Synchrotron Radiation Background

by **Helmut Burkhardt** (CERN)

SR as (the) major IR design constraint

Much progress since FCC-week last year

More SR tolerant optics : IR bends > 100 m , Ecr < 100 keV

- **Short introduction, LEP2**
- **SR source in IR**
- **Next steps : shielding, detailed simulations**

Acknowledgments and links :

FCC-ee MDI + optics teams, with in particular Manuela Boscolo, Nicola Bachetta, Mike Sullivan, Katsunobu Oide, Anton Bogomyagkov

FCC-ee Acc. Session last year and review of FCC-ee 10/2015

MDISIM, Tools for Flexible Optimisation of IR Designs with Application to FCC, tupty031

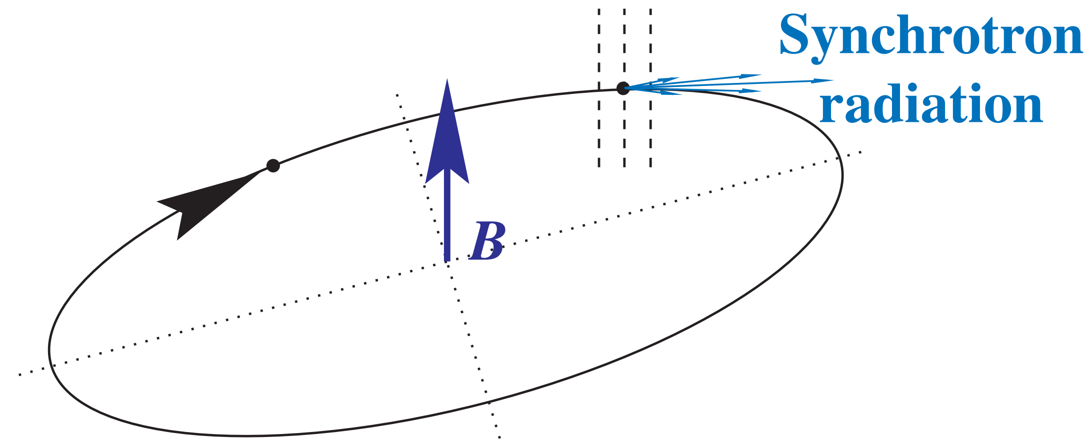
Synchrotron radiation

$$E_c = \frac{3}{2}\,\frac{\hbar c\,\gamma^3}{\rho} = 2.96 \times 10^{-7}\text{eV m}\;\frac{\gamma^3}{\rho}$$

$$\langle E_\gamma \rangle = \frac{8}{15\sqrt{3}}\,E_c \approx 0.308\;E_c$$

$$U_0 = \frac{e^2}{3\epsilon_0}\,\frac{\gamma^4}{\rho} \approx 6.0317 \cdot 10^{-9}\text{ eV m}\quad\frac{\gamma^4}{\rho}$$

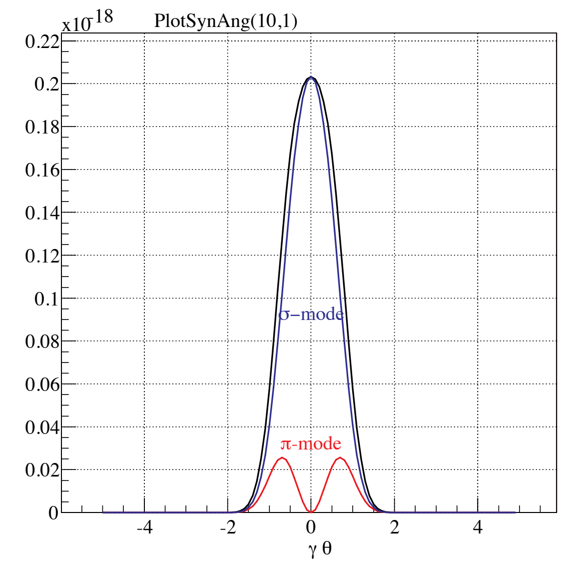
$$P_b = \frac{U_0\,I_b}{e}$$



mean free path length λ between radiation

$$\lambda = \frac{\lambda_B}{B_\perp} \qquad \text{where} \quad \lambda_B = \frac{2\sqrt{3}}{5}\,\frac{m\,c}{\alpha\,e} = 0.16183\,\text{Tm}$$

LEP2, FCC-ee, B ≃ O (0.1 T) O (1 m)



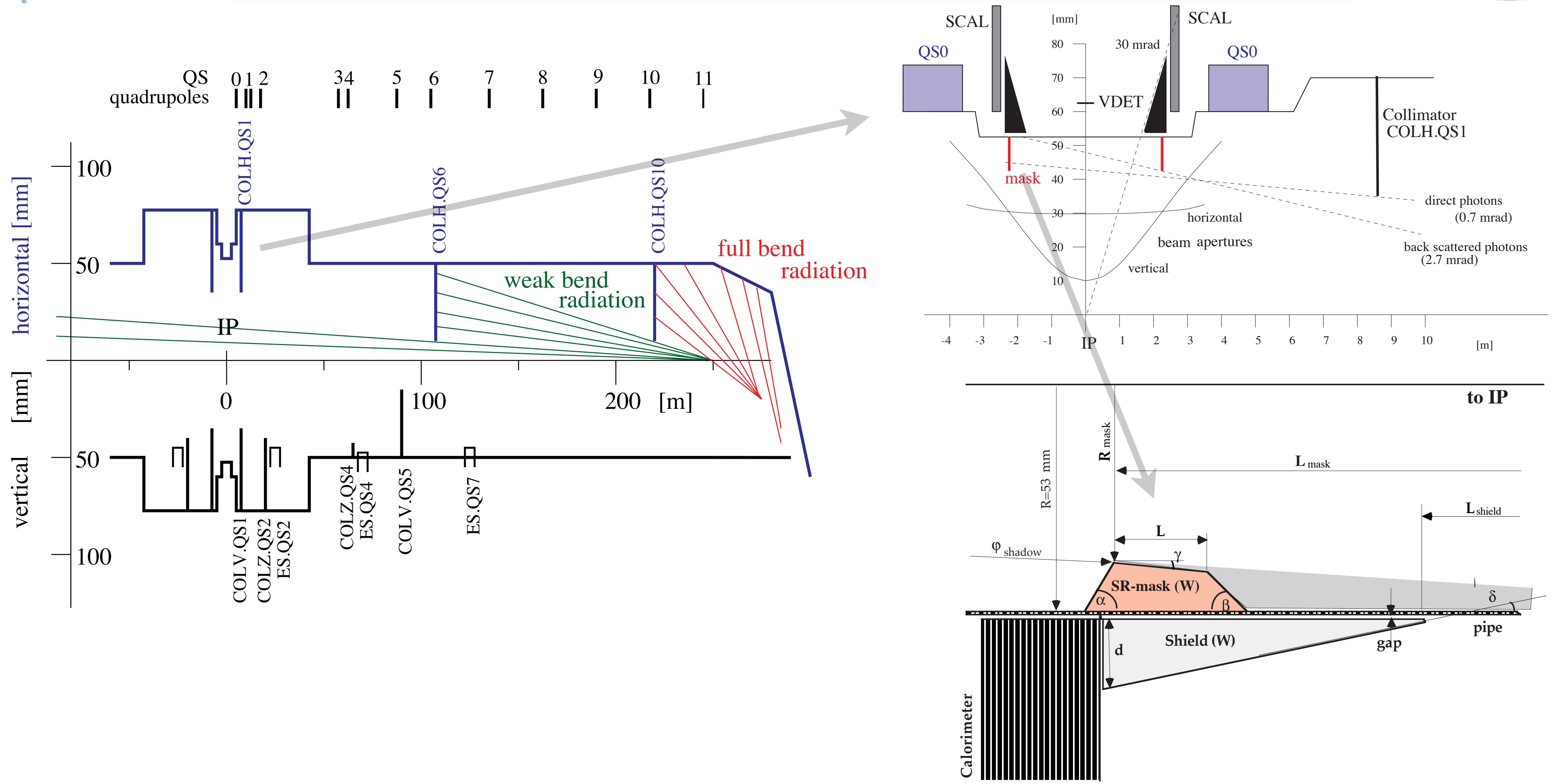
angular distribution (at E_c)

~ $1/\gamma$ = 3 μrad @ 175 GeV

SynRad cone distribution mostly from bending angle O(mrad)

+ minor contribution from
beam divergence O(10 μrad)
and SynRad process

LEP, as example of an IR optimized for SR



Eb = 45 GeV to 105 GeV **the closest we got to FCC-ee**

Machine induced backgrounds, MIB in LEP **~ 100 collimators to reduce MIB**

flat, symmetric machine, no crossing angle, few (4-12) bunches

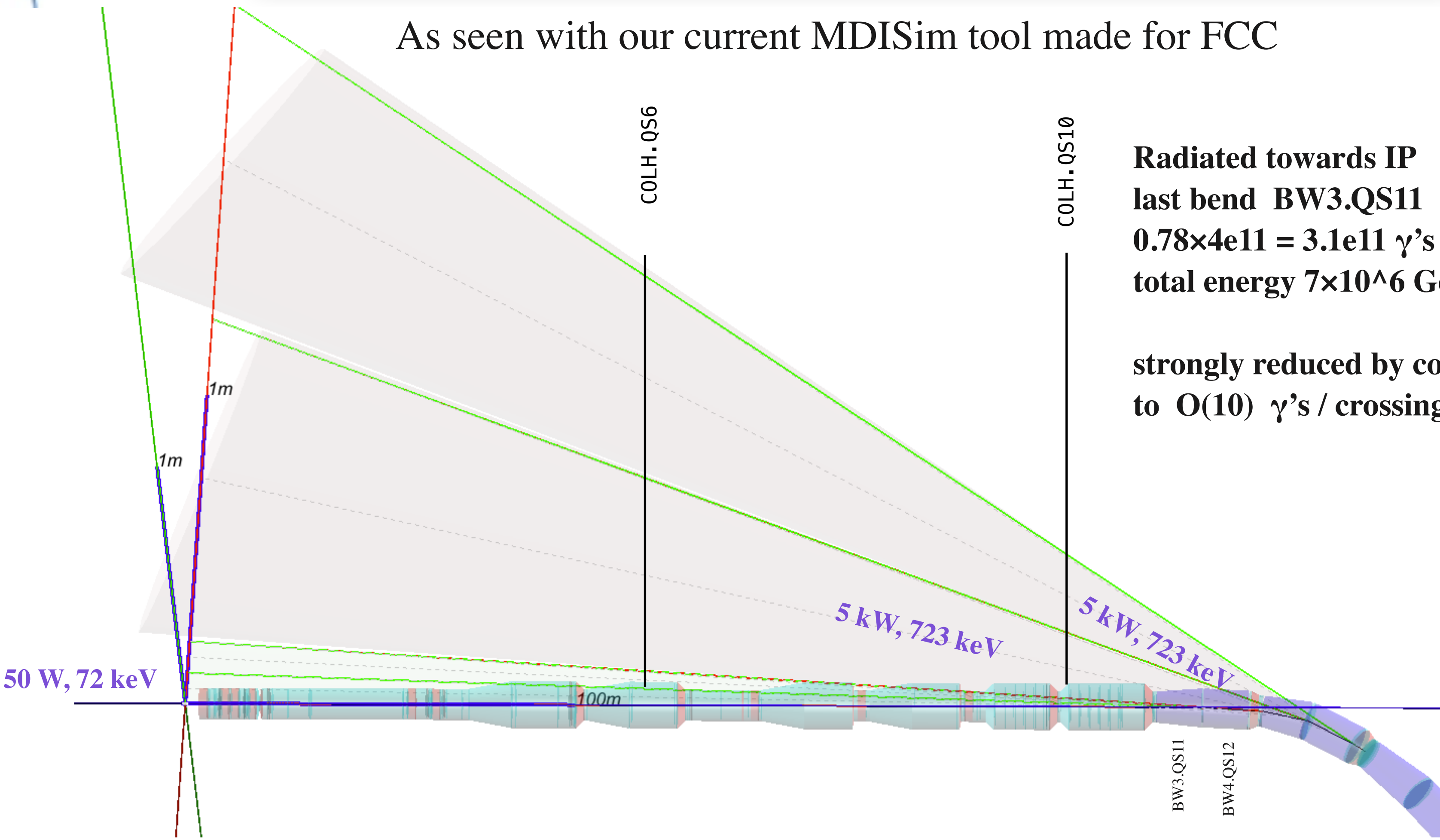
Synchrotron radiation - **no direct and single reflected radiation to experiments in IP region**

Off-momentum beam-gas and thermal photon

G. von Holtey at al., Nucl.Instrum.Meth.A403:205-246, 1998

LEP2 100 GeV

As seen with our current MDISim tool made for FCC



Radiated towards IP
last bend BW3.QS11 248.7 - 260.2 m
0.78×4e11 = 3.1e11 γ's / crossing
total energy 7×10^6 GeV

strongly reduced by collimation and masks to O(10) γ's / crossing interacting in TPC

iele	NAME	KEYWORD	S	L	Angle	Ecrit	ngamBend	rho	B	BETX	SIGX	divx	Power	frac>10MeV
			m	m		keV		m	T	m	mm	mrad	kW	
162	BW3.QS11.R2	RBEND	260.2	11.55	0.0003768	72.37	0.7767	30652.0	0.0109	45.5834	1.4262	0.0379	0.04989	2e-62
164	BW4.QS12.R2	RBEND	272.1	11.55	0.0003768	72.37	0.7767	30652.0	0.0109	33.8668	1.2293	0.0379	0.04989	2e-62
172	B2L.QS12.R2	RBEND	287.3	11.55	0.003768	723.7	7.767	3065.2	0.1088	88.0931	1.9827	0.0637	4.989	6.5e-08
174	B2R.QS13.R2	RBEND	299.2	11.55	0.003768	723.7	7.767	3065.2	0.1088	163.5957	2.7019	0.0636	4.989	6.5e-08

