Muon decay:

Measurement of the

transverse e^+ polarization

and its implications on

- **G_F (Fermi coupling constant)**
- **TRI (time reversal invariance)**

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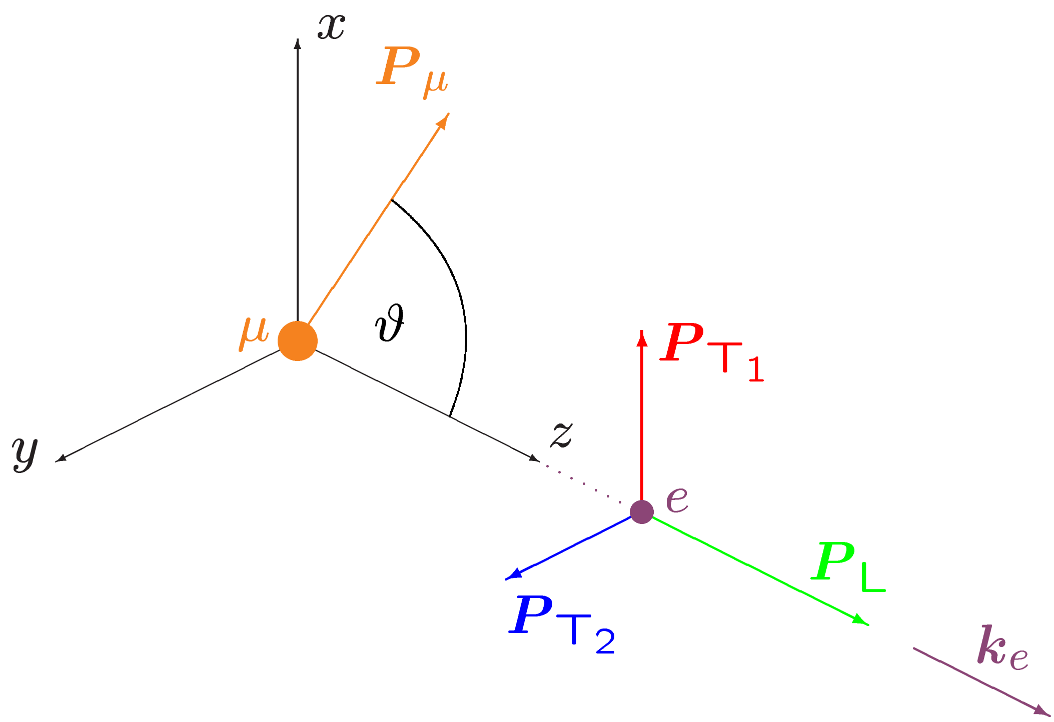
2. Observables



$$P_{\mathsf{T}_1} = f_1(E, \vartheta, \eta, \eta'')$$

$$P_{\mathsf{T}_2} = f_2(E, \vartheta, \tfrac{\alpha}{A}, \tfrac{\beta}{A})$$

The standard model predicts:

$$\langle P_{\mathsf{T}_1} \rangle_E = -3 \times 10^{-3}$$

$$P_{\mathsf{T}_2} \equiv 0$$

A nonzero P_{T_2} would signal violation of time reversal invariance. This is the only purely leptonic reaction for which TRI has been tested up to now.

3. Matrix Element

$$\mathcal{M} = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \varepsilon,\mu=R,L}} g^{\gamma}_{\varepsilon\mu} \langle \overline{e}_{\varepsilon} | \Gamma^{\gamma} | (\nu_e)_n \rangle \langle \overline{\nu}_m | \Gamma_{\gamma} | (\mu)_{\mu} \rangle$$

The index γ labels the type of interaction:

Γ^S	$=$	4-scalar
Γ^V	$=$	4-vector
Γ^T	$=$	4-tensor

The indices ε, μ indicate the chiralities of the spinors of the observed (charged) leptons. The chiralities n, m of the neutrinos are uniquely determined for given γ, ε and μ.
The transverse polarization component P_{T_1} yields the low energy parameter η *without* the suppression factor m_e/m_μ of η in the energy spectrum of the decay positron. These interference terms allow for sizeable effects.

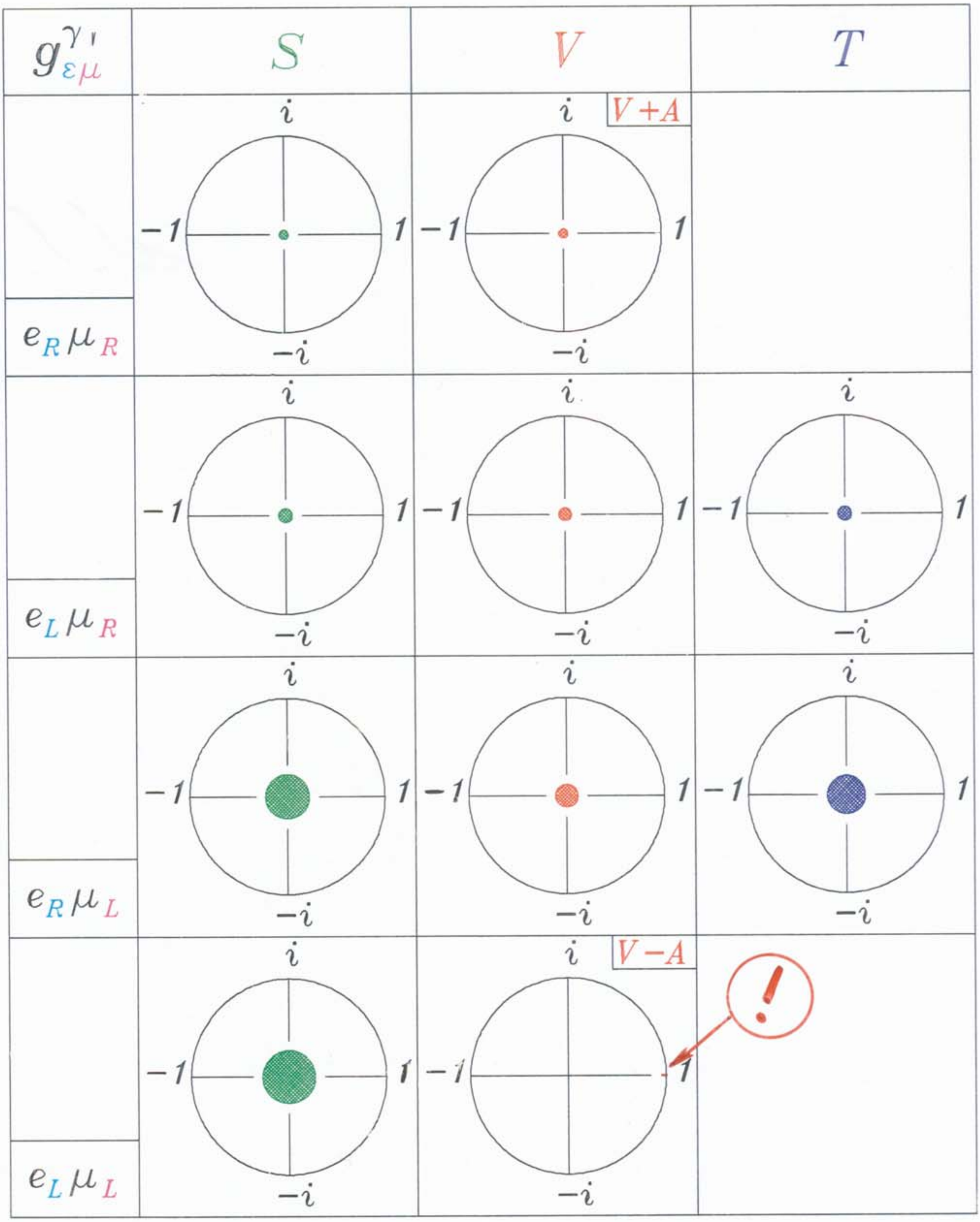
$$\eta = \frac{1}{2} Re \{ g^V_{LL} g^{S*}_{RR} + g^V_{RR} g^{S*}_{LL} + g^V_{LR} (g^{S*}_{RL} + g^{T*}_{RL}) + g^V_{RL} (g^{S*}_{LR} + g^{T*}_{LR}) \}$$

