

# **Performance and Background Analysis of CEPC Vertex Detector**

**On behalf of the CEPC VTX study group**

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CEPC VXD Geometry & Performance

**02**

CEPC VXD Background Analysis

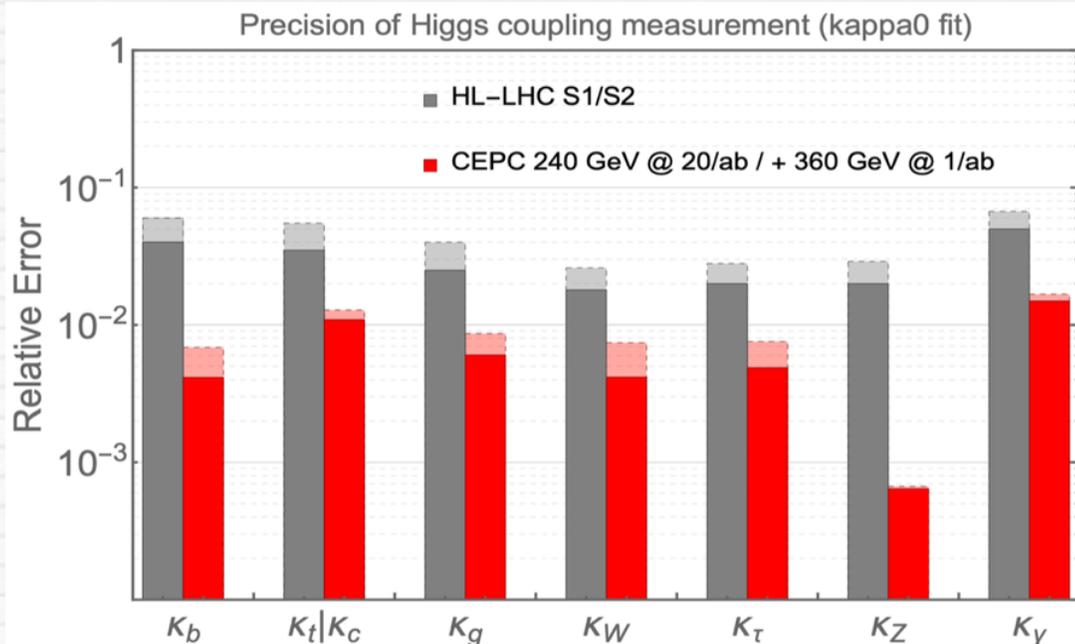
**03**

Summary



As the next generation collider, CEPC is far beyond a Higgs factory:

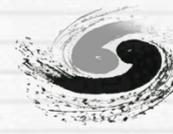
- Searching for exotic or rare decays of H, Z, B and  $\tau$ , and new physics
- Huge measurement potential for precision tests of SM: Higgs, electroweak physics, flavor physics, QCD/Top



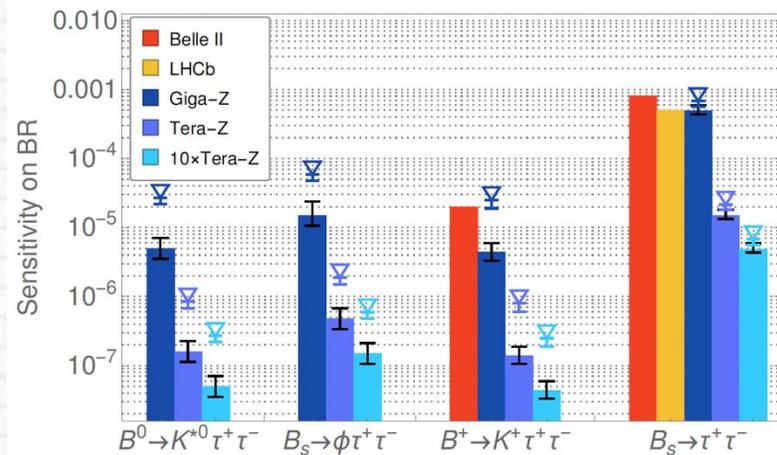
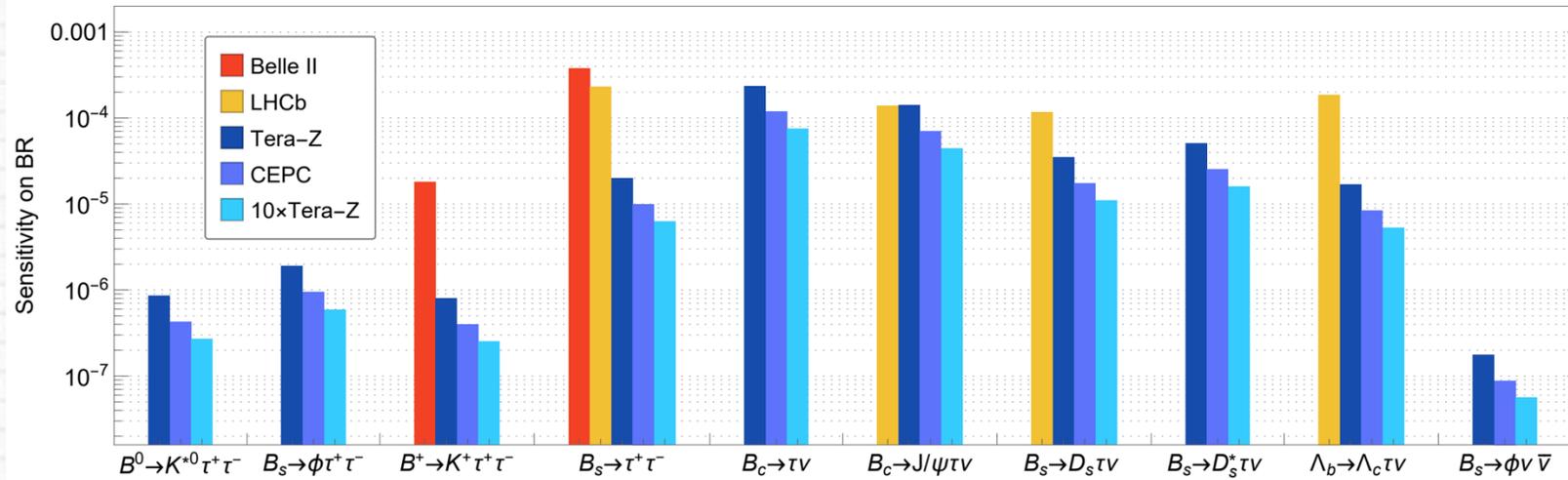
Translated the latest accelerator performance into Higgs measurements

Observable	Higgs	
	HL-LHC projections	CEPC precision
$M_H$	20 MeV	3 MeV
$\Gamma_H$	20%	1.7%
$\sigma(ZH)$	4.2%	0.26%
$B(H \rightarrow bb)$	4.4%	0.14%
$B(H \rightarrow cc)$	-	2.0%
$B(H \rightarrow gg)$	-	0.81%
$B(H \rightarrow WW^*)$	2.8%	0.53%
$B(H \rightarrow ZZ^*)$	2.9%	4.2%
$B(H \rightarrow \tau^+\tau^-)$	2.9%	0.42%
$B(H \rightarrow \gamma\gamma)$	2.6%	3.0%
$B(H \rightarrow \mu^+\mu^-)$	8.2%	6.4%
$B(H \rightarrow Z\gamma)$	20%	8.5%
$B_{\text{upper}}(H \rightarrow \text{inv.})$	2.5%	0.07%

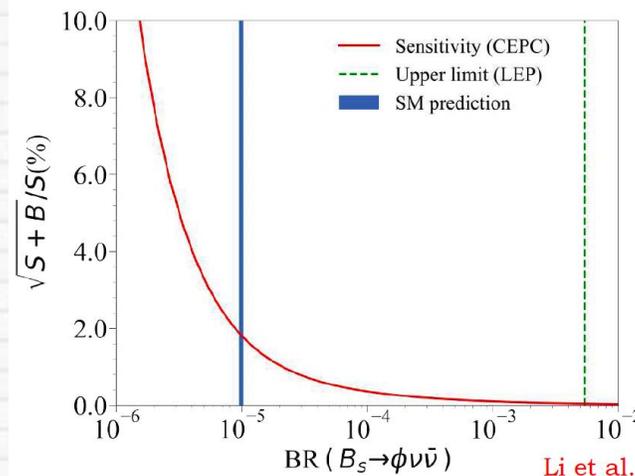
# CEPC Physica Goal



At Z Pole ,CEPC provides a unique opportunity to study Z LFV decays, rare B decays, tests of LFU in tau decays or Bc decays etc.



