- Real-time luminosity monitor for a B-factory experiment https://www.sciencedirect.com/science/article/pii/S016890020000766X?via%3Dihub
- Beamstrahlung Monitor for SLC Final Focus Using Gamma Ray Energies https://inspirehep.net/literature/230105
- Beamstrahlung Monitor for SLC Final Focus Using Visible Wavelengths https://inspirehep.net/literature/230103
- Luminosity optimization feedback in the SLC https://inspirehep.net/literature/496269
- Luminosity Measurements And Calculations Https://Cds.Cern.Ch/Record/261063/
- Beam-Beam Simulations With Guinea-Pig http://cds.cern.ch/record/2828391?ln=en
- Lep Luminosity Revisited: Design And Reality https://accelconf.web.cern.ch/a01/PDF/WEAU01.pdf
- Beam Blow Up due to Beamstrahlung in Circular e^+e^- Colliders https://cds.cern.ch/record/261063/files
- Challenges for FCC-ee Luminosity Monitor Design https://arxiv.org/abs/2107.12837
- Lecture Notes for: Accelerator Physics and Technologies for Linear Colliders https://hep.uchicago.edu/~kwangje/LectureNotes_Zimmermann.pdf

BACKUP SLIDES

Beamstrahlung measurements

Synchrotron radiation emitted by a beam in the electromagnetic field of the incoming beam near IP

Classical Description of Beamstrahlung

Beamstrahlung parameter: $\Upsilon = \frac{2}{3} \frac{\hbar\omega_c}{E_o}$

$\hbar\omega_c = \frac{3}{2} \frac{\hbar c \gamma^3}{\rho}$

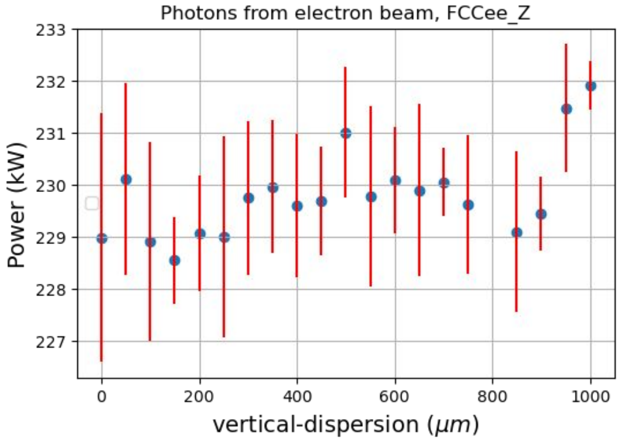
For FCCee, $\Upsilon << 1$: Classical regime

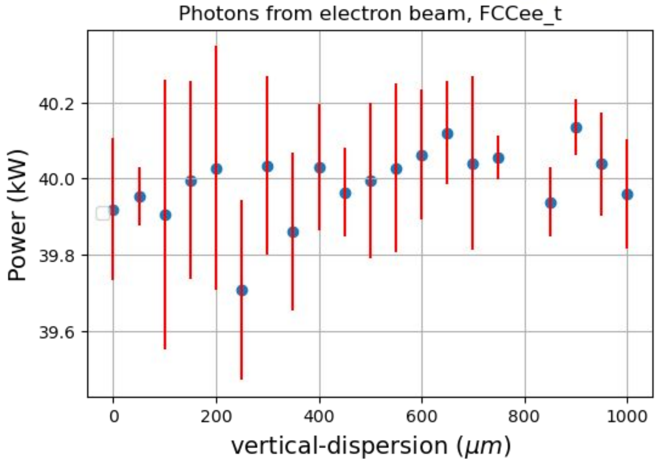
$$\langle \Upsilon \rangle = \frac{5}{6} \frac{r_e^2 \gamma N_e}{\alpha \sigma_z (\sigma_x^* + \sigma_y^*)}$$

- QM nature of Beamstrahlung- increases energy spread- in turn increases bunch length.
- Reduces luminosity. Reduction of dynamic aperture- increased loss rate of particles
- Photon number and emitted energy proportional to beamstrahlung parameter

