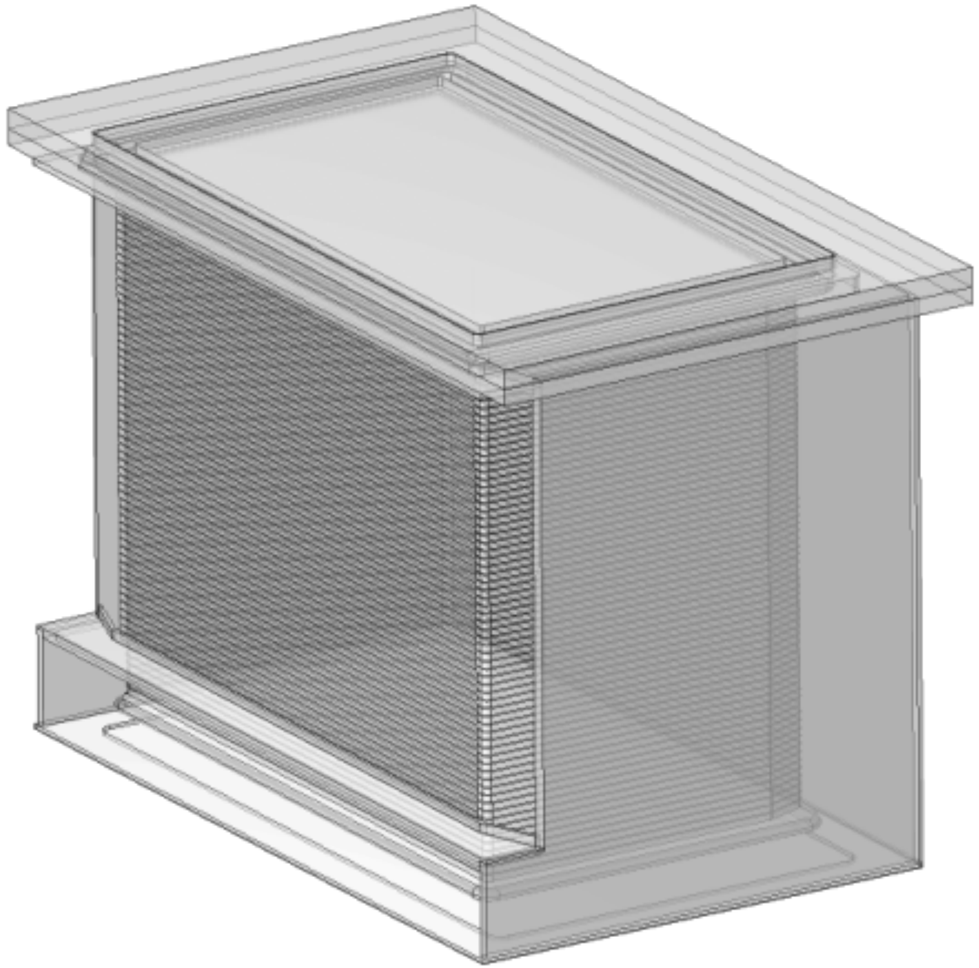
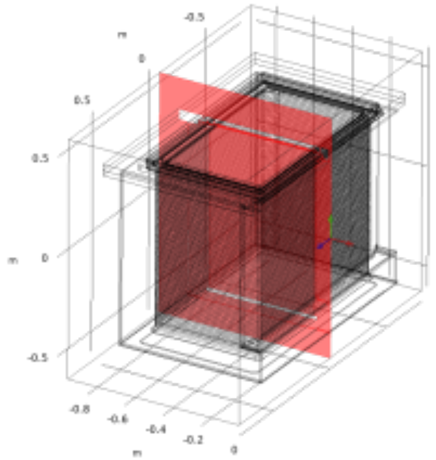
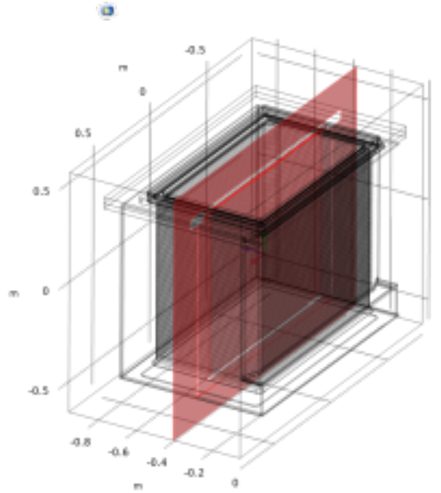
CEE TPC electric-field distortion calibration

Xiuxian Wang
Superviser: Hao Qiu
Institute of Modern Physics, CAS
2026.11

COMSOL中TPC的建模

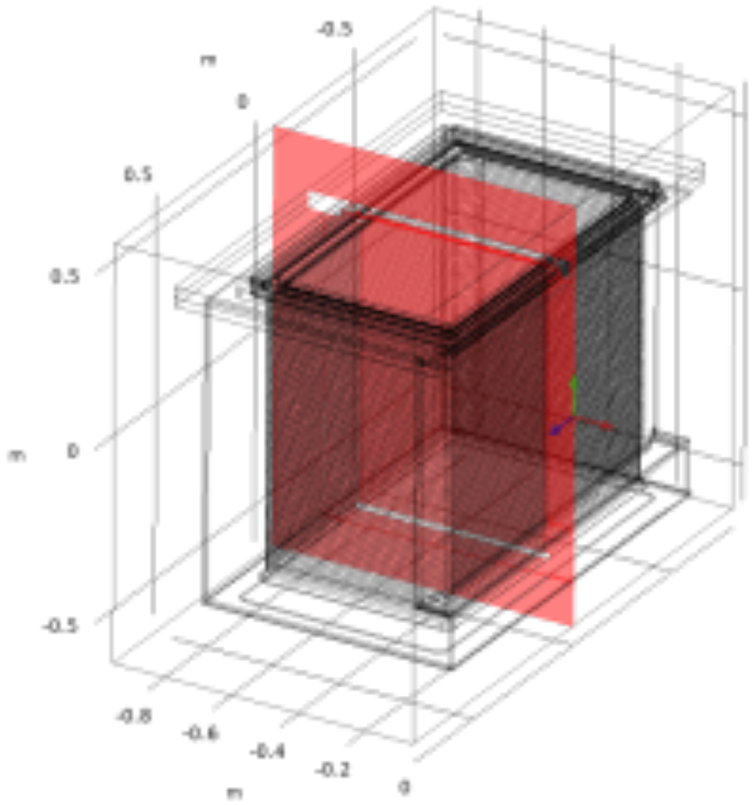


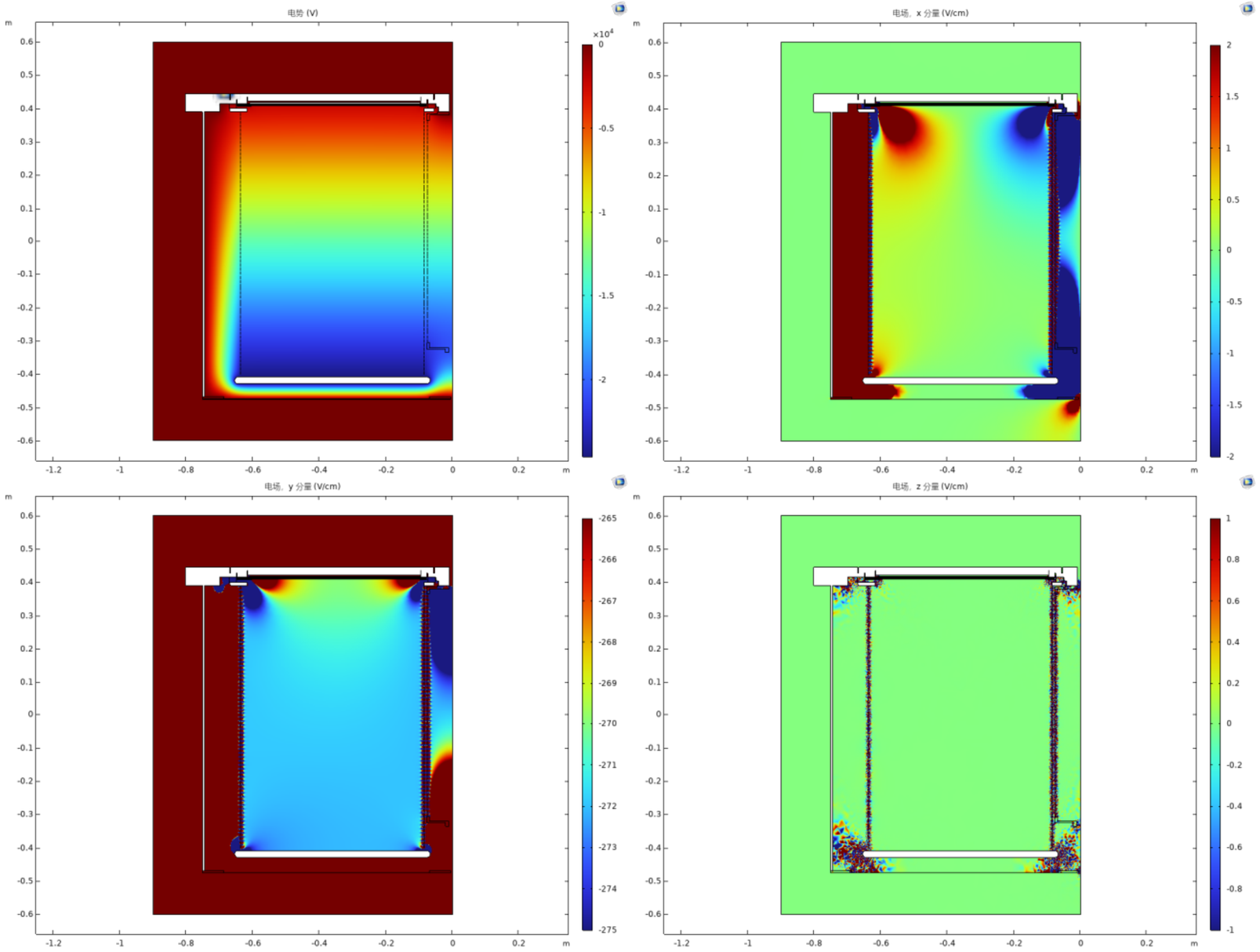




- 基于3D设计图
- 压缩了所有螺孔、销钉孔
- 压缩了场笼支撑陶瓷杆和电阻杆
- 压缩了场笼外部分结构复杂的绝缘体
- 条带膜简化为零厚度面
- 共用于畸变电场以及空间电荷电场的计算

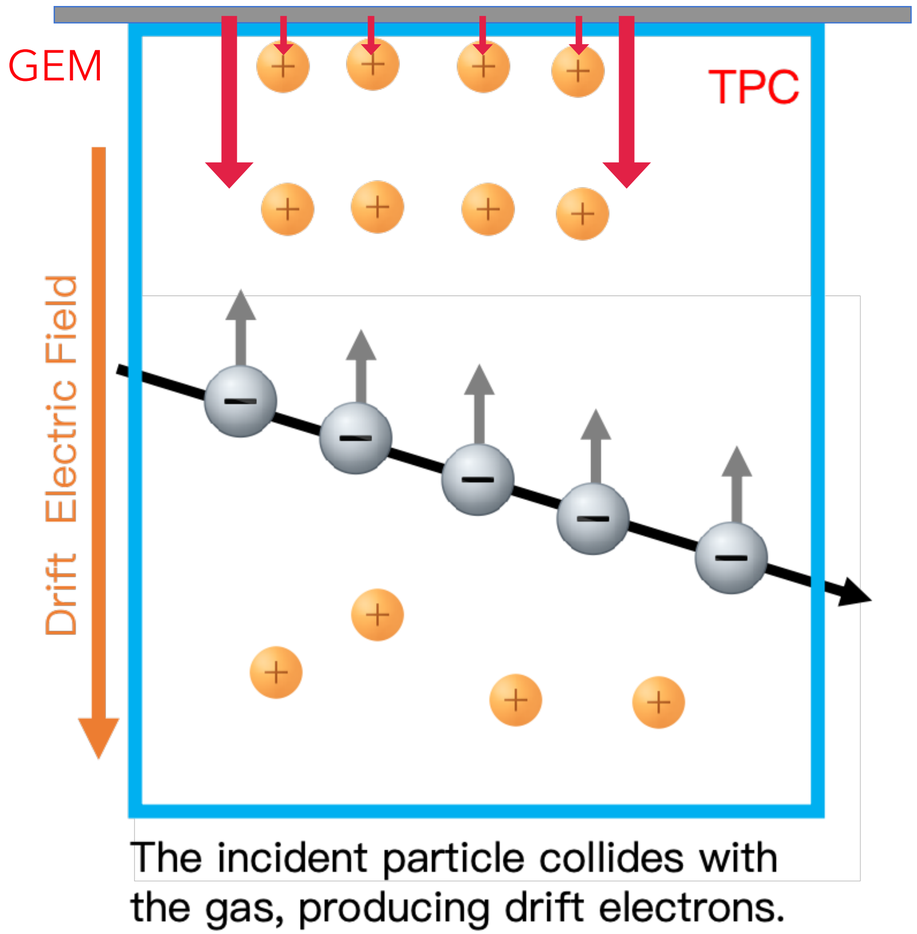
COMSOL中畸变电场的计算



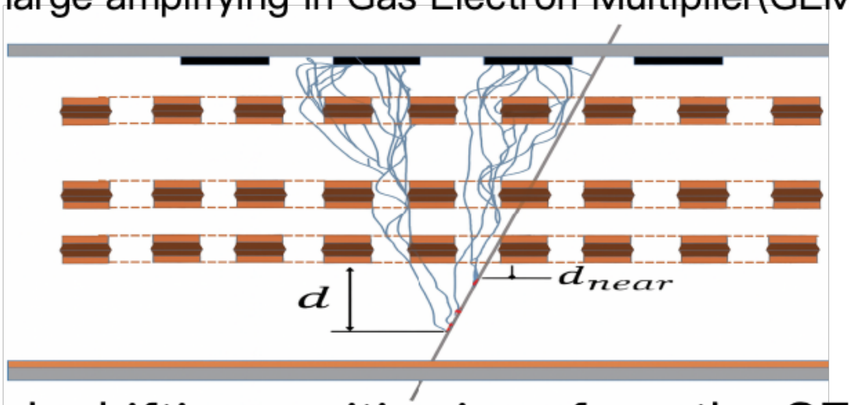


CEE TPC Space charge effect

Space change 的产生和影响



The incident particle collides with the gas, producing drift electrons.



Slowly drifting positive ions from the GEM gain process accumulate in the TPC, generating an electric field that affects electron drift

修正核心思路：

1.使用大量模拟事件计算平均每个碰撞事例对空间电荷电场的贡献

2.通过实时的束流强度，拟合叠加两个空间电荷电场

3.逐hit计算空间电荷电场对每个hit的影响，得到更真实的位置

CEE TPC Space charge calibration progress

Space change 修正流程

1.事例产生器+GEANT产生大量事件分布（模型+runsim得到CEETPC Point）

目前使用的模拟数据JAM2 C+C/Pb 100k events

2.计算这些事件电离出的电子最终在GEM模上的分布

3.计算GEM模反馈出的正离子在TPC中的分布

先假设事例率均匀，正离子在y方向上均匀分布，目前使用的正离子反馈率统一为2.6%，GEM增益系数为1500

根据正离子最大漂移时间以及这段时间内事例率的变化，线形拟合将其分为一个矩形和一个三角形区域，叠加形成总电场再修正hit

4.根据空间电荷分布，在Comsol中计算电场

5.根据电场文件，逐hit修正位置信息

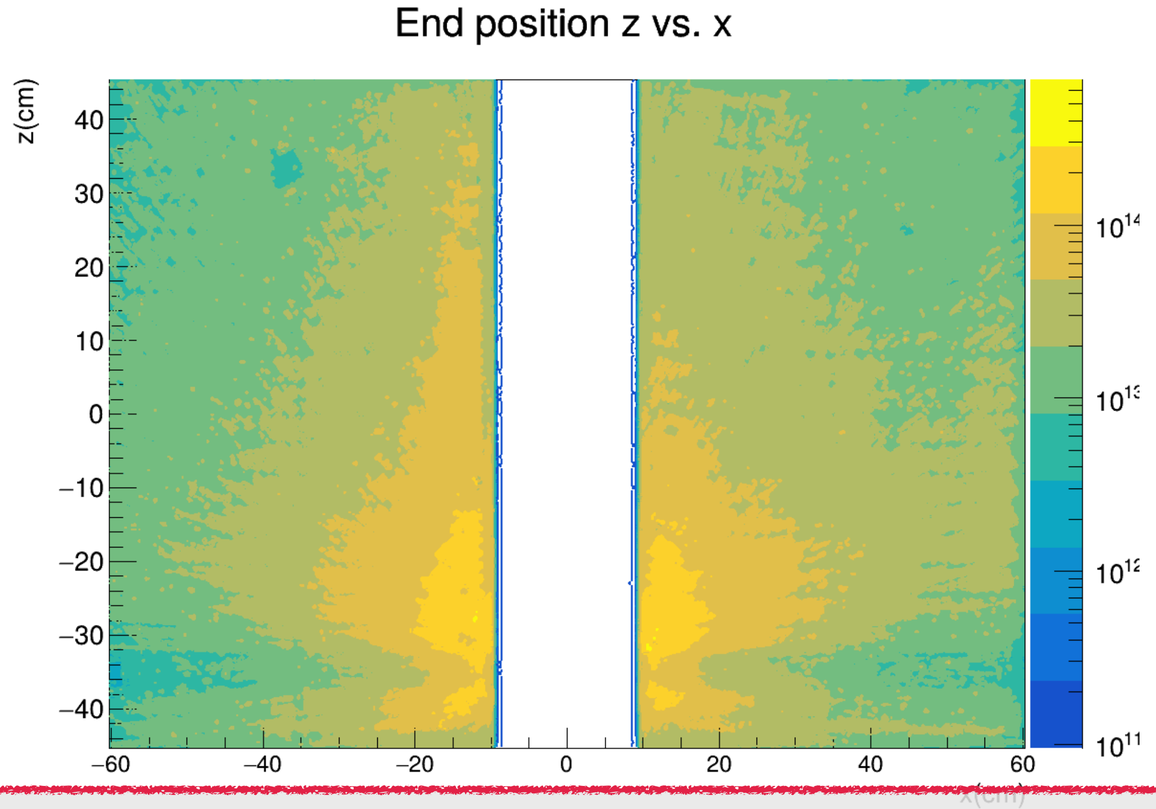
CEE TPC Space charge calibration progress (step1~2)

