Optimization of Silicon Pixel Vertex Detector for CEPC

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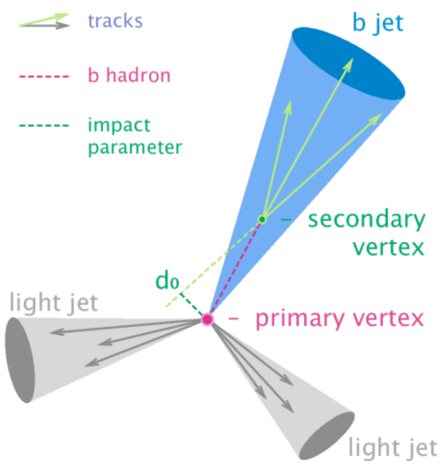
CEPC Physics Requirements

- 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
- τ identification is also depending on the vertex displacement and jet structure
- Silicon vertex detector is essential to measure the vertex displacement
  - An impact parameter resolution of about 5 μm is required

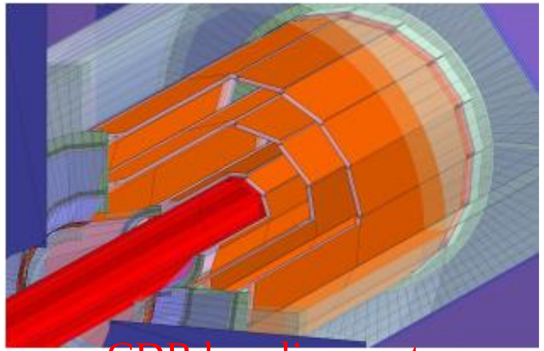
Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	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	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

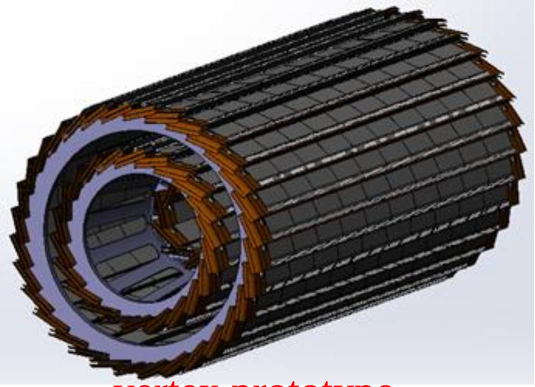
Table 3.3: Physics processes and key observables used as benchmarks for setting the requirements and the optimization of the CEPC detector.



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)
  - Considering beam pipe, MDI, cooling

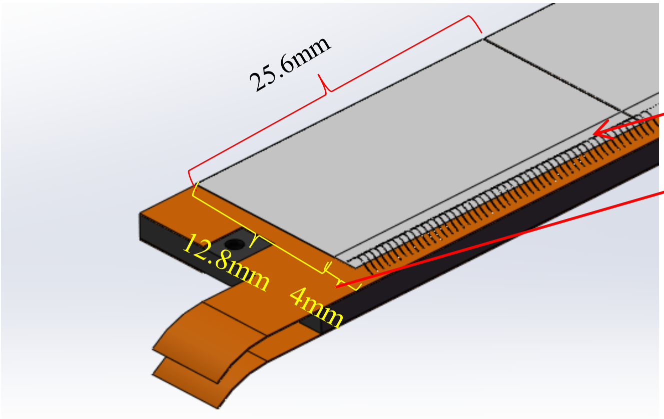

CDR baseline vertex


vertex prototype

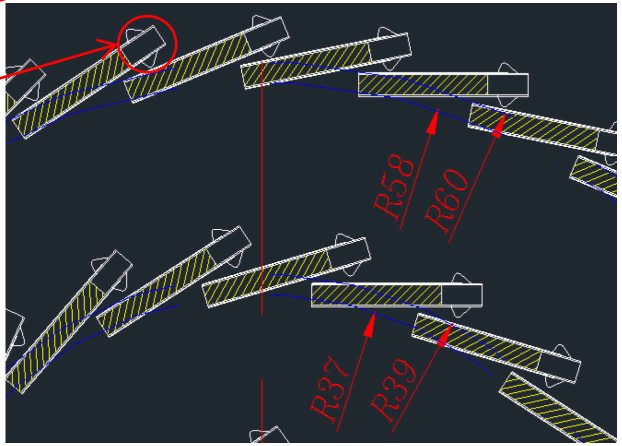

Belle II vertex detector

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)

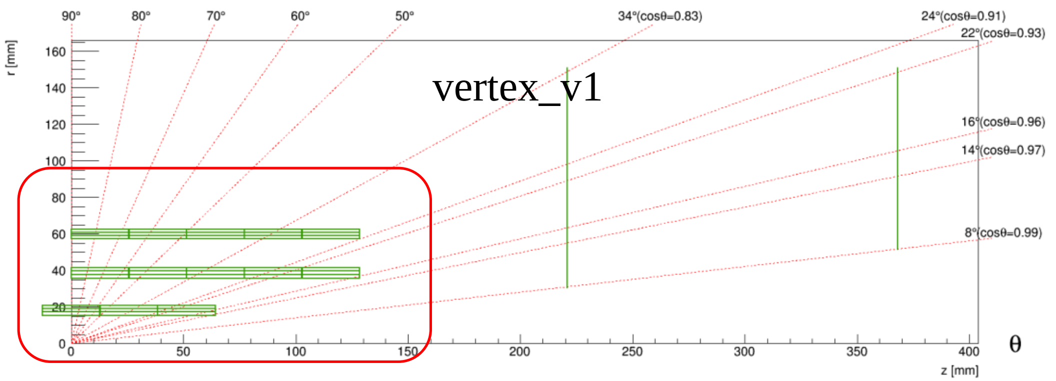
(1) Sensor
(2) Flex cable
(3) Ladder support
(4) Flex cable
(5) sensor

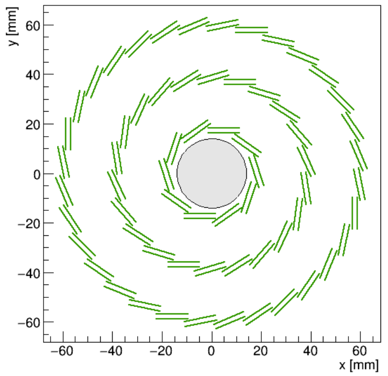
	Thickness	Optimization goal
Polyimide	25um	12
Adhesive	28um	15
Plating Al	17.8um	?
kapton	50um	50
Plating Al	17.8um	?
Adhesive	28um	15
Polyimide	25um	12

Flex cable material from Mingyi

CDR Vertex Layout Implementation

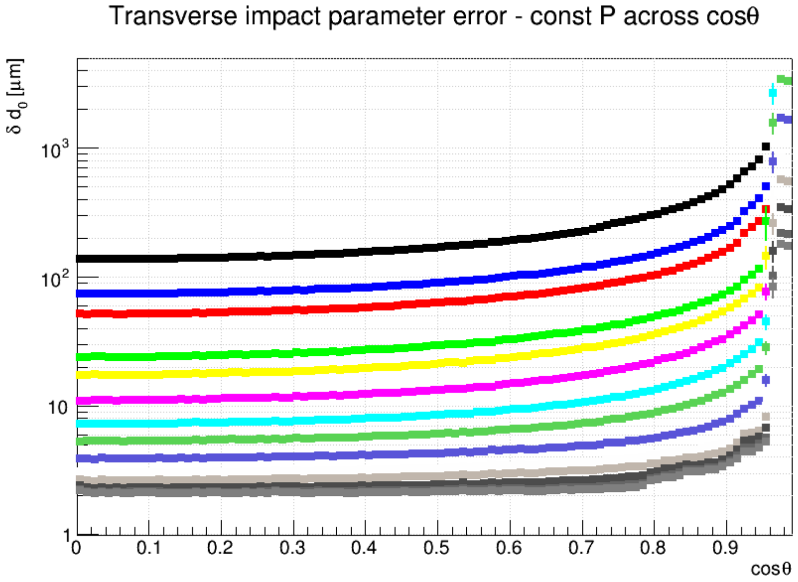
- vertex_v1: realistic implementation of CDR vertex
  - Barrel: 3 double-layers
  - Endcap: 2 single disks
  - Only consider the barrel for MOST2 project
  - total average material budget is about 1.3% for vertex barrel, much more than CDR 0.9% (0.15% × 6)

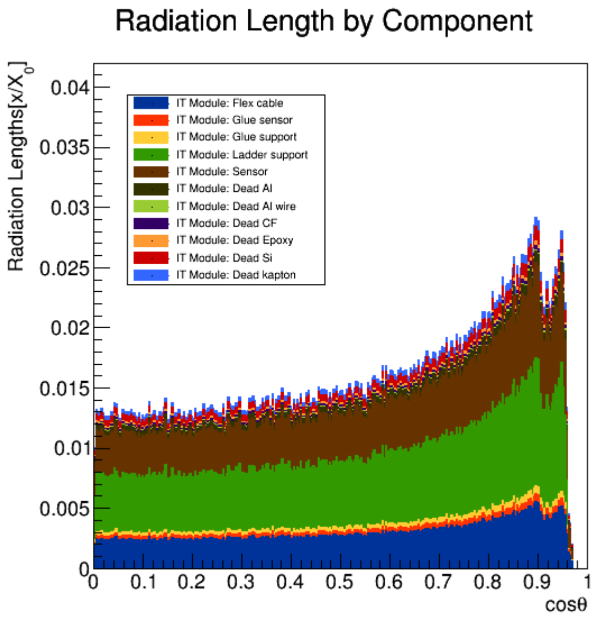




	Average R(mm)	# ladder		# chip on 1 ladder	Total # chips
Layer 1	18	10	L1_inner	5	50
			L1_outer	5	50
Layer 2	38	22	L2_inner	10	220
			L2_outer	10	220
Layer 3	60	32	L3_inner	10	320
			L3_outer	10	320
					1280

