

基于深度学习的气体X射线偏振探测器光电子径迹 重建方法

姜维春

代表eXTP-PFA载荷团队



中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences



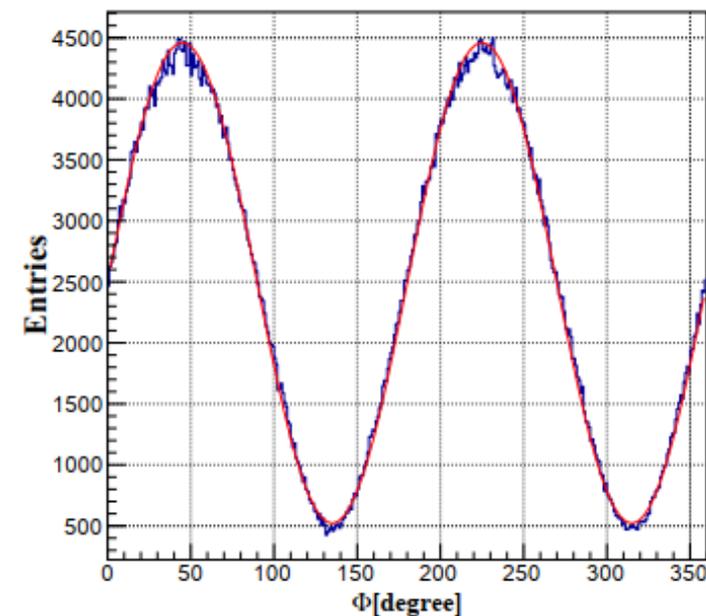
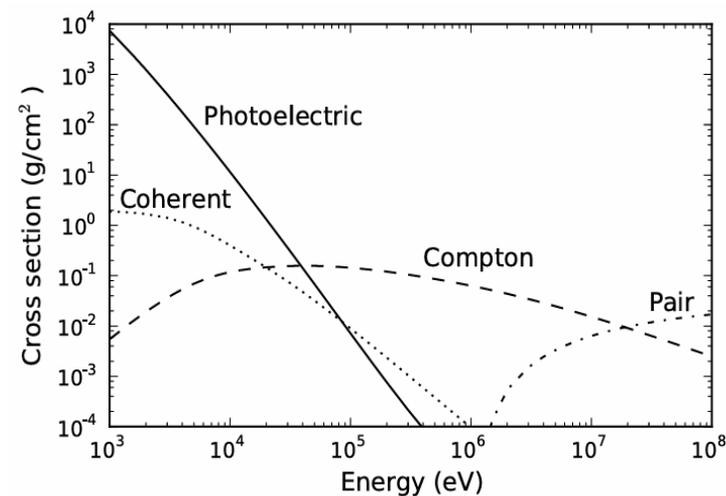
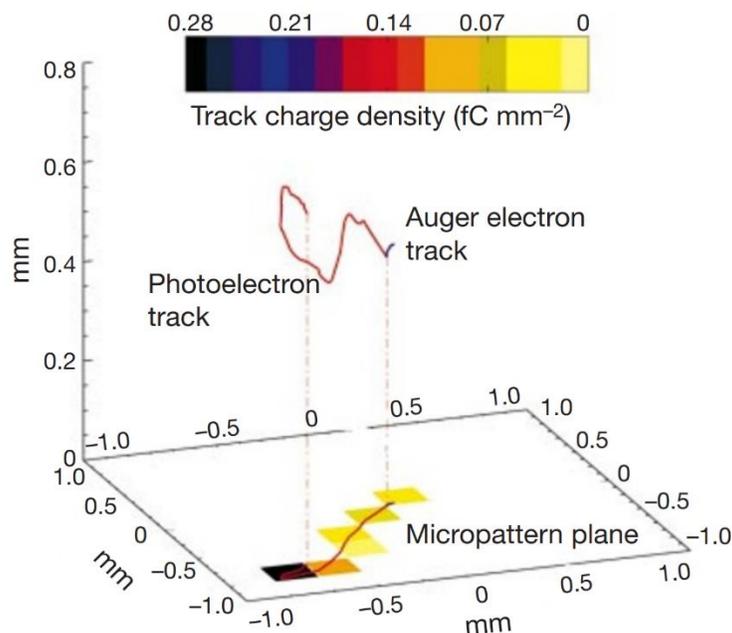
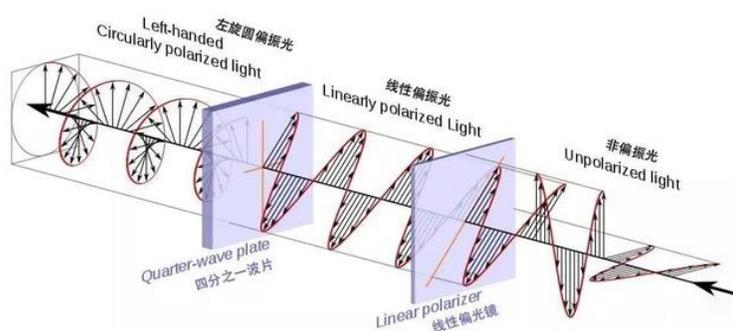
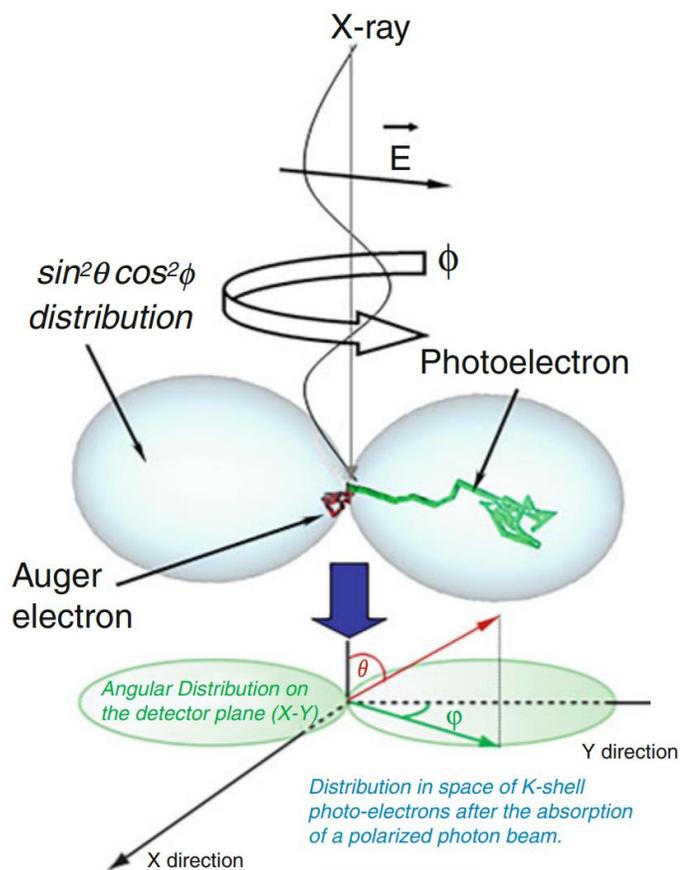
中国科学院粒子天体物理重点实验室
KEY LABORATORY OF PARTICLE ASTROPHYSICS, CAS



