MACE Experiment in China

Jian Tang (Sun Yat-sen University, China)

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Osaka University—Chen Wu

Muonium to Antimuonium Conversion Experiment(MACE)

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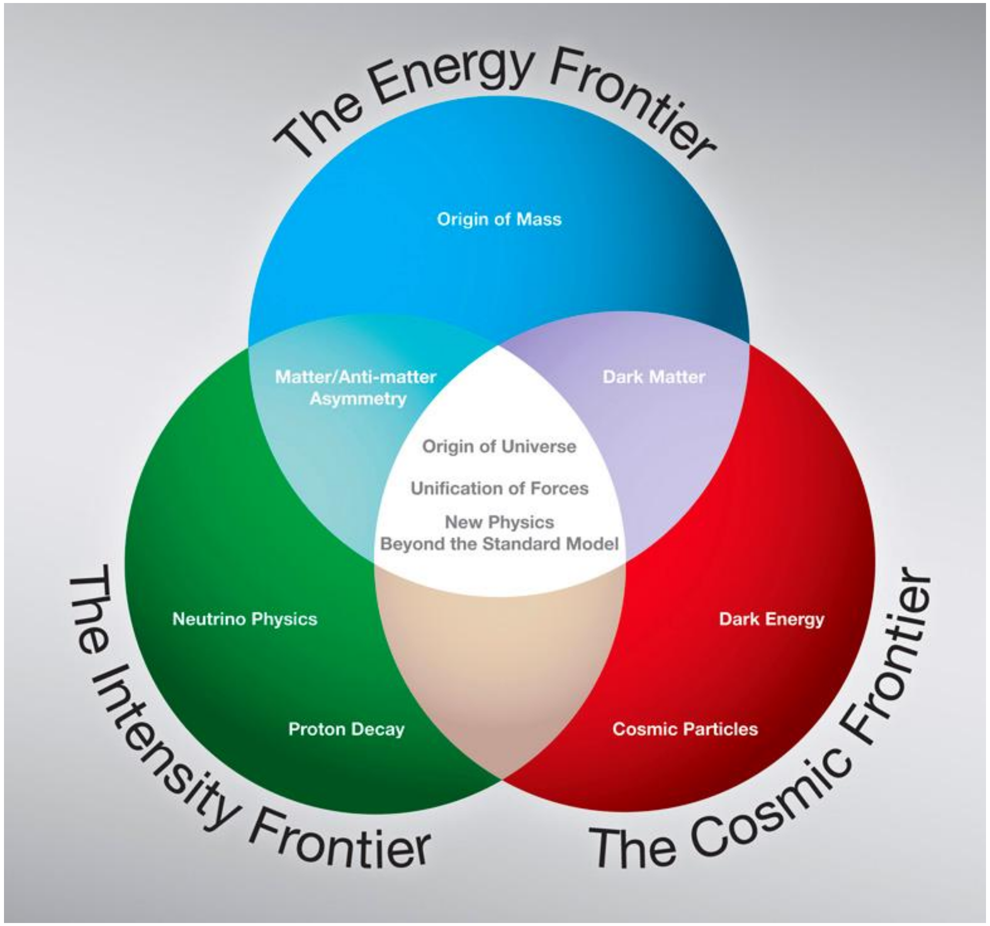
Frontiers in Particle Physics



- High Energy Frontier
- High Intensity Frontier
- Cosmic Frontier

Searching for BSM:

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

The Intensity Frontier

- Neutrino Experiments:
  - T2K, NOvA, T2HK, DUNE…
  - JUNO…
- Search for cLFV：
  - Mu2e $\mu^- + \text{Al} \to e^- + \text{Al}$
  - COMET $\mu^+ \to e^+\gamma$
  - MEG $\mu^+ \to e^+e^-e^+$
  - Mu3e
- Precision measurements with muons：
  - Muon lifetime measurments: MuLan and FAST (PSI).
  - Singlet muon capture on proton: MuCap.
  - Muon capture on the deuteron: MuSun.
  - Michel parameters of muon decay: TWIST (TRIUMF).
  - Muon magnetic momentum: E821, Fermilab g-2, J-PARC g-2.
  - Muonium hyper-fine structure: MeuSEUM (J-PARC).

Snowmass2021 - Letter of Interest **RF5-RF0-126**

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)]*

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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.

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Probing the doubly charged Higgs boson with a muonium to antimuonium conversion experiment

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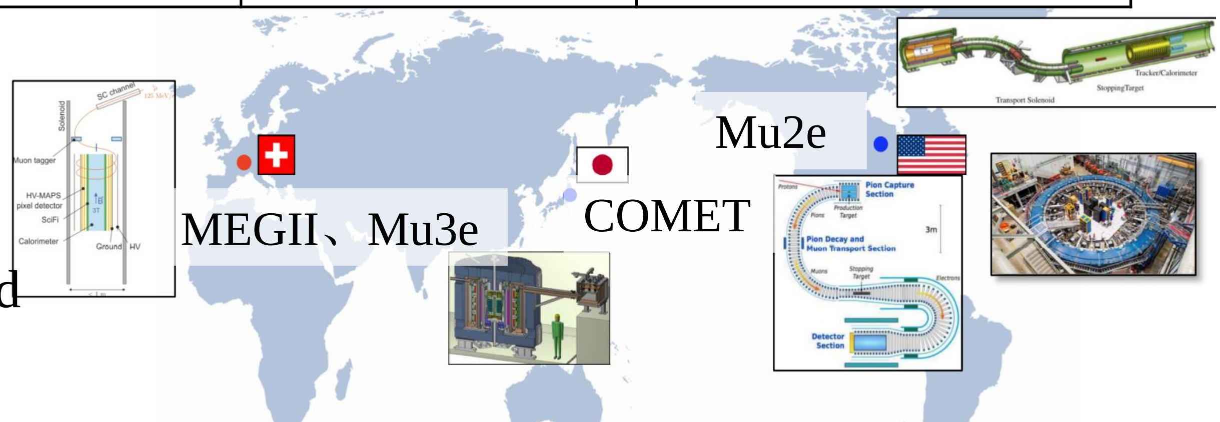
Searching for cLFV: Experimental Efforts

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

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



- With the improvement of beam and the progress of detector technology, it is expected to make a breakthrough.

