Beam-Beam Background and Beamstrahlung studies at FCC-ee

01/07/2021 - FCC Week 2021 - Andrea Ciarma, Manuela Boscolo, Helmut Burkhardt, Gerardo Ganis

FUTURE CIRCULAR COLLIDER

Layout of the presentation

- Overview of the beam background studies
- Sources of radiation at the IP - Beamstrahlung and Radiative Bhabhas
- Spent beam tracking
- Incoherent pairs production

Simulation of backgrounds in the MDI region

The design and optimization of both the detector and the machine require realistic estimations of beam induced backgrounds. The **FCCee MDI Group** is therefore working to identify the most suitable generators for these backgrounds and embed them in the **FCCSW key4hep** (see G.Ganis talk on 28/06). For each of these backgrounds the relevant studies to perform for the MDI are:

- Tracking **secondary particles** in the detector using experimental software for the evaluation of the background in the detector
- Tracking of the **spent beam** through the optics using tools such as MADX for the evaluation of loss maps (extremely important for the background study in the MDI area) and beam lifetime
- Tracking of the **produced radiation** in the MDI area using dedicated tools to assess produced background, power deposition

For this talk I will give an overview on the status of the work on the two beam-beam induced radiation sources at the IP - **beamstrahlung** and **radiative Bhabhas** - and also on the production of **incoherent pairs**.

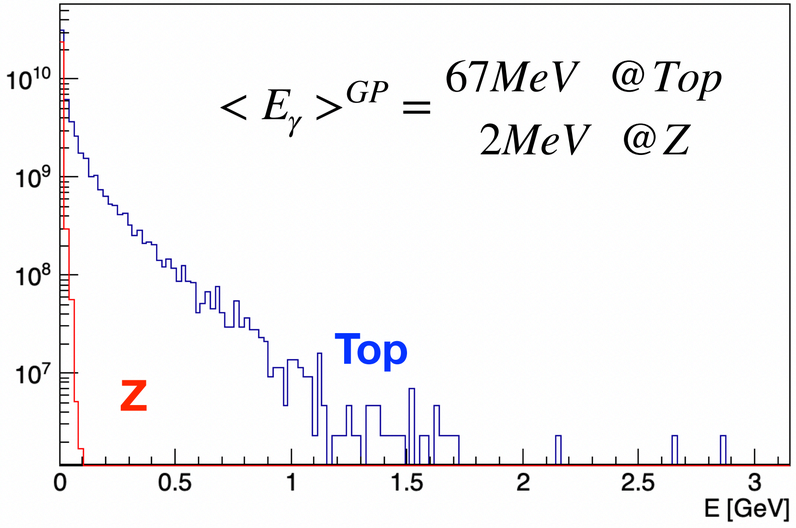
Beamstrahlung

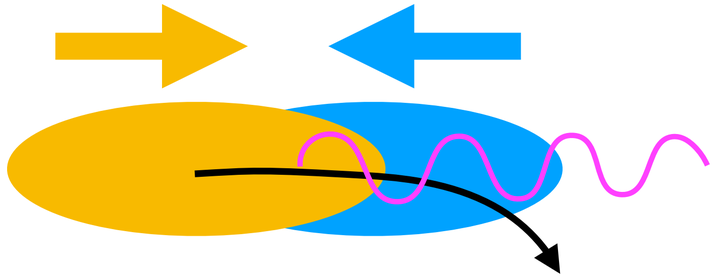
GuineaPig++ simulations have been performed at both Z (45.6 GeV) and Top (182.5 GeV) working points, using **gaussian beams** with the nominal parameters from CDR and a **30mrad crossing angle**.

The outcome of this simulations shows that the beamstrahlung photon beam produced at both beam energies is **very intense**. While the photon beam is more intense at the Z, at the 182.5GeV beam energy photons are much more energetic, with the tail of the energy spectrum reaching **~1 GeV.**

To study the effect of this radiation on the beam pipe, the photons have been tracked in the pipe and the **interaction probability** was evaluated, to give an estimate on the absorbed power.

Bunch Energy [GeV]	Beamstrahlung Parameter Υ	Photons per particle n_γ	Average photon energy [MeV] $< E_\gamma >$	Total photon beam power [kW]
45.6	1.81×10^{-4}	148	2	390
182.5	9.12×10^{-4}	242	67	88



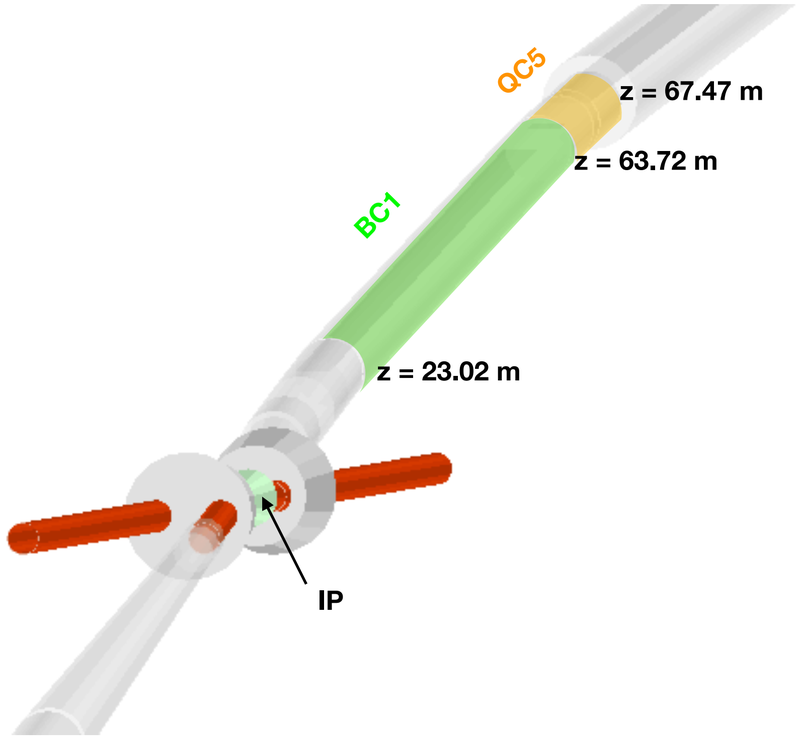


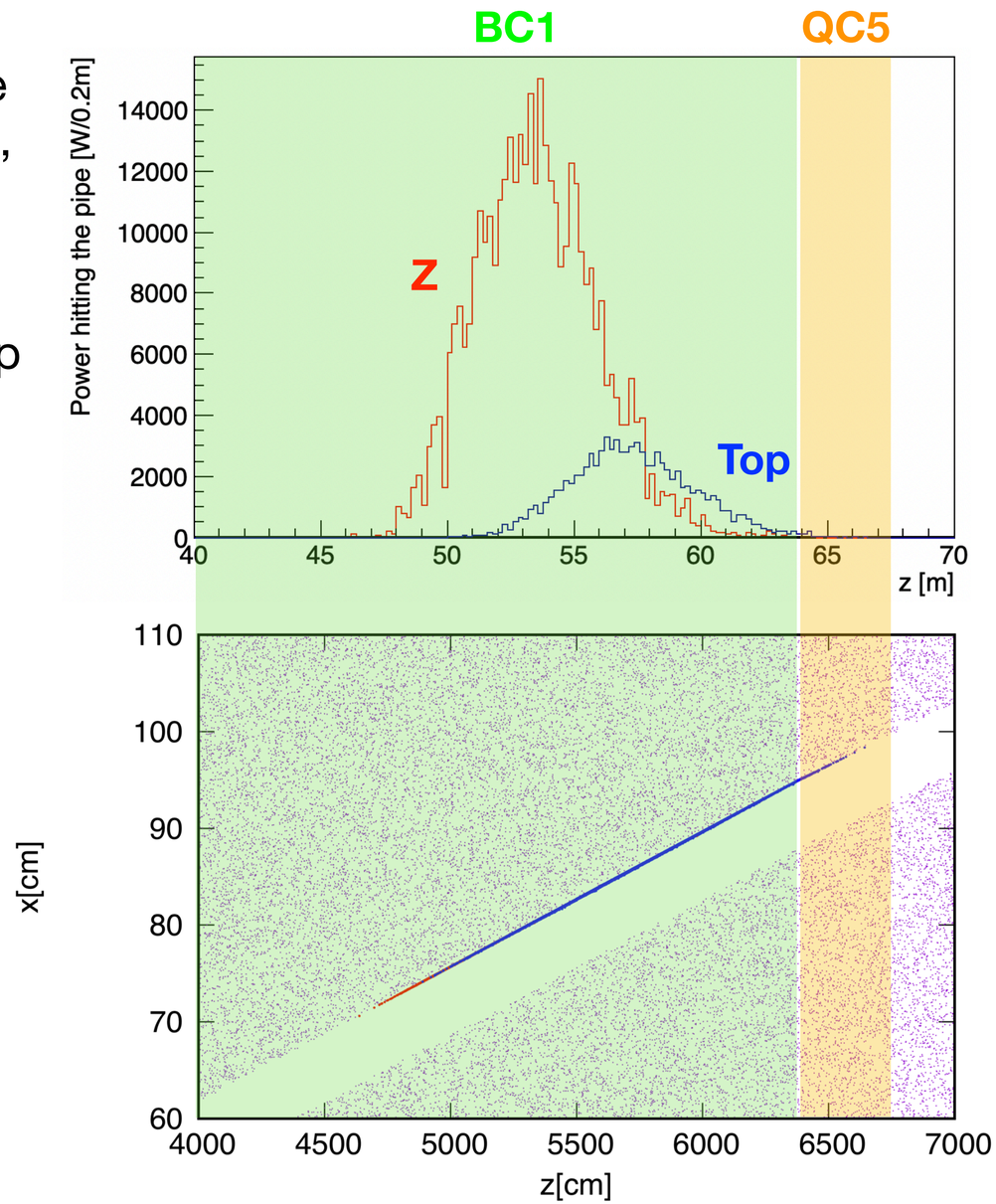
Results for the 45.6 GeV are in **agreement** with what previously presented by H. Burkhardt (FCC-ee MDI meeting #24 2/12/2019)

