Optimization of CEPC Vertex Detector

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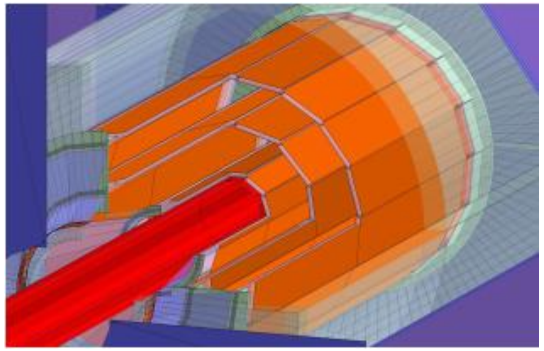
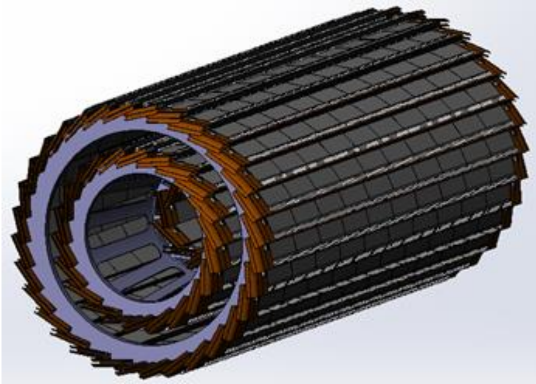
CEPC vertex study overview

- 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
- Optimization for a realistic vertex detector for CEPC:
  - based on vertex prototype (mechanics, electronics)
    - Module and material
  - full-size vertex detector (barrel + endcap)
    - Barrel optimization
    - Disk optimization
    - Long barrel vertex design
  - beam pipe, MDI, cooling

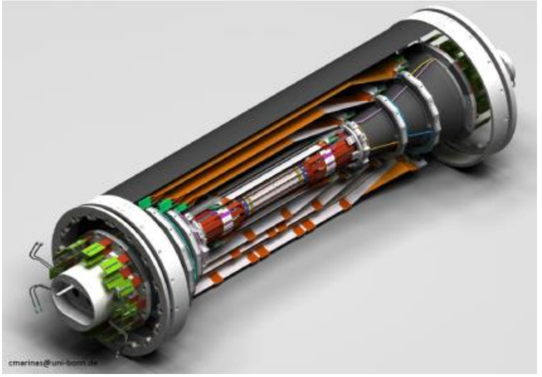
CDR baseline vertex



vertex prototype

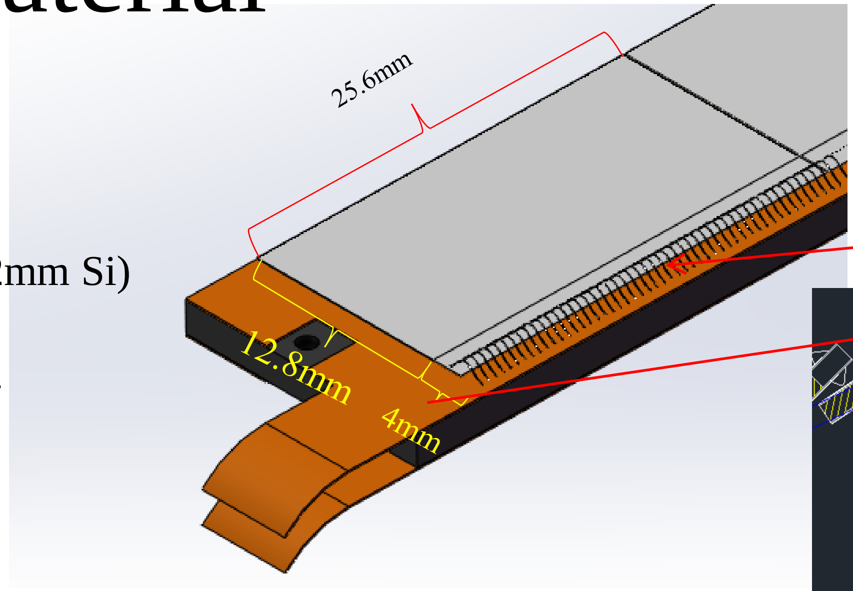


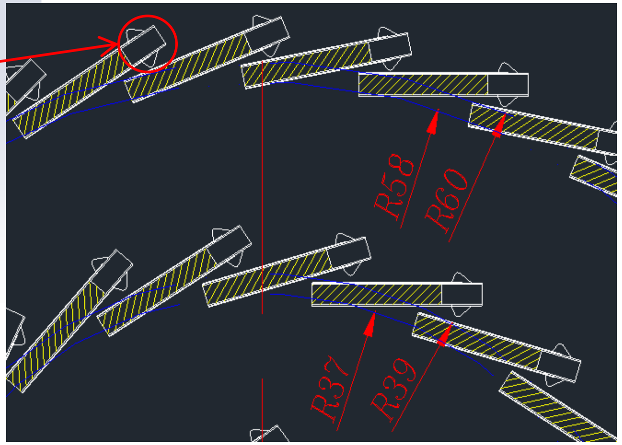
Belle II vertex detector



Module and 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

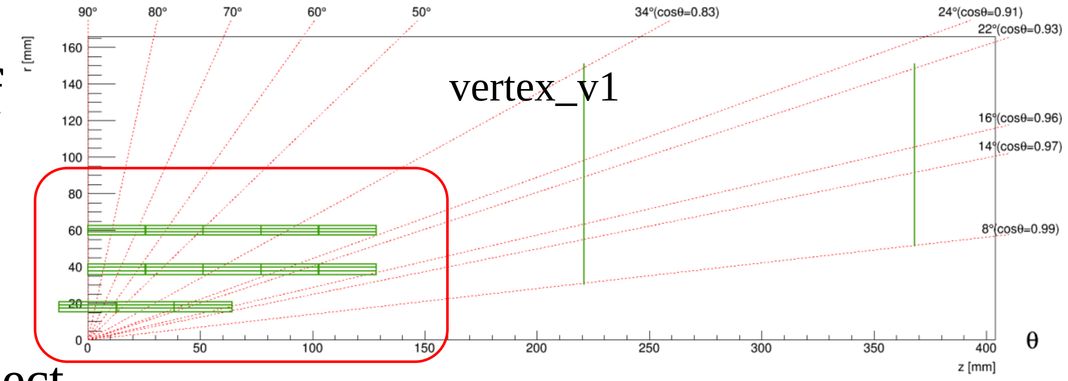
material of flex cable:

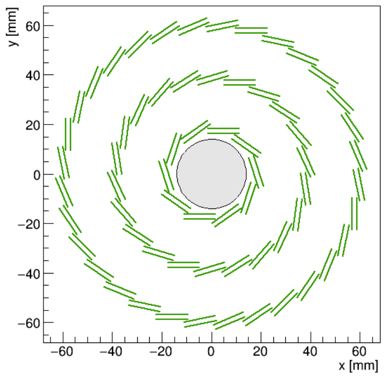
	We can do Thickness	Optimization goal
Polyimide	25um	12
Adhesive	28um	15
Plating Al	17.8um	?
kapton	50um	50
Plating Al	17.8um	?
Adhesive	28um	15
Polyimide	25um	12

Al: 17.8um*1.5=26.7um

Vertex layout optimization

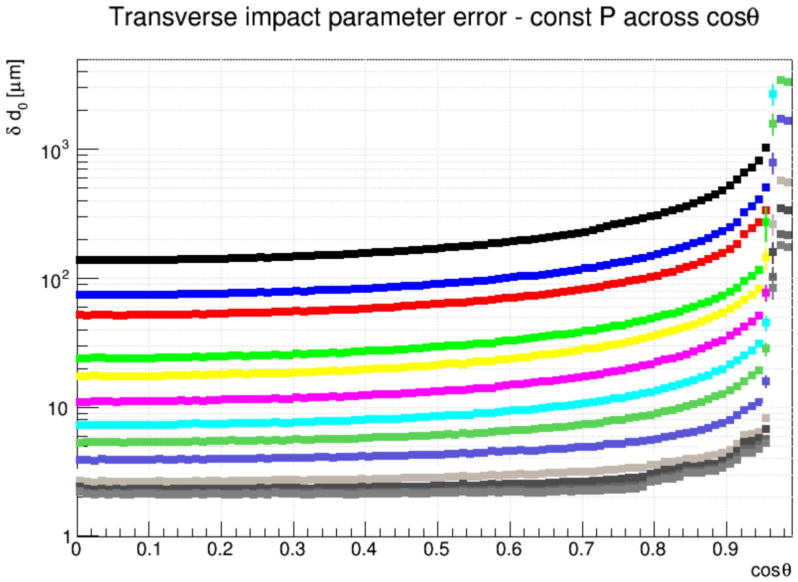
- vertex_v1: realistic implementation of CDR vertex
  - Barrel: 3 double-layers
  - Endcap: 2 single disks
  - Only consider the barrel for MOST2 project
  - total average material budget is about 1.3% for vertex barrel, much more than CDR 0.9% (0.15% × 6)

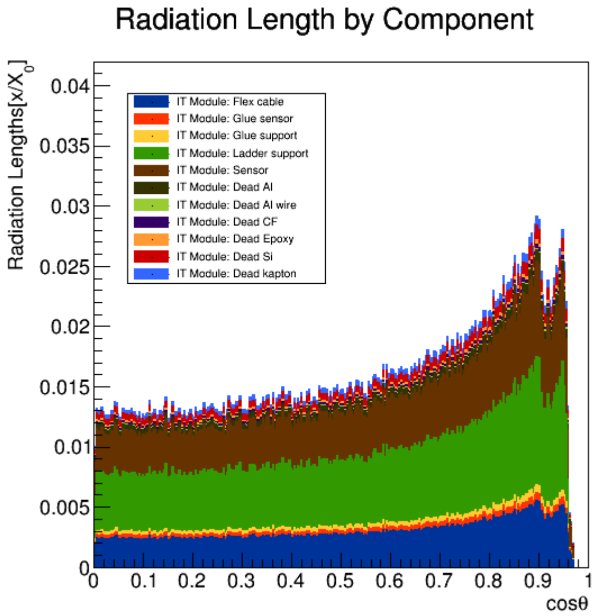




	Average R(mm)	# ladder		# chip on 1 ladder	Total # chips
Layer 1	18	10	L1_inner	5	50
			L1_outer	5	50
Layer 2	38	22	L2_inner	10	220
			L2_outer	10	220
Layer 3	60	32	L3_inner	10	320
			L3_outer	10	320
					1280

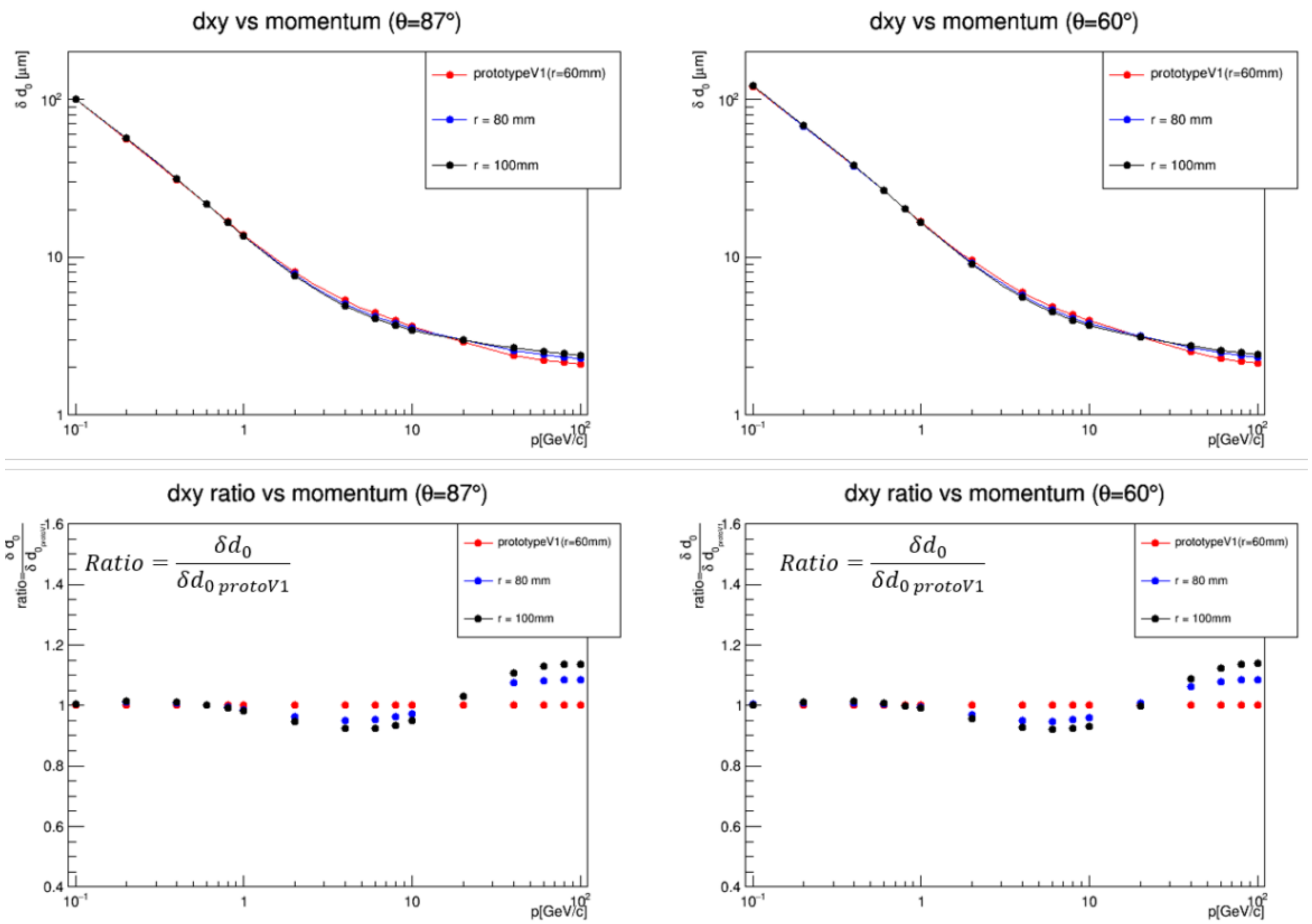
Barrel parameters



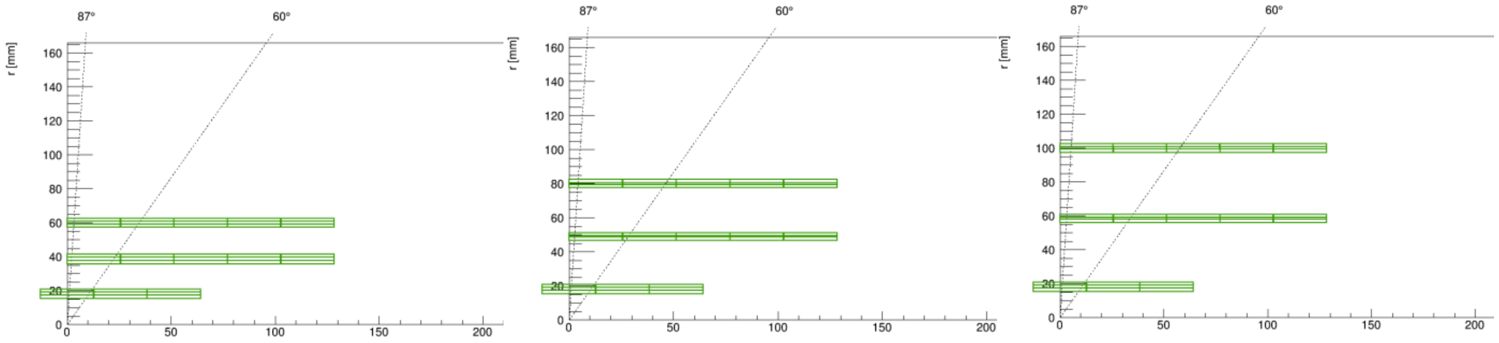


Barrel optimization

- Changing the radius of vertex detector
  - the d0 resolution is no big difference for different detector size at very low momentum like 0.1GeV to 1GeV
  - while the d0 resolution is different at higher momentum like 1GeV to 100GeV.
    - bigger vertex detector has better resolution with momentum from 1GeV to 10GeV
    - smaller vertex detector has better resolution with momentum from 10GeV to 100GeV



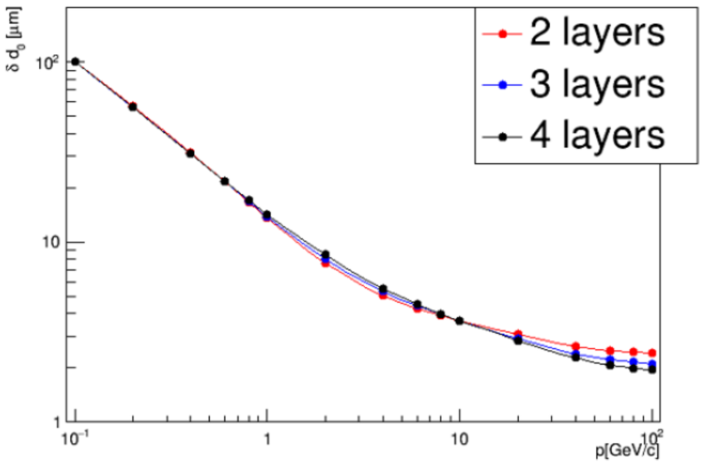
	prototype_v1	R=80mm	R=100mm
double-layer	R (mm)	R (mm)	R (mm)
Layer 1	18	18	18
Layer 2	38	49	59
Layer 3	60	80	100

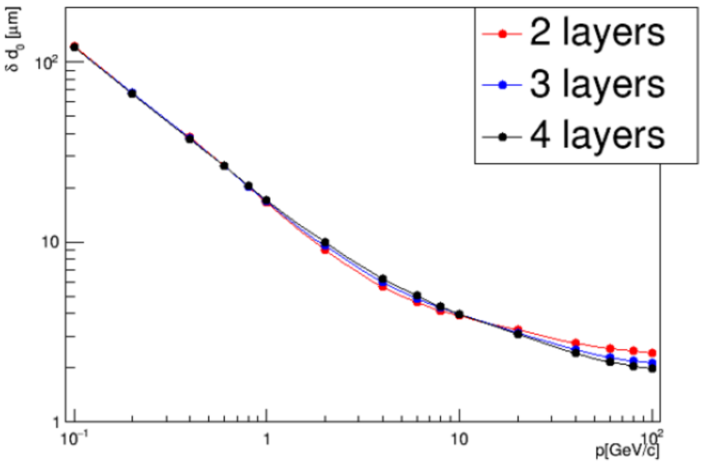


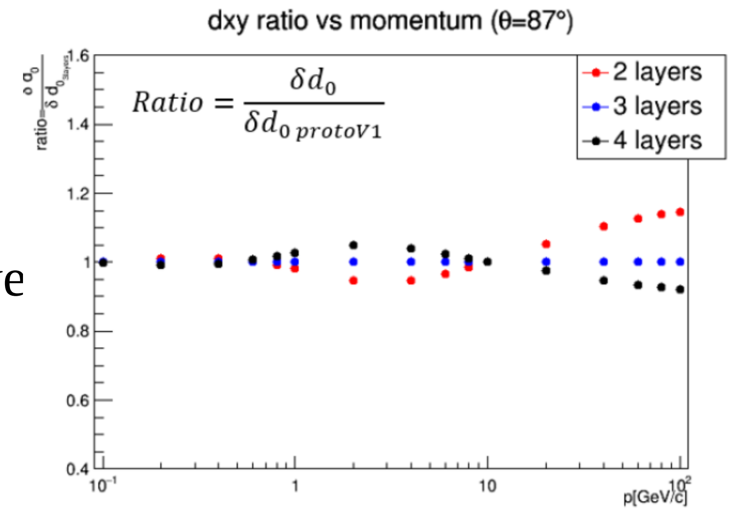
Barrel optimization

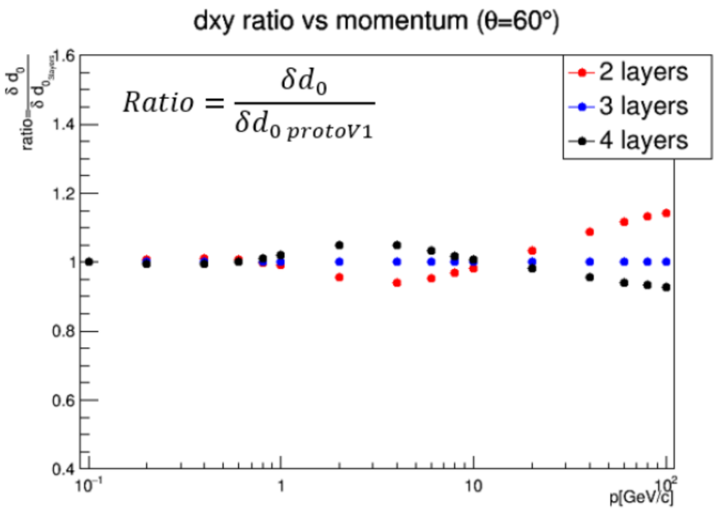
- Changing the number of layers
  - 0.1GeV-1GeV: The effect of number of layers on d0 resolution is very small.
  - 1GeV-10GeV: The vertex with less layers has better d0 resolution, which is probably because material effect dominate in this momentum range.
  - 20GeV-100GeV: The vertex with more layers has better d0 resolution, which is because vertex with more layers will have more measurement points for track reconstruction.

