Studies of beam-induced background effects in the Time Projection Chamber at CEPC

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——on behalf of the CEPC gaseous tracker R&D group

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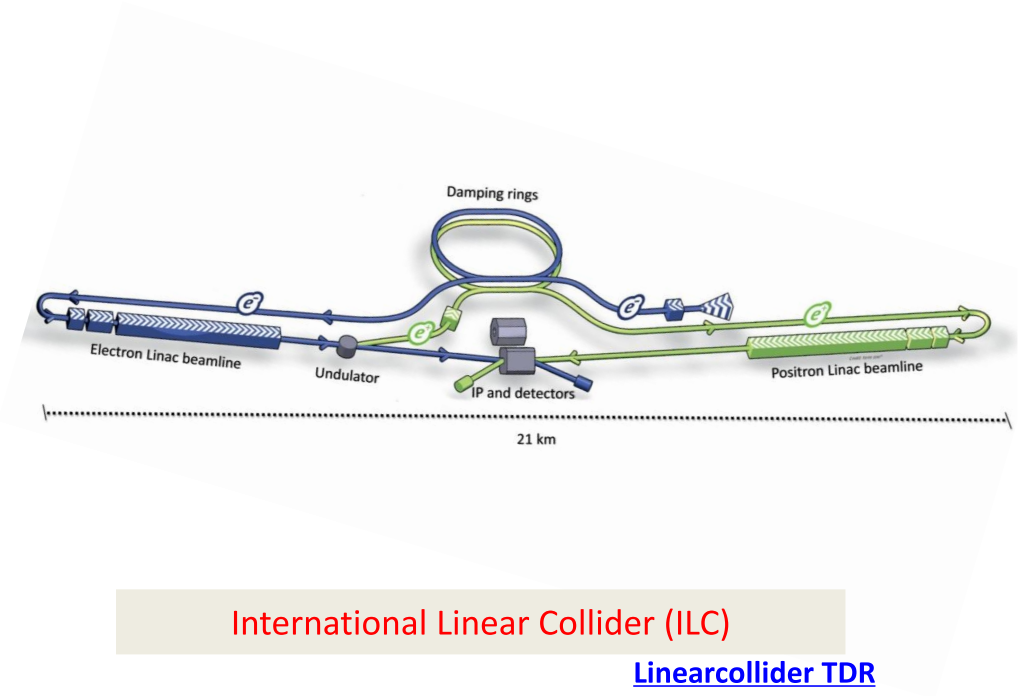
Content

- Motivation and Physics requirements
- Beam-induced background in the TPC
- Tracking performance estimation
- Summary

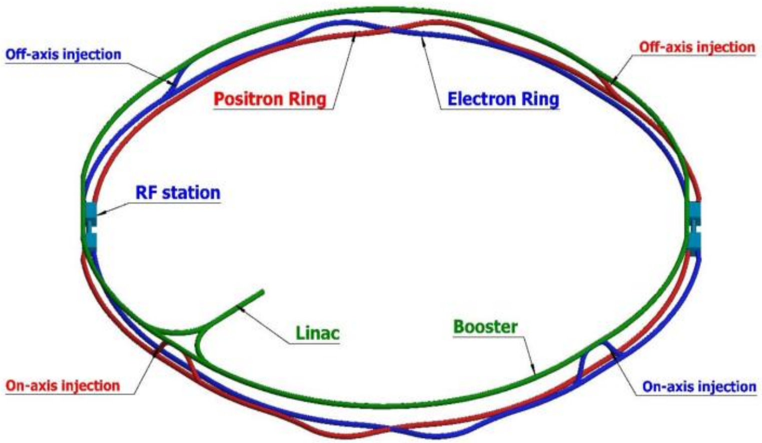
TPC detector for future e$^+$e$^-$ collider

- The TPC is a promising main tracker detector candidate for some future e$^+$e$^-$ collider experiments
  - Baseline detector in the ILD and CEPC-CDR
  - **High-granularity readout TPC** has been selected as the baseline main tracker detector in the CEPC Ref-TDR
- High-granularity readout TPC is potential to improve PID performance.
- TPC technology can be interest for other future colliders (FCC-ee, EIC…)



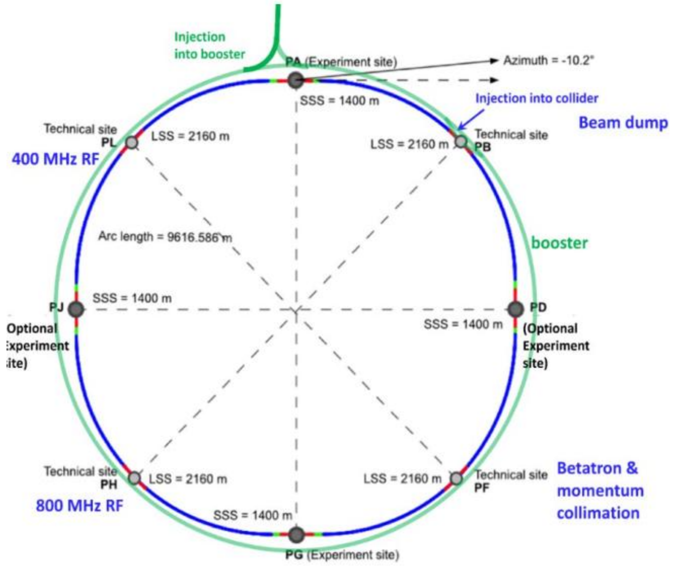
International Linear Collider (ILC)

Linearcollider TDR



Circular Electron Positron Collider (CEPC)

https://arxiv.org/abs/1811.10545



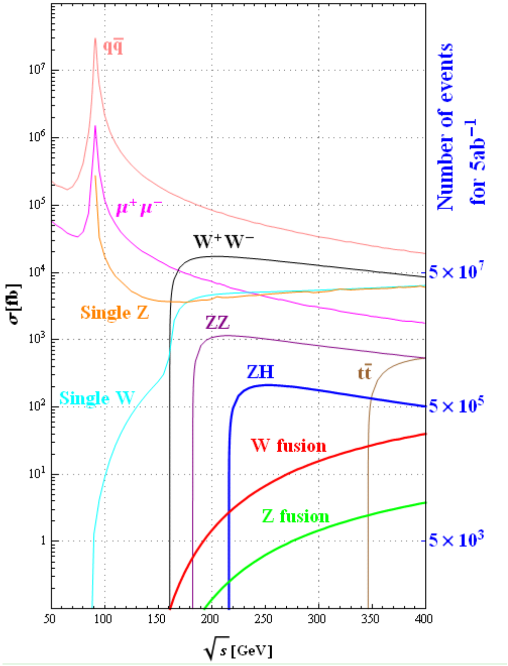
Future Circular Collider (FCCee)

https://arxiv.org/abs/2203.08310

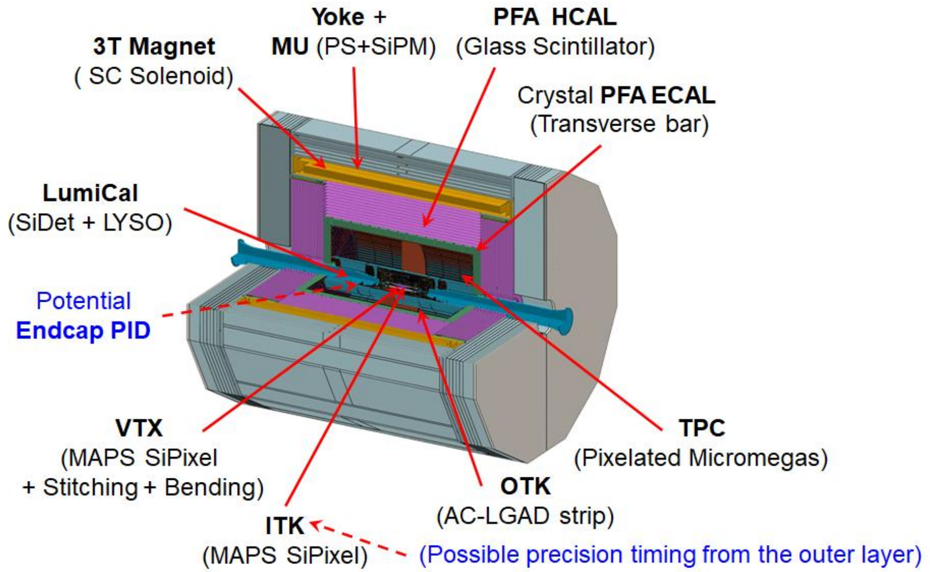
CEPC operation

- The CEPC is designed as a powerful factory of Higgs, Z and W bosons.
  - Operating at between 91 to 240 GeV
  - Mainly in the Higgs, and the low-luminosity Z modes during the **first 10-year** operation (3T magnetic field)
- The Reference Detector comprises a high-granularity readout TPC, surrounded by silicon detectors.
  - Designed and optimized primarily for the Higgs and low-luminosity Z runs

Calibration: Low luminosity Z at 3T
Approximately $10^{35}cm^{-2}s^{-1}$
1%-20% of high luminosity Z



