Optimizing the layout of the CEPC tracking system

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and many people

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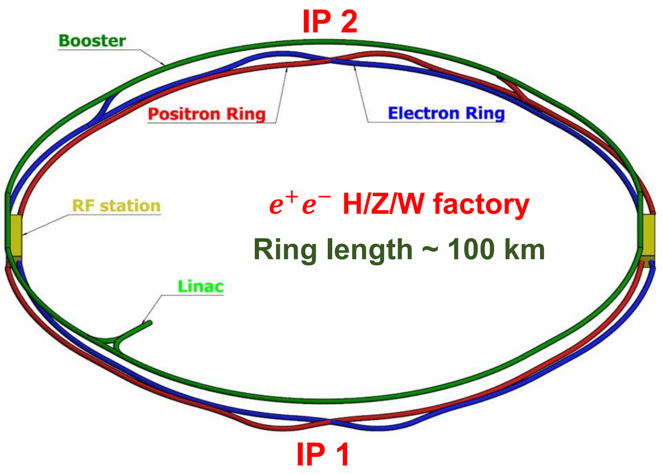
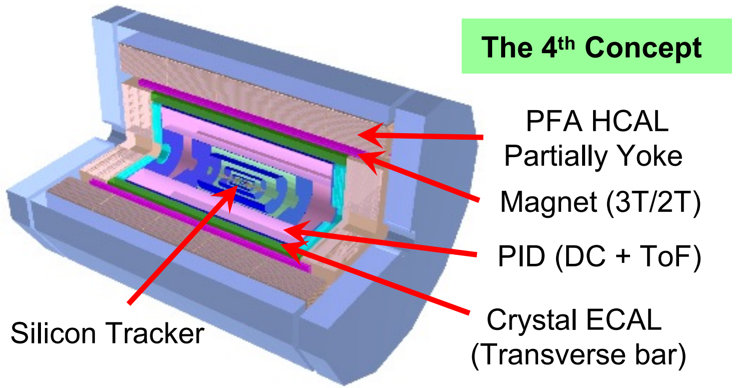
Outline

- Introduction
- Some results with toy studies
- Interpretation with the CEPC tracker system as an example
- Summary

Future Electron Positron Colliders

- Various future electron positron collider experiments proposed, take the CEPC as an example **http://cepc.ihep.ac.cn/**
- Aims to cover a wide energy range: H/Z/W factories
- To run at $\sqrt{s}$ ~ 240 GeV, just above the **ZH** threshold for ~4M Higgs; at the **Z** pole for ~4 Tera Z; and lots of **W^+W^-** pairs, and possible $t\bar{t}$ pairs.
- Higgs, EW, flavor physics & QCD, BSM physics (eg. dark matter, EW phase transition, SUSY, LLP, ….)
- Tracker system important to handle the charged tracks in a wide momentum range





Introduction

- Charged particles in a collision event carry > 60% energy, provide the most precise information
- Tracking system is one of the key sub-detectors
  - Determining the impact parameters and momenta of charged particles
  - Finding secondary vertex of long lived particles
  - Being essential input for Particle Flow reconstruction
- Future collider experiments require extra high momentum resolution: d(1/p) ~ 10^{-5} level, i.e, CEPC:

Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$

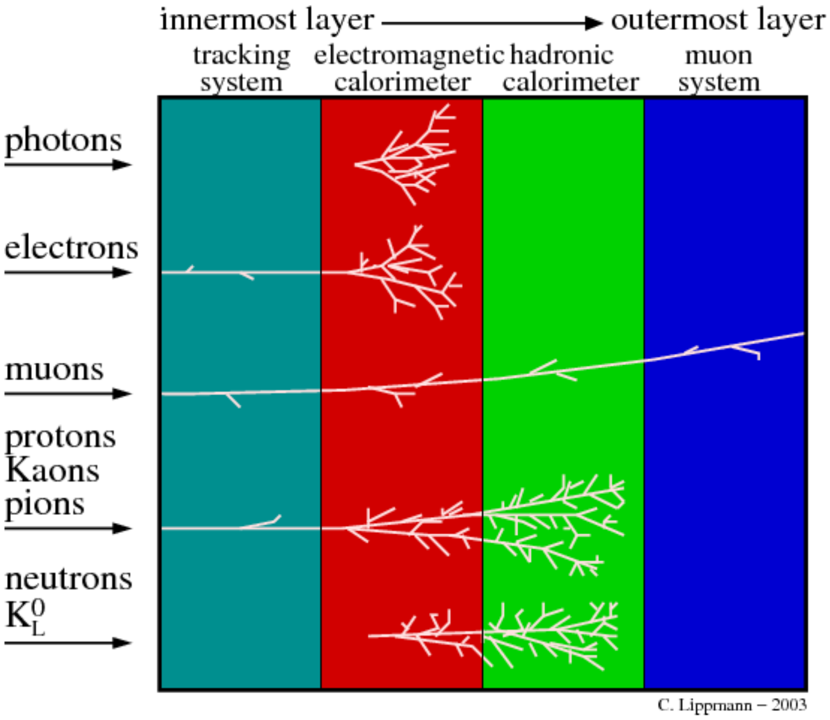
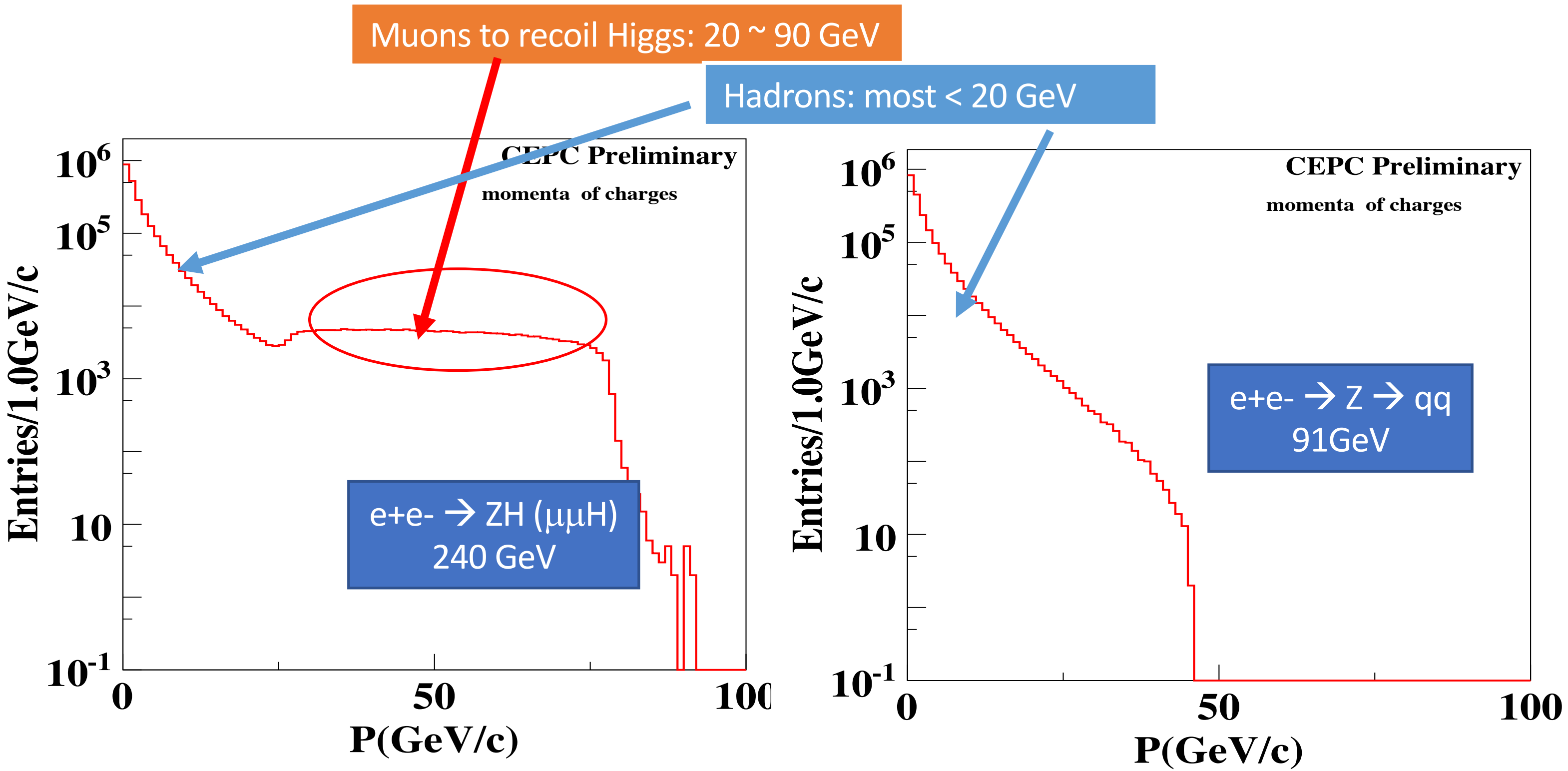
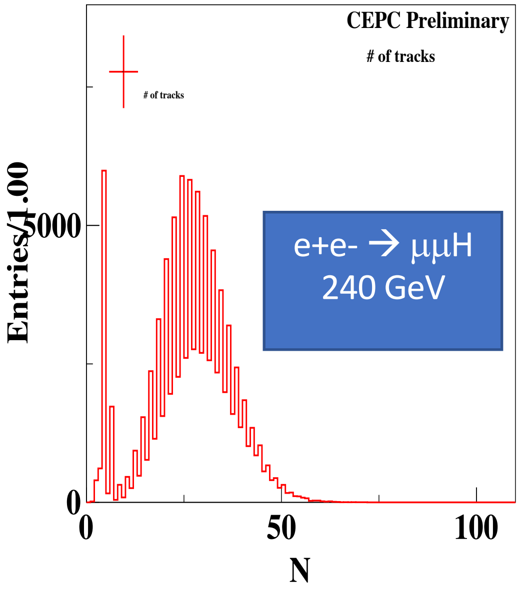