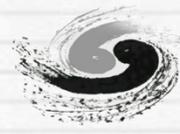
Li L. and Liu T. '20



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High-precision vertex detectors are crucial for the realization of the CEPC physics goals

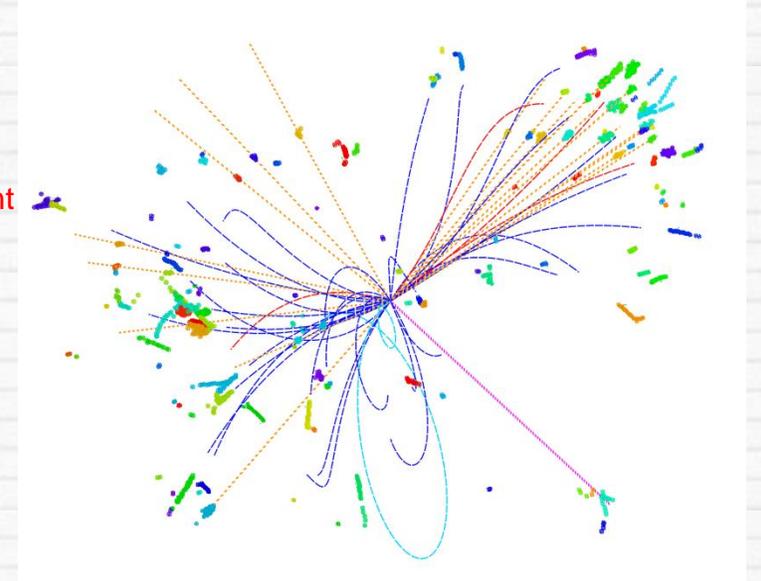
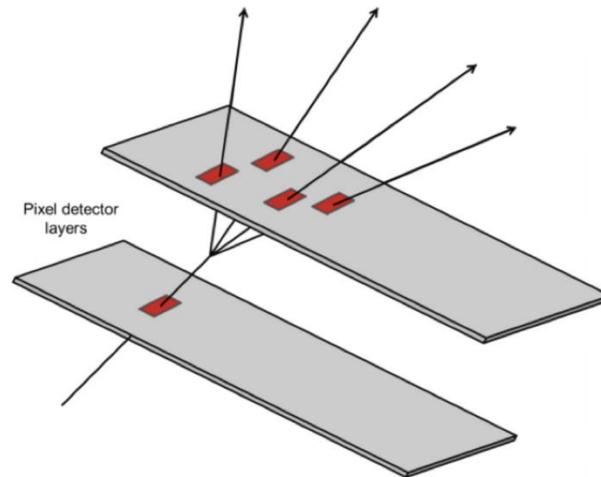
- Flavor physics (a large number of  $b/c$  quark jets,  $\tau$  leptons)
- Higgs physics ( $H \rightarrow bb/cc/gg$  and  $H \rightarrow \tau\tau$ )

Precise vertex measurement is an essential requirement

Goal:  $\sigma(\text{IP}) \sim 5\mu\text{m}$  for high P track

CDR design specifications

- Single point resolution  $\sim 3\mu\text{m}$
- Low material ( $0.15\% X_0/\text{Layer}$ )
- Low power ( $< 50\text{mW}/\text{cm}^2$ )
- Radiation hard (1 Mrad/year)

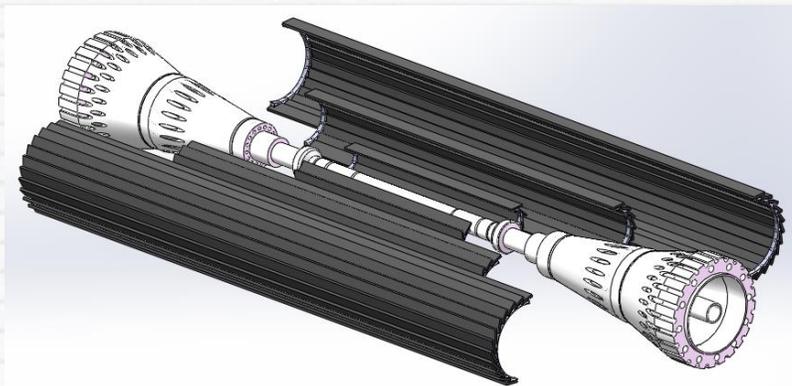




To meet the design specifications and enhance performance, VXD has undergone multiple iterations in various aspects such as geometric structure.

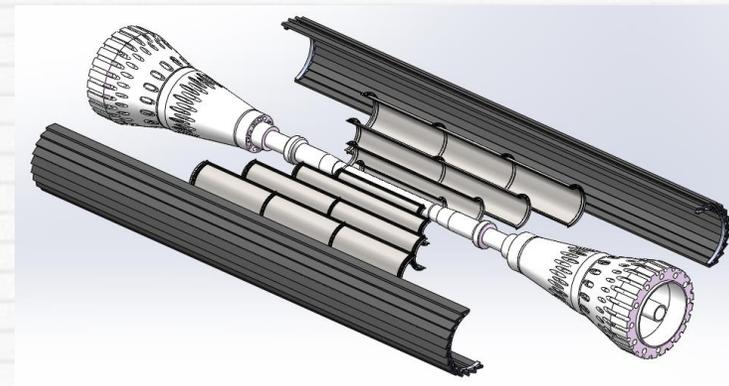
Con Figure.	layer/VXD X	radius .mm	length .mm	arc length .mm	height .mm	support thickness .um
Backup	VXD1	12.46	260.0	-	1.7	334
	VXD2	27.89	494.0	-	2.5	358
	VXD3	43.79	749.0	-	3.2	370
Baseline	layer 1	11.06	161.4	69.108	-	45
	layer 2	16.56	242.2	103.662	-	32
	layer 3	22.06	323.0	138.216	-	31
	layer 4	27.56	403.8	172.770	-	29
	VXD5	43.79	500.0	-	3.2	370

- Better spatial resolution
- Lower material budget
- Closer to beam pipe



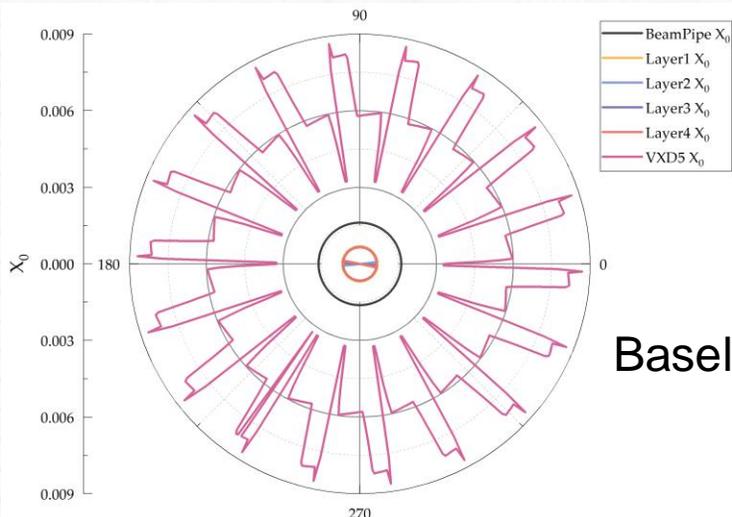
Backup Scheme

- Series of modules
- Two layers attached together
- Nearly cylindrical

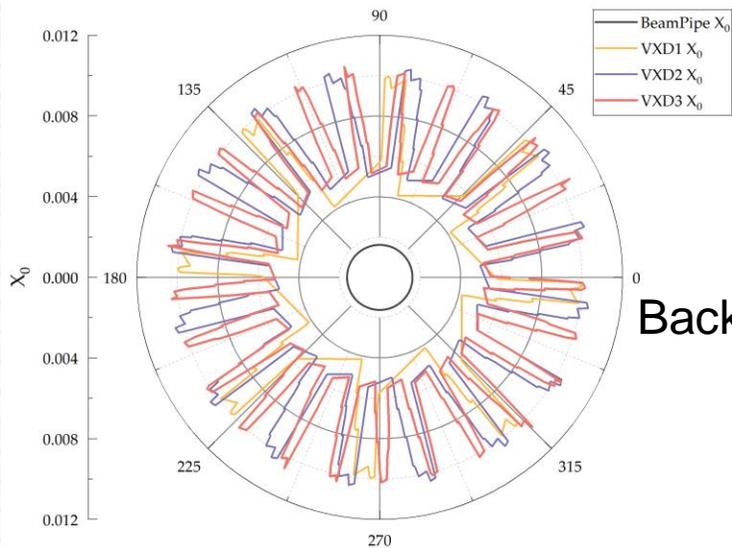


Baseline Scheme

- Each layer is relatively scattered
- Inner layer is cylindrical

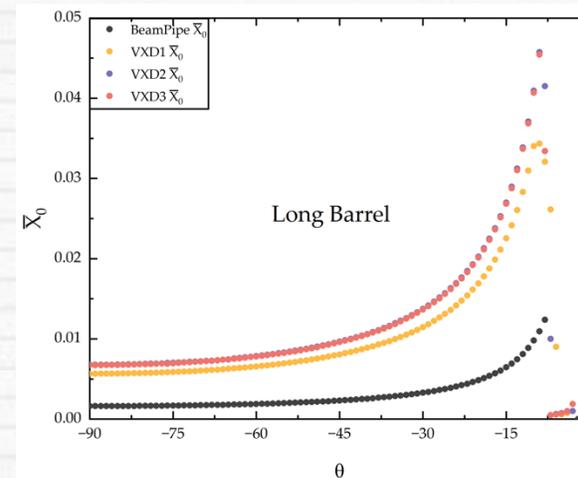
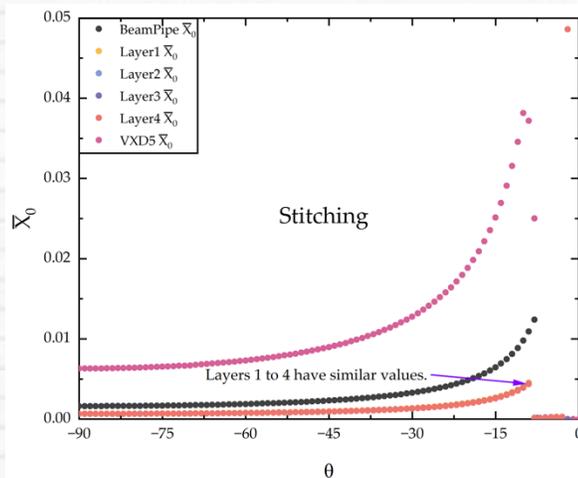


