超级陶粲装置
Super Tau-Charm Facility

STCF径迹探测器几何与重建算法优化

张晋（中山大学）
代表STCF软件工作组
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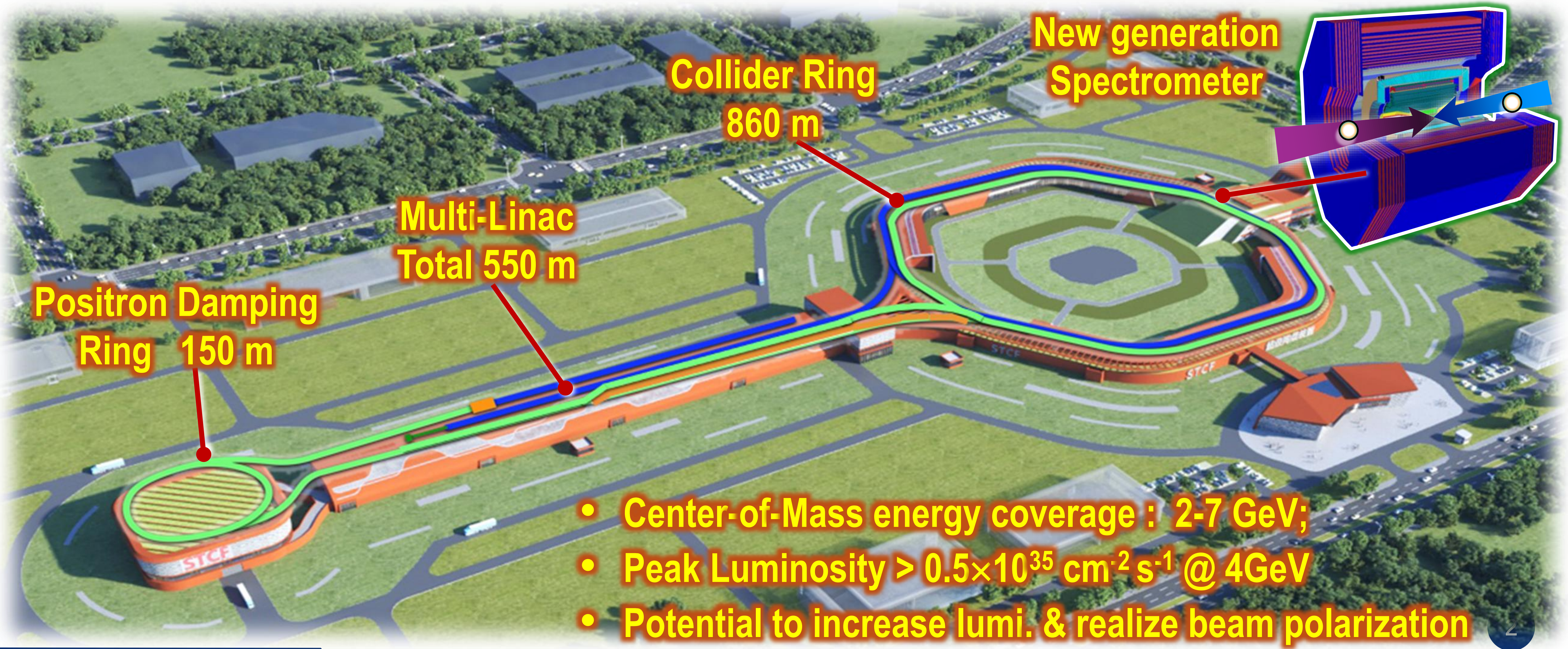
Super Tau-Charm Facility

A factory produced massive tau lepton and hadrons, to unravel the mystery of how quarks form matter and the symmetries of fundamental interactions



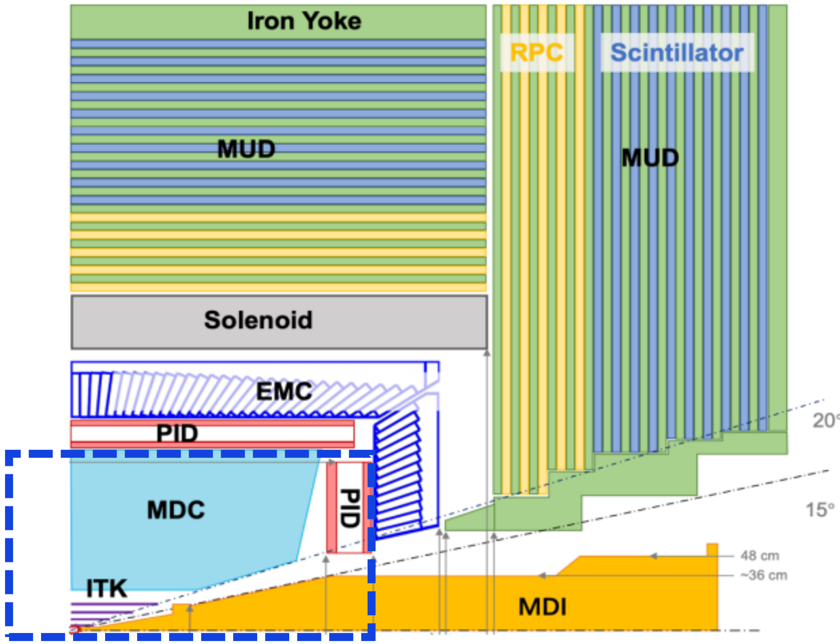
- Center-of-Mass energy coverage : 2-7 GeV;
- Peak Luminosity > 0.5×10^{35} cm^{-2} s^{-1} @ 4GeV
- Potential to increase lumi. & realize beam polarization

Tracking System: MDC + ITK

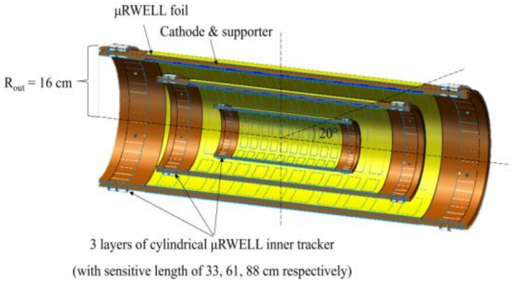
Works in a **1T magnetic field**

CDR:

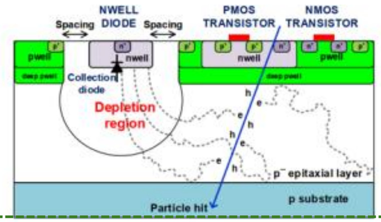
- **MDC**: main drift tracker with large detection volume range
  - 48 layers, 4 stereo super – layers, 4 axial super layers
- **ITK**: 3 layers of detectors with high counting rate capability
  - Placed in the area close to the beam pipe $(3-20\ \mathrm{cm})$
  - Two options: MPGD / MAPS

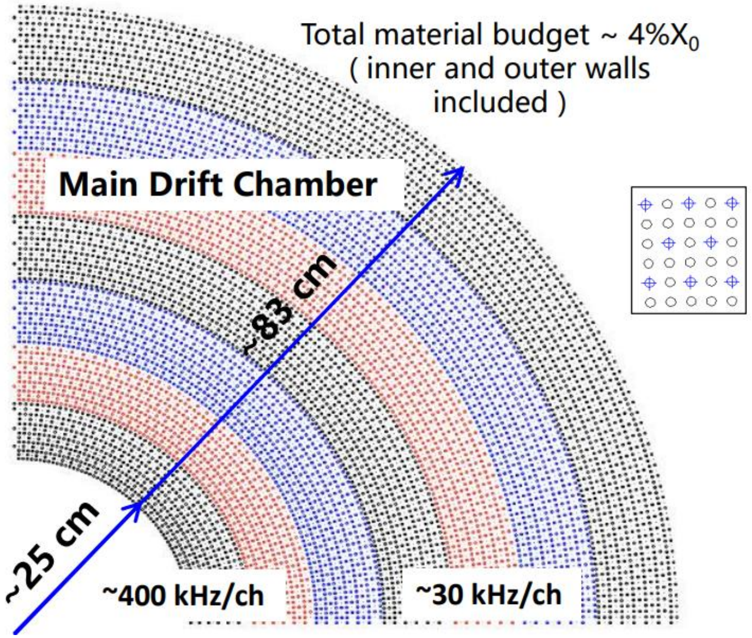


ITK Gaseous option : MPGD



ITK Silicon option: CMOS MAPS





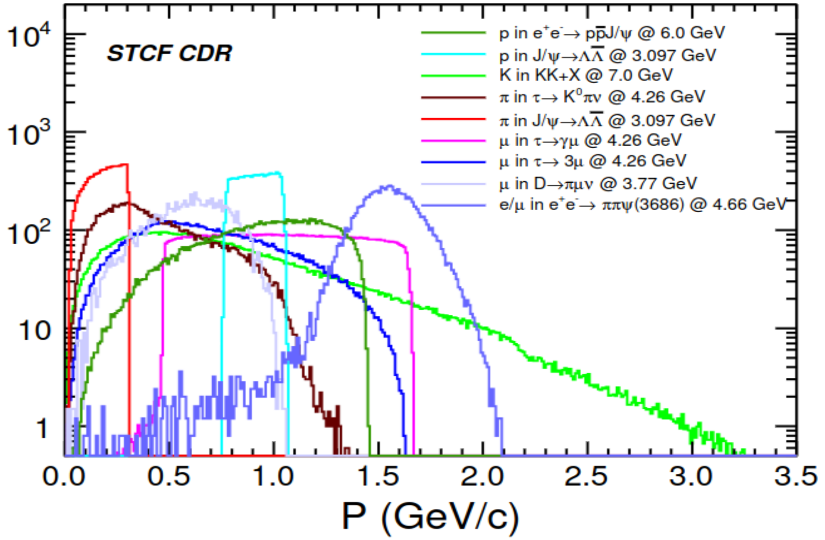
Superlayer	Radius (mm)	Num. of Layers	Stereo angle (mrad)	Num. of Cells	Cell size (mm)
A	200.0	6	0	128	9.8 to 12.5
U	271.6	6	39.3 to 47.6	160	10.7 to 12.9
V	342.2	6	-41.2 to -48.4	192	11.2 to 13.2
A	419.2	6	0	224	11.7 to 13.5
U	499.8	6	50.0 to 56.4	256	12.3 to 13.8
V	578.1	6	-51.3 to -57.2	288	12.6 to 14.0
A	662.0	6	0	320	13.0 to 14.3
A	744.0	6	0	352	13.3 to 14.5
total	200 to 827.3	48		11520	

