Optimization of Silicon Pixel Vertex Detector for CEPC

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Outline

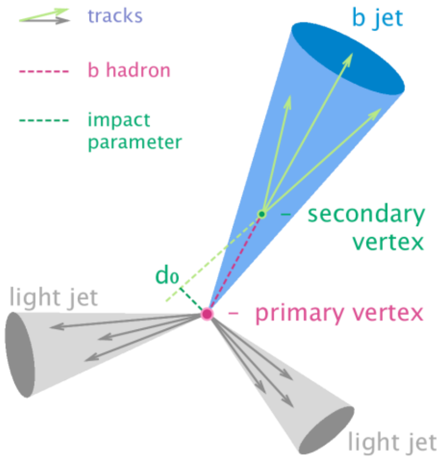
- Introduction and Motivation
  - CEPC physics requirements
  - MOST2 indicators
  - CEPC vertex study overview
- Optimization study for CEPC vertex
  - Vertex layout
  - Long barrel vertex
  - Beam pipe
  - Optimal vertex layout
- Air cooling for vertex detector
- Summary & plan

CEPC physics requirements

- Jet flavor tagging is important for CEPC Higgs study, ~70% of Z, W, and H decay products are jets
- Jet flavor is determined with its vertex displacement and kinematics — jet sub-structure
- Silicon vertex detector is essential to measure the vertex displacement
  - an impact parameter resolution of about 5 μm is required

Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

Table 3.3: Physics processes and key observables used as benchmarks for setting the requirements and the optimization of the CEPC detector.



MOST2 task and indicators

Achievement Presentation and Assessment Methods

Silicon Detector

考核指标				
指标名称	立项时已有指标值/状态	中期指标值/状态	完成时指标值/状态	考核方式(方法)及评价手段
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]

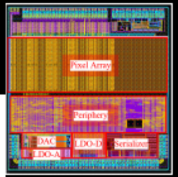
W. Wei
Z. Liang

Task 2: build a silicon pixel detector prototype

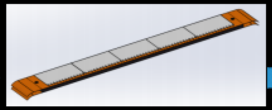
Overview of Task 2:

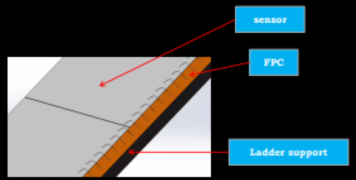
- Can break down into sub-tasks:
  - CMOS imaging sensor chip R & D
  - Detector layout optimization, Ladder and vertex detector support structure R & D
  - Detector assembly
  - Data acquisition system R & D

CMOS imaging sensor prototyping

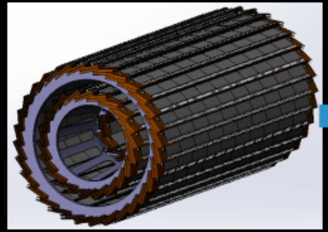


Detector module (ladder) Prototyping

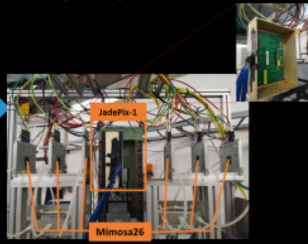




Full size vertex detector Prototype



Beam test to verify its spatial resolution



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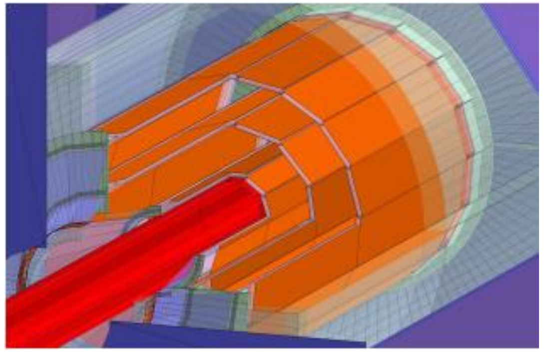
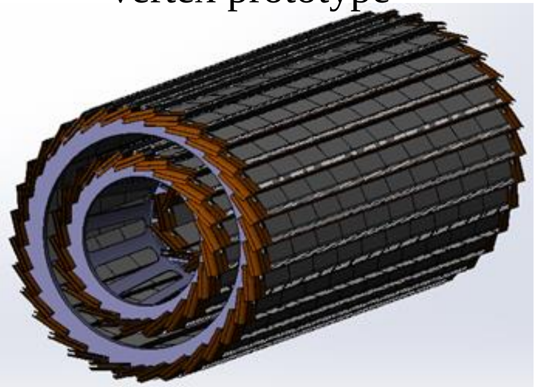
CEPC vertex study overview

- 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

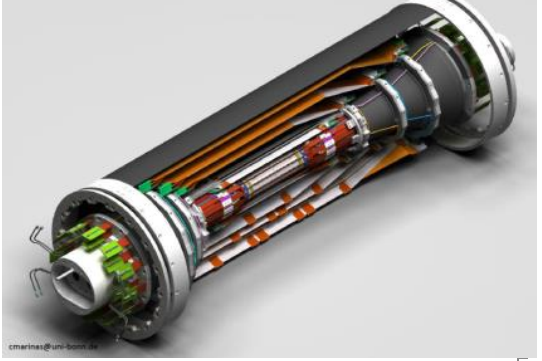
CDR baseline vertex



vertex prototype



Belle II vertex detector



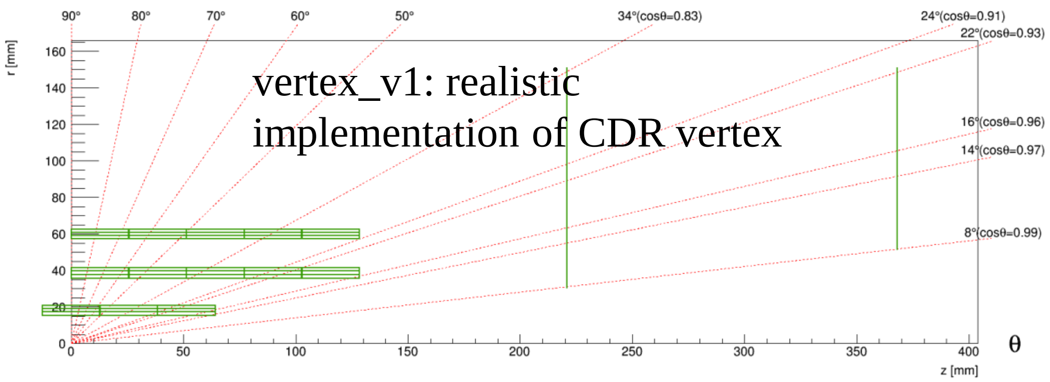
Vertex layout optimization

- 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

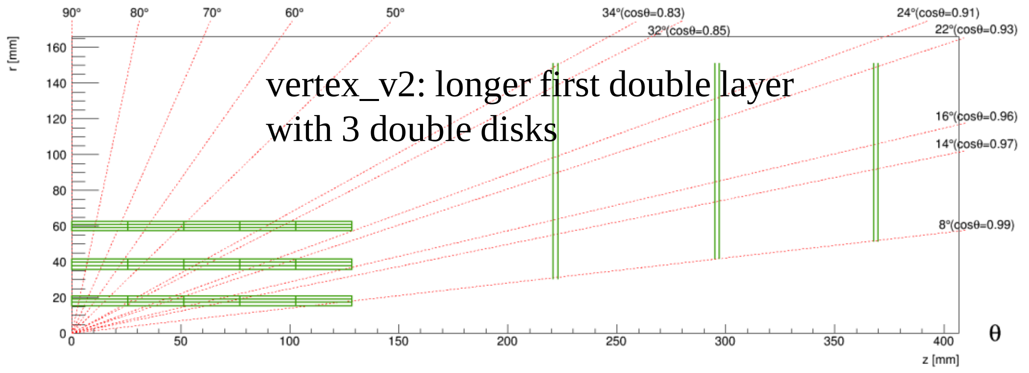
Layout with 3 equidistance double layers is best

Z. Drasal , W. Riegler

improve the d0 resolution in front region

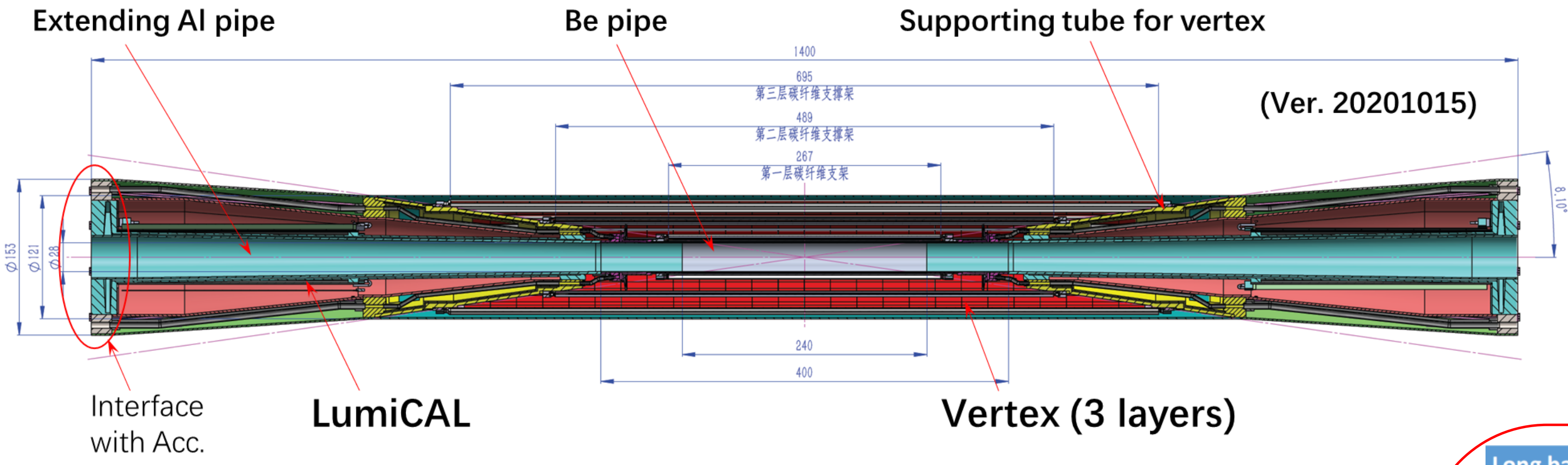


- ➢ Full silicon tracker as outer tracker: FST
- ➢ Not consider cable & cooling for the transition region between barrel and endcap

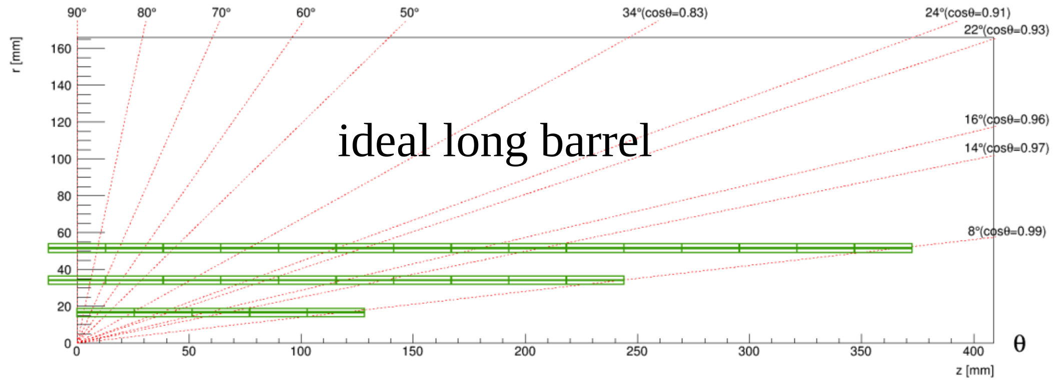


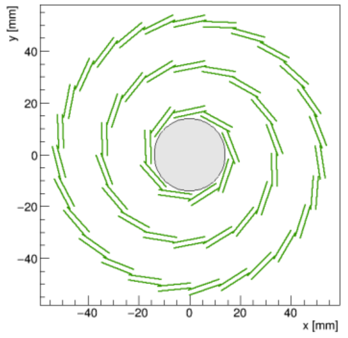
All layout tuning results simulated by tkLayout, which was developed by CMS, customized for CEPC tracker fast simulation(on-going). More information in github.

