



中国科学院近代物理研究所  
Institute of Modern Physics, Chinese Academy of Sciences



中国科学院大学  
University of Chinese Academy of Sciences

# 用于低本底核反应研究的 $\alpha$ 粒子 Bragg 波形分析与判别方法研究

范翊华 唐晓东 张宁涛

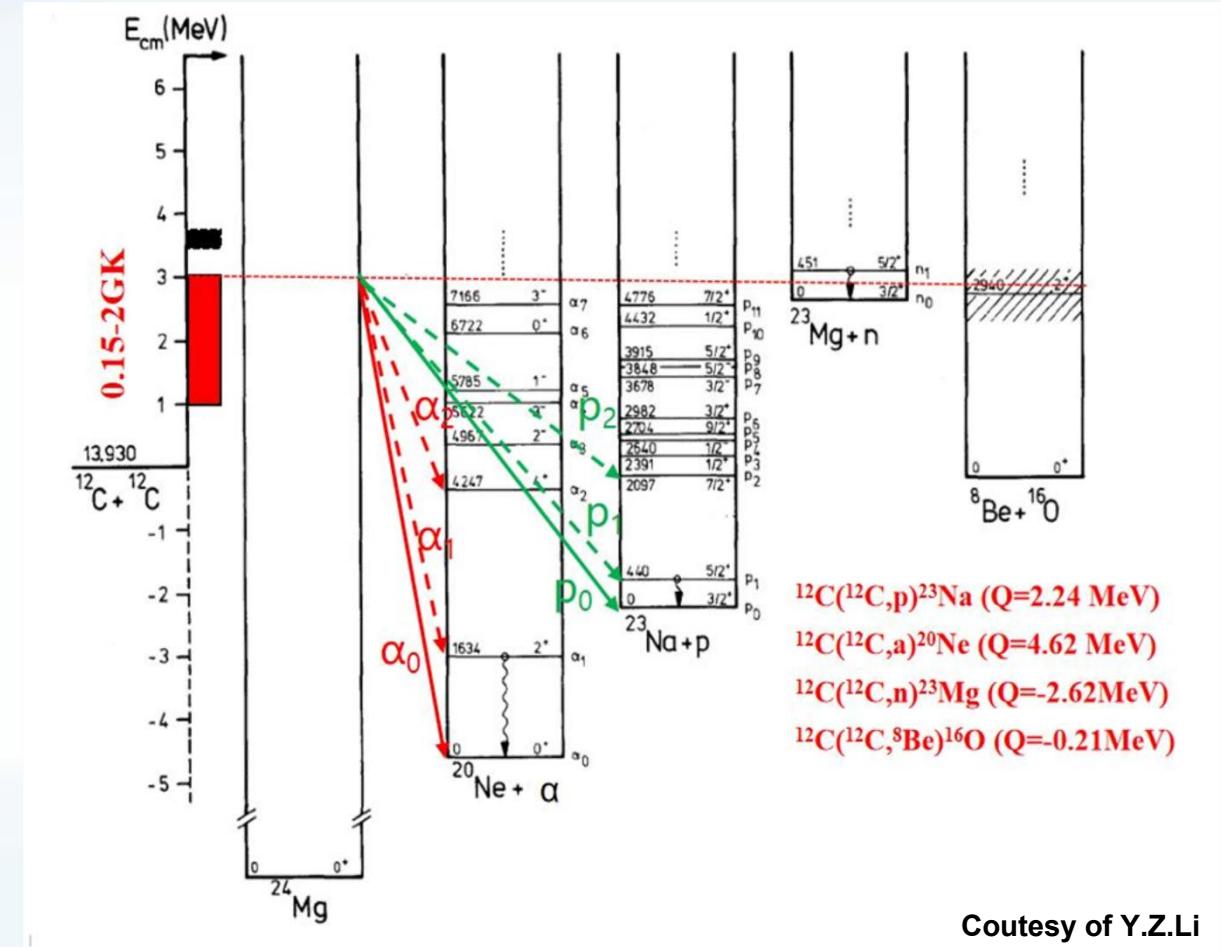
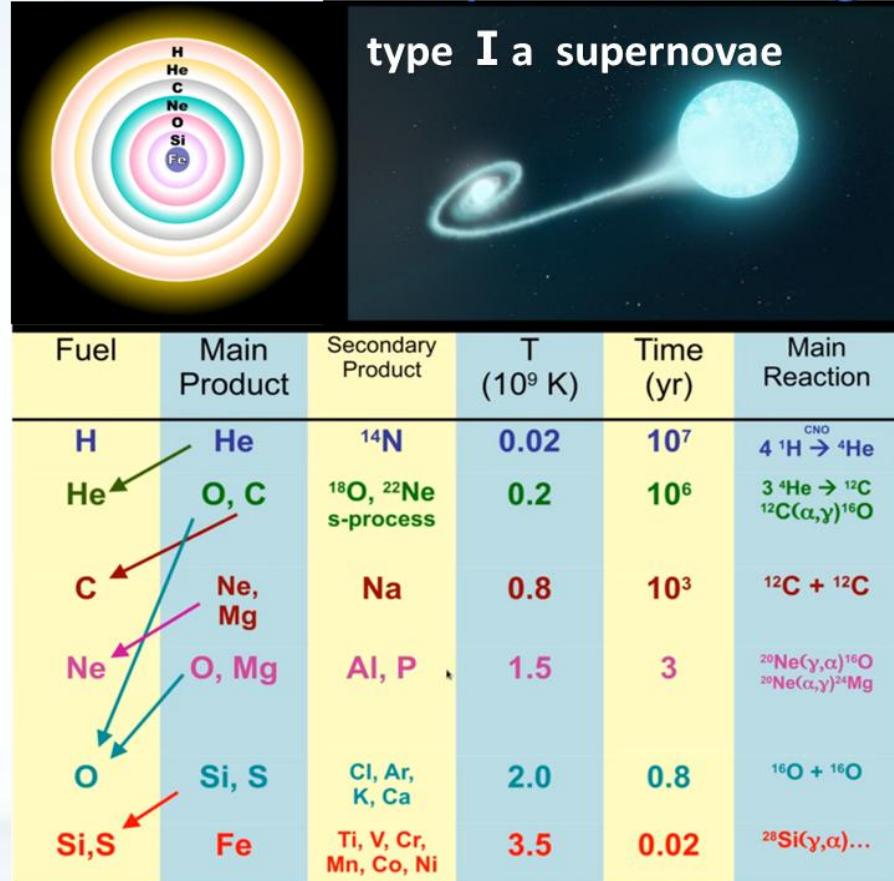
MateTPC合作组  
中国科学院近代物理研究所

中国科学院大学

2025-12-30

# 背景

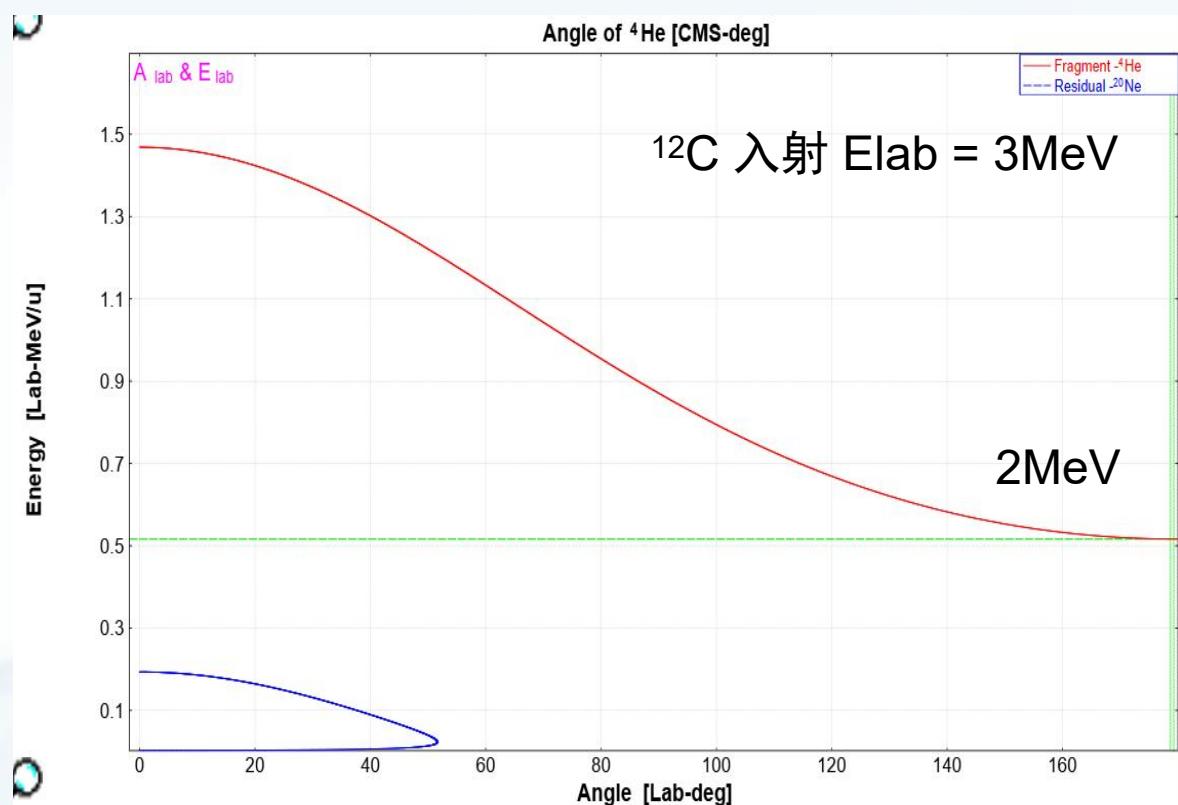
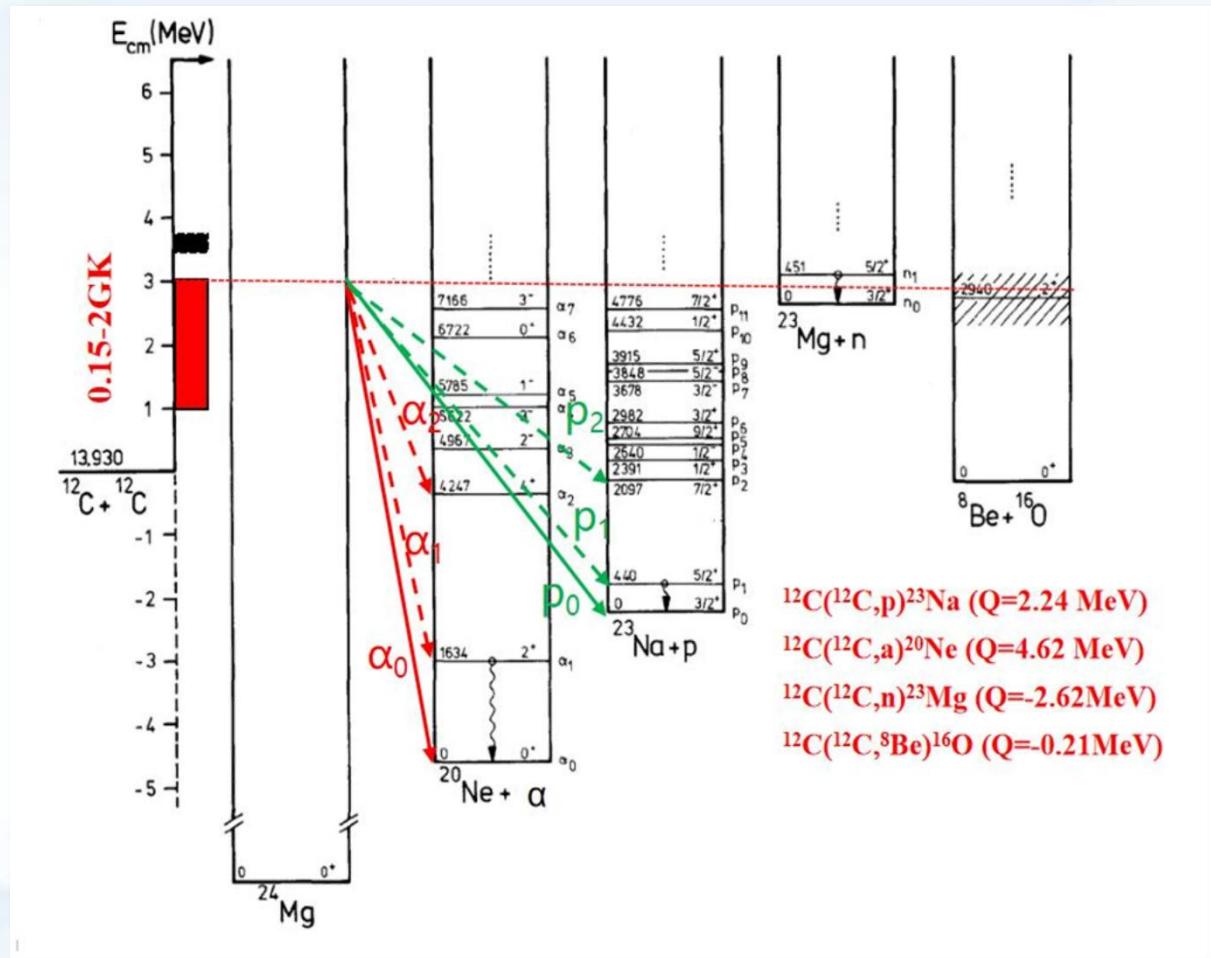
## Stable burning Explosive burning



Courtesy of Y.Z.Li

- <sup>12</sup>C+<sup>12</sup>C熔合反应是大质量恒星燃烧阶段的关键反应( $T_9 \sim 0.8 - 1.2$ )和Ia型超新星和超级暴的点火反应( $T_9 \sim 0.15 - 0.7$ )

