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V.A.Bednyakov

EXTRA Z' BOSON AND TOP QUARK MASS

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Today almost nobody has doubts that the top quark exists. The determination of the top mass m_t is one of the main tasks of the experiment. Unfortunately the search for the t quark creation on contemporary colliders has not been successful, only low limits on m_t were obtained. The indirect estimations [1-4] from the precise neutral current data analysis gave nearly 130 GeV for m_t with accuracy of 30-40 GeV and

$$\sin^2\theta_W \equiv 1- m_W^2/m_Z^2 \cong 0.2276 \pm 0.009 \qquad (1)$$

for the weak angle, where m_W and m_Z are the W- and Z-boson masses. The minimal standard model (SM) was assumed to be correct with one-loop radiative corrections, which are very sensitive to the t mass m_t [5]. Roughly speaking, wanted m_t is connected with the X-coordinate of the intersect point of two curves in fig.1 [1]. The first curve, marked by $\sin^2\theta_W(\nu\text{-q})$ and almost independent of m_t, corresponds to $\sin^2\theta_W$ obtained from the ratio:

$$R_\nu = \sigma^{NC}_{\nu N}/\sigma^{CC}_{\nu N} \cong \rho^2\{\varepsilon_L^2(u)+\varepsilon_L^2(d)+ r[(\varepsilon_R^2(u)+\varepsilon_R^2(d)]\}. \qquad (2)$$

For SM $\varepsilon_L(q)=T_{3L}-Q^{em}\sin^2\theta_W$, $\varepsilon_R(q)=-Q^{em}\sin^2\theta_W$ and $R_\nu=\rho^2[1/2-\sin^2\theta_W+5/9(1+r)\sin^4\theta_W]$; $r=\sigma^{CC}_{\bar\nu N}/\sigma^{CC}_{\nu N}\cong 0.4$ where $\sigma^{NC}_{\nu N}$, $\sigma^{CC}_{\nu N}$ are the neutrino scattering cross sections on the isoscalar target in neutral and charged currents (for simplicity the modification of relation (2) by means of radiative corrections and hadron structure is not written). The second curve, marked by $\sin^2\theta_W$(VBM), was obtained from a relation between the SM parameters α, G_F, m_Z and $\sin^2\theta_W$:

$$\sin^2\theta_W = \tfrac{1}{2}\left[1- \left\{1- \frac{4\pi\alpha}{\sqrt{2}G_F m_Z^2}\,\frac{1}{1-\Delta r}\right\}^{1/2}\right], \qquad (3)$$

The top mass m_t arises in $\sin^2\theta_W$(VBM) by means of the loops contribution Δr [4,5]:

$$\frac{1}{1-\Delta r} \cong \frac{\alpha(m_Z)}{\alpha}\left\{ 1+ \frac{\cos^2\theta_W}{\sin^2\theta_W}\left\{ \frac{3G_F m_t^2}{8\sqrt{2}\pi^2} + \left(\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\right)^2 \frac{19-2\pi^2}{3} +\ldots\right\}\right\}^{-1}, \qquad (4)$$

thus $\sin^2\theta_W$(VBM) decreases if m_t increases. So simultaneous precise determination of $\sin^2\theta_W(\nu\text{-}q)$ and $\sin^2\theta_W$(VBM) allows indirect estimation of m_t (and $\sin^2\theta_W$ too). For more accurate determination of the central value m_t of the top quark mass and the error Δm_t it is necessary, however, to take into consideration the whole set of the neutral current data as done in [1-4].

The m_t-independent value of $\sin^2\theta_W = 0.220 \pm 0.009$, calculated with formula (1) using the experimental values of the mass ratio m_W/m_Z [6] is shown in fig.1 too. This value is essentially smaller than $\sin^2\theta_W(\nu\text{-}q)$ but still has considerable experimental uncertainties, therefore we don't use this value here. However, more precise determination of the ratio m_W/m_Z can yield a significantly larger extracted m_t.

