



高亮度正负电子对撞机中TPC径迹探测器研究进展

余信, 祁辉荣, 常悦, 王建春, 张锦闲, 张建, 毛涵钰
邓智, 李刚, 纪全, 石澔琦, 赵明锐, 阮曼奇, 许威
以及LCTPC国际合作组贡献

中国科学院大学, 中国科学院高能物理研究所
核探测与核电子学国家重点实验室, 南开大学物理科学学院, 清华大学

NED&CAGD2024 中国, 青岛
July 17, 2024

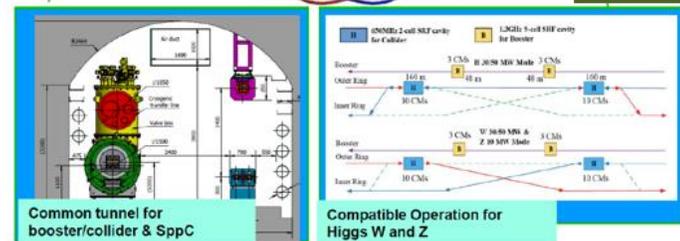
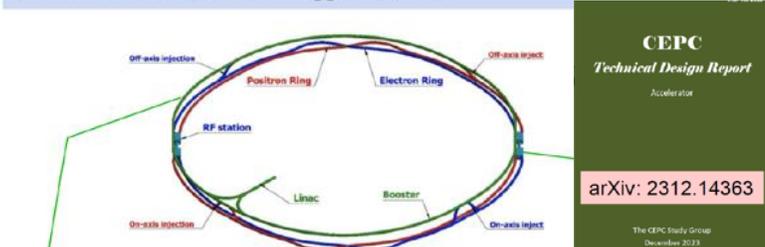
报告内容

- 环形正负电子对撞机物理需求
- 面向高对撞亮度的时间投影室技术
- 高颗粒度读出TPC研究进展
- 小结

环形正负电子对撞机物理需求

- 环形正负电子对撞机作为高亮度的Higgs,W/Z top工厂，特别对于Z-pole运行在 $10^{36}\text{cm}^{-2}\text{s}^{-1}$ 亮度
 - Higgs玻色子质量分辨测量要求：~3%
 - 加速器技术设计报告(TDR)于2023年12月，已经发布，CEPC运行：10年Higgs→2年Z-pole→1年W
 - 物理和探测器技术设计报告(Phys.&Det. TDR)将于2025年发布, 硅+气体探测器作为径迹探测(Tracker)以及提供粒子鉴别(PID)

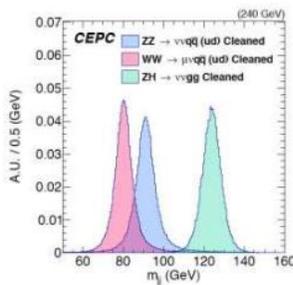
- **Circular collider:** Higher luminosity than a linear collider
- **100km circumference:** Optimum total cost, good also for SppC
- **Shared tunnel:** Accommodate CEPC booster & collider and SppC
- **Switchable operation:** Higgs, W/Z, top



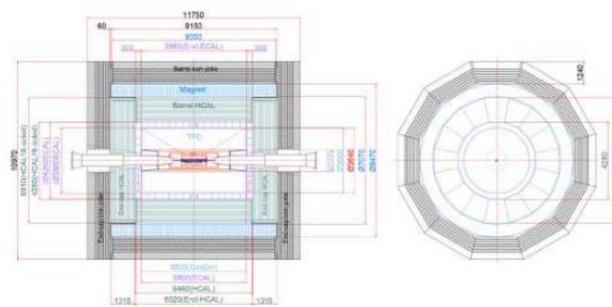
CEPC Detector TDRrd (rd=reference design) will be released in June, 2025

Requirements
boson mass resolution (BMR ~3%)

Challenges
➢ Support Particle flow with
➢ High granularity
➢ High precision



Novel detector design based on PFA calorimeter to improve the BMR from 4% to 3%



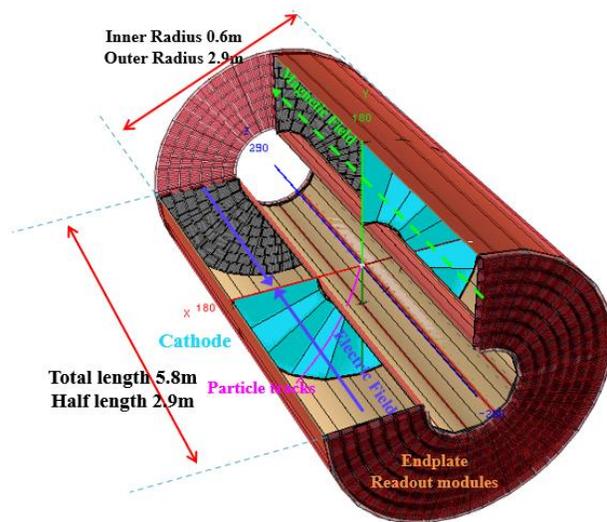
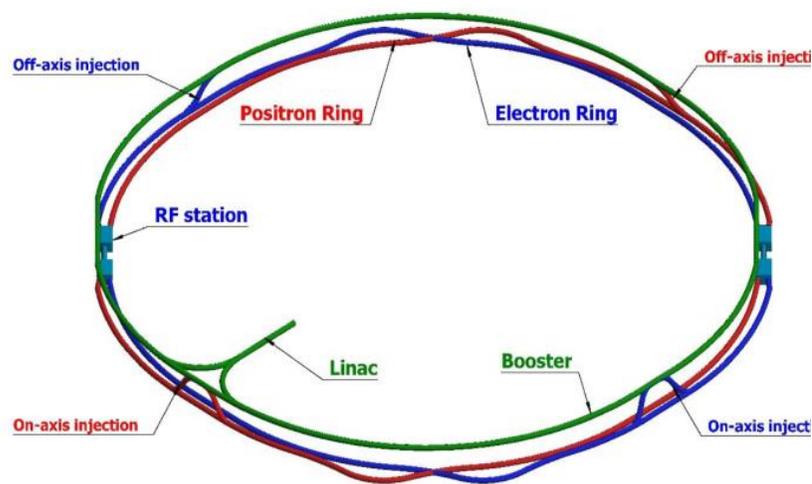
Detector	Key parameter	World level	4 th concept
PFA based EM calorimeter	EM shower E resolution	~20%/√E	<3%/√E
PFA based Hadron calorimeter	Single hadron E resolution	~50%/√E	~40%/√E

- Silicon combined with gaseous chamber as the tracker and PID
- ECAL based on crystals with timing for 3D shower profile for PFA and EM energy
- Scintillation glass HCAL for better hadron sampling and energy resolution

气体时间投影室应用于环形正负电子对撞机

高颗粒度读出的时间投影室，是CEPC物理和探测器技术设计报告中**主径迹探测器的基准选型**

- 技术优势: 极低质量($\sim 0.1X_0$), 精确位置测量($\sim 100\mu\text{m}$), 动量分辨高, 优异模式识别能力(Pattern Recognition)
- 径迹探测: 带电粒子动量分辨 $\delta Pt/Pt \sim 0.1\%$
- 粒子鉴别: $dE/dx + dN/dx$ 分辨好于3%



Differential Efficiency.

Requirement: Pt threshold $\sim o(100)$ MeV, $|\cos(\theta)| < 0.99$

Ref: CDR baseline design

Differential Material Budget.

Requirement: $< 10\%/50\% X_0$ in Barrel/endcap

Ref: CDR baseline design + BMR & Material Dependence

Differential Resolution of 5 track parameters.

Requirement: In the barrel

$\delta(D_0/Z_0) \sim < 3$ micro meter at 20 GeV

$\delta(Pt)/Pt \sim o(0.1\%)$

Ref: CDR baseline performance

Differential Pid Capability: eff*purity of Kaon id @ Z pole.

Requirement: eff*purity $> 90\%$ for all charged Kaon (@ Z pole)

\sim relative resolution of dE/dx (or dN/dx) be better than 3%

ToF of 50 ps

Ref: Nuclear Inst. and Methods in Physics Research, A 1047 (2023) 167835

Sep. power: On 3 prong tau decay @ Z pole.

Requirement: efficiency $> 99\%$ at 3-prong tau

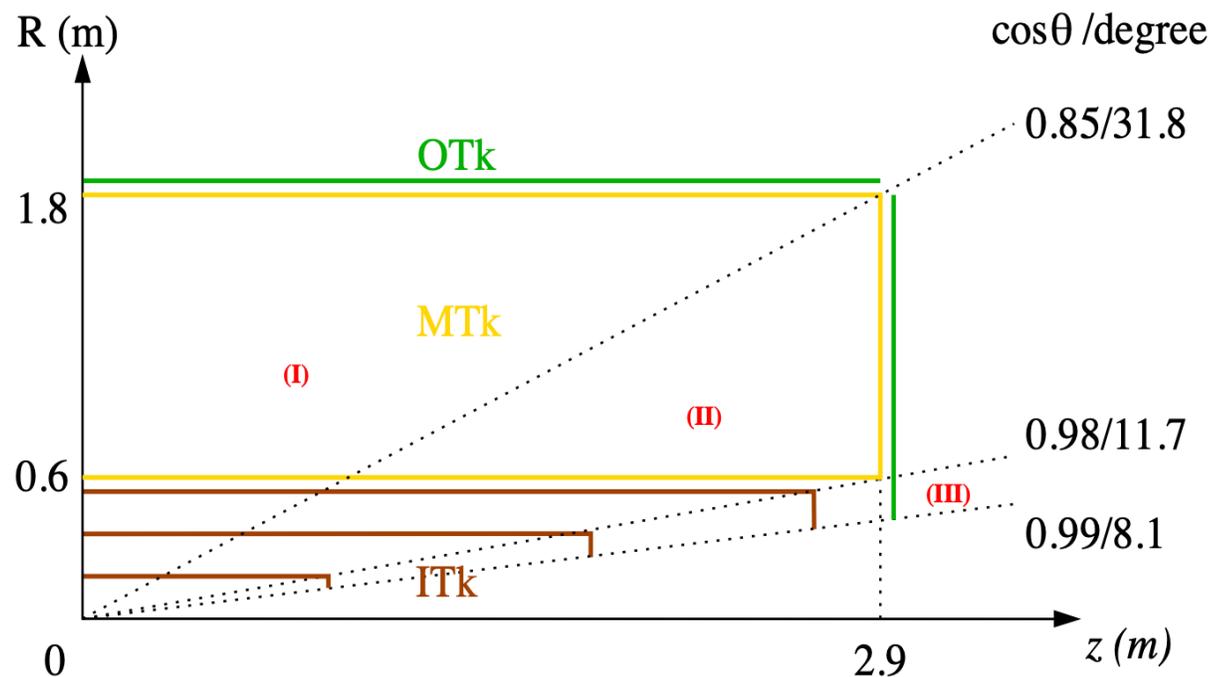
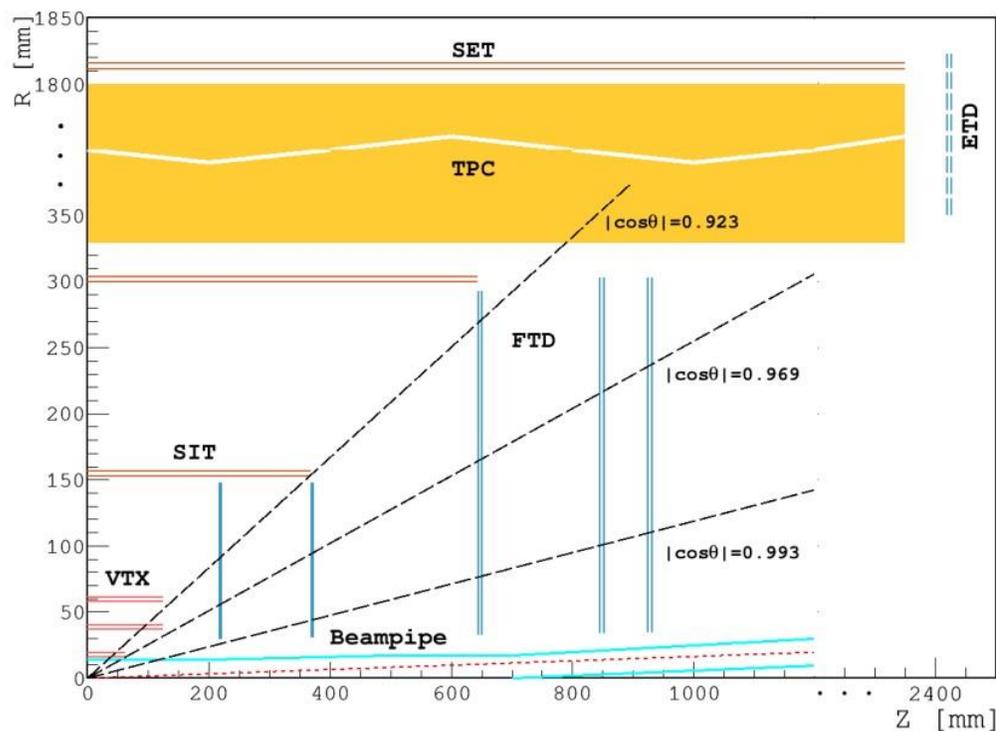
Ref: CDR baseline performance

