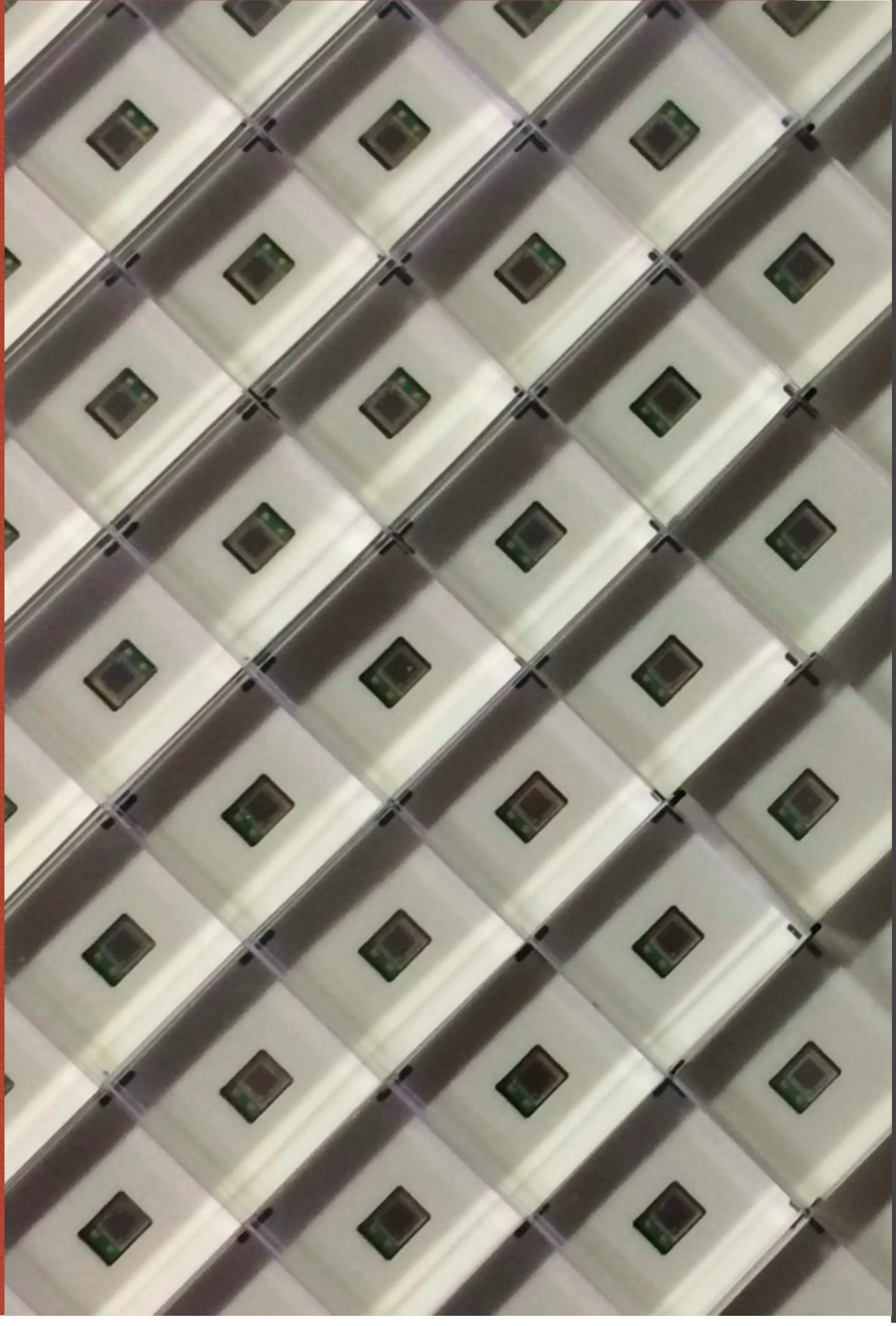
A search for Majoranality of neutrinos in muon decay using a positron polarimeter



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arXiv:1908.01630

- We propose a new experiment to search for Majorana neutrinos by measuring the polarizations of positrons from muon decay.
- Contents of this talk are based on arXiv:1908.01630

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High Energy Physics – Experiment

Hunting for T-violation and Majoranality of Neutrinos in Muon Decays

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(Submitted on 5 Aug 2019)

We propose a new experiment to search for a time-reversal (T) symmetry breaking process in muon decay and the Majoranality of the neutrinos. In the presence of V+A interactions, the Majoranality appears as a T-violating term in the muon decay width as shown by Doi et al, while in the Standard Model such a T-violating term is negligibly small. The presences of V+A interactions and the corresponding heavy right-handed Majorana neutrinos give us an important clue to solve two major issues in particle physics, the deficit of baryon asymmetry in the universe and the Majoranality of neutrinos. In the experiment, the polarization of positrons from muon decays is measured using a polarimeter consisting of a magnetized foil and a segmented calorimeter. According to our result of numerical calculation, a factor of ten improvement in sensitivity to the T-violating process is expected by a year of measurement at J-PARC Materials and Life Science Experimental Facility, compared to the most recent precursor experiment.

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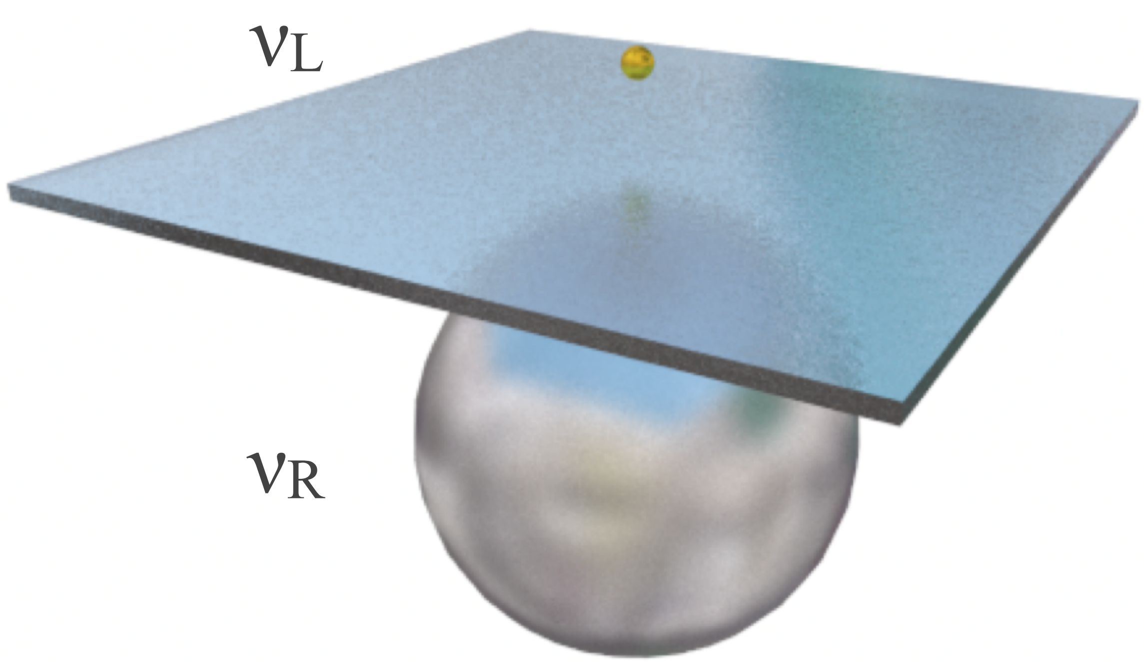
(or arXiv:1908.01630v1 **[hep-ex]** for this version)

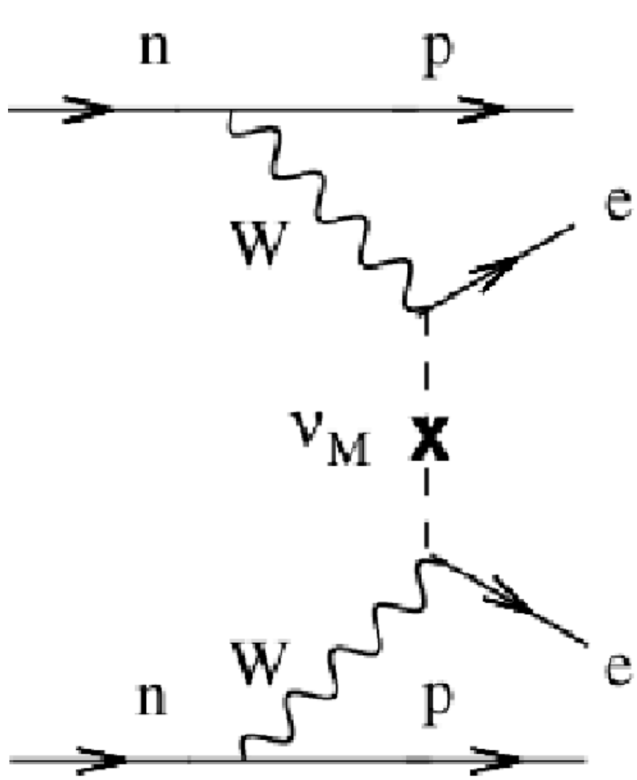
https://arxiv.org/abs/1908.01630

Majoranality of the Neutrinos

- One of the most important open questions in particle physics is whether the neutrinos are Dirac or Majorana particles.
- The seesaw mechanism involving heavy right-handed Majorana neutrinos explains the tiny masses of the neutrinos.