1. 气体像素探测器（GPD）光电子径迹重建
2. 时间投影室（TPC）光电子径迹重建
3. 3D光电子径迹重建

X射线偏振探测原理

$$\frac{\partial \sigma}{\partial \Omega} = r_0^2 \frac{Z^5}{137^4} \left(\frac{mc^2}{h\nu} \right)^{7/2} \frac{4\sqrt{2} \sin^2 \theta \cos^2 \phi}{(1 - \beta \cos \theta)^4}$$



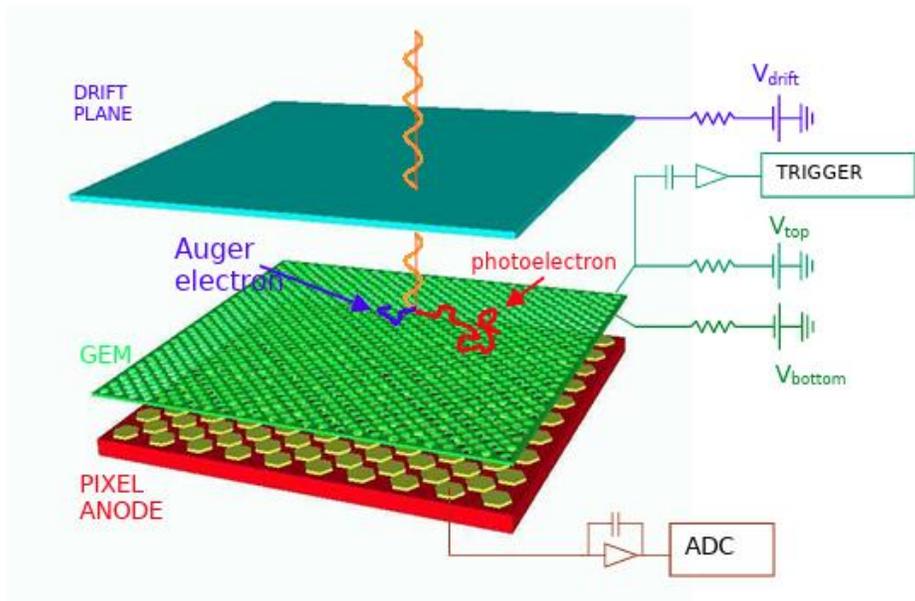
eXTP — 机器学习在光电子径迹重建中的应用

$$\mu = \frac{S_{\max} - S_{\min}}{S_{\max} + S_{\min}}$$

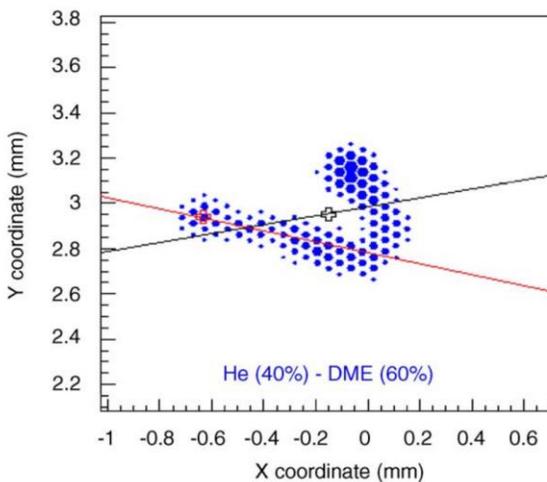
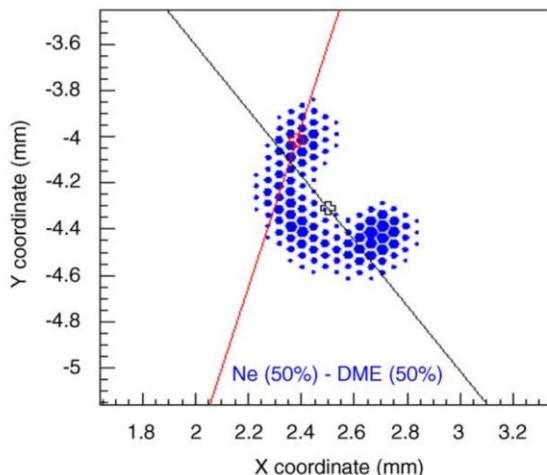
利用机器学习重建X射线偏振探测器光电子径迹的出射方向和作用点位置

■ 读出平面垂直于入射X射线

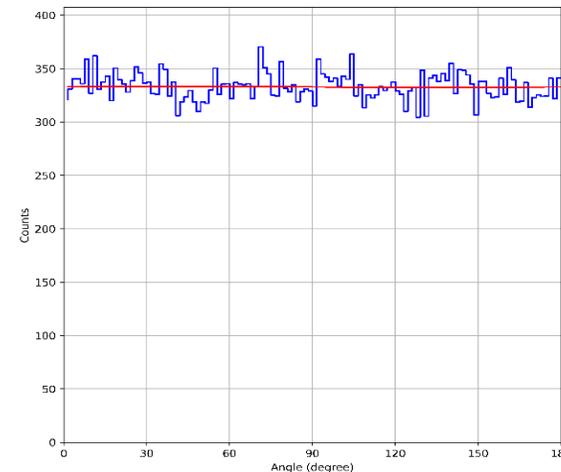
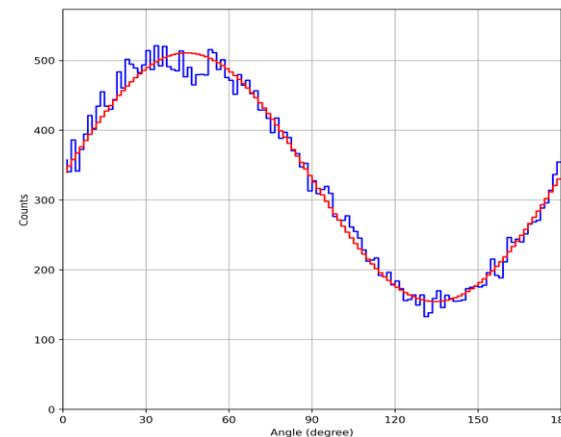
- 2001年, E.Costa发明气体像素探测器 (GPD)
- 首次实现光电型X射线偏振探测器
- 0.44 @ 5.4keV, 0.16(FWHM) @ 5.4keV



