Updates: Mechanical design and optimization of the Silicon Vertex

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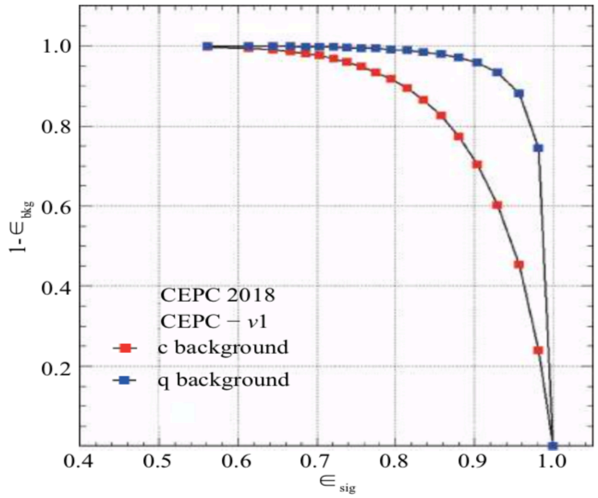
Outline

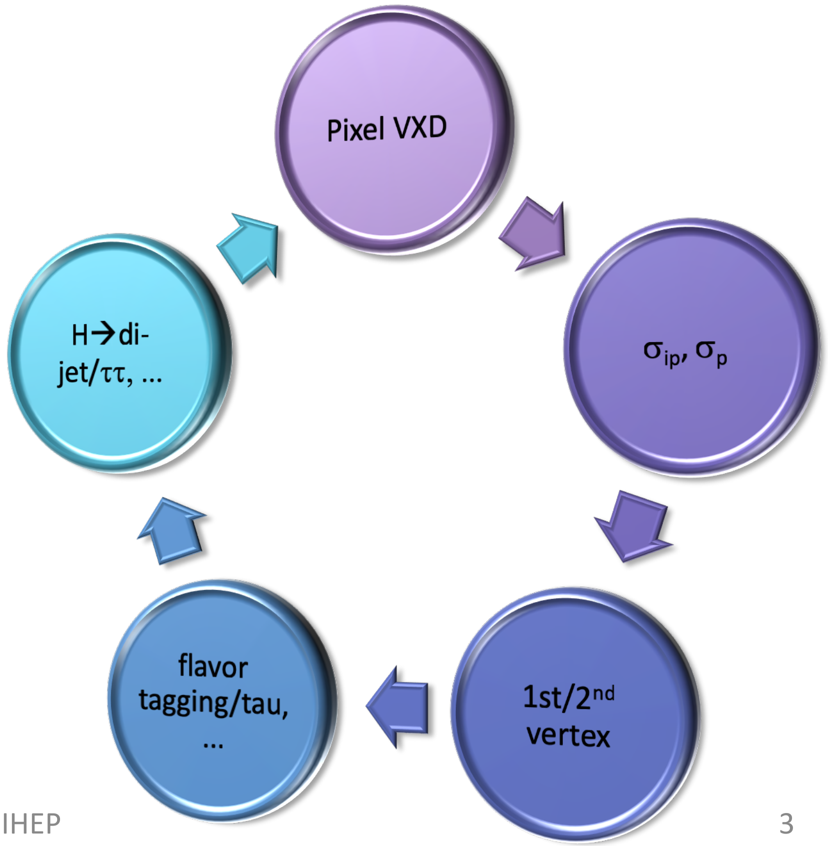
- Introduction
- Mechanical design & study
- Simulation and layout optimization
- Plan

Motivation



- Detector design motivated by physics motivation
  - Jet identification strongly depends on impact parameter precision

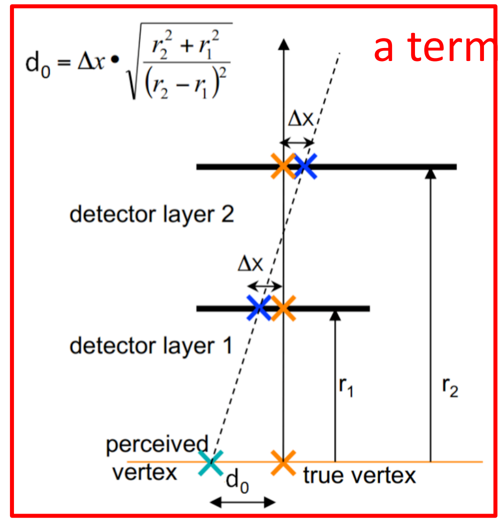
- CEPC dedicated to Higgs study, as well as SM and flavor physics
  - B, D, τ and other long-lived particles
- Physics always wants detector as good as possible
- Hardware gives the boundary
  - Resolution
  - Material budget
  - Power consumption
  - Layout
  - …
- Optimization …

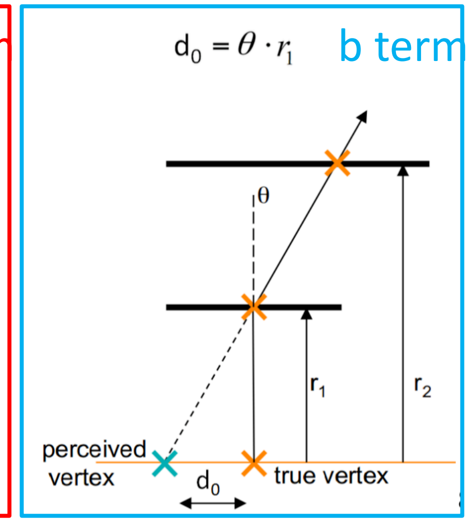


Impact Parameter Resolution:

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

- p: the track momentum
- Θ: the polar track angle
- ‘a’ term: the intrinsic resolution of the vertex detector in the absence of multiple scattering, independent of the track parameters.
- ‘b’ term reflects the effects of multiple scattering.
- a = 5 μm and b = 10 μm · GeV from CDR.
- 3 double- layer pixelated vertex detector.

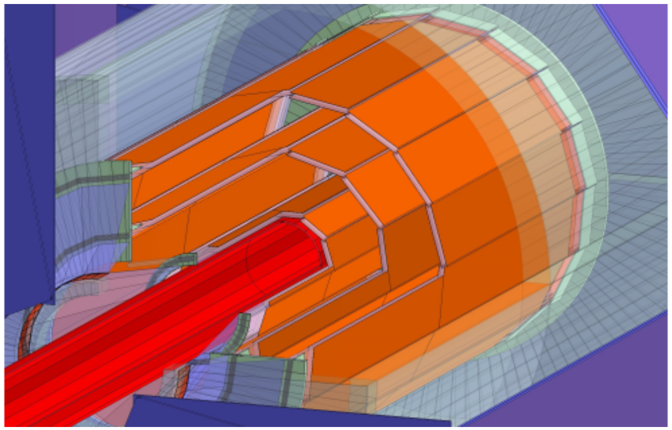




	R (mm)	$\lvert z \rvert$ (mm)	$\lvert\cos\theta\rvert$	σ (μm)
Layer 1	16	62.5	0.97	2.8
Layer 2	18	62.5	0.96	6
Layer 3	37	125.0	0.96	4
Layer 4	39	125.0	0.95	4
Layer 5	58	125.0	0.91	4
Layer 6	60	125.0	0.90	4

Design goal

CDR vertex detector concept



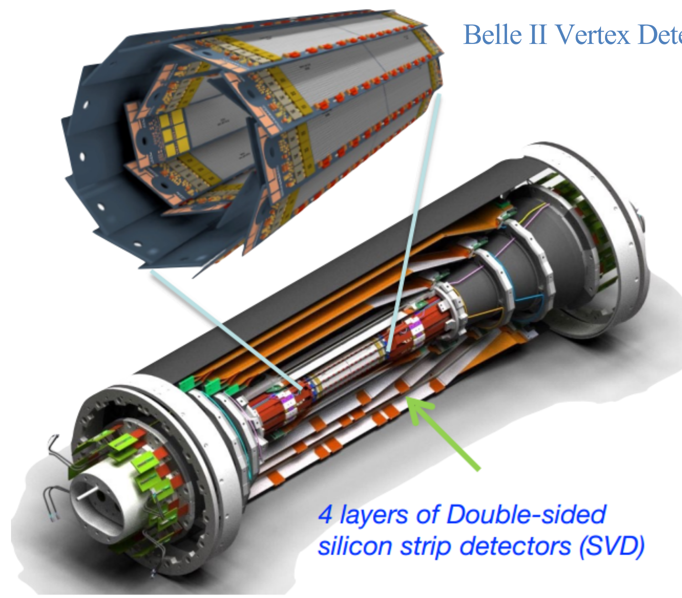
Vertex detector prototype

+ mechanics

+ electronics

+ cooling system

+ cable



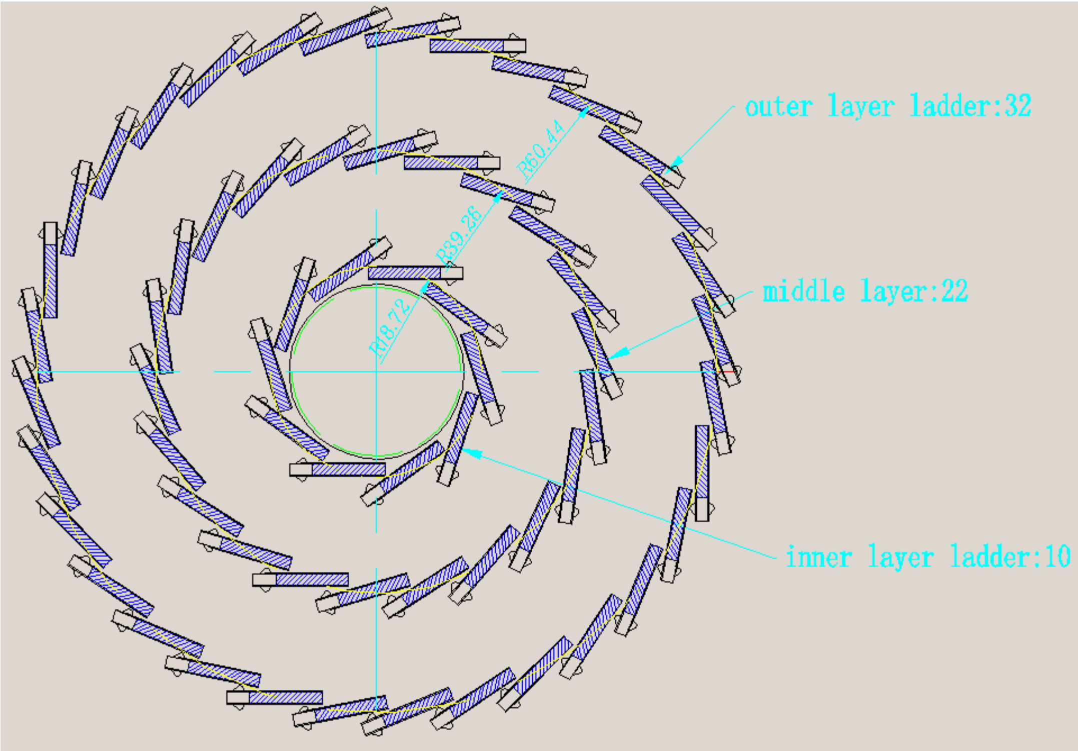
	R (mm)	$\|z\|$ (mm)	Current z in total
Layer 1	16	62.5	130.6 mm
Layer 2	18	62.5	
Layer 3	37	125.0	263.1 mm
Layer 4	39	125.0	
Layer 5	58	125.0	263.1 mm
Layer 6	60	125.0	

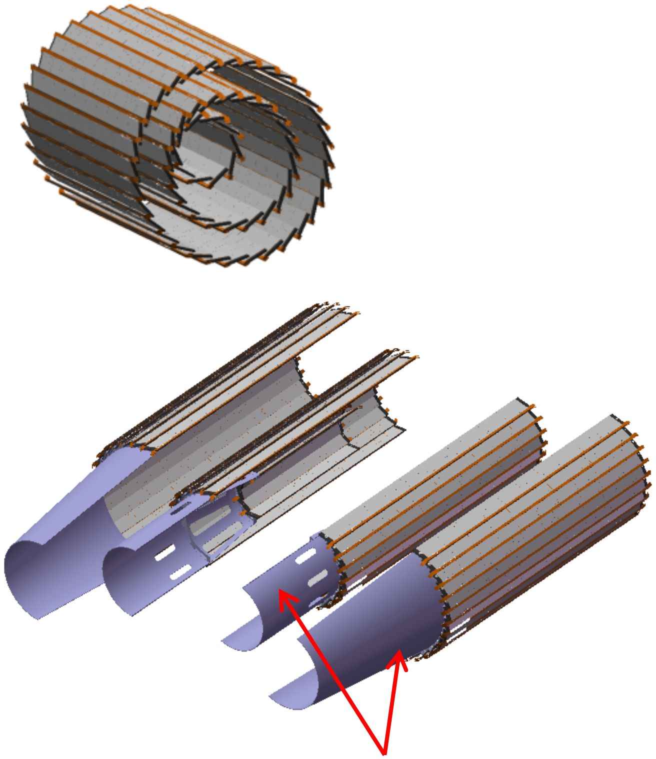
- 3 double layer barrels
- Power dissipation: Final goal: ≤ 50 mW/cm2
- Current goal: ≤ 200 mW/cm2. (air cooling)
- Working temperature range: 20-50 ℃
- Single point resolution: from 2.8-6 µm in CDR,
- Aim for only one type of pixel sensor of 3-5 µm.

Mechanical design and study

Prototype design of VXD

Ladder layout - optimized





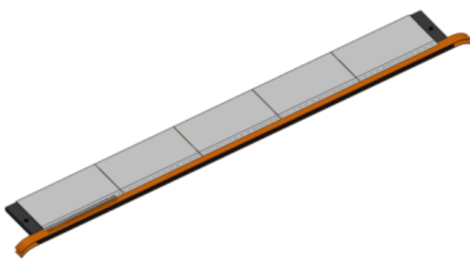
Half support barrel

Prototype design of VXD

Sensor chip : 14.8 x 25.6 x 0.05 mm (2 mm wide margin at one side for wire bonding)

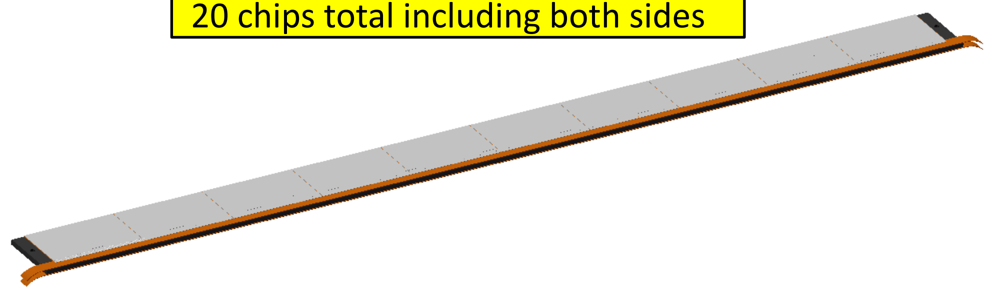
Ladder: support + chips + FPC

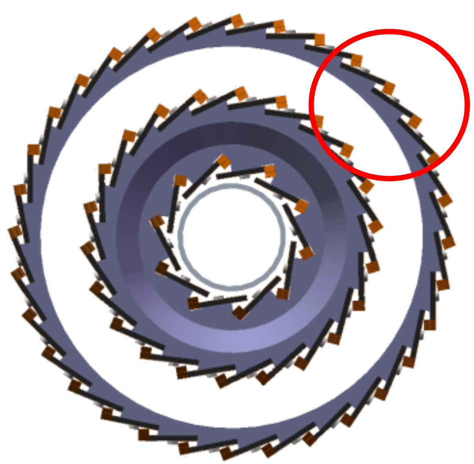
Ladder of inner layer:
10 chips total including both sides



0.1mm gap between chips

Ladder of outer two layers:
20 chips total including both sides





Ladder support

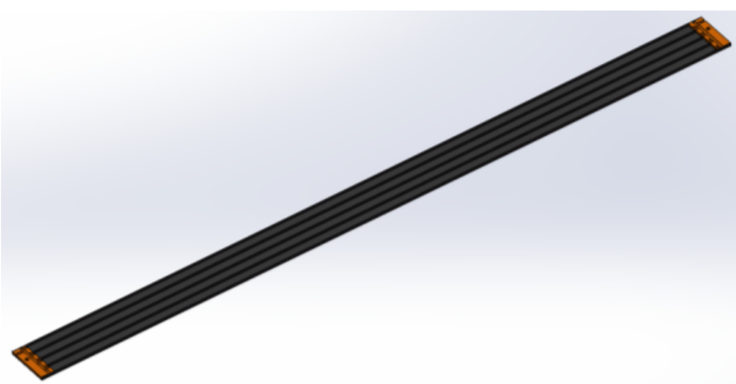
End Ring (CFRP): fix the end of ladder support.

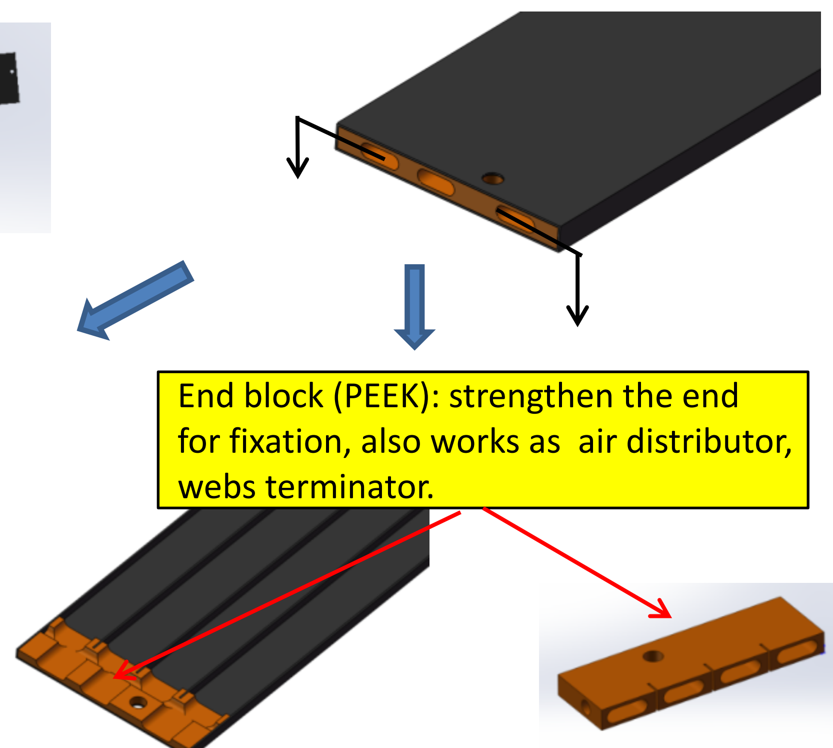
Ladder - support

Size: 264.1 x 16.8 x 2 mm (L x W x H), for outer and middle barrels.
131.6 x 16.8 x 2 mm for inner barrel. W is 2 mm wider than sensor.

Material: Carbon fiber in thickness of 0.15 mm (3 layers).