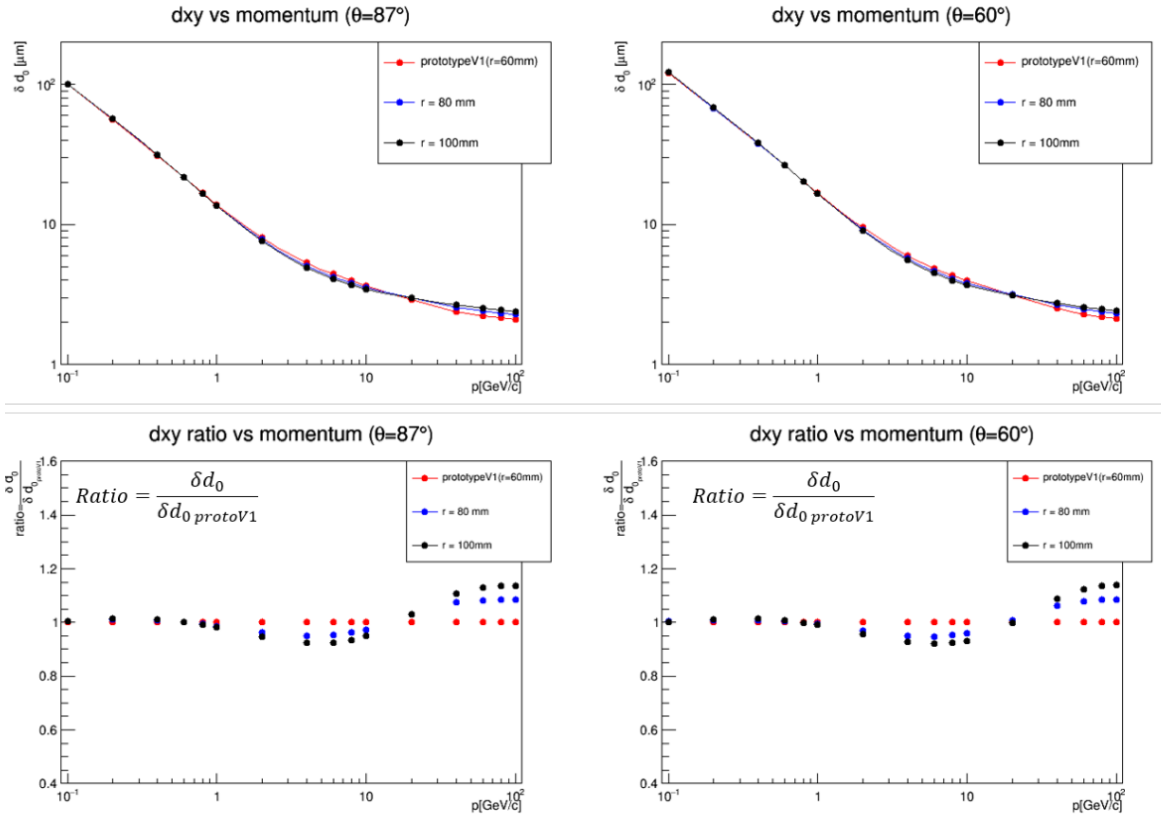
Barrel parameters



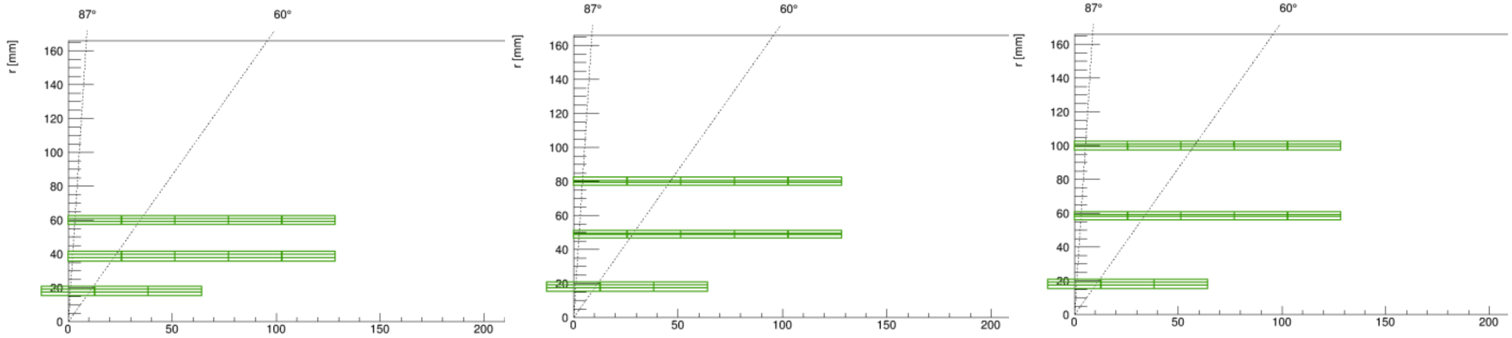


Barrel Optimization: Radius of the Vertex

- 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



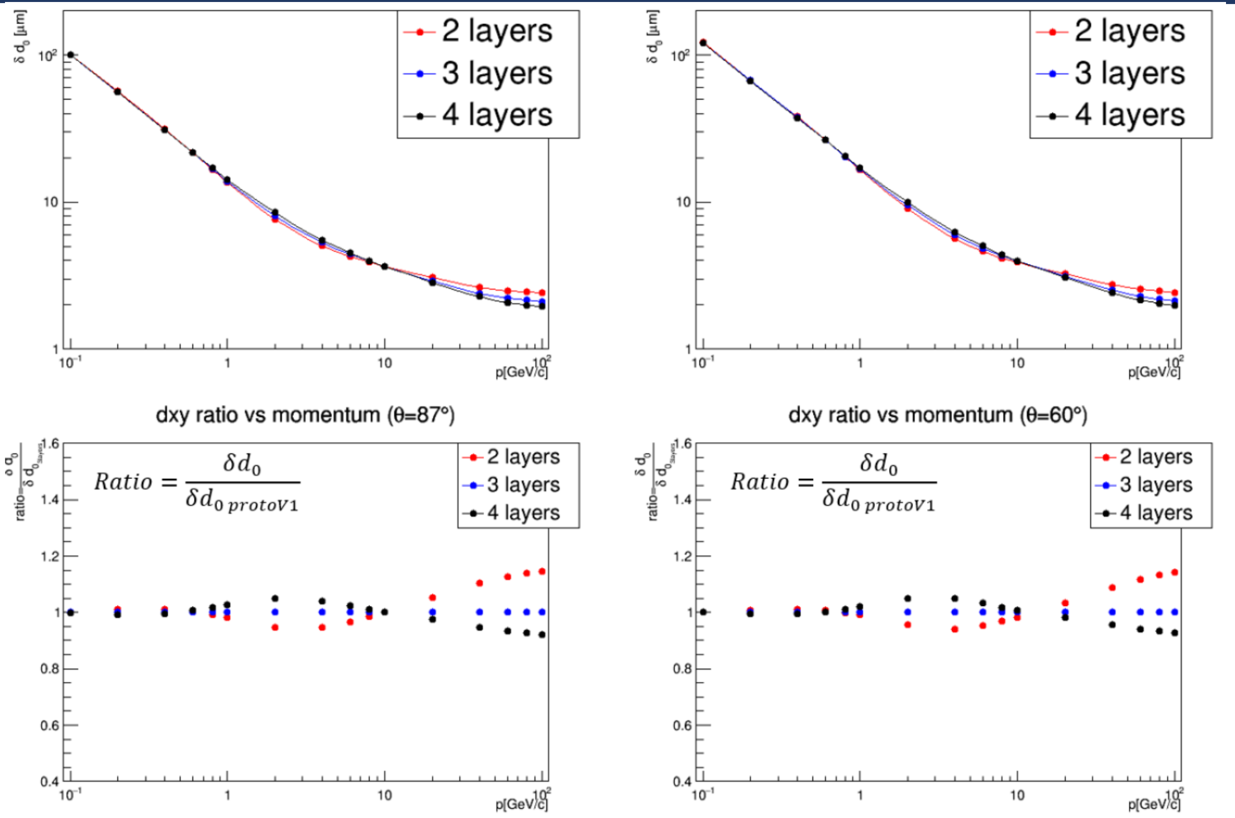
	prototype_v1	R=80mm	R=100mm
double-layer	R (mm)	R (mm)	R (mm)
Layer 1	18	18	18
Layer 2	38	49	59
Layer 3	60	80	100

