Experimental Prospects for Fundamental Physics with Muonium

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Reference: Snowmass2021 Whitepaper: Muonium to antimuonium conversion, arXiv:2203.11406

Content

- **Motivation**
- **Conceptual Design of MACE**
- **Simulation Result**
- **Summary**

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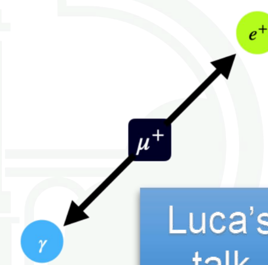
Searching for cLFV

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

Andrew's talk

Jian's talk

Frederik's talk



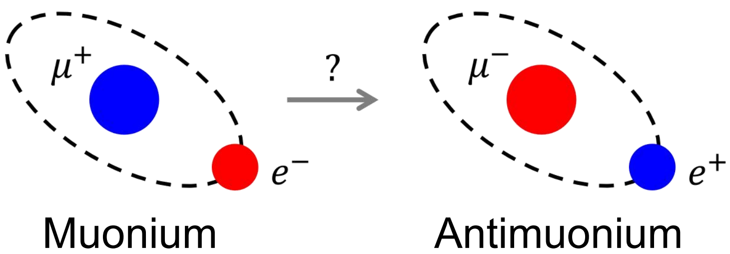
Luca's talk

- 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.

Muonium Conversion: a cLFV Process

- Muonium ($\mu^+ e^-$): a leptonic isotope of hydrogen;
- Muonium conversion is induced by an interesting pheno-menological possibility: muonium mixing.

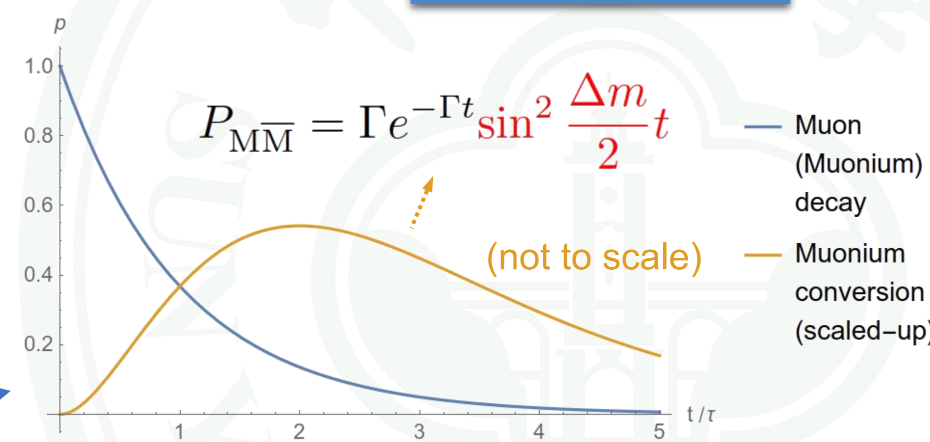
Yuichi Uesaka's talk

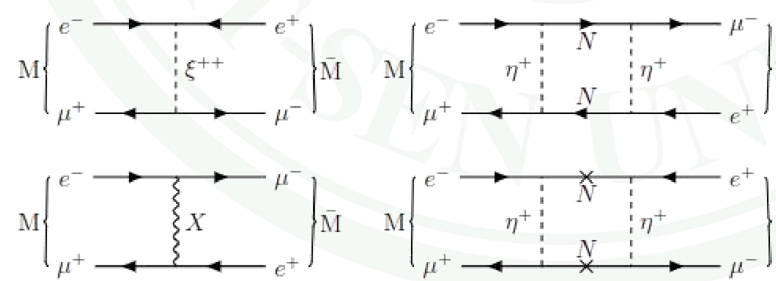


$$i\frac{\partial}{\partial t}|\psi\rangle = \mathcal{M}|\psi\rangle \qquad |\psi\rangle = \alpha(t)|\mathrm{M}\rangle + \beta(t)|\overline{\mathrm{M}}\rangle$$

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

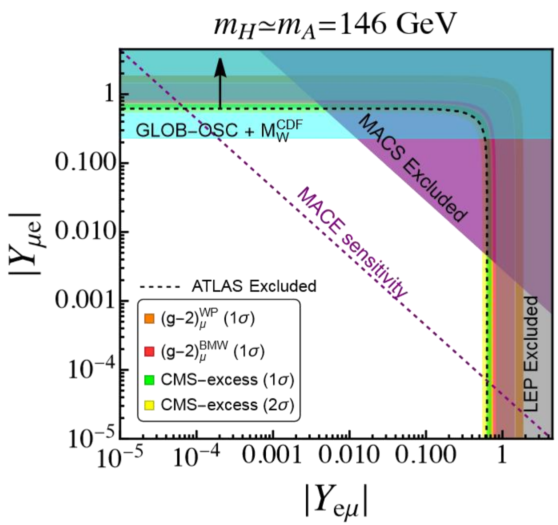
$$\mathcal{L} \supset \sum_{i=1}^{5} \frac{-G_i(\mathcal{M})}{\sqrt{2}} \langle\overline{\mathrm{M}}|Q_i|\mathrm{M}\rangle$$





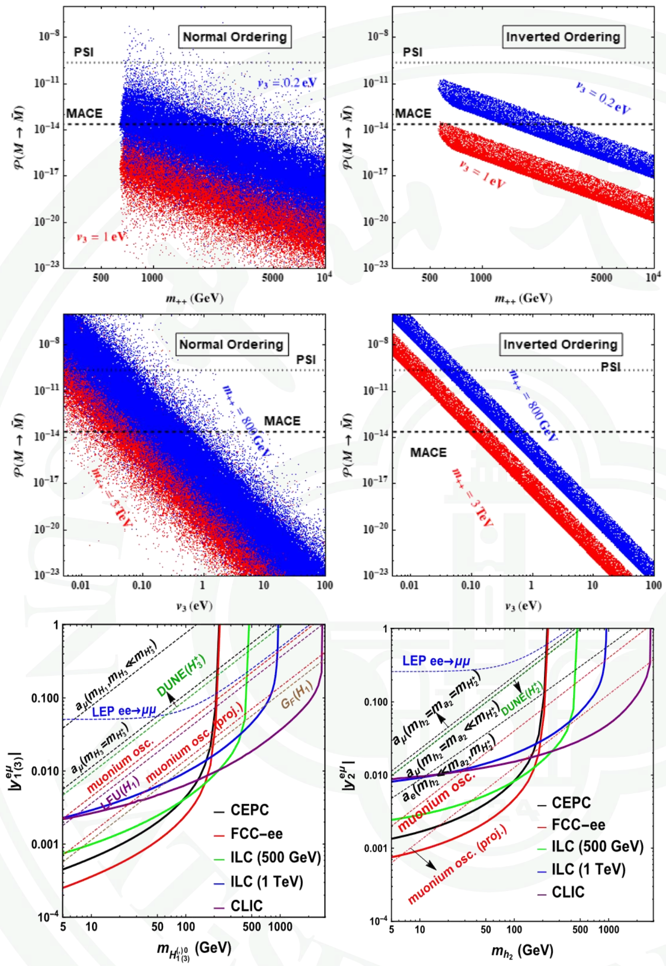
Why Muonium Conversion?

- 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

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

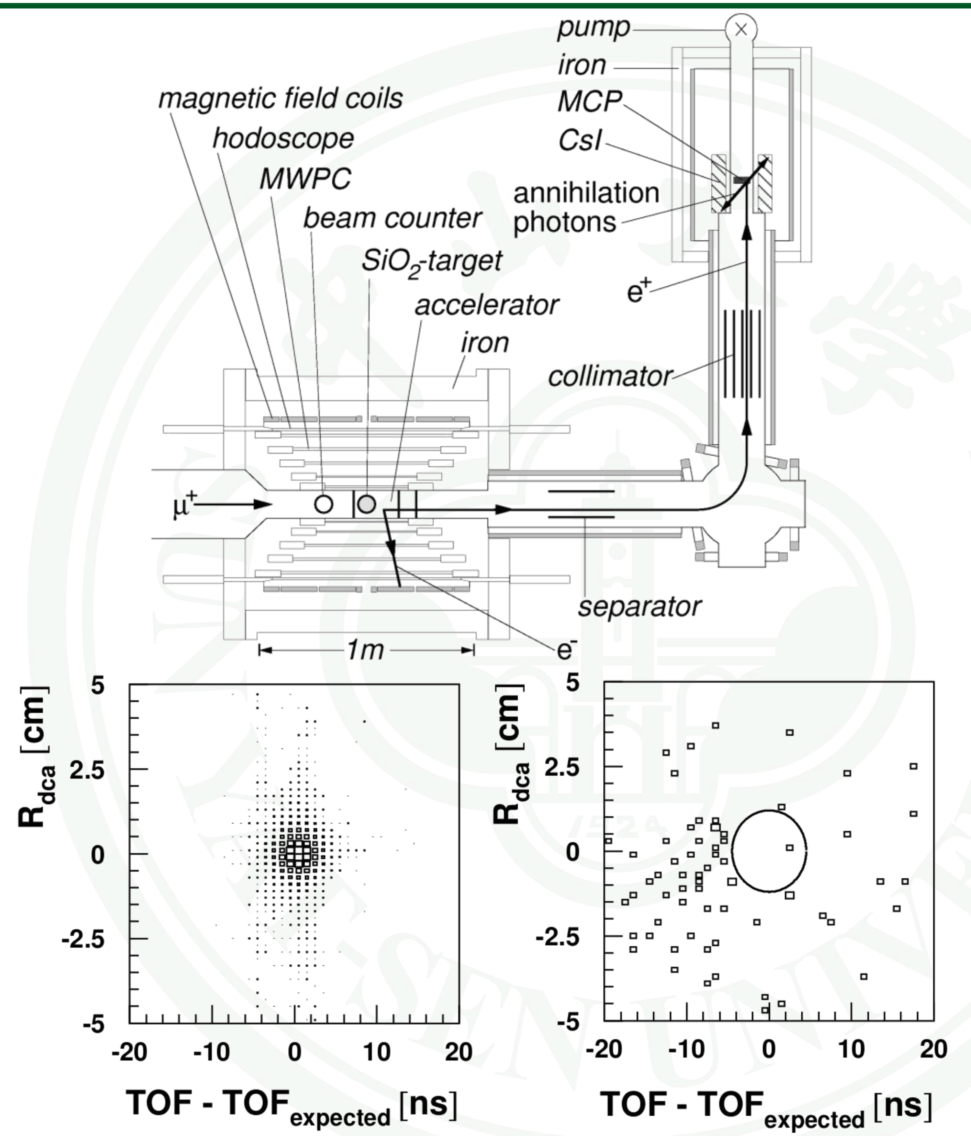
What Happened in History?

- Current limit (L. Willmann, 1999):

  $P_{M\bar{M}}$ < 8.3×10^{-11} (90% C.L.).

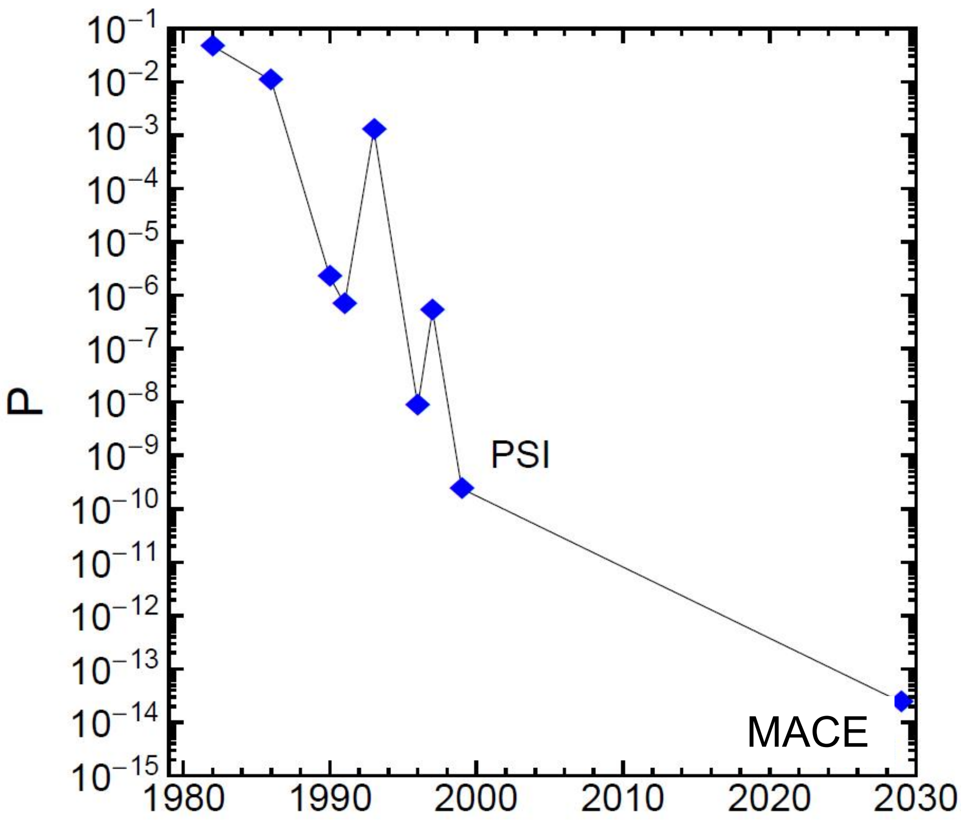
- Can we do substantially better?