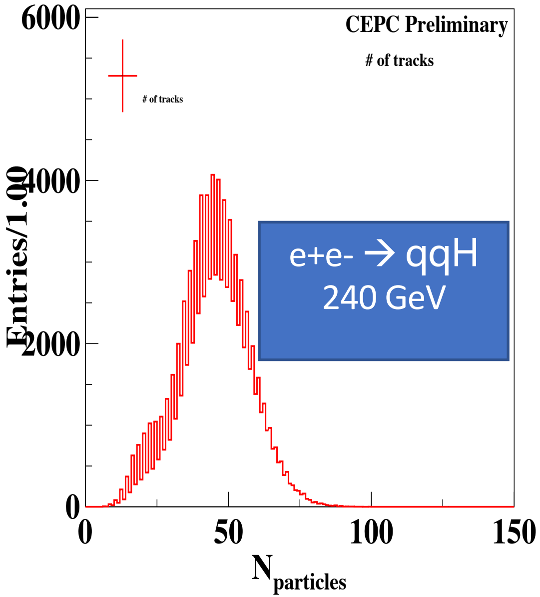
Figure from arXiv:1101.3276

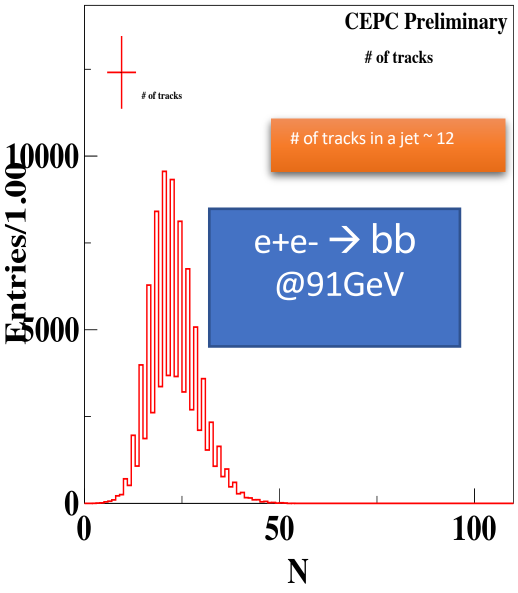
Momenta of tracks @ 240 & 91 GeV



Number of tracks in a event







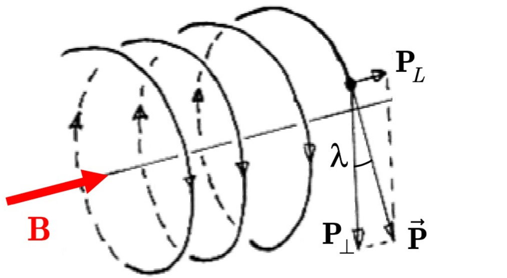
Introduction

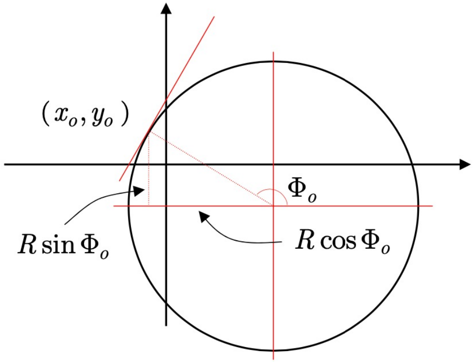
- Track reconstruction
- Inference the track parameters from hits

$$(d_0, z_0, \lambda, \phi_0, \kappa)$$

helix:

$$\begin{aligned} x &= d_0 \cos\phi_0 + \alpha/\kappa(\cos\phi_0 - \cos(\phi_0+\varphi)) \\ y &= d_0 \sin\phi_0 + \alpha/\kappa(\sin\phi_0 - \sin(\phi_0+\varphi)) \\ z &= z_0 - \alpha/\kappa \tan\lambda \cdot \varphi \end{aligned}$$

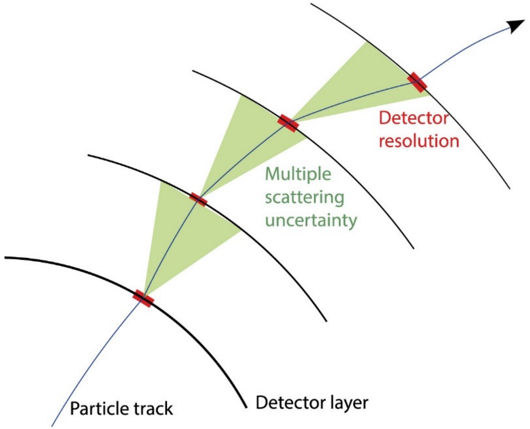




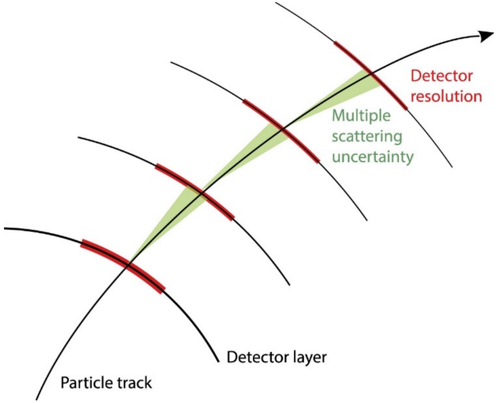
Momentum resolution determined by various factors

Tracker volume, B-field, spatial resolution, efficiency, material budget, layout, noise …