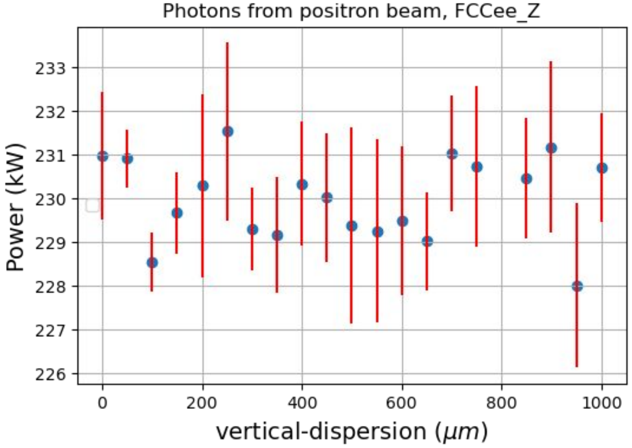
Power Measurements

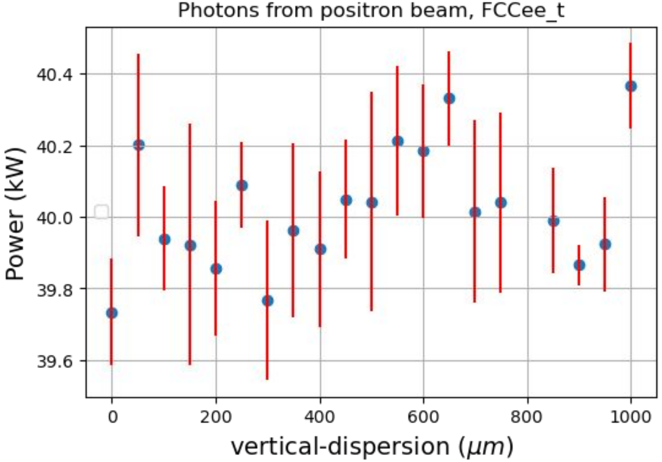
Vertical dispersion in both beams





Electron beam power

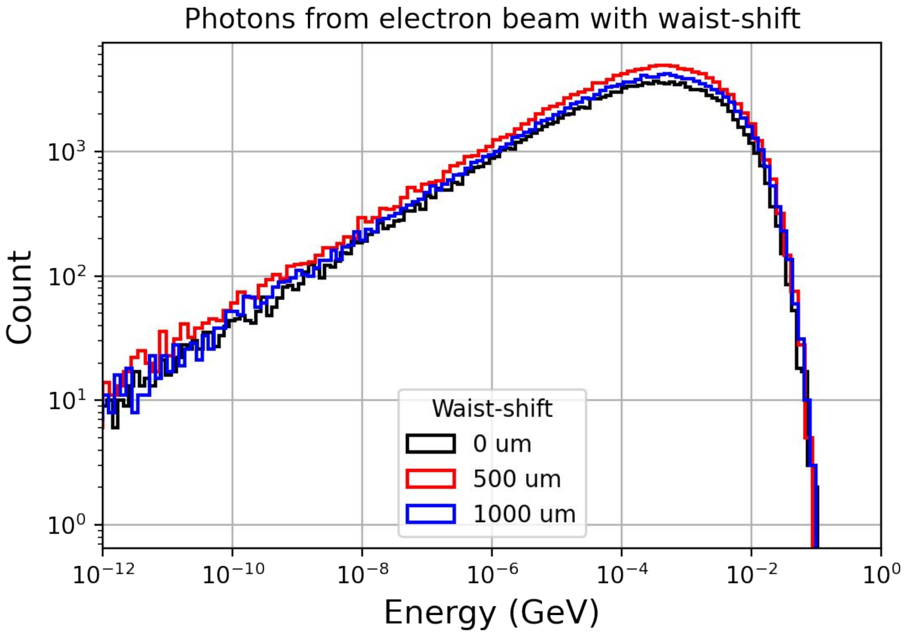


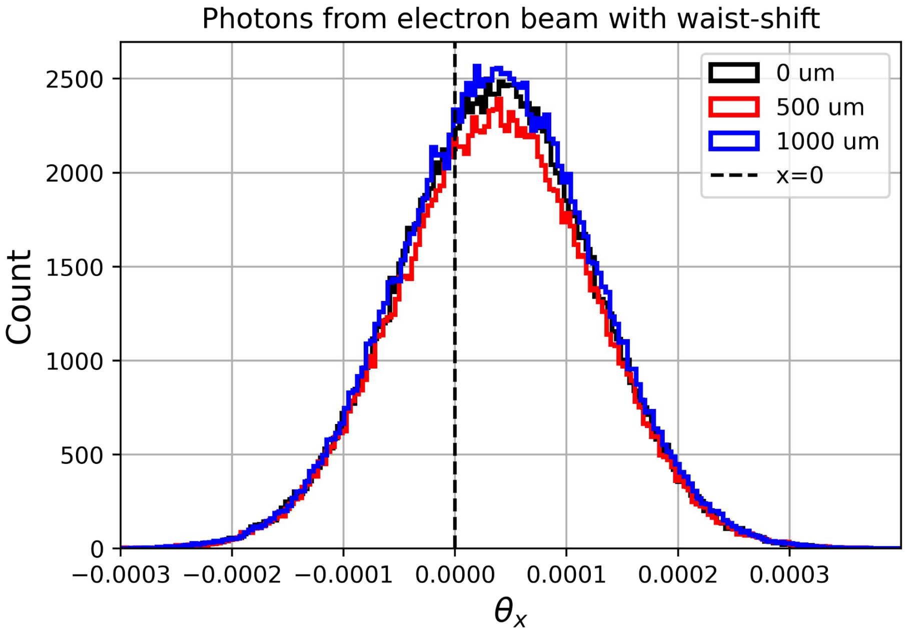


Positron beam power

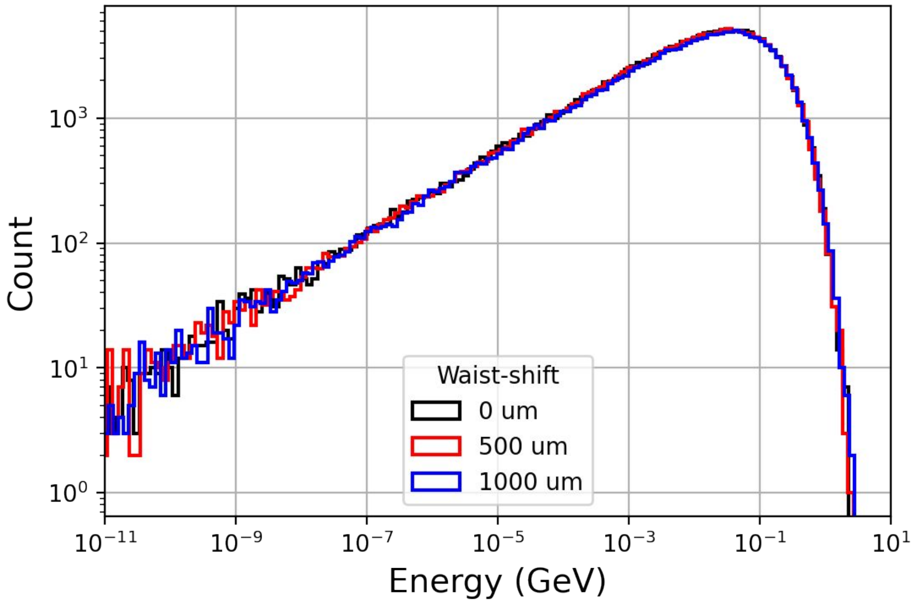
Waist Shifts (in electron beam)

