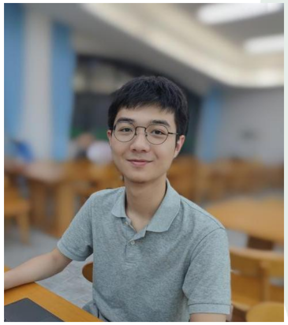
Progress of Muonium-to-Antimuonium Conversion Experiment (MACE)

Workshop on a Future Muon Program at Fermilab



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Muonium-to-
Antimuonium
Conversion
Experiment

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

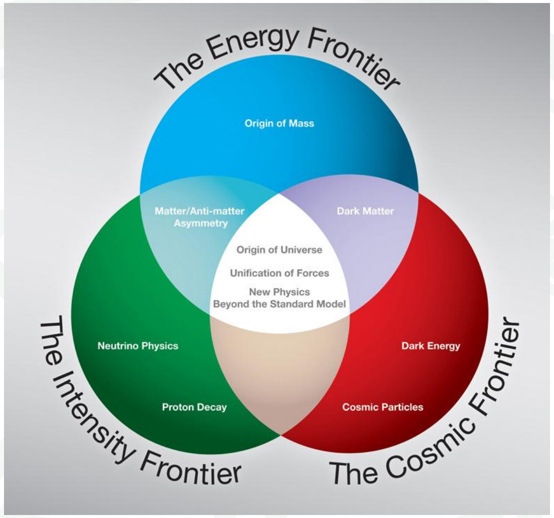
Content

- **Motivation**
- **Conceptual Design of MACE**
    - ➢**Muonium Production: Simulation and Optimization**
    - ➢**Drift Chamber Design and Simulation**
    - ➢**Offline Software R&D**
- **Preliminary analysis**
- **Summary**

Content

Frontiers of Particle Physics

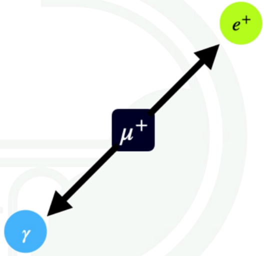
- **3 Major frontiers of Particle Physics:**
  - The Energy Frontier
  - The Intensity Frontier
  - The Cosmic Frontier



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

At the Intensity Frontier: Search for cLFV

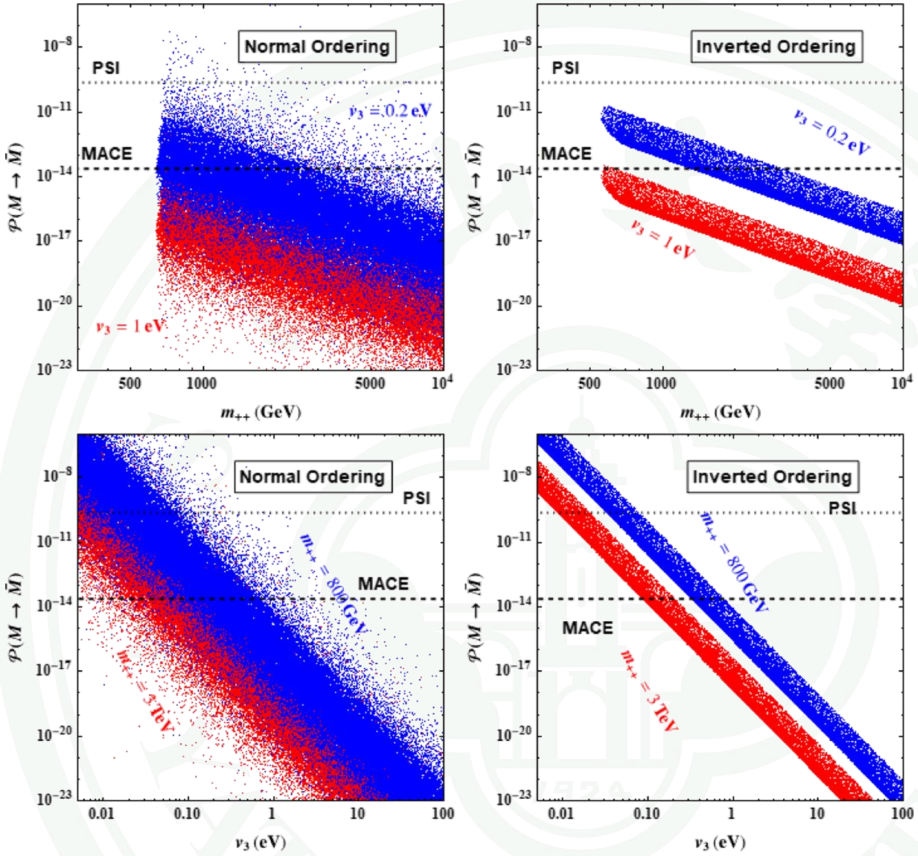
- Searching for charged lepton flavor violation (cLFV):
  - Mu2e } μ-e conversion
  - COMET }
  - Mu3e → $\mu \to eee$
  - MEGII → $\mu \to e\gamma$



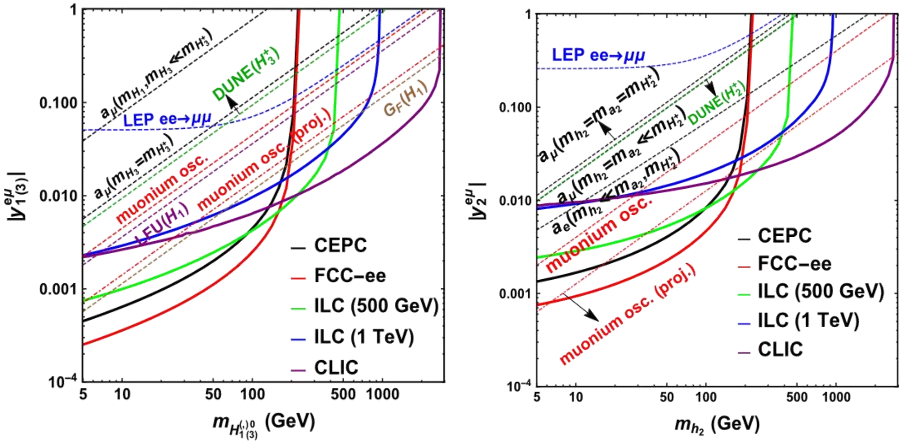
- Why cLFV:
  - cLFV, as a neutrino-less lepton flavor violating process, is forbidden in SM.
  - Precise (high-intensity) experiment searching for cLFV, is an sensitive probe of BSM.
  - New scalar or vector particles can be constrained.

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, $\mu \to eee$, $\mu \to e\gamma$).
  - Collider experiments.



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



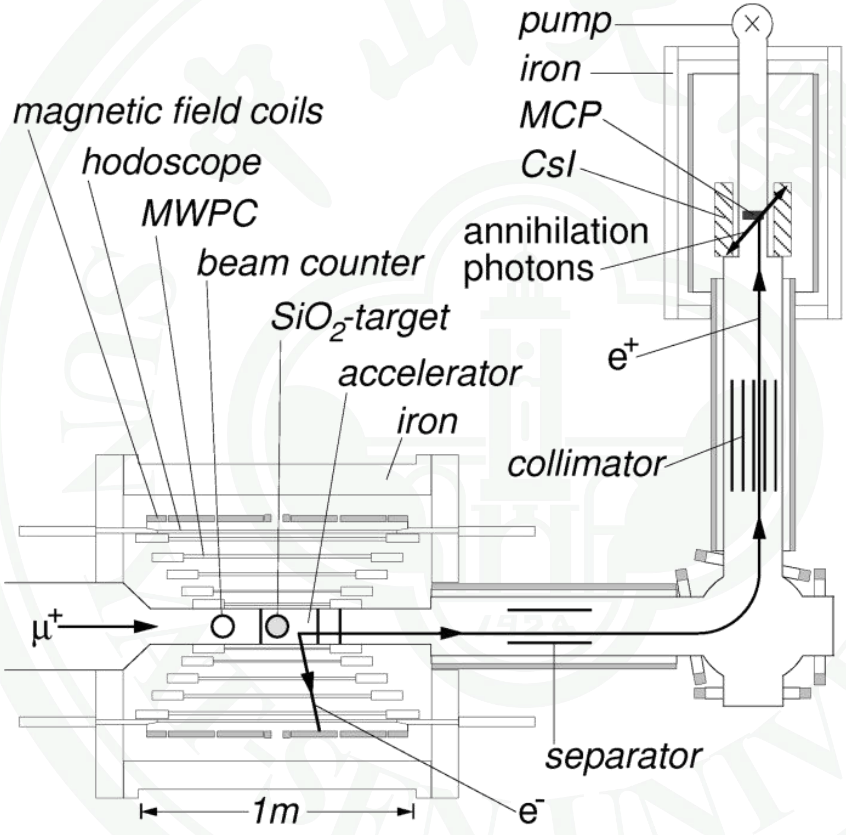
Tong Li, Michael A. Schmidt. Sensitivity of future lepton colliders and low-energy experiments to charged lepton flavor violation from bileptons. Phys.Rev.D 100 (2019) 11, 115007

Why Muonium Conversion?

- Current limit (L. Willmann, 1999):

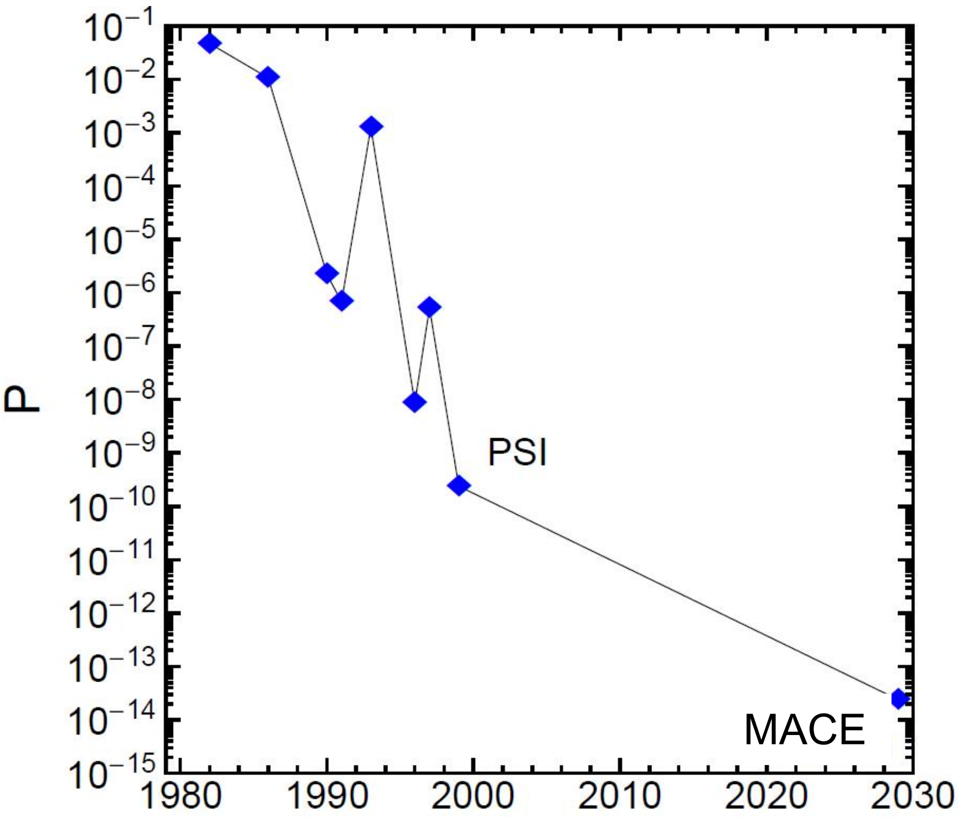
  $P_{M\bar{M}} < 8.3 \times 10^{-11}$ (90% C.L.).

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



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, MACE will shed light on the mystery of the neutrino masses.

