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# PHYSICS AT THE $Z^0$*

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## ABSTRACT

With the next generation of electron-positron colliders on the immediate horizon, we review the standard model and the precision tests of it which can be carried out at the $Z^0$ peak. Emphasis is put on the possibilities for discovering new physics, from additional quarks and leptons to extra neutral gauge bosons.

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# 1. INTRODUCTION

The cross section for electron-positron annihilation into hadrons is shown in Figure 1. After the valley following charmonium and bottomonium physics, the cross section for electron-positron annihilation into hadrons rises to about 40 nb or 4000 times the "point" cross section for $e^+e^- \to \gamma \to \mu^+\mu^-$ at the peak of the $Z$. After struggling in the valley, there is no doubt as to where we want to do physics next.

There are two machines designed to do this physics, SLC and LEP. Construction of both is proceeding apace. At SLAC, the construction project is in its final stages. The tunnels are finished and the magnets are being installed. The single interaction region is also nearing completion, with the first experimental apparatus, the Mark II detector, being moved from PEP. Hopefully, there will be beams in the interaction region by the end of this calendar year and experimentation can begin next Spring. At the end of the decade, the Mark II will be superceded by a more powerful detector, the SLD. At CERN, much of the tunnelling for LEP and its interaction regions is finished. Four experiments are planned: ALEPH, DELPHI, L3, and OPAL. Data taking is to begin in 1989.

With the era of $Z^0$ physics approaching, it is an opportune time to take another look at what can be discovered at these "$Z$ factories". There have been rather complete and extensive examinations of this subject.[1,2] The increase in our understanding since some of the work was done, plus the immediacy of experiments with well defined detectors, has led to further work.[3] In the following I will attempt to give a brief overview of what we hope to learn from $Z$ physics. I start with the standard model and the accuracy with which we can now test it, and proceed to what new physics will soon be within our reach.

# 2. THE STANDARD MODEL

The standard model for electroweak physics is based on the gauge theory $SU(2) \times U(1)$, spontaneously broken so as to have massive $W^+$, $W^-$, and $Z$ vector bosons and a massless photon.[4] Within the gauge theory sector itself there are three parameters: $g$, the $SU(2)$ coupling; $g'$, the $U(1)$ coupling; and the vacuum expectation value, $v$, of the Higgs field that is associated with spontaneous breaking of the continuous symmetry.

We usually do not work in terms of these three parameters. After defining the weak mixing angle through

$$\cos\theta_W = \frac{g}{(g^2 + g'^2)^{1/2}}, \tag{1}$$

and identifying the electromagnetic coupling

$$e = g \sin\theta_W, \tag{2}$$

and the Fermi effective coupling

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8\, M_W^2}, \tag{3}$$

it has often been convenient to use $\alpha = e^2/4\pi$, $G_F$ and $\sin^2\theta_W$ as the three parameters of the theory. This is related to the very accurate experimental determinations of the first two, $\alpha$ and $G_F$, leaving $\sin^2\theta_W$ to be pinned down as the characteristic parameter expressing the unification of weak and electromagnetic interactions. The $W$ and $Z$ boson masses are related by

$$M_W = M_Z \cos\theta_W, \tag{4}$$

and the W mass itself, using Eqs. (2) and (3) in lowest order, is given numerically by

$$M_W = \frac{37.3\ GeV}{\sin\theta_W}. \tag{5}$$

While up to the present it is $\sin^2\theta_W$ that is commonly used as the third parameter, Eqs. (4) and (5) make it clear that we could use $M_W$ or $M_Z$. Until their discovery this made no sense, but already the experimental uncertainty on their masses gives a comparable accuracy in the determination of $\sin^2\theta_W$ to that from measurements in low energy neutral current experiments.[5] In fact, once we enter the era of $Z$ physics, it is much more appropriate to use $\alpha$, $G_F$, and $M_Z$ as the three parameters of the electroweak gauge theory, since $M_Z$ will be fairly easily measured to an accuracy which will far exceed its equivalent in other determinations of $\sin^2\theta_W$.

In any case, once these three parameters are all accurately measured, any independent measurement of a coupling or of $M_W$ will give a test of the standard model. We recall that the couplings of the $Z$ to a fermion, $f$, are given by (where $Q_f$ is the electric charge of the fermion in units of the proton charge):

$$Q_R = \frac{-g\ Q_f \sin^2\theta_W}{\cos\theta_W}, \tag{6}$$

and

$$Q_L = \frac{g\ (I_{3L} - Q_f \sin^2\theta_W)}{\cos\theta_W}, \tag{7}$$

making explicit their dependence on $\sin^2\theta_W$.

In order to make a precision test of the standard model, we need to take account of something we have slid over in the previous discussion. The electroweak radiative corrections change the relationship between $\sin^2\theta_W$ and the gauge boson masses. At the same time, we need to be careful to specify at what momentum scale we define the parameters of the theory. For $\alpha$ and $G_F$ this scale is taken to be zero, as these two quantities are taken from experiments at zero momentum transfer (or very close to it). As a result of the electroweak radiative corrections calculated to one loop level[6-8] $M_W$ and $M_Z$ get corrected upward by about $(1.07)^{1/2}$, so that

$$M_W = \frac{38.65\ GeV}{\sin\theta_W} \tag{8}$$

and

$$M_Z = \frac{77.3\ GeV}{\sin 2\theta_W}, \tag{9}$$

where $\sin\theta_W$ is defined at the scale $M_W$. For a value of $\sin^2\theta_W = 0.22$ the corresponding value of $M_Z$ from Eq. (9) is 93.3 GeV (as compared with 90.0 GeV without one loop radiative corrections). The present accuracy of experimental measurements either of the masses of the gauge bosons or of $\sin^2\theta_W$ in neutral current experiments does not permit an incisive test of the radiative corrections at the one loop level. Note that the fractional errors in $M_Z$ and $\sin^2\theta_W$ are related by:

$$\frac{\delta M_Z}{M_Z} = -0.36\,\frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W}, \tag{10}$$

so that a 5% measurement of $\sin^2\theta_W$ is equivalent to a 1.8% measurement of $M_Z$.

# 3. TESTING THE STANDARD MODEL

Let us start with one of the first things to be determined with high accuracy at the SLC: the $Z$ mass. With extraction-line spectrometers to measure the collision energy pulse by pulse, the measurement of $M_Z$ will be limited ultimately by a systematic uncertainty at the level[9] of ±45 MeV. This corresponds, by Eq. (10), to an uncertainty of $\delta(\sin^2\theta_W) = \pm 0.0003$, about 30 times smaller than the present combined statistical and systematic uncertainties from low energy neutral current measurements. Moreover, a statistical uncertainty comparable to this systematic uncertainty is achievable in about one month of running at a luminosity of $5 \times 10^{28}/cm^2\ sec$, one hundredth of the design luminosity!

