Measurement of the polarization vector of the e^+ from the decay of polarized μ^+ as a test of time reversal invariance

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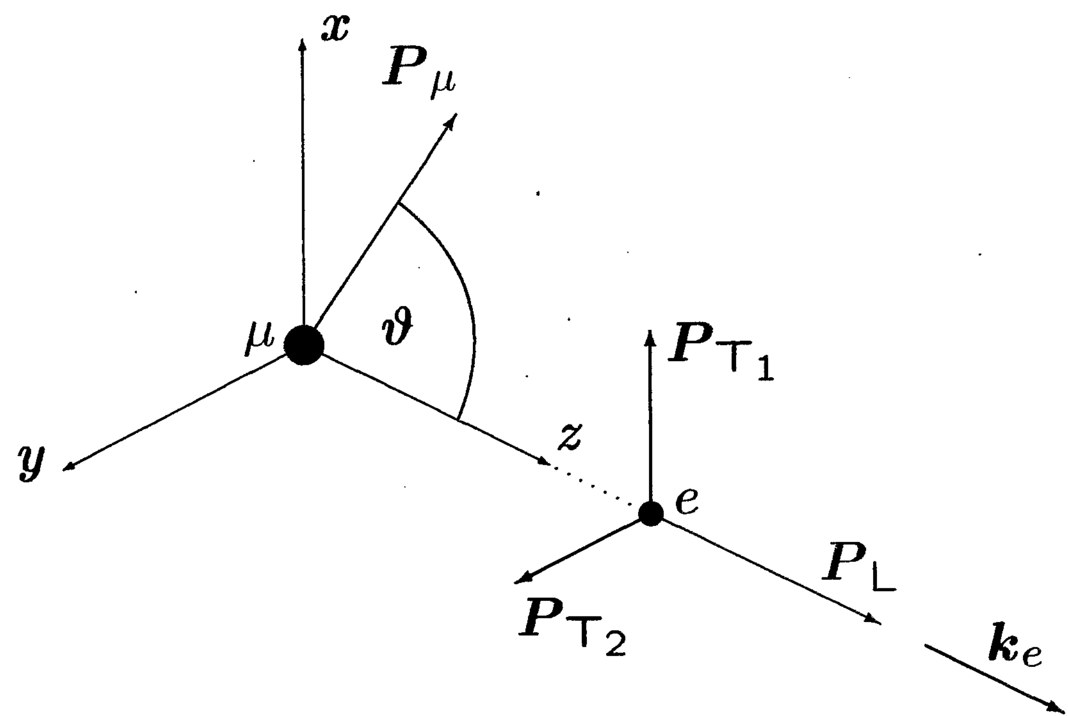


$$P_{\mathrm{T}_1} = f_1(E, \vartheta, \eta, \eta'')$$

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

The standard model predicts:

$$\langle P_{\mathrm{T}_1} \rangle_E = 0.003$$

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

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

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

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

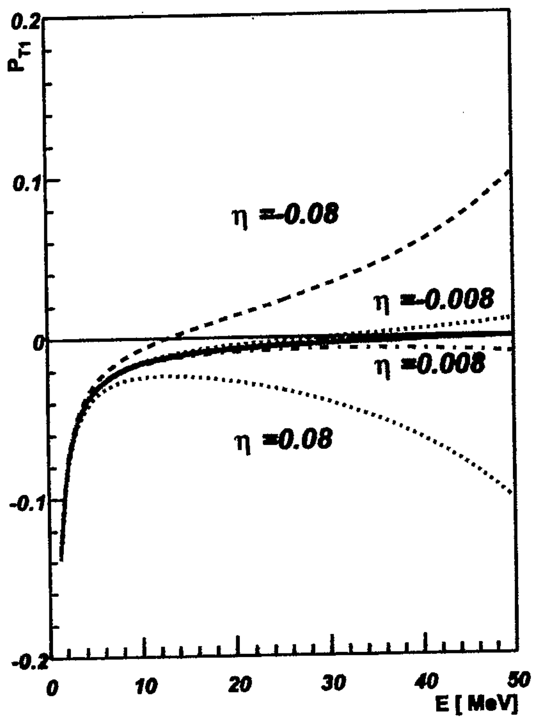
$$g^V_{LL} = 1$$

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

Assuming 1 additional interaction and knowing that

$$g_{LL}^{V} \approx 1,$$

one deduces:



$$P_{T_1}(E_e) \rightarrow \eta \approx \frac{1}{2} Re\{g_{RR}^{S}\}$$

$$P_{T_2}(E_e) \rightarrow \frac{\beta'}{A} \approx \frac{1}{4} Im\{g_{RR}^{S}\}$$

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:

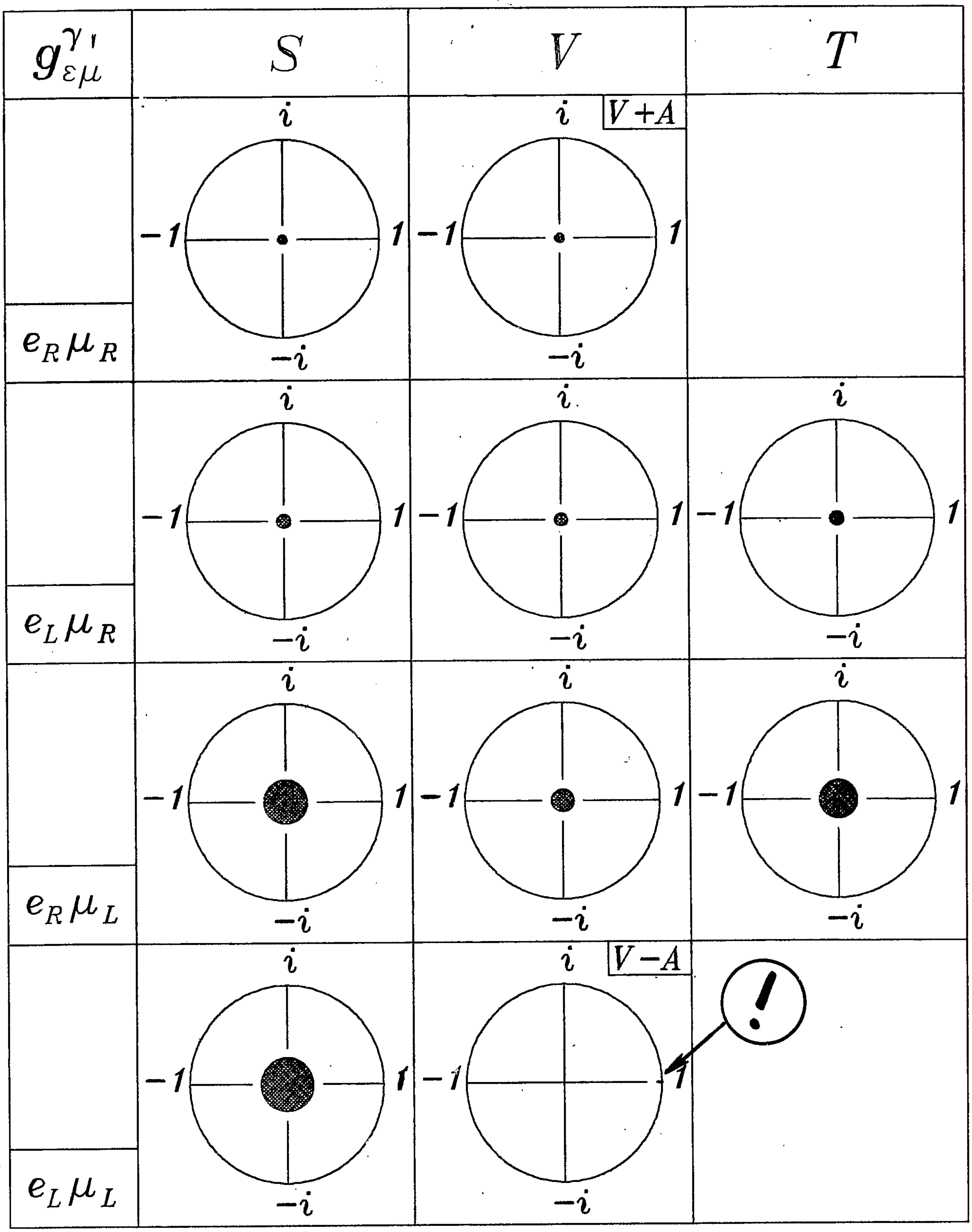
$$\lambda \approx \frac{1}{2} Re\left\{g_{LL}^{V} \cdot g_{LR}^{V*}\right\}$$

In left-right symmetric models with mixing angle ζ:

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

Contribution from	$\frac{\Delta G_F}{G_F}$ [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
$\Delta \eta$	193.0	6 500
$\Delta \Gamma_{\tau \to \mu}$	-	100 000

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



5. Experimental method

Measure the complete polarization vector of the decay positrons:

$$\boldsymbol{P}_{e^+} = \begin{pmatrix} P_{\mathrm{T}_1} \\ P_{\mathrm{T}_2} \\ P_{\mathrm{L}} \end{pmatrix} \equiv \begin{pmatrix} P_{\mathrm{T}} \cdot \cos\varphi \\ P_{\mathrm{T}} \cdot \sin\varphi \\ P_{\mathrm{L}} \end{pmatrix}$$

with 3 simultaneous and independent measurements:

Observable	Method
P_{T}	Time dependence of annihilation
φ	Remnant μSR effect
P_{L}	Spatial dependence of annihilation

6. Experimental setup

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

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

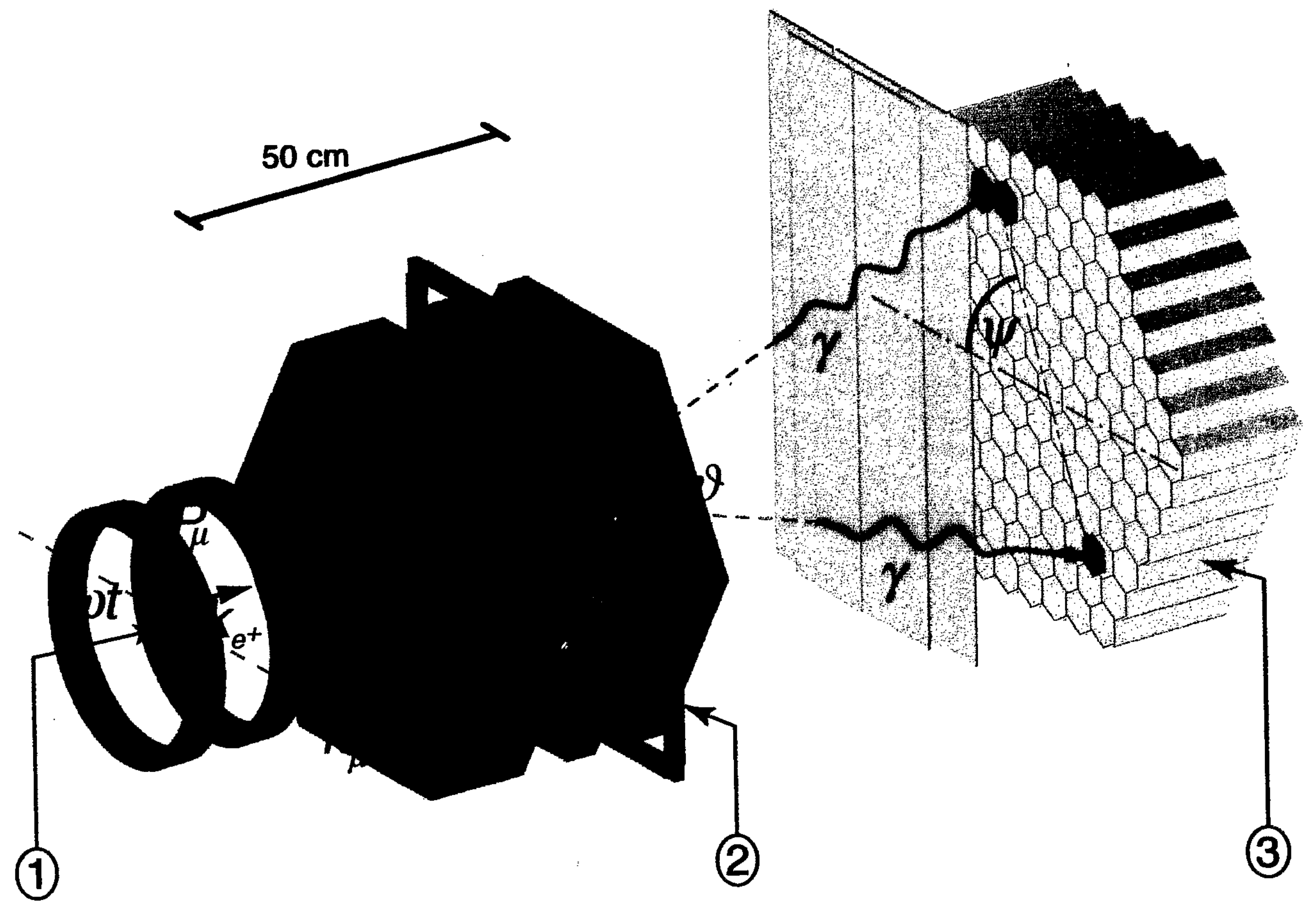
6.3 Precession in homogeneous B field; precession frequency = cyclotron frequency (50.8 MHz)

