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

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on behalf of the MACE working group

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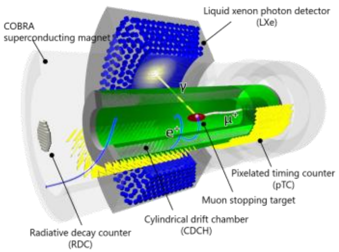
Search for cLFV

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

  } $\mu N \to eN$

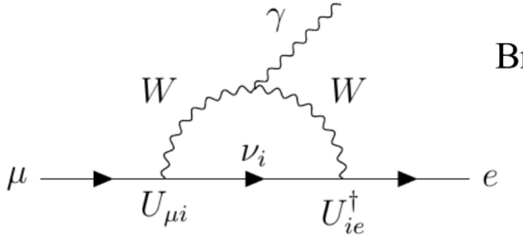
Mihara's talk yesterday



Kuno's talk yesterday

Zhengyun You's talk yesterday

- cLFV = new physics beyond Standard Model (SM)
  - ✓ cLFV is **forbidden** in SM.
  - ✓ Many new physics model beyond SM predict cLFV.
  - ✓ Tiny contribution from neutrion oscillation (currently not detectable).
  - ➢ **A clear evidence of new physic if found!**



$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi m_W^4}\left|U_{\mu 2}U^\dagger_{2e}\Delta m^2_{21} + U_{\mu 3}U^\dagger_{3e}\Delta m^2_{31}\right|^2$$

$$\sim 10^{-54}$$

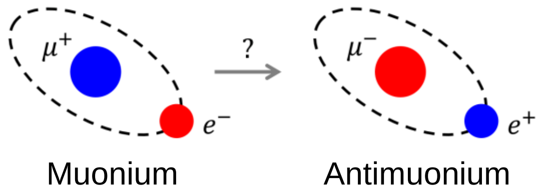
Muonium conversion: a cLFV process

- Muonium ($\mathrm{M} = \mu^+ e^-$): a leptonic isotope of hydrogen.
- **M-$\overline{\mathrm{M}}$ mixing**: an phenomenological possibility leads to **M-to-$\overline{\mathrm{M}}$ conversion**.

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

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

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



$$p_{\mathrm{M}\to\overline{\mathrm{M}}}(t) = \frac{P_{\mathrm{M}\to\overline{\mathrm{M}}}}{2\tau} t^2 e^{-t/\tau}$$

Current bound:
$P_{\mathrm{M}\to\overline{\mathrm{M}}} < 8.3 \times 10^{-11}$
(in 0.1T field, 90% C.L.)

L. Willmann et al., Phys. Rev. Lett. 82 (1999), 49-52.

- $\mathrm{M} \to \overline{\mathrm{M}}$: an $\Delta L_\mu = -\Delta L_e = 2$ process.
  - ✓ Different EFT operators from $\Delta L_\mu = -\Delta L_e = 1$ proc. ($\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$).
  - ✓ $\Delta L_\mu = -\Delta L_e = 2$ can be possible even if $\Delta L_\mu = -\Delta L_e = 1$ is suppressed.
  - ✓ Complementary to $\Delta L_\mu = -\Delta L_e = 1$ process searches.

	e^-	μ^-	τ^-	e^+	μ^+	τ^+
L_e	+1	0	0	-1	0	0
L_μ	0	+1	0	0	-1	0
L_τ	0	0	+1	0	0	-1

T. Fukuyama, Y. Mimura, and Yuichi Uesaka, Phys. Rev. D 105, 015026 (2022). (arXiv: 2108.10736)

How to detect M-to-$\bar{\mathrm{M}}$ conversion?

- Two approaches in history:
  1. look for nucleus μ^- capture gamma
  2. look for final states (both a fast e^- and a slow e^+)

L. Willmann et al., Phys. Rev. Lett. 82 (1999), 49-52.

✓ Best limits was achieved by looking for antimuonium decay final states.

- Two approaches in the future:

Yoshioka's talk yesterday
(J-PARC g-2 muon cooling)

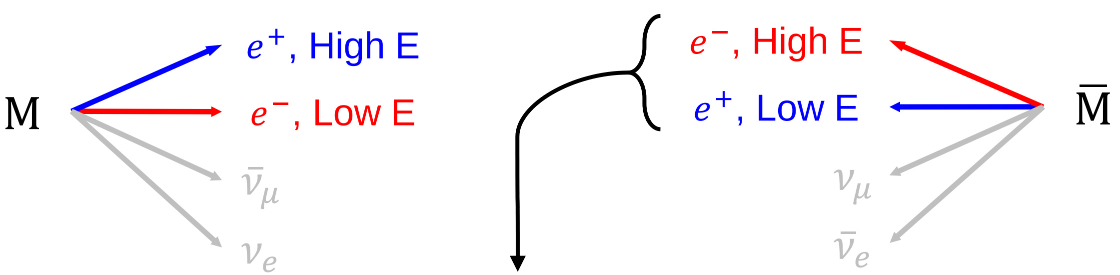
  1. Ionize antimuonium and detect nucleus μ^- (proposed in J-PARC)
  2. Look for decay final states with even higher precision (MACE)

N.Kawamura et al., JPS Conf. Proc. 33, 011120 (2021)

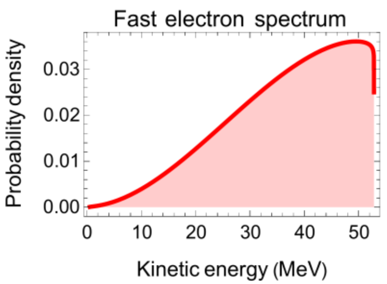
A.-Y. Bai et al. (MACE working group), Snowmass2021 Whitepaper: Muonium to antimuonium conversion, arXiv:2203.11406

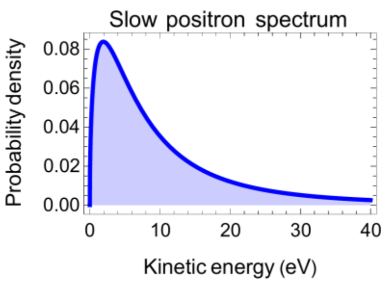
Muonium decay:
$\mathrm{M} \rightarrow e^- e^+ \nu_e \bar{\nu}_\mu$

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



Search for the conversion by **vertex coincidence** and **charge identification.**



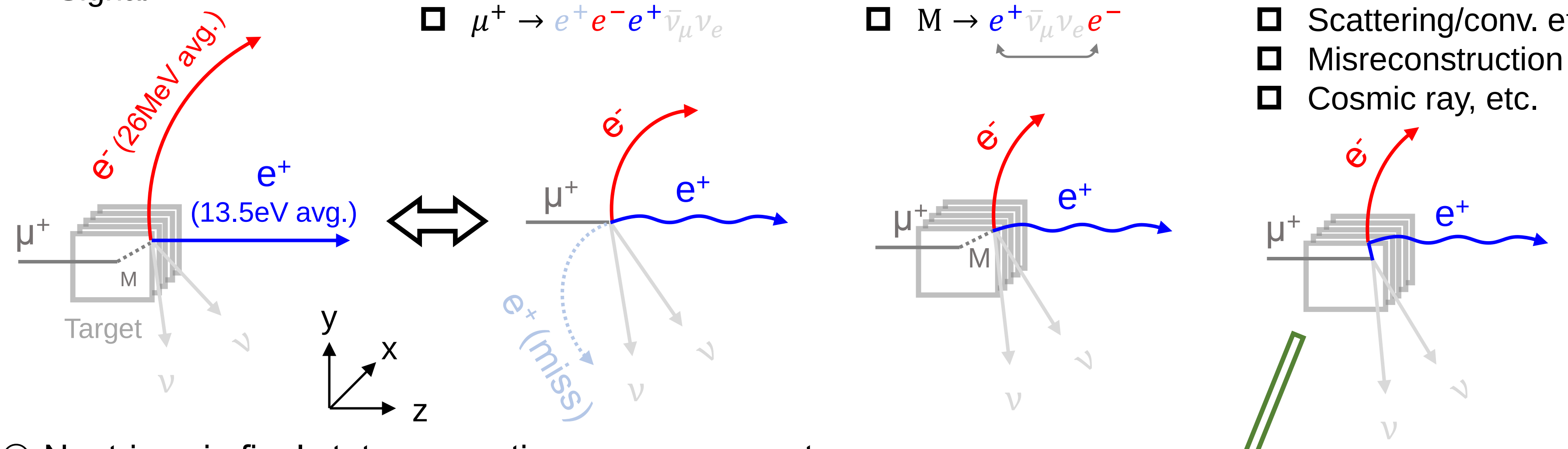


Signal and background

1. Internal conv. (IC) decay
   - $\mu^+ \to e^+ e^- e^+ \bar{\nu}_\mu \nu_e$

2. Final state scattering
   - $M \to e^+ \bar{\nu}_\mu \nu_e e^-$

3. Accidental bkg.
   - Scattering/conv. e^-
   - Misreconstruction
   - Cosmic ray, etc.



☹ Neutrinos in final state → continous energy spectrum

☺ Very low energy e^+ → a clear signature

- **Common vertex (by limiting e^+/e^- track DCA)**
  - ✓ Select p_{xy} of e^+
  - ✓ Reject accidental e^-
- **Time coincidence (by limiting e^+ TOF)**
  - ✓ Select p_z of e^+
  - ✓ Reject e^+ from IC decay or Bhabha scattering
- **Charge identification (by e^- track & e^+ annihilation)**

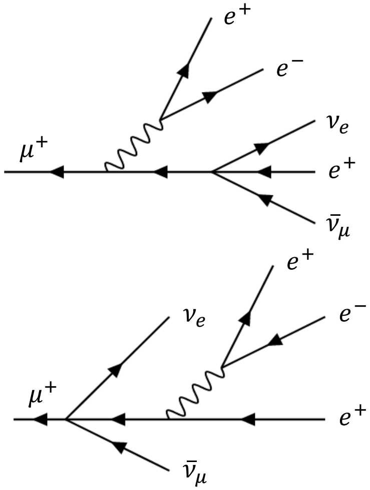
➢ A clean data taking duration

➢ Excellent vertex resolution
- e^+/e^- spatial resolution
- Precise e^+ transport in EM field

➢ Excellent time resolution
- e^+/e^- time resolution

Suppression of background

1. Internal conversion (IC) decay
- $\mu^+ \to e^+ e^- e^+ \bar{\nu}_\mu \nu_e$



2. Final state scattering
- $M \to e^+ \bar{\nu}_\mu \nu_e e^-$

3. Accidental background
- Scattering/conv. e-
- Misreconstruction
- Cosmic ray, etc.

- Challenge from IC decay background:

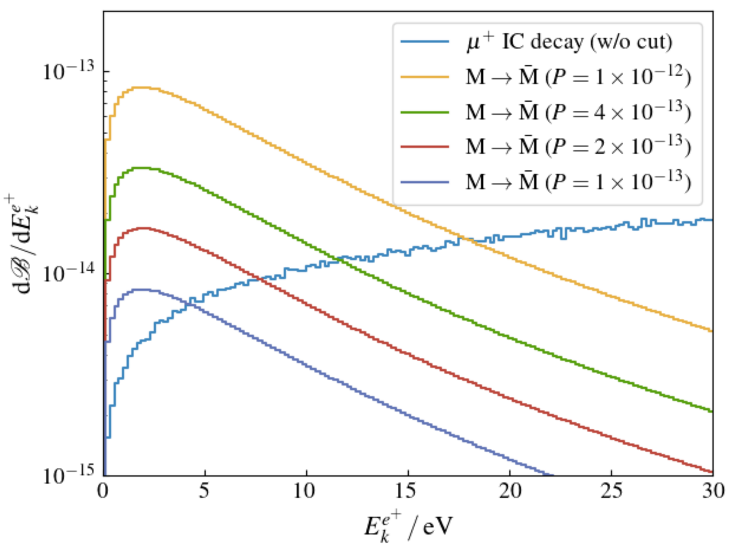
  😐 $BR(\mu \to eee\nu\nu) = 3.4 \times 10^{-5}$, High branching fraction even at low e^+ energy:

  $BR(\mu \to eee\nu\nu \mid E_k^{1e^+} < 100\ \text{eV}) = 3 \times 10^{-12}$ (LO prediction)