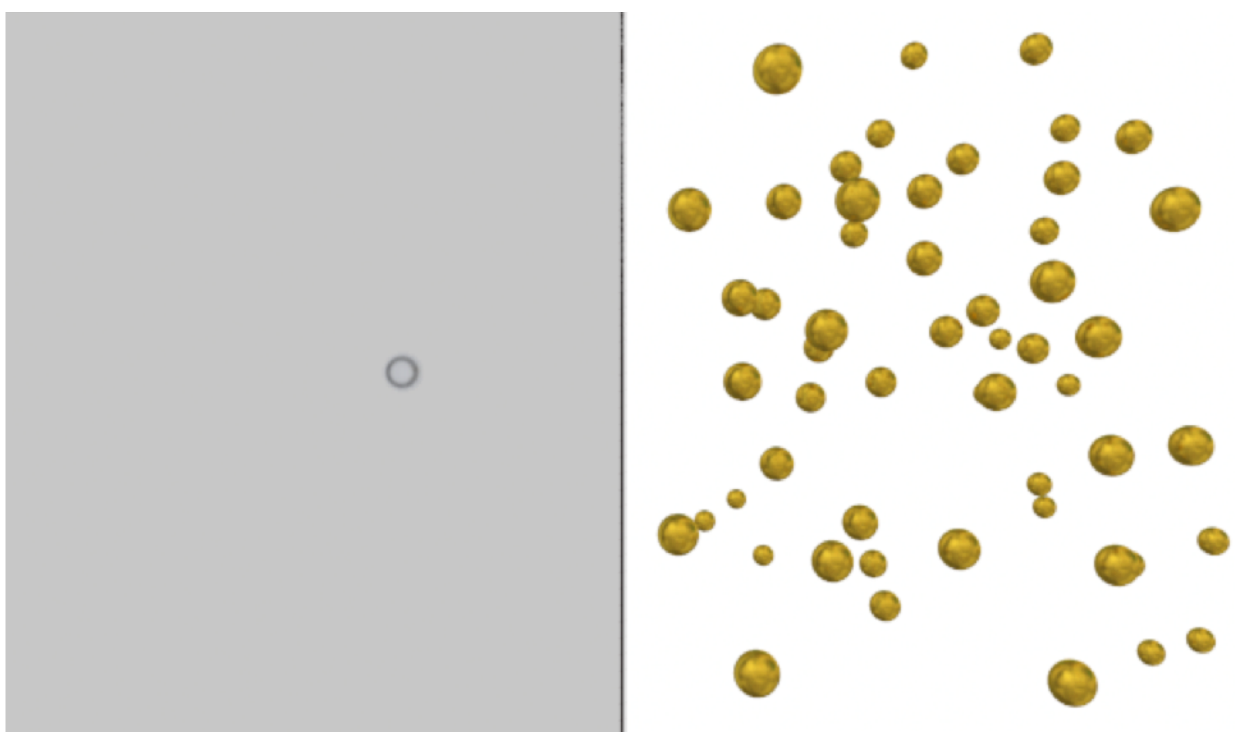
Light ν_L and heavy ν_R



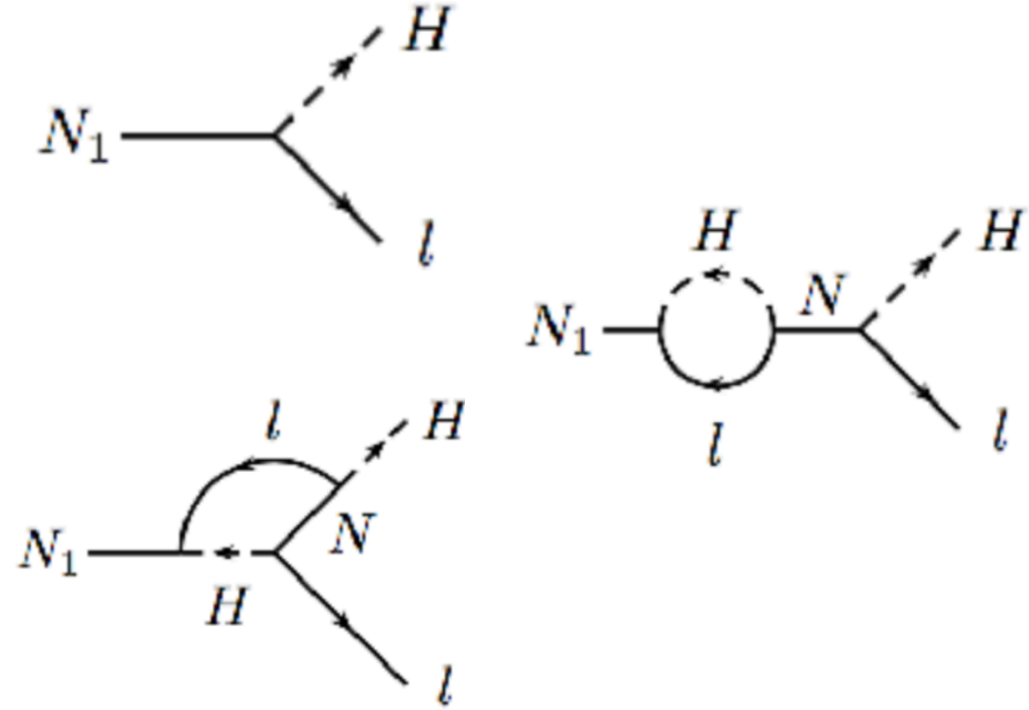
Neutrinoless double beta decay

Baryon Asymmetry in the Universe

- Baryon asymmetry in the universe is one of the great mysteries in physics.
- Decay of Majorana neutrinos induce asymmetry in the lepton number, leading to baryogenesis via a sphaleron effect.



Anti-matter Matter



Decay of Majorana neutrino inducing the lepton number asymmetry

GUT and V+A Interactions

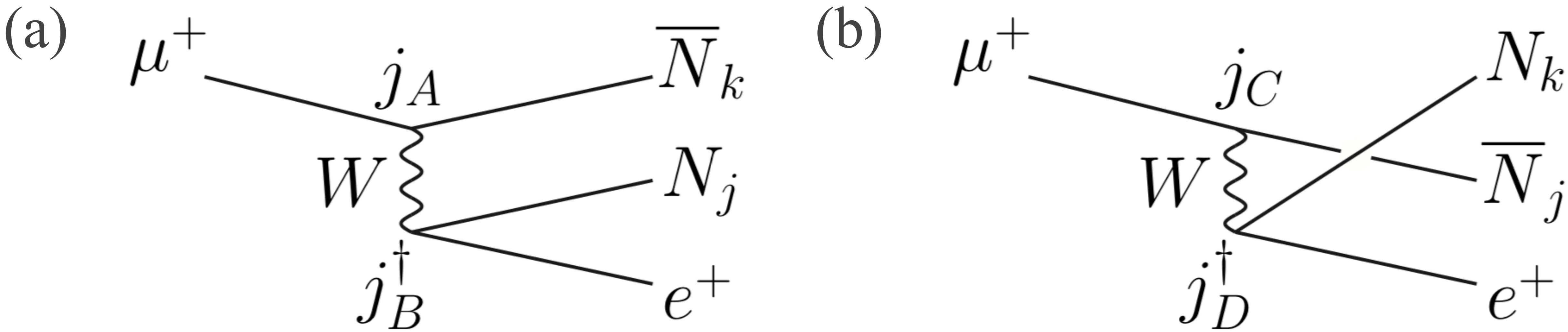
- Majorana neutrinos are predicted in various Grand Unified Theories (GUTs) where the existence of V+A interactions is also predicted.
- For example, in the process of the symmetry breaking from SO(10) GUT to the SM, the right-handed current naturally appears in a symmetry breaking sequence like

$$\mathrm{SO}(10) \to \mathrm{SU}(4)_\mathrm{C} \otimes \mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{SU}(2)_\mathrm{R} \to \mathrm{SU}(3)_\mathrm{C} \otimes \mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{SU}(2)_\mathrm{R} \otimes \mathrm{U}(1)_{\mathrm{B-L}} \to \mathrm{SM}.$$

- How can we detect Majoranality and V+A interaction?

Neutrino Interference in Muon Decay

- In the presence of V+A interactions, neutrinos from muon decay interfere.



- The interference of diagrams (a) and (b) with (A, B, C, D) = (L, L, R, R) and (R, R, L, L) results in P-odd and T-odd contribution to muon decay.
- This interference takes place only if the neutrinos are Majorana particles.

Muon Decay Rate

- The general form of the muon differential decay rate in the rest frame of μ∓ is

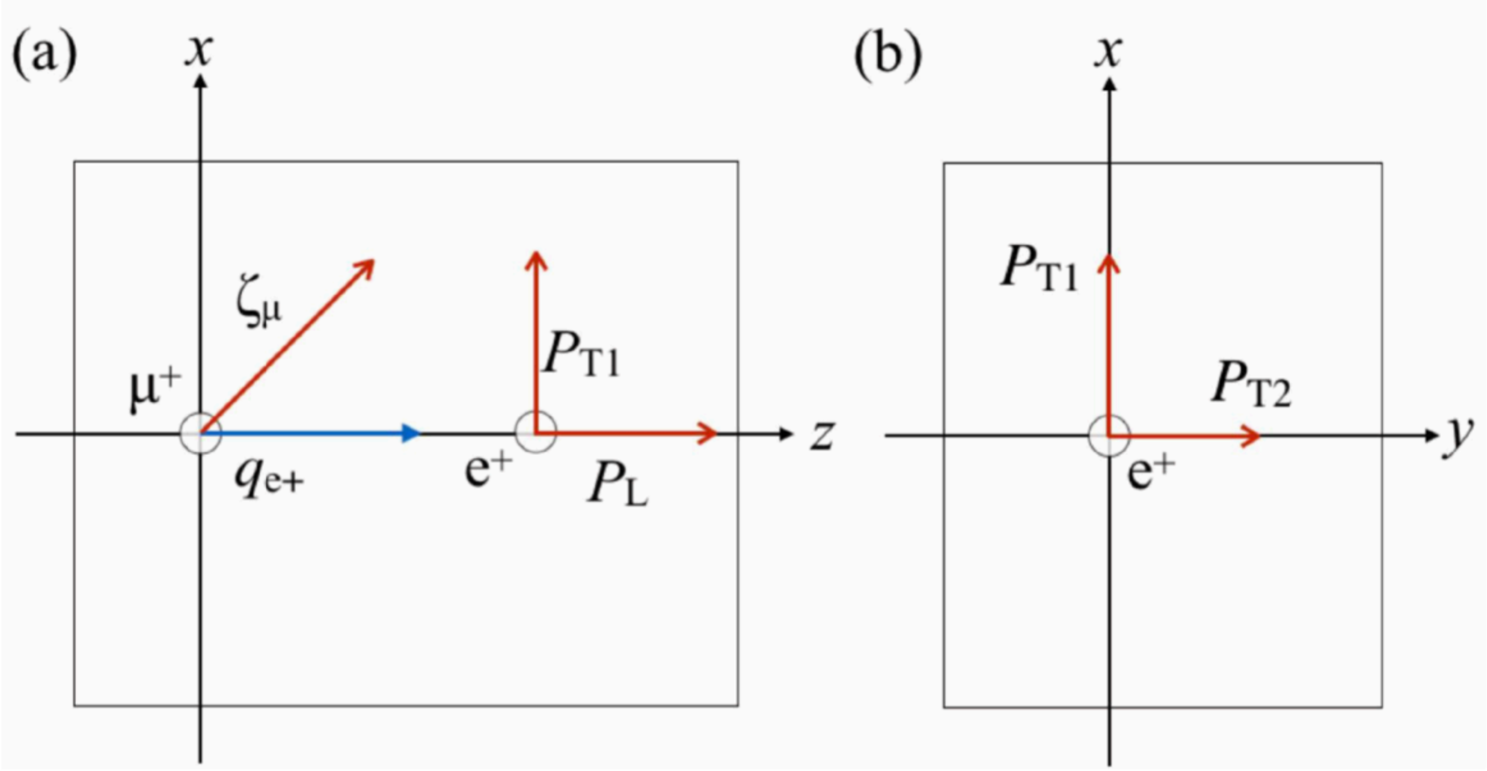
$$\frac{d\Gamma}{d\mathbf{q}_e} = \frac{m_\mu G_F^2}{3(2\pi)^4}\left\{ N(e) \pm \frac{(\,\mathbf{q}_e \cdot \boldsymbol{\zeta}_\mu\,)}{E} P(e) \mp \frac{(\,\mathbf{q}_e \cdot \boldsymbol{\zeta}_e\,)}{E} Q(e) - \frac{(\mathbf{q}_e \times \boldsymbol{\zeta}_\mu) \cdot (\,\mathbf{q}_e \times \boldsymbol{\zeta}_e\,)}{|\mathbf{q}_e|^2} R(e) - \frac{(\,\mathbf{q}_e \cdot \boldsymbol{\zeta}_\mu\,)(\,\mathbf{q}_e \cdot \boldsymbol{\zeta}_e\,)}{|\mathbf{q}_e|^2} S(e) + \frac{\boldsymbol{\zeta}_\mu \cdot (\,\mathbf{q}_e \times \boldsymbol{\zeta}_e\,)}{E} T(e) \right\}.$$

(E: energy, q: momentum, ζ: spin)

- N, S, R are P-even terms. P and Q are P-odd terms.
- T is P-odd and T-odd term. It comes from the neutrino interference in the previous page.
- The T-term indicates time-reversal symmetry breaking and Majoranality of neutrinos.

Measurement Principle

- The T-term $\zeta_\mu \cdot (q_e \times \zeta_e)\ T(e)/E$ can be observed only if the transverse polarization of muon decay positron is non-zero.