EXPERIMENT	FACILITY	STATUS
MACS (1999)	PSI (Switzerland)	Completed
MACE	Muon beamline (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

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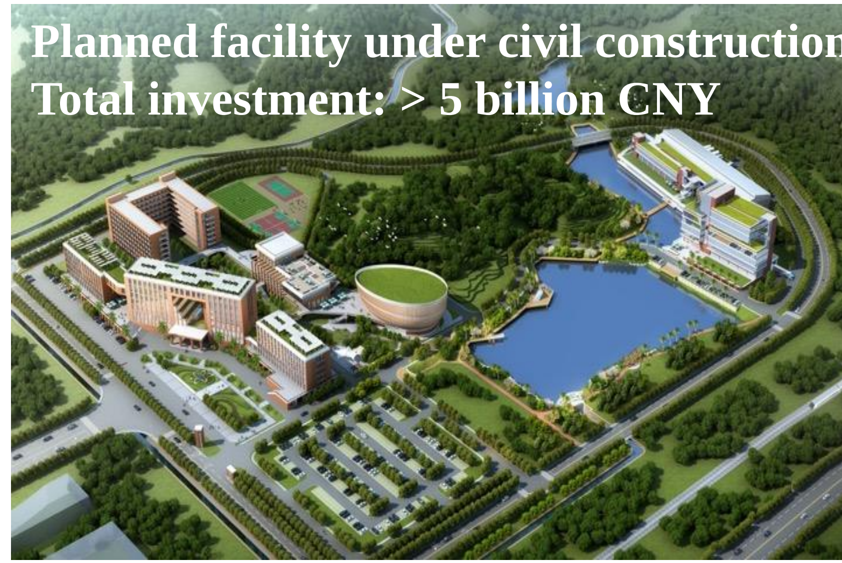
The spontaneous muonium to antimuonium conversion is one of the interesting charged lepton flavor violation processes. It serves as a clear indication of new physics and plays an important role in constraining the parameter space beyond Standard Model. MACE is a proposed experiment to probe such a phenomenon 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

Heavy Ion Accelerator Facility (HIAF) &
China initiative Accelerator Driven Sub-critical system (CiADS): 500MeV 5mA CW proton beam



Ref：Sheng Wang from IHEP

Ref：Wen-Long Zhan from IMP

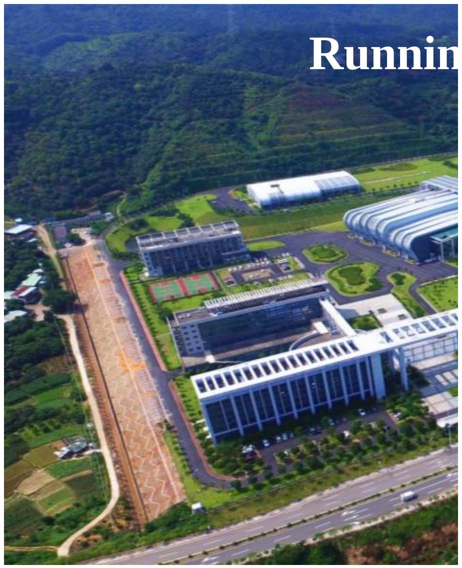
Three accelerator facilities in this bay area: CSNS v.s CiADS&HIAF

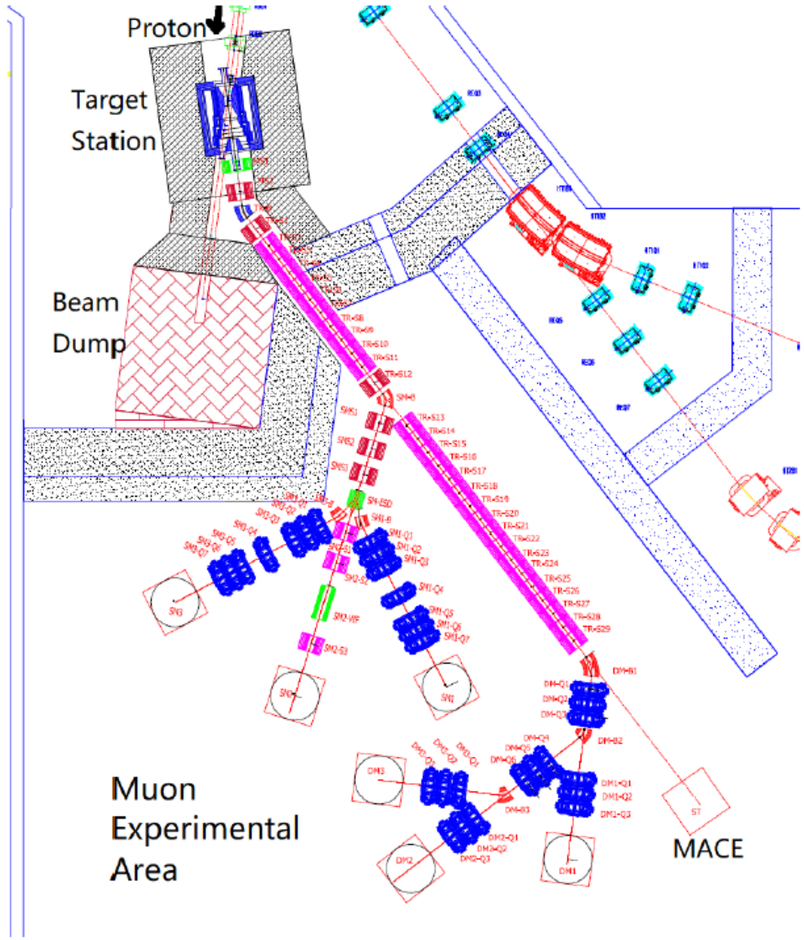
- Which one will build the first accelerator muon source in China within next 5 years?
- Time to propose something on fundamental physics with accelerator muons.