Tracking of Beamstrahlung photons

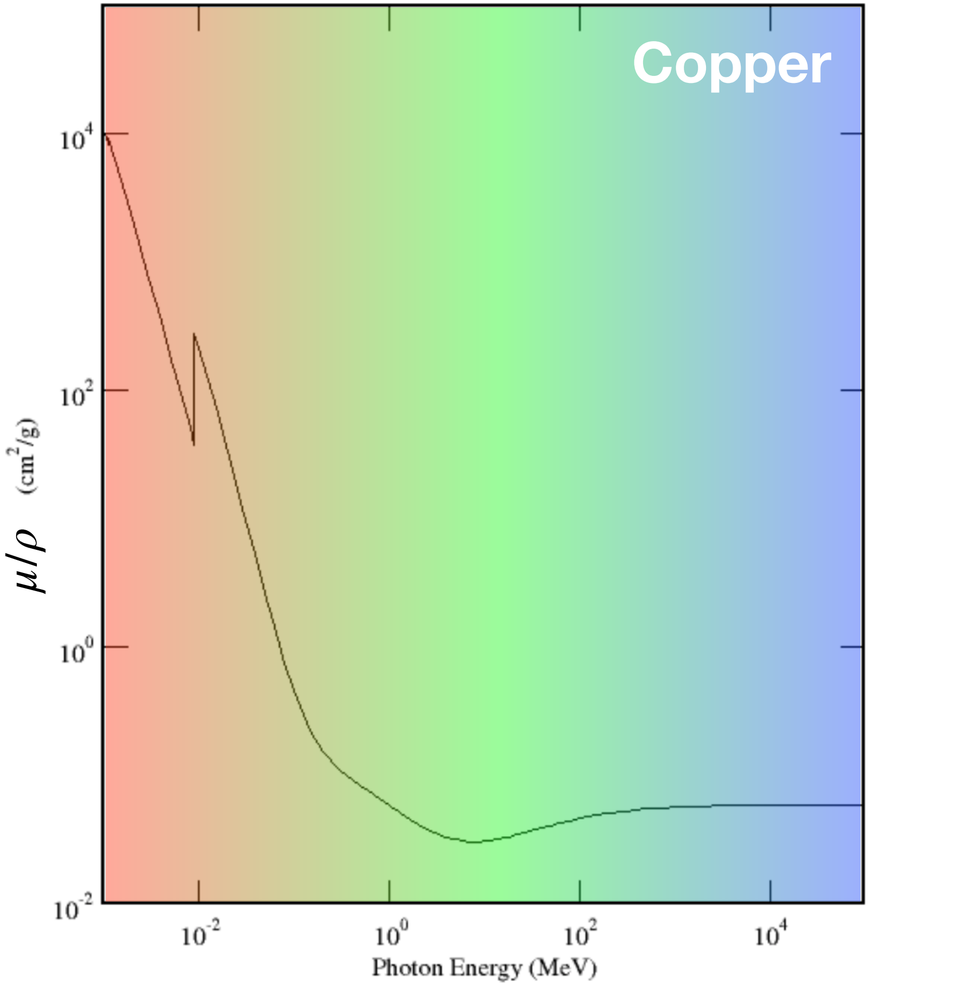
The photons have been tracked using the detailed description of the IR and beam pipe in a region of ±300m around the crossing point [1], using a simple *step-by-step* approach (2cm steps)

For both beam energies, all photons are lost around **55m from the IP**, mostly at the end of **BC1** (with the very edge of the tails ending up also in **QC5**)

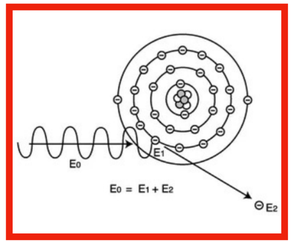


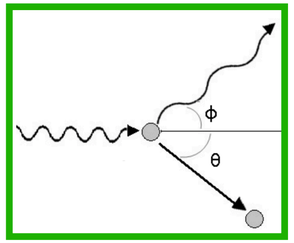


[1] provided in GDML format by M. Luckhof



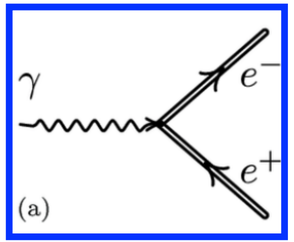
Photoelectric





Compton

Pair production



Interaction of photons with the pipe

The photon interaction probability has been evaluated for a **1mm thick Copper beam pipe**.

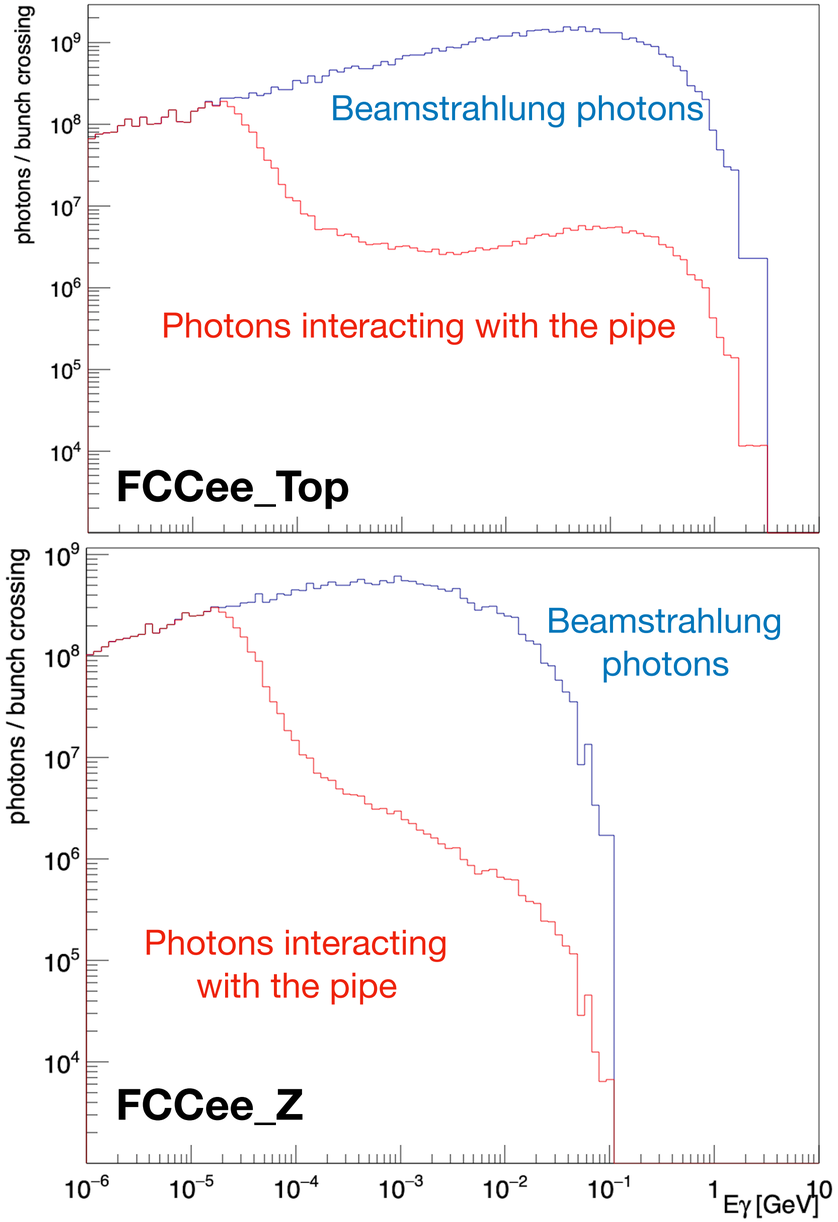
A lookup table for the **attenuation coefficient** in Copper was produced by the NIST tool at:

https://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html

and together with the **impinging angle** of each photon on the pipe, it was used to evaluate the interaction probability with the beam pipe for each beamstrahlung photon

$$P_{int}(x, E) = 1 - e^{-\mu(E)x}$$

Notice that not every interacting photon is completely absorbed by the pipe (fluorescence, Compton, pairs escaping the material…)