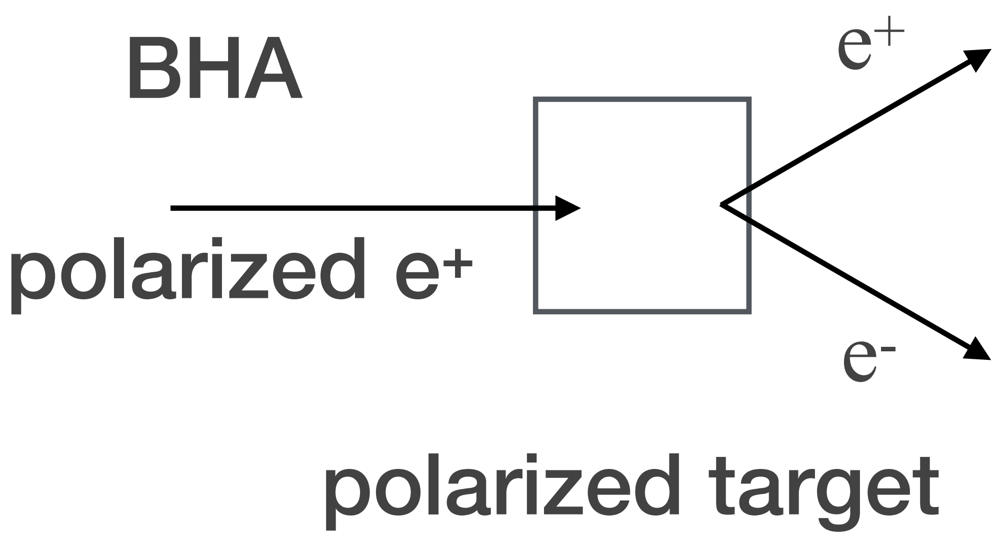
q: momentum
ζ: spin vector
P: polarization

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

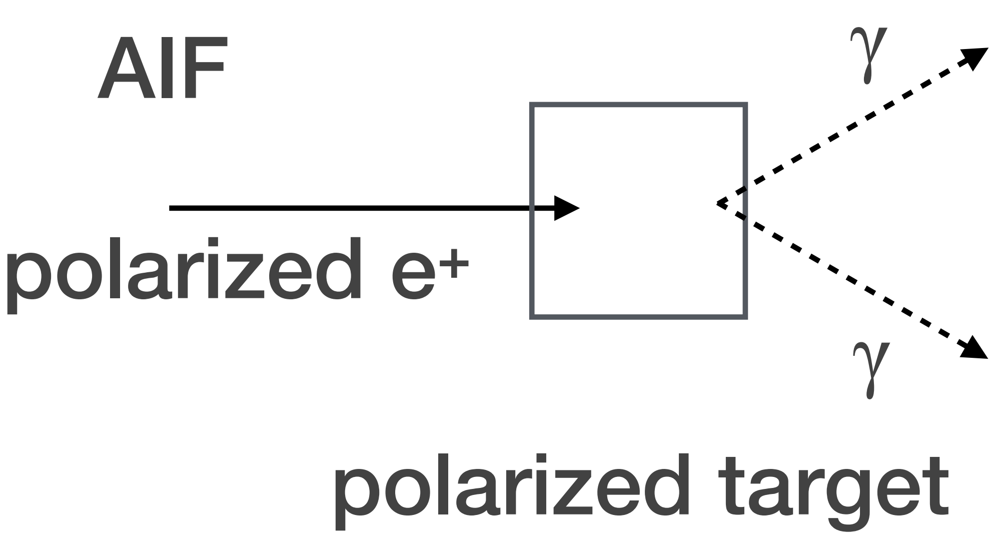
- A non-zero P_{T2} indicates the CP violation.
- Positron polarimetry opens a portal to search.

Muon Decay Positron Polarimetry

- We need a positron polarimeter which utilizes the spin dependent cross section of a particular electromagnetic process.
- In the energy range of interest (E~50 MeV), Bhabha scattering (BHA) and positron annihilation-in-flight (AIF) are feasible.



$P_{e^+} || P_{tgt} \rightarrow$ less events



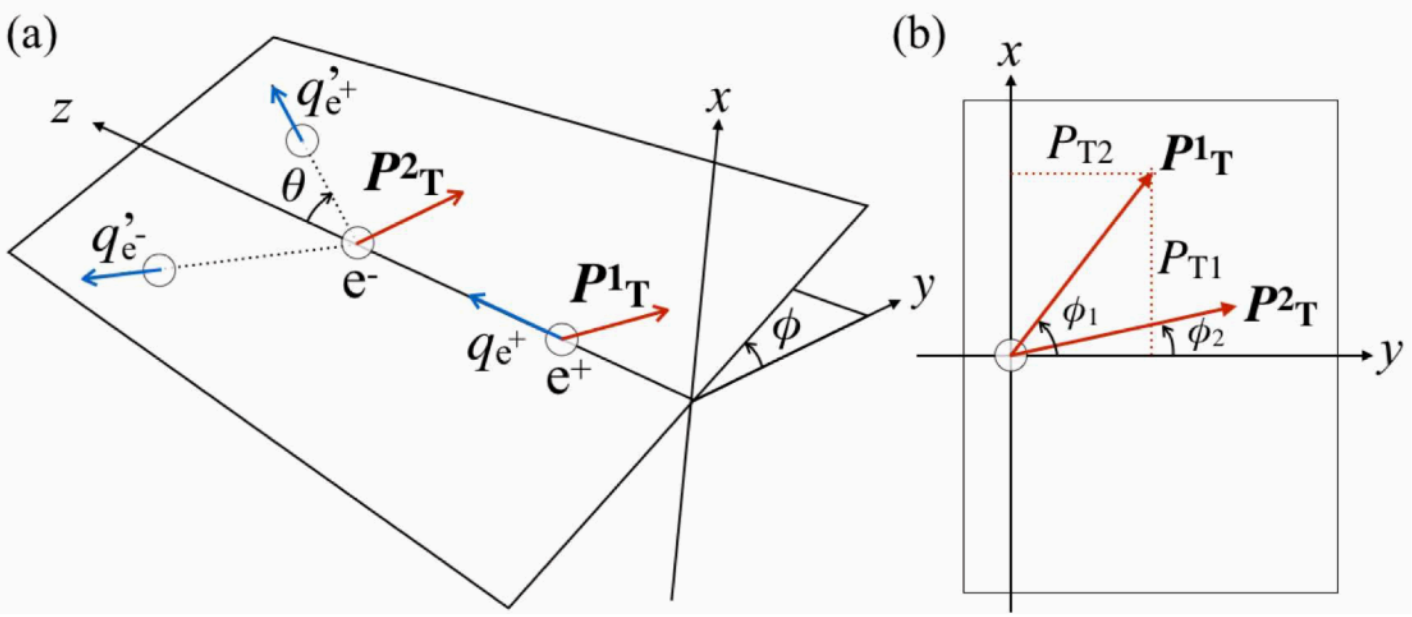
$P_{e^+} || P_{tgt} \rightarrow$ more events

Cross-section and Asymmetry

- **The differential cross sections of the processes**

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

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



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

- **The longitudinal and transverse asymmetries**

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

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

Muon Decay Experiment at PSI

- **Annihilation-in-flight measurement**

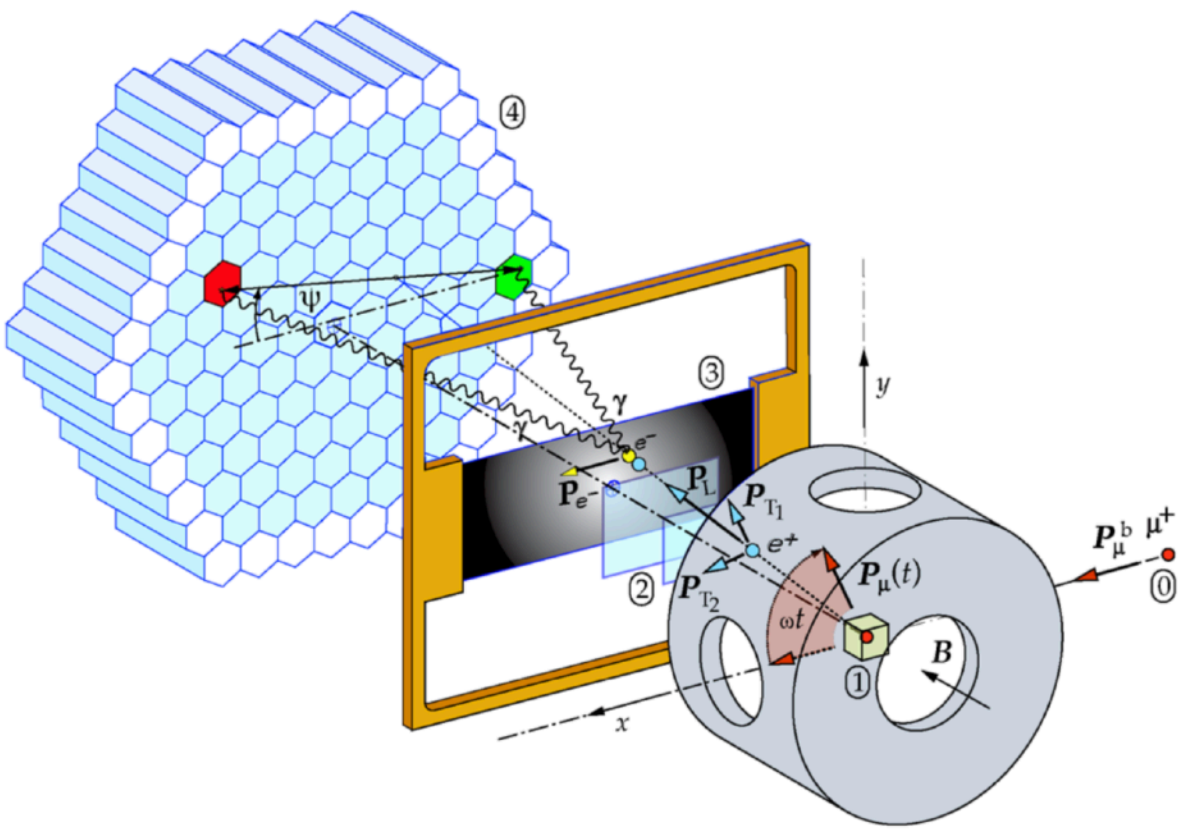
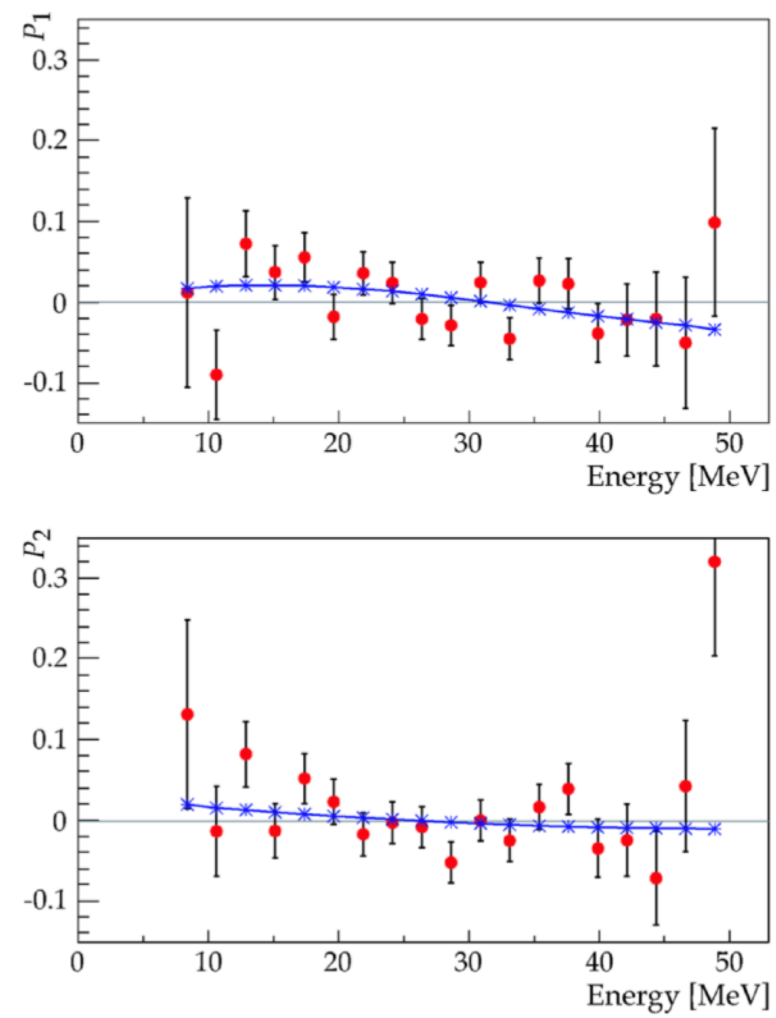


FIG. 1 (color online). Schematic view of the experimental setup. 0: Burst of polarized muons (angular frequency ω, polarization P_μ^b). 1: Be stop target and precession field $\boldsymbol{B}$. 2: Two plastic scintillation counters selecting decay positrons. 3: Magnetized Vacoflux 50^{TM} foil serving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