X射线偏振探测原理



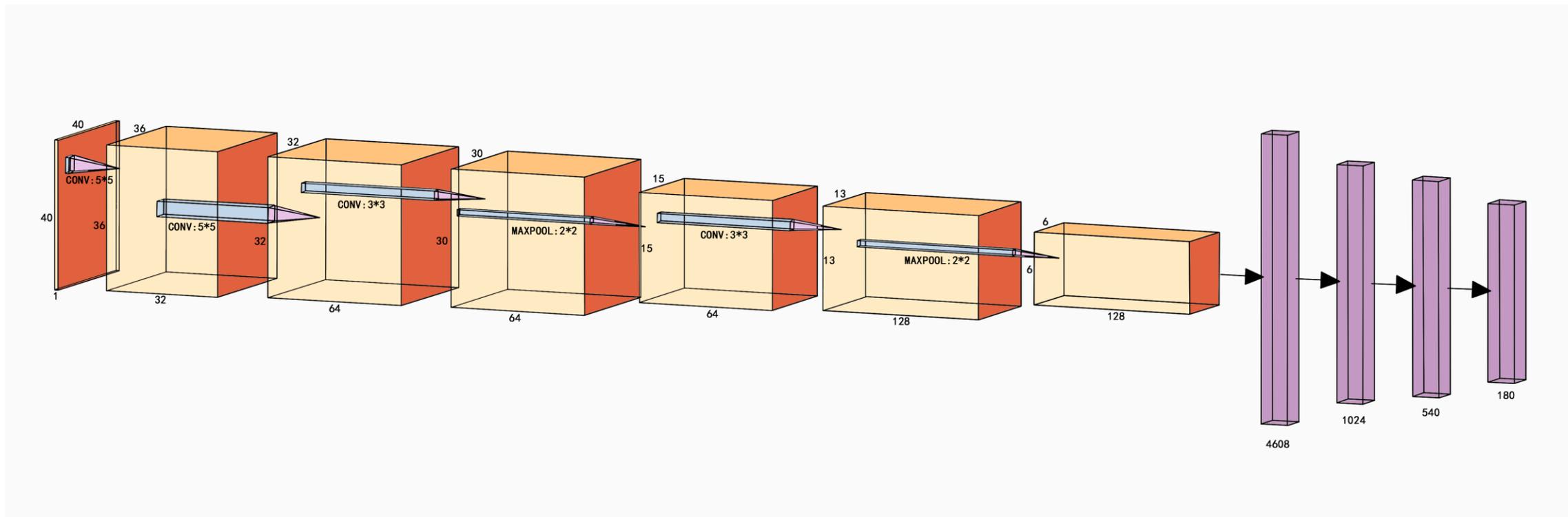
光电子径迹及重建



判据

- 对偏振X射线源测量数据的调制因子高
- 对无偏X射线源的调制因子低

卷积神经网络 VGG



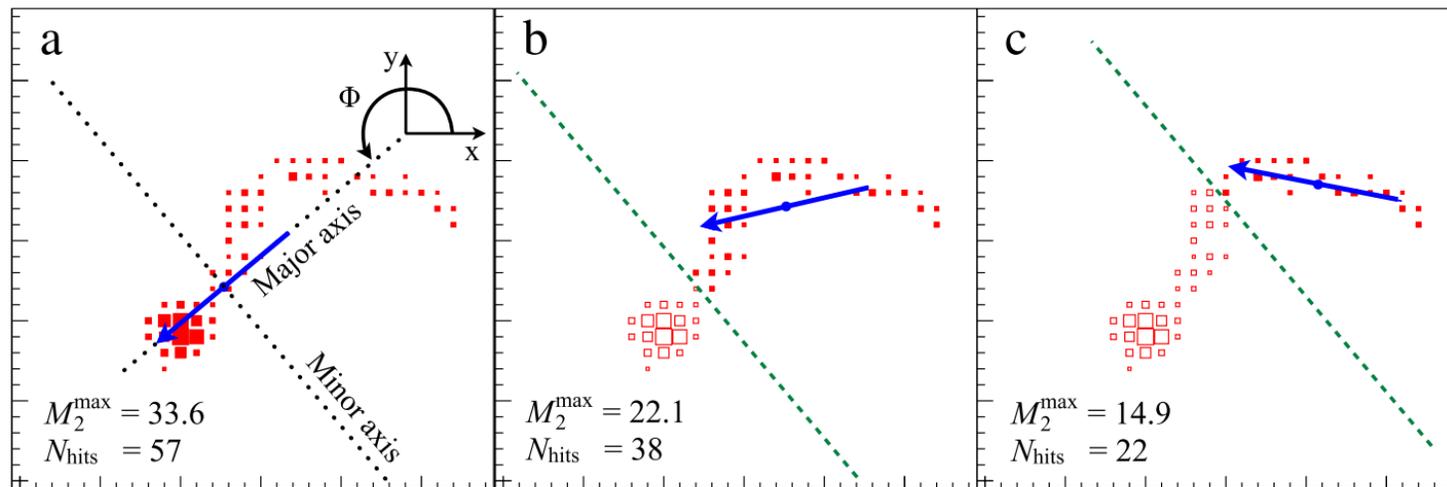
It consists of four convolutional layers. In the first two layers, we used 32 single-channel and 64 32-channel 5x5 convolutional kernels to extract features. We chose to use 5x5 convolutional kernels because we aimed to enlarge the receptive field to enable the recognition of the surrounding pixels of each hexagonal pixel by a single convolutional kernel. To retain sufficient features, we did not use pooling layers for compression in the middle of the first two convolutional layers. The subsequent two layers consisted of 64 64-channel and 128 64-channel 3x3 convolutional kernels for further feature extraction, along with the addition of 2x2 max-pooling layers for data compression. ReLU activation

