CEPC Detector Trigger System

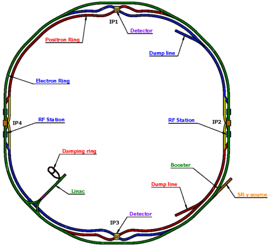
Boping Chen

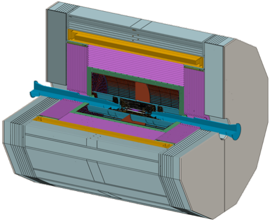
中国科学院高能物理研究所 IHEP
On behalf of CEPC TDAQ Group

Jun. 17, 2025

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



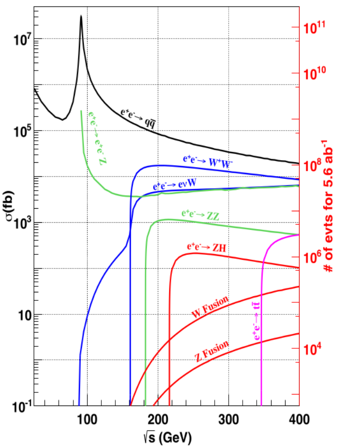


Outline for this talk

- Trigger overall design
- Simulation and performance
- Future and summary

- 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: 10/40 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

CEPC Physics & Detector CDR

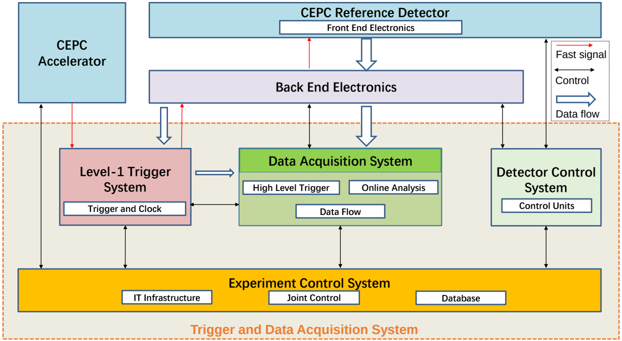


	Higgs	Z	W	$t\bar{t}$
SR power per beam (MW)	50			
Bunch number	446	13104	2162	58
Bunch spacing (ns)	346.2 (×15)	23.1 (×1)	138.5 (×6)	2700.0 (×117)
Train gap (%)	54	9	10	53
Luminosity per IP (10^{34} cm^{-2} s^{-1})	8.3	192	26.7	0.8

CEPC Accelerator TDR

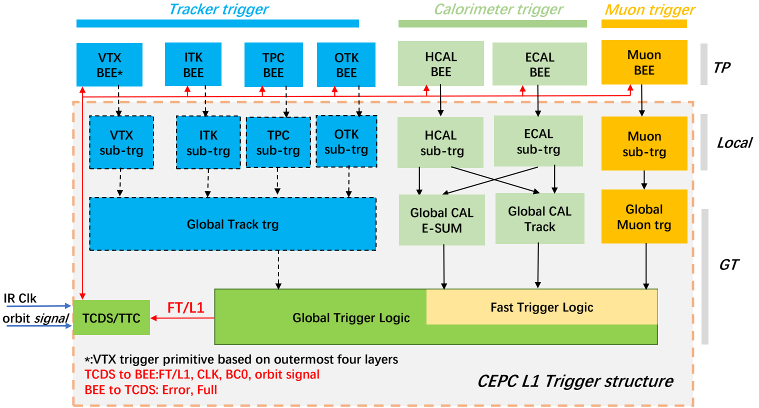
TDAQ overall design

- Electronics framework schema
  - Full data transmission from Front-End Elec
  - Connect trigger with Back-End Elec
  - More detail was presented by W. Wei.
- Trigger strategy
  - Baseline option: hardware trigger(L1) + high level trigger(HLT)
    - L1: **Calorimeter** and **Muon** detector (presented in this talk)
    - L1: may be able to use vertex, tracker and even TPC (30 us time window), to be studied
    - L1 trigger rate: Higgs: O(10k) Hz; Z: O(100k) Hz
    - HLT: Full detector information (to be studied)
    - HLT trigger rate: Higgs: O(1k) Hz; Z: 20kHz
  - Other option: full software trigger
    - More complicated algorithm, may be helpful for new physics
- DAQ will be introduced by X. Ji



