Update on CEPC Vertex Detector Optimization

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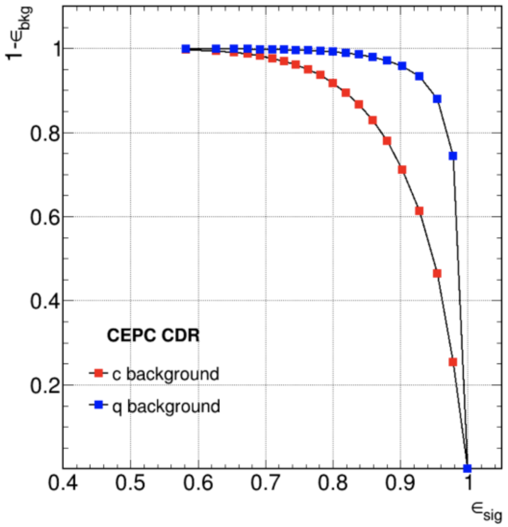
Outline

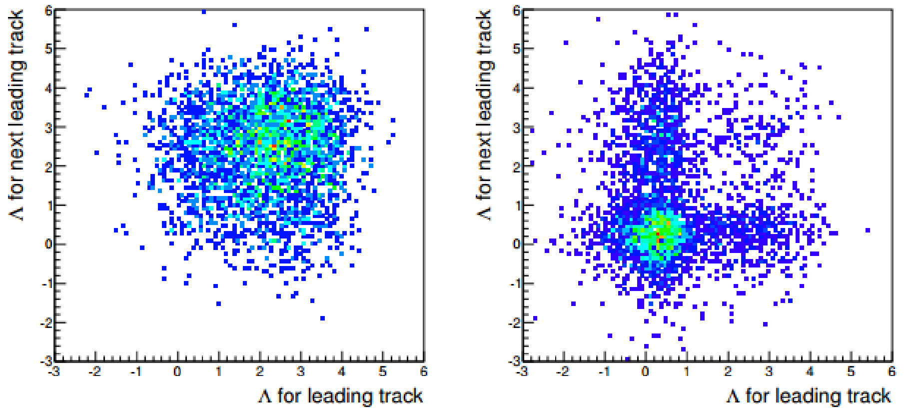
- Introduction and Motivation
  - CEPC physics requirements
  - MOST2 indicators
  - CEPC vertex study review
- Previous study
  - Vertex layout
  - Beam pipe
- Updates
  - Smaller beam pipe
  - Ladders arrangement
  - Long barrel design
- Summary & plan

CEPC physics requirements

$$\Lambda = \log_{10}\left[\left(\frac{D_0}{\sigma_{d_0}}\right)^2 + \left(\frac{Z_0}{\sigma_{z_0}}\right)^2\right]$$

- Impact parameter resolution
  - Crucial for primary, 2nd , and 3rd vertices …, reconstruction → jet flavor tagging, tau finding, and flavor physics

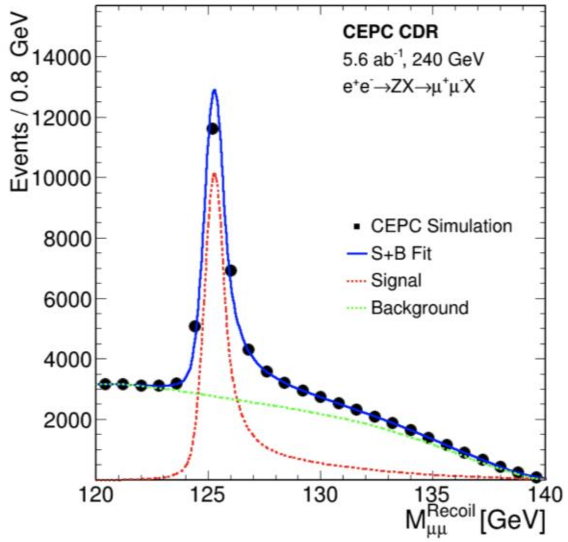




(a) signal (b) background

Z. Wu et al

- Momentum resolution
  - Recoil Higgs mass e+e- →uuH
  - Lots of narrow resonances in flavor physics



MOST2 task and indicators

Achievement Presentation and Assessment Methods

Silicon Detector

考核指标[2]				
指标名称	立项时已有指标值/状态	中期指标值/状态[3]	完成时指标值/状态	考核方式(方法)及评价手段[4]
硅径迹探测器原型机的空间分辨率	无	研制出小型传感器芯片，像素单元尺寸小于或等于 25 微米 ×25 微米。	3-5 微米	同行专家评审。(通过束流实验，离线分析数据获得空间分辨率。该测试结果写入原型机设计与测试报告，以供同行专家评审)
所设计的抗辐照硅传感器能承受的总剂量	无	完成传感器的初步设计，通过仿真初步验证其抗辐照性能	1 MRad	同行专家评审（提供传感器的设计与测试报告供专家评审)

Assessment index

Spatial resolution

- Mid-term: produce 25*25 μm pixel size chip
- Final : 3-5 μm resolution in Beam test

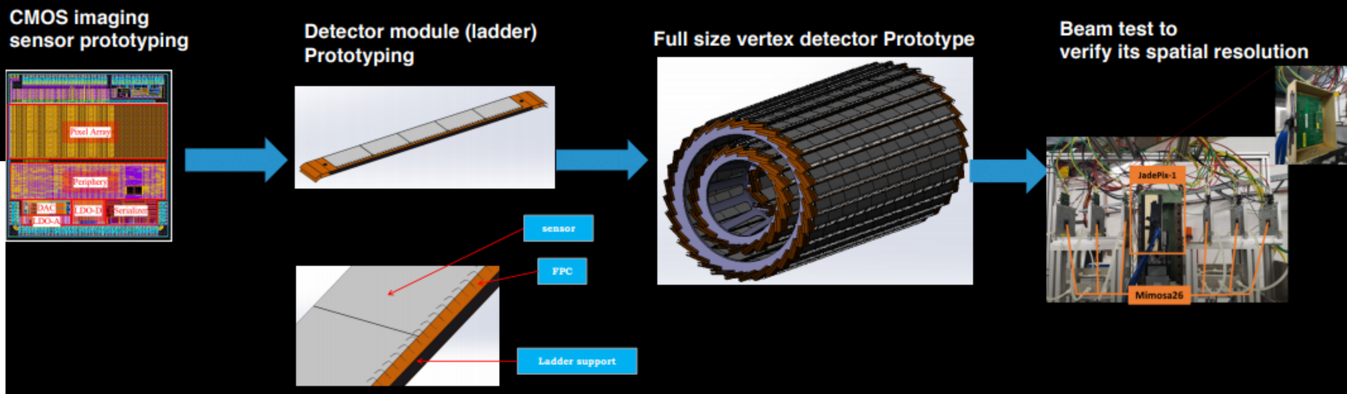
Radiation hardness

- mid-term: verified by TCAD simulation
- Final : Total ionization dose >1 Mrad

See details: [indico link]

Overview of Task 2:

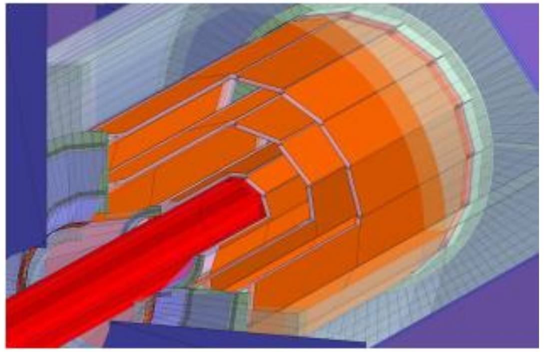
- Can break down into sub-tasks:
  - CMOS imaging sensor chip R & D
  - Detector layout optimization, Ladder and vertex detector support structure R & D
  - Detector assembly
  - Data acquisition system R & D



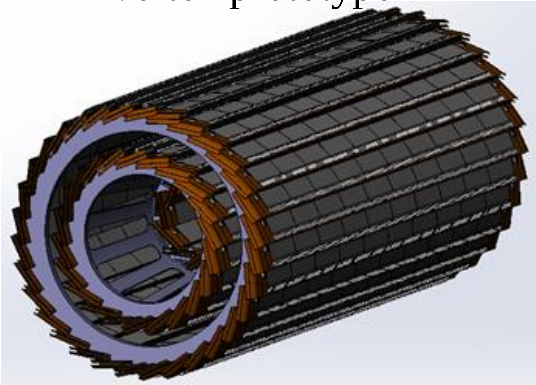
CEPC vertex study review

- CDR vertex:
  - based on ILD
  - ideal concept vertex(Z. Wu et al)
- Vertex prototype for MOST2:
  - realistic implementation of CDR vertex (barrel)
  - mechanics: ladder design, support structure, ladder arrangement (indico link)
  - electronics: chips, read-out
  - cooling: air cooling
- Realistic vertex detector for CEPC:
  - based on vertex prototype (mechanics, electronics)
  - full-size vertex detector (barrel + endcap)
  - beam pipe, MDI, cooling

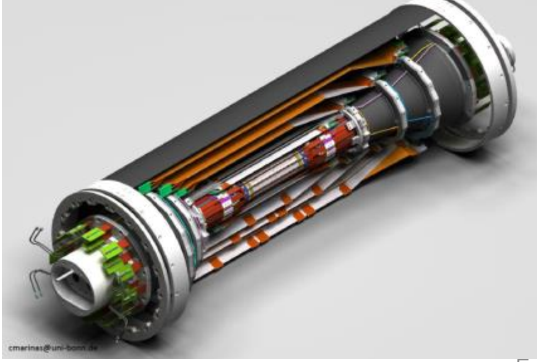
CDR baseline vertex



vertex prototype



Belle II vertex detector

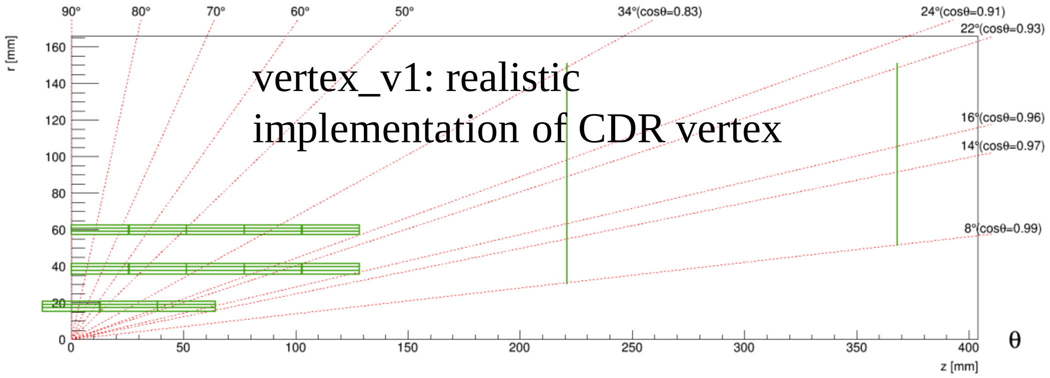


Vertex layout optimization review

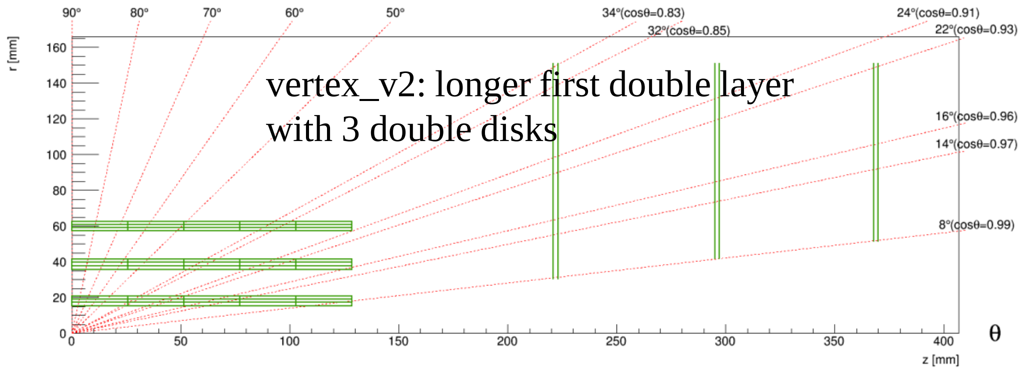
- Base on the design of vertex prototype (mechanics, electronics), we try to optimize the full-size vertex detector (d0 resolution as criteria):
  - Barrel optimization
    - The radius of vertex detector
    - The number of layers
    - The radius of second layer
    - Lengthen the innermost layer
  - Disk optimization
    - The number of disks
    - Single-disk or double-disk
    - The putting place of the disk
    - 3 double-disks in endcap is the best

Layout with 3 equidistance double layers is best
Z. Drasal , W. Riegler

improve the d0 resolution in front region



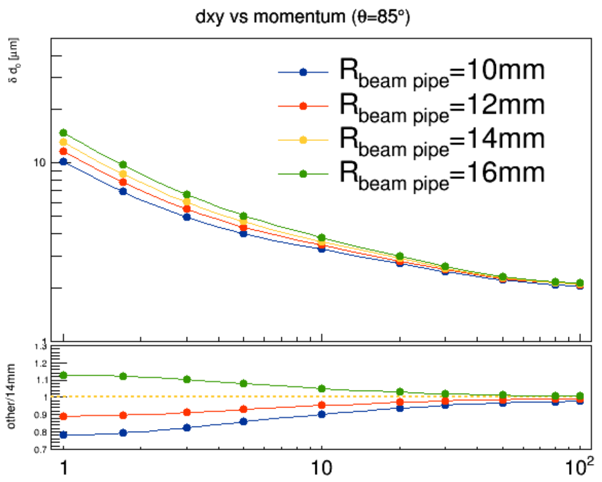
- ➢ Full silicon tracker as outer tracker: FST
- ➢ Not consider cable & cooling for the transition region between barrel and endcap



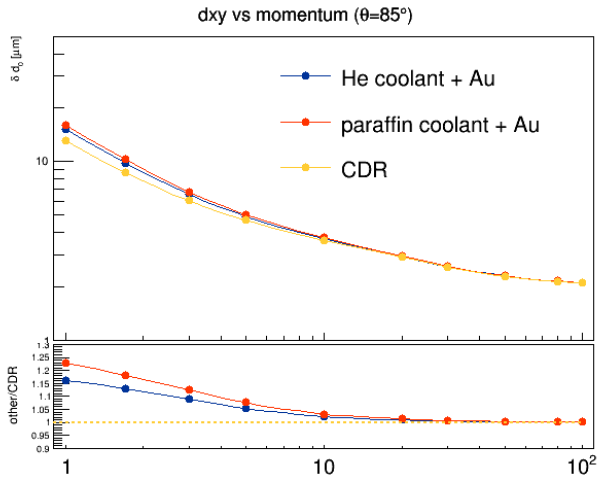
All layout tuning results simulated by tkLayout, which was developed by CMS, customized for CEPC tracker fast simulation(on-going). More information in github.

Beam pipe study review

- Beam pipe radius
  - Big effect on low momentum track
  - Beam pipe radius is smaller, resolution is better
  - Improve d0 resolution 21% if reduce beam pipe radius to 10 mm
- Beam pipe material
  - Beam pipe structure:
    - innermost Au: T=5 um
    - inner Beryllium layer: T= 0.5 mm
    - gap: T=0.5 mm (coolant)
    - outer Beryllium layer: T= 0.35 mm
  - 24% worse if use paraffin coolant +Au
  - might cancel the material effect if reduce beam pipe radius to 10mm



Reduce the beam pipe radius!!!



Reduce the beam pipe material!!!
Make the beam pipe thinner!!!