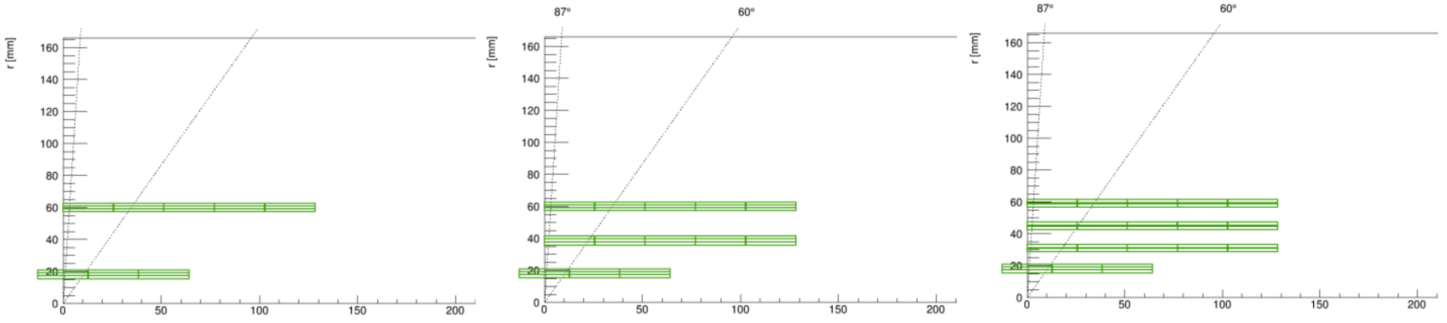


Barrel optimization: Number of Layers

- 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



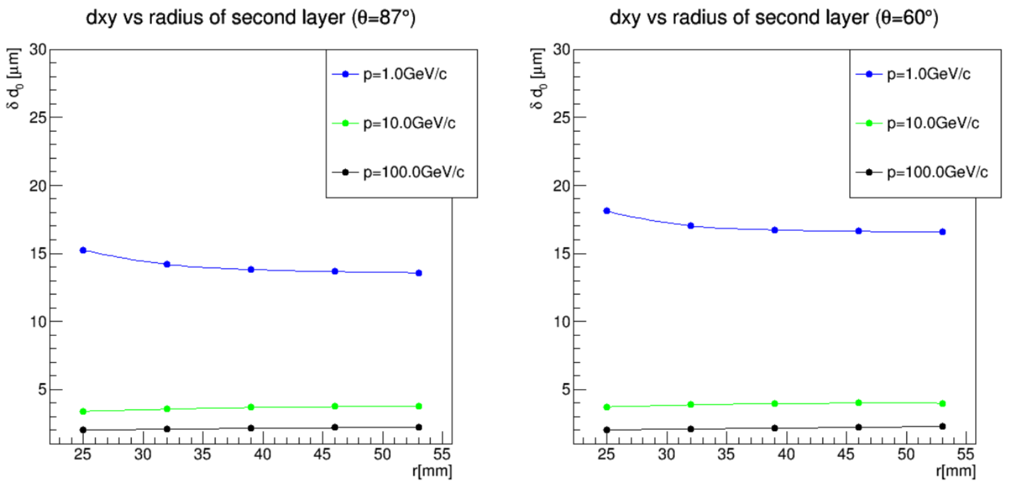


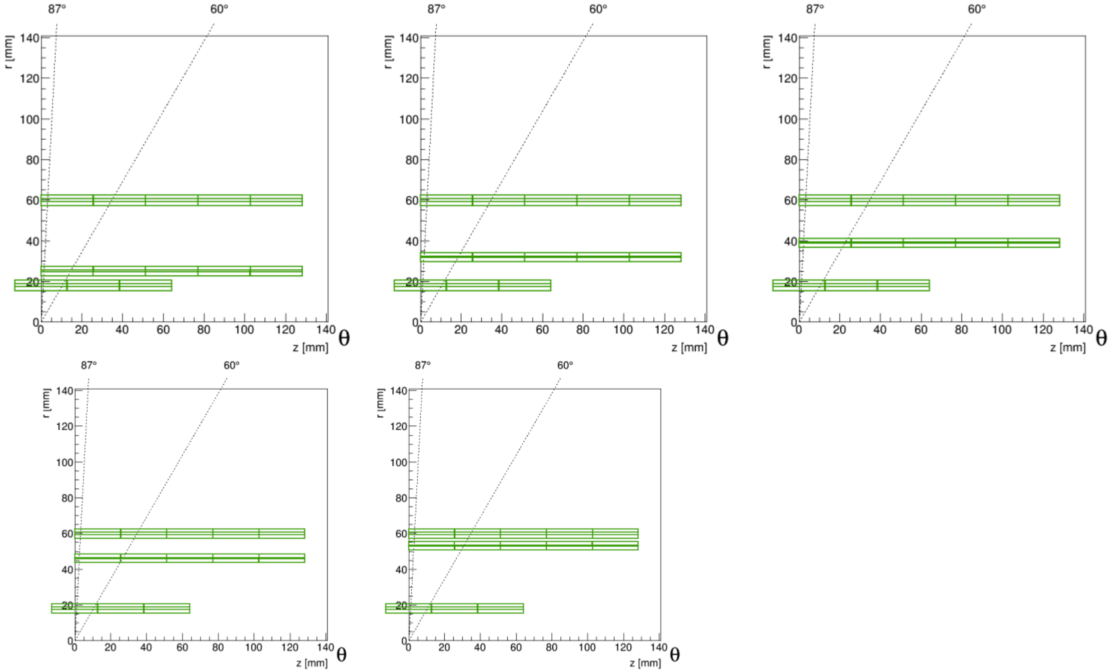
Barrel Optimization: Radius of Second Layer

- 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.

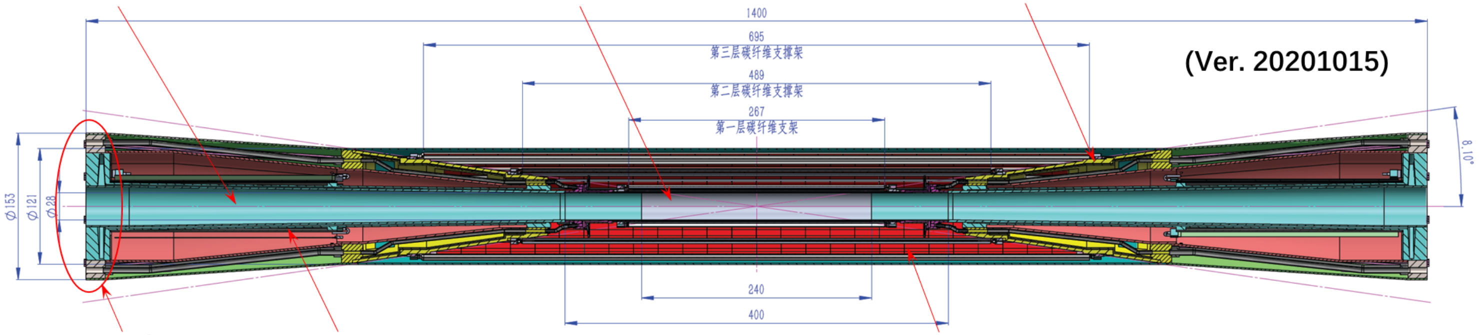
	r_2=25mm	r_2=32mm	r_2=39mm	r_2=46mm	r_2=53mm
double-layer	R (mm)	R (mm)	R (mm)	R (mm)	R (mm)
Layer 1	18	18	18	18	18
Layer 2	25	32	39	46	53
Layer 3	60	60	60	60	60

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.

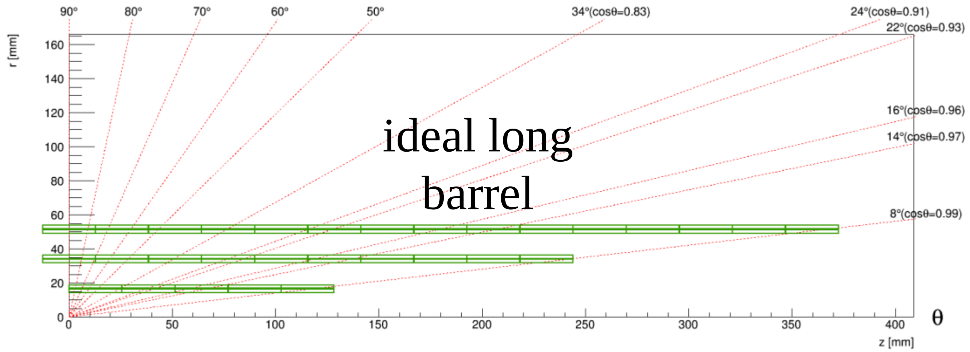


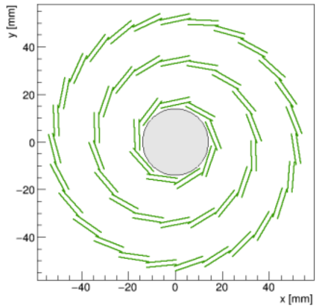


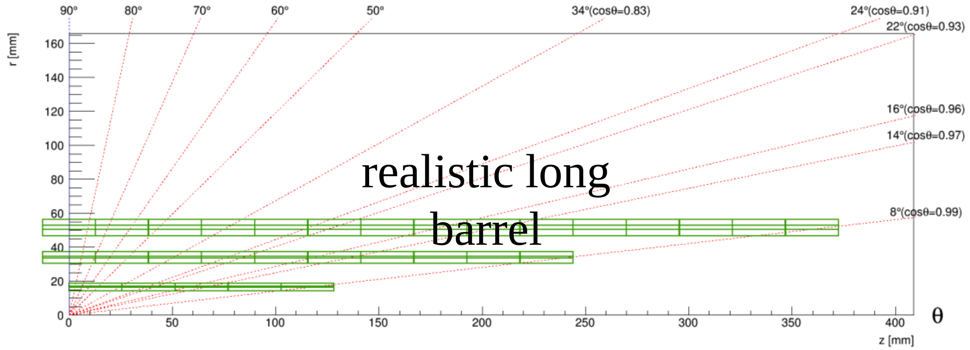
Long Barrel Vertex

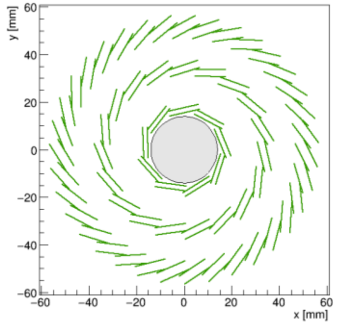


- Feasible solution for air cooling
- Simple structure
- Realistic long barrel vertex:
  - stiffer carbon fiber ladder support
  - more cable for read-out
  - vibration of long ladder









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

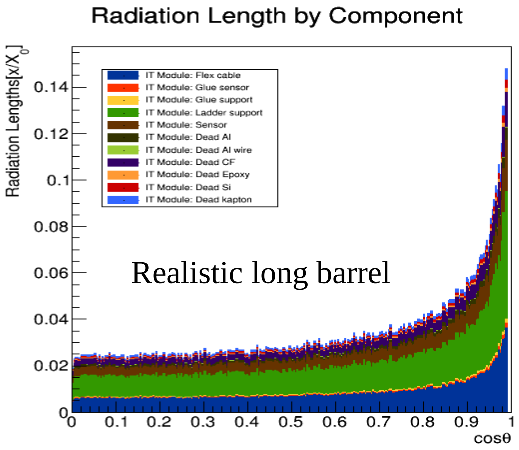
2 flex layers

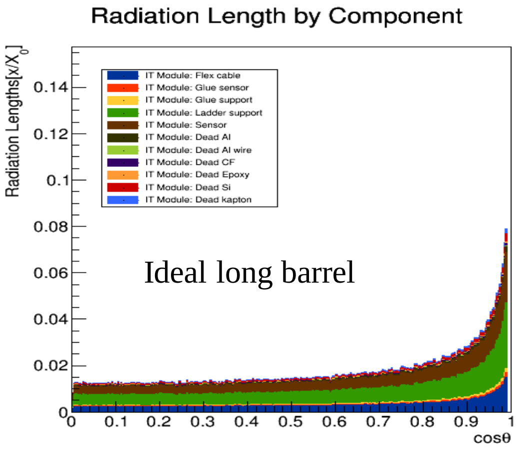
	Thickness	Optimization goal
Polyimide	25um	12
Adhesive	28um	15
Plating Al	17.8um	?
kapton	50um	50
Plating Al	17.8um	?
Adhesive	28um	15
Polyimide	25um	12