光电子径迹重建方法国际现状



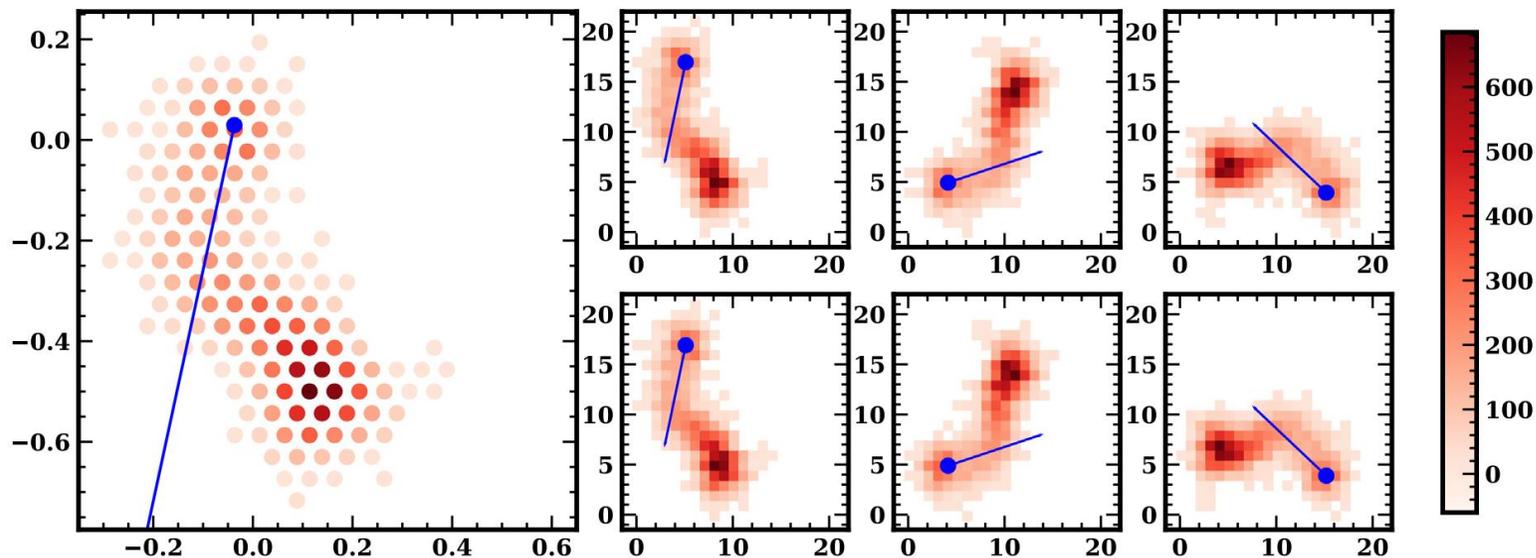
- 力矩法

- 筛选
- 权重



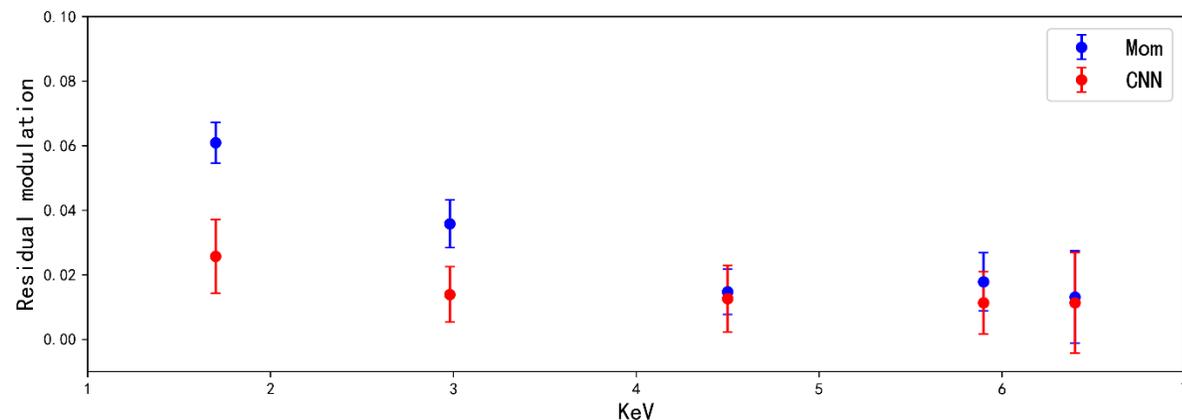
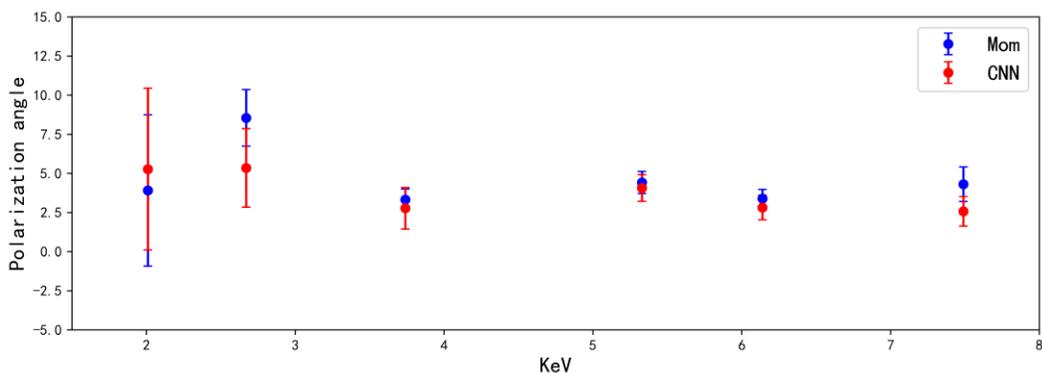
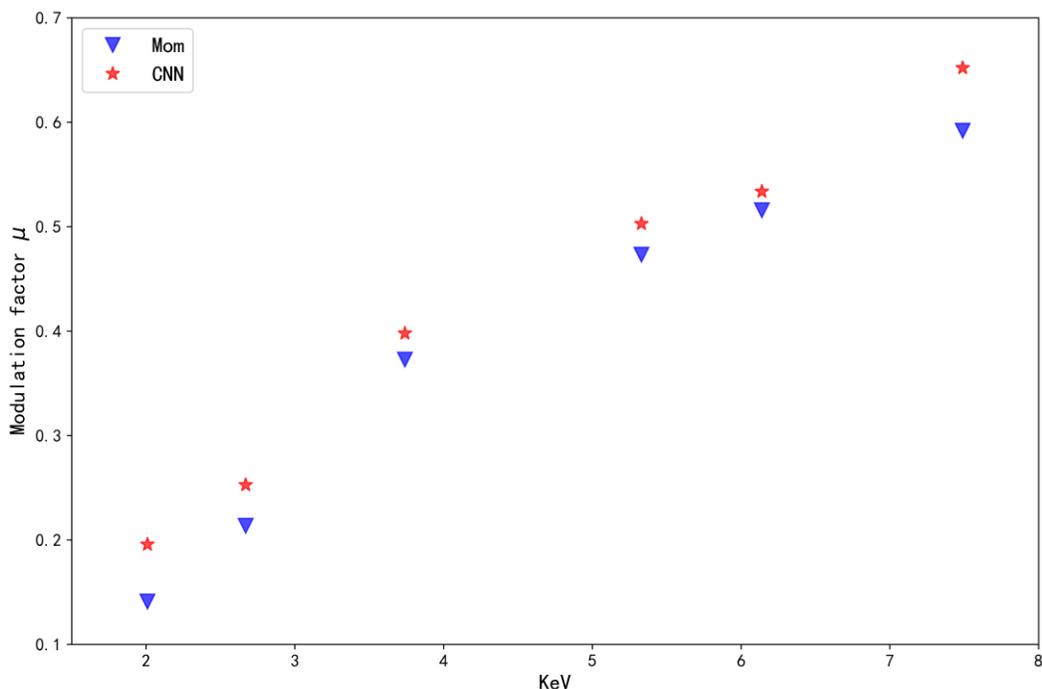
- 机器学习