Circular Electron Positron Collider (CEPC) & CEPC TPC geometry in CEPC software

CEPC TDR中TPC几何参数

CEPC探测器概念设计报告(CDR)与技术设计报告(TDR)中TPC几何参数对比

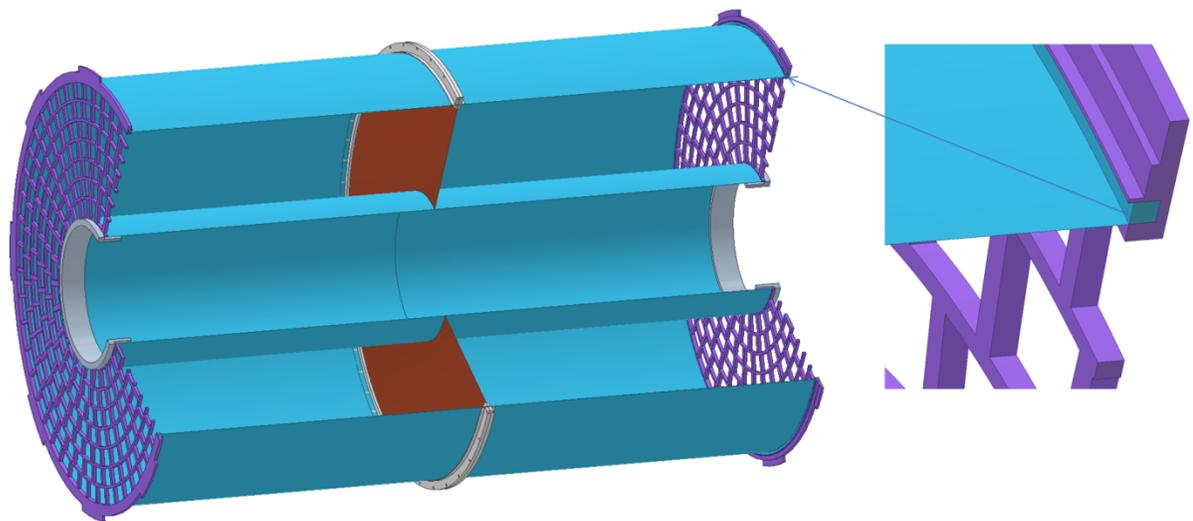
- 内径:0.30m (CDR) → **0.60m (TDR)**
- 外径:1.80m (CDR) → 1.80m (TDR)
- 最大漂移距离:2.35m (CDR) → **2.90m (TDR)**, $\cos\theta\sim 0.98$



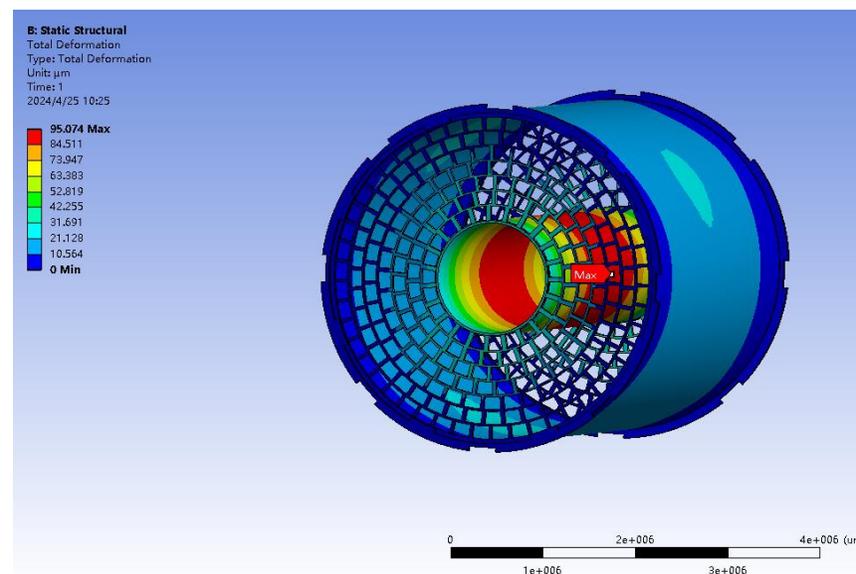
CEPC TPC layout in CDR(left) & CEPC TPC layout in TDR(right)

高颗粒度读出时间投影室技术（高对撞亮度）

- 径迹探测器系统边界已经确定，采用高颗粒度读出TPC可以更好满足CEPC在不同运行模式下的物理需求
 - 相比于pad(1mm×6mm)读出，高颗粒度读出(500μm×500μm)可以适应更高的计数率环境(MHz/cm²)，更好的动量分辨，提供粒子鉴别(In Space)
- 面向CEPC在高亮度Z-pole的运行环境，TPC运行的关键技术问题
 - 高对撞亮度 (10³⁶cm⁻² s⁻¹) 下TPC读出像素单元的击中率 (Hit Density) ， 占空比 (Occupancy)
 - TPC中空间电荷效应 (Space charge effect) ， 空间畸变(distortion)



碳纤维板



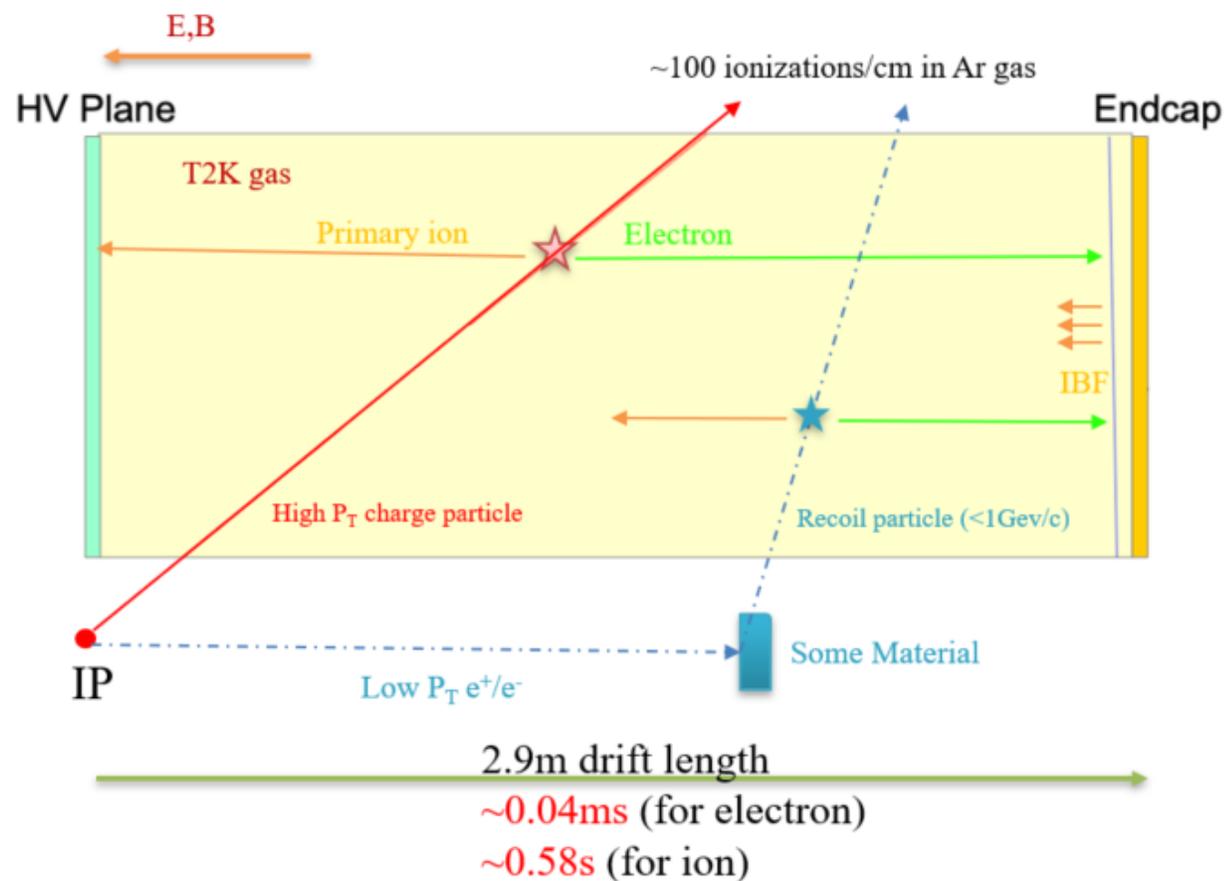
高亮度环境下TPC中事例来源分析

■ 高对撞亮度下TPC中的hit以及空间电荷来源:

- 物理事例($Z \rightarrow qq$)直接产生
- 束流本底效应间接产生
 - Beamstrahlung
 - Beam-Gas等
- 读出MPGD的正离子反馈

■ 对于Z-pole模式~40MHz对撞频率(23ns时间间隔):

- 每次对撞, **Beamstrahlung**过程将产生~650 e^+/e^- pairs
- 束流本底效应是TPC灵敏体积内击中hit density, 空间电荷产生的主要来源
- 研究高粒度读出TPC读出像素Hit density和空间畸变

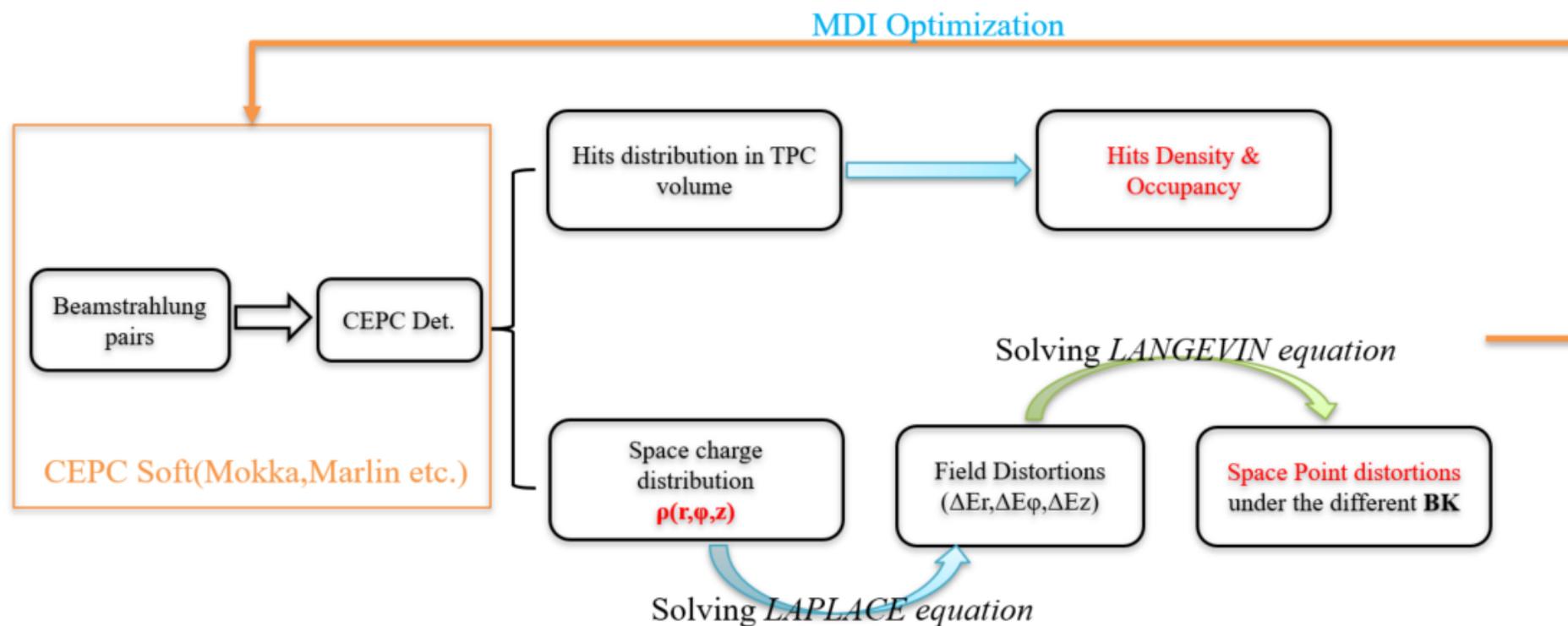


高亮度环境下TPC不同事例来源

研究方案及科学目标

研究技术方案及目标:

- 基于CEPC Software实现对Z-pole模式下, 本底效应全模拟, 给出**新几何尺寸下**TPC读出像素的**Hits Density & Occupancy**
- 计算本底效应在TPC灵敏体积中产生空间电荷效应分布, 给出不同本底水平下TPC空间畸变**Space Point distortion**
- 为CEPC机械探测器接口(MDI)的优化, 提供重要参考

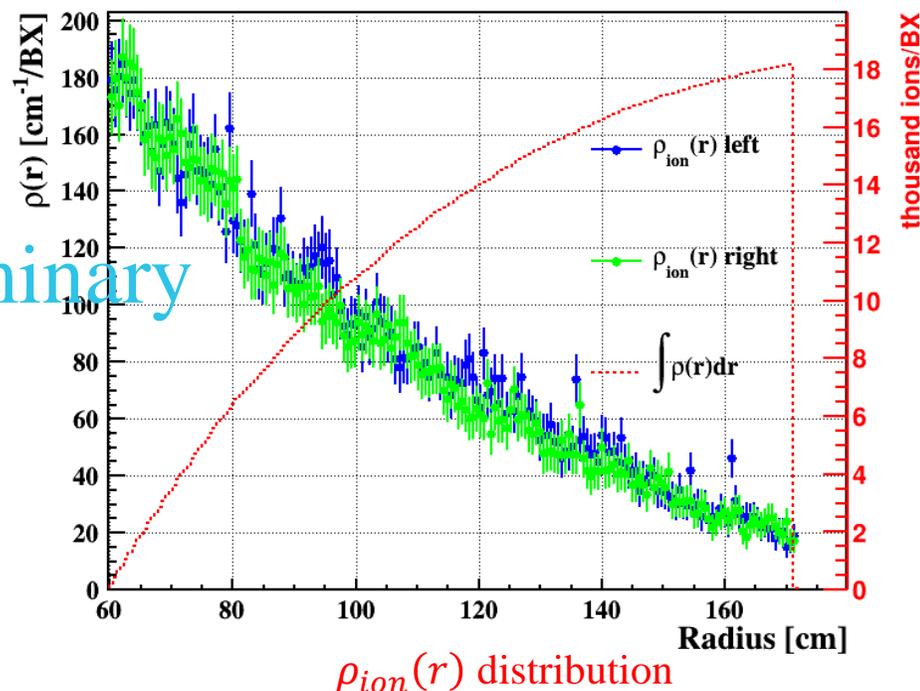
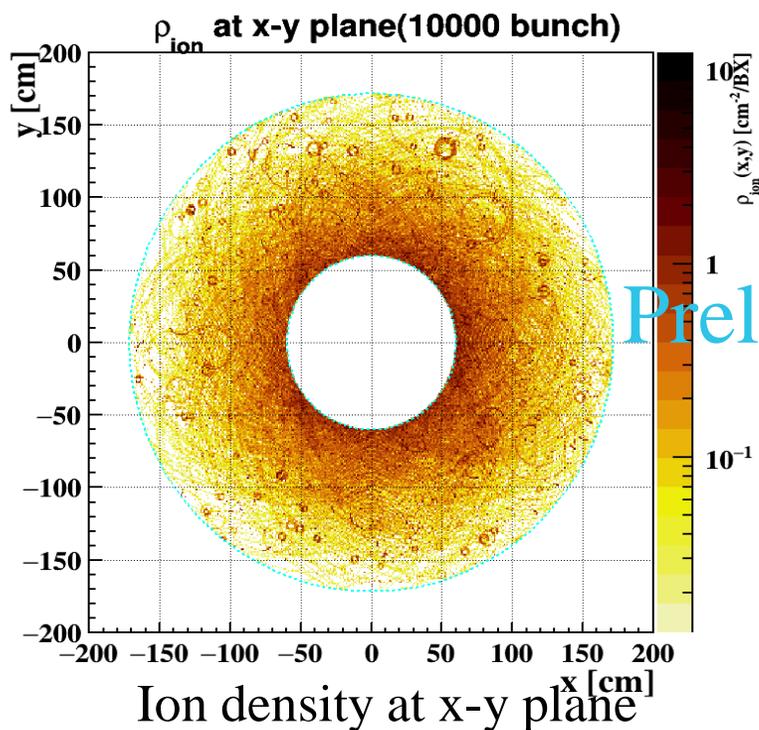


Simulation flow of CEPC Beam Backgrounds

■ 高对撞亮度TPC击中率和像素单元占空比研究进展

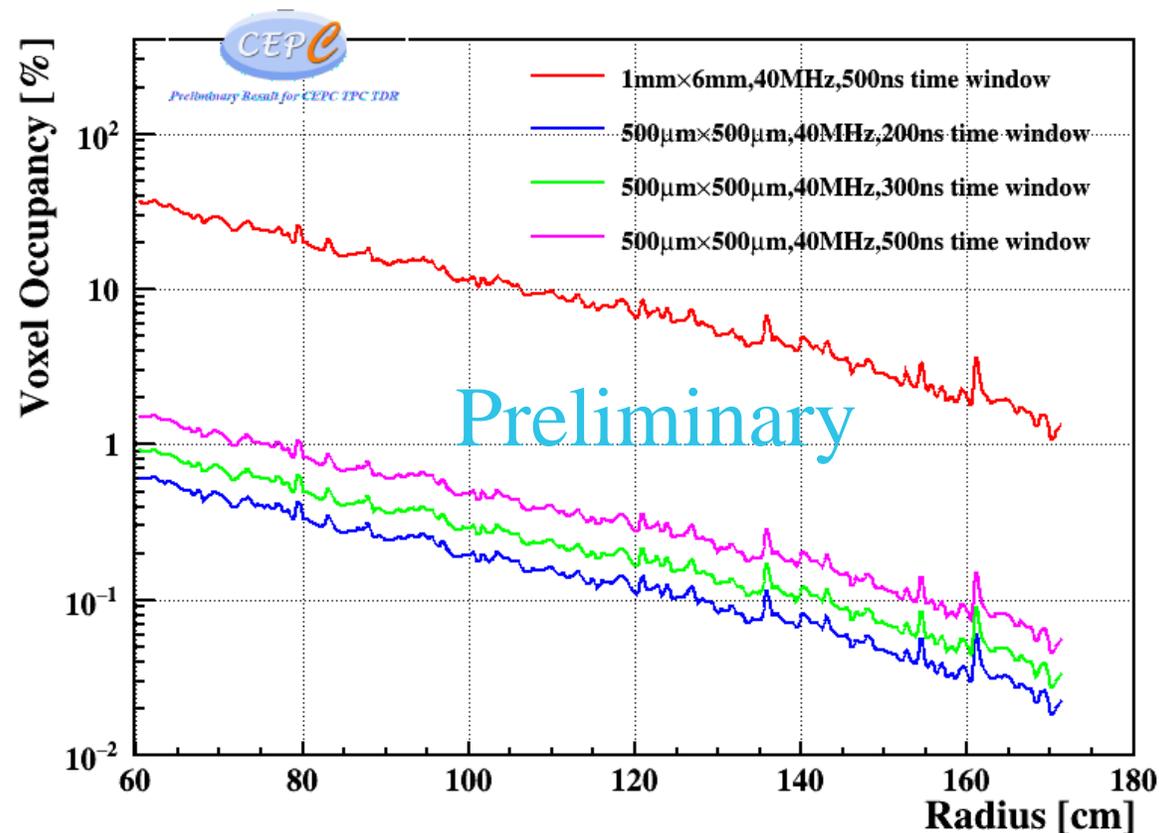
高对撞亮度TPC研究进展1——Hit Density by Beamstrahlung

- 基于CEPC Software完成了束流本底效应导致原初电离的Hit density分布模拟研究
- Z-pole (2T) 运行模式下TPC灵敏体积内原初电子-离子对数(electrons/ions)分布:
 - 总原初电子-离子对数: Edep/effective ionization potential of Ar [26eV] $\sim 18.20\text{k ions/BX}$ (左右两个Chamber)
 - 最内层(半径60cm), $\sim 180\text{ ions/electrons/cm/BX}$, hits density $\sim 0.48\text{ hits/cm}^2/\text{BX}$ BX freq. $\sim 1/23\text{ns}$
 - 对于高粒度读出TPC $500\mu\text{m} \times 500\mu\text{m}$ 的读出像素, 最内层击中率 $\sim 31.5\text{k hits/sec}$ (60% coverage)



高对撞亮度读出TPC研究进展2——占空比 by Beamstrahlung

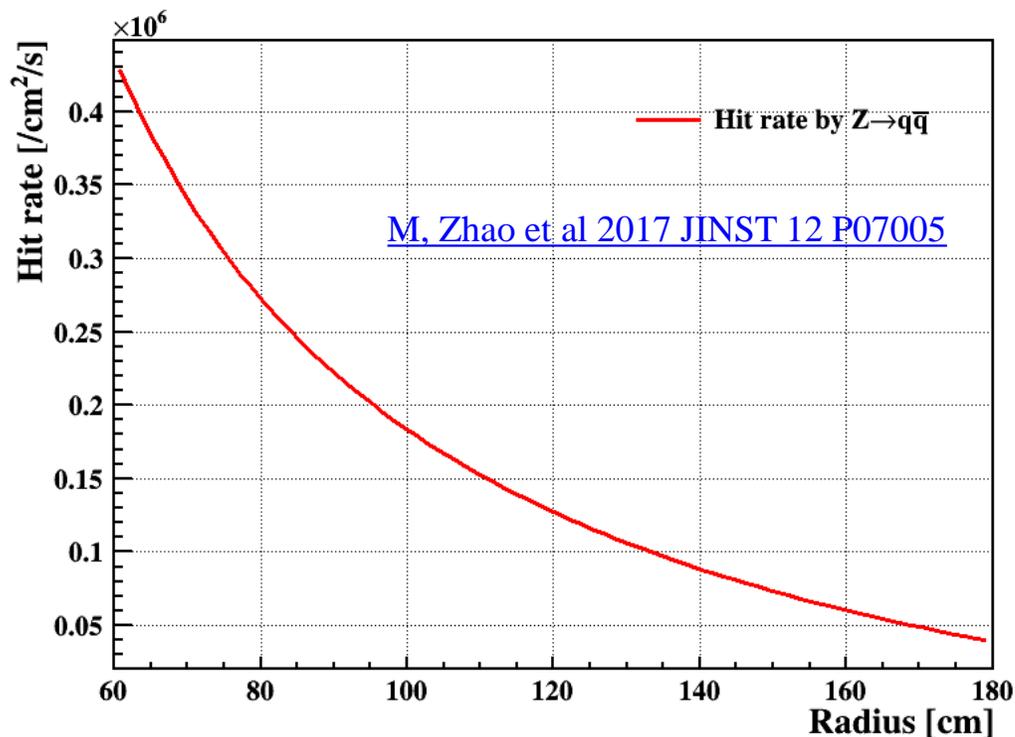
- 本底效应导致的TPC读出像素单元的占空比
 - 对于单个 $500\mu\text{m}\times 500\mu\text{m}$ 读出像素, 40MHz采样率, 单位时间总的Voxel数为 $4\times 10^7/\text{s}$
 - z向Voxel大小为 $V_d\times 25\text{ns}\sim 2\text{mm}$, 单个Voxel大小 $\sim 0.5\times 0.5\times 2=0.5\text{mm}^3$
 - 对于200ns时间窗, z向平均占用8个voxel
 - 最内层Voxel Occupancy= $8\times 31.5\text{k}/4\times 10^7\sim 0.63\%$
 - 对于 $1\text{mm}\times 6\text{mm}$ Pad, 最内层Voxel Occupancy $\sim 35\%$
- 相比于传统大pad读出, 高粒度读出TPC占空比非常低, 更适合高计数率环境



