Mitigation of occupancies in the CLIC HCal and MuonID endcaps

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LCWS 2019
2019-10-29

Overview

Motivation:

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- Obtain the beam-induced background yields and their distributions at all energy stages as good knowledge of unwanted particles creation is required for a quality detector design and precise physics studies
- Estimate the arising occupancies in all subdetectors, if they are found to be too high it may trigger a change in the detector design
- High occupancies were found in the HCal and Muon Identification System endcaps and need to be mitigated

Introduction:

Introduction

Analysis environment

Combining occupancies & treating high-occupancies

Analysis environment

- PLACET, a beam tracking code, was used to tracked the beams from the end of Main Linac up to the IP
- Guinea-Pig, software that brings the beams into collisions and creates background particles
- These particles are embedded in the detector model and are boosted to take into account the crossing angle
- DD4hep/lcgeo provided the tools to transport background particles through the DD4hep CLIC detector model on the Grid and which was managed by ILCDirac
- FTFP_BERT_HP physics list was used in all DD4hep simulations
- The statistics used was equal to three bunch trains for incoherent pairs and two thousand bunch trains for $\gamma\gamma \rightarrow$ hadron events

Proper treatment of high occupancy regions

Proper way of calculating occupancy taking into account calorimeter cell saturation effects:

$$O = 1 - (1 - O_i)^{SF}, \tag{1}$$

where: O_i - occupancy without safety factor applied, SF - safety factor, 5 for incoherent pairs, 2 for $\gamma\gamma \rightarrow$ events
In a limit of low O_i and after a Taylor expansion it can be simplified to:

$$O = SF \cdot O_i \tag{2}$$

Combining two sources of occupancy also needs to take into account the upper limit at 100%:

$$O_{combined} = 1 - (1 - O_{pairs}) \cdot (1 - O_{hadrons}), \tag{3}$$

which can be simplified in a low occupancy regime to:

$$O_{combined} = O_{pairs} + O_{hadrons} \tag{4}$$

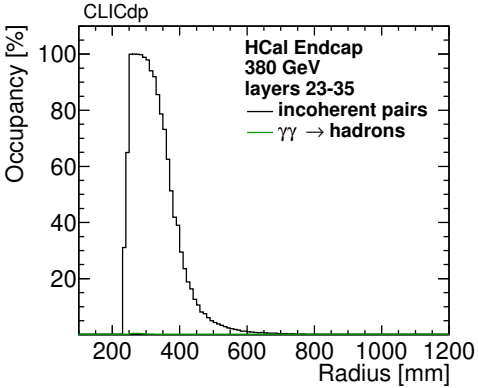
- This approach ensures proper treatment of both the safety factors and combining two (or more) sources of background in highly occupied regions
- It has been recently applied to all results in calorimeters

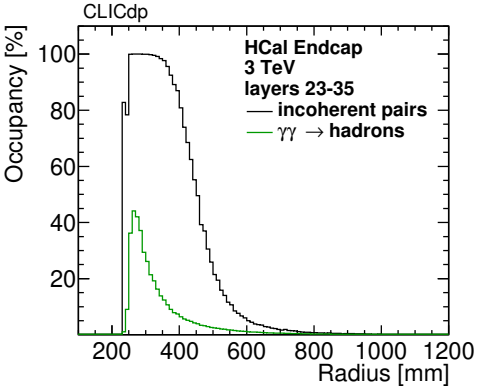
Occupancy distributions:

Occupancy distributions

- Calorimeters
- Muon identification system

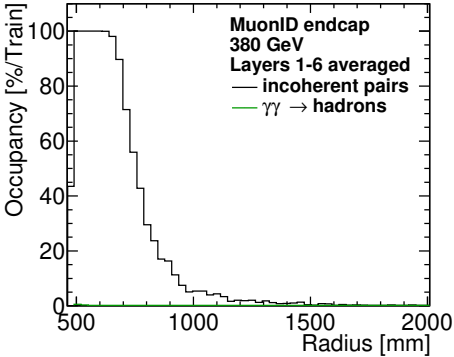
HCal endcap radial occupancies

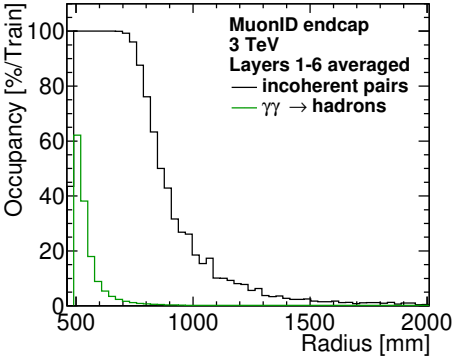




- Full saturation at both energy stages
- The innermost part is impacted primarily by incoherent pairs interactions with BeamCal material
- At 3 TeV $\gamma\gamma \rightarrow$ hadrons events also become relevant