Channels inside the local support: to increase stiffness with less material, also work as a backup for air cooling from inside of the support.





Ladder - FPC & wire boding

FPC: shape and size of FPC of each ladder base on the current layout?

Can FPC be narrowed where it comes out of the ladder? The minimum width can be achieved?

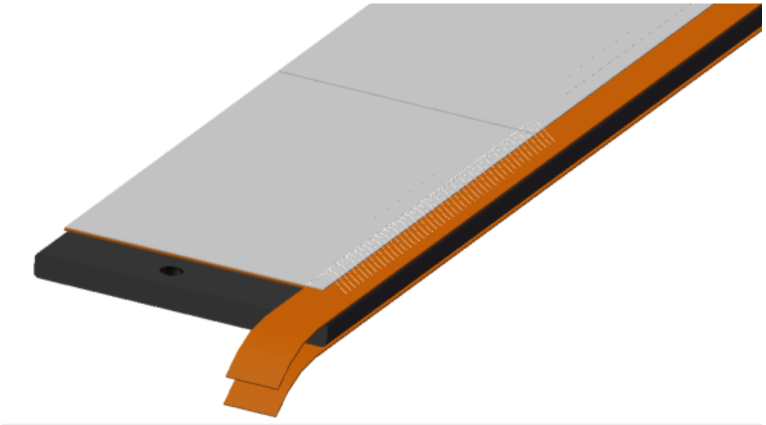
Will there be connectors of the FPC and where?

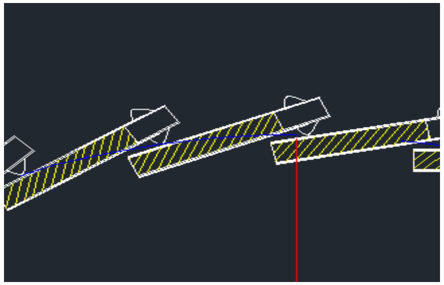
Wire bonding: Height?

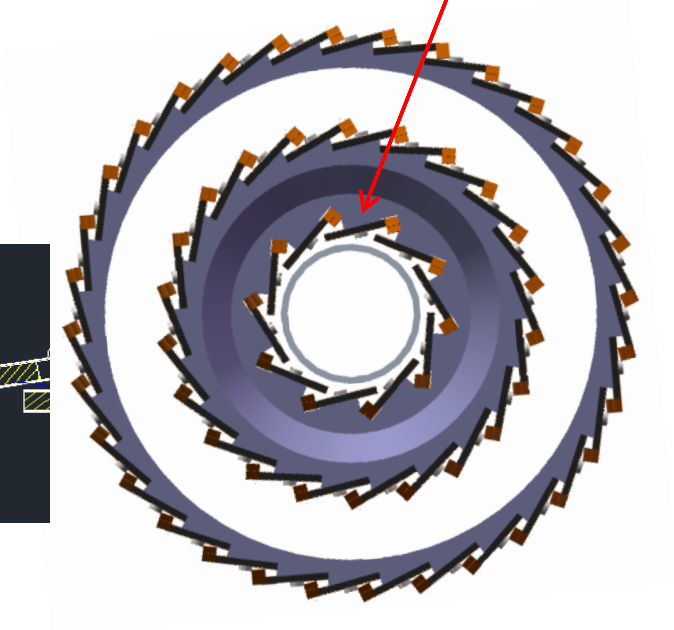
Materials of the ladder(?)- one side:

- FPC: kapton 50, Cu two layer 12x2=24, adhesive 15x2=30 um(Mingyi)
- the ladder: glue + flex+ sensor 15+105 +15+50= 185 um
- support : equivalent total thickness 0.15mmx3=0.45 mm
- Material budget need to be comfirmed.

Due to limited space and for easy installation, the ladders of inner layer are fixed onto the inner side of the neck flange, while those on middle and outer layers are fixed from outer side.



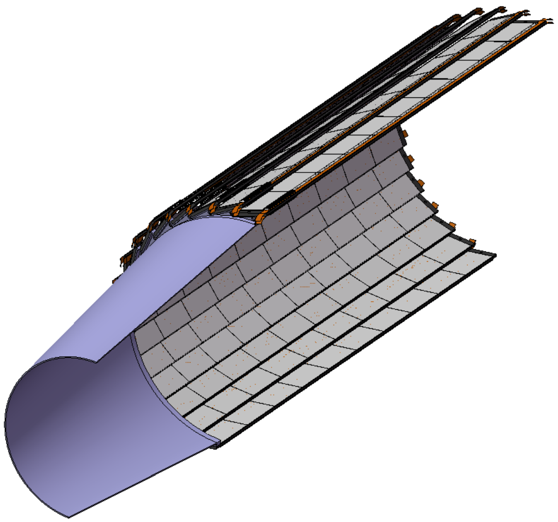


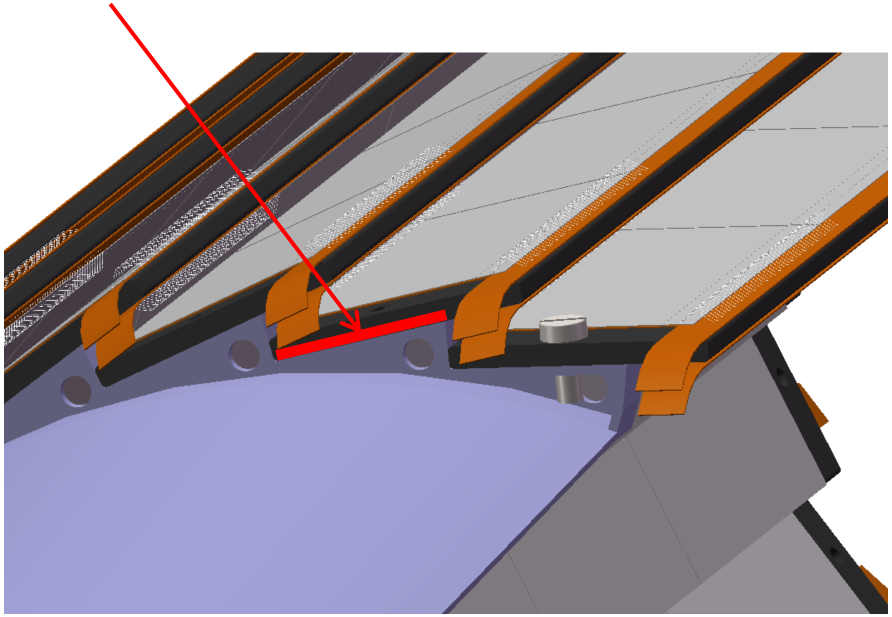


Ladder fixation

Option1: gluing.

Adhesive to be investigated, which has a good bonding strength at temperature lower than 80 ℃(?) but can be easily peeled off under certain temperature or by chemical method?

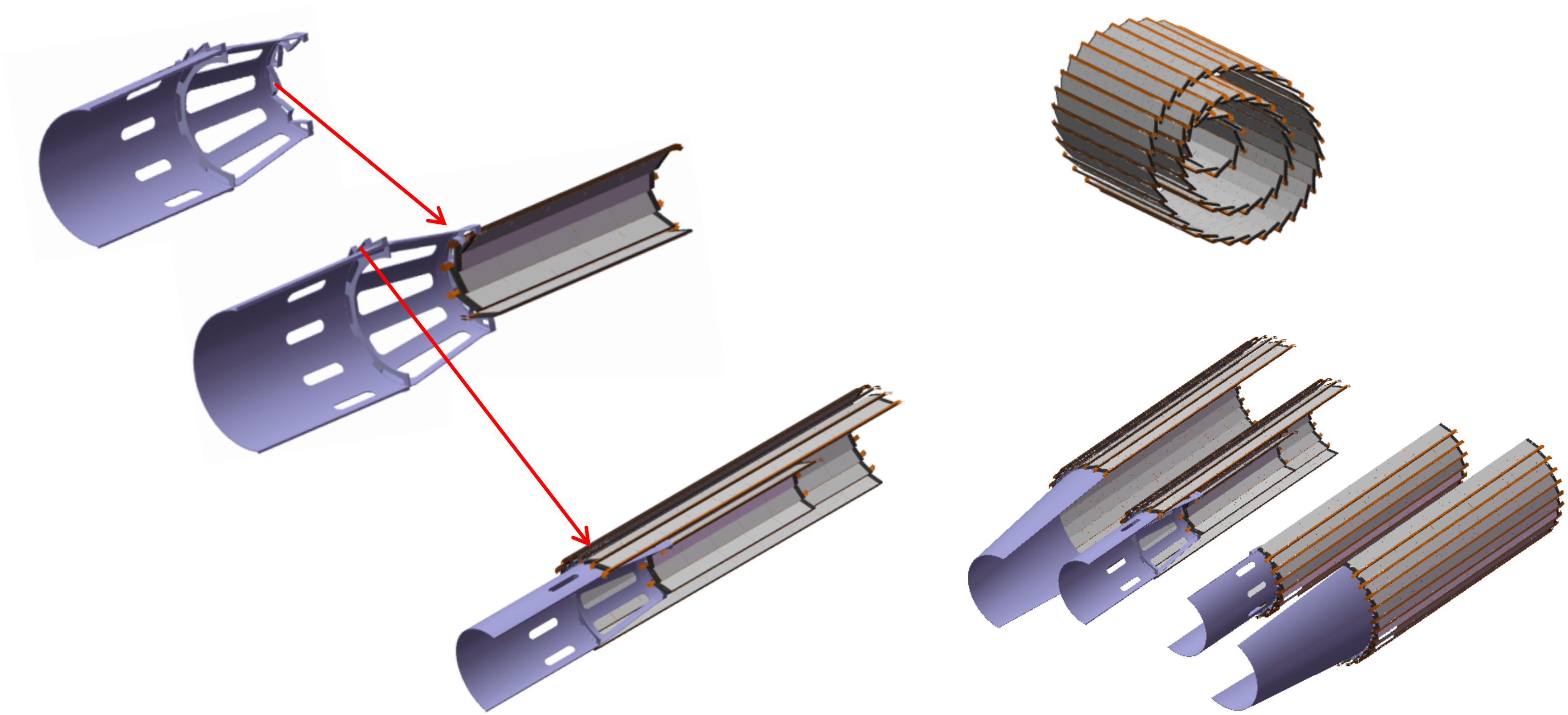




Option2: as a backup, using non-magnetic screw(e.g. copper) and nut (e.g. made of PEEK) glue on back side of the flange?

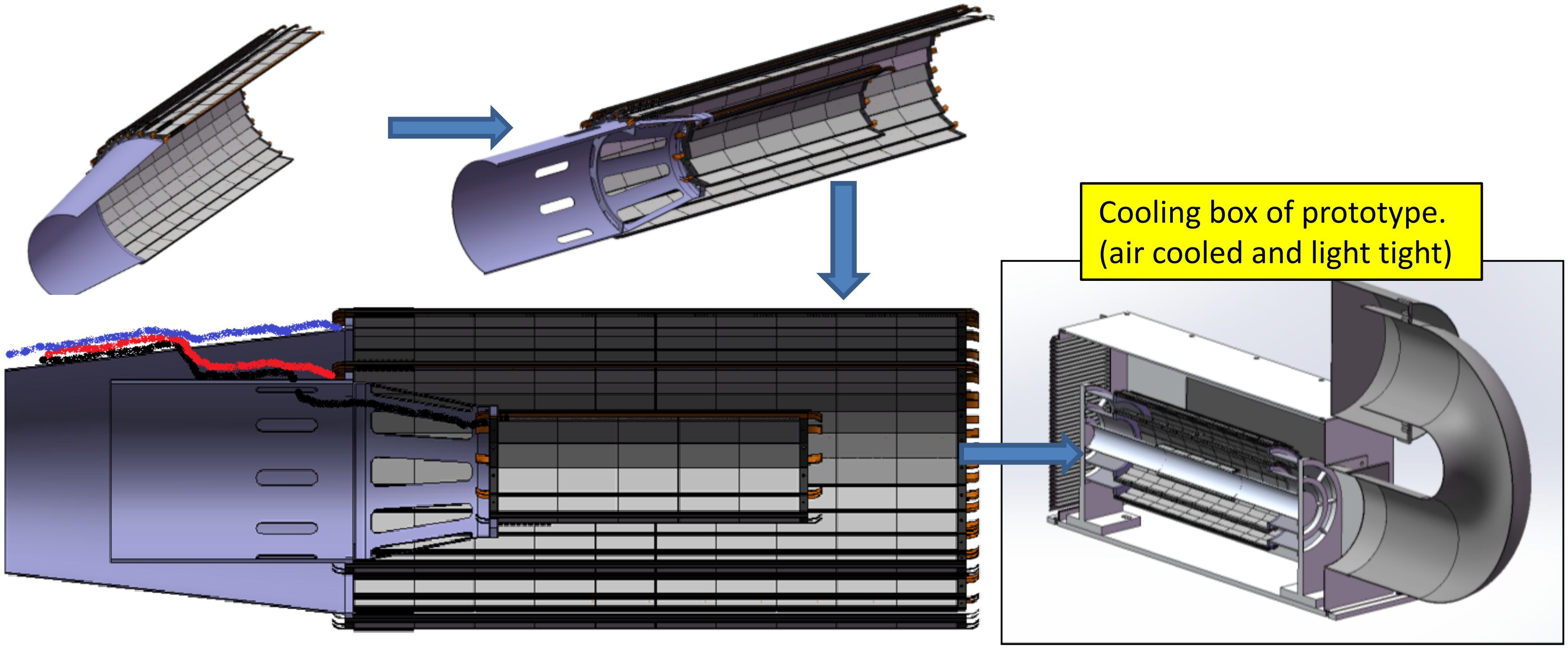
Vertex assembling and cable routing

Ladders of inner and middle layers mounted to a half support barrel with double toothed rings.



Vertex assembling and cable routing

Ladders of outer layer mounted to a half support barrel which has one toothed ring.



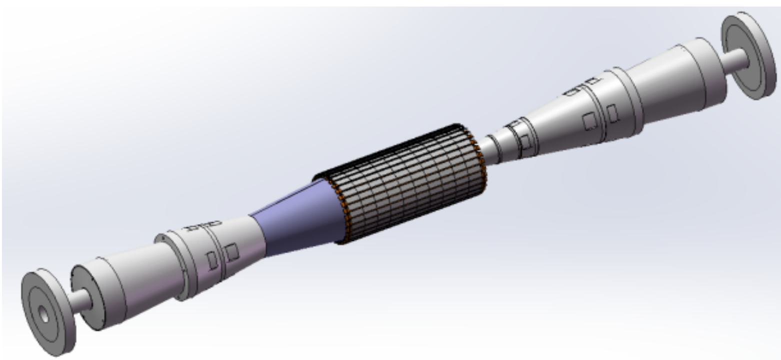
Assuming FPCs or cables of several ladders can be put together to form a bundle, and then rout out from the slotted hole on the support neck to next layer. Finally, go out to the outer layer and lead out together 。

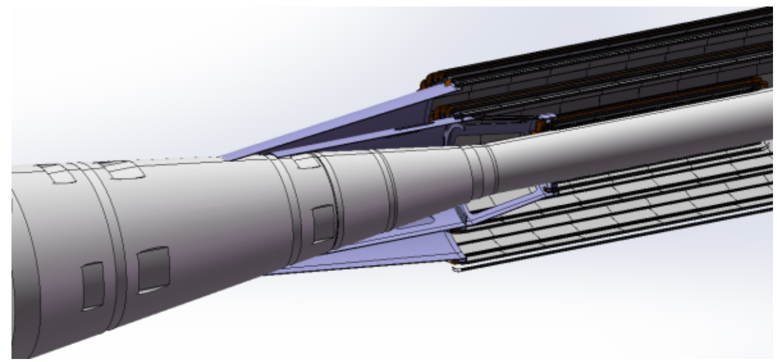
In CEPC, What else are outside the vertex can block the cable routing this way? e.g. End cap?

Installation of the VXD on CEPC
-interface with beam pipe

VXD interface with beam pipe:

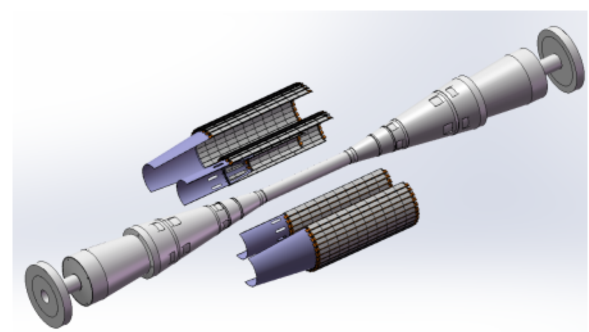
1-fixation of VXD support inside beam pipe
2-space for FPC or cable routing
3-inlets and outlets for cooling air, volume control



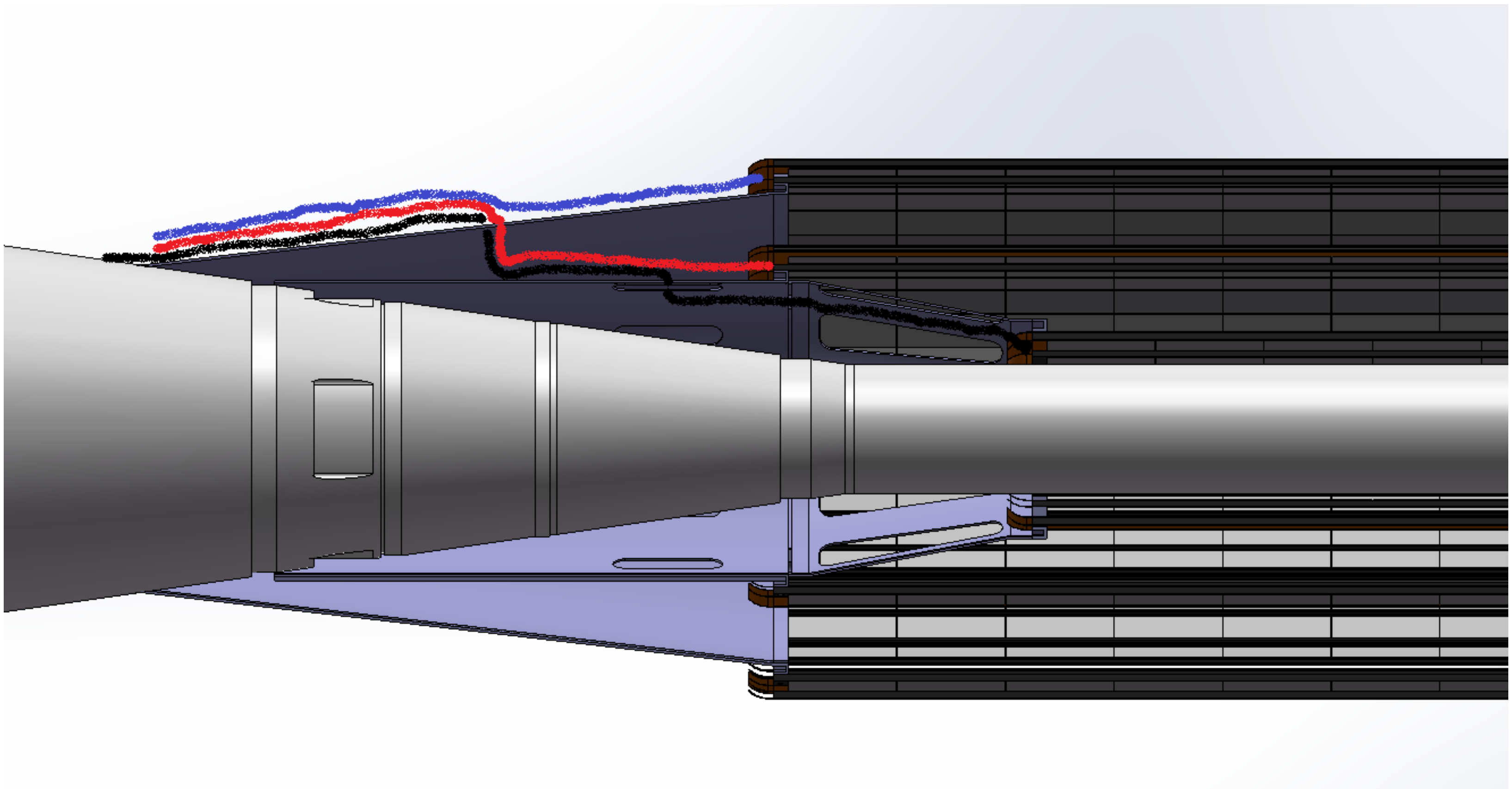


The latest ladder layout and preliminary estimation of air volume required by VXD has been provided to Quan.

