LEPTONIC DECAYS OF THE τ-LEPTON AND THE STRUCTURE OF THE CHARGED LEPTONIC WEAK INTERACTION

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Abstract

The Lorentz structure of leptonic τ decays cannot be determined by measuring the Michel parameter ρ precisely. It is known from muon decay, however, that the interaction can be fixed by measuring the life-time and four additional parameters yielding information about the lepton chiralities. Two of these, the asymmetry parameters ξ and δ, could be measured at the proposed Tau-Charm-Factory at a c.m. energy of 4 GeV. This would limit five of the ten complex coupling constants. In addition to a more precise measurement of ρ also the low energy spectrum parameter η_μ can be measured with good precision. Its measurement is needed for the test of the universality of the weak interaction.

1. Introduction

The universality of the charged weak interaction allows to describe on the same basis such a wide range of phenomena as nuclear beta decay, muon decay, and semileptonic decays of hadrons. This has led to the proposition of the Standard Model which is characterized by left- handed fermions ("V-A") and by the universal Fermi coupling constant G_F.

The experimental investigation of the charged weak interaction is especially rewarding in the case of leptonic decays of heavy leptons where one is not hampered by the strong interaction. Thus, for example, the Fermi coupling constant is deduced from muon decay assuming a "V-A" interaction. The experimental verification of this assumption, however, was found only recently [1] by H.J. Gerber, K. Johnson and the author. Their analysis, moreover, allows to derive upper limits for all of the other nine possible couplings, valid independent of specific models. The method used there can readily be applied to the two decays $\tau \to \mu\bar{\nu}_\mu\nu_\tau$ and $\tau \to e\bar{\nu}_e\nu_\tau$ as well.

2. Muon Decay Interaction

Leptonic decays can be described by the most general, local, derivative-free and lepton-number conserving four-fermion point interaction hamiltonian [2]. It contains ten complex coupling constants corresponding to 19 independent parameters to be determined. The observables are described most conveniently in terms of a hamiltonian in charge changing and "helicity projection" form [3,4] which is characterized by fields of definite handedness. The matrix element for μ decay is given by [1]

$$M \;=\; 4\frac{G_o}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \varepsilon,\mu=R,L \\ (n,m)}} g^{\gamma}_{\varepsilon\mu} < \overline{\epsilon_e}|\Gamma^{\nu}|(\nu_e)_n >< (\overline{\nu_\mu})_m|\Gamma_{\gamma}|\mu_{\mu} > \quad .$$

γ labels the type of interaction: Γ^S, Γ^V, Γ^T (scalar, vector, tensor). The indices ε and μ indicate the chiral projection (left-handed, right-handed) of the spinors of the experimentally observed particles, $\varepsilon \mathrel{\hat{=}}$ electron, $\mu \mathrel{\hat{=}}$ muon. The helicities n and m for the ν_e and the ν_μ, respectively, are uniquely determined for given γ, ε, μ. In this picture, the standard model corresponds to g^V_{LL}=1, all other couplings being zero.

The strength of the interaction is determined by the μ lifetime. Since we are only interested in the relative weights of the different couplings, the $g^{\gamma}_{\varepsilon\mu}$ are normalized:

$$\begin{aligned} A \;\equiv\;& 4\left(|g^S_{RR}|^2 + |g^S_{LR}|^2 + |g^S_{RL}|^2 + |g^S_{LL}|^2\right) \\ &+16\left(|g^V_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RL}|^2 + |g^V_{LL}|^2\right) \\ &+48\left(|g^T_{LR}|^2 + |g^T_{RL}|^2\right) := 16 \end{aligned}$$

This allows to define the four probabilities $Q_{\varepsilon\mu}$ of obtaining an electron of handedness ε and a muon of handedness μ in μ decay:

$$\begin{aligned} Q_{RR} &\equiv \frac{1}{4}|g^S_{RR}|^2 + |g^V_{RR}|^2 &&= 2(b+b')/A \\ Q_{LR} &\equiv \frac{1}{4}|g^S_{LR}|^2 + |g^V_{LR}|^2 + 3|g^T_{LR}|^2 &&= [(a-a') + 6(c-c')]/2A \\ Q_{RL} &\equiv \frac{1}{4}|g^S_{RL}|^2 + |g^V_{RL}|^2 + 3|g^T_{RL}|^2 &&= [(a+a') + 6(c+c')]/2A \\ Q_{LL} &\equiv \frac{1}{4}|g^S_{LL}|^2 + |g^V_{LL}|^2 &&= 2(b-b')/A \end{aligned}$$

We note that $0 \leqq Q_{\varepsilon\mu} \leqq 1$ and $\sum_{\varepsilon,\mu} Q_{\varepsilon\mu}=1$. The parameters { a/A, $\cdots$, c′/A} have been introduced [5] to express all possible results of the measurements on the positron in the decay of polarized (and unpolarized) muons. Their values have been derived for muon decay [1,6] from the following, complete set of measurements:

Shape of positron energy spectrum

(1) $\rho = 0.752 \pm 0.0027$ [7]

Decay asymmetry between μ spin and e momentum

At spectrum end point:

(2) $\xi\delta/\rho = 0.9989 \pm 0.0023$ [8]

Differential:

(3) $\delta = 0.7502 \pm 0.0043$ [9]

The polarization vector (P_L, P_{T_1}, P_{T_2}) of the positron yields the remaining six parameters:

Longitudinal polarization

(4) $< P_L > \equiv \xi' = 0.998 \pm 0.045$ [10]

Angular dependence of P_L

(5) $\xi'' = 0.65 \pm 0.36$ [10]

Energy dependence of P_{T_1}

(6) $\alpha/A = 0.015 \pm 0.052$ [6]

(7) $\beta/A = 0.002 \pm 0.018$ [6]

Energy dependence of P_{T_2}

(8) $\alpha'/\mathrm{A} = -\,0.047 \pm 0.052$ [6]

(9) $\beta'/\mathrm{A} = 0.017 \pm 0.018$ [6]

