CEPC 4th detector readout constrain estimation

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Introduction

- CEPC Experiment: future lepton collider as W/Z/Higgs/top factory
  - Plan to have 1 Million Higgs, 100 Million W, 1 Tera Z and 1 Million top.
  - High Lumi. Higgs mode $\sqrt{s} = 240GeV$: $\mathcal{L}{\sim}5{\times}10^{34}\ cm^{-2}s^{-1}$, bunch spacing 636ns.
  - High Lumi. Z mode @ $\sqrt{s} = 91.2GeV$: $\mathcal{L}{\sim}115{\times}10^{34}\ cm^{-2}s^{-1}$, bunch spacing 25ns.

From Yiwei Wang's report @ Workshop 2021

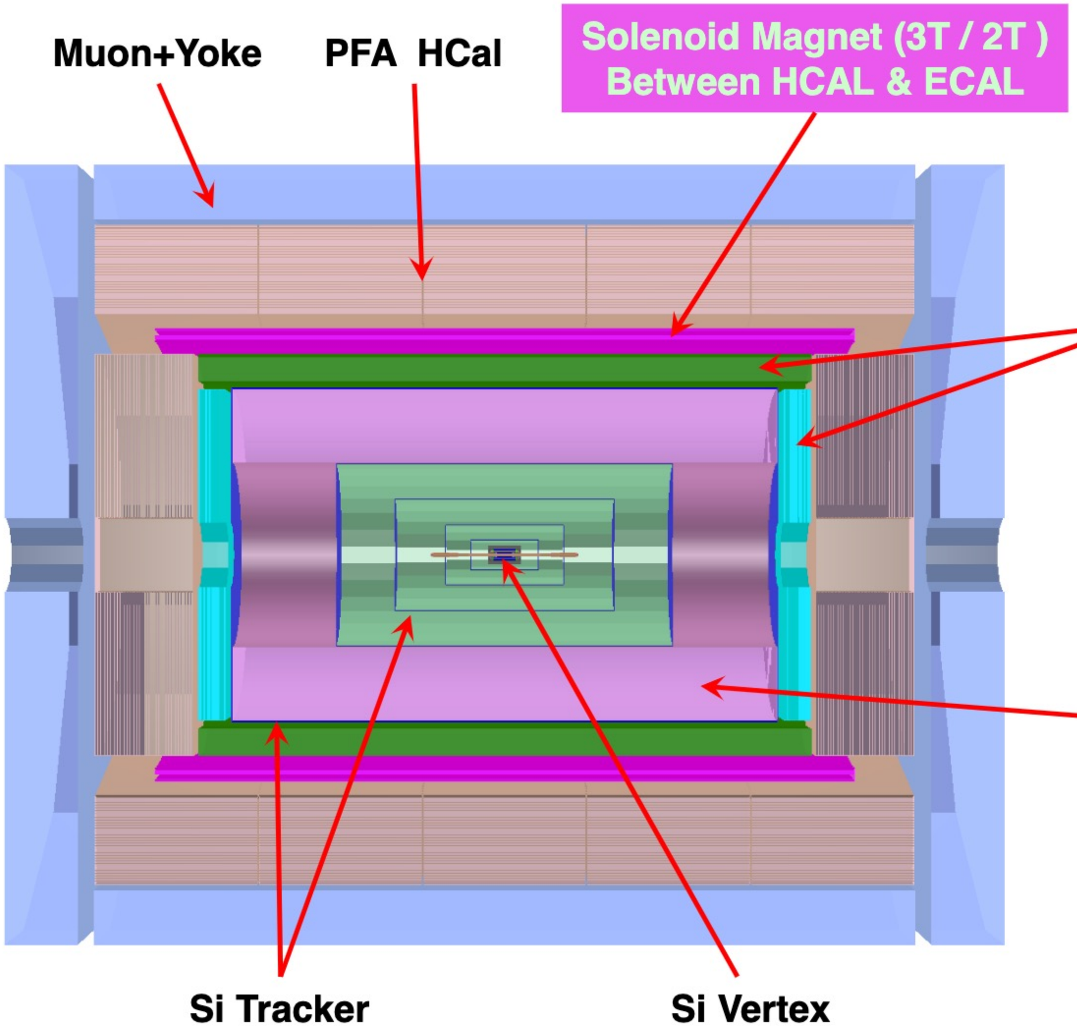
Physics Process @ Higgs mode	σ (pb) @ $\sqrt{s} = 240GeV$	Rate (Hz)
ffH signal	0.203	0.10
Bhabha	930	46.5
$e^+e^- \rightarrow q\bar{q}$	54.1	2.7
$e^+e^- \rightarrow W^+W^-$	16.7	0.84
$e^+e^- \rightarrow \mu^+\mu^-/\tau^+\tau^-$	5.3	0.26
Total signal		~50
Beam bunch		$1.57{\times}10^6$

Physics Process @ Z mode	σ (nb) @ $\sqrt{s} = 91.2GeV$	Rate (Hz)
$e^+e^- \rightarrow q\bar{q}$	30.20	34.7k
$e^+e^- \rightarrow \mu^+\mu^-$	1.51	1.73k
Total signal		<50k
Beam bunch		$40{\times}10^6$

- Studying the performance and rate is the first step for detector trigger design.

Introduction

- CEPC 4th conceptual detector design:



Advantage: the HCAL absorbers act as part of the magnet return yoke.

Challenges: thin enough not to affect the jet resolution (e.g. BMR); stability.

Advantage: better π^0/γ reconstruction.