More interactive work can be foreseen.



Cable routing at interaction area of CEPC

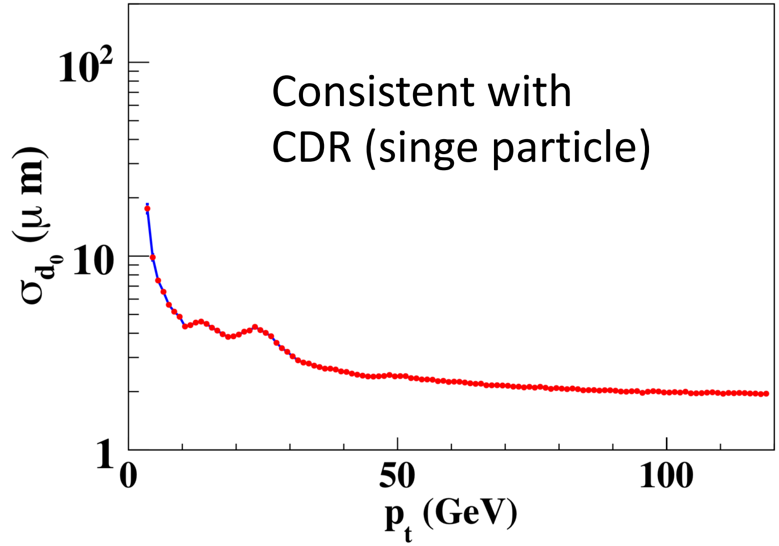


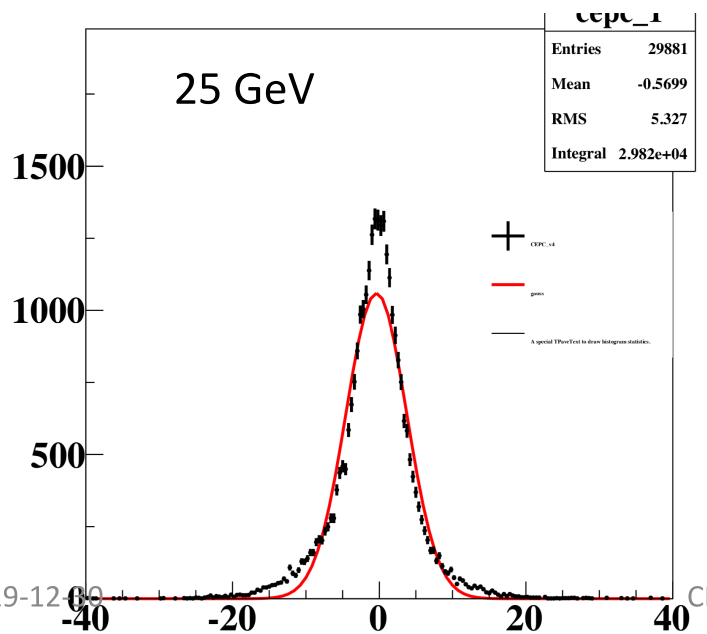
The same scheme as the cable routing inside the cooling box.

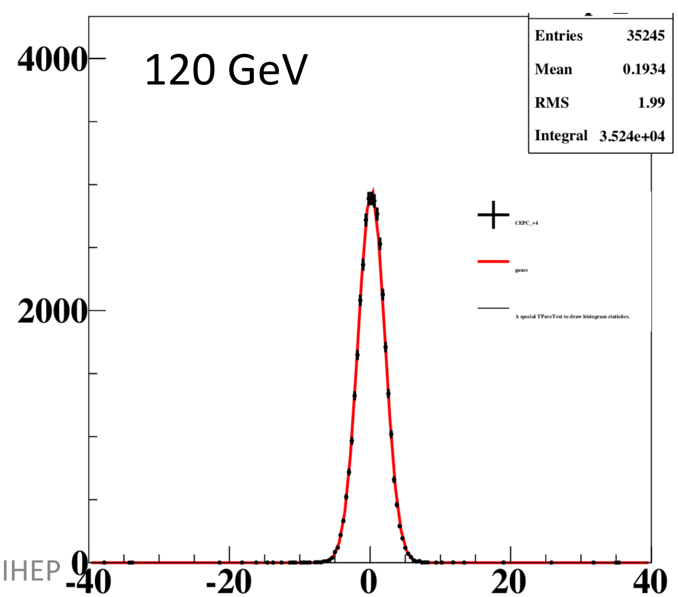
Simulation and optimization

Full Simulation baseline design in CDR

- $e^+e^- \rightarrow \mu^+\mu^-$ @ 240GeV
- Full simulation : MokkaC & Marlin
- Point-like beam spot
- Energy = 3-120 GeV & full angle
- Best resolution ~ 2 μm

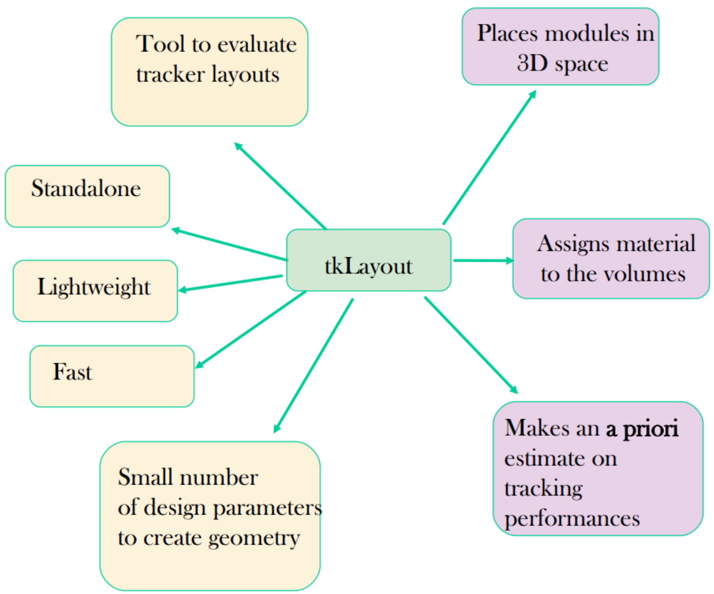






Fast simulation tool - tkLayout

What is tkLayout?



- Compare different detector layouts
- Fair comparison of layouts with a priori estimate of performance(occupancy, tracking and trigger approximate efficiencies, approximate financial cost, power consumption)
- Narrow down the parameter space
- Pre-optimized designs
- Does not depend on optimised reco algorithms

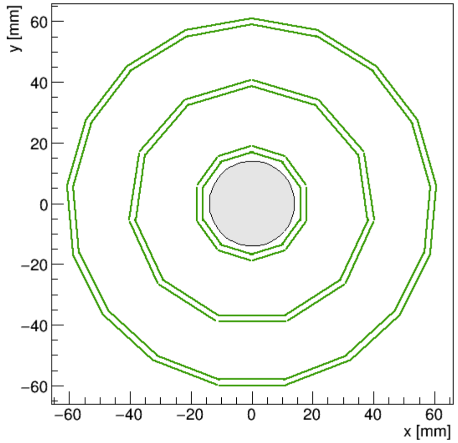
- IS NOT a replacement for the MC simulation
  - estimate impact on trigger
  - physics channels
  - occupancy
  - efficiency
  - ……

- From/validated by CMS
- Fast
- Flexibility to change detector design
- Automatic optimization
- Optimizing given layouts
- Realistic material description, power consumption, backgrounds, an so on

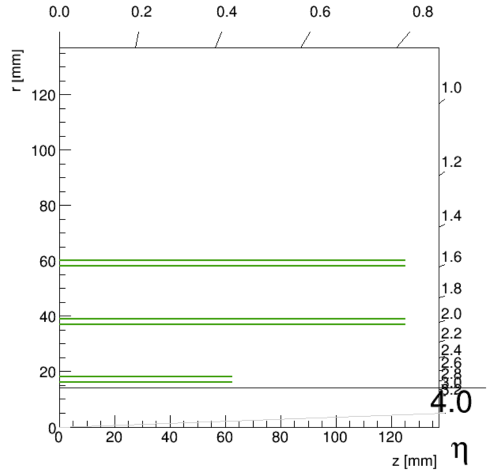
- Useful tool for CEPC vertex prototype layout optimization

Vertex geometry simulation results

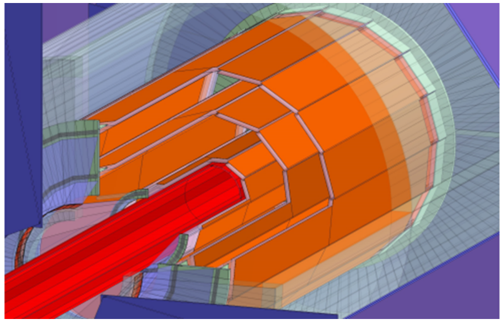
- CDR vertex detector geometry



XY Section of the tracker barrel. - (png) - (pdf) - (root)



RZ positions of the barrel modules. - (png) - (pdf) - (root)



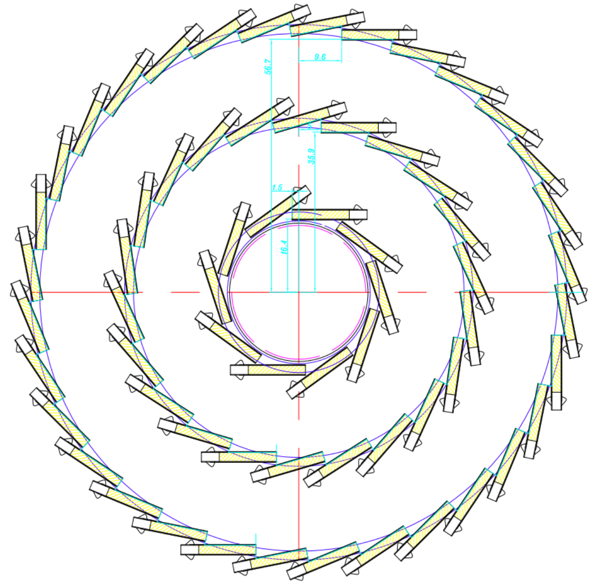
Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	16.004	18.004	37.003	38.995	57.989	59.995	
z_max	62.500	62.500	125.000	125.000	125.000	125.000	
# rods	10	10	11	11	17	17	
# mods	40	40	88	88	136	136	528

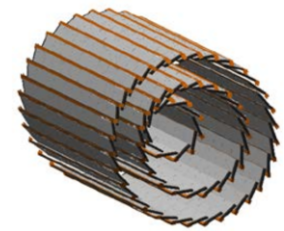
	R (mm)	$\|z\|$ (mm)	$\|\cos\theta\|$	$\sigma(\mu\text{m})$
Layer 1	16	62.5	0.97	2.8
Layer 2	18	62.5	0.96	6
Layer 3	37	125.0	0.96	4
Layer 4	39	125.0	0.95	4
Layer 5	58	125.0	0.91	4
Layer 6	60	125.0	0.90	4

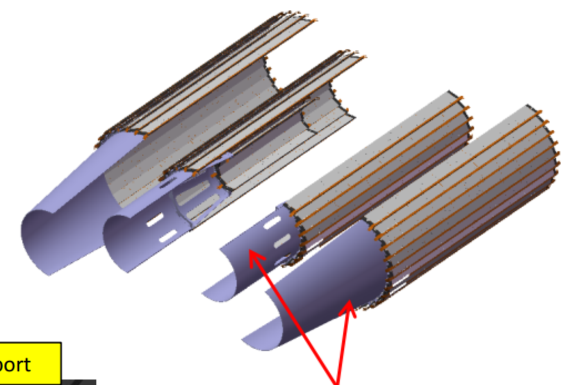
Prototype design by Jinyu

Prototype V1

- 3 layers of double-sided ladder
- Only need to rotate one ladder around Z axis with a fixed angle to cover the whole barrel
- Sensors are on both sides of the yellow slash region

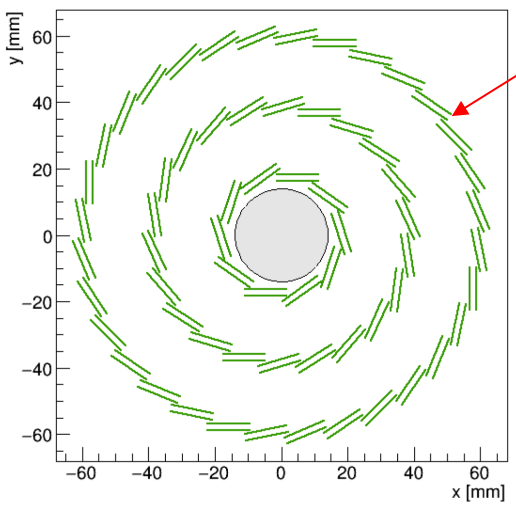






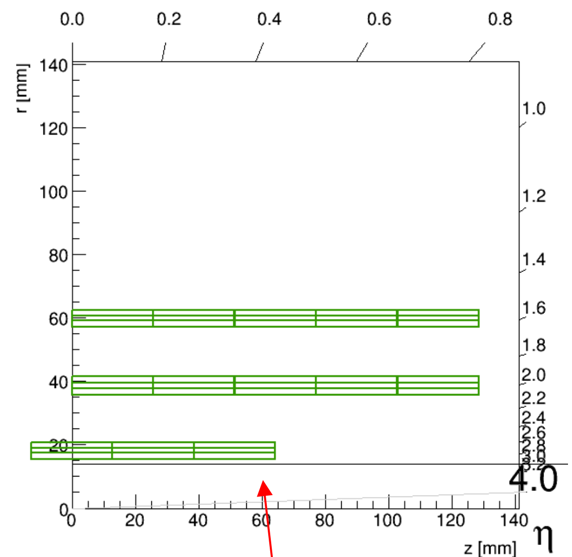
Vertex geometry simulation results

- Prototype V1



XY Section of the tracker barrel. - (png) - (pdf) - (root)

Contact the authors to change source code, Add skewed layer mode



RZ positions of the barrel modules. - (png) - (pdf) - (root)

	numRods	R(mm)	skewAngle(rad)	module width(mm)
Layer 1	10	17.11637	0.290338	12.8
Layer 2	10	19.04127	0.260264	12.8
Layer 3	22	37.66656	0.307478	12.8
Layer 4	22	39.57739	0.292183	12.8
Layer 5	32	58.91426	0.275036	12.8
Layer 6	32	60.84152	0.266108	12.8

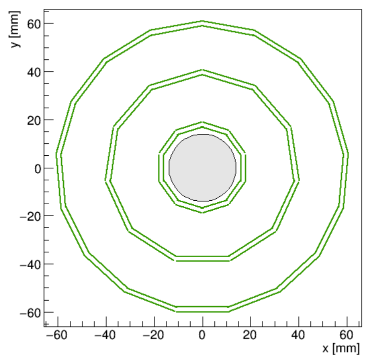
Calculated value

Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	17.116	19.041	37.667	39.577	58.914	60.842	
z_max	64.200	64.200	128.450	128.450	128.450	128.450	
# rods	10	10	22	22	32	32	
# mods	50	50	220	220	320	320	1180

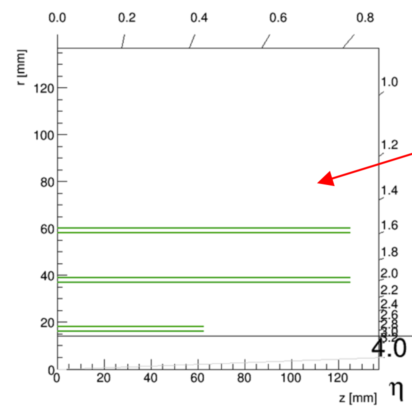
Output value of tkLayout

Comparing CDR baseline with Prototype V1

CDR



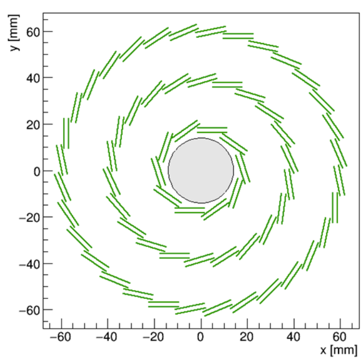
XY Section of the tracker barrel. - (png) - (pdf) - (root)



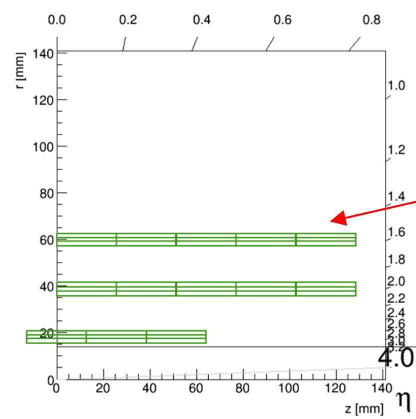
RZ positions of the barrel modules. - (png) - (pdf) - (root)

Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	16.004	18.004	37.003	38.995	57.989	59.995	
z_max	62.500	62.500	125.000	125.000	125.000	125.000	
# rods	10	10	11	11	17	17	
# mods	40	40	88	88	136	136	528

Prototype V1



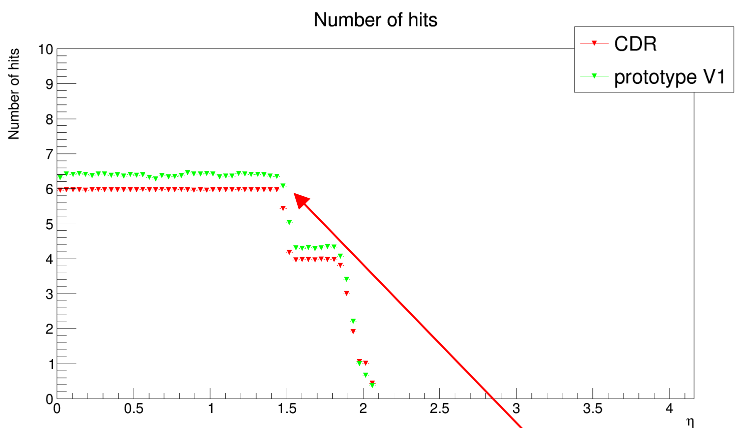
XY Section of the tracker barrel. - (png) - (pdf) - (root)