## 背景

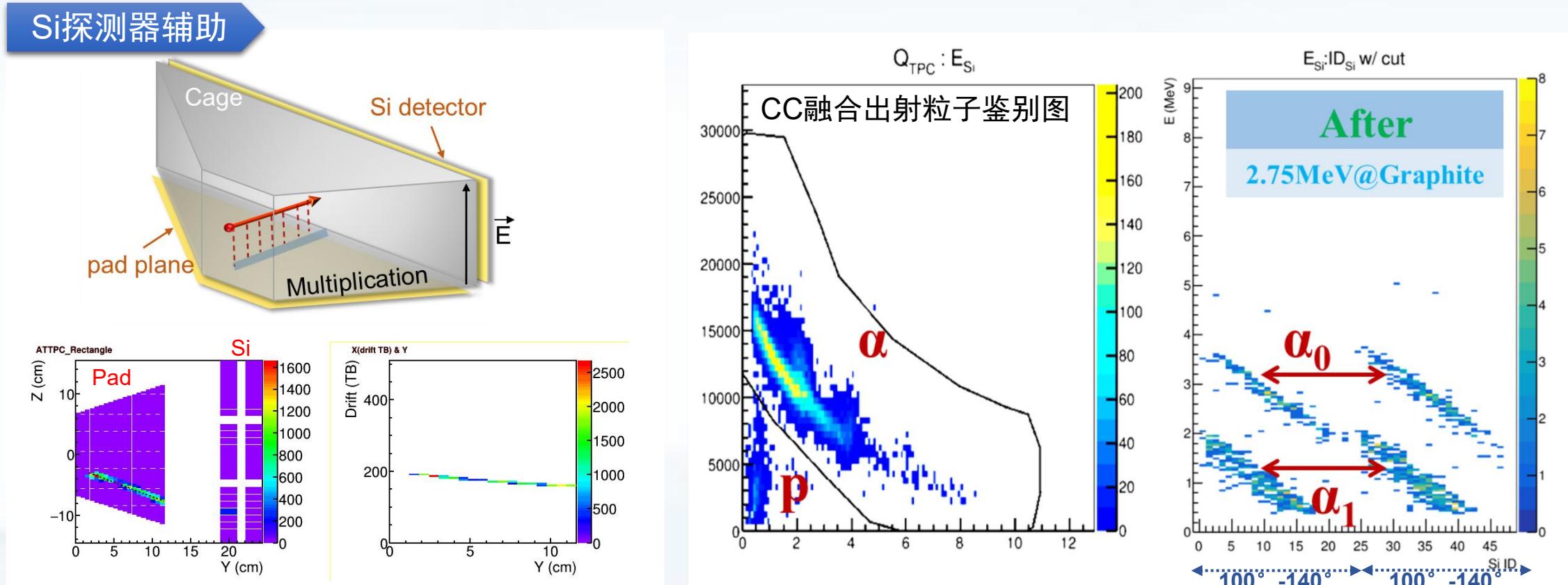


- $^{12}\text{C}$ 入射能量为3MeV时，反应截面  $10^{-22} \text{ bar}$   $\alpha_1$ 道出射能量最低为2MeV

# TPC探测器



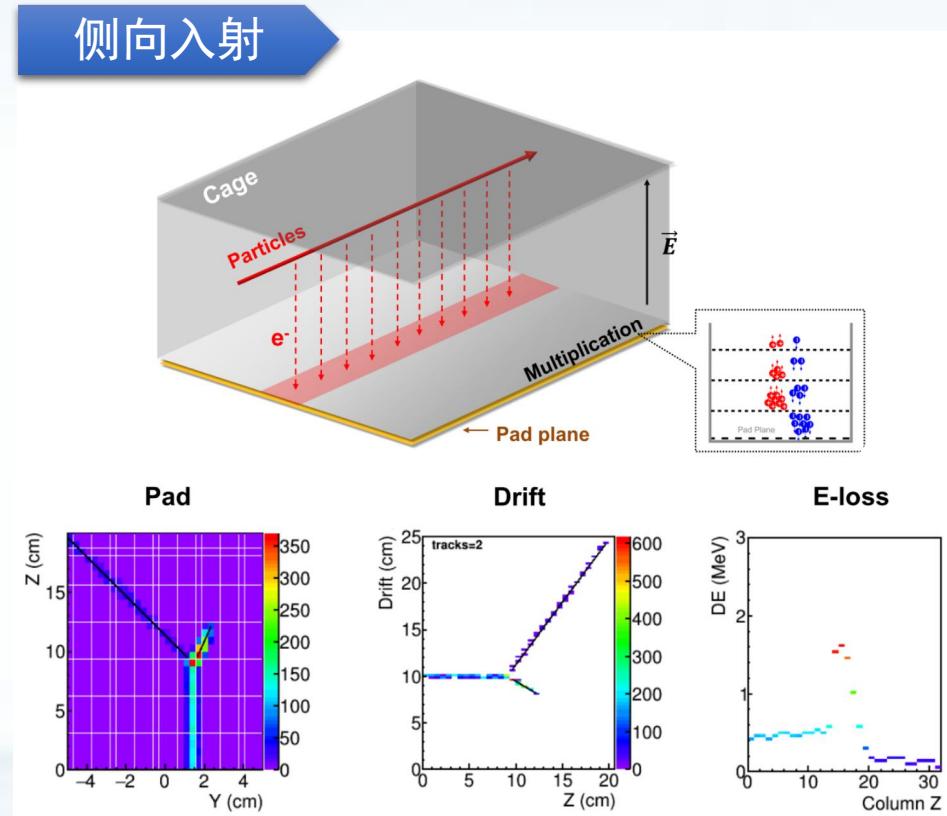
时间投影室（TPC）具备三维径迹重建、高位置分辨、大立体角覆盖的探测效率等优点：



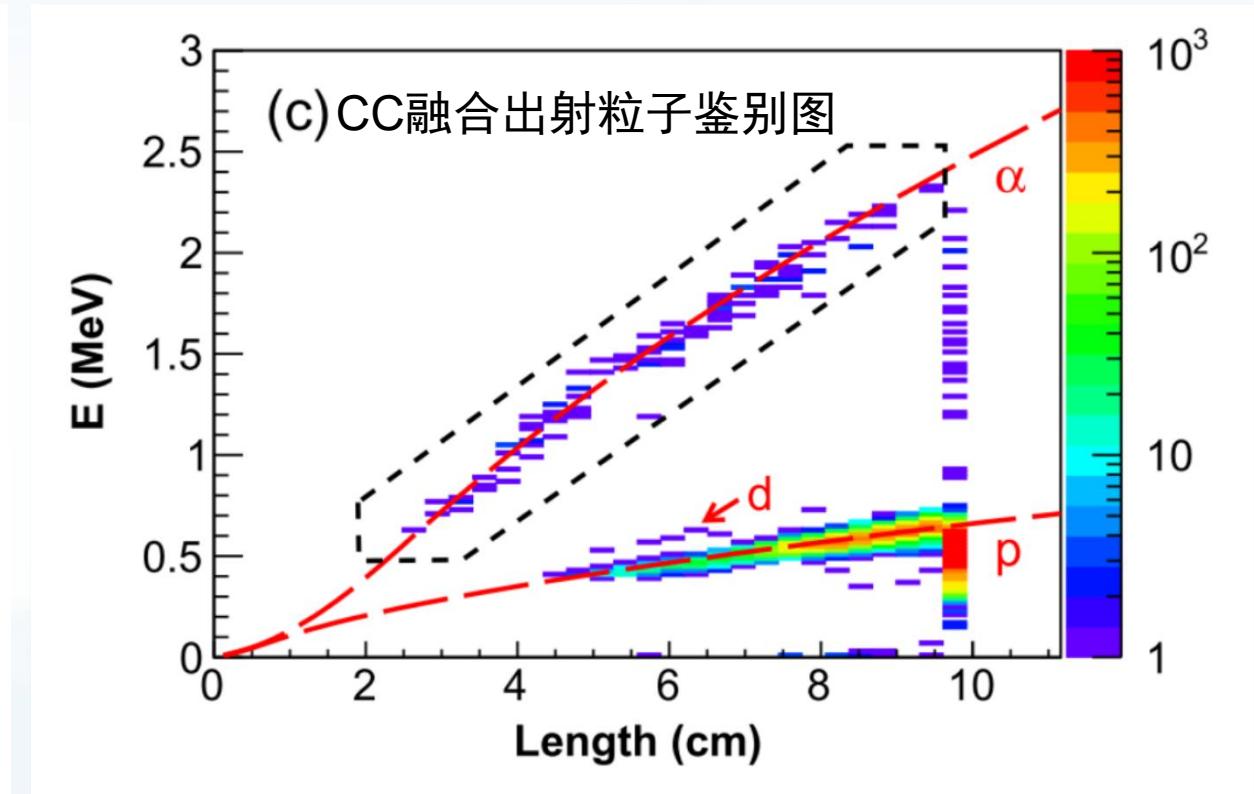
- dE-E粒子鉴别，高能量分辨，Si阵列提供绝对位置
- 探测阈值较高：Si 阈值 500keV  $E_\alpha = 2.8\text{MeV}$

# TPC探测器

时间投影室（TPC）具备三维径迹重建、高位置分辨、大立体角覆盖的探测效率等优点：



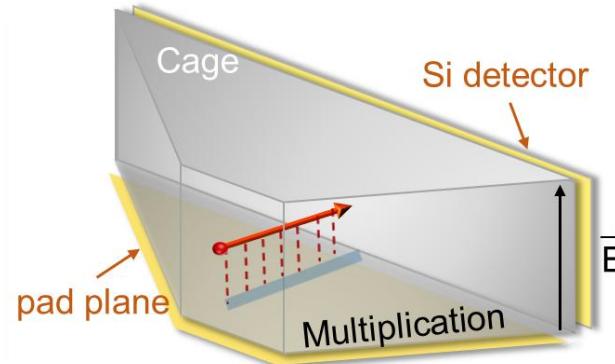
Zhang, Z. C. et al(2021).NIMA,1016, 165740.



- 低探测阈值：灵敏区域 150keV；极低本底：0.29/h
- THGEM触发，无绝对入射位置

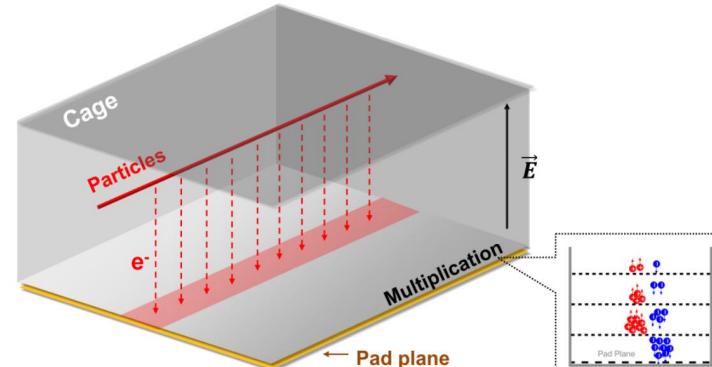
时间投影室（TPC）具备三维径迹重建、高位置分辨、大立体角覆盖的探测效率等优点：

## Si探测器辅助



- dE-E粒子鉴别，高能量分辨
- Si阵列提供绝对位置
- 探测阈值较高：500keV

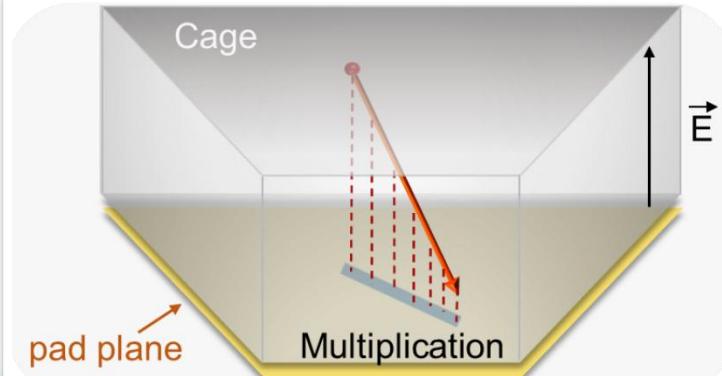
## 侧向入射



- 低探测阈值：灵敏区 150keV；
- 极低本底：0.29/h
- THGEM触发，无绝对入射位置

Zhang, Z. C. et al(2021).NIMA,1016, 165740.

## 漂移方向入射



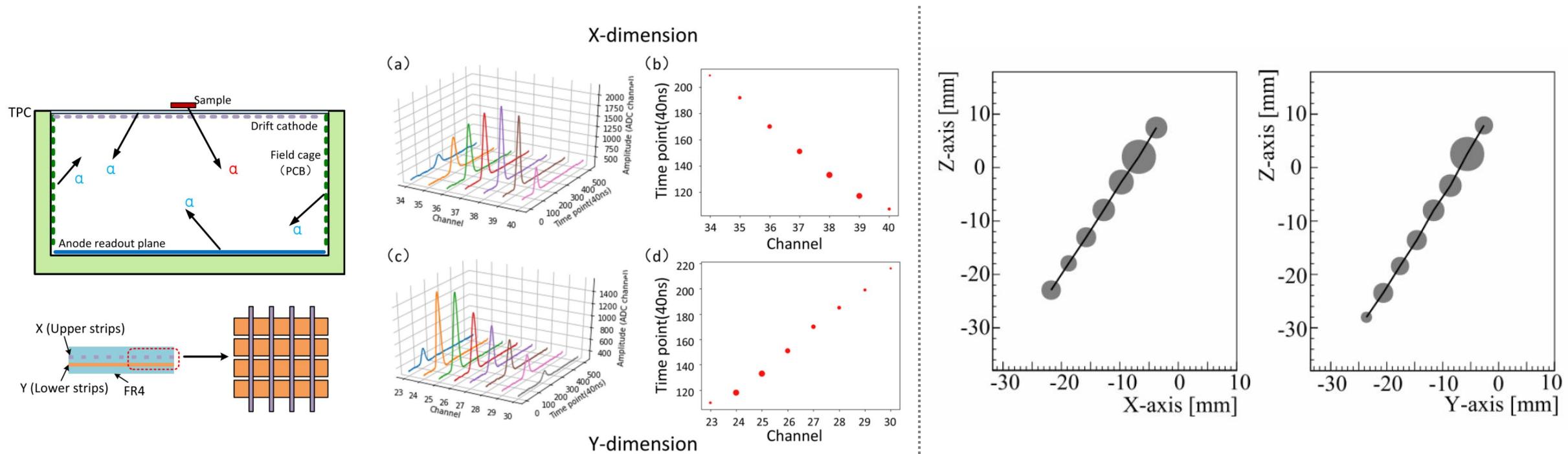
- 低探测阈值，2MeV的 $\alpha$ 粒子：  
灵敏区沉积 500keV
- 更好的射程分辨
- 本底抑制