MACE: Muonium-to-Antimuonium Conversion Experiment

Content

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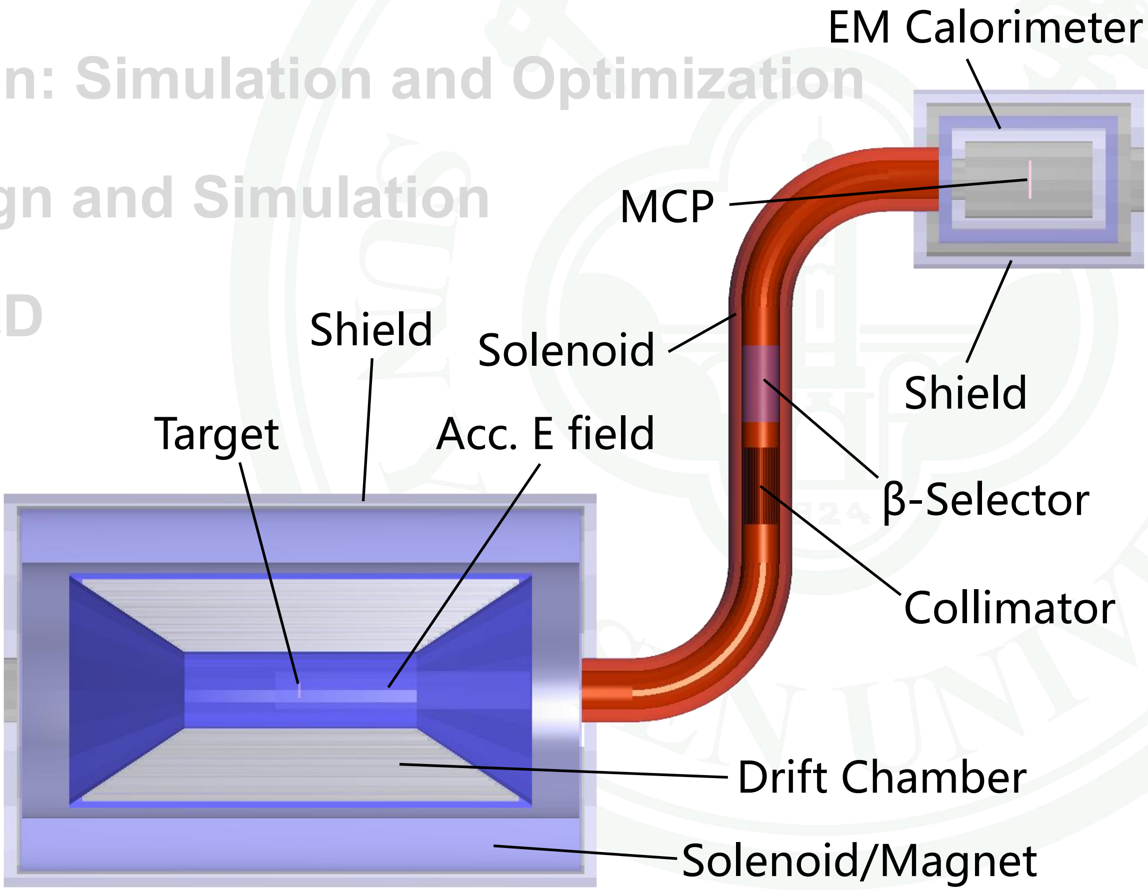
- **Conceptual Design of MACE**
  - ➢Muonium Production: Simulation and Optimization
  - ➢Drift Chamber Design and Simulation
  - ➢Offline Software R&D
- Preliminary analysis
- Summary

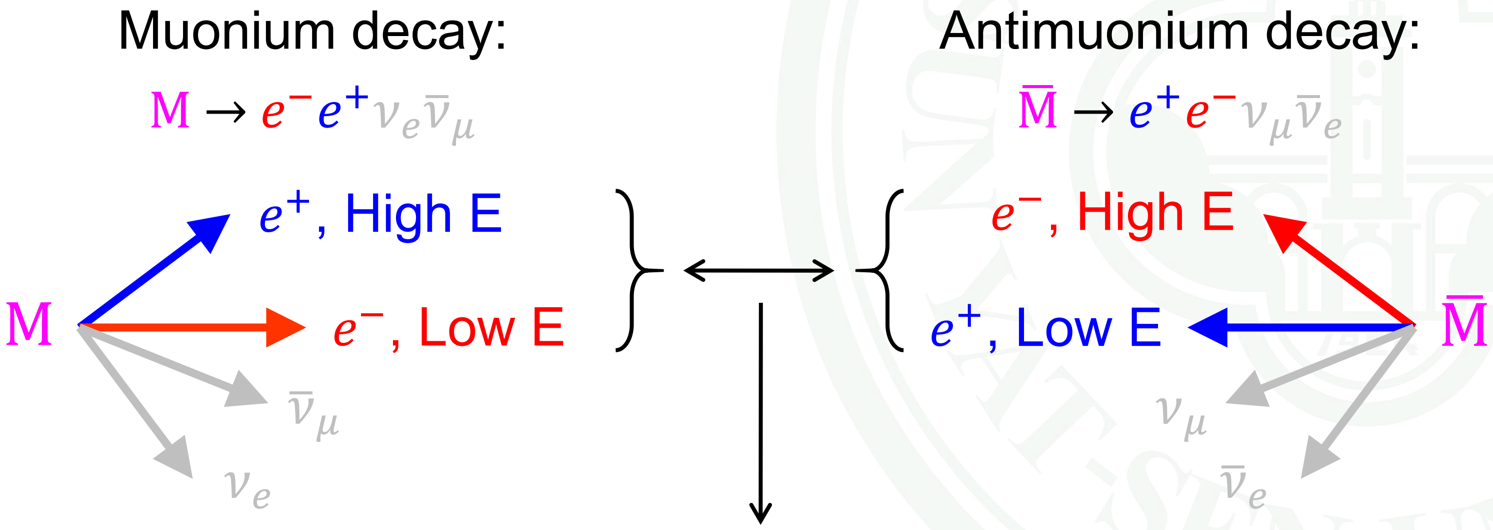


Conceptual Design of MACE

- How to detect the muonium-antimuonium conversion?

$$\mu^+ e^- \longrightarrow \mu^- e^+$$

- We can achieve this by identifing the final states:



Muonium decay:

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

Antimuonium decay:

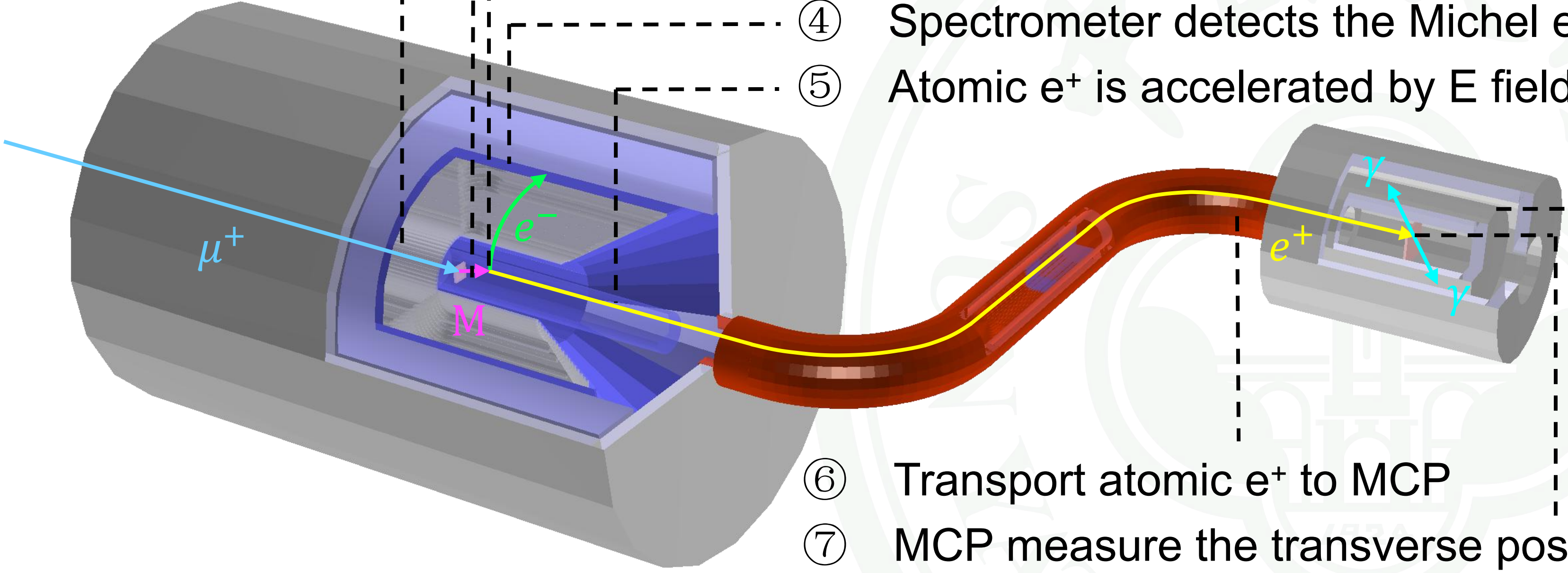
$\bar{\mathrm{M}} \rightarrow e^+ e^- \nu_\mu \bar{\nu}_e$

Search for the conversion by vertex coincidence and charge identification.

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

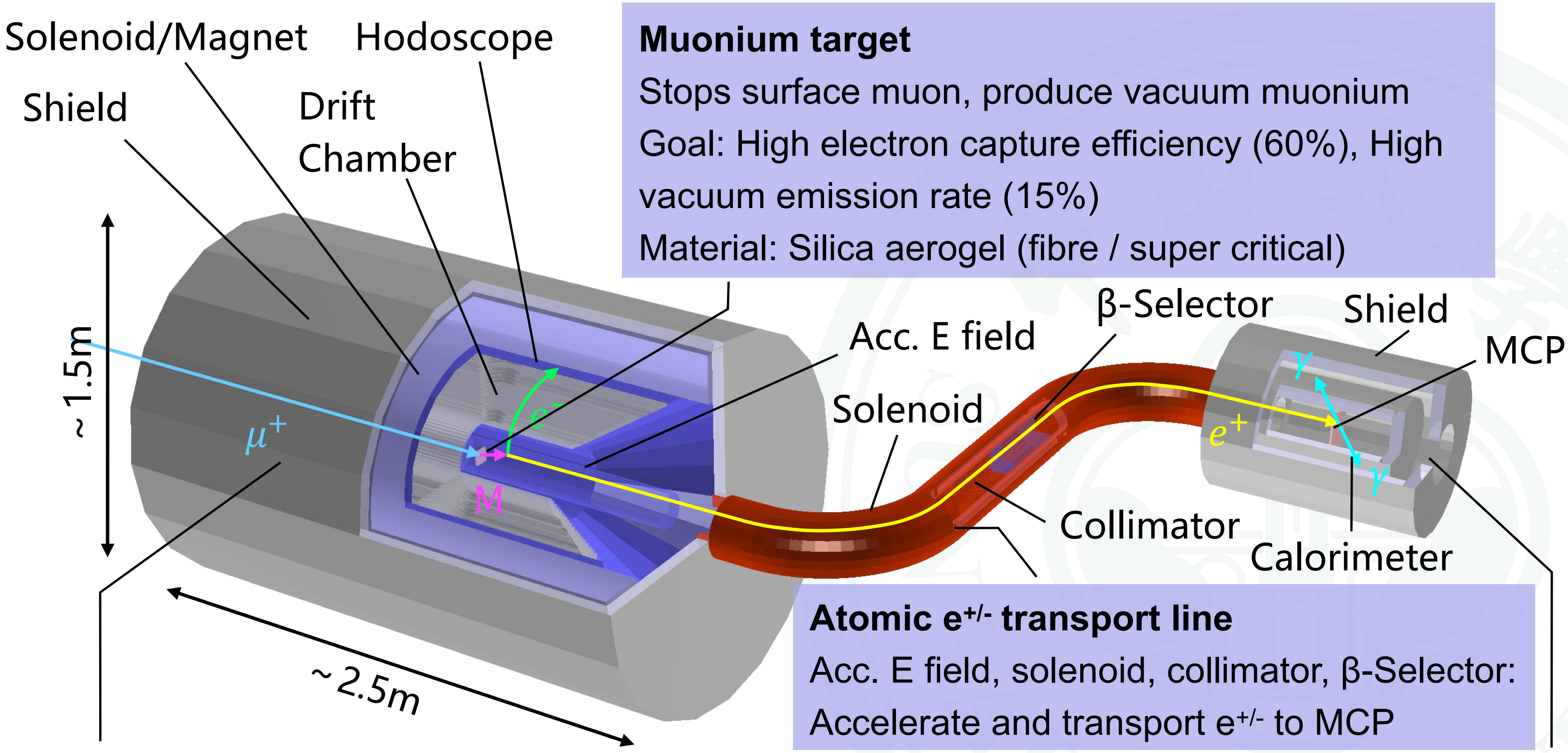
⑧ Calorimeter detect the e^+ annihilation

- 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.