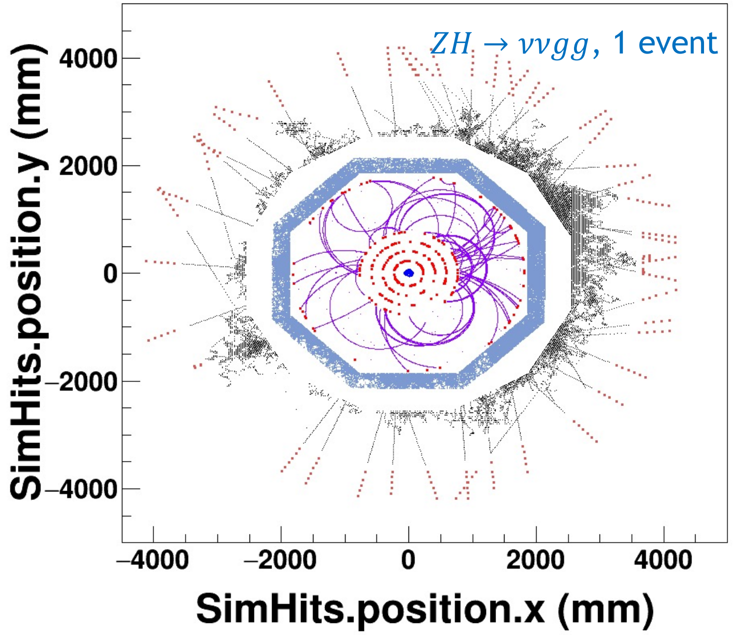
Challenges: minimum number of readout channels; compatible with PFA calorimeter; maintain good jet resolution.

Advantage: Work at high luminosity Z runs

Challenges: sufficient PID power; thin enough not to affect the moment resolution.

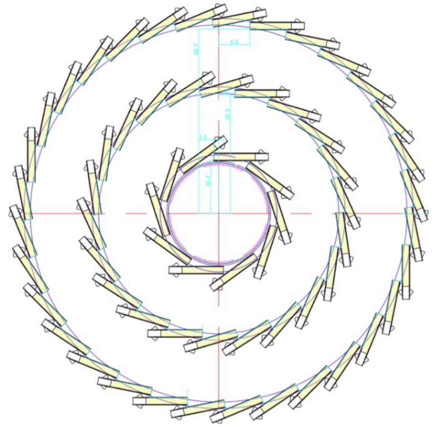
Introduction

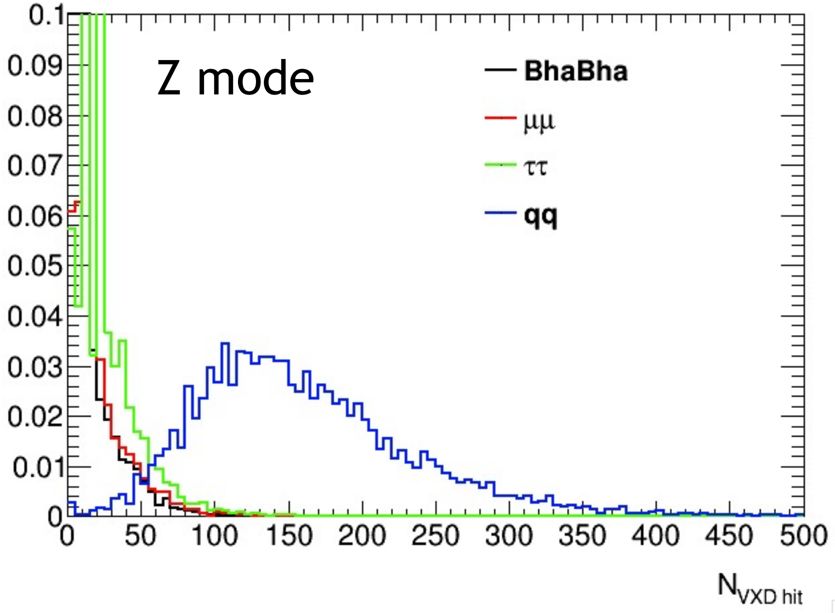
- Readout constraint estimation for CEPC 4th conceptual detector:
  - An update based on Zhen-an et.al.'s reports @ CEPC Workshop 2020.
  - Based on full simulation of physics processes ⇨ Maximum readout capacity and data rate.
    - Higgs mode ($\sqrt{s} = 240GeV$): Higgs signal (ffH), 2 fermion background($ee \rightarrow qq, ee, \mu\mu, \tau\tau, \nu\nu$).
    - Z mode ($\sqrt{s} = 91GeV$): Bhabha, $ee \rightarrow \mu\mu, \tau\tau, qq$.
    - Beam background events are not simulated.
  - Considered sub-detector in simulation: beam pipe, Si vertex, Si tracker, drift chamber, crystal ECAL barrel, Coil, RPC HCAL barrel + endcap, Muon/Yoke (No ECAL endcap and LumiCal).
    - No results from Muon for lack of digitization.
  - No noise or threshold in simulation/digitization.
  - Impact from beam background is roughly estimated, but is not the latest results (In Haoyu Shi's report tomorrow).

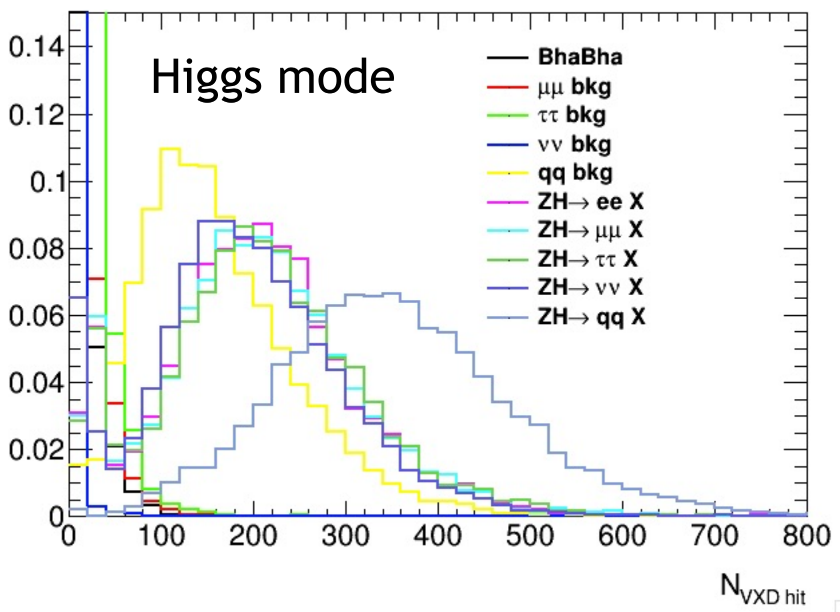


Detector readout with full sim.