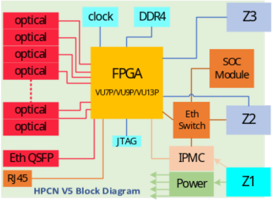
Hardware trigger design

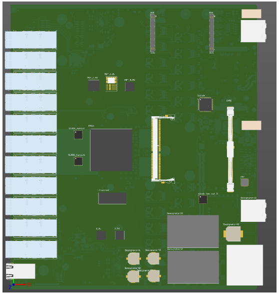
- Trigger primitive(TP) extracted from BEE
- Local detector trigger: cluster and tracking
- Global trigger： Fast trigger(FT) and L1 generation on demand
- TCDS (Trigger Clock Distribution System)
  - Distribute clock and fast control signals to BEE



Common trigger board

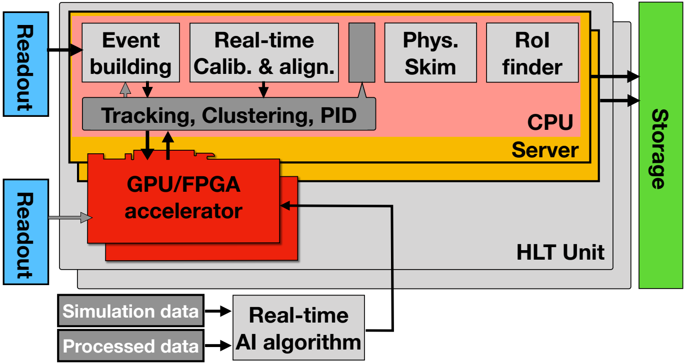
- Developed a series of xTCA boards
  - Started the design of an ATCA common trigger board for CEPC
- Common Trigger board function list
  - ATCA standard
  - Virtex Ultrascale Plus FPGA
  - Optical channel: 10-25 Gbps/ch
  - Channel number:36-48 channels
  - Optical Ethernet port: 40-100GbE
  - DDR4 for mass data buffering:16GB
  - SoC module for board management
  - IPMC module for Power management





HLT design

- Event selection and data reduction
  - Distributed Computing
  - Advanced Software Tools
  - Real-Time Constraints
  - Detector Limitations (pile-up)
  - Performance vs. cost-effective
- Implement feature
  - Feature Extraction
  - Track Seed Finding
  - Lightweight PID
  - Calibration
  - Physics Skim/ROI
- Need R&D a compatible and high-efficiency interface software for offline algorithm.
- Accelerated by GPUs and FPGAs in addition to CPUs



MC Simulation at Higgs mode

Signal

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

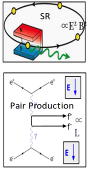
Background

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

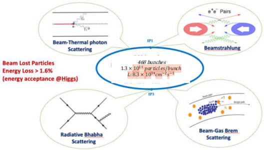
MC Simulation: beam induced background

- Single Beam
  - Touschek Scattering
  - Beam Gas Scattering(Elastic/inelastic)
  - Beam Thermal Photon Scattering
  - Synchrotron Radiation
- Luminosity Related
  - Beamstrahlung
  - Radiative Bhabha Scattering
- Combine 10 bunch crossings into one event: safety factor 10
- More detail will be presented by H. Shi tomorrow