- 回归
- 分类



eXTP — 机器学习在光电子径迹重建中的应用

目前机器学习在试验数据中的分析结果已经优于传统的力矩法。



当前进展：

左上侧图片为机器学习法（CNN，红）和力矩法（Mom，蓝）重建出的不同能量下的调制因子。
左下侧图片为机器学习法与力矩法重建的对应能量下偏振角度。

右上侧图为机器学习法与力矩法对不同能量下无偏数据重建所产生的残余调制的对比。

eXTP — 机器学习在光电子径迹重建中的应用

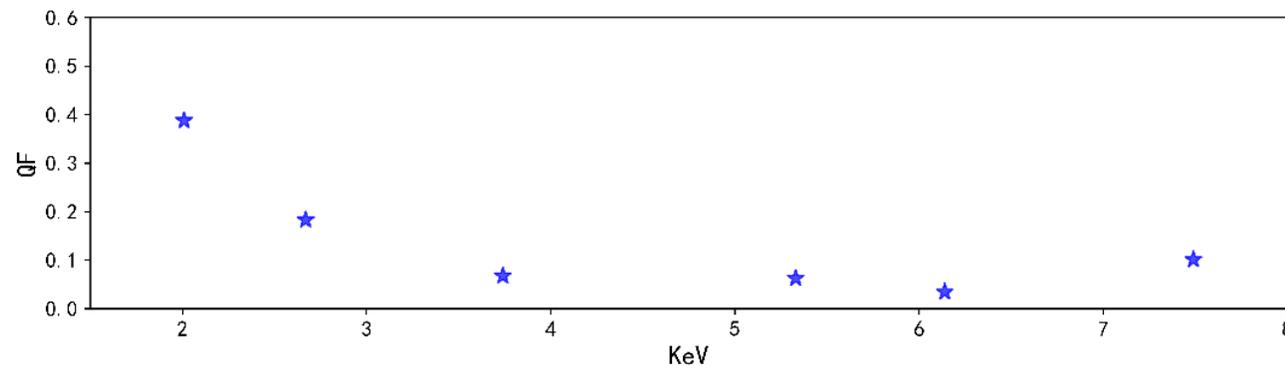


Figure 10. The improvement of Quality Factors by deep learning methods.

be due to the fact that training the deep learning model with the photoelectron emission angle reconstructed by the moment analysis as the training target has stronger learnability and universality. Training on simulated data may have enhanced the deep learning model's resistance to interference to some extent, thus achieving better experimental results than the moment analysis during the experimental process with real data. Since $QF = \mu\sqrt{\epsilon}$, the improvement of the modulation factor (as shown in Figure 10) can lead to an increase equivalent to 10-40% of the detector's effective area. This implies that in the low-energy range (approximately 2keV), the new reconstruction algorithm can significantly improve the sensitivity of the detector, such as enabling three PFA (polarization payload of eXTP) payloads to achieve an observational capacity equivalent to that of four payloads.

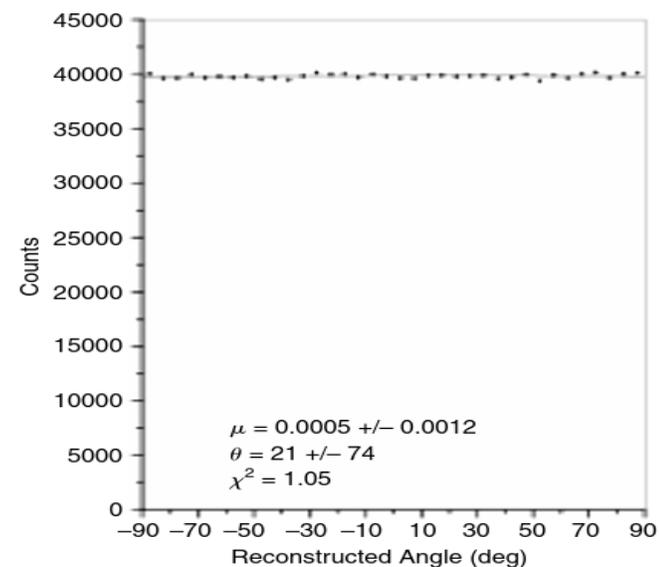
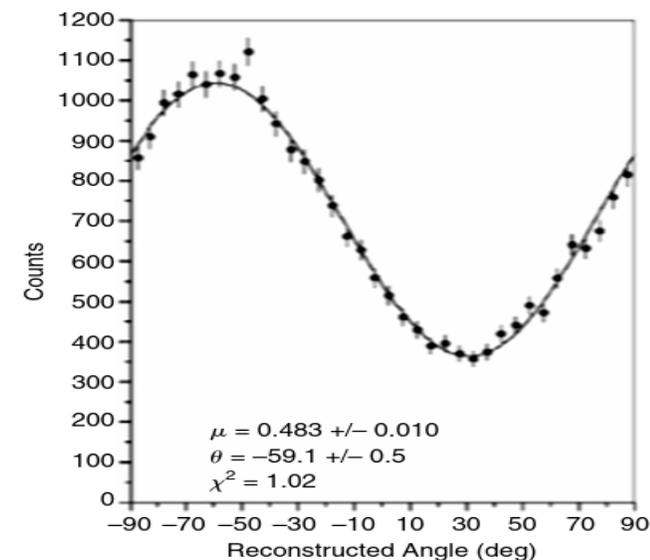
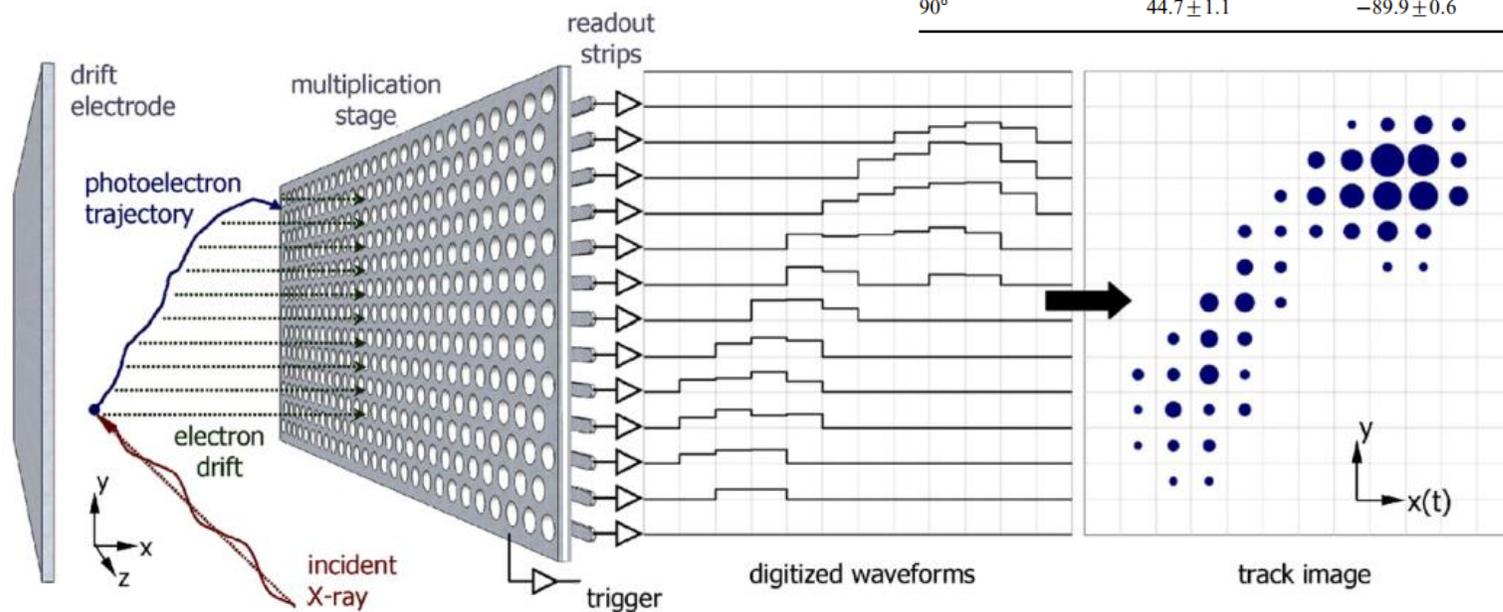
X射线偏振探测原理