- Silicon vertex: three double layer vertex detector.
  - Radius: 16mm, 37mm, 58mm.
  - Length: 125mm, 250mm, 250mm.
  - Record the simulated hits from G4, and suppose no more than 1 hits per pixel
  - Hit density is dominant by beam background, but lack of simulation now.







Detector readout with full sim.

- Silicon vertex: three double layer vertex detector.

Z mode	BhaBha	mumu	tautau	qq
Mean Nhit	11.7534	15.3504	20.4219	160.627
Max Hit density* [cm^{-2}/event]	0.036	0.047	0.063	0.496

Hit density @ VXD is dominant by beam background.

Higgs mode	BhaBha	mumu	tautau	nunu	qq	ZH->eeX	ZH->mumuX	ZH->tautauX	ZH->nunuX	ZH->qqX
Mean Nhit	7.694	12.7707	18.7911	0.318993	162.557	202.644	204.512	208.069	192.168	354.745
Max Hit density* [cm^{-2}/event]	0.024	0.039	0.058	0.001	0.502	0.626	0.632	0.643	0.594	1.096

*Mean value multiplied by safe factor 5.

Table. 1 The hit density of CEPC

Parameter	Unit	Higgs	W	Z
Bunch spacing	ns	680	210	25
Hit density	hits/bunch/cm²	2.5	2.5	0.2
	hits/bunch	8.2	8.2	0.66
	pixels/bunch	25	25	2
Hit pixel rate	MHz/cm²	11	36	24
	MHz/chip	36	120	80
Chip data rate (triggerless)	Gbps	1.15	3.84	2.56
	MHz/32bit	36	120	80

- **If triggerless, all the raw hit data should be sent off chip (most are background events)**
  - **The data rate: ~32bits*120MHz= 3.84Gbps**
- **In trigger:**
  - **Data rate@W: ~32bit * 25pixels/bunch * 20kHz trigger rate * 7 error windows= 112Mbps ~160Mbps**
  - **Data rate@Z: ~32bit * 2pixels/bunch * 100kHz trigger rate *7 error windows= 44.8Mbps < 160Mbps**

6

Estimation from Wei Wei @2020 workshop

Higgs mode

Background Type	Hit Density($cm^{-2}\cdot BX^{-1}$)
Pair production	1.91
Synchrotron Radiation	0.026
Radiative Bhabha	0.34
Beam Gas	0.9607
Beam Thermal Photon	0.02
Total	3.2567

Z mode

Background Type	Hit Density($cm^{-2}\cdot BX^{-1}$)
Pair production	0.012
Beam Gas	2.89×10^{-3}

Beam background study by Haoyu Shi @ 2020 workshop

Detector readout with full sim.

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Max Hit density* [cm^{-2}/event]	0.024	0.039	0.058	0.001	0.502	0.626	0.632	0.643	0.594	1.096

*With safe factor 5. Event rate is not considered.

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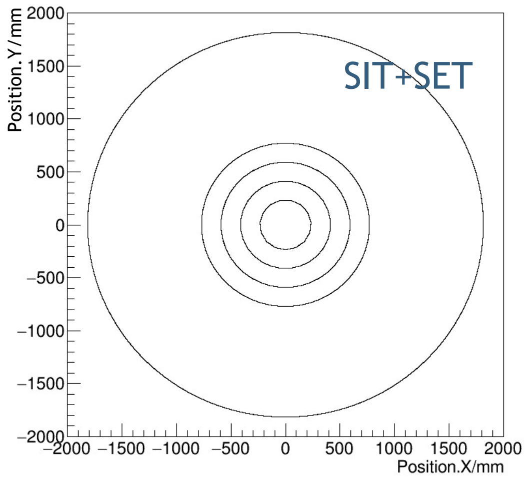
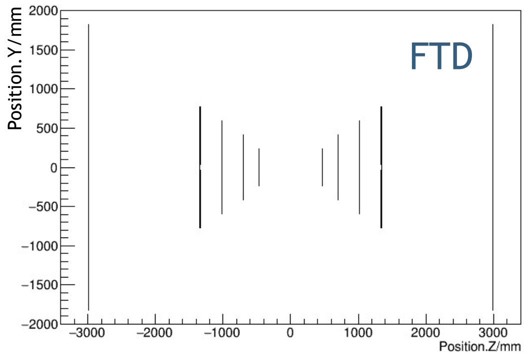
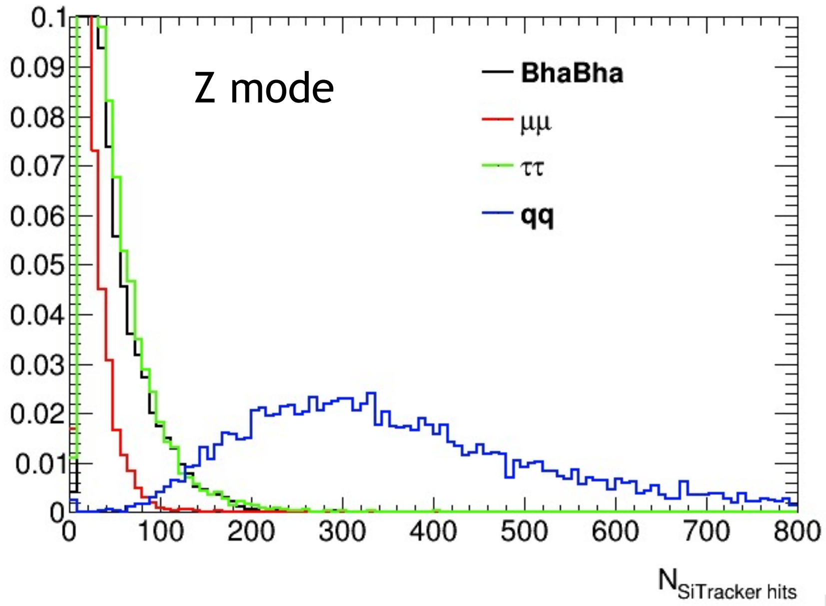
Beam background study by Haoyu Shi @ 2020 workshop

