FCCee MDI & IR Mockup Workshop

First Assessments of Luminosity-related signals at FCC-ee

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Outline

- Luminosity Determination
- Work Plan / Constraints
- Beamstrahlung
- GUINEA-PIG
- Preliminary plots

Luminosity Determination in Colliders

- Luminosity Determination:

  1. Measuring rate of low angle Bhabha interactions (e+e- → e+e-) - LEP
     --Radiative Bhabha scattering for relative luminosity measurements

  2. Detecting photons from radiative bhabha scattering (e+e- → e+e- gamma) - SuperKEKB

  3. Cherenkov detector to monitor beamstrahlung flux - SLC

  4. The Van Der Meer method (using vertical beam steering) - ISR, LHC

Luminosity	Z	W	ZH	$t\bar{t}$
$10^{34} cm^{-2} s^{-1}$	140	20	5.0	1.25

- Targeted accuracy for FCCee: 0.01% or 10e-4 for absolute luminosity
- Acceptance limit: um precision in the LumiCal for small-angle Bhabhas (due to steep angular dependence of the Bhabha scattering)

Luminosity Determination in FCC-ee

- Luminosity Determination: Rate of low angle Bhabha interactions (e+e- → e+e-)

  - ❏ Has well understood, calculable and large cross section
  - ❏ Sufficient Statistical Precision,
  - ❏ Separation from background radiation

- The photons detected by luminometer are plagued by background radiations: Beamstrahlung, pair-production, radiative Bhabha , Additionally: SR, Solenoid

Beam-Beam backgrounds

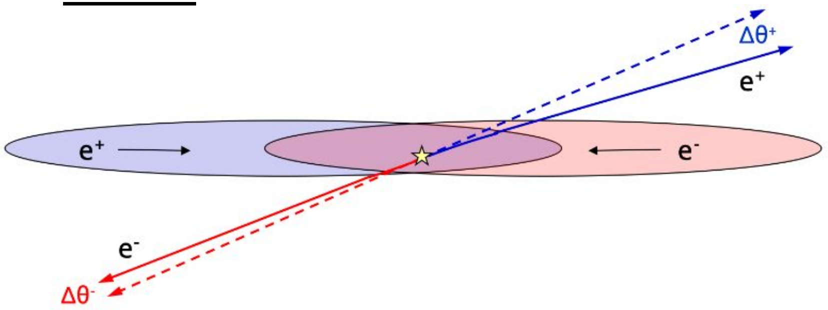
↓

Affects the effective acceptance of luminometer

↓

Systematic Bias in total Luminosity measurement, Changes the luminosity spectrum

<u>The radiation processes and their impact on luminosity can be measured for luminosity optimization during the collision</u>



Work Plan and Constraints

- 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

Combine this information for Luminosity tuning and optimization

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Luminometer and Beamstrahlung Monitor

- Bhabha scattering: provides low instantaneous counting rate
- Very high power from beamstrahlung photons
- Handling the backgrounds resulting from beamstrahlung photon (could affect detector/ SVD): incoherent e+e- pair production
- Distinguishing and shielding beamstrahlung photons from synchrotron and low energy radiative-Bhabha photons

Beamstrahlung

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

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

- Affects the bunch length and energy spread- and hence the beam lifetime + luminosity
- Photon number and emitted energy proportional to beamstrahlung parameter

Measurements based on the Beamstrahlung Monitor

- Transverse sizes of e+ and e- beam: Analysis of beamstrahlung energy patterns
- IP beam-beam steering: Angular shift in in centre of beamstrahlung distribution (in gamma region- at small angles)
- Luminosity, beam size variation:
  Visible (light) beamstrahlung at fixed angle.
  Radiation intensity depends on-