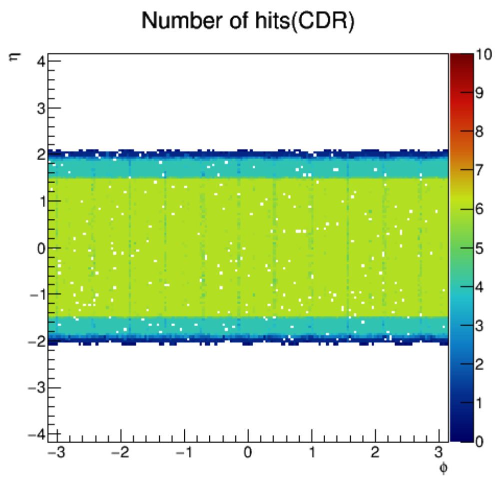


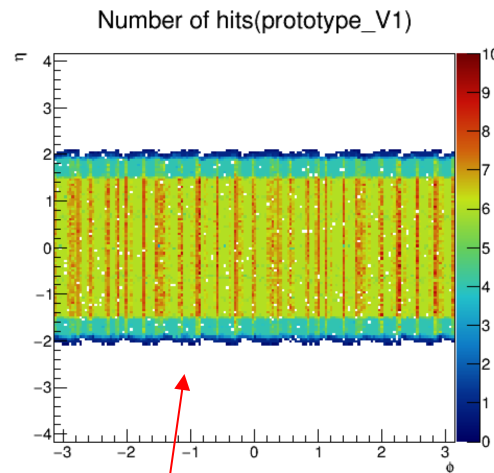
RZ positions of the barrel modules. - (png) - (pdf) - (root)

Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	17.116	19.041	37.667	39.577	58.914	60.842	
z_max	64.200	64.200	128.450	128.450	128.450	128.450	
# rods	10	10	22	22	32	32	
# mods	50	50	220	220	320	320	1180

Hit map and statistics of baseline design and prototype V1





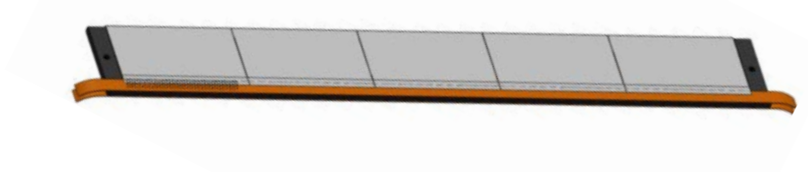


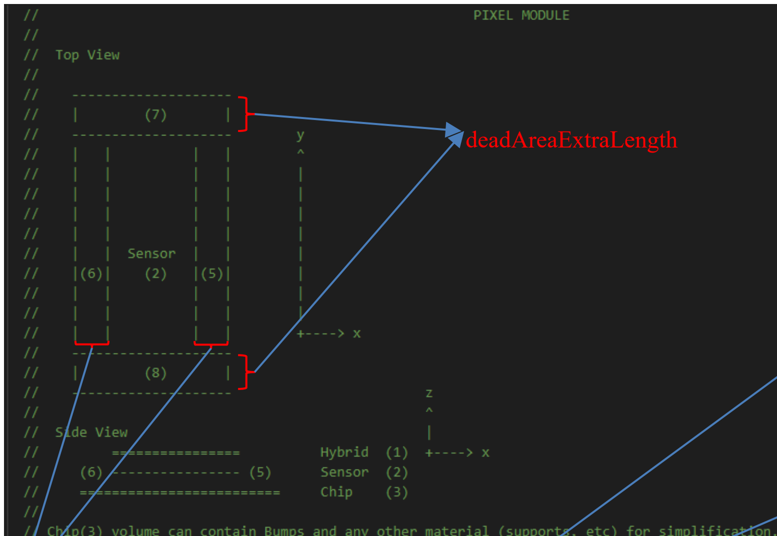
	R (mm)	$\lvert z \rvert$ (mm)	$\lvert\cos\theta\rvert$	$\sigma(\mu m)$	η
Layer 1	16	62.5	0.97	2.8	2.09
Layer 2	18	62.5	0.96	6	1.95
Layer 3	37	125.0	0.96	4	1.95
Layer 4	39	125.0	0.95	4	1.83
Layer 5	58	125.0	0.91	4	1.53
Layer 6	60	125.0	0.90	4	1.47

On average, more hits for prototype V1, because of more overlaps.

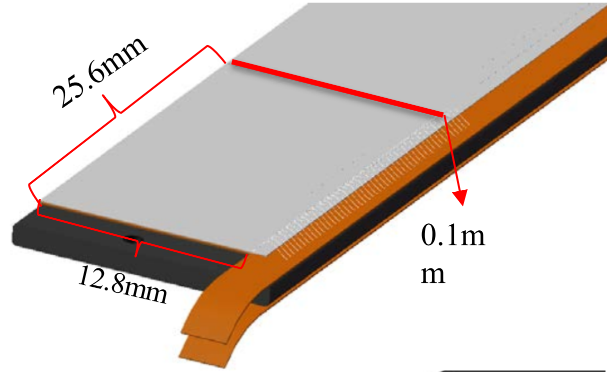
Vertical bands in 2D hits distribution. At Φ , our prototype V1 is not very uniform due to overlaps.

PrototypeV1 module





Top view:
Only consider the sensor area:
12.8mm × 25.6mm
Not consider the sensor dead area and electronics
Side view:
5 symmetric layer, gluing together.
From Jinyu(replace copper with aluminum)



Dead Area Extra Width

Outer pixel module:
Sensor (2)
Chip (3)

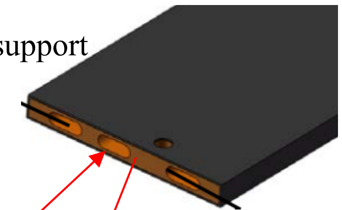
Carbon fiber with an equivalent thickness of 450 microns

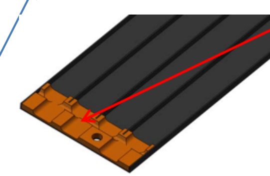
inner pixel module:
Hybrid (1)
Sensor (2)

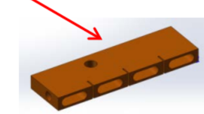
Sensor(Si, 50um)
glue(Epoxy, 15um)
Al(12um)
Adhesive(Epoxy, 15um)
Kapton(50um)
Adhesive(Epoxy, 15um)
Al(12um)
Glue(Epoxy, 15um)
Ladder support(carbon fiber,450um)
Glue(Epoxy,15um)
Al(12um)
Adhesive(Epoxy, 15um)
Kapton(50um)
Adhesive(Epoxy, 15um)
Al(12um)
Glue(Epoxy, 15um)
Sensor(Si, 50um)

(1) Sensor
(2) FPC
(3) Ladder support
(4) FPC
(5) sensor

hollow support



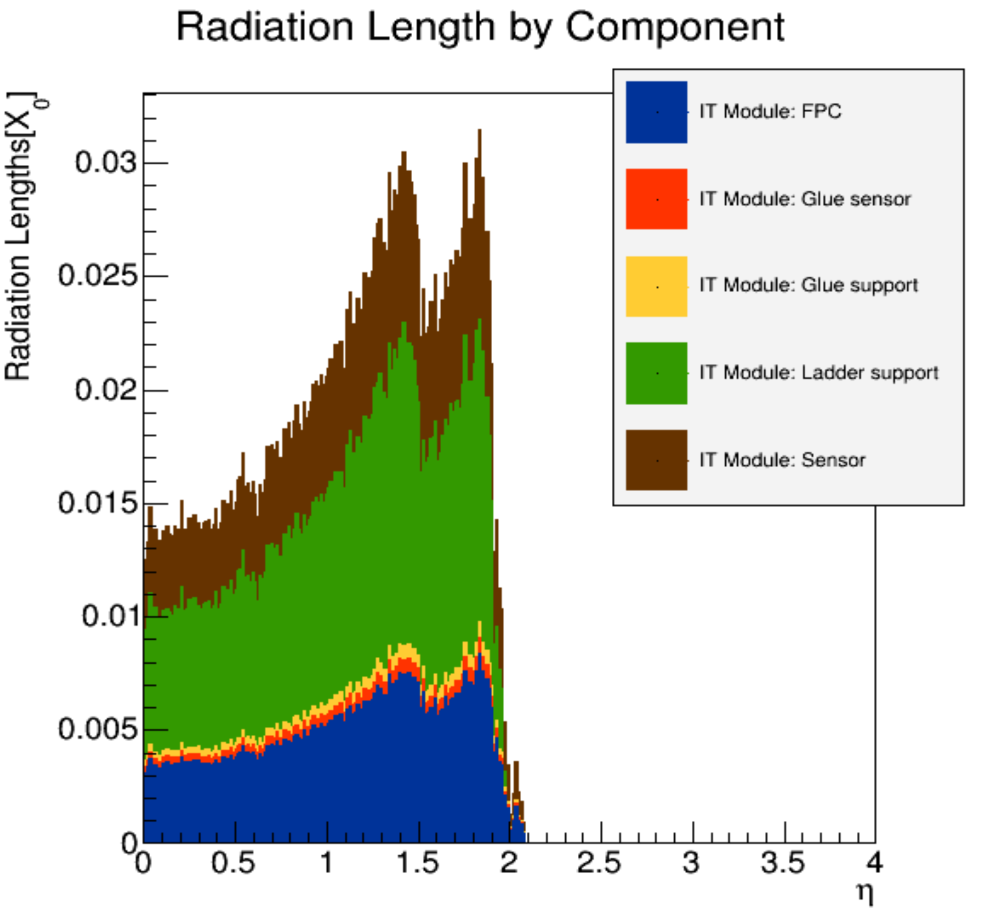




PrototypeV1 material budget

Components details:

Average (eta = [0, 4.0])	Radiation length	Interaction length
IT Module: FPC	0.00256	0.00092
IT Module: Glue sensor	0.00021	0.00010
IT Module: Glue support	0.00021	0.00010
IT Module: Ladder support	0.00444	0.00221
IT Module: Sensor	0.00256	0.00052
Services	0.00000	0.00000
Supports	0.00000	0.00000



Material budget in CDR: 0.15%X_0 per layer

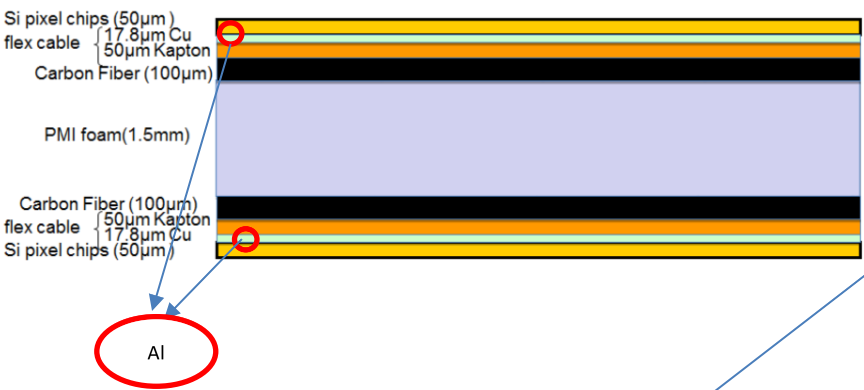
$0.15\% \times 6 = 0.9\% < 0.01$

Bear in mind: 0.9% is on average

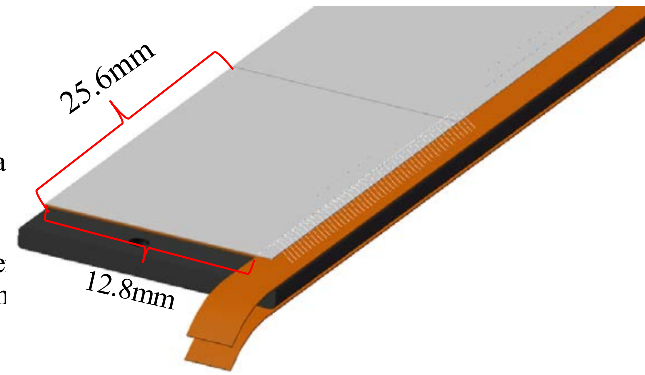
Too much material!

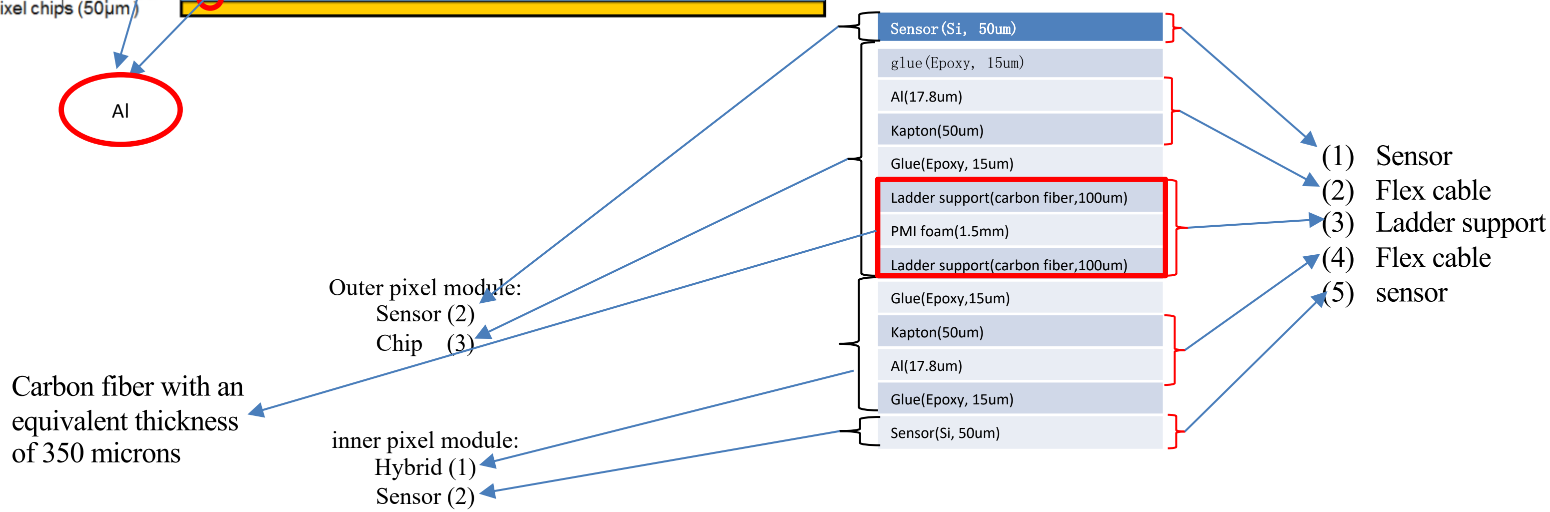
Material budget: alternative design

From Mingyi DONG

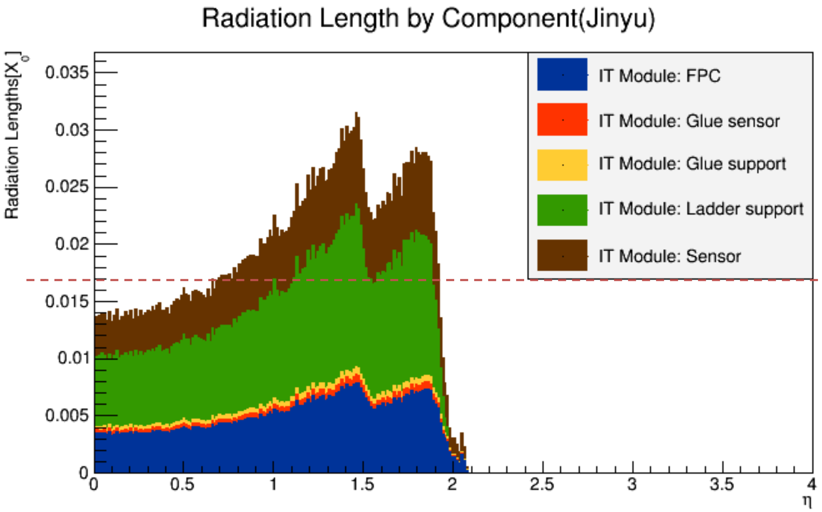


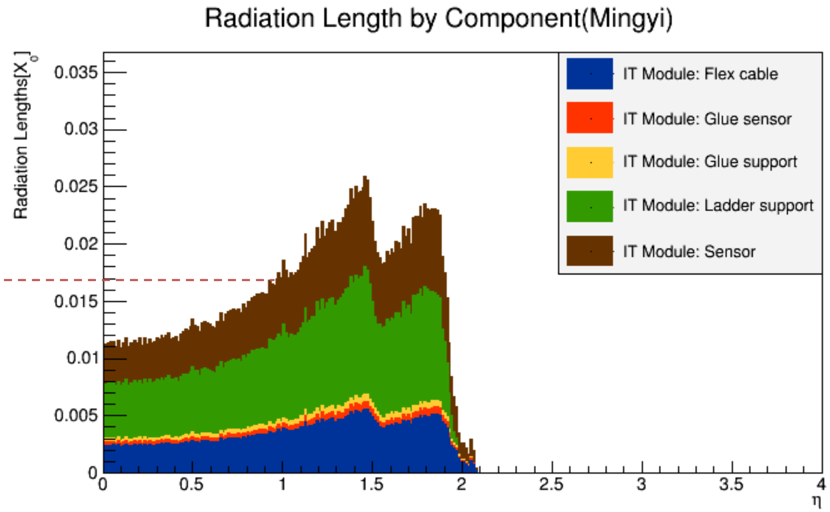
Top view:
Only consider the sensor area:
12.8mm × 25.6mm
Not consider the sensor dead area and electronics
Side view:
5 symmetric layer, gluing togethe
From Mingyi(replace copper with aluminum)