Muon identification endcaps





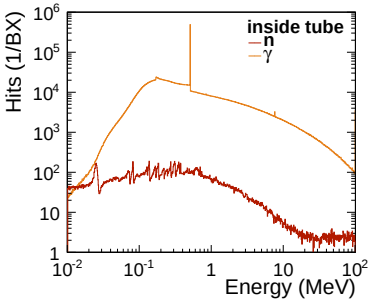
- No cavern and no shielding - as currently implemented in CLIC_o3_v13 CLICdet model
- Full saturation in the innermost region caused mostly by the incoherent pairs
- Possible to address the issue with additional shielding in area previously occupied by the support tube

Modification of the geometry:

Modification of the geometry

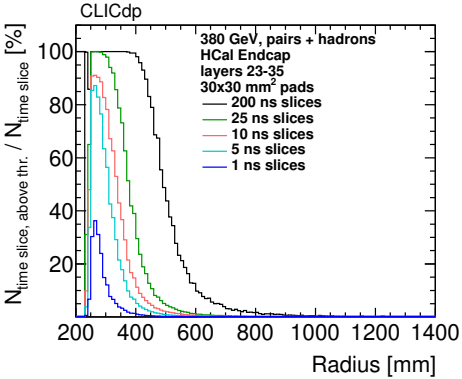
- HCal endcap
- Muon identification endcap

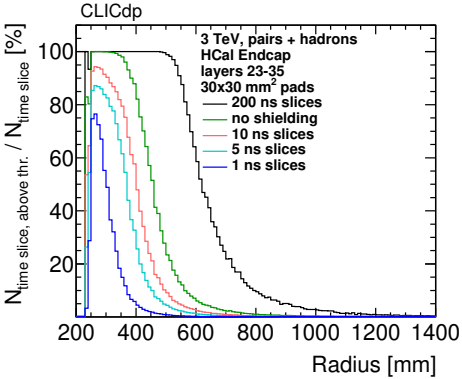
HCal endcap occupancies mitigation



- High occupancy levels in the low radii region can be addressed through varying the calorimeter granularity, integration time of clusters, and shielding
- Shielding and granularity dependence has been studied for CLIC_ILD in CLICdp-Note-2014-004
- The base used for comparison assumes 30x30 mm^2, integration time of 200 ns, and a single time slice, the same assumptions as supplied for the data rates in the Yellow report
- The largest shield that doesn't impact the HCal acceptance could be around 80 mm thick, made of tungsten or lead, and a neutron absorber

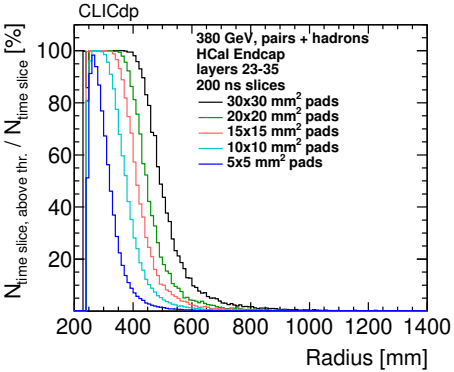
HCal endcap occupancies - time slices

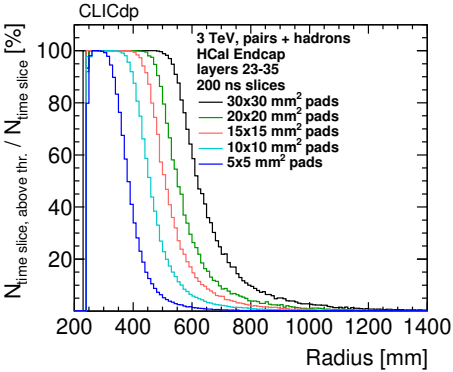




- Data rate assumption with single time slice yields a significant occupancy
- Positive response to increasing number of time slices
- Does not provide a solution on its own even with currently unattainable time slices of 1 ns