Beamstrahlung: Photons interacting with the pipe

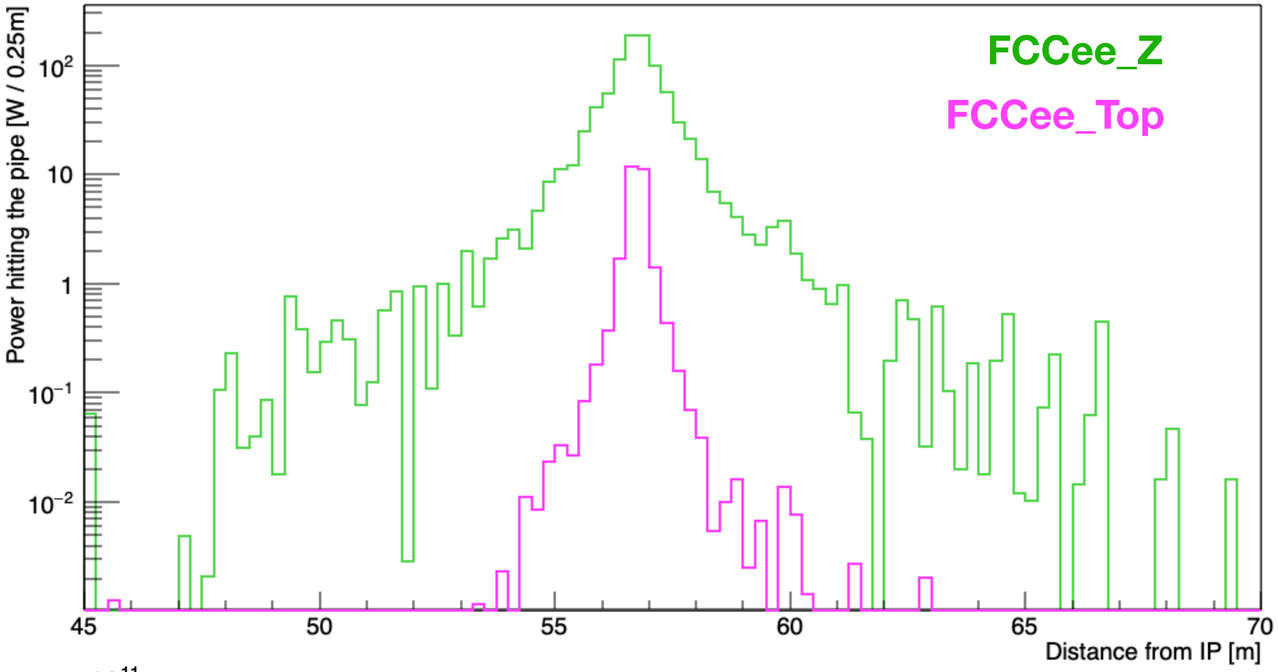
Assuming a total absorption of all the interacting photons, an **upper limit** for the deposited power on the 1mm copper beam pipe can be given.

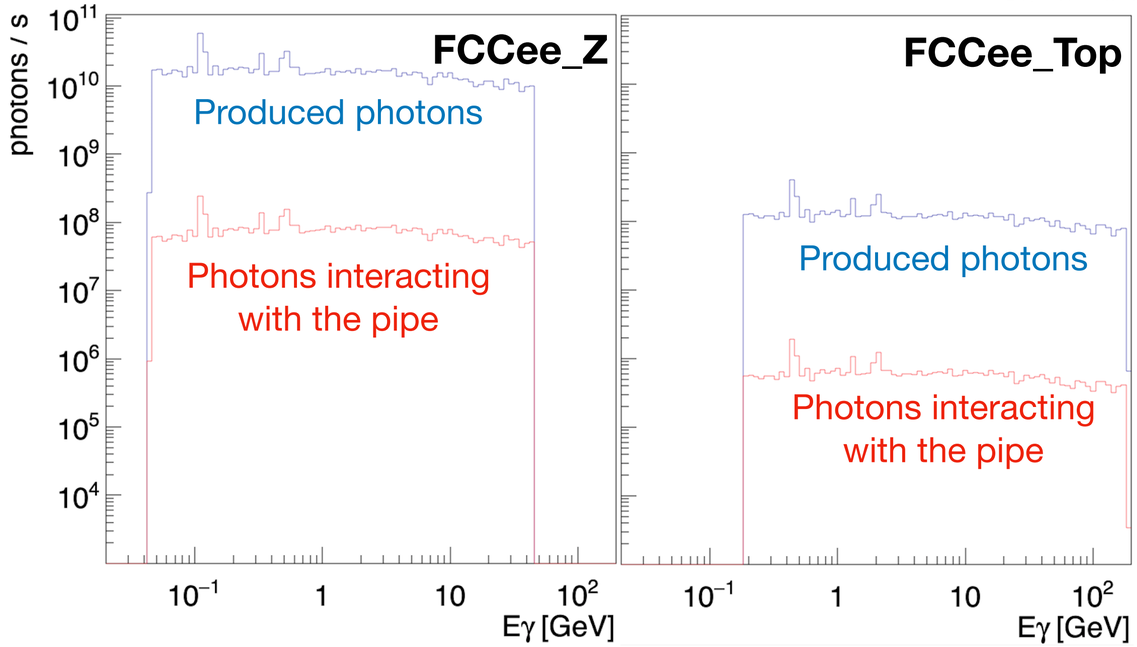
	FCCee_Z	FCCee_Top
Total BS power	$386.9[kW]$	$88.5[kW]$
Interacting photon power	$1.746[kW]$	$0.39[kW]$

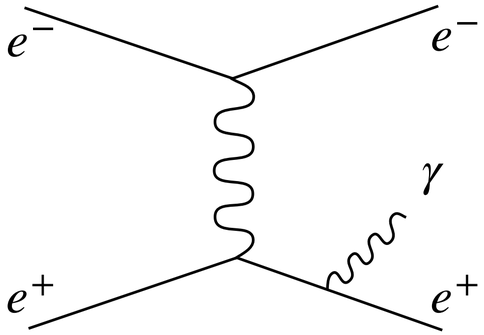
$$P[W] = n_{bunch}\ f_{rev}[Hz]\ E[GeV]\ 1.602 \cdot 10^{-10} \left[\frac{J}{GeV}\right]$$

Only **a small fraction** of the power is deposited in the pipe (~0.5% of the total power)

More detailed simulation considering also **secondary effects** should be performed with dedicated tools (Geant4, SYNRAD+) to have a more precise estimate of the deposited power and to study the **radiation hazard** in that area.







