# *A Search for Time Reversal Invariance Violation in $\mu$ Decay*

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***Ph.D. Seminar ETH / Uni Zurich***

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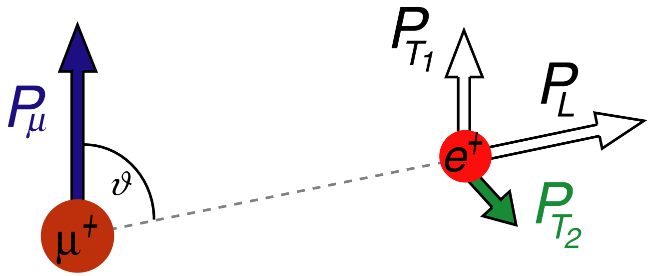
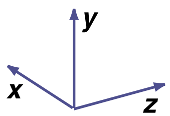
# Search for physics beyond the Standard Model with `small` experiments

## Transversal polarization of $e^+$ from $\mu^+$ decay would be an indication of new physics

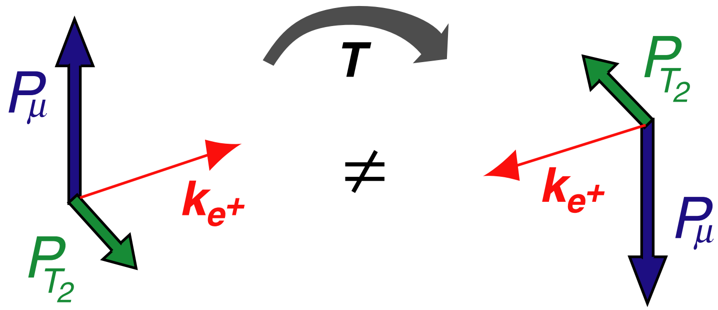



| SM: | beyond SM:[1)] | current limits |
|---|---|---|
| $P_{T_1} \approx 0$ | $P_{T_1}(x) \approx -\frac{2\eta}{3-2x}$ | $0.016 \pm 0.021$ |
| $P_{T_2} = 0$ | $P_{T_2}(x) \approx 2\,\frac{2\frac{\beta'}{A}}{3-2x}$ | $0.007 \pm 0.022$ |

[1)] *x is the reduced energy* $x = \frac{E_{e+}}{E_{max}}$, $\eta$ *and* $\beta/A$ *are Michel parameters*

## Time Reversal Violation in a purely leptonic decay



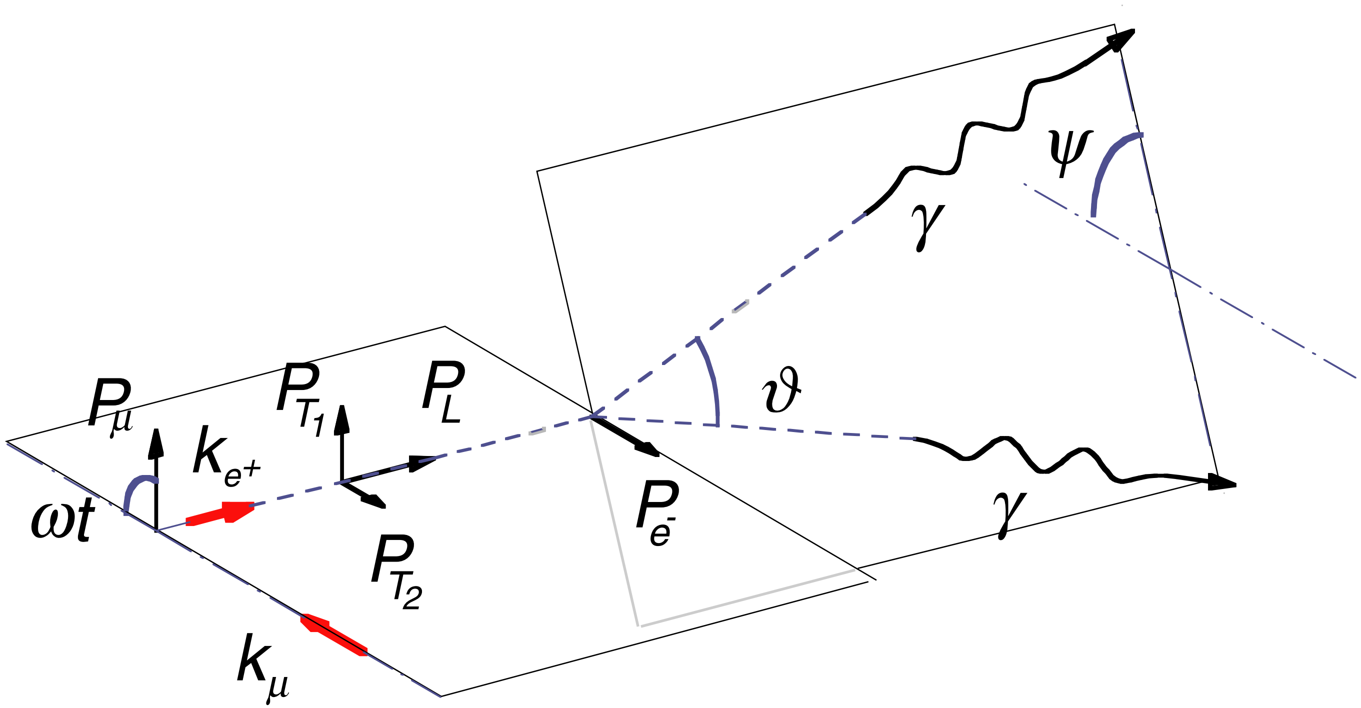

## Search for new scalar couplings

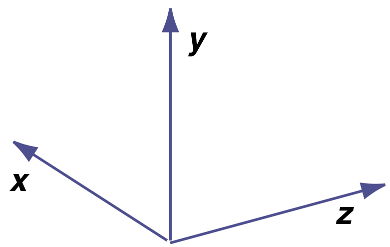
$$\eta = \frac{1}{2} Re\left\{g^S_{RR}\right\}$$

## Model independent measurement of $G_F$

$$G_F = \sqrt{192\,\pi^3 \frac{1}{\tau_\mu m_\mu^5}\left(1 - 4\,\eta \frac{m_e}{m_\mu}\right)}$$

# Measure $e^+$ Polarization via the Spin Dependent $e^+ e^-$ Annihilation-Cross-Section

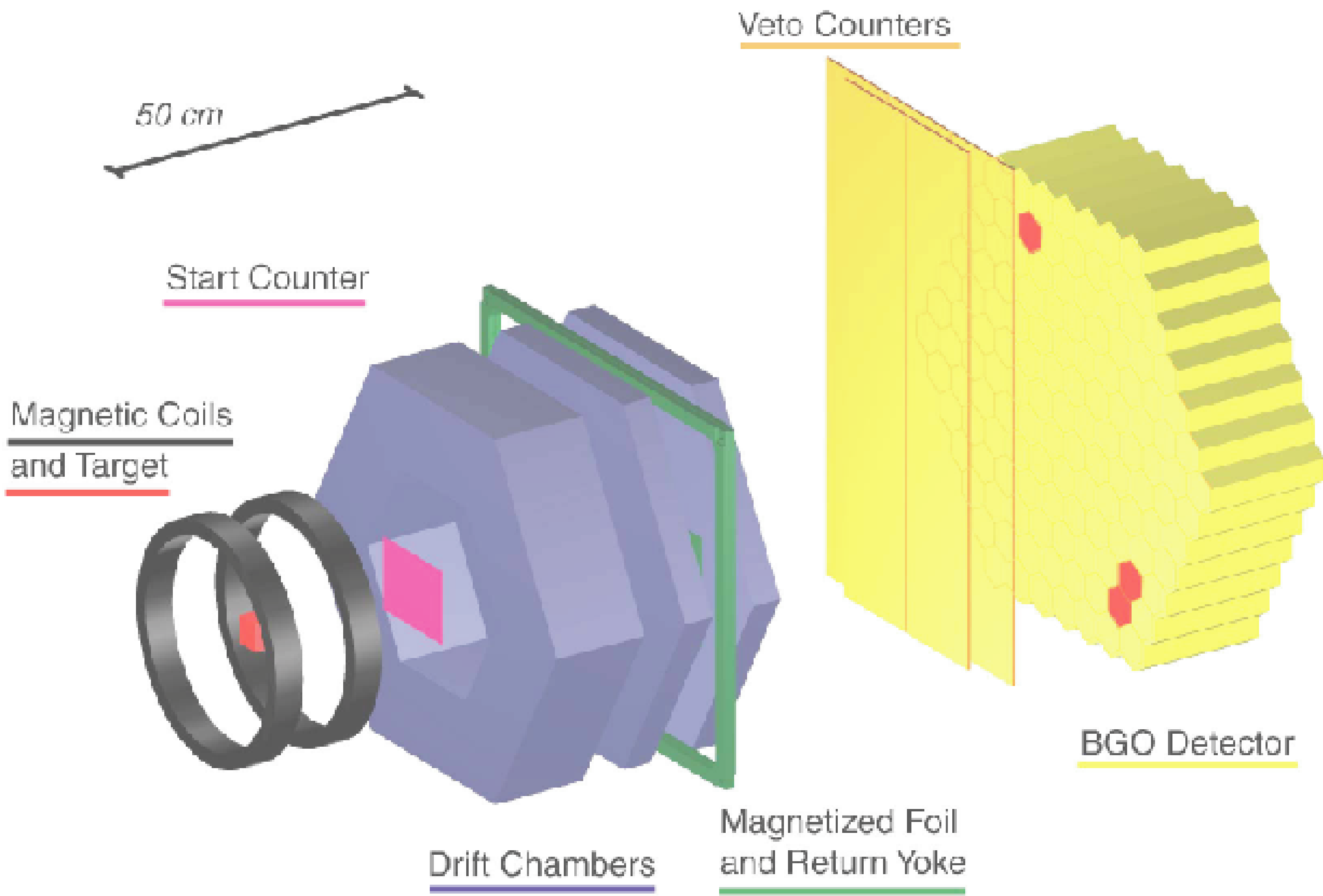



***$\mu$ Spin rotates with $\omega$ around z axis***

***Decay $e^+$ and polarized $e^-$ annihilate into two detected photons***

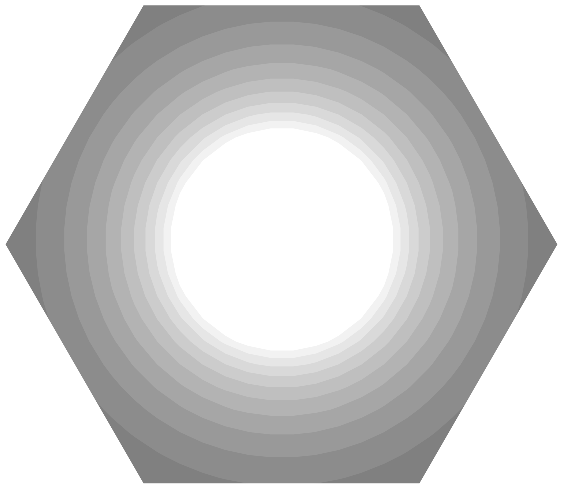
***$\Psi$ depends on $e^+$ polarizaton***