$$\frac{N_2 L}{\theta^3} e^{\frac{-\sigma_s^2\theta^4\omega^2}{16c^2}}$$

GUINEA PIG

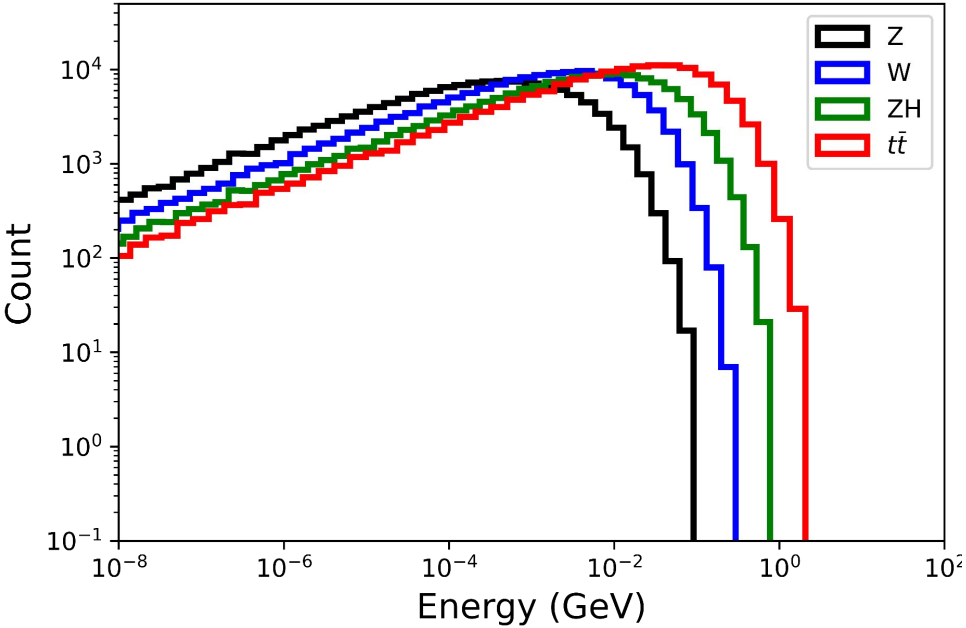
Generator of Unwanted Interactions for Numerical Experiment Analysis: Program Interfaced to GEANT

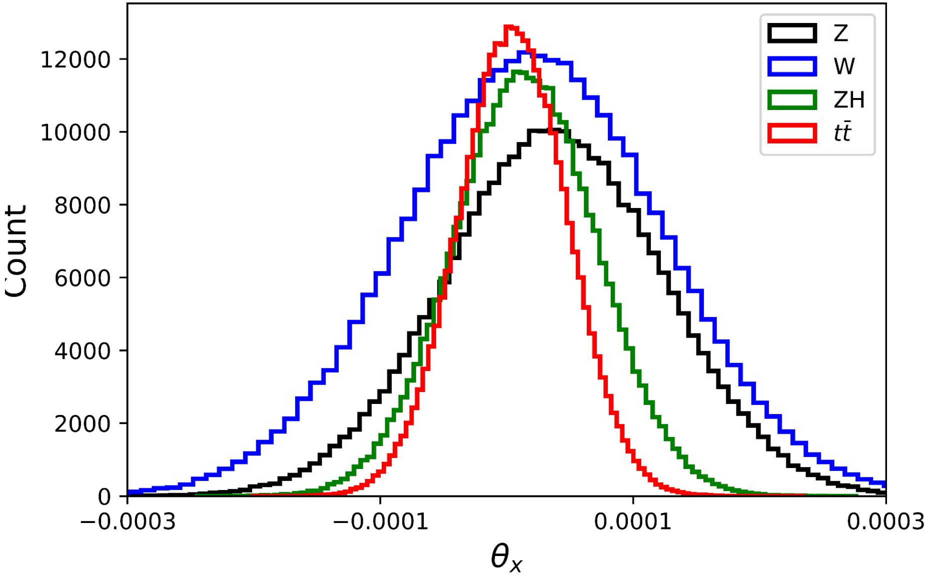
- Implements full beam dynamics for particle generation, generates radiative Bhabha and Beamstrahlung, interaction effects on luminosity and background
- Both classical and quantum description of beamstrahlung can be used
- Simulation code also includes pinch effect, pair creation, hadronic background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

Preliminary results

Beamstrahlung flux at four working points of FCCee

45.6 GeV, 80.0 GeV, 120.0 GeV, 182.5 GeV





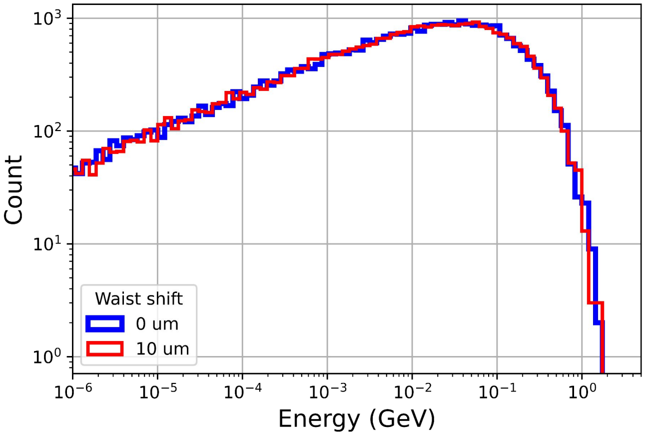
Preliminary results: Vertical waist shifts