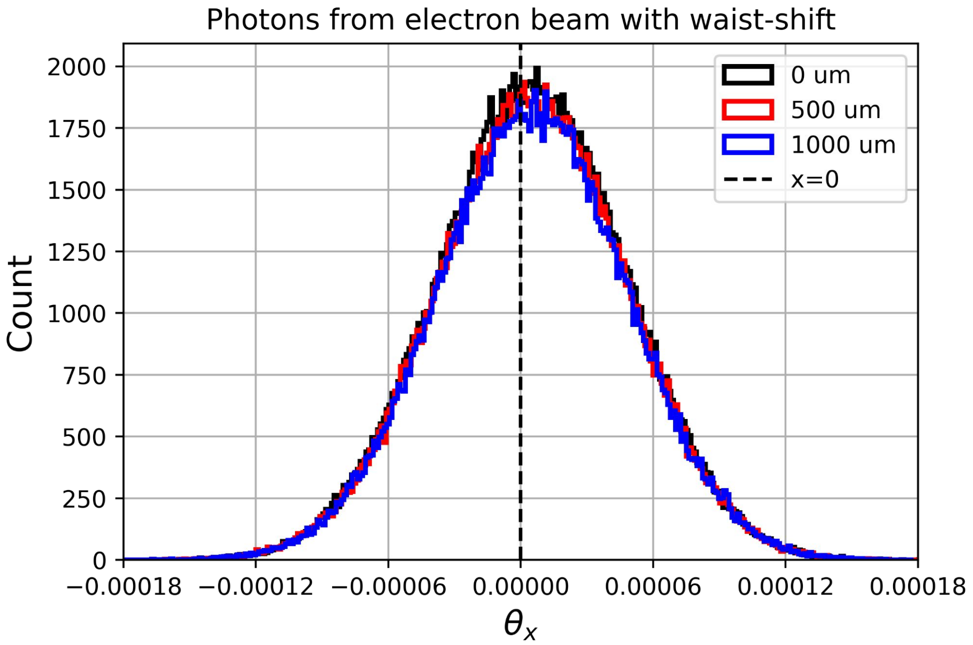
Waist Shifts (in electron beam) FCCee_Z





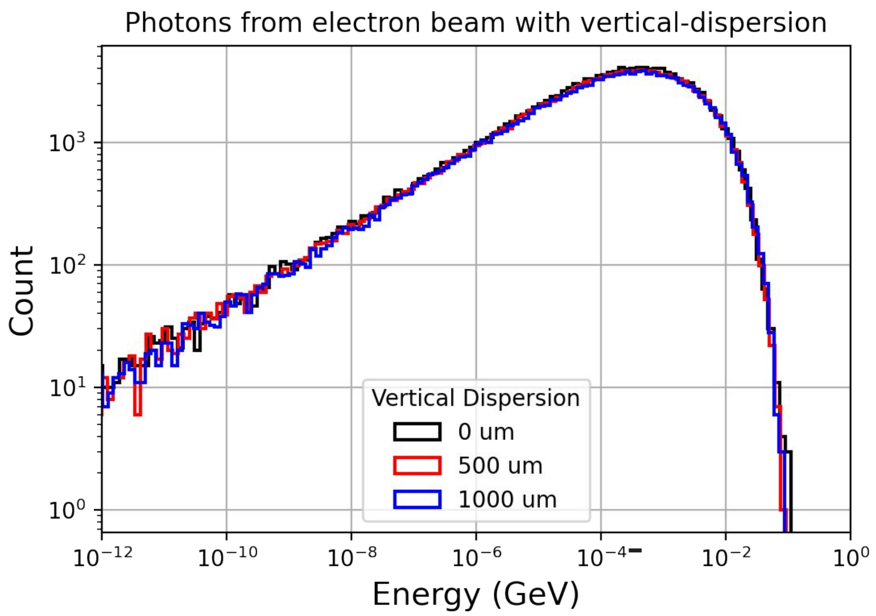
Waist Shifts (in electron beam) FCCee_t

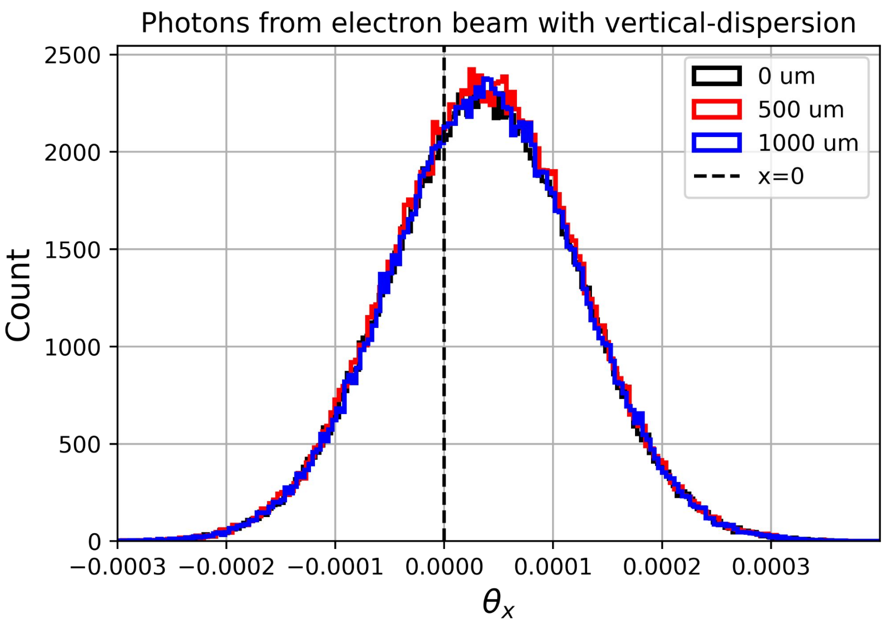




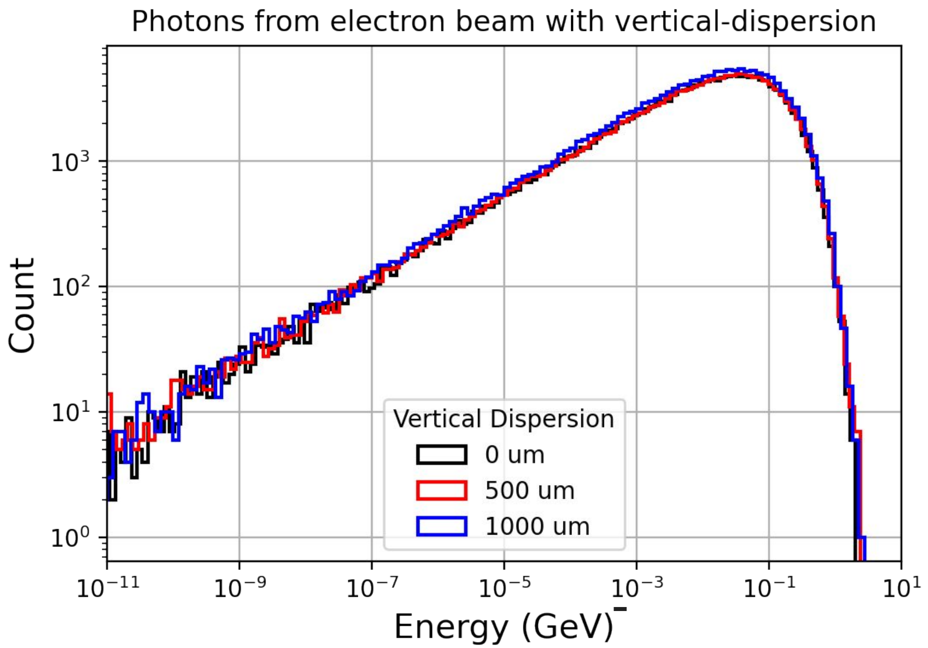
Vertical Dispersion (in electron beam)

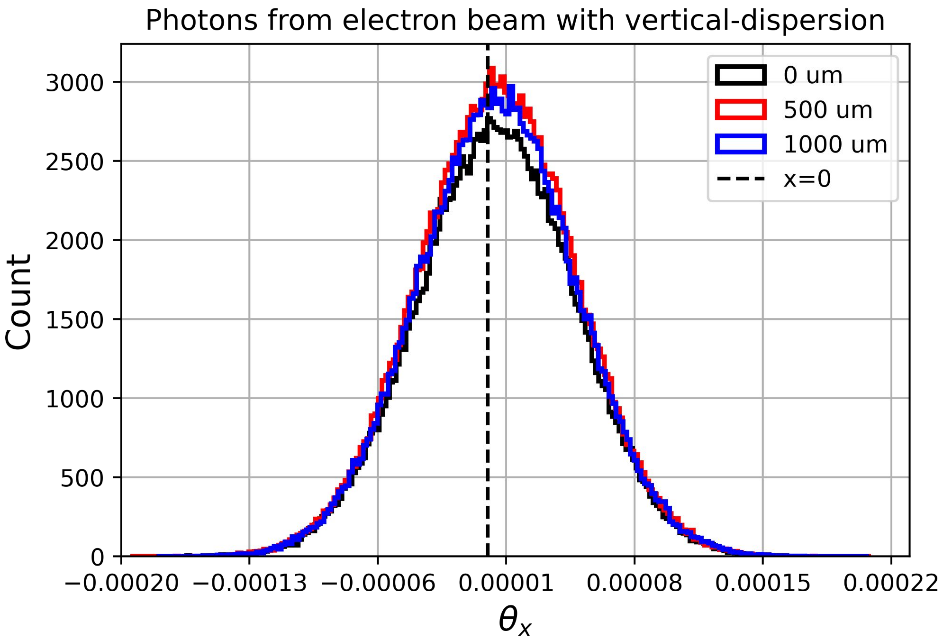
Vertical dispersion (in electron beam) FCCee Z