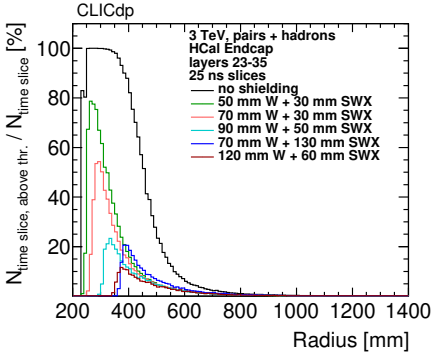
HCal endcap occupancies - granularity

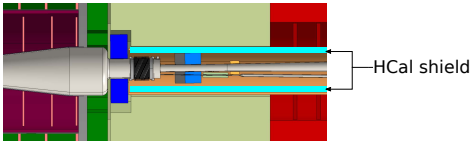




- Decreasing the sizes of pads for HCal helps improve to decrease the high occupancy region
- The improvement is not vast even with 25-fold increase in granularity
- Does not provide a solution on its own - has to be combined with other mitigation techniques

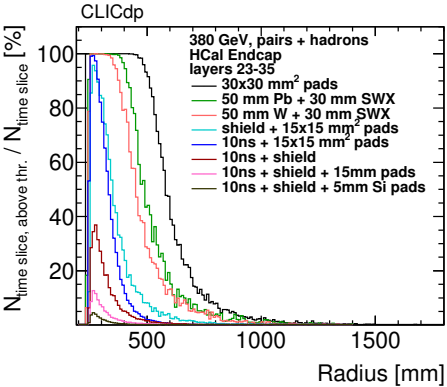
HCal endcap occupancies - shielding

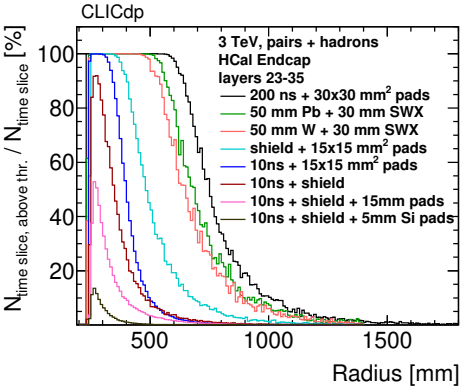




- Significant occupancy reduction possible without an excessive detriment to detector's acceptance
- Tungsten more efficient per length but has to be combined with a neutron absorbing material - SWX (95% polyethylene, 5% boron carbide)
- The preferred design consists of 50 mm tungsten or lead and 30 mm SWX - doesn't impact acceptance and absorbs 95% energy of the background particles
- Safety factors not included; the figure demonstrates only the relative efficiency of different shielding solutions
- Combination of shielding with other mitigation methods still required to fully address the high occupancy

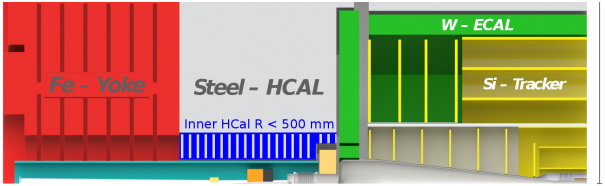
HCal endcap occupancies - combinations





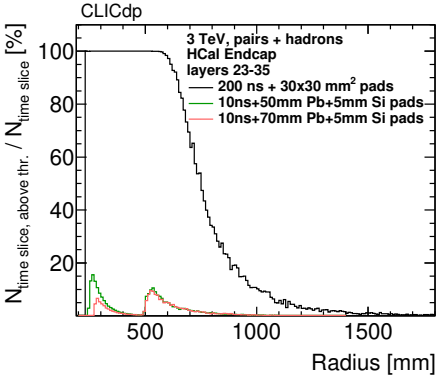
- Combination of different approaches provide a significant improvement
- Best results yielded by shielding combined with 10 ns slicing and 15x15 mm^2 pads
- At 380 GeV no change in granularity required to achive occupancy under 10%

HCal endcap - two granularity regions



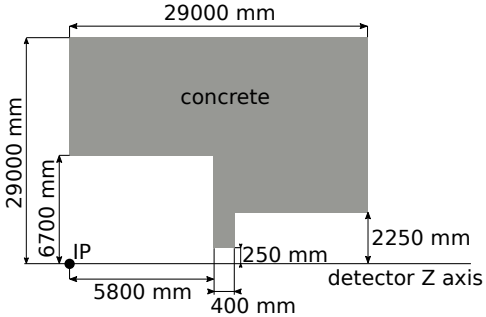
Stainless steel absorber 19 mm	
Steel 0.5 mm	Steel 0.5 mm
Si 0.5 mm	Polystyrene 3 mm
Cu 0.1 mm	Cu 0.1 mm
PCB 1.3 mm	PCB 1.0 mm
Steel 0.5 mm	Steel 0.5 mm
Air 4.6 mm	Air 2.7 mm