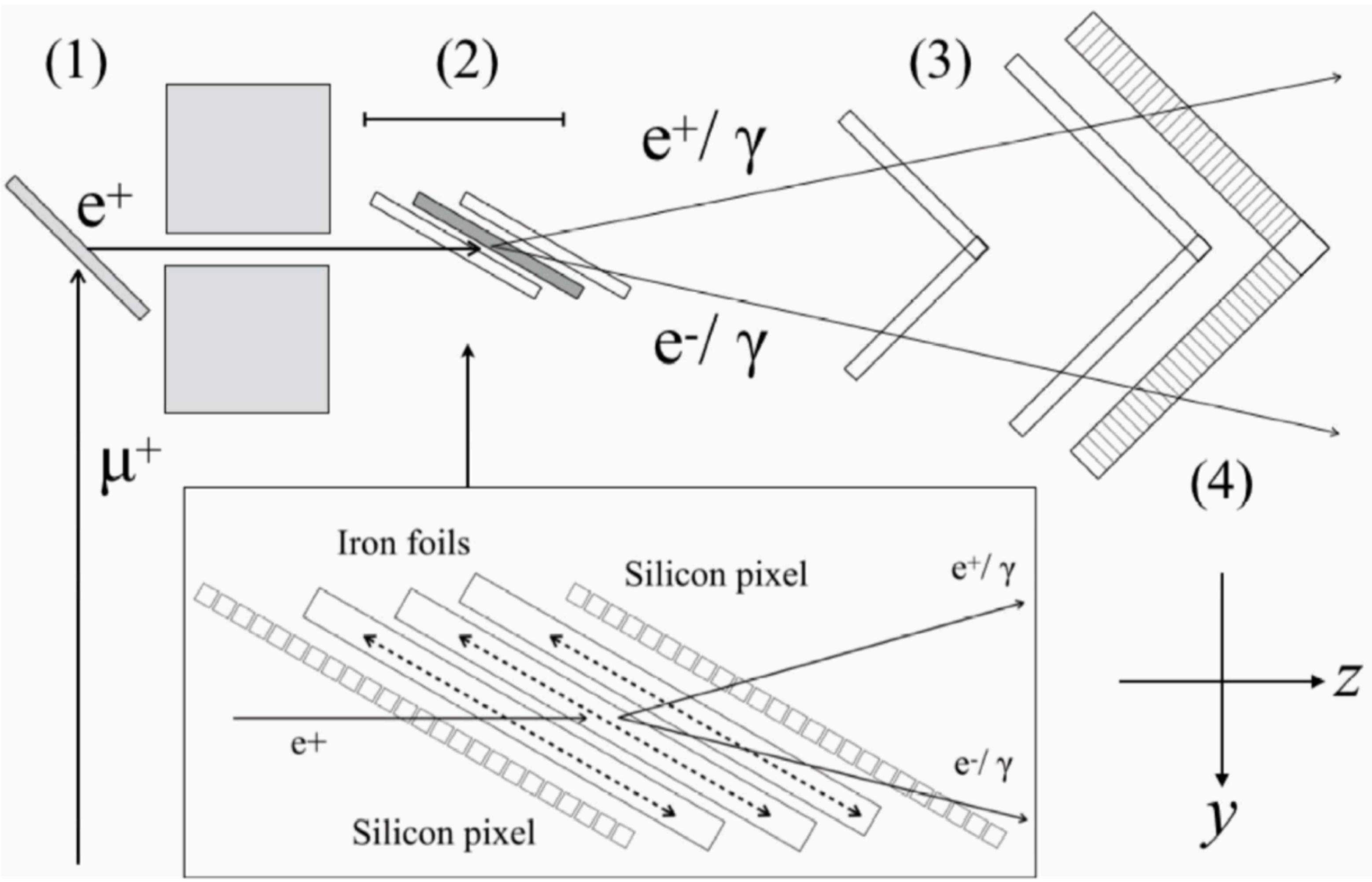


$$P_{T1} = (6.3 \pm 7.7 \pm 3.4) \times 10^{-3},$$
$$P_{T2} = (-3.7 \pm 7.7 \pm 3.4) \times 10^{-3}.$$

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

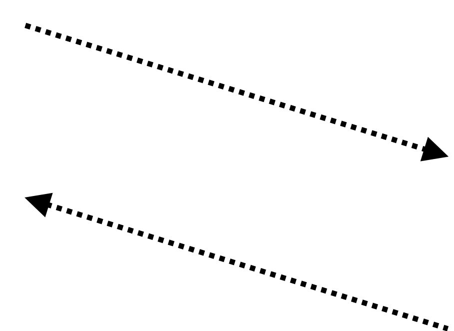
New Experiment at J-PARC

- **Simultaneous measurements of AIF and BHA**



(1) muon-stopping target
(2) spin-analyzing target
(3) tracking detector
(4) segmented calorimeter

Two polarization configurations



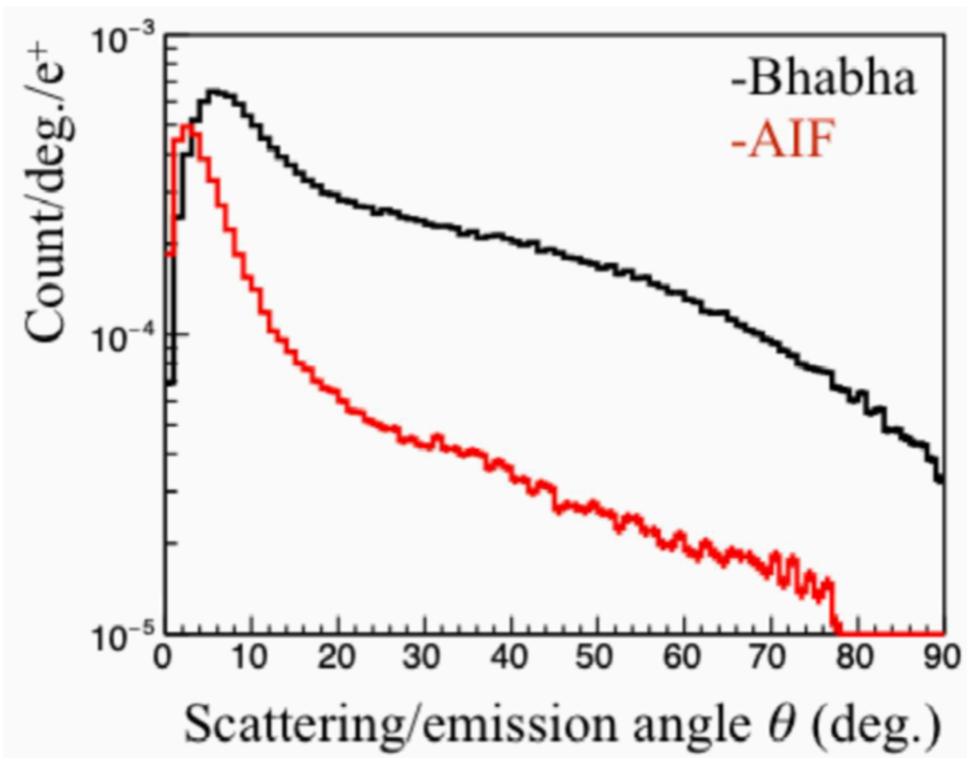
"positive"

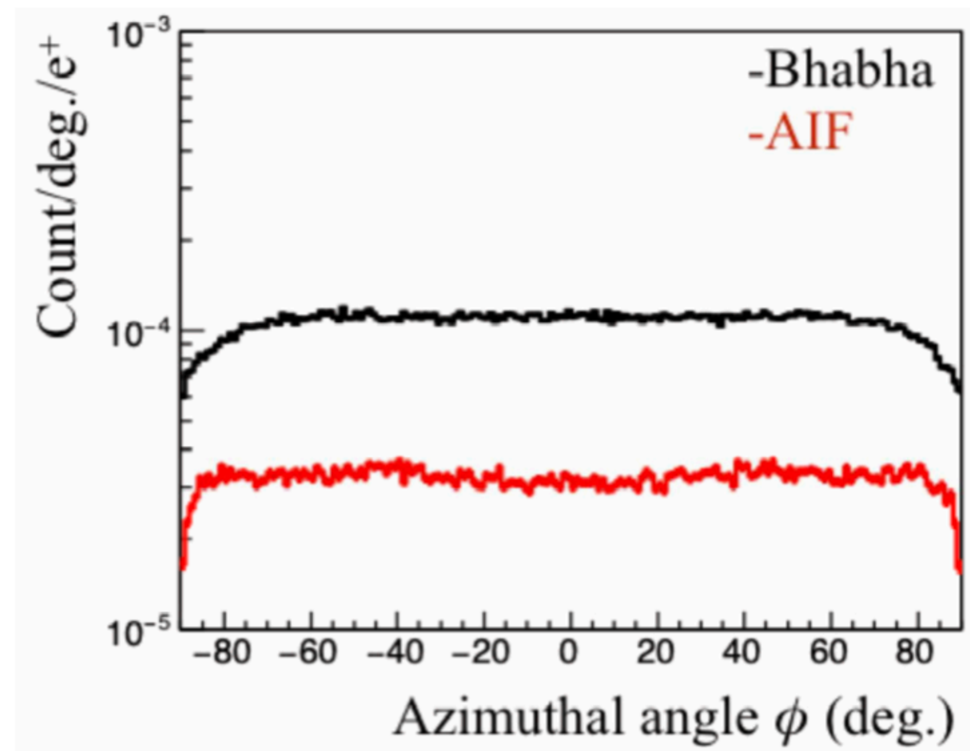
"negative"

- Plurality of polarimeters can be placed to multiply statistics.
- BHA signature: two charged particle tracks.
- AIF signature: two calorimeter hits w/o tracker hits.

Angular Distribution

- Bhabha scattering and annihilation-in-flight are simulated using GEANT4.



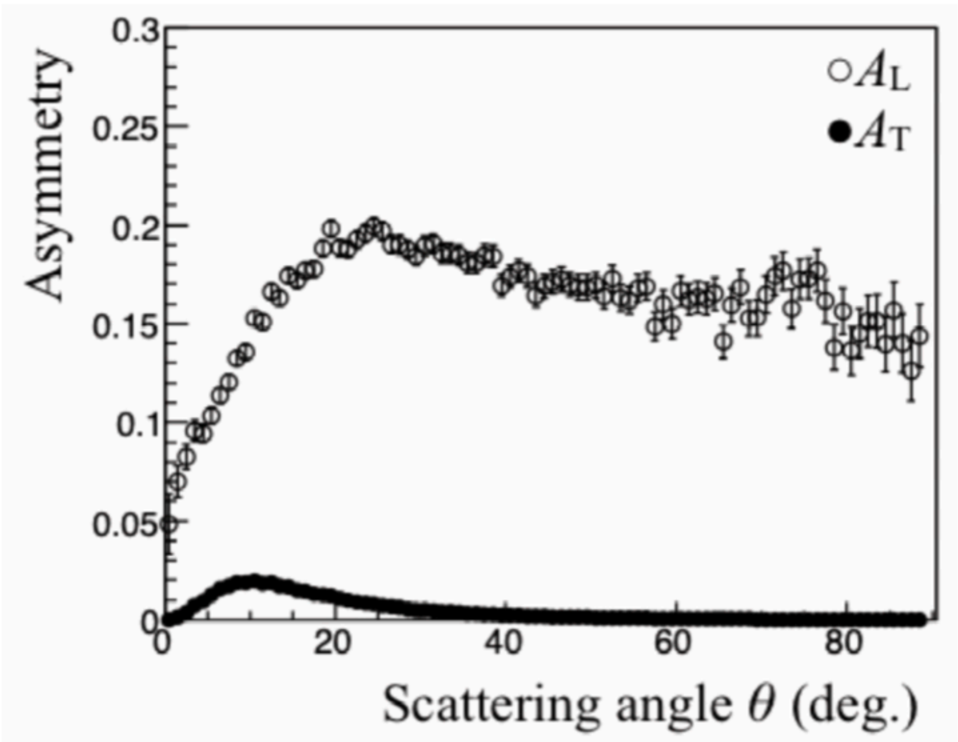


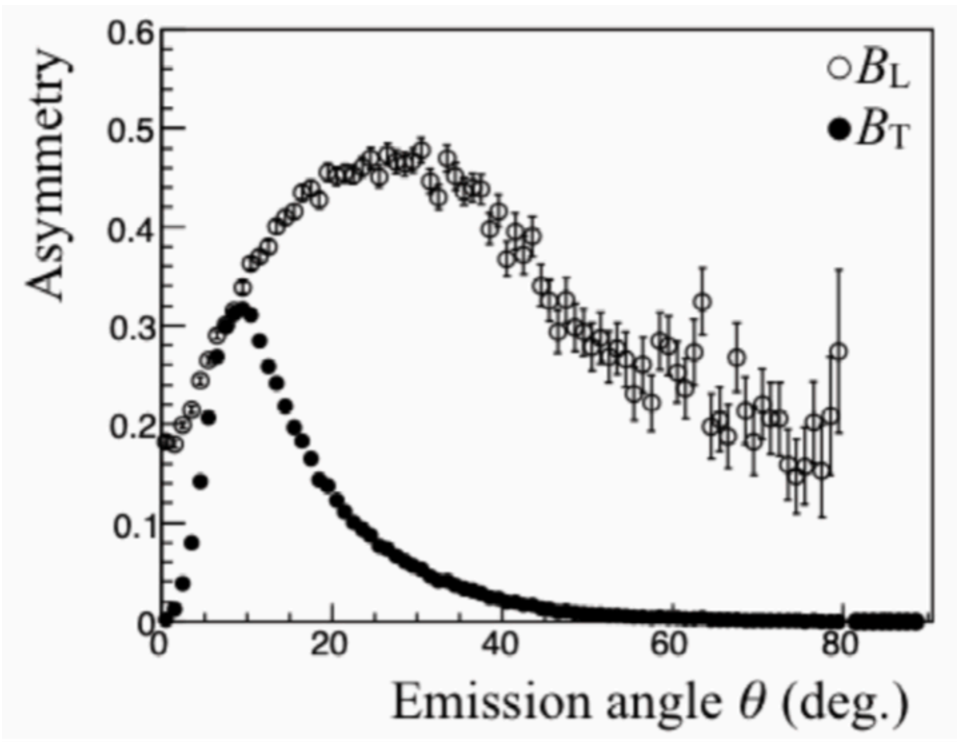
- Positive muons having the kinetic energy of 4 MeV irradiate the muon stopping target.
- Between the muon stopping target and spin analyzing target, a lead collimator with 2 mm aperture is placed.