Conceptual Design of MACE



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

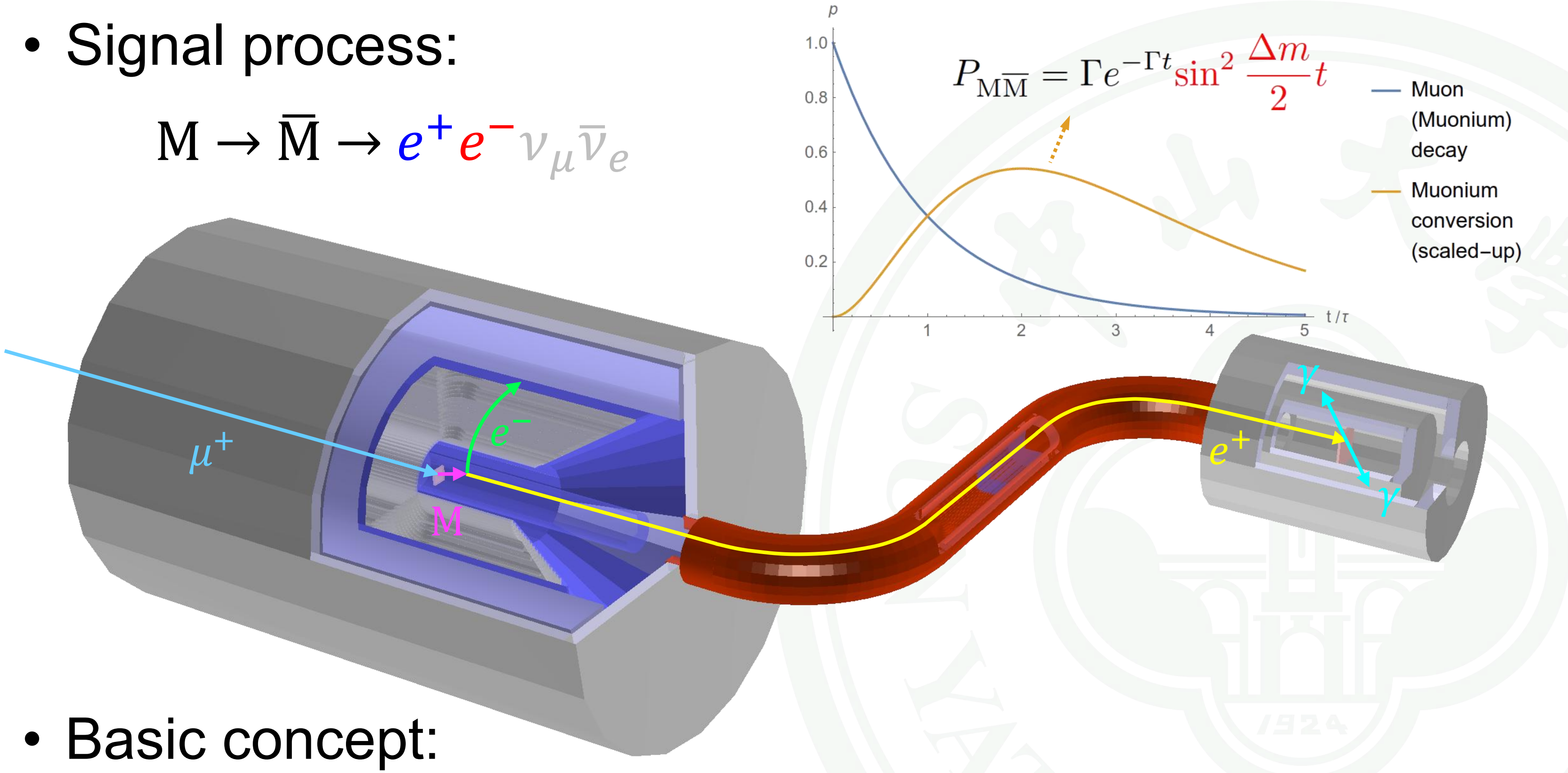
MCP: measures transverse position of $e^{+/-}$.

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

Conceptual Design of MACE: Summary

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

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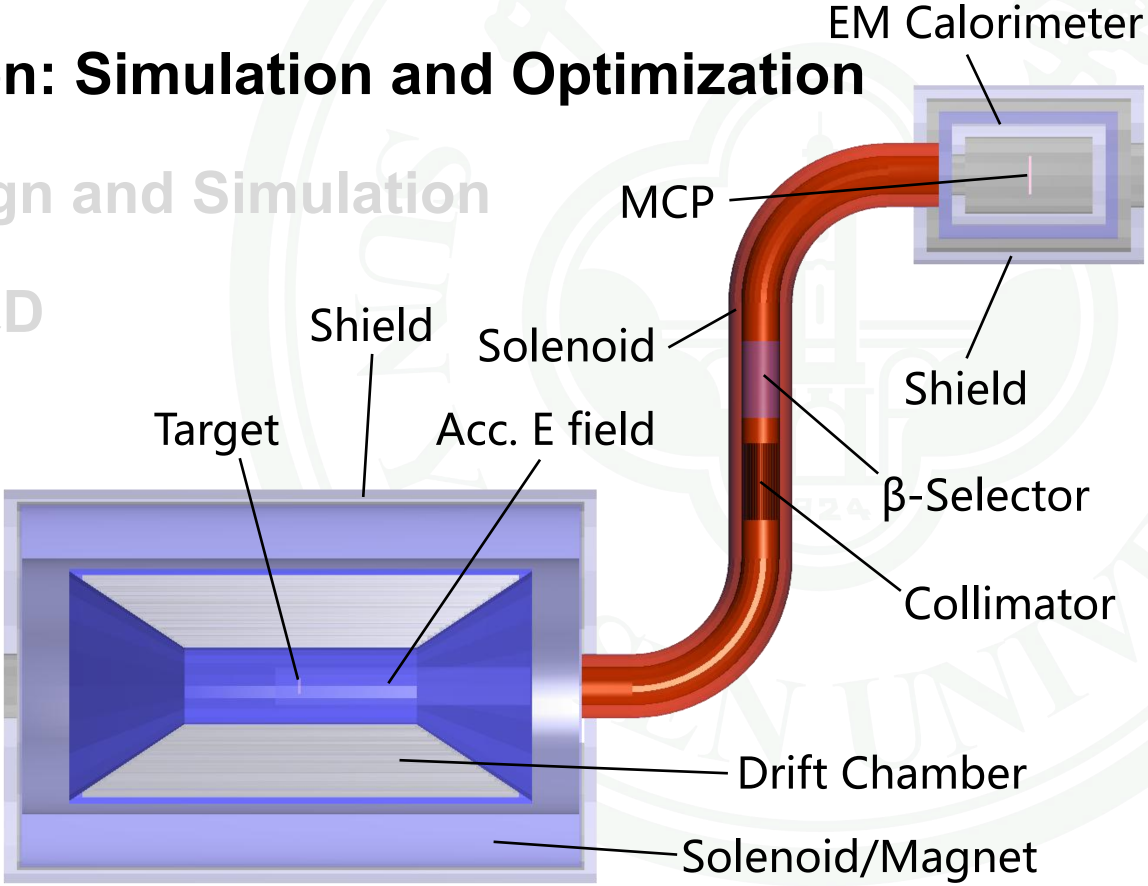


MACE Upper Bound & Muonium Yield

- 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

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

Comprehensive 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).

Muonium Production and Transport

μ^+ (~1MeV) scattering

↓

Electron capture (~1keV)

↓

Muonium (~100eV)
Epithermal scattering

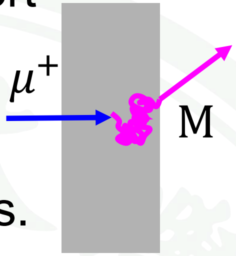
↓

Random walk (room temp.)

↓

Emission to vacuum

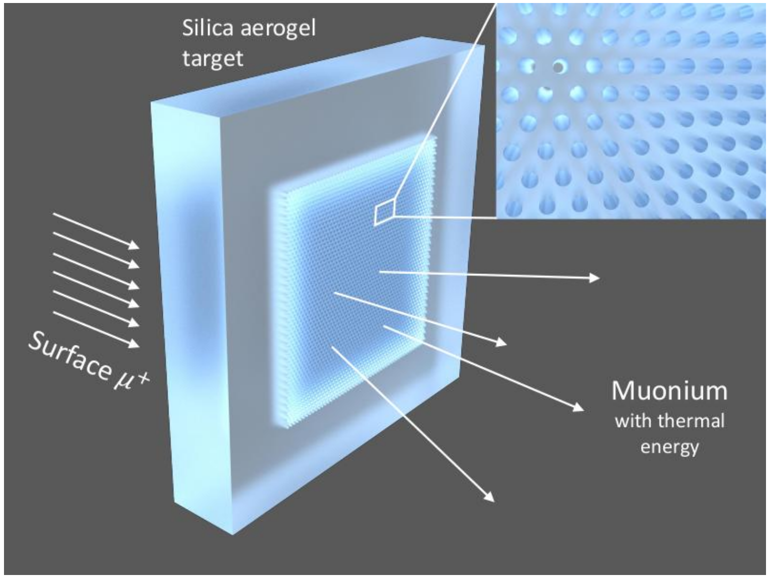
MC simulation for muonium transport has been developed under the MACE offline software framework.



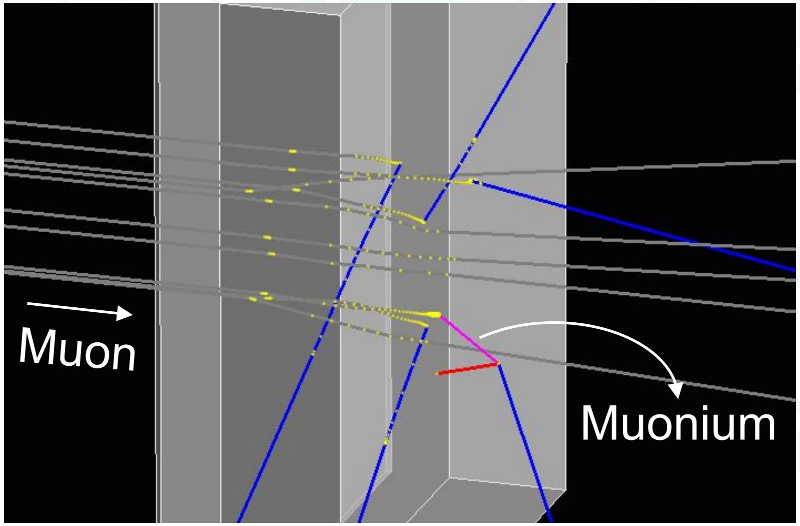
① Geant4 low-energy EM process.

② Geant4 AtRest process, modeled phenomenologically.

③ Random walk approach to thermal muonium tracking.

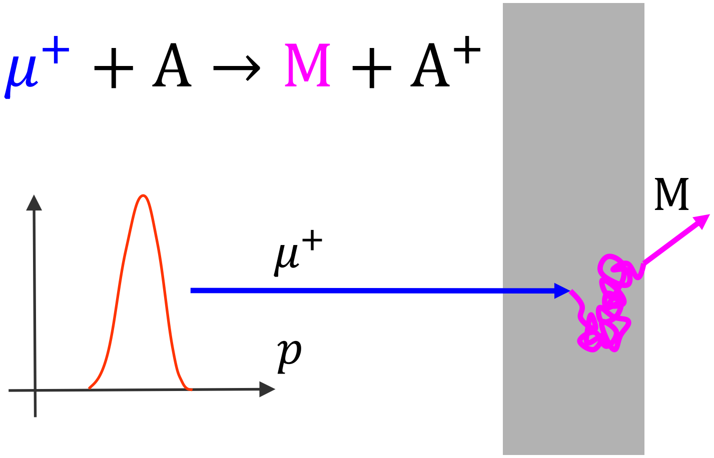


Simulation:

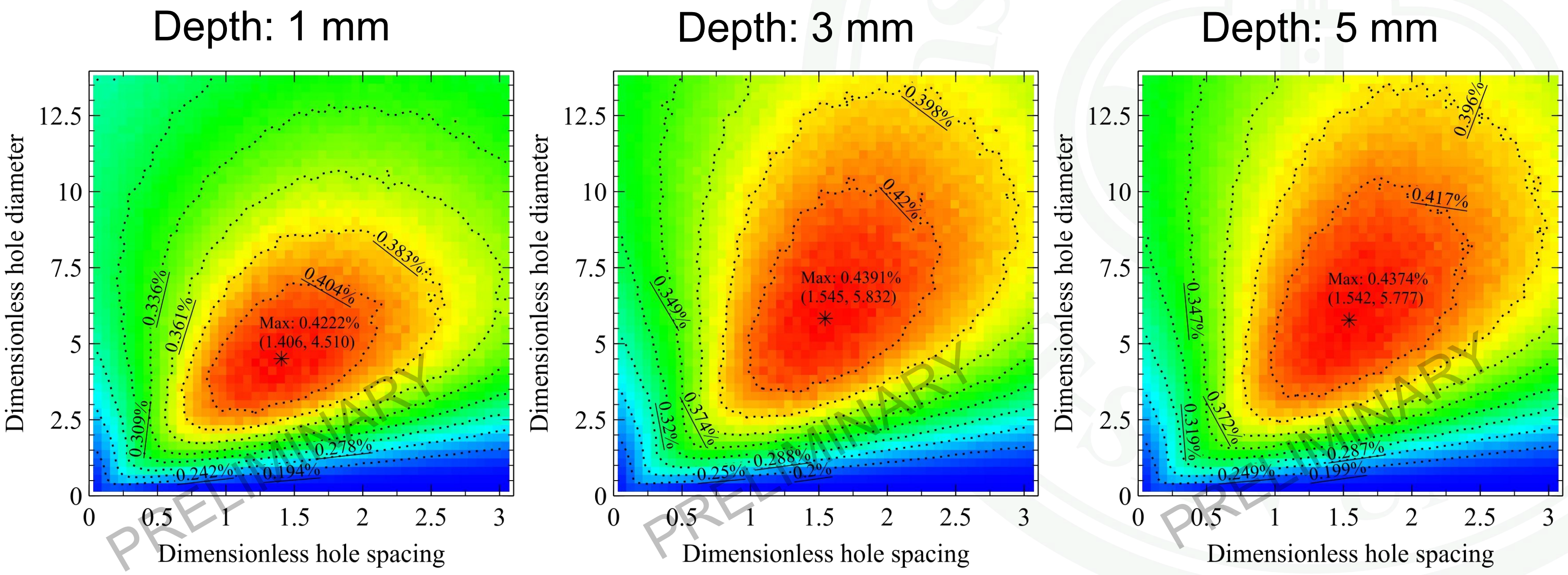


Muonium Yield Simulation

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



- 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%

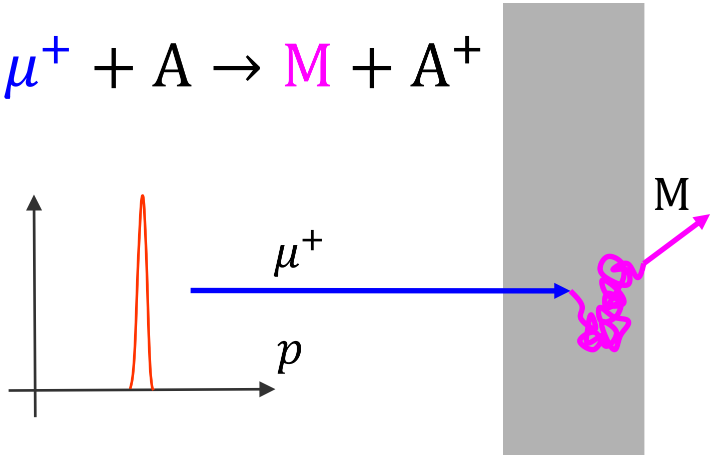

Depth: 1 mm

Depth: 3 mm

Depth: 5 mm

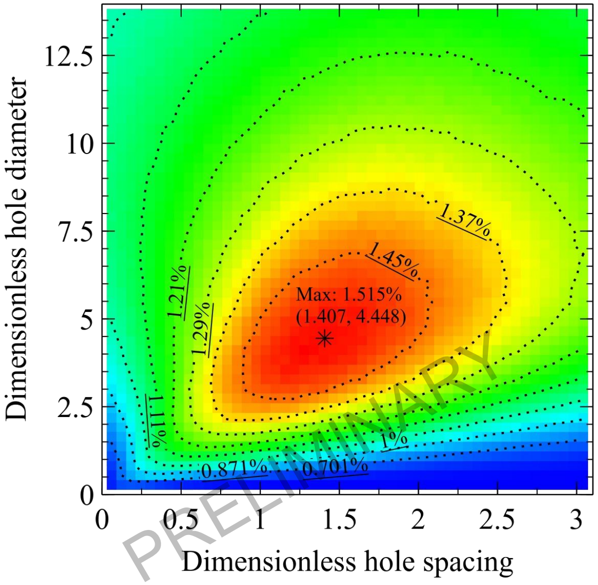
Muonium Yield Simulation - Low σ_p Beam

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

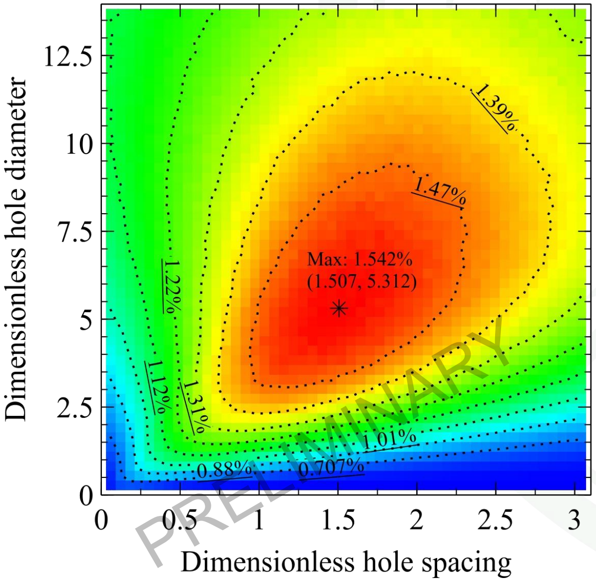


- Surface muon beam momentum spread: 2.5%
- Muonium mean free path: 200 nm, temp.: 300 K
- Optimal diameter: $1.51\sqrt{D\tau}$ (49.5 μm)
- Optimal spacing: $5.31\sqrt{D\tau}$ (175 μm)
- Max vacuum muonium yield: 1.54%

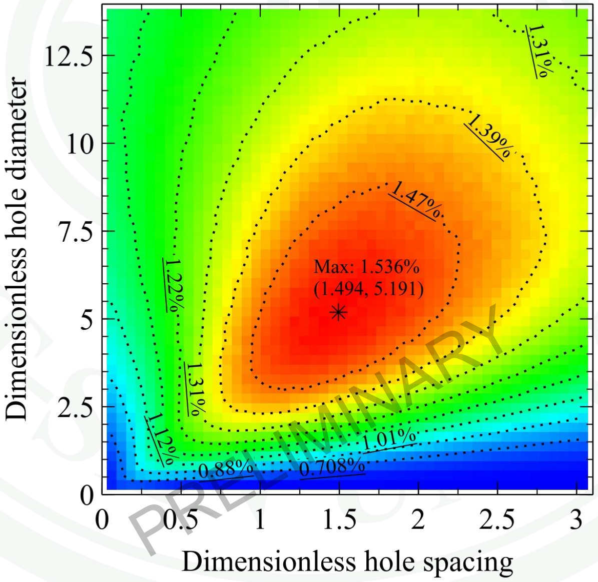
Depth: 1 mm



Depth: 3 mm



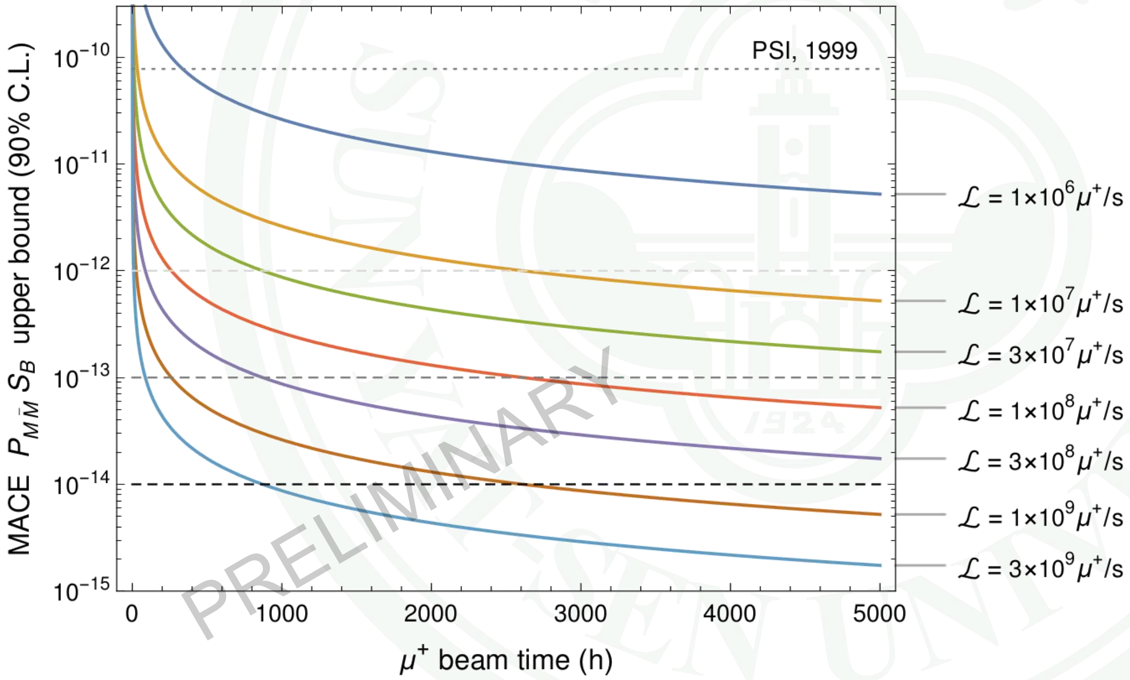
Depth: 5 mm



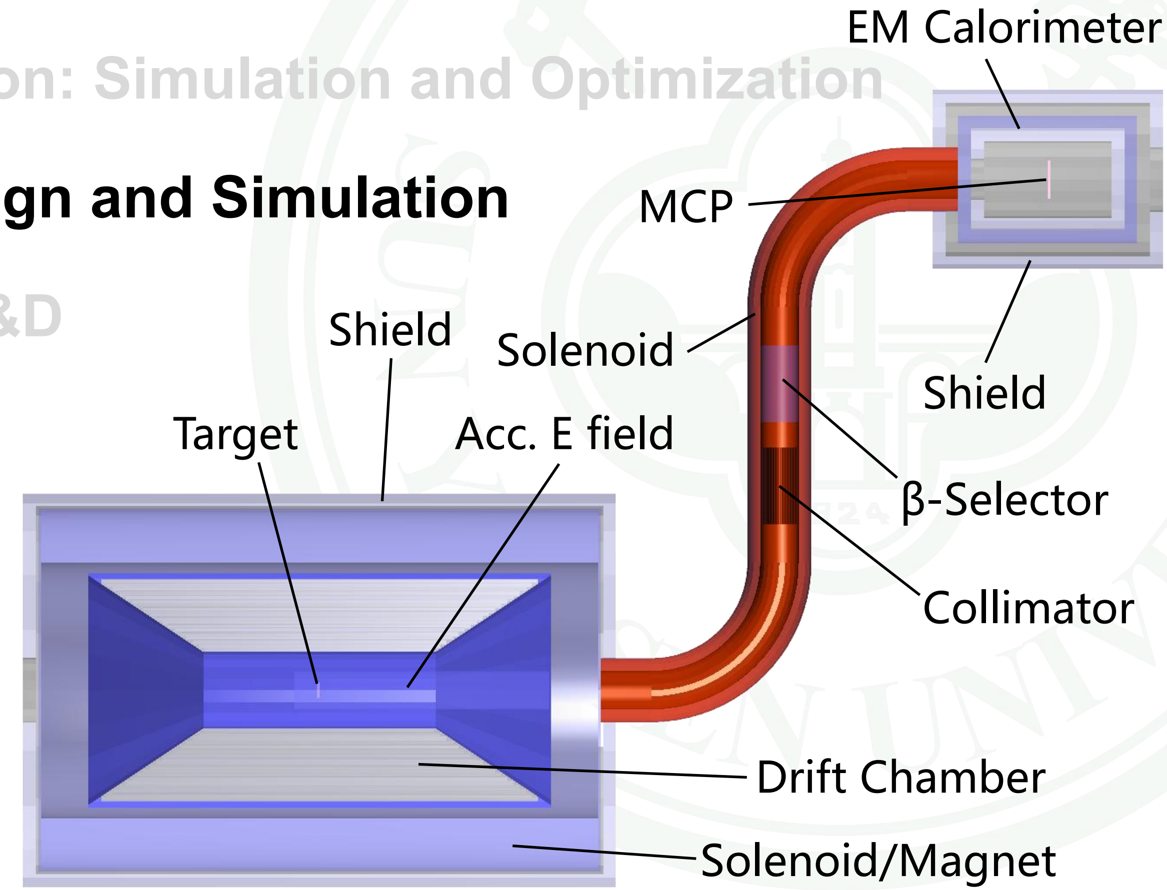
Comments on Muonium Yield

- 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 3-4 orders of magnitude.
- The improvement of detector performance will make contributions, correspondingly.