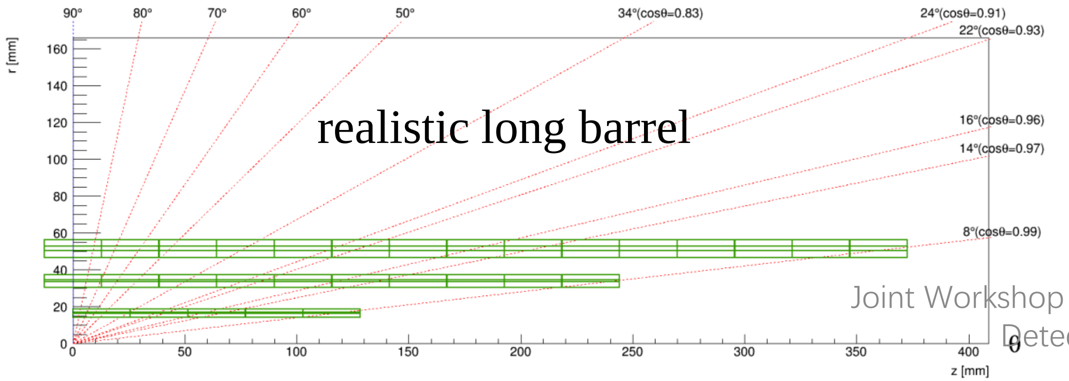
Long barrel vertex

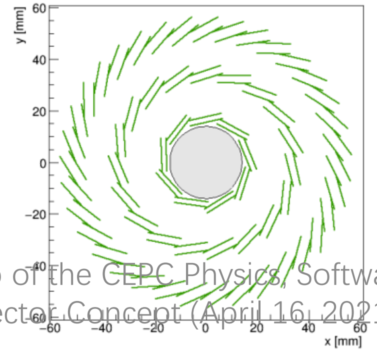


- Feasible solution for air cooling
- Simple structure
- Realistic long barrel vertex:
  - stiffer carbon fiber ladder support
  - more cable for read-out
  - vibration of long ladder









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

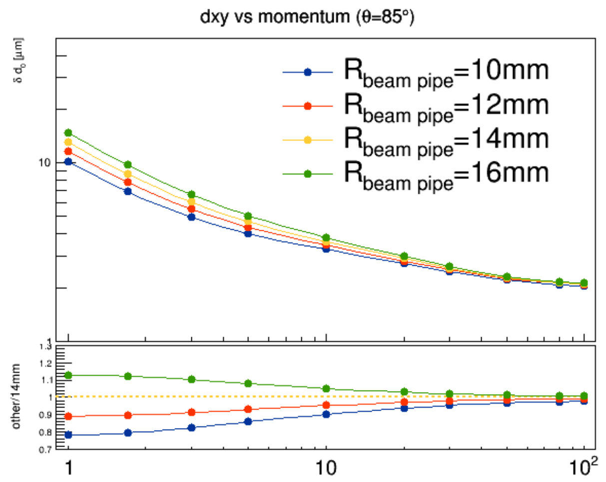
4 flex layers

	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

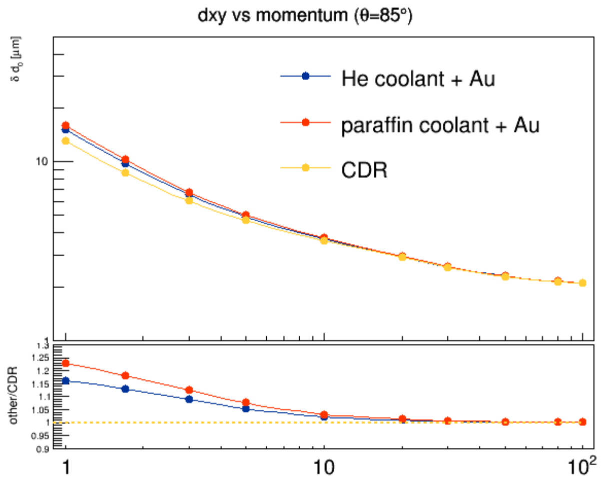
Beam pipe study overview

- 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

    4 layers
  - 24% worse if use paraffin coolant +Au
  - might cancel the material effect if reduce beam pipe radius to 10mm



Reduce the beam pipe radius!!!



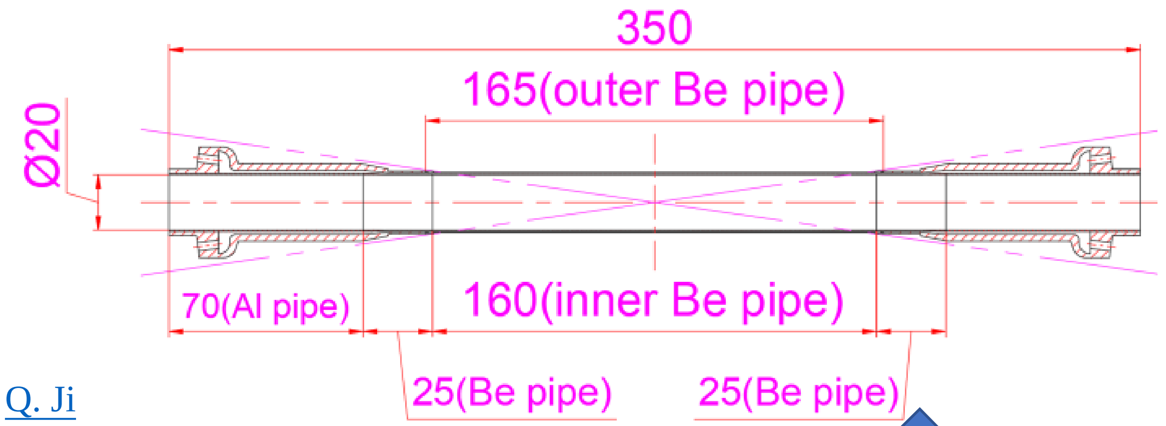
Reduce the beam pipe material!!!
Make the beam pipe thinner!!!

	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

Radiation length of beampipe

New beam pipe with diameter of 20 mm

Detailed structure of the central beryllium pipe



Q. Ji

According to processing capacity:

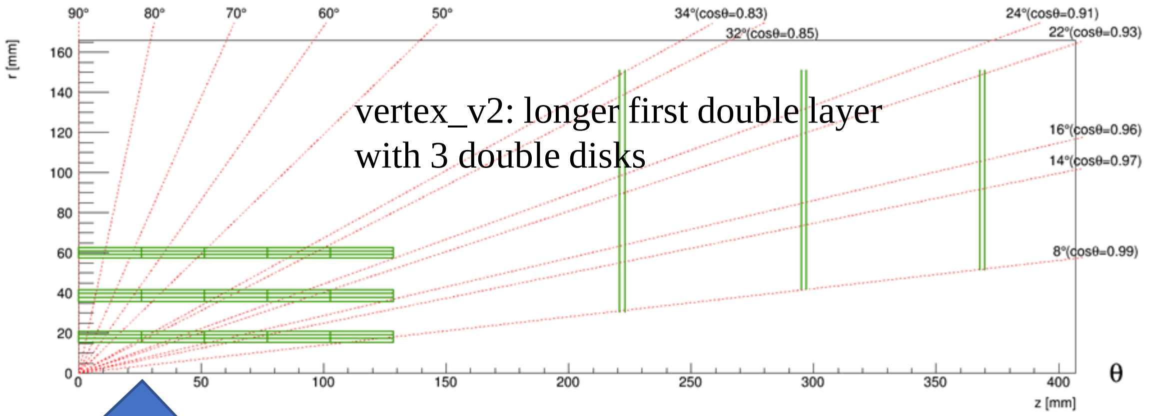
Inner Be pipe: 0.20mm thick, 210(25+160+25)mm long

Outer Be pipe: 0.15mm thick, 165mm long

thinner

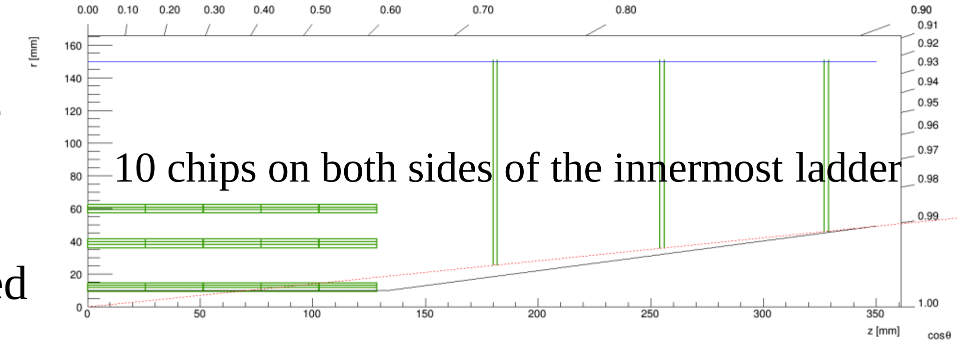
inner Beryllium layer: T= 0.5 mm

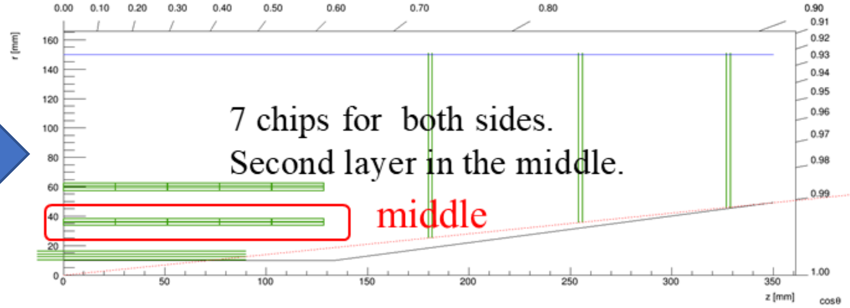
outer Beryllium layer: T= 0.35 mm



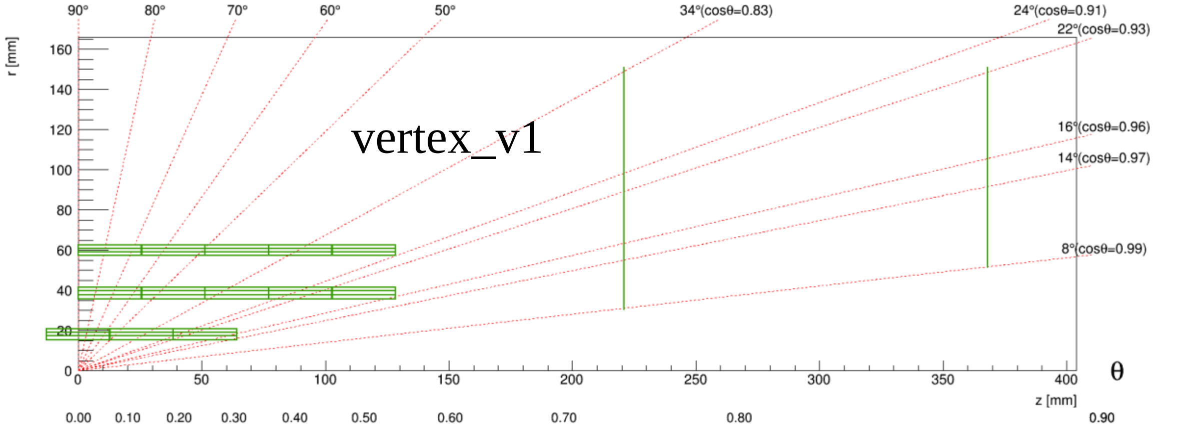
Innermost layer will be inside the boundary line, which defines the vertex detector coverage.