One finds upper limits for Q_{RR}, Q_{LR} and Q_{RL}, which in turn yield upper limits for the absolute values of eight complex coupling constants $g^{\gamma}_{\epsilon\mu}$. Since Q_{LL} is bounded by a lower limit, it is not possible to deduce an upper limit for $|g^S_{LL}|$ from normal muon decay without detecting the neutrini. In fact, with the data from normal muon decay we cannot tell if

$g^S_{LL} = 0,\ g^V_{LL} = 1$ (V-A), or

$g^S_{LL} = 2,\ g^V_{LL} = 0$

This kind of ambiguity has been noted by C. Jarlskog [11] in the context of a different form of the hamiltonian. She proposed to measure electron-neutrino correlations to resolve it, experiments which have not been performed to date. We use instead the data from inverse muon decay:

$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e \quad .$$

The total rate S, normalized to the rate predicted by V-A, is found to be S = 0.98 ± 0.12 [12]. S has been calculated in terms of the charge changing hamiltonian in the parity representation [13]. In terms of our $g^{\gamma}_{\epsilon\mu}$ one gets

$$
\begin{aligned}
S &= (1/2)(1-h)\left\{|g_{LL}^V|^2 + (3/8)|g_{RL}^V|^2\right.\\
&+ \left.(3/32)|g_{LR}^S - (10/3)g_{LR}^T|^2 + (3/32)|g_{RR}^S|^2 + (4/3)|g_{LR}^T|^2\right\}\\
&+ (1/2)(1+h)\left\{|g_{RR}^V|^2 + (3/8)|g_{LR}^V|^2\right.\\
&+ \left.(3/32)|g_{RL}^S - (10/3)g_{RL}^T|^2 + (3/32)|g_{LL}^S|^2 + (4/3)|g_{RL}^T|^2\right\} \quad ,
\end{aligned}
$$

where h is the helicity of the ν_μ from pion decay. The deviation of |h| from 1 is known very precisely: 1 − |h| < 4.1 x 10^{-3} [14,8]; the sign of h has been determined by **electromagnetic** interaction for ν_μ and $\bar{\nu}_\mu$ [15,16]. Thus S gives information about the first 5 coupling constants g_{LL}^V, g_{RL}^V, g_{LR}^S g_{LR}^T and g_{RR}^S, all of which couple to left-handed ν_μ. The influence of four of them on S is found to be negligible with the upper limits derived from **normal** muon decay. One obtain

$$
S = |g_{LL}^V|^2 \quad ,
$$

which yields a **lower** limit for $|g_{LL}^V|$, and through the normalization requirement one gets an upper limit for the remaining $|g_{LL}^S|$:

$$
|g_{LL}^S|^2 < 4(1-S)
$$

Thus the weak interaction has been completely determined between the electron and the muon and their neutrini in normal and inverse muon decay using only **leptonic** data. The results are shown in Fig. 1, where each of the ten coupling constants is given within one of the squares defined uniquely by the handednesses of electron and muon and by the type of interaction. The outer circles display the mathematical limits for the $g_{e\mu}^\gamma$ in the complex plane, the inner circles for nine of the $g_{e\mu}^\gamma$ show the areas still allowed by experiment (90% c.l.). For g_{LL}^V, which has been chosen to be real, one get the small line close to $g_{LL}^V = 1$ in agreement with V-A.

3. Key Experiments

We have seen in muon decay that it is not necessary to measure all of the 19 observables in order to determine the interaction. We can even find a minimal set of measurements by calculating the probability $P_R^e \equiv Q_{RR} + Q_{RL}$ to obtain a right–handed electron and $P_R^\mu \equiv Q_{RR} + Q_{LR}$ for a right-handed muon [17]:

$$
\begin{aligned}
P_R^e &= \frac{1}{4}|g_{RR}^S|^2 + \frac{1}{4}|g_{RL}^S|^2 + |g_{RR}^\nu|^2 + |g_{RL}^\nu|^2 + 3|g_{RL}^T|^2 = \frac{1}{2}(1-\xi')\\
P_R^\mu &= \frac{1}{4}|g_{RR}^S|^2 + \frac{1}{4}|g_{LR}^S|^2 + |g_{RR}^V|^2 + |g_{LR}^V|^2 + 3|g_{LR}^T|^2 = \frac{1}{2}\left\{1 + \frac{1}{9}(3\xi - 16\xi\delta)\right\}
\end{aligned}
$$

By measuring the positron polarization ξ' one obtains upper limits for 5 complex coupling constants, by measuring the decay asymmetry three additional ones. We can conclude: Only five experiments are necessary to determine the interaction:

(1) τ_μ $\longrightarrow$ Fermi coupling constant
(2) δ
(3) ξ $\longrightarrow$ 16 decay parameters
(4) ξ'
(5) S $(\nu_\mu + e^- \rightarrow \mu^- + \nu_e)$ $\rightarrow$ "V-A"

4. Universality

The universality of the charged weak interaction for the three decays

$$\mu \rightarrow \nu_\mu e \overline{\nu_e} \quad , \quad \tau \rightarrow \nu^\tau \mu \overline{\nu_\mu} \quad \mathit{and}\ \tau \rightarrow \nu_\tau e \overline{\nu_e}$$

can be checked by testing if

a) the couplings are equal and b) the strength is the same. The Fermi coupling constant is given by [18]

$$G_F^2 \;=\; \frac{1}{\tau_\ell} \;\cdot\; \frac{192\pi^3}{m_\ell^5} \cdot \frac{1}{1 + 4\eta \cdot m_{\ell'}/m_\ell} \quad ,$$

where τ_ℓ is the lifetime of the lepton ℓ, m_ℓ its mass and m'_ℓ the mass of the daughter lepton. Higher order corrections have been neglected here. η is the low energy spectrum parameter. It is important for the muonic decay of the τ [19], since $m_\mu/m_\tau \approx 1/17$. With $|\ \eta_\mu\ | \leqq 1$ this gives a relative error $\Delta G_F/G_F \leqq 12\%$! η can be determined a) by direct measurement and b) by deriving upper limits for the coupling constants by measuring ξ'_μ, ξ_μ and δ_μ.

