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Measurement of the integral asymmetry in μ-decay and implication for the Wino mass

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Abstract

A new lower limit for the mass of the $\widetilde{W}$ (Wino), the supersymmetric partner of the gauge boson W, is derived from a measurement of the integral asymmetry of the directional distribution of the positrons from the decay of polarized muons. Two experimental approaches are discussed. Using the μSR-technique we obtain a new (preliminary) value of $P_\mu \xi = 1.0030 \pm 0.0085$. Assuming light scalar neutrini ($m_{\tilde{\nu}} \ll m_\mu$), we deduce $m_{\widetilde{W}} > 270\ GeV/c^2$ (90% C.L.).

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1. Introduction

As shown recently, the classical four fermion weak interaction describing the muon decay $\mu \rightarrow e\nu\bar{\nu}$ has been completely determined by existing experiments [1]. It is in agreement with the standard "V-A"-interaction. Due to experimental uncertainties however, a few percent admixture of the non-standard forms is still permitted by the current data, namely, for instance, a "V+A"-interaction mediated by a right-handed vector boson W_R [2,3,4], or muon decays into photini mediated by a scalar lepton [5] or into the supersymmetric partners of the neutrini, mediated by a wino [6]. It turns out that the integral asymmetry in μ-decay, ξ, is very sensitive to such admixtures.

The angular distribution of the positrons from the decay $\mu \rightarrow e\nu\bar{\nu}$ of polarized muons is given by [4,7,8]

$$\frac{d^2\Gamma}{dx\,d\cos\varphi} \sim (x^2 - x^3)(1 + \frac{1}{3}P_\mu\xi\cos\varphi) + \frac{2}{9}\rho(4x^3 - 3x^2)(1 + P_\mu\frac{\xi\delta}{\rho}\cos\varphi)$$

where the electron mass has been neglected with respect to the muon mass, φ is the angle between the muon polarization P_μ and the positron momentum, x is the reduced positron energy. The parameters ξ, δ and ρ are functions of the different coupling constants which appear in the general four fermion Hamiltonian. For the maximum positron energy (x=1) the angular distribution simplifies to:

$$\frac{d\Gamma}{d\cos\varphi} \sim 1 + P_\mu\frac{\xi\delta}{\rho}\cos\varphi$$

To derive $P_\mu\xi$ alone we need to integrate over all energies x. This yields

$$\frac{d\Gamma}{d\cos\varphi} \sim 1 + \frac{1}{3}P_\mu\xi\cos\varphi$$

The most accurate previous measurement of $P_\mu\xi = 0.975 \pm 0.015$ was performed in 1968 [9]. It deviates slightly from the "V-A"-value $P_\mu\xi = 1$. The recent measurement [10] of $P_\mu\xi\delta/\rho > 0.9975$ with 90% C.L. sets a new boundary on the W_R mass, but it is not sensitive to the supersymmetric theory of ref.[6] mentioned above.

2. Method

Figure 1 shows the experiment [11], which is performed in the πE1-area at SIN. The muon beam is extracted from a 150 MeV/c parallel π-beam. Muons created by pion decay in flight exhibit a sharp cut-off angle, in our case $\theta_0 = 15.2^o$, called Jacobian edge. The polarization vector lies in the plane formed by the pion and