For the $Z$ width, the ultimate accuracy at SLC is limited by systematics at the level[9] of about ±35 MeV. At LEP, a precision of ±20 MeV for both the mass and the width is hoped for, again limited by systematics.[10] Note that with a standard model prediction of 2.7 GeV for the $Z$ width, a $t$ quark with a mass of 35 GeV increases the width by about 60 MeV and an extra sequential neutrino increases the Z width by 180 MeV. While there are other ways to discover and then to sort out each of these aspects of new physics, this already shows that a total width measurement is a simple and effective probe of additional physics.

The couplings of the $Z$ to fermions can be determined from the width for $Z \to f\bar{f}$, which is proportional to $Q^2_{R,f} + Q^2_{L,f}$, or equivalently to $v_f^2 + a_f^2$ where $v$ and $a$ are the vector and axial-vector couplings of the $Z$ to the fermion, $f$. The tests of the standard model obtainable from such measurements are not very stringent. This is because the width depends quadratically on the couplings, which are either slowly varying with $\sin^2\theta_W$, or very small (like $v_e$) and make a negligible contribution to the width.

Of much higher sensitivity is the polarization asymmetry. If the electron beam can be longitudinally polarized, we can form the asymmetry

$$A_{POL} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{2\, v_e\, a_e}{|v_e|^2 + |a_e|^2}, \tag{11}$$

where $\sigma_R$ and $\sigma_L$ are the cross sections (integrated over final angles for any particular final state or sum of final states) for right- and left-handed incident electrons, respectively. With $\sin^2\theta_W = 0.22$, the polarization asymmetry has a value of about $-0.24$. More importantly, since $v_e$ is proportional to $1-4\sin^2\theta_W$, and small compared to $a_e$,

$$\delta A_{POL} \approx -8\, \delta(\sin^2\theta_W) \tag{12}$$

Therefore, as seen[11] in Figure 2, with $10^4$ produced $Z$'s and a 5% systematic uncertainty in the polarization, one can determine the polarization asymmetry to an accuracy that corresponds to $\delta(\sin^2\theta_W) = \pm 0.002$. With $10^6$ $Z$'s and a systematic uncertainty of 1%, the equivalent accuracy in $\sin^2\theta_W$ is $\pm 0.0004$. The accuracy here is comparable to that from measuring $M_Z$ when the two measurements are transformed to an equivalent basis. Here is the high precision test of the standard model; nothing else is so powerful or direct.

There are many other measurements of couplings that can be made from front-back asymmetries (without a polarized beam), from tau polarization, and from using longitudinal electron polarization with measurement of particular $f\bar{f}$ final states. For both quarks and leptons there is the definite possibility of reducing the present experimental uncertainty in the vector current couplings of the $Z$ to fermions by about an order of magnitude.[12]

# 4. LOOKING FOR NEW PHYSICS

In the following we review rather quickly many of the possible new physics areas which can be explored in $Z$ decays. The reader interested in examining further a particular topic should consult Refs. 1, 2 and 3.

• The top quark should be easy to find if $m_t \leq M_Z/2$. Fairly straightforward cuts, motivated by the fact that two and three jet events are approximately planar while weakly decaying top quarks give quite spherical events when one is not far from threshold, are quite effective in separating out a sample of $Z \to t\bar{t}$ events. Furthermore, in the semileptonic decays of the $t$ quark, the charged lepton typically has a rather high momentum relative to the final quark jet, and additional cuts on lepton transverse momenta produce a fairly clean signal within events which are preselected to be aplanar.[13] With $10^3$ to $10^4$ $Z$'s one should already have a good hint of top quarks if they are present in $Z$ decays, and with $10^5$ $Z$'s it will be possible to pin down the mass to within a few GeV.

• That brings us to toponium, the bound states of top and anti-top. There is important mixing[14] between the $Z$ and vector toponium bound states through the off-diagonal term in the mass-squared matrix:

$$\delta m^2 = 2\sqrt{3}\,|\Psi(0)|\,M_{t\bar{t}}^{1/2}\,v_t. \tag{13}$$

Here $\Psi(0)$ is the value of the wave function of the toponium vector state at the origin, and $v_t$ is the vector coupling of the $Z$ to the top quark. This produces deep minima at the bare mass of the toponium state in the cross section for $e^+e^- \to f\bar{f}$, as shown in Figure 3. Here the top quark mass was optimally chosen to place the spectrum of toponium bound states within the $Z$ peak. Unfortunately, even if we should be so lucky, the spread in beam energy at SLC, and to a lesser extent LEP, washes out much of the beautiful structure (see Figure 4). Still, it should be possible to delineate the lowest few bound states and make a very accurate measurement of the top quark mass even with a fairly broad beam energy spread.

• Charged heavy leptons are also relatively "easy" to find. With a branching ratio of about 3% aside from a kinematic factor plus a clean and simple signature from their purely leptonic modes, the search procedure would parallel that which found the tau. Mirror leptons, which couple through V+A to the charged weak boson, have a characteristic change in sign of the front-back asymmetry which makes them very distinguishable from the "usual" sequential leptons which couple through $V - A$.[15]

• The existence of additional neutrinos can be deduced first from the increase in the total $Z$ width of 180 MeV per sequential neutrino mentioned previously. Much more incisive "neutrino counting"[16] is achieved by running above the $Z$ mass and tagging the $Z$ by detecting the radiated photon from the process $e^+e^- \rightarrow Z + \gamma$. This will permit a measurement of the branching ratio for $Z$ decays into "nothing" once corrections are made for those events with charged particles or photons from $Z$ decays which manage to escape the detector.

• As for heavy neutral leptons, we should be able to make a rather complete sweep almost to the kinematic limit. For example, a fourth generation heavy neutrino which mixes with one of the lighter neutrinos (permitting it to decay; otherwise it is picked up by "neutrino counting") would be susceptible to detection if the square of the mixing matrix element was as small as $10^{-10}$ and/or its mass was as large as 45 GeV.[17]

• For quarks and leptons which have a sufficiently high mass that the $Z$ can not decay into them, there is still a sensitivity to their presence in the one loop electroweak radiative corrections. Figure 5 shows the effect[7] on $A_{POL}$ of a new quark doublet, lepton doublet, or full generation of quarks and leptons relative to its value in the standard model with three generations. Unfortunately, the sizes of the effects are at best only of a few standard deviations significance even with only a 1% systematic error in the measured polarization of the beam.

• There have been extensive studies of how to detect supersymmetric particles if they are light enough to be produced in $Z$ decays.[18] Branching ratios are sizable, if allowed at all, and standard techniques of picking out events with missing transverse momentum would appear to suffice for at least establishing the existence of new physics with properties consistent with supersymmetry.

