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Optimization on silicon detectors at CEPC

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Outline

- Introduction
- Fast simulation and full simulation results
- Flavor tagging performance with different vertex geometry
- Influence of the material budget near beam pipe
- Performance of an ultra lightweight vertex layout
- Influence of SET on track and Higgs mass reconstruction

Introduction

- H -> bb, cc and gg is the core part of the CEPC Higgs program
- Vertex system with high impact parameter resolution is crucial

Table 6.1 Required performance of the CEPC sub-detectors for critical benchmark Higgs processes.

Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_T) \sim 2 \times 10^{-5}$
$H \to \mu^+\mu^-$	$\mathrm{BR}(H \to \mu^+\mu^-)$		$\oplus 1 \times 10^{-3}/(p_T \sin\theta)$
$H \to b\bar{b},\ c\bar{c},\ gg$	$\mathrm{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu\mathrm{m}$
$H \to q\bar{q},\ VV$	$\mathrm{BR}(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^{\mathrm{jet}}/E \sim 3-4\%$
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

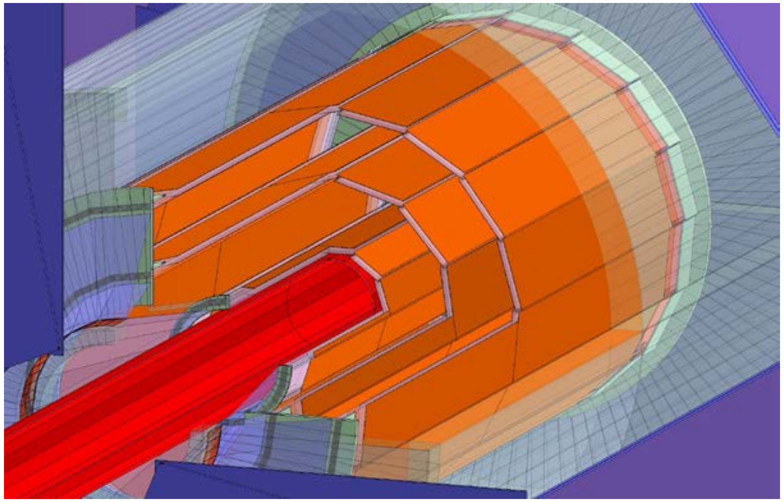

Table 1. Design parameters of the CEPC vertex system.

	R(mm)	| Z |(mm)	$\sigma(\mu m)$	material budget
Layer 1	16	62.5	2.8	$0.15\%/X_0$
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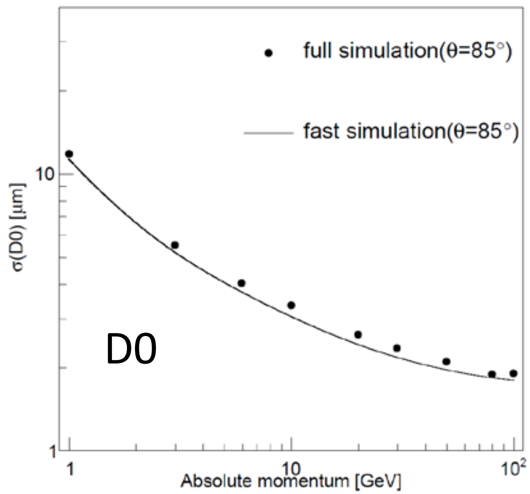
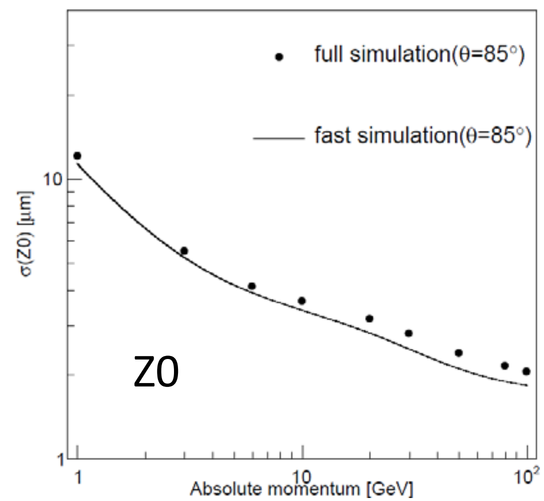
Simulation tools

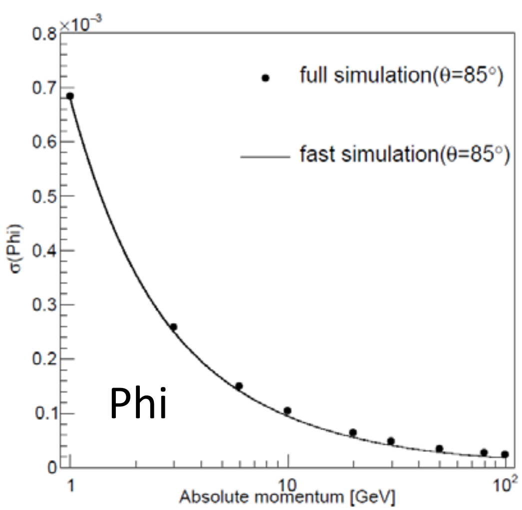
- Fast simulation："LiC Detector Toy" (LDT) software tool
- Full simulation： Mokka and Marlin

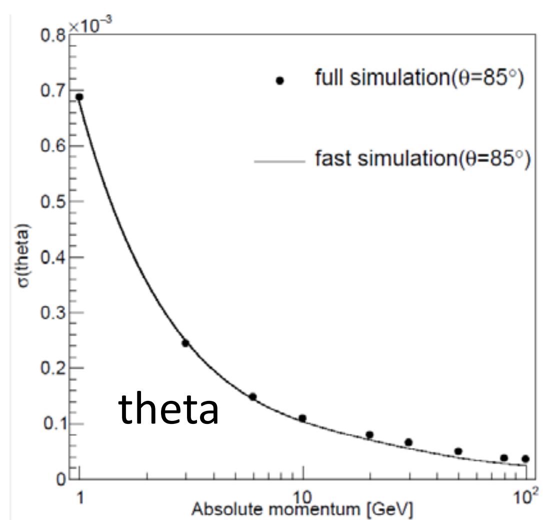
consistent





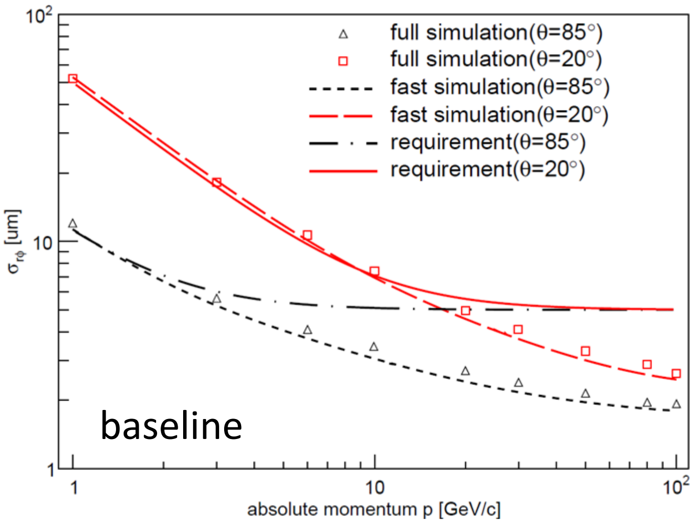
The key parameters' resolution of a helix track

