What is beam halo and how do we measure it?

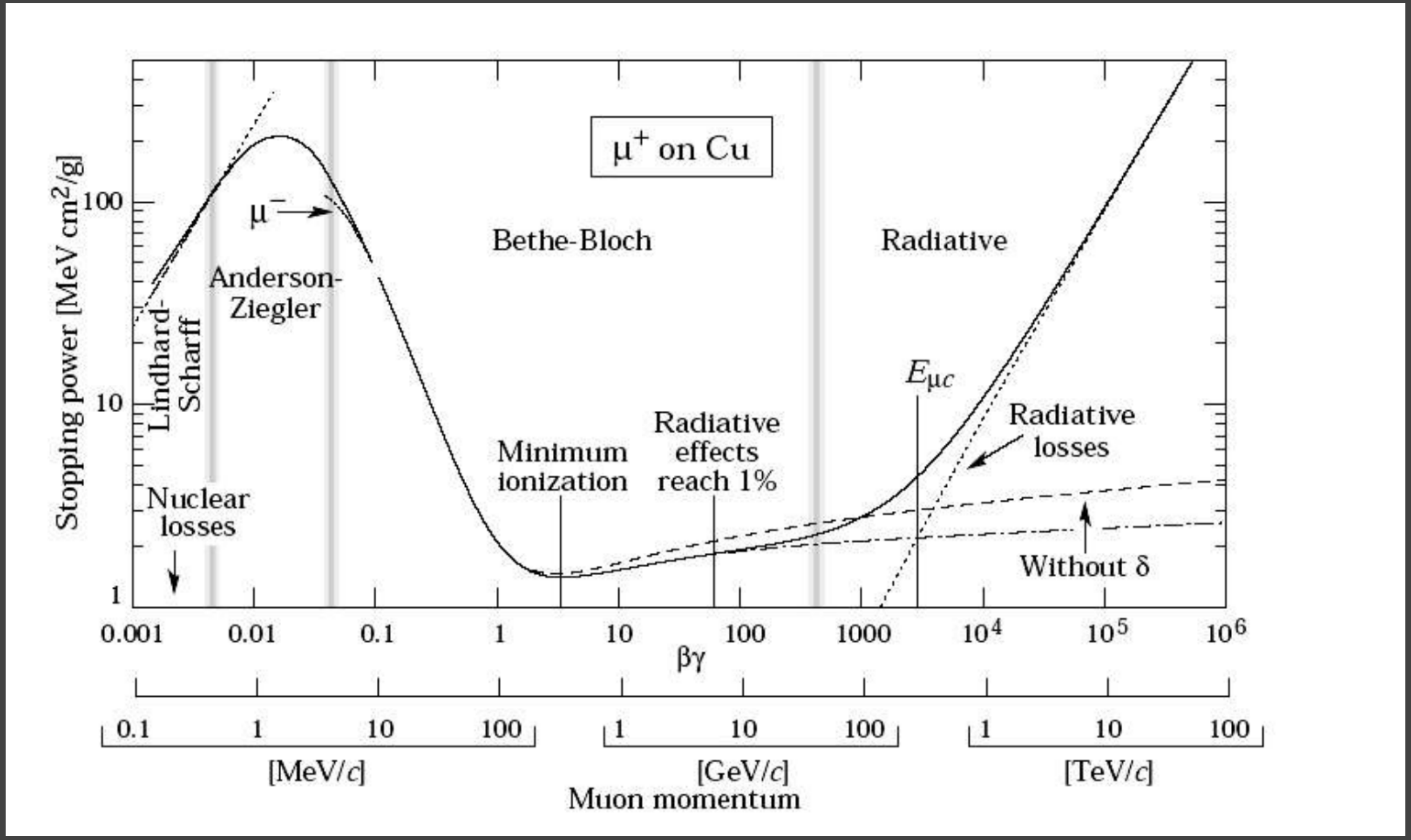
ROGER RUSACK, SHILPI JAIN
UNIVERSITY OF MINNESOTA

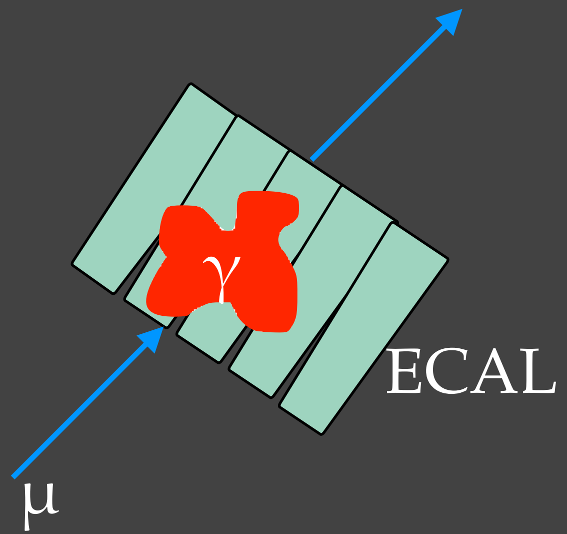
Protons inside LHC beams

- There are ~10^{11} protons/bunch in LHC beam.
- The bunches are quite packed - transverse spread is ~15μm
- There are inter-particle interactions, beam-gas interactions and synchrotron radiation
- All of these processes can make protons diffuse to a higher radius
- Dedicated collimator system is in place in the LHC system to scrape these particles off.
  - Still some particles escape and form ‘beam halo’

Machine induced background

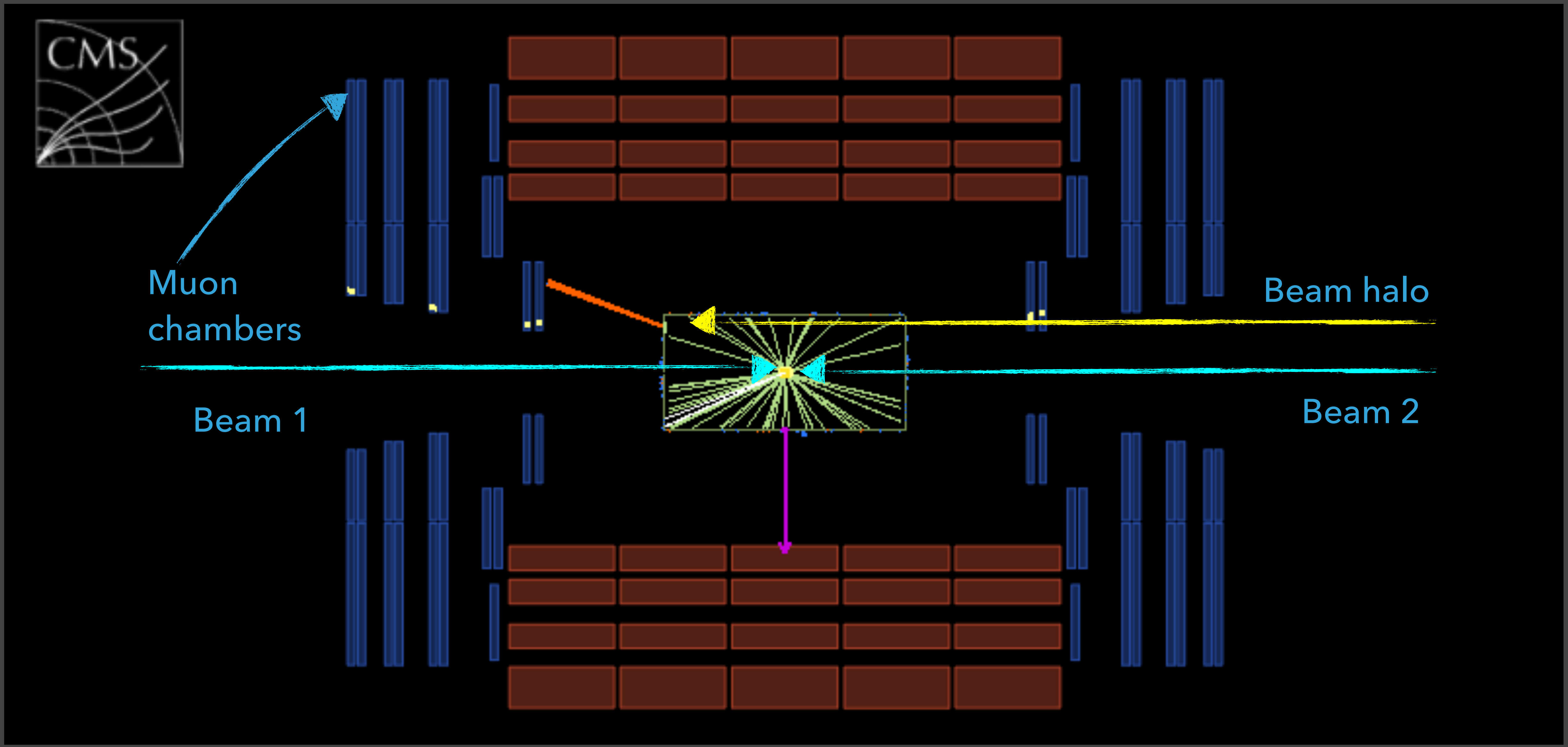
- Due to collision of these protons with the LHC collimator system, shower particles can be produced
- These particles travel **parallel** to the beam
- The ones which reach and are important for the CMS detector are muons
- These highly energetic muons can interact with the sub-detector giving rise to a high energy deposit in the calorimeter





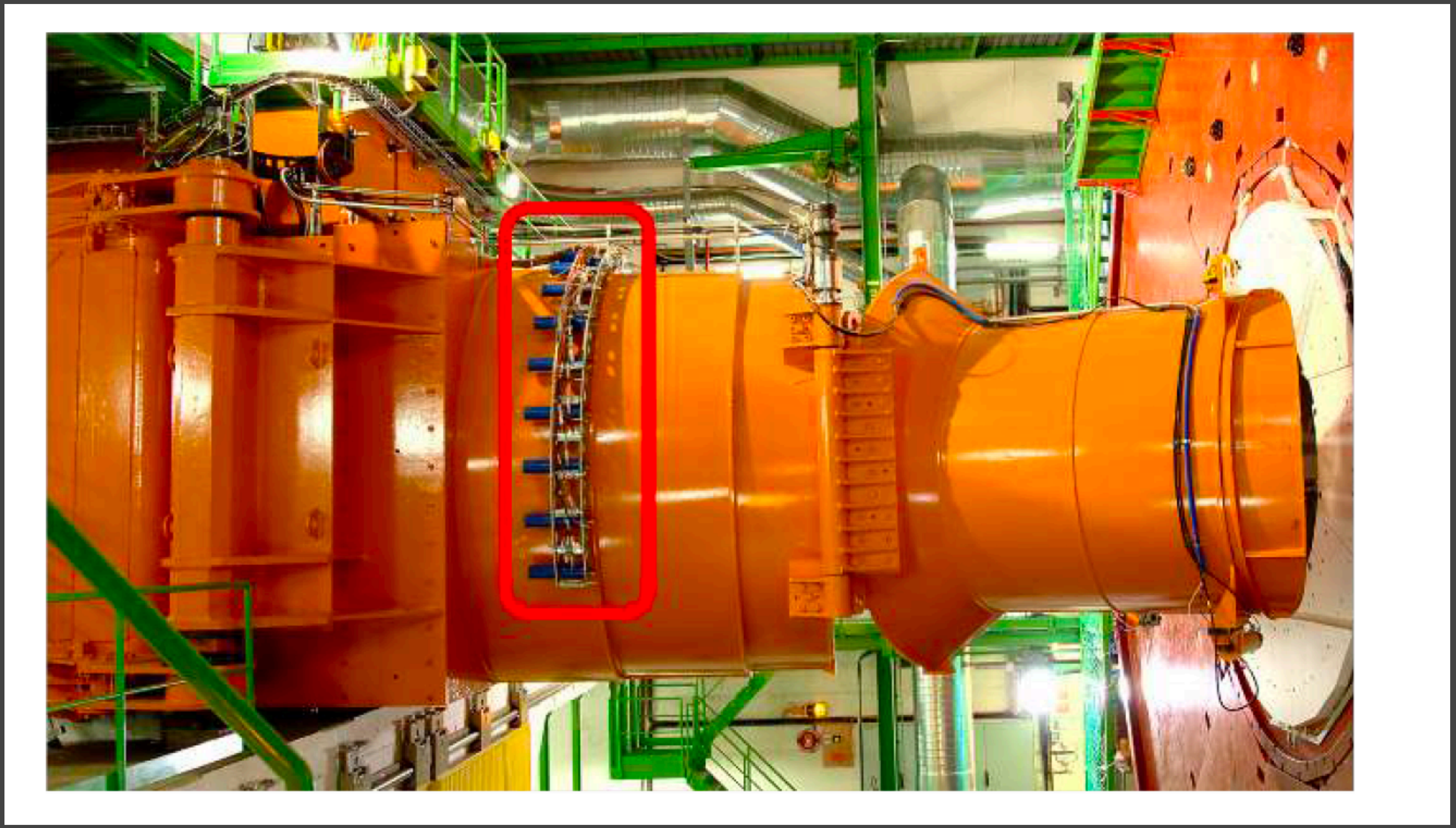
- A muon with pT > 100 GeV becomes radiative and can do bremsstrahlung dominantly

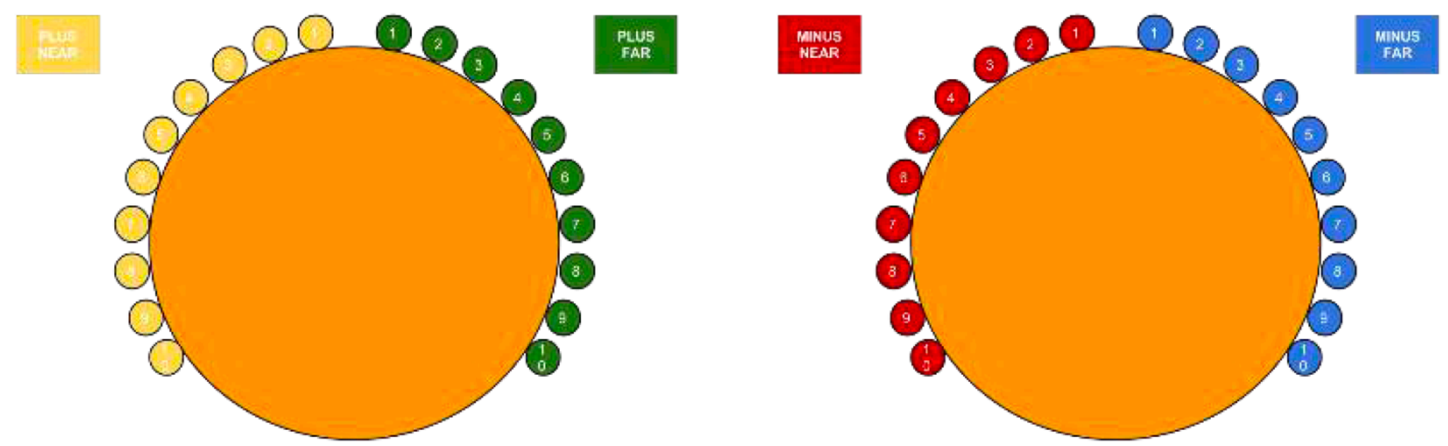
Beam halo



- A large deposit in ECAL can be seen in line with hits in the muon chambers - typical of beam halo
- Beam halo is a potential background to many analyses in CMS

Beam halo monitors



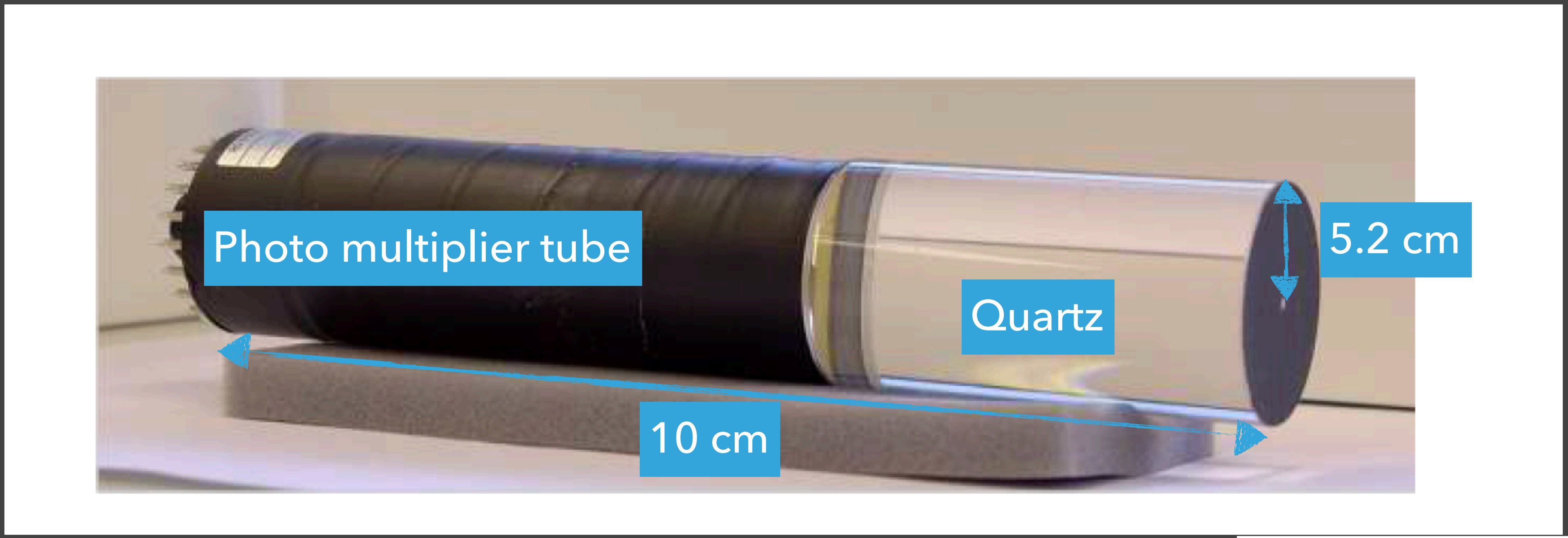


(a) +Z distribution

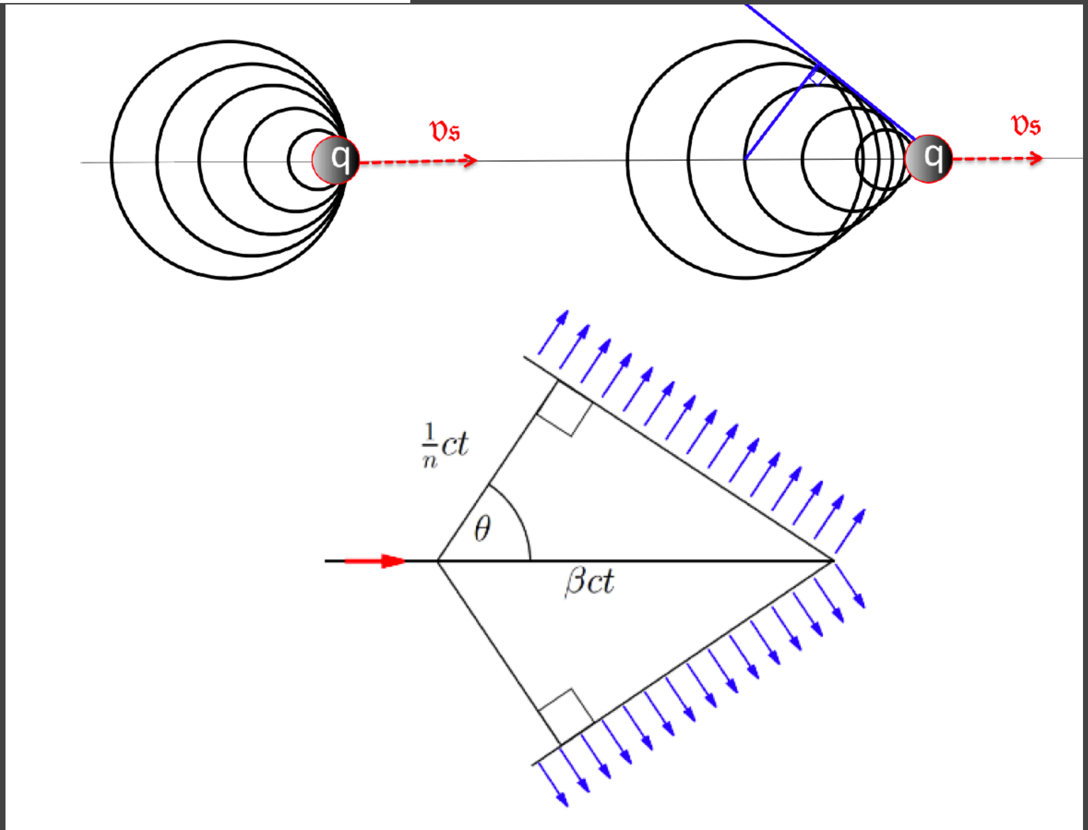
(b) -Z distribution

- To detect such a background, there are beam halo monitors
- Mounted on rotating shielding
- 20 on each side of the CMS detector

Detector unit



- Best suited for this purpose: cherenkov light based detector
  - Suitable material: Fused silica (quartz)
  - Good transmission in the UV range
- Photodetector choice: Photo multiplier tube
  - Sensitive to UV down to 160 nm
  - High gain and fast rise time



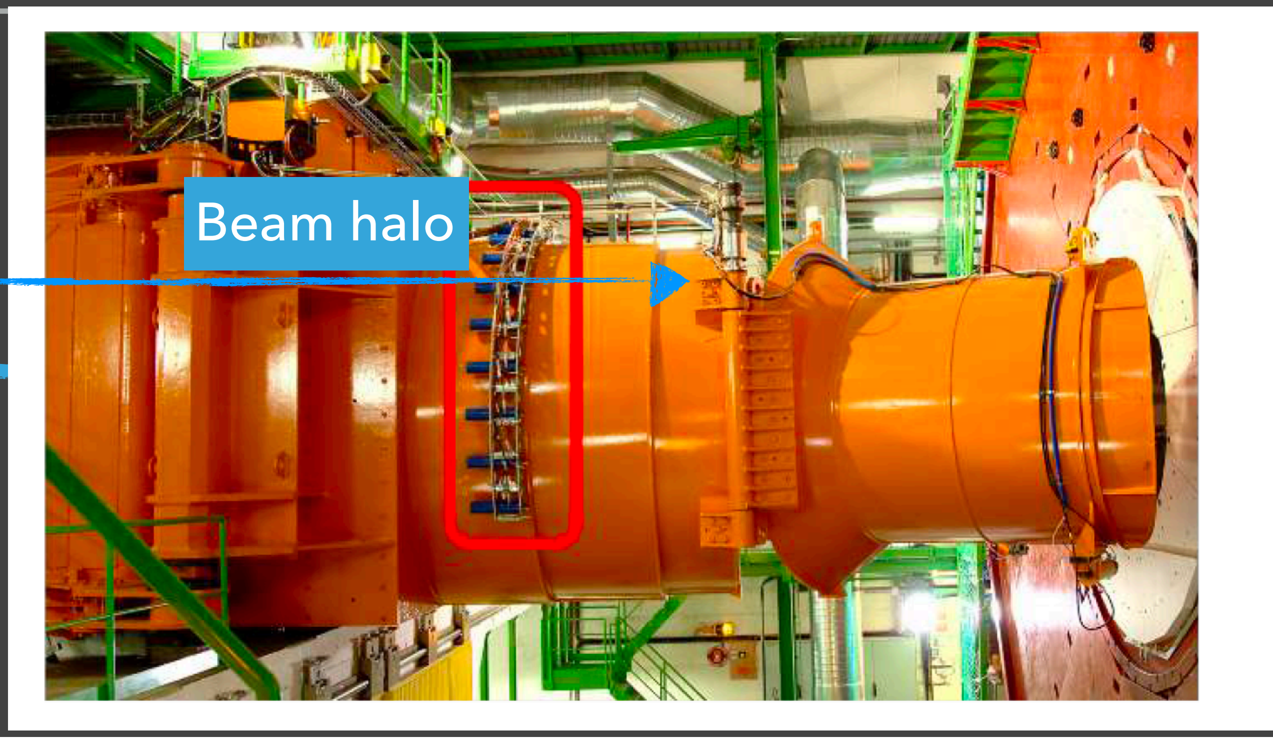
n = refractive index
β = v/c ; v = velocity of the particle

