IP-GENERATED RADIATION MONITOR FOR CENTER-OF-MASS ENERGY MEASUREMENTS

Andrea Ciarma

5th FCC Physics Workshop

7 - 11 February 2022

Thanks to A.Blondel, M.Boscolo, E.Perez, R.Kersevan

Outline

- Center-of-mass Energy Monitor
- IP-generated radiation:
    - Beamstrahlung
    - Radiative Bhabha
    - Comparison and resolution estimate
- Possible Background sources:
    - Synchrotron Radiation
    - Compton Scattering on Thermal Photons
    - Inelastic Beam Gas Scattering
- Conclusions and Plans

Center-of-mass Energy Measurements

Measured by Resonant Depolarisation

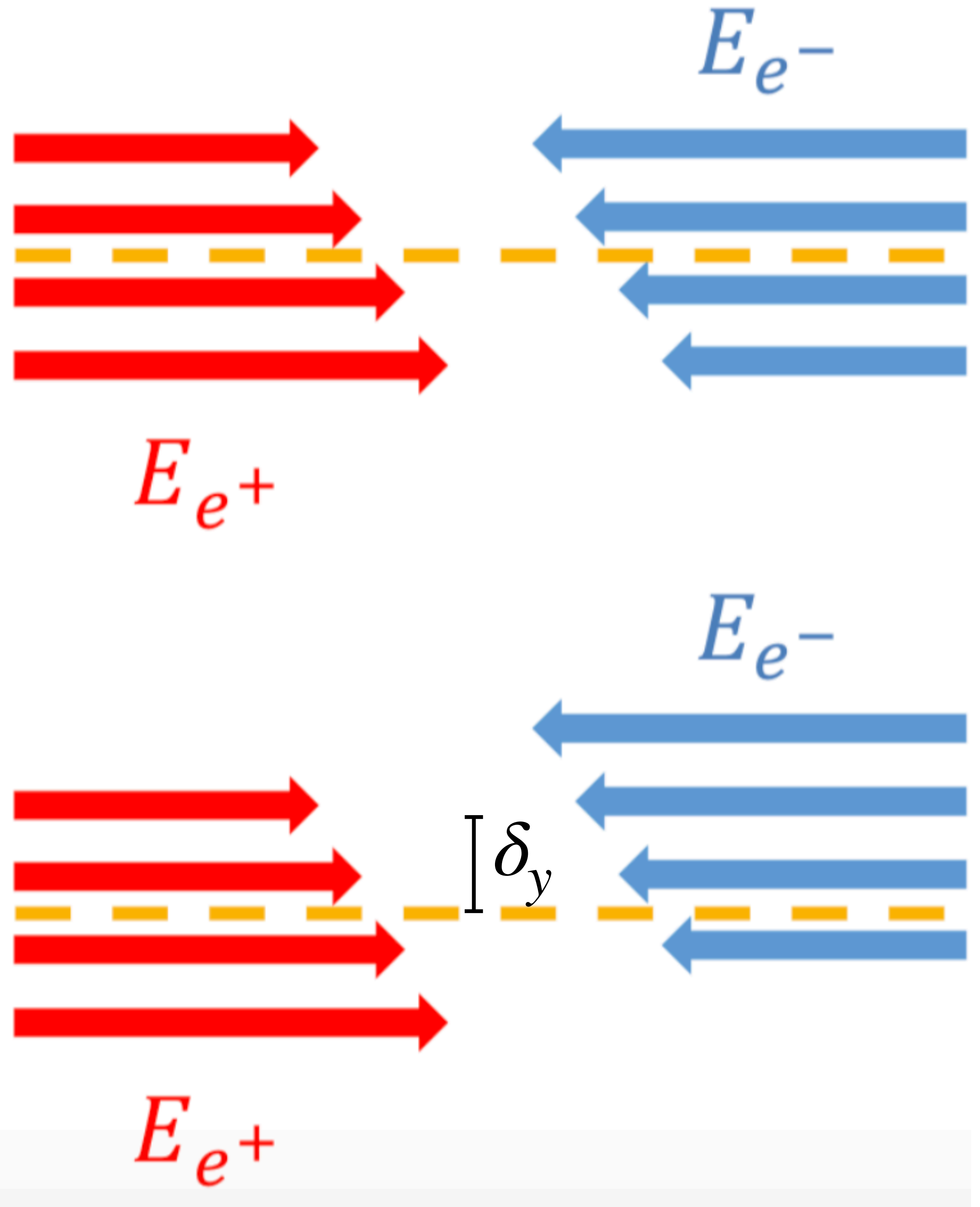
$$E_{CM} = E_{e^+} + E_{e^-} + \Delta E_{CM}$$

$$\Delta E_{CM} = -\frac{\delta_y}{\sigma_y}\frac{\frac{D_{e^+}+D_{e^-}}{2}\frac{\sigma_E}{E}}{\sigma_y}\sigma_E$$

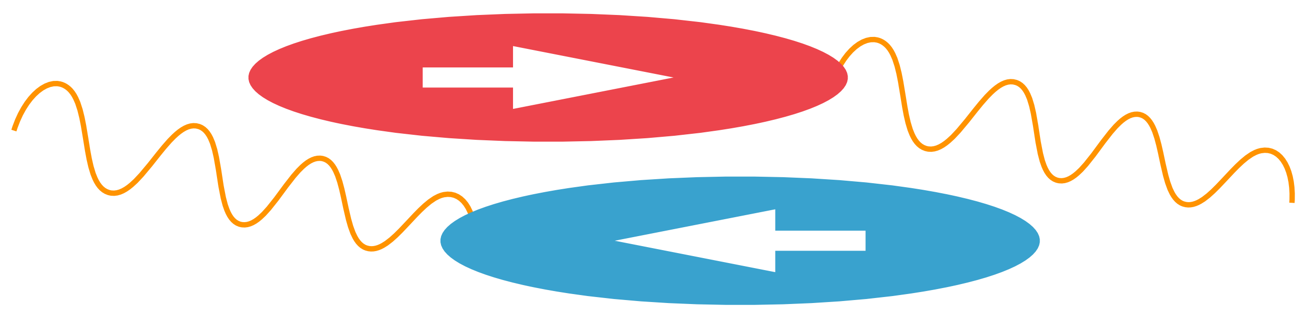
Non-zero **dispersion at the IP** modifies the center-of-mass energy in the case of an **offset** between the colliding beams. For very flat beams, the effect of **spurious vertical dispersion** will be relevant.

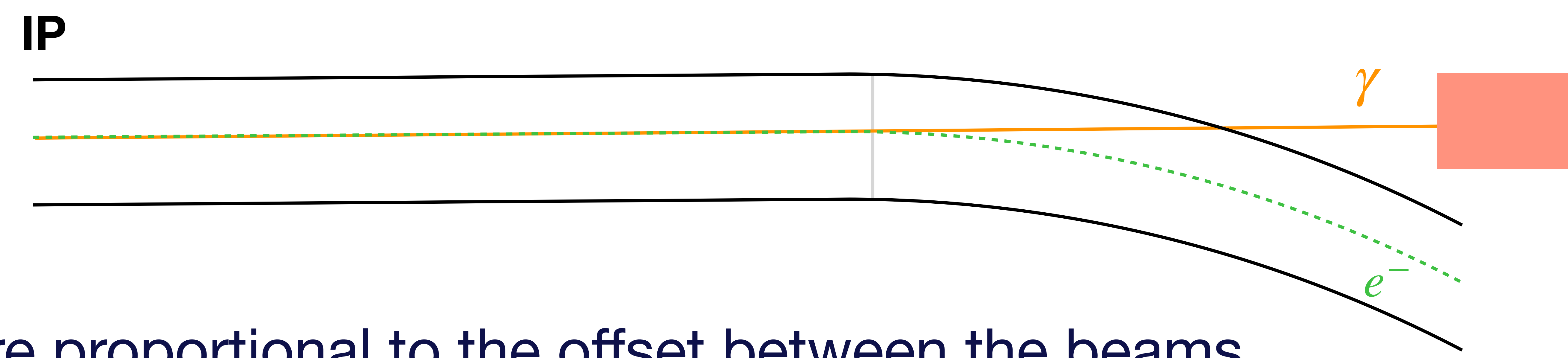
An online monitor for this offset could be obtained by detecting **hard photons produced at the IP** (i.e. radiative bhabhas, beamstrahlung), as the direction of this radiation is proportional to the beam-beam offset.

Simulation studies have been performed in order to evaluate the photon energy and angular distributions, and to understand the feasibility of such monitor.



IP-generated Radiation Monitor





The direction and intensity of the **beam-beam kick** are proportional to the offset between the beams. Because the radiation is produced collinear to the beams, it will carry the information of the offset. This radiation is emitted at **very low angles** and will hit the beam pipe at the **first dipole downstream**.

Ideal monochromatic Gaussian beams with the nominal parameters from the CDR at the Z energy have been considered for this study.

For both beamstrahlung and radiative Bhabha, a **scan on the vertical offset** between the two beams has been performed in order to estimate the photon angular distribution and the number of photons produced.

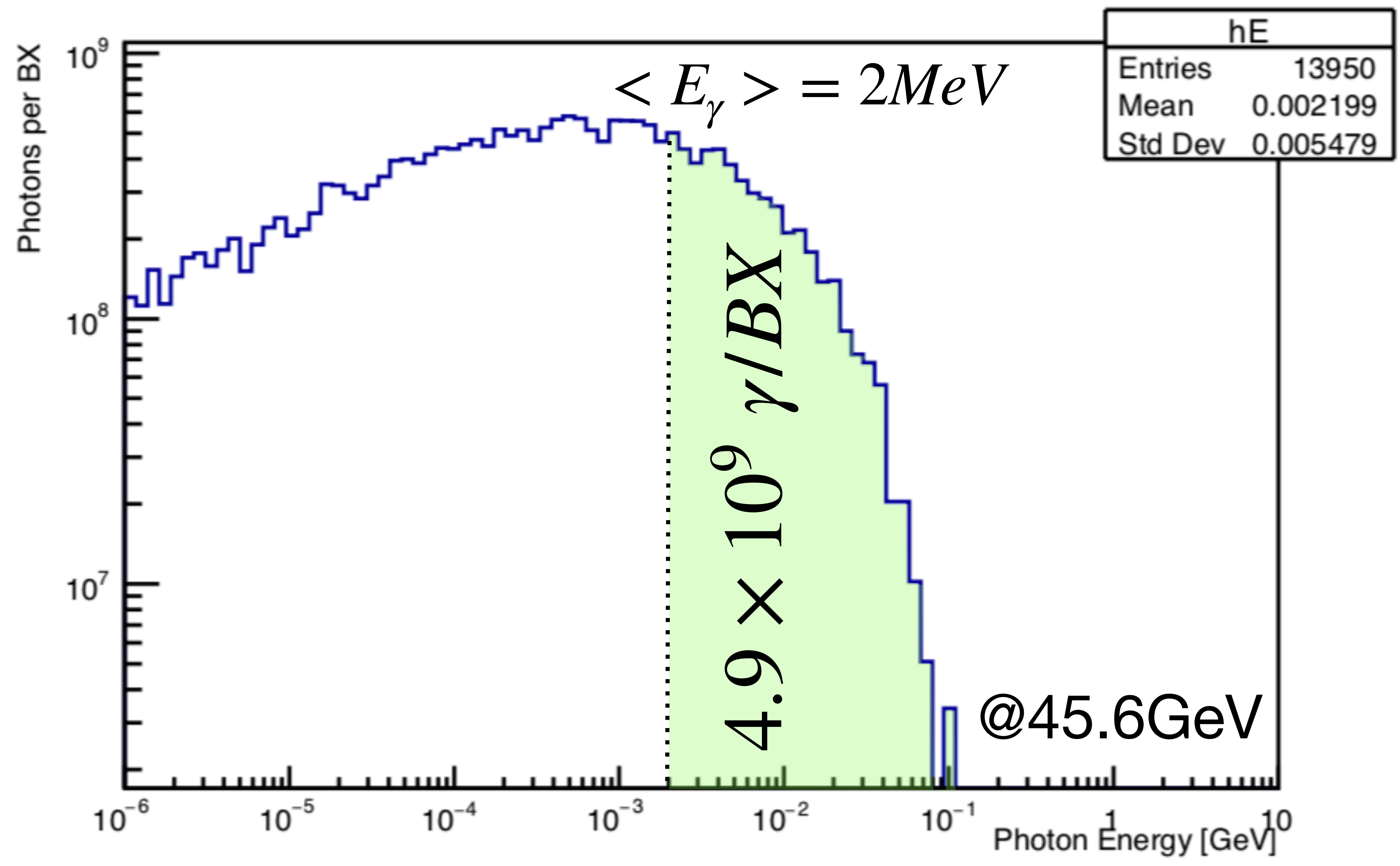
The beam-beam interaction has been simulated with **GuineaPig++**, while the Monte Carlo for the photon generation are **BBBrem** for radiative Bhabha and **GuineaPig++** for beamstrahlung.

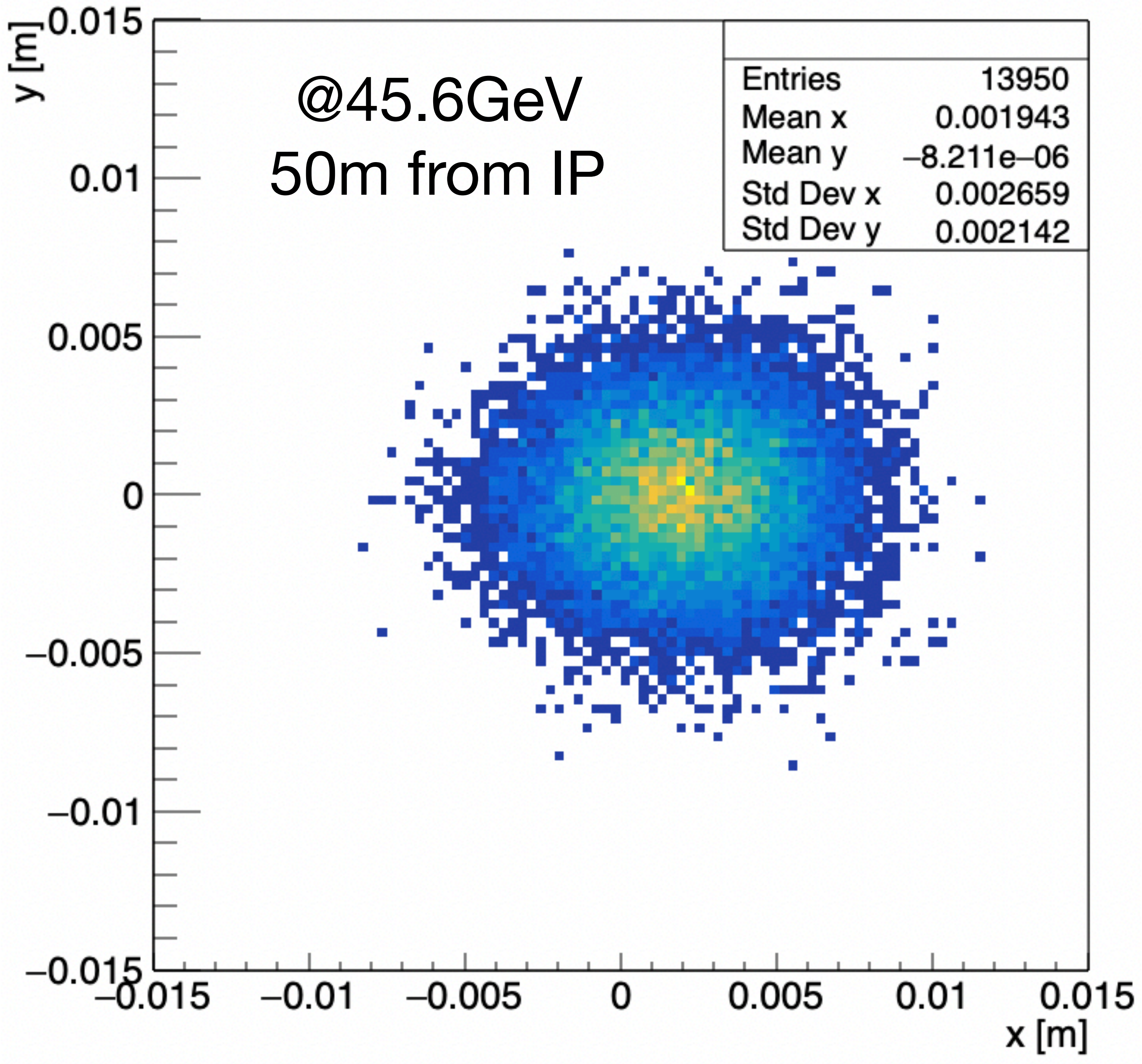
Beamstrahlung

Beamstrahlung photons have been generated using **GuineaPig++**.