Material budget comparison



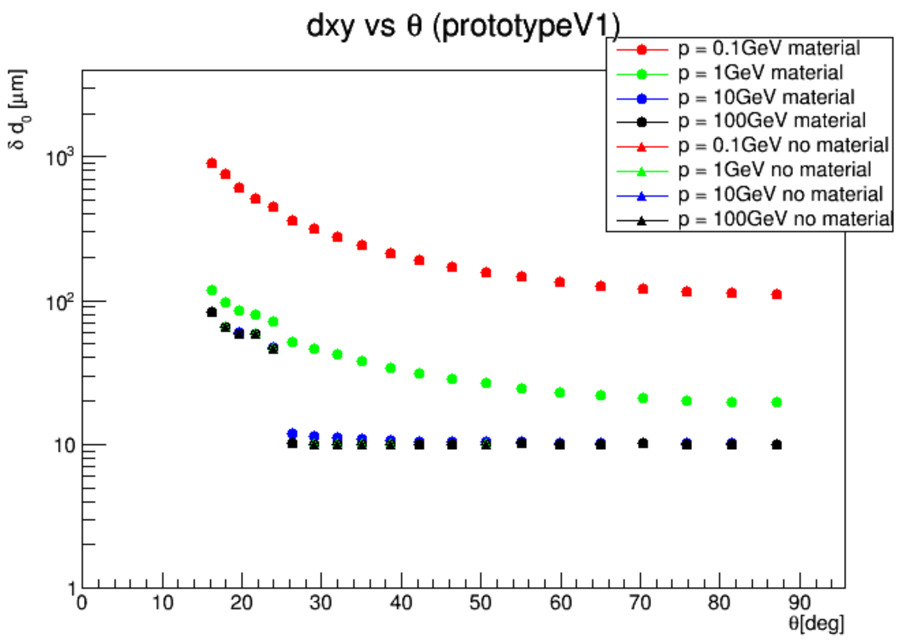


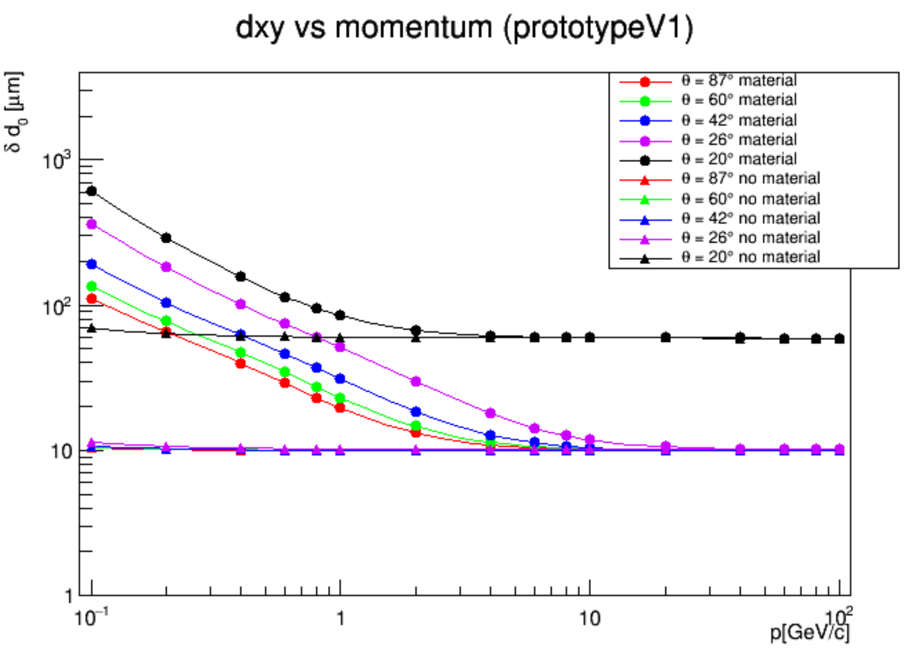
Material budget in CDR: $0.15\%X_0$ per layer

$0.15\% \times 6 = 0.9\%$

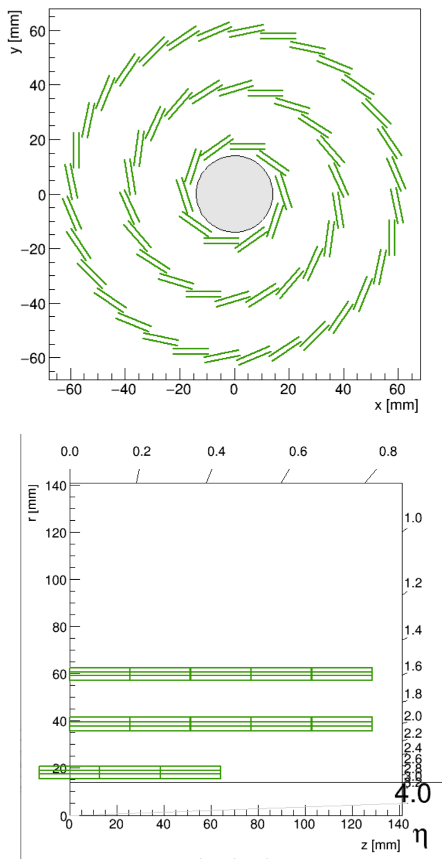
The alternative design still has too much material even at $\theta = 90^\circ$

Impact parameter resolution of Prototype V1

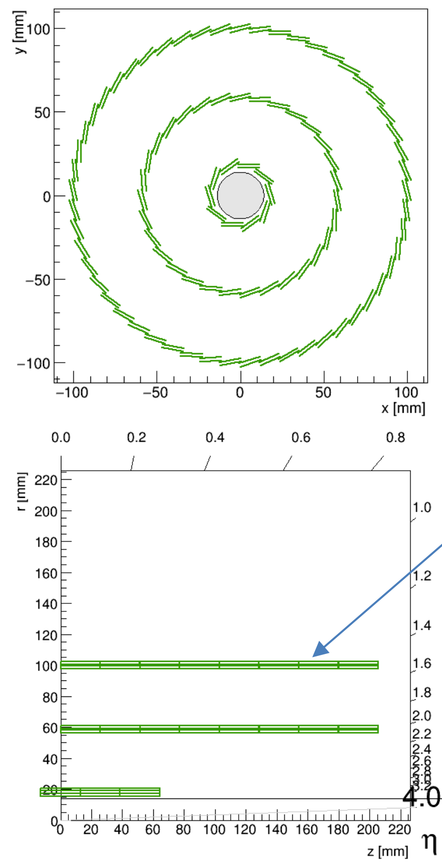




Changing radius

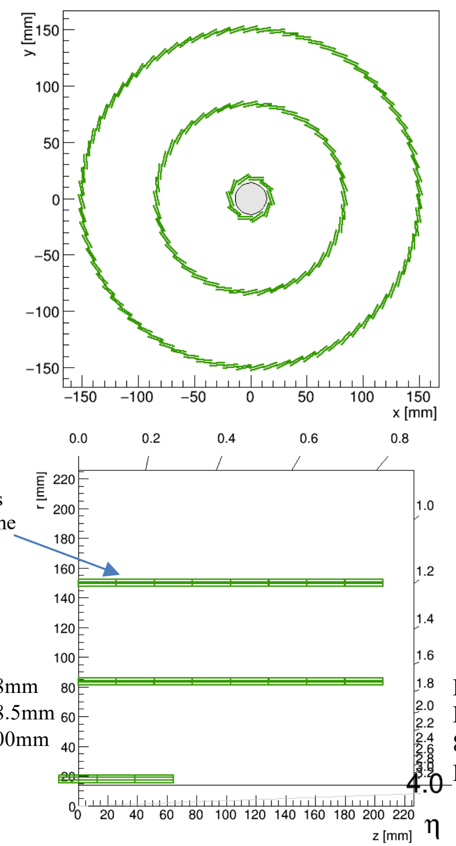


Layer 1: 18mm
Layer 2: 38mm
Layer 3: 60mm



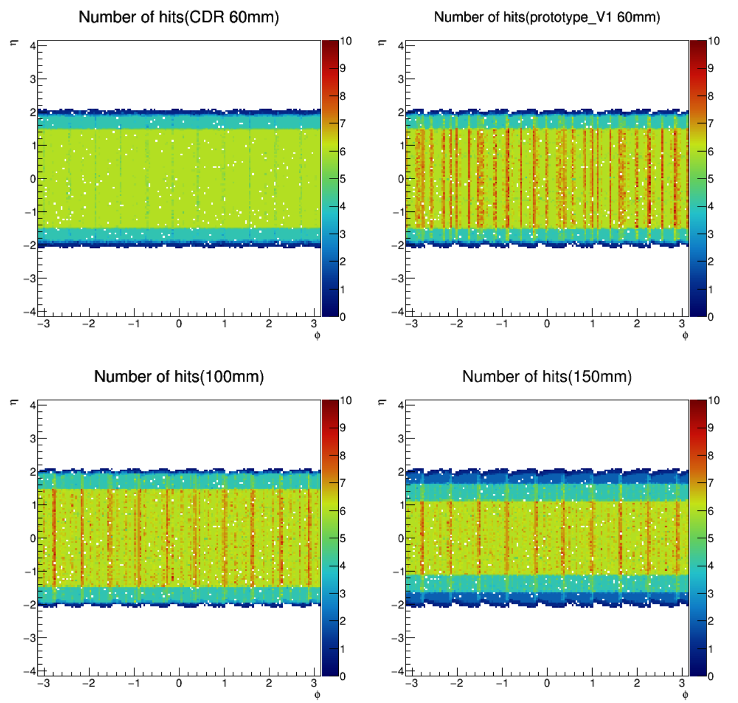
Z lengths are the same

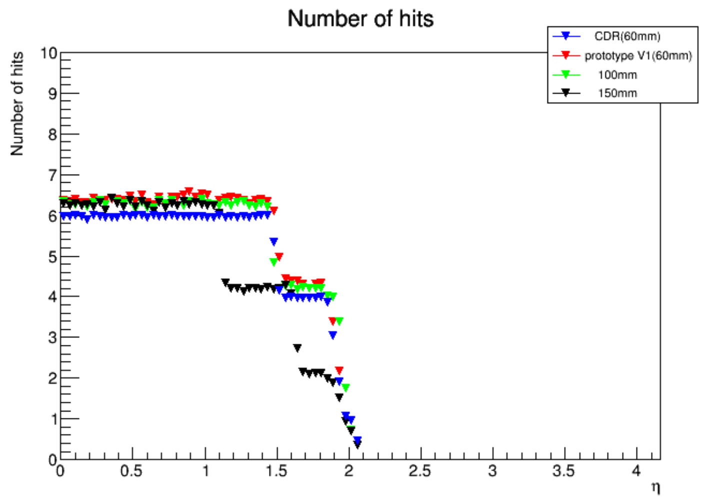
Layer 1: 18mm
Layer 2: 58.5mm
Layer 3: 100mm

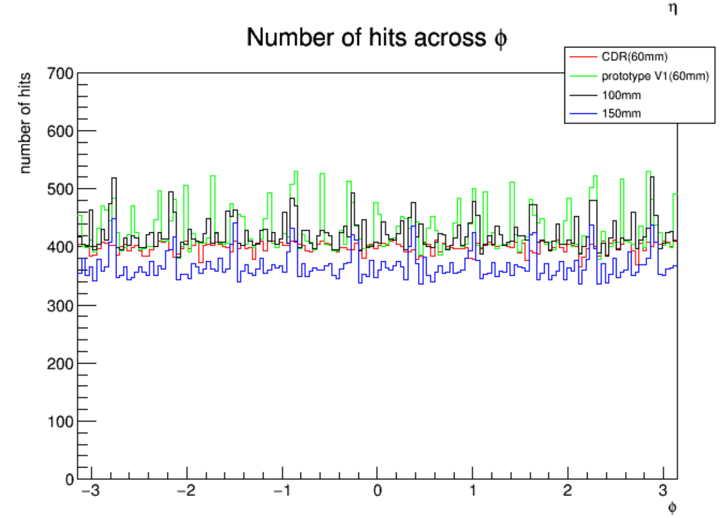


Layer 1: 18mm
Layer 2: 83.5mm
Layer 3: 150mm

Hit map and statistics of different radius

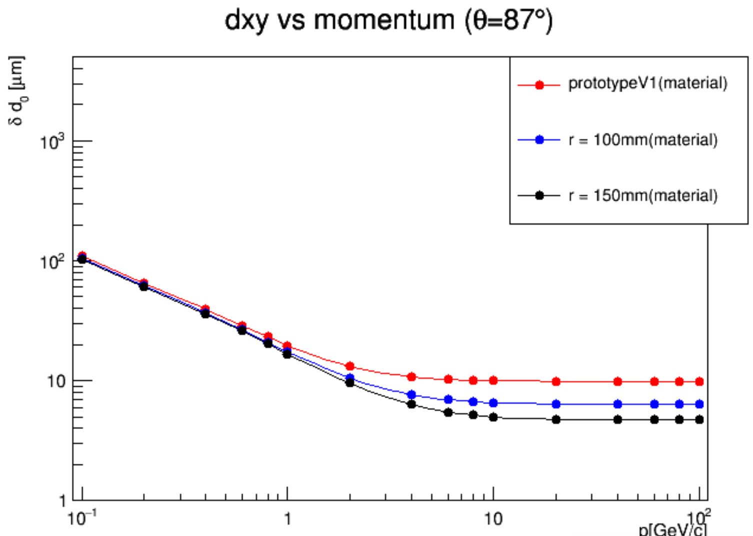


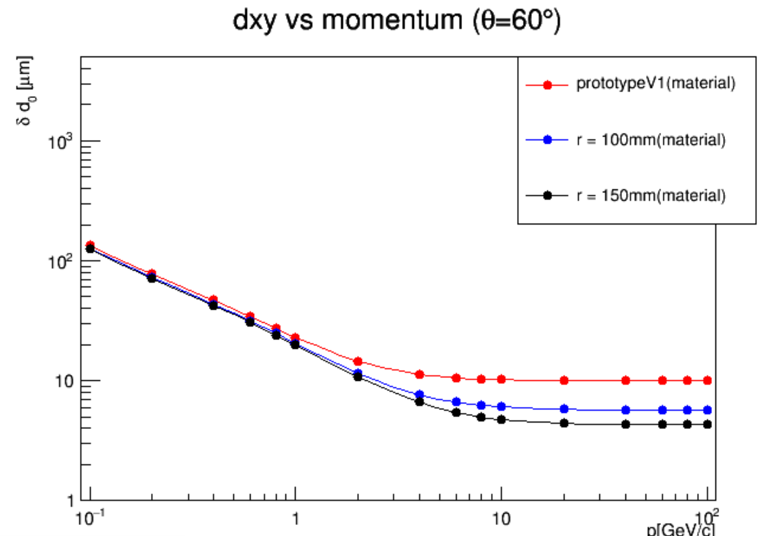




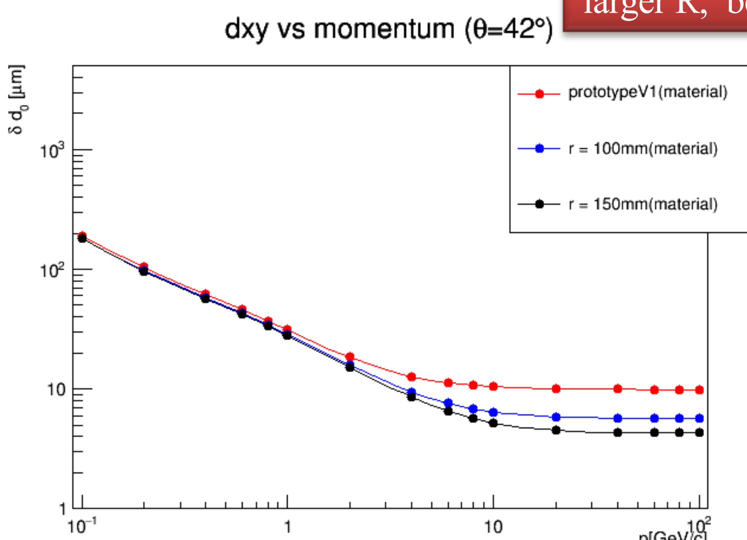
increase radius, number of stripes approaches 10.
Equal to the number of ladders of the first layer.

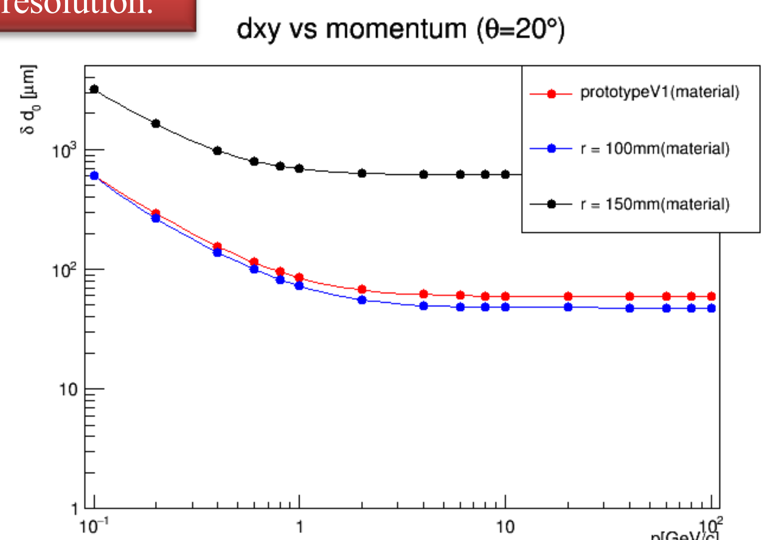
Impact parameter resolutions of different radius



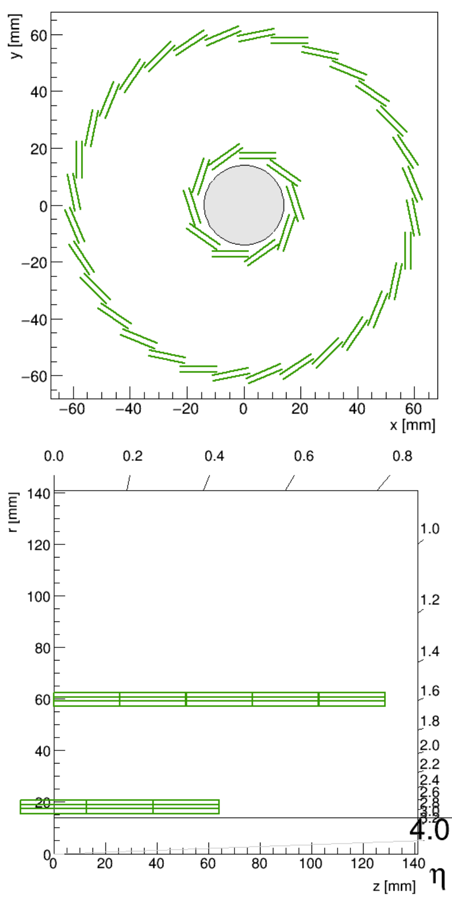


larger R, better resolution.