- 20 years later:
  - Detector technology and design is improving.
  - Muon beam luminosity is much higher.
  - Better muonium targetry.



L. Willmann et al. New bounds from searching for muonium to anti-muonium conversion, Phys.Rev.Lett. 82 (1999), 49-52.

MACE: Shed Light on New Physics



- **MACE**: The first proposed muonium-to-antimuonium conversion experiment since 1999, we plan to improve the sensitivity by more than two orders of magnitude.
- Together with other flavor and collider searches, we will shed light on the mystery of new physics.

MACE: Muonium-to-Antimuonium Conversion Experiment

Content

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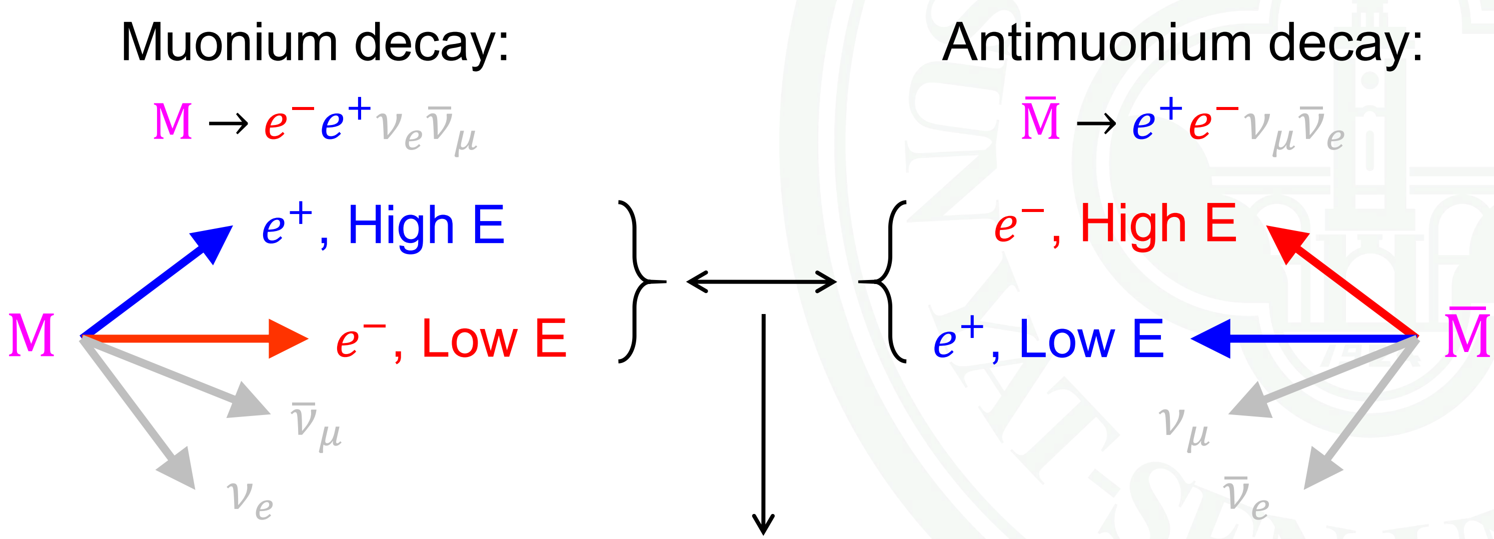
Conceptual Design of MACE

- How to detect the muonium-antimuonium conversion?

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

- We can achieve this by identifying the final states:

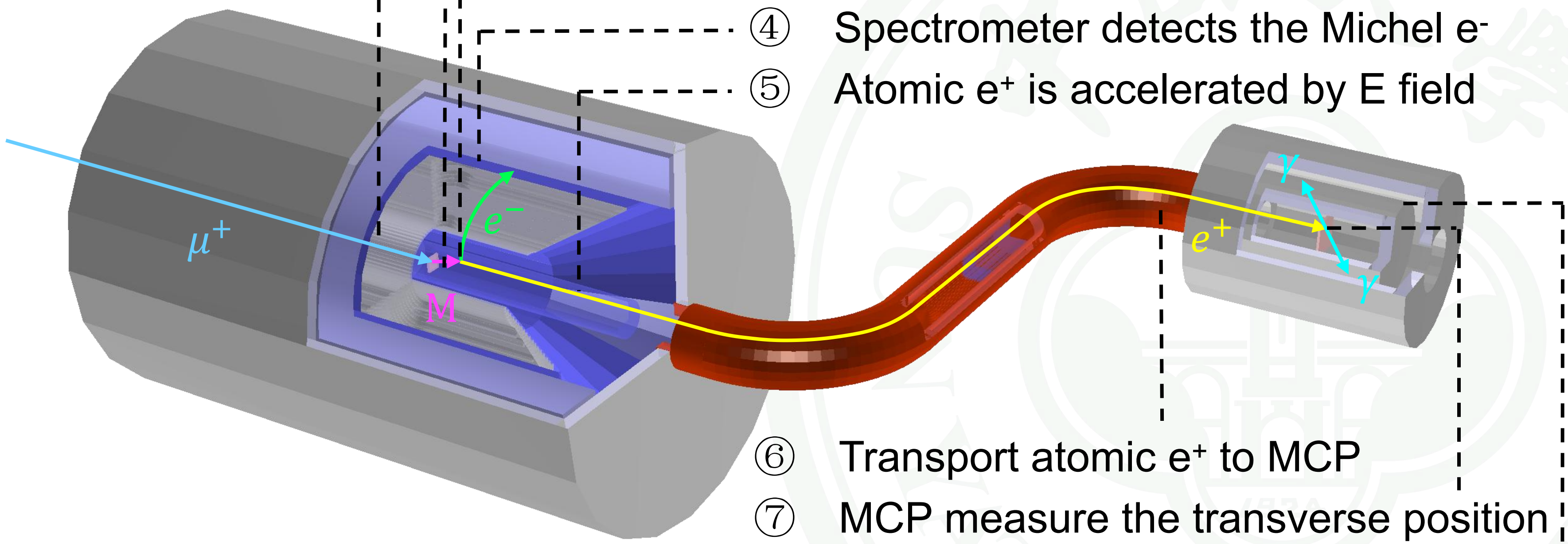


Search for the conversion by vertex coincidence and charge identification.

Conceptual Design of MACE

Signal process:

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



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

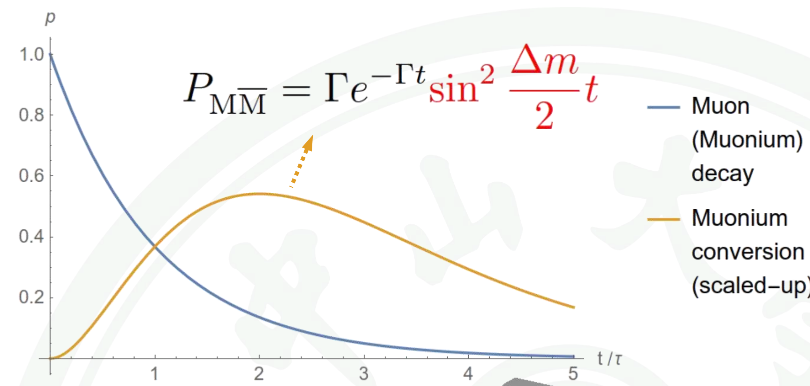
- Spectrometer: identifies Michel e^-.
- Vertex coincidence: Michel e^- track and e^+ transverse position projection.
- Calorimeter: identifies atomic e^+.

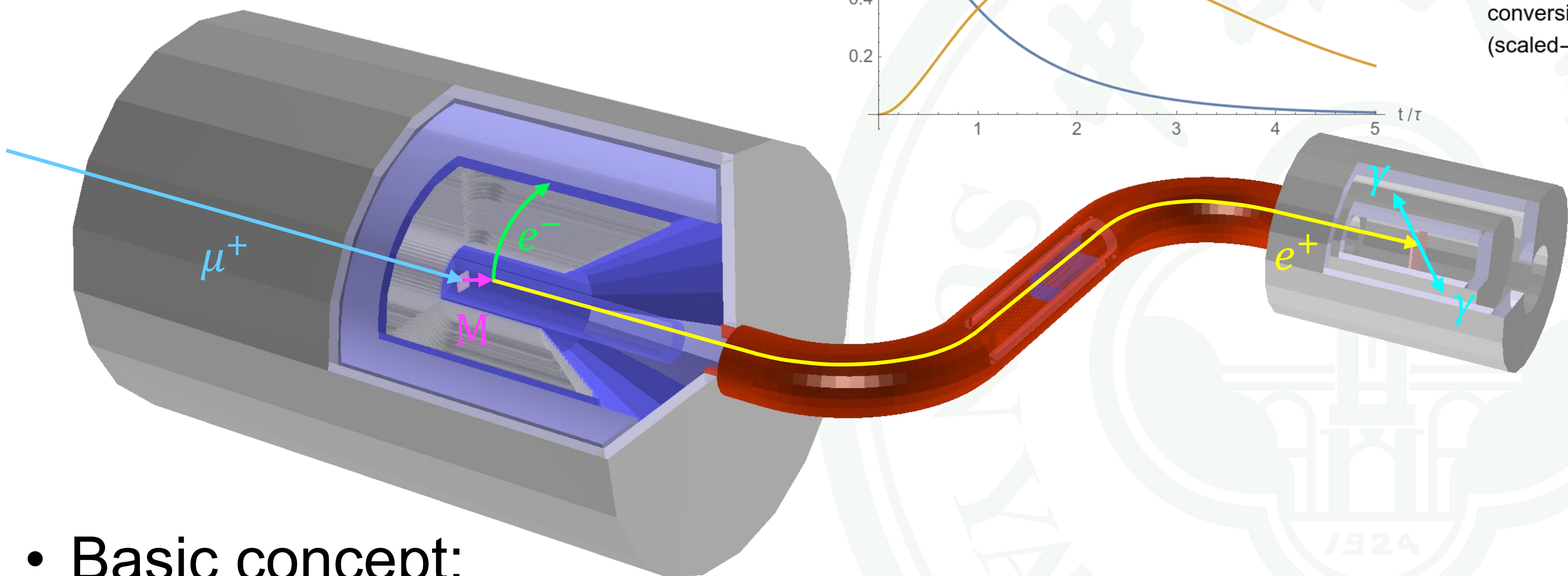
Basic concept:
Coincidence of spectrometer, MCP, and calorimeter.