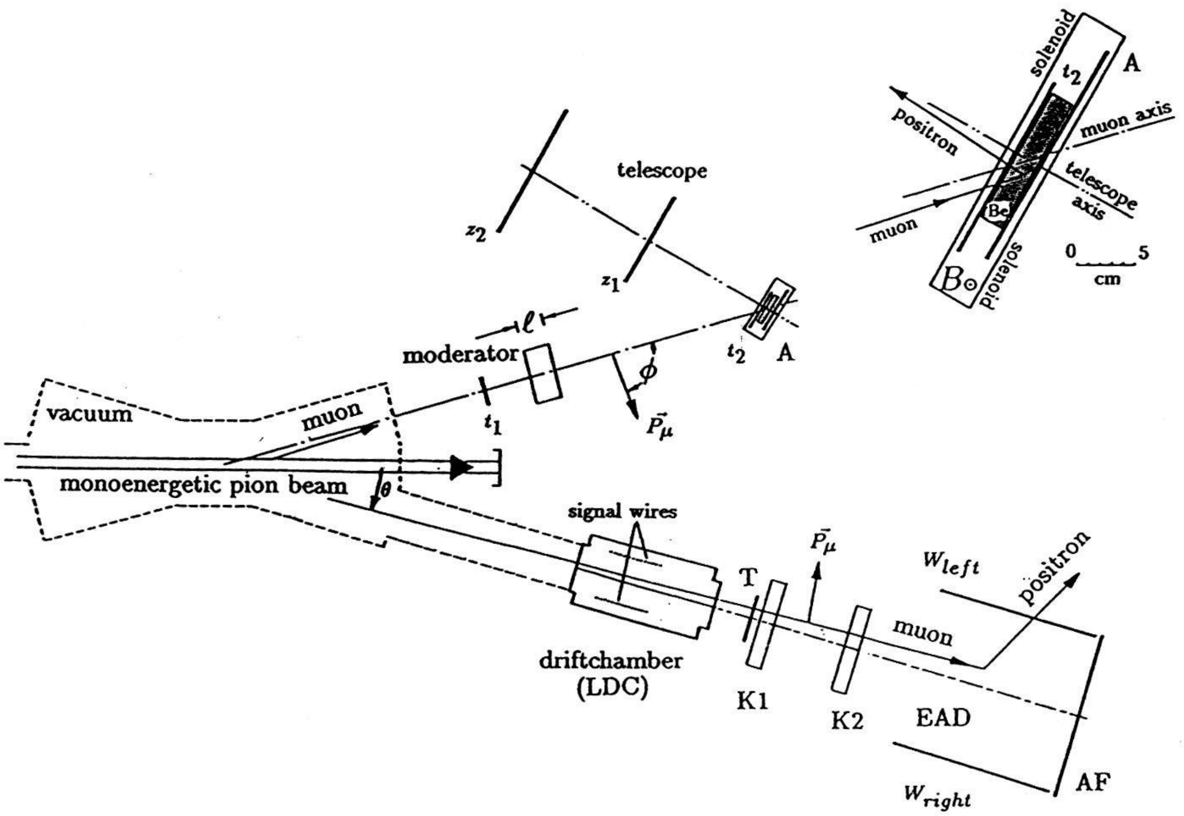

Fig. 1: Apparatus to measure the asymmetry of the directional distribution of positrons from the decay of polarized muons. The transversely polarized muons were extracted at 15.2° from a parallel π-beam. The two approaches to observe the μ-decay are shown:

(1) μ-decay in flight: A driftchamber (LDC) measures the μ-emission angle θ. From this the transverse polarization P_T is deduced. The electron-asymmetry-detector (EAD) consists of two MWPC's K1 and K2 to measure the trajectories of the muons. The space between K2 and AF defines the decay volume. The μ-decay is observed by the coincidence $T \cdot (W_{left} \vee W_{right}) \cdot \overline{AF}$. From the asymmetry in the rates, $W_{left} - W_{right}$, of the plastic counter walls we get $P_\mu \xi$.

(2) stopped muons: Muons with a well defined energy interval are stopped in a beryllium plate. Due to a constant vertical magnetic field $\vec{B}$, the polarization vector $\vec{P_\mu}$ precesses in a horizontal plane. A telescope of the scintillation counters t_2, z_1 and z_2 detects the positrons from the decay of the muons. Runs with magnetic fields up and down and with various modulation phases ϕ (selected by the length ℓ of the moderator) have been performed.

muon line of flight. The transverse component of the muon polarization P_T is given by

$$P_T = \frac{\sin\theta}{\sin\theta_0} \cdot |h_{\nu_\mu}|,$$

where h_{ν_μ} is the neutrino helicity in π decay. For muons emitted under their maximum laboratory angle θ_o the polarization vector is thus perpendicular to the muon momentum. Additionally, the pion decay probability as seen in the laboratory is strongly enhanced near θ_o, a fact which we exploit to prepare a highly transversely polarized μ-beam. The polarizations of the muons are measured by comparing their trajectories with the Jacobian edge. For this purpose a specially adapted driftchamber was developed [12]. Figure 2 shows the measured distribution of the muon emission angles and the polarization $P_T(\theta)$ deduced from it.