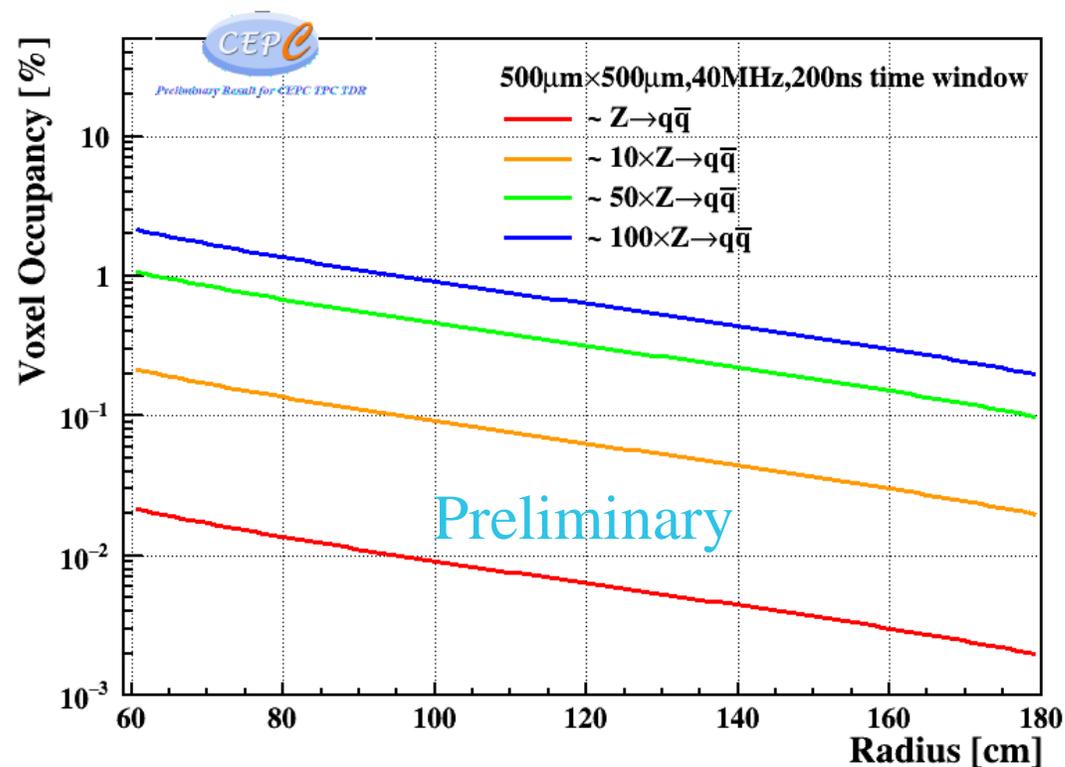
半径方向上TPC不同大小读出像素单元, 时间窗下Occupancy

高对撞亮度读出TPC研究进展3——不同本底水平下占空比

- 对于物理事例 $Z \rightarrow qq$, TPC最内层像素任意时刻Hit density $\sim 1.1\text{k hits/sec}$
- 考虑200ns时间窗, $500\mu\text{m} \times 500\mu\text{m}$ 读出像素, 40MHz采样率, 不同本底水平下($10\times, 50\times, 100\times Z \rightarrow qq$)沿半径方向占空比
 - 相同大小像素, 时间窗下, 本底效应的占空比与40倍的 $Z \rightarrow qq$ 的VO接近, 约 $\sim 1\%$
 - 现有MDI设计下, 采用像素型TPC占空比可以**满足探测与物理需求**



沿半径方向 $Z \rightarrow qq$ 导致的hit density分布

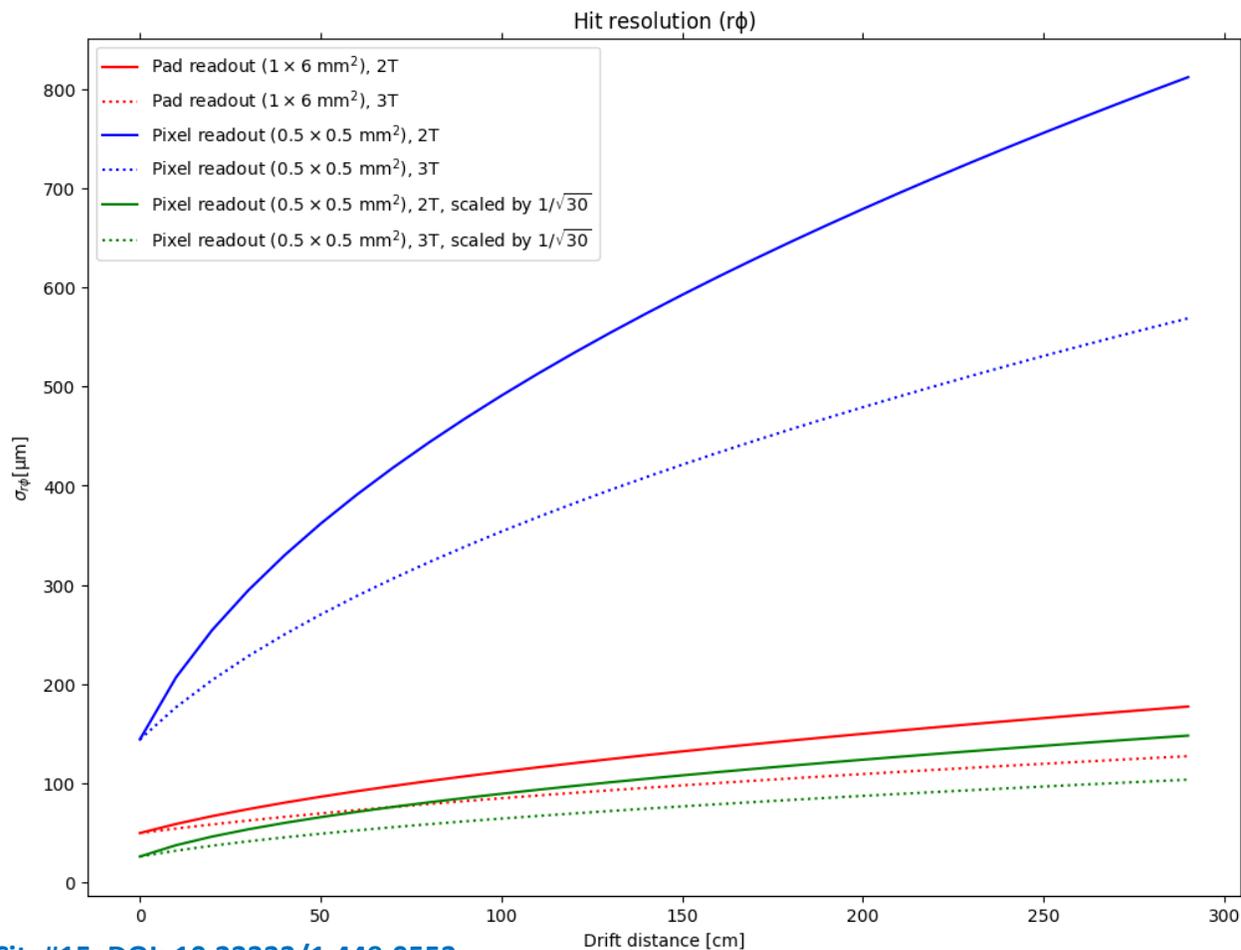
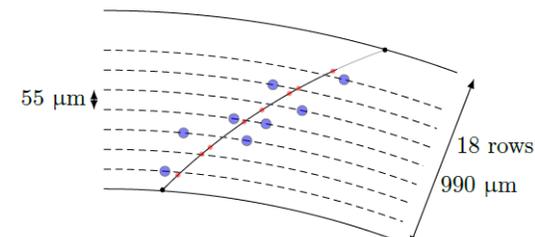
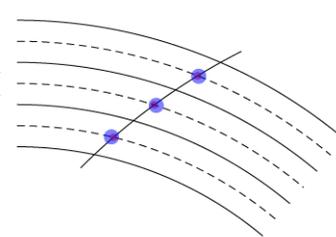


不同本底水平下TPC读出像素Occupancy

■ 高对撞亮度TPC空间电荷效应及畸变研究进展

像素型读出空间分辨率的研究

- 相比于传统大pad读出，高颗粒度像素型读出TPC可以取得更高精度的空间位置分辨，**满足Z-pole(2T)下径迹探测的物理需求**
- Z-pole模式下空间电荷效应，**径迹畸变影响需要仔细考虑**



Pad readout:

(a) Pads

(b) Pixels

$$\sigma_{r\phi}^{\text{pad}} = \sqrt{(\sigma_{r\phi 0}^{\text{pad}})^2 + \sigma_{\phi 0}^2 \sin^2(\phi_{\text{track}}) + L \frac{D_{r\phi}^2}{N_{\text{eff}}} \sin^2(\theta_{\text{track}}) \left(\frac{6 \text{ mm}}{h_{\text{pad}}} \right) \left(\frac{4.0 \text{ T}}{B} \right)^2}$$

- $\phi_{\text{track}} = 0^\circ, \theta_{\text{track}} = 90^\circ$
- $\sigma_{r\phi 0} = 50 \mu\text{m}$
- $N_{\text{eff}} = 22$
- $D_{r\phi} = 46.9 \mu\text{m}/\sqrt{\text{cm}}(2\text{T}), 32.3 \mu\text{m}/\sqrt{\text{cm}}(3\text{T})$

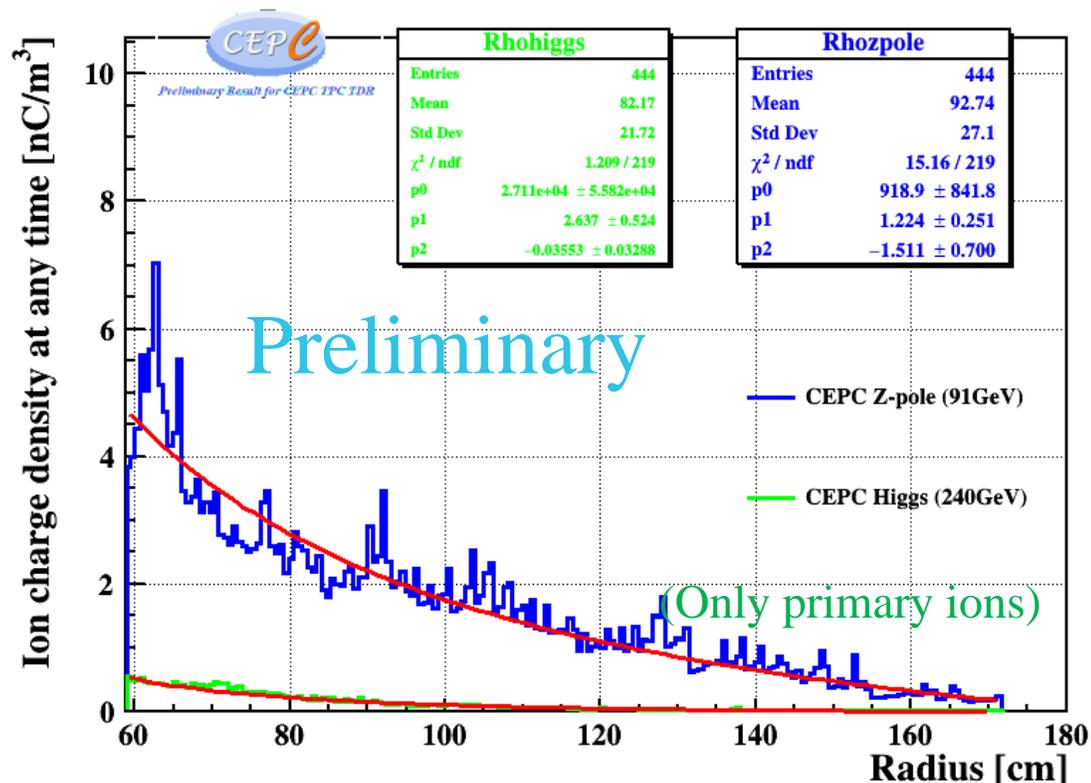
Pixel readout:

$$\sigma_r^{\text{pixel}} = \sigma_{r\phi}^{\text{pixel}} = \sqrt{(\sigma_{r\phi 0}^{\text{pixel}})^2 + L D_{r\phi}^2 \left(\frac{4.0 \text{ T}}{B} \right)^2}$$

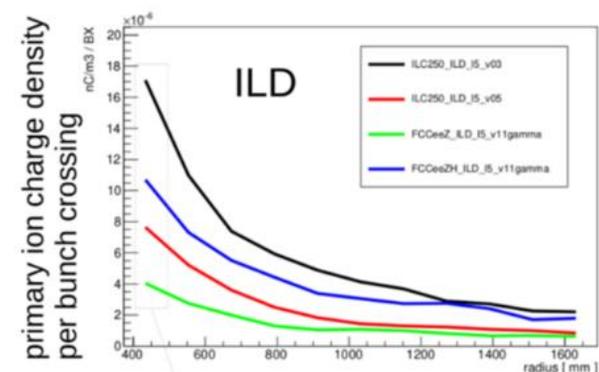
- $\sigma_{r\phi 0} = \frac{500}{\sqrt{12}} = 144 \mu\text{m}$
- $D_{r\phi} = 46.9 \mu\text{m}/\sqrt{\text{cm}}(2\text{T}), 32.3 \mu\text{m}/\sqrt{\text{cm}}(3\text{T})$

高对撞亮度TPC研究进展4——空间电荷密度模拟计算

- ◆ 完成Z-pole和Higgs运行模式下TPC中束流本底效应导致空间电荷密度计算
- ◆ CEPC在两种运行模式下TPC中最大空间电荷密度 ρ_{sc} 分别为 5.46nC/m^3 , 0.62nC/m^3
- ◆ 参考KEK *Daniel Jeans* FCCee模拟结果, CEPC TPC中空间电荷密度小~4-5倍