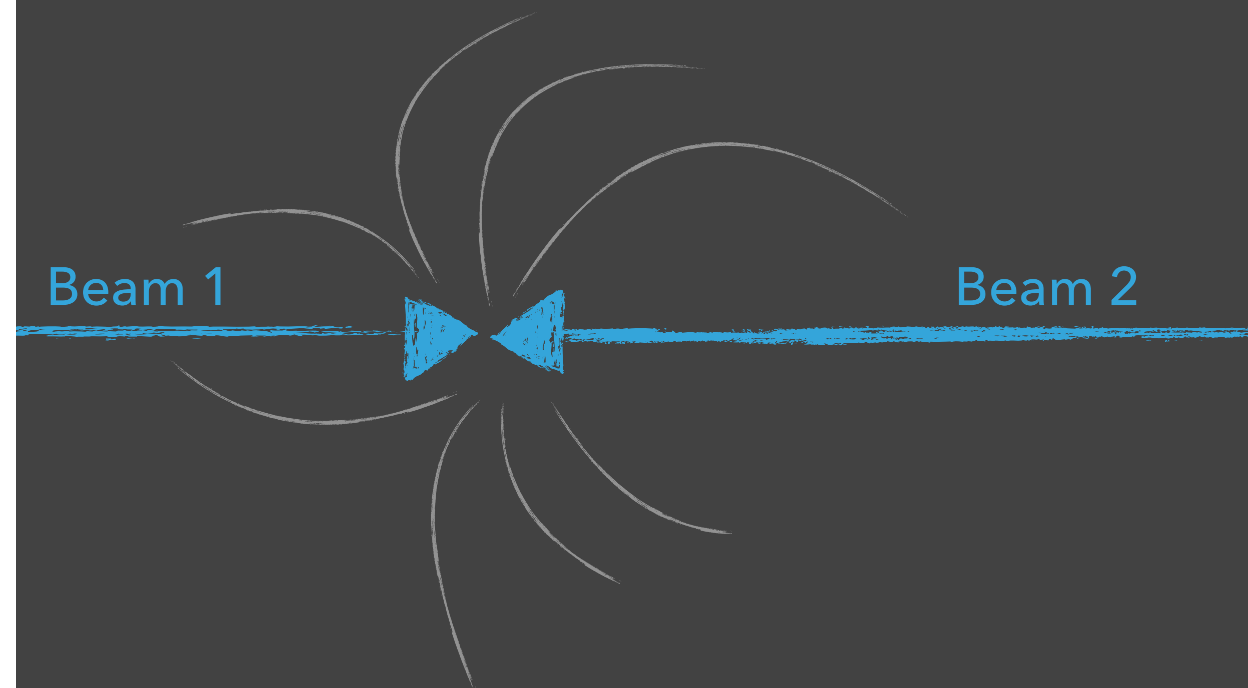
angle at which light is emitted

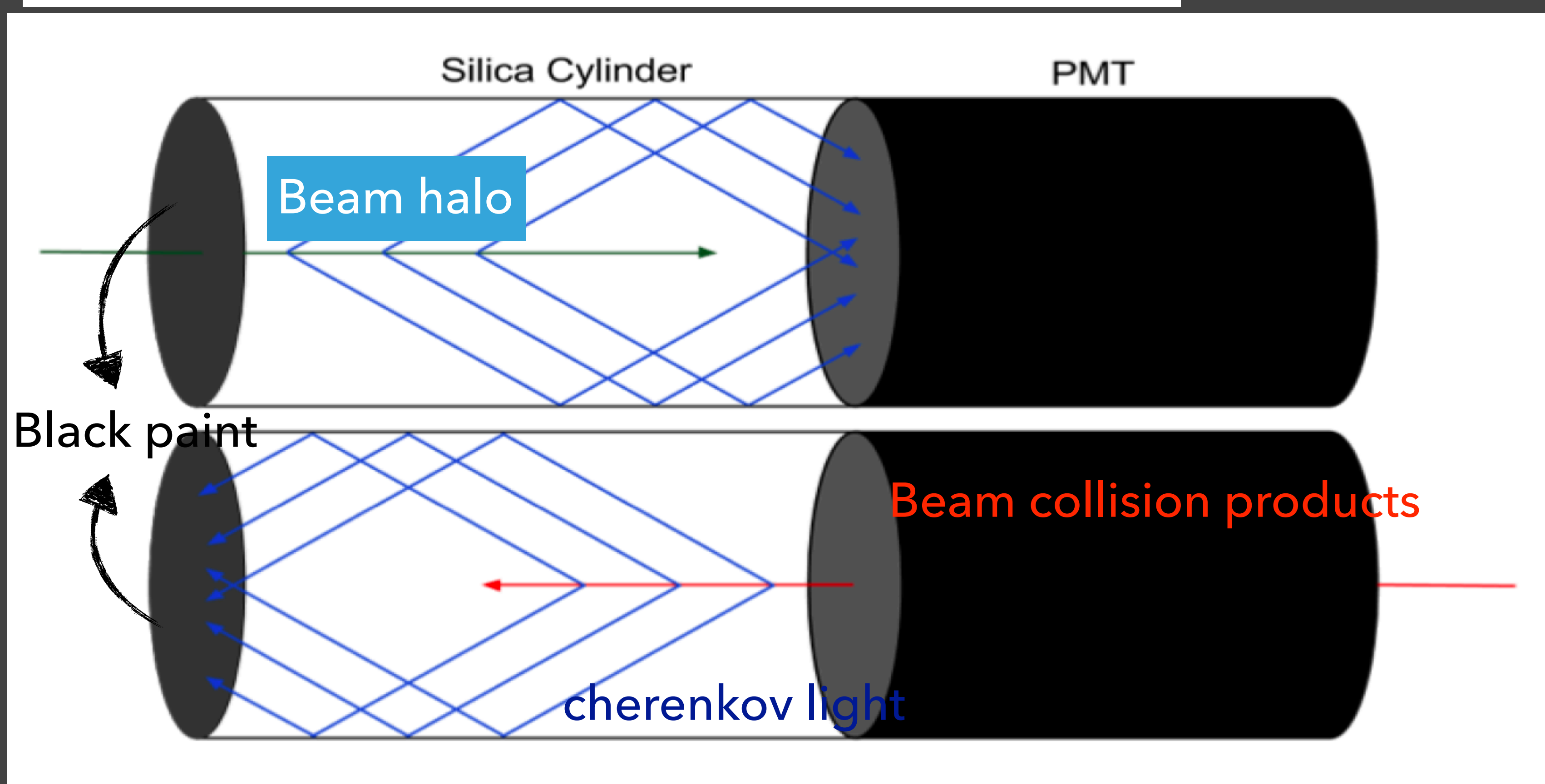
$$\cos\theta = \frac{c}{n\beta c} = \frac{1}{\beta n}.$$

Cherenkov radiation is emitted when particle moves faster than light in that medium - it has directional nature

Basic principle

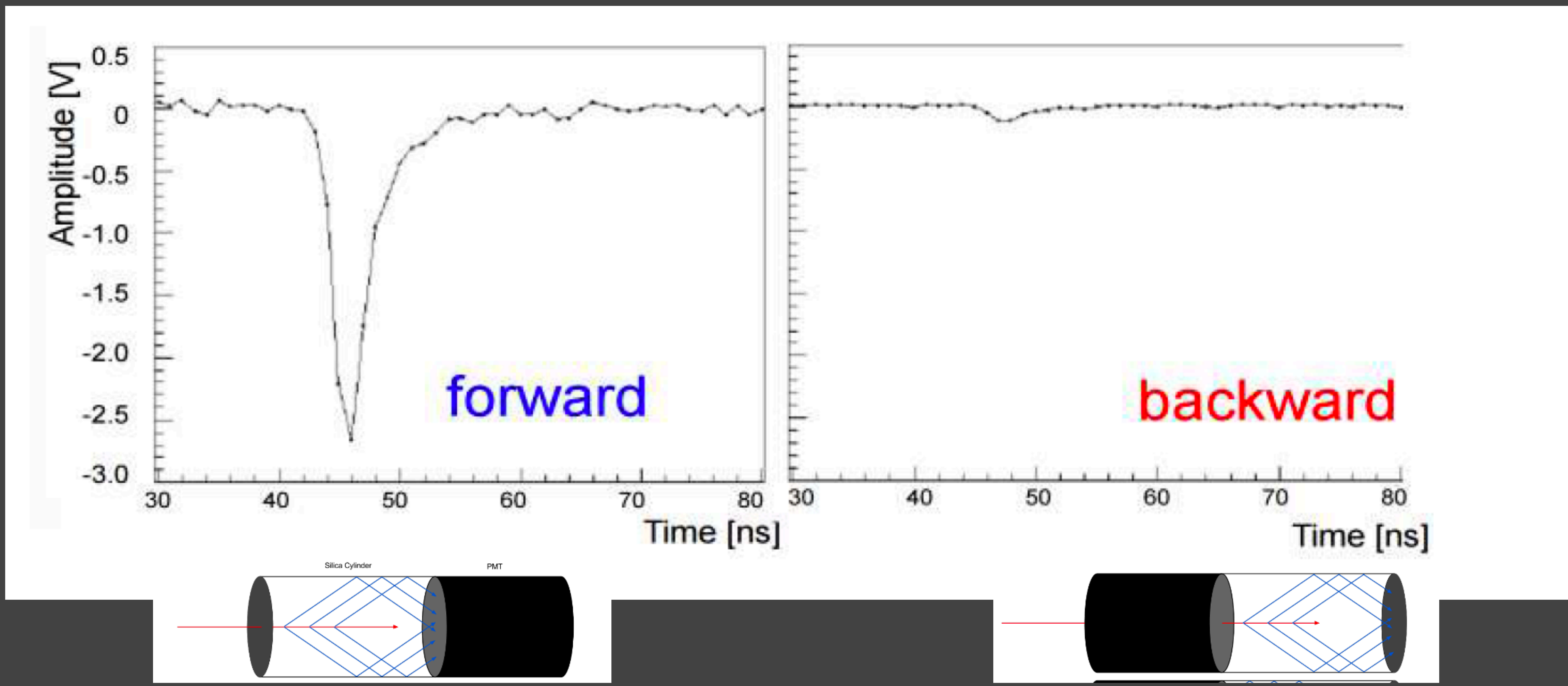






- Directional property is exploited:
  - Signal is generated when beam halo crosses the detector
  - The collision products do not cause any appreciable signal

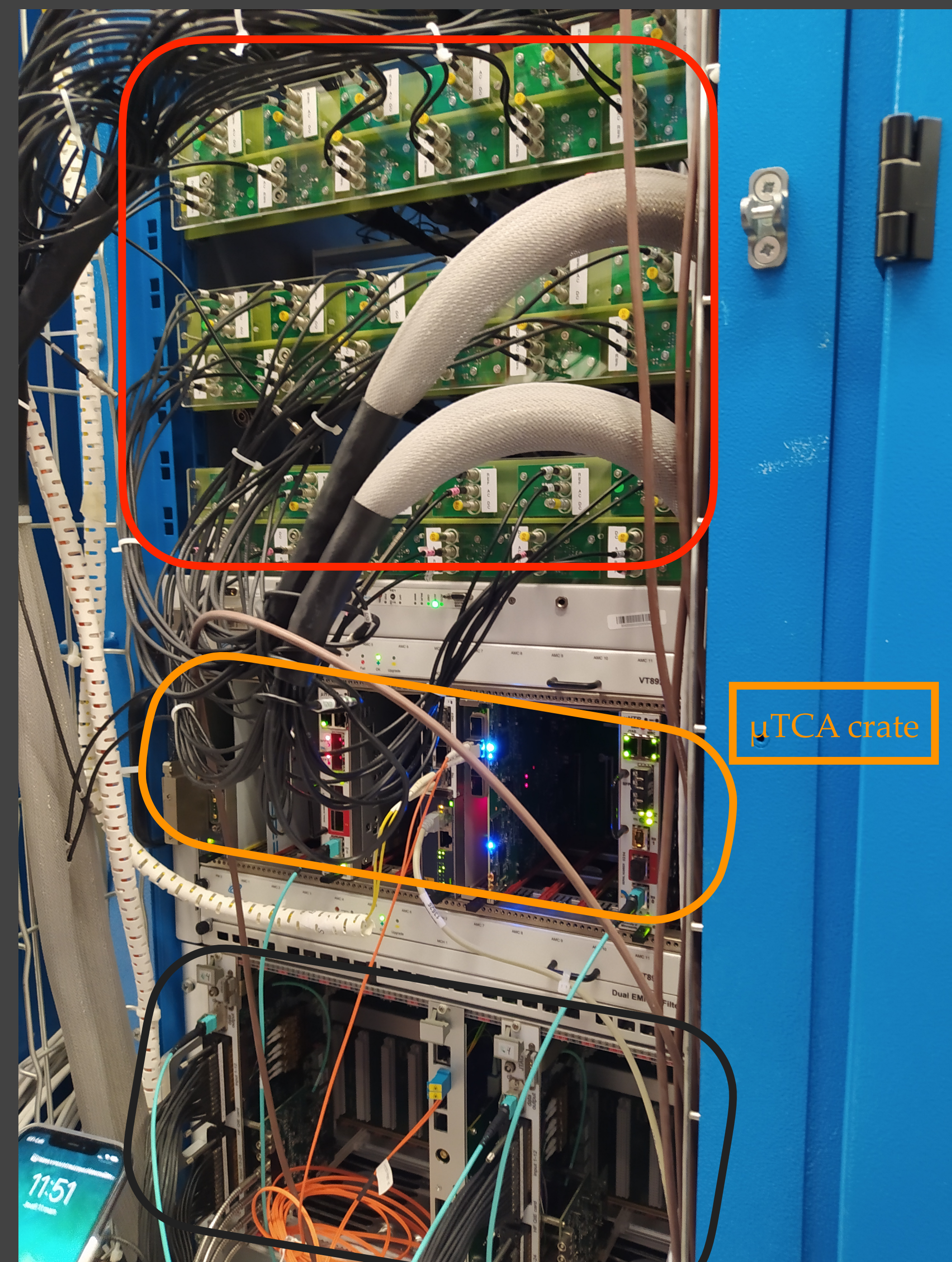
Signal for forward and backward traveling particles



- Test beam at CERN in 2012 using muons

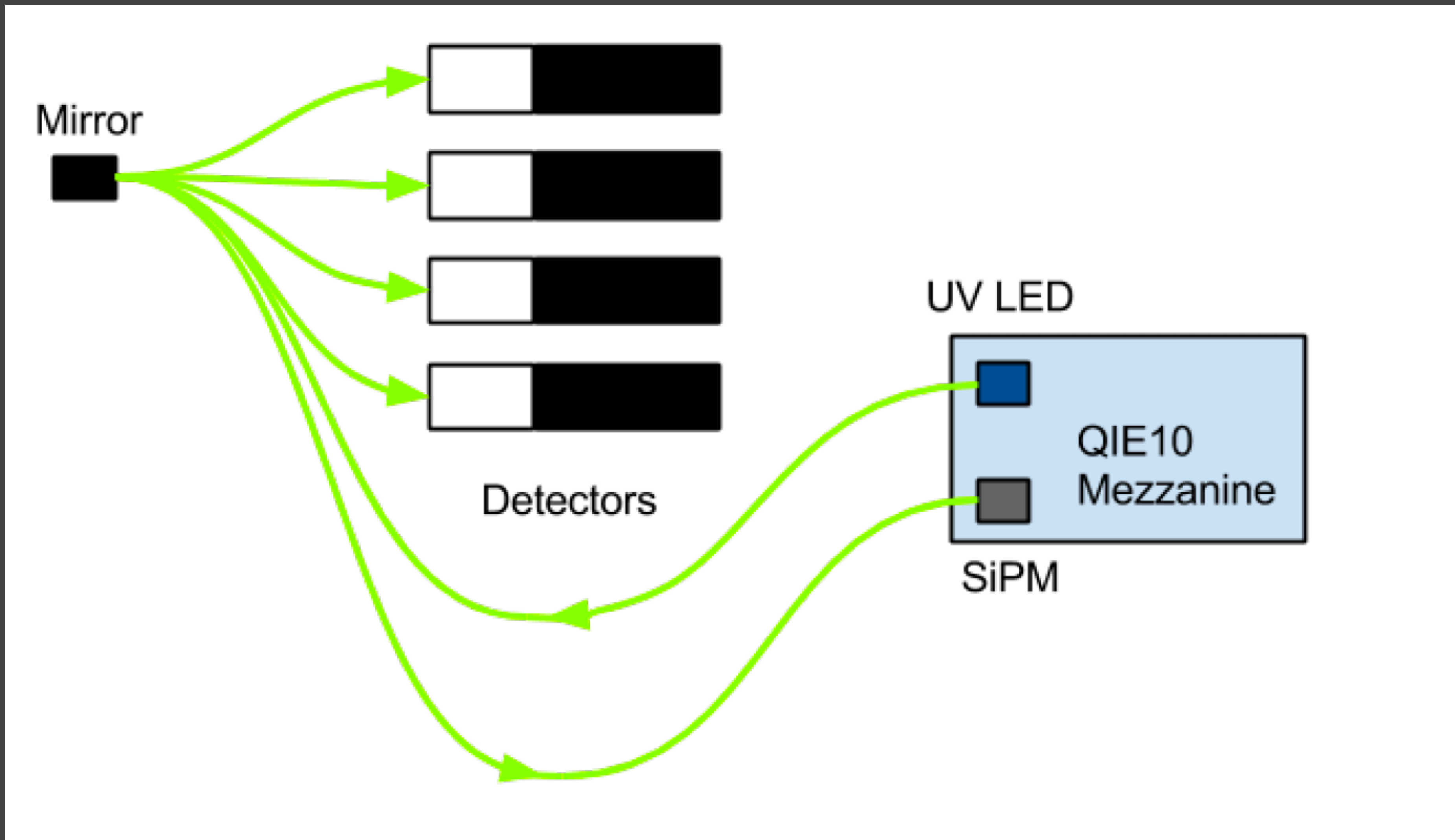
Readout system in USC (service cavern)

Signal cables (brown)



QIE: Integrates and digitizes. It has TDC as well for timing information

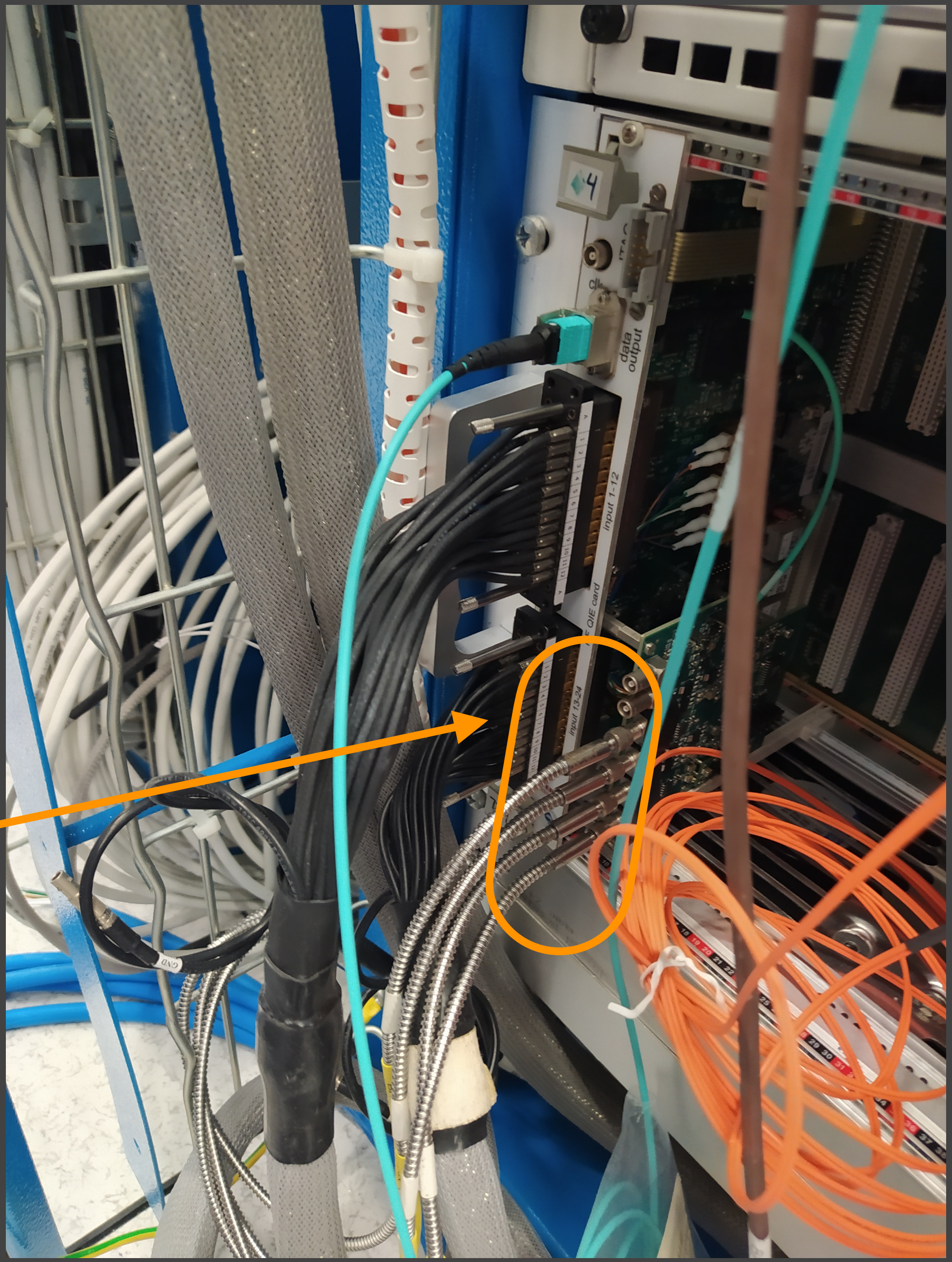
Calibration system



- A pulser circuit can be triggered in empty bunch crossings at fixed intervals to track the performance of the PMTs