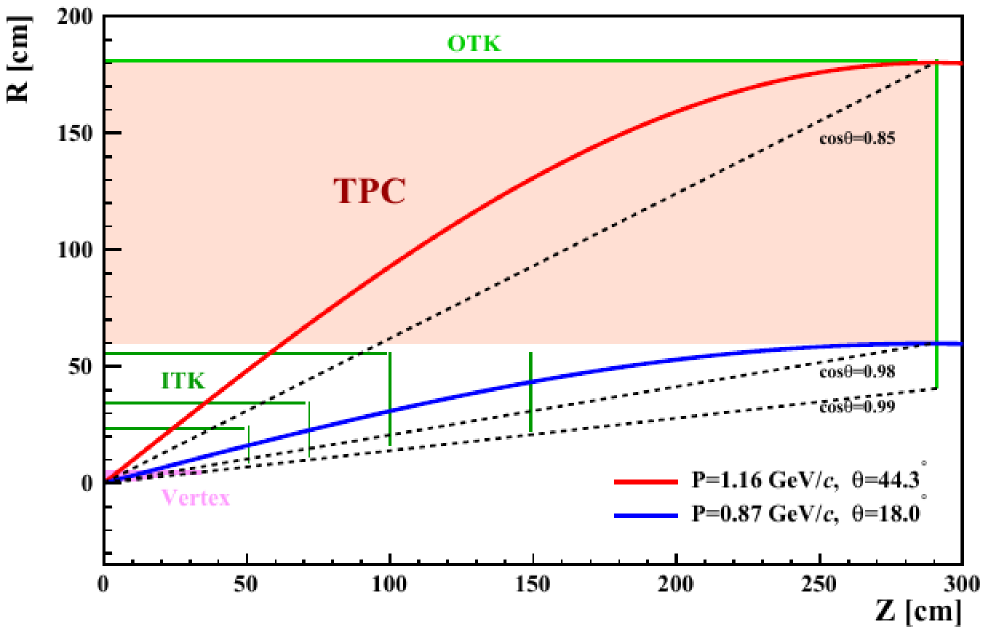
Operation mode		ZH	Z	W^+W^-	$t\bar{t}$
$\sqrt{s}$ [GeV]		~240	~91	~160	~360
Run Time [years]		10	2	1	5
30 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.65
	Event yields [2 IPs]	2.6×10^6	2.5×10^{12}	1.3×10^8	4×10^5
50 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**8.3**	**192**	**26.7**	**0.8**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	21.6	100	6.9	1
	Event yields [2 IPs]	4.3×10^6	4.1×10^{12}	2.1×10^8	6×10^5



CEPC Reference Detector design, arxiv:2510.05260

Physics requirements of the CEPC

- Physics Requirements for the **TPC**
  - Tracking: $\sigma(1/P_T)\sim10^{-4}$ (GeV/c)$^{-1}$ (TPC only), $\sigma(1/P_T)\sim3\times10^{-5}$ (GeV/c)$^{-1}$ (TPC+Si detectors)
  - PID for flavor physics and jet reconstruction: π/K separation power better than 3σ
- Challenges:
  - Beam-induced background
  - Space Charge effect and Distortions



Physics objects	Measurands	Detector subsystem	Performance requirement
Tracking	Coverage Recon. efficiency Resolution in barrel Resolution in endcap	Tracker	$\lvert\cos\theta\rvert \leq 0.99$ $\geq 99\%$ ($p_T > 1$ GeV/c) $\sigma_{p_T}/p_T < 0.3\%$ ($\lvert\cos\theta\rvert \leq 0.85$) $\sigma_{p_T}/p_T < 3\%$ ($\lvert\cos\theta\rvert > 0.85$)
Leptons (e, μ)	PID efficiency Mis-ID rate	Tracker, ECAL HCAL, Muon	$\geq 99\%$ ($p > 5$ GeV/c, isolated) $\leq 2\%$ ($p > 5$ GeV/c, isolated)
Photons	PID efficiency Mis-ID rate Energy resolution	ECAL, HCAL	$\geq 95\%$ ($E > 3$ GeV, isolated) $\leq 5\%$ ($E > 3$ GeV, isolated) $\sigma_E/E \leq 3\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$
Vertex	Position resolution	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV})\times\sin^{3/2}\theta}$ (μm)
Hadronic jets	Energy resolution Mass resolution	Tracker ECAL, HCAL	$\sigma_E/E \sim 30\%/\sqrt{E(\mathrm{GeV})} \oplus 4\%$ BMR $\leq 4\%$
Jet flavor tagging	b-tagging efficiency c-tagging efficiency	Full detector	$\sim 80\%$, mis-ID of uds $< 0.3\%$ $\sim 50\%$, mis-ID of uds $< 1\%$
Charged kaon	PID efficiency, purity	Tracker, TOF	$\geq 90\%$ (inclusive Z sample)

CEPC Tracker system layout and Physics requirements

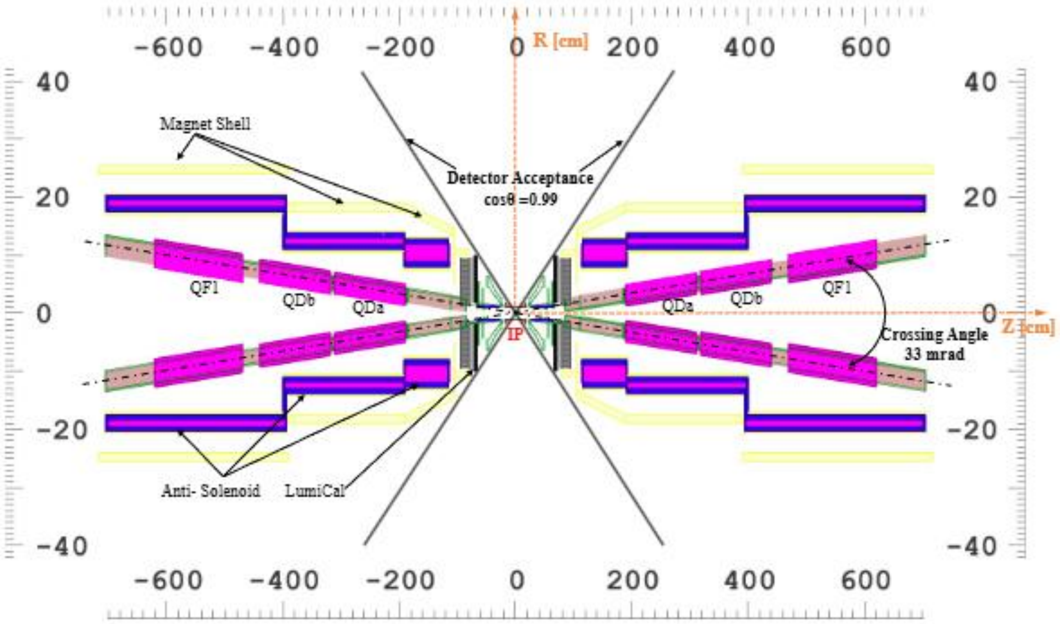
■ Beam-induced background in the TPC (Challenges)

- CEPC MDI design
- Beam-induced backgrounds simulation
- Space charge density caused by BG
- Electron drift deviations

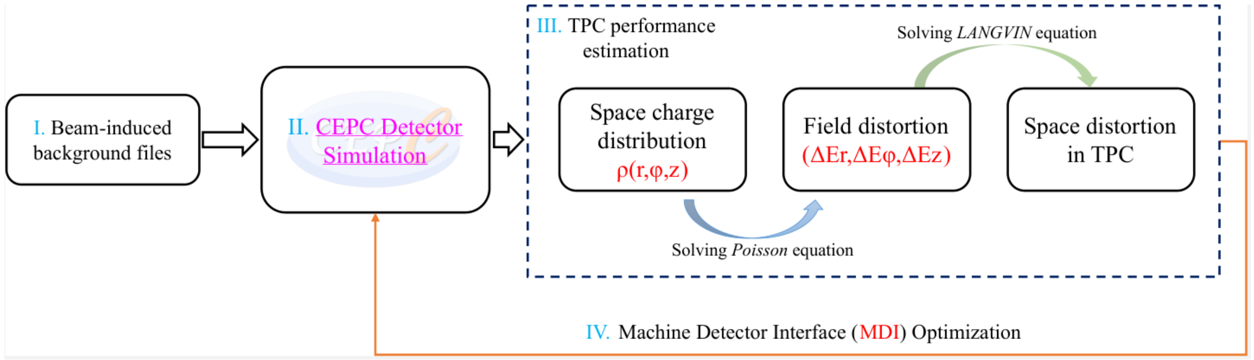
Simulation flow of beam-induced background

- MDI stands for “Machine-Detector Interface”, **33 mrad** crossing angle
- Beam-induced backgrounds seeds generation
  - Pair production (beamstrahlung) → luminosity related
  - Single-Beam (BGC,BGB,BTH,TSC) → Single Beam
- Full Detector simulation in CEPCSW (based on Geant4)
- TPC space charge density and distortions estimation

Backgrounds	Generation	Tracking	
Pair production	Guinea-Pig++	SAD	Luminosity related (BS files)
Beam-Gas Coulomb (BGC)	BGC in SAD		Single-Beam (Lost maps)
Beam-Gas Bremsstrahlung (BGB)	PyBGB		
Beam-Thermal Photon (BTH)	PyBTH		
Touschek Scattering (TSC)	TSC in SAD		