Angular Asymmetry

- **The analyzing power $A = (N_+ - N_-)/(N_+ + N_-)$ is calculated for each process.**

N_+: events with "positive" target configuration, N_-: events with "negative" target configuration.





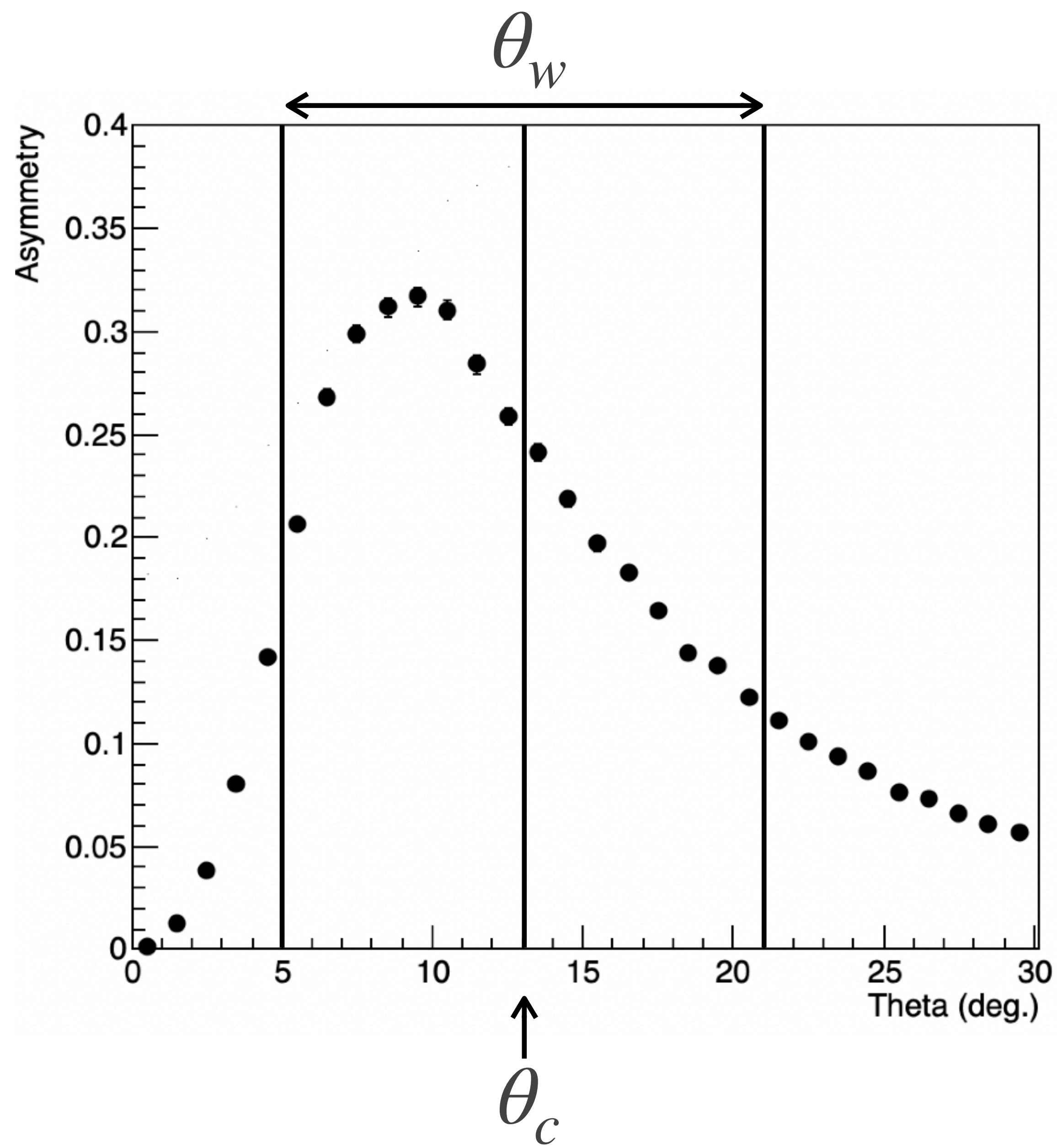
$$\frac{A_T(\theta^*)\cos(2\phi-\phi_1-\phi_2)}{A_L(\theta^*)} = \frac{\sin^2\theta^*}{7+\cos^2\theta^*}\cos(2\phi-\phi_1-\phi_2)$$

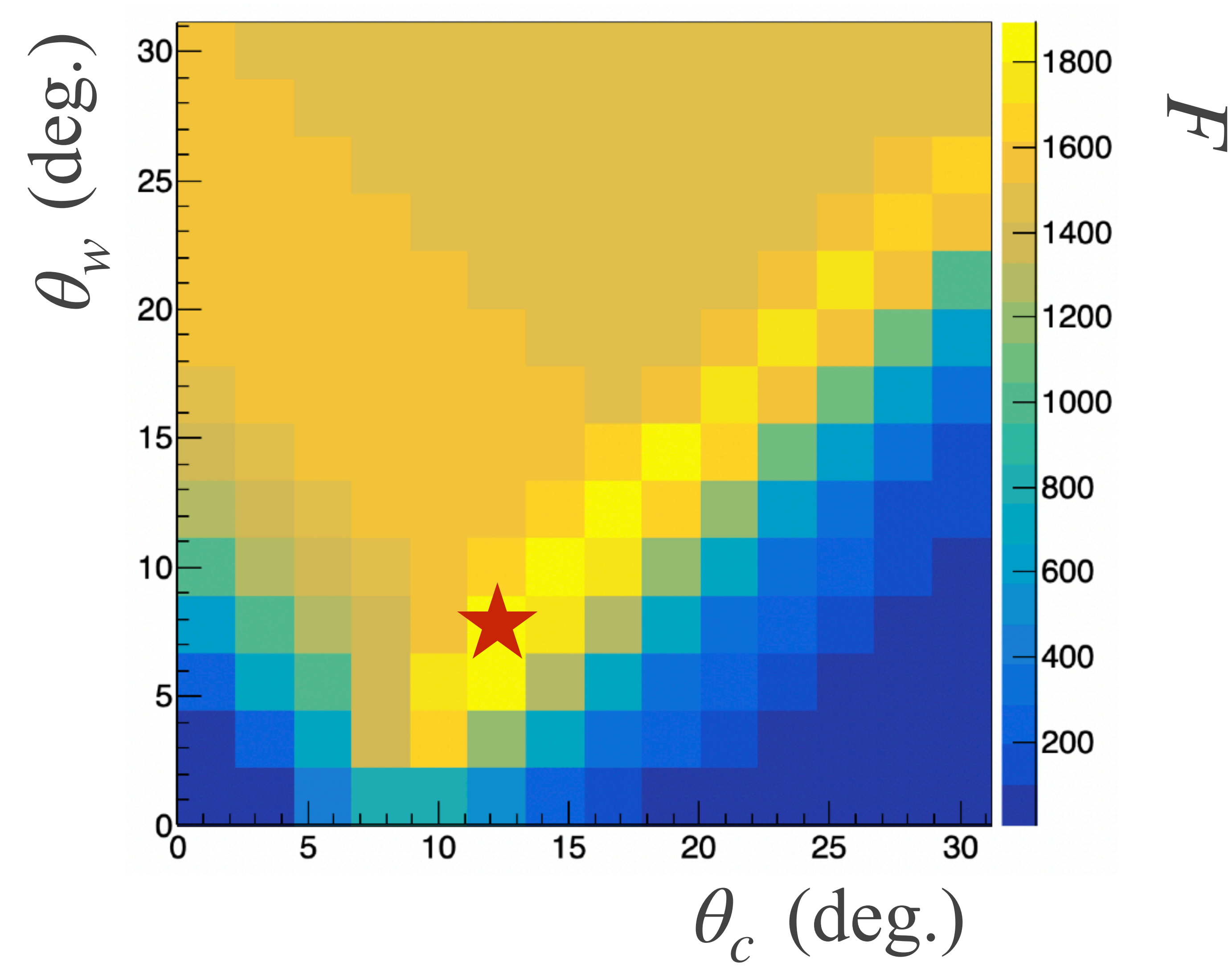
$$\frac{B_T(\theta^*)\cos(2\phi-\phi_1-\phi_2)}{B_L(\theta^*)} = \frac{\sin^2\theta^*}{1+\cos^2\theta^*}\cos(2\phi-\phi_1-\phi_2)$$

- **AIF is good for a transverse asymmetry measurement.**
- **BHA serves for beam polarization monitoring.**

Angular Acceptance Optimization

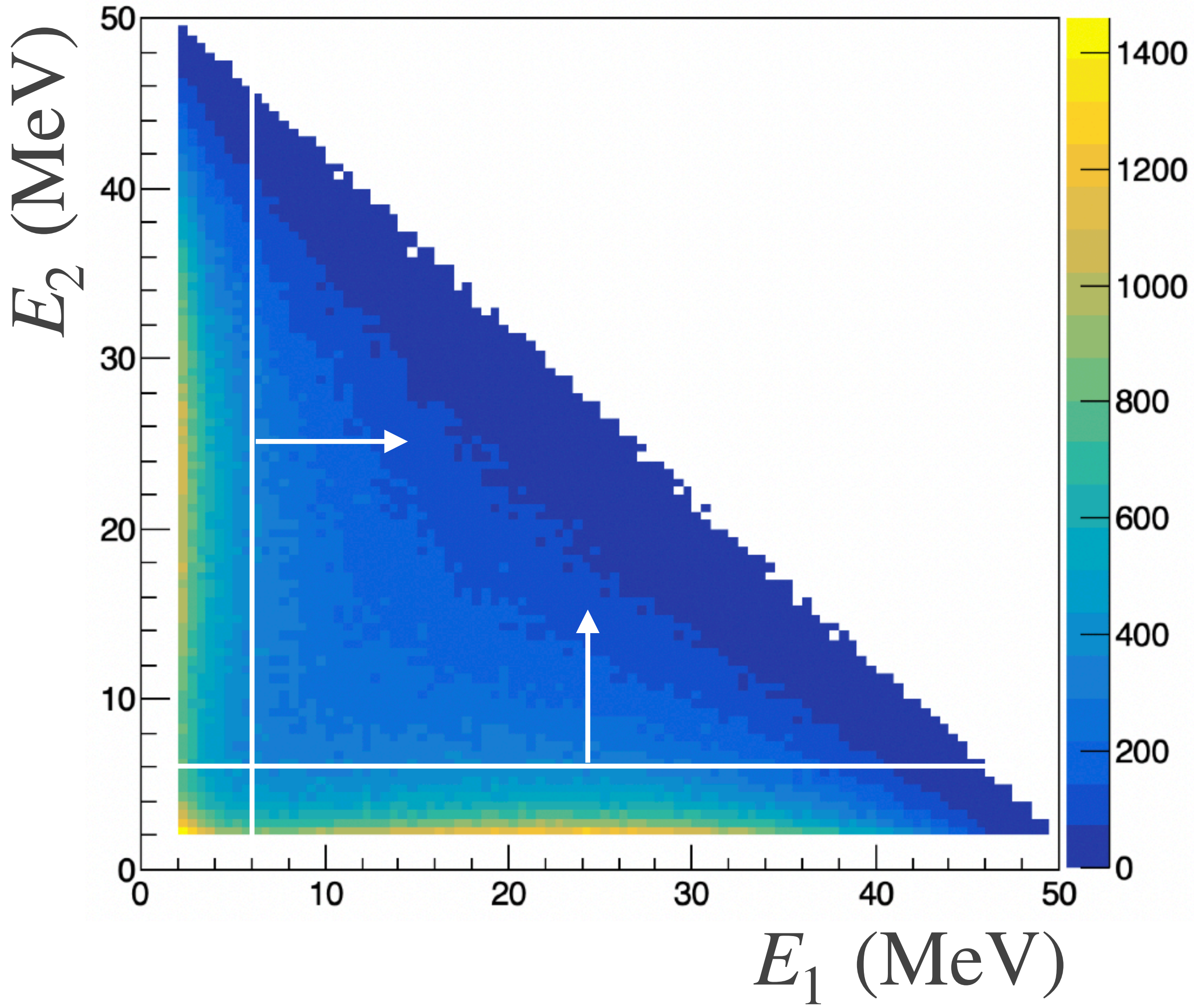
- The figure of merit $F = NA^2$ is calculated to optimize an analysis window for θ.

