



中国科学技术大学

University of Science and Technology of China

# A hybrid muon detector for the Super Tau-Charm Facility experiment: concept, design optimization and particle identification

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STCF muon detector concept

Design optimization of MUD

Particle identification

Summary and Plans



STCF muon detector concept

Design optimization of MUD

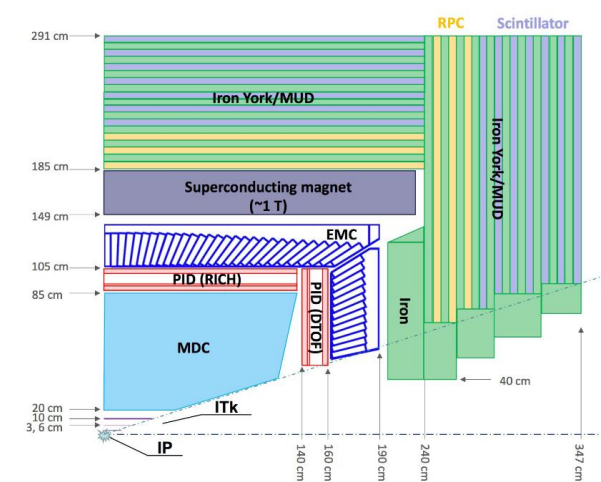
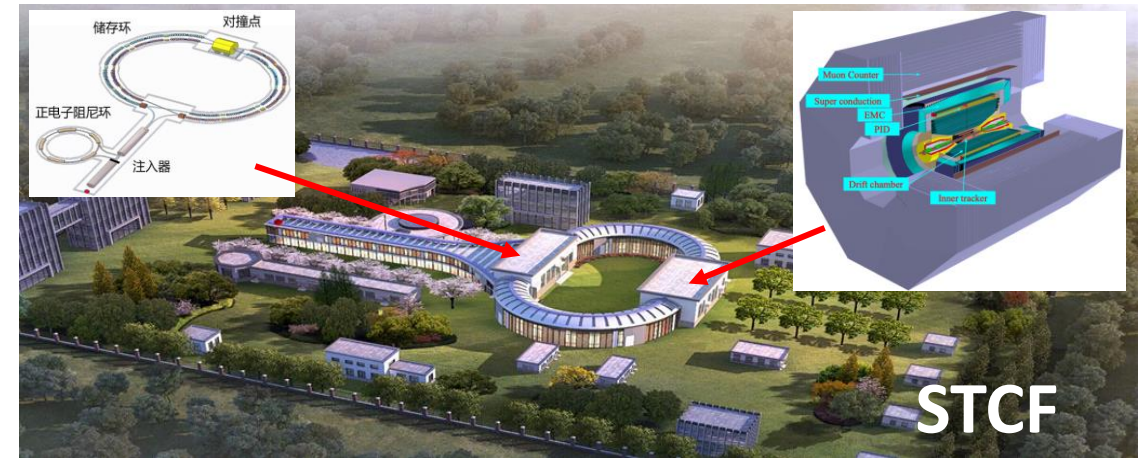
Particle identification

Summary and Plans

# Introduction of STCF MUD



- Super Tau-Charm Facility (STCF)
  - Electron-positron collider
  - Center of mass energy: 2-7 GeV
  - Peak luminosity:  $> 0.5 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$  @4GeV
  - Challenge for spectrometer
- Muon detector (MUD)
  - Located in the outermost of the spectrometer
  - Covering a range close to the full space ( $94\% \times 4\pi$ )
- Requirements of MUD
  - $\mu/\pi$  identification:  $\text{eff}_{\mu \rightarrow \mu} > 95\%$  @ 1-2 GeV with  $\pi$  suppression power over 30 ( $\text{eff}_{\pi \rightarrow \mu} < 1/30$ )
  - Neutral hadrons ( $n, K_L$ ) identification: MUD provides a certain identification capability for neutral hadrons

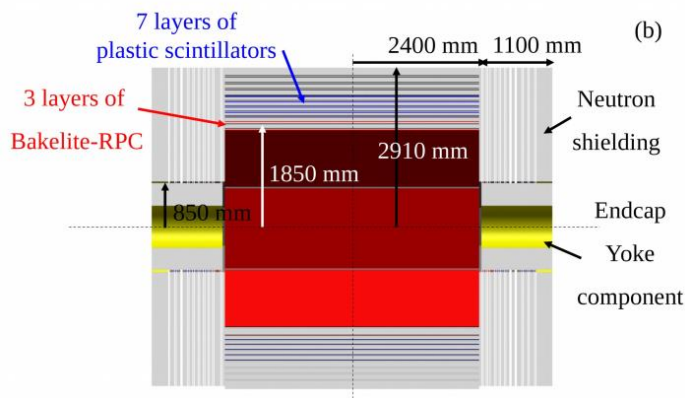


ITK	<ul style="list-style-type: none"> <li>• <math>&lt; 0.25\% X_0 / \text{layer}</math></li> <li>• <math>\sigma_{xy} &lt; 100 \mu\text{m}</math></li> </ul>	Cylindrical $\mu\text{RWELL}$ CMOS MAPS
MDC	<ul style="list-style-type: none"> <li>• <math>\sigma_{xy} &lt; 130 \mu\text{m}</math></li> <li>• <math>\sigma_{\eta/p} \sim 0.5\%</math> @ 1 GeV</li> <li>• <math>dE/dx \sim 6\%</math></li> </ul>	Cylindrical Drift chamber
PID	<ul style="list-style-type: none"> <li>• <math>\pi/K</math> (and <math>K/p</math>) <math>3-4\sigma</math> separation up to 2GeV/c</li> </ul>	RICH with MPGD DIRC-like TOF
EMC	E range: 0.025-3.5GeV $\sigma_{\epsilon} (\%)$ @ 1 GeV Barrel: 2.5 Endcap: 4 Pos. Res.: 5 mm	pCsI + APD
MUD	<ul style="list-style-type: none"> <li>• 0.4 - 2 GeV</li> <li>• <math>\pi</math> suppression <math>&gt; 30</math></li> </ul>	RPC + scintillator

# Design of MUD

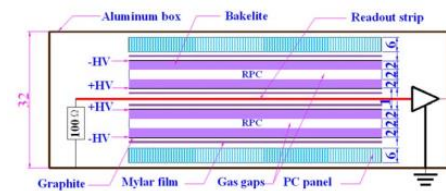


- The typical structure of MUD is multiple layers of sensitive detectors and iron yokes
  - Iron yokes: absorb the energy of particles, and provide a magnetic circuit for superconducting magnet
  - Sensitive detectors: resistive plate chamber (RPC) and plastic scintillator are commonly used in muon detector of collision experiments
- Characteristics of two sensitive detectors
  - RPC: not affected by background noise, not sensitive to neutral hadrons
  - Plastic scintillator: sensitive to neutral hadrons, more affected by background noise
  - Consider the advantages of two detectors, a hybrid design of 3 RPCs and 7 plastic scintillators is proposed in STCF CDR

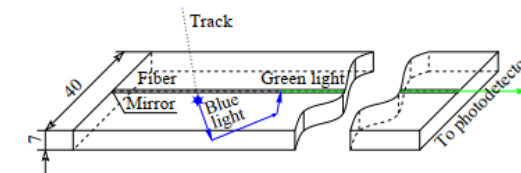
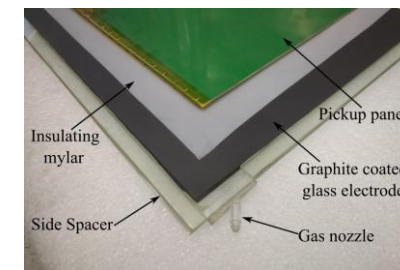


Schematic of MUD design in CDR

RPC detector



Plastic Scintillator





STCF muon detector concept

Design optimization of MUD

Particle identification

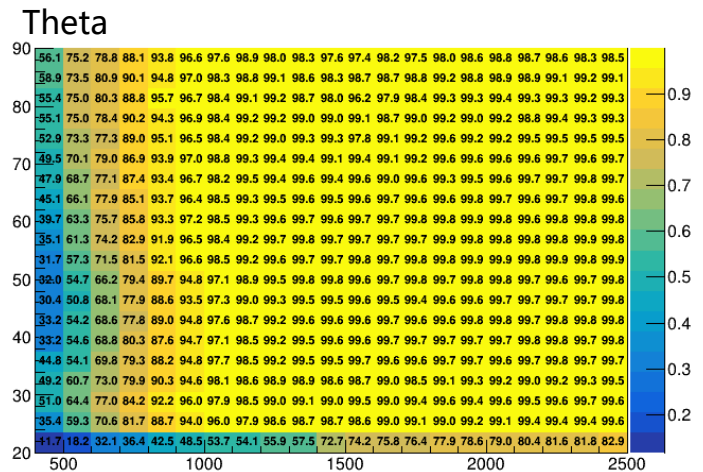
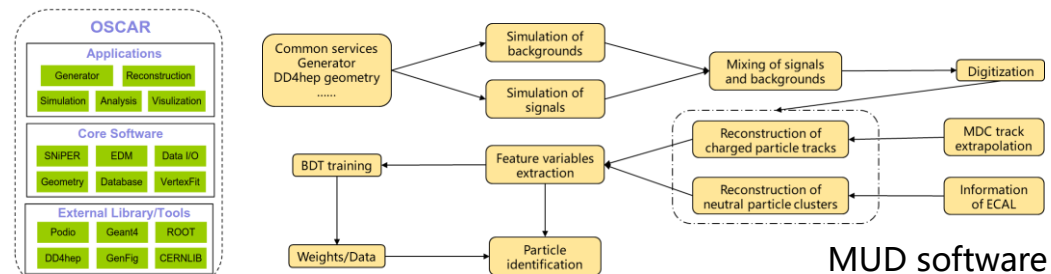
Summary and Plans

# Issues in CDR design

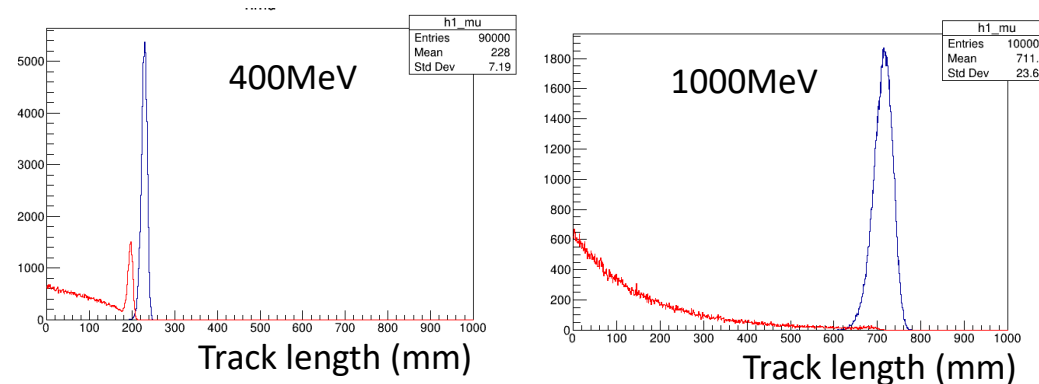


- Low efficiency in 400-1000 MeV
  - Optimize layer number and thickness of iron yokes
- Detector details
  - Detector choice, efficiency, strip width
- Mechanical design
  - Influence of dead area