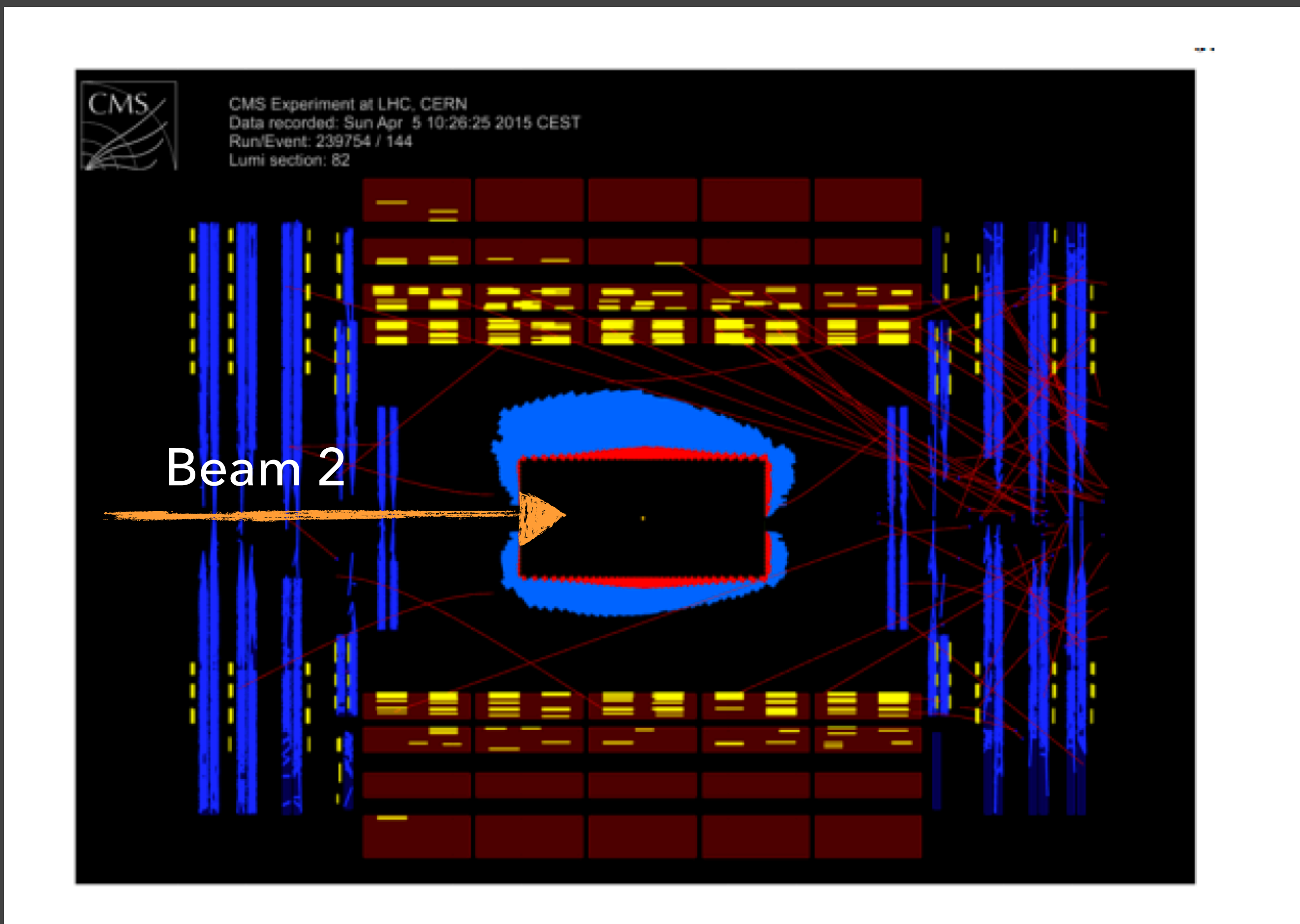
Calibration system

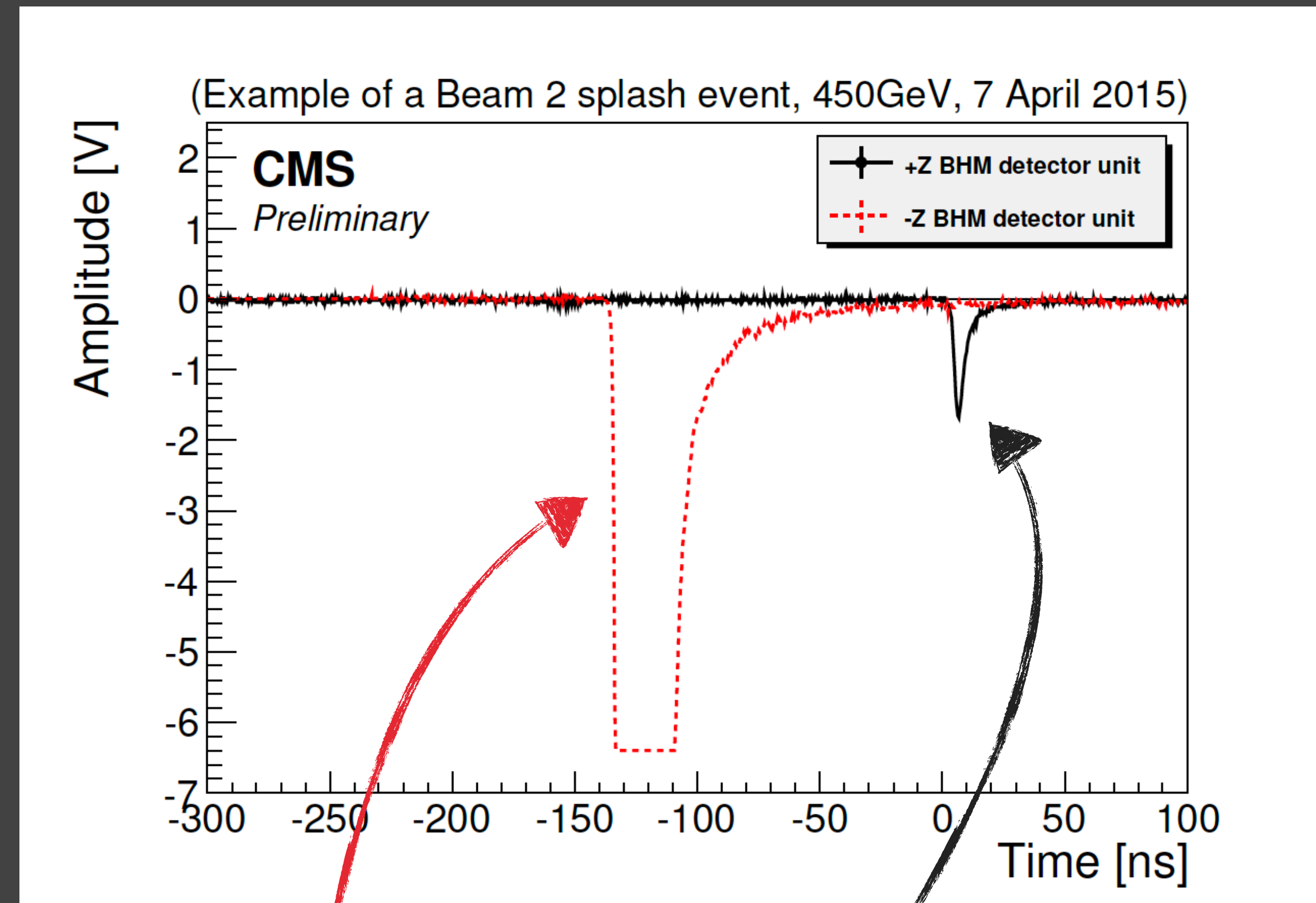
Main crate - SF108

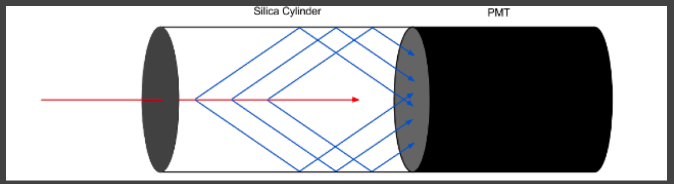


Optical fibers

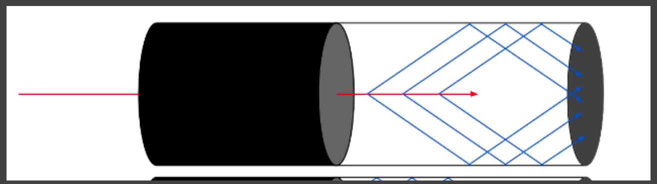
Signals during beam splash in 2015







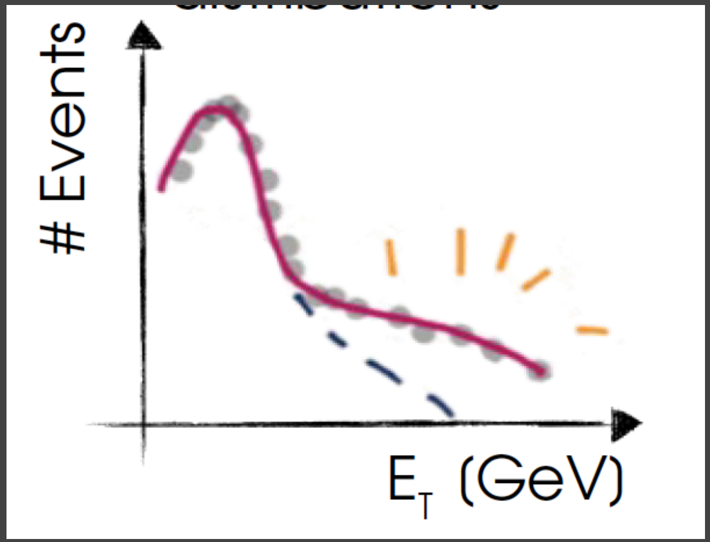
Beam 2



Beam 1

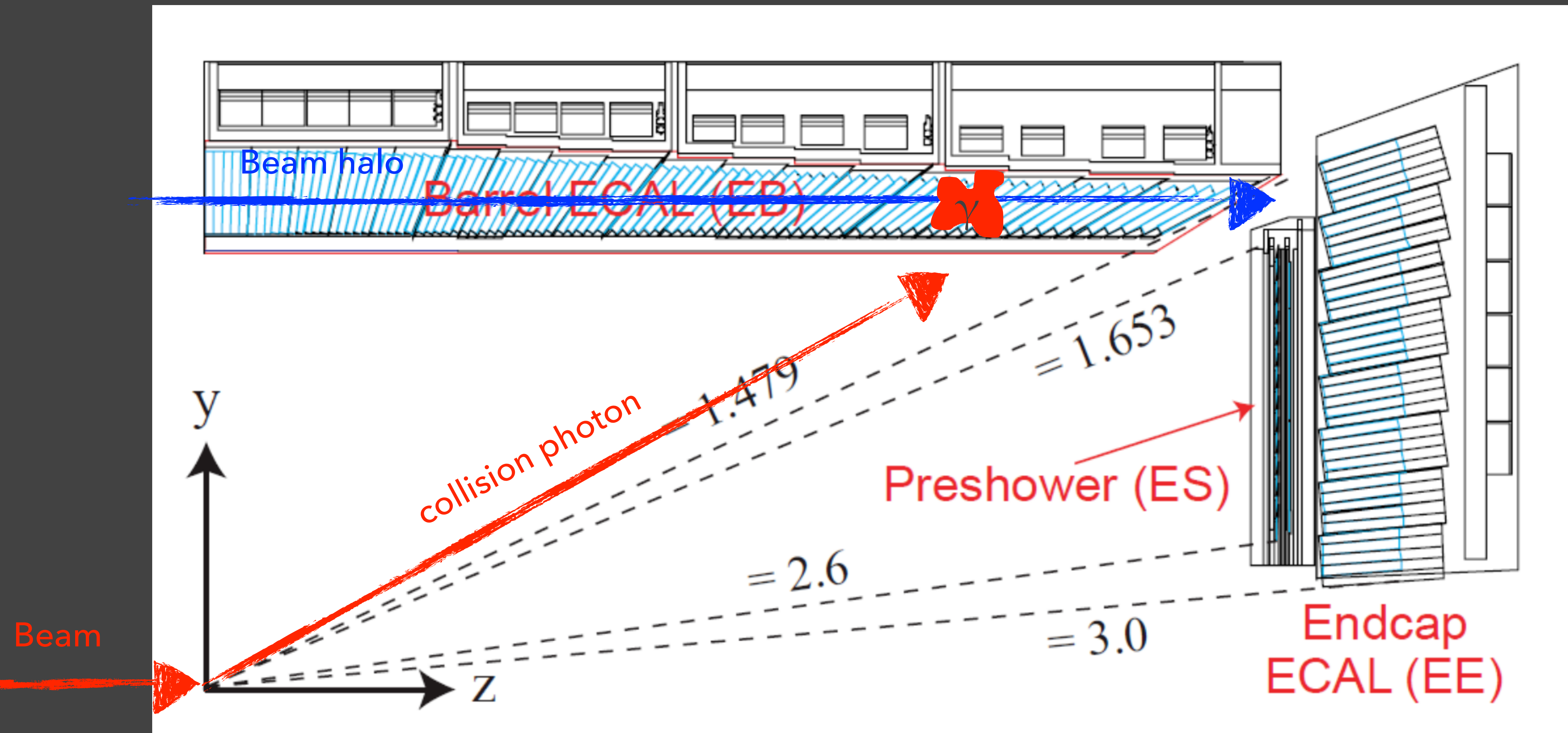
- During 2015, during the splash event (i.e. one of the beams directed to the collimators), output from BHMs were recorded.
- As can be seen, the +Z BHM detector unit does not give any significant signal, where the -Z gives
  - Demonstration of directional nature of the detector

- The beam halo monitors integrate information over ~1.4 s (1 bunch crossing is 25 ns)
  - In case of any excess of events, the data can be divided into periods of low beam halo and high beam halo
  - However, with this system, currently there is no per event information available



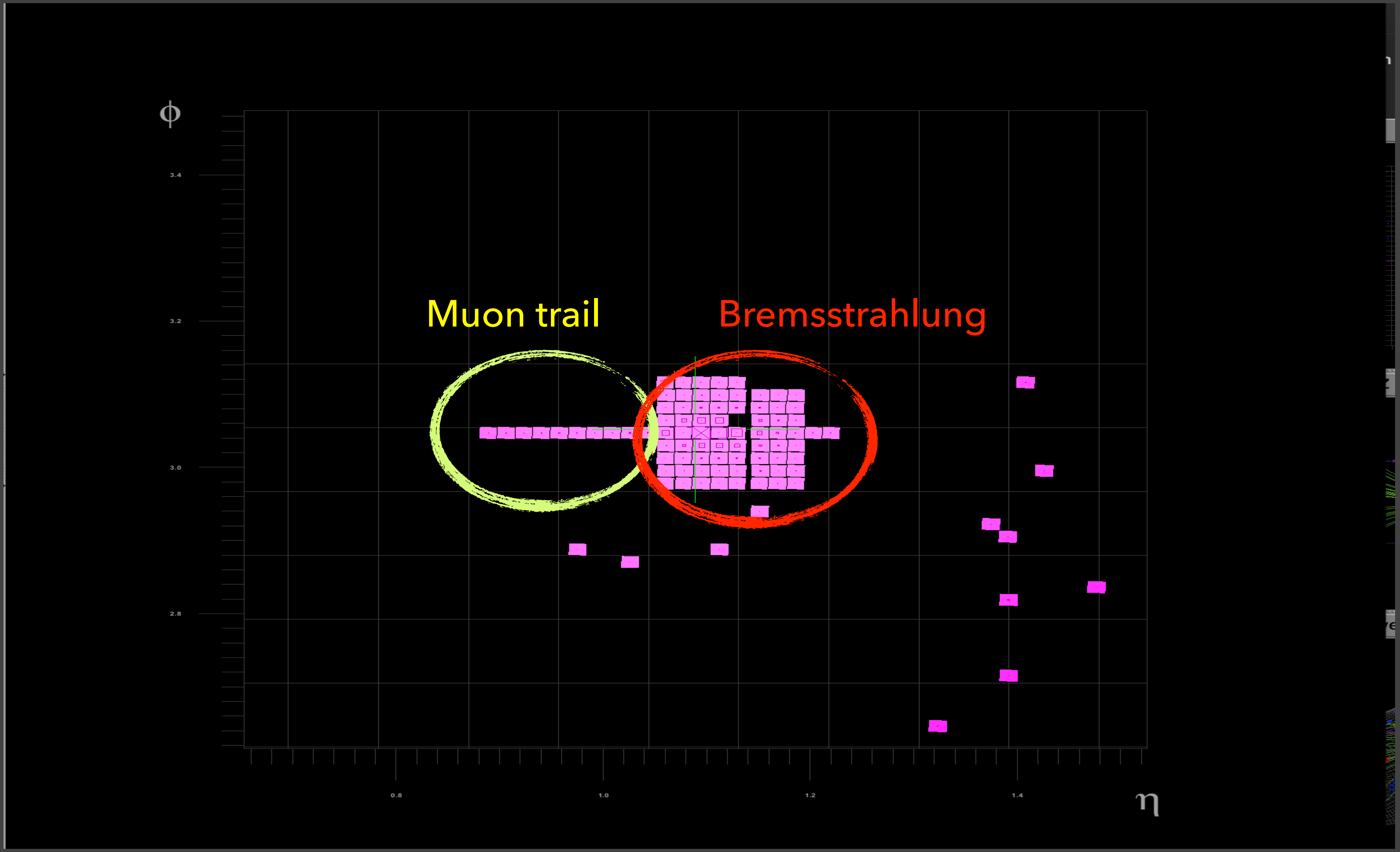
- We can still use the CMS calorimeter to build up a per-event decision about the possibility of a beam halo
  - Different ways to tackle in EB and EE

Beam halo in the ECAL Barrel



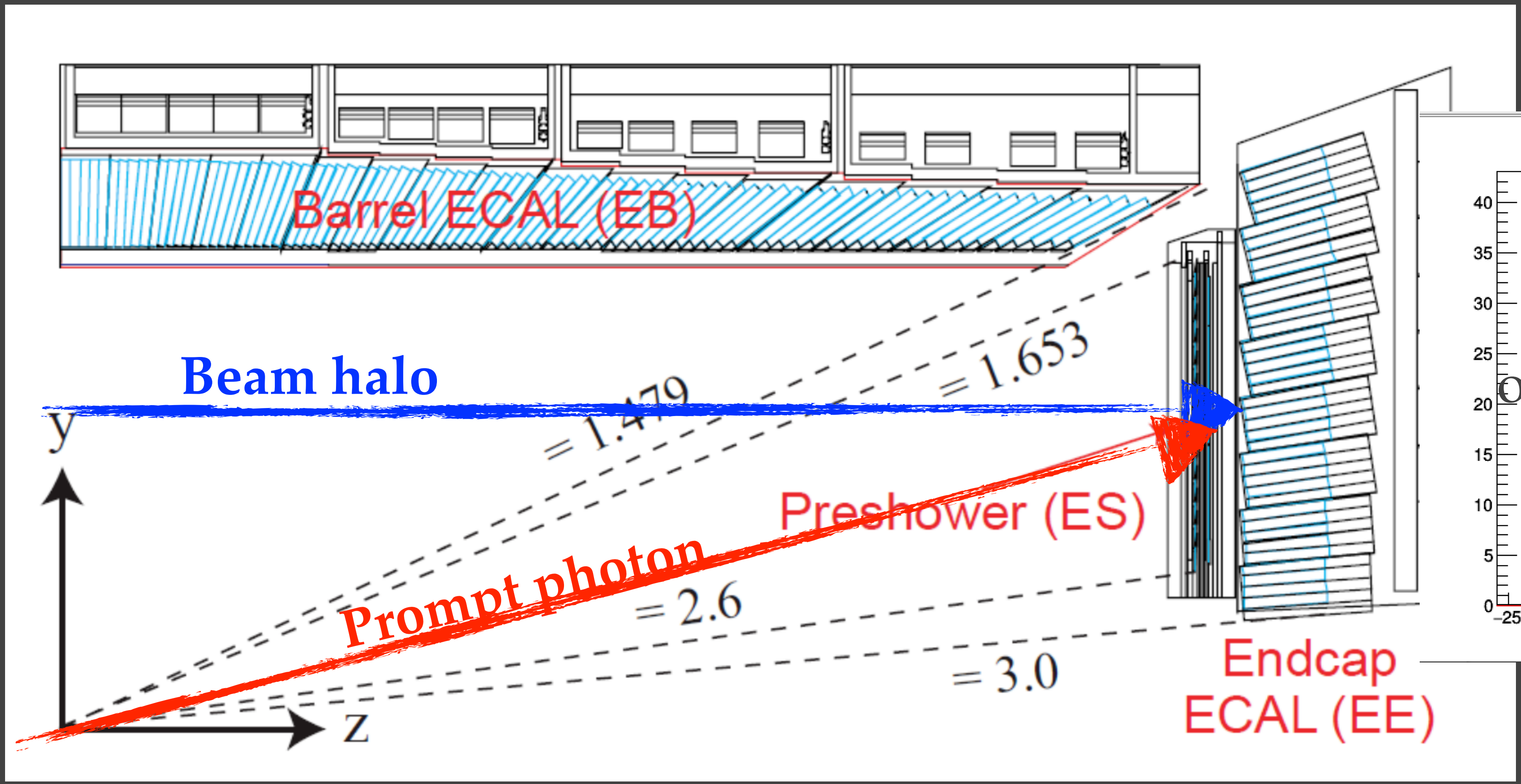
- The beam halo in the EB arrives earlier than the collision, so timing can be used to handle the background

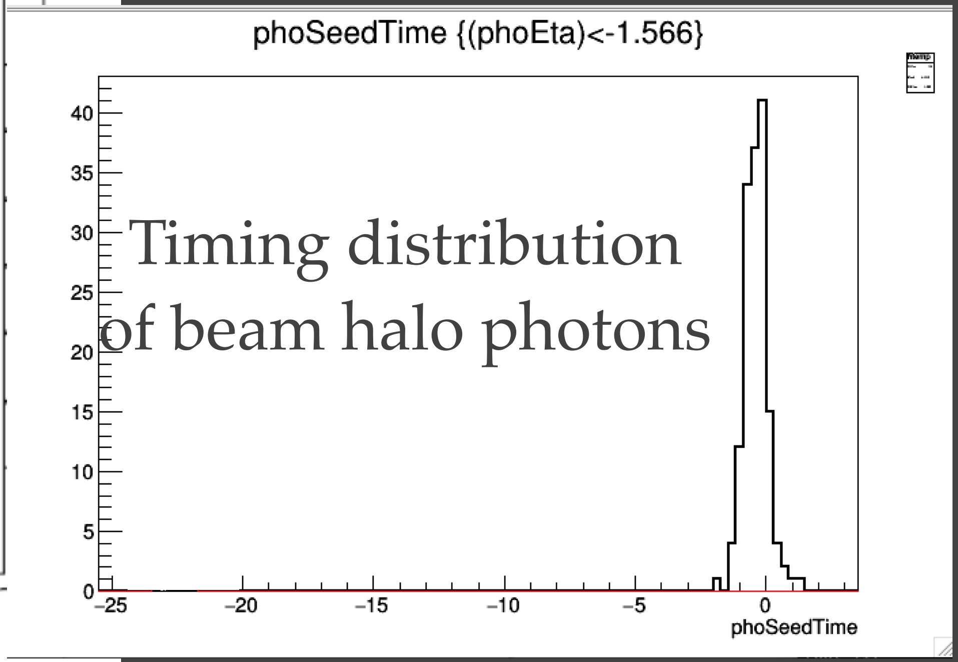
Inside CMS ECAL Barrel and its removal at the analysis level



- By collecting the hits from the muon trail and their total energy, this background can be handled

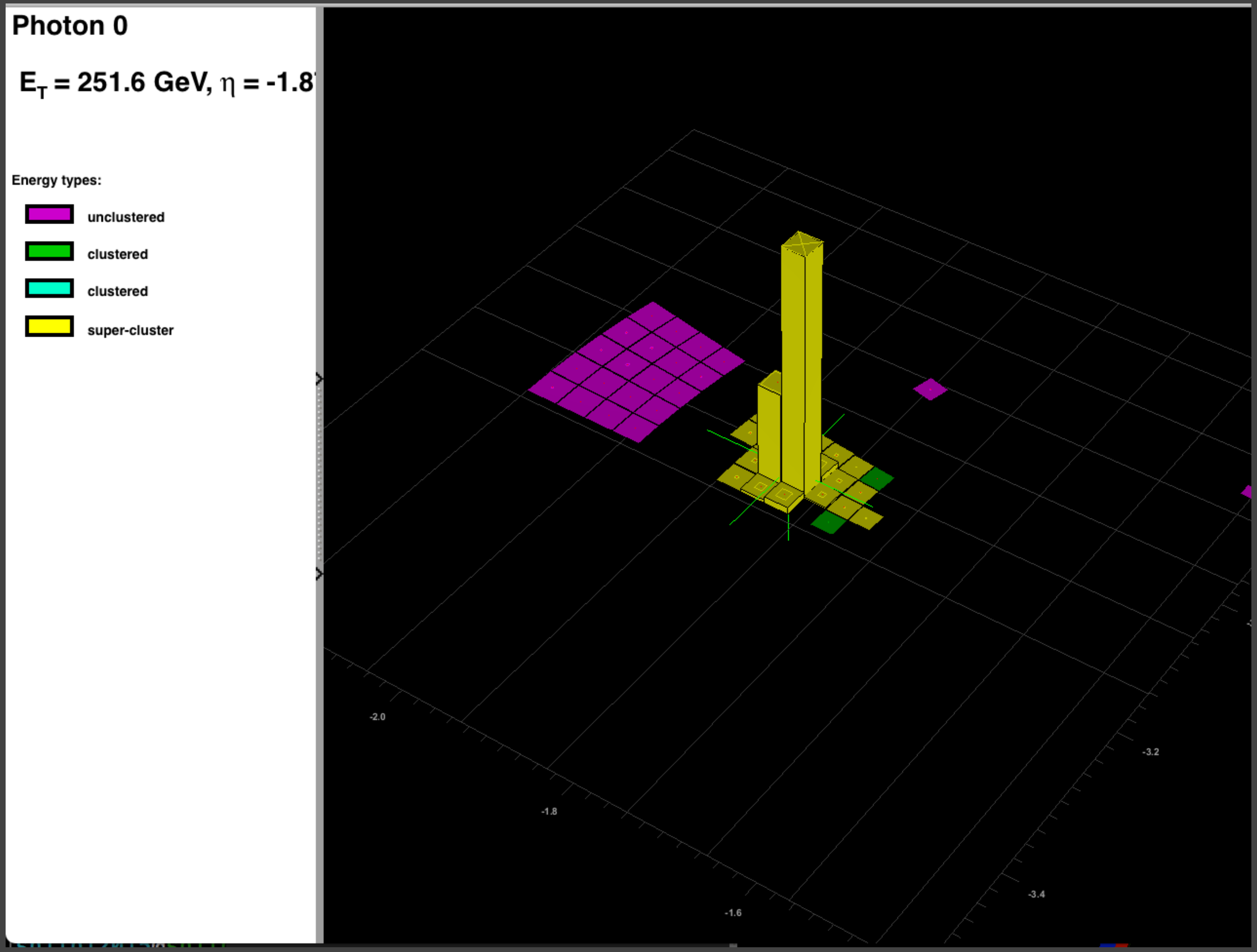
Beam halo in the EE – I





- Timing cut:
    - A beam halo coming at a distance of 129./2 will hit at ~0.2 ns earlier compared to a prompt photon (EE is at a distance of 317 cm)
    - Timing distribution of the beam halo photons fall within 3 ns - very similar to that of prompt photons
- Removes those that interact on the same side as the source, but cannot be used to identify those that interact on the opposite side

Why is beam halo large in the EE? – II (signature in the EE)

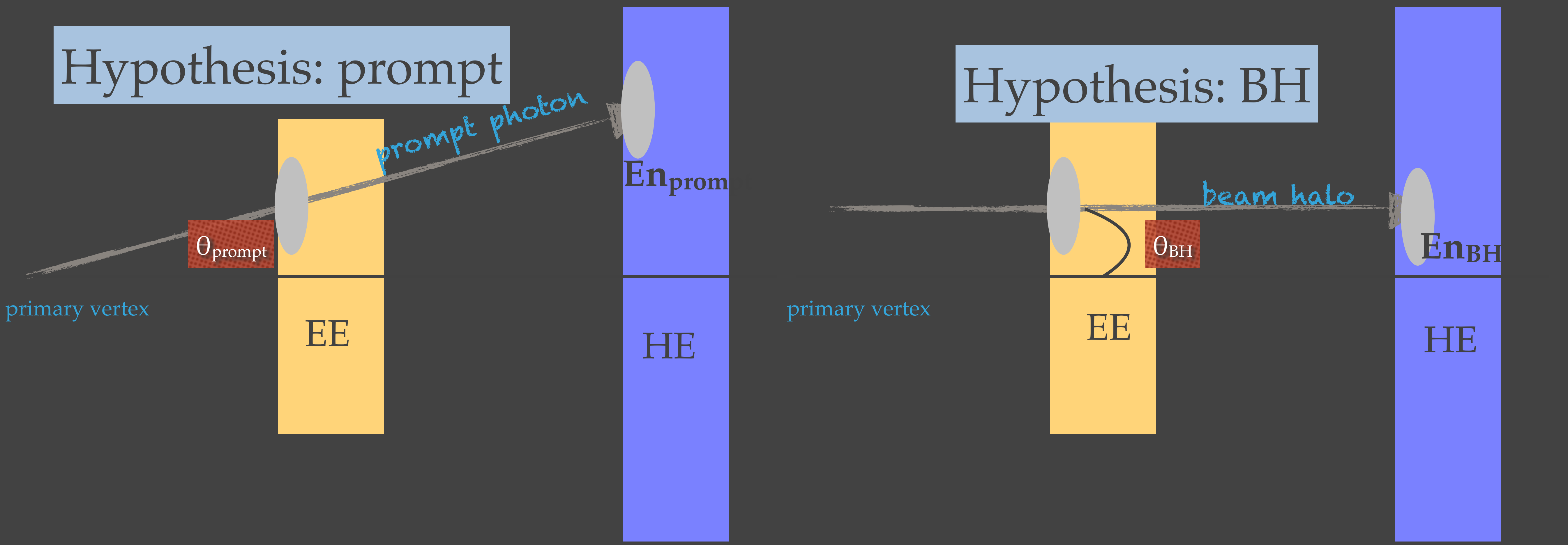


- No particular muon trail as seen in the EB

Basic idea

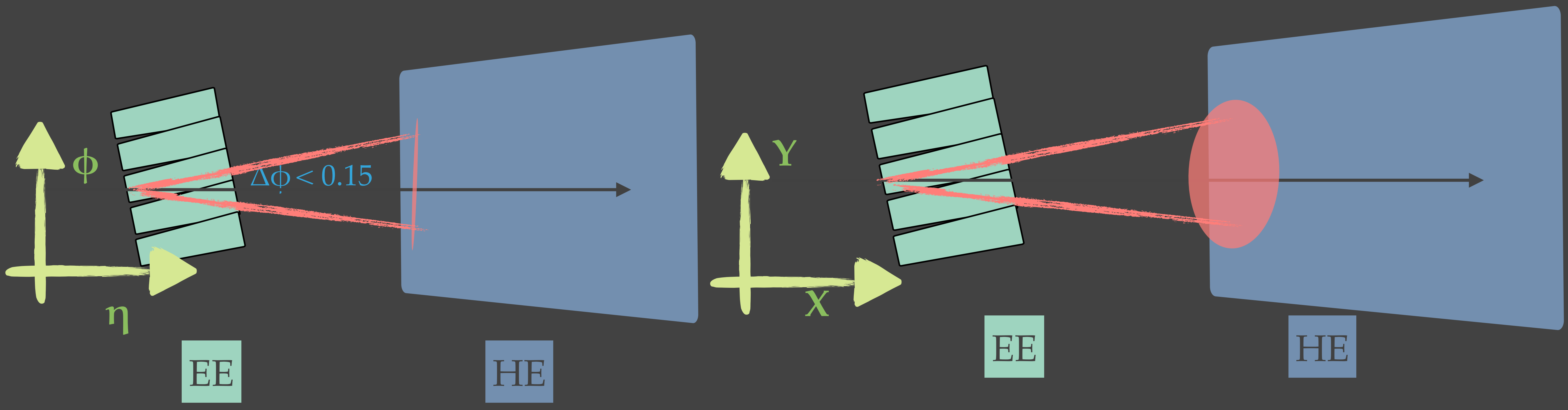
- To tackle this background in the EE, we developed an idea of using the information from various sub-detectors :
    - ECAL endcap, HCAL endcap and preshower