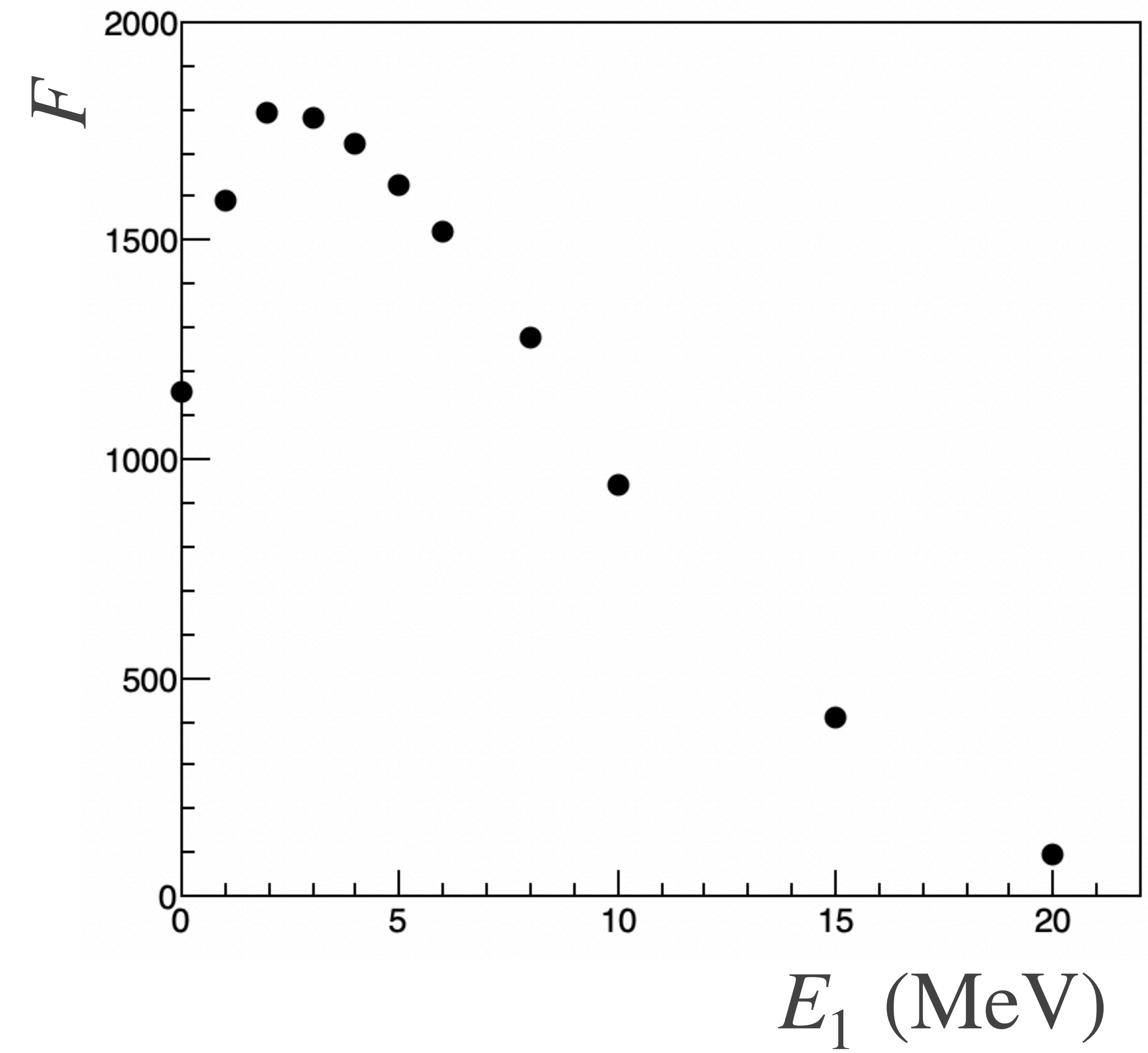




Energy Threshold Optimization

- The figure of merit $F = NA^2$ is calculated to optimize energy thresholds.