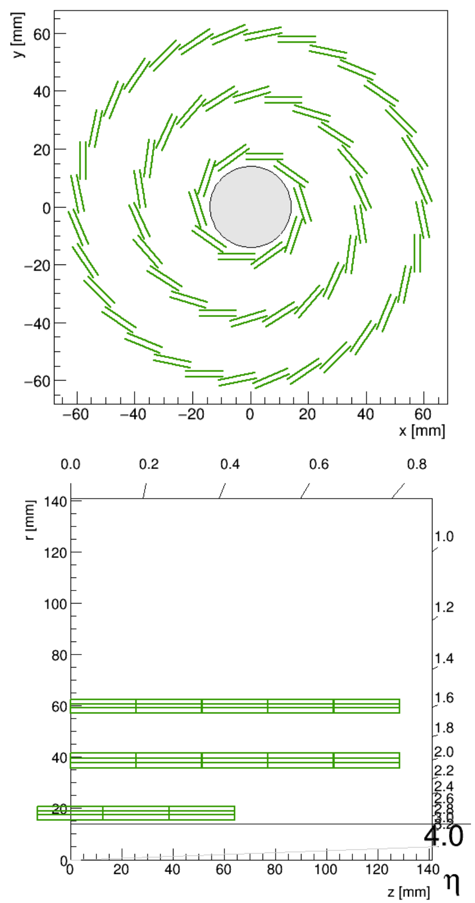




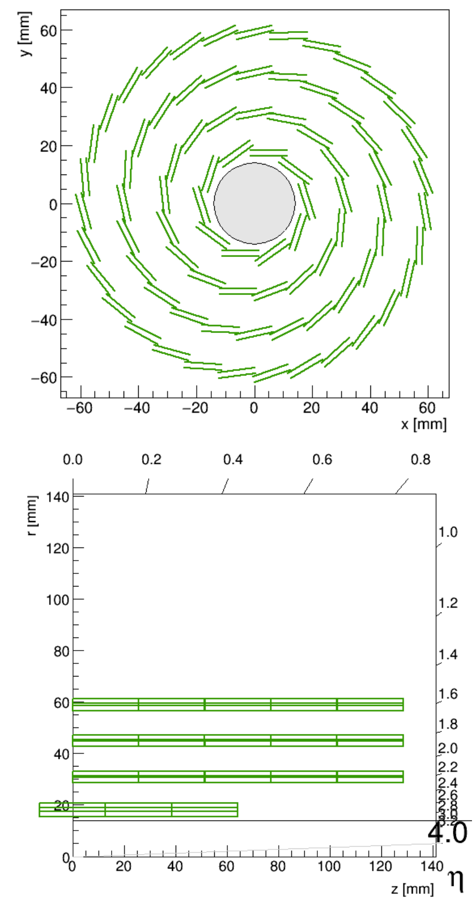
Changing the number of layers



Layer 1: 18mm
Layer 3: 59mm

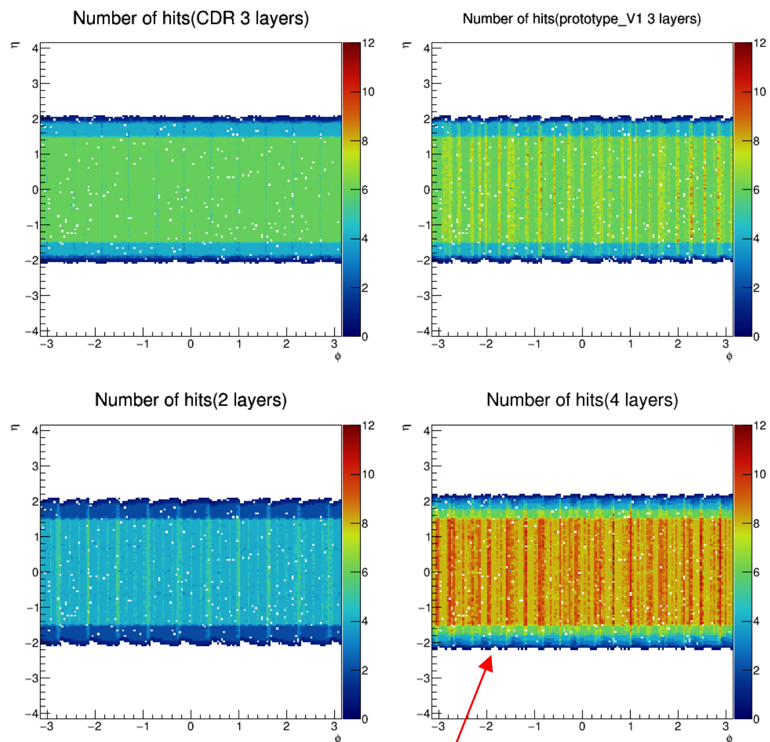


Layer 1: 18mm
Layer 2: 38mm
Layer 3: 60mm

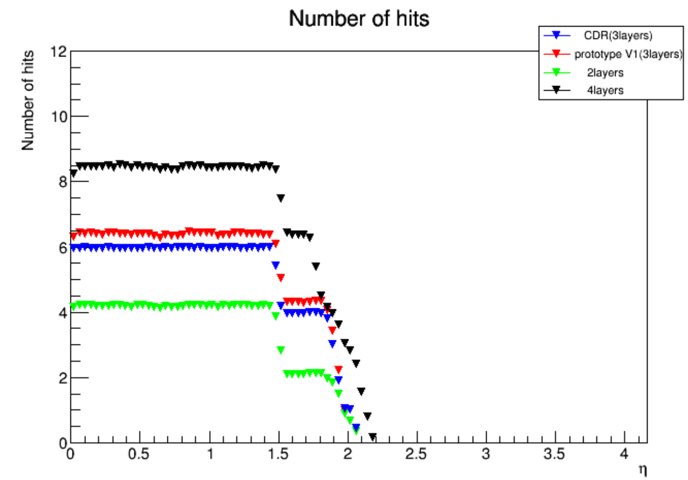


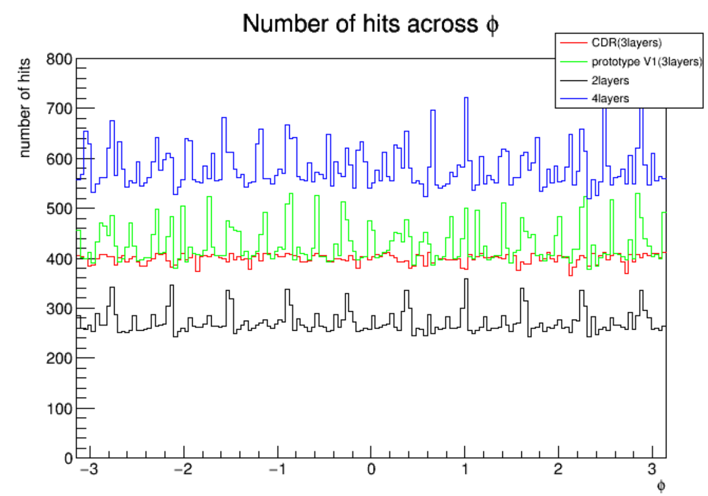
Layer 1: 18mm
Layer 2: 31mm
Layer 3: 45mm
Layer 4: 59mm

Hit coverage comparison

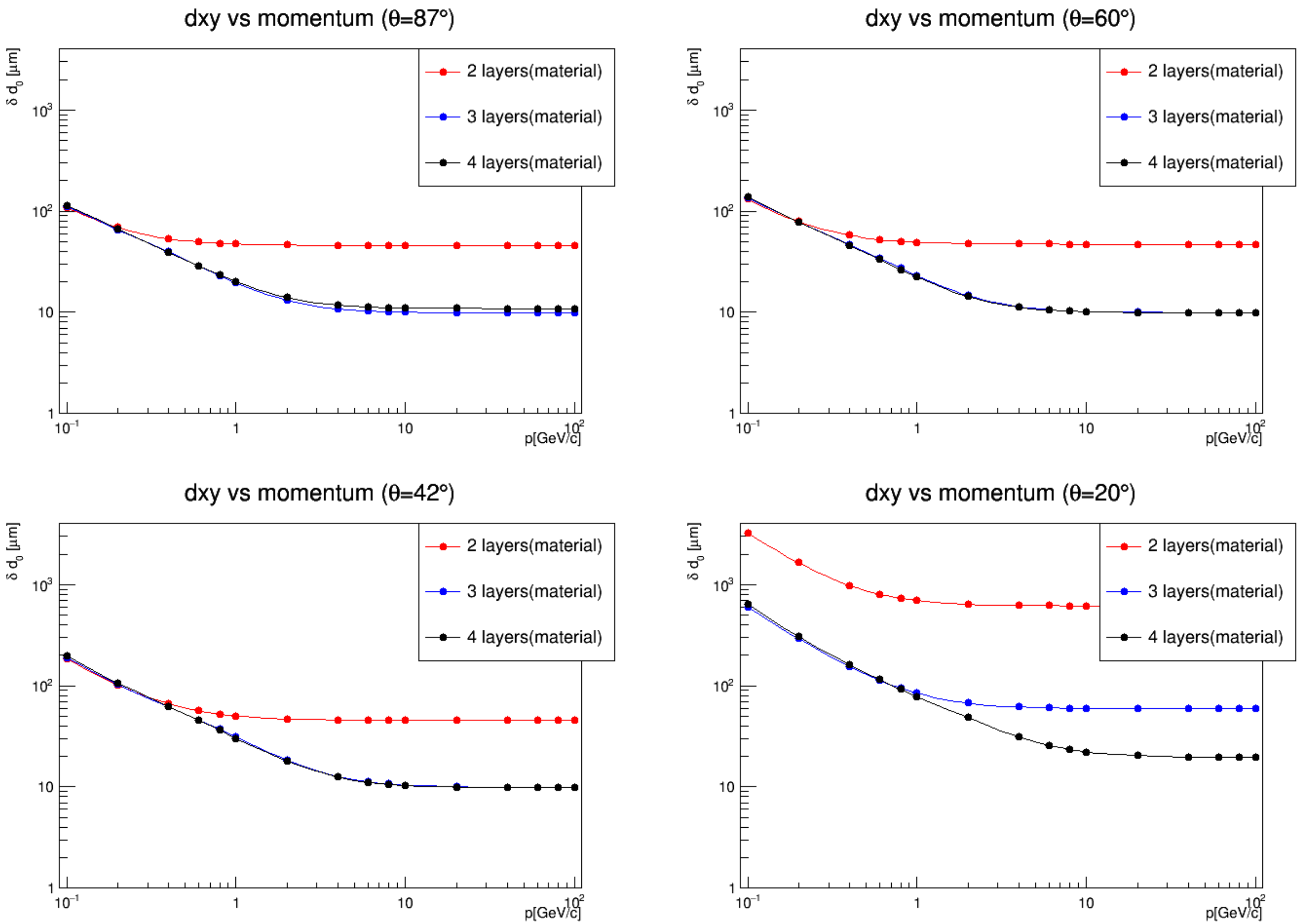


More layers, more stripes.

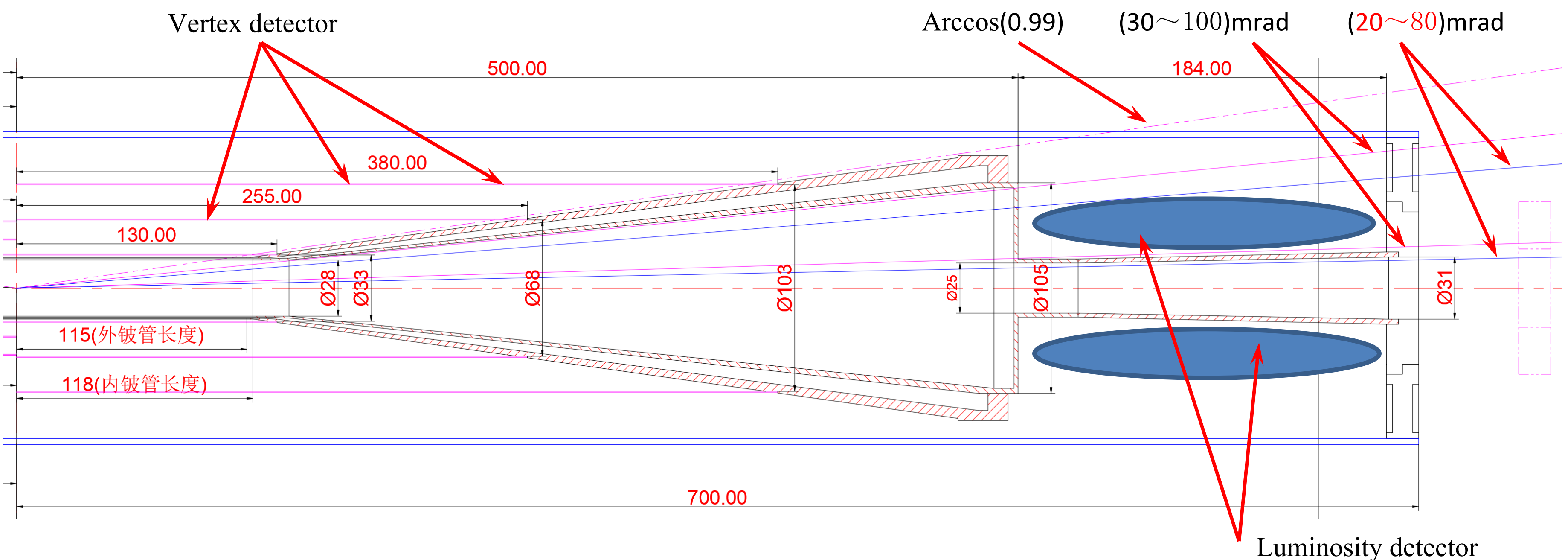




Impact parameter resolutions of different number of layers



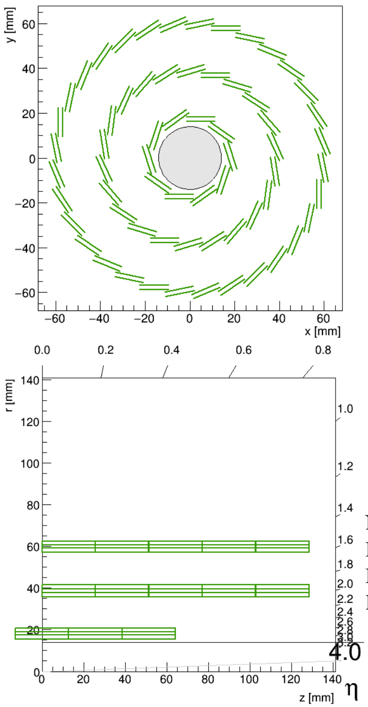
New beampipe

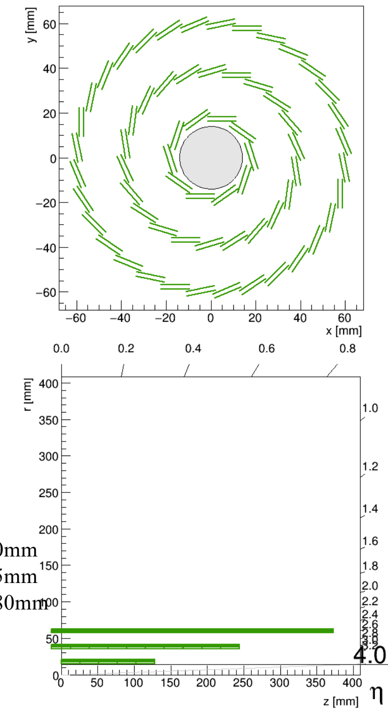


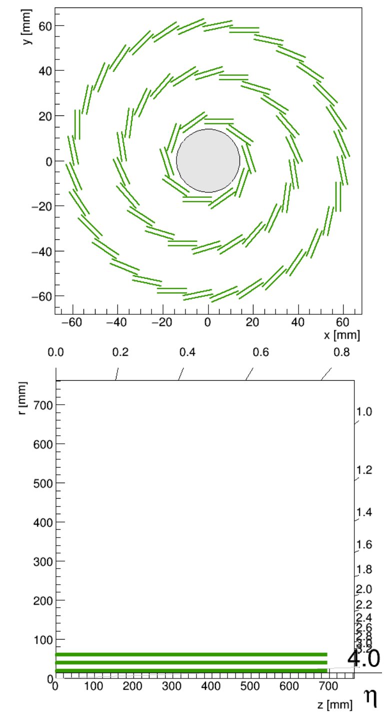
Design by Ji Quan

first layer: Ø33mm, +z=130mm
second layer: Ø68mm, +z=255mm
third layer: Ø103mm, +z=380mm

Layouts comparison







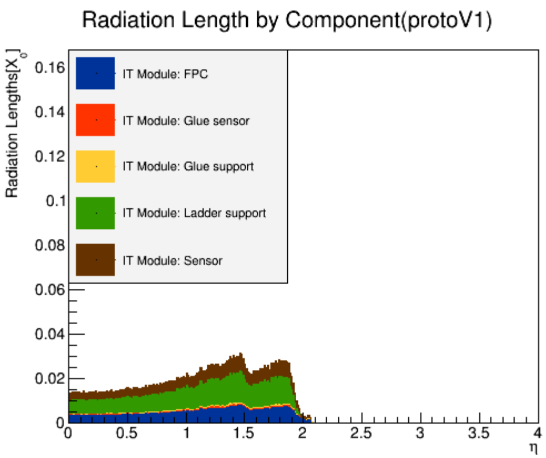
New beam pipe:
Layer 1: Ø33mm, +z=130mm
Layer 2: Ø68mm, +z=255mm
Layer 3: Ø103mm, +z=380mm

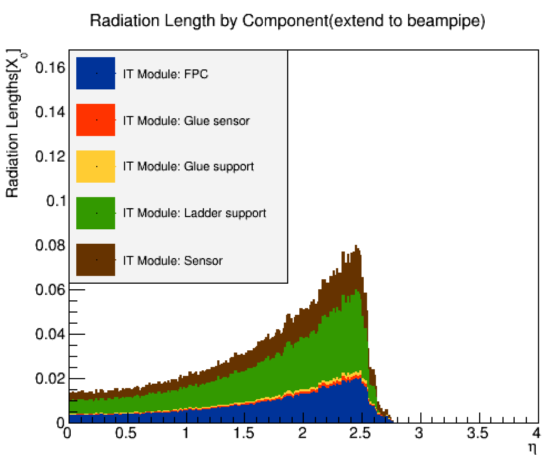
Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	17.116	19.041	37.667	39.577	58.914	60.842	
z_max	64.200	64.200	128.450	128.450	128.450	128.450	
# rods	10	10	22	22	32	32	
# mods	50	50	220	220	320	320	1180

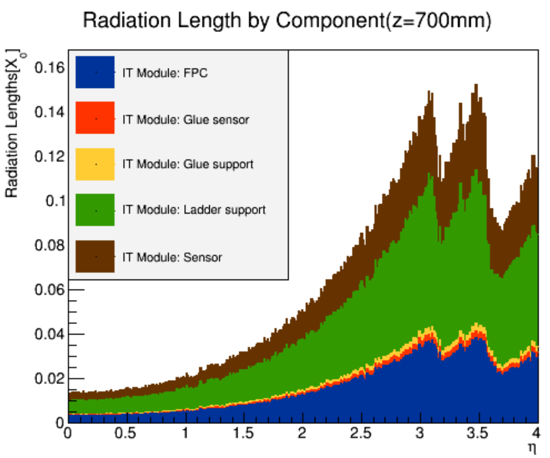
Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	17.116	19.041	37.667	39.577	58.914	60.842	
z_max	128.450	128.450	244.100	244.100	372.600	372.600	
# rods	10	10	22	22	32	32	
# mods	100	100	418	418	928	928	2892

Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	17.116	19.041	37.667	39.577	58.914	60.842	
z_max	693.850	693.850	693.850	693.850	693.850	693.850	
# rods	10	10	22	22	32	32	
# mods	540	540	1188	1188	1728	1728	6912