Basic idea between HE-EE



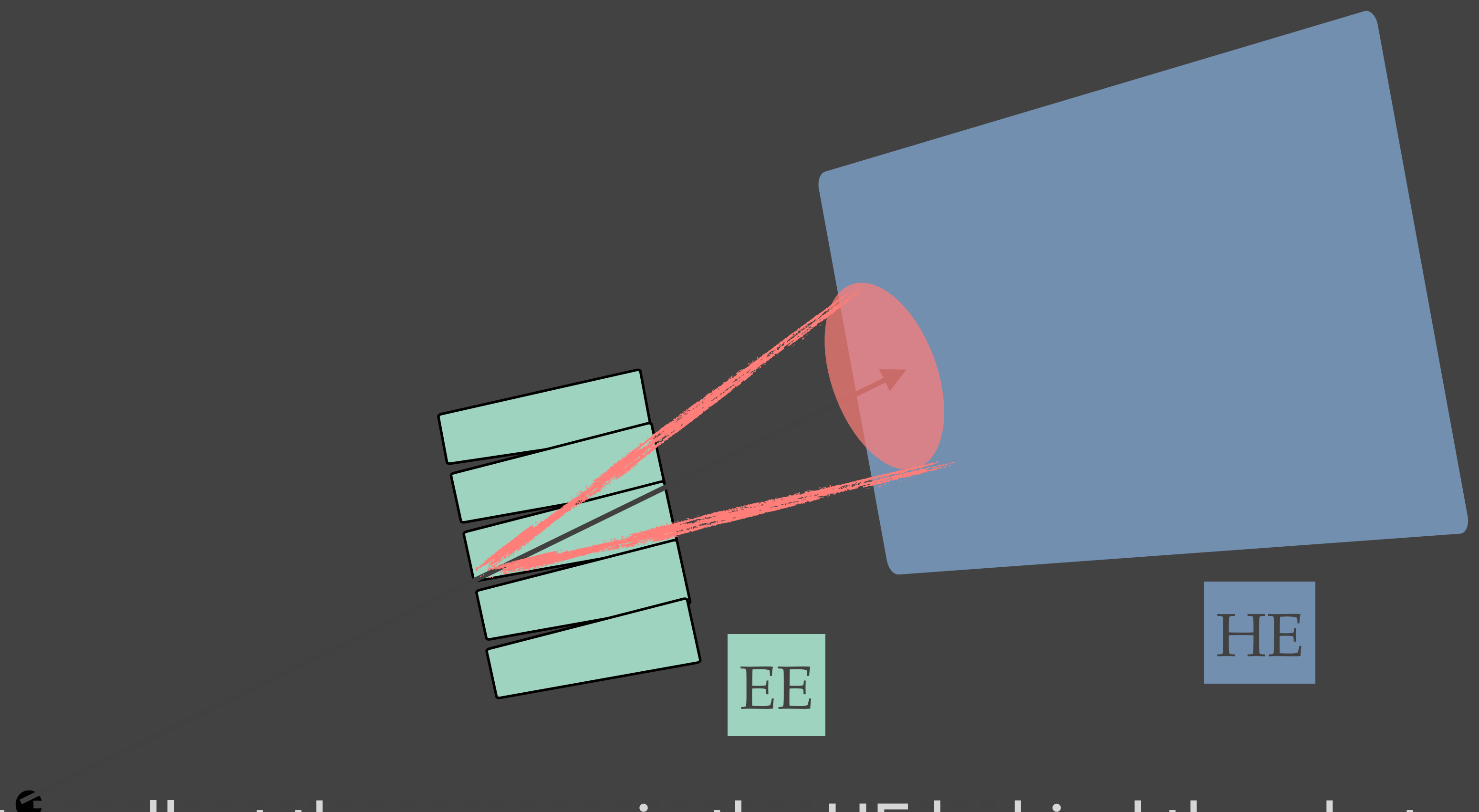
- A photon in the EE can either be a prompt photon (i.e. coming from the collision vertex) or a beam halo (i.e. traveling parallel to the z axis)
- Thus two hypothesis are formed:
  - prompt
  - BH (beam halo)

Angle and energy estimation in 'beam halo' hypothesis



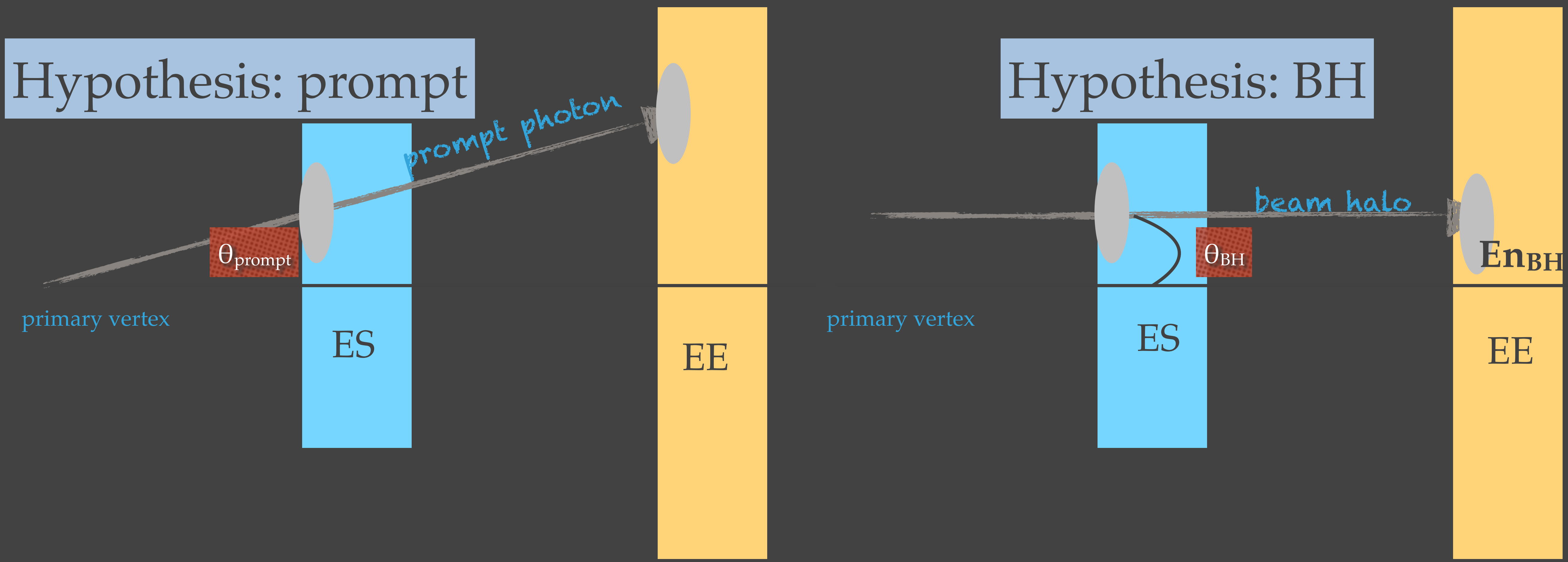
- Idea is to collect the energy in the HE behind the photon in both the hypothesis.
- In addition an angle is formed between the line joining the cluster in the EE and the HE
- In both the hypothesis, a cone is open and hits are collected
    - For BH hypothesis, the cone is formed in Δφ (since the BH travels parallel)

Angle and energy estimation in 'prompt photon' hypothesis



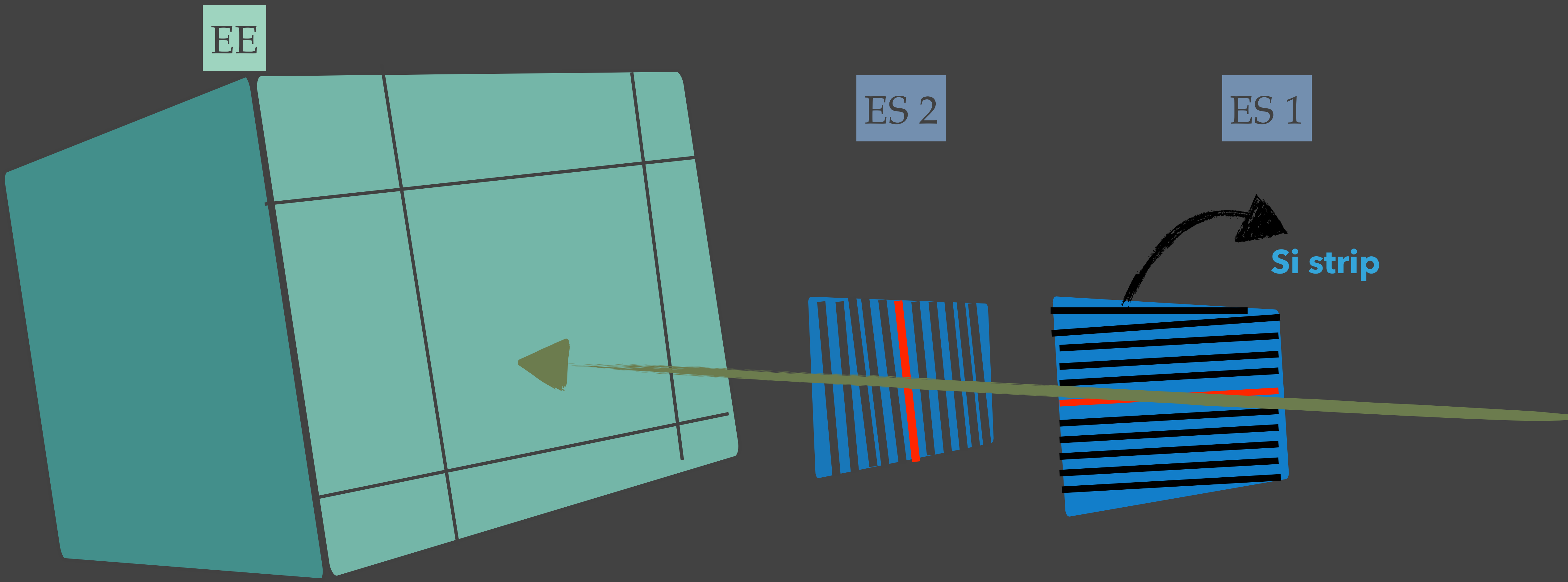
- Idea is to collect the energy in the HE behind the photon in both the hypothesis
- In addition an angle is formed between the line joining the cluster in the EE and the HE
- In both the hypothesis, a cone is open and hits are collected
  - For BH hypothesis, the cone is formed in $\Delta\varphi$ (since the BH travels parallel)
  - In case of prompt hypothesis, a cone is opened in $dR = \mathrm{sqrt}(\Delta\eta^2 + \Delta\varphi^2)$

Idea between preshower (ES) and the EE



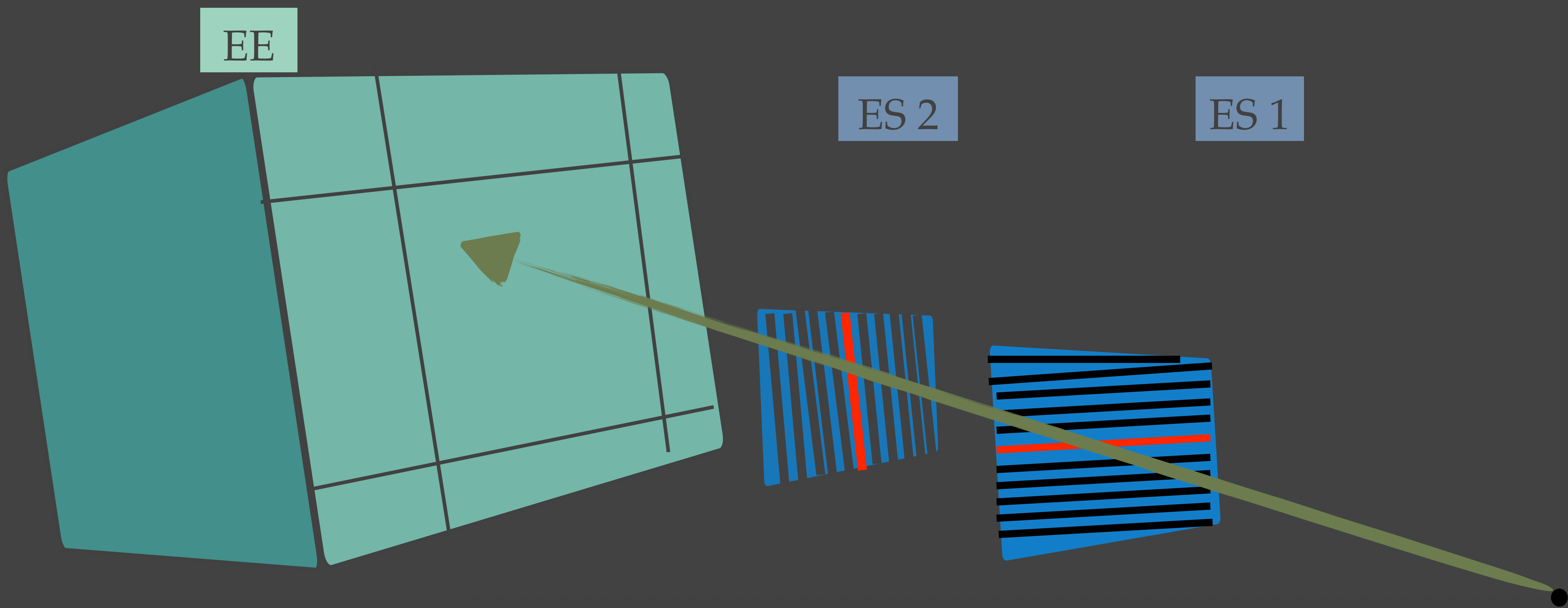
- Exactly the same idea of two hypothesis between the preshower and the EE

Angle and energy estimation in 'beam halo' hypothesis



- Extrapolate from the position of the photon in the EE to that in the ES assuming the photon traveled parallel to the beam axis
- Collect the hits in the preshower planes
- Again form the angle between the line joining the position in the ES and the EE and collect the energy in the ES

Angle and energy estimation in 'prompt photon' hypothesis



- Extrapolate from the position of the photon in the EE to that in the ES assuming the photon came from the collision vertex
- Collect the hits in the preshower planes
- Again form the angle between the line joining the position in the ES and the EE and collect the energy in the ES

Input variables

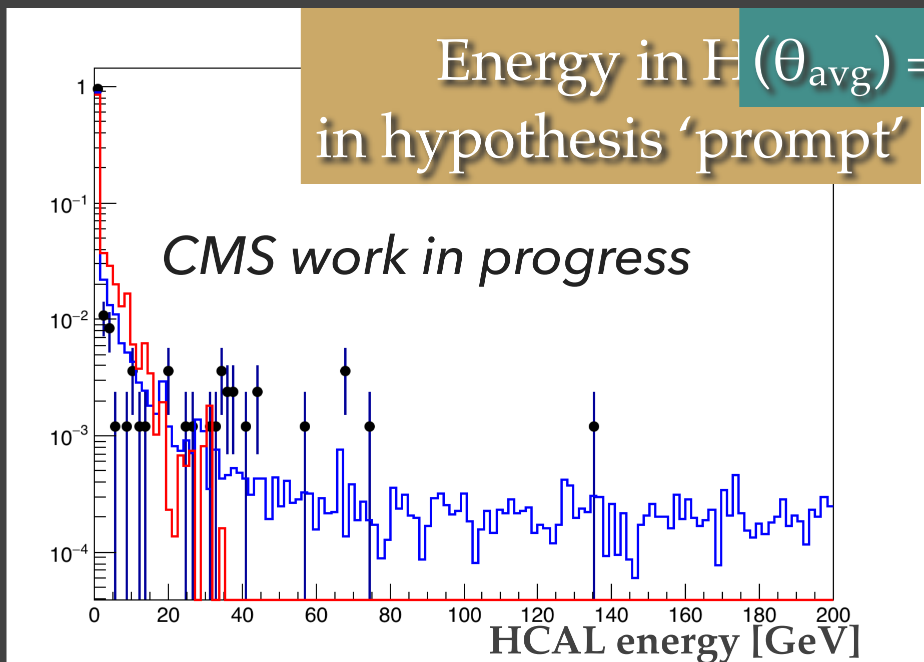
- Energy in HE/ES in both the hypothesis
- Energy weighted average angle (average over both the hypothesis to see which one is more favored) the cluster of deposited in the HE/ES with that in the EE wrt the Z axis

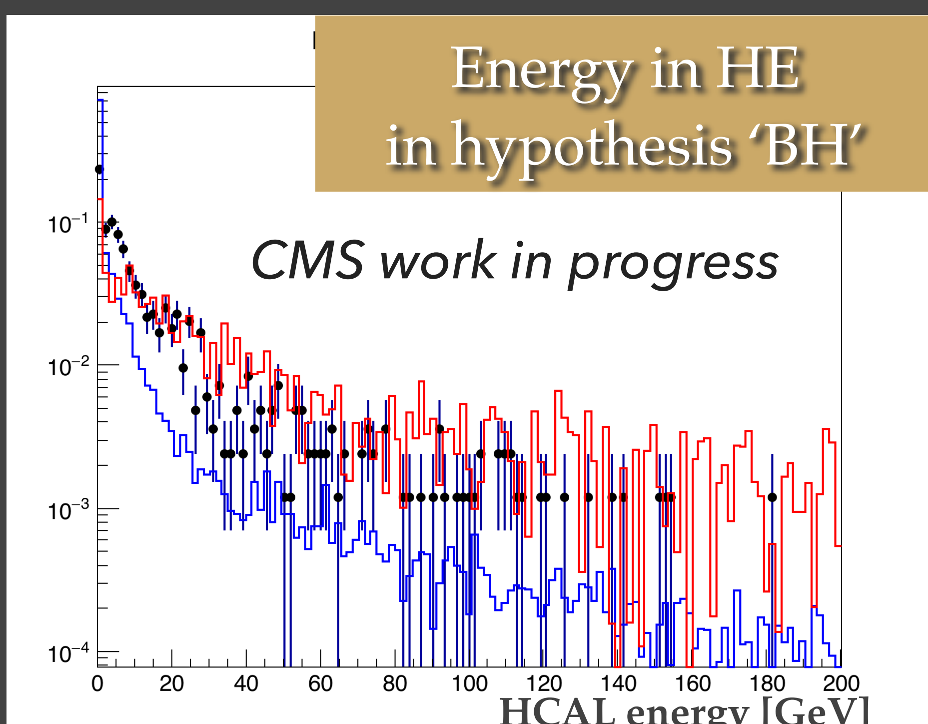
$$(\theta_{avg}) = (En\_prompt * \theta\_prompt + En\_BH*\theta\_BH)/(En\_prompt+En\_prompt)$$

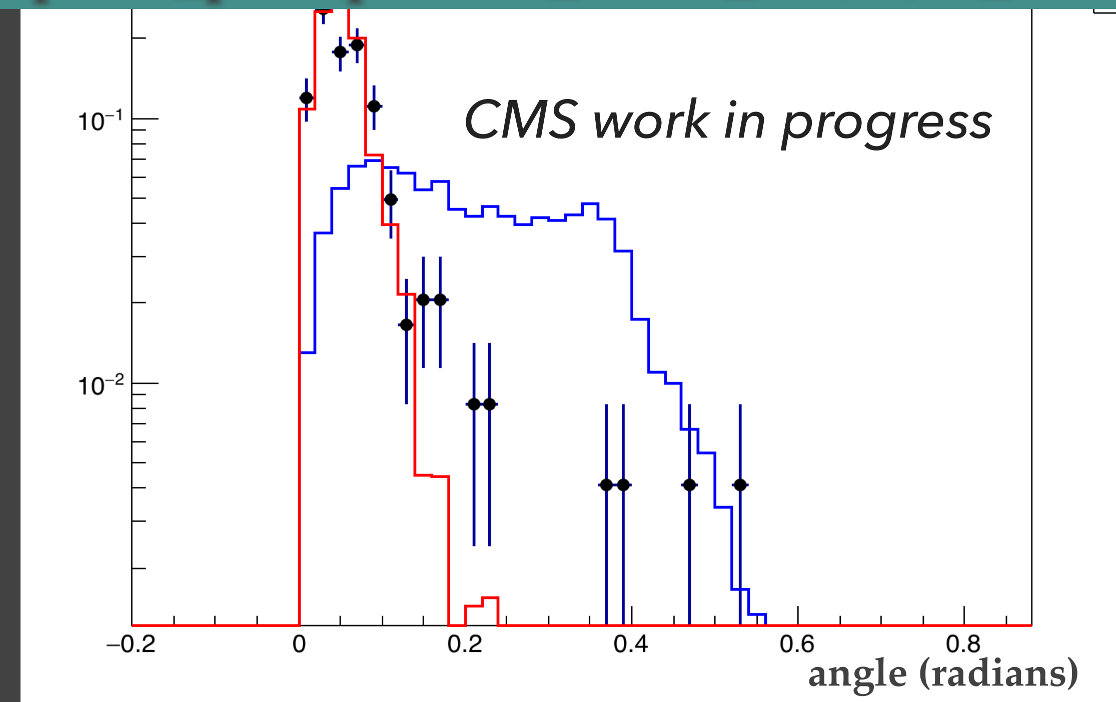
- where θ_prompt is the angle made by the photon in hypothesis 'prompt' and θ_BH is the angle in hypothesis 'BH'. En_prompt is the energy in the HE/ES in the 'prompt' hypothesis and Eb_BH is the energy in the hypothesis 'BH'
- Beam being parallel to the Z axis would tend to have angles ~0

Energy and angle variables in the HE

$(\theta_{avg}) = (En\_prompt * \theta\_prompt + En\_BH*\theta\_BH)/(En\_BH+En\_prompt)$







Data BH

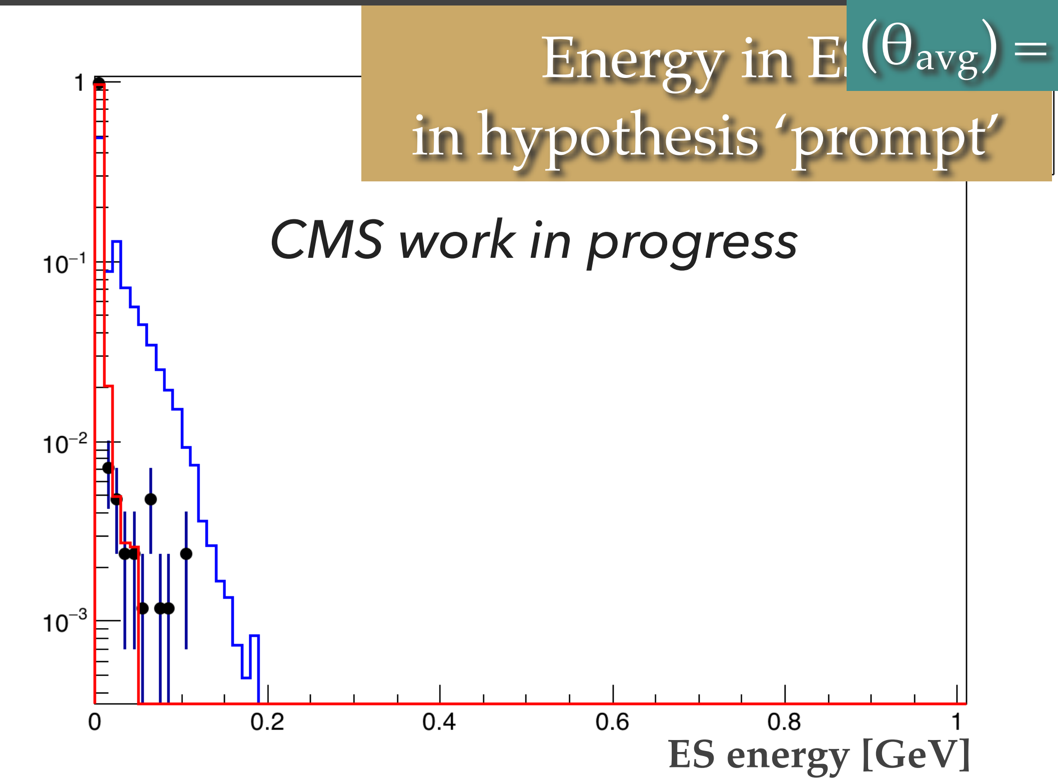
MC BH

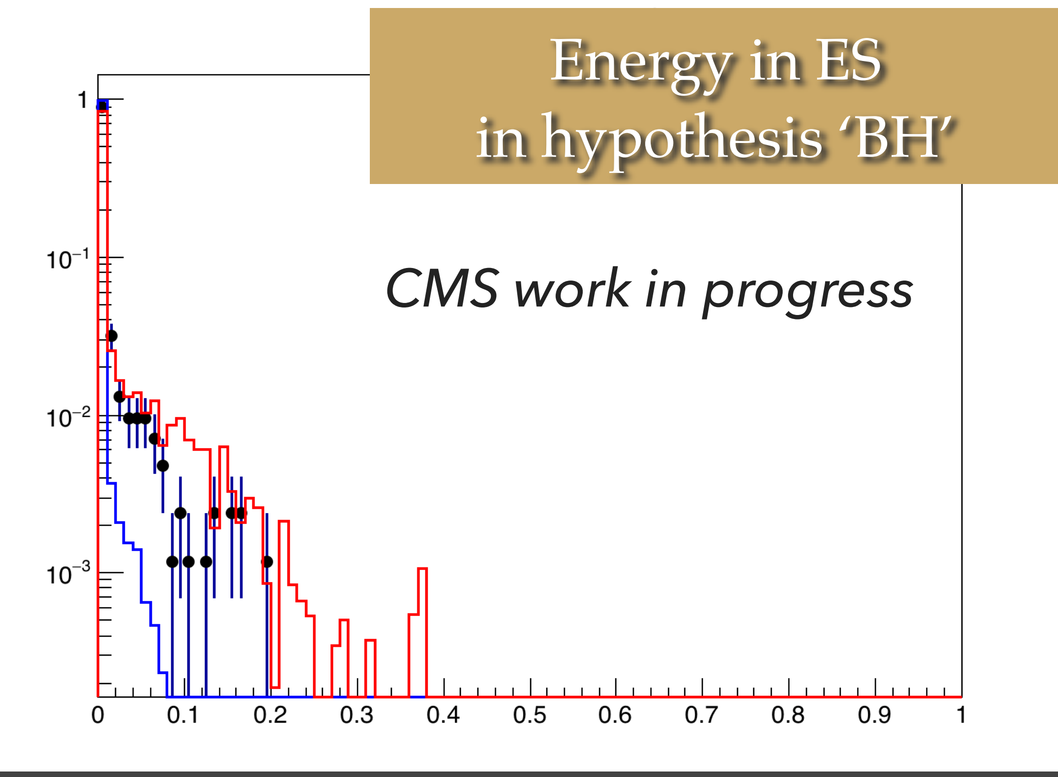
MC prompt

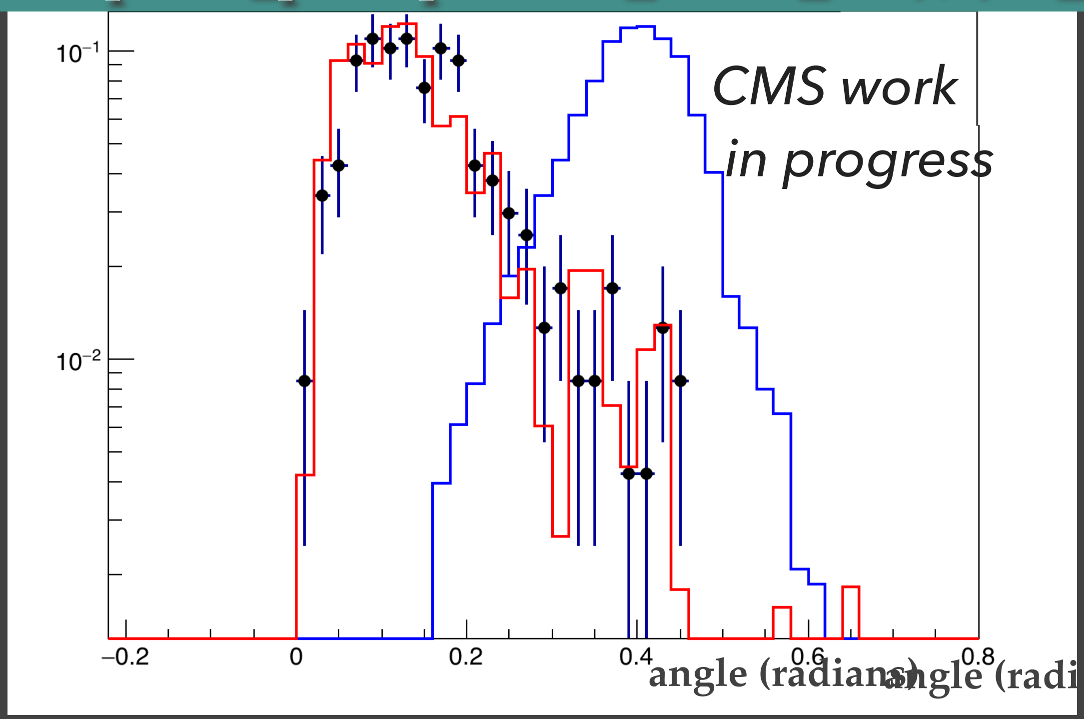
- As expected beam halo in both data and MC peak ~0 whereas the prompt photons are away from 0

