Luminosity Tuning and Optimization

Using Luminometer, Beamstrahlung, and Vertex Detector

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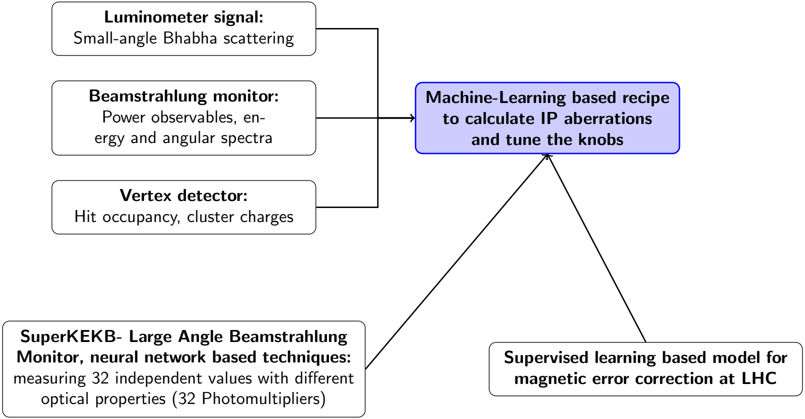
Outline

- Introduction
- Observables
- IP Tolerances

- Luminosity
- Beamstrahlung
- Pair Production

- Guinea-Pig vs X-suite
- Next Steps

Introduction



Observables

- **Luminometer: Luminosity**
- **Beamstrahlung monitor: Photon Power**
- **Vertex detector: Pair production**

Monitor the variations in above quantities and their observables for luminosity tuning with respect to three IP tolerances

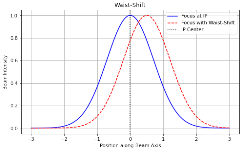
IP Spot Size Tolerances

- Consequence of horizontally/vertically displaced sextupoles, displaced quadrupoles, change in quadrupole strength, or rolls of bending magnets and quadrupoles

- Causes an increase in IP spot size, affects the overall luminosity, beamstrahlung emission, and pair production

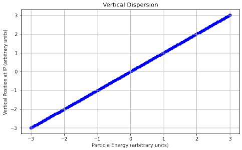
Waist Shift

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



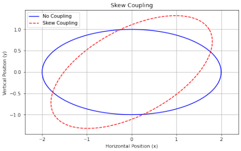
Vertical Dispersion

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



Skew Coupling

- $y^* \to y^* + ax^*$
- $y^* \to y^* + bx'^*$



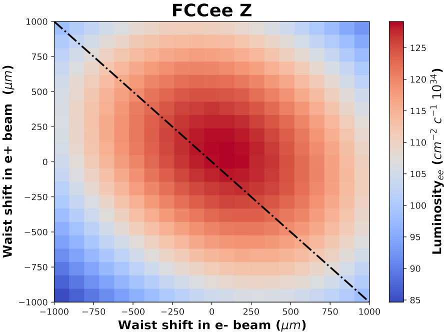
Measurements

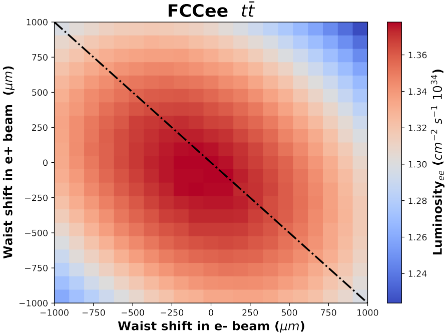
- **Luminometer: Luminosity measurements varying waist-shifts, vertical-dispersion, and skew coupling**
  Put initial luminosity-based constraints on IP aberrations

