Ultimate precision of a tracker

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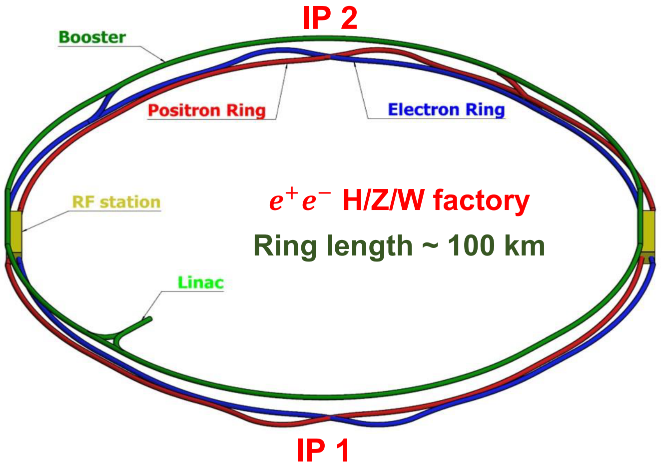
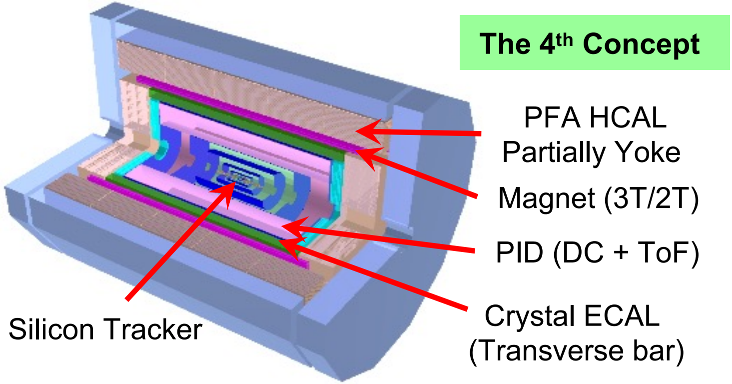
Outline

- Introduction
- Some fast results with a toy full silicon tracker
- 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, 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 is important for those experiments 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-detector for an experiment
  - 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: $d(1/p) \sim 10^{-5}$ level, i.e, CEPC:

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

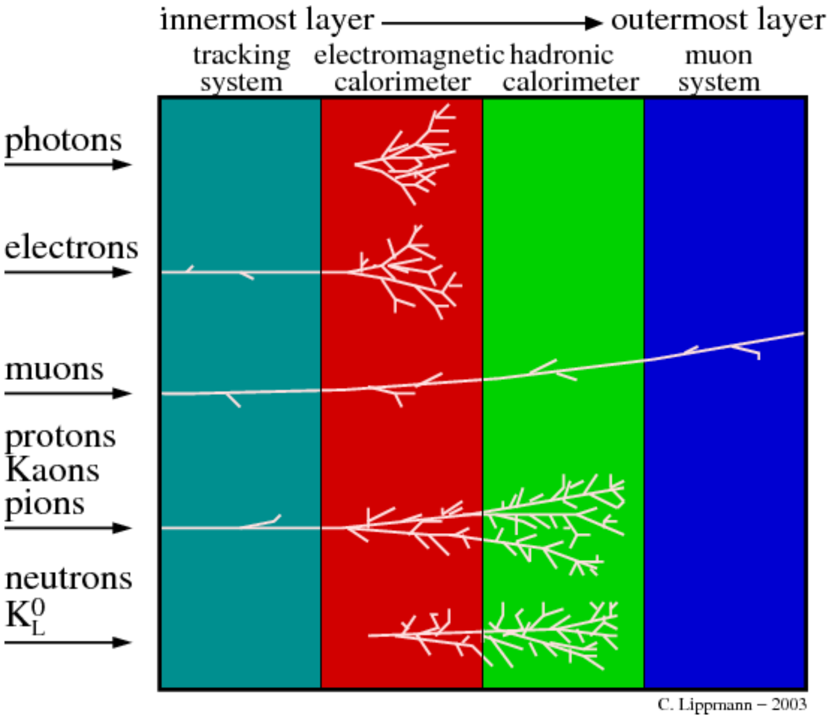


Figure from arXiv:1101.3276

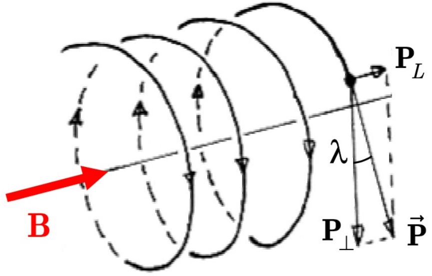
Introduction

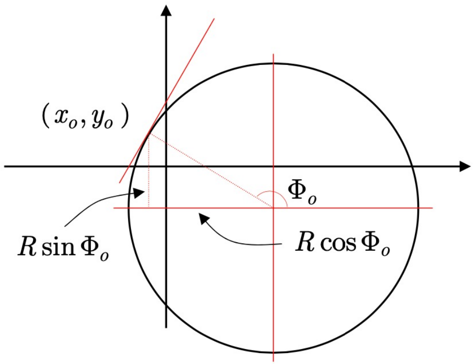
- Track reconstruction
- Inference the track parameters from hits