Quads, at 1 sigmax, horizontal

iele	Element	s	L	betx	sigx	divx	K1L	k0	x	Angle	Ecrit	ngam	Power
		m	m	m	mm	mrad	m-2	m-1	mm		keV		kW
2	QS0.R2	5.7	2	27.8	1.115	0.04003	-0.327	0.0003474	-0.0524	0.0006948	770.7	1.432	0.9798
10	QS1B.R2	11.2	2	226	3.176	0.01405	0.06314	0.0001918	-0.1377	0.0003836	425.5	0.7907	0.2987
12	QS1A.R2	13.7	2	278	3.523	0.01267	0.06314	0.0002129	-0.1509	0.0004259	472.4	0.8778	0.3681
20	QS2.R2	18	1.6	276	3.507	0.01272	0.01788	6.006e-05	-0.1471	9.61e-05	133.2	0.1981	0.023423
36	QS3.R2	59	2	39.4	1.326	0.03366	0.01879	2.45e-05	-0.02171	4.9e-05	54.35	0.101	0.004873

Optics MDI design - SR criteria

Following last years FCC-week, stimulated by the request of Katsunobu Oide to provide simple guidelines for optics development to make synchrotron radiation effects tolerable :

Proposal, based on LEP2 :

1. Weak bends Ecr < 100 keV	LEP2 72 keV
2. far from IP	260 m from IP
3. Keep Ecr ≲ 1 MeV in whole ring, to minimize n-production	LEP2 0.72 MeV

In fact possible to design optics including crab waist guided by these criteria,
early version used for 10/2015 review :

`/afs/cern.ch/eng/fcc/ee/Oide/Lattices/FCCee_t_45_16_cw_nosol.seq` from 31/08/2015
with first bend 50 m from IP

Now
`/afs/cern.ch/user/k/koide/Oide/Lattices/FCCee_t_74_11_nosol.seq` from 30/03/2016
with first bend 100 m from IP

Look at these optics using our generic MDISim tools --->

KO lattice FCCee_t_74_11

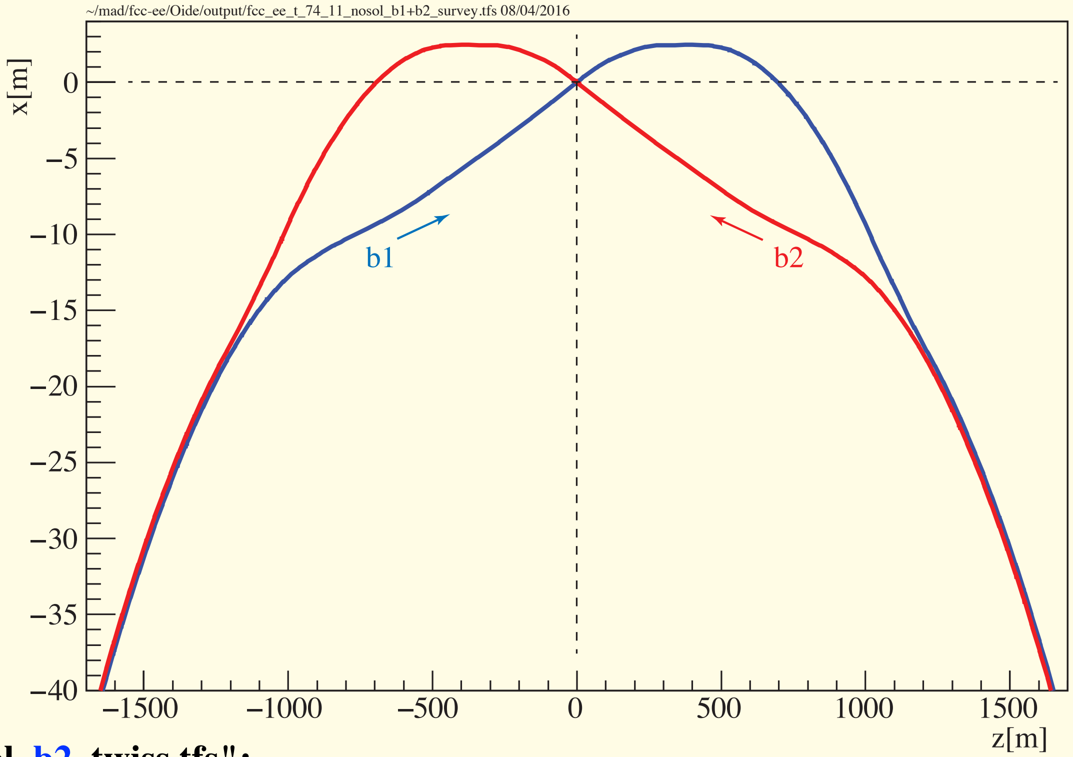
1. step : MAD-X twiss and survey

FCCee_t_74_11_nosol.seq   bare sequence, single 99983.8 m ring, no aperture
adjust beam parameters to for 50 MW SR; make 2nd beam and introduce crossing on survey level

```
beam, particle = positron, npart=2.3e11, kbunch=60, energy = 175,  radiate=false;    (otherwise twiss fails )
twiss,  chrom,                file="fcc_ee_t_74_11_nosol_b1_twiss.tfs";
survey, theta0 = +0.015, file="fcc_ee_t_74_11_nosol_b1_survey.tfs";
```

started to define apertures around IP :

```
BpipeRadiusIP :=  0.020;  // 20 mm radius
IP,    apertype=circle, aperture={ BpipeRadiusIP };
QC1R1, apertype=circle, aperture={ BpipeRadiusIP };
QC1R2, apertype=circle, aperture={ BpipeRadiusIP };
..
IP.4,  apertype=circle, aperture={ BpipeRadiusIP };
QC2L2, apertype=circle, aperture={ BpipeRadiusIP };
QC2L1, apertype=circle, aperture={ BpipeRadiusIP };
..
```




```
seqedit, sequence=L000004;  ! construct beam2
  cycle, start=L000004$END; ! start at end
  reflect;
endedit;
```

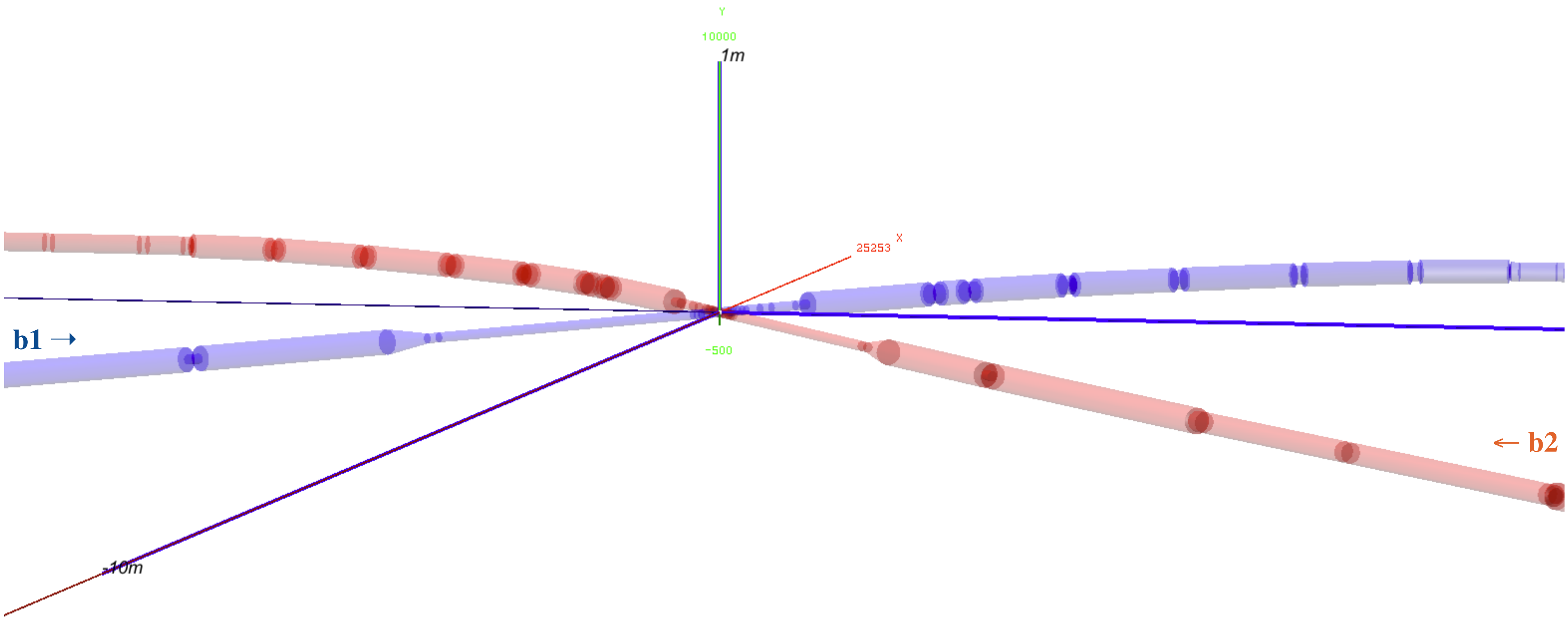
```
twiss,  chrom,                file="fcc_ee_t_45_16_cw_nosol_b2_twiss.tfs";
survey, theta0 = - 0.015, file="fcc_ee_t_45_16_cw_nosol_b2_survey.tfs";
```

KO lattice FCCee_t_74_11

MDISim 2. step : Generate Geometry, ROOT with EVE and OpenGL, 3d display

MyNtuple2Geom -acsV -- fcc_ee_t_74_11_nosol IP -zmin zmax scalefac=100 icolb1=600
fcc_ee_t_74_11_nosol_b1_twiss.tfs + b1_survey.tfs icolb2= 632 fcc_ee_t_74_11_nosol_b2_twiss.tfs + b2_survey.tfs

where not specified on MAD-X level, use default apertures
RF = 6 cm, bend r = 5cm, quad r = 4 cm, sext r =3 cm to make geometry visible




```
root
.x $MDISim_dir/MDISim_init.C
StartEveWithGeomDisplay("http://hbu.web.cern.ch/hbu/Geom/fcc_ee_t_74_11_nosol.root");
Plot_axis_arrows(-10,1,500);
```

MDISim 3. step : CalcSynrad ; Plot_Bend_SR_Cones ➜

KO lattice FCCee_t_74_11 SR tables

Based MAD-X tfs files

Eb=175 GeV L = 99983.8 m RFHV= 9.44 GV Harm = 133404

Qs=0.0663524 frev = 2.99841 kHz fRF= 400 MHz ibun=110.492 muA ibeam= 6.6295 mA SR Power / beam = 51.2935 MW

Bend radiation incoming

iele	NAME	S	L	Angle	Ecrit	ngamBend	rho	B	BETX	SIGX	divx	Power	frac>10MeV
		m	m		keV		m	T	m	mm	mrad	kW	
12	BWL.2	155.1	55.08	-0.0004633	99.98	1.671	118905.6	-0.0049	1867.9935	1.5820	0.0099	0.3411	8.783e-46
16	BC1L.2	268.4	109.2	-0.0009187	100	3.314	118886.3	-0.0049	447.4507	0.7743	0.0075	0.6764	8.927e-46
27	BC2L.2	512.2	65.06	-4.99e-05	9.117	0.18	1303954.4	-0.0004	283.0169	0.6158	0.0090	0.00335	0
31	BC3L.2	560.1	43.8	-0.001076	292.1	3.883	40694.5	-0.0143	104.9664	0.3750	0.0063	2.315	5.61e-17
35	BC4L.2	608	43.8	-0.001653	448.7	5.963	26495.4	-0.0220	288.4402	0.6217	0.0063	5.462	1.072e-11
39	BC5L.2	677.2	65.06	-0.001116	203.9	4.025	58313.8	-0.0100	16.5528	0.1489	0.0090	1.675	1.713e-23
56	BL1.2	877.5	28.66	0.002241	929.7	8.085	12787.8	0.0456	38.7623	0.2279	0.0059	15.34	1.58e-06

PowSum=51.2935 MW first 250m PowSum250=341.063 W

Outgoing

iele	NAME	S	L	Angle	Ecrit	ngamBend	rho	B	BETX	SIGX	divx	Power	frac>10MeV
14	BC1.1	65.24	38.04	0.002211	691	7.976	17205.6	0.0339	57.0549	0.2765	0.0080	11.25	3.305e-08
18	BC2.1	76.69	7.352	0.0004251	687.5	1.534	17293.6	0.0338	101.3174	0.3684	0.0120	2.152	3.062e-08
22	BC3.1	109.7	28.96	0.003586	1472	12.94	8073.9	0.0723	16.2869	0.1477	0.0099	38.88	0.0001053
29	BC4.1	149.2	34.76	0.000867	296.6	3.127	40088.5	0.0146	142.0180	0.4362	0.0100	1.893	9.411e-17
33	BC5.1	192.8	39.54	0.001772	532.9	6.393	22308.1	0.0262	28.9694	0.1970	0.0078	6.955	3.962e-10
37	BC6.1	236.5	39.54	0.001443	433.9	5.206	27396.4	0.0213	145.1191	0.4410	0.0078	4.611	4.941e-12