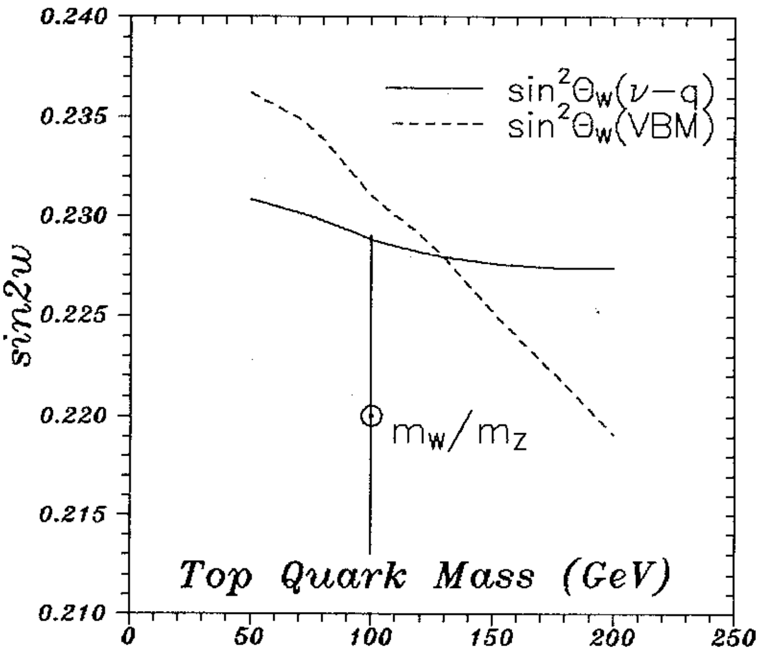

Fig.1. $\sin^2\theta$ obtained from $m_Z(\sin^2\theta_W(\text{VBM}))$, m_W/m_Z and $R(\sin^2\theta_W(\nu\text{-}q))$ as a function of top mass m_t. (Figure is taken from [1]).

There is only one vector Z-boson that transfers the neutral weak interactions in SM. Today the possible manifestations of the superstring-inspired extra Z′ boson [7] in a large domain of neutral current processes are widely discussed [8-10]. It is suggested that after superstring compactification the effective theory with E_6 gauge group arises. This group breaks down to the subgroup $G_5 = SU_{3C}\times SU_{2L}\times U_{1Y}\times U_{1\eta}$ [rank 5] or $G_6 = SU_{3C}\times SU_{2L}\times U_{1Y}\times U_{1\psi}\times U_{1\chi}$ [rank 6]. Examination of the rank 6 subgroup yields two extra neutral bosons Z_ψ and Z_χ. Assuming that G_6 spontaneously breaks on intermediate scale $M_I \approx 10^{10-11}$GeV one has only one "light" Z′-boson [7]. The corresponding U_1' charge is

$$Q'(\vartheta_{E6}) = Q_\psi \cos\vartheta_{E6} + Q_\chi \sin\vartheta_{E6}, \qquad (5)$$

$Q_{\psi,\chi}$ are $U_{1\psi,\chi}$-charges. The angle ϑ_{E6} parametrises the scheme of the symmetry breaking at the intermediate scale. The charge Q_η of subgroup $U_{1\eta}$ corresponds to the fixed value of the angle $\vartheta_{E6}=142.2^\circ$.

The Z, Z′ mass matrix is non-diagonal in the general case. After diagonalization the Z_1 and Z_2 fields with the definite masses m_1 and m_2 arise. The Z-Z′ mixing angle is determined by relation

$$tg^2\theta = \frac{m_0^2 - m_1^2}{m_2^2 - m_0^2}, \qquad (6)$$

here $m_0=m_W/\cos\theta_W$ is a mass parameter coinciding with SM Z boson mass. For the Z_1 and Z_2 fields the Lagrangian takes the form [9]

$$L_{NC} = e\sum_{\imath=1}^{2} g_\imath \, Z_\imath^\mu \, (\varepsilon_L^\imath \, \bar{f}_L\gamma_\mu f_L + \varepsilon_R^\imath \, \bar{f}_R\gamma_\mu f_R), \qquad (7)$$