• A similar situation holds for technicolor theories. The characteristic signal involves production of pairs of light spin zero particles called technipions. If they are light enough, the Z should decay into pairs of technipions with a sizable branching fraction.[19]

In both the case of supersymmetry and in the case of technicolor, the effect of virtual particles on the one loop electroweak corrections is comparable to that from adding a new generation of degenerate quarks and leptons. For the case of technicolor the effect may be particularly large, and a many standard deviation effect in $A_{POL}$ is predicted if the polarization of the electron beam can be measured to 1%.[7]

• The Higgs boson (like the $t$ quark) should not really be included in a list of new physics topics, for it is a particle contained in the standard model. Nevertheless, it is new since it is as yet undiscovered. The standard technique[20] of looking for $Z \rightarrow H^0 \ell^+ \ell^-$ is quite clean and should be decisive, but requires something like $10^6$ $Z$'s if the Higgs mass is in the 10 to 30 GeV region. With its even smaller branching ratio,[21] $Z \to H^0 \gamma$ requires more events yet. On the other hand, studies of using the decay $Z \to H^0 \nu\bar{\nu}$, with about six times the branching ratio of $Z \to H^0 \ell^+ \ell^-$, look possible with the SLD and LEP detectors, as well as with the Mark II if recent studies[22] are extended and continue to be positive.

• Compositeness is an idea most often considered for quarks and leptons, but in a more radical form may be taken to include the $W$ and $Z$ as well. In the former case one looks for a modification of the interactions of the point Dirac fermions, excited quarks and leptons, and exotic states.[23] In the latter case, the $Z$ could itself have an enhanced rate (compared to standard model expectations) for some decays, such as $Z \to 3\gamma$, or new decays, such as those involving associated composite scalars (if they are light enough).[24]

• The possibility of enlarging the electroweak gauge group beyond the $SU(2) \times U(1)$ of the standard model has had various theoretical motivations over the years. Grand unified theories, such as $O(10)$, generally lead to additional gauge bosons, as do left-right symmetrical theories such as $SU(2)_L \times SU(2)_R \times U(1)$.

The great burst of interest in superstring theories[25] has revitalized research in this area, as the combined low energy gauge group will generally be larger than $SU(3)_C \times SU(2)_L \times U(1)_Y$ in these theories.[26,27] An early favorite in this regard is to have[28] $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)$ at "low" energies, but this choice seems to be by no means unique.[26–29]

Nevertheless, most attention has been focused phenomenologically on the implications that follow from this last possibility: the electroweak gauge group is $SU(2)_L \times U(1)_Y \times U(1)$ and there is just one "extra" neutral gauge boson, a $Z'$. We will concentrate on this case here as well, mostly for definiteness, but also because it serves as a generic model of how electron- positron physics is changed by the presence of a $Z'$.

The Lagrangian describing the interaction of the neutral gauge bosons of the theory with the corresponding currents now has the form

$$\mathcal{L} = e\, A_\mu\, J^\mu_{em} + \frac{e}{\sin\theta_W \cos\theta_W} Z_\mu\, J^\mu_Z + \frac{e}{\cos\theta_W} Z'_\mu J^\mu_{Z'}, \tag{13}$$

with the last term being new and giving additional neutral current effects. The weak charges of quarks and leptons which the $Z'$ "sees" are contained in $J^\mu_{Z'}$ and are well-defined in a particular model. We take those charges which correspond to the favorite $Z'$ of superstrings, for which these charges have been worked out elsewhere.[30]

The presence of an extra neutral gauge boson, $Z'$, will generally entail mixing with the $Z$ of the standard model. The two channel mass matrix has the form

$$M^2 = \begin{pmatrix} M_Z^2 - iM_Z\Gamma_Z & \delta M^2 \\ \delta M^2 & M_{Z'}^2 - iM_{Z'}\Gamma_{Z'} \end{pmatrix} \tag{14}$$

and for $\delta M^2$ small will be diagonalized by a rotation through an angle

$$\theta_{MIX} \approx \frac{\delta M^2}{M_Z^2 - M_{Z'}^2}. \tag{15}$$

The physical $Z$ mass will be shifted downward from its "bare", standard model value, just as the $Z'$ will be shifted upward:

$$\Delta M_Z \approx \frac{M_Z^2 - M_{Z'}^2}{2M_Z}\, \theta^2_{MIX}. \tag{16}$$

In a given theory, the Higgs content gives restrictions on the elements of the mass matrix in Eq. (14). There are consequent correlations between $\theta_{MIX}$ and $M_{Z'}^2$ if these restrictions are imposed.

The constraints which the measured as compared to expected (in the standard model) $Z$ mass, the neutral current data, and the Higgs content of superstring models impose have been examined separately or in combination in a number of papers[31] in order to constrain the values of the $Z'$ mass and mixing angle. As shown in Figure 6, the region of masses allowed for the $Z'$ which has (unmixed) gauge couplings corresponding to $Z_\eta$ starts at about 130 GeV and the allowed mixing angles obey $|\theta_{MIX}| \lesssim 0.1$. For $Z'$ masses up to several times the $Z$ mass, it is the neutral current data and/or the measured value of the $Z$ mass being consistent with the standard model value which provide more stringent constraints than the Higgs content. The surprisingly low mass value allowed for the $Z'$ is due to the small (compared to the $Z$) couplings to ordinary fermions of the $Z_\eta$ with which we are dealing with here.

Measurements at the $Z$ peak will serve to restrict much more the values of $\theta_{MIX}$ and $M_{Z'}$ as compared to the present limits.[32] Figure 7 shows the change in the cross sections for particular final state fermion pairs in electron-positron annihilation at the (mixed) $Z$ peak as a function of $\theta_{MIX}$ when $M_{Z'}$ is fixed at 200 GeV. There are changes of roughly 10% for variations of $\theta_{MIX}$ by $\pm 0.1$. Such a change should be significant, particularly for $e^+e^- \to Z \to e^+e^-$ (or equivalently, $e^+e^- \to Z \to \mu^+\mu^-$), where a 3% measurement of the cross section seems possible.[33]

Of course the mass of the $Z$ itself, as noted previously, will be very accurately determined. The impediment to using this information as a constraint is the accuracy of the prediction of the (unmixed) value of $M_Z$ in the standard model from an independent measurement of $\sin^2\theta_W$ (from $M_W$ or couplings). If we can assume an order of magnitude improvement in the constraint on $\Delta M_Z$, the shift in the $Z$ mass from its standard model value, then from Eq. (16) we can entertain a factor of 3 improvement in the constraint on $\theta_{MIX}$ for a given value of $M_{Z'}$. Altogether, just the measurement of the $Z$ mass and the peak height in particular channels will very much improve the limits on the parameters of a potential $Z'$.

Far more dramatic yet are the limits provided by the use of a longitudinally polarized electron beam. In Figure 8 are displayed the changes in $A_{POL}$ at the $Z$ peak due to a $Z'$ as a function of $\theta_{MIX}$. Now we have roughly $\pm 50\%$ changes for $\theta_{MIX}$ varying by $\pm 0.1$. Even with a 5% uncertainty in the beam polarization and a modest number of $Z$'s, it should be possible to constrain $|\theta_{MIX}| \lesssim 0.01$.

There still is the possibility that $\theta_{MIX} = 0$. Then the $Z$ is just the good old one from the standard model, and there is no effect worth speaking about at $\sqrt{s} = M_Z$. But now there are still dramatic effects at somewhat higher energies. Figure 9 shows the front-back and polarization asymmetries as a function of $\sqrt{s}$ for several $Z'$ masses and values of $\theta_{MIX}$. Already there are measurable deviations at $\sqrt{s} = 110$ GeV or so if the $Z'$ mass is not many times $M_Z$.