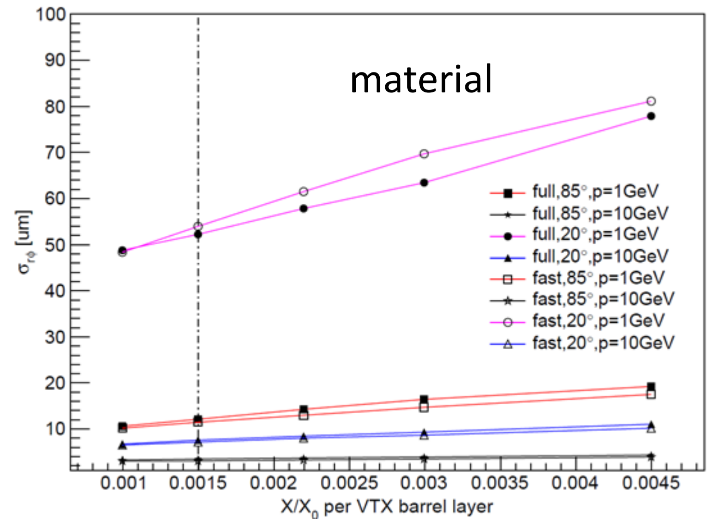


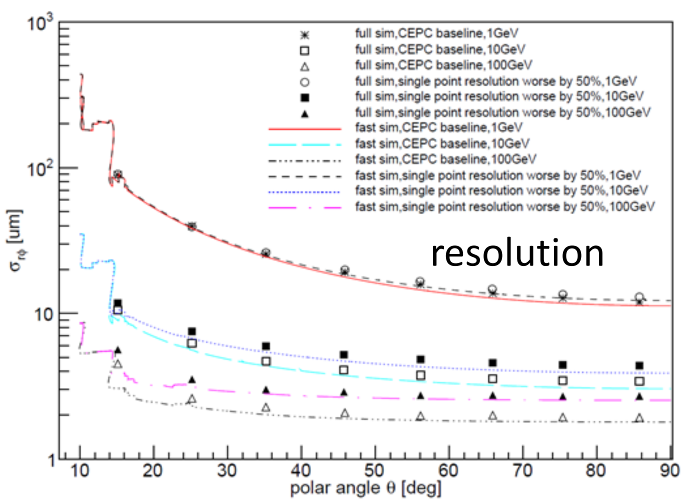


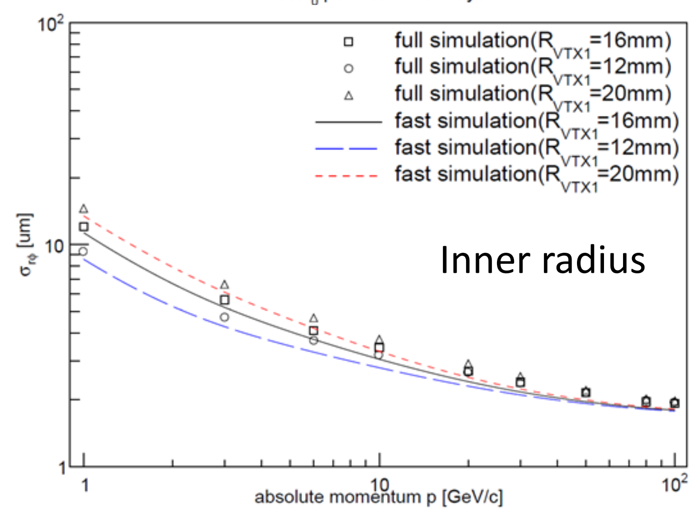
Key geometry parameters

- The influence of the geometry parameters on the impact parameter resolution
  - Inner radius, Material budget, Spatial resolution



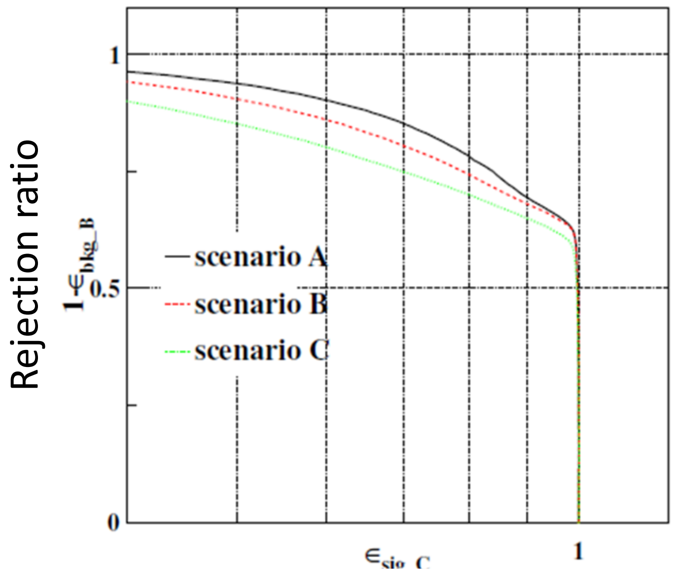


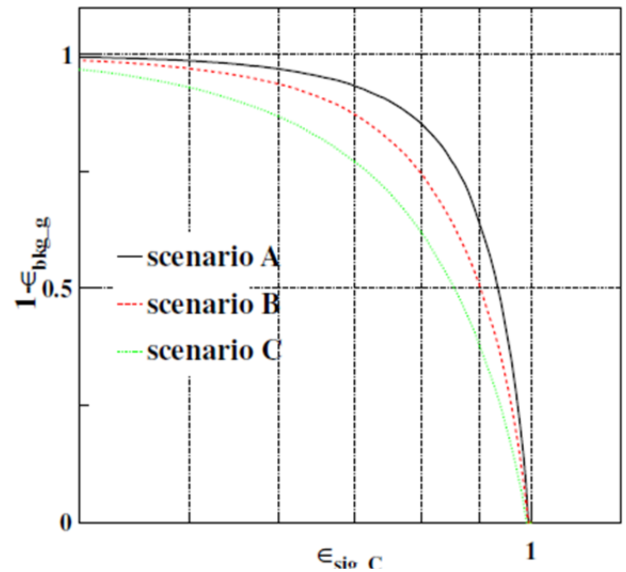




Flavor tagging performance

- Only di-jet final modes (bb, cc, gg) are considered, evaluated by ROC
  - SM bkg and other decay mode of Higgs can be effectively reduced
- Case C: upgraded ALICE ITS; Case A: half values of the baseline design