OSCAR下带电粒子径迹重建的目标和挑战

目标：对大动量范围(50MeV-3.5GeV/c)径迹的高精度、高效率重建

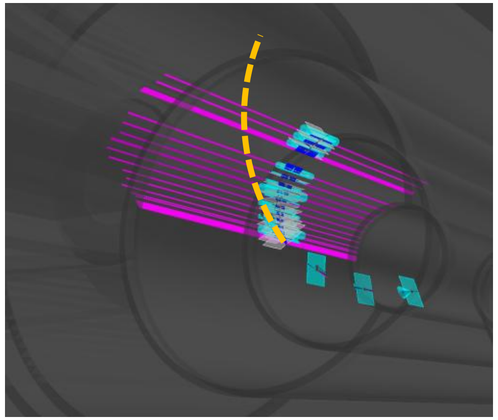
- 0.1GeV/c以上效率高于90%，0.3 GeV/c以上效率高于99%；
- 1GeV/c的动量分辨好于0.5%；位置分辨好于130 um;

Momentum distributions of charged particles

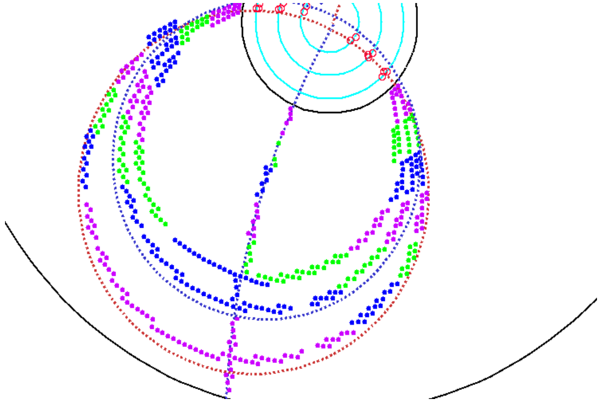


- **高本底：对寻迹带的挑战，影响径迹分辨**
- **大多数物理分析道包含(p<0.4GeV/c)的带电粒子**
  - **显著的物质效应：多次散射，电离能损，特别是ITK、束流管**
  - **pT< 125MeV的低动量径迹在径迹室打圈；大角度径迹击中少，更高的物质效应**
  - **长寿命粒子位移径迹重建的挑战**

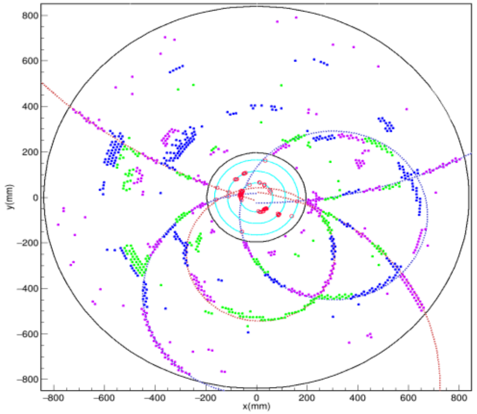
a low p_T track occurs large scattering



a track with multi-turn loops

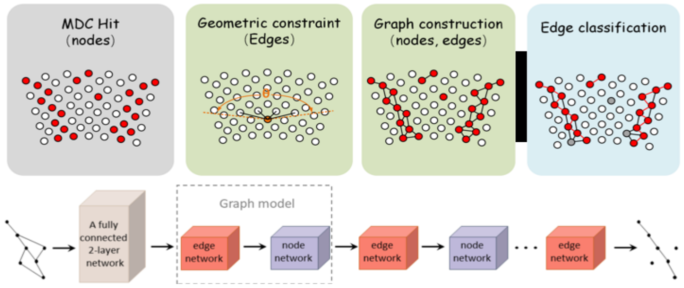


Displaced tracks from long-live particles

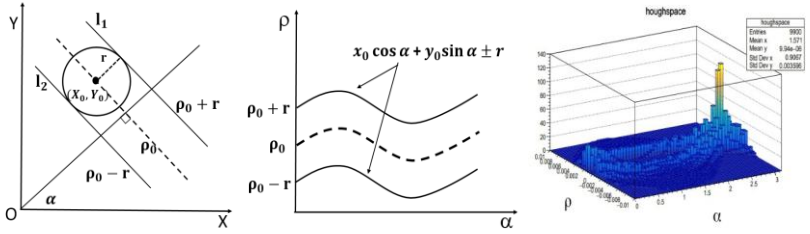


基于Hough变换的基线重建算法

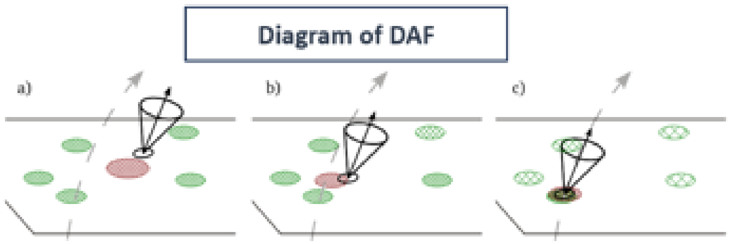
图神经网络去噪(GNN)



全局寻迹(Hough/Legendre)



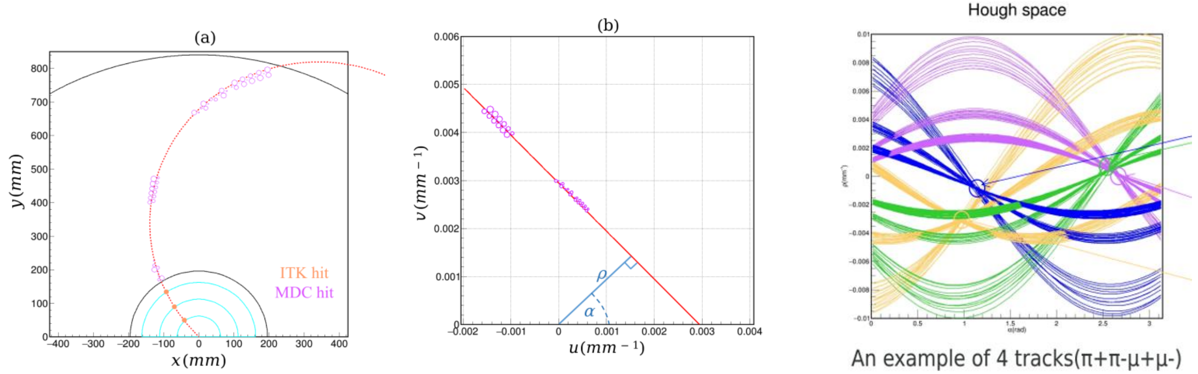
自适应的卡曼滤波(DAF in Genfit2)