- Beamstrahlung monitor: Photon Power

- Vertex detector: Pair production

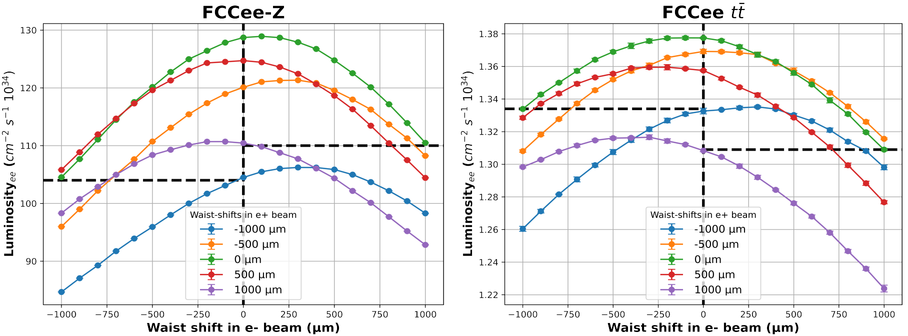
Luminosity and Waist-Shifts





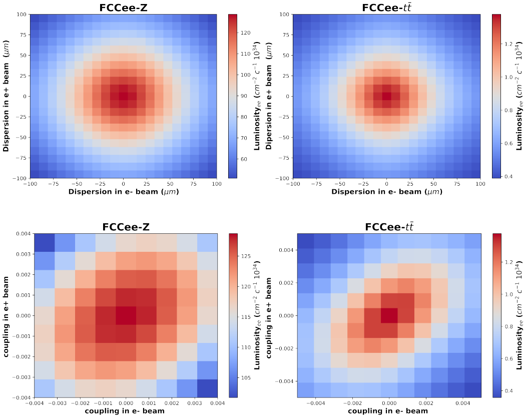
- Forward waist-shift in FCCee-Z shows increased luminosity
- The effect for FCCee-$t\bar{t}$ is 'opposite'
- $\sigma_{z,BS}$ for FCCee-Z: 15.5mm, while for FCCee-$t\bar{t}$: 2.33mm

Luminosity and Waist-Shifts



- In linear colliders, travelling waist effects focus the beam 'ahead of the collision point'
- The effect in FCCee-$t\bar{t}$ could be due to strong focusing forced by short bunch length and high bunch density

Luminosity: Dispersion and Coupling



Vertical Dispersion

- Symmetric reduction in luminosity for -ve, +ve values of dispersion
- Dispersion to be ideally contained within 50 μm

Skew Coupling

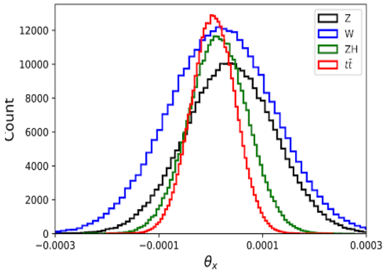
- Luminosity drops drastically for coupling ($a \sim 0.004$)
- Largely impacts FCCee-$t\bar{t}$

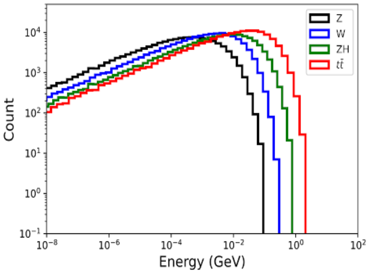
Measurements

- Luminometer: Luminosity measurements
- **Beamstrahlung: Photon Power with varying waist-shifts, vertical-dispersion, and skew coupling**
  expected power output, requirements for beamstrahlung monitor
- Vertex detector: Pair production

Beamstrahlung

- Beamstrahlung is a direct consequence of beam-beam interactions: diagnostic tool for understanding IP beam dynamics
- Noticeable variations in BS power output with IP tolerances
- IP tolerances increases BS power, leads to a direct decrease in luminosity and increase in machine backgrounds





Previous Measurements

SLC

- Transverse sizes of e+/e- beam: Analysis of BS energy patterns
- IP steering: Angular shift in centre of BS distribution (gamma region)
- Beam size variation: Visible(light) beamstrahlung at fixed angle

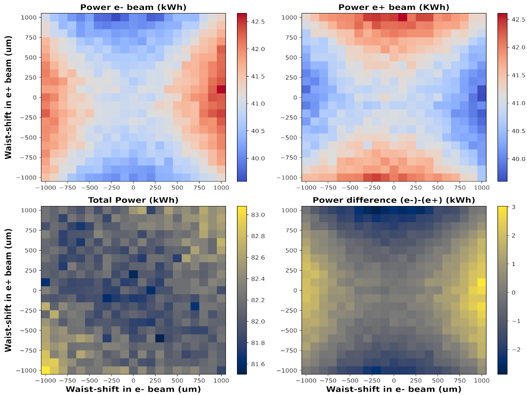
CESR and EIC studies

- Moments of beam distribution: From polarization data of BS photons
- Monitoring beam position and size: BS polarization and spectra

SuperKEKB

- Beam length and collision timing: BS time profile
- Relative height of beams, vertical offsets: Polarization observables (ratios)
- Information about IP geometry: Angular scans