Baseline



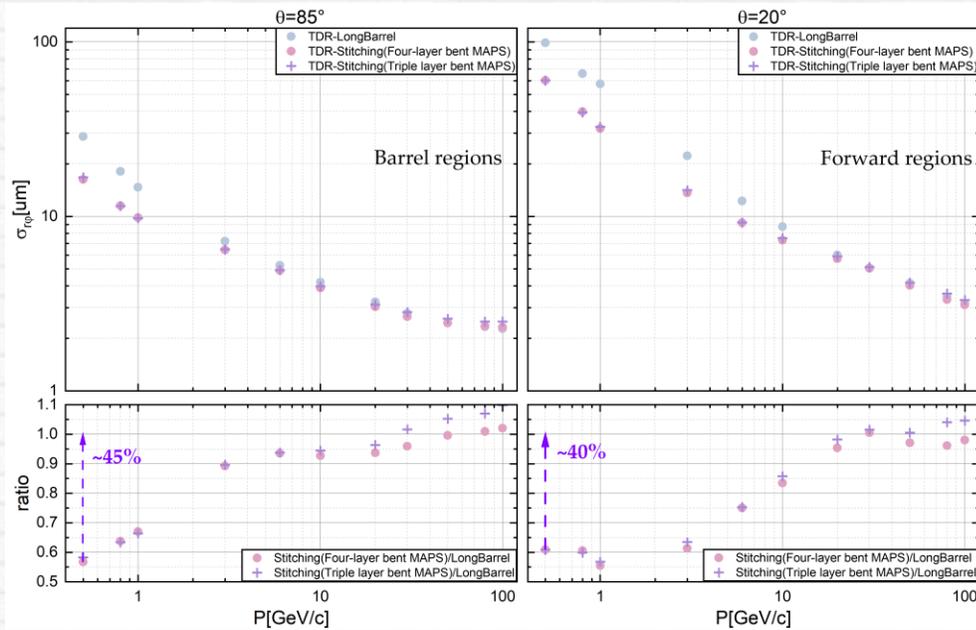
Backup

- Material budget of baseline is much less than backup
- The average material budget per layer of the TDR Baseline scheme is less than **0.15% $X_0$** .

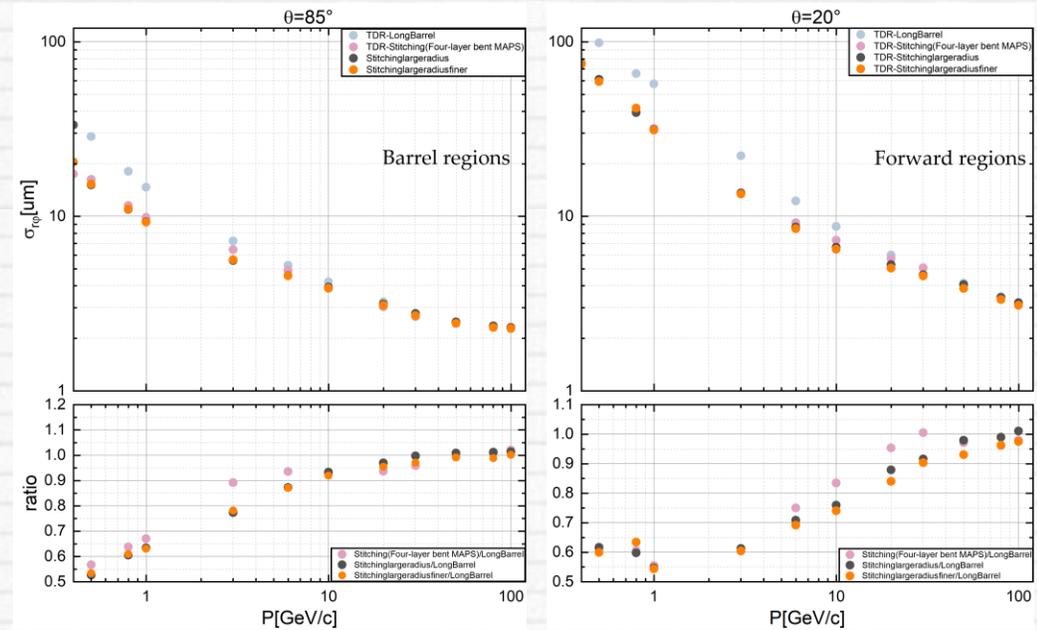


Average material budget of each layer with different  $\theta$

Mat.	BeamPipe	Layer /VXD 1	Layer/VXD 2	Layer/VXD 3	Layer 4	VXD5
<b>Backup</b>	0.162%	0.565%	0.676%	0.672%		
<b>Baseline</b>	0.162%	~0.06%	~0.06%	~0.06%	~0.06%	0.629%



Spatial resolution with different stitching layer



Spatial resolution with different radius for ladder layer

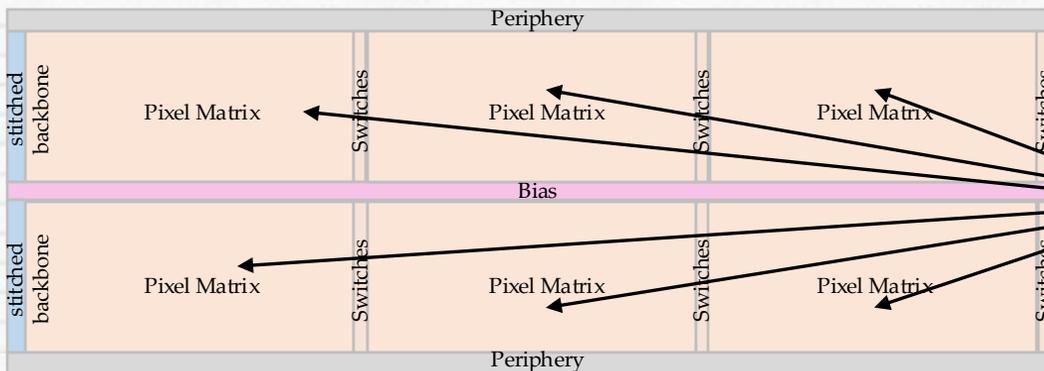
- Spatial resolution of baseline(stitching) scheme is better than backup(long barrel) scheme.
- Triple layer scheme might be taken into consideration.
- The radius of ladder layer in baseline scheme has little impact on spatial resolution.

The spatial resolution at forward regions is quite low, **we need a better digitization model.**

# CEPC VXD: Chip Geo

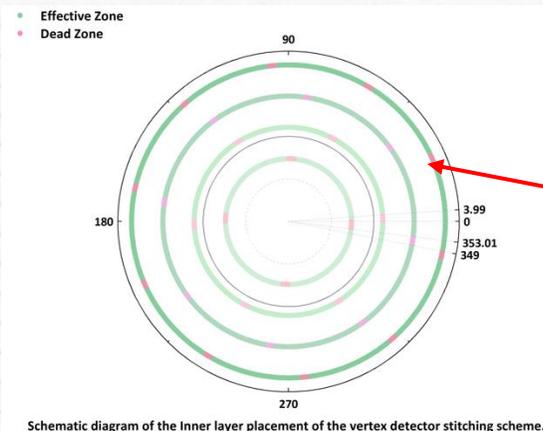


	Pixel Matrix	Bias	periphery	stitched backbone	switches	RSU	supply(LEC)	supply(REC)
width[mm]	8.409	0.106	0.177	8.409	8.409	17.277	17.277	17.277
length[mm]	3.296	10	10	0.055	0.019	20	4.154	1.385



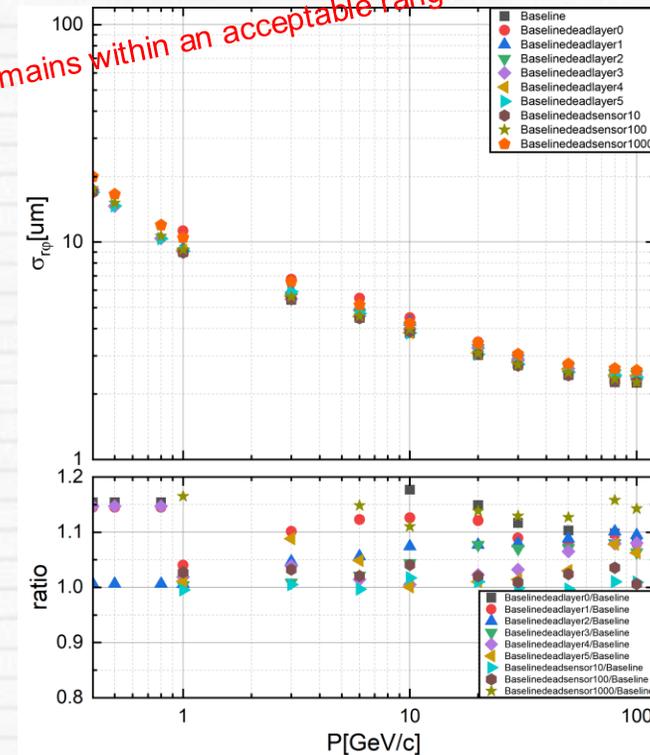
Effective zone

Dead zone is not neglectable.



Need to carefully adjust the distribution of dead zone to achieve maximum detection efficiency.