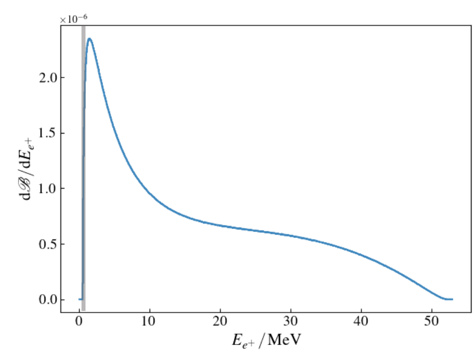
- MACE needs

  ✓ Excellent vertex & time resolution to cut p_{xy} & p_z

  ✓ Optimized copper sheet collimator to select p_{xy}



Low energy end ←



← e^+ energy spectrum of $\mu^+ \to e^+ e^- e^+ \bar{\nu}_\mu \nu_e$

Suppression of background

1. Internal conversion (IC) decay
- $\mu^+ \to e^+ e^- e^+ \bar{\nu}_\mu \nu_e$

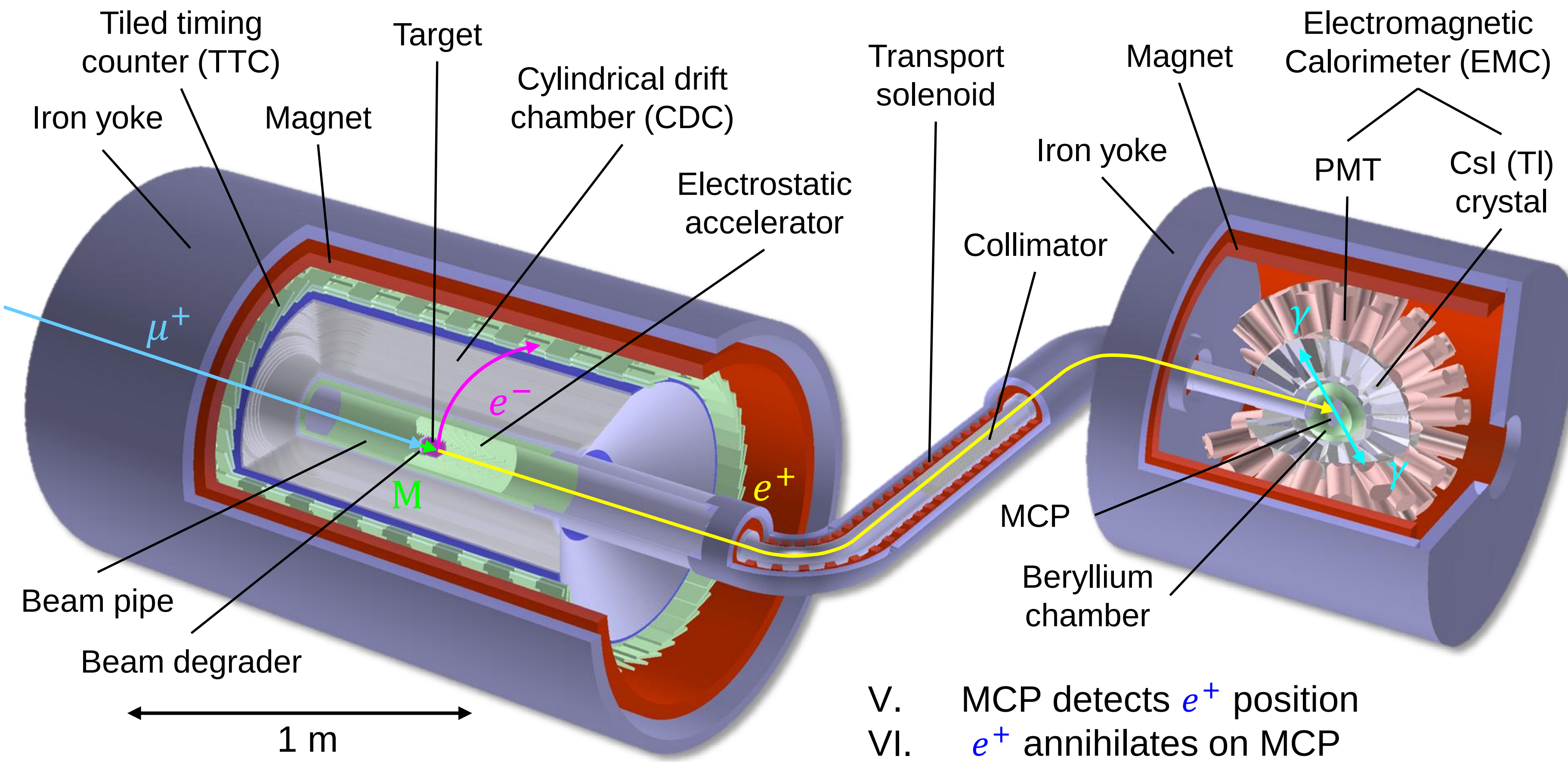
2. Final state scattering
- $\mathrm{M} \to e^+ \bar{\nu}_\mu \nu_e e^-$

3. Accidental background
- Scattering/conv. e^-
- Misreconstruction
- Cosmic ray, etc.

- Muonium final state scattering background:
  - Final state Bhabha scattering: fast e^+ + slow e^- → slow e^+ + fast e^- (signal-like)
  - $\mathrm{BR}(\mathrm{M} \to e^+ \bar{\nu}_\mu \nu_e e^- \mid E_{e^-} > 10\ \mathrm{MeV}) \approx 10^{-10}$, estimated by semiclassical Michel spectrum - Bhabha cross section folding.
  - Expected considerably low BR when $E_{e^+} \sim 0$.
  - ➢ Detailed background study in progress.

- To reduce accidental background, MACE needs
  - ✓ Excellent vertex & time resolution
  - ✓ A plused muon beam
  - ✓ Cosmic ray background: cosmic ray veto (design in progress)

Design of MACE



I. Surface muon → target → muonium
II. Decay in a vacuum: $\overline{\mathrm{M}} \to e^+ e^- \nu_\mu \bar{\nu}_e$
III. CDC detects Michel e^- track
IV. Transport atomic e^+ to MCP (conserving transverse position)
V. MCP detects e^+ position
VI. e^+ annihilates on MCP
VII. EMC detects 2 back-to-back annih. γ

Triple coincidence:

➢ **CDC/TTC + MCP + EMC**

CDC/TTC ↓ Michel e^- ; MCP + EMC → Atomic e^+

Plan and beamline

Conceptual design	Phase-I technical design	Phase-I installation & test run	Phase-I physical run	Phase-I analysis & Phase-II engineering	MACE Phase-II
2024	2025	2026	2027	2028	2030+

- Phase-I: O(10^{-11}) sensitivity for rare muonium decay (e.g. M→ee / M→γγ)
- Data taking duration: 1 year
- Beam condition:
  - Surface muon, 10^5 ~ 10^6 μ^+/s
  - Plused or CW beam
  - Momentum spreading: $\Delta p/p$ < 5%
  - Beam spot radius ~10 mm

- Phase-II: O(10^{-14}) sensitivity for muonium conversion
- Data taking duration: 1 year
- Beam condition:
  - Surface muon, 10^8 μ^+/s
  - Plused beam, repetition rate 20 ~ 50 kHz
  - Momentum spreading: $\Delta p/p$ < 3%
  - Beam spot radius < 10 mm

Why plused beam?

- Plused beam can reduce accidental background.
  - ✓ Beam-related backgrounds (e.g. e^+ in beam) follow a bunch arrival.
  - ✓ Scattering e^- or photon conversions raise with muon decay.
  - ✓ Signal conversion events are late.

CiADS?

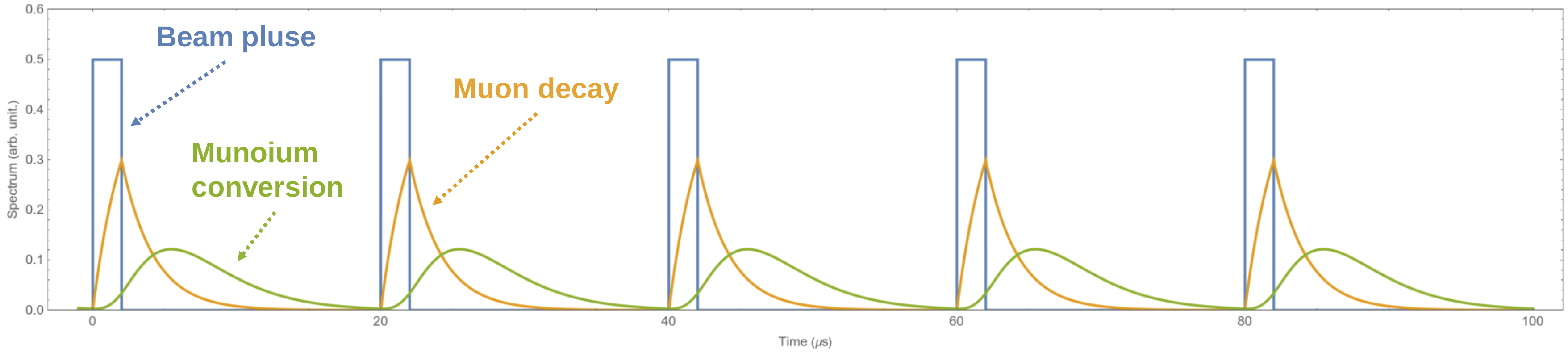
Hanjie Cai's talk yesterday

- Prompt background ↔ delayed signal
  - ➢ Possible to suppress background by specific data taking duration.

SHINE?

Takeuchi's talk yesterday

- MACE prefer a repetition rate of 20 ~ 50 kHz.



Design and simulation of muonium target

- Intensity of in-vacuum muonium source:

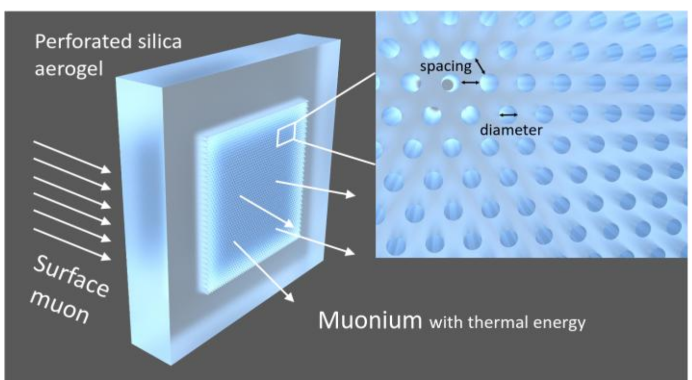
  $I_{\mathrm{M}}^{\mathrm{vac}} = I_{\mathrm{beam}} Y_{\mu\to\mathrm{M}}$

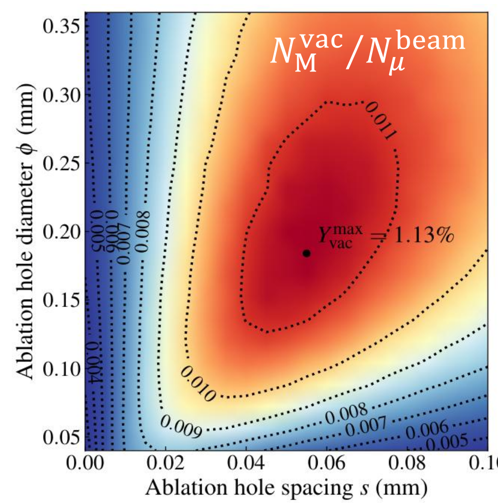
- $Y_{\mu\to\mathrm{M}}$ can be improved by utilizing porous materials, ideally perforated silica aerogel.
- An simulation method is developed to accurately simulate muonium production and diffusion.

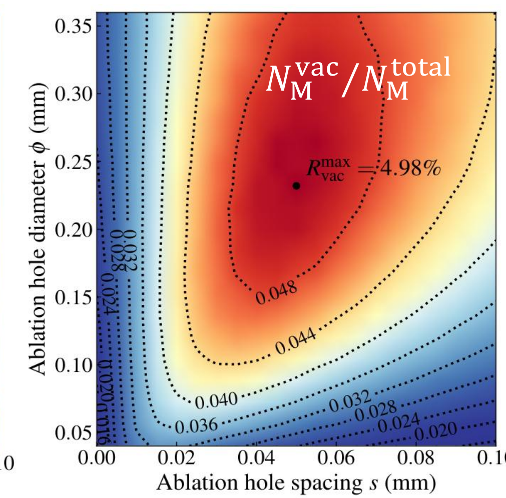
Yoshioka's talk yesterday (J-PARC g-2 muonium target)

- The simulation is validated by muonium yield data measured in TRIUMF.
- Optimize $Y_{\mu\to\mathrm{M}}$ in perforated bulk target by scanning parameters, it can achieve
  - ✓ Max $Y_{\mu\to\mathrm{M}} = N_{\mathrm{M}}^{\mathrm{vac}}/N_{\mu}^{\mathrm{total}} = 1.134\%$, with 2mm hole depth, $p_{\mathrm{beam}} = 28\ \mathrm{MeV}/c$ and $\frac{\sigma_{p_{\mathrm{beam}}}}{p_{\mathrm{beam}}} = 2.5\%$.

Shihan Zhao and Jian Tang, Optimization of muonium yield in perforated silica aerogel, Phys. Rev. D 109, 072012

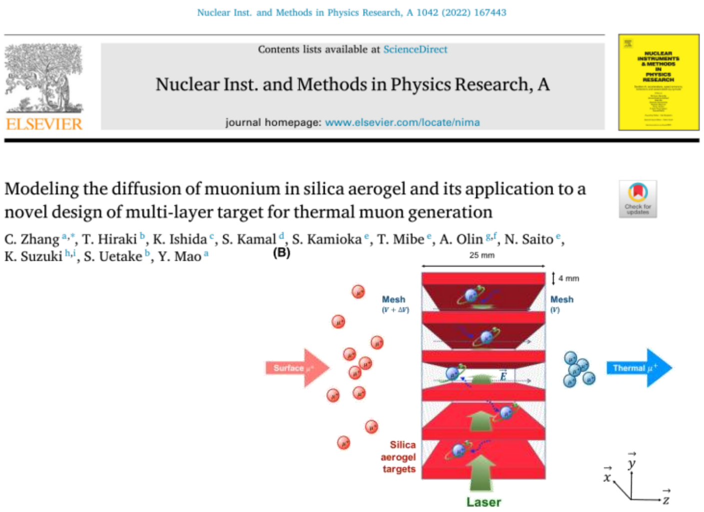






Design and simulation of muonium target

- A novel multi-layer design is expected considerably increase muonium yields in a vacuum (Ce Zhang et al.).
- The simulation result achieves
  - ✓ $Y_{\mu\to\mathrm{M}} = N_{\mathrm{M}}^{\mathrm{vac}}/N_{\mu}^{\mathrm{total}} = 4.08\%$
  - ✓ Nearly an order of magnitude improvement on $N_{\mathrm{M}}^{\mathrm{vac}}/N_{\mu}^{\mathrm{total}}$.
  - ➢ Still room for further optimization.
- Multi-layer target + intensive muon beam → intensive in-vacuum muonium source:
  - ✓ $I_{\mathrm{M}}^{\mathrm{vac}} = I_{\mathrm{beam}} Y_{\mu\to\mathrm{M}} = 4\times10^{6}/\mathrm{s}$, assuming $I_{\mathrm{beam}} = 10^{8}/s$
  - ➢ For comparison, MACS 1990s: $I_{\mathrm{M}}^{\mathrm{vac}} = 4\times10^{4}/s$
  - ➢ Expected two orders of magnitude improvements in in-vacuum muonium source intensity!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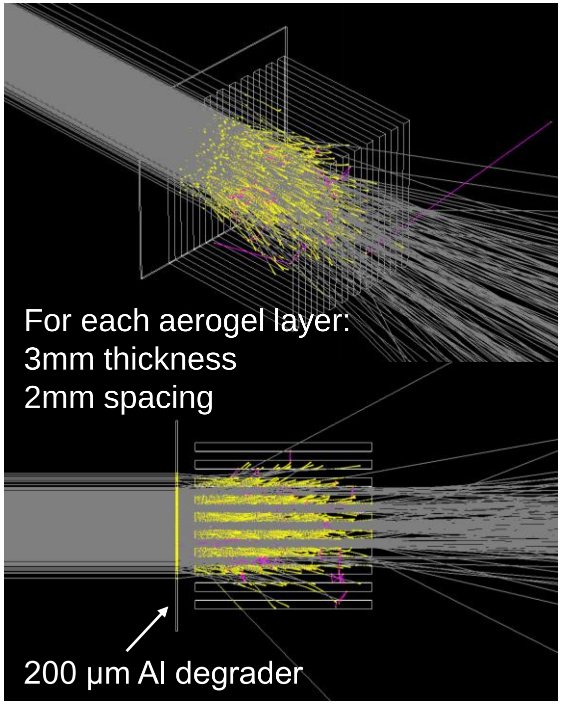
ELSEVIER