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

with helix:

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

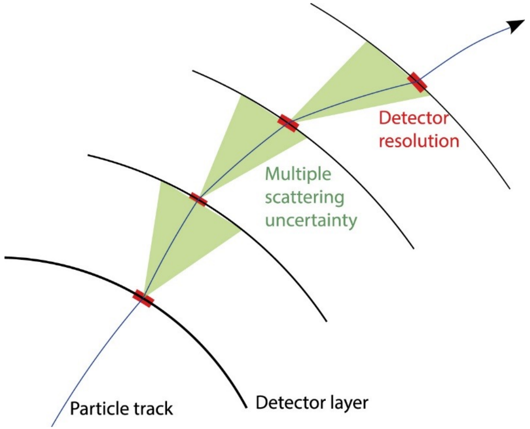




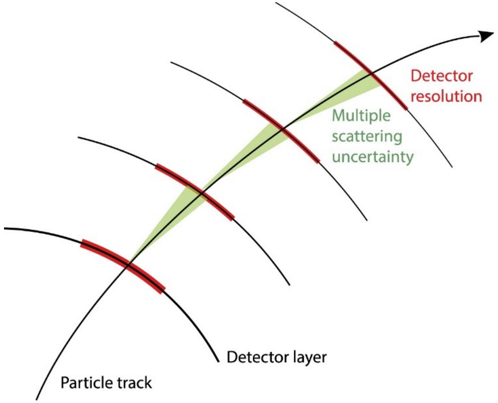
Momentum resolution determined by various factors

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

MS > σ



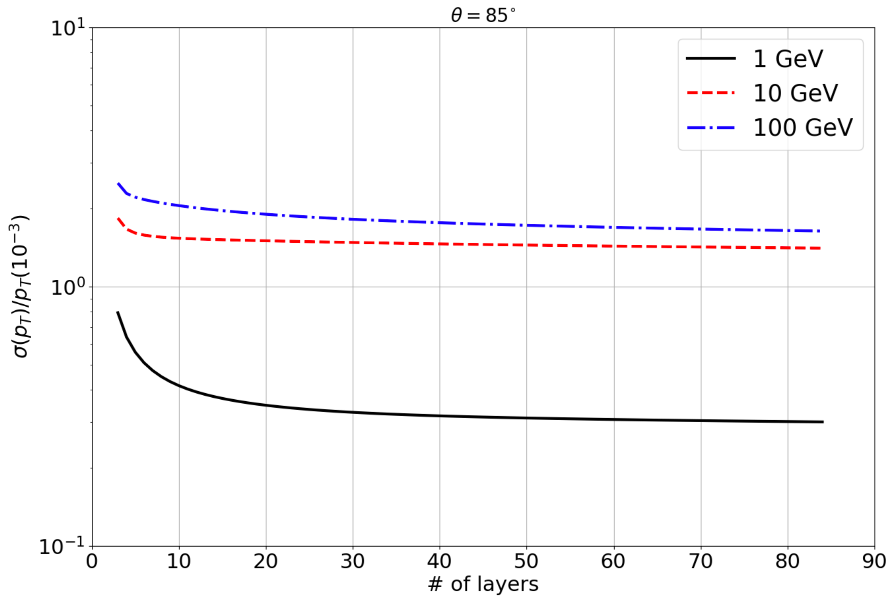
σ > MS



- **A complicated optimization problem, if taking into account all above**
- **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, …**

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 varies
- 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



Method : NIM, A 910 (2018) 127–132

Let`s recall least square fit

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

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 its minimum when the derivatives are zeros