核心思路：通过粒子入射与漂移同向，由Pad提供精确入射位置，进一步压低本底。

# 极低本底探测器



时间投影室（TPC）具备三维径迹重建、高位置分辨、大立体角覆盖的探测效率等优点：

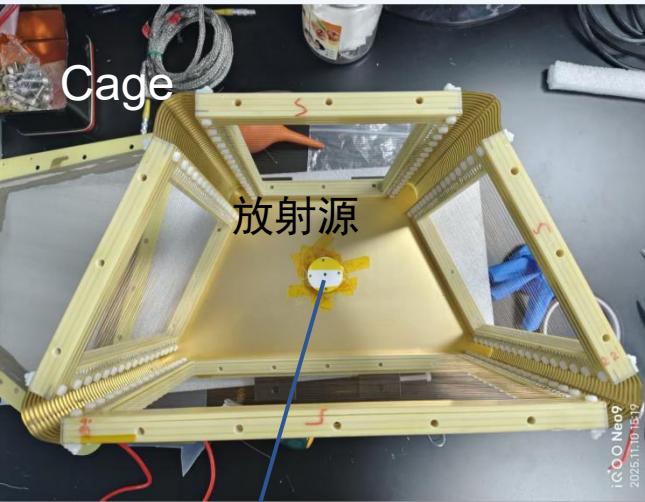
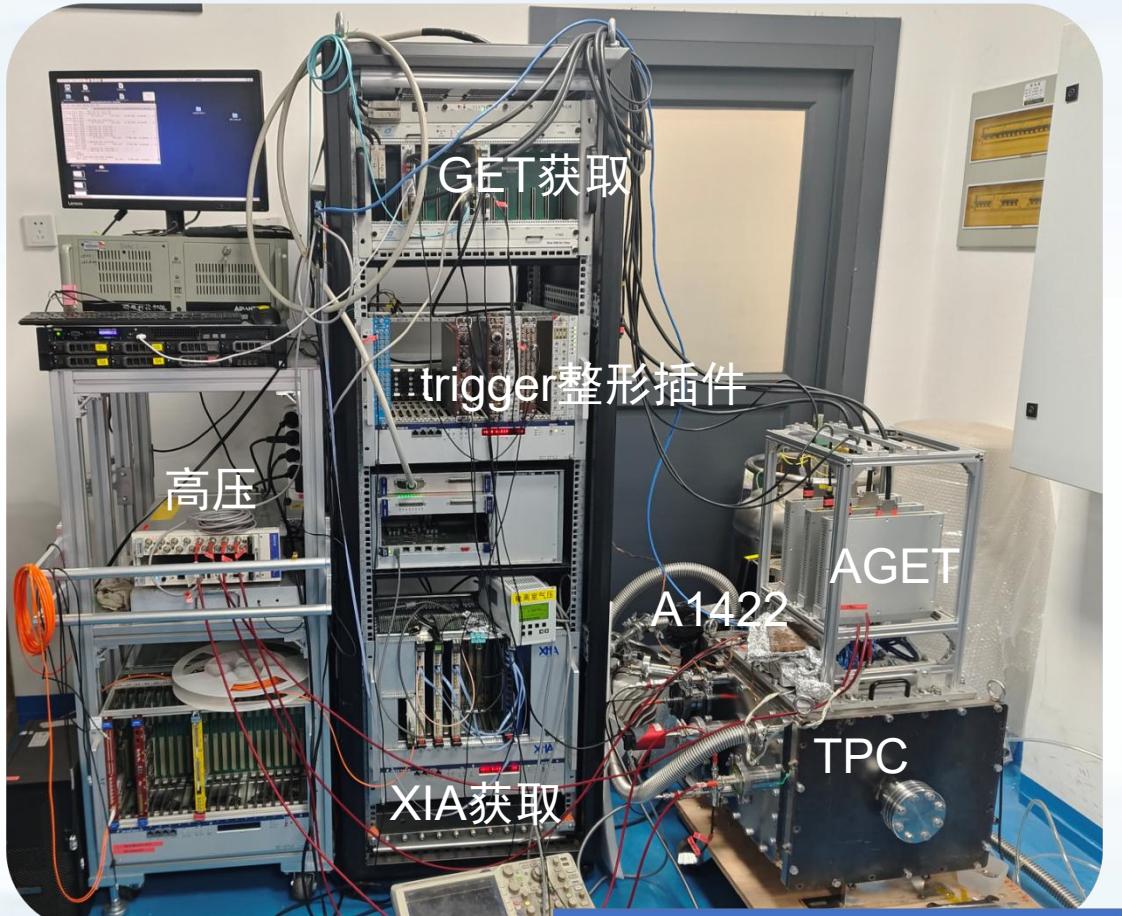


Pan, J., Zhang, Z., Feng, C. et al.(2022)*Review of Scientific Instruments*, 93(1).

Du, H., Du, C., Han, K .et al.(2023).*Radiation Detection Technology and Methods*.

- 中科大团队：中心 $5 \times 5 \text{ cm}^2$ 有效区域本底计数率在95%置信水平下低于 $1.6 \times 10^{-3}$ 计数/分钟， $0.00384 / (\text{h} \cdot \text{cm}^2)$ 。
- 上海交大团队：无窗TPC，实现了 $(0.13 \pm 0.03) \times 10^{-6} \text{ Bq/cm}^2$ 的本底计数率， $0.00047 / (\text{h} \cdot \text{cm}^2)$

# 实验测试



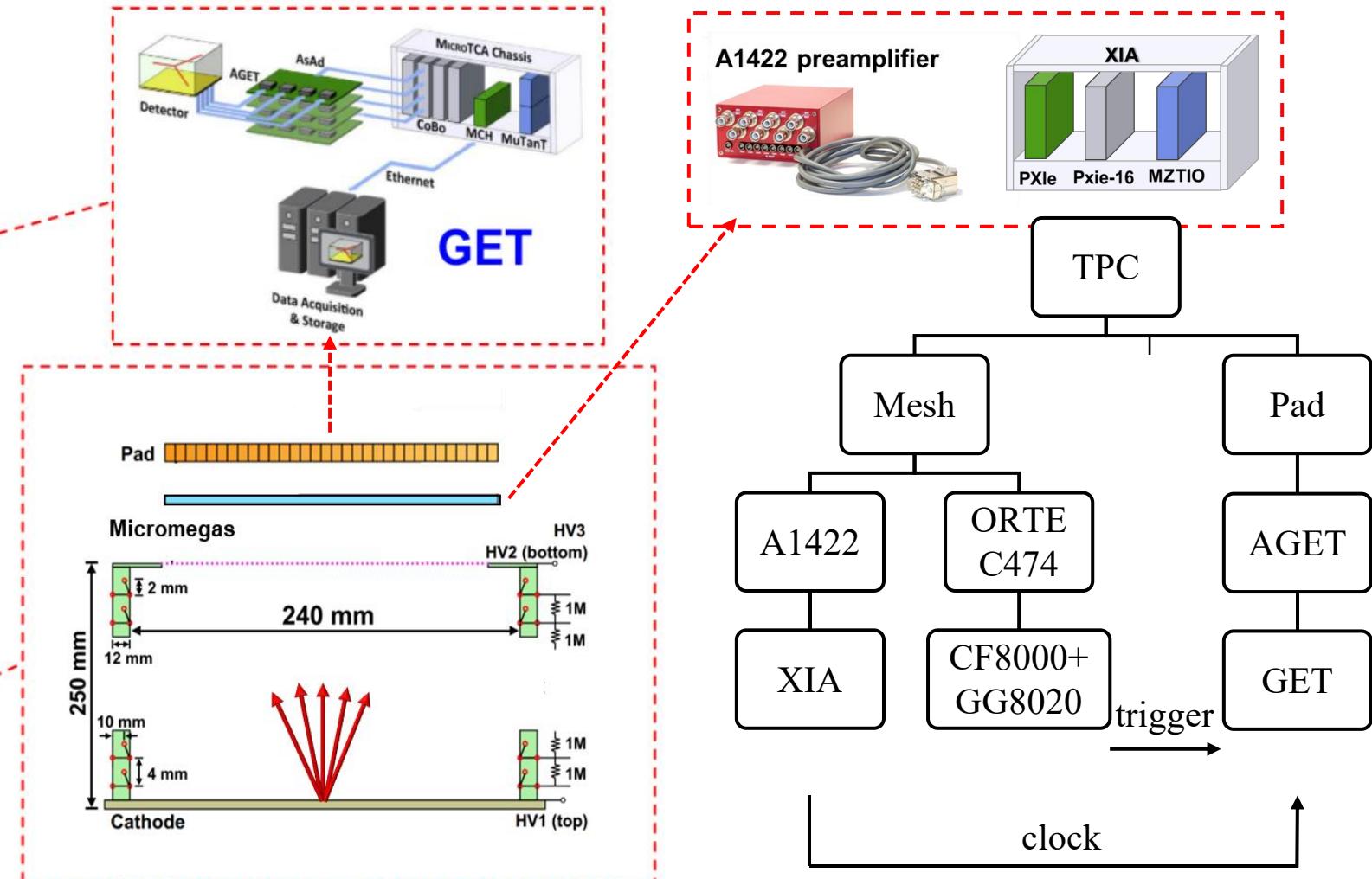
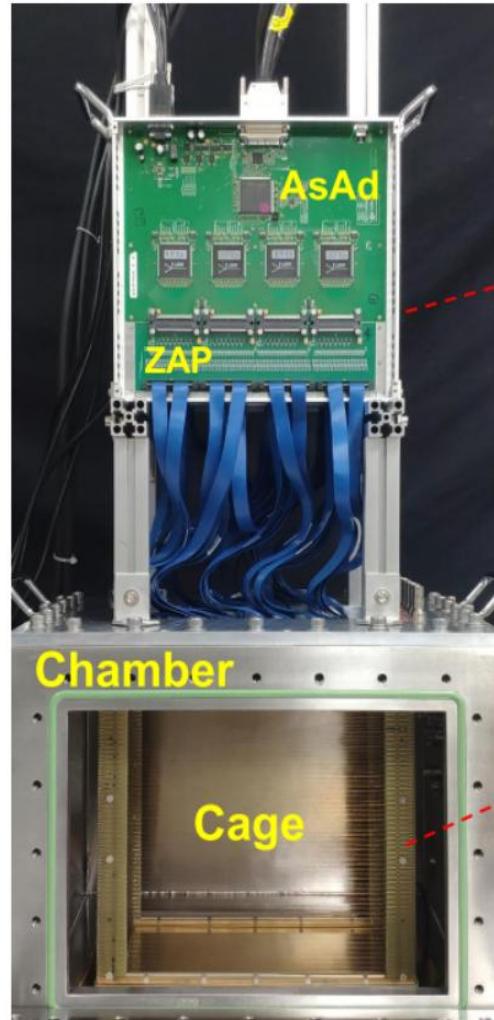
实验条件：常温20°C

- 95%Ar+5%CO<sub>2</sub> 300mbar
- 漂移速度0.72cm/us by garfiled++
- Cathode -1500V 阳极反馈-657.9V
- mesh -540V

距离放射源表面5mm高度的，有  
5mm厚度的聚乙烯盖子准直

- 流气、温度监控、气压监控
- 684块5\*6mm<sup>2</sup> pad读出
- 3组分α放射源
- 63h长时间本底测试

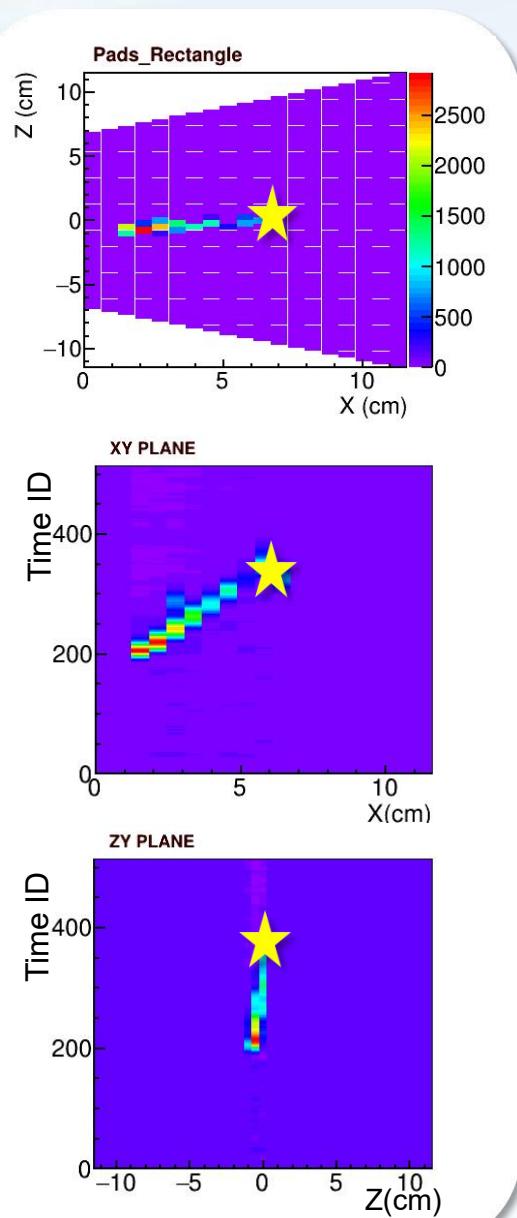
# Bragg型TPC探测器



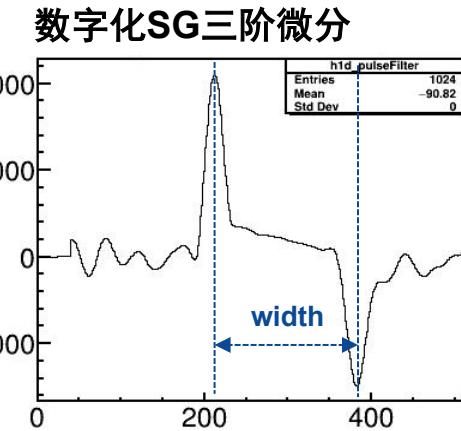
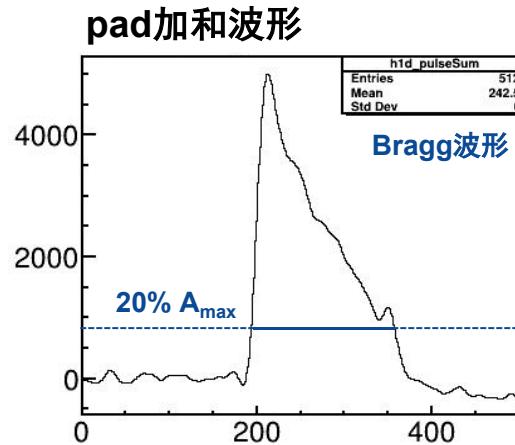
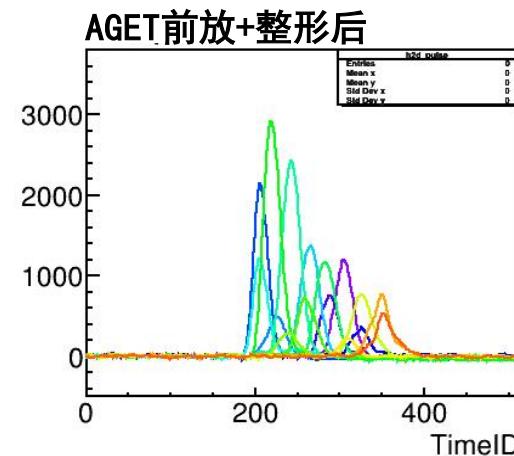
Z.C.Zhang, thesis[D],(2021)