Energy and angle variables in the ES

$(\theta_{avg}) = (En\_prompt * \theta\_prompt + En\_BH*\theta\_BH)/(En\_BH+En\_prompt)$







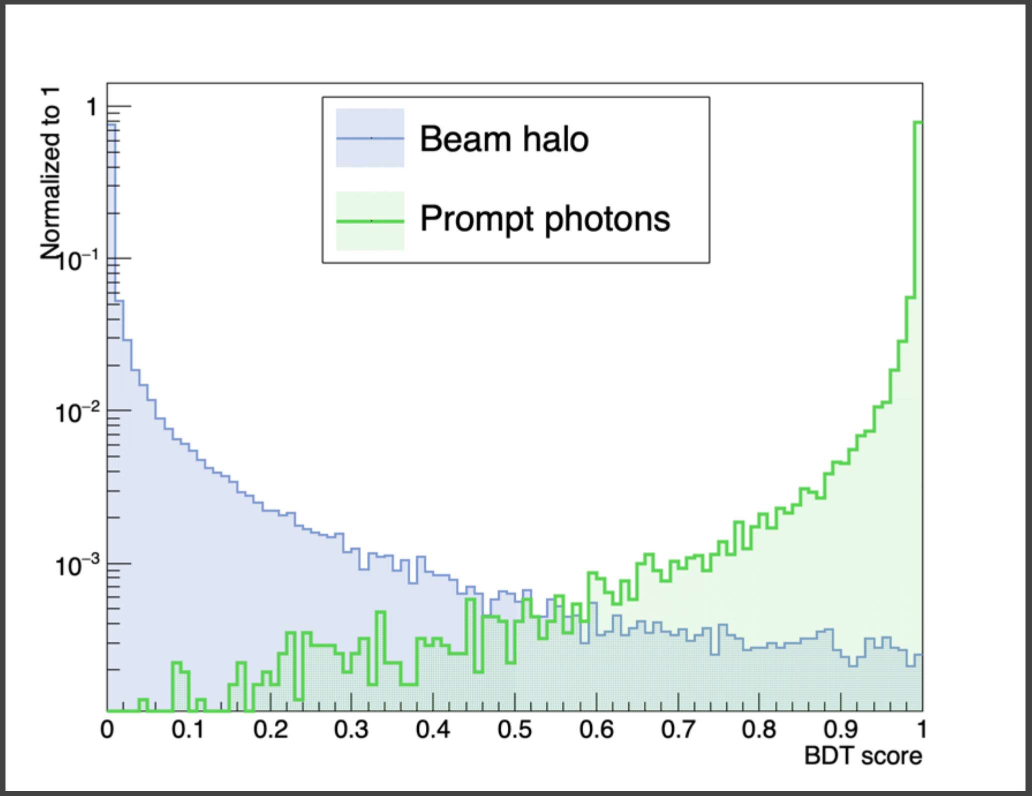
Data BH

MC BH

MC prompt

- As expected beam halo in both data and MC peak ~0 whereas the prompt photons are away from 0

- The variables thus formed + a few more shower shape variables in the EE are fed to an xgboost
- The output of xgboost is used to reject the beam halo in the analysis
- This tagger is being used in the mono-photon analysis
  - Extends the acceptance of this analysis to EE



Plans for run 3 and beyond with the BHMs

- Currently this detector is under testing and preparation phase
- Since quartz and PMTs are radiation hard detectors, plan for run 3 is to continue using the current detectors with an upgrade to the firmware
- For HL-LHC, there is a possibility to readout the BHM into L1 trigger system and provide an independent measurement of the beam halo for the CMS searches
- References: 1, 2, 3

BACKUP

Particle spectrum

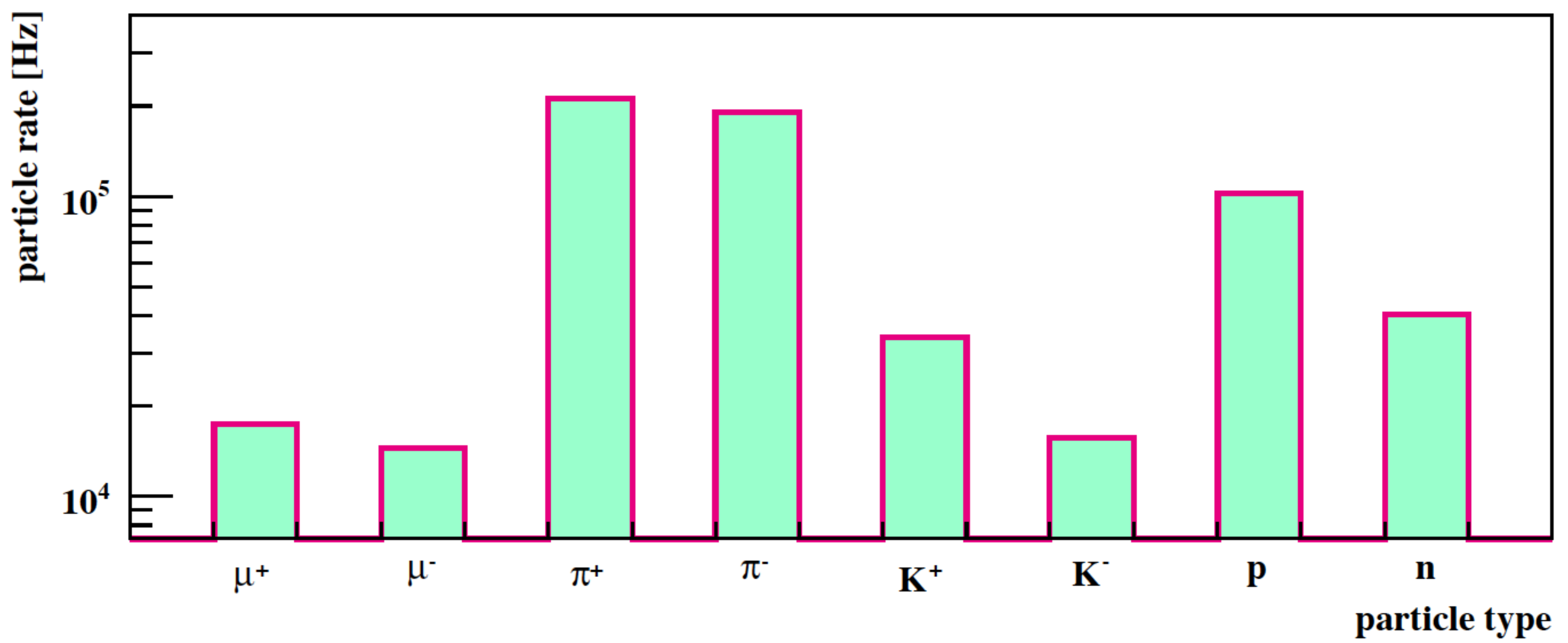


Figure 3: *Rates of the different generated particles at the scoring planes at* $z = \pm 23\,m$.

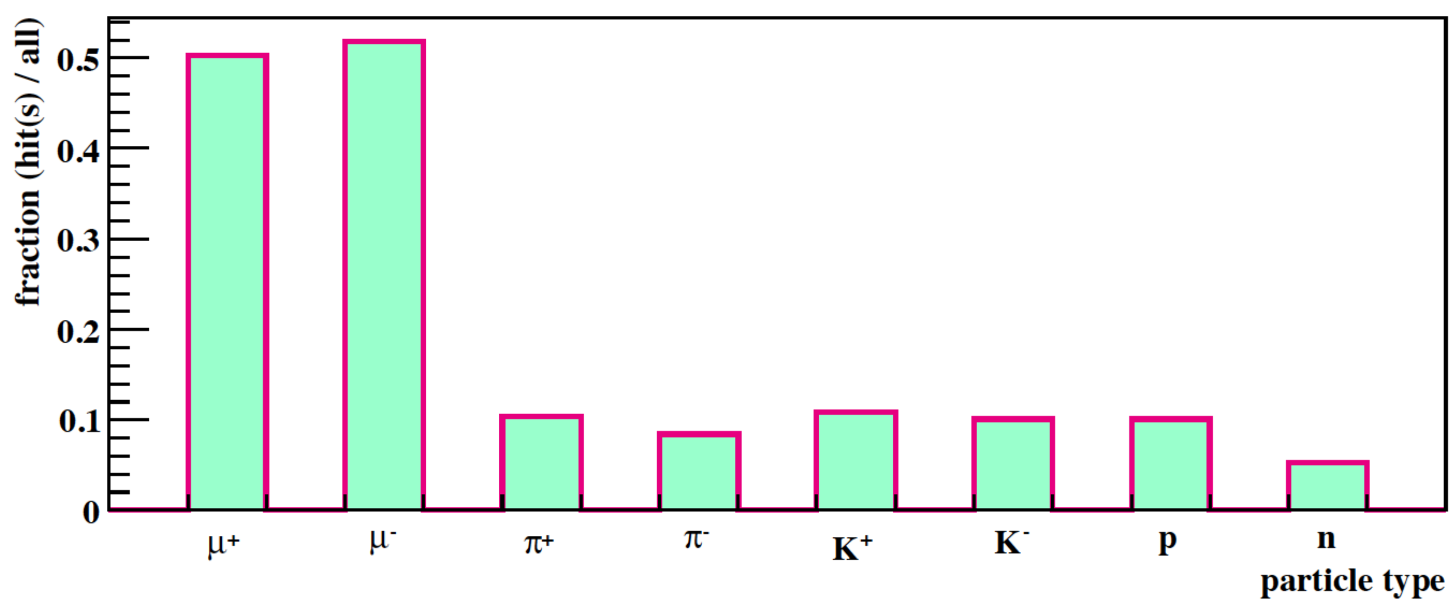
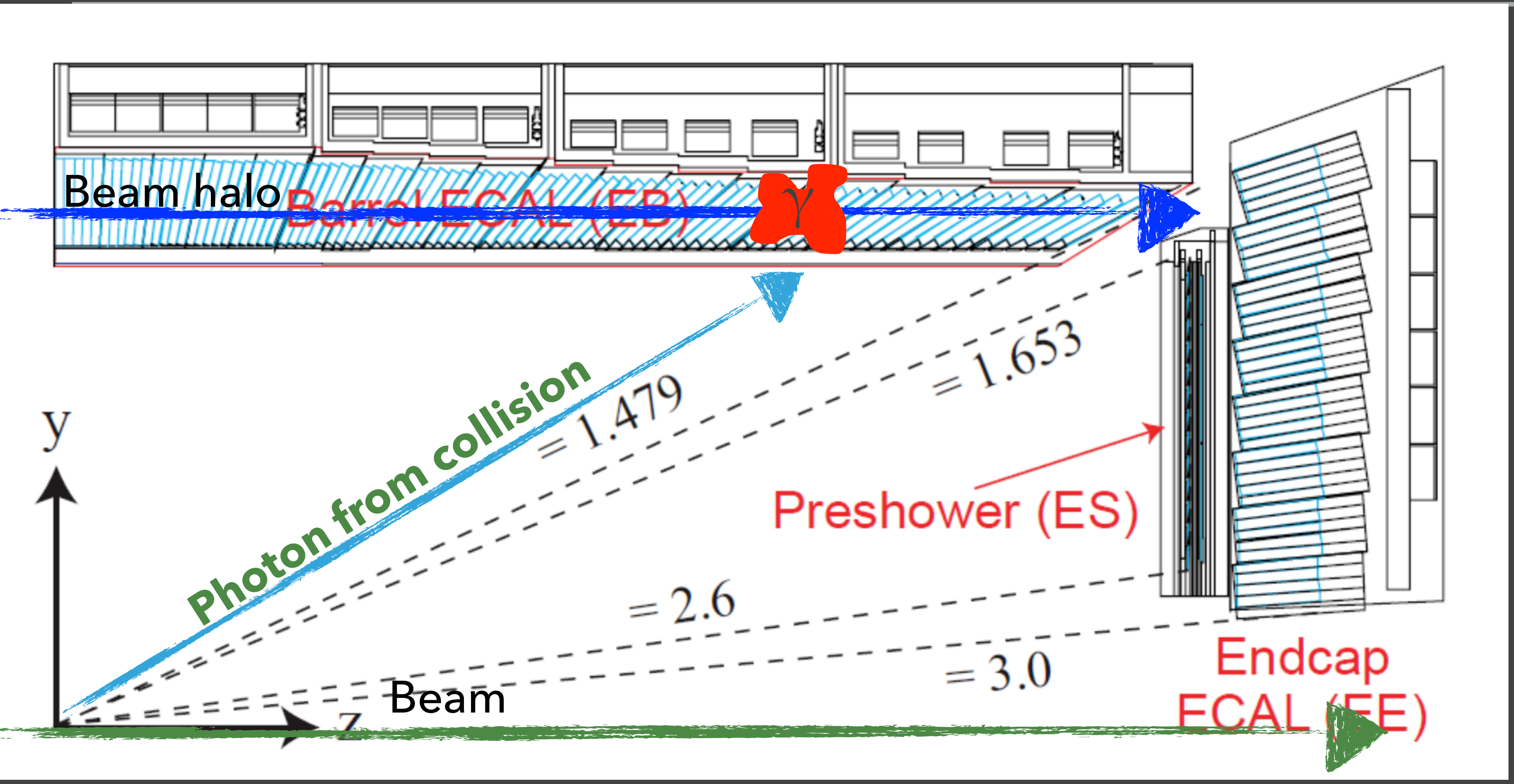
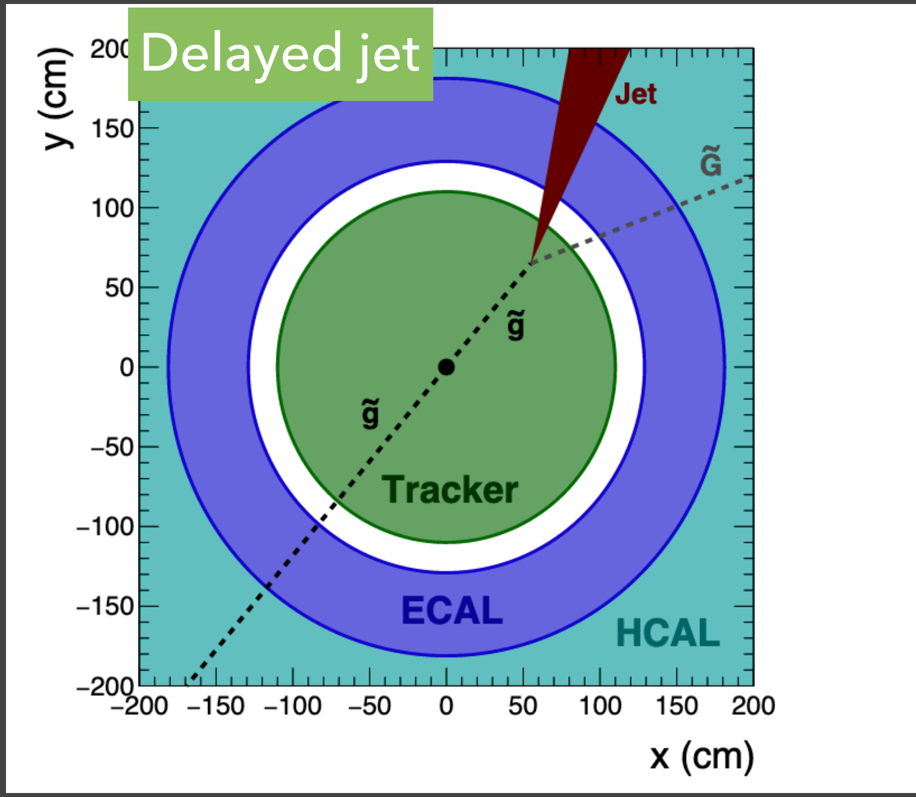


Figure 4: *Fraction of generated particles that cause at least one hit in the CMS detector. Whereas this about 50% for muons it is only about 10% for hadrons.*

Beam halo as background to several searches



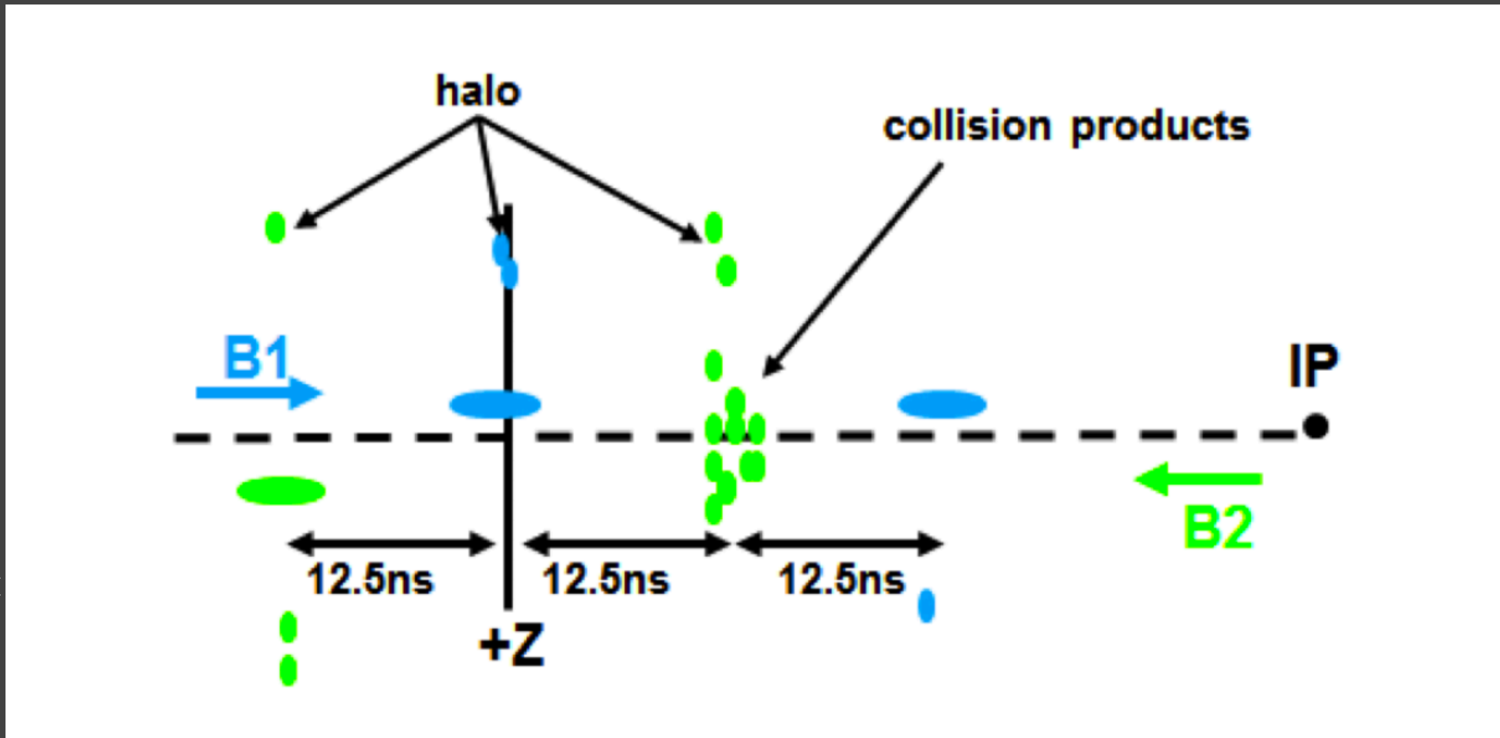
- The beam halo **arrives at a different time (in the ECAL barrel) compared to the collision products**
- Usually to reject such background, timing of the photon is required to be within some window consistent with collisions.

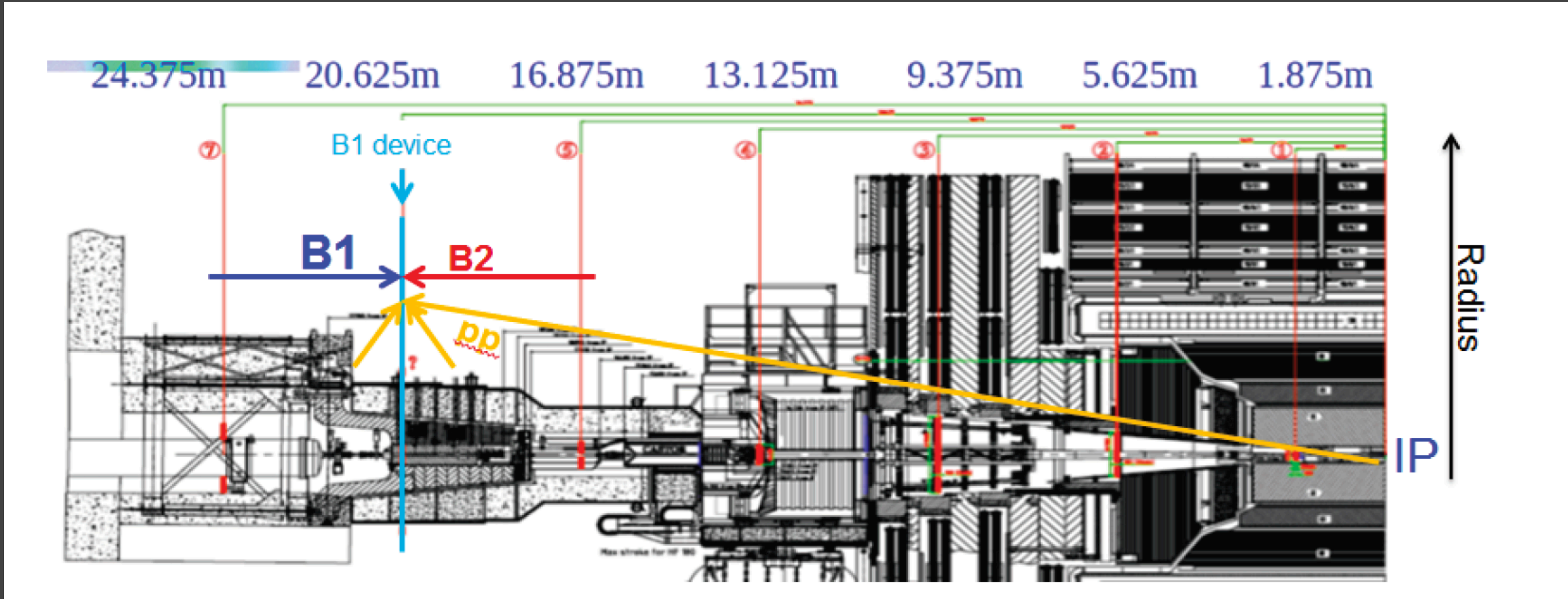


- However, in searches like:
  - Delayed jet: Pair of long-lived gluinos travel ~1 m such that the decayed product (gluon)
    - Jet is delayed in time (matches with the time of beam halo) and is only reconstructed only in the calorimeter
    - Beam halo can be huge