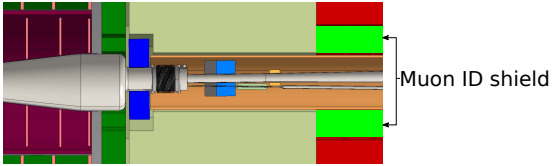
Silicon sensor cell | Scintillator sensor cell



- Two granularity regions for HCal endcap: one with scintillator, one with silicon sensors

Muon ID endcap geometry modifications

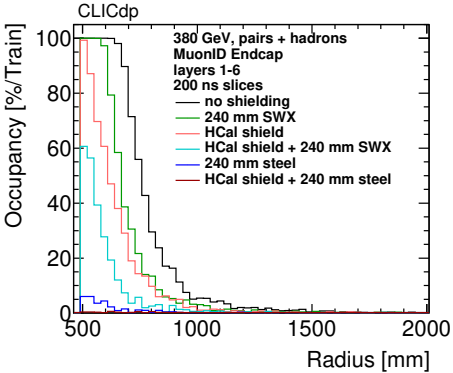


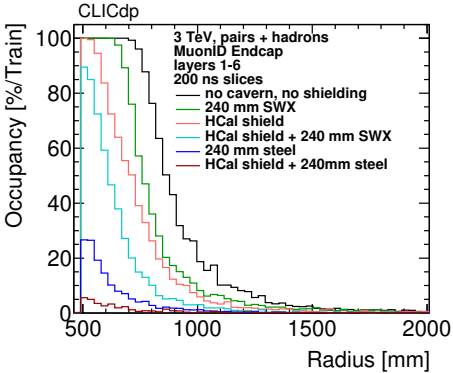


- Lack of cavern in the simulation model was expected[1] to be the source of occupancy in the MuonID endcap, not found to be true
- The shield based on experiences from HCal endcap can be located between the HCal endcap radius and the inner radius of MuonID endcap
- Space available for shielding has a radius of 240 mm and is contained between the HCal endcap and outer edge of yoke

[1] Andre Sailer, *Radiation and Background Levels in a CLIC Detector due to Beam-Beam Effects*

MuonID shielding options





- Borated polyethylene (SWX) does not provide efficient shielding, even when layered with lead as in the HCal shield
- Best solution: the HCal endcap shield + 240 mm of stainless steel

Summary:

Summary

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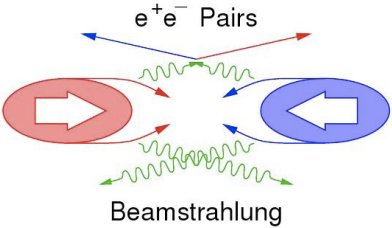
- Mathematically rigorous methods of combining occupancies and treating high occupancy regions are applied to all shown results
- High occupancy can be found in the HCal and Muon identification system endcaps
- Various combinations of granularity, time slicing and adding shielding have been studied, the best effect is achieved when the methods are combined together
- Increasing granularity by a factor of 36, decreasing time slicing to 10 ns and implementing shielding decreases the occupancy below 20% at 3 TeV and below 5% at 380 GeV, including all safety factors
- The granularity increase may be implemented only for radii below 500 mm in the HCal endcap and still provide the desired mitigation
- Cavern has been implemented in the simulation model, the impact of back-scattering of incoherent pairs in the outgoing beam pipe is now negligible
- Using the experience from HCal in the Muon Identification System, shielding made of 240 mm thick steel and the HCal shield is proposed that brings the occupancy down to below 5% at both energy stages

Additional material

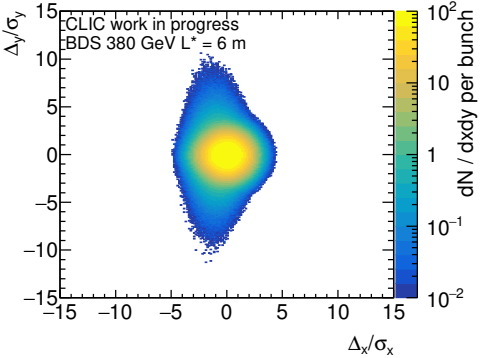
Background creation

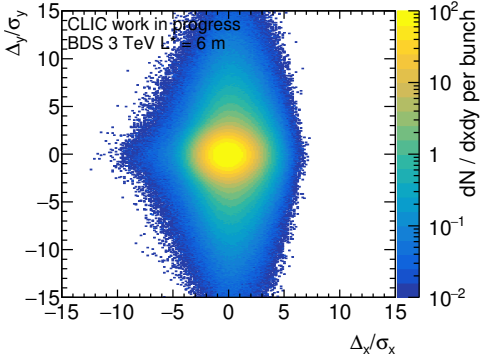


- Synchrotron radiation is created in strong focusing magnets of the Final Focus System
- Beamstrahlung photons, another type of synchrotron radiation caused by charged particles' interactions with the electromagnetic field of the incoming beam, are produced in large quantities and with high energies