First test measurements [13] were done to observe the complete $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain with both decays occurring in flight. A multiwire proportional chamber, MWPC K2, and plastic scintillators AF define a 1.2 m long decay region (Fig. 1). Positrons having polar emission angles greater than 30^o and originating from inside the decay volume are detected by two plastic scintillator walls (W_{left} and W_{right}) (Fig. 1). Figure 3 shows the measured kinematical relation between the muon's flight direction and its time of flight for the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain. The asymmetry of the W_{left}- and W_{right}-rates will enable us to measure $P_\mu\xi$. Because the muons decay in flight we expect no significant depolarization.

As an alternative to the above scheme and in view of a verification of the polarization $P_T(\theta)$ (Fig.2) we stopped polarized muons in a metal plate (Fig. 1). The beam layout is similar to the one used in [14]. Based on extensive studies on the behaviour of the muon polarization in metals [10,15], we expect only a small depolarization which we account for in the analysis. The metal plate (as well as the counters T_2 and A) is placed inside a $3mT$ solenoid in order to obtain muon spin rotation (μSR). A stopped muon is signalled by a fast coincidence between $t_1t_2\overline{A}$. The positron is recorded by a fast coincidence between $t_2z_1z_2$ within $20\mu s$ after a muon has stopped. The most important off-line condition is set by allowing only a medium muon and a small positron pulse height in t_2. About 60% of all events recorded pass this condition and yield a sample of 580000 $\mu \rightarrow e$ decays. The desired asymmetry C is finally obtained by fitting the expected distribution $N(t_\mu)$ to the data (see Fig. 4)

$$N(t_\mu) = N_0 \cdot e^{-t_\mu/\tau} \cdot (1 + A(t_\mu)),$$

where

$$A(t_\mu) = \frac{1}{3} \cdot C \cdot e^{-t_\mu/T_0} \cdot \cos(\omega t_\mu + \varphi),$$

and t_μ: individual muon decay time, τ: average muon life time, $C = P_\mu\xi(1-\epsilon)$