100k 个事件在GEM模上接收到的电子分布

Sim data: JAM2 C+C/Pb 100k

Geometry: TPC_full.root (以靶点为原点，灵敏体积中心点为)

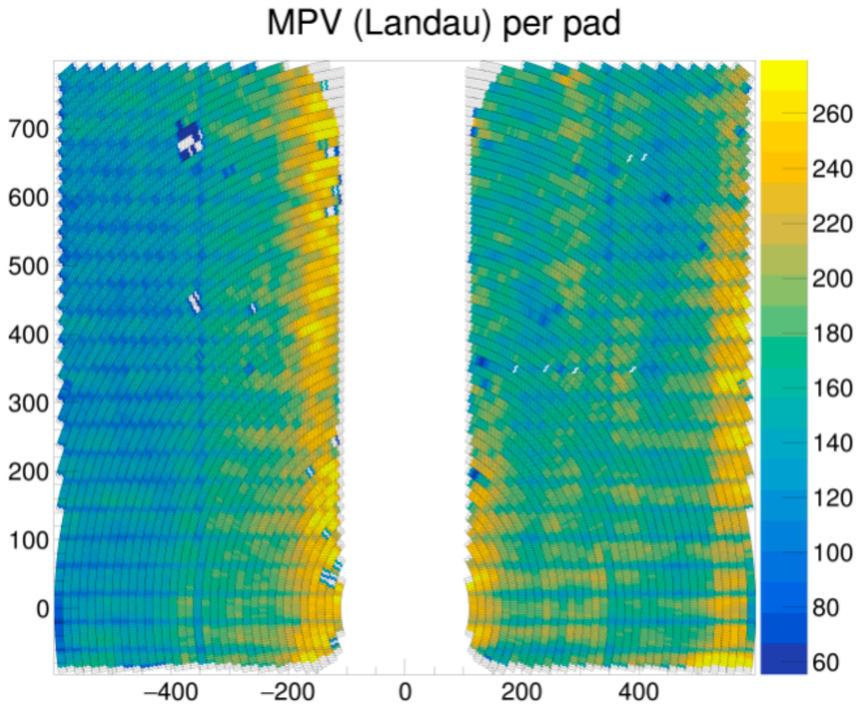
No magnetic field



CeeTpcPoint(100k Events) → CalculateDriftCharge.C → The final position of the charges in XZ plan

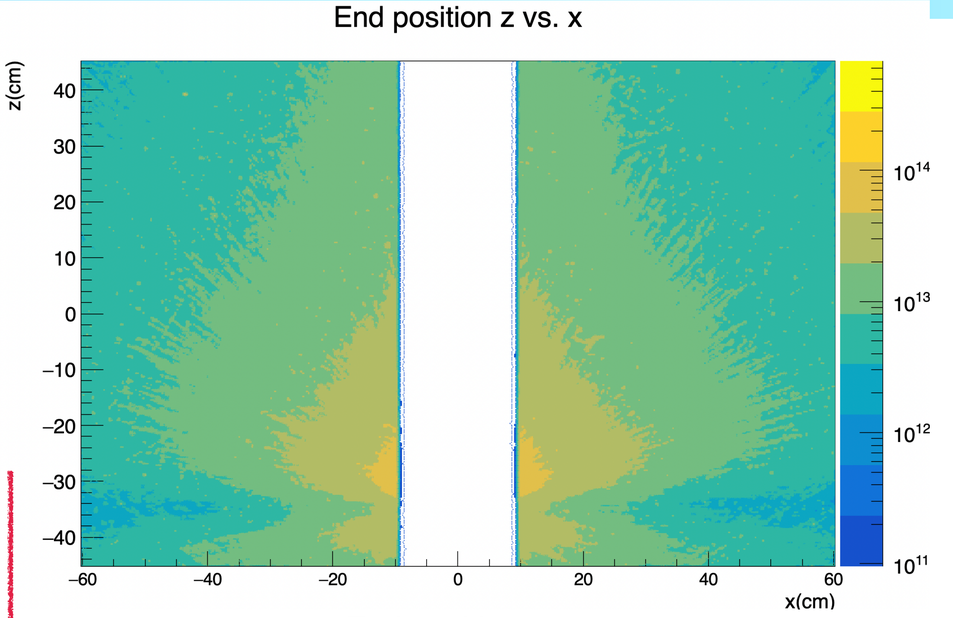
Sensitive volume: 9.7<|x|<60.3, |y-1.45|<40.9, |z-35|<45.3 cm

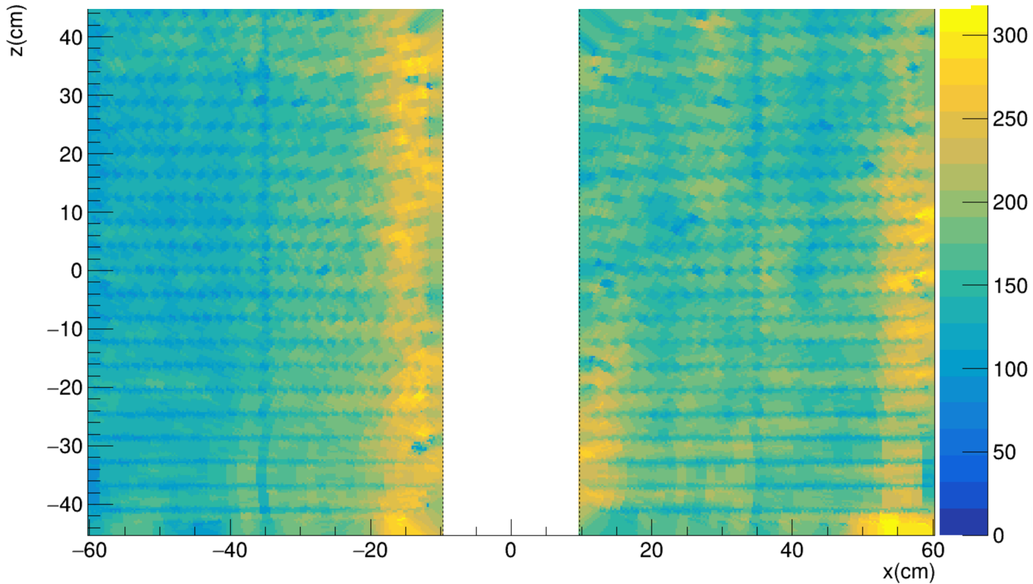
CEE TPC Space charge calibration progress (step1~2)

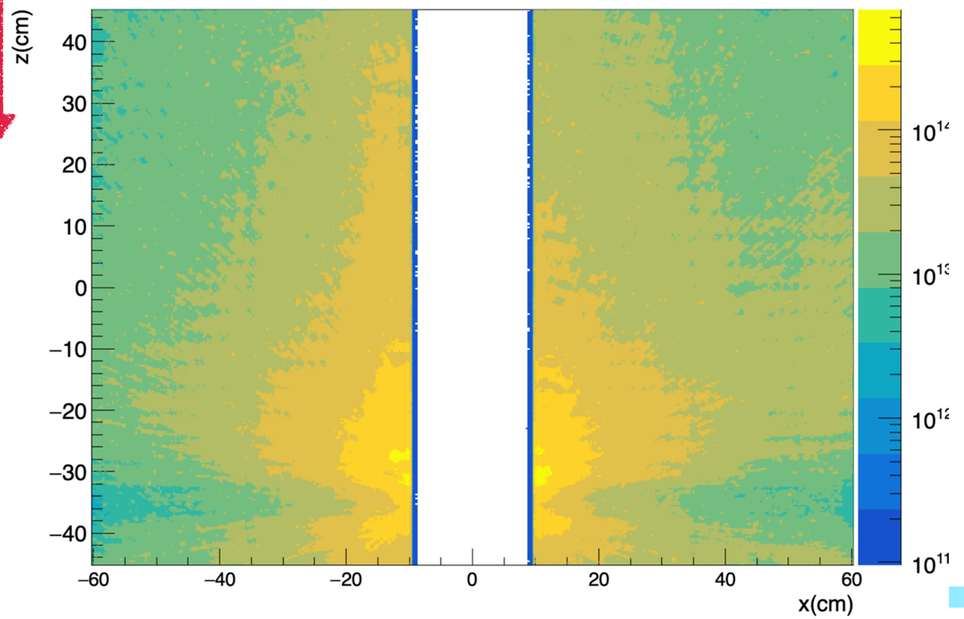


The distribution of MPV is related to the electronic gain coefficient (obtained by Zihe Su).

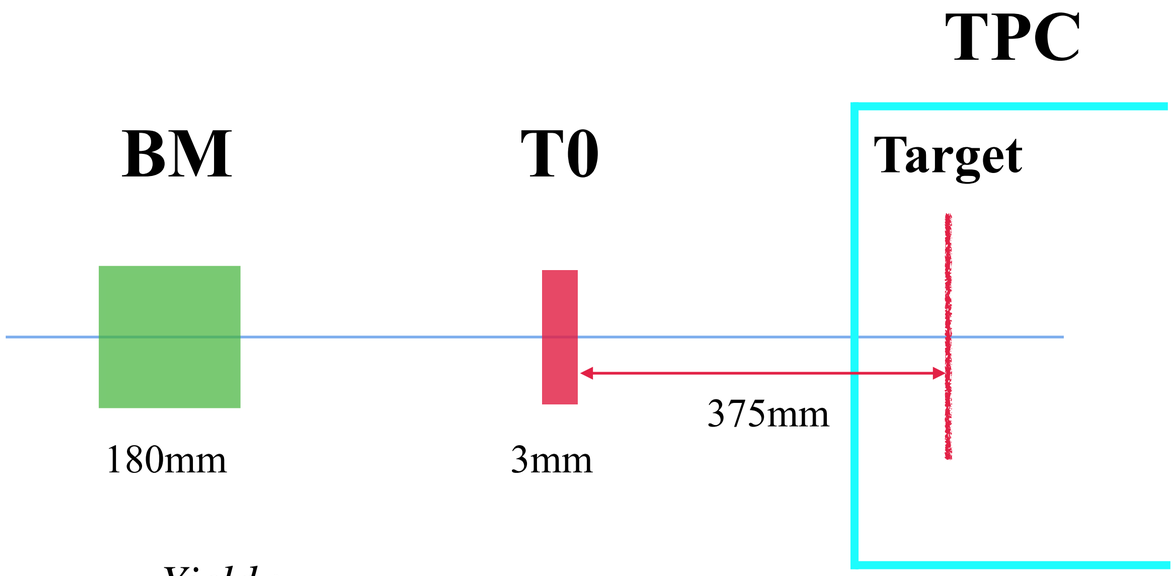
multiplied by MPV distribution







Yield estimates for T0 and BM



Yield :

$$Y = \sigma N l$$

$$= \pi[r_0(A_{beam}^{\frac{1}{3}} + A_{target}^{\frac{1}{3}})]^2 \cdot Nl$$

σ is the reaction cross-section, N is the number of atoms per unit volume, and l is the thickness of the material, r0=1.2fm.

T0 directly gives the content of each atom per unit volume, and for BM, N is calculated using the following ideal gas law:

$$N = \frac{P}{kT}$$

T0:

PROPERTIES	EJ-200	EJ-204	EJ-208	EJ-212
Light Output (% Anthracene)	64	68	60	65
Scintillation Efficiency (photons/1 MeV e⁻)	10,000	10,400	9,200	10,000
Wavelength of Maximum Emission (nm)	425	408	435	423
Light Attenuation Length (cm)	380	160	400	250
Rise Time (ns)	0.9	0.7	1.0	0.9
Decay Time (ns)	2.1	1.8	3.3	2.4
Pulse Width, FWHM (ns)	2.5	2.2	4.2	2.7
No. of H Atoms per cm^3 ($x10^{22}$)	5.17	5.15	5.17	5.17
No. of C Atoms per cm^3 ($x10^{22}$)	4.69	4.68	4.69	4.69
No. of Electrons per cm^3 ($x10^{23}$)	3.33	3.33	3.33	3.33
Density (g/cm^3)	1.023	1.023	1.023	1.023
Polymer Base	Polyvinyltoluene			
Refractive Index	1.58			
Softening Point	75°C			
Vapor Pressure	Vacuum-compatible			
Coefficient of Linear Expansion	7.8×10^{-5} below 67°C			
Light Output vs. Temperature	At 60°C, L.O. = 95% of that at 20°C No change from -60° to 20°C			
Temperature Range	-60°C to 60°C			

聚乙烯基甲苯[CH2 CH(C6 H4 CH3)]n

$$Y_H = 0.478 \times 10^{-24} \times 5.17 \times 10^{22} \times 0.3 \approx 0.714\,\%$$

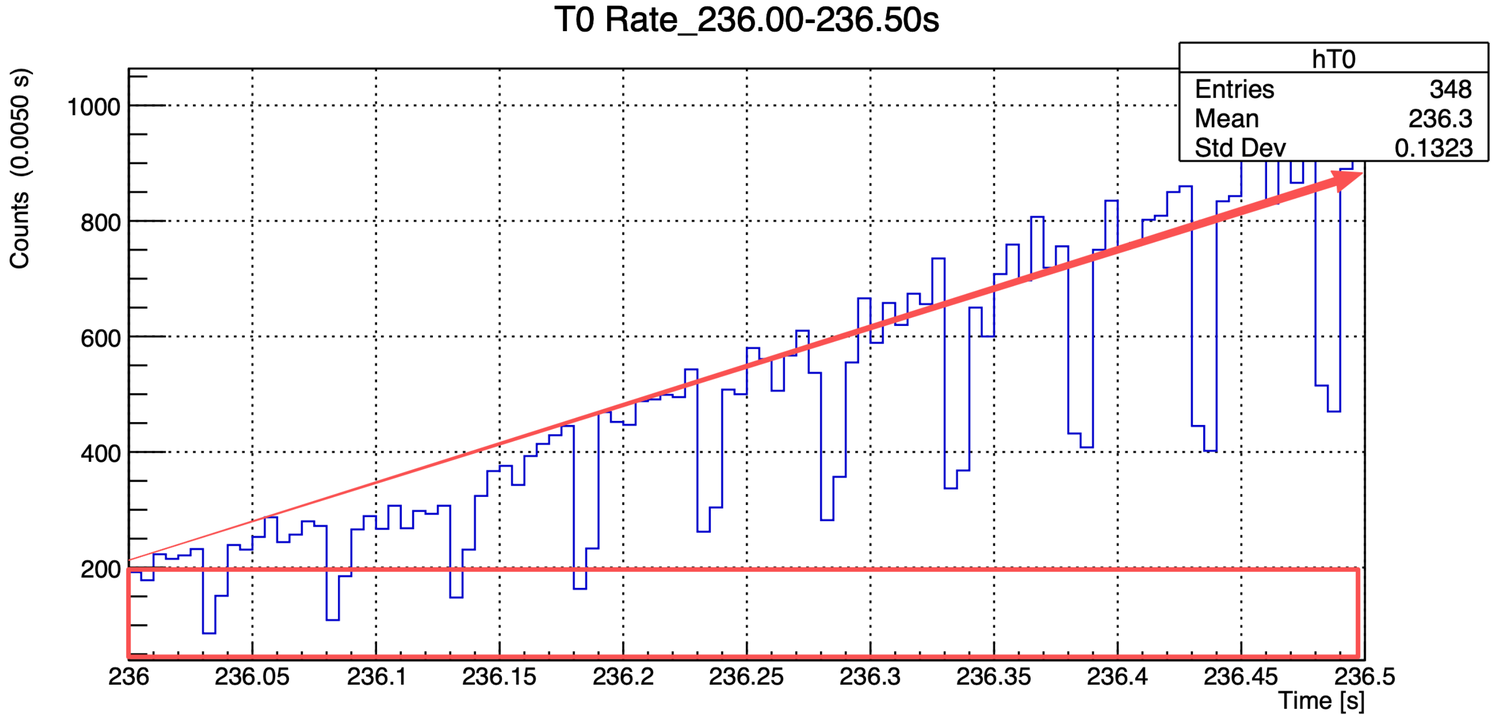
$$Y_C = 0.934 \times 10^{-24} \times 4.69 \times 10^{22} \times 0.3 \approx 1.314\,\%$$

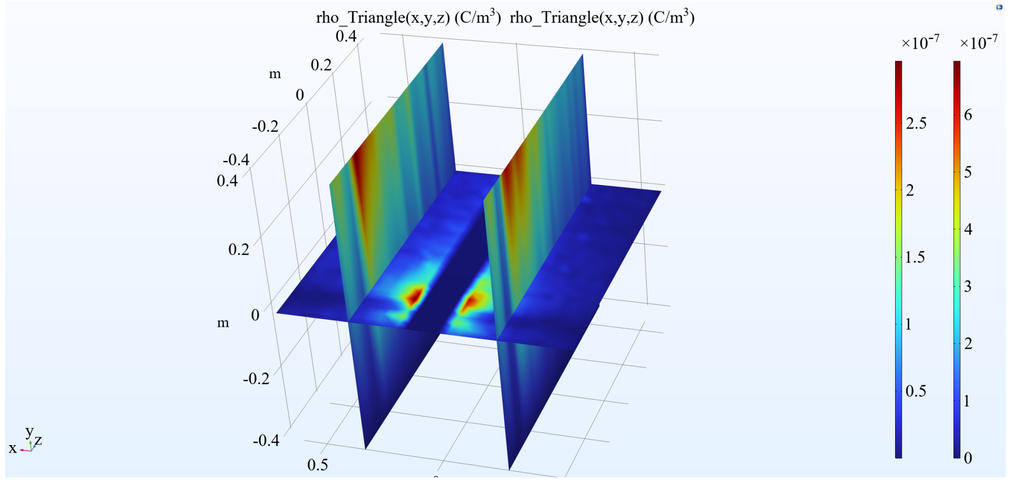
Do not need to consider the influence of oxygen

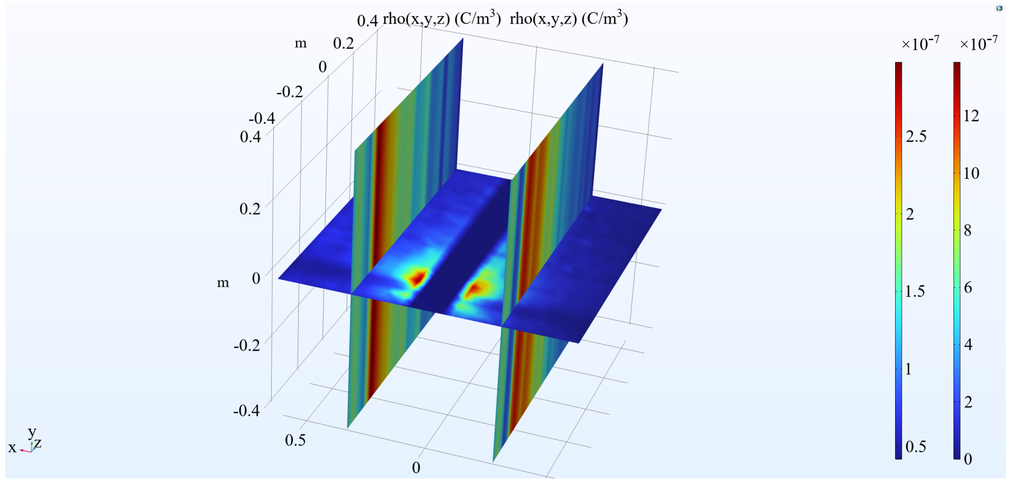
CEE TPC Space charge calibration progress (3～5)

The space-charge electric field is decomposed into two contributions:

- Rectangular (constant) part — from the uniform beam baseline.
- Triangular (time-varying) part — from the linearly rising beam rate.