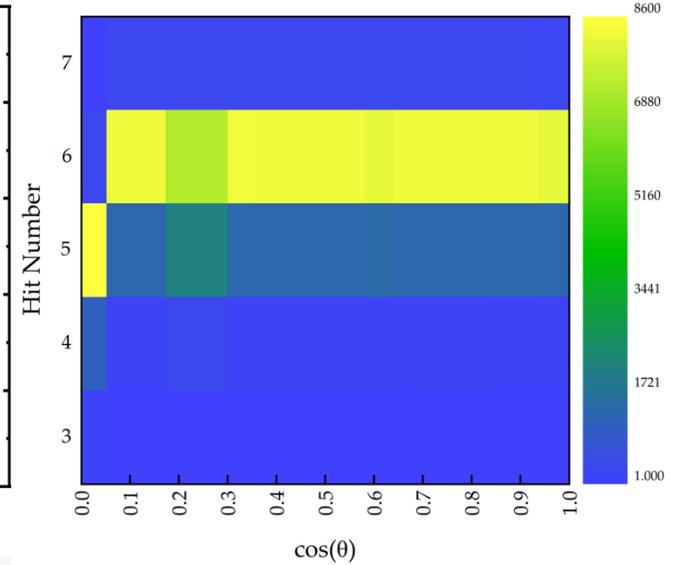
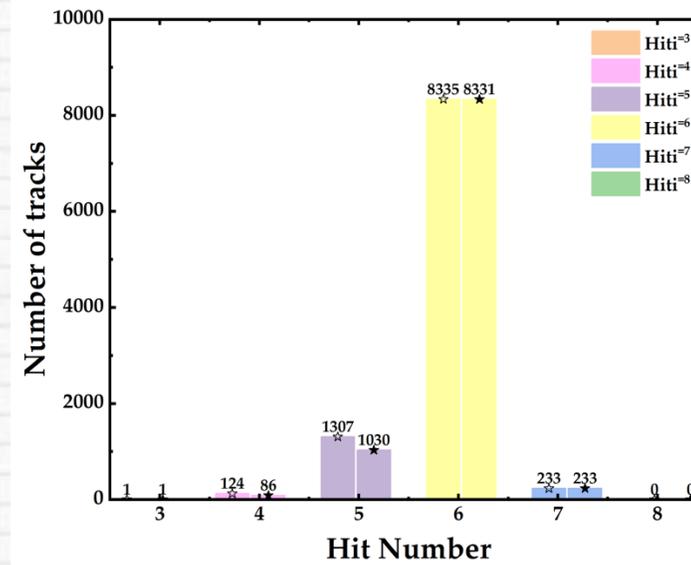
Remains within an acceptable range



Spatial resolution after randomly set dead pixel matrix



	1 <sup>st</sup> hit on 1 <sup>st</sup> layer	Not on 1 <sup>st</sup> layer
3 Hits	97.79%	95.19%
4 Hits	97.79%	95.19%



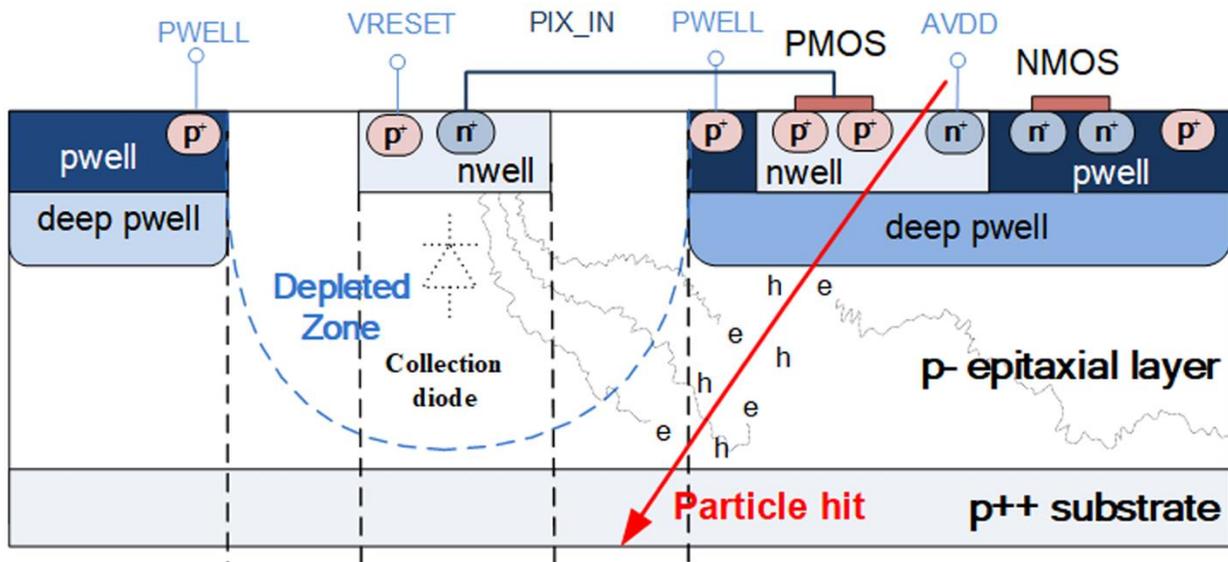
$$\text{Hit Efficiency} = \frac{\sum_i^N \text{Hits}_i^{(\geq 4)}}{N \times L}$$

N: Total number of events  
L: Total layer number

For example, there are 10000 events whose outgoing particles (chargedgeantino) have a momentum of 20 GeV and an angle of 85° .

Need a better digitization model !

# Cluster Size



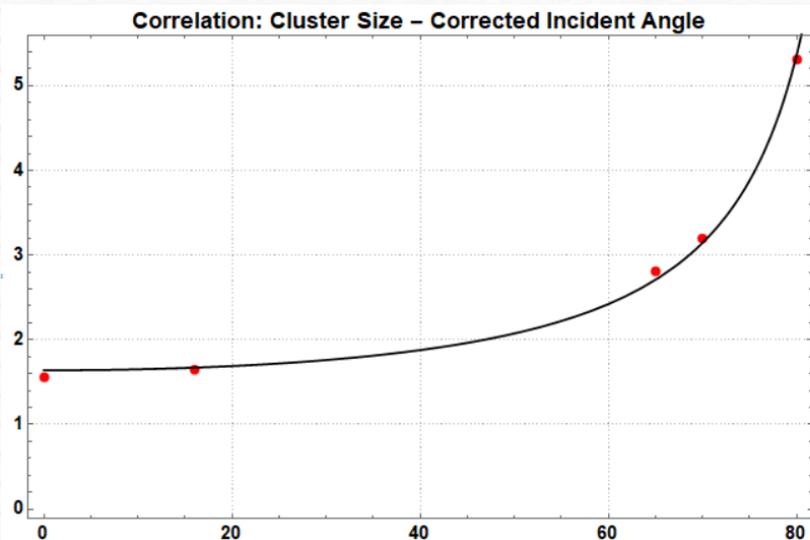
- Low accuracy in the forward region.
- The performance simulation does not include the complete physical processes.

A model is developed to estimate cluster size.

Based on beam test result and AP2 simulation.

$$C = a \sec \theta + b$$

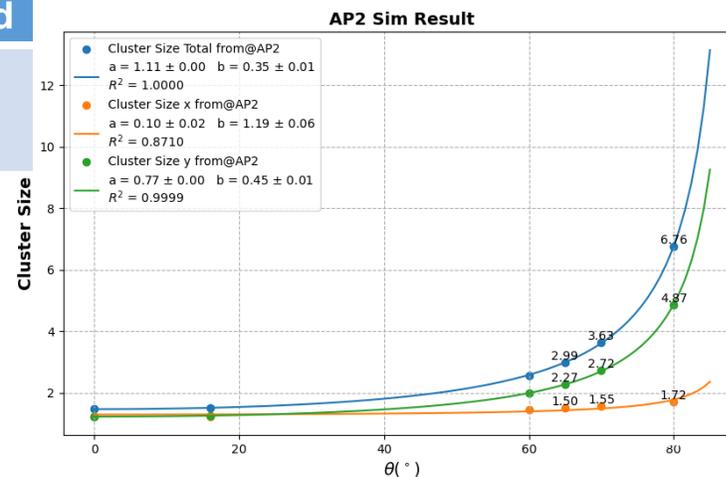
$C$  is the Cluster Size, and  $\theta$  is the incident angle

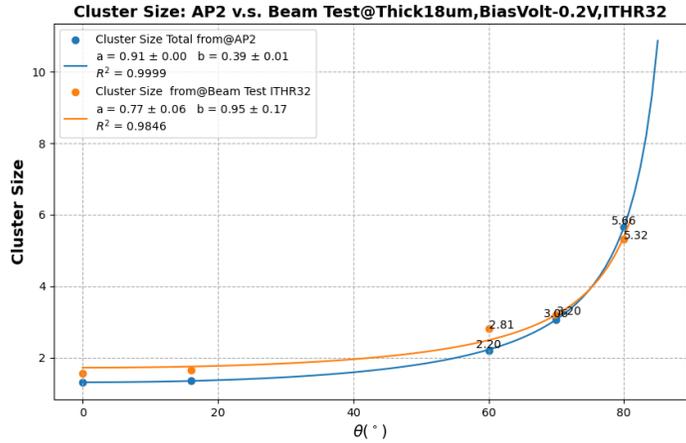
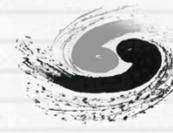


