缪子素转换实验MACE研究进展

Jian Tang (唐健)
tangjian5@mail.sysu.edu.cn

基于HIAF集群的高精度测量和新物理研讨会，广东惠州
2023-07-05

合作者：中山大学物理学院SMOOTH实验室—陈羽、沈韩、黄臻成、徐宇、赵诗涵、孙铭辰、余涛、杨航、胡碧莹、钟嘉豪、蒋辉、宁云松、周逸行、白爱毓等，

IHEP—唐靖宇、袁野、李海波、张瑶、赵光、nikos、妙晗等，日本大阪大学—吴琛，

中科院近物所—陈良文、何源、贾欢、陈旭荣等，上海交通大学—许金祥，南华大学—王晓冬等

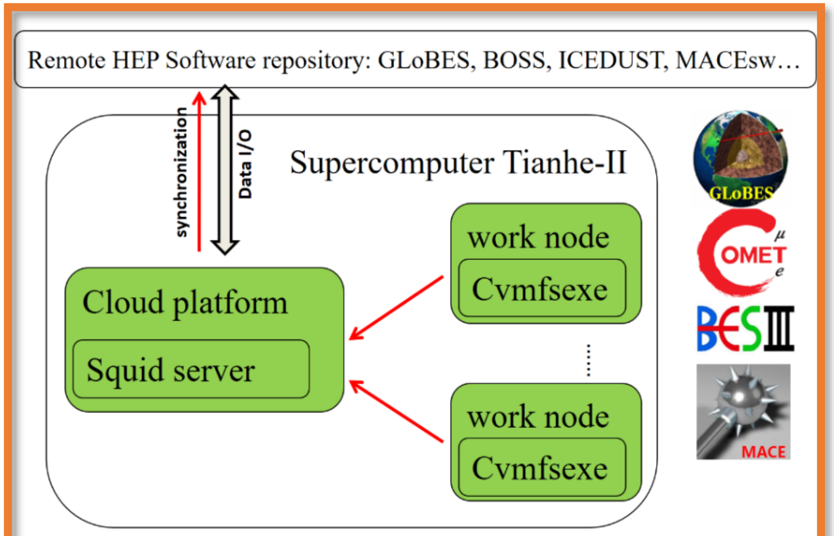
Reference: Snowmass2021 Whitepaper: Muonium to antimuonium conversion, arXiv:2203.11406
Invited talk@ International workshop of CLFV2023, Heidelberg, Germany

Content

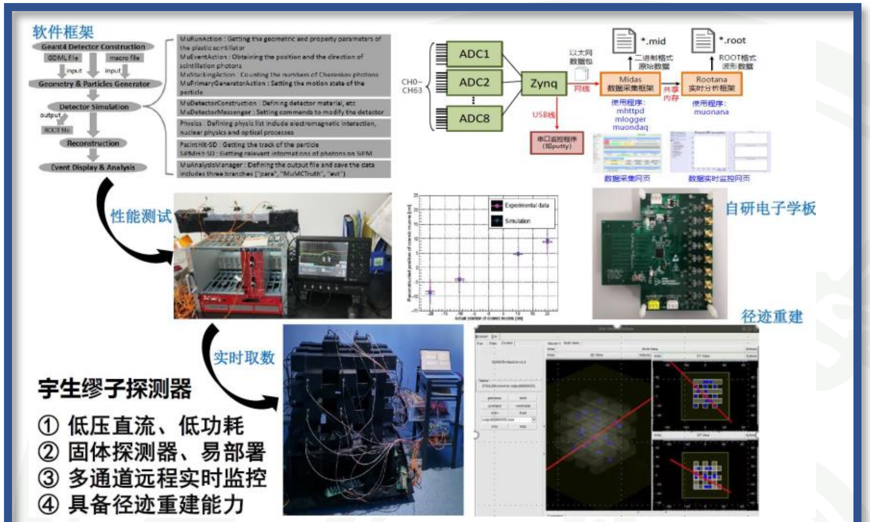
- 中山大学缪子科学与技术实验室**SMOOTH**简介
- **MACE**实验简介及其研究动机
- **MACE**实验概念设计
- **MACE**实验模拟结果
- 总结和展望

Jian Tang(tangjian5@mail.sysu.edu.cn)

以轻子为探针寻找超越标准模型新物理



依托超级计算机“天河二号”
建设粒子物理实验大数据平台



MuRunAction : Getting the geometric and property parameters of the plastic scintillator
MuEventAction : Obtaining the position and the direction of scintillation photons
MuStackingAction : Counting the numbers of Cherenkov photons
MuPrimaryGeneratorAction : Setting the motion state of the particle
MuDetectorConstruction : Defining detector material, etc
MuDetectorMessenger : Setting commands to modify the detector
Physics : Defining physic list include electromagnetic interaction, nuclear physics and optical processes
PscintHit-SD : Getting the track of the particle
SiPMHit-SD : Getting relevant informations of photons on SiPM
MuAnalysisManager : Defining the output file and save the data includes three branches ("para", "MuMCTruth", "evt")

宇生缪子探测器

① 低压直流、低功耗
② 固体探测器、易部署
③ 多通道远程实时监控
④ 具备径迹重建能力

建设缪子前沿科学与技术应用实验室
积累探测器核心技术面向多学科应用

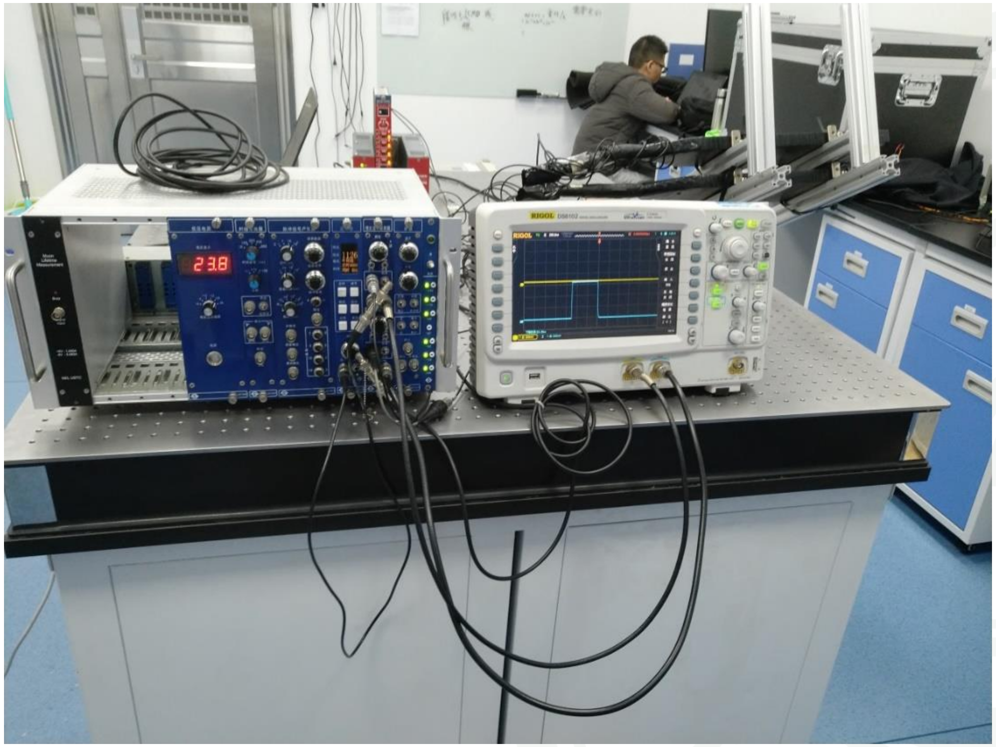
工欲善其事必先利其器，软件平台和硬件研发同步推进

→ 指方向，搭平台，组团队，续经费，育人才，出成果！

科研团队情况

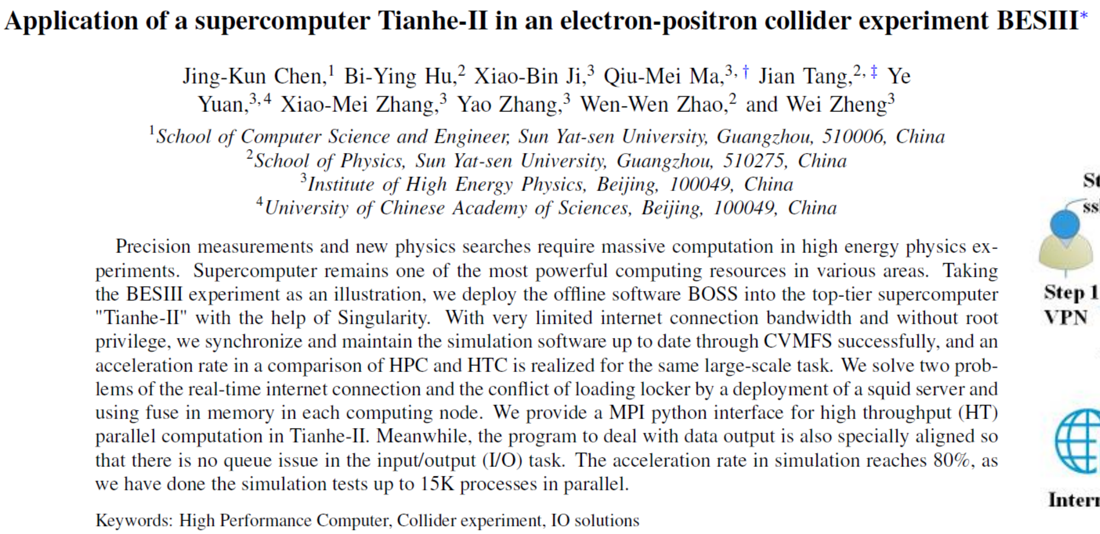
- 当前团队成员：博士后2名，博士生3名，在读硕士生8名，本科生科研项目学生10+名，科研助理2名，电子学工程师1名，超算平台维护1名……
- 校内合作伙伴：物理实验中心，测试中心，超算中心，材料科学与工程学院等
- 校外合作伙伴：中科大电子学实验室，中科院近代物理研究所，中国散裂中子源等
- 国际合作伙伴：德国Mainz大学，日本Osaka大学和KEK，意大利INFN-Padova等

科研平台情况



- 从无到有建设缪子前沿科学与技术应用实验室
- SMOOTH实验室：30平米x2，教学型→科研型探测器
- 物理学院公共科研平台：300平米，核电子学实验室、对撞机物理实验室等
- “天河二号”超算中心—粒子物理实验大数据平台
- 参与国际合作实验：JUNO、COMET、缪子对撞机等

超算中心“天河二号”部署粒子物理实验大数据平台



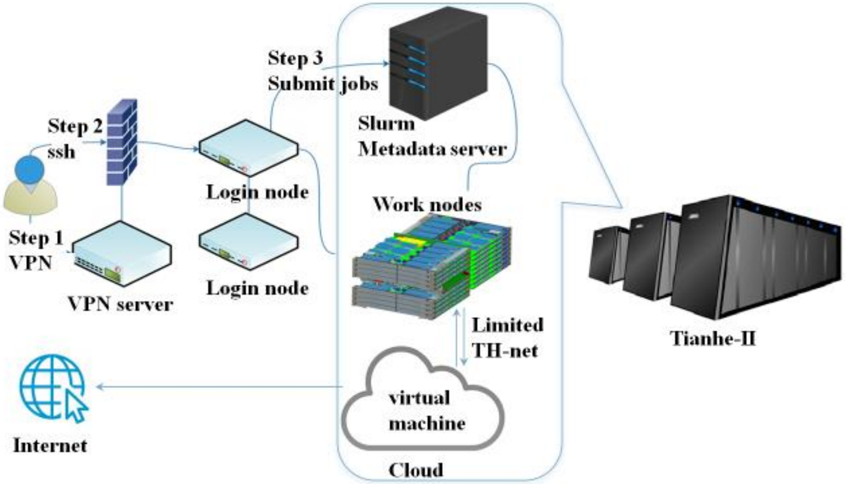
Application of a supercomputer Tianhe-II in an electron-positron collider experiment BESIII*

Jing-Kun Chen,[1] Bi-Ying Hu,[2] Xiao-Bin Ji,[3] Qiu-Mei Ma,[3,†] Jian Tang,[2,‡] Ye Yuan,[3,4] Xiao-Mei Zhang,[3] Yao Zhang,[3] Wen-Wen Zhao,[2] and Wei Zheng[3]

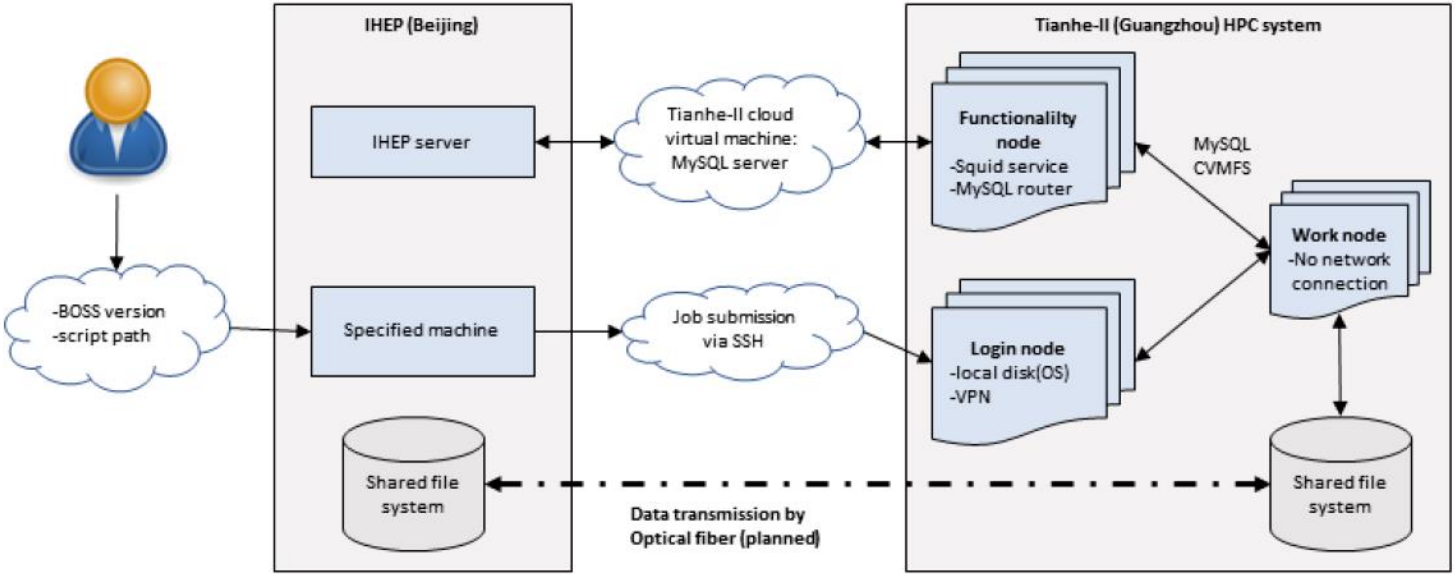
[1]*School of Computer Science and Engineer, Sun Yat-sen University, Guangzhou, 510006, China*
[2]*School of Physics, Sun Yat-sen University, Guangzhou, 510275, China*
[3]*Institute of High Energy Physics, Beijing, 100049, China*
[4]*University of Chinese Academy of Sciences, Beijing, 100049, China*

Precision measurements and new physics searches require massive computation in high energy physics experiments. Supercomputer remains one of the most powerful computing resources in various areas. Taking the BESIII experiment as an illustration, we deploy the offline software BOSS into the top-tier supercomputer "Tianhe-II" with the help of Singularity. With very limited internet connection bandwidth and without root privilege, we synchronize and maintain the simulation software up to date through CVMFS successfully, and an acceleration rate in a comparison of HPC and HTC is realized for the same large-scale task. We solve two problems of the real-time internet connection and the conflict of loading locker by a deployment of a squid server and using fuse in memory in each computing node. We provide a MPI python interface for high throughput (HT) parallel computation in Tianhe-II. Meanwhile, the program to deal with data output is also specially aligned so that there is no queue issue in the input/output (I/O) task. The acceleration rate in simulation reaches 80%, as we have done the simulation tests up to 15K processes in parallel.