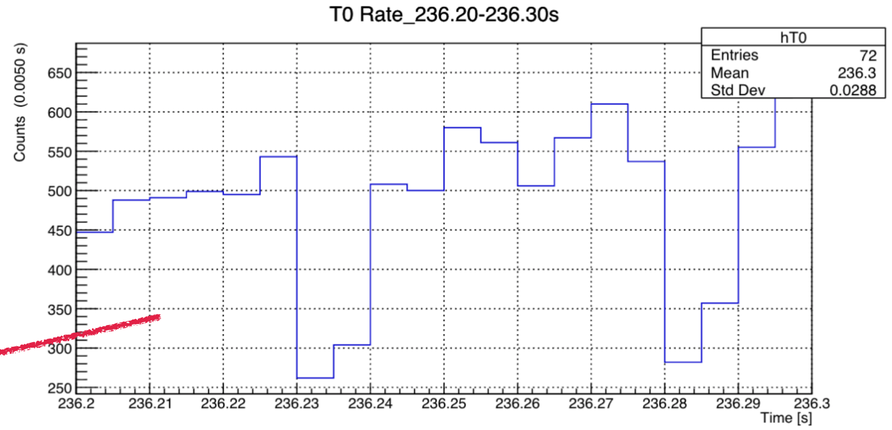


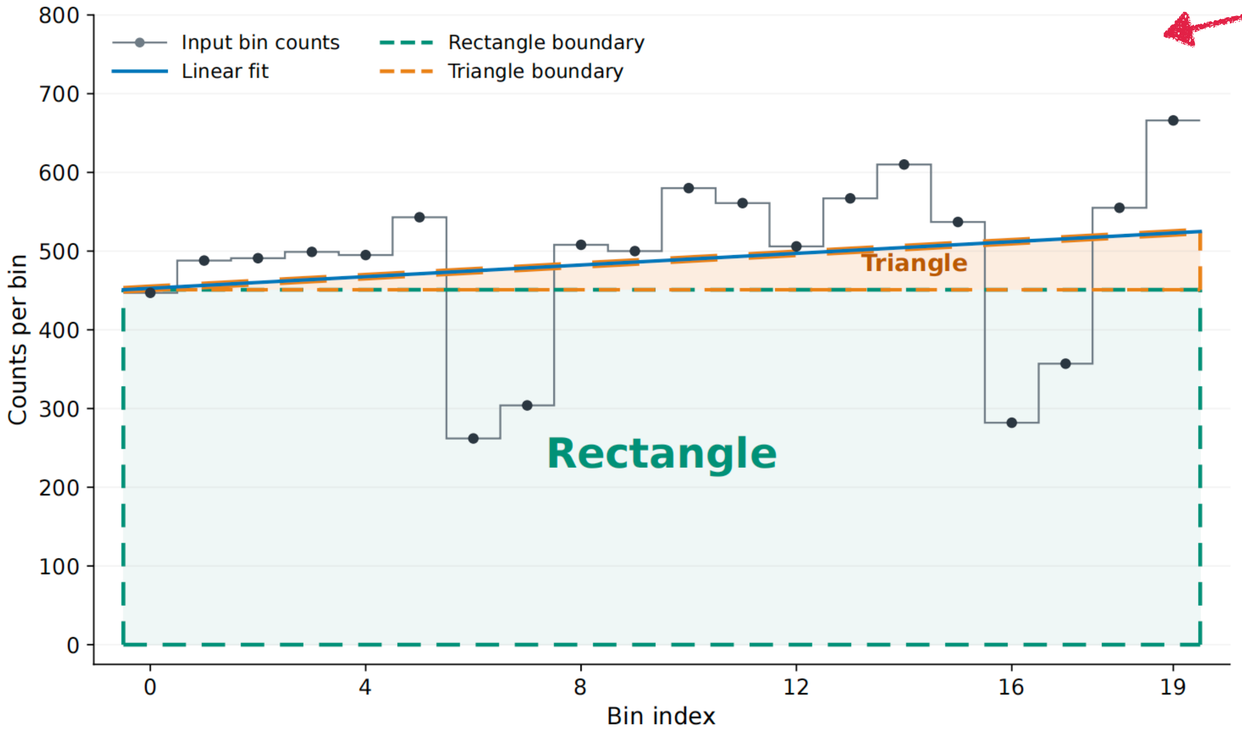




CEE TPC Space charge calibration progress (step4～5)

The space-charge electric field is decomposed into two contributions:
- Rectangular (constant) part — from the uniform beam baseline.
- Triangular (time-varying) part — from the linearly rising beam rate.





FITTED LINE

$f(x) = ax + b$

$a = 3.697744$

$b = 452.771429$

RECTANGLE

$N_R = 9018.451$

TRIANGLE

$N_T = 739.549$

Least-squares method fit

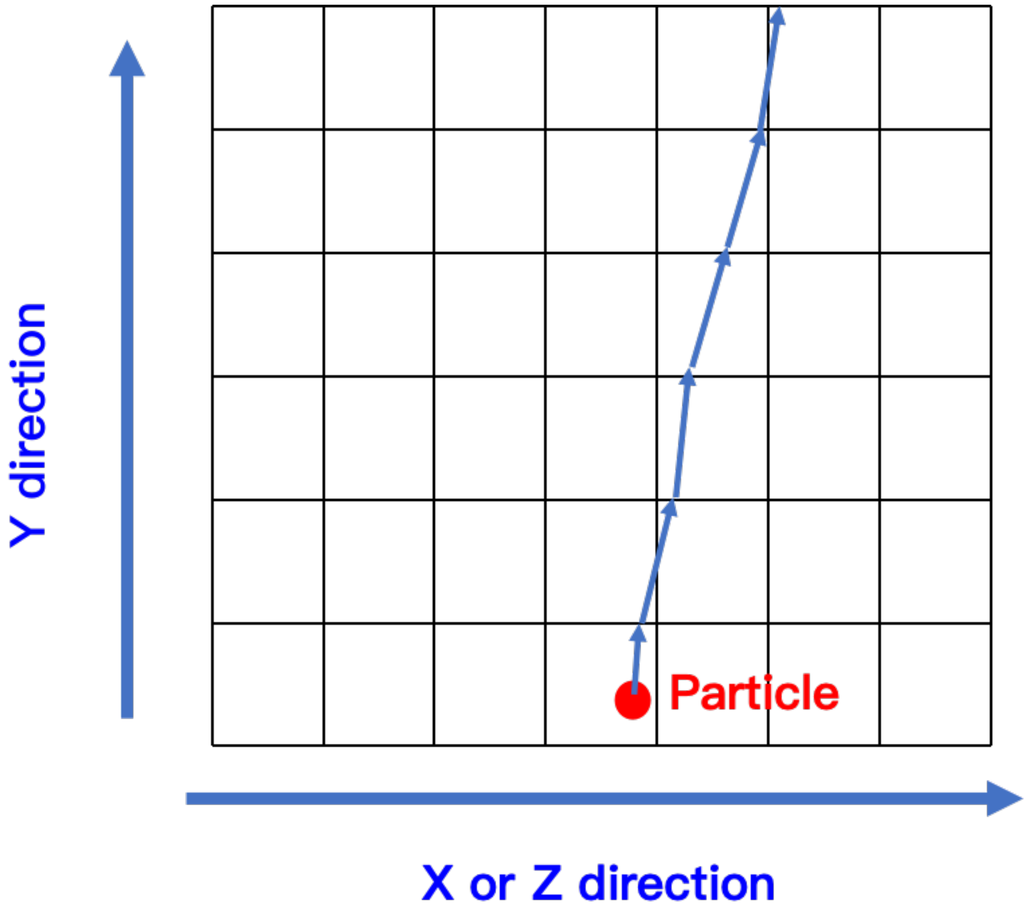
$$a = \frac{\sum_{i=0}^{m-1}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=0}^{m-1}(x_i - \bar{x})^2}, \qquad b = \bar{y} - a\bar{x}$$

$$N_R = m(b - a/2), \qquad N_T = am^2/2$$

$$E_{sc} = E_R \frac{N_R}{N_{Sim}} + E_T \frac{N_T}{N_{Sim}/2}$$

$m = number\ of\ bins$

CEE TPC Space charge calibration progress (step5)



x, z轴每0.3cm一个bin, y轴0.818cm一个bin

根据Comsol拿到的电场文件修正每个hit的位置

- 空间位置分格子，根据不同Event的时间拿到前一段时间T0事例率
- 对事例率曲线线形拟合，叠加矩形和三角形电场
- 根据hit所在位置算出电子总飞行时间
- 再根据粒子xz位置让粒子从GEM膜往下一格格回到真实的位置
- 根据电场和磁场算出电子在此格的速度向量
- 每漂一格减去运动时间，如此循环至到飞行时间减为0
- 得到被空间电荷影响前的hit坐标

```
fSpaceChargeCaliPtr = new Space_Charge_Effect();
fSpaceChargeCaliPtr->SetFieldMode(fSpaceChargeCali);
fSpaceChargeCaliPtr->SetGridCsvFile(GridcsvFile.Data(), iGridFileEvents); // 三行 list；矩形参考事例数，三角形参考数为其一半
// 直接传入 E/P；类内乘以 pressure 得到实际标称场，默认 -320 * 0.85 = -272 V/cm。
fSpaceChargeCaliPtr->SetE_TPCAndIonDriftVelocity(e_tpc_val, K0_90Ar10CO2, pressure, Temp_K);
fSpaceChargeCaliPtr->Space_Charge_Ini(); // 初始化空间电荷效应
// Ini clears the electron velocity; set it for each event after pressure/DB updates.

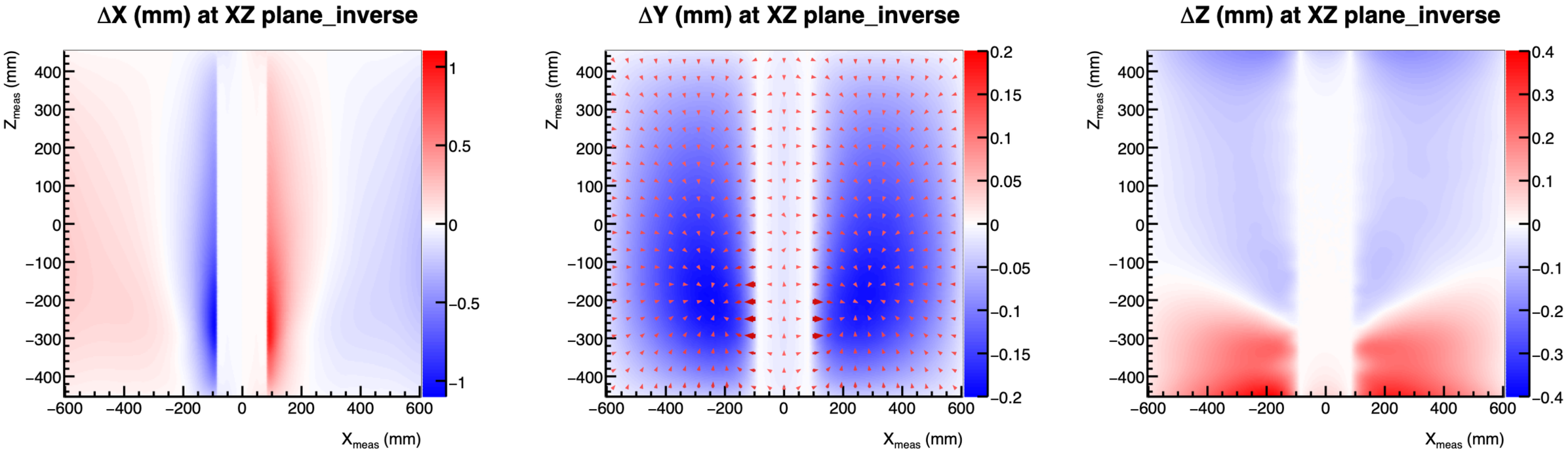
eventRates.resize(fSpaceChargeCaliPtr->Get_nSy(), 0.);
ftimeRange = fSpaceChargeCaliPtr->GetIonDriftTime(); // in seconds
```

CEE TPC Space charge calibration progress (step5)

测量的位置-修正后的位置(纯空间电荷电场的影响）

x方向偏移量(mm)　　y方向偏移量(mm)　　z方向偏移量(mm)

Inverse: Measured Position - Inferred True Position　(Y_{meas} = 4.09 mm)

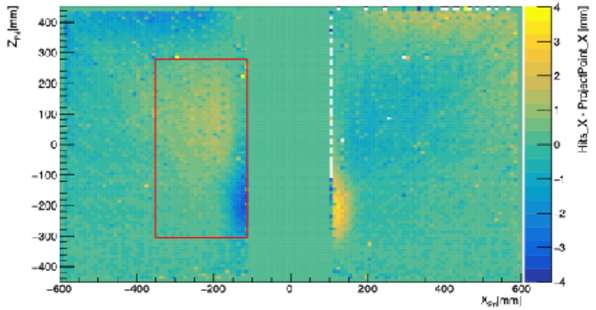


- 本次空间电荷刻度使用了JAM2 C+C/Pb的模拟数据，大致计算了GEM膜反馈出来的正离子形成的空间电荷对径迹在xyz三个方向的影响（假设约化正离子迁移率为1.75cm^2/(V*s)）。
- 这里的图展示了在5.8～8.1kHz事例率下，y=0附近的xz平面上xyz的偏移量。
- 目前结果中y=0平面x方向最大偏离为1mm左右，z方向为0.4mm左右，由于时间方向均匀，y方向偏移量很小。

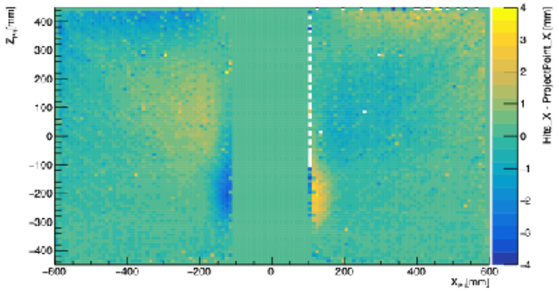
模拟和真实电子分布差距可能的原因

	导致差距的的原因	影响
1	模拟的算法问题	质心系随碰撞核子不同算法发生偏差 (已修正)
2	几何和材料设置	没有加入固定靶的圆环，没挡住应档的事例 (已修正)
3	靶反应率的估算方法	核子核子反应率估算模型的不同会影响电子分布形状
4	电子增益系数不同的影响	倍增系数有分布，导致不同pad增益的电子倍数不同 (已修正)
5	来源于周围探测器的影响	会增加TPC中接受到的事例 (已修正)
6	trigger bias引起的refmult不同	真实数据由于效率原因小refmult部分变少，平均refmult高
7	PileUp 事件模拟中没有	导致模拟总电子数减少
8	缺少多靶碰撞事件	预估少了10%左右事件
9	电子漂移速度计算的误差	每个bin内真实的电子漂移速度可能和计算的漂移速度有所差距