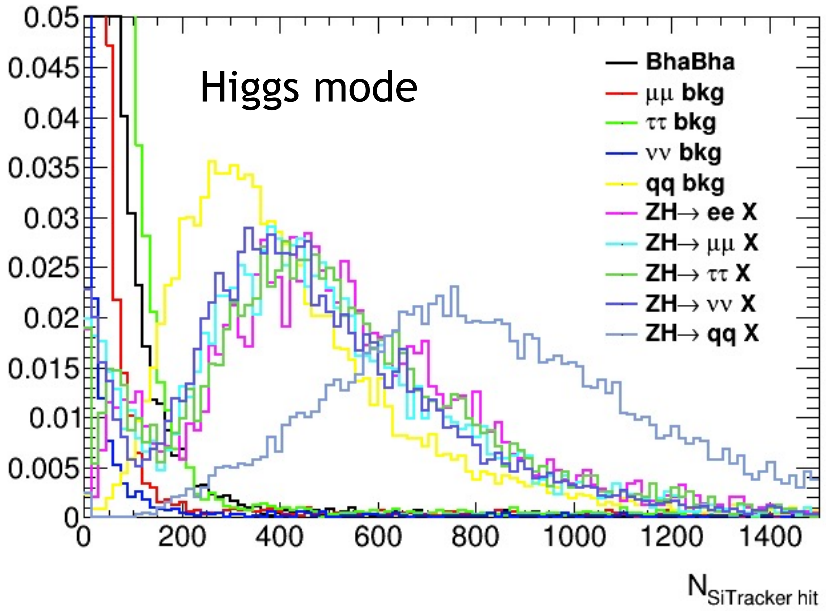
Detector readout with full sim.

- Silicon tracker: SIT, SET, FTD.
  - 4 layers of Silicon Inner Tracker (SIT): R=230mm, 410mm, 590mm, 770mm, half length Z=0.46m, 0.691m, 1.0m, 1.34m.
  - 1 layer of Silicon External Tracker (SET): R=1.8m, Z=2.98m.
  - A set of Forward Tracking Detector (FTD) disks that compose a cylinder with SIT/SET.
  - Similar simulation and record methods as VXD.









Detector readout with full sim.

- Silicon tracker: SIT, SET, FTD.

Higgs mode	BhaBha	mumu	tautau	nunu	qq	ZH->eeX	ZH->mumuX	ZH->tautauX	ZH->nunuX	ZH->qqX
Event rate [Hz]	46.5	0.26	0.24	2.7	2.7	0.1 in total				
Mean SIT Hit	11.445	16.815	27.731	3.578	205.614	275.937	263.161	274.597	258.261	451.472
Max Hit density* [m^{-2}/event]	2.265	3.328	5.488	0.708	40.692	54.609	52.081	54.344	51.111	89.349
Mean SET Hit	15.343	10.293	24.884	3.317	82.029	105.589	85.503	98.858	84.211	155.042
Max Hit density* [m^{-2}/event]	1.138	0.764	1.846	0.246	6.085	7.833	6.343	7.334	6.247	11.502
Mean FTD Hit	37.235	24.711	35.793	8.357	149.509	128.970	117.519	123.796	117.587	220.127
Max Hit density* [m^{-2}/event]	13.461	8.934	12.940	3.021	54.052	46.627	42.487	44.756	42.512	79.583

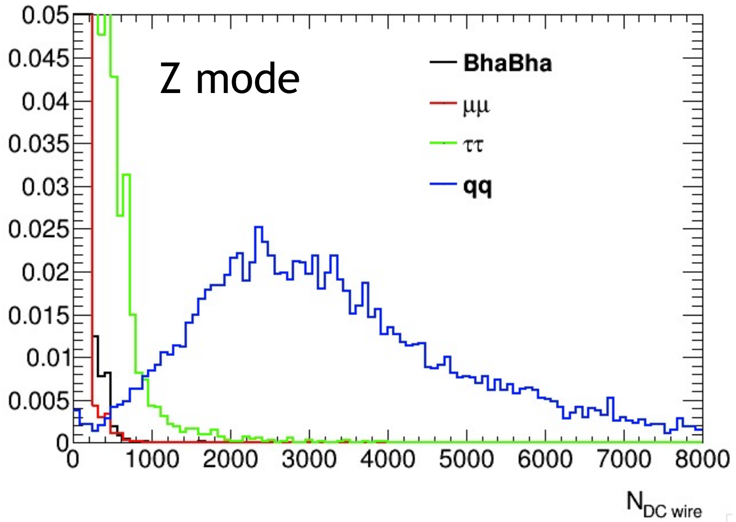
Z mode	BhaBha	mumu	tautau	qq
Event rate	-	1.5k	-	30.5k
Mean SIT Hit	10.825	10.701	20.494	219.649
Max Hit density* [m^{-2}/event]	2.142	2.118	4.056	43.470
Mean SET Hit	13.491	3.133	14.514	65.446
Max Hit density* [m^{-2}/event]	1.001	0.232	1.077	4.855
Mean FTD Hit	18.120	3.985	10.928	104.810
Max Hit density* [m^{-2}/event]	6.551	1.441	3.951	37.892

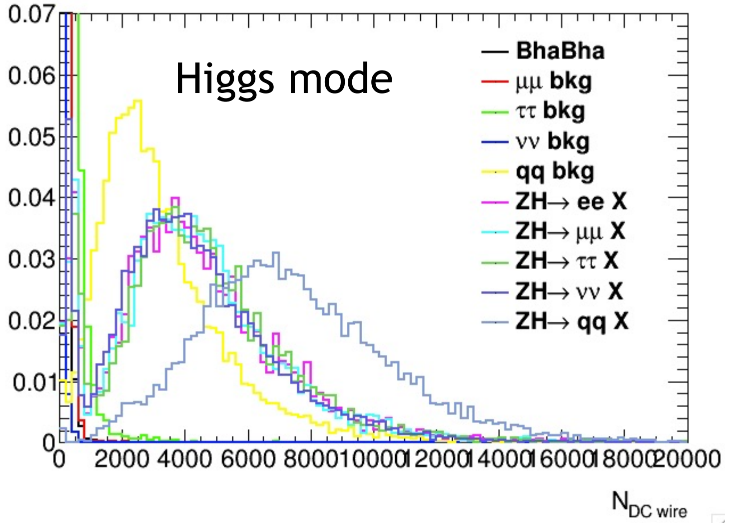
*With safe factor 5.