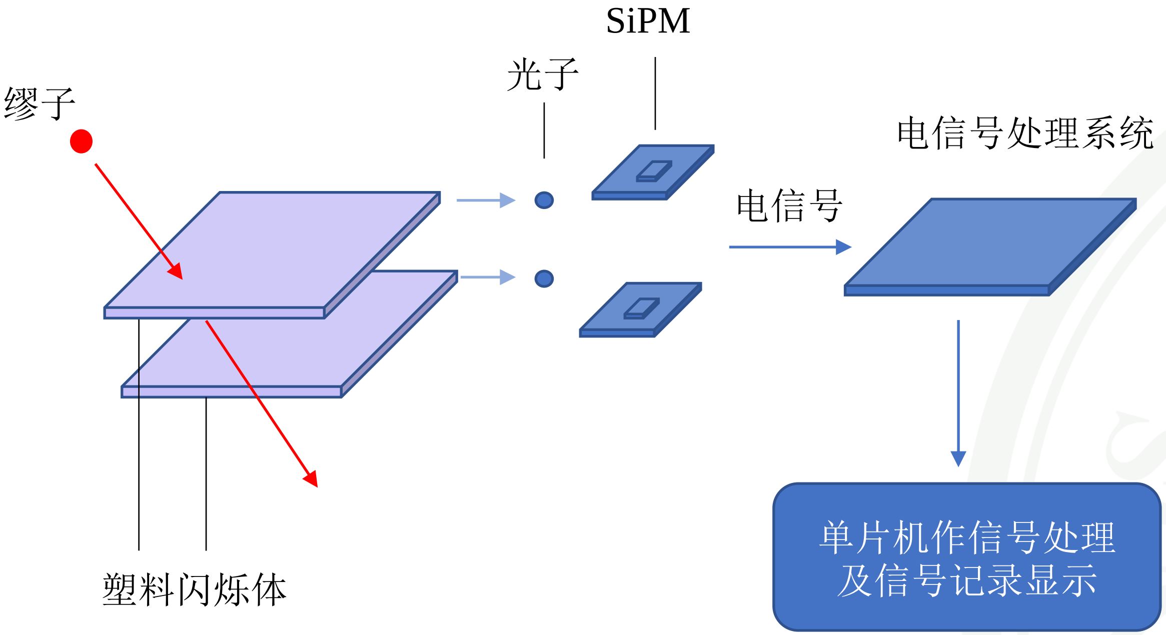
Keywords: High Performance Computer, Collider experiment, IO solutions



JINST 18 (2023) 03, T03003



SMOOTH-CRμ教学型探测器


缪子

光子

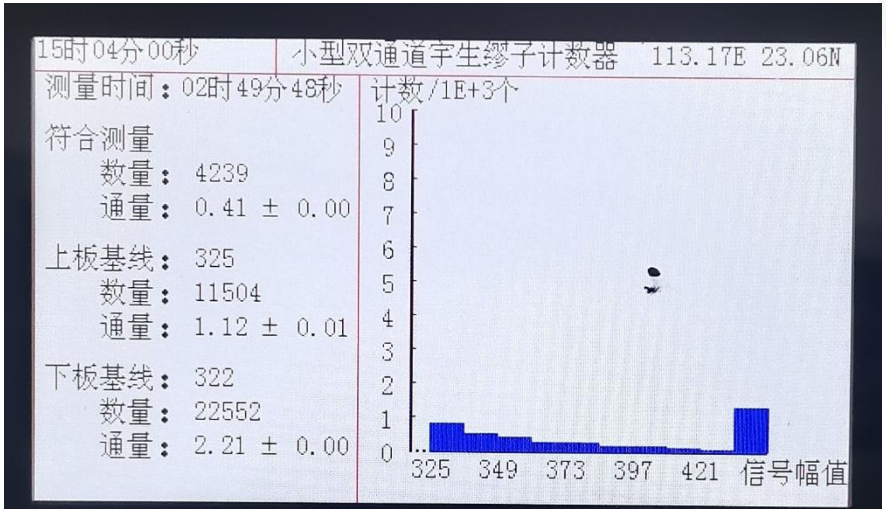
SiPM

电信号处理系统

电信号

塑料闪烁体

单片机作信号处理及信号记录显示


15时04分00秒　小型双通道宇生缪子计数器　113.17E 23.06N

测量时间：02时49分48秒　计数/1E+3个

符合测量
数量：4239
通量：0.41 ± 0.00

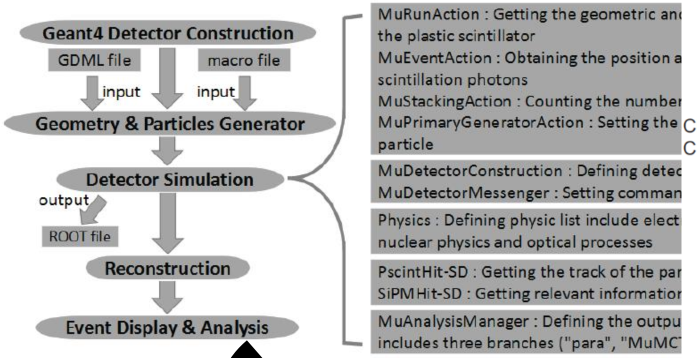
上板基线：325
数量：11504
通量：1.12 ± 0.01

下板基线：322
数量：22552
通量：2.21 ± 0.00

- 特点：便携式，北斗定位和授时，无线传输云平台，微信小程序，阵列集群…
- 已用于中山大学《专业物理实验》教学
- 开展科学普及、产学研推广等

SMOOTH-MuGrid宇生缪子径迹探测

MC模拟



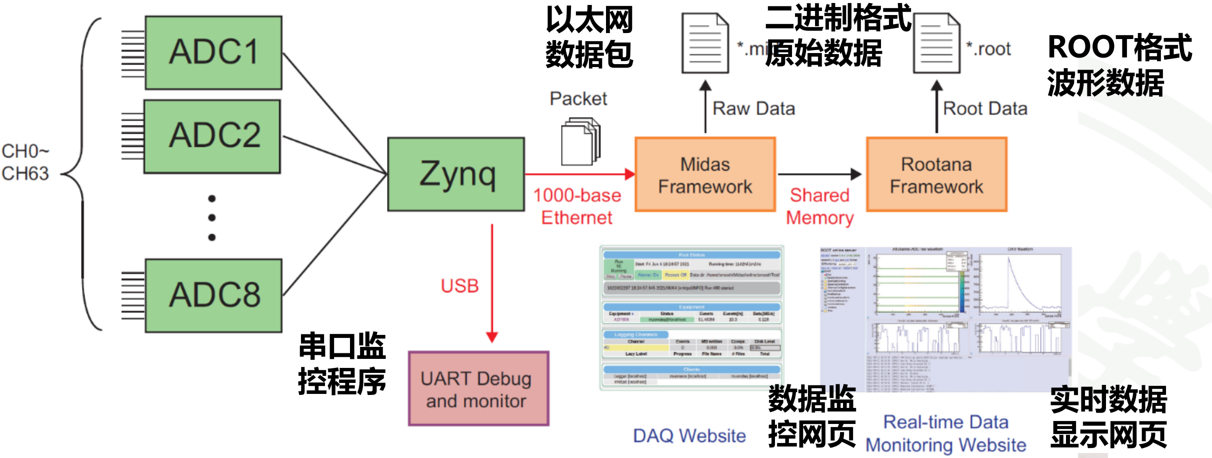
MuRunAction : Getting the geometric anc
the plastic scintillator
MuEventAction : Obtaining the position a
scintillation photons
MuStackingAction : Counting the number
MuPrimaryGeneratorAction : Setting the
particle

MuDetectorConstruction : Defining detec
MuDetectorMessenger : Setting comman

Physics : Defining physic list include elect
nuclear physics and optical processes

PscintHit-SD : Getting the track of the par
SiPMHit-SD : Getting relevant informatior

MuAnalysisManager : Defining the outpu
includes three branches ("para", "MuMC



以太网数据包

二进制格式原始数据

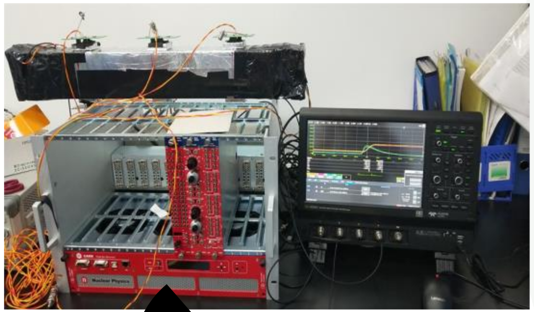
ROOT格式波形数据

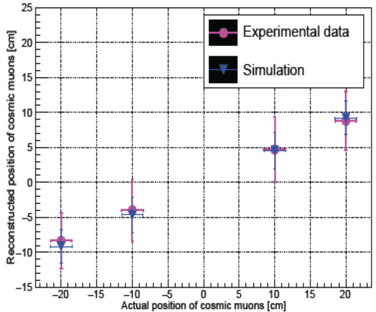
串口监控程序

数据监控网页

实时数据显示网页

性能测试





自研电子学板

径迹重建

多通道宇生缪子探测器

① 低压直流、低功耗

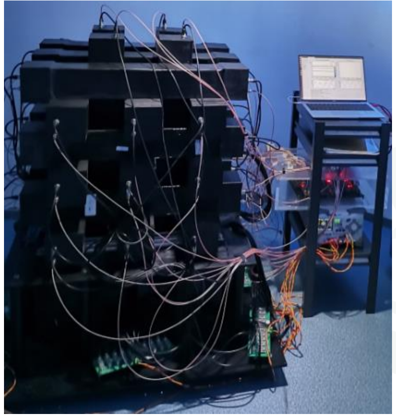
② 固体探测器、易部署

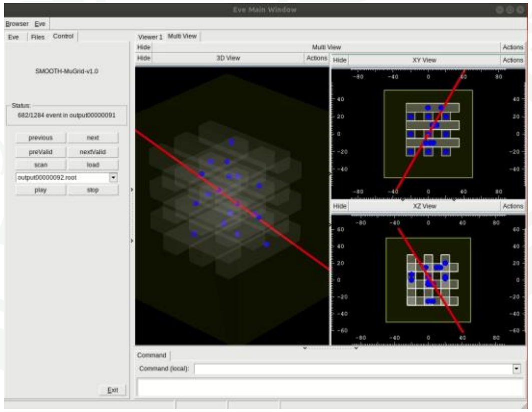
③ 多通道远程实时监控

④ 具备径迹重建能力

Nucl. Instrum. Meth. A 1042 (2022) 167402

实时取数



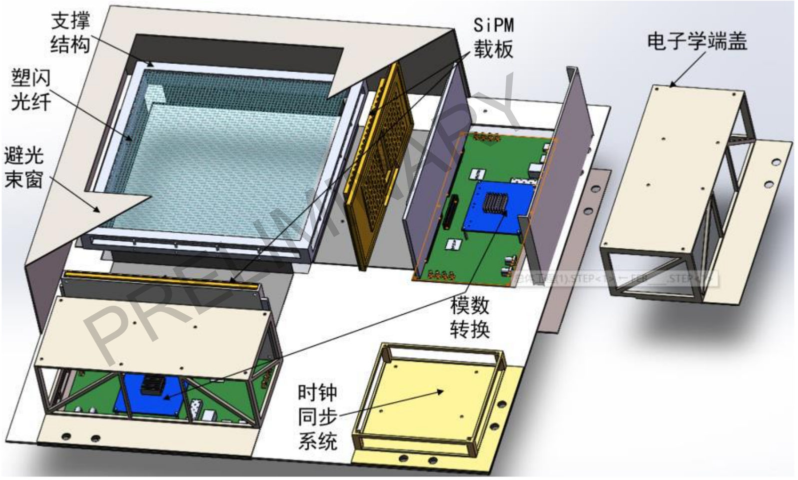


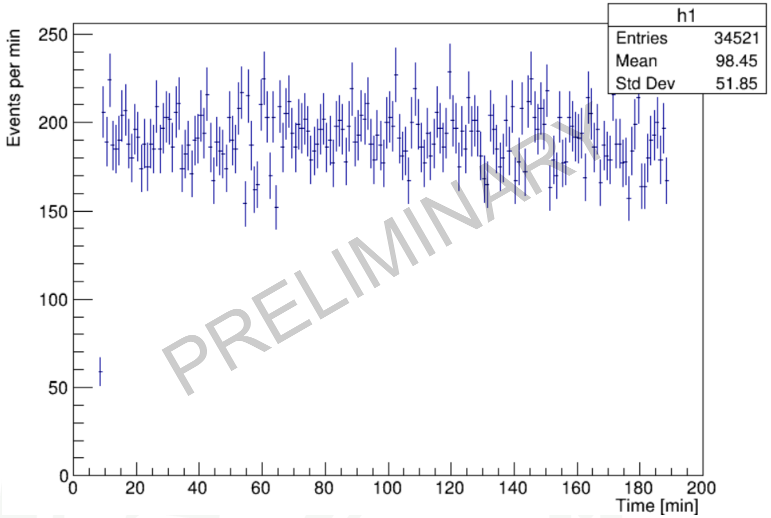
SMOOTH-MuGrid-v1.0

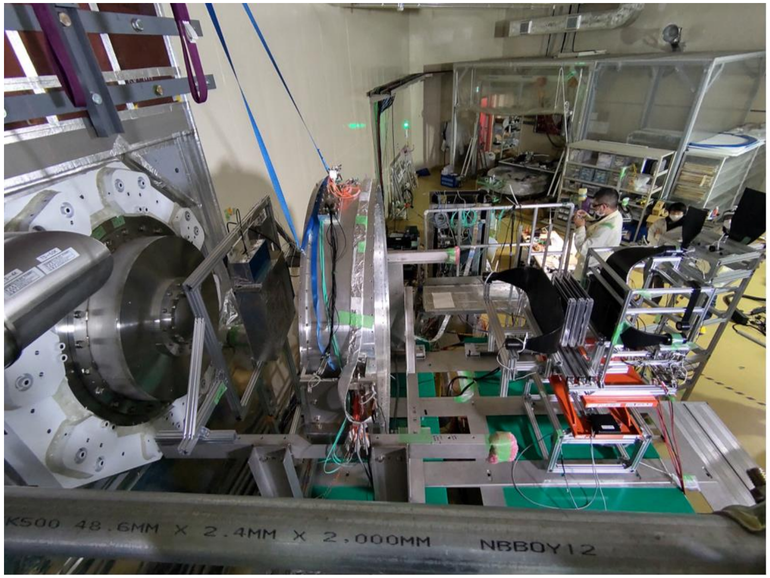
Status:
682/1284 event in output00000091

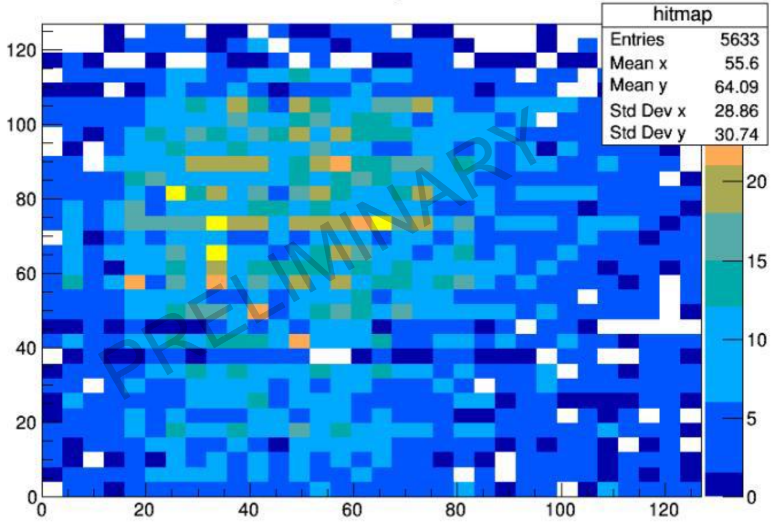
output00000092.root

COMET实验缪子束流监测器研制成功

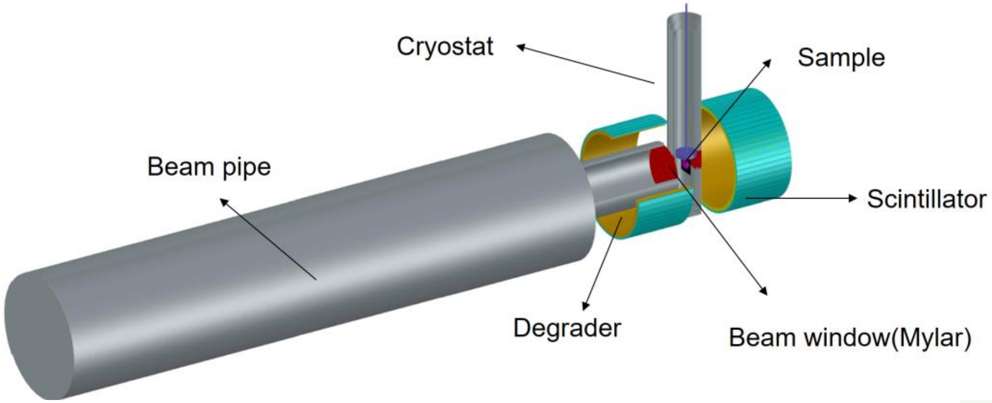




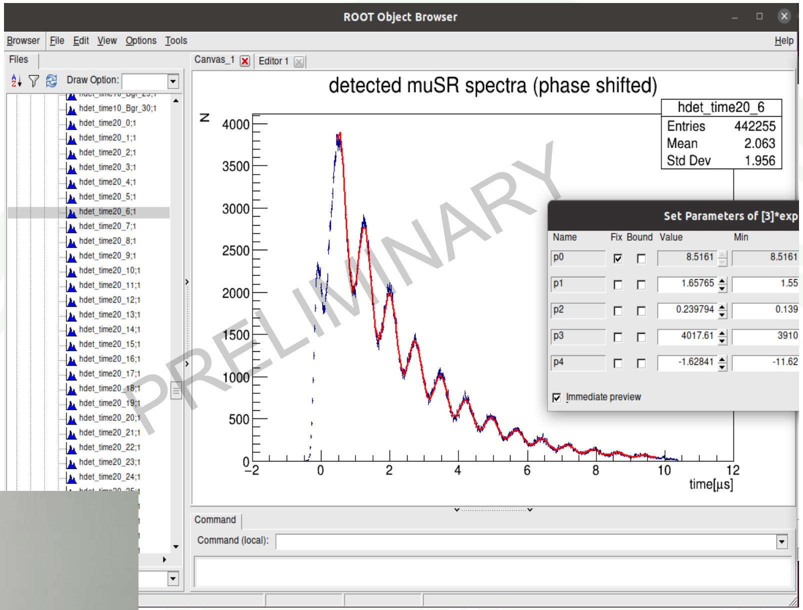




SMOOTH-μSR谱仪设计、模拟和样机研制



μSR谱仪的CAD设计



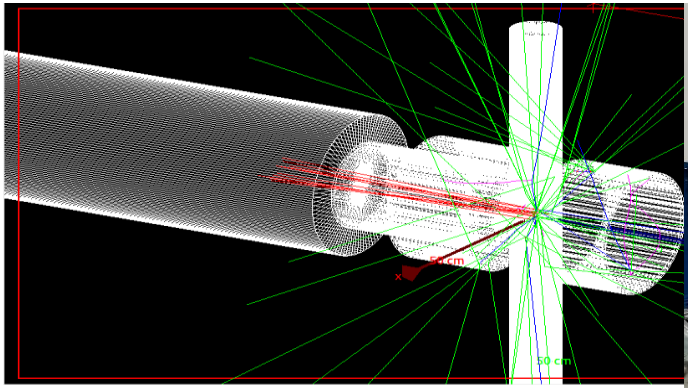
hdet_time20_6	
Entries	442255
Mean	2.063
Std Dev	1.956

Set Parameters of [3]*exp

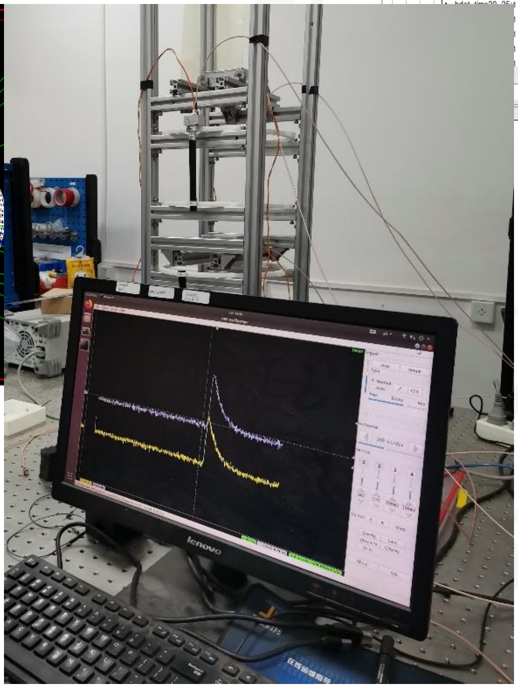
Name	Fix	Bound	Value	Min
p0	☑	☐	8.5161	8.5161
p1	☐	☐	1.65765	1.55
p2	☐	☐	0.239794	0.139
p3	☐	☐	4017.61	3910
p4	☐	☐	-1.62841	-11.62

☑ Immediate preview

μSR模拟数据分析和拟合



μSR谱仪MC模拟和仿真



μSR谱仪protype的测试

Credit: 周逸行

Jian Tang(tangjian5@mail.sysu.edu.cn)