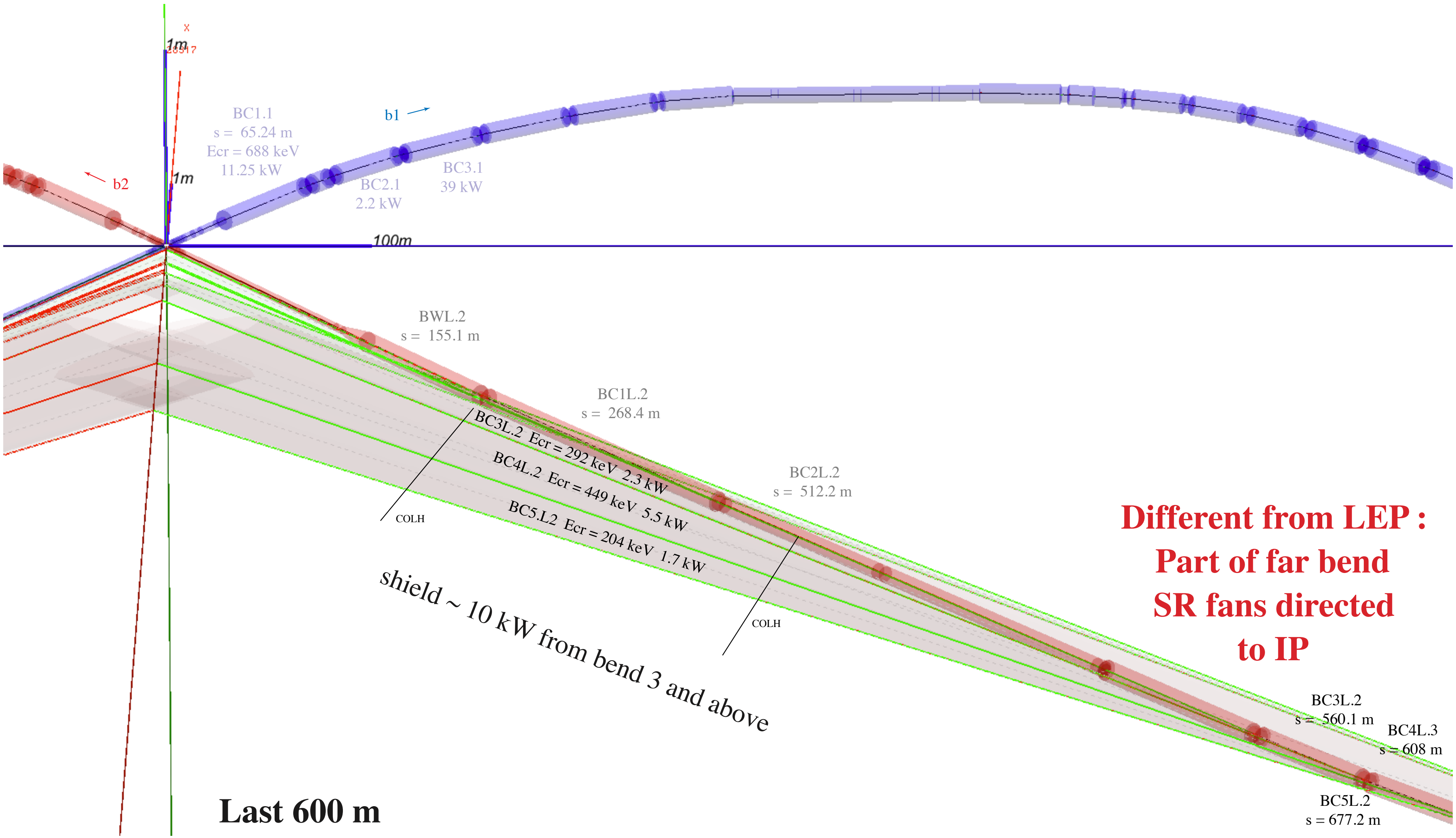
first 250m PowSum250=65.7467 kW

red color : critical energy over 100 keV, Power > 1kW and within 250 m of IP, here only on outgoing beam

Quads, at 1 sigmax, horizontal, incoming beam

iele	Element	s	L	betx	sigx	divx	K1L	k0	x	Angle	Ecrit	ngam	Power
		m	m	m	mm	mrad	m-2	m-1	mm		keV		kW
3	QC1L1.2	3.8	1.6	39.6	0.2304	0.005815	-0.2692	6.203e-05	1.636e-26	9.924e-05	737.4	0.358	0.5389
4	QC1L2.2	5.4	1.6	149	0.4474	0.002995	-0.2692	0.0001204	1.93e-26	0.0001927	1432	0.6951	2.032
6	QC2L1.2	6.95	1.25	350	0.6844	0.001958	0.1374	9.4e-05	2.396e-26	0.0001175	1118	0.4239	0.967
7	QC2L2.2	8.2	1.25	420	0.7501	0.001786	0.1374	0.000103	2.329e-26	0.0001288	1225	0.4646	1.162
10	QC3L.2	88.1	3.5	639	0.9256	0.001448	-0.008346	7.724e-06	-1.525e-25	2.704e-05	91.83	0.09752	0.01828
14	QC4L.2	159	3.5	1880	1.589	0.0008432	0.01088	1.729e-05	-9.698e-19	6.053e-05	205.6	0.2183	0.09163
18	QC5L.2	272	3.5	437	0.7653	0.001751	-0.01402	1.073e-05	-7.213e-18	3.756e-05	127.6	0.1355	0.03529
20	QC6L.2	347	3.5	753	1.004	0.001334	0.01296	1.301e-05	-2.024e-17	4.554e-05	154.7	0.1643	0.05188
22	QC7L.2	446	3.5	16.5	0.1486	0.009019	-0.01743	2.59e-06	-1.257e-17	9.065e-06	30.79	0.0327	0.002055
29	QY2L.4	516	3.5	290	0.6234	0.002149	0.0235	1.465e-05	-2.133e-17	5.127e-05	174.2	0.1849	0.06575

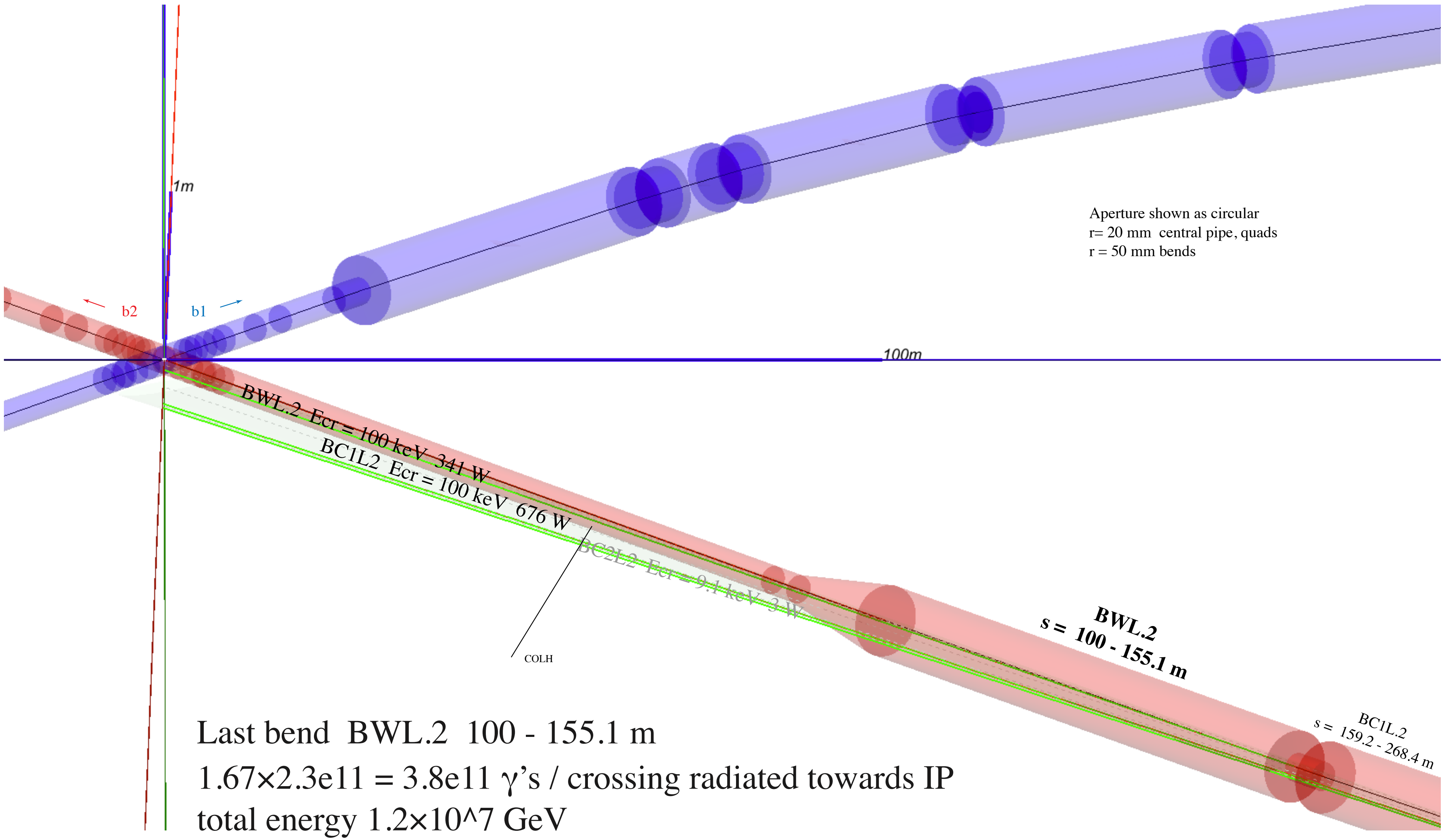
KO lattice fcc_ee_t_74_11_nosol



Different from LEP :
Part of far bend
SR fans directed
to IP

Last 600 m

KO lattice fcc_ee_t_74_11_nosol   last ~ 200m



Last bend BWL.2 100 - 155.1 m

1.67×2.3e11 = 3.8e11 γ's / crossing radiated towards IP

total energy 1.2×10^7 GeV

γ-radiated from last bend towards IP

	LEP2, 100 GeV	FCCee_t_74_11 175 GeV
Eb	100 GeV	175 GeV
Ecr	72 keV	100 keV
bunch X freq	45 kHz	180 kHz
γ's / crossing	3E+11	4E+11
γ's Σ energy / crossing	7.e6 GeV	1.2e7 GeV

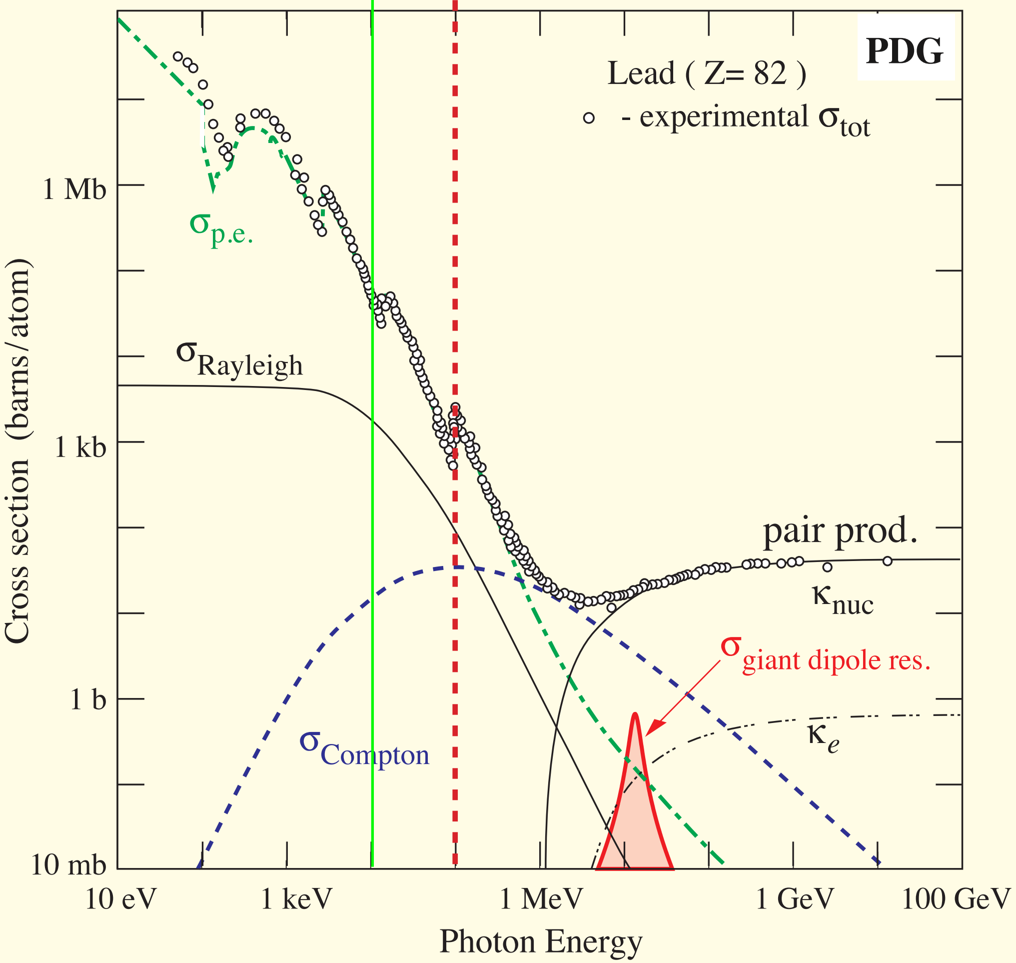
γ rates and energies from last bend now of same order of magnitude as LEP2

However :
closer than in LEP2 (250 m / 100 m)^2 = 6.25 more solid angle
less space of collimators, part for far bend - SR fans directed towards IP

Photon shielding

✔ < 10 keV

> 100 keV very difficult
10 MeV significant neutron flux, giant dipole res.