Accelerator centers in the YGA Bay area

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

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

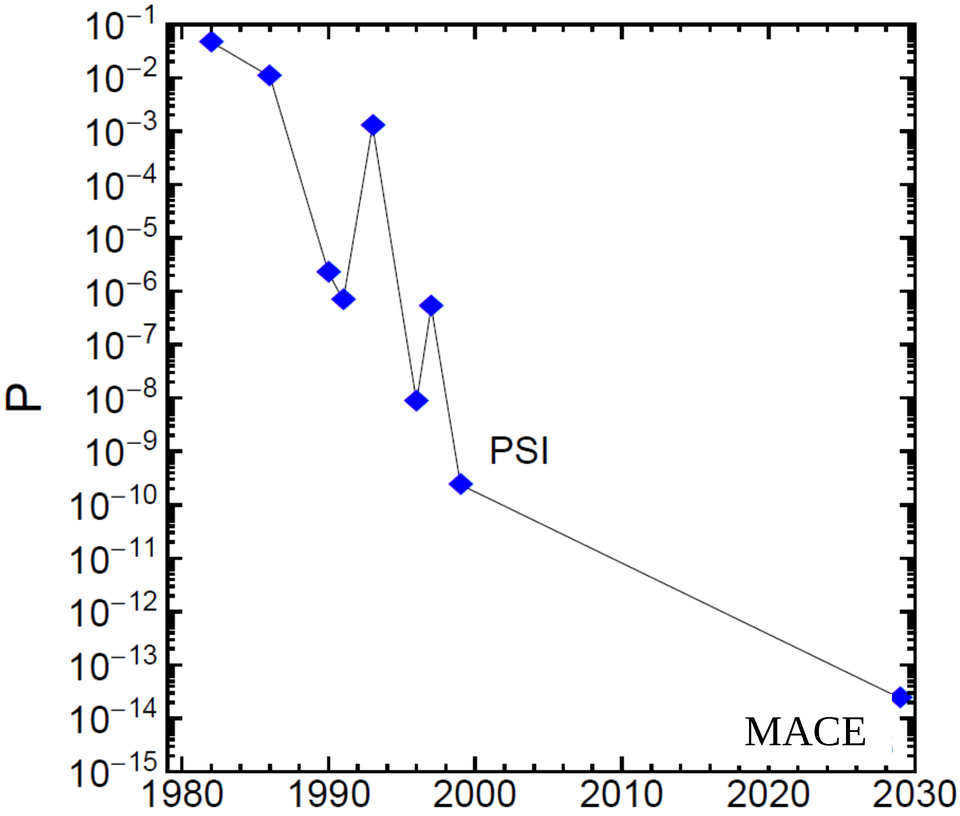




Ref: Sheng Wa ı-Long Zhan from IMP

Three accelerator faci IAF

- Which one will bui ıina within next 5 years?
- Time to propose s ccelerator muons.



- Latest result of muonium-antimuonium conversion (MACS, PSI, 1999):

  $P_{M\bar{M}} < 8.3 \times 10^{-11}$ (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

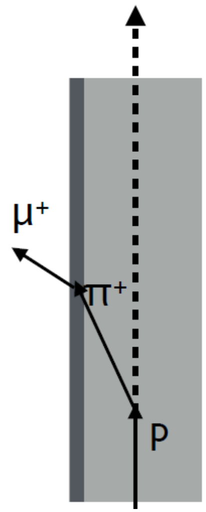
Muon and muonium production

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

$$\propto n \cdot \sigma_{\pi^+} \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_C (6/12)_C}{\rho_x (Z/A)_x}$$

$$\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z}$$

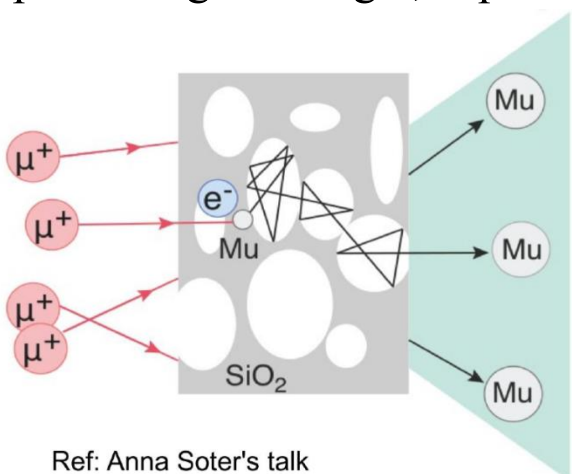
$$\propto \frac{1}{Z^{2/3}}$$



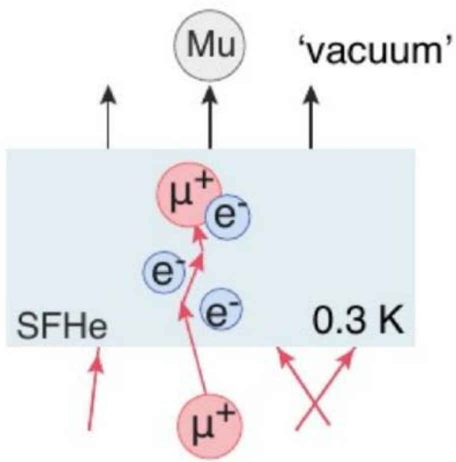
Previous experience

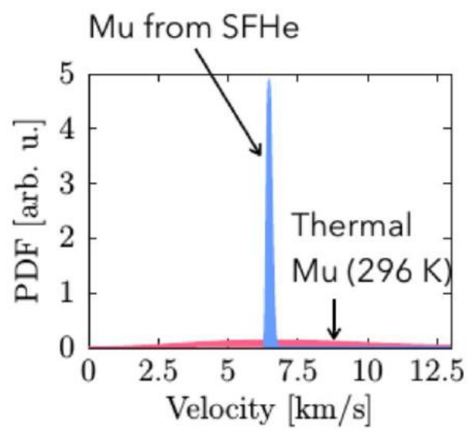
- Hot tungsten in 1986: 4% from 4 MeV μ^+
- SiO_2 powder in 1990: 1%-2% from 4 MeV μ^+
- SiO_2 film(cold) in 2012: 40% from 5 keV μ^+

Proposed target: aerogel, super fluid helium…



Silica powder





Super Fluid Helium

Muonium production and transportation

μ^+ (~1MeV) scattering

↓

Electron capture (~1keV)

↓

Muonium (~100eV)
Epithermal scattering

↓

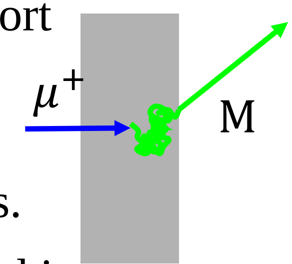
Random walk (Room temp.)