Vertical Dispersion (in electron beam) FCCee_t

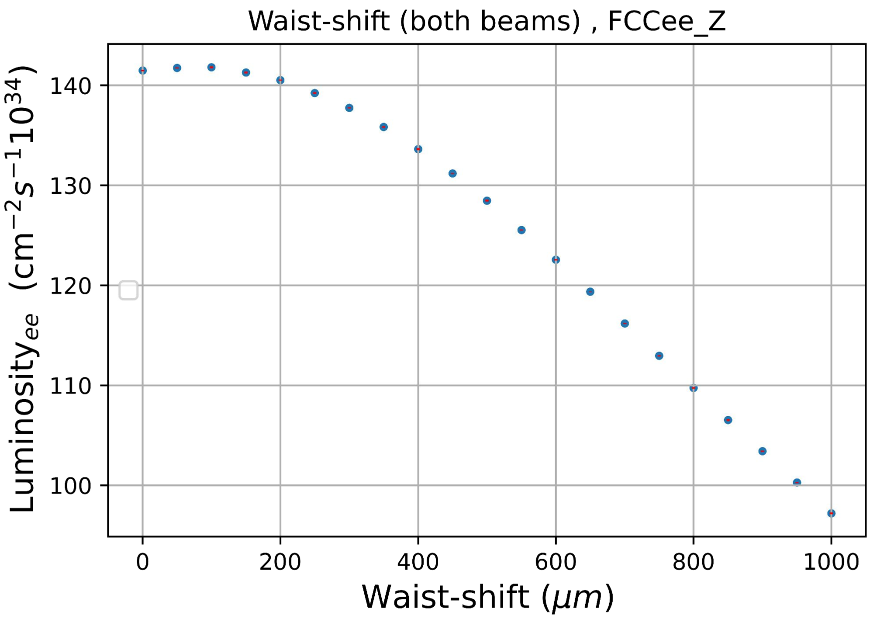




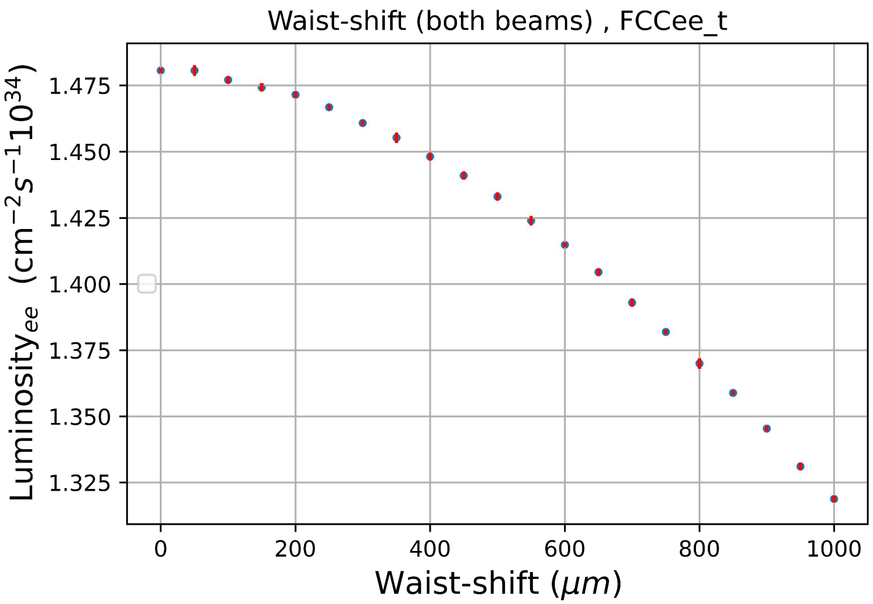
Waist shift (in both beams)

Waist-shift (both beams)

FCCee_Z

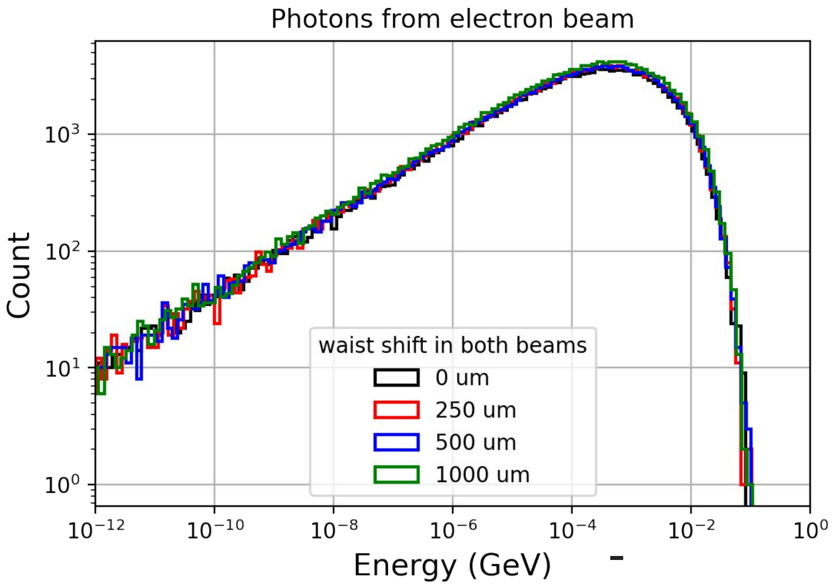


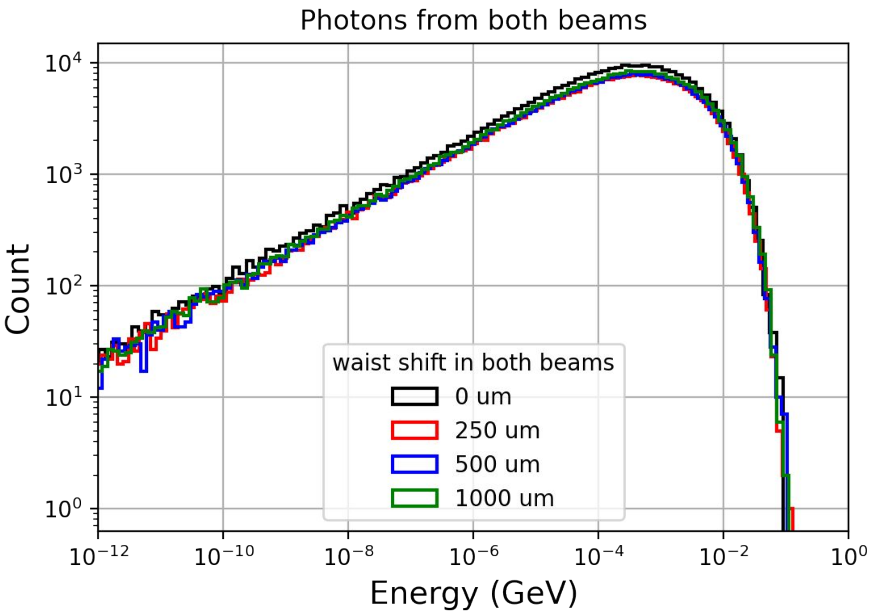
FCCee_t



Waist-shift (both beams)