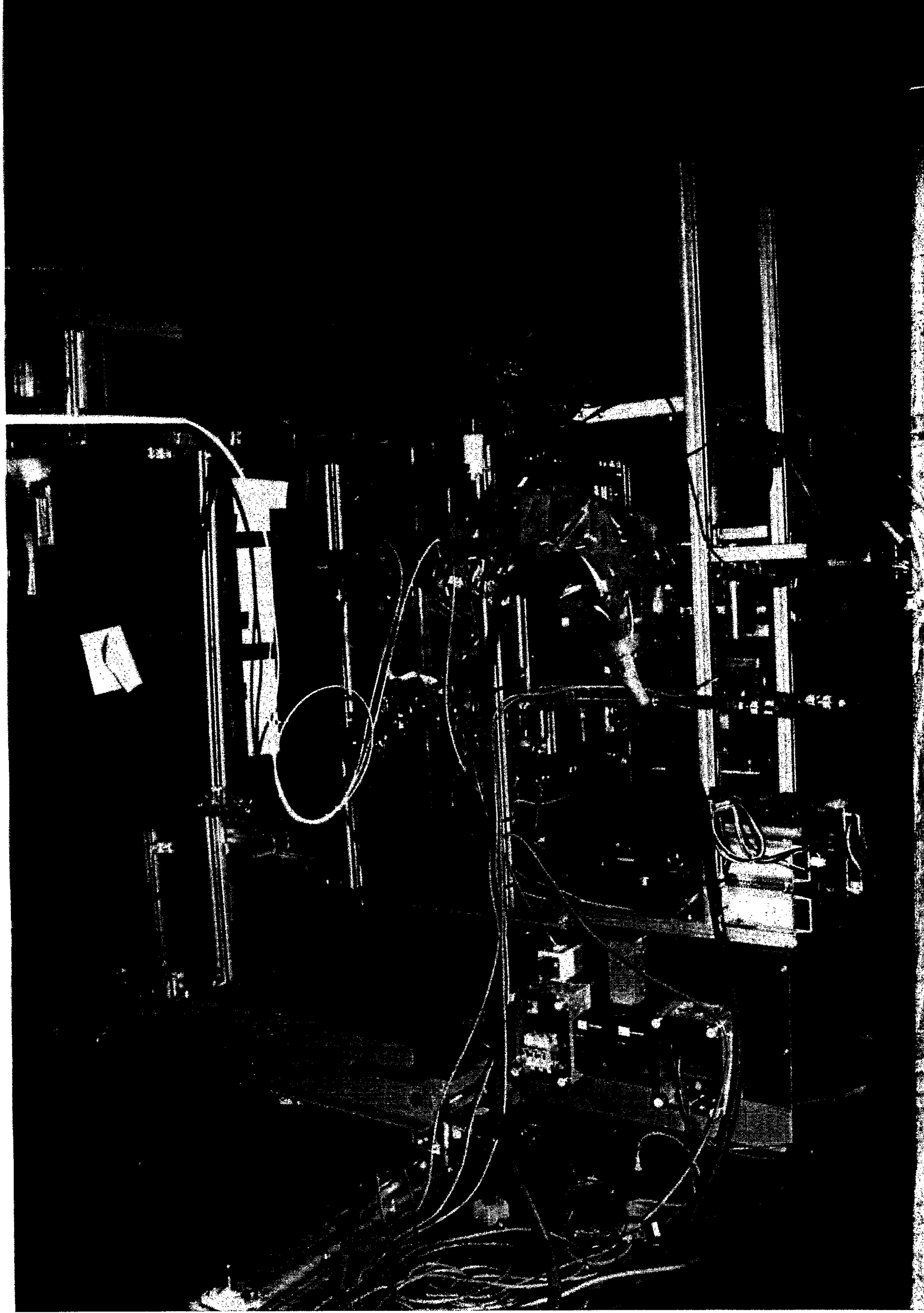
6.4 Burst width 3.9 ns (FWHM)
$\Longrightarrow$ 80% muon polarization in Be stop target