↓

Emission to vacuum

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

MC simulation for muonium transport has been developed.



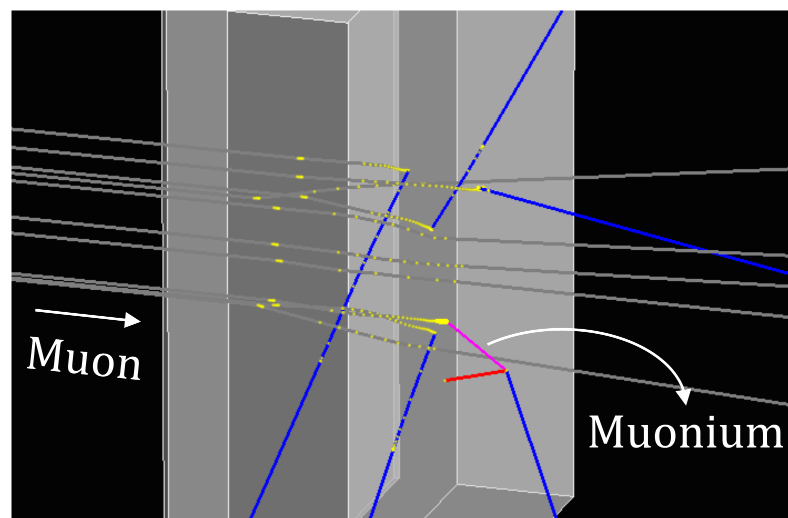
① Geant4 low-energy EM process.

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:



Content

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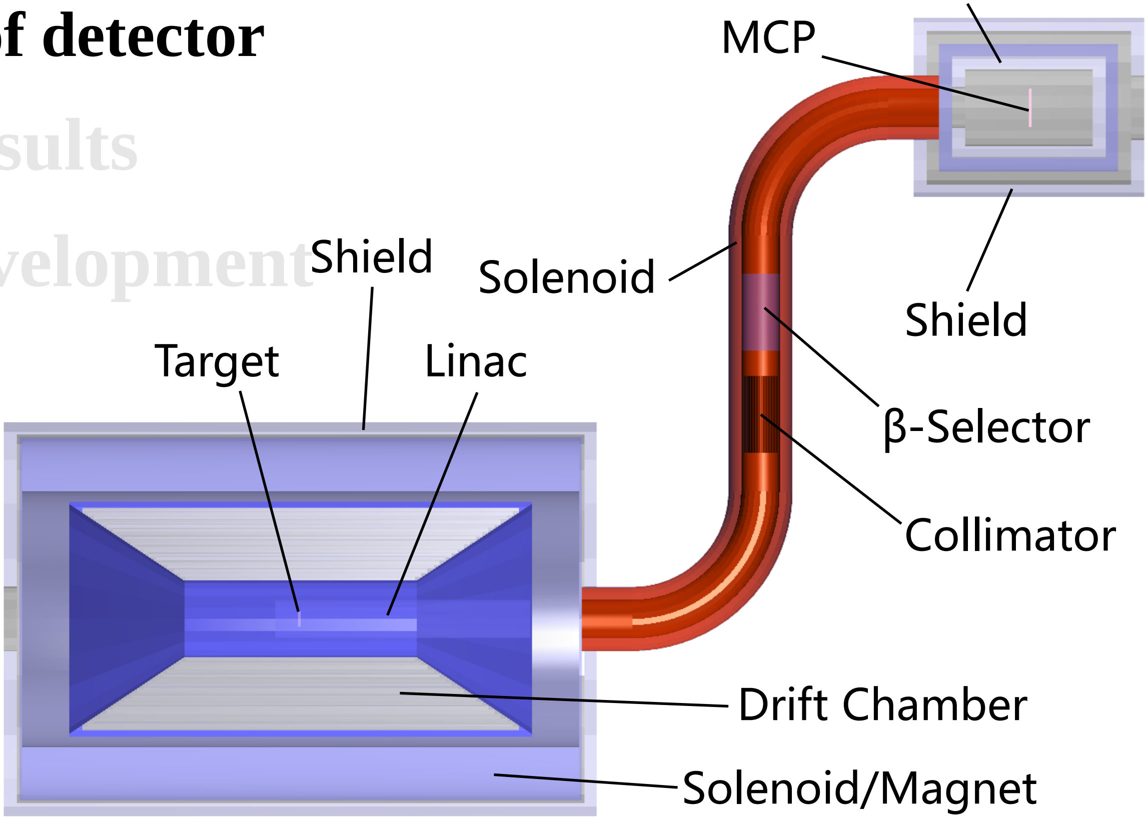


Conceptual design

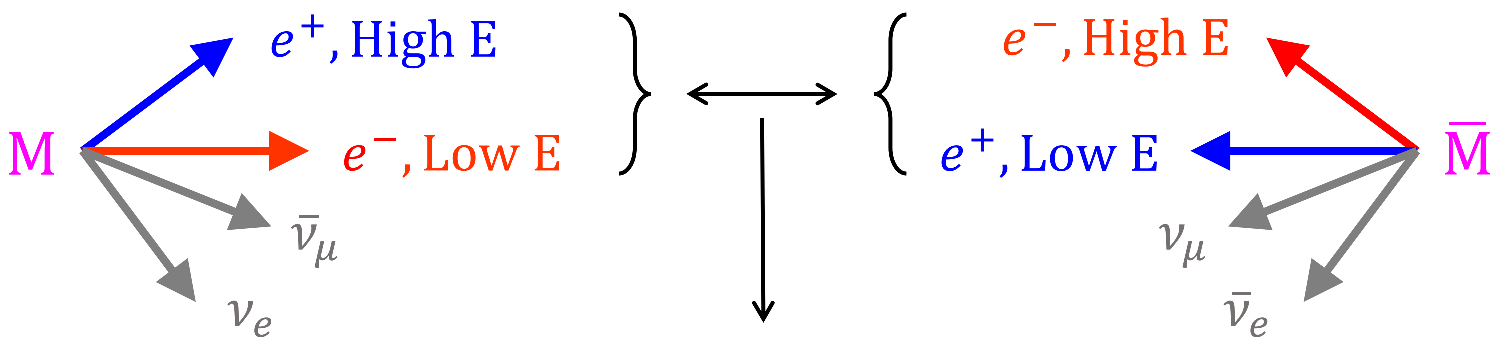
- How to detect the muonium-antimuonium conversion?

