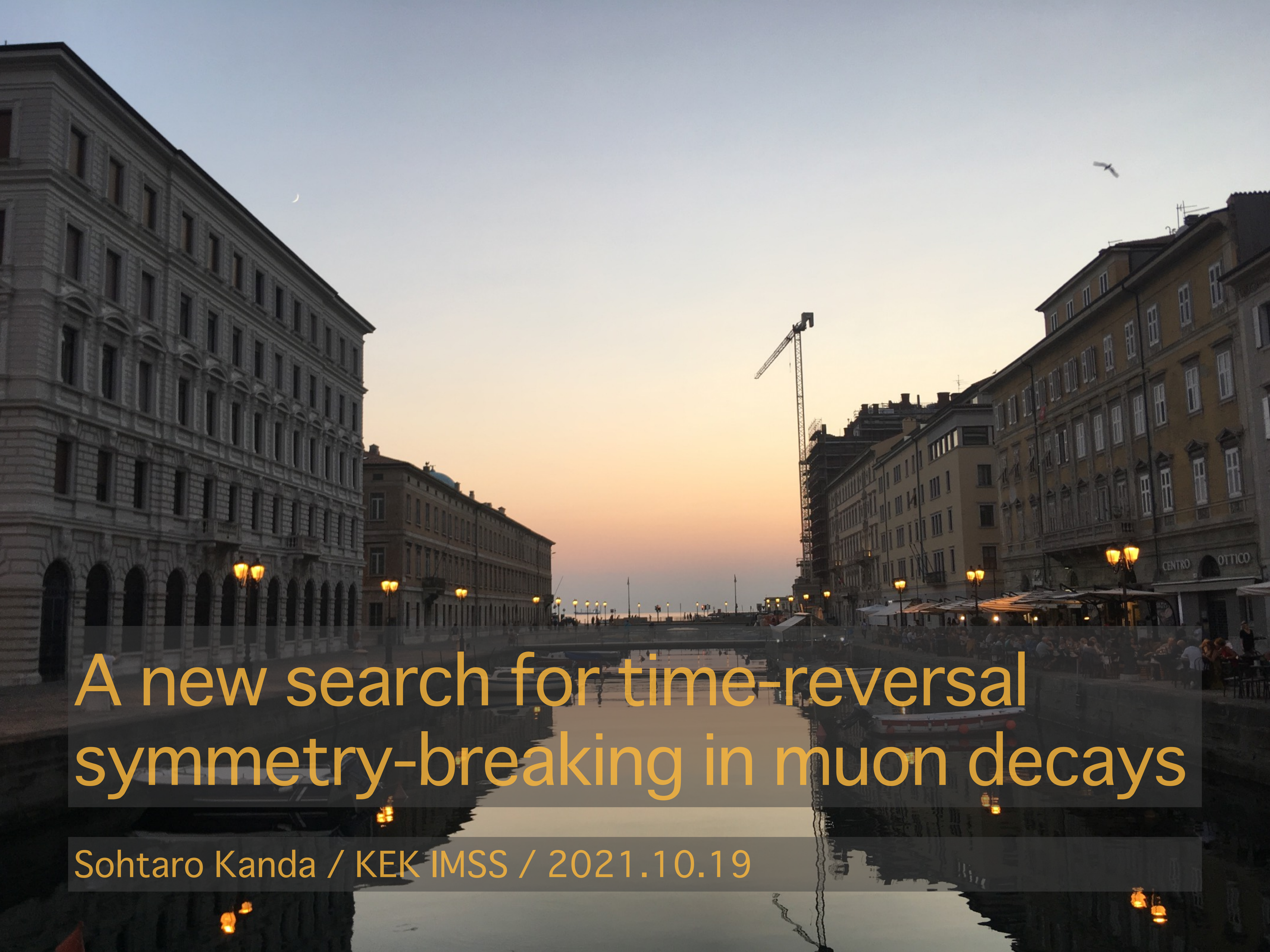


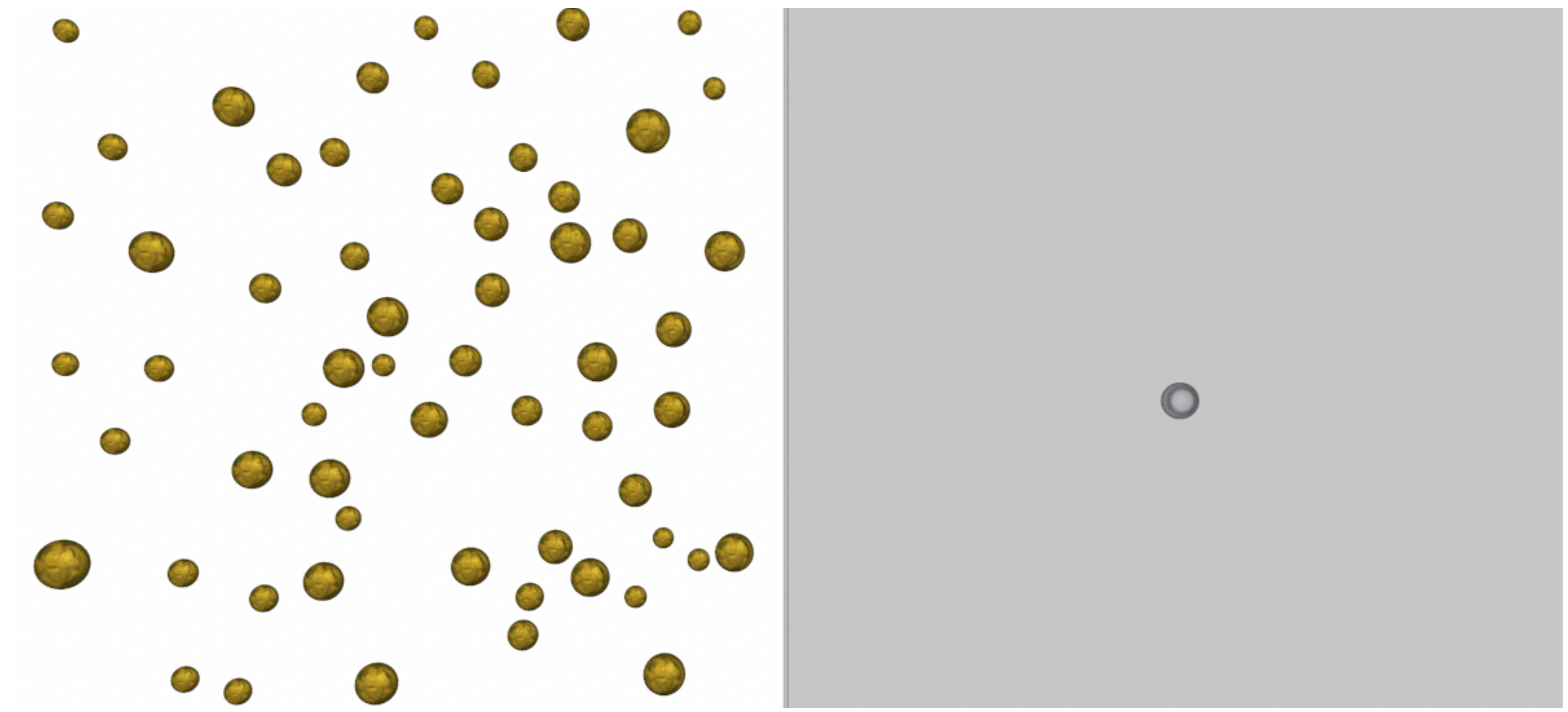
A new search for time-reversal symmetry-breaking in muon decays