Critical photon energies

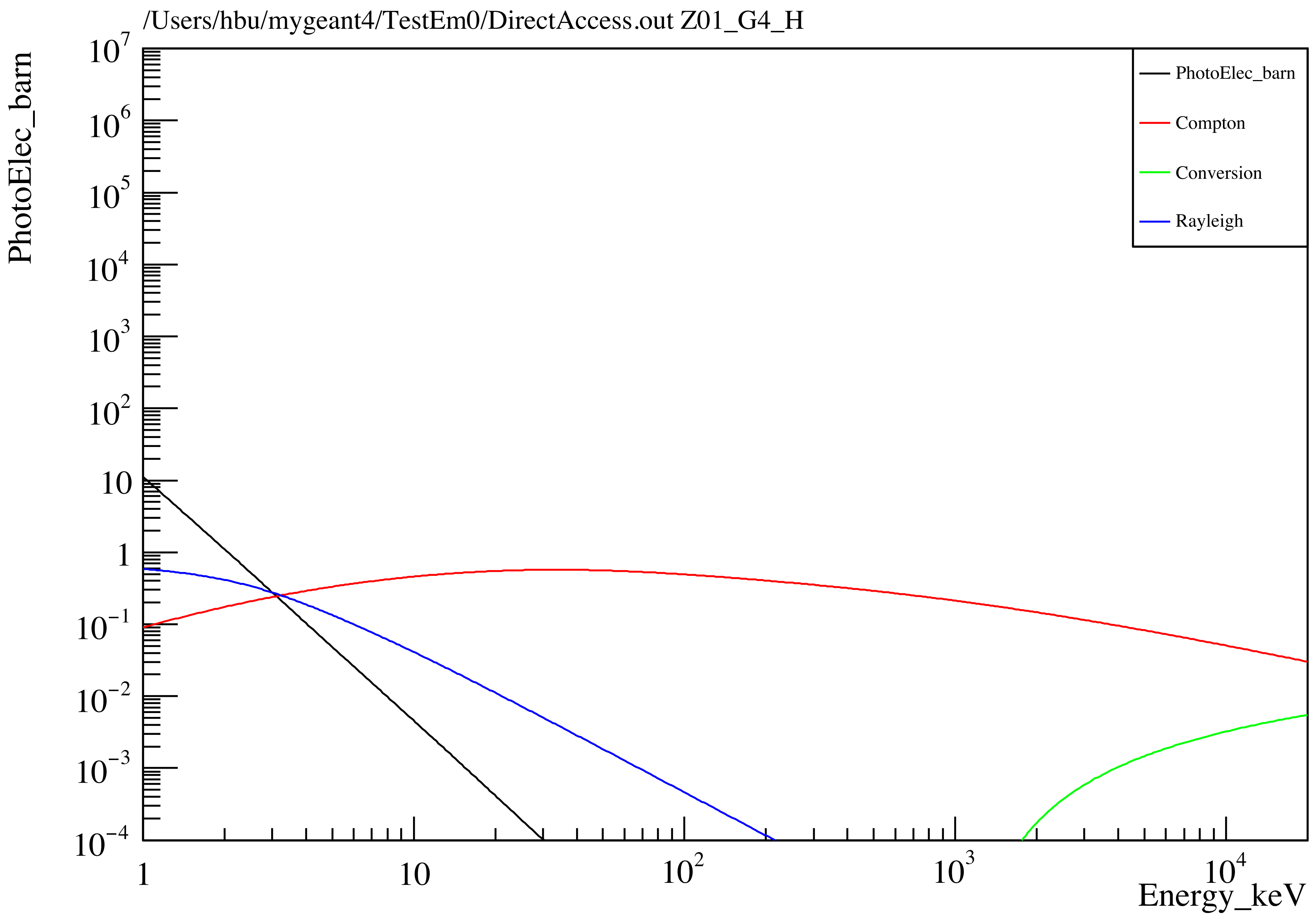
SuperKEKB ~ 2 keV (LER)
FCC-hh ~ 5 keV

LEP1 : 69 keV
LEP2 : 724 keV (arc, last bend 10× lower)

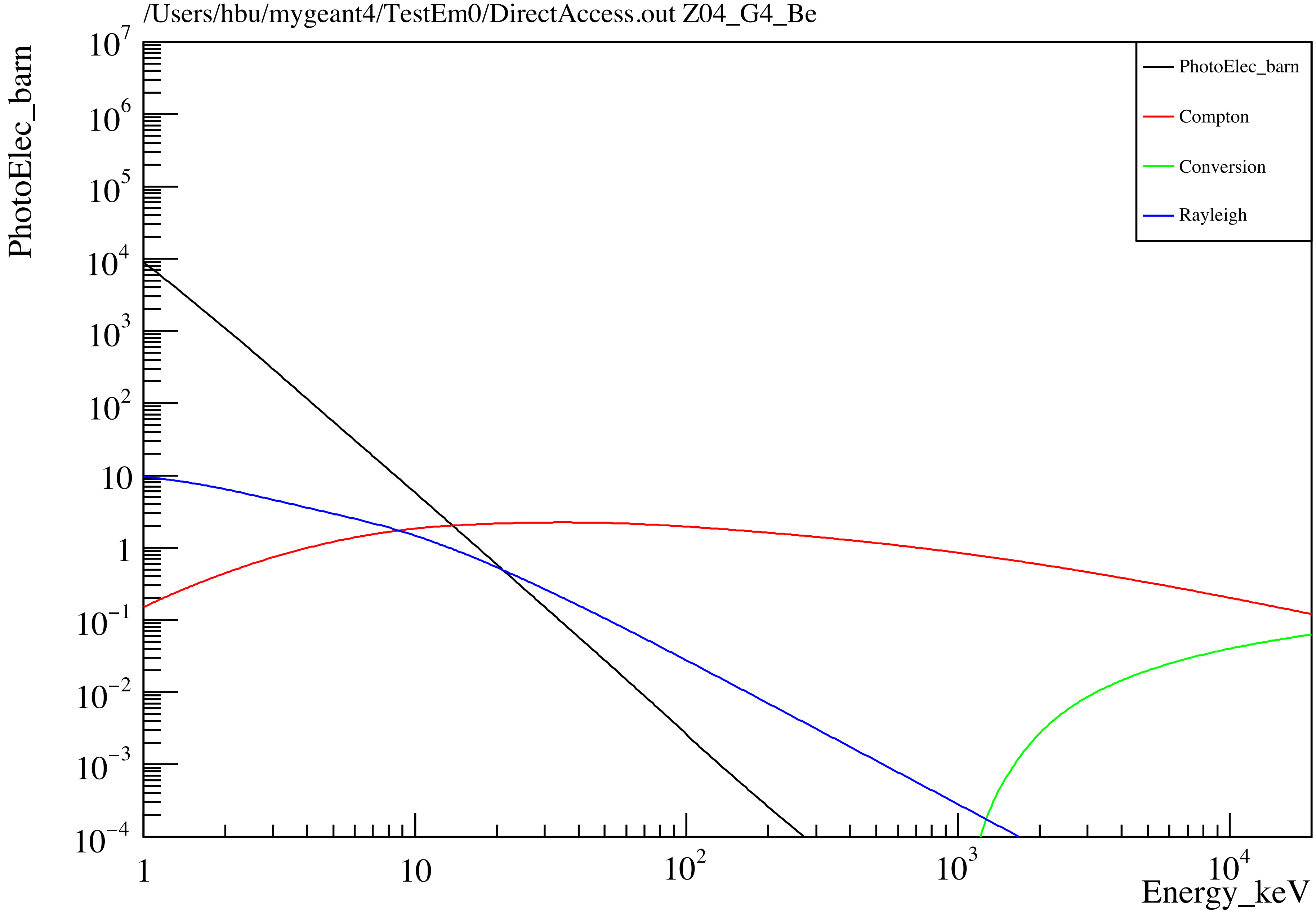
FCC-ee : ~ 1 MeV (arc, 175 GeV)
bit higher than LEP2
Enormous photon flux, MWs of power
can get kW locally, melt equipment, detectors
Very difficult but not impossible as
demonstrated in LEP2

as long as no hard synchrotron radiation
is generated towards experiments in the IR !!

