Trigger simulation progress

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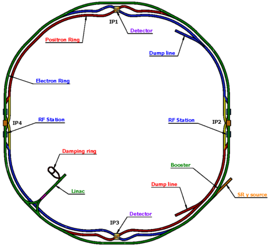
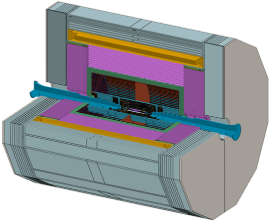
Circular Electron Positron Collider (CEPC)

- Proposed by the Chinese particle physics community in 2012 to explore the aforementioned physics program
- Double-ring collider with electron and positron beams circulated in opposite directions in separate beam pipes, with two interaction points (IPs)
- Four different modes: **Higgs**, Z, W and $t\bar{t}$
- Higgs factory for precision measurements and searches for BSM physics





Outline for this talk

- Simulation and performance
- Future and summary

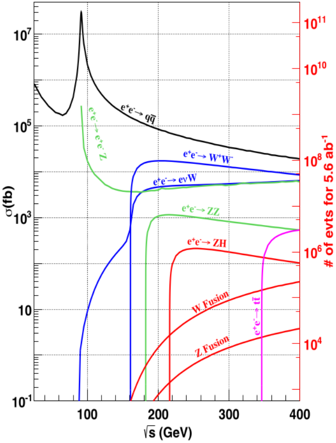
Physical Event Rate

- Higgs mode (240GeV) bunch crossing rate: $\sim$1.34 MHz
  - Higgs boson production rate: $\sim$0.017 Hz
  - $q\bar{q}$ rate: $\sim$5 Hz
- Z mode (91GeV) bunch crossing rate: 12/39.4 MHz
  - Visible Z: 10/76 kHz
- Very low physical event rates compared to the bunch crossing rate
- Trigger: remove as much background as possible, and keep physical events as more as possible

	Higgs	Z	W	$t\bar{t}$
SR power per beam (MW)	50			
Bunch number	446	13104	2162	58
Bunch spacing (ns)	346.2 (×15)	23.1 (×1)	138.5 (×6)	2700.0 (×117)
Train gap (%)	54	9	10	53
Luminosity per IP (10^{34} cm^{-2} s^{-1})	8.3	192	26.7	0.8

CEPC Accelerator TDR

CEPC Physics & Detector CDR



MC Simulation at Higgs mode

Signal

- $ee \rightarrow$ZH
  - Z$\rightarrow$ ee, $\mu\mu$, $\tau\tau$, $\nu\nu$
  - H$\rightarrow$ bb, WW, $\tau\tau$, cc, ZZ, $\gamma\gamma$, Zγ, $\mu\mu$...
- $ee \rightarrow qq$, WW, ZZ...
- Optional signal, di-photon: $ee \rightarrow ee\gamma\gamma$ ($\gamma\gamma \rightarrow bb$, $\gamma\gamma \rightarrow cc$)

Background

- Beam induced background
- Detector noise and other background(to be studied)

MC Simulation: beam induced background

- Single Beam
  - Touschek Scattering
  - Beam Gas Scattering(Elastic/inelastic)
  - Beam Thermal Photon Scattering
  - Synchrotron Radiation
- Luminosity Related
  - Beamstrahlung
  - Radiative Bhabha Scattering
- Combine 2 bunch crossings into one event: safety factor 2
- More detail was presented by H. Shi in the CEPC 2025 Barcelona workshop.