C-tagging efficiency | C-tagging efficiency

	Scenario A (Aggressive)	Scenario B (Baseline)	Scenario C (Conservative)
Material per layer/X_0	0.075	0.15	0.3
Spatial resolution/μm	1.4 - 3	2.8 - 6	5 - 10.7
R_{in}/mm	8	16	23

Br(H->bb, cc) measurement

- Br (H -> cc) is extremely sensitive to the vertex design
- Br (H -> bb) is less sensitive to the vertex design

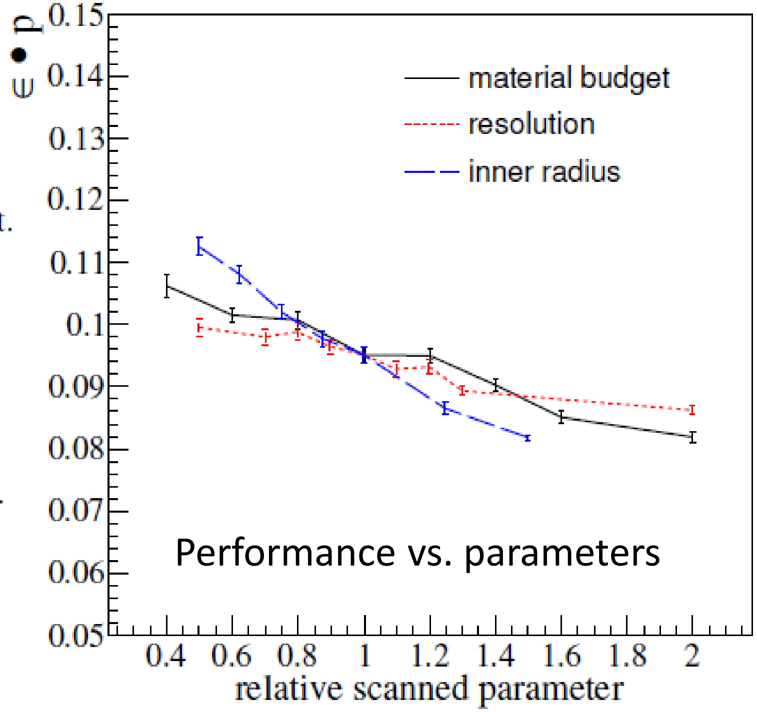
$$\frac{\delta_\mu}{\mu} \propto \frac{\sqrt{S+B}}{S} = \sqrt{\frac{1}{S}}\sqrt{\frac{S+B}{S}} \propto \frac{1}{\sqrt{\epsilon \cdot p}}.$$

Table 3. Maximum $\epsilon \cdot p$ value comparison for the $Br(H \to c\bar{c})$ measurement.

	Scenario A	Scenario B	Scenario C
$\epsilon \cdot p$	0.133 ± 0.002	0.095 ± 0.001	0.078 ± 0.001
	41%		-22%

Table 4. Maximum $\epsilon \cdot p$ value comparison for the $Br(H \to b\bar{b})$ measurement.

	Scenario A	Scenario B	Scenario C
$\epsilon \cdot p$	0.925 ± 0.001	0.914 ± 0.001	0.900 ± 0.001
	1%		-1.5%



Performance vs. parameters

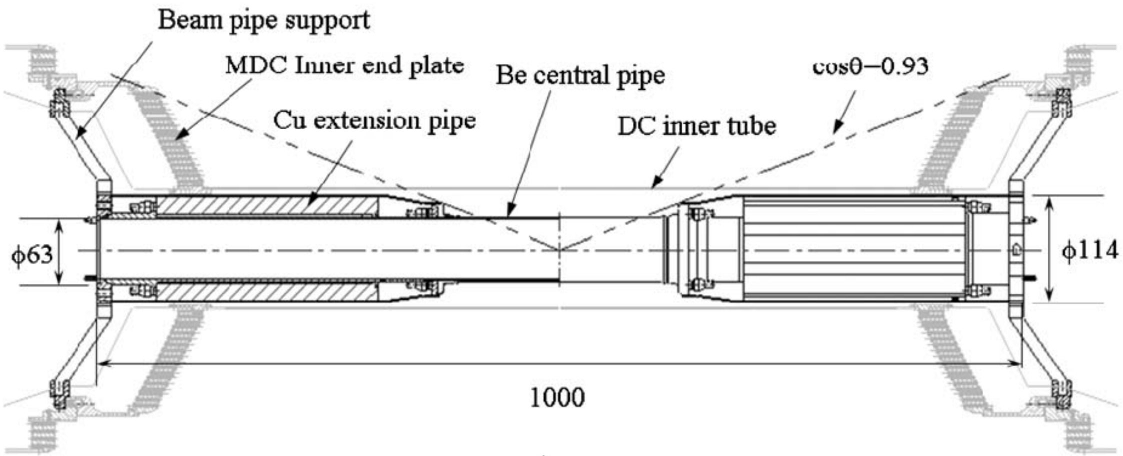
$$\epsilon \cdot \mathrm{p} = 0.095\left(1-0.14\frac{\Delta x_{material}}{x_{material}}\right)\left(1-0.09\frac{\Delta x_{resolution}}{x_{resolution}}\right)\left(1-0.23\frac{\Delta x_{radius}}{x_{radius}}\right)$$

Inner radius is the most sensitive parameter

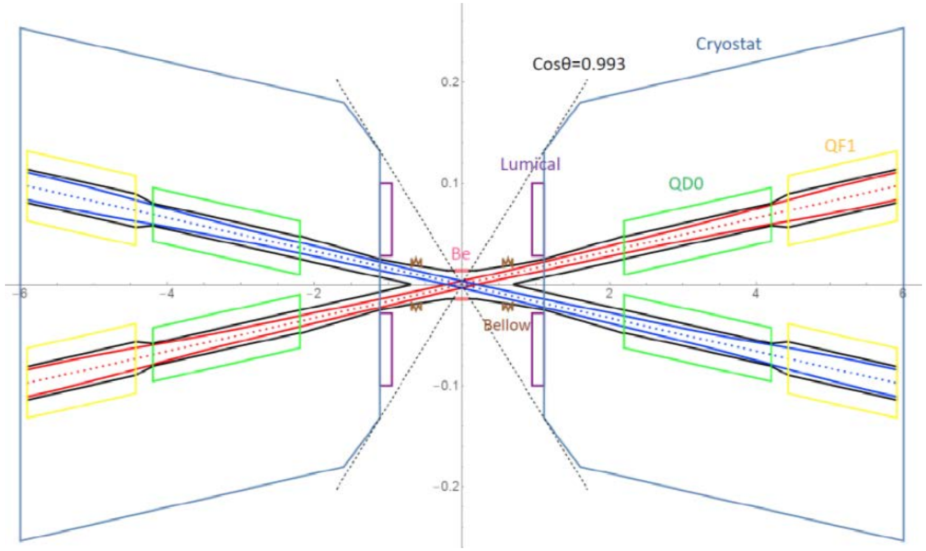
Material budget near beam pipe

- BESIII beam pipe material: 1.04%/X_0 (Be: 0.4%, gold: 0.44%, SMO: 0.2%)
- CEPC beam pipe material: 0.14%/X_0 Be, heat load more than 1000 W
- Have to increase the material budget near beam pipe due to cooling