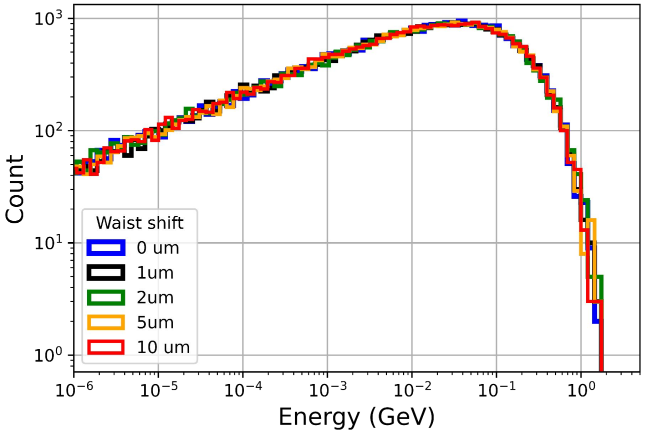
- Waist shift: increases IP spot size
  Cause: horizontal sextupole or upstream quadrupole displacement, change in quadrupole strength

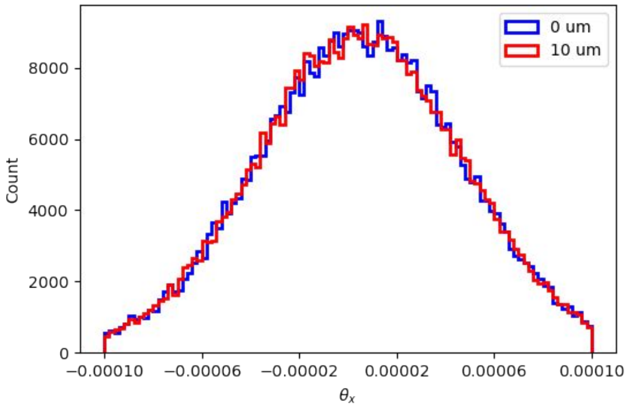
- $y^* \rightarrow y^* + l y'^*$

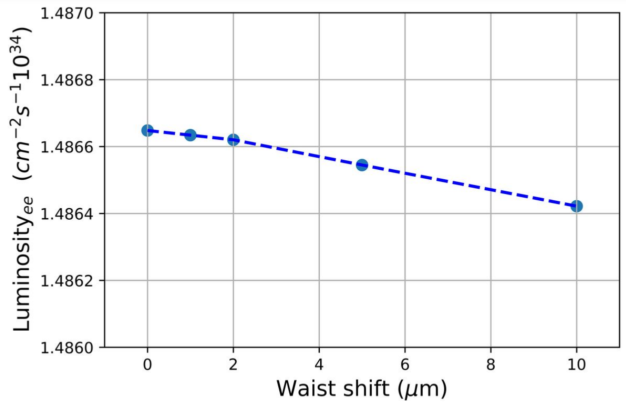
Working point:
ttbar, 182.5 GeV

BS photons distributions





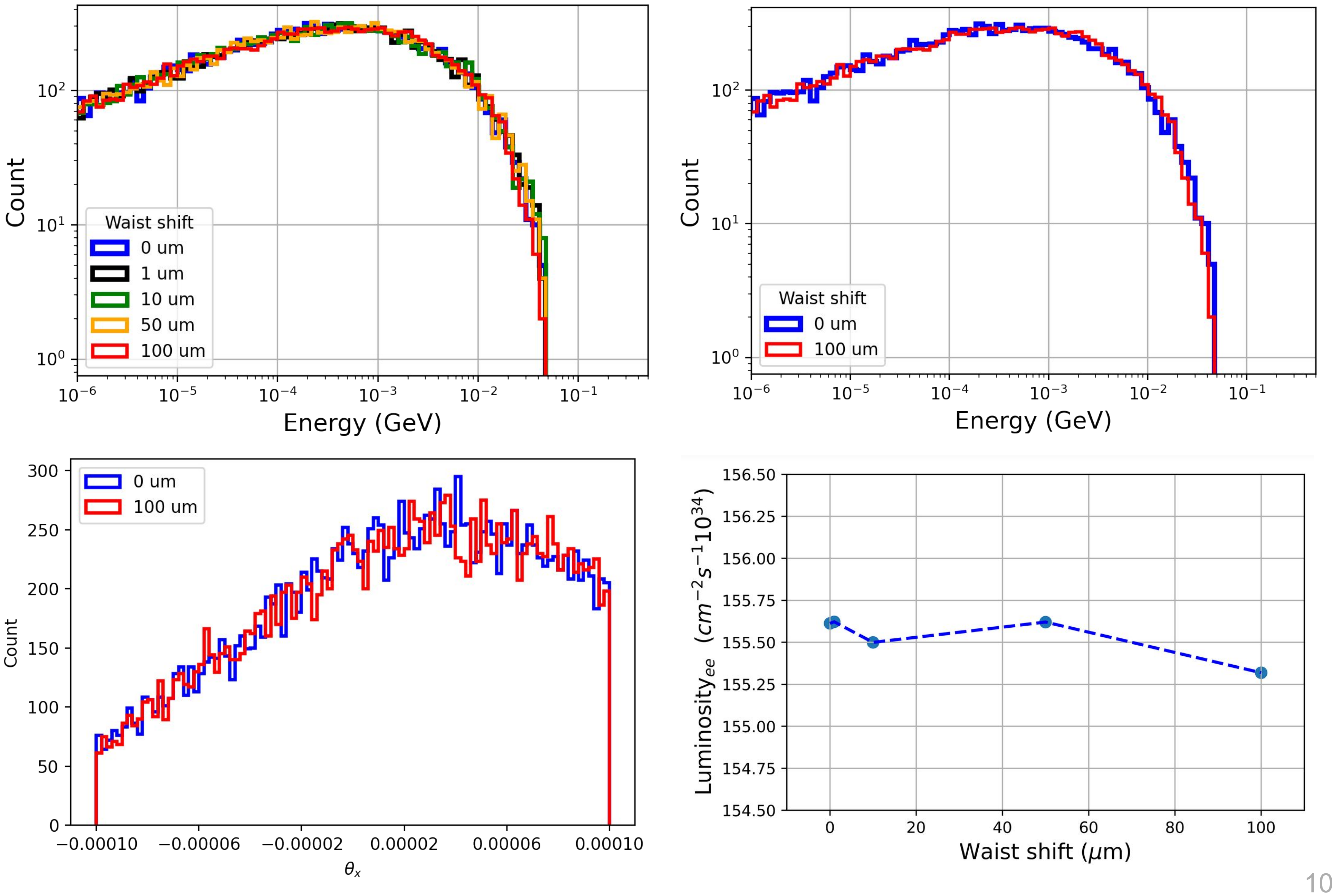




Preliminary results: Vertical waist shifts

Working point:
Z, 45.6 GeV

BS photons distributions



References

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- Beam-beam deflection as a beam tuning tool at the SLAC linear collider https://www.sciencedirect.com/science/article/pii/016890029090203I
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- 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

Acknowledgements

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Thank you all!

Thank you all!

BACKUP SLIDES

Summary slide

- 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 waist shifts, vertical dispersions etc on BS spectrum, power output, and luminosity at four different working points
- Additional beam-generation code to set-up switches unavailable in GP.

Measurements possible from Beamstrahlung

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

Luminosity Tuning

Bremsstrahlung

- Event rates proportional to luminosity
- Detection of hard photons or remnant beam particles

- Detected photon accompanied by number of soft photons
- Need to avoid detecting beamstrahlung related or pair-production related low energy particles.

Beamstrahlung

- Affects the bunch length and energy spread- and hence the beam lifetime and luminosity
- Photon number and emitted energy proportional to beamstrahlung parameter: simplifies power estimation