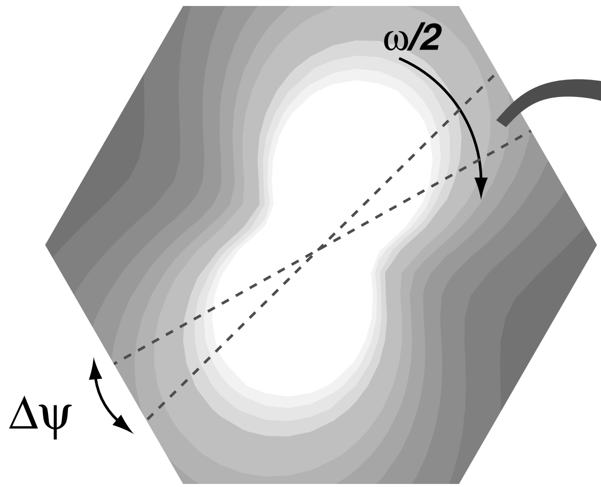
Veto Counters
50 cm
Start Counter
Magnetic Coils
and Target
BGO Detector
Drift Chambers
Magnetized Foil
and Return Yoke

# How would a $P_T$ Signal look like ?

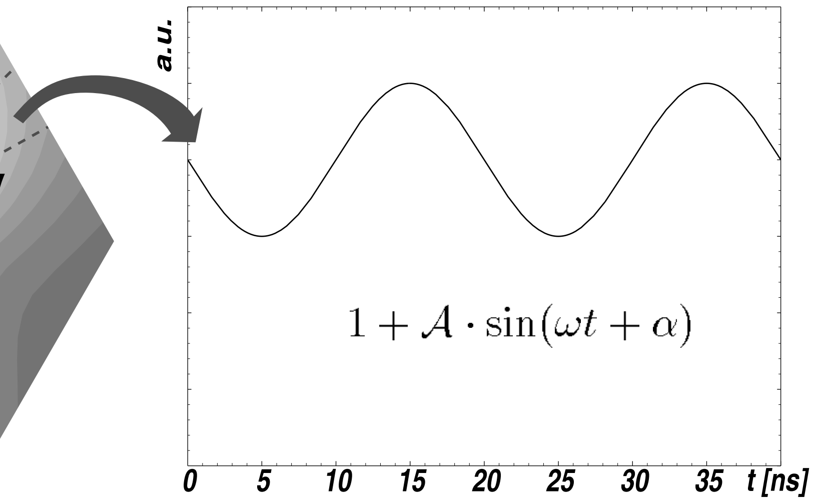
## Simulated photon intensity distribution on the BGO wall [1)]



**No Transversal Polarisation**




**$|P_T| = 1$**



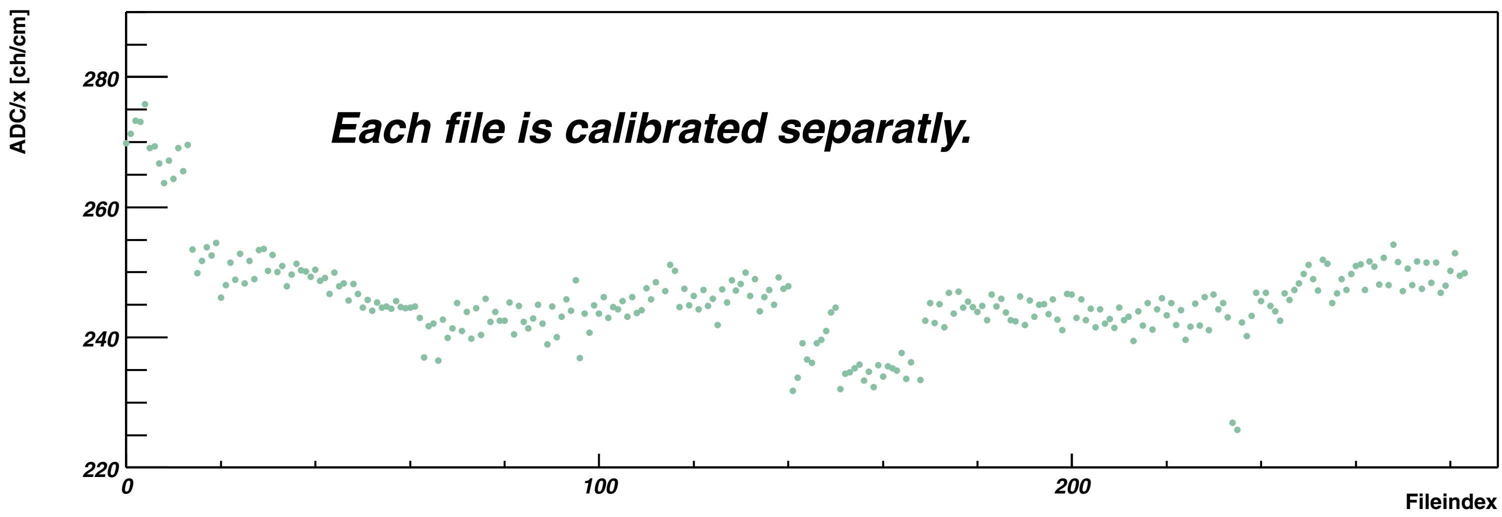

**Time spectrum for fixed $\Delta\psi$**
**$\mathcal{A}$ and $\alpha$ are functions of $P_{T_1}$ and $P_{T_2}$**

**Transverse polarization gives an oscillation signal with frequency $\omega$ in the time spectrum of the annihilation photons. Here $\omega$ is the spin precession frequency and t is the time from $\mu$-stop to its decay.**

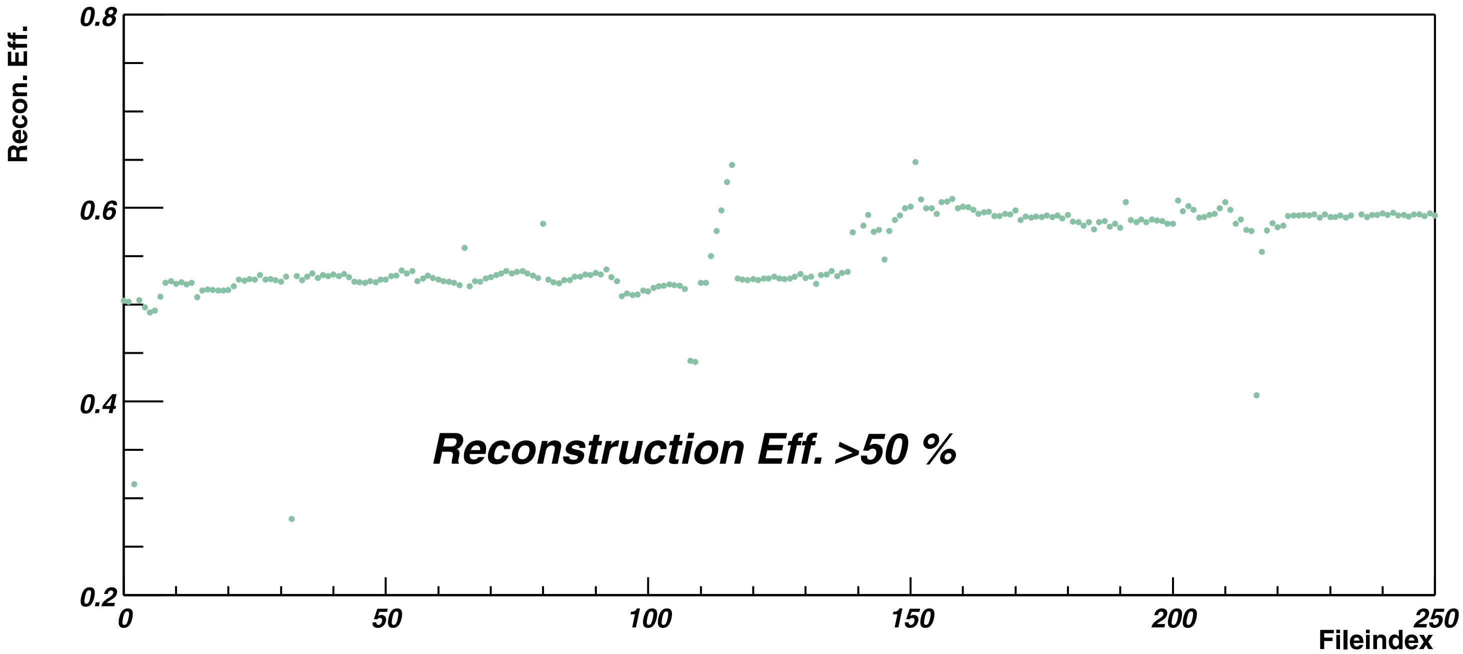
[1)] $P_T$ @ 45°, $E_{\gamma_1} = E_{\gamma_2}$ = 10 MeV, $e^-$ Polarisation in magn. Foil 100%