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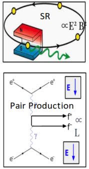
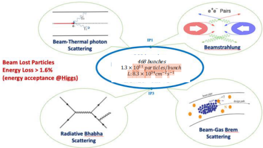
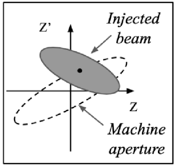


Photon BG



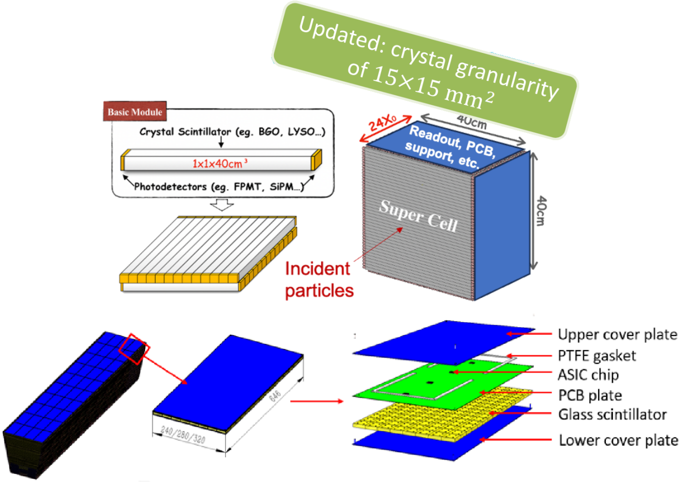
Beam Loss BG



Injection BG

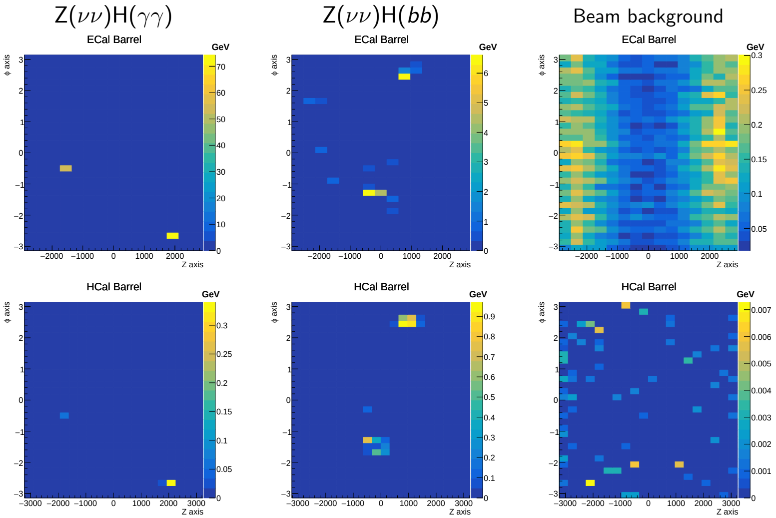
Calorimeter trigger primitive

- Basic module for EM Calorimeter (ECal): $\sim$1.5x1.5x40cm^3
  - Cluster modules into 40x40cm^2 supercell as trigger input
  - 15(Z)x32(ϕ) in Z-ϕ plane
- Basic module for HCal: Barrel-Box (240/280/320 x 646mm^2)
  - Combine two in ϕ and split into two in Z
  - 20(Z)x32(ϕ) in Z-ϕ plane ($\sim$match ECal)



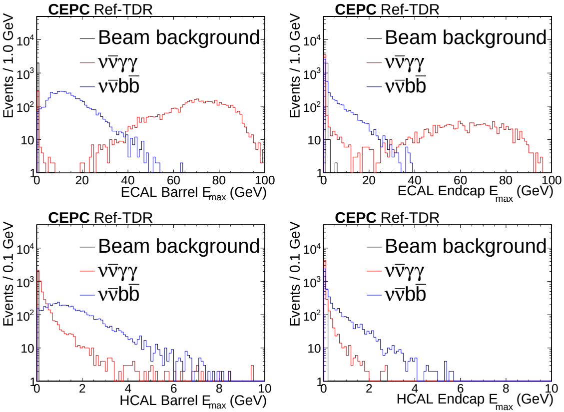
Barrel energy distribution

- Large energy deposition($>$ 10 GeV) for signal (photon, and Jet)
- Very tiny energy deposition($<$0.5 GeV) for beam background, mostly from pair production