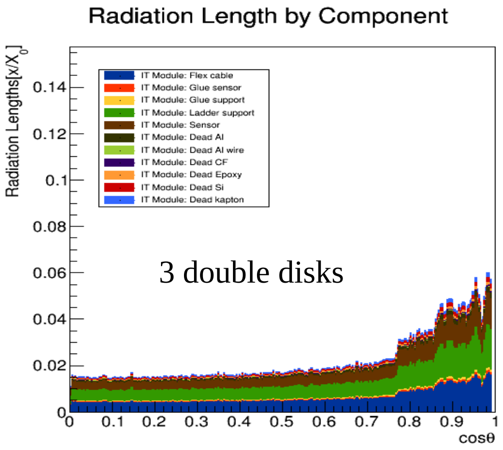
4 flex layers

	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

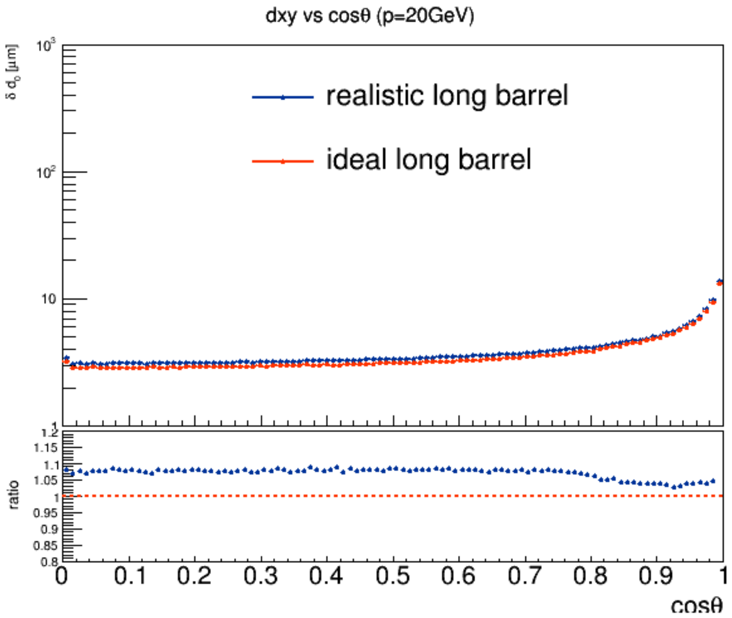
Long Barrel Vertex: Material Budget





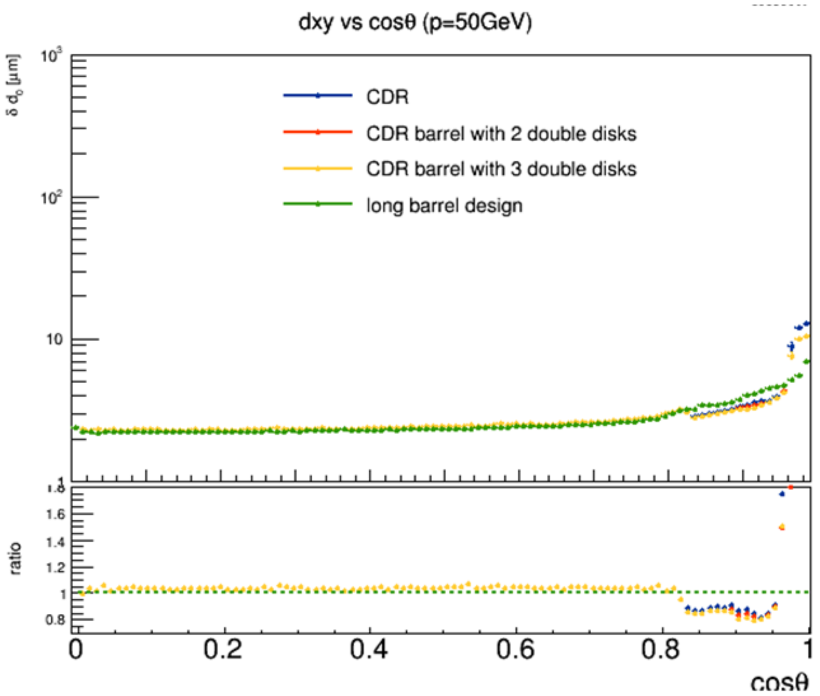


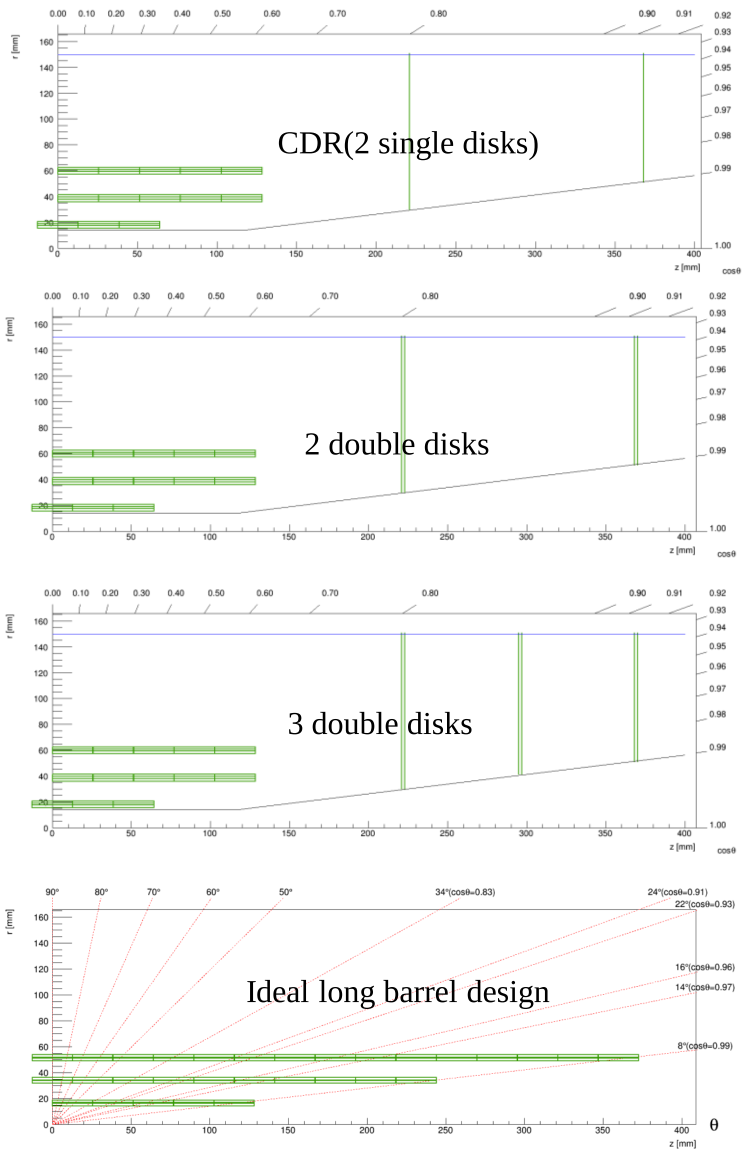
- The material budget of realistic long barrel vertex is about twice as much as the ideal long barrel vertex.
- Much more material in the front region than disk version layout.



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

Long Barrel Vertex Performance

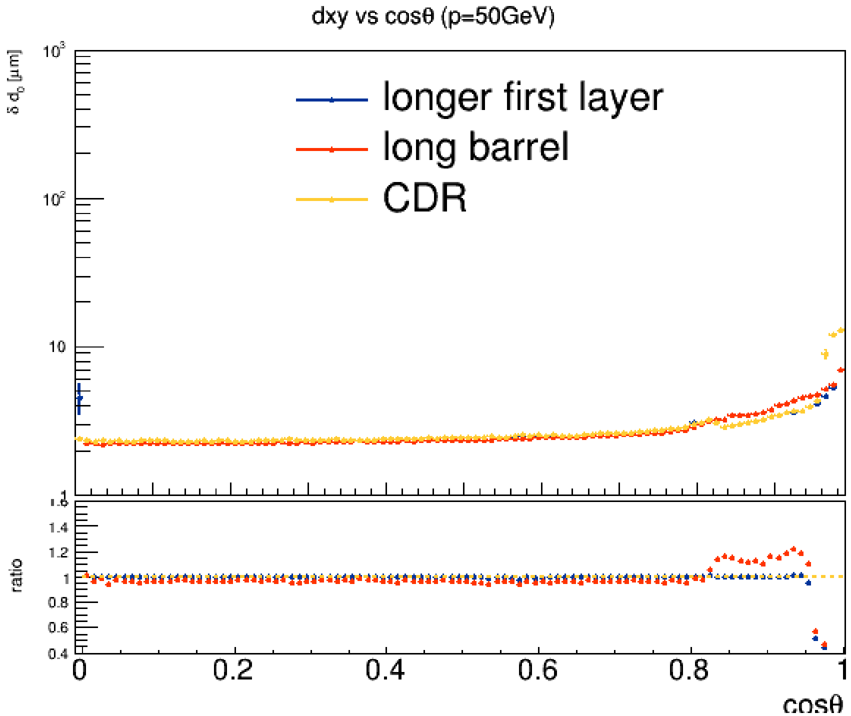


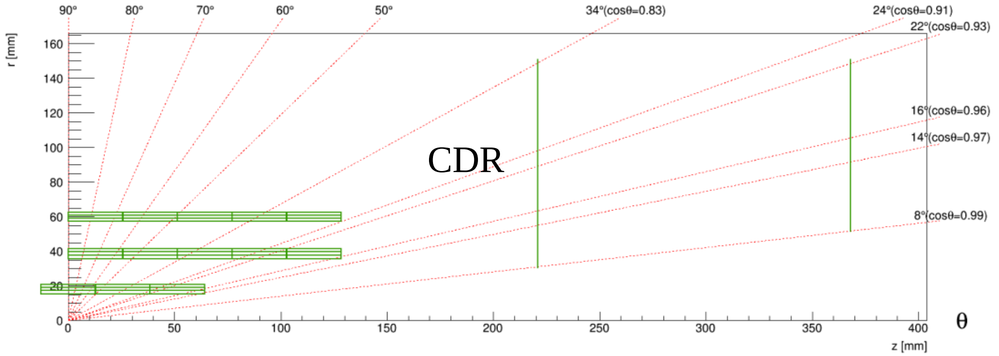


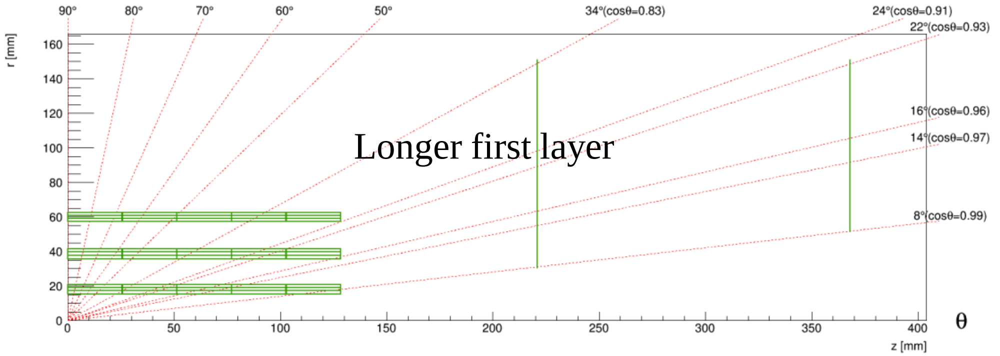
- cosθ: 0.82-0.96, disk version better than long barrel design
- cosθ> 0.96: long barrel design better CDR barrel with disk version, because innermost layer of long barrel provides closer first hit to IP