BESIII

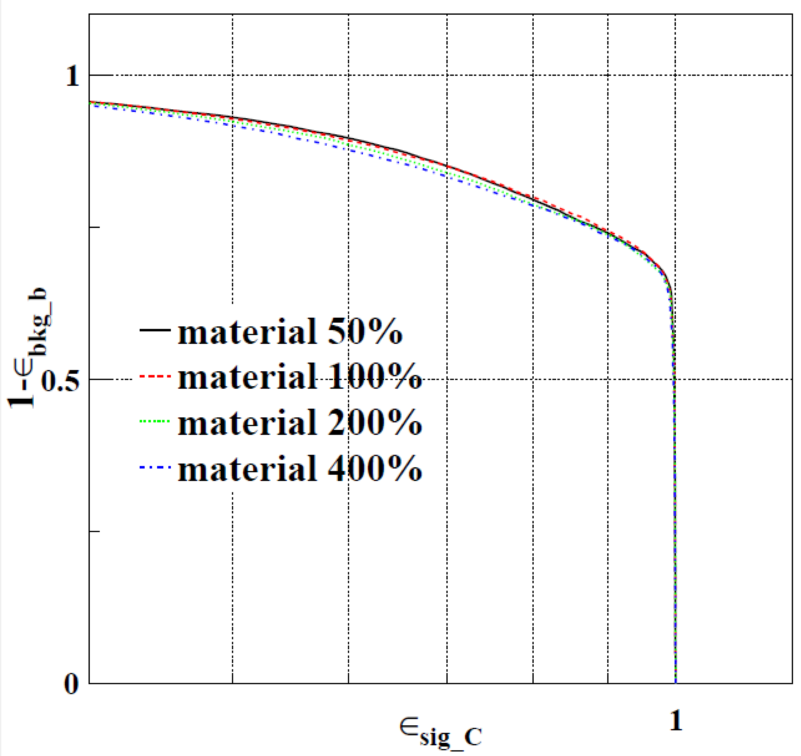


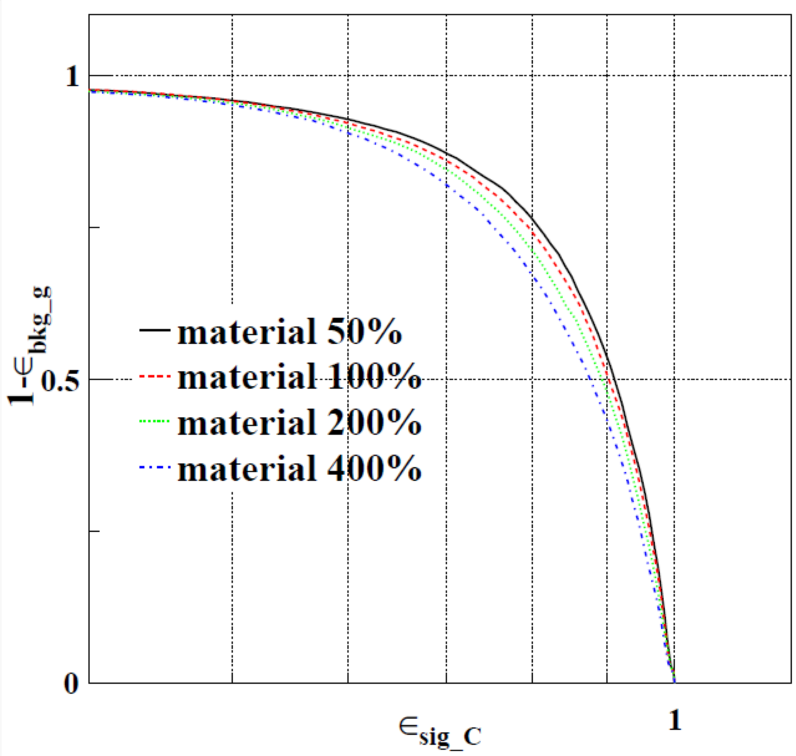
CEPC



Material budget near beam pipe

- Have to increase the material budget near beam pipe due to cooling system
- Influence is comparable with the material change of vertex detector





material	50%	100%	200%	400%
ε•p	0.1175	0.1145	0.1092	0.1057

-10%

$$\varepsilon \bullet p \propto 1 - 0.025 \frac{\Delta x_{material}}{x_{material}}$$

ALICE ITS3

- EoI details milestones for all activities, grouped by:
  - Sensor Chip
  - Thinning and bending
  - Mechanics and cooling
  - Beam pipe
- R&D starts now
- TDR is foreseen for 2022

See: M. Mager , | ITS3 | VERTEX 2019 | 17.10.2019 |

ALICE-PUBLIC-2018-013

Letter of Intent
for an
ALICE ITS Upgrade in LS3

ALICE Collaboration, CERN, Geneva, Switzerland

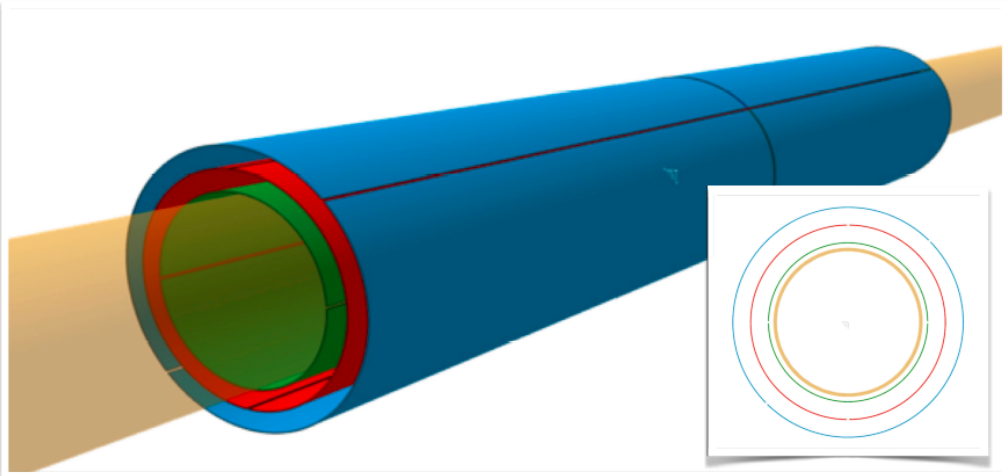
Abstract

Recent innovations in the field of silicon imaging technology for consumer applications open extraordinary opportunities for new detector concepts, and hence offer strongly improved physics scope. This document presents a proposal for the construction of a novel vertex detector consisting of curved wafer-scale ultra-thin silicon sensors arranged in perfectly cylindrical layers, featuring an unprecedented low material budget of 0.05 % X_0 per layer, with the innermost layer positioned at only 18 mm radial distance from the interaction point. This new vertex detector is planned to be installed during the LHC LS3 to replace the innermost three layers of the ALICE Inner Tracking System. It will provide a large reduction of the material budget in the region close to the interaction point and a large improvement of the tracking precision and efficiency at low transverse momentum. The combination of these two improvements will lead to a significant advancement in the measurement of low momentum charm and beauty hadrons and low-mass dielectrons in heavy-ion collisions at the LHC, which are among the main objectives of the ALICE physics programme in the next decade.