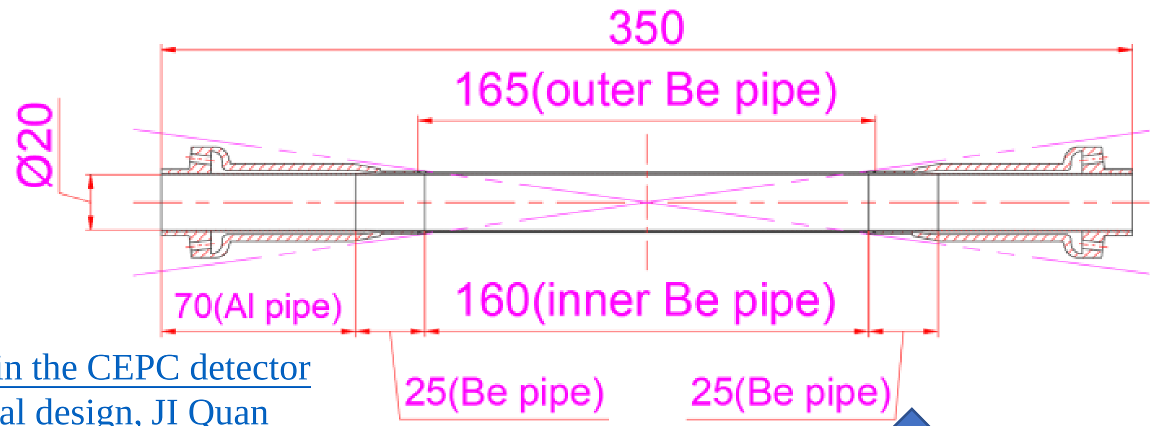
Radiation length	CDR	Helium gas coolant	Paraffin coolant
Au	0	0.001495	0.001495
Beryllium	0.001417	0.002409	0.002409
coolant	0	≈0	0.001037
total	0.001417	0.003905	0.004941

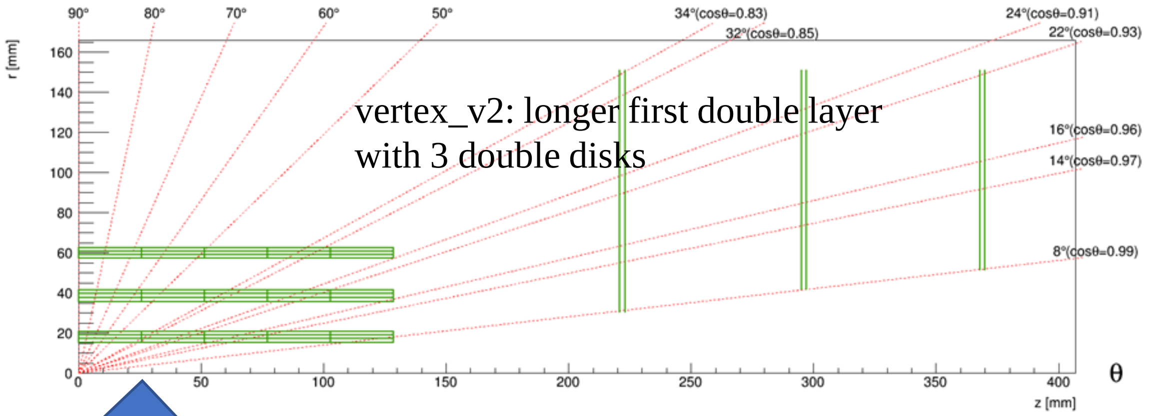
Updates

- New beam pipe radius=10mm
- New ladder arrangements for innermost layer
- Long barrel vertex design

New beam pipe with diameter of 20 mm

Detailed structure of the central beryllium pipe





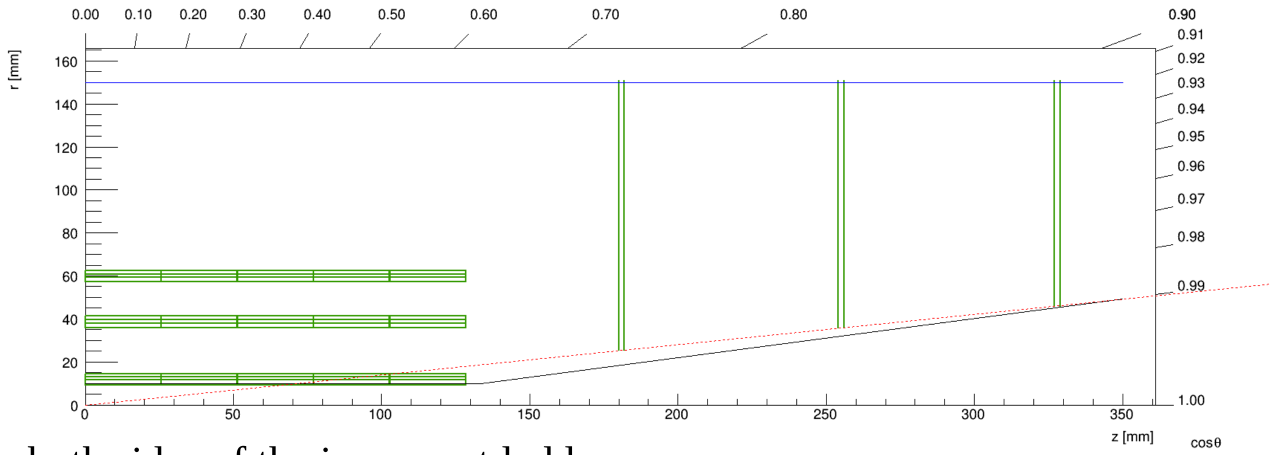
[Progress in the CEPC detector mechanical design, JI Quan]

According to processing capacity:
Inner Be pipe: 0.20mm thick, 210(25+160+25)mm long
Outer Be pipe: 0.15mm thick, 165mm long

thinner

inner Beryllium layer: T= 0.5 mm
outer Beryllium layer: T= 0.35 mm

Innermost layer will be inside the boundary line, which defines the vertex detector coverage.
Shorter innermost layer is required



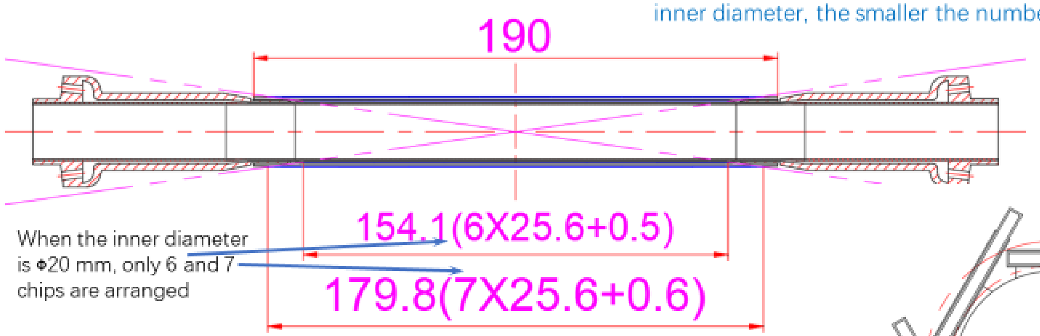
10 chips on both sides of the innermost ladder

7 ladders arrangement for innermost layer

Comparison of air-cooled structures with different vertex arrangements

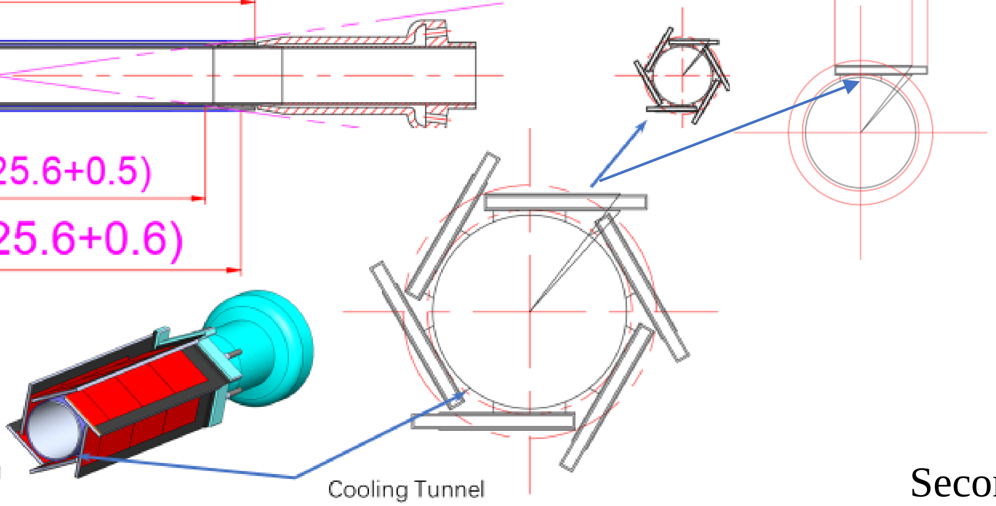
Single layer:

Due to the limitation of detection angle, the smaller the inner diameter, the smaller the number of chips

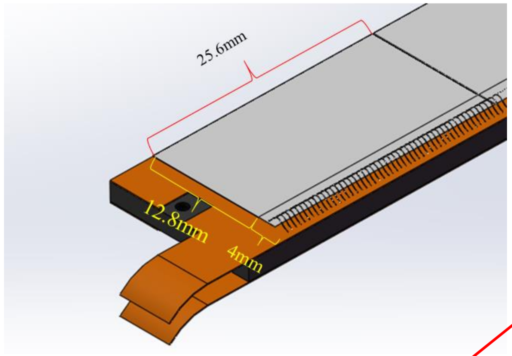


Pros:
All silicon chips are in same radius and close to the beam pipe.

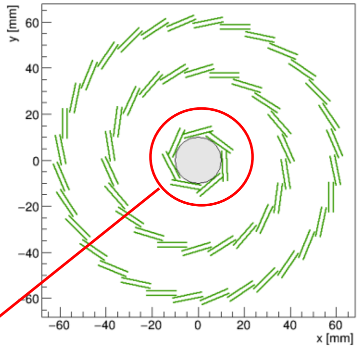
Cons:
It's hard to cool the inner silicon chips which close to the beam pipe using air-forced cooling



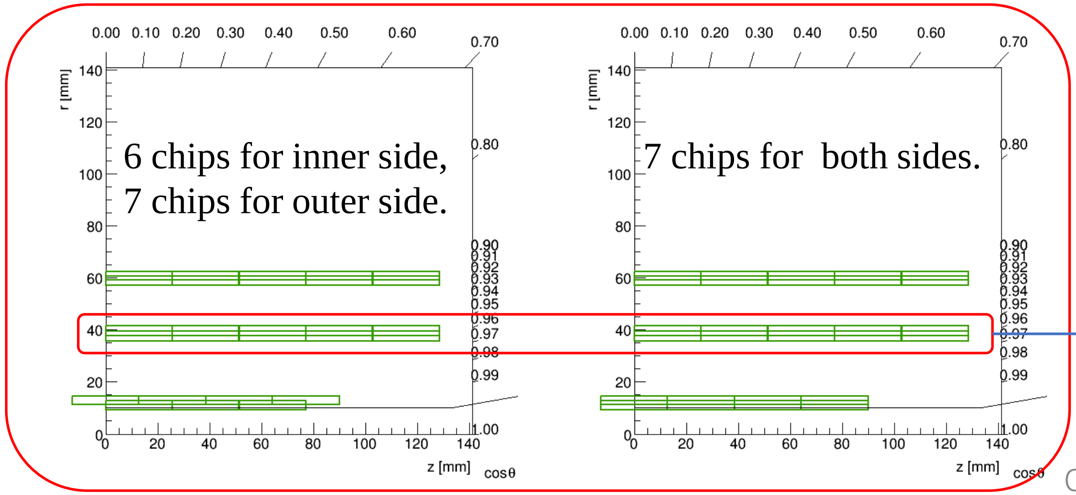
Our present ladder design:



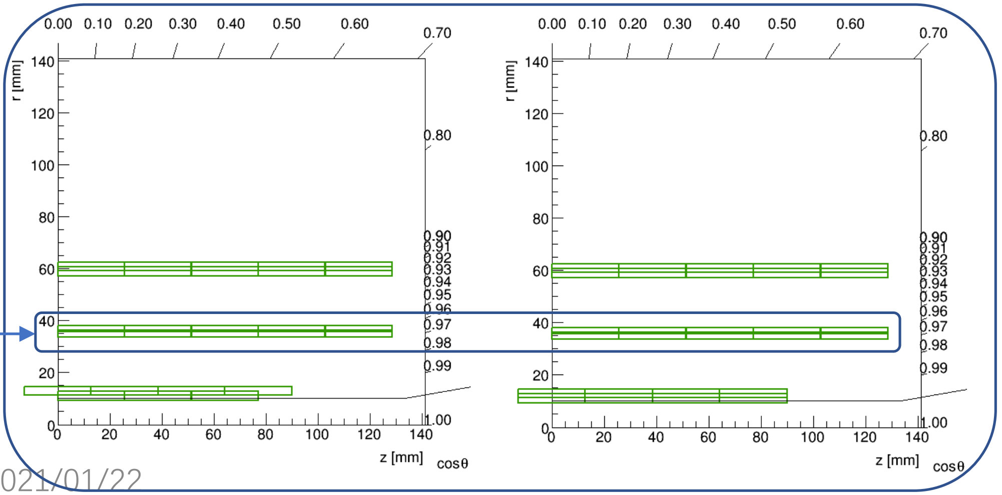
At least 7 ladders for innermost layer



Second layer in the middle:

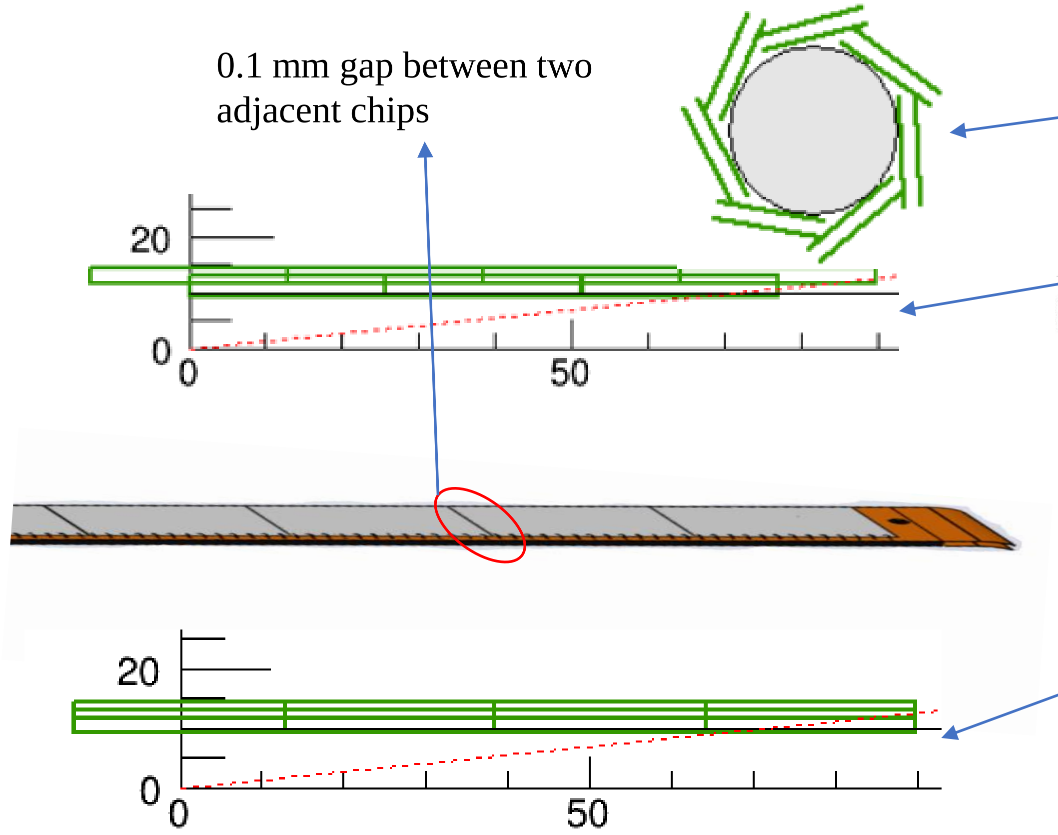


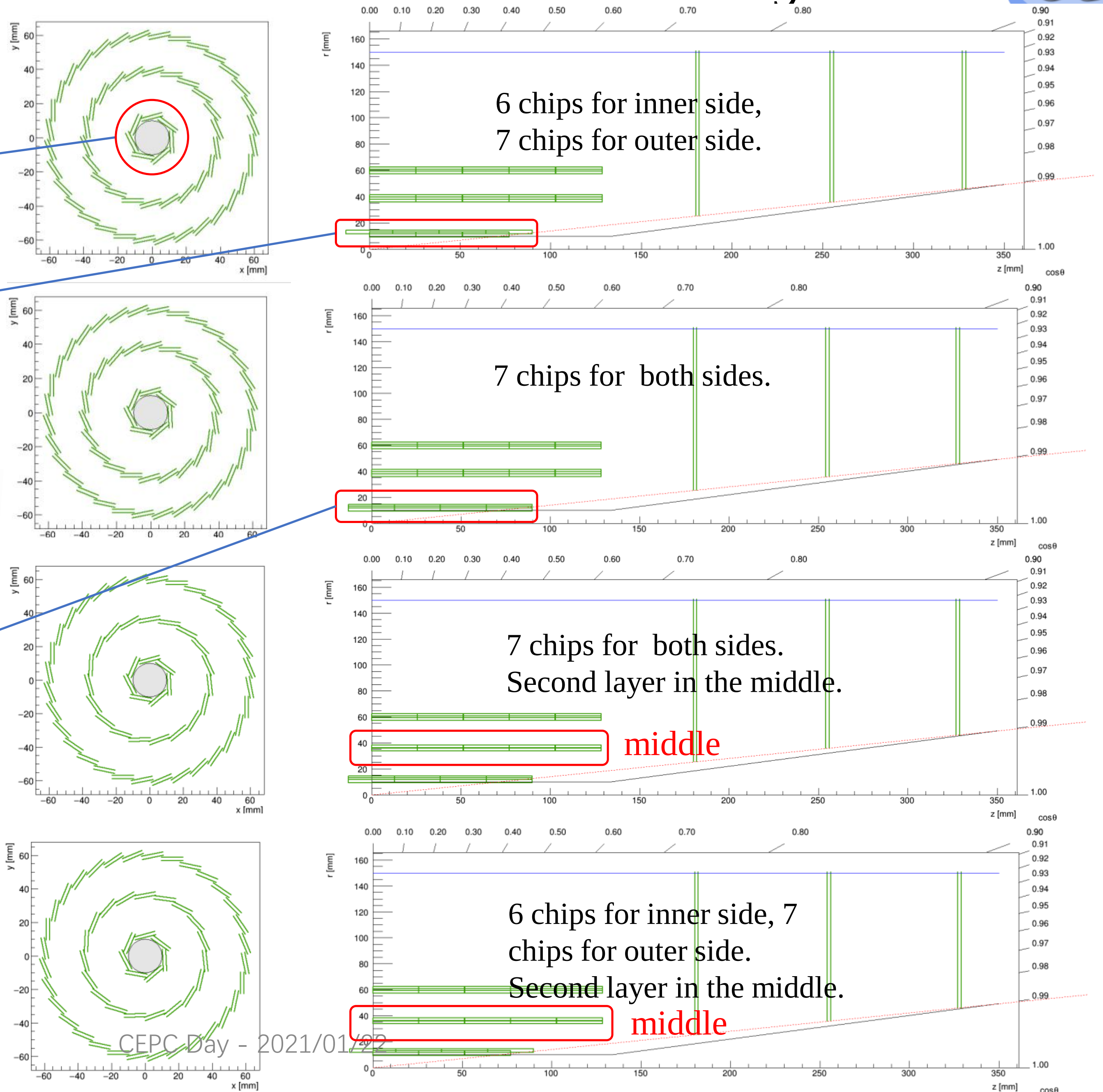
Move to the middle



7 ladders arrangement for innermost layer

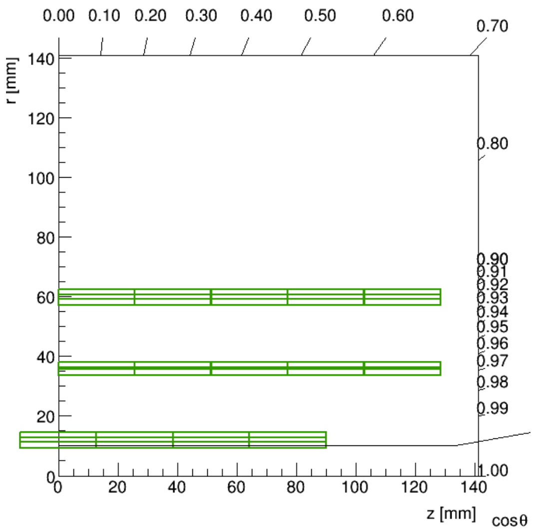
0.1 mm gap between two adjacent chips

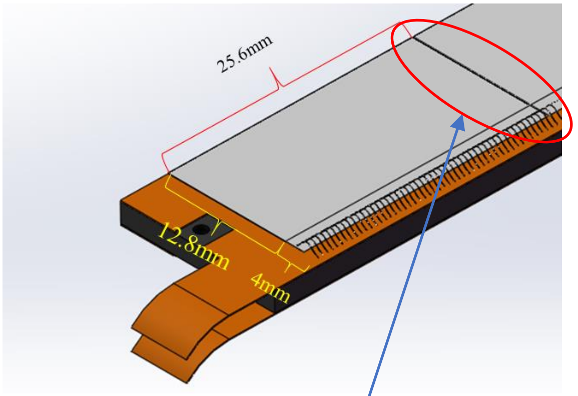




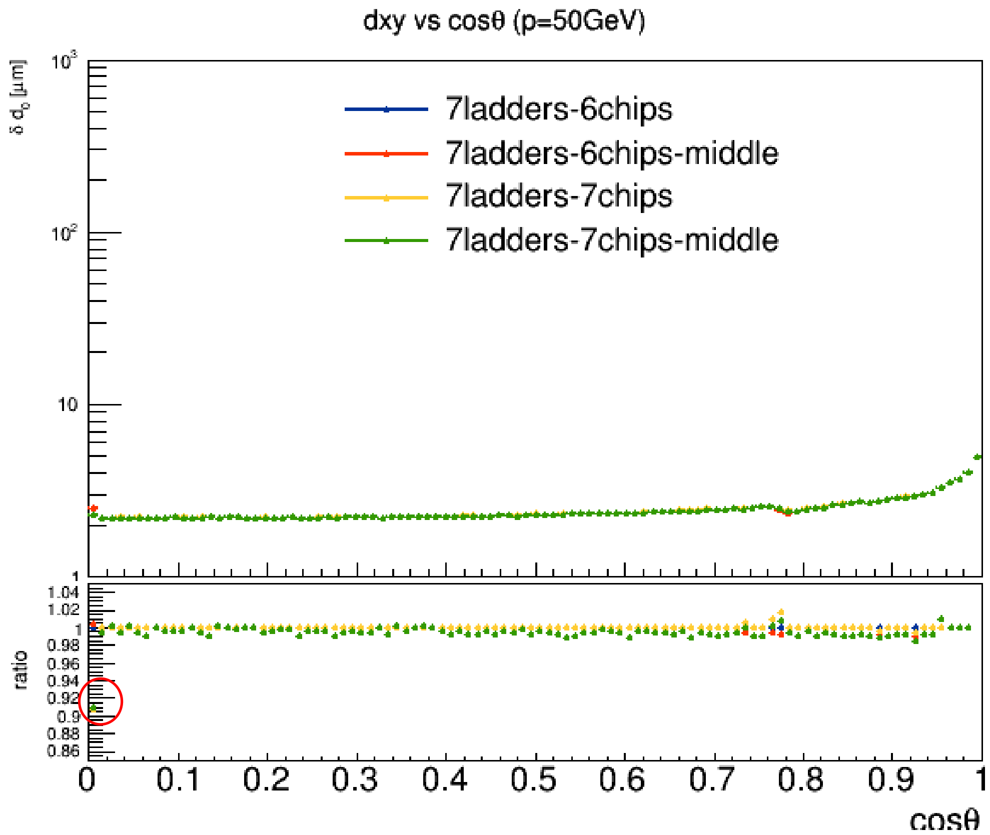
7 ladders arrangement for innermost layer

- The effect of whether placing second layer in the middle or not on d0 resolution is very small.
- Using 7 ladders for the innermost layer improves d0 resolution a lot at cosθ=0.
- For mechanical consideration, I prefer placing second layer in the middle.



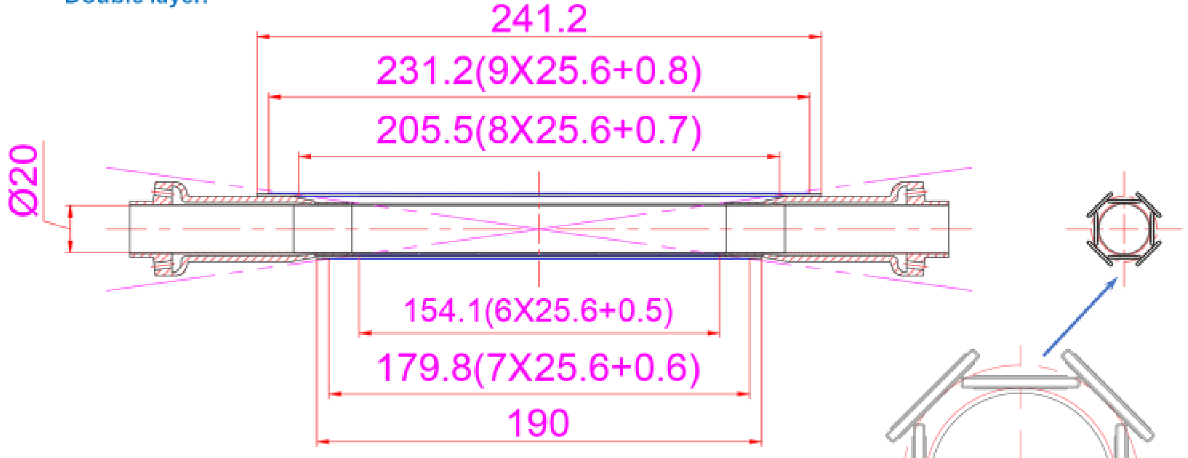


0.1 mm gap between two adjacent chips



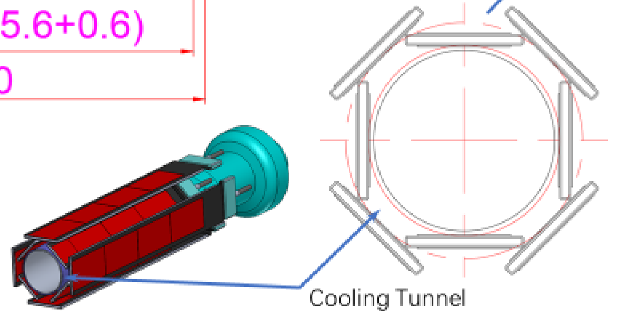
8 ladders arrangement for innermost layer

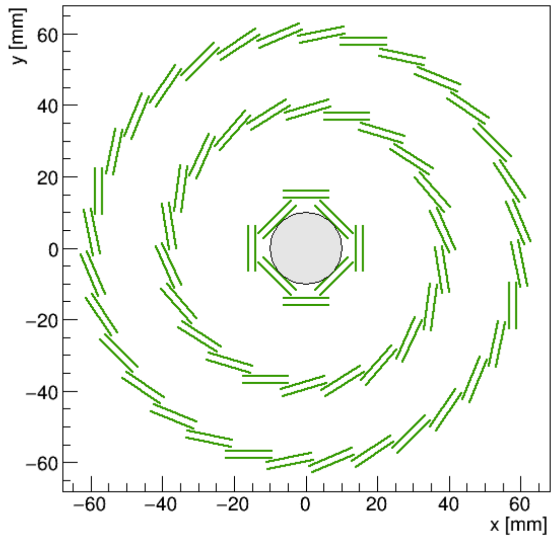
Double layer:



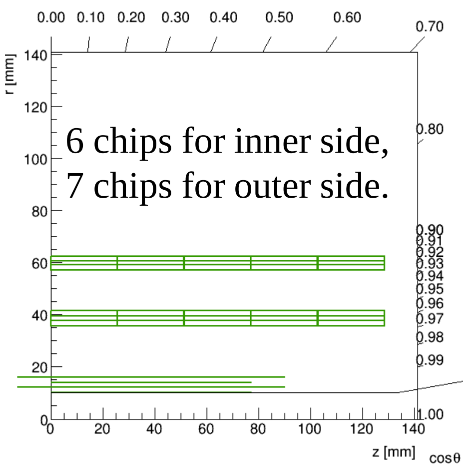
Pros:
The area of cooling tunnel has been extended.

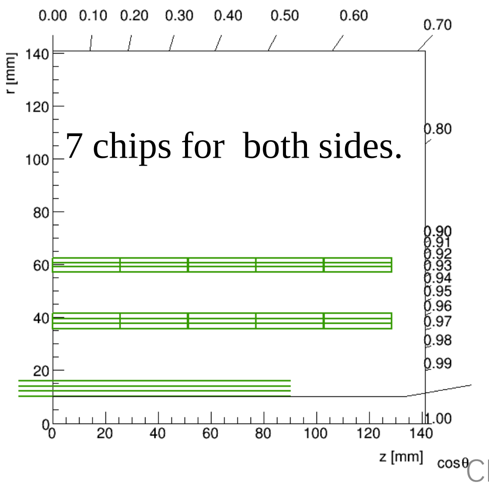
Cons:
The detecting distance of two layer is different.



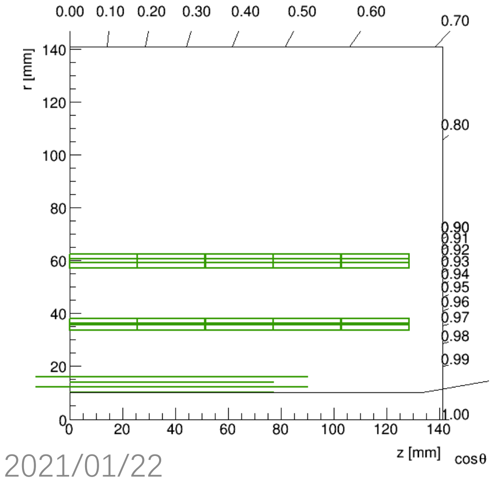


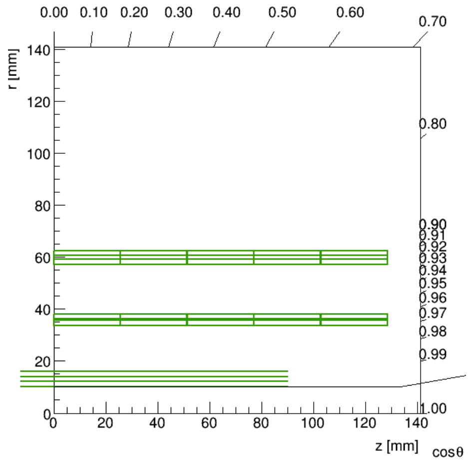
ideal condition excluding dead area of the ladders



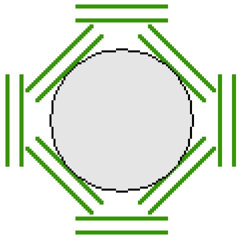


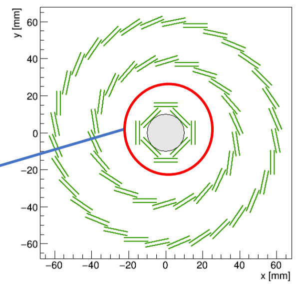
Second layer in the middle:

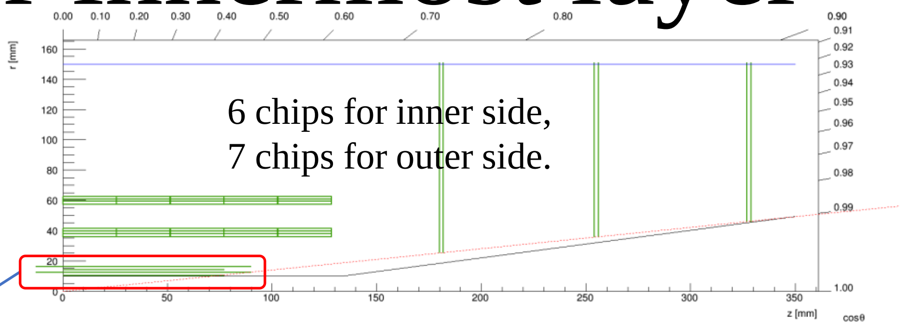




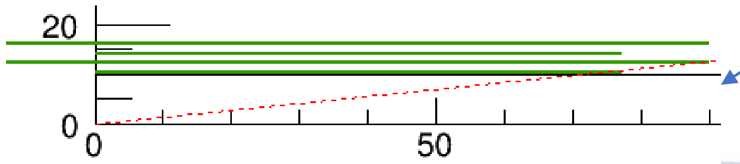
8 ladders arrangement for innermost layer

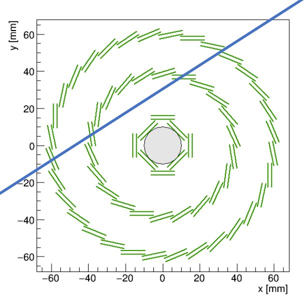


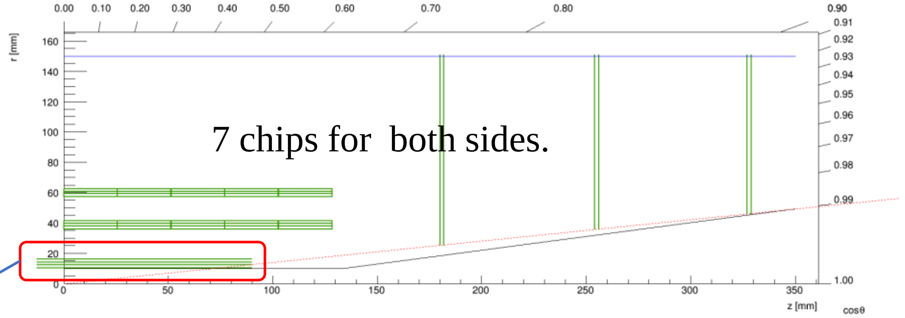




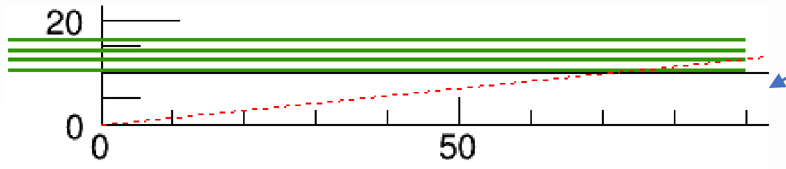
6 chips for inner side,
7 chips for outer side.

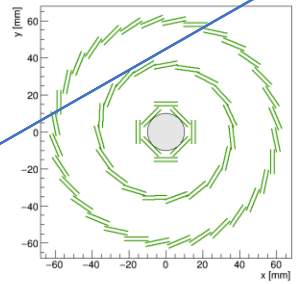


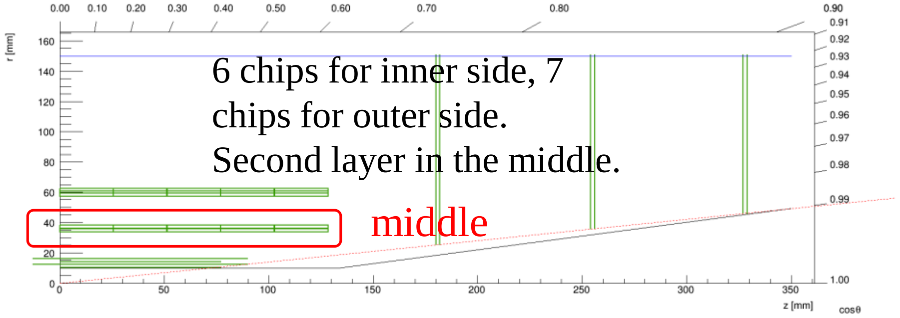




7 chips for both sides.