Beam background in a TPC at a circular collider



maximum steady state space-charge ~
 $\text{max space-charge/BX} * \text{BX freq} * \text{max drift time} * 50\%$

FCCee91
 FCC240
 ILC250 (v5)

max (single BX) BX freq
 4e-6 nC/m³ 30M
 1e-5 nC/m³ 800k
 8e-6 nC/m³ 6.6k

ALICE

50k

max (steady state)
 26 nC/m³
 2 nC/m³
 0.01 nC/m³
 120 nC/m³ with IBF=20

primary ions only: IBF=0

高对撞亮度TPC研究进展5——空间电荷效应解析计算

◆ 基于Green's function, 实现对TPC内任意空间电荷密度分布 ρ_{sc} , 电场畸变和空间畸变快速数值求解

➤ 任意空间电荷分布激发的电势:

$$\Phi(r, \varphi, z) = \frac{1}{\epsilon_0} \int r' dr' \int d\varphi' \int dz' \rho_{sc}(r', \varphi', z') \cdot \overset{\text{Green's function}}{G(r, \varphi, z; r', \varphi', z')}$$

➤ E_r 畸变电场解析式(represented through I,K modified Bessel functions):

$$E_r(r, z) = \frac{2}{\epsilon_0 L} \sum_{n=1}^{\infty} \frac{\sin \beta_n z}{R_0^0(\beta_n, a, b)} \int_0^L \sin(\beta_n z') dz' [(K_0(\beta_n a) I_1(\beta_n r) + I_0(\beta_n a) K_1(\beta_n r)) \int_r^b r' R_0^0(\beta_n, b, r') \rho_{sc}(r') dr' + (K_0(\beta_n b) I_1(\beta_n r) + I_0(\beta_n b) K_1(\beta_n r)) \int_a^r r' R_0^0(\beta_n, a, r') \rho_{sc}(r') dr']$$

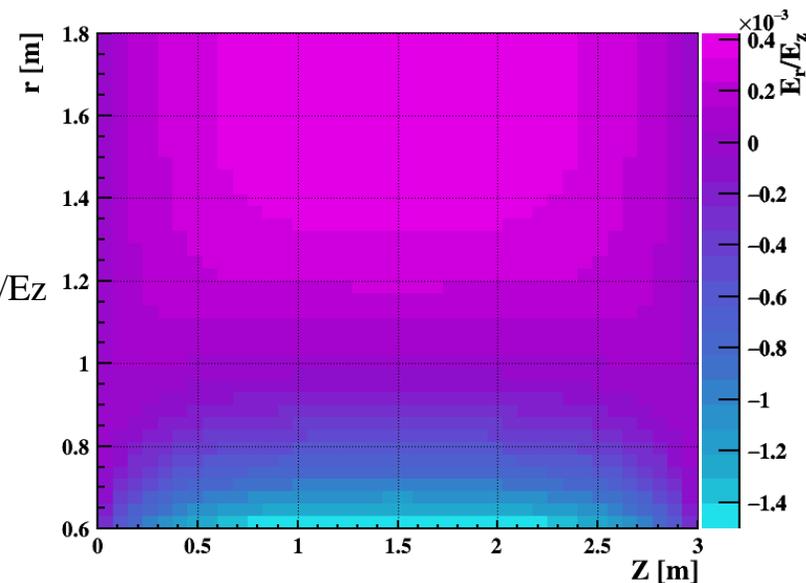
实际数值计算 $n > 200$, $\beta_n = n\pi/L$

➤ 空间畸变Distortion:

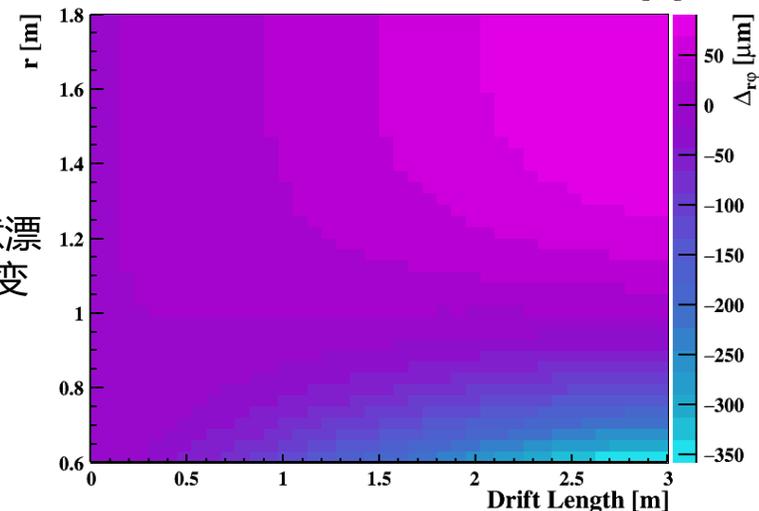
LANGEVIN equation: $m_e \frac{d\vec{v}}{dt} = e \cdot \vec{E} + e \cdot (\vec{v} \times \vec{B} - k \cdot \vec{v})$

$$\Delta_{r\varphi} = \int_{z_1}^{z_2} \frac{\omega \tau}{1 + \omega^2 \tau^2} \times \frac{E_r}{E_z} dz$$

I: TPC全空间内 E_r/E_z distribution

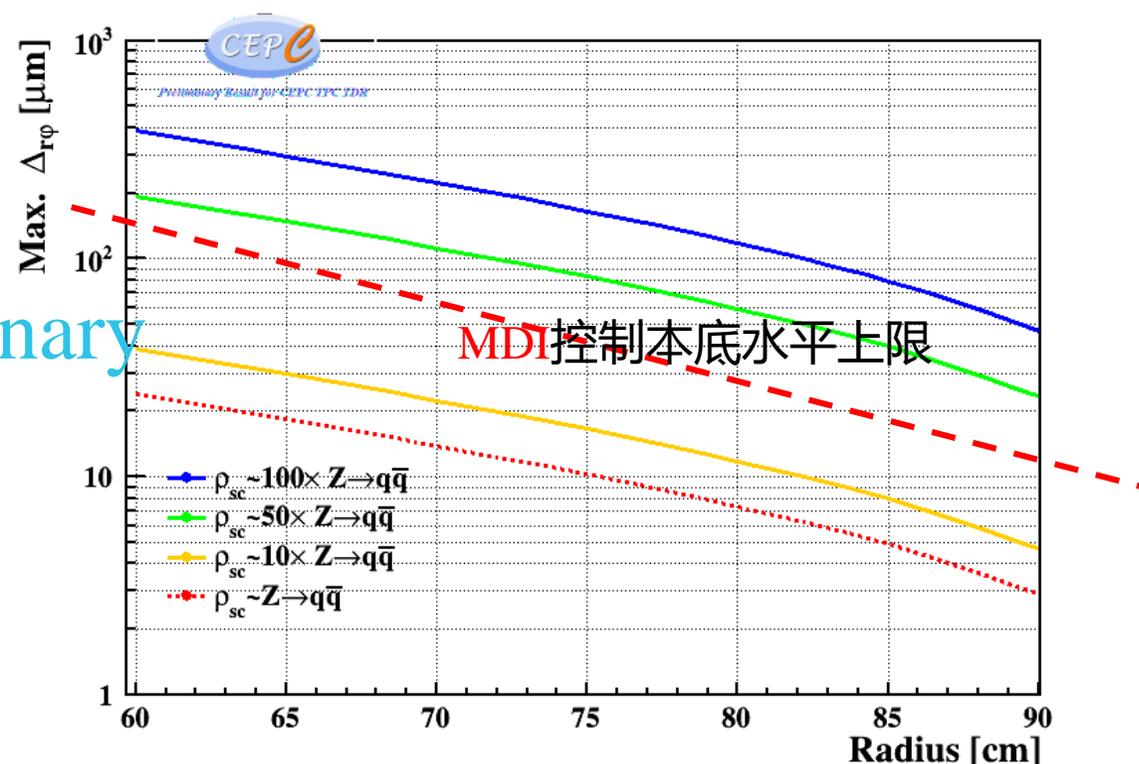
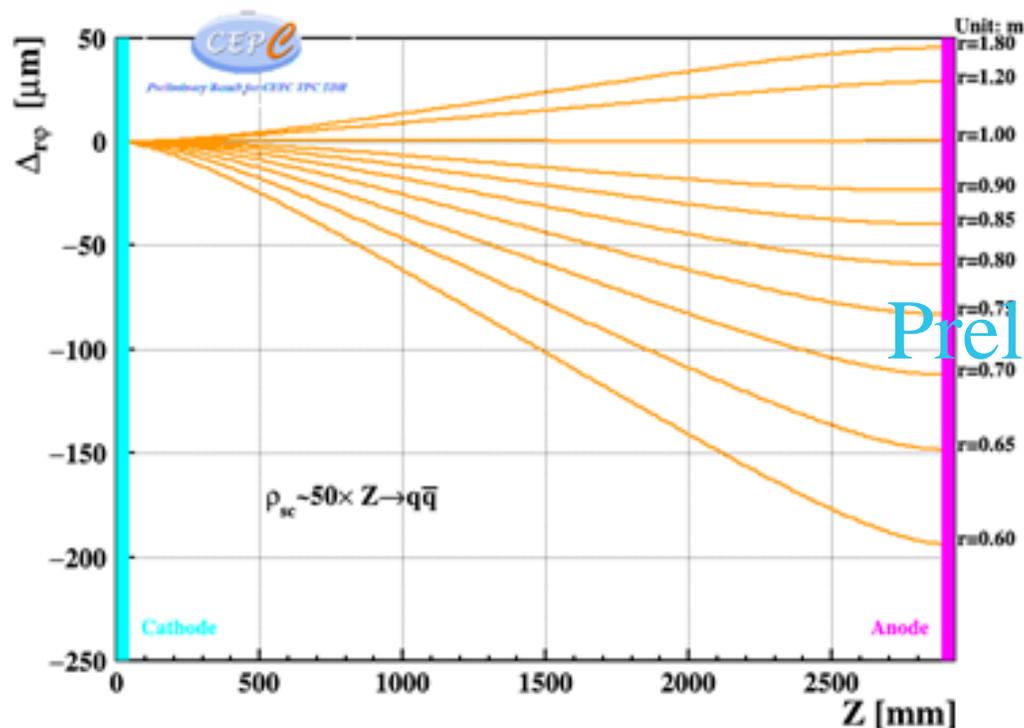