The Fisher information (I) in our study is

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

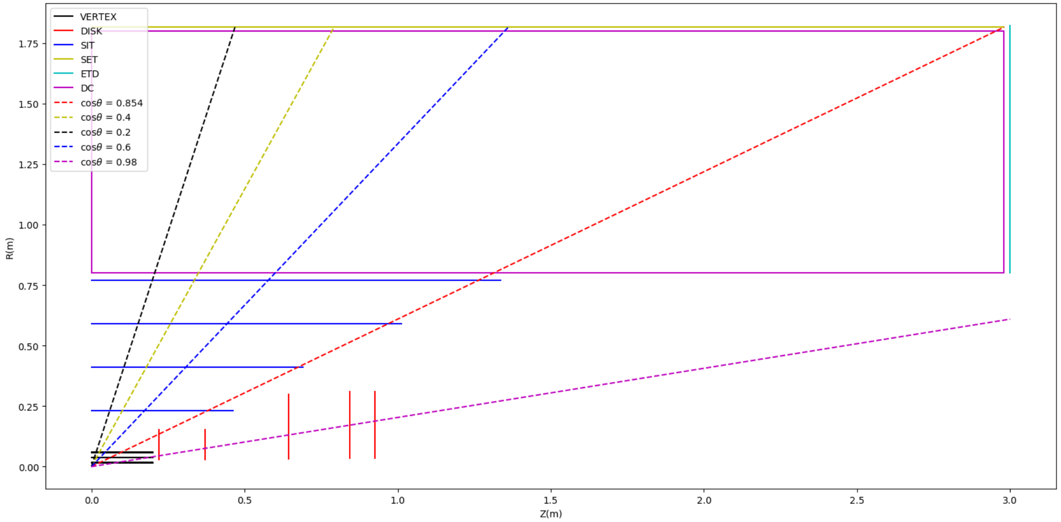
- Weighted sum of the squared derivatives
- The weights are the inverse squared errors

Stat. error related to $\boxed{\sigma_p^2 \geq \frac{1}{I}}$ 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

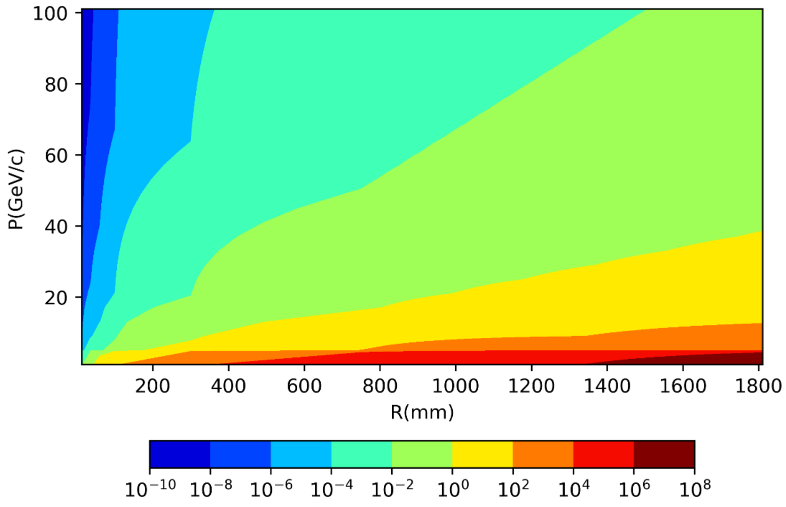


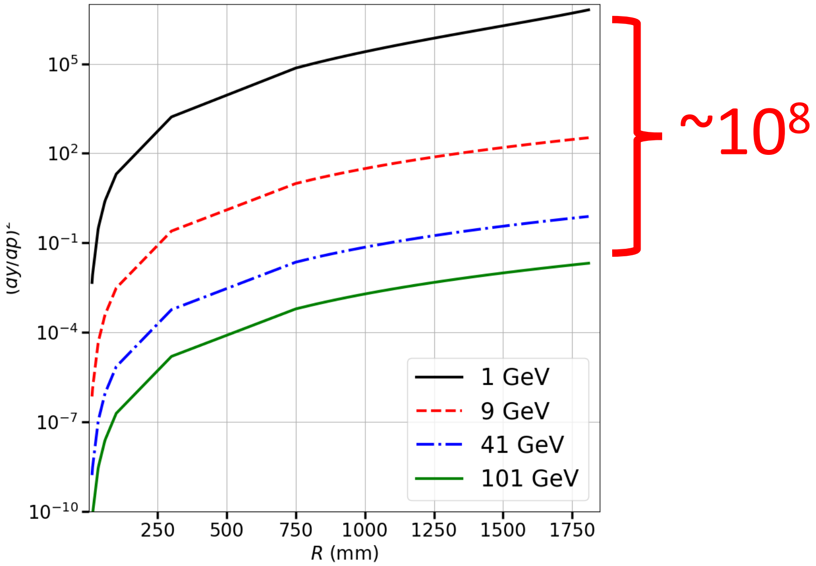
Components	**Radius(μm) or layers**	$\sigma_{R\phi}$**(μm)**	**Thickness** X_0 **%**
Beam Pipe	10.5	-	0.15
VTX	3 double layers	~4	0.3
VTX-shell	1 layer	-	0.15
SITs	3 layers	7.2	0.65
DC inner wall	1 layer	-	0.104
DC cell	---	100	~0.012
DC outer wall	1803.0	-	1.346
SET	1811.0	7.2	0.65

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

Nominator: Squared Derivatives(SD)