Geneva, Switzerland
October 8, 2019

[ALICE-PUBLIC-2018-013]

ALICE ITS3 Layout



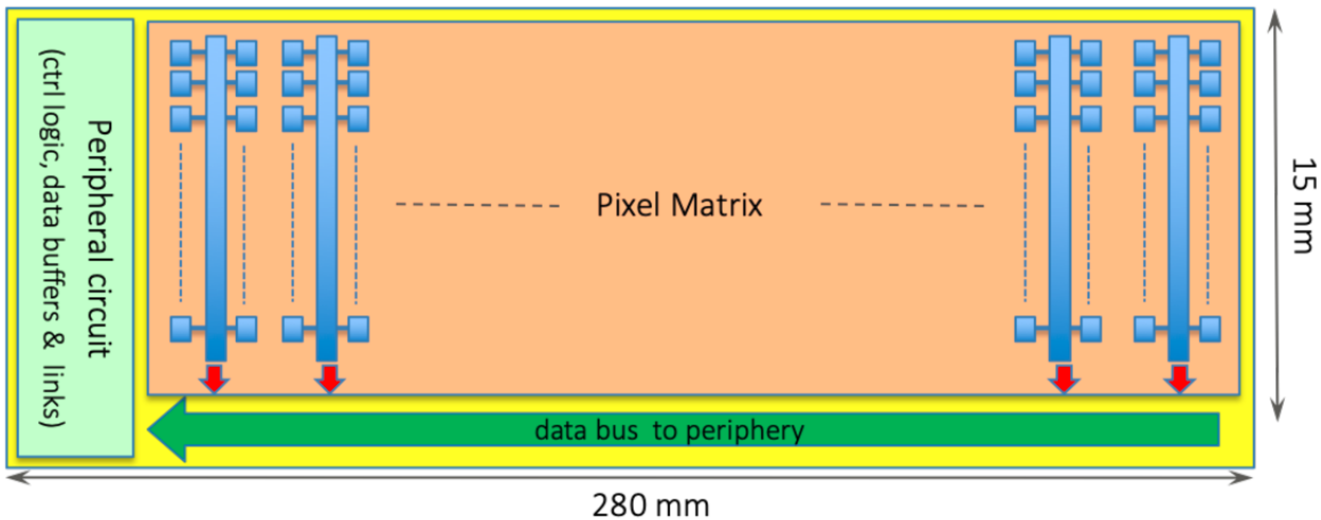
Beam pipe Inner/Outer Radius (mm)	16.0/16.5		
IB Layer Parameters	Layer 0	Layer 1	Layer 2
Radial position (mm)	18.0 **16mm**	24.0	30.0
Length (sensitive area) (mm)	300 **250mm**		
Pseudo-rapidity coverage	±2.5	±2.3	±2.0
Active area (cm²)	610	816	1016
Pixel sensor dimensions (mm²)	280 x 56.5	280 x 75.5	280 x 94
Number of sensors per layer	2		
Pixel size (μm²)	O (10 x 10)		

- New beam pipe:
  - "old" radius/thickness: 18.2/0.8 mm
  - new radius/thickness: 16.0/0.5 mm
- Extremely low material budget:
  - Beam pipe thickness: 500 μm (0.14% X0)
  - Sensor thickness: 20-40 μm (0.02-0.04% X0)
- Material homogeneously distributed:
  - essentially zero systematic error from material distribution

Similar layout with CEPC layer 1-3

Wafer-scale chip (2)

Possible architecture



- Starting from ALPIDE architecture
- Porting to 65 nm technology node
  - smaller pixels
  - larger wafers (300 mm instead of 200 mm)
- Basic building block of 15 mm height
  - to be repeated n times in vertical direction to obtain the sizes needed per layer

CEPC layer 6: L=190mm

Stitching and thinning

CMOS APS – wafer-scale integration

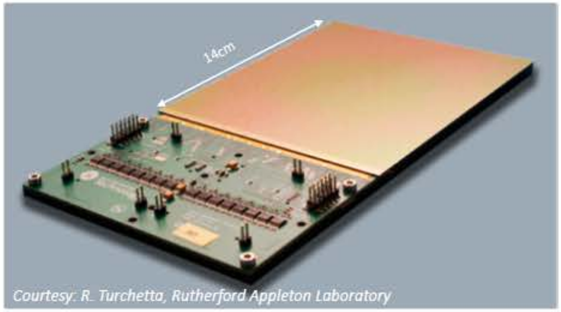
Photolithographic process defines wafer reticles size ➪ Typical field of view O(2 x 2 cm^2)

Reticle is stepped across the wafers to create multiple identical images of the circuit(s)

A stepping process called "stitching" allows building sensors of arbitrary size, the only limit being the size of the wafer.

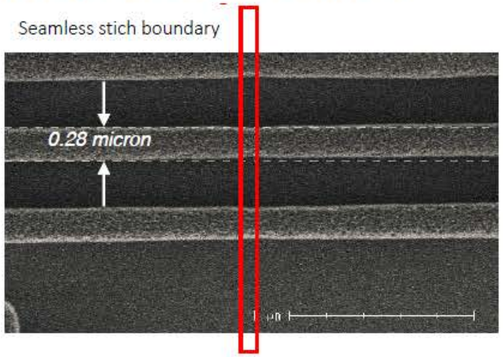
- Reticle made of blocks
- Printing only individual blocks at each step with a tiny well-defined overlap

These days, stitching is widely applied in the digital imaging industry (e.g. large flat panels for medical and dental X-rays)