II: 任意半径, 任意漂移距离下空间点畸变



高对撞亮度TPC研究进展6——不同本底水平下TPC空间畸变

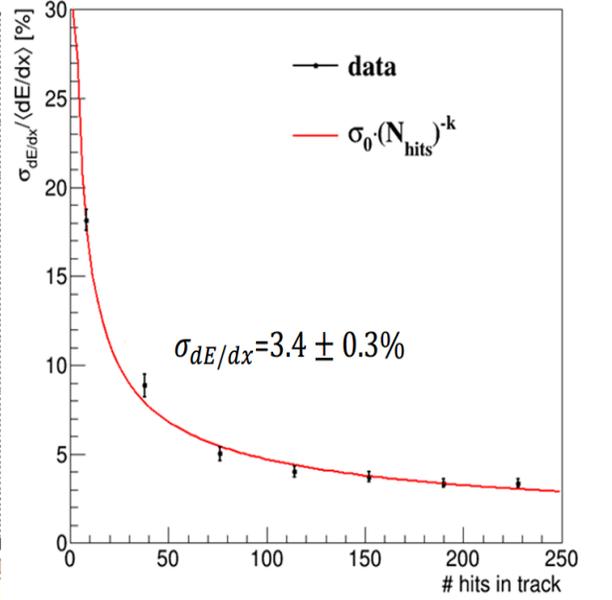
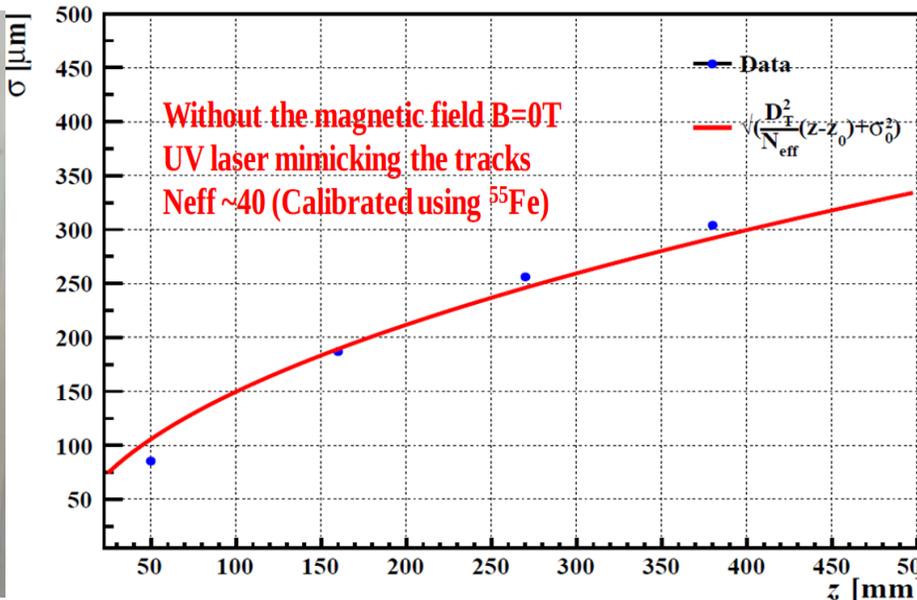
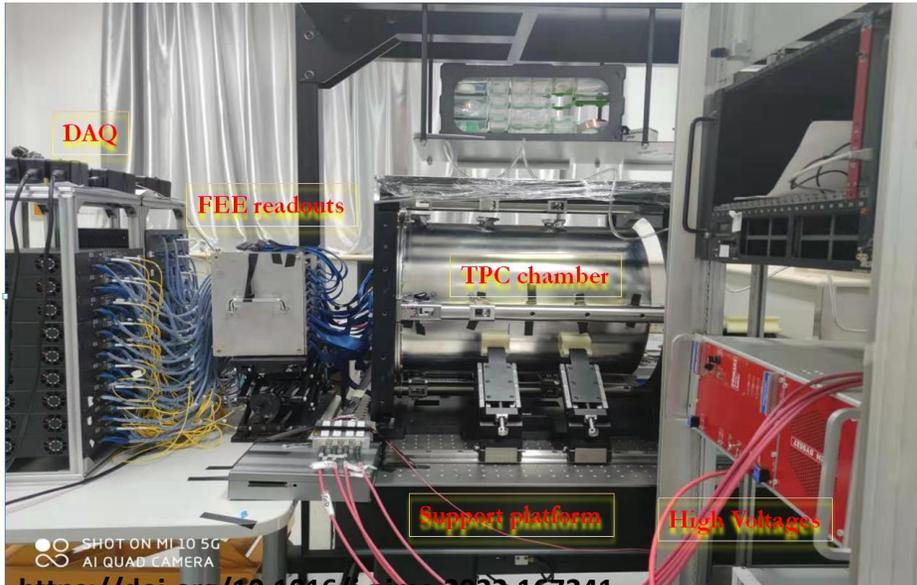
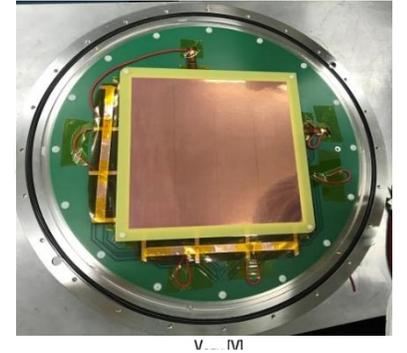
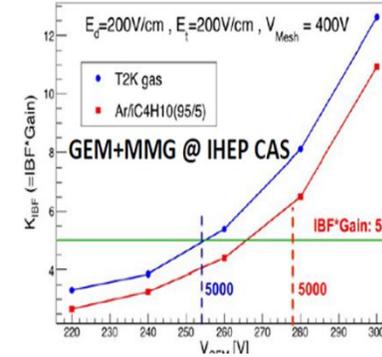
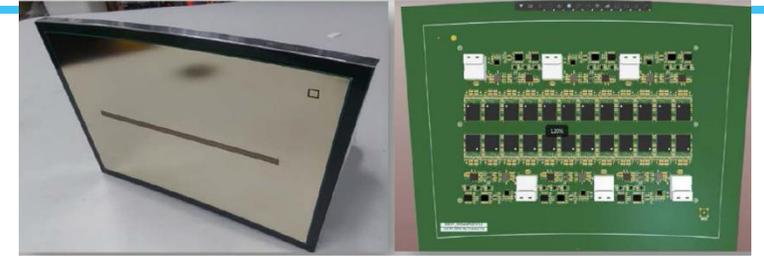
- 完成不同本底水平下($\times 10, \times 50, \times 100 Z \rightarrow qq$)TPC空间畸变解析计算
 - 空间电荷密度 $\rho_{sc} \sim 50 \times Z \rightarrow qq$, 漂移距离2.9m下, TPC空间点 $r\phi$ 方向最大畸变 $\sim 200 \mu\text{m}$
 - 目前MDI设计满足CEPC TDR径迹探测的物理的需求, 同时给出了MDI要控制的本底水平参考数据



不同半径, 位置 $r\phi$ 方向畸变 (左), 不同本底水平下最大畸变 (右)

面向高亮度对撞物理需求已开展的TPC研究进展

- GEM+MM混合读出模块研究完成, $IBF \times \text{Gain} \sim 1$ @Gain=2000
- 集成紫外激光TPC原型研制完成, $\sigma_{r\phi} < 100 \mu\text{m}$, $dE/dx \sim 3.4 \pm 0.3\%$ (220层)
- 像素型读出TPC原型机研制正在进行, 已完成探测器模块和读出电路设计([常悦报告](#))
- 低功耗读出ASIC芯片TEPIX研制完成 (清华大学合作)

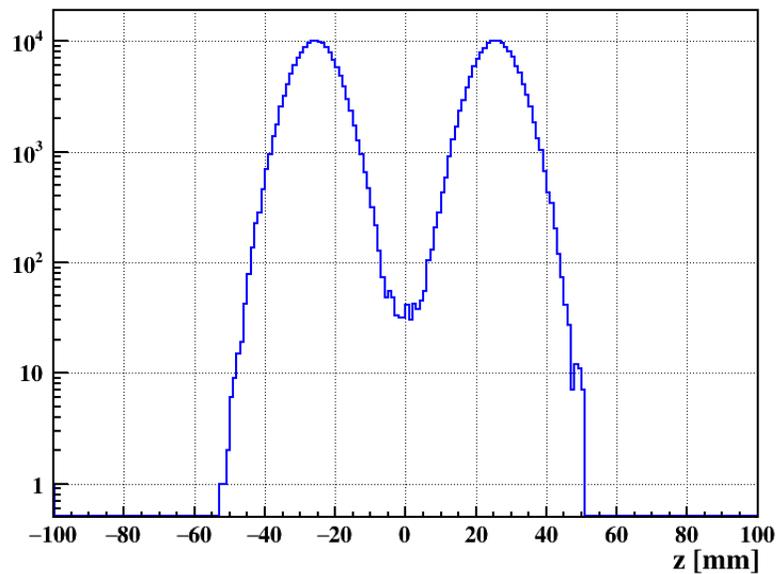
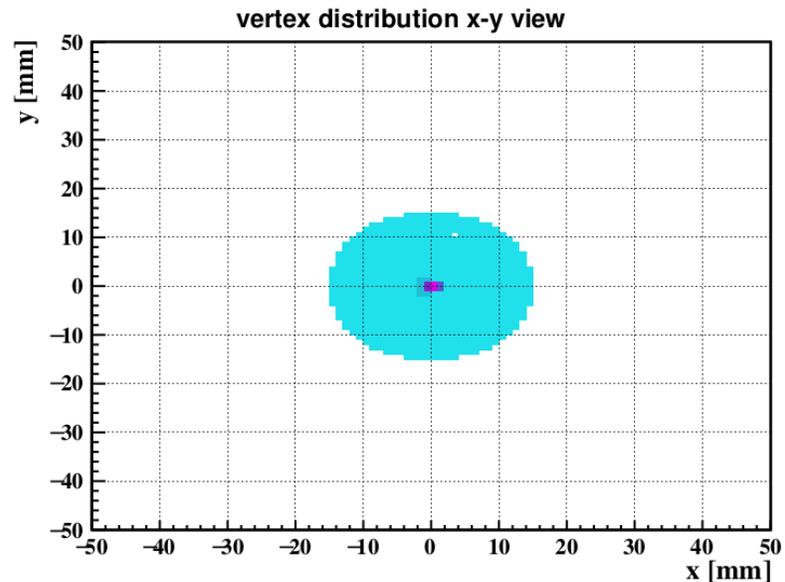
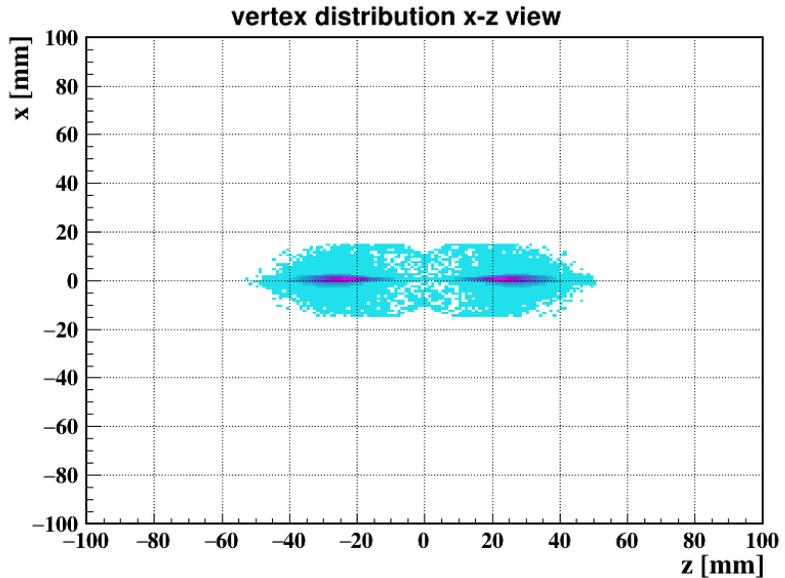
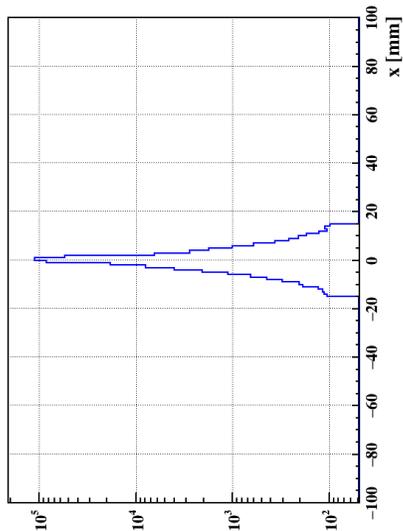


小结

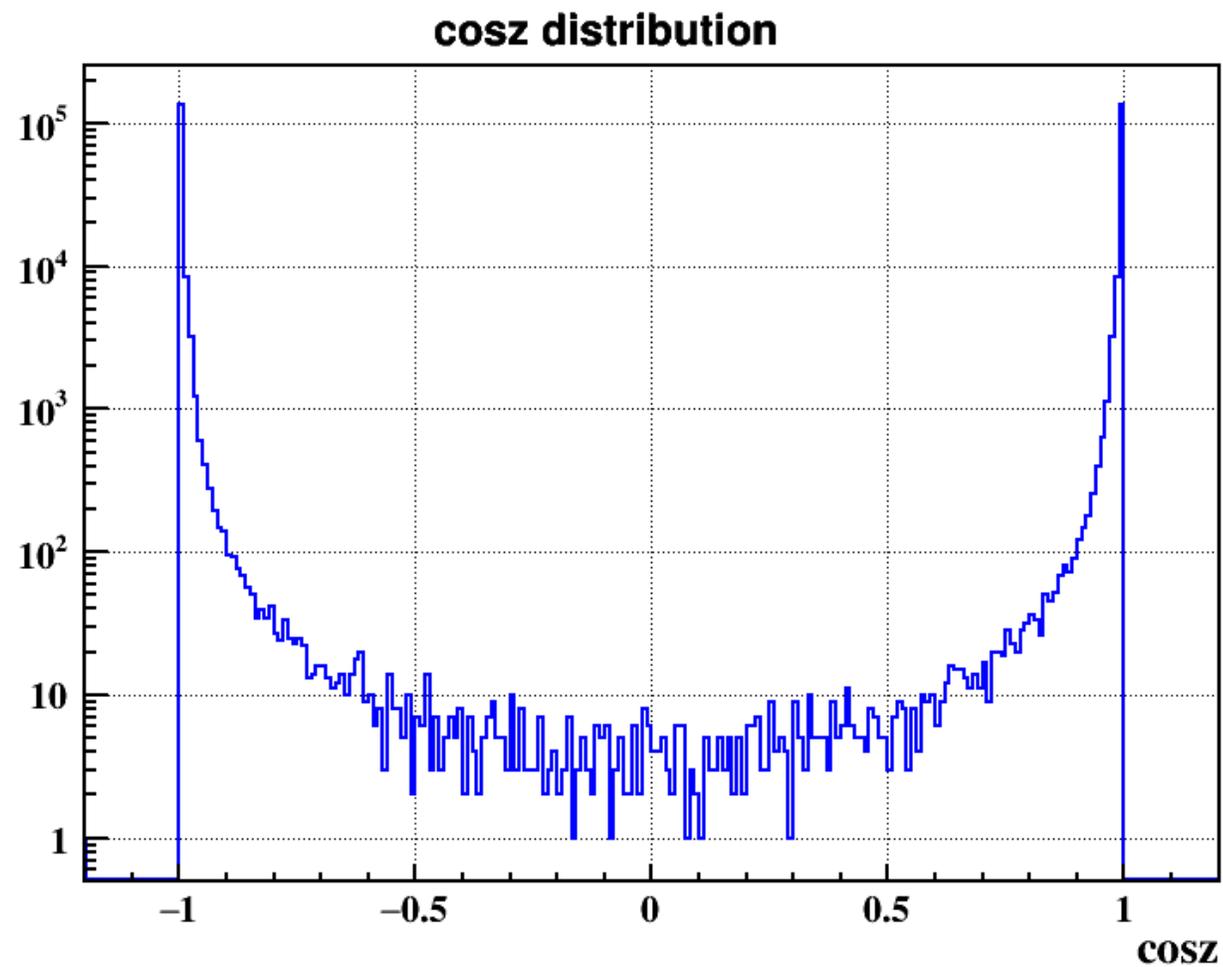
- 高粒度读出的TPC作为未来环形正负电子对撞机物理和探测器技术设计报告TDR中的主径迹探测器
- 基于现有软件框架和更新的探测器几何尺寸，分析了TPC中不同来源事例来源，完成了对不同本底水平下TPC读出像素击中率和占空比的研究；
- 完成对TPC中空间电荷密度以及对应空间畸变的计算，给出了不同本底水平下整个TPC内电场畸变和空间畸变，为机械探测器接口优化设计（MDI）提供了重要数据参考；