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



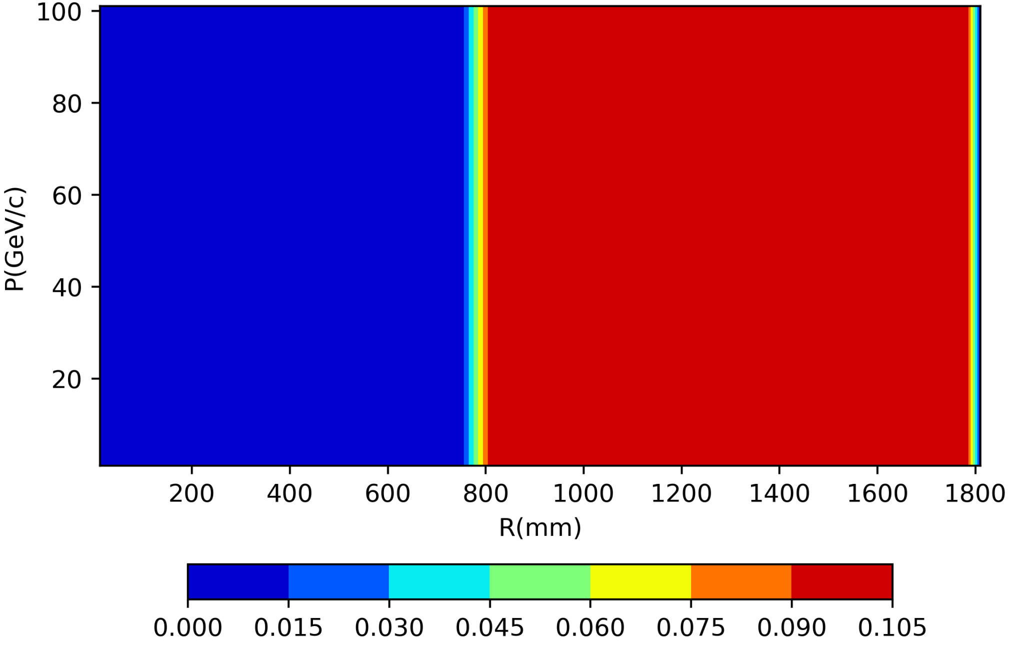


SD varies in a very large range

~ 8 orders of magnitudes

Denominator: SR only

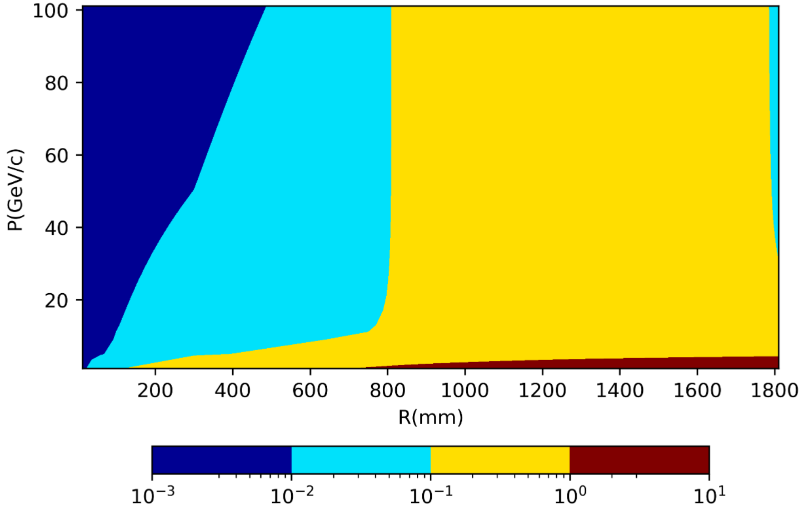
$$I_i = \frac{\left(\frac{\partial y_i}{\partial p}\right)^2}{\sigma_i^2}$$