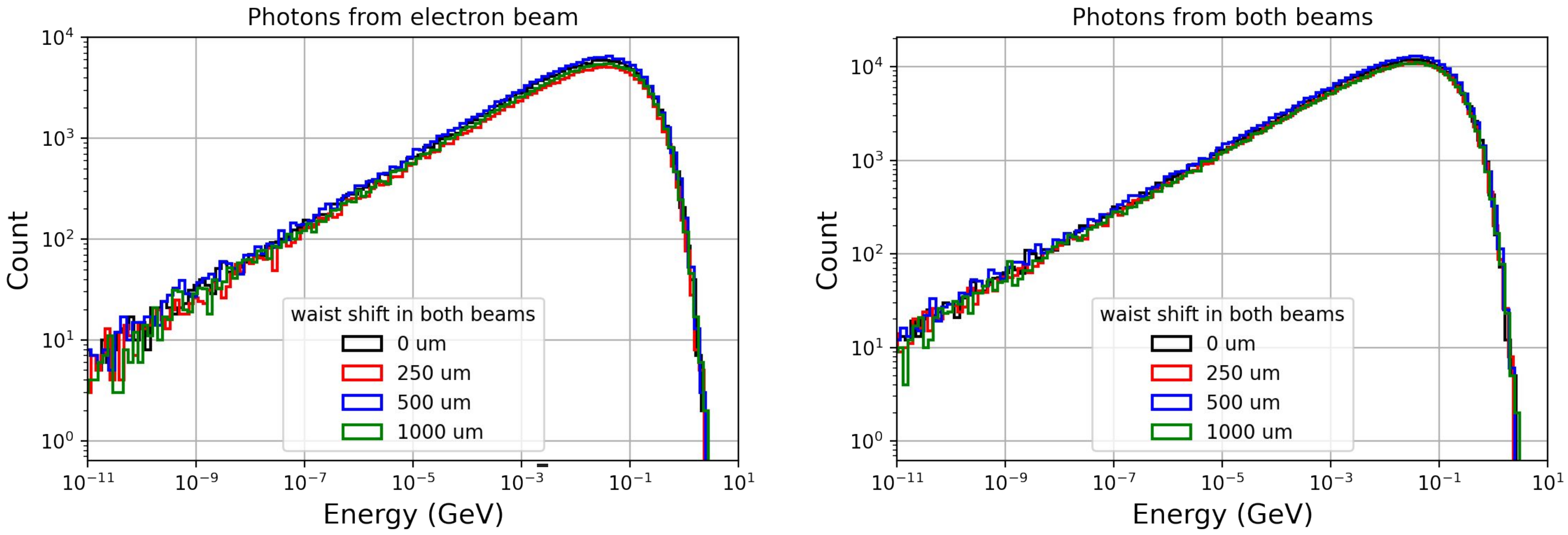
FCCee_Z





Waist-shift (both beams)

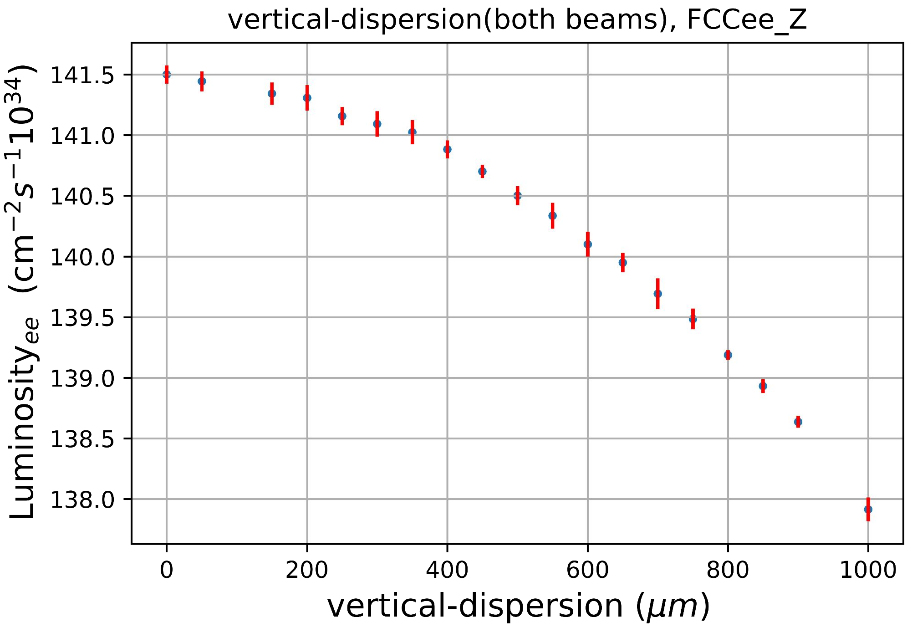
FCCee_t



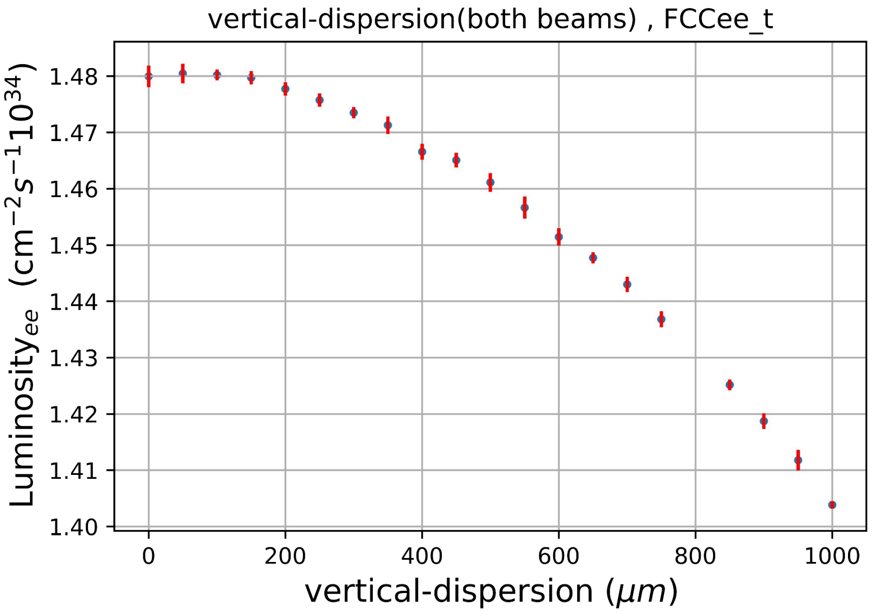
Vertical Dispersion (in both beams)

Vertical Dispersion (both beams)