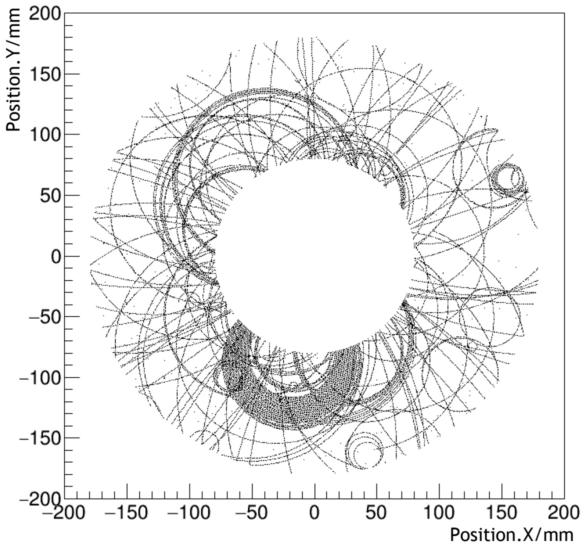
No precise previous estimation about readout, no beam background simulation at SiTracker region. So not sure about final rate/bandwidth.

Detector readout with full sim.

- Drift chamber:
  - Inner R=0.8m, outer R=1.8m, half length Z=3m, around 100 wires.

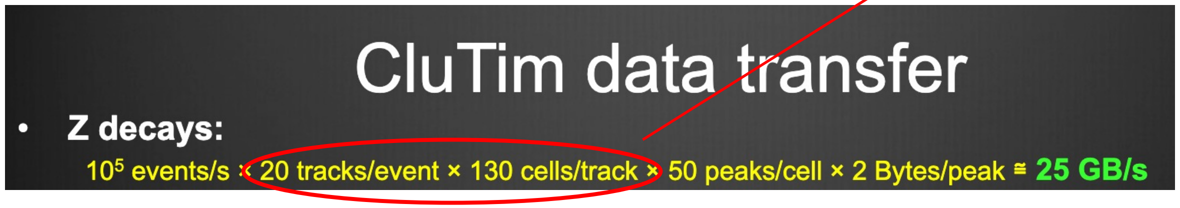






Higgs mode	BhaBha	mumu	tautau	nunu	qq	ZH->eeX	ZH->mumuX	ZH->tautauX	ZH->nunuX	ZH->qqX
Mean Nwire	77.8392	153.917	312.955	5.55793	3274.43	4327.93	4296.52	4413	4189.95	7509.82

Z mode	BhaBha	mumu	tautau	qq
Mean Nwire	124.597	180.713	337.755	3264.96

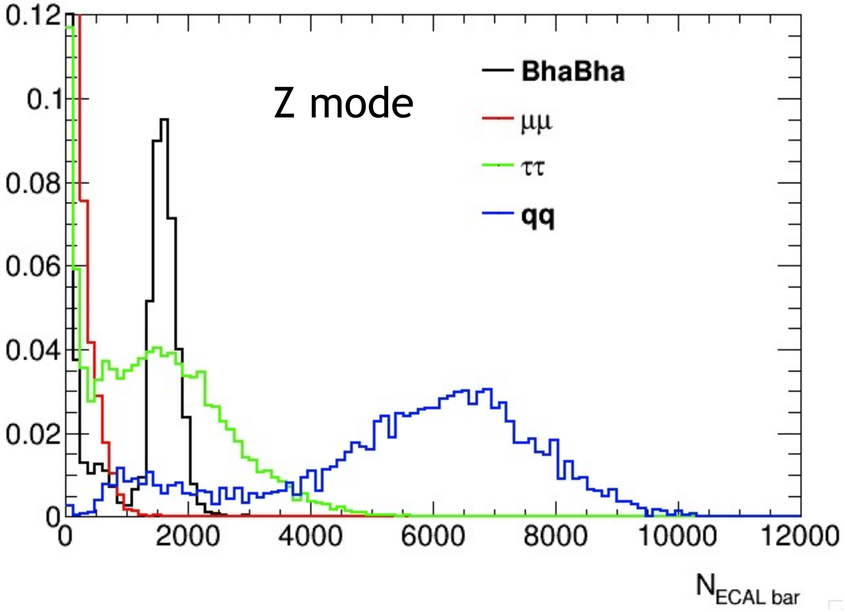


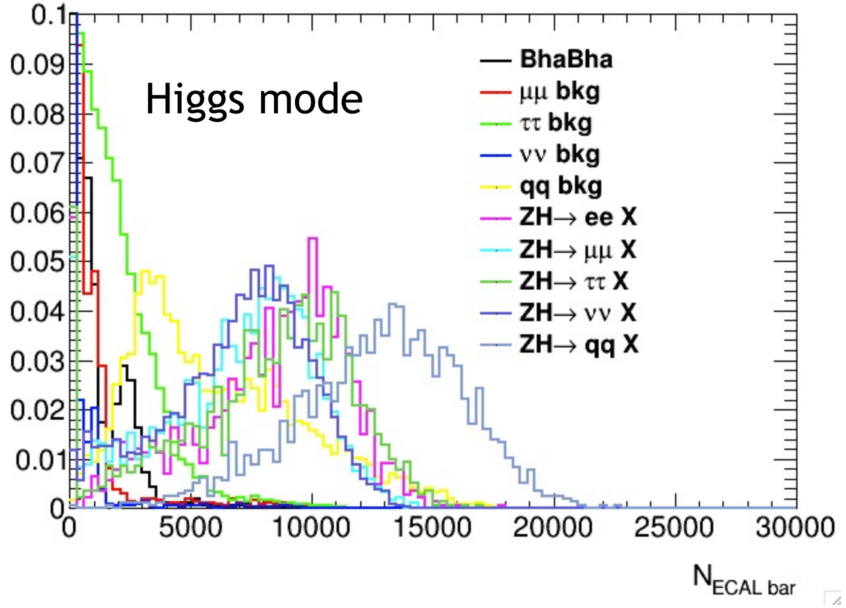
Previous estimation from F.Grancagnolo @ 2020 workshop