Energy Threshold Optimization

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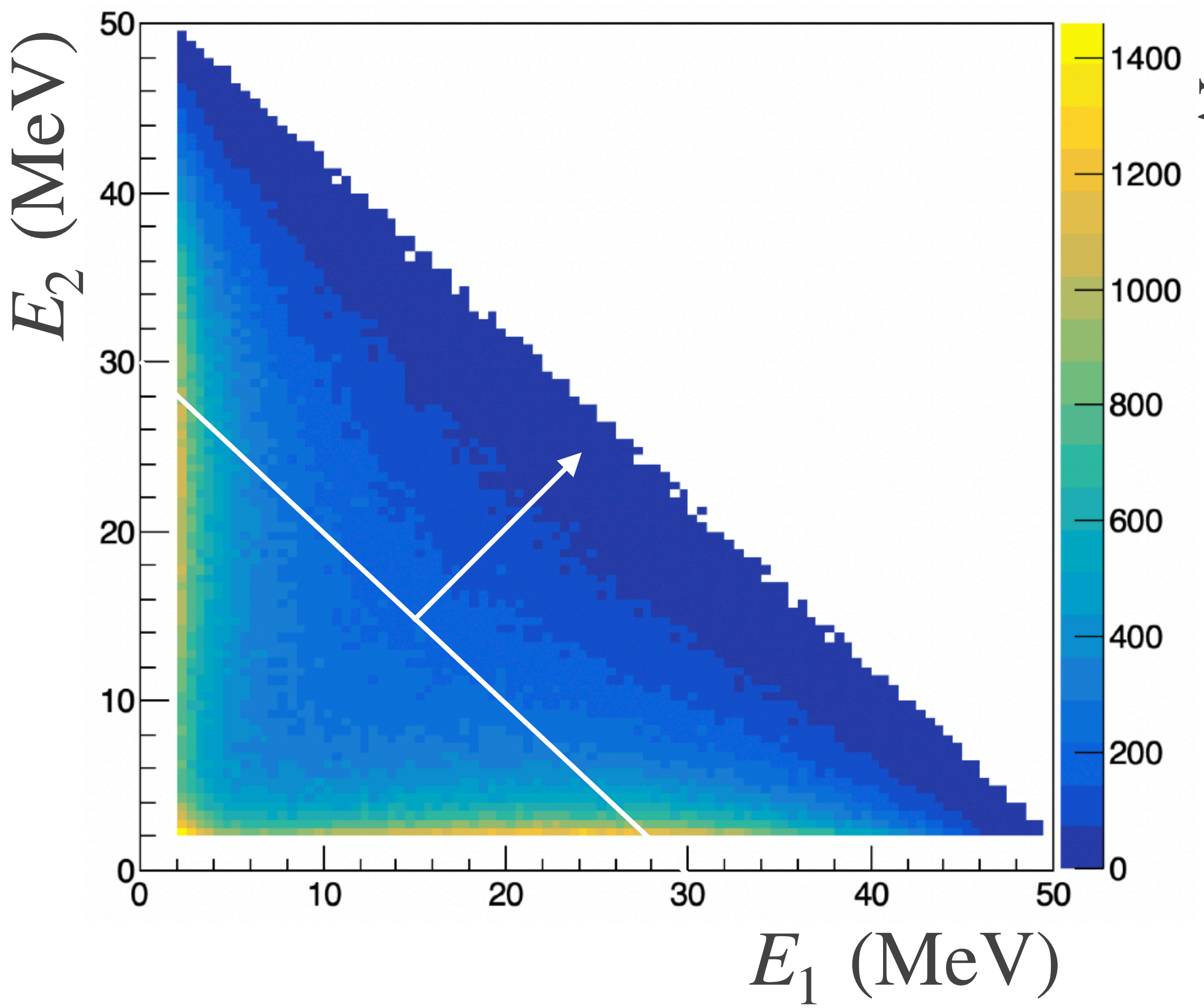
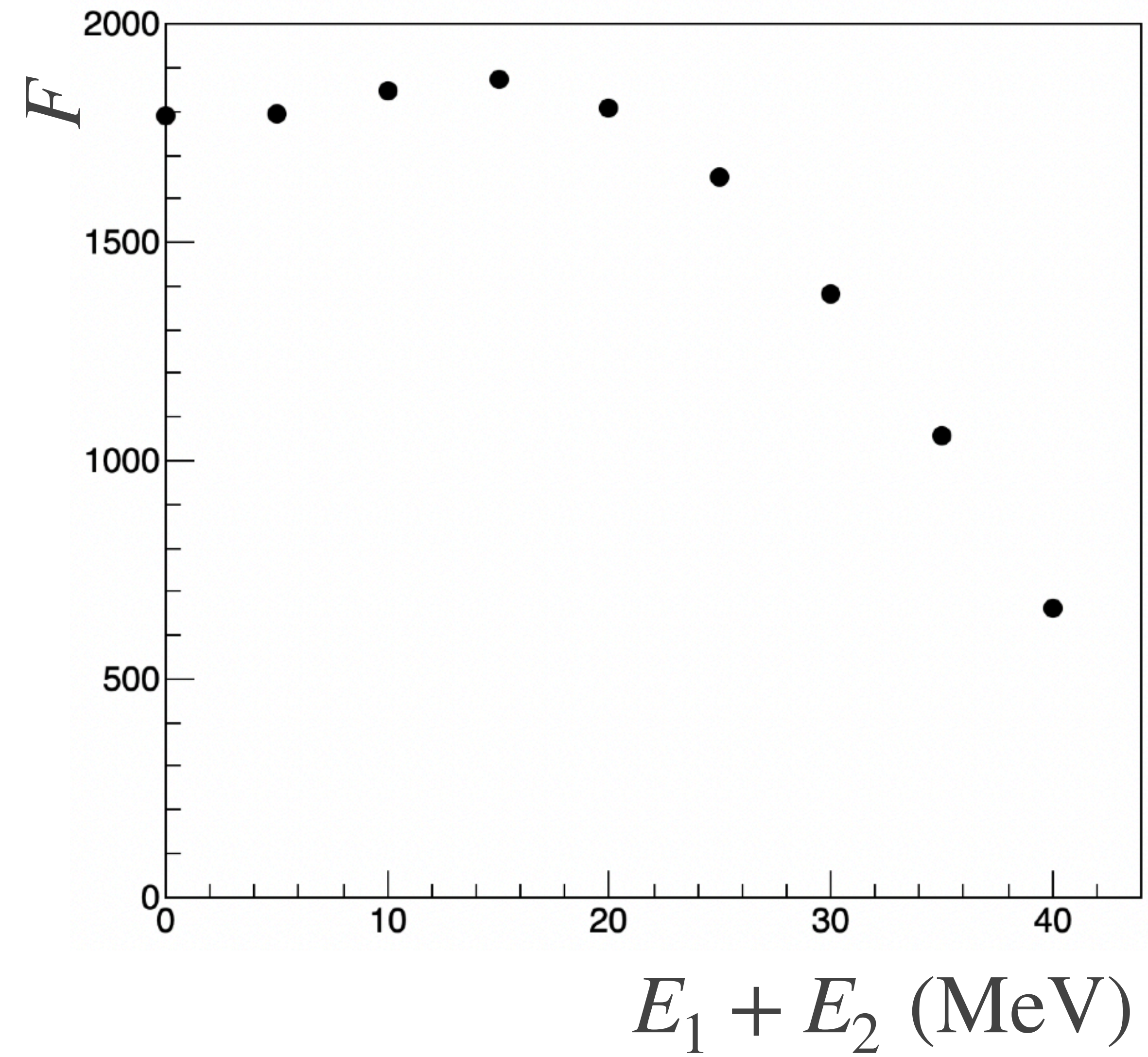
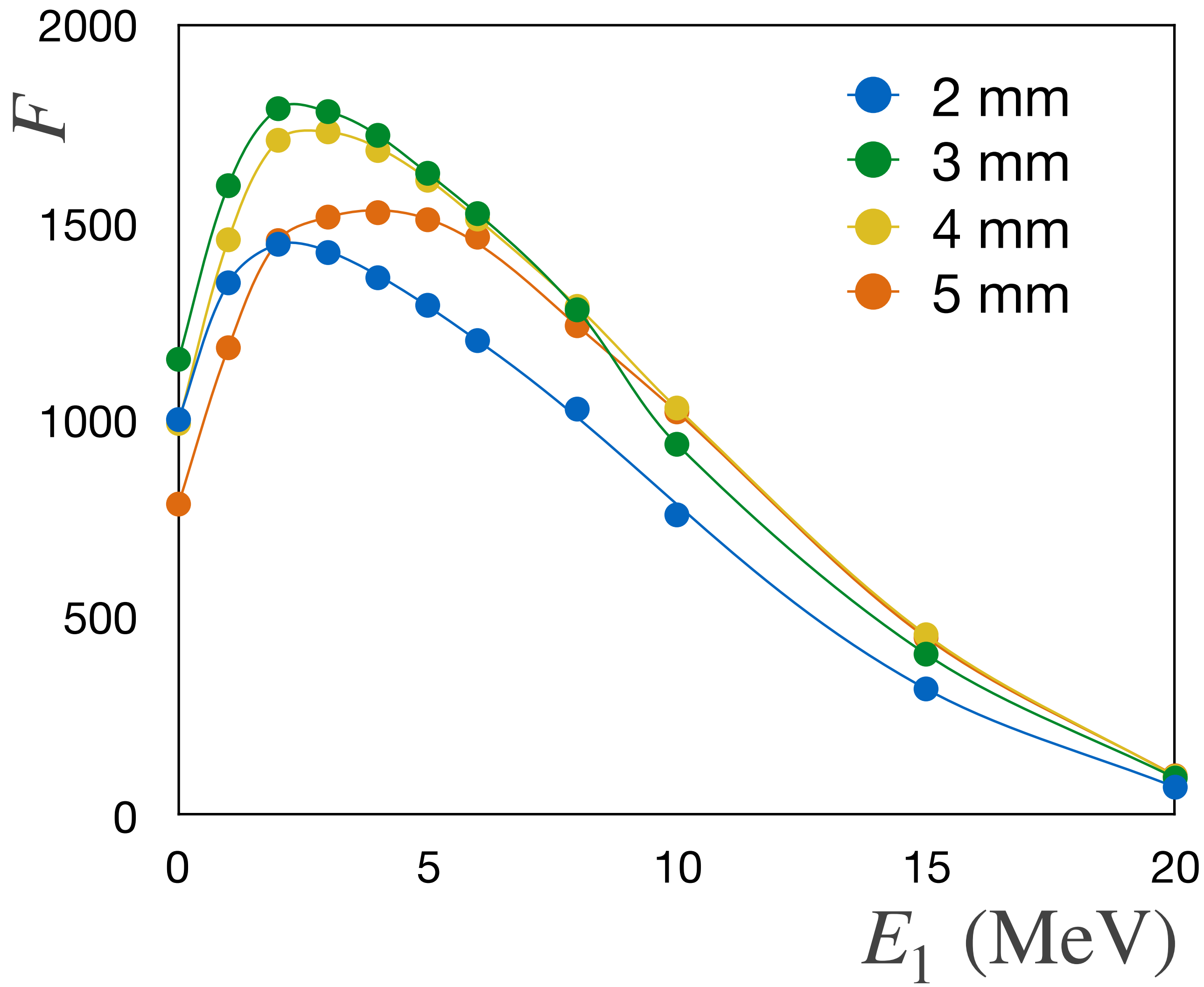
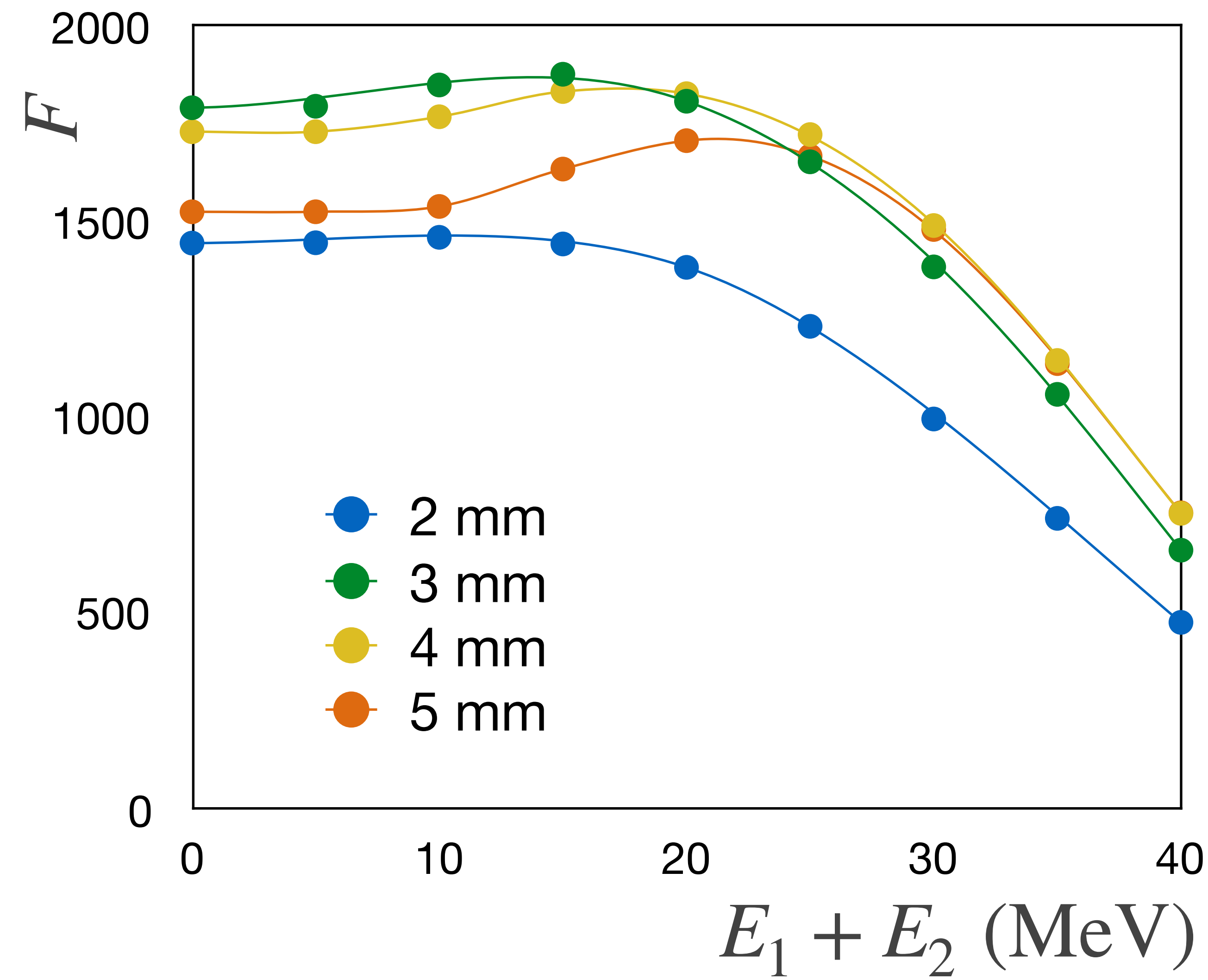




Target Thickness Optimization

- The figure of merit $F = NA^2$ is calculated to optimize the thickness of the spin analyzing target.





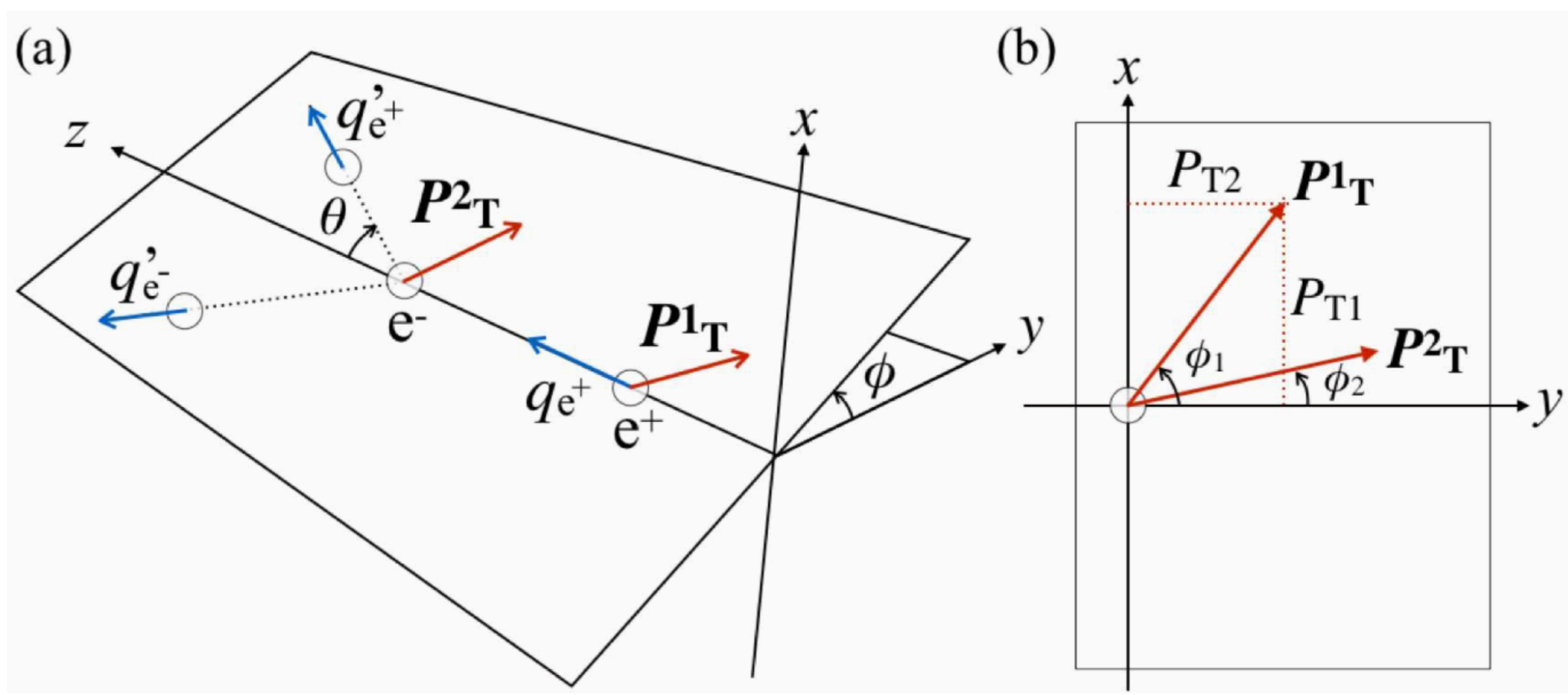
- The thickness of 3 mm is optimum with

$$E_1 > 2\ \mathrm{MeV},\ \mathrm{E}_2 > 2\ \mathrm{MeV}, \mathrm{E}_1 + \mathrm{E}_2 > 15\mathrm{MeV}.$$

Azimuth Dependence

- **The transverse asymmetry depends on the scattering azimuth ϕ, the positron polarization azimuth ϕ_1, and the target polarization azimuth ϕ_2.**
- **The asymmetry is proportional to $\cos(2\phi - \phi_1 - \phi_2)$.**