5. Spectrum Shape: Scalar Observables

5.1 Michel parameter ρ

This is the only decay parameter measured up to date [20]. Although it is not one of the key experiments, it would be very exciting if $\rho \neq 3/4$ as has been discussed elsewhere [21]. If $\rho = \frac{3}{4}$, we do not learn very much: **Any** combination of the six couplings g^S_{LL}, g^S_{LR}, g^S_{RL}, g^S_{RR}, g^V_{RR}, g^V_{LL} yields $\rho = \frac{3}{4}$. This can be seen from

$$\rho \;=\; \frac{3}{4} - \frac{3}{4}\left\{|g^V_{LR}|^2 + |g^V_{RL}|^2 + 2|g^T_{LR}|^2 + 2|g^T_{RL}|^2 + Re\left(g^S_{LR} g^{T\star}_{LR} + g^S_{RL} g^{T\star}_{RL}\right)\right\}$$

$$\rho \;=\; \frac{3}{4} \Longrightarrow \left\{|g^V_{LR}|^2 + |g^V_{RL}|^2 + 2|g^T_{LR}|^2 + 2|g^T_{RL}|^2\right\} = -Re\left(g^S_{LR} g^{T\star}_{LR} + g^S_{RL} g^{T\star}_{RL}\right)$$

Let, for example, $g^T_{LR} = g^T_{RL} = 0 \Longrightarrow g^V_{LR} = g^V_{RL} = 0$, with all other couplings being arbitrary!

We note especially that "V+A" cannot be excluded if ρ is found to be 3/4. There are three possible contributions:

$$\begin{aligned}
\alpha)\ g^V_{RL} \ &: \ \begin{cases} coupling\ to\ RH\ \mu \\ coupling\ to\ LH\ \tau \end{cases} \\
\beta)\ g^V_{LR} \ &: \ \begin{cases} coupling\ to\ LH\ \mu \\ coupling\ to\ RH\ \tau \end{cases} \\
\gamma)\ g^V_{RR} \ &: \ \begin{cases} coupling\ to\ RH\ \mu \\ coupling\ to\ RH\ \tau \end{cases}
\end{aligned}$$

As seen above $\rho = \frac{3}{4}$ excludes only g^V_{RL} and g^V_{LR} ($\hat{=}$ mixing of right- and left-handed currents).

5.2 Low energy parameter η

Although η is not a restrictive parameter, it has to be measured in order to be able to derive the Fermi coupling constant. In terms of our $g^{\nu}_{\epsilon\mu}$:

$$\begin{aligned}
\eta \ = \ & \frac{1}{2} Re \left\{ 6 g^V_{RL} g^{T\star}_{LR} + 6 g^V_{LR} g^{T\star}_{RL} + g^S_{RR} g^{V\star}_{LL} \right. \\
& \left. + \ g^S_{RL} g^{V\star}_{LR} + g^S_{LR} g^{V\star}_{RL} + g^S_{LL} g^{V\star}_{RR} \right\}
\end{aligned}$$

Thus $\eta \neq 0$ shows there are at least two different couplings with opposite chiralities for the charged leptons which would result in nonmaximal parity and charge conjugation violation. In this case if we assume "V-A" (g^V_{LL}) to be dominant, then the second coupling would be a Higgs type coupling (g^S_{RR}) with right handed τ and μ.

6. Lepton Chiralities: Pseudoscalar Observables

As mentioned earlier, the key experiments in leptonic decays consist of determining the lepton chiralities. For muon decay all of these experiments have been performed:

1. positron polarization,

2. positron decay asymmetry for polarized muons,

3. cross section for inverse muon decay with ν_μ of negative helicity.

The first two of these can also be done for τ decays, though the methods are somewhat different due to the short τ lifetime.

The polarization of the μ^+ from τ^+ decay can be analyzed by measuring the decay asymmetry of the stopped muons [19]. One needs a polarimeter outside of the main detector, so the τ-charm factory does not seem to be well suited for this experiment, since most of the muons will stay in the main detector.

The decay asymmetry, however, can be measured by making use of the spin correlation of the two τ's [19]. We consider all possible combinations of the decays

$$\begin{aligned} \tau &\longrightarrow \mu\bar{\nu}_\mu\nu_\tau \\ &\longrightarrow e\bar{\nu}_e\nu_\tau \\ &\longrightarrow \pi\nu_\tau \end{aligned}$$

A particularly useful set of observables consists of the momenta p_3 and p_4 and the opening angle ϑ_{34}, where particle 3 and 4 are the detected particles (μ, e or π).

The decay distributions have been calculated in the rest system of the τ [22,23]. These distributions were integrated analytically [19] over $d\Omega_\tau$, $d\Omega_3$ and $d\Omega_4$ and can be expressed by

$$\frac{d^3\Gamma}{dp_3 dp_4 dcos\theta_{34}} \equiv \; R = (2\gamma^2+1)f_1(\rho,\eta) + \xi_3\xi_4[(2\gamma^2-1)f_2(\delta) + f_3(\delta)]$$

with the abbreviation

$$f_1 \equiv f_1\left(p_3, p_4, cos\theta_{34}, \rho_3, \rho_4, \eta_3, \eta_4\right) \quad , \quad f_{2,3} \equiv f_{2,3}\left(p_3, p_4, cos\theta_{34}, \delta_3, \delta_4\right)$$

Similarly the corresponding two-fold differential decay rates $d^2\Gamma/dp_3dp_4 \equiv$ S were calculated. Based on 10^7 events, contour lines were calculated for the following quantities:

$$A \;=\; \frac{(2\gamma^2-1)f_2(\delta) + f_3(\delta)}{(2\gamma^2+1)f_1(\rho,\eta)}$$

with $-1 \leqq A \leqq +1$ and for the figures of merit of the different decay parameters, for example

$$FoM \;\; (\rho_3) \;=\; \frac{1}{S}\left(\frac{\partial S}{\partial \rho_3}\right)^2 \quad ,$$

from which, after numerically integrating over phase space, the statistical error for the particular parameter was derived:

$$\Delta\rho_3 = \frac{1}{\sqrt{\sum_{P.S.} FoM(\rho_3)}}$$

7. Results

All of the calculations were performed for a total energy E_o=4 GeV. As expected, the FoM of ρ and η depends only slightly on the opening angle. Figures 2 and 3 show the FoM-distribution for these two variables. As in μ decay, they are strongly correlated.