To solve those issues, a MUD software based on OSCAR is developed



Identification efficiency of CDR MUD design

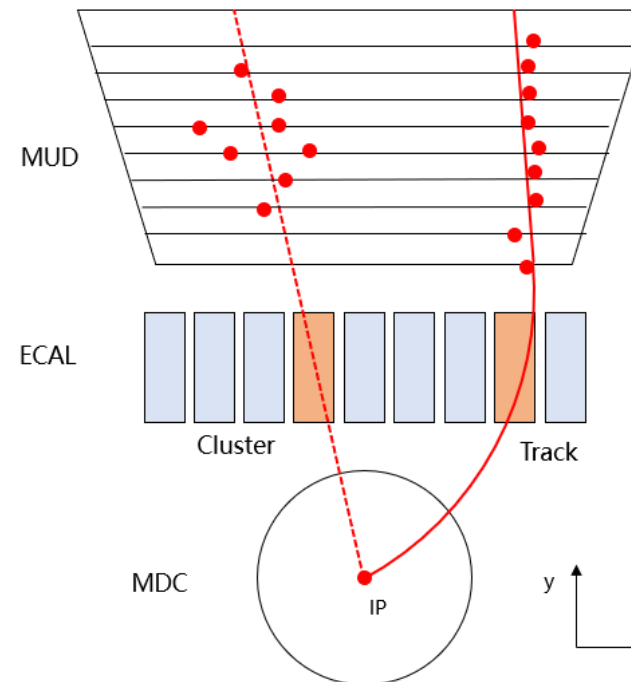


The track length of muon/pion in iron

# Reconstruction algorithm



- Distinguish track/cluster
  - Use MDC extrapolation as the track seed, for charged particles reconstruction
  - Match ECAL shower to extrapolation track. If not matched, use it as the cluster seed, for neutral particles reconstruction
- Track/cluster reconstruction
  - Track: calculate the angle of each hit and the extrapolation track. Associate hits smaller than the angle window
  - Cluster: line each hit and IP, calculate the angle between the line and ECAL shower. Associate hits smaller than the angle window ( $30^\circ$ )
- Extract information
  - Depth, MaxHitInLayer, etc.



Schematic of track/cluster reconstruction

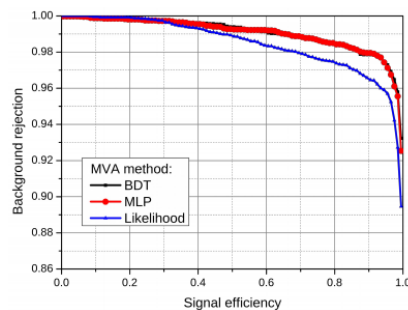
TrackMom	BarrelLayerMean
TrackTheta	BarrelLayerSigma
TrackPhi	EndcapLayerMean
TrackMudDeltaTheta	EndcapLayerSigma
TrackMudDeltaPhi	HitTimeMean
IronIncidentDepth	HitTimeSigma
GlassIncidentDepth	EcalEnergy
PsIncidentDepth	EcalSeedEnergy
MaxHitLayer	EcalESeed/E3x3
MaxHit	EcalESeed/E5x5
BarrelLastLayer	EcalE3x3/E5x5
EndcapLastLayer	EcalSeedTime
TotalLayer	EcalTrackDeltaTheta
HitEntries	EcalTrackDeltaPhi
RpcHitEntries	EcalMudDeltaTheta
PsHitEntries	EcalMudDeltaPhi
HitsPerLayer	EcalE/p
Linearity	EcalA20Moment
Anisotropy	EcalA42Moment
Flatness	EcalLatMoment
	EcalSecMoment

Identify parameters

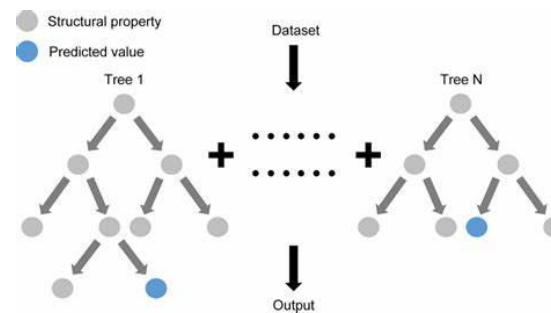
# Identification algorithm



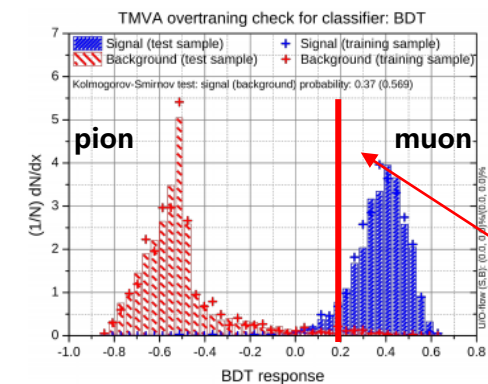
- The identification of MUD uses multivariate analysis (MVA) method, such as Likelihood, BDT, MLP
- BDT (Boosting Decision Tree) is a statistical learning method
  - Basic classifier is Decision Tree
  - An initial basic classifier is trained, and the sample distribution is adjusted when the new classifier is subsequently trained, so that the previously incorrectly classified samples receive greater attention. Finally, all classifiers are weighted and combined to output results
  - When calculating the signal efficiency, we need to specify the rejection rate to the background, corresponding to a BDT cut. When the BDT output is greater than this value, it is considered a signal, otherwise it is the background



Comparison of three MVA methods



Structure of BDT



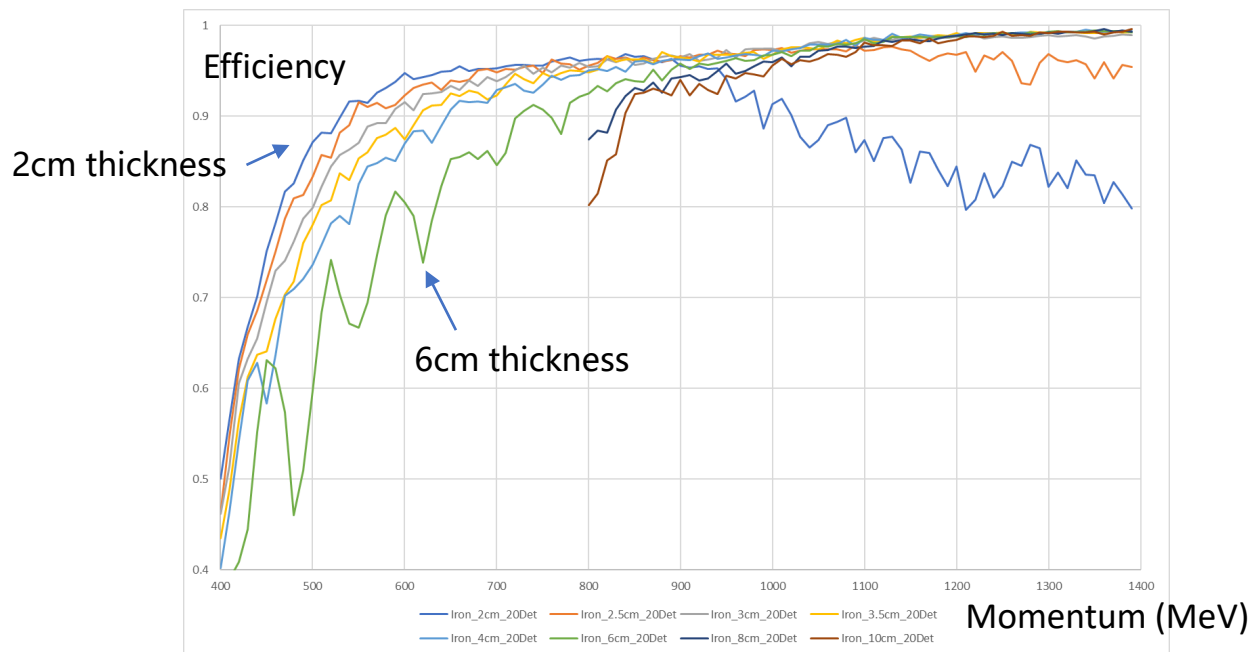
Distribution of BDT output

BDT cut

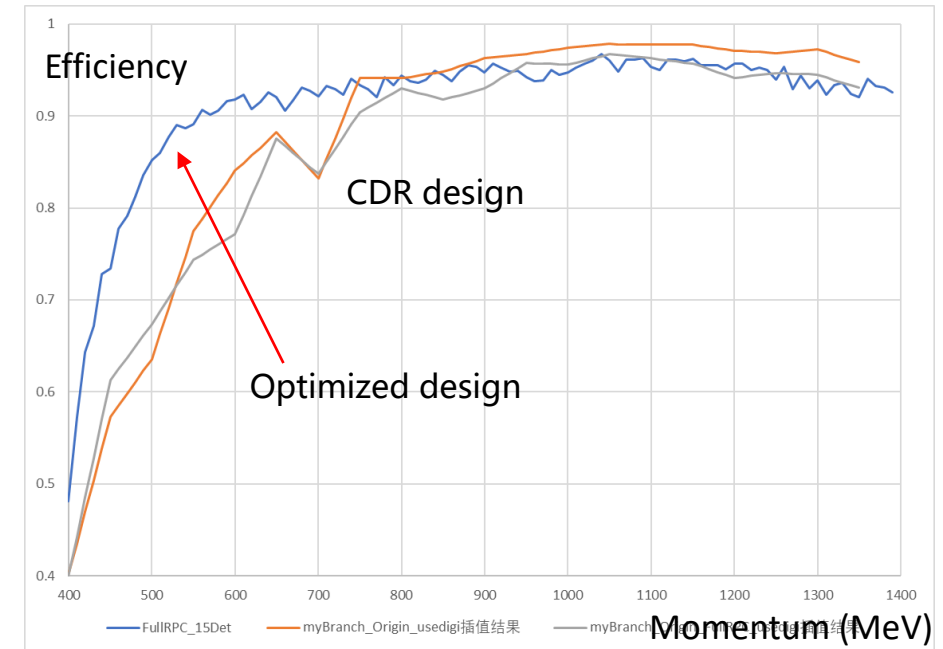
# Iron yoke thickness optimization



- From the principle of  $\mu/\pi$  identification, the first few layers should be thin and the total thickness should be thick enough.
- The design parameters such as number of layers and iron yoke thickness have been scanned
- A new MUD design is proposed. It uses 15 detectors and 14 layers of iron yokes. The thicknesses of iron yokes is 2, 2, 2, 2, 2, 2.5, 3, 3, 3.5, 4, 4, 5, 6, 10cm



Efficiency of different iron yoke thickness (2cm~10cm)