In the standard model

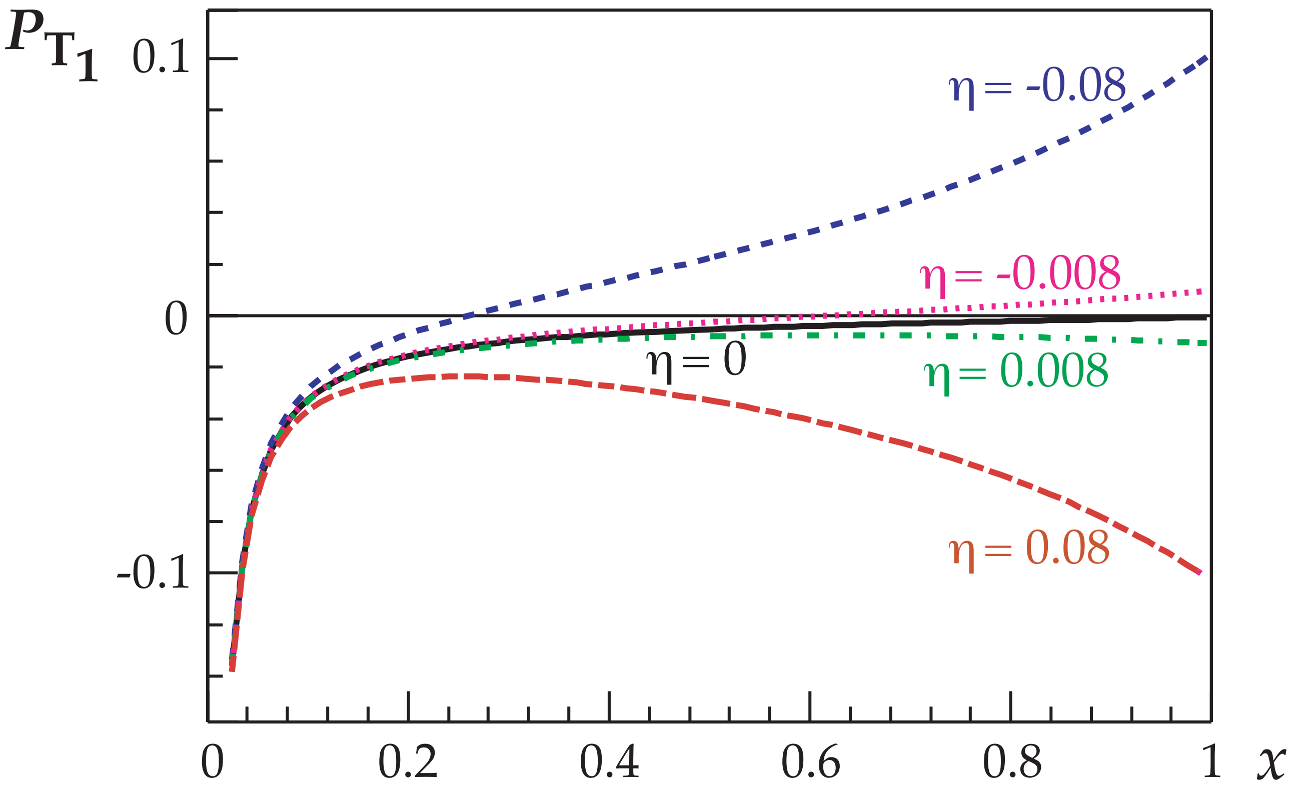
$$g^V_{LL} = 1$$

$$g^{\gamma}_{\varepsilon\mu} = 0 \quad \text{(all other interactions)}$$

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$



Experimental limits for the normalized coupling constants $g^{\gamma'}_{\varepsilon\mu} = \frac{g^{\gamma}_{\varepsilon\mu}}{|g^{\gamma}_{\varepsilon\mu}|}$.



Assuming 1 additional interaction and knowing that

$$g^V_{LL} \approx 1,$$

one deduces:

$$P_{T_1}(E_e) \to \eta \approx \frac{1}{2} Re\{g^S_{RR}\}$$

$$P_{T_2}(E_e) \to \frac{\beta'}{A} \approx \frac{1}{4} Im\{g^S_{RR}\}$$

Main scientific interests:

P_{T_1}: Precise determination of Fermi coupling constant G_F

P_{T_2}: Test of time reversal invariance

4. Fermi coupling constant

Should be independent of masses and radiative corrections:

Universal coupling constant

$$G_F^2 = 192\pi^3 \cdot \frac{\hbar}{\tau_\mu} \cdot \frac{1}{m_\mu^5} \cdot \left\{1 + \frac{\alpha}{2\pi}\left(\pi^2 - \frac{25}{4}\right)\right\} \cdot \left\{1 - \frac{3}{5}\left(\frac{m_\mu}{m_W}\right)^2\right\} \cdot \left\{1 - 4\eta \cdot \frac{m_e}{m_\mu} - 4\lambda \cdot \frac{m_{\nu_\mu}}{m_\mu} + 8\left(\frac{m_e}{m_\mu}\right)^2 + 8\left(\frac{m_{\nu_\mu}}{m_\mu}\right)^2\right\}$$

New:

$$\lambda \approx \frac{1}{2} Re\left\{g_{LL}^V \cdot g_{LR}^{V*}\right\}$$

In left-right symmetric models with mixing angle ζ:

$$\lambda \approx \frac{1}{2}\zeta$$

Contribution from	$\frac{\Delta G_{\mathsf{F}}}{G_{\mathsf{F}}}$ [10^{-6}]	
	$\mu^+ \to \overline{\nu}_\mu e^+ \nu_e$	$\tau^+ \to \overline{\nu}_\tau \mu^+ \nu_\mu$
Δm_W	0.0	1
$\Delta m_{\mu,\tau}$	0.2	421
$\Delta \tau$	9.1	2 070
$\Delta(\lambda m_{\overline{\nu}})$	70.0	22 500
$\Delta \eta$	126.0	6 500
$\Delta \Gamma_{\tau \to \mu}$	-	100 000