6.5 Positron tracking with drift chambers

6.6 Annihilation with polarized e^-

6.7 Detection of annihilation quanta with 127 BGO crystals


50 cm
γ
ψ
ϑ
γ
e^+
1
2
3



7. Event reconstruction and data analysis

7.1 e^+ annihilation-in-flight as analysing reaction for transverse polarization

7.2 Muon decay asymmetry (μSR yields time zero)

7.3 Energy calibration with cosmic rays

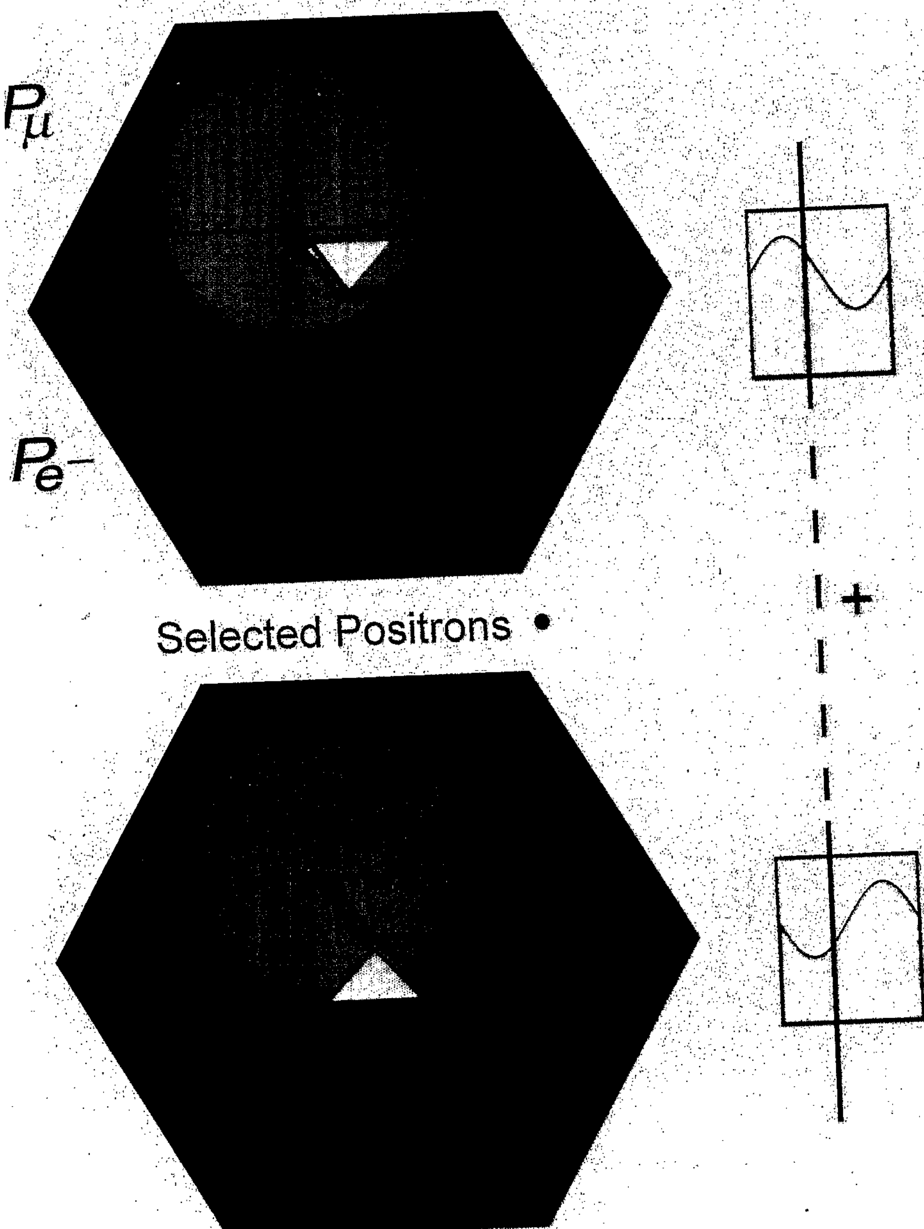
7.4 Cluster recognition

7.5 Background suppression

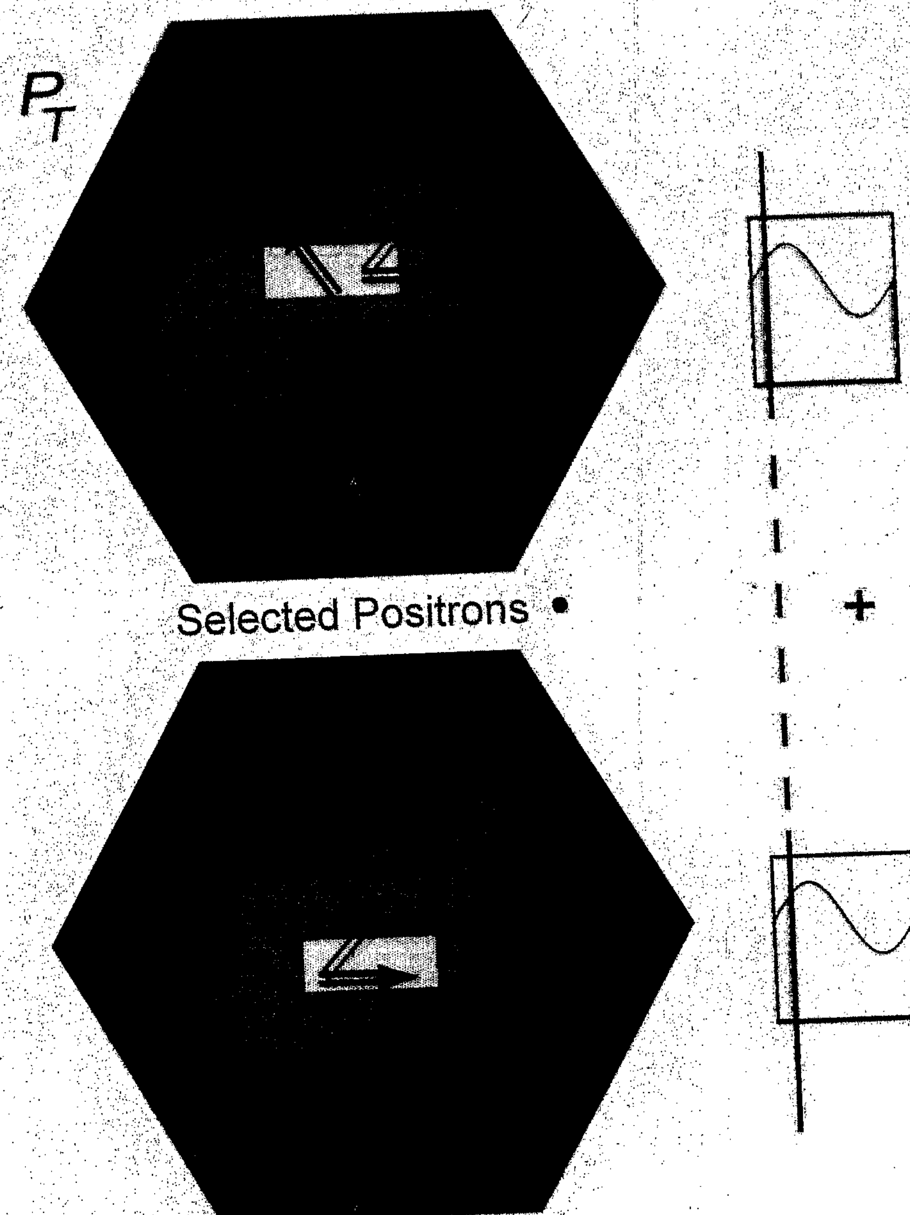
7.6 Analysing power of annihilation events

7.7 Energy distribution of transverse polarization

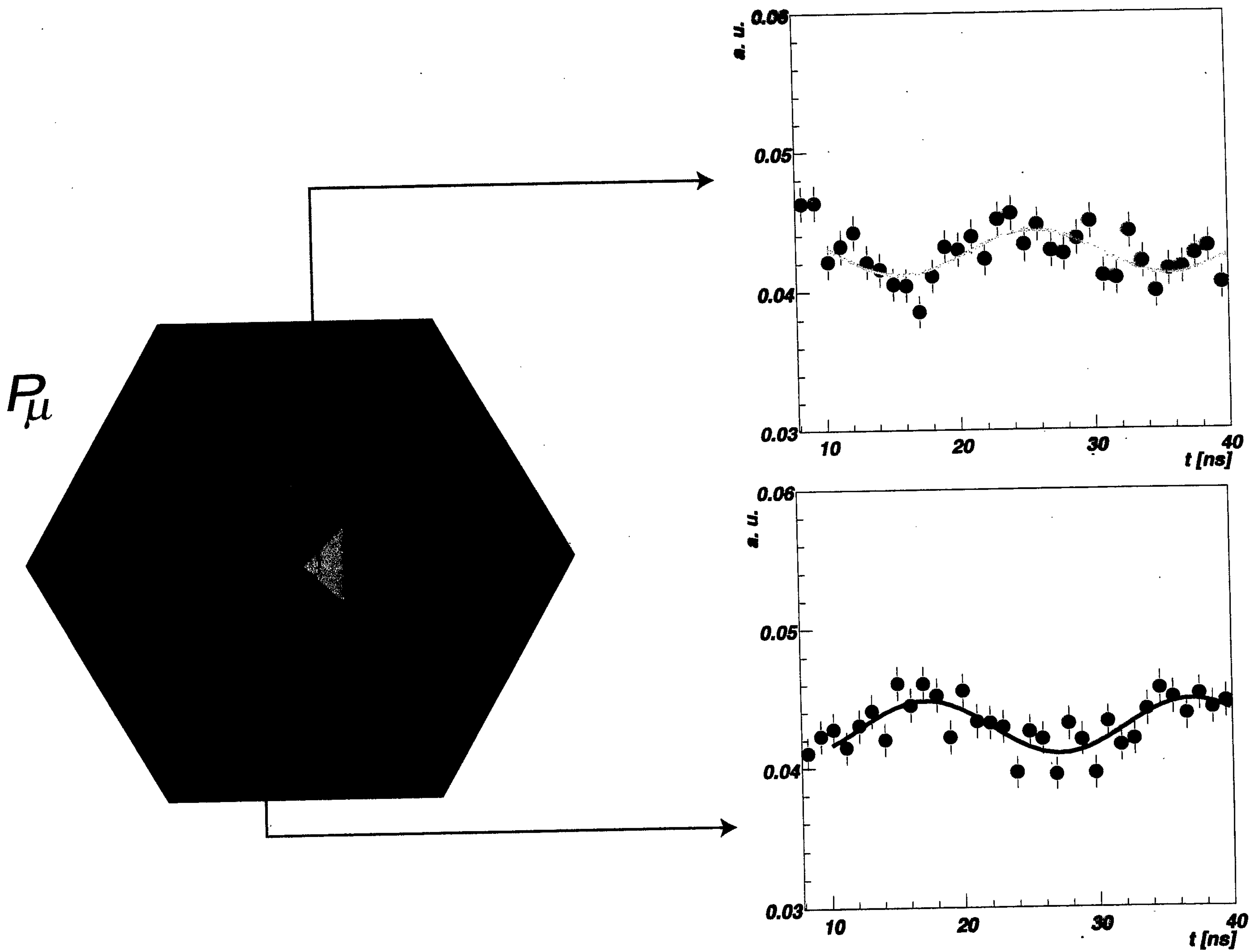
7.8 Longitudinal polarization



μSR Effect



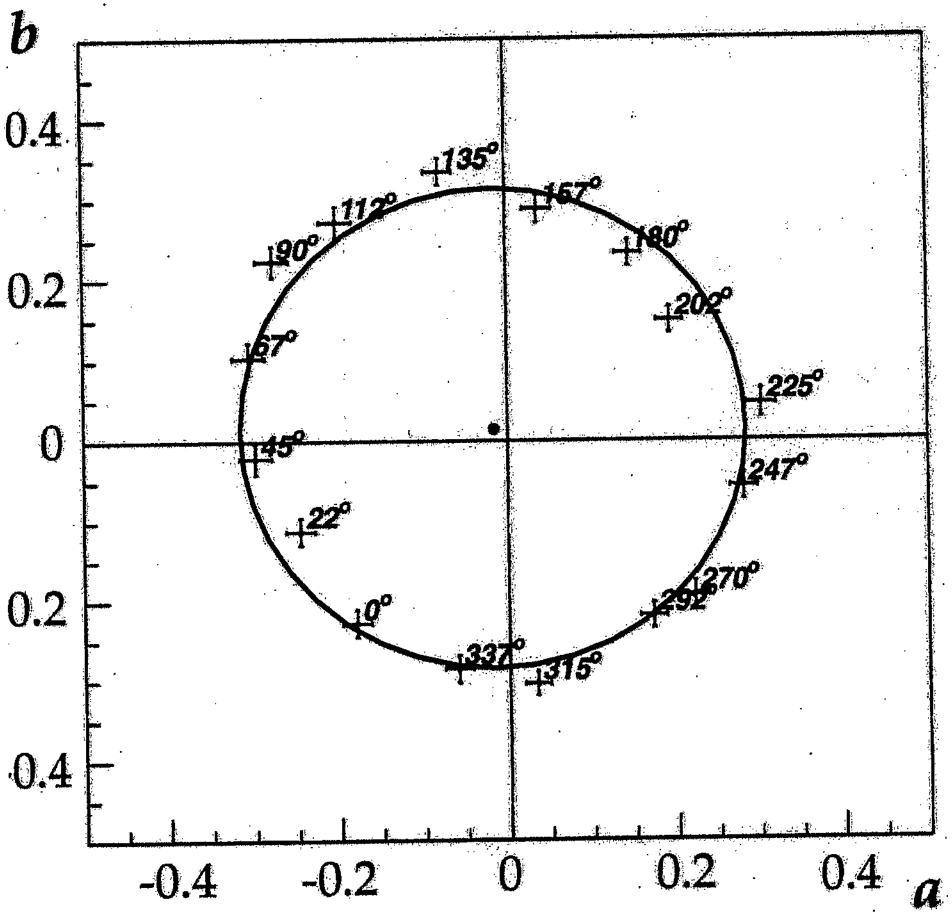
P_T Effect



P_μ
a. u.
0.06
0.05
0.04
0.03
10
20
30
40
t [ns]
a. u.
0.06
0.05
0.04
0.03
10
20
30
40
t [ns]

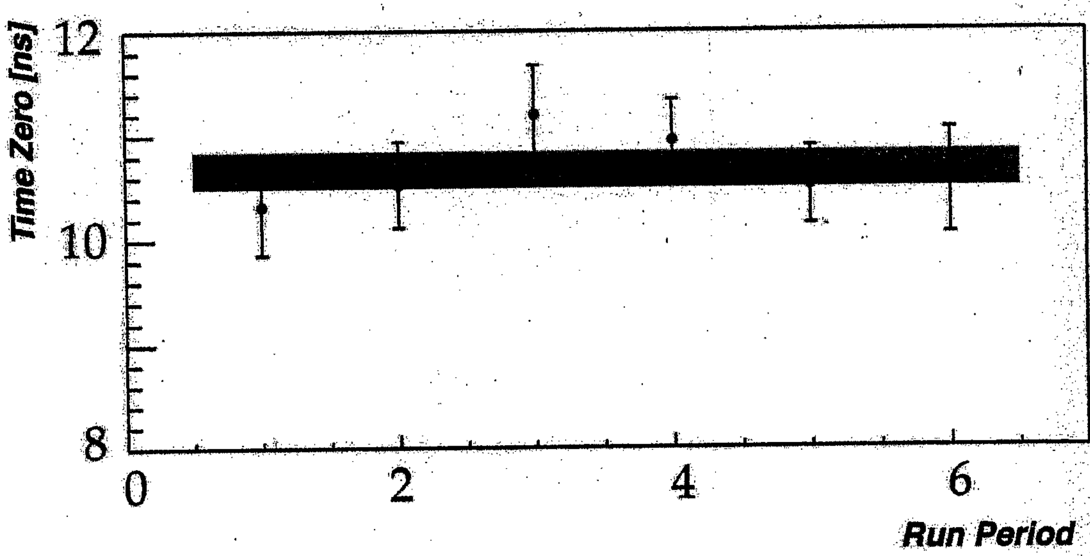
Phases and Amplitudes for all azimuthal bins (φ)

$N \sim (1 + a \cos \omega t + b \sin \omega t)$



Average μSR amplitude: 0.297 ± 0.004, consistent with theory.