Courtesy: R. Turchetta, Rutherford Appleton Laboratory

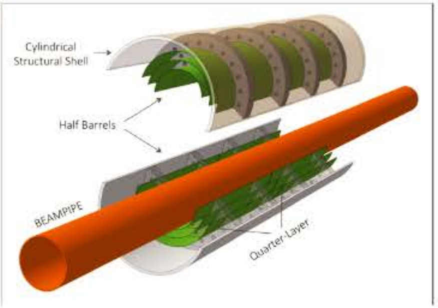
Seamless stich boundary



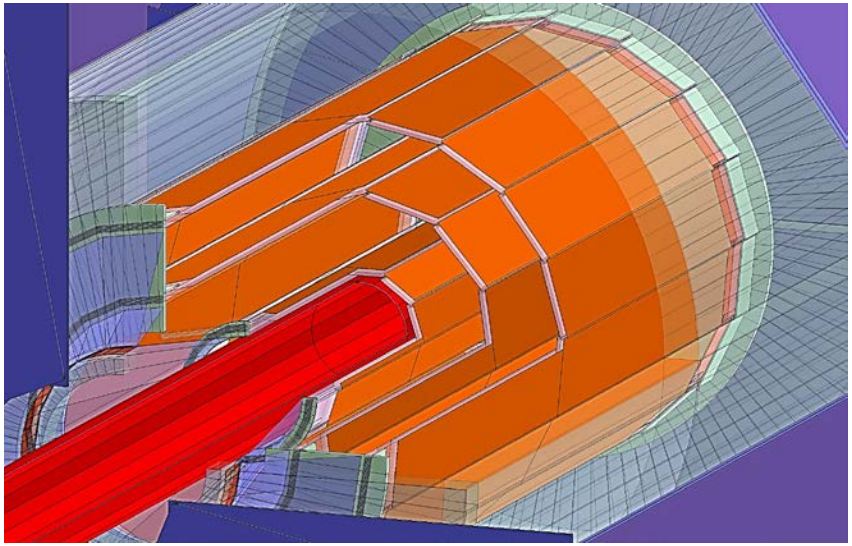
Ultra-thin chip (<50 um): flexible with good stability

Truly cylindrical vertex detector

New ultra-light Inner Barrel in LS3 (CDS, ALICE-PUBLIC-2018-013)



Vertex layout with 6 single ultra lightweight layers — comparing with Baseline Design



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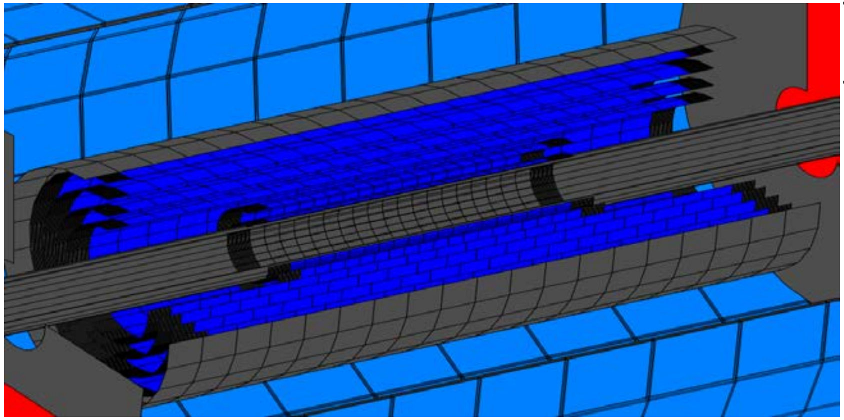
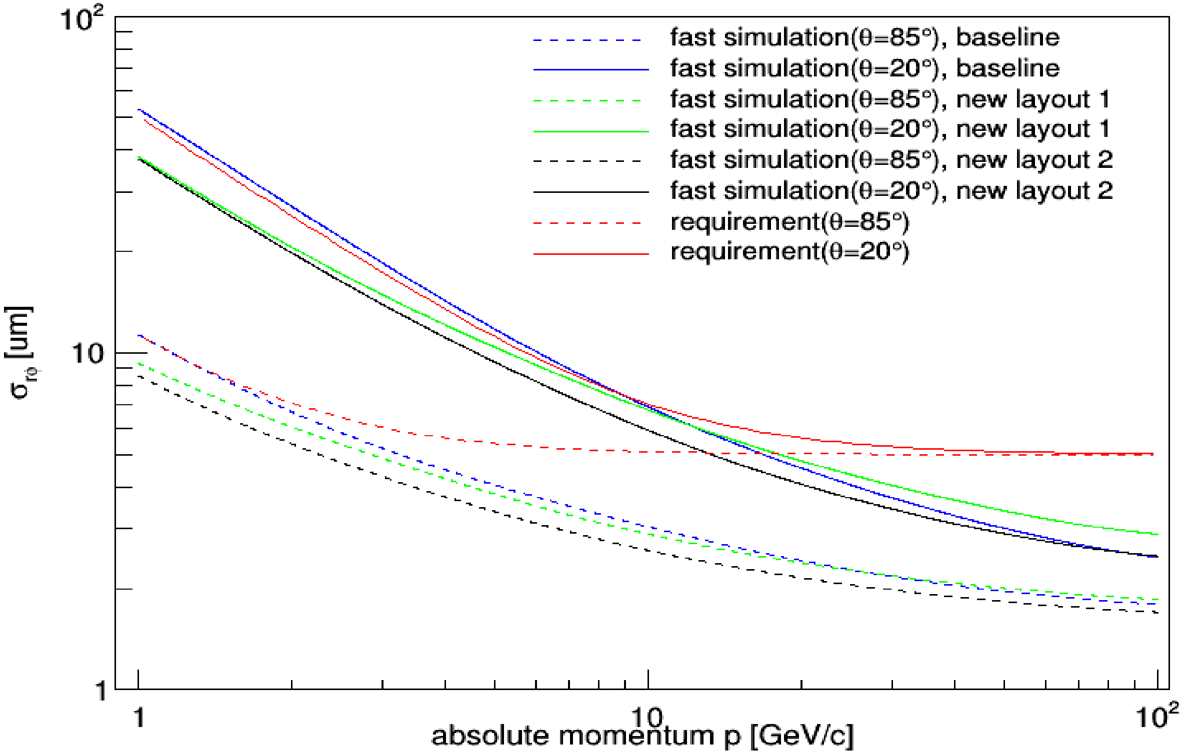


	R(mm)	|Z|(mm)	$\sigma(\mu m)$ (layout1/layout2)	material
Layer1	16	62.5	4/2.8	$0.05\%X_0$
Layer2	24	62.5	4/4	$0.05\%X_0$
Layer3	32	125	4/4	$0.05\%X_0$
Layer4	40	125	4/4	$0.05\%X_0$
Layer5	50	125	4/4	$0.05\%X_0$
Layer6	60	125	4/4	$0.05\%X_0$