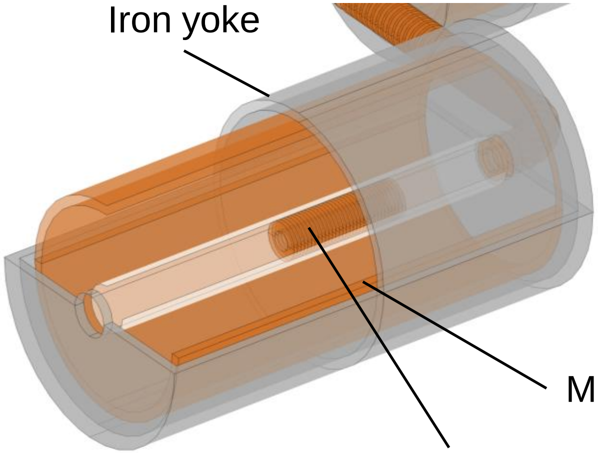
Modeling the diffusion of muonium in silica aerogel and its application to a novel design of multi-layer target for thermal muon generation

C. Zhang[a,*], T. Hiraki[b], K. Ishida[c], S. Kamal[d], S. Kamioka[e], T. Mibe[e], A. Olin[g,f], N. Saito[e], K. Suzuki[h,i], S. Uetake[b], Y. Mao[a]

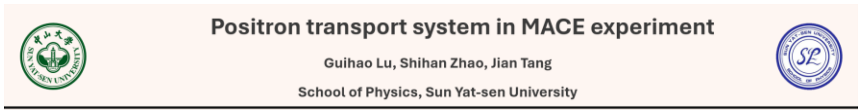


Electromagnetic field design

Iron yoke

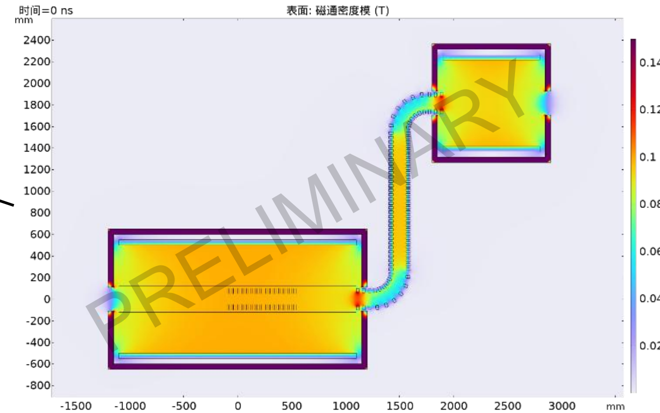


See Guihao Lu's poster

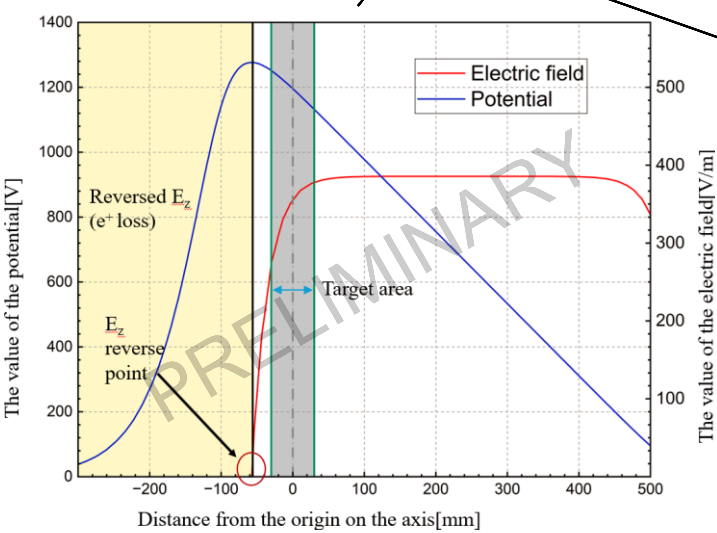


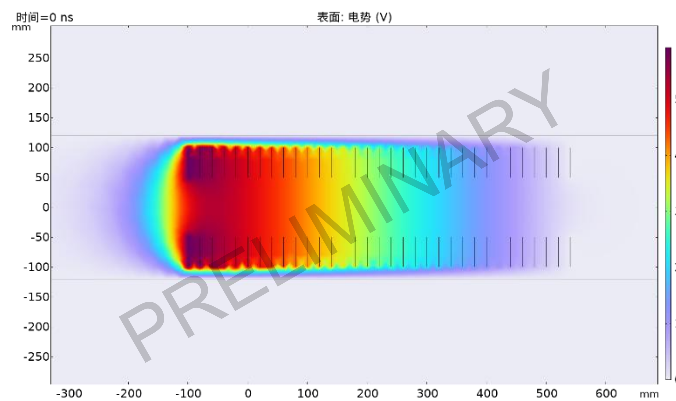
Magnet

Electrostatic accelerator



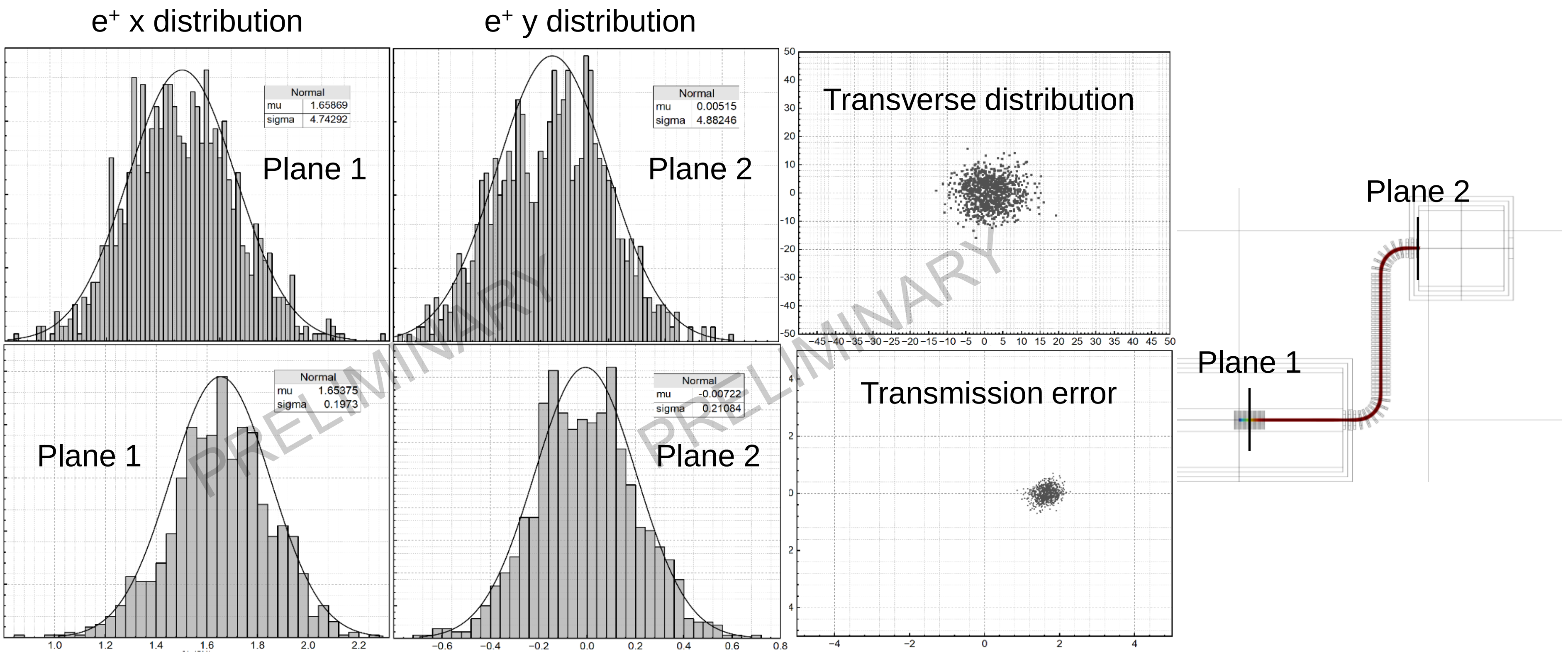
B=0.1T





U=500V

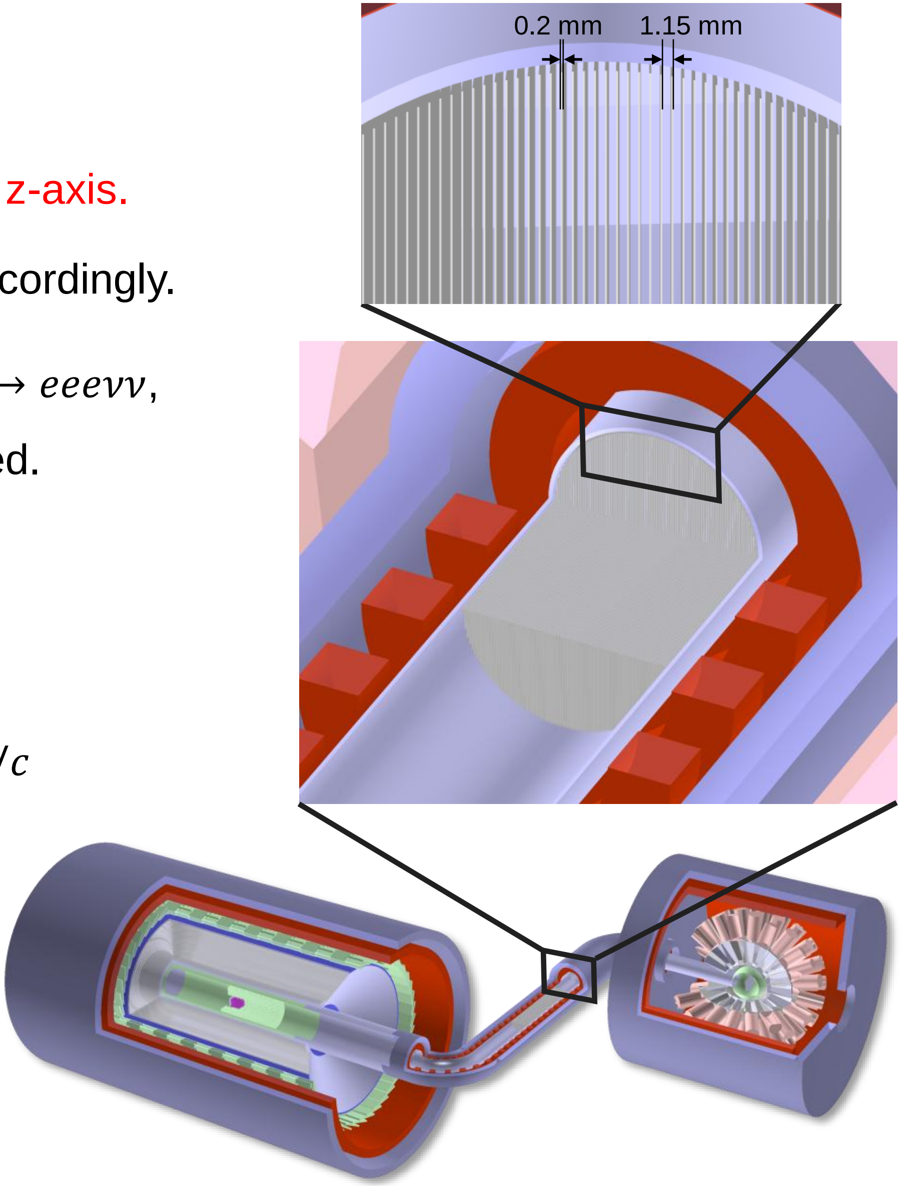
Electromagnetic field design



- Transmission efficiency w/o collimator: >99%
- Excellent transmission precision: $\sigma_{\Delta x} = 0.197\ \mathrm{mm}$, $\sigma_{\Delta y} = 0.211\ \mathrm{mm}$
- Magnetic leakage → drift along x. Can be fixed by magnetic compensation.