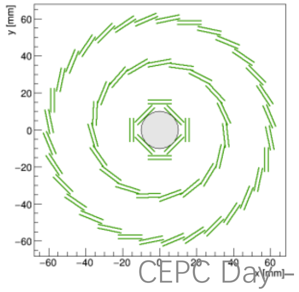


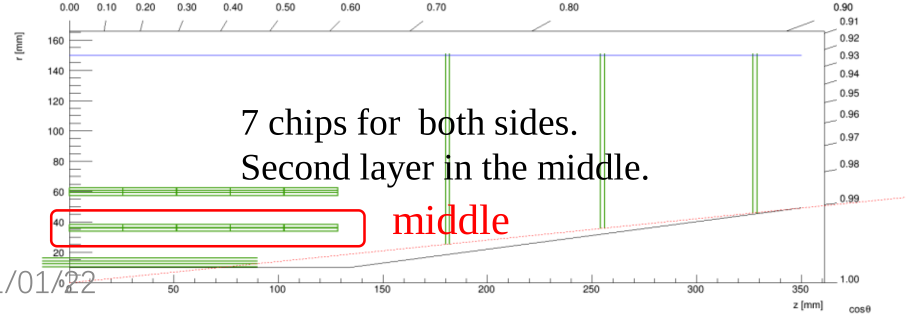




6 chips for inner side, 7
chips for outer side.
Second layer in the middle.

middle



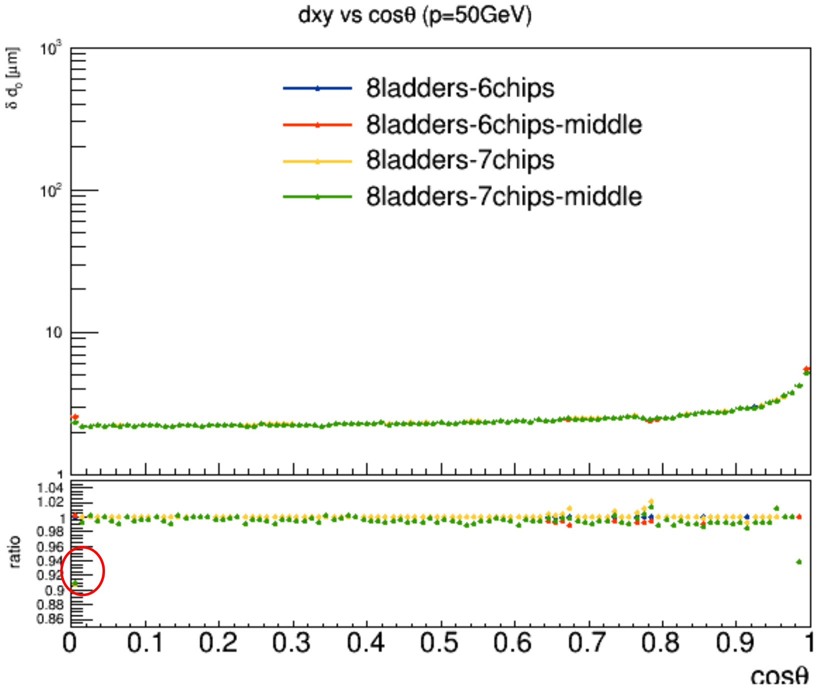


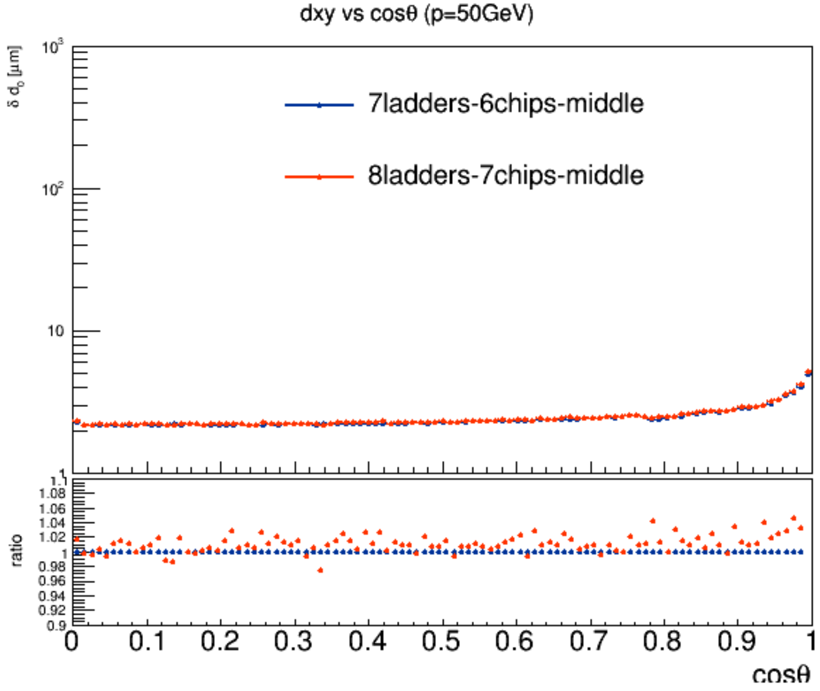
7 chips for both sides.
Second layer in the middle.

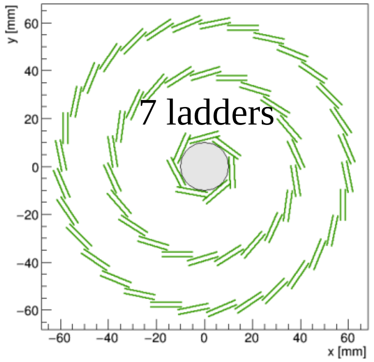
middle

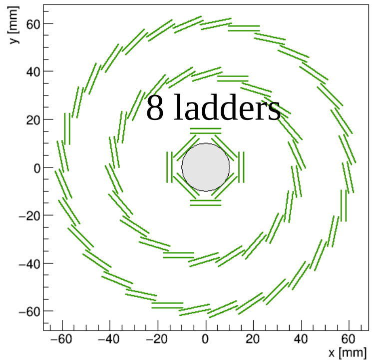
8 ladders arrangement for innermost layer

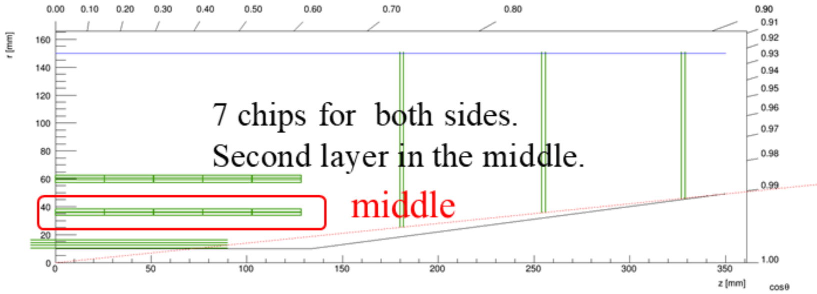
Comparison of different ladder arrangements for innermost layer:









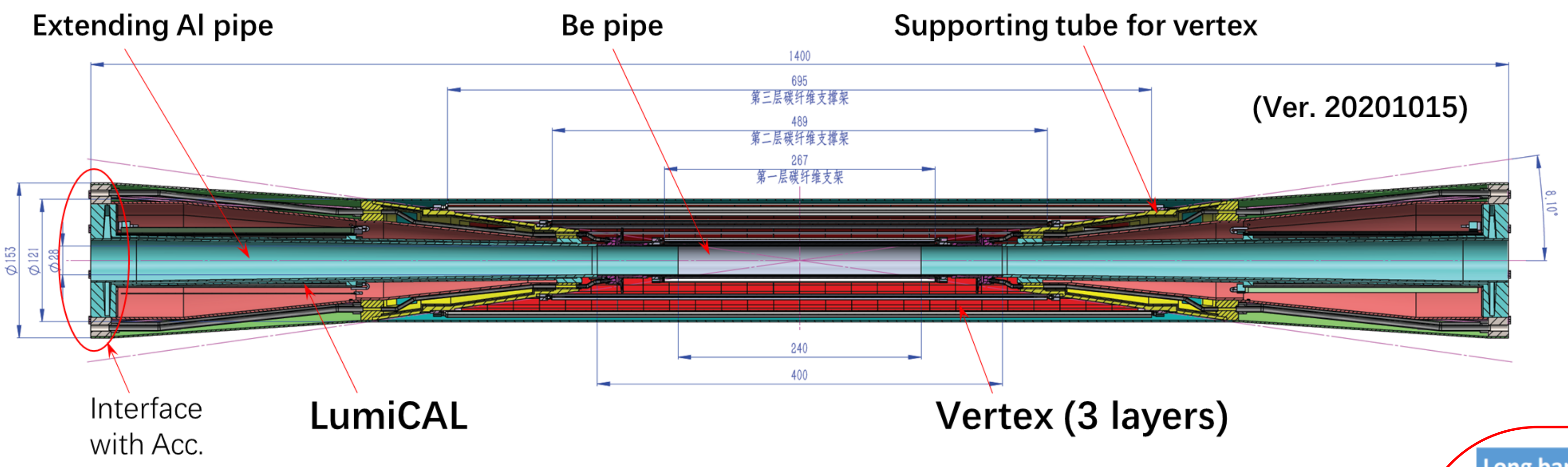


7 chips on both sides for innermost layer and second layer in the middle is better.

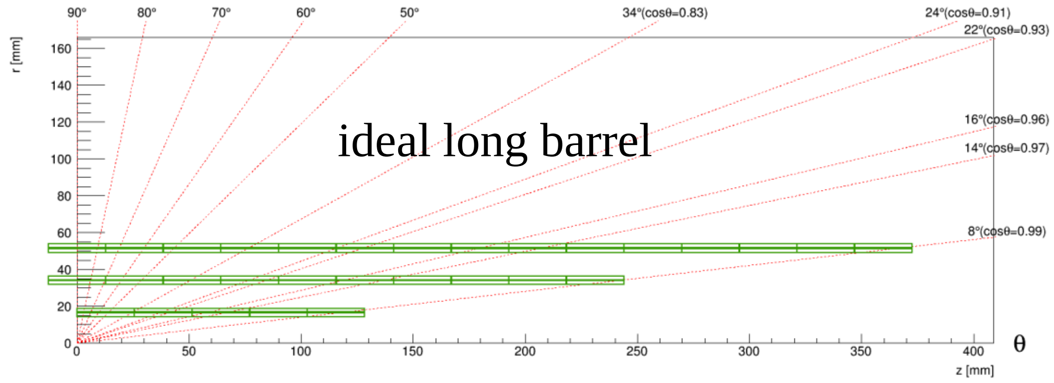
- 7-ladders arrangement is better than 8-ladders arrangement.
  - less material
  - 7 ladders are close to beam pipe.

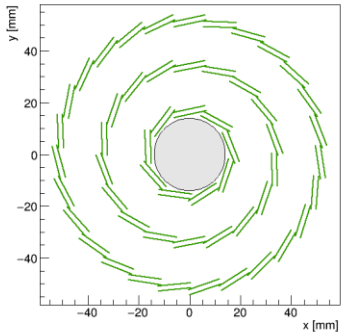
Best! Optimal vertex layout!

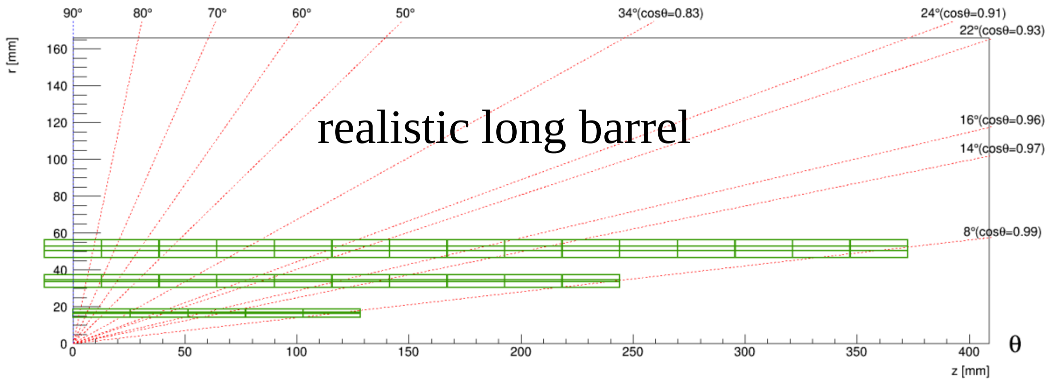
Realistic long barrel vertex

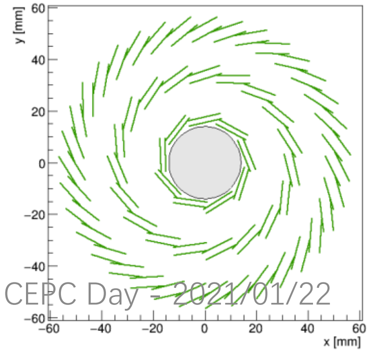


- Feasible solution for air cooling
- Simple structure
- Realistic long barrel vertex:
  - stiffer carbon fiber ladder support
  - more cable for read-out
  - vibration of long ladder









Long barrel design	Length of ladder	Chips / ladder	Readout mode	No. of flex Layers
layer1	250	10	Single end	2
layer2	500	20	double ends	2
layer3	750	30	double ends	4

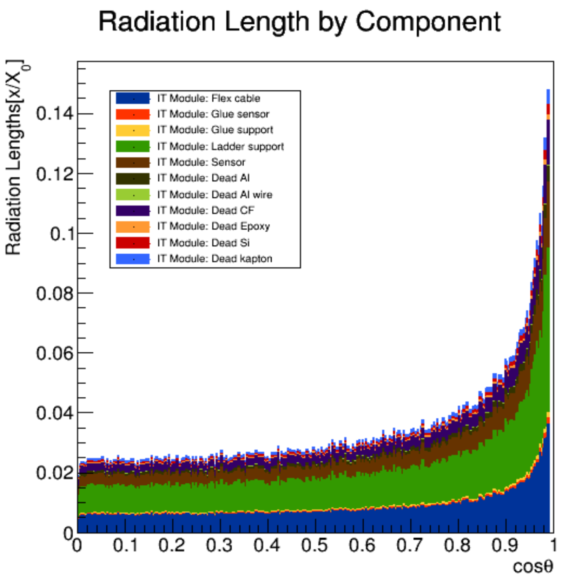
2 flex layers

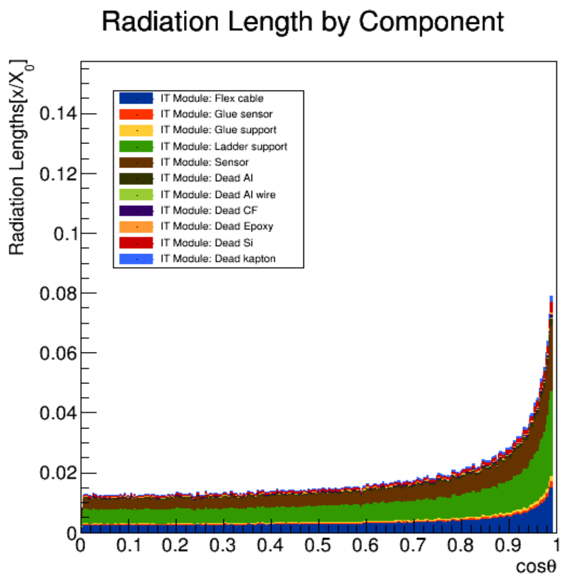
	Thickness	Optimization goal
Polyimide	25um	12
Adhesive	28um	15
Plating Al	17.8um	?
kapton	50um	50
Plating Al	17.8um	?
Adhesive	28um	15
Polyimide	25um	12

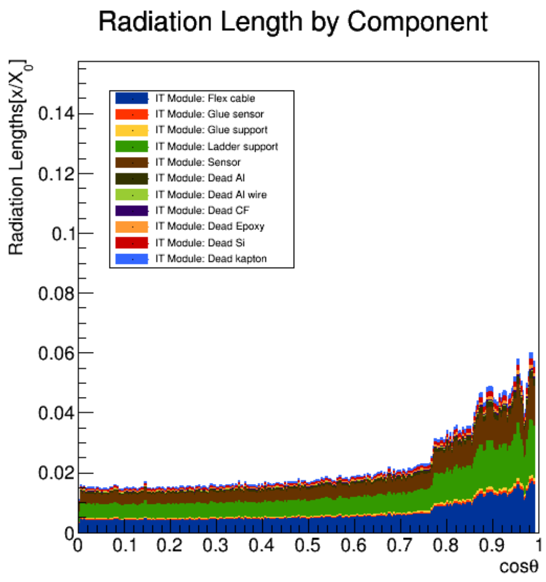
4 flex layers

	thickness	Optimization goal
Polyimide	25um	12
Adhesive	28um	15
Plating Al	17.8um	?
kapton	50um	50
Plating Al	17.8um	?
kapton+adhesive	50um	50
Plating Al	17.8um	?
kapton	50um	50
Plating Al	17.8um	?
Adhesive	28um	15
Polyimide	25um	12