# 5. CONCLUSION

I hope to have indicated, if only in a sketchy manner given limited space and time, the exciting era of physics at the $Z$ which is on the immediate horizon. With $10^4$ $Z$'s one can already do some very interesting physics: the value of $M_Z$, the cross section for $e^+e^- \to Z \to f\bar{f}$, a signal for the $t$ quark if it is at all accessible kinematically. With $10^5$ $Z$'s plus a longitudinally polarized beam or $10^6$ $Z$'s, we not only have the possibility of making a high precision check of the standard model and a very thorough sweep of the existence of particles with masses below $M_Z/2$, but we have a window on new physics up to several hundred GeV.

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# FIGURE CAPTIONS

1. A somewhat schematic view of the electron-positron landscape as a function of center-of-mass energy.

2. The uncertainty in the longitudinal polarization asymmetry, $A_{POL}$, and the corresponding uncertainty in $\sin^2\theta_W$ as a function of the number of $Z$'s detected (from Ref. 11).

3. The cross section for $e^+e^- \to \mu^+\mu^-$ in units of $\sigma_{pt} = 4\pi\alpha^2/3s$ for $m_t = 47$ GeV. The dotted curve shows the cross section with the $Z$ present, but no toponium (from Franzini and Gilman, Ref. 14).

4. Same as Figure 3, but smeared using a beam energy spread of $\sigma_{E_b} = 40$ MeV (roughly characteristic of LEP, solid curve) and $\sigma_{E_b} = 100$ MeV (roughly characteristic of SLC, dashed curve). The dotted curve again shows the effect of the $Z$ pole without toponium present (from Franzini and Gilman, Ref. 14).

5. Change in $A_{LR} = -A_{POL}$ due to virtual degenerate generations of quarks and leptons as a function of their mass (from Lynn, Peskin, and Stuart, Ref. 7).

6. Constraints on the Z prime mass and mixing angle at present following from the Higgs content in superstring theories (region bounded by the solid curve), $\Delta M_Z \leq 3$ GeV (region bounded by the dash-dot curve), and neutral current data and the gauge boson masses (region bounded by the dashed curve from Durkin and Langacker, Ref. 31).

7. Change in the mass, width, and peak cross sections for $e^+e^- \to \mu^+\mu^-, u\bar{u}$ and $d\bar{d}$ at the Z (in units of $\sigma_{pt} = 4\pi\alpha^2/3s$ ) as a function of $\theta_{MIX}$ for

mixing with $Z_\eta$ (from Franzini and Gilman, Ref. 32).

8. Change in $A_{POL}$ at the $Z$ peak as a function of $\theta_{MIX}$ for mixing with $Z_\eta$ (from Franzini and Gilman, Ref. 32).

9. The front-back asymmetry, $A_{FB}$, and the longitudinal polarization asymmetry, $A_{POL}$ for $e^+e^- \rightarrow \mu^+\mu^-$ as a function of $\sqrt{s}$ for: (a) and (d) $M_{Z_\eta} = 150$ GeV and $\theta_{MIX} = 0$ (solid curve) and $-0.2$ (dashed curve); (b) and (e) $M_{Z_\eta} = 200$ GeV, $\theta_{MIX} = -0.15$ (solid curve) and $M_{Z_\eta} = 295$ GeV, $\theta_{MIX} = -0.05$ (dashed curve); (c) and (f) $M_{Z_\chi} = 200$ GeV, $\theta_{MIX} = -0.1$ (solid curve) and $\theta_{MIX} = 0$ (dashed curve). The dotted curve is in all cases the expectation without a $Z'$ (from Franzini and Gilman, Ref. 32).