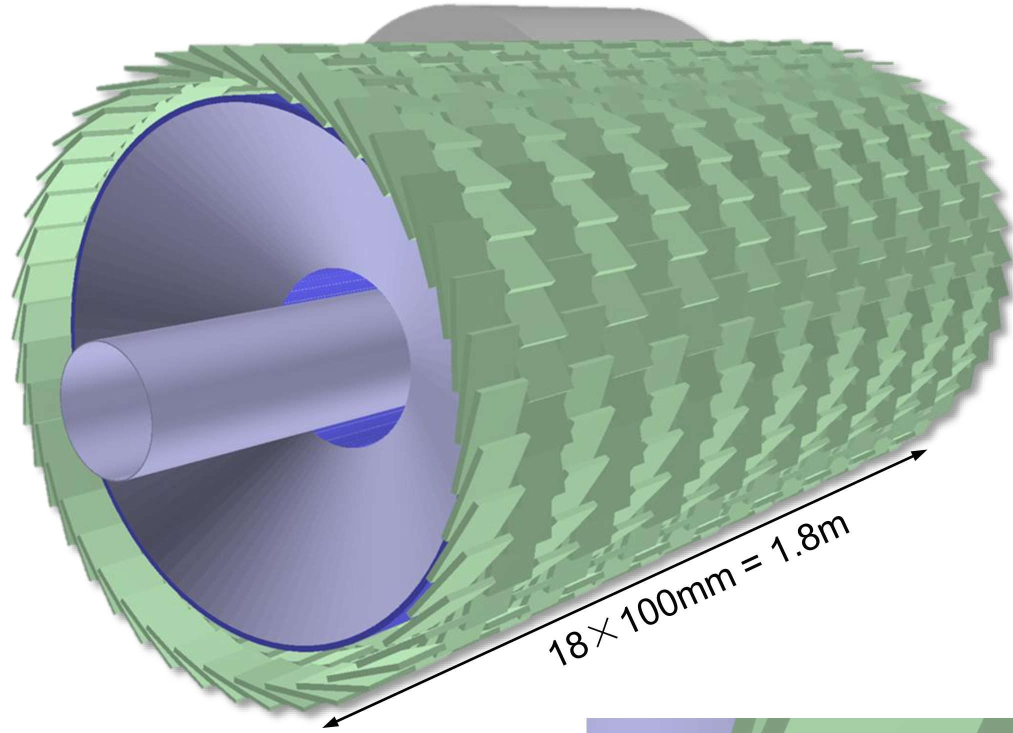
Collimator design

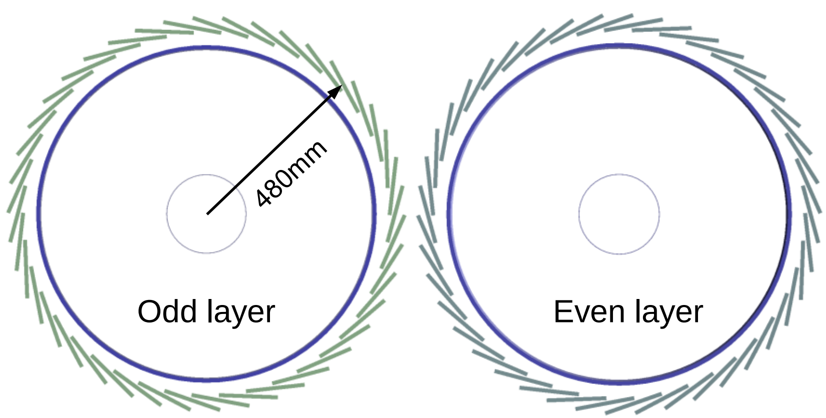
- Collimator selects $p_{\rm xy}$ of transported particles.
  - Narrowly spaced copper sheets, parallel to z-axis.
  - Sheet thickness: 0.2 mm, optimize pitch accordingly.
- Background level is simulated by McMule LO $\mu \to eee\nu\nu$, MACE detector & simple signal region cut applied.
- Optimize pitch by maximize $\varepsilon_s/(b+1.5)$.
- Optimization result:
  - ✓ Optimal pitch: 1.15 mm $\rightarrow$ $p_{\rm xy}^{\rm max} = 14\ {\rm keV}/c$
  - ✓ Signal e^+ efficiency: 68%
  - ✓ Reject 98% of $\mu \to eee\nu\nu$ background

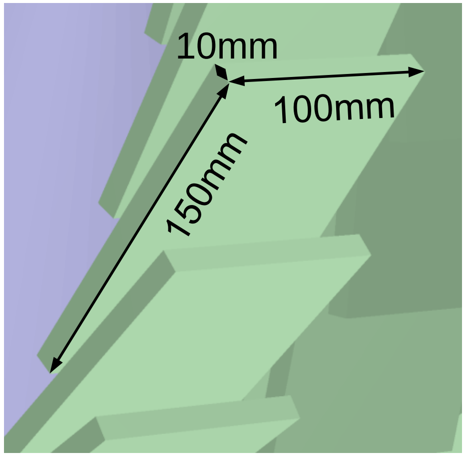


Timing counter design

- Design goal:
  - ✓ High rate capability
  - ✓ Excellent time resolution (<100 ps)
  - ✓ Good spatial resolution (10 cm)
- Specifications:
  - ✓ Two tile coincidence
  - ✓ Overall efficiency same for e^+ / e^-
- Preliminary design:
  - ➢ Plastic scintillator array
  - ➢ 18 (ϕ) × 42 (z) = 756 tiles
  - ➢ Center radius: 480 mm
  - ➢ Slant angle: ±15 deg

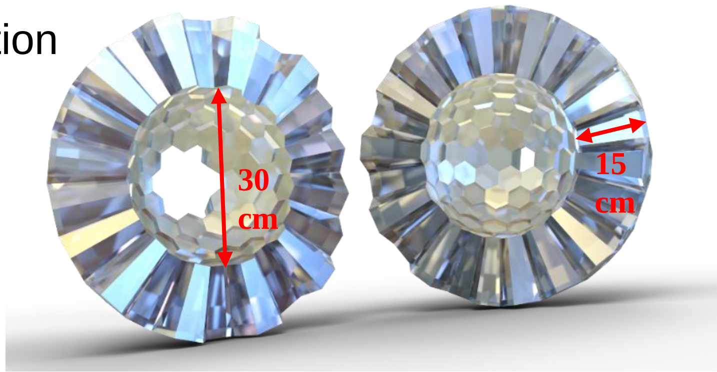


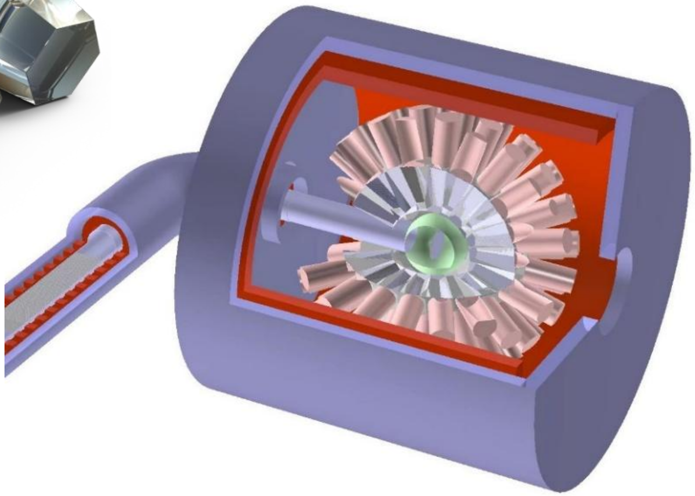




Design of calorimeter

- Specification:
  - Excellent energy resolution for background discrimination
  - High signal efficiency
- Geometry:
  - Class I *GP*(4,0) Goldberg polyhedron
  - 154 inorganic scintillators with PMTs (preliminarily CsI:Tl)
  - 97.5% solid angle coverage
  - Inner diameter: 30 cm
  - Crystal length: 15 cm
- Advantages:
  - Large solid angle coverage
  - Symmetry for precise reconstruction
  - Self-supporting structure





Design of calorimeter

- Signal and Background
  - Energy resolution: 8.4% at 0.511 MeV, 6% at 1.022 MeV
  - 68.1% signal efficiency (3σ region)

See Siyuan Chen's poster

Preliminary Design of a CsI(Tl) Calorimeter for Muonium-to-Antimuonium Conversion Experiment

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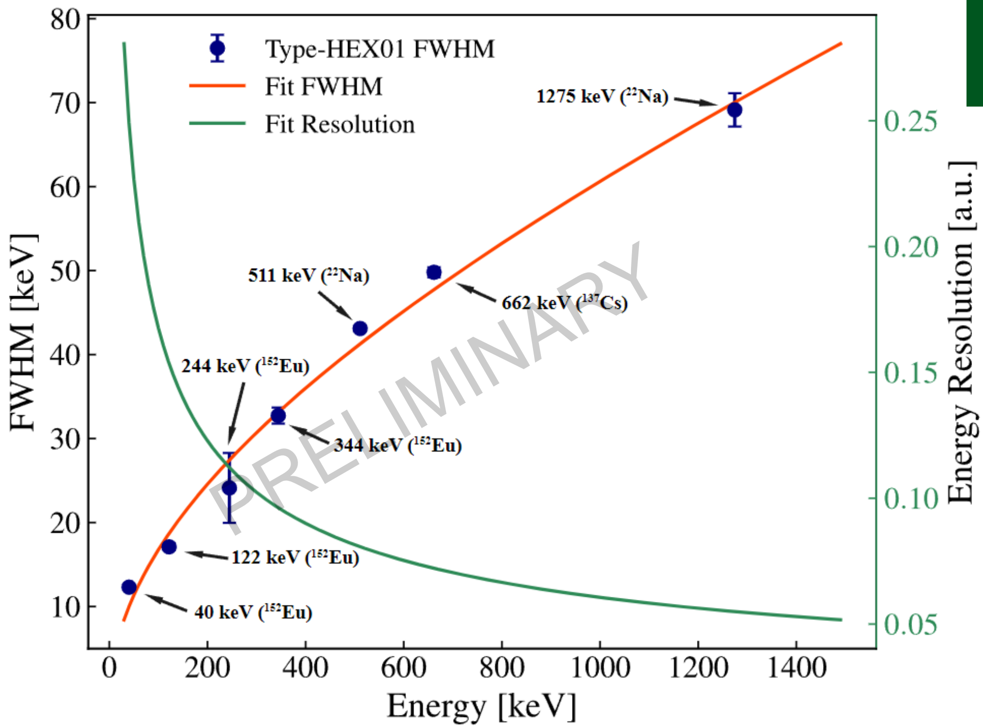
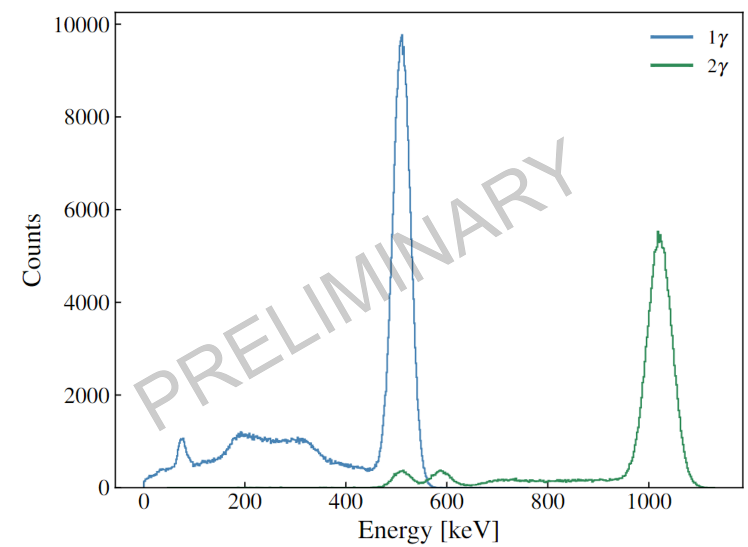
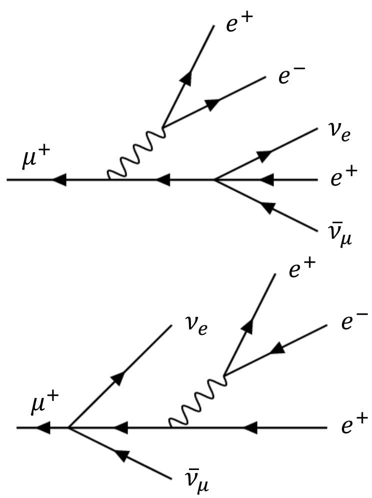
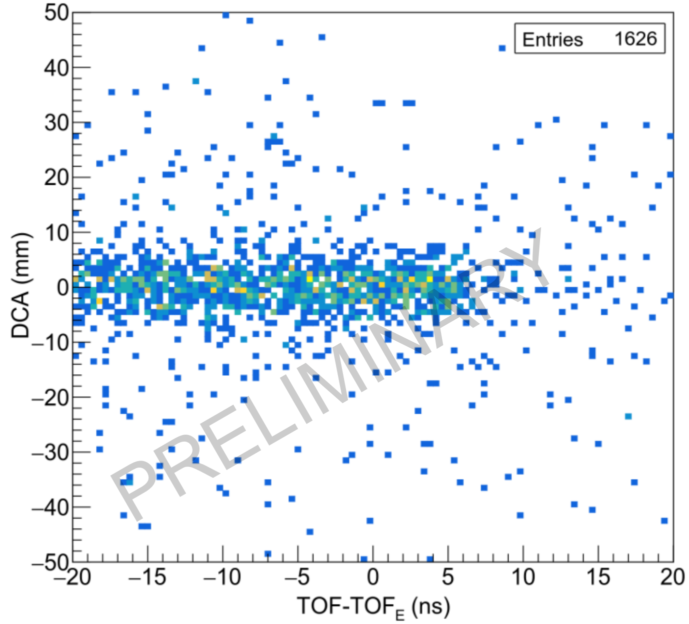