Pad、Mesh双读出结构互相验证

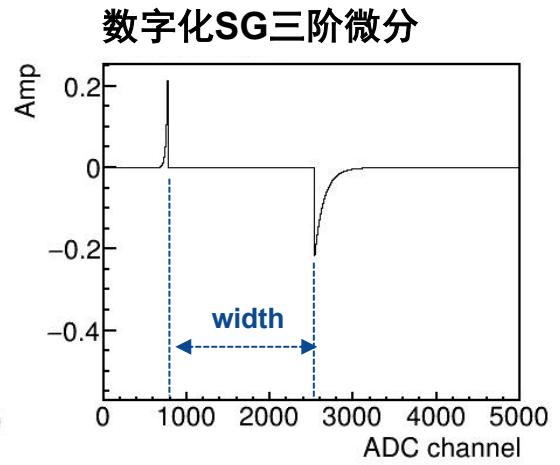
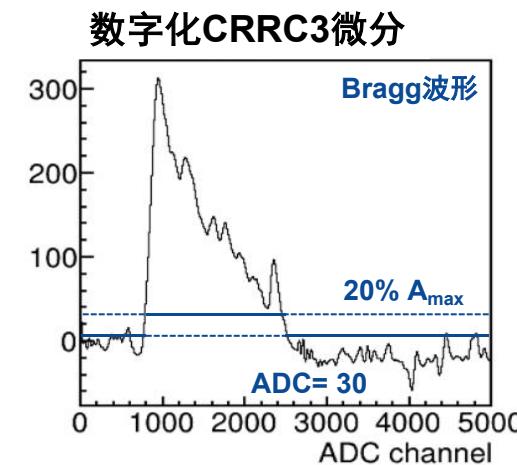
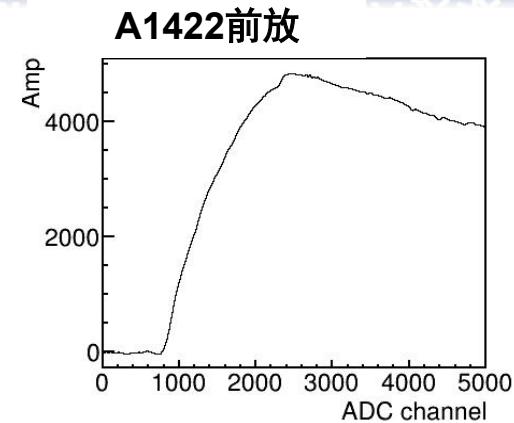
# 波形处理 | 射程信息



## Pad信号 —— GET获

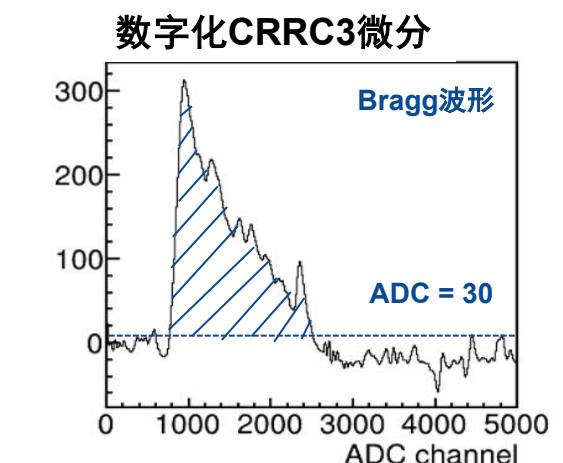
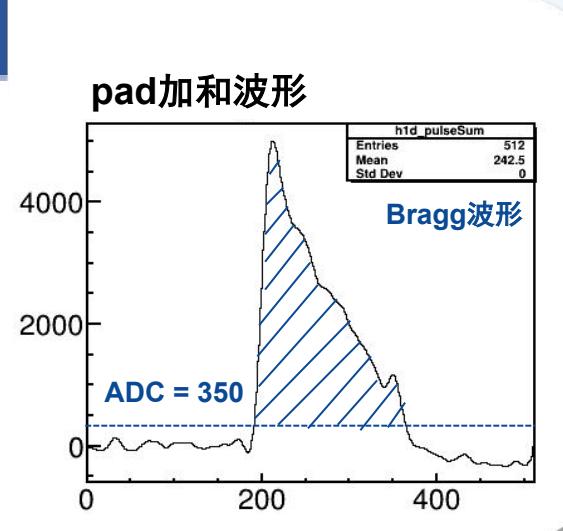
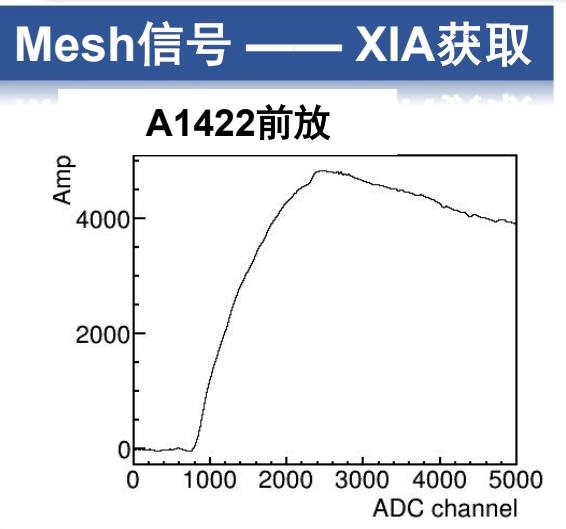
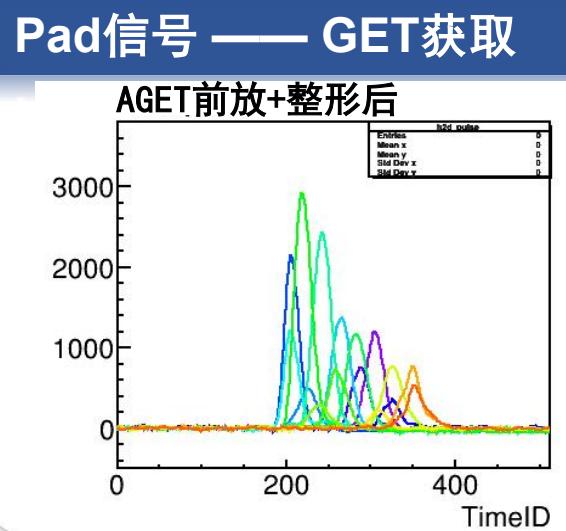
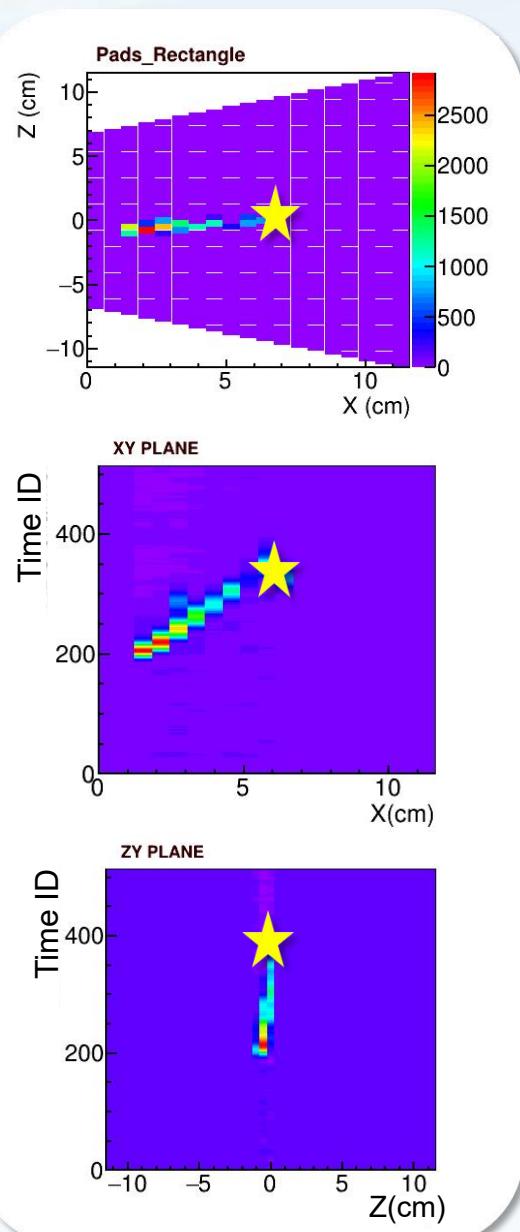


## Mesh信号 —— XIA获取



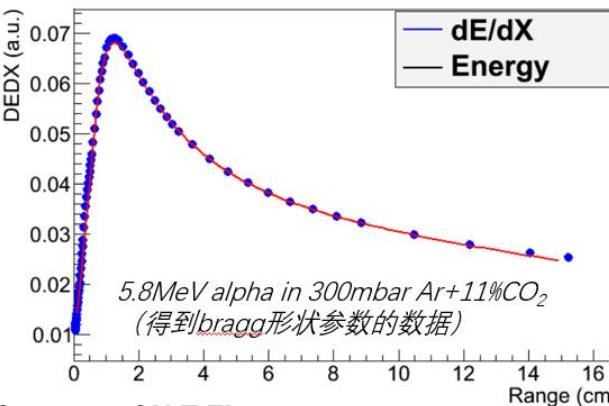
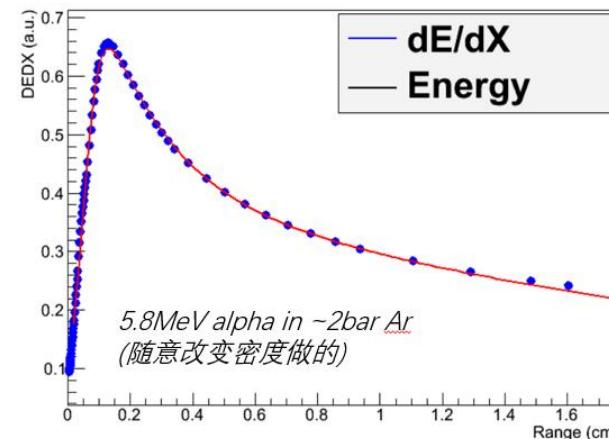
Pad二维径迹 + 波形宽度 构成三维射程长度信息

# 波形处理 | 能量信息



Bragg波形的过阈积分 构成粒子能量信息

# Bragg波形拟合



Courtesy of N.T.Zhang

## SRIM模拟数据的训练 (stopping power calc)

✓  $X=(r-[1])/[2]$

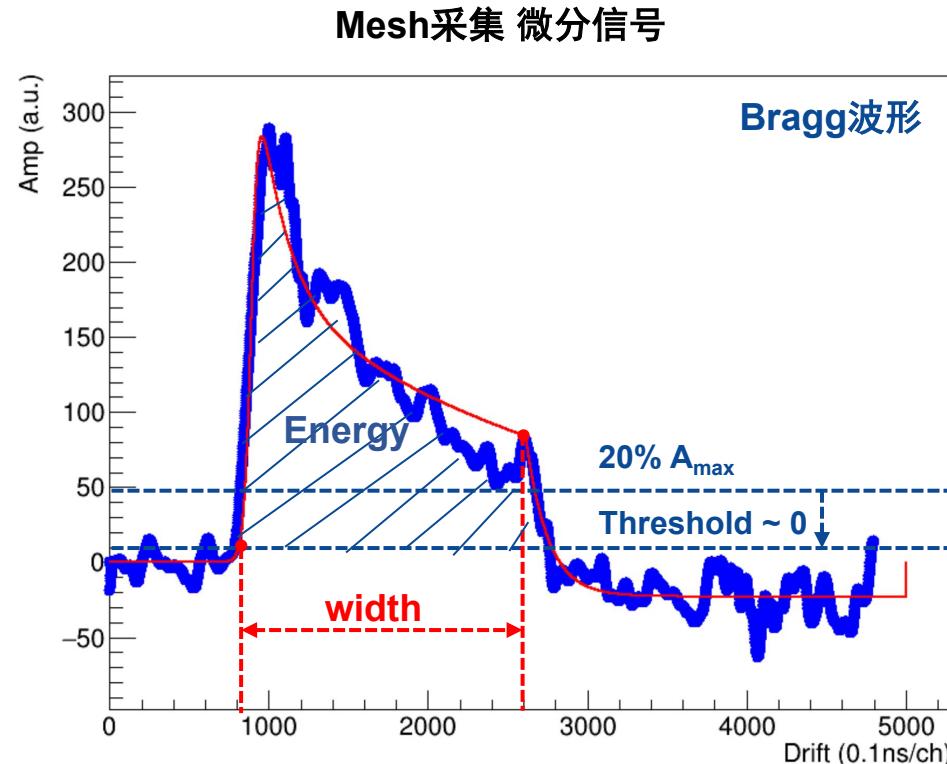
- ✓ [1] 定义实际中射程的offset (起点未必是0)
- ✓ [2] 定义入射角度不同带来的效应

✓  $DEDX = [0] \frac{Ae^{Bx} + Ce^{Dx}}{500 + Ee^{Fx}}$

- ✓ [0] 定义 DEDX 不同单位引起的高度不同
- ✓ 其中 ABCDEF 参数是事先在 300mbar Ar+11% CO<sub>2</sub> 中拟合出来的，然后就固定下来