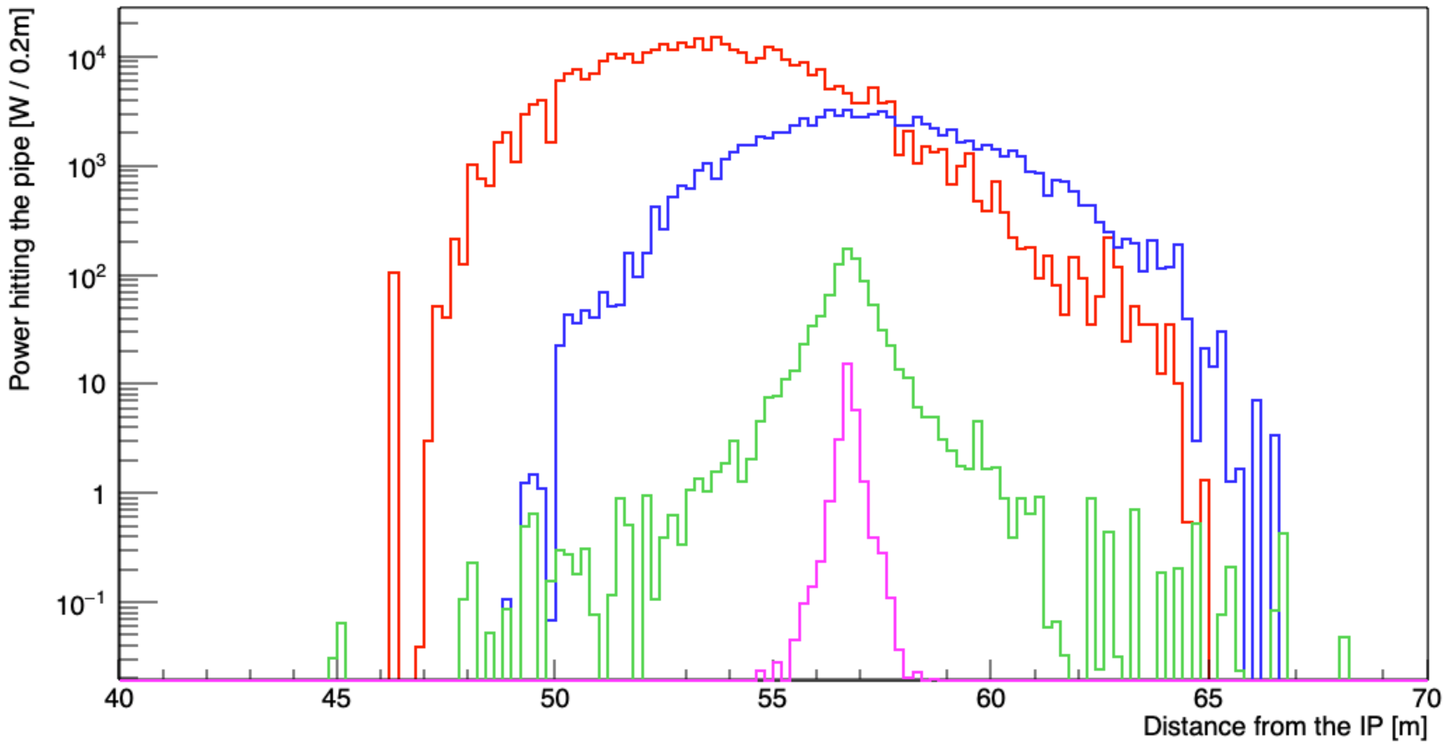
$$e^+e^- \rightarrow e^+e^-\gamma$$

Radiative Bhabha: Photons interacting with the pipe

The same study has been performed on the collinear photons produced by **radiative Bhabhas**, generated using the tool BBBrem [2].

	FCCee_Z	FCCee_Top
Mean energy	$6.6[GeV]$	$26.4[GeV]$
Total power	$928[W]$	$27.9[W]$
Deposited power	$4.73[W]$	$0.14[W]$

[2] BBBREM — Monte Carlo simulation of radiative Bhabha scattering in the very forward direction - R.Kleiss H.Burkhardt



	Mean Energy	Tot Power	Deposited Power
Radiative Bhabha @182.5	26.4 GeV	27.9 W	0.14 W
Radiative Bhabha @45.6	6.6 GeV	928 W	4.73 W
Beamstrahlung @182.5	67 MeV	88.5 kW	0.39 kW
Beamstrahlung @45.6	2 MeV	386.9 kW	1.746 kW

Radiation produced at the IP: Comparison

The comparison of these two radiation sources shows that in both cases the radiation **hits the pipe at ~55m**, i.e. at the end of the first dipole.

Radiative Bhabha photons are much **more energetic** than beamstrahlung, but the total power is much lower due to the small cross section.

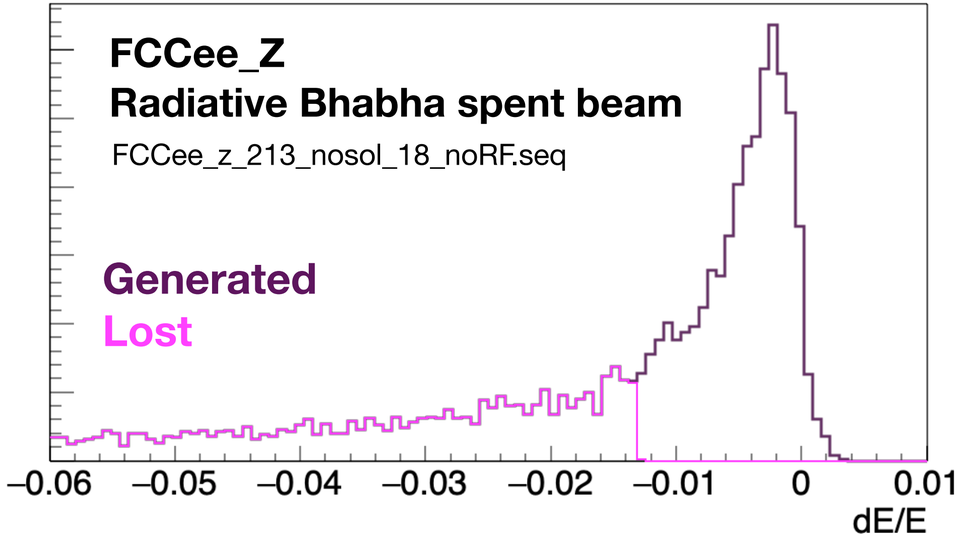
MADX-PTC Tracking of the Spent Beam

The spent beams were tracked through the FCCee optics using the tracking code **MADX-PTC** for 10 turns.

No losses were observed for the **beamstrahlung spent beam** because the energy lost in this way is just a **very small fraction** of the total, and it is not enough to cause particles to go out of the energy acceptance of the ring.
A more realistic simulation would require a **multi-turn tracking** evaluating the beam-beam interaction at each IP, but with the current approach (see [3]) the required **CPU time** makes this option not viable.

With **Radiative Bhabha** particles can instead lose virtually all of their energy, therefore the tracking of the spent beam can be performed even by evaluating the interaction only once. At both energies most of the particles are **lost in the first turn** after the interaction. The so found **lifetimes** are in agreement with those reported in the CDR.

	FCCee_Z	FCCee_Top
Generated Macroparticles	8737	8739
Lost Macroparticles	5479	4827
Lifetime	64 min	39 min
Rate in the first 50m	53 GHz	0.4 GHz