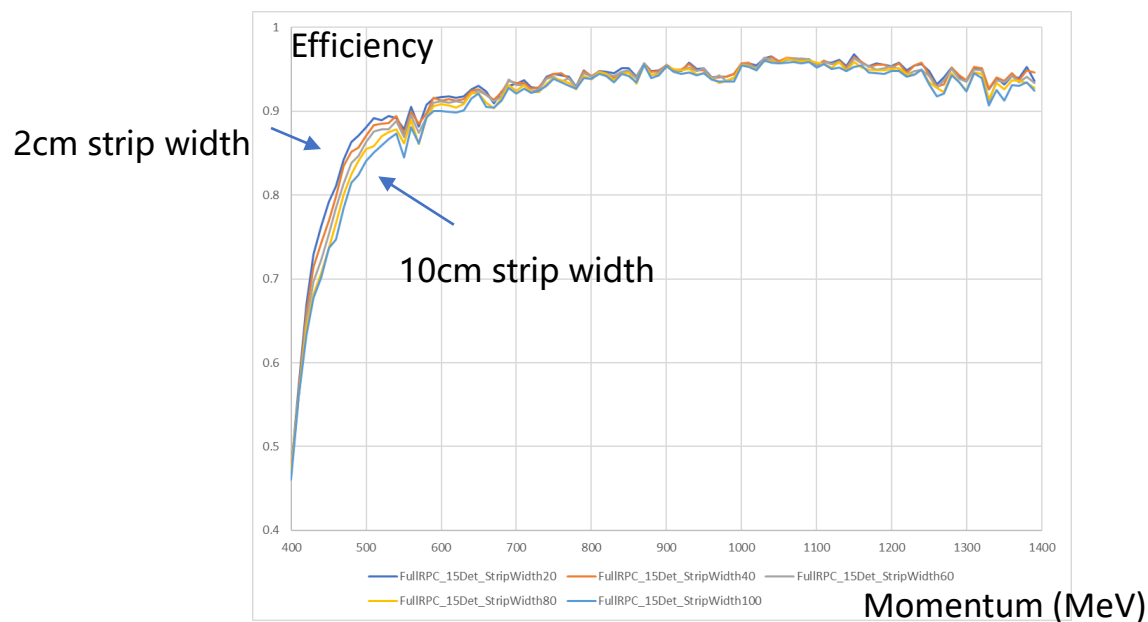


Efficiency of CDR design and optimized design

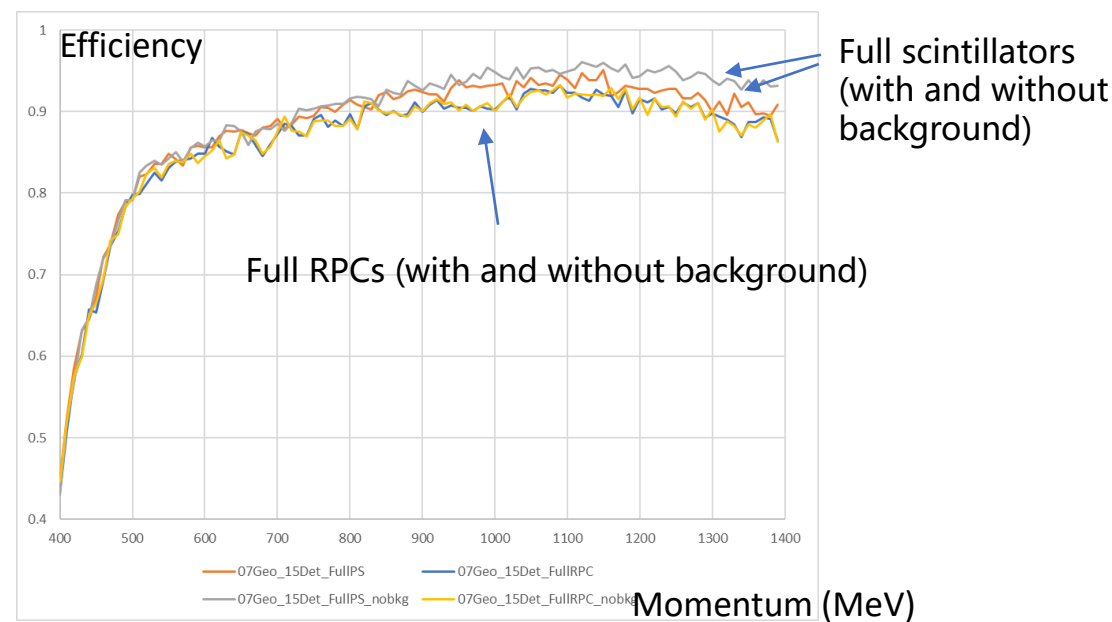
# Strip width and detector choice



- The efficiency with different strip width
  - The efficiency is sensitive to strip width in the low momentum range, but insensitive in the high momentum range
  - The detectors of last several layer may use wider strips
- The efficiency comparison of full RPCs and full scintillators
  - Consider the influence of background noise, a hybrid design of 5 RPCs and 10 plastic scintillators is proposed



Efficiency of different strip width (20mm~100mm)

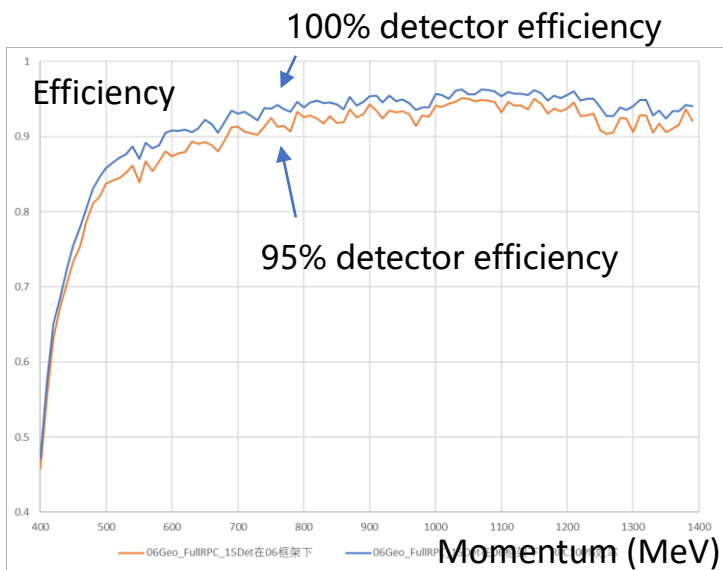


Compare of full RPCs and full scintillators

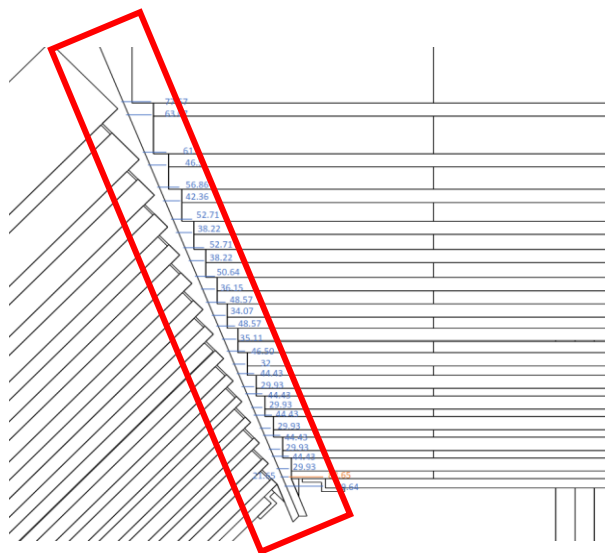
# Detector efficiency and dead area



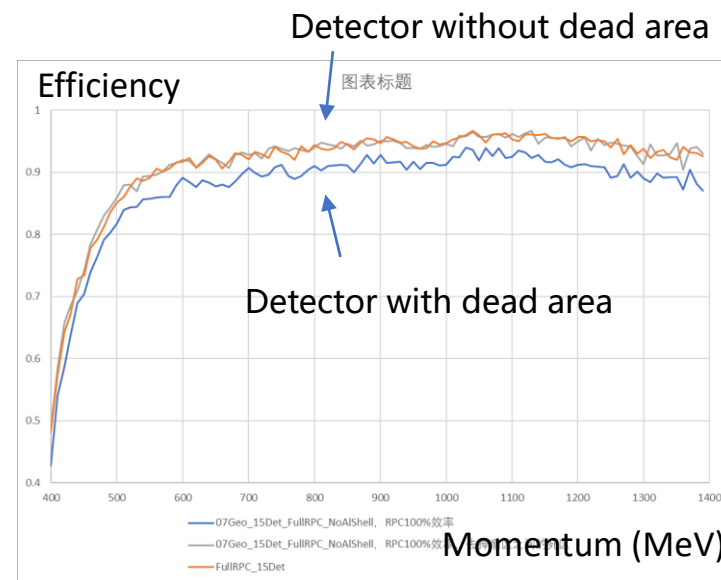
- The detector efficiency and dead area may cause hit lost in the last layer of muon tracks, which is important in mu/pi identification
- The requirements of higher detector efficiency and lower dead area are proposed, for example the double-gap RPC



Compare of 100% and 95% detector efficiency



Dead area of MUD barrel



Compare of detector with and without dead area



STCF muon detector concept

Design optimization of MUD

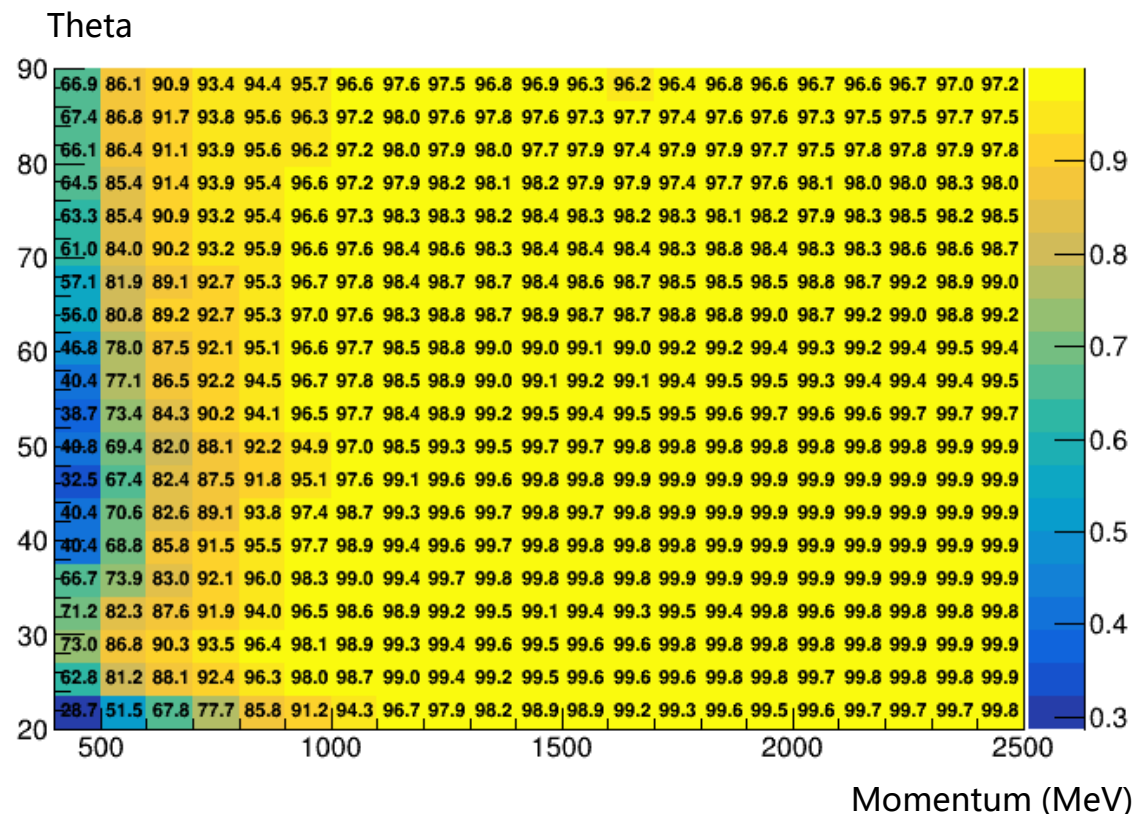
Particle identification

Summary and Plans

# Results of identification



- Scan the identify efficiency of  $\mu/\pi$ 
  - Detector: 5 RPCs and 10 scintillators
  - Theta:  $20^\circ \sim 90^\circ$
  - Momentum: 400~2500 MeV
  - The detector efficiency and dead area are considered
  - Identify efficiency > 95% @ mom > 1000MeV
  - Efficiency raises in low momentum range



With background  
Efficiency of  $\mu^+/\pi^+$  @ supp=30



STCF muon detector concept

Design optimization of MUD

Particle identification

Summary and Plans



- Summary
  - The MUD software is developed and used to optimize the MUD design
  - The iron yoke layer number and thickness are scanned, and a new design with 5 RPCs and 10 scintillators is proposed
  - The different strip width are simulated and the wider strips in last several layers are suggested
  - The influence of detector efficiency and dead area is evaluated, with the requirements for hardware are suggested
  - The efficiency of new MUD design is simulated, with efficiency rises in low energy region
- Plans
  - Optimize the reconstruction algorithm of neutral particles
  - Develop the algorithm for physical analysis

Thanks!