Sohtaro Kanda / KEK IMSS / 2021.10.19

Baryon Asymmetry

One of the great mysteries in physics

Matter

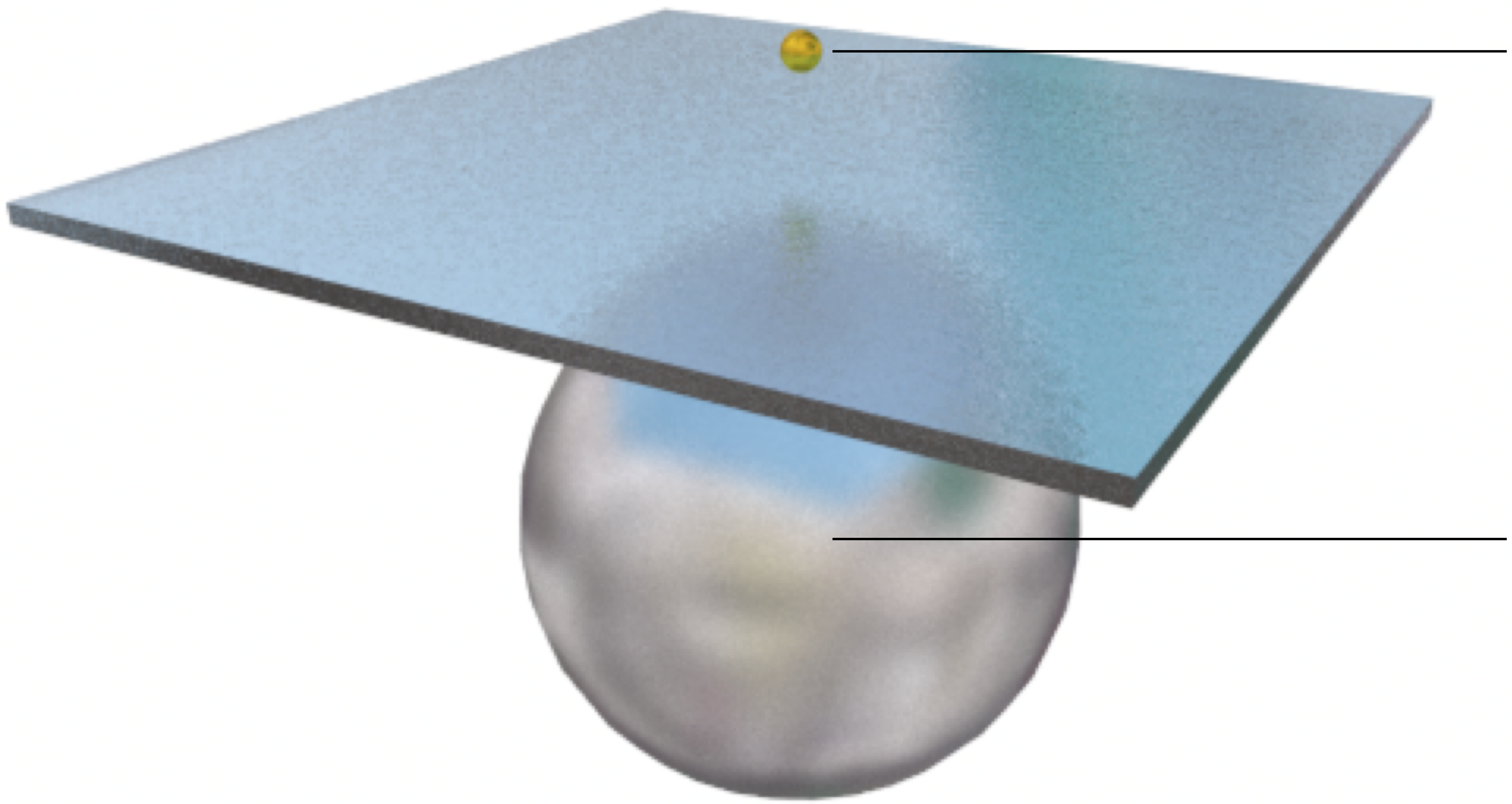


Anti-Matter

- The imbalance in matter and anti-matter in the universe.
- $\eta = \dfrac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$ (n_b: baryon density, n_γ: photon density).
- Baryogenesis is necessary.
  - B-L non-conservation, CP violation, non-equilibrium in the early universe.

Majorana Neutrinos

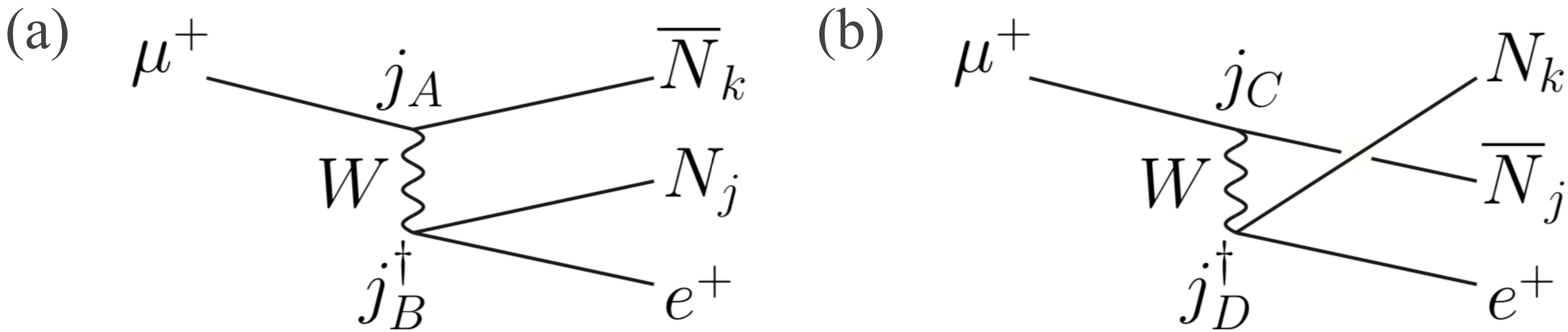
As an answer to the mystery



- Decay of ν_R leads to B-L non-conservation (Leptogenesis).
- Small neutrino masses can be explained by seesaw mechanisms.
- Unification of the quarks and leptons can be realized.

Muon Decay

Neutrino Interference



- If the neutrinos are Majorana particles, neutrinos from muon decay interfere in the presence of V+A interactions.
- The interference of diagrams (a) and (b) above with (A,B,C,D)=(L, L, R, R) and (R,R,L,L) leads to P-odd and T-odd contributions to muon decay.
- How can we observe this interference?

Muon Decay

Generalized Expression

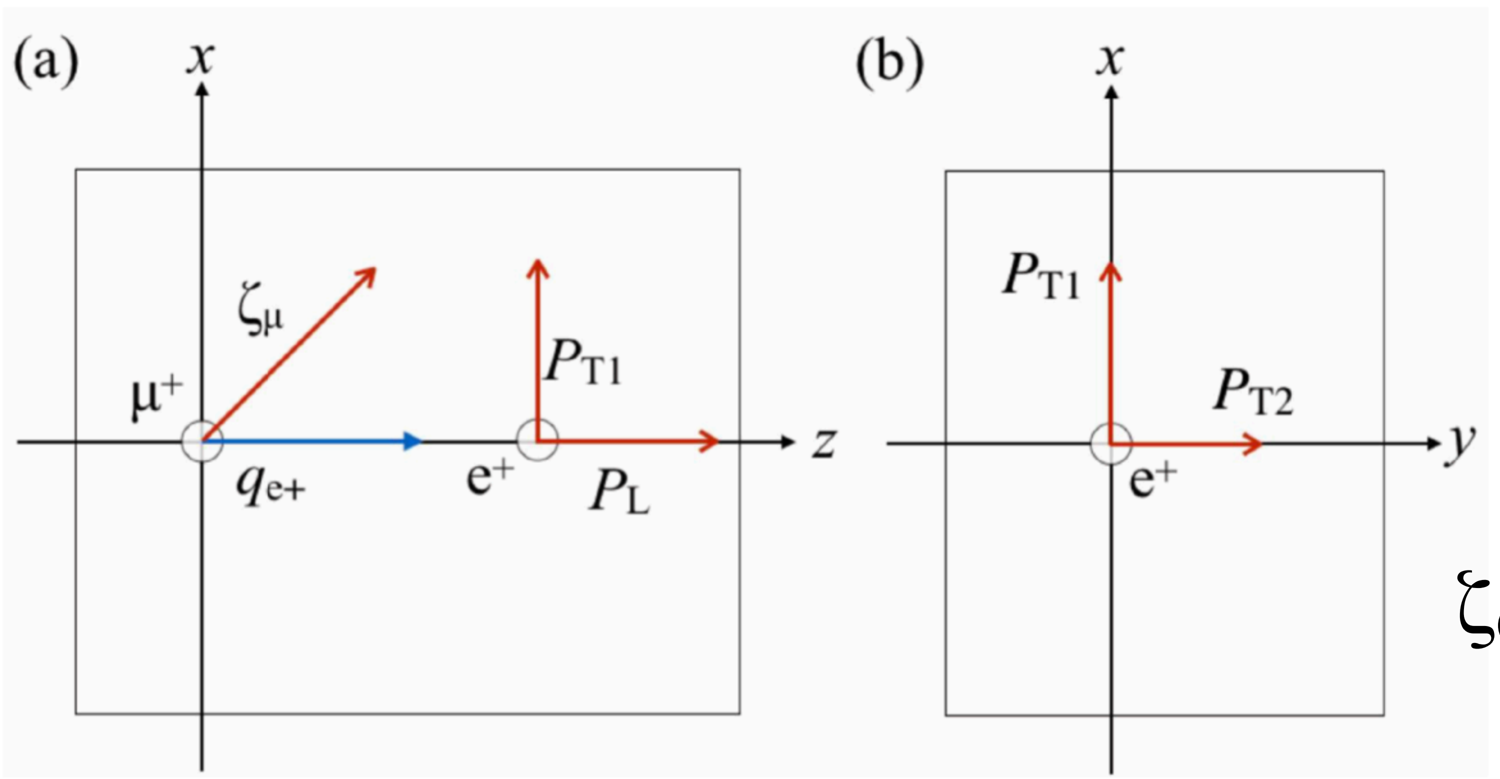
$$
\begin{aligned}
\frac{d\Gamma}{d\mathbf{q}_e} = \frac{m_\mu G_{\mathrm{F}}^2}{3(2\pi)^4} \Bigg\{ & N(e) \pm \frac{(\,\mathbf{q}_e \cdot \boldsymbol{\zeta}_\mu\,)}{E} P(e) \mp \frac{(\,\mathbf{q}_e \cdot \boldsymbol{\zeta}_e\,)}{E} Q(e) \\
& - \frac{(\mathbf{q}_e \times \boldsymbol{\zeta}_\mu) \cdot (\,\mathbf{q}_e \times \boldsymbol{\zeta}_e\,)}{|\mathbf{q}_e|^2} R(e) - \frac{(\,\mathbf{q}_e \cdot \boldsymbol{\zeta}_\mu\,)(\,\mathbf{q}_e \cdot \boldsymbol{\zeta}_e\,)}{|\mathbf{q}_e|^2} S(e) \\
& + \frac{\boldsymbol{\zeta}_\mu \cdot (\,\mathbf{q}_e \times \boldsymbol{\zeta}_e\,)}{E} T(e) \Bigg\}.
\end{aligned}
$$

(E: energy, q: momentum, ζ: spin)

- N, S, R : Parity-even.
- P, Q: Parity-odd.
- T: P-odd and T-odd. This comes from the neutrino interference.
- The T-term indicates time-reversal symmetry-breaking in muon decays.