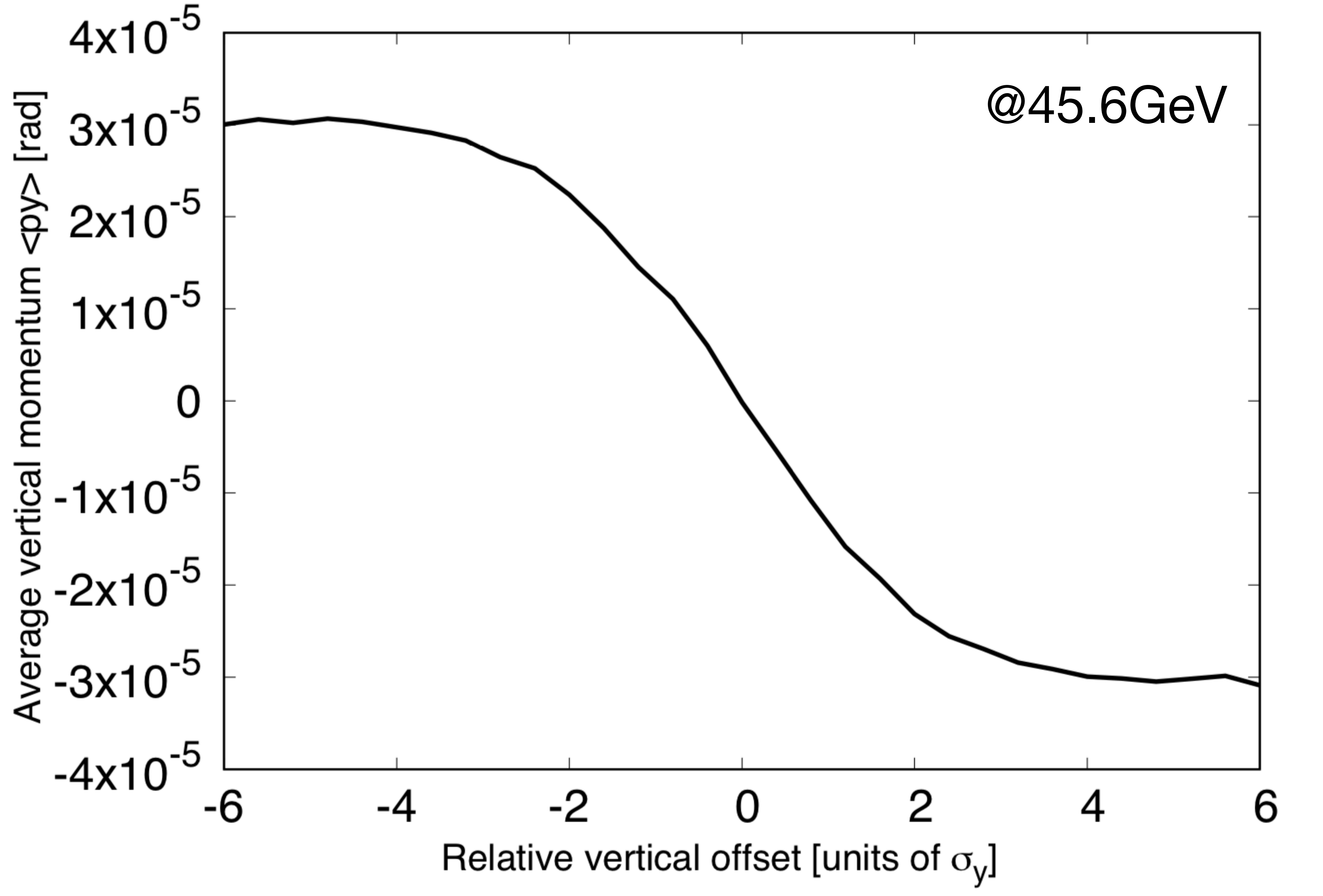
This radiation is intense and the low Beamstrahlung parameter implies a critical energy in the range of the ~MeV

$$<\Upsilon> = \begin{matrix} 9.12 \cdot 10^{-4} & @t\bar{t} \\ 1.81 \cdot 10^{-4} & @Z \end{matrix} \qquad <E_\gamma> = \begin{matrix} 67MeV & @t\bar{t} \\ 2MeV & @Z \end{matrix} \qquad n_\gamma = \begin{matrix} 0.242 & @t\bar{t} \\ 0.148 & @Z \end{matrix}$$





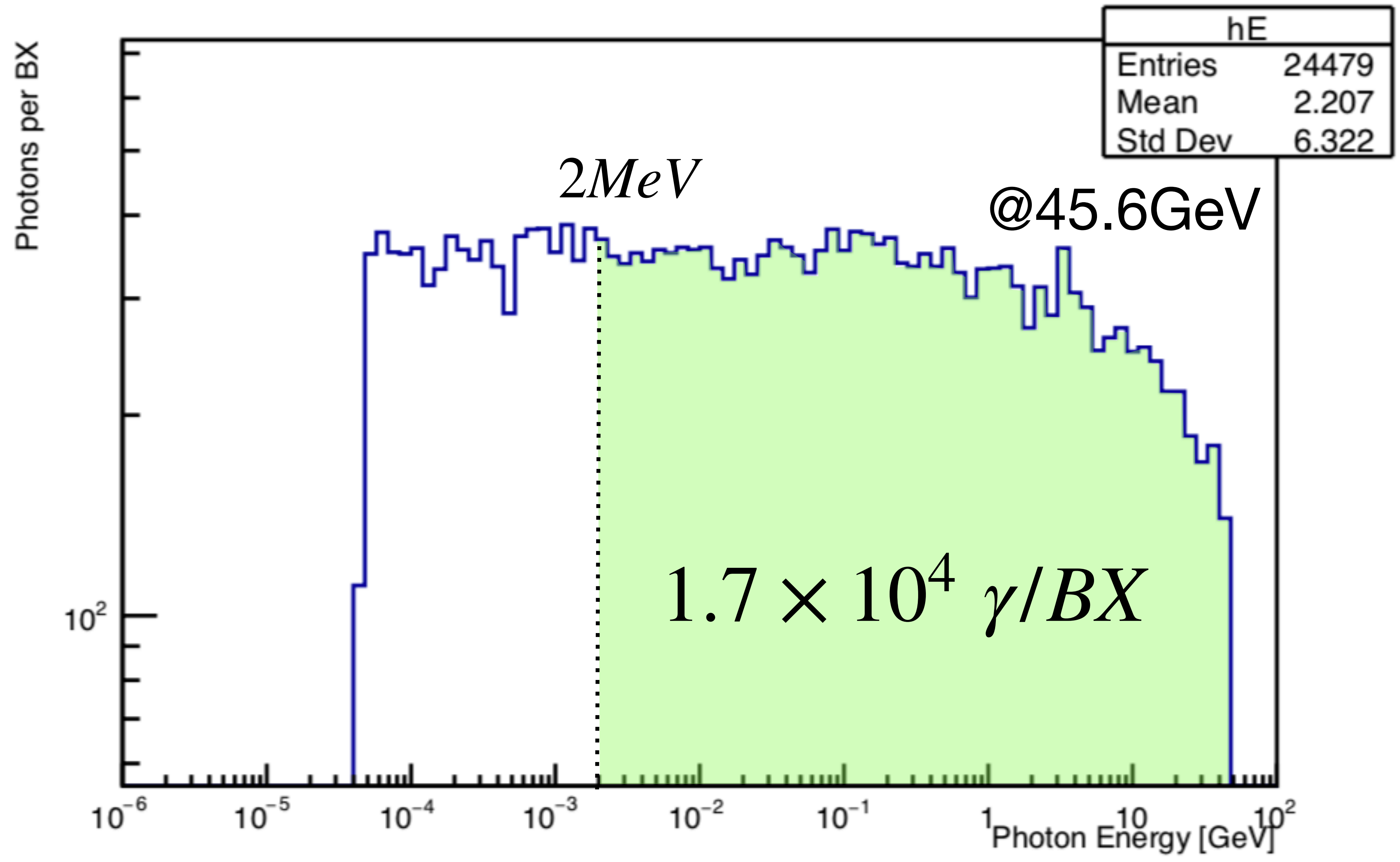
The photon angular emission is **proportional to the vertical offset** between the two beams for small offsets, while it saturates when the beams are several sigmas apart.

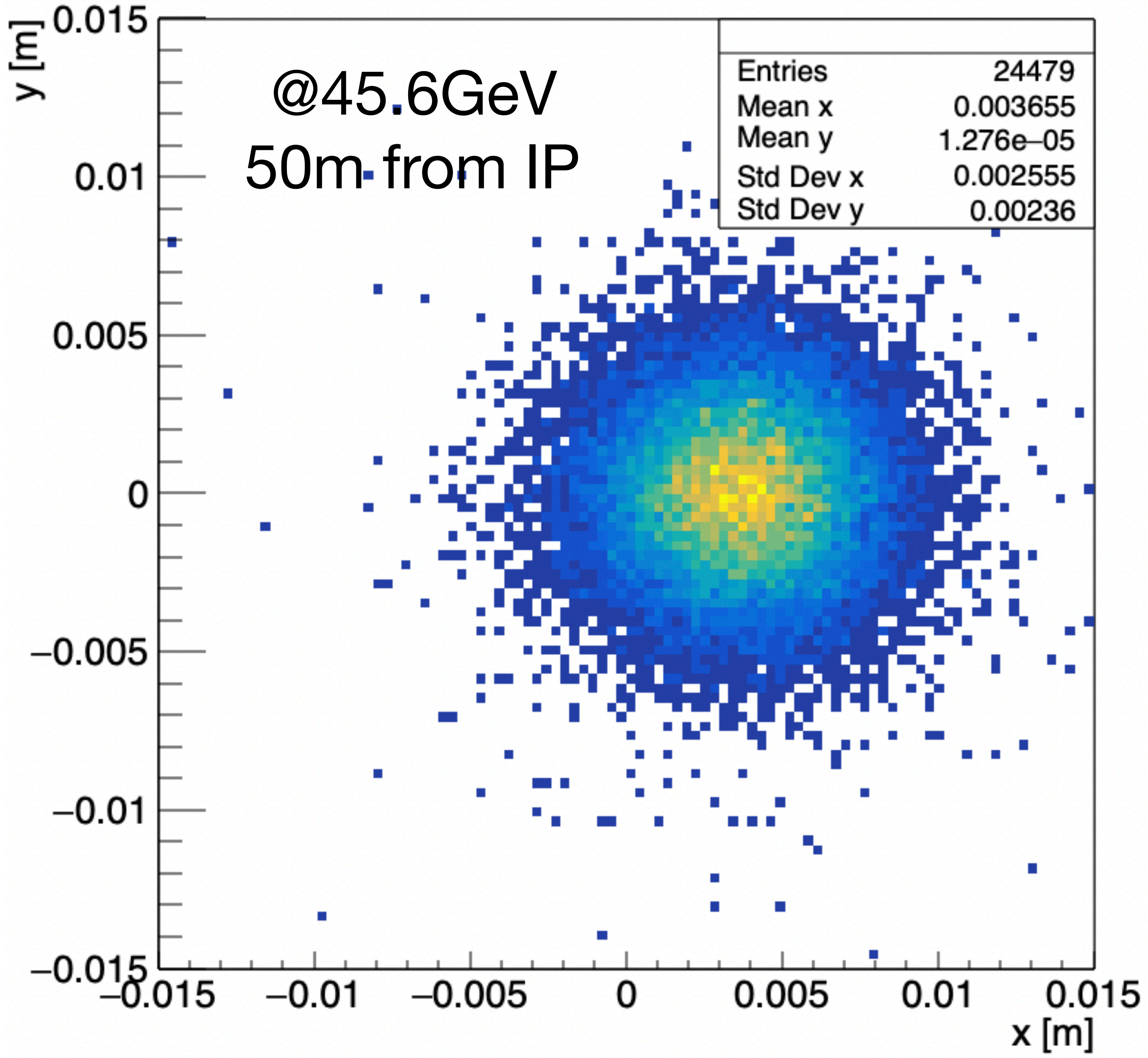


Radiative Bhabha

BBBrem generates single photon events considering head-on on-axis collisions.