MS > σ



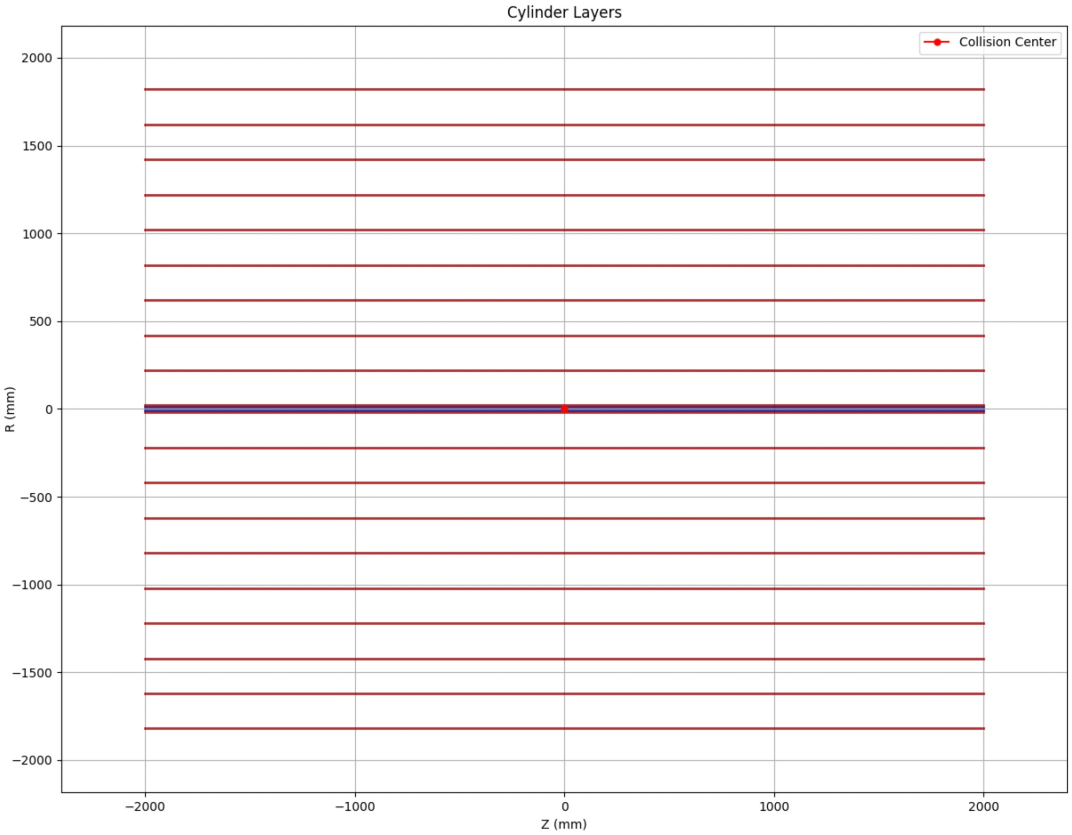
σ > MS



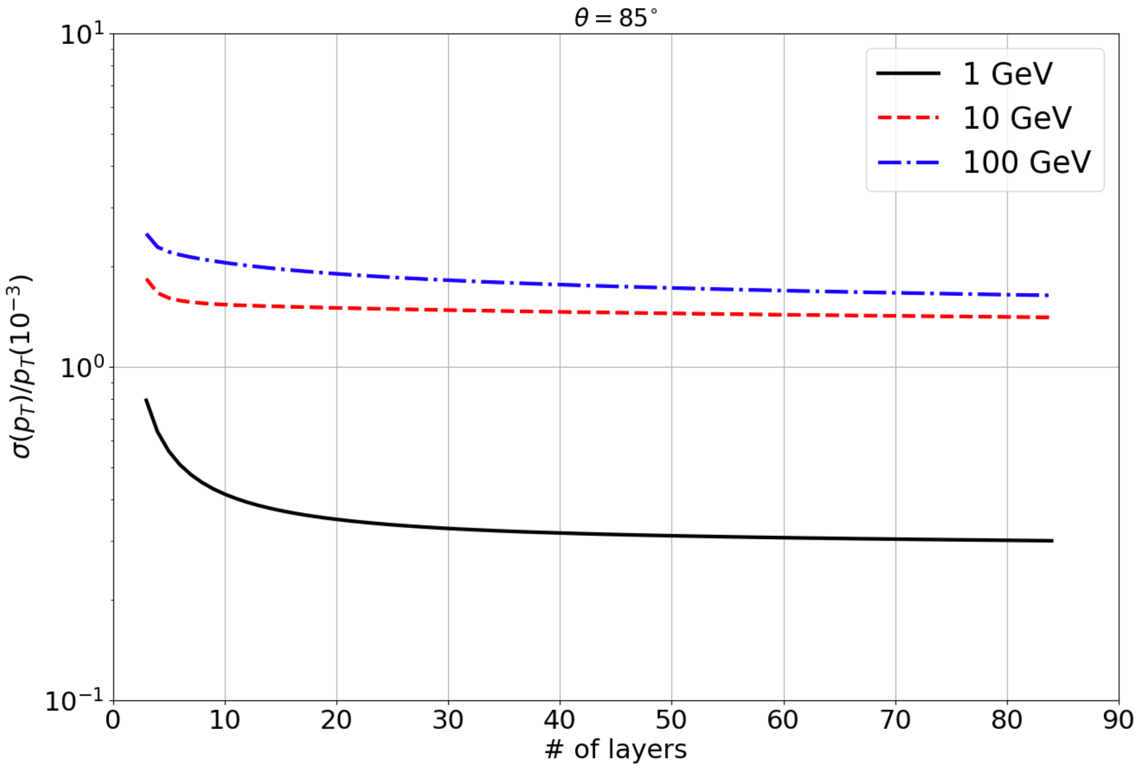
- **A complicated optimization problem, hard to take into all the above account**
- **Various technologies**
  - **Gaseous detector: less materials, more hits, high tracking efficiency, but poor spatial resolution**
  - **Silicon pixel, silicon strip: excellent resolution, but less # of hits, more materials, higher cost, …**

A full silicon tracker as a toy example

- Tracker volume R=1.8 meter
- A thin beam pipe at r = 10 mm with X/X_0=0.15%
- # of silicon layers could vary
- Spatial resolution: 5 μm and 7 μm
- Uniformly distributed along R
- Total X = 5% is fixed: it means that the thickness is 0.5% if # of layers is 10
- Efficiency = 100%
- Only barrel considered



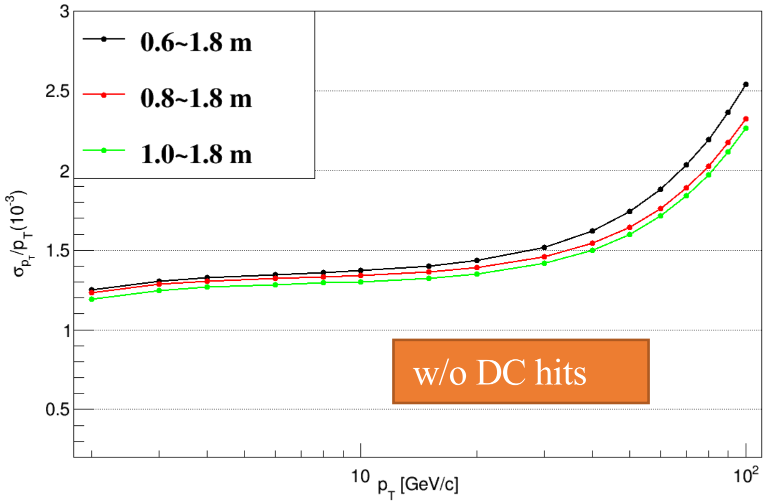
A full silicon tracker as a toy example

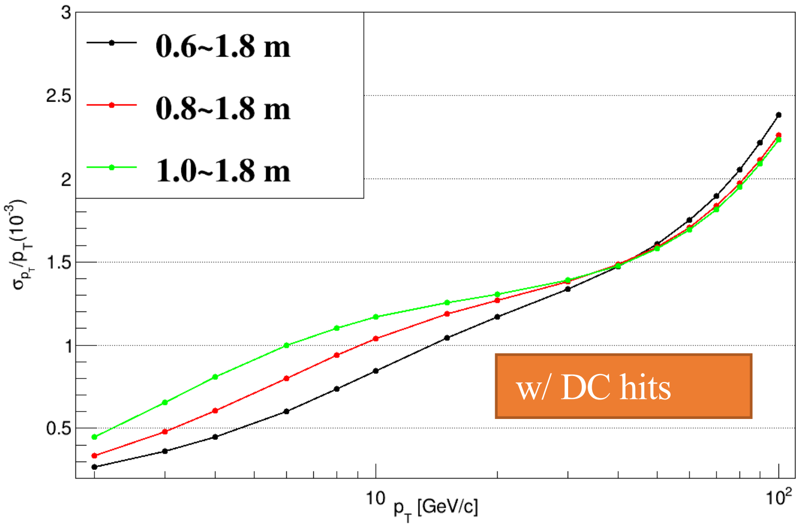


More silicon layers cannot help too much!