Conceptual Design of MACE

- Signal process:

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





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

1. Spectrometer — $\overline{\mathrm{M}} \to \nu\nu e^- e^+$
2. MCP — $\overline{\mathrm{M}} \to \nu\nu e^- e^+$
3. Calorimeter — $\overline{\mathrm{M}} \to \nu\nu e^- e^+,\ e^+ \xrightarrow{\text{annihilate on MCP}} \gamma\gamma$

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

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

- Signal effiency
- B field surpression
- Muonium yield
- Muon beam luminosity
- Acquisition time

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

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

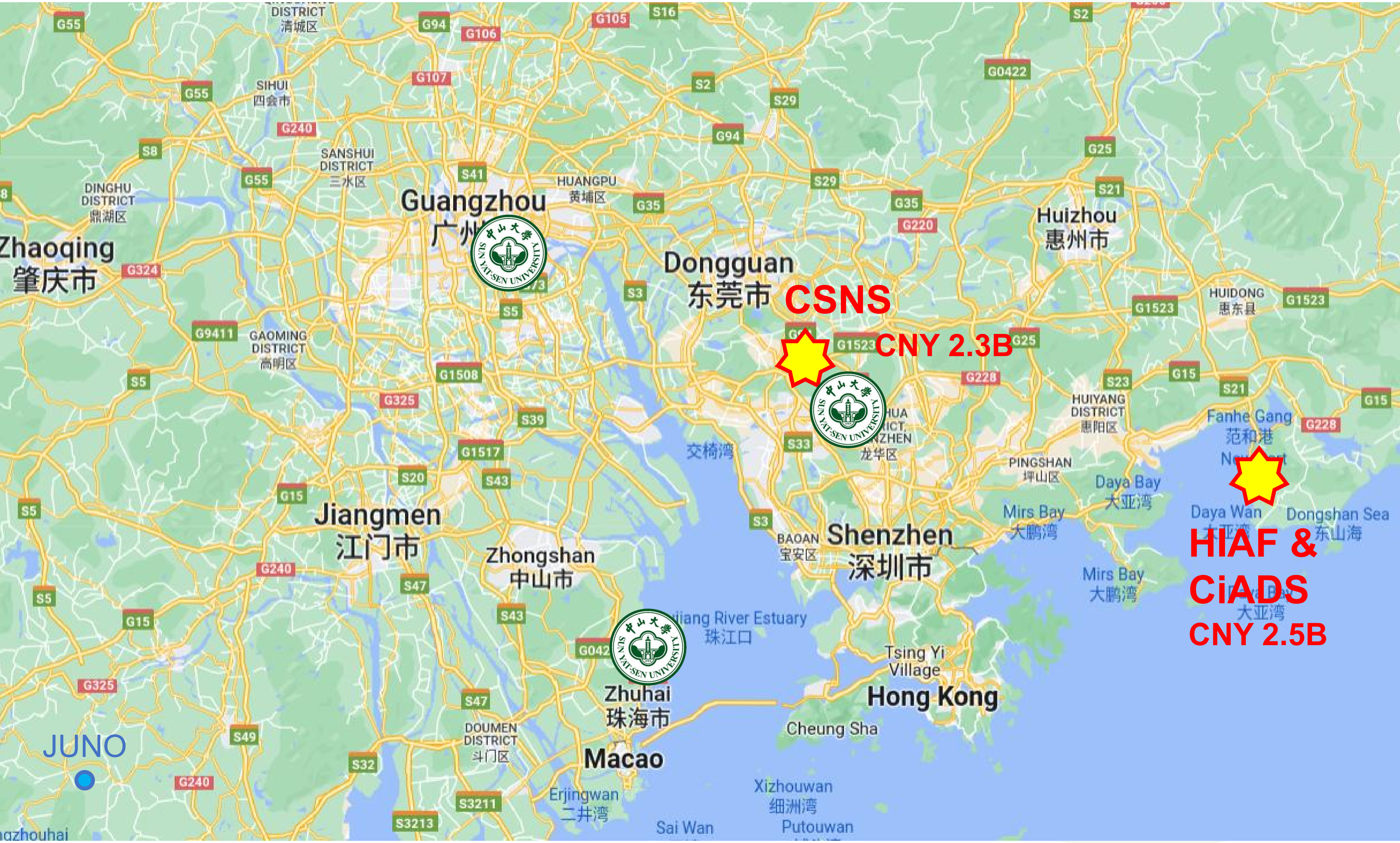
1. Enhance beam luminosity L_μ:

   → $10^8 \sim 10^{10}$ 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



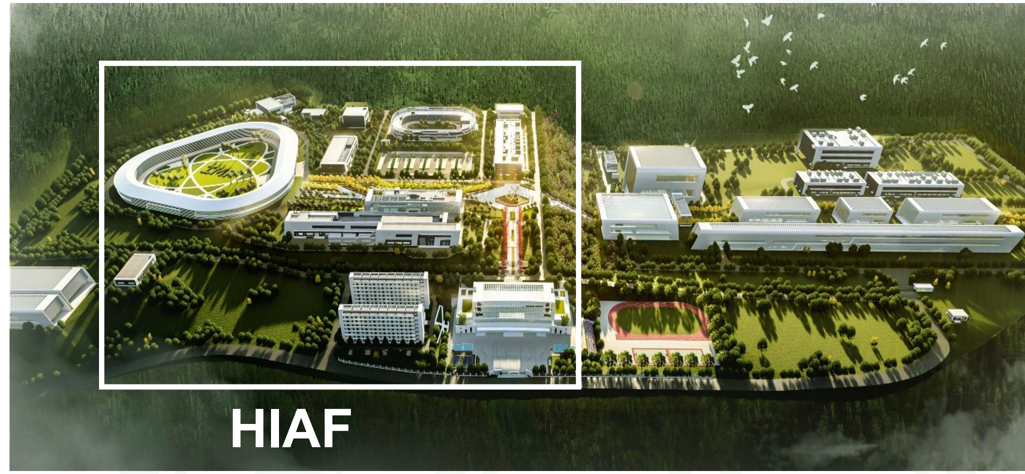
Muon Source Proposed at CiADS

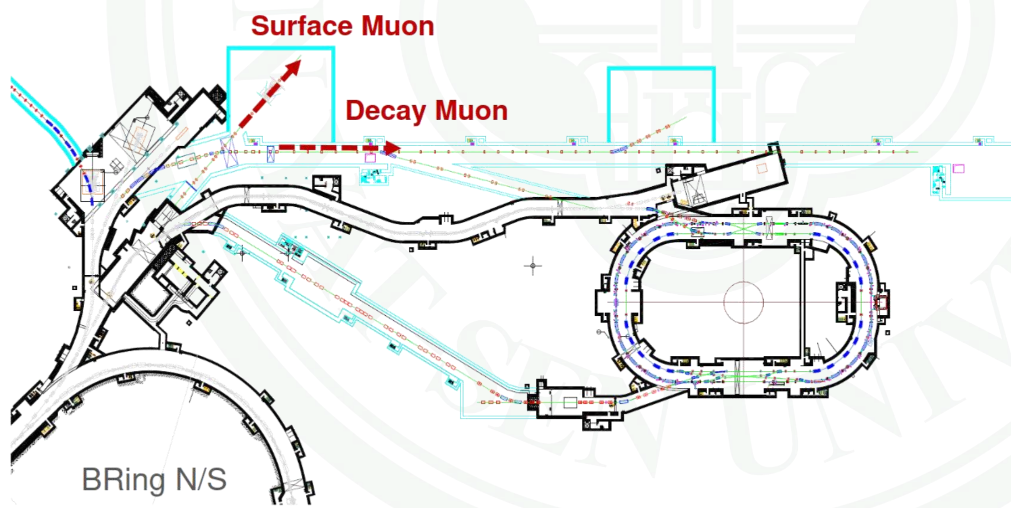
- Proton accelerator.
- Located in Huizhou, Guangdong, PRC.
- Status: constructing (accelerator), conceptual (muon source).
- Intensity: $\mathbf{10^9 \sim 10^{10}\ \mu^+/s}$
- Beam mode: CW
- Available at ~2030s.

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: CW
- Available at ~2030s.

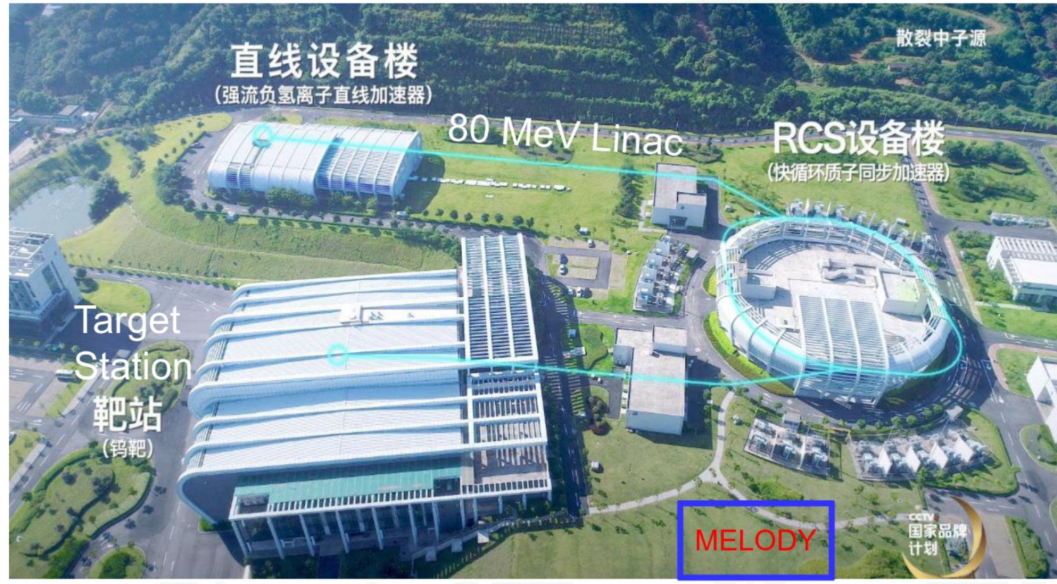


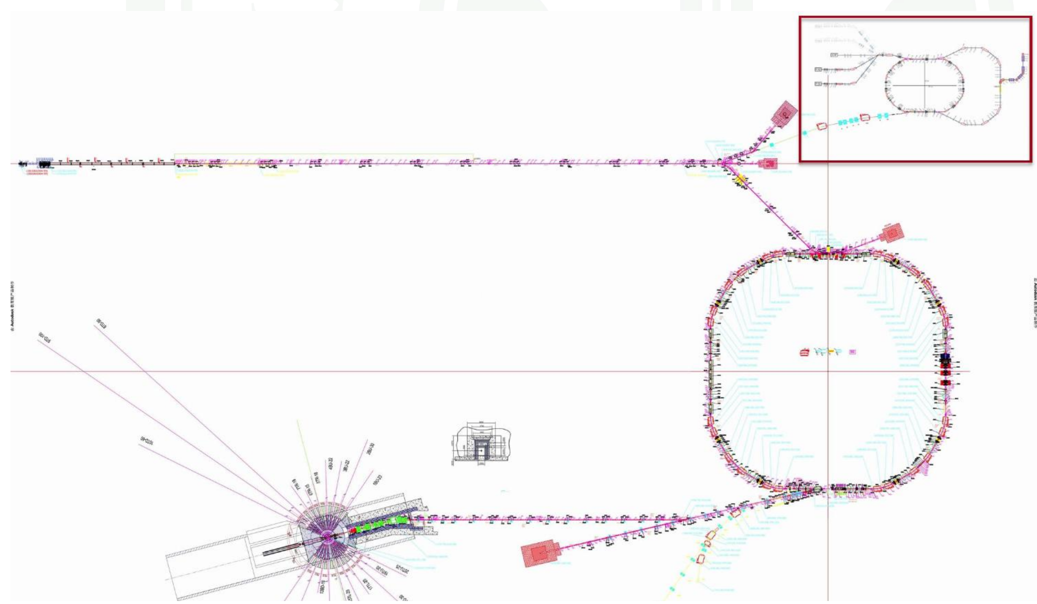


Reference: Yuan He, MIP2023, 15 Apr. 2023

Muon Source Proposed at CSNS

- Proton accelerator.
- Located in Dongguan, Guangdong, PRC.
- Status: **running** (accelerator), conceptual (EMuS), **approved** (MELODY), conceptual (HEMS).
- Intensity: $10^5 \sim 10^6$ μ^+/s
- Beam mode: Pulsed (MELODY: 1Hz, HEMS: 100Hz)
- Available at 2028.





Reference: Yu Bao, MIP2023, 15 Apr. 2023

Muonium Production and Transport

μ^+ (~1MeV) scattering

↓

Electron capture (~1keV)

↓

Muonium (~100eV)
Epithermal scattering

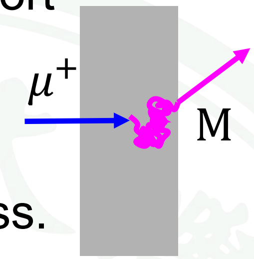
↓

Random walk (room temp.)

↓

Emission to vacuum

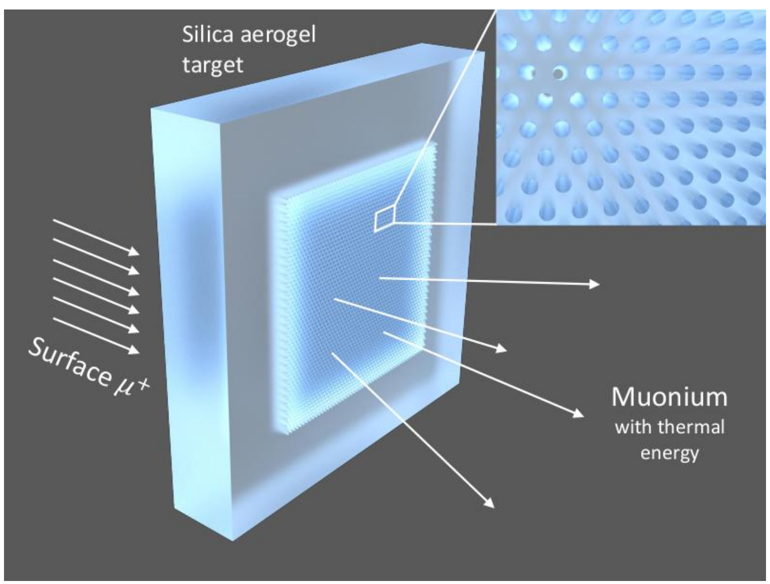
MC simulation for muonium transport has been developed under the MACE offline software framework.