Measurement Principle

Transverse polarization of decay positrons



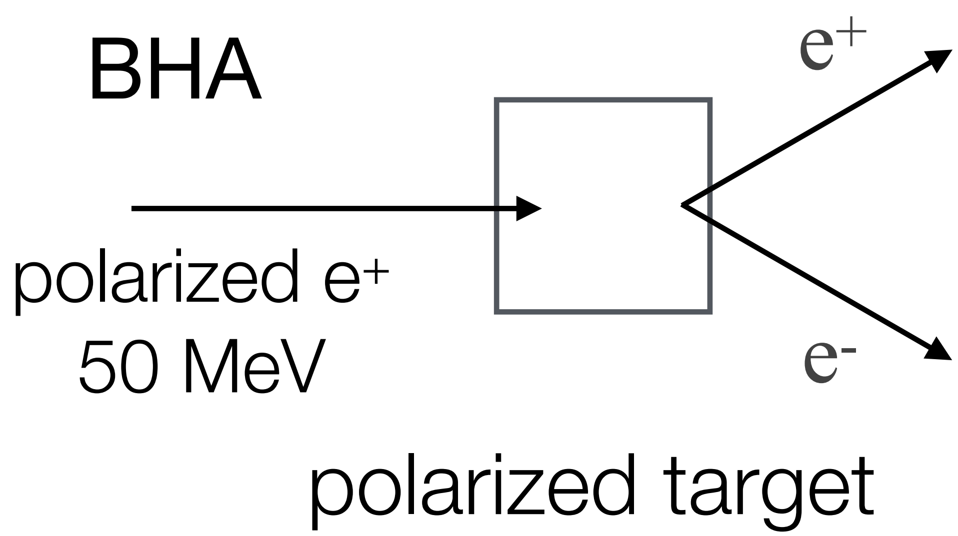
q: momentum
ζ: spin vector
P: polarization

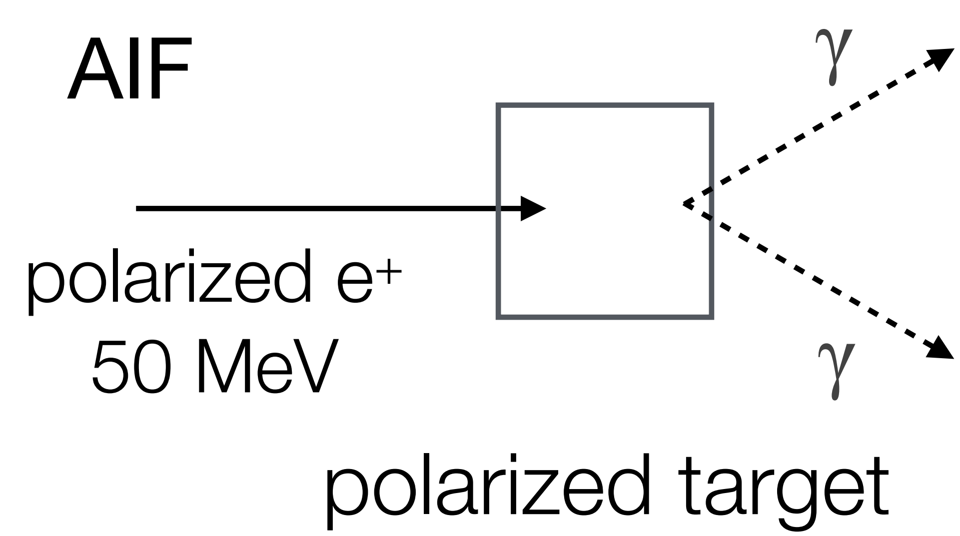
$$\zeta_{e^+} = (P_{T1}, P_{T2}, P_L) \equiv (P_T, P_L)$$

- The T-term $\zeta_\mu \cdot (q_e \times \zeta_e)\ T(e)/E$ can be observed only if the transverse polarization of e^+ from μ^+ decay is non-zero.
- A non-zero P_{T2} leads to the CP violation.
- We can search for P_{T2} by positron polarimetry.

Positron Polarimetry

Bhabha scattering and annihilation-in-flight





$P_{e^+} || P_{tgt}$ → less events

$P_{e^+} || P_{tgt}$ → more events

- A positron polarimeter utilizes the spin-dependent cross-section of a particular electromagnetic process.
  - Mott scattering, Bhabha scattering, Compton transmission···
- In the energy range of interest (50 MeV), Bhabha scattering (BHF) and annihilation-in-flight (AIF) are suitable.

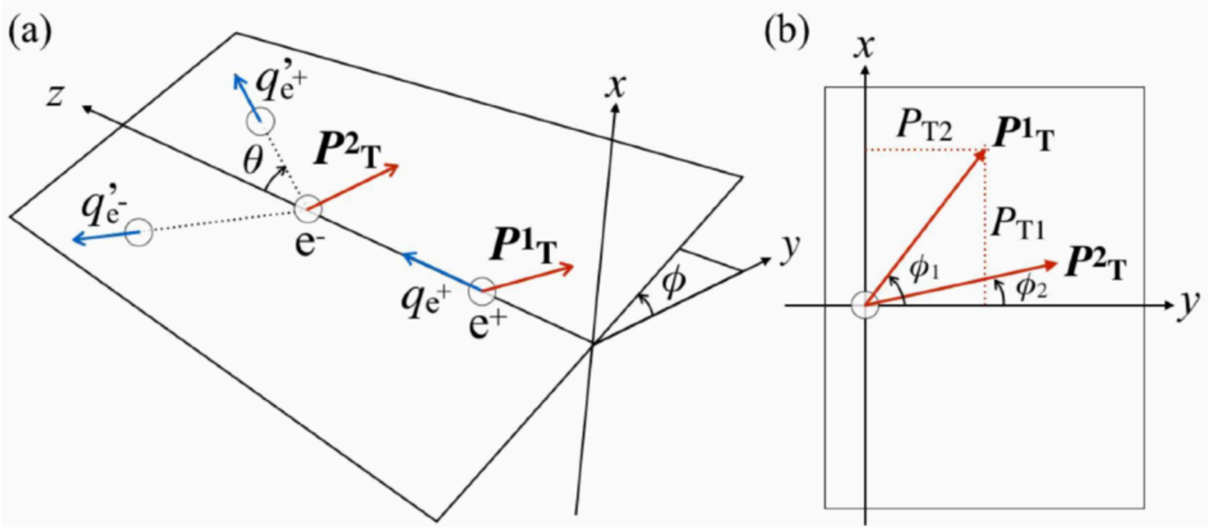
Spin-dependent Cross-sections

and asymmetries of BHA and AIF

○ The difference cross-sections

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{BHA}} = \frac{\alpha^2(3+\cos^2\theta^*)^2}{4s(1-\cos\theta^*)^2}\Big(\,1 - P^1_{\mathrm{L}}P^2_{\mathrm{L}}A_{\mathrm{L}}(\theta^*) - |\boldsymbol{P}^1_{\mathrm{T}}||\boldsymbol{P}^2_{\mathrm{T}}|A_{\mathrm{T}}(\theta^*)\cos(2\phi-\phi_1-\phi_2)\,\Big)$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{AIF}} = \frac{\alpha^2(1+\cos^2\theta^*)}{s\sin^2\theta^*}\Big(\,1 + P^1_{\mathrm{L}}P^2_{\mathrm{L}}B_{\mathrm{L}}(\theta^*) + |\boldsymbol{P}^1_{\mathrm{T}}||\boldsymbol{P}^2_{\mathrm{T}}|B_{\mathrm{T}}(\theta^*)\cos(2\phi-\phi_1-\phi_2)\,\Big)\,,$$



θ^*: scattering angle in center-of mass frame, $\sqrt{s}$: center-of-mass energy, ϕ: scattering azimuth