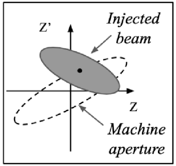
A. Natochii



Photon BG



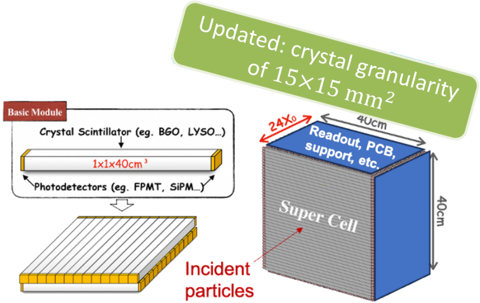
Beam Loss BG

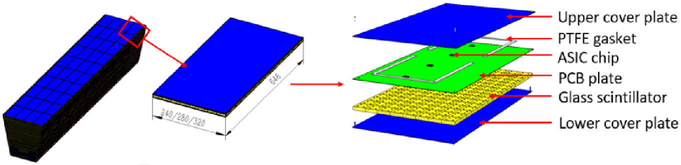


Injection BG

Calorimeter trigger primitive

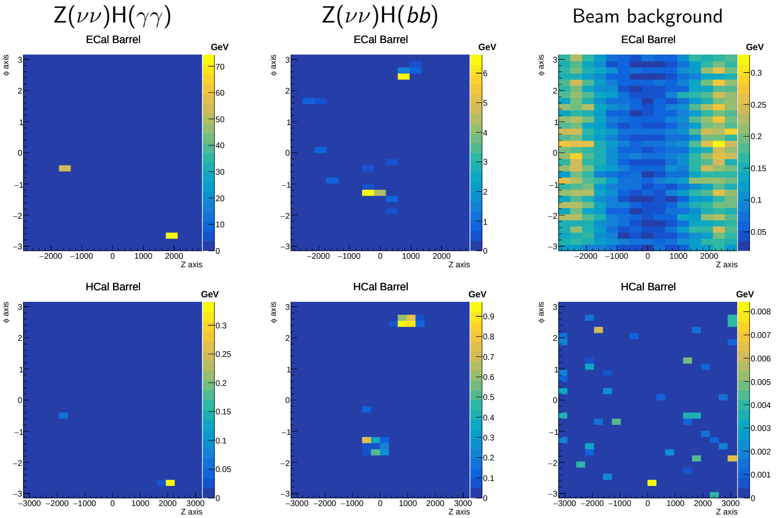
- Basic module for EM Calorimeter (ECal): ~1.5x1.5x40cm^3
  - Cluster modules into 40x40cm^2 supercell as trigger input
  - 15(Z)x32(ϕ) in Z-ϕ plane
- Basic module for HCal: Barrel-Box (240/280/320 x 646mm^2)
  - Combine two in ϕ and split into two in Z
  - 20(Z)x32(ϕ) in Z-ϕ plane (~match ECal)





Barrel energy distribution

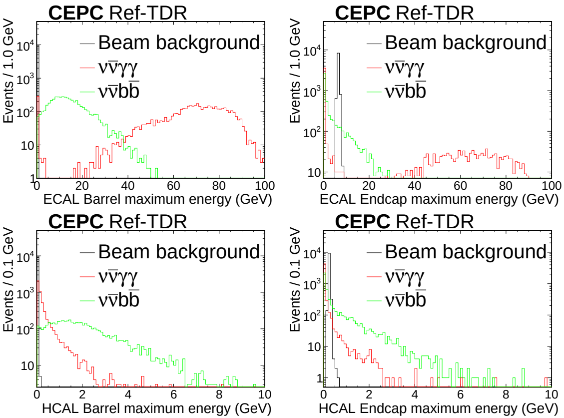
- Large energy deposition($>$ 10 GeV) for signal (photon, and Jet)
- Very tiny energy deposition($<$0.5 GeV) for beam background, mostly from pair production



Maximum energy distribution

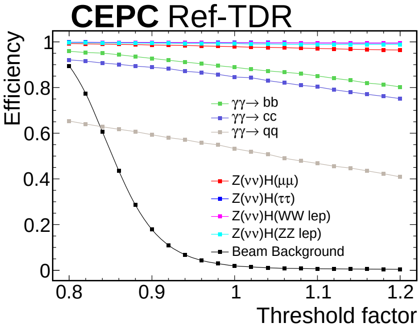
- Maximum energy distribution
- Beam induced background contributes little(<1GeV) on calorimeter, except ECal Endcap
- A baseline set of energy threshold

Sub-detector	Energy threshold
ECal Barrel	>0.38 GeV
or HCal Barrel	>0.05 GeV
or ECal Endcap	>7.7 GeV
or HCal Endcap	>0.33 GeV



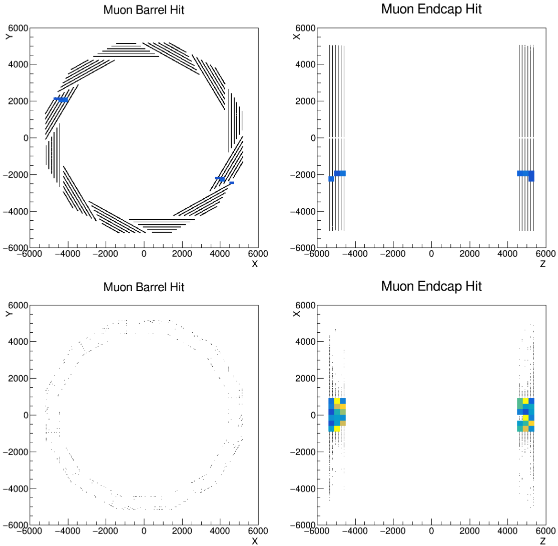
Efficiency vs. Calo. energy threshold

- 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
- Only the ZH production with an efficiency below 99%, the di-photon processes and background are shown
- Signal processes are affected if the final state contains only neutrinos and muon