# Analysis Step One: Reconstruction

## Calibration constant




## Reconstruction efficiency

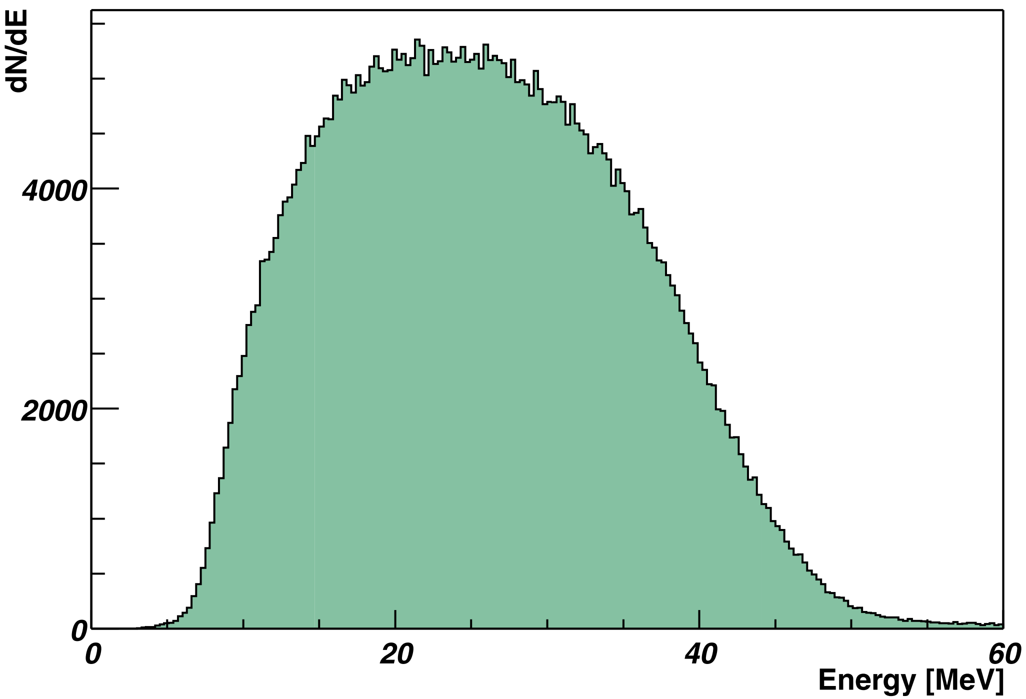



*Two clusters and at leaset one reconstructed track required*

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

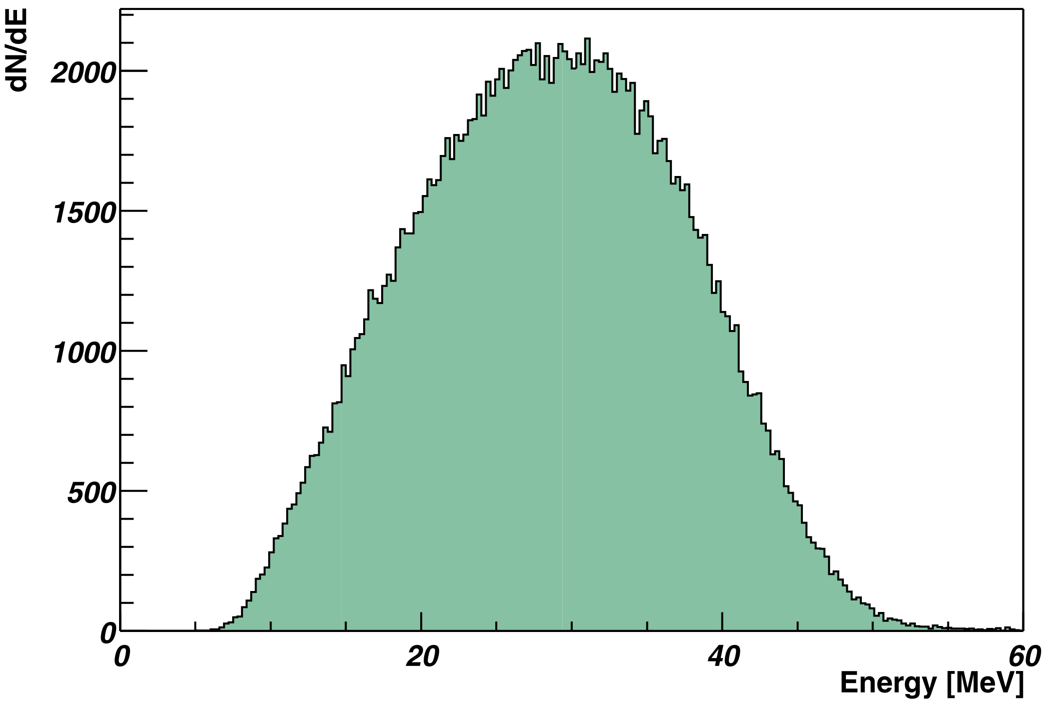
## Energy ($E_{tot} = E_{\gamma 1} + E_{\gamma 2}$) spectra of annihilation events

**After reconstruction (≈50 % Eff.)**




*charged track reconstructed,*
*exactly two clusters in the BGO.*

**After selection (≈34 % Eff.)**

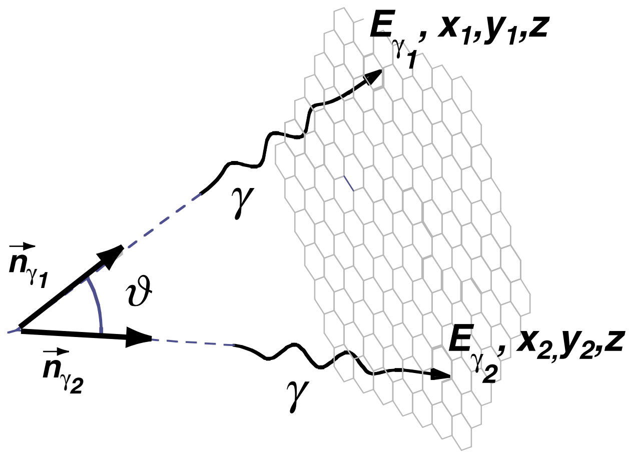



*event kinematics must be*
*consistent with annihilation*
*hypothesis.*

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

# *Cut on the Kinematics to Extract the 'Good' Events*

***Calculate $\vartheta$ in two different ways:***




***Energy:***

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

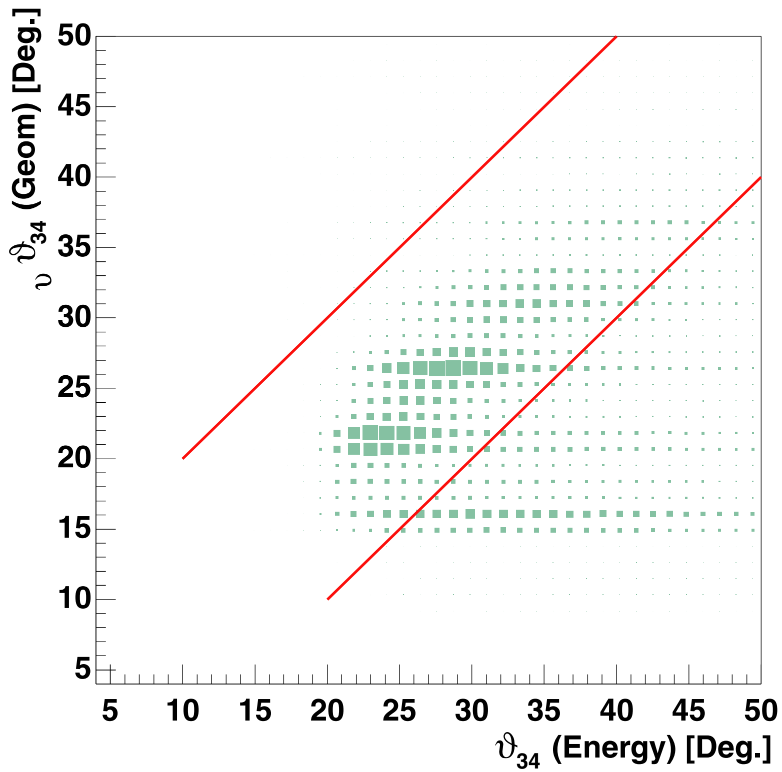
***Geometry***

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

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

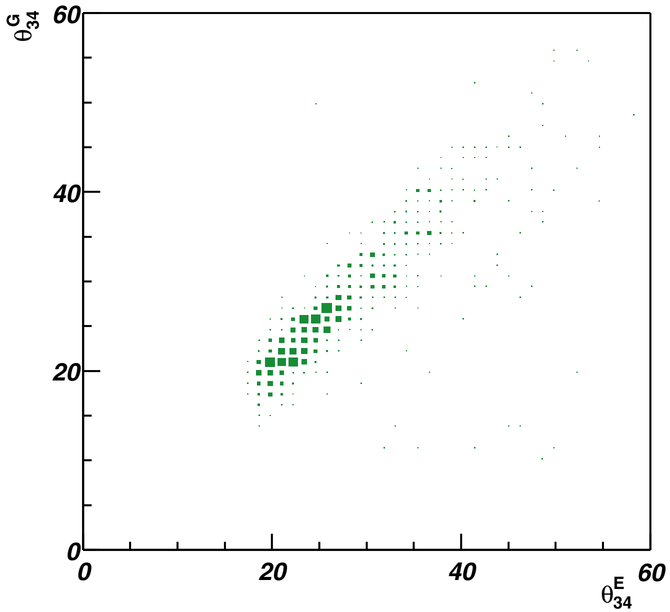
***for 'good' annihilations***

***Sample from the last run***

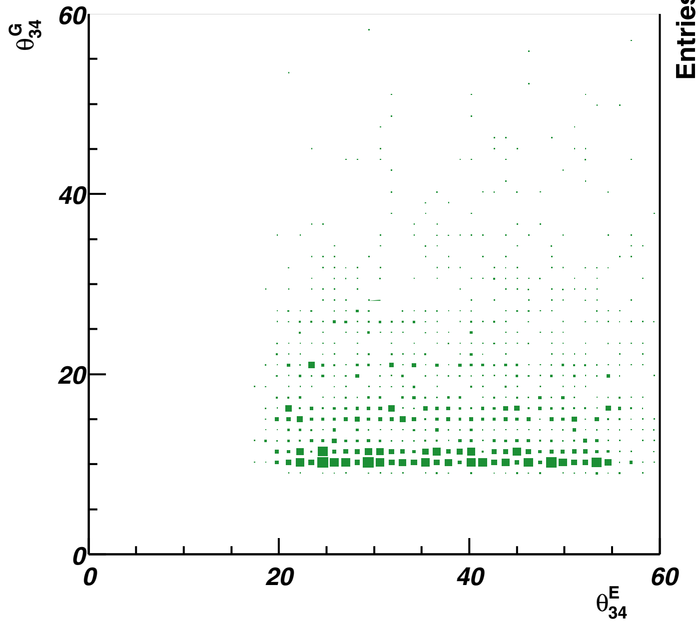


# Use Monte Carlo to Find Optimal $\vartheta$ Cut

**Annihilations in the foil**

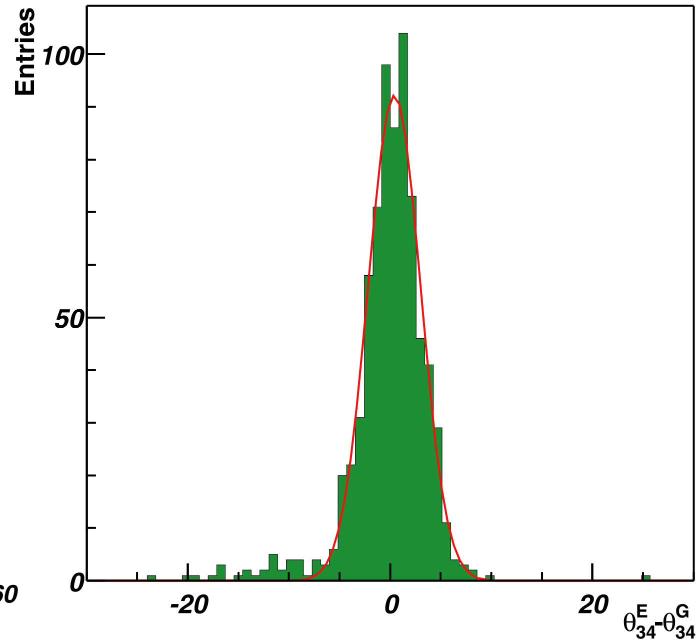



**Background**




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

**for good annihilations**




$$|\vartheta^{Geom} - \vartheta^{Energy}| < 10^{o}$$

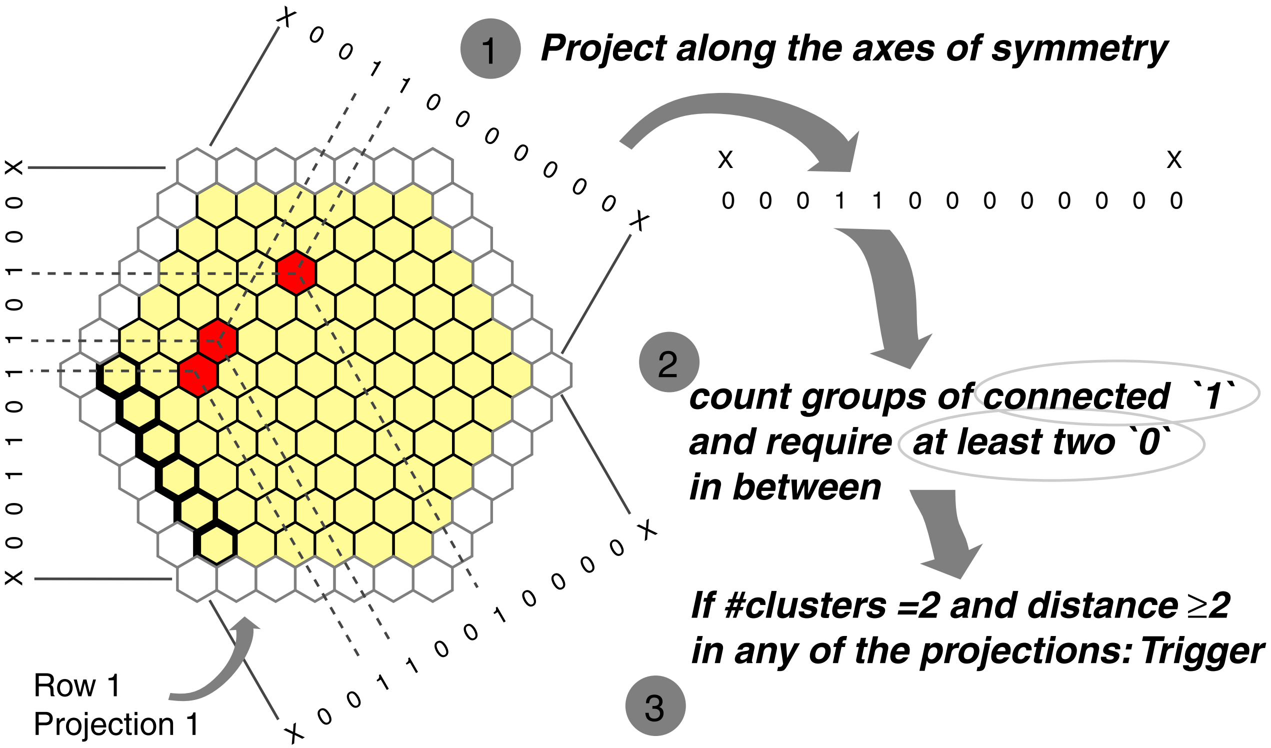
# Triggering on Two Photons at a minimal Distance: The Cluster Recognition Unit