SMOOTH-μSR谱仪设计、模拟和样机研制

系统设计指标：

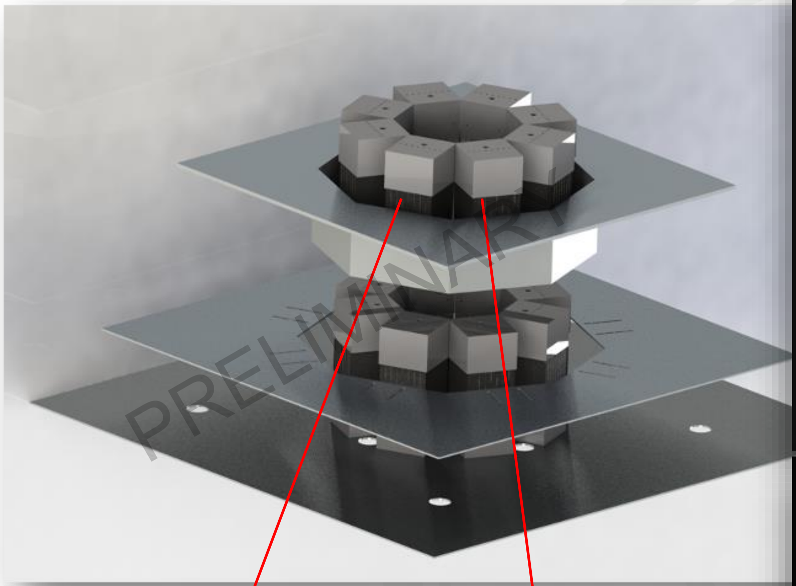
- 512 个探测器模块，包括塑料闪烁体、光导纤维以及SiPM在内的探测通道；
- 时间分辨率< 1 ns

探测器模块：

- 光导纤维阵列探测器（LGA）
- 环形正电子探测器
- 反符合探测器

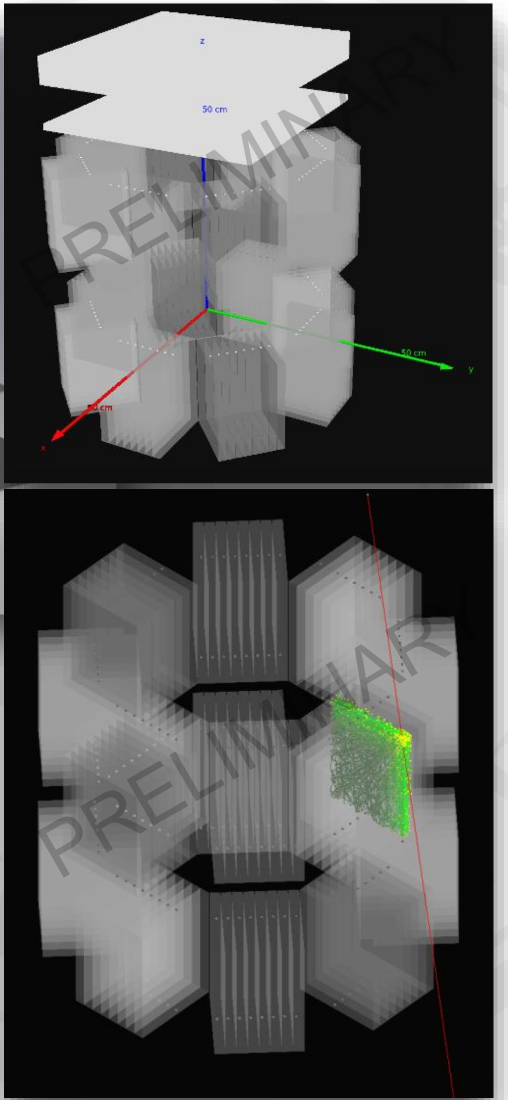
Credit: 孙铭辰、余涛

环形正电子探测器



环形正电子探测器模块
封装后的实物图

MC模拟示意图



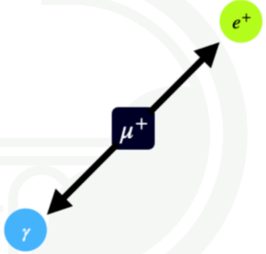
Content

- 中山大学缪子科学与技术实验室SMOOTH简介
- **MACE实验简介及其研究动机**
- MACE实验概念设计
- MACE实验模拟结果
- 总结和展望

Jian Tang(tangjian5@mail.sysu.edu.cn)

带电轻子味道破坏cLFV：缪子源寻找BSM新物理

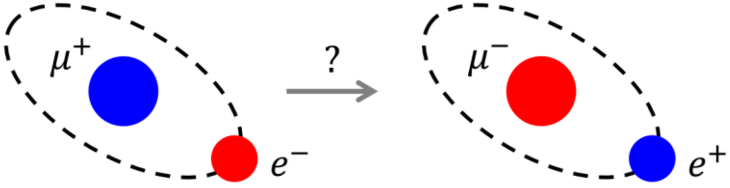
- Searching for charged lepton flavor violation (cLFV):
  - Mu2e
  - COMET } μ-e conversion
  - Mu3e → $\mu \to eee$
  - MEGII → $\mu \to e\gamma$



- Why cLFV:
  - cLFV, as a neutrino-less lepton flavor violating process, is forbidden in SM.
  - Precise (high-intensity) experiment searching for cLFV, is an sensitive probe of BSM.
  - New scalar or vector particles can be constrained.

正反缪子素转化过程: a cLFV Process

- Muonium (μ^+e^-): a leptonic isotope of hydrogen;
- Muonium conversion is induced by an interesting phenomenological possibility: muonium mixing.

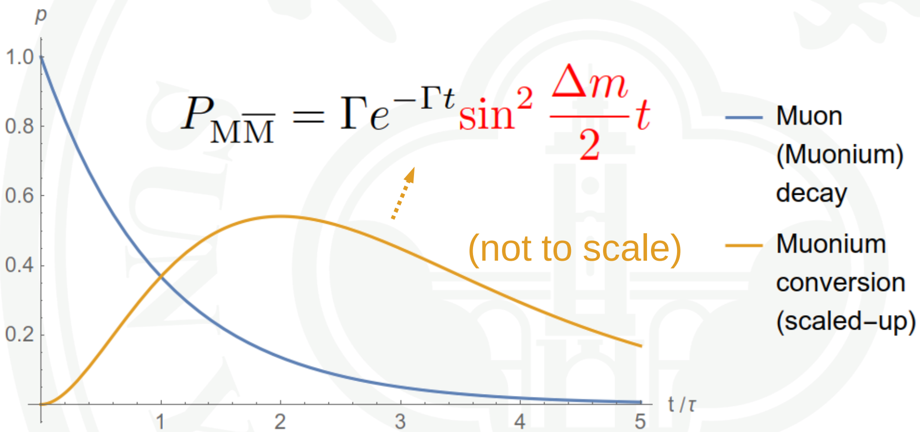


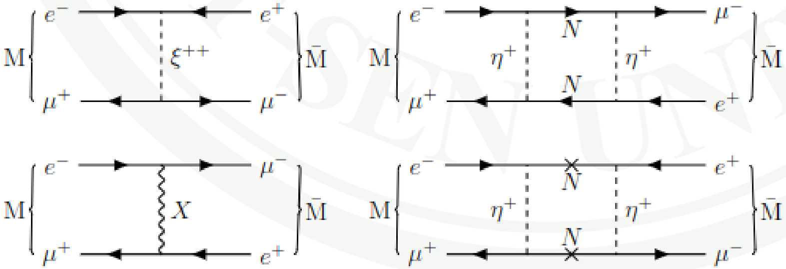
Muonium Antimuonium

$$i\frac{\partial}{\partial t}|\psi\rangle = \mathcal{M}|\psi\rangle \qquad |\psi\rangle = \alpha(t)|\mathrm{M}\rangle + \beta(t)|\overline{\mathrm{M}}\rangle$$

$$\mathcal{M} = \begin{pmatrix} m - i\Gamma/2 & \Delta m/2 - i\Delta\Gamma/4 \\ \Delta m/2 - i\Delta\Gamma/4 & m - i\Gamma/2 \end{pmatrix}$$

$$\mathcal{L} \supset \sum_{i=1}^{5} \frac{-G_i(\mathcal{M})}{\sqrt{2}} \langle\overline{\mathrm{M}}|Q_i|\mathrm{M}\rangle$$

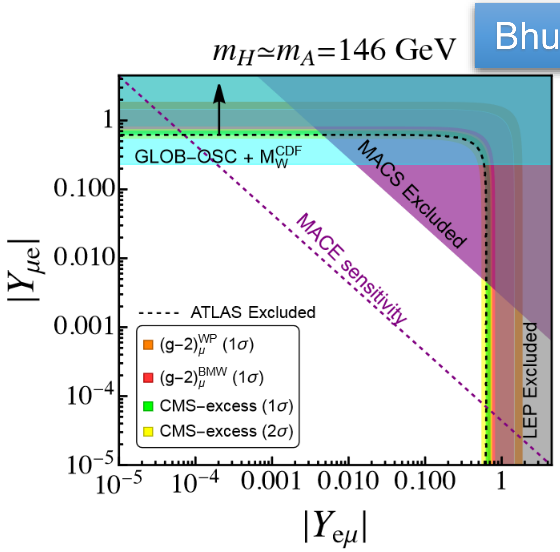




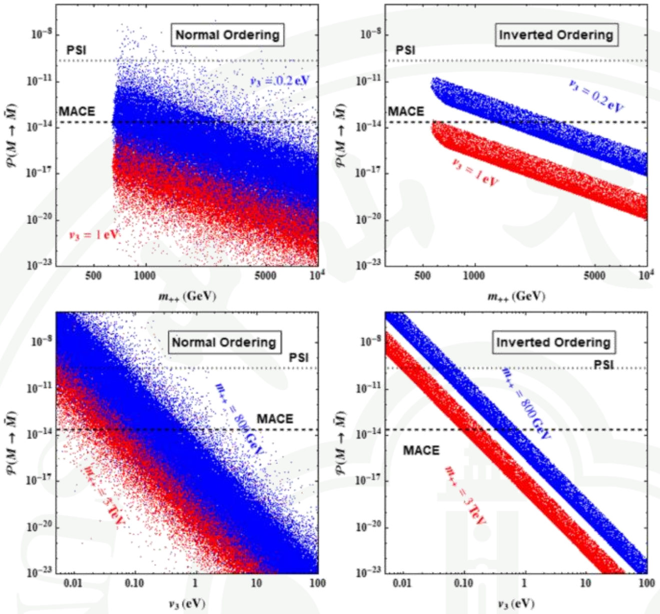
研究动机

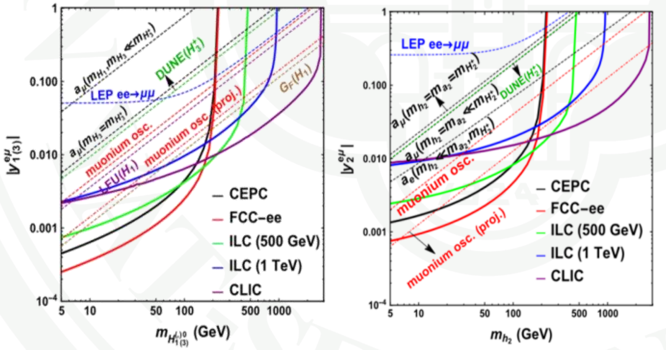
- Muonium conversion: a ΔL=2 cLFV process.
- Neutrino mass model: doubly charged TeV Higgs boson can be constrained.
- Complementary to:
  - ΔL=1 cLFV experiments (*μ*-*e* conversion, *μ* → *eee*, *μ* → *eγ*).
  - Collider experiments.

Bhupal's talk@CLFV2023



Afik, BD, Thapa, Hints of a new leptophilic Higgs sector? arXiv 2305.19314



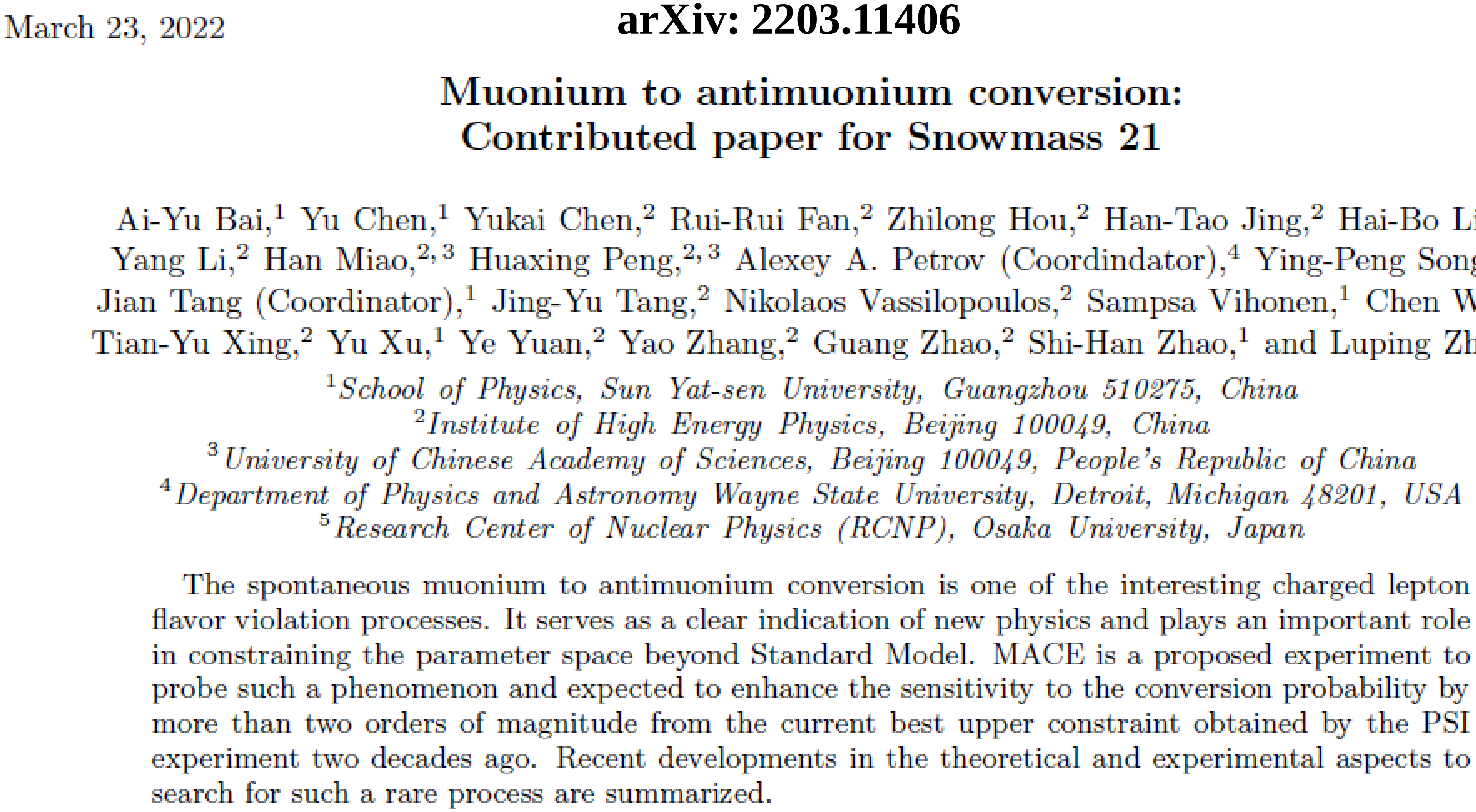


Chengcheng Han, Da Huang, Jian Tang, Yu Zhang. Probing the doubly charged Higgs boson with a muonium to antimuonium conversion experiment. Phys.Rev.D 103 (2021) 5, 055023

Tong Li, Michael A. Schmidt. Sensitivity of future lepton colliders and low-energy experiments to charged lepton flavor violation from bileptons. Phys.Rev.D 100 (2019) 11, 115007

高亮度前沿/高精度前沿—Snowmass whitepaper

arXiv: 2203.11406



March 23, 2022

Muonium to antimuonium conversion: Contributed paper for Snowmass 21

Ai-Yu Bai,[1] Yu Chen,[1] Yukai Chen,[2] Rui-Rui Fan,[2] Zhilong Hou,[2] Han-Tao Jing,[2] Hai-Bo Li,[2]
Yang Li,[2] Han Miao,[2, 3] Huaxing Peng,[2, 3] Alexey A. Petrov (Coordindator),[4] Ying-Peng Song,[2]
Jian Tang (Coordinator),[1] Jing-Yu Tang,[2] Nikolaos Vassilopoulos,[2] Sampsa Vihonen,[1] Chen Wu,[5]
Tian-Yu Xing,[2] Yu Xu,[1] Ye Yuan,[2] Yao Zhang,[2] Guang Zhao,[2] Shi-Han Zhao,[1] and Luping Zhou[2]

[1]*School of Physics, Sun Yat-sen University, Guangzhou 510275, China*
[2]*Institute of High Energy Physics, Beijing 100049, China*
[3]*University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
[4]*Department of Physics and Astronomy Wayne State University, Detroit, Michigan 48201, USA*
[5]*Research Center of Nuclear Physics (RCNP), Osaka University, Japan*

The spontaneous muonium to antimuonium conversion is one of the interesting charged lepton flavor violation processes. It serves as a clear indication of new physics and plays an important role in constraining the parameter space beyond Standard Model. MACE is a proposed experiment to probe such a phenomenon and expected to enhance the sensitivity to the conversion probability by more than two orders of magnitude from the current best upper constraint obtained by the PSI experiment two decades ago. Recent developments in the theoretical and experimental aspects to search for such a rare process are summarized.