Method based on : NIM, A 910 (2018) 127–132

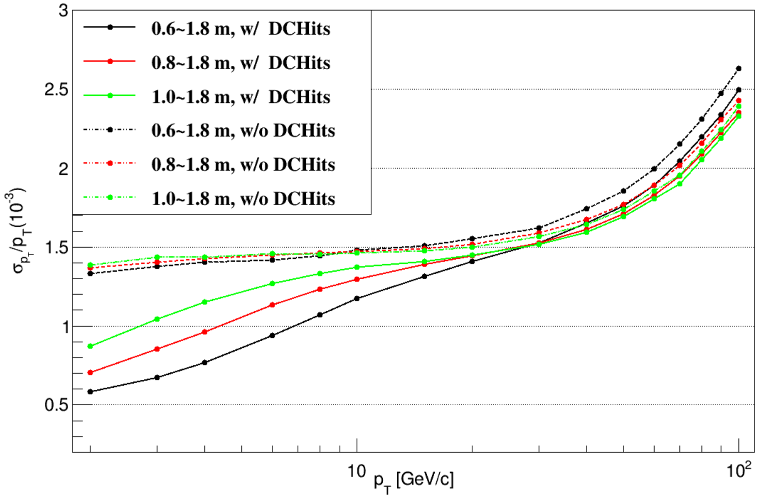
The same tool: DC plays an important role for low pt tracks

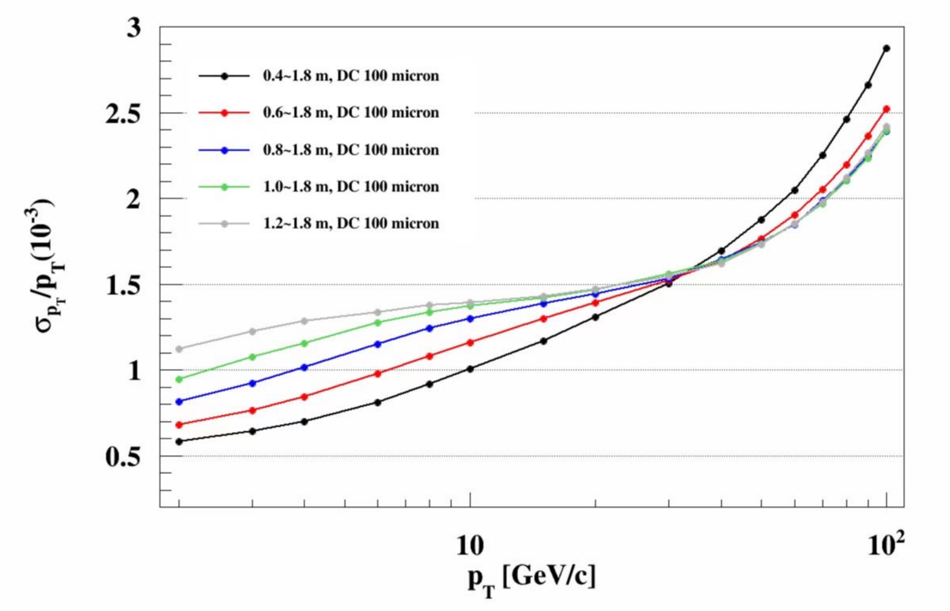




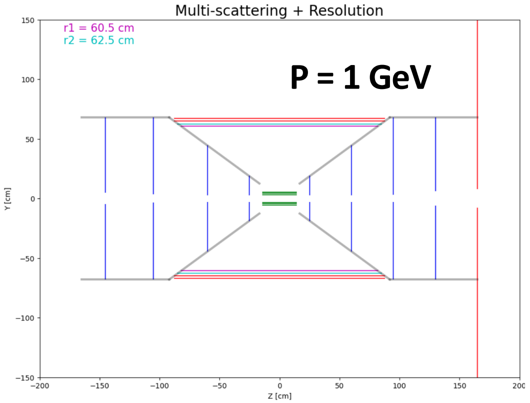
- DC improves momentum resolution significantly for low pt
- The larger, the more significant

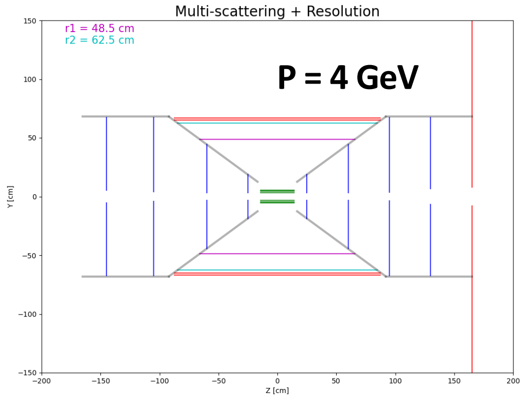
Full simulation confirms this trend

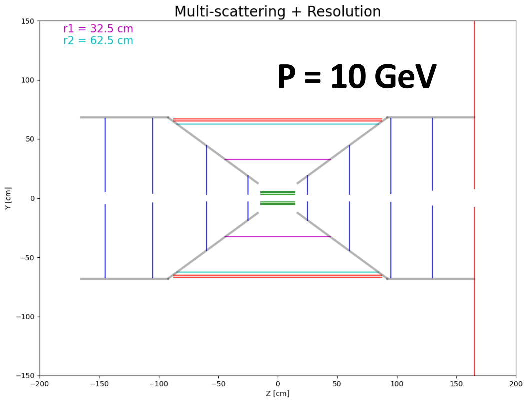




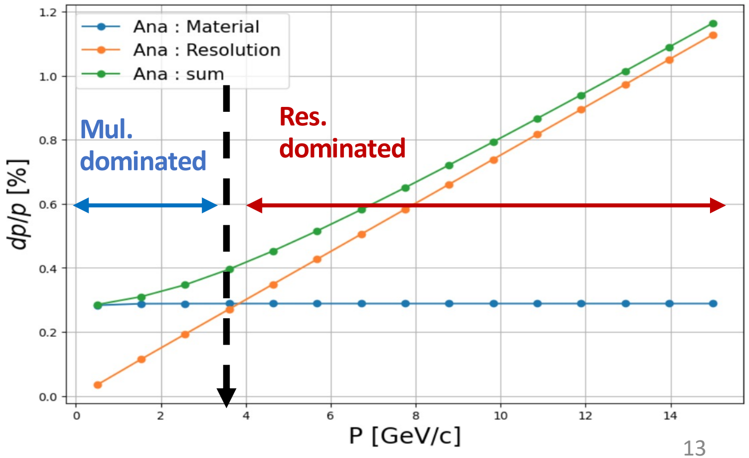
Experience from EicC, by Aiqiang Guo







- The multi-scattering effect will push all two tracker layers to the outer-most layer
- The resolution effect will pull the inner tracker towards the middle of detector



How to understand this

- Why DC affect low pt measurement so much, even the best layers are not at sagitta?

8.2.6 *Optimal Spacing of Wires*

With a given number $N+1$ of wires and a given chamber length L the elements of the covariance matrix can be minimized by varying the wire positions. Summarizing Gluckstern [GLU 63] we mention that the optimal spacing is different for different correlation coefficients, and that for a minimal $[c^2]$ the best wire positions are ideally the following:

$$(N+1)/4 \quad \text{wires at } x=0, \quad (N+1)/2 \quad \text{wires at } x=L/2\,,$$
$$(N+1)/4 \quad \text{wires at } x=L\,.$$

Particle Detection with Drift Chambers, ISBN: 978-3-540-76683-4

Let`s recall the least square fit

$$\chi^2 \quad = \quad \sum \frac{(y - y_i)^2}{\sigma_i^2}$$

Neglecting the correlations

$$\frac{\partial \chi^2}{\partial p} = 2 \sum \frac{y - y_i}{\sigma_i^2} \frac{\partial y_i}{\partial p} = 0$$

It reaches the minimum when the derivatives are zeros

The Fisher information (*I*) in our study is

$$I = \sum I_i = \sum \frac{\left(\frac{\partial y_i}{\partial p}\right)^2}{\sigma_i^2} = \sum \left\langle \left[\frac{y - y_i}{\sigma_i^2} \frac{\partial y_i}{\partial p} \right]^2 \right\rangle$$

- Weighted sum of the squared derivatives with the inverse squared errors as weights

Stat. error related to

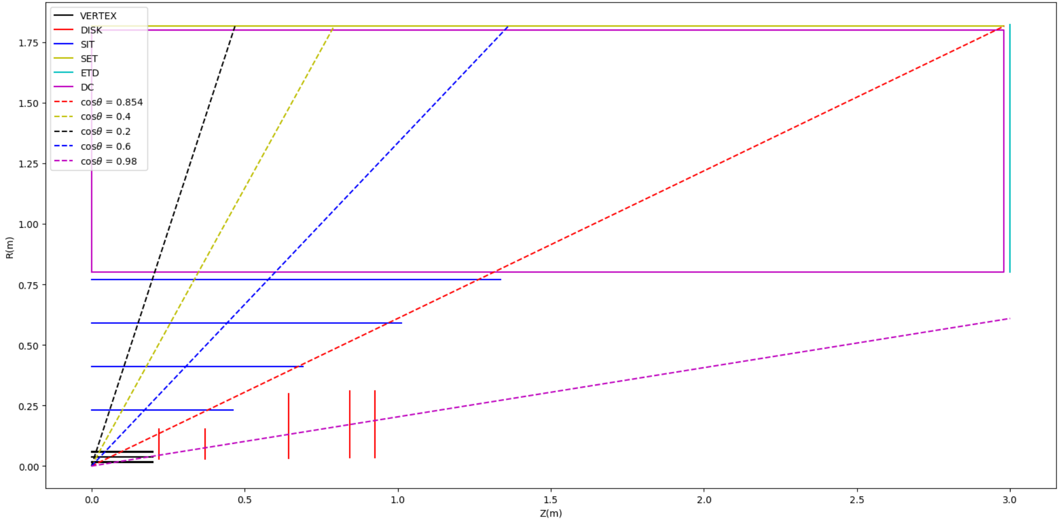
$$\sigma_p^2 \geq \frac{1}{I}$$

Cramer-Rao bound

Two ingredients of ***I***

- Nominator : derivatives of helix to measurements y_i
- Denominator: the σ_i including both Spatial Resolutions (SR) and Multiple Scattering (MS)