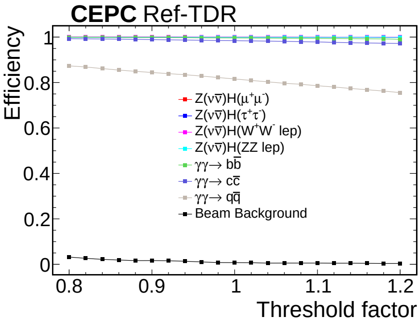
- Maximum energy distribution
- Beam induced background contributes little(<1GeV) on calorimeter, except ECal Endcap
- A baseline set of energy threshold

Sub-detector	Higgs mode	Z mode
ECal Barrel	>0.2 GeV	>0.113 GeV
or HCal Barrel	>0.023 GeV	>0.017 GeV
or ECal Endcap	>2.57 GeV	>0.96 GeV
or HCal Endcap	>0.16 GeV	>0.059 GeV



Efficiency vs. Calo. energy threshold

- Threshold value can be modified for different physics requirement
- A group of sets is tested based on the baseline set, by multiplying a "threshold factor" to all the four thresholds
- For most of the processes, the efficiencies are higher than 99.9% even with larger threshold factor
- Only the di-photon processes efficiencies decrease much

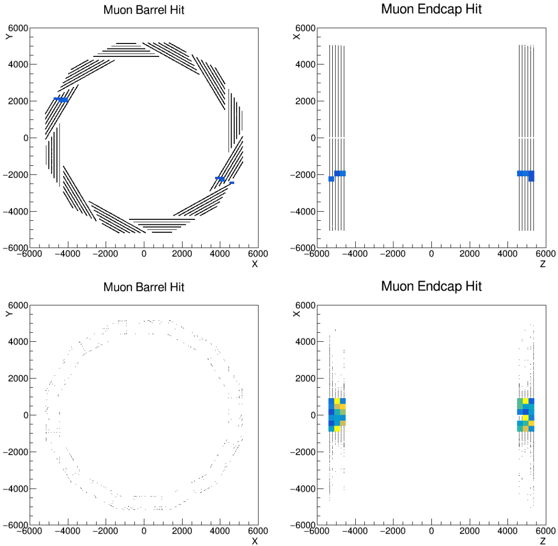


Background tolerance factor study

- Different tolerance factors (bunch crossings) are studied: 1, 2, and 10
- Thresholds are higher with a larger factor
- The tolerance factor of the overall trigger system can be at least 10

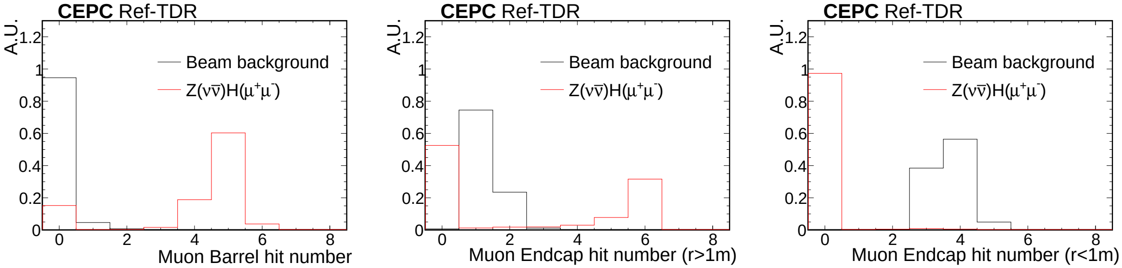
Tolerance factor	2		10	
Threshold	Higgs mode	Z mode	Higgs mode	Z mode
ECal Barrel	>0.2 GeV	>0.113 GeV	>0.39 GeV	>0.14 GeV
or HCal Barrel	>0.023 GeV	>0.017 GeV	>0.05 GeV	>0.03 GeV
or ECal Endcap	>2.57 GeV	>0.96 GeV	>9.6 GeV	>1.9 GeV
or HCal Endcap	>0.16 GeV	>0.059 GeV	>0.34 GeV	>0.09 GeV
Efficiency	Higgs mode	Z mode	Higgs mode	Z mode
Beambackground	0.7%	0.7%	1.7%	0.8%
$Z(\nu\bar{\nu})H(\mu^+\mu^-)$	>99.9%	-	97.5%	-
$\mu^+\mu^-$	99.6%	>99.9%	94.1%	>99.9%
$\tau^+\tau^-$	99.6%	>99.9%	98.2%	99.7%