5. Experimental setup

5.1 Highly polarized μ^+ beam at μE1 area of PSI: (91%)

5.2 Muon stop rate in Be target: $(20 - 80) \times 10^6$ s^{-1}

5.3 Precession in homogeneous $\boldsymbol{B}$ field; precession frequency = cyclotron frequency (50.8 MHz)

5.4 Burst width 3.9 ns (FWHM)

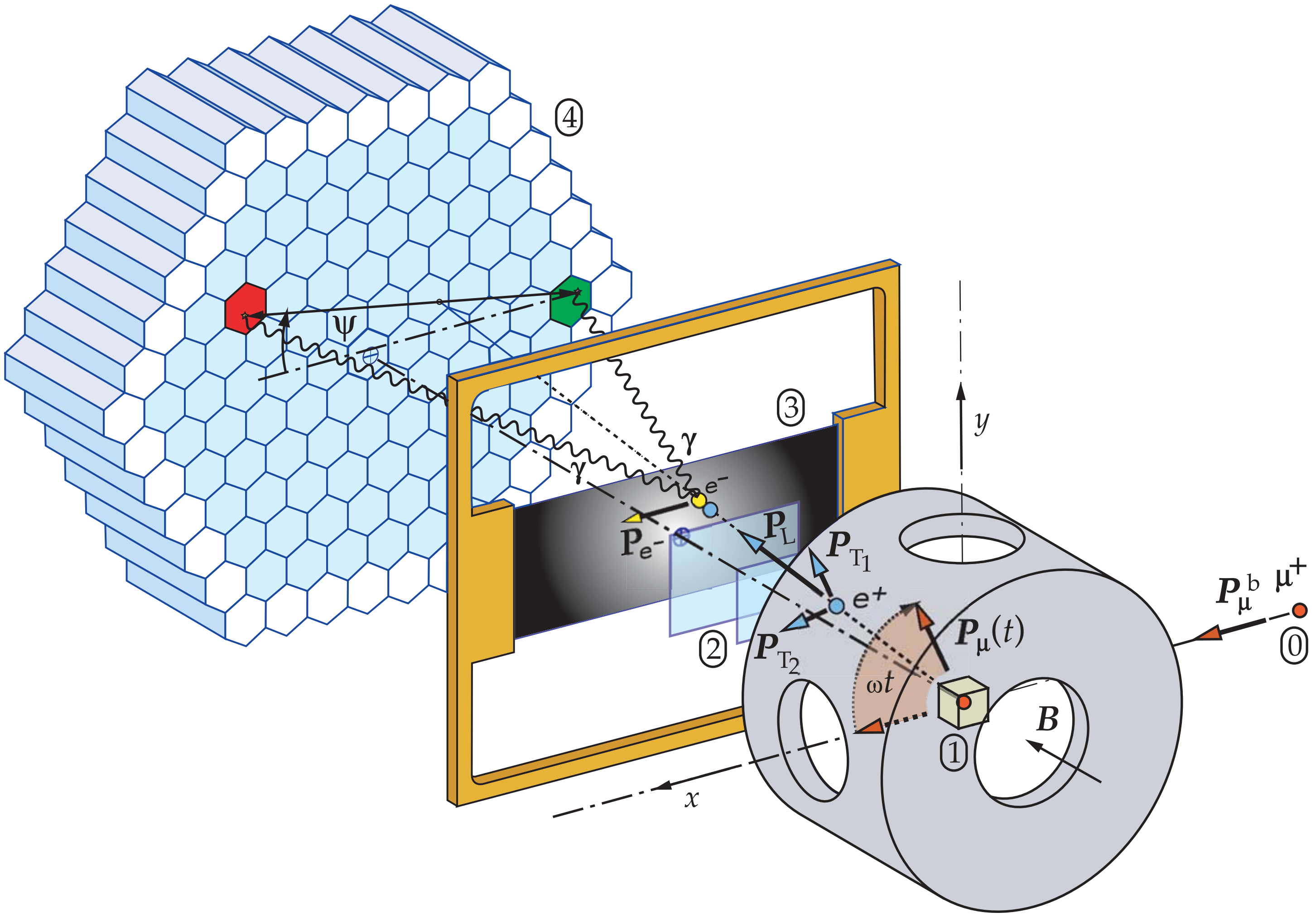
$\Longrightarrow$ 80% muon polarization in Be stop target

5.5 Positron tracking with drift chambers

5.6 Annihilation with polarized e^-

5.7 Detection of annihilation quanta with 127 BGO crystals

Setup of the Experiment and Principle of Measurement



0: Burst of polarized muons

1: Be stop target

2: Plastic scintillators

3: Magnetized Vacoflux foil

4: 127 BGO scintillators

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Measurement of $|\boldsymbol{P}_{\mathsf{T}}|$:

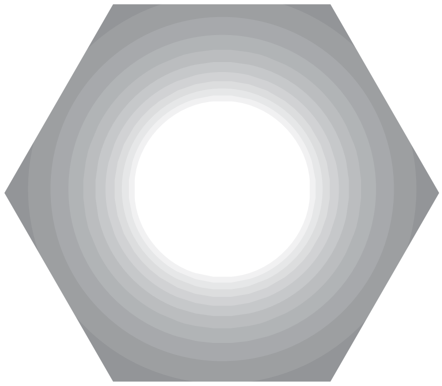
We make use of the dependence of the annihilation cross section on the relative orientation of the spins.

Simulation of photon intensity distributions in the BGO calorimeter: BGO-Kalorimeter :

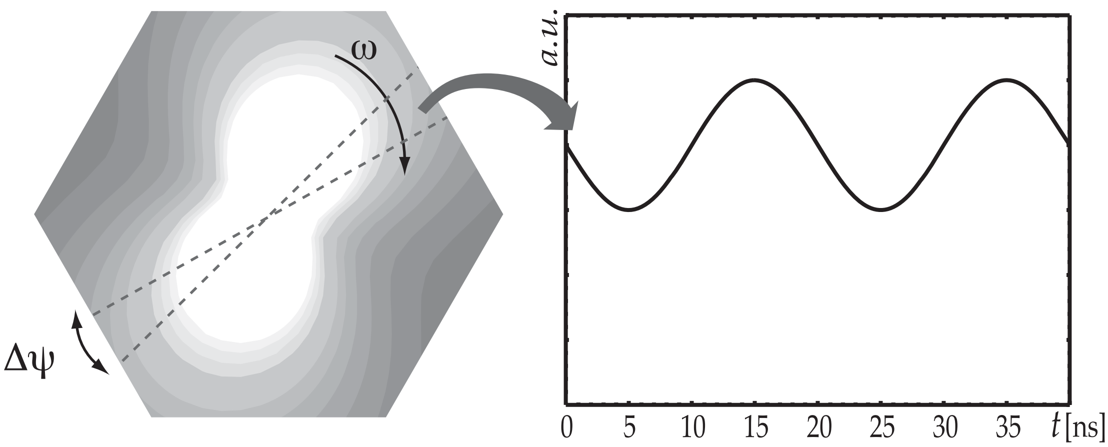
Simplifying assumptions :