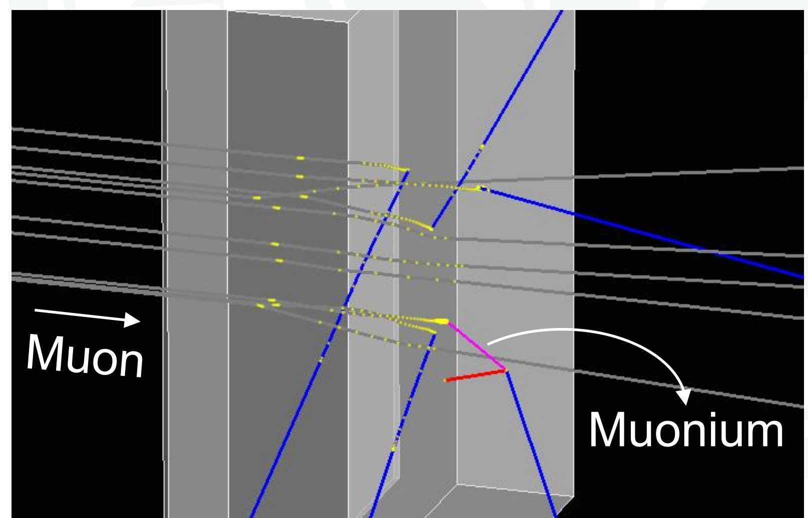
① Geant4 low-energy EM process.

② Geant4 AtRest process, modeled phenomenologically.

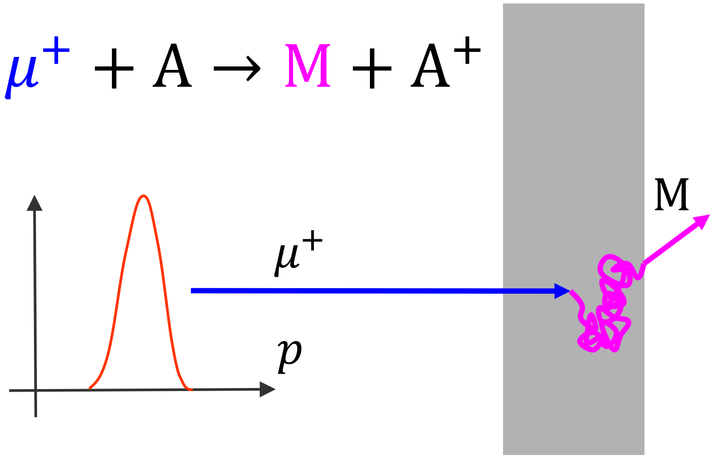
③ Random walk approach to thermal muonium tracking.



Simulation:

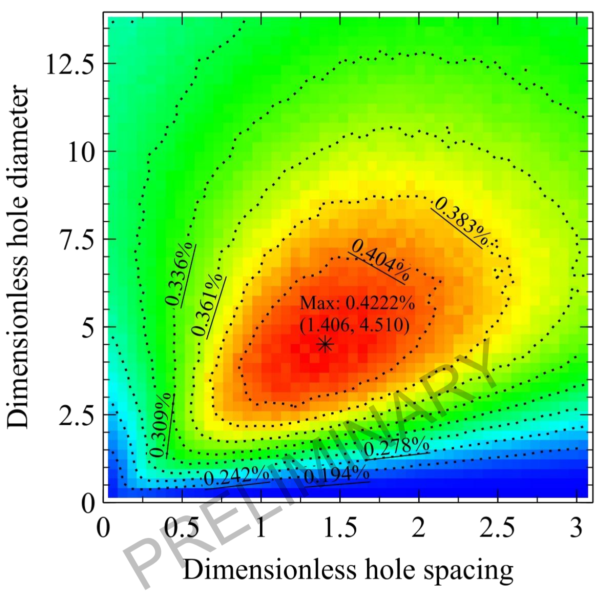


Muonium Yield Simulation

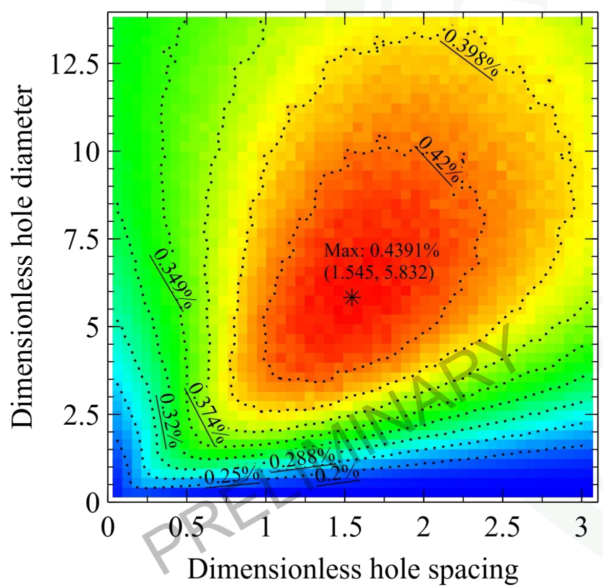


- Surface muon beam momentum spread: 10%
- Muonium mean free path: 200 nm, temp.: 300 K
- Optimal diameter: $1.55\sqrt{D\tau}$ (50.8 μm)
- Optimal spacing: $5.83\sqrt{D\tau}$ (191 μm)
- Max vacuum muonium yield: 0.44%

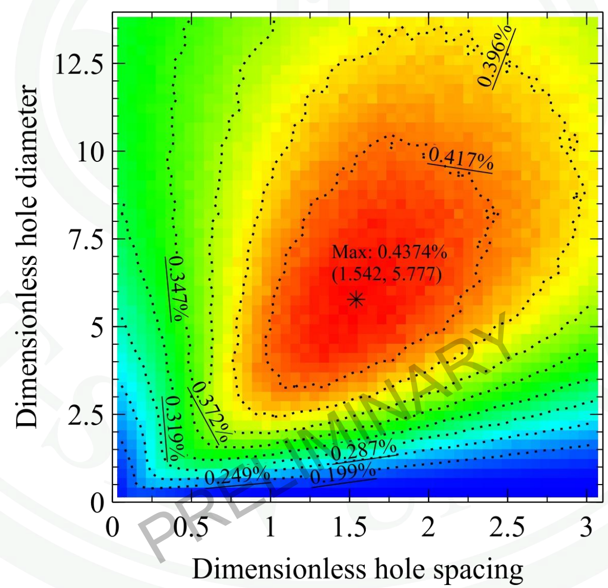
Depth: 1 mm



Depth: 3 mm

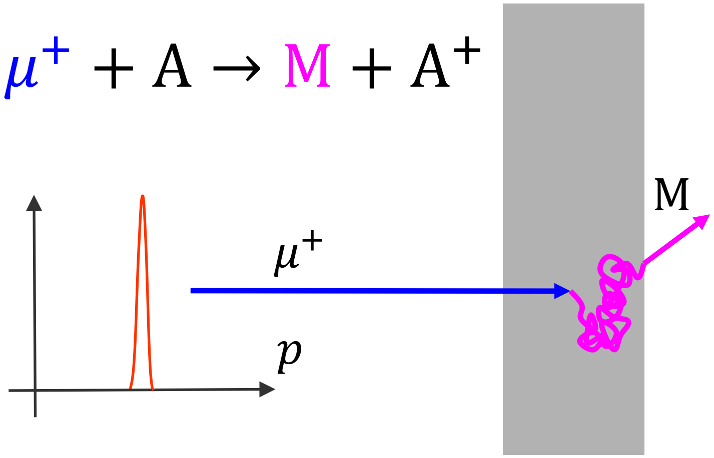


Depth: 5 mm



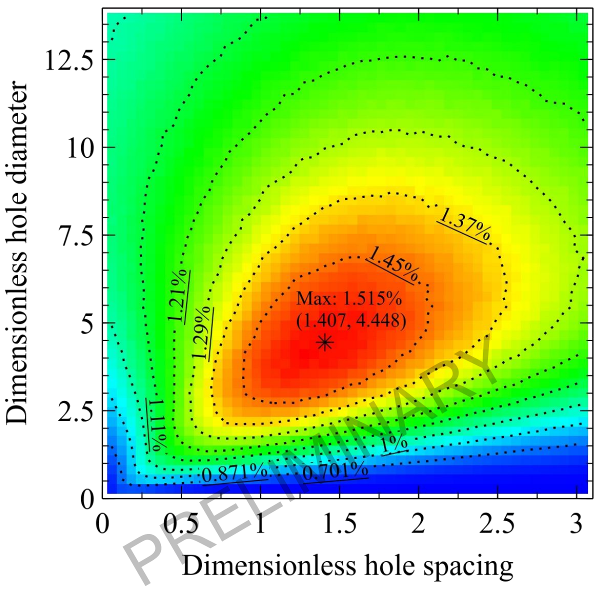
Muonium Yield Simulation - Low σ_p Beam

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

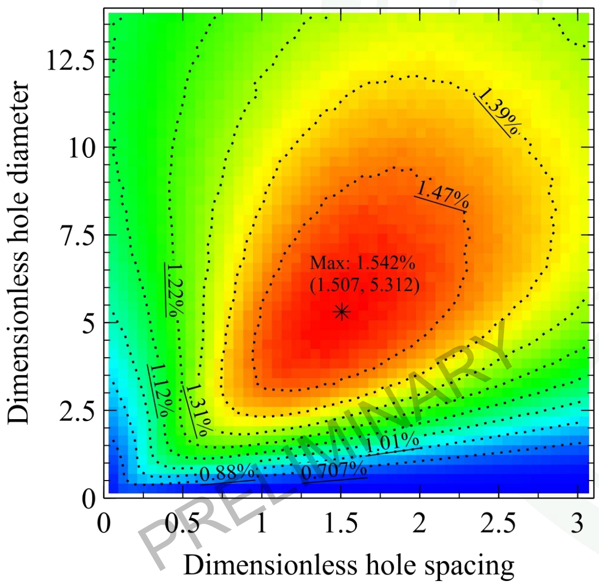


- Surface muon beam momentum spread: 2.5%
- Muonium mean free path: 200 nm, temp.: 300 K
- Optimal diameter: $1.51\sqrt{D\tau}$ (49.5 μm)
- Optimal spacing: $5.31\sqrt{D\tau}$ (175 μm)
- Max vacuum muonium yield: 1.54%