- Top: signal $Z(\nu\nu)H(\mu\mu)$
- Bottom: beam background
  - Black hits: hits for all 2000 events
  - Color hits: hits for single events
- Count number of muon hit inside a small cone(baseline radius)
  - dR=$\sqrt{\mathrm{d}\phi^2 + \mathrm{d}\theta^2}$
  - Barrel: dR<0.05
  - Endcap: dR<0.02



Number of hit distribution

- Baseline cut for the number of hit:
  - Barrel: >2
  - Endcap ($r > 1\text{m}$): >3
- Background efficiency: 0.1%
- $Z(\nu\nu)H(\mu\mu)$ efficiency: 99.8%; $\mu\mu$ efficiency: 97.6%



L1 global efficiency for baseline selection

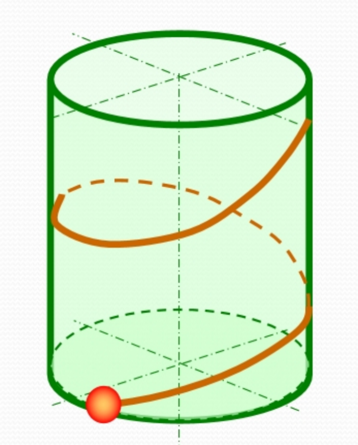
- L1 global trigger efficiency
  - >99% for most of the physical processes; <1% for beam background

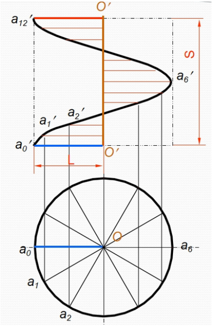
Higgs mode	**Efficiency(%)**	**Z mode**	**Efficiency(%)**
Higgs Boson production	>99.9	$q\bar{q}$	>99.9
$q\bar{q}$	>99.9	$\mu^+\mu^-$	>99.9
$\mu^+\mu^-$	99.8	$\tau^+\tau^-$	>99.9
$\tau^+\tau^-$	99.6	Bhabha	>99.9
Bhabha	99.9		
Di-photon processes		**Di-photon processes**	
Di-photon event rate	**Efficiency(%)**	**Di-photon event rate**	**Efficiency(%)**
9.1 kHz	40.3	Low Lumi: 18.5 kHz	42.9
Beam Background		**Beam Background**	
Background event rate	**Veto efficiency(%)**	**Background event rate**	**Veto efficiency(%)**
11.4 kHz	99.2	Low Lumi: 90.0 kHz	99.3
Total		**Total**	
20.6 kHz		Low Lumi: 118.9 kHz	

- High lumi Z mode using higher energy threshold:
  - ECAL Barrel>0.23GeV; ECAL Endcap>2.61GeV;
  - HCAL Barrel>0.027GeV; HCAL Endcap>0.14GeV;
  - Physics processes: >99.9%; Background: 99.3%

Preliminary track trigger study

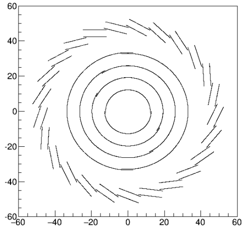
- Trajectory of charge particle: helix
- Circle in xy plane
- Trigonometric function in xz(yz) plane
- Equation in the cylindrical coordinate (r z):
    - $\frac{r\kappa}{2} = sin(\phi - \phi_0), z = tan\lambda \cdot s$
    - Assuming IP at origin
    - κ: curvature of the helix
    - ϕ_0: azimuth angle of the track at the IP
    - λ: helix angle
    - s: helix arc length from the IP to the hit
        - $s = R\theta = 2R(\phi - \phi_0)$