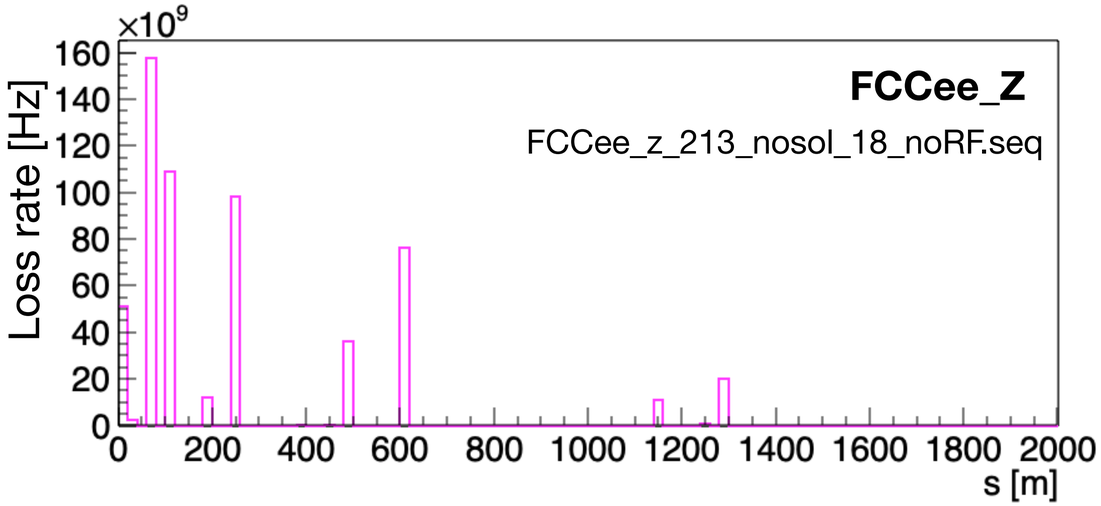


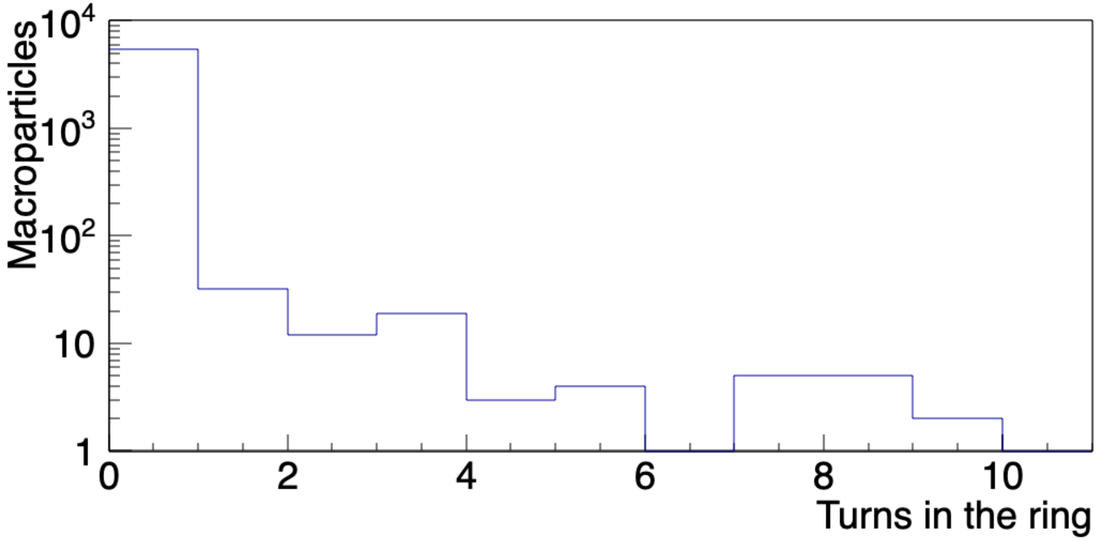
[3] A.Ciarma - 3rd FCC-ee MDI workshop - Multi-turn particle tracking for FCC-ee background studies: first results for Coulomb scattering beam losses

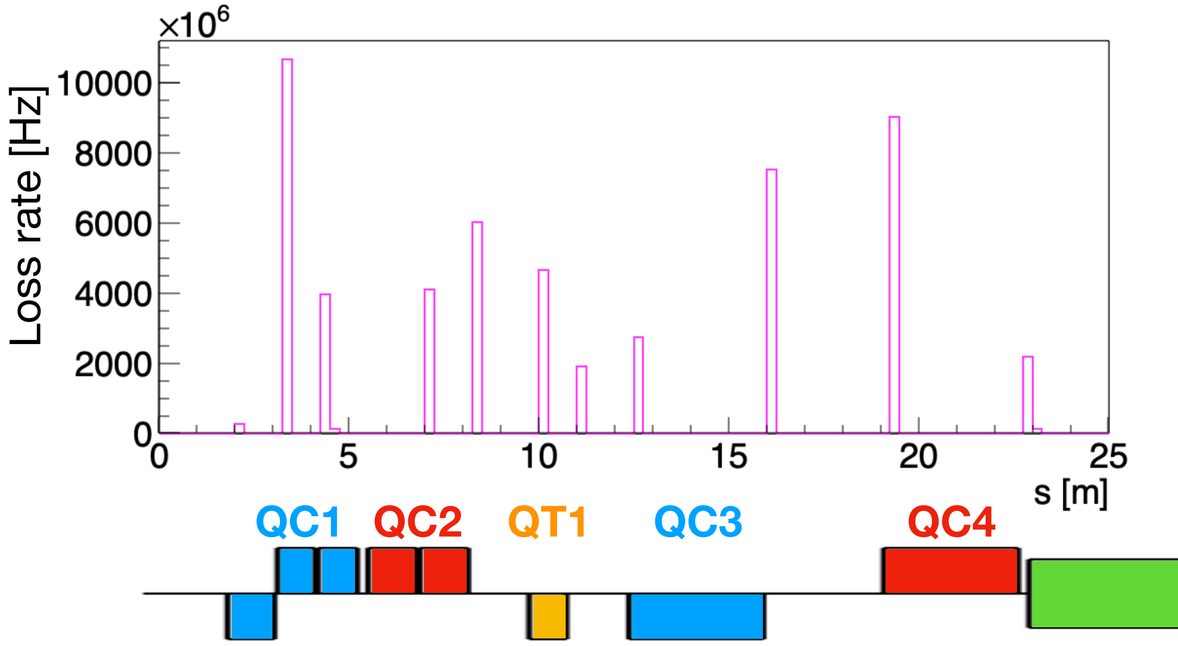
Radiative Bhabha: MADX-PTC Tracking of the Spent Beam

Particles which radiate a large fraction of energy are **lost almost immediately**, also in the final focus quadrupoles. Similar results have been obtained also at 182.5 GeV.

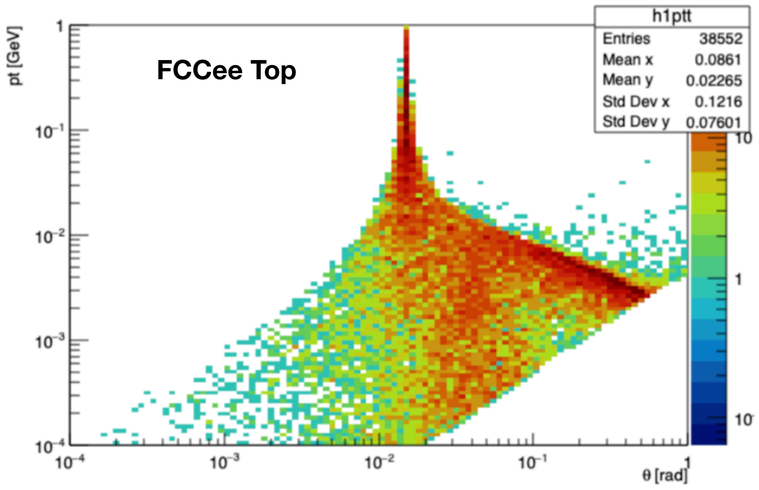
These particles could be the cause of **background** in the detector and therefore more detailed studies - with MDISim and Geant4 - should be performed to verify this.