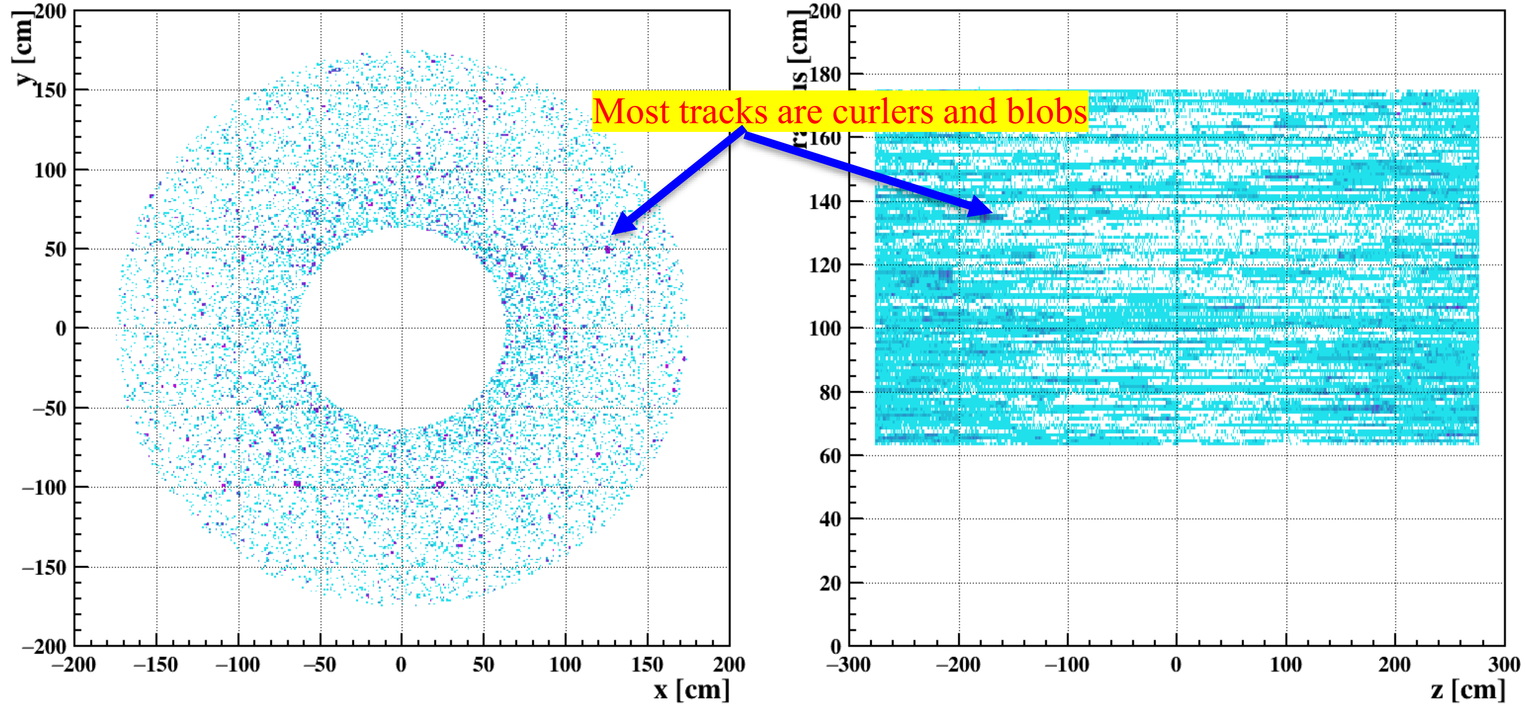
MDI designs in the CEPC ref-TDR



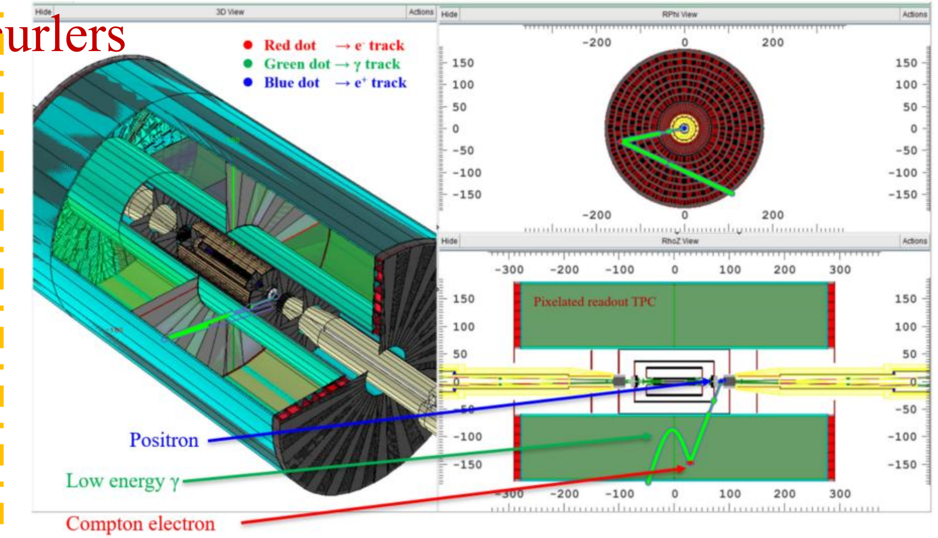
estimate number of **primary ions** produced in the TPC per bunch crossing
→ geant4 energy deposit / effective ionisation potential of Ar [26 eV]

BG event display

- Very few particles that have enough energy to leave TPC
- Most of BG hits consist of more or less randomly distributed blobs or curlers
  - Sometimes called "salt and pepper" background
  - Caused by extremely low-energy photons



TPC hits distributions at the xy and rz plane from 100 BX crossings

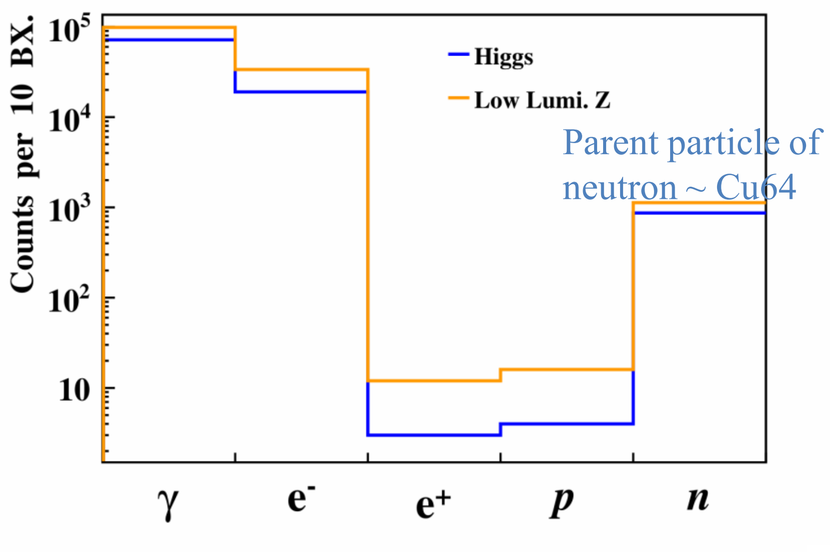


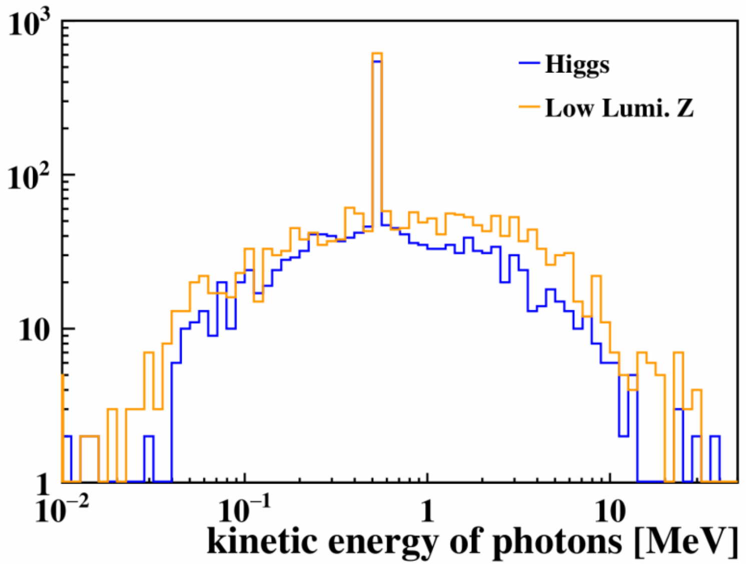
$$background\ e^{+} annihilation \rightarrow \gamma(0.511 MeV) \rightarrow Compton\ e^{-}$$