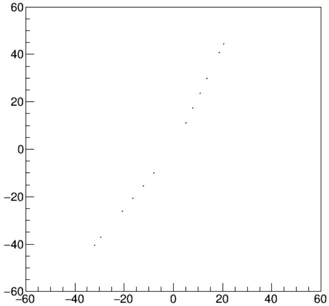


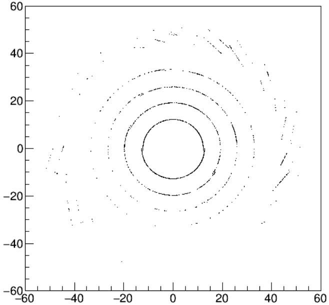


Vertex

- Left: one ZH$\rightarrow \nu\nu\mu\mu$ event
- Right: one beam background event
- Too many hits from beam bkg for the innermost two layers
- Use outermost four layers for track

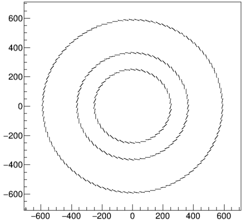


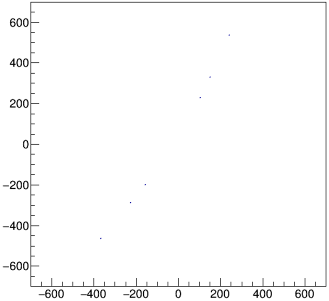


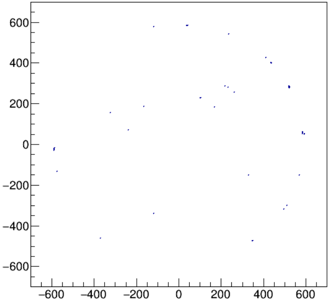


ITK

- Left: one ZH$\rightarrow \nu\nu\mu\mu$ event
- Right: one beam background event
- Less hits than vertex
- Combine Vertex(outermost 4 layers)/ITK/OTK for track

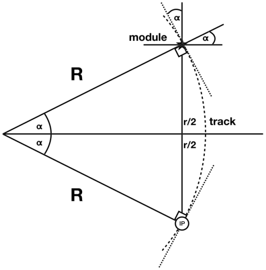


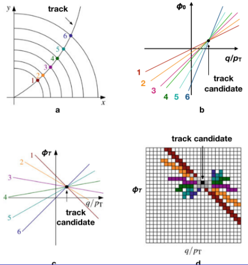




Hough transform

- Transform 3D spatial coordinates(cylindrical coordinate $r\phi z$) into parameter space
- Each hit in 3D space corresponds to a curve in the parameter space
- Get track candidate parameters with most number of hits
- Assuming large track p_T(p_T>2GeV)
    - Small angle approximation:
    - $\frac{r\kappa}{2} \approx \phi - \phi_0, z \approx tan\lambda \cdot r$
- $0 < \kappa < 0.0025, -\pi < \phi_0 < \pi, -\pi < \lambda < \pi$
- 50 bins for each parameters
- Background efficiency(two bunch crossing per event): 0.9%
- $Z(\nu\nu)H(\mu\mu)$ efficiency: 94.9%; $Z(\nu\nu)H(bb)$ efficiency: >99.9%