Table 1: Figures of merit for the decay parameters ρ, η, δ and ξ describing leptonic τ decays, calculated for a Tau-Charm- Factory (E=4 GeV) and for a B-Factory (E=10 GeV). The FoM's and the statistical errors σ are based on 10^7 events with one τ decaying into a μ and the other τ into an e. The errors given are calculated for an ideal detector, making no cuts on phase space.

	$S(p_3,p_4)$		$R(p_3,p_4,\cos\vartheta_{34})$	
E=4 GeV	FoM	10^3xσ	FoM	10^3xσ
ρ	18 300 000	0.2	20 800 000	0.2
η_e	219	68.0	225	67.0
η_μ	6 300 000	0.4	6 500 000	0.4
$\xi\delta$	9 500	10.0	177 000	2.4
ξ	4 400	15.0	15 400	8.0
	$S(p_3,p_4)$		$R(p_3,p_4,\cos\vartheta_{34})$	
E=10 GeV	FoM	10^3xσ	FoM	10^3xσ
ρ	4 350 000	0.5	8 350 000	0.3
η_e	78	11.3	106	97.0
η_μ	2 600 000	0.6	3 200 000	0.6
$\xi\delta$	66 700	3.9	220 000	2.1
ξ	18 608	7.3	35 300	5.3

Somewhat unexpected are the results for the asymmetry parameters ξ and δ. While the twofold differential distribution $S = d^2\Gamma/(dp_3dp_4)$ contains virtually no information of these two observables, the distribution $R = d^3\Gamma/(dp_3 dp_4 d\cos\theta_{34})$ is still rather sensitive to ξ and δ. Figures 4 and 5 show the asymmetry A, which is sensitive to $\xi_3 \cdot \xi_4$, for two different angles, Figs. 6 and 7 the FoMs for ξ and δ in percent. The results for $e^+e^- \to \tau^+\tau^- \to (\mu^+\nu_\mu\bar{\nu}_\tau)(e^-\bar{\nu}_e\nu_\tau)$ are summarized in Table 1 and compared to measurements at 10 GeV. They are based on 10^7 events. The statistical error σ given has been derived for the complete phase space. It has to be regarded as lower limit which will increase due to cuts in phase space, resolution of the detectors and background.

Nevertheless, we find that not only ρ_μ and ρ_e, but also the low energy parameter η_μ can be measured with a statistical error of less than 10^{-3}! This should be compared with the η measurement in μ decay, where the experimental value was η=(-120$\pm$210)x10^{-3} [24], until it was improved in 1985 to η=(-7$\pm$13)x10^{-3} [6]. Clearly the excellent sensitivity to η_μ is due to the good mass ratio m_μ/m_τ.

Although asymmetry effects are lower at 4 GeV than at 10 GeV due to lower τ polarization correlation and a smaller Lorentz boost, it still seems possible to measure ξ with a reasonable error. The parameter δ can even be measured with an accuracy as at 10 GeV. We emphasize that the actual result depends strongly on the momentum range in which a particular particle can be identified.

Table 2 finally shows a minimal set of measurements which allows to derive ξ_e^2, ξ_μ^2 and $h_{\nu_\tau}^2$ separately. The sign of these quantities can be determined in a separate experiment [19,25].

Table 2: Minimal set of measurements needed to determine ξ_μ, ξ_e and h_{ν_τ}.

$\tau^+ \to$	$\tau^- \to$	Quantity measured
$\mu^+\nu_\mu\bar{\nu}_\tau$	$e^-\bar{\nu}_e\nu_\tau$	$\xi_\mu \cdot \xi_e$
$\mu^+\nu_\mu\bar{\nu}_\tau$	$\pi^-\nu_\tau$	$h_{\nu_\tau} \cdot \xi_\mu$
$e^+\nu_e\bar{\nu}_\tau$	$\pi^-\nu_\tau$	$h_{\nu_\tau} \cdot \xi_e$

8. Conclusions

At the proposed Tau-Charm-Factory the measurements of the asymmetry parameters for leptonic τ decays ξ_e, ξ_μ, δ_e and δ_μ appear feasible. This will constrain the vector couplings g^V_{RR} and g^V_{LR}, the scalar (Higgs) couplings g^S_{RR} and g^S_{LR} and the tensor coupling g^T_{LR}. In addition to a better determination of ρ_e and ρ_μ, the low energy parameter η_μ can be measured for the first time. The measurement of η_μ is essential for the determination of the Fermi coupling constant for the muonic tau decay and thus for the test of the universality of the interaction.

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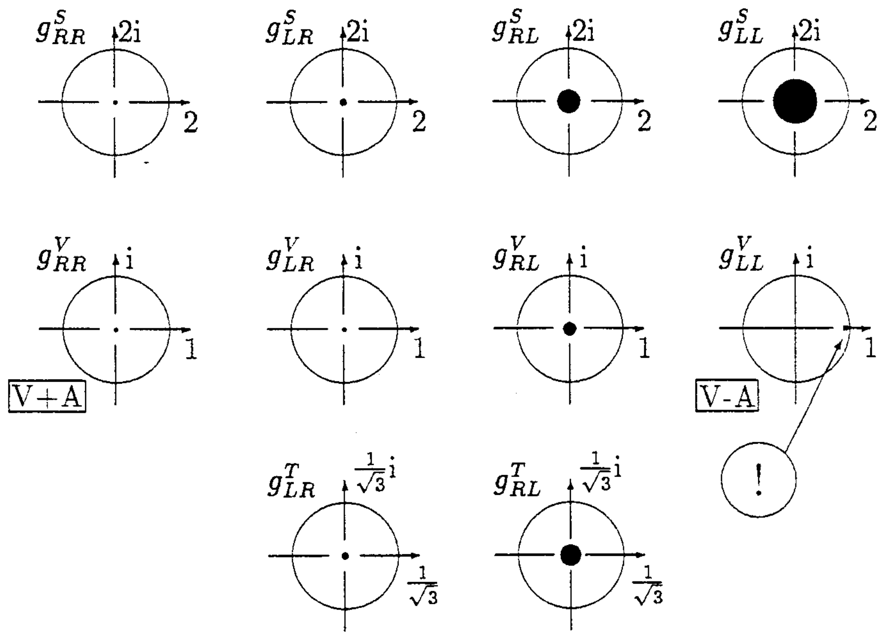

Figure 1: 90% c.l. limits for the coupling constants $g^\gamma_{\varepsilon\mu}$. Each coupling is uniquely determined by the handedness ε and μ of the electron and the muon, respectively, and the type of interaction γ=S, V or T.