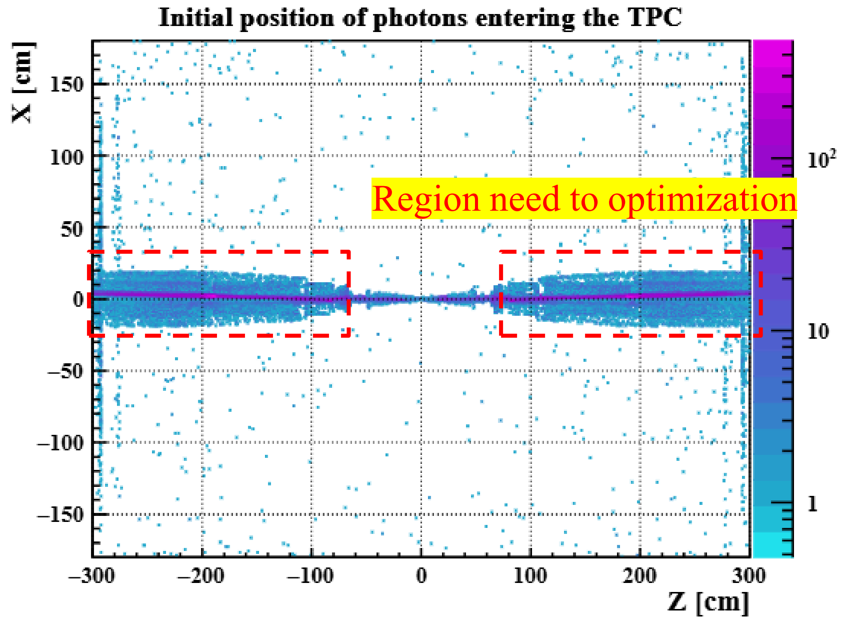
- Typical event display：
  - e+ annihilation
  - Low energy (0.511 MeV) γ incident TPC and interact with the T2K gas
  - generate secondary Compton electron

BG Particles in the TPC

- Photons and electrons (produced by low energy photons) are the main components in the TPC volume
  - The rest of particles, like positrons, proton and neutron, are negligible
- Low-energy photons (< 10 MeV) are the main contribution of the space charge
  - Photons originating from the downstream beam pipe make a significant contribution



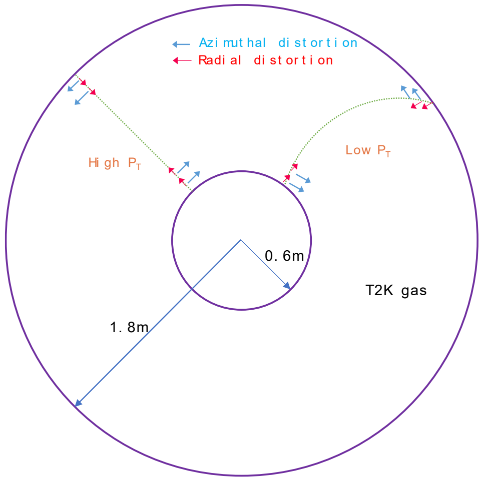


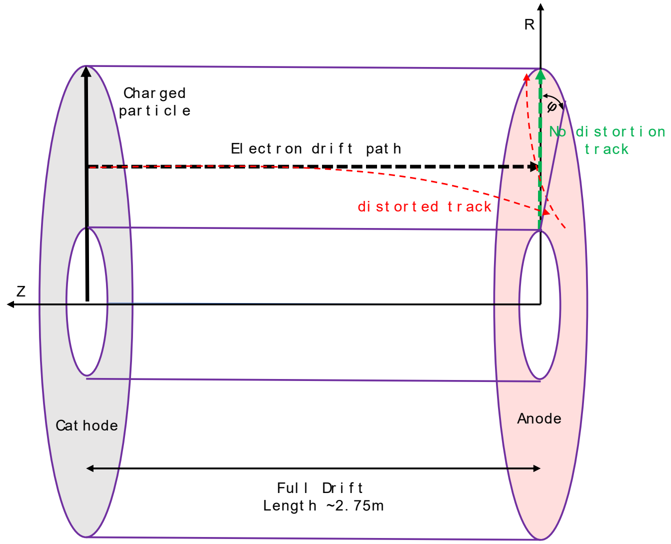


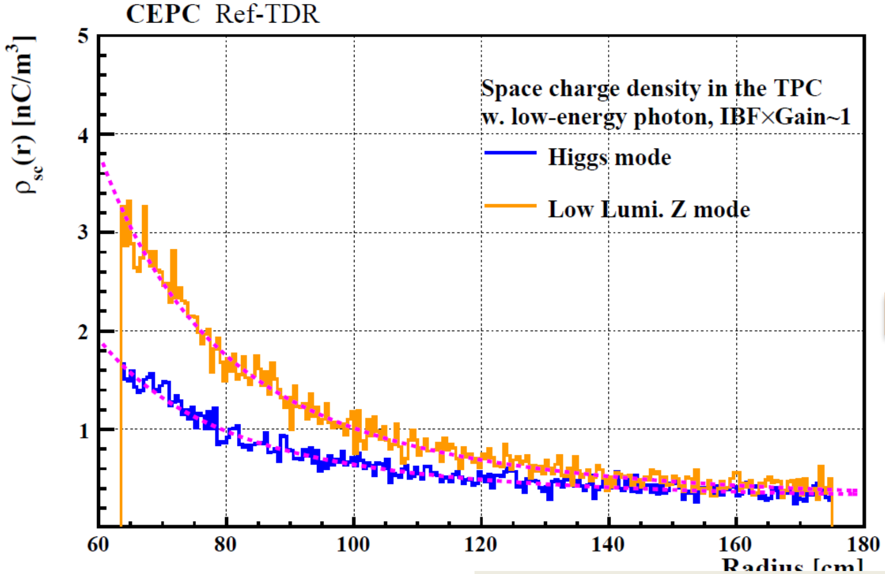
Particle type, Energy and initial position of low-energy photons entering the TPC

Space charge density and deviations

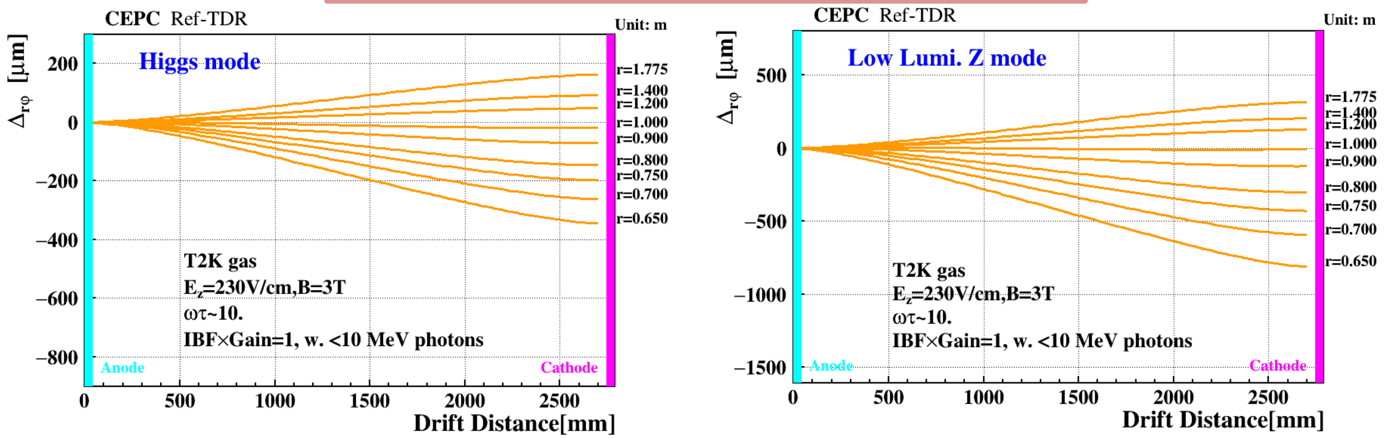
- The max. space charge density reaches 1.7 and 3.3 nC/m^3
  - With the contributions of the IBF (IBF×Gain~1) and low-energy photons
- Deviations occur both in radial and azimuthal directions along the electron drift paths
  - Azimuthal deviations have much serious impact on momentum measurement
  - The max. $\Delta r\varphi$ reaches 800μm in the low-Z mode (need to optimization and calibration)







IBF×Gain=1 && w. low-energy photons



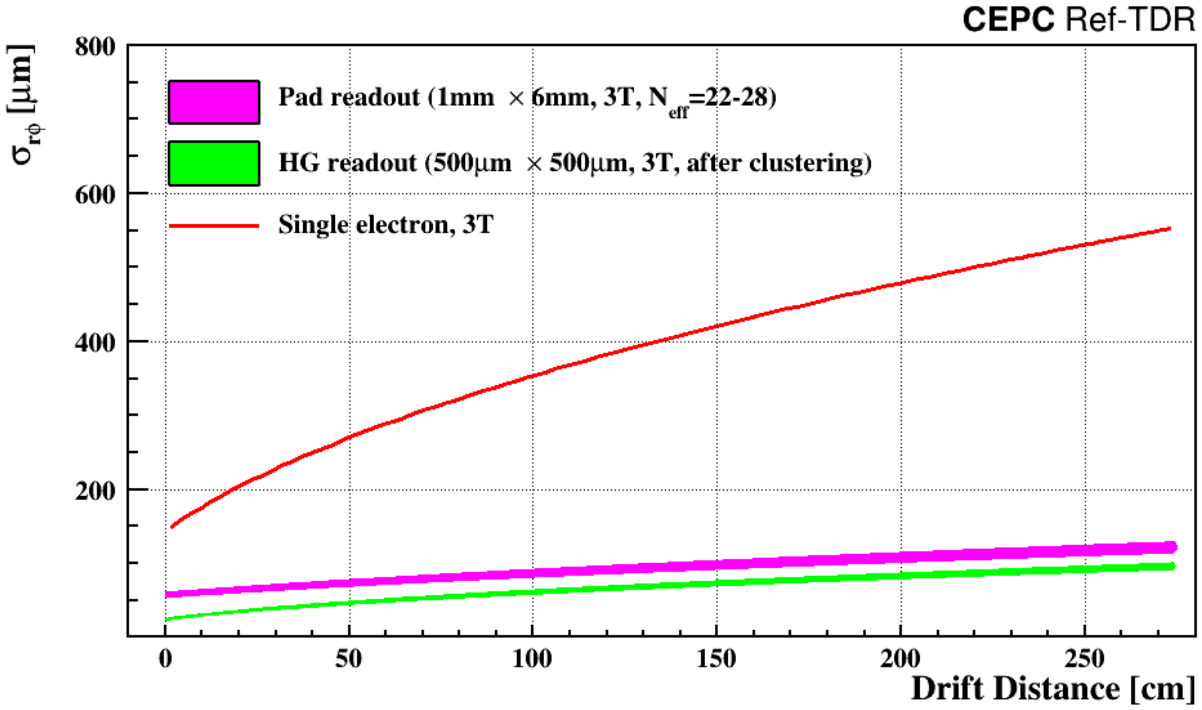
Space charge density and distortions in the Higgs and low-luminosity Z modes