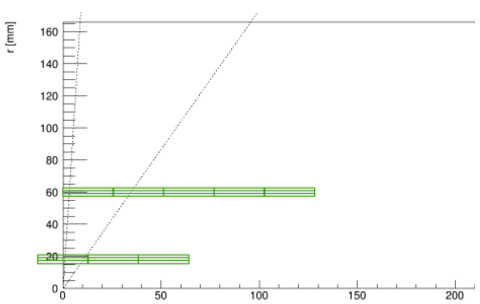
	2 layers	3 layers	4 layers
double-layer	R (mm)	R (mm)	R (mm)
Layer 1	18	18	18
Layer 2	60	38	31
Layer 3		60	45
Layer 4			60

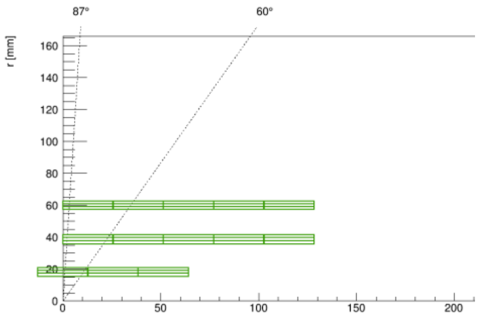


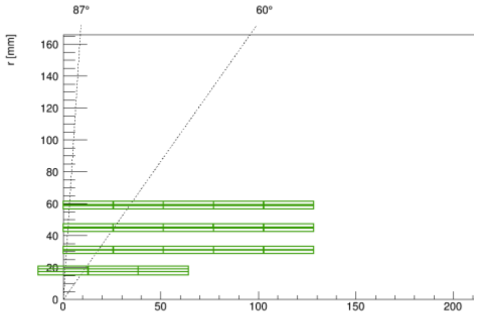






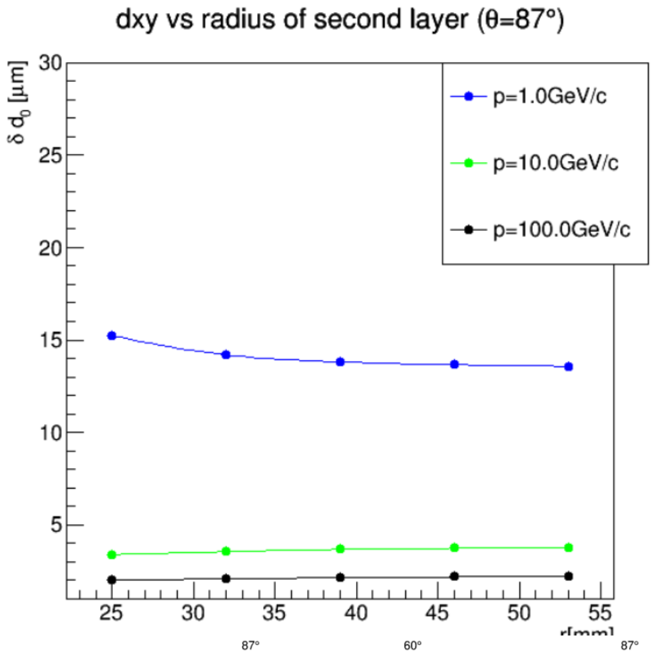


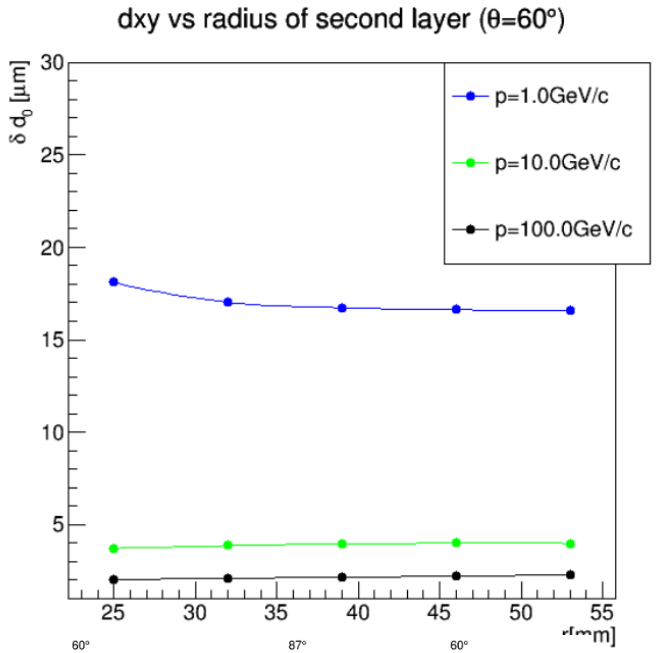




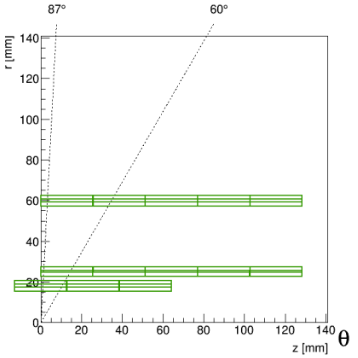
Barrel optimization

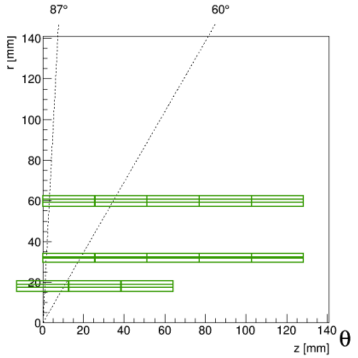
- Changing the radius of second layer
  - second layer radius has very small effect on d0 resolution.
  - In addition, second layer closer to first layer has better resolution for 10GeV and 100GeV tracks
  - second layer closer to first layer will get worse resolution for 1GeV tracks.
  - However, second layer in middle is a better choice for mechanics design.

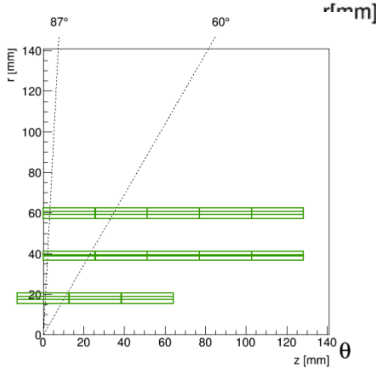


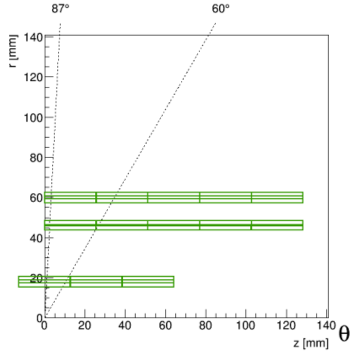


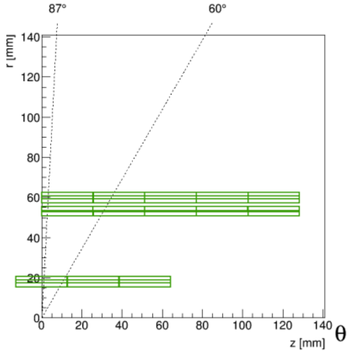
	r_2=25mm	r_2=32mm	r_2=39mm	r_2=46mm	r_2=53mm
double-layer	R (mm)	R (mm)	R (mm)	R (mm)	R (mm)
Layer 1	18	18	18	18	18
Layer 2	25	32	39	46	53
Layer 3	60	60	60	60	60





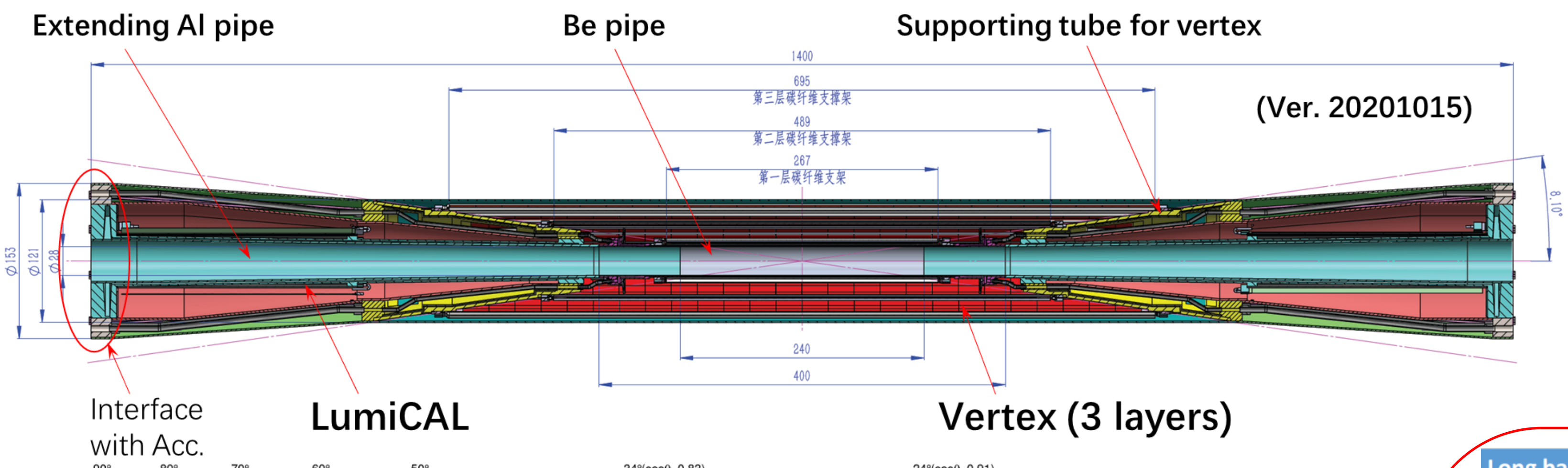




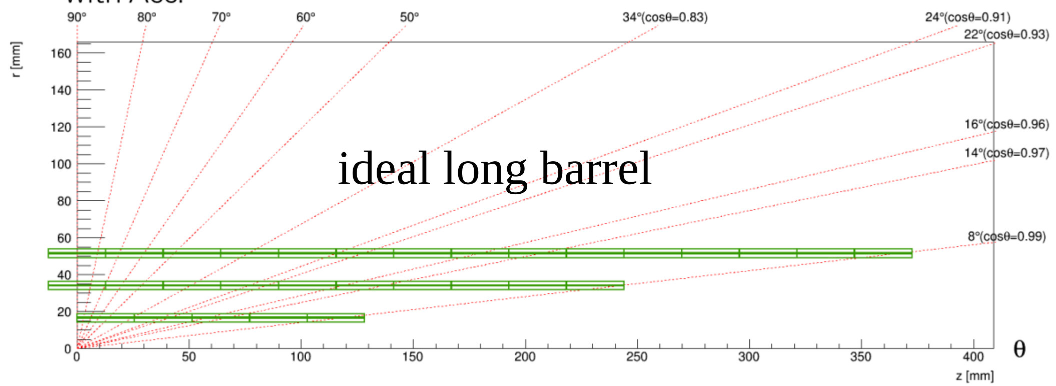


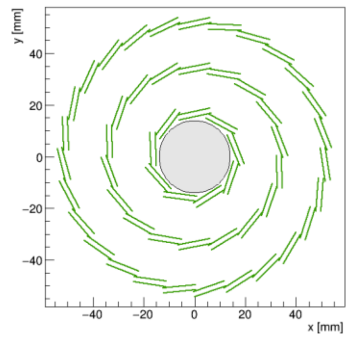
Finally, we choose the barrel with a radius of 60mm and 3 equispaced double-layers considering the mechanics and material, which is the CDR layout.

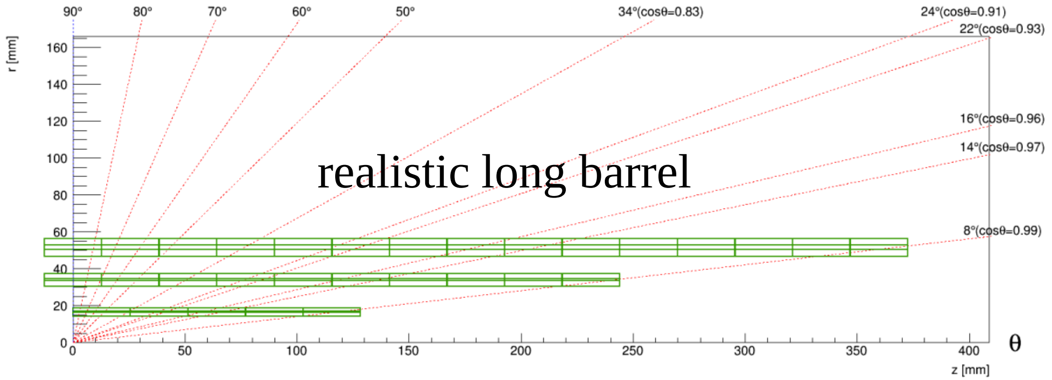
Long barrel vertex

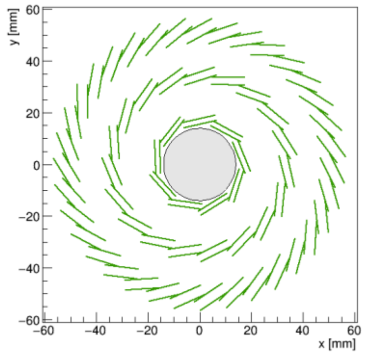


- Feasible solution for air cooling
- Simple structure
- Realistic long barrel vertex:
  - stiffer carbon fiber ladder support
  - more cable for read-out
  - vibration of long ladder









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

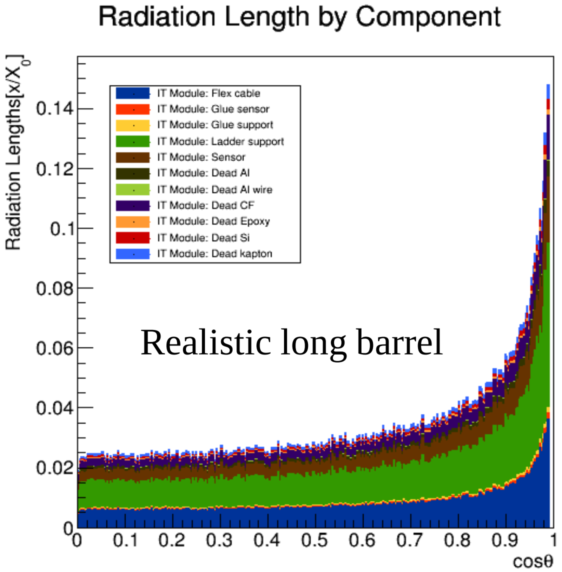
2 flex layers

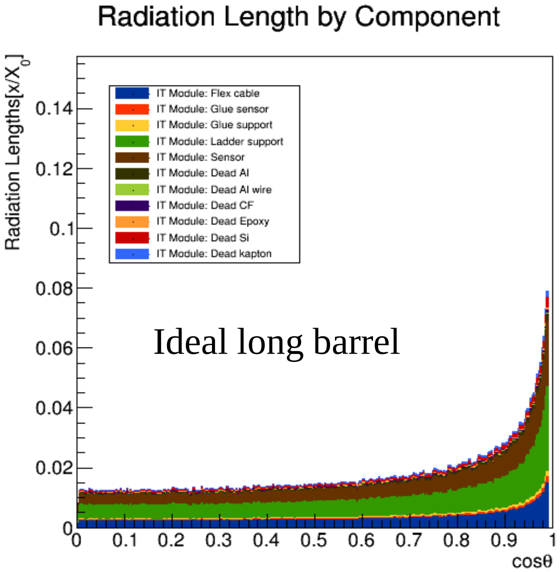
	Thickness	Optimization goal
Polyimide	25um	12
Adhesive	28um	15
Plating Al	17.8um	?
kapton	50um	50
Plating Al	17.8um	?
Adhesive	28um	15
Polyimide	25um	12

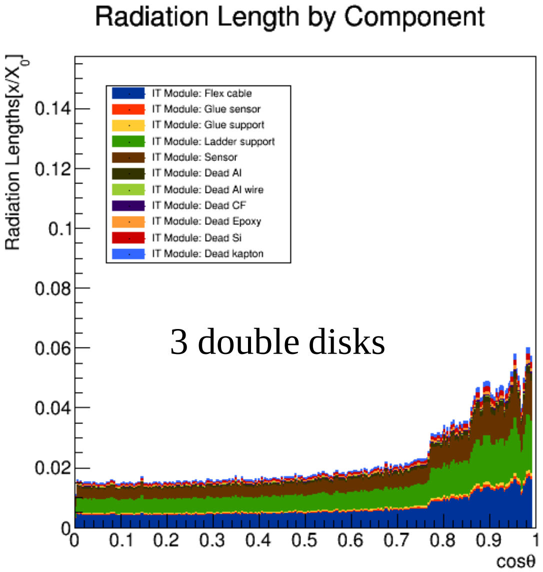
4 flex layers

	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

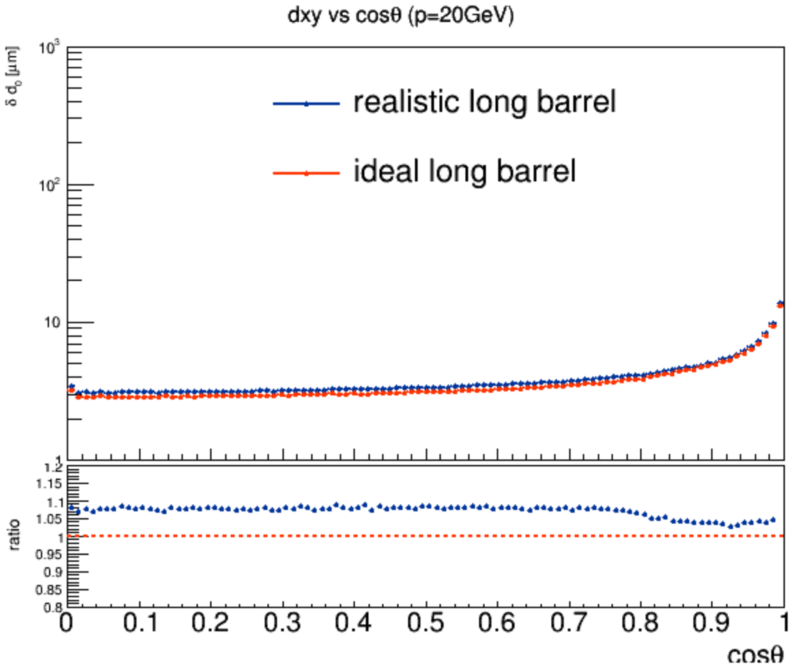
Long barrel vertex





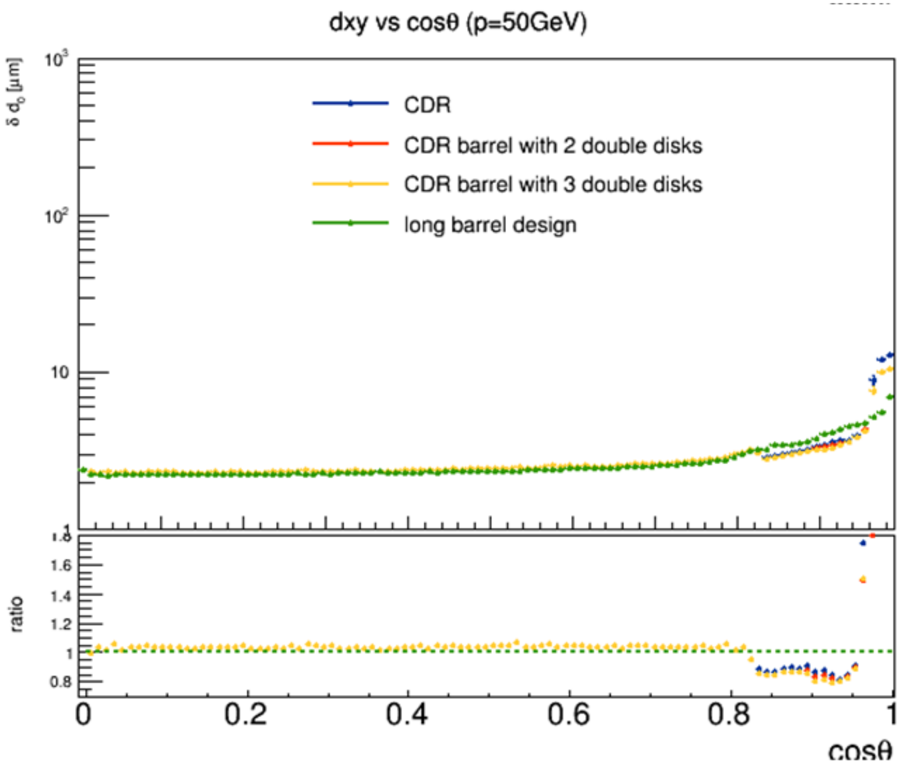


- ➢ The material budget of realistic long barrel vertex is about twice as much as the ideal long barrel vertex.
- ➢ Much more material in the front region than disk version layout.

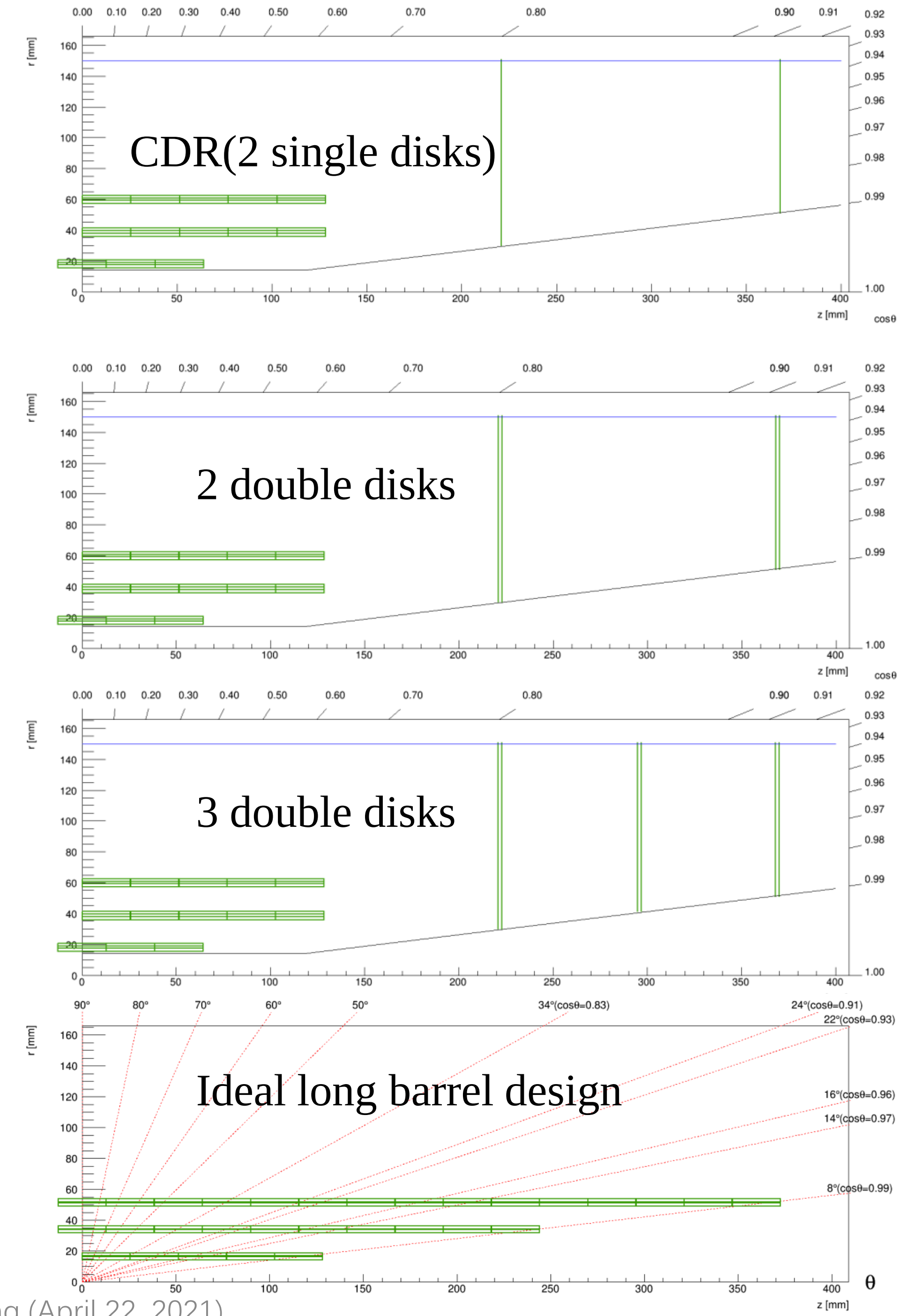


- ➢ The d0 resolution of realistic long barrel vertex is worse about 7% than ideal long barrel vertex.