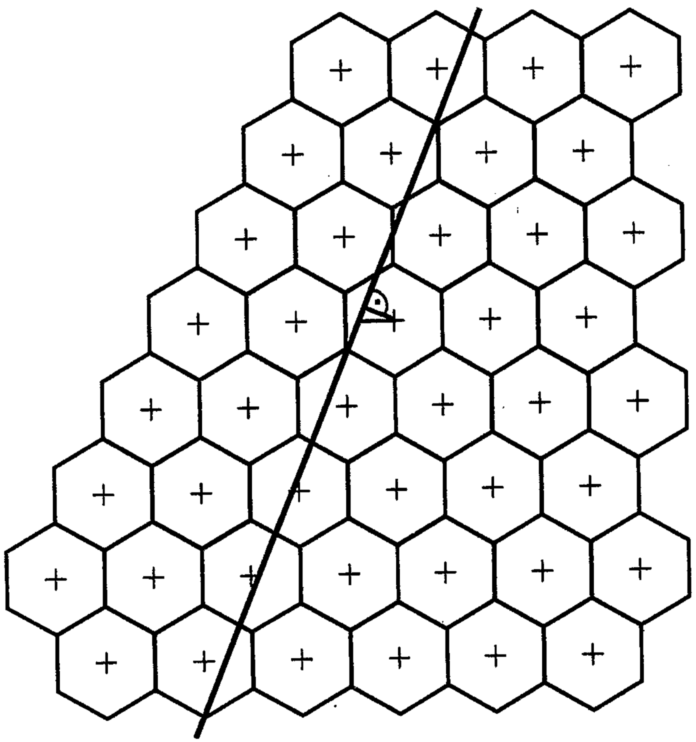
Stability of the Time-Zero during the whole run



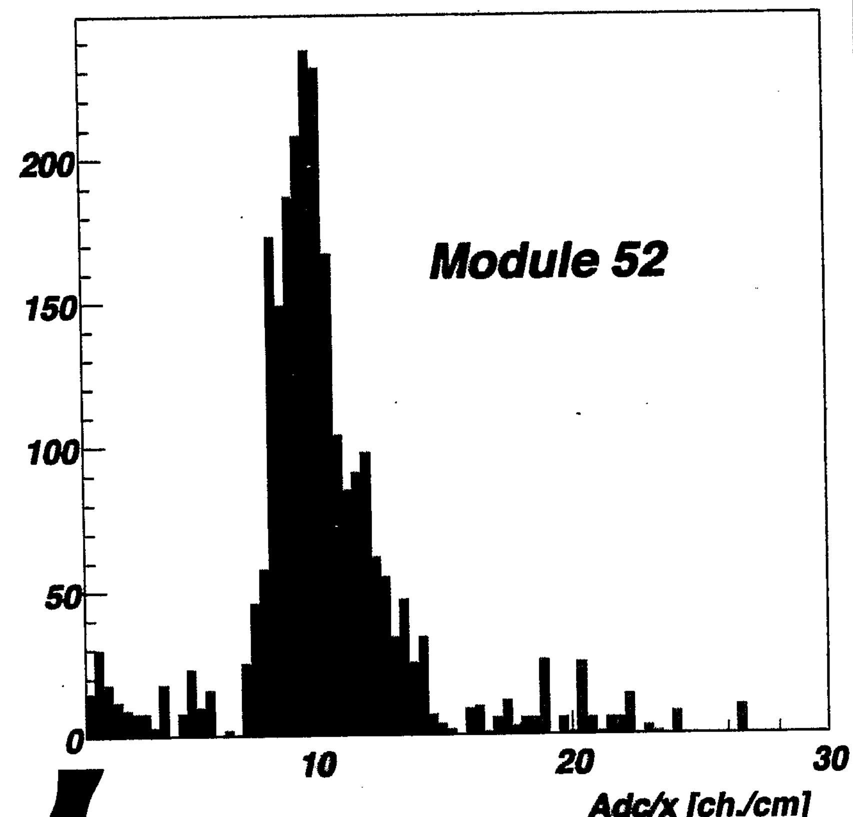
Time-Zero : 10.67 ±0.187 ns gives the time, when the muon spin shows upward.