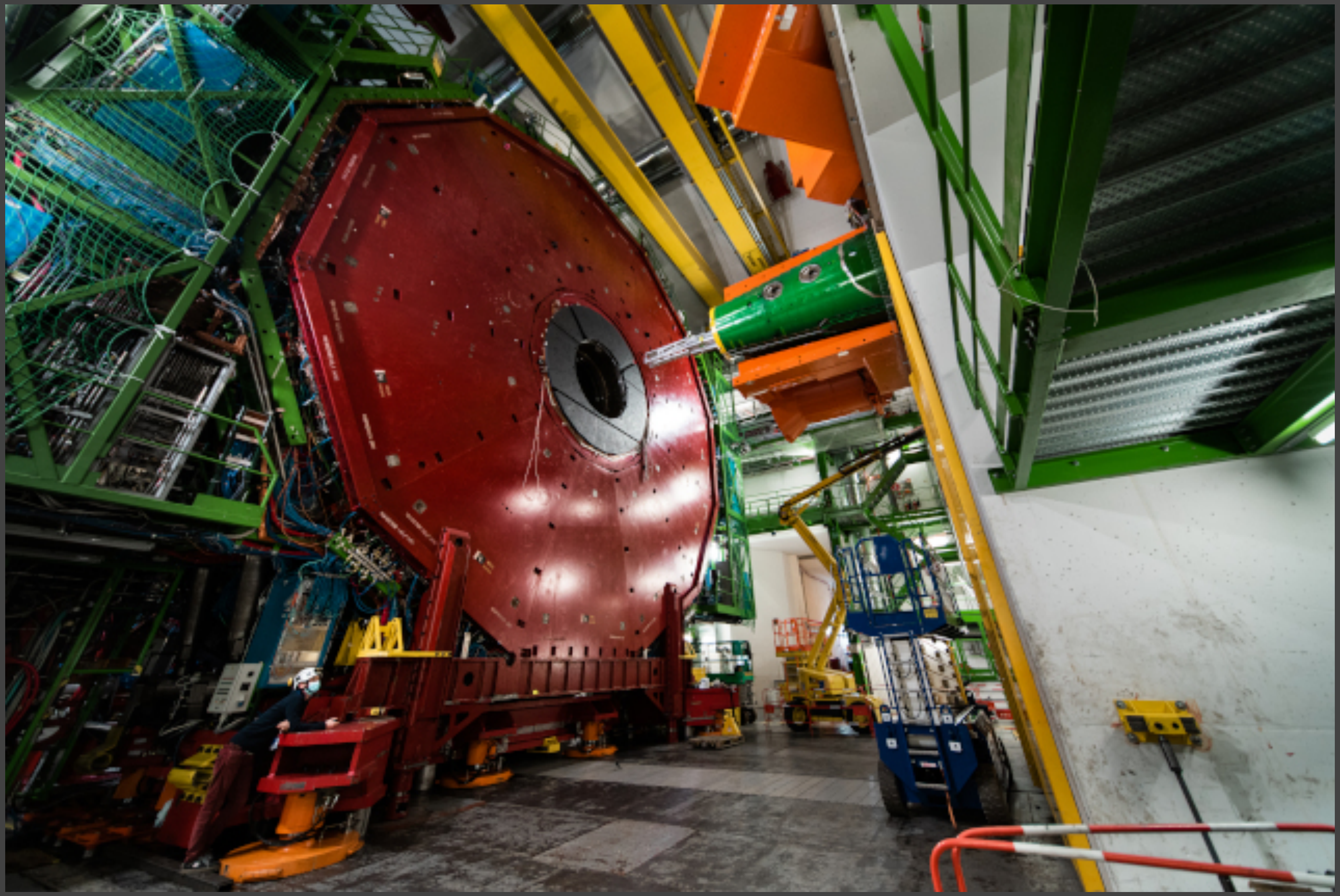
Choice of placement – golden locations

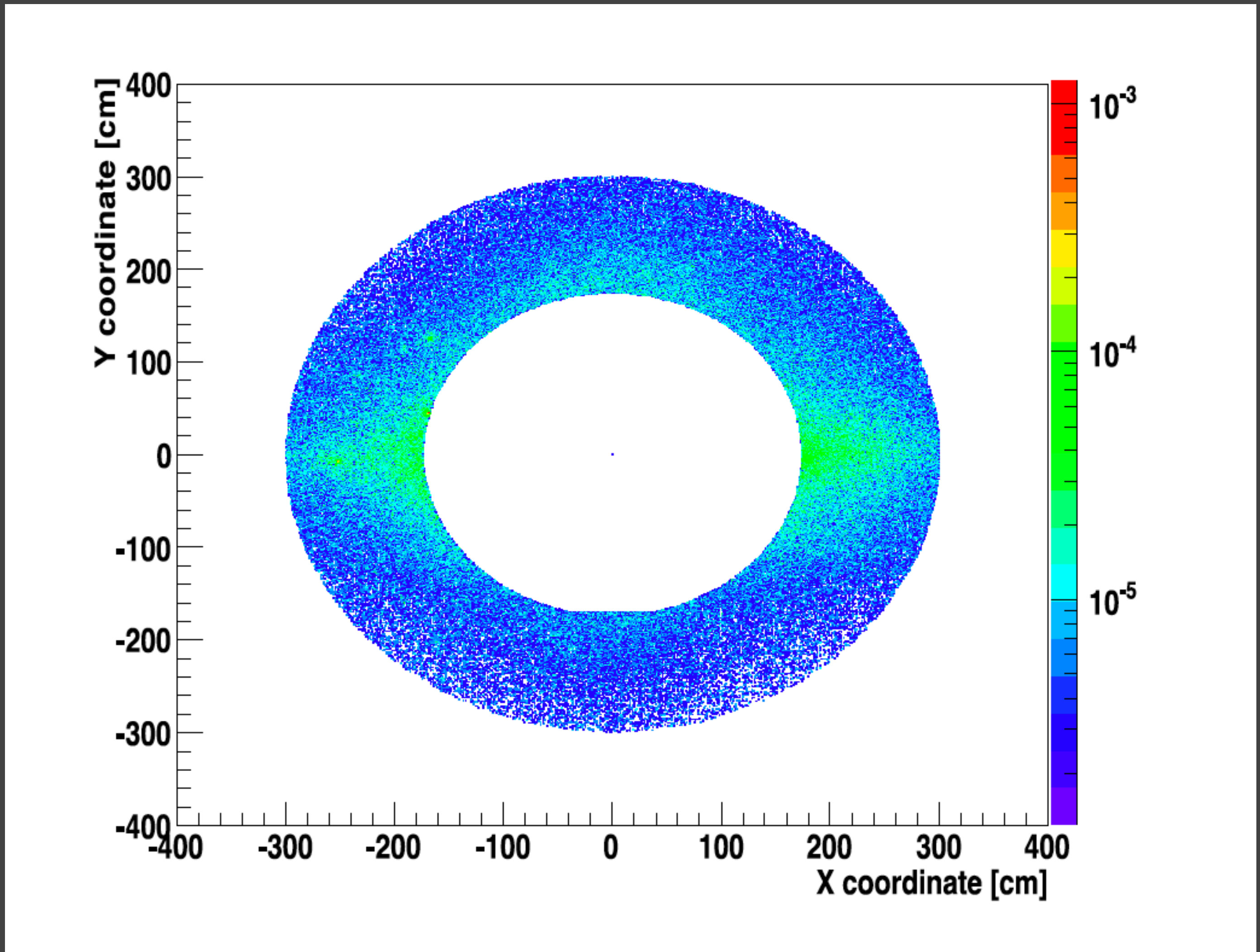
- Bunch spacing of 25 ns imposes a maximum time separation of 12.5 ns between the incoming beam halo and the outgoing beam (and its halo) and the collision products
- 7 golden locations which correspond to this maximum time
- Final choice is at a distance 20.625 m away : less harsh environment, less impact of the CMS magnetic field and least effected by the magnetic field





Rotating shielding




Y coordinate [cm]
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400
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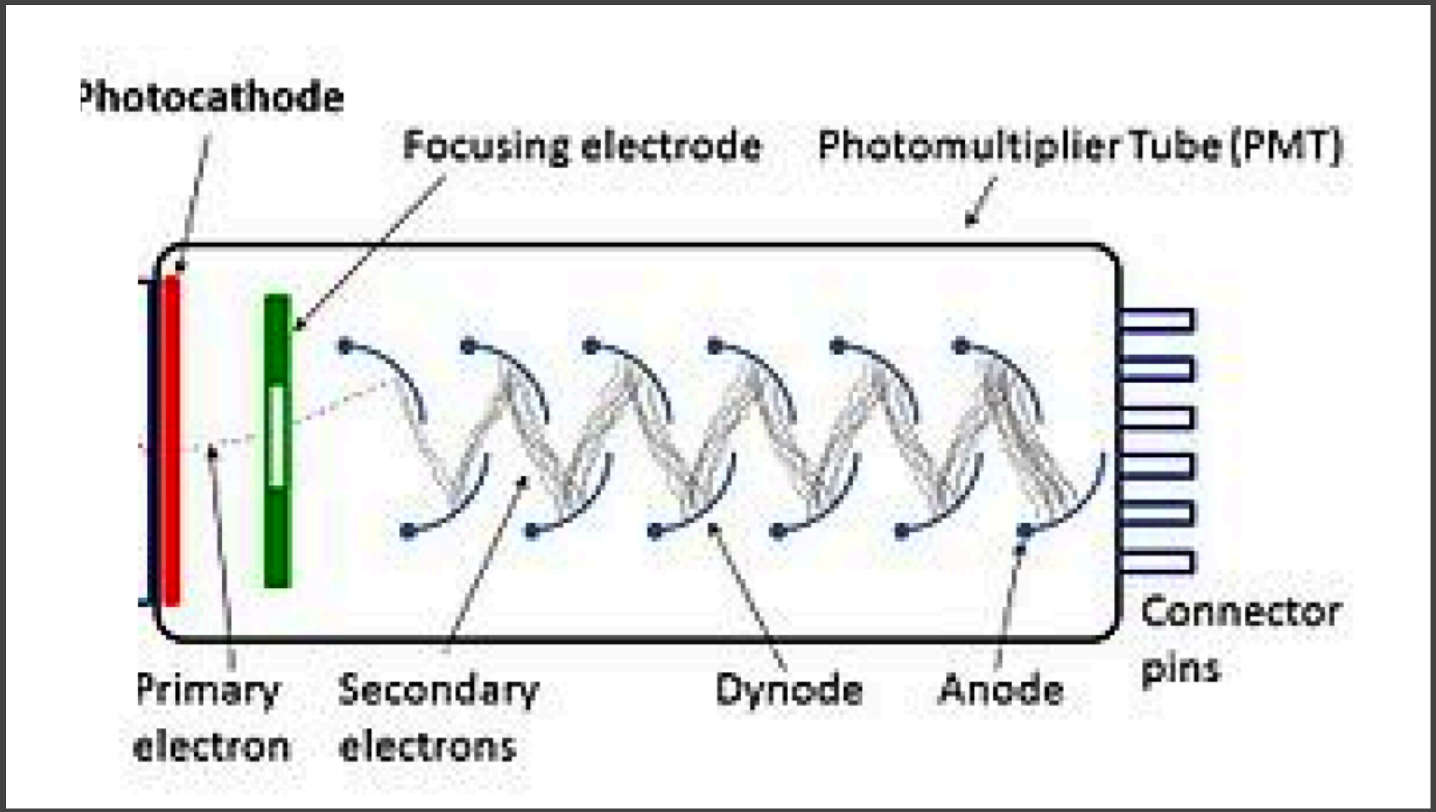
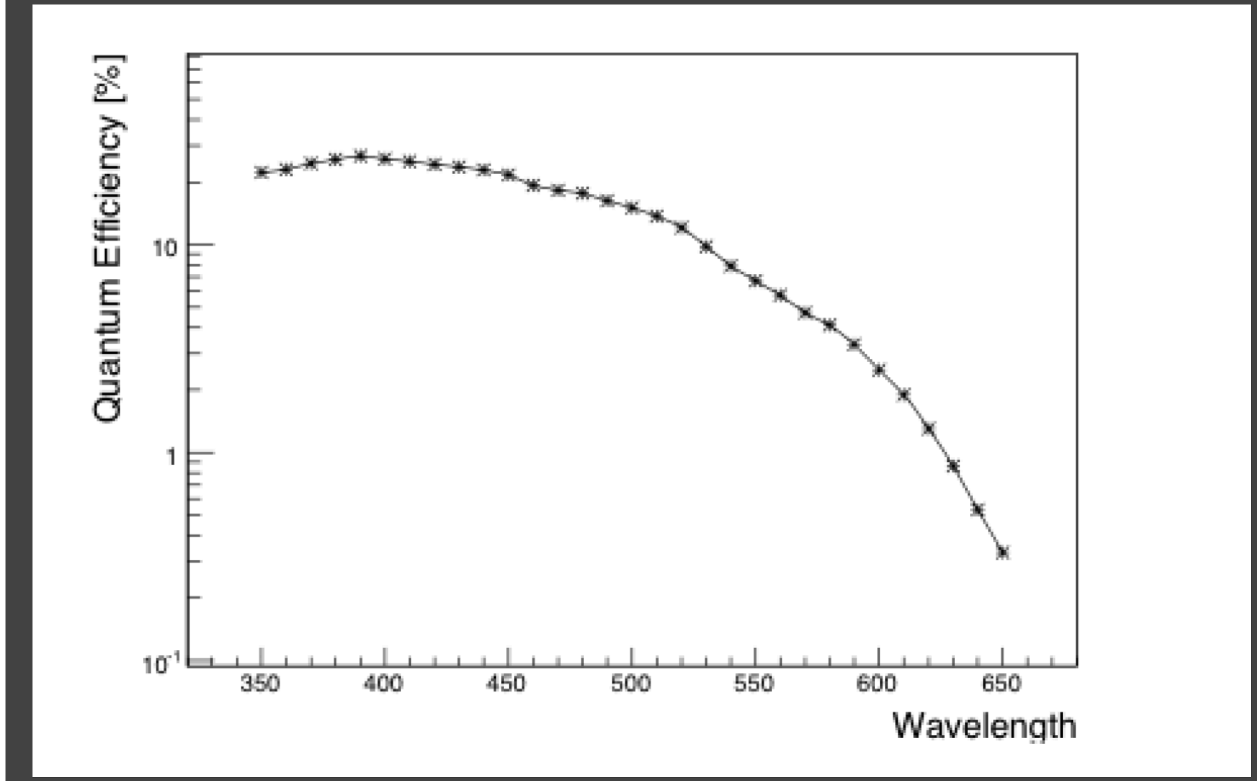
300
400
10^{-3}
10^{-4}
10^{-5}

Photomultiplier tube





~25% at 400 nm

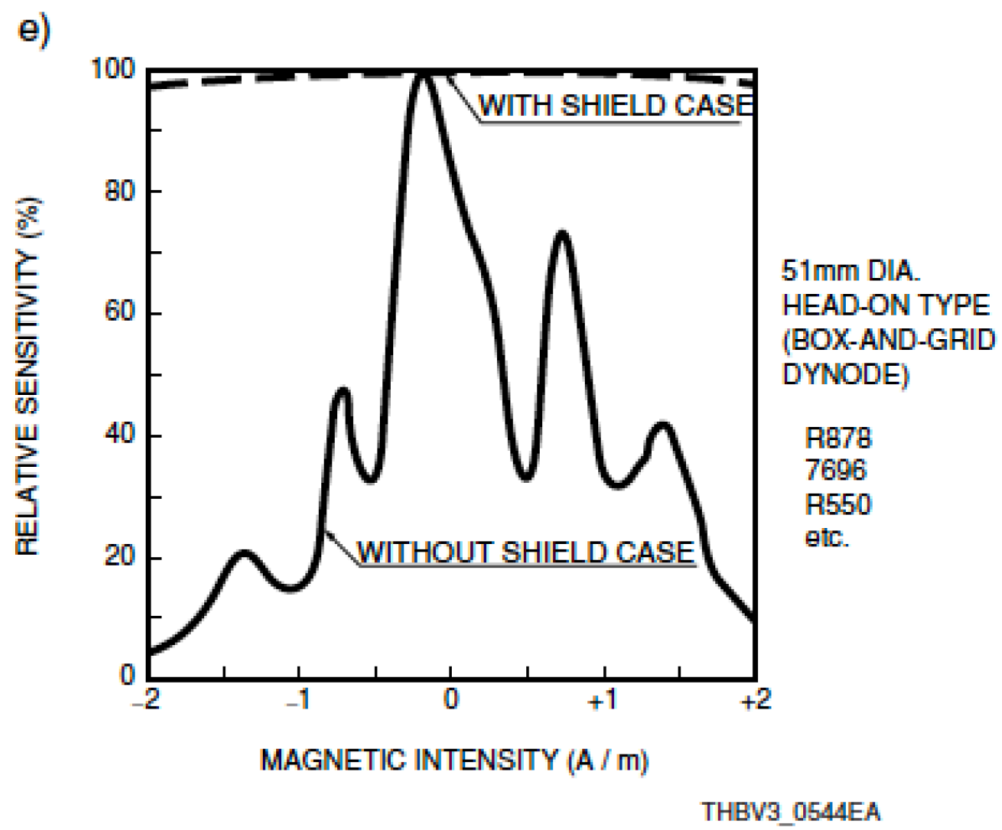


Figure 6.1: Magnetic Characteristics of 51 mm head-on photomultiplier tube as the one used for the BHM detector unit [Hama].

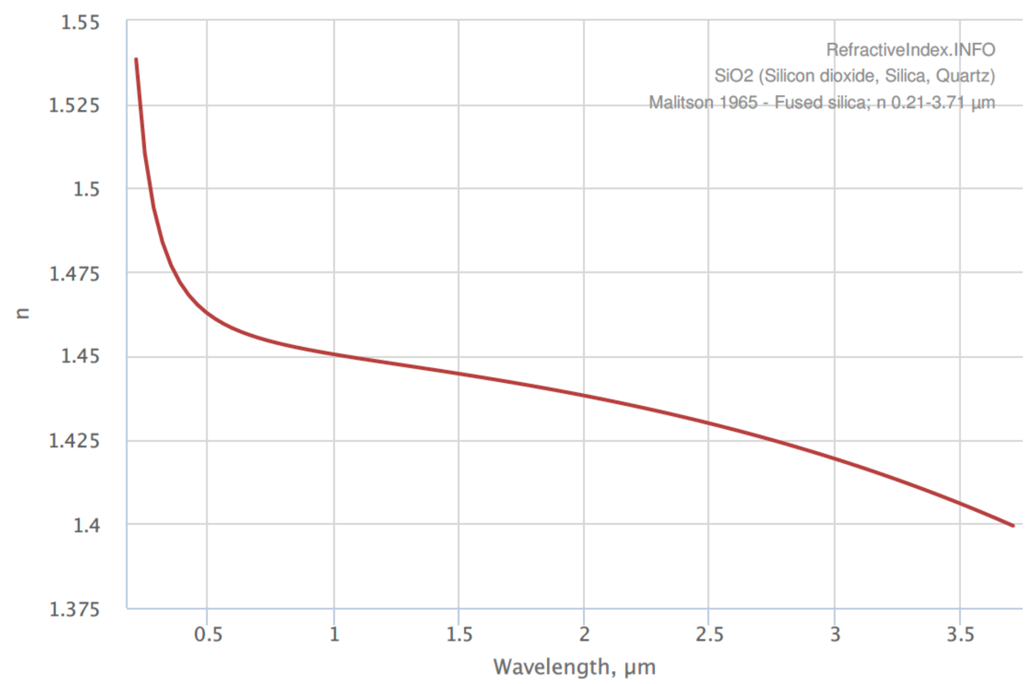


Figure 3.3: The index of refraction of quartz as a function of the wavelength [Pol].

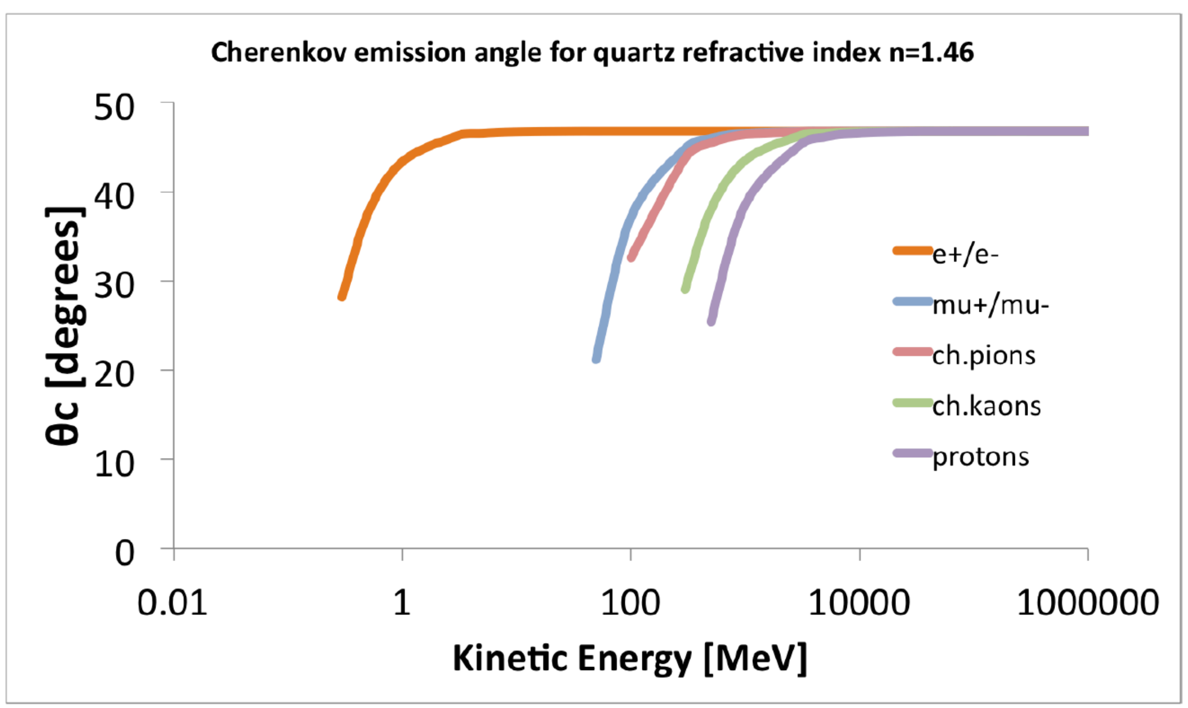
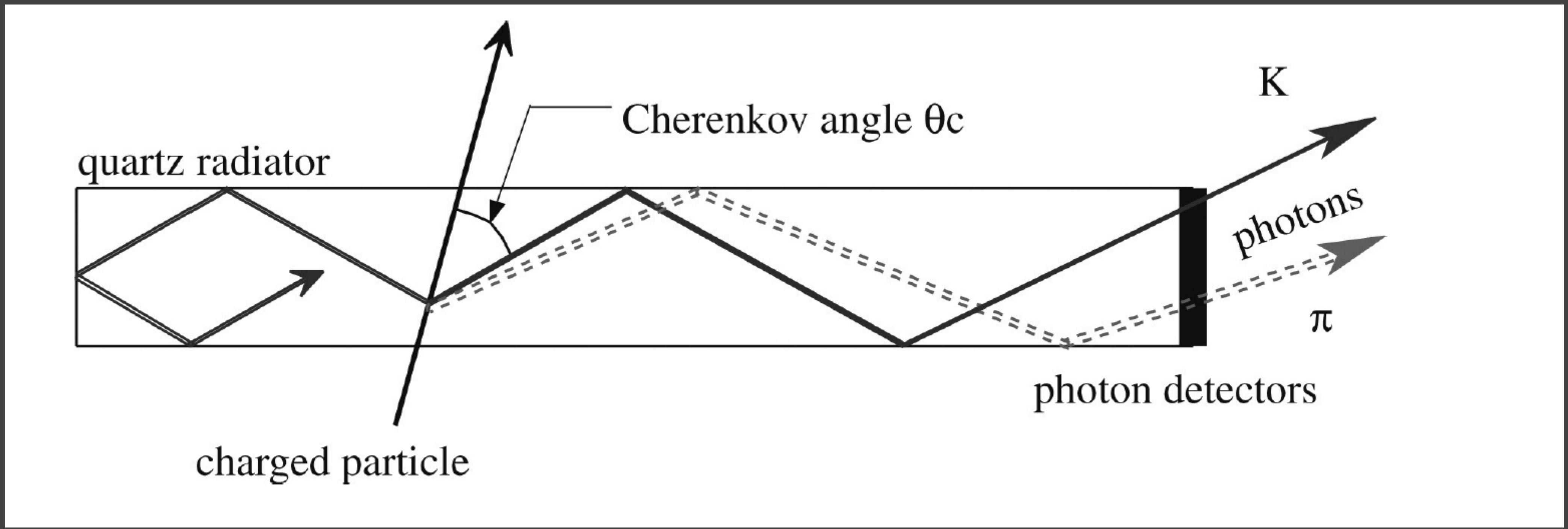


Figure 3.4: Cherenkov angles as a function of momentum for different particle species for n=1.46.



$$\theta_0(\lambda) = \arcsin\left(\frac{n_1(\lambda)}{n_2(\lambda)}\right) = \arcsin\left(\frac{1}{n_2(\lambda)}\right) = \arcsin\left(\frac{1}{1.46}\right) \approx 43^\circ$$

λ (nm)	n	$\beta_{threshold}$	θ_c for $\beta = 1$
200	1.55	0.645	49.5°
300	1.485	0.673	48.0°
400	1.47	0.680	47.2°
500	1.465	0.683	47°
600	1.46	0.685	46.8°

Table 3.1: Index of refraction of quartz n, threshold velocity $\beta_{threshold}$ and angle of emission of Cherenkov photon $\theta_c(\beta = 1)$ for various wavelengths.

particle type	Rest mass (MeV)	E (MeV) for $\beta = 0.65$	E (MeV) for $\beta = 0.99$
e^+, e^-	0.511	0.161	0.190
mu^+, mu^-	105.7	33.38	39.37
protons	938.2	296.38	349.58
charged kaons	493.6	155.93	183.92
charged pions	139.6	44.09	52.00

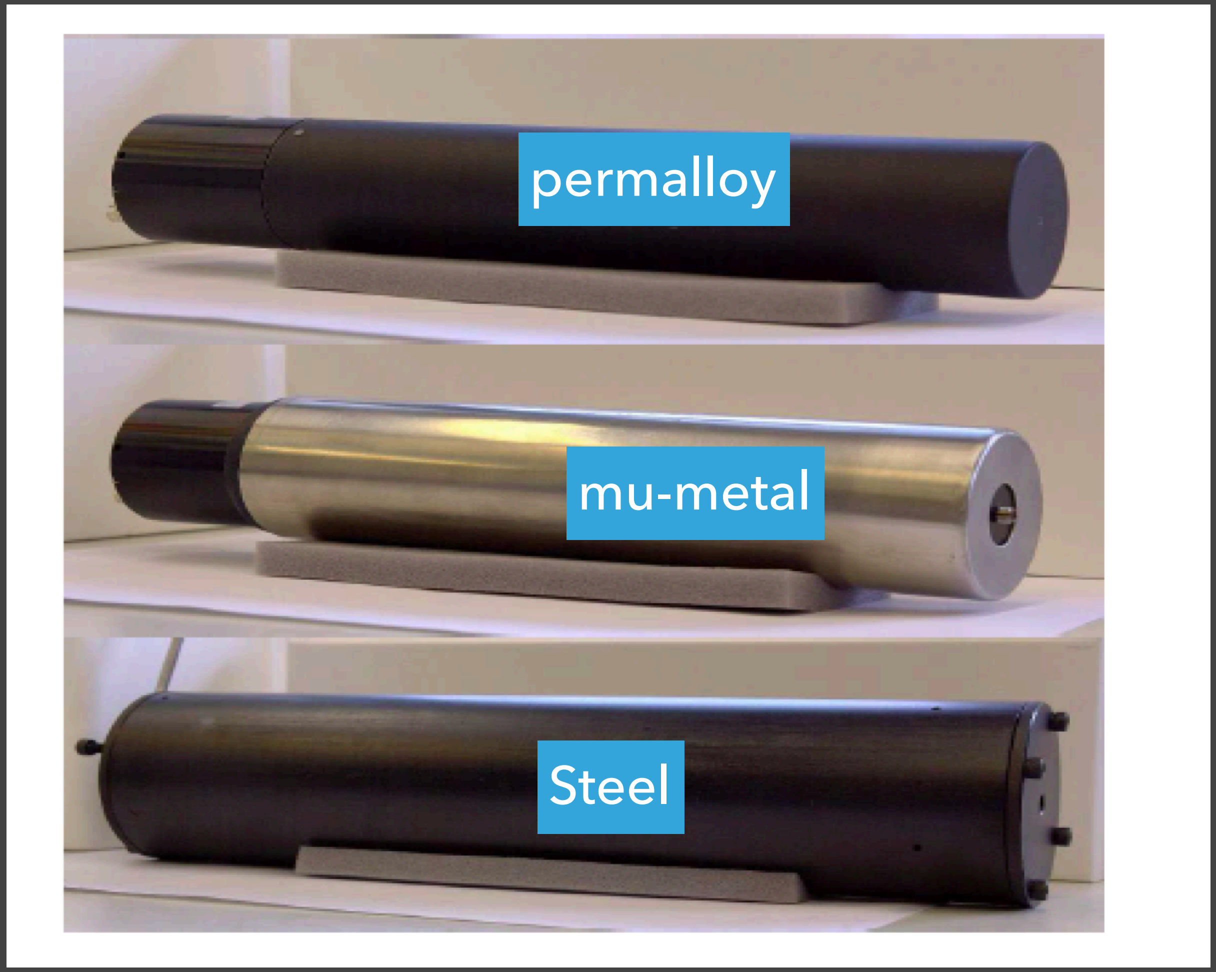
Table 3.2: Total energy for β=0.65 and β=0.99 for various charged particles.