Param	Estimate	Std Error	RSquared
a	0.783	0.022	0.9995
b	0.856	0.069	

• Data from Beam Test  
— Fit Model

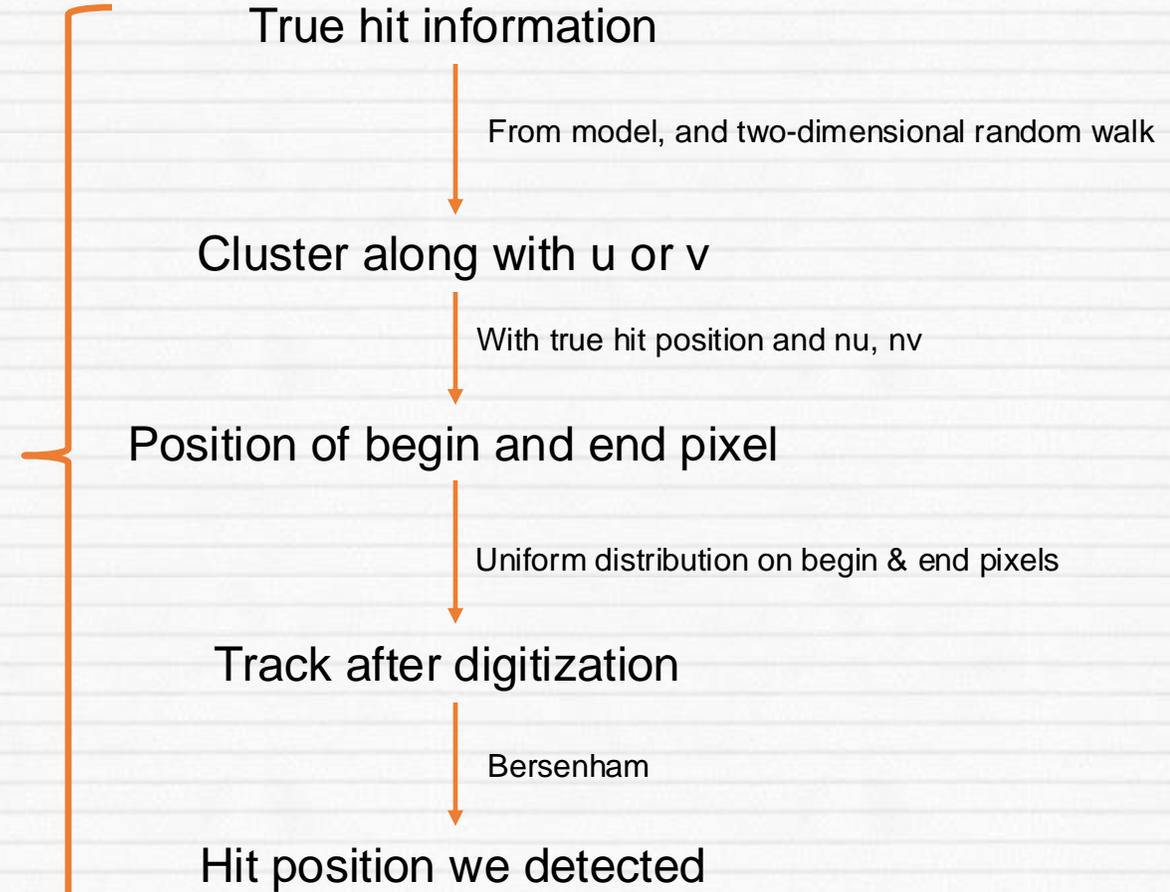
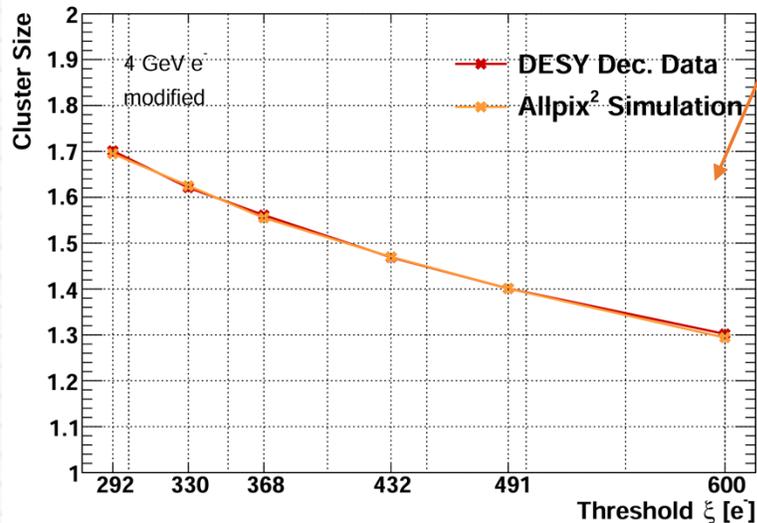
The model is reasonable





Based on beam test and AP2 simulation.

Light version has been used on background analysis.





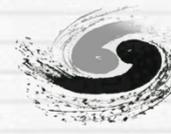
- **Signal-to-noise ratio is very low**, makes background analysis very important
- Provide directions for **improving geometry, estimate power consumption**...

Background	Generation	Detector Simulation	Analysis Status
BGB	PyBGB	CEPCSW	Done
BGC	BGC in SAD		Done
BTH	PyBTH		Done
TSC	TSC in SAD		Done
Pair	Guinea-Pig++		Done
SR	BDSim		Undergoing
RBB	BBREM		Undergoing

The beam background we need to take into considering:

- Pair Production (Pair)
  - Beam Gas Coulomb (BGC)
  - Beam Gas Brems (BGB)
  - Beam Thermal Photon (BTH)
  - Touscheck (TSC)
- Whole: Done
- Synchrotron Radiation (SR)
  - Raditive Bhabha (RBB)
- Undergoing

# Summarization of hit rate



Layer	Ave. Hit Rate MHz/cm <sup>2</sup>	Max. Hit Rate MHz/cm <sup>2</sup>	Ave. Hit Rate × C MHz/cm <sup>2</sup>	Ave. Hit Rate × C MHz/cm <sup>2</sup>	Ave. Data Rate Mbps/cm <sup>2</sup>	Max. Data Rate Mbps/cm <sup>2</sup>
Higgs: DataRate = HitRate × 32 bit / pixel × ClusterSize @(Bunch Spacing: 346ns, 53%Gap, 25 × 25 μm <sup>2</sup> / pixel)						
1	1.043	1.210	5.735	6.819	183.518	218.204
2	0.303	0.528	1.581	2.684	50.597	85.901
3	0.074	0.172	0.387	0.768	12.375	24.584
4	0.029	0.078	0.157	0.623	5.027	19.945
5	0.007	0.045	0.038	0.304	1.231	9.719
6	0.005	0.029	0.025	0.175	0.806	5.605
Low Lumi Z: DataRate = HitRate × 32 bit / pixel × ClusterSize @(Bunch Spacing: 69ns, 0%Gap, 25 × 25 μm <sup>2</sup> / pixel)						
1	12.671	18.574	91.859	140.683	2939.486	4501.851
2	6.561	9.164	46.832	75.307	1498.619	2409.834
3	3.926	6.446	27.935	56.620	893.908	1811.832
4	2.556	4.999	17.838	40.694	570.806	1302.215
5	0.374	0.728	2.450	5.037	78.399	161.172
6	0.291	0.529	1.837	3.832	58.783	122.616
High Lumi Z <sup>†</sup> : DataRate = HitRate × 32 bit / pixel × ClusterSize @(Bunch Spacing: 23ns, 0%Gap, 25 × 25 μm <sup>2</sup> / pixel)						
1	43.439	62.236	291.679	426.711	9333.716	13654.756
2	22.592	29.172	150.256	211.783	4808.194	6777.072
3	14.115	19.830	93.412	148.986	2989.190	4767.562
4	10.211	15.815	66.195	121.296	2118.228	3881.487
5	2.212	3.510	13.884	25.824	444.279	826.383
6	1.758	2.737	10.533	17.895	337.054	572.636

No trigger and error window here.

Threshold has been taken into consideration. (ITHR 32 = 368e, 1.3keV/pixel )