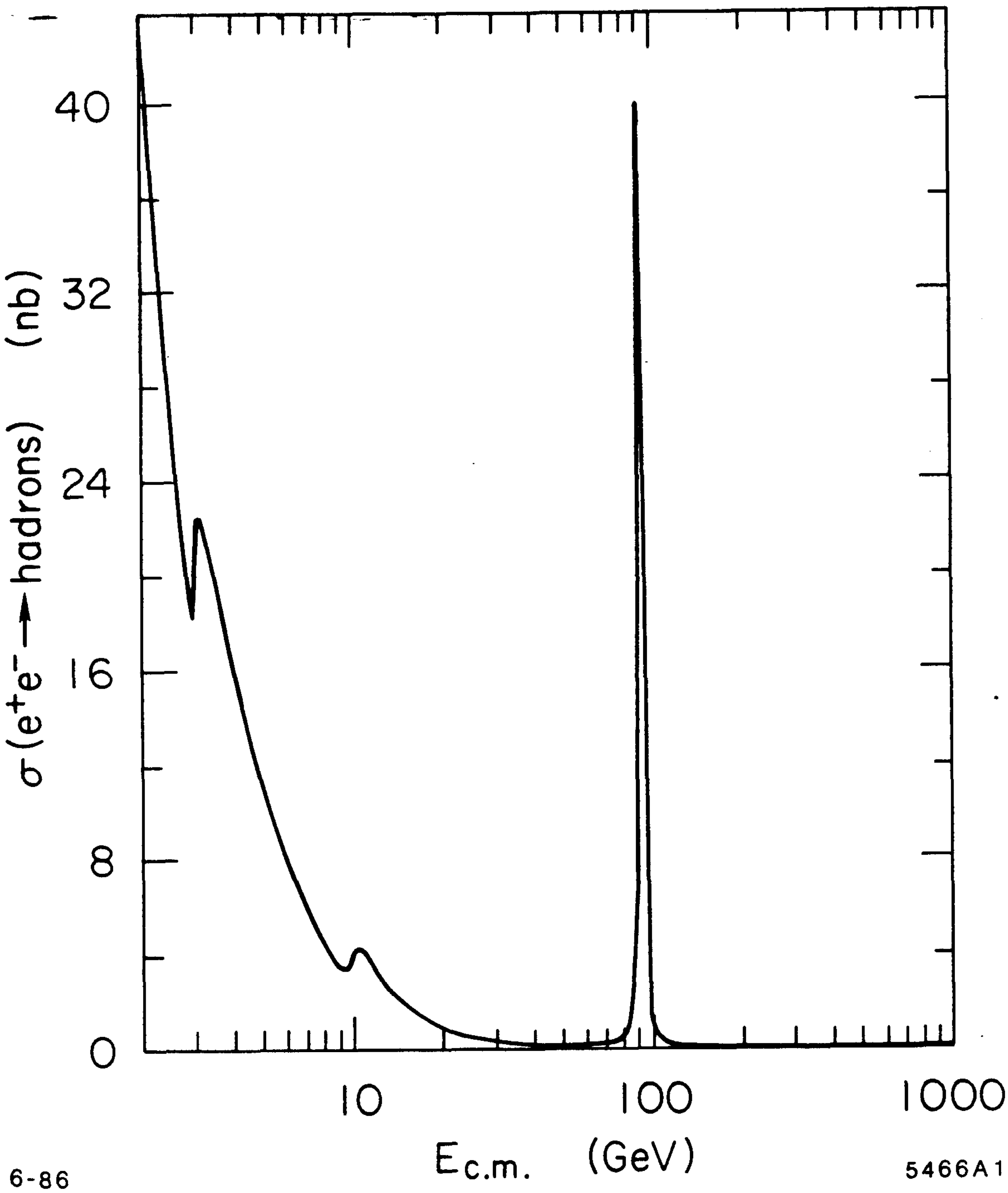



Fig. 1

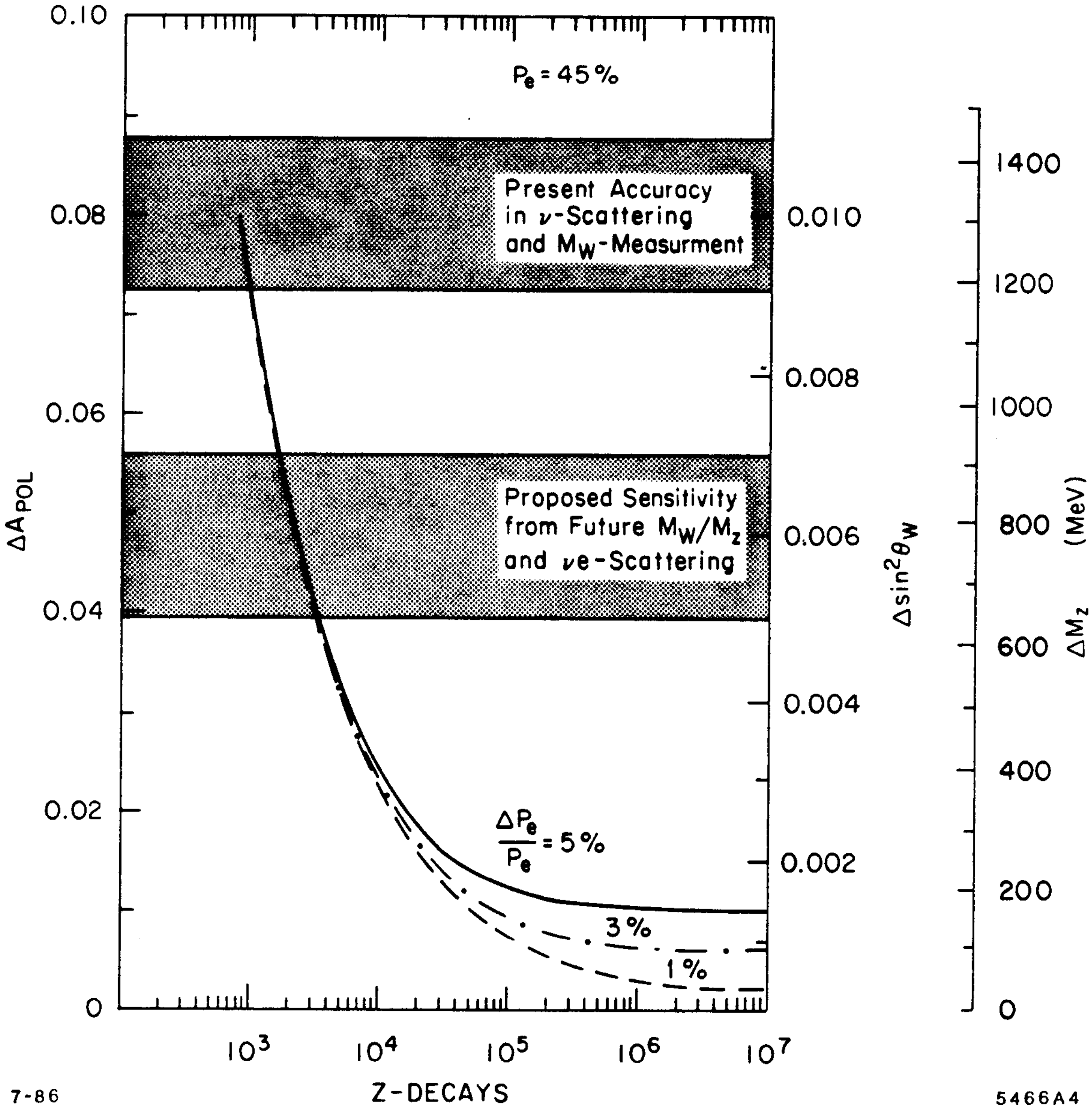

0.10
$P_e = 45\%$
Present Accuracy
in ν-Scattering
and $M_W$-Measurment
0.08
0.010
1400
1200
0.008
0.06
1000
$\Delta A_{POL}$
Proposed Sensitivity
from Future $M_W/M_Z$
and νe-Scattering
0.006
800
$\Delta \sin^2\theta_W$
$\Delta M_Z$ (MeV)
0.04
600
0.004
400
0.02
$\frac{\Delta P_e}{P_e} = 5\%$
0.002
200
3%
1%
0
0
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
Z-DECAYS
7-86
5466A4