## How does it work?

**Kinematics require a minimal cluster distance**

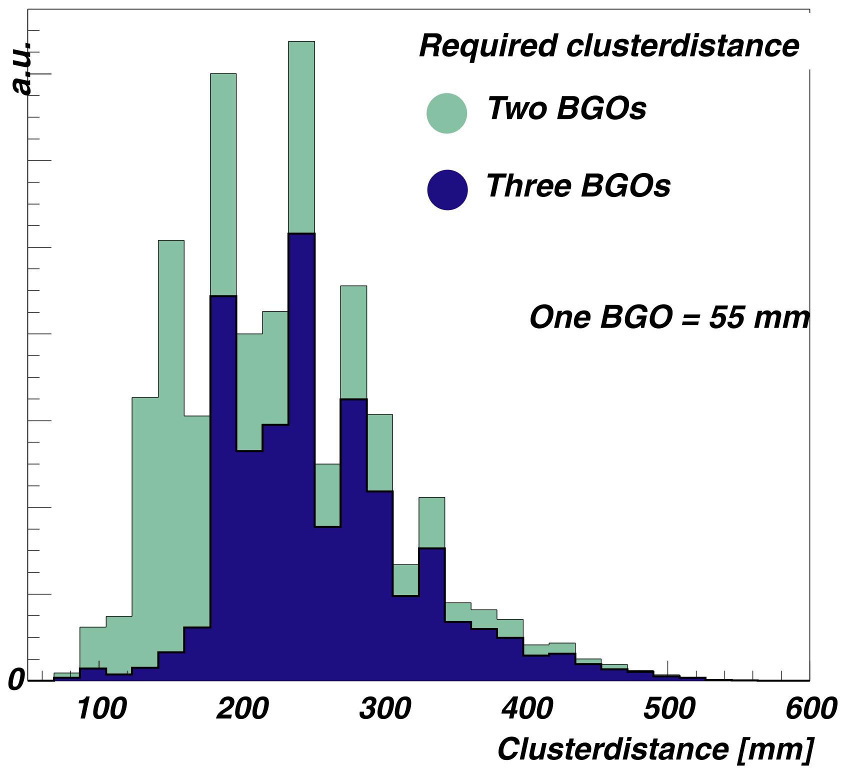
$$\cos\vartheta = 1 - m_e \frac{4}{E_{e^+}} \qquad d = 2z\tan\frac{\vartheta}{2}$$