Content

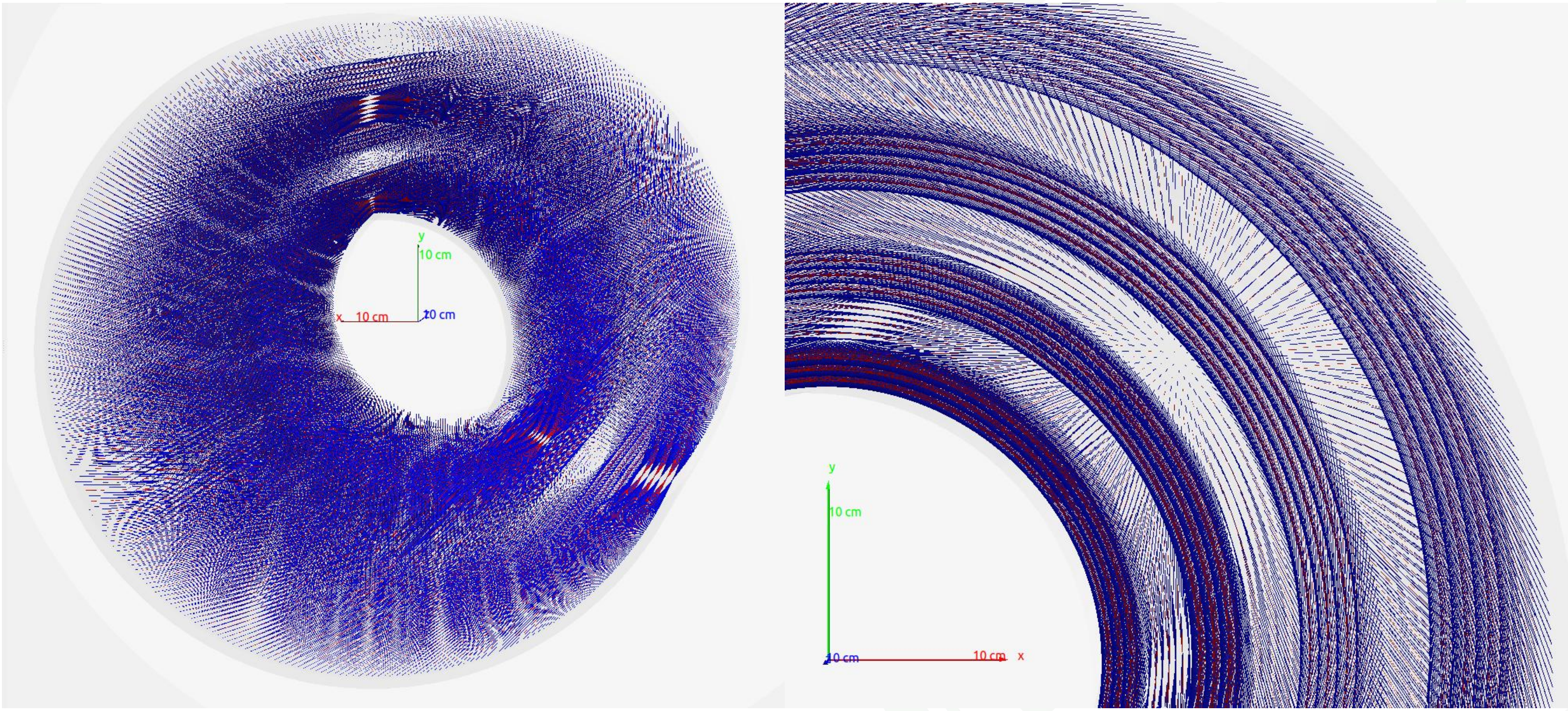

EM Calorimeter
MCP
Shield
Solenoid
Shield
Target
Acc. E field
β-Selector
Collimator
Drift Chamber
Solenoid/Magnet

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).

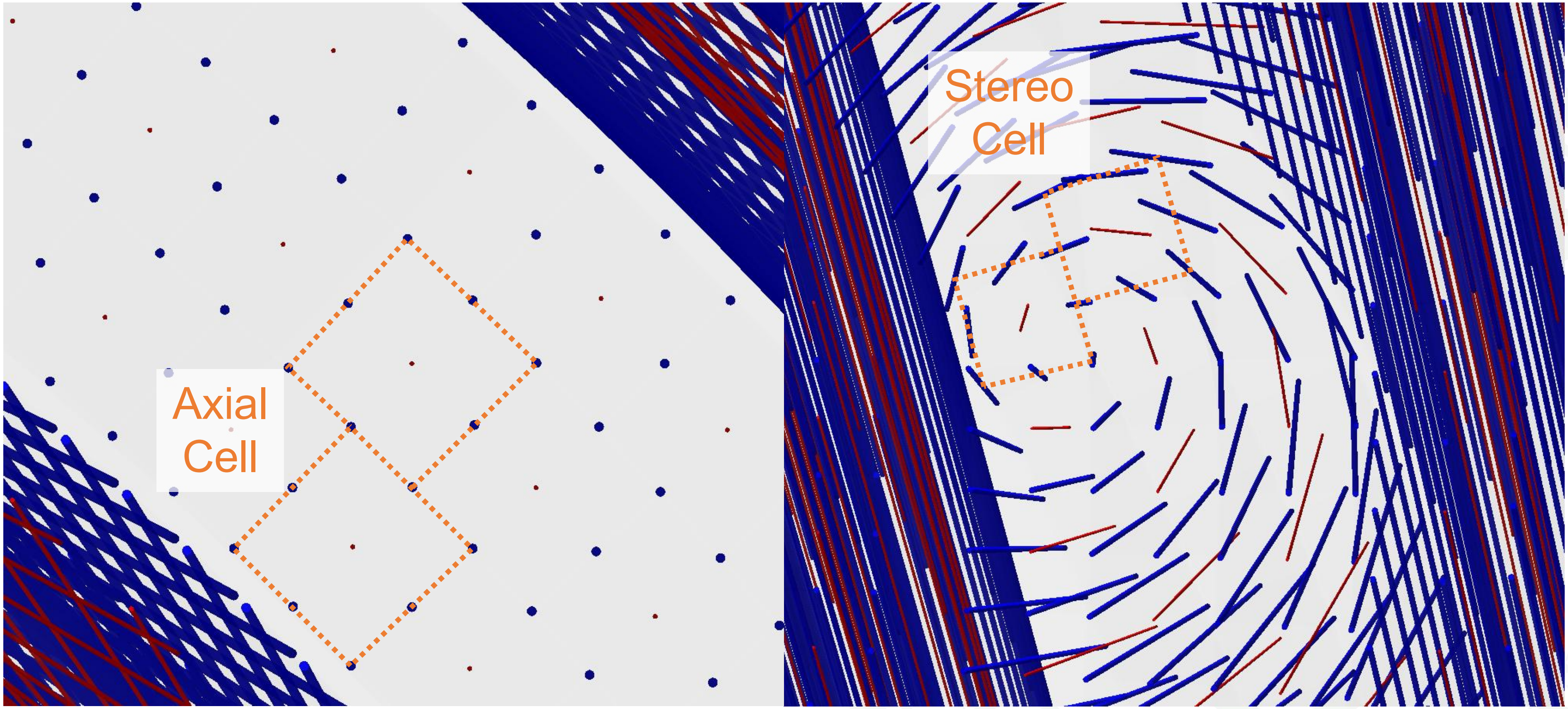
Design of Drift Chamber

- 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).

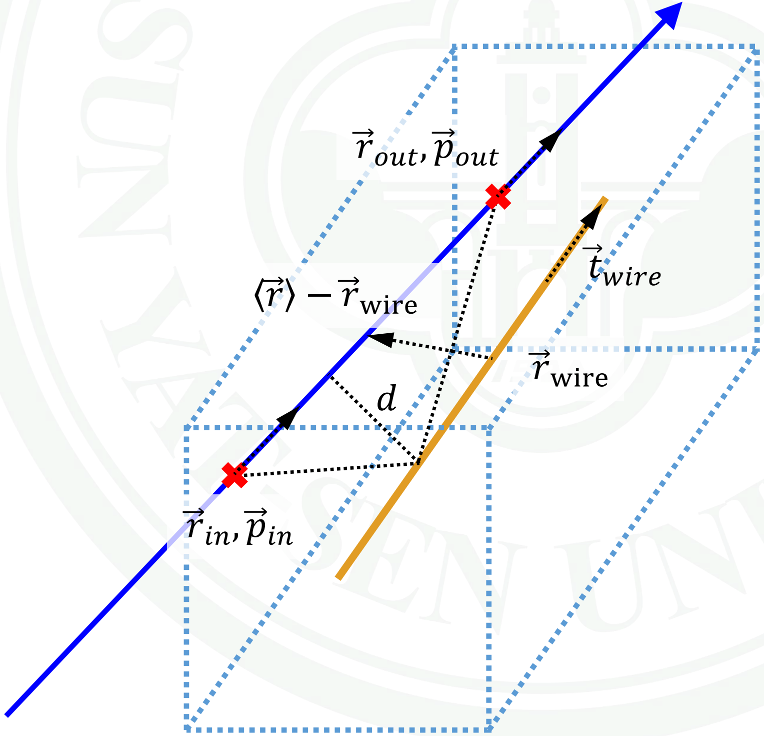
Fast Simulation of Drift Chamber

- 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:

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

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

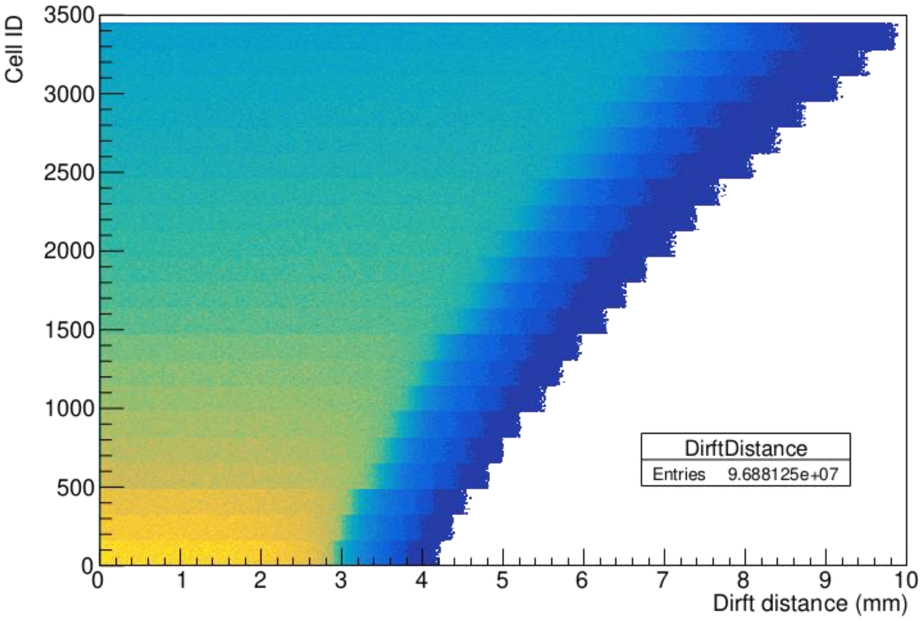
$$\langle\vec{r}\rangle = \frac{\vec{r}_{\mathrm{in}} + \vec{r}_{\mathrm{out}}}{2}$$



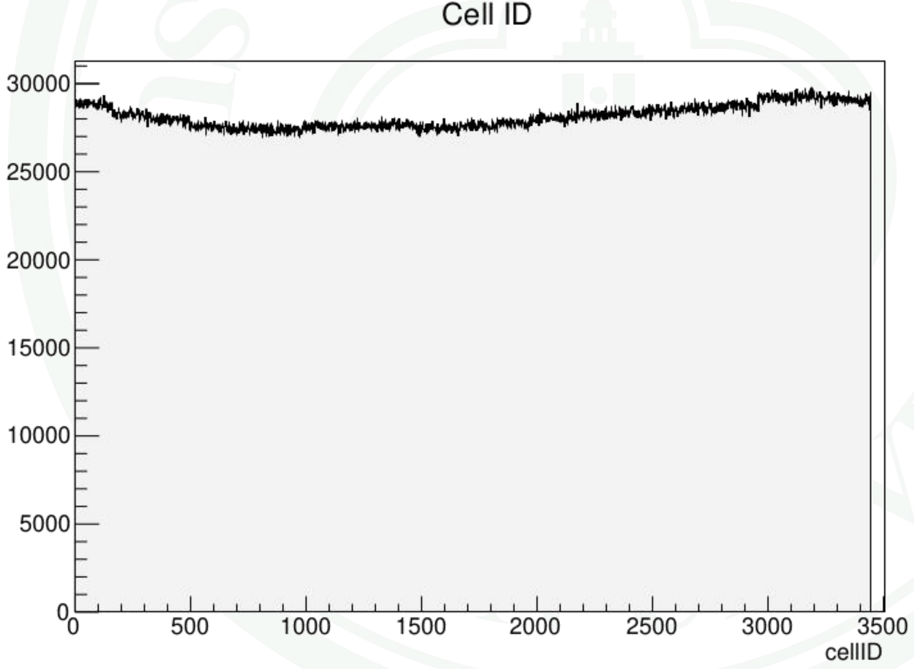
- $\vec{r}_{\mathrm{wire}}$: A point on the sense wire (e.g. the point at z=0)
- $\vec{t}_{\mathrm{wire}}$: Direction of the sense wire