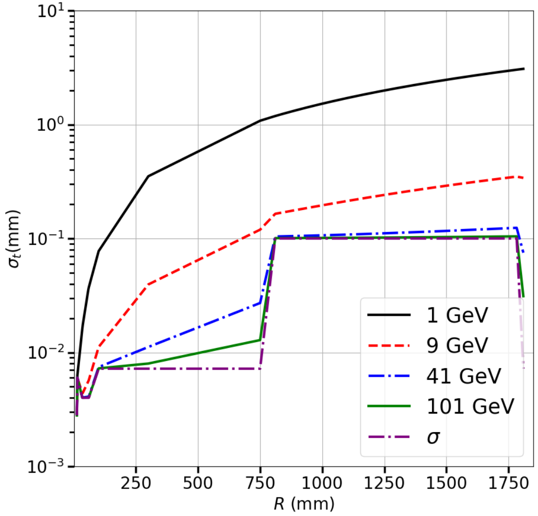


- No dependence on p
- while MS depends on p

Denominator: combined SR and MS

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



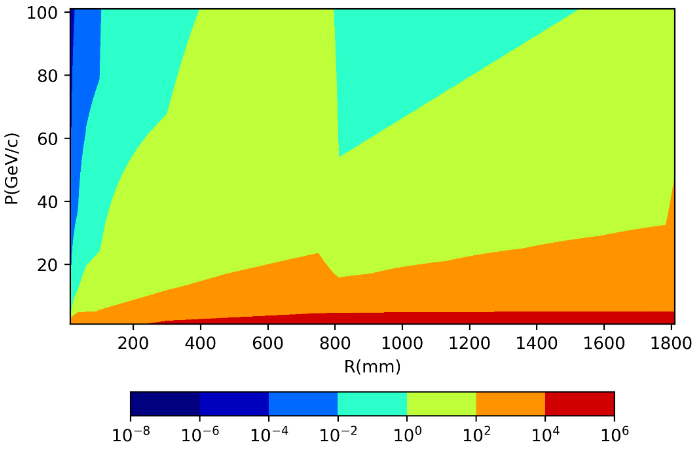


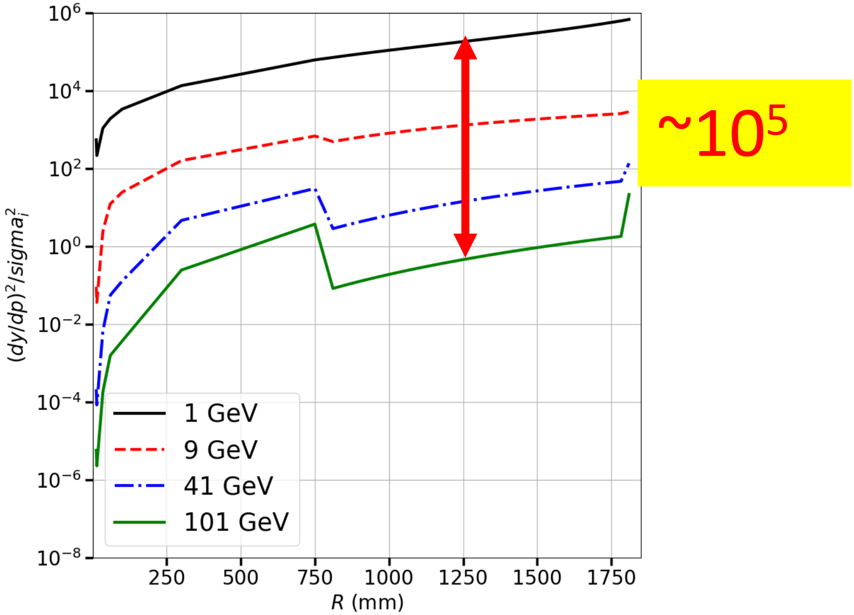
~10^2

- MS: negligible for sufficiently high pt (>10 GeV)
- MS: ~3 order of magnitudes between 1 and 100 GeV at R = 1.8 m

I = SD/(SR²+MS²)