Long barrel vertex performance

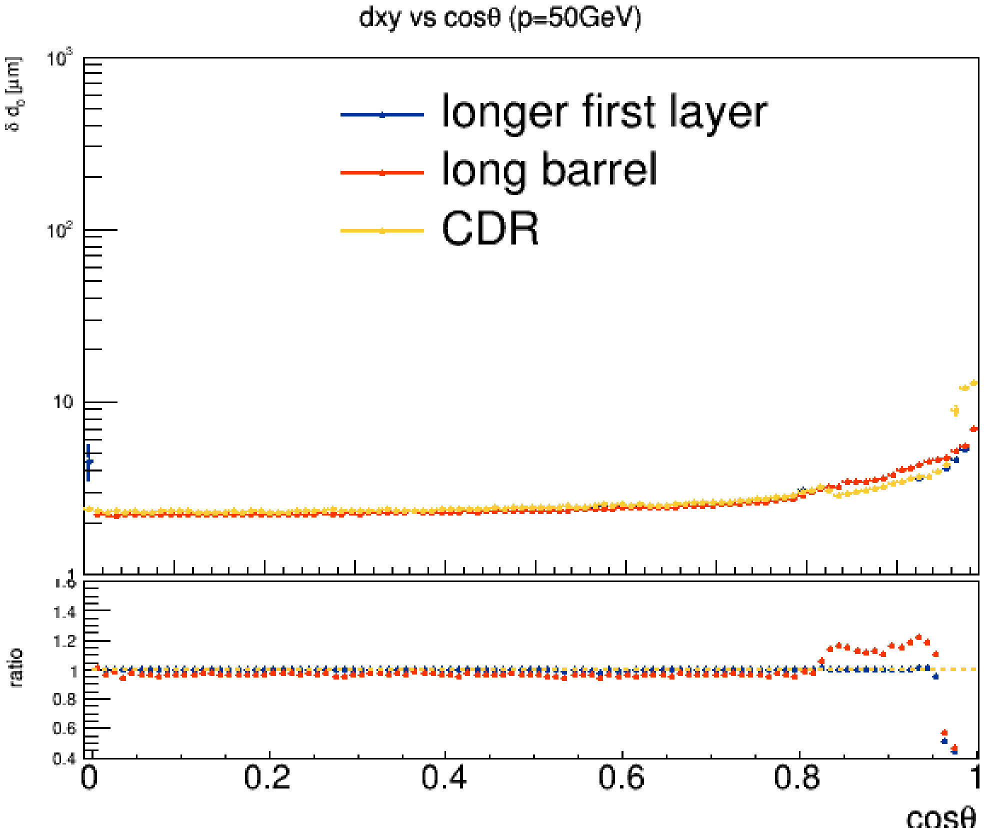


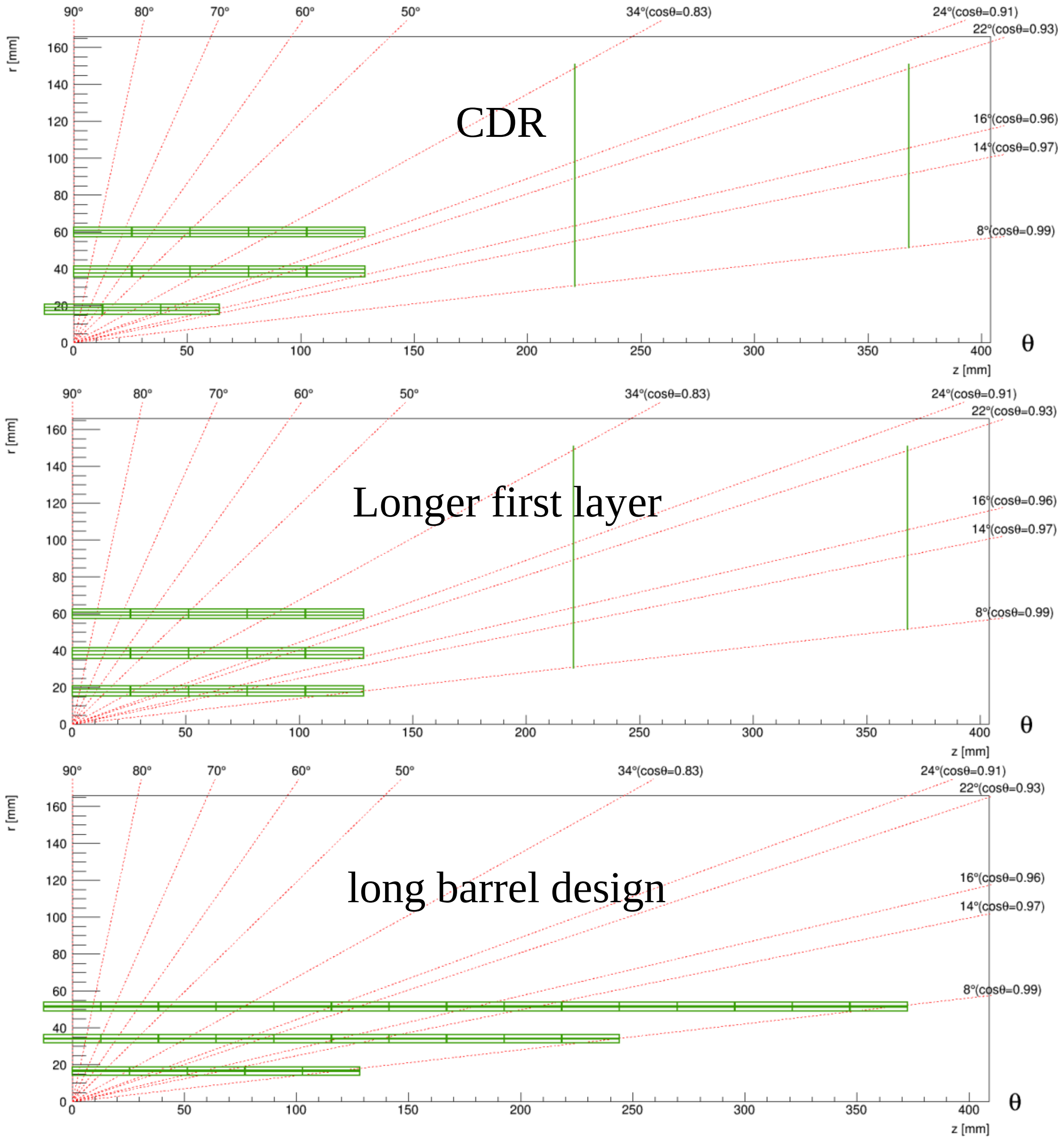
- cosθ: 0.82-0.96, disk version better than long barrel design
- cosθ> 0.96: long barrel design better CDR barrel with disk version, because innermost layer of long barrel provides closer first hit to IP



Barrel optimization

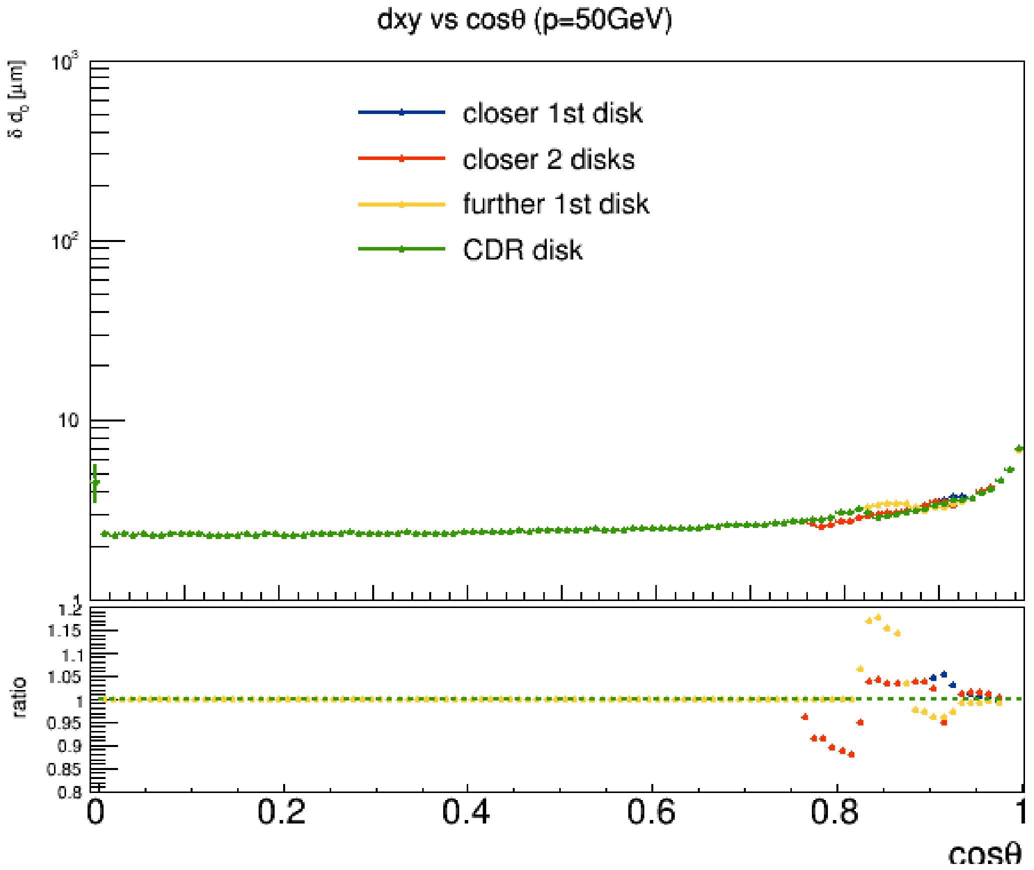
- Lengthen the innermost layer
  - longer first layer design has the advantages of long barrel design and disk design
  - cosθ: 0.82-0.96, same as CDR
  - cosθ> 0.96: similar to long barrel design (even a little better), better than CDR

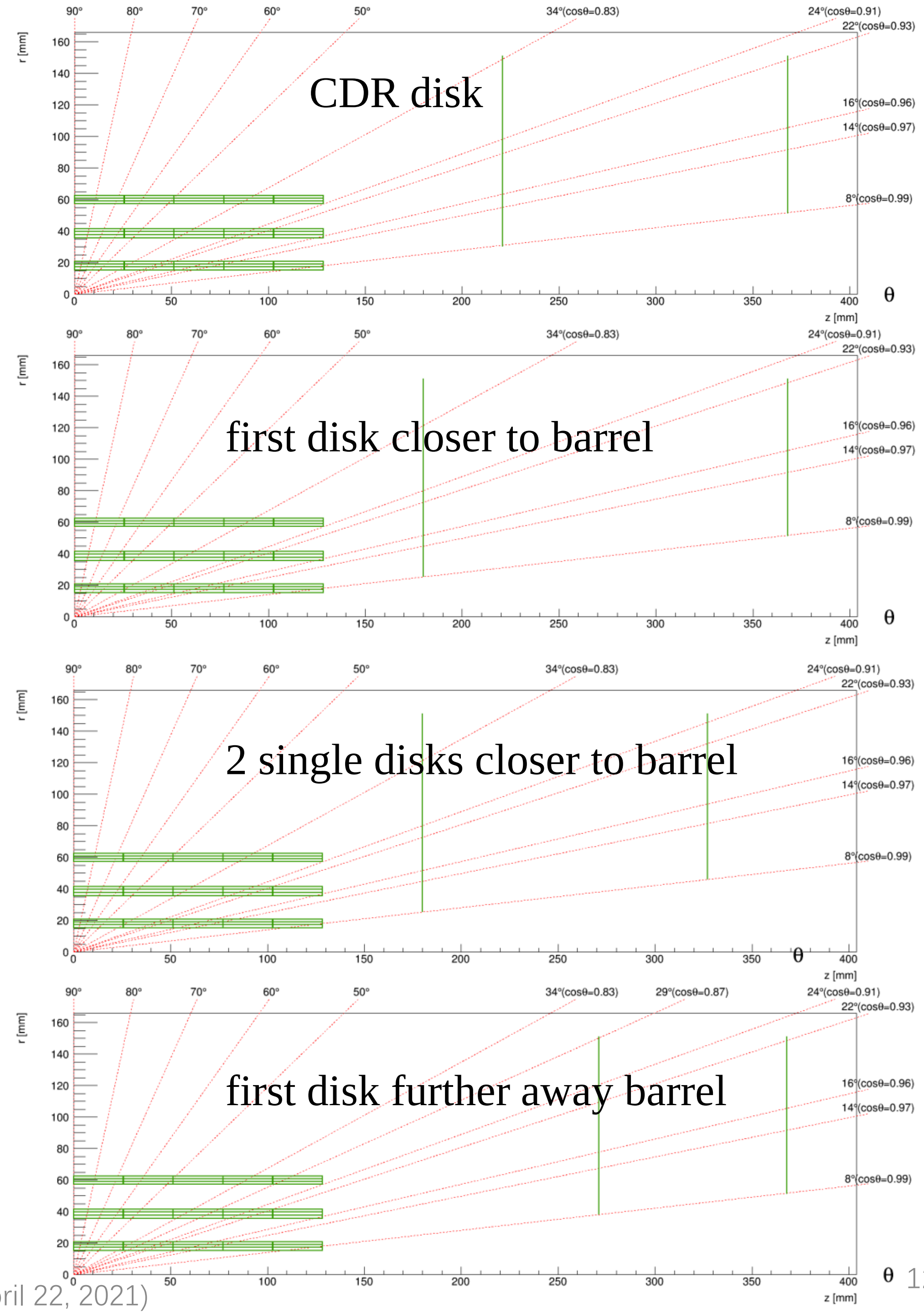




Disk optimization

- Different position of 2 single-layer disks
  - not always improve resolution, some points better, some worse
  - moving disk closer to barrel can improve resolution at $\cos\theta \approx 0.8$ (more hits)





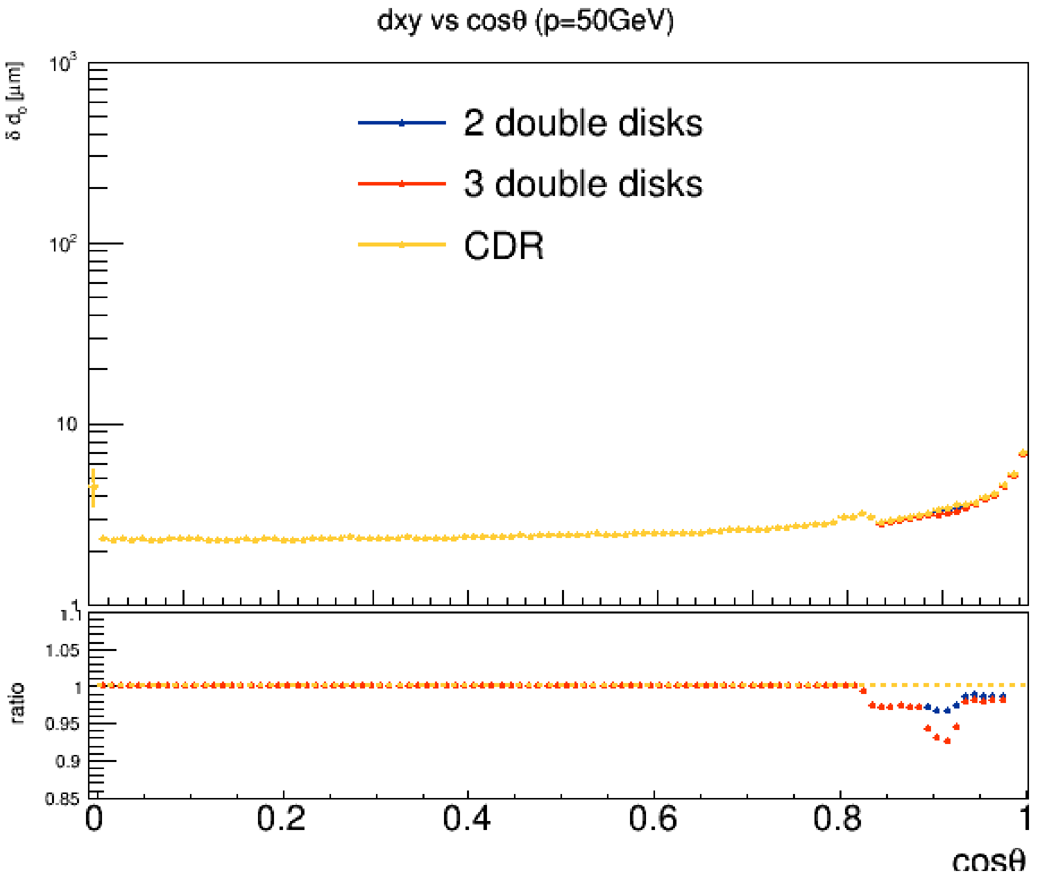
Disk optimization

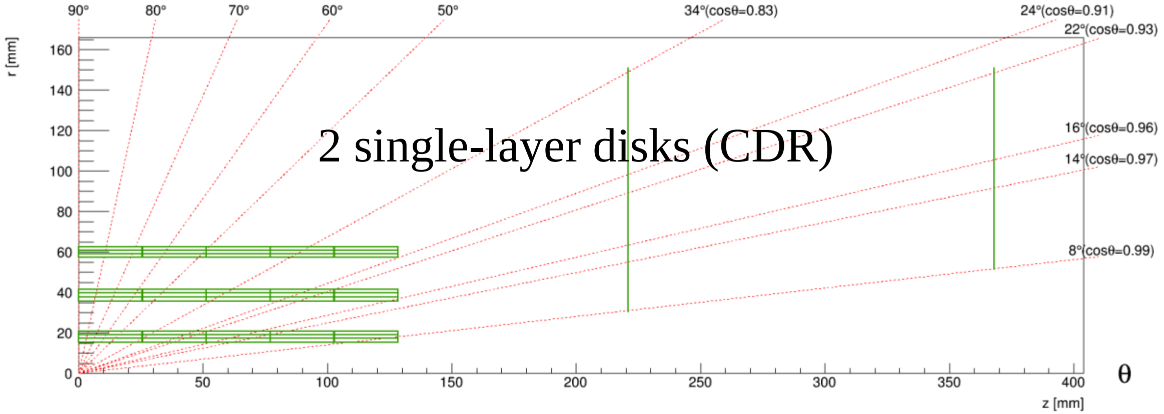
Longer first layer with different number of disk:

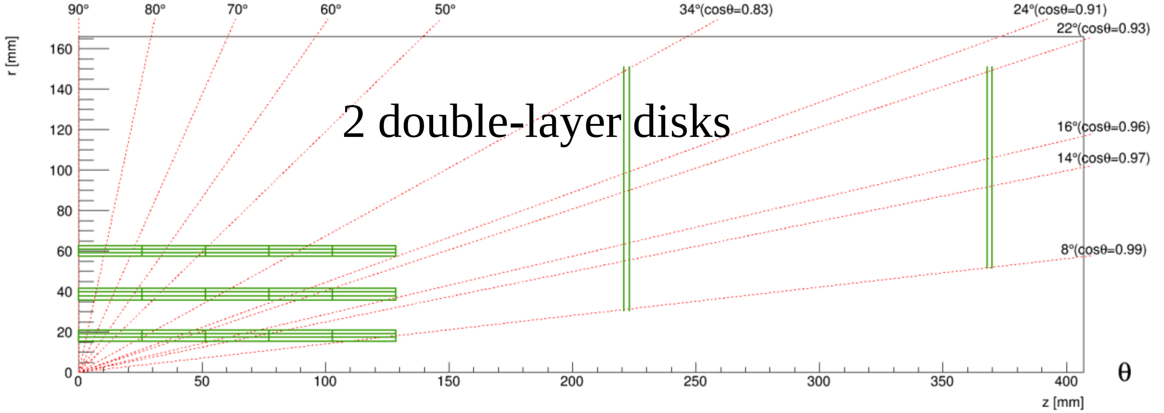
2 ways to improve resolution:

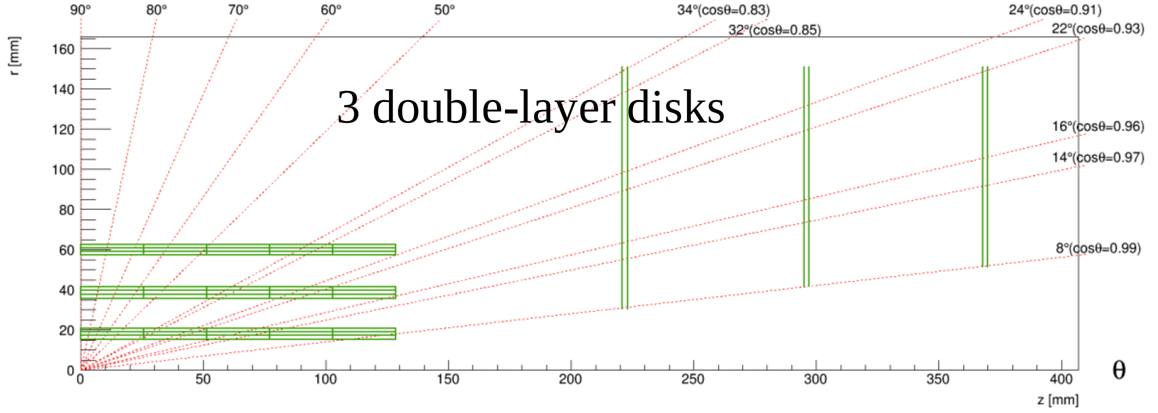
- ➢ increase the number of disk
- ➢ replace single disk with double disk