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 distribution



Distribution of hit rate

Fast Simulation of Drift Chamber

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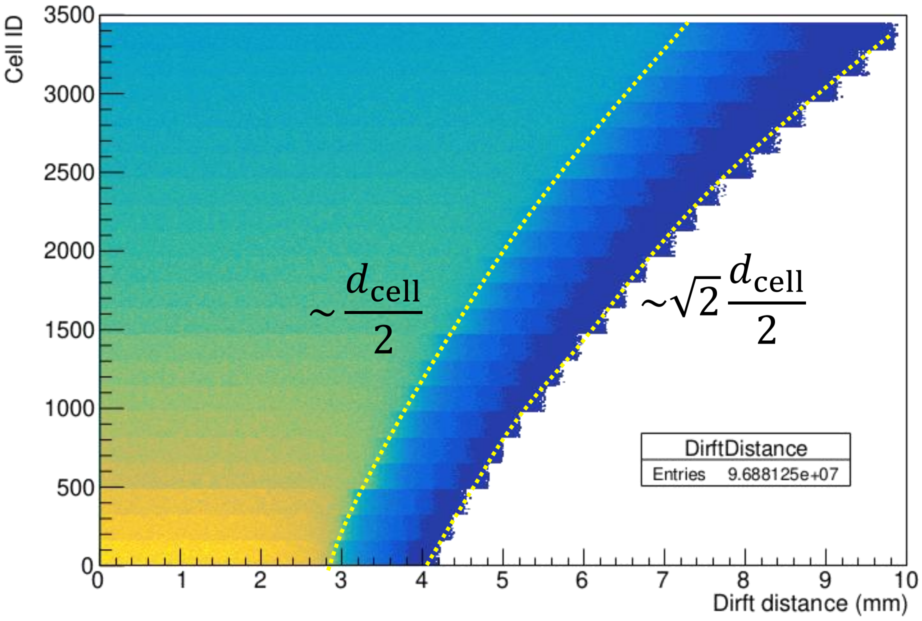
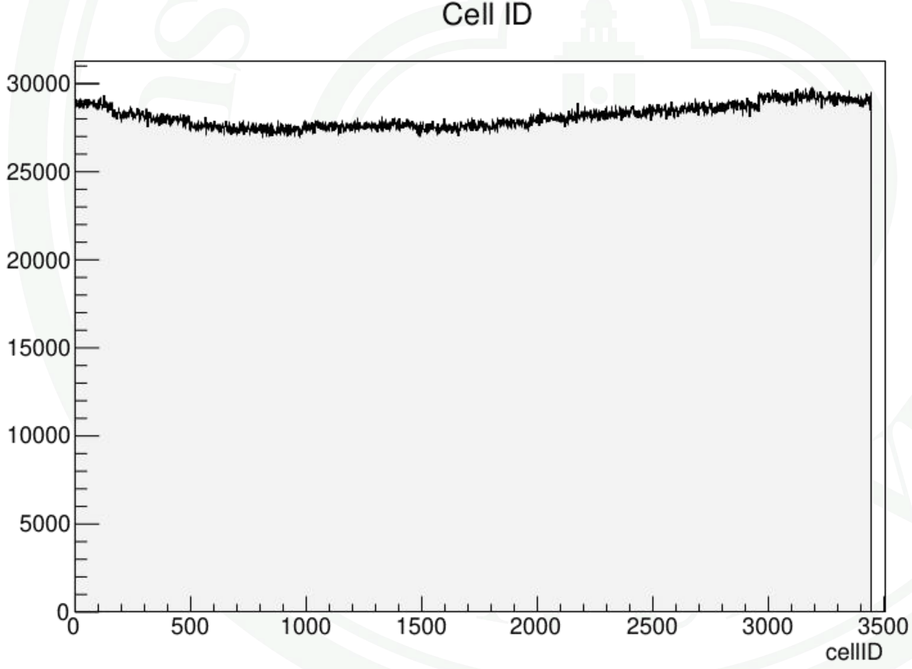


Distribution of drift distribution



Distribution of hit rate

Track Reconstruction

- Evalulated 15 geometry designs of drift chamber, 1.6×10^6 μ^+ for each simulation:
  - Directly records drift distances.
  - Stereo wire not implemented yet, records z_{hit}.
  - Smears drift distance with $\sigma_d = 0.2\text{mm}$.
  - Smears z_{hit} with $\sigma_z = 3\text{mm}$.

*To be updated after full reconstruction.

- Direct least χ^2 fit:

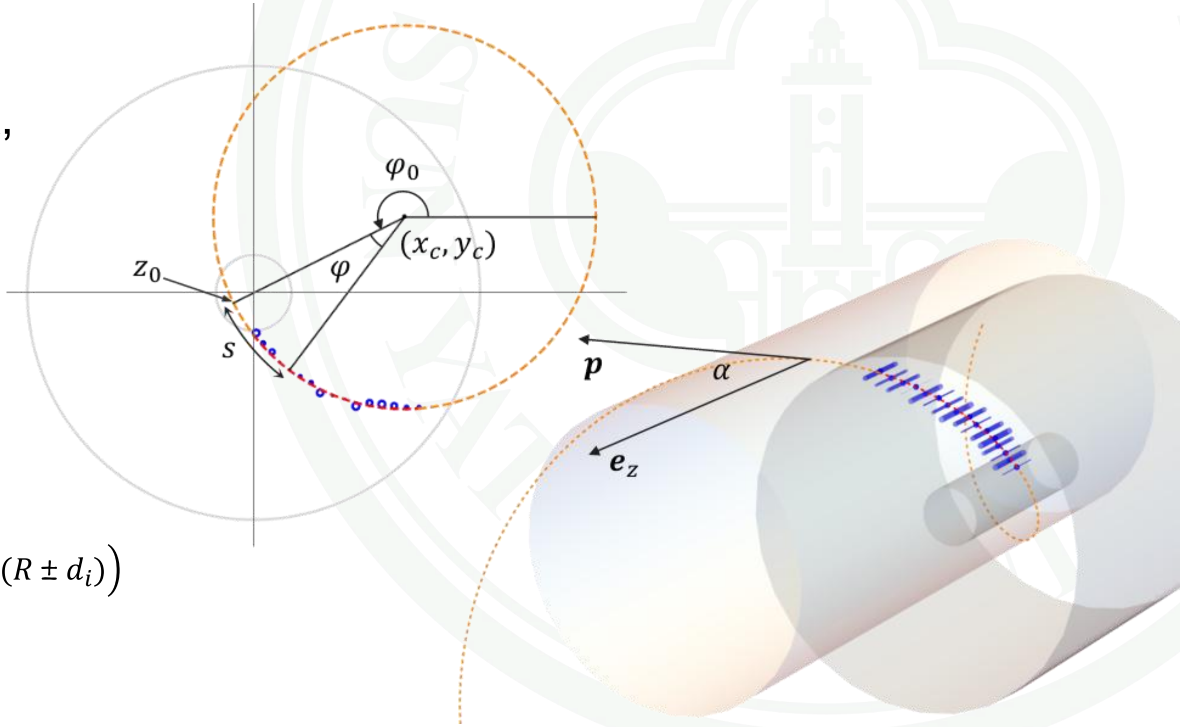
Track model: 5-parameters helix,

$$\begin{cases} x = x_c + R\cos(\varphi + \varphi_0) \\ y = y_c + R\sin(\varphi + \varphi_0) \\ \quad z = z_0 + s\cot\alpha \end{cases}$$

- Minimizer: Newton and CG,

Minimizes:

$$f(x_c, y_c, R) = \sum_i \min\left(\sqrt{(x_i - x_c)^2 + (y_i - y_c)^2} - (R \pm d_i)\right)$$



Track Reconstruction

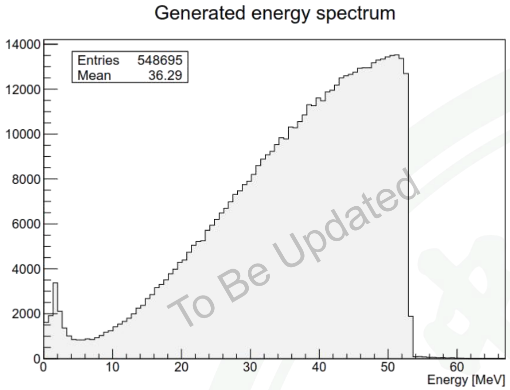
15 geometry designs have been evaluated:

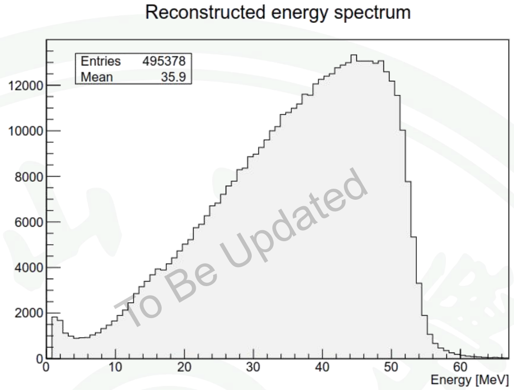
- Inner radius: 20~60 cm,
- Outer length 1.2~2 m,
- # sense layers: 12～24,
- Identical solid angle: 89.4% (out).

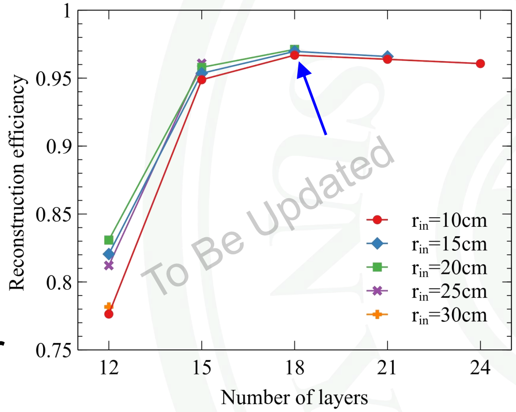
Conclusions:

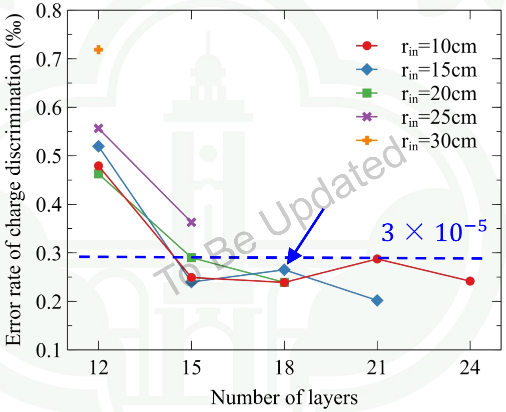
- For # sense layers >15, reach the limit of reconstruction effiency and charge identification capability.
- Choose the benchmark design: inner/outer radius 15/45cm, inner/outer length 90/180cm, 18 sense layers.
- The resolution is limited by the naive reconstruction algorithm. It's excepted to achieve charge error rate<10^{-5}, momentum resolution<500keV/c.

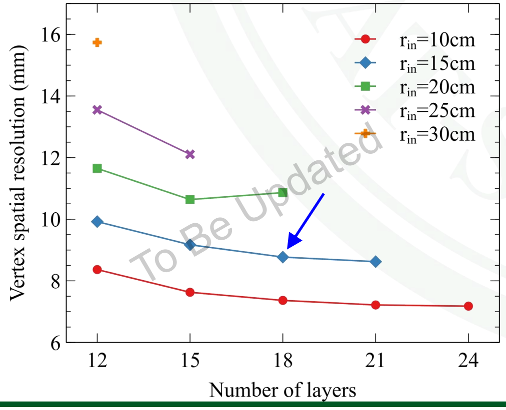
*To be updated after full reconstruction.

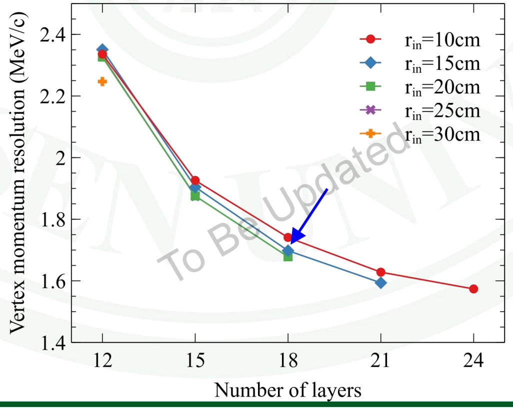












Outlook of Drift Chamber Design

- We have developed an algorithm to generate the drift chamber geometry, allowing us to evaluate and optimize the geometry design of drift chamber.
- We have performed the fast simulation using the simple and classical DOCA method.
- Fast simulation data can be smeared according to the spartial resolution of the drift cells.
- Tracks reconstructed from the smeared data will carry the resolution information of the detector: planned to implement Kalman filter, improvement on the way.