谢谢！

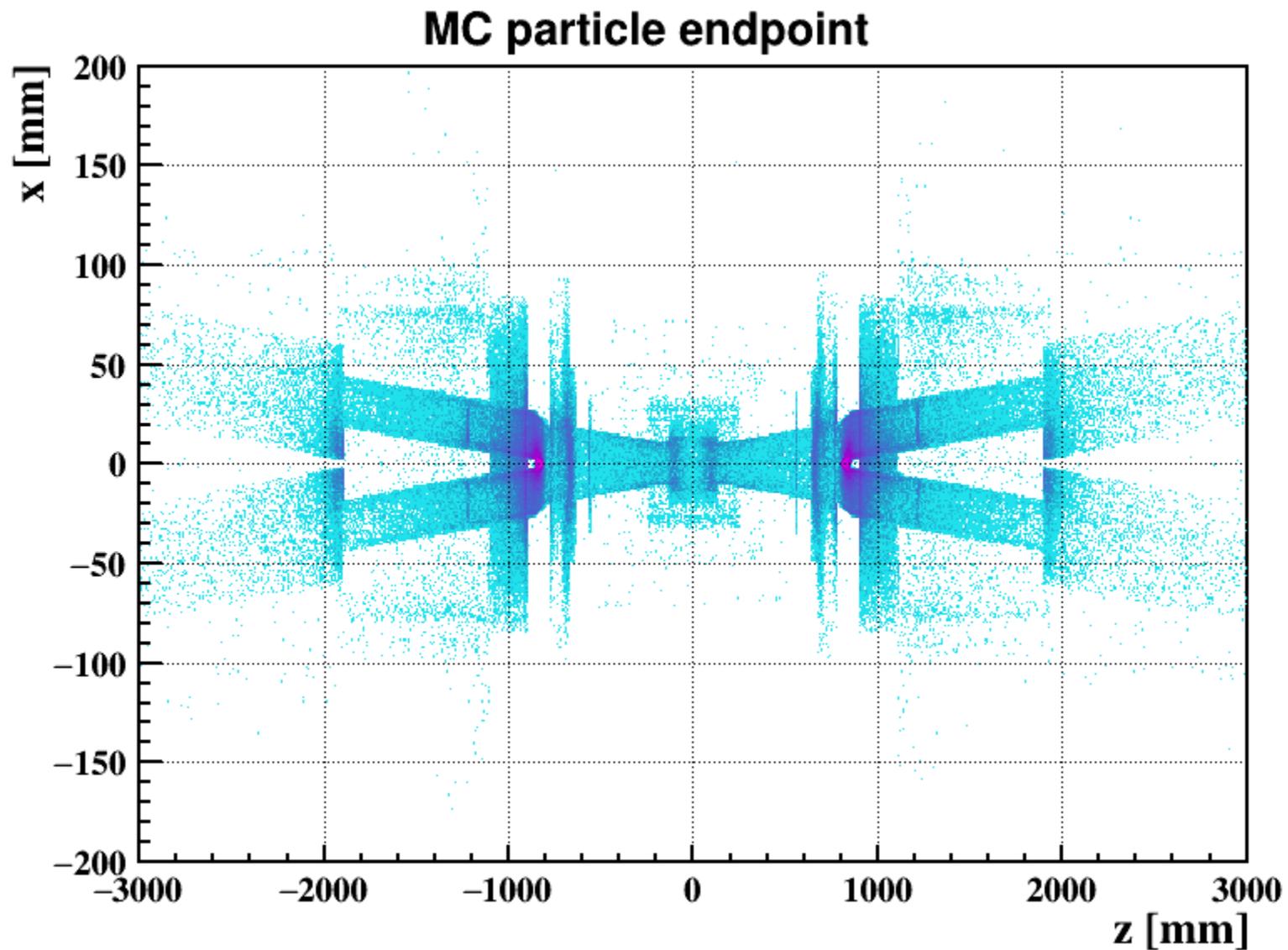
Back up 1: BS pairs 产生子初始顶点分布



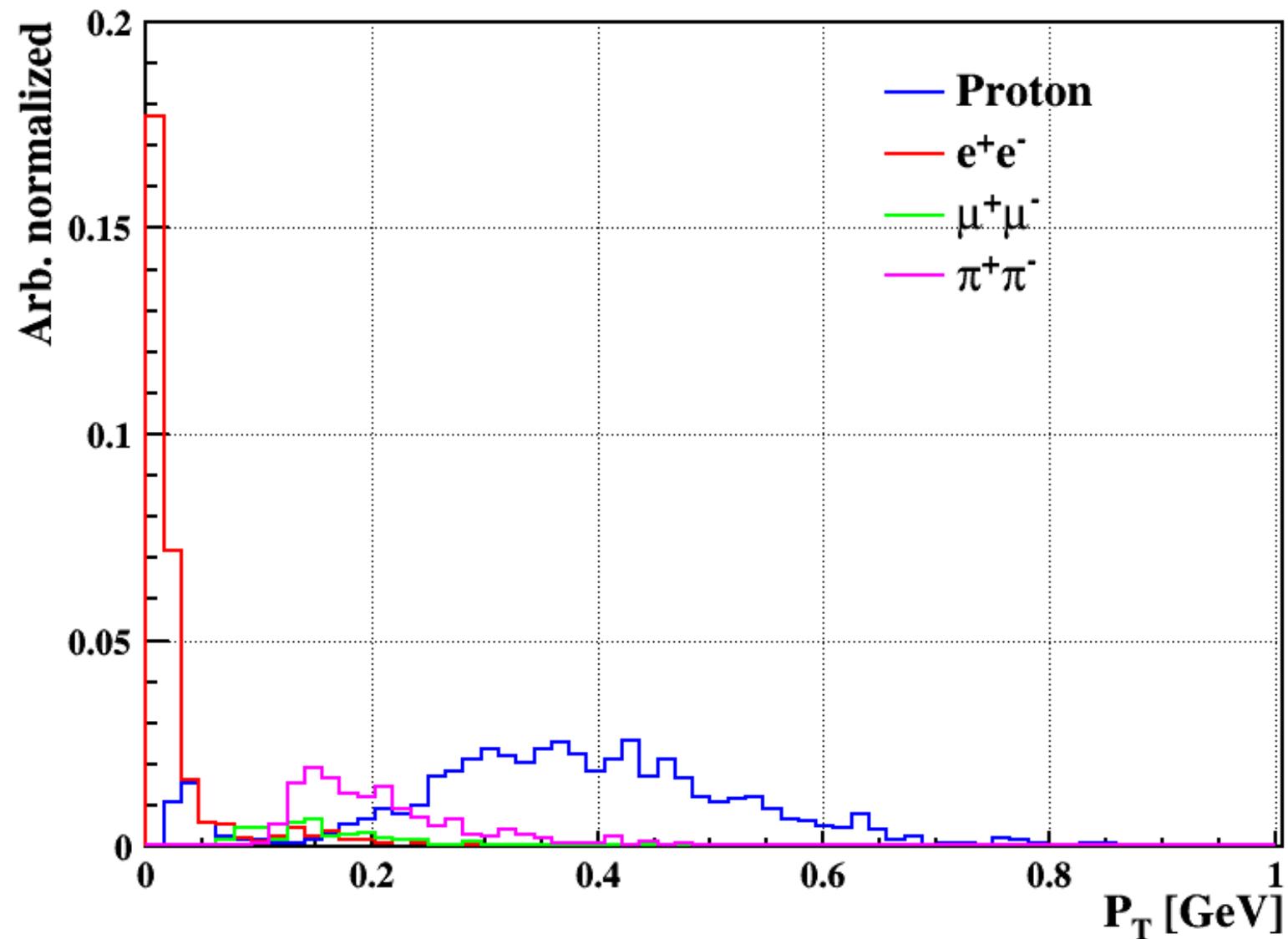
Back up 2: BS pairs 发射方向 $\cos\theta$ 分布