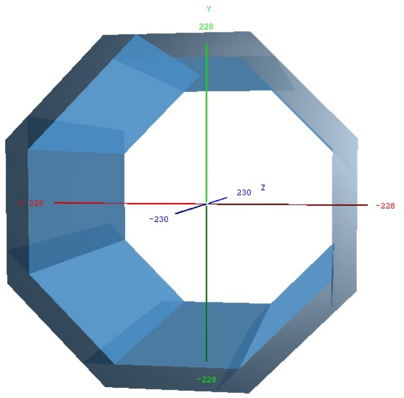
- At DC the physics process should be dominant.
- Previous result underestimated the track number in physical event. And dN/dx requires a very large bandwidth for transfer and DAQ.
- A trigger or fast track fitting to reduce little tracks might be essential.

Detector readout with full sim.

- Crystal ECAL (barrel only)
  - Octagonal geometry, with inner R=1.86m, outer R=2.3m, thickness 28cm, half length Z=3.4m.
  - Crystal bar size ~$1 \times 1 \times 40\ cm^3$, totally ~0.4M bars, double-side readout.







Detector readout with full sim.

- Crystal ECAL (barrel only)

Z mode	BhaBha	mumu	tautau	qq
Mean Nbar	722.381	167.234	1449.41	5553.52
Occupancy* [%]	0.542	0.125	1.087	4.165

Higgs mode	BhaBha	mumu	tautau	nunu	qq	ZH->eeX	ZH->mumuX	ZH->tautauX	ZH->nunuX	ZH->qqX
Mean Nbar	589.829	444.264	1750.2	128.807	6207.31	7956.27	6846.04	8046.34	6997.86	12829.9
Occupancy* [%]	0.442	0.333	1.313	0.097	4.655	5.967	5.135	6.035	5.248	9.622

*With a safe factor 3.

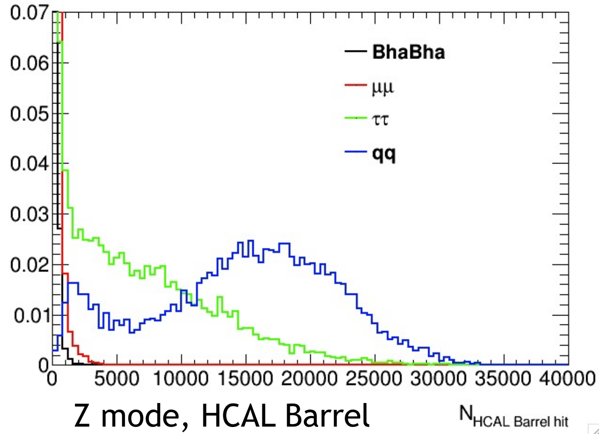
DAQ for crystal ECAL: considerations

ECAL options	#Channels [Million]	Occupancy [%]	#bit per channel	#readout channels/event	Data Volume per event	Data rate at 100kHz
Crystal ECAL with long bars (Barrel)	0.85	3.4	32	28.9 k	116 kByte	11.6 GBytes/s
Crystal ECAL with long bars (Endcap)	0.36	6.2	32	22.4 k	90 kByte	9.0 Gbytes/s

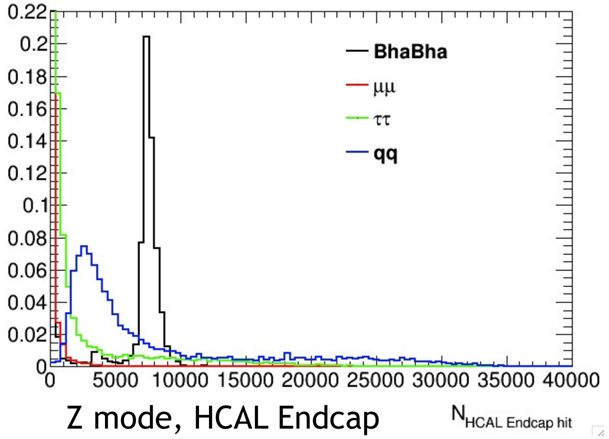
Estimation from Yong Liu @ 2020 workshop

Detector readout with full sim.

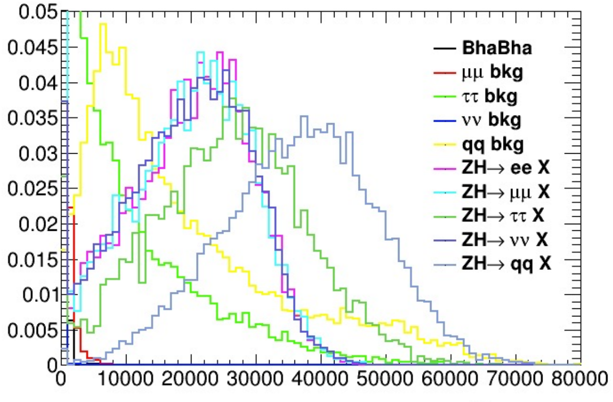
- RPC HCAL (barrel + endcap)
  - Inner R = 2.5m, outer R = 3.6m, half length Z = 4.8m, 12 staves in ϕ, 35 layers in R.
  - $1 \times 1\ cm^2$ RPC pads as sensitive readout, ~32M in total.