Beamstrahlung: waist shift at $t\bar{t}$

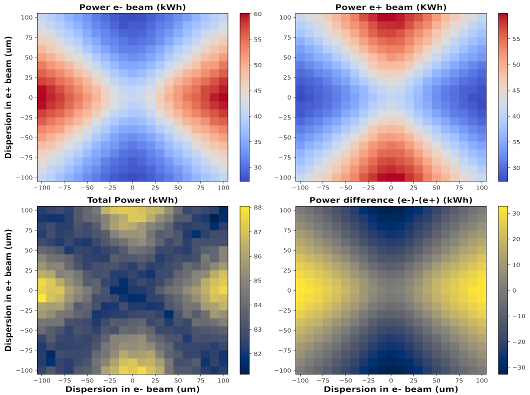


FCCee-$t\bar{t}$

- Higher waist shifts increase power emission
- "$\text{waist}_{e+} = \text{waist}_{e-}$" and "$\text{waist}_{e+} = -(\text{waist}_{e-})$" emits similar power

*mean power over five repeats

Beamstrahlung: dispersion at $t\bar{t}$

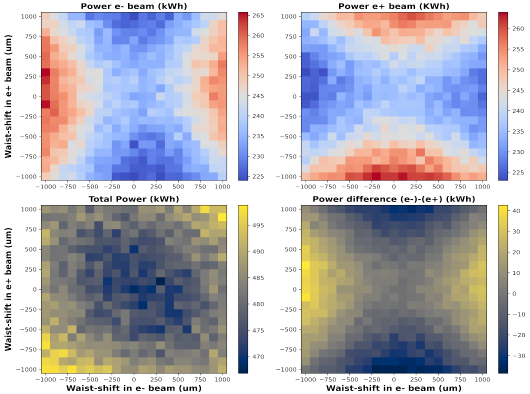


FCCee-$t\bar{t}$

- vertical dispersion leads to drastic changes in emitted power
- all four power observables can be exploited

*mean power over five repeats

Beamstrahlung: waist shift at Z

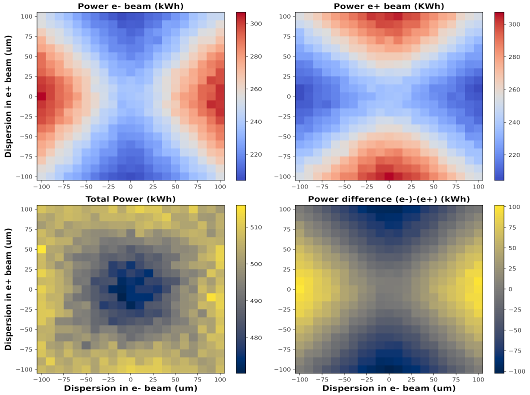


FCCee-Z

- BS power of a beam goes up there is waist shift
- while it goes down when the opposite beam has a waist-shift
- Power difference: better observable than total power for waist-shift

*mean power over five repeats

Beamstrahlung: dispersion at Z



FCCee-Z

- Qualitatively behaves similar to waist shift
- Quantitatively- the change is much larger

*mean power over five repeats

Measurements

- Luminometer: Luminosity
- Beamstrahlung monitor: Photon Power
- **Vertex detector: Pair production with varying waist-shifts, vertical-dispersion, and skew coupling** utilising measured machine backgrounds within detector limits

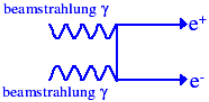
Pair Production

Pair production is a 'secondary' effect of Beamstrahlung- beam-beam field creates e+e- pairs from energetic BS photons

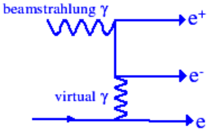
Beamstrahlung photons produce e+e- pairs via 3 major processes:

- Interaction of two BS photons
- Interaction of BS photon with EM field of an electron
- EM interaction involving virtual photons