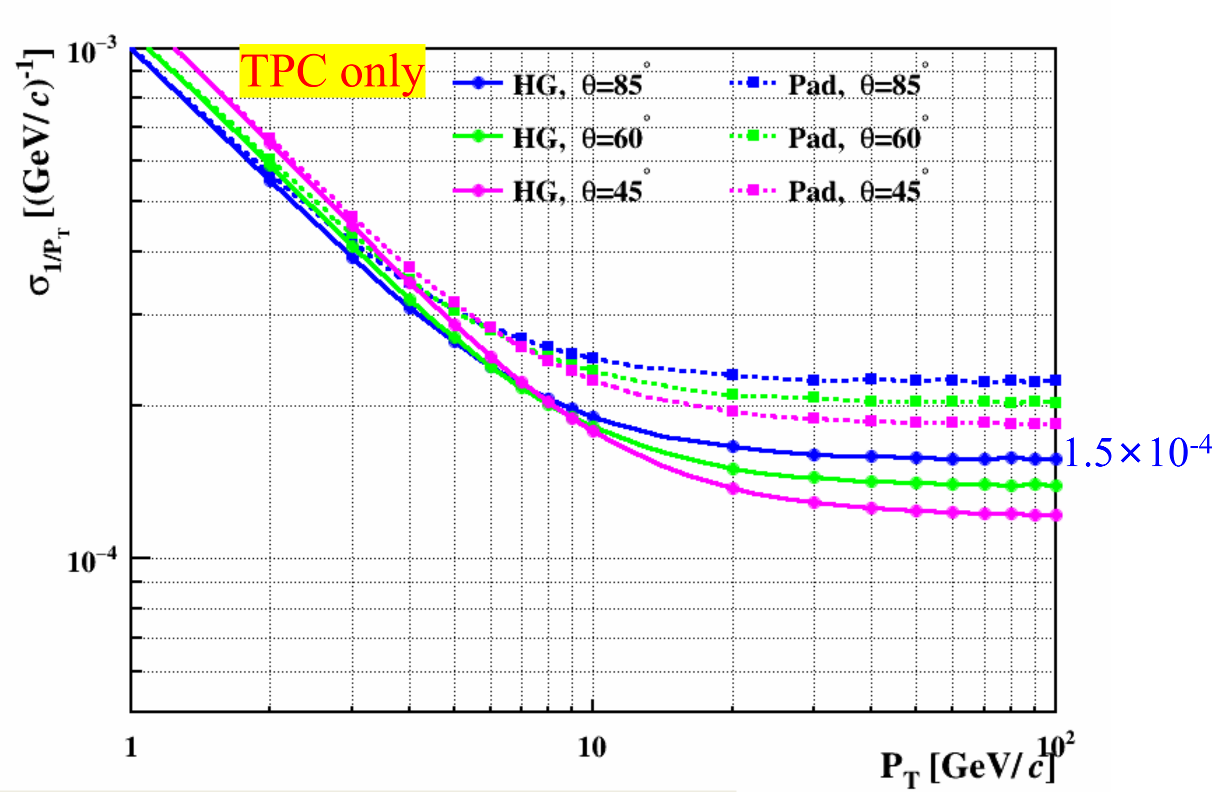
TPC tracking performance estimation

- Intrinsic performance
- Momentum resolution with Space Charge Effect
- MDI region optimization

Tracking performance

- Estimation of the **intrinsic** spatial and momentum resolution **(w.o. deviations caused by SCE)**.
  - The granularity readout and the transverse diffusion are also taken into consideration..
  - **H**igh-**G**ranularity readout TPC (500μm×500μm) can achieve better spatial resolution than pad readout TPC
  - Momentum resolution $\sigma(1/P_T)\sim10^{-4}$ (GeV/c)$^{-1}$

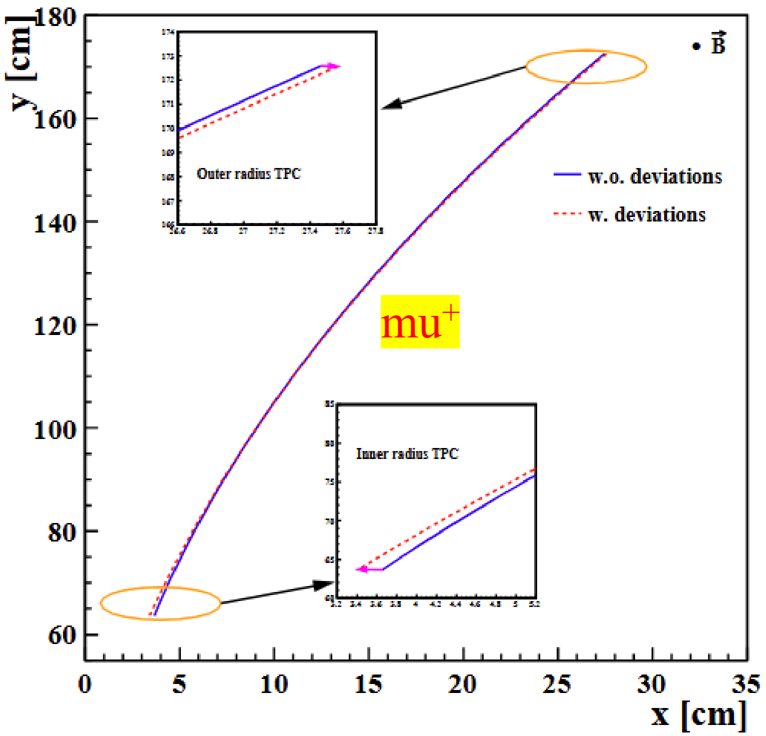


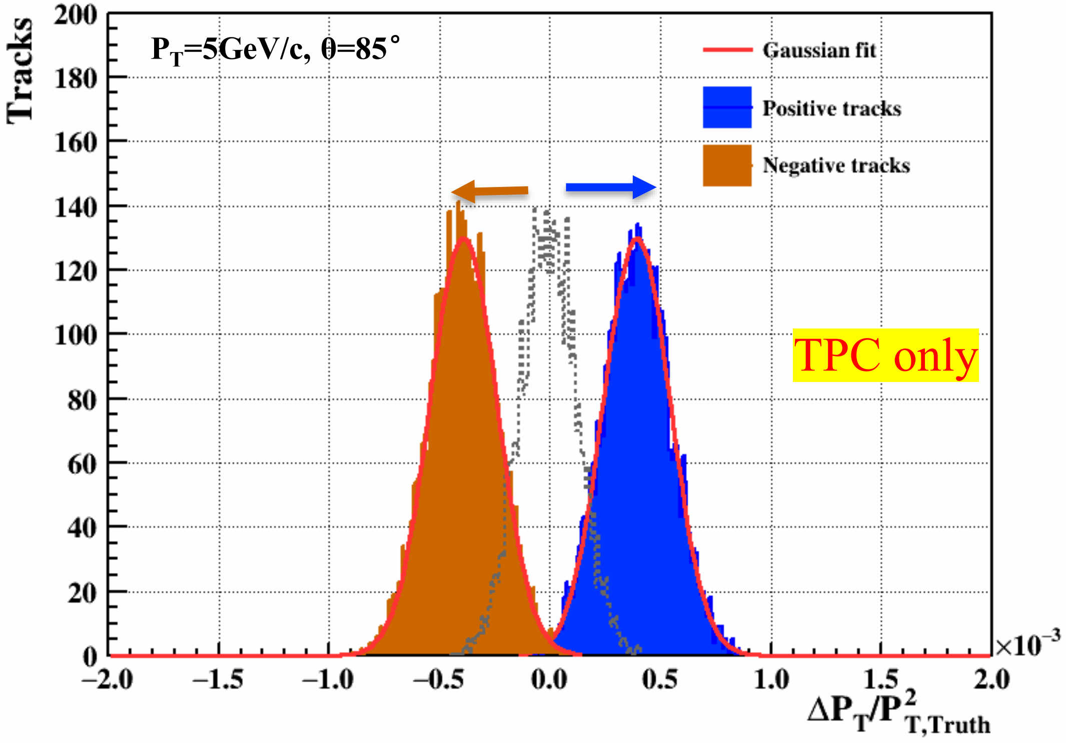


Spatial resolution as a function of drift distance (left) and Momentum resolution (right)

Influence on momentum measurement

- General impacts of the space charge effect:
  - The drift deviations are serious at the inner radius and much small around the centre of the TPC
  - Resulting in either straightening or bending of the measured tracks (the momenta of μ^+ are expected to be shifted towards higher values and μ^- towards lower values)
  - Degrading TPC hits resolution.