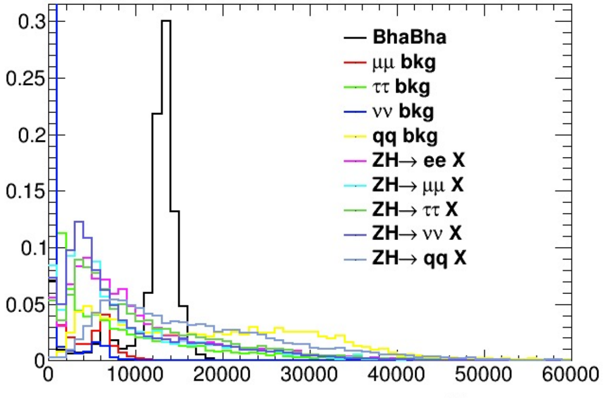
Z mode, HCAL Barrel



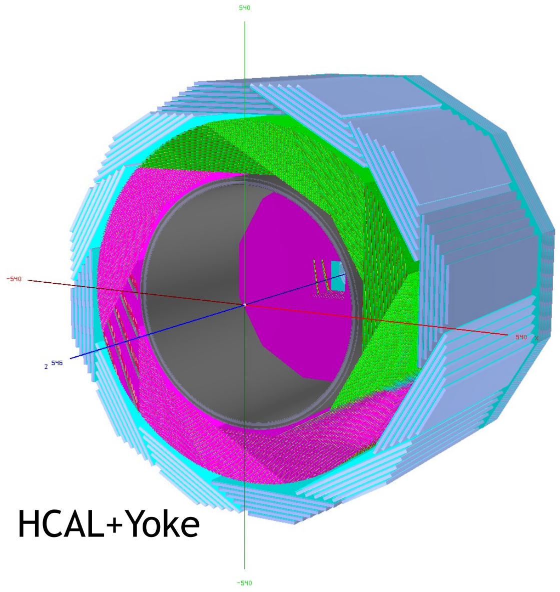
Z mode, HCAL Endcap



Higgs mode, HCAL Barrel



Higgs mode, HCAL Endcap



HCAL+Yoke

Detector readout with full sim.

- RPC HCAL (barrel + endcap)

Z mode	BhaBha	mumu	tautau	qq
Mean Nbar Barrel	89.8778	254.36	5764.35	14784.1
Occupancy* [%]	0.001	0.002	0.054	0.139
Mean Nbar Endcap	4626.79	107.055	2368.34	8162.44
Occupancy* [%]	0.043	0.001	0.022	0.077

Higgs mode	BhaBha	mumu	tautau	nunu	qq	ZH->eeX	ZH->mumuX	ZH->tautauX	ZH->nunuX	ZH->qqX
Mean Nbar Barrel	90.8384	255.212	8097.52	44.2944	19158.5	19369.1	19388.8	25632.8	19587.2	36750
Occupancy* [%]	0.001	0.002	0.076	0.000	0.180	0.182	0.182	0.240	0.184	0.345
Mean Nbar Endcap	11565.1	932.183	5816.96	369.141	19555.9	10048.1	8632.15	10680.4	8751.7	17104.6
Occupancy* [%]	0.108	0.009	0.055	0.003	0.183	0.094	0.081	0.100	0.082	0.160

*With a safe factor 3.

ECAL options	#Channels [Million]	Occupancy [%]	#bit per channel	#readout channels/evt	Data Volume per event	Data rate at 100kHz
Scintillator HCAL Barrel	3.6	0.02	32	0.72 k	2.9 kByte	0.3 GBytes/s
Scintillator HCAL Endcap	3.1	0.12	32	3.72 k	15 kByte	1.5 Gbytes/s
RPC HCAL Barrel	32	0.004	8	1.28 k	1.28 kByte	0.13 GBytes/s
RPC HCAL Endcap	32	0.01	8	3.2 k	3.2 kByte	0.32 Gbytes/s

Estimation from Yong Liu @ 2020 workshop

Bandwidth estimation

- Total bandwidth needed for detector readout in two scheme:
  - If with an extremely efficient (100% for physics process, 0 for beam background) L1 trigger: maximum bandwidth is limited by most complex physics process($ZH \rightarrow 4\ jets$ @ Higgs mode, $ee \rightarrow 2\ jets$ @ Z mode)
  - If in trigger-less scheme: beam background + maximum physics event.

Trigger rate	Higgs mode	Z mode	*Note
trigger-less	1.6 MHz	40 MHz	Beam bunch rate
Ideal L1 trigger	50 Hz	40 kHz	100kHz as a safe rate for both

Bandwidth estimation

- Vertex detector:
  - Use the results from Wei Wei last year, due to lack of latest beam background simulation.
  - Update the maximum #pixel/event with detector simulation:

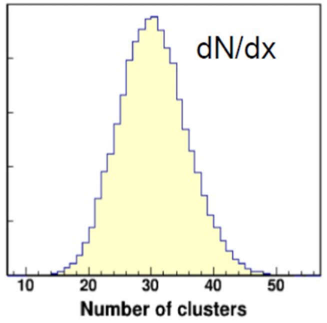
		Higgs	W	Z
Trigger-less		1.15 Gbps	3.84 Gbps	2.56 Gbps
Trigger	Trigger rate	1kHz	20kHz	100kHz
	Max #pixel/event	500	-	300
	bandwidth	16 Mbps		960 Mbps

32 bit per pixel for readout from Wei Wei.

- Drift chamber:
  - use CluTim data transfer to save time and amplitude of electron peak for cluster counting.
  - Beam background from rough estimation: #wire/bunch ~O(1k), #peak/wire~10.

		Higgs	Z
Trigger-less		256 Gbps	6.4 Tbps
Trigger	Trigger rate	1 kHz	100 kHz
	Max #wires/event	25k	10k
	bandwidth	20 Gbps	800 Gbps

50 peaks/wire*, 16bit/peak from F.Grancagnolo



From Shuiting's report:
#cluster for a wire in full simulation

Bandwidth estimation

- Crystal bar ECAL barrel:
  - Beam background from rough estimation: O(100) bars/event.