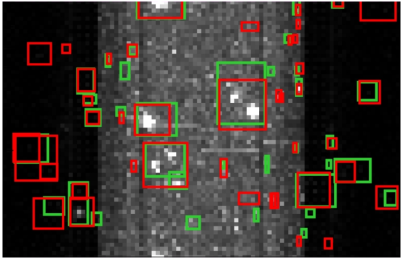
R&D following the TDR: background study

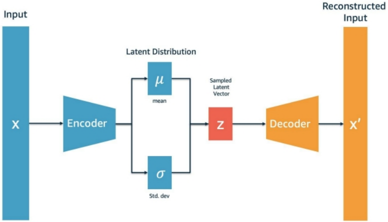
- More simulation and research need to be done
  - Signal background mixing
  - Cosmic ray study
  - Electronic noise
  - ...
  - Is it enough for the minimal trigger for L1 (Cal+Muon)
- Beam background simulation study
  - Pair production is generated by Guinea-Pig++
  - Based on the paper by the GPig author, BDT can be used for comparison

σ (mb)	GUINEA-PIG	CAIN	BDK
All processes	101	89.5	
Breit-Wheeler	1.01	1.11	
Bethe-Heitler	66.3	61.7	
Landau-Lifshitz	33.9	26.7	31.8

R&D following the TDR: trigger algorithm

- Trigger algorithm study
  - Hardware algorithm: fast track reconstruction, calorimeter cluster, Muon track...
  - Software algorithm: track trigger(Offline tracking reconstruction), event size compress(for TPC, Calorimeter), PID...
  - ML(BDT, DNN, CNN···)
  - Trigger for BSM (long life particle)



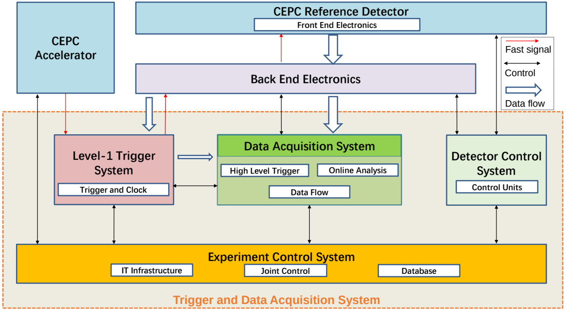


Identifying Regions of Interest in the ATLAS Calorimeter with Deep Convolutional Neural Networks

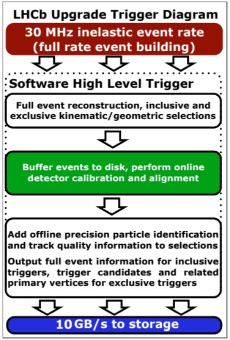
Anomaly Detection in the CMS Global Trigger Test Crate for Run 3

R&D following the TDR: trigger overall strategy

- Trigger overall system strategy
  - Classical trigger(L1+HLT) vs. fully software trigger
  - Use GPU for acceleration， software algorithm



vs.



Upgrade trigger selection studies

Summary

- Baseline L1 trigger algorithm shows good efficiency for the current simulation result
- Further R&D study need to be done for both simulation and algorithm

Backup

Physical event rate

- Top priority for Higgs and Z production
- Low priority for $\gamma\gamma$ events (hadronic final state, $b\bar{b}$, $c\bar{c}$)
- Event rate: ZH: ~500Hz; Z: 10kHz
- Data rate before trigger
  - 1000 Gb/s for Higgs mode
  - 1770 Gb/s for Z mode

Running mode **SR power**	**Higgs** **50 MW**	**Z** **12.1 MW**
Non-empty bunch crossing rate (MHz)	1.34	12
Luminosity ($10^{34}/cm^2/s$)	8.3	26
Physical event rate (kHz)	0.5	10
L1 triger rate (kHz)	20	120
DAQ readout rate (Gbyte/s)	5.34	11.9
HLT rate (kHz)	1	20
Raw event size (kbyte)	405	333
DAQ storage rate (Gbyte/s)	0.405	6.66