Muon IC decay background full simulation

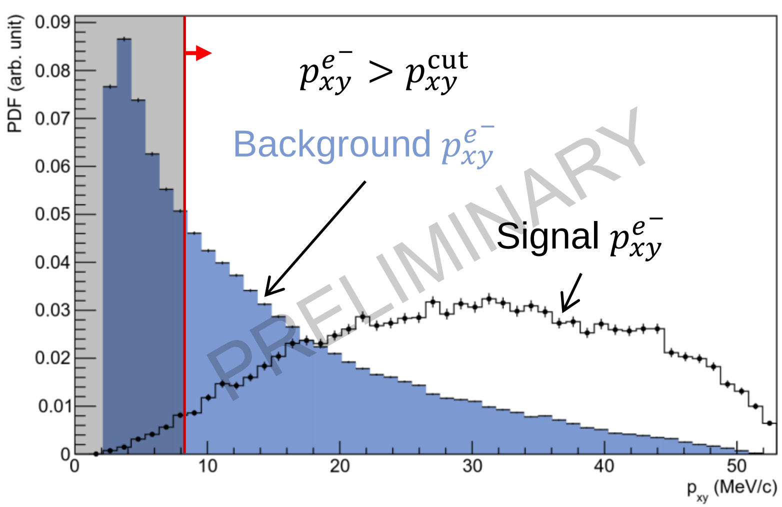


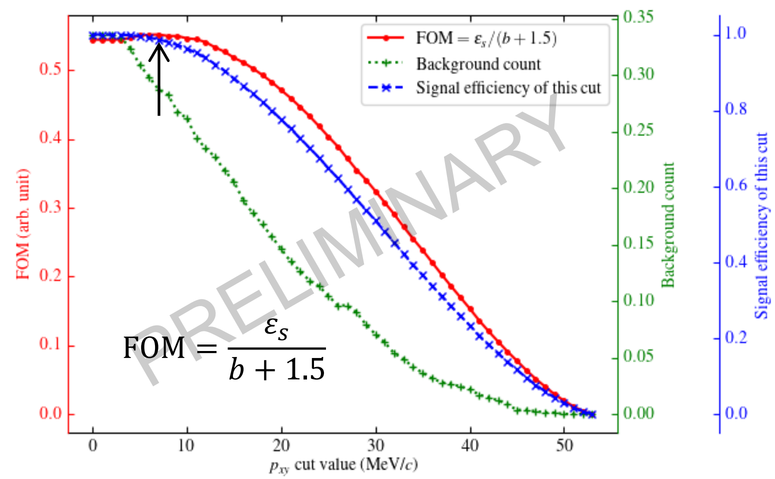


Simulation data equivalant to

140 × (10^8 μ/s × 365 d)

- Optimal $p_{xy}^{\text{cut}} = 7\ \text{MeV}/c$
- $\varepsilon_{\text{pxy cut}} = 0.926$
- $\varepsilon_{\text{all cut}} = 0.914$
- $N_{\text{bkg}} = 0.287 \pm 0.020$





MACE: Towards O(10^{-14}) sensitivity

- During 1 year data taking duration, MACE will produce $N_{\mathrm{M}} = 10^8 \mu^+/s \times 0.04\mathrm{M}/\mu^+ \times 365\mathrm{d} = 1.3 \times 10^{14}$ muonium atoms in vacuum.

Background	Counts / (10^8 μ/s×365 d)
μ^+ IC decay	0.287 ± 0.020
Beam e^+	< 0.07
Cosmic ray (w/ veto)	~ 0
Total	< 1

Detector / cut	Efficiency
$\varepsilon_{\mathrm{Geom}}$	0.61
$\varepsilon_{\mathrm{CDC\ Recon.}}$	~ 0.9
$\varepsilon_{\mathrm{MCP}}$	0.7
$\varepsilon_{\mathrm{EMC}}$	0.72
$\varepsilon_{\mathrm{cut}}$	~ 0.7

✓ MACE is expected to achieve O(10^{-14}) single event sensitivity:

$$\mathrm{SES} = \frac{1}{\varepsilon_{\mathrm{Geom}}\varepsilon_{\mathrm{CDC\ Recon.}}\varepsilon_{\mathrm{MCP}}\varepsilon_{\mathrm{EMC}}\varepsilon_{\mathrm{cut}}N_{\mathrm{M}}} = 3 \times 10^{-14}$$

More Physics with MACE detectors

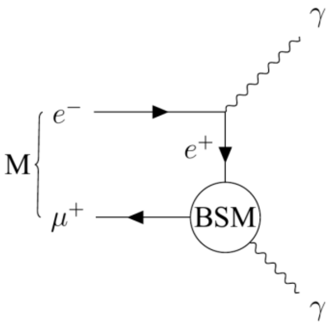
- Multi-electron muon decays:
  - Internal conversion: $\mu^+ \to e^+e^+e^-e^+e^-\overline{\nu}_\mu\nu_e$
  - Neutrinoless decay: $\mu^+ \to e^+e^+e^-e^+e^-$
- Muonium decays:
  - Annihilation: $\mu^+e^- \to \gamma\gamma$
  - Two-body decay: $\mu^+e^- \to e^+e^-$

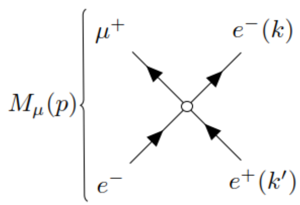
  Suitable for MACE phase-I

  - Exotic decay: $\mu^+e^- \to \gamma_d\gamma_d \to e^+e^-e^+e^-$
  - Invisible decay: $\mu^+e^- \to \overline{\nu}_\mu\nu_e$
- Other interesting topics:
  - Search for X(17), dark matter physics
  - Dark photon

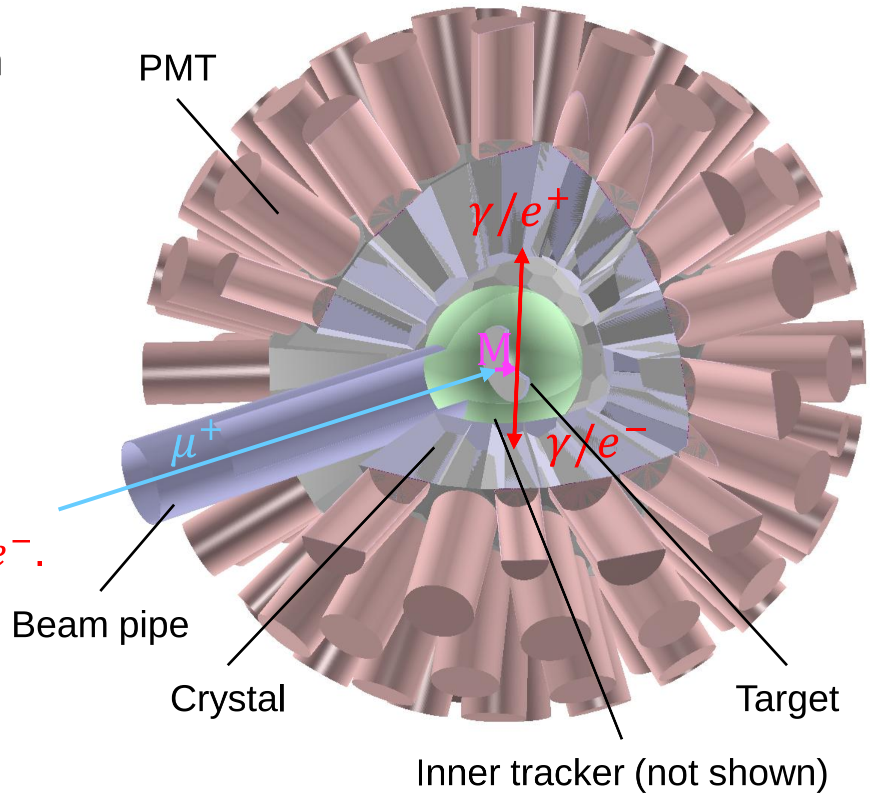
MACE Phase-I

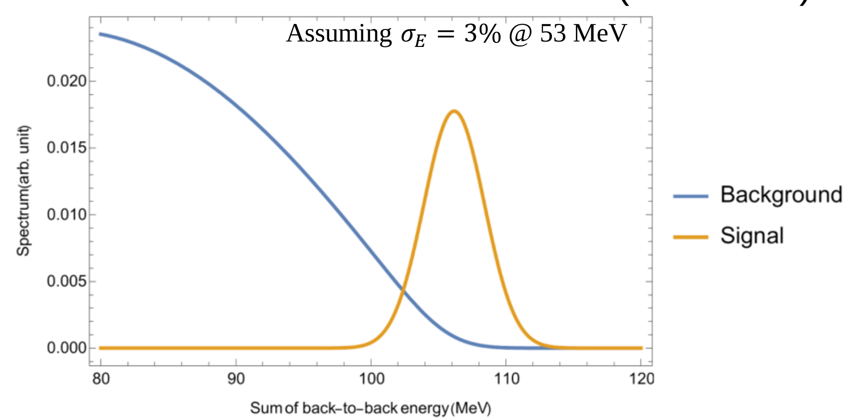
- We propose searching for $\mathrm{M} \to \gamma\gamma$ or $\mathrm{M} \to e^+e^-$ in MACE Phase-I.





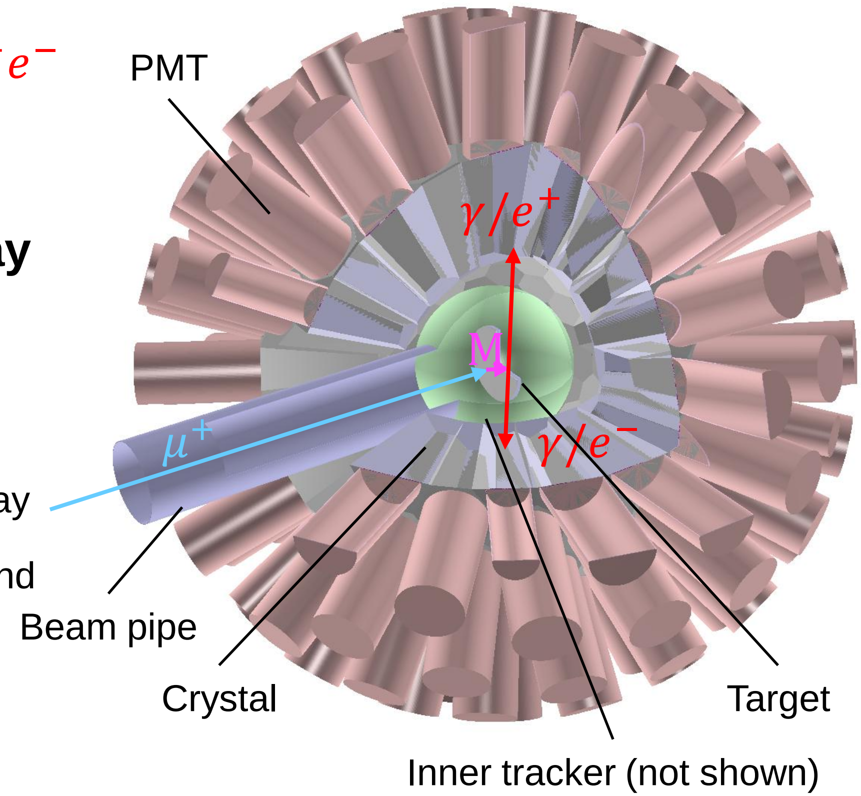
- Clear signature: 53.1 MeV back-to-back $\gamma\gamma$ or e^+e^-.
- Background and sensitivity:
  - ➢ Back-to-back crystal accidental coincidence.
  - ➢ No SM intrinsic background → background-free search is possible.
- Challenge: event pile up.

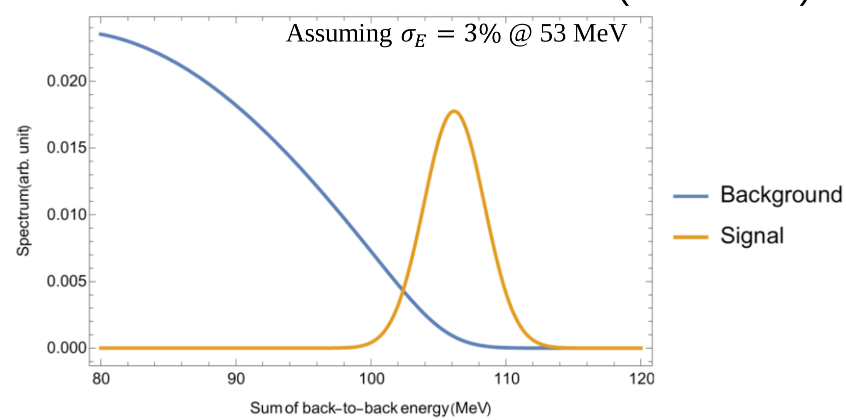




MACE Phase-I

- We propose searching for $\mathrm{M} \to \gamma\gamma$ or $\mathrm{M} \to e^+e^-$ in MACE Phase-I.
- Detector: **EMC** & **inner tracker** & **cosmic ray veto** & **Target**.
  - ☐ Scintillator
    - ➢ CsI(Tl): excellent energy resolution, slow decay
    - ➢ LYSO: balance with good energy resolution and fast response
  - ☐ Inner tracker might be needed for PID
- **Estimated to achieve O(10^{-11}) SES in one year data taking duration.**





Summary and outlook

- 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.

Thanks!