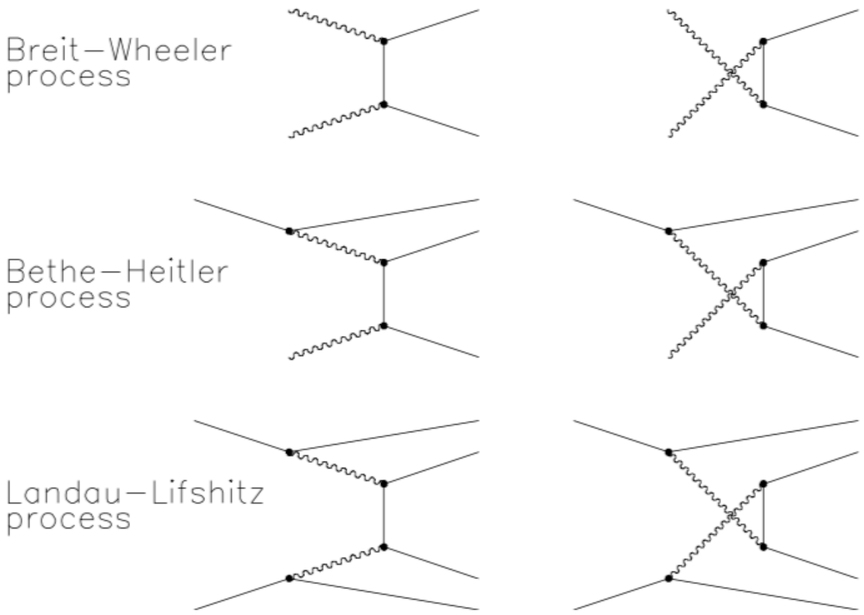






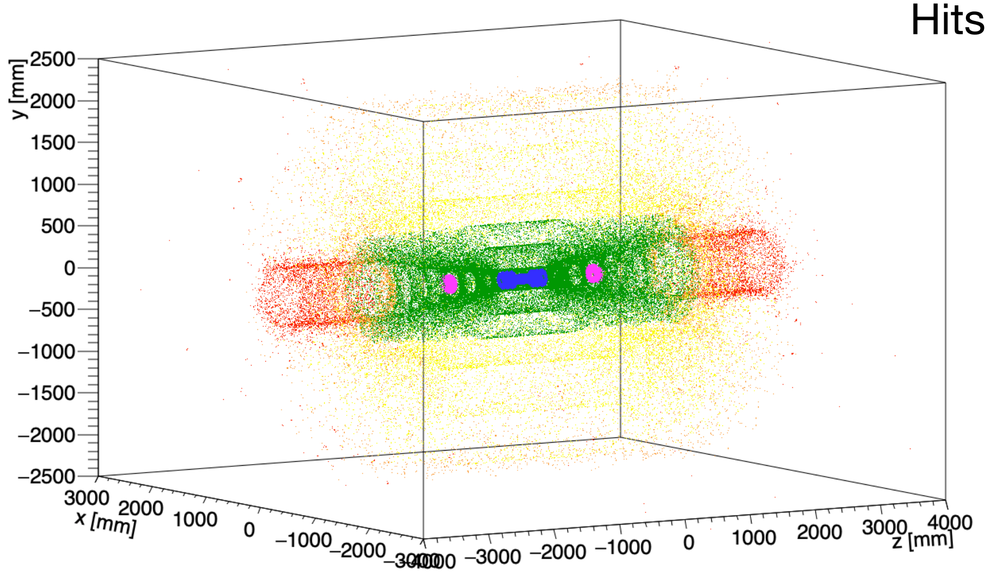
Incoherent pairs production





- Latest version of GuineaPig++ was included in the **key4hep** stack on **LXPLUS**
- Managed to reproduce **results from the CDR** for the kinematics of the pairs
- The **full simulation** of the produced pairs in the CLD detector with Geant4 can be performed correctly in key4hep framework
- Event reconstruction is currently **work in progress** (only the hits in the detectors are available now)

Hits in the CLD sub-detectors



Detector
Hcal Endcap
Hcal Barrel
Ecal Endcap
Ecal Barrel
OT Endcap
OT Barrel
IT Endcap
IT Barrel
VXD Endcap
VXD Barrel
Lumical

In conclusion

Preliminary studies on the radiation produced at the IP via beamstrahlung and radiative Bhabhas have been presented:

- All of the radiation hits the beam pipe at **~55m from the IP** (end of the first dipole)
- **Beamstrahlung** is the most intense source ~O(100kW), but despite this only a small fraction of power is actually deposited on the beam pipe.
- **Radiative Bhabha** radiation have a much lower power but the mean photon energy is of the order of several GeV. Also, the **spent beam** could represent a source of background in the detector as lots of the particles are lost in the first elements after the IP

Upcoming studies include:

- More detailed estimation of **detector occupancies** and backgrounds using the experimental software
- More detailed simulations of the **interaction of photons with the beam pipe** to assess power deposition and secondaries production
- Further study of the radiative Bhabha spent beam **lost in the MDI area** to understand possible related backgrounds in the detectors
- Continue the studies on **other sources** of beam induced background (i.e. beam-gas, thermal photons, synchrotron radiation, …)

Thank You For Your Attention!

Backups

Beamstrahlung radiation

Formulas for head-on gaussian beams

$$\Upsilon \sim \frac{5}{6}\frac{r_e^2 \gamma N_e}{\alpha \sigma_z(\sigma_x+\sigma_y)} = \begin{matrix} 7.67\cdot 10^{-4} & @Top \\ 1.77\cdot 10^{-4} & @Z \end{matrix}$$

$$< E_\gamma > \sim E \times 0.462\Upsilon \ (\Upsilon \to 0) = \begin{matrix} 65MeV & @Top \\ 3.7MeV & @Z \end{matrix}$$

$$n_\gamma \sim 2.54 \left[\frac{\alpha^2 \sigma_z}{r_e \gamma}\Upsilon\right] \frac{1}{[1+\Upsilon^{2/3}]^{1/2}} = \begin{matrix} 0.26069 & @Top \\ 1.14923 & @Z \end{matrix}$$

$$P = N_{part}\, n_\gamma < E_\gamma > f_{rev}\, n_{bunch} = \begin{matrix} 91.3kW & @Top \\ 5960kW & @Z \end{matrix}$$

GuineaPig++ simulations (crossing angle 30mrad)

$$\Upsilon^{GP} = \frac{5}{12}\Upsilon^{GP}_{max} = \begin{matrix} 9.12\cdot 10^{-4} & @Top \\ 1.81\cdot 10^{-4} & @Z \end{matrix}$$

$$< E_\gamma >^{GP} = \begin{matrix} 67MeV & @Top \\ 2MeV & @Z \end{matrix}$$

$$n_\gamma^{GP} = \begin{matrix} 0.242 & @Top \\ 0.148 & @Z \end{matrix}$$

$$P^{GP} = \begin{matrix} 88kW & @Top \\ 390kW & @Z \end{matrix}$$

Important difference in particular for the number of photons per particle @Z. This is due to the fact that formulas are for gaussian beam impacting without a **crossing angle**. The bunches at FCCee_Z are very long (12.1mm) and therefore even a “small” crossing angle is relevant for the photon production.

Lengths and angles in scale, thickness not in scale

Summing up

significant flux of photons generated in the IP in very forward direction

numbers depend on details, **rough** estimates for FCC-ee Z, CDR parameters :

4x1m solenoids FCCee_t_213_sol_13 , with fringe and overlap (quad estimate from total IR - solenoid)

		$\langle E\gamma \rangle$
• **SR solenoid / anti solenoid**	**~ 37 kW**	**~ 0.02 MeV**
• **SR IR quadrupoles**	**~ 7 kW**	**~ 0.02 MeV**
• **em-fields of colliding bunches (Beamstrahlung)**	**~ 400 kW**	**~ 2 MeV**
• **radiative Bhabha (beam-beam Bremsstrahlung)**	**~ 0.7 kW**	**~ 5000 MeV**

adding a bit in total power and a lot to the high energy tail of the γ - spectrum

all hitting the beam pipe in the 49-55 m region downstream of the IP

(need for cooling, special magnet + beam pipe geometry ?)

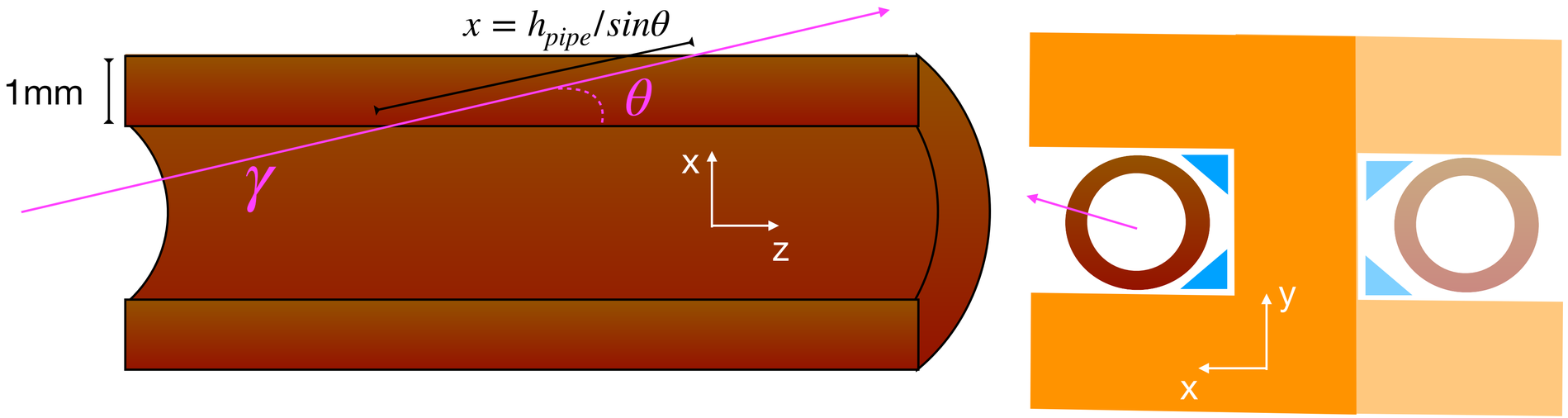
H. Burkhardt
(FCC-ee MDI meeting #24 2/12/2019)