- This emission is the main cause of the lower energy tail in e^-e^+ luminosity spectrum
- Beamstrahlung interactions with e^-, e^+ or other photons lead to production of unwanted particles: incoherent pairs, hadrons, coherent pairs and trident cascades (for $\sqrt{s} > 1$ TeV)

Beam distributions at IP

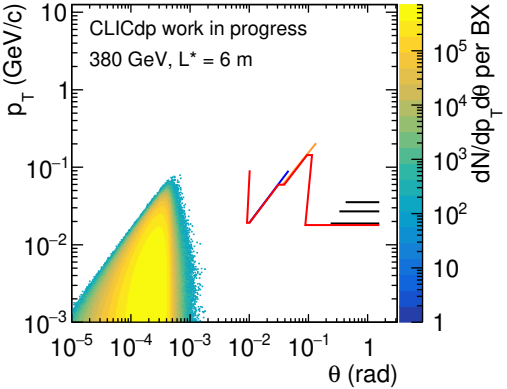


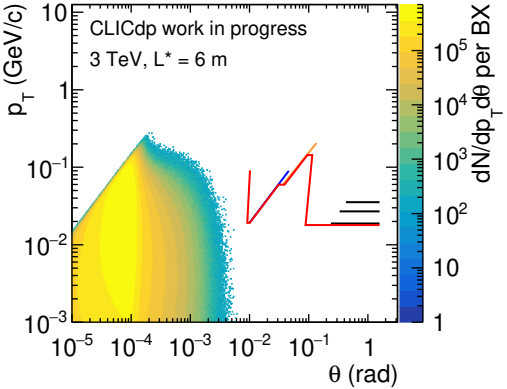


design	σ_x (nm)	σ_y (nm)
baseline 380 GeV	149	2.9
PLACET 380 GeV L*=6 m (core)	151.8	3.1
PLACET 350 GeV L*=6 m (core)	157.4	3.2
baseline 3 TeV	40	1.0
PLACET 3 TeV L*=6 m (core)	48.4	1.2

- Beam core sizes of 380 GeV and 3 TeV are comparable to the with the nominal values
- The core is well contained in the 380 GeV design with 99.99% of particles inside $3\sigma_x \times 3\sigma_y$ surface, while at 3 TeV it is 96.6%

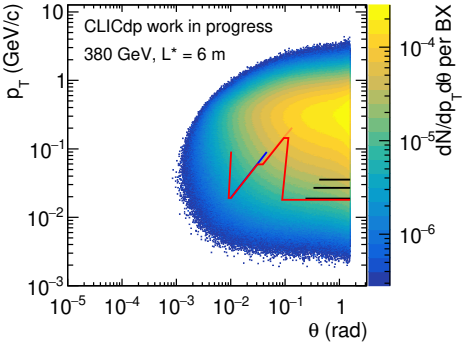
Beamstrahlung energy spectrum

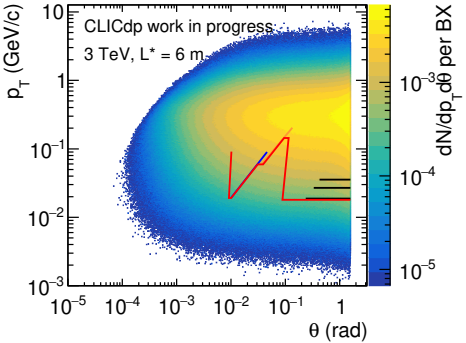




- Beamstrahlung, as required by design, is not a source of direct background in the detector
- There are 1.35 beamstrahlung photons per electron at 380 GeV, 1.31 at 350 GeV, and 2.8 at 3 TeV