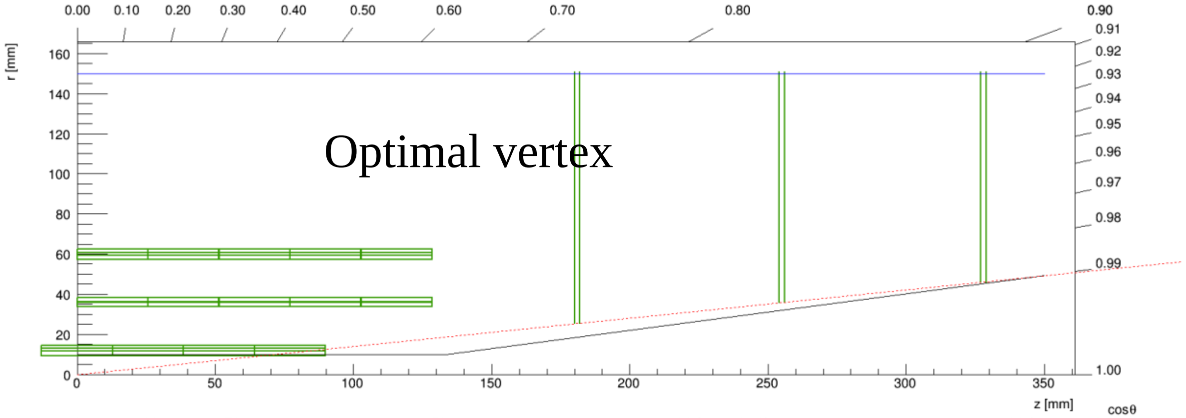
Shorter innermost layer is required

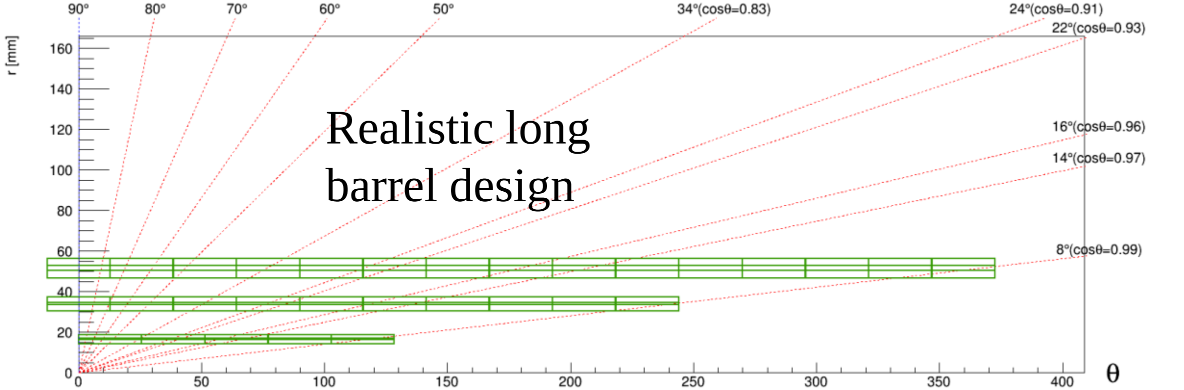


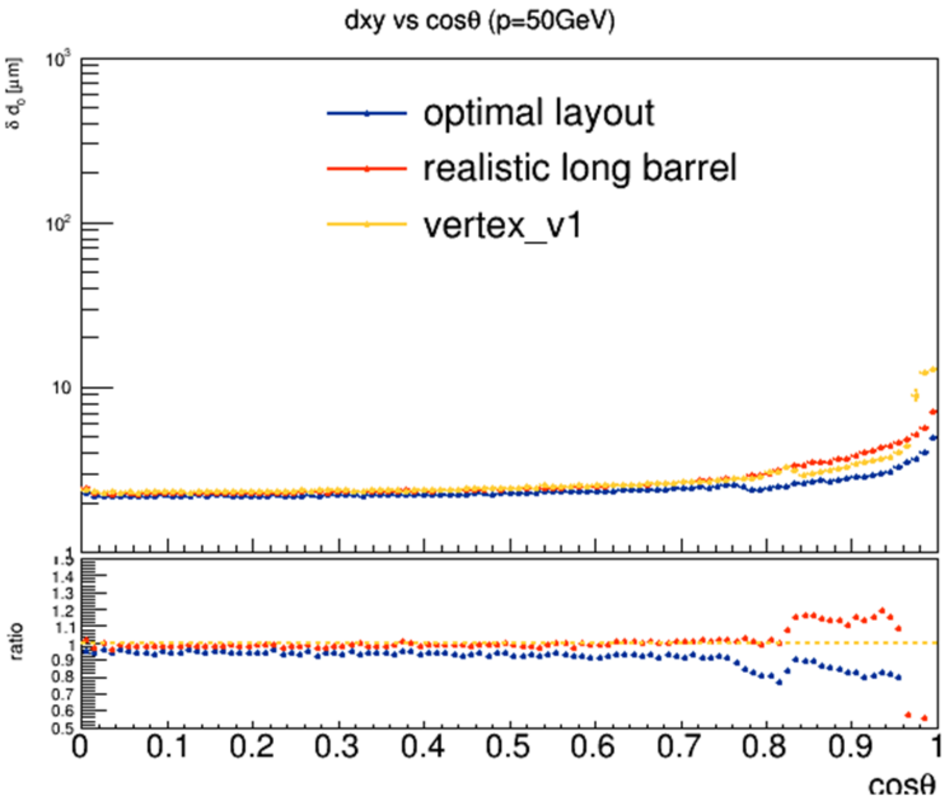


Optimal vertex layout





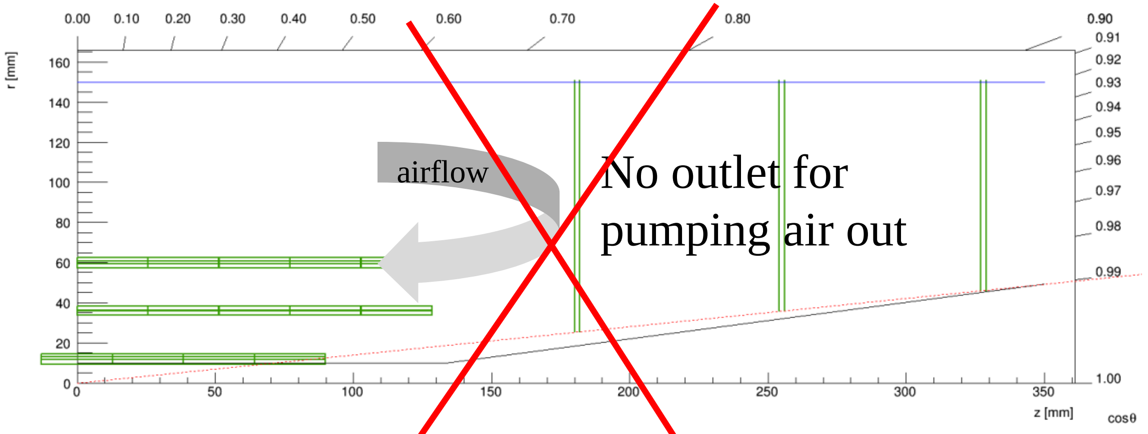


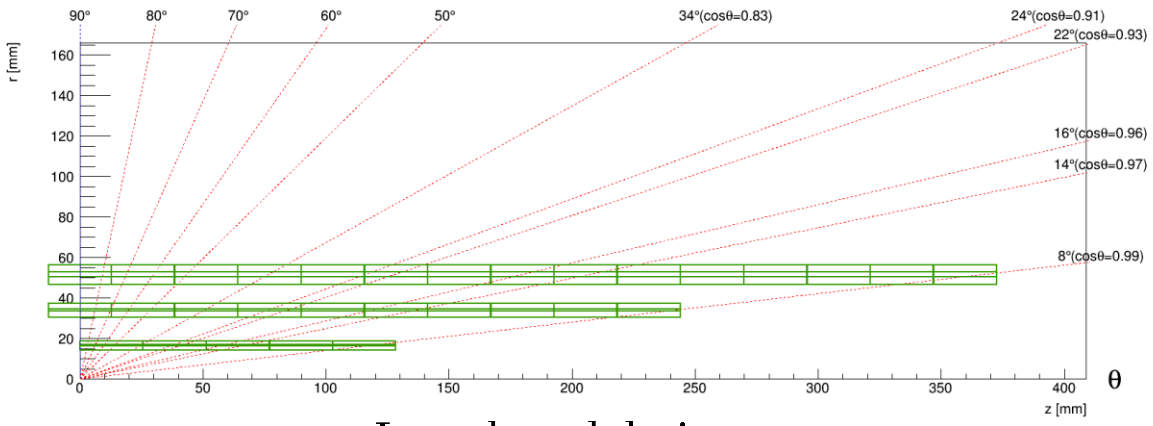


The d0 resolution of optimal vertex layout is much better than realistic long barrel vertex and vertex_v1 (realistic implementation of CDR vertex) layout, especially in the front region (20% and even more).

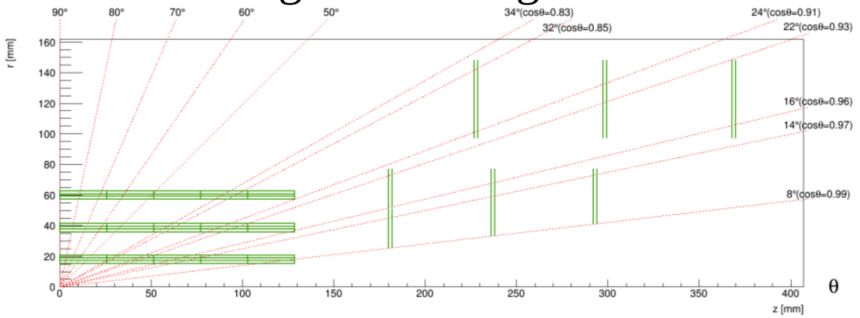
- smaller radius of beam pipe
- more disks
- longer innermost layer

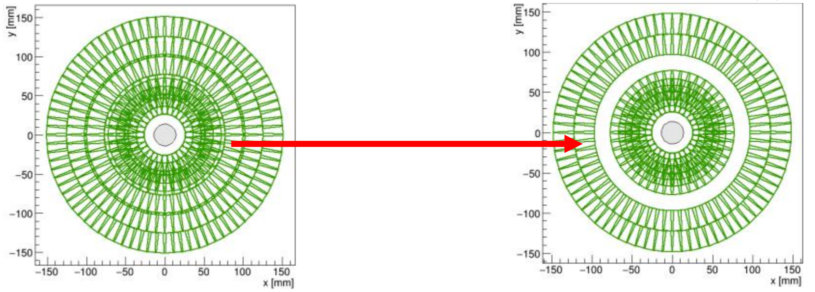
Vertex design considering air cooling

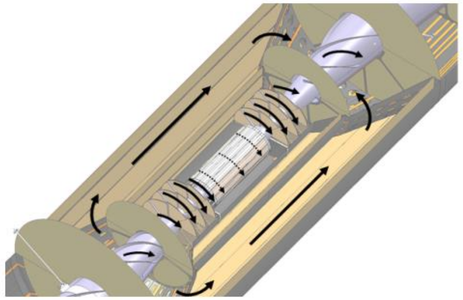


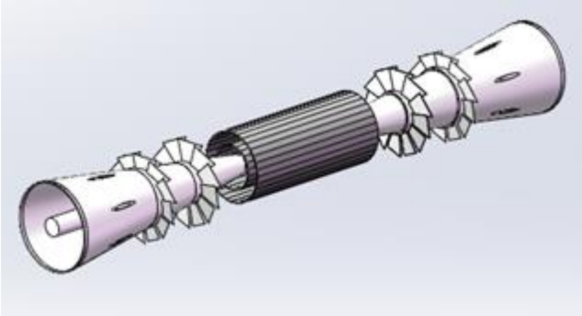


Long barrel design

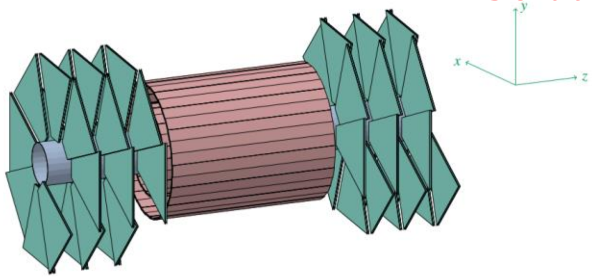


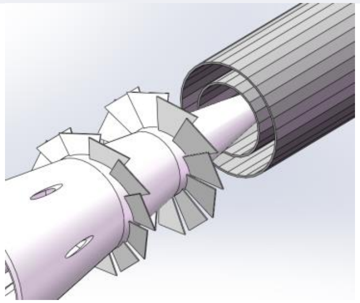






Solution?





CLIC spiral disk concept

CLICdp-Note-2014-002

rotate the disk, from Jinyu

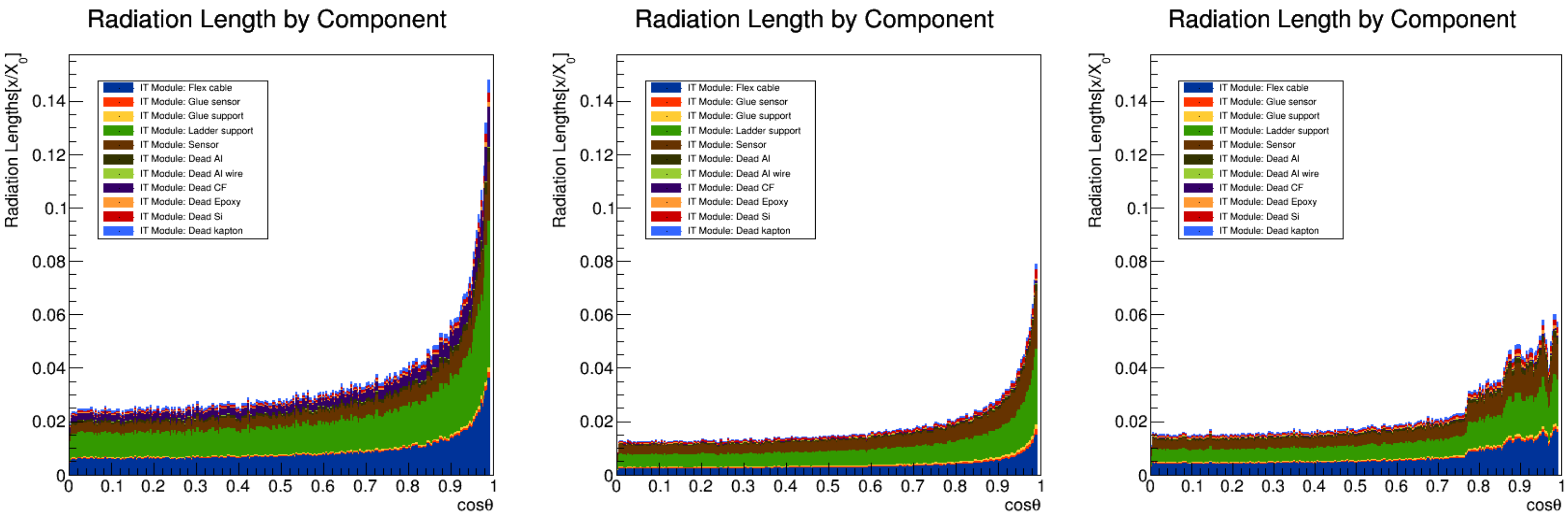
Make a hole in disk

Summary & Plan

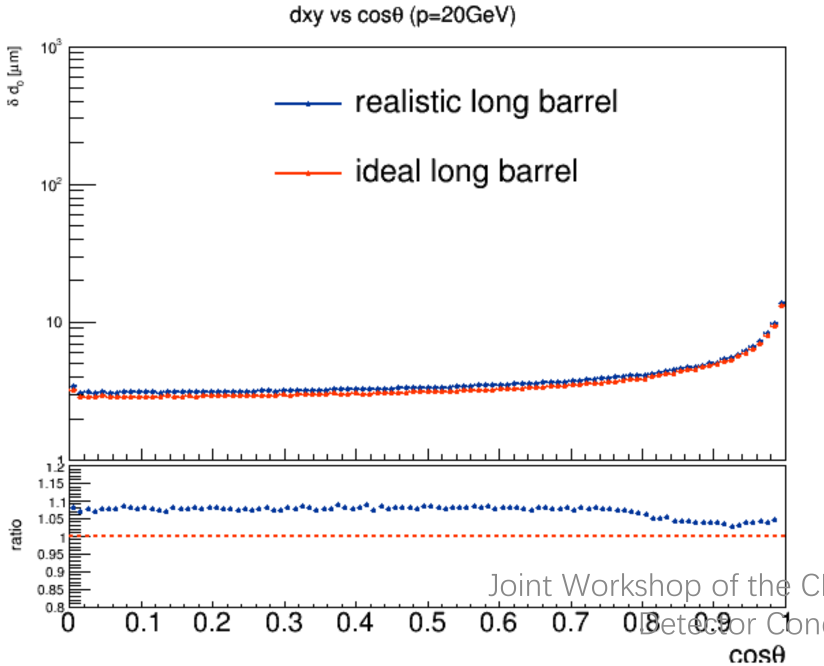
- Considering the mechanics, electronics and the beampipe, we got an optimal vertex layout which contains three double-layers in the barrel and three double-disks in the endcap.
- The d0 resolution of this optimal vertex is much better than the realistic implementation of CDR vertex and realistic long 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
  - Global tracker consideration, overall mechanics of the CEPC

Backup

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.