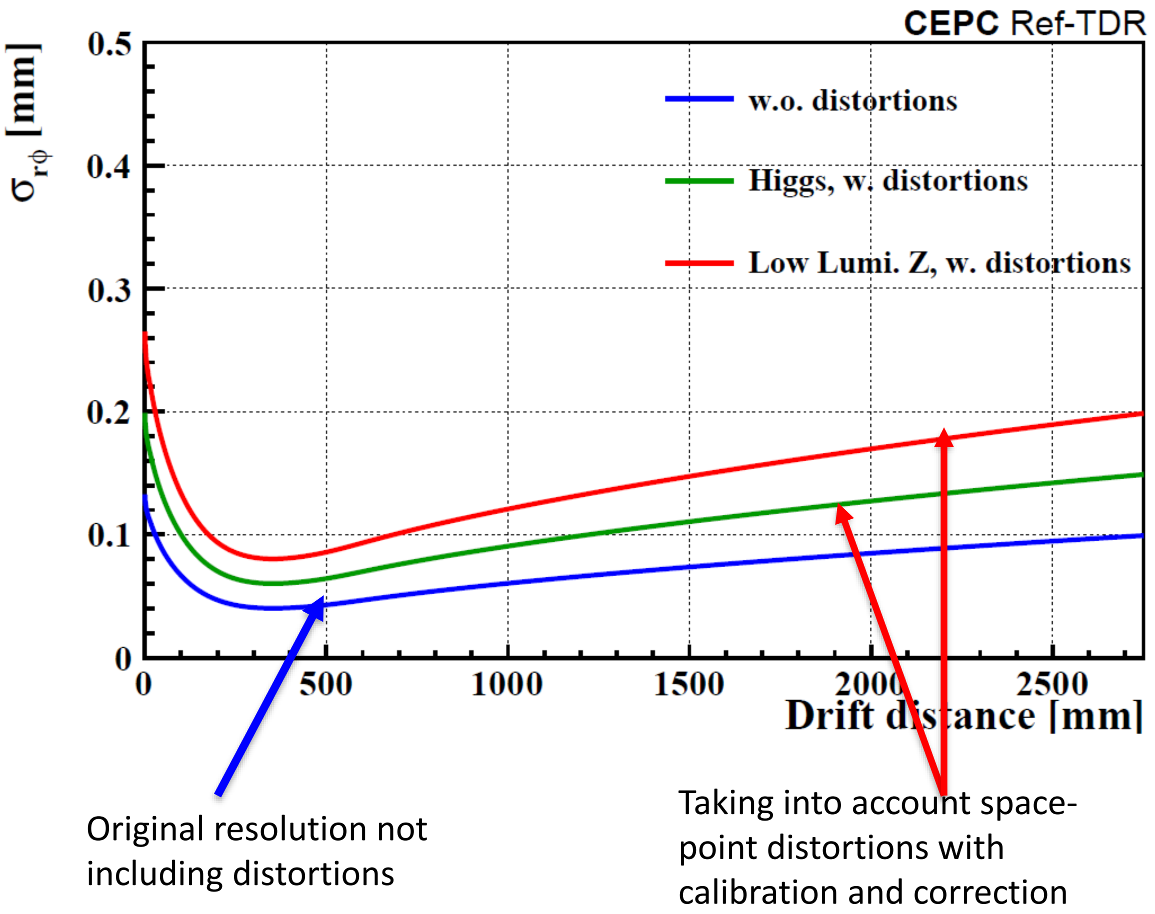




Impact on momentum measurement of the space charge effect

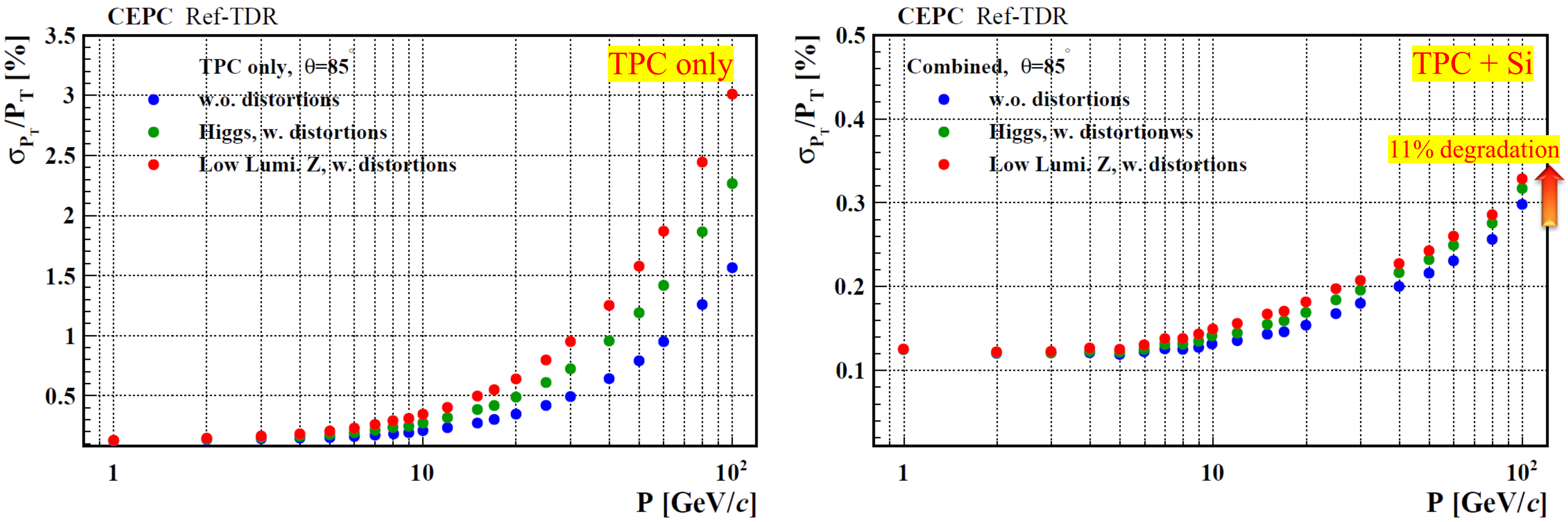
Spatial resolution with space charge effect

- Space-point deviations can be corrected by the data-driven track-based calibration by combining inner and outer silicon detectors
- Error contributions to the calibrated spatial resolution :
  - Space-charge distortion: < 80μm in Higgs mode, < 160μm in low-lumi. Z, dependent on the drift distance
  - NUMF effects on the drift process (after correction with magnetic field map): <65 μm
  - Mechanical deformation affecting the electric field and drift process : <40 μm
- Conservatively estimated, the calibrated spatial resolution degrades by ~50% and 100% at the point with the longest drift distance in Higgs and low-luminosity Z modes, respectively



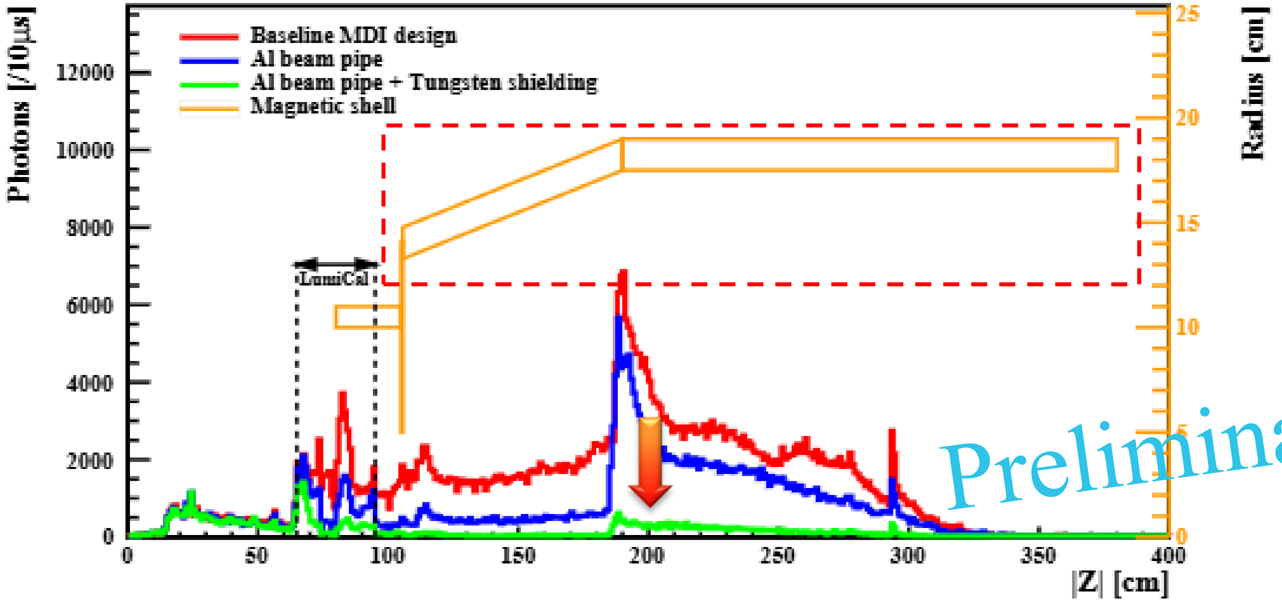
Momentum resolution with space charge effect