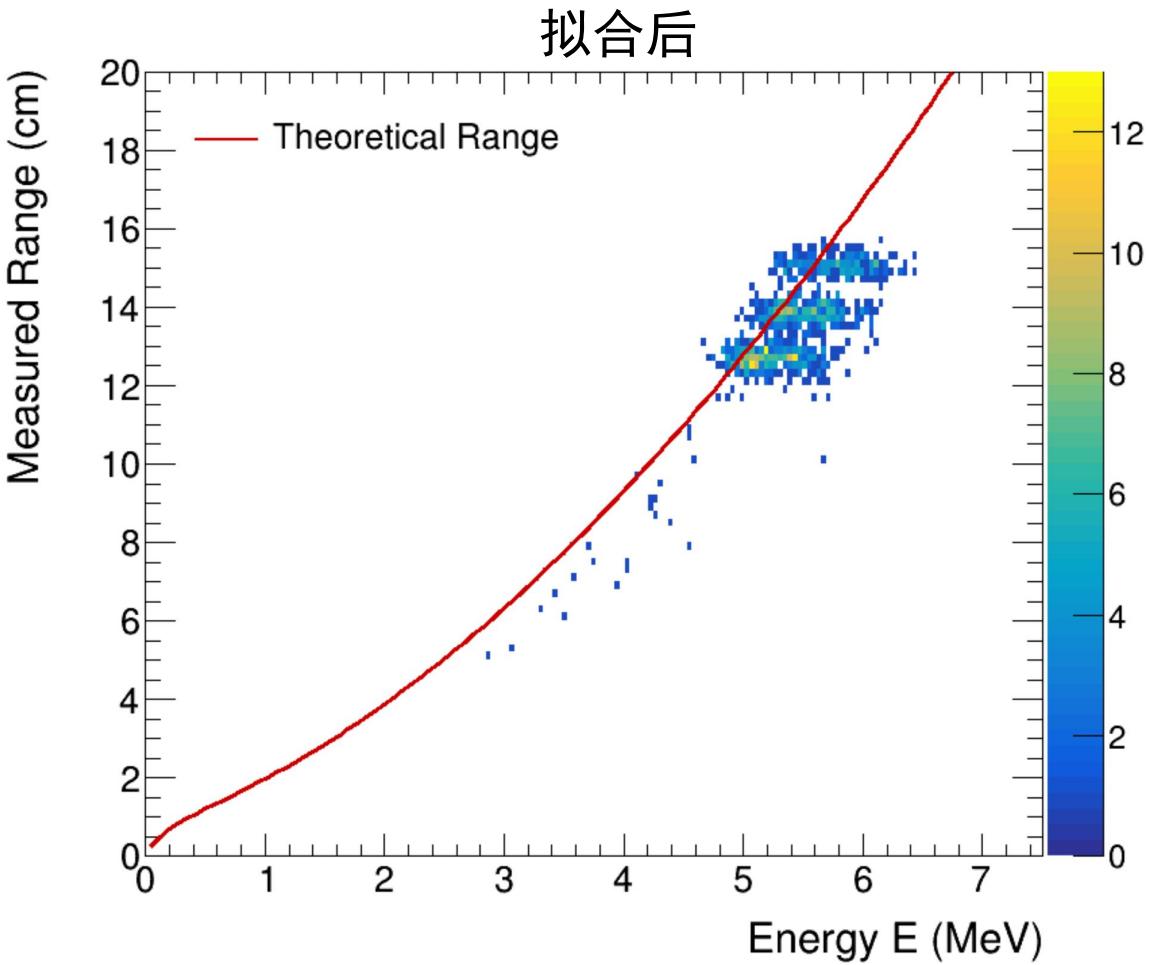
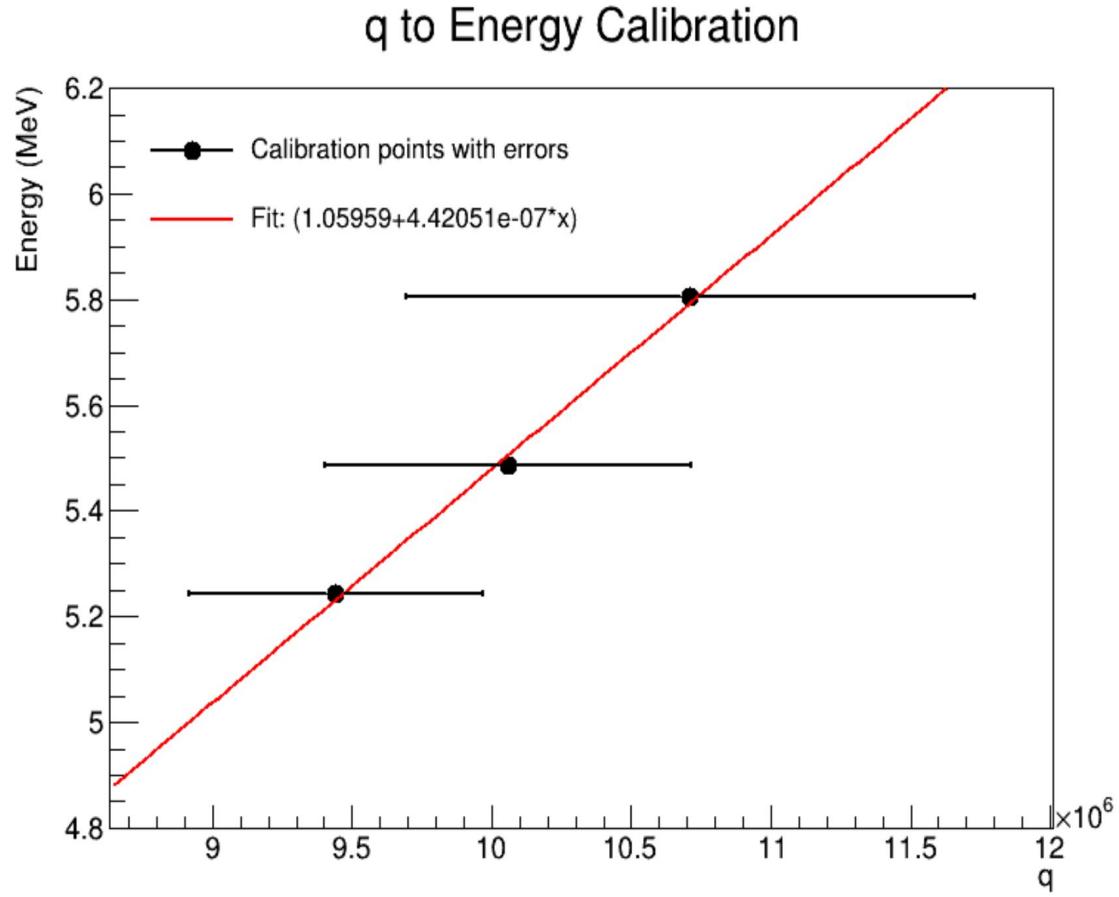
## 下降沿由指数项拟合：

✓  $[0] + [1] * \exp(-x/[2])$



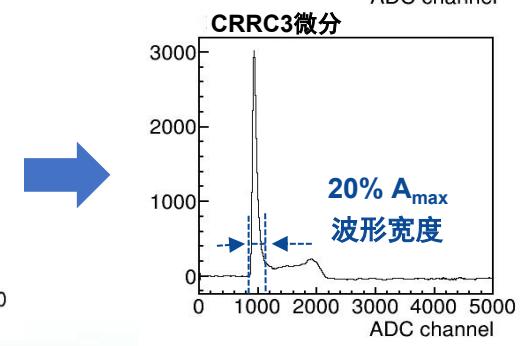
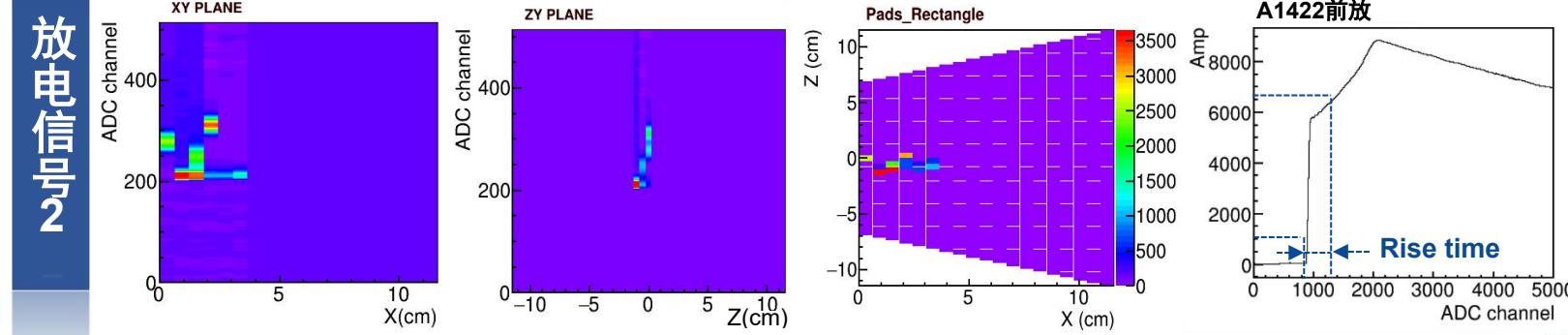
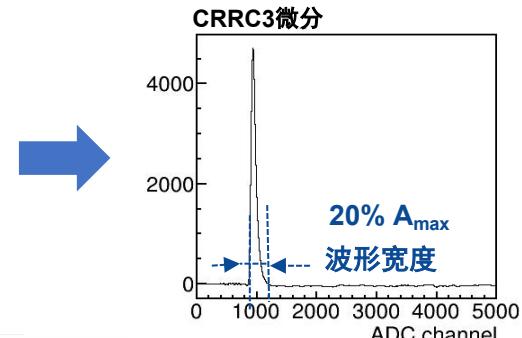
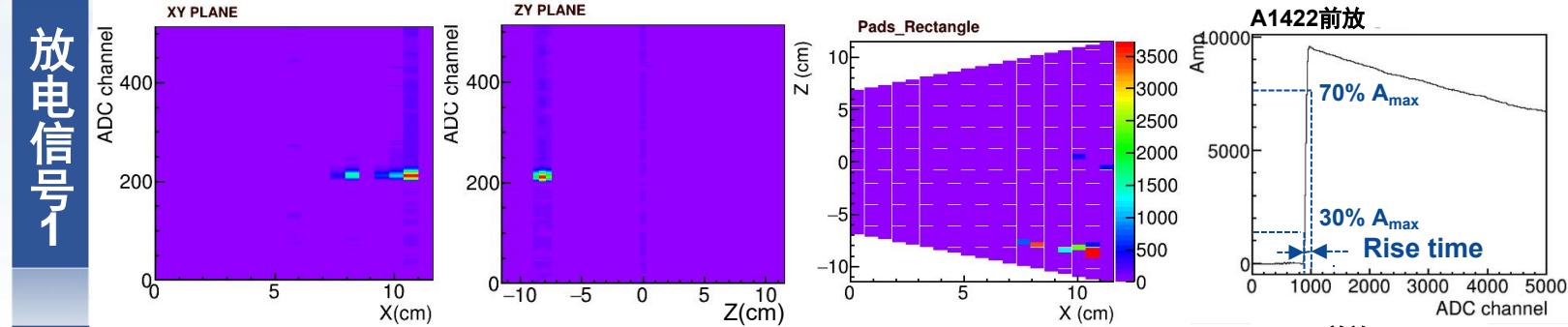
由SRIM模拟数据曲线和指数项对Bragg波形进行了简单的形状拟合，压低了阈值，减小了滤波成型影响

# 能量刻度



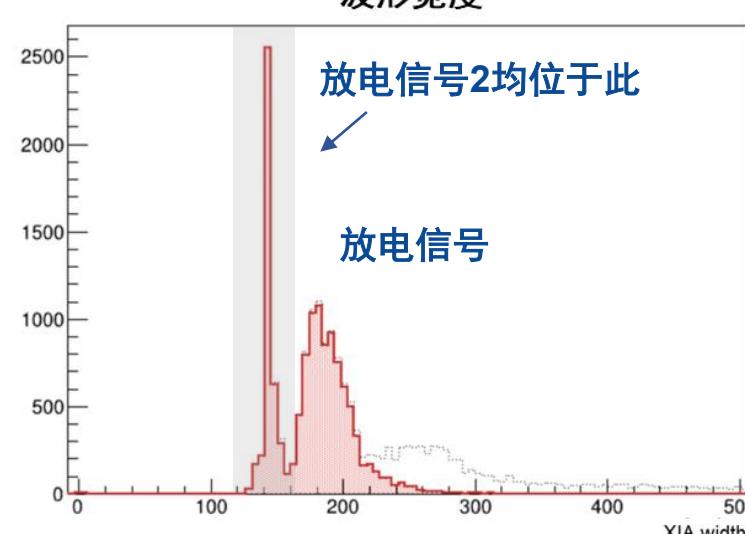
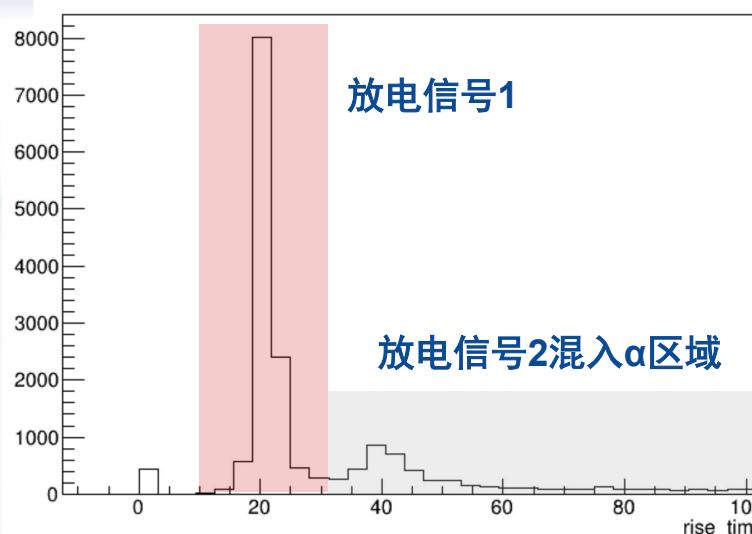
对Bragg波形进行了简单的形状拟合，压低了阈值、减小了滤波成型影响，刻度后和理论线符合的很好