Higgs mode processes	**Cross section (fb)**	**Event rate (Hz)**
Physical events (top priority)		
Higgs production	203.7	0.017
Two Fermions processes (exclude Bhabha)	6.4×10^4	5.3
Four Fermions processes	1.9×10^4	1.6
Bhabha	1.0×10^6	80
Diphoton process (low priority)		
$\gamma\gamma \to b\bar{b}$	1.6×10^6	136
$\gamma\gamma \to c\bar{c}$	2.1×10^6	173
$\gamma\gamma \to q\bar{q}$	6.0×10^7	4963
$\gamma\gamma \to \mu^+\mu^-$	2.1×10^8	17210
$\gamma\gamma \to \tau^+\tau^-$	2.3×10^6	193

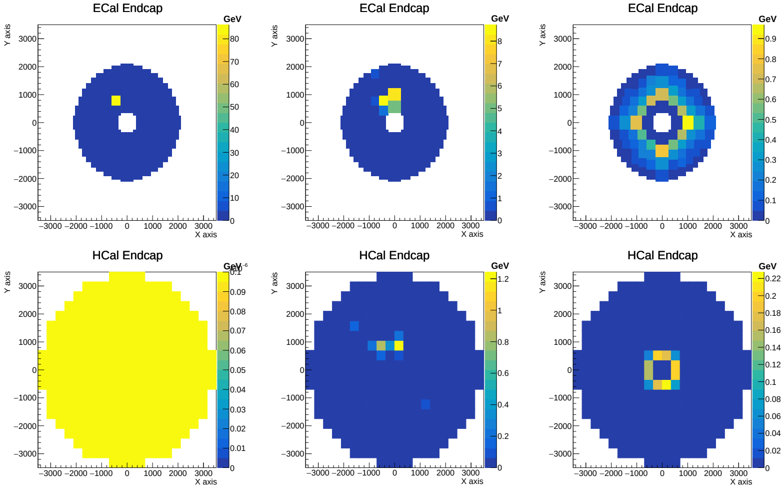
Z mode processes	**Cross section (fb)**	**Event rate (Hz)**
Physical events (top priority)		
$q\bar{q}$	3.1×10^7	7970
$\mu^+\mu^-$	1.5×10^6	400
$\tau^+\tau^-$	1.5×10^6	396
Bhabha	6.6×10^6	1714
Diphoton process (low priority)		
$\gamma\gamma \to b\bar{b}$	2.7×10^5	71
$\gamma\gamma \to c\bar{c}$	5.1×10^5	132
$\gamma\gamma \to q\bar{q}$	3.5×10^7	9014
$\gamma\gamma \to \mu^+\mu^-$	1.3×10^8	33696
$\gamma\gamma \to \tau^+\tau^-$	6.3×10^5	163

Time window

	VTX	ITK	OTK	TPC	ECAL	HCAL	Muon	Total
Time windows (ns)	69	69	69	34000	69	1000	69	
50 MW Higgs mode Full Data (Gbps)	130	21.2	82.7	26.4	752	26.6	<1	1040
Data size / bunch (kB)	12.1	1.98	7.71	2.46	70.1	2.48	<0.1	96.9
Data size / event (kB)	12.1	1.98	7.71	303	70.1	9.92	<0.1	405
12.1 MW Z mode Full Data (Gbps)	307	37.8	139	57.1	1202	27.2	<1	1771
Data size / bunch (kB)	3.20	0.394	1.45	0.595	12.5	0.283	<0.1	18.4
Data size / event (kB)	6.40	0.788	2.90	293	25.0	4.53	<0.1	333