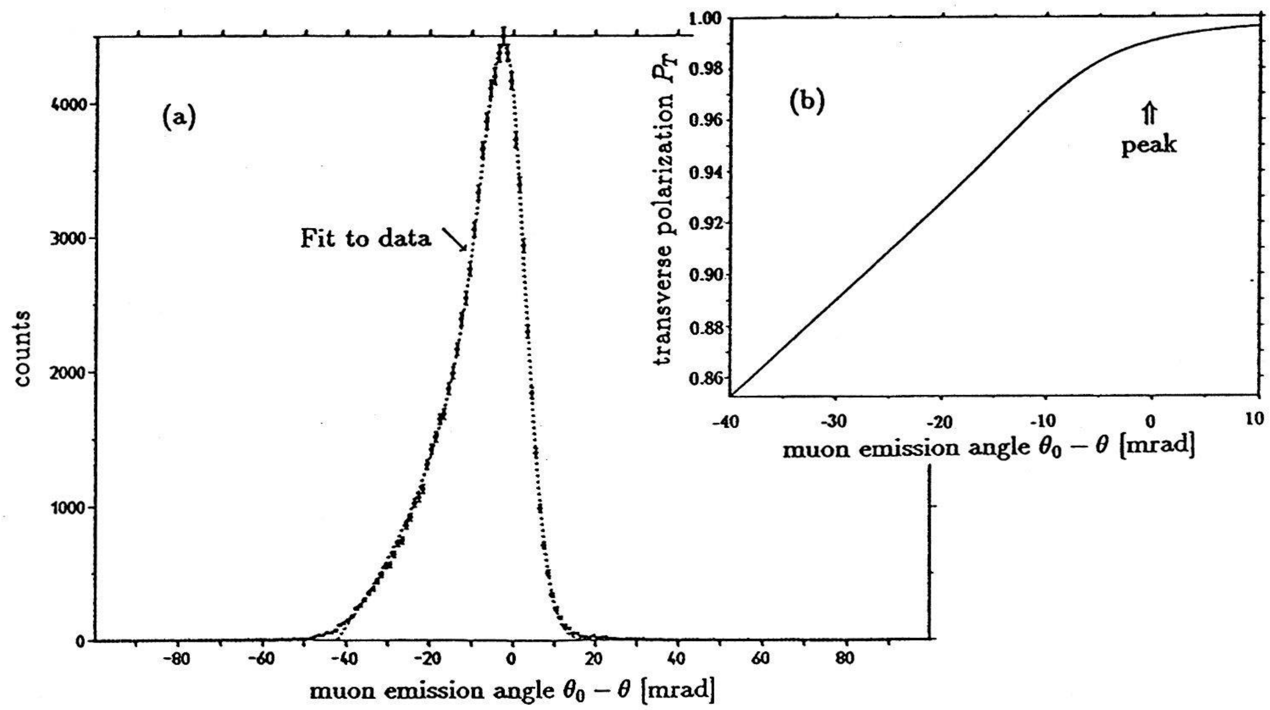

Fig. 2: Determination of the muon polarization.
Picture (a) shows the measured μ-emission angle θ together with a fit based on the theoretical angular distribution, a gaussian angular spread and the geometrical acceptance. From this fit we deduce the transverse polarization $P_T = P_T(\theta)$ (picture b) (assuming the neutrino helicity $|h_{\nu_\mu}| = 1$).

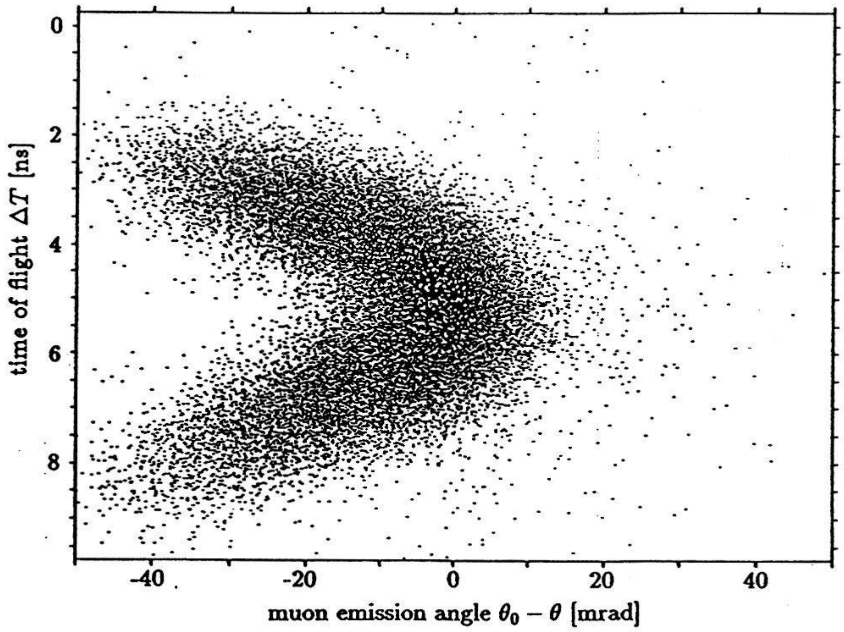

Fig. 3: Confirmation of a kinematical relation in π decay using the events as selected by the apparatus. The measured time of flight (deduced from the RF of the cyclotron and the T-counter in the muon beam) vs the muon emission angle θ for $\pi \to \mu \to e$ decay events (both decays in flight). Due to the monoenergetic π-beam and the relatively small π-decay region, the time interval is proportional to the muon time of flight and it is therefore uniquely related to the muon energy. Note the high and low energy branch from the forward and backward emission in pion decay.