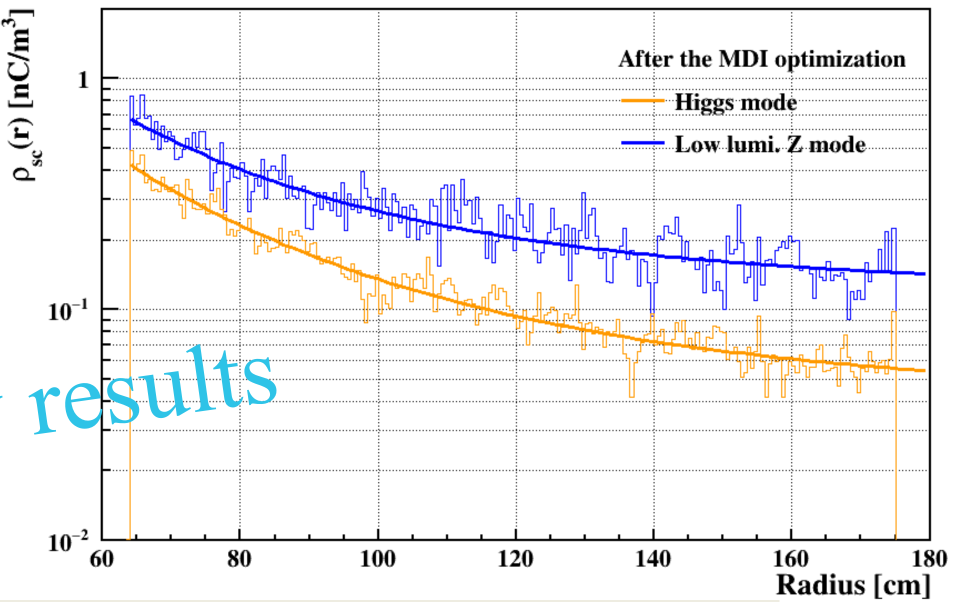
- Momentum resolution
  - Compared to idea scenario, resolution with the TPC standalone degrades seriously for high momentum particles
  - 11% degradation after combining the silicon trackers in low lumi. Z mode
  - Would not suffer too much from the electron drift deviations
- Further simulation with a complicated model is ongoing.



Space charge migration—— MDI region optimization

- The low-energy photons (<10 MeV) are the main contribution of space charge in the TPC
- Some preliminary optimization can reduce the space charge by approximately one orders of magnitude.
  - The layout of some equipment of the MDI region
  - Lighter beam pipe material
  - Shielding of the magnetic shell
- The max. space charge density can be less than 0.8 nC/m^3 after optimization.





Distributions of the initial |z| positions entering the TPC and space charge density after optimization

Summary

Summary

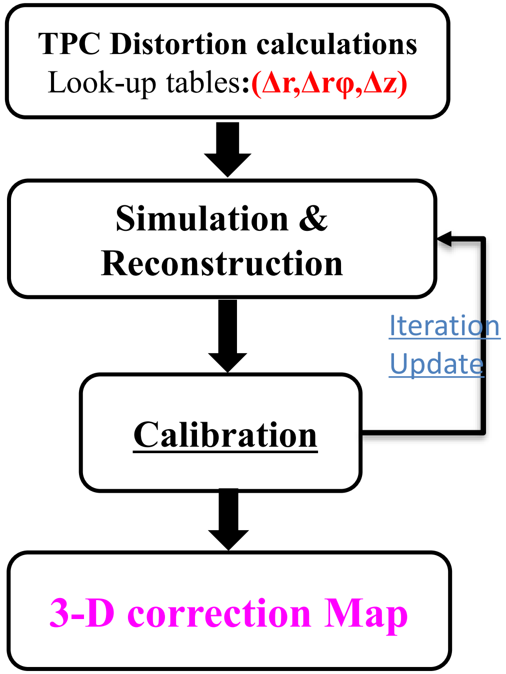
- The TPC has been **selected** as the baseline main track (MTK) detector in CEPC ref-TDR.
- The full simulation flow of the BG has been established
  - The BG and tracking performance has been studied
    - $\sigma(1/P_T) \sim 10^{-4}\ (GeV/c)^{-1}$, standalone momentum resolution w.o. SCE
    - Tracking performance would not suffer too much from the deviations by combining inner and outer silicon detectors
  - Further optimization of the MDI region and dedicated correction algorithm are needed.

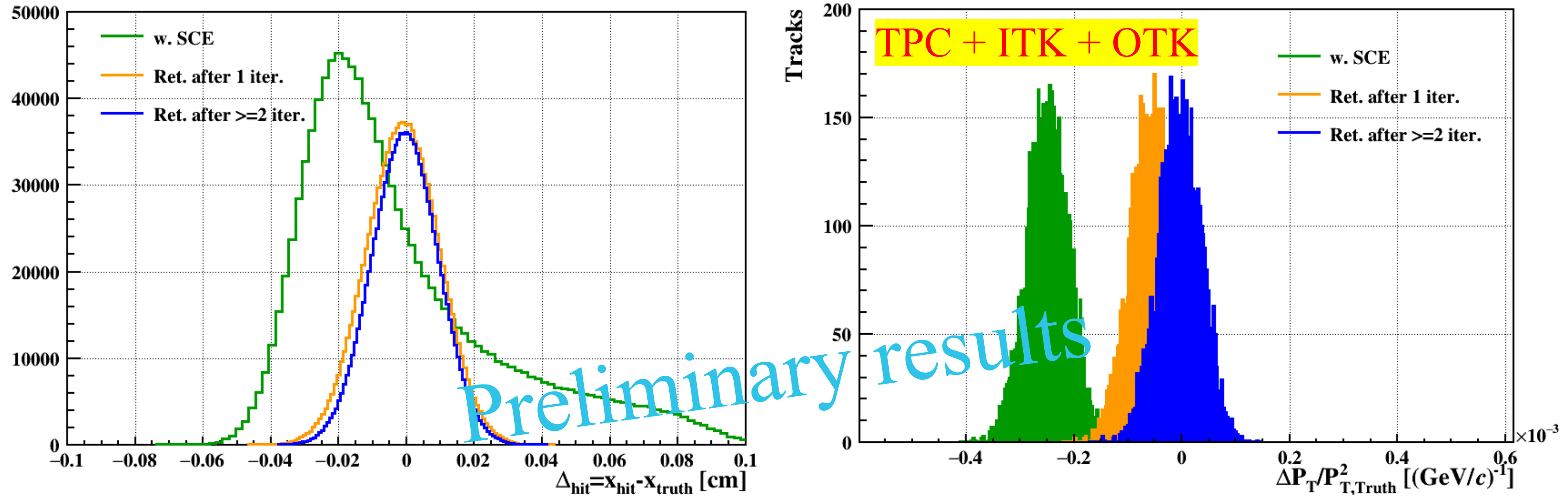
Many thanks!

- **Back-up**

Space charge correction

- The inner and outer silicon detectors (ITK+OTK) can provide a precision reference track
- Assuming the space charge caused by BG is stable:
  - These deviations should be correctable
  - After ≥2 iterations, significant improvements in both the residual distribution of the TPC hits and that of momentum residuals