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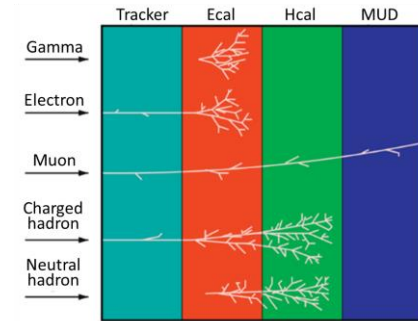
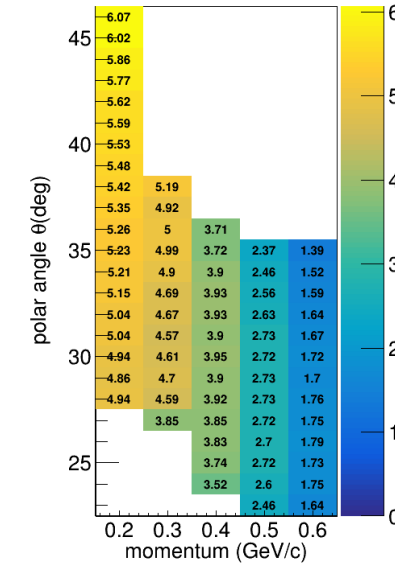
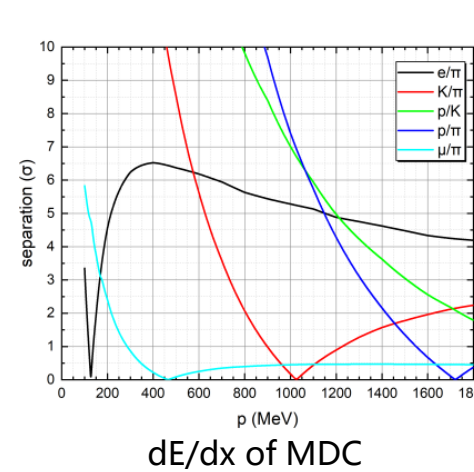
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Backup

# Principle of MUD



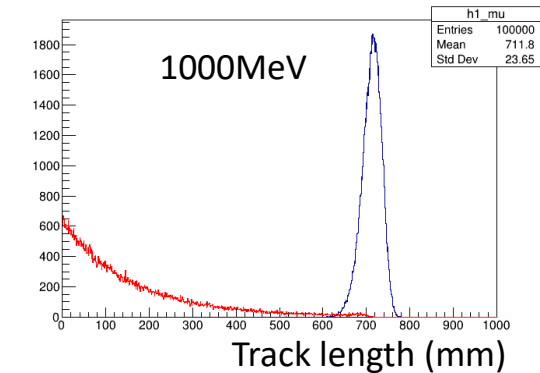
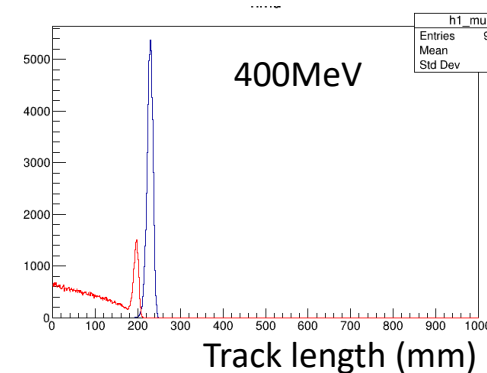
- $\mu/\pi$  have similar masses
  - $m_\mu = 105.66\text{MeV}$ ,  $m_\pi = 139.57\text{MeV}$
  - Traditional methods are hardly to distinguish them in high momentum area
- The  $\pi$  is different from  $\mu$  for nuclear interaction and higher ionization energy loss
  - In low momentum region, nuclear interaction is not enough to distinguish  $\mu/\pi$ . But  $\pi$  has less track length because of higher ionization energy loss
  - In high momentum region, when the  $\pi$  passes through the thick yoke irons, the probability that no nuclear interaction occurs is lower than 3%



Different particles interact with spectrometer

$\mu/\pi$  identification of DTOF

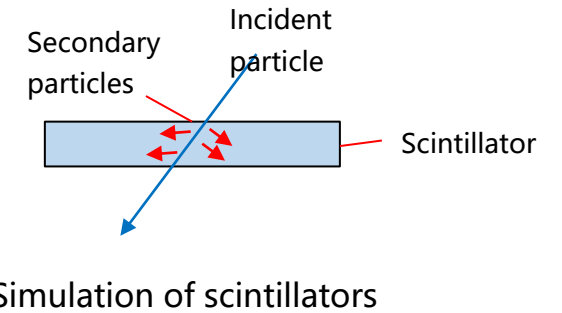
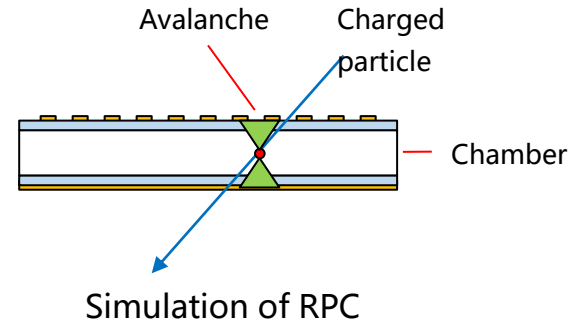
The track length of muon/pion in iron



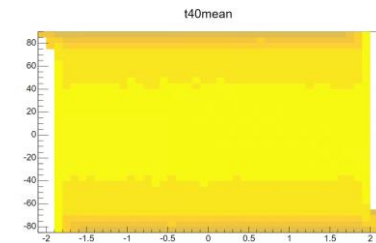
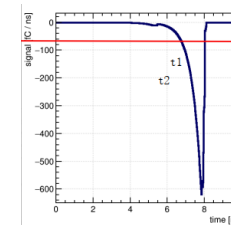
# Simulation and digitization



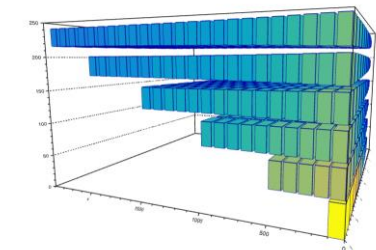
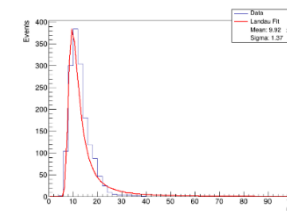
- Simulation of MUD
  - Simulation based on Geant4
  - When particles incident the sensitive area of RPC/scintillator, record every steps in sensitive area
  - If the incident particle generates some secondary particles, relate each step to the primary step of incident particle
- Digitization of RPC
  - Convert hits in chamber to the signals of readout strips using digitization parameters
  - Add the errors of electronics response
  - Parameters are simulated using Garfield
- Digitization of scintillator
  - Consider all the steps in scintillator as a set
  - Convert the sets to signals of SiPM using parameters
  - Add simulation of the waveform of electronics
  - The parameters and waveform are simulated using standalone geant4 and verified by experiments

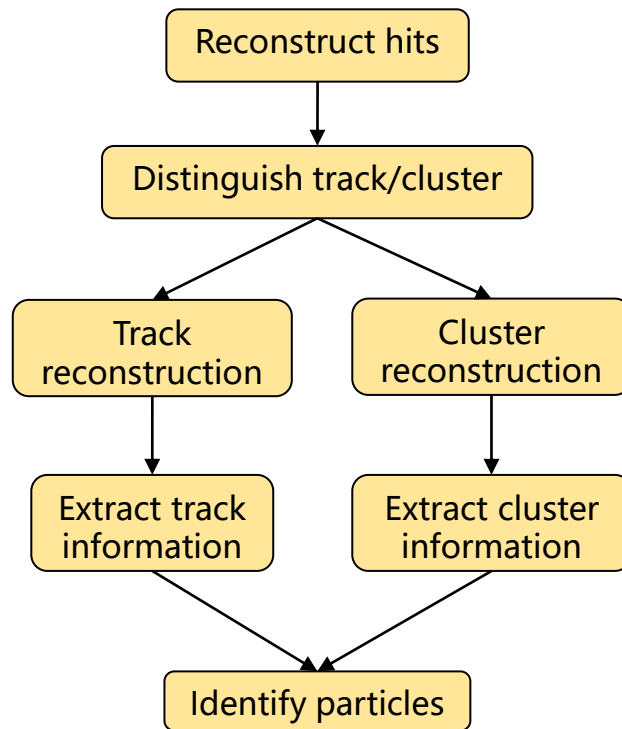


RPC parameters



Scintillator parameters

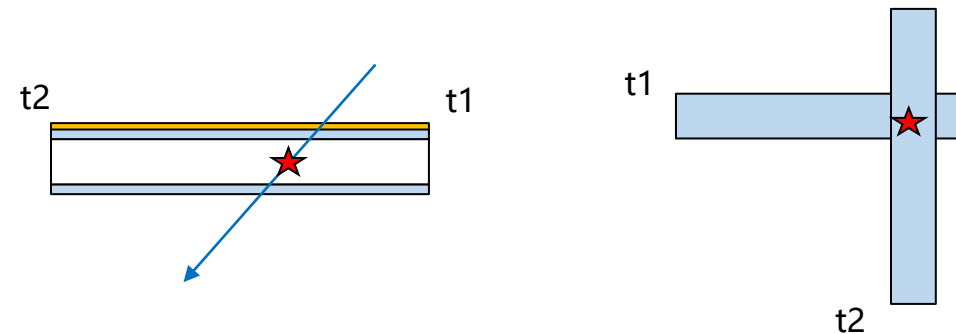




Process of reconstruction

- Reconstruct hits

- The RPC uses double-end readout and plastic scintillator uses intersection readout
- Associate the digitization data using time windows and reconstruct the hits

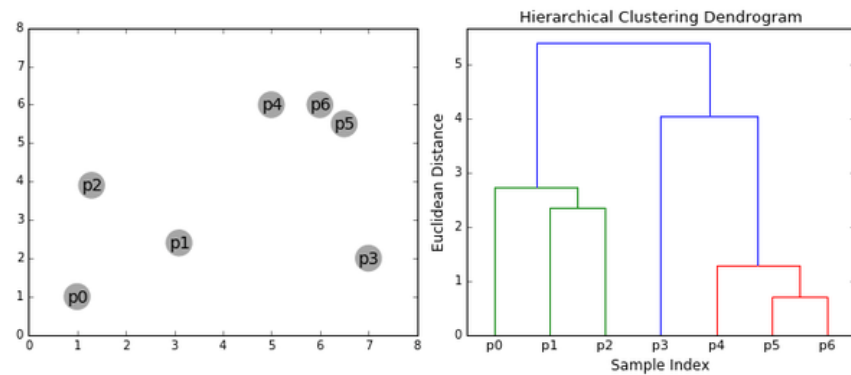


Schematic of double-end readout of RPC, and intersection readout of scintillator

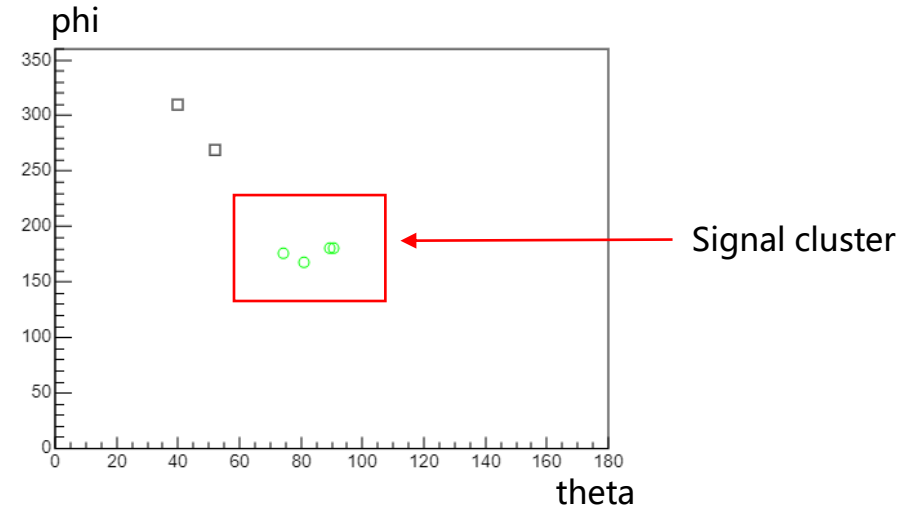
# Self-reconstruction algorithm



- About 40% of neutral hadrons have no energy deposition in ECAL, requires MUD to have self-reconstruction ability
  - An algorithm based on hierarchical cluster has been proposed, and the results should be evaluated. It's still in progress

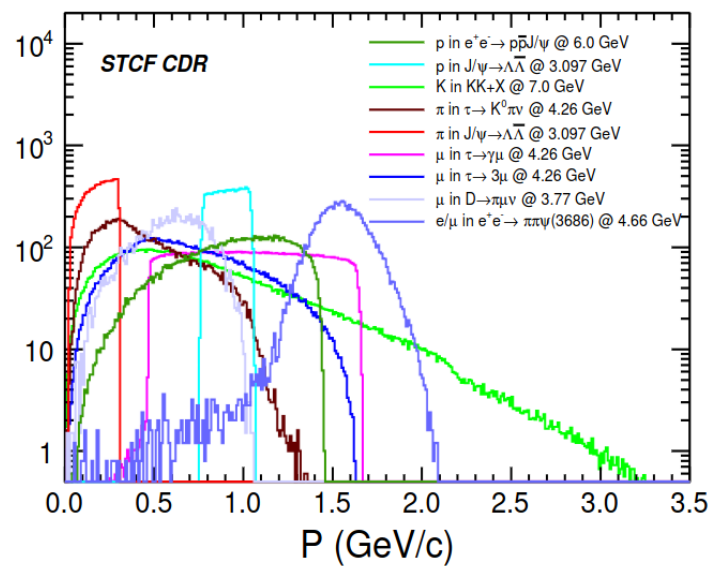


Hierarchical cluster

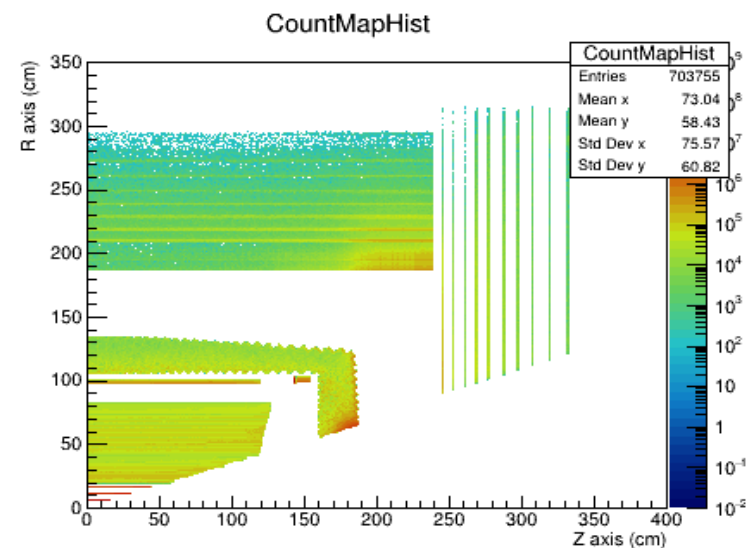


Angular distribution of MUD hits

# Physical requirements



带电粒子动量分布

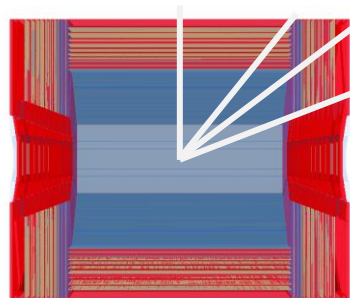


STCF谱仪本底计数率

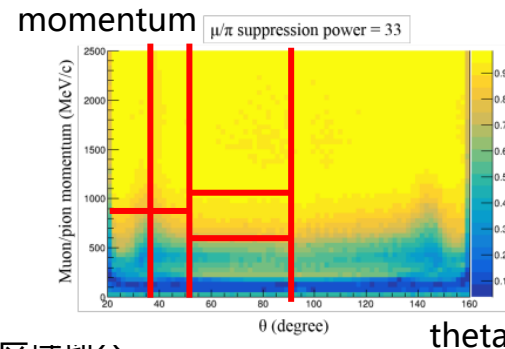
# Sub-area training



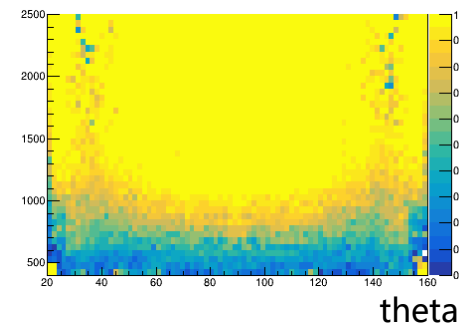
- 使用单一权重文件对所有动量、角度的粒子进行鉴别存在很大误差
- 需要按照粒子的角度、动量、电荷等划分不同区域，分别训练
  - 按角度划分为：20-37deg; 37-50deg; 50-90deg
  - 按动量划分
    - 20-50deg: 400-800MeV, 800-2500MeV
    - 50-90deg: 400-600MeV, 600-1000MeV, 1000-2500MeV
  - 按电荷划分
- 此外，BDT Cut的计算也是按照角度动量分bin计算的
- 分区域训练相比全区域的结果，在低动量和大角度有较大提升



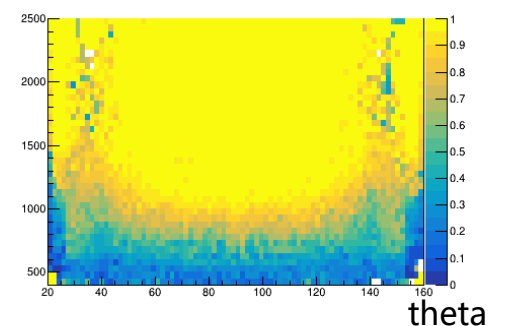
训练区域划分



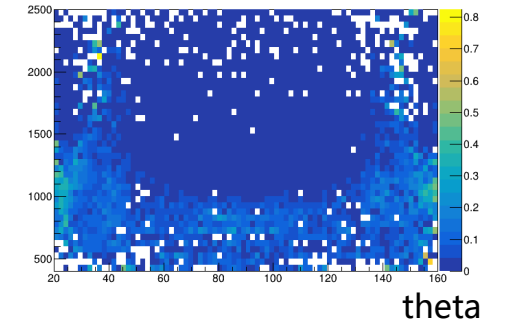
momentum



momentum

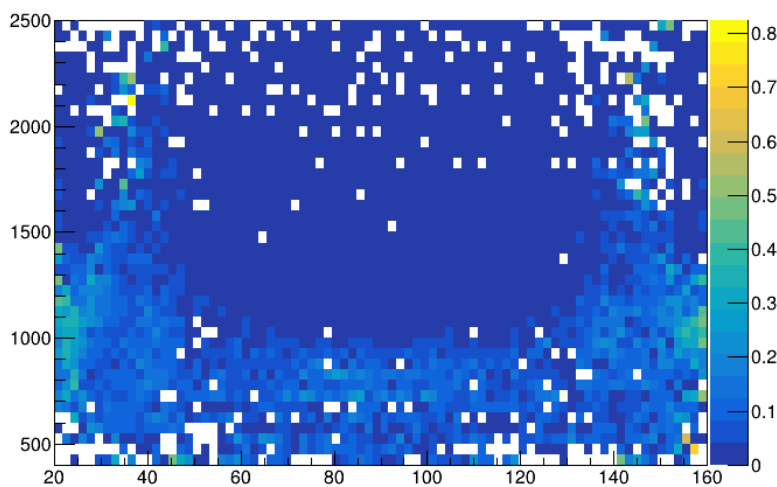


momentum

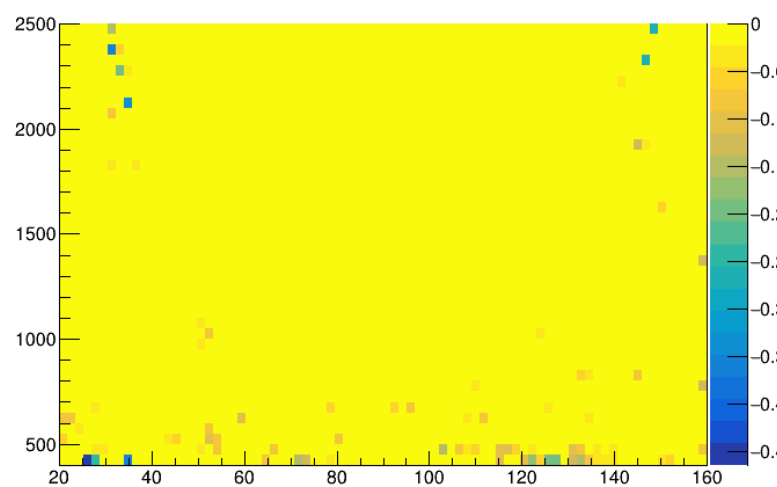


comparison  
Sub-area (left)  
All (right)  
difference (below)

- 将每个bin的值相减，分别画了结果 $>0$ 的图和结果 $<0$ 的图，否则不易分辨
- 在低动量和大角度处提升明显

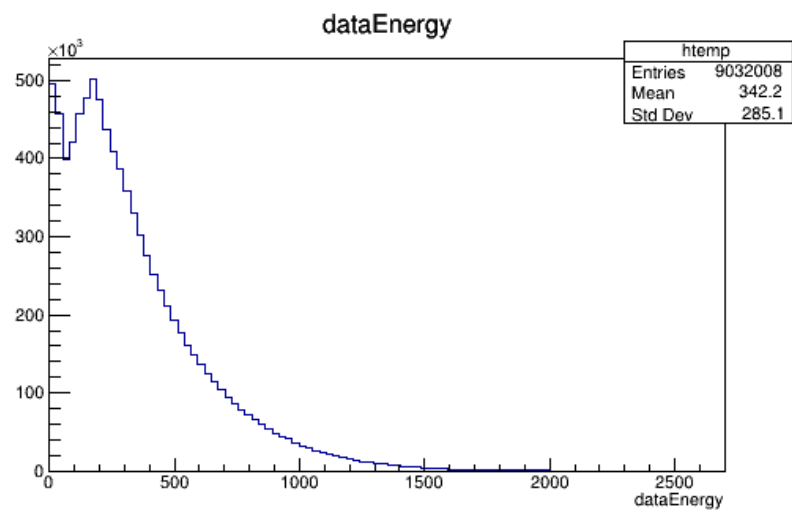


$\mu^+/\pi^+ @ \text{supp}=30$   
 $\text{diff} > 0$

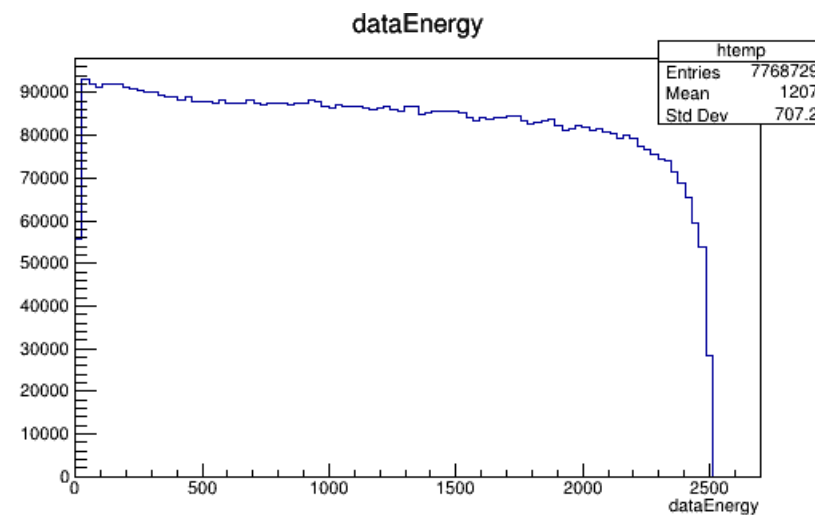


$\mu^+/\pi^+ @ \text{supp}=30$   
 $\text{diff} < 0$

# 中性粒子能量分布图

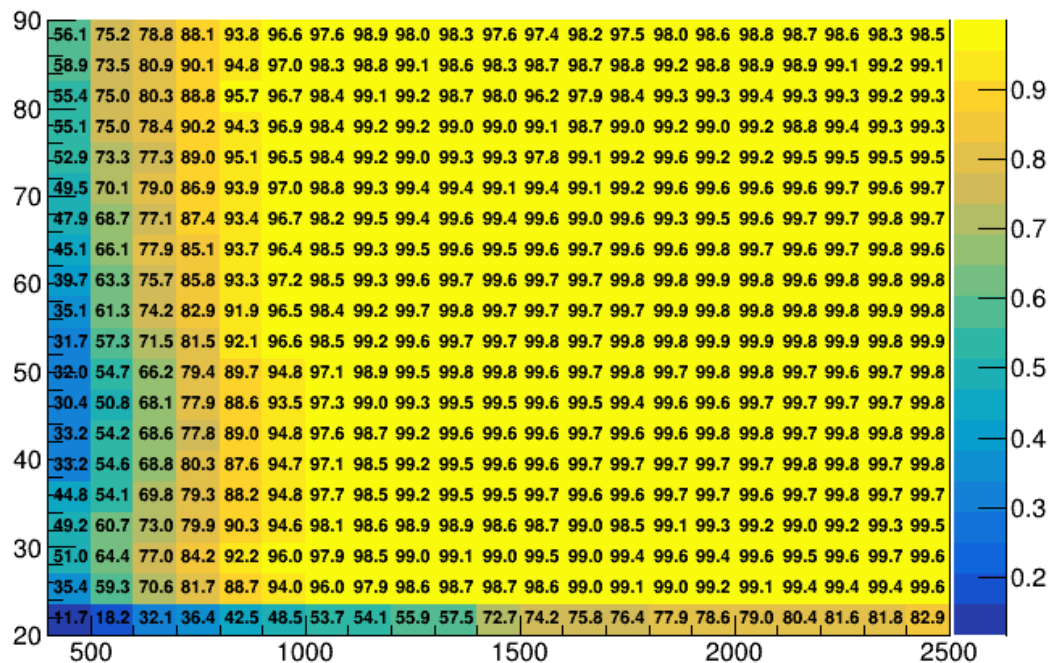


中性强子 (n, KL)

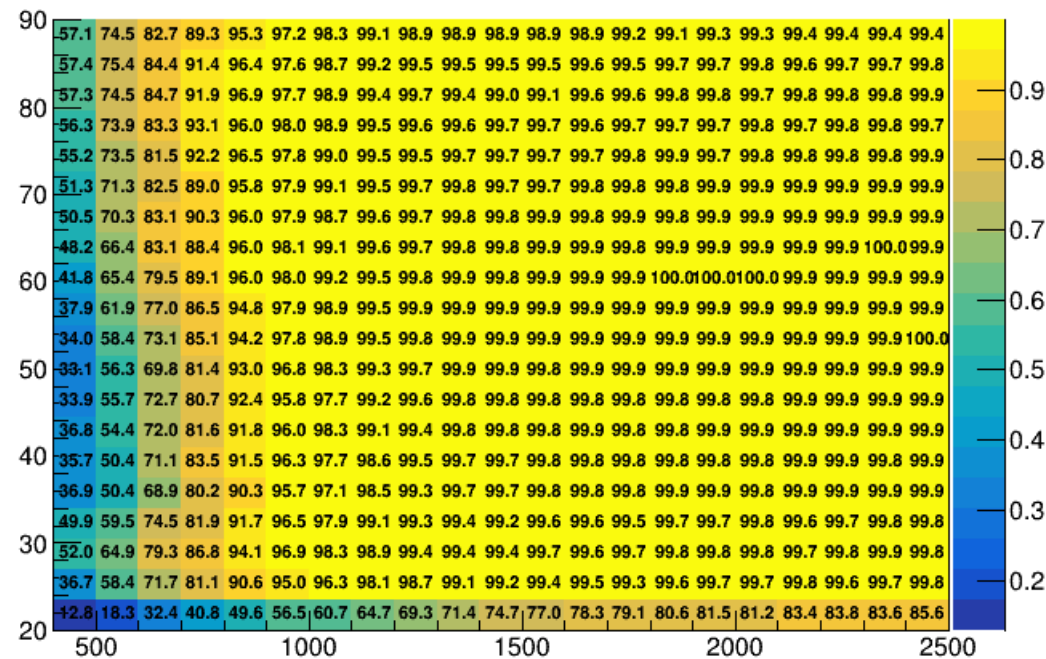


gamma

# CDR结构的TH2D



不分区域



分区域

- 直线拟合算法重写，使用PCA方法对三维直线直接进行拟合
- 其中三个特征值，最大和最小值代表空间中最大和最小方差的方向
- 由此组成描述击中分布的参数
- 线性度 $(\lambda_0 - \lambda_1) / \lambda_0$
- 平面度 $(\lambda_1 - \lambda_2) / \lambda_0$
- 各向异性 $(\lambda_0 - \lambda_2) / \lambda_0$

步骤 1: 计算质心 (均值点)

$$\mathbf{c} = (\bar{x}, \bar{y}, \bar{z}) = \left( \frac{1}{n} \sum x_i, \frac{1}{n} \sum y_i, \frac{1}{n} \sum z_i \right)$$

质心  $\mathbf{c}$  作为直线上的基点  $\mathbf{p}_0$ .

步骤 2: 计算协方差矩阵

$$\mathbf{M} = \frac{1}{n} \sum_{i=1}^n (\mathbf{p}_i - \mathbf{c})(\mathbf{p}_i - \mathbf{c})^T$$

展开为  $3 \times 3$  矩阵:

$$\mathbf{M} = \begin{pmatrix} \text{Var}(x) & \text{Cov}(x, y) & \text{Cov}(x, z) \\ \text{Cov}(y, x) & \text{Var}(y) & \text{Cov}(y, z) \\ \text{Cov}(z, x) & \text{Cov}(z, y) & \text{Var}(z) \end{pmatrix}$$

其中:

- $\text{Var}(x) = \frac{1}{n} \sum (x_i - \bar{x})^2$
- $\text{Cov}(x, y) = \frac{1}{n} \sum (x_i - \bar{x})(y_i - \bar{y})$

步骤 3: 特征分解

计算  $\mathbf{M}$  的特征值和特征向量:

$$\mathbf{M}\mathbf{v}_j = \lambda_j\mathbf{v}_j, \quad j = 1, 2, 3$$

- 方向向量: 最大特征值  $\lambda_1$  对应的特征向量  $\mathbf{v}_1$  即直线方向  $\mathbf{d}$ .
- 单位化:  $\mathbf{d} = \frac{\mathbf{v}_1}{\|\mathbf{v}_1\|}$



- 几何:
  - 交界处轭铁厚度修正——对低动量效率提升较大，但会造成高动量效率下降，需要综合考虑
  - 端盖第一层删去——影响不大
  - 粒子入射倾斜角问题——会对低动量效率有一定影响，主要由于散射引起，但是目前的几何不需要太过考虑
  - 粒子入射交界处的结构——对效率影响不大
- 重建:
  - Hit关联算法bug修正（逐层寻找hit改为不判断hit的层数）——对交界处的效率提升较大
  - Hit窗口大小选择新的3倍角度窗口——对低动量效率提升较大
- 鉴别:
  - BDT变量默认值设为-10
  - BDT添加入射深度等变量，删去不必要的变量
- 其它：离IP点的距离对高动量效率的影响较大，尚不清楚原因

- 动量维度

$$\theta_{plane}^{rms} = \frac{13.6}{\beta c p} \sqrt{\frac{x}{X_0}}$$

- 距离维度, 通过几何关系可以计算出:

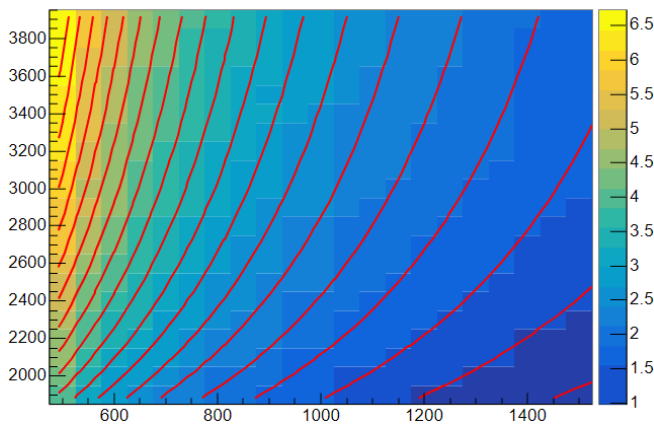
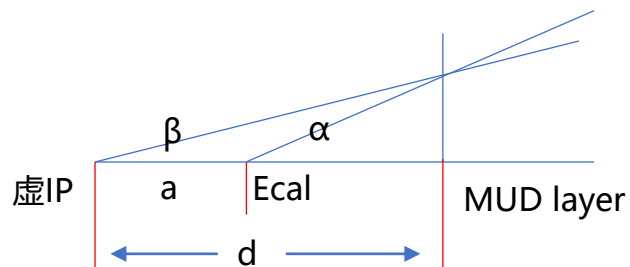
- $\beta = \arctan(\tan \alpha - \frac{a}{d} \tan \alpha)$
- 简化为  $\beta = \alpha - \frac{a}{d} \alpha = A - \frac{B}{d}$

- 因此直接使用两个倒数函数进行拟合即可

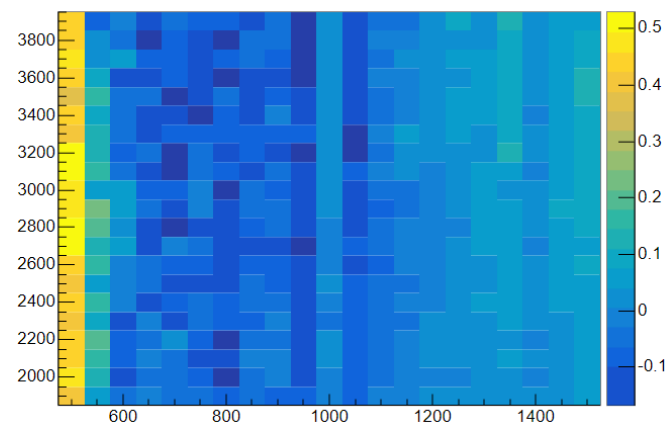
- 对高斯分布进行拟合得到

- $\theta = \left(-0.341 + \frac{1920}{p}\right) * \left(2.55 - \frac{2961}{d}\right)$

- 效果比之前好, 不考虑小范围重新拟合了



拟合结果

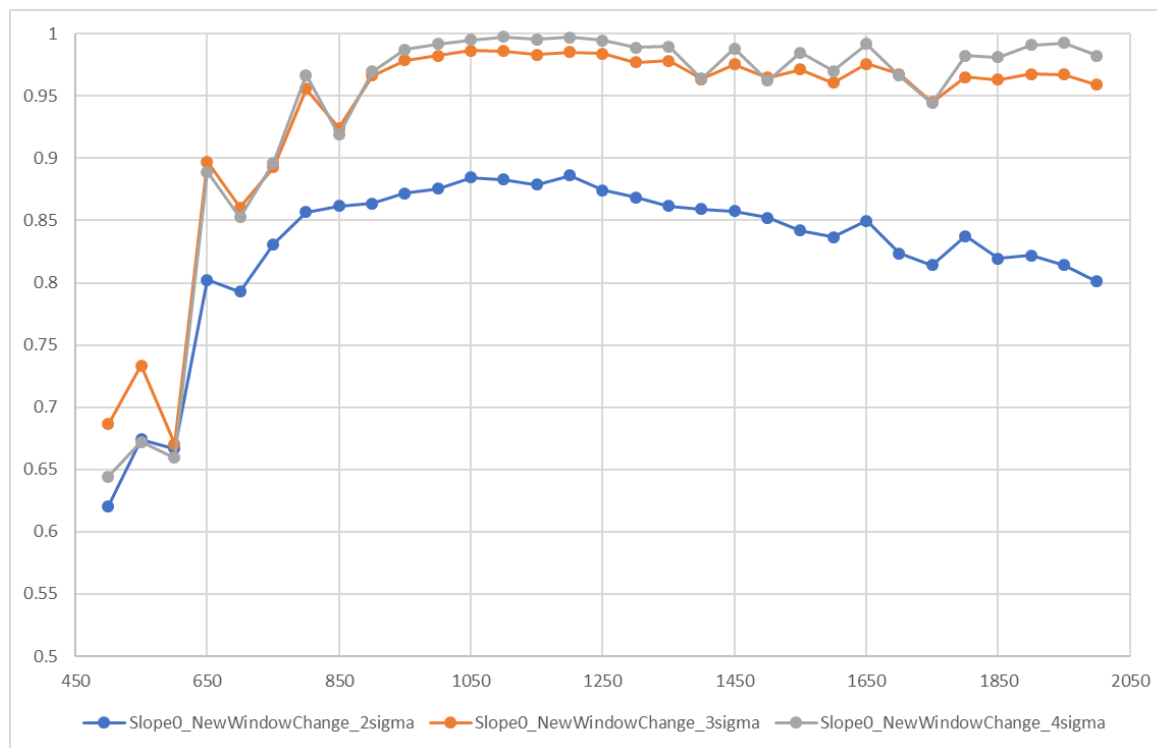


实际值-拟合值

# 不同窗口大小的效率差别



- 对比了2、3、4倍sigma的效率
- 3、4不相上下，但可以看到低动量时，更大的窗口明显受本底影响更大

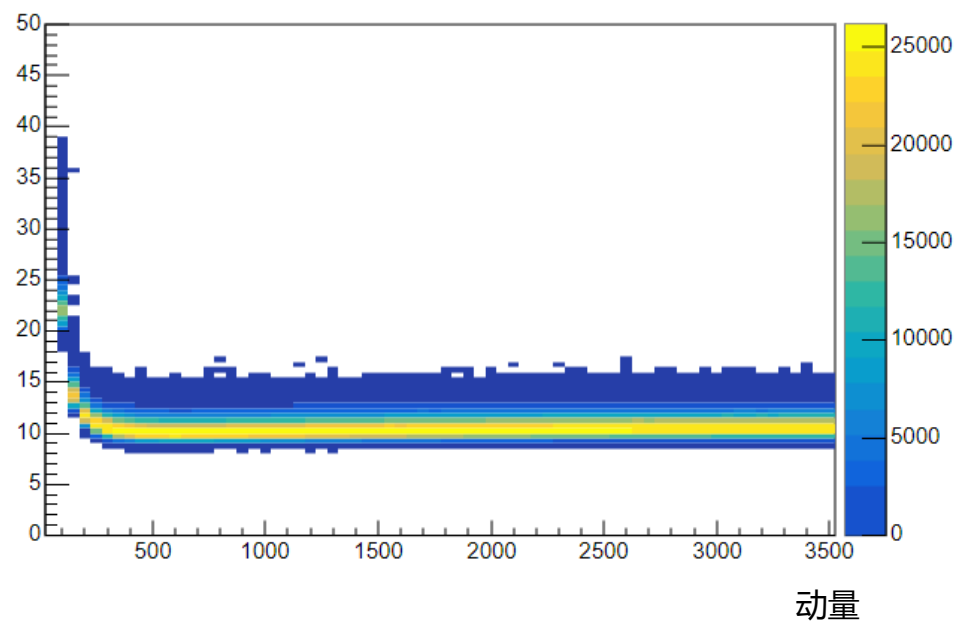


# Mu/Pi的相互作用

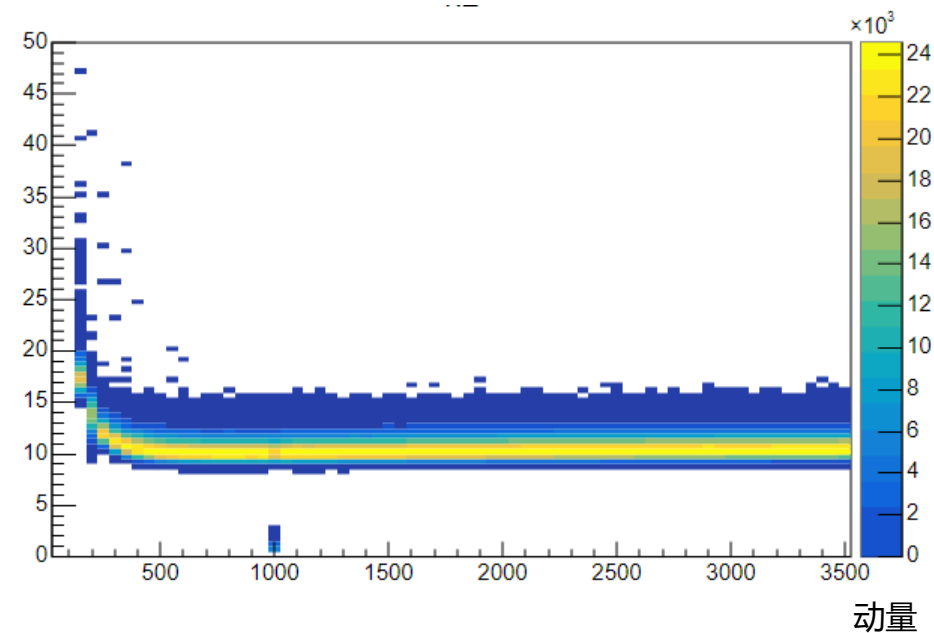


- 放置一个1cm厚铁板，统计不同动量muon/pion穿过铁板的各种相互作用，统计10w个事例

MeV/cm



muon总电离能损



pion总电离能损

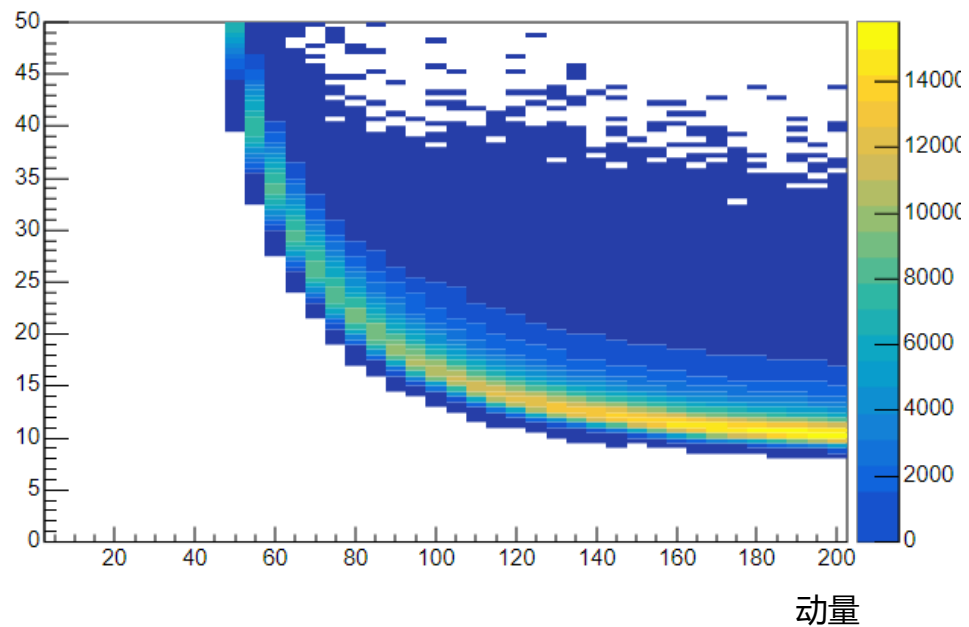
# Mu/Pi的相互作用



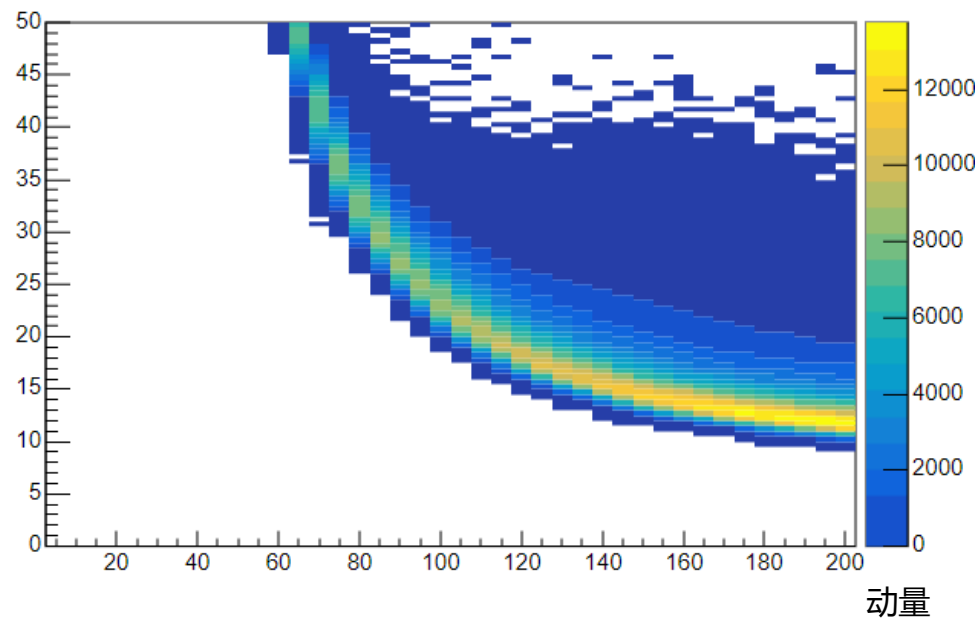
- 为测量更低动能的特性，铁板厚度变为1mm

低动量时两者差别较为明显

MeV/cm



muon总电离能损



pion总电离能损

- 核相互作用长度：
  - 塑闪: 107.2cm
  - 玻璃: 54.36cm
  - Fe: 20.42cm
  - Cu: 18.51cm
  - Al: 50.64cm
- RPC的组成：
  - 0.1mm Cu + 1.8mm FR4 + 2.2mm Glass
  - 忽略FR4, 等效0.94mm钨铁
  - 新几何添加了铝壳4mm, 等效1.61mm钨铁
- 塑闪的组成：
  - 每层塑闪厚10mm, 等效1.9mm钨铁
  - 新几何添加了铝壳4mm, 等效1.61mm钨铁
- CDR的设计中：
  - 全RPC探测器: 等效51.94cm钨铁
  - 全塑闪探测器: 每层探测器有2层塑闪, 等效54.8cm钨铁

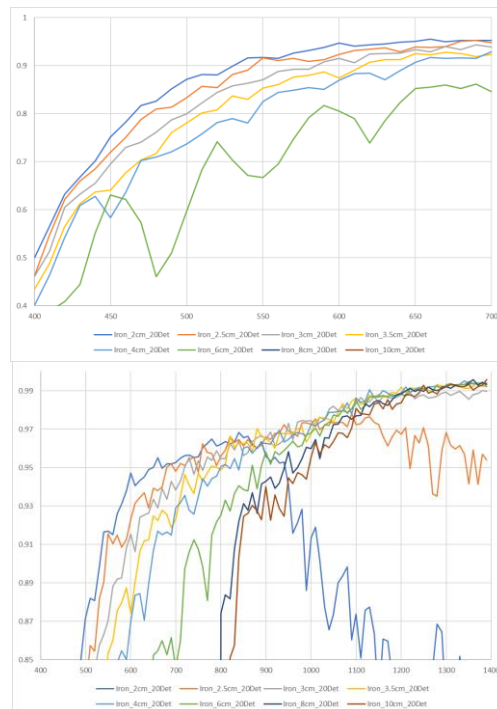
因此, 将钨铁+塑闪结构直接转化为钨铁+RPC(仅空气)的过程中, 相当于少计算了13层探测器的厚度, 等效约

- 1.2cm(全RPC无铝壳)
- 3.3cm(全RPC带铝壳)
- 5cm(全塑闪无铝壳)
- 7cm(全塑闪带铝壳)

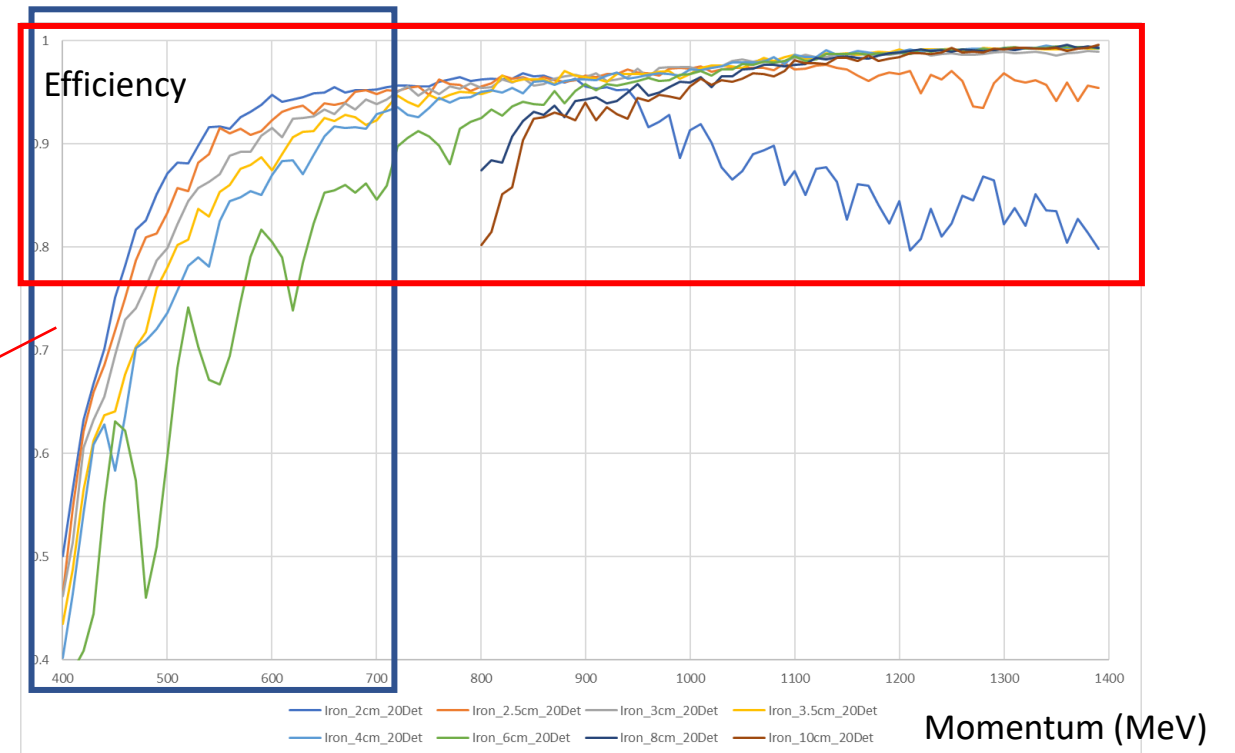
# MUD design optimization

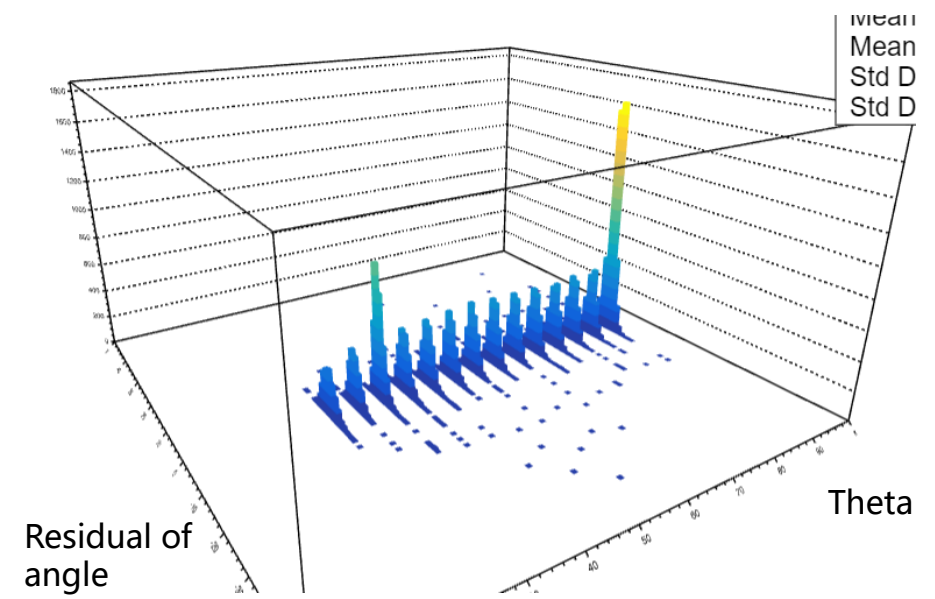
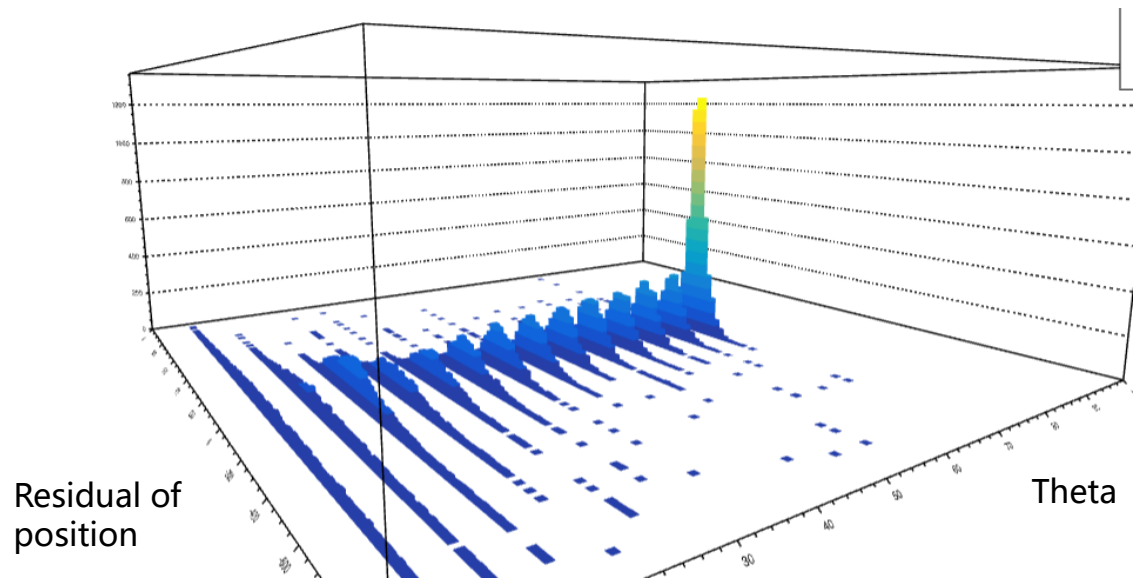


- From the principle of  $\mu/\pi$  identification, the first few layers should be thin and the total thickness should be thick enough
- A new geometry with 19 layers of yoke of the same thickness and 20 RPCs is created
- The muon identification efficiency versus particles momentum is drawn, with different iron layer thickness



Zoom in







中国科学技术大学  
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