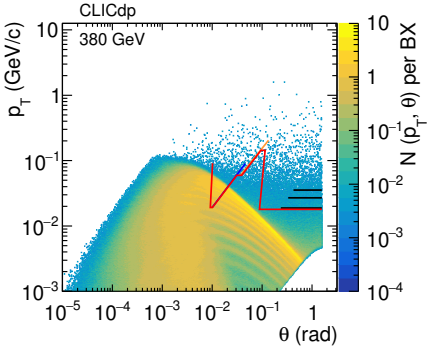
$\gamma\gamma \rightarrow$ hadrons overview

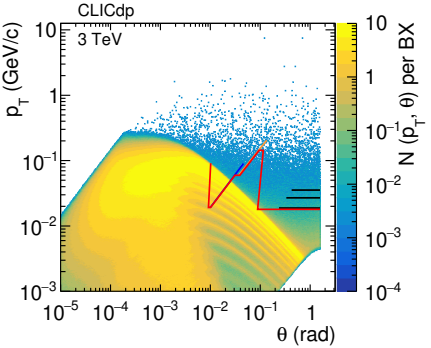




- Over 90% of produced hadrons have transverse momentum high enough to reach the barrel region and thus they are one of the major sources of direct background and occupancies
- There are 0.17 $\gamma\gamma \rightarrow$ hadron events per BX at 380 GeV, 0.16 at 350 GeV and 3.9 at 3 TeV

Incoherent pairs overview

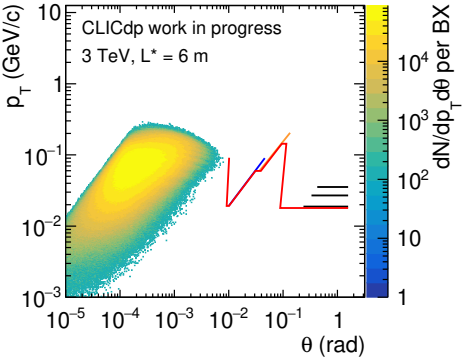




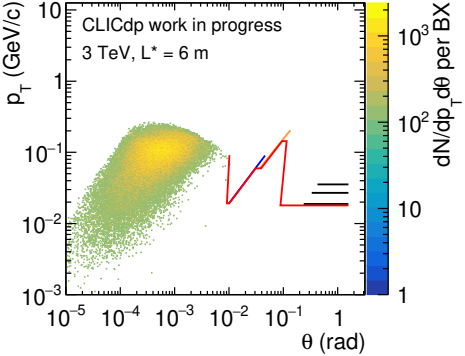
- There are on average 84k incoherent pairs per bunch crossing at 380 GeV, 74k at 350 GeV, and 290k at 3 TeV
- In all cases only around 10% of the incoherent pairs are a source of direct background, mostly in the forward detector region, irradiating BeamCal and LumiCal subdetectors

Coherent pairs and trident cascades at 3 TeV

coherent pairs

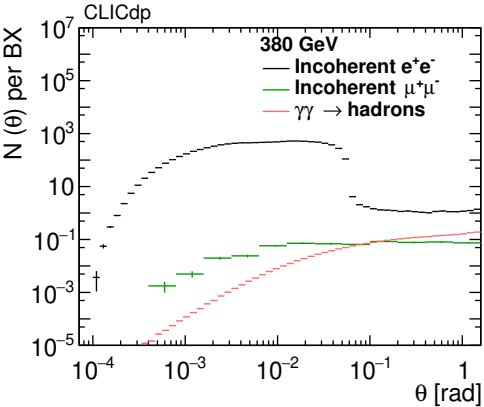


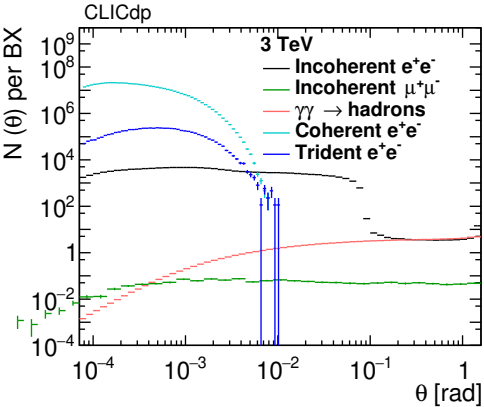
trident cascades



- There are on average $8.3 \cdot 10^8$ coherent pairs per bunch crossing at 3 TeV, L* = 6 m in comparison with $6.8 \cdot 10^8$ value from the CDR
- In addition, there are 10^7 trident cascades per bunch crossing
- The coherent pairs nor trident cascades do not introduce direct background in the detector