■ 读出平面平行于入射X射线

- 2007年, J.K. Black发明微结构时间投影室(TPC)
- 时间+位置组成光电子二维图像
- 0.45 @ 6.4keV

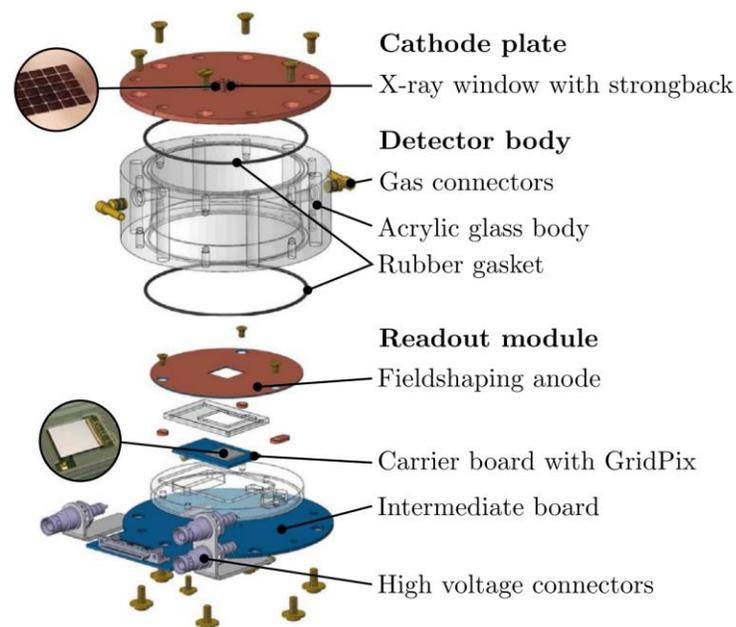
Polarization phase	Measured parameters		
	Modulation (%)	Phase (degrees)	χ^2
Unpolarized	0.49 ± 0.54	44.6 ± 28.7	1.2
0°	45.0 ± 1.1	0.3 ± 0.6	1.1
45°	45.3 ± 1.1	45.2 ± 0.6	1.0
90°	44.7 ± 1.1	-89.9 ± 0.6	1.4



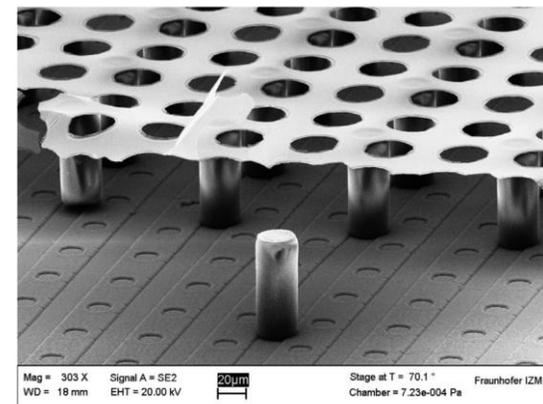
基于GridPixes的新一代3D光电子径迹X射线偏振探测器

基于GridPixes的新一代3D光电子径迹X射线偏振探测器。该探测器基于具有单像素时间分辨、二维位置分辨和能量分辨的4D灵敏ASIC以及直接生长在ASIC上的集成微网结构 (InGrids) 来实现。

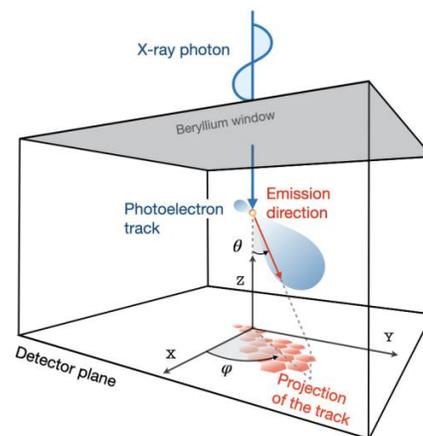
- 利用InGrids更好的增益一致性，更高的位置分辨能力；
- 利用4D灵敏ASIC实现3D光电子径迹读出，从而实现GPD架构和TPC架构合二为一，并且提高低能端调制因子；
- 死时间：由200 μ s提高至几十ns，可以匹配更大面积的聚焦镜；
- 位置分辨：更高的位置分辨、更好的成像和偏振探测能力；
- 从而获得更高的偏振探测灵敏度。