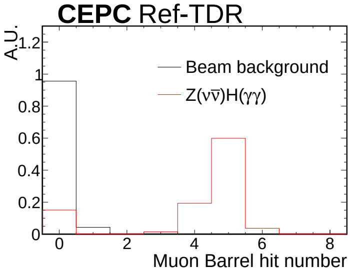
Muon detector

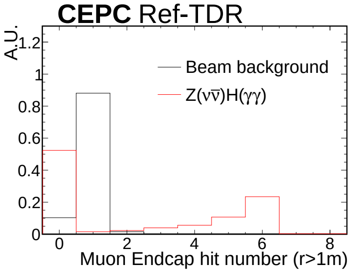
- Top: signal $Z(\nu\nu)H(\mu\mu)$
- Bottom: beam background
  - Black hits: hits for all 2000 events
  - Color hits: hits for single events
- Count number of muon hit inside a small cone(baseline radius)
  - Barrel: dR<0.05
  - Endcap: dR<0.01

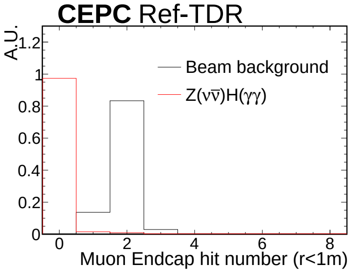


Number of hit distribution

- Baseline cut for the number of hit:
  - Barrel>1
  - Endcap with radius > 1m: >1
- Background efficiency: 1.6%
- $Z(\nu\nu)H(\mu\mu)$ efficiency: 99.8%; $\mu\mu$ efficiency: 97.9%







L1 global efficiency for baseline selection & HLT

- L1 global trigger efficiency
  - >99% for most of the physical processes
  - <5% for beam background

Higgs mode	**Efficiency(%)**	***Z* mode**	**Efficiency(%)**
Higgs production	>99	$q\bar{q}$	>99.9
$q\bar{q}$	99.8	$\mu^+\mu^-$	>99.9
$\mu^+\mu^-$	99.4	$\tau^+\tau^-$	99.5
$\tau^+\tau^-$	96	Bhabha	>99.9
Bhabha	99.8		
Beam Background		**Beam Background**	
Background event rate	**Veto efficiency(%)**	**Background event rate**	**Veto efficiency(%)**
46.9 kHz	96.5	108 kHz	99.1

- Offline tracking reconstruction are test for HLT:
  - <20% of background events contains 1 track

Future

- More simulation and research need to be done
  - Signal background mixing
  - Cosmic ray study
  - Electronic noise
  - ...
- Trigger algorithm study
  - Hardware algorithm: fast track reconstruction, calorimeter cluster, Muon track...
  - Software algorithm: track trigger, event size compress(for TPC, Calorimeter), PID...
  - ML(BDT, DNN, CNN···)
  - Trigger for BSM
- Hardware firmware simulation

Summary

- Optimized and detailed baseline technical design of Trigger system
    - L1+HLT
- The L1 trigger system design a general-purpose processing board
- Baseline L1 trigger algorithm achieved very 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
  - 600 GB/s for Higgs mode
  - Several TB/s for Z mode