○ The longitudinal and transverse asymmetries

BHA

$$A_{\mathrm{L}} = \frac{(7+\cos^2\theta^*)\sin^2\theta^*}{(3+\cos^2\theta^*)^2},\qquad A_{\mathrm{T}} = \frac{\sin^4\theta^*}{(3+\cos^2\theta^*)^2}.$$

AIF

$$B_{\mathrm{L}}(\theta^*) = 1,\qquad B_{\mathrm{T}}(\theta^*) = \frac{\sin^2\theta^*}{1+\cos^2\theta^*}.$$

Experiment at PSI

AIF measurement

○ Continuous beam + μSR technique

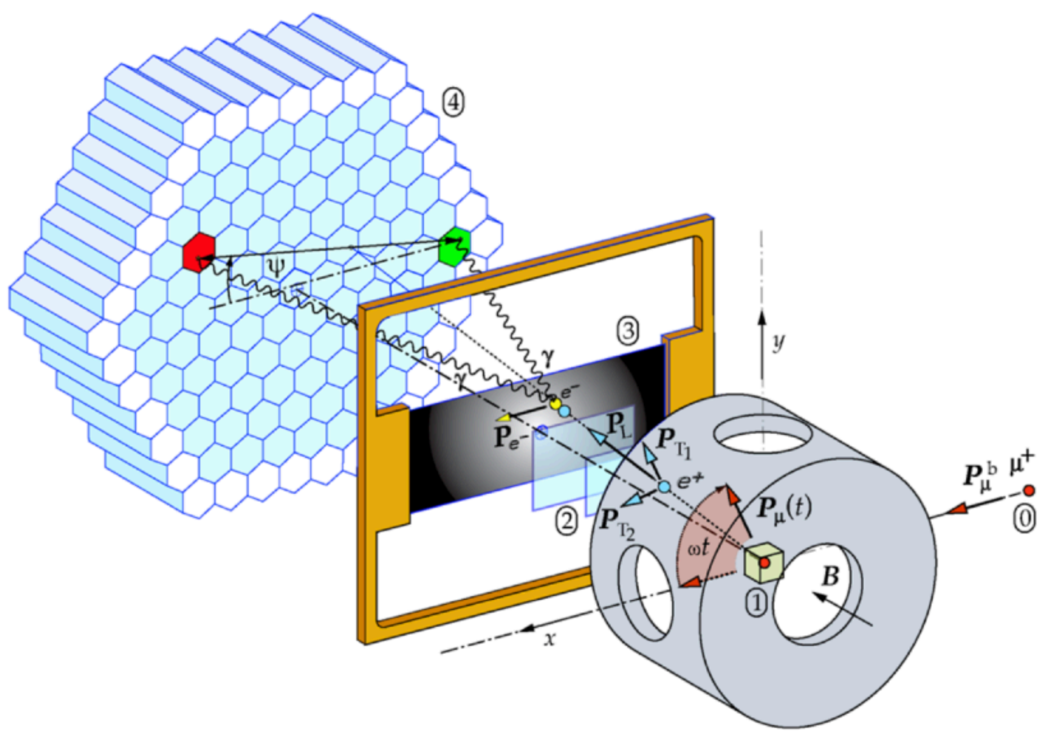
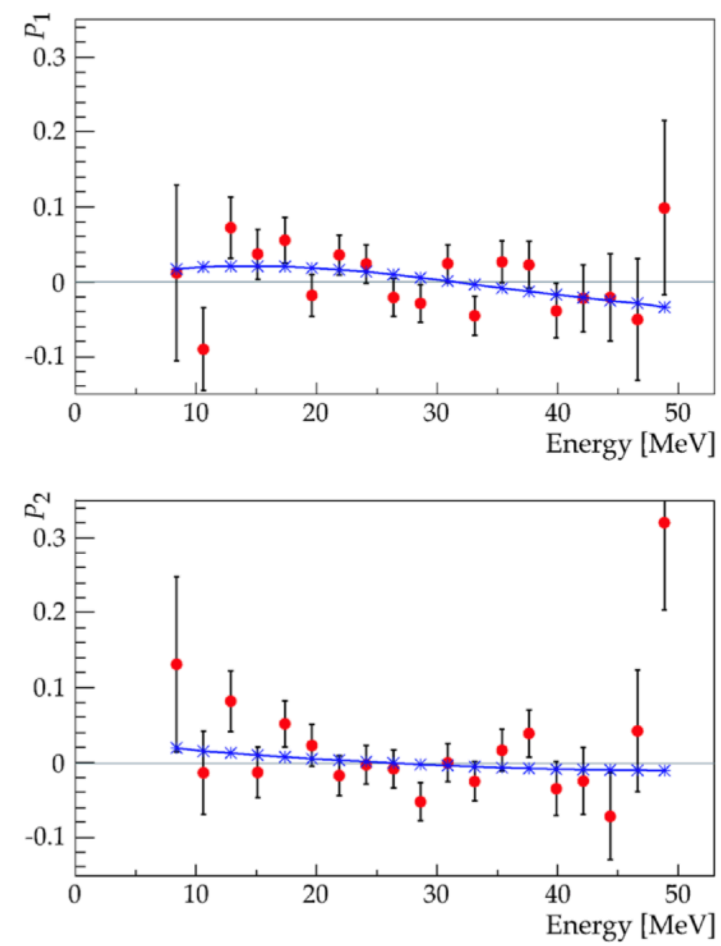


FIG. 1 (color online). Schematic view of the experimental setup. 0: Burst of polarized muons (angular frequency ω, polarization P_μ^b). 1: Be stop target and precession field $\boldsymbol{B}$. 2: Two plastic scintillation counters selecting decay positrons. 3: Magnetized Vacoflux 50$^{\mathrm{TM}}$ foil serving as polarization analyzer. 4: Array of 127 BGO scintillators to detect the two γ's from e^+ annihilation-in-flight.



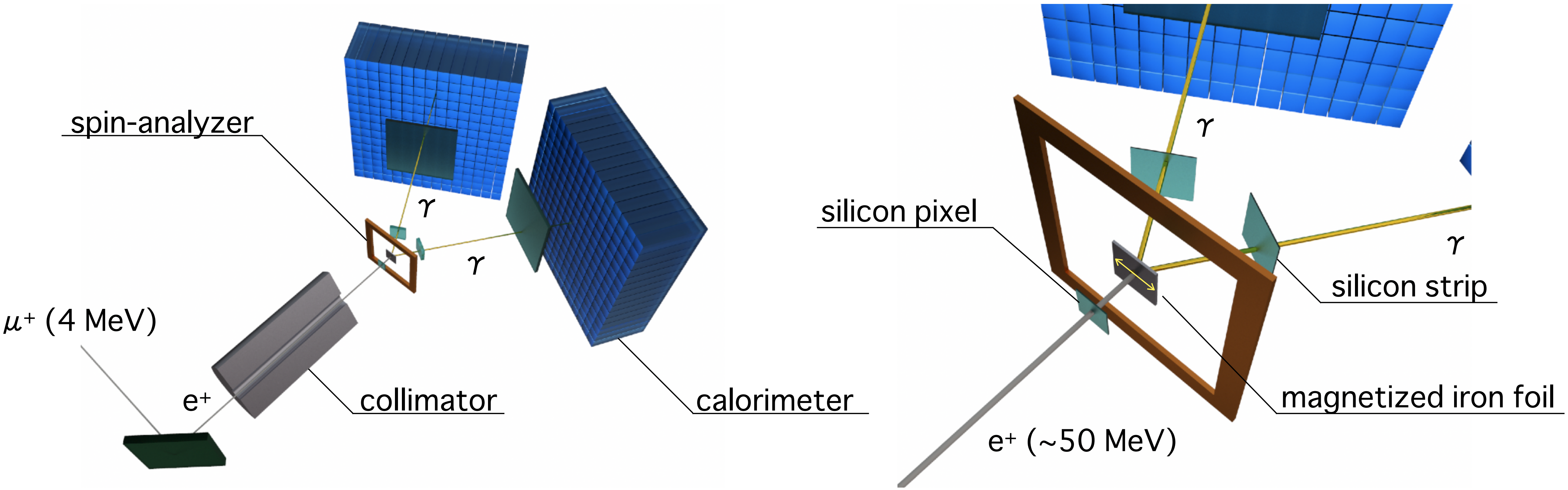
$$P_{T1} = (6.3 \pm 7.7 \pm 3.4) \times 10^{-3},$$
$$P_{T2} = (-3.7 \pm 7.7 \pm 3.4) \times 10^{-3},$$