Optimization thickness of beryllium pipe

Relationship table between diameter, thickness and pressure: (Φ63mm)

BESIII(63)	inner *Be* pipe	R1(inner radius)	thickness	Gap	R2(outer radius)	R	E(GPa)	μ	Pcr(MPa)	
		31.5	0.8	0.8	32.3	31.9	303	0.1	1.2068	
	outer *Be* pipe		δe	Di			$[\sigma]^t$	Φ		Pw(MPa)
		33.1	0.6	66.2	33.7		110	1		1.9760

Relationship table between diameter, thickness and pressure: (Φ28mm)

CEPC(28)	inner *Be* pipe	R1(inner radius)	thickness	Gap	R2(outer radius)	R	E(GPa)	μ	Pcr(MPa)	
(safety)		14	0.35	0.5	14.35	14.175	303	0.1	1.1518	
	outer *Be* pipe		δe	Di			$[\sigma]^t$	Φ		Pw(MPa)
		14.85	0.25	29.7	15.1		110	1		1.8364
CEPC(28)	inner *Be* pipe	R1(inner radius)	thickness	Gap	R2(outer radius)	R	E(GPa)	μ	Pcr(MPa)	
(Performance)		14	0.3	0.5	14.3	14.15	303	0.1	0.7292	
	outer *Be* pipe		δe	Di			$[\sigma]^t$	Φ		Pw(MPa)
		14.8	0.2	29.6	15		110	1		1.4765

Relationship table between diameter, thickness and pressure: (Φ20mm)

CEPC(20)	inner *Be* pipe	R1(inner radius)	thickness	Gap	R2(outer radius)	R	E(GPa)	μ	Pcr(MPa)	
(safety)		10	0.25	0.5	10.25	10.125	303	0.1	1.1518	
	Al pipe	10	0.5		10.5	10.25	68.2	0.32	2.2049	
	outer *Be* pipe		δe	Di			$[\sigma]^t$	Φ		Pw(MPa)
		10.75	0.2	21.5	10.95		110	1		2.0276
CEPC(20)	inner Be pipe	R1(inner radius)	thickness	Gap	R2(outer radius)	R	E(GPa)	μ	Pcr(MPa)	
(Performance)		10	0.2	0.5	10.2	10.1	303	0.1	0.5941	
	Al pipe	10	0.5		10.5	10.25	68.2	0.32	2.2049	
	outer Be pipe		δe	Di			$[\sigma]^t$	Φ		Pw(MPa)
		10.7	0.15	21.4	10.85		110	1		1.5313

The thinner the Beryllium pipe

↓

The less the mass

↓

The better the performance

The optimization results show:
Under the same flow channel pressure,
The smaller the diameter,
the smaller the thickness

In the choice of thickness, we have two options

- Safety first

  inner diameter Φ28mm

  Thickness of outer Be pipe: 0.35 mm
  Thickness of inner Be pipe: 0.25 mm

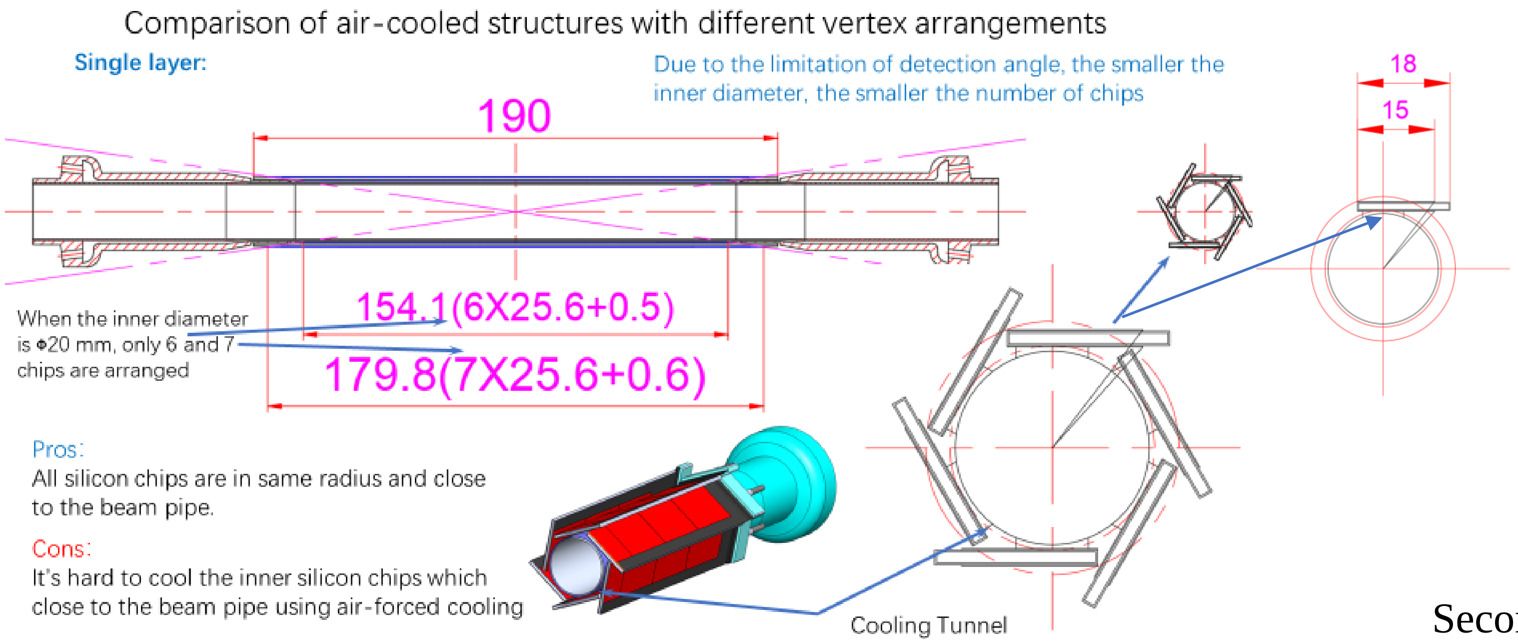
  inner diameter Φ20mm

  Thickness of outer Be pipe: 0.25 mm
  Thickness of inner Be pipe: 0.20 mm

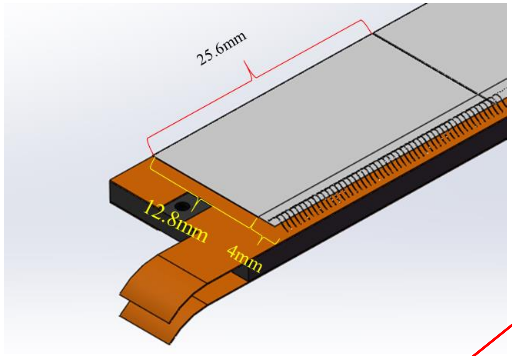
- performance first

  Thinner (As shown in the left table)

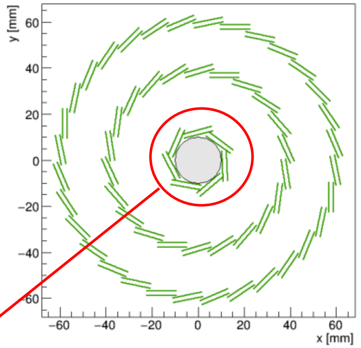
7 ladders arrangement for innermost layer



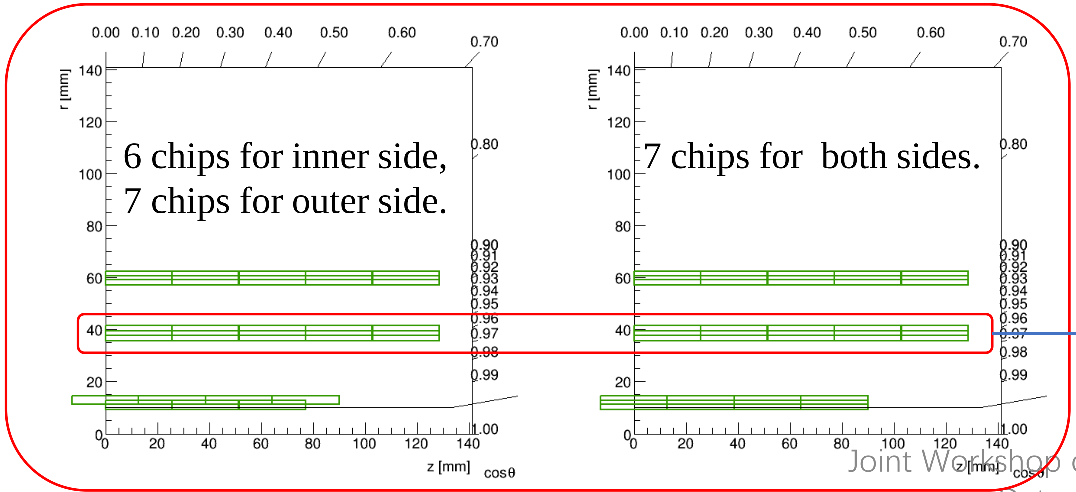
Our present ladder design:



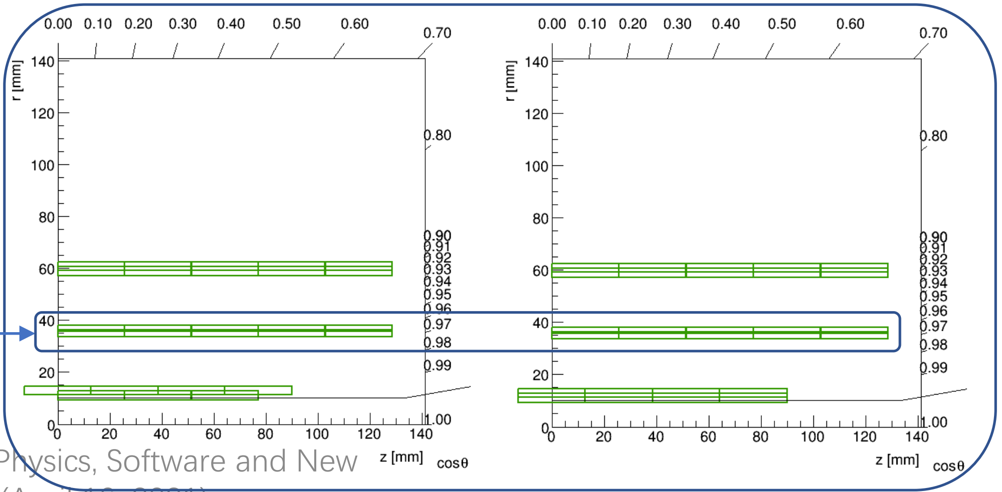
At least 7 ladders for innermost layer



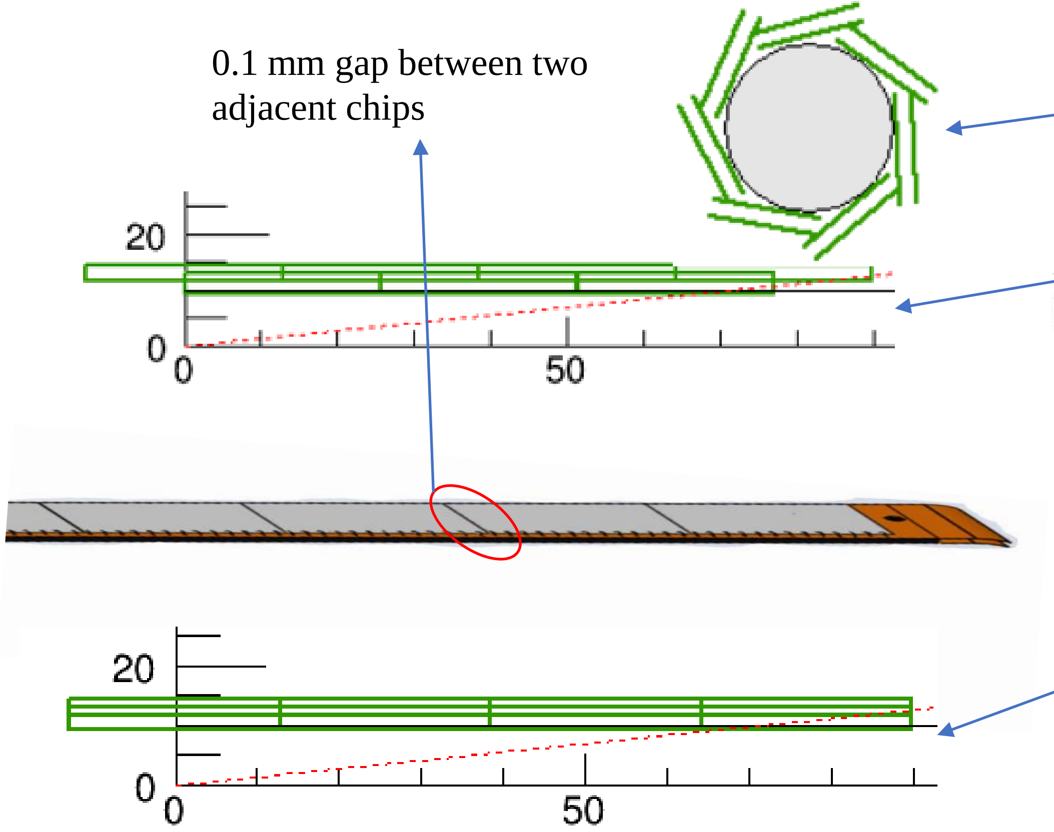
Second layer in the middle:

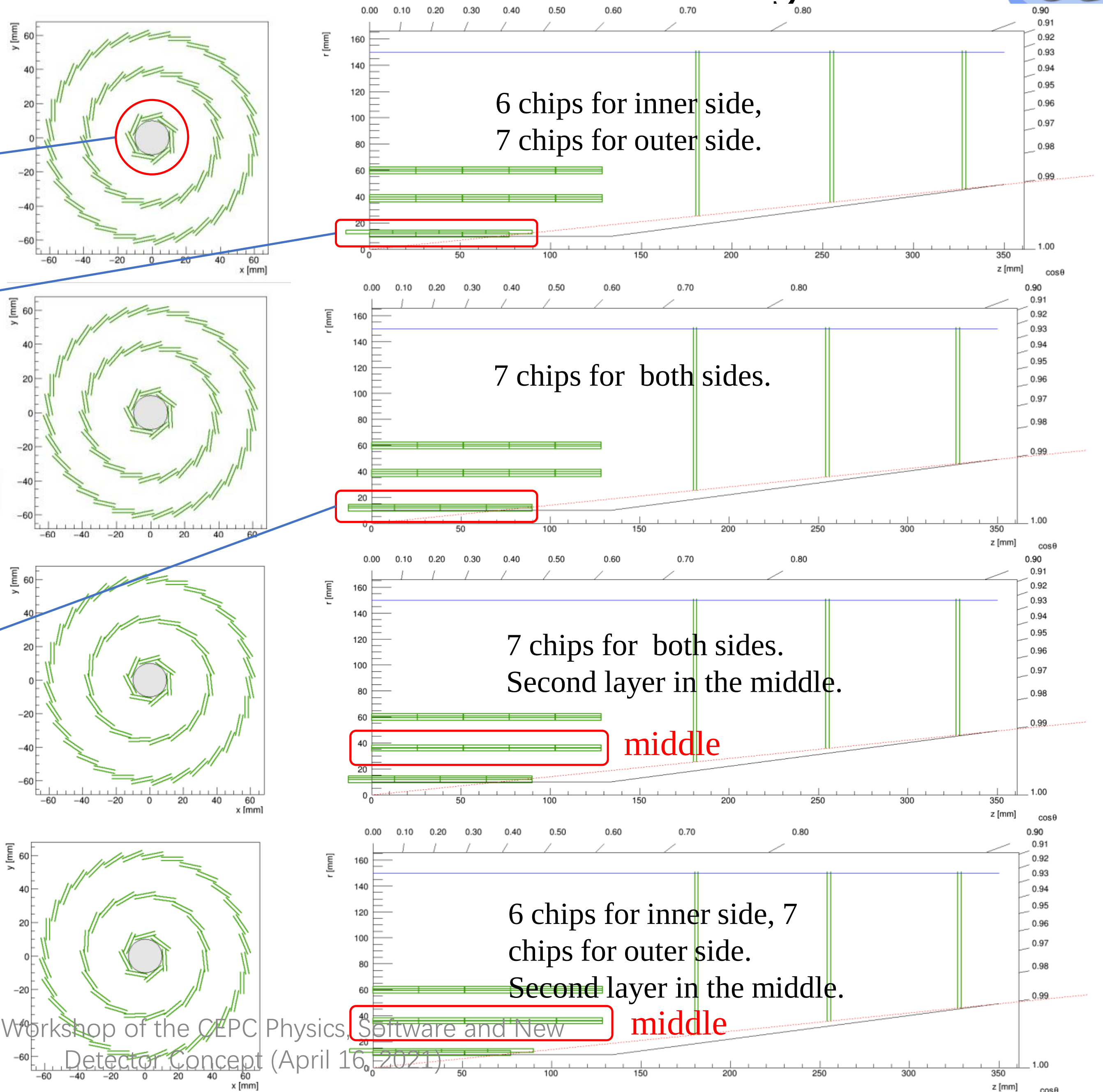


Move to the middle



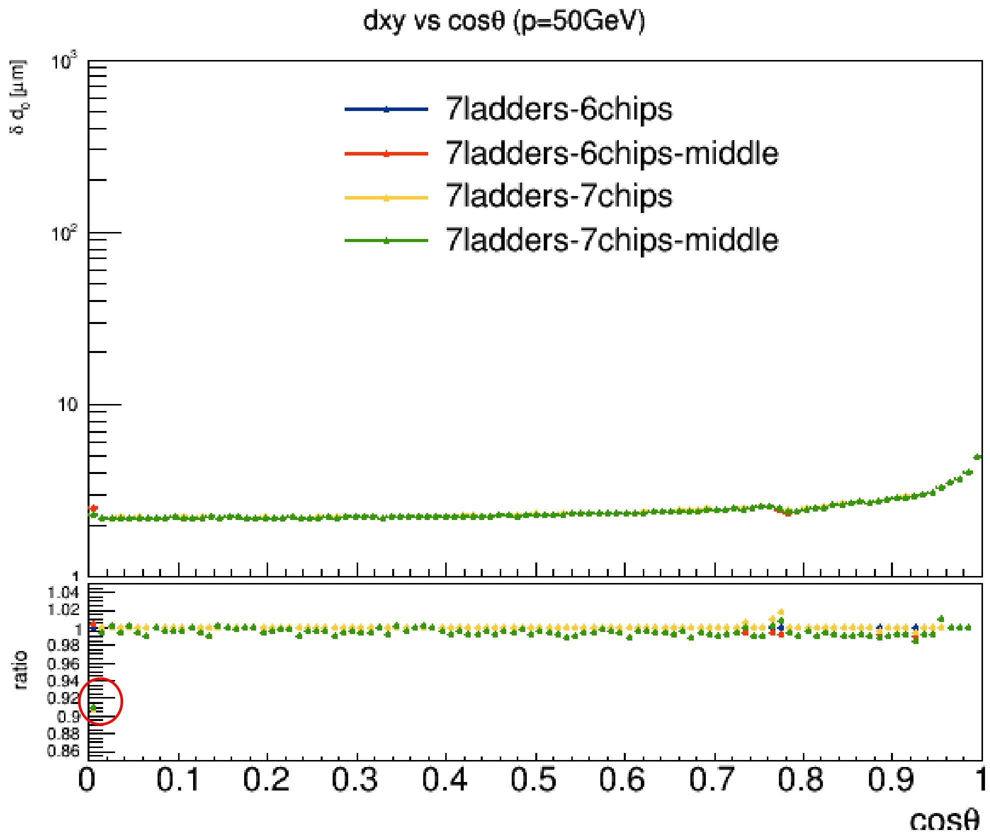
7 ladders arrangement for innermost layer

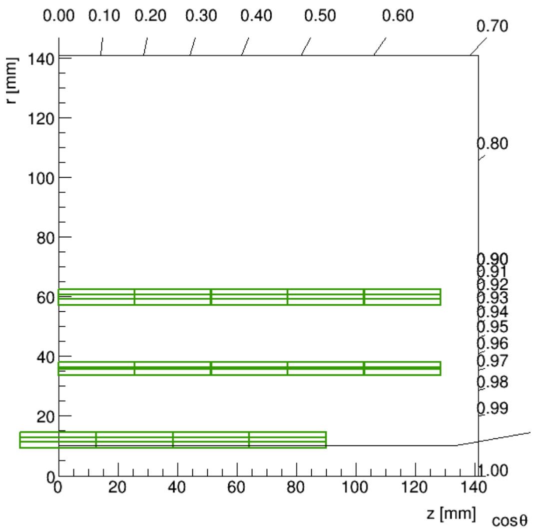


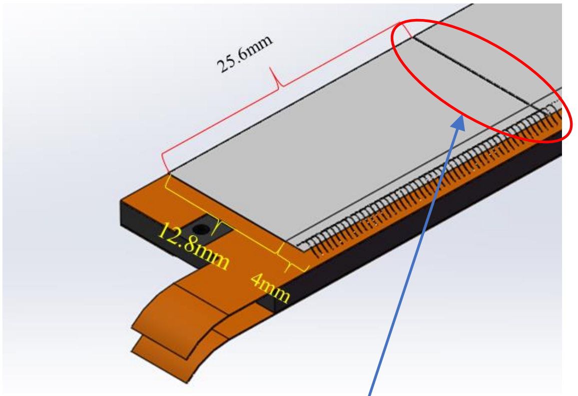


7 ladders arrangement for innermost layer

- 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.

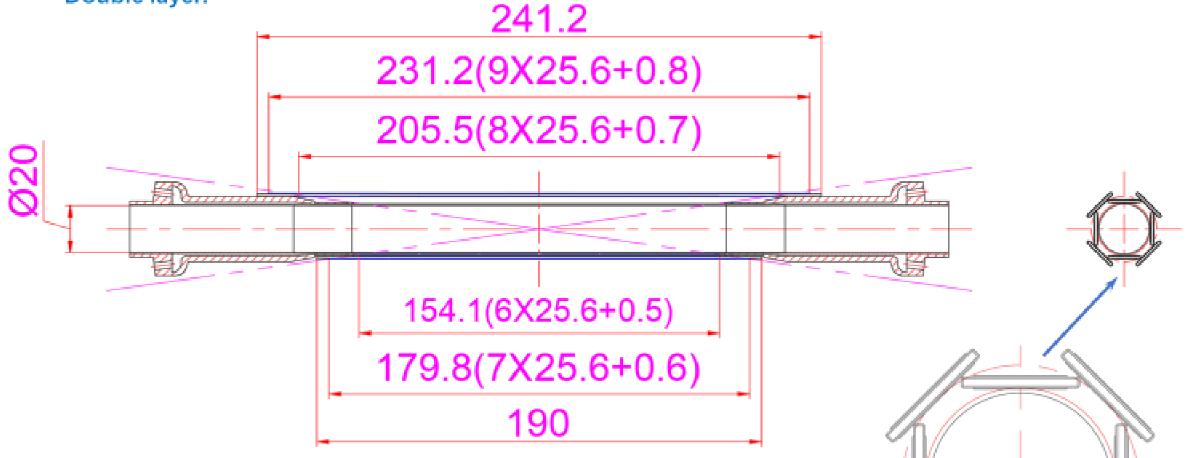






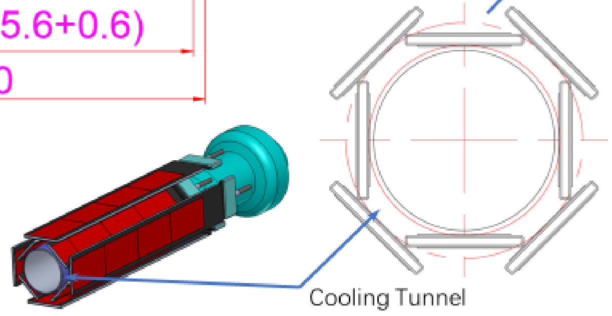
0.1 mm gap between two adjacent chips

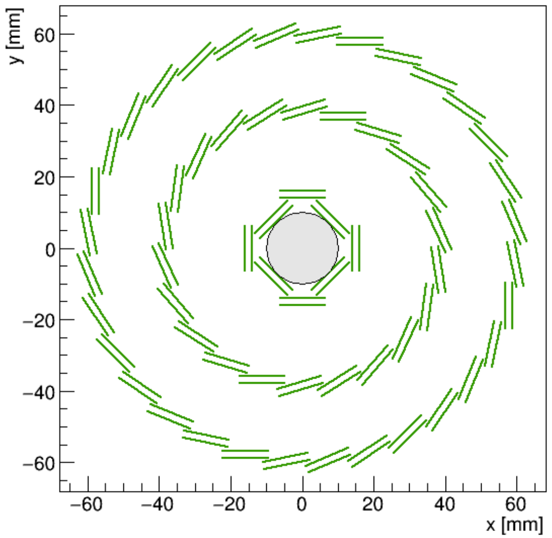
8 ladders arrangement for innermost layer



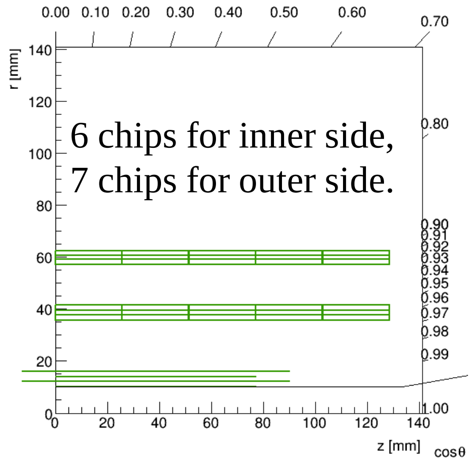
Pros:
The area of cooling tunnel has been extended.