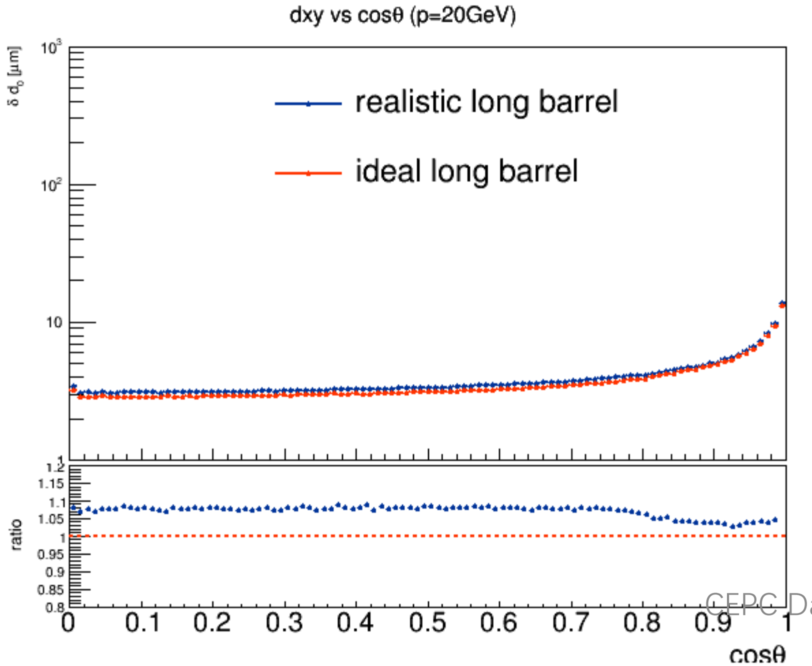
Realistic long barrel vertex





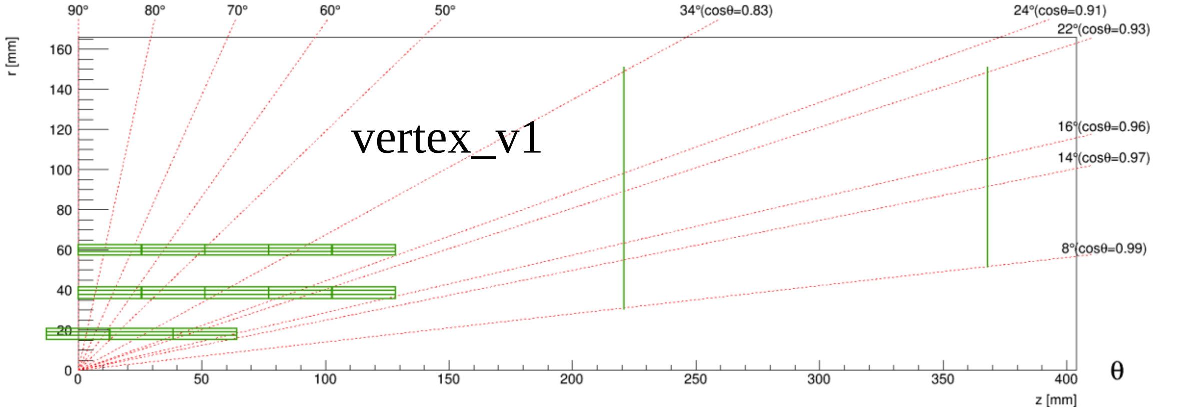


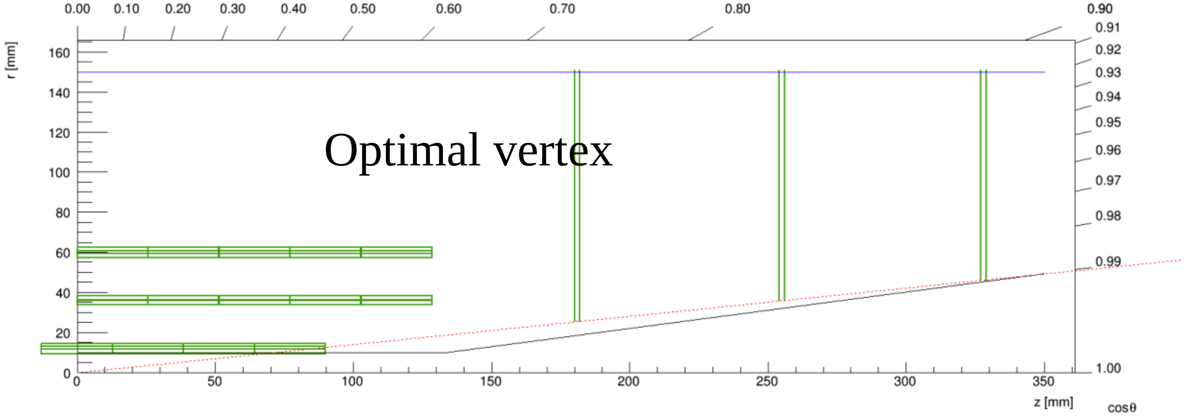
- The material budget of realistic long barrel vertex is about twice as much as the ideal long barrel vertex.
- Much more material in the front region than optimal vertex layout.

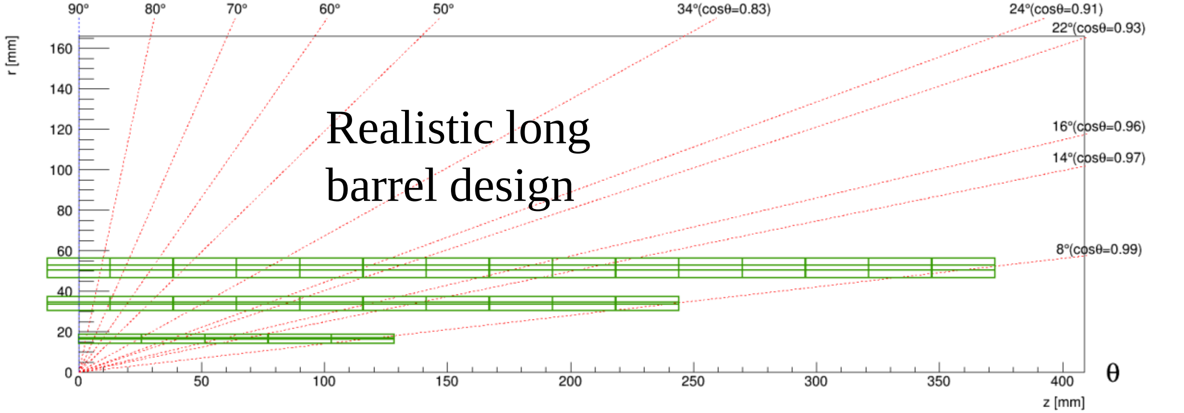


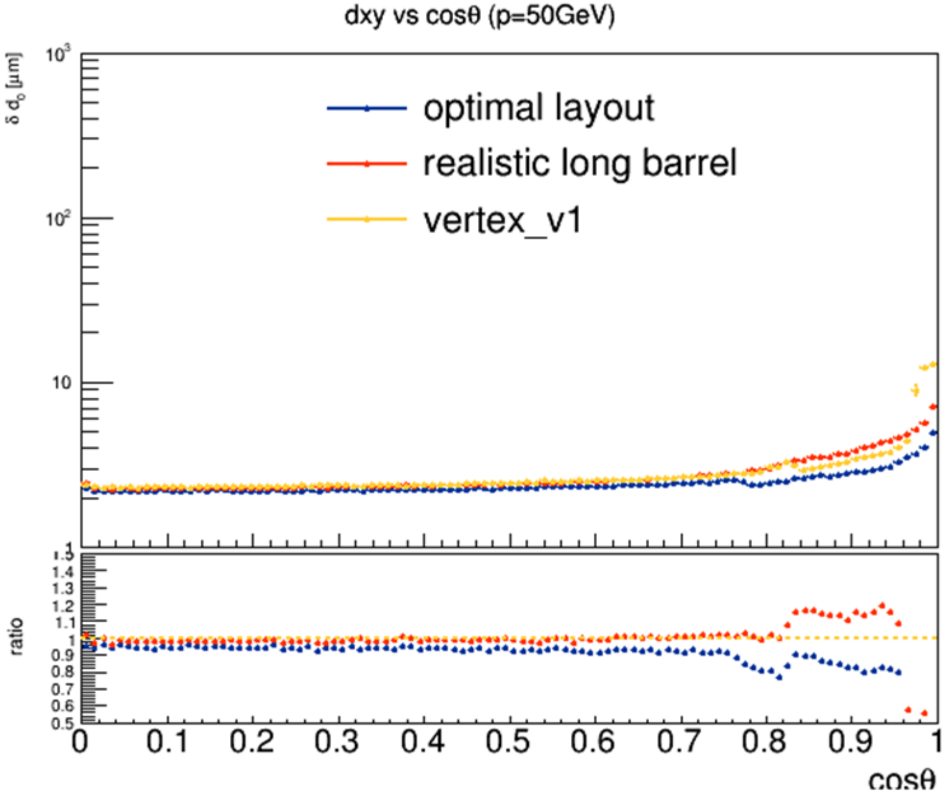
The d0 resolution of realistic long barrel vertex is worse about 7% than ideal long barrel vertex.

Optimal vertex layout





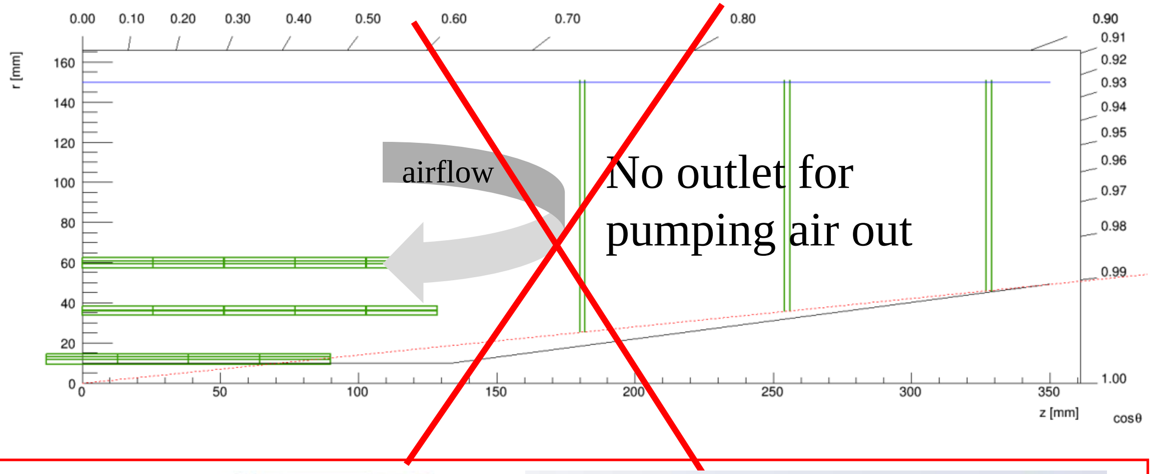


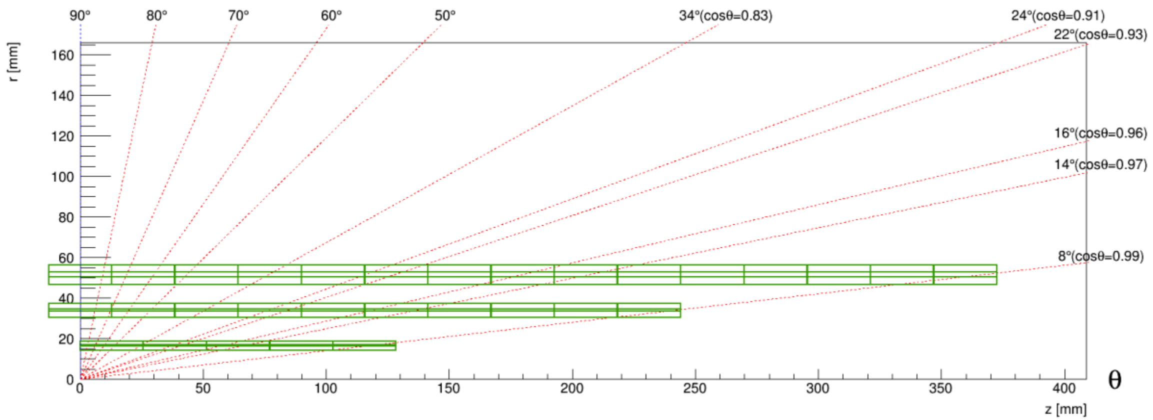


The d0 resolution of optimal vertex layout is much better than realistic long barrel vertex and vertex_v1 (realistic implementation of CDR vertex) layout, especially in the front region (20% and even more).

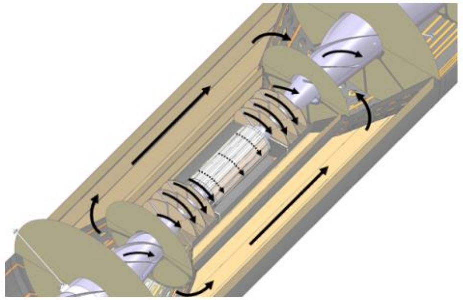
- smaller radius of beam pipe
- more disks
- longer innermost layer

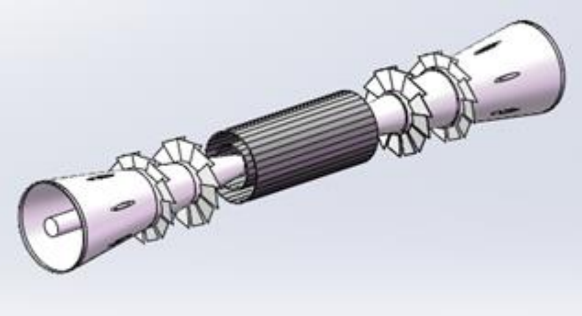
Vertex design considering air cooling



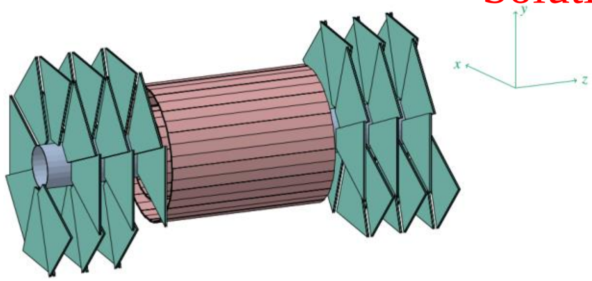


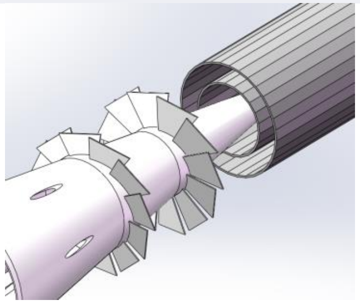
Long barrel design





Solution?

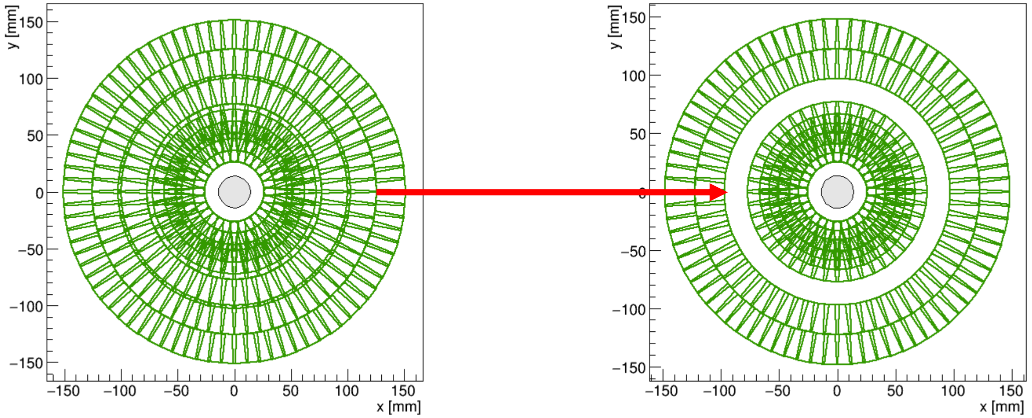




CLIC spiral disk concept

rotate the disk, from Jinyu

CLICdp-Note-2014-002



Make a hole in disk

Summary & Plan

- New optimal vertex layout has been studied:
  - beam pipe radius of 10mm & previous optimal vertex layout
  - New ladder arrangements for innermost layer
    - 7 ladders & 7 chips on both sides of each ladder
    - Placing second layer in the middle is better considering both mechanics and performance.
  - The d0 resolution of this new optimal vertex is much better than the realistic implementation of CDR vertex and realistic long barrel vertex (20% and even more).
- Next:
  - Air cooling for this optimal vertex layout
    - thermal simulation,
    - vibration studies
  - Implement this layout using Geant4 full simulation (WU Kewei)
  - Global tracker consideration

Backup

Gluckstern formulae

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An extension of the Gluckstern formulae for multiple scattering: Analytic expressions for track parameter resolution using optimum weights

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ABSTRACT

Momentum, track angle and impact parameter resolution are key performance parameters that tracking detectors are optimised for. This report presents analytic expressions for the resolution of these parameters for equal and equidistant tracking layers. The expressions for the contribution from position resolution are based on the Gluckstern formulae and are well established. The expressions for the contribution from multiple scattering using optimum weights are discussed in detail.