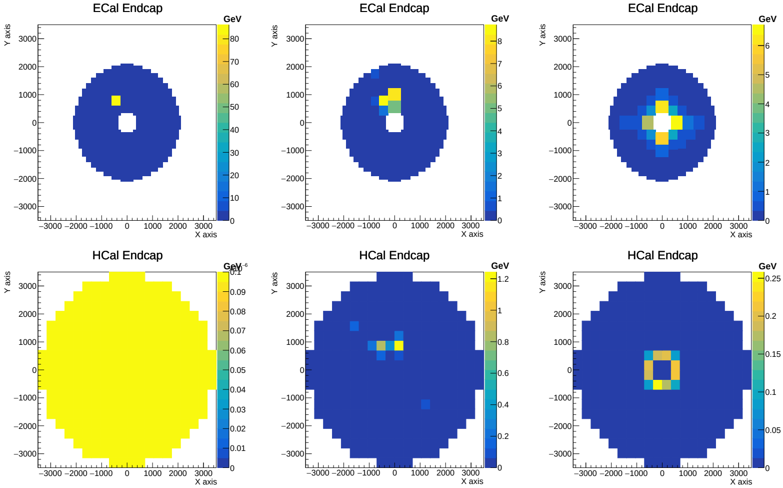
Operation phase		**I**		**II**	**III**
Condition	**Higgs**	**Z (12.1 MW)**	**W**	**Z (50 MW)**	**$t\bar{t}$**
Non-empty bunch crossing rate(MHz)	1.34	12	6.5	39.4	0.17
Luminosity ($10^{34}/cm^2/s$)	8.3	26	26.7	95.2	0.8
Physical event rate (kHz)	0.5	10	1.1	40	5.7×10^{-2}
L1 triger rate (kHz)	50	120	65	400	2
DAQ readout rate (Gbyte/s)	49.0	72.8	-	555	-
HLT rate (kHz)	1	20	2	80	1
Raw event size (kbyte)	1453.5	801.1	1500	2042	1000
DAQ storage rate (Gbyte/s)	1.5	16	3	163	1

Higgs mode processes	**Cross section (fb)**	**Event rate (Hz)**
Physical events (top priority)		
Higgs production	203.7	1.7×10^{-2}
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)**	
		12.1 MW	**50 MW**
Physical events (top priority)			
qq	3.1×10^7	7970	29181
$\mu\mu$	1.5×10^6	400	1462
$\tau\tau$	1.5×10^6	396	1452
Bhabha	6.6×10^6	1714	6277
Diphoton process (low priority)			
$\gamma\gamma \to b\bar{b}$	2.7×10^5	71	260
$\gamma\gamma \to c\bar{c}$	5.1×10^5	132	482
$\gamma\gamma \to q\bar{q}$	3.5×10^7	9014	33006
$\gamma\gamma \to \mu\mu$	1.3×10^8	33696	123379
$\gamma\gamma \to \tau\tau$	6.3×10^5	163	598

Endcap energy distribution

- Similar to Barrel for signal
- Relatively large energy deposition(∼5 GeV) for beam background
- Use supercell energy as input



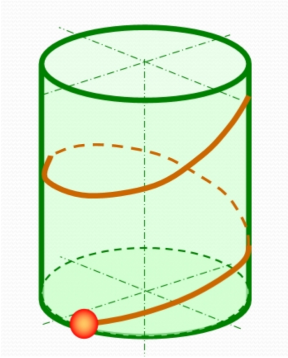
Efficiency for baseline L1 Calo threshold

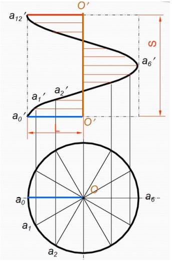
- The baseline threshold is chosen to show the efficiency
- Efficiency $> 99\%$ for most of the physical process
- Higher energy threshold doesn't affect the physical processes much, but reduce the background $<1\%$

Process	**Efficiency(%)**		**Process**	**Efficiency(%)**		**Process**	**Efficiency(%)**	
Higgs 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	
$Z(\nu\bar{\nu})H(\mu^+\mu^-)$	97.9		$Z(\nu\bar{\nu})H(\tau^+\tau^-)$	99.6		$Z(\nu\bar{\nu})H(W^+W^-)$	>99.9	
$Z(\nu\bar{\nu})Z(W^+W^-)$lep	99.5		$Z(\nu\bar{\nu})H(ZZ)$	>99.9		$Z(\nu\bar{\nu})H(ZZ)$lep	99.2	
Two Fermions	**Higgs mode**	**Z mode**		**Higgs mode**	**Z mode**		**Higgs mode**	**Z mode**
$q\bar{q}$	99.8	>99.9	$\mu^+\mu^-$	94.9	>99.9	$\tau^+\tau^-$	95.8	99.5
Bhabha	99.8	>99.9						
Di-photon process	**Higgs mode**	**Z mode**		**Higgs mode**	**Z mode**		**Higgs mode**	**Z mode**
$\gamma\gamma \to b\bar{b}$	88.8	99.6	$\gamma\gamma \to c\bar{c}$	84.6	97.3	$\gamma\gamma \to q\bar{q}$	53.3	70.6
$\gamma\gamma \to \mu^+\mu^-$	15.4	25.8	$\gamma\gamma \to \tau^+\tau^-$	51.4	78.5			
Background	**Veto efficiency**							
	Higgs mode	**Z mode**						
Beam Background	98.2	99.1						