no worse resolution points





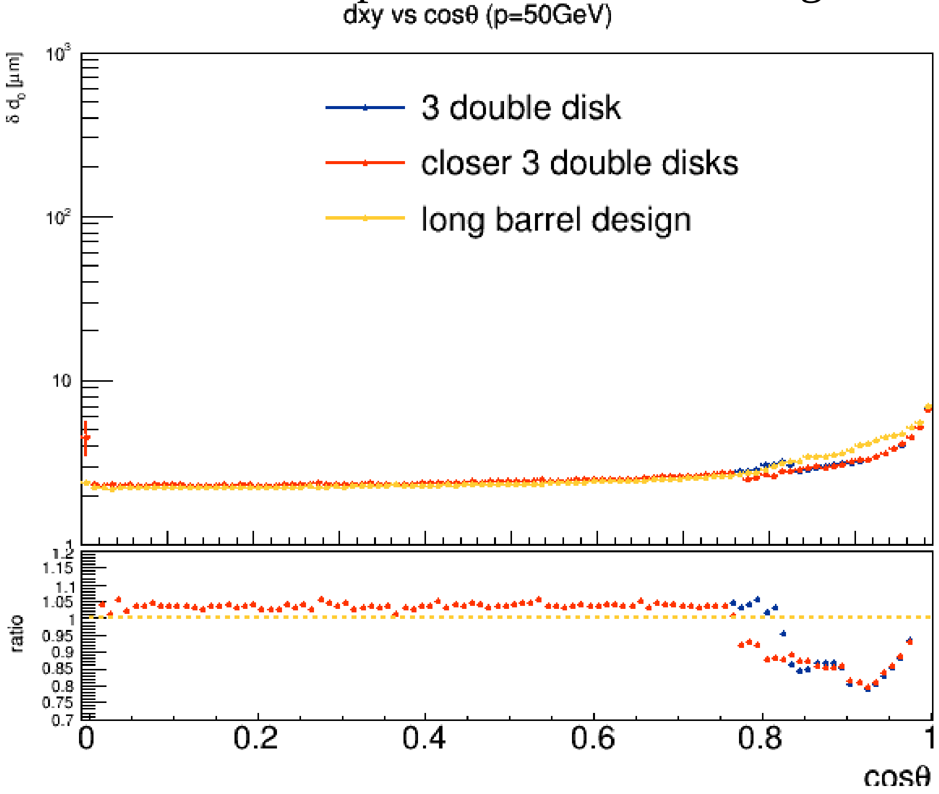




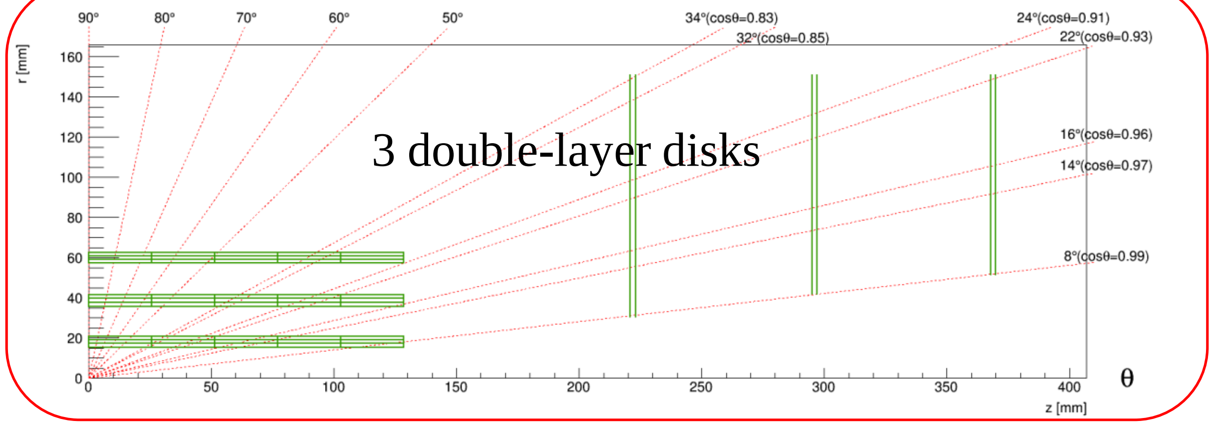
Disk optimization

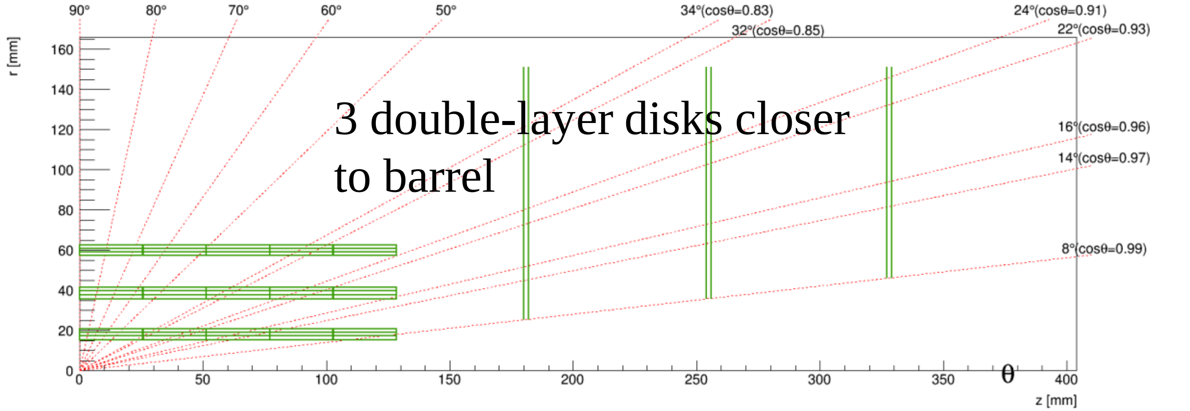
3 double-layer disks closer to barrel

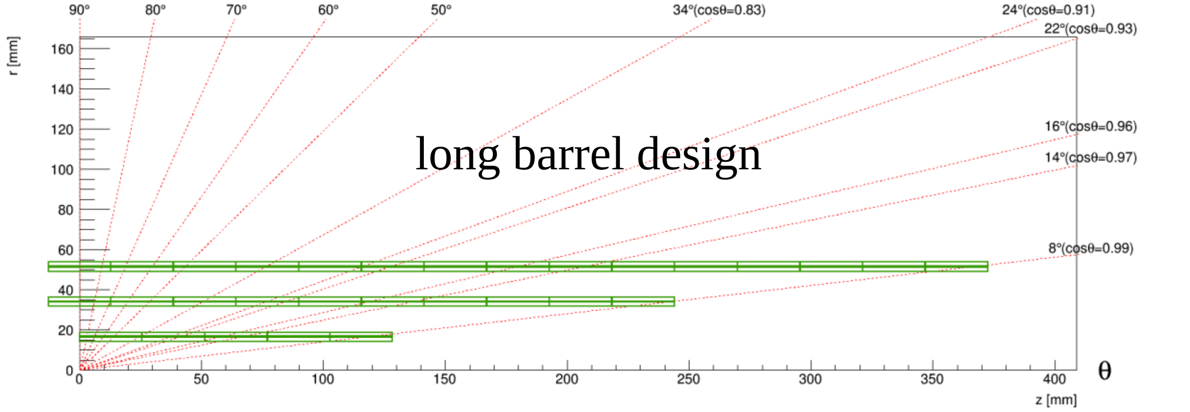
- longer innermost layer with disk has better resolution than full barrel design in front region
- moving disk closer to barrel will enlarge the improved region
- considering the mechanics, putting 3 double disk at CDR disk position is a better design.



Better layout after barrel optimization and disk optimization





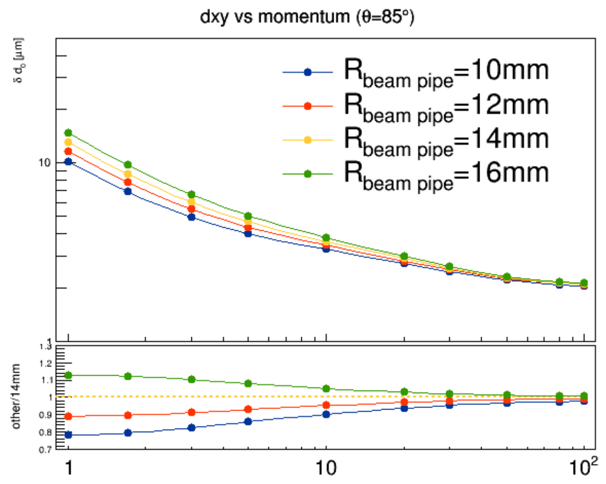


Beam pipe study overview

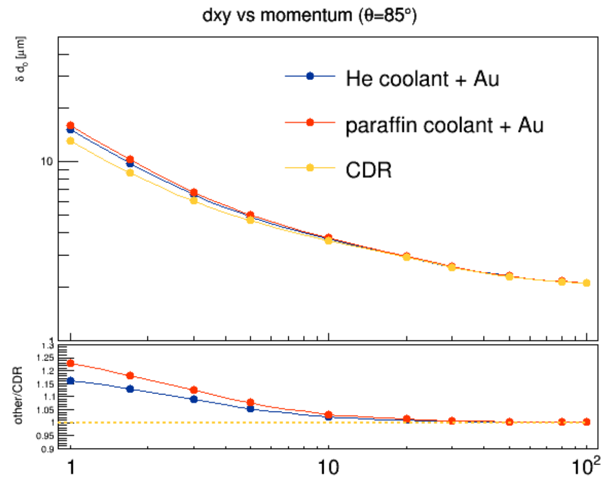
- Beam pipe radius
  - Big effect on low momentum track
  - Beam pipe radius is smaller, resolution is better
  - Improve d0 resolution 21% if reduce beam pipe radius to 10 mm
- Beam pipe material
  - Beam pipe structure:

4 layers

    - 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!!!

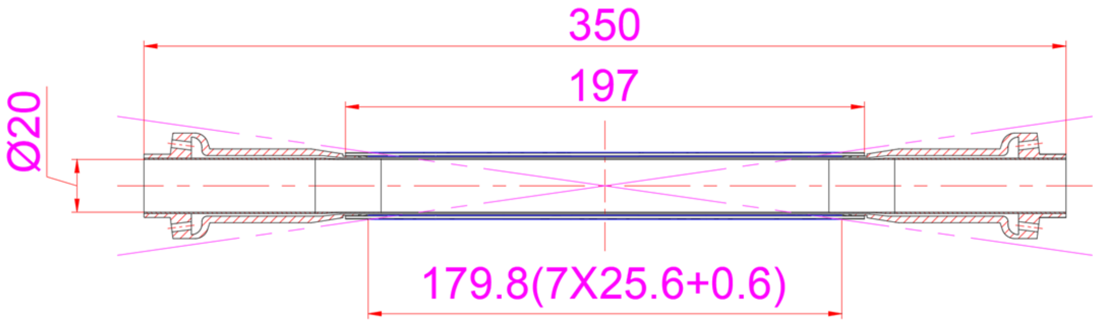


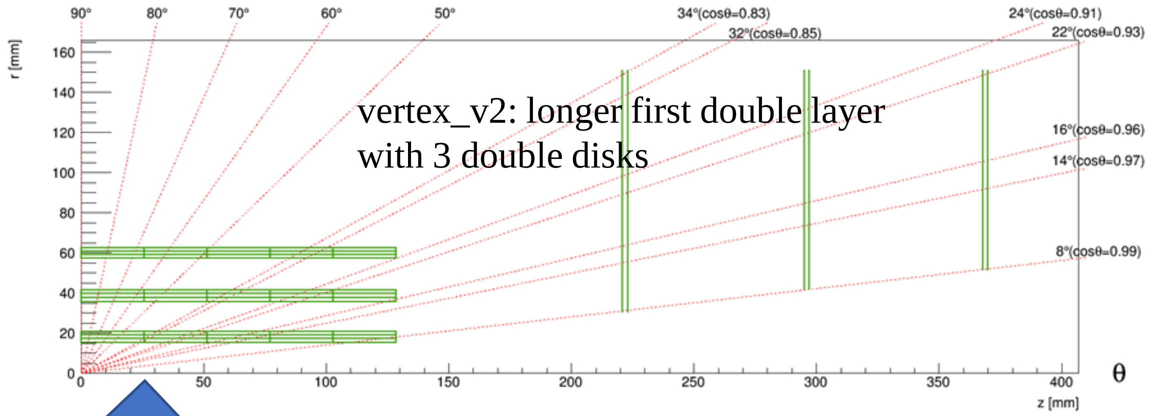
Reduce the beam pipe material!!!
Make the beam pipe thinner!!!

	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





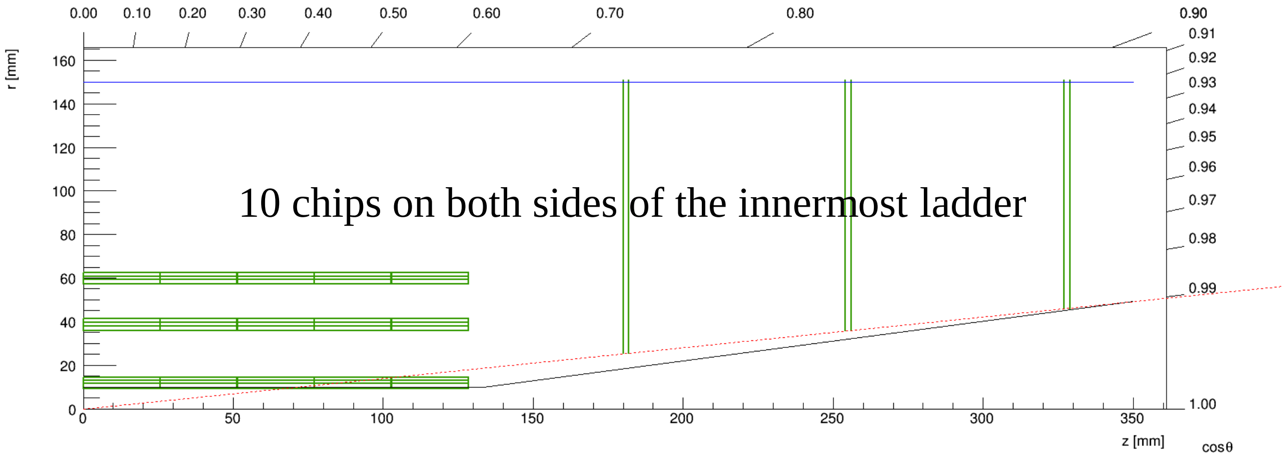
Q. Ji

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

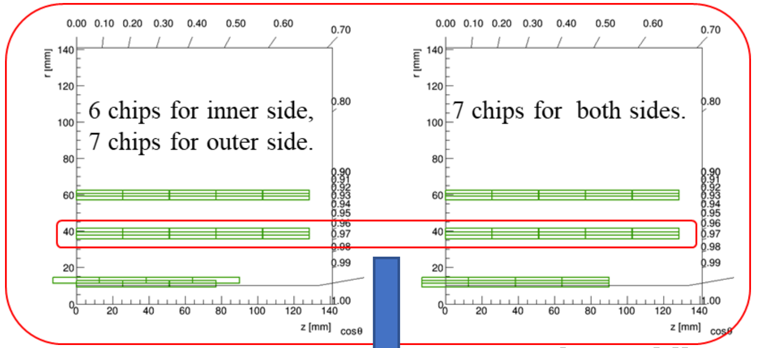
thinner

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

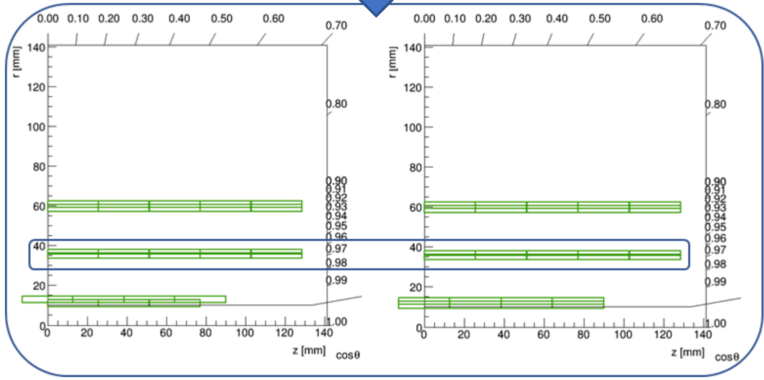
Innermost layer will be inside the border line, which defines the vertex detector coverage.
Shorter innermost layer is required



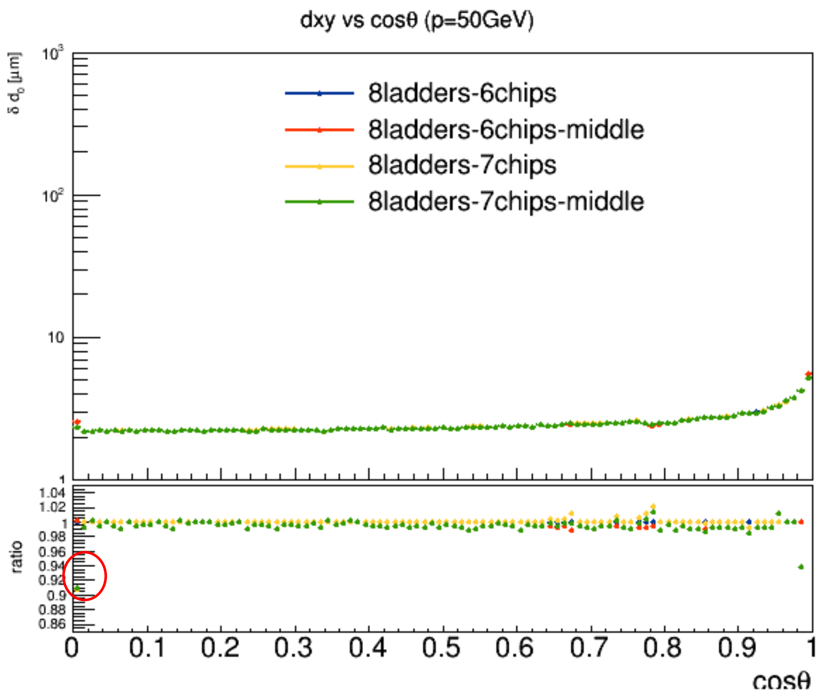
Different ladder arrangements and chips for innermost layer

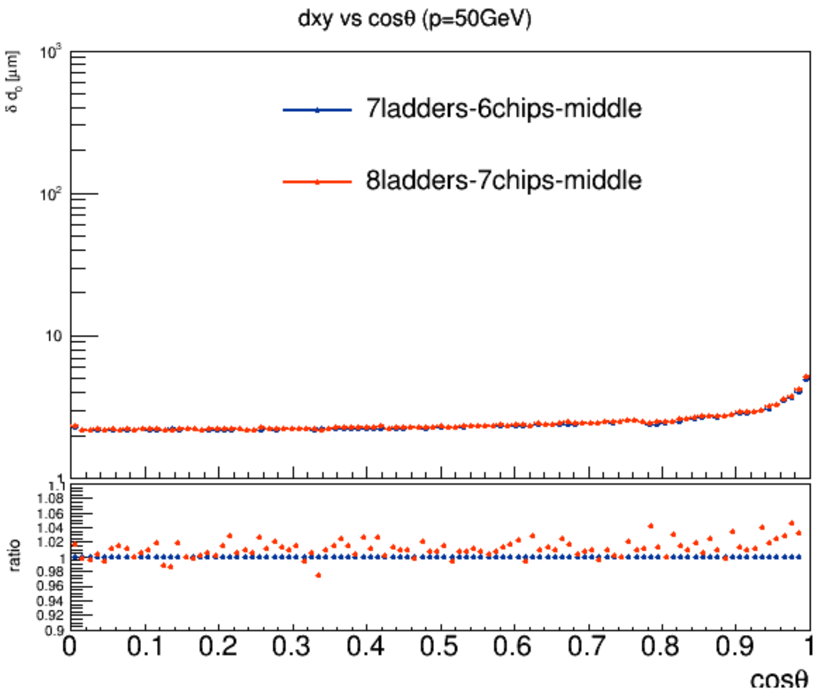


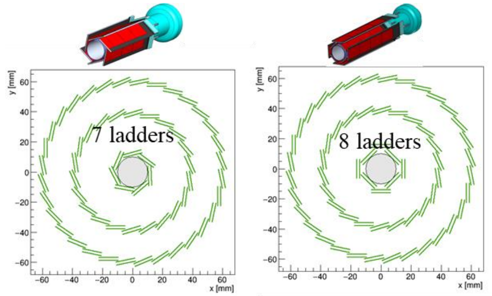
Move to the middle



Comparison of different ladder arrangements for innermost layer:

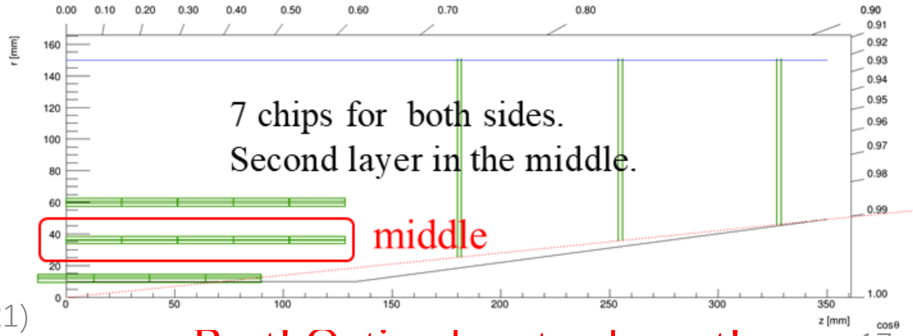






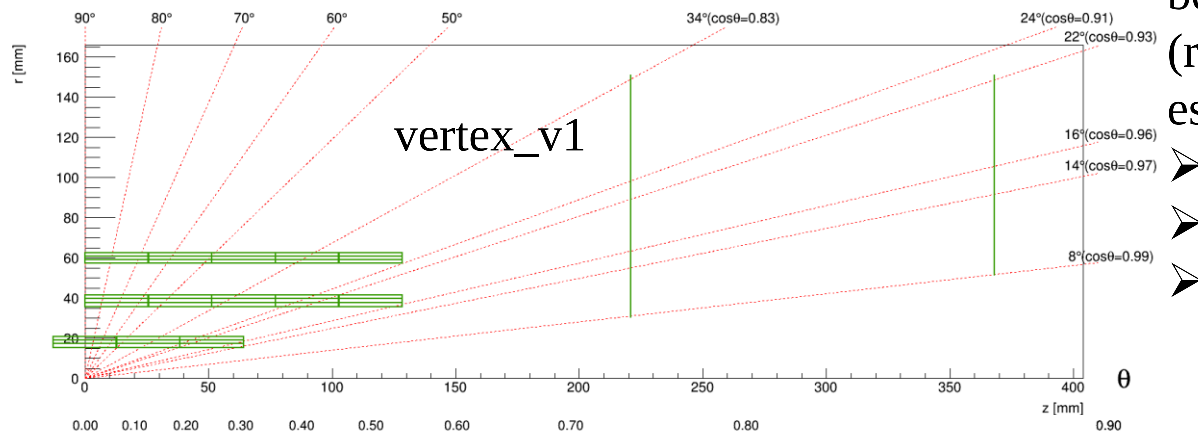
7 chips on both sides for innermost layer and second layer in the middle is better.

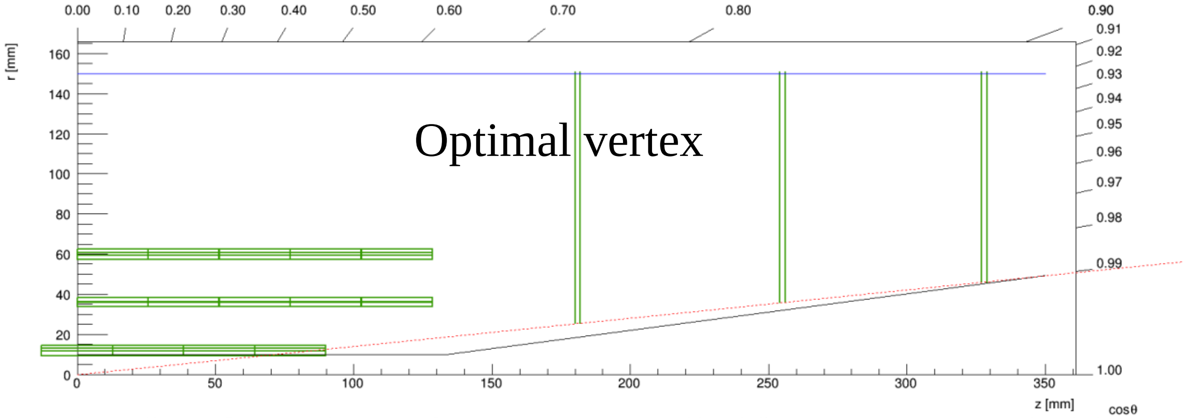
- 7-ladders arrangement is better than 8-ladders arrangement.
  - less material
  - 7 ladders are close to beam pipe.