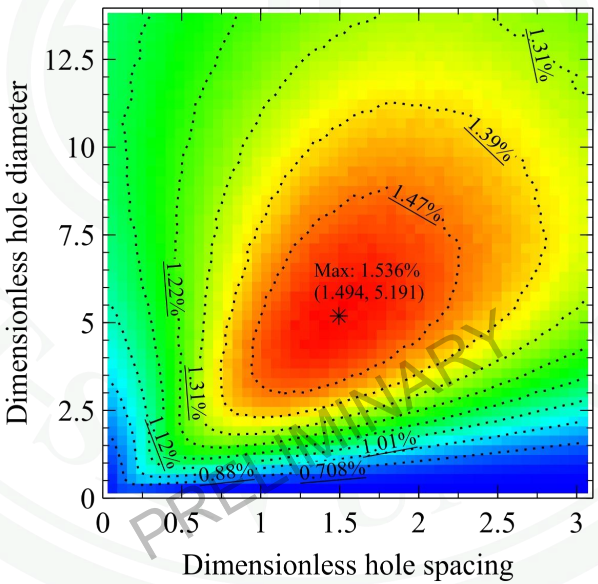
Depth: 1 mm



Depth: 3 mm



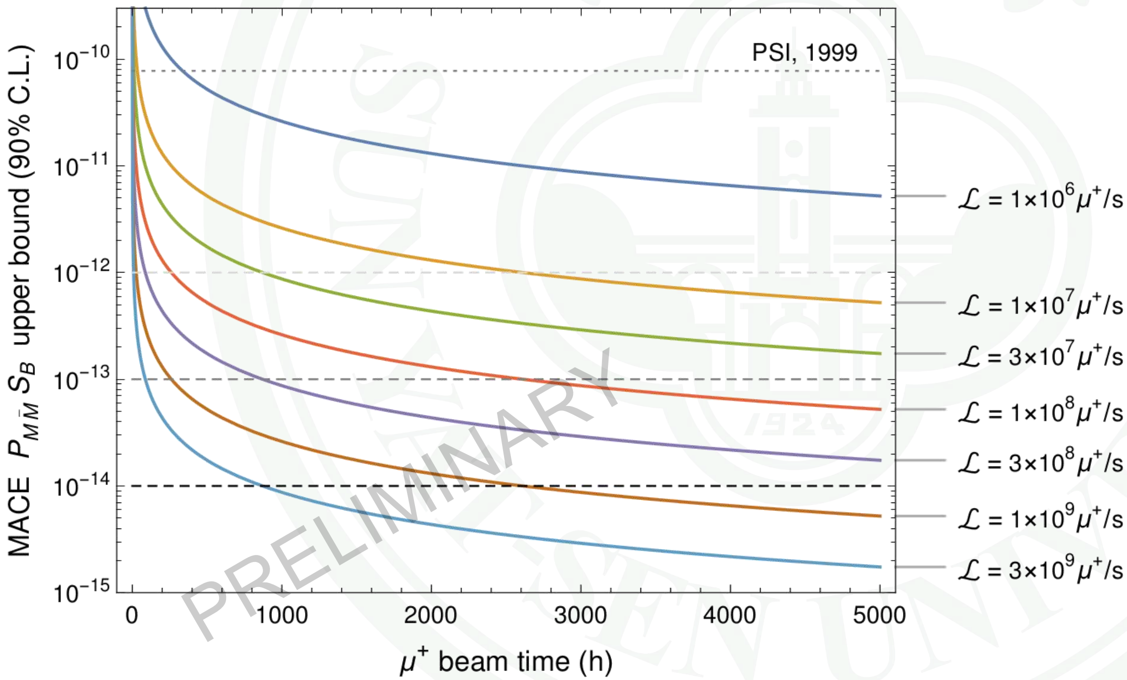
Depth: 5 mm



Muonium Yield and Upper Bound

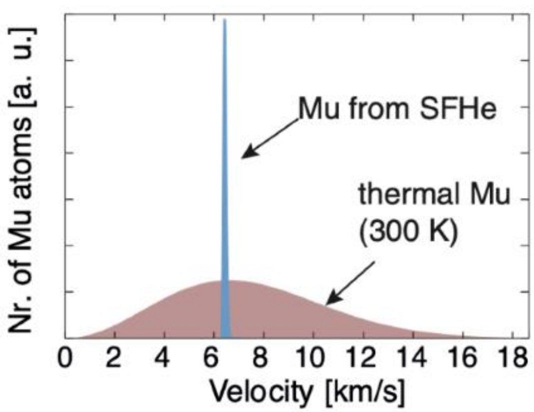
- Acquisition time is precious, the upper bound is limited by the number of muoniums (N_{M}).
- The more muoniums the merrier.

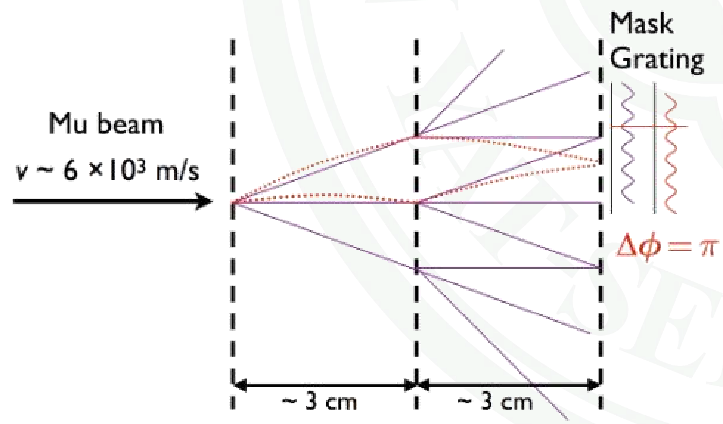
- If the beam luminosity reaches 10^8 μ^+/s and the muonium yield increases by 2 orders of magnitude, MACE can improve the upper bound by 3 orders of magnitude.
- The improvement of detector performance will make contributions, correspondingly.

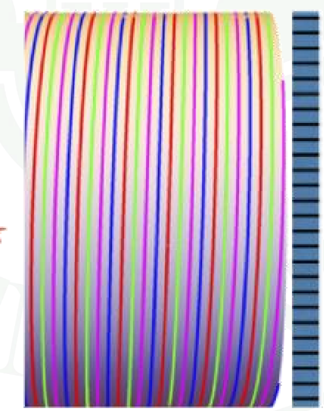


Muonium Gravity Experiment (MAGE) in US

- Weak equivalence principle of GR is assume to apply to anti-matter.
- However, no direct test of antimatter gravity has been made.
- Challenge: MAGE needs low-divergence source of slow muonium traveling in vacuum.
- Possible solution: SFHe muonium targetry & intensive muon beam.







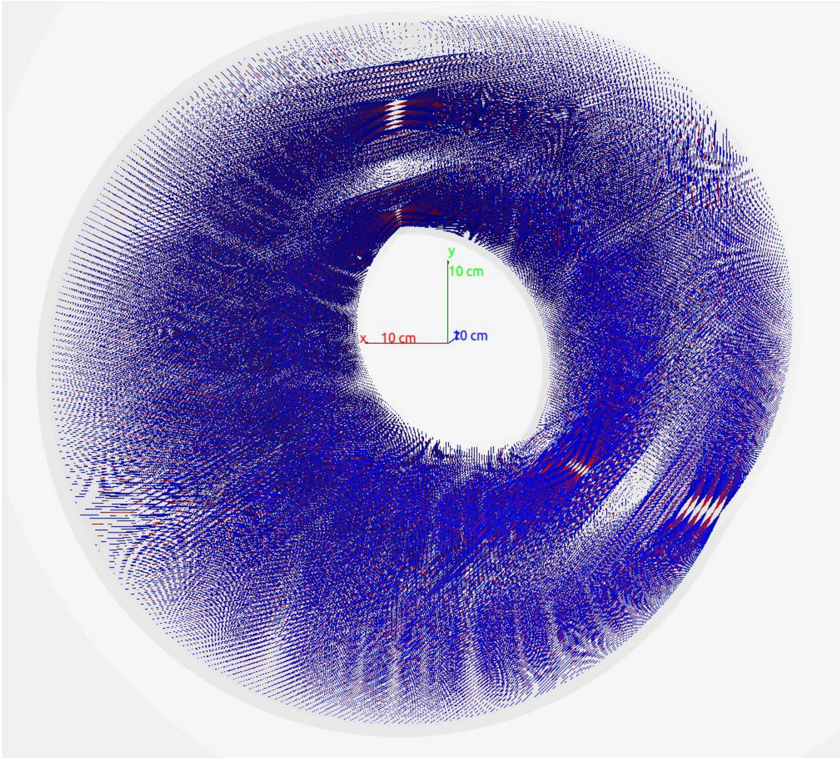
Reference: Daniel Kaplan, Caltech Workshop, 28 Mar. 2023

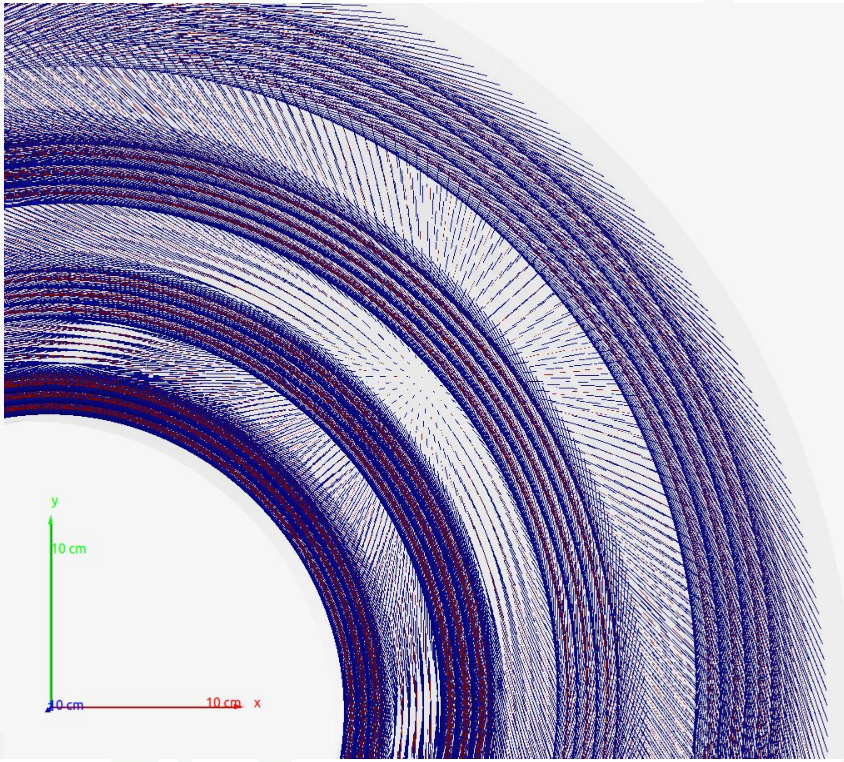
Design of Drift Chamber

- 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).

Design of Drift Chamber

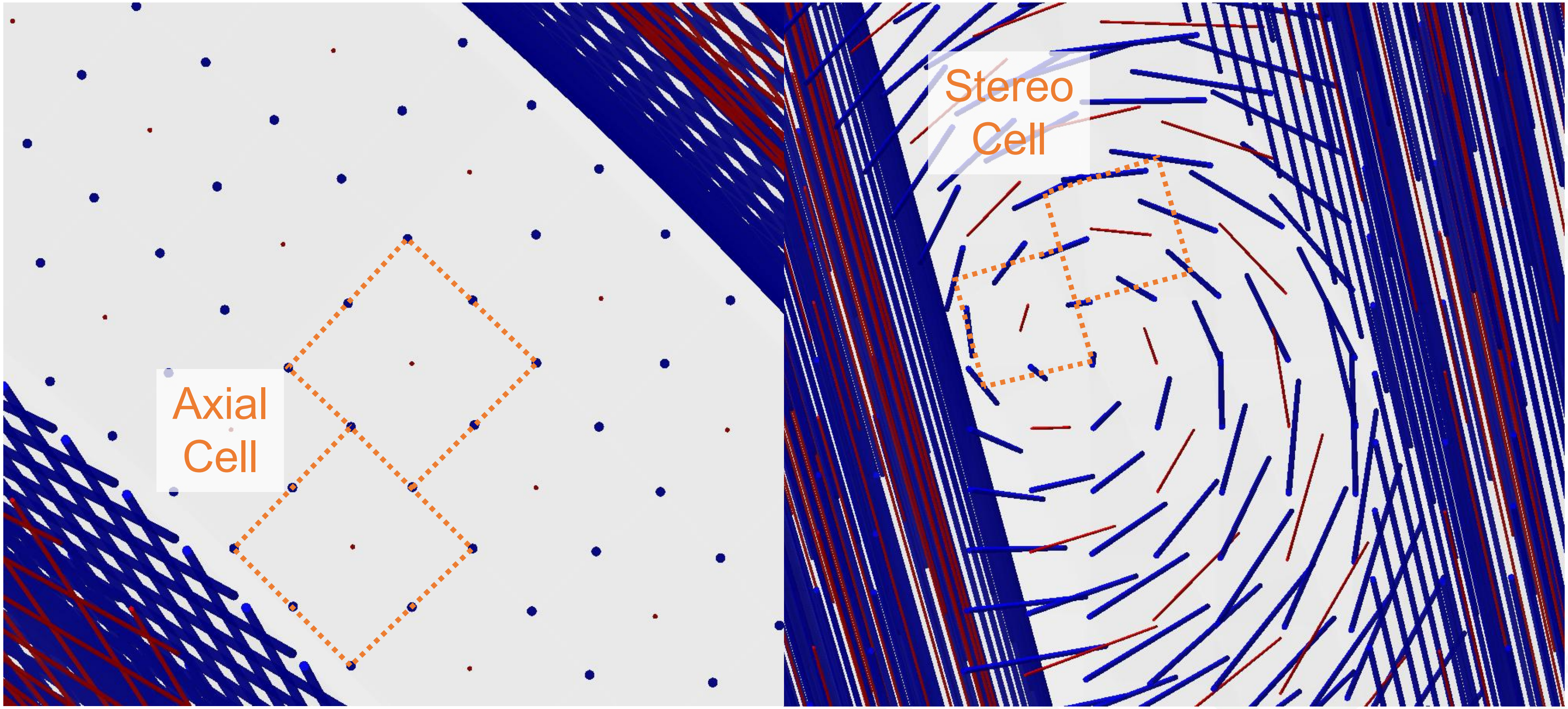
- We have developed an algorithrm to generate the drift chamber geometry, allowing us to evaluate and optimize the geometry design of drift chamber.