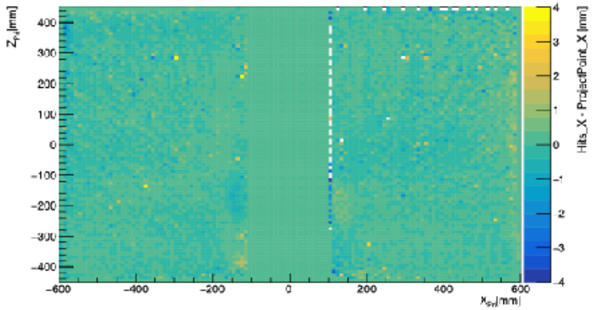
根据真实实验数据scale空间电荷电场



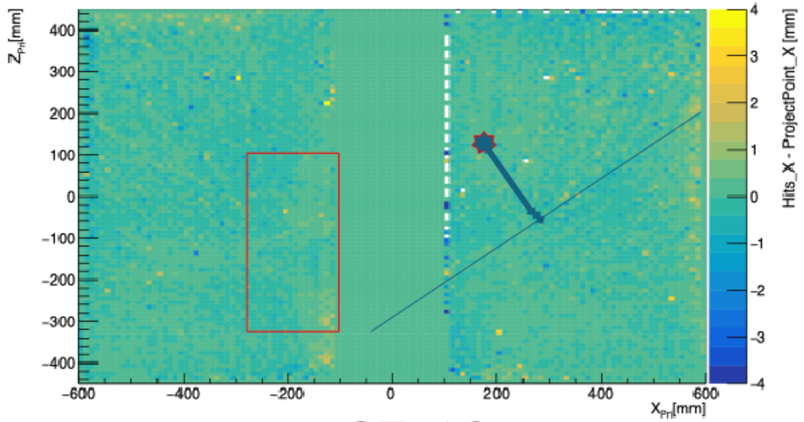
SF=0



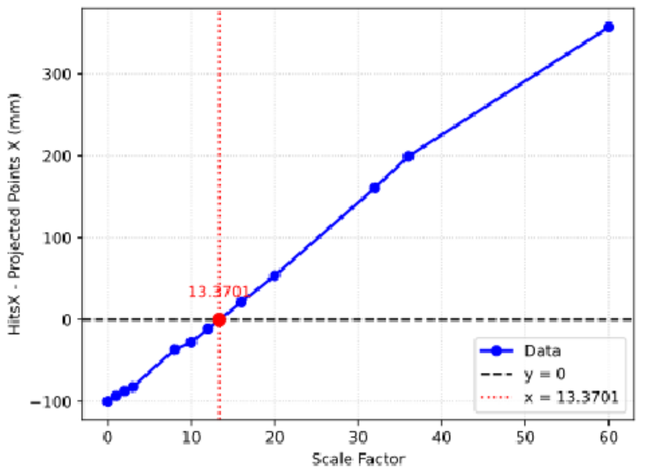
SF=1

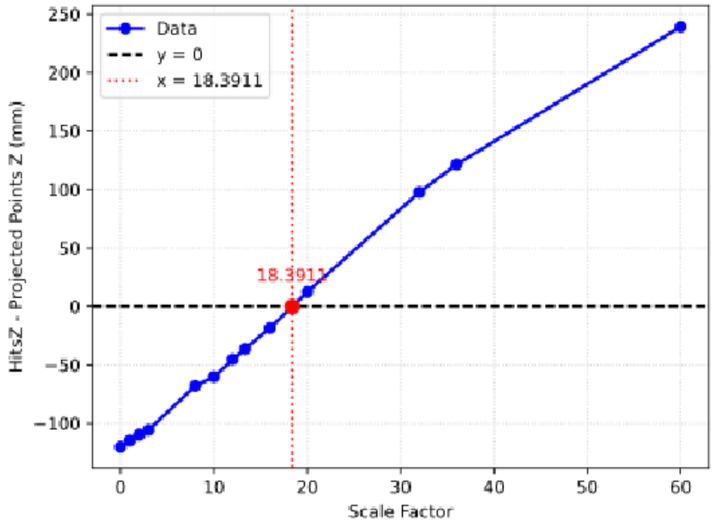


SF=16



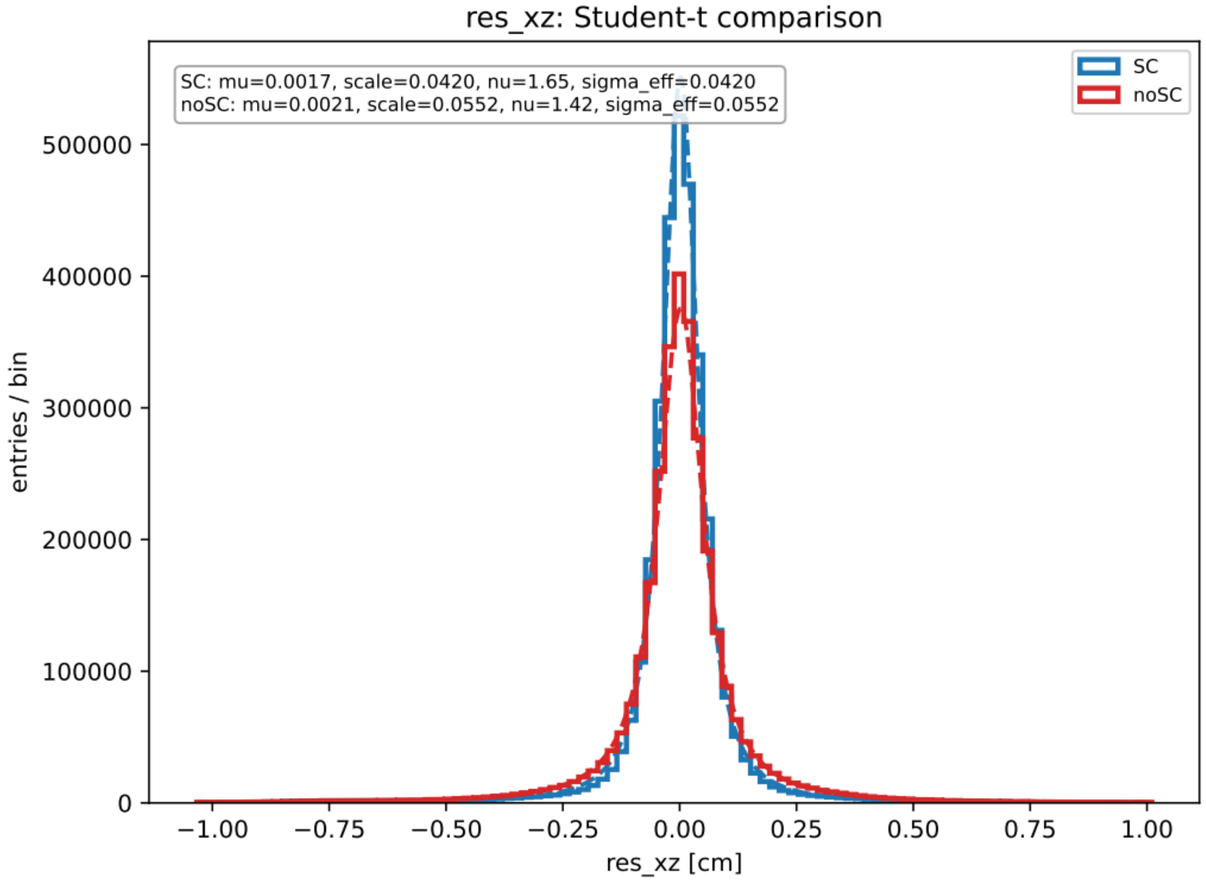
SF=20

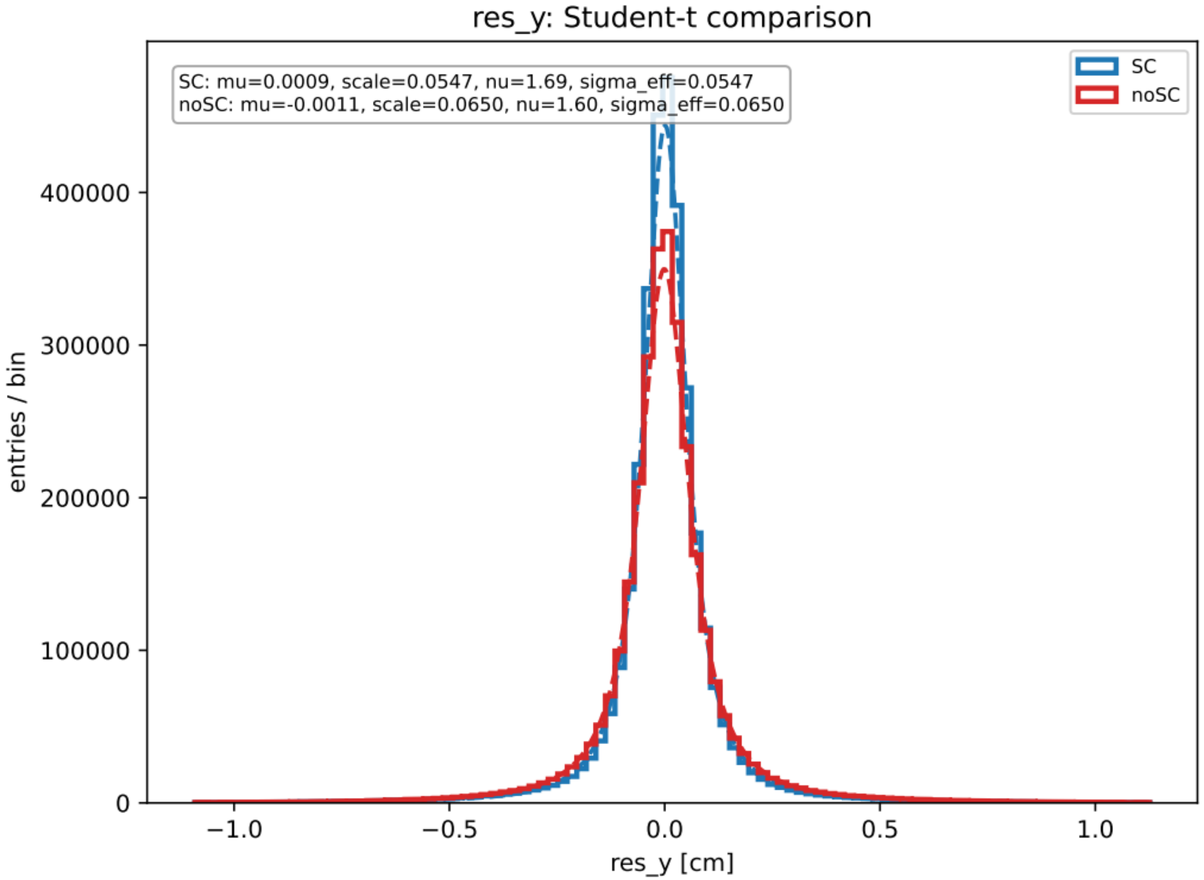




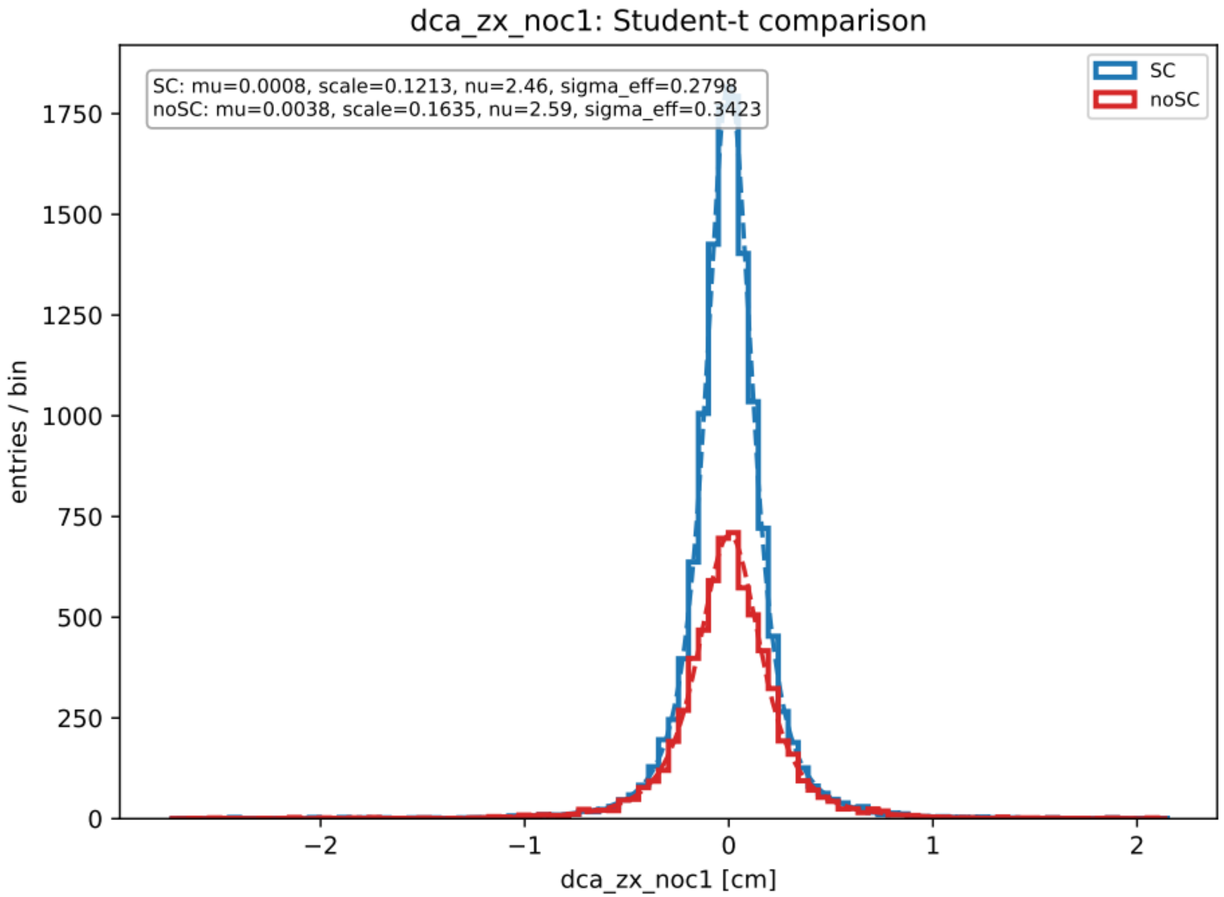
求和红色方块内参数之后，当偏离接近于0的时候，找到修正因子。大约是13–18

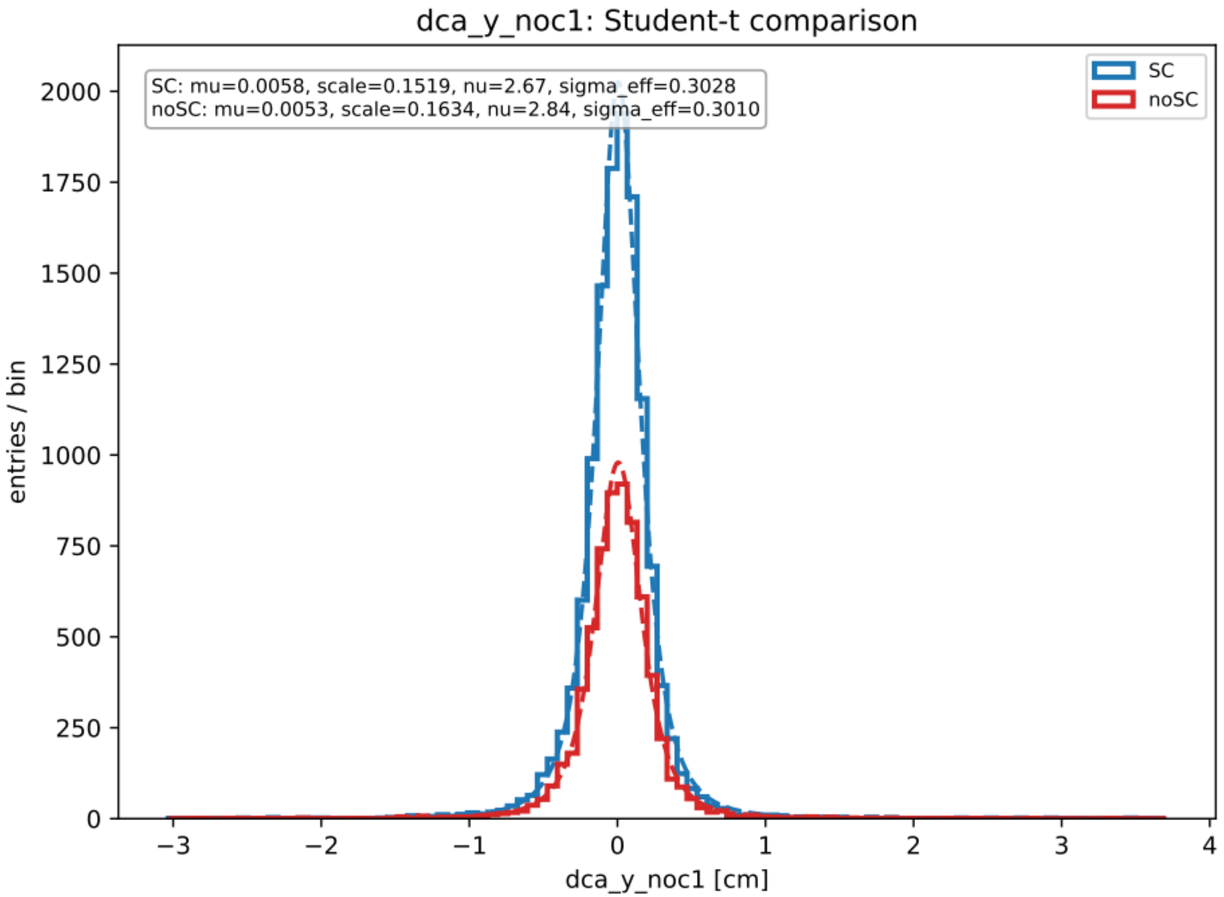
真实数据使用空间电荷电场修正之后各方向位置分辨率有所提升





真实数据使用空间电荷电场修正之后xz方向DCA分辨率有所提升

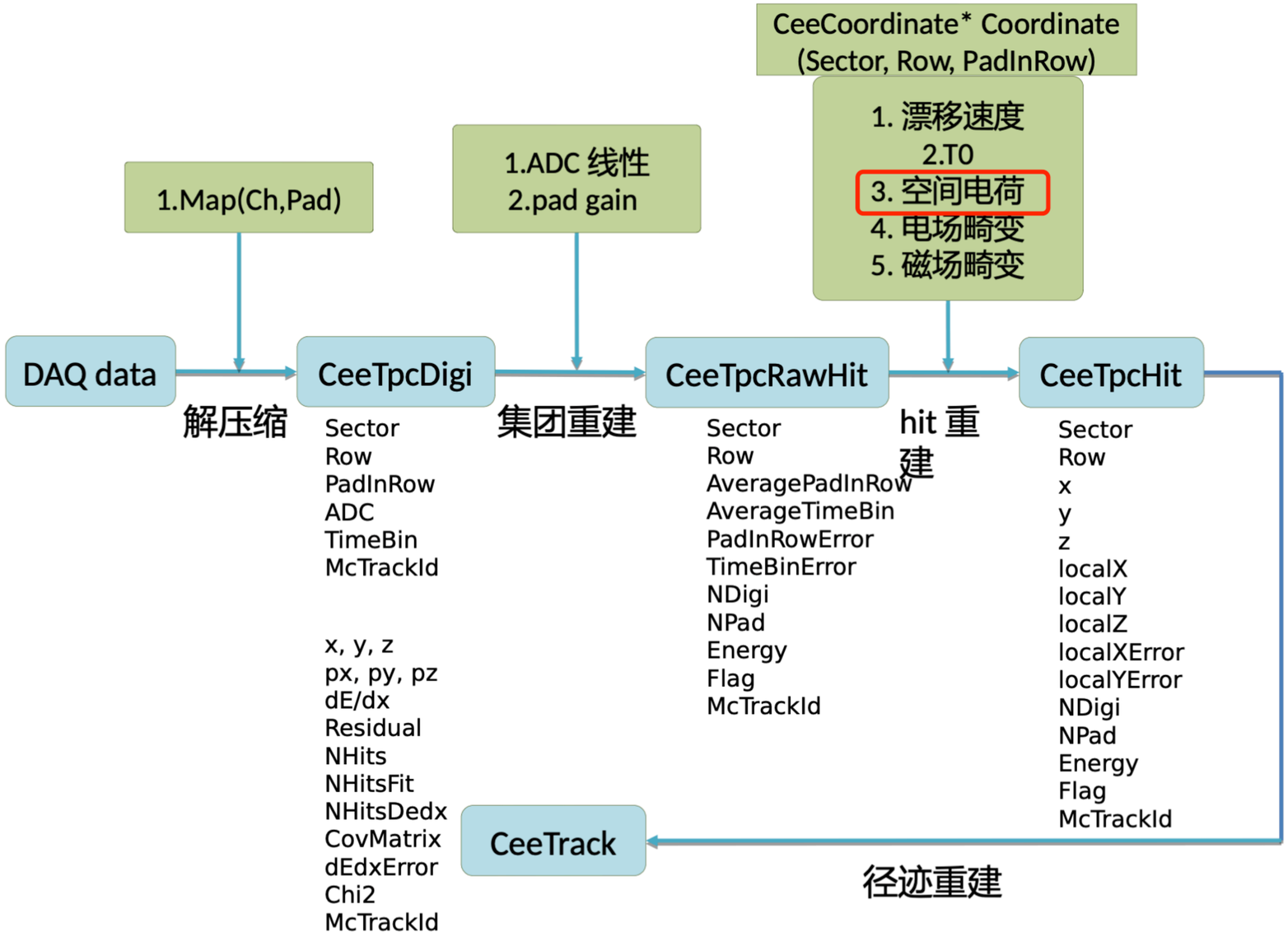




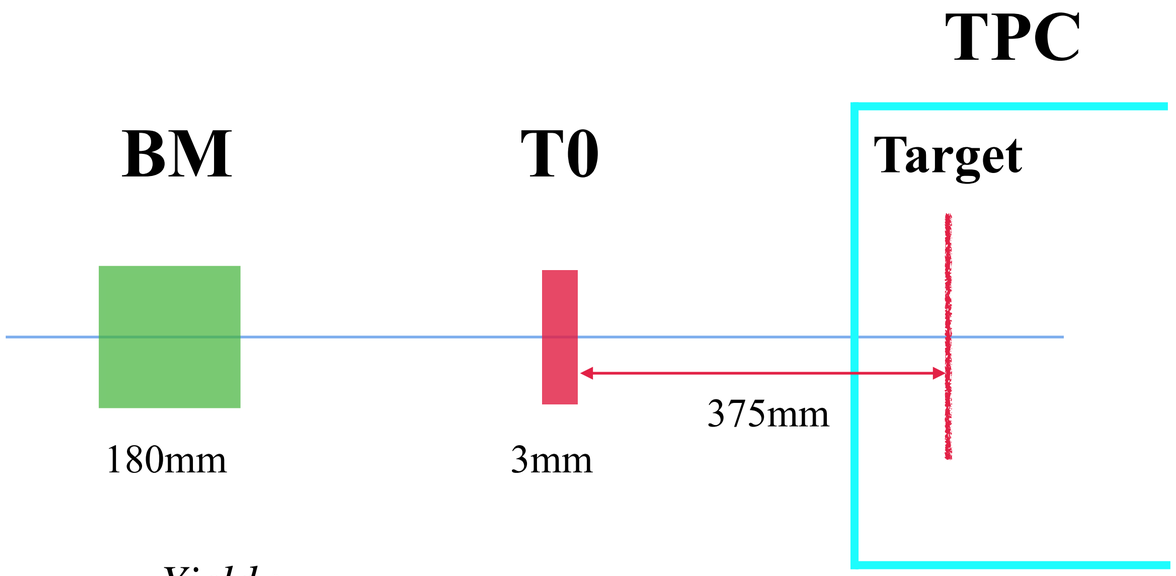
Thanks for Listening!

Buck-up

CEE TPC 空间电荷效应修正



Yield estimates for T0 and BM



Yield :

$$Y = \sigma N l$$

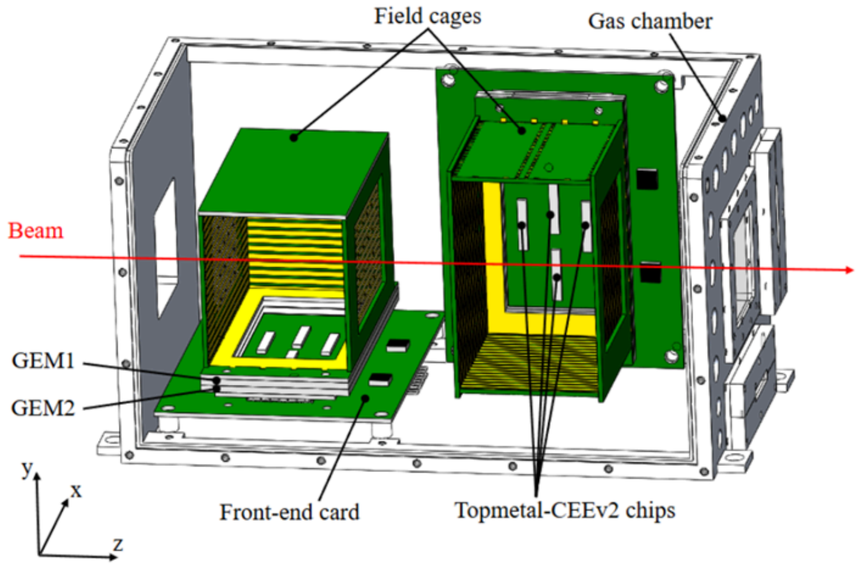
$$= \pi[r_0(A_{beam}^{\frac{1}{3}} + A_{target}^{\frac{1}{3}})]^2 \cdot Nl$$

σ is the reaction cross-section, N is the number of atoms per unit volume, and l is the thickness of the material, r0=1.2fm.

T0 directly gives the content of each atom per unit volume, and for BM, N is calculated using the following ideal gas law:

$$N = \frac{P}{kT}$$

BM:



Window: A total of 6 layers of windows were passed through.

Each layer consists of 2 um of mylar and 100 nm of aluminum.

$$Y_{Windows} < 0.01\ \%$$

Gas: $Ar : CO_2 = 7 : 3,\ P = 0.85atm$

$$Y_{Ar} \approx 0.0385\ \%,\ Y_C \approx 0.0107\ \%$$

$$Y_O \approx 0.0236\ \%,\ Y_{Total} \approx 0.0728\ \%$$

Do not need to consider the influence of BM

Space Charge Effect

Electric force

Frictional force

$$m\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = \boldsymbol{eE} + \boldsymbol{e}[\boldsymbol{u}\times\boldsymbol{B}] - \boldsymbol{Ku},$$

Magnetic force

$$\tau = \frac{m}{K}.$$

***K*:** Friction coefficient (electrons && gas)

steady state $\frac{1}{\tau}u - \frac{e}{m}[u\times B] = \frac{e}{m}E.$ (2.3)

In order to solve for $\boldsymbol{u}$, we write $(e/m)B_x = \omega_x$ etc., $(e/m)E_x = \varepsilon_x$, etc., and express (2.3) in the form of the matrix equation

$$Mu = \varepsilon,$$