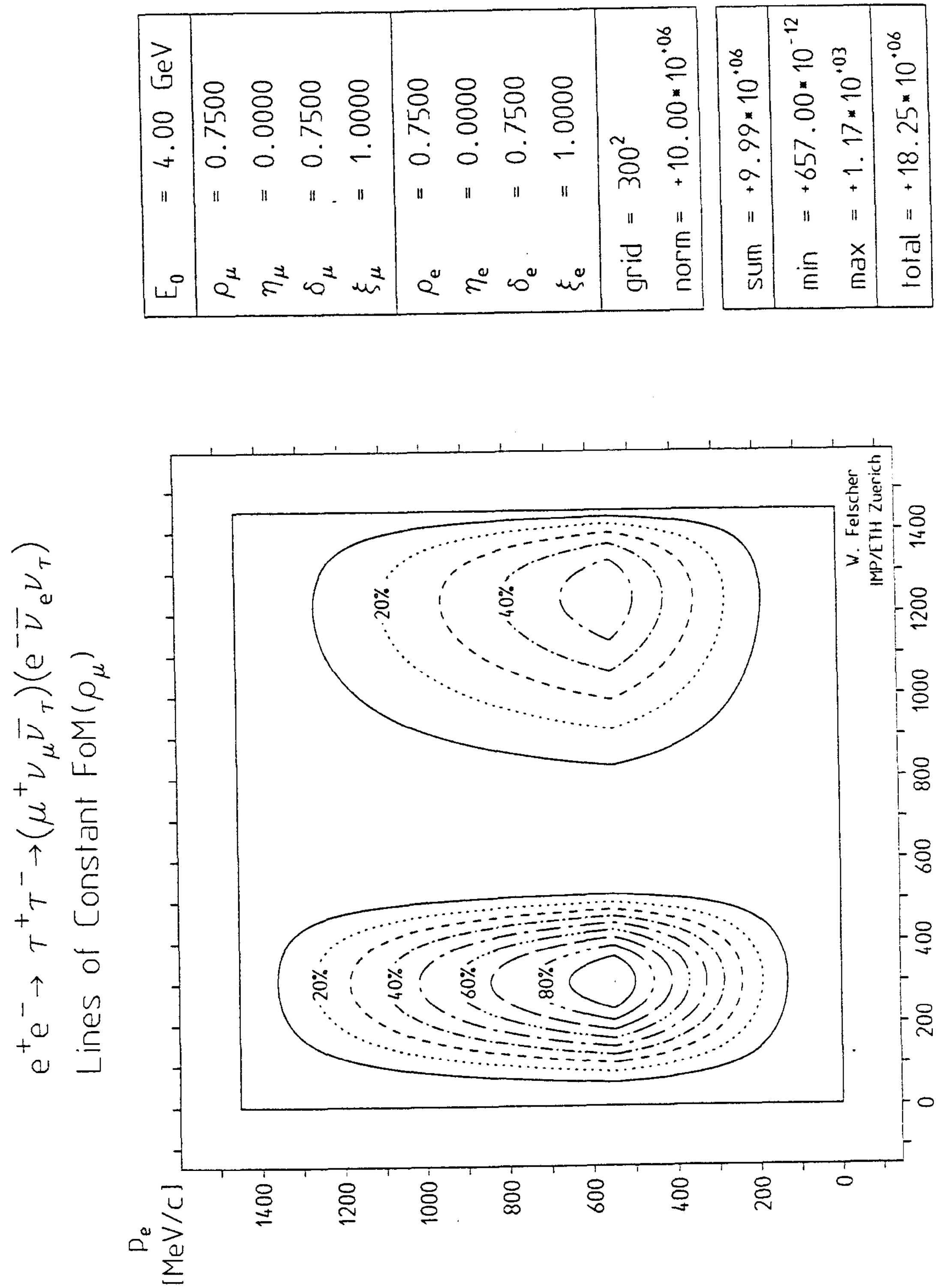

Figure 2: Lines of constant figure of merit for ρ_μ.