Tracking system of the CEPC 4th conceptual detector

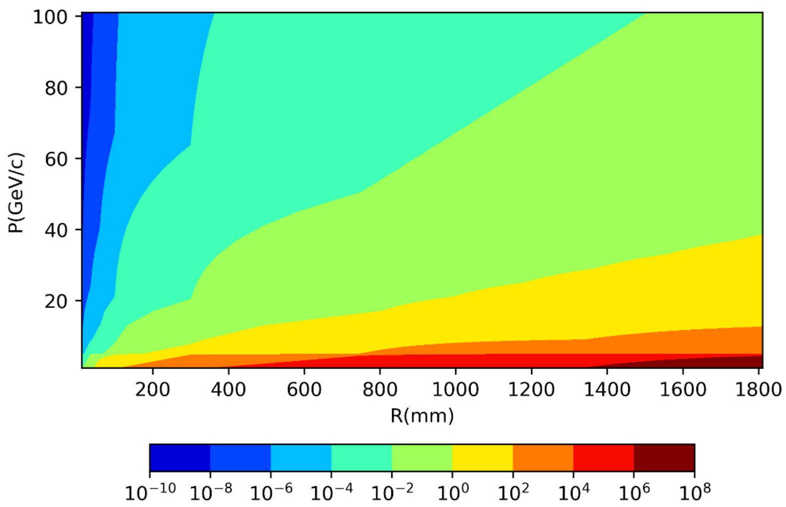


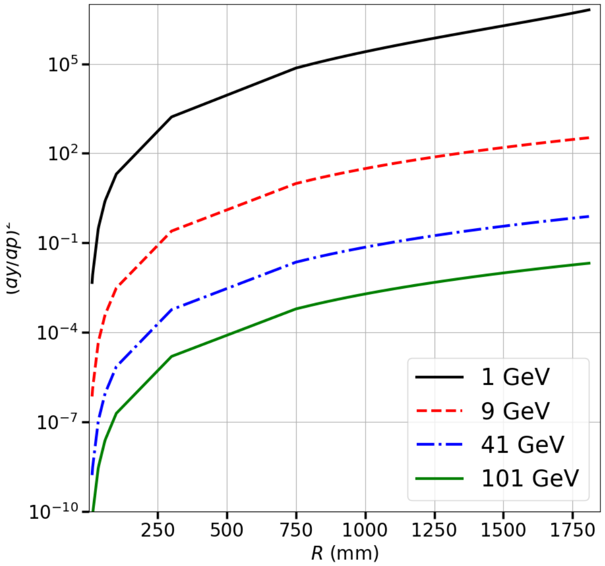
Components	Radius(μm) or layers	$\sigma_{R\phi}$(μm)	Thickness X_0 %
Beam Pipe	10.5	-	0.15
VTX	3 double layers	~4	0.3
VTX-shell	1 layer	-	0.15
SITs	3 layers	7.2	0.65
DC inner wall	1 layer	-	0.104
DC cell	---	100	~0.012
DC outer wall	1803.0	-	1.346
SET	1811.0	7.2	0.65

Hybrid system of silicon pixel, HV-CMOS, and a drift chamber

Nominator: Squared Derivatives(SD)

$$I_i = \frac{\left(\frac{\partial y_i}{\partial p}\right)^2}{\sigma_i^2}$$





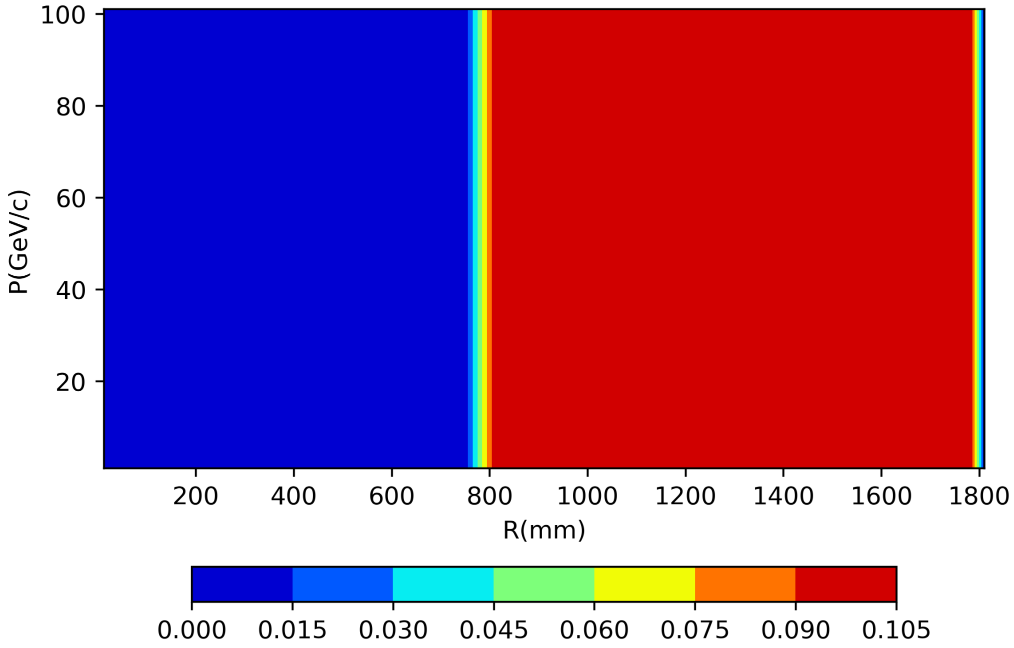
~10^8

SD varies in a very large range

~ 8 orders of magnitudes

Denominator: Spatial Res. only (SR)

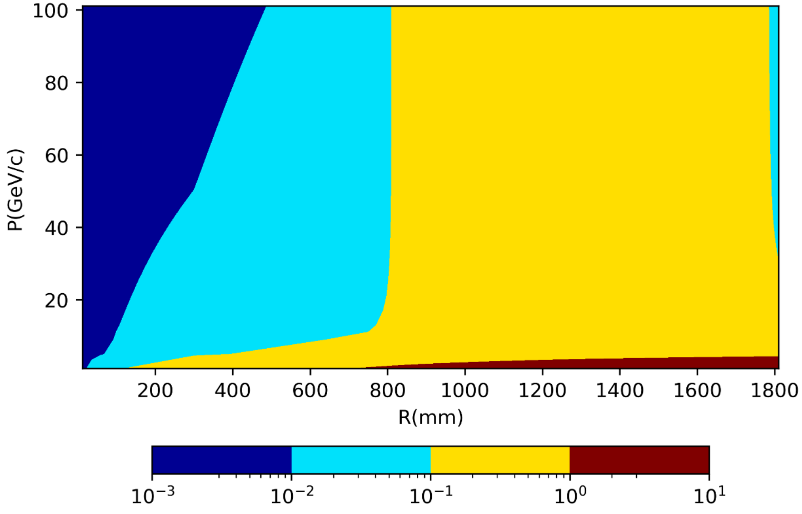
$$I_i = \frac{\left(\frac{\partial y_i}{\partial p}\right)^2}{\sigma_i^2}$$