MACE working group list

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Acknowledgement

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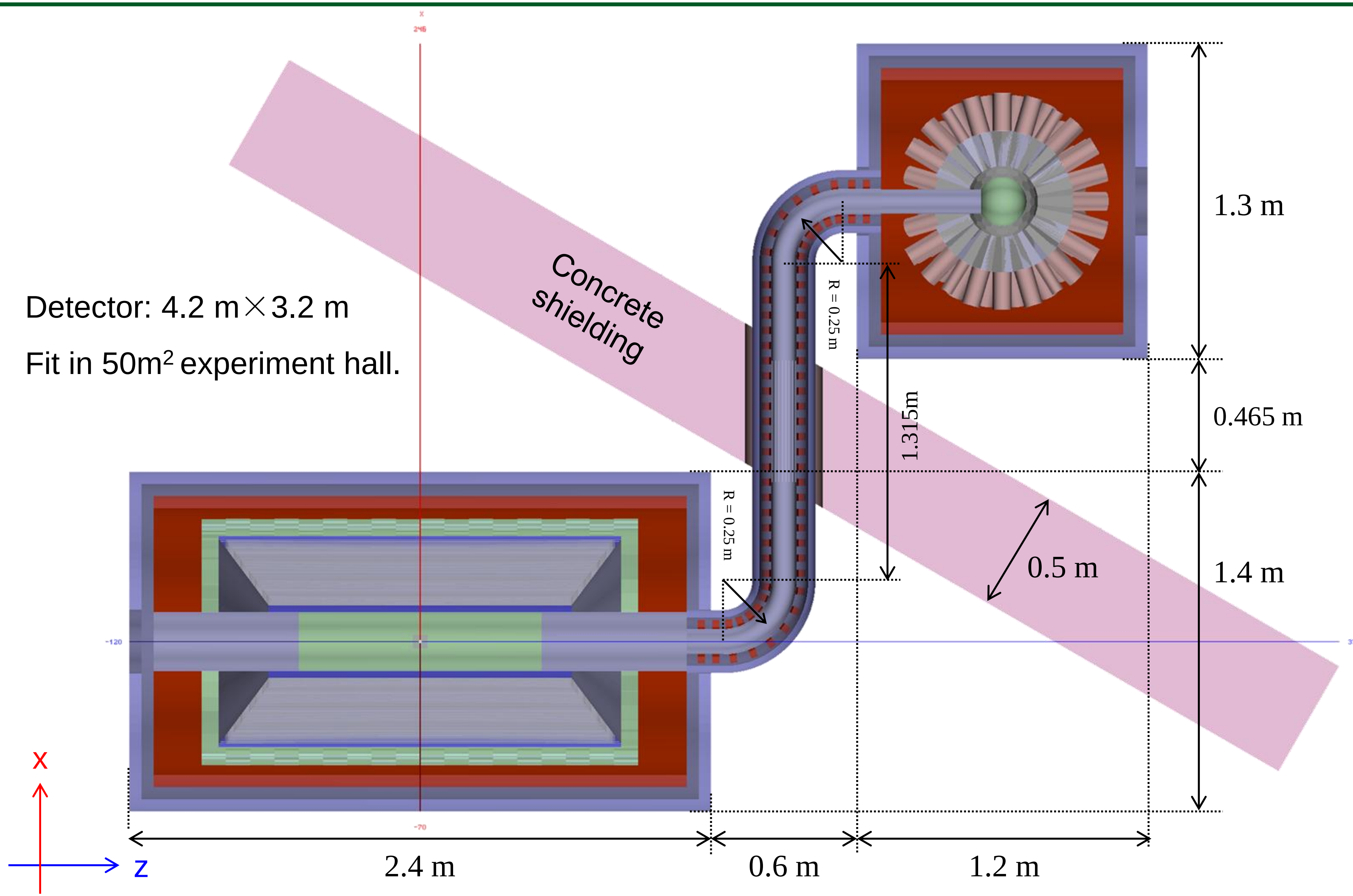
Collaboration welcome!

Backup

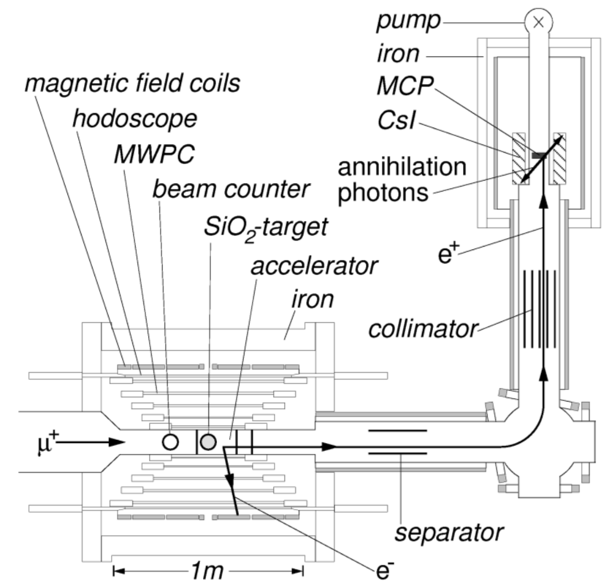
MACE dimensions

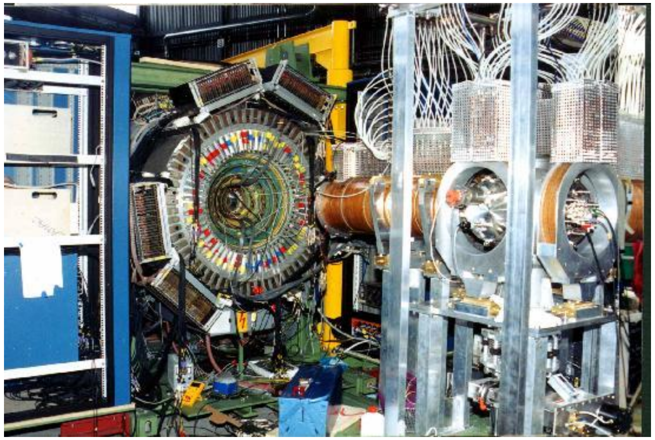
- Detector: 4.2 m×3.2 m
- Fit in 50m^2 experiment hall.

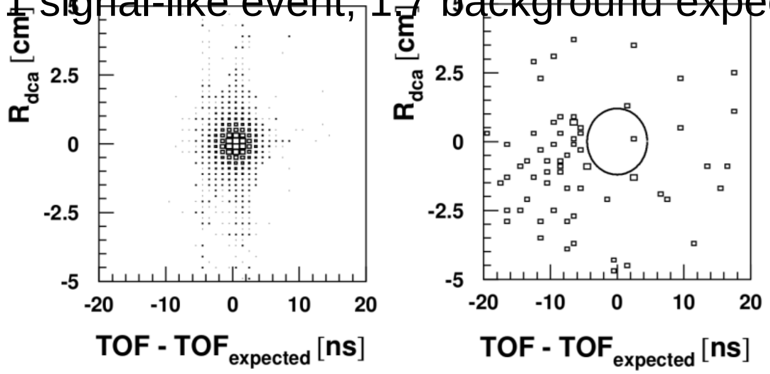


MACS

- Search for M-to-$\bar{\mathrm{M}}$ conversion at PSI in 1990s:
  - ➢ $P_{\mathrm{M}\to\bar{\mathrm{M}}} < 8.3 \times 10^{-11}$ (in 0.1T field, 90% C.L.)
- Muonium source:
  - DC muon beam, $8 \times 10^{6}\ \mu^{+}/s$, $p = 26\ \mathrm{MeV}/c$, $\Delta p/p = 5\%$
  - SiO_2 powder target: 0.5% $\mu^{+} \to \mathrm{M}_{\mathrm{vac}}$ rate
- During 1730 hr data taking:
  - $N_{\mathrm{M}} = 5.6 \times 10^{10}$
  - 1 signal-like event, 1.7 background expected.







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

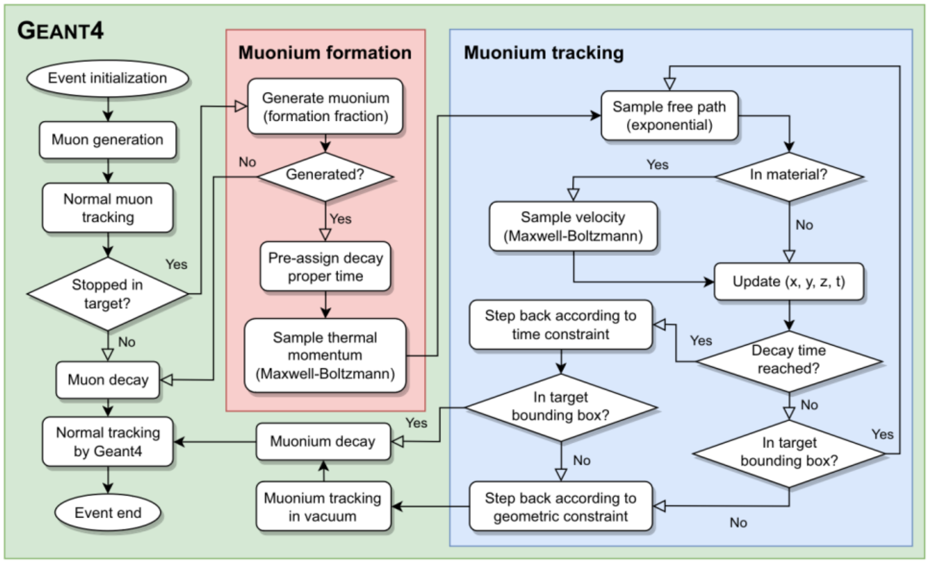
Design and simulation of muonium target

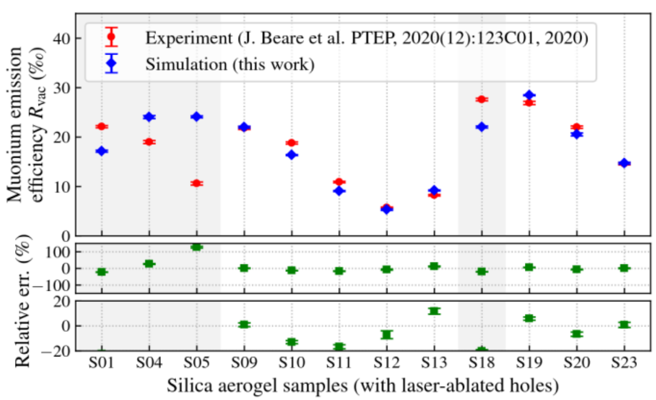
- Intensity of in-vacuum muonium source:

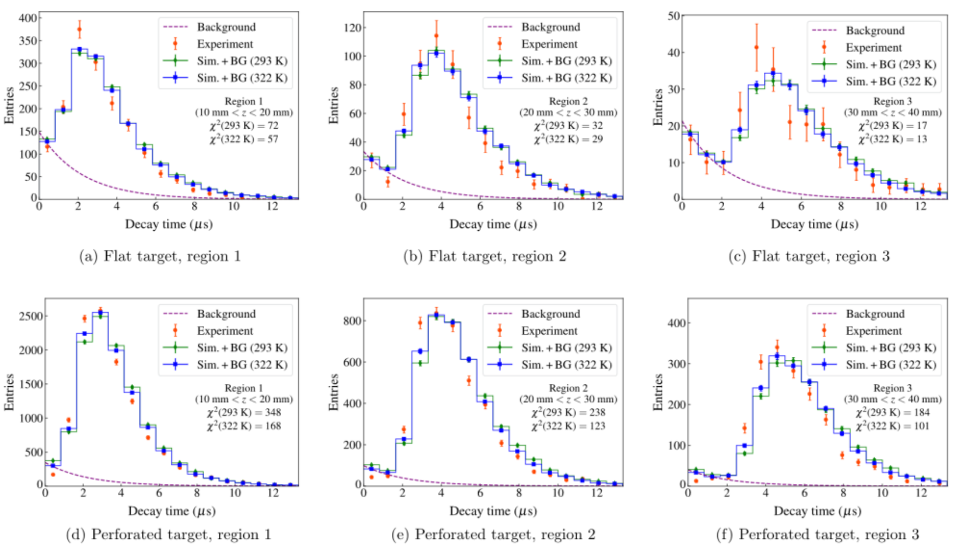
$$I_{\mathrm{M}}^{\mathrm{vac}} = I_{\mathrm{beam}} Y_{\mu\to\mathrm{M}}$$

- $Y_{\mu\to\mathrm{M}}$ can be improved by utilizing porous materials, ideally perforated silica aerogel.
- An simulation method is developed to accurately simulate muonium production and diffusion.
- The simulation is validated by muonium yield data measured in TRIUMF and J-PARC.

Shihan Zhao and Jian Tang, Optimization of muonium yield in perforated silica aerogel, Phys. Rev. D accepted. arXiv 2401.00222



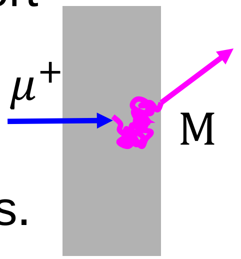




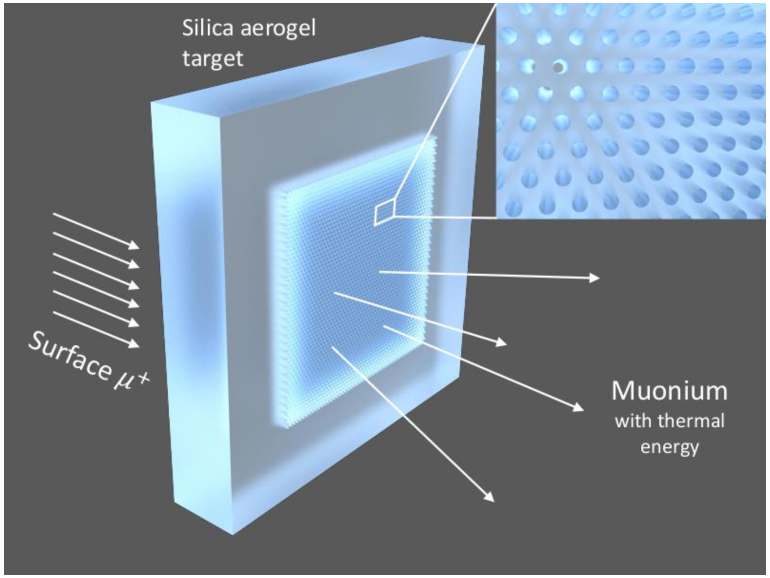
Muonium yield simulation

μ^+ (~1MeV) scattering
↓
Electron capture (~1keV)
↓
Muonium (~100eV)
Epithermal scattering
↓
Random walk (room temp.)
↓
Emission to vacuum

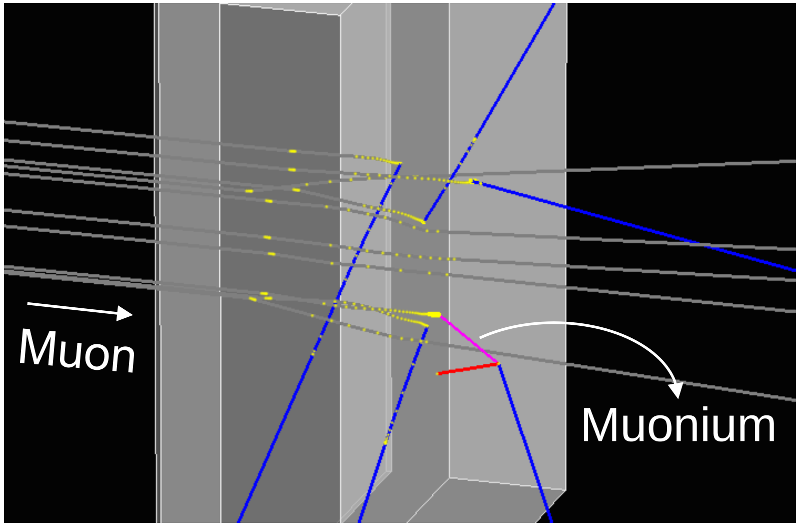
MC simulation for muonium transport has been developed under the MACE offline software framework.