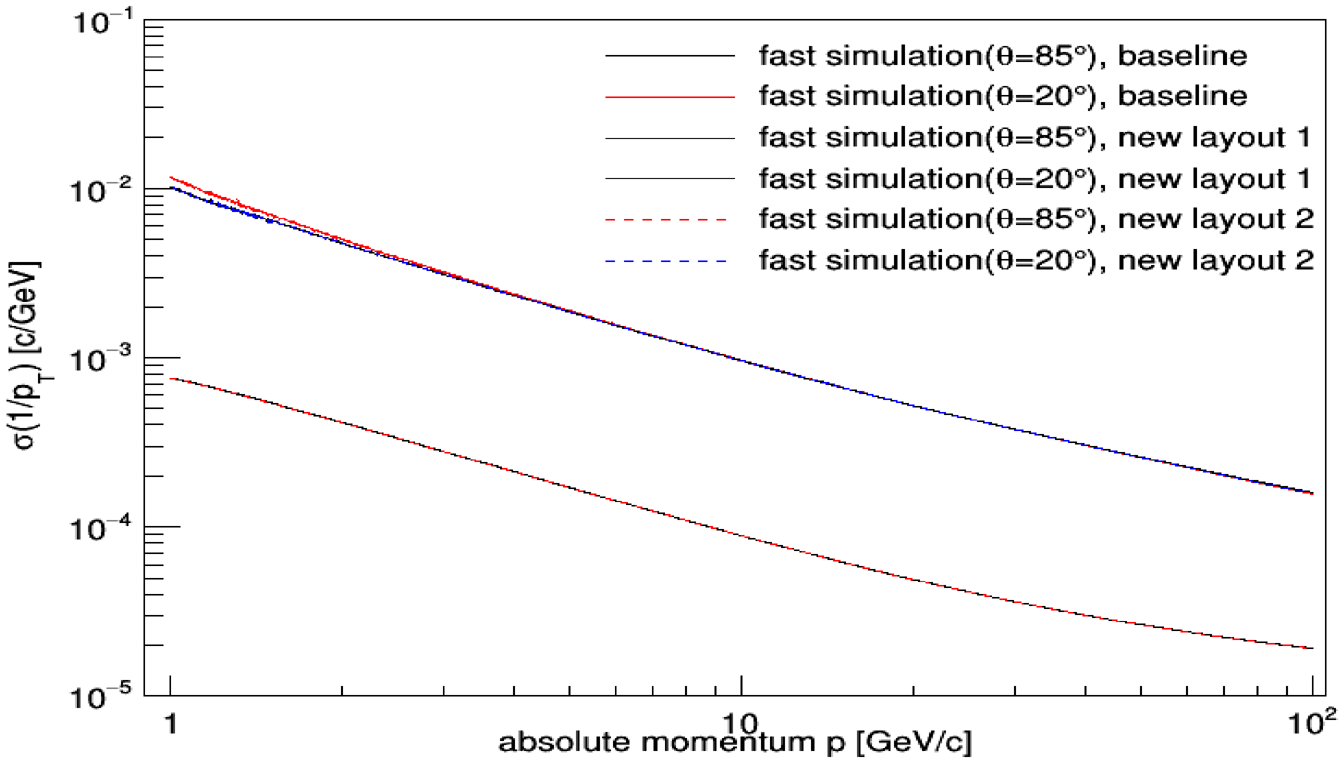
Impact parameter resolution: *fast simulation*



- better performance (~20% improvement) for layout1 at low momentum, but poor performance at high momentum
- The performance of layout2 is better than baseline design
- both within the requirement

Material budget plays a major role at low momentum, while resolution plays a major role at high momentum.

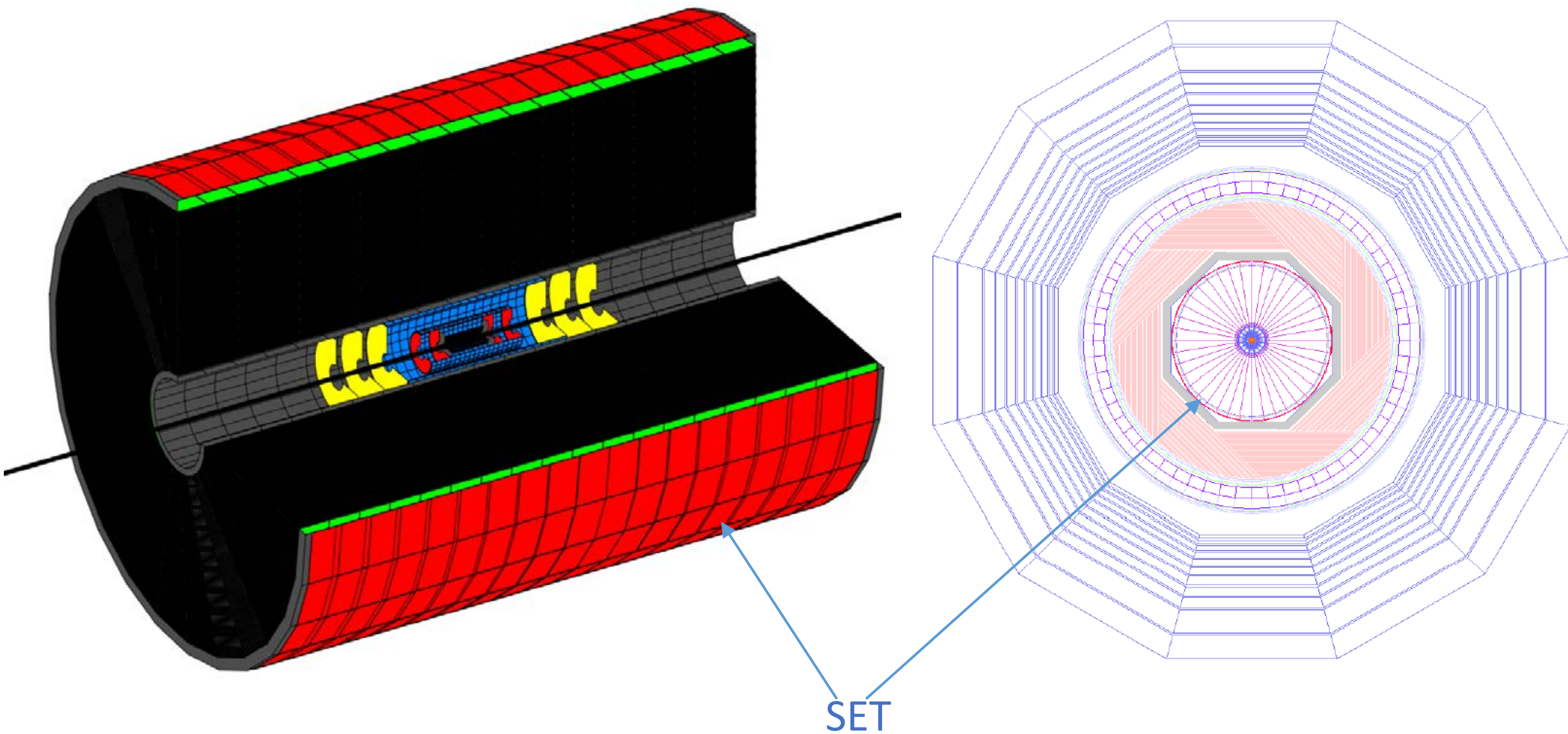
Momentum resolution : *fast simulation*



effect on p_T resolution is negligible

SET introduction

- Silicon External Tracker, providing precise hit points after the TPC
- Improving the overall tracking performance in the central region
- Extrapolating from the TPC to the calorimeter