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



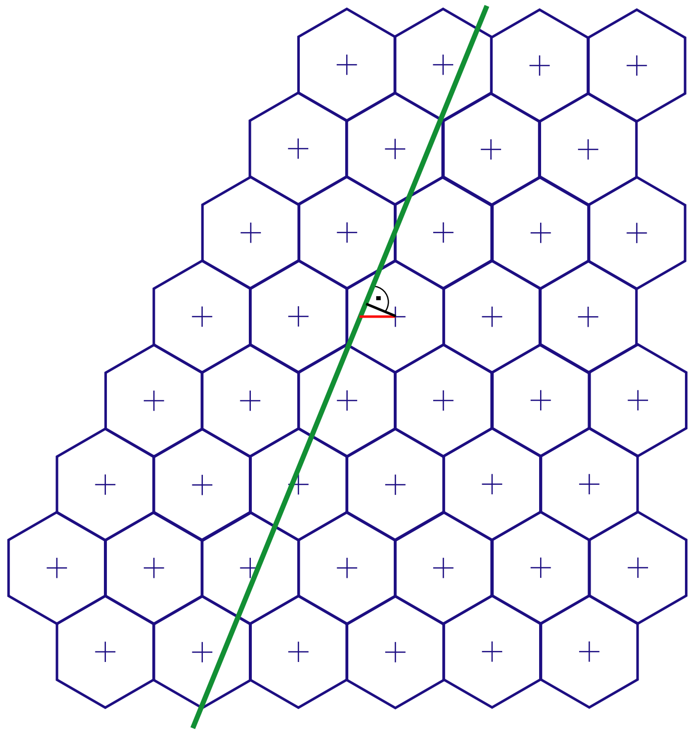

## FPGA aproach allows redefining trigger conditions `on the fly`

**Distance between two clusters**

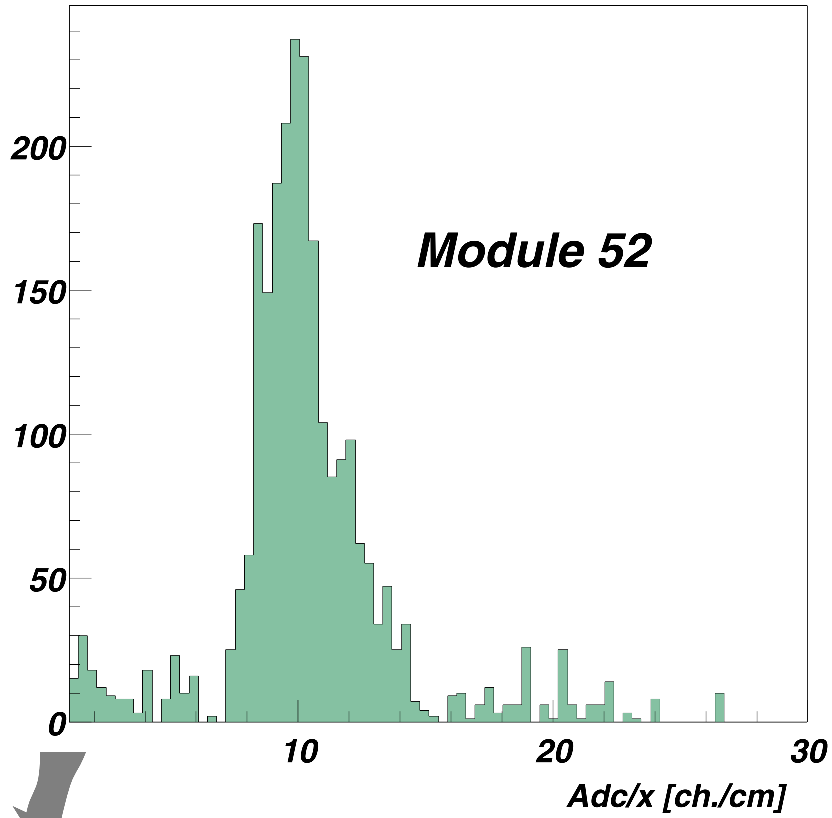


# Data is Calibrated with Cosmic Muons

***Reconstructing the cosmic tracks gives the tracklength in BGOs***



***Histogram Adc/x for cosmics***

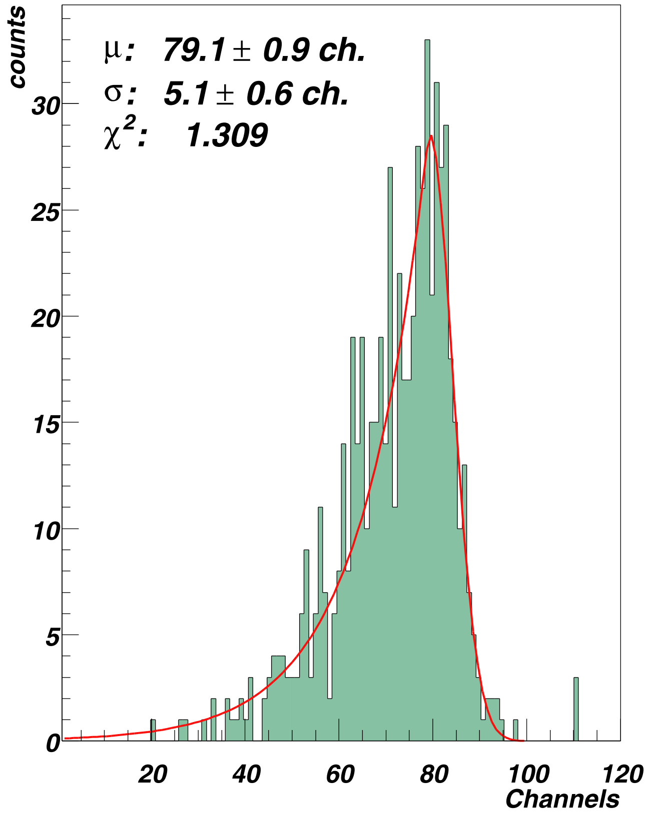


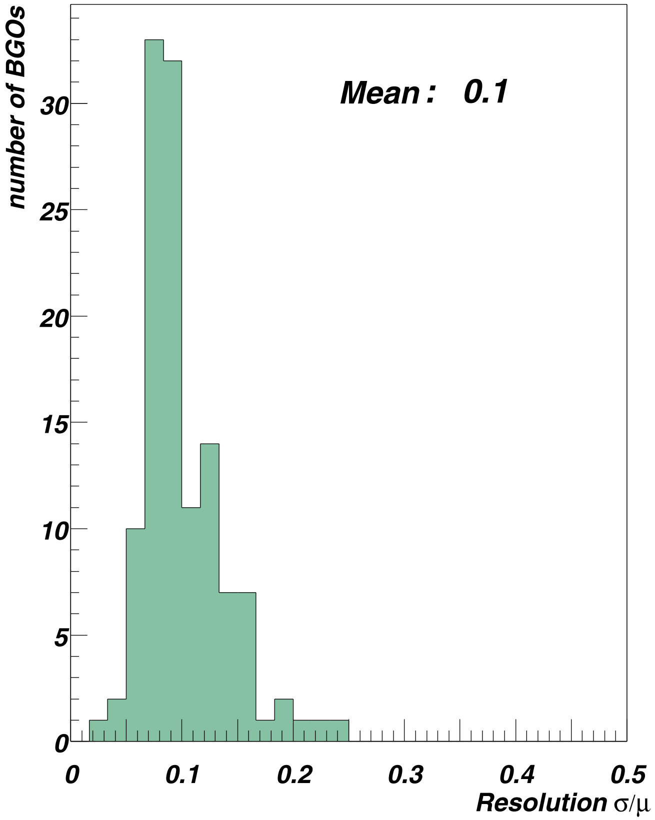

***Monte Carlo***

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

***Calibration constant for BGO number i***

# Energy Resolution Was Measured With a Am-Be Source

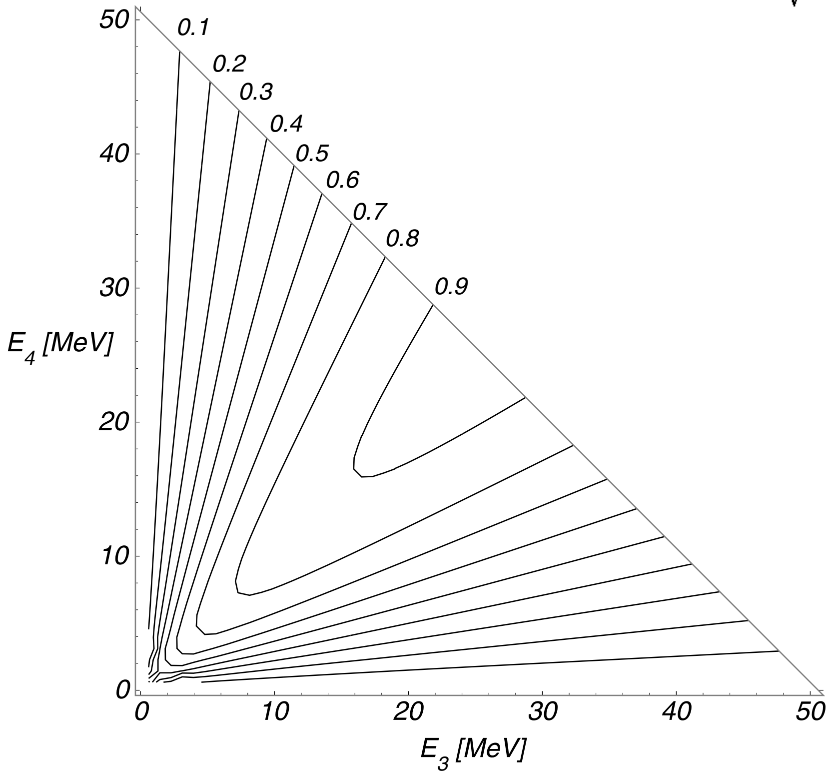


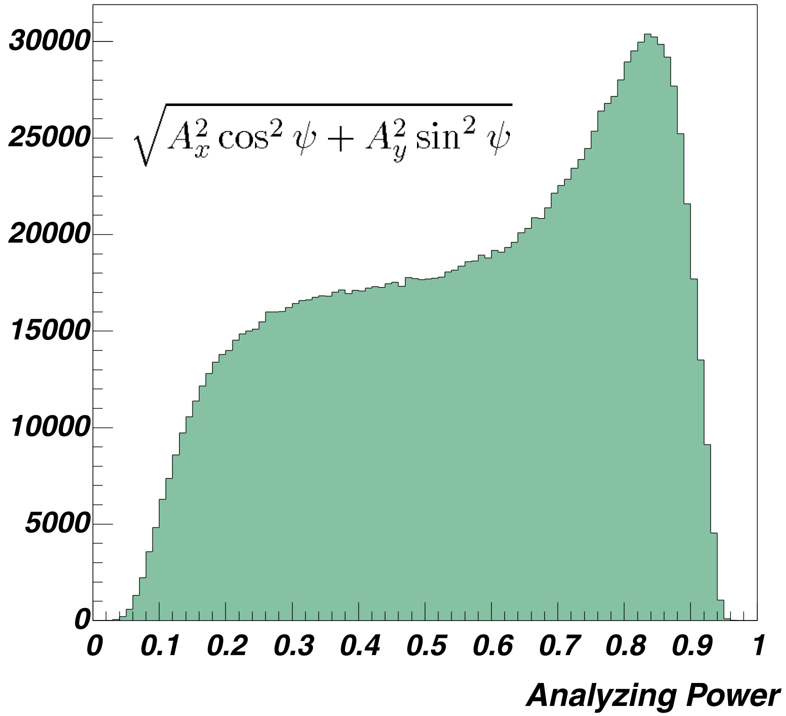
# *Theoretical and Experimental Analyzing Power*

## *The analyzing power is the amplitude of the expected oszillation*

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



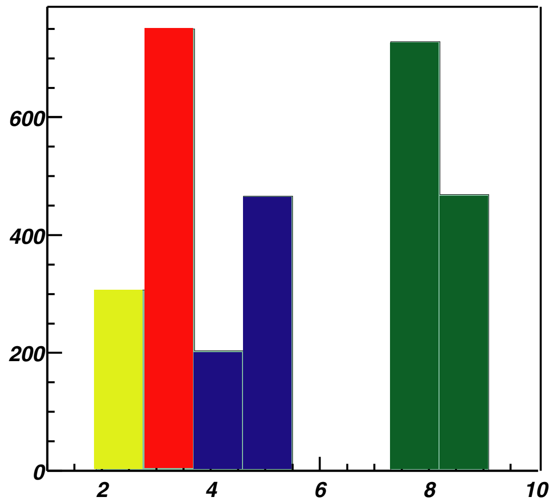

***Theoretical analyzing power,***
***$\Psi$= 90$^o$ $P_{e^-}$ = 100%, |$P_T$| =1***



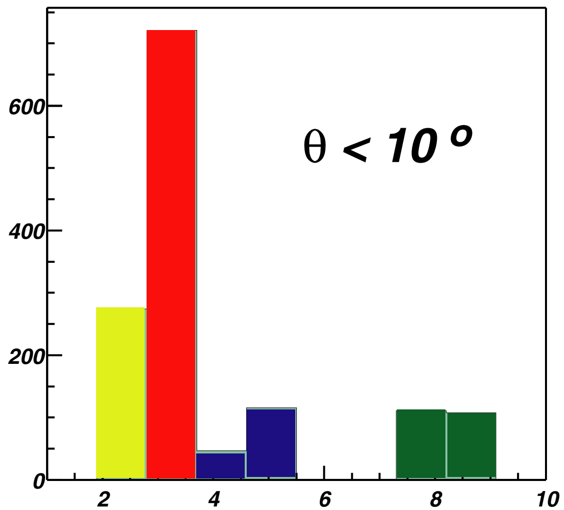

***Analyzing Power of `good` annihilation events, $P_{e^-}$ = 100%, assumed.***
***$A_x$ and $A_y$ are functions of the photon energies***