Hough 算法在OSCAR下的实现

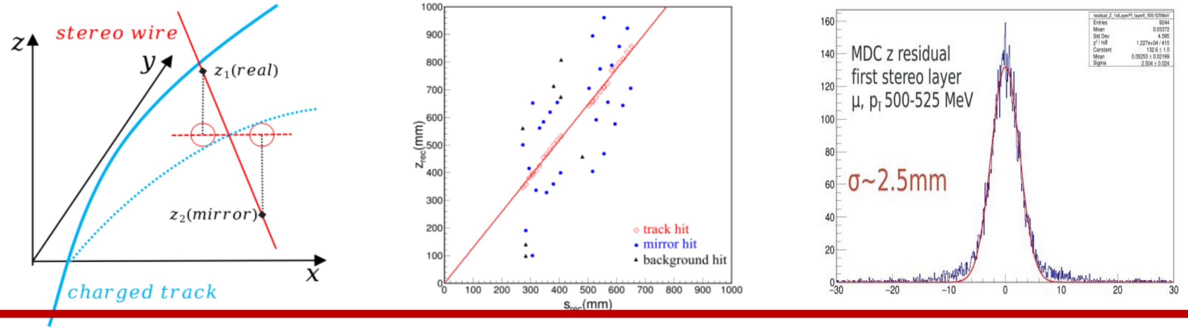
2D

共形变换 → Hough变换 ρ-θ参数平面构建 → 寻峰算法/候选径迹构建 → 圆径迹拟合 击中筛选



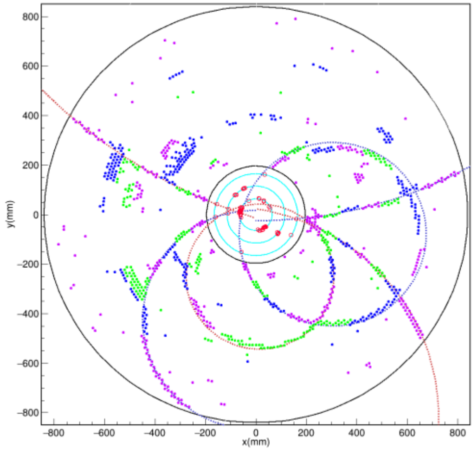
3D

MDC斜丝 击中计算 → Hough变换 Z-S参数平面寻迹 → 斜丝左右判别/三维螺旋线拟合 → 径迹合并/剪除 螺旋线拟合



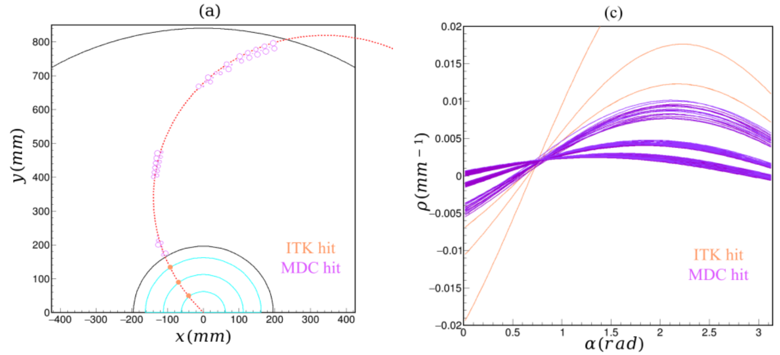
基于Hough变换的基线重建算法 – 位移径迹重建

长寿命粒子径迹重建对传统的Hough变换方法带来挑战：



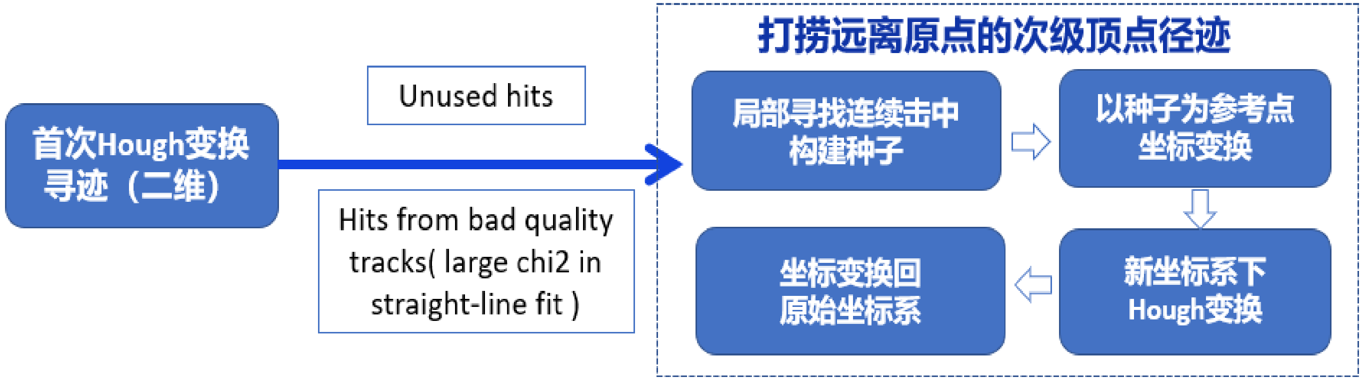
- ◆ **长寿命粒子径迹特点：衰变产生的末态粒子可能在远离原点的位置生成**
  - $J/\psi \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$ **(低动量pion)**
  - $J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda\pi^-\bar{\Lambda}\pi^+ \to p\pi^-\pi^-\bar{p}\pi^+\pi^+$ **(低动量pion, 且径迹数多)**

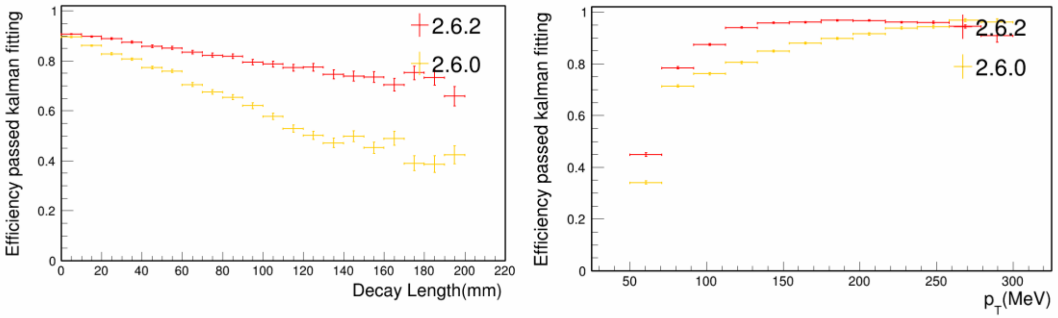
- ➢ **传统Hough变换是一种全局方法：原点依赖的局限性，离原点近的径迹才会在Hough平面形成一个峰**



➢ 针对位移径迹，在OSCAR下开发了一种与径迹局部信息相结合的Hough变换方法：

A Hybrid Hough Transform Incorporating Local Approach





- 相对于传统Hough算法(OSCAR v.2.6.0)，新方法 (OSCAR v2.6.2)对长寿命粒子重建效率有显著提升
- 在低动量区间仍有明显的提升空间

径迹探测器几何优化方案

- 径迹重建性能（尤其是低横动量径迹的重建性能）以及高计数率环境是主要考虑因素

1 布局优化的方向

全动量区间高效率和分辨
- 提升低动量/次级粒子效率
- 内径迹室高计数率

→

2 几何方案

- 不同ITK布局
- 不同探测器和束流管物质
- ITK与MDC的交界方案

→

3 性能研究

全模拟，单粒子/物理事例
- 重建效率，动量、顶点分辨
- 性能差异的来源

→

4 算法优化

通过性能研究和经验，确定重建算法的优化方向，适配探测器几何

→

5 确定几何与重建算法

确定算法的基准方案
研究新本底环境下的性能

迭代（4 → 3）

Layout Options	Beam Pipe	ITK	MDC
CDR	high material budget	3 layer, 36~168mm	48 layers, 20~80 cm
1		3 layer, 36~168mm	Inner chamber with super small cells + 42 layer regular layers, 20~83cm
2	low material budget	3 layer, 36~168mm	Inner chamber with super small cells + 42 layer regular layers, 20~83cm
3		4 layer, 36~168mm	Inner chamber with super small cells + 42 layer regular layers, 20~83cm
4		4 layer 36~210mm	42 regular layers without inner chamber, starting with 10 axial layers, 25~83cm

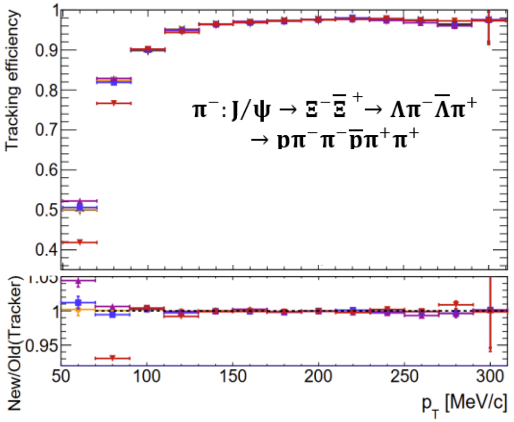
- 选取四种代表方案
- 在OSCAR下对探测器几何布局、探测器物质材料、机械支撑等做了完整的建模和模拟

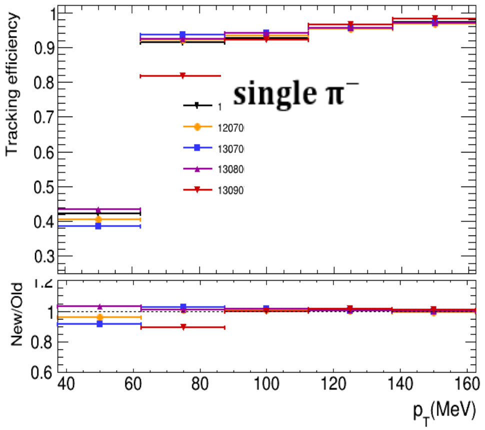
方案4
- 增加 MDC最内侧轴向(直丝)超层的丝层数(6->10), 提升二维寻迹效率与种子质量
- 在外侧扩展一层 ITK, 补强三维寻迹约束, 增强子探测器的独立寻迹能力