- 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).

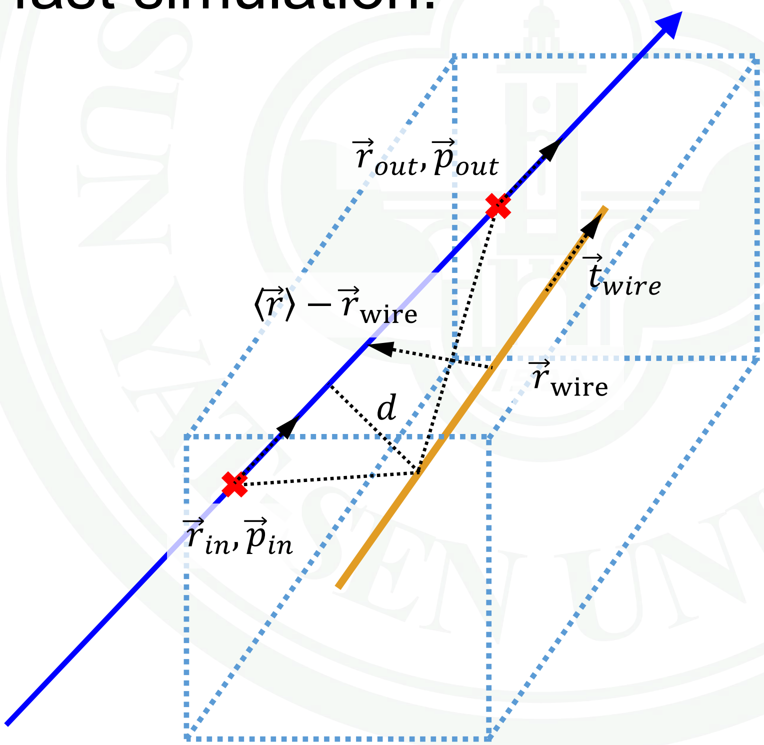
Fast Simulation of Drift Chamber

- 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:

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

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

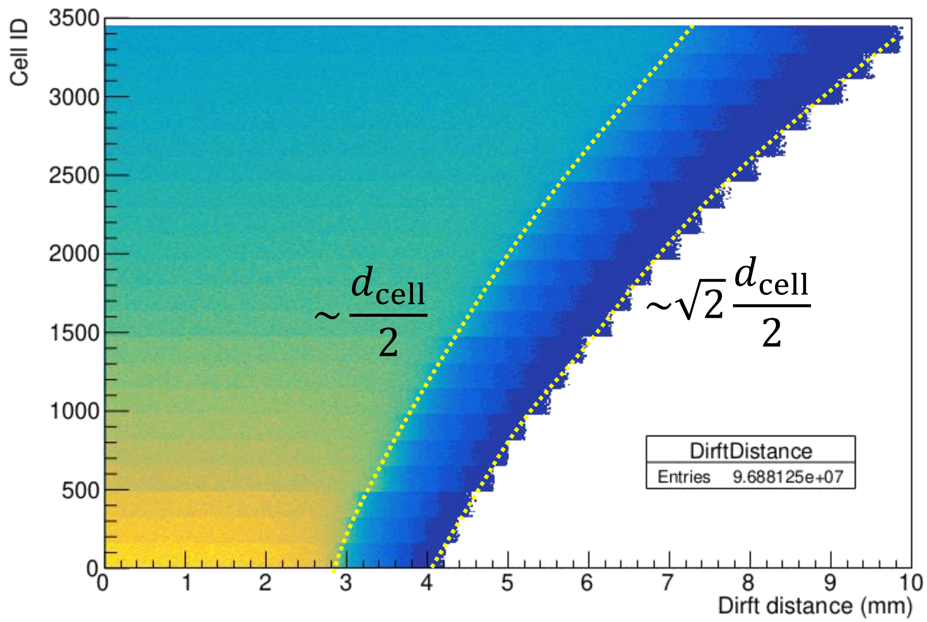
$$\langle\vec{r}\rangle = \frac{\vec{r}_{\text{in}} + \vec{r}_{\text{out}}}{2}$$



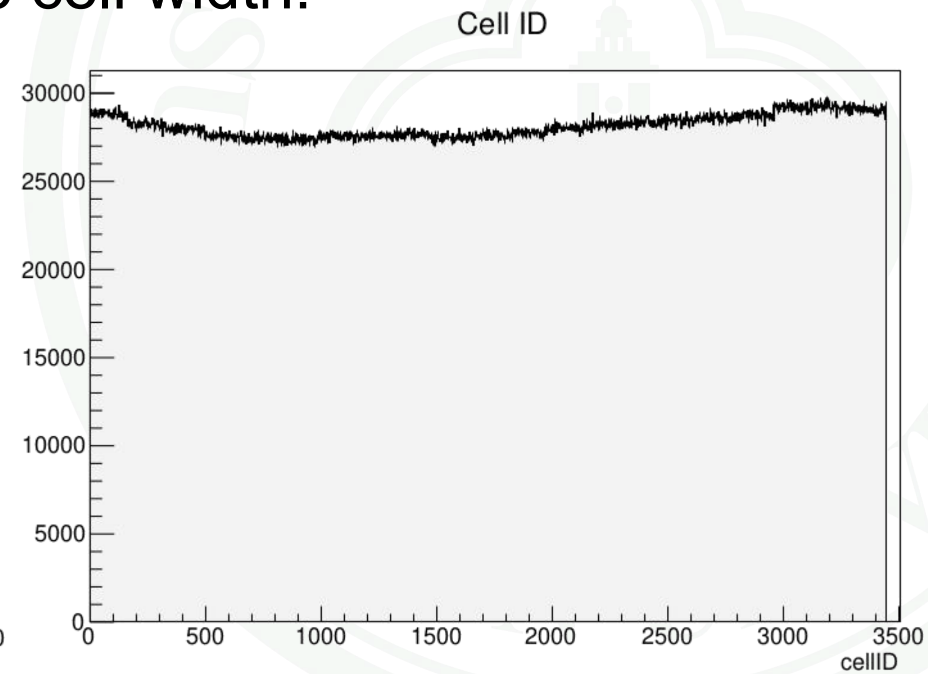
- $\vec{r}_{\text{wire}}$: A point on the sense wire (e.g. the point at z=0)
- $\vec{t}_{\text{wire}}$: Direction of the sense wire

Fast Simulation of Drift Chamber

- Using the pure geometrical DOCA method, drift distances are directly readout.
- We can check the implementation by drawing its distribution.
- For example, the drift distance and hit rate distribution of a Drift chamber with 10 mm reference cell width:



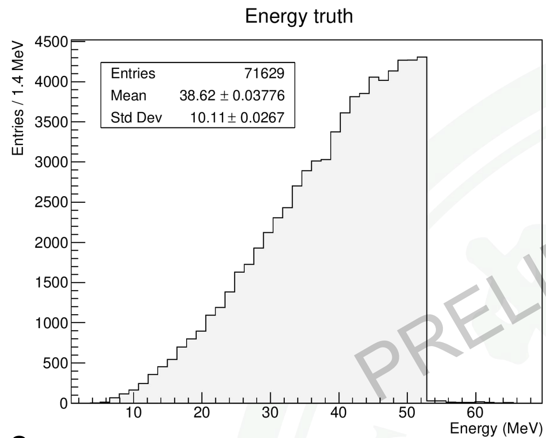
Distribution of drift distance

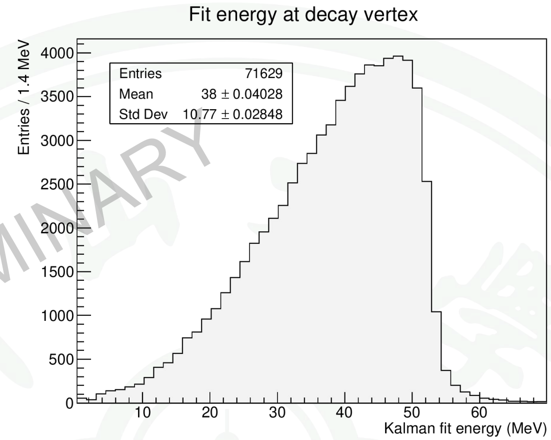


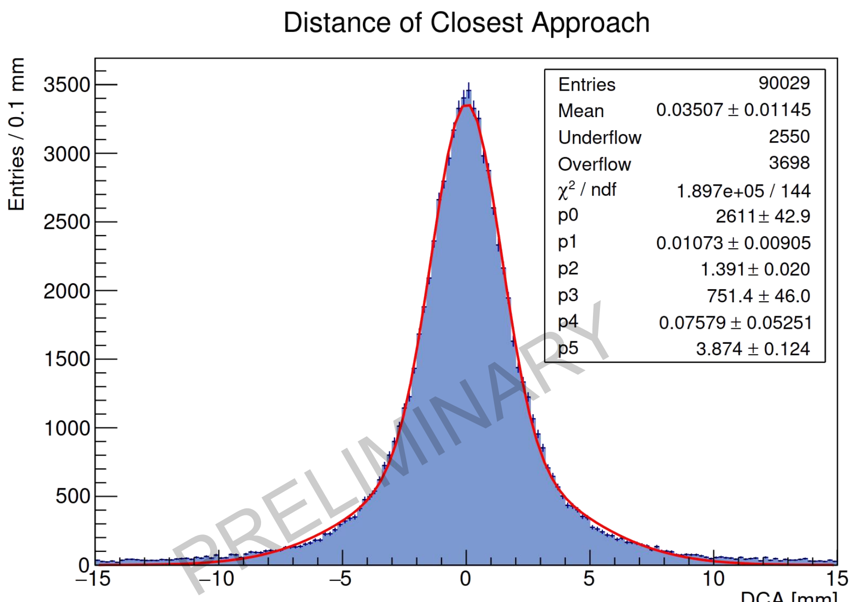
Distribution of hit rate

Track Reconstruction in Spectrometer

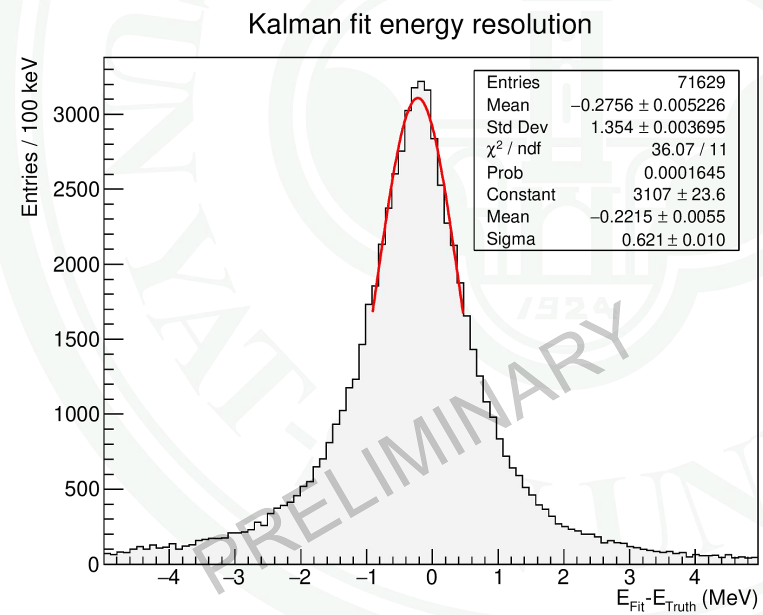
- Kalman-filter-based track reconstruction has been performed, with 100μm drift distance resolution.
- The resolution of the drift chamber has improved compared with simple least χ^2.