- 欢迎更多同行共同推进MACE实验

Snowmass LOI后的国际反响

A New Charged Lepton Flavor Violation Program at Fermilab

Bertrand Echenard – Caltech

with Robert Bernstein (FNAL) and Jaroslav Pasternak (ICL/RAL SCTF)

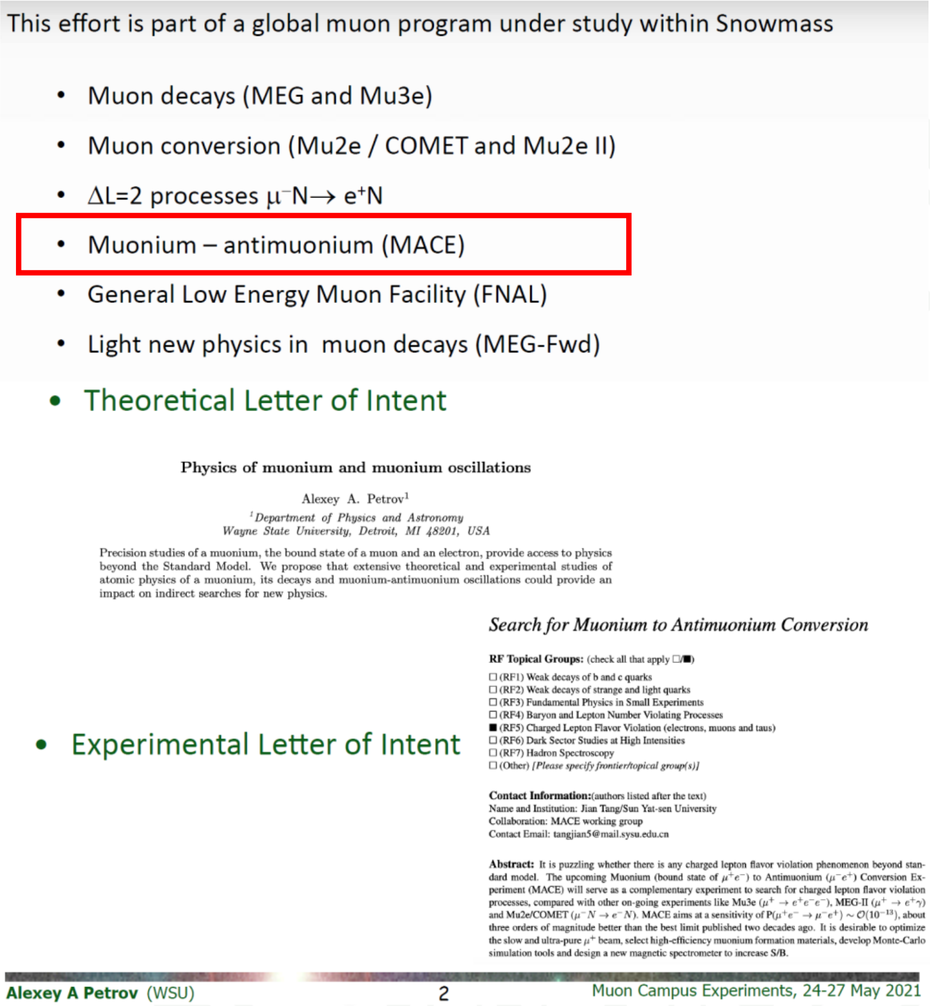
Potential Fermilab Muon Campus & Storage Ring Experiments Workshop
May 2021

Snowmass process and contributed papers

Frontier for Rare Processes and Precision Measurements

Alexey A. Petrov

Wayne State University



This effort is part of a global muon program under study within Snowmass

- Muon decays (MEG and Mu3e)
- Muon conversion (Mu2e / COMET and Mu2e II)
- $\Delta L=2$ processes $\mu^- N \to e^+ N$
- Muonium – antimuonium (MACE)
- General Low Energy Muon Facility (FNAL)
- Light new physics in muon decays (MEG-Fwd)

- Theoretical Letter of Intent

Physics of muonium and muonium oscillations

Alexey A. Petrov[1]

[1] *Department of Physics and Astronomy*
Wayne State University, Detroit, MI 48201, USA

Precision studies of a muonium, the bound state of a muon and an electron, provide access to physics beyond the Standard Model. We propose that extensive theoretical and experimental studies of atomic physics of a muonium, its decays and muonium-antimuonium oscillations could provide an impact on indirect searches for new physics.

- Experimental Letter of Intent

Search for Muonium to Antimuonium Conversion

RF Topical Groups: (check all that apply ☐/■)

☐ (RF1) Weak decays of b and c quarks
☐ (RF2) Weak decays of strange and light quarks
☐ (RF3) Fundamental Physics in Small Experiments
☐ (RF4) Baryon and Lepton Number Violating Processes
■ (RF5) Charged Lepton Flavor Violation (electrons, muons and taus)
☐ (RF6) Dark Sector Studies at High Intensities
☐ (RF7) Hadron Spectroscopy
☐ (Other) *[Please specify frontier/topical group(s)]*

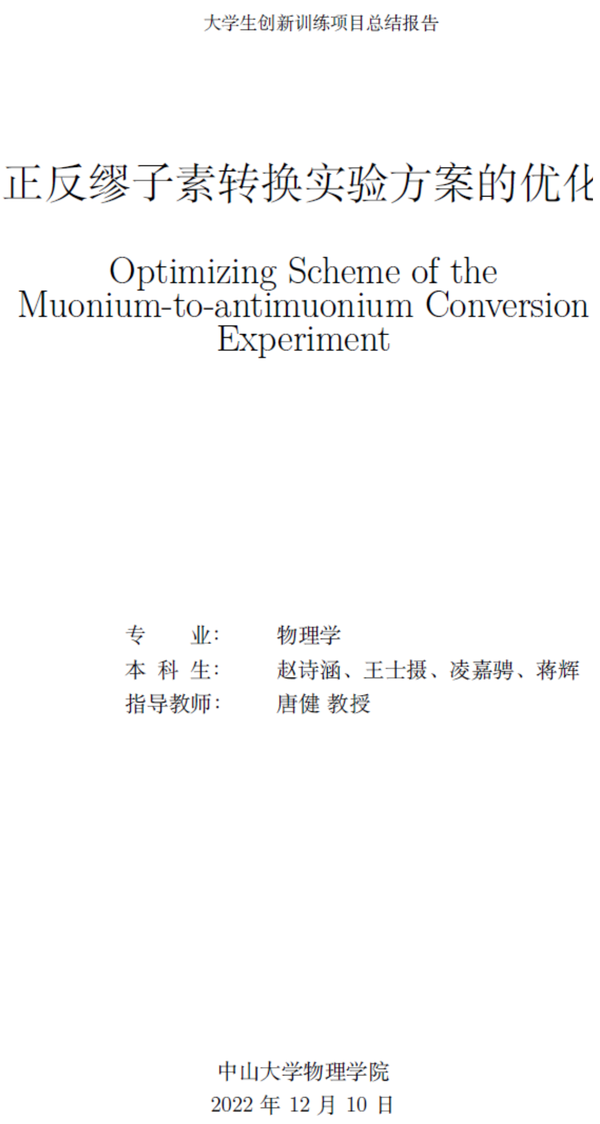
Contact Information:(authors listed after the text)
Name and Institution: Jian Tang/Sun Yat-sen University
Collaboration: MACE working group
Contact Email: tangjian5@mail.sysu.edu.cn

Abstract: It is puzzling whether there is any charged lepton flavor violation phenomenon beyond standard model. The upcoming Muonium (bound state of μ^+e^-) to Antimuonium (μ^-e^+) Conversion Experiment (MACE) will serve as a complementary experiment to search for charged lepton flavor violation processes, compared with other on-going experiments like Mu3e ($\mu^+ \to e^+e^-e^-$), MEG-II ($\mu^+ \to e^+\gamma$) and Mu2e/COMET ($\mu^- N \to e^- N$). MACE aims at a sensitivity of $P(\mu^+e^- \to \mu^-e^+) \sim \mathcal{O}(10^{-13})$, about three orders of magnitude better than the best limit published two decades ago. It is desirable to optimize the slow and ultra-pure μ^+ beam, select high-efficiency muonium formation materials, develop Monte-Carlo simulation tools and design a new magnetic spectrometer to increase S/B.

Alexey A Petrov (WSU) 2 Muon Campus Experiments, 24-27 May 2021

- Invited talk@Workshop on a Future Muon Program at Fermilab, Caltech
- Invited talk@CLFV2023 workshop, Heidelberg, Germany

国家级大学生创新项目



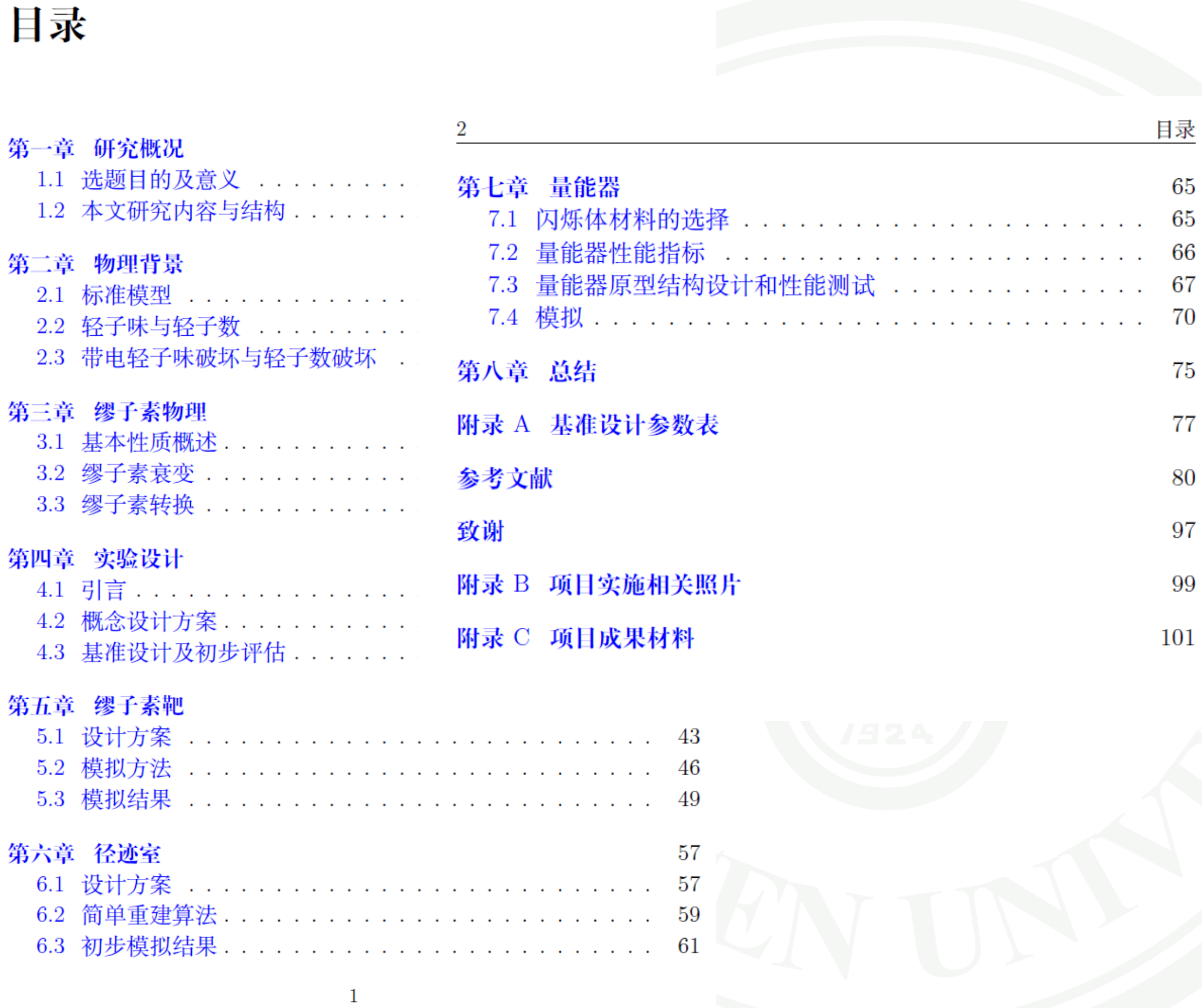
大学生创新训练项目总结报告

正反缪子素转换实验方案的优化

Optimizing Scheme of the Muonium-to-antimuonium Conversion Experiment

专　　业:　物理学
本 科 生:　赵诗涵、王士摄、凌嘉骋、蒋辉
指导教师:　唐健 教授

中山大学物理学院
2022 年 12 月 10 日



目录

1

2　目录

中山大学优秀本科毕业论文

本科生毕业论文（设计）

题目：MACE 实验模拟软件开发和粒子重建研究

姓　　名	赵 诗 涵
学　　号	19341157
院　　系	物理学院
专　　业	物理学
指导教师	唐健 (教授)

2023 年 5 月 10 日

目录

粤港澳大湾区是强流加速器的聚集地

Ref：中科院高能所，王生研究员报告

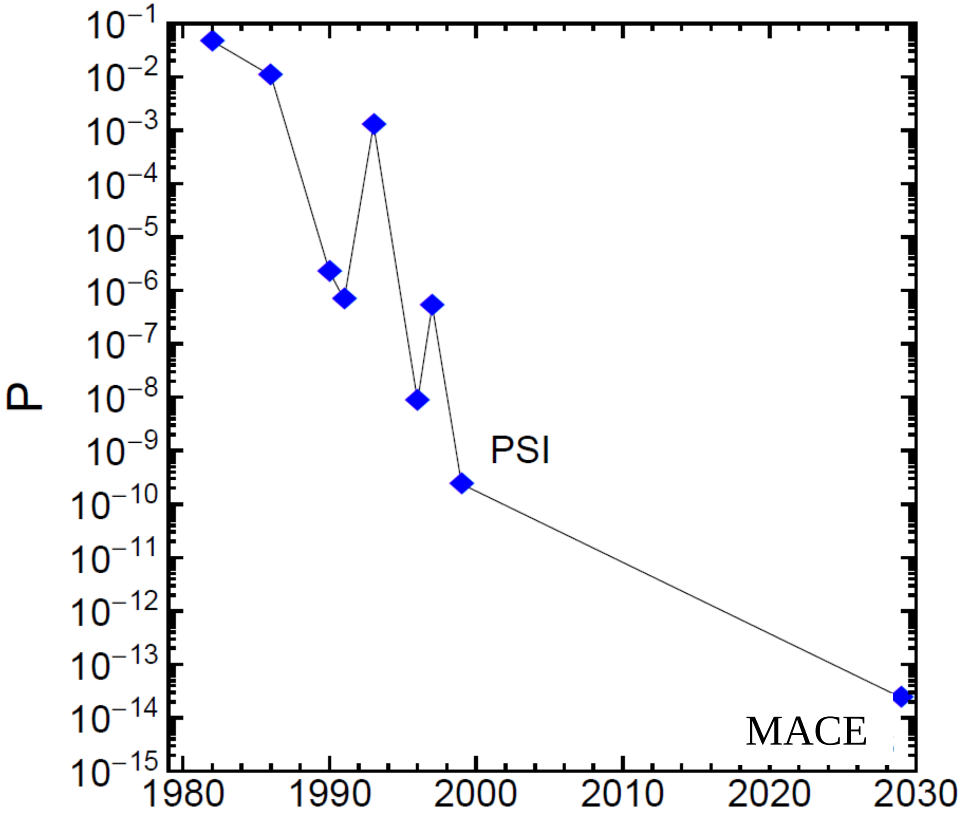
Ref：中科院近物所，东江实验室詹文龙院士

(1）国际上已有美国FNAL，瑞士PSI，日本J-PARC）

(2）即将建设国内首个强流加速器缪子源？

(3）依托粤港澳大湾区的强流加速器（CiADS, HIAF, CSNS），基于加速器缪子源开展前沿研究?

MACE：基础前沿研究从“0”到“1”的突破口



- 最新的实验结果是1999年PSI完成，缪子通量$8 \times 10^6 \mu^+/s$。
- 我国加速器缪子源提供$10^8 \mu^+/s$，表面缪子E=29.8 MeV，动量展宽<10%?
- 20+年，探测器技术长足进步；
- 我国加速器技术和粒子探测突飞猛进；
- 目前国际上没有正在进行的相关实验；
- 新一代实验探测灵敏度相比1999年PSI实验结果，预期提高**两个数量级以上**!
- MACE实验有望走到世界前列！

MACE实验: Muonium to Antimuonium Conversion Experiment.

Jian Tang(tangjian5@mail.sysu.edu.cn)

Content

- 中山大学缪子科学与技术实验室SMOOTH简介
- MACE实验简介及其研究动机
- **MACE实验概念设计**
- MACE实验模拟结果
- 总结和展望

Jian Tang(tangjian5@mail.sysu.edu.cn)

MACE实验信号和本底的鉴别方法

- How to detect the muonium-antimuonium conversion?

$$\mu^+e^- \to \mu^-e^+$$

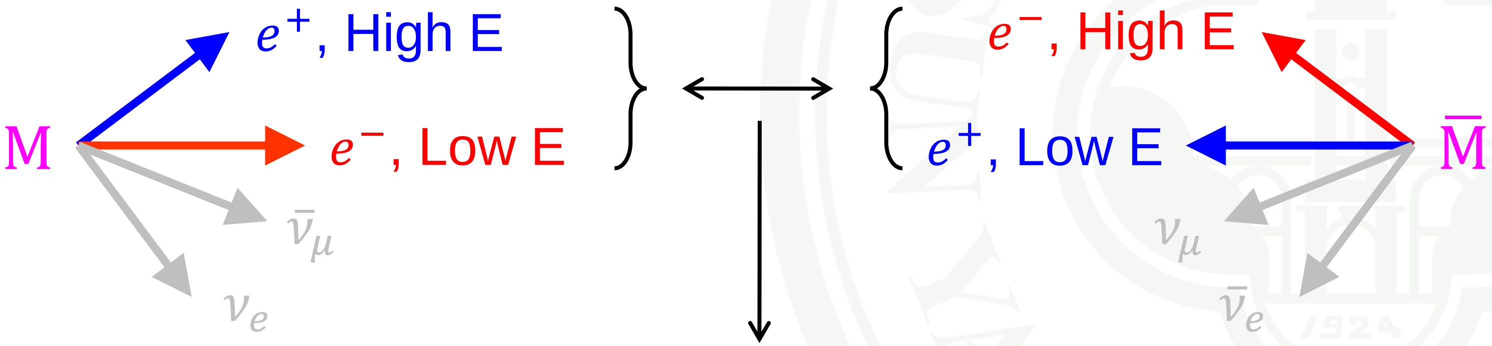
- We can achieve this by identifying the final states:

Muonium decay:

$\mathrm{M} \to e^- e^+ \nu_e \bar{\nu}_\mu$

Antimuonium decay:

$\bar{\mathrm{M}} \to e^+ e^- \nu_\mu \bar{\nu}_e$



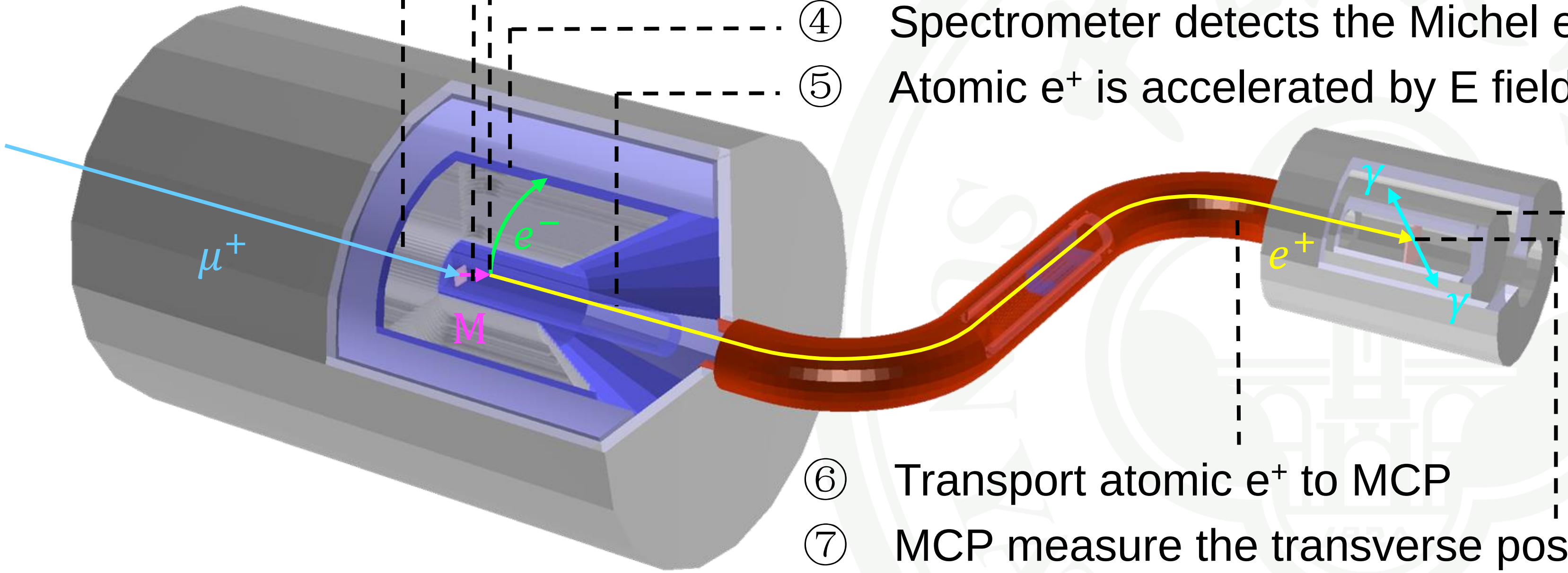
Search for the conversion by vertex coincidence and charge identification.