Data is Calibrated with Cosmic Muons

Reconstructing the cosmic tracks gives the tracklength in BGOs



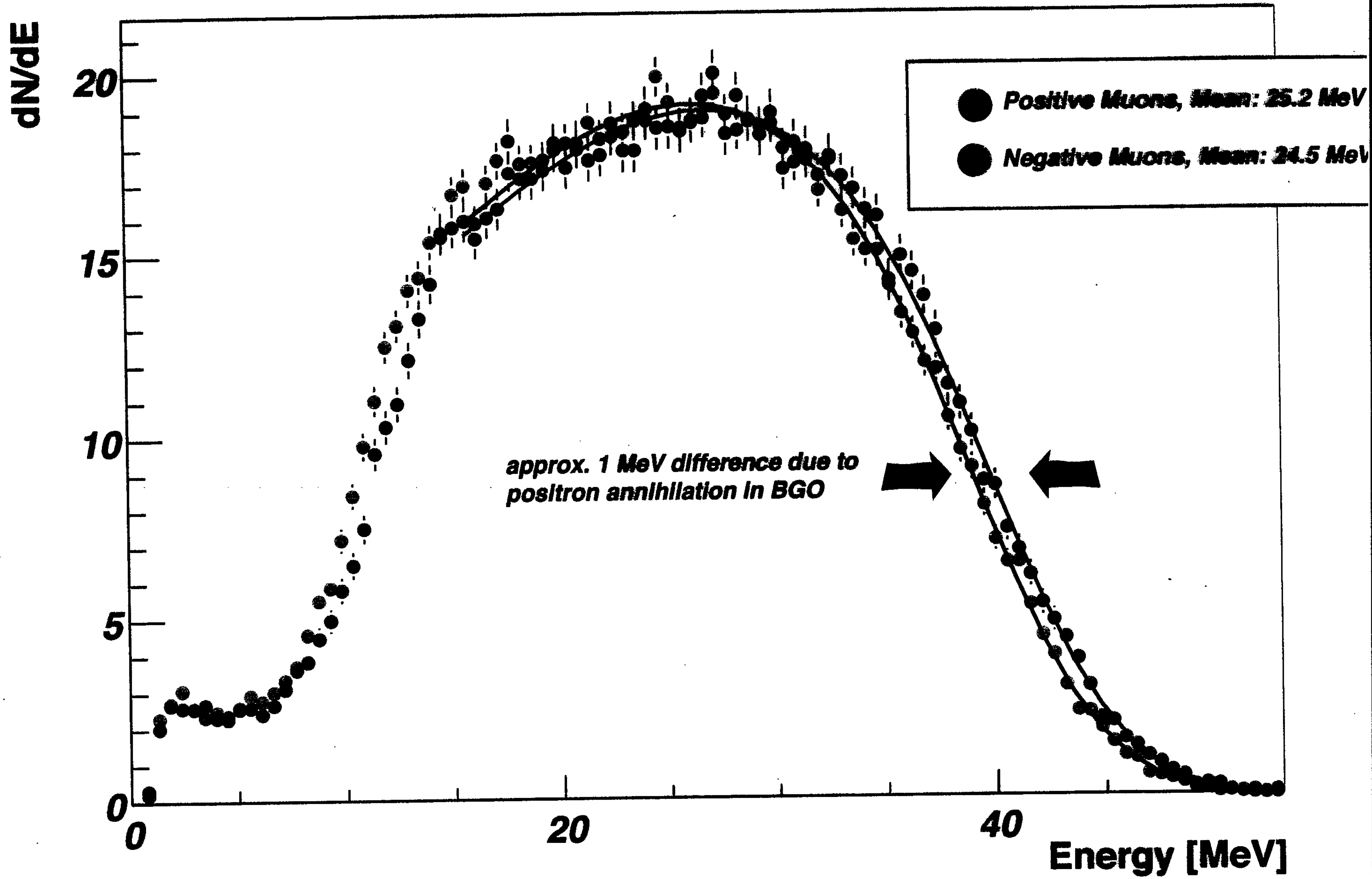
Histogram Adc/x for cosmics

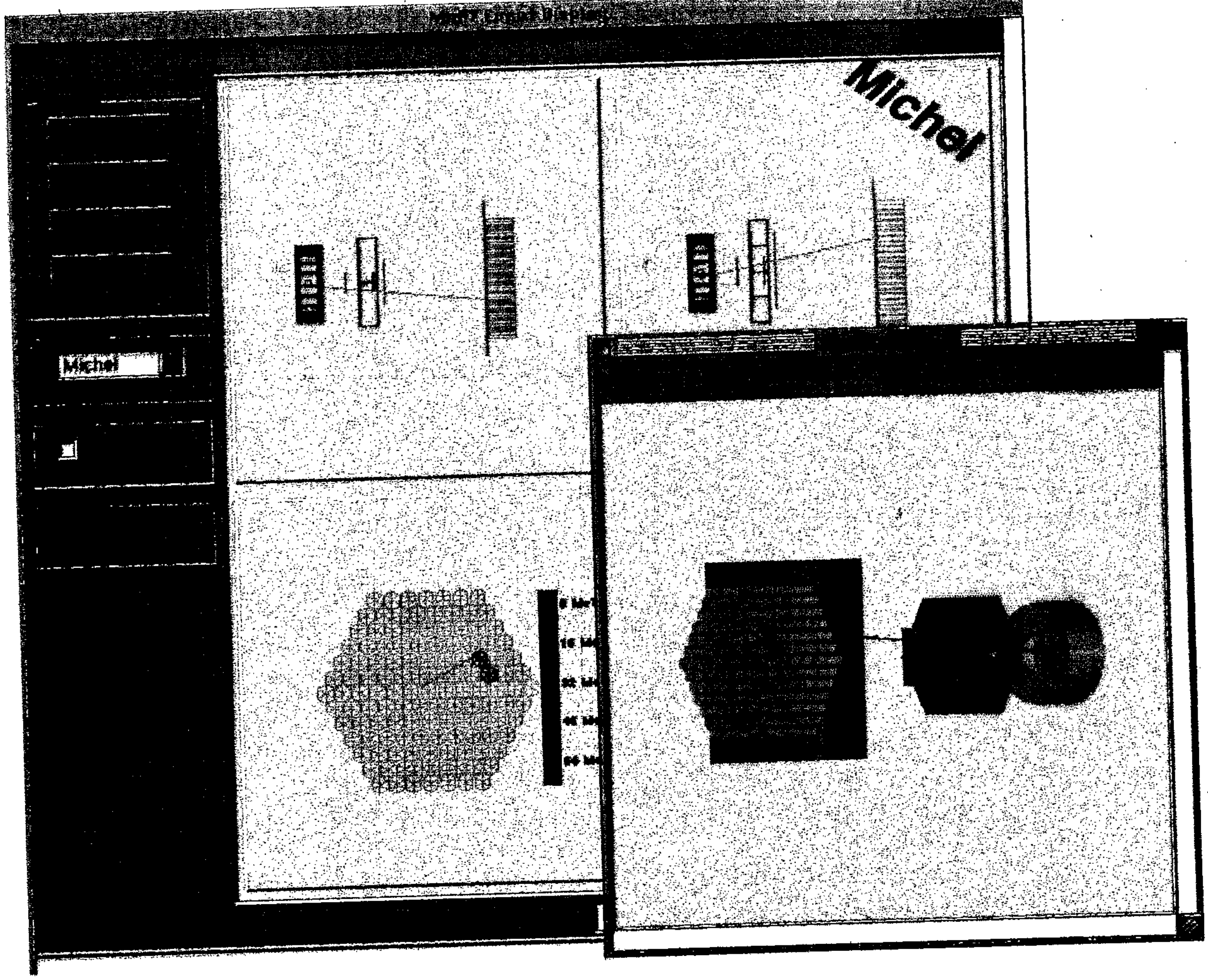


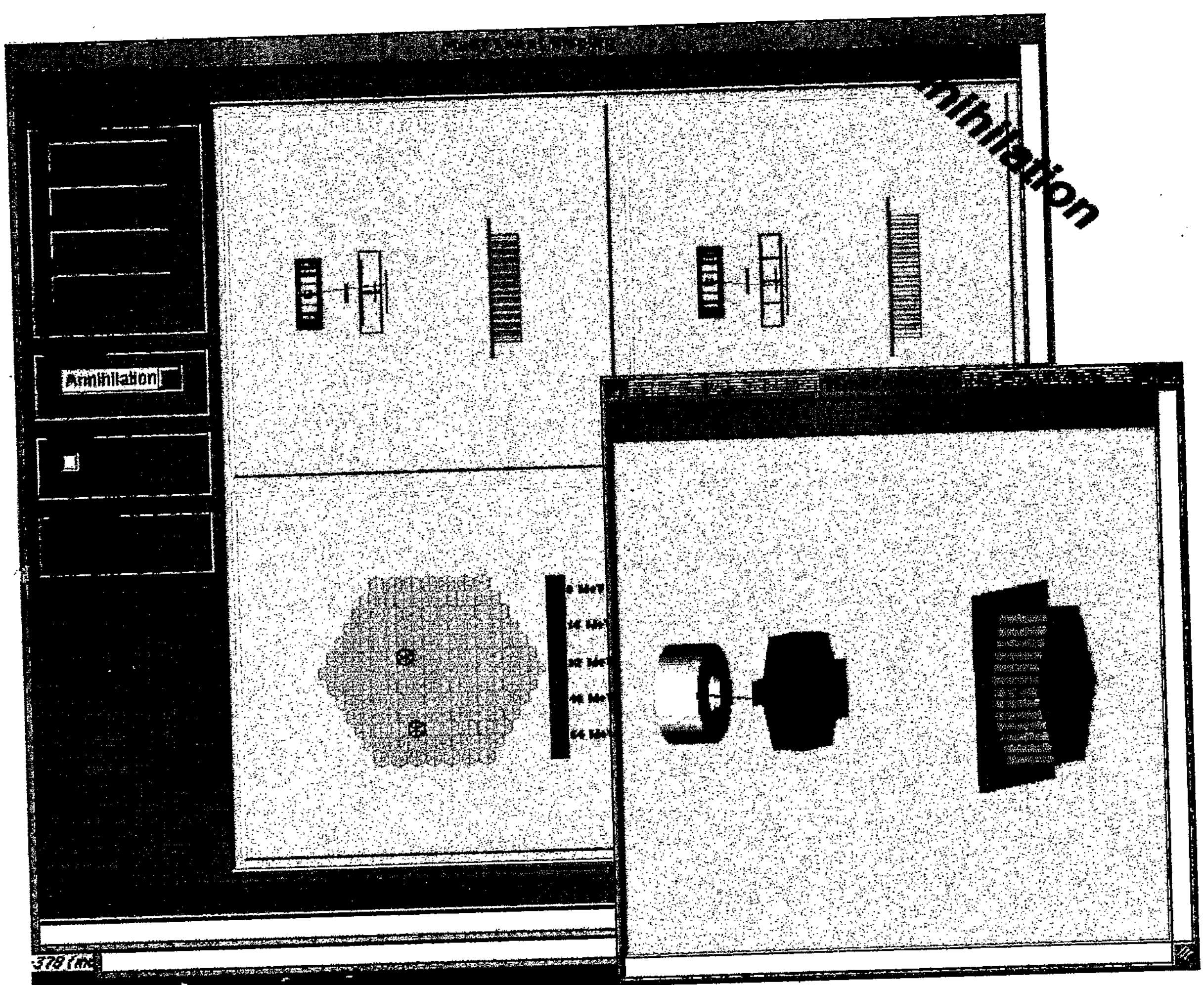
Monte Carlo

$$\frac{1}{E_i/x_i} \times \frac{ADC_i}{x_i} = \frac{ADC_i}{E_i} = c_i$$

Calibration constant for BGO number i


dNdE
20
15
10
5
0
0
20
40
Energy [MeV]
Positive Muons, Mean: 25.2 MeV
Negative Muons, Mean: 24.5 MeV
approx. 1 MeV difference due to
positron annihilation in BGO


Michel
Michel


nihilation
Annihilation

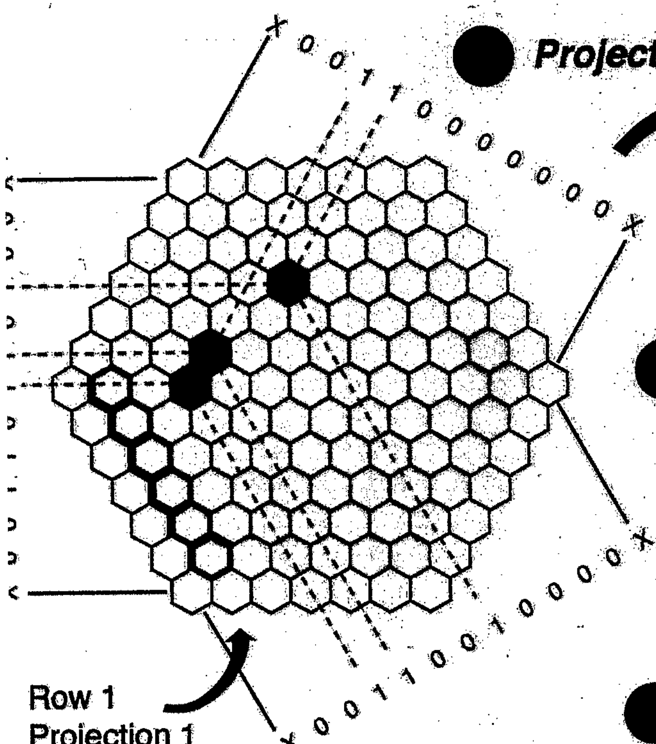
Triggering on Two Photons at a minimal Distance: The Cluster Recognition Unit

How does it work?

Kinematics require a minimal cluster distance

$$\cos\vartheta = 1 - m_e \frac{4}{E_{e^+}} \qquad d = 2z \tan\frac{\vartheta}{2}$$

$$d_{min} = d(E_{e^+} = 50 MeV) \approx 16\,cm$$



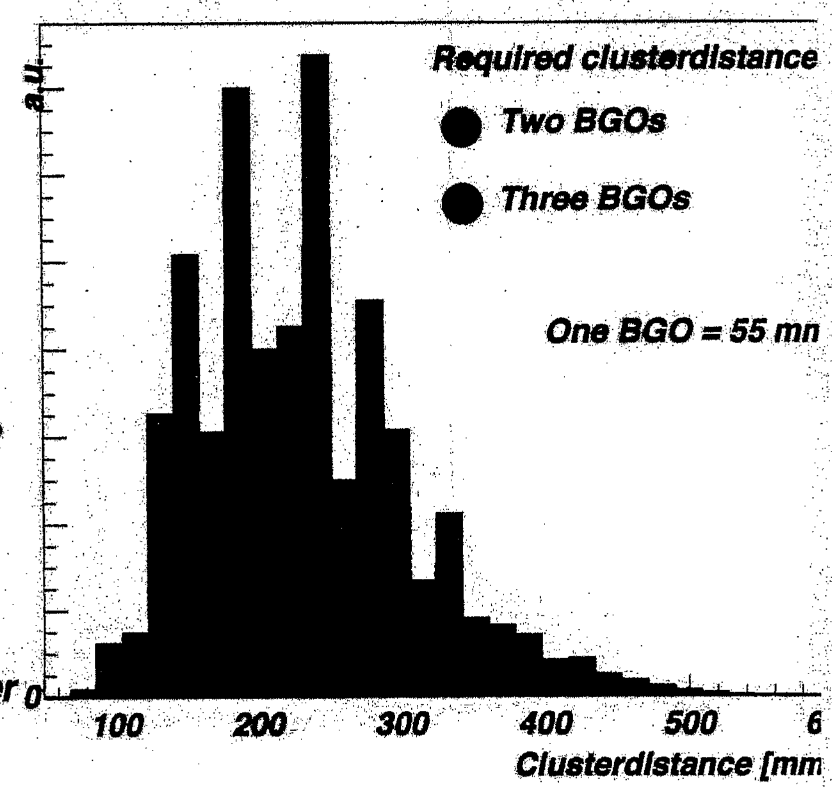
- **Project along the axes of symmetry**

x 0 0 0 1 1 0 0 0 0 0 0 0 0 x

- **count groups of connected \`1\` and require at least two \`0\` in between**
- **If #clusters =2 and distance ≥2 in any of the projections: Trigger**

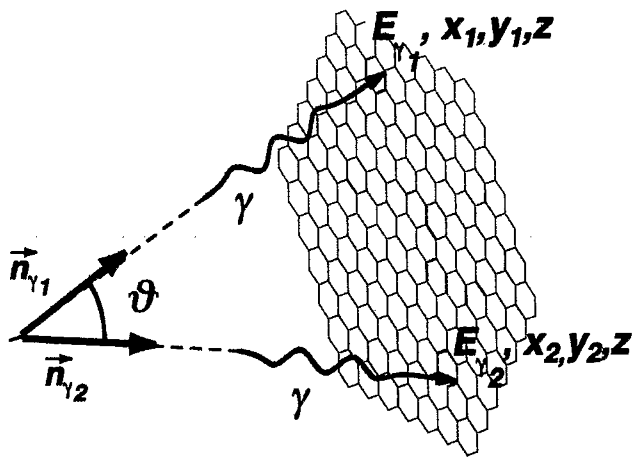
FPGA aproach allows redefining trigger conditions \`on the fly\`

Distance between two clusters

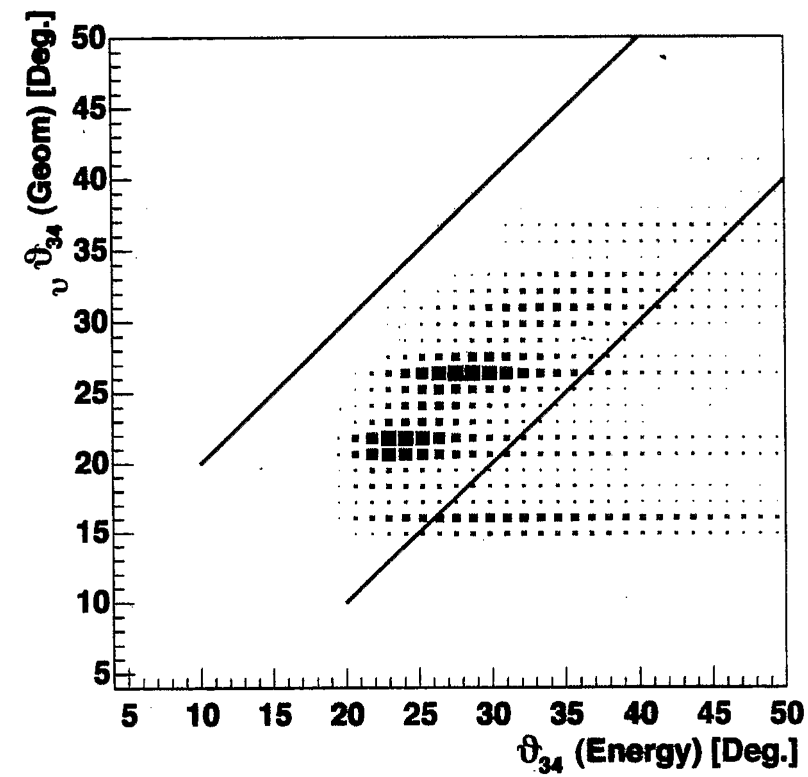


Cut on the Kinematics to Extract the 'Good' Events

Calculate ϑ in two different ways:



Sample from the last run



Energy:

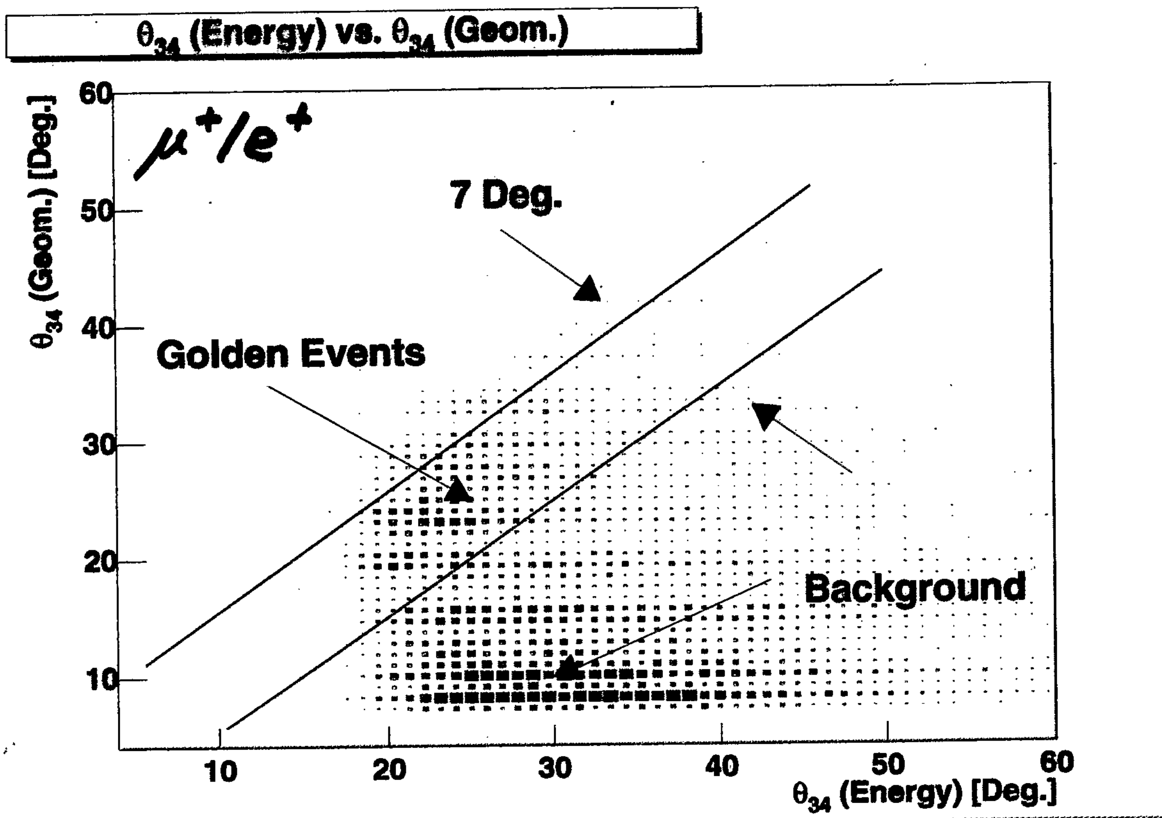
$$\cos\vartheta = 1 - m_e \frac{E_{\gamma_1} + E_{\gamma_1}}{E_{\gamma_1} \cdot E_{\gamma_1}}$$

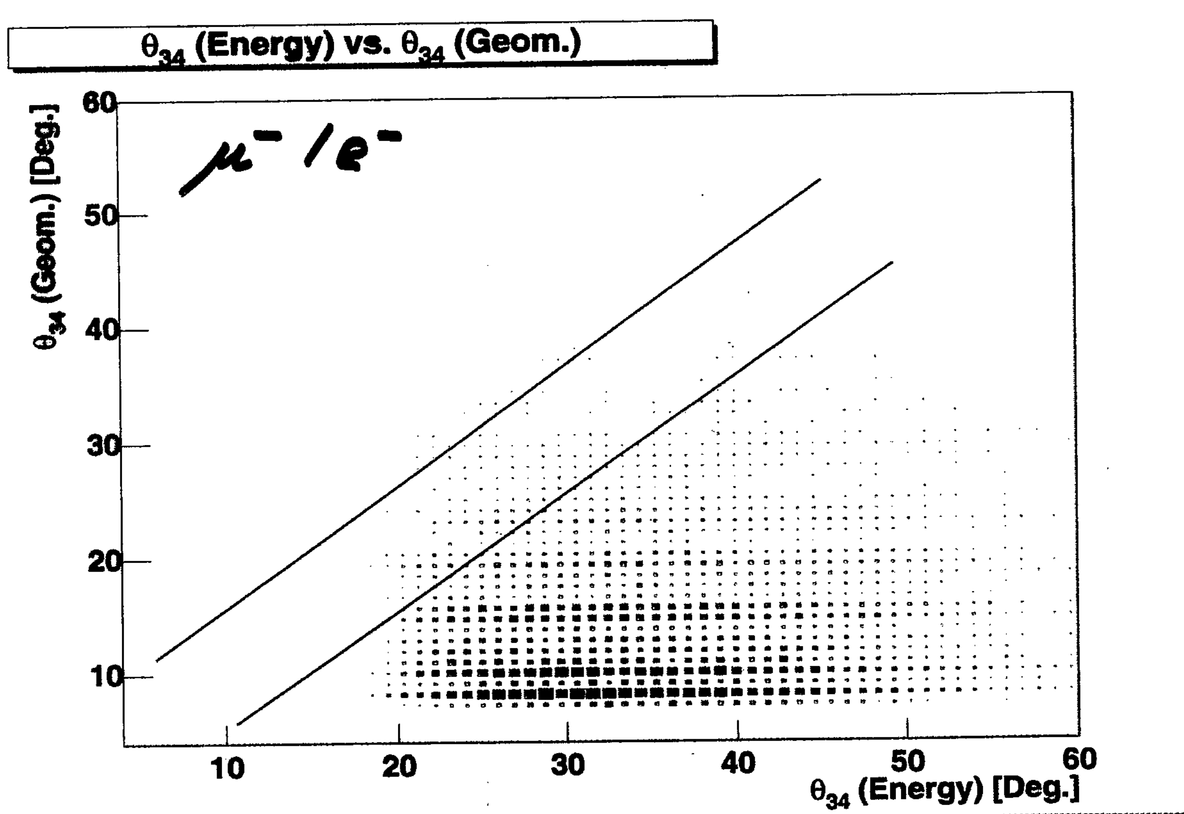
Geometry

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

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

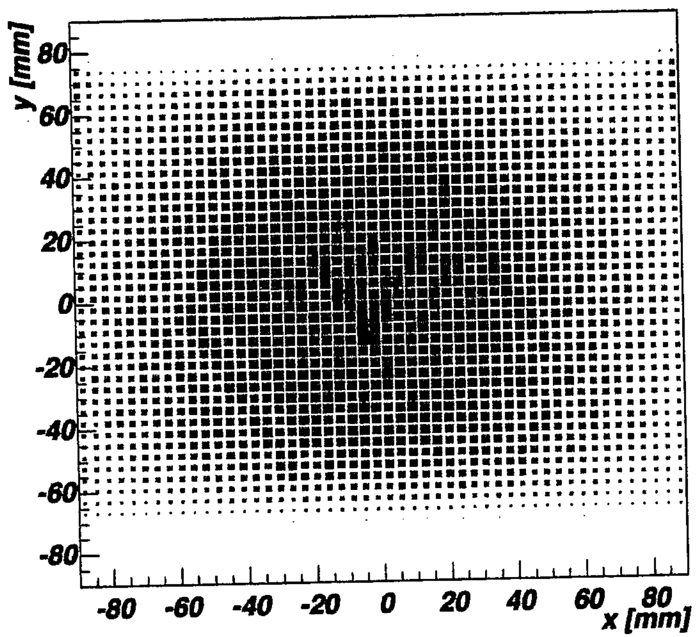
for 'good' annihilations


θ34 (Energy) vs. θ34 (Geom.)
μ+/e+
7 Deg.
Golden Events
Background
θ34 (Geom.) [Deg.]
θ34 (Energy) [Deg.]
10
20
30
40
50
60

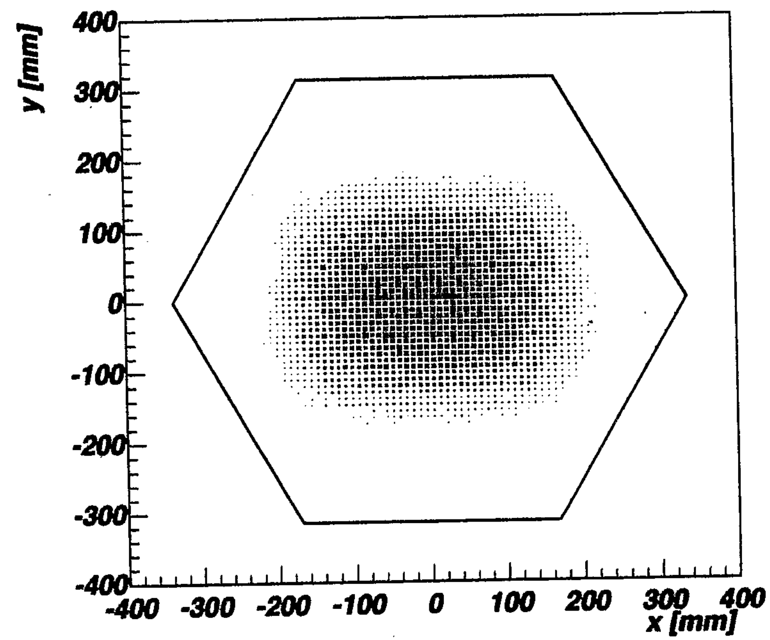

θ34 (Energy) vs. θ34 (Geom.)
μ−/e−
θ34 (Geom.) [Deg.]
θ34 (Energy) [Deg.]
10
20
30
40
50
60

Where do `good` annihilations

come from, and where do they go?