$$\mu^+ e^- \rightarrow \mu^- e^+$$

- We can do this by identifying the final states:

Muonium decay:
$\mathrm{M} \rightarrow e^- + e^+ + \nu_e + \bar{\nu}_\mu$

Antimuonium decay:
$\overline{\mathrm{M}} \rightarrow e^+ + e^- + \nu_\mu + \bar{\nu}_e$

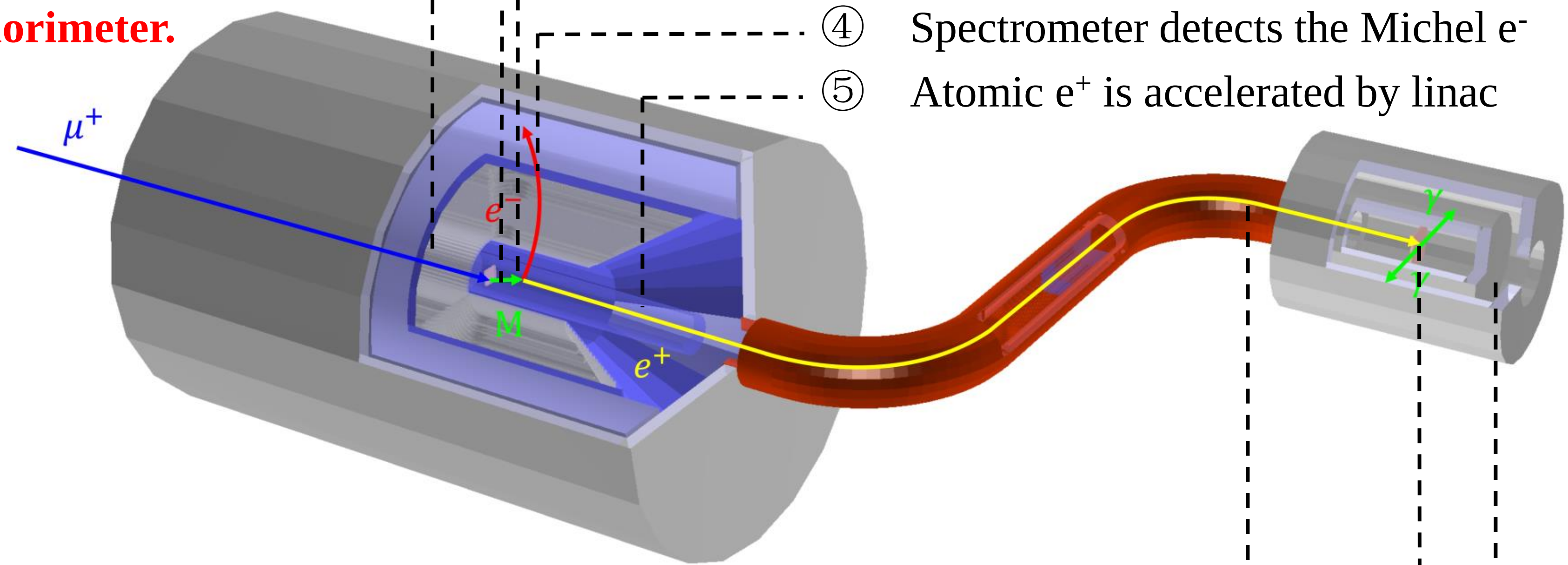


Searching for the conversion by vertex coincidence and charge identification.

Conceptual design

Basic concept:
The coincidence of spectrometer, MCP, and calorimeter.

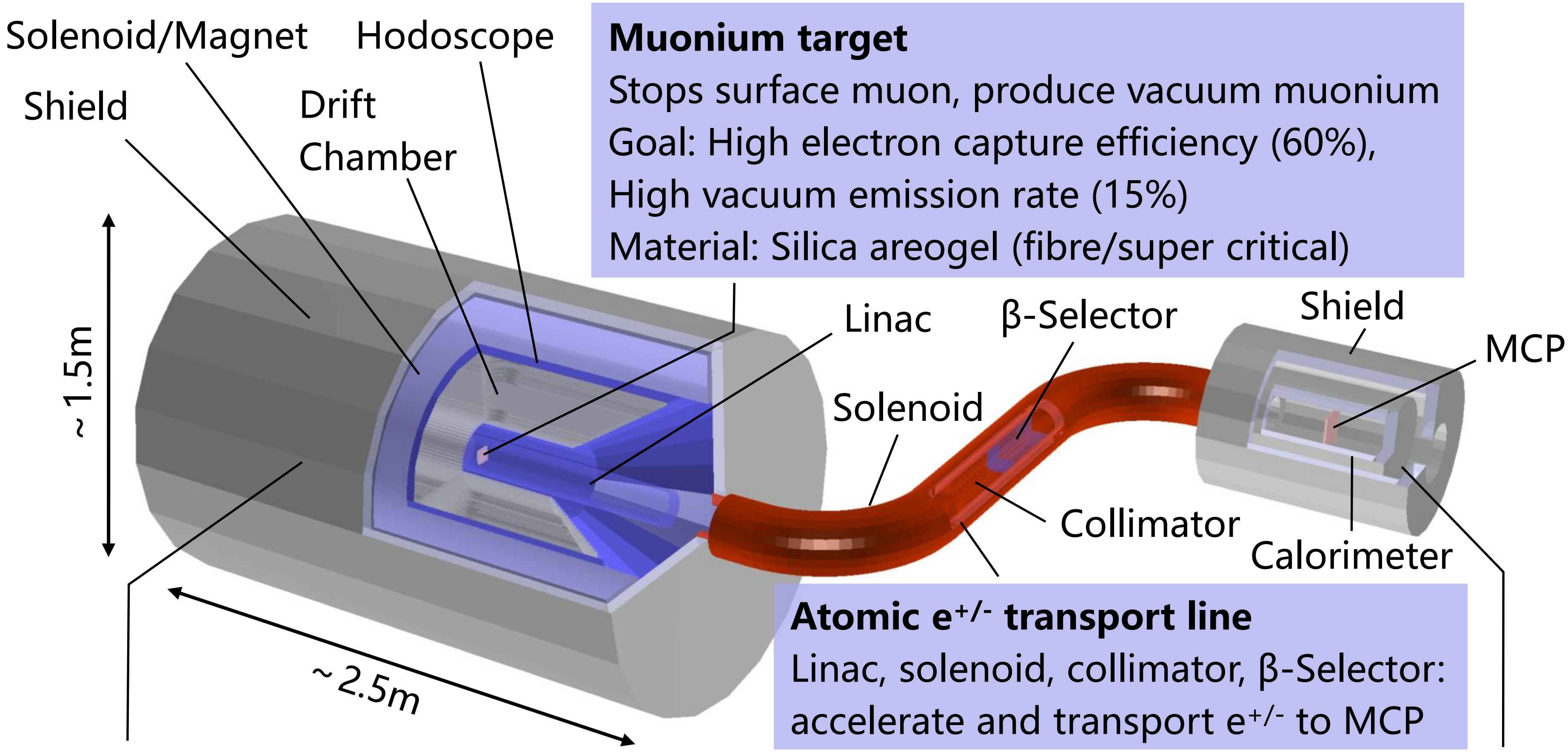
① Surface muon → Muonium
② Muonium emission to vacuum
③ M converts to $\overline{\mathrm{M}}$ and decay
④ Spectrometer detects the Michel e^-
⑤ Atomic e^+ is accelerated by linac