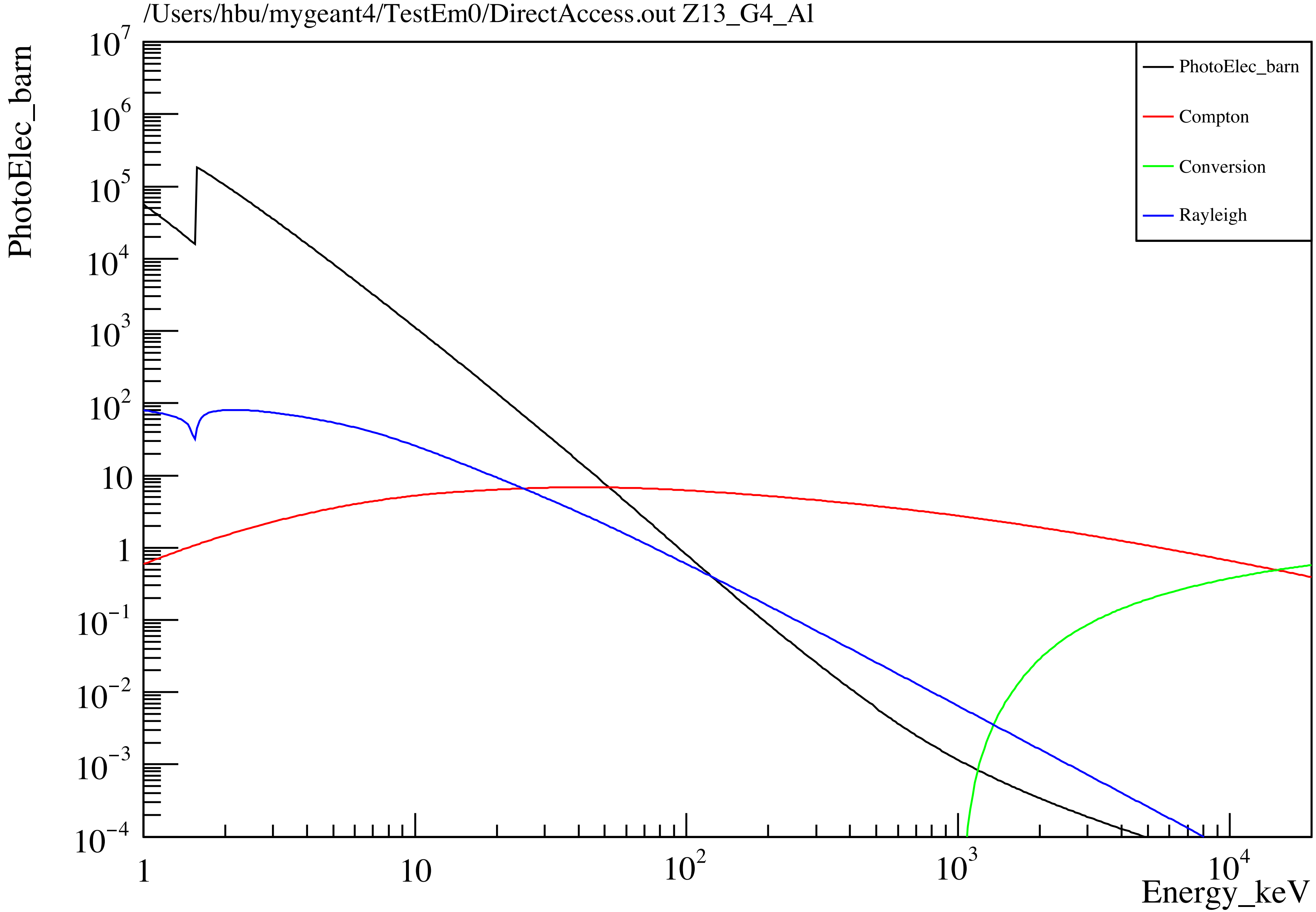
Photon cross sections, Geant4



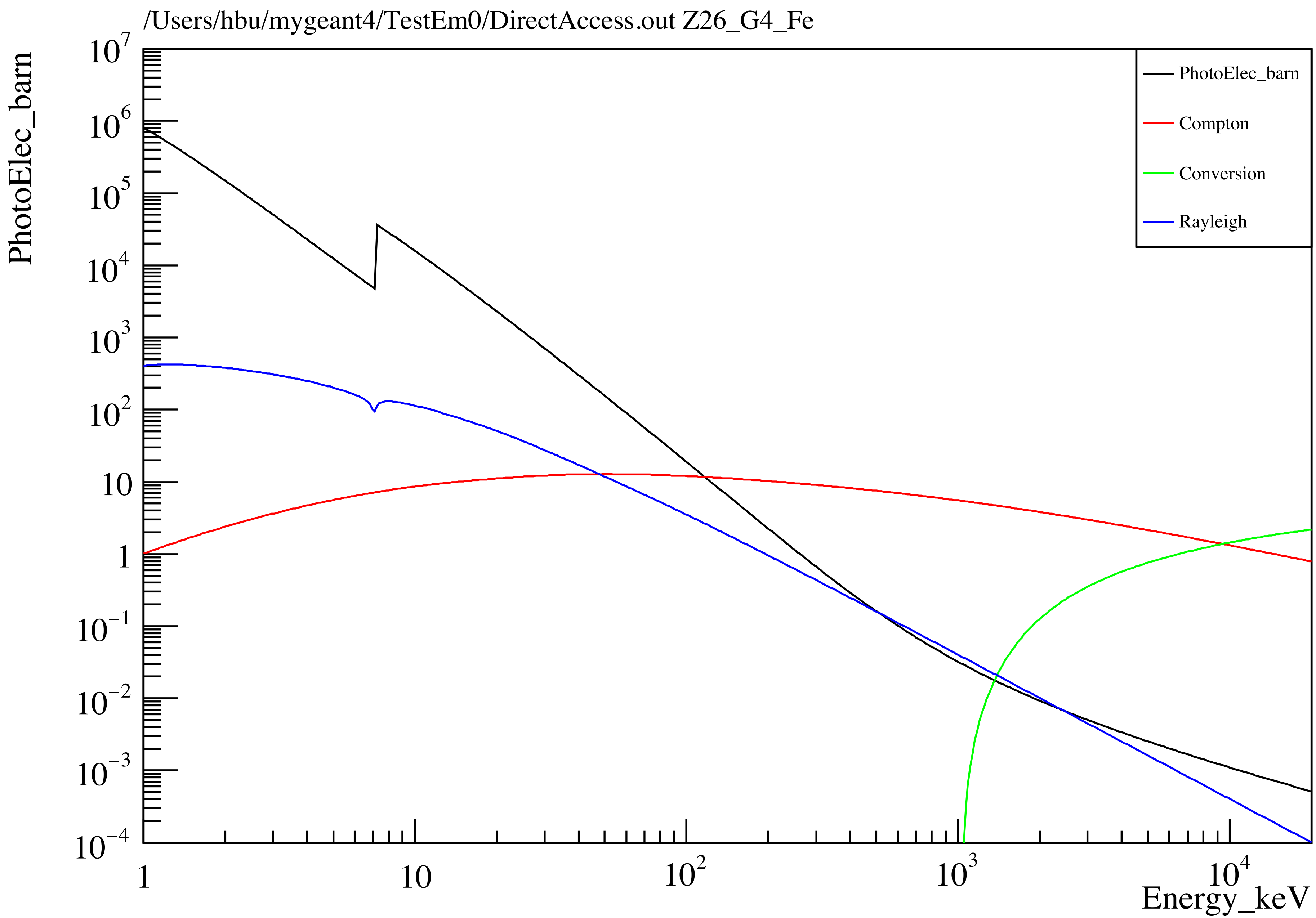
Photon cross sections, Geant4



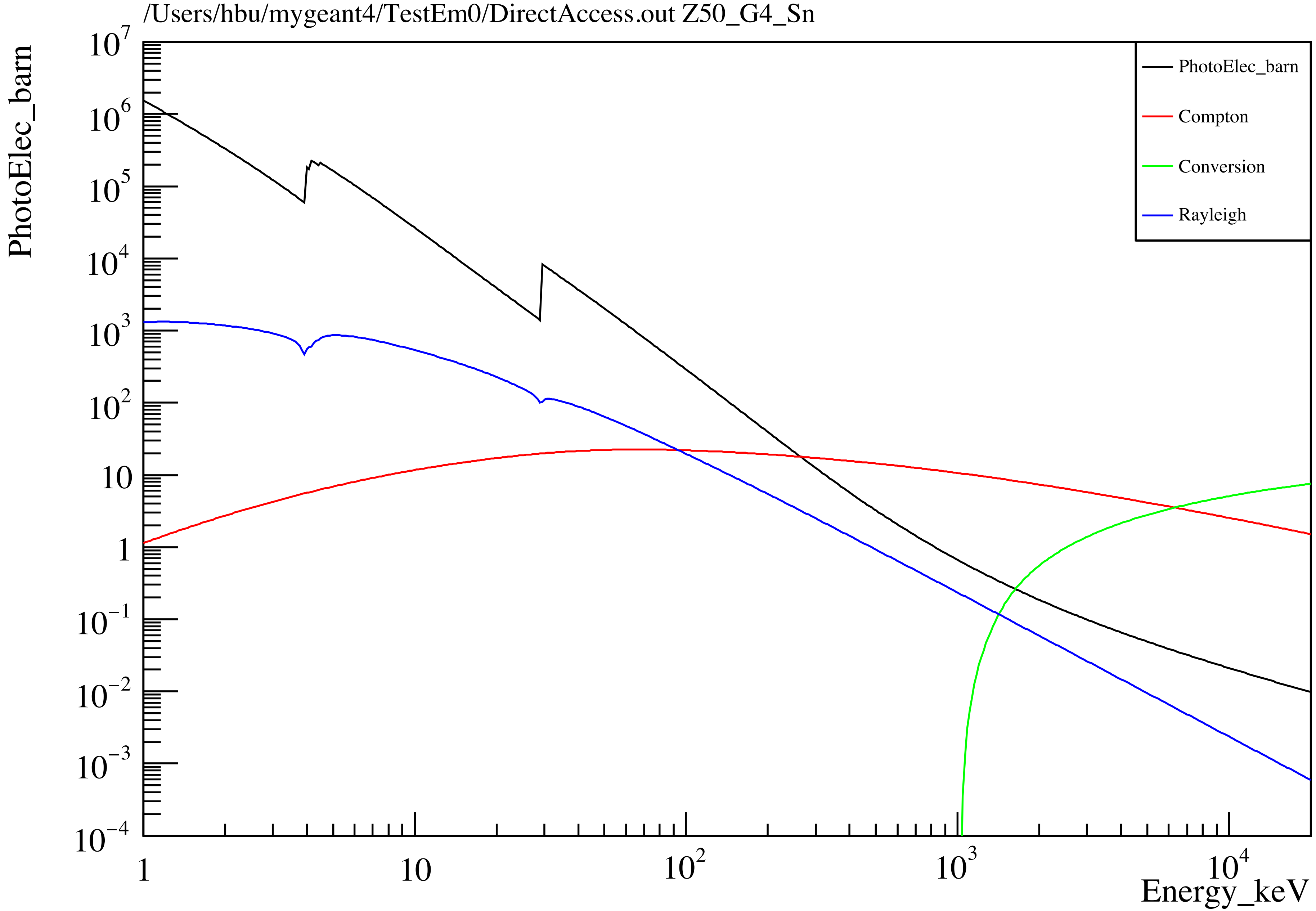
Photon cross sections, Geant4



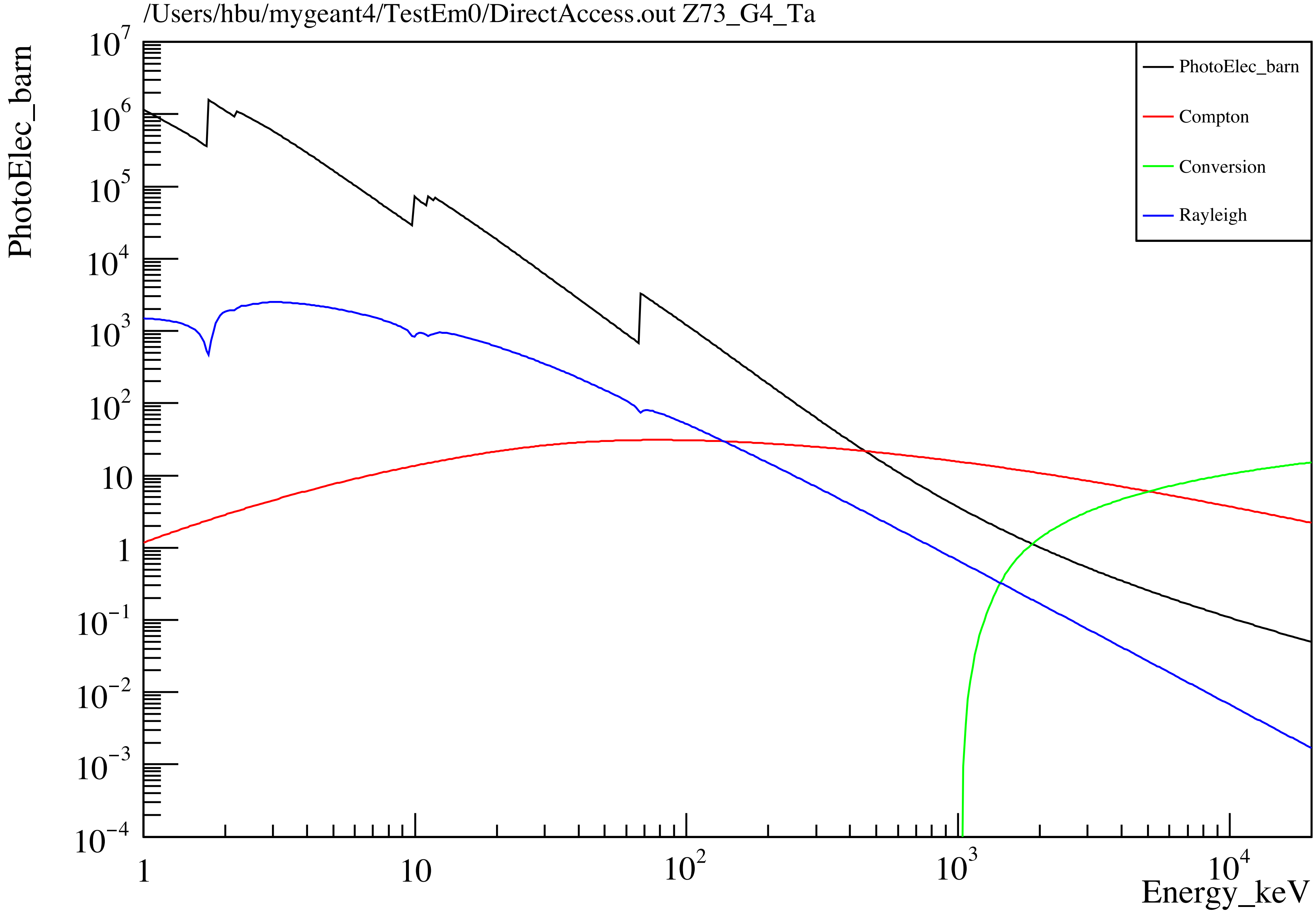
Photon cross sections, Geant4



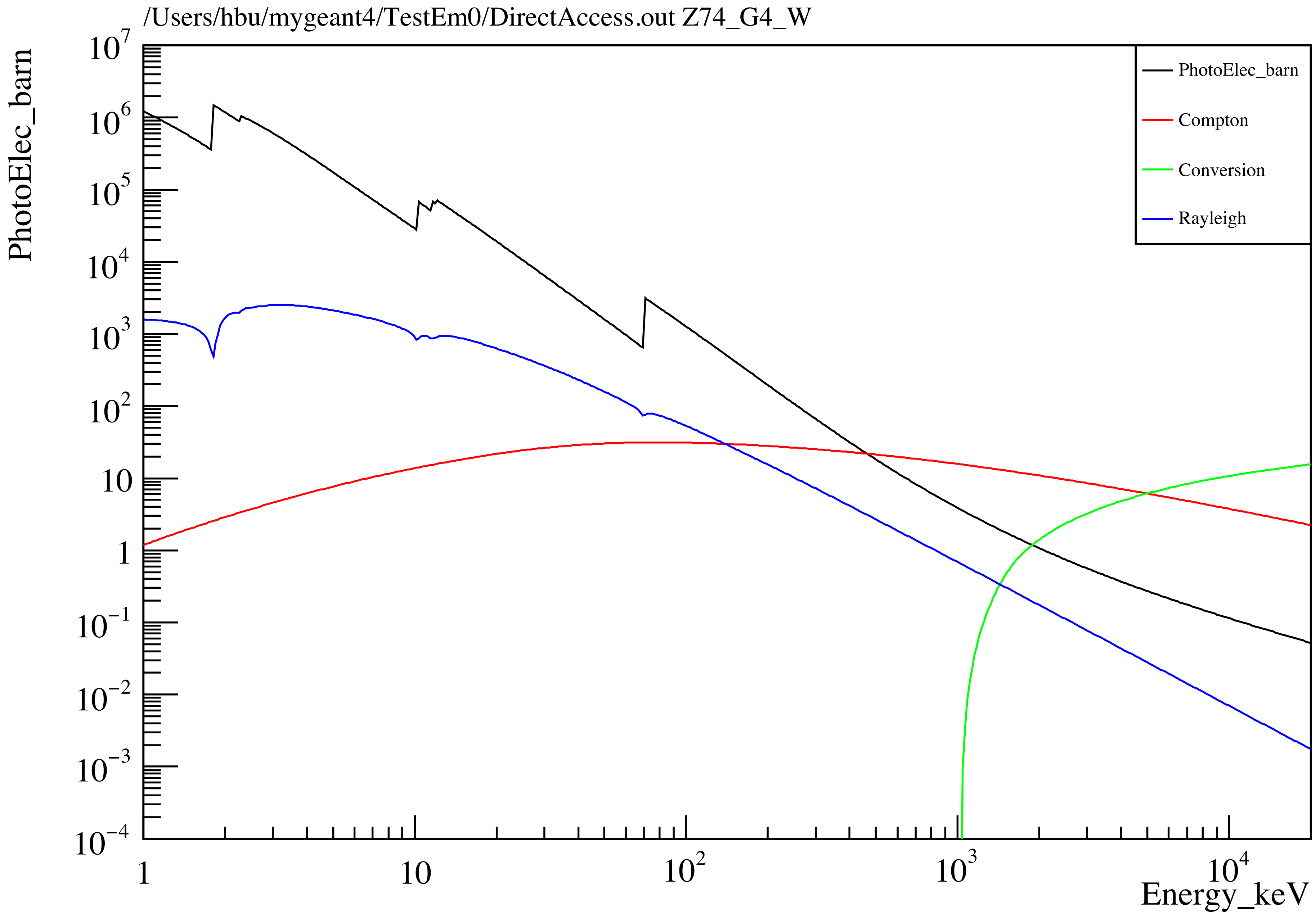
Photon cross sections, Geant4



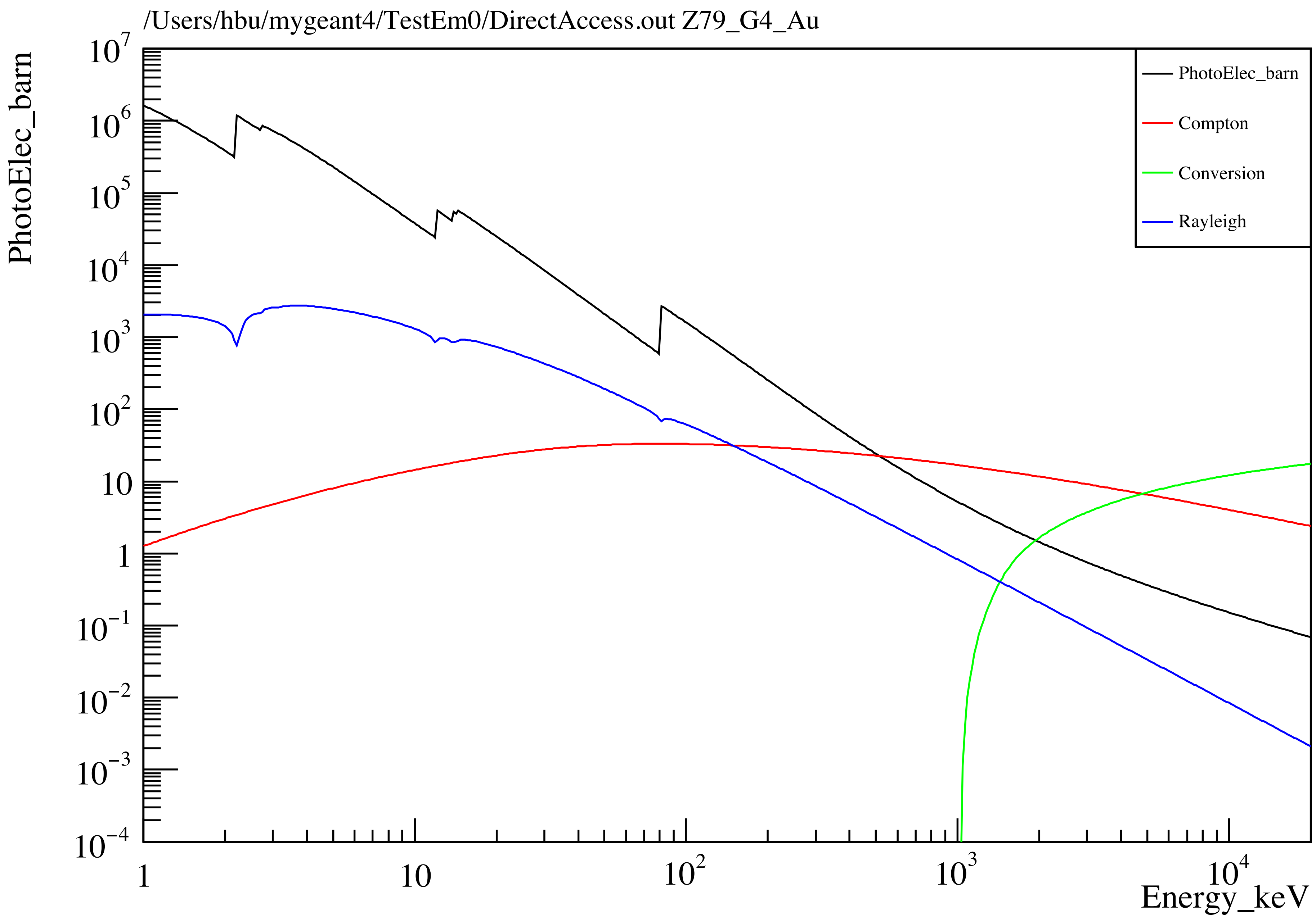
Photon cross sections, Geant4



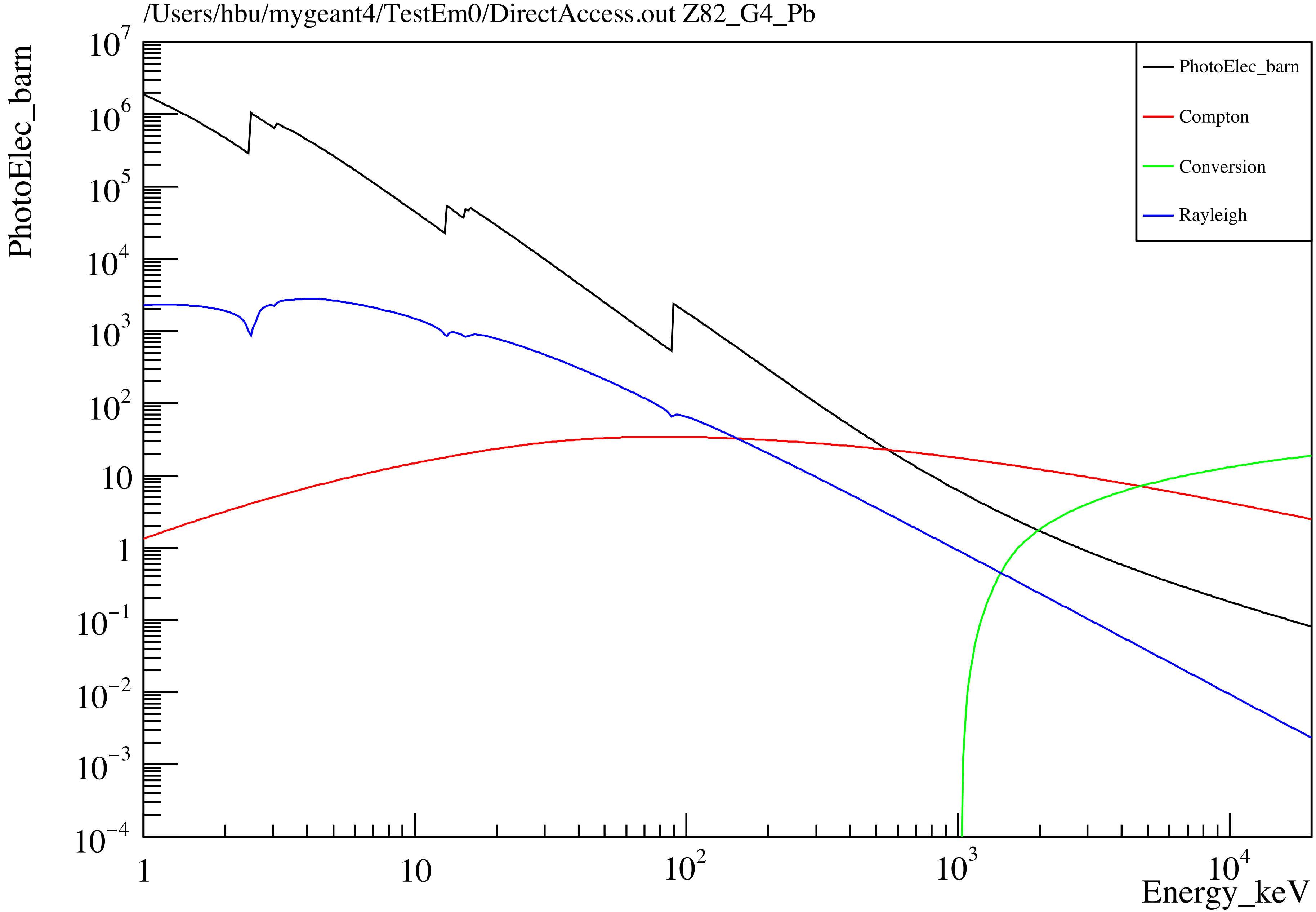
Photon cross sections, Geant4



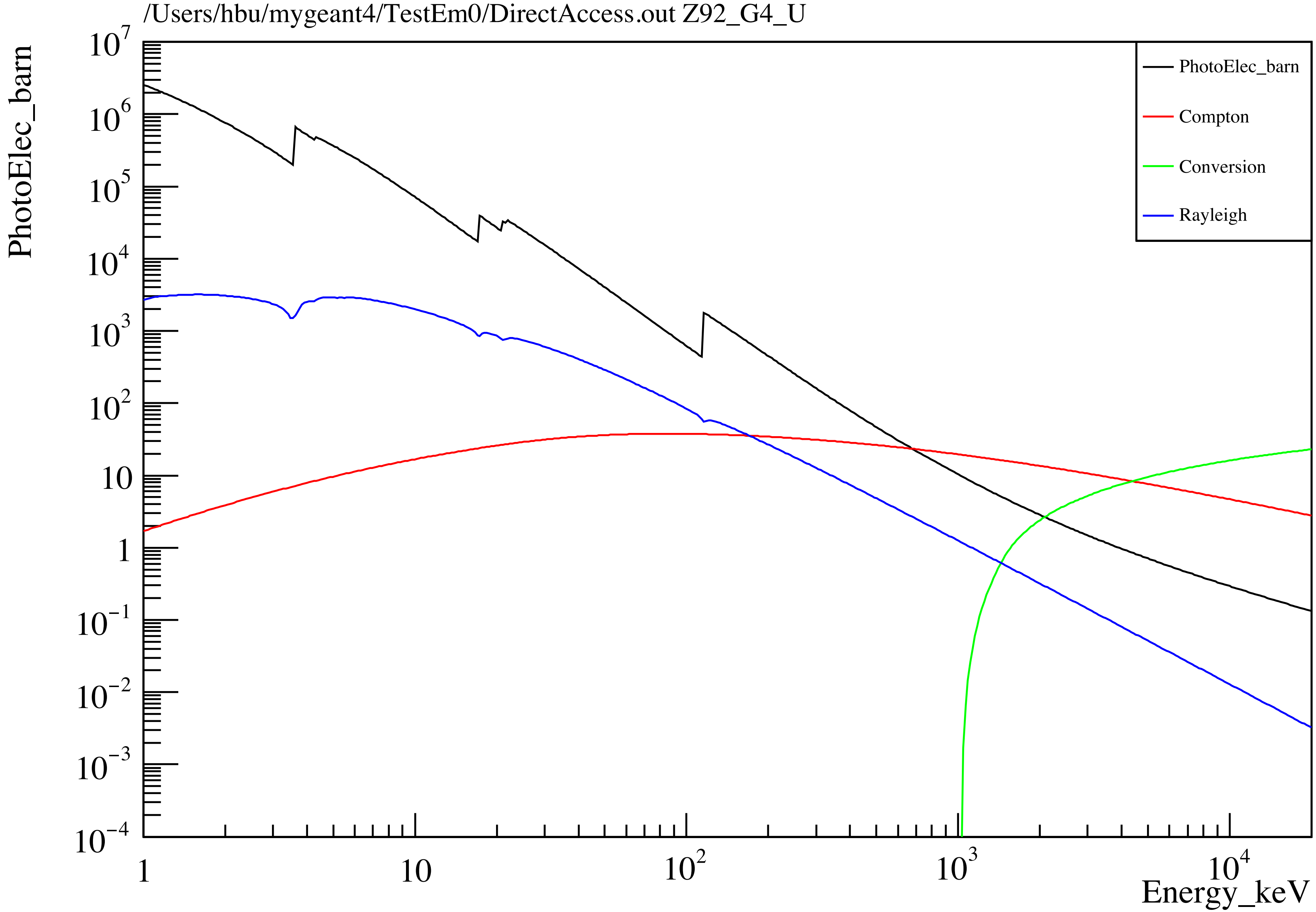
Photon cross sections, Geant4



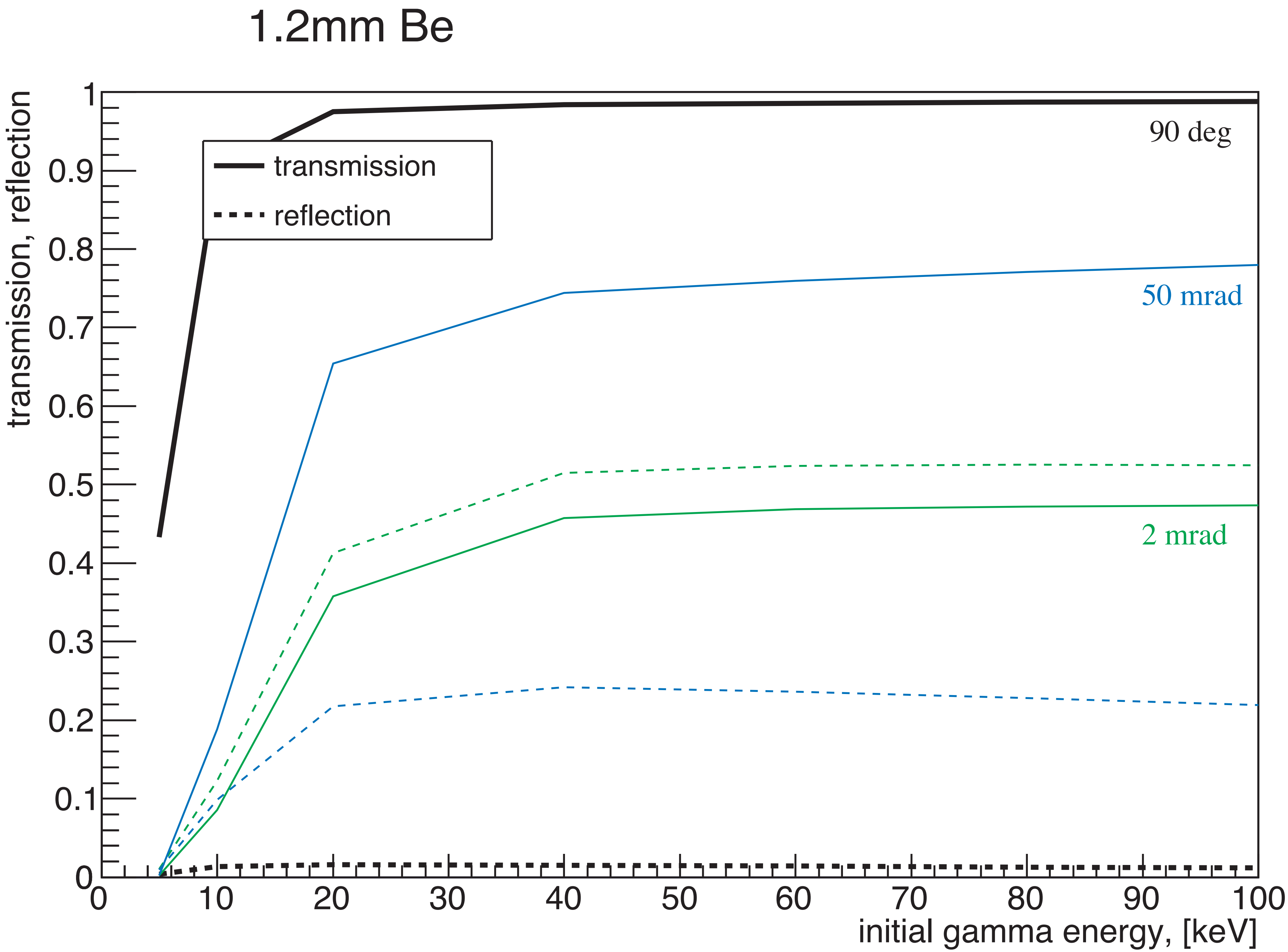
Photon cross sections, Geant4



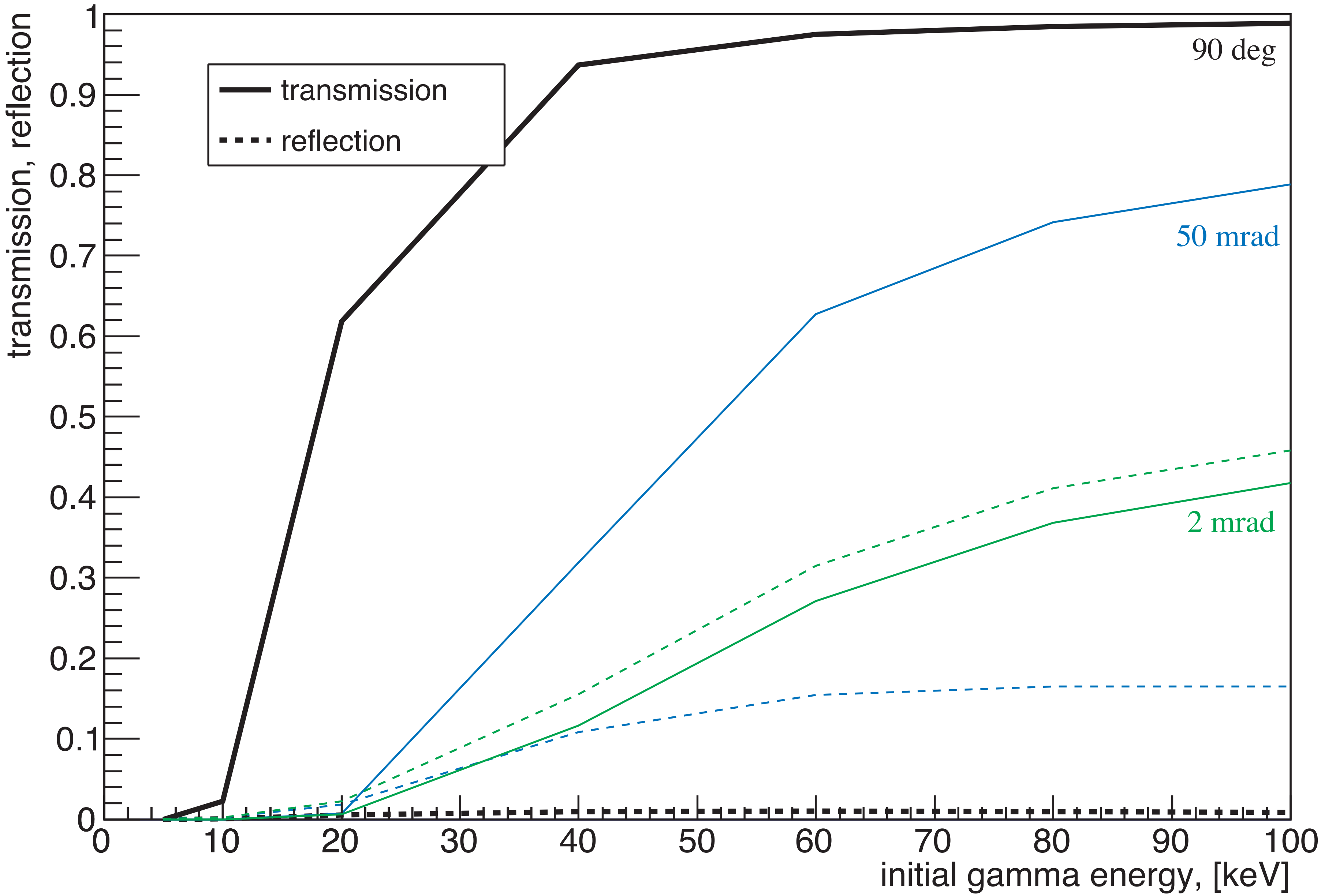
Photon cross sections, Geant4



Transmission, absorption

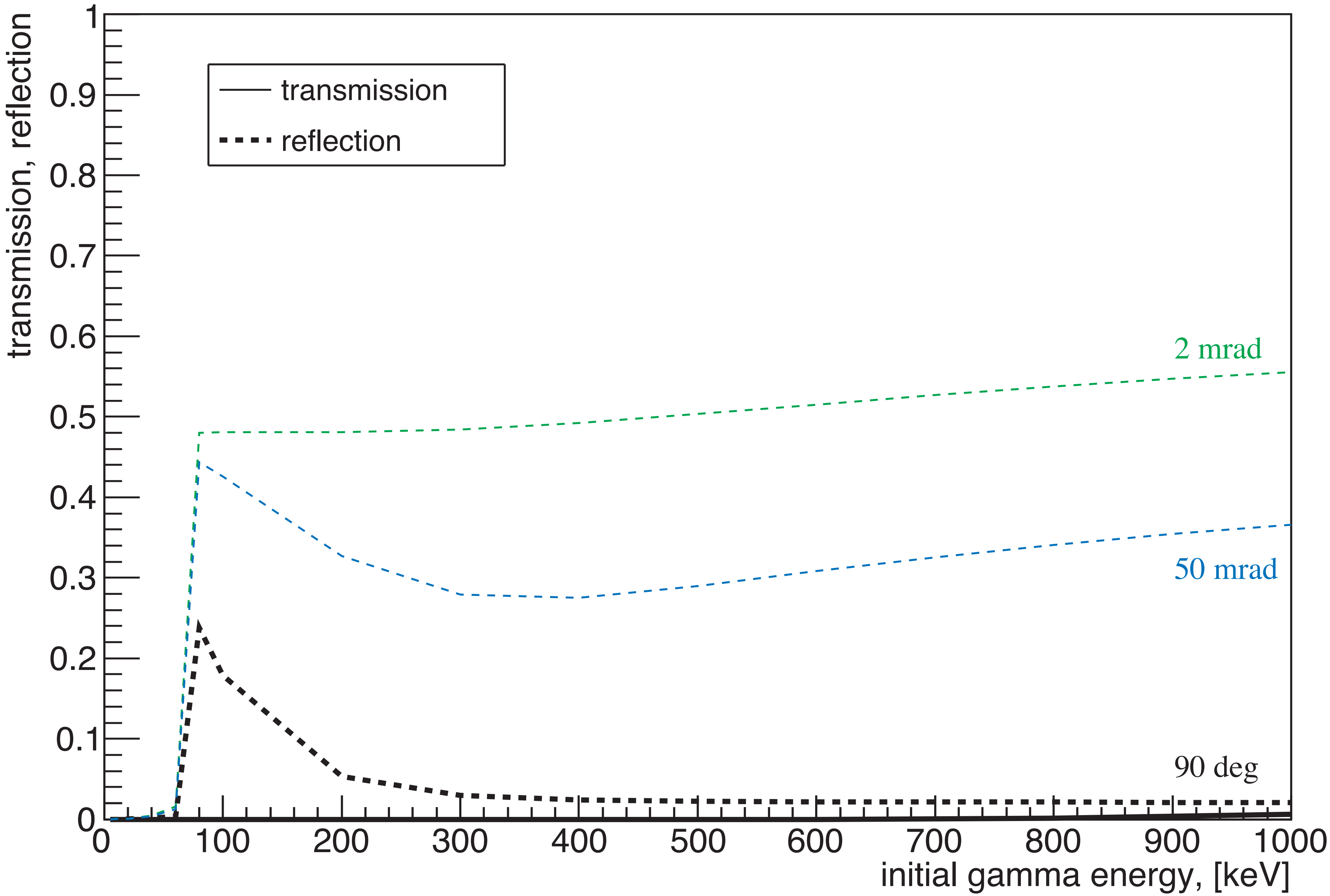