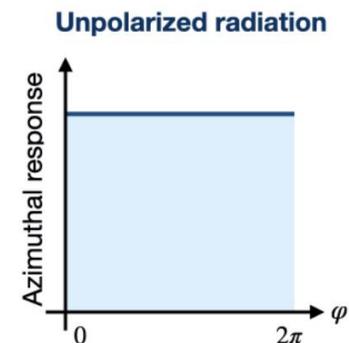
探测器组成示意



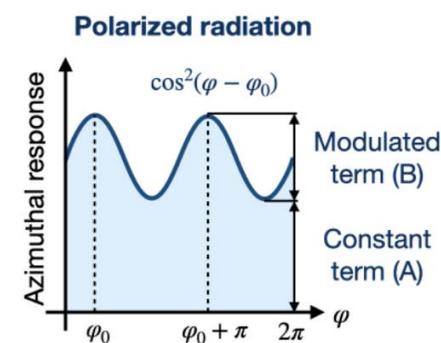
微网结构 InGrid



3D光电子径迹



残余调制



调制因子

欢迎各位专家批评指正！

光电子径迹重建与调制曲线

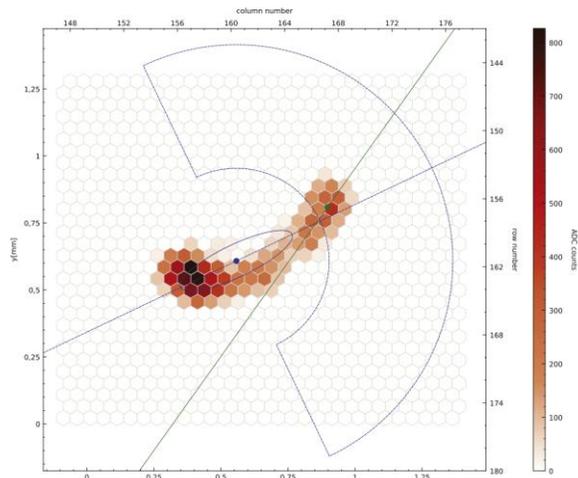
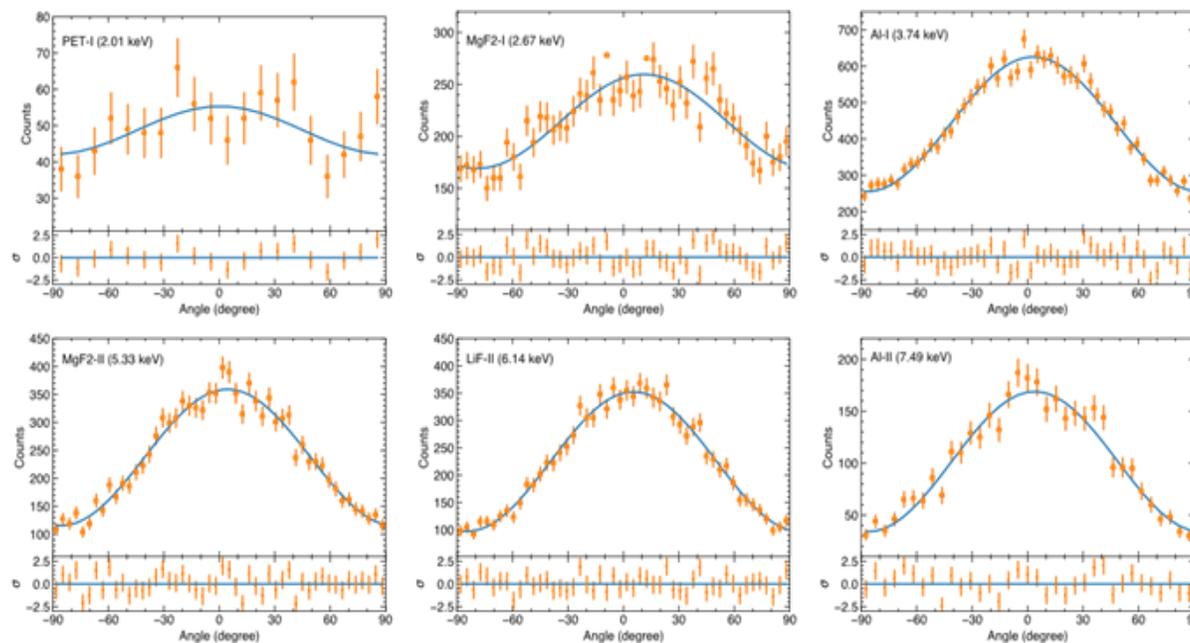
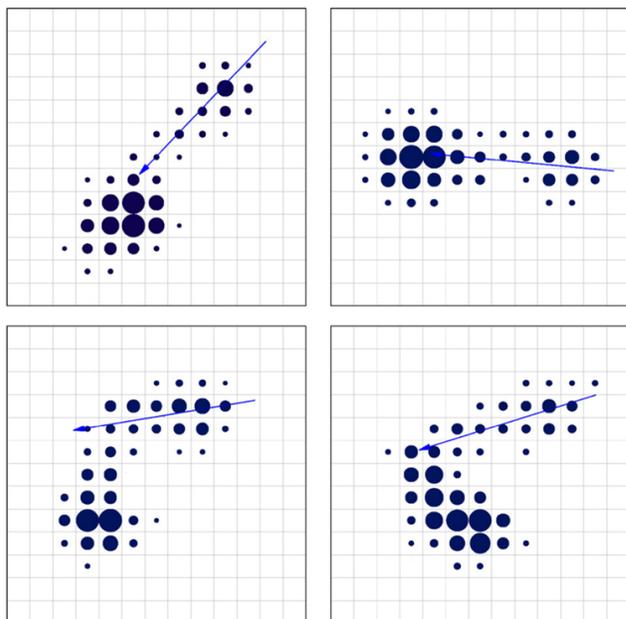
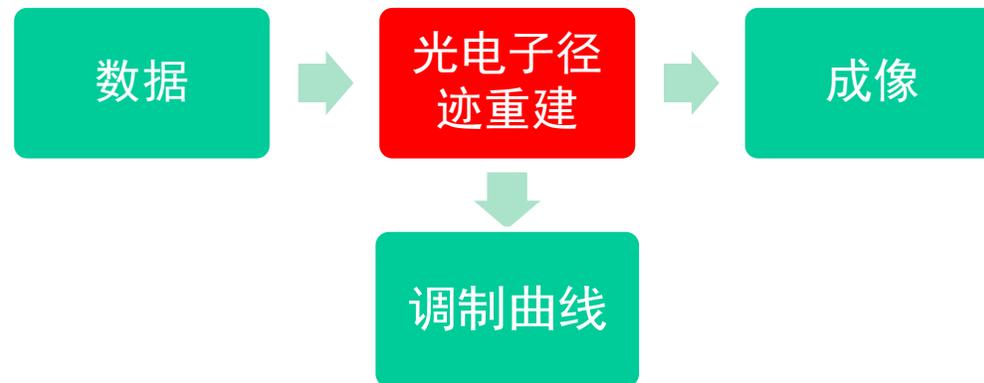