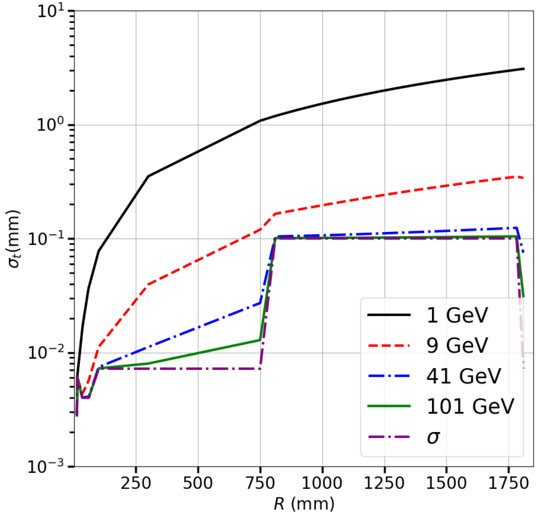


- No dependence on p while MS depends on p

Denominator: combined SR and MS

$$I_i = \frac{\left(\frac{\partial y_i}{\partial p}\right)^2}{\sigma_i^2}$$



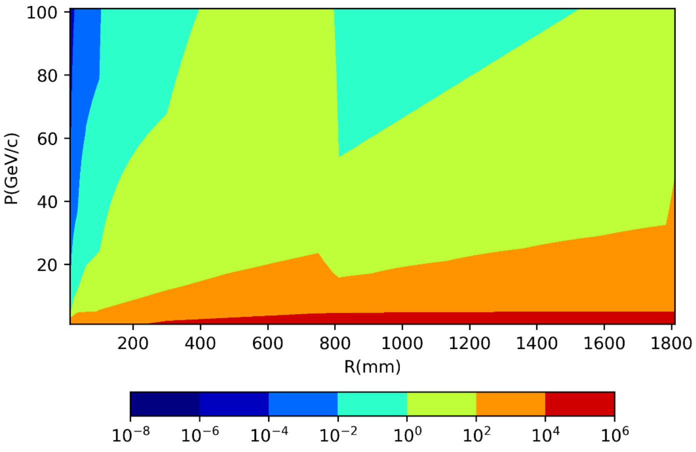


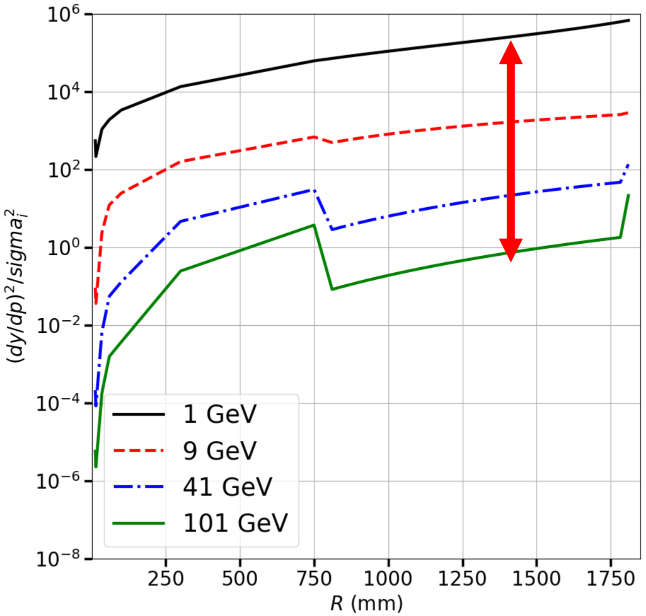
$\sim 10^2$

- MS: negligible for sufficiently high pt (>10 GeV) ; ~3 order of magnitudes difference between 1 and 100 GeV

I = SD/(SR^2+MS^2)

$$I_i = \frac{\left(\frac{\partial y_i}{\partial p}\right)^2}{\sigma_i^2}$$



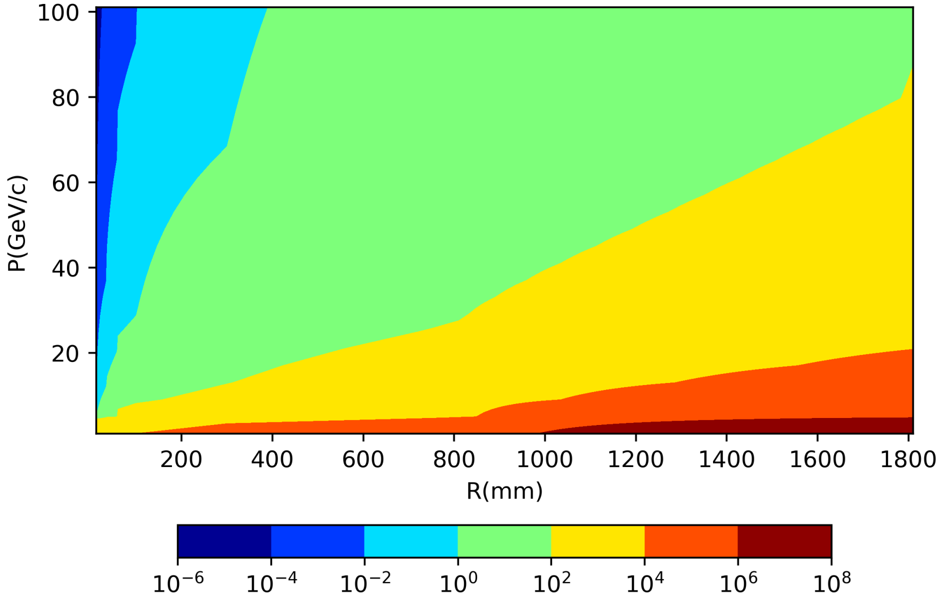


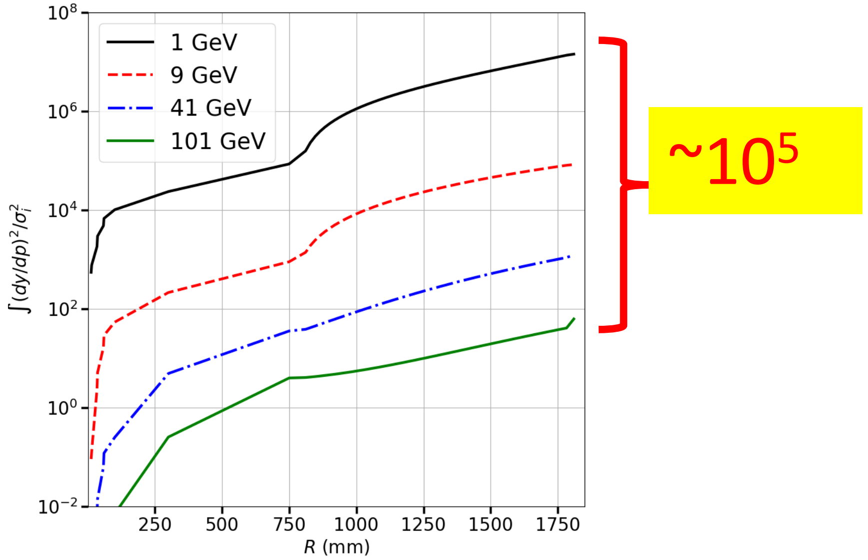
~10^5

Even taking MS into account, DC contributes much information to low pt tracks → derivates dominant.