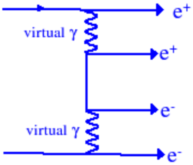
Breit-Wheeler



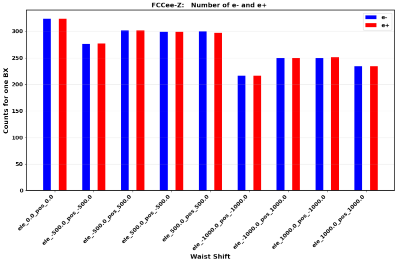
Bethe-Heitler

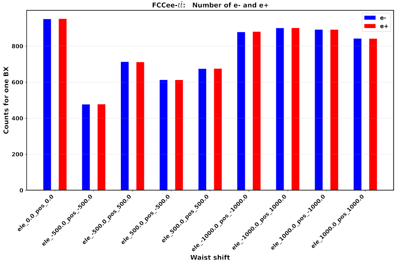


Landau-Lifshitz



Detector backgrounds: waist shift

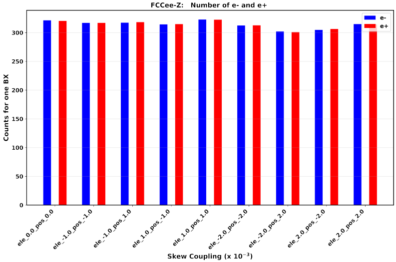


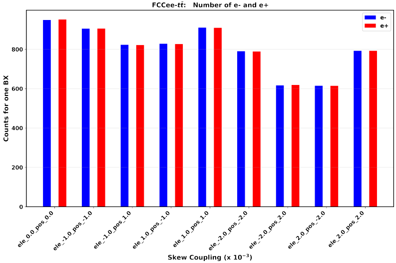


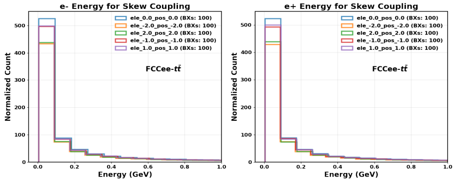
- waist-shifts of 500um at Z-working points produces more pairs than 1000um (expected)
- Unusual reverse effect at the $t\bar{t}$ working point is seen
- Some unequal count of e+,e-: particles out of grid?

*normalized counts over 100 BXs

Detector backgrounds: coupling





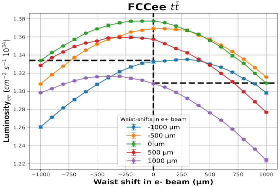


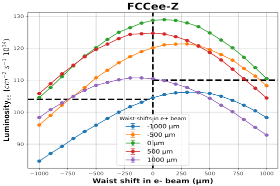
- skew coupling has minimal effect on pair production at Z-working point
- Minimum pair production at increased beam overlap

*normalized counts over 100 BXs, $y^* \rightarrow y^* + ax^*$

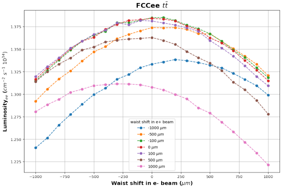
Benchmarking X-Suite: waist shifts

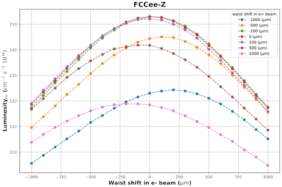
Guinea Pig





Xsuite Strong-Strong



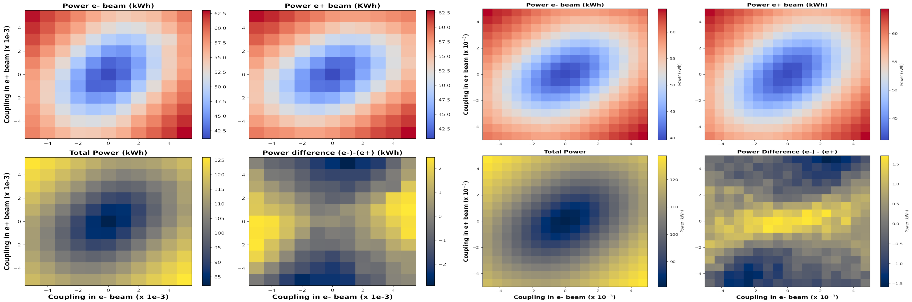


- Shift in the peak luminosity (forward for Z, and backwards for $t\bar{t}$ is not reproduced in Xsuite strong-strong simulations.

Benchmarking X-Suite: coupling

FCCee-$t\bar{t}$

Guinea Pig | **Xsuite Strong-Strong**



- coupling effects on beamstrahlung power are well reproduced for single turn in Xsuite
- except for a slight uncertainty in positron beam power and power difference

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

Next Steps

- Xsuite PIC solver simulations, and multiturn sims

  (reproduce waist-shift effects etc)
- Pair production in Xsuite
  for detector background studies

- Measurable detector background (hit occupancies), kinematics within detector limits

- Integrating the observables into machine learning based-data acquisition framework

Thank You!

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FCCee Beam-Beam-Team

Additional Slides and Backups

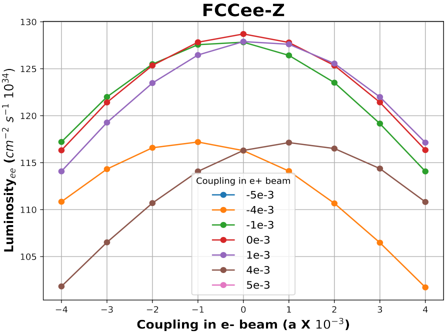
FCC-ee collider parameters as of July 30, 2023.