$$M = \begin{bmatrix} 1/\tau & -\omega_z & \omega_y \\ \omega_z & 1/\tau & -\omega_x \\ -\omega_y & \omega_x & 1/\tau \end{bmatrix}. \quad (2.4)$$

$$u = M^{-1}\varepsilon,$$
$$M^{-1} = \begin{bmatrix} 1+\omega_x^2\tau^2 & \omega_z\tau+\omega_x\omega_y\tau^2 & -\omega_y\tau+\omega_x\omega_z\tau^2 \\ -\omega_z\tau+\omega_x\omega_y\tau^2 & 1+\omega_y^2\tau^2 & \omega_x\tau+\omega_y\omega_z\tau^2 \\ \omega_y\tau+\omega_x\omega_z\tau^2 & -\omega_x\tau+\omega_y\omega_z\tau^2 & 1+\omega_z^2\tau^2 \end{bmatrix} \times \frac{\tau}{1+\omega^2\tau^2},$$

Zhi-Hui Xu, IMP, CAS. 7/29/2025 1

TPC正离子迁移率计算

Chengyang Liu

$K_0^{Ar} = 1.94 \pm 0.01,\ K_0^{CO_2} = 1.10 \pm 0.01\ \mathrm{cm^2/(V\,s)}$

Data from refer(1)

CO_2 -based cluster ion drift

$$\frac{1}{K_0^{mix}} = \frac{x_{Ar}}{K_0^{Ar}} + \frac{x_{CO_2}}{K_0^{CO_2}}$$

$$K_0^{mix} = \frac{1}{0.9/1.94 + 0.1/1.10} \approx 1.80\ \mathrm{cm^2/(V\,s)}$$

Due to $K = K_0 \cdot \frac{T}{T_0} \cdot \frac{P_0}{P}$

Consider the temperature is 15 between 10 ~ 20 degrees Celsius

P = 0.85 atm

Setting: $T_0 = 273.15\ \mathrm{K},\ P_0 = 1\ \mathrm{atm},\ T = 288.15\ \mathrm{K},\ P = 0.85\ \mathrm{atm}$

$$K \approx 1.802 \times \frac{288.15}{273.15} \times \frac{1}{0.85} = 2.237\ \mathrm{cm^2/(V\,s)}$$

The author clearly explains in Section 4.3 that since there are no signs of multiple ions drifting simultaneously in the data, and it conforms to the expectation of "only one (CO_2 -based cluster) ion drifting".

$v = KE = 2.237 \times 300 = 671\ \mathrm{cm/s} = 6.71\ \mathrm{m/s}$ //Voltage is

$v = KE = 2.237 \times 320 = 715.84\ \mathrm{cm/s} = 7.16\ \mathrm{m/s}$ //Voltage is 320V/cm

(1)Deisting, A.; Garabatos, C.; Szabo, A. Ion mobility measurements in Ar-CO2, Ne-CO2, and Ne-CO2-N2 mixtures, and the effect of water contents. arXiv:1804.10288 [physics.ins-det], 2018 (preprint submitted to NIM A, June 2018

TPC正离子迁移率

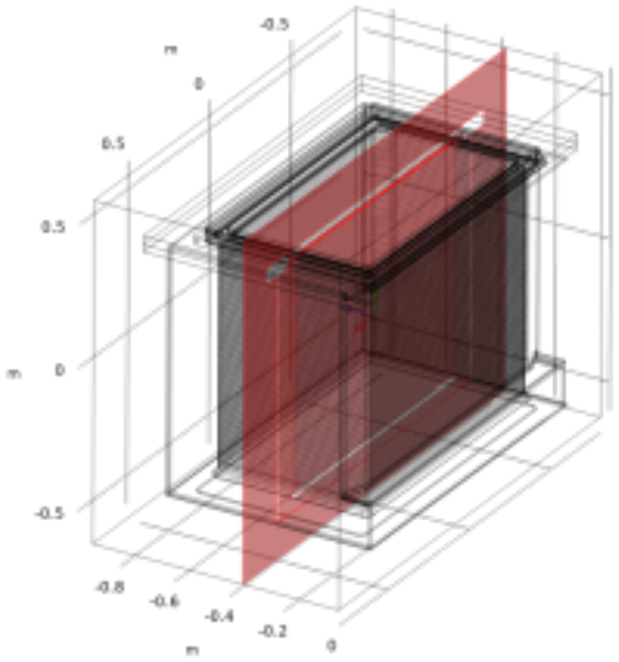
Chengyang Liu

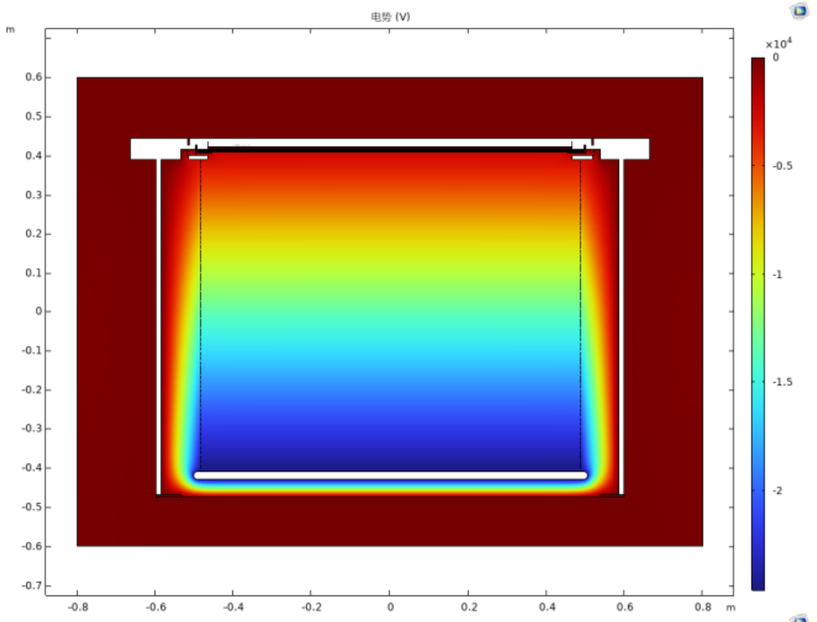
TPC 集团重建代码本身从unpacker后文件中能获得的信息有 ： 1、当前所处runid 2、当前事件所处的run的时间（这个事件发生在当前run的XXX秒）。