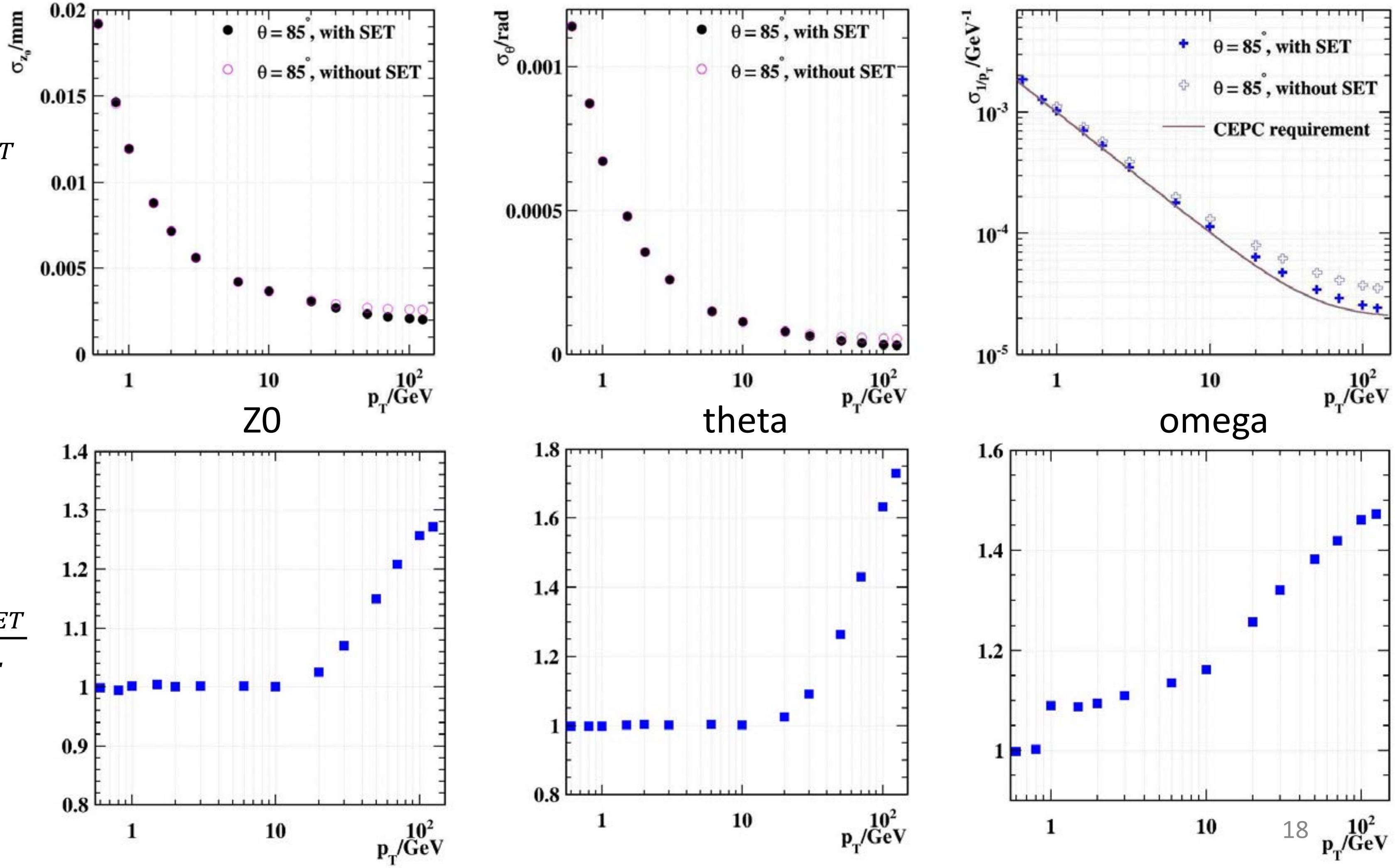
Effect of SET on track reconstruction

- SET has a high influence on the resolution of Z0, theta and omega
  - ☐ When Pt is high

Made by Taifan.

$\sigma_{withoutSET}$ and $\sigma_{withSET}$

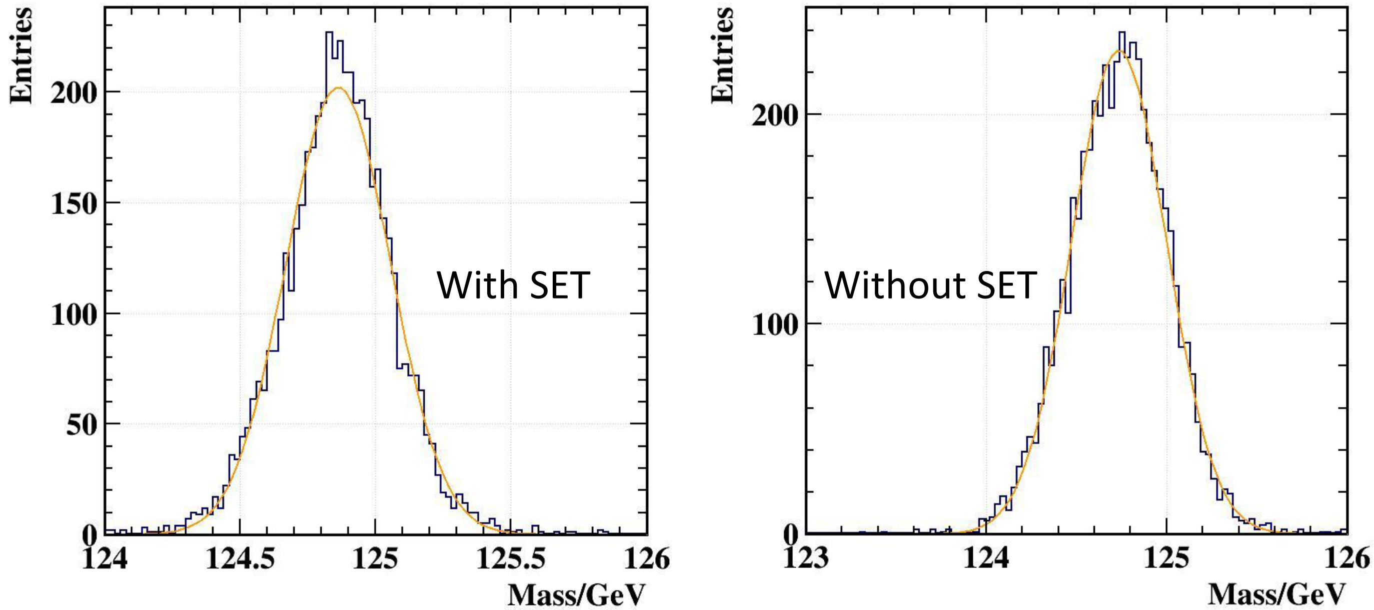
$\frac{\sigma_{withoutSET}}{\sigma_{withSET}}$



Effect of SET on Higgs Mass reconstruction

- Higgs mass resolution in H->$\mu^+\mu^-$. Use MC information to find out true μ tracks
- High influence on Higgs Mass resolution

Made by Taifan.



Higgs mass resolution/MeV

	ZH recoil	nnH
withSET	213.4+-4.7	193.7+-2.2
w/o SET	297.5+-6.3	263.5+-2.7
	+39%	+36%

Thanks for your attention!