# 本底抑制 | 放电信号去除



**Rise time**

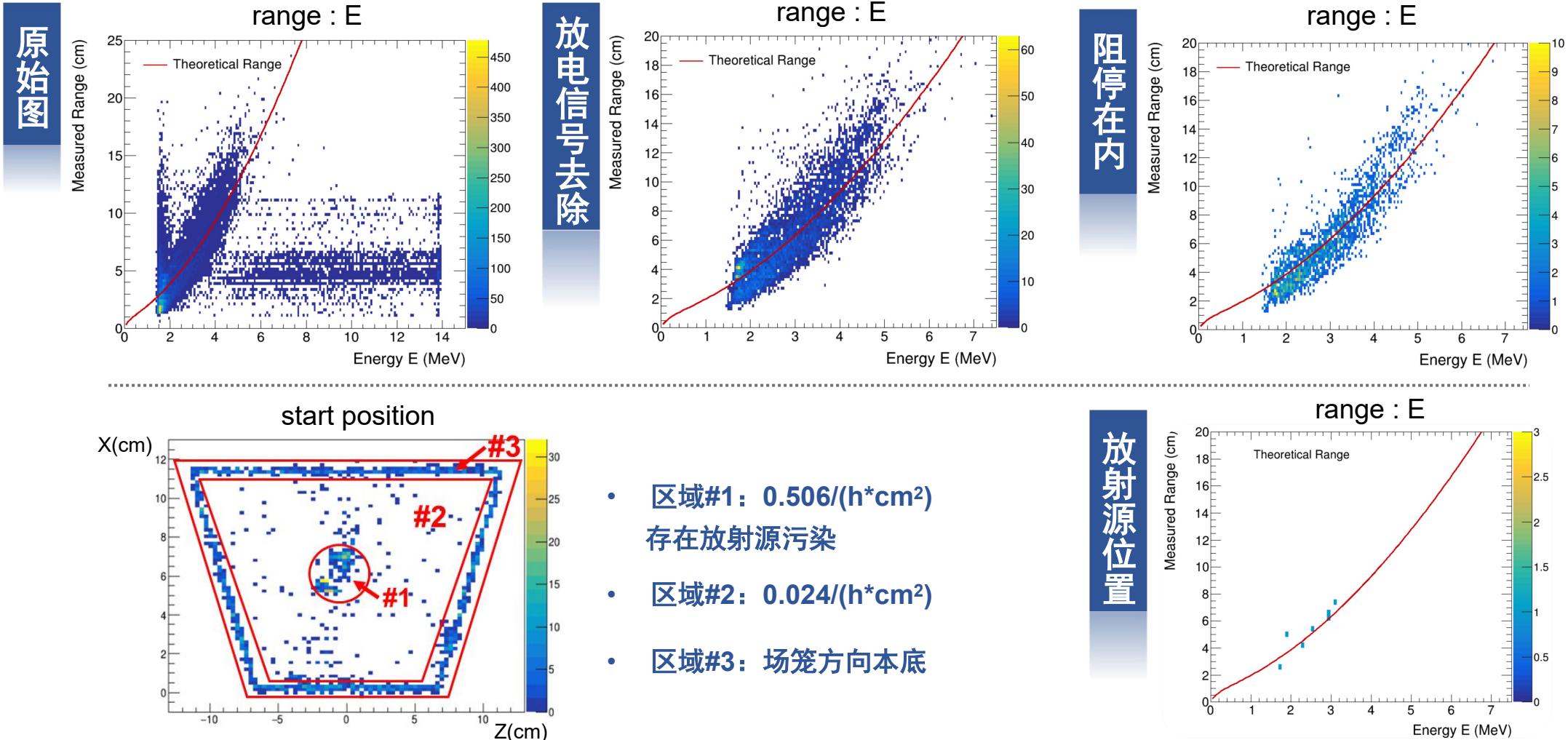
**波形宽度**



在波形宽度谱中，放电信号2  
与 $\alpha$ 区域区分开

➤ 选择cut:  
 $\text{Rise\_time} > 30 \ \&\& \text{ 波形宽度} > 160$

# 本底抑制

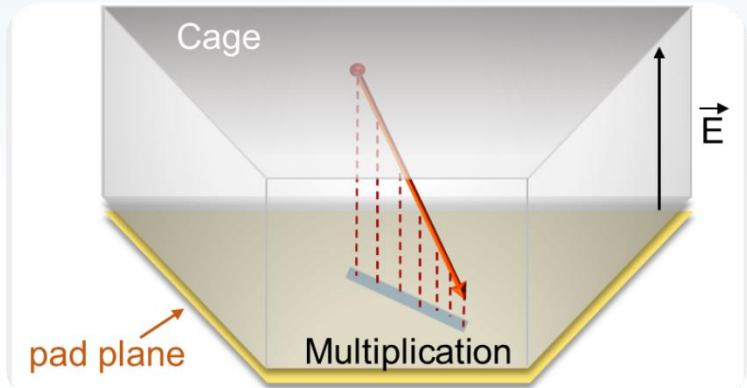


经63.35h本底测量，在阈值为1.4MeV情况下将靶点位置α本底抑制为原来的0.08%以下，最低本底区域0.024/(h\*cm<sup>2</sup>)

# 总结

基于现有电子学和探测器设置，测试了以漂移方向为入射方向的TPC：

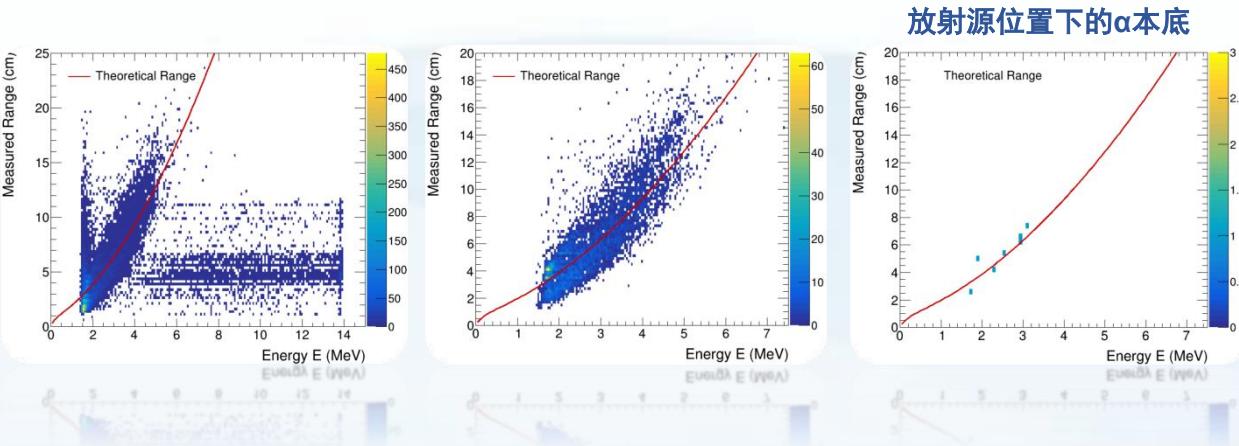
- 实现了 $\alpha$ 能量刻度、波形处理、事件甄别，进行了初步的Bragg波形拟合，优化了径迹长度分辨。
- 进行了稳定的长时间本底测量，**本底可以压制到 $0.024/(h^*cm^2)$**
- 目前气压、电压下，能量阈值为 $1.4\text{MeV}$**



未来工作：

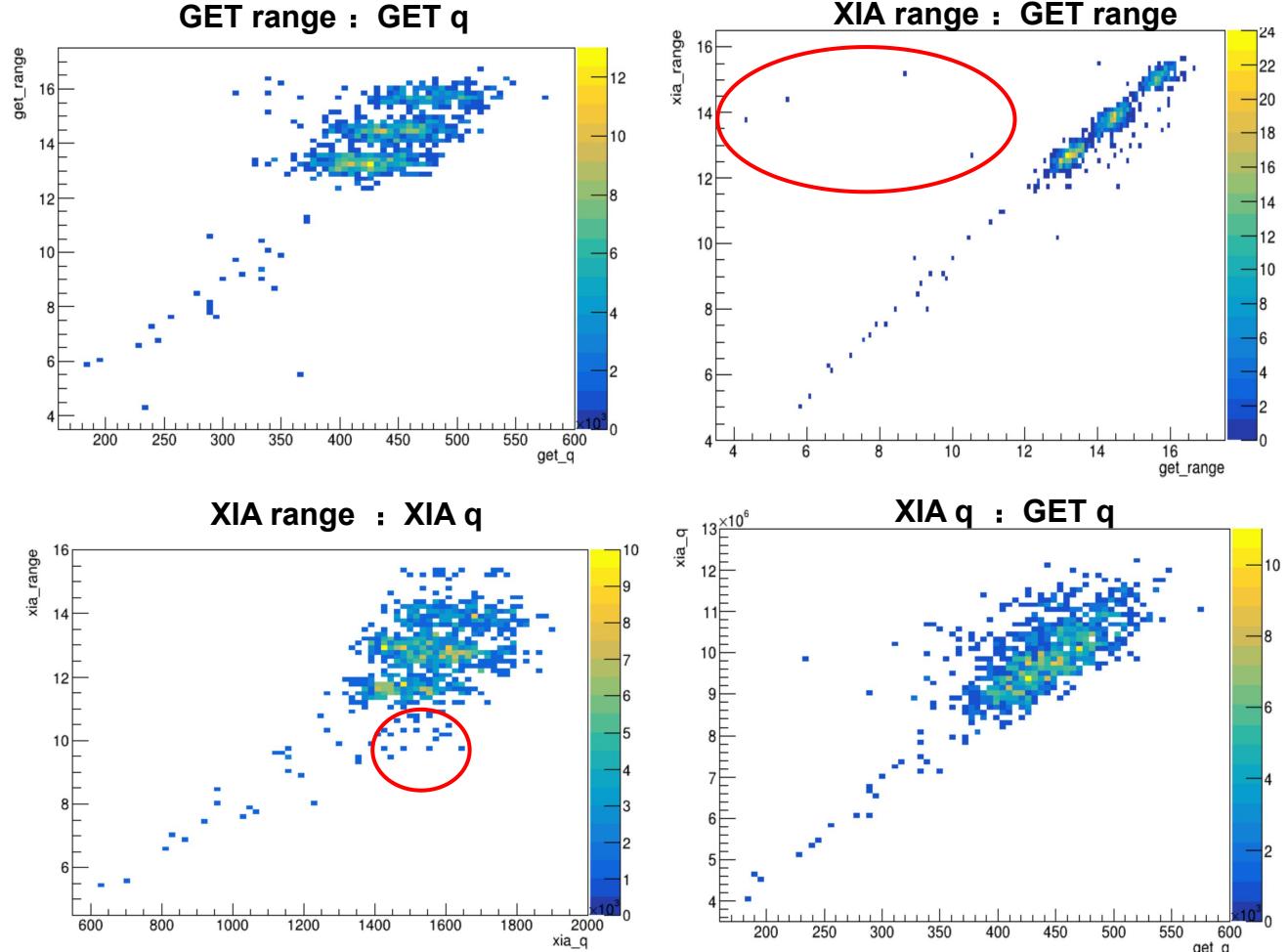
- 引入电子学卷积 → 提高 Bragg 曲线拟合精度
- 阳极XY读出
- 阴极丝网mylar入射窗 进一步压低本底
- 优化气压、场强、采样率，进一步降低阈值
- 引入 proton / deuteron 低能束线测试

目标：面向低本底核天体物理反应测量



# 附录

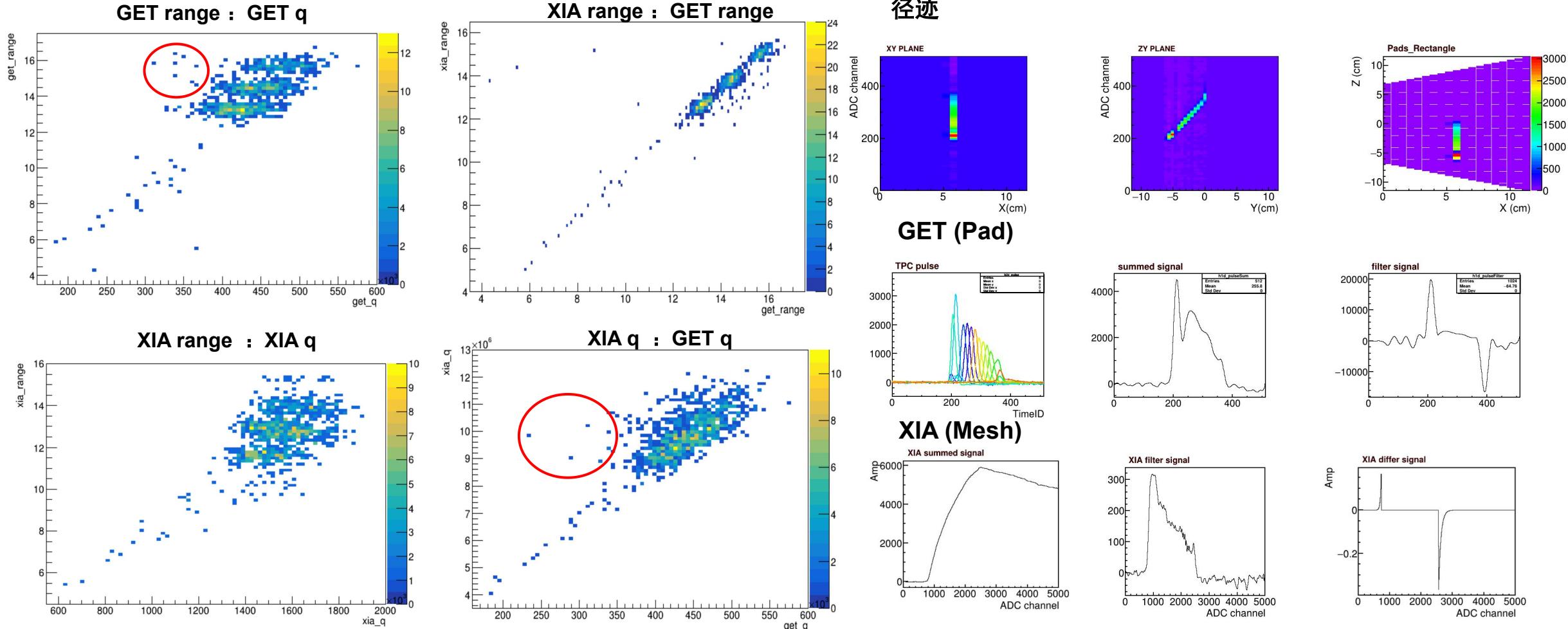
## GET (Pad) 与 XIA (Mesh) 信号的处理结果对比 (无拟合)



射程误判是因为XIA在无拟合时噪声引起的时间误判

# 附录

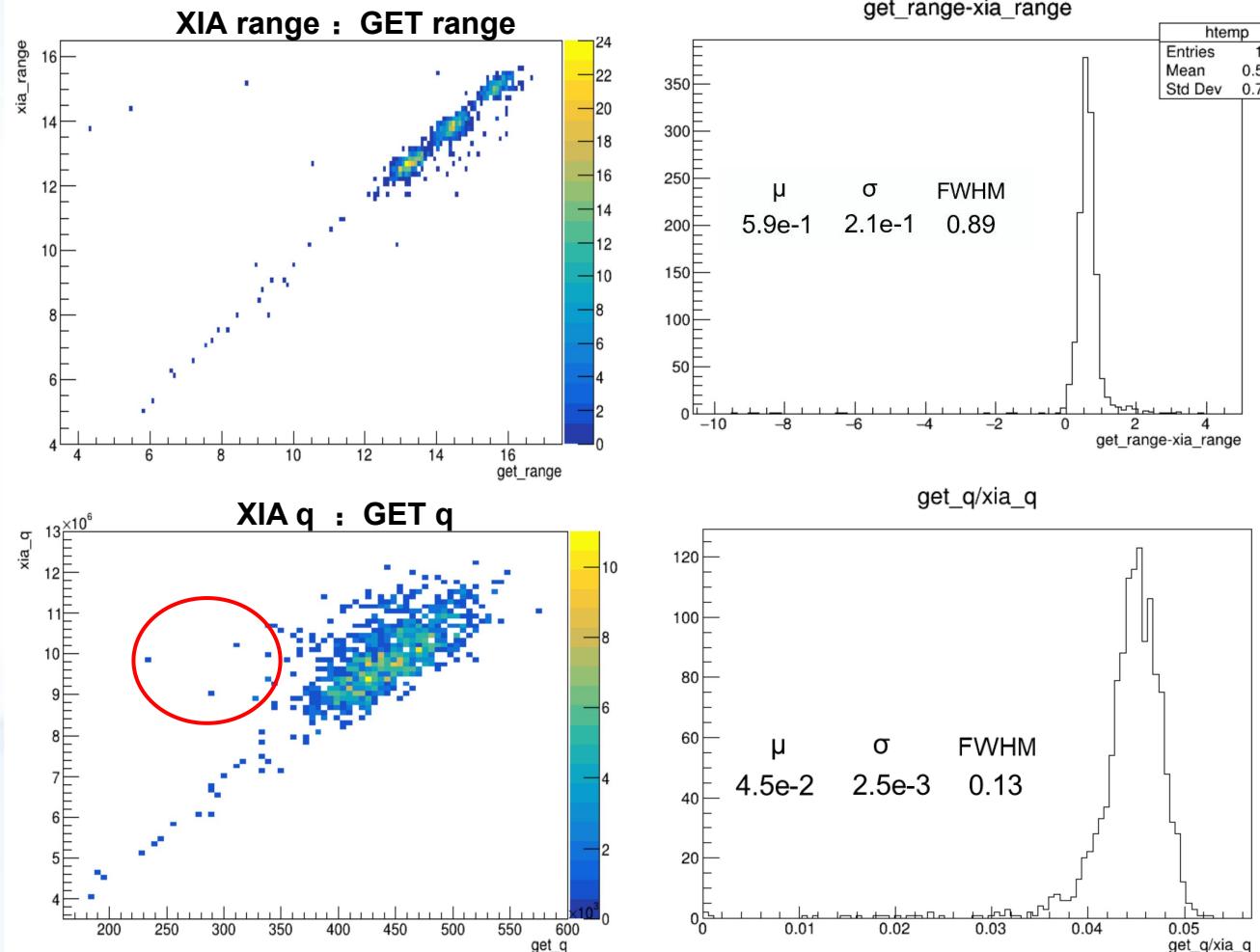
## GET (Pad) 与 XIA (Mesh) 信号的处理结果对比 (无拟合)