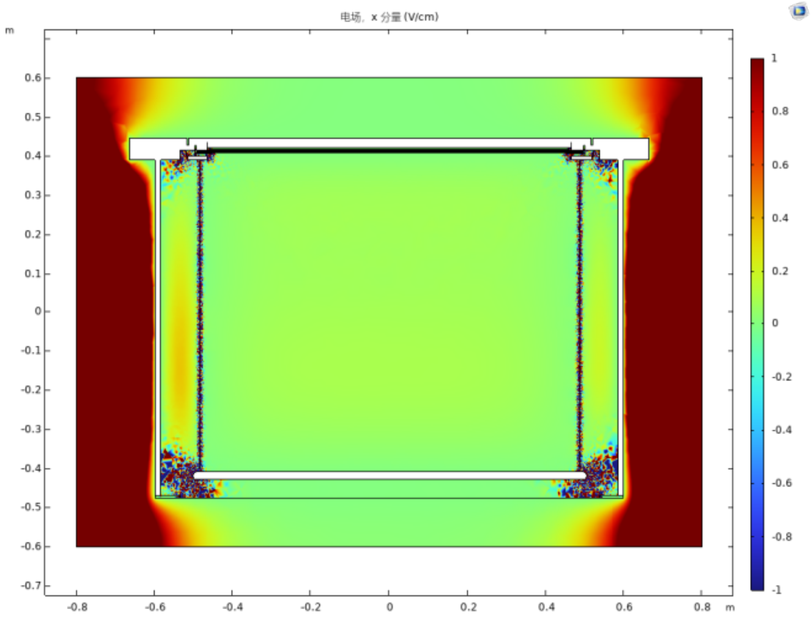
TPC会告诉慢控TPC需要的某个时间段的T0计数信息 来获取这部分信息

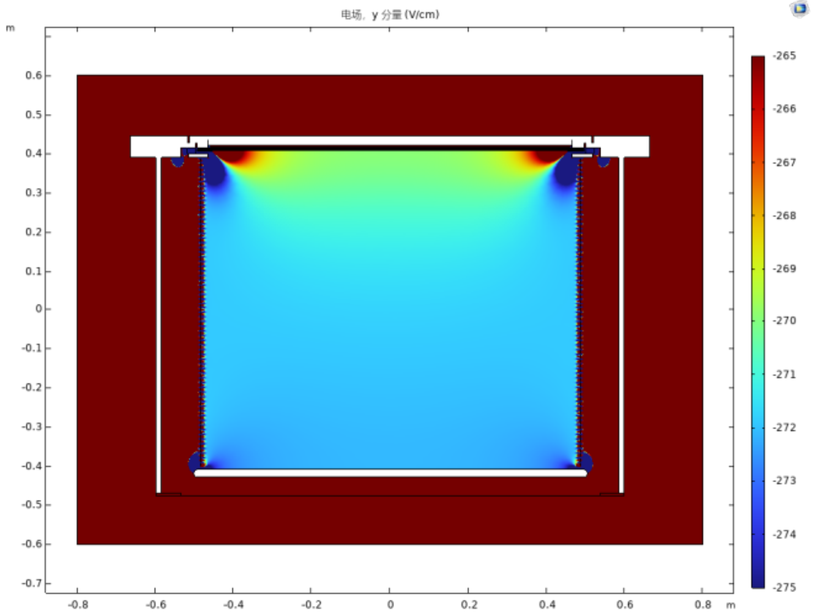
TPC根据T0计数来估计事例率的时间分别进而转化成反馈的正离子的空间分布

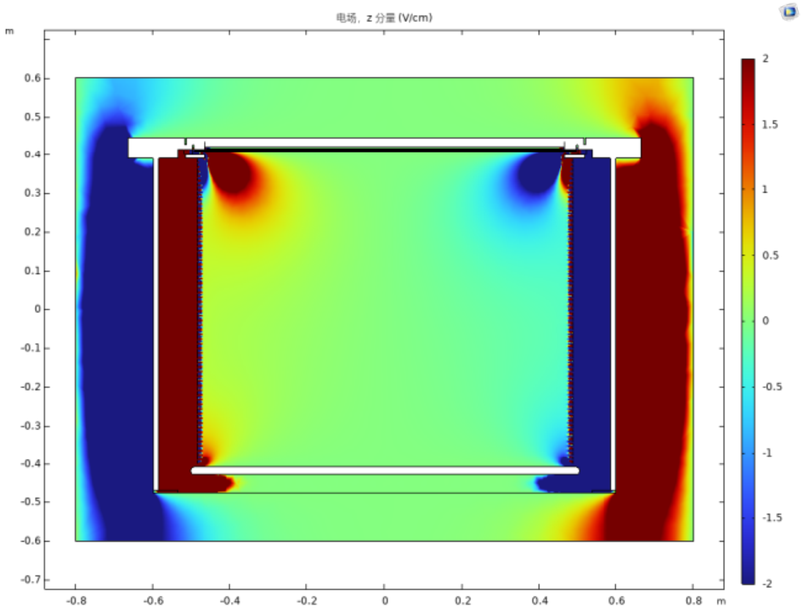
COMSOL中畸变电场的计算







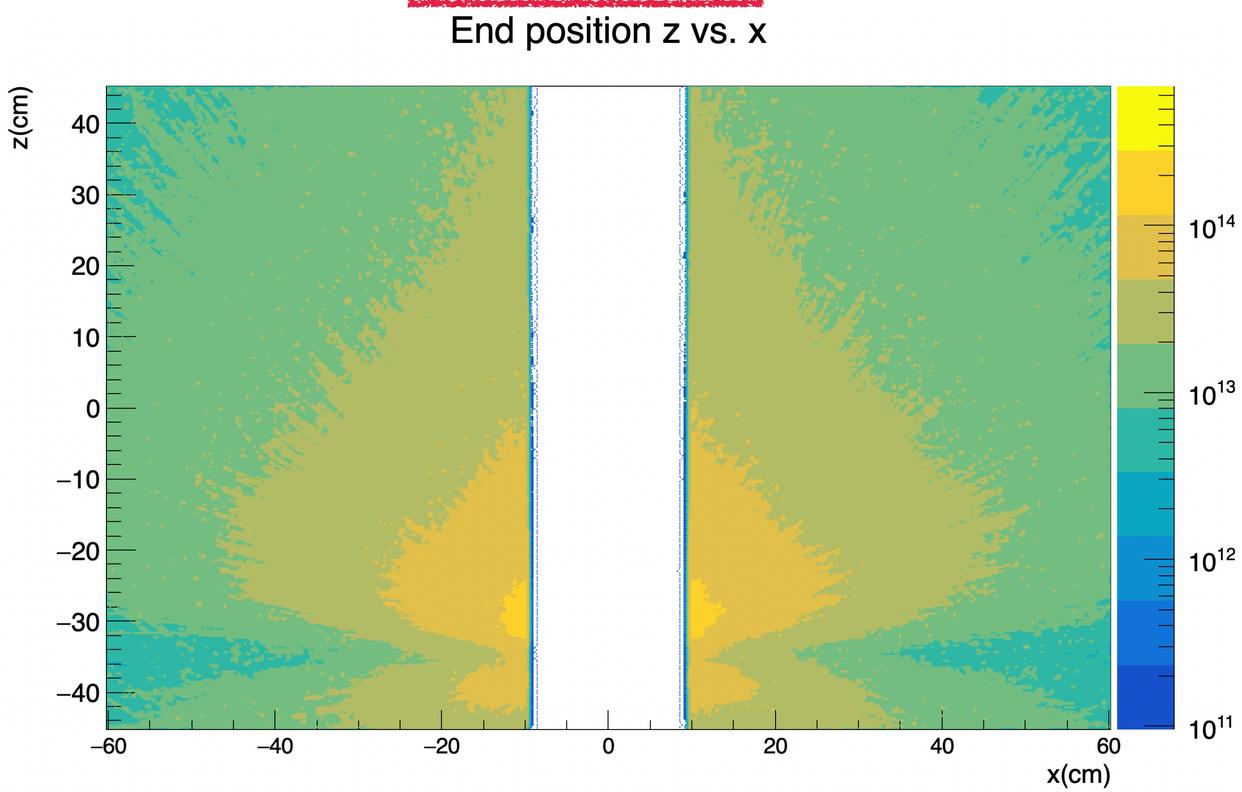




Comparison of electron number density ($/m^2$)distribution between simulated and real data

Sim data: add T0(100k event)

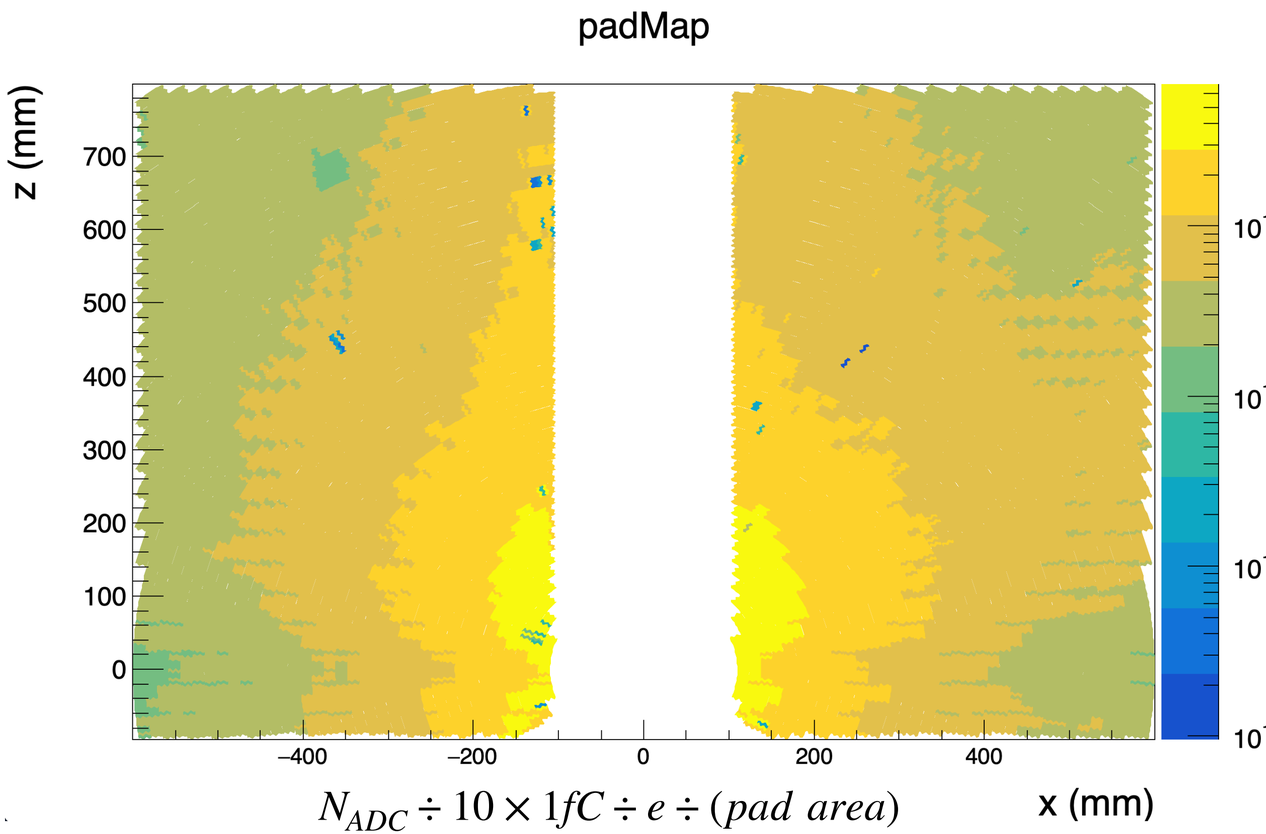
C+C:C+Pb = 2.5:1



$N_e \times Coefficient \div (bin\ area) = N_e \times 1500 \div (3 \times 3 \times 10^{-6})$

Simulated ionized electron number multiplied by gain coefficient (1500), and divide by the area of bin(3x3 mm).

Real data: digi (2026.1.13, 100k event)



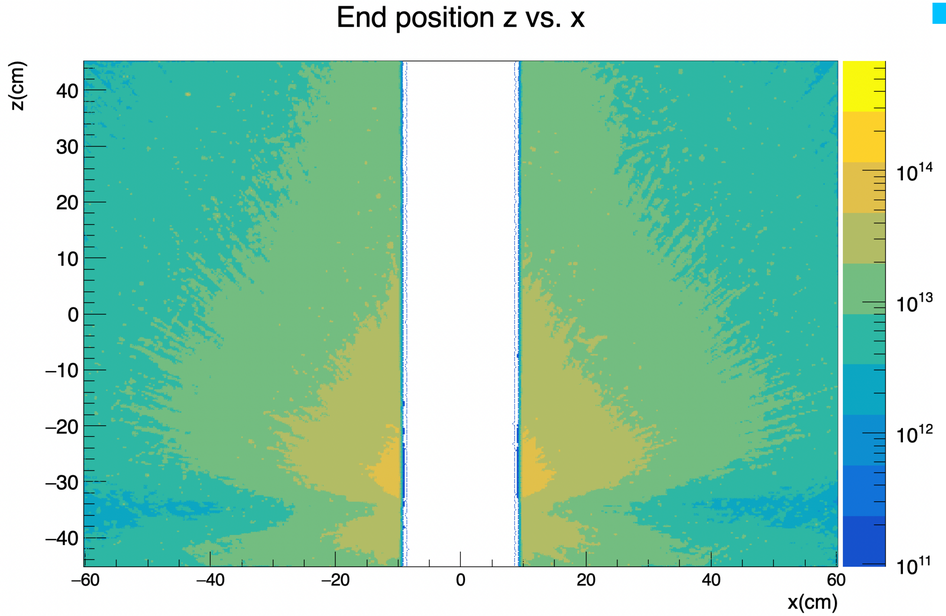
$N_{ADC} \div 10 \times 1fC \div e \div (pad\ area)$

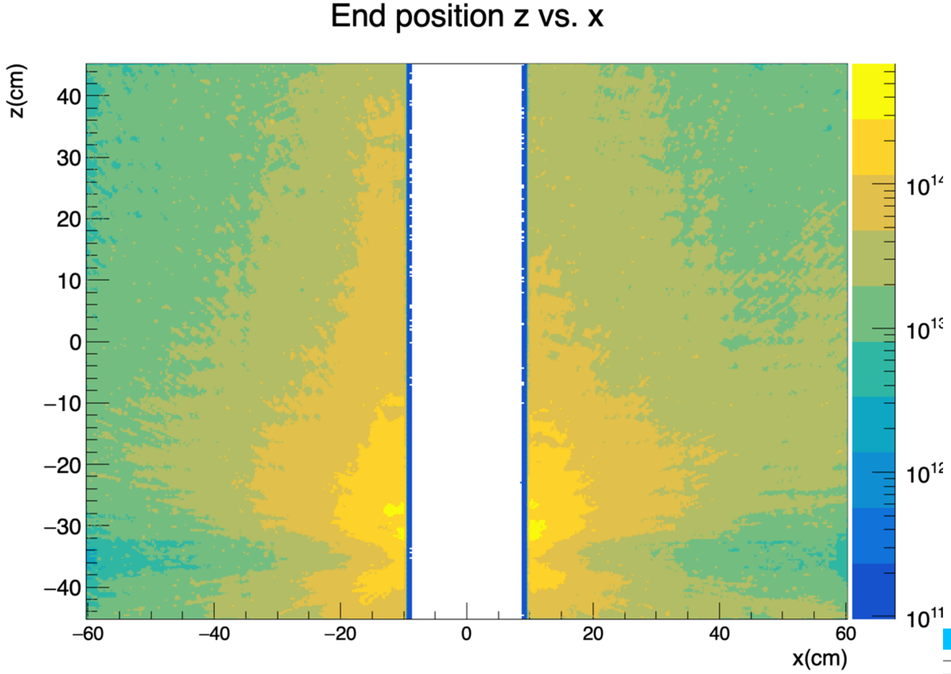
$= N_{ADC} \times 10^3 \div 1.602 \div (14 \times 4 \times 10^{-6})$

10 ADCs represent the charge quantity of 1fC.

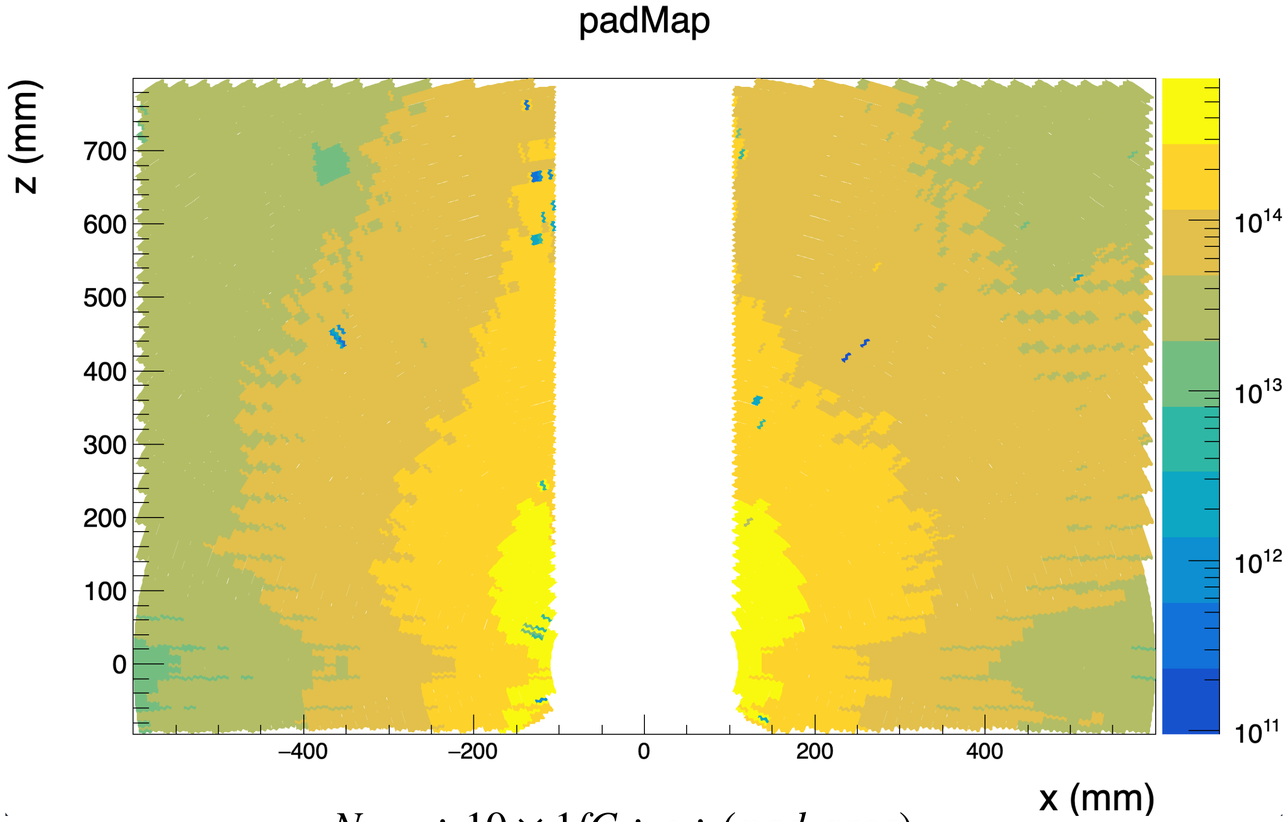
Total number of electrons: Real data:Sim data =3.7:1

Comparison of electron number density ($/m^2$)distribution between simulated and real data