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

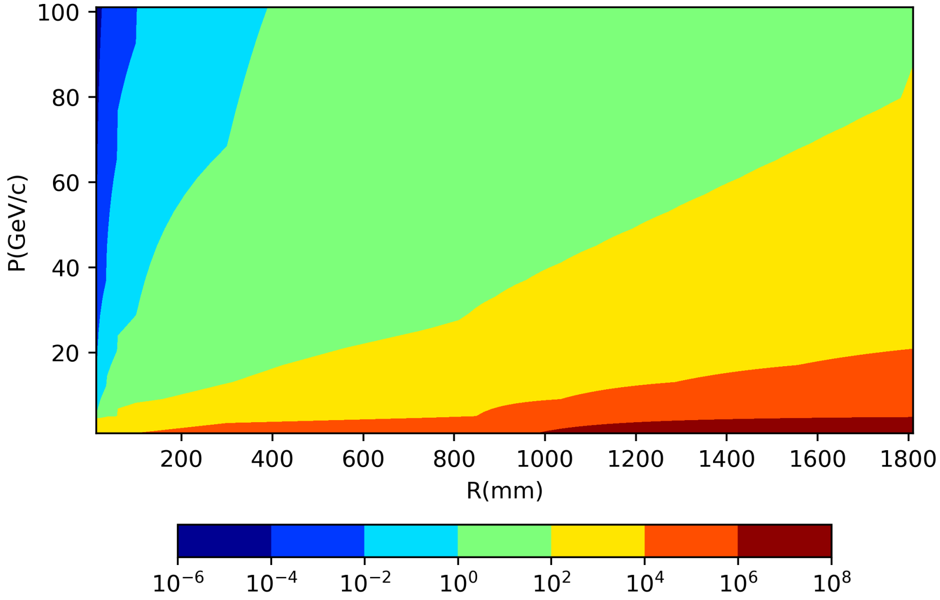


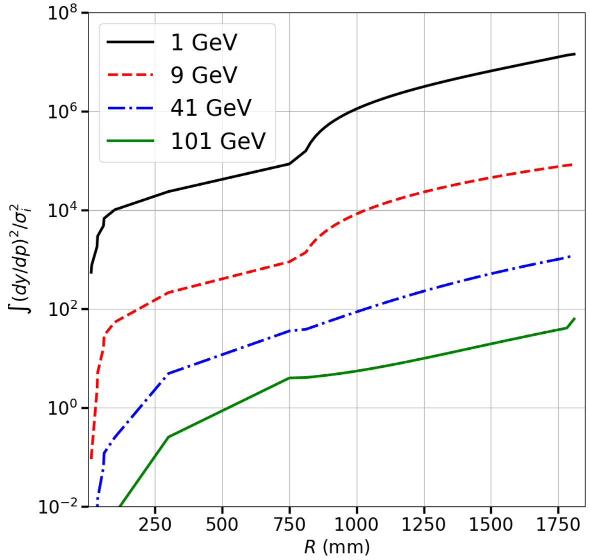


Even taking MS into account, DC contributes much information to low pt tracks → derivates dominant.

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

$$I = \sum I_i$$





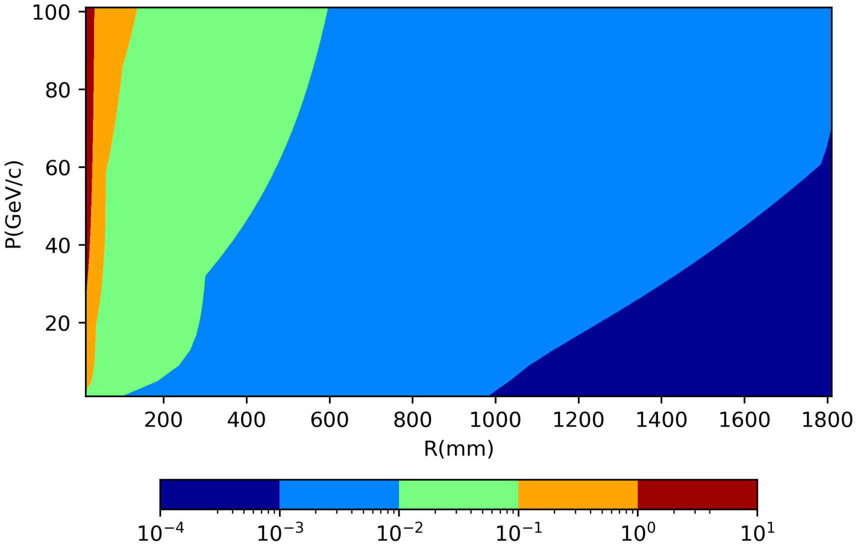
~10^5

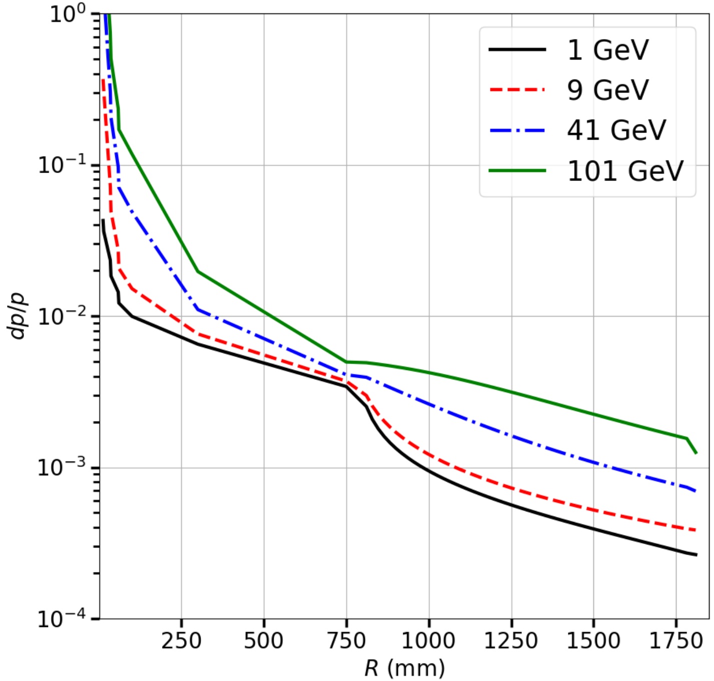
Conclusion

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

P_t resolution

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





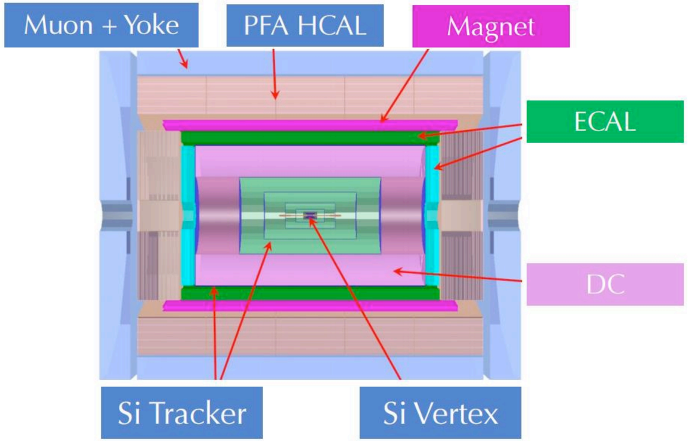
Low p_t tracks gain more information from a gaseous detector