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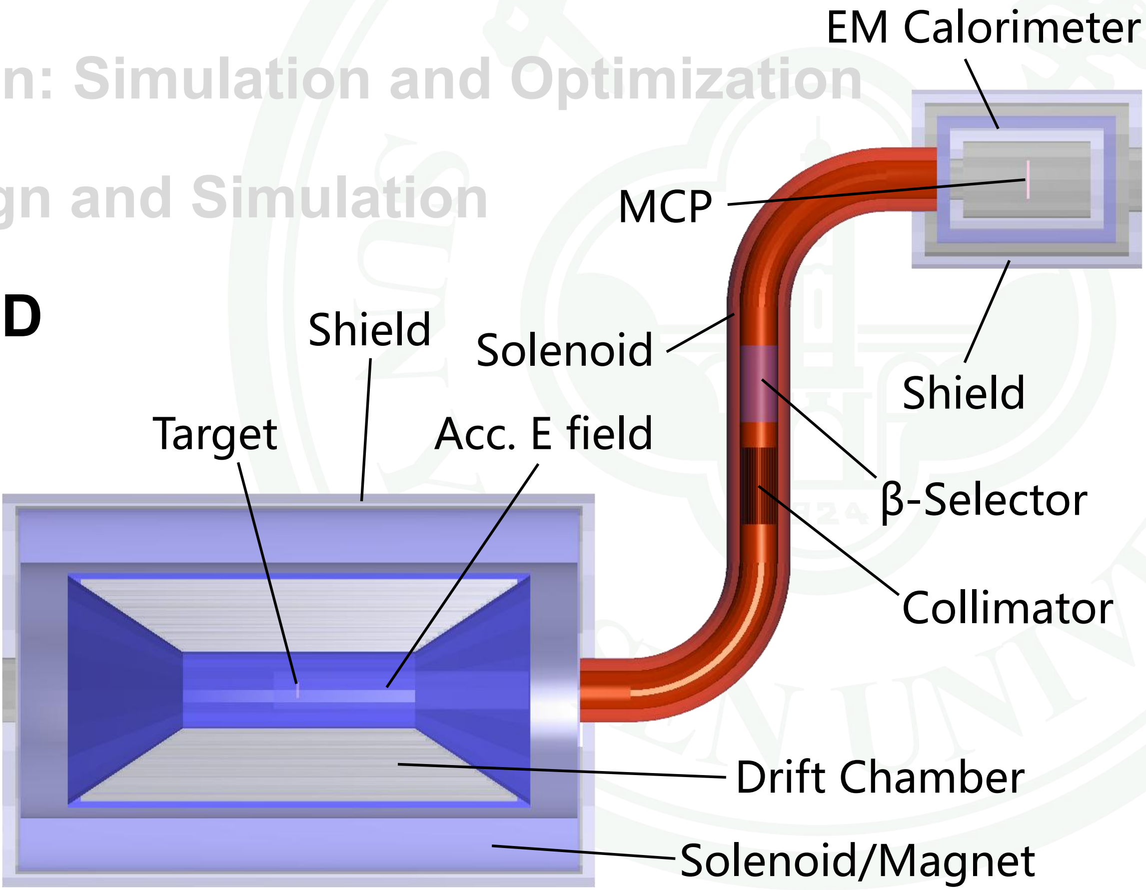
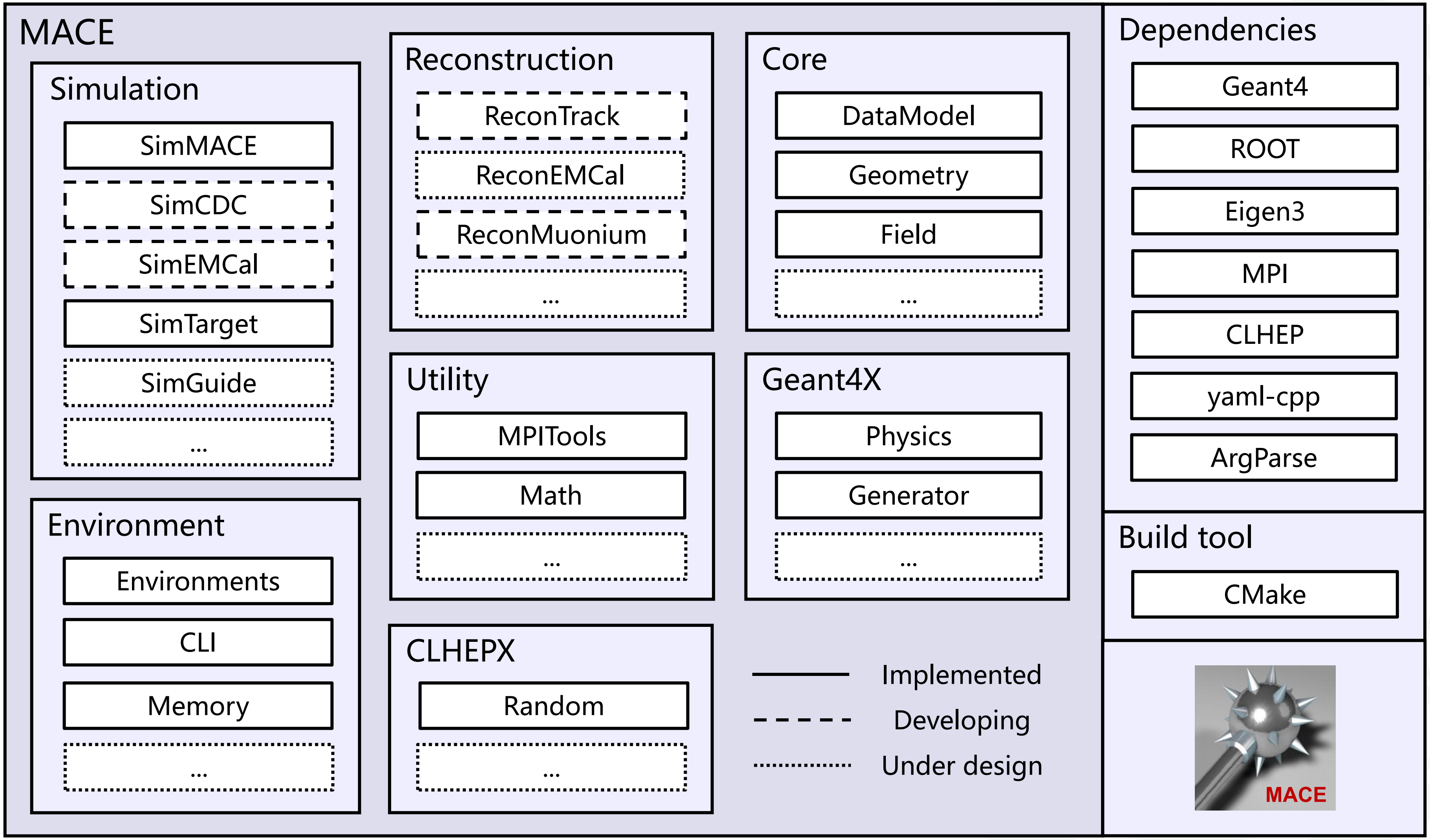


MACE Offline Software



MACE

Simulation
- SimMACE
- SimCDC
- SimEMCal
- SimTarget
- SimGuide
- …

Environment
- Environments
- CLI
- Memory
- …

Reconstruction
- ReconTrack
- ReconEMCal
- ReconMuonium
- …

Utility
- MPITools
- Math
- …

CLHEPX
- Random
- …

Core
- DataModel
- Geometry
- Field
- …

Geant4X
- Physics
- Generator
- …

Implemented

Developing

Under design

Dependencies
- Geant4
- ROOT
- Eigen3
- MPI
- CLHEP
- yaml-cpp
- ArgParse

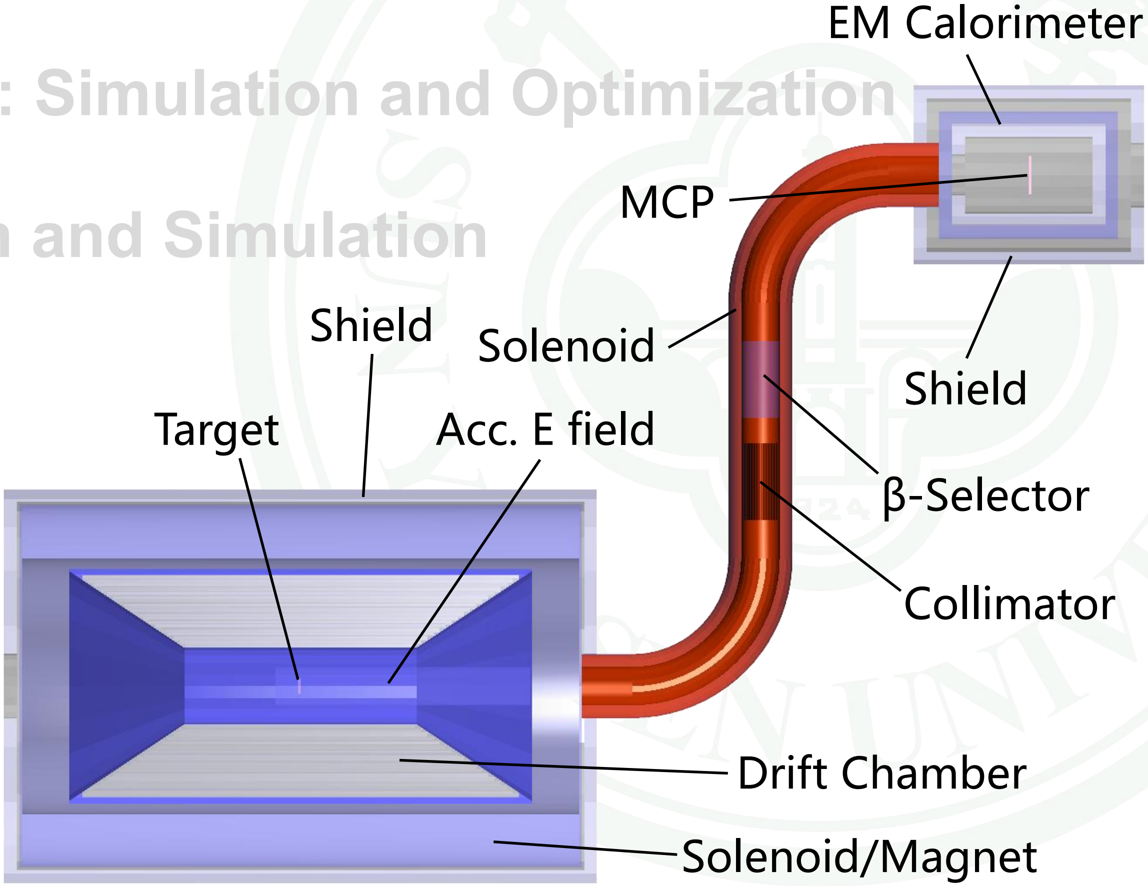
Build tool
- CMake

MACE Offline Software

- MACE offline software: designed for experiment R&D, simulation, and offline reconstruction.
- Preliminary 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 - clear code style and design for future.
- Currently, main tasks:
  - Develop offline track reconstruction module.
  - Refine physics processes.
  - Improve and API and UI.

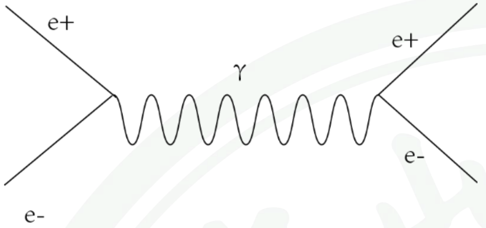
Content

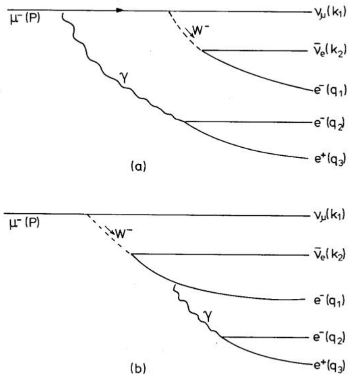
- Motivation
- Conceptual Design of MACE
- Muonium Production: Simulation and Optimization
- Drift Chamber Design and Simulation
- Offline Software R&D
- **Preliminary analysis**
- Summary



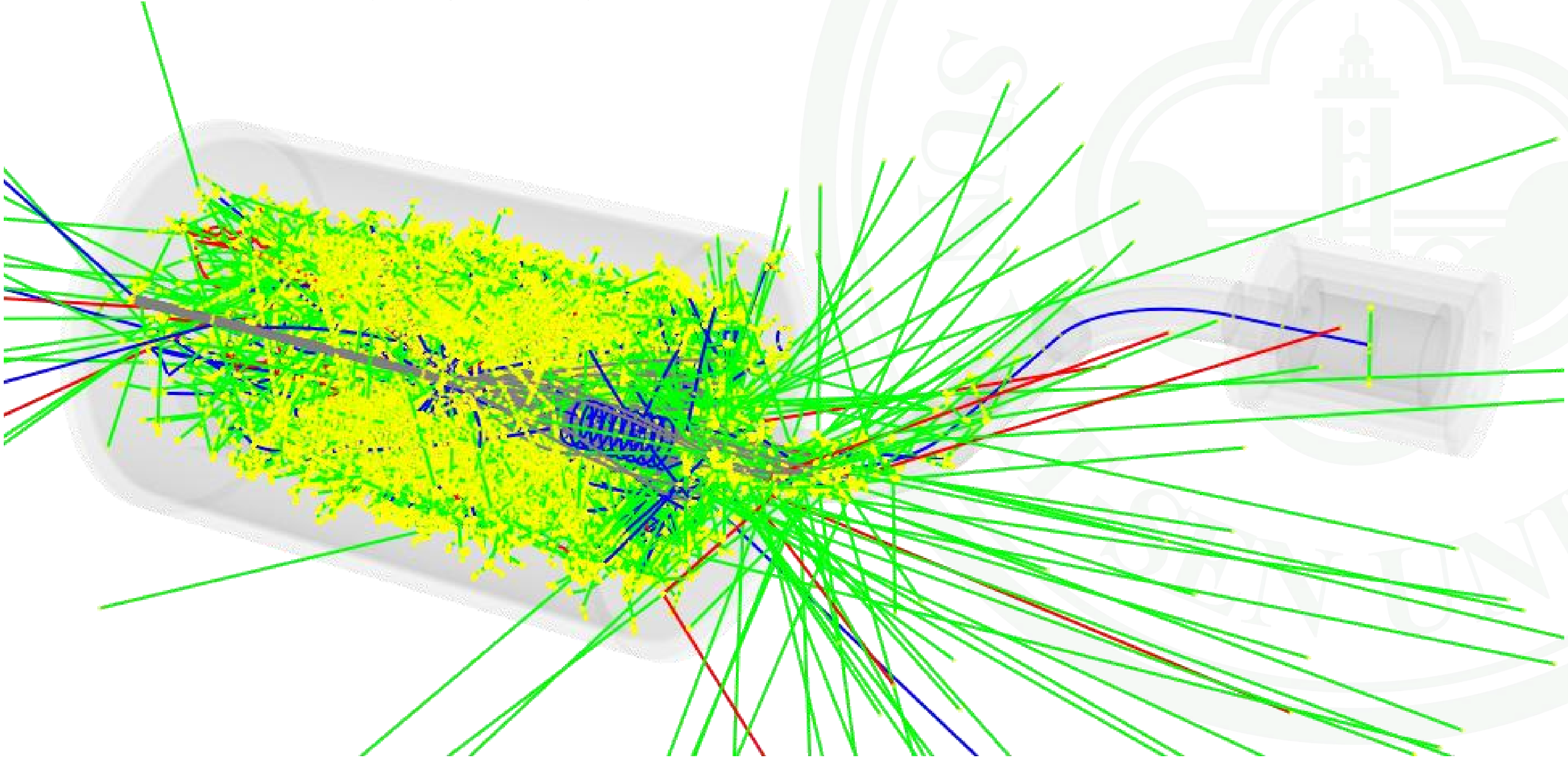
Monte Carlo: Fast Simulation

- Backgrounds:
  - μ^+ decays to e^+, Bhabha scattering to generate high-energy e^- in coincident with low-energy e^+
  - μ^+ decays: $\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu} e^+ e^-$