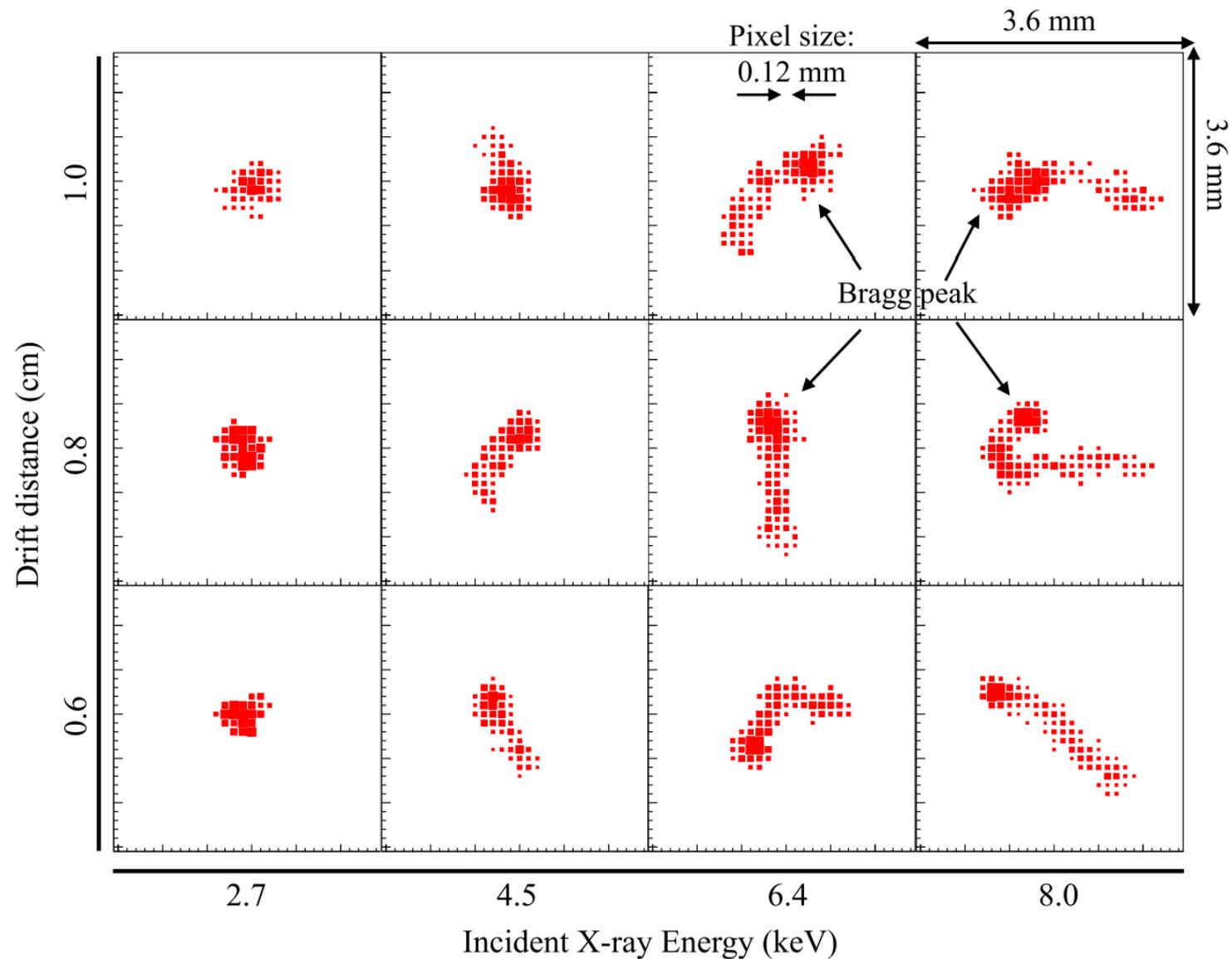
Figure 5. Real photoelectron track at 5.9 keV with reconstructed direction of emission and absorption point.



光电子径迹实例



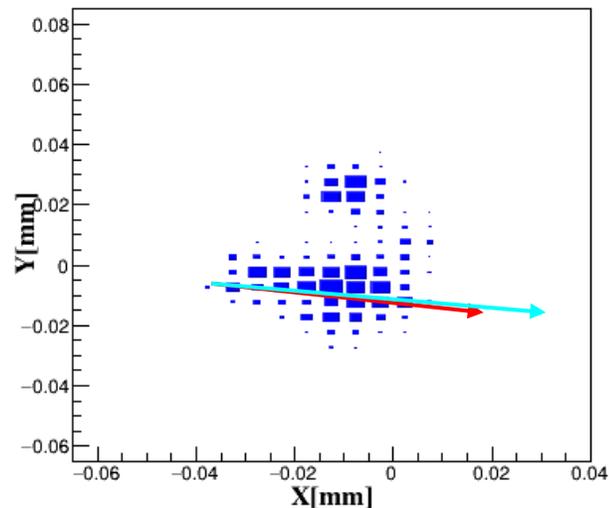
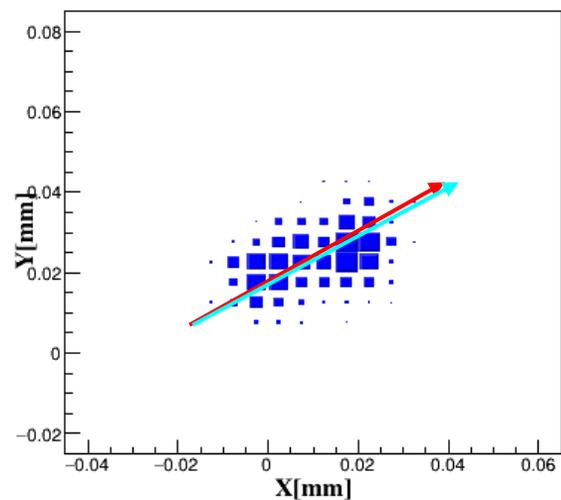
- 布拉格峰
- 俄歇电子
- 库仑散射



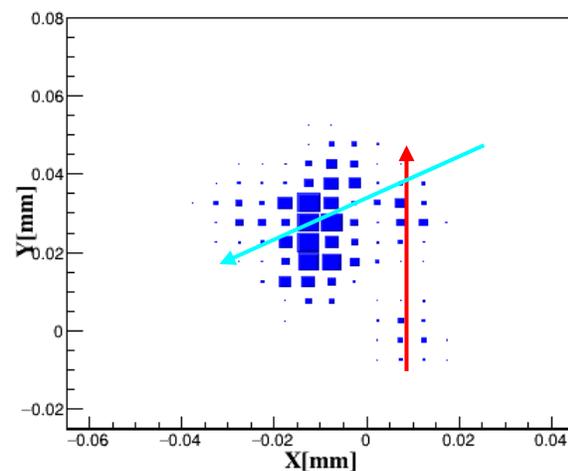
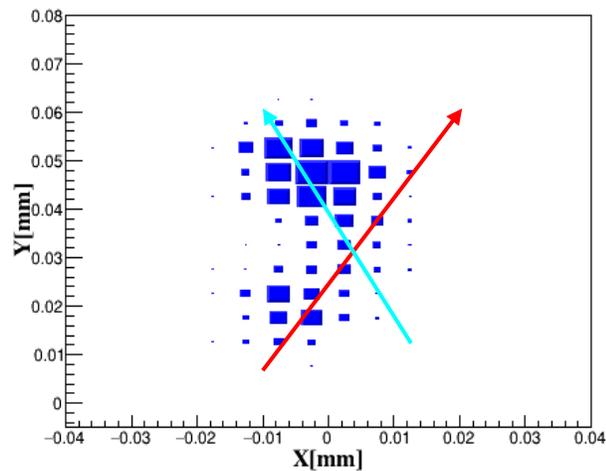
光电子径迹实例



- 布拉格峰
- 俄歇电子
- 库仑散射



→ Ang_{in}
→ Ang_{re}



~18%
Events
 Δ_{ang}
> 45°