Real data: digi (2026.1.13, 100k event)



$$N_{ADC} \div 10 \times 1fC \div e \div (pad\ area)$$

$$= N_{ADC} \times 10^3 \div 1.602 \div (14 \times 4 \times 10^{-6})$$

10 ADCs represent the charge quantity of 1fC.

Total number of electrons: Real data:Sim data = 2.7:1

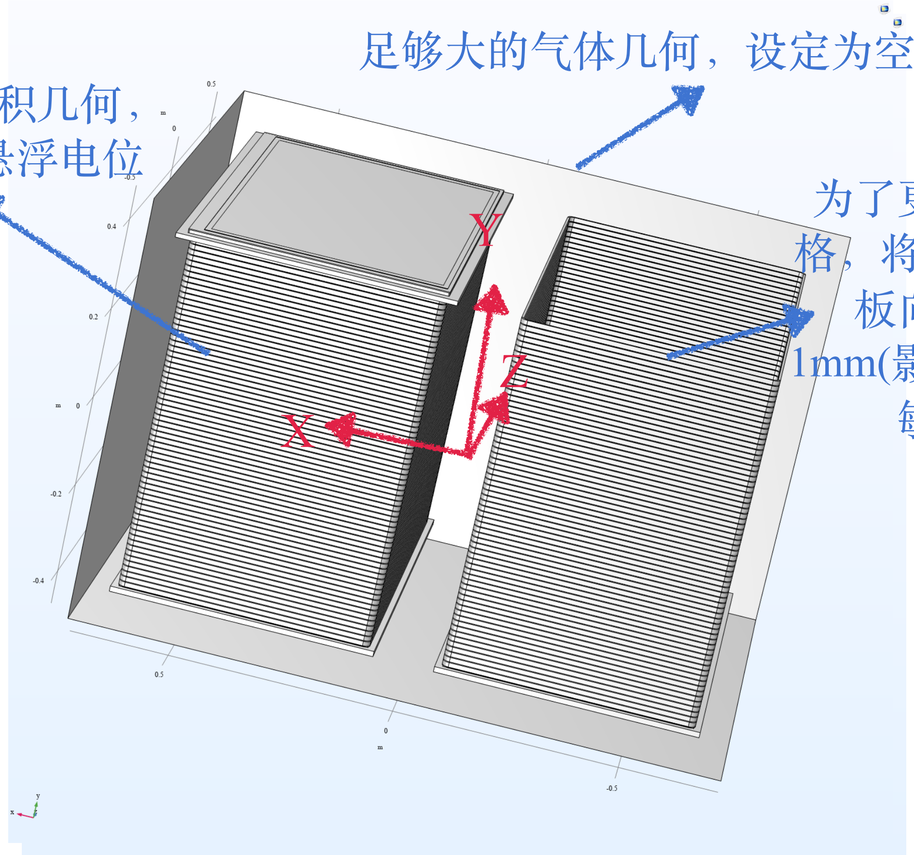
CEE TPC Space charge calibration progress (step3~4)

Simple Geometry in Cosmol

足够大的气体几何，设定为空气，接地

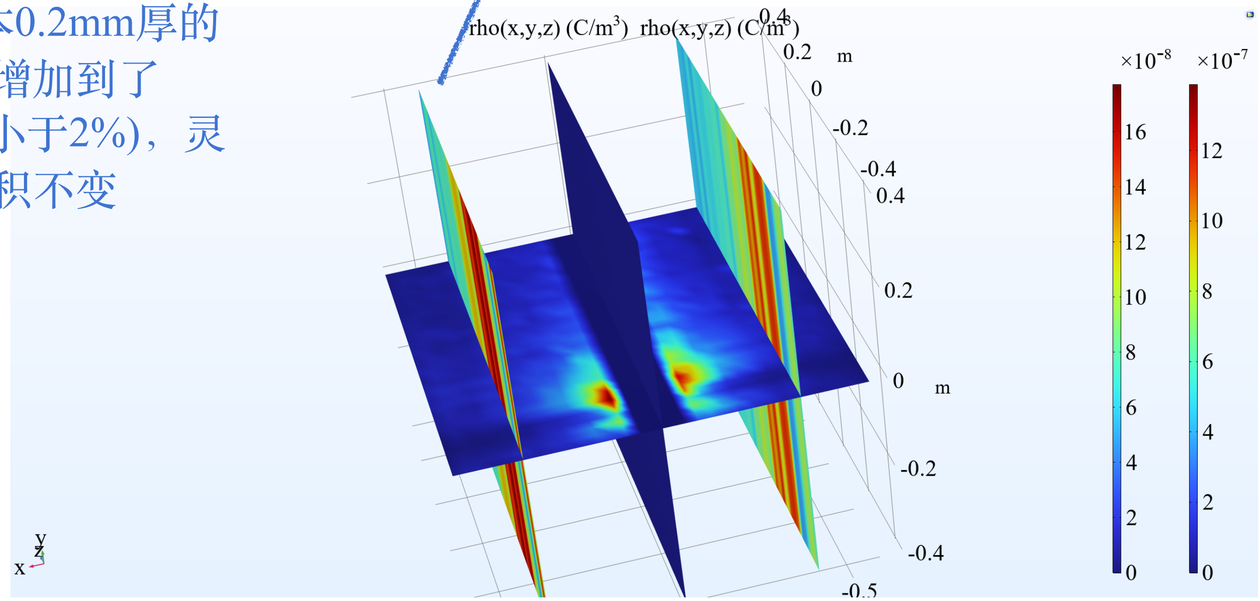
简化的灵敏体积几何，设定为铝，悬浮电位

为了更好划分计算网格，将原本0.2mm厚的板向外增加到了1mm(影响小于2%)，灵敏体积不变



Space charge distribution

XZ平面漂移电子分布乘GEM膜正离子反馈系数再均分到y方向（假设流强稳定）

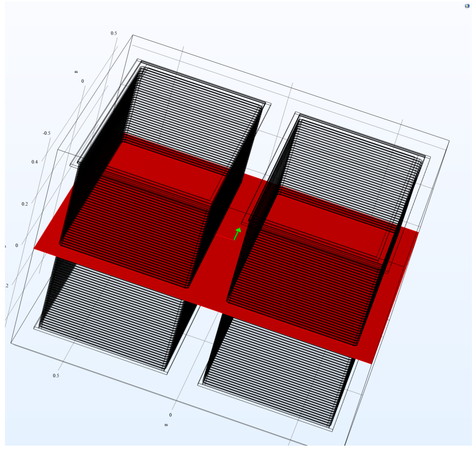


未来需要更详细的正离子反馈系数，以及增加了正离子迁移率的气体文件

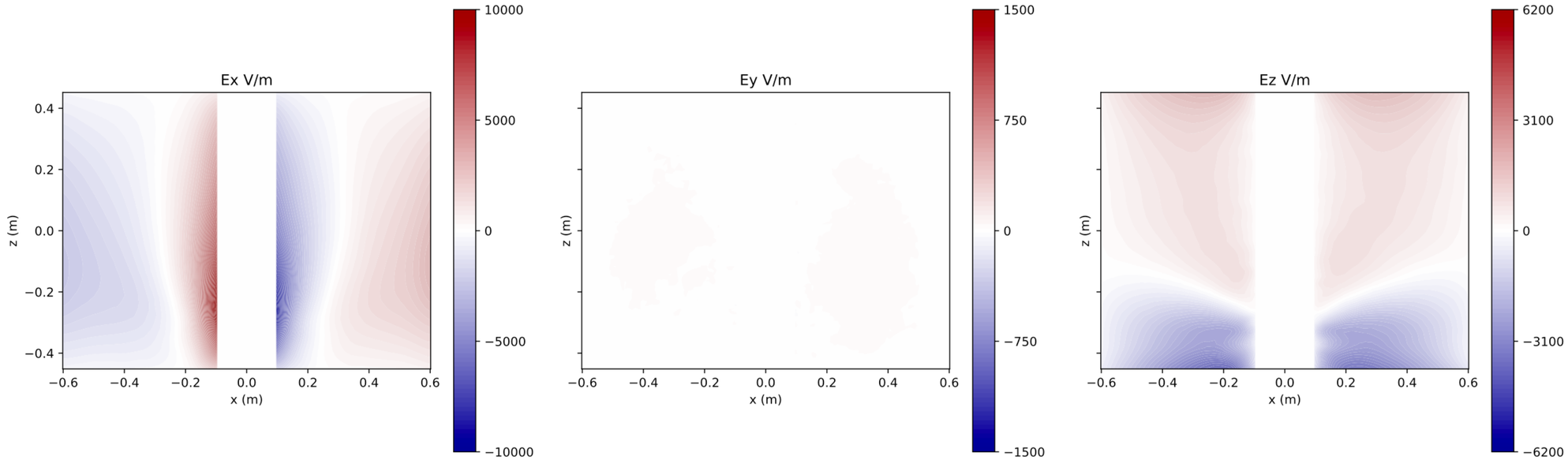
/public/home/wxiuxian/data/SpaceCharge_test.mph

CEE TPC Space charge calibration progress (step4)

电场截面示意图



XZ平面，y = 0cm

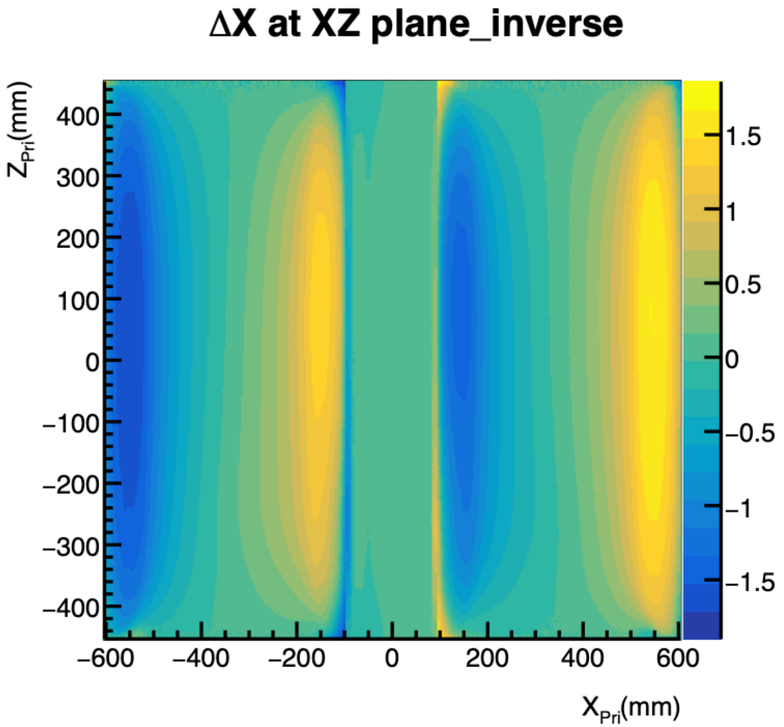


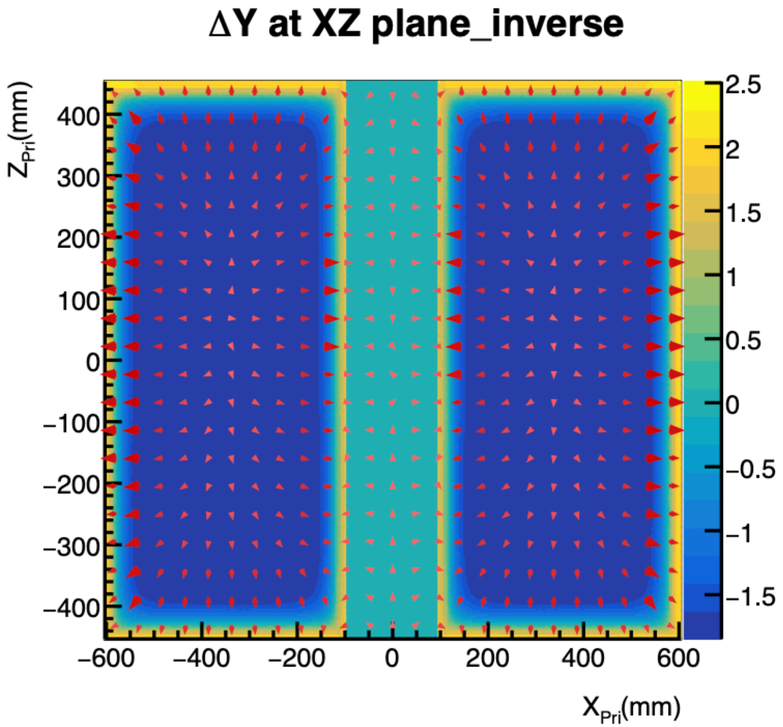
CEE TPC Space charge calibration progress (step5)

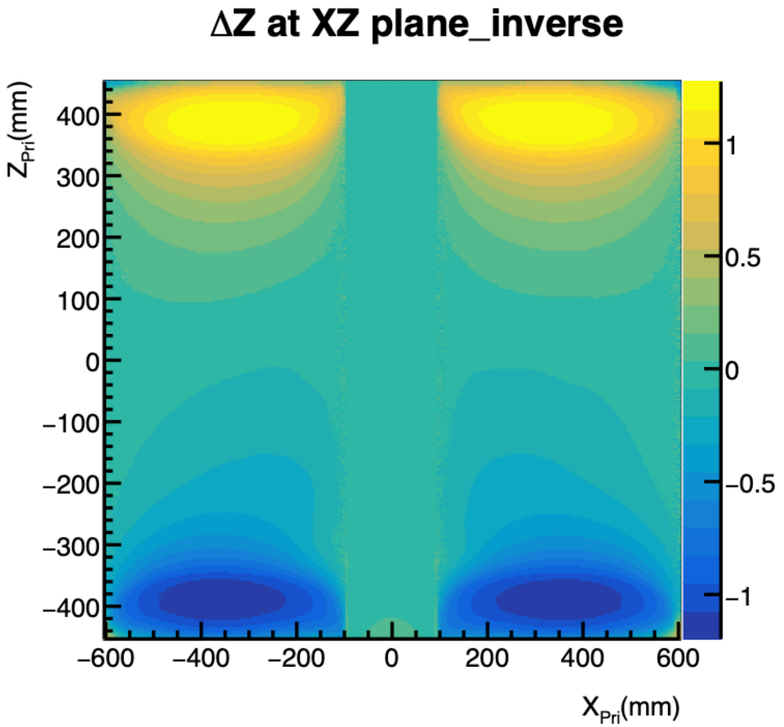
2026.11 加上电场畸变电场结果

畸变电场+空间电荷效应*1

ΔX = Measured Position - True Position







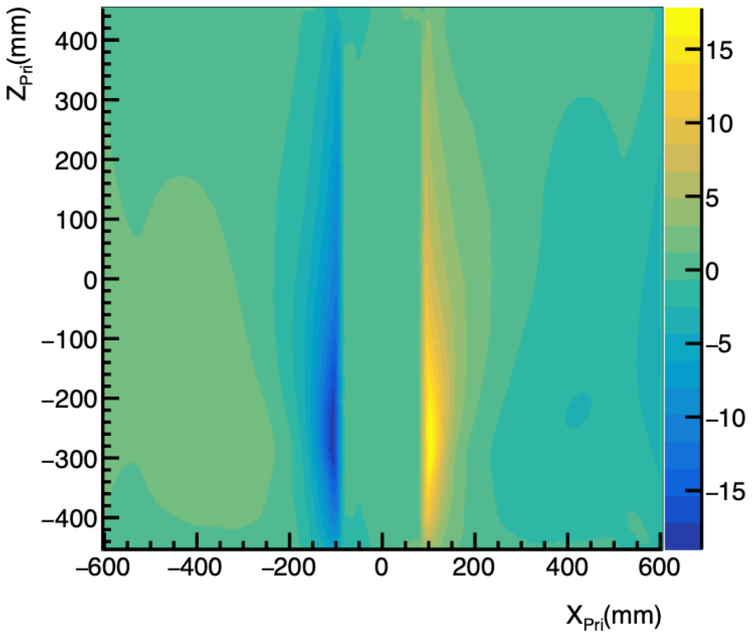
CEE TPC Space charge calibration progress (step5)