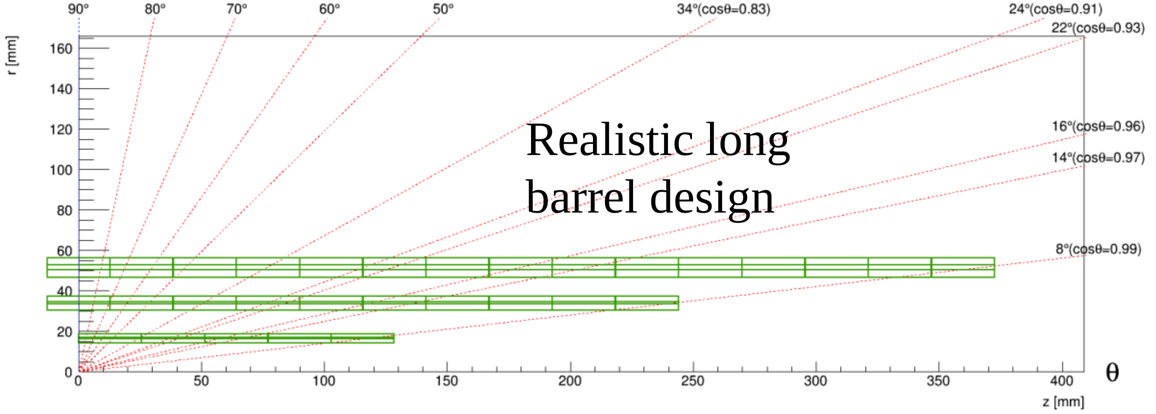


Best! Optimal vertex layout!

Optimal vertex layout

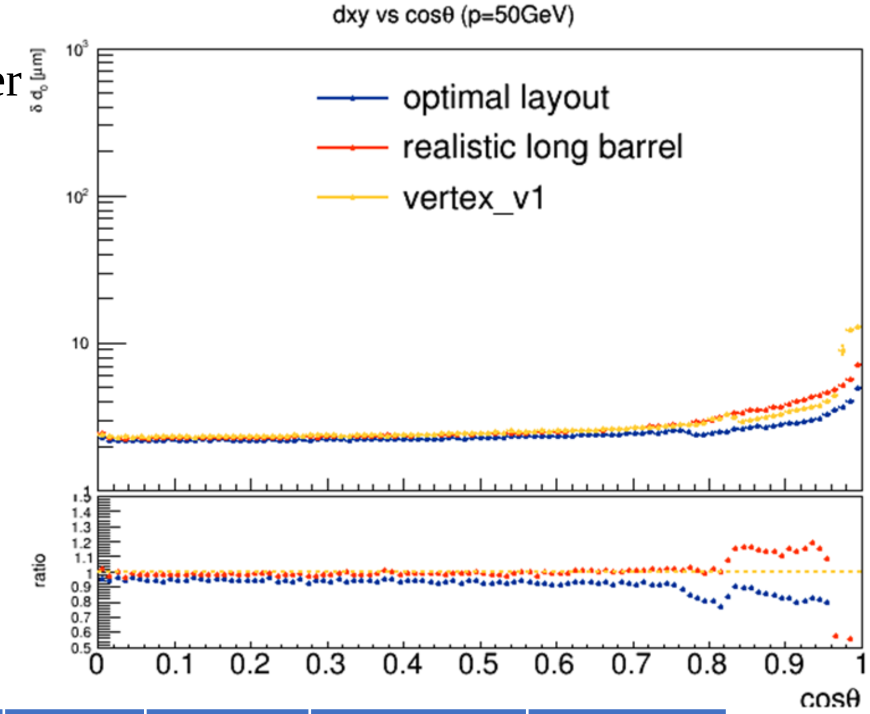






The d0 resolution of optimal vertex layout is much better than realistic long barrel vertex and vertex_v1 (realistic implementation of CDR vertex) layout, especially in the front region (20% and even more).

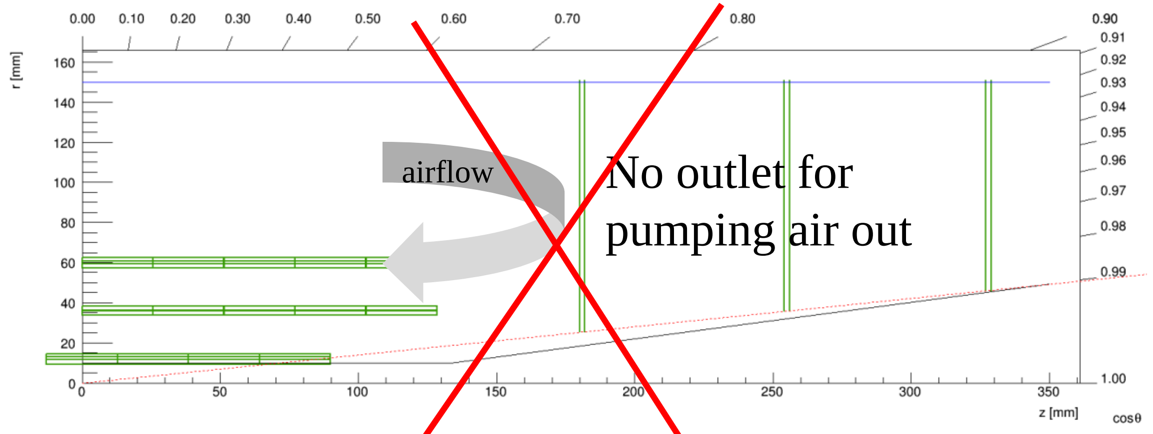
- smaller radius of beam pipe
- more disks
- longer innermost layer

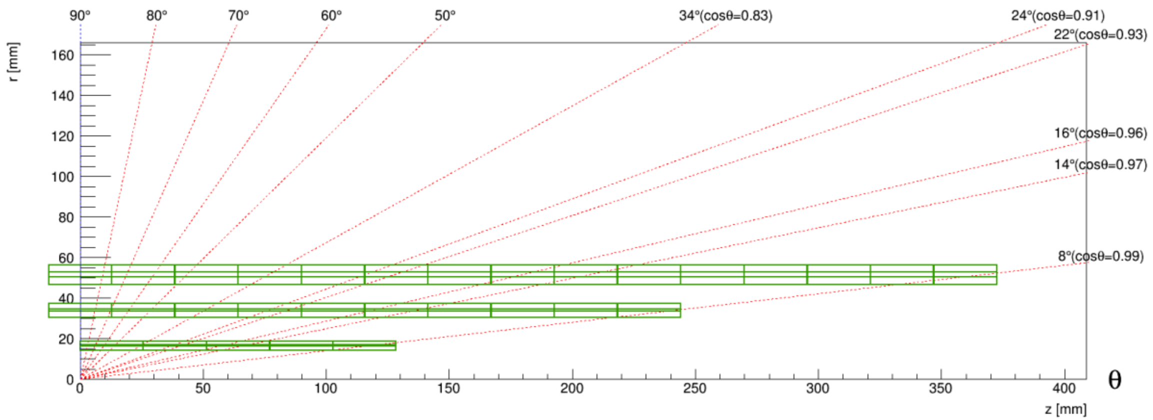


	Average R(mm)	# ladder		# chip on 1 ladder	Total # chips
Layer 1	12	7	L1_inner	7	49
			L1_outer	7	49
Layer 2	36	19	L2_inner	10	190
			L2_outer	10	190
Layer 3	60	32	L3_inner	10	320
			L3_outer	10	320
					1118

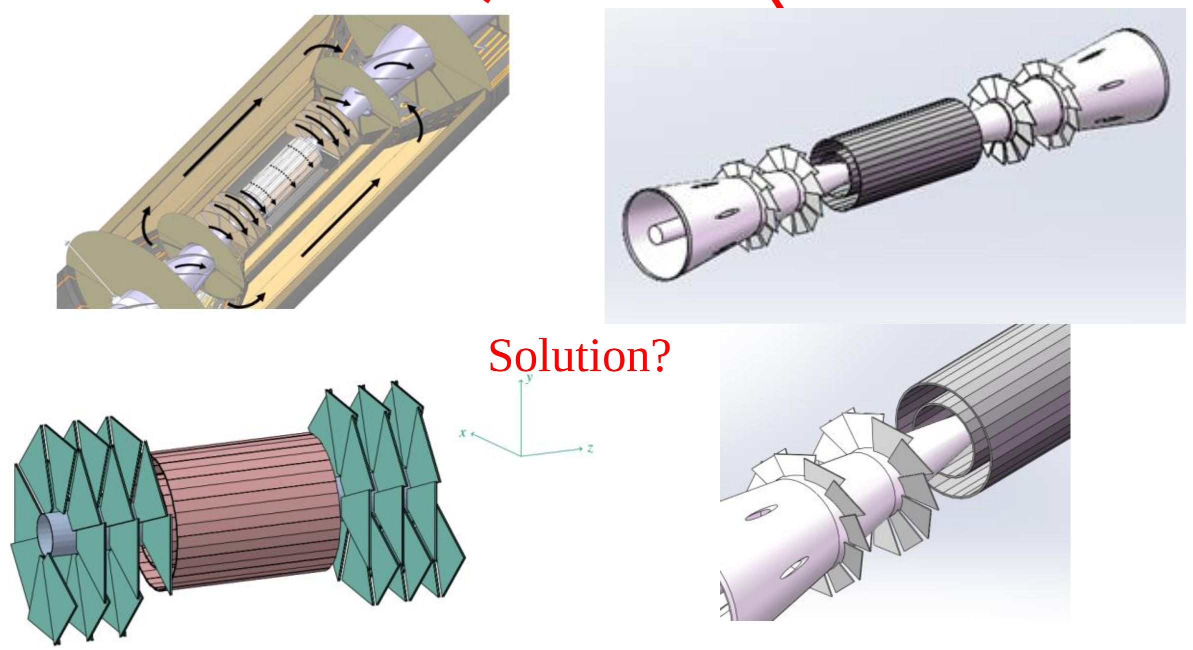
number of chips is reduced

Vertex design considering air cooling





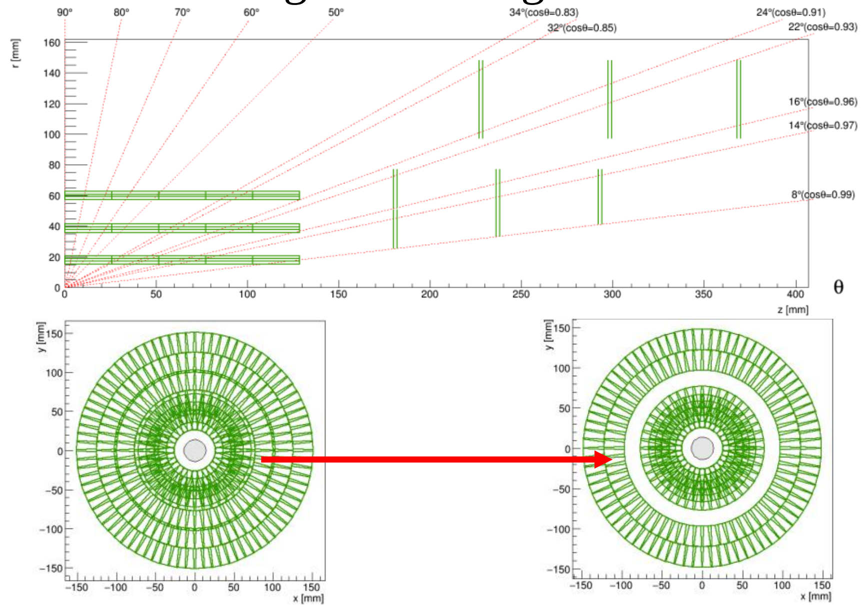
Long barrel design



CLIC spiral disk concept

CLICdp-Note-2014-002

rotate the disk, from Jinyu



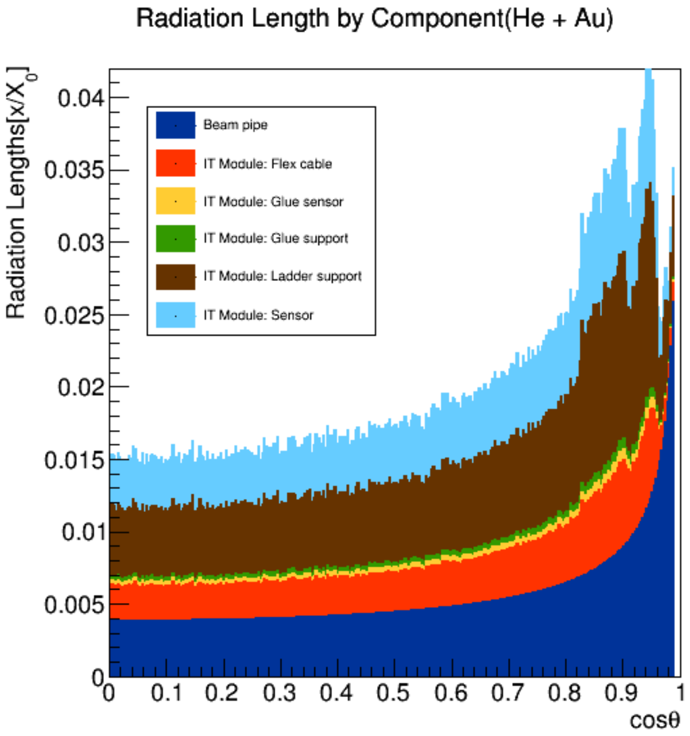
Make a hole in disk

Summary & Plan

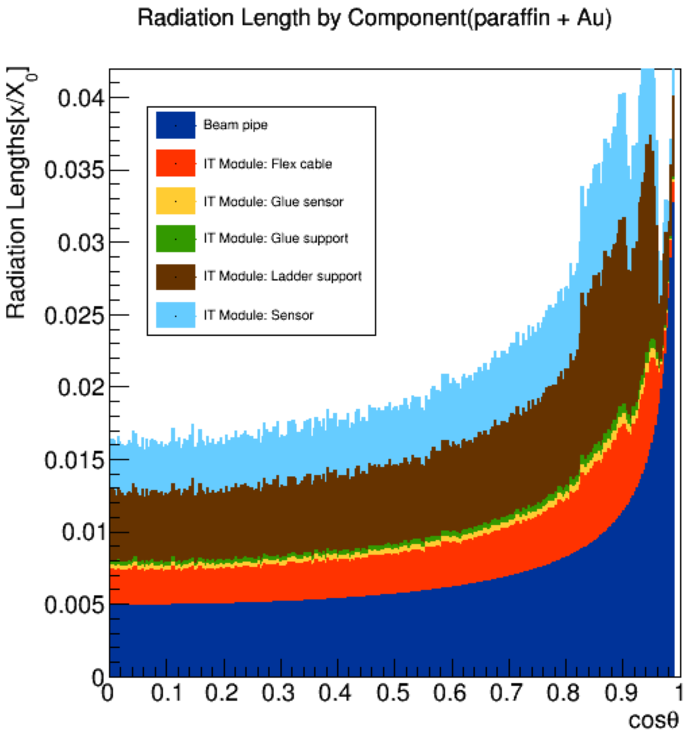
- Considering the mechanics, electronics and the beampipe, we got an optimal vertex layout which contains three double-layers in the barrel and three double-disks in the endcap.
- The d0 resolution of this optimal vertex is much better than the realistic implementation of CDR vertex and realistic long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

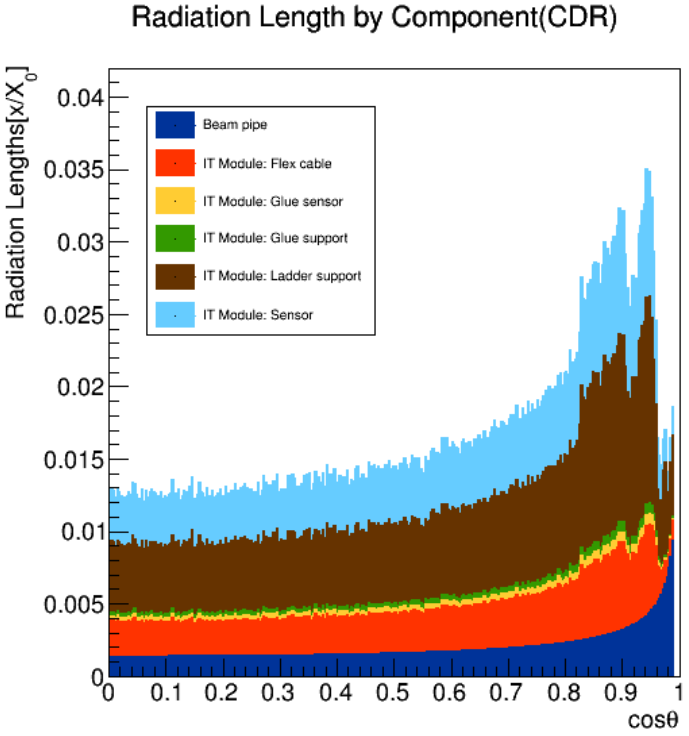
Material budget vs cosθ



Average (cosθ = [0, 0.99])	Radiation length
Beam pipe	0.00558
IT Module: Flex cable	0.00312
IT Module: Glue sensor	0.00037
IT Module: Glue support	0.00037
IT Module: Ladder support	0.00643
IT Module: Sensor	0.00444
total	0.02031

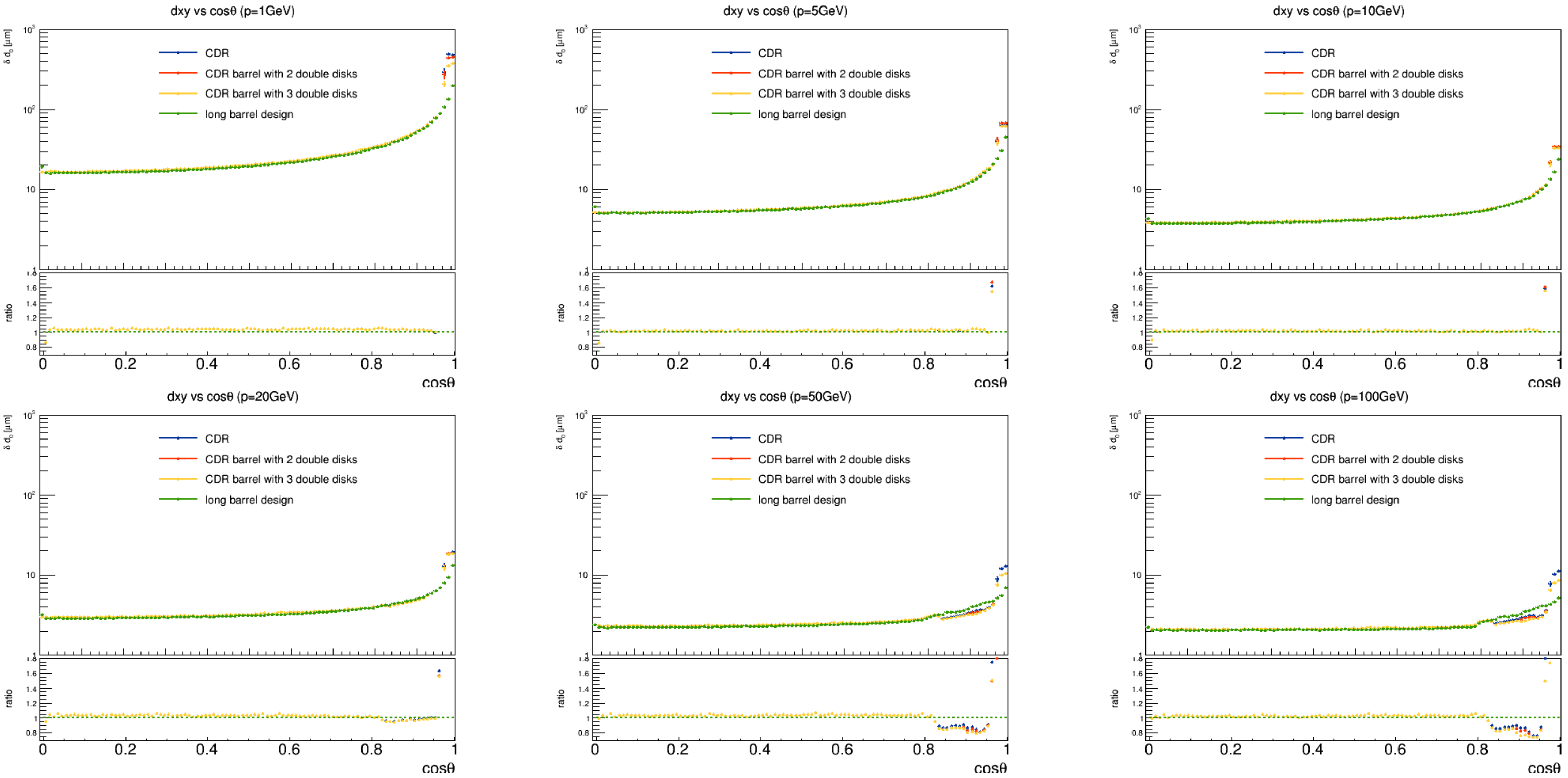


Average (cosθ = [0, 0.99])	Radiation length
Beam pipe	0.00707
IT Module: Flex cable	0.00312
IT Module: Glue sensor	0.00037
IT Module: Glue support	0.00037
IT Module: Ladder support	0.00643
IT Module: Sensor	0.00444
total	0.02180

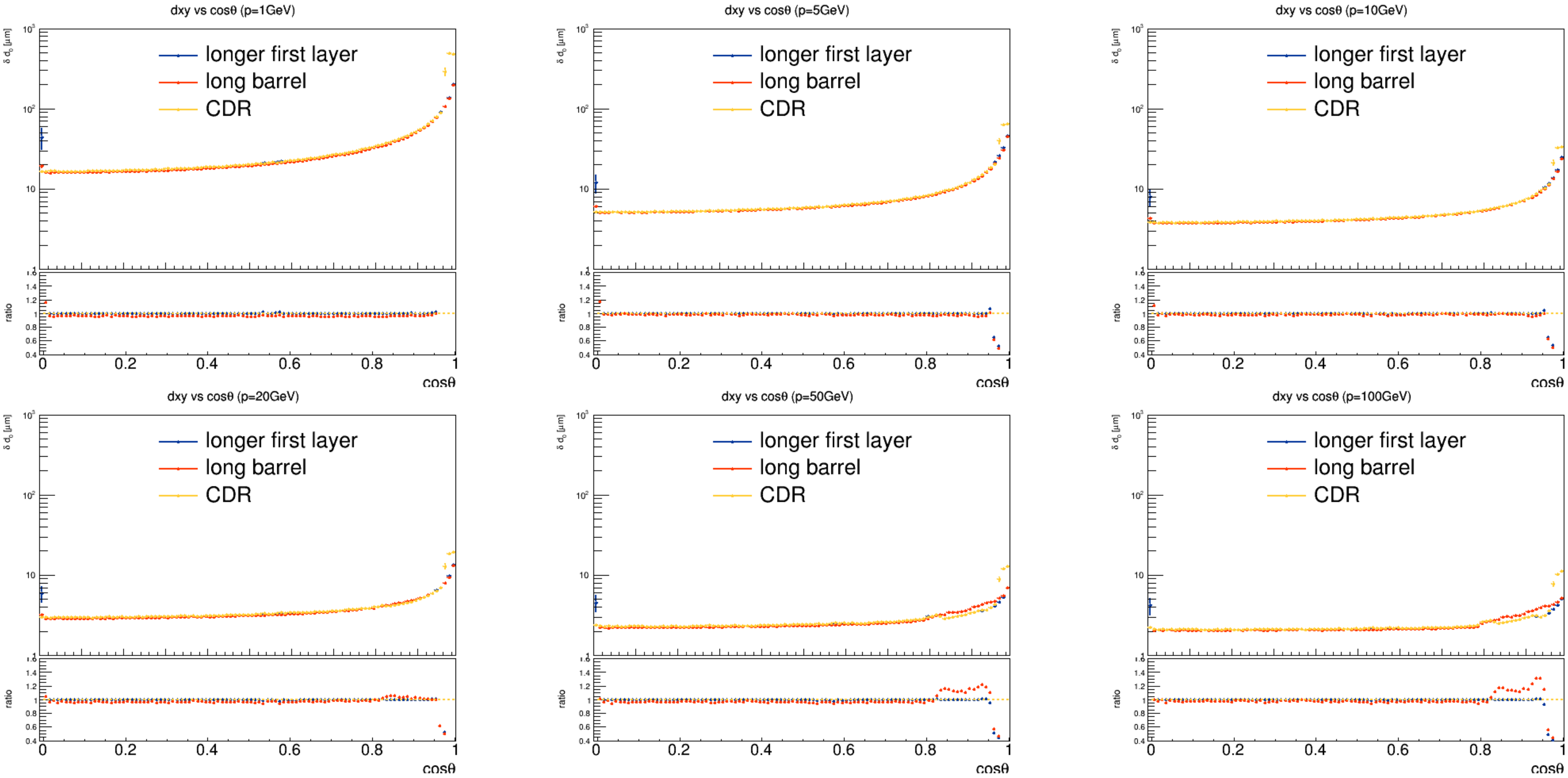


Average (cosθ = [0, 0.99])	Radiation length
Beam pipe	0.00203
IT Module: Flex cable	0.00312
IT Module: Glue sensor	0.00037
IT Module: Glue support	0.00037
IT Module: Ladder support	0.00643
IT Module: Sensor	0.00444
Total	0.01676