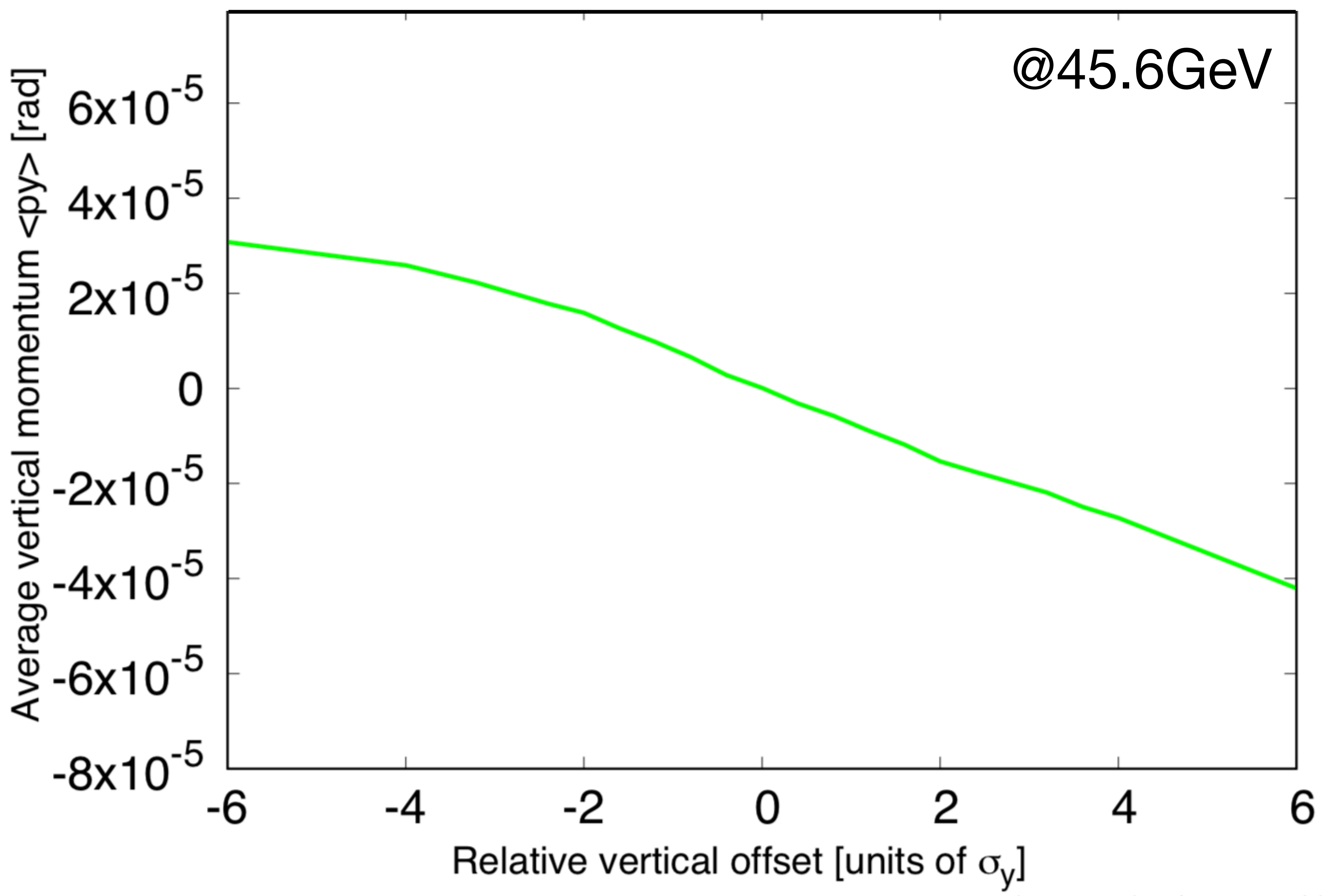
These events are used as inputs in **GuineaPig++** which will boost them in the correct frame (considering also the crossing angle) and smear them along the nominal particles distribution during the step-by-step tracking.





Also in this case the vertical kick depends **linearly** from the offset between the beams.

Radiative Bhabha radiation has a **lower flux** w.r.t. the beamstrahlung, but the photons can reach **much higher energies**.



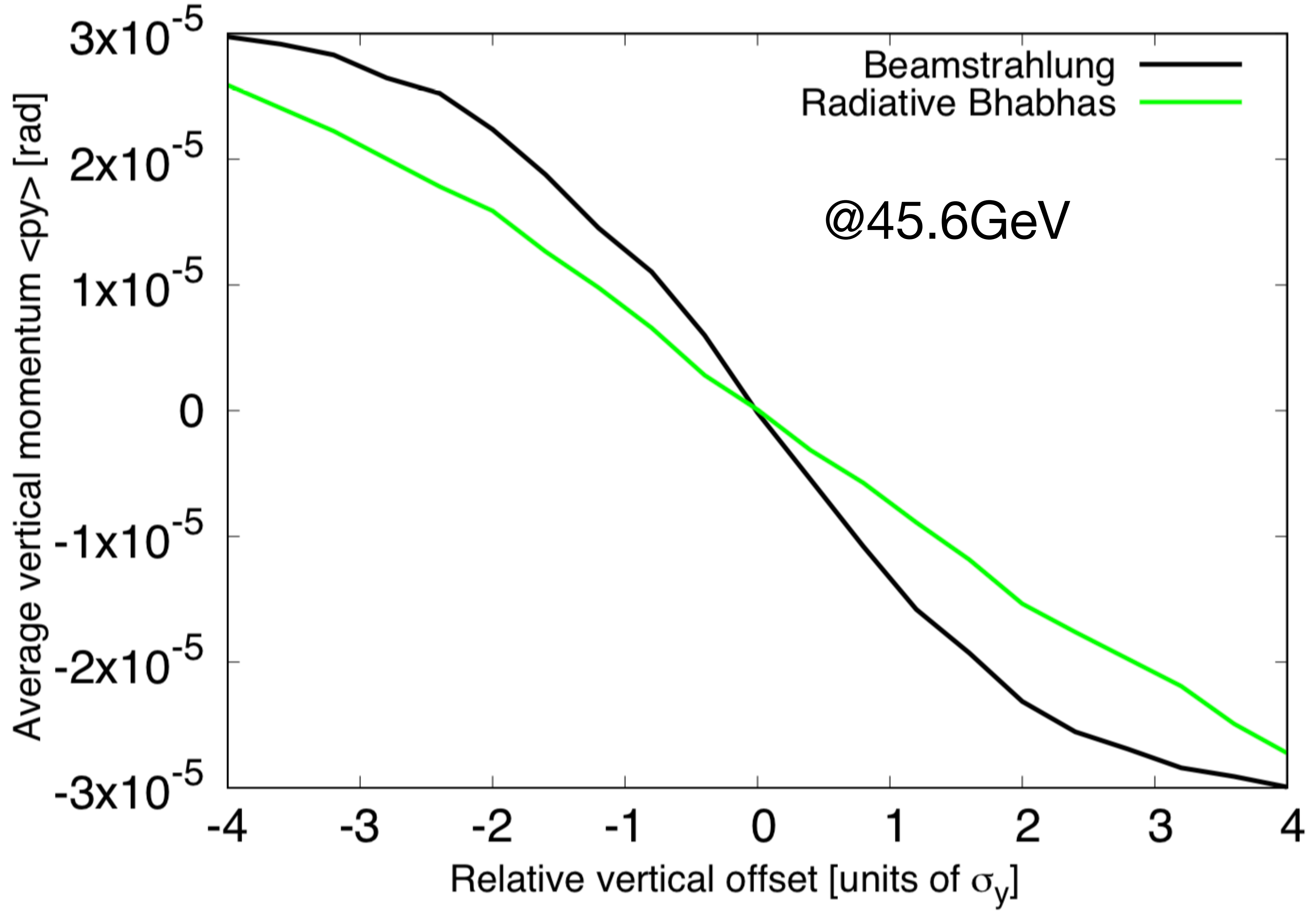
BBBREM - Monte Carlo simulation of radiative Bhabha scattering in the very forward direction - R.Kleiss, H.Burkhardt - CERN SL/94-03 (OP)

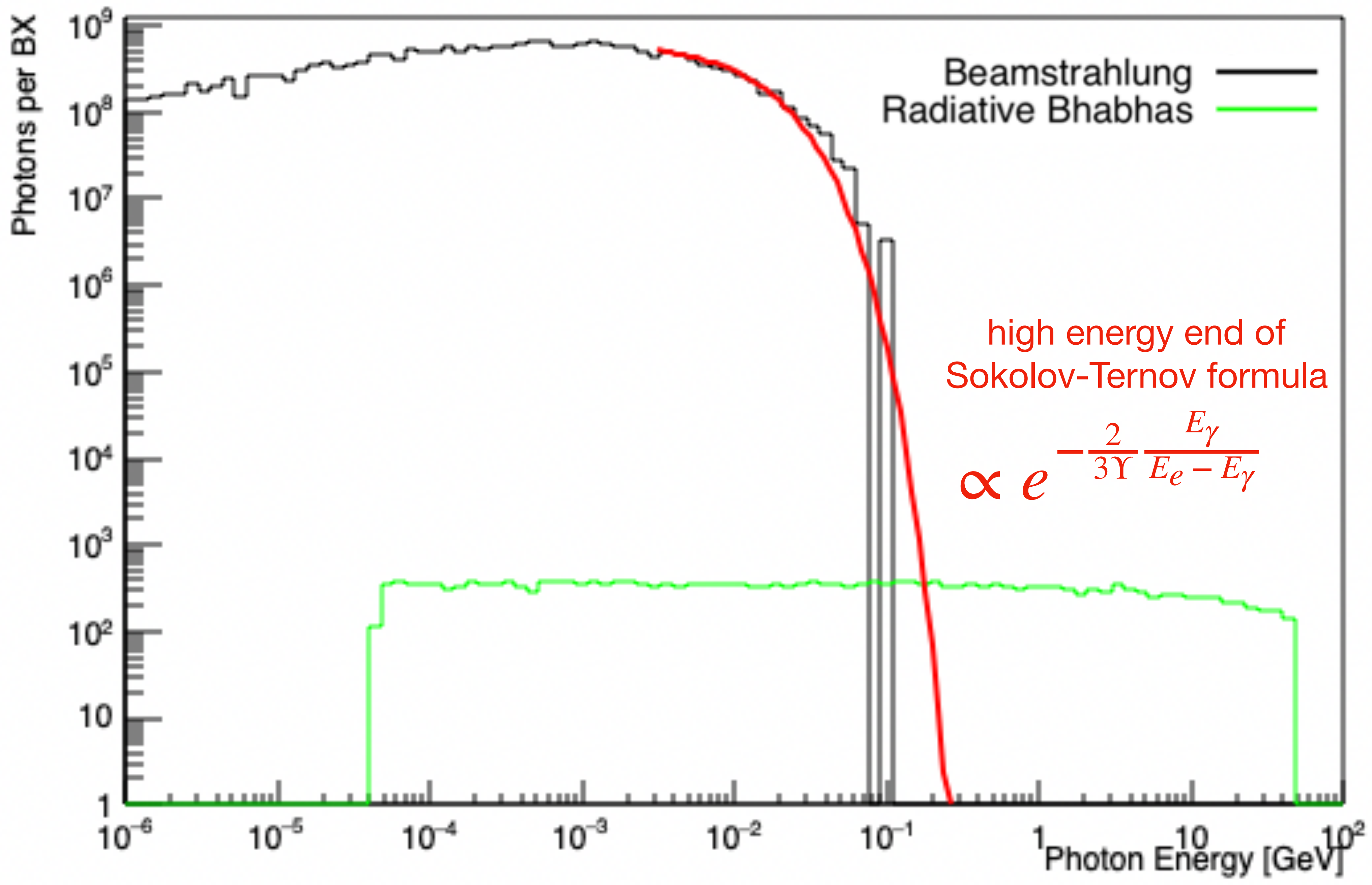
Comparison

For both sources the photon average vertical momentum distribution is **directly proportional** to the beam-beam offset up to $\pm 2\sigma_y$ and in this range the radiation angle varies of $\pm 20\mu rad$

The energy spectra of these two sources differ in both **intensity** and **energy range**: beamstrahlung is much more intense, but radiative bhabhas produce a significant number of photons per BX even near the nominal beam energy.

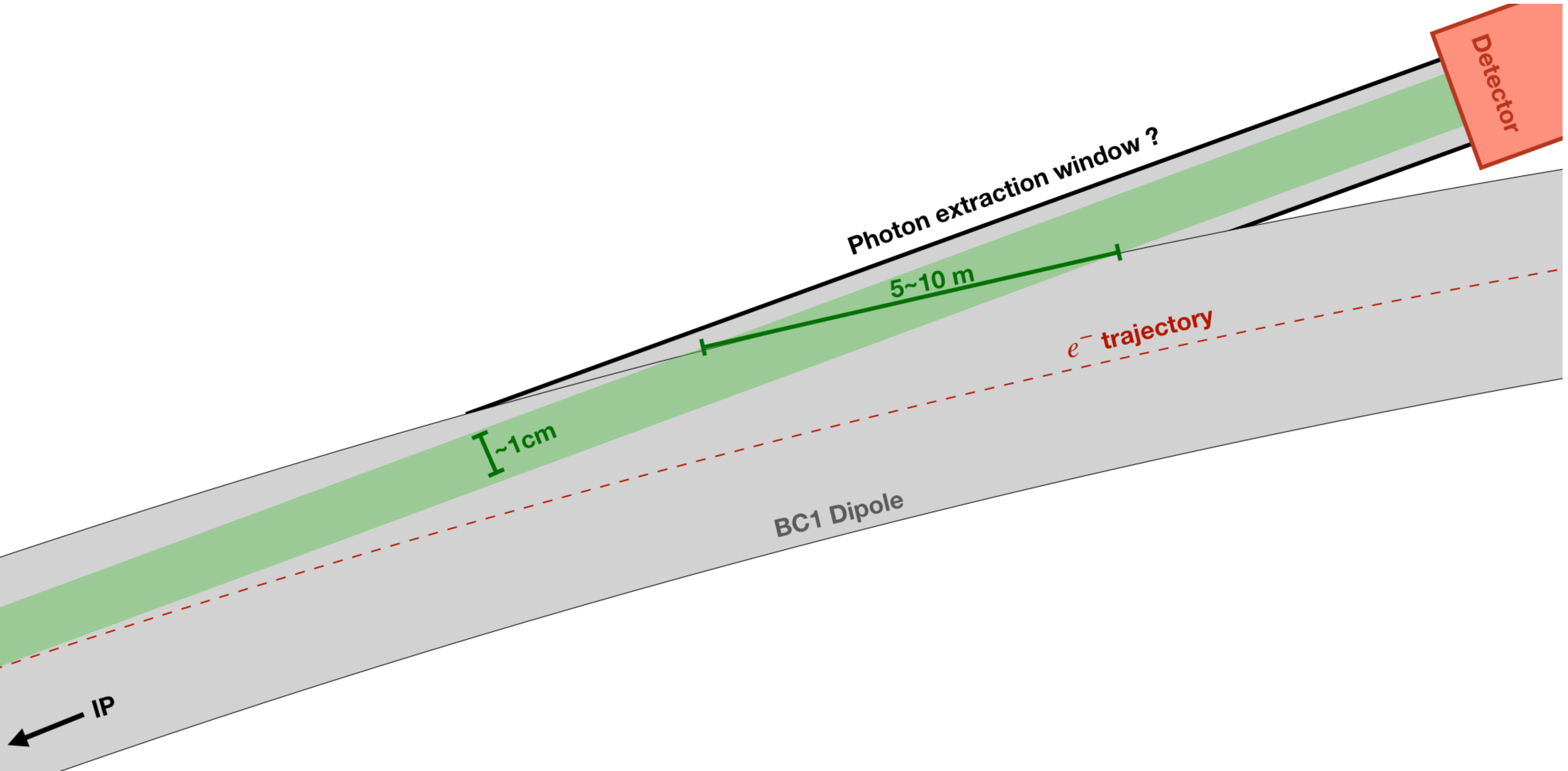
The choice of which of these sources to use will depend on the backgrounds and on the detector characteristics.