FCCee_Z

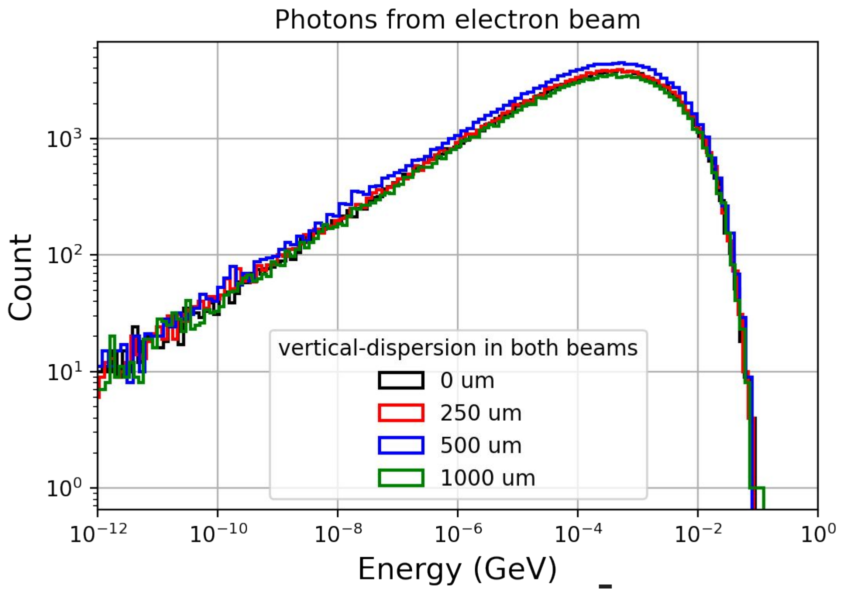


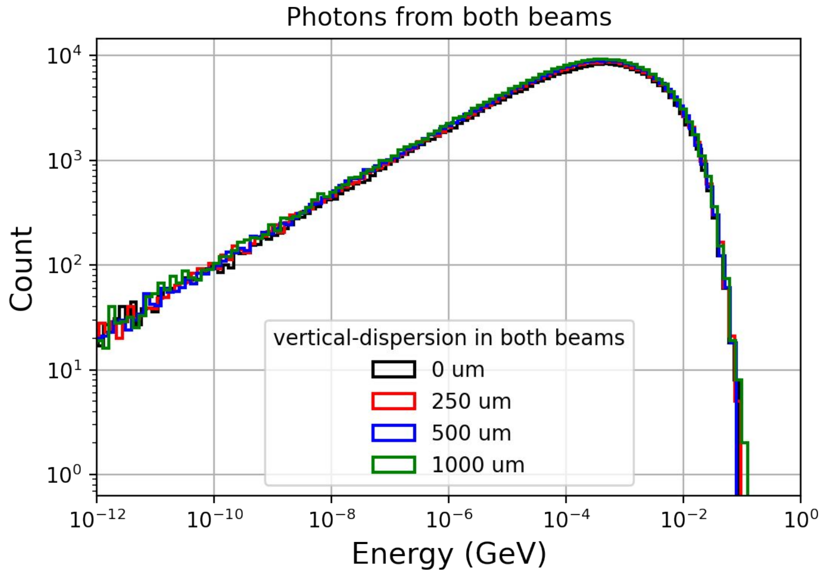
FCCee_t



Vertical-dispersion (both beams)