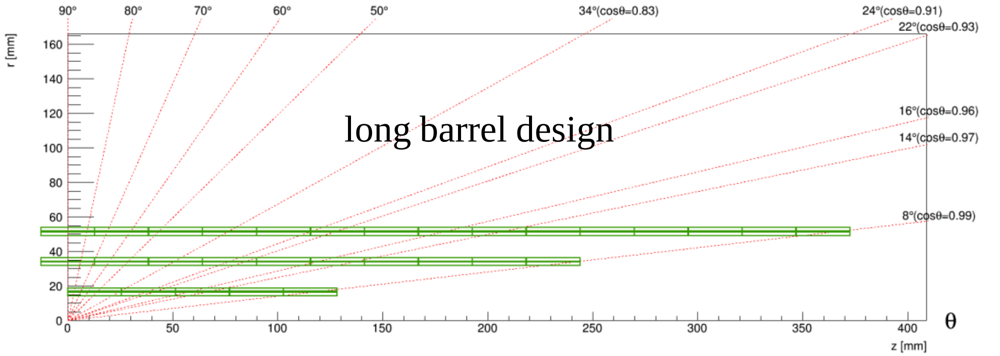
Barrel Optimization Summary

- 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



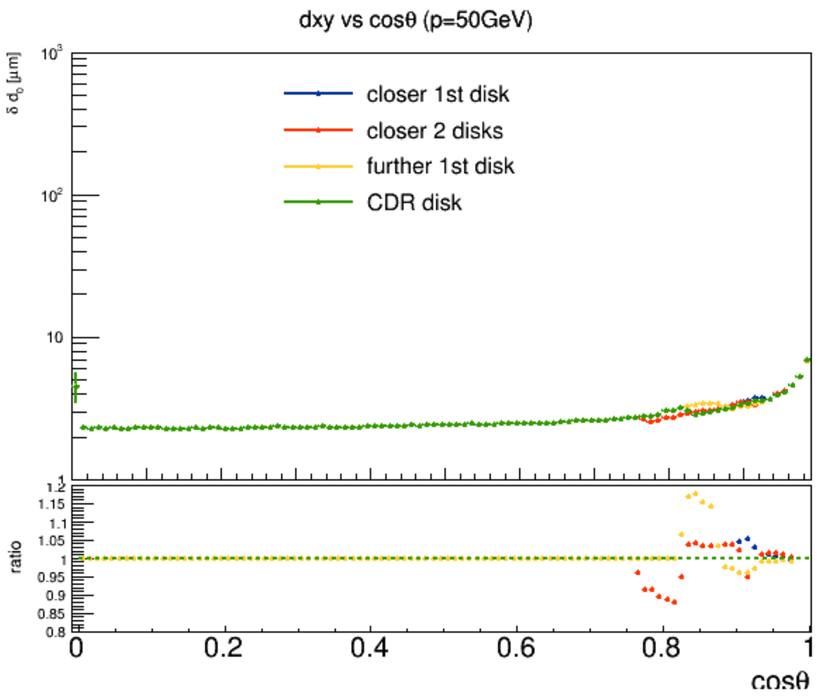


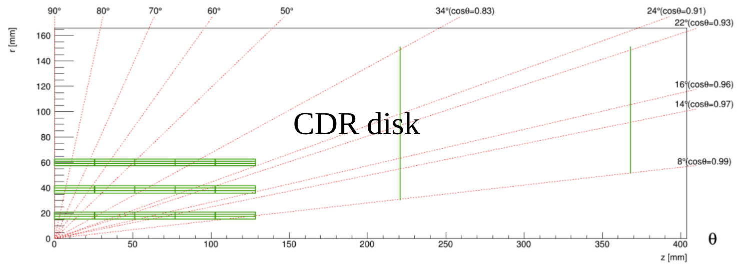


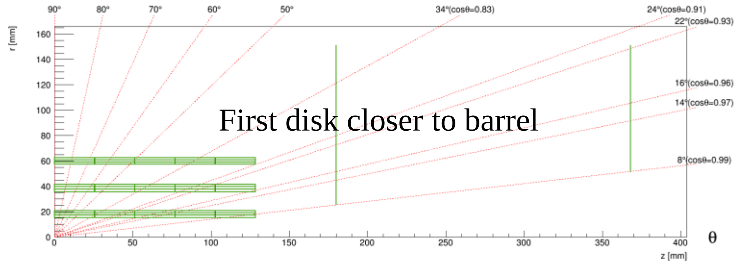


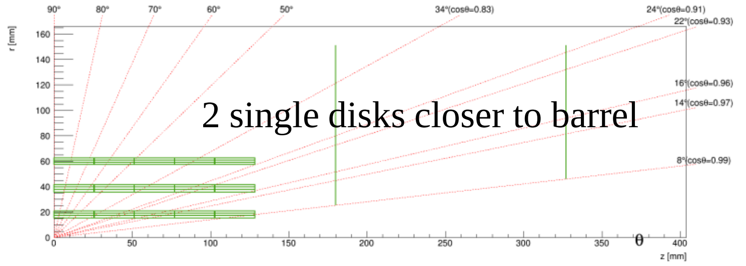
Disk Optimization: Position of 2 Single-layer Disks

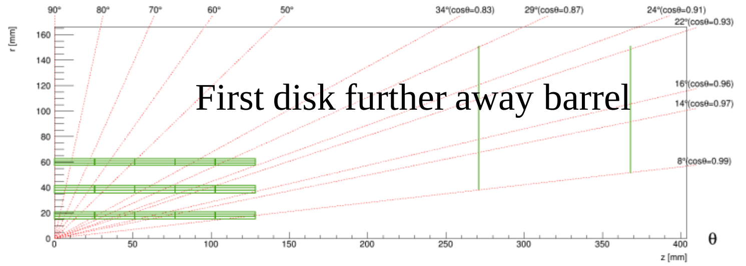
- Different position of 2 single-layer disks
  - not always improve resolution, some points better, some worse
  - moving disk closer to barrel can improve resolution at $\cos\theta \approx 0.8$ (more hits)











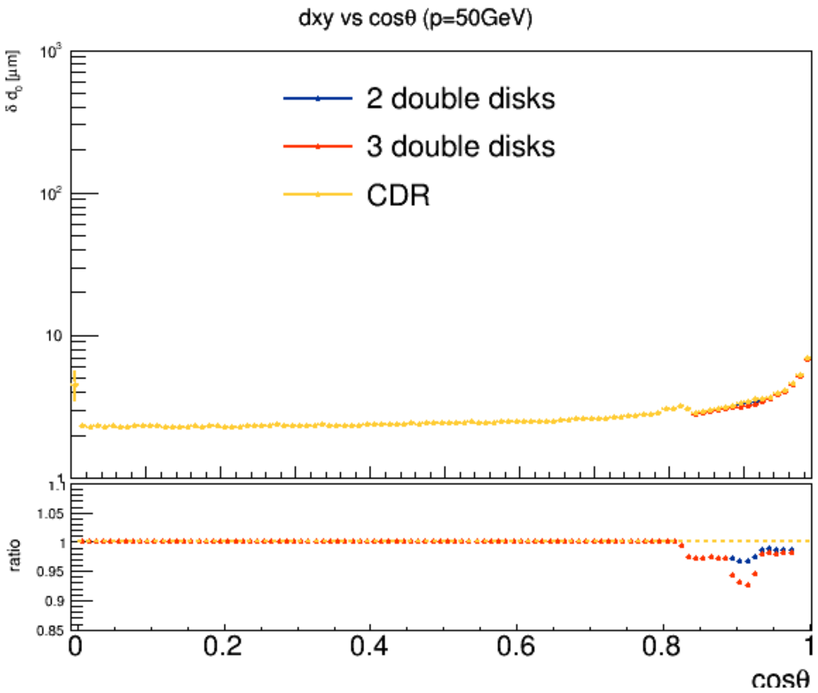
Disk Optimization: Number of disks

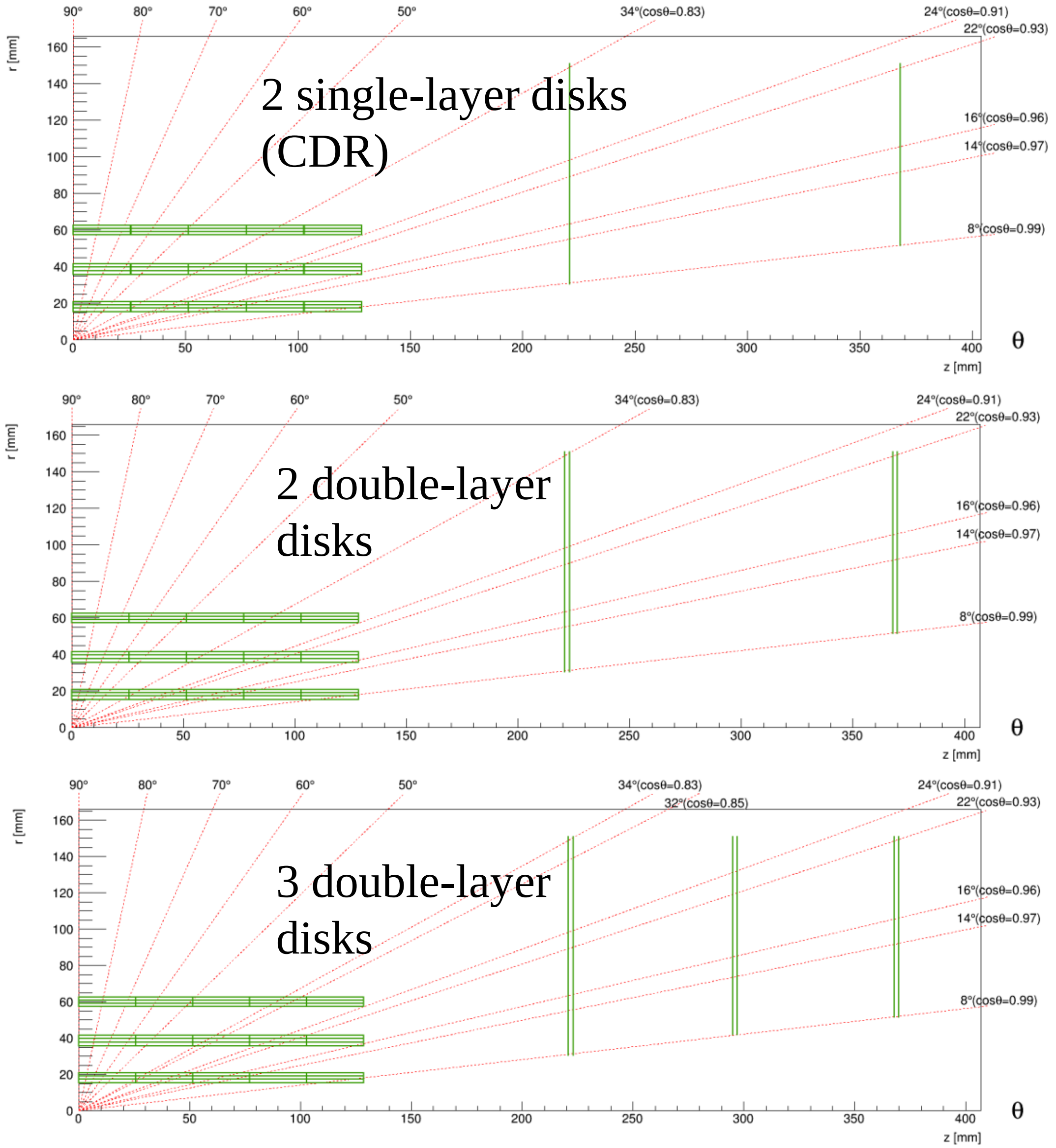
Longer first layer with different number of disk:

2 ways to improve resolution:

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

no worse resolution points

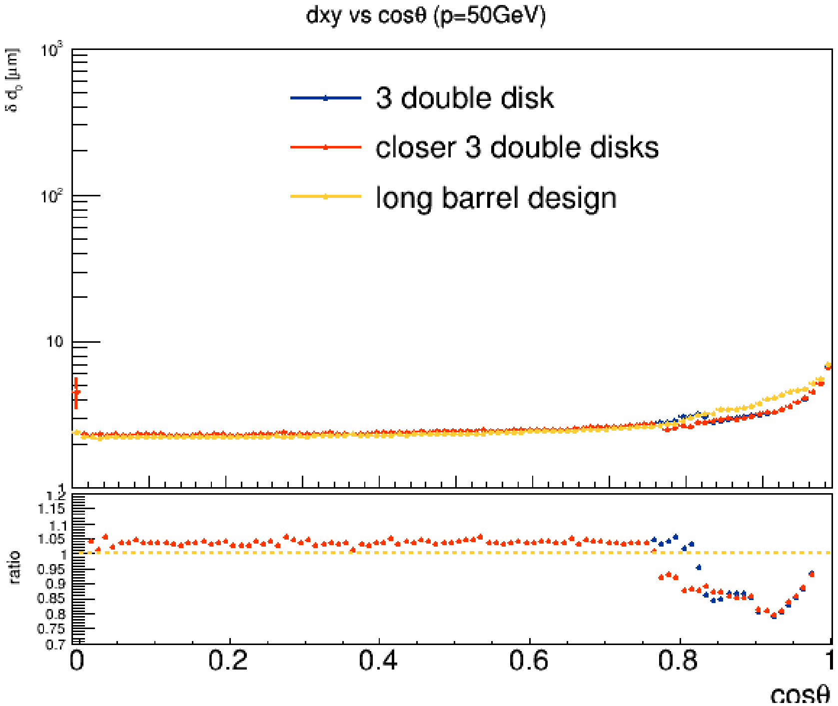


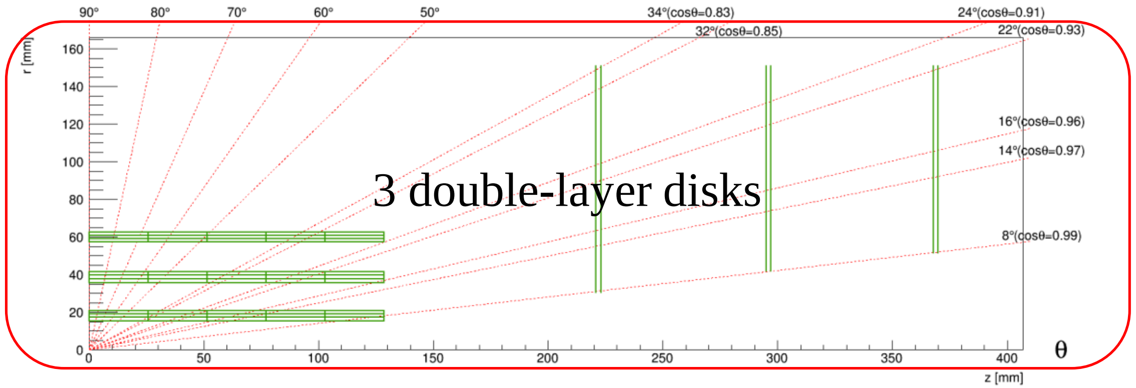


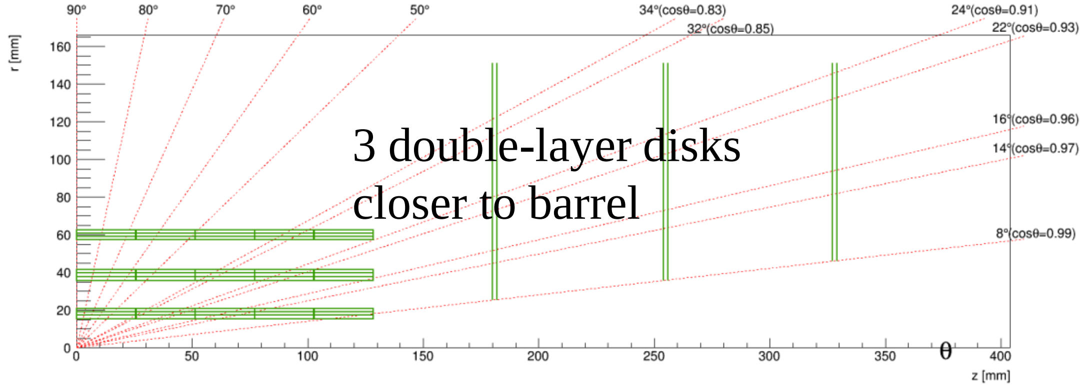
Disk Optimization

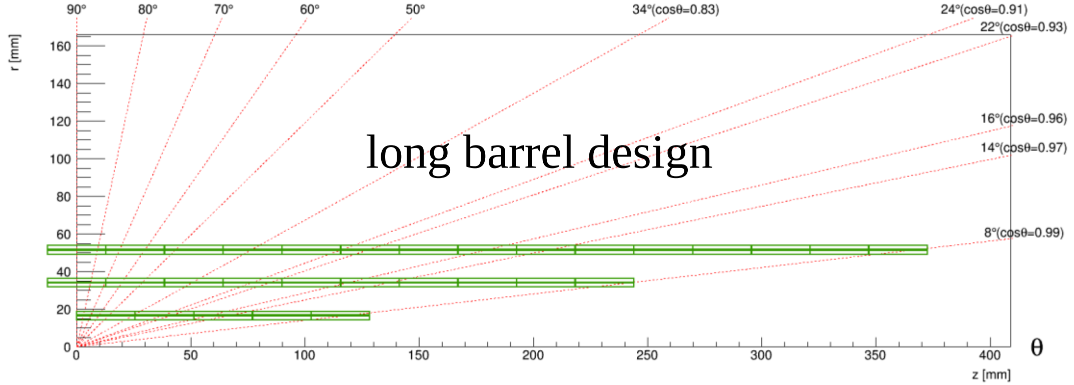
3 double-layer disks closer to barrel

- 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.









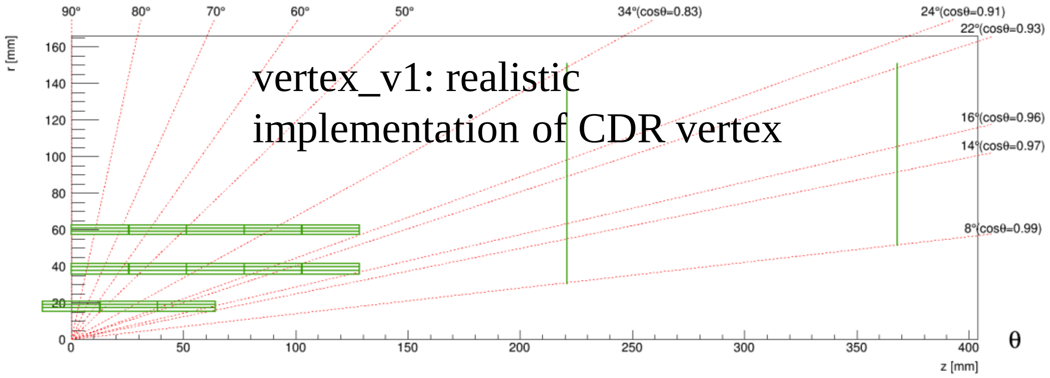
Vertex Layout Optimization Summary

- 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

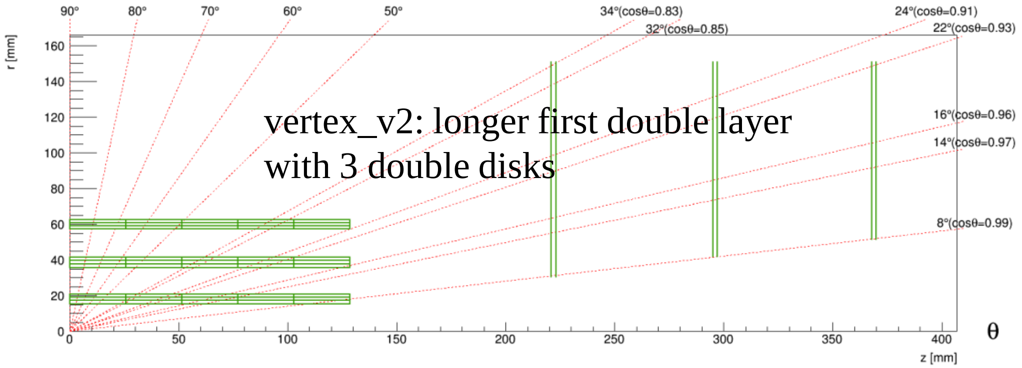
Layout with 3 equidistance double layers is best

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

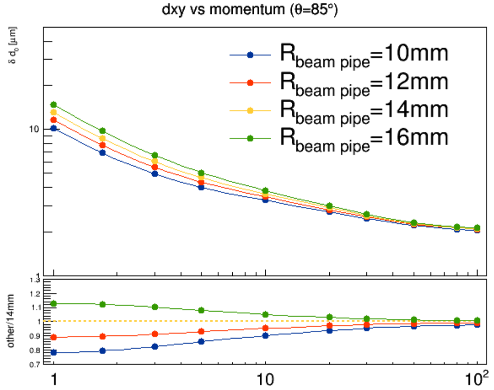


All layout tuning results simulated by tkLayout, which was developed by CMS, customized for CEPC tracker fast simulation(on-going). More information in github.

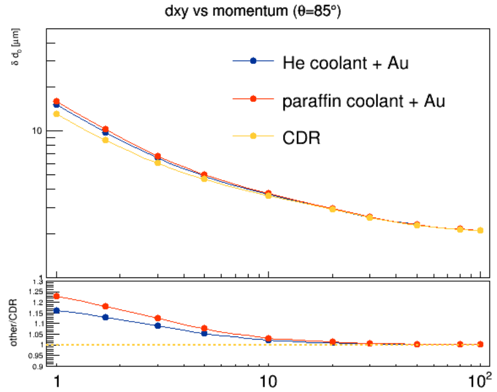
Beam Pipe Study

- 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

4 layers



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

Documentation of the Vertex Optimization Work

- All the work I mentioned in the previous slides are documented in a note.
- Then we made a vertex prototype for MOST2 project.
- We did two test-beam at DESY.
- The MOST2 project is very successful.

But it is not the end of the vertex story!!!