0.56mm Al


transmission
reflection
90 deg
50 mrad
2 mrad
transmission, reflection
initial gamma energy, [keV]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100

Transmission, absorption

5cm tungsten



Photon collimation, shielding

Roughly

Beryllium, Z= 3, transparent for Eγ > 10 keV

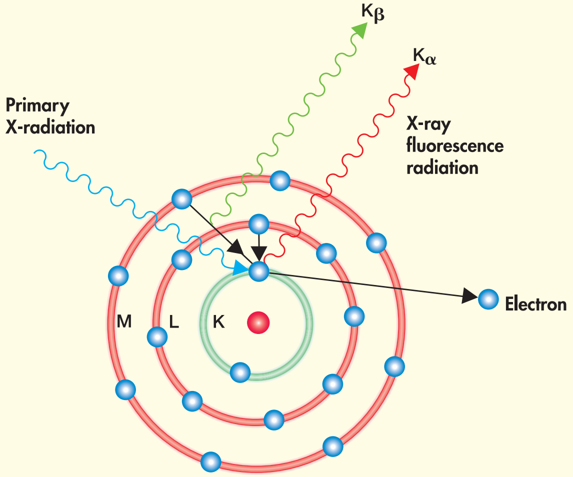
Aluminimum, Z=13, transparent for Eγ > 40 keV

i.e. beam pipes rather transparent for FCC-ee photons, also at small impact angles

The photons can be mostly be absorbed by several cm of collimators / shielding material like Tantalum Z=73 or Tungsten Z=74

However :

Significant secondary emission (large angle) + at very small angle specular reflection



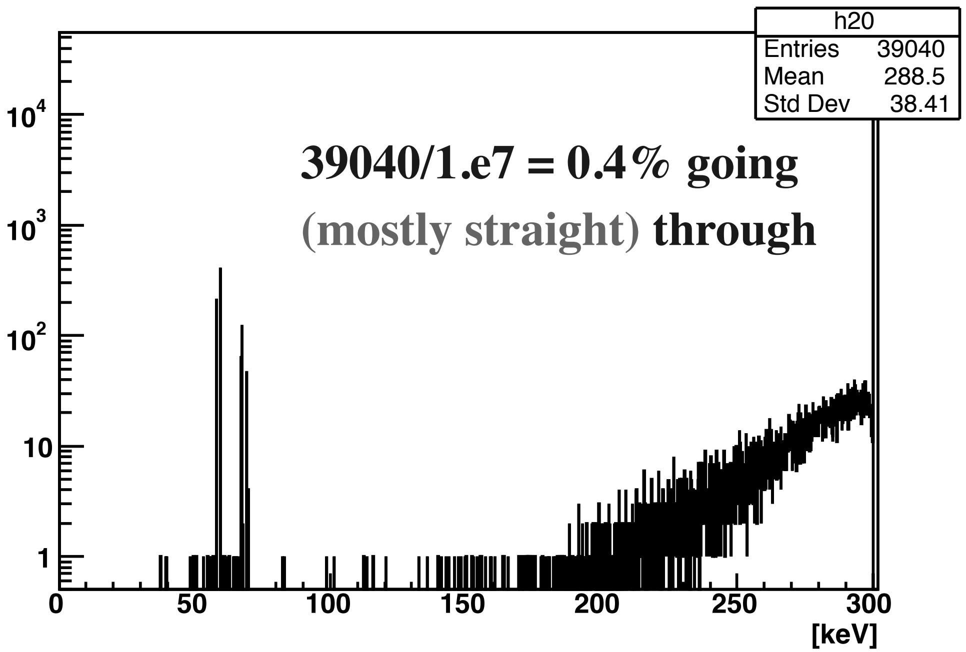
X-ray fluorence and (multiple) Auger is simulated in detail by GEANT4