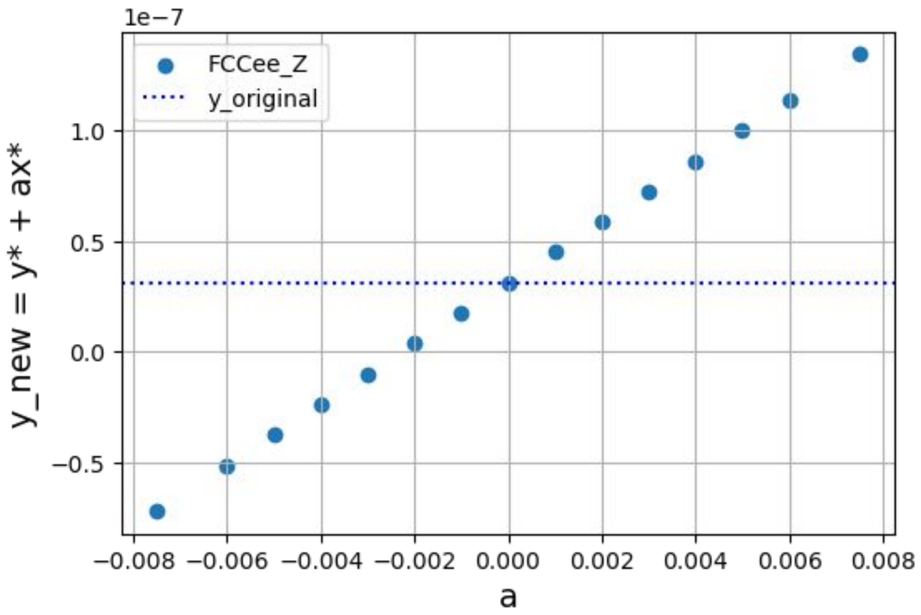
FCCee_Z

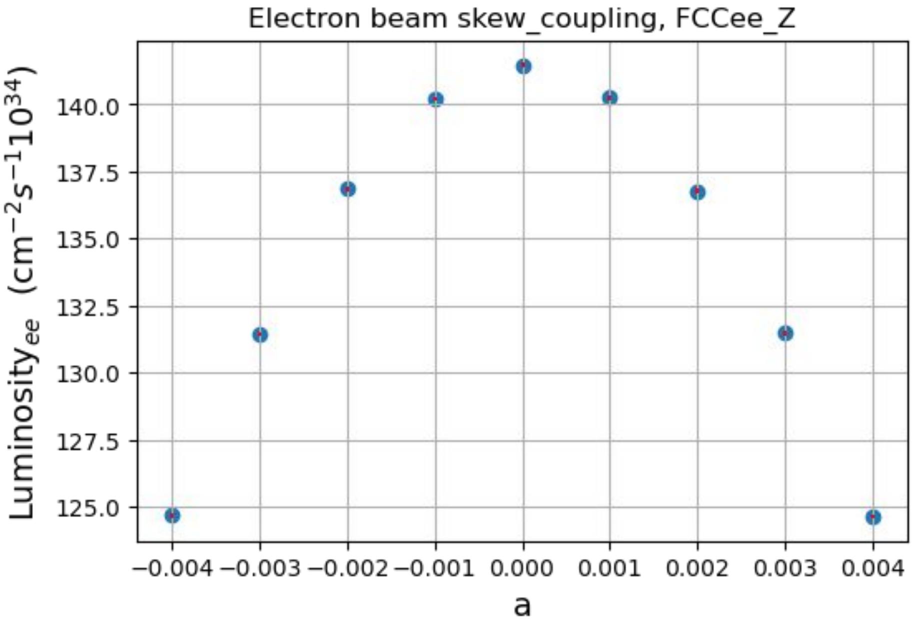




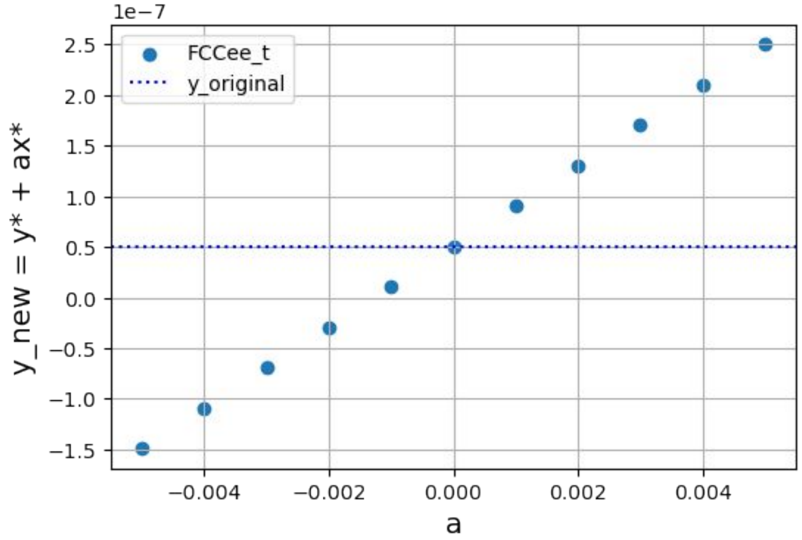
Skew Coupling

FCCee_Z

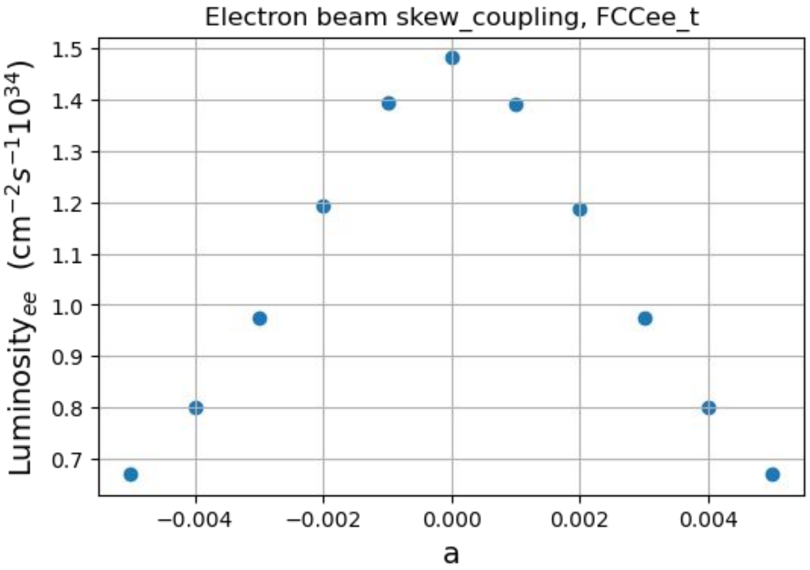

1e−7
FCCee_Z
y_original
1.0
0.5
0.0
−0.5
y_new = y* + ax*
−0.008
−0.006
−0.004
−0.002
0.000
0.002
0.004
0.006
0.008
a


Electron beam skew_coupling, FCCee_Z
140.0
137.5
135.0
132.5
130.0
127.5
125.0
$Luminosity_{ee}$ $(cm^{-2}s^{-1}10^{34})$
−0.004
−0.003
−0.002
−0.001
0.000
0.001
0.002
0.003
0.004
a

FCCee_t

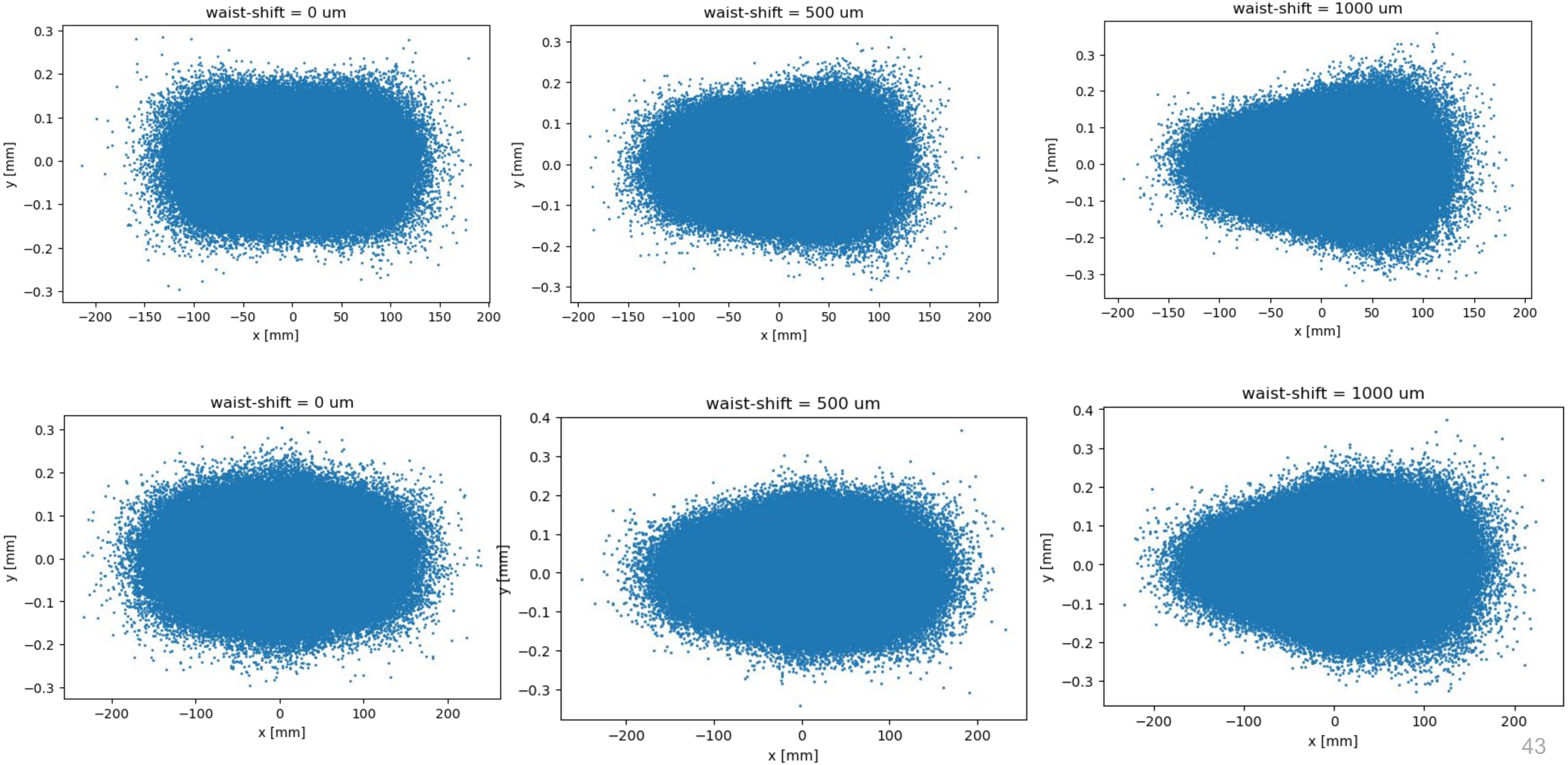


1e−7
FCCee_t
y_original
y_new = y* + ax*
a
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−0.004
−0.002
0.000
0.002
0.004

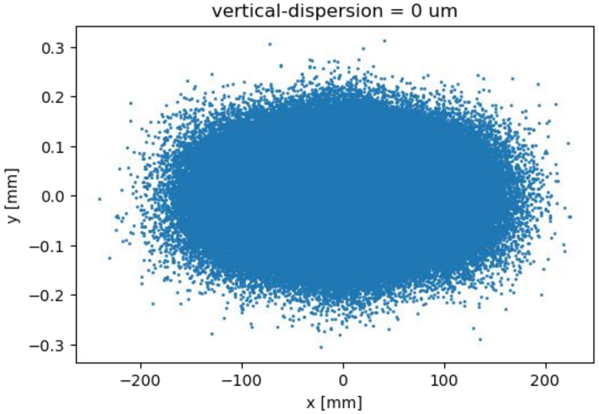


Electron beam skew_coupling, FCCee_t
Luminosity$_{ee}$ $(cm^{-2}s^{-1}10^{34})$
a
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
−0.004
−0.002
0.000
0.002
0.004