$g_1=\cos^{-1}\theta_W \sin^{-1}\theta_W$, $g_2=g_1 w=g_1\frac{\sqrt{5}}{\sqrt{3}}\sin\theta_W$[9] and $f_{L,R}=\frac{1}{2}(1\mp\gamma_5)f$. For $\imath\neq0$ and B=L,R:

$$\varepsilon_B^1(f) = \varepsilon_B^{sm}(f)\cos\theta + w\ \varepsilon_B'(f)\sin\theta,$$

$$\varepsilon_B^2(f) = \varepsilon_B'(f)\cos\theta - w^{-1}\varepsilon_B^{sm}(f)\sin\theta. \qquad (8)$$

The chiral couplings $\varepsilon_B^{sm}(f)$ and $\varepsilon_B'(f)$ are given in the table.

Table

	$\varepsilon_L(u)$	$\varepsilon_R(u)$	$\varepsilon_L(d)$	$\varepsilon_R(d)$	$\varepsilon_L(\nu)$
Z_{sm}	$\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$	$-\frac{2}{3}\sin^2\theta_W$	$-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W$	$\frac{1}{3}\sin^2\theta_W$	$\frac{1}{2}$
Z_χ	$-\frac{1}{2\sqrt{10}}$	$\frac{1}{2\sqrt{10}}$	$-\frac{1}{2\sqrt{10}}$	$-\frac{3}{2\sqrt{10}}$	$\frac{3}{2\sqrt{10}}$
Z_ψ	$\frac{1}{\sqrt{24}}$	$-\frac{1}{\sqrt{24}}$	$\frac{1}{\sqrt{24}}$	$-\frac{1}{\sqrt{24}}$	$\frac{1}{\sqrt{24}}$
Z_η	$-\frac{1}{\sqrt{15}}$	$\frac{1}{\sqrt{15}}$	$-\frac{1}{\sqrt{15}}$	$-\frac{1}{2\sqrt{15}}$	$\frac{1}{2\sqrt{15}}$

The top quark mass m_t(and $\sin^2\theta_W$) dependence upon extra Z′ boson parameters is investigated in this paper. The Z′ existence must manifest itself in deviations from SM already at the tree level. Particularly, due to non-zero Z-Z′ mixing the measured Z boson mass m_1 has to be slightly less than the Z boson mass m_0 expected in SM (when there is no mixing). So in formulae (1),(3) one has to take for m_Z not the experimentally determined mass m_1 but m_0 defined by formula (6). So one has a decrease of the ratio m_W/m_Z and hence an increase of $\sin^2\theta_W$ calculated by (1) as well as a decrease of $\sin^2\theta_W$(VBM) independently of m_t. The value of $\sin^2\theta_W(\nu\text{-}q)$ will change too. Actually, to take Z′ boson into consideration one must change the chiral couplings $\varepsilon_{L,R}^{sm}(q)$ in formula (2) to the low-energy effective chiral couplings in the form [9]

$$E_B(q) = \frac{\sqrt{2}}{2G_F}\sum_{i=1}^{2}\varepsilon_L^i(\nu)\varepsilon_B^i(q)\,g_i^2/m_i^2. \qquad (9)$$

As a result, the functional connection between R_ν and $\sin^2\theta_W$ changes and another value will be extracted for $\sin^2\theta_W(\nu\text{-}q)$, which depends on Z′ parameters. The radiative corrections can give a slightly different contribution too, but we ignore their modifications. The top mass decrease is expected owing to all these changes [10].

So two different $\sin^2\theta_W$ as a function of m_t take place. The first one, $\sin^2\theta_W(\nu\text{-}q)$, is obtained from ν-q scattering using formulae (2) and (9). The second one, $\sin^2\theta_W(\text{VBM})$, is calculated using formulae (3) and (6) with measured Z boson mass m_1. The condition $\sin^2\theta_W(\text{VBM}) = \sin^2\theta_W(\nu\text{-}q)$ gives the desired estimation for the top quark mass m_t (and $\sin^2\theta_W$) as a function of Z′ boson parameters.