Accumulated I: the sum of the first *n* layers

$$I = \sum I_i$$

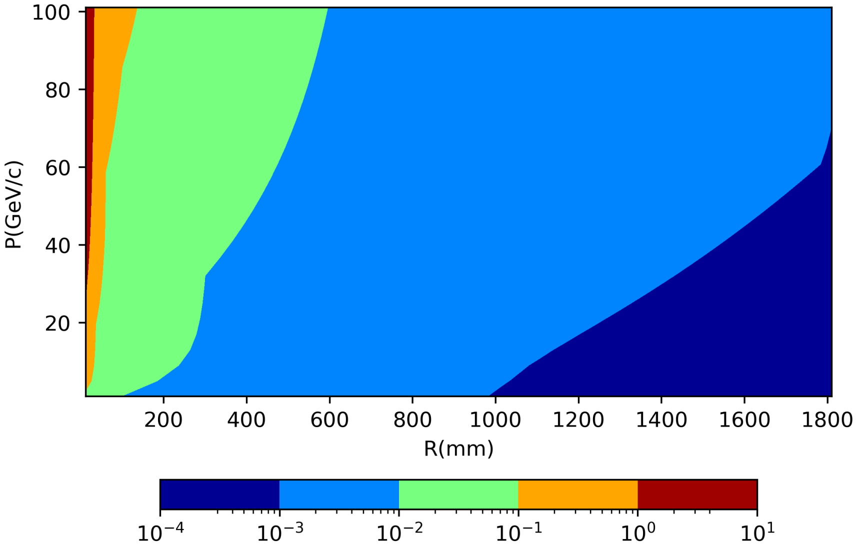


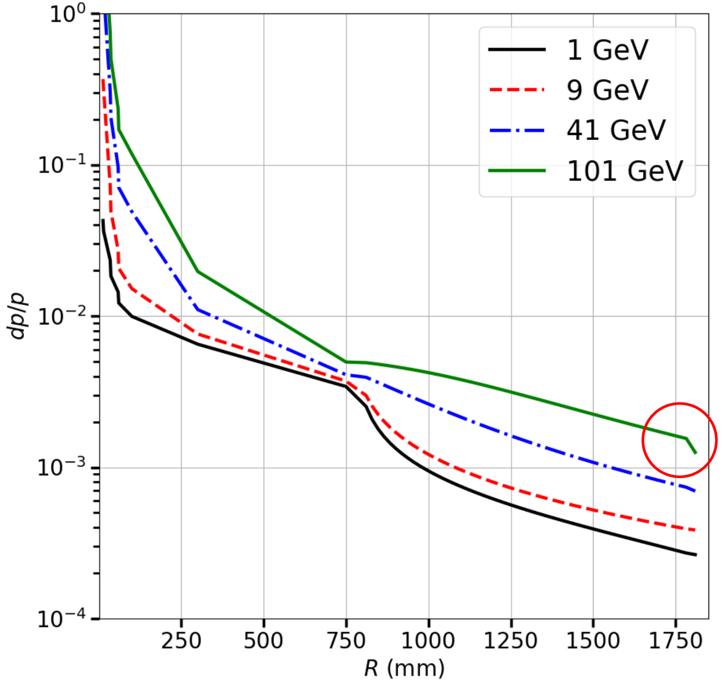


Gaseous detector does play an important role for low p_t due to its large derivatives

P_t resolution

$$\sigma_p = \frac{1}{\sqrt{I}}$$





Low p_t tracks gain more information from a gaseous detector

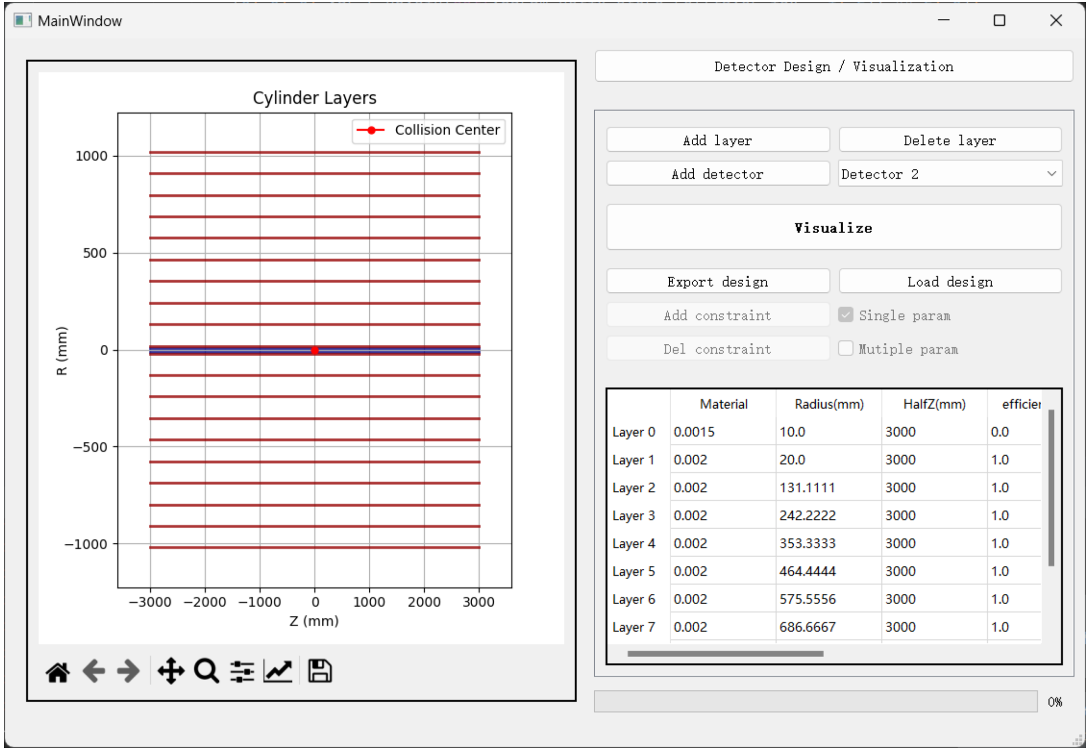
~ 10 times difference

Summary

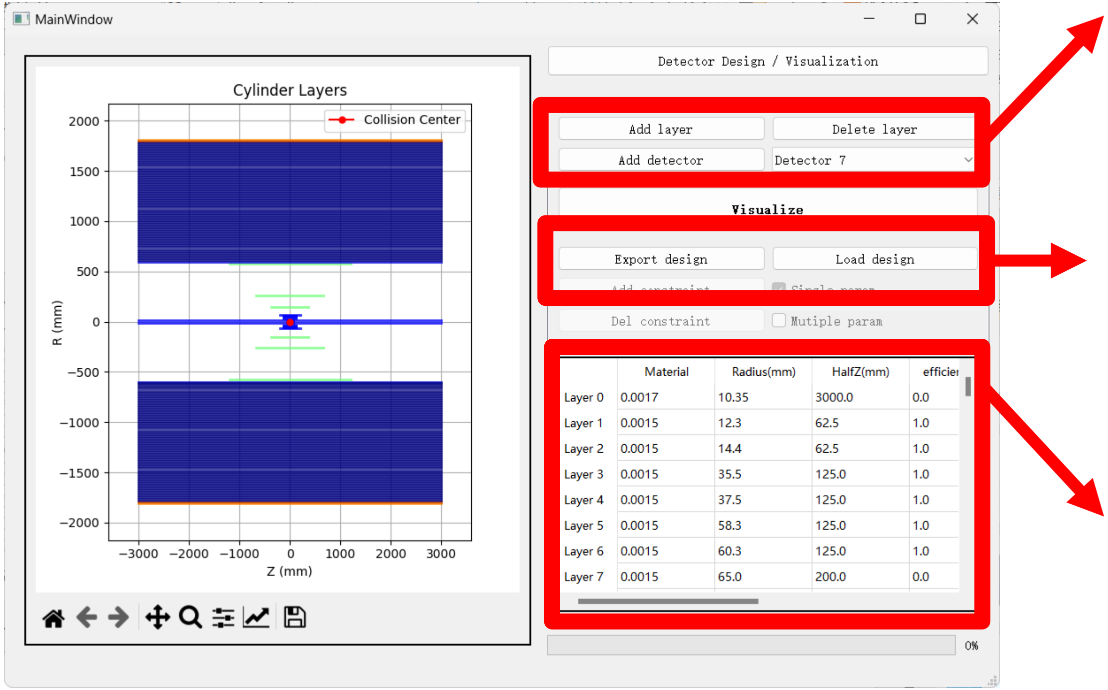
- ✓ Future Higgs factories try to cover very wide energy region
- ✓ Low momentum tracks dominant, especially for jets and flavor physics
- ✓ Study shows
  - ➢ $d(1/p_t) \sim 10^{-5}$ is already the limit with B=3 Tesla and tracker radius of 1.8 meter
  - ➢ Silicon tracker is good for high momentum tracks
  - ➢ However, low p_t tracks still need a gaseous tracker
- ✓ A hybrid tracker of silicon and gaseous technologies is a good option
- ✓ Pay more attention on some realistic factors
  - ➢ alignment, beam background, mechanics, cooling, …

Advertisement ： Python Fast Simulation Tool

- **Used for detector design / visualization**
- **Implemented in python**
- **Fast simulation based on**
  - ✓ **Kalman filter**
  - ✓ **Analytic calculation**
- **Interactive and batch mode**