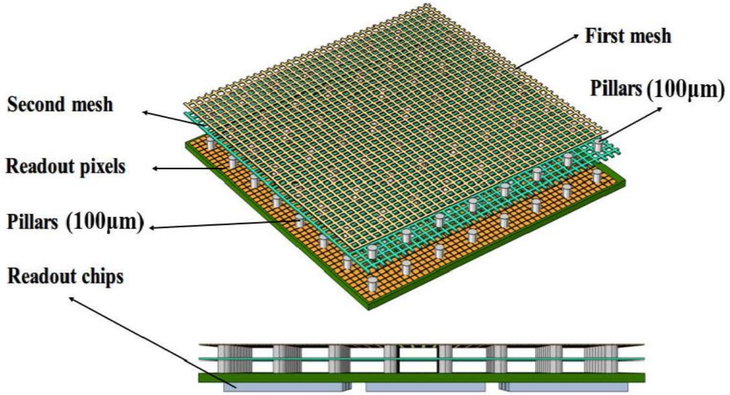


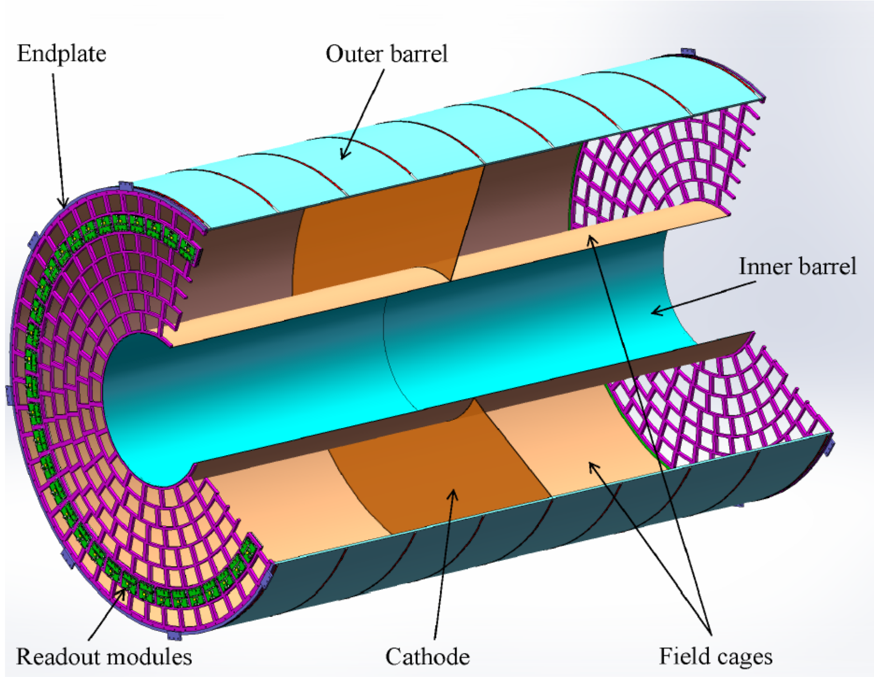


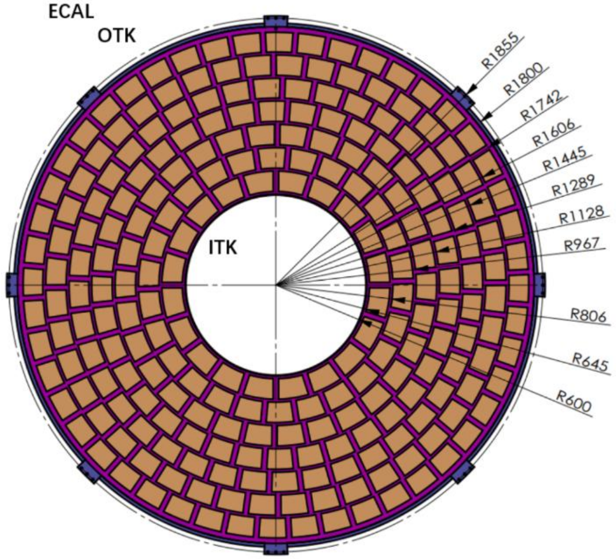
Residual of the TPC hits and momenta distributions

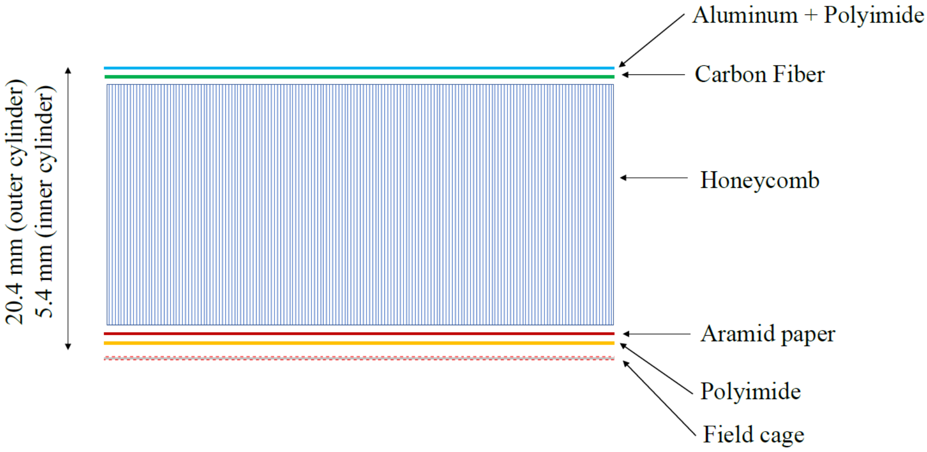
Baseline design of the TPC

- Overall design of the TPC in CEPC Ref-TDR
  - TPC inner radius=0.6m, outer radius=1.8m, max. drift length~2.75m (52.48m^3)
  - End-plate: 248×2 Modules, Double-Micomegas + 500μm×500μm readout pad size
  - Light barrel: 0.69% X_0 for the outer cylinder and 0.45% X_0 for the inner cylinder wall



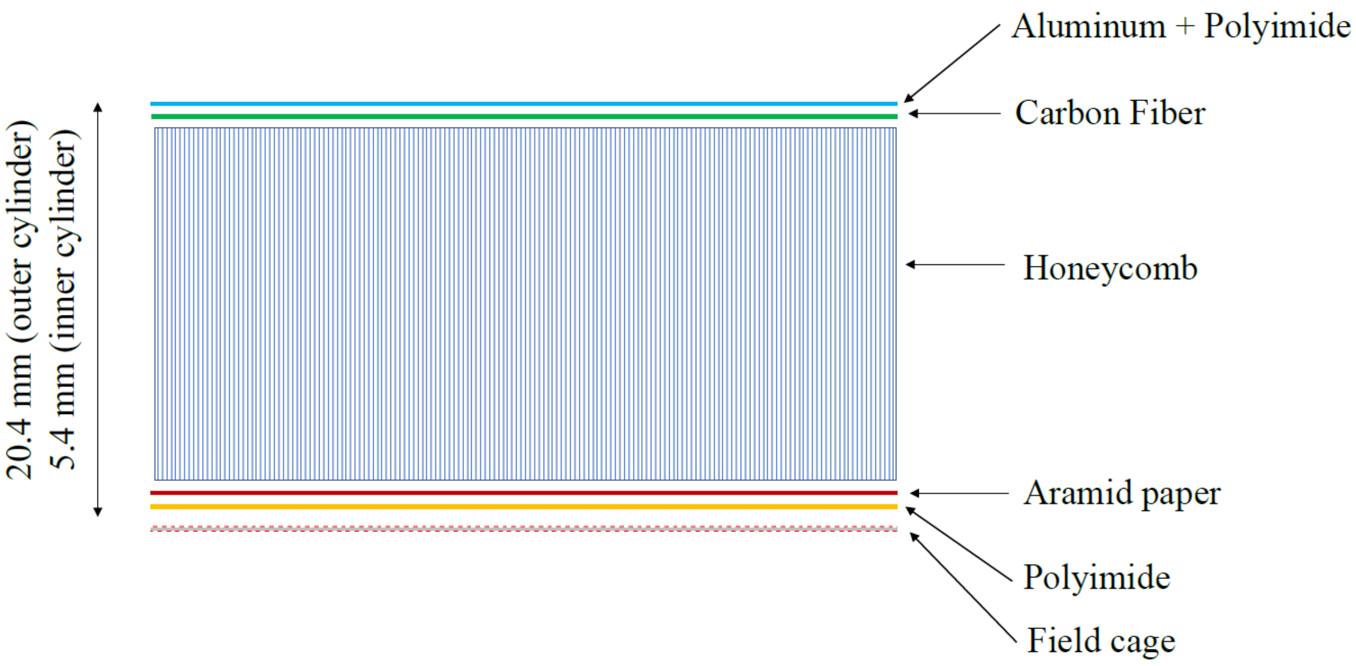






Baseline design of the TPC detector in Ref-TDR

- To reduce mechanical deformation, improve insulation performance, and minimize the material budget
  - Sandwich structure
  - Outer cylinder thickness: 20.4mm, Material budget: 0.69% X_0
  - Inner cylinder thickness: 5.4mm, Material budget: 0.45% X_0
  - Sufficient insulation can withstand a voltage of 62kV



Component	Layers	X [cm]	X_0 [cm]	X/X_0 [%]
		TPC outer wall		
Faraday cage shield	Aluminum	0.005	8.9	0.06
Faraday cage shield substrate	Polyimide	0.005	28.6	0.02
Outer wall support cylinder	Carbon fiber	0.02	25.28	0.08
Outer wall support cylinder	Nomex honeycomb	1.96	800	0.25
Outer wall support cylinder	Aramid paper	0.01	35	0.03
Insulating layer	Polyimide	0.01	28.6	0.03
Mirror strips layer	Copper	0.0012×0.95	1.44	0.08
Field cage substrate	Polyimide	0.005	28.6	0.02
Field strips layer	Copper	0.0012×0.95	1.44	0.08
Glue	Epoxy	0.02	35.3	0.06
		TPC inner wall		
Field strips layer	Copper layer	0.0012×0.95	1.44	0.08
Field cage substrate	Polyimide	0.005	28.6	0.02
Mirror strips layer	Copper	0.0012×0.95	1.44	0.08
Insulating layer	Polyimide	0.01	28.6	0.03
Inner wall support cylinder	Aramid paper	0.01	35	0.03
Inner wall support cylinder	Nomex honeycomb	0.46	800	0.06
Inner wall support cylinder	Carbon fiber	0.020	25.28	0.08
Faraday cage shield substrate	Polyimide	0.005	28.6	0.02
Faraday cage shield	Aluminum	0.005	8.9	0.06
Glue	Epoxy	0.02	35.3	0.06