① Geant4 low-energy EM process.
② Geant4 AtRest process, modeled phenomenologically.
③ Random walk approach to thermal muonium tracking.



Simulation:

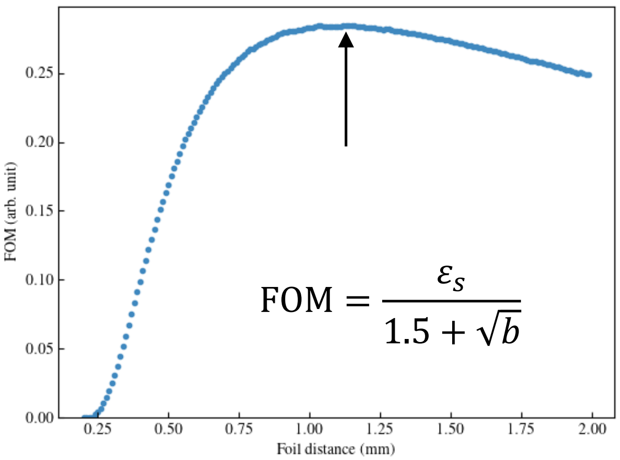


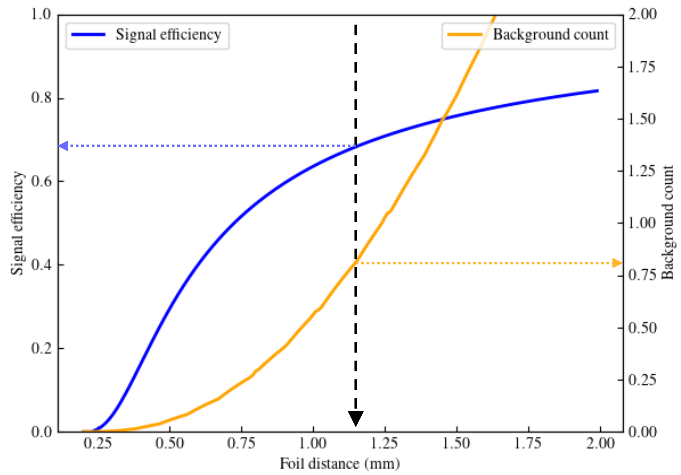
Collimator

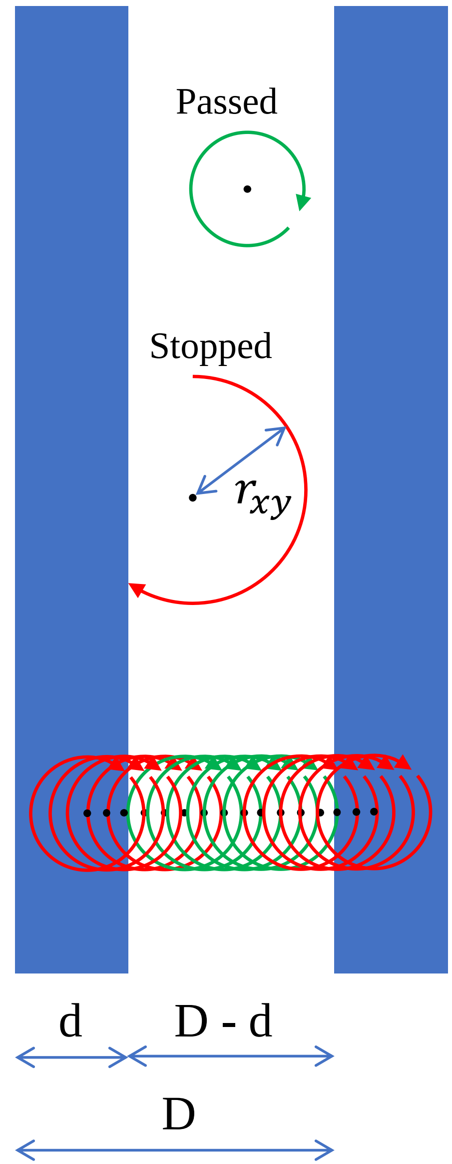
- Pass probability esimate by

$$r_{xy} = \frac{p_{xy}}{eB}, d_{xy} = 2r_{xy}$$

$$p_{\text{pass}} = \begin{cases} \frac{D - d - d_{xy}}{D} & 0 < d_{xy} < D - d \\ 0 & \text{else} \end{cases}$$

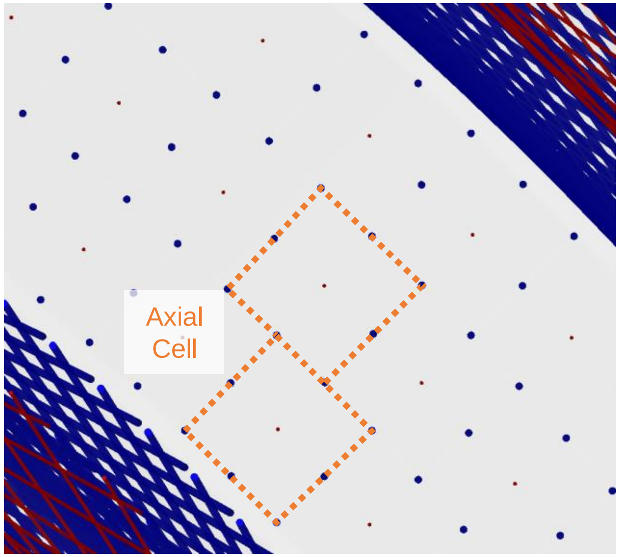


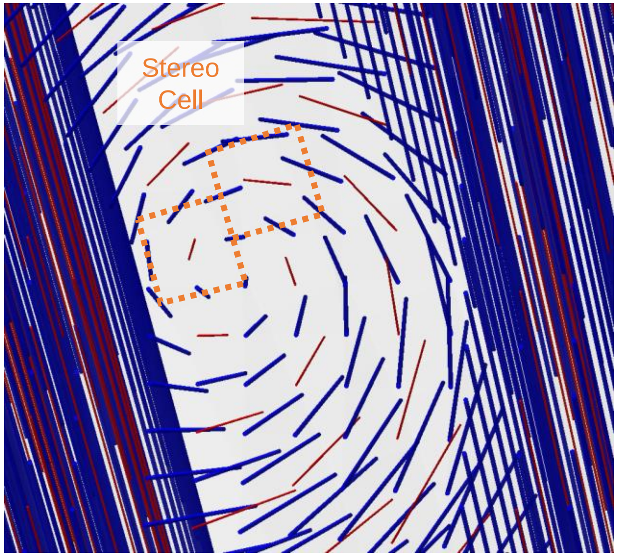




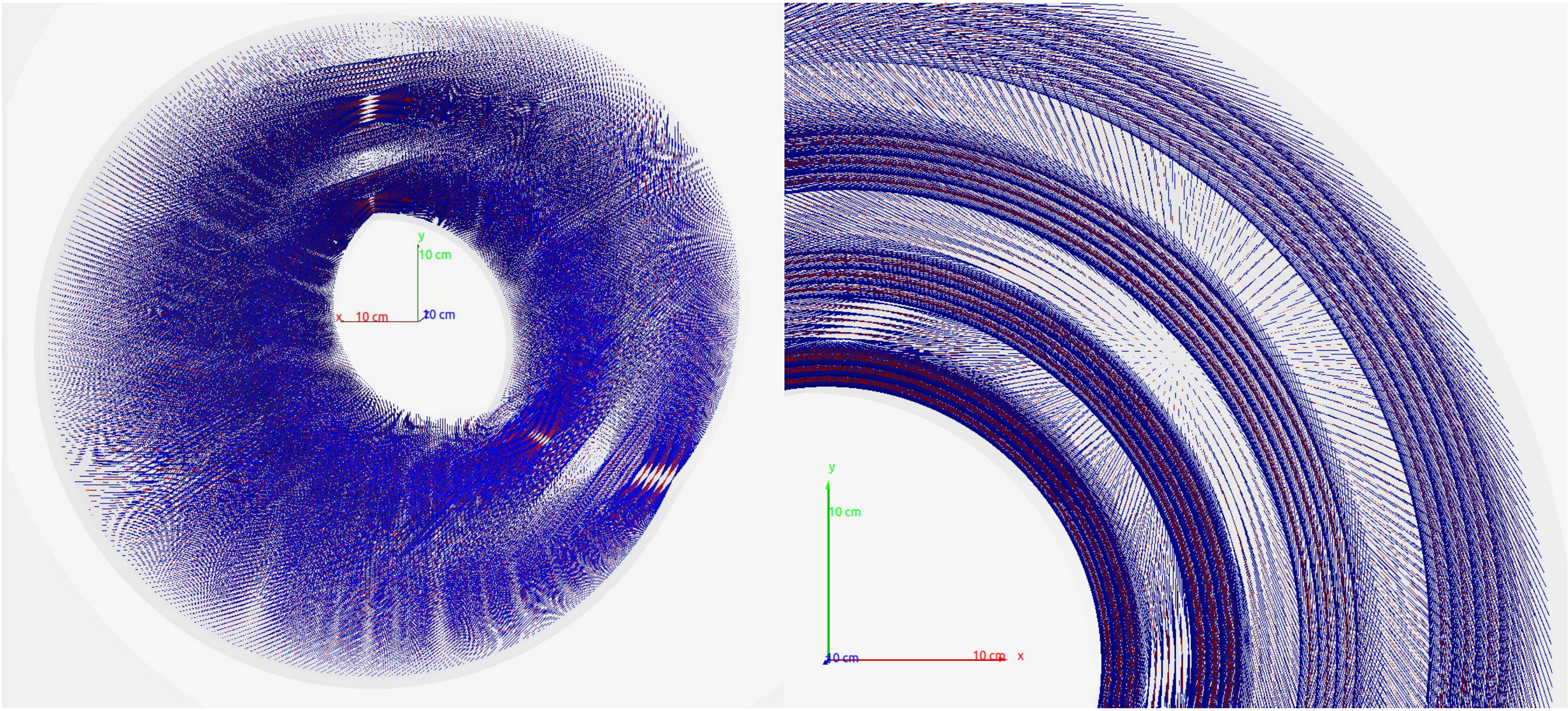
Design of cylindrical drift chamber

- Design goal:
  - ✓ Large acceptance
  - ✓ High rate capability
  - ✓ Excellent vertex resolution (O(1) mm)
  - ✓ Good momentum resolution (O(1) MeV in 0.1 T field)
- Specifications:
  - ✓ Near-square drift cell, minimum deformation
  - ✓ Alternated axial / stereo layer
- Preliminary design:
  - ➢ 7 (super) × 3 (sense) = 21 layers
  - ➢ 12 stereo layers, 9 axial layers
  - ➢ Cell width: 8 mm ~ 12 mm
  - ➢ Length: 1.2 m (inner) / 1.6 m (outer)
  - ➢ Radius: 150 mm (inner) / 417 mm (outer)
  - ➢ Acceptance: 89% ~ 97%
  - ➢ Stereo layer angle: 6 deg at minimum
  - ➢ Gas: He:C_4H_{10} = 85:15



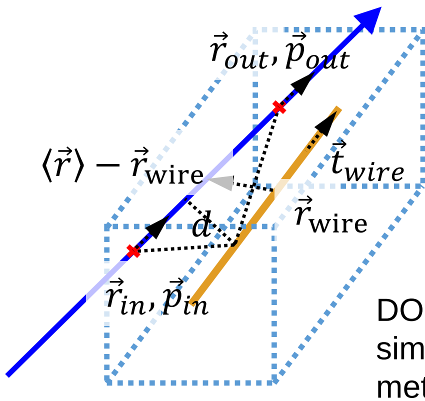


Design of cylindrical drift chamber

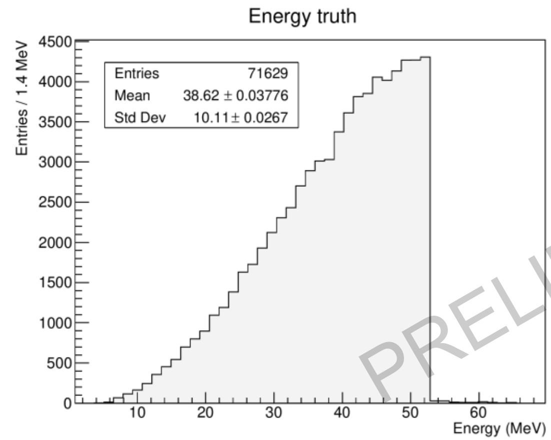


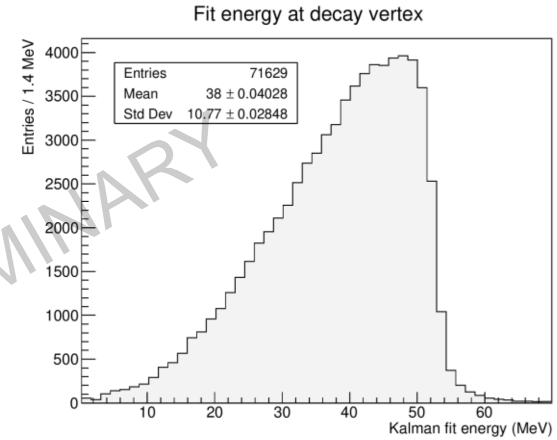
- We have developed an parameterized drift chamber geometry, allowing us to continue to optimize the geometry design of drift chamber.
- Figure: generated drift chamber preliminary design. Wires are scaled to be clearly visible (blue: field wire, red: sense wire).