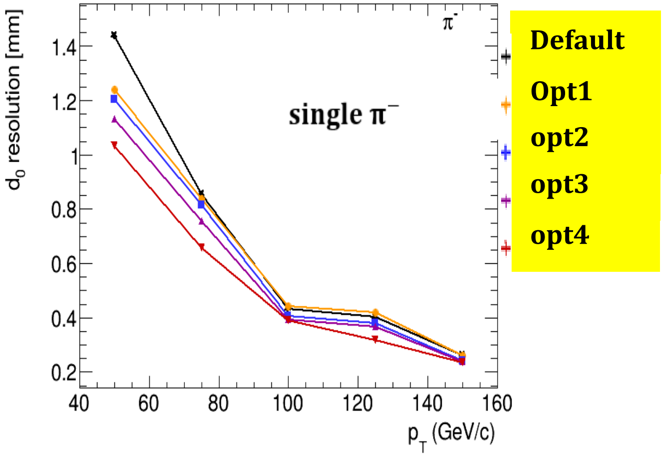
不同几何设计的性能研究

Figures from（刘国豪, 范北昆, 李豪, 陆珍娜, 莫泓琨）

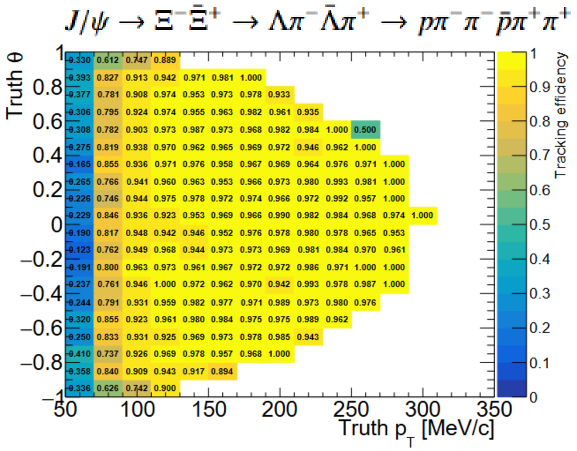
- 在OSCAR下基于Hough+Genfit重建流程对重建性能进行评估
  - 各个方案的重建效率基本相近，方案4低动量(pT<100MeV)重建效率略低

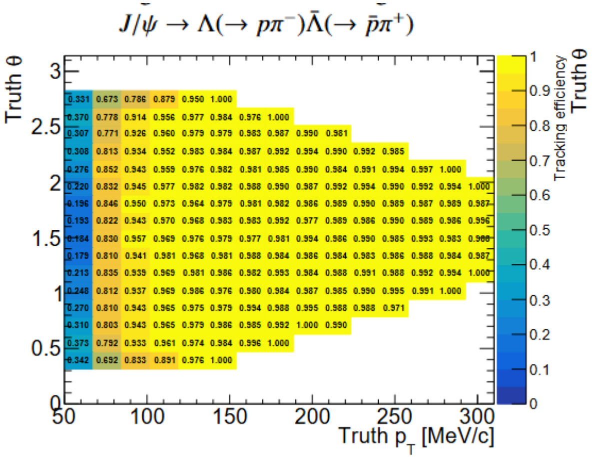


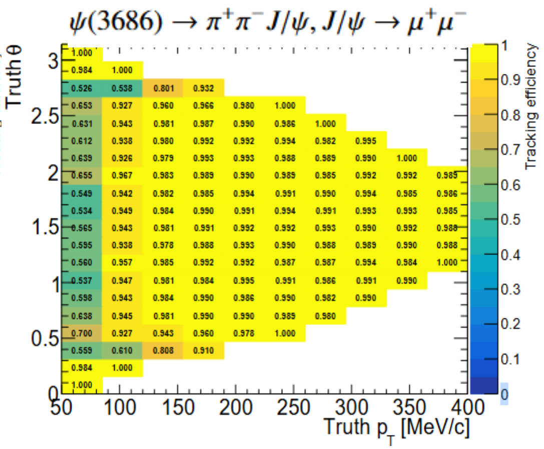




- 方案4低动量径迹效率的下降来自几何与算法的不适配







综合考虑重建性能的潜力，以及机械、计数率，选取方案4作为新径迹探测器方案

针对新几何Hough算法的优化

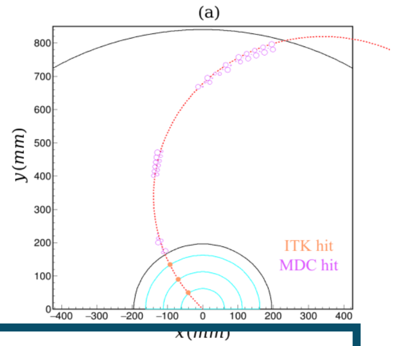
刘国豪，周杭

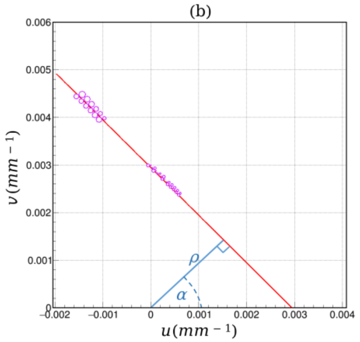
- 基于方案4，针对低动量、位移径迹、多径迹的算法优化
  - MDC几何变动 -> 算法流程中的参数条件适配新几何
  - 新增一层ITK -> ITK测量的打捞
  - 低动量径迹明显的物质效应 -> ITK+MDC测量的联合，径迹质量筛选

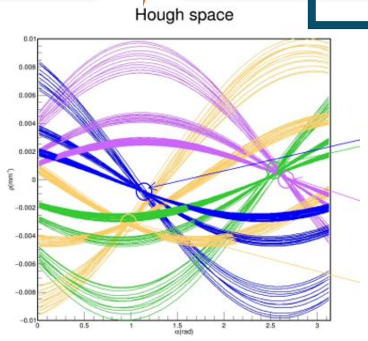
共形变换 → Hough变换 ρ-θ参数平面构建 → 寻峰算法/候选径迹构建 → 圆径迹拟合击中筛选

增加ITK击中打捞方法；优化位移径迹打捞算法

优化ITK+MDC联合拟合；优化二维径迹质量的条件





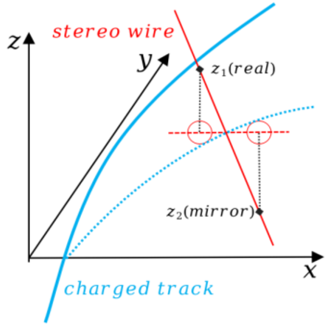


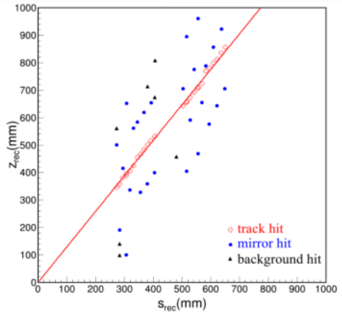
An example of 4 tracks(π+π-μ+μ-)