# Background is Dominated by Bremsstrahlung

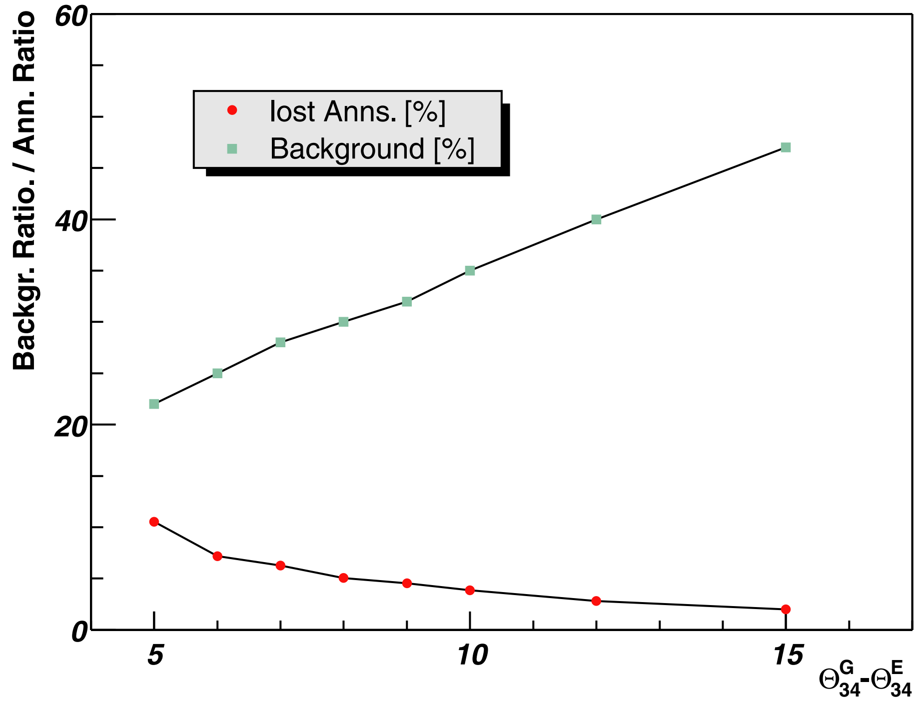
## No cuts applied




## Kinematics cut applied




## Background as a function of the cut

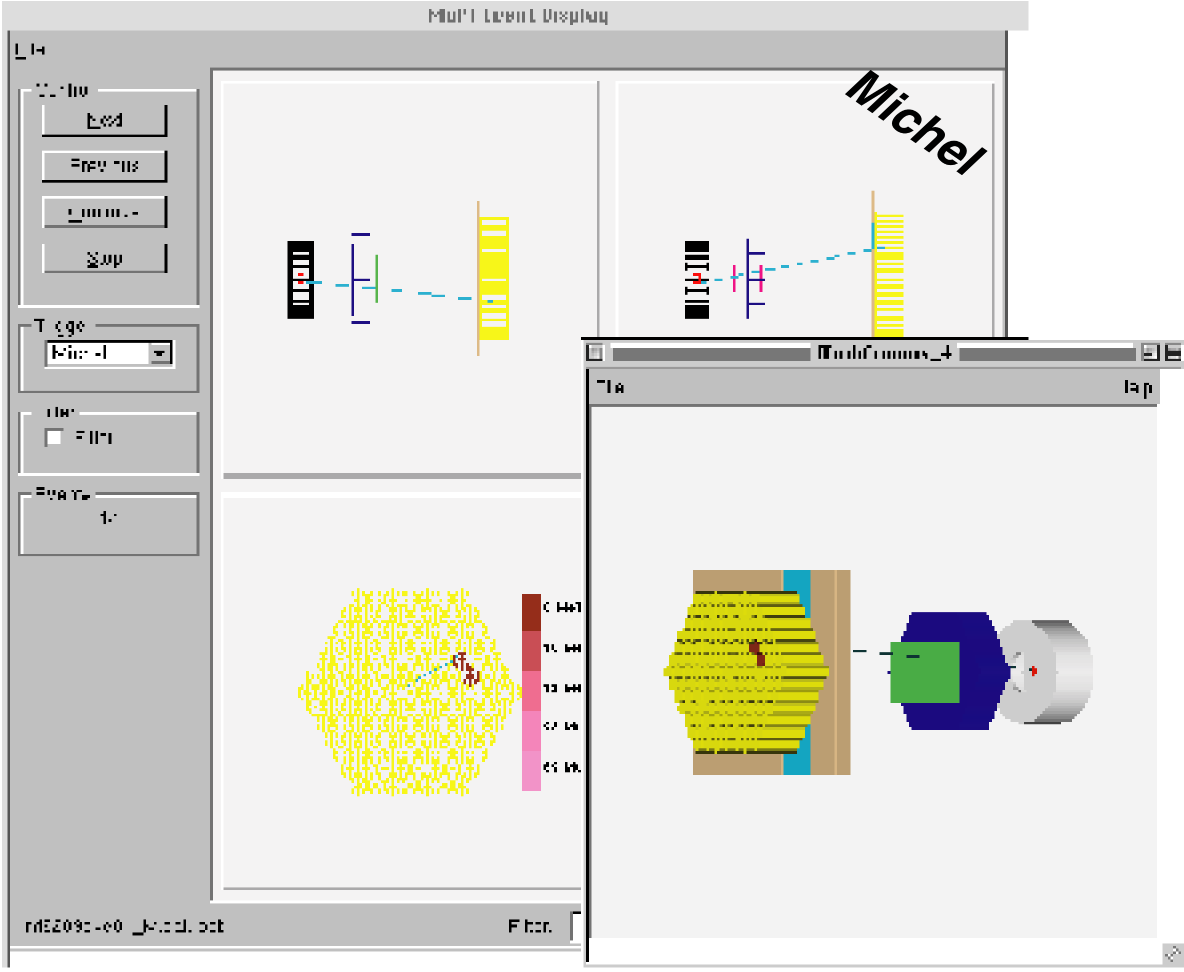


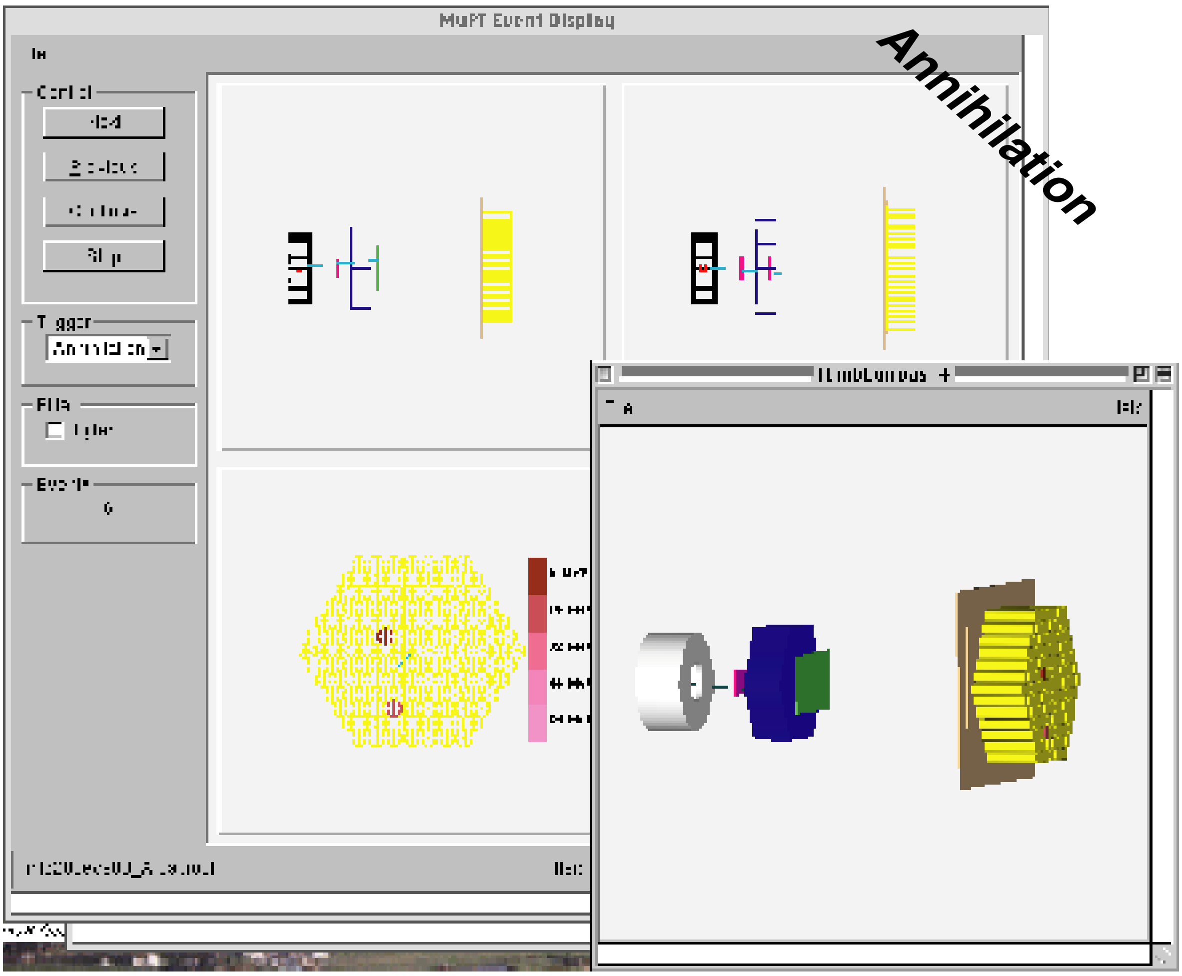

*Annihilations elsewhere*

*Annihilations in Foil*

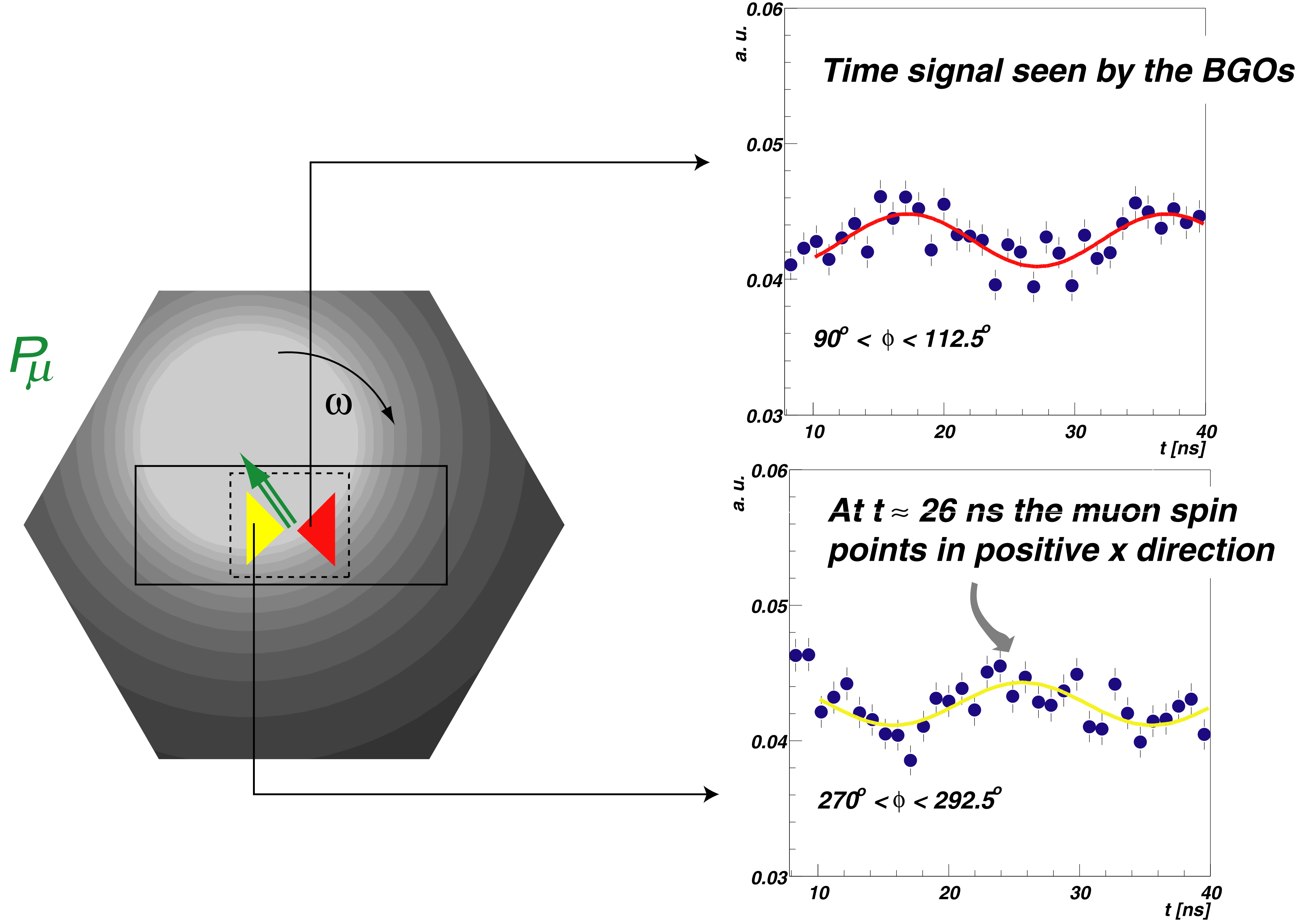
*Single Bremsstrahlung*

*Double Bremsstrahlung*


Michel

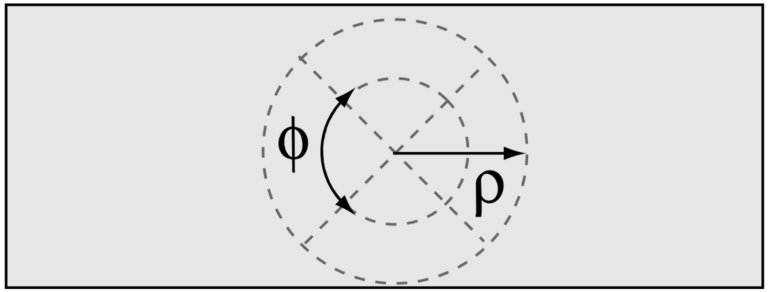

MuPT Event Display
Annihilation

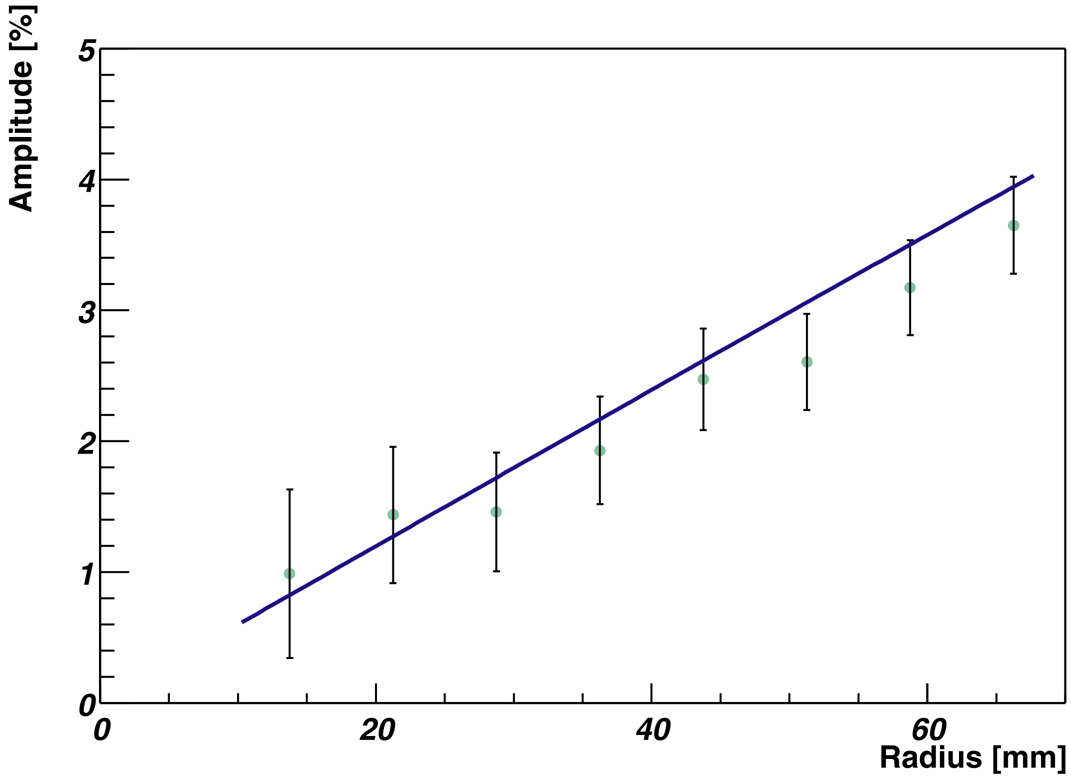
# μSR Effect is used to find the direction of the Muon Spin