reconstructed position
of annihilations on the foil

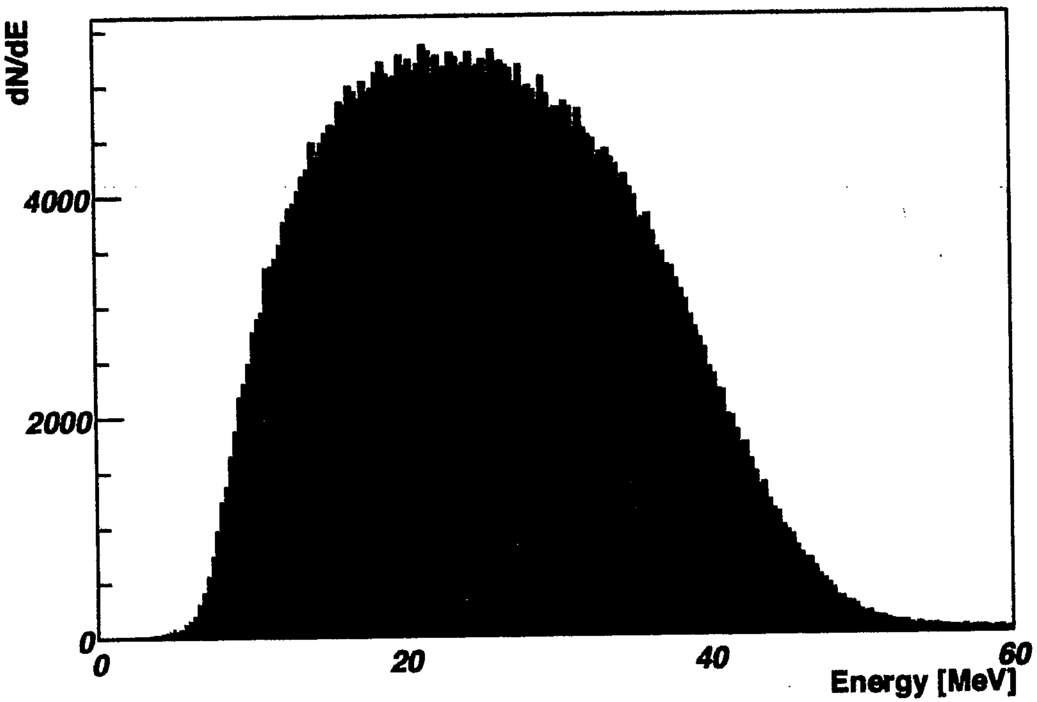


center of energy on the BGO-wall

Analysis, Step Two: From Raw Data to `Good` Events

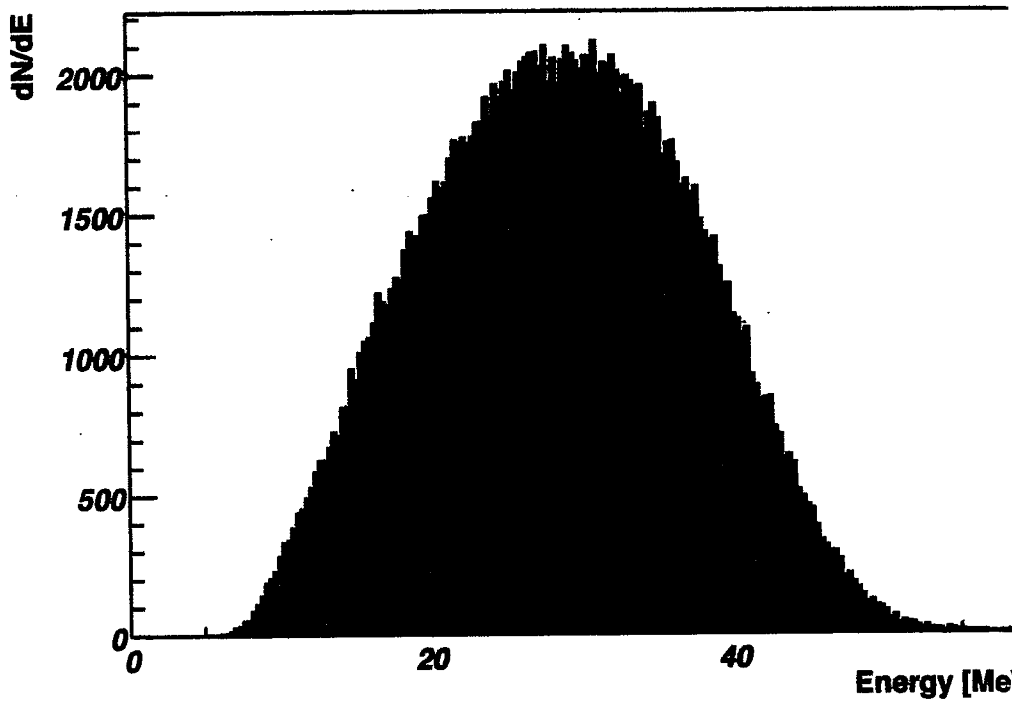
Energy ($E_{tot} = E_{\gamma 1} + E_{\gamma 2}$) spectra of annihilation events

After reconstruction (≈50 % Eff.)



charged track reconstructed, exactly two clusters in the BGO.

After selection (≈34 % Eff.)



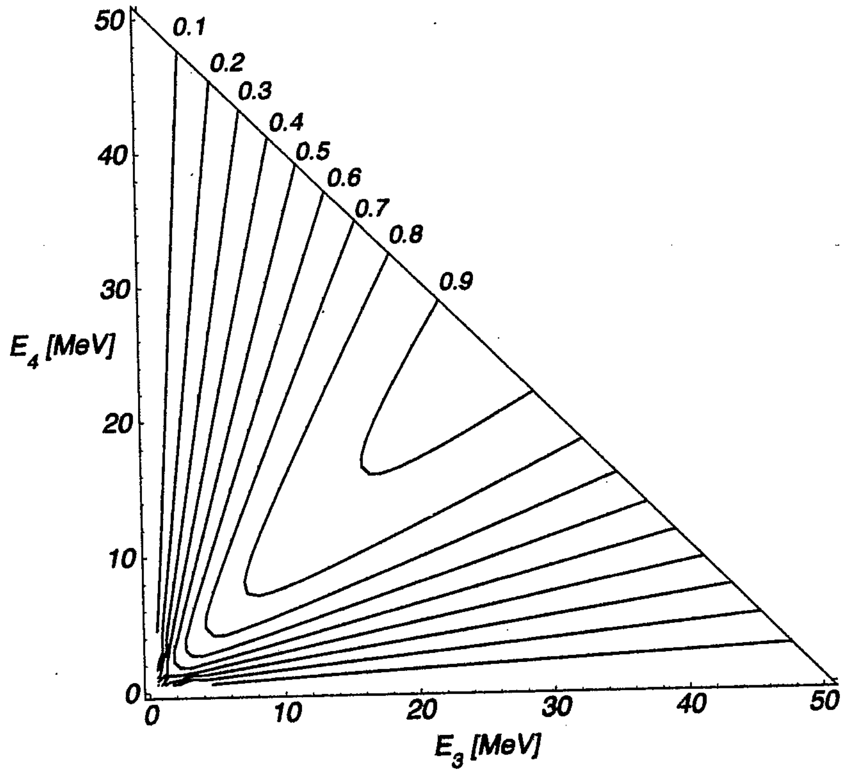
event kinematics must be consistent with annihilation hypothesis.

After all cuts ≈17% `good` annihilation events remain.

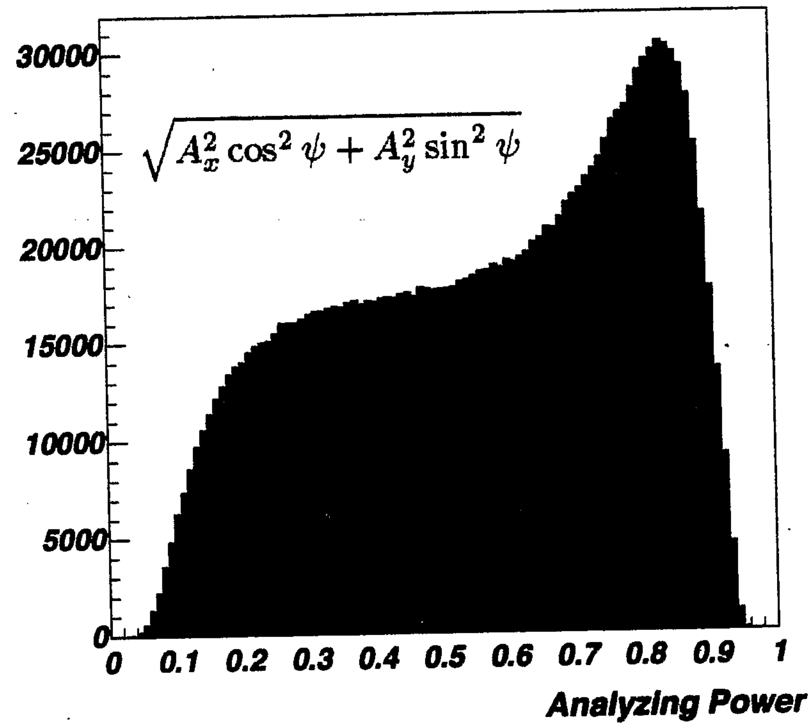
Theoretical and Experimental Analyzing Power

The analyzing power is the amplitude of the expected oszillation

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



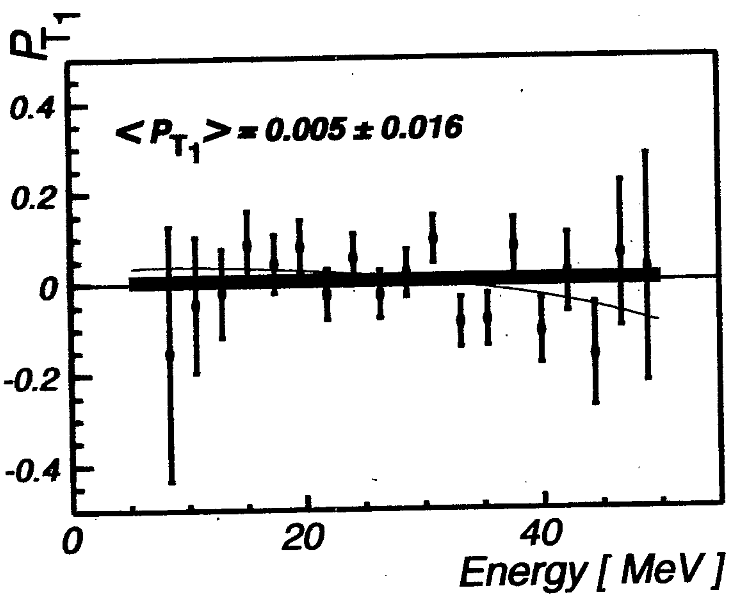
Theoretical analyzing power,
$\Psi = 90^o$ $P_{e^-} = 100\%$, $|P_T| = 1$

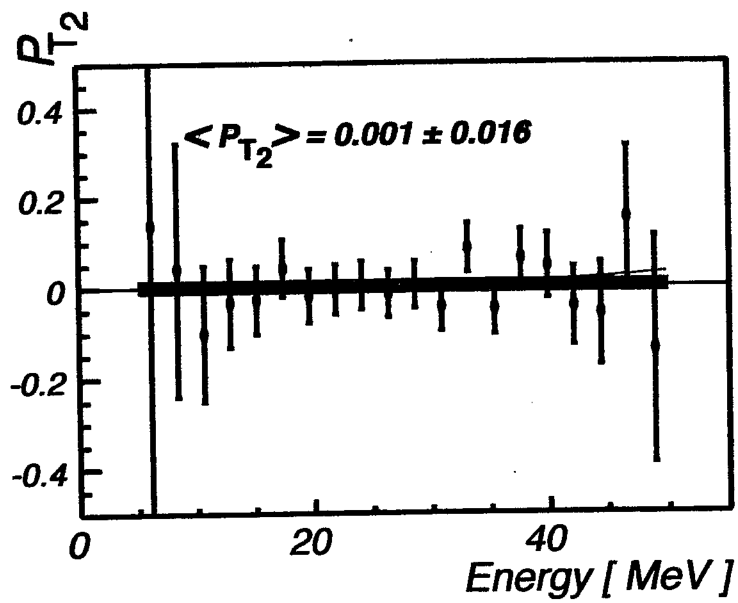


Analyzing Power of `good` annihilation events.
A_x and A_y are functions of the photon energies

Transverse Polarization Components P_{T_1} and P_{T_2}

- time zero from μSR Effect (→ orientation of muon spin relative to P_1 and P_2)
- rotation of transverse polarization components in the field of the spin precessing magnet (MC)
- convolution with energy loss of the positron in the apparatus (MC)
- sums of P_{T_1} and P_{T_2} for negative and positive foil polarization