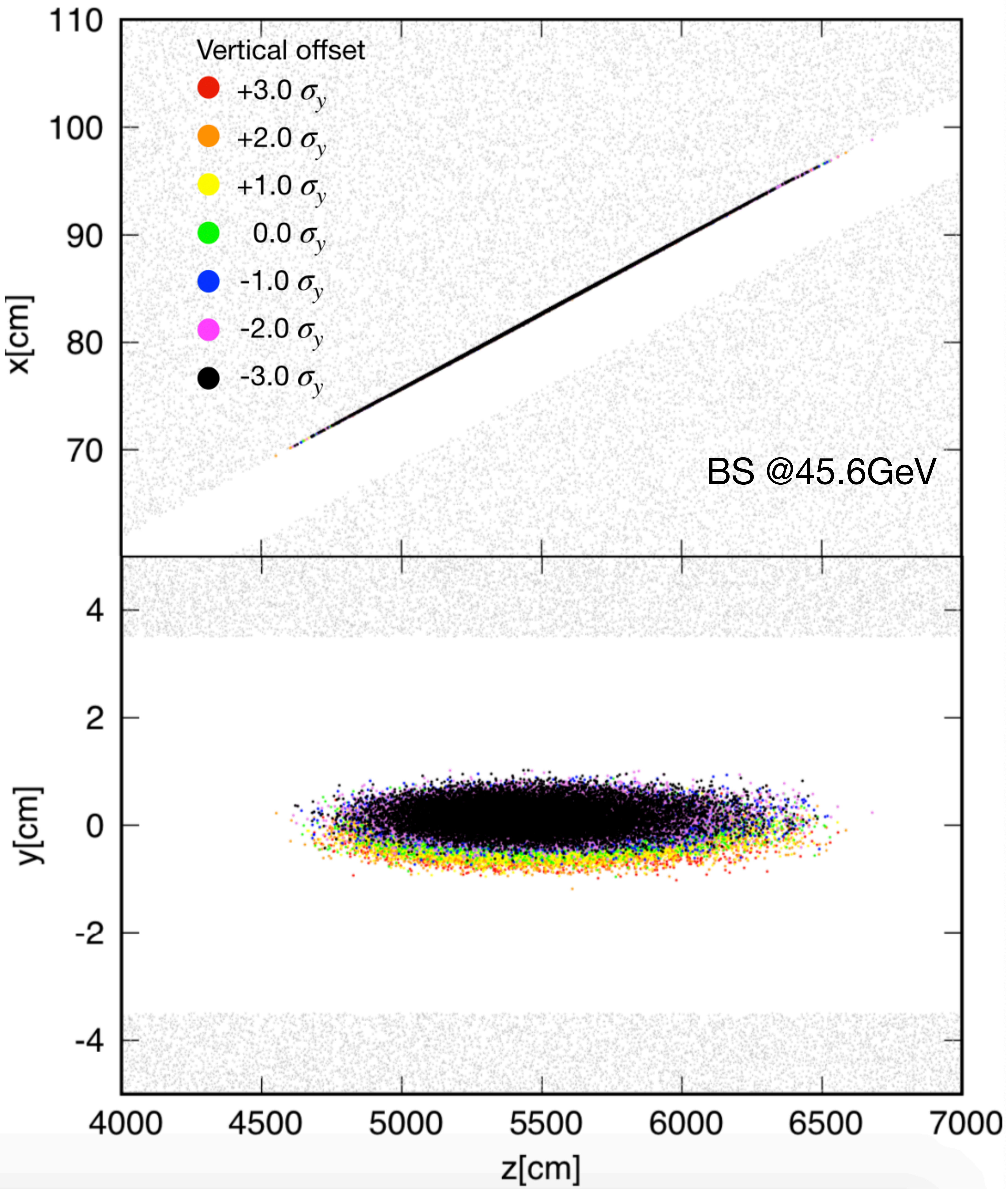




The so produced radiation was **tracked** in the GDML description of the beam pipe, and will hit the beam pipe at the end of the **first downstream dipole** BC1.

While the spot size is ~1x1cm², due to the very small impinging angle on the beam pipe wall (~1mrad) the region hit by the photons is **several meters long** on the longitudinal dimension, so this should be taken in consideration when designing the photon extraction window.

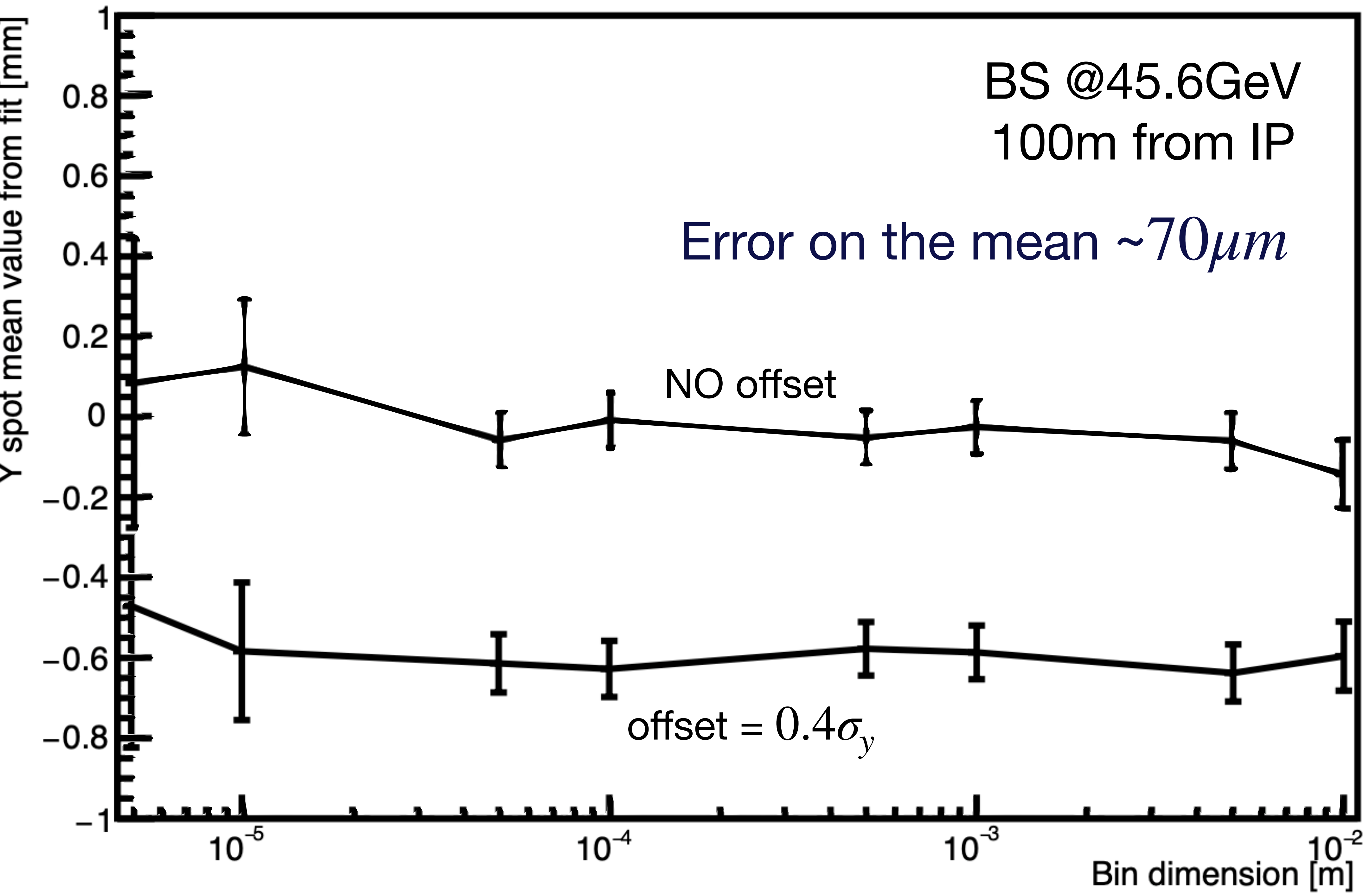


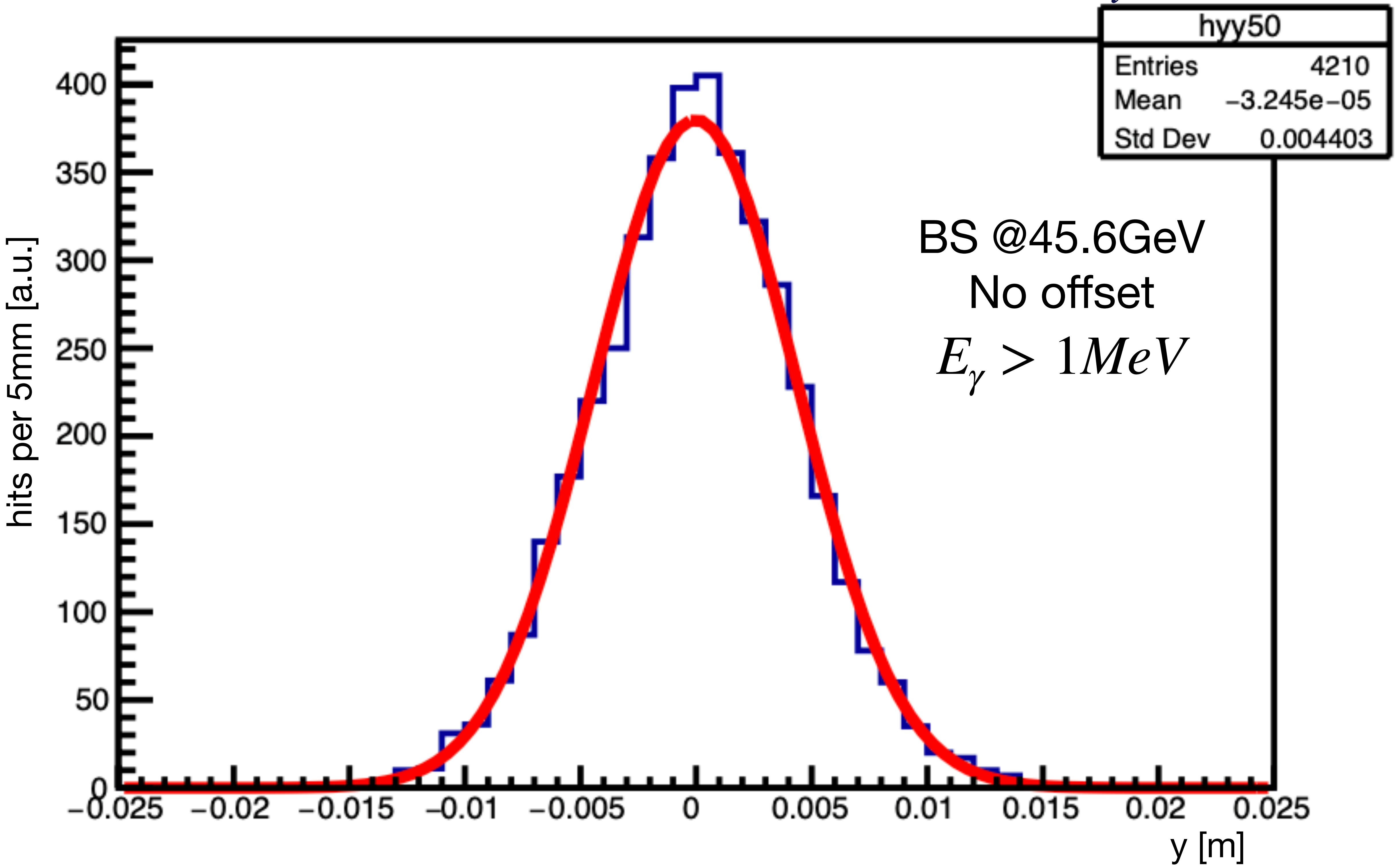


Required resolution estimate

A **gaussian fit** on the hits-per-bin distribution on the vertical axis showed that even with only ~4000 hits (macroparticles from the simulation), a spatial resolution of O(mm) is enough to have an error on the mean of $70\mu m$ (at 100m from the IP), which should be sufficient to discriminate vertical offsets of O($5\ \%\ \sigma_y$).

The error on the mean scales with $\sigma/\sqrt{N}$, so supposing an ideal detector with efficiency=1 and the $\sim 5 \times 10^9\ \gamma/BX$ coming from BS, the error could go down to $65\ nm$ (which at 100m corresponds to an offset of O($0.005\ \%\ \sigma_y$)