Draft version 0.2

CEPC NOTE

CEPC_DET_2021_001

December 25, 2020

Optimization studies for the CEPC Vertex Detector

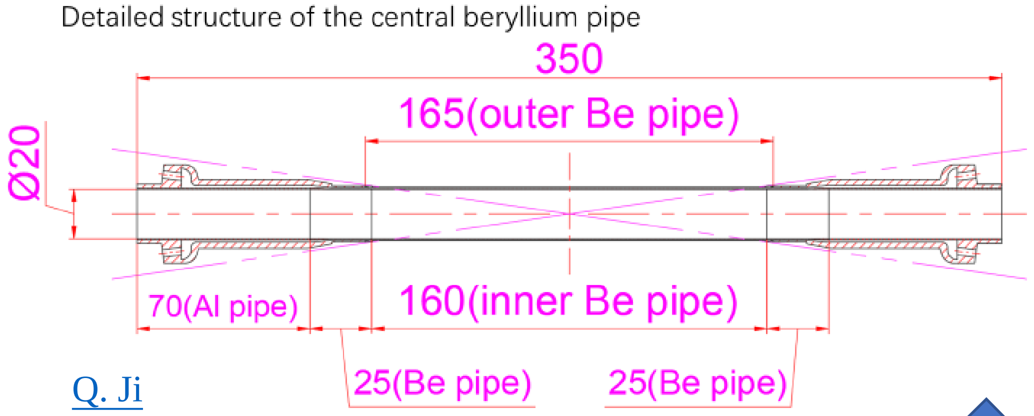
Hao Zeng

Abstract

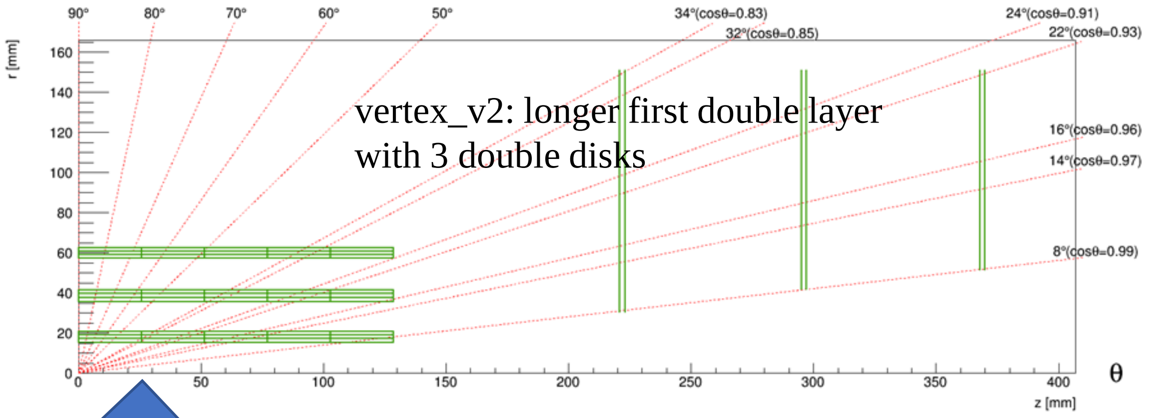
After the CEPC Conceptual Design Report was released, the optimization of detectors is very important for the proposal of the Technical Design Report. A vertex detector prototype will be built around 2022. This note focuses on the optimization of the vertex detector based on full silicon outer tracker and including mechanics structure. A preliminary optimal vertex layout including 3 double disks and 3 same length barrel is obtained. Three new disk arrangements considering air cooling are studied. The impact of different beam pipe radius and different beam pipe material budget on vertex impact parameter resolution is investigated. The study is based on a fast silicon tracker simulation tool tkLayout.

E-mail address: zenghao@ihep.ac.cn

New beam pipe with diameter of 20 mm



Q. Ji

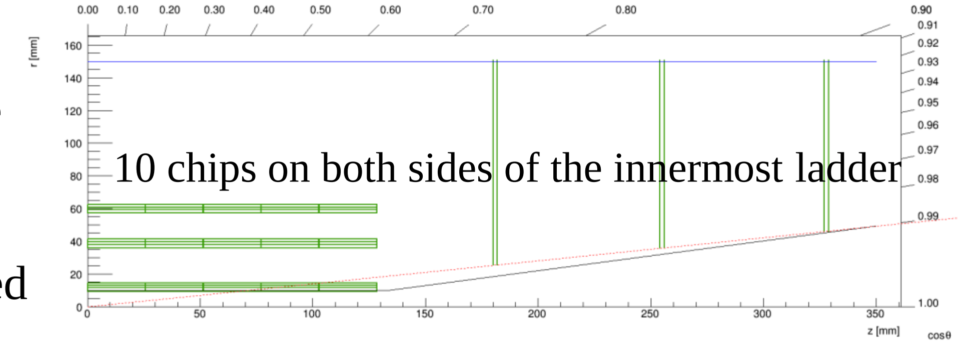


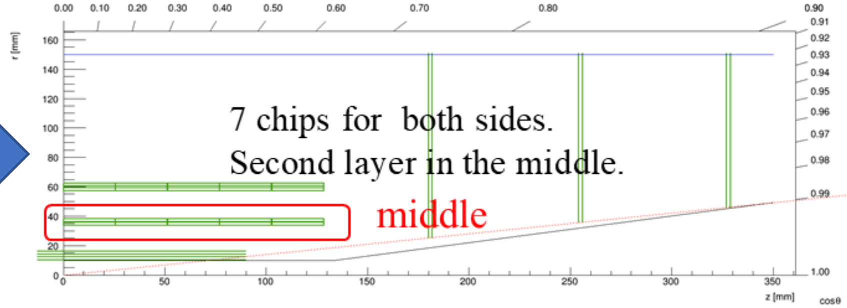
~~According to processing capacity:~~
Inner Be pipe: 0.20mm thick, 210(25+160+25)mm long
Outer Be pipe: 0.15mm thick, 165mm long

thinner

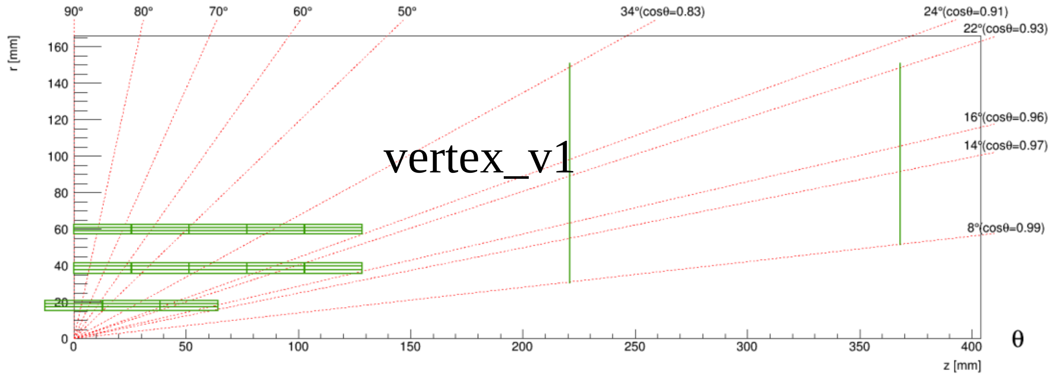
inner Beryllium layer: T= 0.5 mm
outer Beryllium layer: T= 0.35 mm

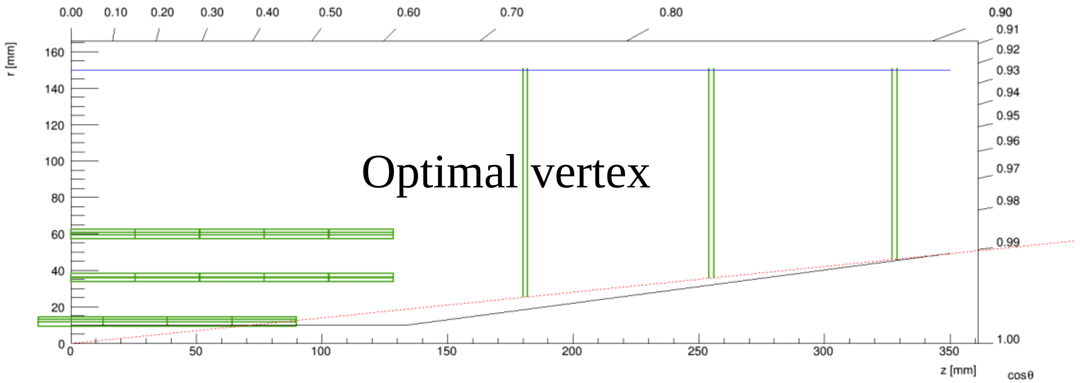
Innermost layer will be inside the boundary line, which defines the vertex detector coverage.
Shorter innermost layer is required