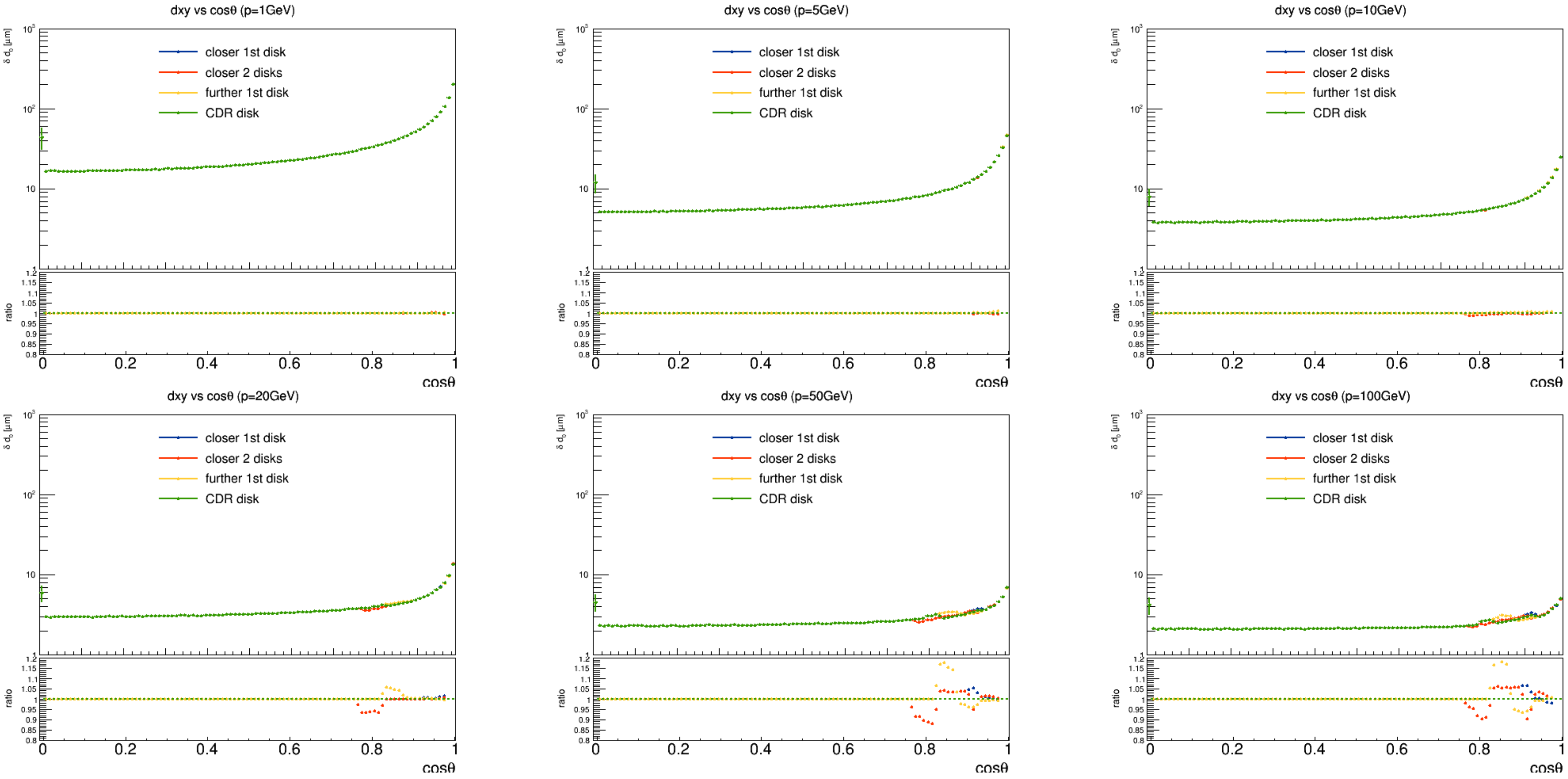
CDR barrel with different disk



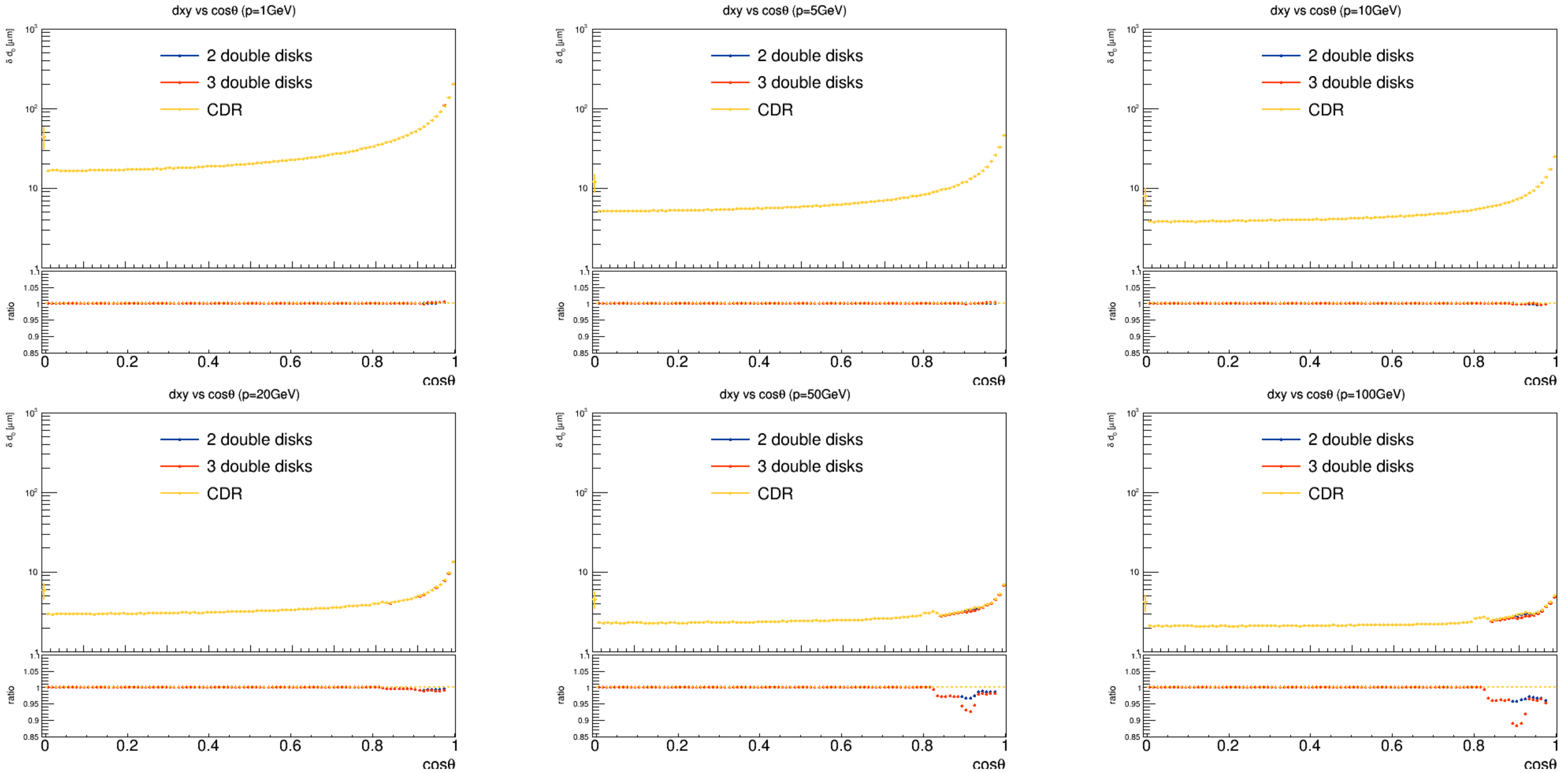
Longer first layer



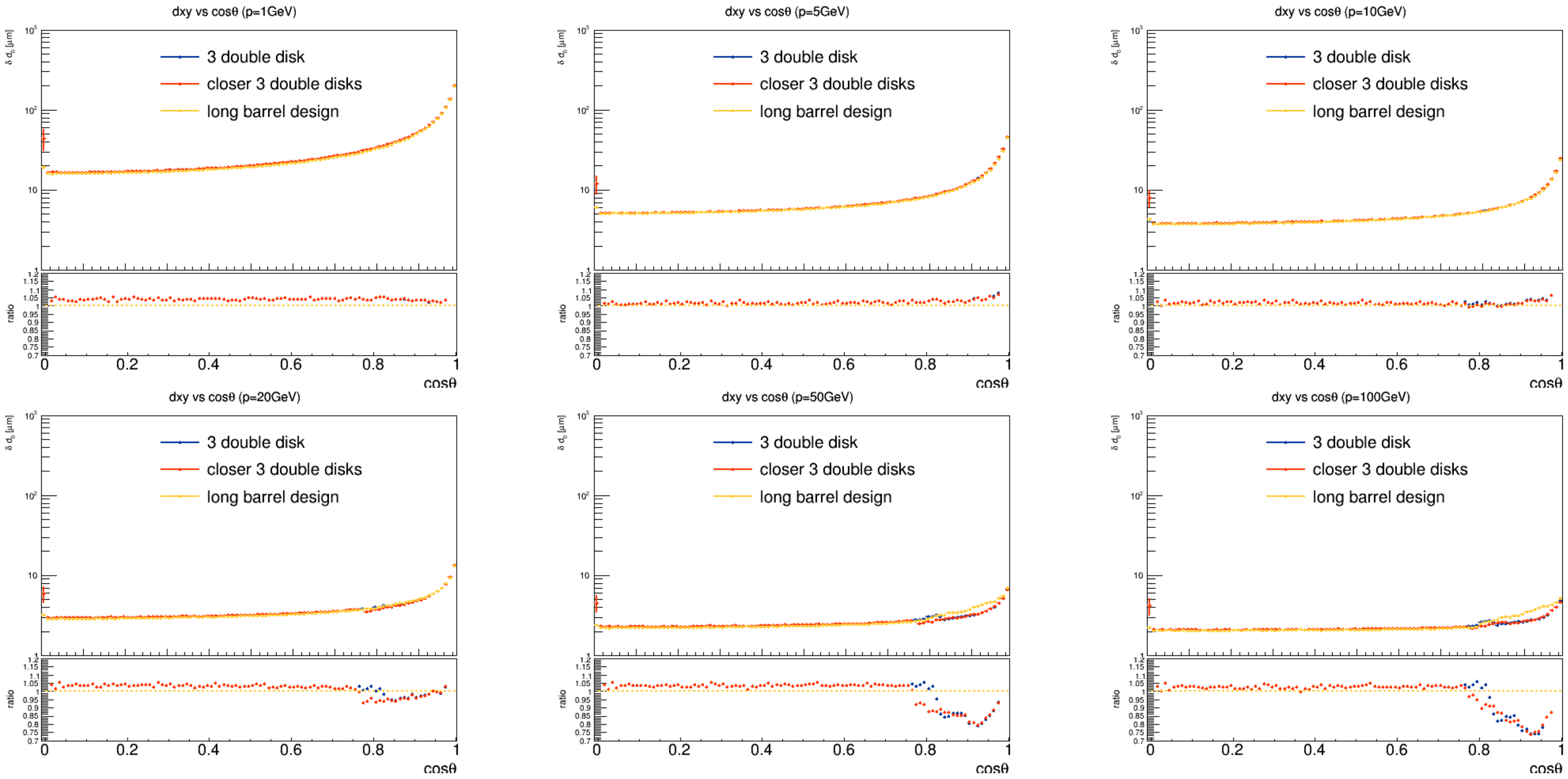
Different position of 2 single-layer disks



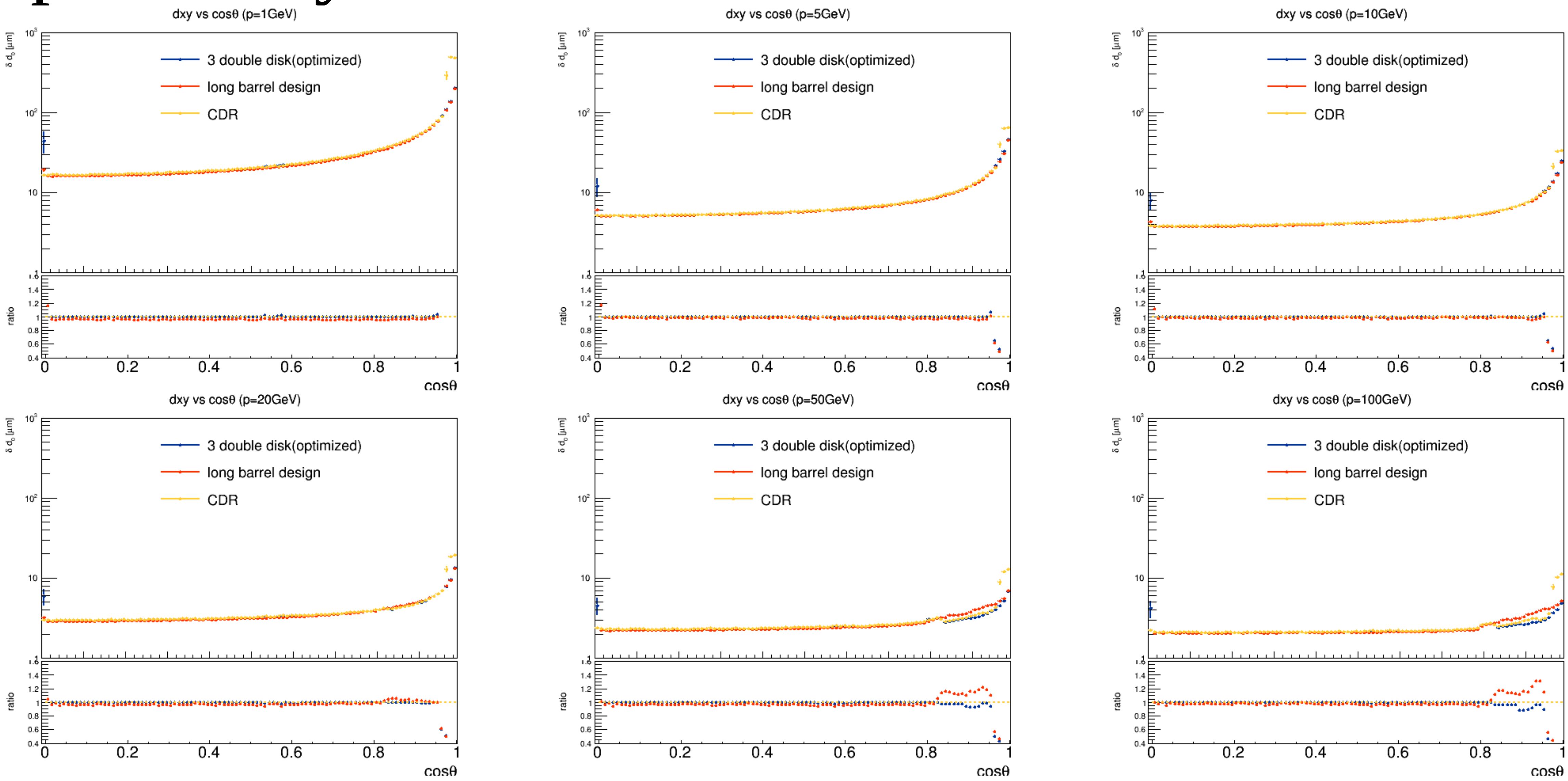
Longer first layer with different number of disk



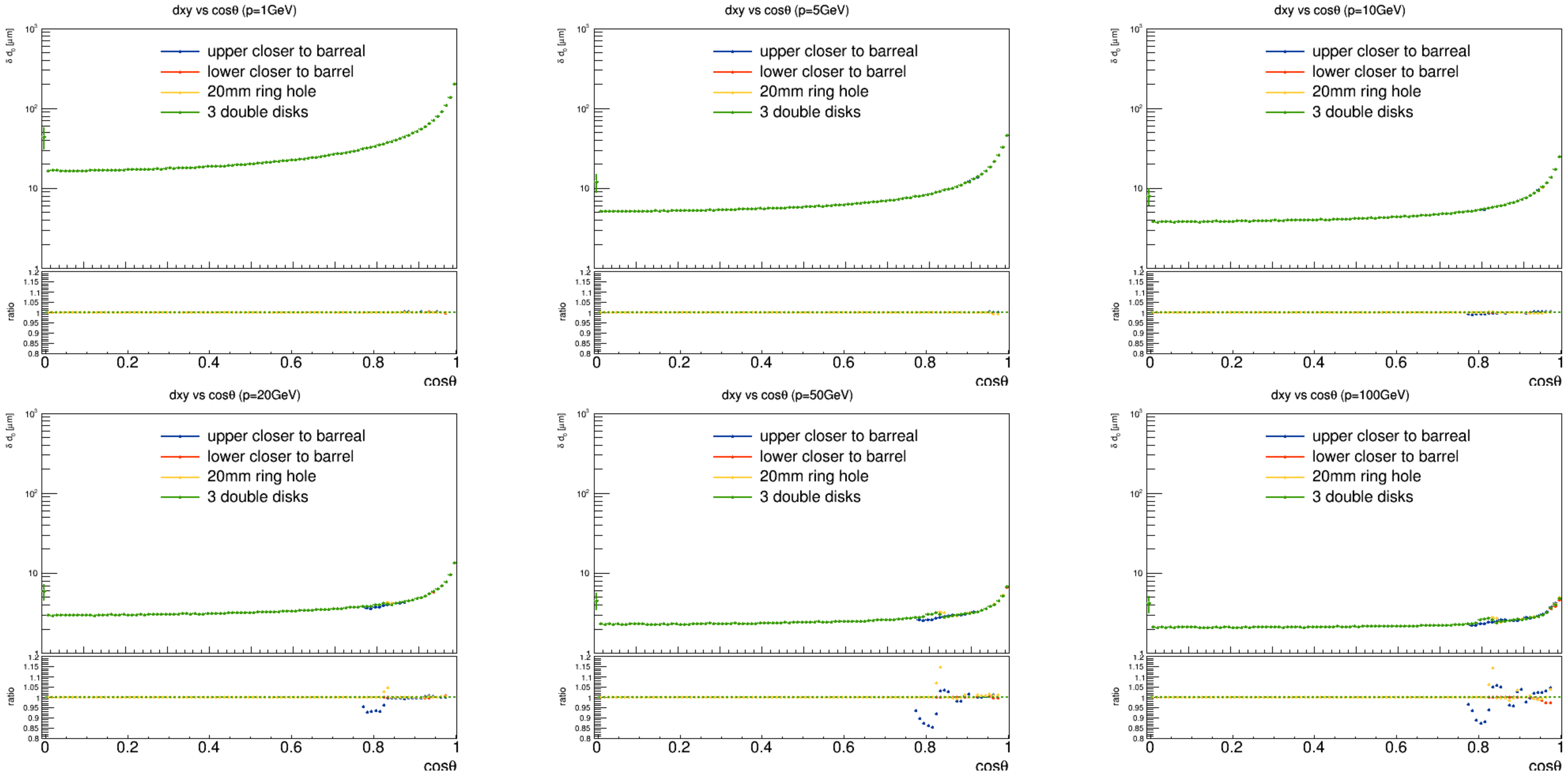
3 double-layer disks closer to barrel



Optimal layout



New disk arrangements



Optimization **thickness of beryllium pipe**

The thinner the Beryllium pipe

The less the mass

The better the performance

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) (safety)	inner ***Be*** pipe	**R1(inner radius)**	**thickness**	**Gap**	**R2**(outer radius)	R	E(GPa)	μ	Pcr(MPa)	
		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) (Performance)	inner ***Be*** pipe	**R1(inner radius)**	**thickness**	**Gap**	**R2**(outer radius)	R	E(GPa)	μ	Pcr(MPa)	
		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) (safety)	inner ***Be*** pipe	**R1(inner radius)**	**thickness**	**Gap**	**R2**(outer radius)	R	E(GPa)	μ	Pcr(MPa)	
		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) (Performance)	inner Be pipe	**R1(inner radius)**	**thickness**	**Gap**	**R2**(outer radius)	R	E(GPa)	μ	Pcr(MPa)	
		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 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

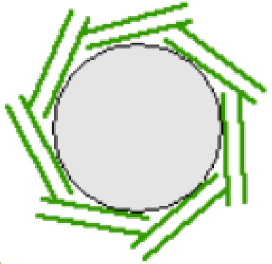
  Thickness of outer Be pipe: 0.25 mm
  Thickness of inner Be pipe: 0.20 mm

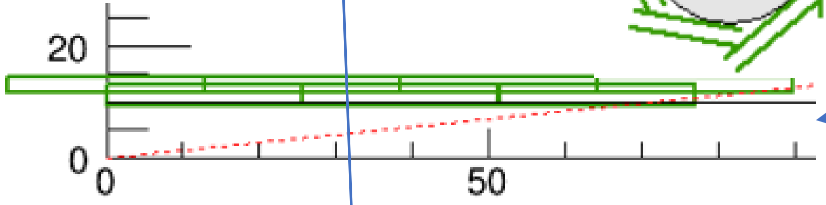
- performance first

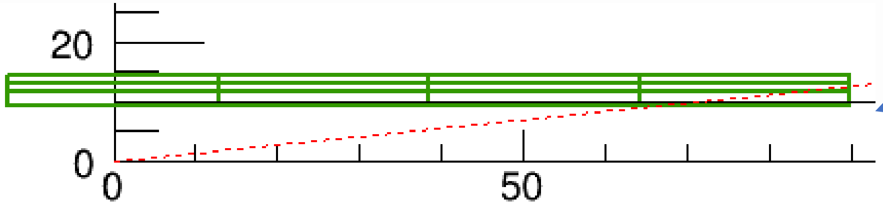
  Thinner (As shown in the left table)