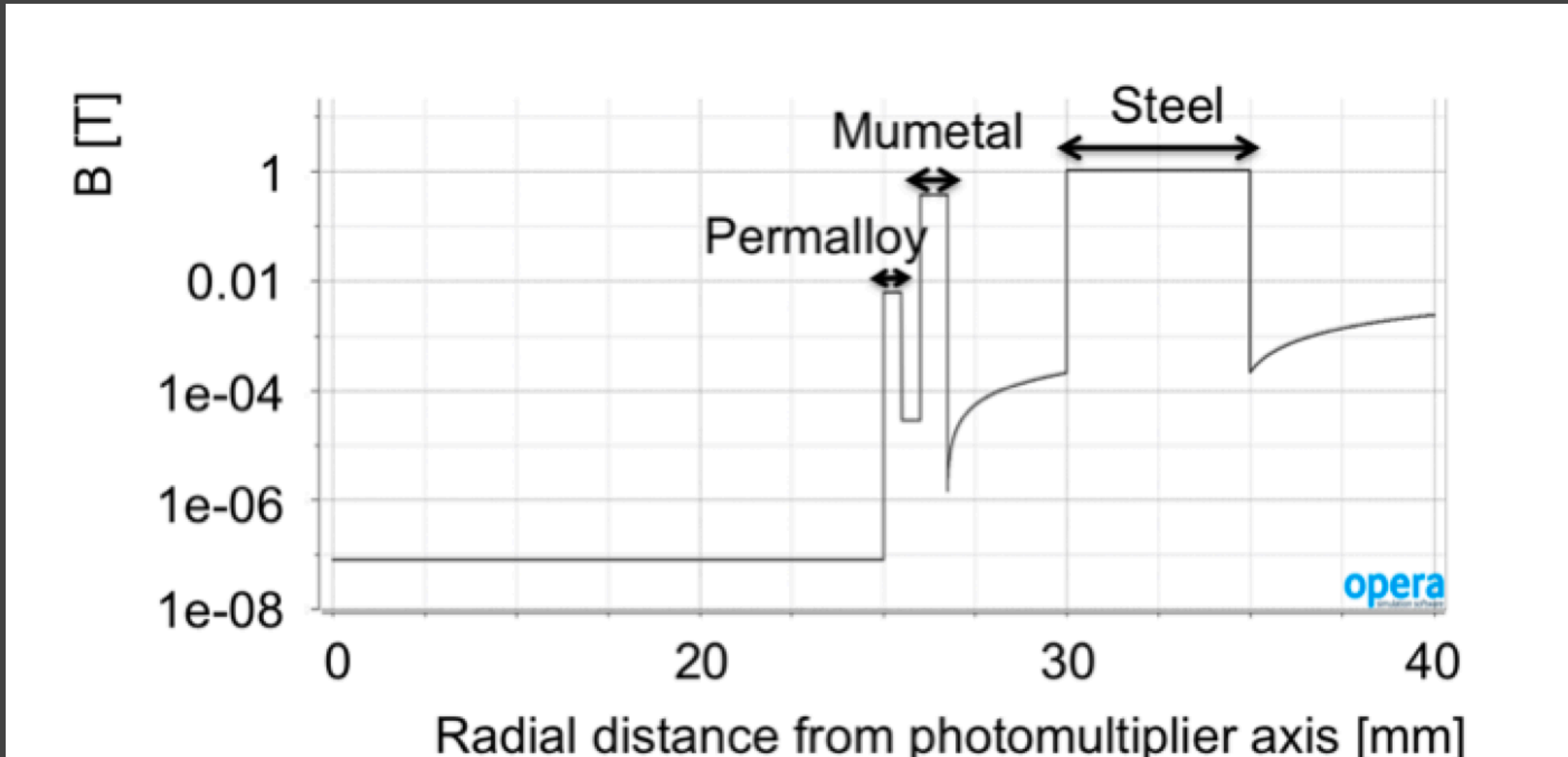
BHM requirements

Characteristic	Value
Acceptance per beam	$300\,cm^2$
Time resolution	ns
Particle sensitivity	Direction-sensitive response to charged particles with a rejection power of $O(10^3)$
	Insensitive to γ 's and thermal neutrons
Radiation hardness	100 krad
Magnetic field tolerance	18 mT with angle of 20°to beam axis
Logistical issues	Cost effective
	Robust mechanics
	Limited weight

Table 4.2: The summary of the BHM design requirements.

Magnetic shielding of a BHM unit





- PMT has increased sensitivity to the magnetic field
- To take care of this, it is shielded with a specific casing
- Shielding consists of 3 highly permeable materials which reduce the field to a very low level:
  - permalloy
  - mu-metal
  - Steel

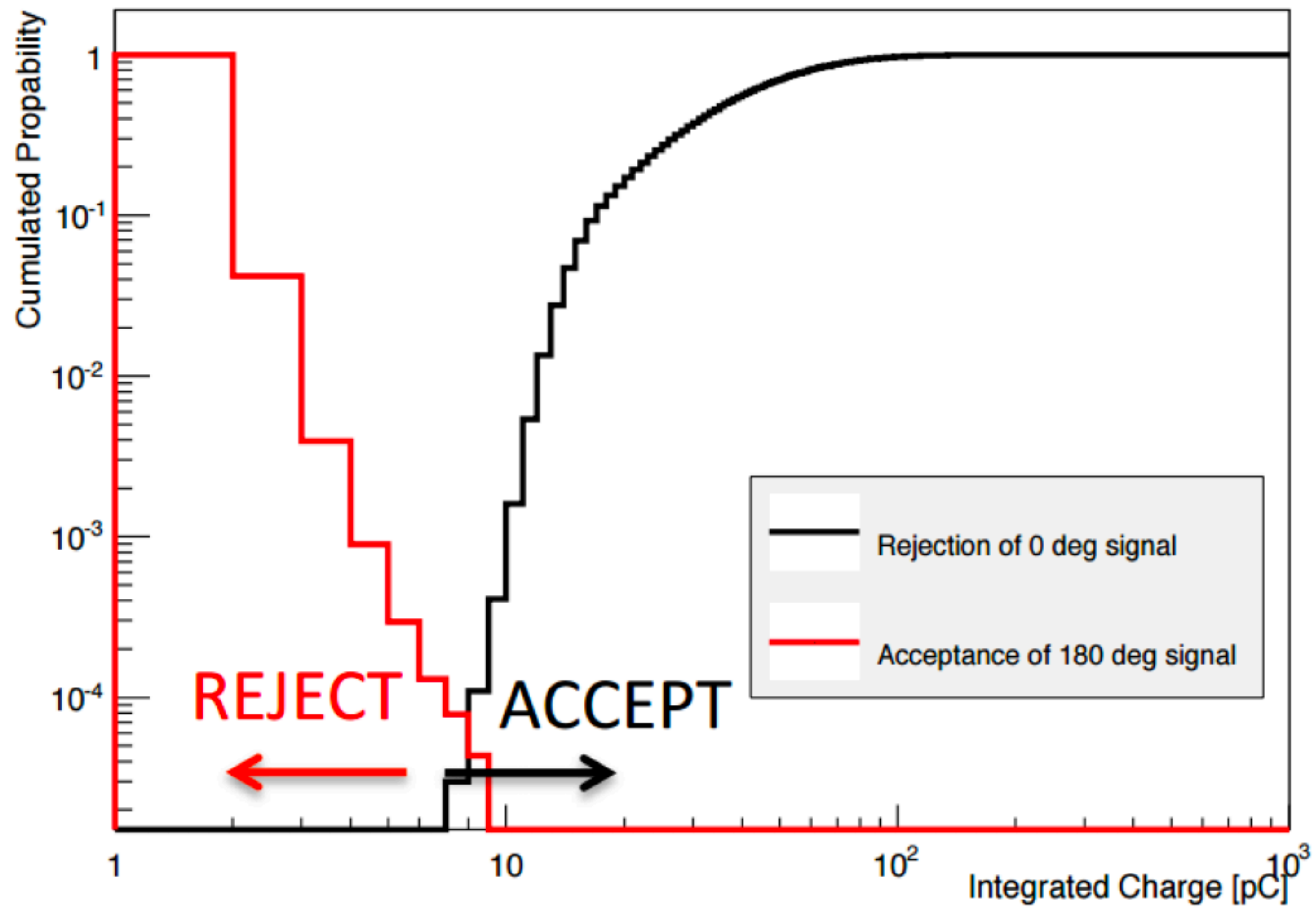
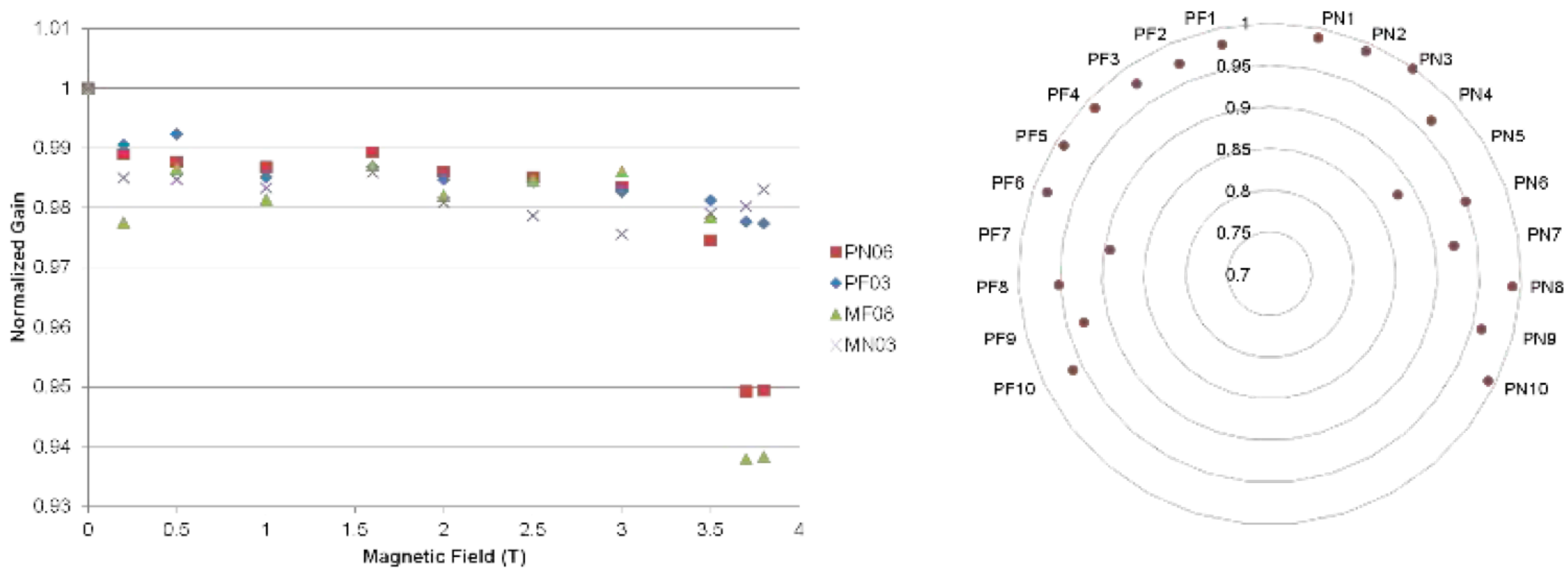


Figure 3.8: Cumulative integral of the normalized distributions of the signal charge measured for electrons with angles of 0° and 180°.



(a) PMT gain vs. Magnetic field

(b) % decrease in PMT gain at 3.8 T

Figure 4.7: *Top:* Normalized PMT gain versus magnetic field strength, shown for four sample units. *Bottom:* Percentage decrease in PMT gain at maximum field of 3.8T, shown for all units measuring beam 1.

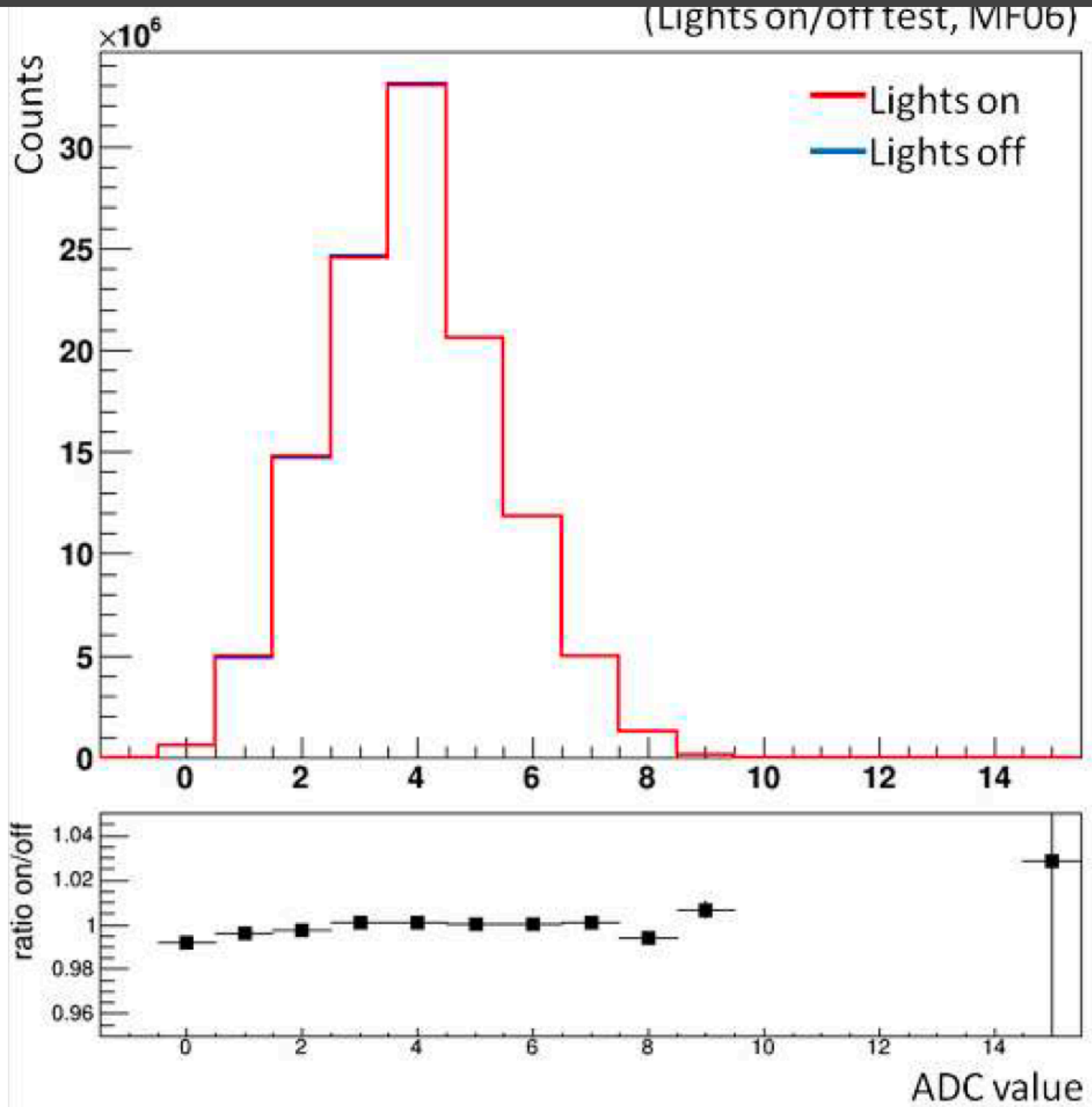


Figure 4.8: Detector units showed no change in response, regardless of light in the CMS cavern.

Location	Distance from IP [m]	MIB flux [particles $/cm^2]/s$	Ratio of MIB flux/Collision products flux
4	13.125	(0.108±0.022)-(0.868± 0.343)	2×10^{-3}-8×10^{-2}
5	16.875	(0.135±0.017)-(1.556± 0.335)	4×10^{-4}-2×10^{-3}
6	20.625	(0.113±0.016)-(1.883±0.843)	4×10^{-4}-4×10^{-3}

Table 4.1: Comparison of the ratio and the absolute flux in the candidate locations.

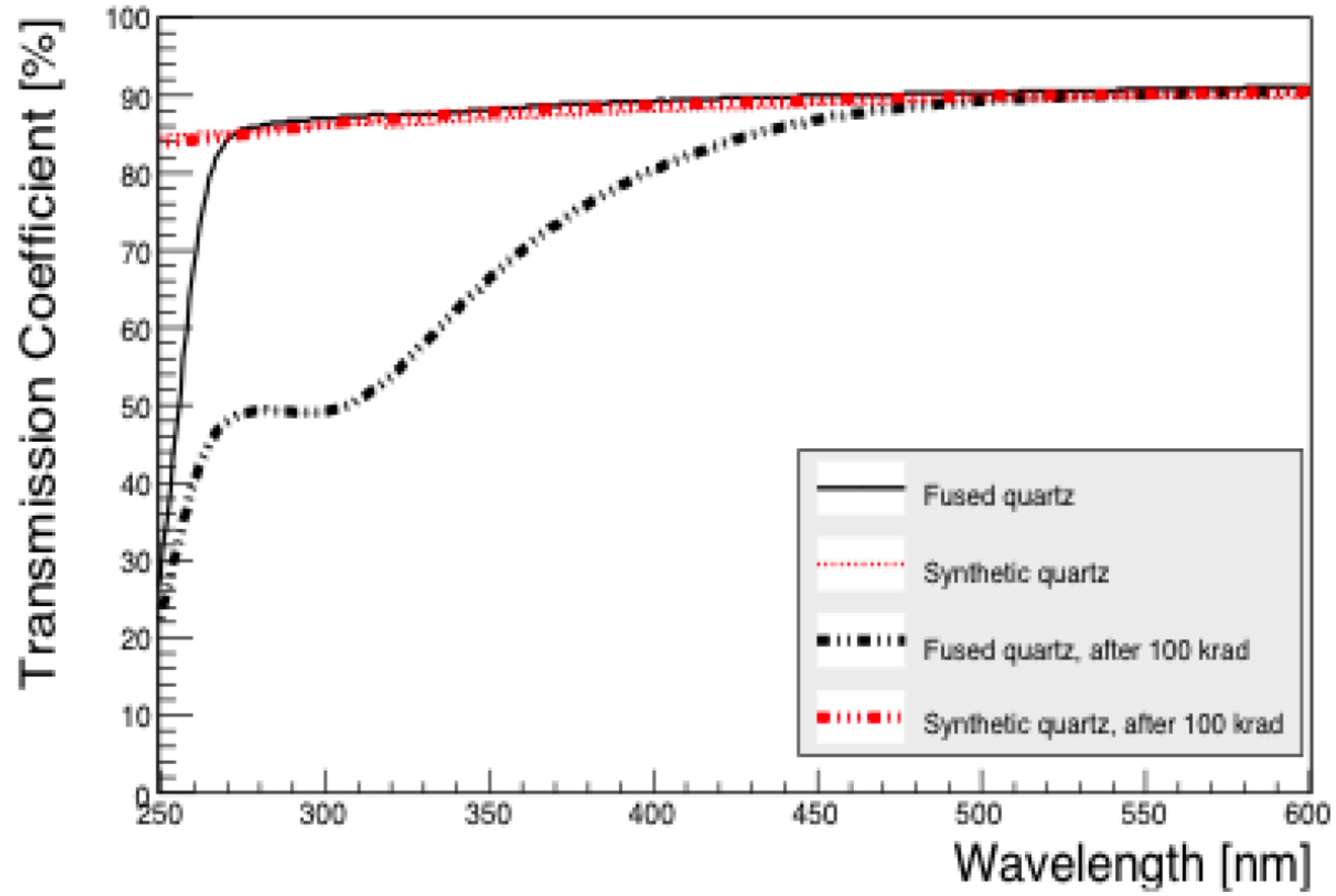


Figure 5.2: The transmission coefficients for natural and synthetic fused quartz as a function of the wavelength before and after irradiation with a dose of 100 krad.

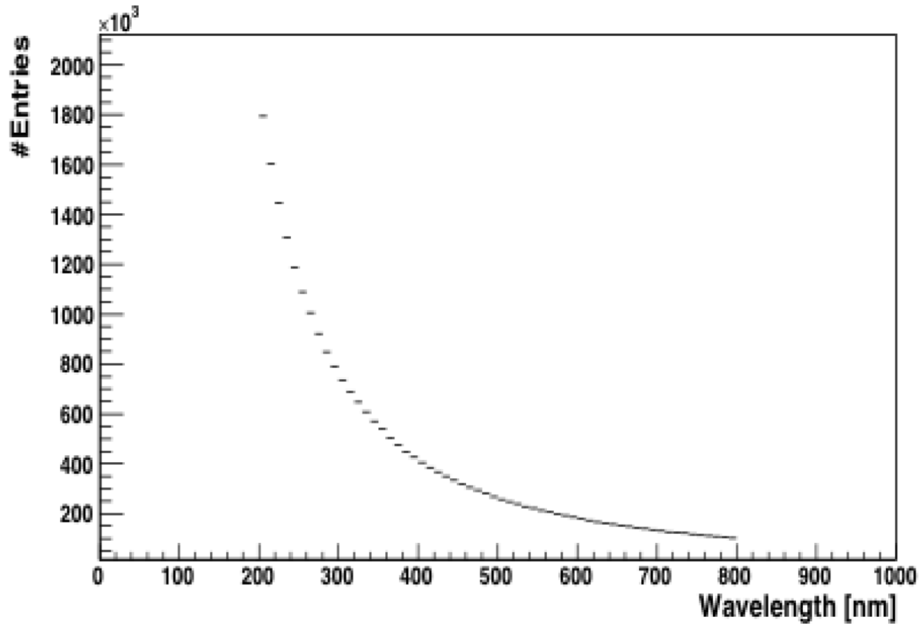


Figure 5.4: The wavelength of the light produced, as simulated when a muon of 4 GeV crosses 10 cm long quartz radiator, entering from the center of the front face of the bar.

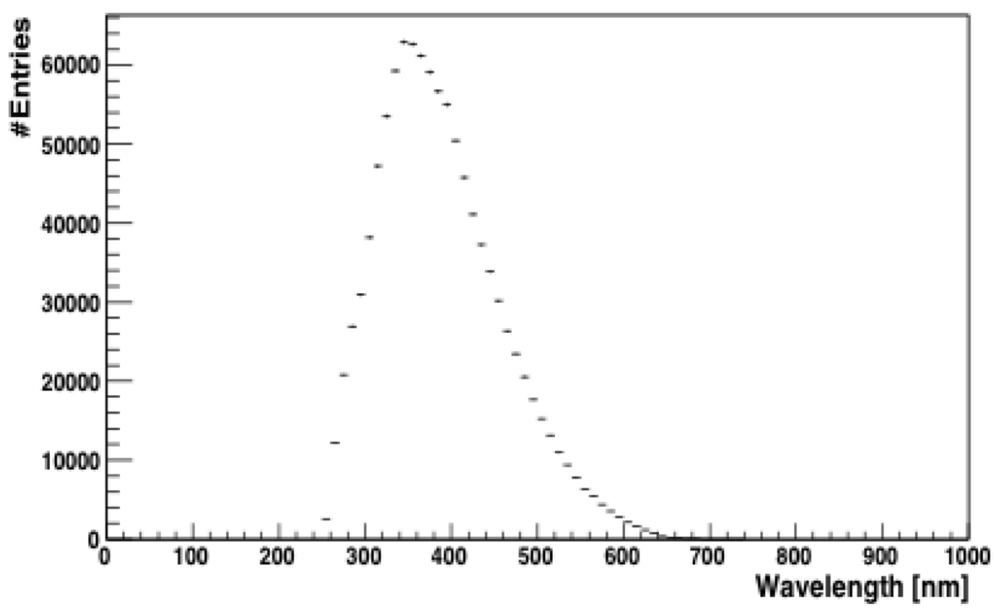


Figure 5.5: The wavelength of the light detected by the photocathode, as simulated when a muon of 4 GeV crosses 10 cm long quartz radiator, entering from the center of the front face of the bar.

Why 10 cm?

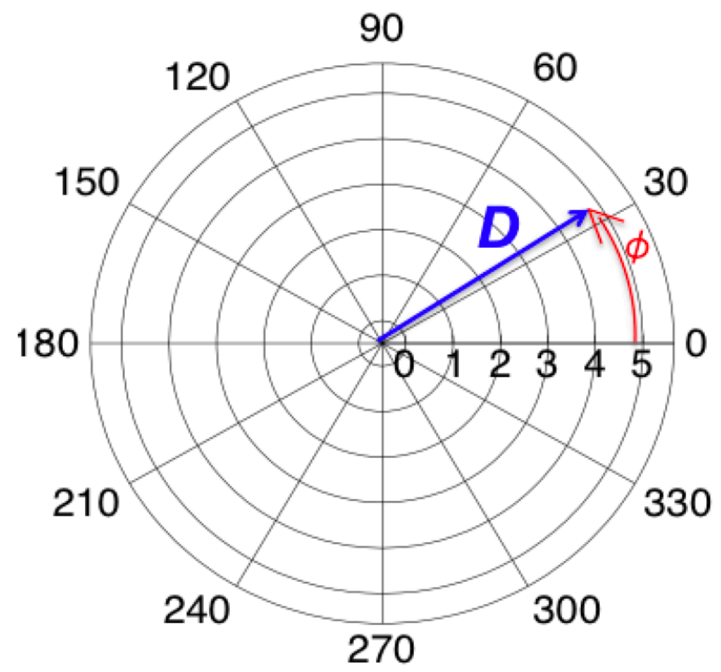


Figure 5.17: A diagram illustrating on a polar plot. The directional gain, D, at a particular impact angle corresponds to the radial length. The rings manifest the radial scale. Impact angles from 0°to 90°correspond to the forward direction (i.e. towards the photocathode), while angles from 90°to 180°correspond to the backward direction (i.e. towards the black painted side of the radiator).

Why 10 cm?