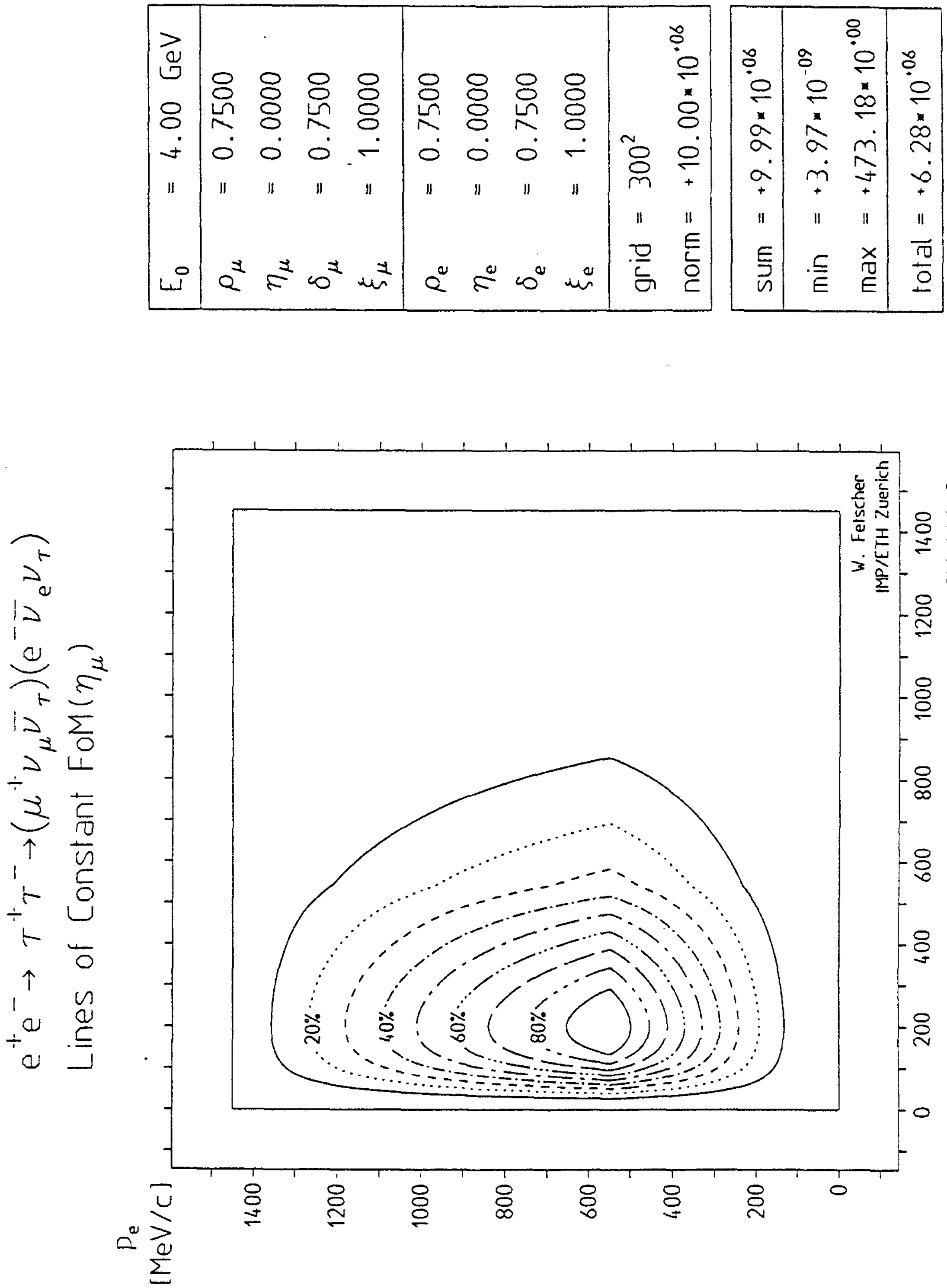

Figure 3: Lines of constant figure of merit for η_μ.

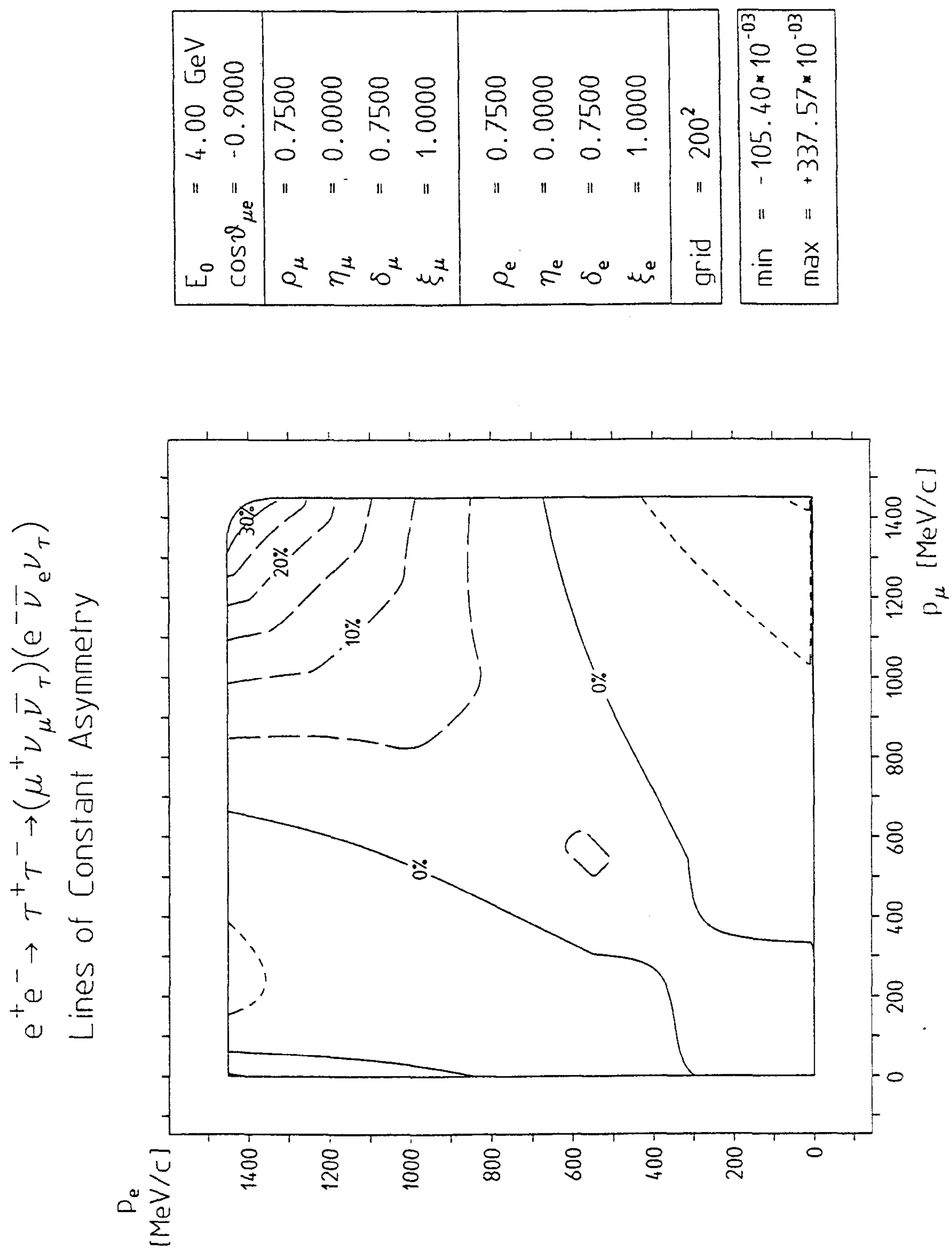

Figure 4: Lines of constant asymmetry for $cos\vartheta_{\mu e}$=-0.9.