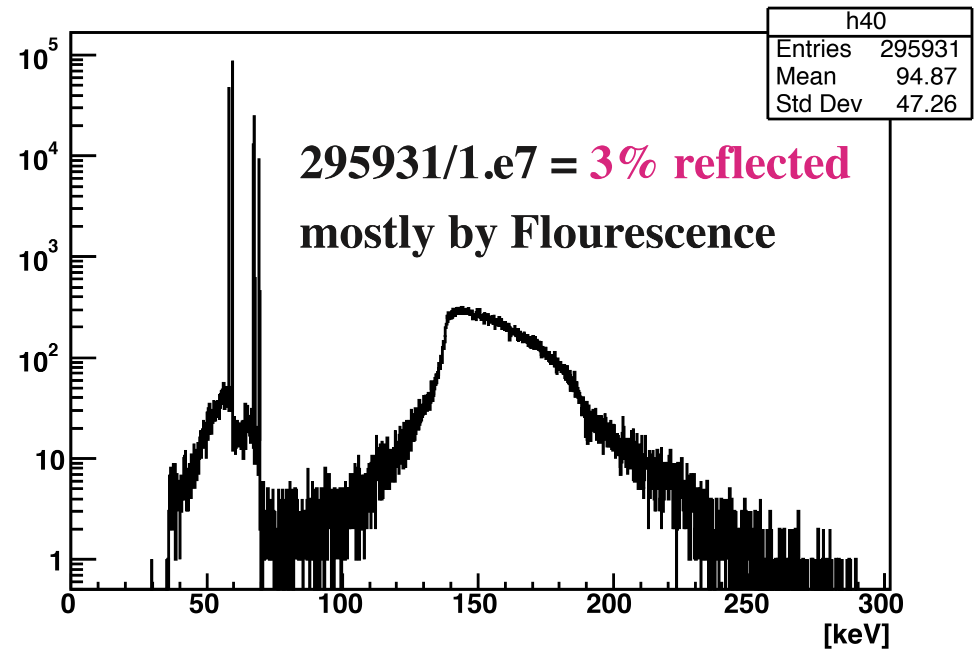
Specular X-ray reflection not yet in standard G4

Shielding / Collimation

GEANT4 simulation, 1.e7 photons of 300 keV perpendicular on 1 cm tungsten

Energy spectra





Increases to

~ 50% at small incident angle

Concluding remarks

Good progress on

reducing synchrotron radiation rates from last bends by lattice design

into the interaction region -- to a level roughly comparable to LEP 2

keep in mind : γ BKG was difficult / performance limiting in LEP

here still many extra challenges :

distance to bend (250 / 100)^2 = 6.25, crossing angle, beam pipe LEP r = 53 mm,

FCC-ee currently 15 - 20 mm

Next steps

detailed design

- **beam-pipe geometry / collimation - shielding**
- **detector and**
- **IR design (next talk)**