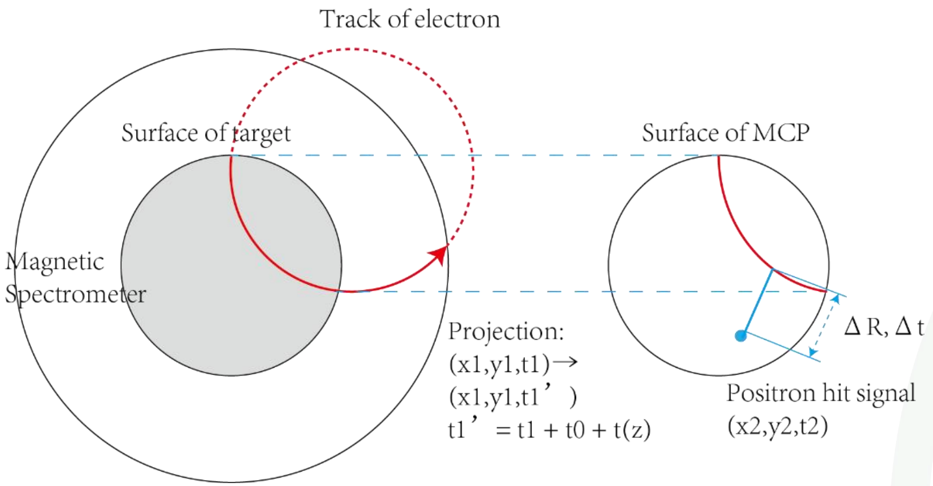


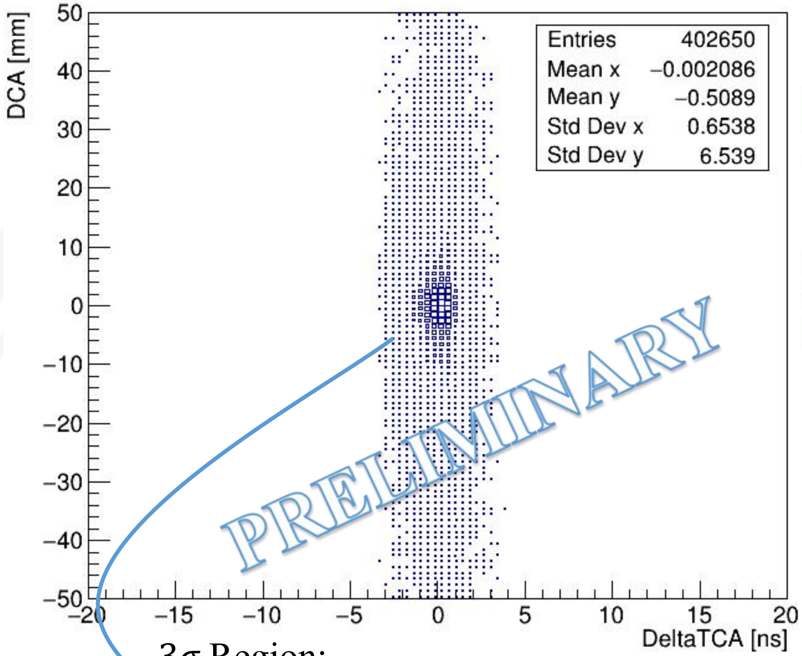


- Anti-muonium decay signals by position-time coincidence

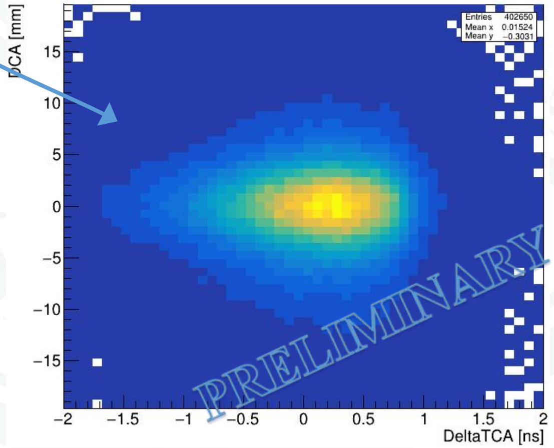


Analysis of Simulated Data





3σ Region:



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

- At the same vertex:

$|\Delta R| \sim DCA < 12.0$ mm

- At the same time:

$|\Delta t| \sim TOF - TOF_{expected} \sim TCA < 4.5$ ns:

$TOF = t_0 + t(z)$

*To be updated after full reconstruction.

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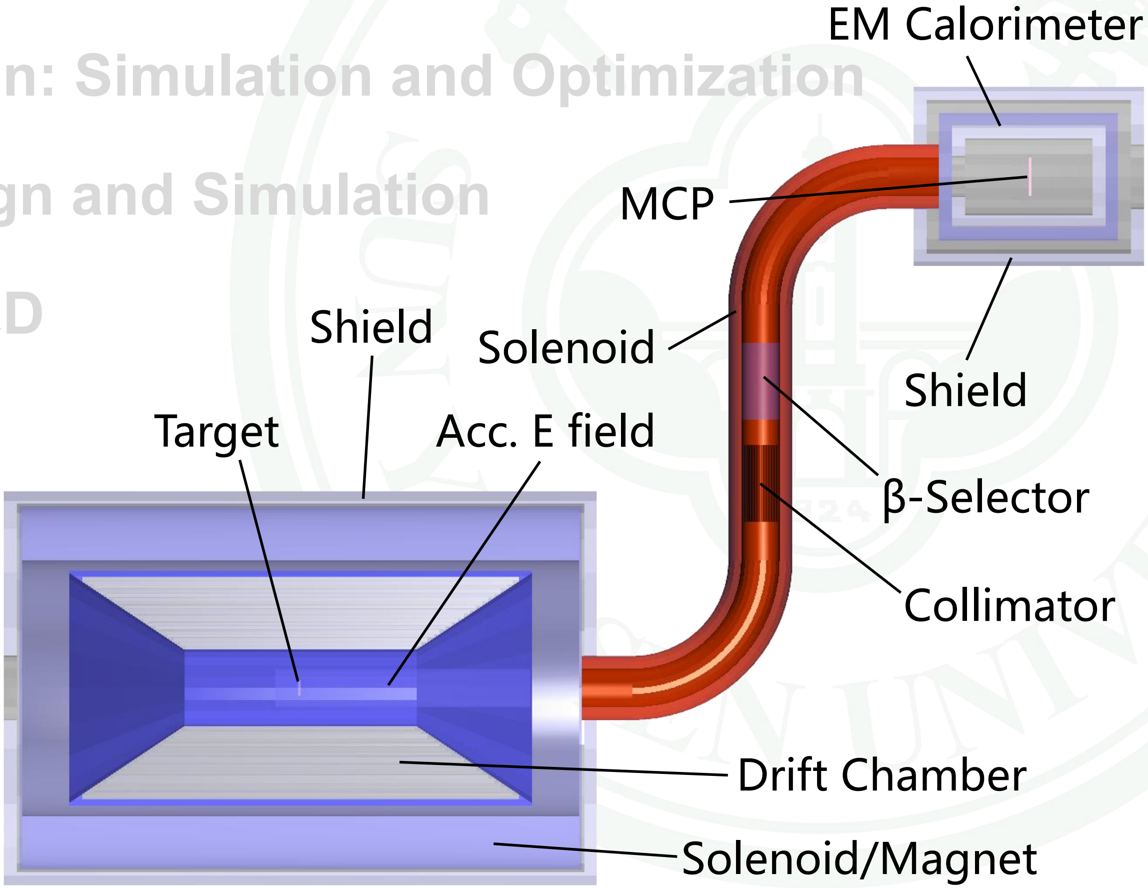


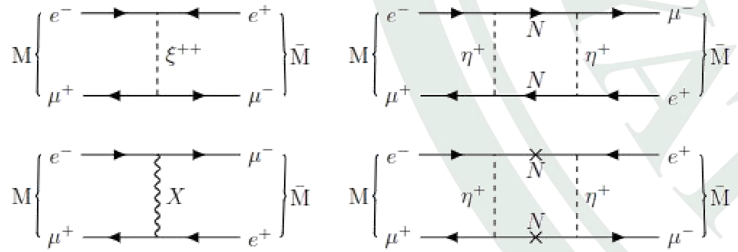
Summary

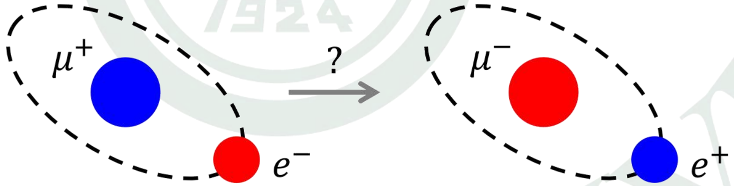
- cLFV, a neutrino-less lepton flavor violating process, is forbidden in SM. Precise (high-intensity) experiment searching for cLFV, is an sensitive probe of BSM.
- MACE is the first proposed muonium-to-antimuonium conversion experiment since 1999, with the development of high-intensity muon beam and 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.

Muonium-to-**A**ntimuonium **C**onversion **E**xperiment

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

THANK YOU





Backup

Monte Carlo: Fast Simulation

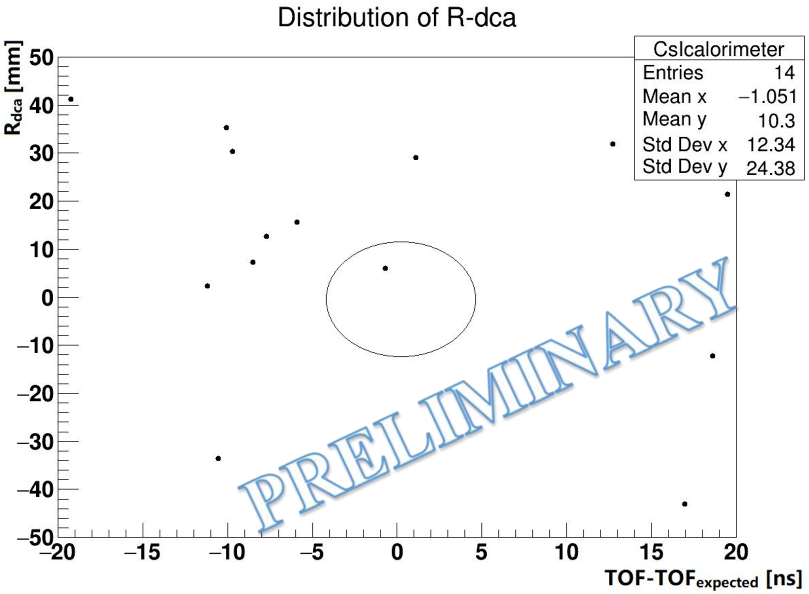
1. Preliminary results in simulation

- 1.056×10^8 of μ^+
- BR of $\mu^+ \rightarrow e^+e^-e^+\nu_e\overline{\nu_\mu}$

is set to 100%.

2. Compared with PSI estimates

- 9.459×10^7 of μ^+ Rare decay
- 1.7 background events expected.



- Happen at the same vertex:

  $|\Delta R| \sim R_{dca} < 12.0$ mm

- Happen at the same time:

  $|\Delta t| \sim \mathrm{TOF}\text{-}\mathrm{TOF}_{expected} < 4.5$ ns:

  TOF = t0 + t(z)

Courtesy: Yu-Zhe Mao → Cross check and improvement on the way.