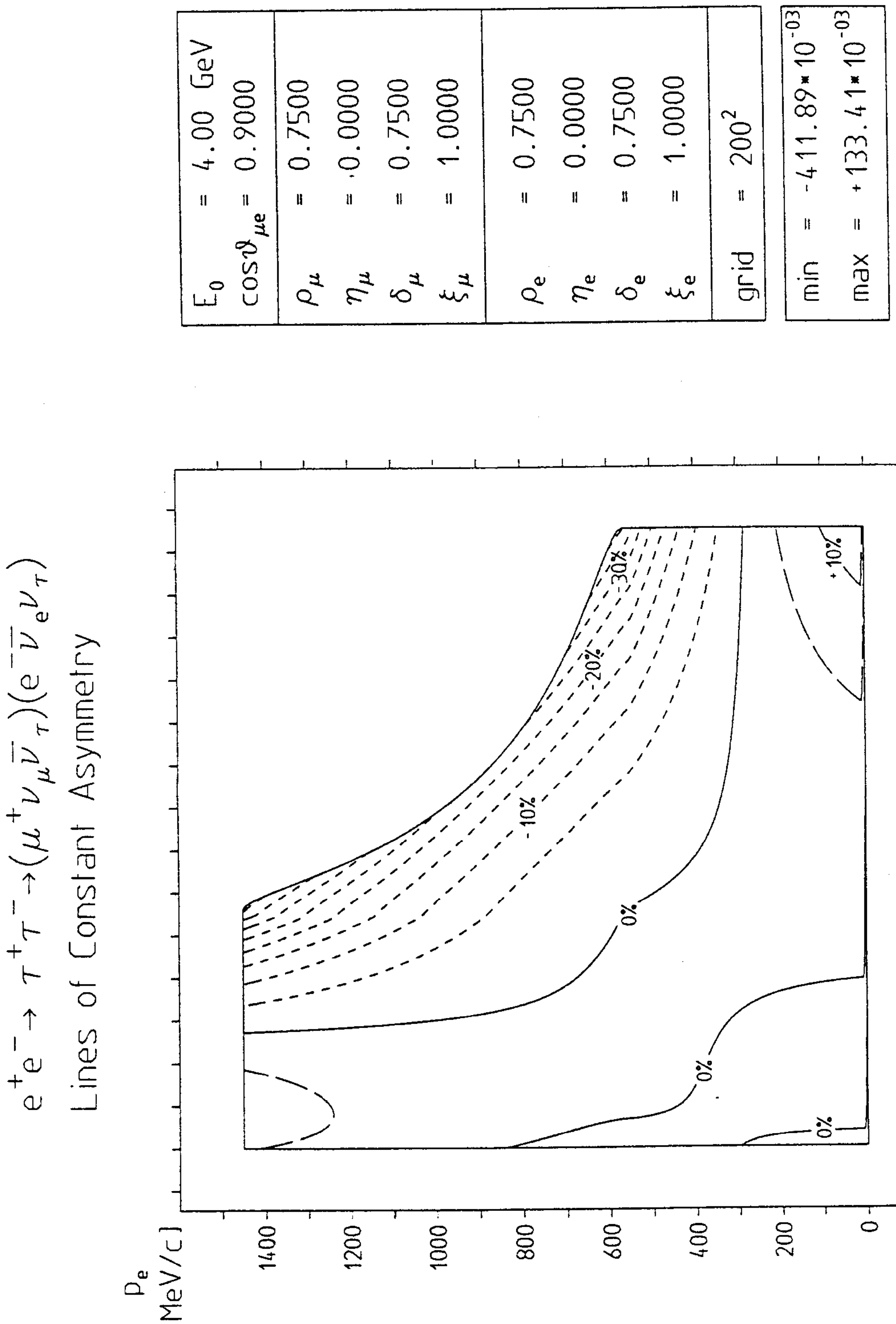

Figure 5: Lines of constant asymmetry for $cos\vartheta_{\mu e}$=+0.9.