- Potential backgrounds: μ⁺ decays to e⁺, Bhabha scattering to generate high-energy e⁻ in coincident with low-energy e⁺

μ⁺ decays: $\mu^+ \to e^+ \nu_e \overline{\nu_\mu} e^+ e^-$

Conceptual Design of MACE

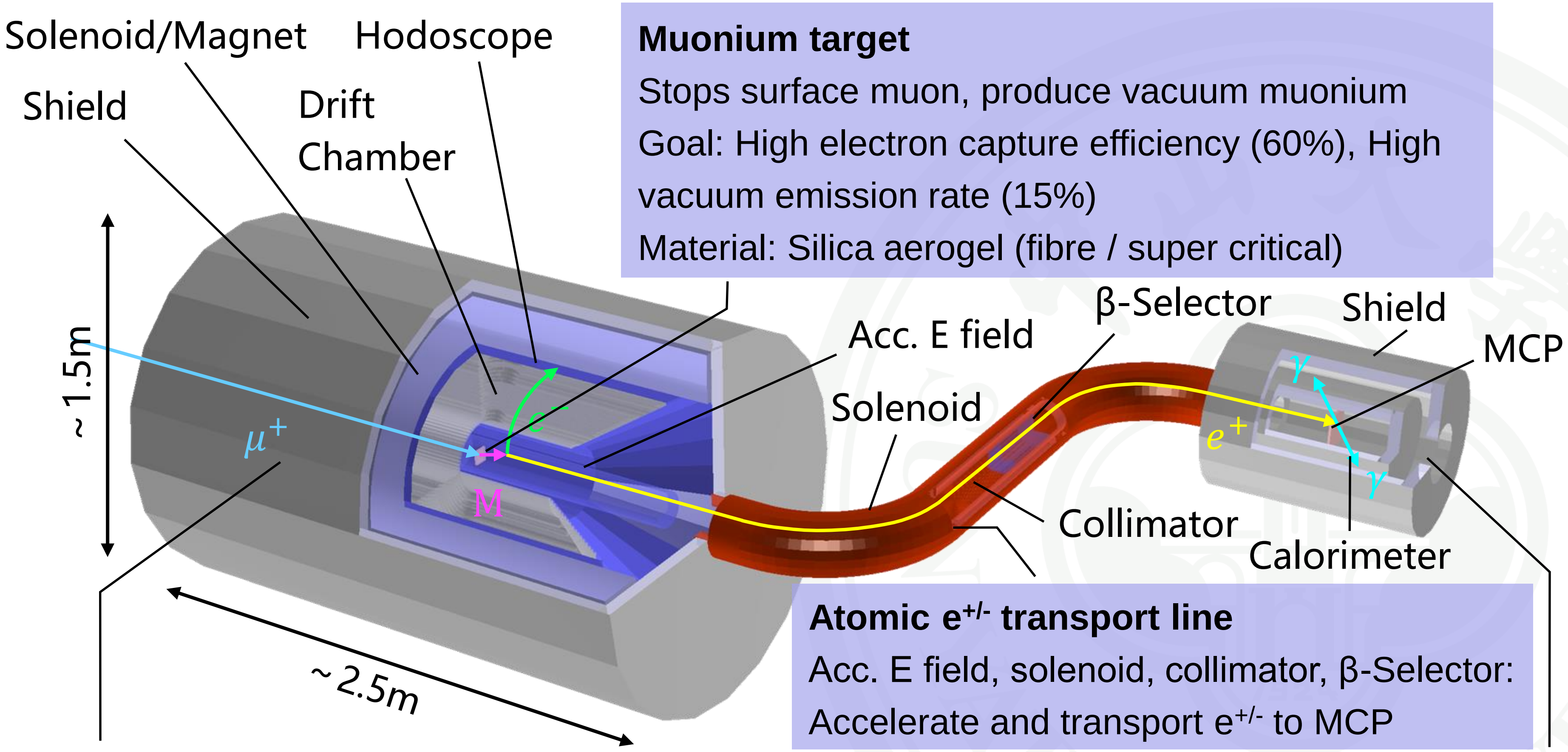
Signal process:
$\mathrm{M} \to \overline{\mathrm{M}} \to e^+ e^- \nu_\mu \bar{\nu}_e$



① Surface muon → muonium
② Muonium emission to vacuum
③ M converts to $\overline{\mathrm{M}}$ and decay
④ Spectrometer detects the Michel e^-
⑤ Atomic e^+ is accelerated by E field
⑥ Transport atomic e^+ to MCP
⑦ MCP measure the transverse position
⑧ Calorimeter detect the e^+ annihilation

- Spectrometer: identifies Michel e^-.
- Vertex coincidence: Michel e^- track and e^+ transverse position projection.
- Calorimeter: identifies atomic e^+.

Basic concept:
Coincidence of spectrometer, MCP, and calorimeter.



Muonium target

Stops surface muon, produce vacuum muonium

Goal: High electron capture efficiency (60%), High vacuum emission rate (15%)

Material: Silica aerogel (fibre / super critical)

Atomic $e^{+/-}$ transport line

Acc. E field, solenoid, collimator, β-Selector: Accelerate and transport $e^{+/-}$ to MCP

Spectrometer

Detects Michel $e^{+/-}$ (37MeV avg., 52.8MeV max)

Goal: Charge misidentify rate $<10^{-5}$, vertex resolution (<3mm), momentum resolution (<500keV/c)

Tracking chamber: drift chamber (cosθ ~ 0.9)

Atomic $e^{+/-}$ detector

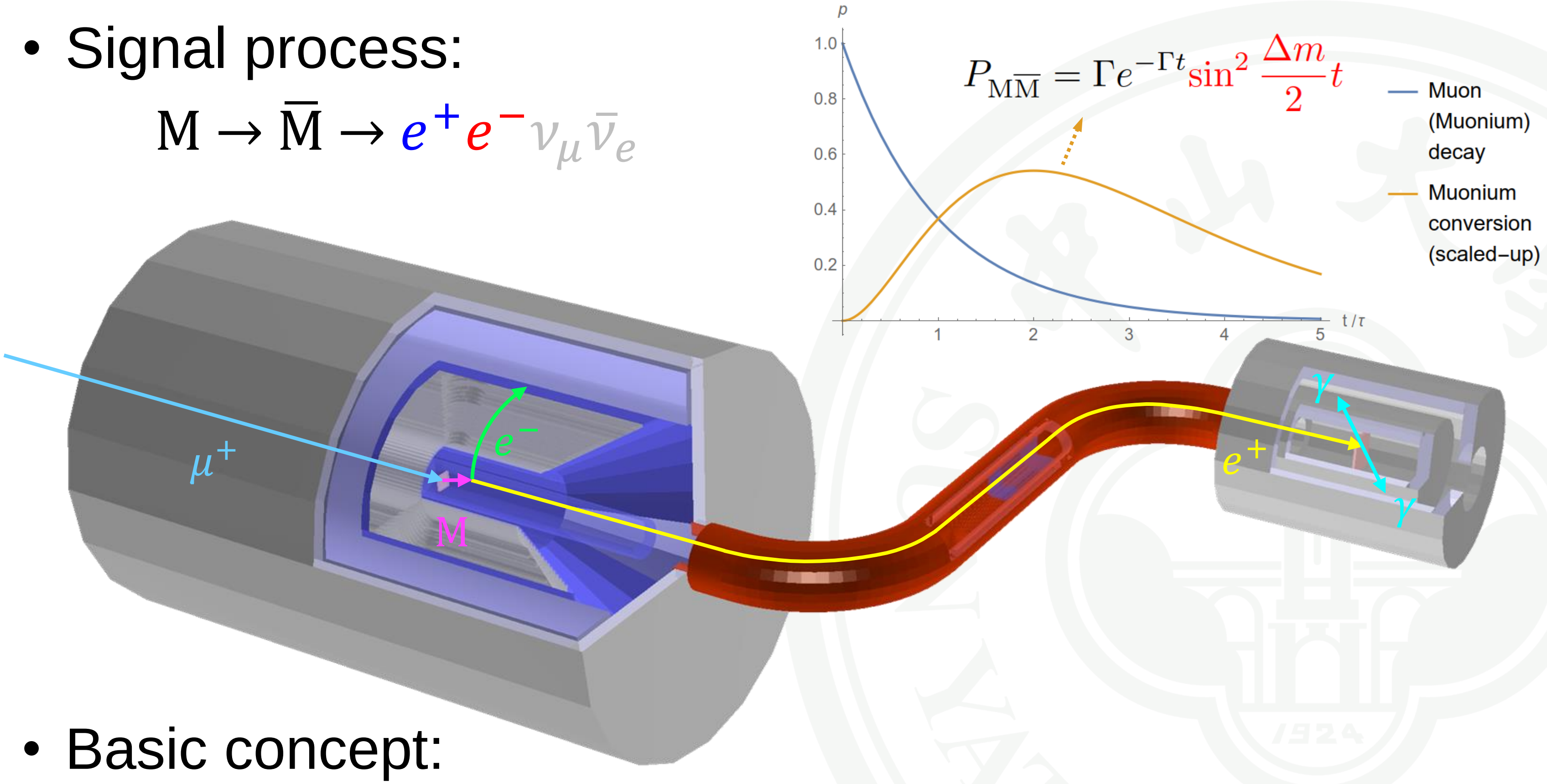
MCP: measures transverse position of $e^{+/-}$.

Calorimeter: Detects γ of 511keV (e^{+} annihilation).

Conceptual Design of MACE

- Signal process:

$$\mathrm{M} \rightarrow \bar{\mathrm{M}} \rightarrow e^{+}e^{-}\nu_{\mu}\bar{\nu}_{e}$$



- Basic concept:
  - Coincidence of a Michel e^- and a e^+ from atomic shell:

1. Spectrometer
2. MCP
3. Calorimeter

$$\bar{\mathrm{M}} \rightarrow \nu\nu e^{-}e^{+}$$

$$\bar{\mathrm{M}} \rightarrow \nu\nu e^{-}e^{+}$$

$$\bar{\mathrm{M}} \rightarrow \nu\nu e^{-}e^{+}, e^{+} \xrightarrow{\text{annihilate on MCP}} \gamma\gamma$$

MACE Upper Bound & Muonium Yield

- As an intensity frontier cLFV experiment, MACE demands as much primary particles as possible:
- A simple estimation: inheriting previous PSI experiment parameters (L. Willmann et al., 1999), we have conversion probability upper bound estimation

$$P_{\mathrm{M}\bar{\mathrm{M}}} < \frac{2.30\ F_C}{\varepsilon_{\mathrm{all}}\ S_B\ Y_{\mathrm{M}}\ L_\mu\ t}$$

Signal effiency

B field surpression

Muonium yield

Muon beam luminosity

Acquisition time

$$\boxed{N_{\mathrm{M}} = Y_{\mathrm{M}} L_\mu t}$$

- Acquisition time is precious, the upper bound is limited by the number of muoniums (N_{M}), we need more muoniums!
- Two approaches:

1. Enhance beam luminosity L_μ:

   → $10^8 \sim 10^{10}$ μ^+/s beam

2. Enhance muonium yield Y_{M}:

   → Optimiztion of silica aerogel target, or new possibilities (e.g. SF-He).

Accelerator Muon Source Proposed in China

Jian Tang(tangjian5@mail.sysu.edu.cn)

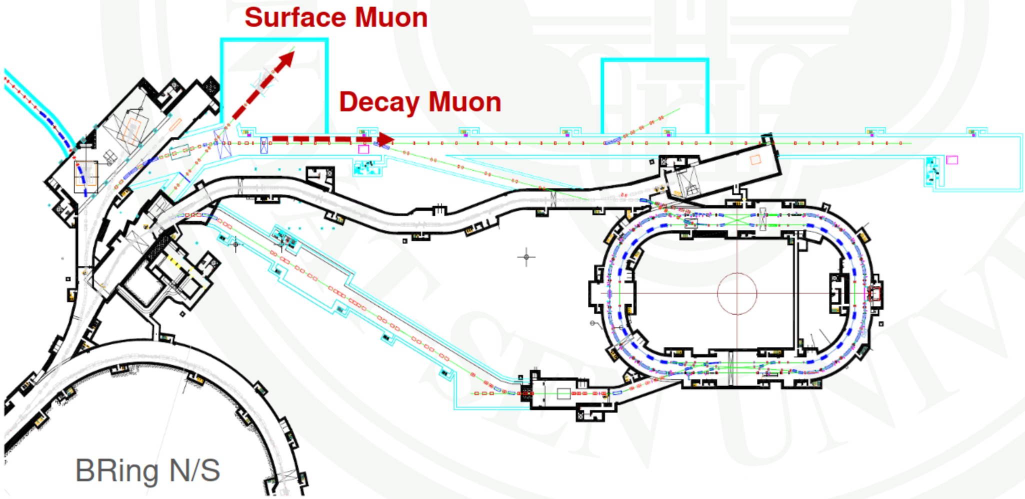
Muon Source Proposed at CiADS

- Proton accelerator.
- Located in Huizhou, Guangdong, PRC.
- Status: constructing (accelerator), conceptual (muon source).
- Intensity: **10^9 ~ 10^{10} μ^+/s**
- Beam mode: CW
- When is it available?

Reference: Jiancheng Yang and He Zhao, MIP2023, 15 Apr. 2023

Muon Source Proposed at HIAF

- Proton / ion accelerator.
- Located in Huizhou, Guangdong, PRC.
- Status: constructing (accelerator), conceptual (muon source).
- Intensity: **10^{10} μ^{+}/s ?**
- Beam mode: Pulse
- When is it available?



Reference: Yuan He, MIP2023, 15 Apr. 2023

Muonium Production and Transport

μ^+ (~1MeV) scattering

↓

Electron capture (~1keV)

↓

Muonium (~100eV)
Epithermal scattering

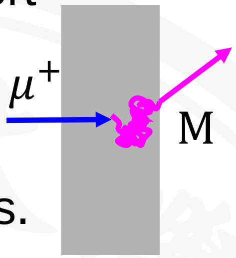
↓

Random walk (room temp.)

↓

Emission to vacuum

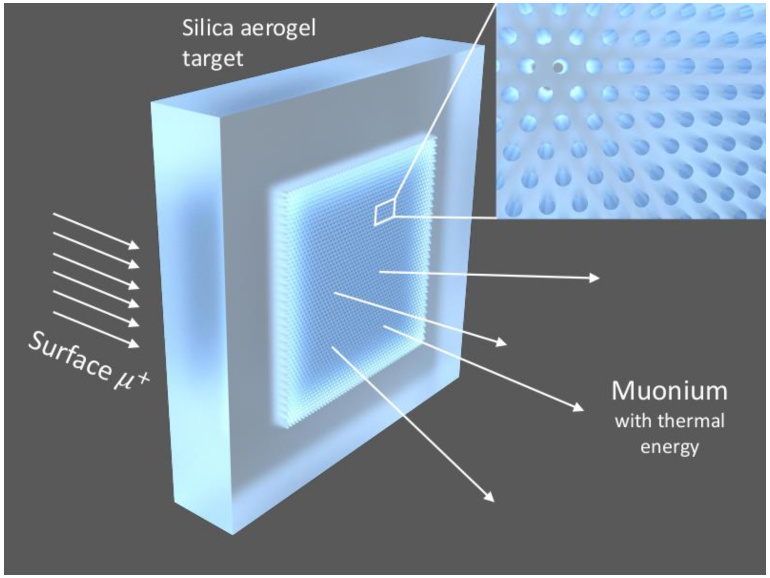
MC simulation for muonium transport has been developed under the MACE offline software framework.



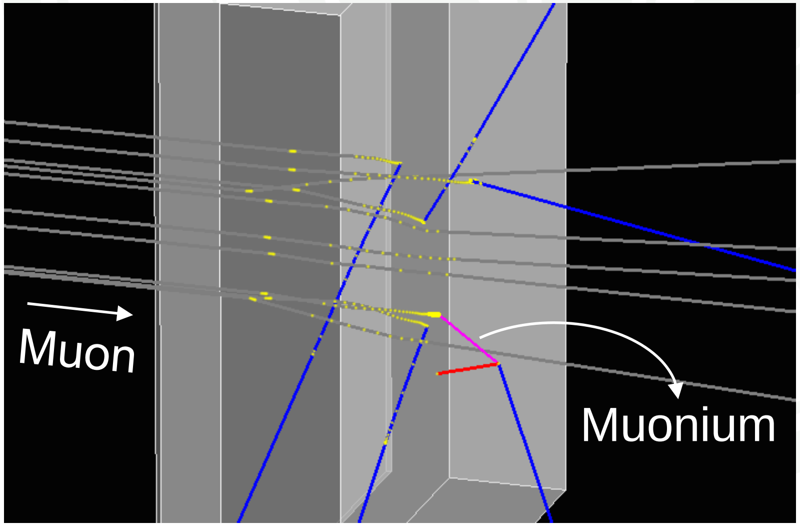
① Geant4 low-energy EM process.

② Geant4 AtRest process, modeled phenomenologically.

③ Random walk approach to thermal muonium tracking.