N. Danneberg et al., Phys. Rev. Lett. 94, 021802 (2005).

New Experimental Proposal

using a high-intensity pulsed muon beam at J-PARC

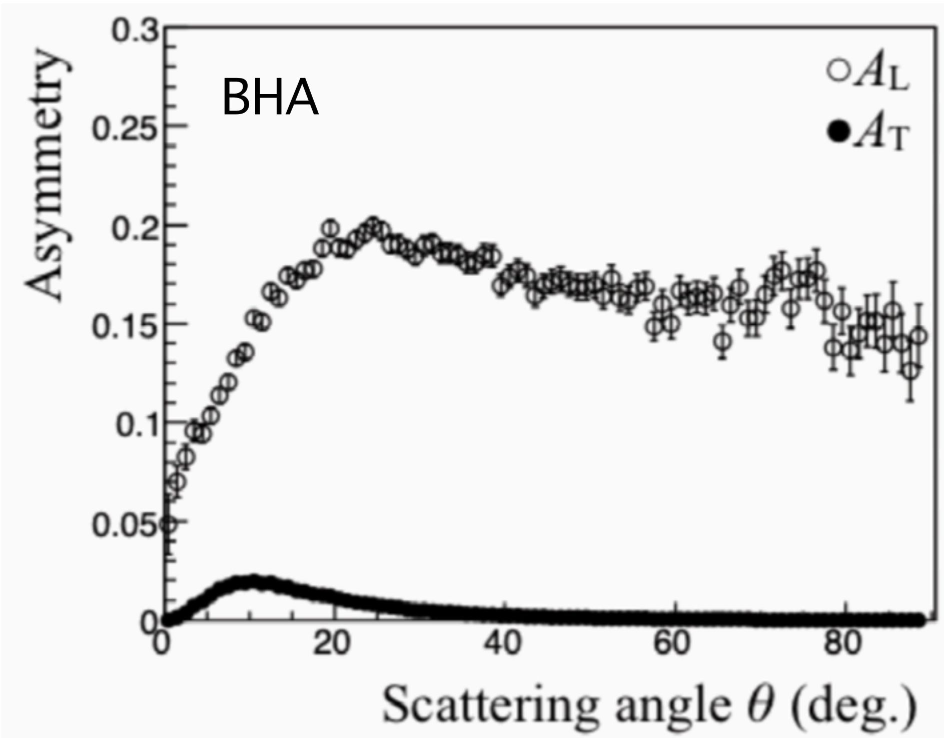
- Pulsed beam + high-rate capable detectors

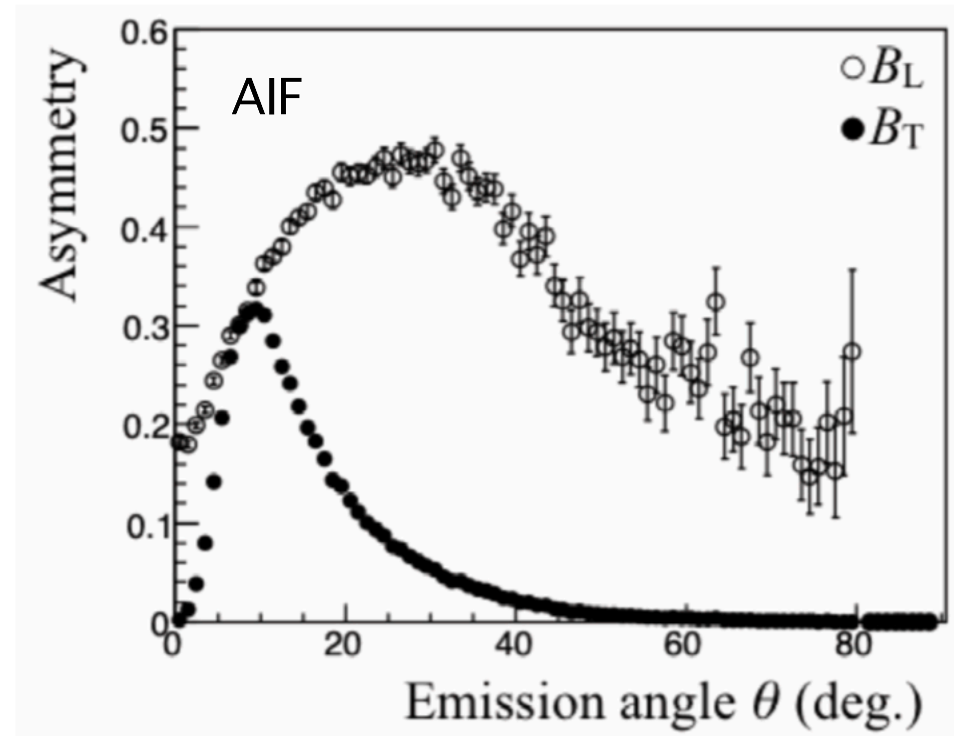


- Simultaneous measurements of Bhabha scattering and annihilation-in-flight (AIF).
- AIF events are selected with two photons in the calorimeter without a hit on the tracker.