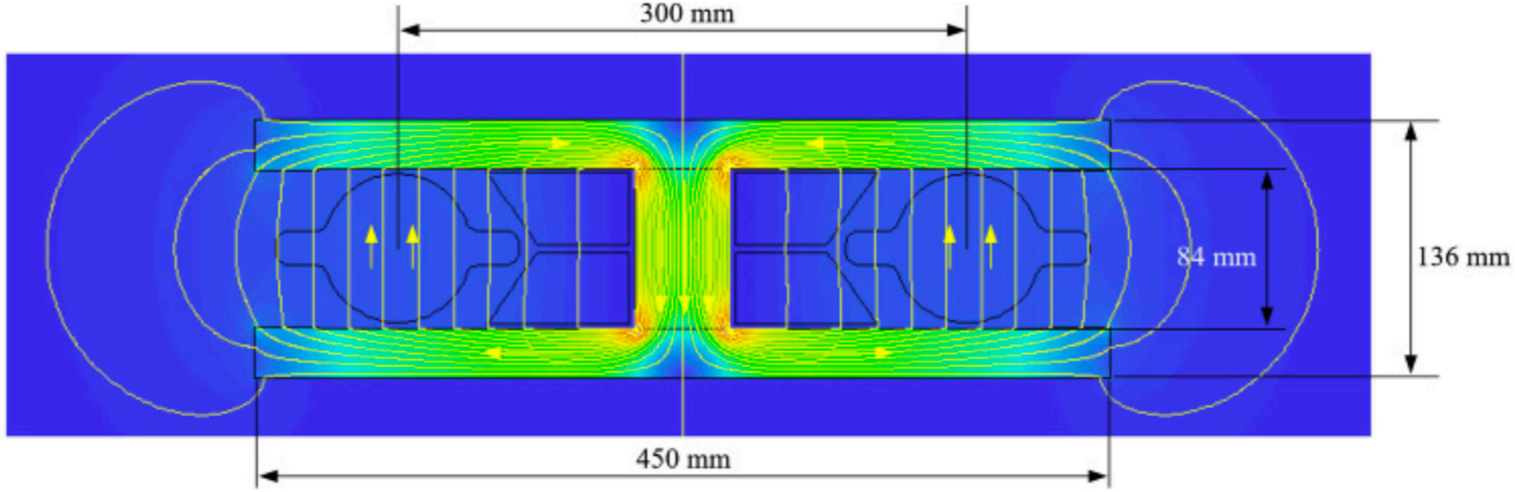
The **interaction probability** is defined as the complementary of the penetration probability

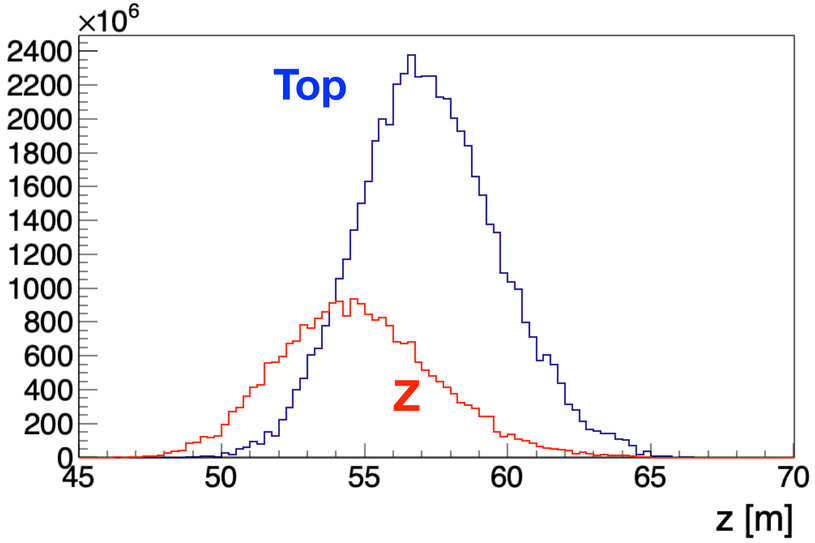
$$P_{int}(x) = 1 - \frac{I(x)}{I_0} = 1 - e^{-\mu x}$$

The **attenuation coefficient** $\mu = \frac{N_A \rho}{A} \Sigma \sigma_i$ is obtained from NIST (actually the tabulated value is the **mass-attenuation coefficient** $\frac{\mu}{\rho}$, where ρ is the material density).

The path of a photon impinging with an angle θ on the beam pipe wall having thickness h_{pipe} is given by $x = h_{pipe}/sin\theta$



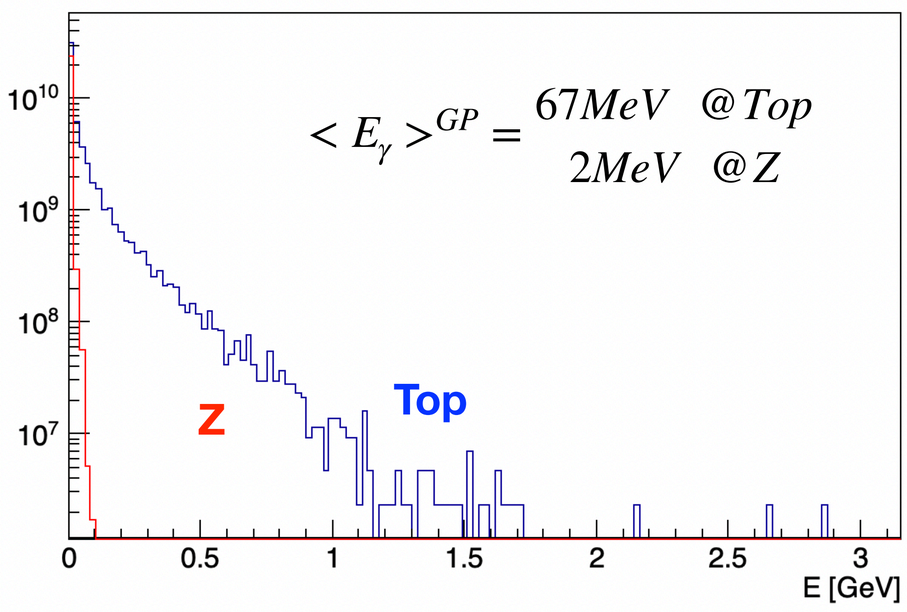




	FCCee_Z	FCCee_Top
Total BS energy	$4.73 \cdot 10^7 [GeV]$	$3.75 \cdot 10^9 [GeV]$
Interacting photon energy	$2.14 \cdot 10^5 [GeV]$	$1.66 \cdot 10^7 [GeV]$
Total BS power	$386.9 [kW]$	$88.5 [kW]$
Interacting photon power	$1.746 [kW]$	$0.39 [kW]$

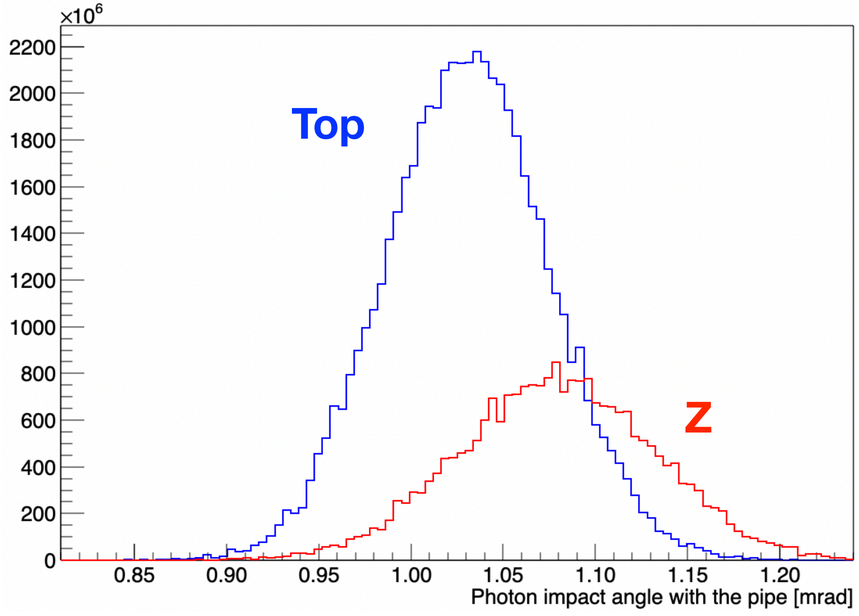
$$P[W] = n_{bunch}\ f_{rev}[Hz]\ E[GeV]\ 1.602 \cdot 10^{-10} \left[\frac{J}{GeV}\right]$$