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

⑥ Transport atomic e^+ to MCP
⑦ MCP measure the transverse position
⑧ Calorimeter detect the e^+ annihilation

Conceptual design



Muonium target
Stops surface muon, produce vacuum muonium
Goal: High electron capture efficiency (60%), High vacuum emission rate (15%)
Material: Silica areogel (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 (<3mm), momentum resolution (<500keV/c)
Tracking chamber: Drift chamber (cosθ=0.9)

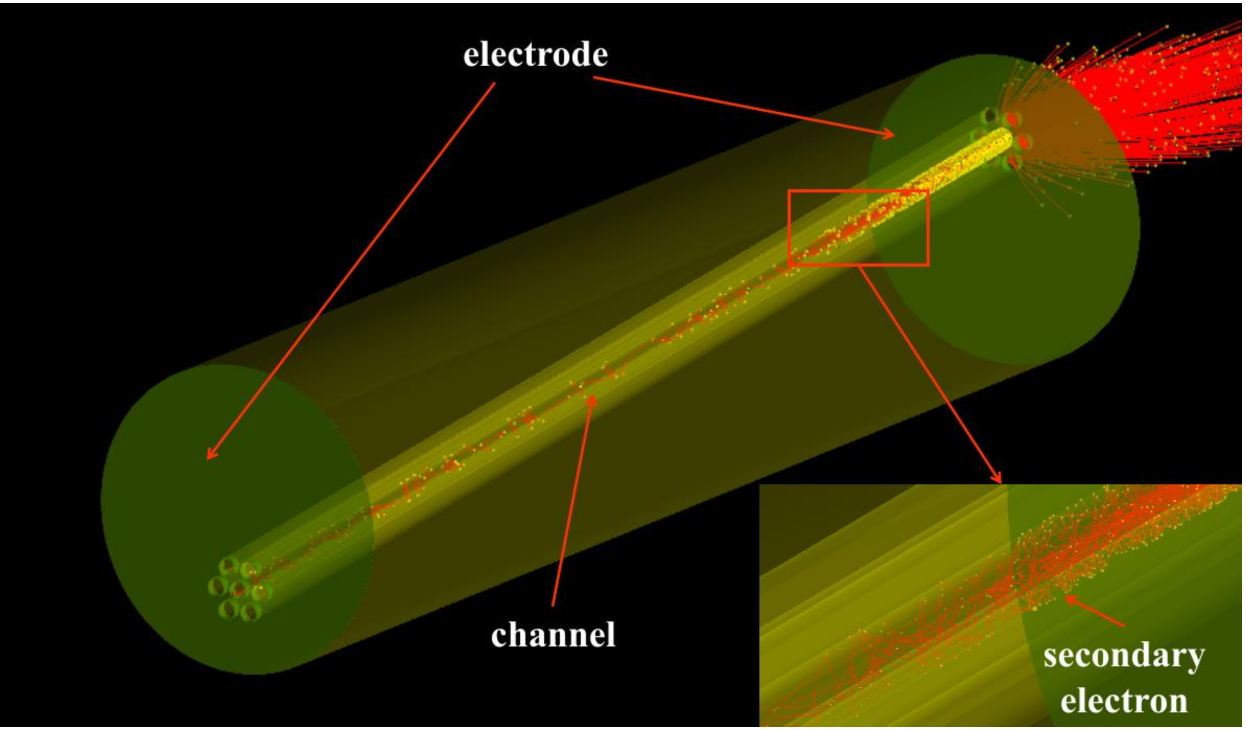
Atomic $e^{+/-}$ detector
MCP: measures transverse position of $e^{+/-}$.
Calorimeter: detects γ of 511keV (e^{+} annihilation).