Monte-Carlo Simulations

Angular asymmetries



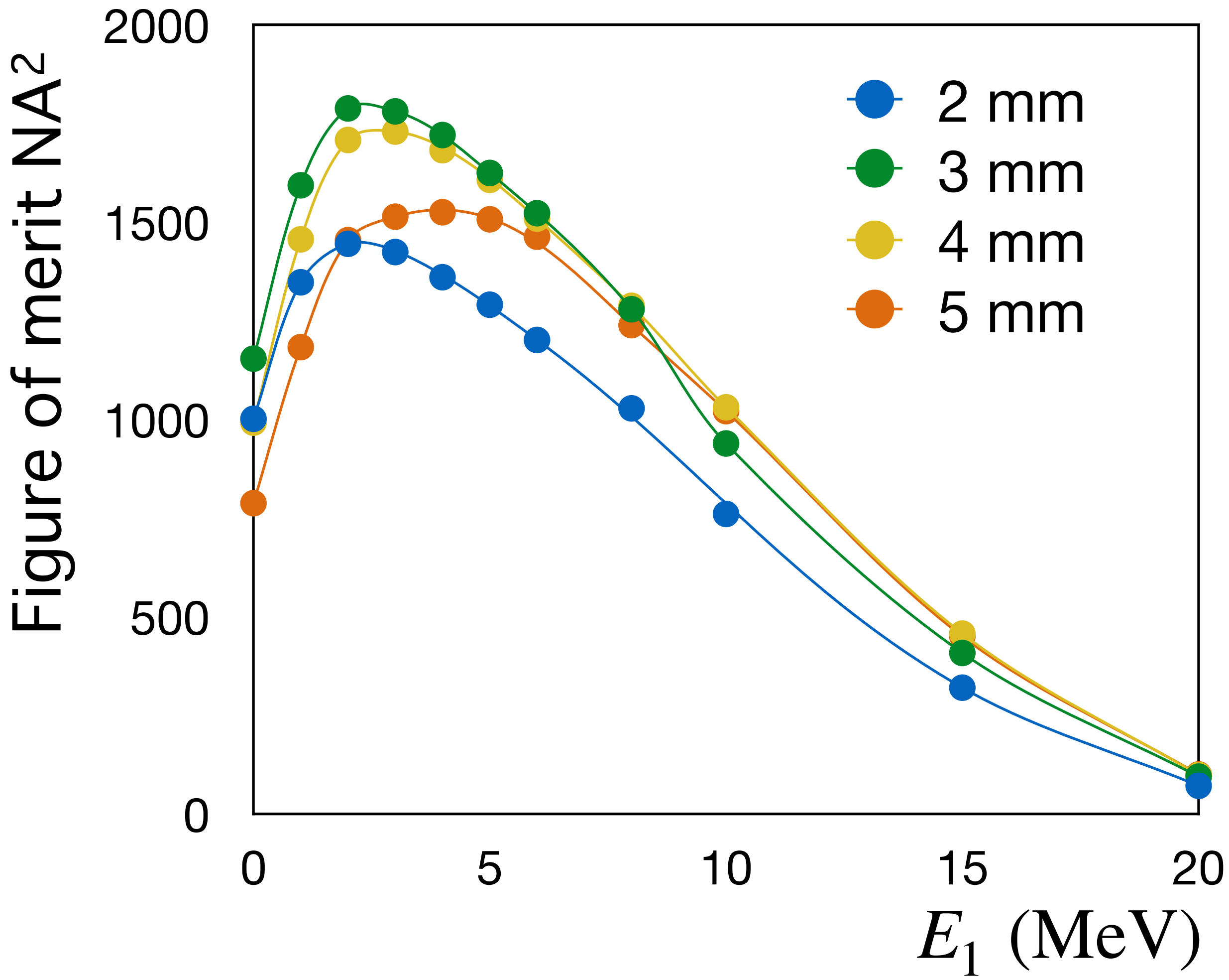


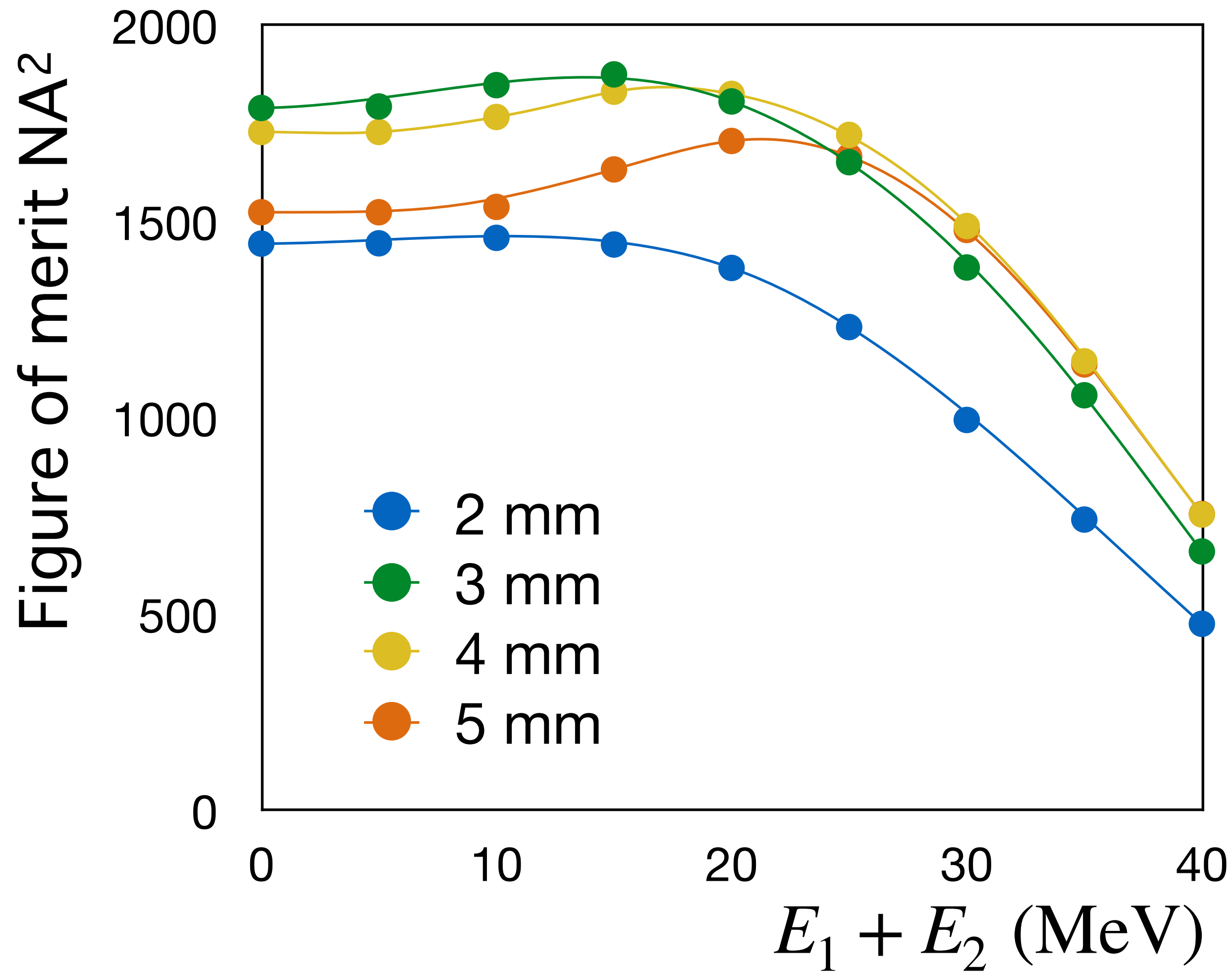
$$\frac{A_T(\theta^*)\cos(2\phi-\phi_1-\phi_2)}{A_L(\theta^*)} = \frac{\sin^2\theta^*}{7+\cos^2\theta^*}\cos(2\phi-\phi_1-\phi_2) \qquad \frac{B_T(\theta^*)\cos(2\phi-\phi_1-\phi_2)}{B_L(\theta^*)} = \frac{\sin^2\theta^*}{1+\cos^2\theta^*}\cos(2\phi-\phi_1-\phi_2)$$

- The analyzing power $A = (N_+ - N_-)/(N_+ + N_-)$ is calculated for each process.
- AIF is good for a transverse polarimetry.
- Bhabha scattering is still useful for beam polarization monitoring.

Monte-Carlo Simulations

Energy thresholds and the target thickness

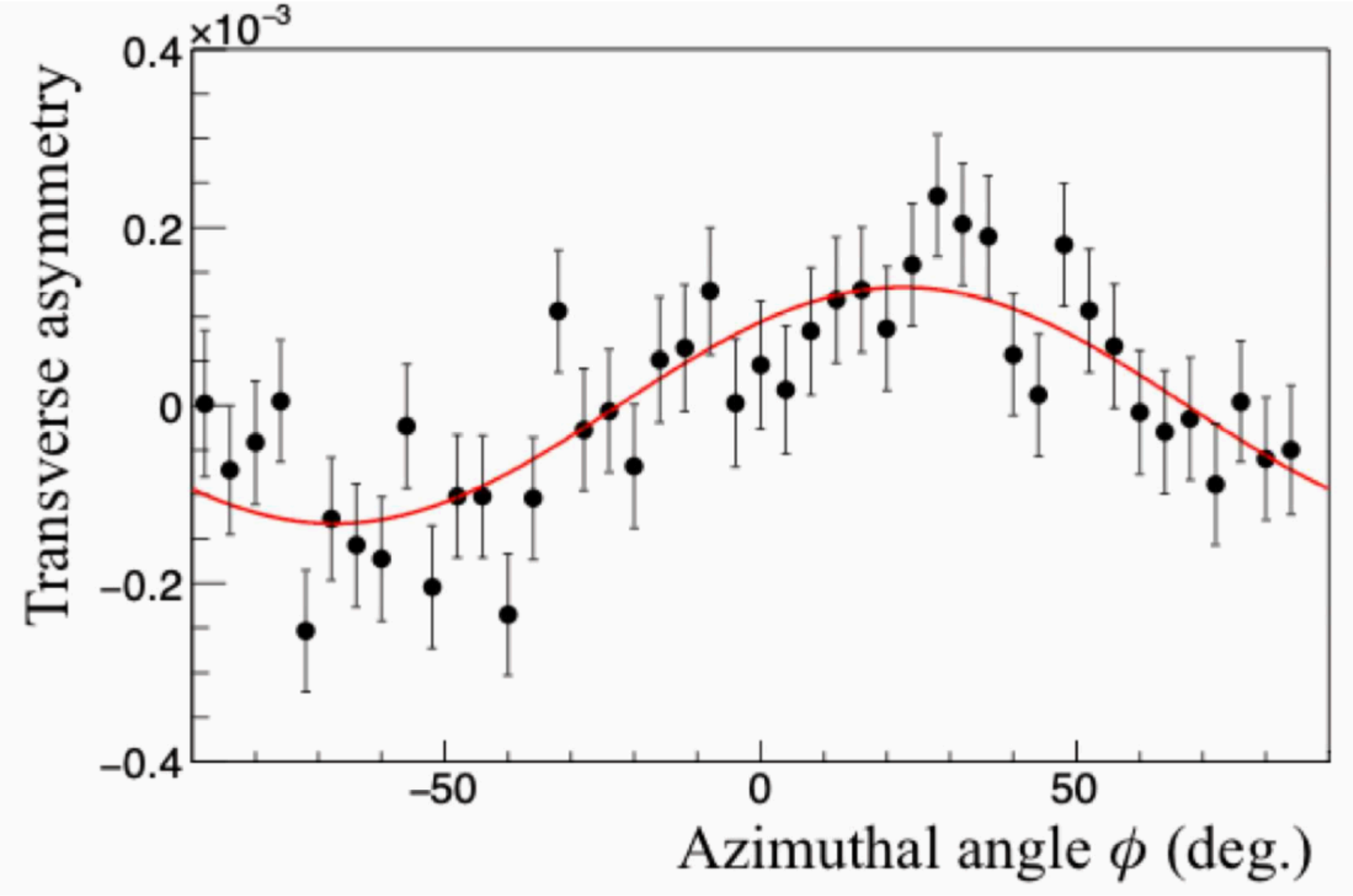




- Considering a threshold for for each gamma-ray energy (E1, E2).
- The energy thresholds are set $E_1 > 2$ MeV, $E_2 > 2$ MeV, $E_1 + E_2 > 15$ MeV.
- The target thickness is optimized to be 3 mm.