e^- - polarization $= 100\%$

$E_{\gamma_1} = E_{\gamma_2} = 10$ MeV



$|\boldsymbol{P}_{\mathsf{T}}| = 0$

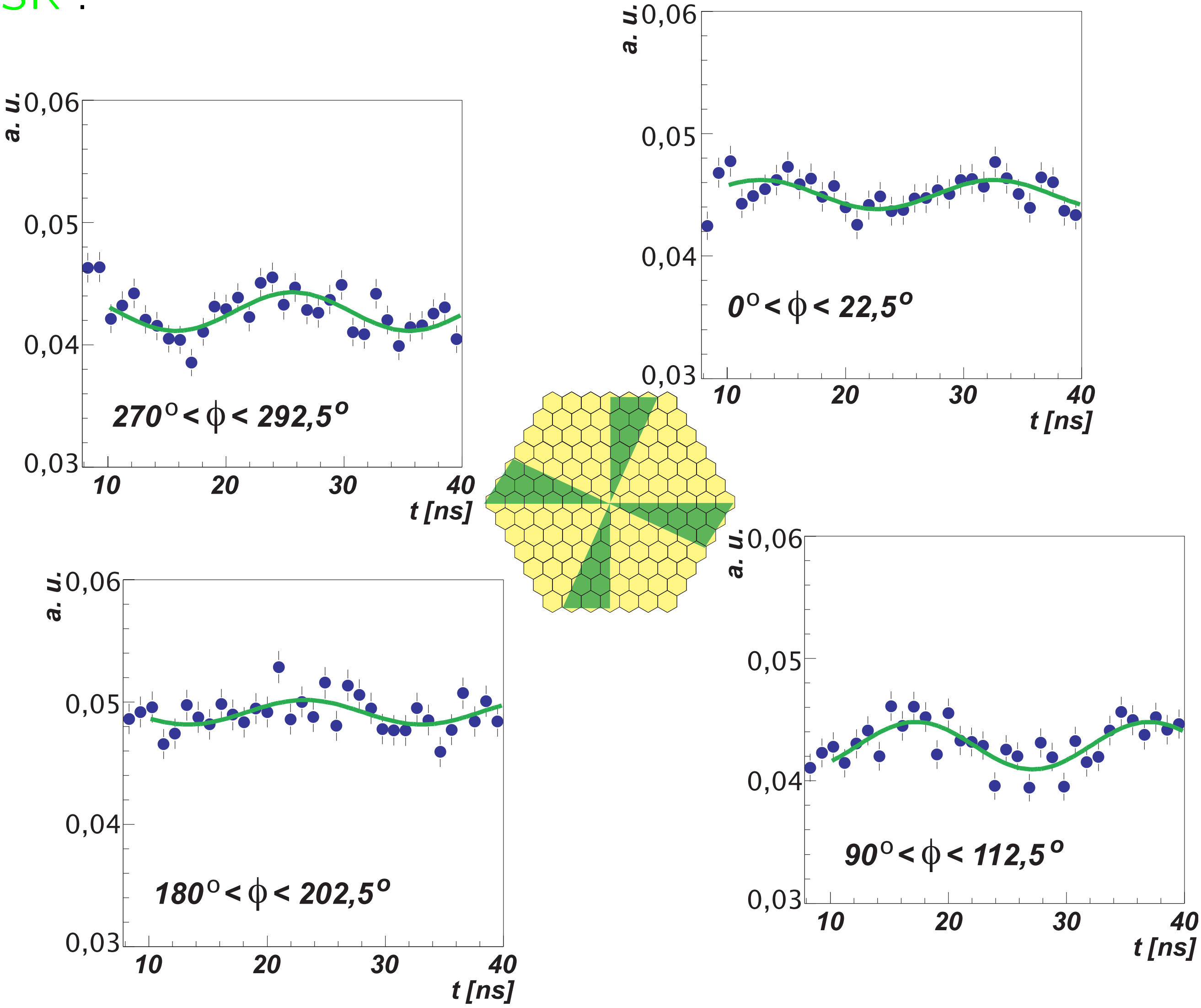


$|\boldsymbol{P}_{\mathsf{T}}| = 1$

Time spectrum for a given detector region $\Delta\Psi$.

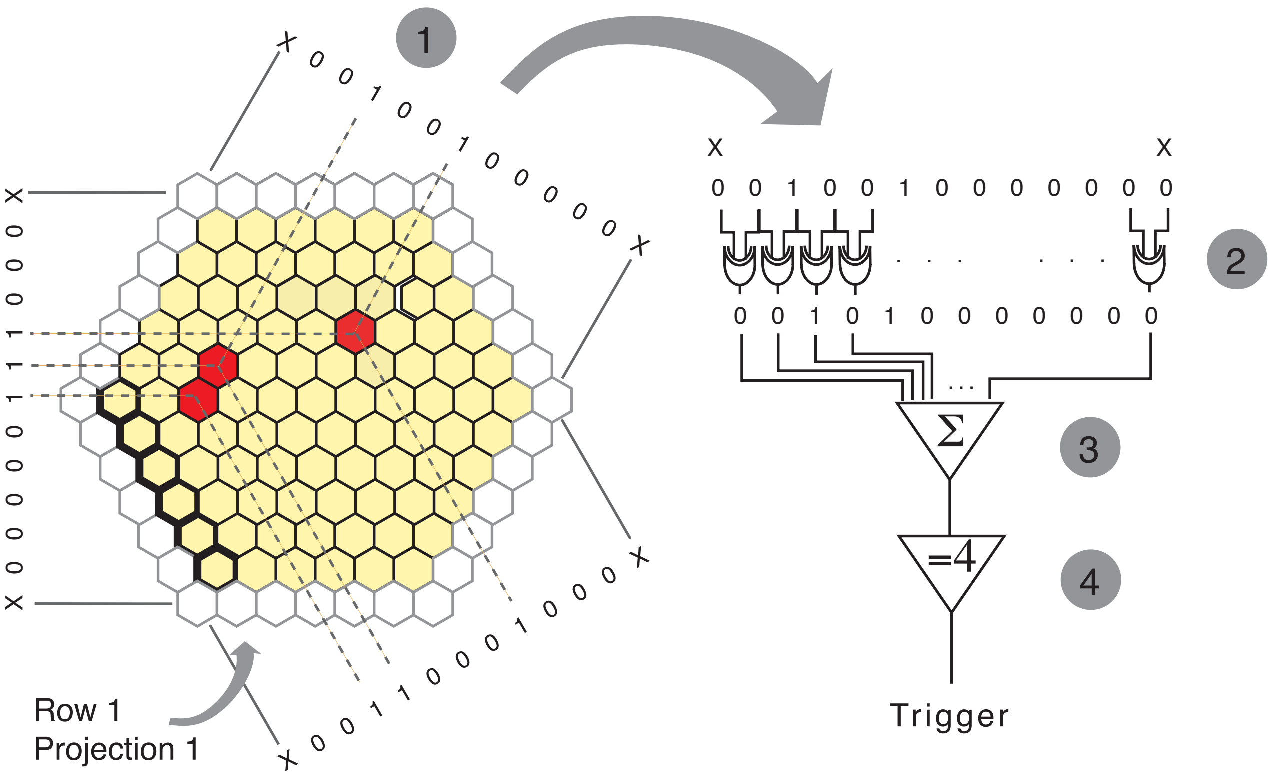
Measurement of the phase φ of $\boldsymbol{P}_{\mathrm{T}}$:

Time variation of the photon intensity for selected angles of emission of the e^+. Effect due to μ^+ decay asymmetry und μSR :



⇒ Relation Time ↔ Direction of μ^+ polarization

6. Experimental details



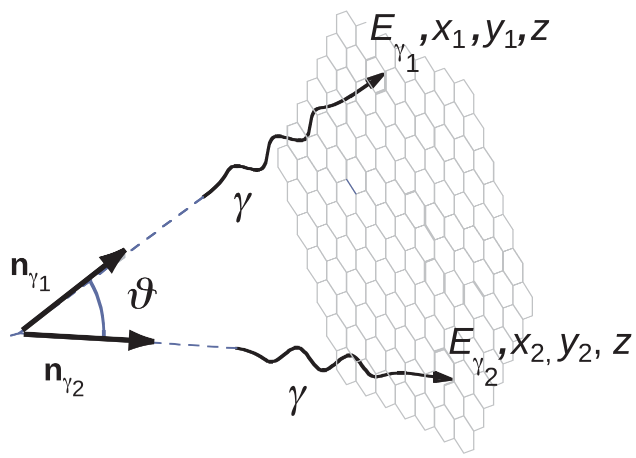
$$\cos\vartheta_{\text{min}} = 1 - 4\frac{m_e}{E_{e^+}}$$

$$d = 2z\tan\frac{\vartheta}{2}$$

$$d_{\text{min}} \approx 160\ \text{mm}$$

Cut on the Kinematics to Extract the 'Good' Events

Calculate ϑ in two different ways:



Energy:

$$\cos\vartheta = 1 - m_e \frac{E_{\gamma_1} + E_{\gamma_2}}{E_{\gamma_1} \cdot E_{\gamma_2}}$$

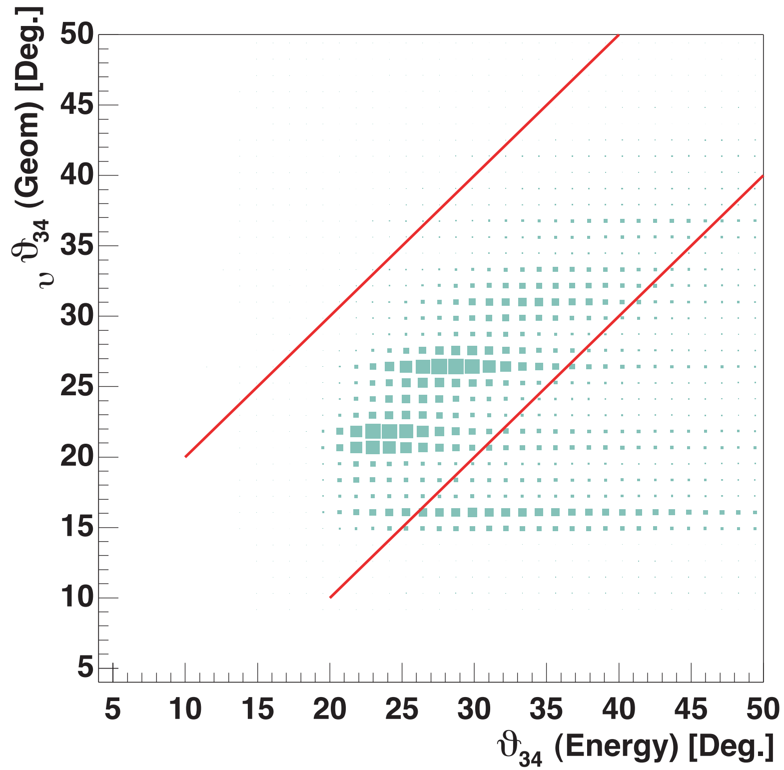
Geometry:

$$\cos\vartheta = \vec{n}_{\gamma_1} \cdot \vec{n}_{\gamma_2}$$

$$\vartheta^{Geom} = \vartheta^{Energy}$$

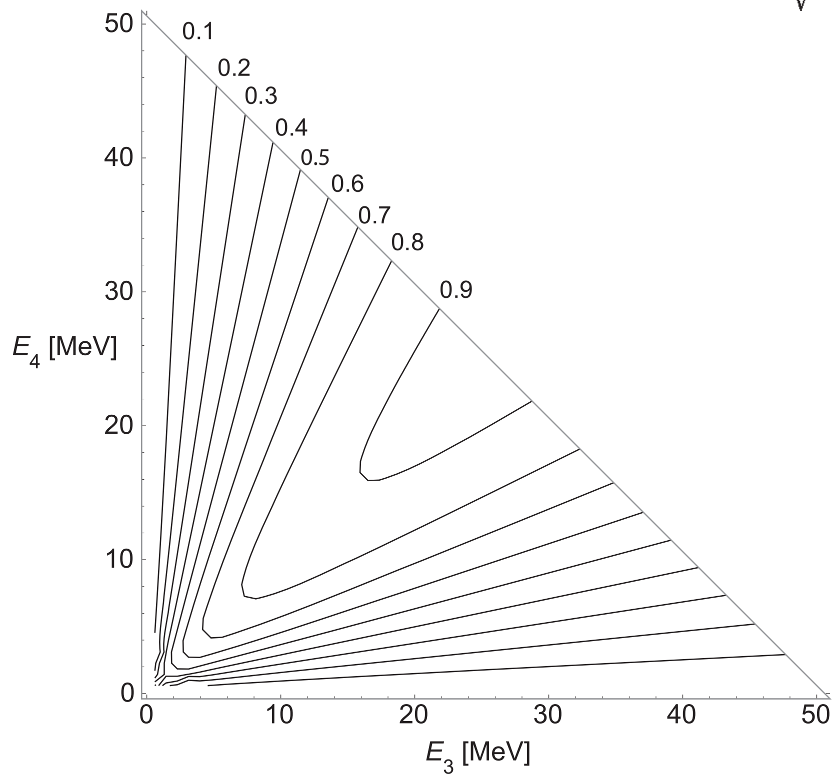
for 'good' annihilations

Sample from the last run

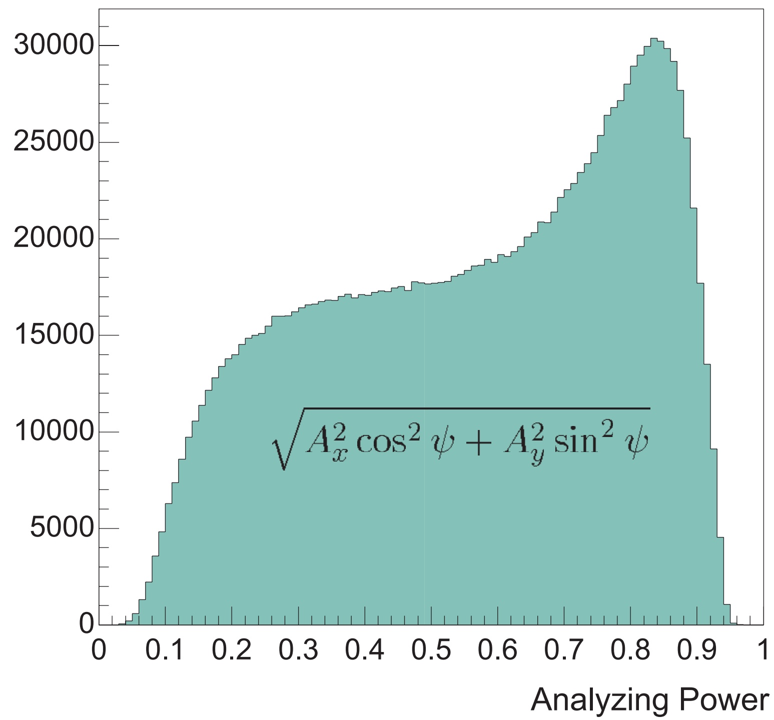


Analyzing Power *A* and amplitude *B* of oscillation

$$B = S \cdot \sqrt{P_1^2 + P_2^2} \cdot \sqrt{A_x^2 \cos^2\psi + A_y^2 \sin^2\psi}$$



Theoretical analyzing power,
$\psi = 90^o$



Analyzing Power of `good` annihilation events, A_x and A_y are functions of the photon energies.

7. Data analysis

How can we extract the e^+ transverse polarization (P_x, P_y) from the data?