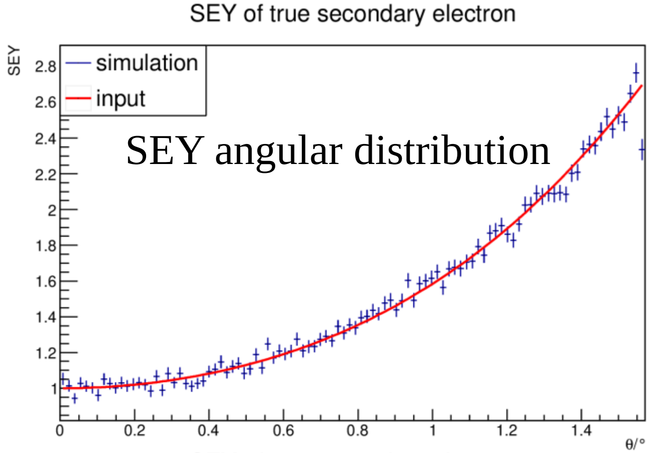
MCP response

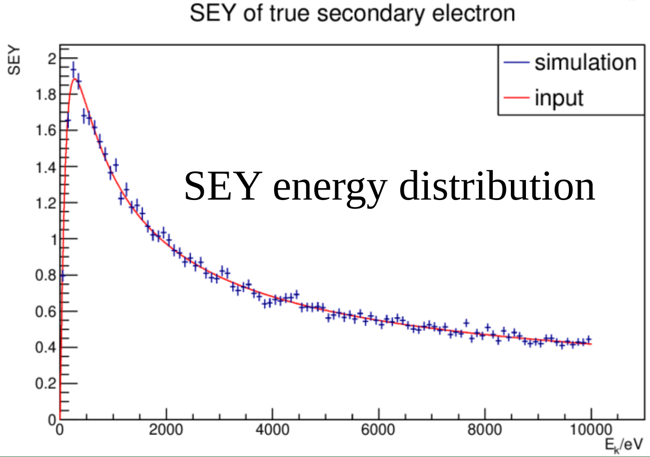
- A general MCP simulation tool has been developed based on Geant4
- Implement Furman model to simulate the production process of secondary electron
- Simulation results are consistent with Furman model

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

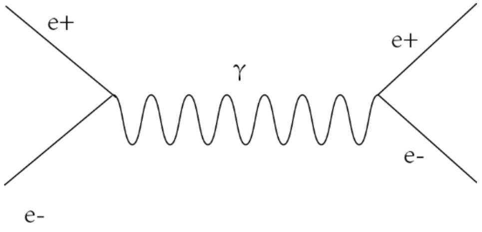


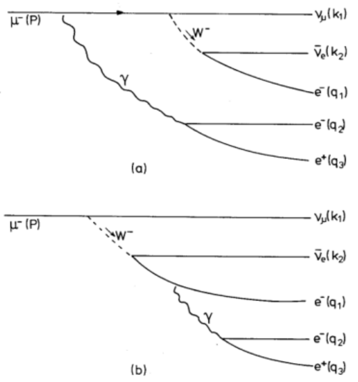


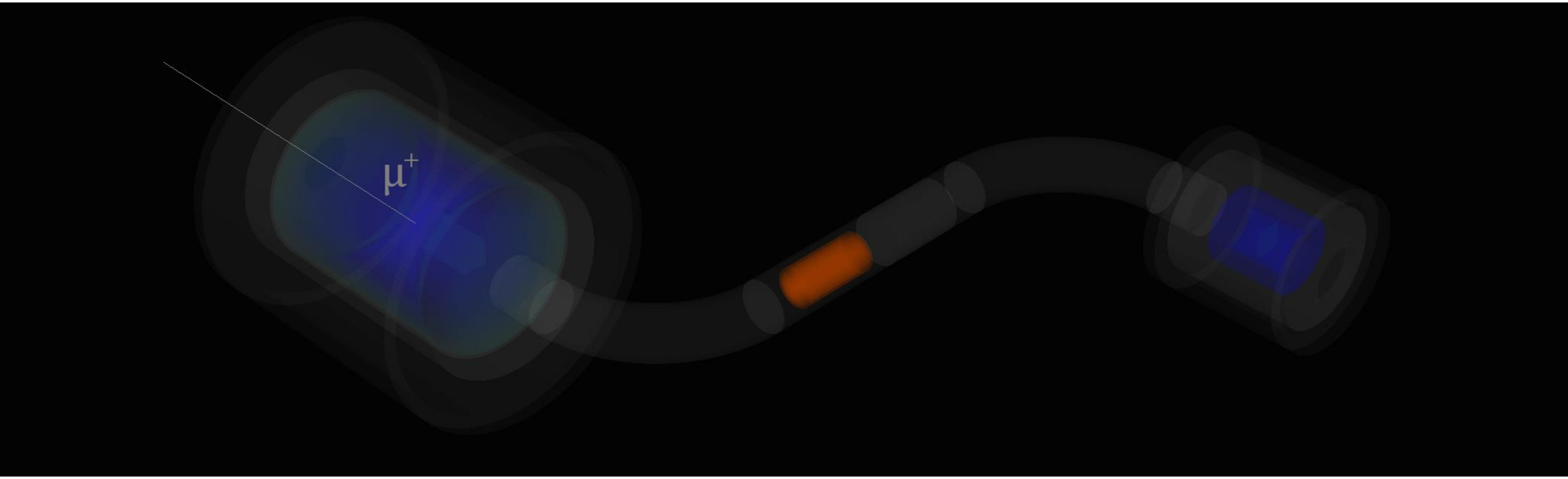


Monte Carlo: Fast Simulation

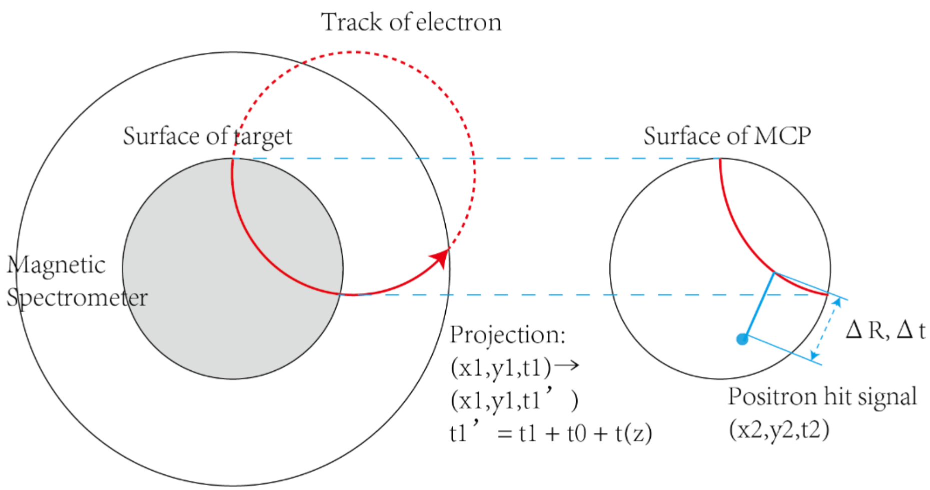
- Backgrounds:
  - μ^+ decays to e^+, Bhabha scattering to generate high-energy e^- in coincident with low-energy e^+
  - μ^+ decays: $\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu} e^+ e^-$
- Anti-muonium decay signals by position-time coincidence