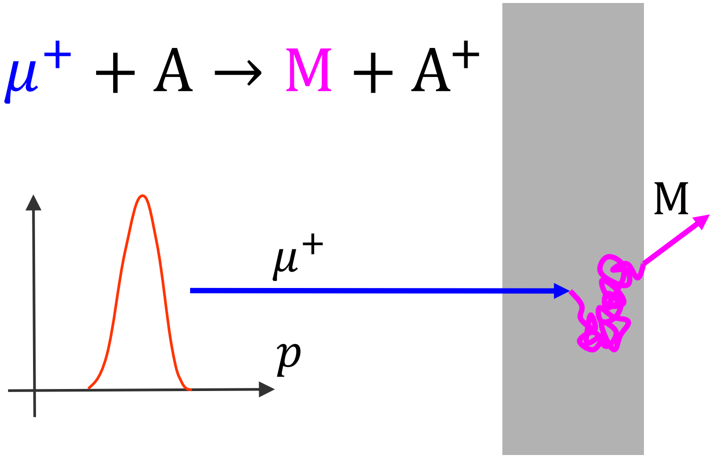


Simulation:



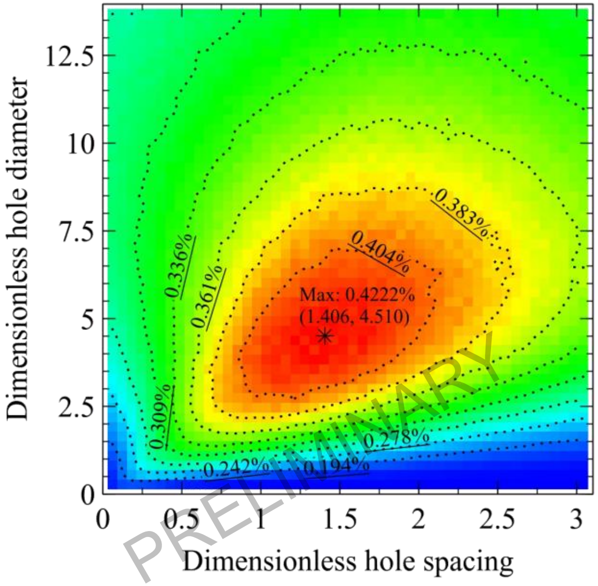
Muonium Yield Simulation

$\mu^+ + \mathrm{A} \rightarrow \mathrm{M} + \mathrm{A}^+$

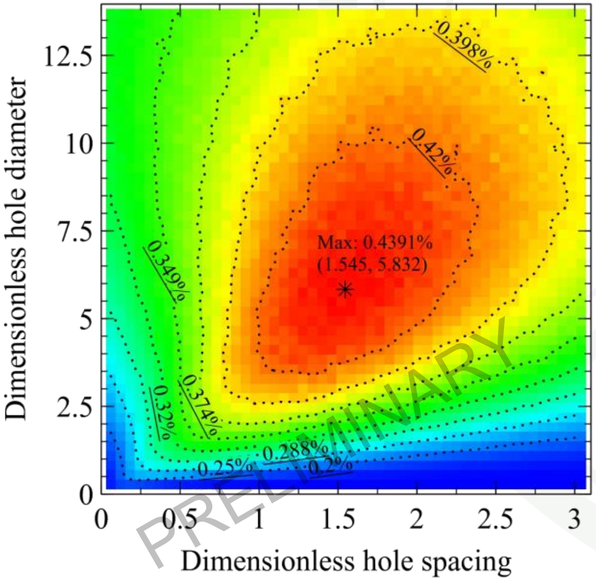


- Surface muon beam momentum spread: 10%
- Muonium mean free path: 200 nm, temp.: 300 K
- Optimal diameter: $1.55\sqrt{D\tau}$ (50.8 μm)
- Optimal spacing: $5.83\sqrt{D\tau}$ (191 μm)
- Max vacuum muonium yield: 0.44%

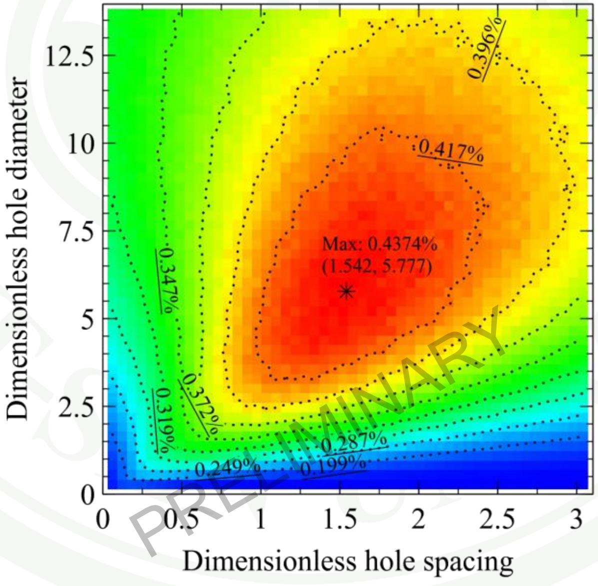
Depth: 1 mm



Depth: 3 mm

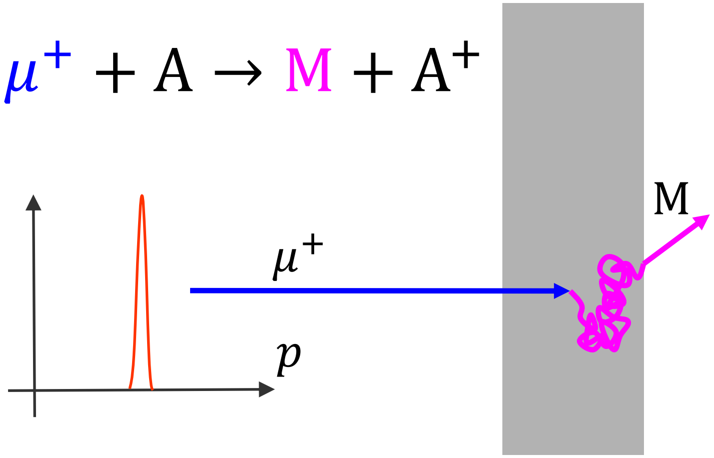


Depth: 5 mm



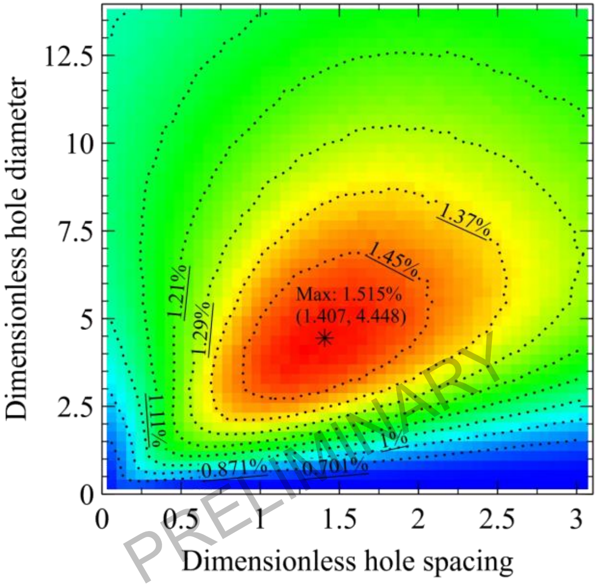
Muonium Yield Simulation - Low σ_p Beam

$\mu^+ + A \rightarrow M + A^+$

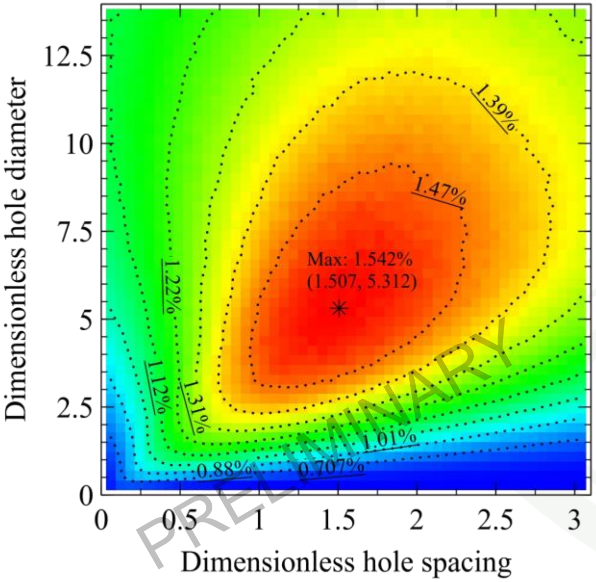


- Surface muon beam momentum spread: 2.5%
- Muonium mean free path: 200 nm, temp.: 300 K
- Optimal diameter: $1.51\sqrt{D\tau}$ (49.5 μm)
- Optimal spacing: $5.31\sqrt{D\tau}$ (175 μm)
- Max vacuum muonium yield: 1.54%

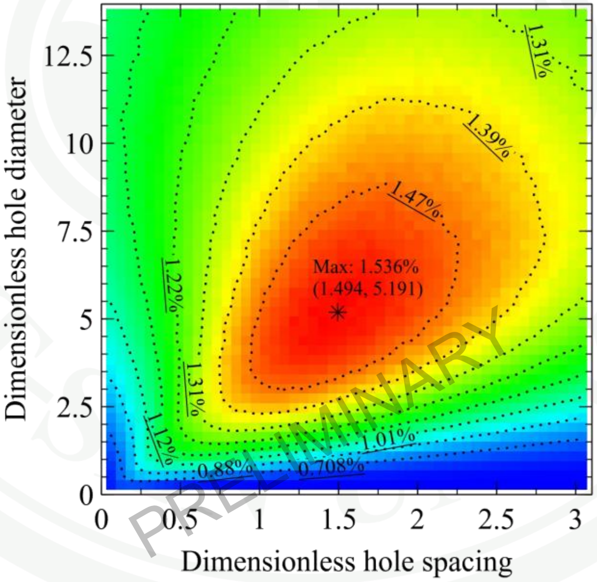
Depth: 1 mm



Depth: 3 mm



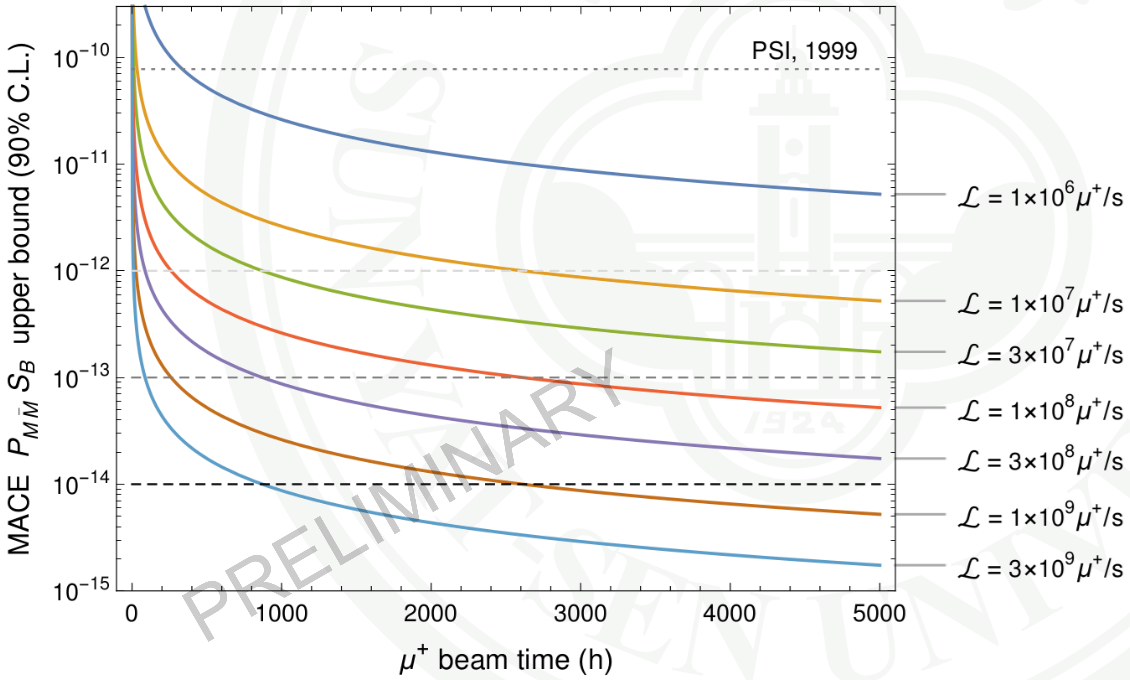
Depth: 5 mm



Muonium Yield and Upper Bound

- Acquisition time is precious, the upper bound is limited by the number of muoniums (N_{M}).
- The more muoniums the merrier.

- If the beam luminosity reaches 10^8 μ⁺/s and the muonium yield increases by 2 orders of magnitude, MACE can improve the upper bound by 3 orders of magnitude.
- The improvement of detector performance will make contributions, correspondingly.



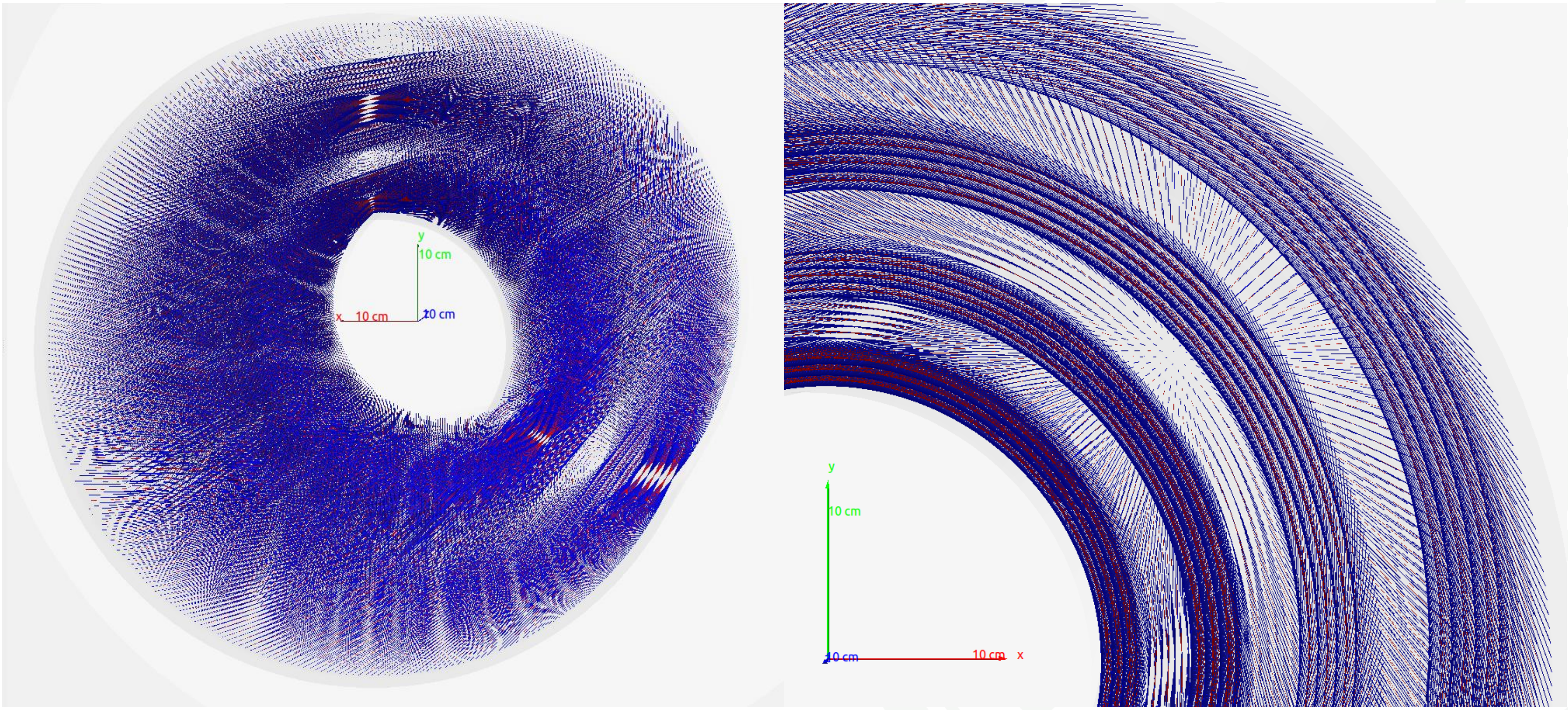
Design of Drift Chamber

- The performance of a drift chamber is largely determined by its geometry design, including:
  - Drift cell design
  - Arrangement of wires (stereo/axial)
  - Solid angle coverage, etc.
- To guarantee the required resolution, we design the drift chamber for MACE with following specifications:
  - Square drift cell with minimum cell deformation.
  - Layers of cells are divided into different super layers, cells in the same super layer are twisted identically (all axial, or all stereo with specific stereo angle).
  - Interlaced axial/stereo layer (e.g. VAUAVAU..., A: axial layer, V: stereo layer with positive stereo angle, U: stereo layer with negative stereo angle).

Jian Tang(tangjian5@mail.sysu.edu.cn)

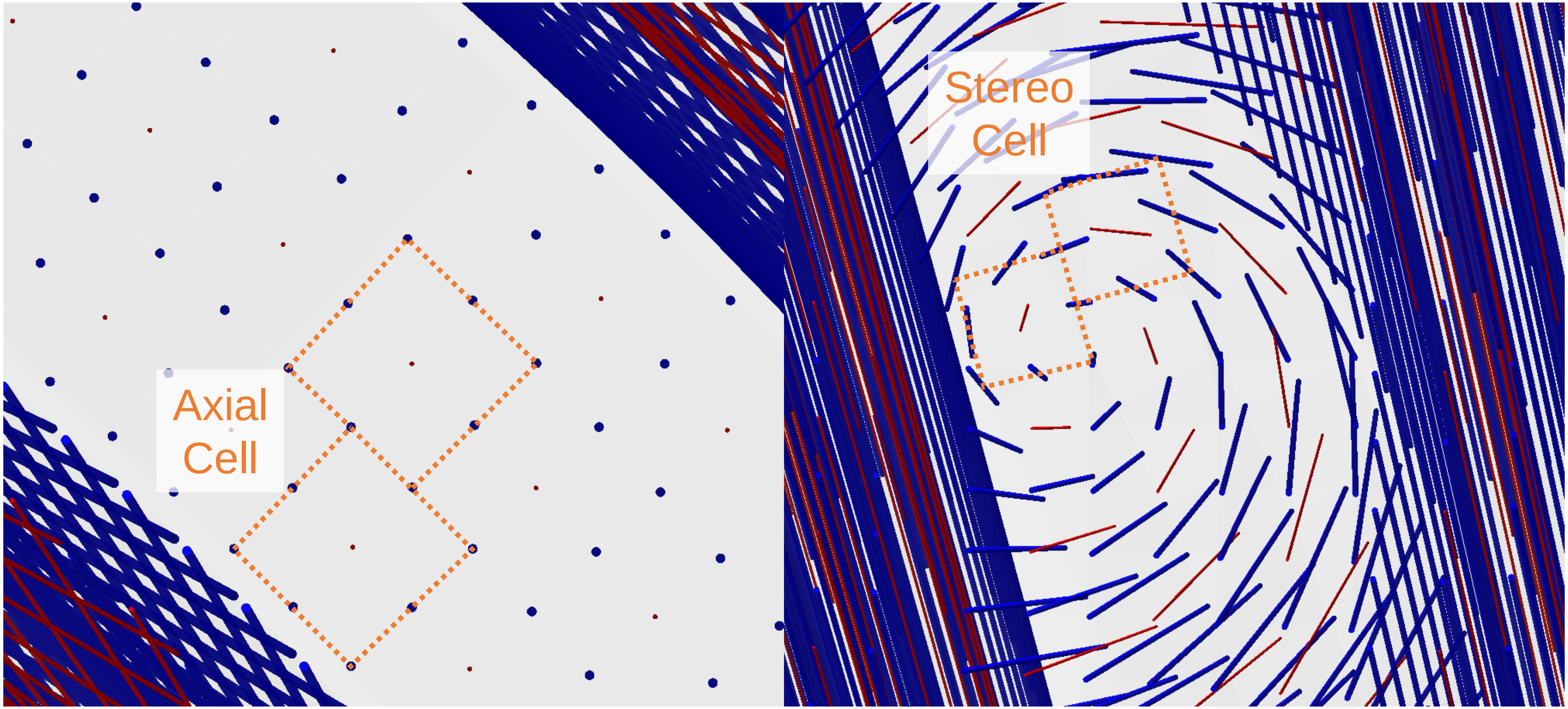
Design of Drift Chamber

- We have developed an algorithrm to generate the drift chamber geometry, allowing us to evaluate and optimize the geometry design of drift chamber.



- Figure: generated Drift chamber geometry.
- This example chamber is consist of 7 super layer, each super layer includes 3 sense layers. They are arranged as VAUAVAU. Wires are scaled to be visible (blue: field wire, red: sense wire).

Design of Drift Chamber



- Left: drift cells in an axial super layer, cells are axial.
- Right: cells in a stereo super layer, cells are twisted.
- Wires are scaled to be clearly visible (blue: field wire, red: sense wire).

Jian Tang(tangjian5@mail.sysu.edu.cn)

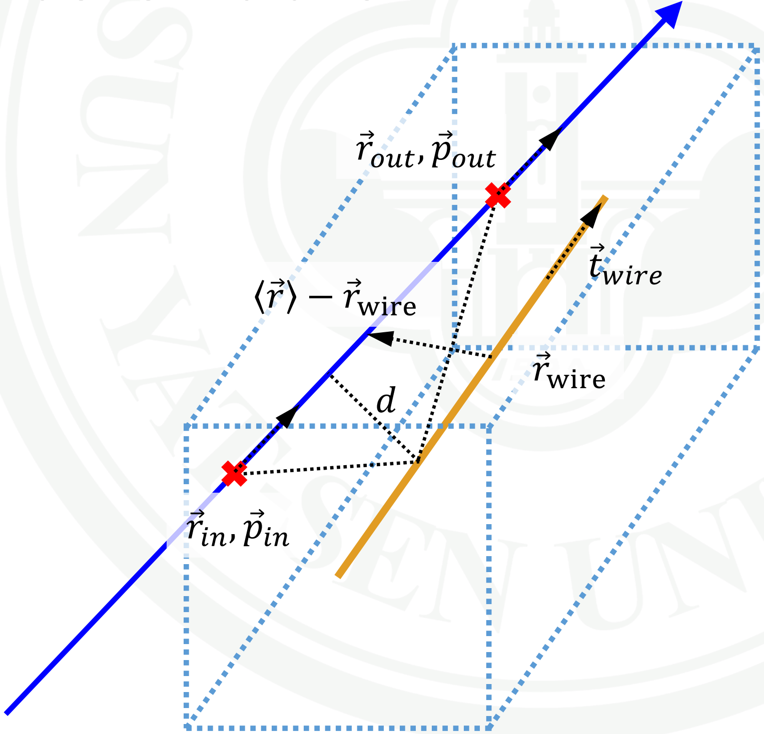
Fast Simulation of Drift Chamber

- When a charged particle passes through a drift cell, the drift distance can then be reconstructed.
- Drift distance: distance between the track and the sense wire.
- We use the simple and classical DOCA (distance of closest approach) method to perform the fast simulation:

$$d = (\langle\vec{r}\rangle - \vec{r}_{\mathrm{wire}}) \cdot \frac{\vec{t}_{\mathrm{wire}} \times \langle\vec{p}\rangle}{\|\vec{t}_{\mathrm{wire}} \times \langle\vec{p}\rangle\|}$$

$$\langle\vec{p}\rangle = \frac{\vec{p}_{\mathrm{in}} + \vec{p}_{\mathrm{out}}}{2}$$

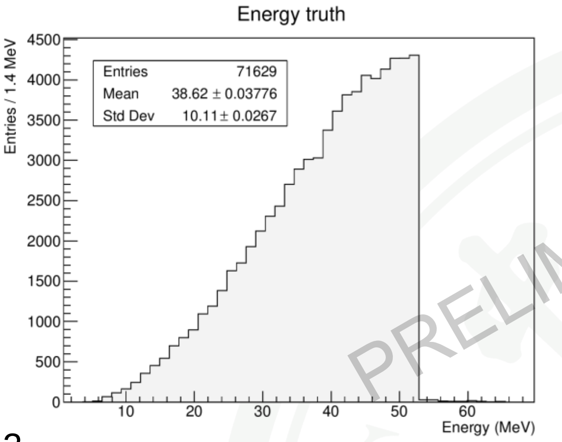
$$\langle\vec{r}\rangle = \frac{\vec{r}_{\mathrm{in}} + \vec{r}_{\mathrm{out}}}{2}$$

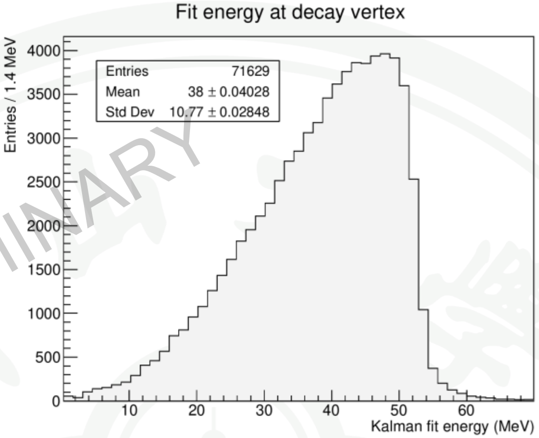


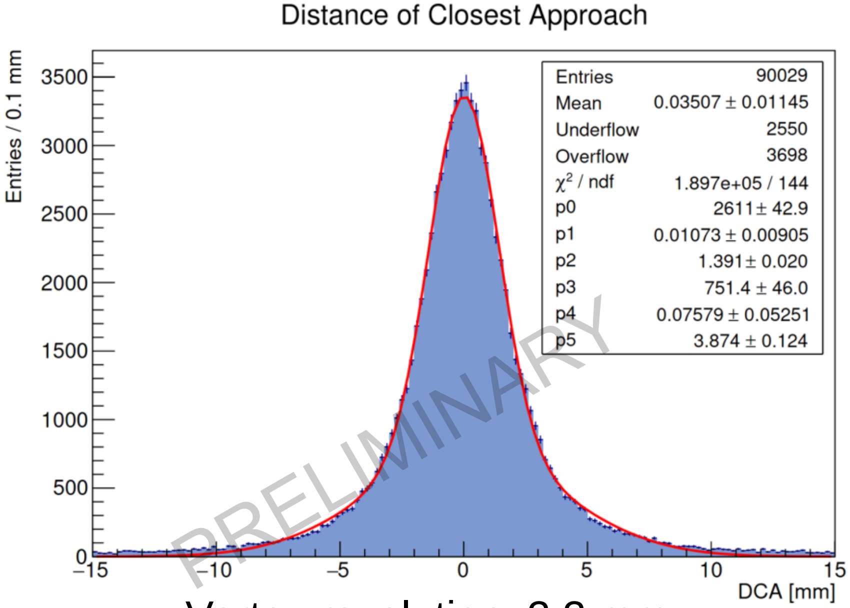
- $\vec{r}_{\mathrm{wire}}$: A point on the sense wire (e.g. the point at z=0)
- $\vec{t}_{\mathrm{wire}}$: Direction of the sense wire

Track Reconstruction in Spectrometer

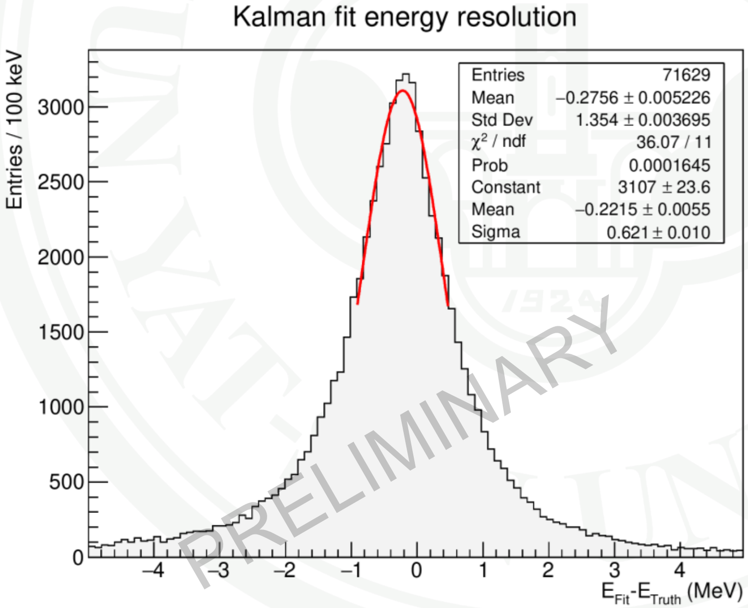
- Kalman-filter-based track reconstruction has been performed, with 100µm drift distance resolution.
- The resolution of the drift chamber has improved compared with simple least χ^2.







Vertex resolution: 2.2 mm (double gaussian fit std. dev.)



Momentum (energy) resolution: ~1.5 MeV (FWHM)

Jian Tang(tangjian5@mail.sysu.edu.cn)

Content

- 中山大学缪子科学与技术实验室SMOOTH简介
- MACE实验简介及其研究动机
- MACE实验概念设计
- **MACE实验模拟结果**
- 总结和展望

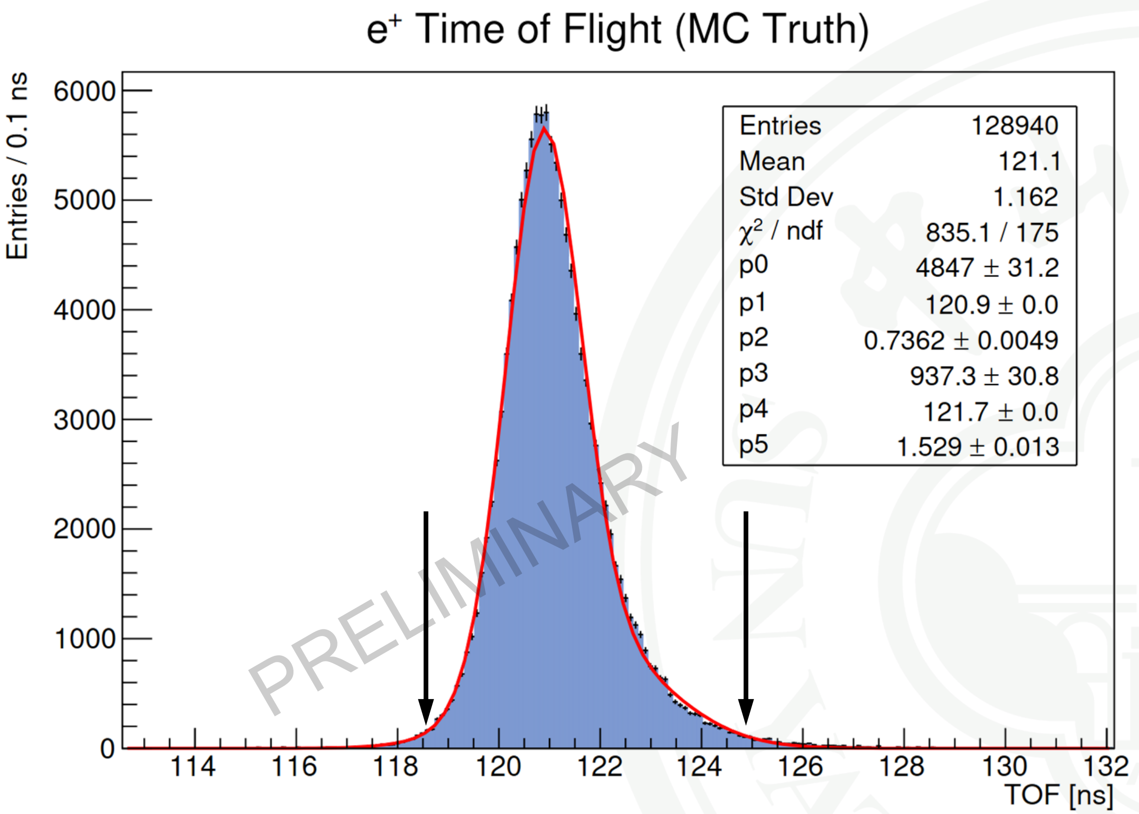
Event Selection

- A antimuonium decay event is identified by coincident signals of spectrometer, MCP, and EMCal.

- Events are selected as follows:
  1. Find time coincident γ events (≥ 2).
  2. Find time coincident e^- track:
     - Find time coincident drift chamber hits
     - Do track reconstructions
  3. Calculate the distance of closest approach (DCA) of e^-/e^+ tracks.
  4. Calculate e^+ time of flight (TOF) and difference between expected TOF.

Time window?

Analysis: Time Aspect



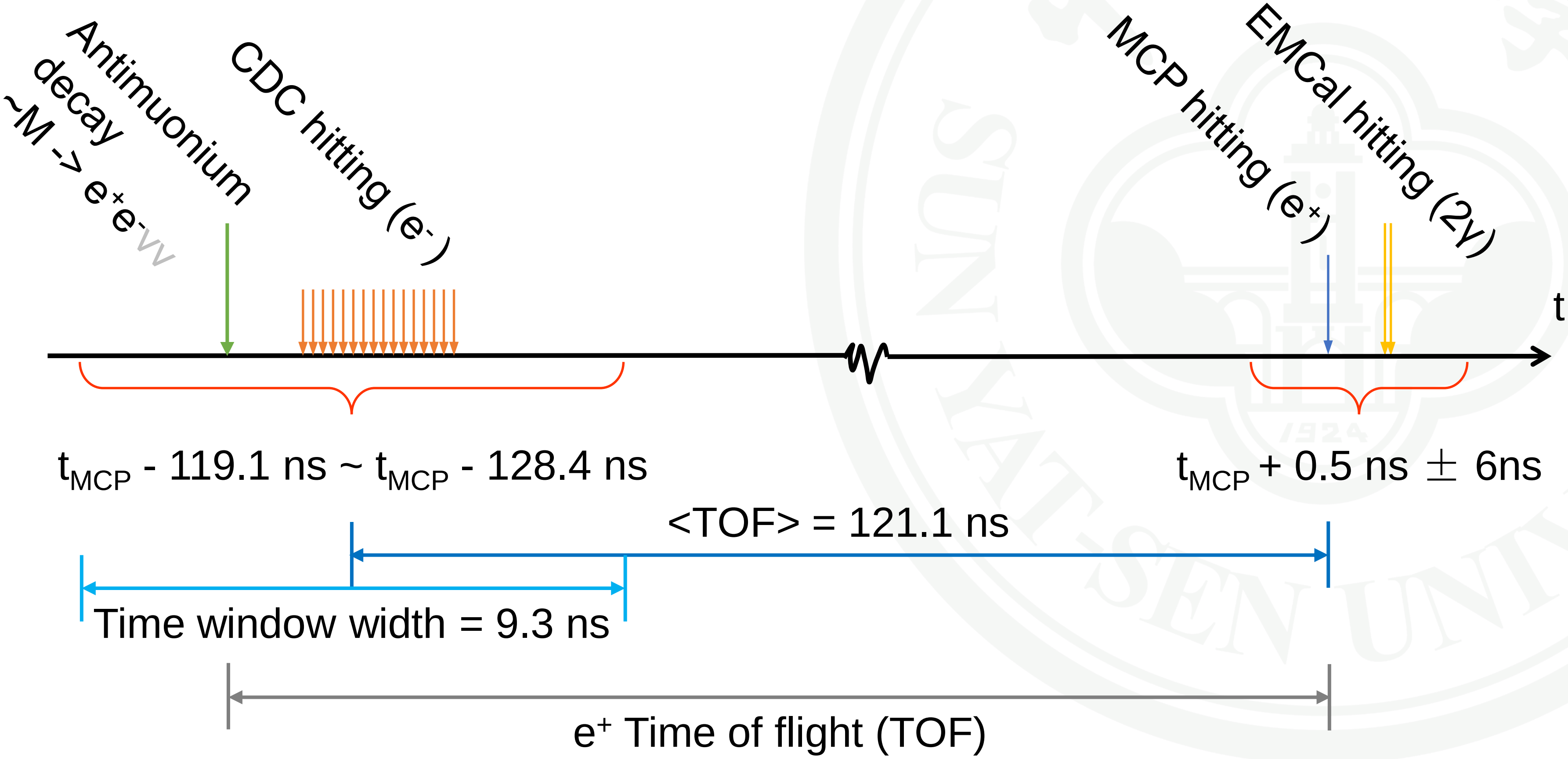
118.6 ns 124.9 ns

Add e$^-$ flight time from target to / inside the drift chamber: 0.5 ns / 3.5 ns,

Time window for drift chamber is t_{MCP} - 119.1 ns ~ t_{MCP} - 128.4 ns.

Analysis: Time Aspect

- Time resolution of the drift chamber (2 ns) and EMCal (4.5 ns) have been considered.
- Time window is determined by the simulated TOF spectrum.



Antimuonium decay

~M -> $e^+e^-\nu\nu$

CDC hitting (e^-)

MCP hitting (e^+)

EMCal hitting (2γ)

t

t_{MCP} - 119.1 ns ~ t_{MCP} - 128.4 ns

t_{MCP} + 0.5 ns ± 6ns

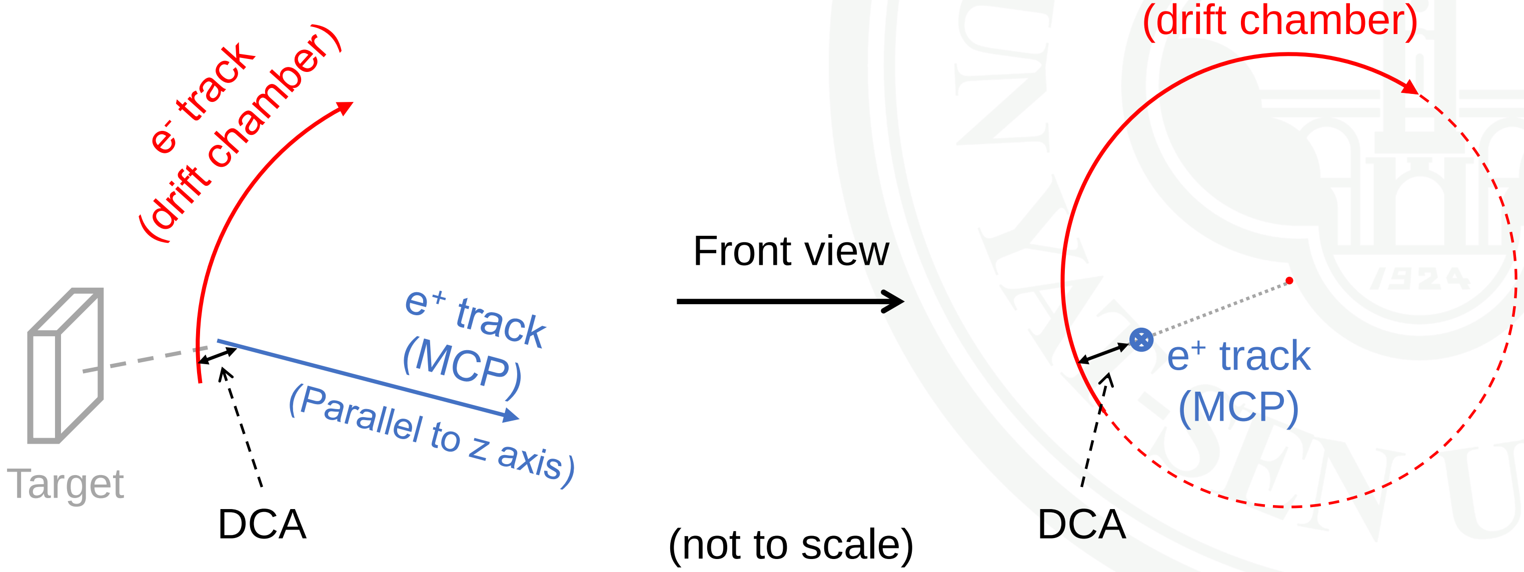
<TOF> = 121.1 ns

Time window width = 9.3 ns

e^+ Time of flight (TOF)

Analysis: Spatial Aspect

- Spatial resolution of the drift chamber cell (100 μm) has been considered.
- Fitted tracks are extrapolated toward the target by helixes.
- Closest distance between extrapolated tracks and low energy atomic e^+ are calculated.

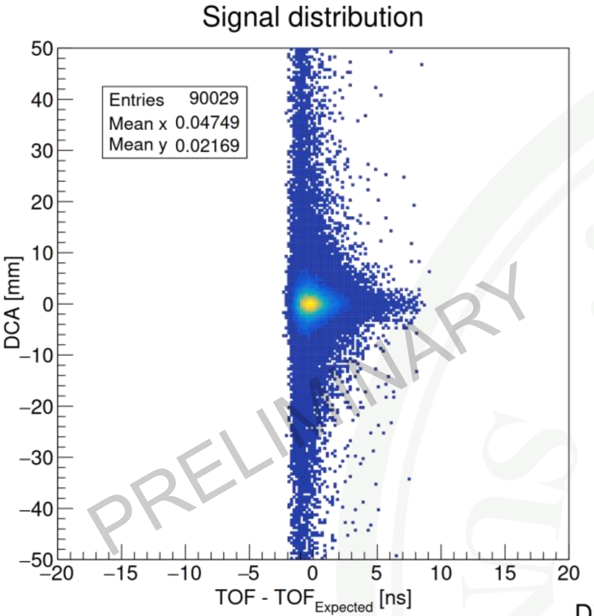


Jian Tang(tangjian5@mail.sysu.edu.cn)

Analysis Result

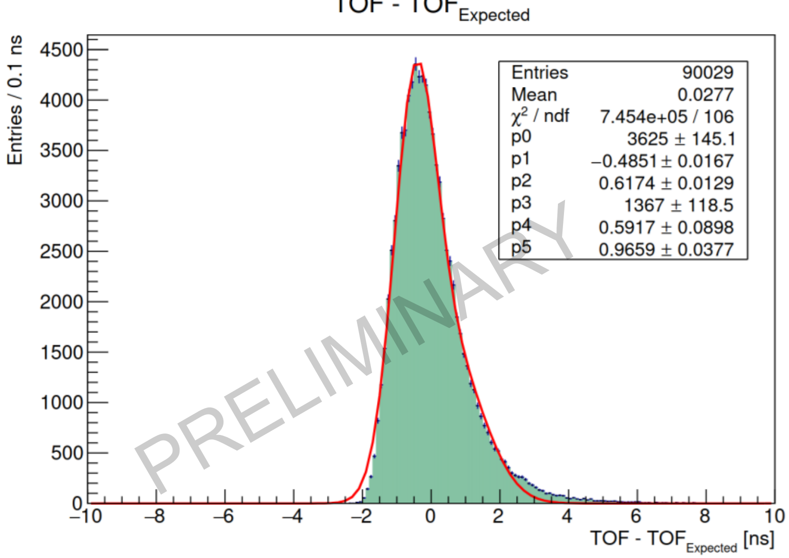
- Following the analysis procedure, the distribution of the signal can be obtained.

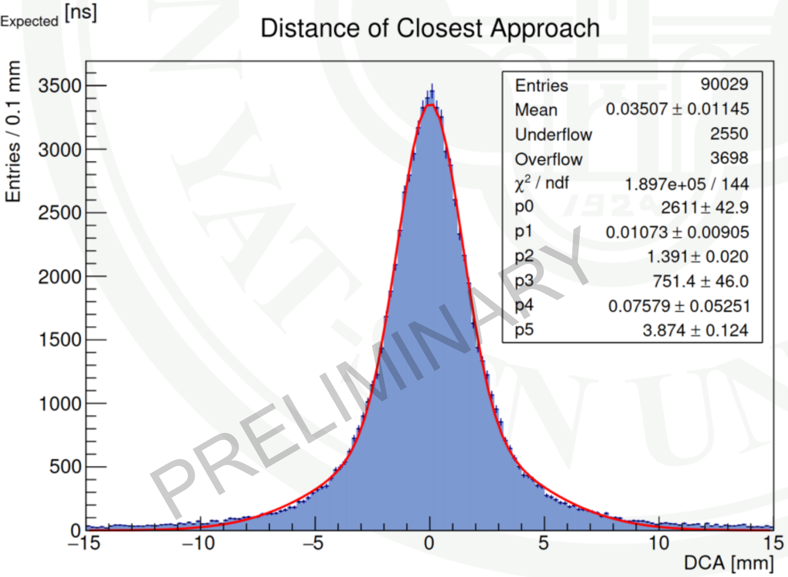
- Space-time resolution improved compared with the previous PSI experiment.



$\sigma_{\Delta TOF}$ = 0.58 ns

σ_{DCA} = 2.2 mm

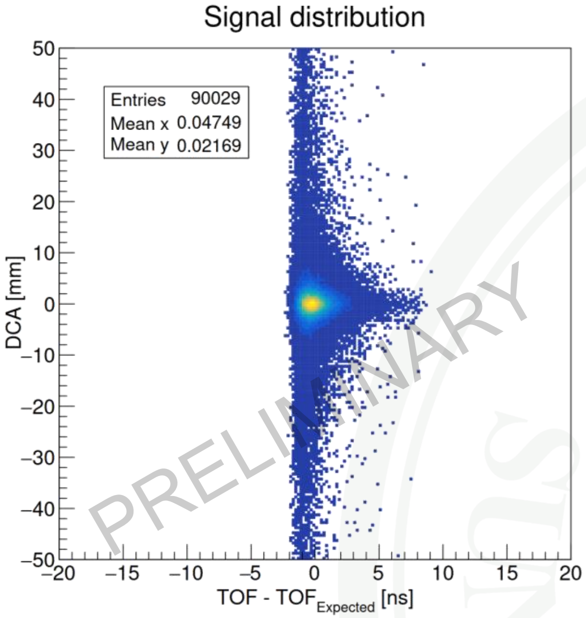




Jian Tang(tangjian5@mail.sysu.edu.cn)

Analysis Result

- Improved resolution - smaller signal region - lower background level expected.

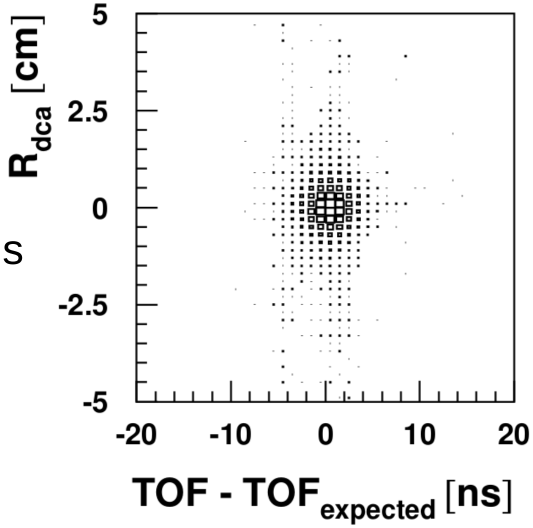

Signal distribution

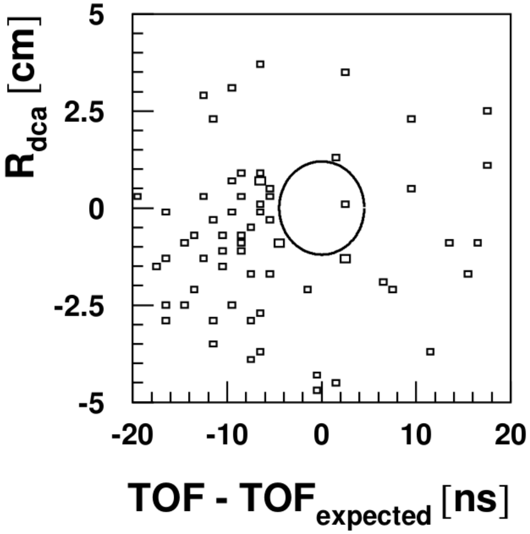
- Backgrounds:
  - $\mu^+ \to e^+ e^- e^+ \nu_e \bar{\nu}_\mu$
  - $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ and accidental e^-
- Background analysis in progress.

$\sigma_{\Delta TOF}$ = 0.58 ns

σ_{DCA} = 2.2 mm

$\sigma_{\Delta TOF}$ = 1.5 ns

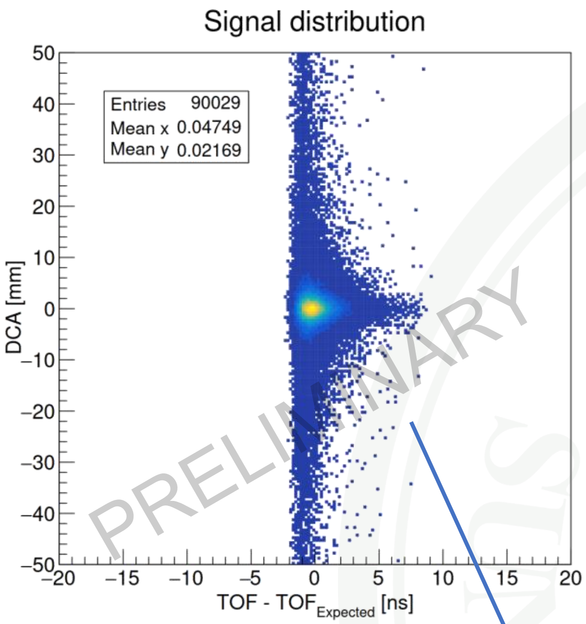




σ_{DCA} = 4.0 mm

Analysis Result

- Improved resolution - smaller signal region - lower background level expected.

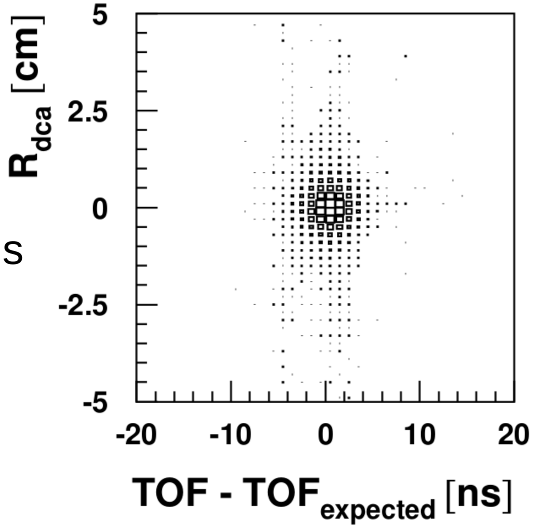


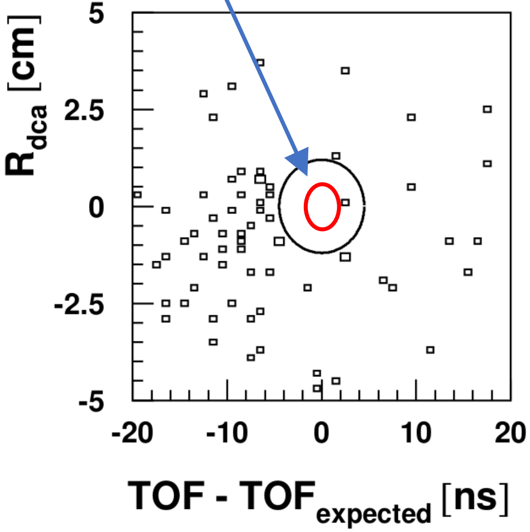
- Backgrounds:
  - $\mu^+ \rightarrow e^+e^-e^+\nu_e\bar{\nu}_\mu$
  - $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ and accidental e^-
- Background analysis in progress.

$\sigma_{\Delta TOF}$ = 0.58 ns

σ_{DCA} = 2.2 mm

$\sigma_{\Delta TOF}$ = 1.5 ns





σ_{DCA} = 4.0 mm

Jian Tang(tangjian5@mail.sysu.edu.cn)

Content

- 中山大学缪子科学与技术实验室SMOOTH简介
- MACE实验简介及其研究动机
- MACE实验概念设计
- MACE实验模拟结果
- 总结和展望

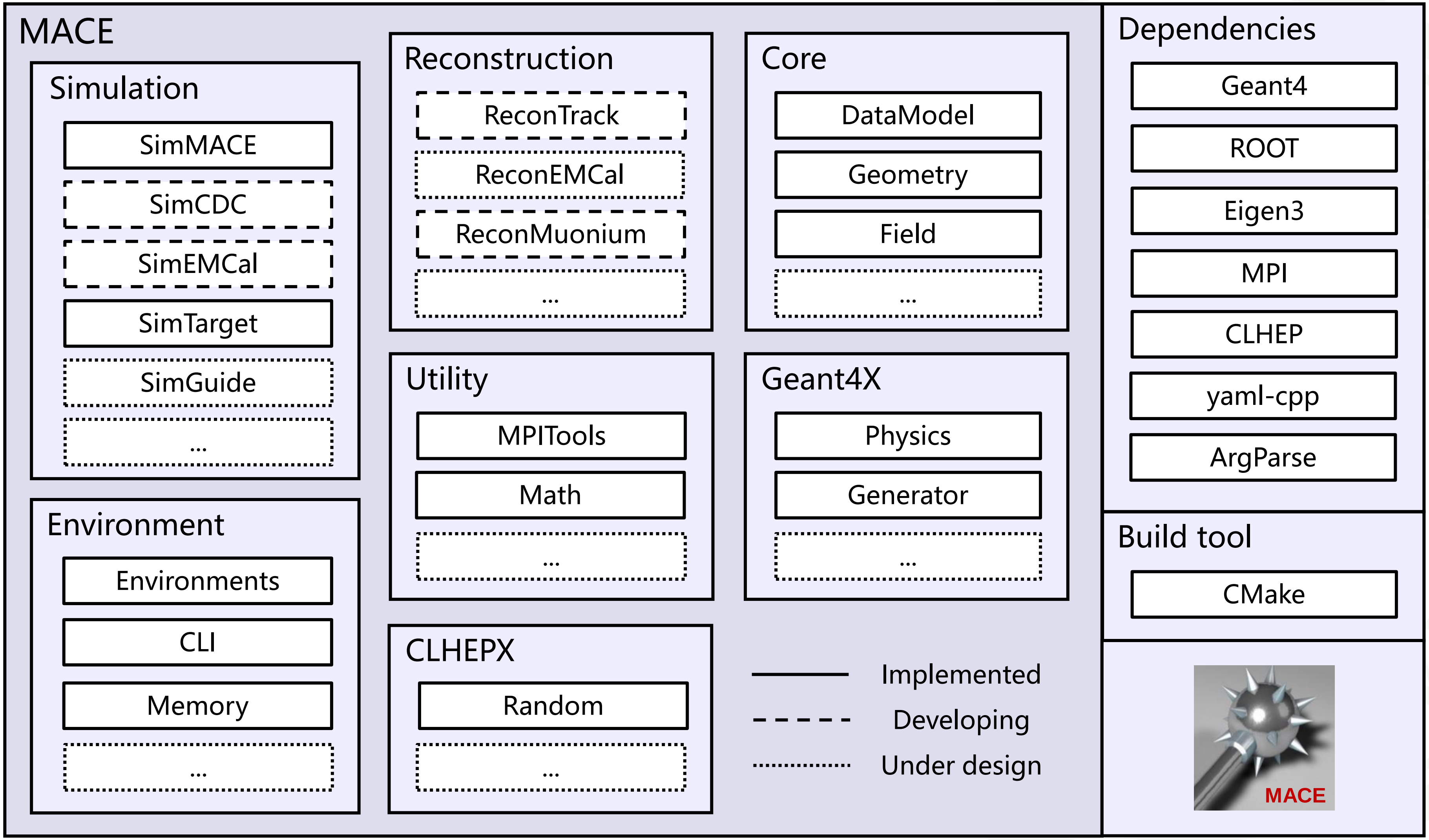
Summary

- 缪子的前沿科学研究方兴未艾，精确检验QED理论，稀有物理过程是研究超越SM新物理的极佳工具。
- 我们提出并推进**MACE实验**，将为我国在缪子物理实验领域**实现零的突破**，做出**世界最好**的物理结果。
- 本土缪子实验项目将在缪子束流、缪子素产生及探测器设计等重要环节上取得“0到1”的重要原始创新，有望将现有实验精度提高**两个量级**以上。
- 我们在MACE实验总体设计、缪子素产生、离线软件研发上已经获得关键性进展；已获得气凝胶靶样品，正在开展新型探测器系统的优化和设计，持续推进各子探测器的研发(MBM、EMCal等)和重建算法的实现。
- 前沿科学必将带动技术应用，SMOOTH-μSR样机研制中，开展多学科应用。
- 缪子物理大有可为，大家精诚合作，早日发布MACE实验的CDR→TDR，推动项目立项建设。

THANK YOU

Backup

MACE Offline Software



Jian Tang(tangjian5@mail.sysu.edu.cn)

MACE Offline Software

- MACE offline software: designed for experiment R&D, simulation, and offline reconstruction.
- The software framework has been established, including / allowing:
  - Simulation of the experiment / detectors
  - Large-scale parallel computing with MPI on supercomputer
  - Data model and data I/O
  - Geometry and material interface
  - Detector parameters management and I/O
  - ...
- Designed and programmed with C++ best practice and pattern - design and develop for future.
- Currently, main tasks:
  - Develop offline analysis module.
  - Refine physics processes.
  - Improve and APIs and UIs.