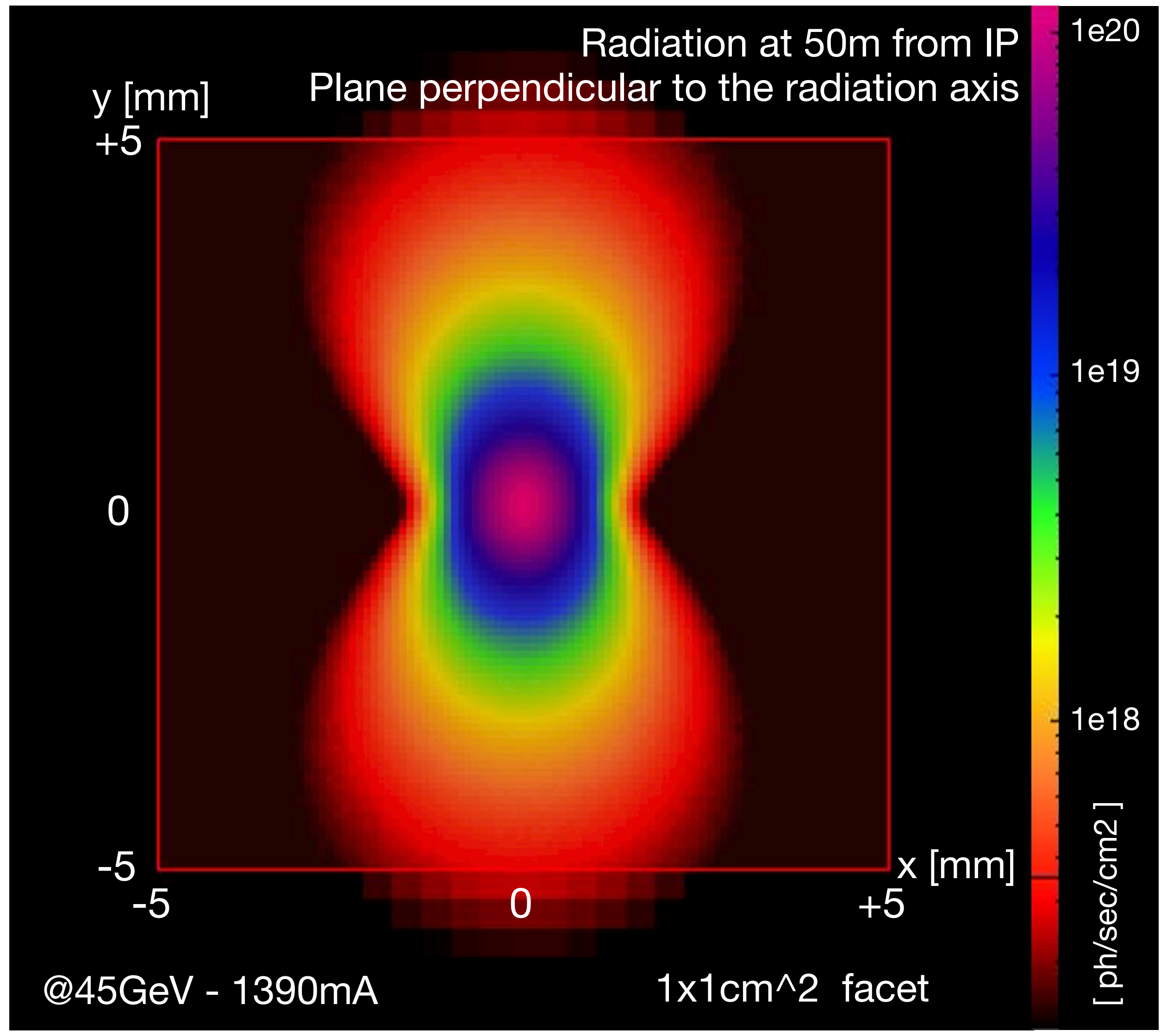


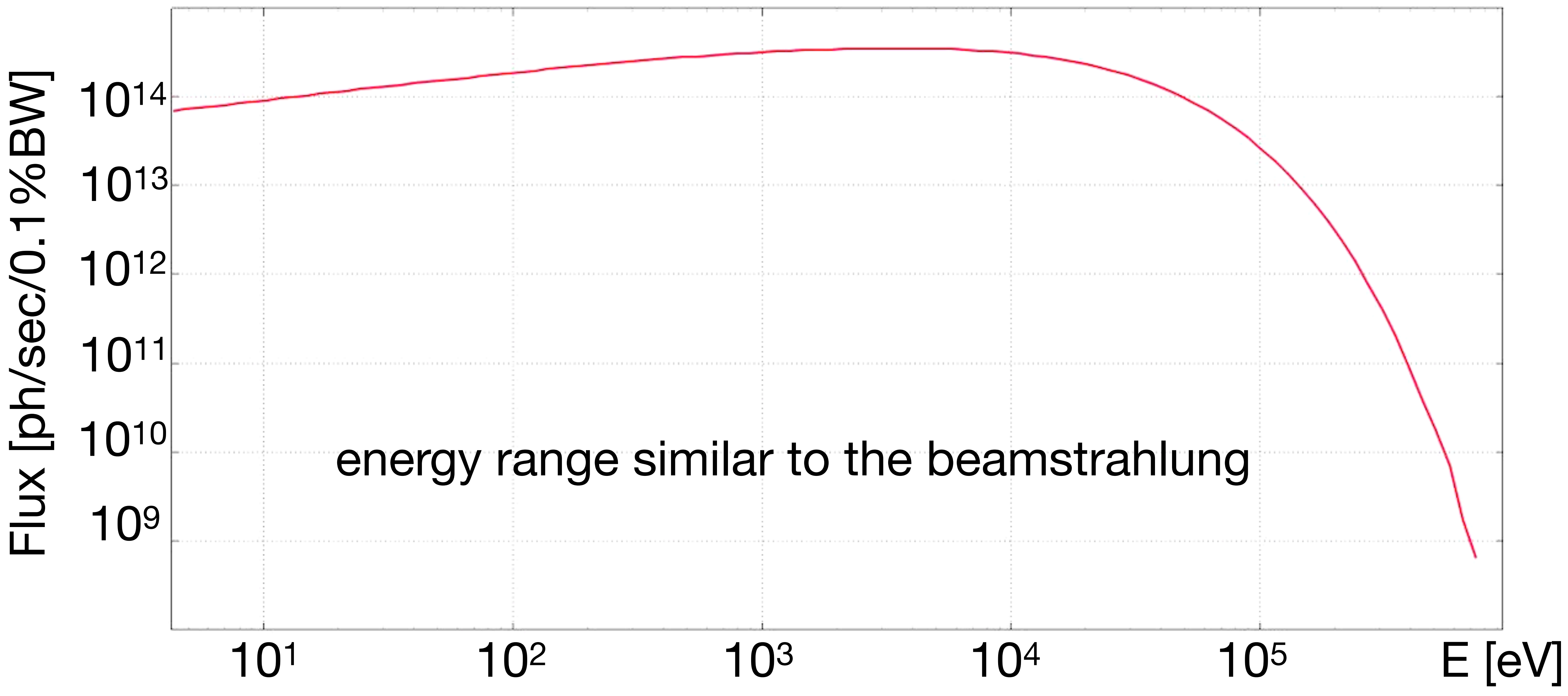
Backgrounds: Synchrotron Radiation

SR simulations courtesy of R. Kersevan

Synchrotron radiation produced by the **final focusing quadrupoles** constitutes a background source for this detector.

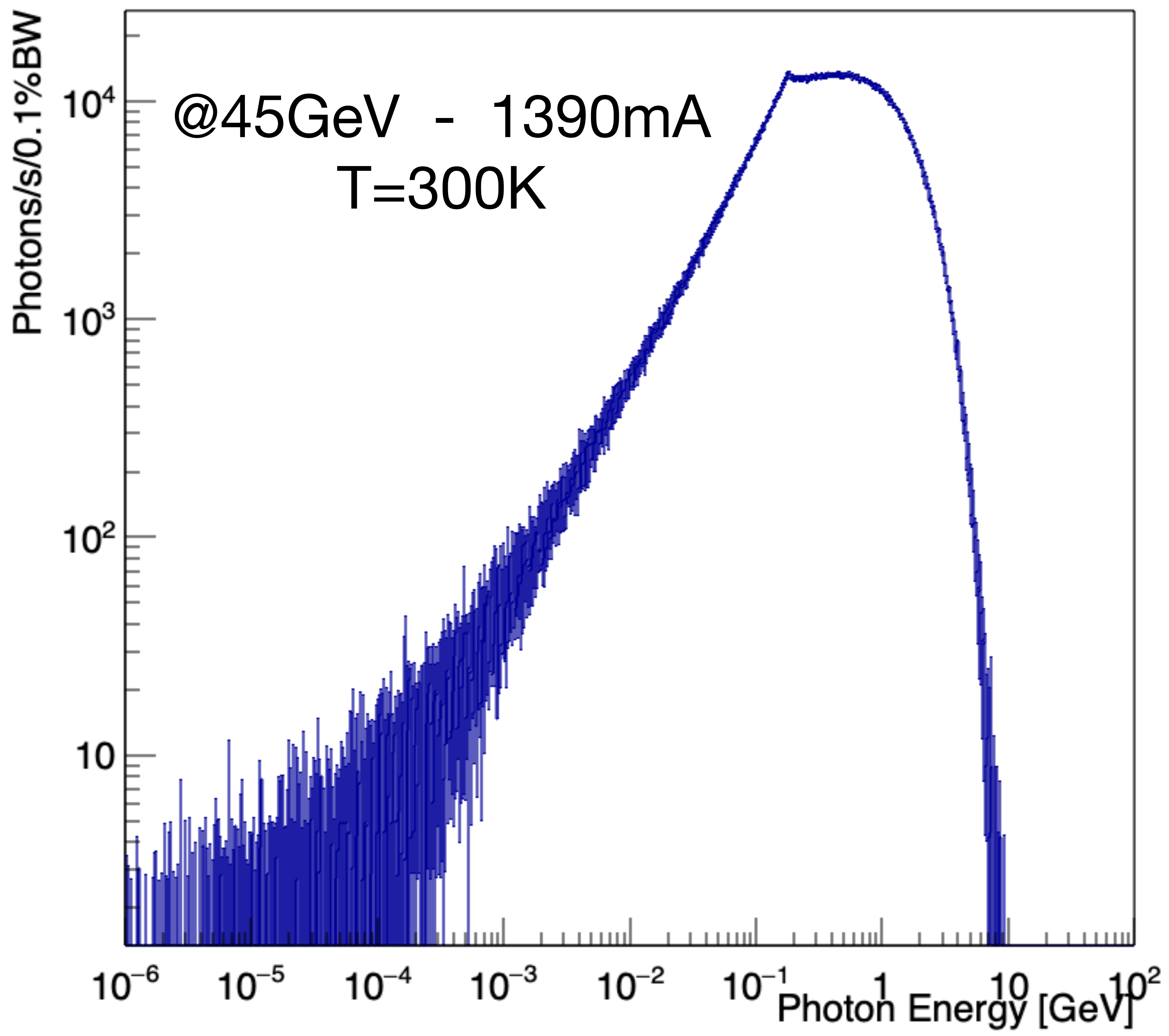
SYNRAD+ has been used to simulate the flux through a 1x1cm^2 facet orthogonal to the photon beam axis placed 50m downstream. The dominant contribution to this radiation comes from the innermost final focusing quadrupoles.

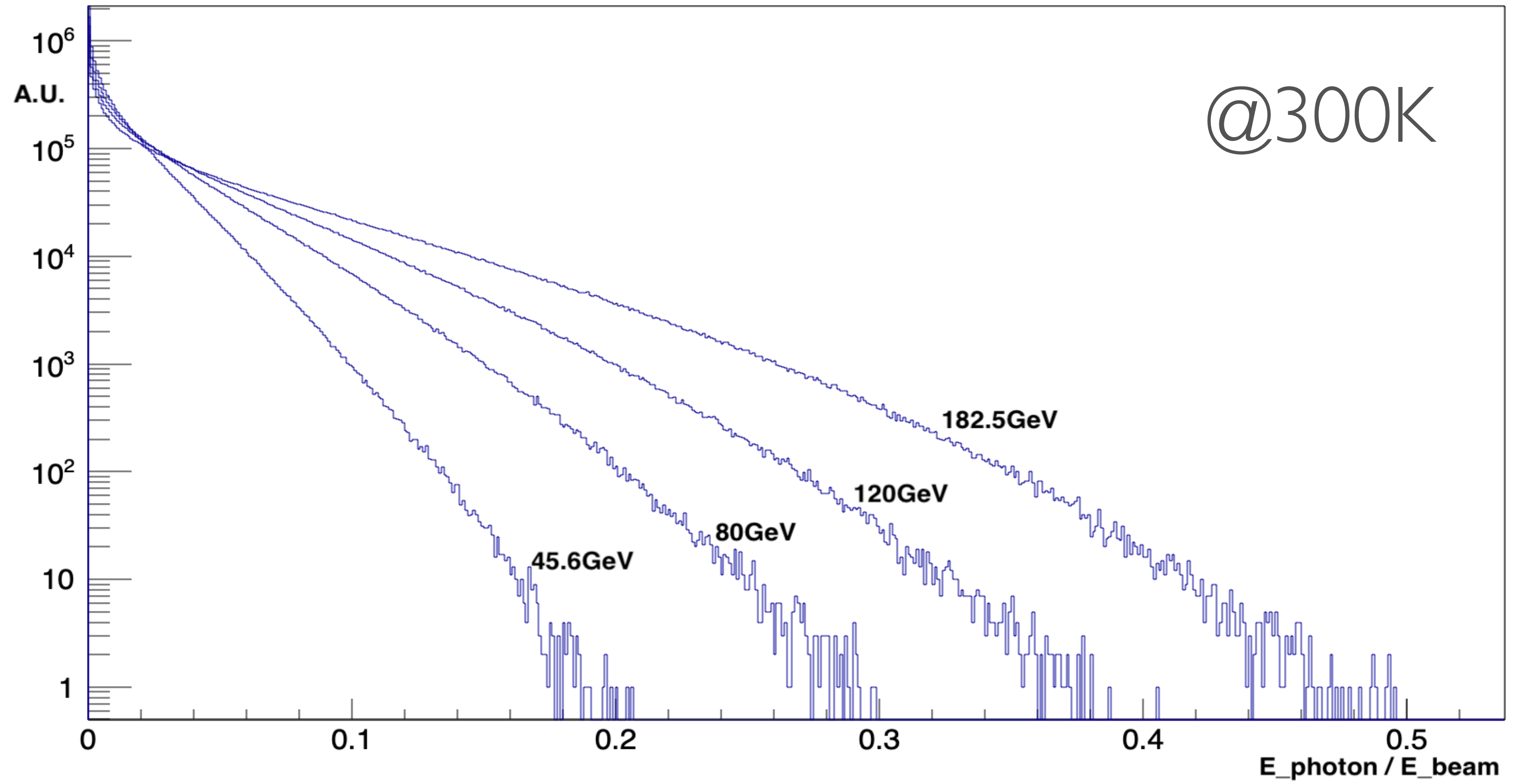




	Flux [10^18 ph/sec]	Power [kW]
Total	2.31	2.57
QC1L	1.04	1.22
QC1R	1.12	1.33
QC2L	0.06	0.01
QC2R	0.09	0.01