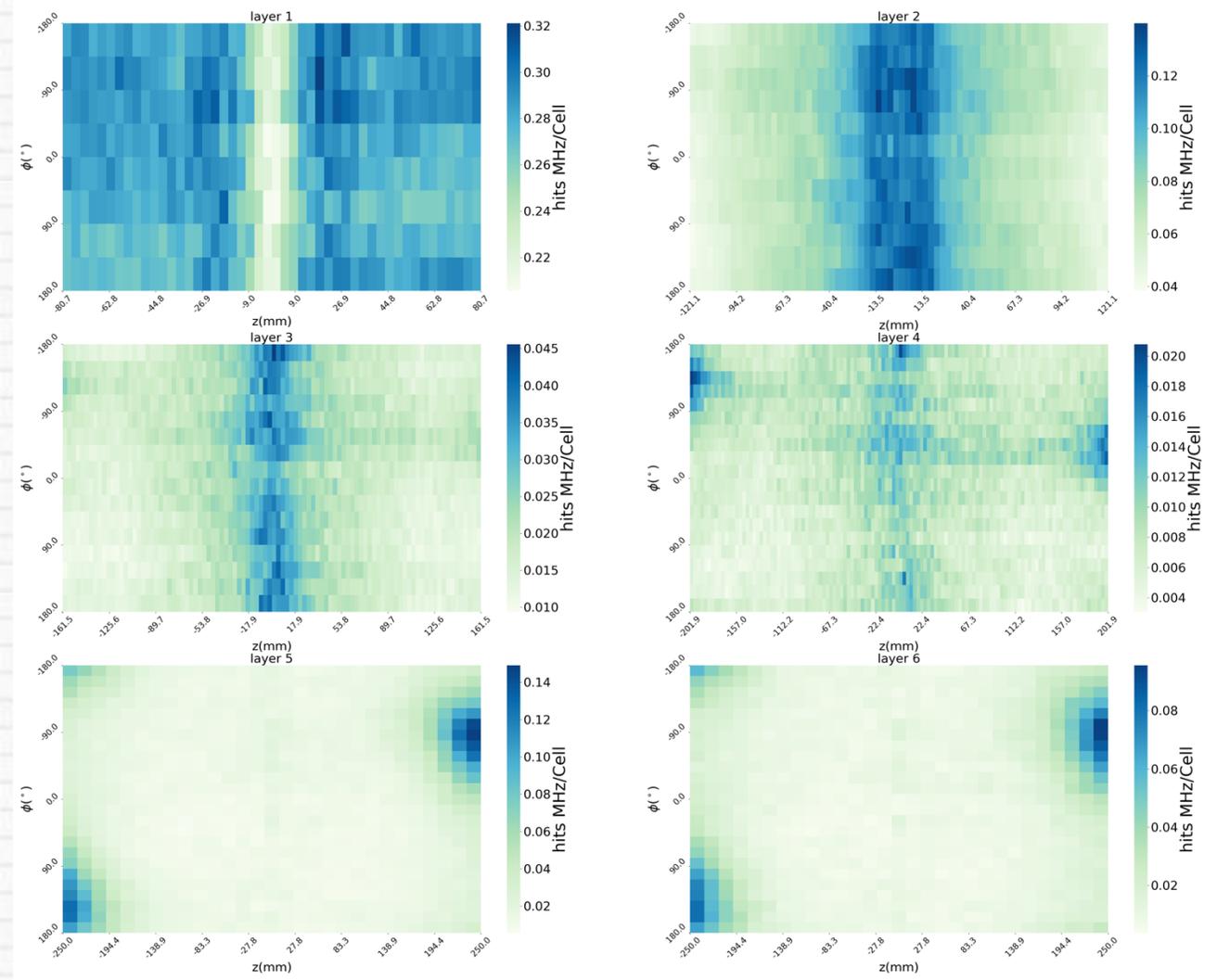
A fast digitization model we mentioned has been applied to the calculation of the data rate.

Most challenging task

Take 32 bit / PixelSignal:

Vaild	Ts_chip	Column	Row	Pattern	Total
1 bit	8 bit	9 bit	10 bit	4 bit	32 bit

# Hit Rate: Higgs



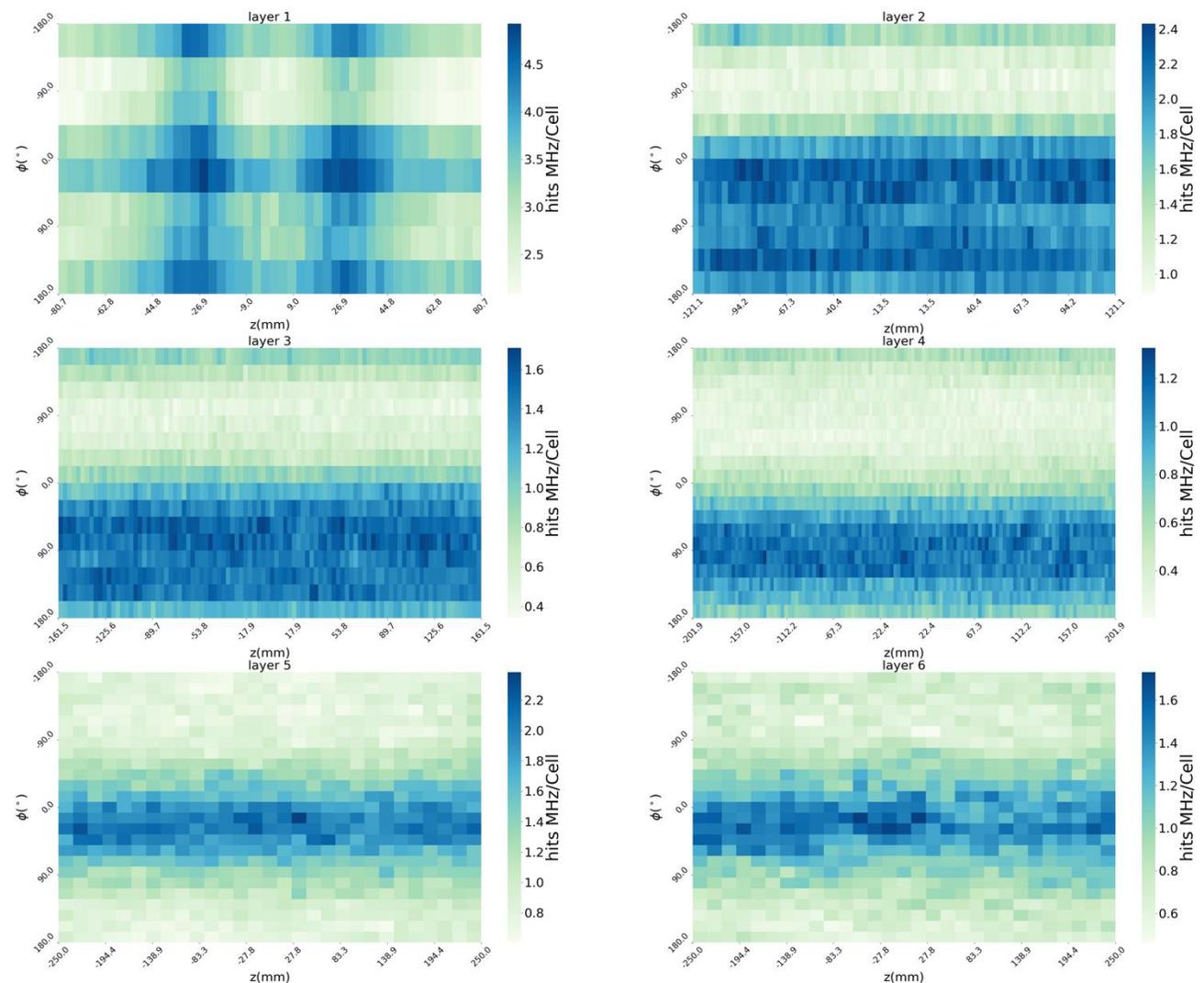
Main contribution:

- Pair production (Pair)

Layer	A hit density MHz/cm <sup>2</sup>	M hit density MHz/cm <sup>2</sup>	A hit density *C MHz/cm <sup>2</sup>	M hit density *C MHz/cm <sup>2</sup>
1	1.043	1.210	5.735	6.819
2	0.303	0.528	1.581	2.684
3	0.074	0.172	0.387	0.768
4	0.029	0.078	0.157	0.623
5	0.007	0.045	0.038	0.304
6	0.005	0.029	0.025	0.175

A for average, M for maximum, and C for cluster size.

# Hit Rate: Low Z



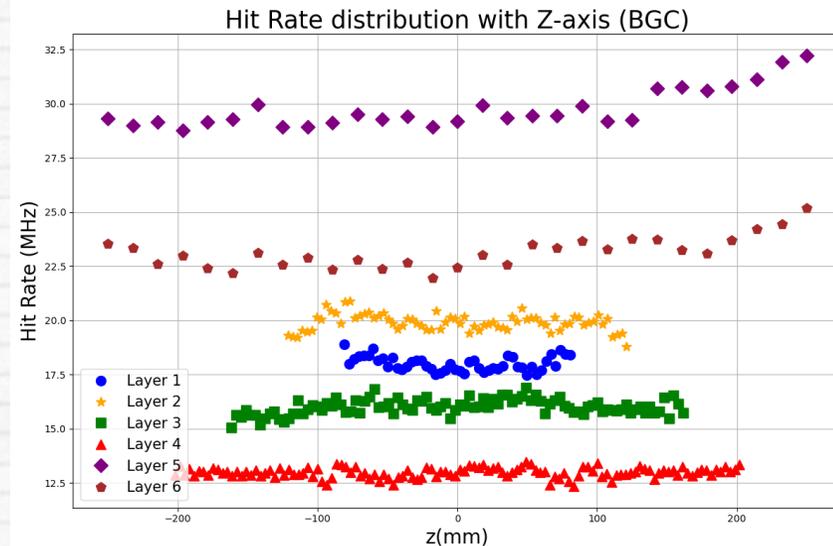
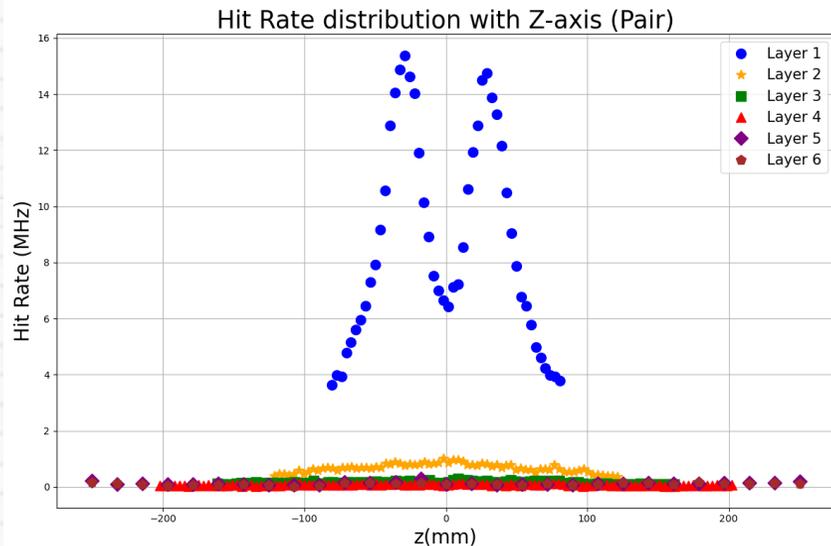
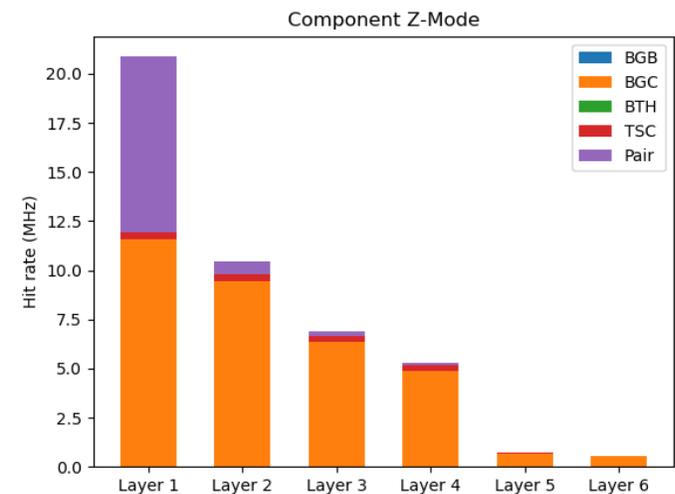
Main contribution:

- Pair production (Pair)
- **Beam Gas Coulomb (BGC)**

Cluster quite large

Layer	A hit density MHz/cm <sup>2</sup>	M hit density MHz/cm <sup>2</sup>	A hit density *C MHz/cm <sup>2</sup>	M hit density *C MHz/cm <sup>2</sup>
1	12.671	18.574	91.859	140.683
2	6.561	9.164	46.832	75.307
3	3.926	6.446	27.935	56.620
4	2.556	4.999	17.838	40.694
5	0.374	0.728	2.450	5.037
6	0.291	0.529	1.837	3.832

A for average, M for maximum, and C for cluster size.



The density of pair production should be higher along with beam direction

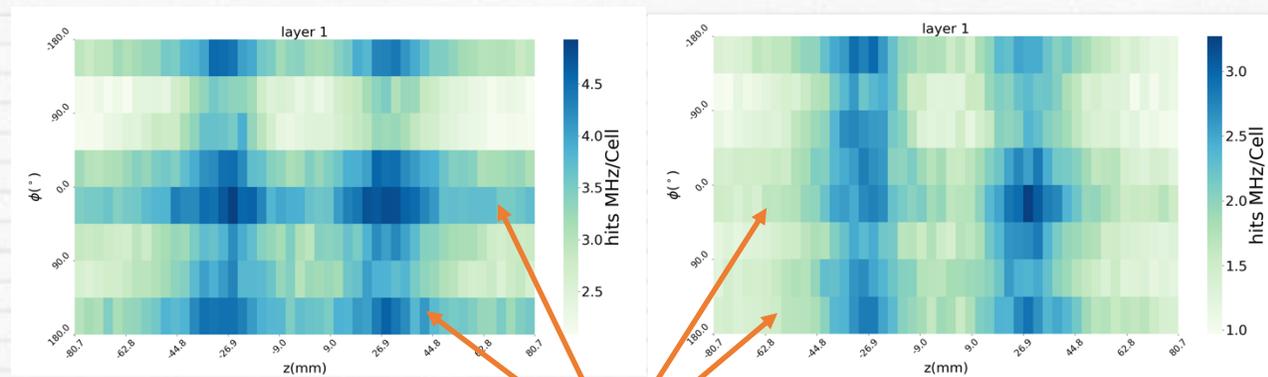
Large incident angle brings large cluster size, leads to high data rate

Main problems of VXD background:

- The distribution of Pair production seems to be wired.
- The hit rate from Beam Gas Coulomb is too high.

Solutions:

- Check the generator of Pair production.
- Add additional shielding for Beam Gas Coulomb.

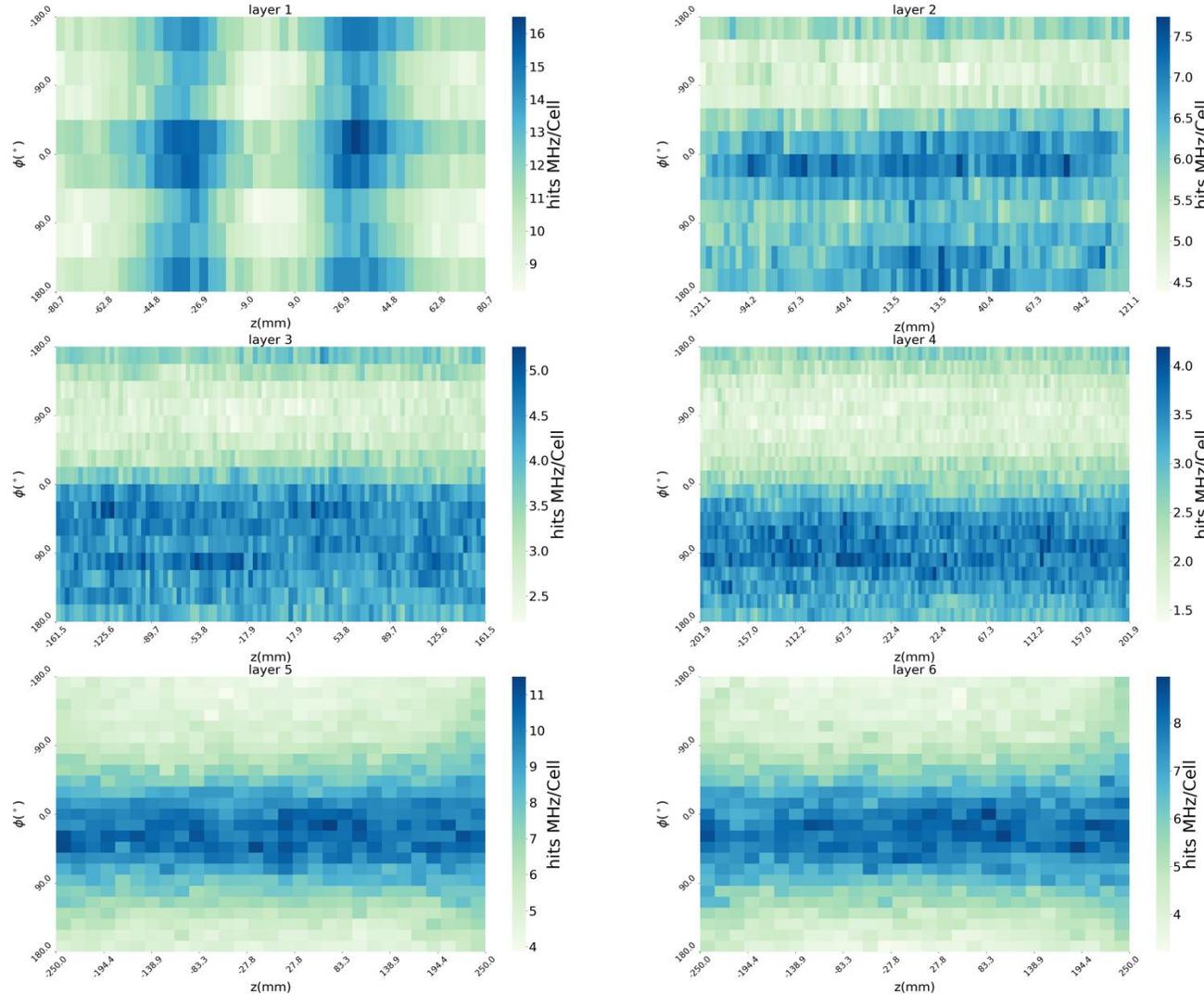


No shielding for BGC

Add shielding for BGC

BGC lower than before

# Hit Rate: High Z



Main contribution:

- Pair production (Pair)
- **Beam Gas Coulomb (BGC)**

Layer	A hit density MHz/cm <sup>2</sup>	M hit density MHz/cm <sup>2</sup>	A hit density *C MHz/cm <sup>2</sup>	M hit density *C MHz/cm <sup>2</sup>
1	43.439	62.236	291.679	426.711
2	22.592	29.172	150.256	211.783
3	14.115	19.830	93.412	148.986
4	10.211	15.815	66.195	121.296
5	2.212	3.510	13.884	25.824
6	1.758	2.737	10.533	17.895

A for average, M for maximum, and C for cluster size.

# Summarization of occupancy



Layer	Mode	Ave. Occupancy@Pixel ( $\times 10^{-5}$ / BX)	Max. Occupancy@Pixel ( $\times 10^{-5}$ / BX)
1	Higgs	2.945	3.697
2		1.014	1.615
3		0.288	0.653
4		0.114	0.272
5		0.023	0.190
6		0.016	0.127
1	Low Lumi Z	4.402	7.008
2		2.247	3.393
3		1.370	2.424
4		0.883	1.757
5		0.138	0.306
6		0.109	0.209
1	High Lumi Z <sup>†</sup>	4.841	7.641
2		2.541	3.292
3		1.594	2.348
4		1.138	1.897
5		0.257	0.428
6		0.210	0.372

$$\text{Occupancy} * T = \frac{N_F}{N_T}$$

$N_F$ : Number of fired pixels

$N_T$ : Number of total pixels in a pixel matrix

T : Time window, take one bunch crossing here

For multiple hits occurring within the same pixel and the same time window, only count **once**.

In the current preset parameters of different mode, the occupancy remains on the order of **10e-5**.