		Higgs	Z
Trigger-less		10 Gbps	256 Gbps
Trigger	Trigger rate	1 kHz	100 kHz
	Max #bars/event	25k	10k
	bandwidth	1.6 Gbps	64 Gbps

double-side readout channel,
32bit per channel from Yong Liu.

- RPC HCAL
  - Beam background from rough estimation: 0

	Higgs		Z	
Trigger rate	1 kHz		100 kHz	
	Barrel	Endcap	Barrel	Endcap
Max #hit/event	80k	60k	35k	35k
bandwidth	640 Mbps	480 Mbps	28 Gbps	28 Gbps

8 bit per channel
from Yong Liu.

Bandwidth estimation

- Summary

	Higgs mode		Z mode		beam background
	Trigger-less	Trigger @ 1kHz	Trigger-less	Trigger @ 100kHz	
VTX	1.15 Gbps	16 Mbps	2.56 Gbps	0.96 Gpbs	Old results @ 2020
Si-tracker	-	-	-	-	
DC	256 Gbps	20 Gpbs	6.4 Tbps	800 Gbps	Rough estimation
ECAL*	20 Gbps	3.2 Gbps	512 Gbps	128 Gbps	Rough estimation
HCAL	1.12 Gbps	1.12 Gbps	56 Gbps	56 Gbps	Rough estimation
Muon	-	-	-	-	
LumiCal	-	-	-	-	

*Suppose ECAL Endcap needs the same bandwidth as ECAL Barrel.

Summary

- CEPC 4th conceptual detector readout constraint estimation:
  - Calculated the #channel for each sub-detector with full simulation of physics processes at CEPC Higgs and Z mode.
  - Presented a very rough estimation on the needed bandwidth, for trigger-less scheme and ideal L1 trigger scheme.
  - Silicon detector, Muon chamber, ECAL endcap and LumiCal are not considered due to some reasons.
  - Beam background processes play an very important role in trigger design, but are not counted this time.

  - A long way to go, but we have started the first step!

Many thanks to the help from each sub-detector people and software group!

Backup

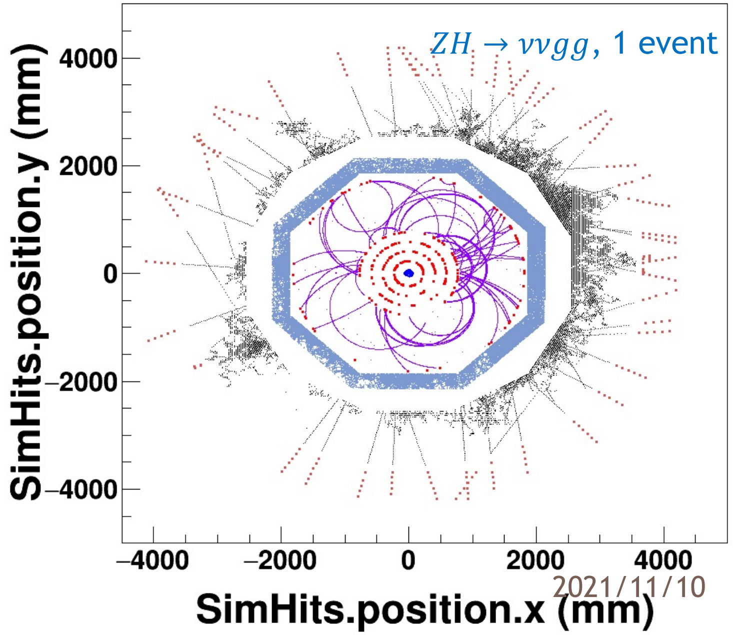
Beam parameters

	ttbar	Higgs	W	Z
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	30			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch spacing [ns]	4524	636	257	25 (10% gap)
Bunch population [10^10]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^-5]	0.71	0.71	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	0.27/1.4
Beam size at IP (sigx/sigy) [um/nm]	39/113	15/36	13/42	6/35
Bunch length (SR/total) [mm]	2.2/2.9	2.3/3.9	2.5/4.9	2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20	0.10/0.17	0.07/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	2.3/2.6	1.7/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	0.071/0.1	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-/1.8/0.9	-/-/5.8
Longitudinal tune Qs	0.078	0.049	0.062	0.035
Beam lifetime (bhabha/beamstrahlung)[min]	81/23	39/40	60/700	80/18000
Beam lifetime [min]	18	20	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

Yiwei Wang's report @ Workshop 2021

Introduction

- CEPC 4th conceptual detector design:
  - Simulate main physics processes at Z/Higgs mode in CEPCSW framework.
    - Higgs mode ($\sqrt{s} = 240GeV$): Higgs signal (ffH), 2 fermion background($ee \to qq, ee, \mu\mu, \tau\tau, \nu\nu$).
    - Z mode ($\sqrt{s} = 91GeV$): Bhabha, $ee \to \mu\mu, \tau\tau, qq$.
  - Considered sub-detector in simulation: beam pipe, Si vertex, Si tracker, drift chamber, crystal ECAL barrel, Coil, RPC HCAL barrel + endcap, Muon/Yoke (No ECAL endcap and LumiCal).
    - For Silicon vertex and tracker: all hits in simulation as fired pixel (suppose no more than 1 hit in each pixel).
    - For Drift chamber: digitalized wires in DC, without track fit.
    - For ECAL barrel: fired crystal bars.
    - For HCAL: fired sensitive cells.
    - No results from Muon due to no digitization.
    - No noise or threshold in simulation/digitization.
  - Only have physics process simulation now, corresponds to necessary maximum channels to record a event.
  - Bandwidth estimation needs beam background simulation.



Beam background in HCAL

- Old simulation result in CEPC_v4 detector:
  - GRPC SDHCAL.
  - SiW ECAL, TPC tracker.
  - Solenoid at outside of HCAL