Fig. 2

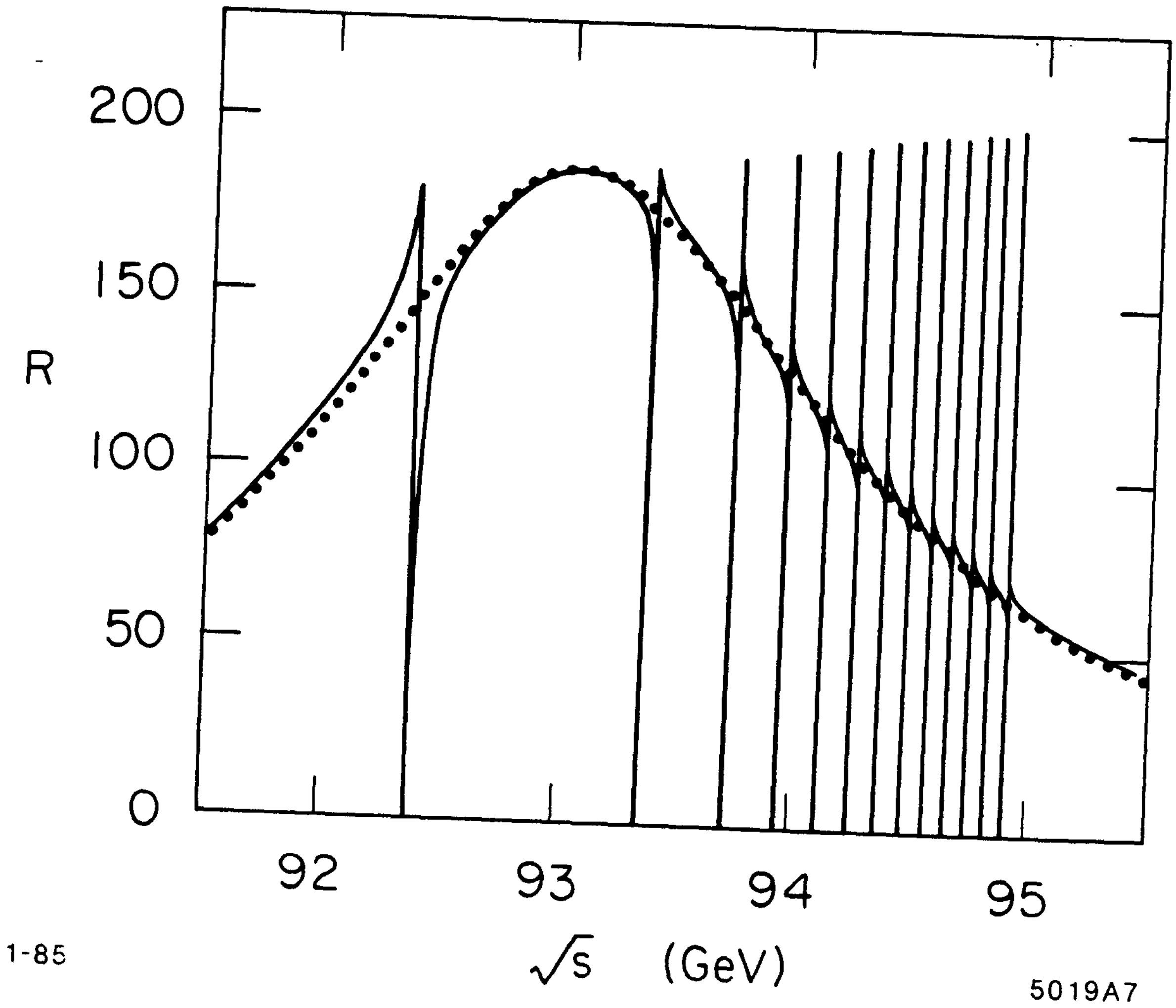



Fig. 3

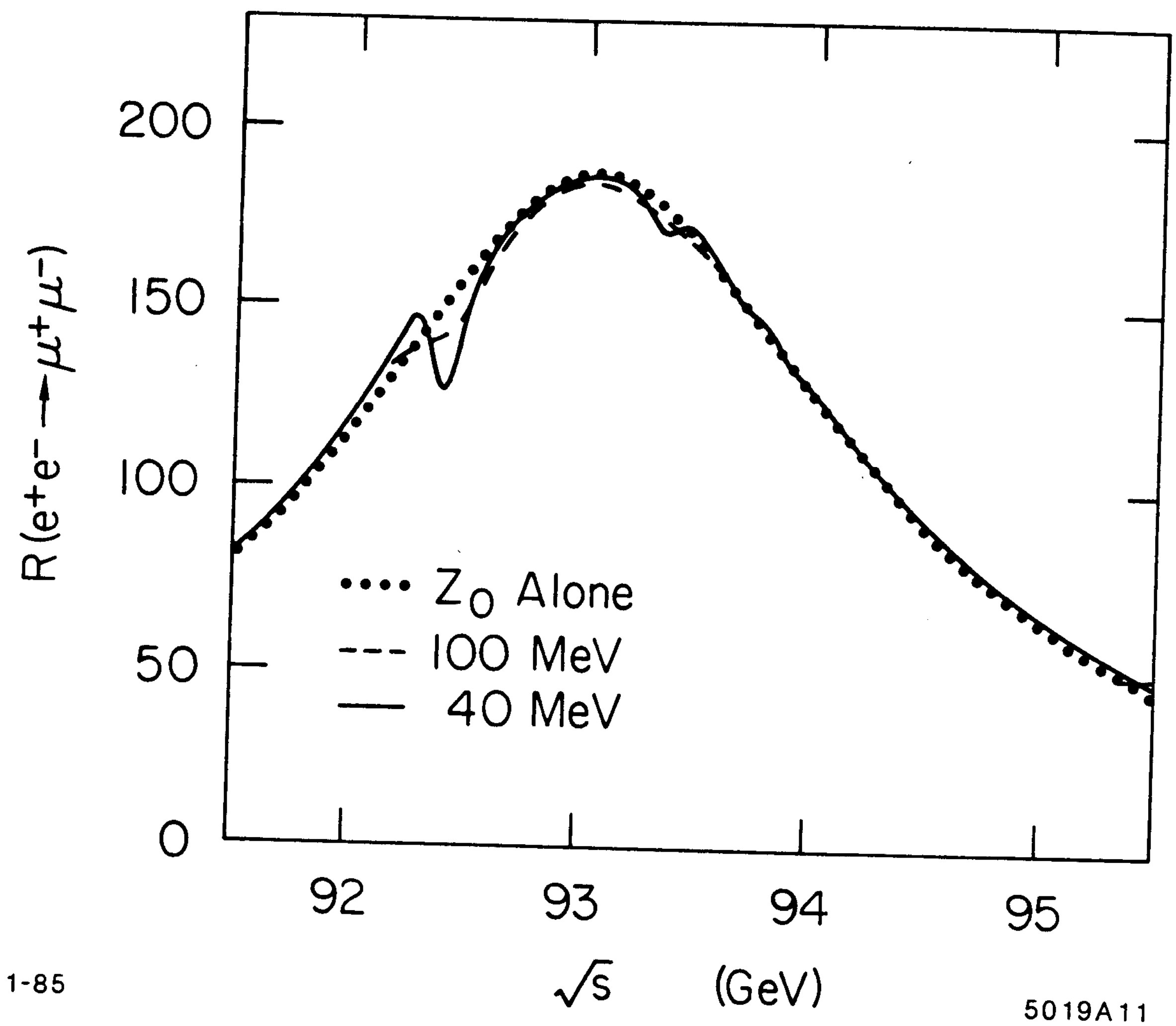

200
150
100
50
0
R(e+e- → μ+μ-)
Z0 Alone
100 MeV
40 MeV
92
93
94
95
1-85
√s (GeV)
5019A11

