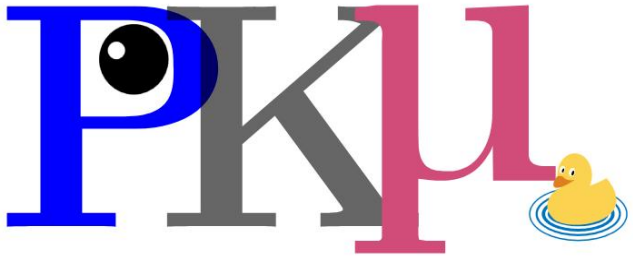
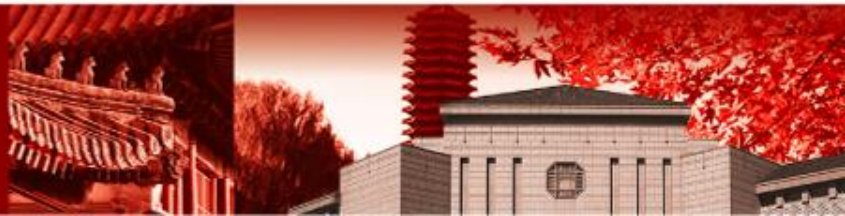


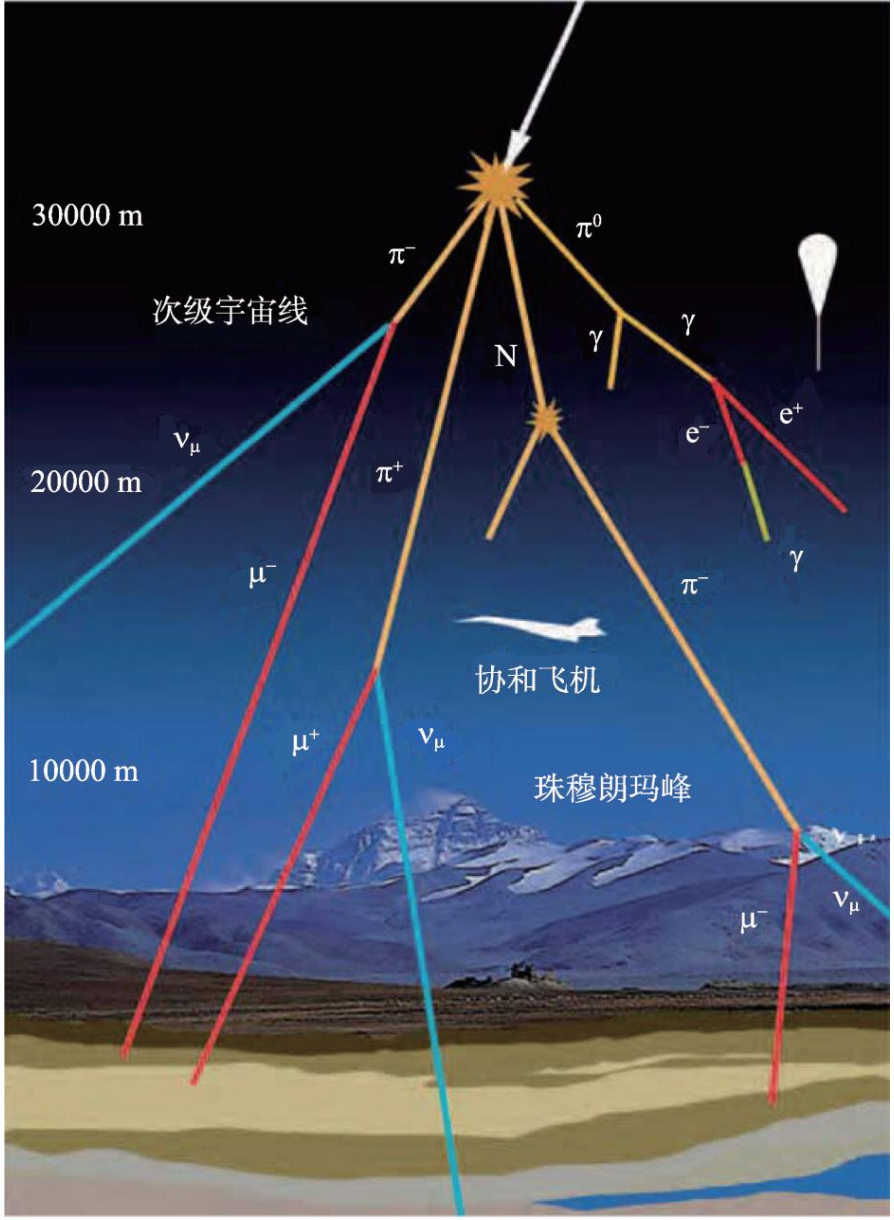
Workshop on Muon Science Technology and Industry
(MELODY 2023)

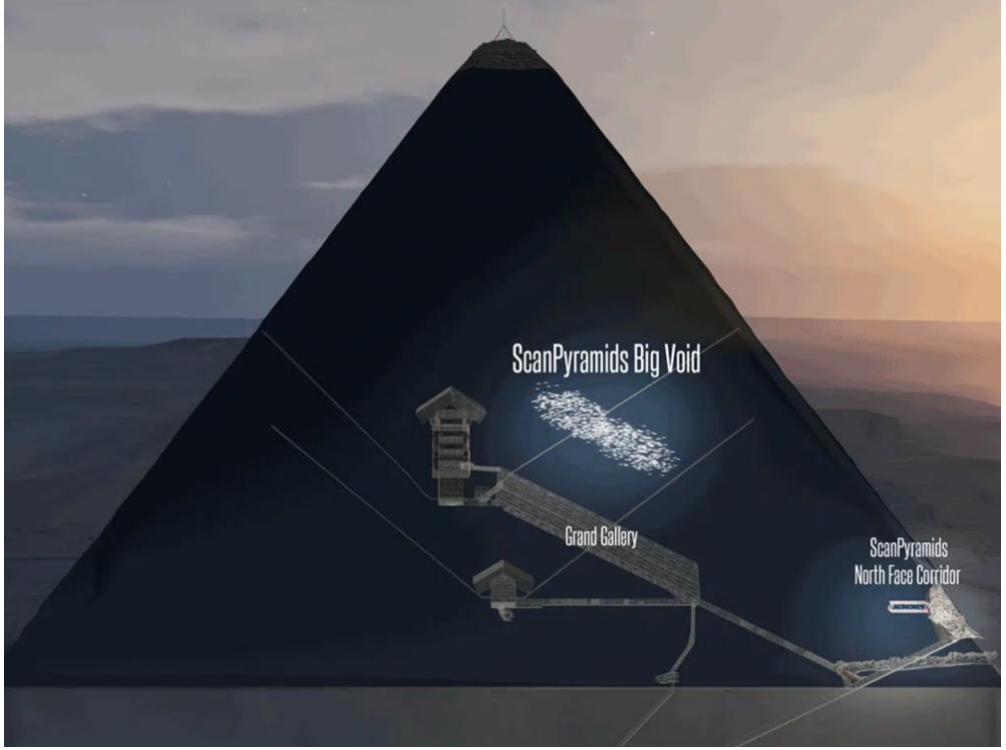
R&D of Cosmic-ray Muon Tomography System Based on RPC
基于RPC的宇宙线缪子成像系统研发进展
and A Brief Introduction of PKMUON Collaboration
暨PKμ合作组简介

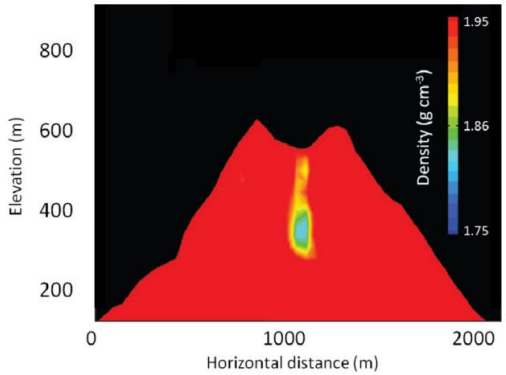
李奇特 Li Qite

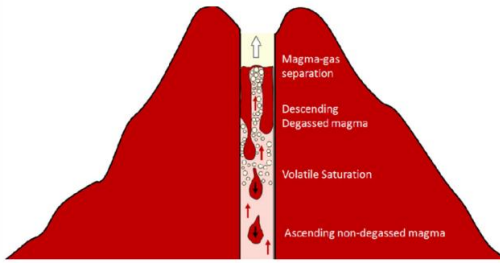
北京大学 Peking University





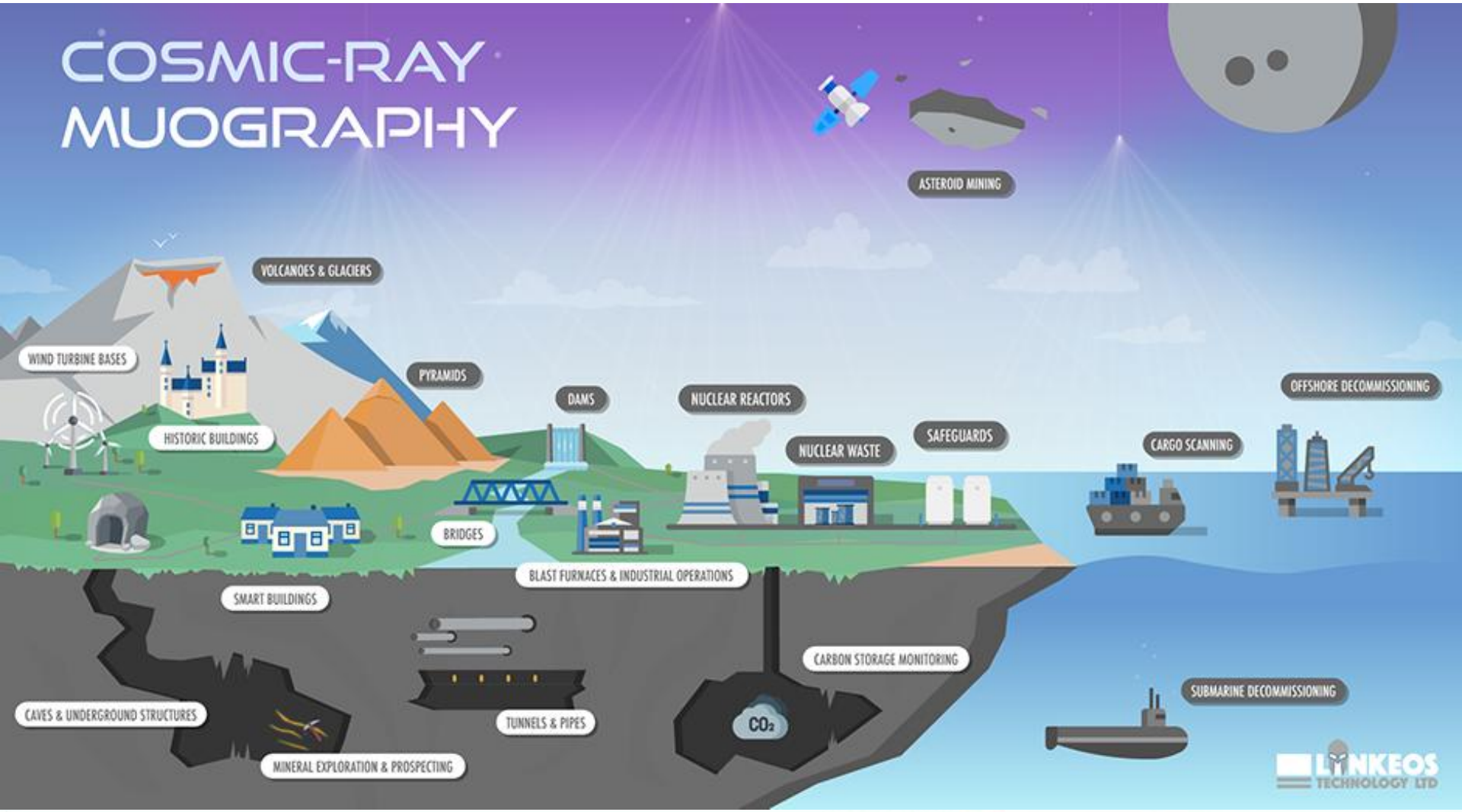




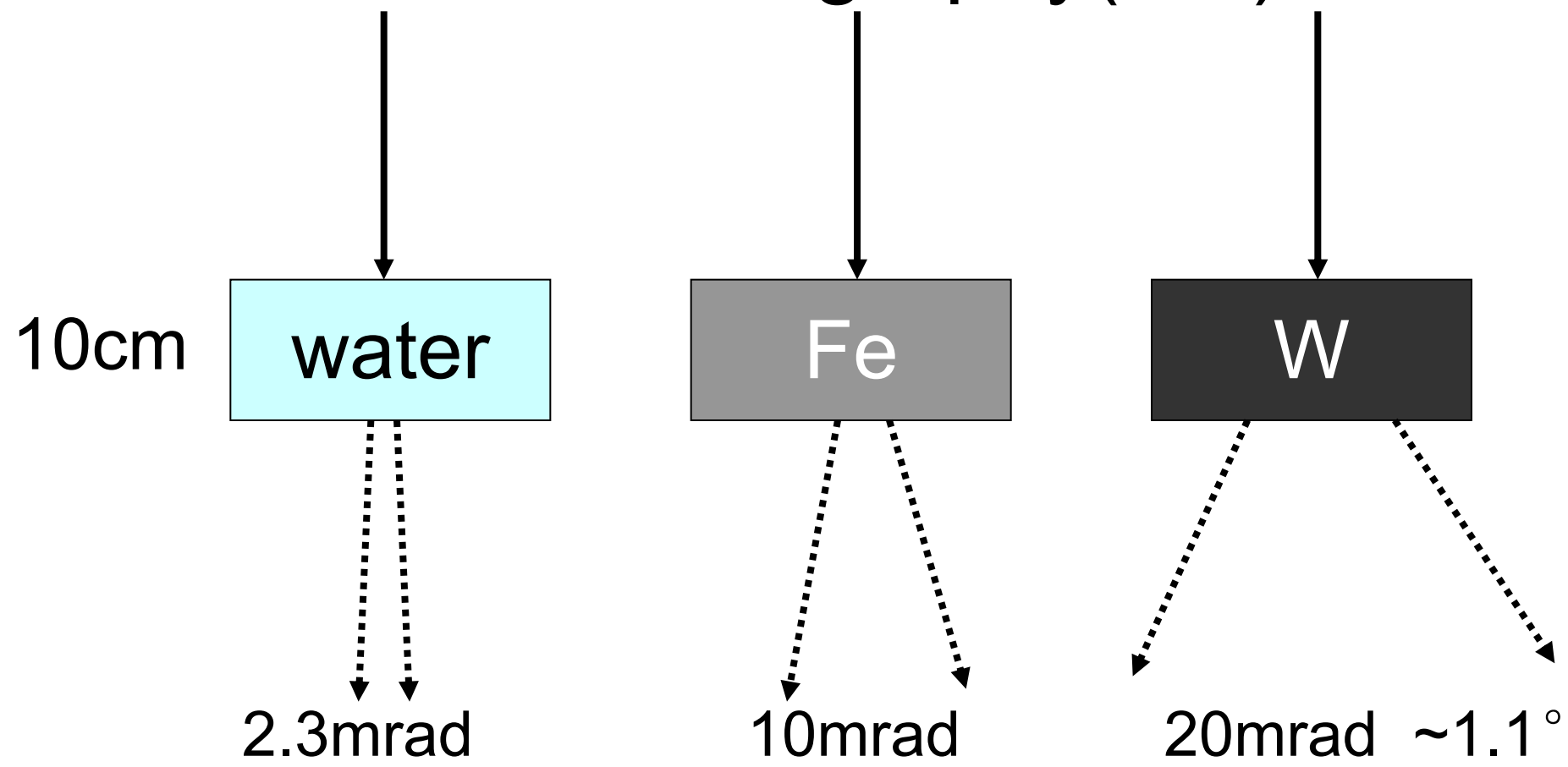


Hiroyuki K. M. Tanaka,et al. Visualization of the Internal Structure of Volcanoes with Cosmic-ray Muons. Journal of the Physical Society of Japan, 85, 091016 (2016) 10.7566/JPSJ.85.091016

Cosmic-ray Muon Radiography and Tomography

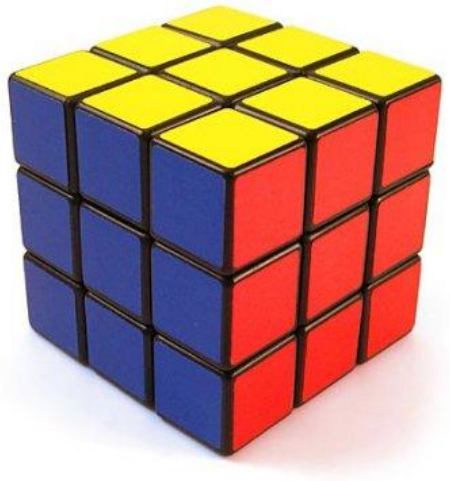


Muon Tomography(MT)



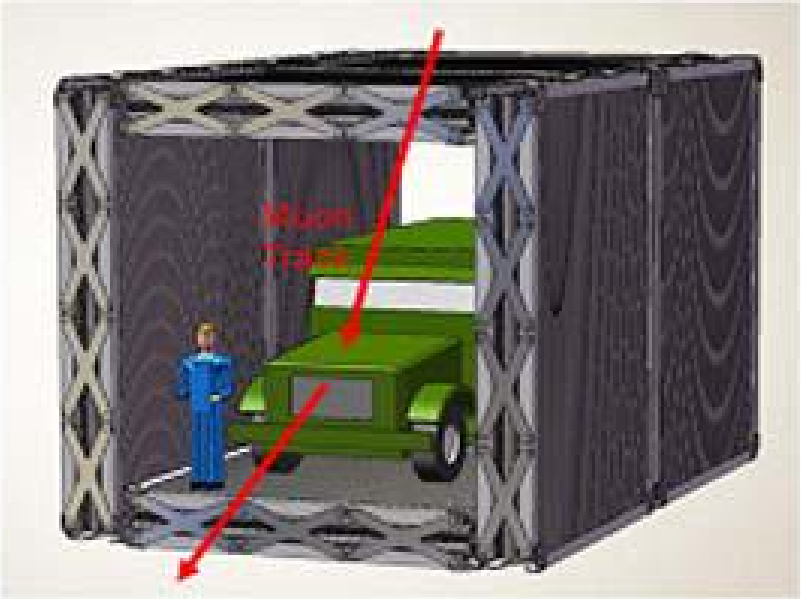
~GeV Muon 1/cm^2/min

- Uranium 90% (HEU)
- Pu-239 93% (WGPu)



- 26 kg HEU / 5kg WGPu
- 11 cm / 6 cm box

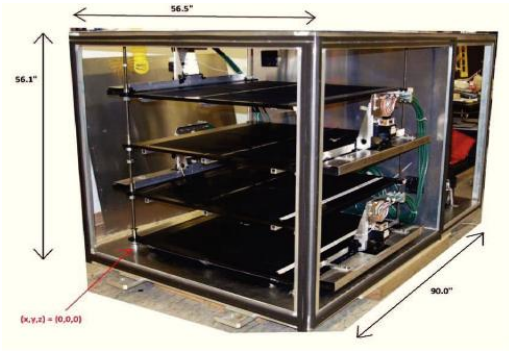
Requirements of Detectors for MT

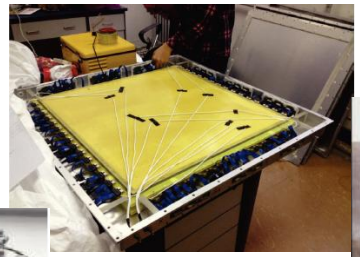


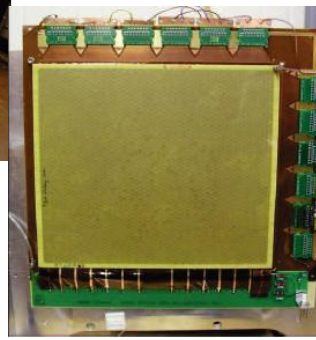
- Large Area (~1m^2)
- High Detction Efficiency (>90%)
- High Spatial Resolution (~1mm)
- Cost-effective

Several Projects worldwide interested in Muon Tomography

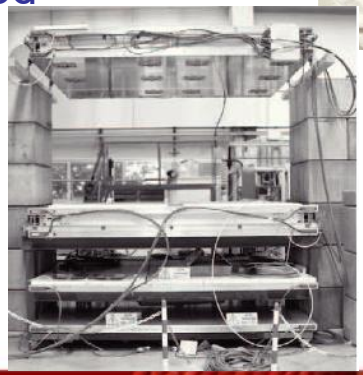
- INFN Padova (Italy)
- Los Alamos National Laboratory (USA)
- Carleton University (Canada)
- Tsinghua University (China)
- Peking University (China)
- CIAE (China)
- USTC(China) WANG YU's Talk
- Bristol University (UK)
- … (a non exhaustive list)







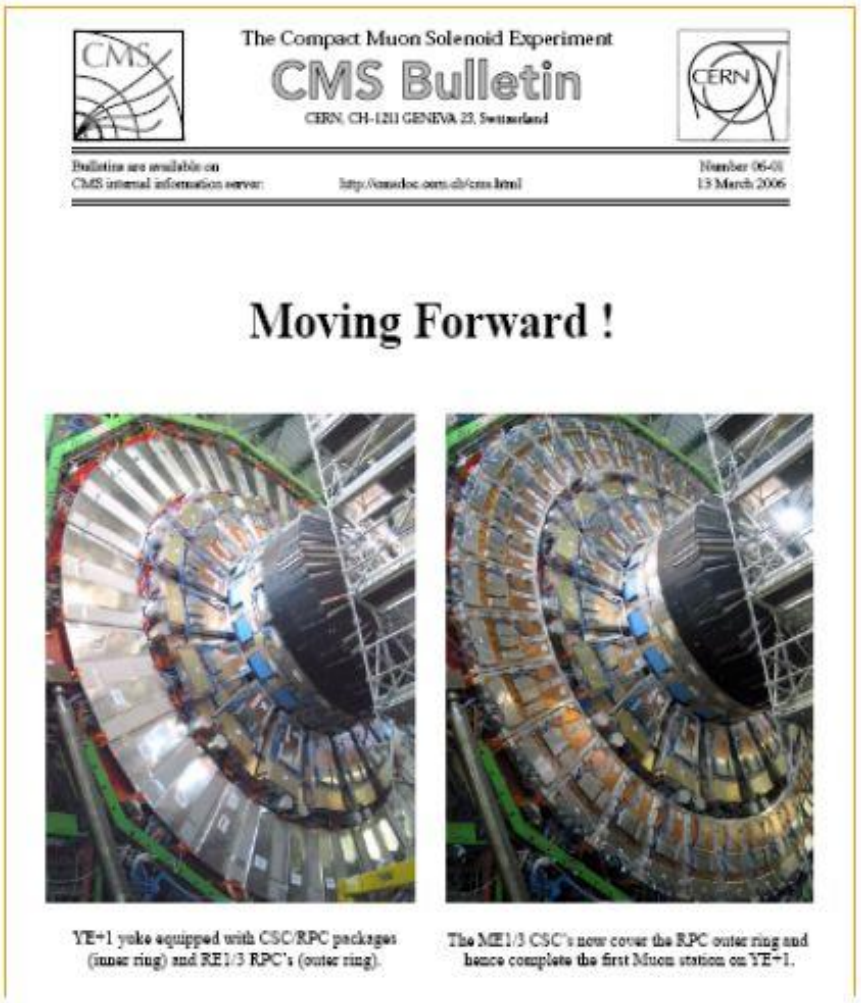
Various detector prototypes built and tested



Various detection techniques employed

- Drift chambers
- Drift tubes
- GEM
- MRPC/RPC

PKU RPC R&D History


The Compact Muon Solenoid Experiment

CMS Bulletin

CERN, CH-1211 GENEVA 23, Switzerland

Bulletins are available on CMS internal information server: http://cmsdoc.cern.ch/cms.html

Number 06-01, 13 March 2006

Moving Forward !

YE+1 yoke equipped with CSC/RPC packages (inner ring) and RE1/3 RPC's (outer ring).

The ME1/3 CSC's now cover the RPC outer ring and hence complete the first Muon station on YE+1.

- Resistive Plate Chamber
  - R. Santonico(in 1980s)

- Large Area ~ m^2
- Good Time Solution~1ns
- Acceptable Spatial Resolution
  - ~3mm ~1cm

CMS Muon Trigger RPCs

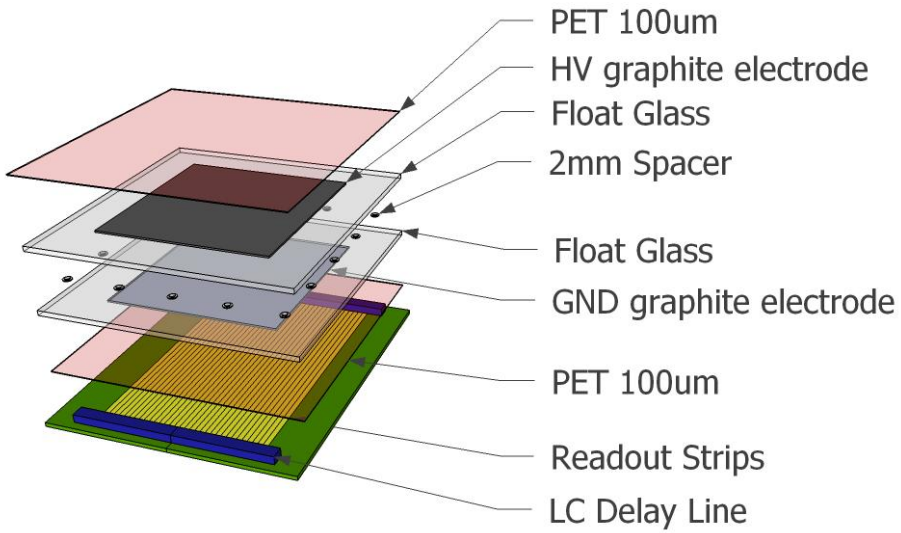
Assembled and tested by PKU (~2002)

Combination of glass RPC & Delay-line Readout


Contents lists available at SciVerse ScienceDirect
Nuclear Instruments and Methods in Physics Research A
journal homepage: www.elsevier.com/locate/nima

Study of spatial resolution properties of a glass RPC

Qite Li, Yanlin Ye *, Chao Wen, Wei Ji, Yushou Song, Rongrong Ma, Chen Zhou, Yucheng Ge, Hongtao Liu
School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

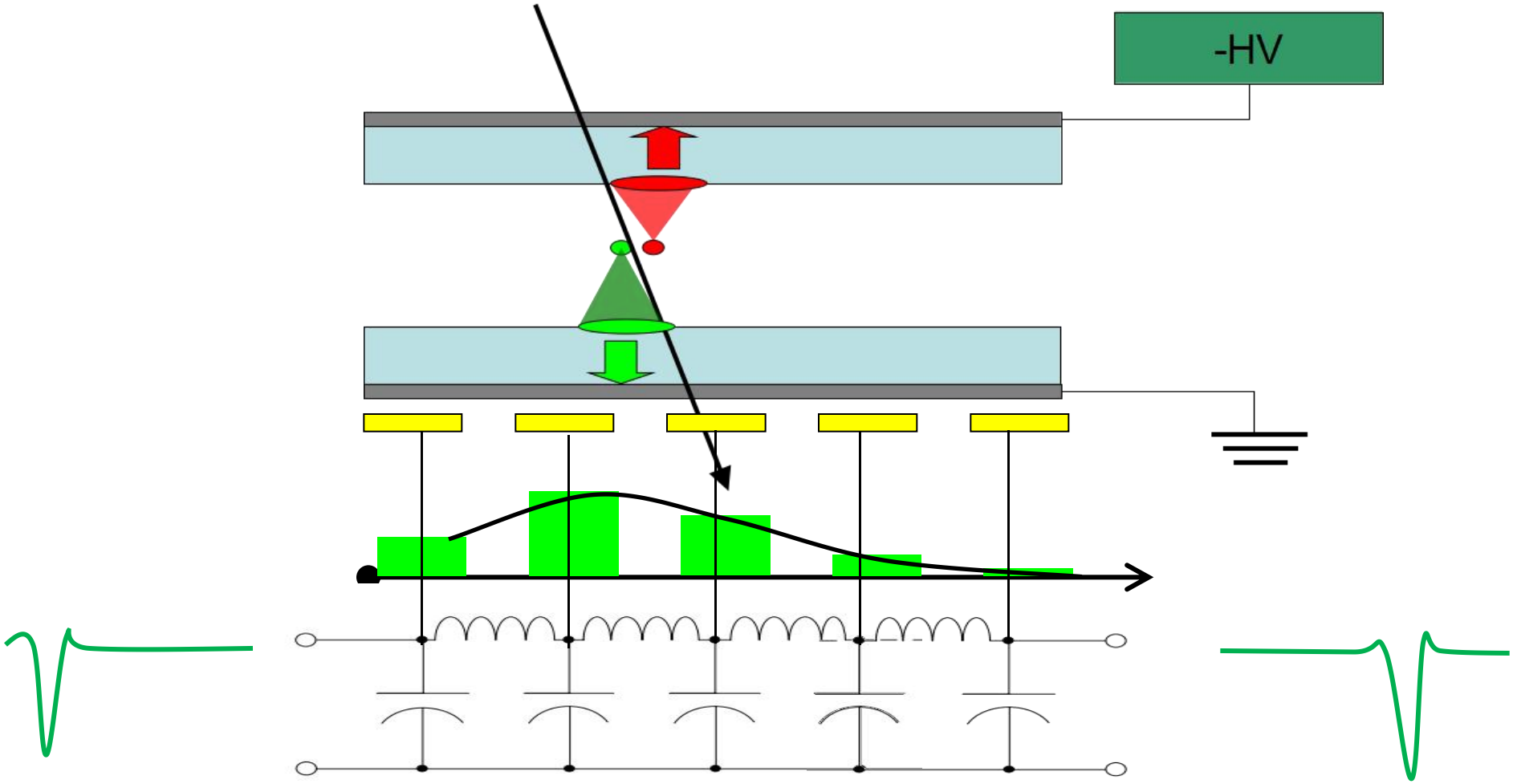


Reference:

- 许金艳,**李奇特***, 等, ***物理实验***, 41(2021)23
- **Qi-Te, Li,** et al. ***Chinese Physics C*** 37 (2013)016002.
- S. Chen, **Q. Li*,** et al, ***JINST***: 10 (2014)10022.

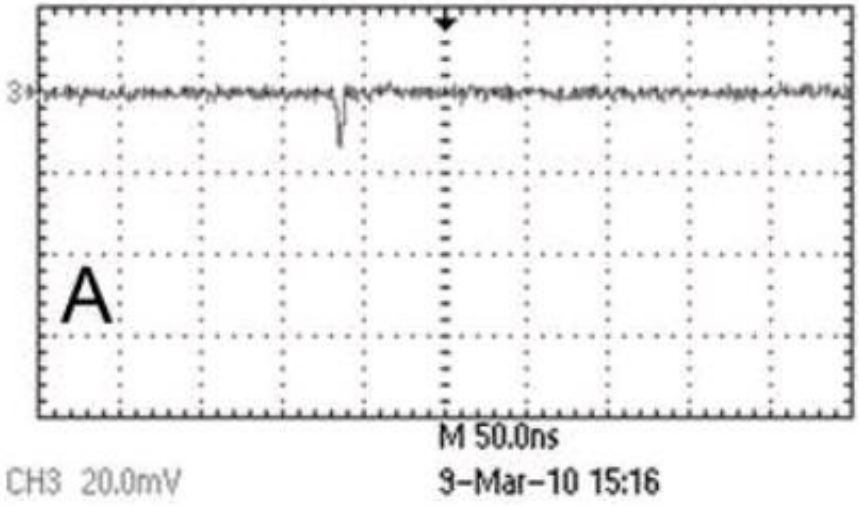
90% R134a+9% i-C_4H_{10}+1% SF_6 50ml/Min

Induced Charge and Signals

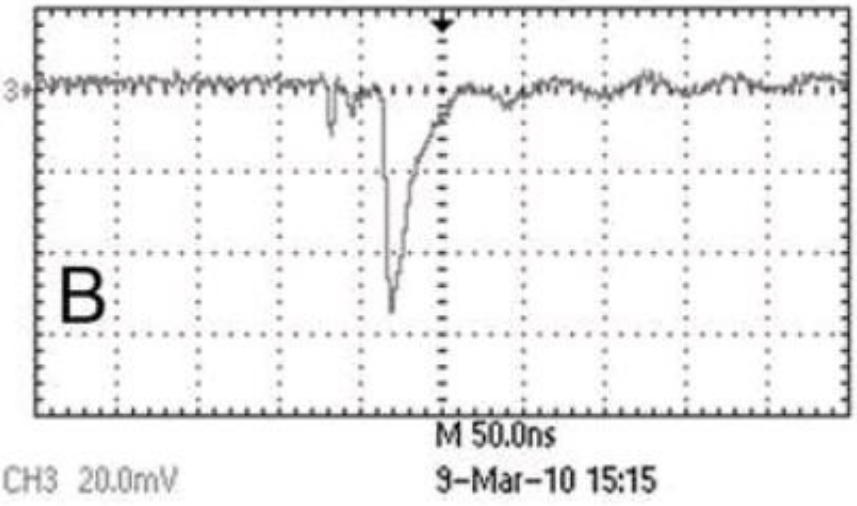


General Properties: Signals

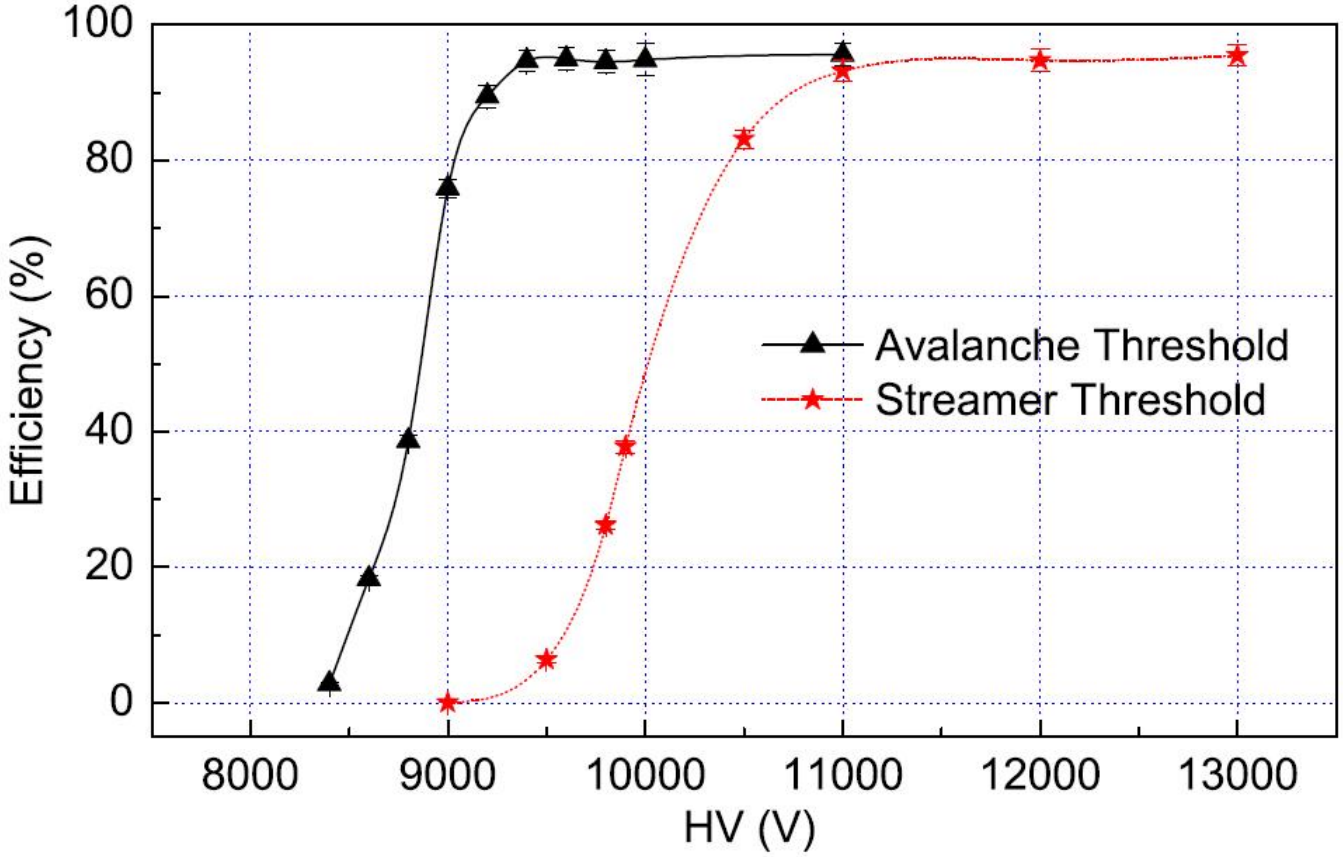
- Avalenche Signal



- Avalenche +Streamer Signal

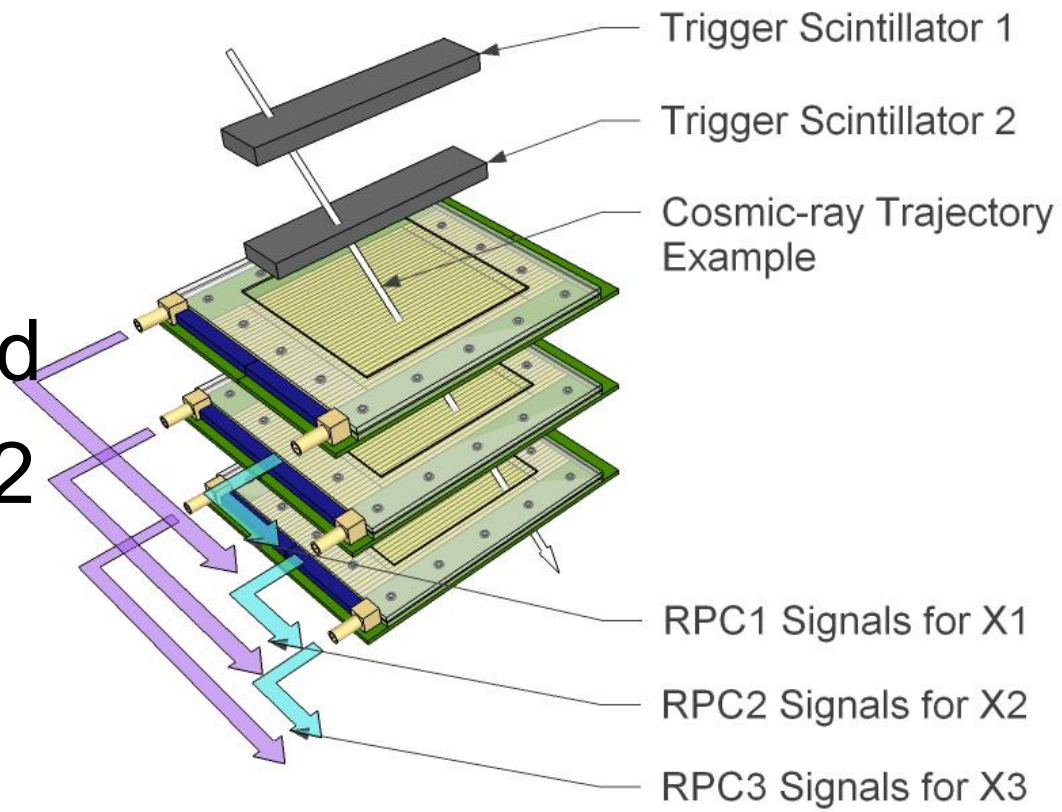


General Properties: Detection Efficiency



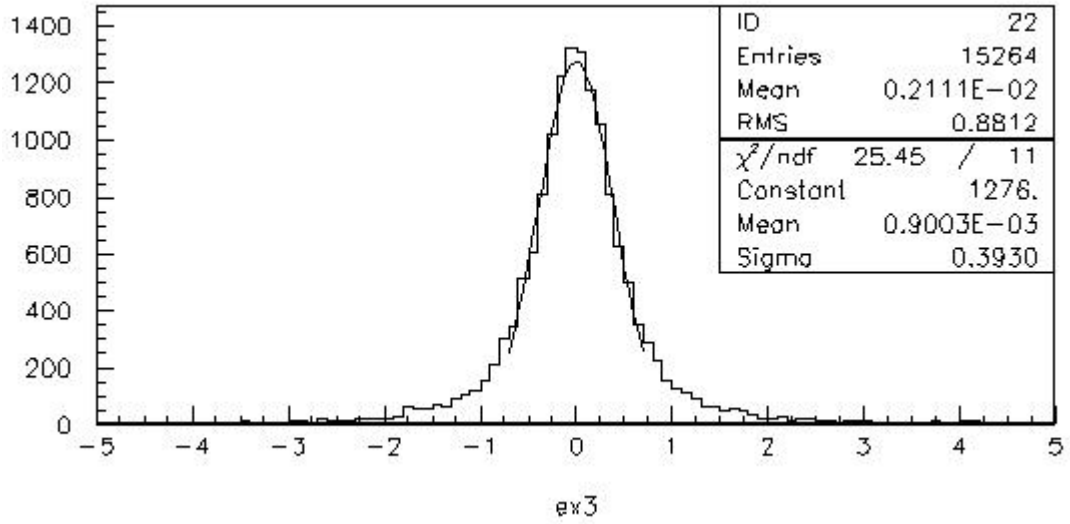
Spatial Resolution Measurement

- Residual Method
- $\Delta X = X_2 - (X_1 + X_3)/2$



Spatial Resolution of Glass RPCs

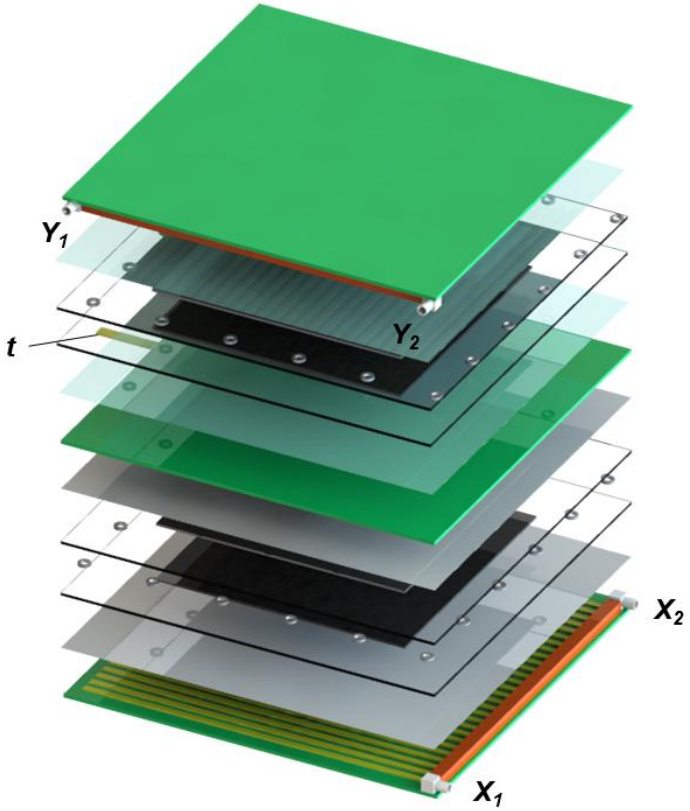
$$f = X_2 - (X_1 + X_3)/2$$

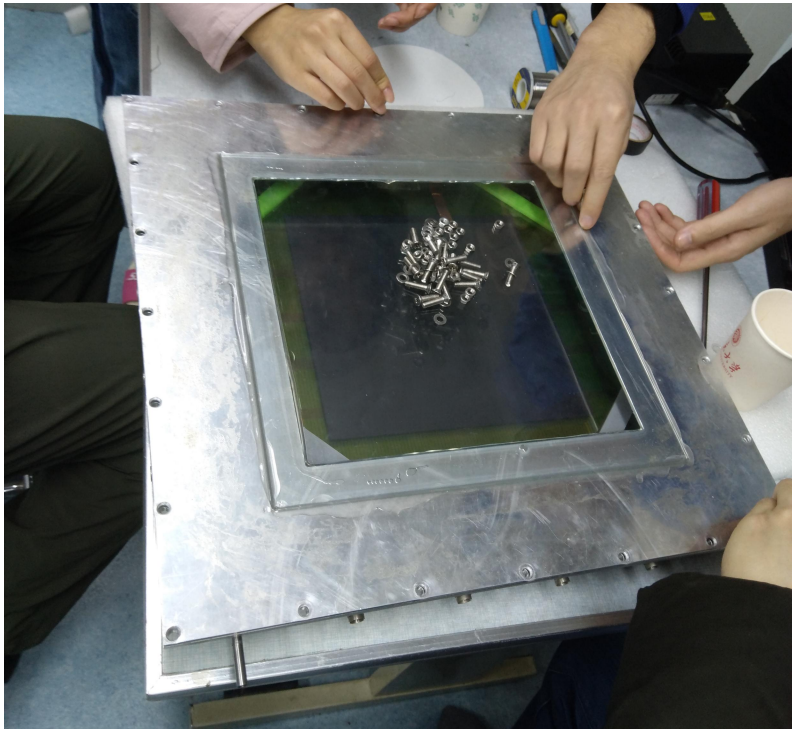


$$\sigma^2 = \sigma_{x2}^2 + (\frac{1}{2})^2\sigma_{x1}^2 + (\frac{1}{2})^2\sigma_{x3}^2 = \frac{3}{2}\sigma_x^2$$

$$\sigma_x = \sqrt{\frac{2}{3}}\sigma = 0.816 \bullet 0.393mm = 0.339mm$$

X-Y readout RPC





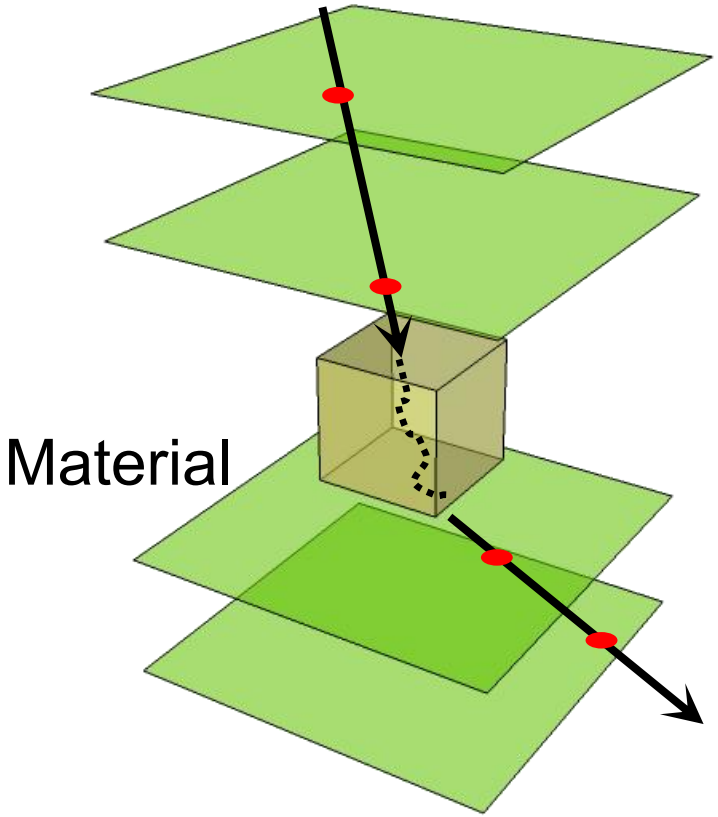
3D Imaging Test(2013~2014)

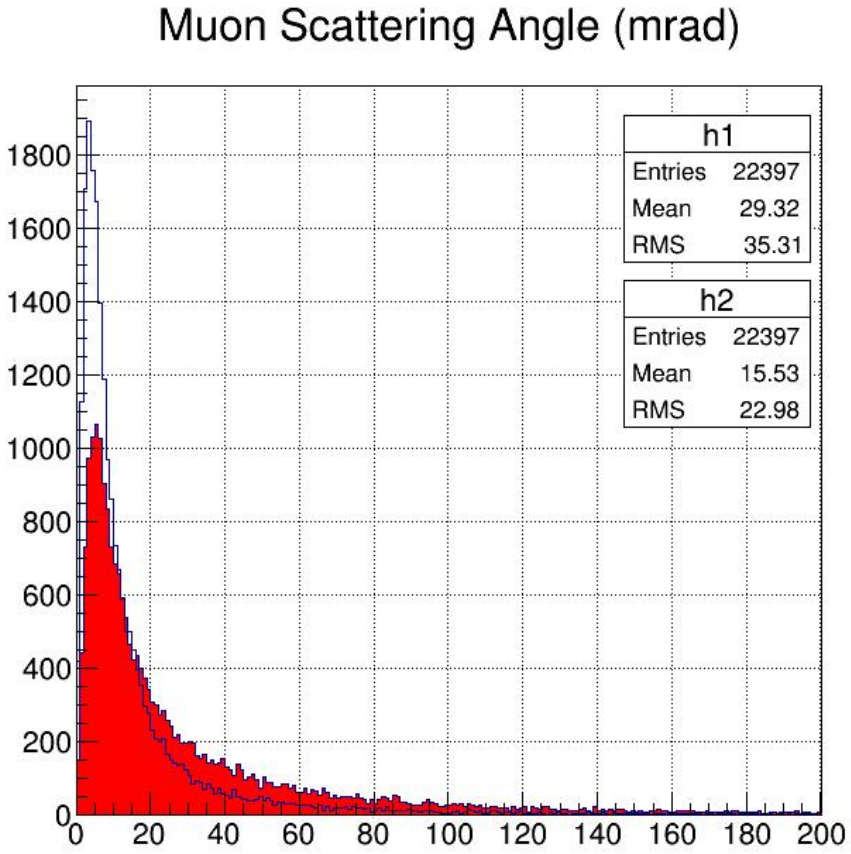
4 X-Y readout RPC Boxs, distance 285mm

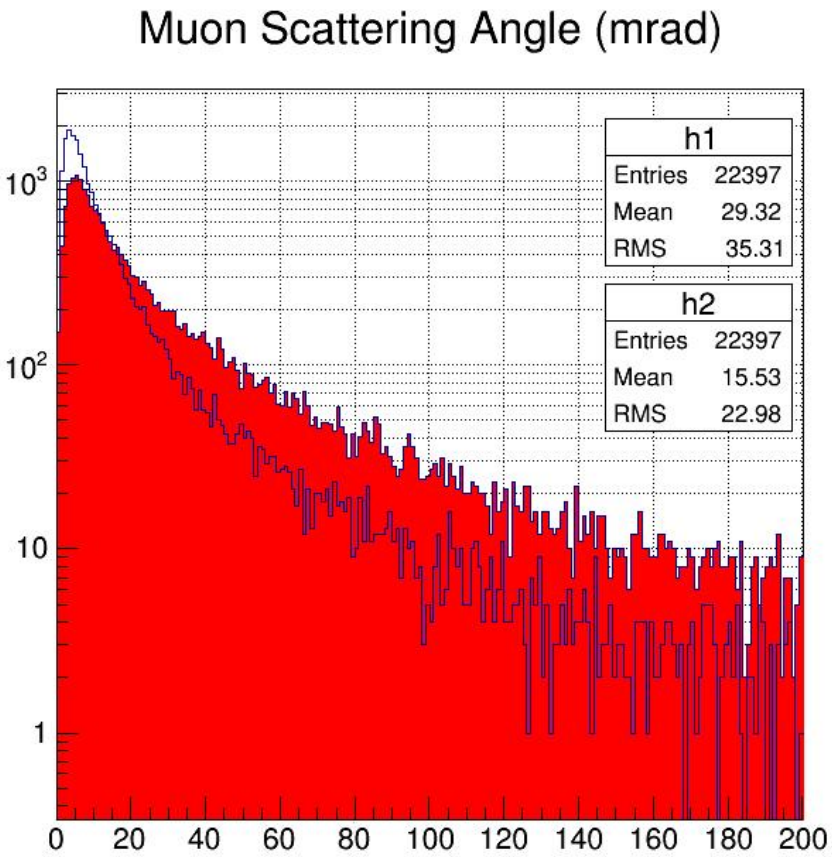
Active area 203mm*203mm

PKU Muon tomography System

Using only 20 TDC channels

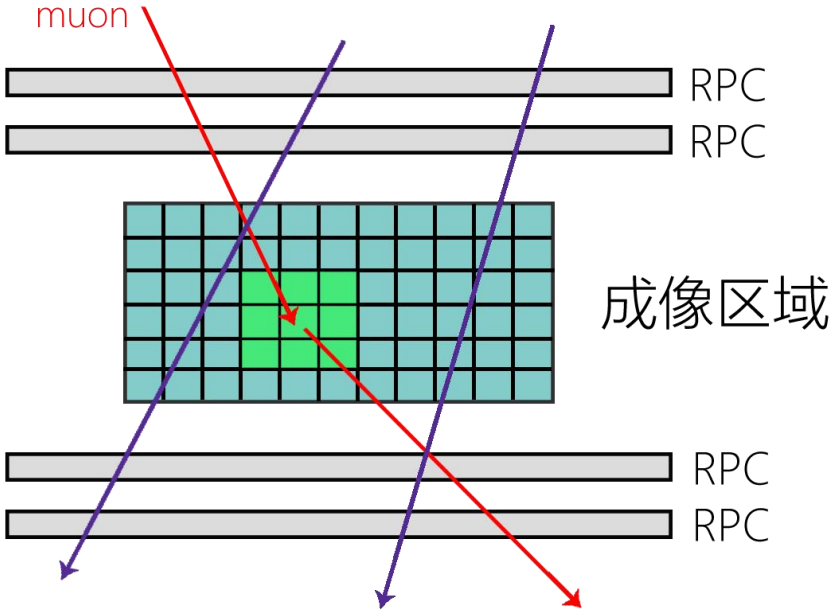






- h1 Red：12*12*12cm^{3}Fe Shell and 6*6*6cm^3 Pb
- h2 White：Empty

Point of Closest Approach (PoCA) algorithm



$$\sigma_{\Delta\theta} = \frac{13.6MeV}{\beta c p_i}\sqrt{\frac{L}{L_{rad}}}$$

$$\lambda = \frac{1}{L}\left(\frac{p_i}{p_0}\right)^2 \sigma_{\Delta\theta}^2$$

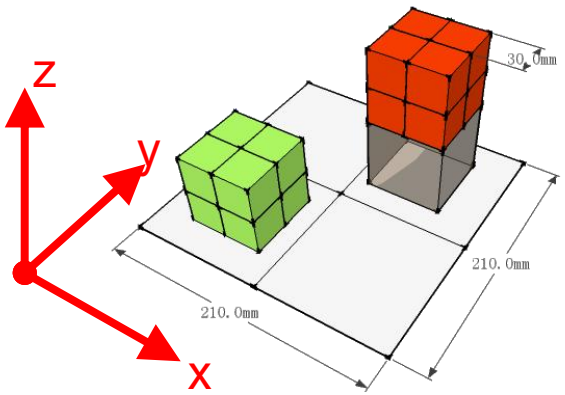
$$\lambda_j = \frac{1}{M_j}\sum_{i=1}^{M_j}\frac{1}{L_{ij}}\left(\frac{p_i}{p_0}\right)^2 \frac{\Delta\theta_{xi}^2 + \Delta\theta_{yi}^2}{2} = \frac{1}{M_j}\sum_{i=1}^{M_j}\lambda_{ij}$$

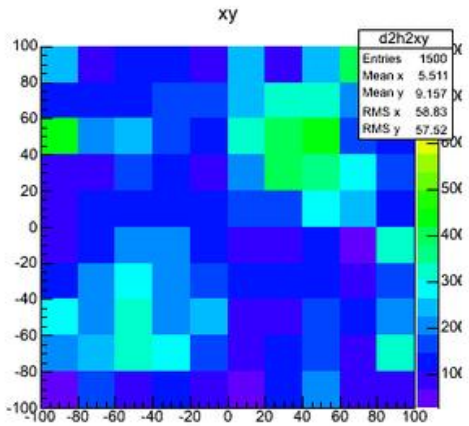
Point of Closest Approach (PoCA) algorithm was used to rapidly reconstruct the image of muon tomography. In PoCA algorithm, multiple Coulomb scattering is reduced to one scattering event. To calculate related PoCA points, we can get the material images.

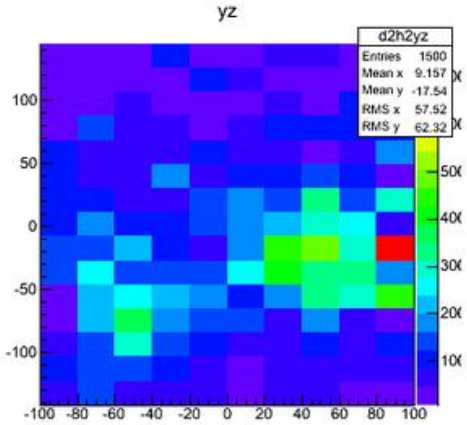
· Schultz L J , Borozdin K N , Gomez J J , et al. Image reconstruction and material Z discrimination via cosmic ray muon radiography[J]. Nuclear Inst & Methods in Physics Research A, 2004, 519(3):687-694.

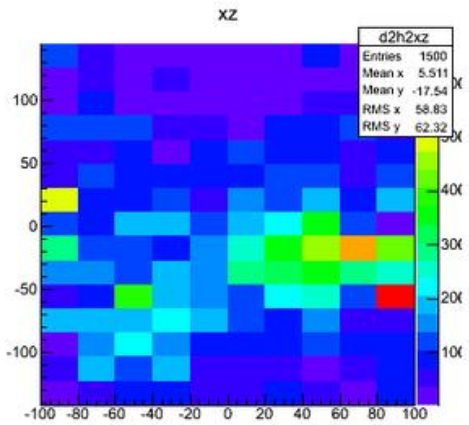
Image result of 6*6*6cm^3 Fe and Pb blocks

24 hrs experiment data
12000 PoCA points



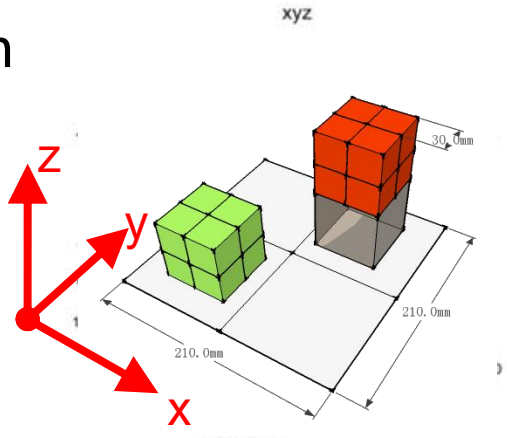


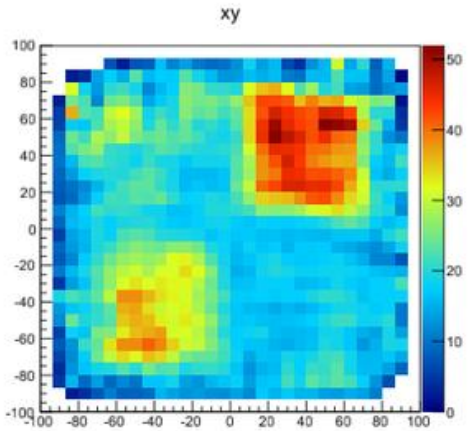


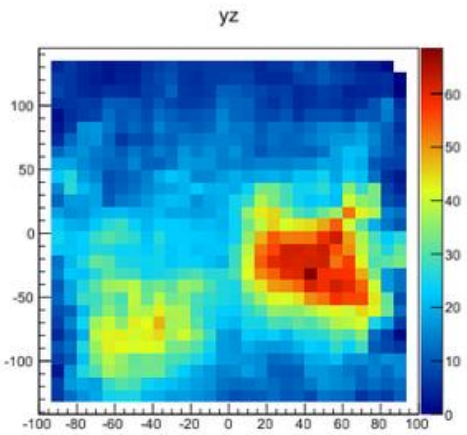


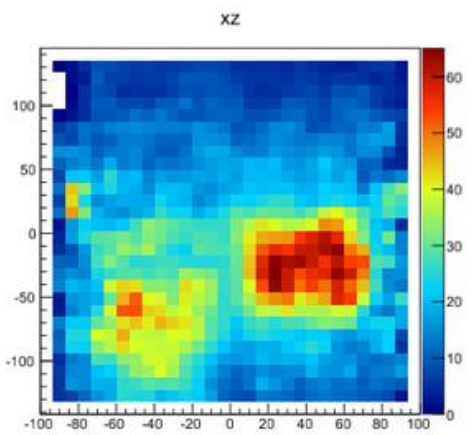
Improved PoCA algorithm

- An improved POCA algorithm has been developed that does not require muon momentum information.
  - The average scattering angle replaces the σ_θ^2
  - PoCA point information from surrounding voxels is used.





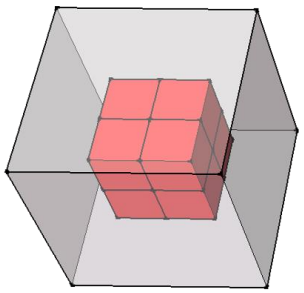


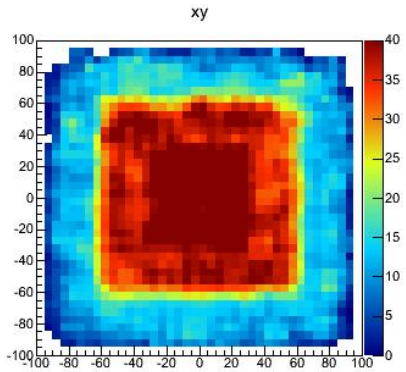


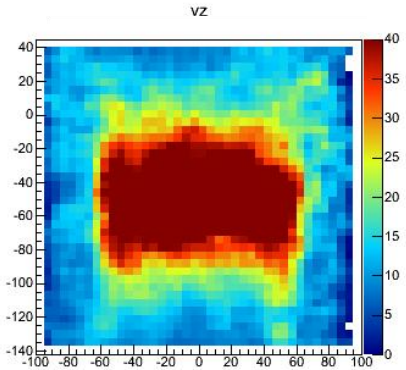
- 非常大角度μ子散射事件并不是库伦散射，而是核散射，成像中是要限制的其影响的
- Very large angle muon scattering events are not Coulomb scattering, but muon-nuclear scattering, and their effects should be eliminated in imaging.

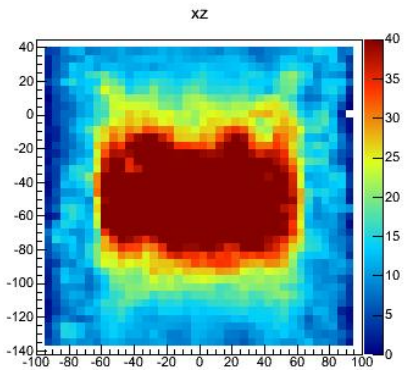
- 使用周围像元去平滑计算是合理的，μ子多重散射在PoCA点外带有信息
- It is reasonable to use surrounding pixels to smooth the calculation. Muon multiple scattering carries information outside the PoCA point.

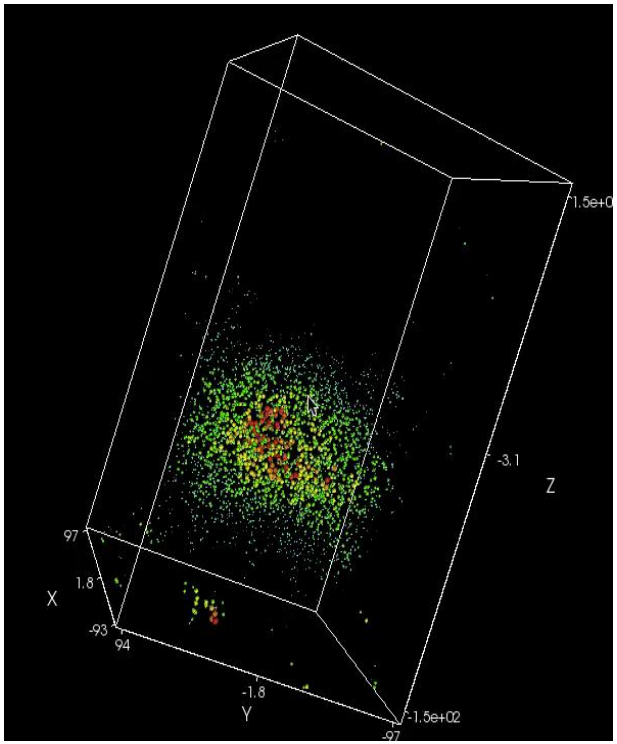
Imaging Results of a 6*6*6cm^3 Square Lead Block Wrapped in a 12*12*12cm^3 Iron Shell





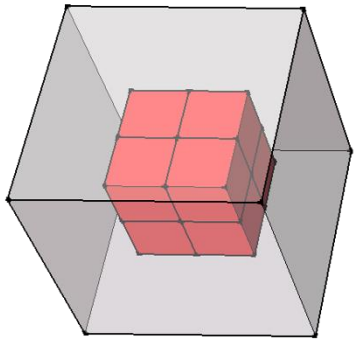


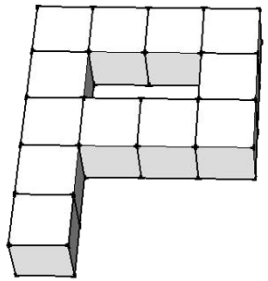


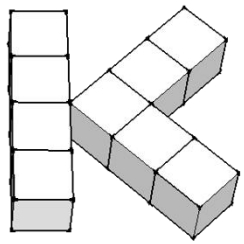


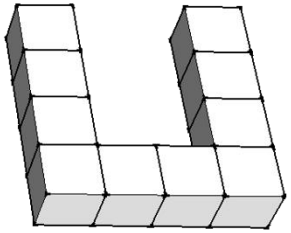
· Liu C M , Wen Q G , Zhang Z Y , et al. Study of muon tomographic imaging for high-Z material detection with a Micromegas-based tracking system[J]. 2020.

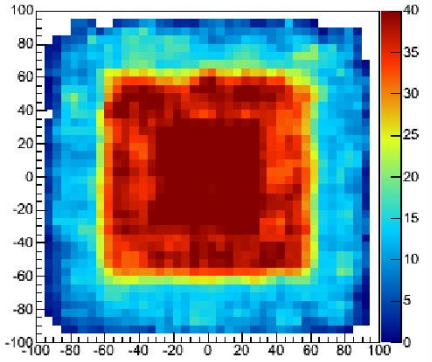
P K U
some 3*3*3cm^3
Fe blocks

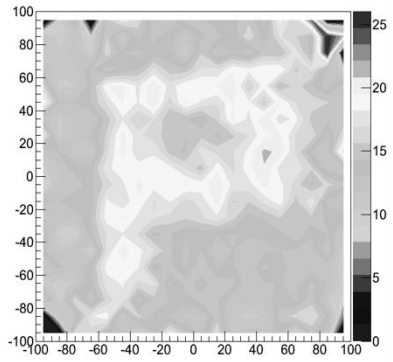


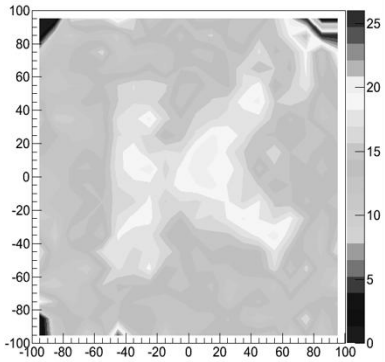


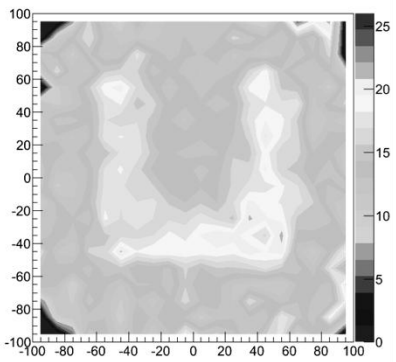




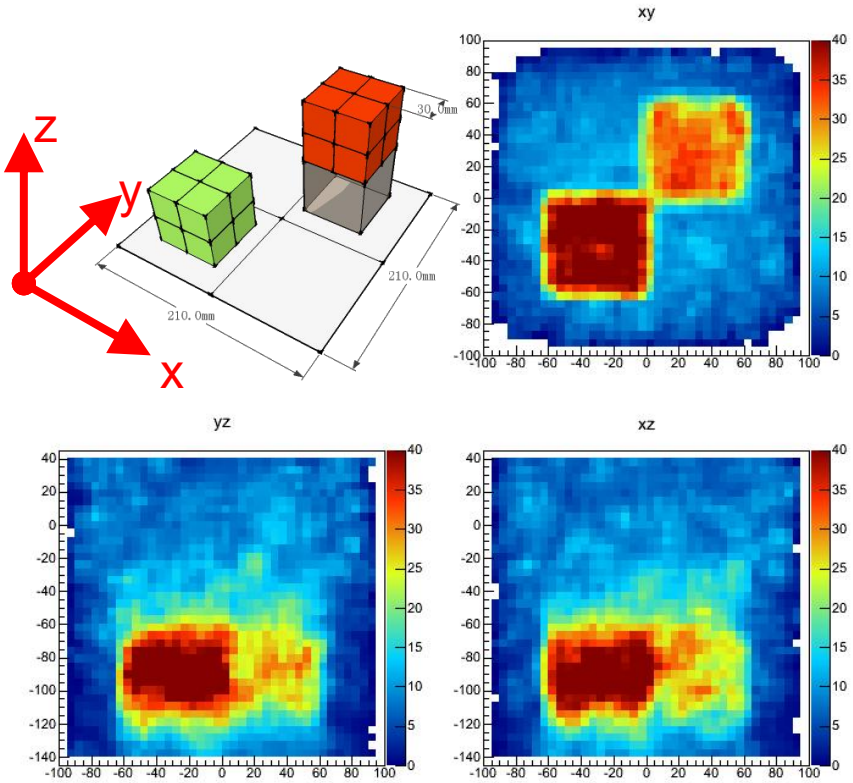


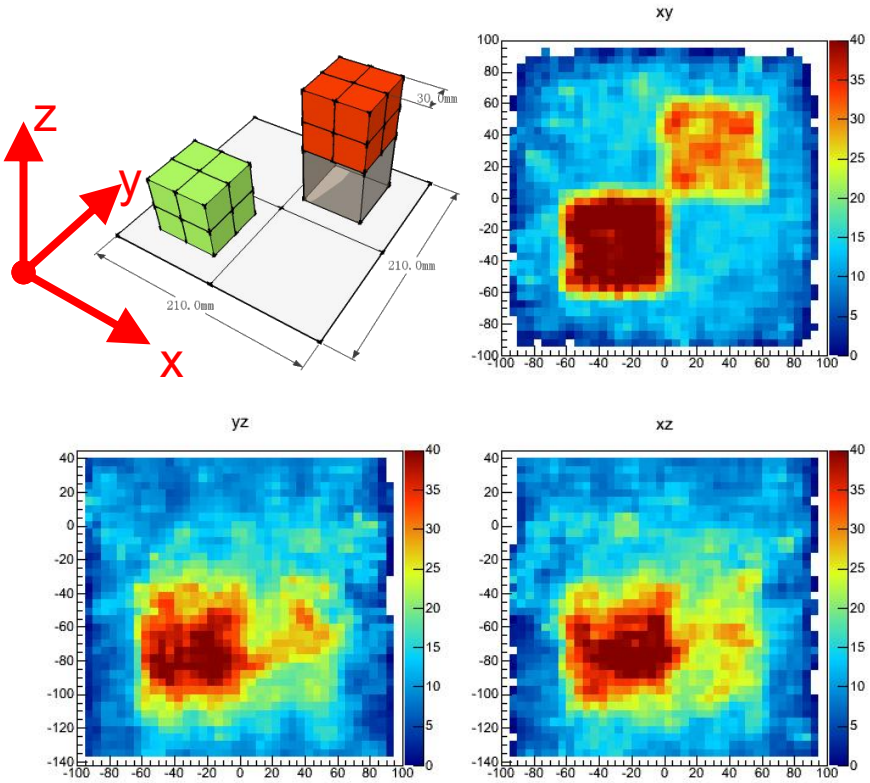


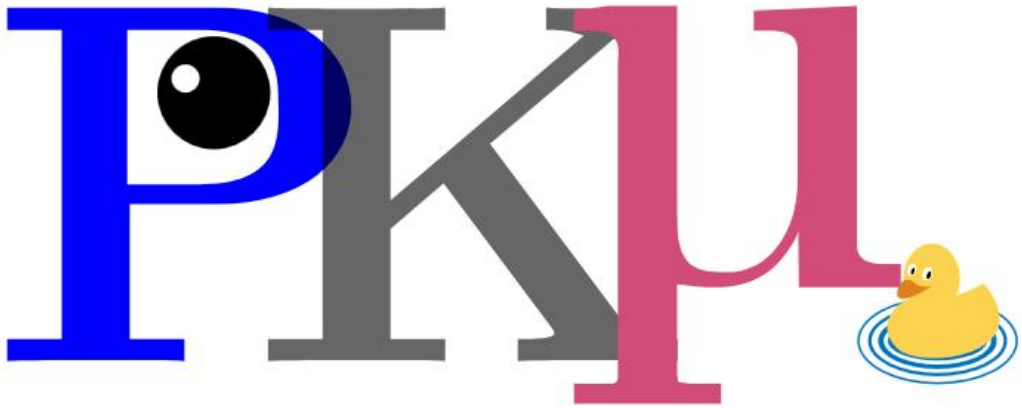




Very good agreement with GEANT4 Simulation







A Brief Introduction of PKMUON

Probing darK Matter Using free leptONs: PKMUON

arXiv:2303.18117 [hep-ph] accpted by International Journal of Modern Physics A

Probing darK Matter Using free leptONs: PKMUON

Alim Ruzi,* Chen Zhou,† Xiaohu Sun, Dayong Wang, Siguang Wang, Yong Ban,‡ Yajun Mao,§ Qite Li,¶ and Qiang Li**
State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing, 100871, China

We propose a new method to detect sub-GeV dark matter, through their scatterings from free leptons and the resulting kinematic shifts. Specially, such an experiment can detect dark matter interacting solely with muons. The experiment proposed here is to directly probe muon-philic dark matter, in a model-independent way. Its complementarity with the muon on target proposal, is similar to, e.g. XENON/PandaX and ATLAS/CMS on dark matter searches. Moreover, our proposal can work better for relatively heavy dark matter such as in the sub-GeV region. We start with a small device of a size around 0.1 to 1 meter, using atmospheric muons to set up a prototype. Within only one year of operation, the sensitivity on cross section of dark matter scattering with muons can already reach $\sigma_D \sim 10^{-19(-20,-18)}\text{cm}^2$ for a dark mater $\text{M}_\text{D} = 100\,(10,\,1000)$ MeV. We can then interface the device with a high intensity muon beam of 10^{12}/bunch. Within one year, the sensitivity can reach $\sigma_D \sim 10^{-27(-28,-26)}\text{cm}^2$ for $\text{M}_\text{D} = 100\,(10,\,1000)$ MeV.

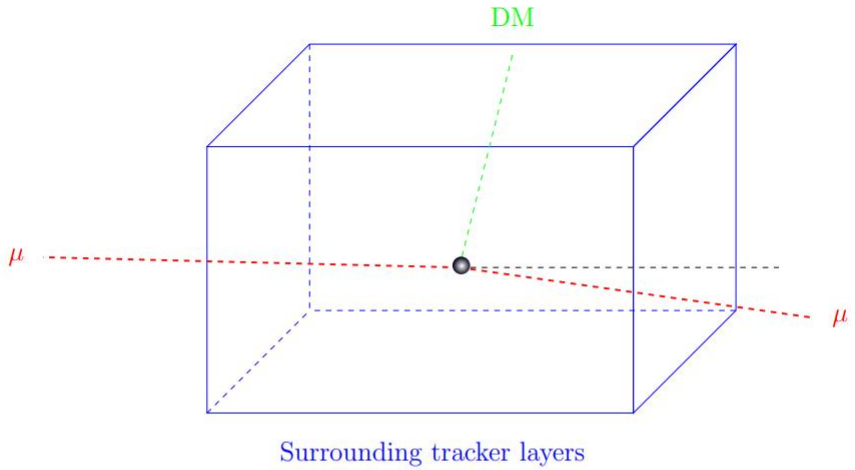
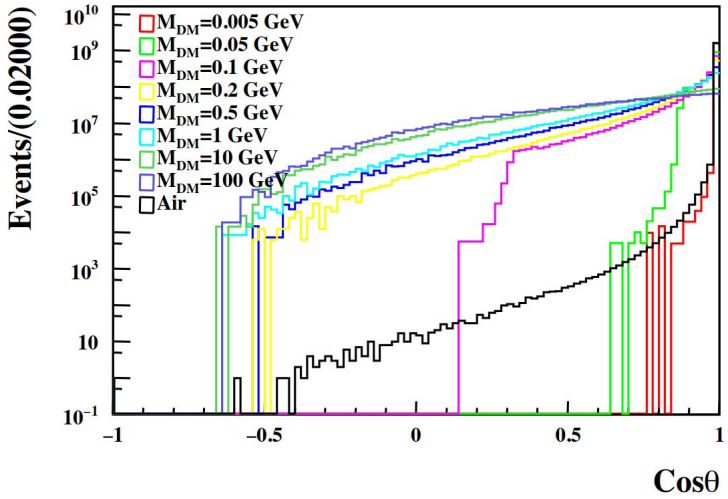


FIG. 1. Illustration of experiments to detect low mass DM with free leptons. The resulting kinematic shifts of leptons kicked by DM can be measurable with tracking detectors surrounding a vacuum region. A veto region along the chamber can be defined based on the cross-point of the in and out tracks to suppress backgrounds.

缪子穿过空气及不同质量暗物质的模拟结果

Geant4 simulation results for muon scattering with air or DM

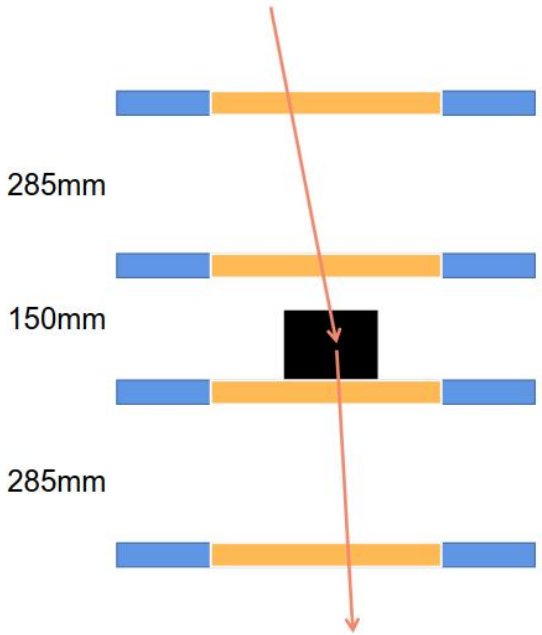


A proposed PKU-Muon experiment for muon tomography and dark matter search

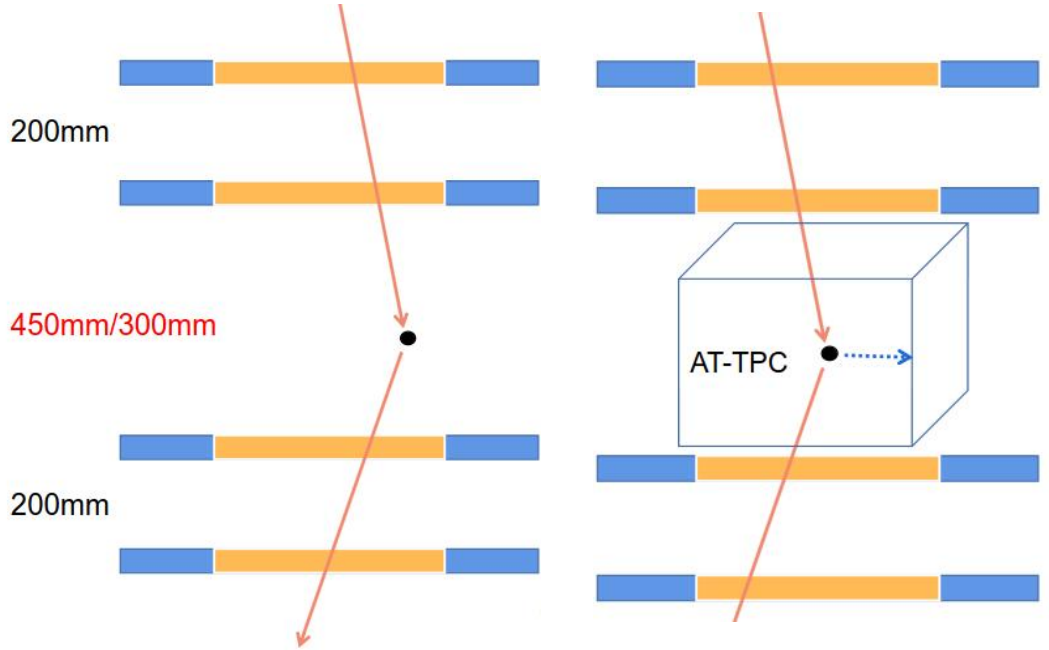
Based on **RPC,** **GEM,** **AT-TPC, etc.**

20cm*20cm 60cm*40cm full tracking

Muon Tomography
缪子成像



Dark Matter Search
暗物质寻找 (2303.18117 accpted by ITJMPA)

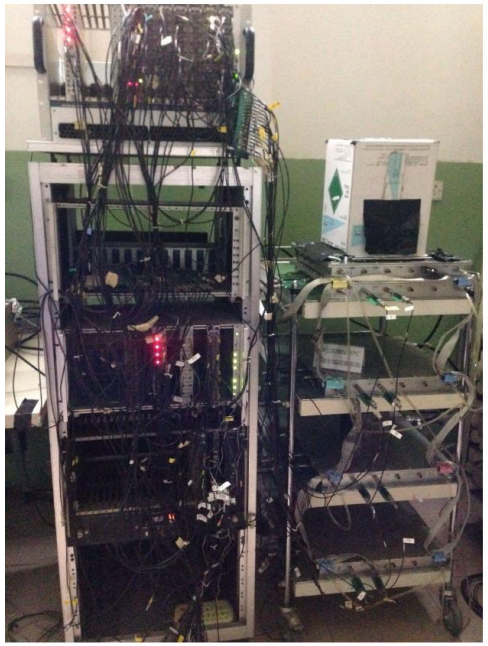


A proposed PKU-Muon experiment for muon tomography and dark matter search

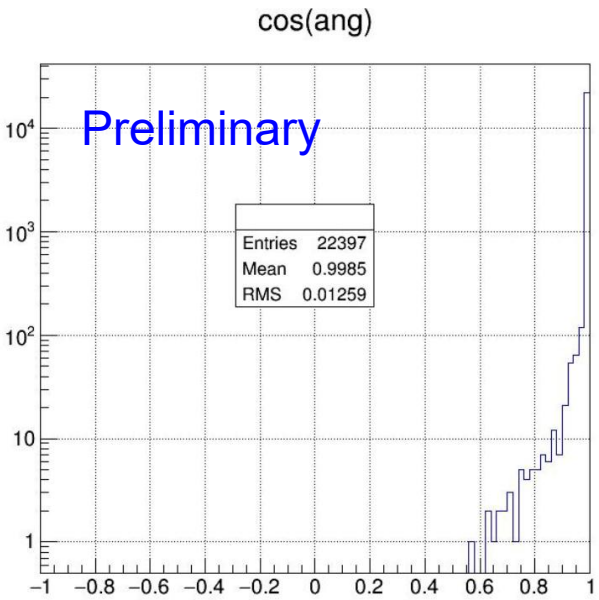
Based on RPC, GEM, AT-TPC, etc.

20cm*20cm 60cm*40cm full tracking

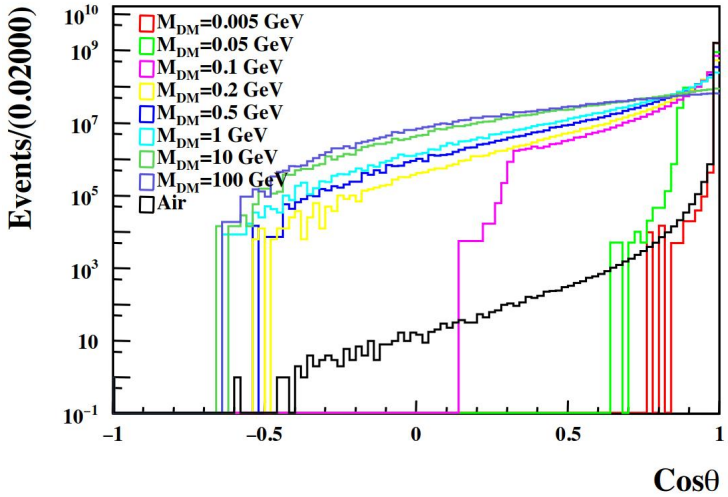
PKU RPC Muon Tomography system (2013-2014) Being Upgraded!



实测偏转角数据(49小时）
Real Data (49 hrs' data)



缪子穿过空气及不同质量暗物质的模拟结果
Geant4 simulation results for muon scattering with air or DM



A proposed PKU-Muon experiment for muon tomography and dark matter search

Based on **RPC,** 20cm*20cm **GEM,** 60cm*40cm **AT-TPC, etc.** full tracking

- **Muon Tomography**
  - RPC (~0.5 year), GEM (~1 year)
  - Algorithm development & fast detection (~1 year)
    - Engineering, Archaeology (2-5 years)
  - Muon Radar: cosmic muon precision measurement
    - Various altitude & direction and/or momentum (~1-2 years)
    - Connects with Atmospheric science (2-3 years)
- **Muon Dark Matter Scattering (also Axion?)**
  - RPC (~0.5-1 year), GEM (~1-1.5 year), AT-TPC (~1-2 year)
  - DM in a box (~0.5-2 year)
  - Angle difference at different altitudes (~2-4 years)
- **Interfacing with Muon Beam?** (~5-10 years)

Summary

- Successfully developed glass RPC based on LC delay line readout.
  - It has a simple structure, stable operation, and high cost-effectiveness.
  - The detection efficiency is between 95% and 98%.
  - the resolution to 0.3-0.4mm (sigma) resolution.

- A 4-layer muon tomography system has been built.
  - Using only 20 TDC channels
  - In preliminary tests (203mm*203mm RPC), it can distinguish between iron and lead blocks at the centimeter level.
  - The imaging results are consistent with the simulation.

- An improved POCA algorithm has been developed that does not require muon momentum information.
  - The average scattering angle replaces the variance
  - PoCA point information from surrounding voxels is used.

- A proposed PKU-Muon experiment for muon tomography and dark matter search. PKMUON

Thank You!