have started

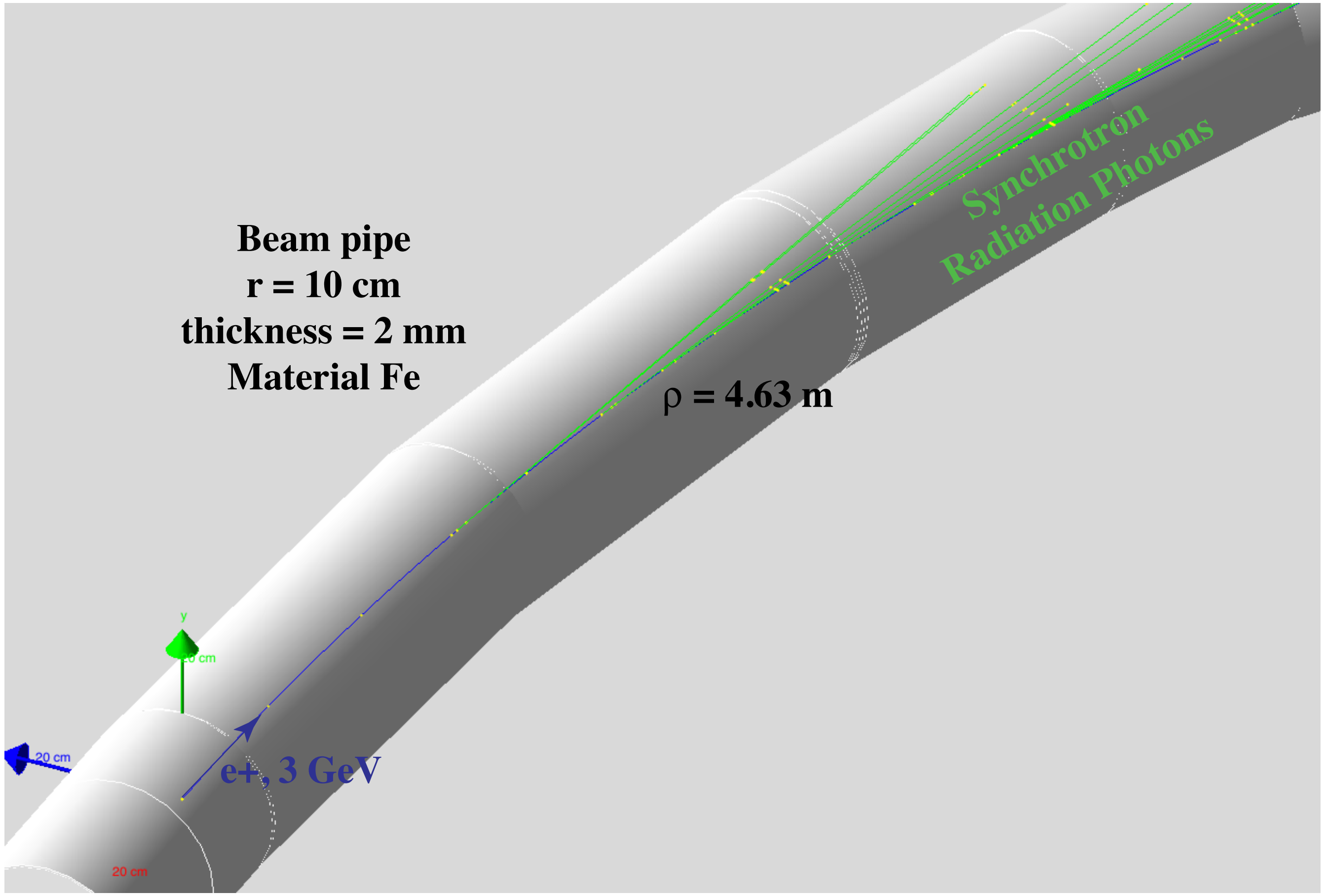
Backup

MDISim - Geant4

Essential information -- directly available on MDISim level

- root display of synchrotron radiation cones
- energy flow tables

set up to be complemented by full shower simulation

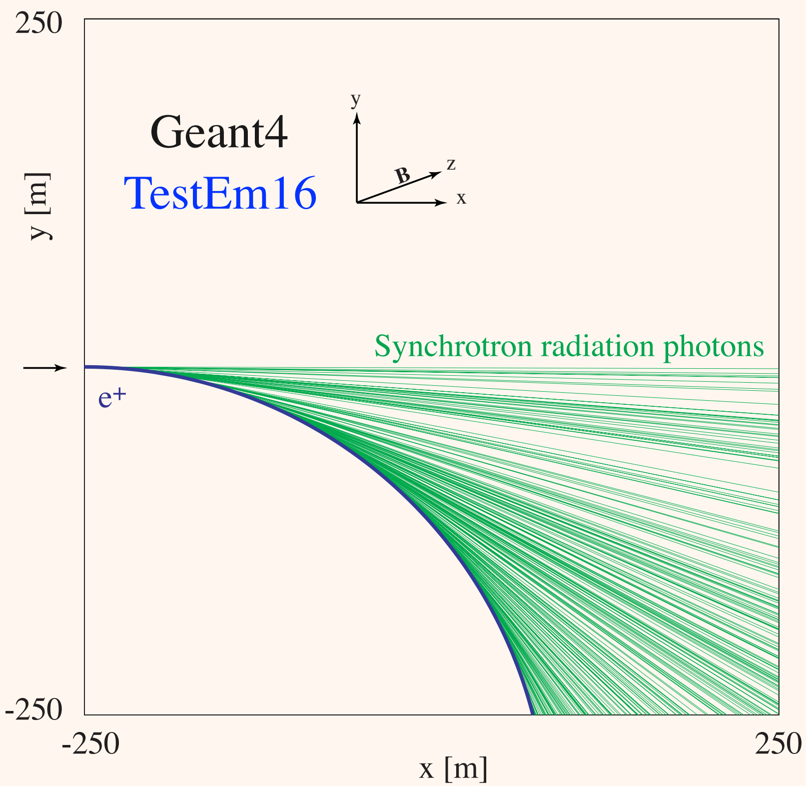


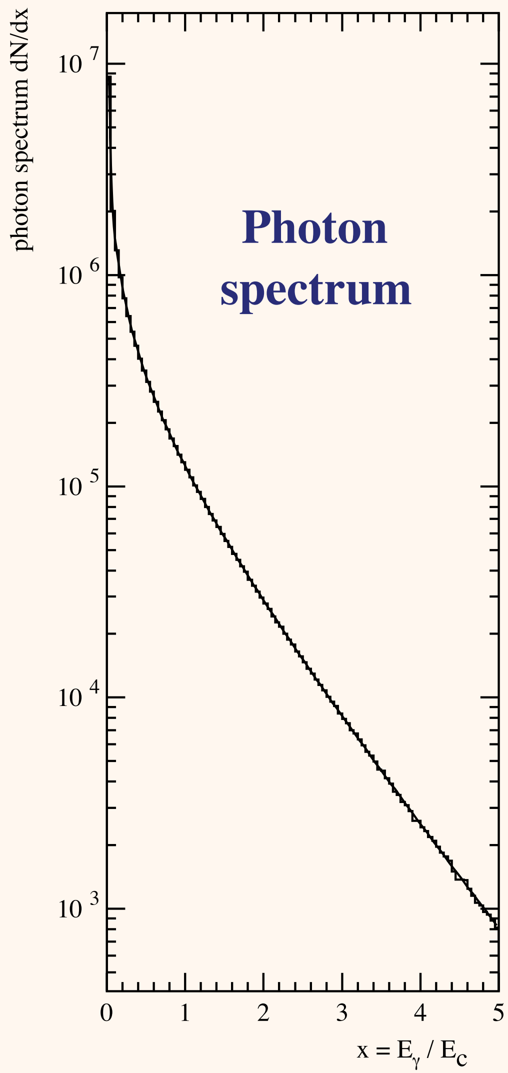
Geant4 tracking with synchrotron radiation generation and absorption --
directly from MDISim generated root geometry imported via gdml to Geant4
Modified TestEM16 shown here for a small (LEIR) geometry, Ecr 14 keV

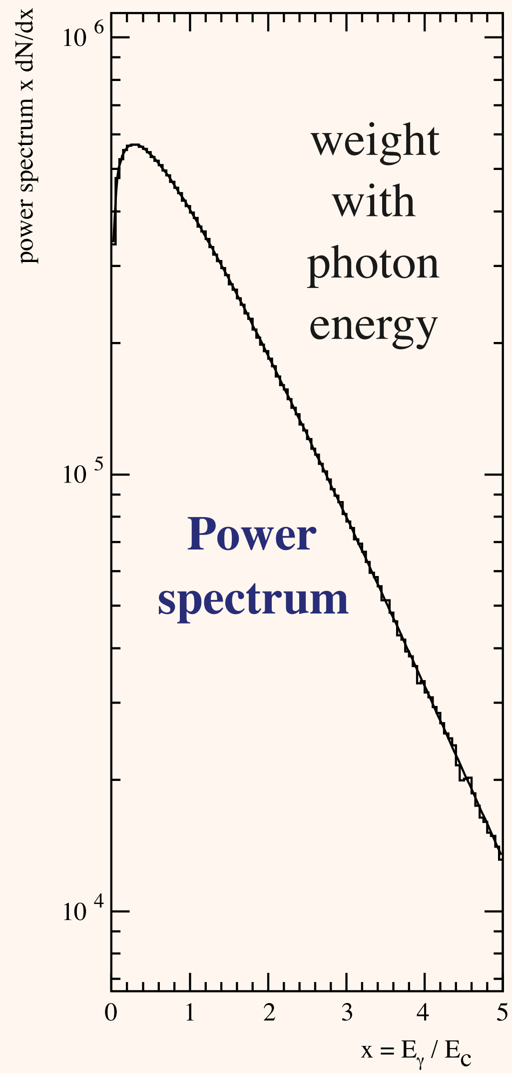
Spectrum

Photon energy in units of the critical energy. $x = E_\gamma / E_c$
For hom. field over formation length : single spectrum

$$\frac{d^2N}{ds\,dx} = \frac{\sqrt{3}\,\alpha}{2\pi}\,\frac{eB_\perp}{mc}\int_x^\infty K_{5/3}(\xi)\,d\xi$$







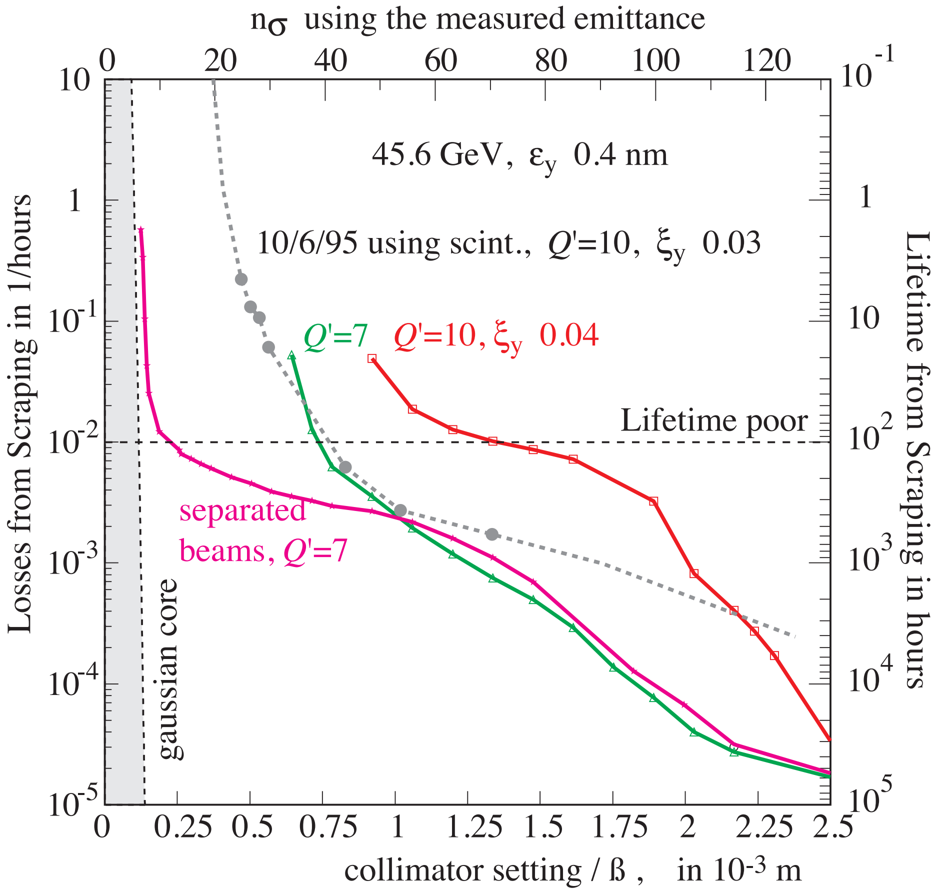
10 GeV e+ moving initially in x-direction, bend downwards on a circular path by a 0.1 T magnetic field in z-direction. Geant4 TestEm16
Recently generalized to all long live charged particles including ions
in Geant4 10.1 released 5/12/2014

Ref. : H.B., CERN-OPEN-2007-018, Geant4 physics-manual Implemented as process G4SynchrotronRadiation

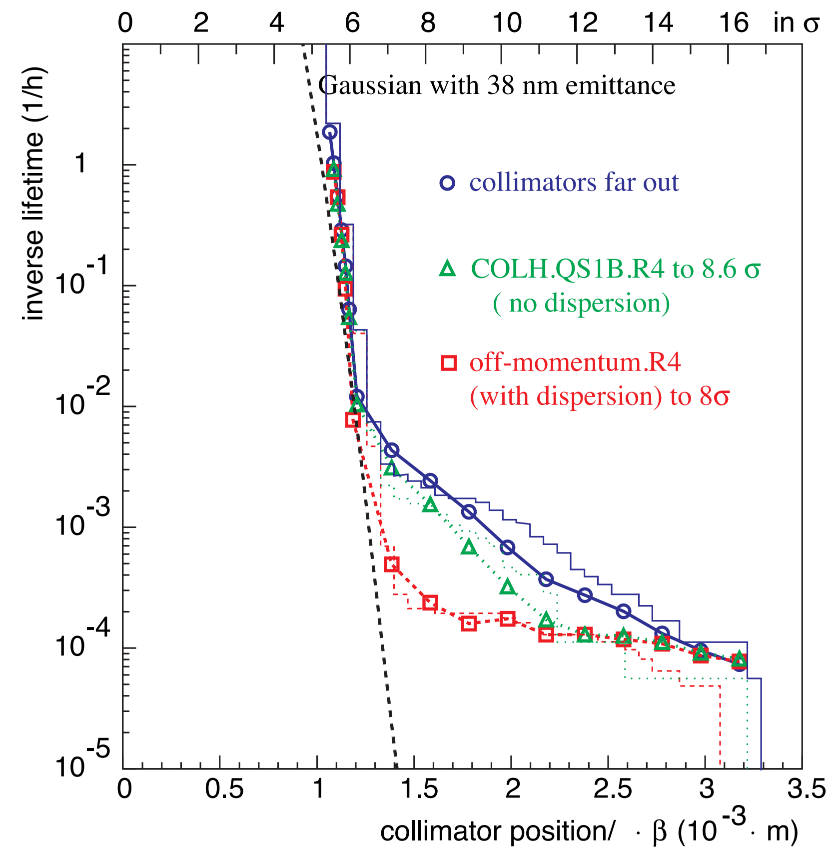
non-Gaussian tails, LEP

measured by scraping with loss monitors

vertical plane, colliding beams



horizontal plane
reproduced by simulation



Tails from : beam-beam, high chromaticity, particle scattering

Background spikes, enhanced synchrotron radiation from quadruples

H. Burkhardt, "BEAM LIFETIME AND BEAM TAILS IN LEP." CERN-SL-99-061-AP and Proc. e+ e+ Factories 1999, KEK, Tsukuba 1999
Transverse beam tails due to inelastic scattering, Phys. Rev. ST Accel. Beams 3, 091001 (2000)