~ 10 times difference

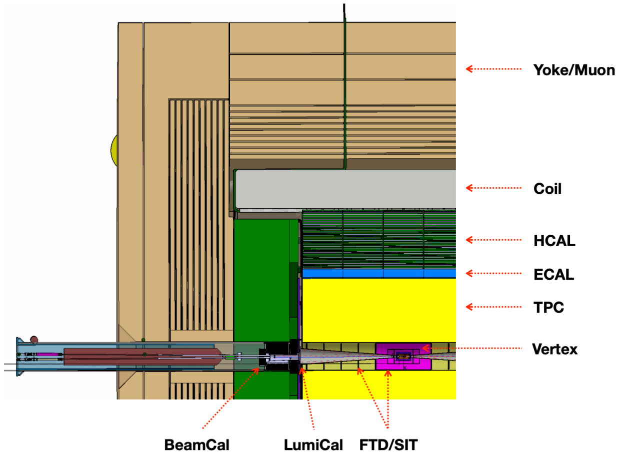
Summary

- Future Higgs factories try to cover very wide energy region: form Z pole to the top threshold
- This study shows
  - $d(1/p_t) \sim 10^{-5}$ is already the limit with B=3 Tesla and R=1.8 meter
  - Silicon tracker is good for high momentum tracks
  - However, low p_t tracks favors a gaseous tracker
- A hybrid tracker system of silicon and gaseous technologies is a good option