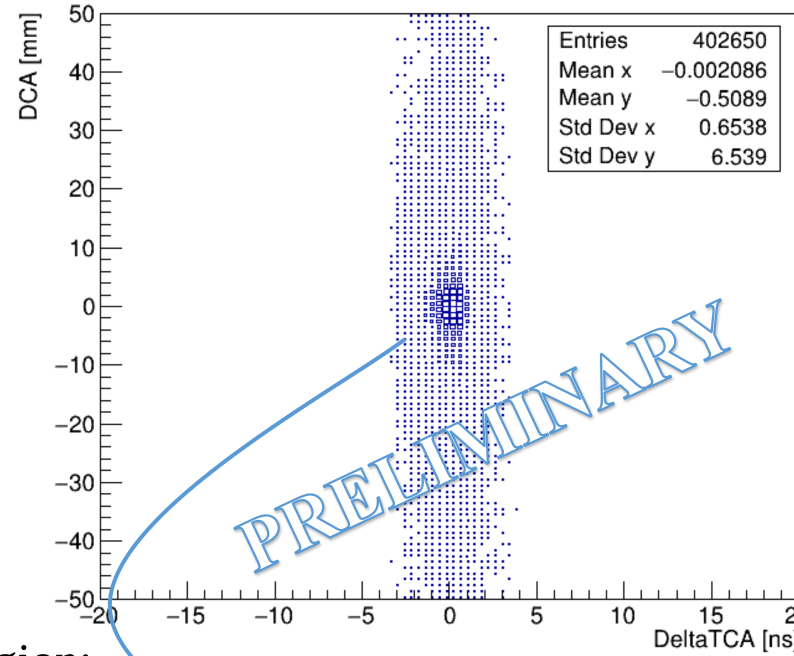




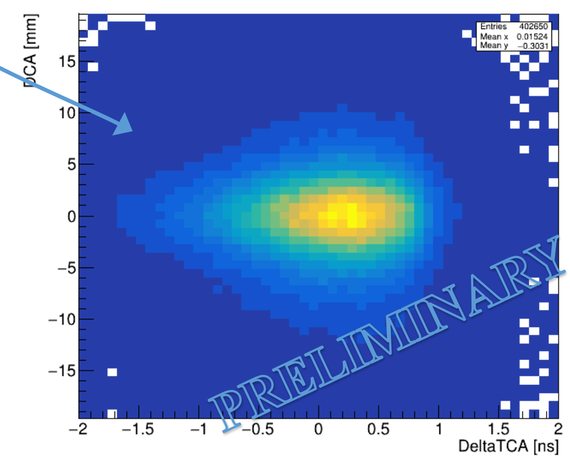


Monte Carlo: Fast Simulation





3σ Region:



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

- Happen at the same vertex:

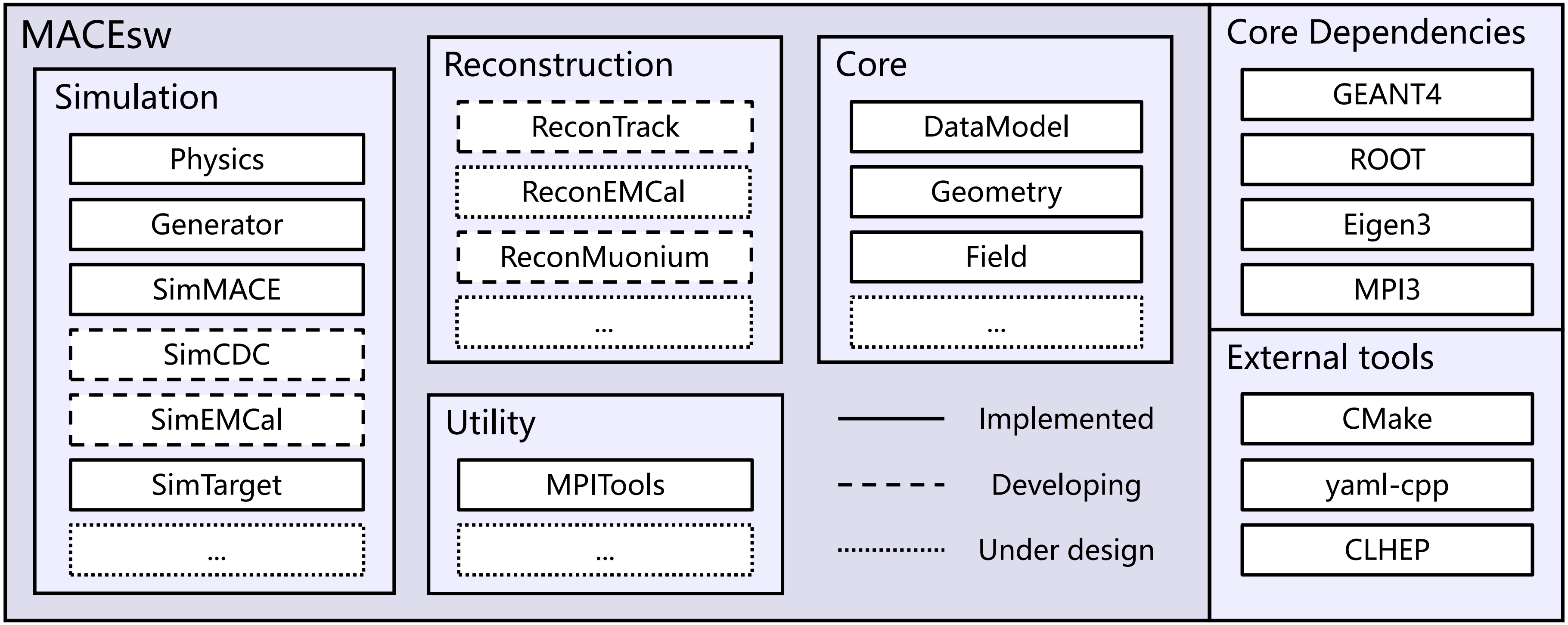
|ΔR|~DCA < 12.0 mm

- Happen at the same time:

|Δt|~TOF-TOF$_{expected}$ ~TCA< 4.5 ns:
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.



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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 related 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. The proposal is still at the preliminary stage→ there is a long way to go!
- Welcome to joining the R&D efforts or offering precious suggestions/comments.

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THANK YOU