Backgrounds: Compton Scattering on Thermal Photons





Thermal photons can gain energy via Compton scattering with the electrons of the beam, according to

$$\frac{d\sigma}{dy} = \frac{2\sigma_0}{x}\left[\frac{1}{1-y} + 1 - y - \frac{4y}{x(1-y)}\left(1 - \frac{y}{x(1-y)}\right)\right]$$

$$x = \frac{4E\omega_0 cos^2(\alpha/2)}{(mc^2)^2}$$

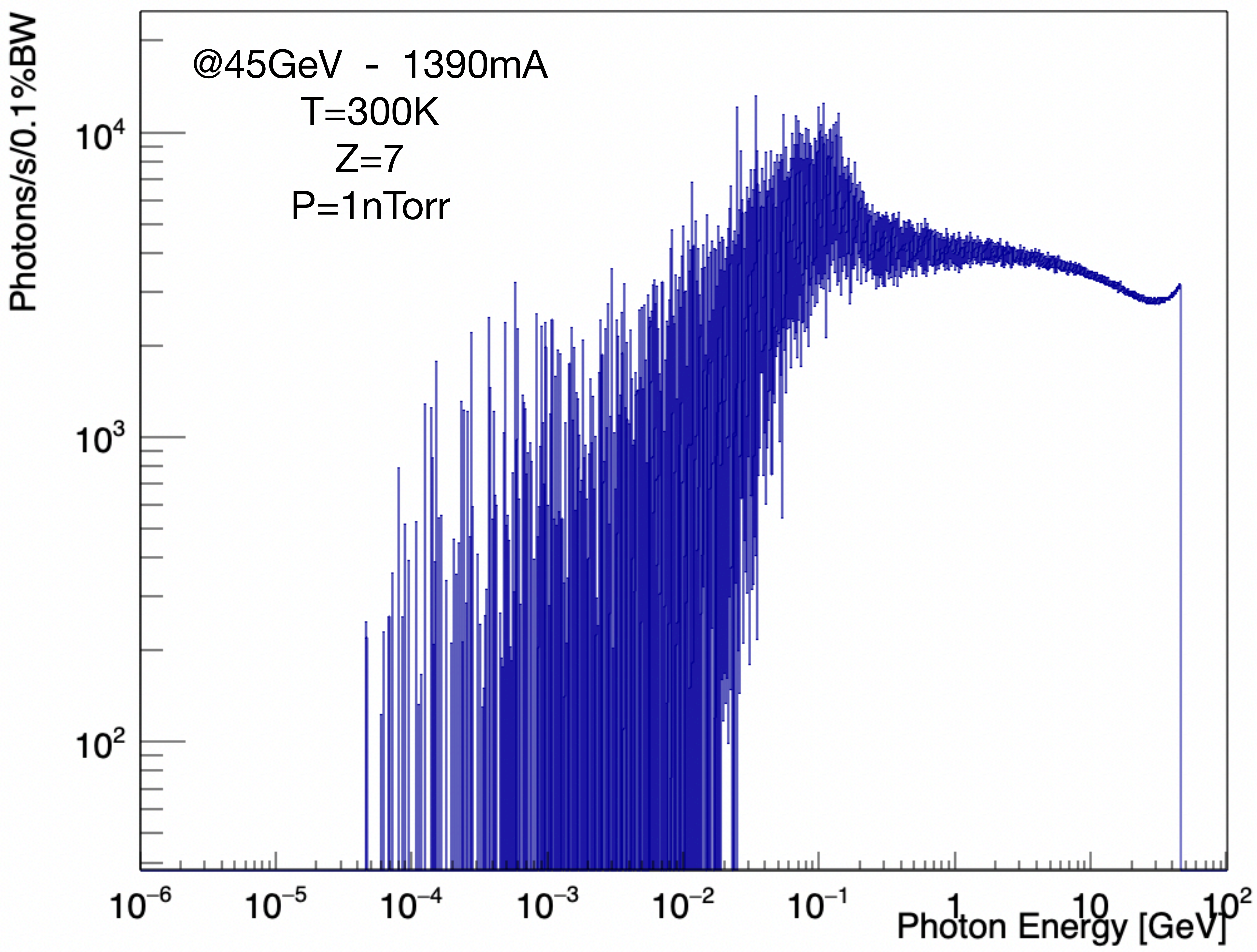
$$y = \omega'/E$$

V. I. Telnov - NIM A260 (1987) 304-308
H. Burkhardt - SL/Note 93-73 (OP)

The photon flux coming from this source has been simulated using a custom generator considering a temperature of 300K.

This photons are emitted in the direction of the beam and can reach energies **up to few GeV**, so this might constitute a source of background for the Radiative Bhabhas.

Backgrounds: Inelastic Beam Gas Scattering

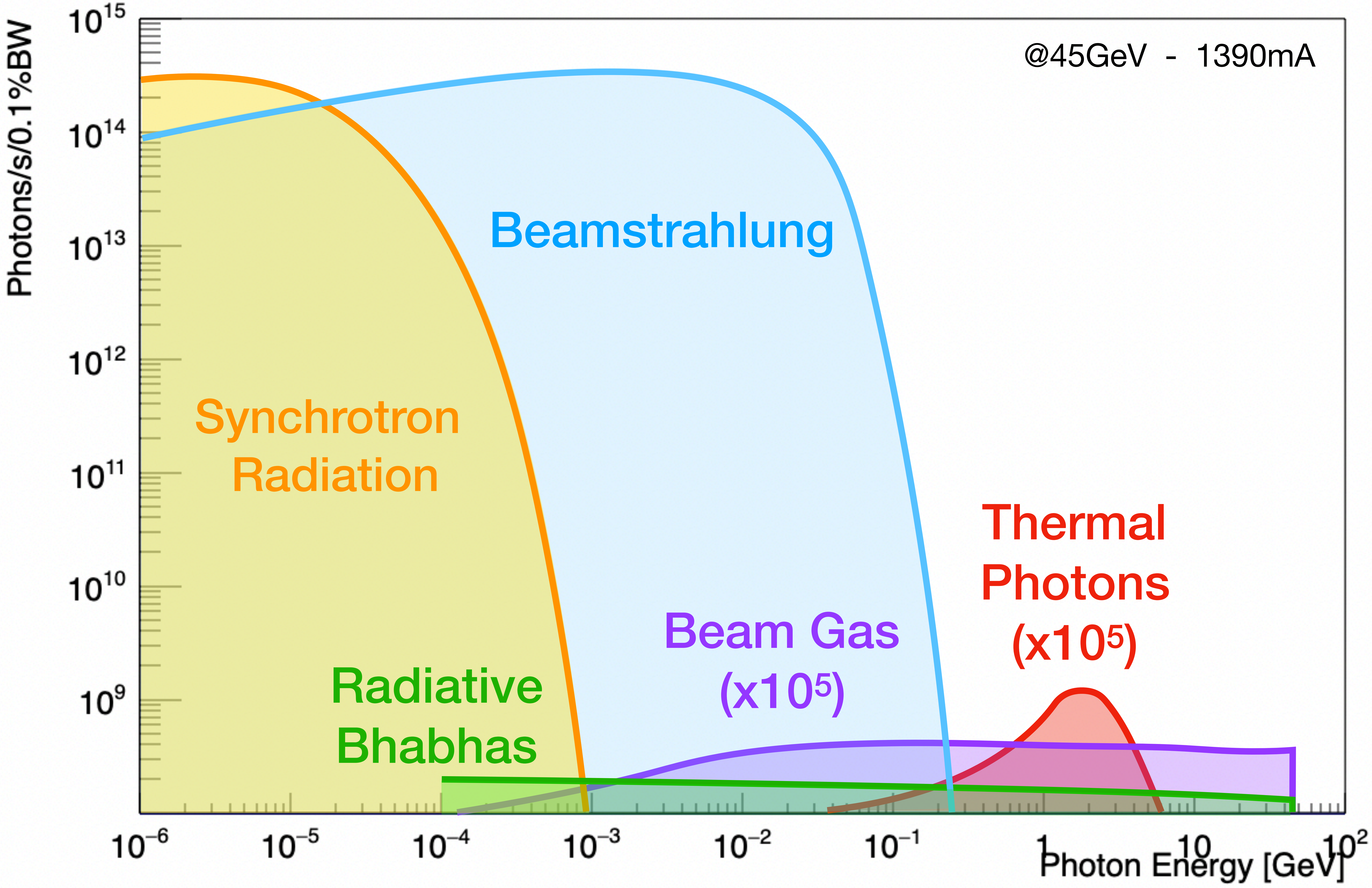


Also the Bremsstrahlung radiation produced by the **inelastic scattering** of the beam particles with **residual gas** in the beam pipe constitutes an unavoidable source of background for this monitor.

$$\frac{d\sigma}{dy} = \frac{16\alpha r_e^2}{3} Z(Z+1)\frac{1}{y}(1 - y - 0.75y^2) log\left(\frac{184.15}{Z^{1/3}}\right)$$

This radiation can reach up to the nominal beam energy, falling therefore in the same range of the radiative bhabha emissions.

Signals vs Background sources



The comparison of the photon flux for the different sources shows that **beamstrahlung** might be a viable signal in the **multi-MeV range**, as its spectrum extends further compared to the synchrotron radiation.

In the **multi-GeV range** instead, **radiative bhabhas** might be detectable, as the flux coming from the backgrounds (i.e. beamgas and thermal photons) is several order of magnitudes smaller.

Both of these options of course require dedicated studies of both the detector and the shielding of the unwanted radiation.

Conclusions and plans

- First feasibility studies for the IP-generated radiation monitor for center-of-mass energy measurements have been presented
- Both Beamstrahlung and Radiative Bhabha radiation show a correlation between the photon emission angle and the vertical offset between the two beams at the IP
- First estimates of the possible backgrounds for this detector (i.e. synchrotron radiation, Compton scattering on thermal photons and inelastic beam gas scattering) have been performed

- Dedicated studies on the detector design and on the background shielding should be performed in order to decide which signal source is the most viable

THANK YOU FOR YOUR ATTENTION

BACK-UPS

Energy calibration via Resonant Depolarisation

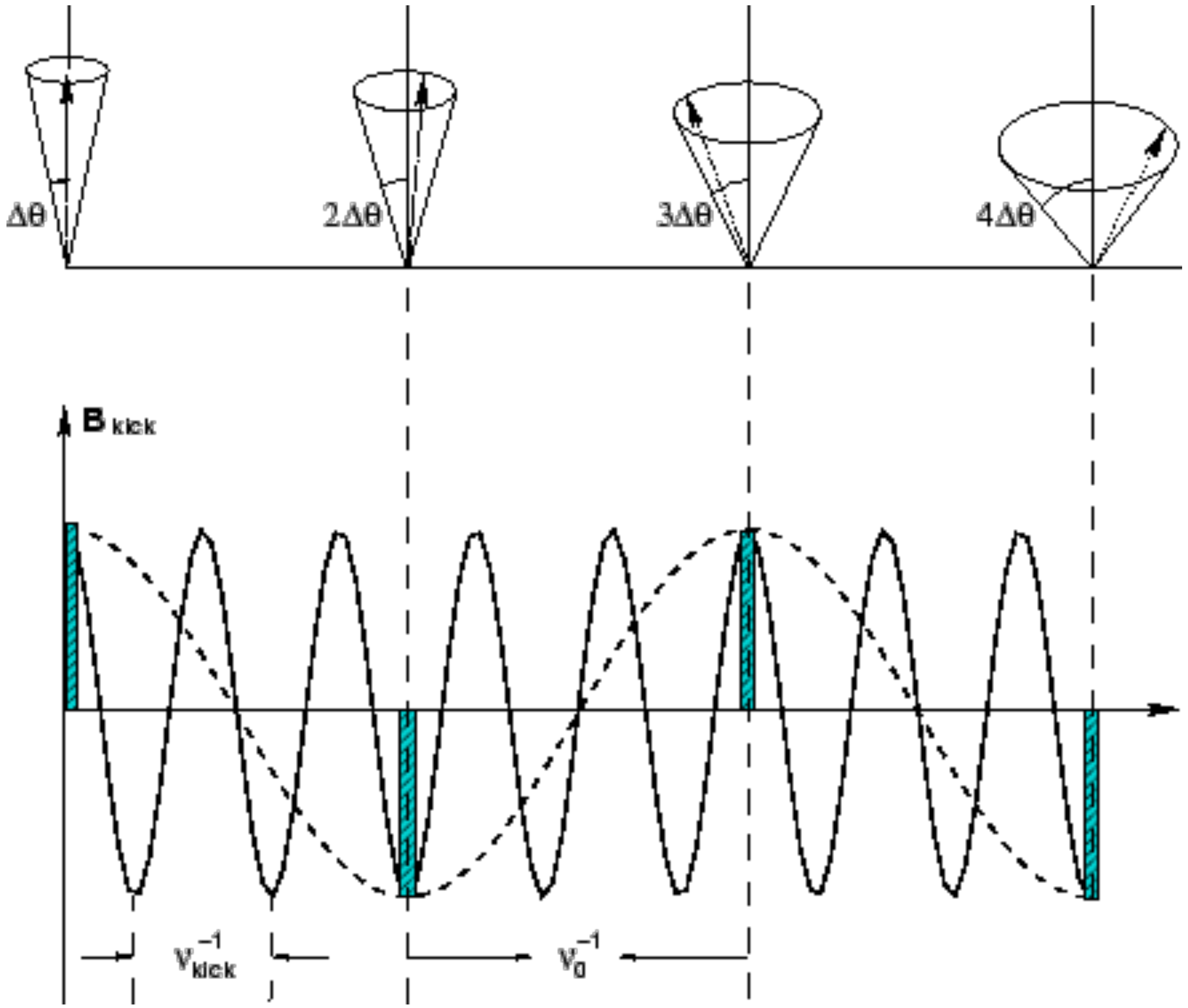
The spin tune is directly related to the beam energy

$$\nu_s = \frac{g-2}{2}\frac{E}{m_e c^2}$$

An oscillating radial field from an RF-magnet is used for the resonant measurement of the spin precession frequency.

If the perturbation from the RF-magnet is in phase with the spin precession, the spin rotations about the radial direction add up coherently from turn to turn, achieving complete depolarisation or spin-flip.

$$f_{RF} = (k \pm [\nu_s])f_{rev} \quad , \nu_s = N + [\nu_s]$$



Energy calibration via Resonant Depolarisation

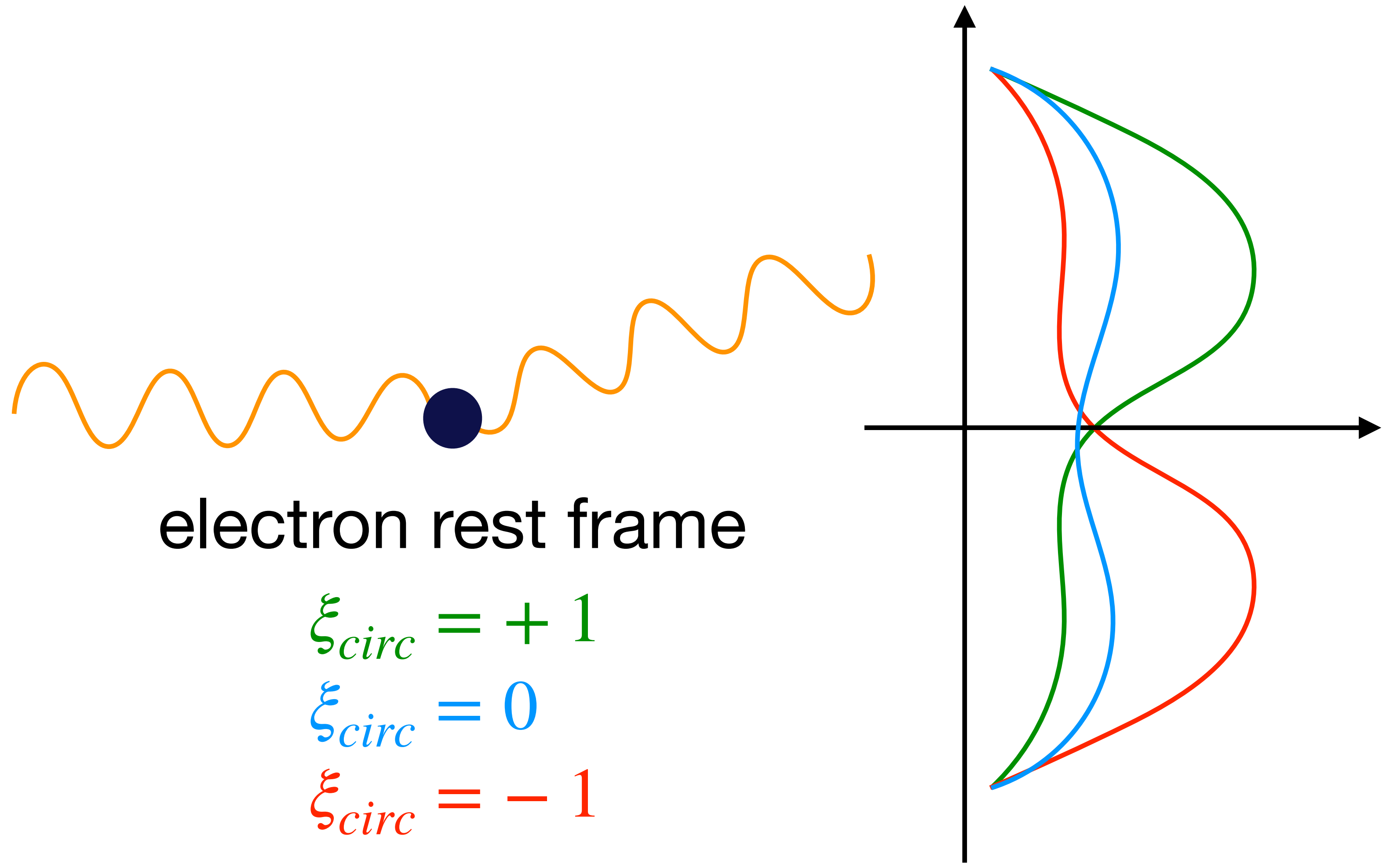
Laser Polarimeter is based on spin-dependent Compton scattering of circularly polarised photons on polarised charged particles.