- Intense/powerful production- upto ~100 kilowatts
- Needs shielding from radiative Bhabha (emitted in same radiation cone)

Pair-Production

- Coherent and incoherent (small epsilon) production
- Breit-Wheeler, Bethe-Heitler and Landau-Lifshitz

Parameters

FCC-ee collider parameters as of June 3, 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]	9.936			
Energy loss / turn	[GeV]	0.0394	0.374	1.89	10.42
SR power / beam	[MW]	50			
Beam current	[mA]	1270	137	26.7	4.9
Colliding bunches / beam		15880	1780	440	60
Colliding bunch population	$[10^{11}]$	1.51	1.45	1.15	1.55
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.71	1.59
Ver. emittance at collision ε_y	[pm]	1.4	2.2	1.4	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.75	1.25	0.85	0.9
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	1000 / 1.6
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.358	398.148 / 398.182
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.089	0.070 / 0.109	0.104 / 0.143	0.160 / 0.192
Bunch length (SR/BS) σ_z	[mm]	5.60 / 12.7	3.47 / 5.41	3.40 / 4.70	1.81 / 2.17
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	0.091
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	2.9
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP $\pm\theta_x$	[mrad]	±15			
Piwinski angle $(\theta_x\sigma_{z,\mathrm{BS}})/\sigma^*_x$		21.7	3.7	5.4	0.82
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y[a]		0.0023 / 0.096	0.013 / 0.128	0.010 / 0.088	0.073 / 0.134
Lifetime (q + BS + lattice)	[sec]	15000	4000	6000	6000
Lifetime (lum)[b]	[sec]	1340	970	840	730
Luminosity / IP	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	140	20	5.0	1.25
Luminosity / IP (CDR, 2 IP)	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	230	28	8.5	1.8

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