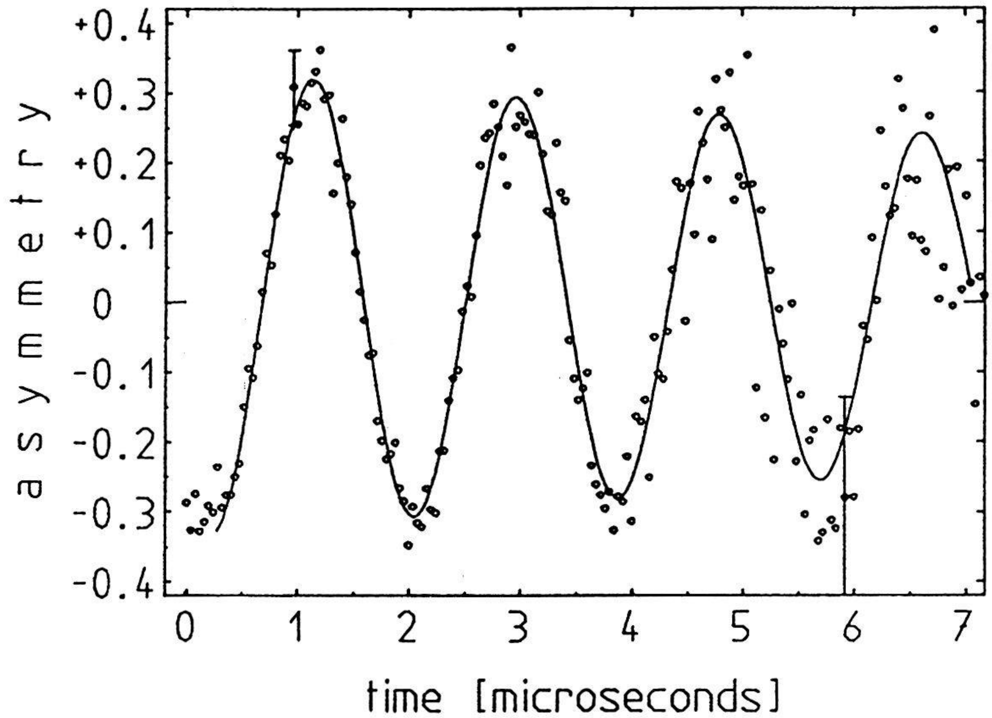

Fig. 4: Measured time distribution between the muon stop in Be and the observation of the decay positron, based on about 100000 events. The exponential μ decay time has been divided out. The solid line is $A(t_\mu)$. The fit yields the desired value of $P_\mu\xi$ as $C/(1-\epsilon)$. (The slow decrease in amplitude (relaxation) is due to internal fields in Be).

with ϵ being a subpercent correction, T_0: muon spin relaxation time, ω: muon spin precession frequency, $\varphi = 135^\circ + \phi$: precession phase. For details of the experiment and the analysis see ref. [13,16].

3. Results

From the μSR experiment we obtain a preliminary value of $P_\mu\xi = 1.0030 \pm 0.0080$ (*statistical*) ± 0.0030 (*systematic*). This translates (using $P_\mu = 0.9986 \pm 0.0009$ [10,17]) into the integral asymmetry parameter $\xi = 1.0045 \pm 0.0086$. It is compatible with the standard "V-A"-interaction. The precision of the agreement excludes sizeable contributions from muon decays into a positron and two scalar neutrini, the supersymmetric partners of the (regular) neutrini. Assuming light scalar neutrini ($m_{\tilde{\nu}} \ll m_\mu$) this may be expressed as a mass limit [6] for the $\widetilde{W}$, the supersymmetric partner of the gauge boson W, as $m_{\widetilde{W}} > 270\ GeV/c^2$ ($90\% C.L.$). Less stringent limits have been deduced before from the muon decay parameters ρ and δ [6,18]. In the near future results with reduced uncertainties are expected.

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[18] from ρ: $m_{\tilde{W}} > 230\ GeV/c^2$, and from δ: $m_{\tilde{W}} > 250\ GeV/c^2$.
Primary inputs to the world average are, of ρ: J. Peoples *et al.*, Nevis Cyclotron Report no 147 (1966), unpublished, and of δ: D. Fryberger *et al.*, Phys. Rev. 166, 1379 (1968)