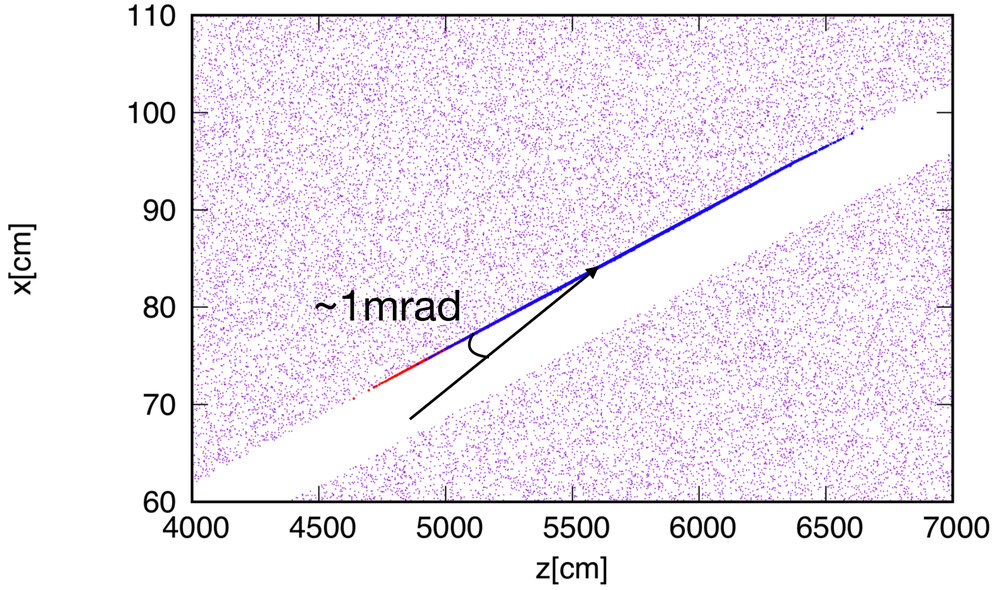
Tracking of Beamstrahlung photons



Even if at the Z the total power hitting the pipe is much larger (due to the higher beam current), the beamstrahlung photons produced at the Top are much more energetic, with tails reaching **above 1GeV.**

At both energies the photons hit the pipe with an angle of **~1mrad.**





Radiative Bhabha weight definition

In BBBrem each event is assigned a weight, which is the proportion between the effective cross section and the approximate cross section

$$w_i = \frac{\sigma_i}{\sigma_{app}}$$

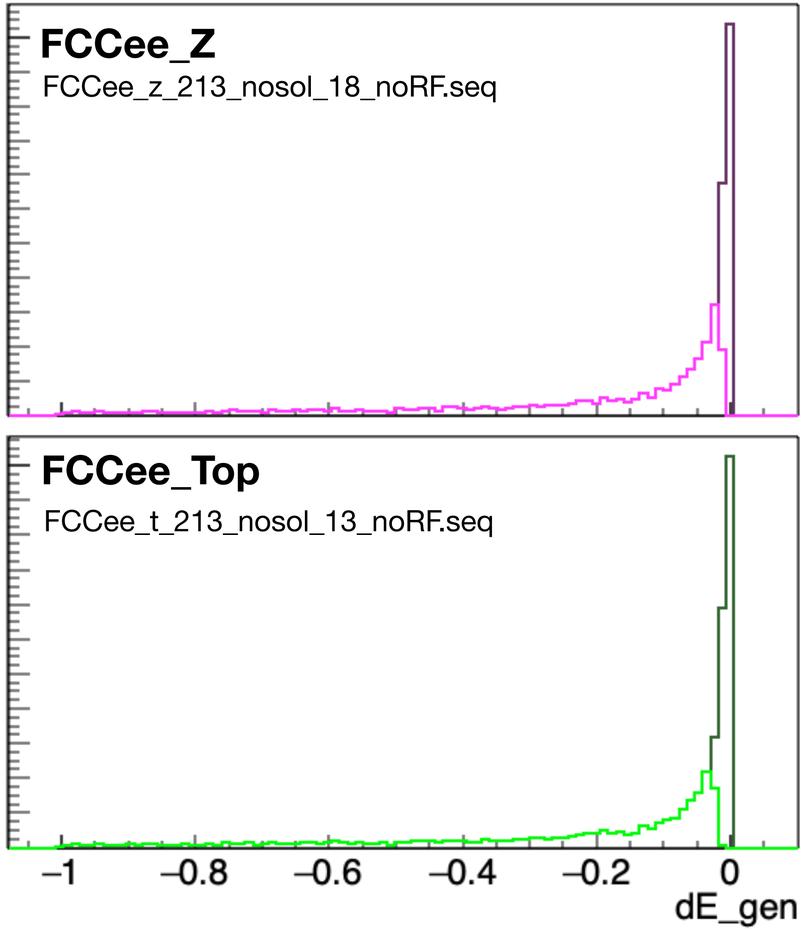
Therefore in order to obtain the number of events that will happen, one must multiply by the luminosity and divide by the number of generated macroparticles. Same thing is true for the total power of the produced radiation

$$\dot{N}_{true} = \frac{L \cdot \sigma_{app}}{n_{macro}} \sum_{i=1}^{n_{macro}} w_i \qquad P_\gamma = \frac{L \cdot \sigma_{app}}{n_{macro}} \sum_{i=1}^{n_{macro}} w_i E_i^\gamma$$

Radiative Bhabha: MADX-PTC Tracking of the Spent Beam

The spent beam was tracked through the FCCee optics using **MADX-PTC** for 10 turns. Most of the particles are lost during the very **first 2km** after the IP at both energies.

	FCCee_Z	FCCee_Top
Generated Macroparticles	8737	8739
Lost Macroparticles	5479	4827
Lifetime	64 min	39 min
Rate in the first 50m	53 GHz	0.4 GHz



Sources of beam backgrounds currently under study

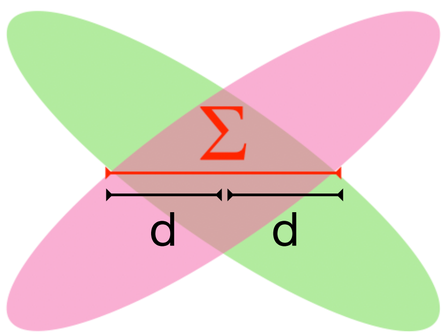
Source	Generator	Analisys	Status
Radiative Bhabha	BBBrem	Tracking of the **spent beam** with MADX-PTC to obtain **loss map** Study of the **interaction of the photons** with the beam pipe	Preliminary loss map produced Preliminary study on the deposited energy on the beam pipe performed
Beamstrahlung	GuineaPig++	Tracking of the **spent beam** with MADX-PTC to obtain **loss map** Study of the **interaction of the photons** with the beam pipe	Tracking of the BS spent beam requires a big effort, still work in progress Preliminary study on the deposited energy on the beam pipe performed
Incoherent pair production	GuineaPig++	Tracking of the produced particles in the CLD detector using the **key4hep** full simulation	Work in progress for the event reconstruction of the hits in the detector

Future steps: perform more detailed studies on the spent beam (**MDIsim + Geant4**) and on the radiation interaction (**SYNRAD**). Also continue former studies on **beam-gas** and **thermal photon** scattering.

VERY VERY VERY PRELIMINARY

	FCC_Z	FCC_Top
sigma_x [m]	6360e-9	38210e-9
sigma_y [m]	28.3e-9	68e-9
sigma_z [m]	12100e-6	2540e-6
Sigma [m]	0.3e-3	1.27e-3
d [m]	0.15e-3	0.636e-3
min photon energy	0.001	0.001
cutoff = ħc/d [GeV]	1.28e-12	3.02e-13
xsec [mbarn]	530.771	584.054
xsec cutoff [mbarn]	409.153	391.879
fraction over cutoff	**0.771**	**0.671**

Cutoff



$$\Sigma = \frac{1}{\sqrt{2\left(\frac{sin^2\alpha}{\sigma_x^2} + \frac{cos^2\alpha}{\sigma_z^2}\right)}}$$

To take into account of the finite interaction range of each particle, a cutoff must be applied to the momentum transfer [*]. The resulting cross-section is ~20% to ~30% lower than that analytically evaluated.

[*] H. Burkhardt Proceedings of the third Workshop on LEP Performance, J. Poole ed CERN SL/93-19 (DI)

PARTICLE TRACKING METHOD

The first and second order transfer matrices of every element of the beamline are evaluated using MAD-X and saved on a file, together with its element name, position (s) and length.

A particle with 6-D phase space coordinates $\overrightarrow{x_0}$ is transported through a given element according to:

$$x[i] = \sum_j R_{ij} x_0[j] + \sum_{j,k} T_{ijk} x_0[j] x_0[k]$$

The transport process was at first performed by MAD-X, but the repeated calls to MAD-X implied extremely long computational times even for small jobs.