# *Amplitude of the μSR Effect as a Function of Distance ρ From the Symmetry Axis*

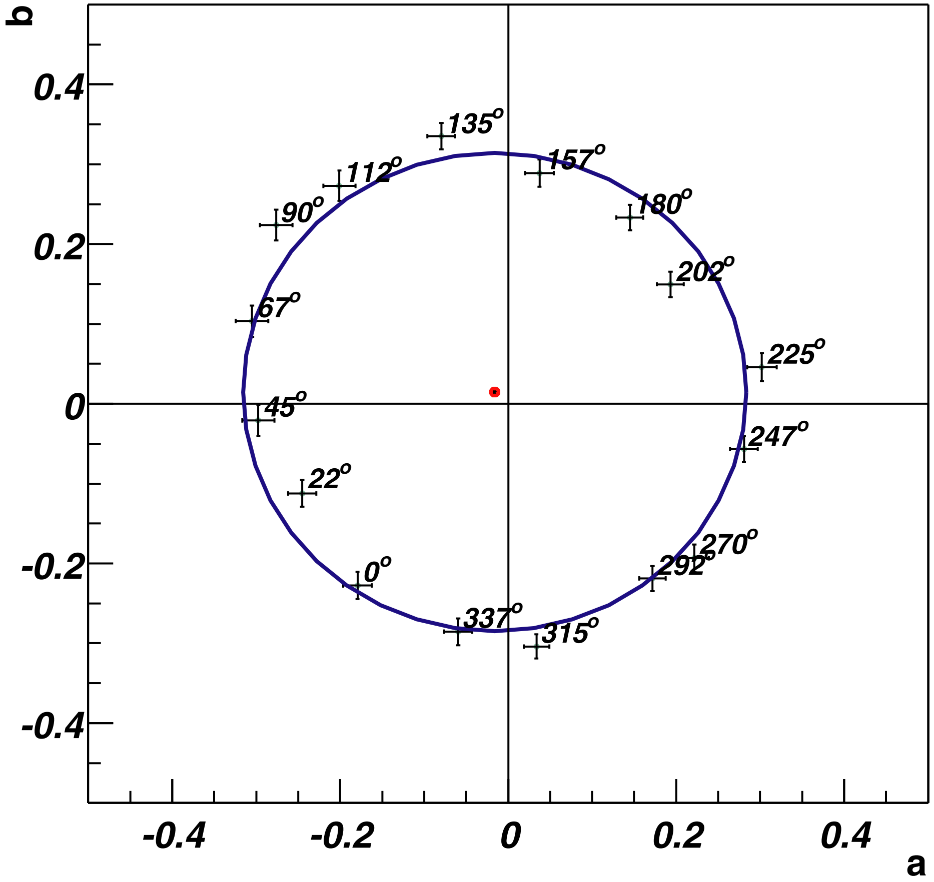
***Divide fiducial area on the magnetized foil into ρ and ϕ bins***



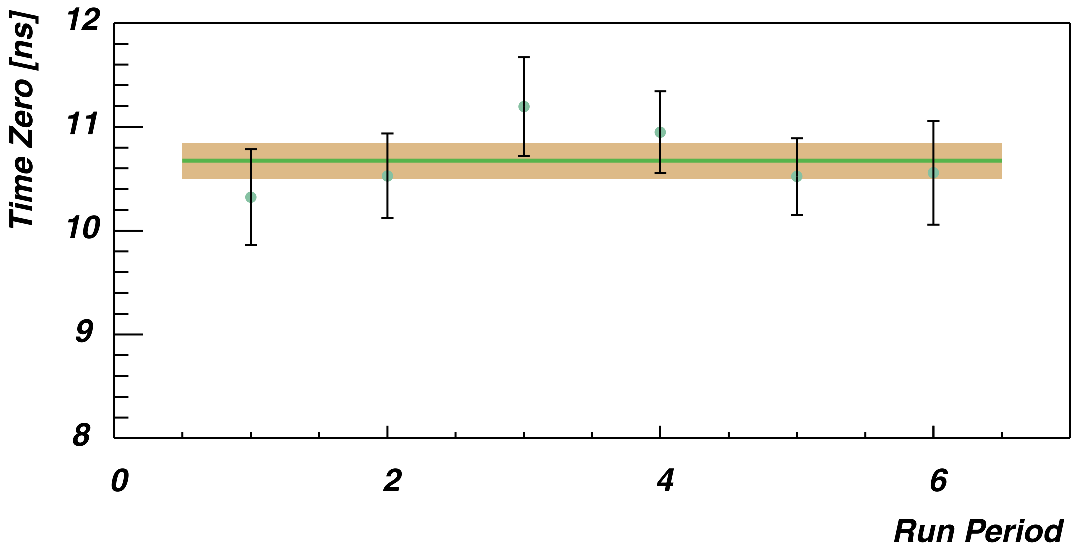

***The blue line indicates theoretical expectation***

# Phases and Amplitudes for all $\phi$- bins




Average $\mu$SR amplitude: 0.297 $\pm$ 0.004, consistent with theory.

Stability of the Time-Zero during the whole run




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

# *A First Fit to the Data: $P_T$ at the Time of Annihilation*

## *Fitting the components $P_1$ and $P_2$ using a Log Likelihood parameter estimation*

***Use the diff. annihilation cross-section***

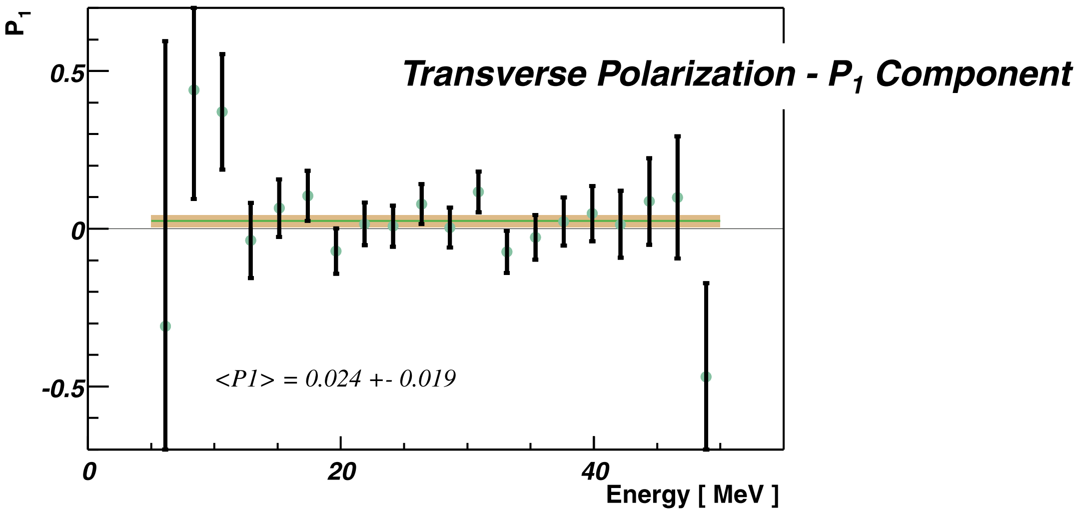
$$\frac{1}{\sigma_0} \cdot \frac{d\sigma}{d\Omega} = 1 + \mathcal{A} \cdot \sin(\omega t + \alpha)$$
$$=: f(P_1, P_2, E_{\gamma_1}, E_{\gamma_2}, \Psi, t)$$

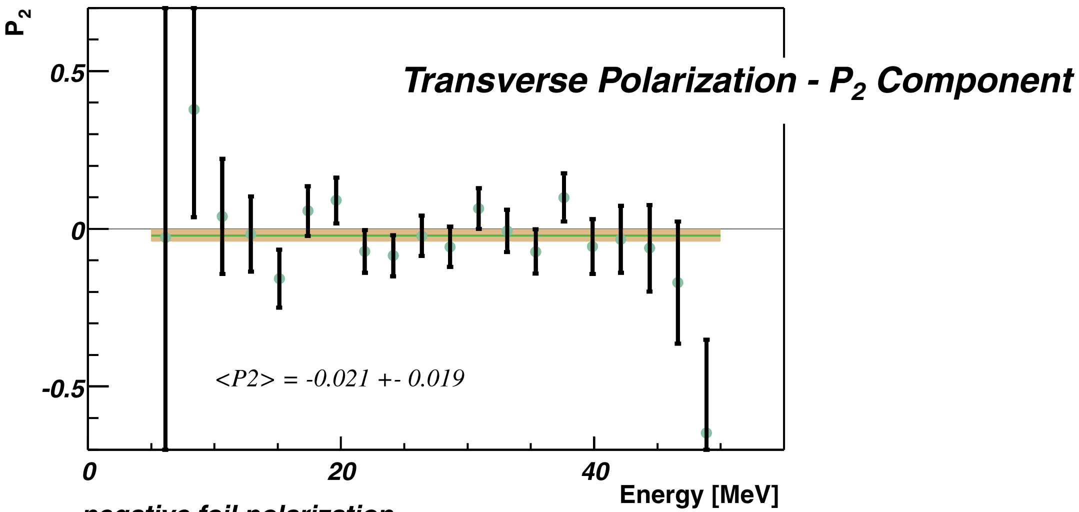
***where amplitude and phase are functions of the Energy and $\Psi$***

$$\mathcal{A} = \mathcal{A}(P_1, P_2, E_{\gamma_1}, E_{\gamma_2}, \Psi)$$
$$\alpha = \alpha(P_1, P_2, E_{\gamma_1}, E_{\gamma_2}, \Psi)$$

$$\mathcal{L}(P_1, P_2) := -\ln \prod_i^n f(P_1, P_2, E^i_{\gamma_1}, E^i_{\gamma_2}, \Psi^i, t^i)$$
$$= -\sum_i^n \ln f^i(P_1, P_2)$$

***where n is the number of 'good' annihilation events***




***negative foil polarization***

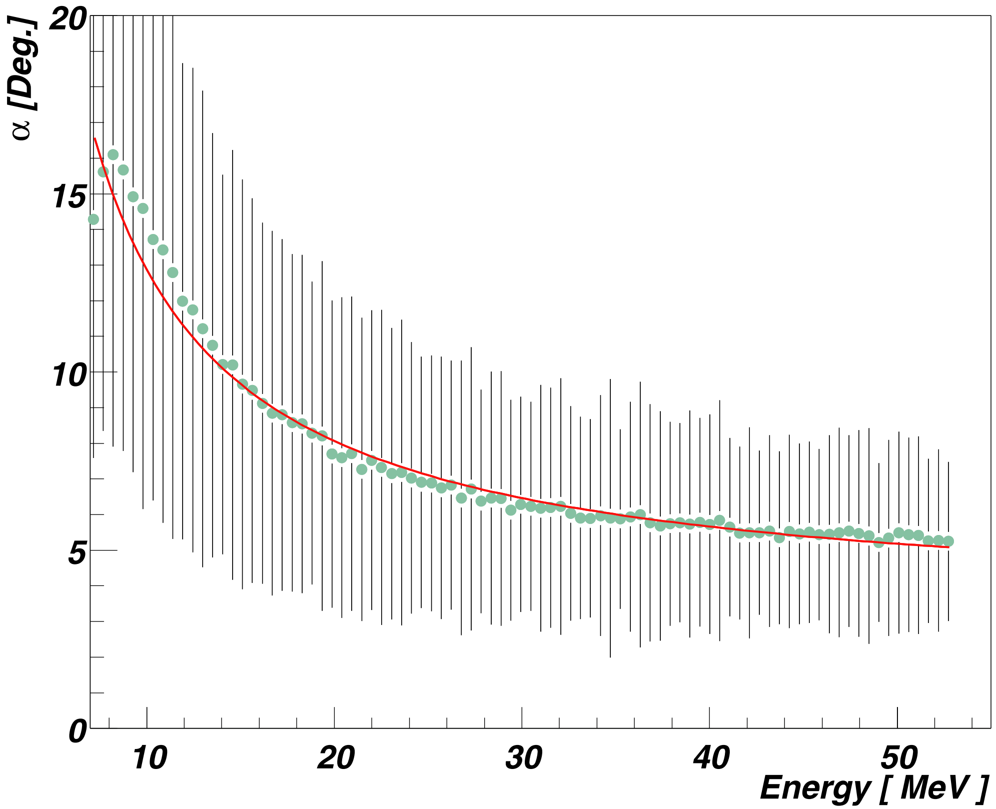
# Final Step: Rotating $P_{1/2}$ to become $P_{T_{1/2}}$