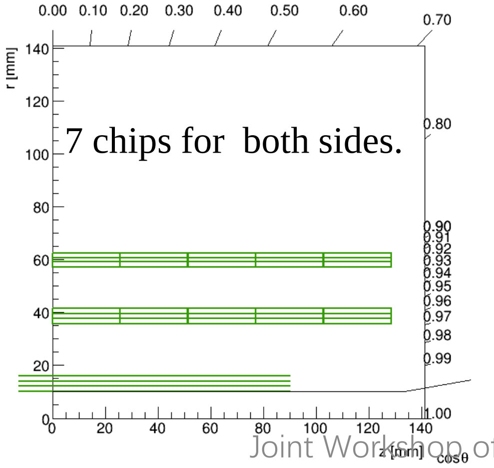
Cons:
The detecting distance of two layer is different.



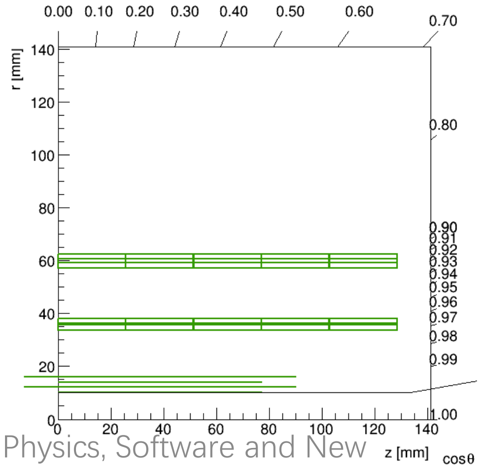


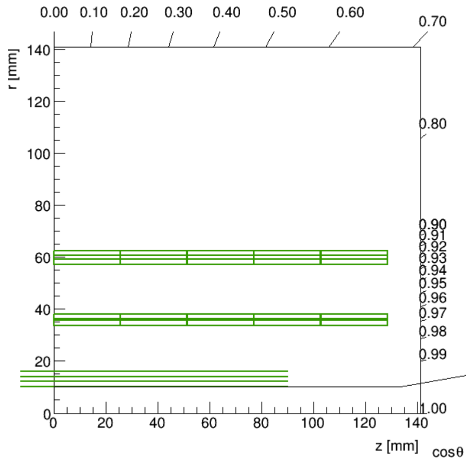
ideal condition excluding dead area of the ladders



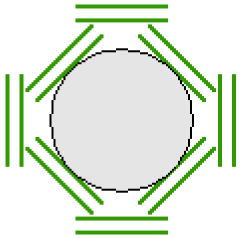


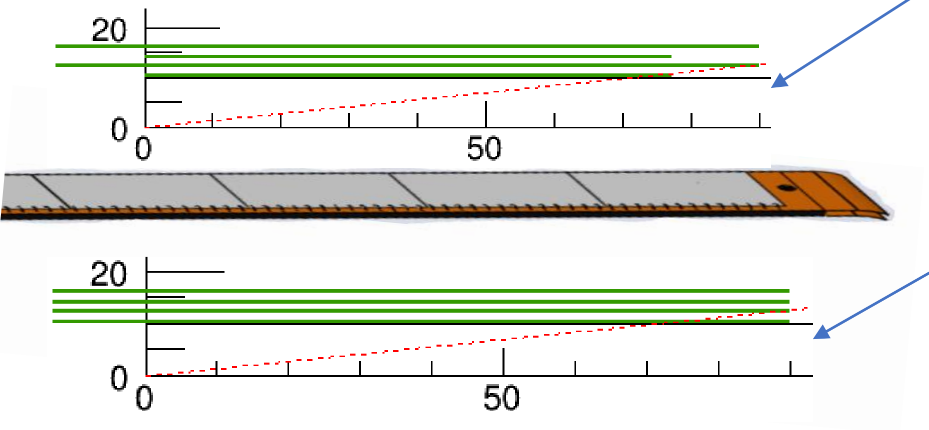
Second layer in the middle:

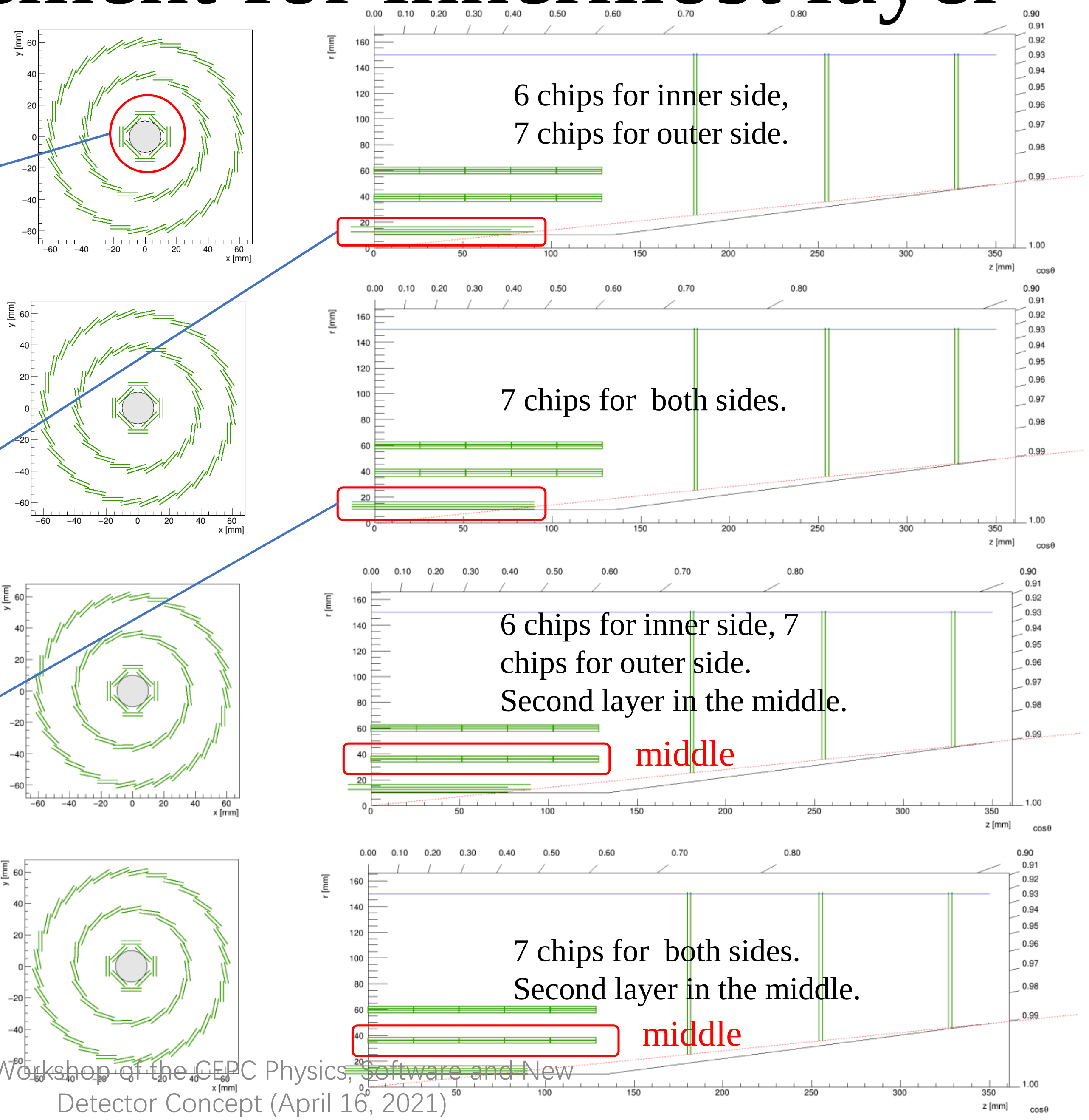




8 ladders arrangement for innermost layer

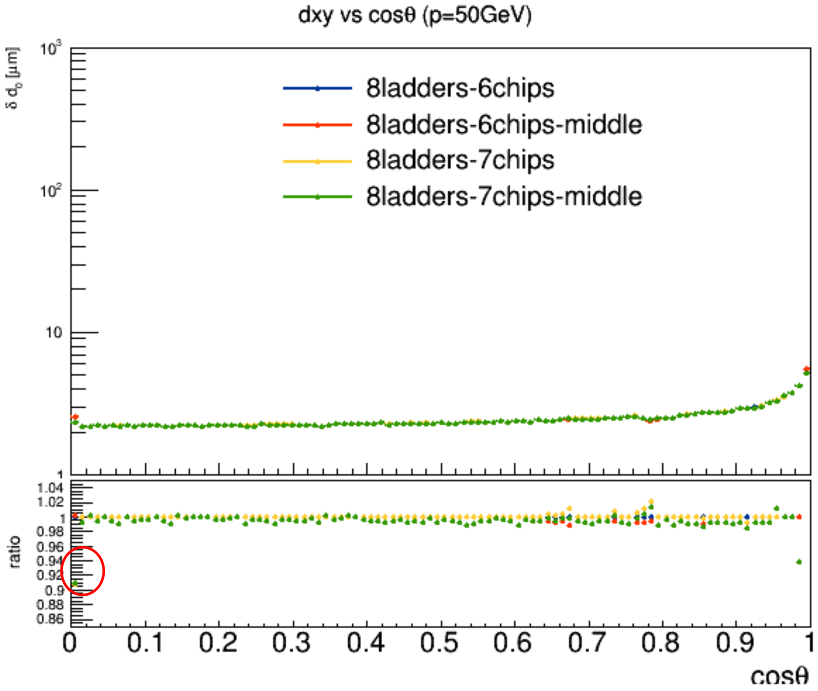


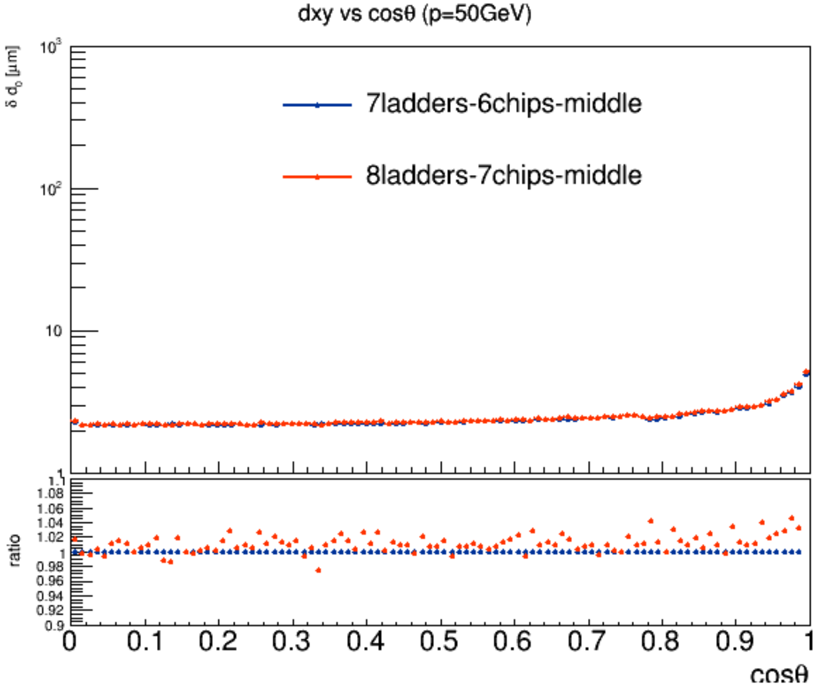


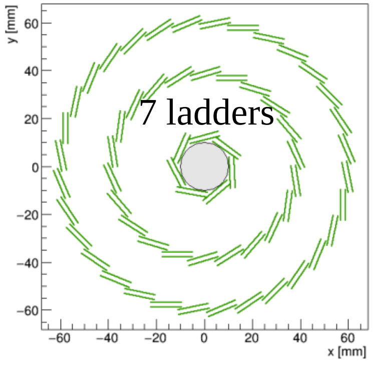


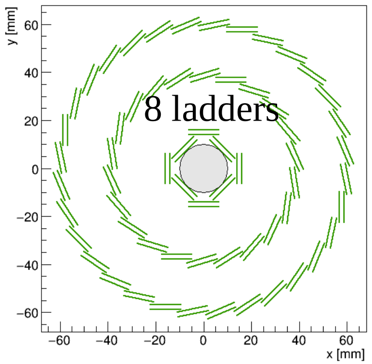
8 ladders arrangement for innermost layer

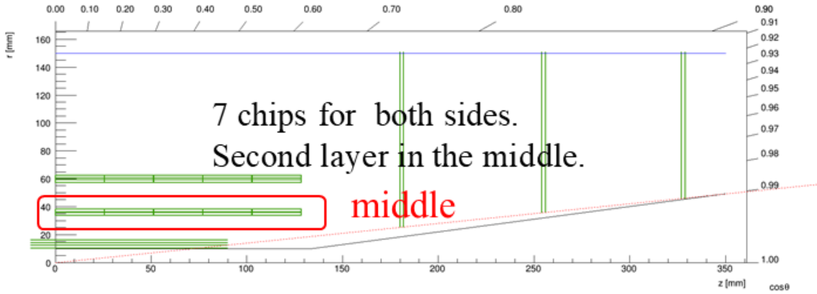
Comparison of different ladder arrangements for innermost layer:









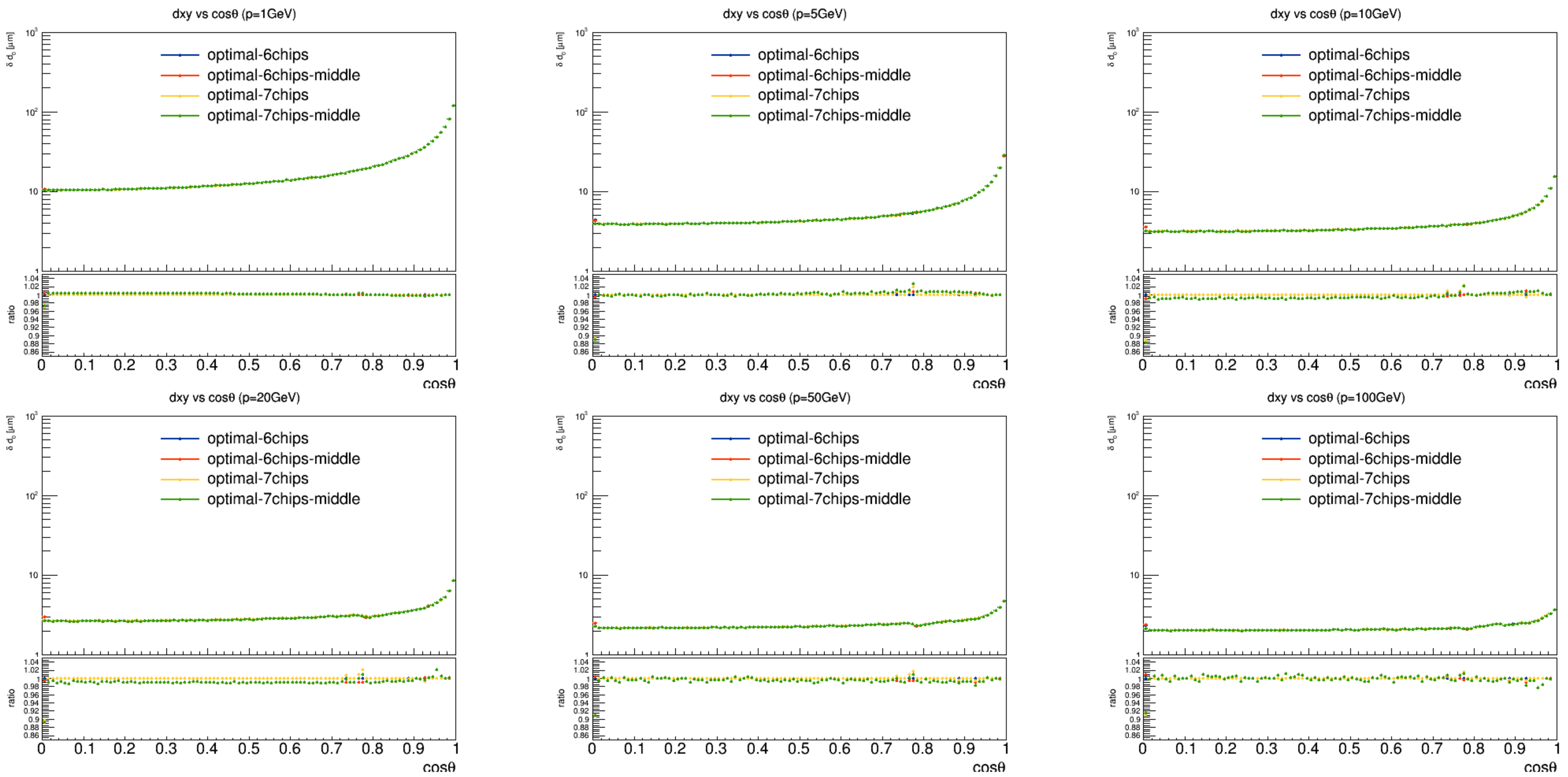


7 chips on both sides for innermost layer and second layer in the middle is better.

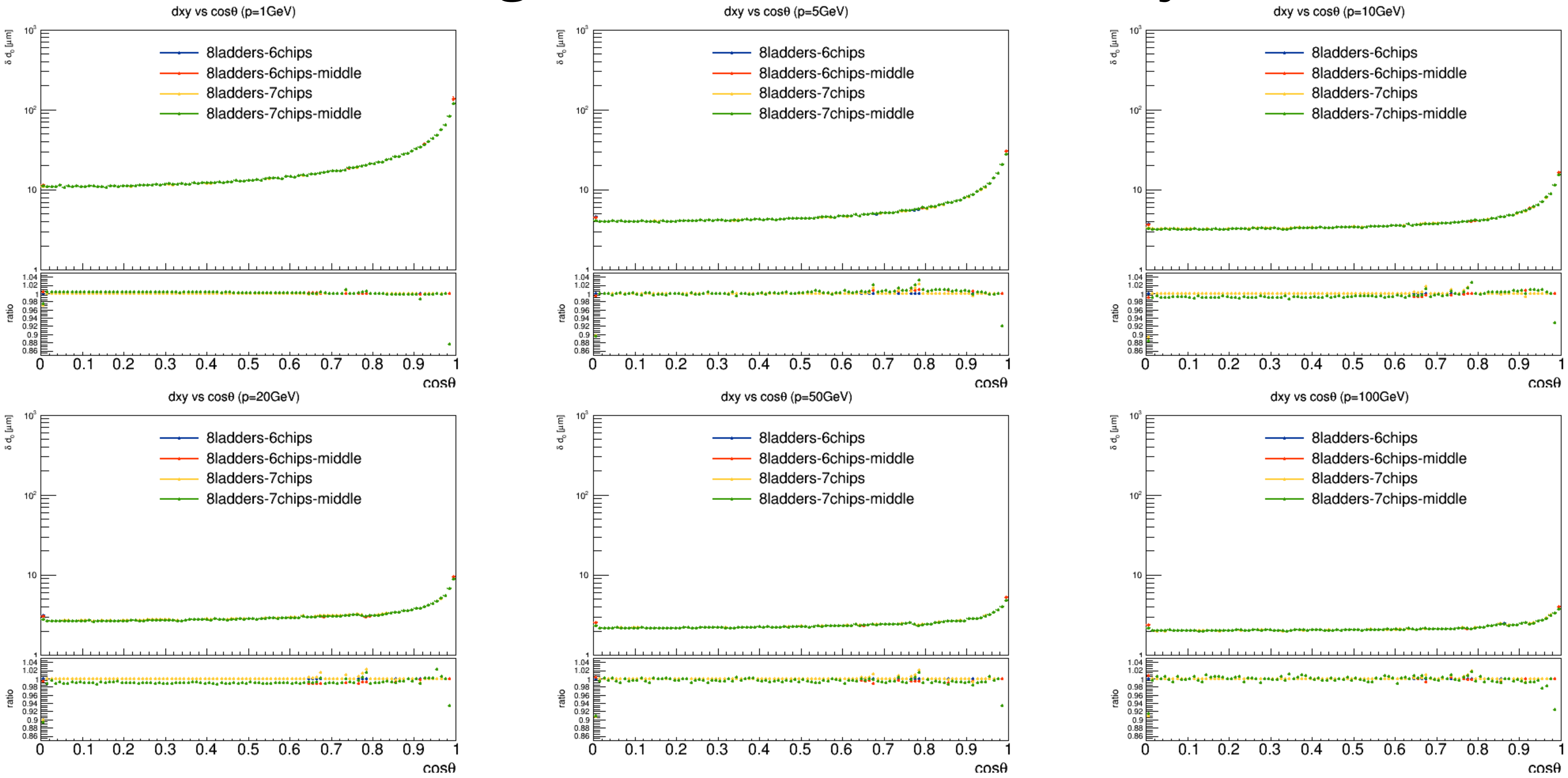
- 7-ladders arrangement is better than 8-ladders arrangement.
  - less material
  - 7 ladders are close to beam pipe.

Best! Optimal vertex layout!

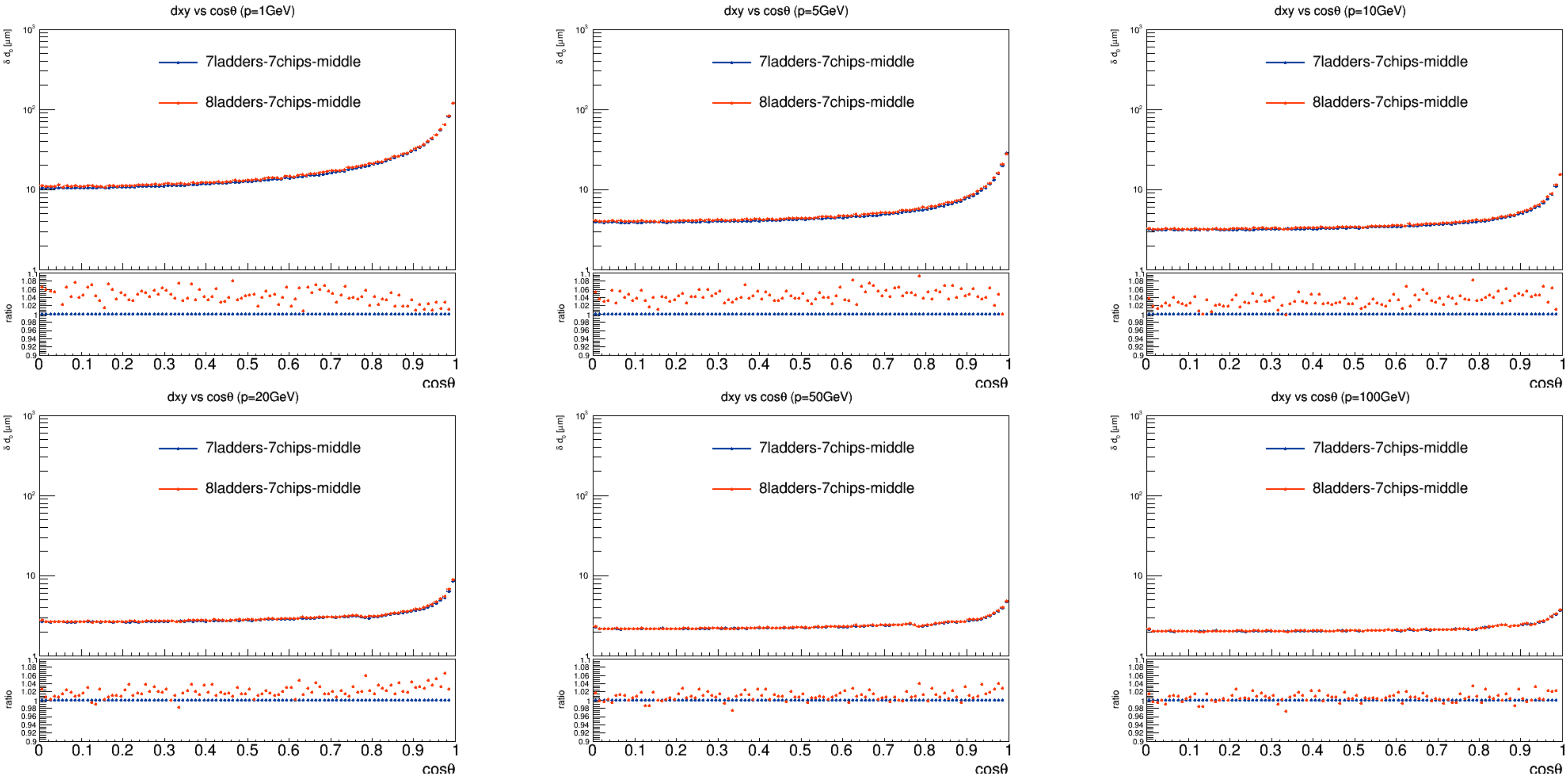
7 ladders arrangement for innermost layer