Fig. 4

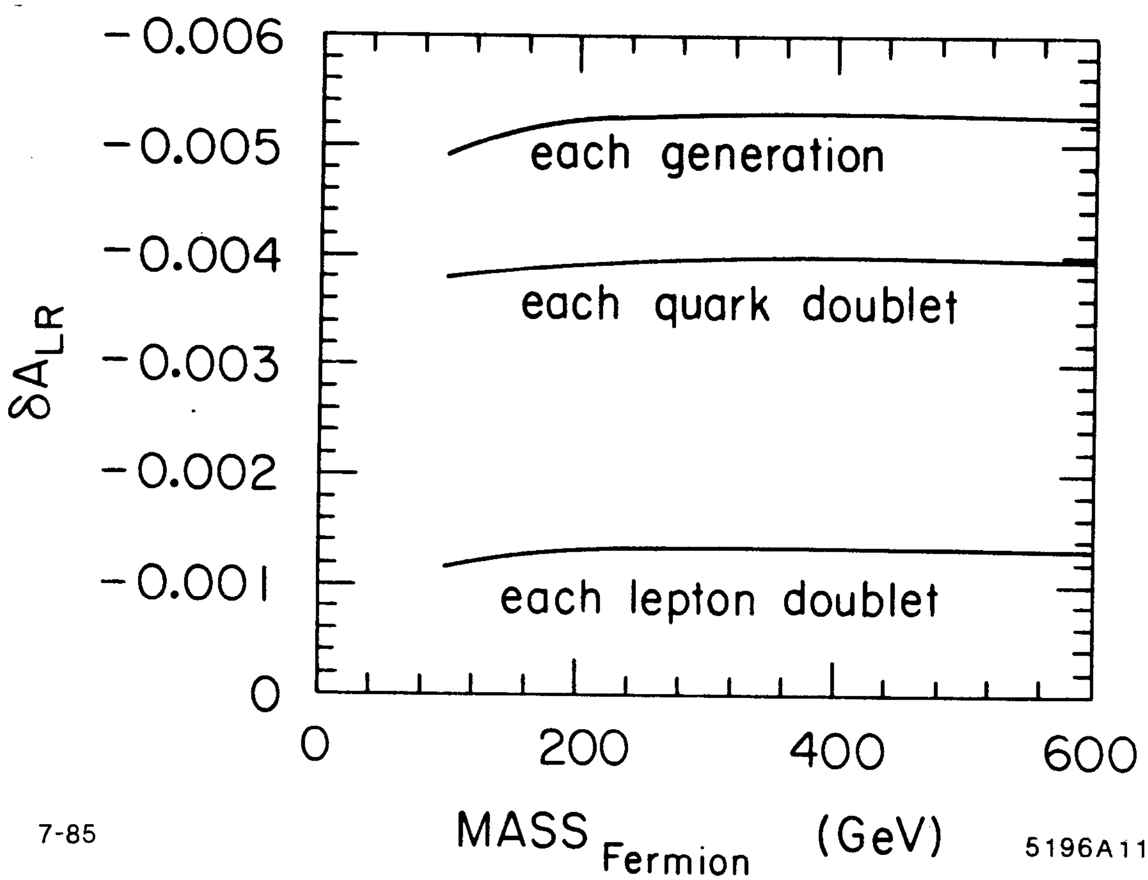

-0.006
-0.005
-0.004
-0.003
-0.002
-0.001
0
δA_LR
each generation
each quark doublet
each lepton doublet
0
200
400
600
MASS Fermion (GeV)
7-85
5196A11

Fig. 5

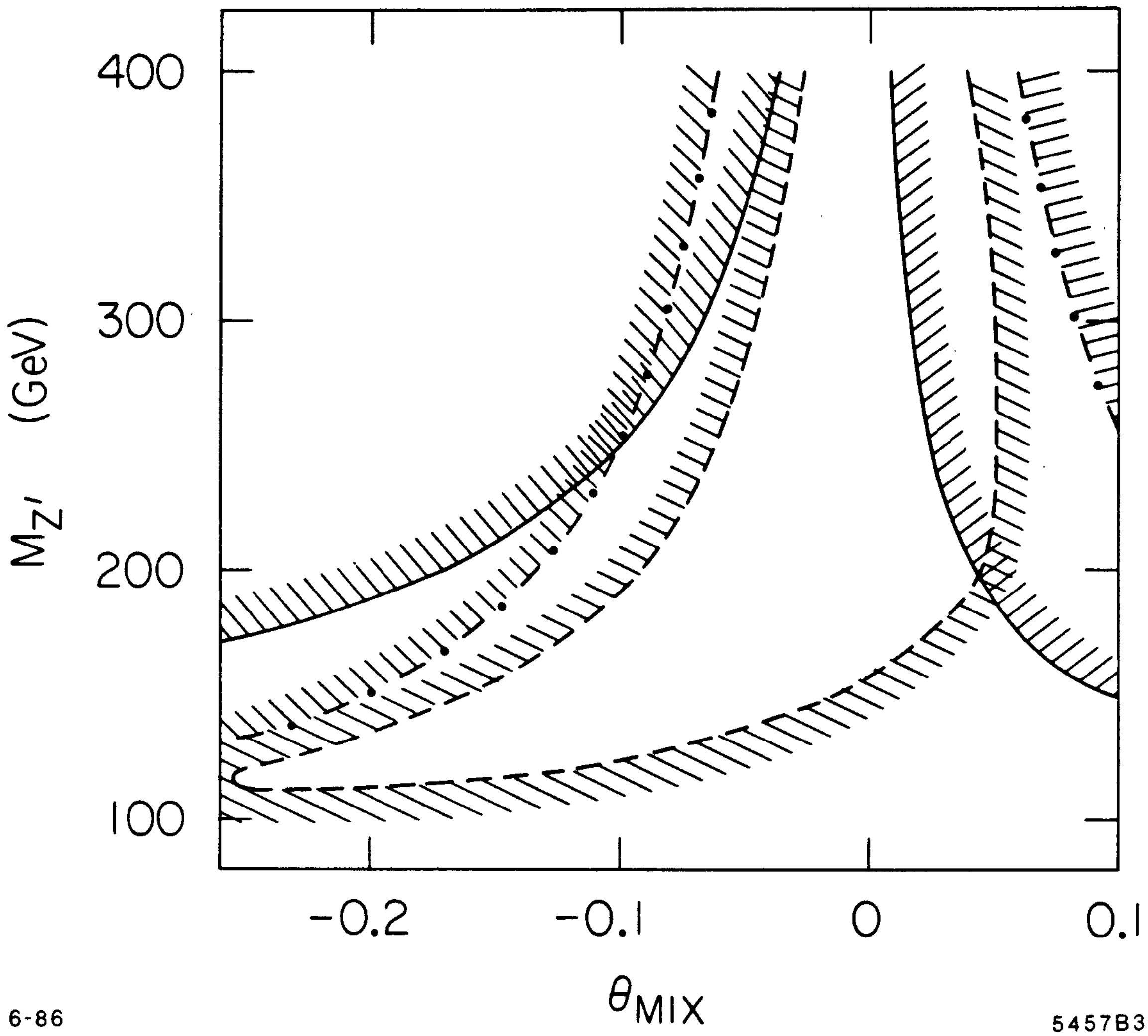
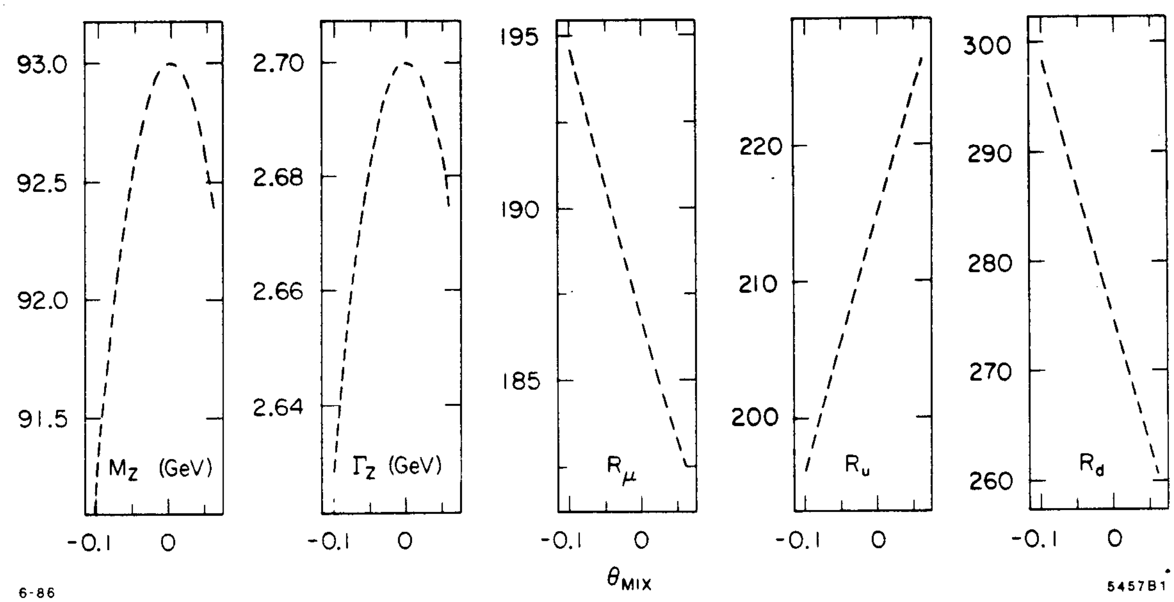