**from μSR Effect**

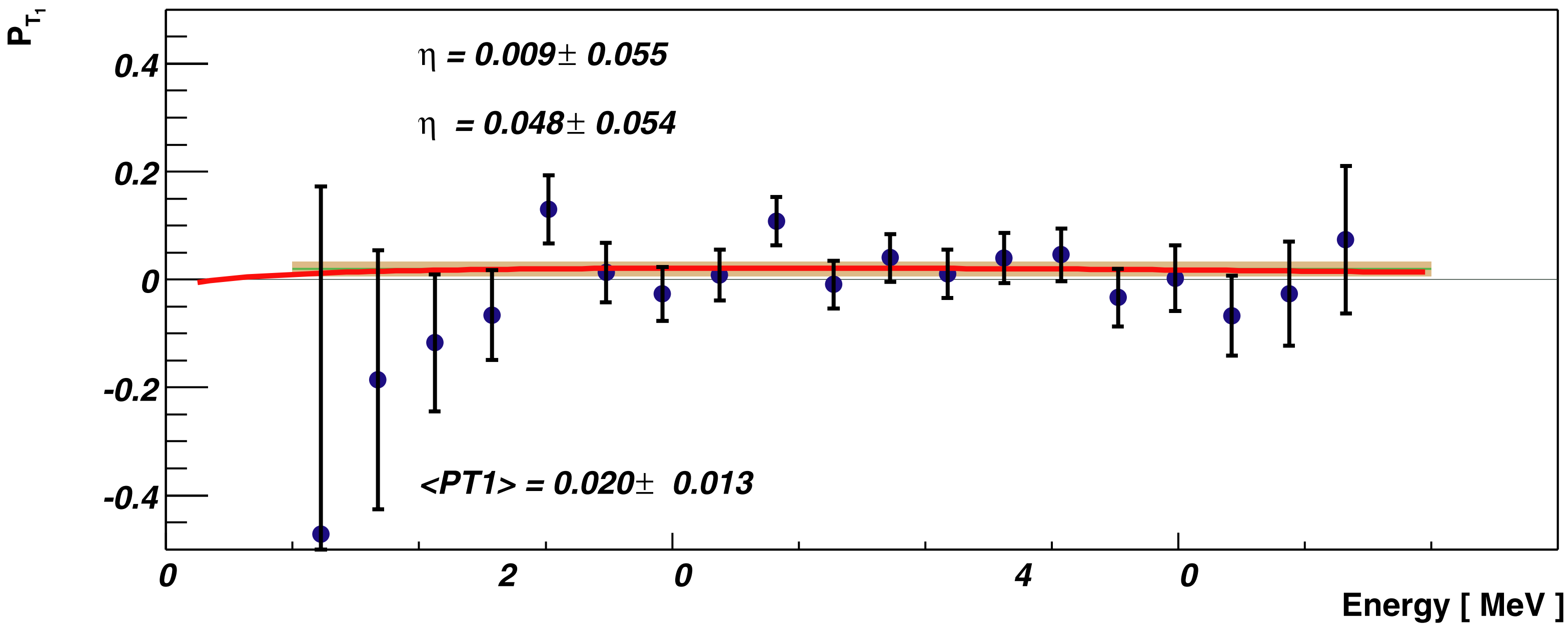
$$\begin{pmatrix} P_{T_1} \\ P_{T_2} \end{pmatrix} = \begin{pmatrix} \cos(\phi_0 + \alpha) & -\sin(\phi_0 + \alpha) \\ \sin(\phi_0 + \alpha) & \cos(\phi_0 + \alpha) \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \end{pmatrix}$$

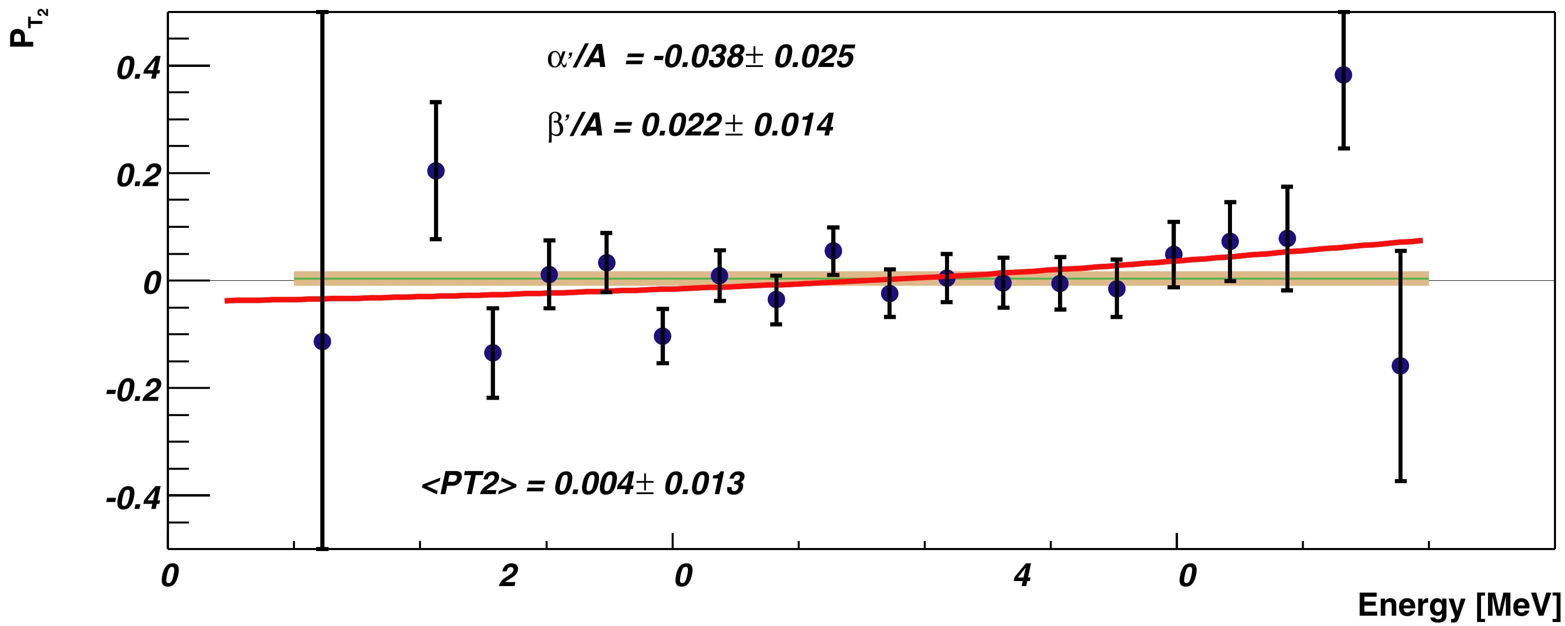
**from $e^+$ spin rotation**

**Rotation of a transverse positron polarization component in the WEB magnetic field (MC)**



# *The Transverse Polarization Components $P_{T_1}$ and $P_{T_2}$*

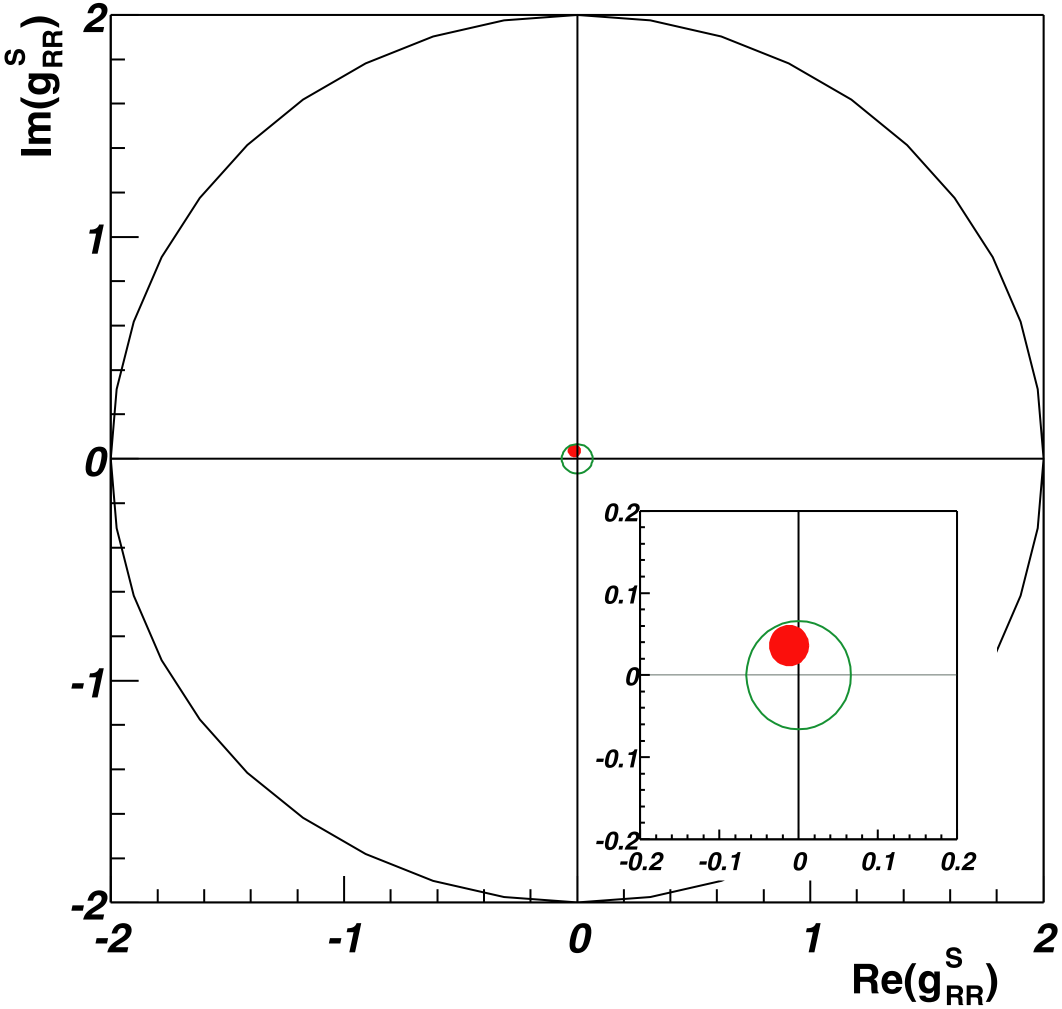


## *Foil Polarization: Sensitivity-Check*
## *Measure the Positrons Longitudinal Polarization*

**You are welcome to visit Kai Köhlers talk on Wednesday at 11:00**

# *No Evidence for Additional Scalar Couplings in Muon Decay*




Green circle: Result of a general analysis including all possible left- righthanded scalar, vector and tensor couplings.
Red circle: Only one additional righthanded scalar coupling interferes with the lefthanded vector coupling in the SM.

# *Outlook*

**You are welcome to visit Kai Köhlers talk on Wednesday at 11:00**