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}/cm^{2}s]	141	20	6.3	1.38
Luminosity / IP (CDR)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

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

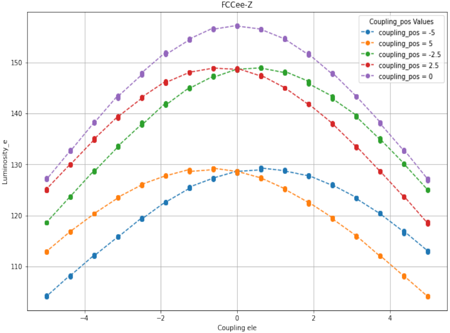
Luminosity: coupling at Z

Guinea Pig



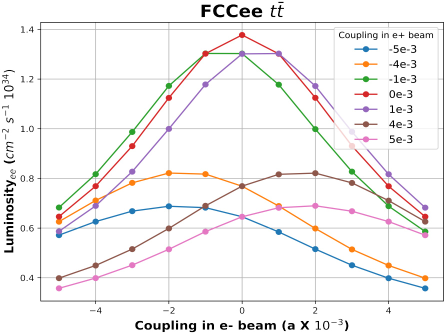
$y^* \rightarrow y^* + ax^*$

Xsuite



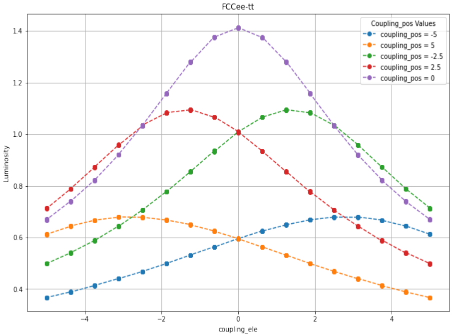
Luminosity: coupling at $t\bar{t}$

Guinea Pig

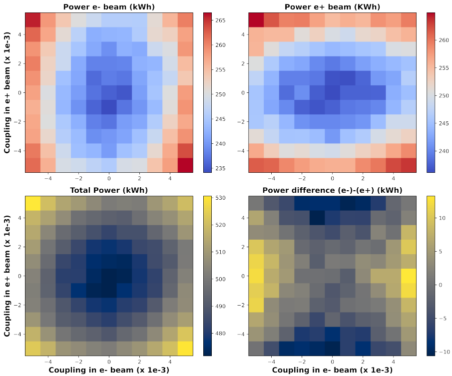


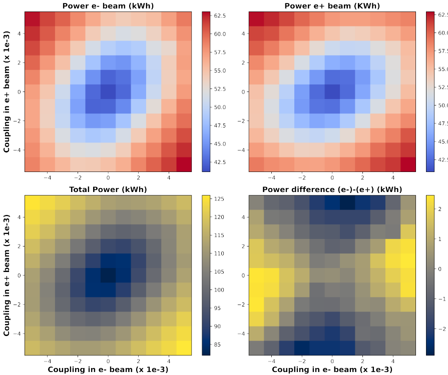
$y^* \rightarrow y^* + ax^*$

Xsuite



Beamstrahlung: coupling at Z and $t\bar{t}$

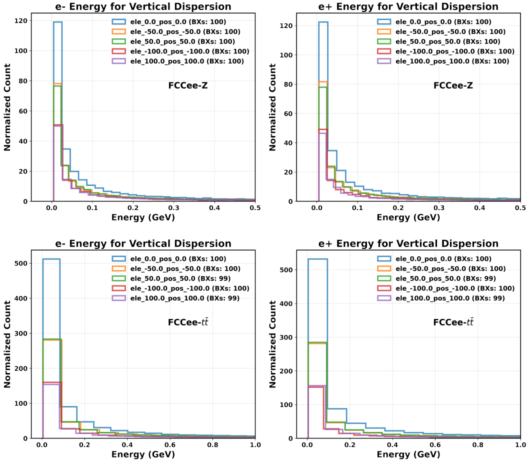




$$y^* \to y^* + ax^*$$

*mean power over five repeats

Detector backgrounds: dispersion



- Peak energy count decrease with non-zero vertical dispersion (as the number of pairs produced also decrease)
- +ve, -ve dispersion values behaves similarly, the combined effect of energy spread and -ve,+ve dispersion changes beam-size in same manner