1. Introduction

The theory of track fitting using global χ^2 minimisation is well established [1,2] and some explicit expressions for geometries with equidistant detector planes are presented in [3–5]. In this report we derive analytic expressions for the resolution of particle momentum as well as track angle and impact parameter in r–ϕ and z direction, as defined in Fig. 1. The calculations are performed for a classic solenoid spectrometer with a constant B-field using $N+1$ equal and equidistant detector planes. We present both the contribution from

two concrete examples that we will discuss later. The parameters a_i are estimated by minimising χ^2 defined as

$$\chi^2 = \sum_{m=0}^{N}\sum_{n=0}^{N}\left[y_m - \sum_{i=0}^{M} a_i g_i(x_m)\right] W_{mn} \left[y_n - \sum_{i=0}^{M} a_i g_i(x_n)\right] \quad (1)$$

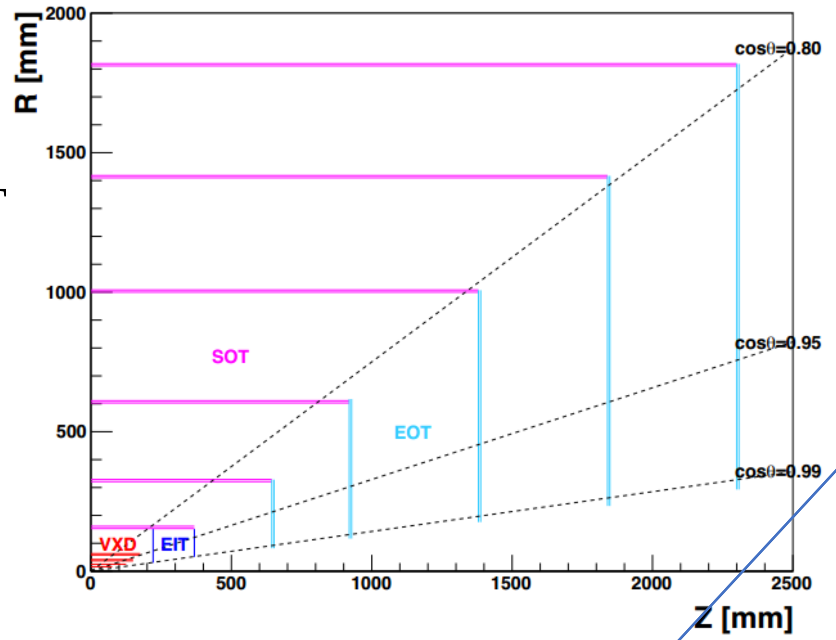
where W_{mn} is the weight matrix that still has to be defined. The above relation can also be written in matrix form

$$\chi^2 = (\mathbf{y} - \mathbf{Ga})^T \mathbf{W} (\mathbf{y} - \mathbf{Ga}) \quad (2)$$

https://doi.org/10.1016/j.nima.2018.08.078

Full silicon tracker layout

FST

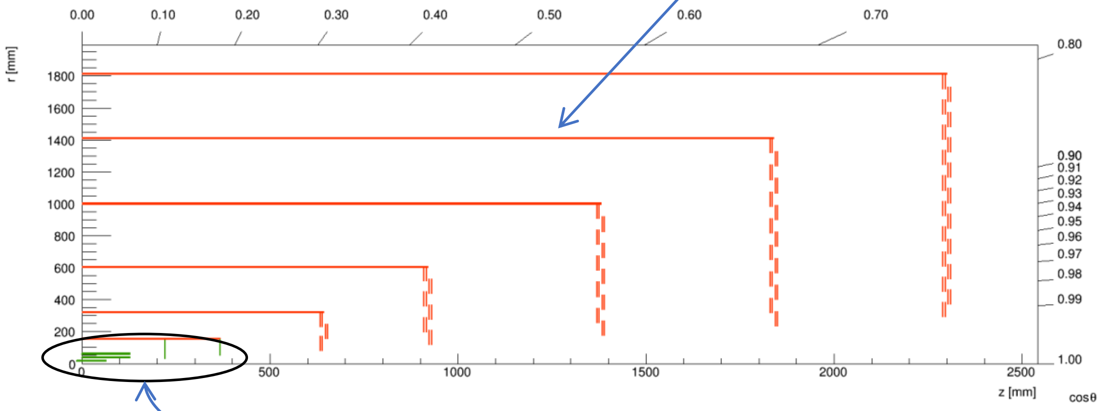


FST

SOT	R (m)		$\pm z$ (m)	Type
Layer 1	0.153		0.368	D
Layer 2	0.321		0.644	D
Layer 3	0.603		0.920	D
Layer 4	1.000		1.380	D
Layer 5	1.410		1.840	D
Layer 6	1.811		2.300	D
EOT	R_{in} (m)	R_{out} (m)	$\pm z$ (m)	Type
Disk 1	0.082	0.321	0.644	D
Disk 2	0.117	0.610	0.920	D
Disk 3	0.176	1.000	1.380	D
Disk 4	0.234	1.410	1.840	D
Disk 5	0.293	1.811	2.300	D

newFST

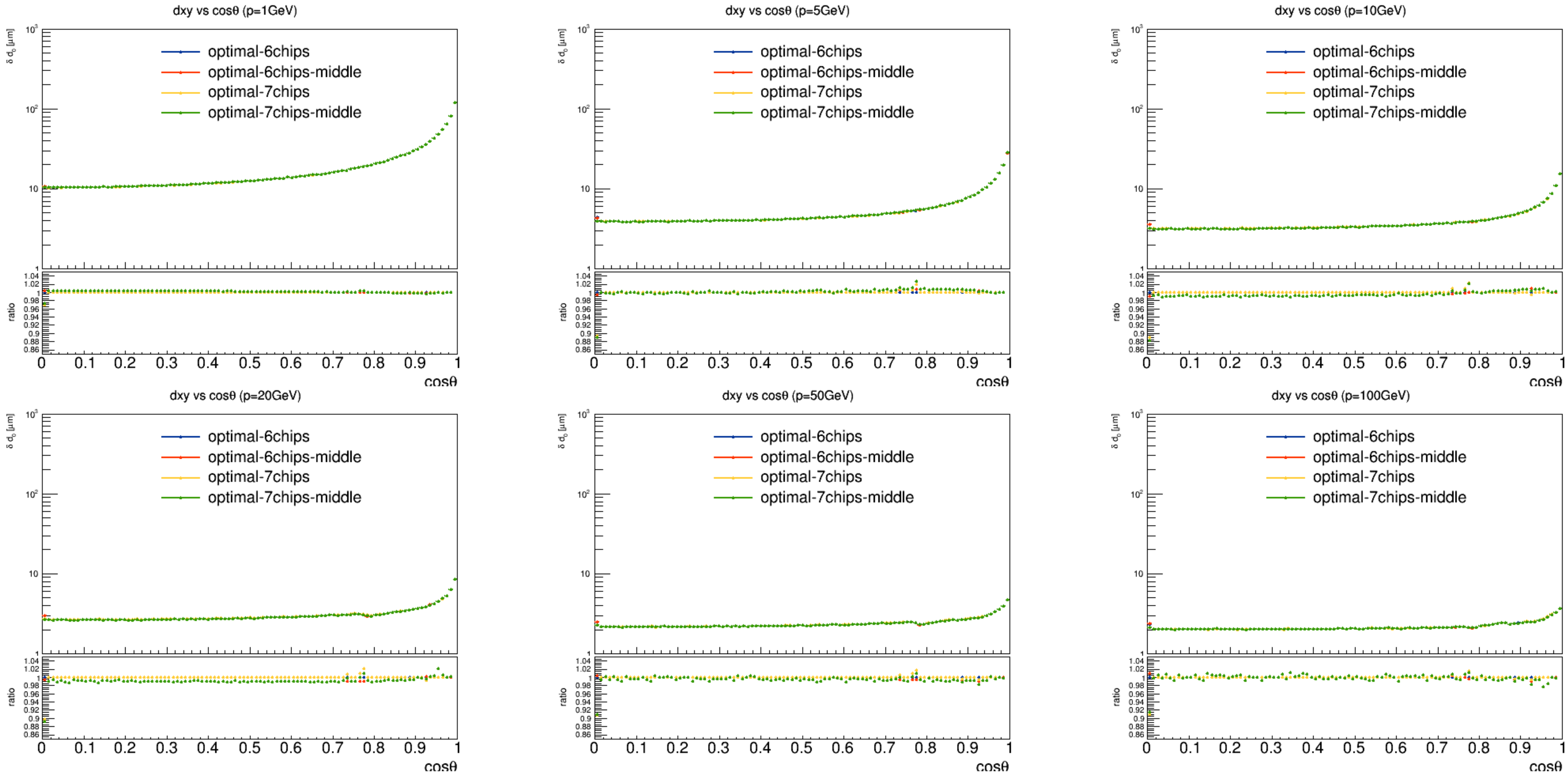
VXD	**R(m)**		**z(m)**
Layer 1	**0.017**		**0.064**
Layer 2	**0.019**		**0.064**
Layer 3	**0.038**		**0.128**
Layer 4	**0.040**		**0.128**
Layer 5	**0.059**		**0.128**
Layer 6	**0.061**		**0.128**
EIT	R_{in} (m)	R_{out} (m)	$\pm z$ (m)
Disk 1	0.030	0.151	0.221
Disk 2	0.051	0.151	0.368
Disk 3			
Disk 4			
Disk 5			



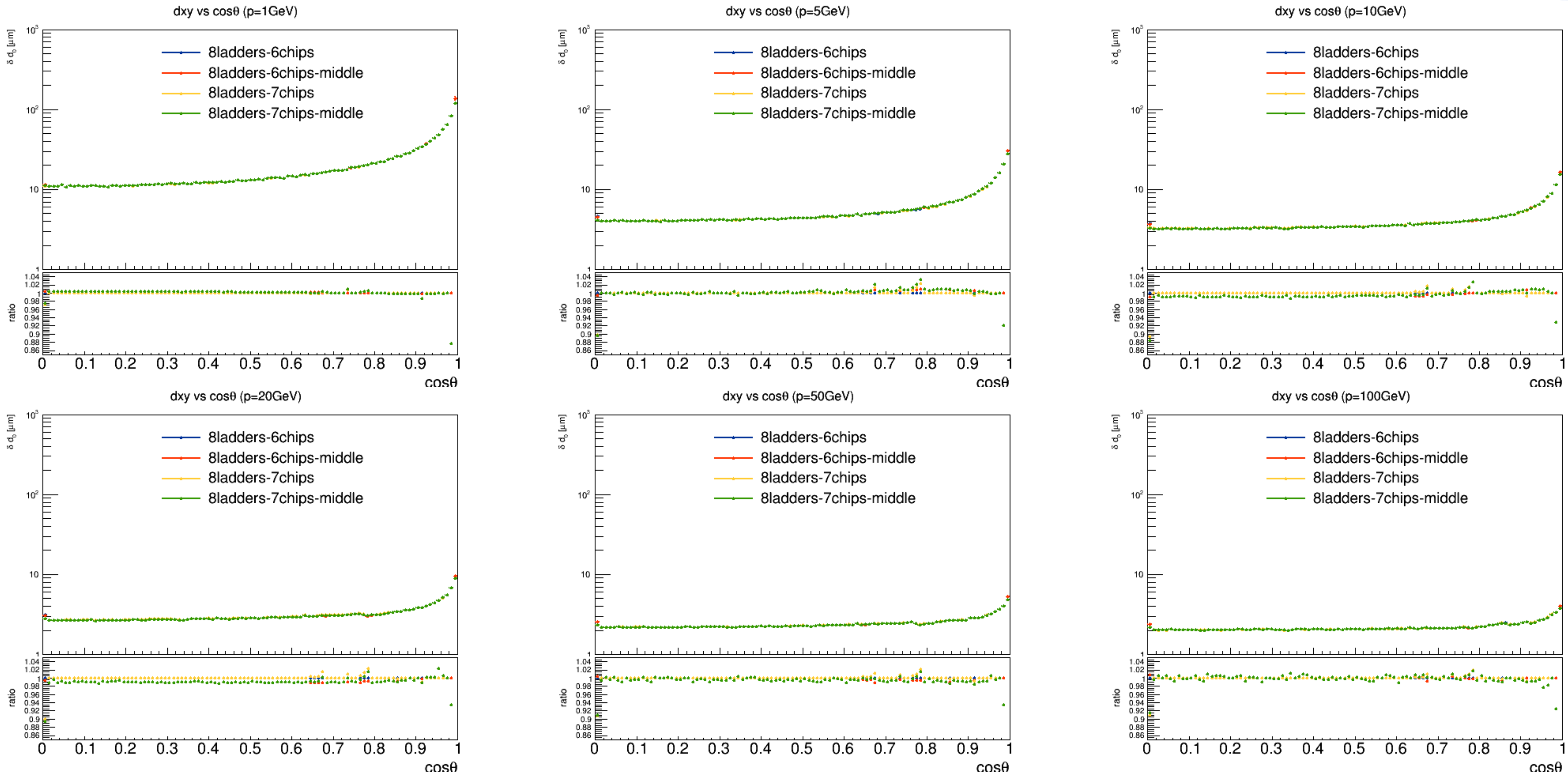
vertex layout optimization

- 4 parts: VXD,EIT,SOT,EOT
- Outer tracker (SOT + EOT): from FST
- The coverage of the whole tracker is over cosθ=0.99
- Outer tracker disk has been adjusted for mechanics

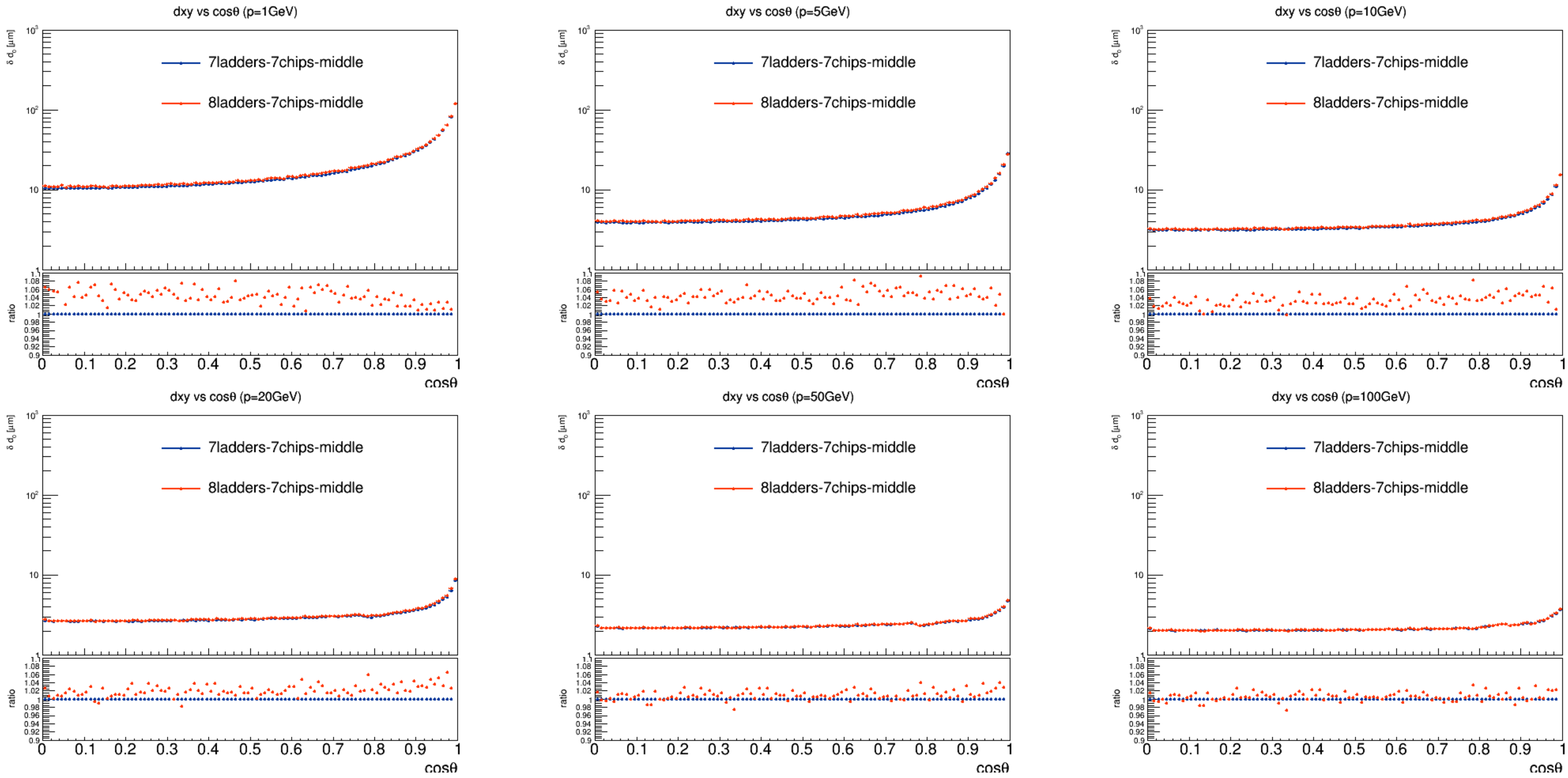
7 ladders arrangement for innermost layer



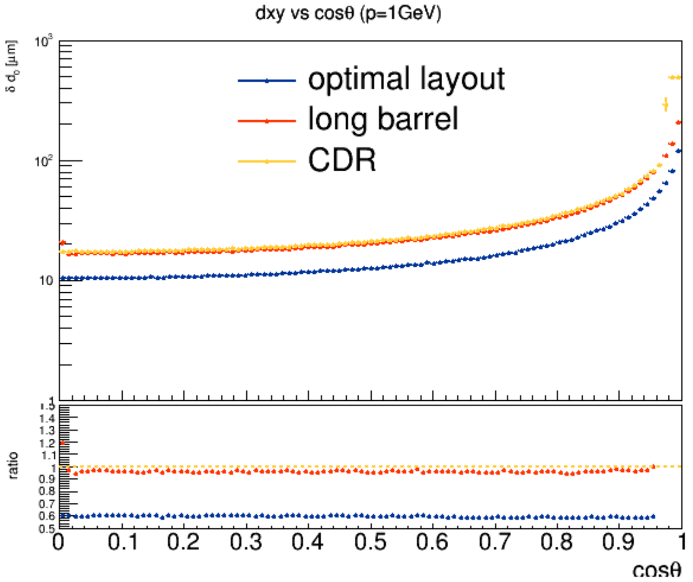
8 ladders arrangement for innermost layer