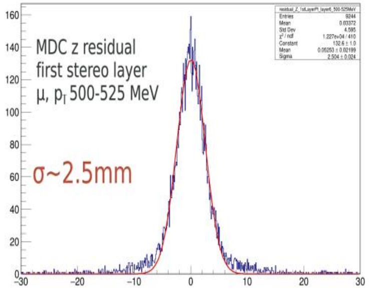
优化ITK击中在Z-S平面的挑选

MDC斜丝击中计算 → Hough变换 Z-S参数平面寻迹 → 斜丝左右判别/三维螺旋线拟合 → 径迹合并/剪除螺旋线拟合

优化径迹质量筛选条件





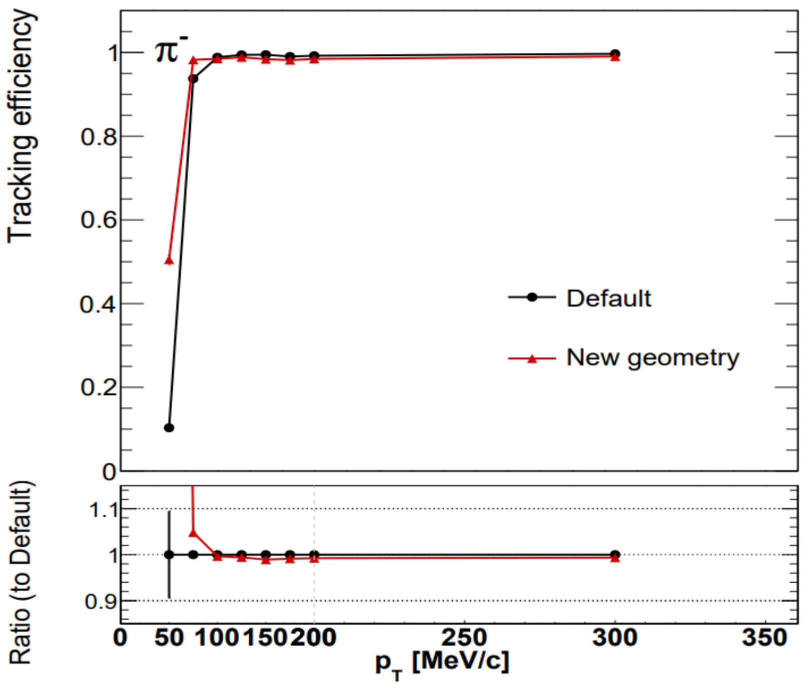


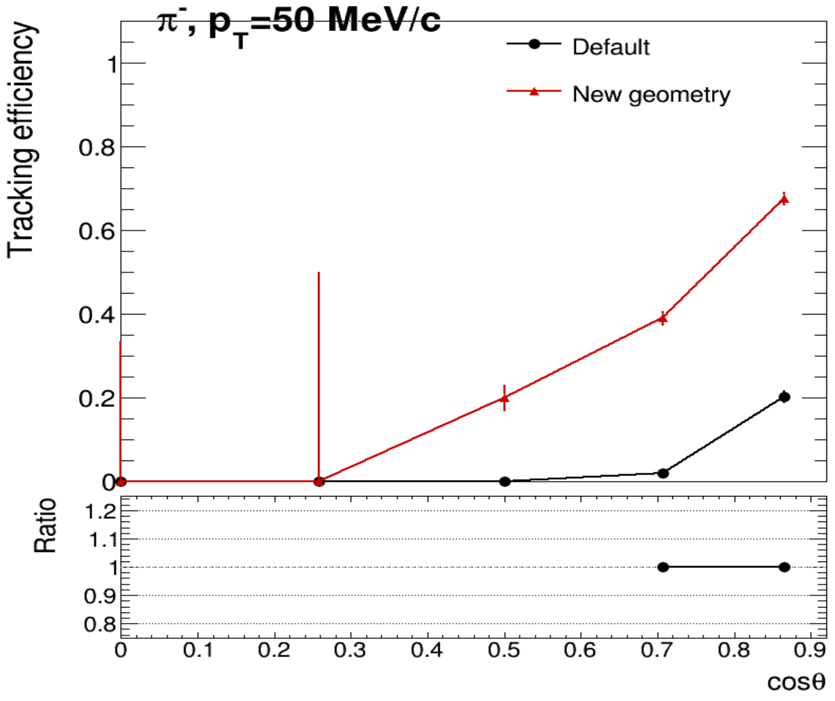
新几何下单粒子的重建性能(无本底)

Figures from（范北昆）

Track finding efficiency： N1 / N2
N1: Number of reconstructed tracks matching with the truth tracks（>80%）
N2: Number of truth tracks with simulated hits >3

单粒子，固定横动量：50, 75, 100, 150, 200, 300MeV/c





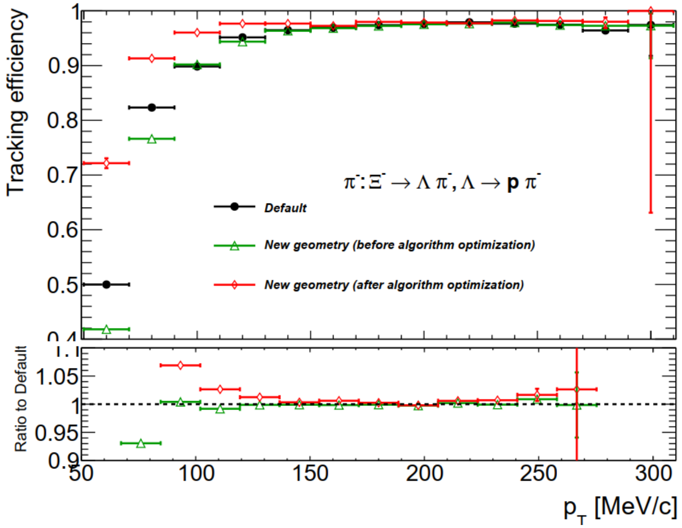
pT = 50MeV的pion粒子穿过探测器层数有限，更依赖于ITK的自寻迹

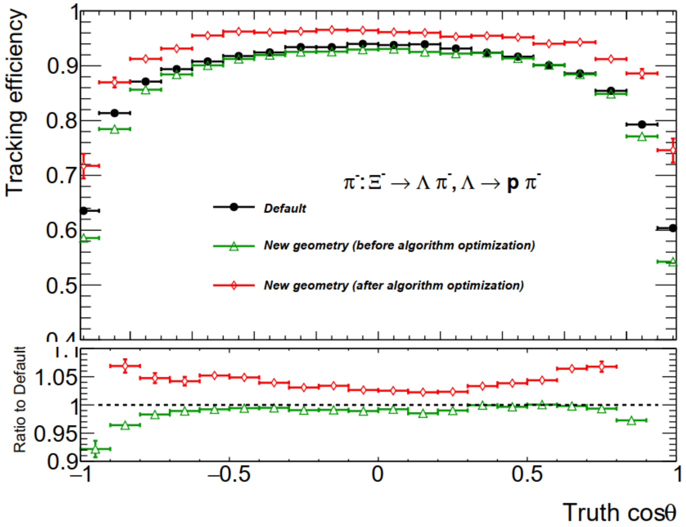
新几何下的重建性能(无本底)

- 新几何方案 + 算法优化，重建效率提升

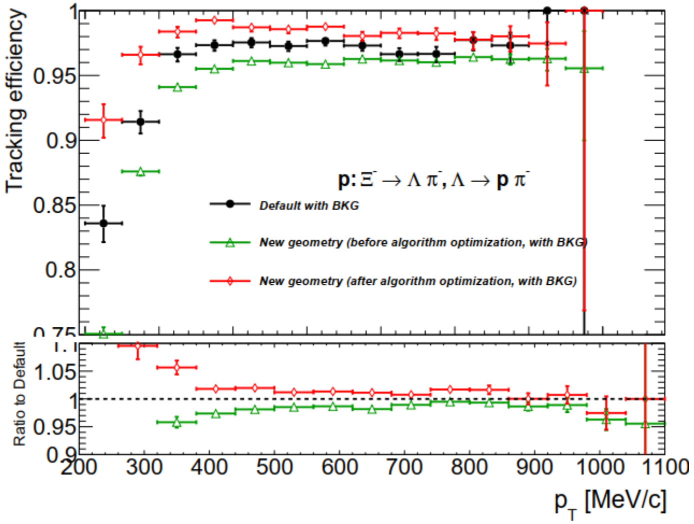
Figures from（刘国豪,p11~14）

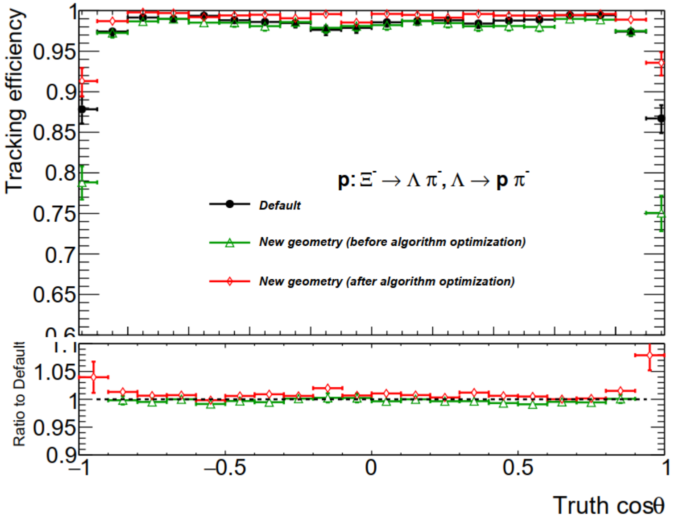
Pion from $J/\psi \to \Xi^- \bar{\Xi}^+ \to \Lambda\pi^- \bar{\Lambda}\pi^+ \to p\pi^-\pi^-\bar{p}\pi^+\pi^+$





Proton from $J/\psi \to \Xi^- \bar{\Xi}^+ \to \Lambda\pi^- \bar{\Lambda}\pi^+ \to p\pi^-\pi^-\bar{p}\pi^+\pi^+$





物理分析事例挑选

Before algorithm optimizations:

Total event = 20000

nGood = 38.77%

SelXi = 34.37%

SelXibar = 33.30%

KFit = 25.02%

After algorithm optimizations:

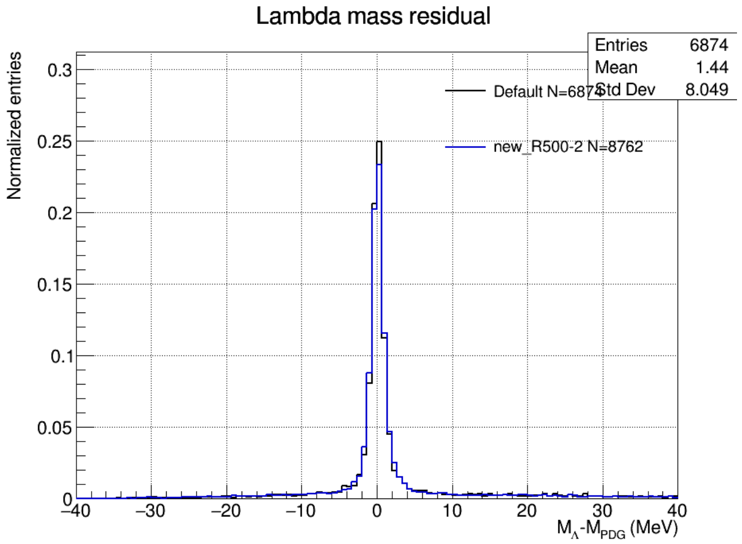
Total event = 19600

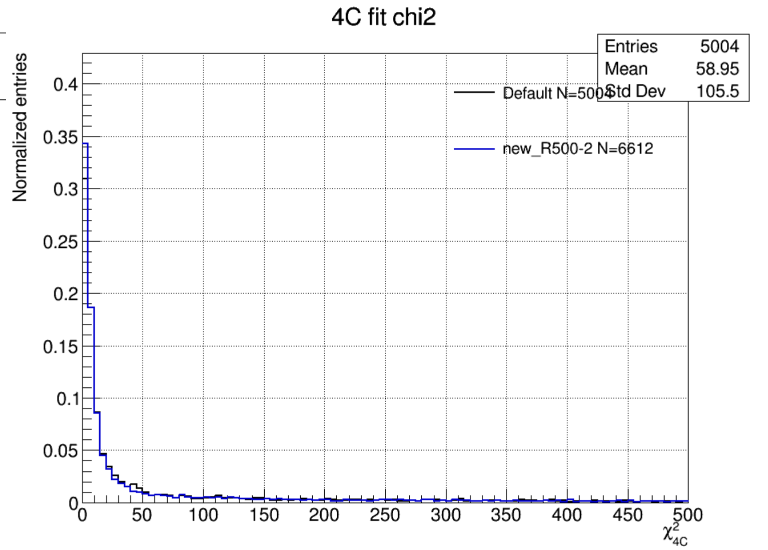
nGood = 49.73%

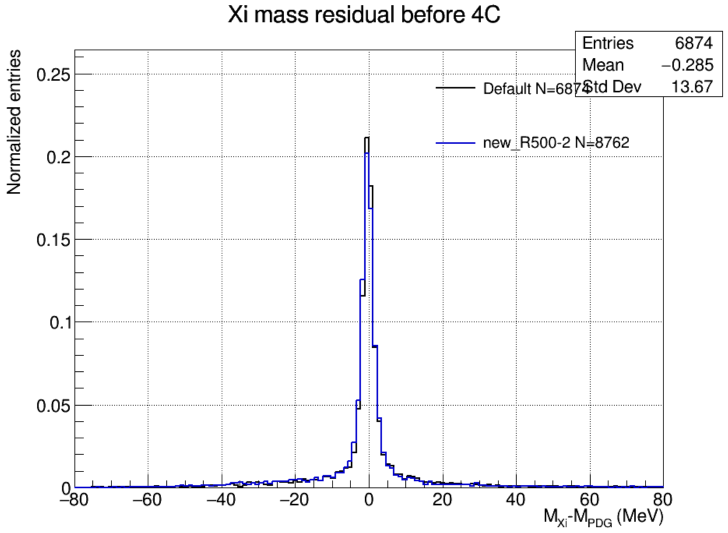
SelXi = 44.70%

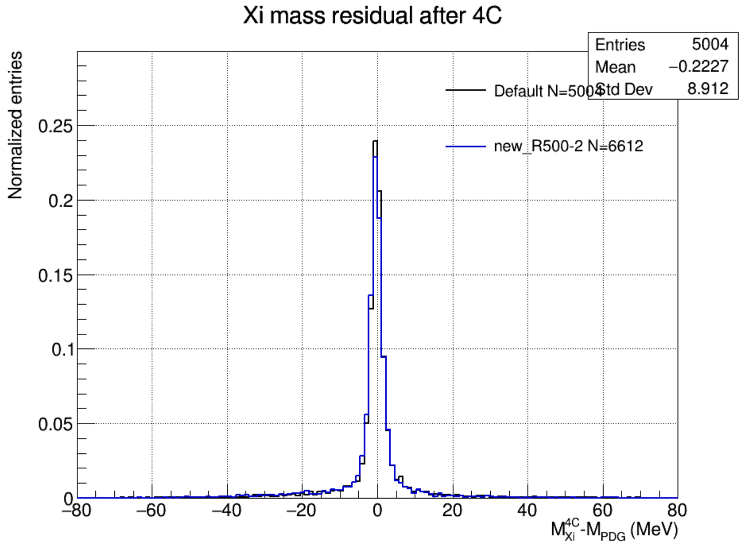
SelXibar = 43.81%

KFit = 33.73%





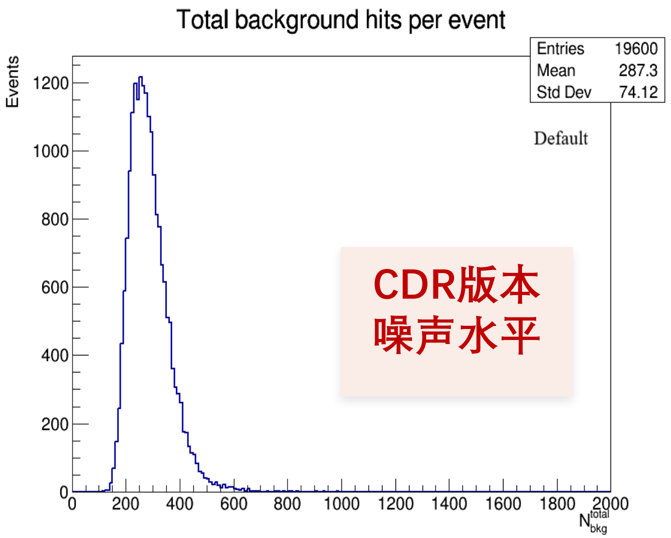


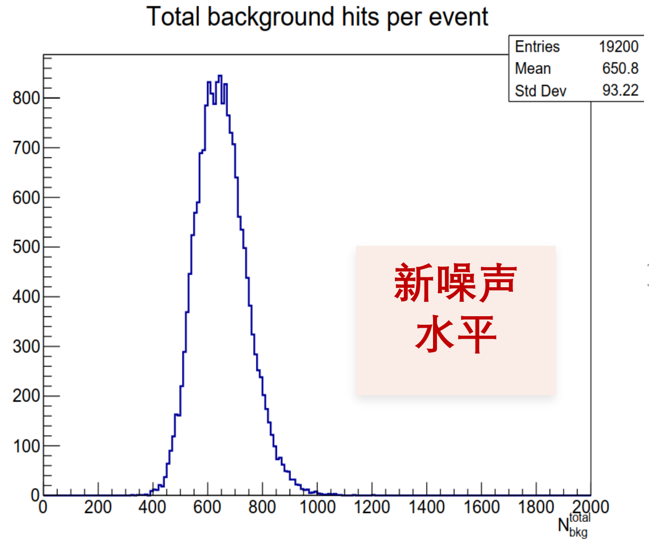


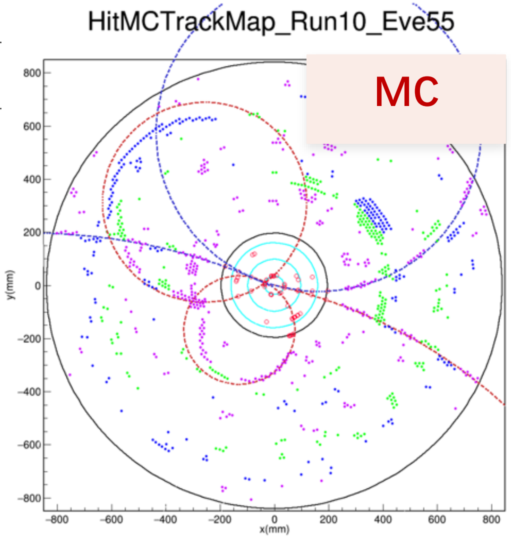
更多物理分析结果在物理分析组研究（徐月，周小蓉）

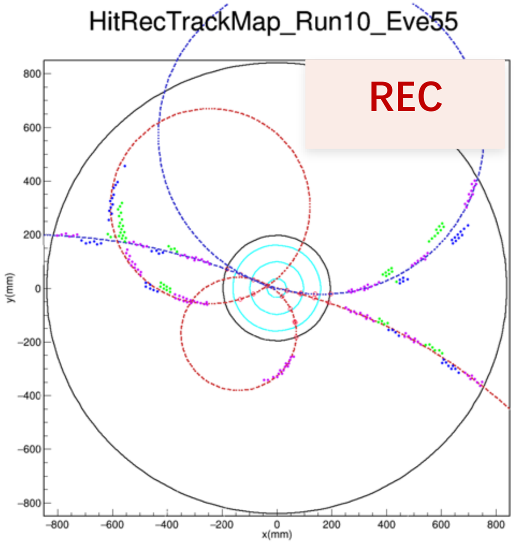
本底水平下的重建性能

相对于CDR，新的噪声水平提高了2~3倍