Detector design / Visualization



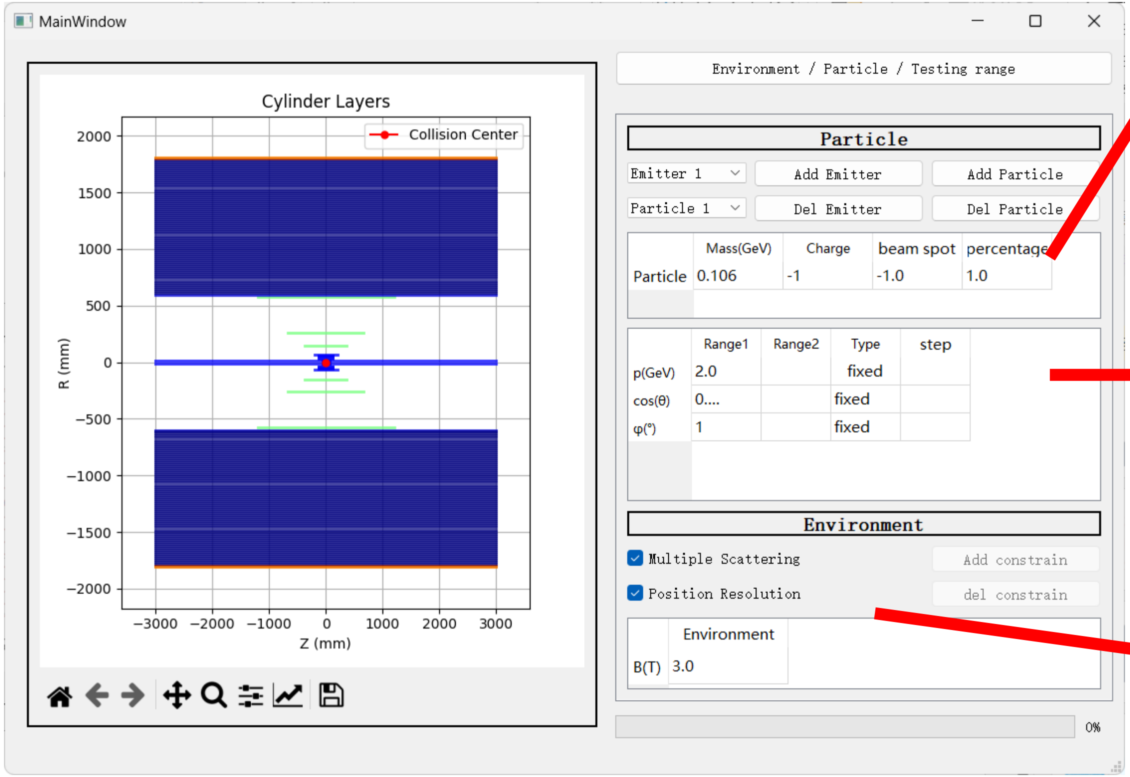
Add new Geometry

Save & Load the Geometry

Easily modify the geometry

Set the parameter for each layer

Parameter Setting



Setting the particle parameter, including,

1, charge (-1 or 1)

2, Mass (Gev)

Set testing parameter, Including

1, p (Gev)

2, cos(θ)

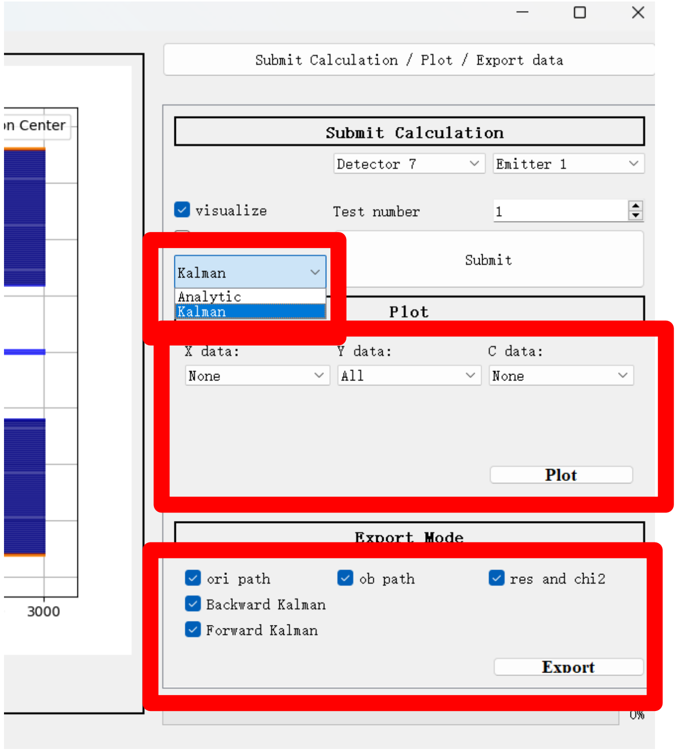
3, ϕ

Each param can select a mode in “fixed”, “even” or “steps” to satisfied different testing requirement

Determine use
Multiple scattering or not

Set magnet -- B (T)

Calculation submission



1、Both analytic method and Kalman method can be estimated

2、Support result visualization(under refine)

3、Support result Export with option

```
pip install dectest-0.0.3.tar.gz
unzip test_dir.zip
cd test_dir
python name.py
```

What is More

The project is packaged as a pip library, so one can also use it in batch mode without GUI interface

In this way,

a、The parameter setting is More freely
b、One can use multi-processing to accelerate the calculation
c、 So on ...

Document is in preparation

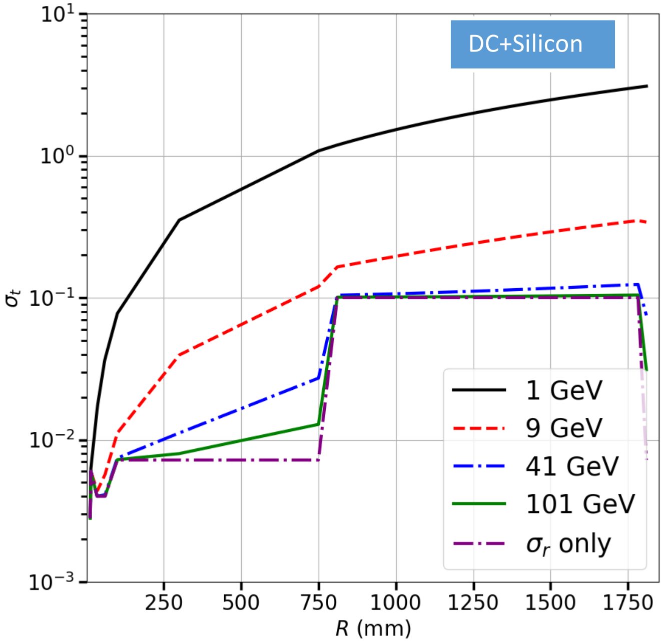
Welcome to use it and feedback …

Extras

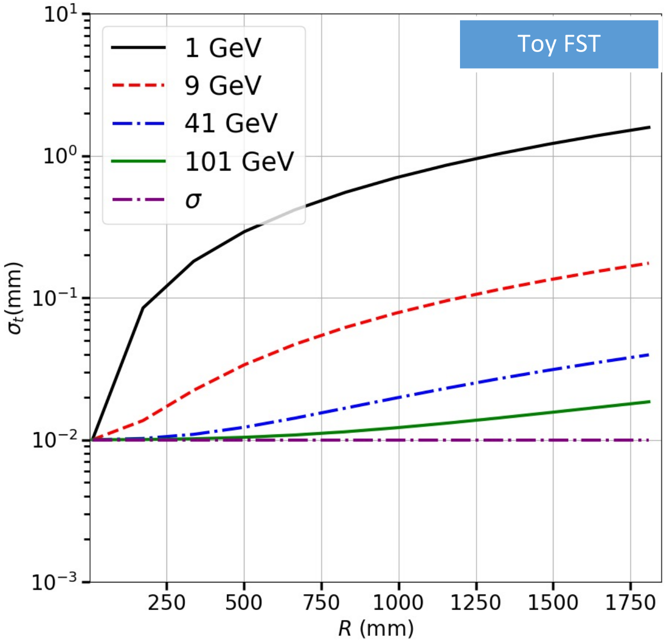
Parameters of the CEPC new tracker

Components	Radius(μm)	$\sigma_{R\phi}$(μm)	σ_{Z}(μm)	Thickness X_0 %
Beam Pipe	10.5	-	-	0.15
VTX	3 double layers	2.8/6/4/4/4/4	2.8/6/4/4/4/4	0.10+0.10+0.10
VTX-shell	1 layer	-	-	0.15
SITs (25x300 mm^2)	3 layers	7.2/7.2/7.2	86.6/86.6/86.6	0.65
DC inner wall	1 layer	-	-	0.104
DC cell (66 x15x15mm)	---	100	2828	0.0081+0.00413
DC outer wall	1803.0	-	-	1.346
SET (25x300 mm^2)	1811.0	7.2	86.6	0.65

Layout still being under optimization



DC+Silicon
σ_t
R (mm)
1 GeV
9 GeV
41 GeV
101 GeV
σ_r only



Toy FST
σ_t(mm)
R (mm)
1 GeV
9 GeV
41 GeV
101 GeV
σ

More options of DC volume by MarlinTrks