在径迹末尾，GET能量有时会丢失

# 附录

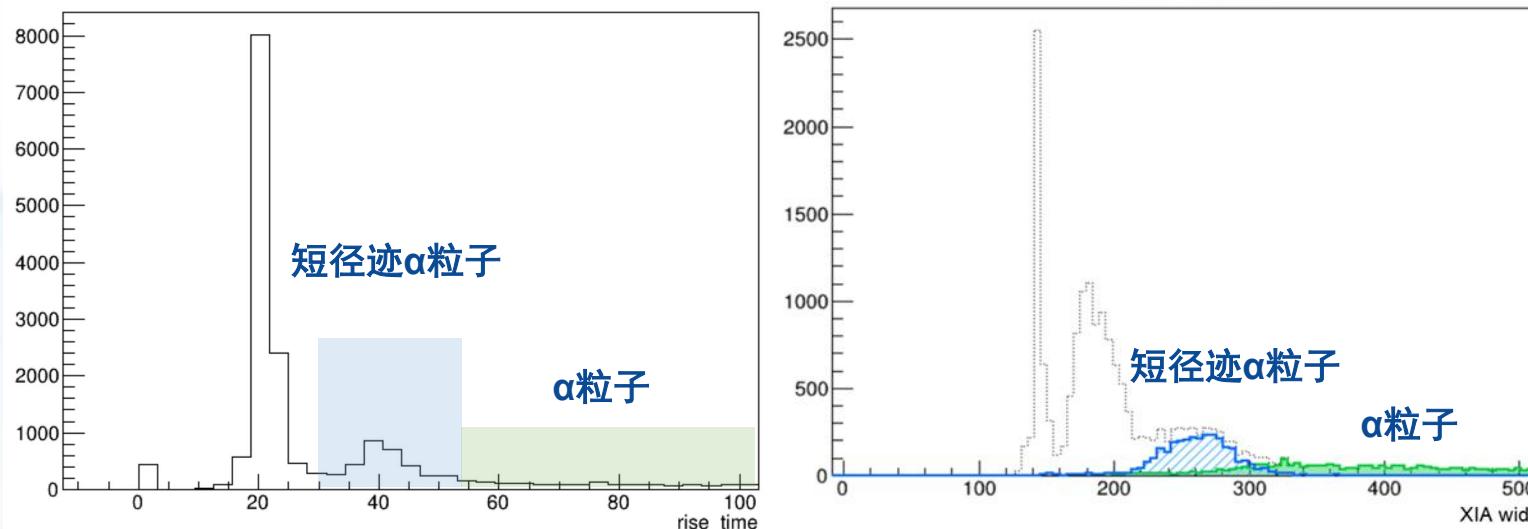
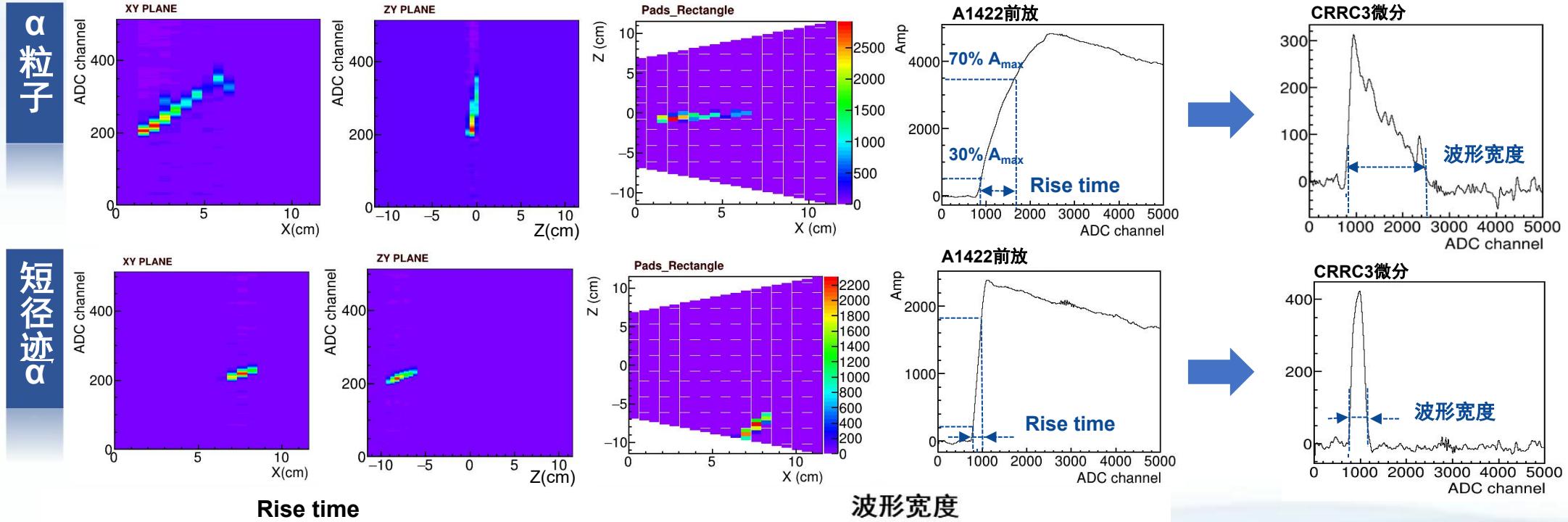
## GET (Pad) 与 XIA (Mesh) 信号的处理结果对比 (无拟合)



- GET射程>XIA射程并相差一个常数，来自于成型时间的影响，但整体分辨较差，可能源自于成型时间本身并不是线性影响

- XIA和GET存在能量scale，来自于成型时间的不同，整体分辨并不差

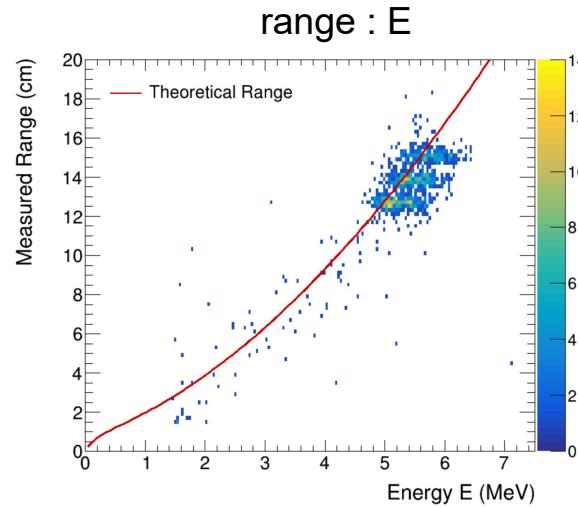
# $\alpha$ 粒子径迹



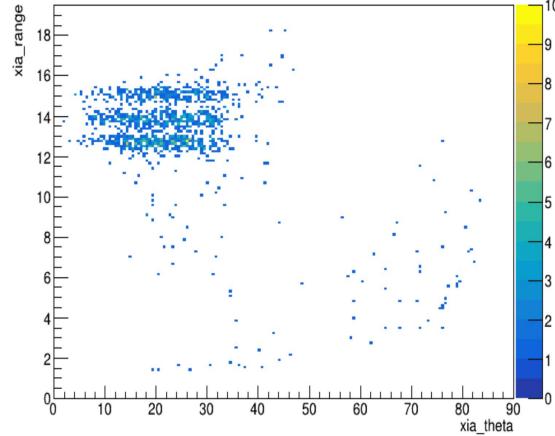
在上升时间谱中，可以更好将  
 $\alpha$ 粒子和放电信号区分开

# 处理结果 | 放射源Alpha

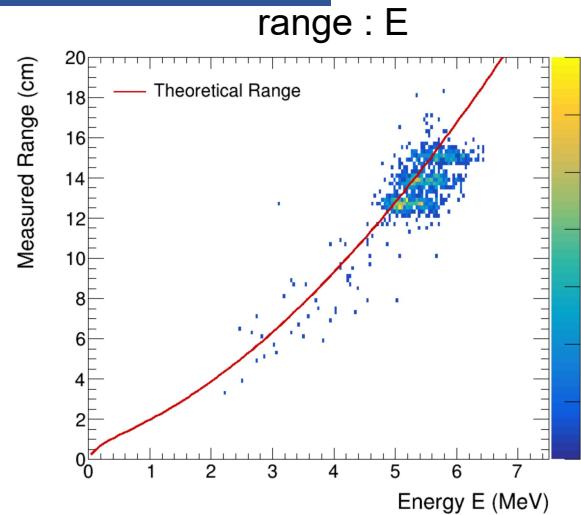
原始图



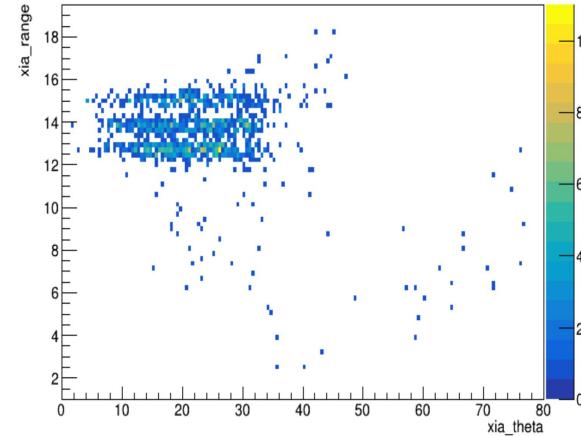
range : theta



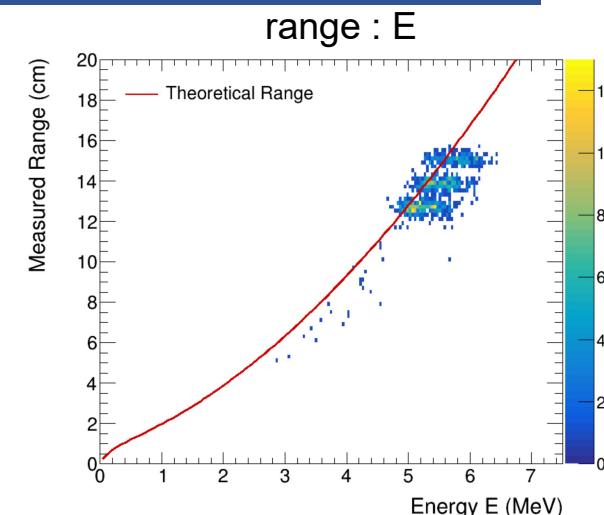
放电信号去除



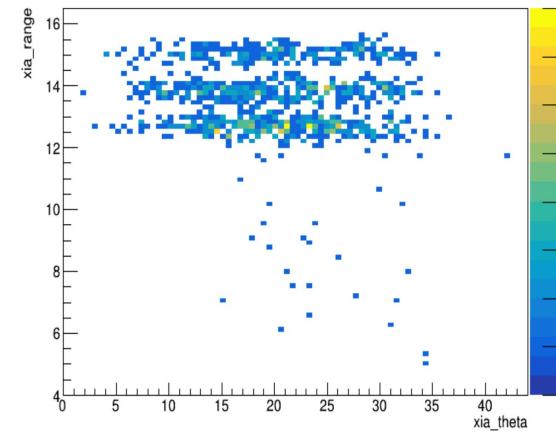
range : theta



过放射源位置+阻停在内

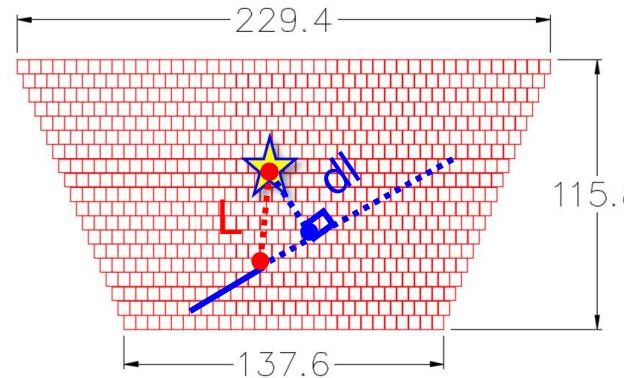
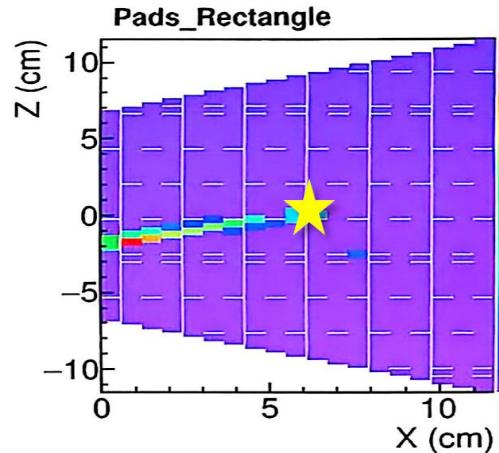