Monte-Carlo Simulations

Azimuth dependence of the asymmetry



Amplitude

$$A = (1.5 \pm 0.2) \times 10^{-4}$$

Phase

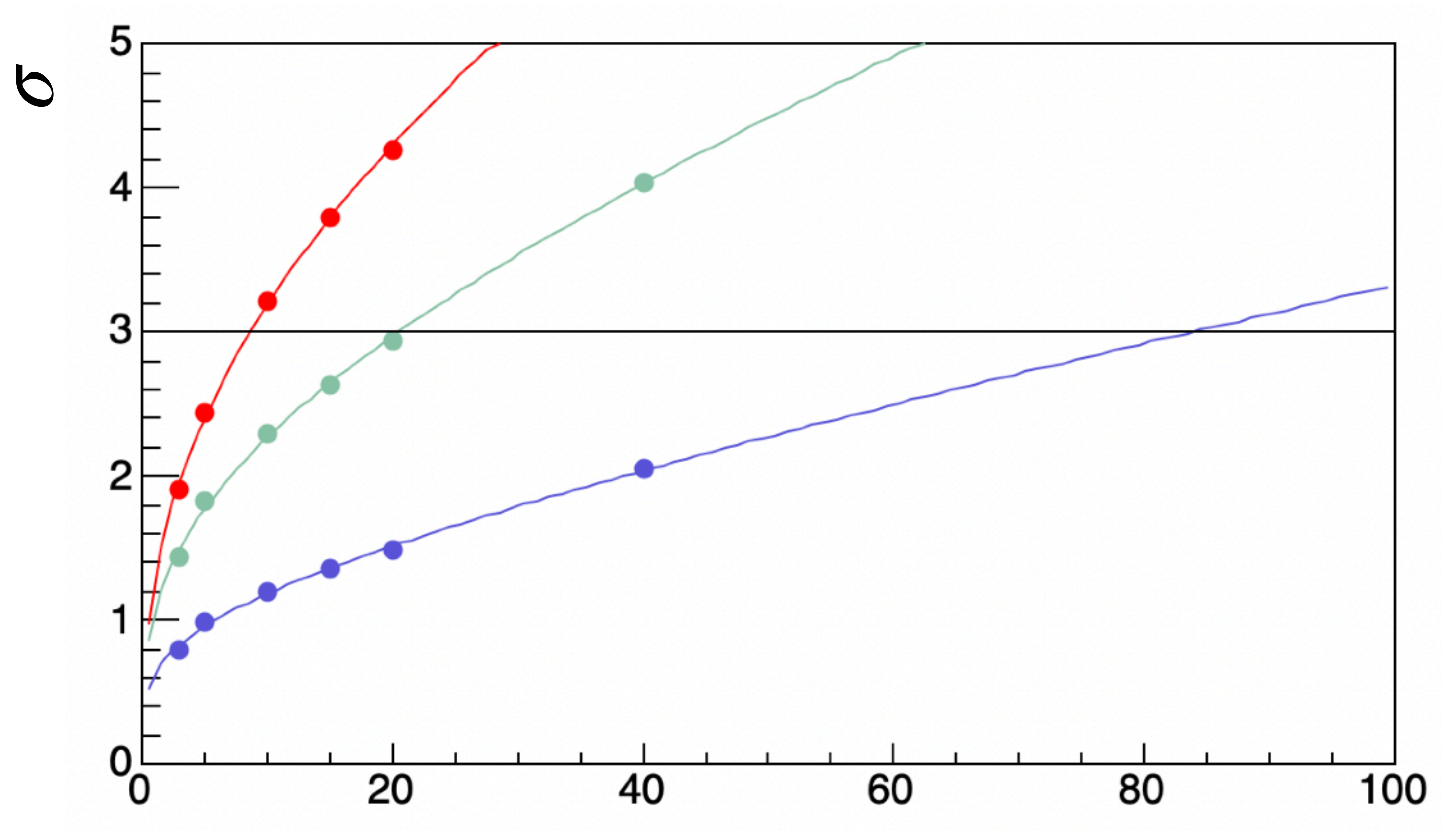
$$\phi_1 = (45.5 \pm 10.7)\ \mathrm{deg}\,.$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm AIF} = \frac{\alpha^2(1+\cos^2\theta^*)}{s\sin^2\theta^*}\left(1 + P_{\rm L}^1 P_{\rm L}^2 B_{\rm L}(\theta^*) + |\boldsymbol{P}_{\rm T}^1||\boldsymbol{P}_{\rm T}^2| B_{\rm T}(\theta^*) \boxed{\cos(2\phi - \phi_1 - \phi_2)}\right),$$

- A simulated asymmetry in a case of $P_{\mathrm{T2}} = 7.7 \times 10^{-3}$, $\phi_1 = 45$ deg.
- The number of simulated muons is 3.3×10^9 (10 days at J-PARC MLF MUSE H-Line).

Statistical Sensitivity

Discovery potential of P_{T2}



- $\phi_1 = 45$ deg.
- $\phi_1 = 60$ deg.
- $\phi_1 = 75$ deg.

$P_{T2} = 5 \times 10^{-3}$

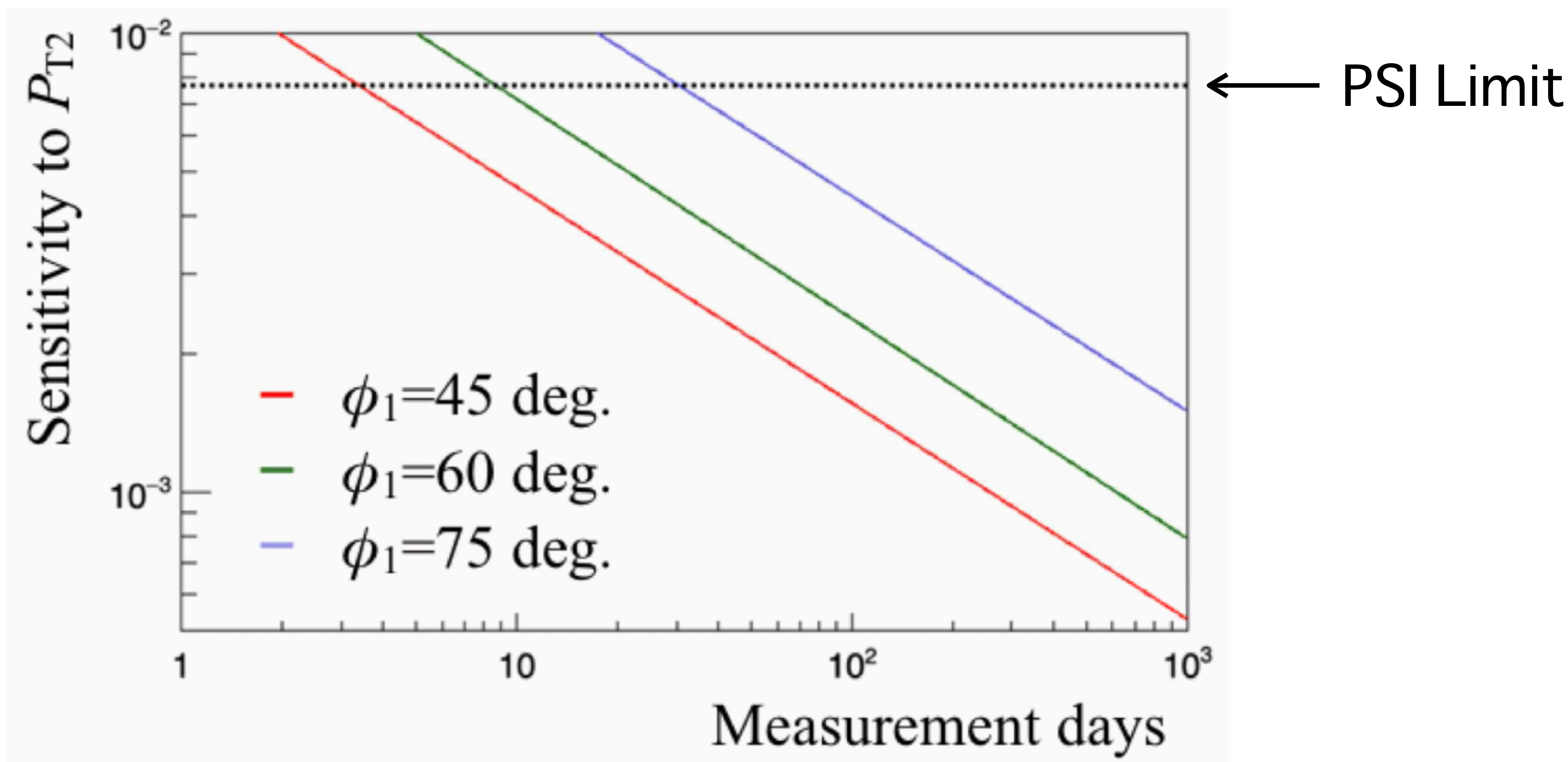
$1 \times 10^{8} \mu^{+}/\mathrm{s}$

○ The statistical significance of the transverse polarization:

$$\sigma \equiv \frac{P_{T2}}{\delta P_{T2}} = \frac{1}{\sqrt{(\delta a/a)^2 + (\delta\phi_1 \tan\phi_1)^2}}.$$