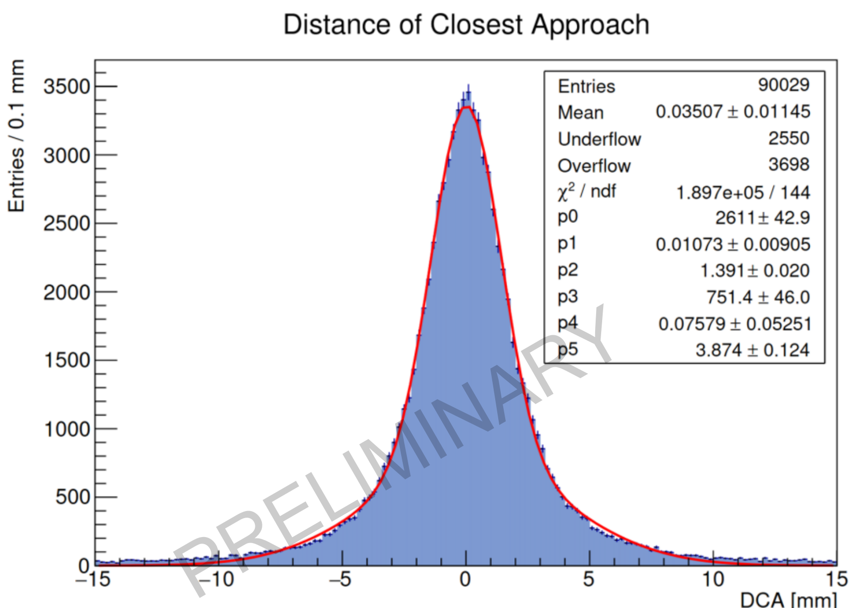
Simulation of magnetic spectrometer



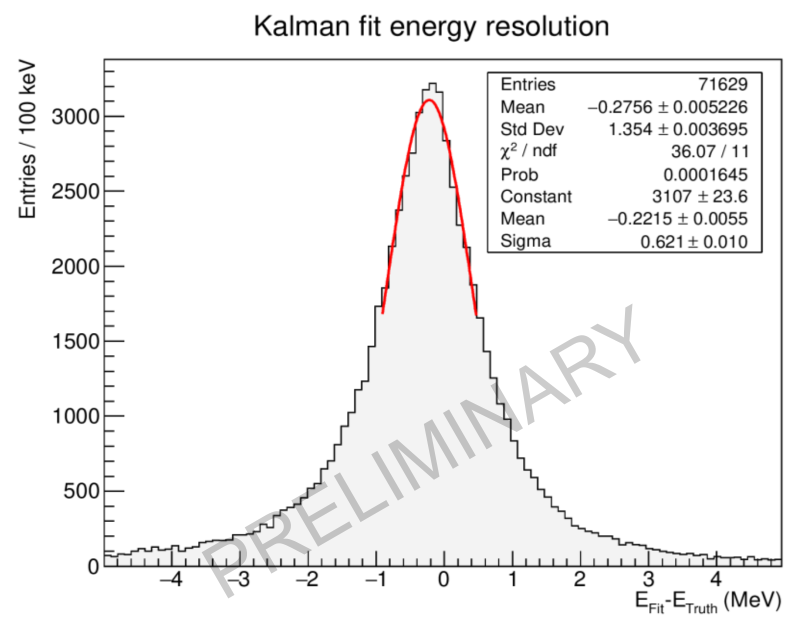
DOCA simulation method







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



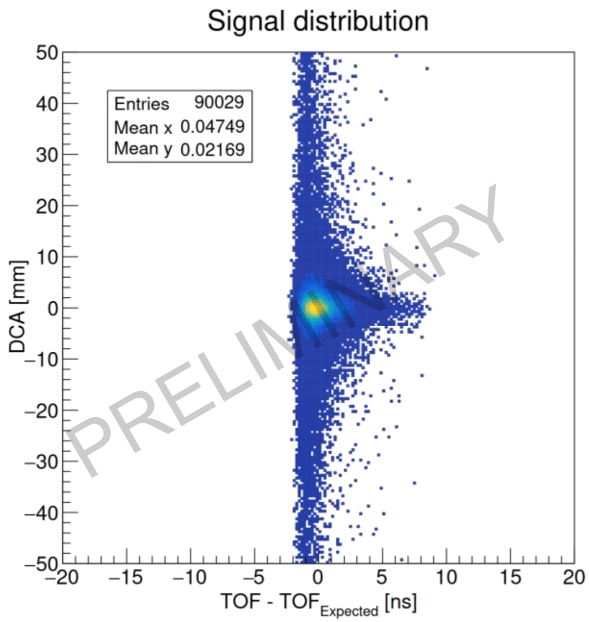
Momentum (energy) resolution: ~1.5 MeV (FWHM)

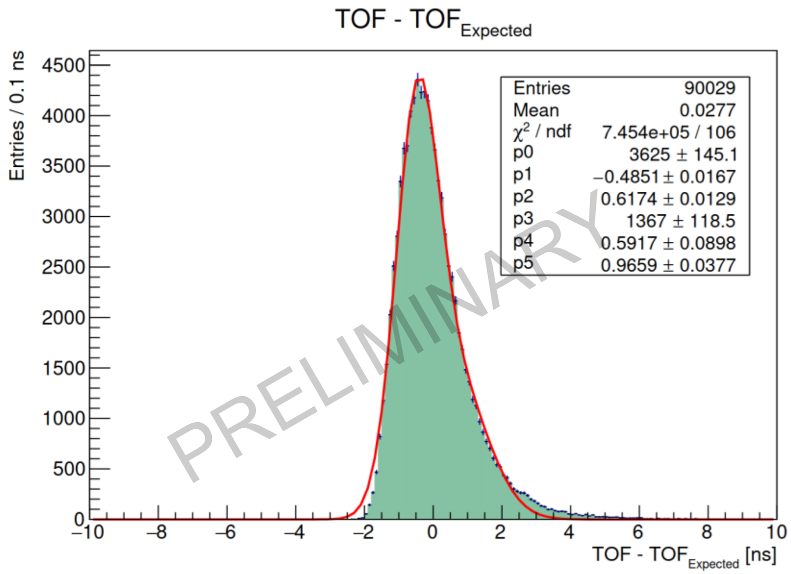
Signal simulation

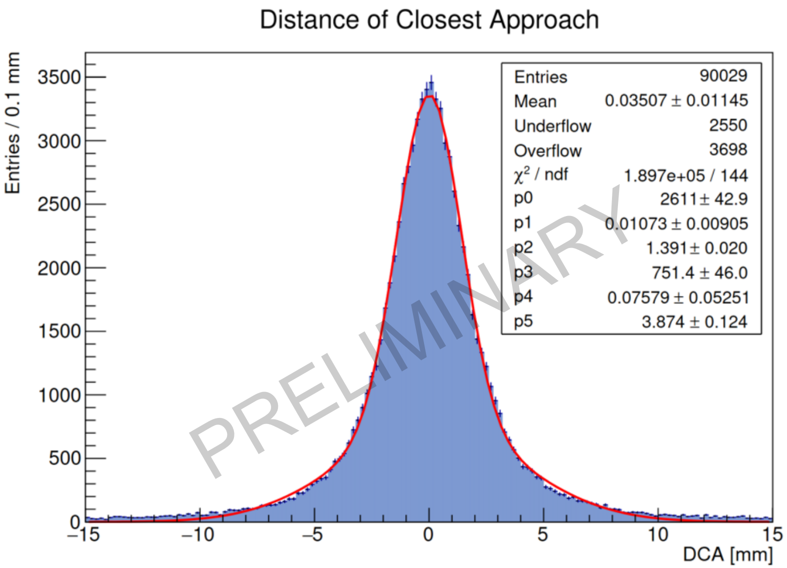
- TOF_E = 121.1 ns
- $\sigma_{\Delta TOF}$ = 0.58 ns, σ_{DCA} = 2.2 mm
- Elliptical 3σ signal region:

$$\left(\frac{\mathrm{TOF}-\mathrm{TOF_E}}{3\sigma_{\mathrm{TOF}}}\right)^2+\left(\frac{\mathrm{DCA}}{3\sigma_{\mathrm{DCA}}}\right)^2<1$$

- $\varepsilon_{\text{sig cut}} = 0.987$



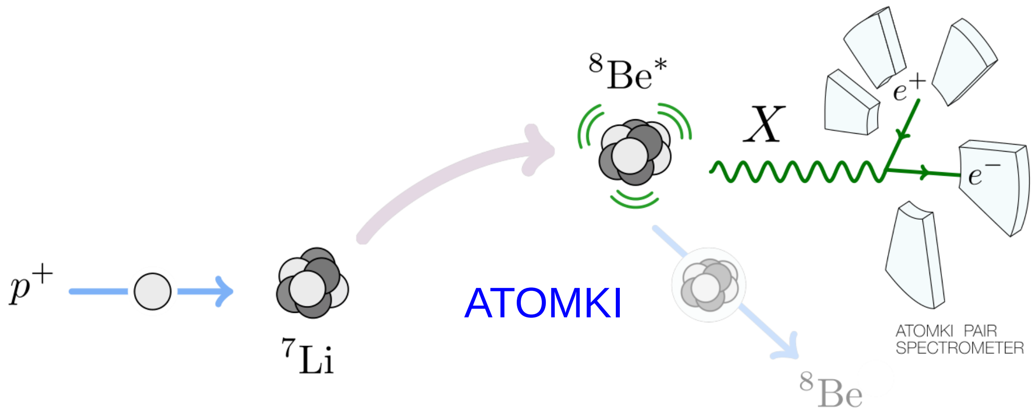


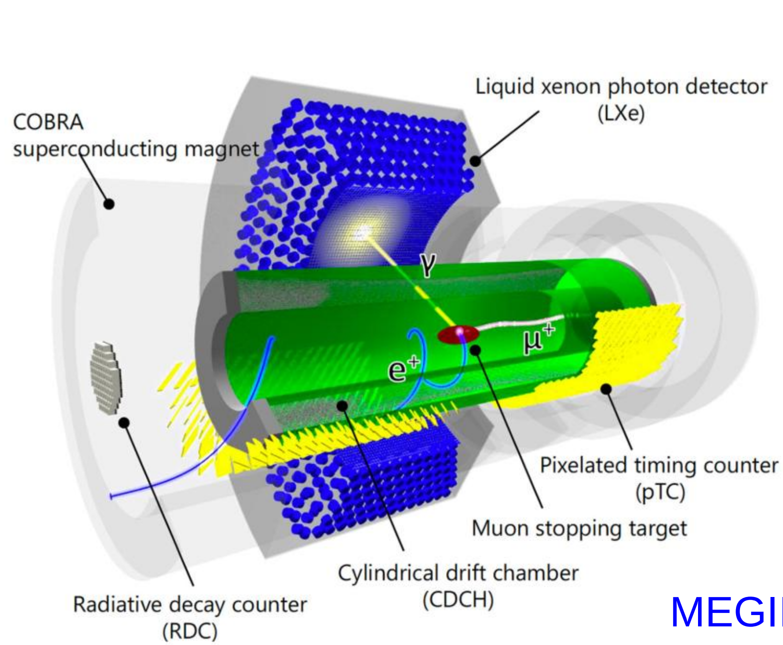


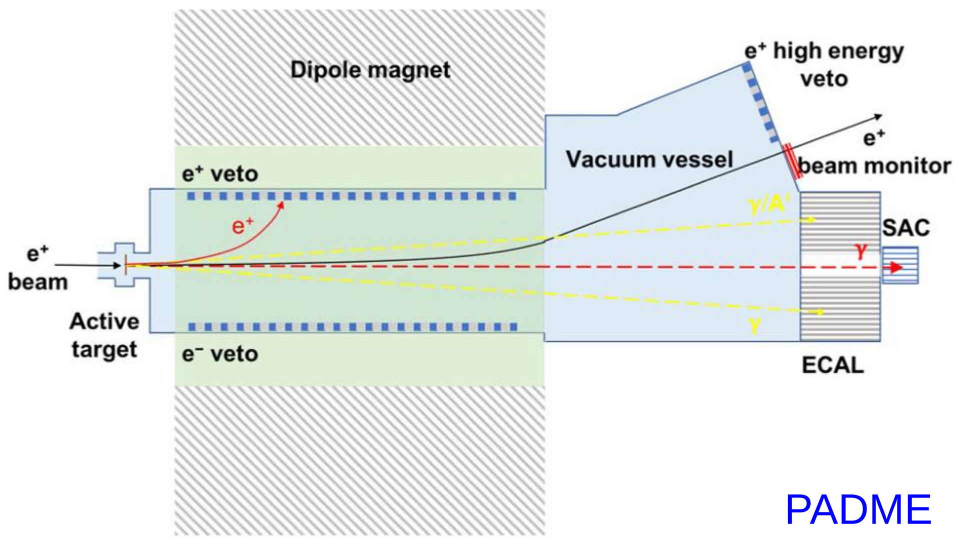
More Physics with MACE detectors

- More than μ:
  - *X17* anomaly in $^{7}\mathrm{Li}(p, e^{+}e^{-})^{8}$Be

PhysRevLett.116.042501







What about MACE?