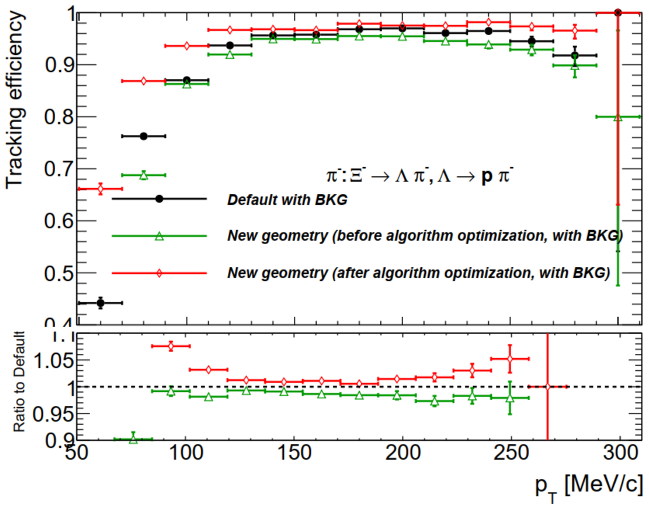


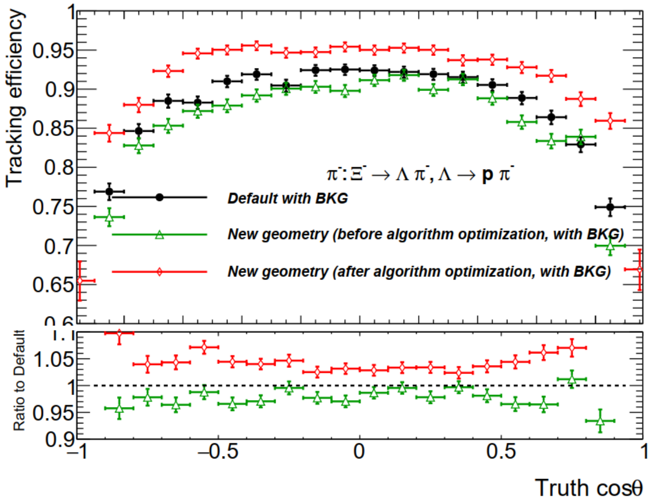




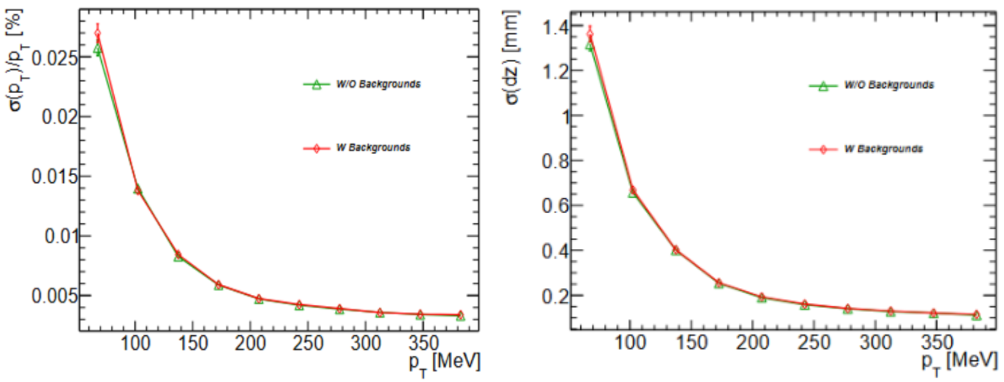


新噪声水平下，径迹重建保持性能较高水平：displaced pion >90% @100MeV



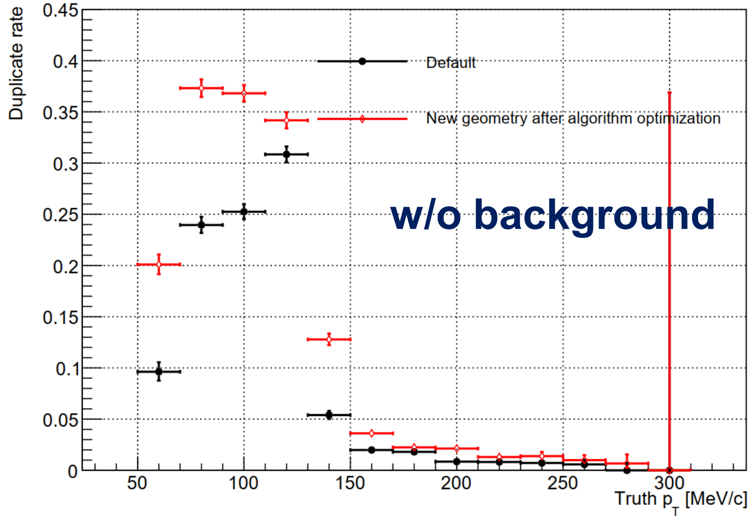


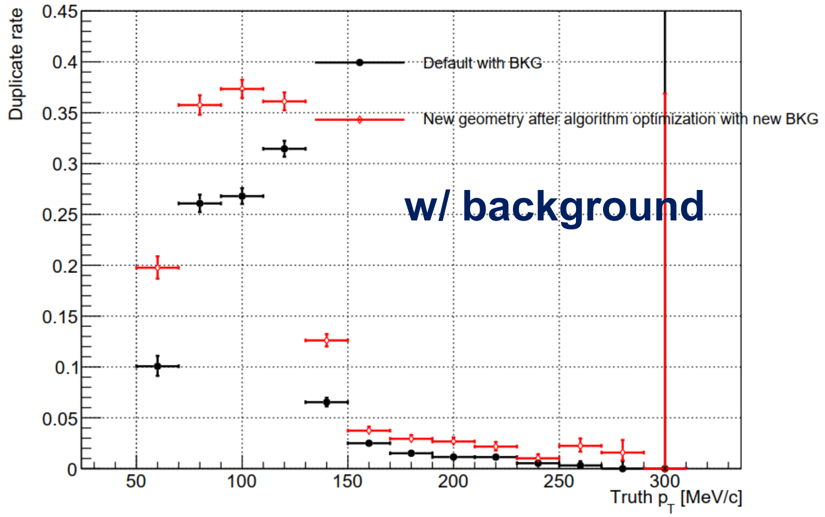
pT and dz resolution of pion in $\psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$



本底水平下的重建性能

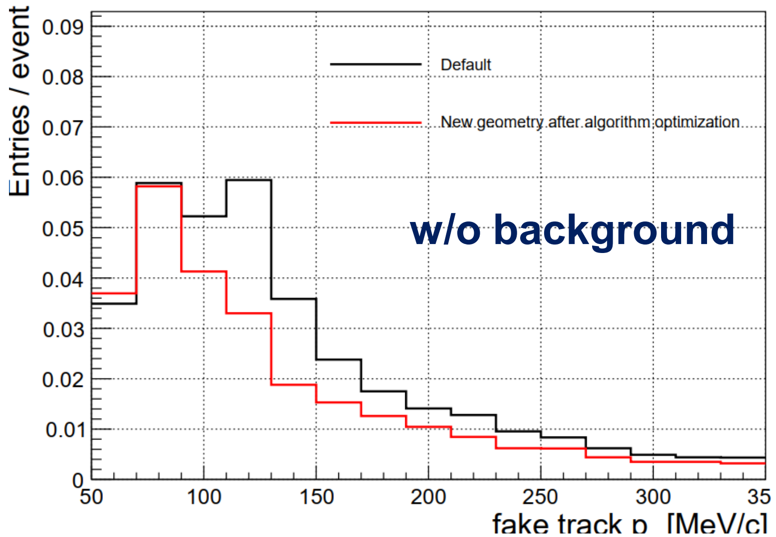
重复径迹：>80% 击中成功与truth track 匹配，超过一条重建径迹匹配到一条truth track