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



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

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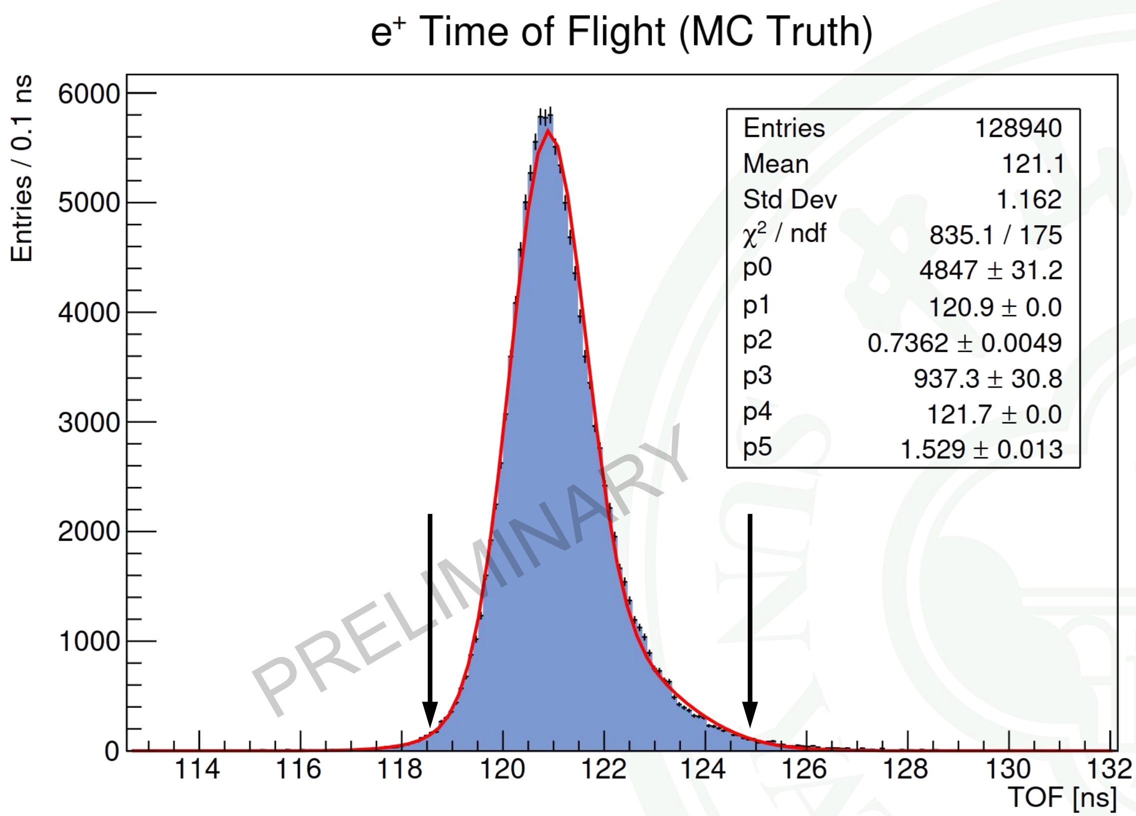
Event Selection

- 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? (steps 1–2)

Analysis: Time Aspect



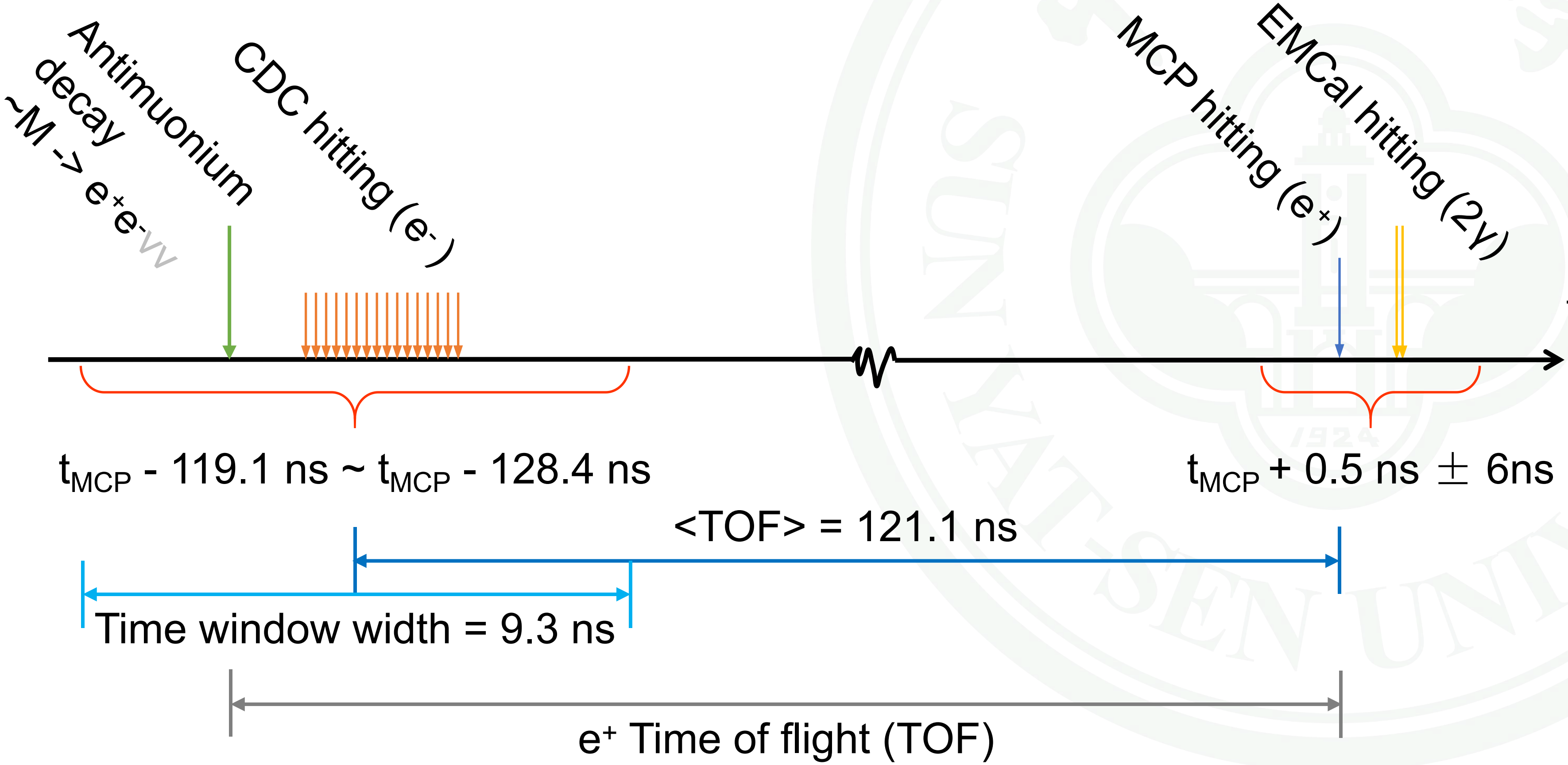
118.6 ns 124.9 ns

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.

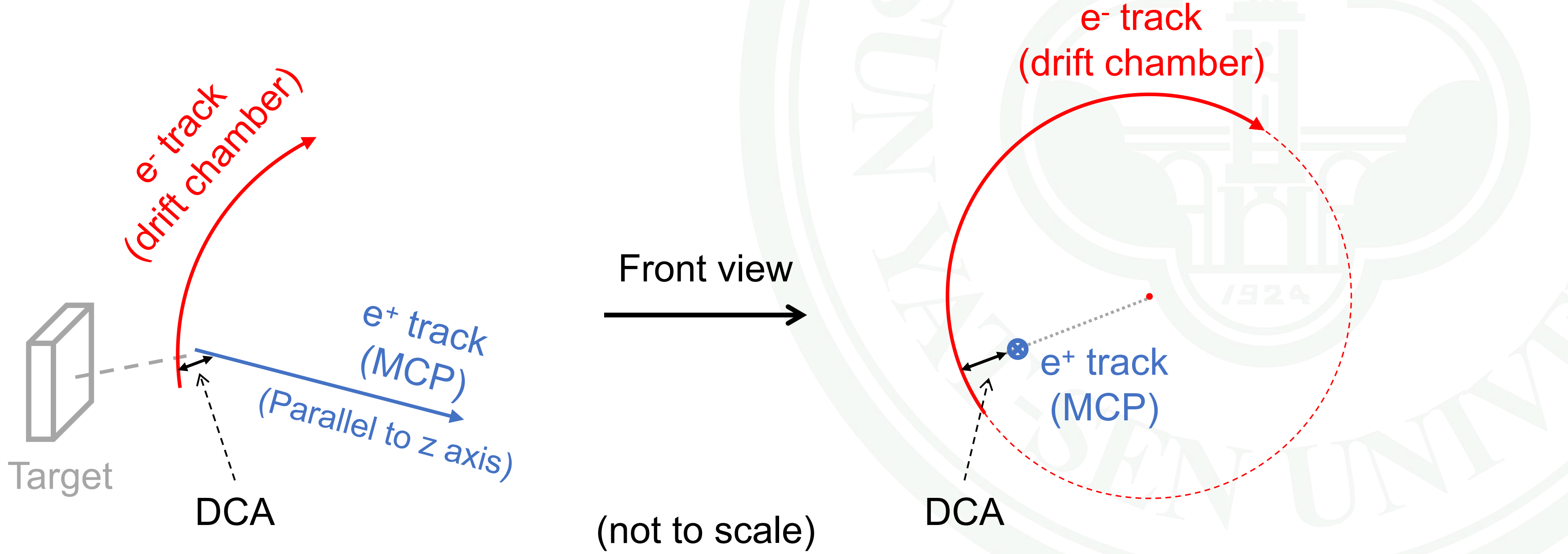
Analysis: Time Aspect

- 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.



Analysis: Spatial Aspect

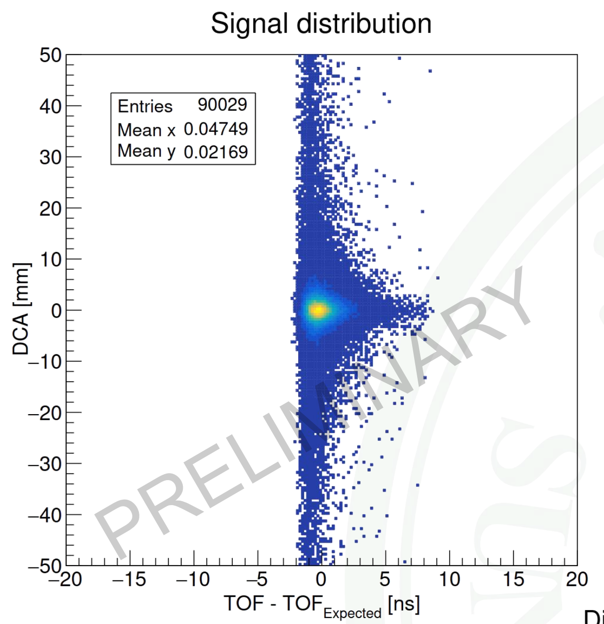
- Spatial resolution of the drift chamber cell (100 μm) has been considered.
- Fitted tracks are extrapolated toward the target by helixes.
- Closest distance between extrapolated tracks and low energy atomic e^+ are calculated.



Analysis Result

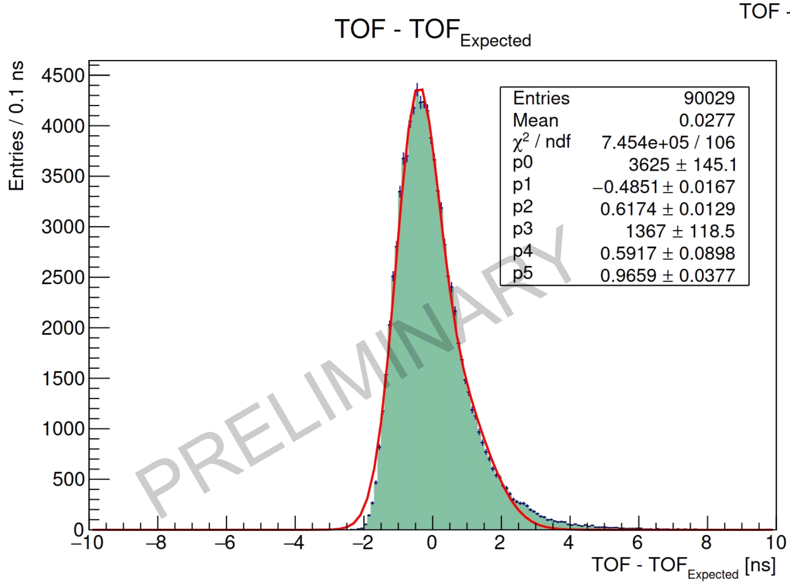
- Following the analysis procedure, the distribution of the signal can be obtained.