Harmonic oscillation:

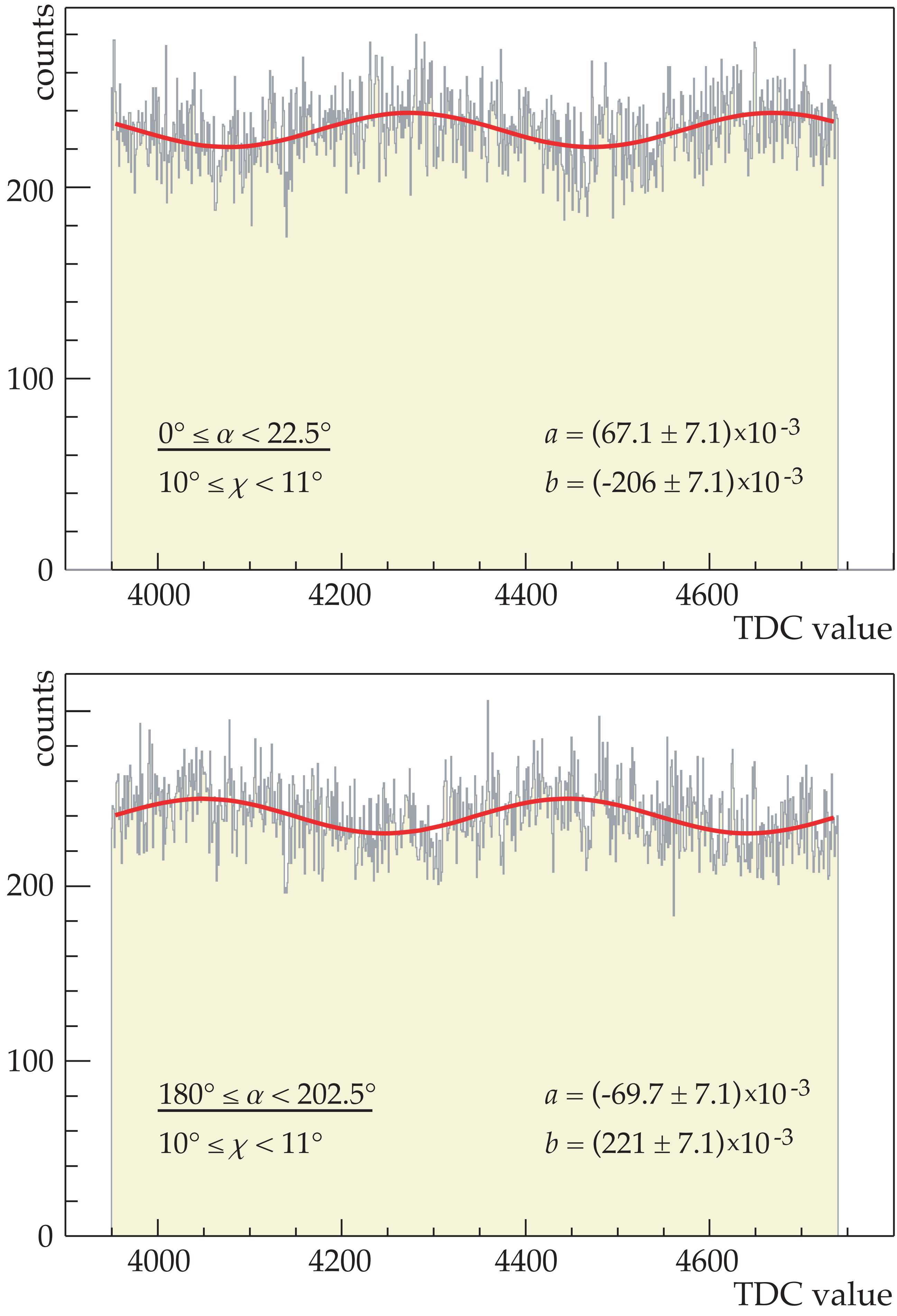
$$\begin{aligned} F(t) &= 1 + a\cos\omega t + b\sin\omega t \\ &= 1 + A_\mathrm{F}\cos(\omega t - \varphi) \end{aligned}$$

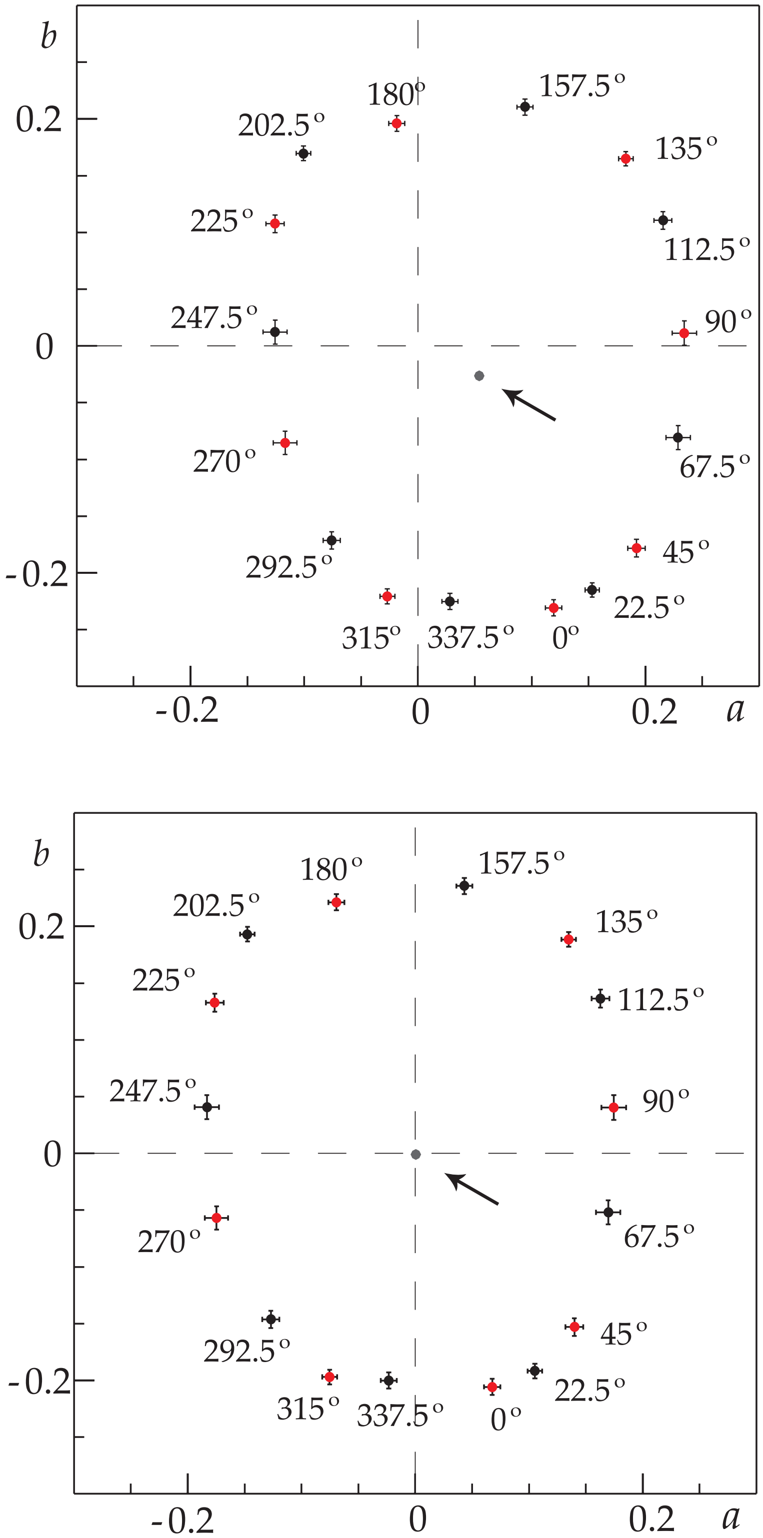
Solution: Fourier analysis; neglect multiples of ω.