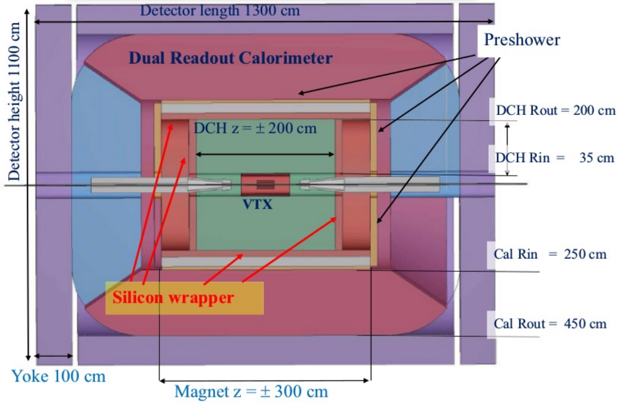
CEPC: 4th → ~360 GeV



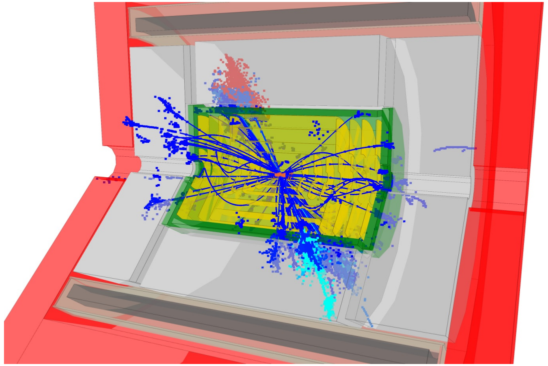
ILD@ILC → 500 GeV



IDEA@FCC-ee → ~360 GeV



CLIC: full silicon → 3 TeV



Extras

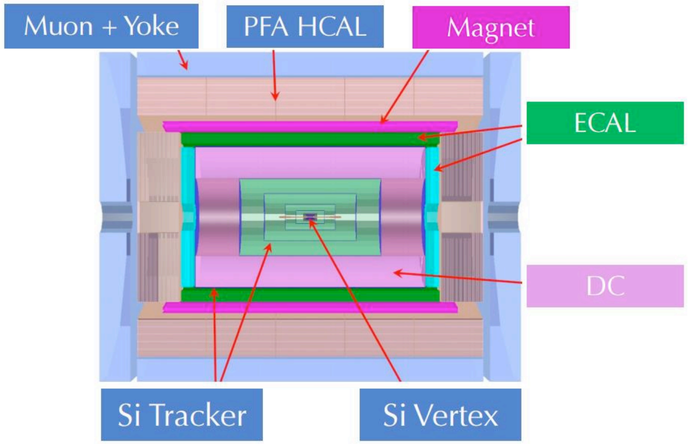
Parameters of the CEPC new tracker

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

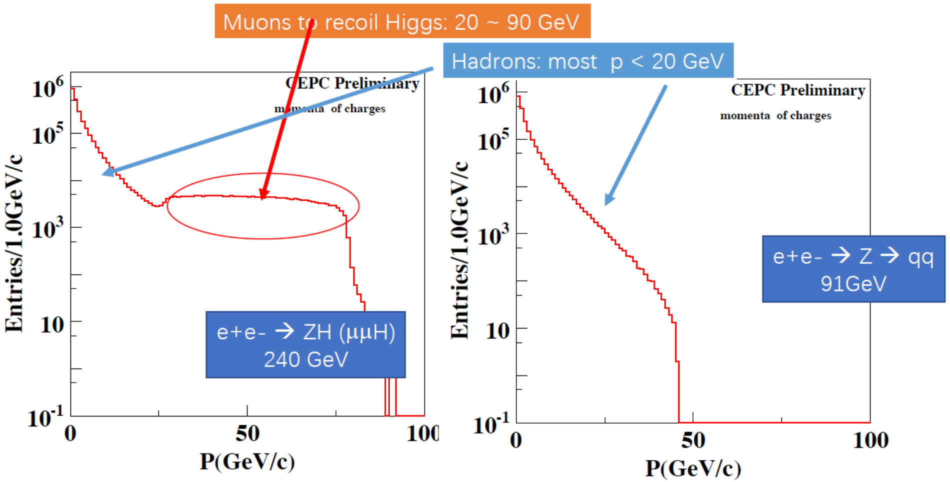
Layout still being under optimization

Introduction

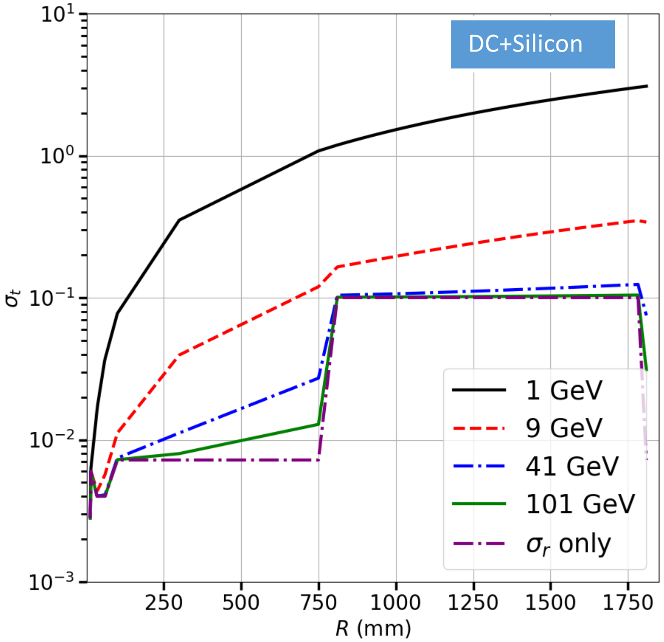
The 4th CEPC conceptual detector

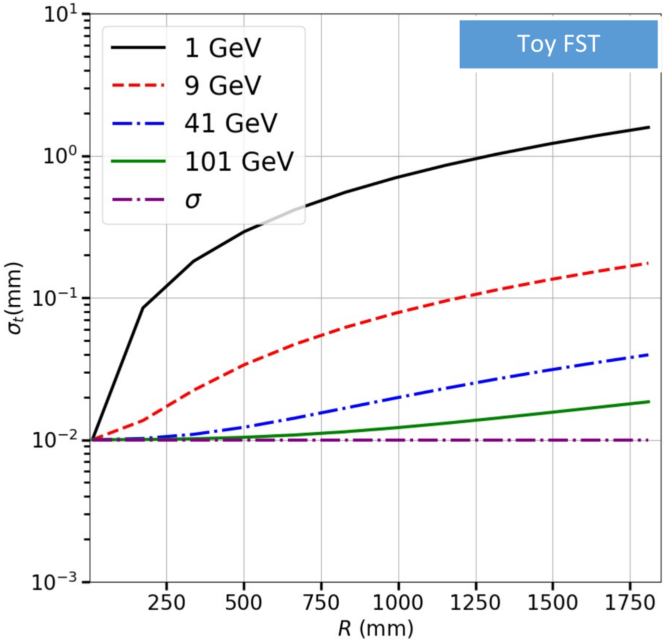


Momenta of tracks @ 240 & 91 GeV



- Tracking system consists with a silicon pixel vertex detector(VXD), a silicon tracker (SIT and SET) of HV-CMOS, and a drift chamber(DC)
  - Particle ID with a drift chamber is a key feature for the 4th conceptual detector
  - Most hadrons (K/pi) of CEPC are below 20 GeV/c
  - Sufficiently good momentum resolution for tracks < 20 GeV/c (flavor and jet study)


DC+Silicon
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
σ_t
250
500
750
1000
1250
1500
1750
R (mm)
1 GeV
9 GeV
41 GeV
101 GeV
σ_r only


Toy FST
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
σ_t(mm)
250
500
750
1000
1250
1500
1750
R (mm)
1 GeV
9 GeV
41 GeV
101 GeV
σ

More options of DC volume by MarlinTrks