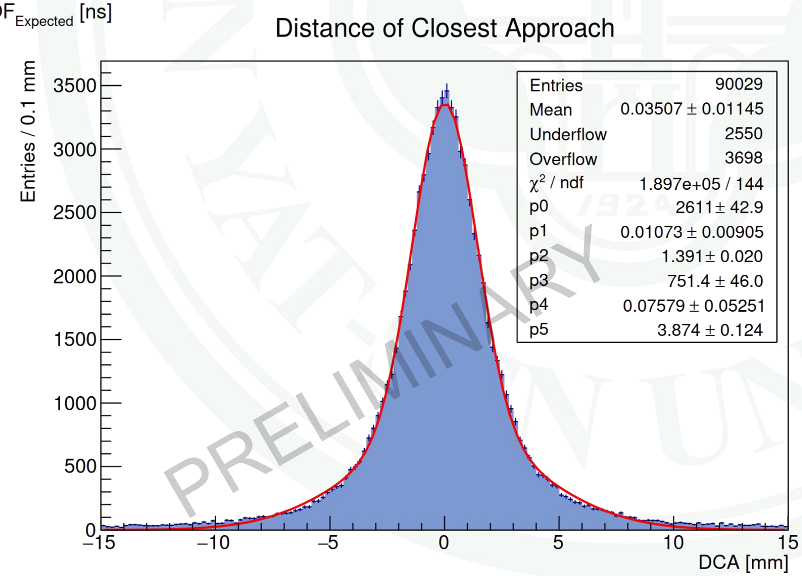
$\sigma_{\Delta TOF}$ = 0.58 ns



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

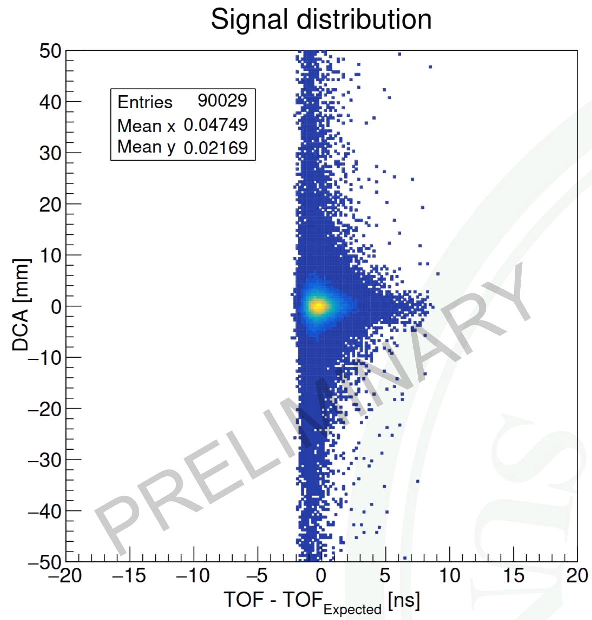
σ_{DCA} = 2.2 mm





Analysis Result

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

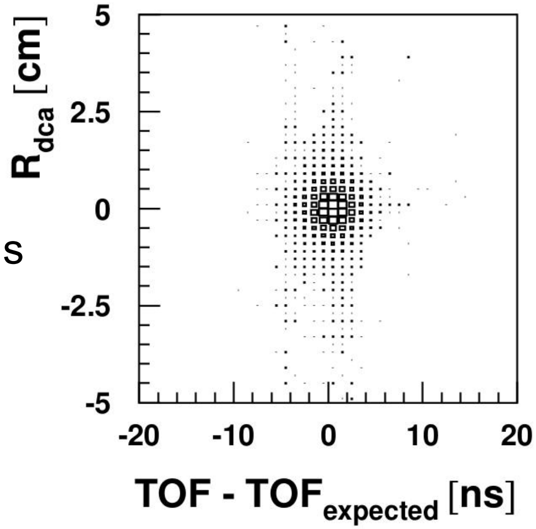


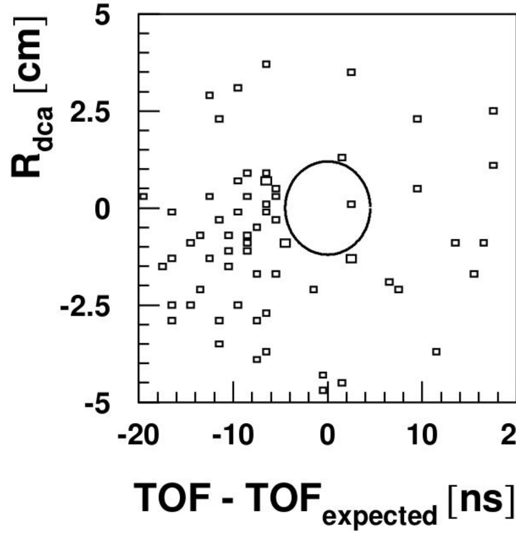
- Backgrounds:
  - $\mu^+ \rightarrow e^+ e^- e^+ \nu_e \bar{\nu}_\mu$
  - $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ and accidental e^-
- Background analysis in progress.

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

σ_{DCA} = 2.2 mm

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

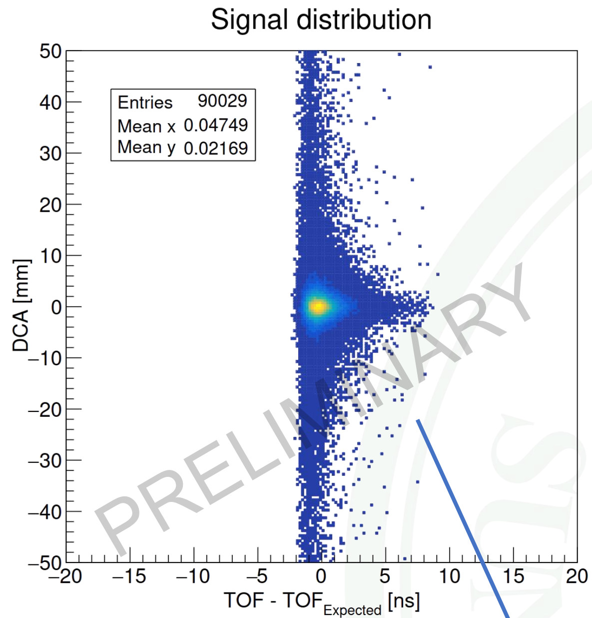




σ_{DCA} = 4.0 mm

Analysis Result

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

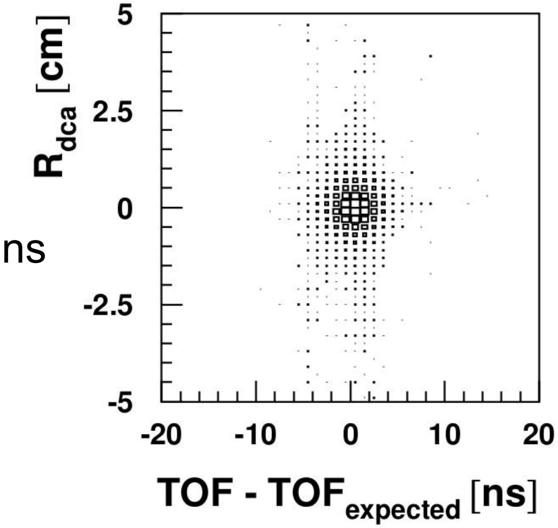


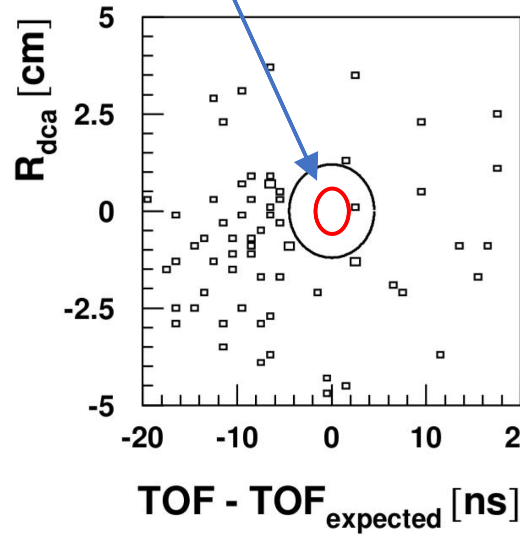
- Backgrounds:
  - $\mu^+ \to e^+ e^- e^+ \nu_e \bar{\nu}_\mu$
  - $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ and accidental e^-
- Background analysis in progress.

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

σ_{DCA} = 2.2 mm

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





σ_{DCA} = 4.0 mm

Content

- Motivation
- Conceptual Design of MACE
- Simulation Result
- **Summary**

Summary

- MACE is the first proposed muonium-to-antimuonium conversion experiment since 1999, with the development of high-intensity muon beam and detector technology, the sensitivity is expected to enhance by more than two orders of magnitude.
- Together with other flavor and collider searches, MACE will shed light on the mystery of the cLFV and new physics.

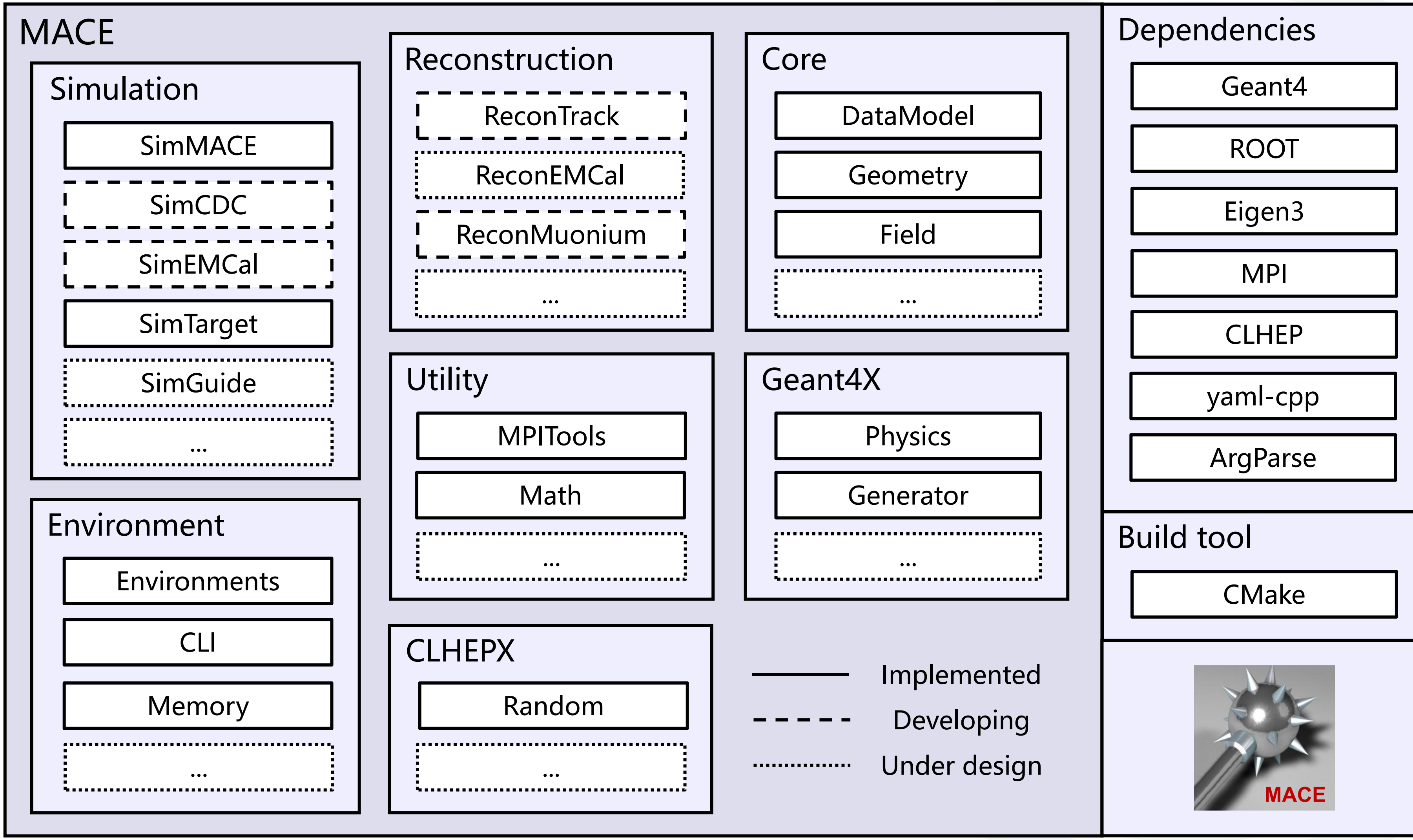
➢Questions and comments welcome!

➢Collaboration welcome!

THANK YOU

Backup

MACE Offline Software



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.