Material budget comparison

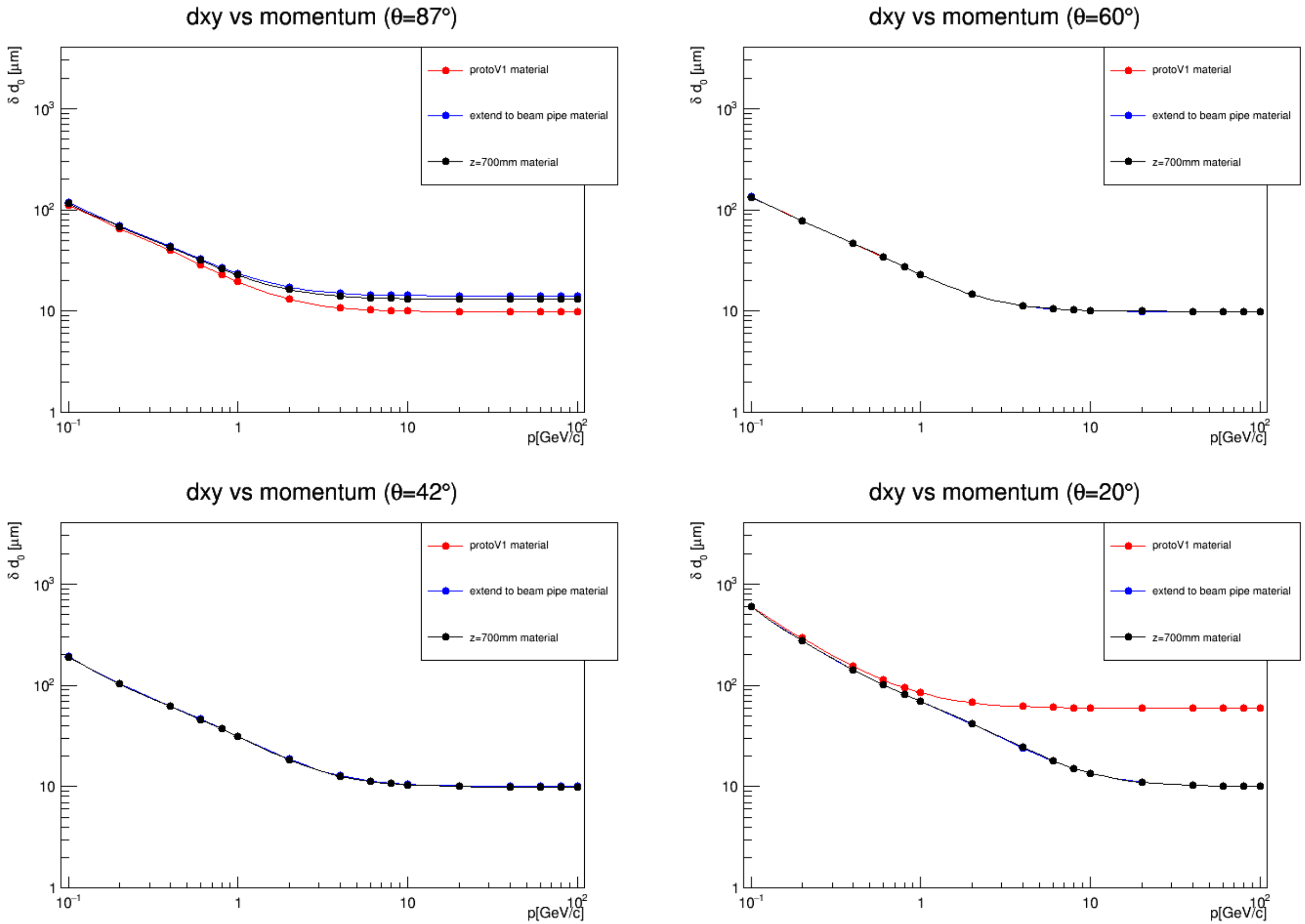






All > 0.9%X_0 !

Impact parameter resolutions of different number of layers

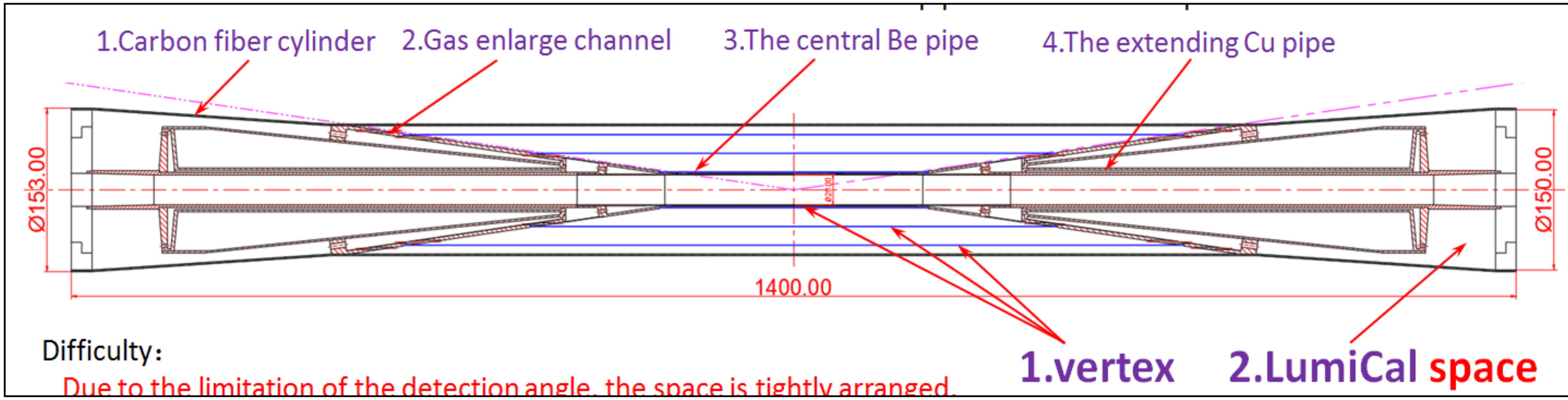


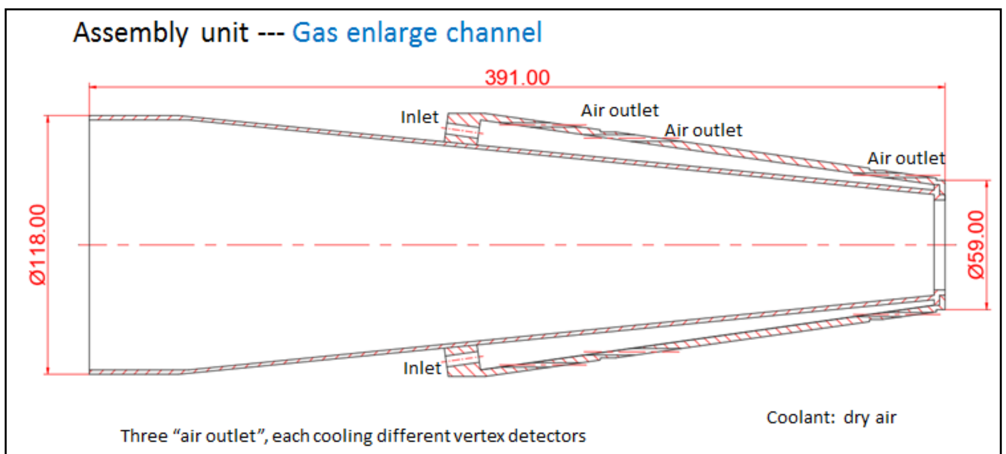
Summary

- Realistic VXD design for both MOST2 prototype and CEPC experiment ongoing.
- Prototype V1 design evaluated with tkLayout fast simulation tool
  - Material budget requirement rather challenge
  - Impact parameter resolution need more check, the trend looks reasonable
- Plan
  - Improve workable mechanical design
  - Understand and validate the simulation tools
  - And evaluate the design with fast simulation → full simulation → physics performance
  - Realistic designs for beam test and CEPC experiment

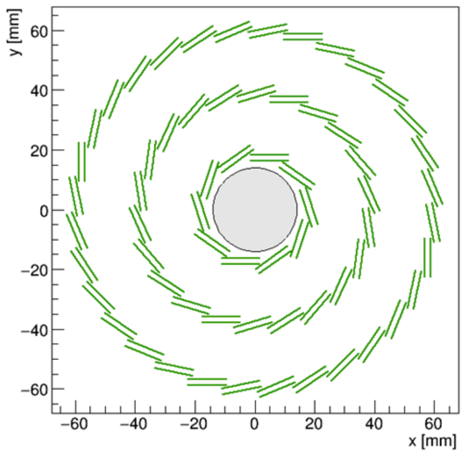
Beam Pipe

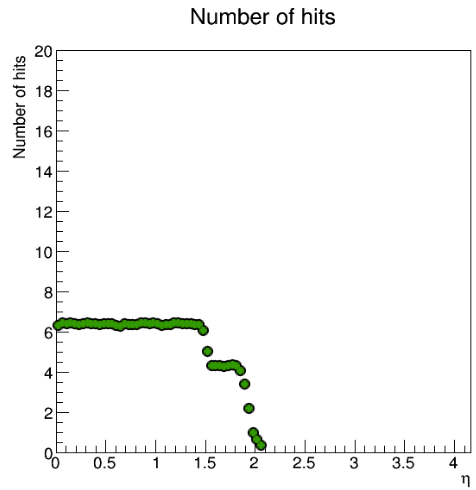
- from Quan Ji



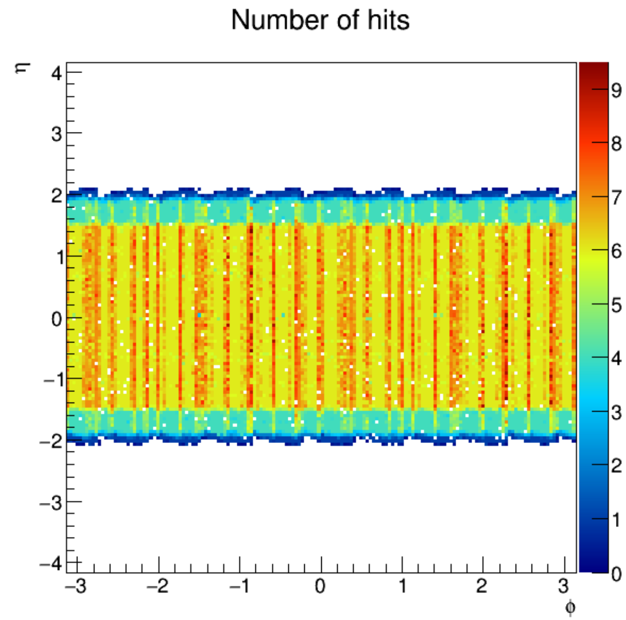


Prototype V1

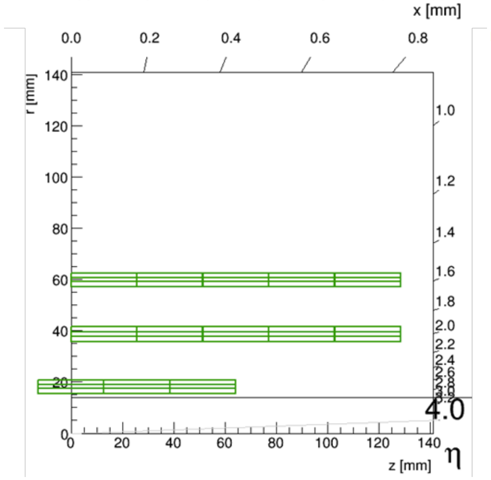




Hit coverage across eta. - (png) - (pdf) - (root)



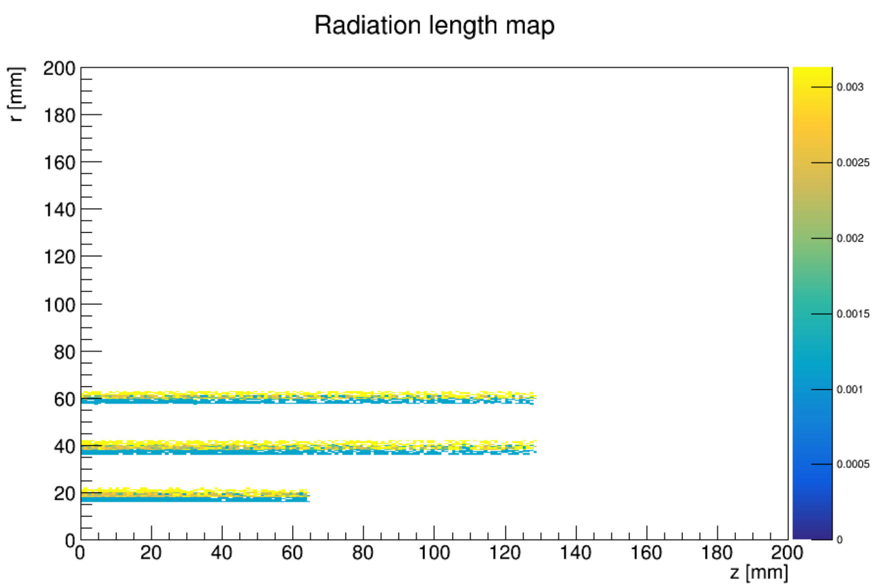
Hit coverage in eta, phi - (png) - (pdf) - (root)

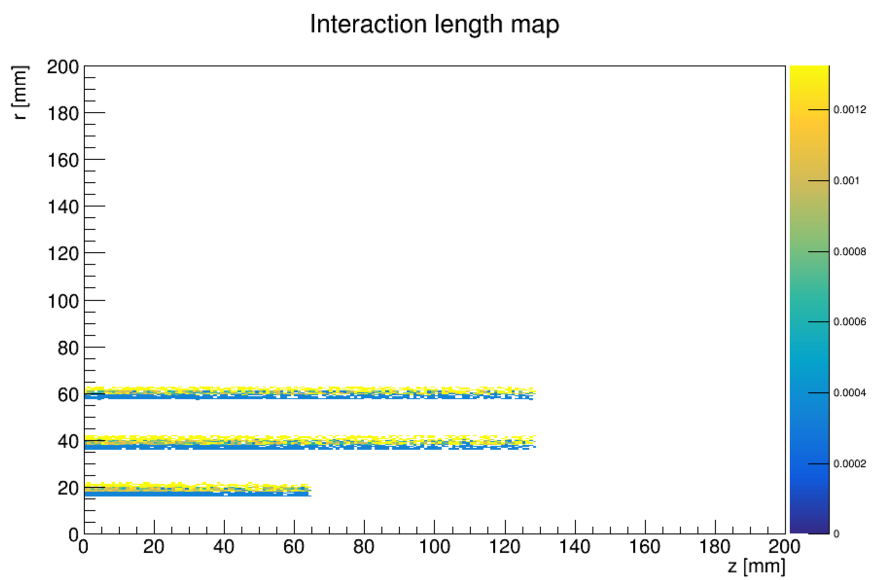


Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	17.116	19.041	37.667	39.577	58.914	60.842	
z_max	64.200	64.200	128.450	128.450	128.450	128.450	
# rods	10	10	22	22	32	32	
# mods	50	50	220	220	320	320	1180

PrototypeV1 material budget

Material distribution:





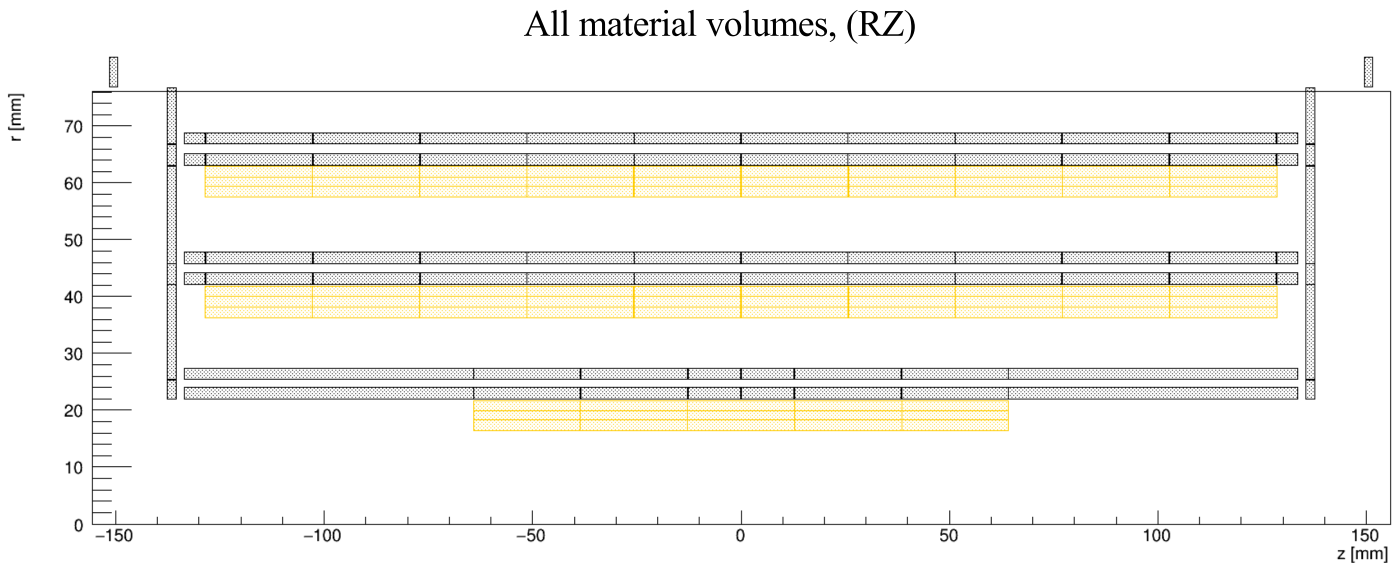
PrototypeV1 material budget

Weight(pixel):