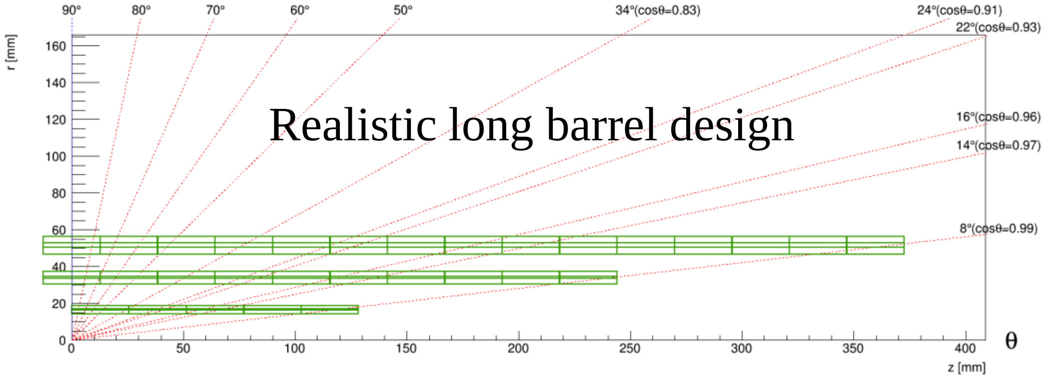


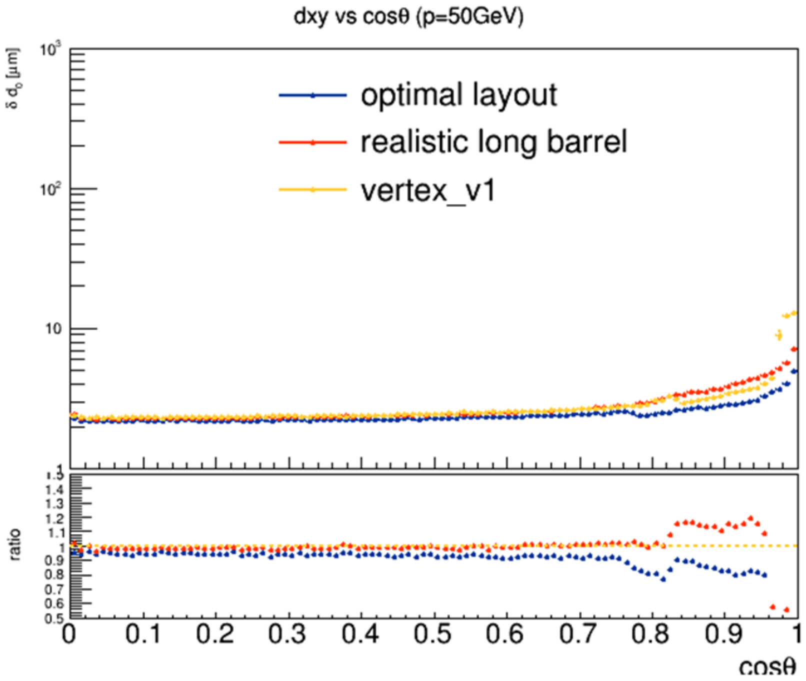


New Optimal Vertex Layout





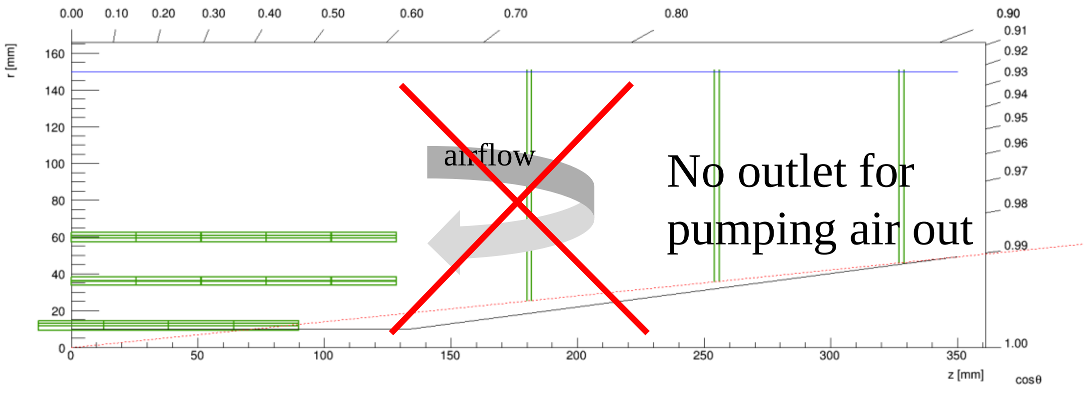




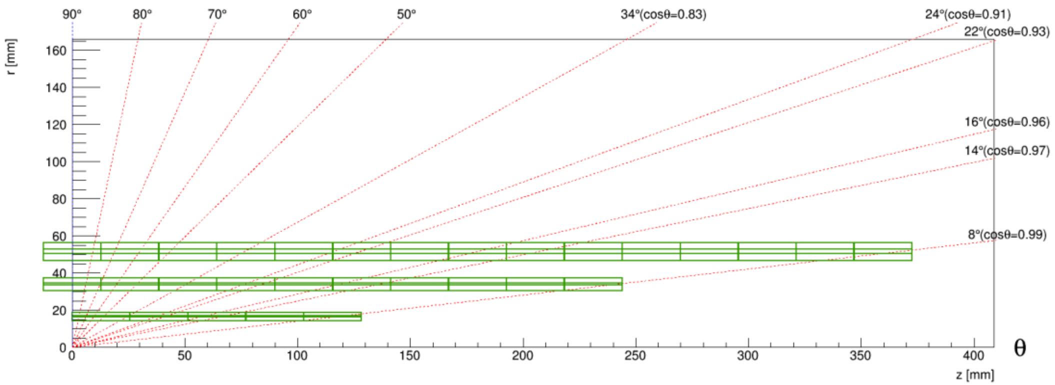
The d0 resolution of optimal vertex layout is much better than realistic long barrel vertex and vertex_v1 (realistic implementation of CDR vertex) layout, especially in the front region (20% and even more).

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

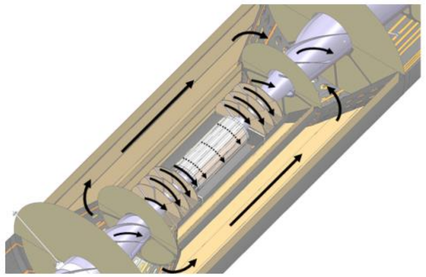
Vertex Design Considering Air Cooling

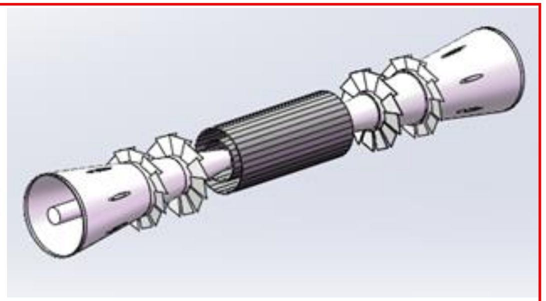


No outlet for pumping air out

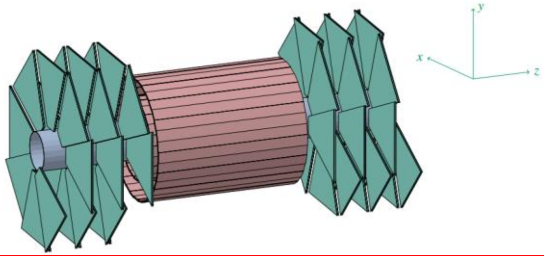


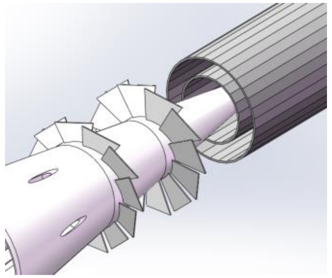
Long barrel design





Solution?

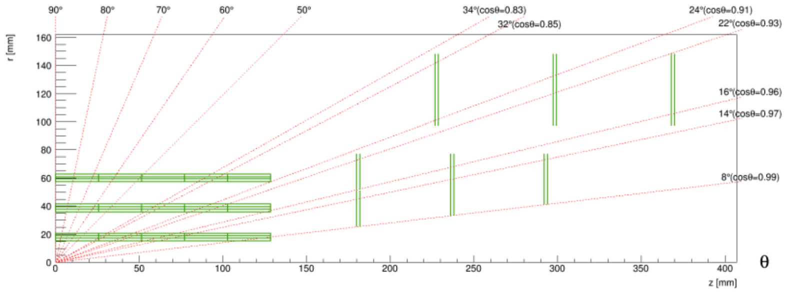


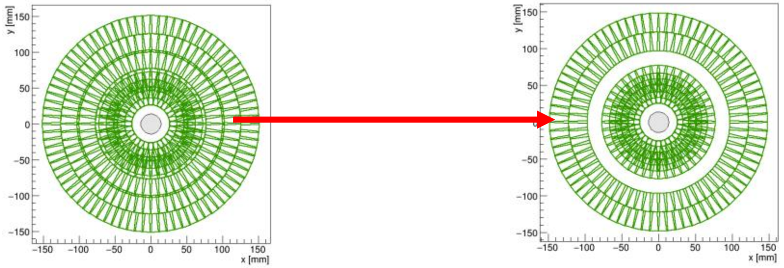


CLIC spiral disk concept

CLICdp-Note-2014-002

Rotate the disk, from Jinyu

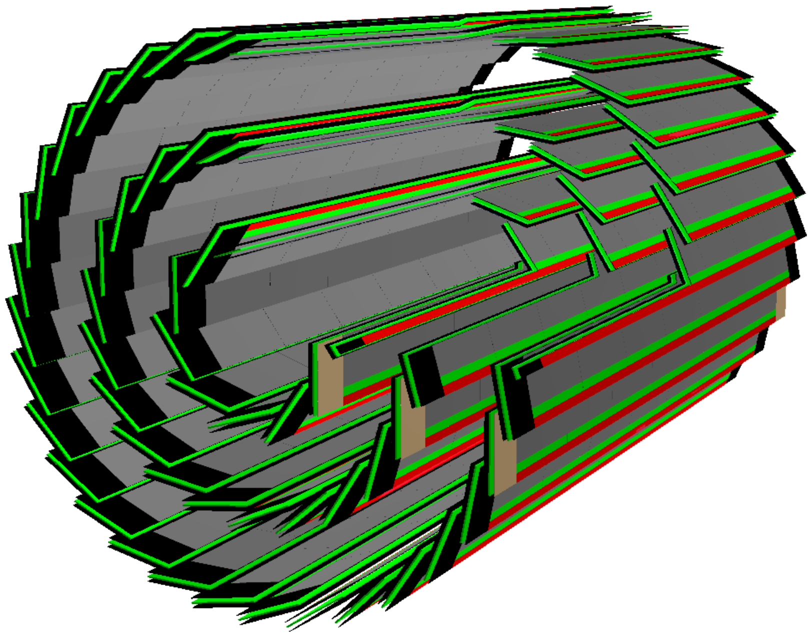




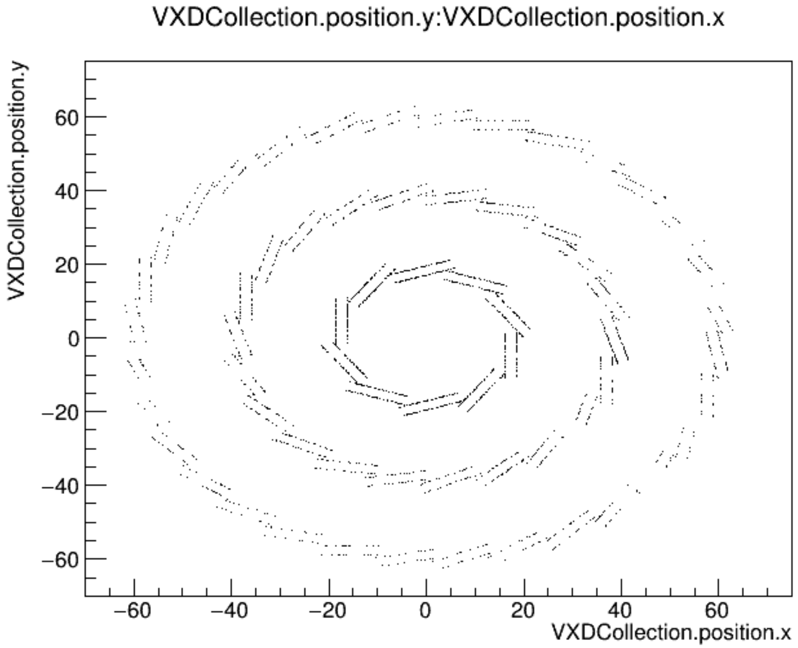
Make a hole in disk, easy simulating in tkLayout

Full Simulation of CEPC Vertex Detector

- The MOST2 vertex geometry and ladder were implemented into the CEPCSW framework.
- Code was reviewed by Chendong and merged into the official CEPCSW github repository.



Geometry (only barrel)



Simulation hits distribution

Vertex Geometry Description

- Vertex xml description
- Layer parameters
  - Ladder
    - Support
    - Flex
    - Pixel sensor

```
<layer layer_id="0" ladder_radius="17.4*mm" ladder_offset="(8.4-1.5)*mm" n_sensors_per_side="VXD1_half_length*2/VXD_sensor_length"
 n_ladders="10" ladder_clearance="0.1*mm" faces_IP="1" is_VXD1="1" is_VXD2="0"  >
  <ladder isDoubleSided="true">
    <ladderSupport height="2*mm" length="200*mm" thickness="350*um" width="16.8*mm" mat="CarbonFiber"/>
    <flex n_layers="9">
      <layer length="200*mm" thickness="15*um" width="16.8*mm" mat="Epoxy"/>
      <layer length="200*mm" thickness="12*um" width="16.8*mm" mat="Kapton"/>
      <layer length="200*mm" thickness="15*um" width="16.8*mm" mat="Epoxy"/>
      <layer length="200*mm" thickness="13.4*um" width="16.8*mm" mat="G4_Al"/>
      <layer length="200*mm" thickness="50*um" width="16.8*mm" mat="Kapton"/>
      <layer length="200*mm" thickness="13.4*um" width="16.8*mm" mat="G4_Al"/>
      <layer length="200*mm" thickness="15*um" width="16.8*mm" mat="Epoxy"/>
      <layer length="200*mm" thickness="12*um" width="16.8*mm" mat="Kapton"/>
      <layer length="200*mm" thickness="15*um" width="14.8*mm" mat="Epoxy"/>
    </flex>
    <sensor n_sensors="7" gap="0.1*mm" thickness="50*um" active_length="25.6*mm" active_width="12.8*mm" dead_width="2*mm" mat="G4_Si"/>
  </ladder>
</layer>
```

Summary and Outlook

- 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
    - Barrel geometry done already
  - Global tracker consideration, overall mechanics of the CEPC

Thank you!

Bakup slides