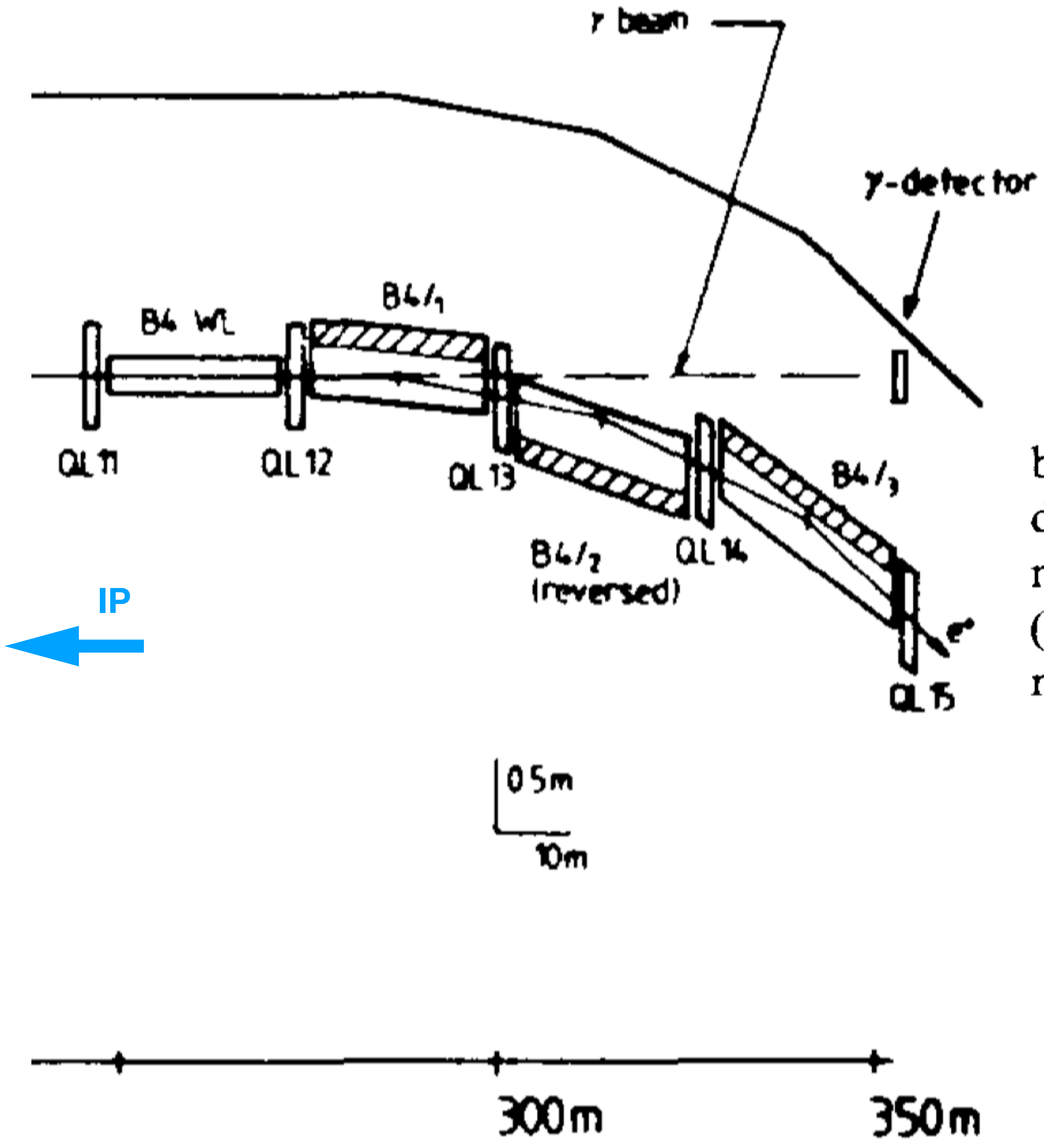
Due to the asymmetry properties of the Scattering Cross Section with respect to the helicity of the incoming photons the study of the spatial distribution of the backscattered photons under reversal of the photon helicity provides information on the beam polarisation.

$$\frac{d\sigma_c(\vec{\xi}, \vec{P}_e)}{d\Omega} = \frac{1}{2}\left(r_e \frac{k'}{k'_0}\right)^2 \left[\Phi_0 + \Phi_1(\xi_{lin}) + \Phi_2(\xi_{circ}, \vec{P}_e)\right]$$

$$A = \frac{[d\sigma/d\Omega]_R - [d\sigma/d\Omega]_L}{[d\sigma/d\Omega]_R + [d\sigma/d\Omega]_L} = \frac{\Phi_2(\xi_{circ}, \vec{P}_e)}{\Phi_0}$$

Laser IR pulses are shined on the beam alternating the photon helicity, and the backscattered Compton photons are detected to measure this asymmetry.





Fast measurement of luminosity at LEP by detecting the single bremsstrahlung photons

C. Bini, G. De Zorzi, G. Diambrini Palazzi, G. Di Cosimo, A. Di Domenico, P. Gauzzi and D. Zanello

Dipartimento di Fisica, Università "La Sapienza", Roma, Italy, and INFN Sezione di Roma, Italy

In order to minimize the absorbing material traversed by SB photons, some modifications of the machine were done near the arc: (i) the vacuum pipe inside the B4/1 magnet has a thin window of 2 cm (vertical) × 5 cm (horizontal); (ii) the coils of the QL13 quadrupole are modified; (iii) the B4/2 dipole is reversed.

Beamstrahlung radiation

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

The outcome of this simulations shows that the beamstrahlung photon beam produced at both beam energies is **very intense**. To study the effect of this radiation on the beam pipe, I have tracked the photons in the pipe and evaluated the interaction probability, to give an estimate on the absorbed power.

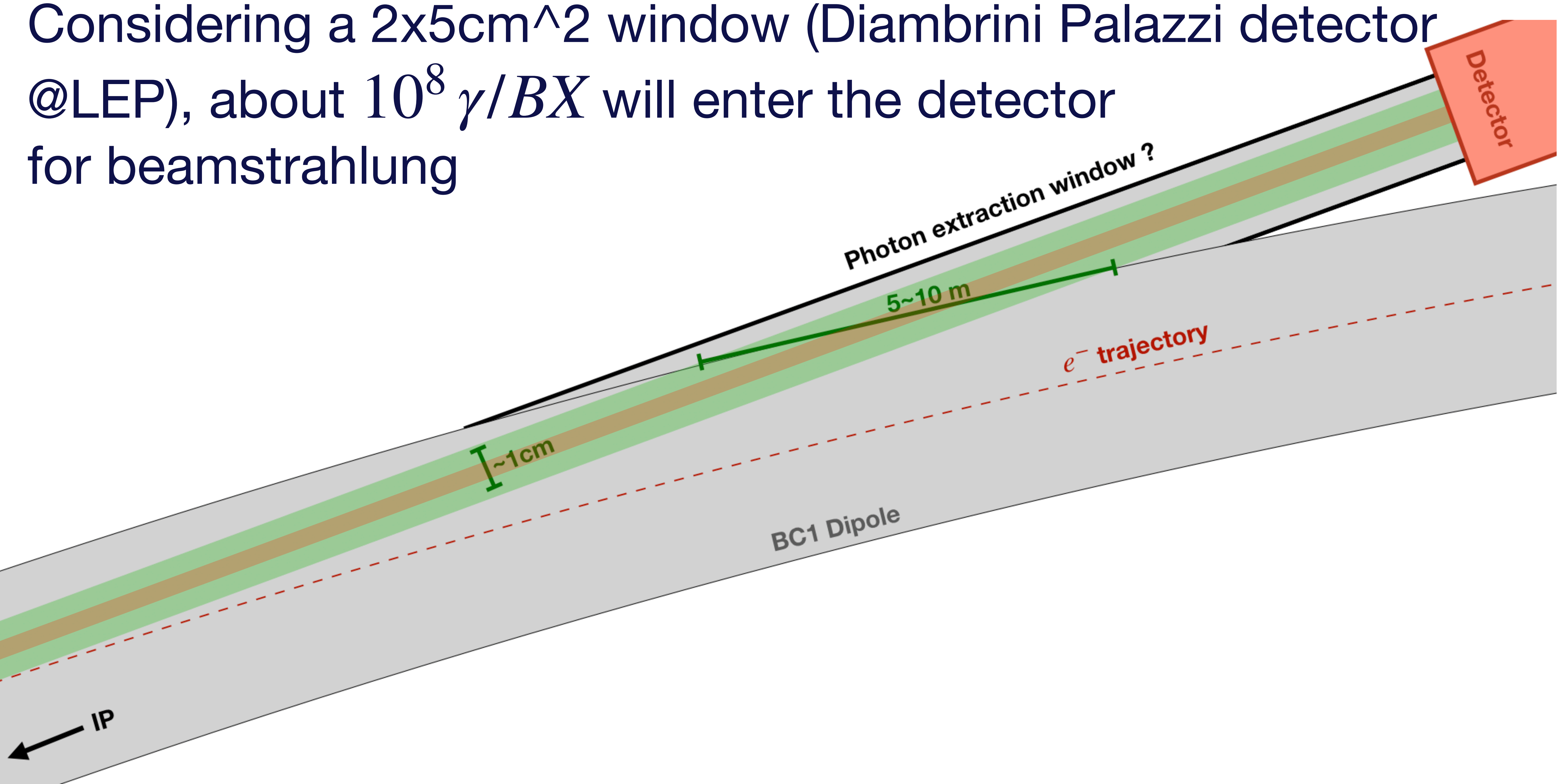
Bunch Energy [GeV]	Beamstrahlung Parameter Υ	Photons per particle n_γ	Average photon energy [MeV] $< E_\gamma >$	Total photon beam power [kW]
45.6	1,81 x 10^{-4}	0,148	2	390
182.5	9,12 x 10^{-4}	0,242	67	88

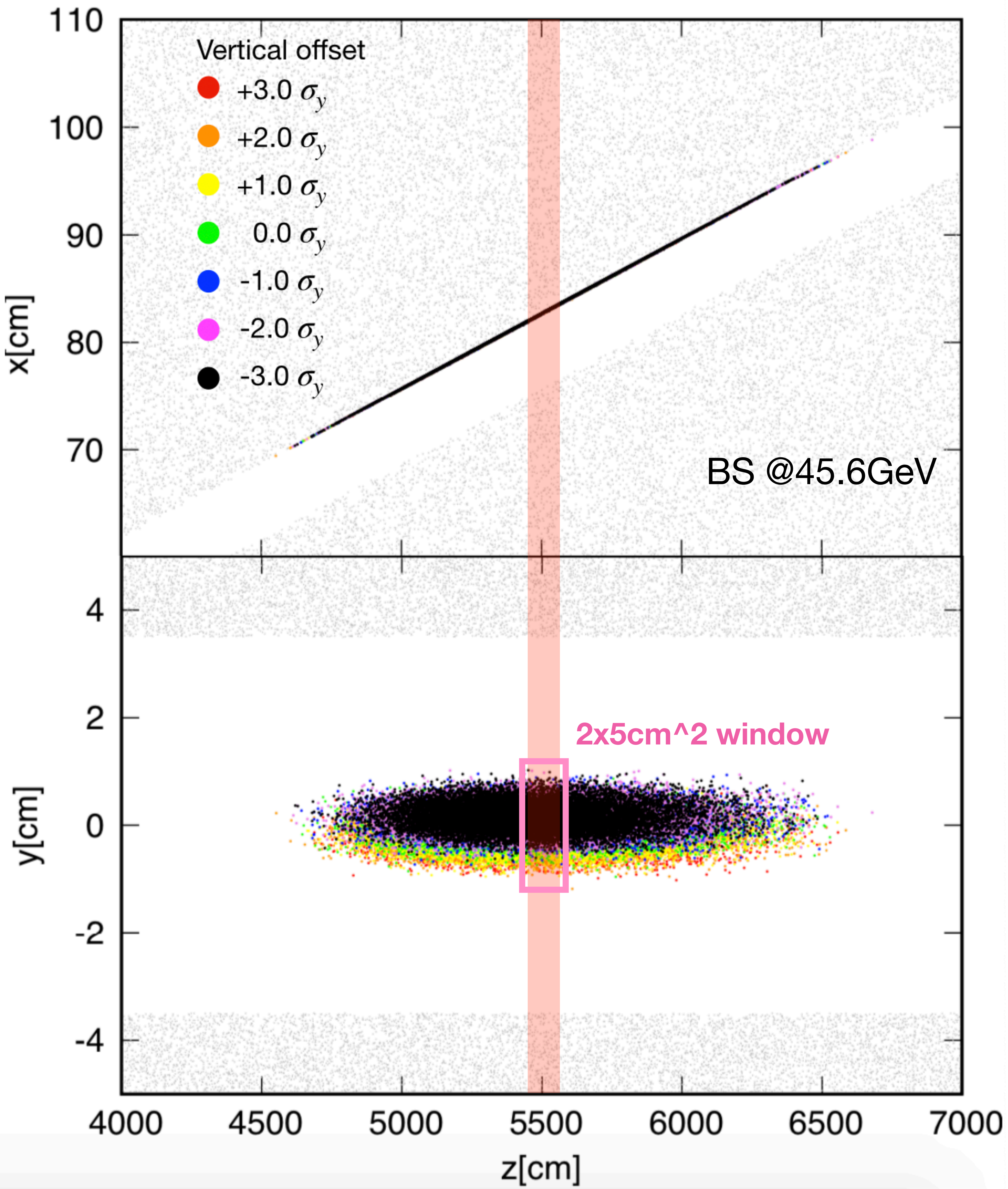
Results for the Z are in **agreement** with what previously presented by H. Burkhardt (FCC-ee MDI meeting #24 2/12/2019)

The so produced radiation was **tracked** in the GDML description of the beam pipe, and will hit the beam pipe at the end of the first downstream dipole BC1.