Track

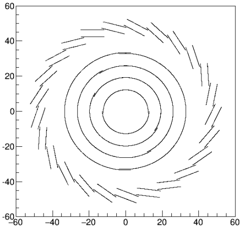
- Trajectory of charge particle: helix
- Circle in xy plane
- Trigonometric function in xz(yz) plane
- Equation in the cylindrical coordinate (r z):
    - $\frac{r\kappa}{2} = sin(\phi - \phi_0), z = tan\lambda \cdot s$
    - Assuming IP at origin
    - κ: curvature of the helix
    - ϕ_0: azimuth angle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

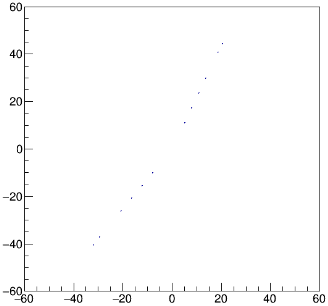


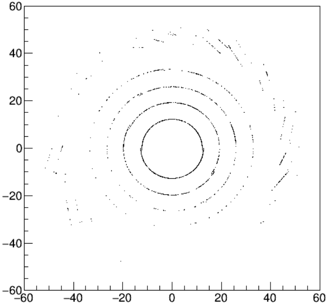


Vertex

- 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

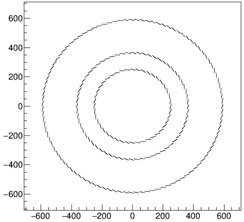


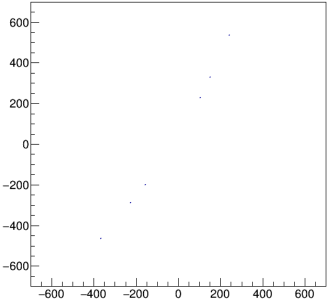


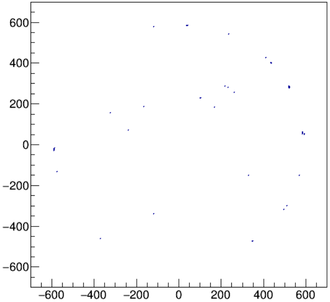


ITK

- 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

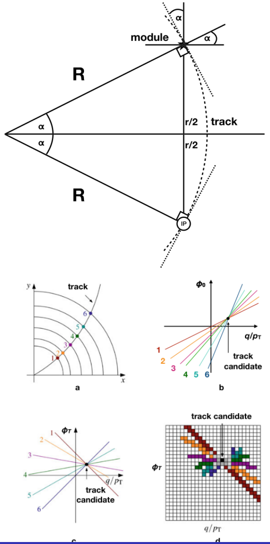






Hough transform

- 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(one bunch crossing/event): 1.2%
- $Z(\nu\nu)H(\mu\mu)$ efficiency: 93.5%; $Z(\nu\nu)H(bb)$ efficiency: 99.5%



Hough transform

- Use only ITK+OTK ($>$2 ITK hits && $>$0 OTK hits)
  - Use 10x
    - Barrel(or)Endcap: Bkg: 100%;
    - Only Barrel: Bkg: 100%;
  - Use 1x
    - Barrel(or)Endcap: Bkg: 100%; $Z(\nu\nu)H(\mu\mu)$: 96%; $Z(\nu\nu)H(bb)$: $>$99
    - Only Barrel: Bkg: 100%; $Z(\nu\nu)H(\mu\mu)$: 89.5%; $Z(\nu\nu)H(bb)$: 98
- Use Vextex 4 layers+ITK+OTK ($>$2 VXD hits && $>$2 ITK hits && $>$0 OTK hits)
  - Use 10x
    - Barrel(or)Endcap: Bkg: 100%;
    - Only Barrel: Bkg: 29.5%;
  - Use 1x
    - Barrel(or)Endcap: Bkg: 1.2%; $Z(\nu\nu)H(\mu\mu)$: 93.5%; $Z(\nu\nu)H(bb)$: $>$99
    - Only Barrel: Bkg: 0.3%; $Z(\nu\nu)H(\mu\mu)$: 88.0%; $Z(\nu\nu)H(bb)$: 97.5