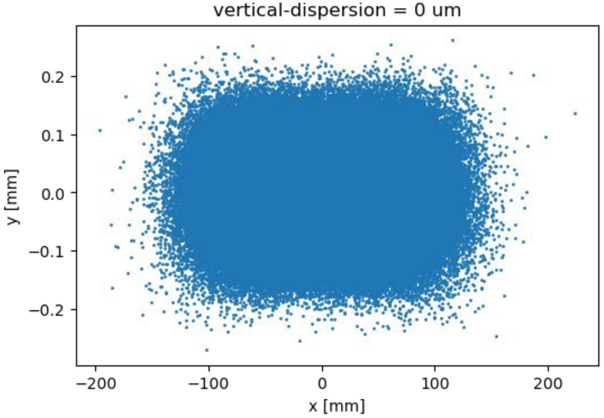
FCCee_t


waist-shift = 0 um
waist-shift = 500 um
waist-shift = 1000 um
waist-shift = 0 um
waist-shift = 500 um
waist-shift = 1000 um
y [mm]
x [mm]

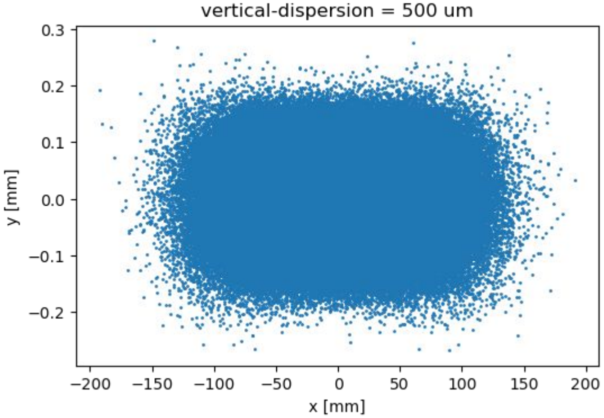
FCCee_t



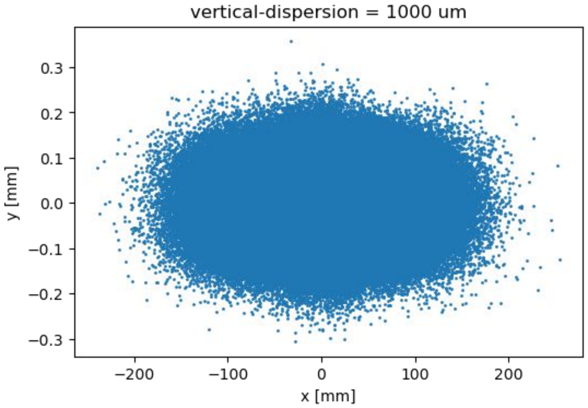
vertical-dispersion = 0 um
y [mm]
x [mm]



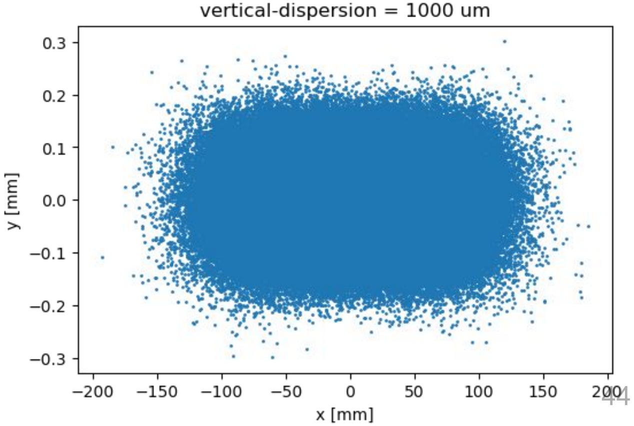
vertical-dispersion = 0 um
y [mm]
x [mm]



vertical-dispersion = 500 um
y [mm]
x [mm]



vertical-dispersion = 1000 um
y [mm]
x [mm]



vertical-dispersion = 1000 um
y [mm]
x [mm]

Parameters

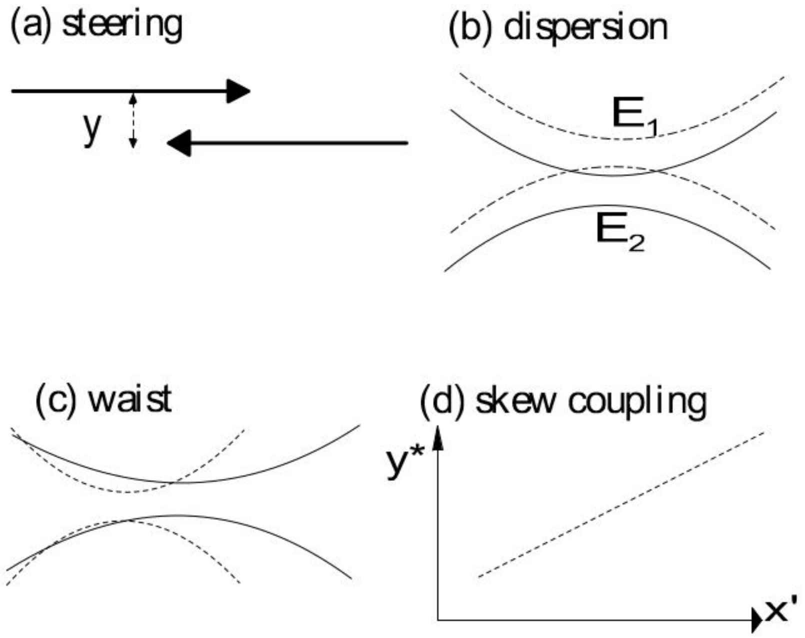
FCC-ee collider parameters as of July 30, 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0391	0.374	1.88	10.29
SR power / beam	[MW]	50			
Beam current	[mA]	1279	137	26.7	4.9
Colliding bunches / beam		11200	1780	380	56
Colliding bunch population	$[10^{11}]$	2.14	1.45	1.32	1.64
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.67	1.57
Ver. emittance at collision ε_y	[pm]	1.9	2.2	1.0	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.85	1.25	0.65	1.1
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	$[10^{-6}]$	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	800 / 1.5
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.360	398.148 / 398.216
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.109	0.070 / 0.109	0.103 / 0.152	0.159 / 0.201
Bunch length (SR/BS) σ_z	[mm]	5.60 / 15.5	3.46 / 5.09	3.40 / 5.09	1.85 / 2.33
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.089
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	3.1
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP	[mrad]	±15			
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y[a]		0.0022 / 0.097	0.013 / 0.128	0.010 / 0.088	0.066 / 0.144
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		26.4	3.7	5.4	0.99
Lifetime (q + BS + lattice)	[sec]	10000	4000	3500	3000
Lifetime (lum)[b]	[sec]	1330	970	660	650
Luminosity / IP	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	141	20	6.3	1.38
Luminosity / IP (CDR)	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	230	28	8.5	1.8

[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section

- Small beams, strong sextupoles to cancel chromaticity and aberrations

Waist shift **Vertical dispersion** **Skew coupling**



Credits: Frank's Notes