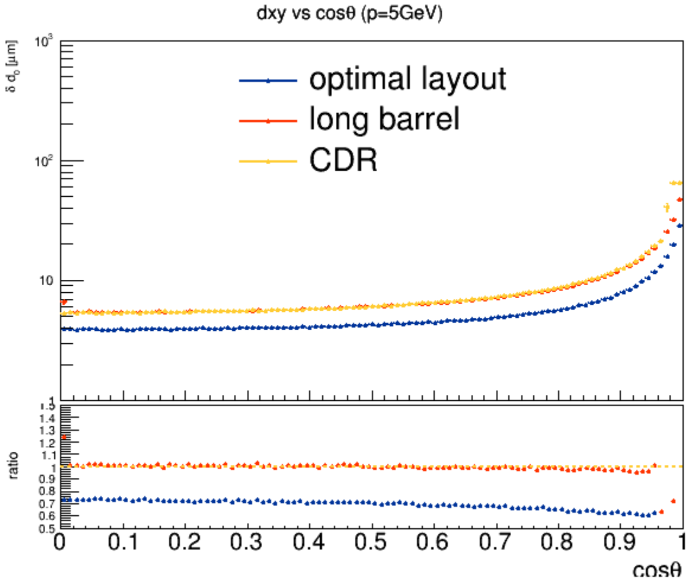


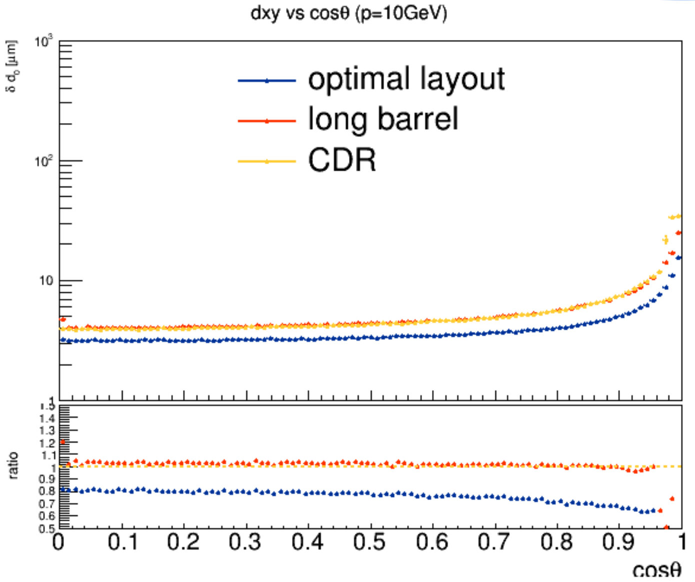
Comparison of different ladder arrangements for innermost layer

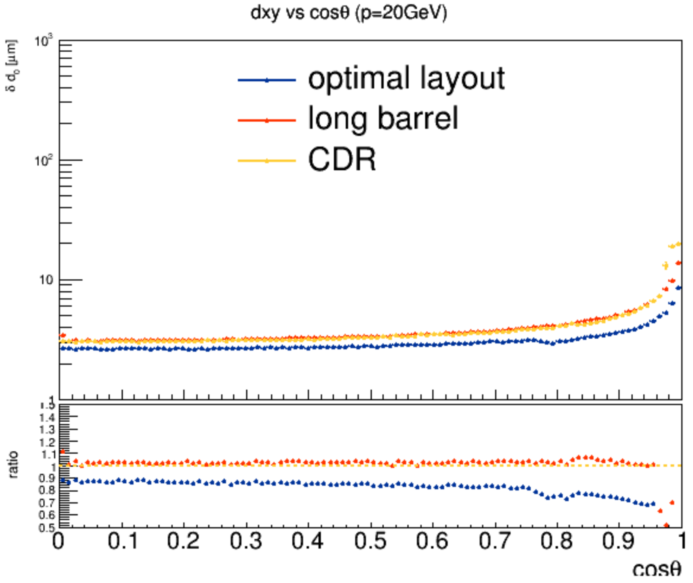


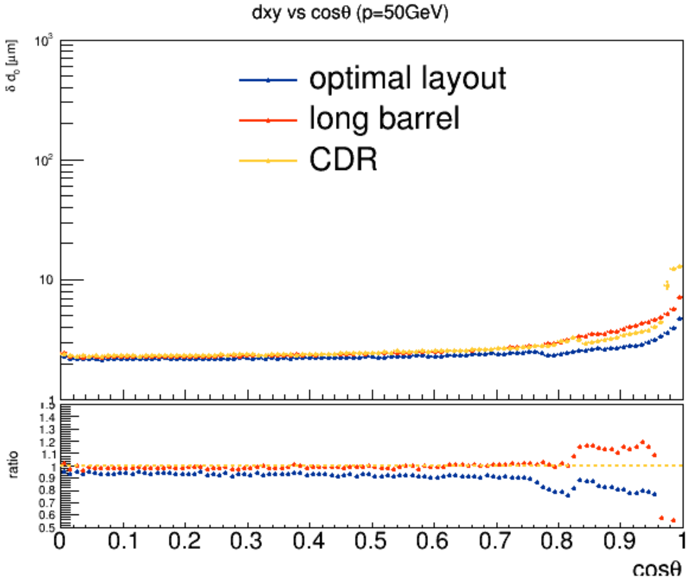
d0 resolution of optimal vertex layout

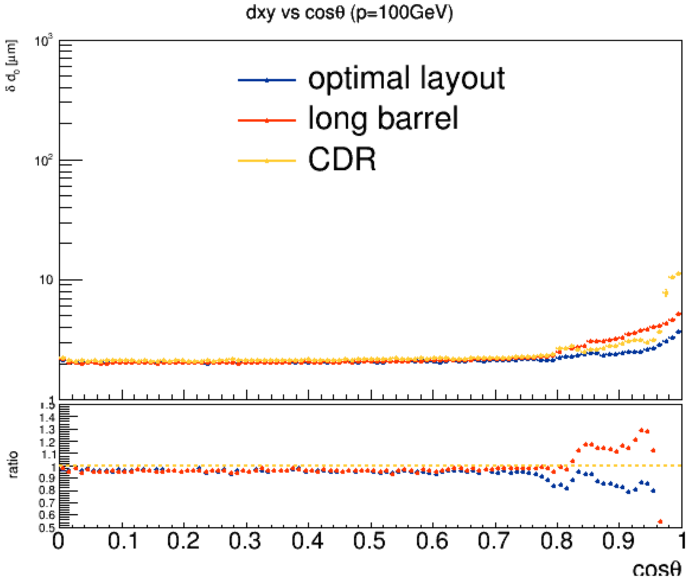




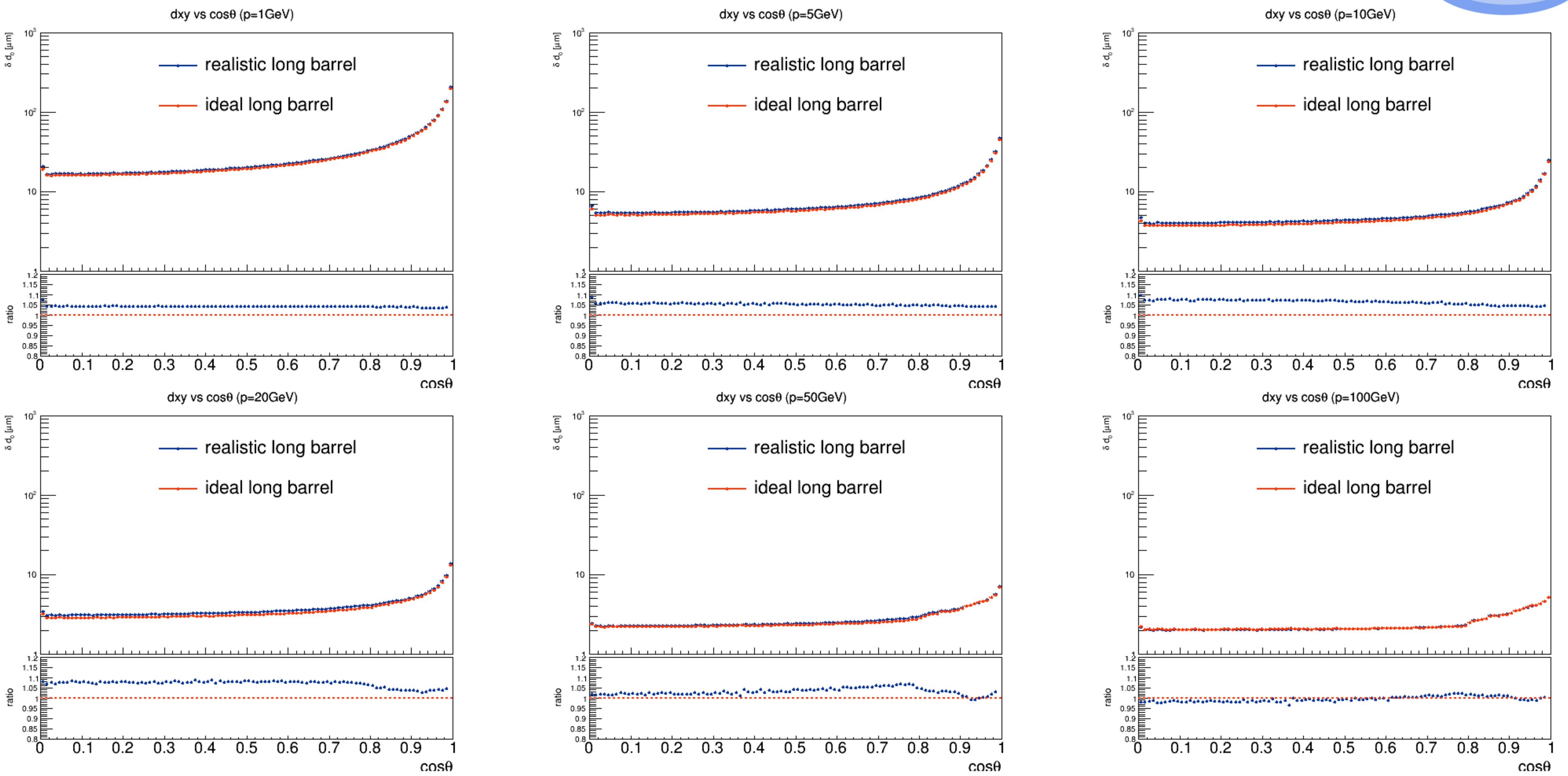




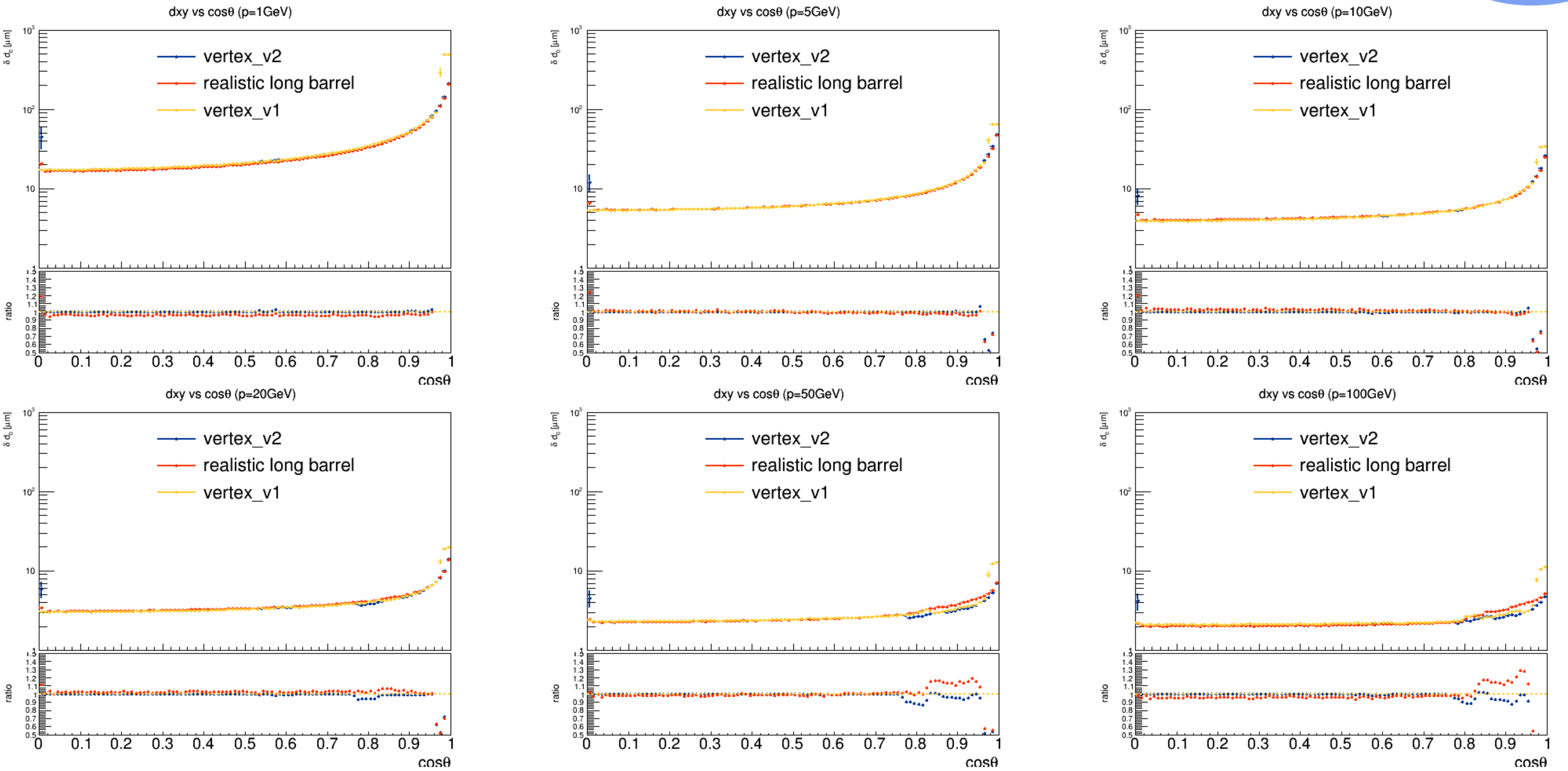




New long barrel

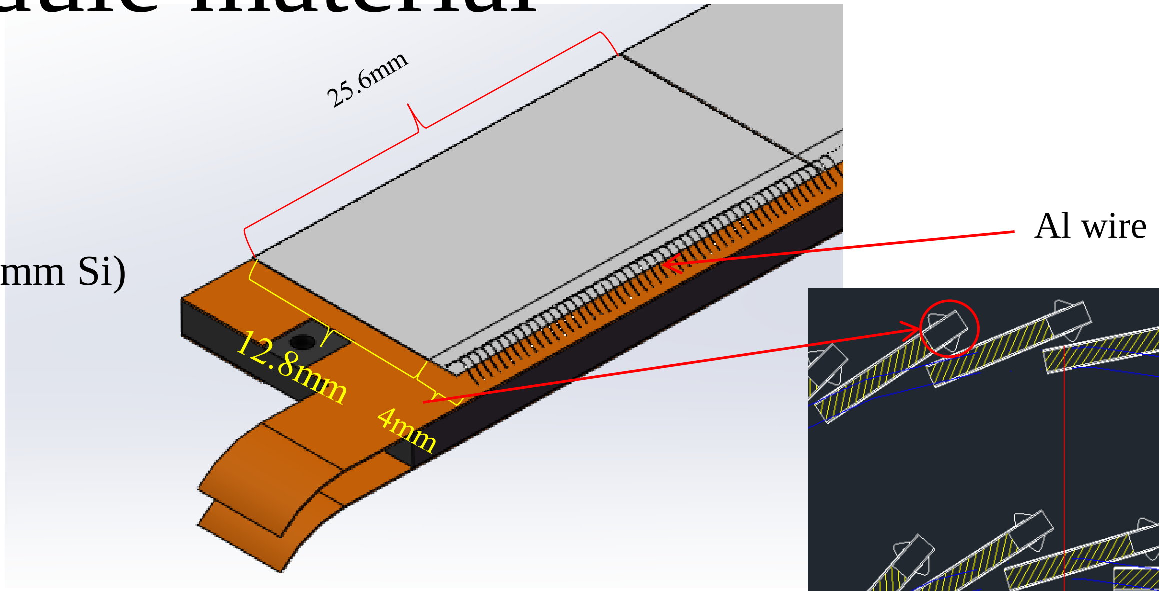


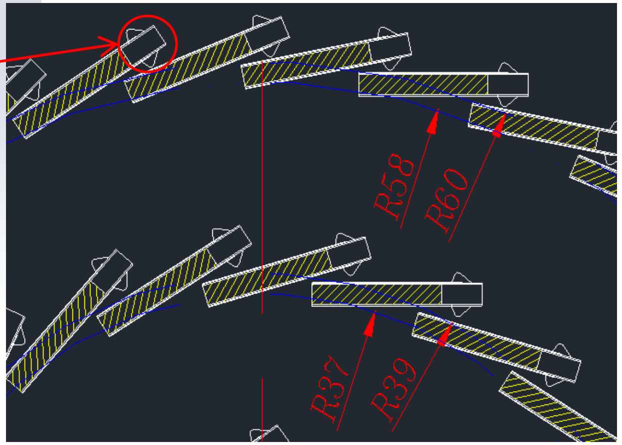
vertex_v2 performance



New pixel module material

Top view:
active area: 12.8mm × 25.6mm
dead area: 4mm × 25.6mm (only 2mm Si)
Side view:
5 symmetric layer, gluing together.