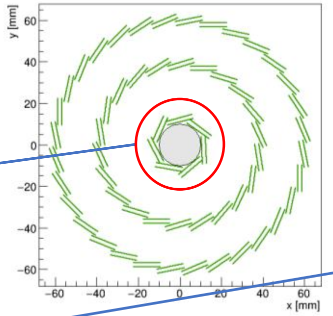
7 ladders arrangement for innermost layer

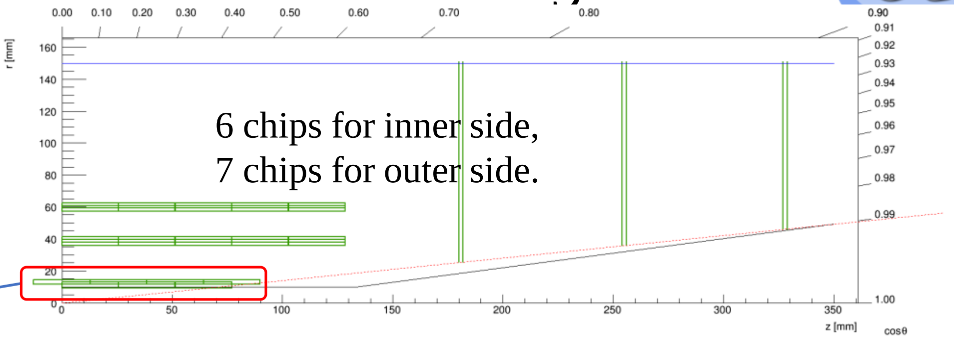
0.1 mm gap between two adjacent chips



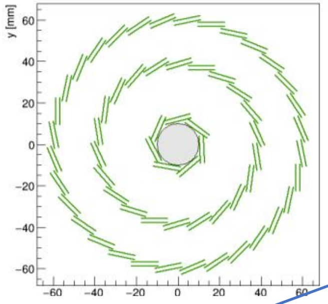


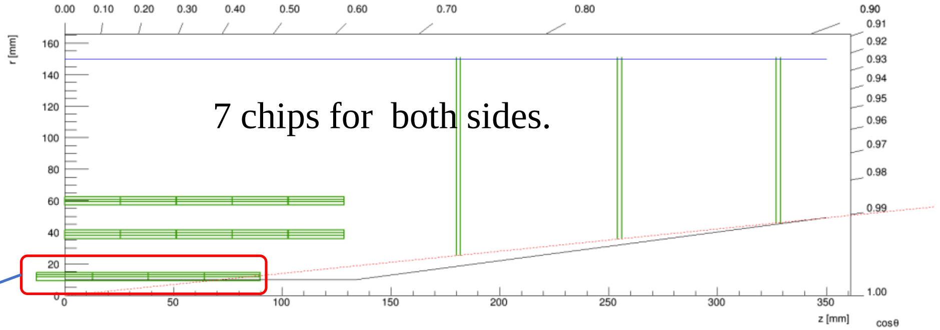




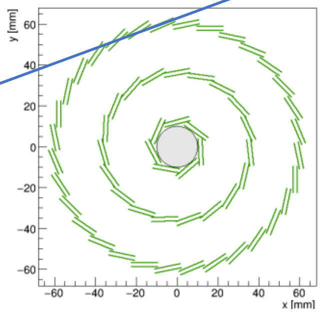


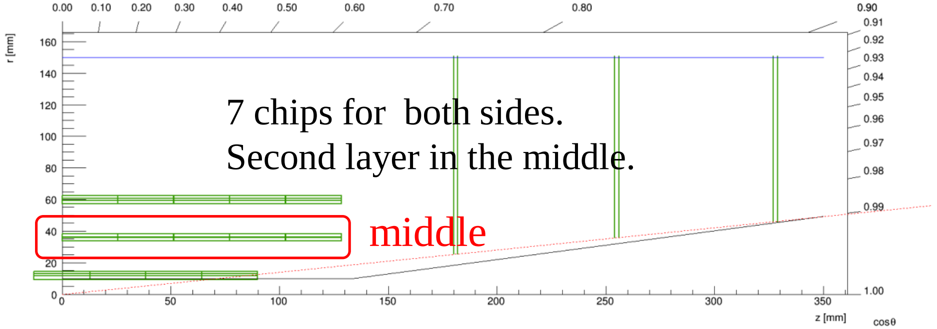
6 chips for inner side,
7 chips for outer side.





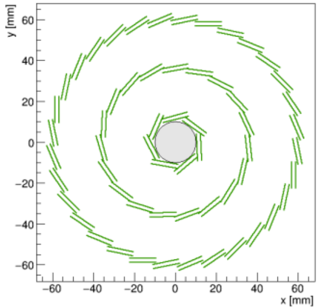
7 chips for both sides.

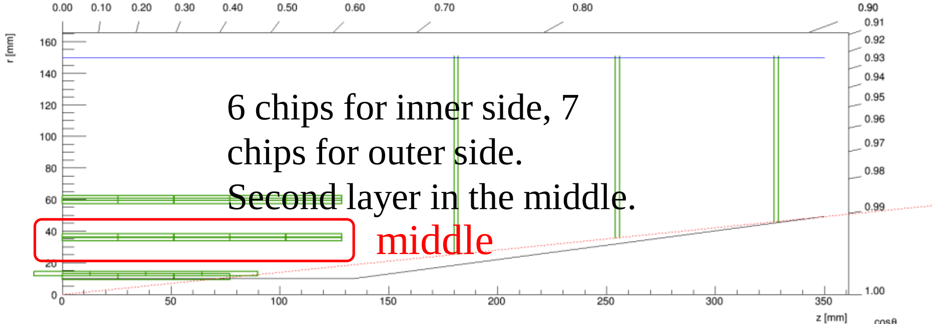




7 chips for both sides.
Second layer in the middle.

middle



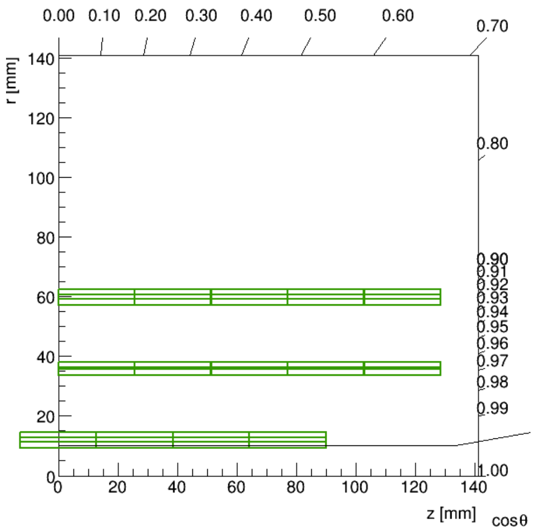


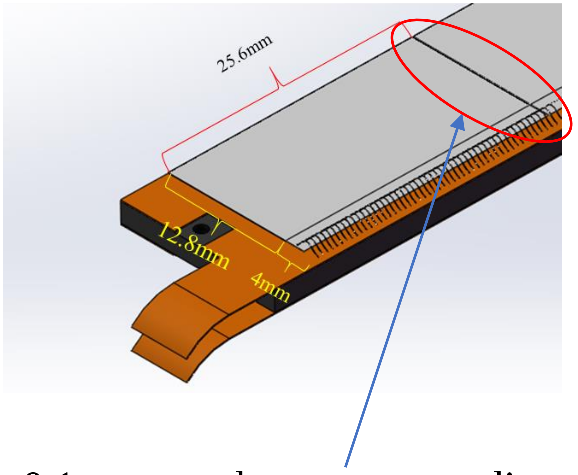
6 chips for inner side, 7 chips for outer side.
Second layer in the middle.

middle

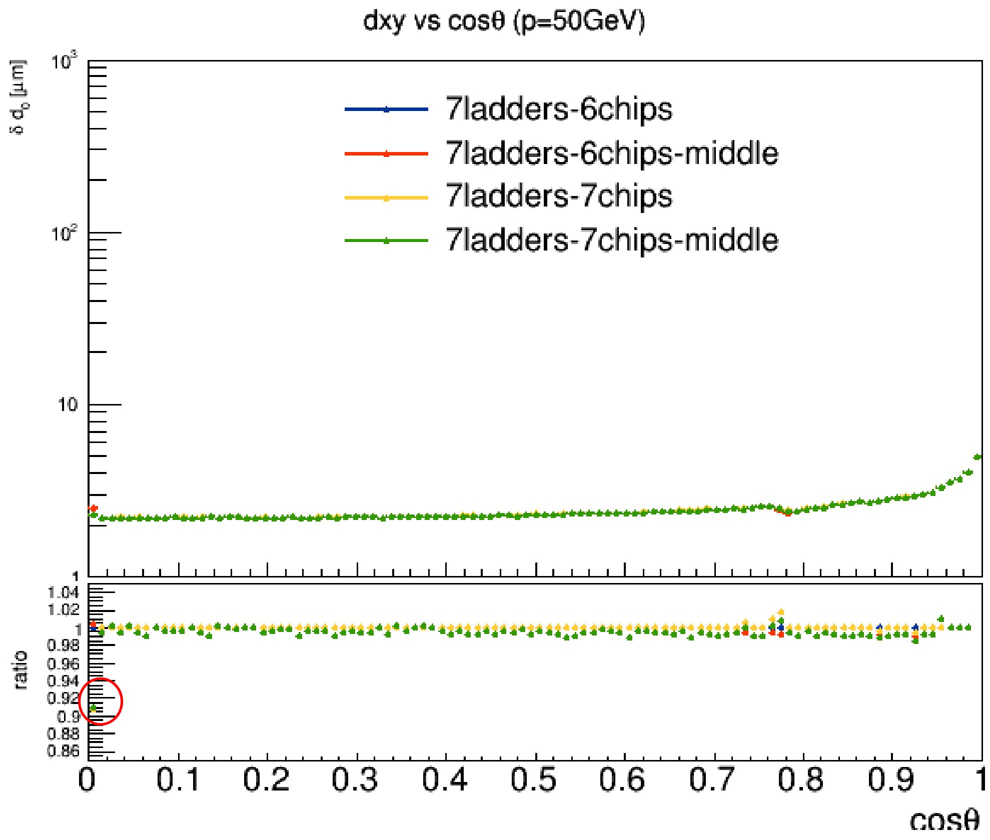
7 ladders arrangement for innermost layer

- 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.



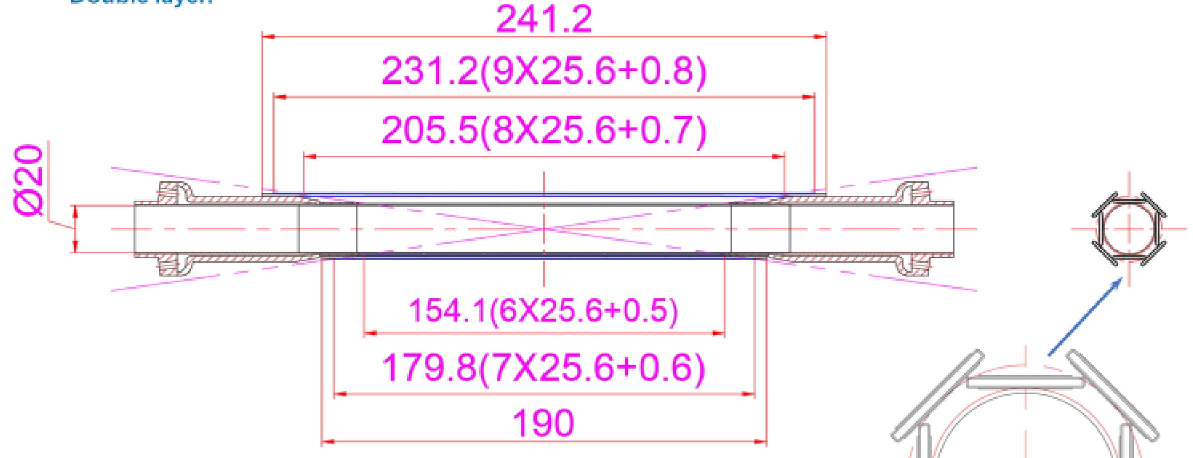


0.1 mm gap between two adjacent chips



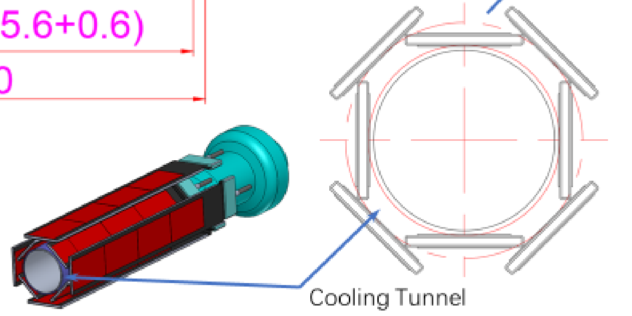
8 ladders arrangement for innermost layer

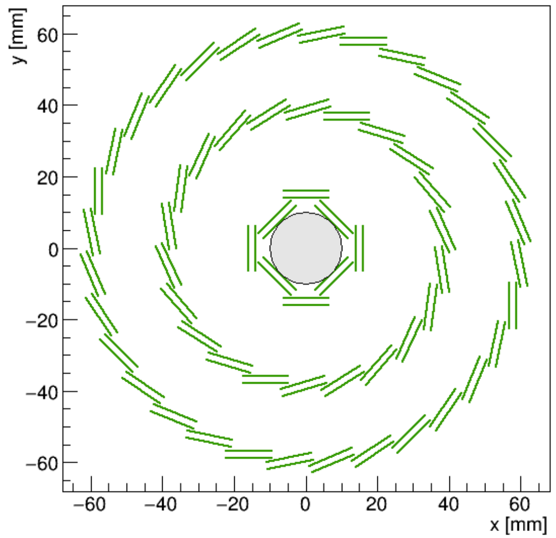
Double layer:



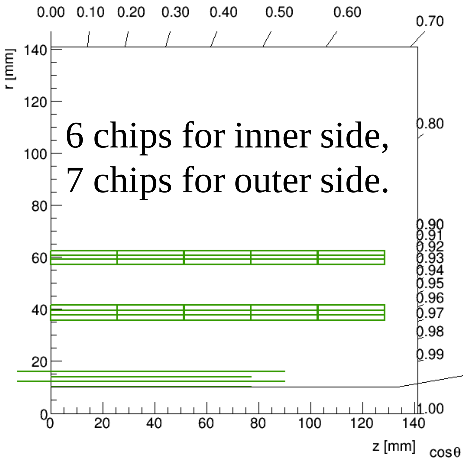
Pros:
The area of cooling tunnel has been extended.

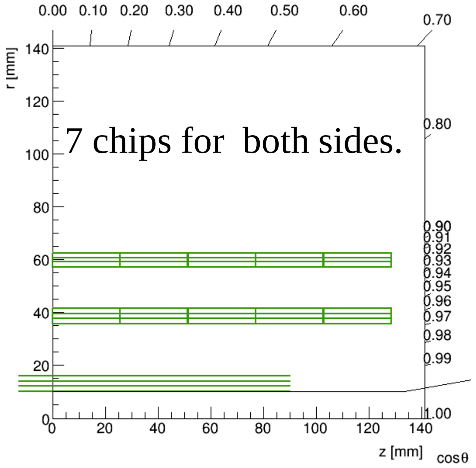
Cons:
The detecting distance of two layer is different.



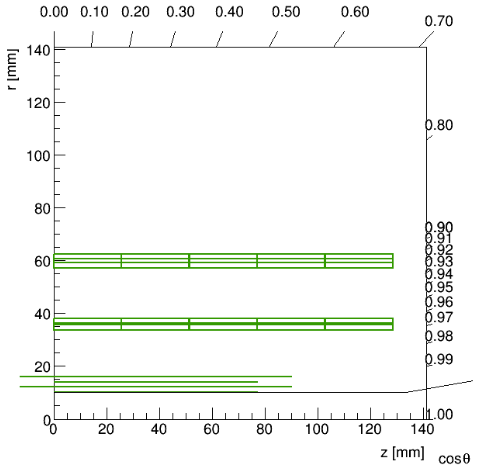


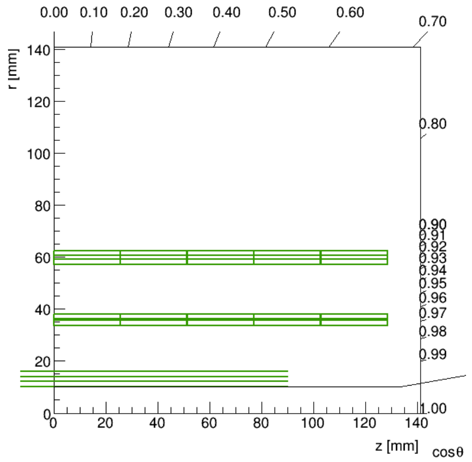
ideal condition excluding dead area of the ladders



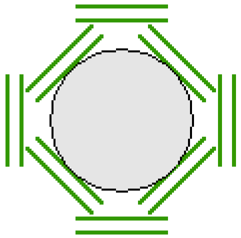


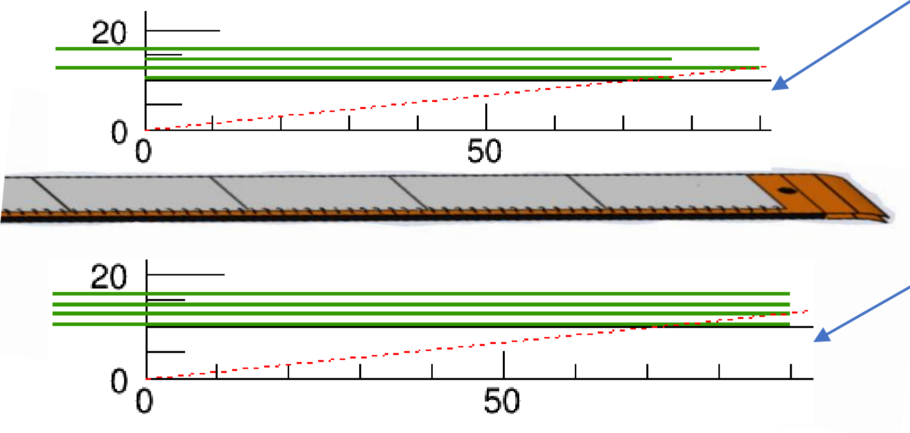
Second layer in the middle:

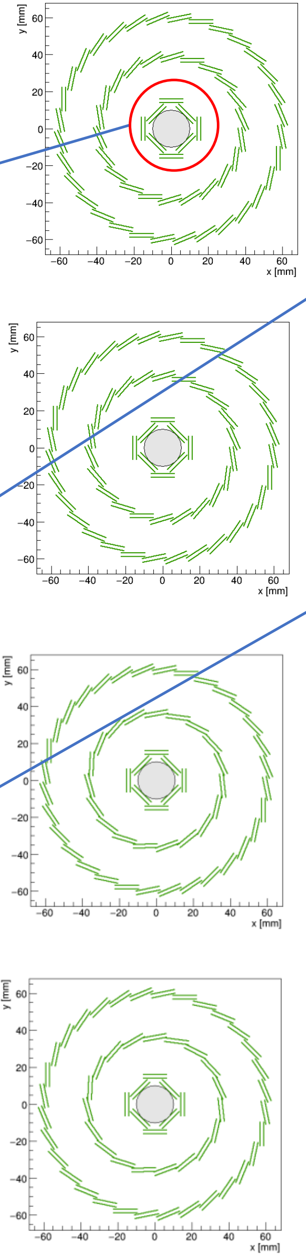


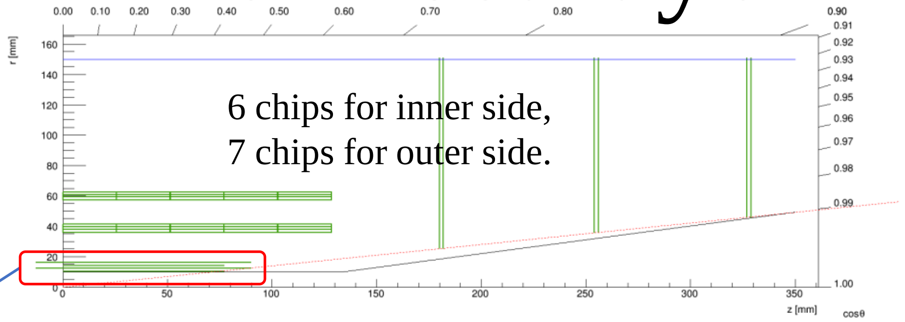


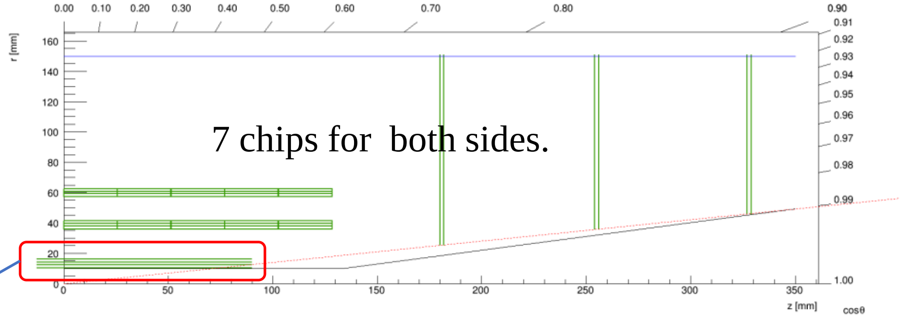
8 ladders arrangement for innermost layer