While the spot size on the vertical axis is ~1cm, due to the very small impinging angle on the beam pipe wall (~1mrad) the region hit by the photons is several meters long on the longitudinal dimension.

Considering a 2x5cm^2 window (Diambrini Palazzi detector @LEP), about $10^8\,\gamma/BX$ will enter the detector for beamstrahlung





Luminosity monitor at SuperKEKB

Two fast luminosity monitors are used at SuperKEKB to detect **electrons** which lost energy due to radiative bhabhas. The two detectors are LumiBelle2 which uses diamond sensors and ZDLM which is a Cherenkov detector plus a scintillator. Both are placed outside the beam pipe and show the same efficiency.

An example of application is for beam orbit offset scan with low bunch current, where the ECL doesn't get enough statistics.

Could this approach be viable also at FCCee?

Required resolution estimate

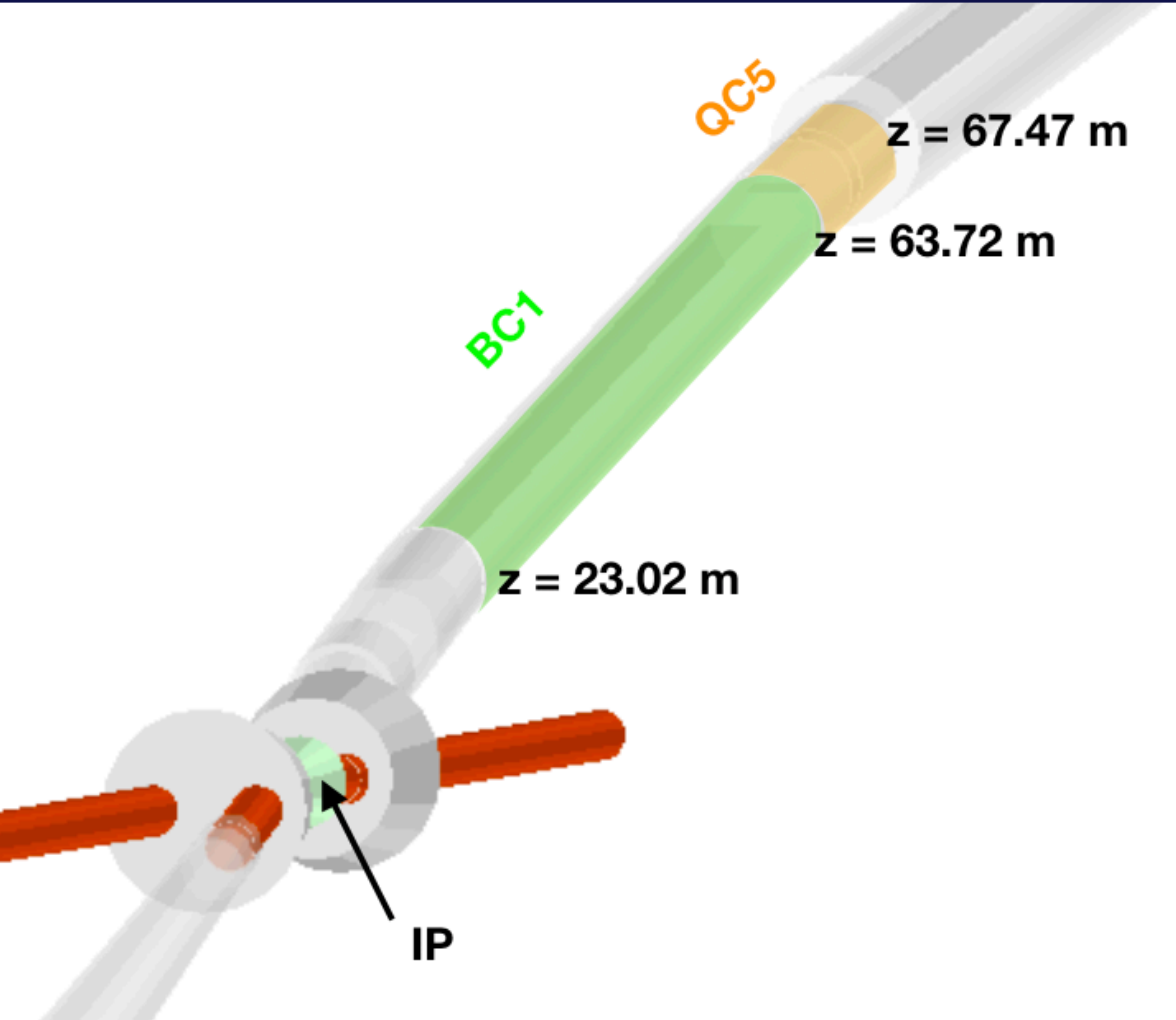
A **gaussian fit** on the hits-per-bin distribution showed that even with only ~4000 hits (macroparticles from the simulation), a spatial resolution of O(mm) is enough to have an error on the mean of $70\mu m$ (at 100m from the IP), which should be sufficient to discriminate vertical offsets of O($5\,\%\,\sigma_y$).

The error on the mean scales with $\sigma/\sqrt{N}$, so supposing an ideal detector with efficiency=1 and the $\sim 5 \times 10^9\,\gamma/BX$ coming from BS, at the same distance the error could go down to $65\,nm$ - corresponding to an offset of O($0.005\,\%\,\sigma_y$)

Considering a value for the spurious vertical dispersion of ~$\Delta D_y^* = 14\mu m$ (see talk from A.Blondel @FCCIS WP2 Workshop 2021), the resolution for the center-of-mass energy at the Z would then be

$$\sigma_y = 28\,nm$$
$$\delta_y = 0.005\,\%\,\sigma_y$$
$$E = 45.6\,GeV$$
$$\sigma_E = 0.132\,\%\,E$$

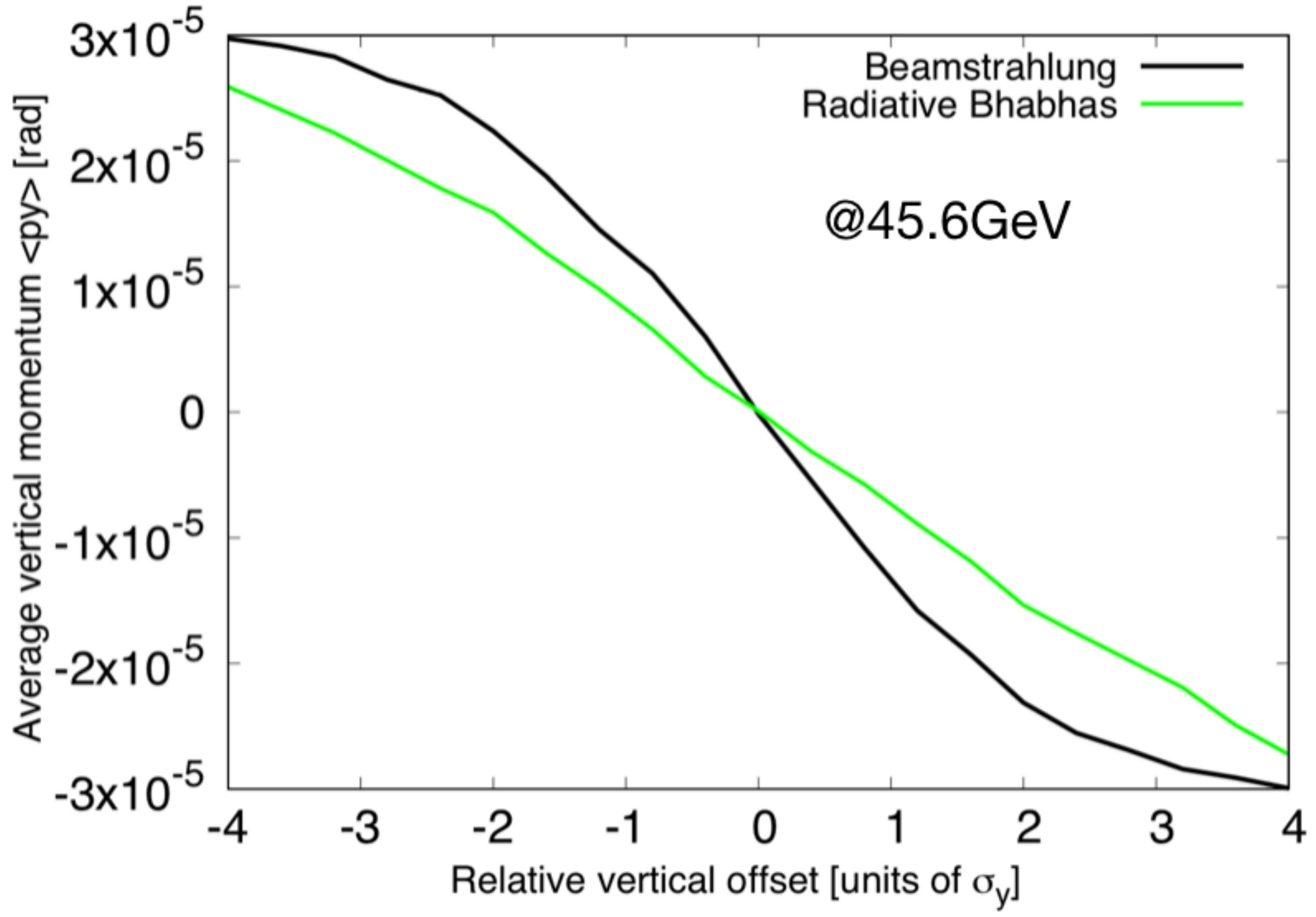
$$\Delta E_{CM} = \frac{\delta_y}{\sigma_y^2}\frac{\sigma_E^2}{E}\Delta D_y^* \sim 2\,keV$$

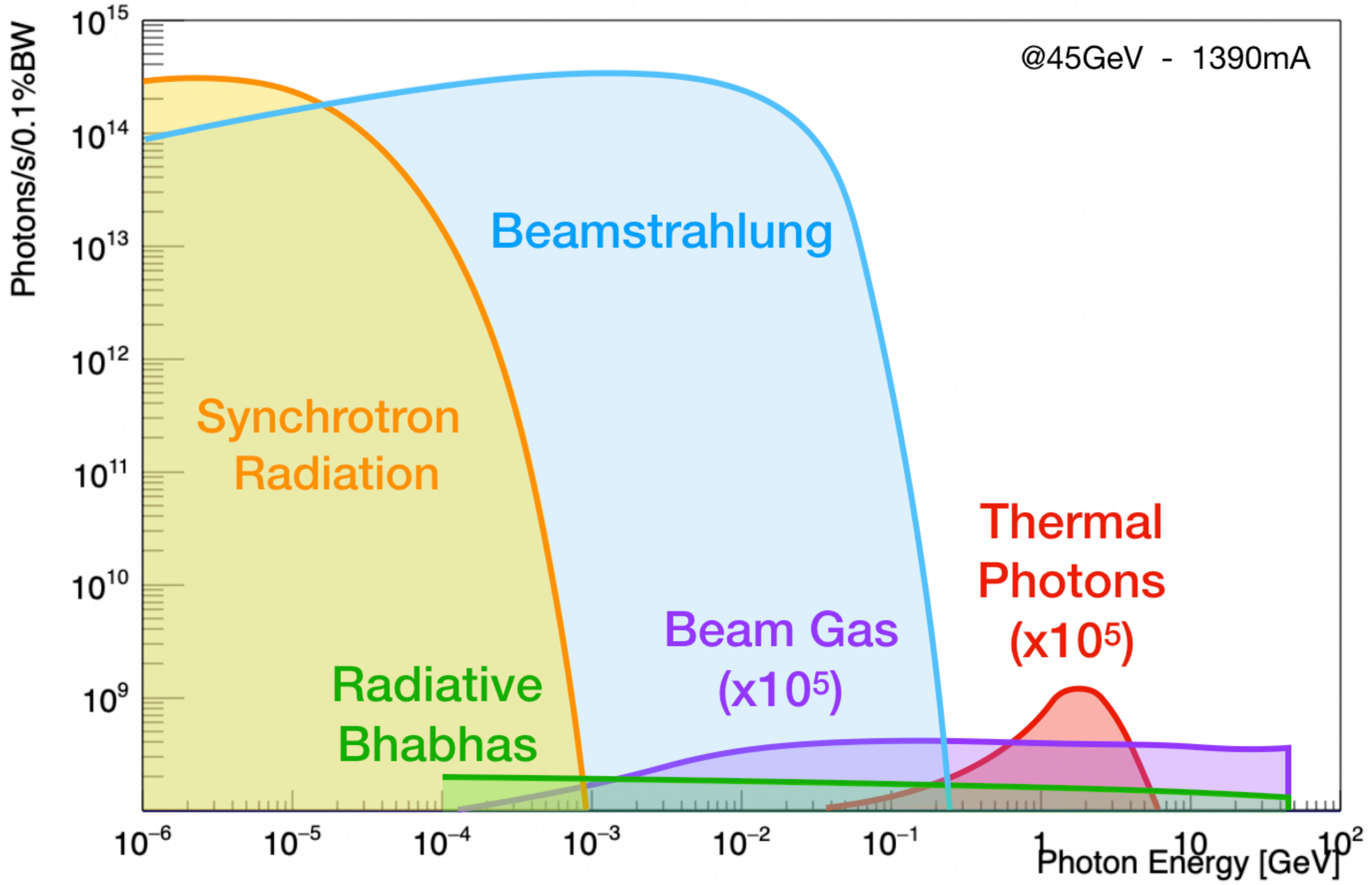

QC5
z = 67.47 m
z = 63.72 m
BC1
z = 23.02 m
IP

IP-generated radiation monitor for center-of-mass energy measurements

Non-zero **dispersion at the IP** modifies the center-of-mass energy in the case of an offset between the colliding beams.

An online monitor for this offset could be obtained by detecting **hard photons produced at the IP** (i.e. radiative bhabhas, beamstrahlung), as the direction of this radiation is proportional to the beam-beam offset.





Simulations have shown the correlation between the photon emission angle and the vertical offset between the two beams at the IP for both **Beamstrahlung** and **Radiative Bhabha** emissions.

The possible **backgrounds** for this monitor (i.e. synchrotron radiation, Compton scattering on thermal photons and inelastic beam gas scattering) have been estimated, showing that beamstrahlung signal is dominant in the multi-MeV range, while radiative Bhabhas in the multi-GeV range.

Dedicated studies on the **detector design** and on the **background shielding** should be performed in order to decide which signal source is the most viable.