One half dead area:

Sensor(Si, 25um)
Al wire
glue(Epoxy, 7.5um)
Al(26.7um)
Kapton(74um)
Glue(Epoxy, 52.5um)
Ladder support(carbon fiber,175um)

Sensor(Si, 50um)
glue(Epoxy, 15um)
Al(26.7um)
Kapton(74um)
Glue(Epoxy, 30um)
Ladder support(carbon fiber,350um)
Glue(Epoxy,30um)
Kapton(74um)
Al(26.7um)
Glue(Epoxy, 15um)
Sensor(Si, 50um)

(1) Sensor
(2) Flex cable
(3) Ladder support
(4) Flex cable
(5) sensor

recent discussion shows that we need at least 2 layer Al in flex cable

	Thickness	Optimization goal
Polyimide	25um	12
Adhesive	28um	15
Plating Al	17.8um	?
kapton	50um	50
Plating Al	17.8um	?
Adhesive	28um	15
Polyimide	25um	12

Ladder of realistic long barrel vertex

detector layers 5-6: width 16.8 mm, high 4 mm

surface thickness: 0.25

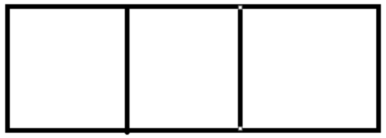
inside ribs thickness : 0.6 number: 2 intotal

detector layers 3-4: width 16.8 mm, high 3 mm

surface thickness: 0.2

inside ribs thickness : 0.6 number: 2 intotal

Carbon fiber support:

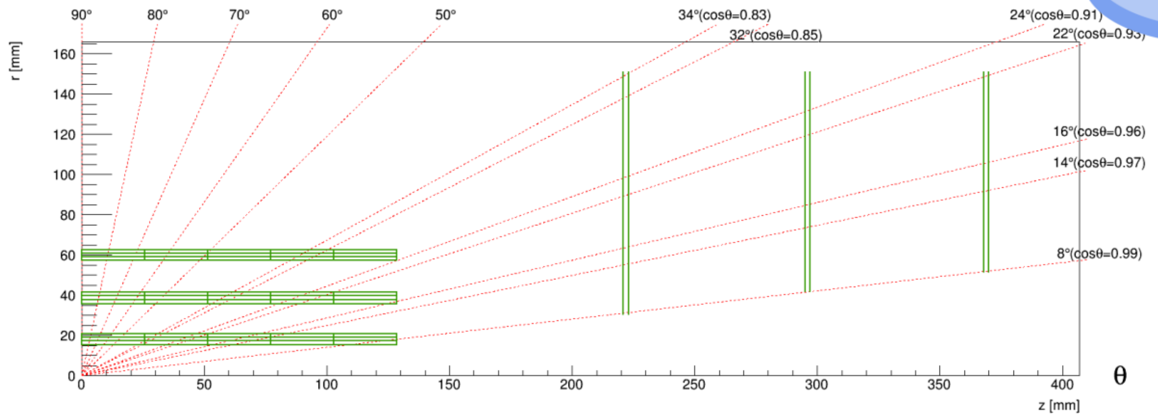


New disk arrangements

3 double-layer disks

Barrel : PXB1						
Layer	1	2	3	4	5	6
r	17.116	19.041	37.667	39.577	58.914	60.842
z_max	128.450	128.450	128.450	128.450	128.450	128.450

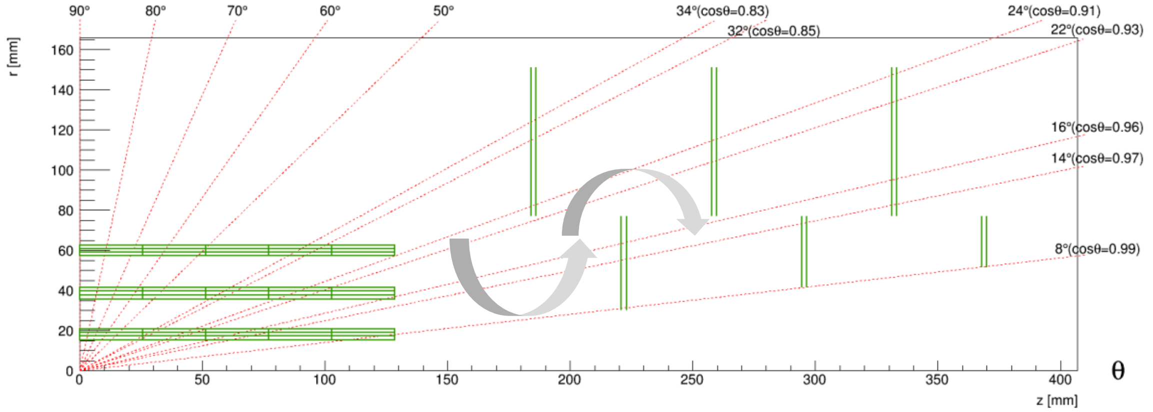
Endcap :	FPIX_1	FPIX_2	FPIX_3	FPIX_4	FPIX_5	FPIX_6
Disk	1	1	1	1	1	1
z	221.000	223.000	295.000	297.000	368.000	370.000



Upper ring set closer to barrel

Barrel : PXB1						
Layer	1	2	3	4	5	6
r	17.116	19.041	37.667	39.577	58.914	60.842
z_max	128.450	128.450	128.450	128.450	128.450	128.450

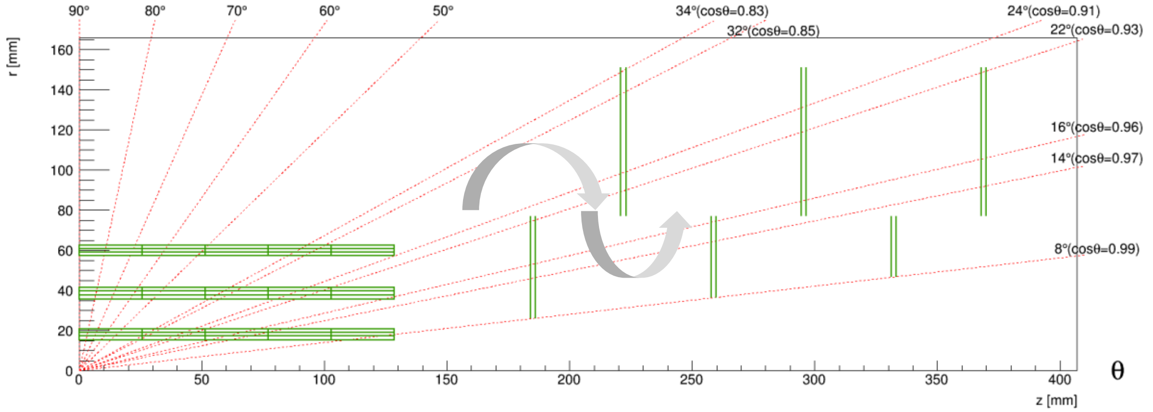
Endcap : FPIX_inner						
Disk	1	2	3	4	5	6
z	184.250	221.000	257.750	294.500	331.250	368.000
FPIX_outer						
	1	2	3	4	5	6
	186.250	223.000	259.750	296.500	333.250	370.000



lower ring set closer to barrel

Barrel : PXB1						
Layer	1	2	3	4	5	6
r	17.116	19.041	37.667	39.577	58.914	60.842
z_max	128.450	128.450	128.450	128.450	128.450	128.450

Endcap : FPIX_inner						
Disk	1	2	3	4	5	6
z	184.250	221.000	257.750	294.500	331.250	368.000
FPIX_outer						
	1	2	3	4	5	6
	186.250	223.000	259.750	296.500	333.250	370.000

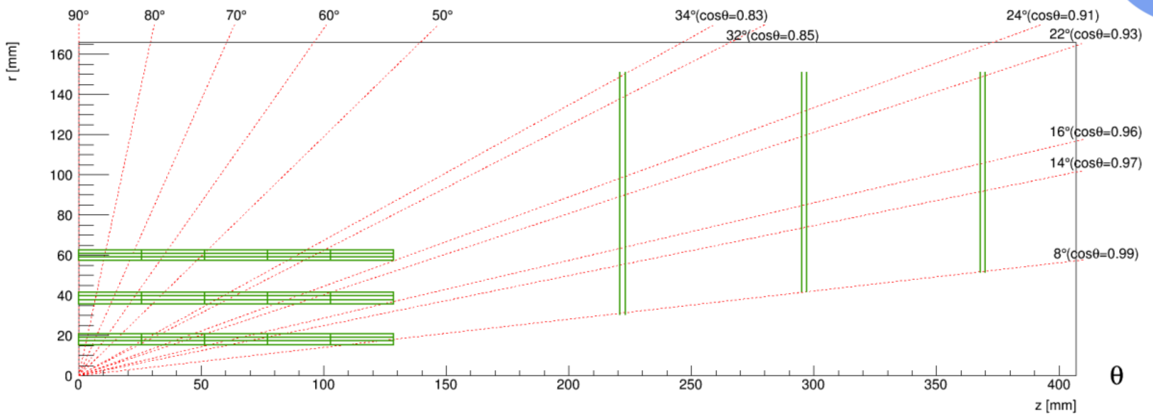


New disk arrangements

3 double-layer disks

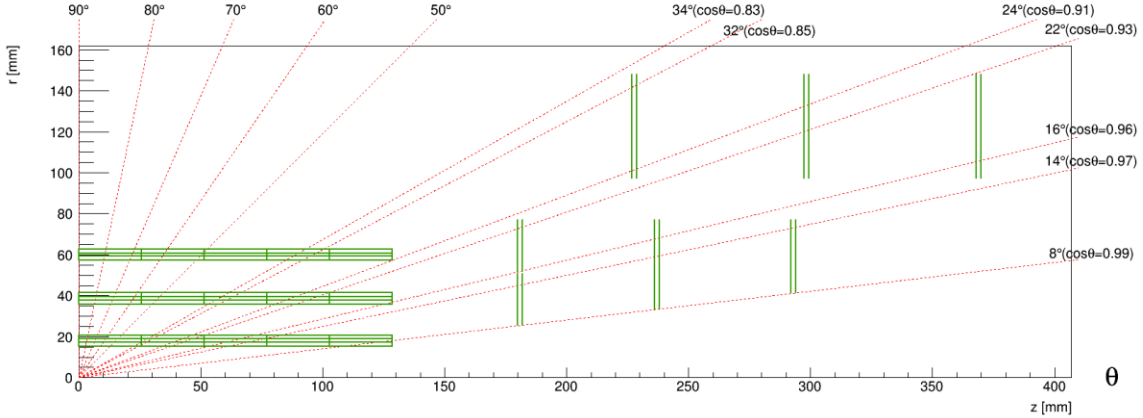
Barrel :	PXB1					
Layer	1	2	3	4	5	6
r	17.116	19.041	37.667	39.577	58.914	60.842
z_max	128.450	128.450	128.450	128.450	128.450	128.450

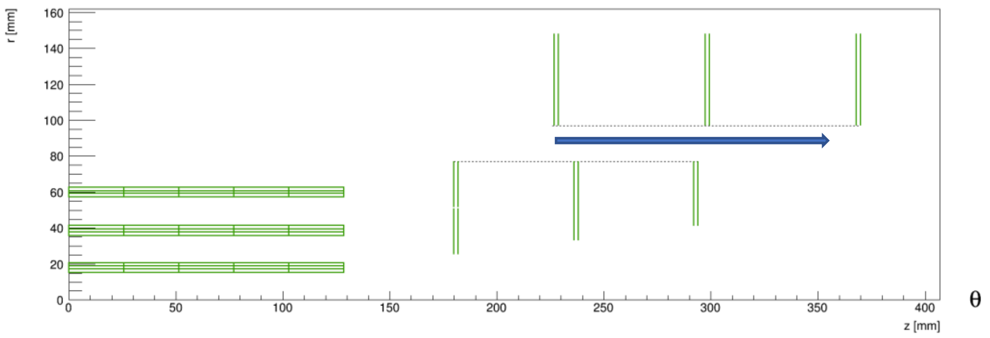
Endcap :	FPIX_1	FPIX_2	FPIX_3	FPIX_4	FPIX_5	FPIX_
Disk	1	1	1	1	1	1
z	221.000	223.000	295.000	297.000	368.000	370.0

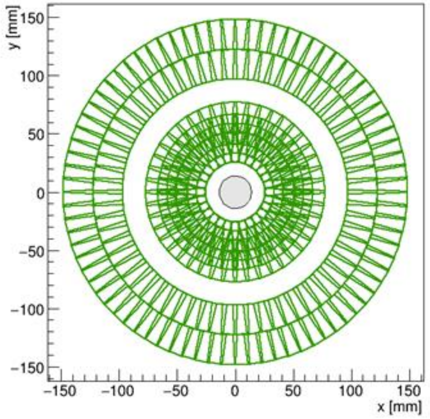


20mm ring hole

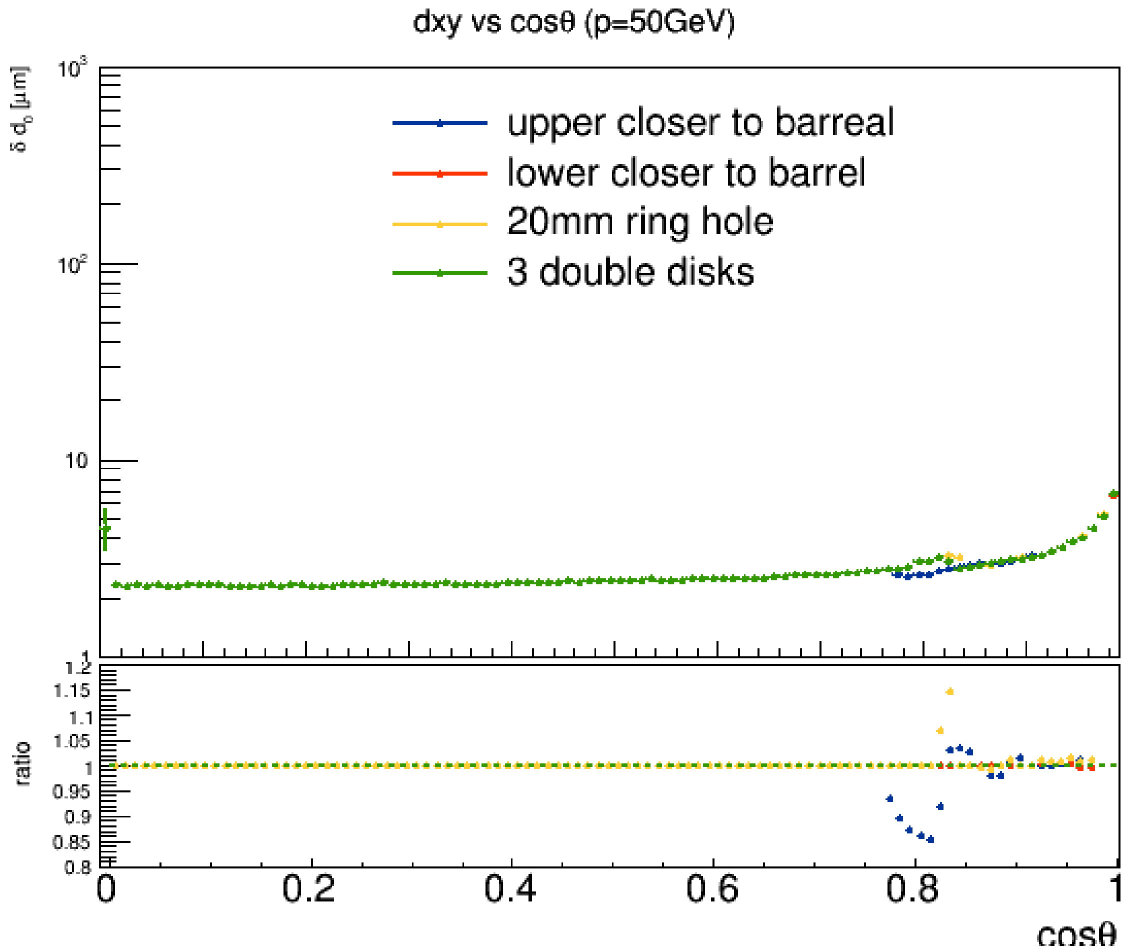
Barrel :	PXB1					
Layer	1	2	3	4	5	6
r	17.116	19.041	37.667	39.577	58.914	60.842
z_max	128.450	128.450	128.450	128.450	128.450	128.450
Endcap :	FPIX_inner					
Disk	1	2	3	4	5	6
z	180.000	226.800	236.050	292.100	297.400	368.000
	FPIX_outer					
	1	2	3	4	5	6
	182.000	228.800	238.050	294.100	299.400	370.000







New disk arrangements



- not make resolution worse much, even improved in some region
- still need considering mechanics and cooling simulation