Backgrounds angular distributions





- Incoherent pairs and $\gamma\gamma \rightarrow$ hadron events are the only significant source of direct background at both at 380 GeV and 3 TeV
- $p_T > 20$ MeV cut applied to charged particles

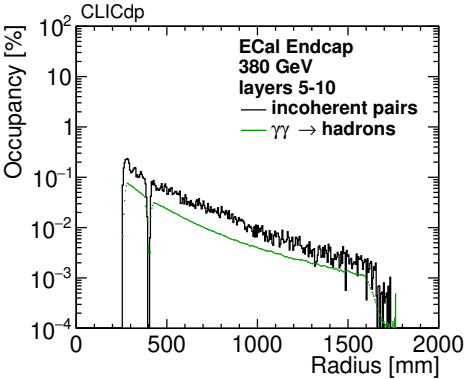
Calorimeteres occupancies

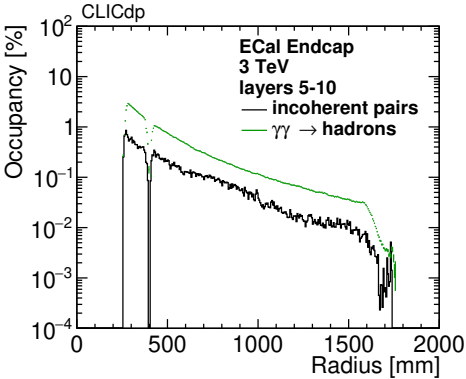
- Initial assumption: calorimeter readout time per bunch train is separated into 8 slices, each 25 ns long, totaling 200 ns from the beggining of a train
- A single time slice was used to establish data rates in the Detector Technologies paper
- Occupancy of a cell is defined as a number of time slices with energy deposition above threshold
- Threshold energy is 40 keV (0.5 MIP) for ECal and 300 keV (0.3 MIP) for HCal
- ECal cell size is 5x5 mm^2 and HCal is 30x30 mm^2
- Occupancy of a detector is defined as an average number of occupied time slices and cells over full integration time divided by the total number of available cells multiplied by the number of time slices

Calorimeter endcaps occupancy calculation

- Hit distributions for each layer are accumulated into 1D histograms as functions of radius
- To obtain the number of cells vs. radius, prepared are 2D cells distributions taking into account dodecagonal shape of the subdetectors
- They are integrated azimuthally and used to normalize the hit distributions to get the ratio of number of hits per bunch train to the number of available cells at given radius
- The average occupancy per layer is an integral of occupied cells divided by the total number of available cells
- The safety factors are applied after the occupancy against R is calculated, only then different sources of background are combined

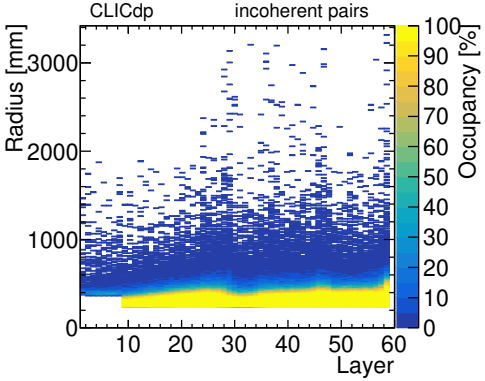
ECal endcap occupancies

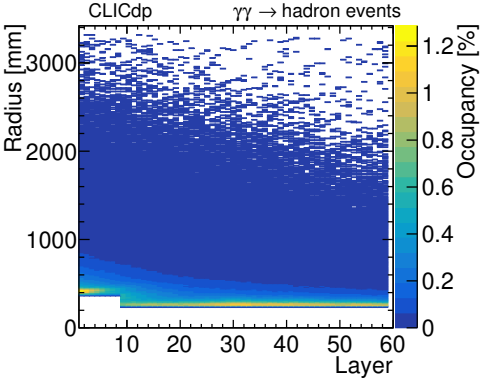




- Occupancies at 380 GeV 6 times lower than the 3 TeV level
- $\gamma\gamma \rightarrow$ hadrons events significantly more prominent at the higher energy stage
- Occupancies below 1% level at 380 GeV but reaching 3% at 3 TeV in the ECal Plug