range : theta

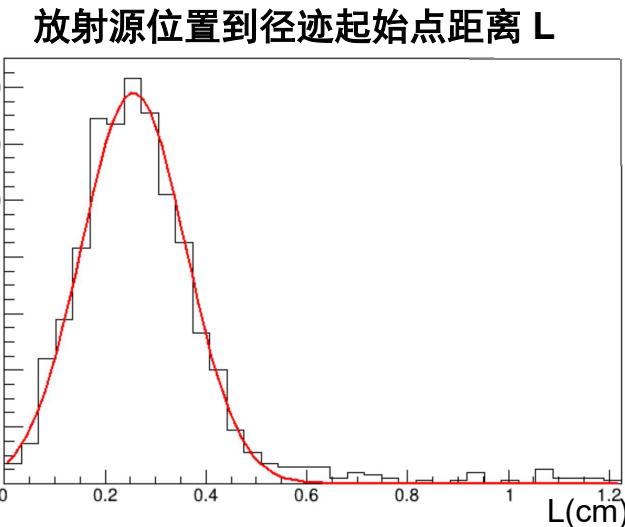
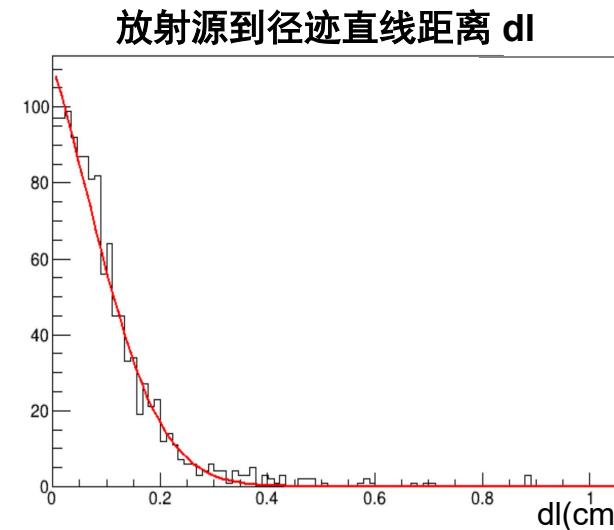
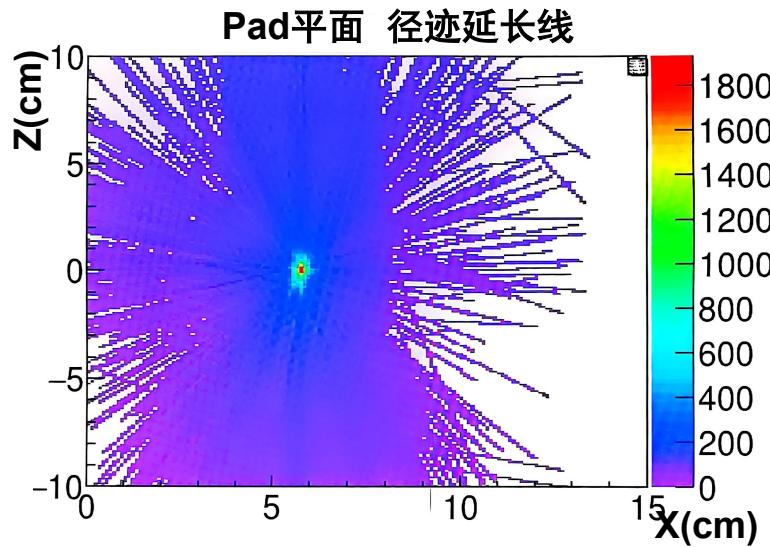


通过波形处理和本底抑制，得到了干净、射程分辨明显改善的谱图

# 放射源位置重构和判别依据



- ✓ Pad共19排
- ✓ 总pad数: 684个 (140pin接头, 6个)
- ✓ Pad间隙: 0.1mm
- ✓ 单pad:  $5 \times 6 \text{mm}^2$

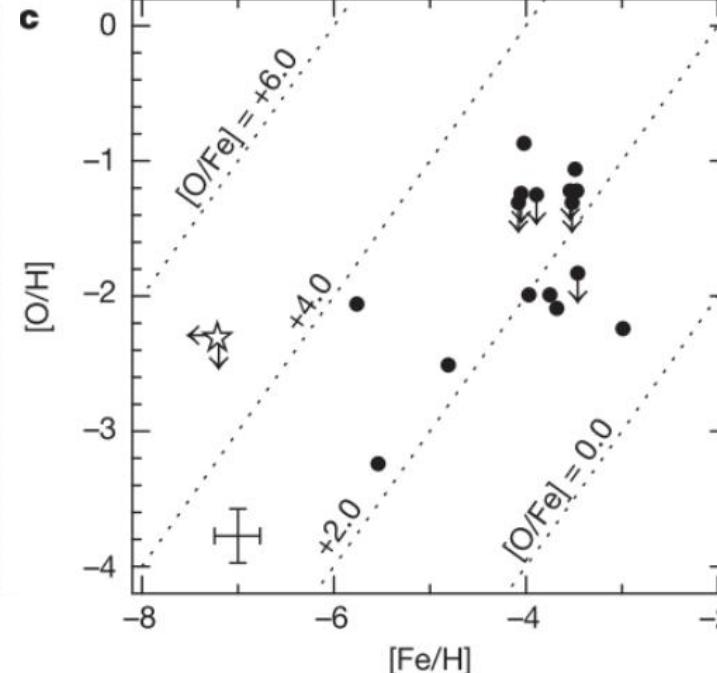
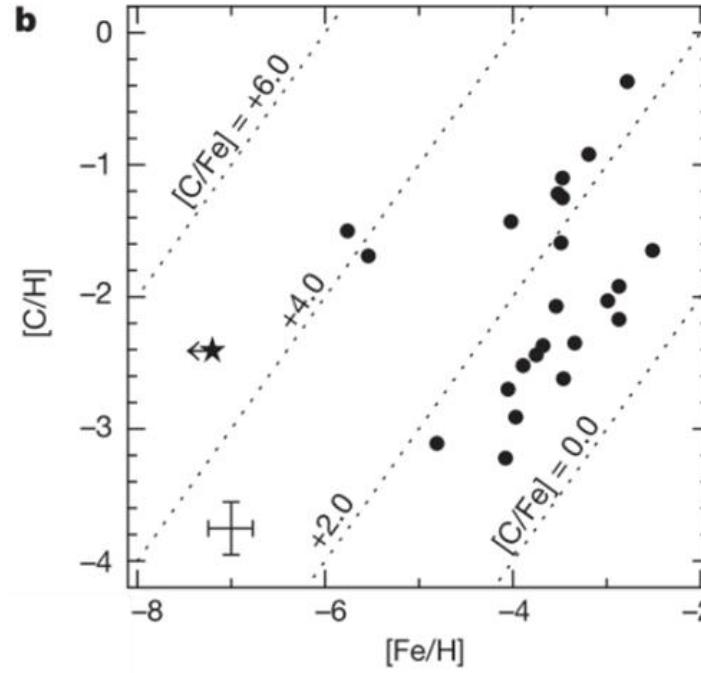


通过始末点延长径迹，重构放射源位置，做放 放射源到径迹直线距离 $dl$  和 起始点到靶点距离 $L$

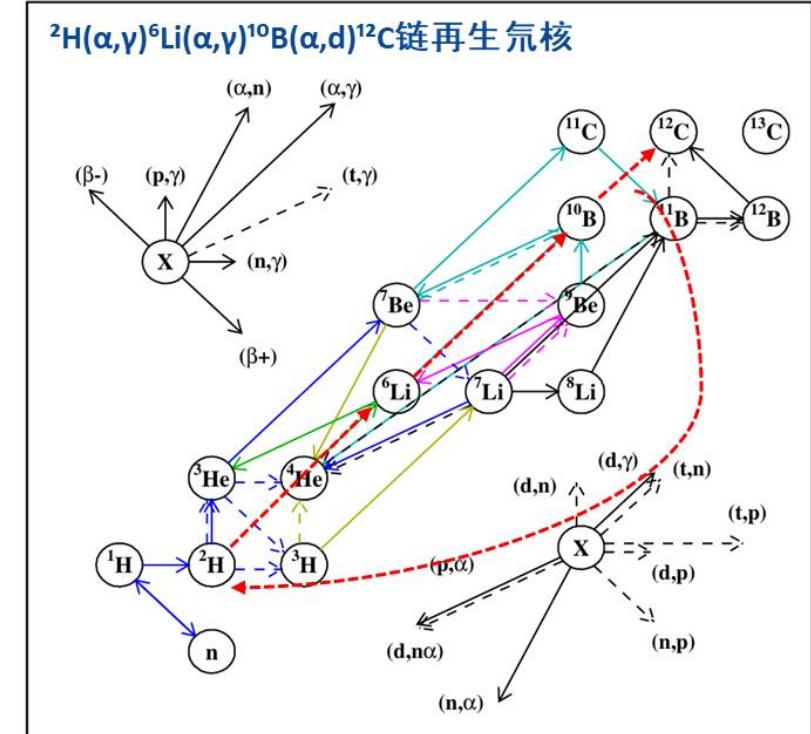
➤ 选择cut :  $dl < 0.334 \text{ cm}$  &&  $L < 0.567 \text{ cm}$

# 背景

C、O丰度超丰： $^{10}\text{B}(\alpha, d)^{12}\text{C}$  是原始恒星中 CNO 种子核再生的关键路径。



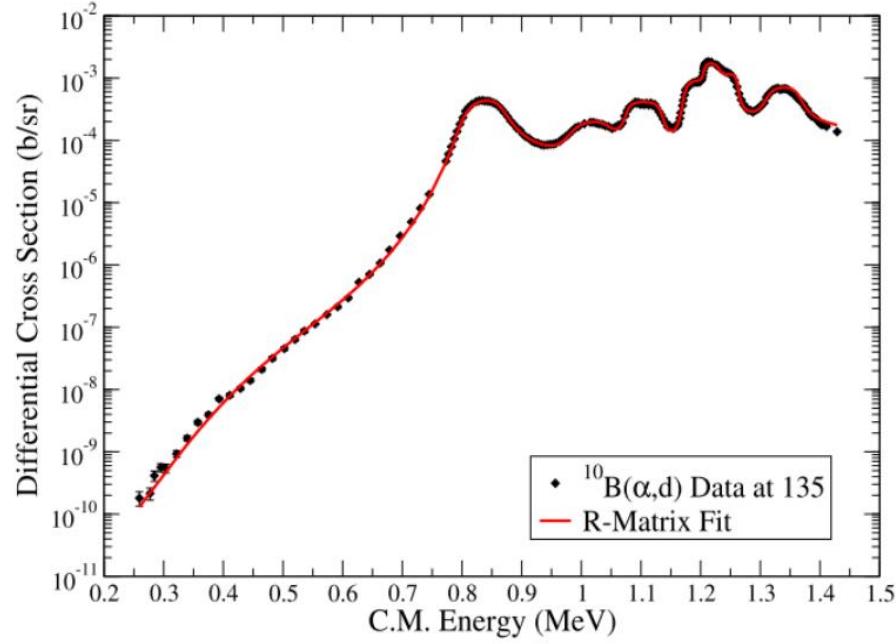
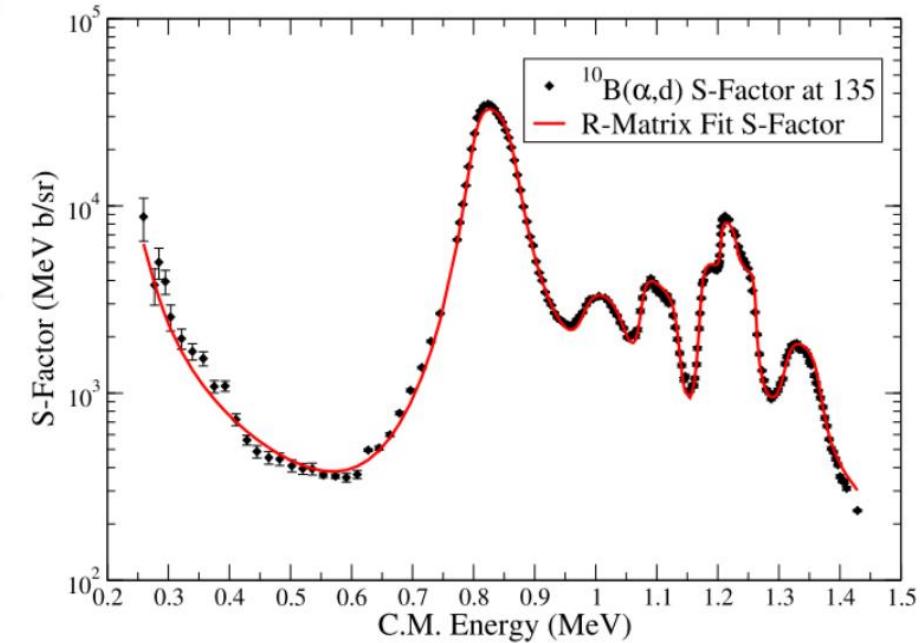
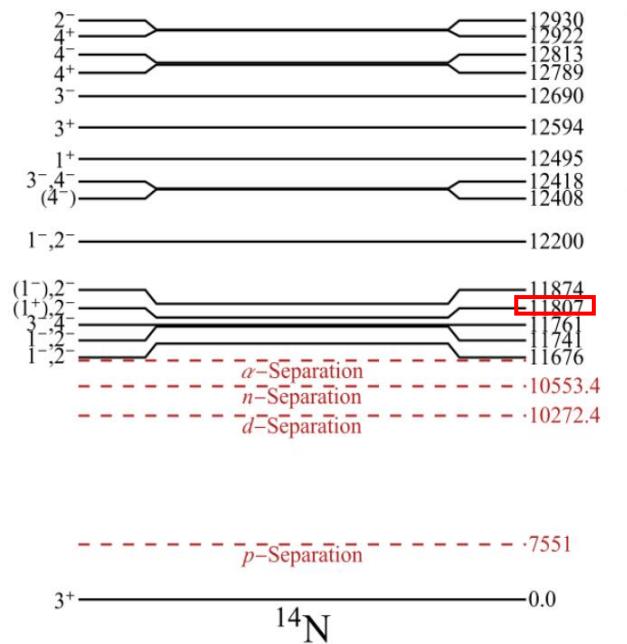
Keller, S. C.(2014). *Nature*, 506(7489), 463–466.



Cyril Pitrou,arXiv:1801.08023v3

- SMSS 031326708 作为已知Fe丰度最低的恒星， $[\text{Fe}/\text{H}]$ 上限为-7.1，钙( $[\text{Ca}/\text{H}]$ =-7.0)、镁( $[\text{Mg}/\text{H}]$ =-3.8)和碳( $[\text{C}/\text{H}]$ =-2.6)相对铁显著增强
- $^2\text{H}(\alpha, \gamma)^6\text{Li}(\alpha, \gamma)^{10}\text{B}(\alpha, d)^{12}\text{C}$ 反应链可以在更低温度下越过不稳定核区( $A=5-8$ )产生 $^{12}\text{C}$ ，同时生成的d又将补充 $^{10}\text{B}$ 丰度。

C、O丰度超丰： $^{10}\text{B}(\alpha, d)^{12}\text{C}$  是原始恒星中 CNO 种子核再生的关键路径。



Gula, A., deBoer, R (2023). PRC, 107(2)

- 发现近阈共振结构 ( $E_x = 11.807 \text{ MeV}$ ),  $\alpha$  团簇结构使得部分能级自旋宇称与旧文献存在差异
- 反应率在 0.1 GK 下较理论预测提高约 1 个量级, 但不确定性仍高达 ~30% (近阈共振强度及能级结构未知)。

反应Q值: 1.3 MeV 极低的反应截面:  $10^{-10} \text{ b/sr}$