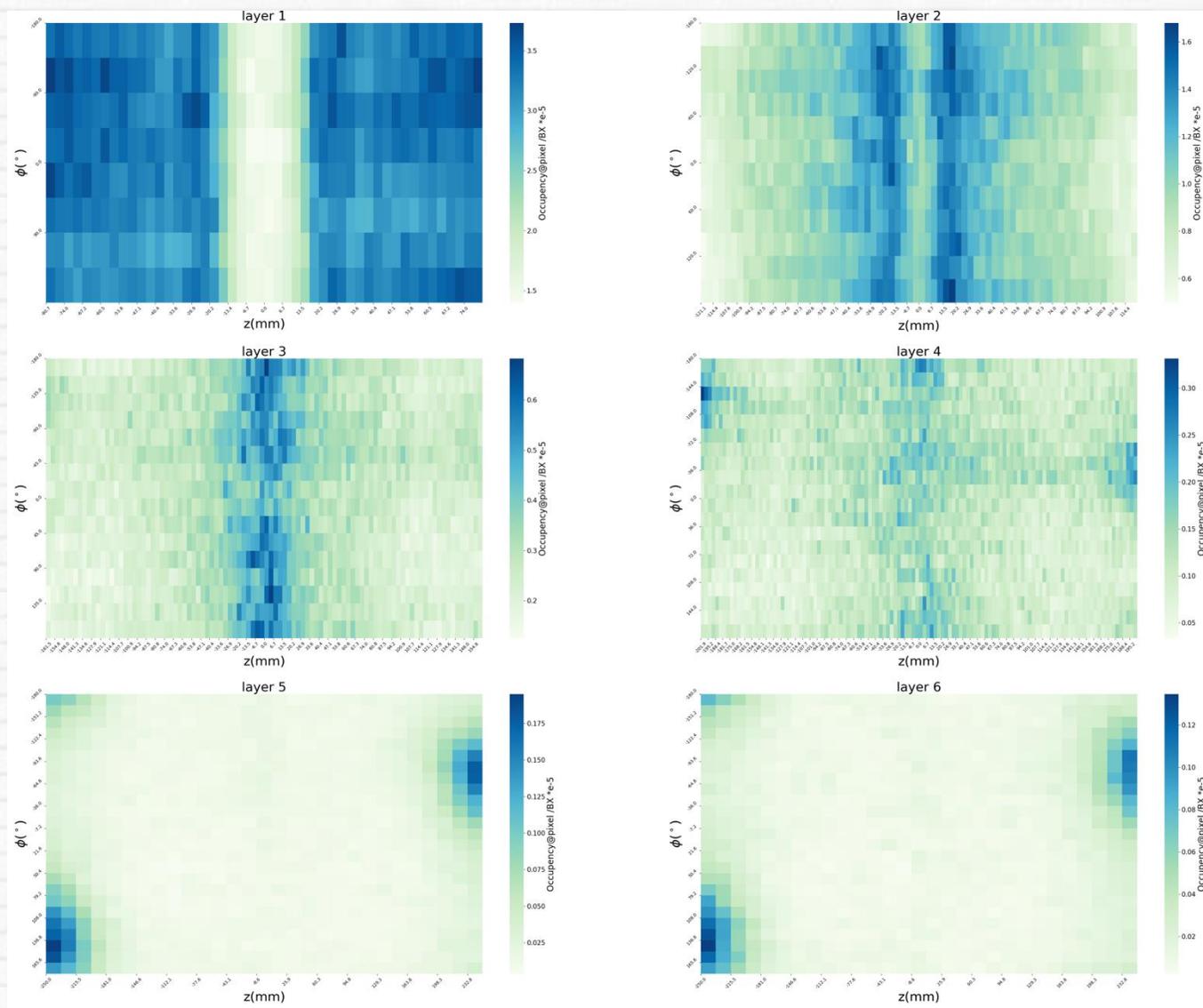
- Vertex detector is the key subdetector of CEPC to meet CEPC physics goal
- Current baseline scheme of VXD has great performance
  - **Low material budget** ( $\sim 0.06\%$  inner layer)
  - **High spatial resolution** ( $\sigma \sim 3 \mu m$  @ 20GeV)
  - **Fine hit efficiency** ( $>97.5\%$  @ 20GeV)
- A precise digitization model is developing
  - Based on beam test result
- **Detailed beam background analysis has been shown**
  - Each running mode: Higgs, Z, High Z
  - Each component: Pair, BGB, BGC .....
  - Analysis of SR and RBB is undergoing
- In the future:
  - **Finish the digitization model** for CEPC VXD
  - Run the performance analysis with **complete physical process**
  - Continue to perfect our baseline scheme
  - .....



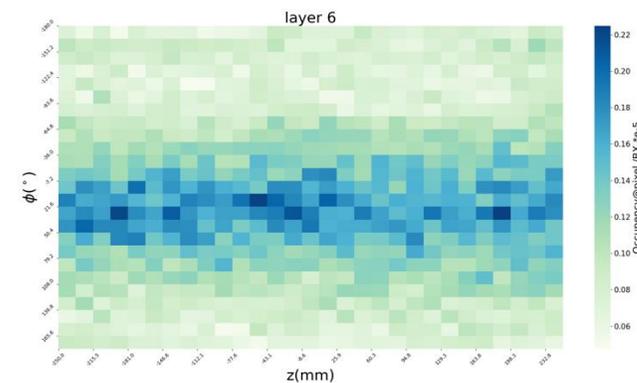
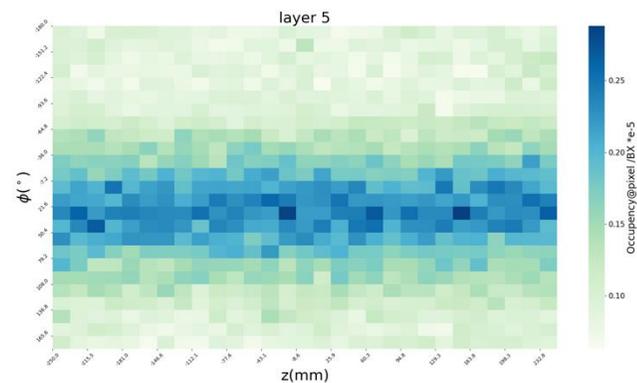
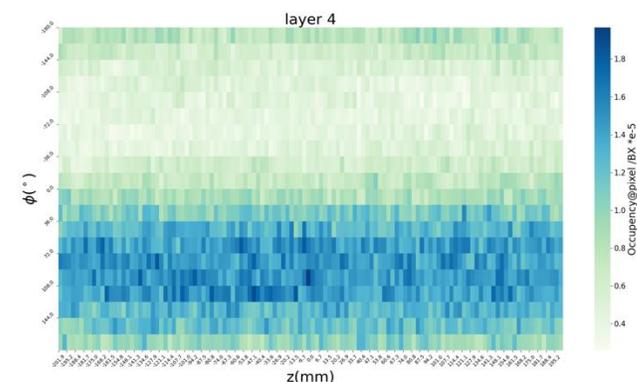
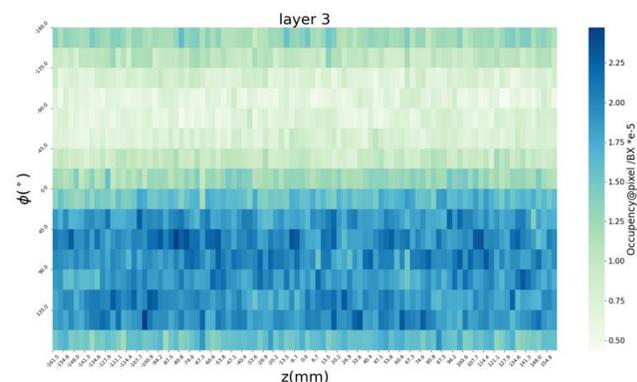
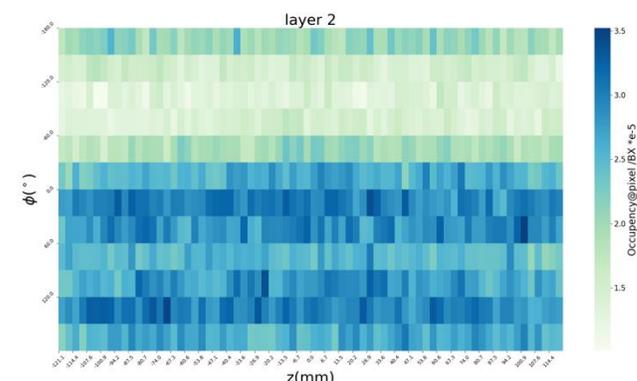
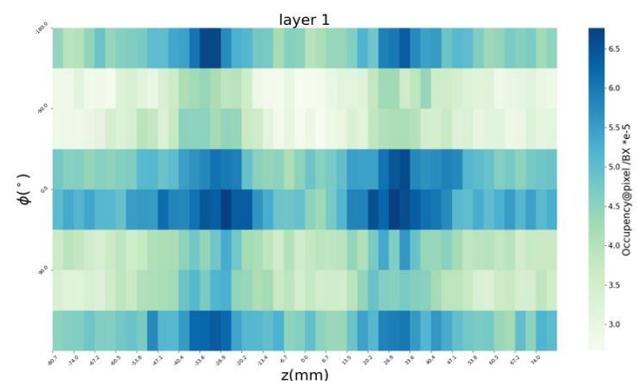
中國科學院高能物理研究所  
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*Thanks for Your Attention!*

# Backup: Occupancy, Higgs



# Backup: Occupancy, Z Mode



# Backup: Occupancy, High Z