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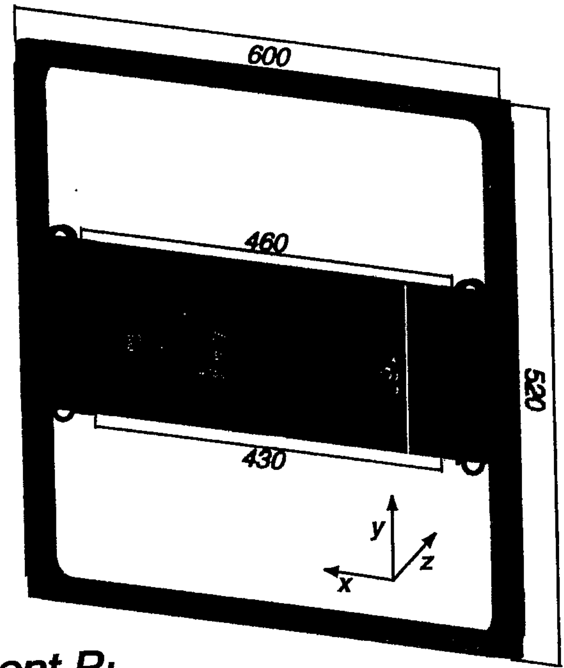
Measurement of the Longitudinal Polarization

using information about position on magnetized Vacoflux foil (determined by tracks reconstructed from drift-chamber data) where annihilations take place

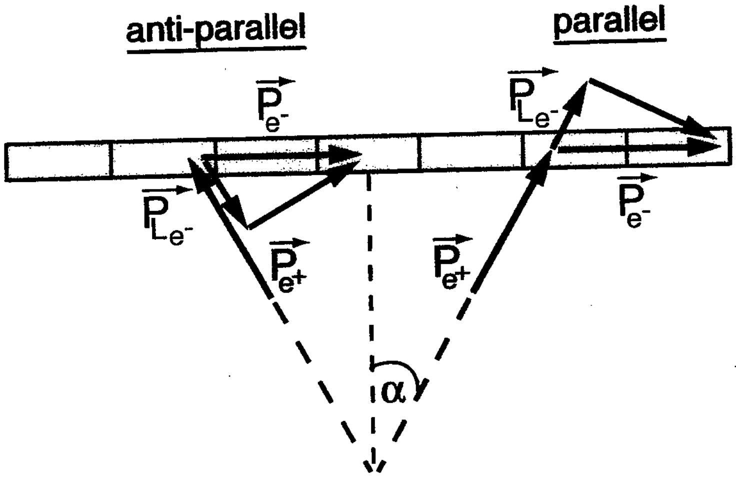


area on foil taken into account: 140^2 mm^2

area divided into rectangular bins (ij), 17 bins in x- and y-direction, respectively

Tracks that do not hit the center of the foil 'see' a longitudinal component $P_{L_{e^-}}$ of the polarization of the electrons in the foil.

This $P_{L_{e^-}}$ can either be parallel or anti-parallel to the positron polarization :



Longitudinal Polarization P_L of the Positrons

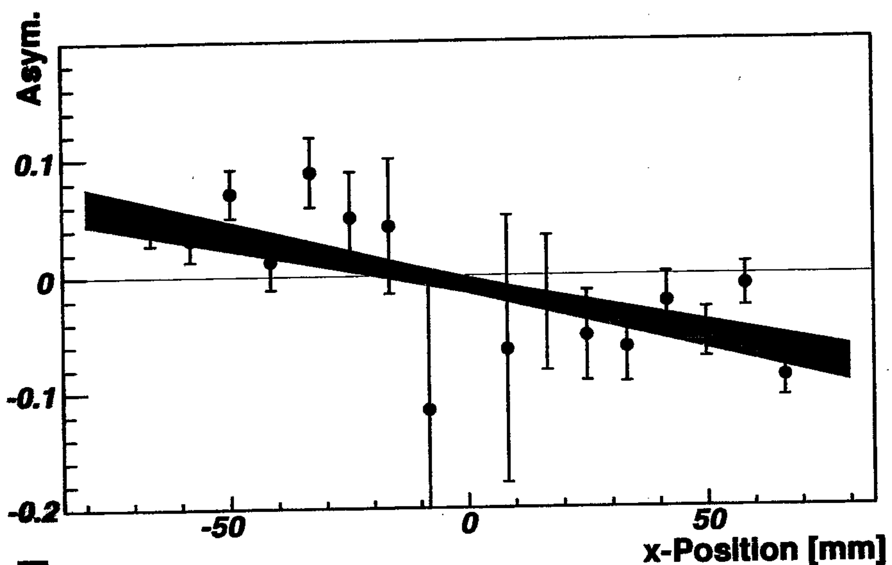
annihilation cross section depends on relative orientations of spins; it is larger if both spins are anti-parallel

Asymmetry: $$A_{ij} = \frac{\frac{n_{ij}^-}{N^-} - \frac{n_{ij}^+}{N^+}}{\frac{n_{ij}^-}{N^-} + \frac{n_{ij}^+}{N^+}}$$

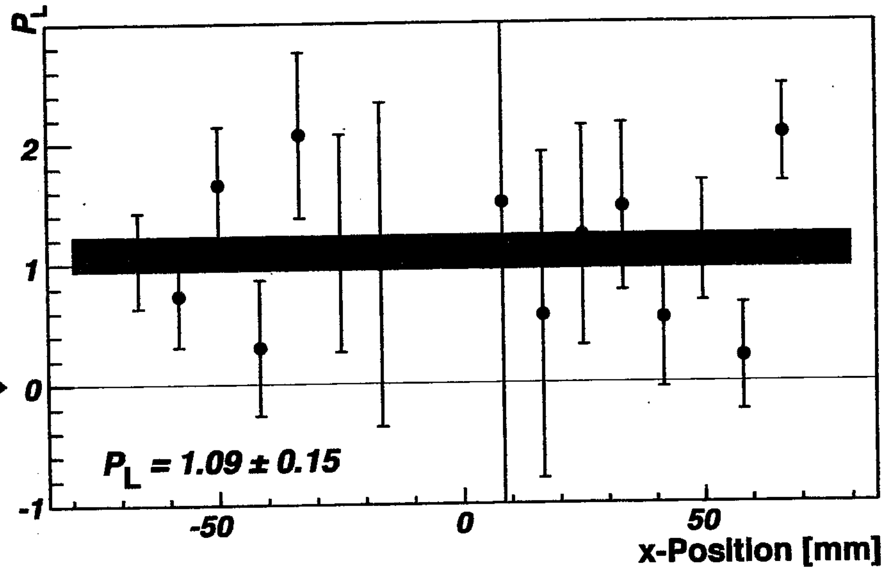
where n_{ij}^+ : number of annihilations in bin *ij* for positive foil polarization

N^+ : total number of annihilations for positive polarization

n_{ij}^-, N^-: same for negative polarization



- angle α
- elektron polarization in foil (P_{e^-} = 7.2 %)
- analysing power of 0.79
- background factor of 0.75 (backgr. ratio 25 %, mainly due to bremsstrahlung)

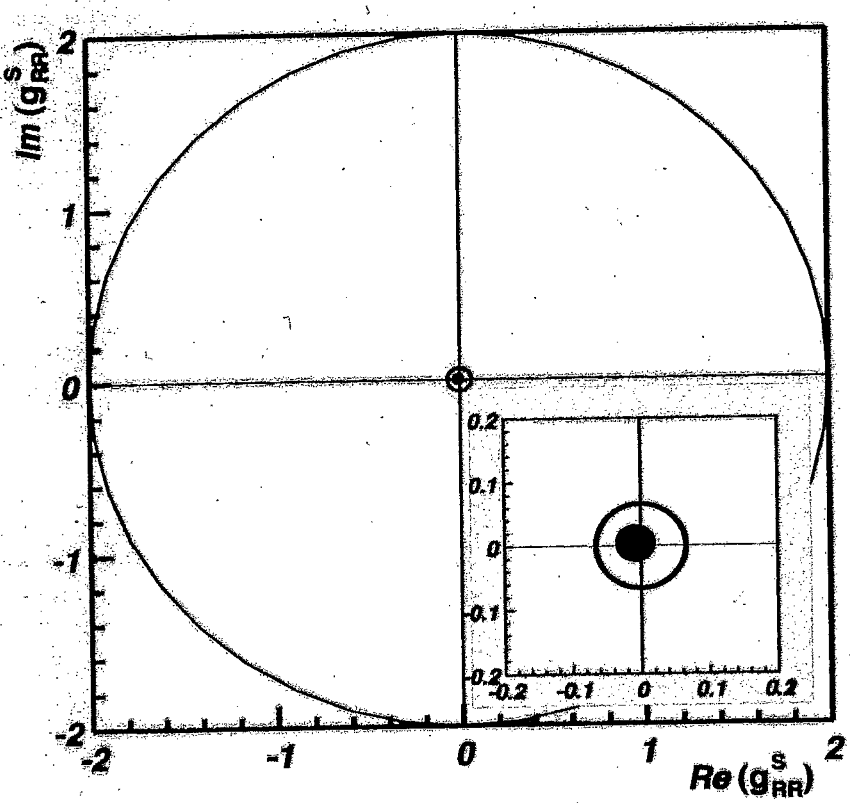


8. Preliminary Results

	General analysis	V - A + g^S_{RR}
$10^3 \times \langle P_{T_1} \rangle_E$	5 $\pm$ 16	5 $\pm$ 16
$10^3 \times \langle P_{T_2} \rangle_E$	1 $\pm$ 16	1 $\pm$ 16
$10^3 \times \eta$	95 $\pm$ 60	-4 $\pm$ 14
$10^3 \times \eta''$	98 $\pm$ 57	$-10^3 \times \eta$
$10^3 \times \alpha'/A$	-13 $\pm$ 29	0
$10^3 \times \beta'/A$	8 $\pm$ 16	1 $\pm$ 7
$10^3 \times$ Re g^S_{RR}	–	-8 $\pm$ 28
$10^3 \times$ Im g^S_{RR}	–	4 $\pm$ 28
$10^3 \times \lvert g^S_{RR} \rvert$	–	9 $\pm$ 28

Implications from the Results

1. No Evidence for Additional Scalar Couplings in Muon Decay



Green circle: Result of a general analysis including all possible left- and righthanded scalar, vector and tensor couplings.

Red circle: Only one additional righthanded scalar coupling interferes with the lefthanded vector coupling in the SM.

$$\eta = -0.004 \pm 0.014$$

$$\frac{\beta'}{A} = 0.001 \pm 0.007$$

$$Im(g^S_{RR}) = 0.004 \pm 0.028$$

$$Re(g^S_{RR}) = -0.008 \pm 0.028$$

$$|g^S_{RR}| = 0.009 \pm 0.028$$

8. Outlook

Improve precision of previous experiment [1] by almost one order in magnitude to:

$$\Delta < P_{T_1} > \; = \; 0.004$$
$$\Delta < P_{T_2} > \; = \; 0.004$$

Assuming $V - A$ and one additional coupling , this will reduce the limits for η and g^S_{RR} to

$$\Delta\eta \; = \; 0.004$$
$$\Delta Re\{g^S_{RR}\} \; = \; 0.009$$
$$\Delta Im\{g^S_{RR}\} \; = \; 0.009$$

[1] H. Burkard, F. Corriveau, J. Egger, W. Fetscher, H.-J. Gerber, K.F. Johnson, H. Kaspar, H-J. Mahler, M. Salzmann, F. Scheck

Phys. Lett. **160B** (1985) 343.