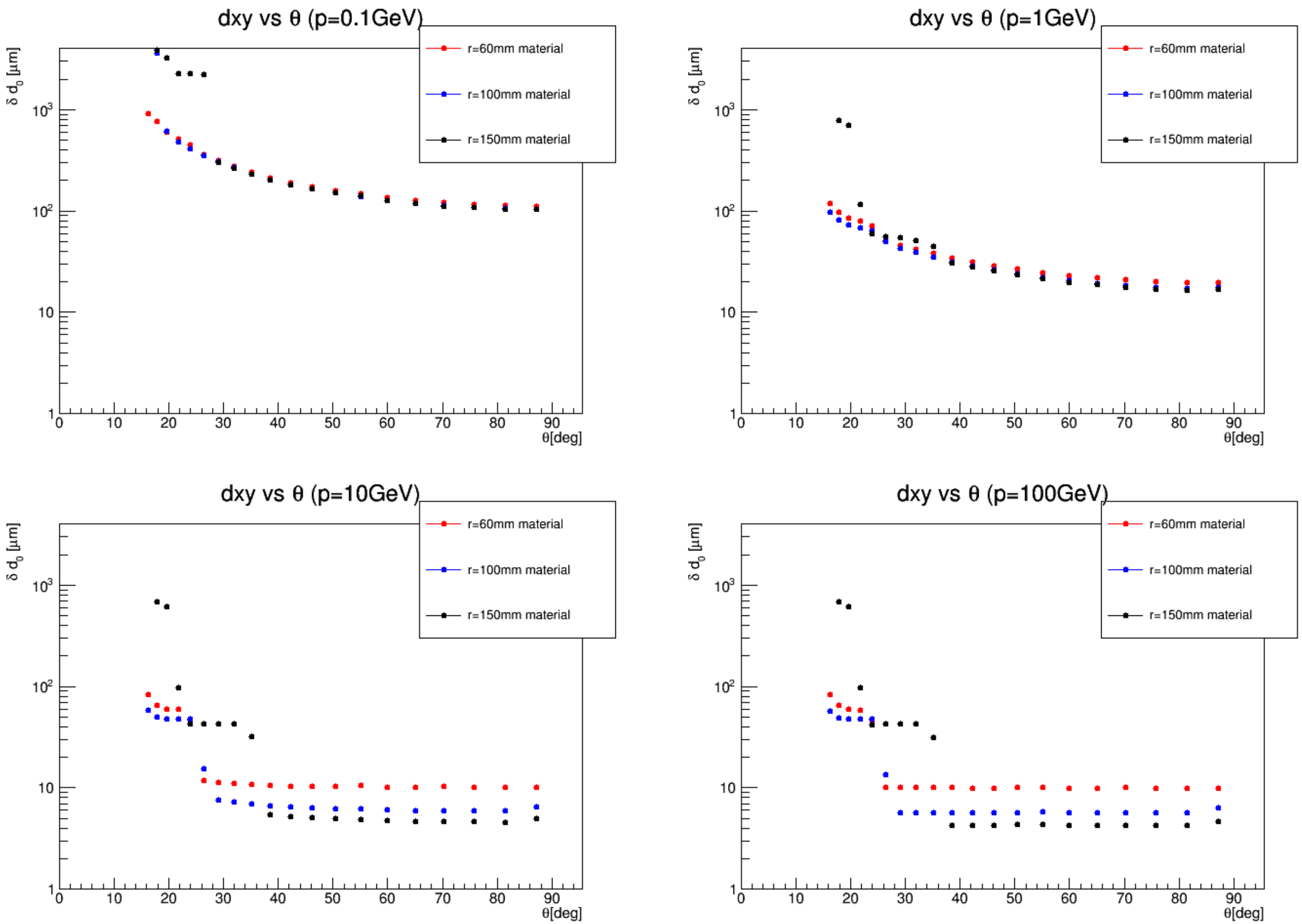
pxb1

MODULE	mass (kg)
IT Module: FPC	0.1
IT Module: Glue sensor	0.0
IT Module: Glue support	0.0
IT Module: Ladder support	0.2
IT Module: Sensor	0.0
TOTAL MODULE	0.3
TOTAL PXB1	0.3

grand total (kg): 0.284519

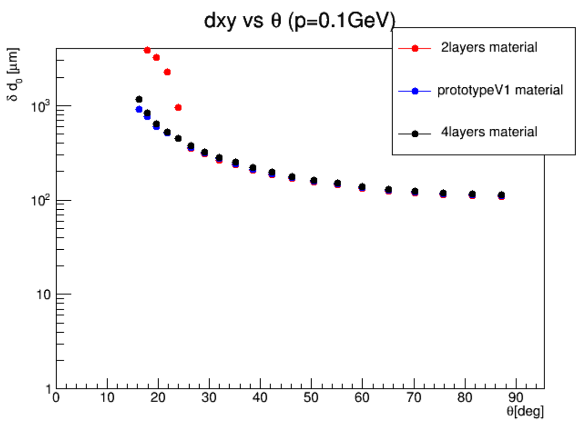


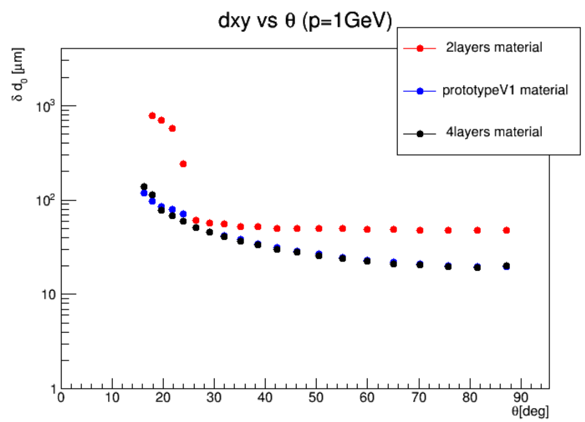
Impact parameter resolutions of different radius

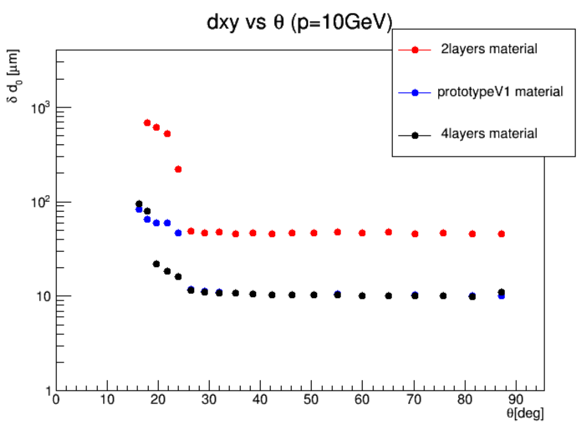


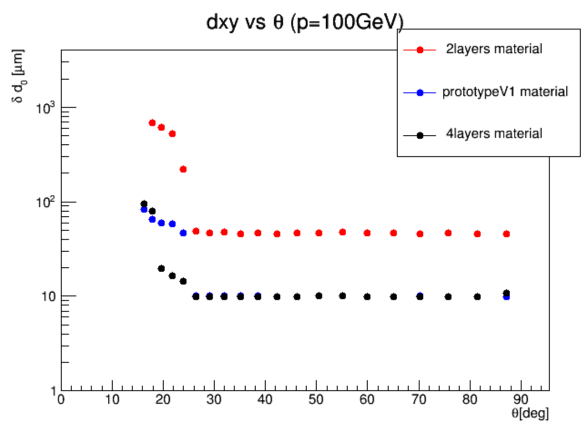
Layouts comparison

- Different number of layers(resolution vs θ)



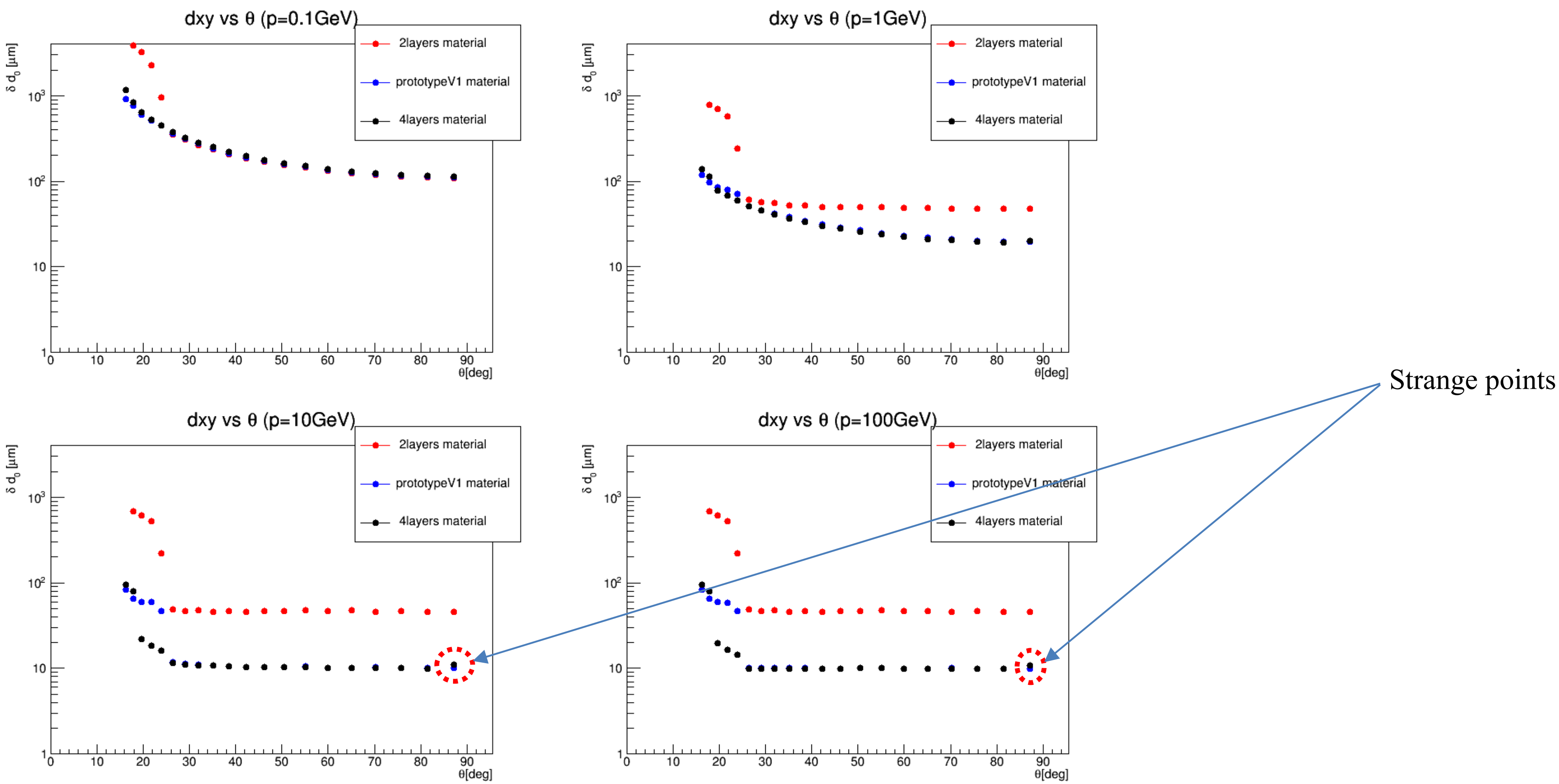






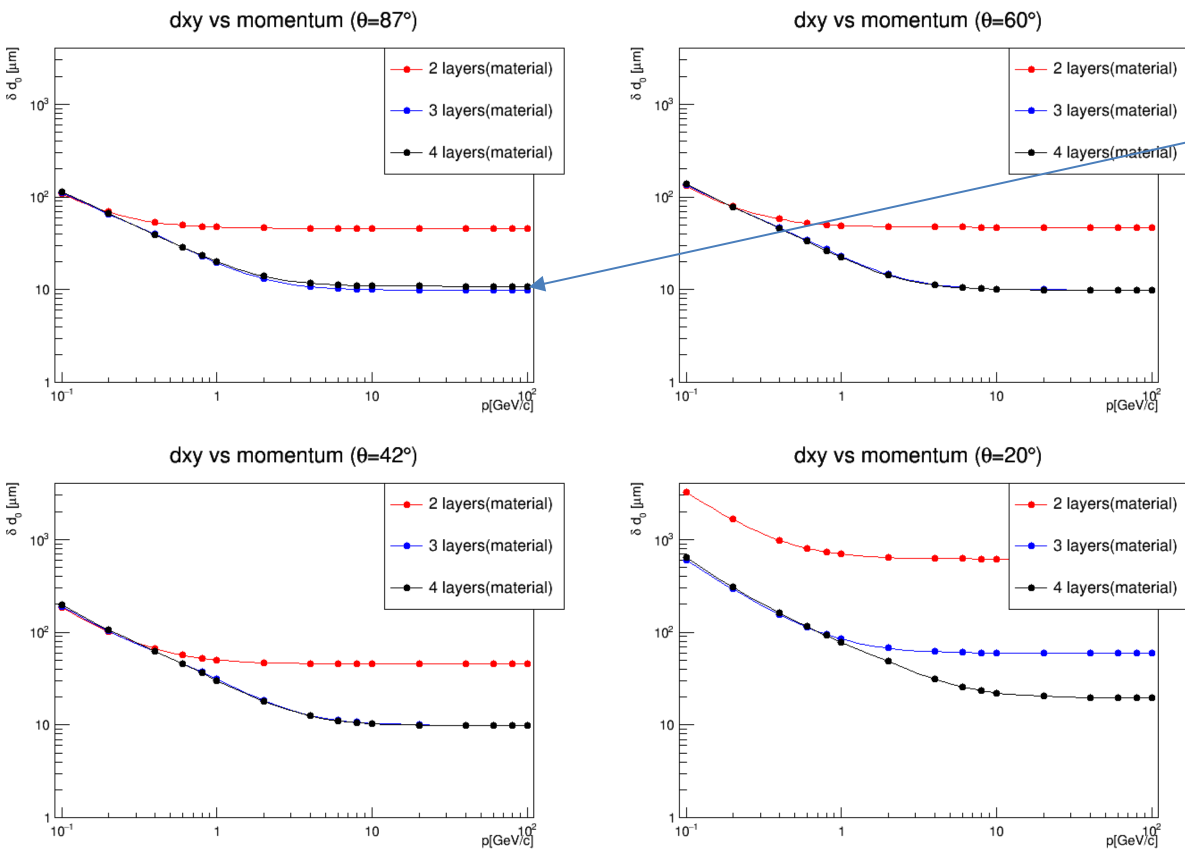
Layouts comparison

- Different number of layers(resolution vs θ)



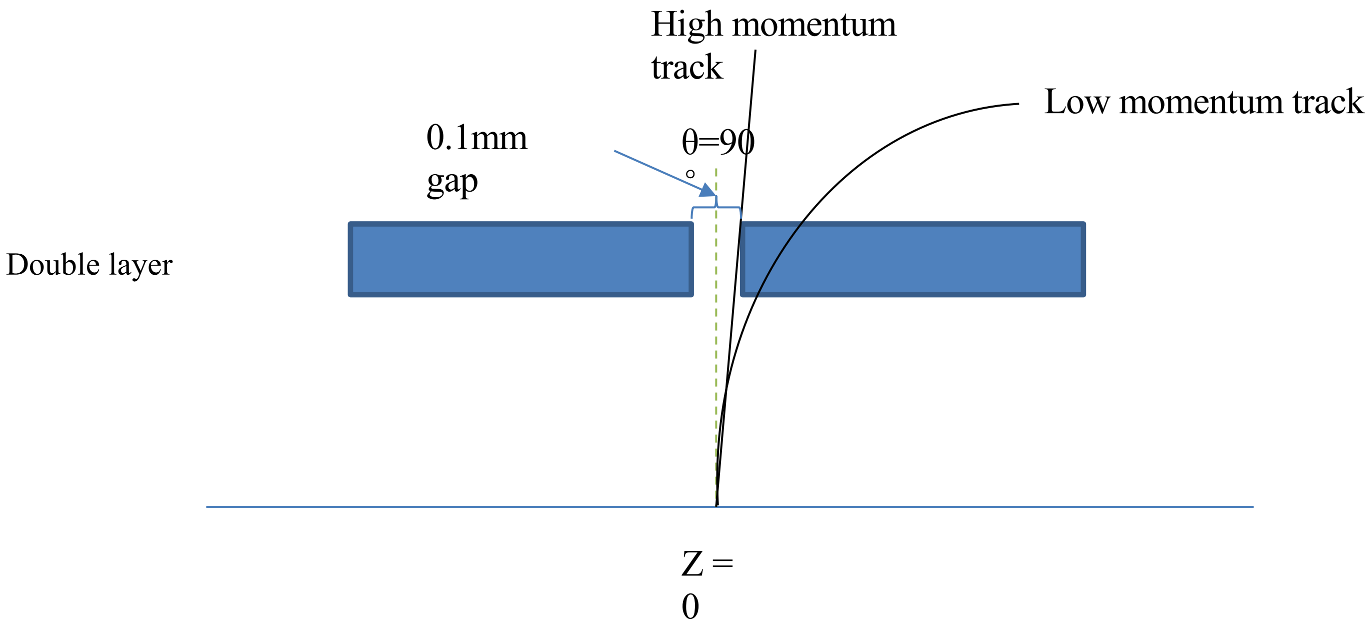
Layouts comparison

- Different number of layers(resolution vs p)



3 layers better than 4 layers???

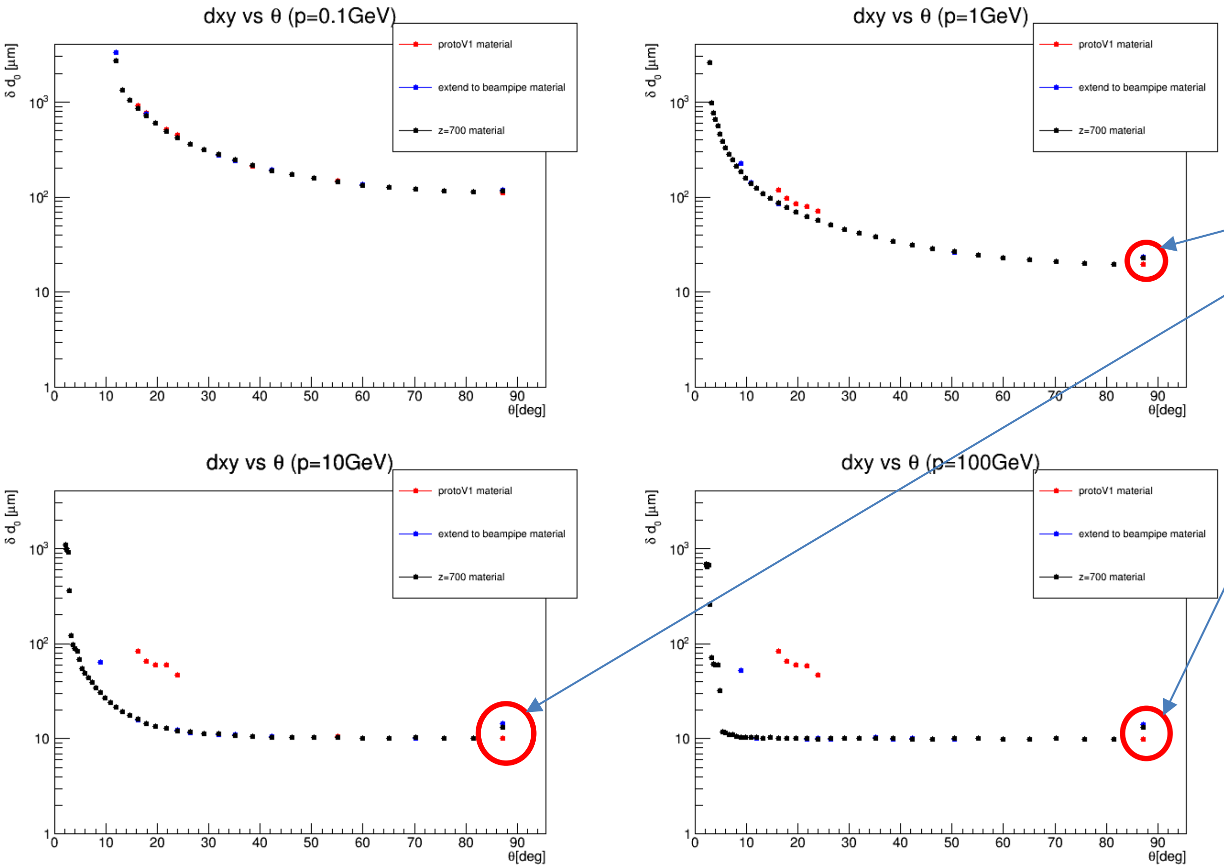
Possible answer



High momentum track can pass through this small gap at θ around 90°, there will be no hits in this double layer.
So the resolution of high p will be worse if there are gaps at z=0.

Layouts comparison

- Resolution for different z length:



No gap at z=0 for protoV1 first layer barrel