$$R(t) = F_\mathrm{res}(t)\cdot F_{\mu\mathrm{SR}}(t)\cdot F_{\gamma\gamma}(t)$$

	$\alpha \to \alpha + 180°$	$P_{e^-} \to -P_{e^-}$	A_F $[10^{-3}]$
F_res	+	+	8.3
$F_{\mu\mathrm{SR}}$	−	+	20.0
$F_{\gamma\gamma}$	+	−	0.3

Symmetry behavior of the three functions F_j.


counts
200
100
0
0° ≤ α < 22.5°
10° ≤ χ < 11°
a = (67.1 ± 7.1)x10 -3
b = (-206 ± 7.1)x10 -3
4000
4200
4400
4600
TDC value
counts
200
100
0
180° ≤ α < 202.5°
10° ≤ χ < 11°
a = (-69.7 ± 7.1)x10 -3
b = (221 ± 7.1)x10 -3
4000
4200
4400
4600
TDC value

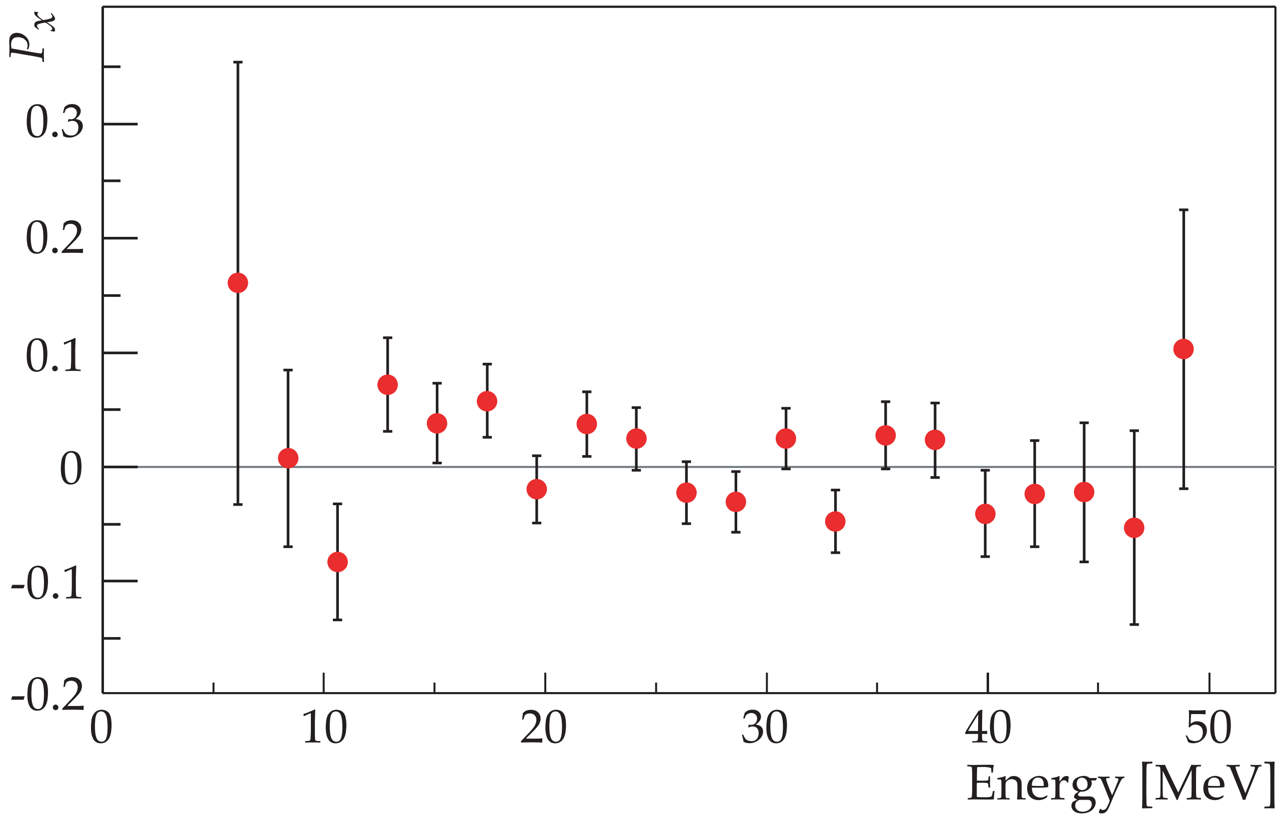


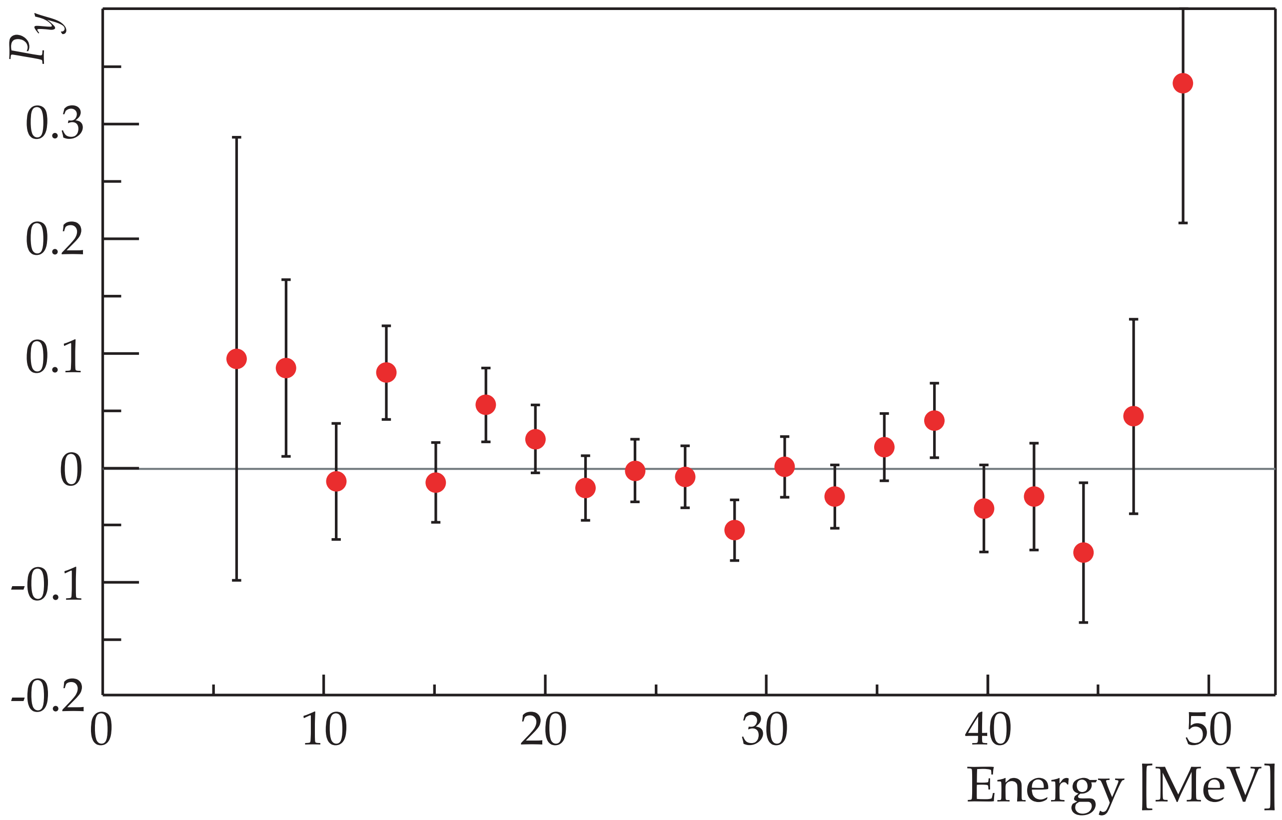
Fourier coefficients $a_{\mu\mathrm{SR}}(\alpha), b_{\mu\mathrm{SR}}(\alpha)$