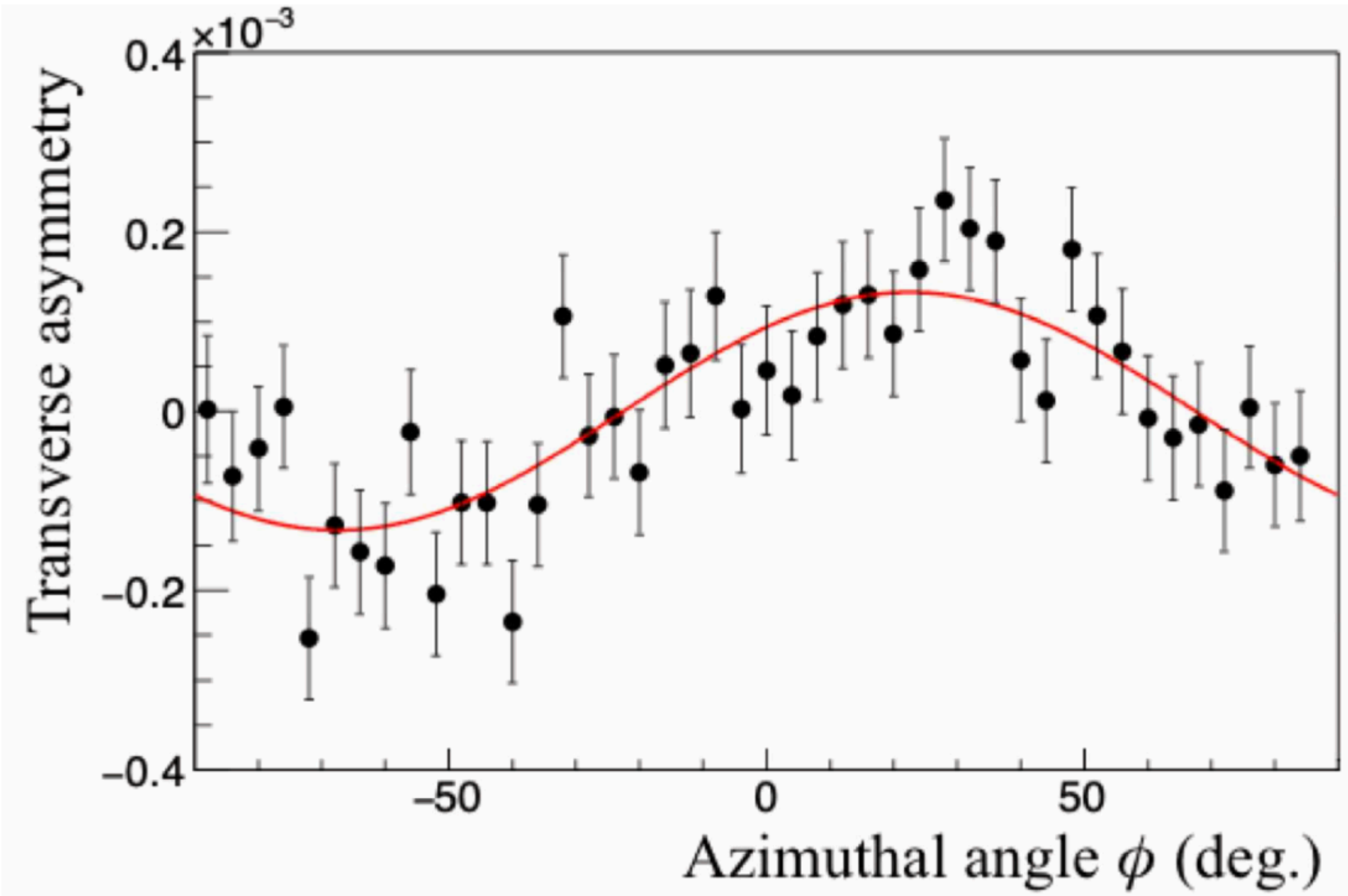
- **ϕ can be obtained by detector hits.**
- **ϕ_1 is unknown parameter which we want to know.**
- **ϕ_2 is controllable (fixed at zero).**



$$\zeta_{e^+} = (P_{T1}, P_{T2}, P_L) \equiv (P^1{}_T, P_L)$$

Azimuth Dependence Analysis

- **The transverse asymmetry is analyzed by fitting with a cosine function to extract ϕ_1.**



Amplitude

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

Phase

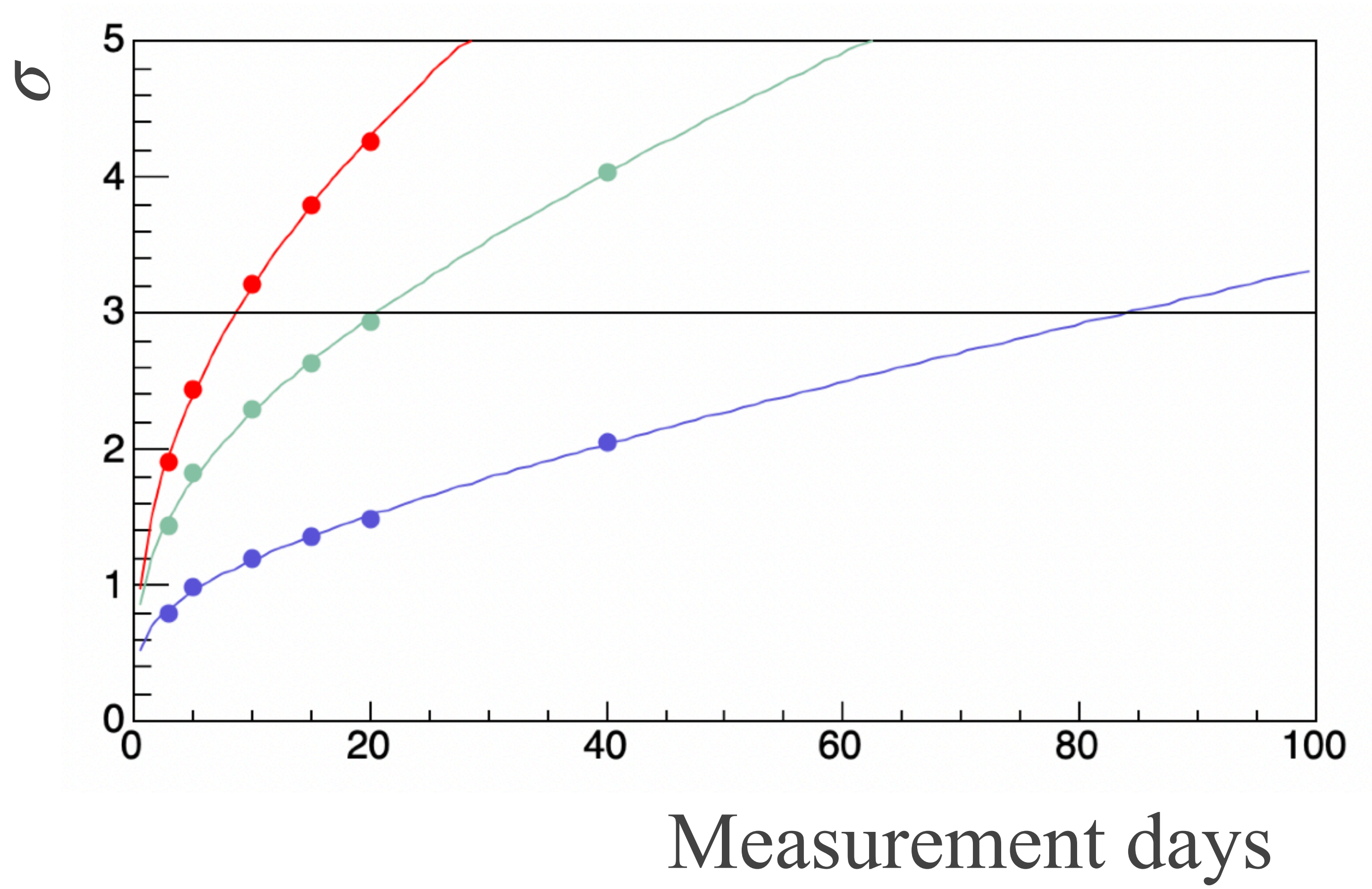
$$\phi_1 = (45.5 \pm 10.7)\ \mathrm{deg}\,.$$

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

Statistical Significance

- **The statistical significance of the transverse polarization is**

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



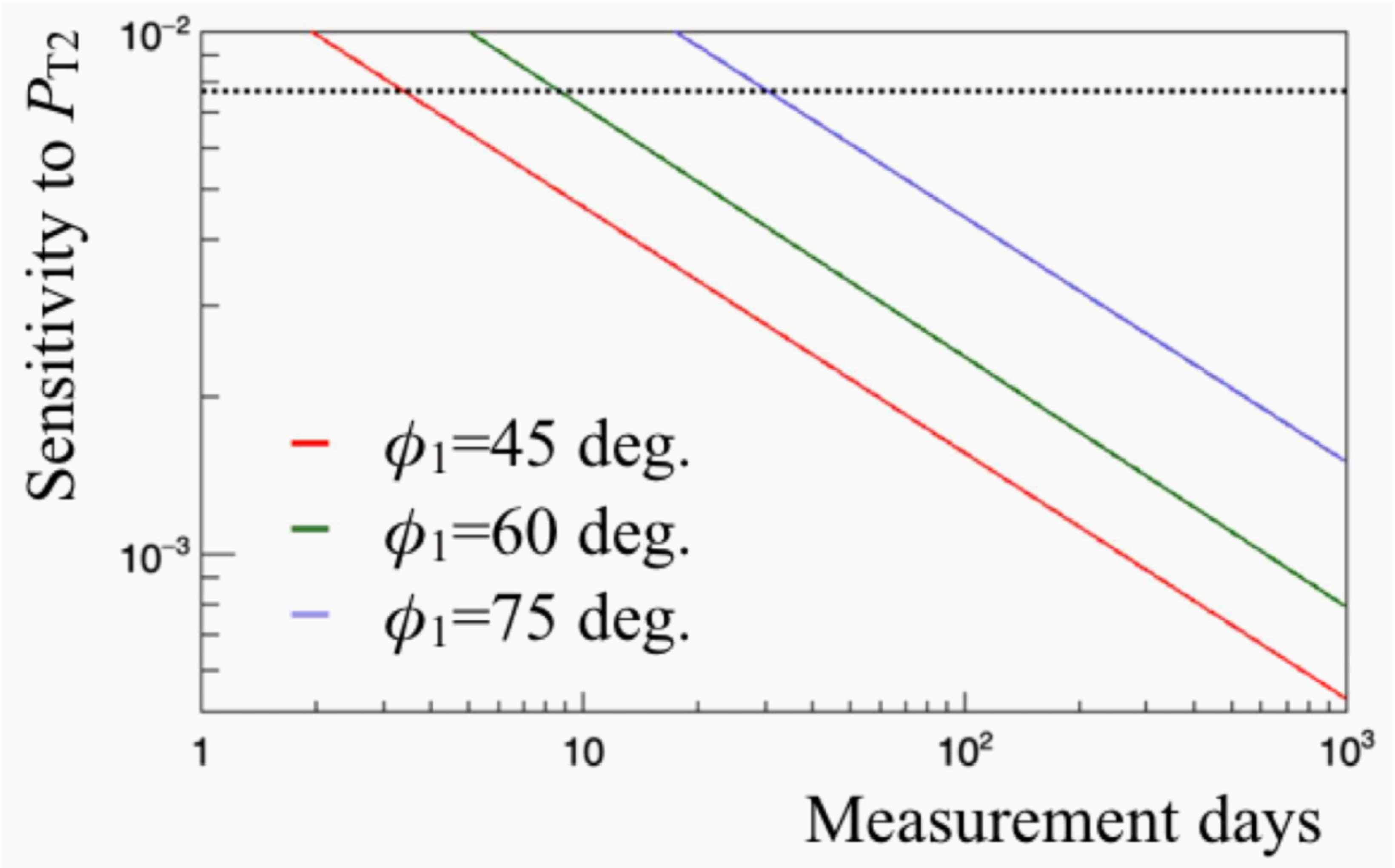
- $\phi_1 = 45$ deg.
- $\phi_1 = 60$ deg.
- $\phi_1 = 75$ deg.

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

$1.0 \times 10^8 \mu^+/\mathrm{s}$

Sensitivity

- **Sensitivity to the transverse polarization**



- **It is feasible to achieve a comparable statistical precision relative to that of the precursor experiment within four days.**

Summary

- T-violation in muon decay indicates the Majoranality 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 new experiment will employ the segmented annihilation-in-flight polarimeter with high-rate capability.
- The sensitivity and feasibility of the polarimeter have been studied.