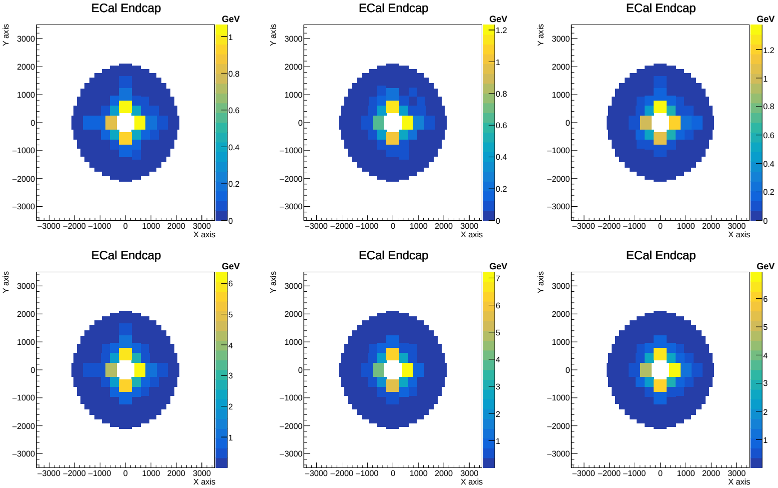
Endcap energy distribution

- Similar to Barrel for signal
- Relatively large energy deposition($\sim$1 GeV) for beam background
- Use supercell energy as input



Endcap energy distribution with different factor

- First row: 2
- Second row: 10
- Larger energy deposition with larger factor
- The energy distributions are not identical for different events



Efficiency for baseline L1 Calo threshold

- The baseline threshold is chosen to show the efficiency
- Efficiency > 99% for most of the physical process
- Higher energy threshold doesn't affect the physical processes much, but reduce the background <1%

Process	Efficiency(%)		Process	Efficiency(%)		Process	Efficiency(%)	
Higgs Boson production								
$Z(\nu\bar{\nu})H(\gamma\gamma)$	>99.9		$Z(\nu\bar{\nu})H(\gamma Z)$	>99.9		$Z(\nu\bar{\nu})H(b\bar{b})$	>99.9	
$Z(\nu\bar{\nu})H(\mu^+\mu^-)$	>99.9		$Z(\nu\bar{\nu})H(\tau^+\tau^-)$	>99.9		$Z(\nu\bar{\nu})H(W^+W^-)$	>99.9	
$Z(\nu\bar{\nu})Z(W^+W^-)$lep	>99.9		$Z(\nu\bar{\nu})H(ZZ)$	>99.9		$Z(\nu\bar{\nu})H(ZZ)$lep	99.9	
Two Fermions	**Higgs mode**	**Z mode**		**Higgs mode**	**Z mode**		**Higgs mode**	**Z mode**
$q\bar{q}$	>99.9	>99.9	$\mu^+\mu^-$	99.6	>99.9	$\tau^+\tau^-$	99.6	>99.9
Bhabha	99.9	>99.9						
Di-photon process	**Higgs mode**	**Z mode**		**Higgs mode**	**Z mode**		**Higgs mode**	**Z mode**
$\gamma\gamma \to b\bar{b}$	99.6	>99.9	$\gamma\gamma \to c\bar{c}$	98.4	99.7	$\gamma\gamma \to q\bar{q}$	81.6	90.7
$\gamma\gamma \to \mu^+\mu^-$	26.9	29.6	$\gamma\gamma \to \tau^+\tau^-$	78.0	92.1			
Background	**Veto efficiency**							
	Higgs mode	**Z mode**						
Beam Background	99.3	99.3						

Hough transform

- Use only ITK+OTK ($>$2 ITK hits && $>$0 OTK hits)
  - Barrel(or)Endcap: Bkg: 69.6%; $Z(\nu\nu)H(\mu\mu)$: 96.5%; $Z(\nu\nu)H(bb)$: $>$99
  - Only Barrel: Bkg: 27.7%; $Z(\nu\nu)H(\mu\mu)$: 91.1%; $Z(\nu\nu)H(bb)$: 98.6
- Use Vextex 4 layers+ITK+OTK ($>$2 VXD hits && $>$2 ITK hits && $>$0 OTK hits)
  - Barrel(or)Endcap: Bkg: 0.9%; $Z(\nu\nu)H(\mu\mu)$: 94.9%; $Z(\nu\nu)H(bb)$: $>$99
  - Only Barrel: Bkg: 0.3%; $Z(\nu\nu)H(\mu\mu)$: 89.4%; $Z(\nu\nu)H(bb)$: 97.7