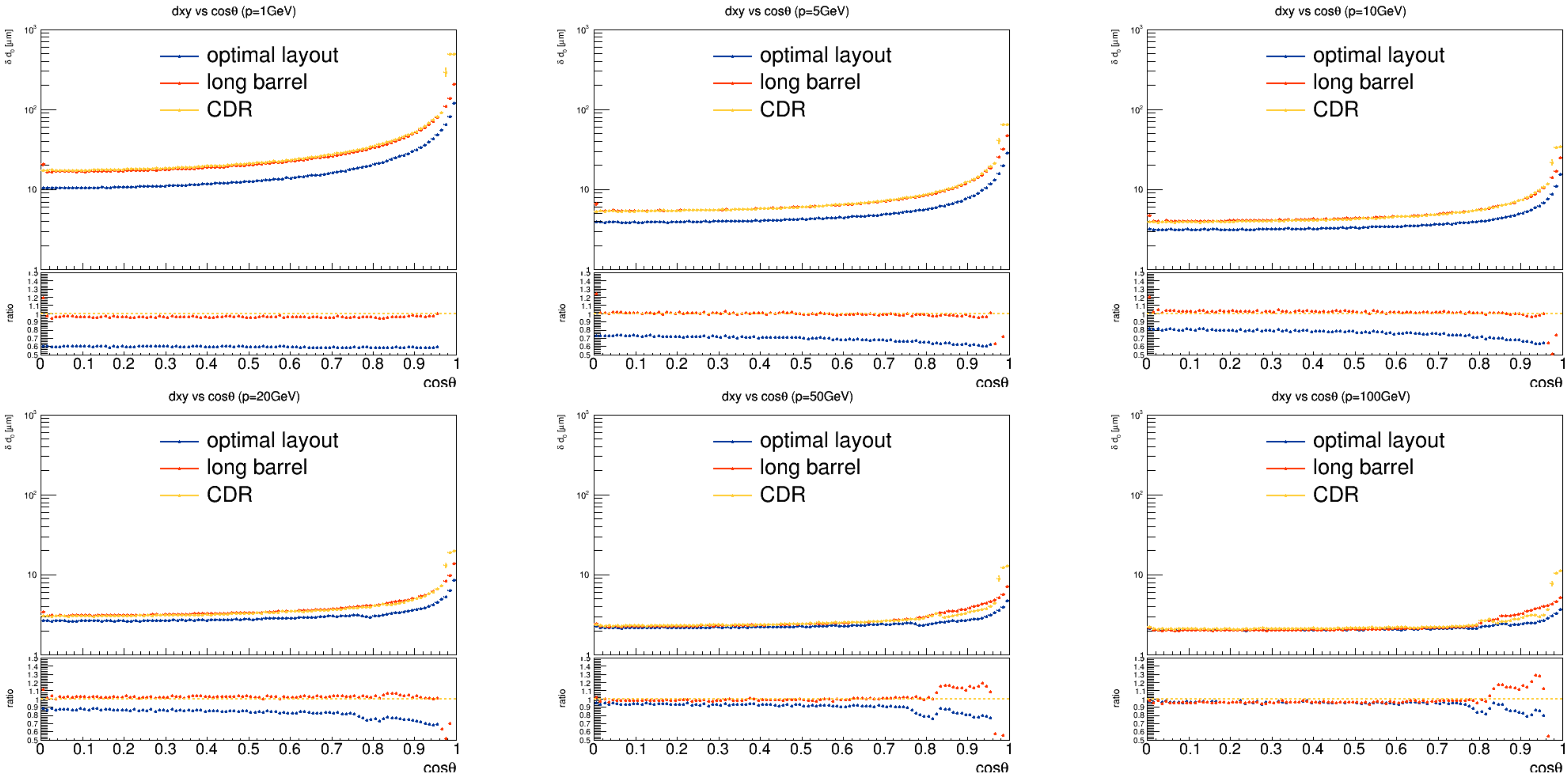
8 ladders arrangement for innermost layer



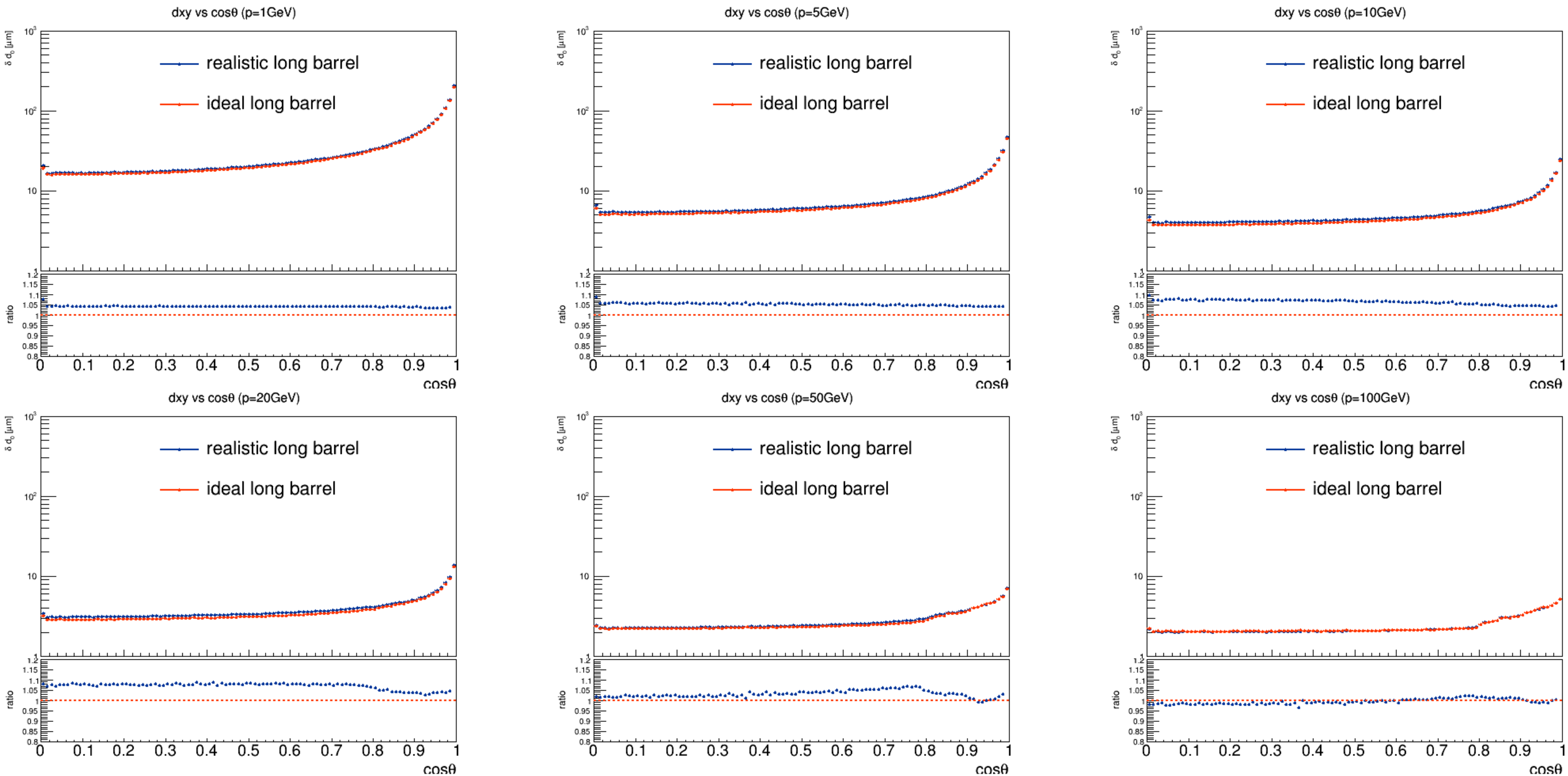
Comparison of different ladder arrangements for innermost layer



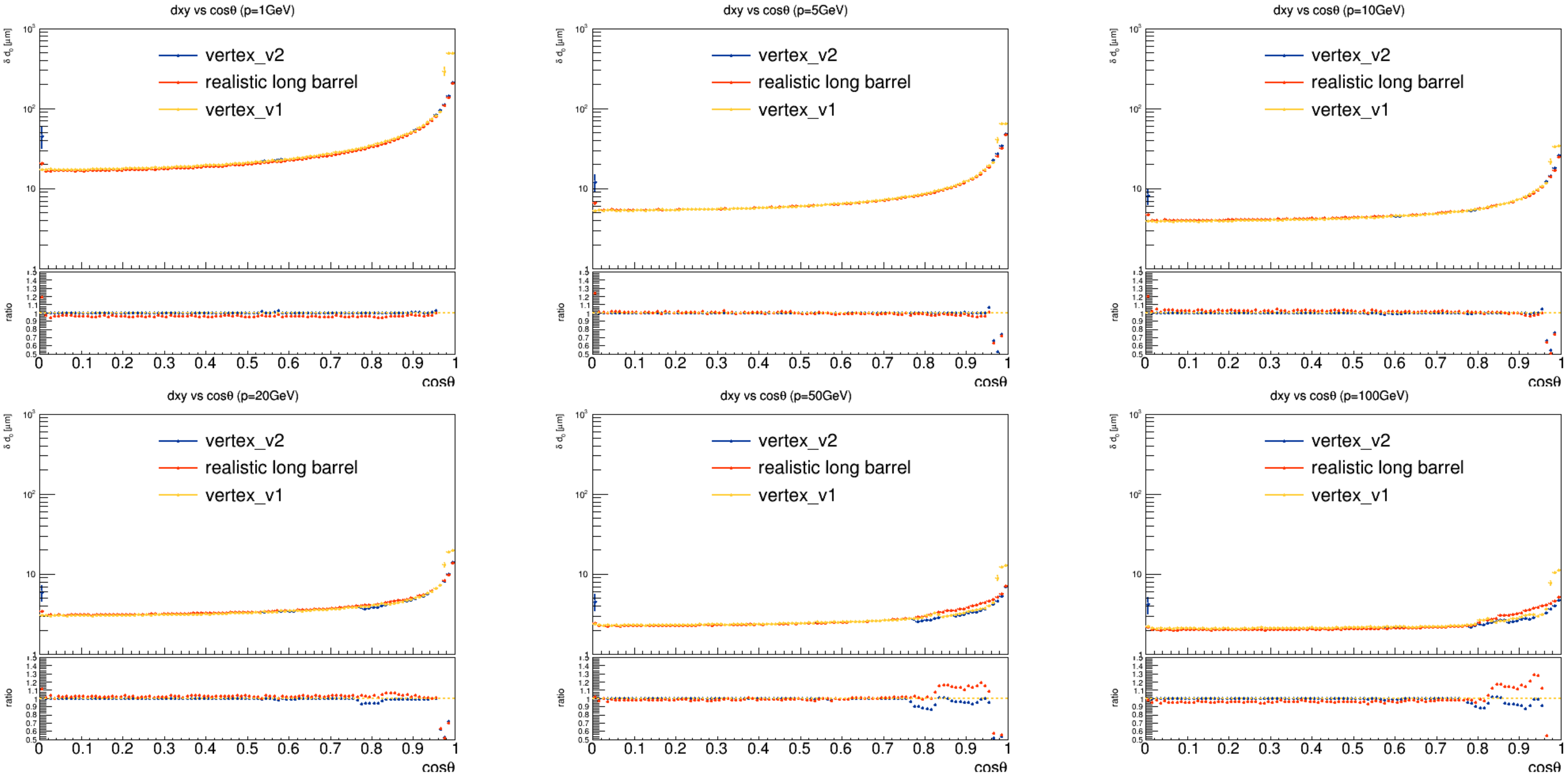
d0 resolution of optimal vertex layout



New long barrel

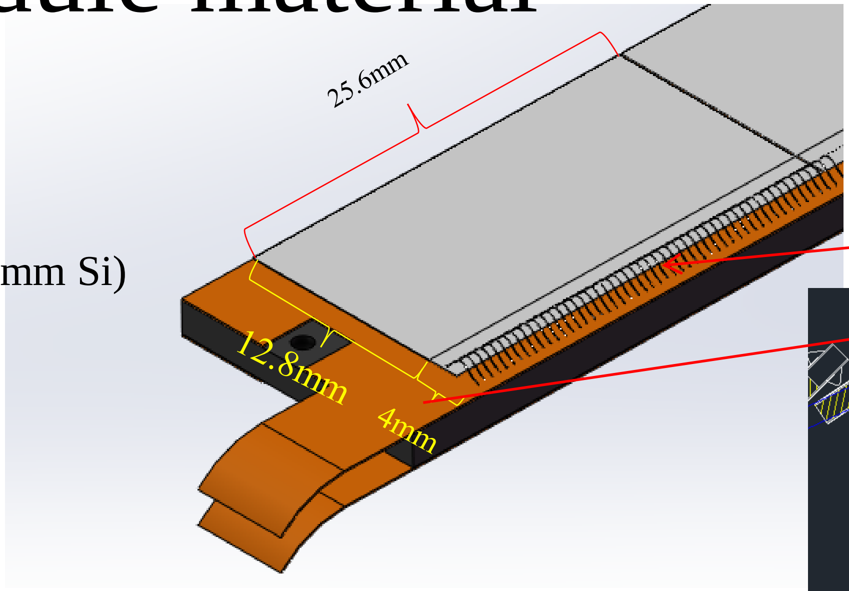


vertex_v2 performance

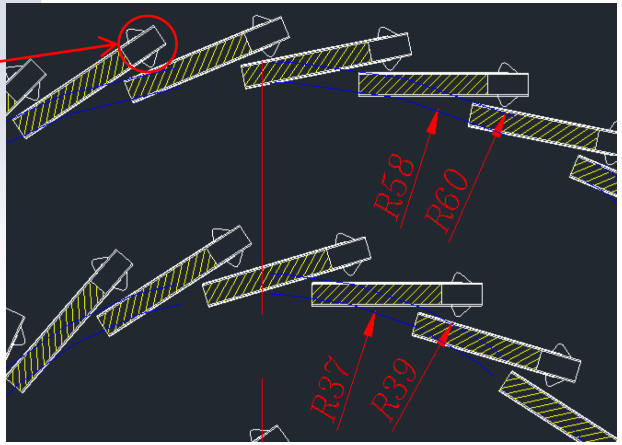


New pixel module material

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



Al wire



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

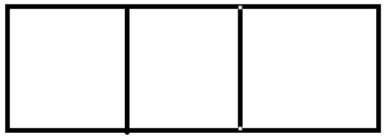
Ladder of realistic long barrel vertex

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

surface thickness: 0.25

inside ribs thickness : 0.6 number: 2 intotal

Carbon fiber support:



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

surface thickness: 0.2

inside ribs thickness : 0.6 number: 2 intotal