Fig. 6



93.0
92.5
92.0
91.5
$M_Z$ (GeV)
-0.1
0
2.70
2.68
2.66
2.64
$\Gamma_Z$ (GeV)
-0.1
0
195
190
185
$R_\mu$
-0.1
0
$\theta_{MIX}$
220
210
200
$R_u$
-0.1
0
300
290
280
270
260
$R_d$
-0.1
0
6-86
5457B1


Fig. 7

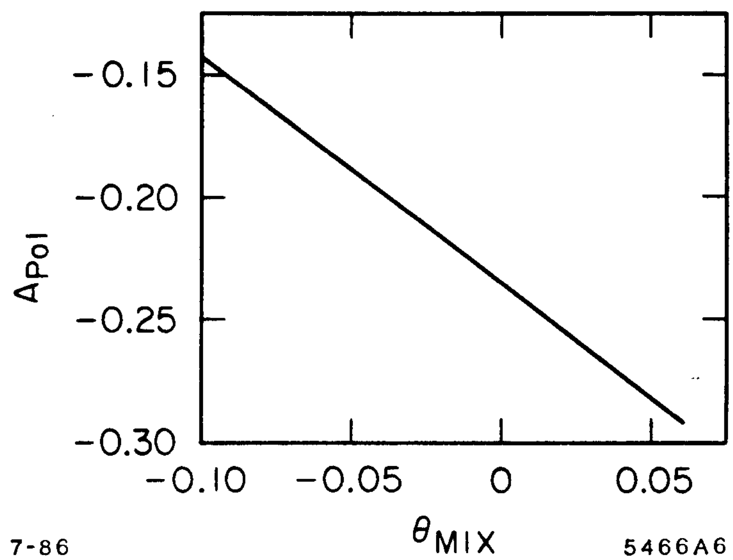
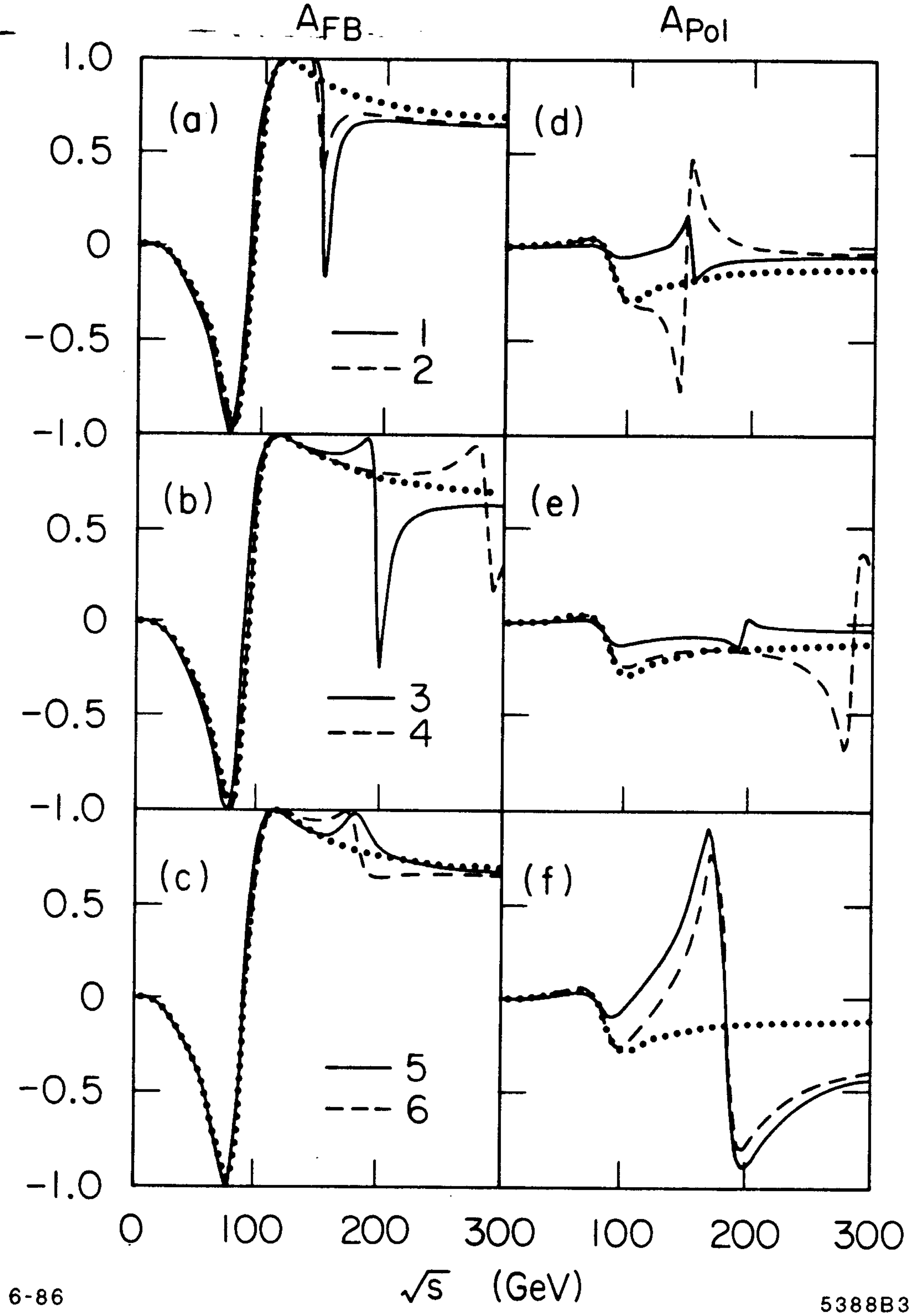



Fig. 8



AFB
APol
1.0
0.5
0
−0.5
−1.0
(a)
(b)
(c)
(d)
(e)
(f)
1
2
3
4
5
6
0
100
200
300
√s (GeV)
6-86
5388B3


Fig. 9