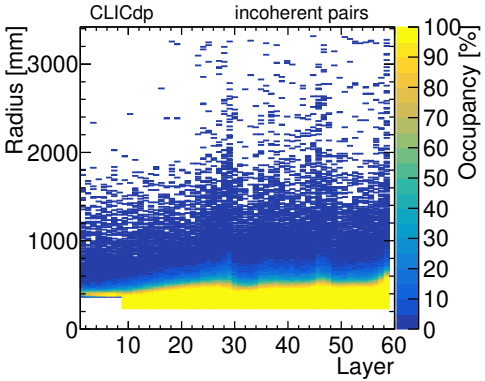
HCal endcap occupancies – 380 GeV

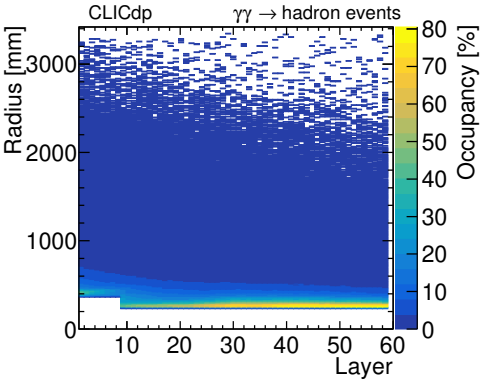




- HCal suffers from higher occupancies than ECal and is fully saturated in the lowest radius region
- Visible gap between ECal Endcap and ECal Plug in $\gamma\gamma \rightarrow$ hadrons occupancies
- Layers 20-25 and 35-60 at lowest radii have the highest background yield, especially coming from incoherent pairs' interactions with BeamCal material

HCal endcap occupancies – 3 TeV





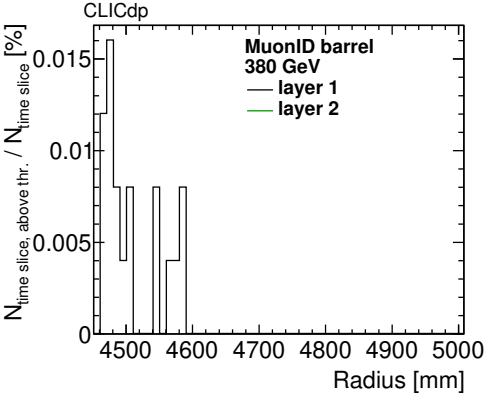
- HCal suffers from almost full saturation in radii below 400 mm
- $\gamma\gamma \rightarrow$ hadrons flux significant at this stage, has to be mitigated along with incoherent pairs

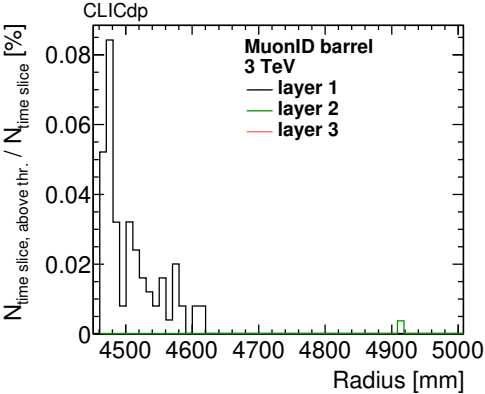
MuonID occupancy calculation

- The same normalization method implemented as for the calorimeters, respective to the region: MuonID barrel has the same approach as ECal/HCal barrel etc.
- Integration time of 200 ns assumed with no time slicing: only one hit in a cell per bunch train recorded
- Energy threshold used: 300 eV[1]
- The safety factors are applied after the occupancy against R is calculated, only then different sources of background are combined

[1] CERN-THESIS-2012-223

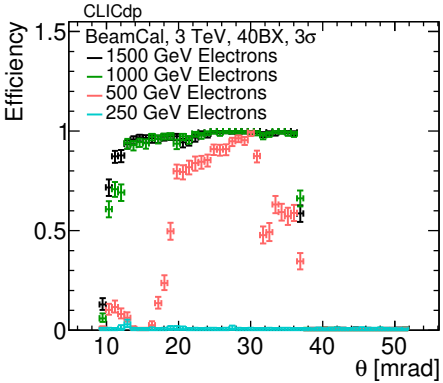
Muon identification barrel





- Negligible occupancy at both energy stages
- Can increase with an introduction of incoherent muons

BeamCal modification



- The reconstruction efficiency in the outer region of the BeamCal was found to be negligible because of the shadow of the LumiCal[1]
- The radius can be limited to 134 mm (from 150 mm), which is 124 mm + safety factor of 9.327 mm (1 Moliere radius of tungsten), and angular acceptance to 42 mrad (from 46 mrad)
- The created empty space can be used for a thicker shielding of the HCal endcap that does not impact the detector acceptance
- Maximal thickness of shielding is increased to 80 mm

[1] CLICdp-Note-2018-005