Statistical Sensitivity

Sensitivity to the transverse polarization

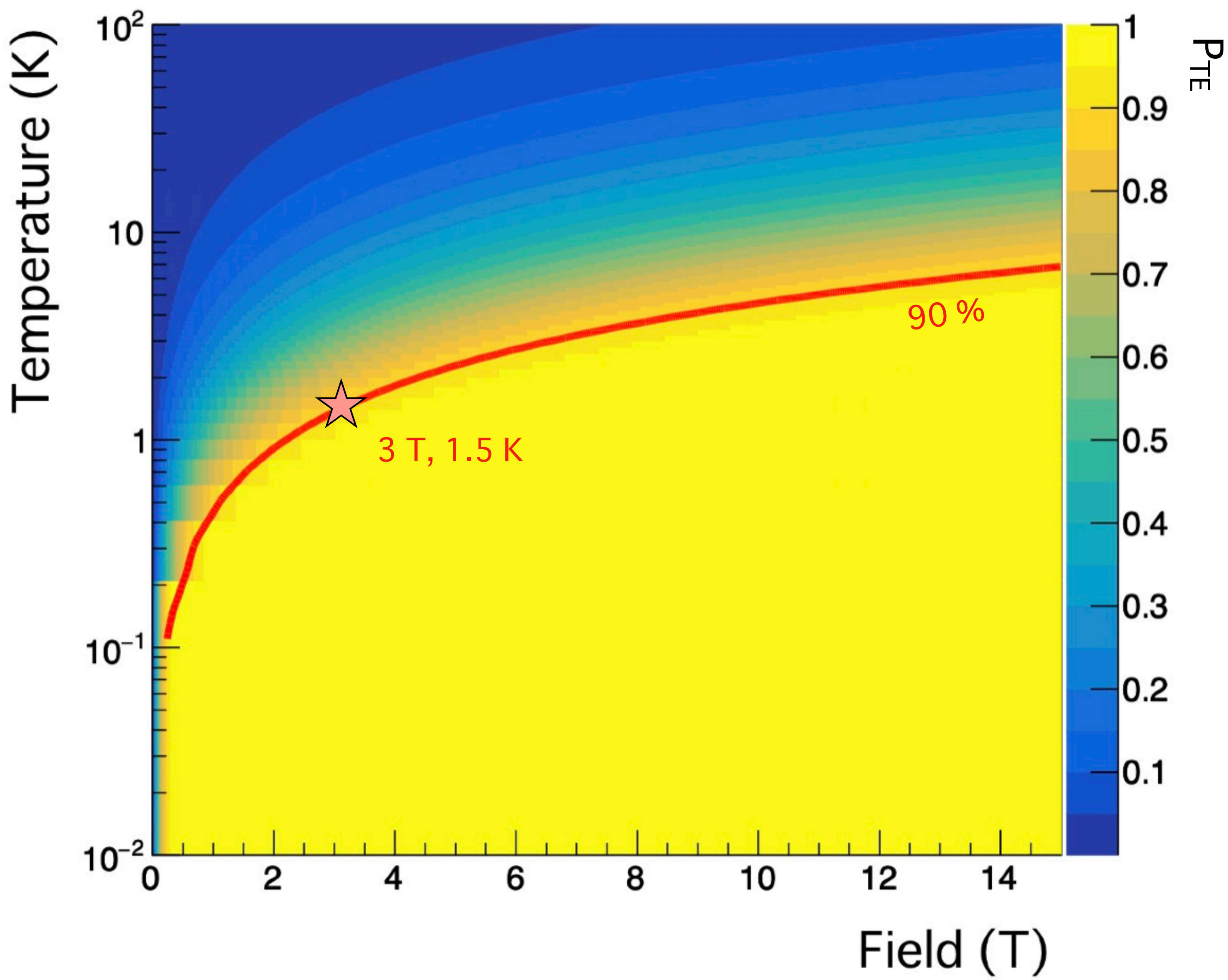


- It is feasible to achieve a comparable statistical precision relative to that of the previous experiment within four days.
- A tenfold improvement will take close to a year.

  → Any ideas to improve the sensitivity more?

Electron Polarized Target

toward sophistication of the experiment



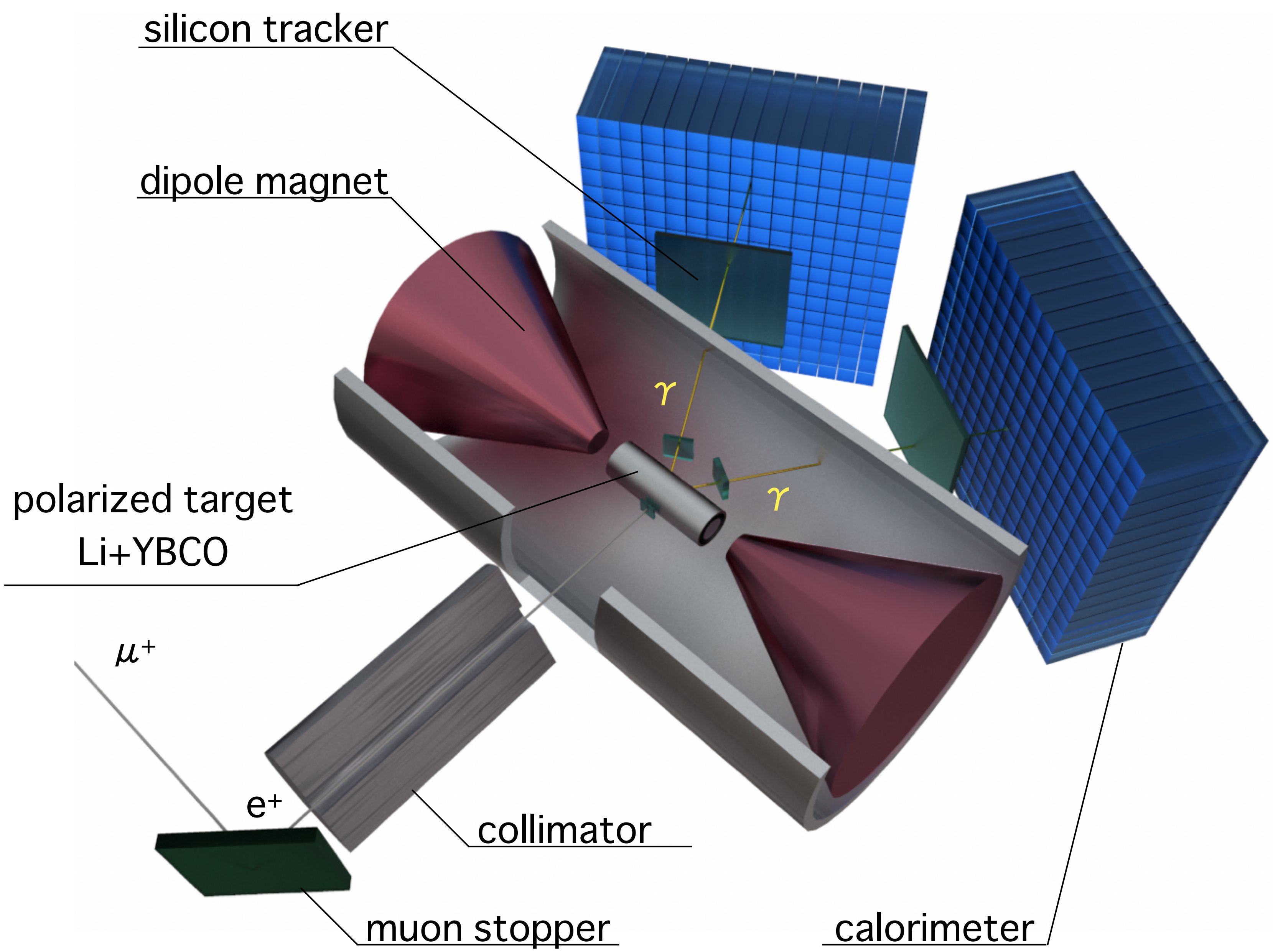
$$P_{TE} = \frac{e^{\frac{\mu B}{kT}} - e^{\frac{-\mu B}{kT}}}{e^{\frac{\mu B}{kT}} + e^{\frac{-\mu B}{kT}}} = \tanh\left(\frac{\mu B}{kT}\right)$$

μ: electron magnetic moment
k: Boltzmann constant
B: magnetic field
T: target temperature

- The electron polarization in the PSI experiment was 7.2 %. If a polarization of 30 % is achieved, the statistical precision will be 14 times better.

Experimental Schematic

using superconducting flux concentrator



- L-shell electrons of solid lithium are polarized by using a dipole magnet with a flux concentrator consisting of YBCO superconducting thin films.
- The superconducting thin films also work as a magnetic shield to prevent positron bends.
- The temperature and magnetic field are 1.5 K and 3 T, respectively.

*cryogenics is not shown

Collaborators

of the project

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- The proposal: arXiv:1908.01630 [hep-ex].
- A new proposal using YBCO superconducting thin films:
    - A letter is in preparation (and will be submitted soon).

Summary

and outlook

- T-violation in muon decay indicates the Majorana nature of neutrinos.
    - It appears as the transverse polarization of decay positrons.
- We have proposed a new experiment with the high-intensity pulsed muon beam at J-PARC.
    - The sensitivity and feasibility of the polarimeter have been studied.
- If the electron spin-polarized target is realized, the upper limit of the previous experiment can be updated significantly.
    - This scheme can be realized by using a superconducting thin film flux concentrator.
    - Feasibility study of electron polarization will be conducted.