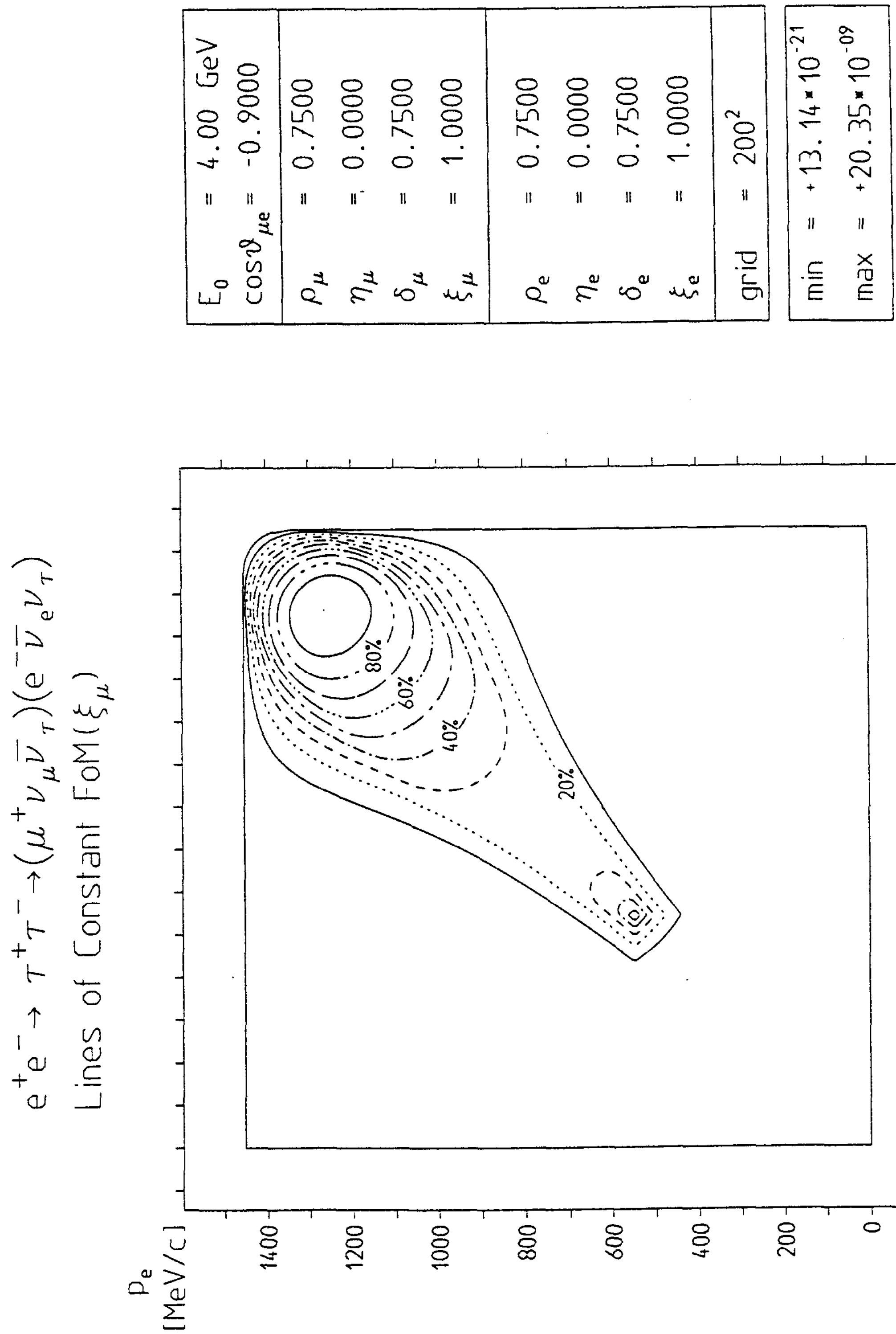

Figure 6: Lines of constant figure of merit for ξ_μ.

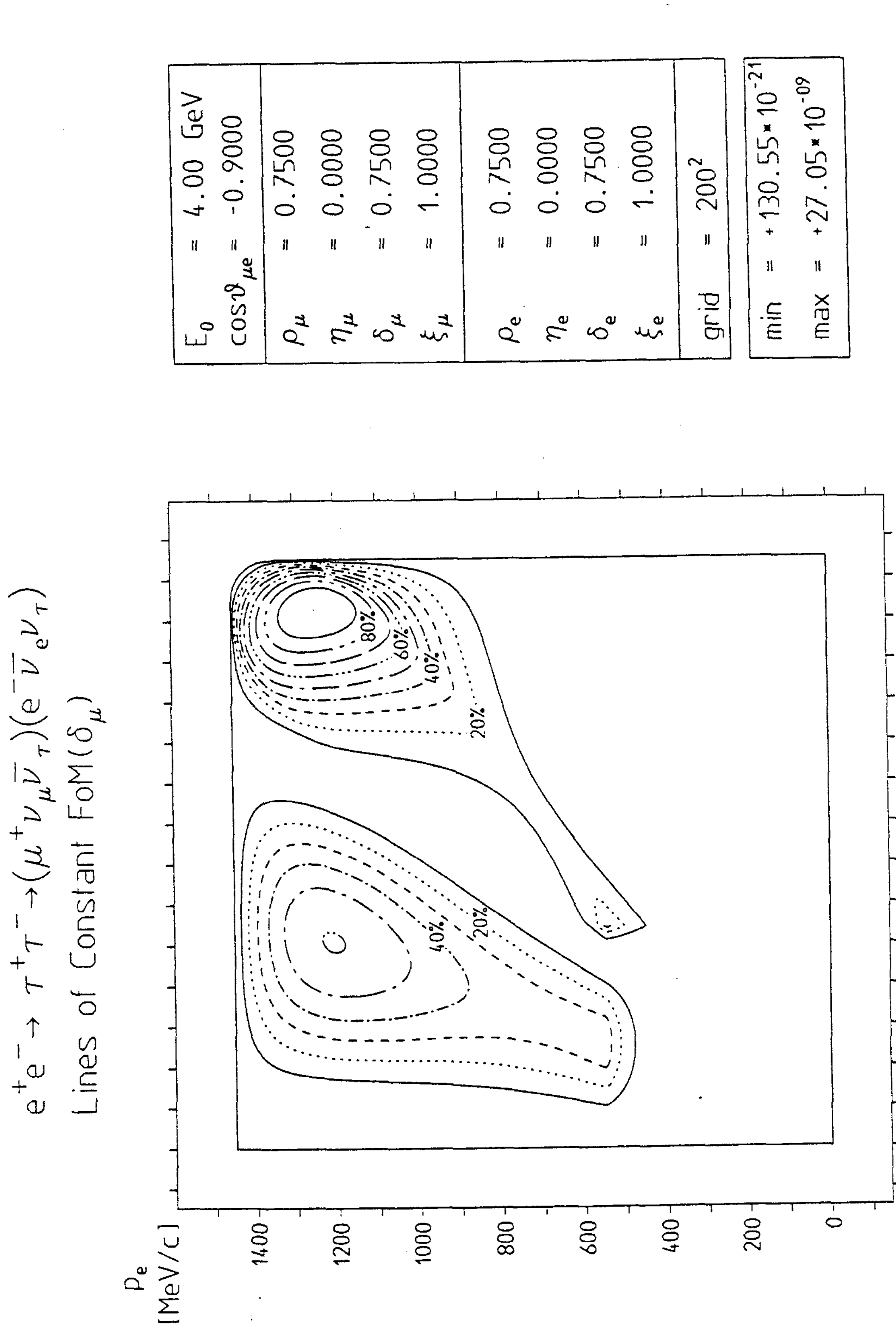

Figure 7: Lines of constant figure of merit for δ_μ.