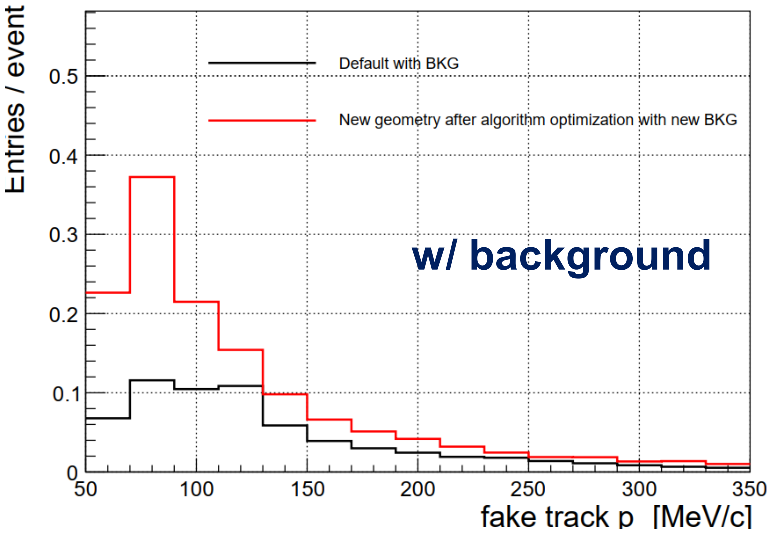




- 重复径迹集中在低动量打圈部分(pT<130MeV)
- 噪声对重复径迹影响不大
- 目前采取的合并重复径迹的条件较为宽松，前后半圈可能同时保留

假径迹：<80% 击中能与与truth track 匹配



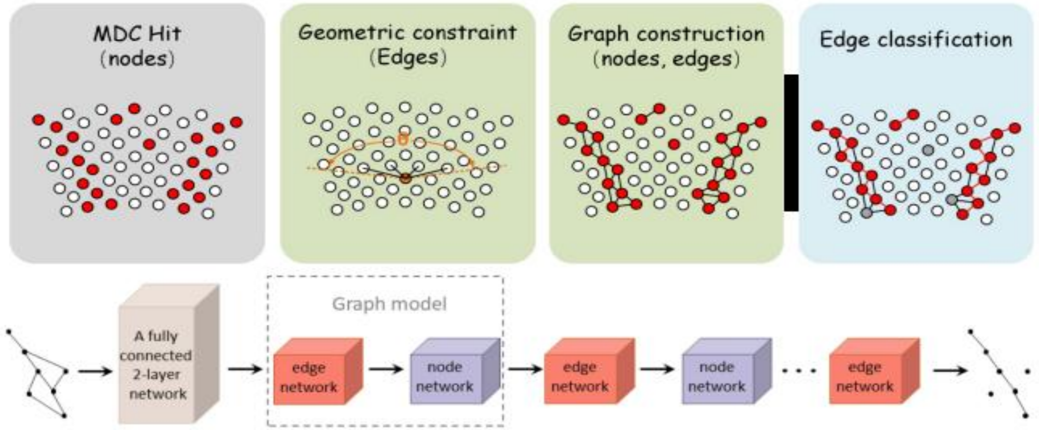


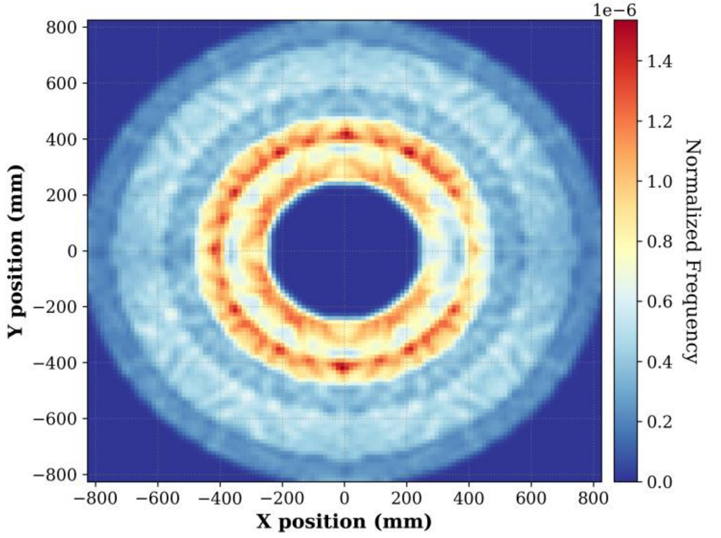
- 重复的低动量径迹（纯度不足80%）是来源之一
- 新噪声水平下，假径迹增多

新几何下GNN除噪

贾晓倩

- 基于新噪声水平的挑战，将GNN应用于MDC去噪





◆ **根据几何关系和超层布局进行构图**

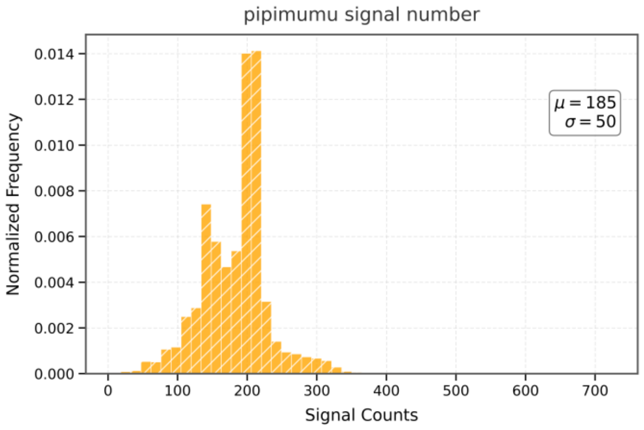
◆ **输入信息：击中TDC, 信号丝 r, φ 坐标，链接矩阵，边标签**

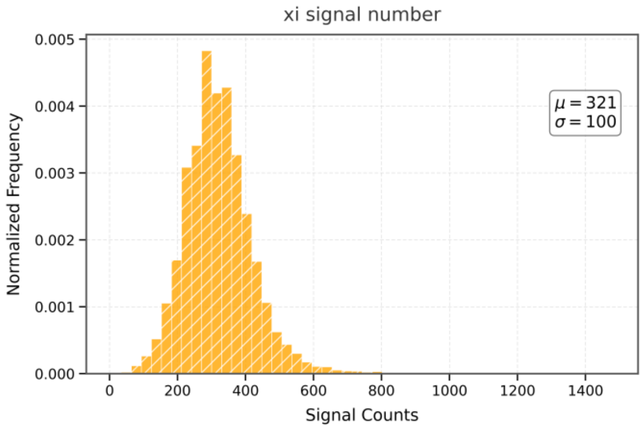
◆ **输出信息：边的权重**

较高权重：该边属于真实粒子径迹

较低权重：该边是伪边或噪声边

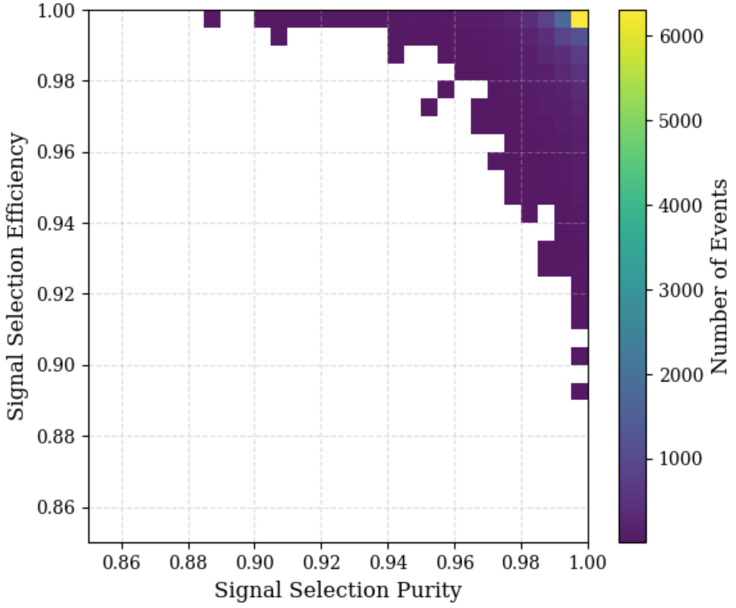
- **训练集，验证集：** MDC新几何下的$\psi(3686) \to \pi^+\pi^- J/\psi,\ J/\psi \to \mu^+\mu^-$样本
- **测试集1:** $\psi(3686) \to \pi^+\pi^- J/\psi,\ J/\psi \to \mu^+\mu^-$
- **测试集2:** from $J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda\pi^-\bar{\Lambda}\pi^+ \to p\pi^-\pi^-\bar{p}\pi^+\pi^+$





新几何下GNN除噪

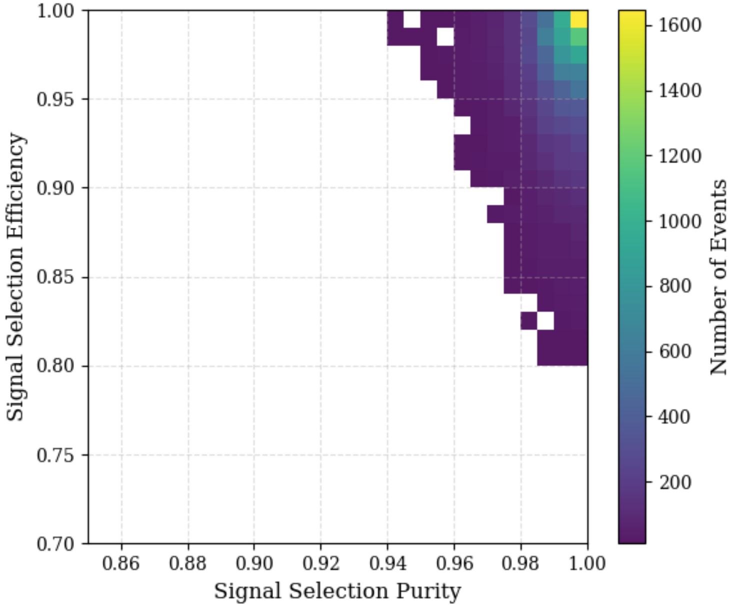
测试集1: $\psi(3686) \to \pi+\pi- \ \ J/\psi,\ J/\psi \to \mu+\mu-$



信号挑选纯度和效率分布图

- 击中分类准确率 99.4%
- 信号挑选效率 98.7%
- 噪声移除率 99.6%

测试集2 $J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda\pi^-\bar{\Lambda}\pi^+ \to p\pi^-\pi^-\bar{p}\pi^+\pi^+$



信号挑选纯度和效率分布图

- 击中分类准确率 98.1%
- 信号挑选效率 95.6%
- 噪声移除率 99.4%

将GNN结合到重建流程的研究和网络参数优化正在进行

总结

- 研究不同的径迹探测器设计下的重建性能， 确定了4层ITK+无内室MDC的基准方案
- 算法优化后，重建性能提升显著

- 高本底下，假径迹重复径迹的去除是重点开展的工作
  - 径迹质量的研究，重复径迹的合并条件
  - GNN去噪工作在持续开展