2026.11 加上电场畸变电场结果

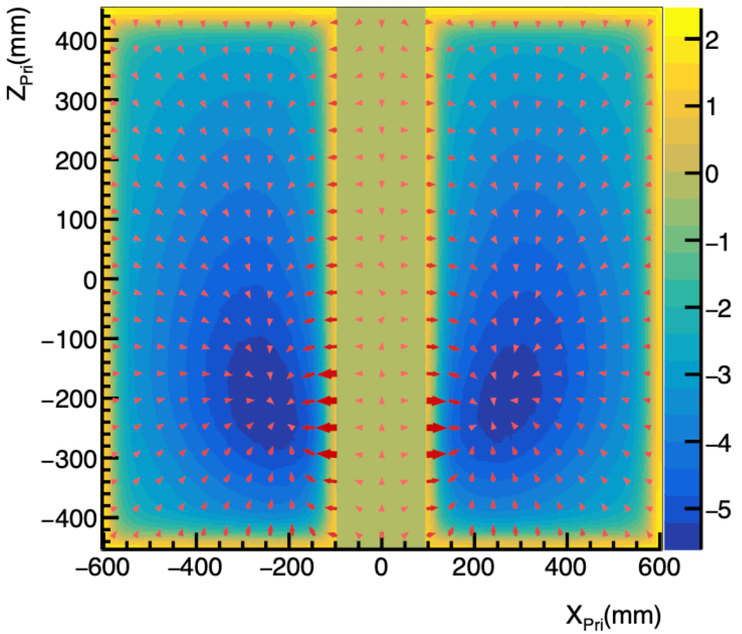
畸变电场+空间电荷效应*修正因子20

ΔX = Measured Position - True Position

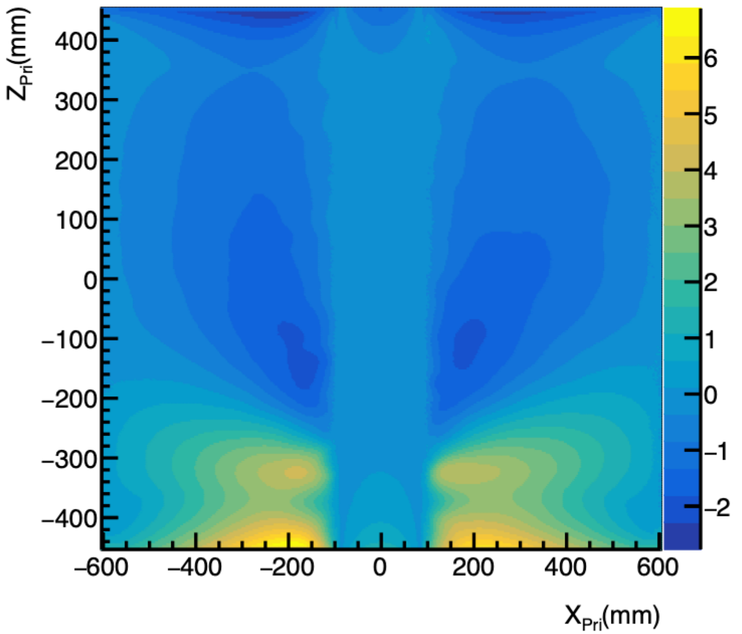
ΔX at XZ plane_inverse

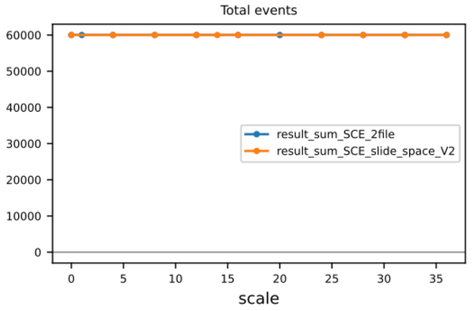


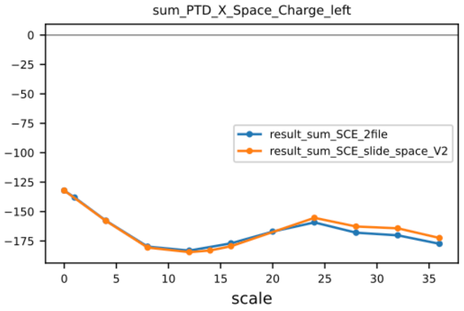
ΔY at XZ plane_inverse

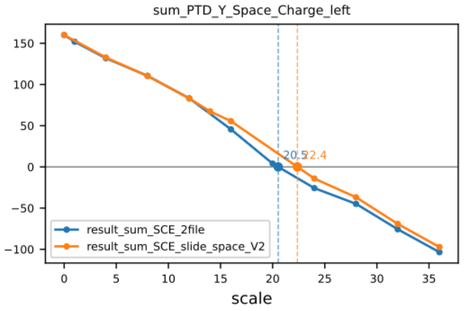


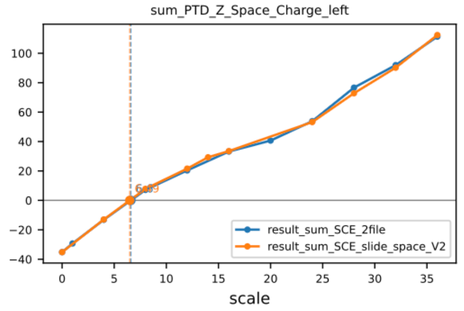
ΔZ at XZ plane_inverse

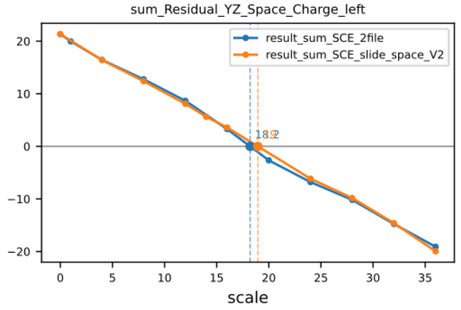


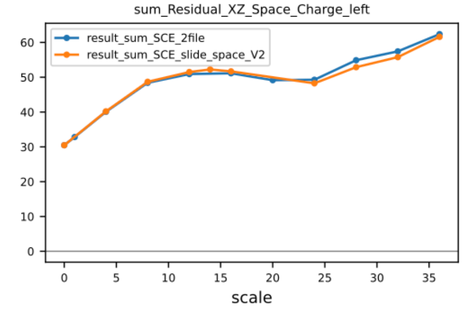

Total events
result_sum_SCE_2file
result_sum_SCE_slide_space_V2
scale

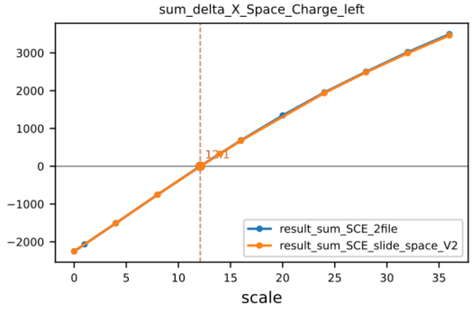

sum_PTD_X_Space_Charge_left
result_sum_SCE_2file
result_sum_SCE_slide_space_V2
scale

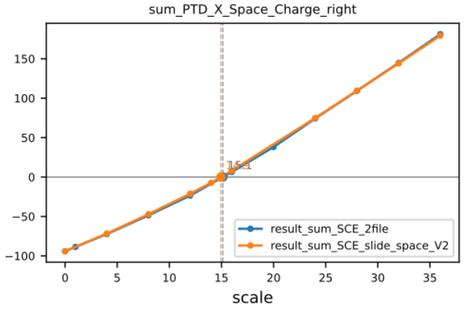

sum_PTD_Y_Space_Charge_left
result_sum_SCE_2file
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scale

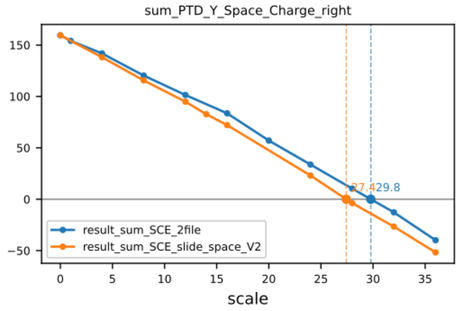

sum_PTD_Z_Space_Charge_left
result_sum_SCE_2file
result_sum_SCE_slide_space_V2
scale

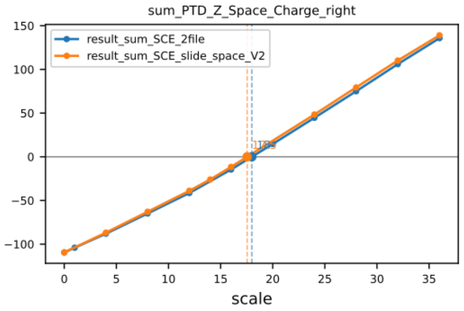

sum_Residual_YZ_Space_Charge_left
result_sum_SCE_2file
result_sum_SCE_slide_space_V2
scale

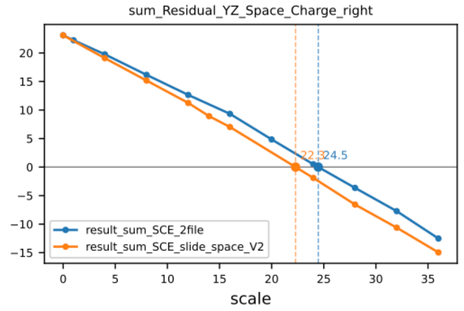

sum_Residual_XZ_Space_Charge_left
result_sum_SCE_2file
result_sum_SCE_slide_space_V2
scale

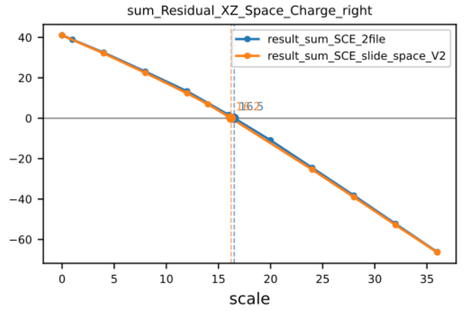

sum_delta_X_Space_Charge_left
result_sum_SCE_2file
result_sum_SCE_slide_space_V2
scale

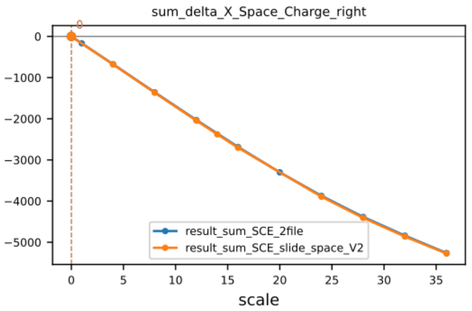

sum_PTD_X_Space_Charge_right
result_sum_SCE_2file
result_sum_SCE_slide_space_V2
scale

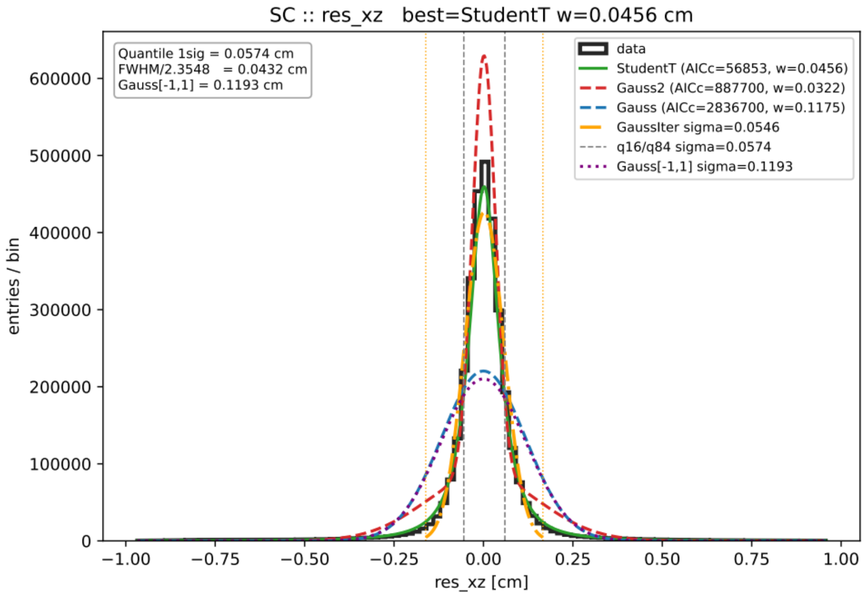

sum_PTD_Y_Space_Charge_right
result_sum_SCE_2file
result_sum_SCE_slide_space_V2
scale

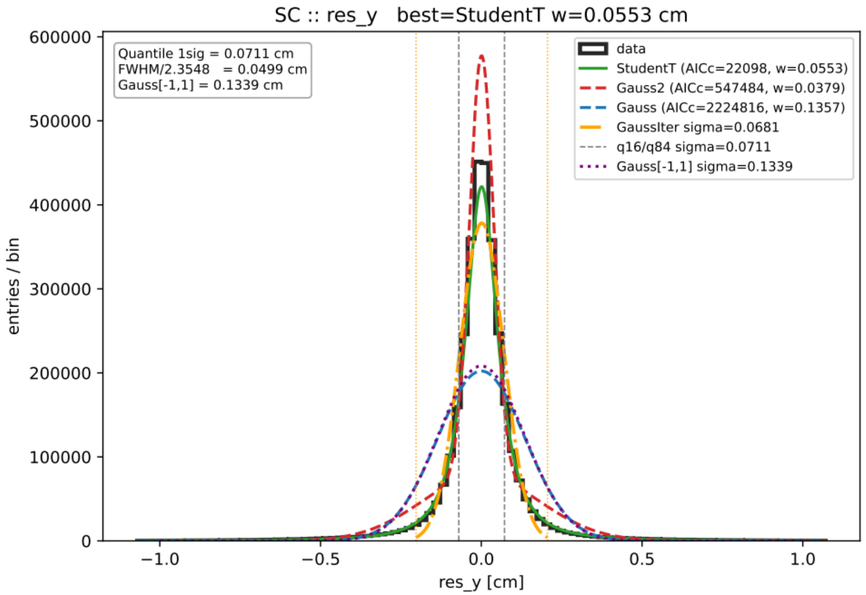

sum_PTD_Z_Space_Charge_right
result_sum_SCE_2file
result_sum_SCE_slide_space_V2
scale

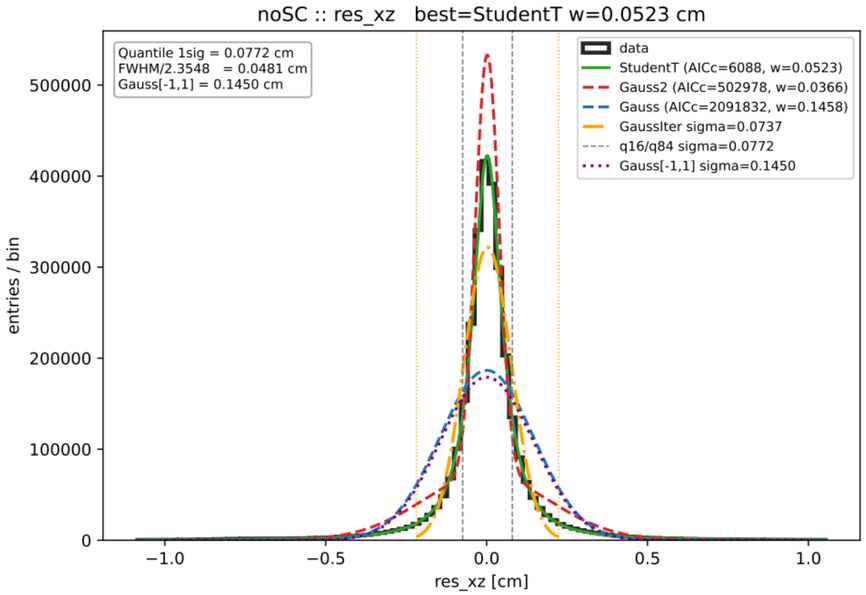

sum_Residual_YZ_Space_Charge_right
result_sum_SCE_2file
result_sum_SCE_slide_space_V2
scale

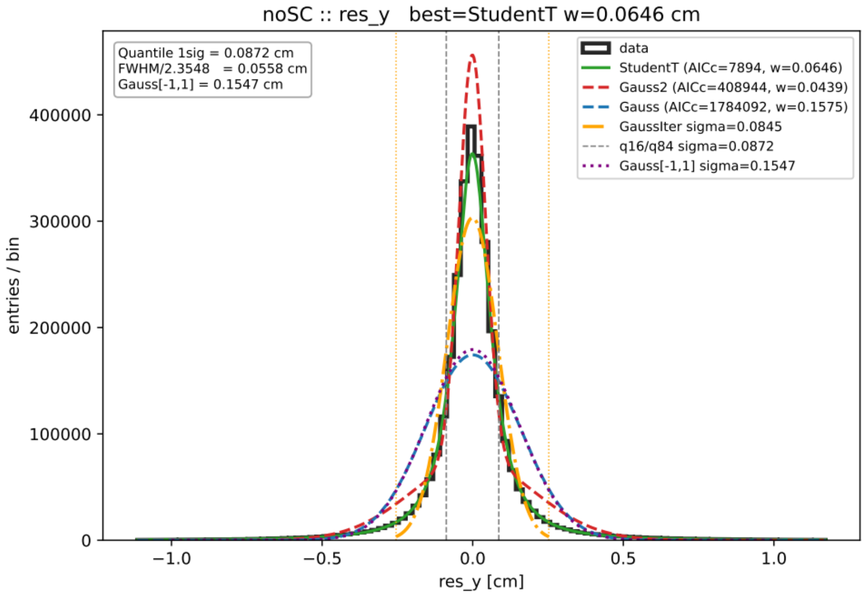

sum_Residual_XZ_Space_Charge_right
result_sum_SCE_2file
result_sum_SCE_slide_space_V2
scale


sum_delta_X_Space_Charge_right
result_sum_SCE_2file
result_sum_SCE_slide_space_V2
scale


SC :: res_xz best=StudentT w=0.0456 cm
Quantile 1sig = 0.0574 cm
FWHM/2.3548 = 0.0432 cm
Gauss[-1,1] = 0.1193 cm
data
StudentT (AICc=56853, w=0.0456)
Gauss2 (AICc=887700, w=0.0322)
Gauss (AICc=2836700, w=0.1175)
GaussIter sigma=0.0546
q16/q84 sigma=0.0574
Gauss[-1,1] sigma=0.1193
entries / bin
res_xz [cm]


SC :: res_y best=StudentT w=0.0553 cm
Quantile 1sig = 0.0711 cm
FWHM/2.3548 = 0.0499 cm
Gauss[-1,1] = 0.1339 cm
data
StudentT (AICc=22098, w=0.0553)
Gauss2 (AICc=547484, w=0.0379)
Gauss (AICc=2224816, w=0.1357)
GaussIter sigma=0.0681
q16/q84 sigma=0.0711
Gauss[-1,1] sigma=0.1339
entries / bin
res_y [cm]


noSC :: res_xz best=StudentT w=0.0523 cm
Quantile 1sig = 0.0772 cm
FWHM/2.3548 = 0.0481 cm
Gauss[-1,1] = 0.1450 cm
data
StudentT (AICc=6088, w=0.0523)
Gauss2 (AICc=502978, w=0.0366)
Gauss (AICc=2091832, w=0.1458)
GaussIter sigma=0.0737
q16/q84 sigma=0.0772
Gauss[-1,1] sigma=0.1450
entries / bin
res_xz [cm]


noSC :: res_y best=StudentT w=0.0646 cm
Quantile 1sig = 0.0872 cm
FWHM/2.3548 = 0.0558 cm
Gauss[-1,1] = 0.1547 cm
data
StudentT (AICc=7894, w=0.0646)
Gauss2 (AICc=408944, w=0.0439)
Gauss (AICc=1784092, w=0.1575)
GaussIter sigma=0.0845
q16/q84 sigma=0.0872
Gauss[-1,1] sigma=0.1547
entries / bin
res_y [cm]