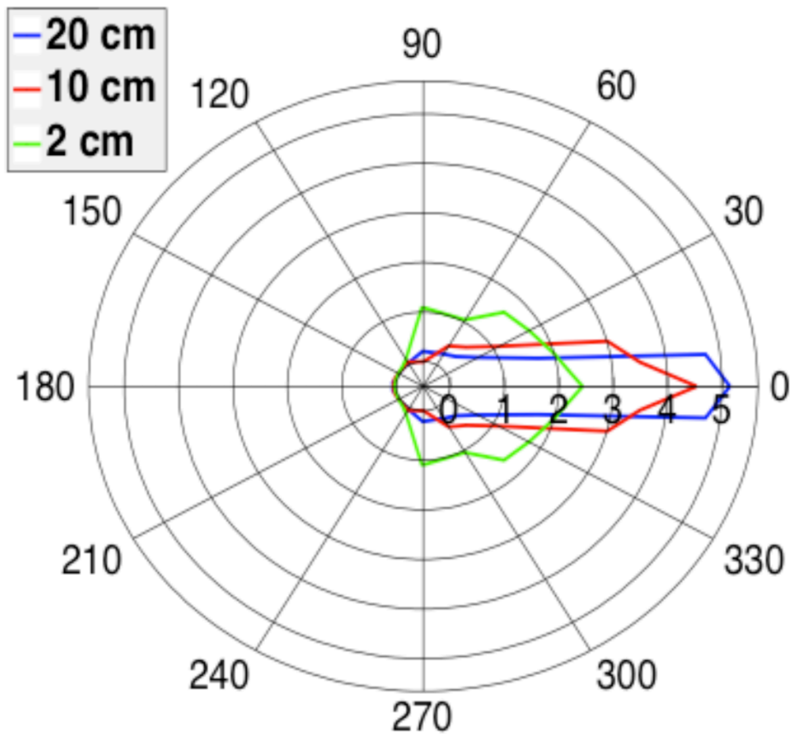
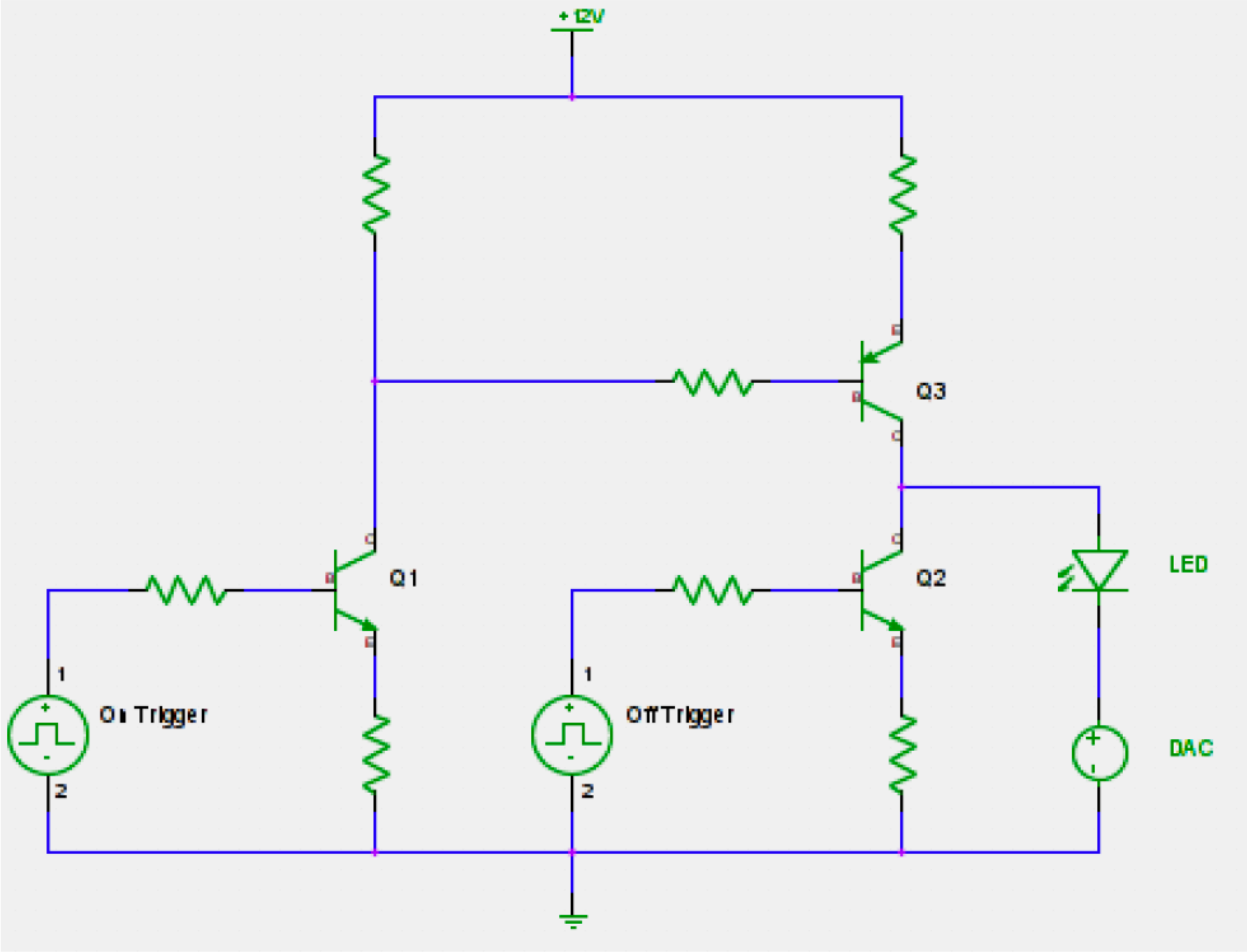


Figure 5.18: The directional gain of three radiators of length 2 cm, 10 cm and 20 cm as function of the impact angle for 4 GeV muons.

$$D(l, \phi) = \frac{\text{Number of photoelectrons}(l, \phi)}{\text{Average number of photoelectrons}(l)}$$

- Average number of photoelectrons = average value of photoelectrons integrated over phi

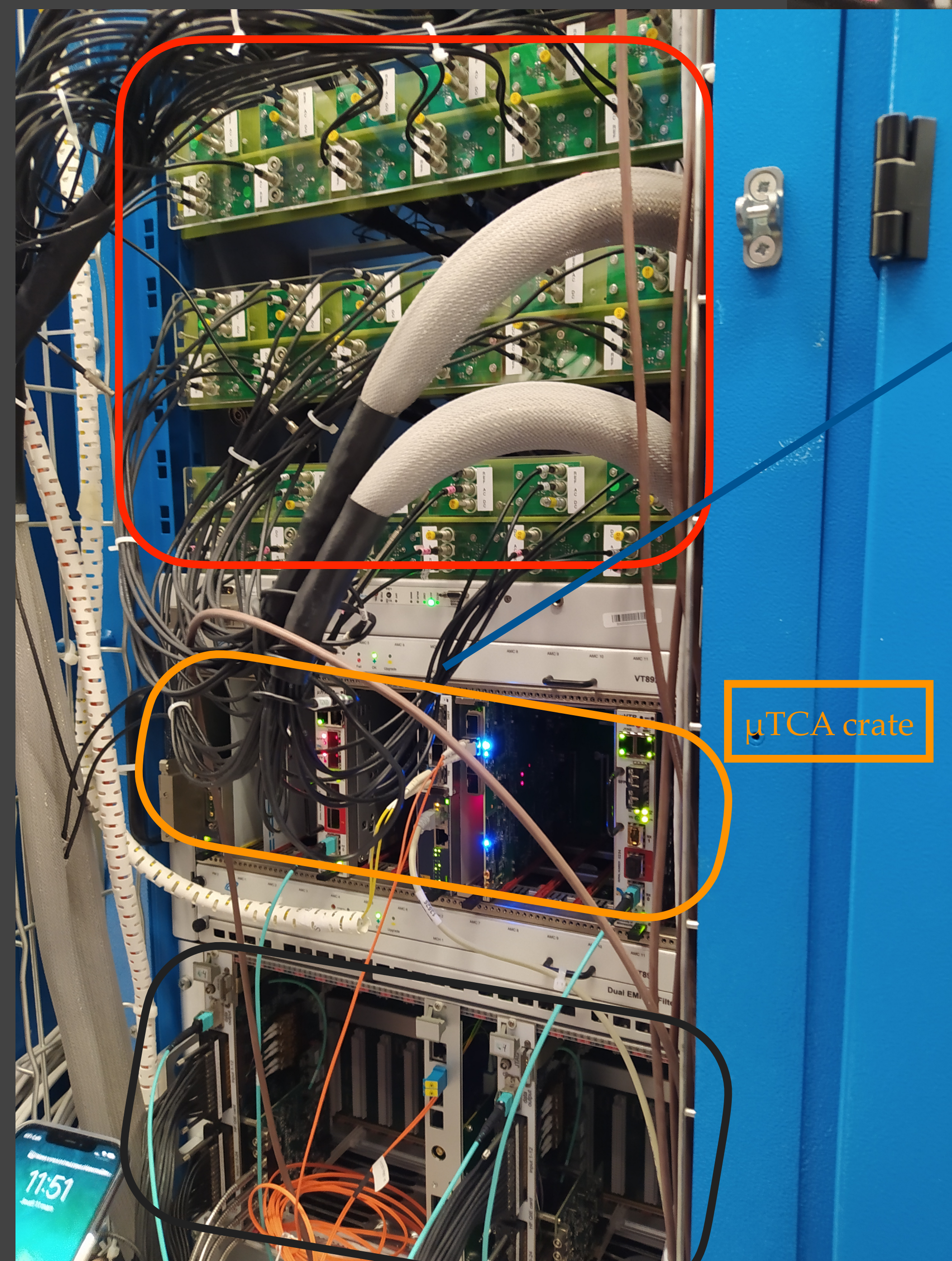
Pulser circuit



Readout system in USC (service cavern)

Signal cables (brown)

Patch panel



μTCA crate

QIE + calibration

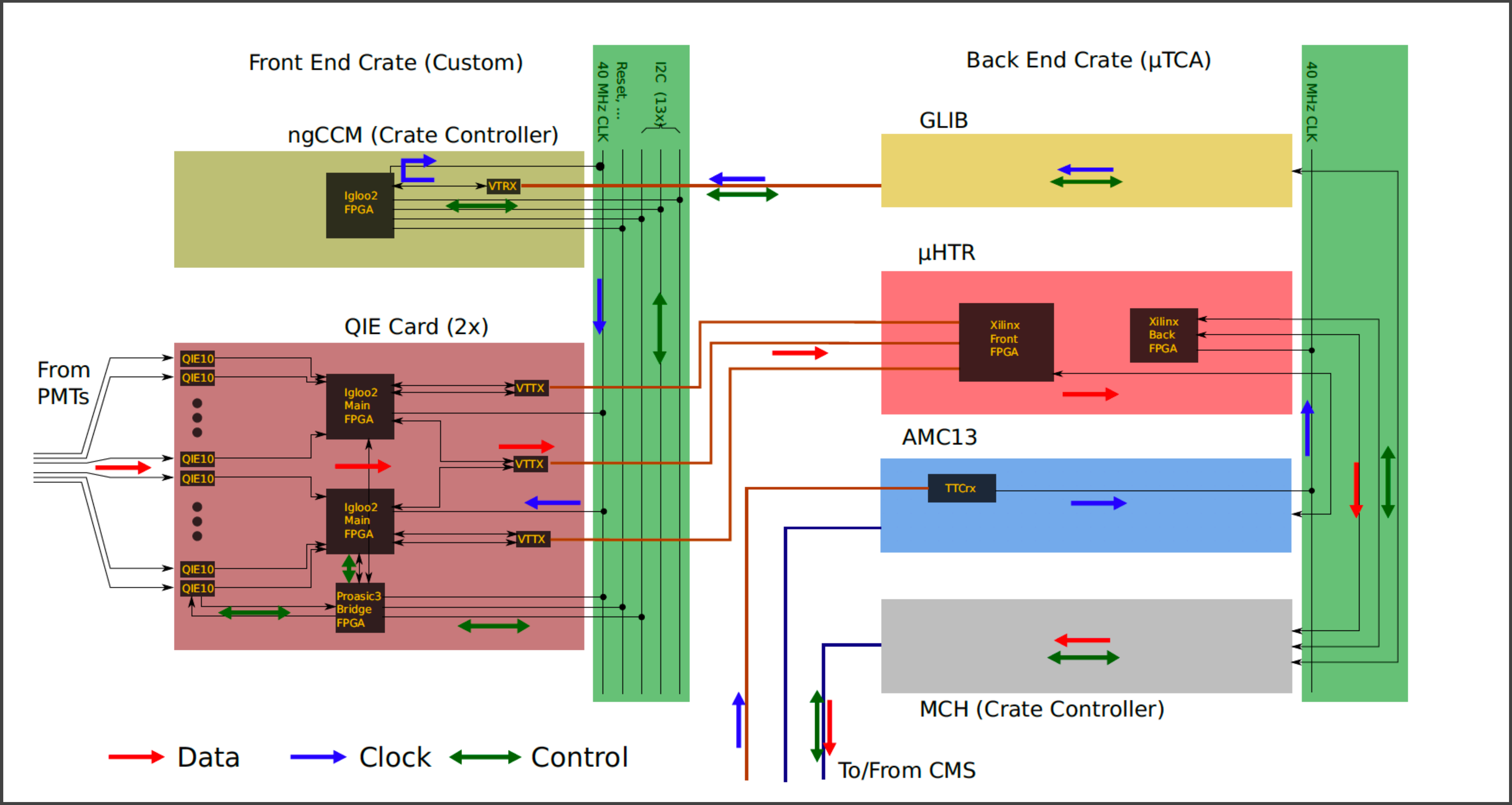
SF108 rack

MCH (μTCA controller hub)

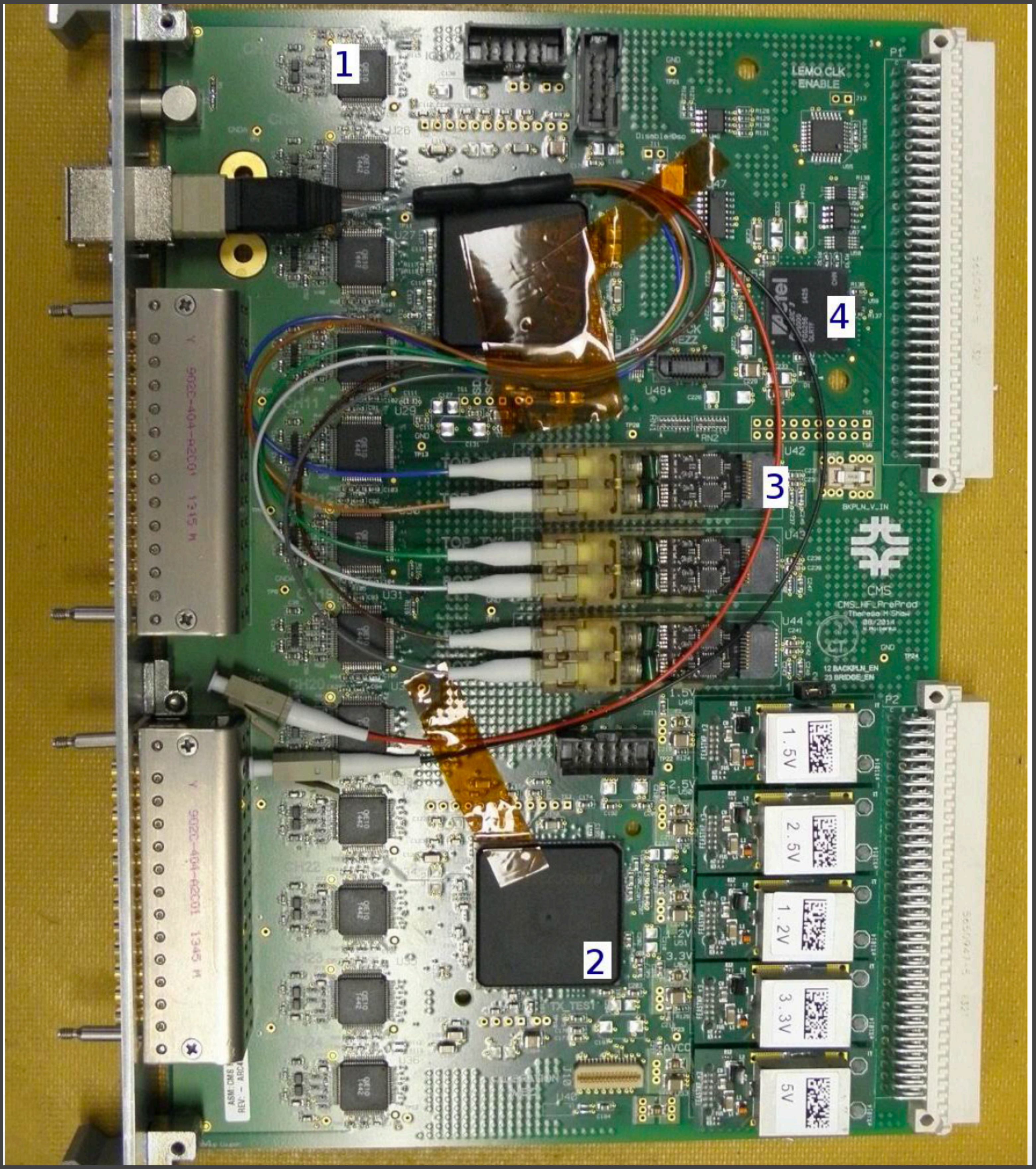
AMC13 (Advanced Mezzanine card - provides clk and TTC to the system)

QIE: Integrates and digitizes. It has TDC as well for timing information

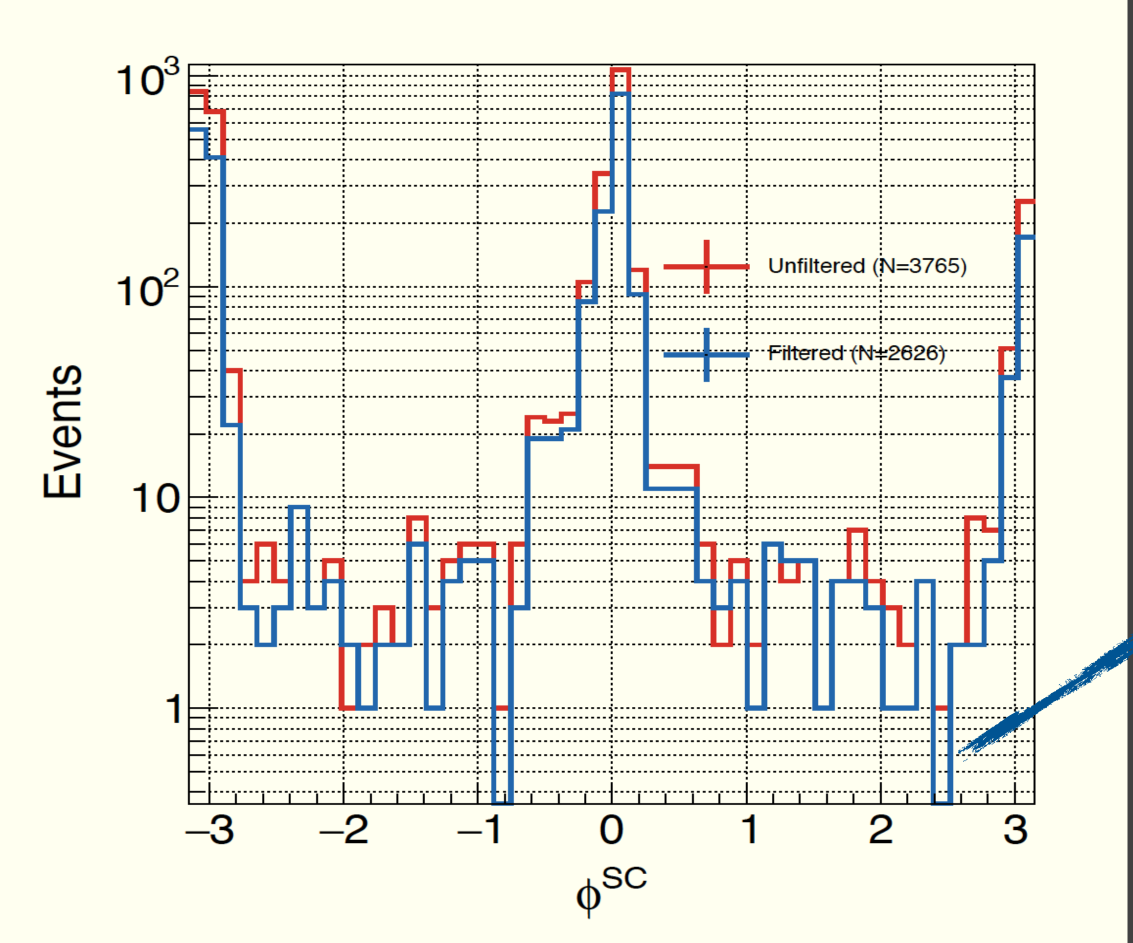
Readout electronics

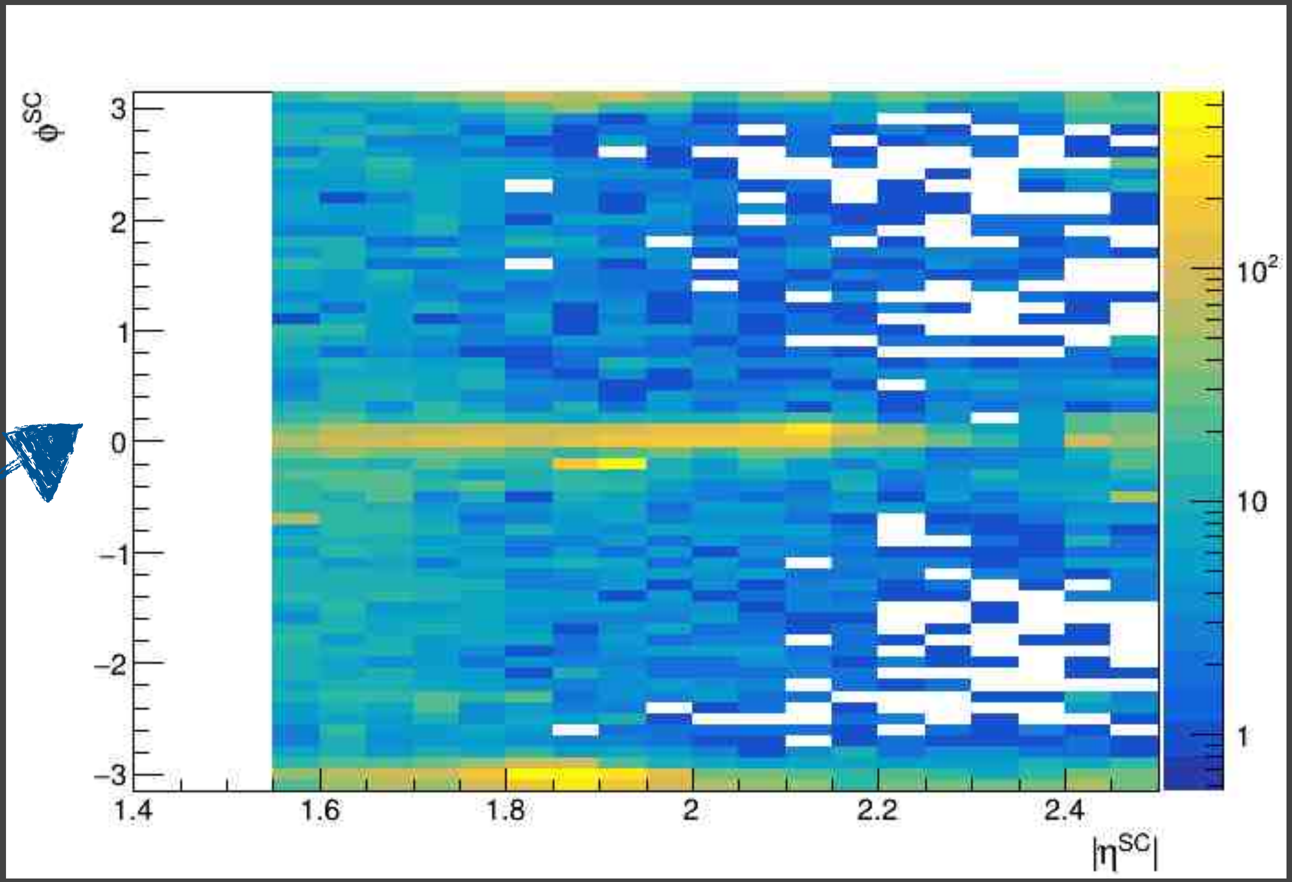


QIE readout board



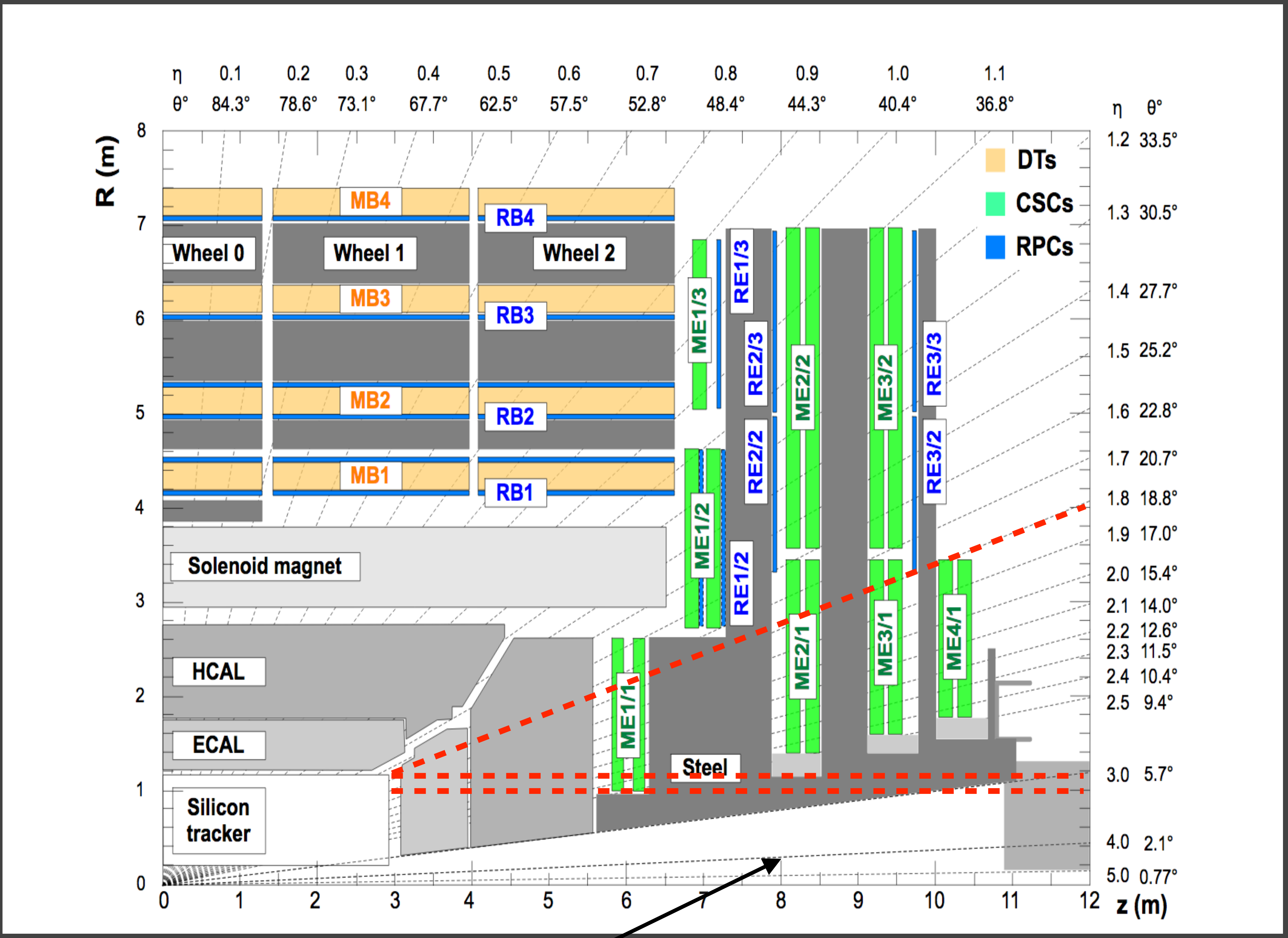
Beam halo in the analysis in the EE





- Most of the beam halo peaks ~eta > 1.8

Reason being



Since beam halo travels parallel:
All of the EE above eta = 1.8 is not covered by the CSCs

- Muon chambers (CSCs) are mostly used to tag muons from the beam halo.
- However, a large region is not covered by the CSCs