Upper figure: Without correction

Lower figure: $(a_{\mathrm{res}}, b_{\mathrm{res}})$ subtracted.

Transverse e^+ polarization components
at the moment of annihilation.





8. Results

Systematic errors:

Main sources:

- Energy loss and spin precession
- Background (mainly from bremsstrahlung)
- Values of P_μ und P_{e^-}
- Energy calibration of the BGO detectors

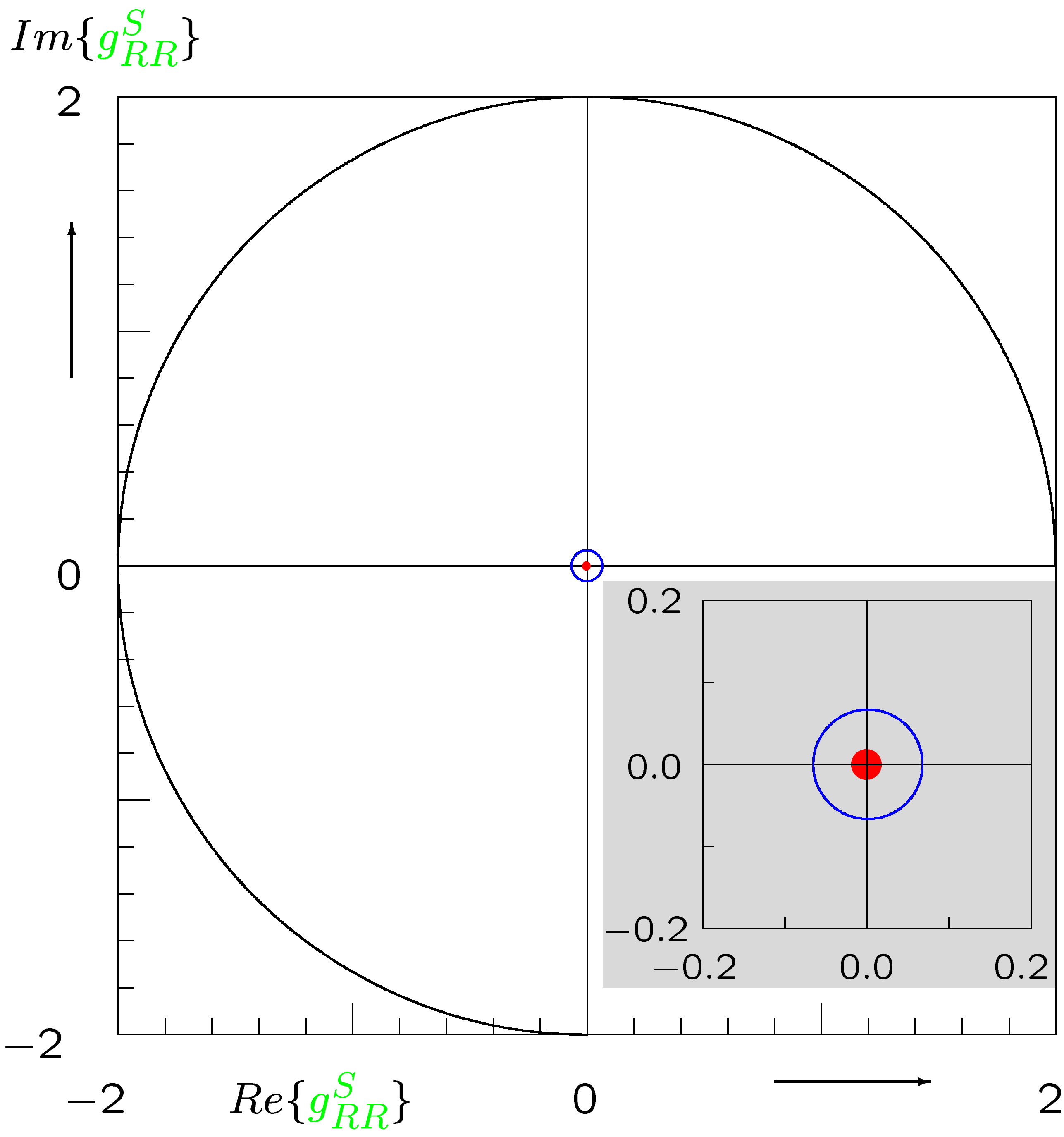
e^+ transverse polarization at the moment of μ^+ decay:

$$\langle P_{\mathrm{T}_1} \rangle_E = \frac{\pi}{48} \left(-9\,\eta + 7\eta'' \right)$$

$$\langle P_{\mathrm{T}_2} \rangle_E = \frac{\pi}{12} \left(\frac{3\,\alpha'}{A} + 8\,\frac{\beta'}{A} \right)$$

Final results (in units of 10^{-3}):

	General analysis	Restricted analysis
η	$71 \pm 37 \pm 7$	$-1.8 \pm 7.0 \pm 1.3$
η''	$105 \pm 52 \pm 8$	$\equiv -\eta$
α'/A	$-3.4 \pm 21.3 \pm 5.5$	$\equiv 0$
β'/A	$-0.5 \pm 7.8 \pm 2.0$	$-1.4 \pm 3.5 \pm 0.8$
$\langle P_{\mathrm{T}_1} \rangle$	$6.3 \pm 7.7 \pm 3.5$	—
$\langle P_{\mathrm{T}_2} \rangle$	$-3.7 \pm 7.7 \pm 3.5$	—



Limits for scalar coupling g^S_{RR}.

Black (outer) circle: by definition.

Blue circle: previous measurement [1]

Inner red circle: this measurement.

Position of red circle: not yet determined.

9. Conclusions

- Experiment to measure the transversal polarization of positrons and the decay parameters for the decay of polarized muons.
- New experimental limits for
  $\langle P_{\mathsf{T}_1} \rangle_E$, $\langle P_{\mathsf{T}_2} \rangle_E$ (Improved by a factor of 3)
  and η , η'' , $\frac{\alpha'}{A}$, $\frac{\beta'}{A}$ (Improved by a factor of 2)
- New experimental limits for scalar right-handed couplings
- Determination of the model-independent Fermi coupling constant G_F

→ All results are in agreement with the standard model

→ Improved limits for the violation of time reversal invariance.

[1] N. Danneberg *et al.*, PRL **94**, 021802 (2005)