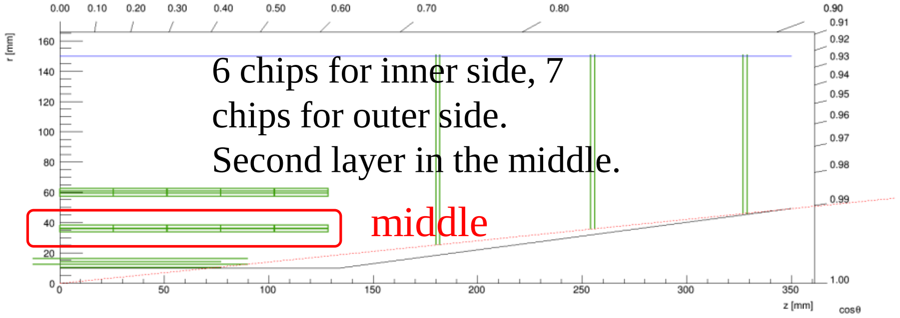


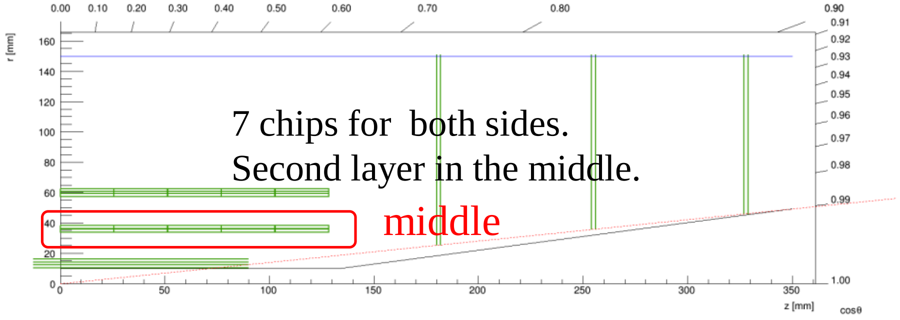




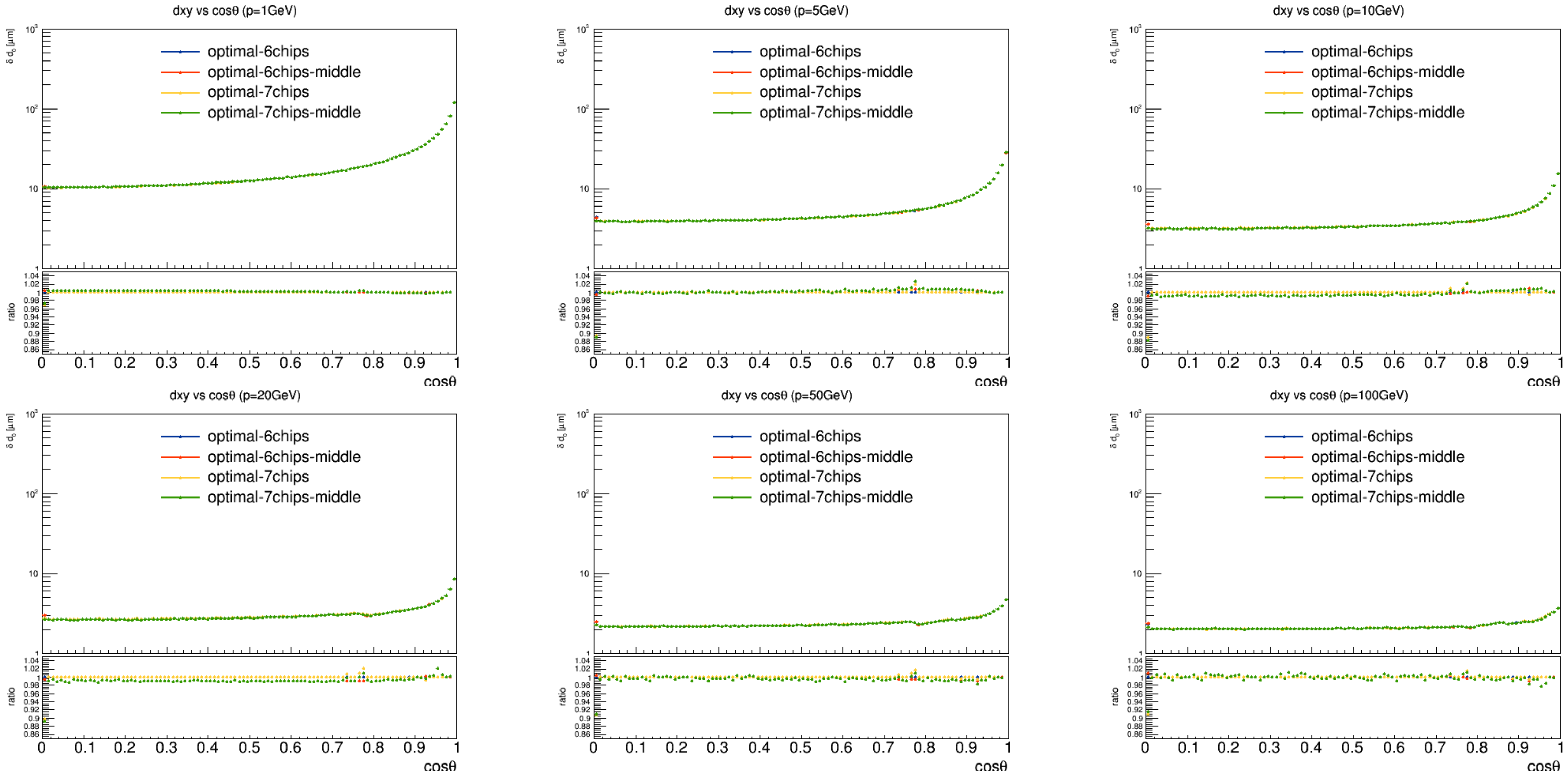




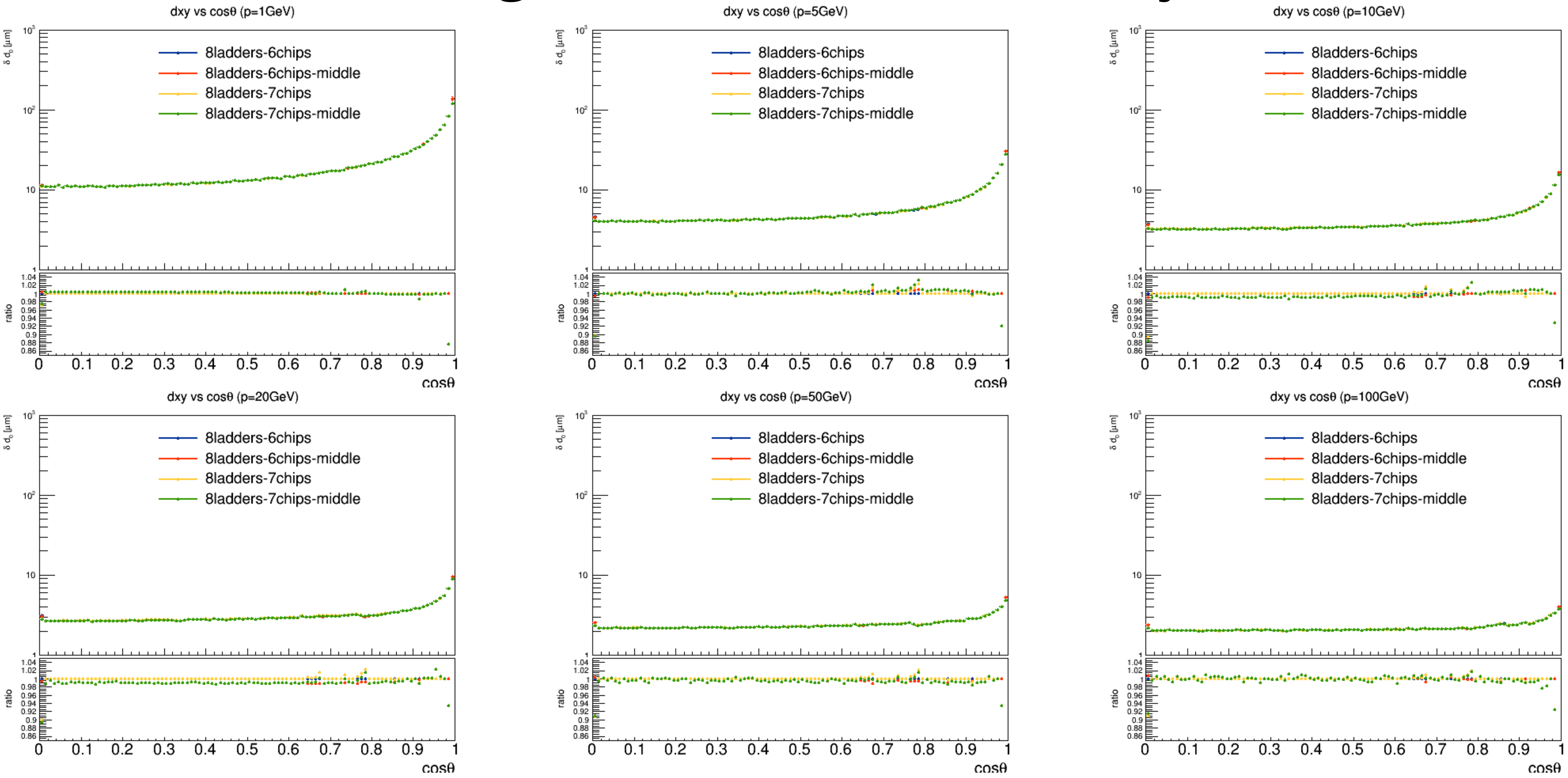




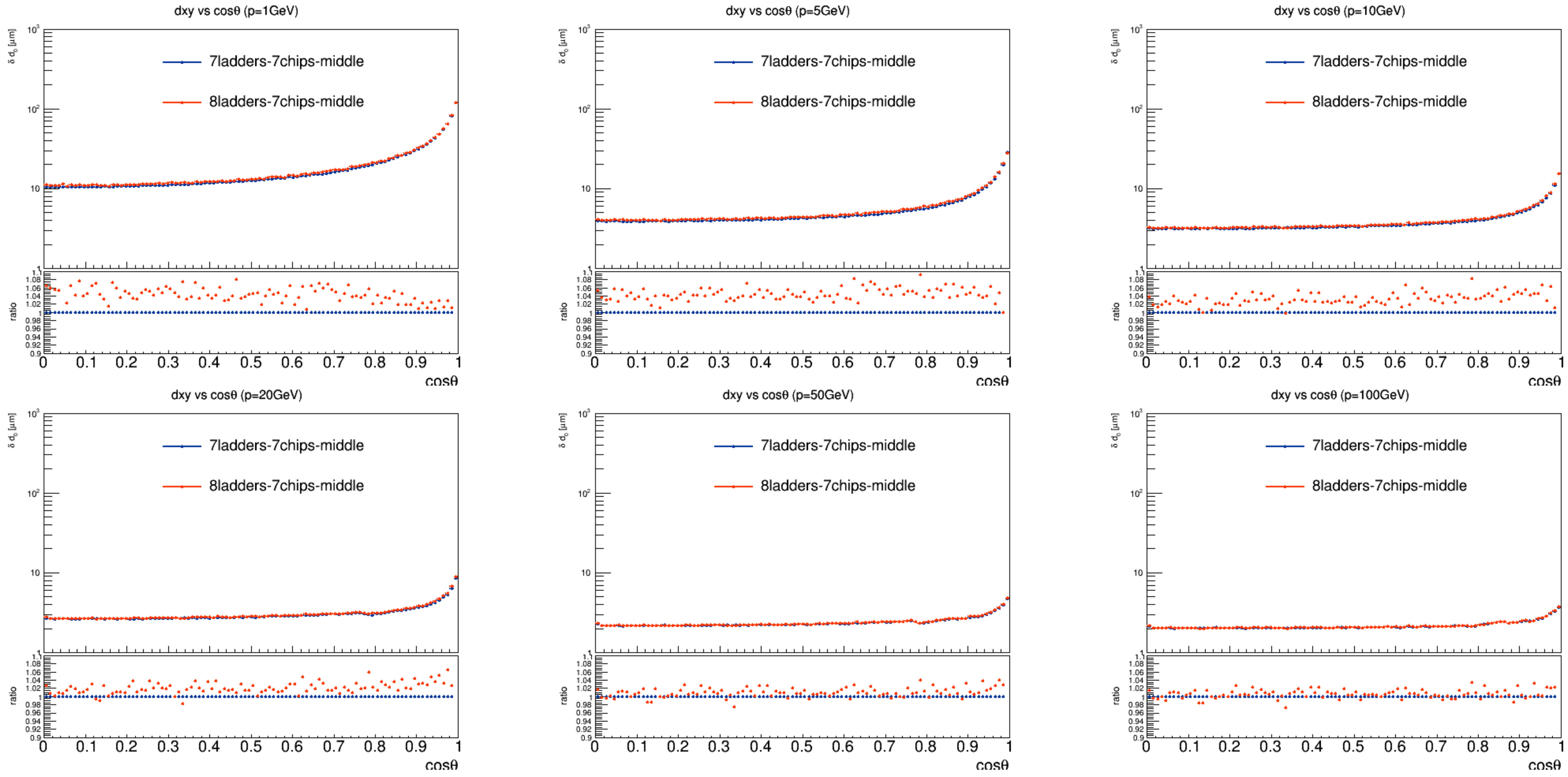
7 ladders arrangement for innermost layer



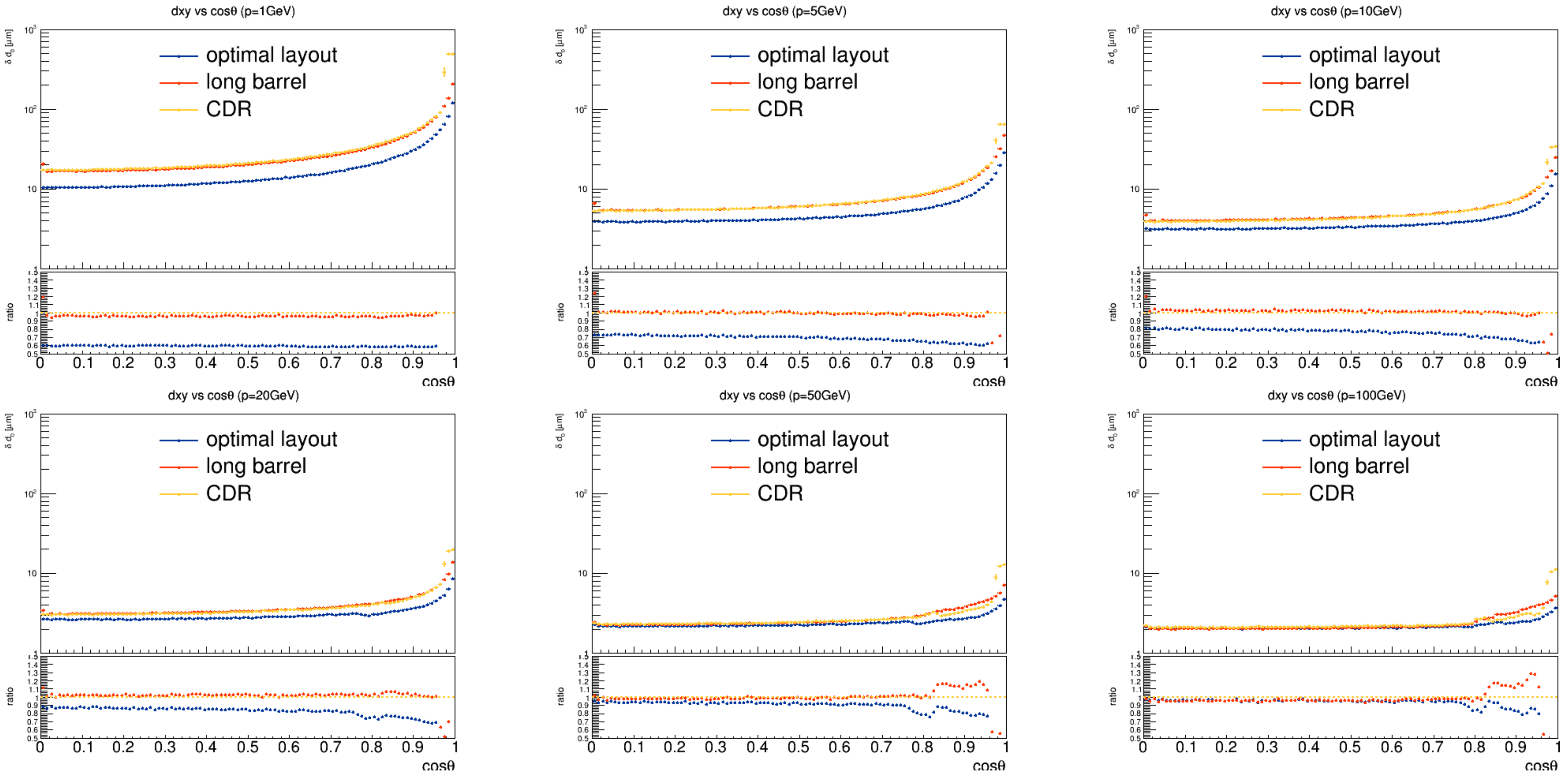
8 ladders arrangement for innermost layer



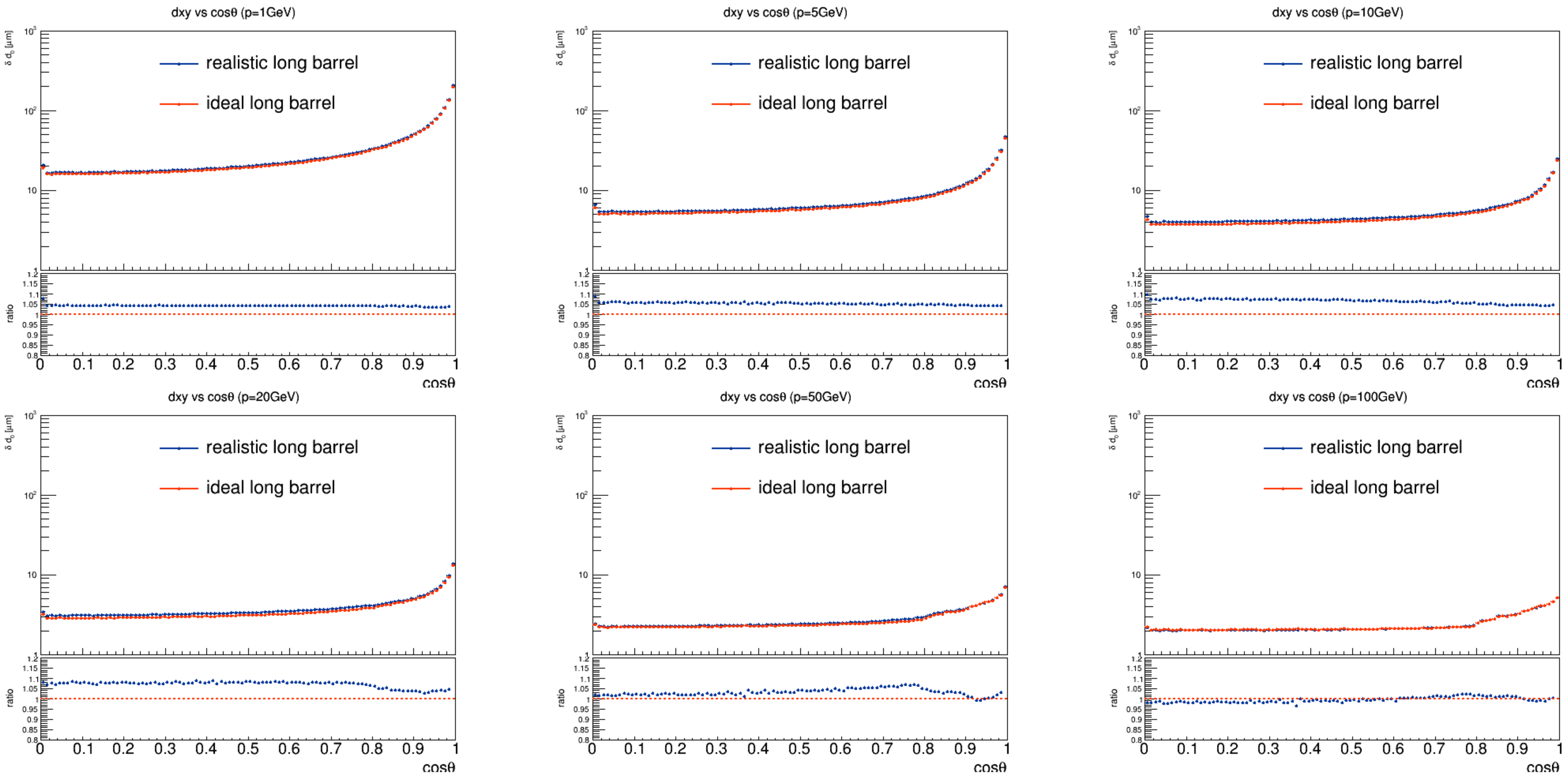
Comparison of different ladder arrangements for innermost layer



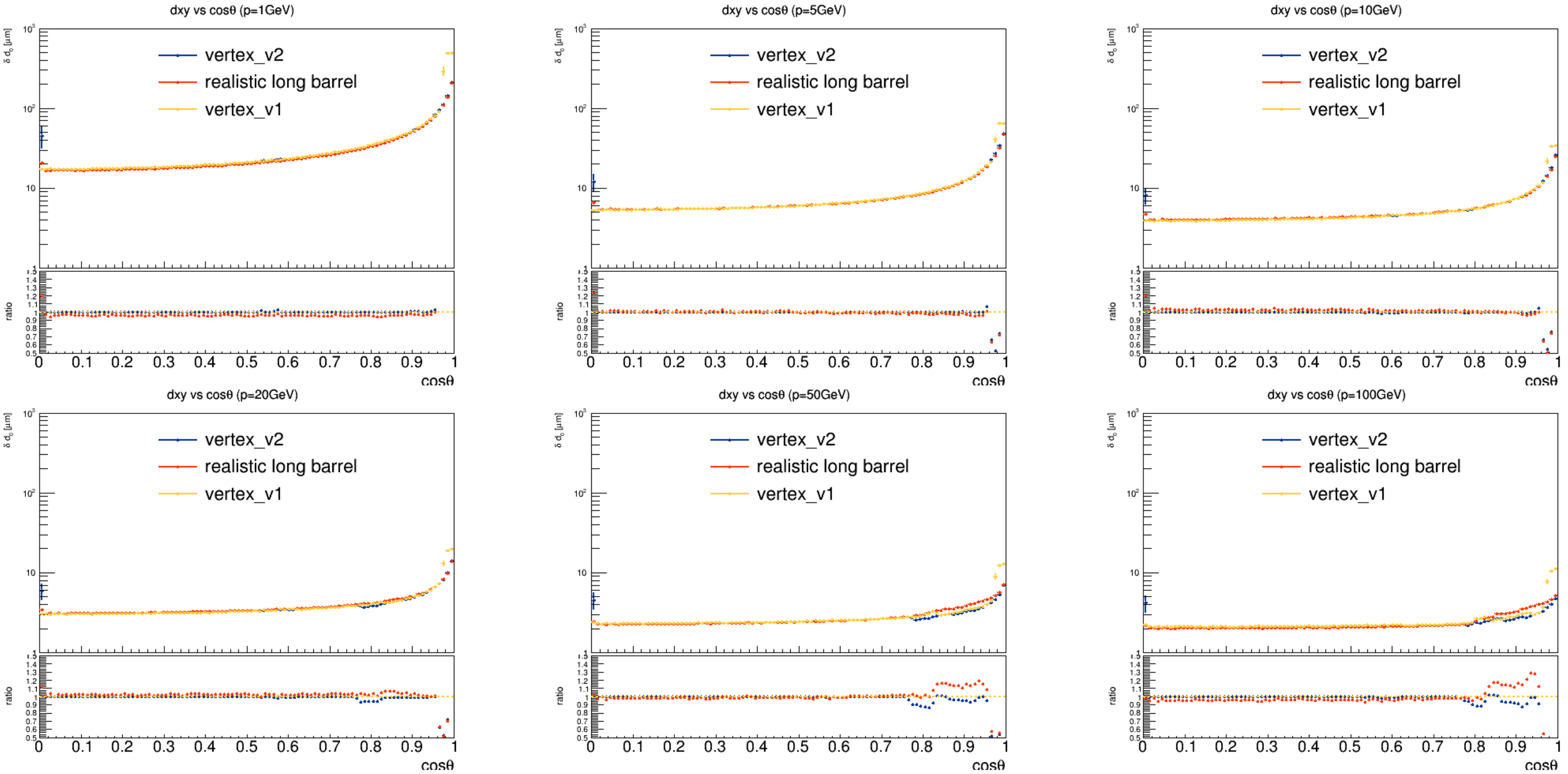
d0 resolution of optimal vertex layout



New long barrel



vertex_v2 performance



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: