



Progress of MACE at Experimental Muon Source



Jian Tang (Sun Yat-sen University, China)

ICHEP2022, July 8th, INFN-Bologna, Italy

Collaborators: SYSU—Yu Chen, Han Shen, Zhen-Cheng Huang, Yu Xu
Shi-Han Zhao, Ming-Chen Sun, Tao Yu, Yun-Song Ning, Yi-Xing Zhou, Ai-Yu Bai,
IHEP—Jing-Yu Tang, Ye Yuan, Hai-Bo Li, Yao Zhang, Guang Zhao, Han Miao, Yu Bao
Osaka University—Chen Wu

Special thanks: IMP—Yuan He, Huan Jia, Liang-Wen Chen, SJTU—Kim-Siang Xu

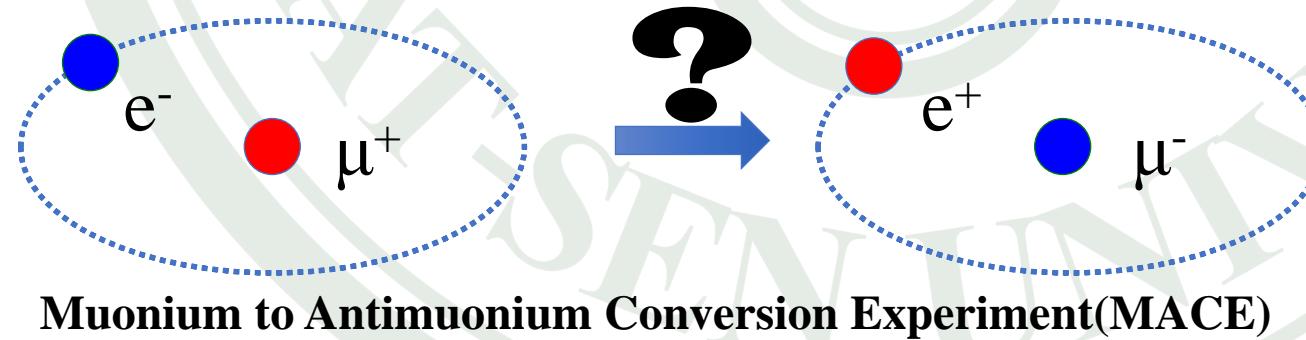
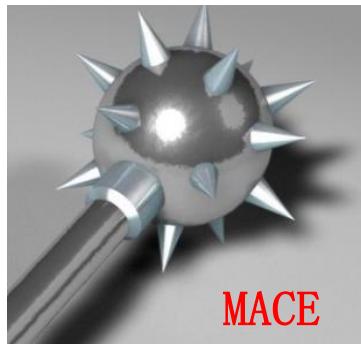
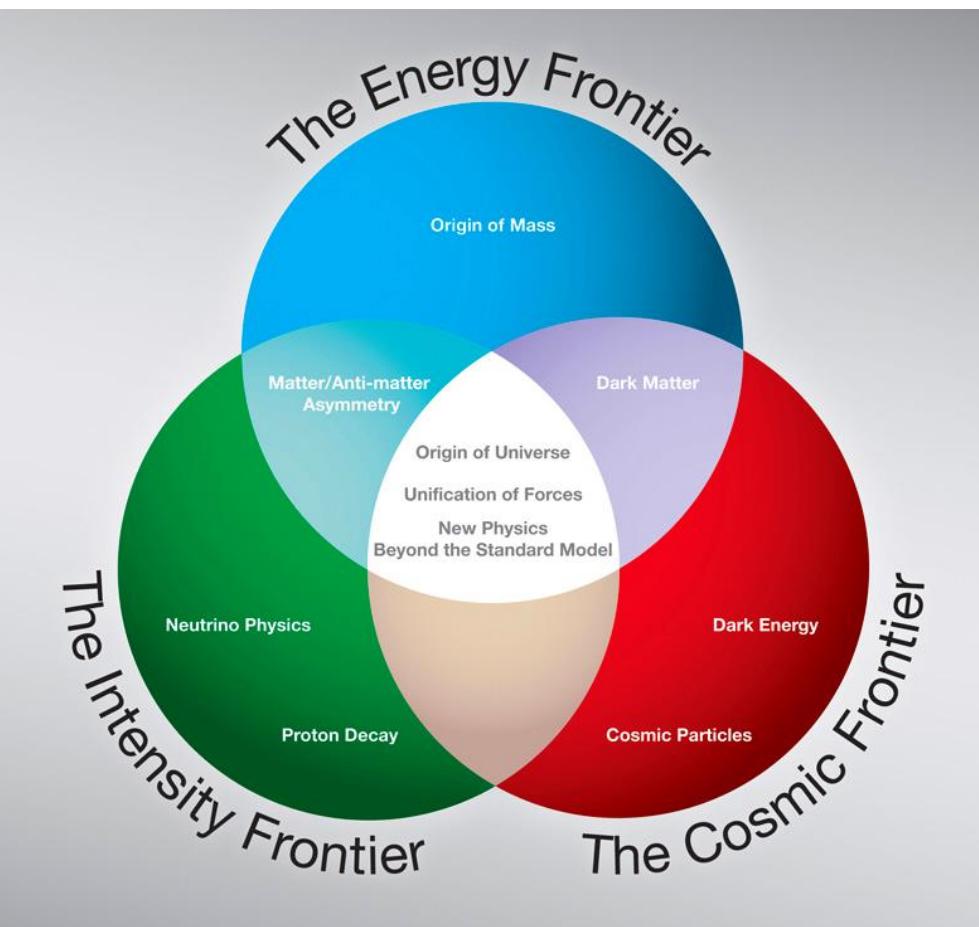




Table of contents

- Motivation
- Simulation and Optimization
 - Muonium Production
 - Conceptual design of detector
- Preliminary simulation results
- Summary

Frontiers of Particle Physics



- The Energy Frontier
- The Intensity Frontier
- The Cosmic Frontier

Searching for BSM:

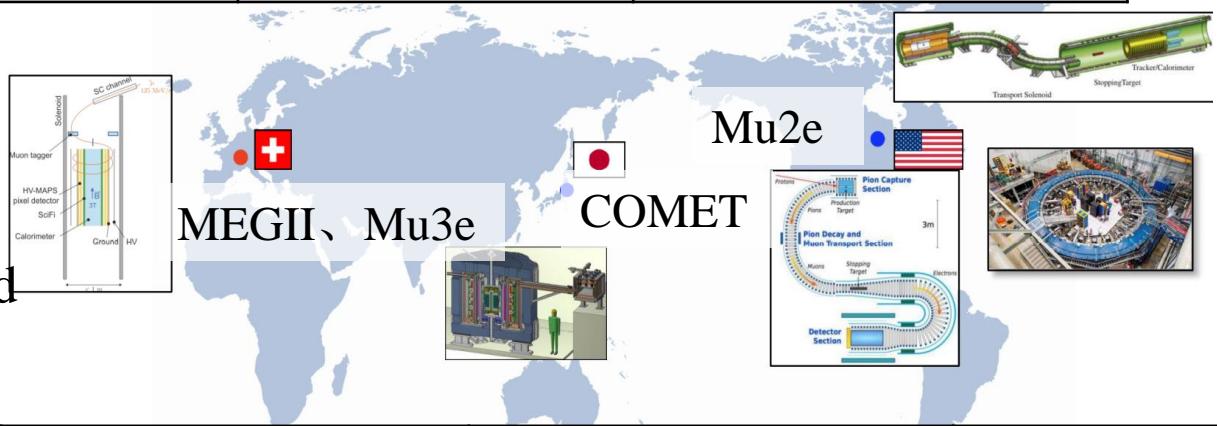
- The origin of neutrino masses?
- Charged lepton flavor violation (cLFV)?
- The mystery of the matter-antimatter asymmetry?
- Dark matter?
-

Searching for cLFV: Experimental Efforts



EXPERIMENT	FACILITY	PROCESS	STATUS
MEGII	PSI (Switzerland)	$\mu^+ \rightarrow e^+ \gamma$	Running
Mu2e	Fermilab (US)	$\mu^- N \rightarrow e^- N$	Installing, about to run
COMET	J-PARC (Japan)	$\mu^- Al \rightarrow e^- Al$	Installing, about to run
Mu3e	PSI (Switzerland)	$\mu^+ \rightarrow e^+ e^- e^+$	Running

- Muonium-antimuonium transition: as an important cLFV process, no more experiments were proposed since 1999;



EXPERIMENT	FACILITY	STATUS
MACS (1999)	PSI (Switzerland)	Completed
MACE	Muon facility (China)	R&D
Muonium conversion experiment	J-PARC (Japan)	R&D

Snowmass whitepaper



March 23, 2022



arXiv: 2203.11406

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 (Coordinator),⁴ Ying-Peng Song,² Jian Tang (Coordinator),¹ Jing-Yu Tang,² Nikolaos Vassilopoulos,² Sampsaa 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 Zhou²

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.

Accelerator centers in the YGA Bay area



**CSNS 1.6 GeV 25 Hz 100 kW proton driver
→ 500 kW upgrade on the way**

Running facility



Ref: Sheng Wang from IHEP

**Heavy Ion Accelerator Facility (HIAF) &
China initiative Accelerator Driven Sub-critical system
(CiADS)**

Planned facility under civil construction



Ref: Wen-Long Zhan from IMP

Three accelerator facilities in this bay area: CSNS v.s CiADS&HIAF

- Which one will build the first accelerator muon source in China within next 5 years?
- Time to propose something on fundamental physics with accelerator muons.

Accelerator centers in the YGA Bay area

CSNS 1.6 GeV 25 Hz 100 kW proton driver
 → 500 kW upgrade on the way

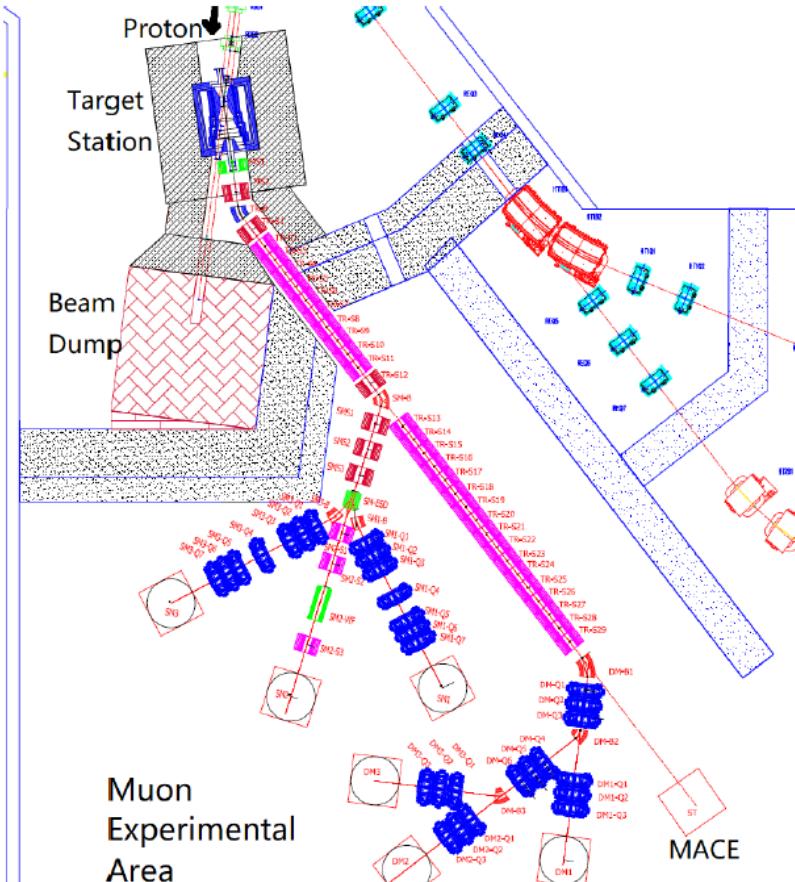


Ref: Sheng Wan

Three accelerator faci

- Which one will bui
- Time to propose s

Heavy Ion Accelerator Facility (HIAF) & China initiative Accelerator Driven Sub-critical system (CiADS)

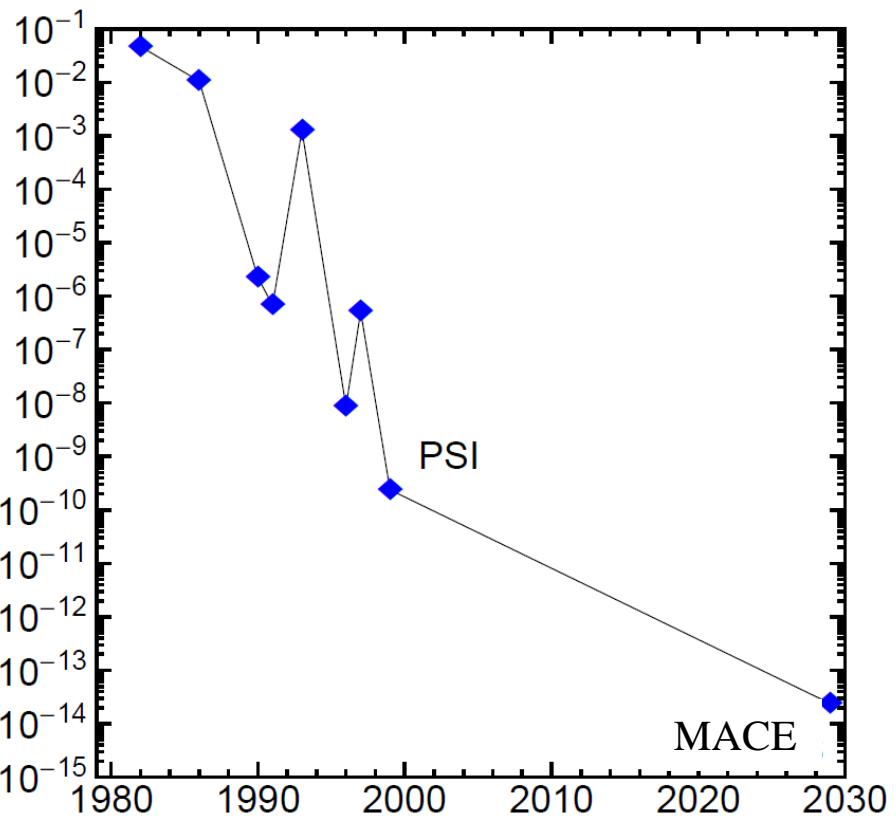


I-Long Zhan from IMP

IAF

China within next 5 years?
 ccelerator muons.

MACE: Muonium to Antimuonium Conversion Experiment



- Latest result of muonium-antimuonium conversion (MACS, PSI, 1999):
$$P_{M\bar{M}} < 8.3 \times 10^{-11} \text{ (90% C.L.)}.$$
- **MACE**: the first proposed muonium-antimuonium conversion experiment since 1999, aim at physics sensitivity by more than two orders of magnitude.
- Together with other flavor and collider searches, MACE will also shed light on the mystery of the neutrino masses.

MACE: Muonium to Antimuonium Conversion Experiment.



Content

● Motivation

● Simulation and Optimization

➤ Muonium Production

➤ Conceptual design of detector

● Preliminary MC Results

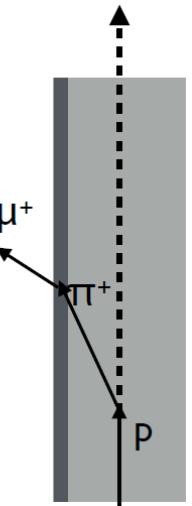
● Offline Software development

● Summary

Muon and muonium production

relative μ^+ yield $\propto \pi^+ \text{stop density} \cdot \mu^+ \text{Range} \cdot \text{length}$

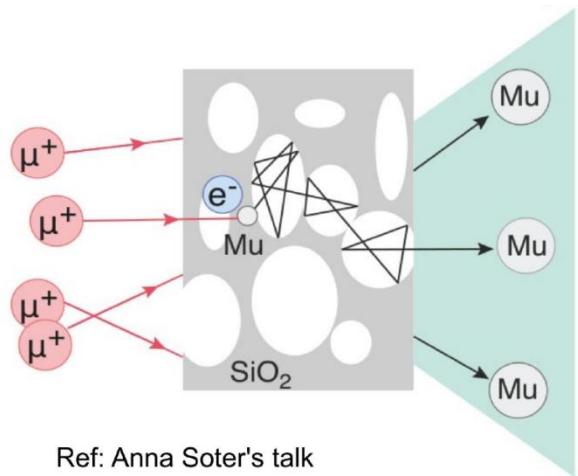
$$\begin{aligned} &\propto n \cdot \sigma_{\pi^+} \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_c (6/12)_c}{\rho_x (Z/A)_x} \\ &\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z} \\ &\propto \frac{1}{Z^{2/3}} \end{aligned}$$



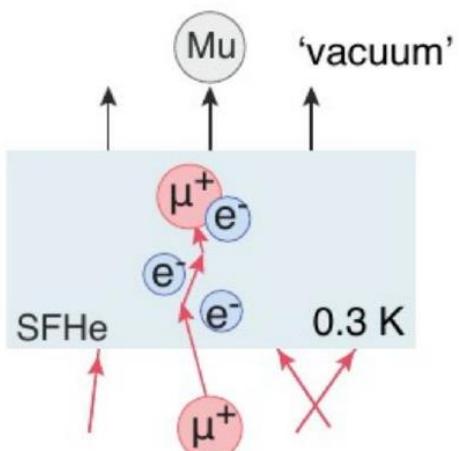
Previous experience

- Hot tungsten in 1986: 4% from 4 MeV μ^+
- SiO_2 powder in 1990: 1%-2% from 4 MeV μ^+
- SiO_2 film(cold) in 2012: 40% from 5 keV μ^+

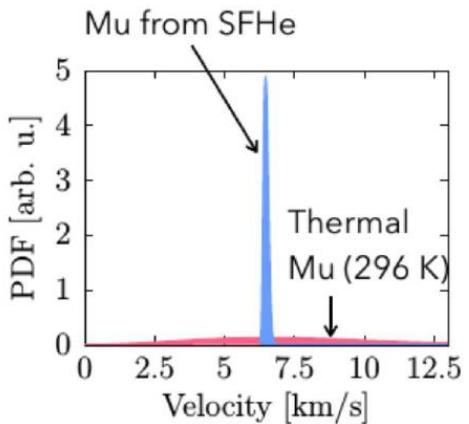
Proposed target: aerogel, super fluid helium...



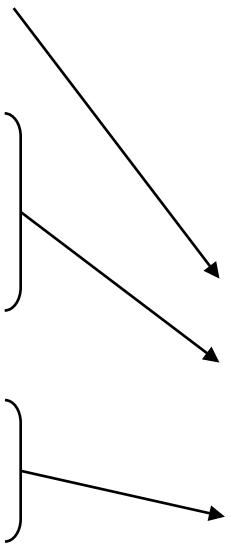
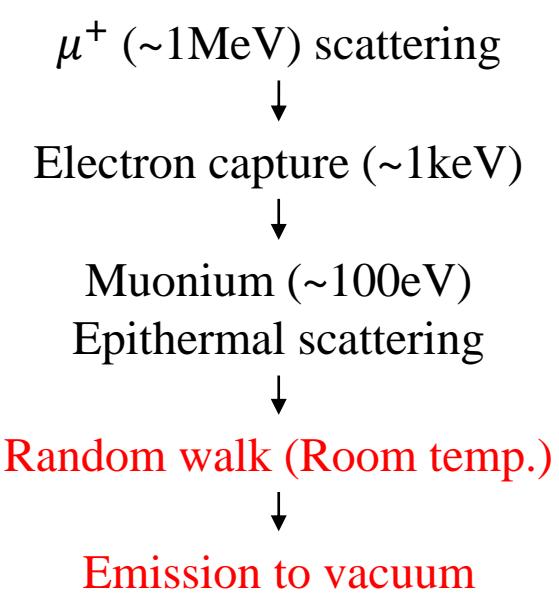
Silica powder



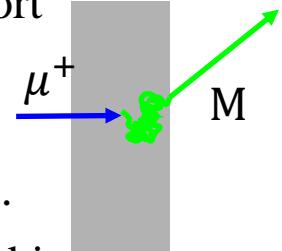
Super Fluid Helium



Muonium production and transportation



MC simulation for muonium transport has been developed.

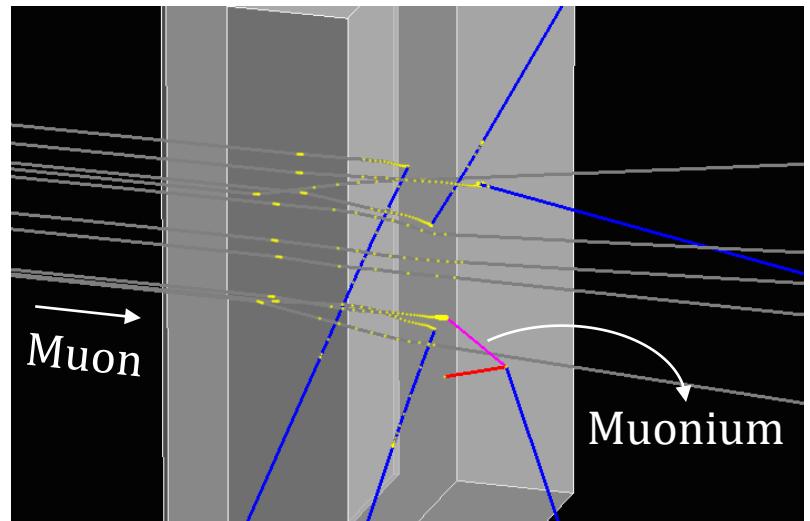


- ① Geant4 low-energy EM process.
- ② Geant4 AtRest process, modeled in house-held code.
- ③ Random walk approach for thermal muonium formation and transportation.

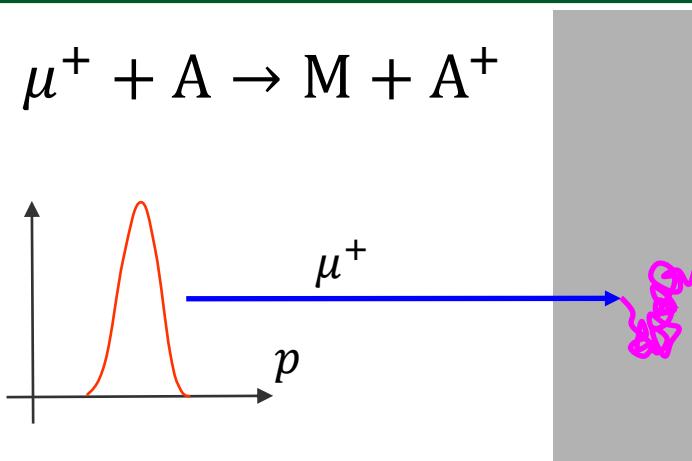
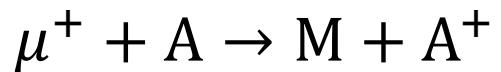
Silica aerogel target sample:



Simulated events of muonium production and emission:

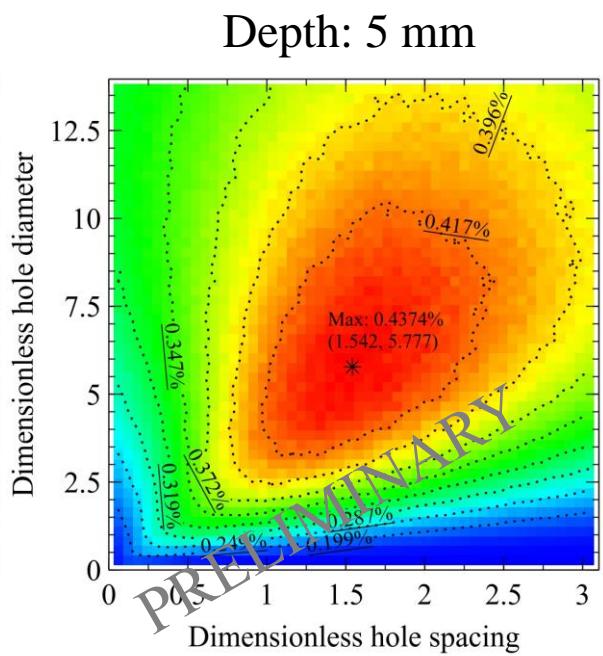
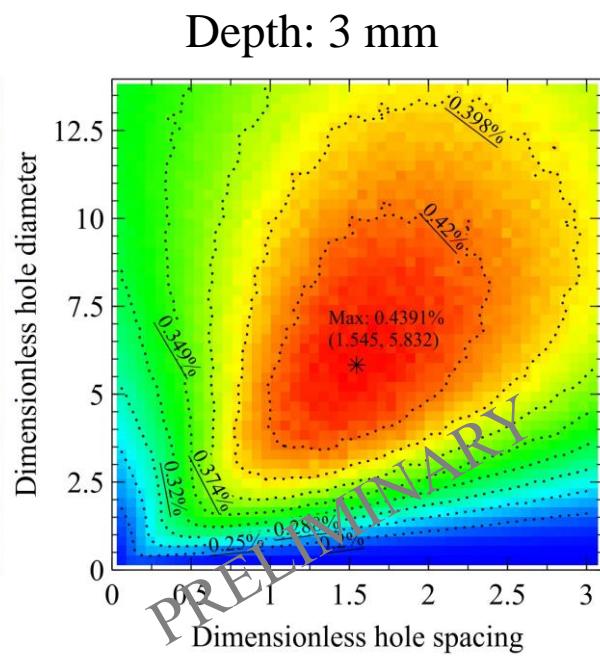
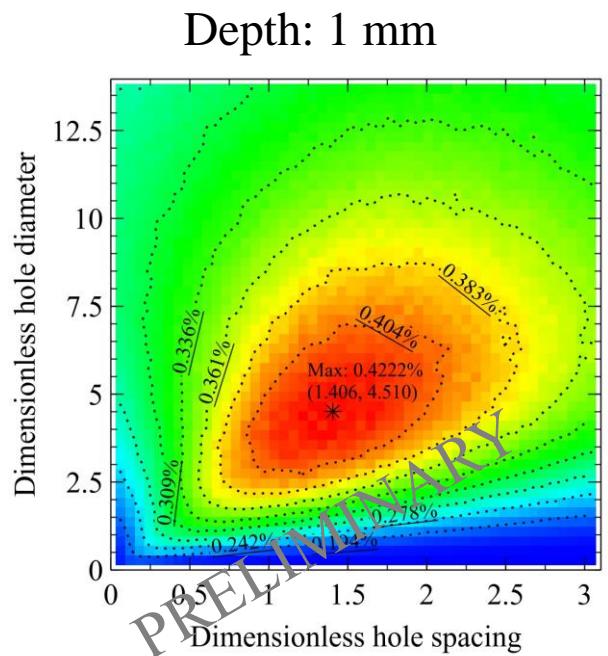


Muonium yield simulation

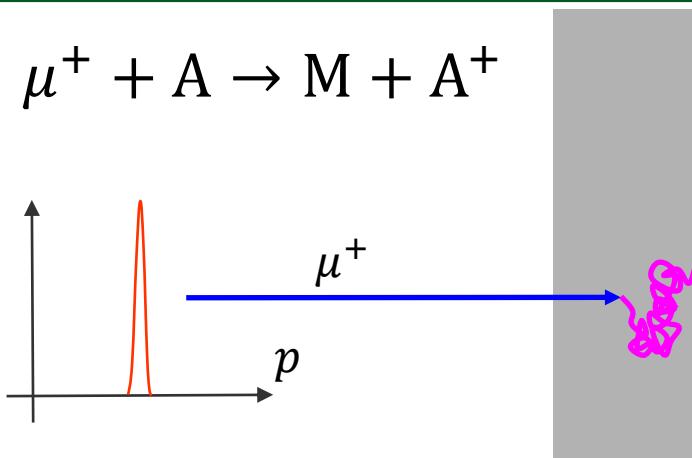


- Surface muon beam momentum spread: 10%
 - Muonium mean free path: 200 nm, temp.: 300 K
 - Optimal diameter: $1.55\sqrt{D\tau}$ (50.8 μm)
 - Optimal spacing: $5.83\sqrt{D\tau}$ (191 μm)
 - Max vacuum muonium yield: 0.44%

Credit: Shihan Zhao.



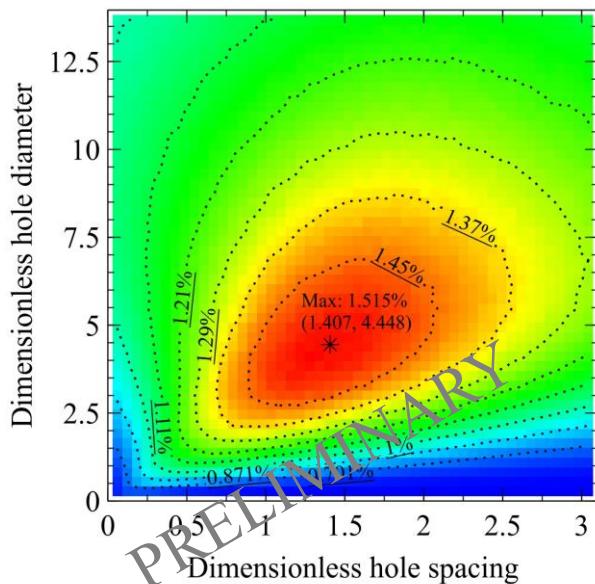
Muonium yield simulation - low beam spread



- 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%

Credit: Shihan Zhao.

Depth: 1 mm



Content

● Motivation

● Simulation and Optimization

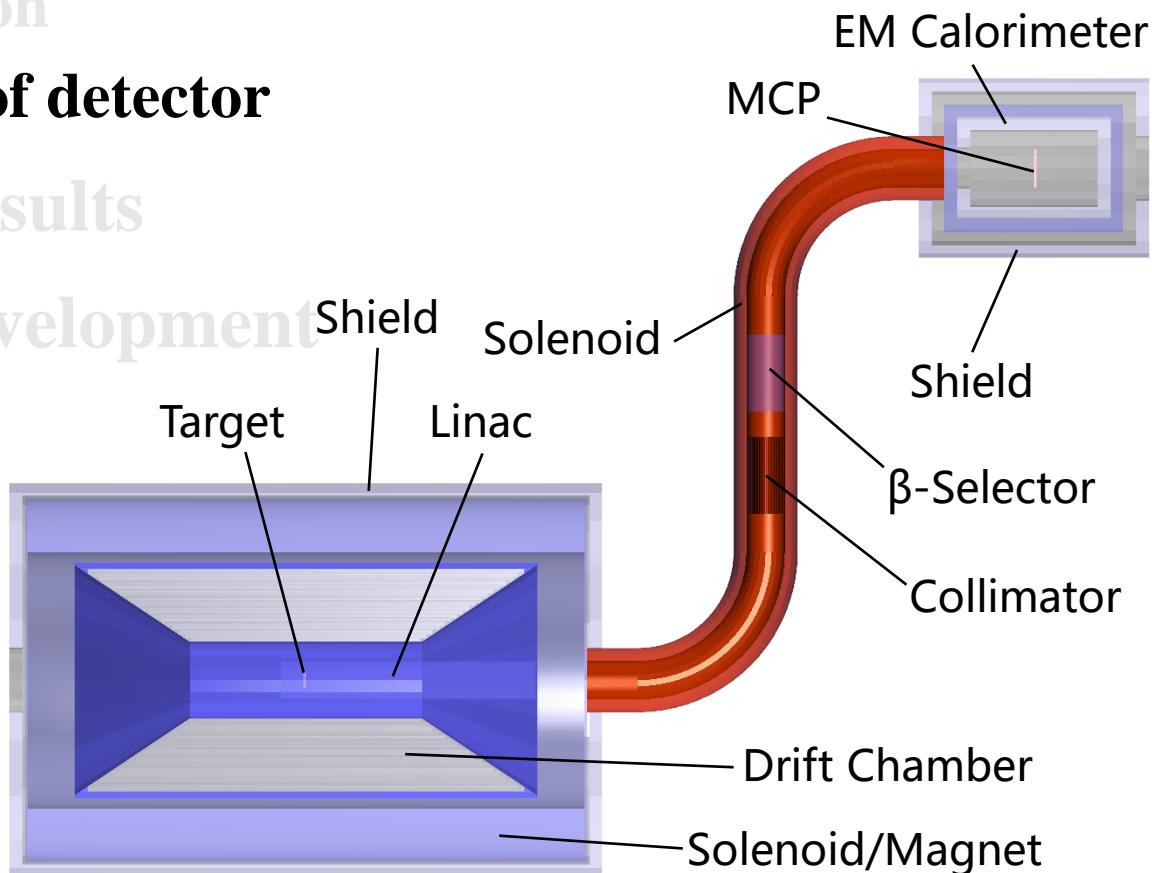
➤ Muonium Production

➤ Conceptual design of detector

● Preliminary MC Results

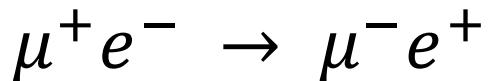
● Offline Software development

● Summary

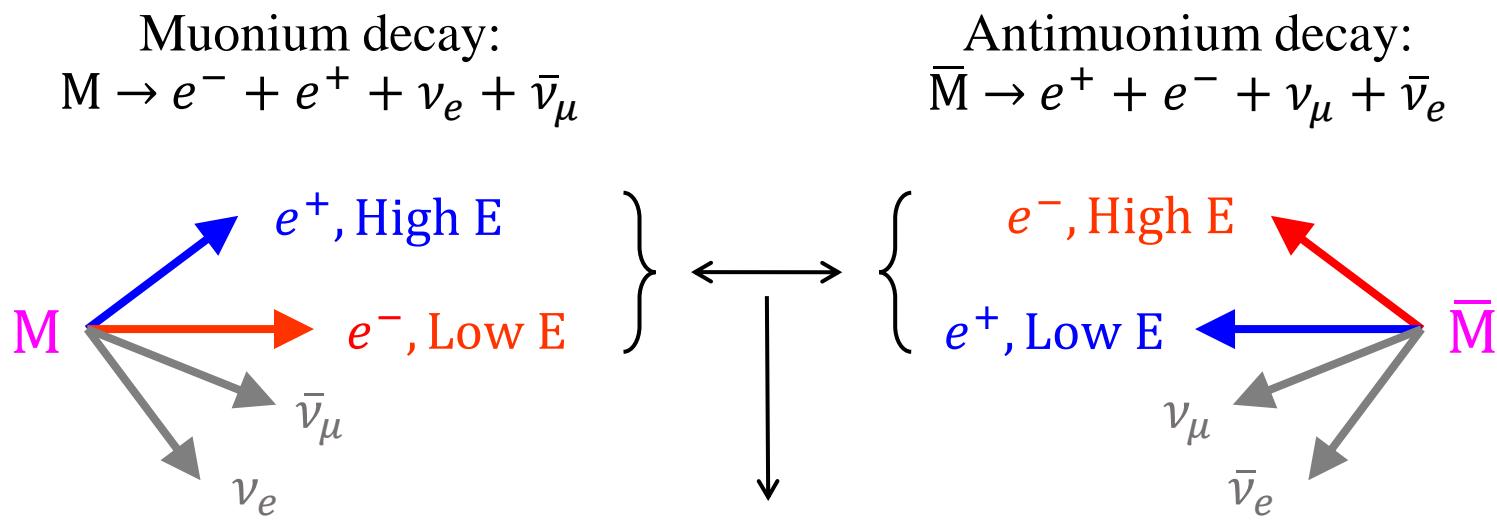


Conceptual design

- How to detect the muonium-antimuonium conversion?



- We can do this by identifying the final states:



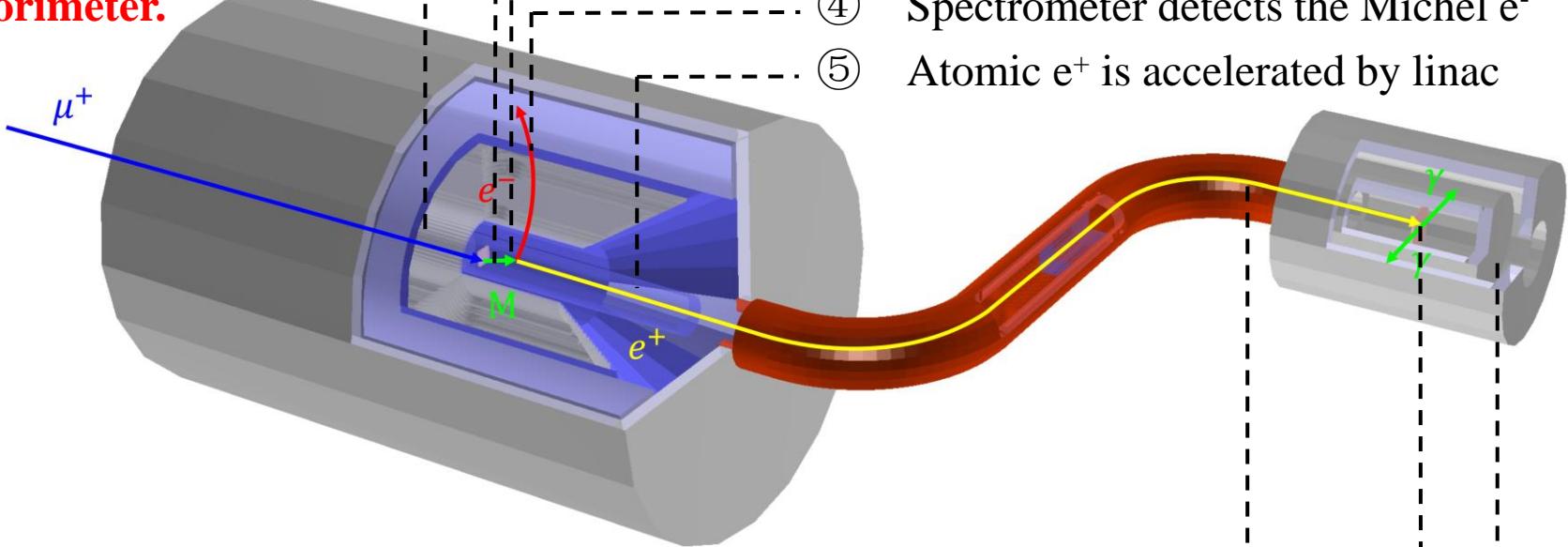
Searching for the conversion by vertex coincidence and charge identification.

Conceptual design



Basic concept:

The coincidence of spectrometer, MCP, and calorimeter.



- Spectrometer: identifies Michel e^- .
 - Vertex coincidence: Michel e^- track and e^+ transverse position projection.
 - Calorimeter: identifies atomic e^+ .
- ① Surface muon → Muonium
 - ② Muonium emission to vacuum
 - ③ M converts to \bar{M} and decay
 - ④ Spectrometer detects the Michel e^-
 - ⑤ Atomic e^+ is accelerated by linac
 - ⑥ Transport atomic e^+ to MCP
 - ⑦ MCP measure the transverse position
 - ⑧ Calorimeter detect the e^+ annihilation

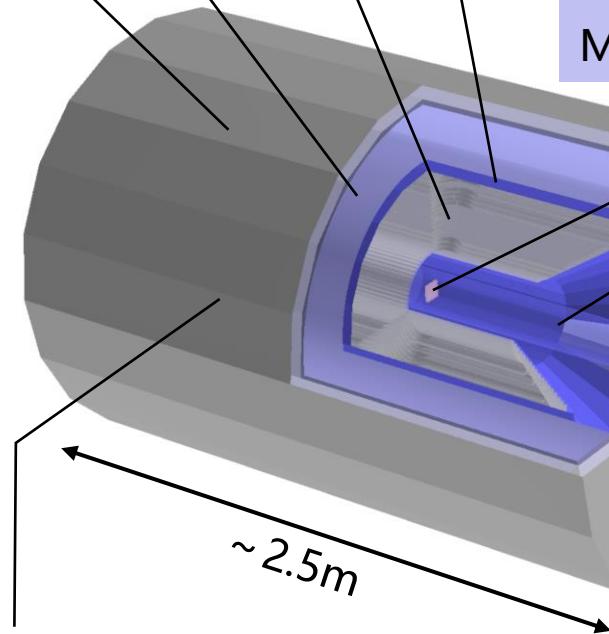
Conceptual design

Solenoid/Magnet Hodoscope

Shield

Drift
Chamber

$\sim 1.5m$



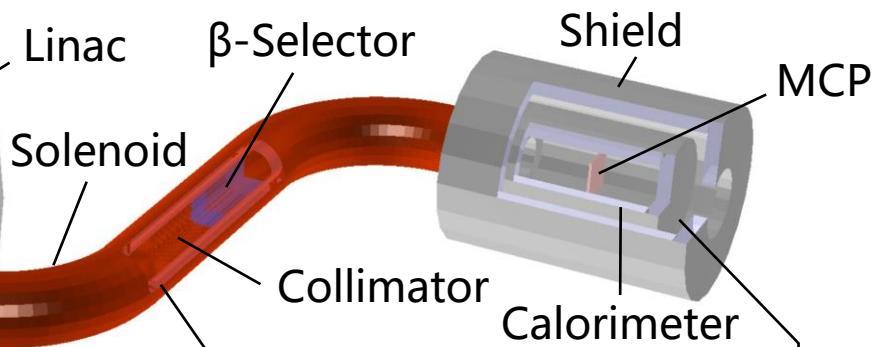
Muonium target

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

Linac, solenoid, collimator, β -Selector:
accelerate and transport $e^{+/-}$ to MCP

Spectrometer

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

Goal: charge error rate $< 10^{-5}$, position resolution ($< 3\text{mm}$), momentum resolution ($< 500\text{keV}/c$)

Tracking chamber: Drift chamber ($\cos\theta=0.9$)

Atomic $e^{+/-}$ detector

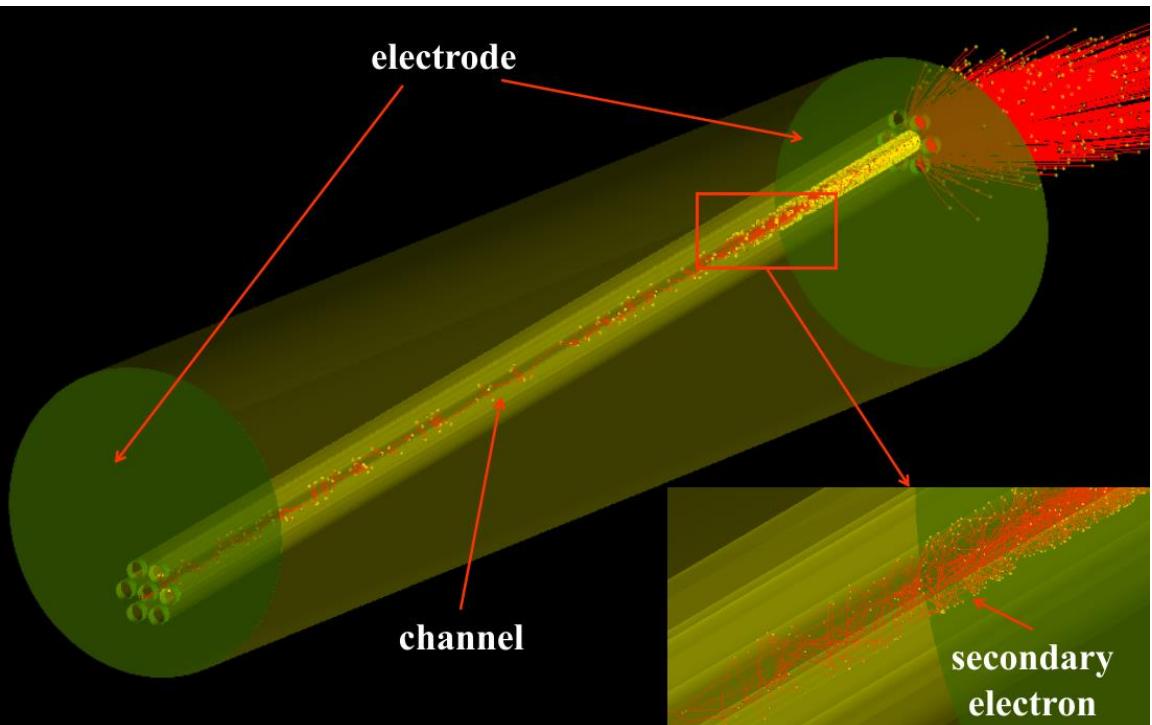
MCP: measures transverse position of $e^{+/-}$.

Calorimeter: detects γ of 511keV (e^+ annihilation).

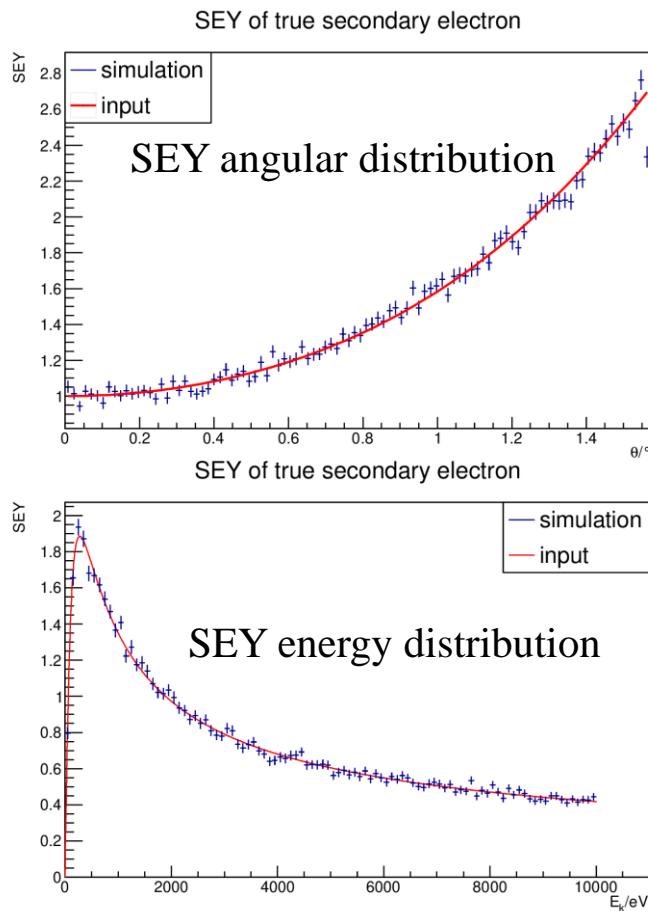
MCP response

- A general MCP simulation tool has been developed based on Geant4
- Implement Furman model to simulate the production process of secondary electron
- Simulation results are consistent with Furman model

Credit: Han Miao.

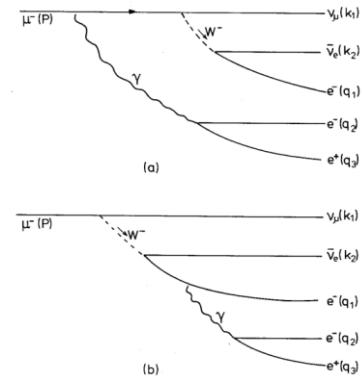
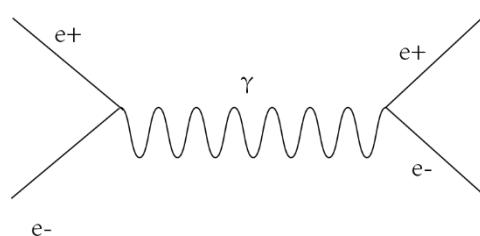


Parameter	Value
Thickness	0.48 mm
Radius of channel	3.0 μm
Angle of inclination	5.5°
Distance between channels	8.0 μm
Thickness of electrode	0.2 μm
Length of electrode in channels	3.0 μm
High voltage	800 V

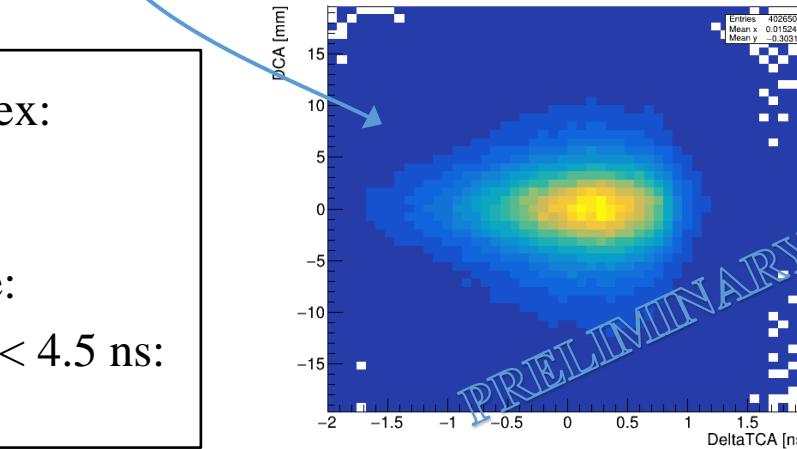
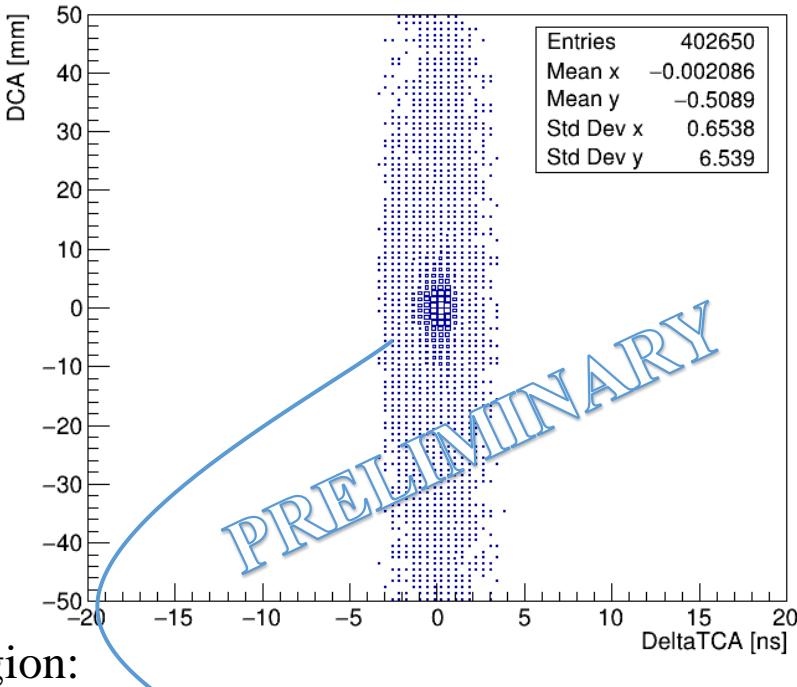
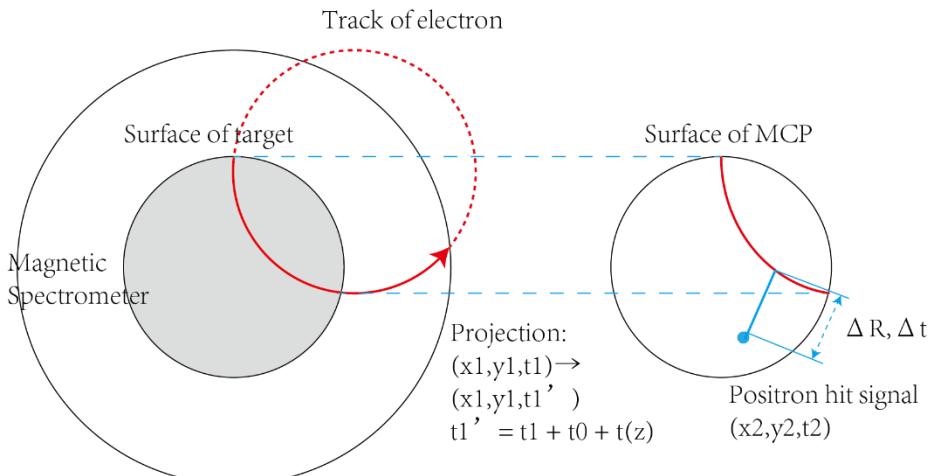


Monte Carlo: Fast Simulation

- Backgrounds:
 - μ^+ decays to e^+ , Bhabha scattering to generate high-energy e^- in coincident with low-energy e^+
 - μ^+ decays: $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu e^+ e^-$
- Anti-muonium decay signals by position-time coincidence



Monte Carlo: Fast Simulation



- Injected muons:
 2×10^8 of μ^+
- Resolution better than PSI muonium formation results.

- Happen at the same vertex:
 $|\Delta R| \sim DCA < 12.0$ mm
- Happen at the same time:
 $|\Delta t| \sim \text{TOF-TOF}_{\text{expected}} \sim TCA < 4.5$ ns:
 $\text{TOF} = t_0 + t(z)$

Status of simulation software

- MACE offline software: designed for R&D, simulation & physics study.
- Designed and programmed with C++ best practice and pattern.

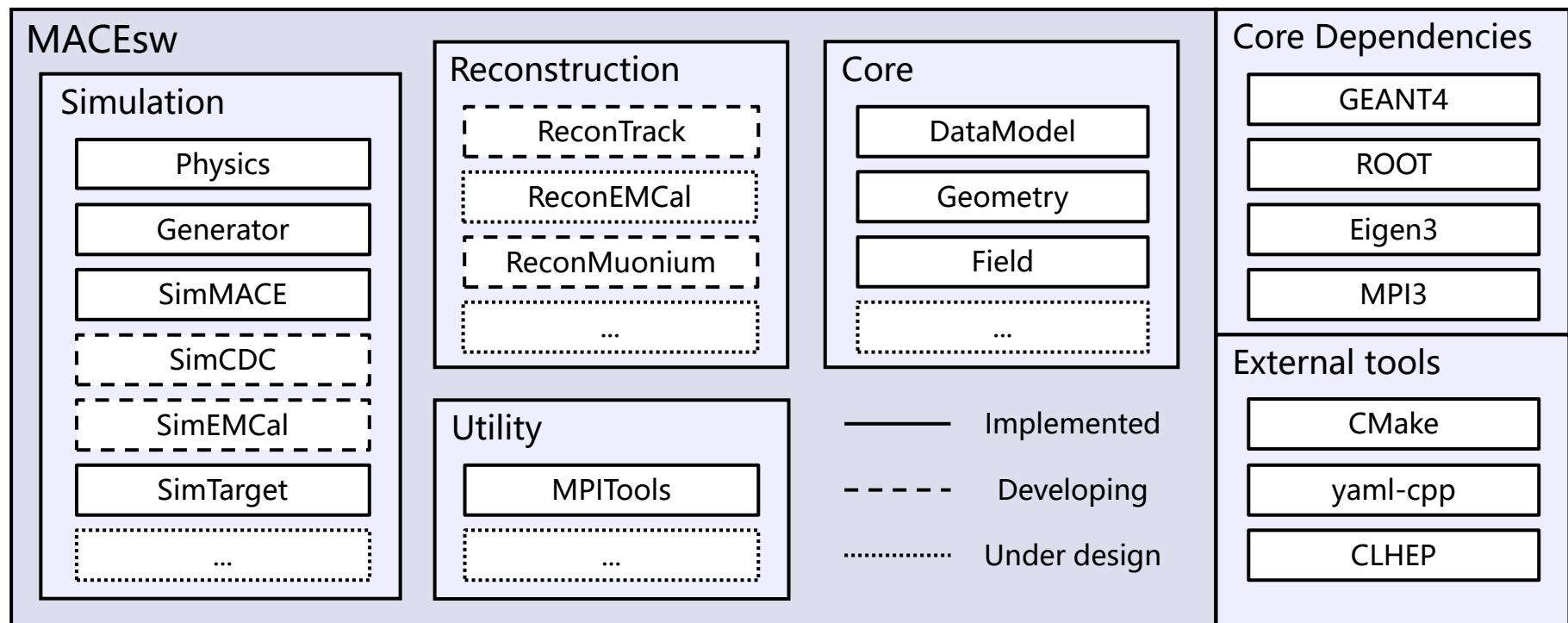




Table of contents

- Motivation
- Simulation and Optimization
 - Muonium Production
 - Conceptual design of detector
- Preliminary simulation results
- Summary

Summary

- Low energy muon beam serves as a probe of physics beyond SM and precision measurement of QED.
- In YGA bay area, it is time to build the first accelerator muon beamline in China and start accelerator muon-based physics study.
- MACE is one of the recently proposed cLFV experiments with a muon source.
- R&D of the muon beamline, muonium production and transportation, design of vertex & timing coincident identification of signals by magnetic spectrometer and MCP.
- Aim at more than two orders of magnitude improvement compared to the latest result in PSI done two decades ago.
- Welcome to joining the R&D efforts or offering precious suggestions/comments.

Acknowledgement:

- *Financial support from NSFC grant no. 1275326.*
- *Innovation Training Program for bachelor students at School of Physics in SYSU.*
- *Silica aerogel sample offered by Prof. Jian Zhang, School of Materials.*

THANK YOU