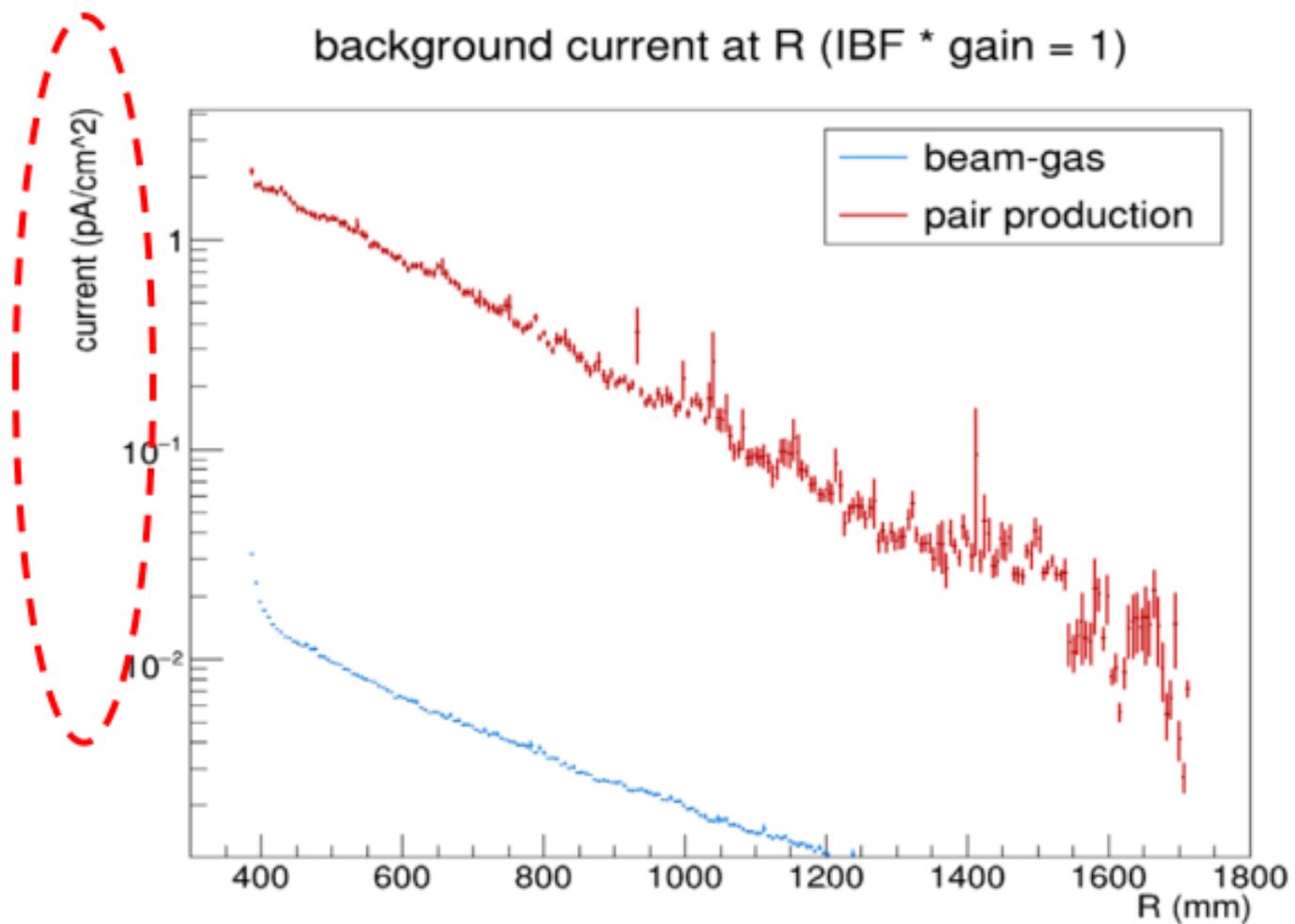
Back up 3: BS pairs endpoint分布



Back up 4: 进入TPC 粒子种类动量分布



Back up 5: BS和BG效应在TPC中产生的电流密度对比



Back up 6: Higgs模式下BS产生的原初离子分布

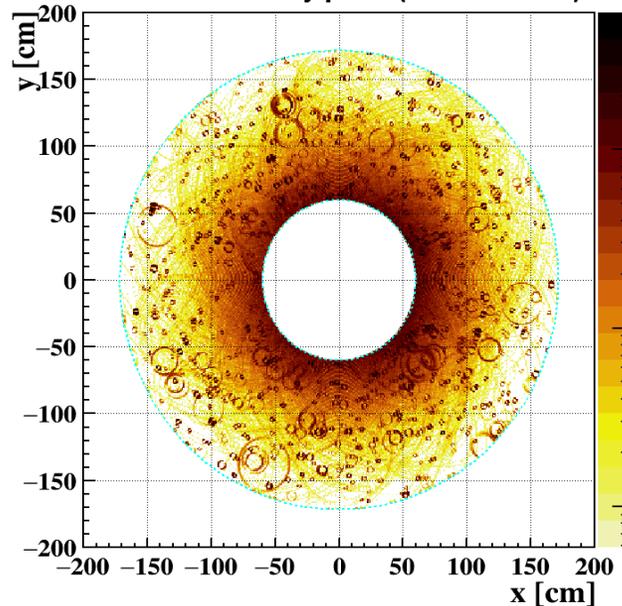
Primary ions per bunch crossing in TPC

Edep: 10.21 GeV in total(10000BX)

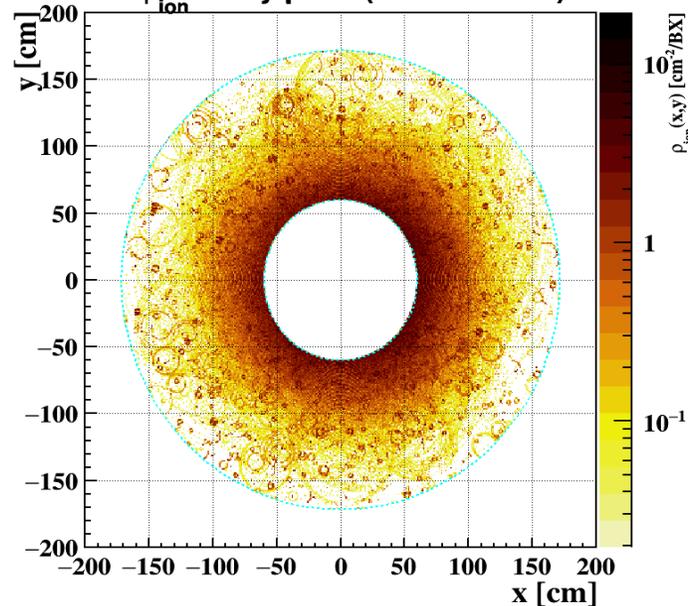
Number of primary ions: BX freq. $\sim 1/680\text{ns}$

- Edep/effective ionization potential of Ar [26eV] $\sim 39.26\text{k ions/BX}$
- Primary ions in TPC at any time $\sim 1.5 \times 10^{10}$
- Average primary ion density $\sim 0.05\text{nC/m}^3$

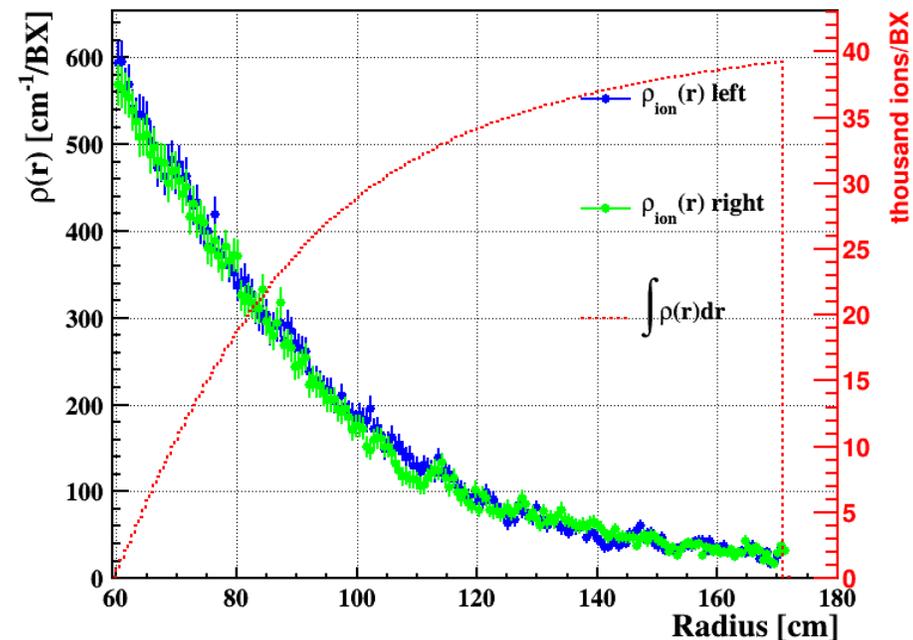
TPC hits at x-y plane(10000 bunch)



ρ_{ion} at x-y plane(10000 bunch)



Hits map (left) & Ion density(right) at x-y plane

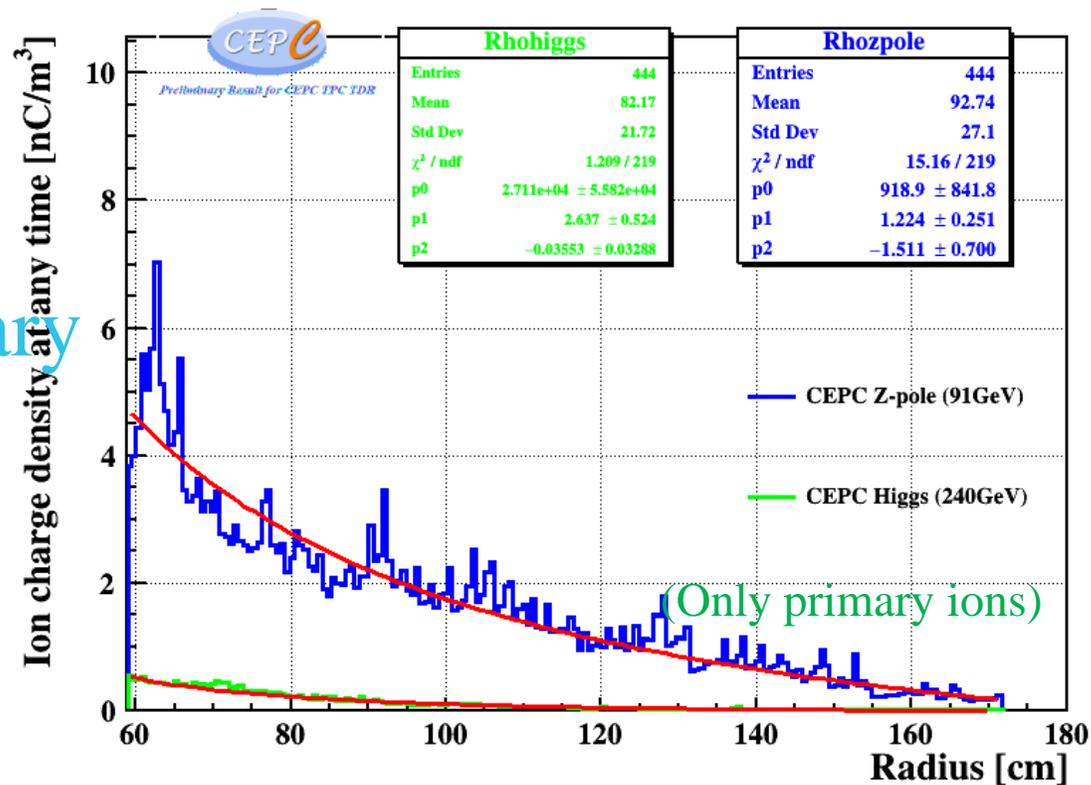
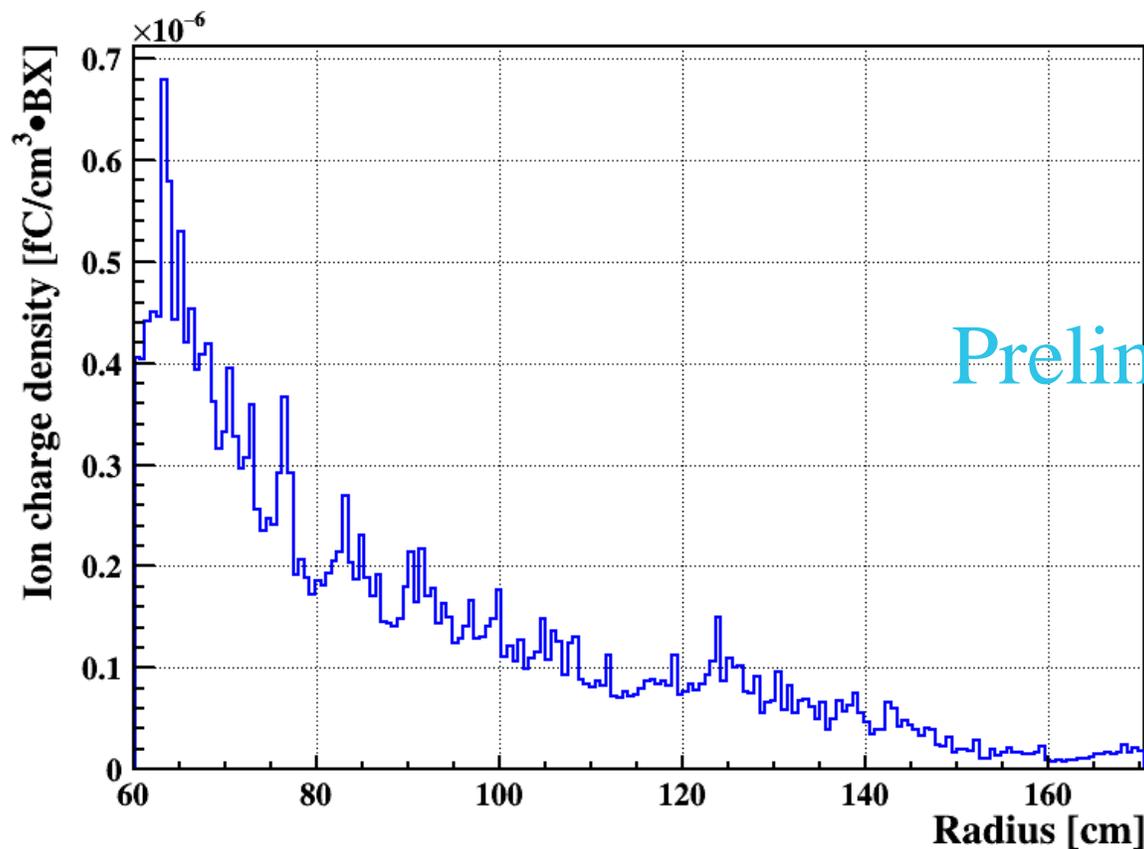


$\rho_{\text{ion}}(r)$ distribution

高对撞亮度TPC研究进展4——空间电荷密度模拟计算

- 单个束团对撞, $\rho_{sc}(\text{single BX}) \sim 0.6e-6 \text{ nC/m}^3/\text{BX}$ @Z-pole
- 稳态: $\rho_{sc}(\text{steady state}) \sim \rho_{sc}(\text{single BX}) \times \text{BX freq.} \times \text{max. drift time} \times 50\% \times \eta = 5.46 \text{ nC/m}^3$ (r=60cm) @Z-pole

Ionization efficiency(90%)



$\rho_{sc}(r)$ (single BX) distribution Left & $\rho_{sc}(r)$ (steady state) Right