We consider three more popular low-energy superstring inspired models usually marked as χ-, ψ-, η-models. The obtained

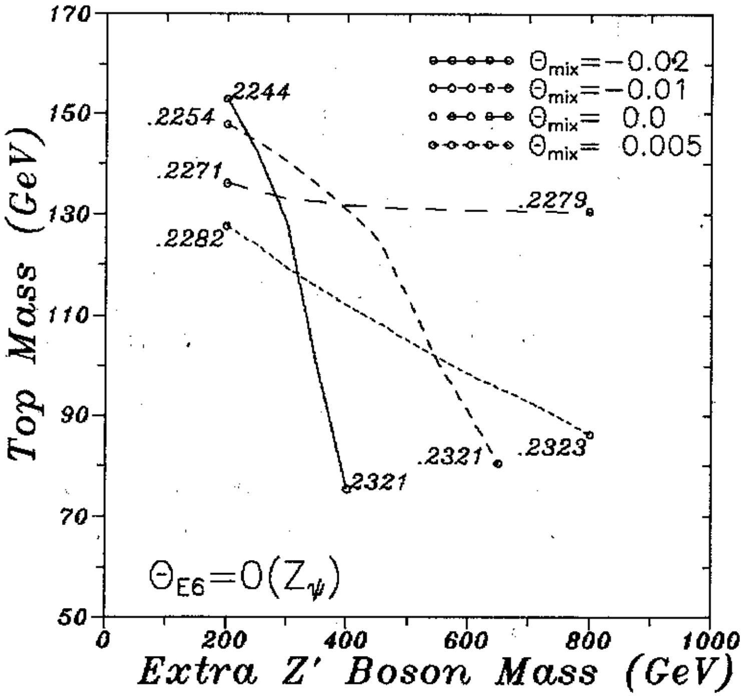

Fig.2a. The dependence of the central values of the top mass m_t on Z′ mass m_2 for some allowed Z-Z′ mixing angles θ_{mix} in the ψ model.

results are shown in fig.2a for model ψ and in fig.2b,c for models χ and η. The top quark mass m_t as a function of the Z′ boson mass m_2 for some allowed [11] Z-Z′ mixing angles θ is reported. The corresponding values of $\sin^2\theta_W$, which practically uniformly varies

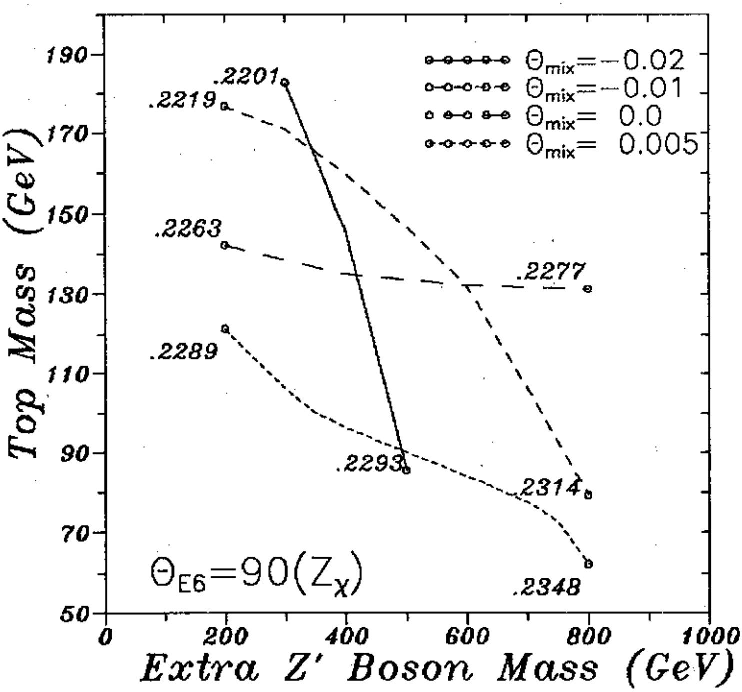

Fig.2b. The same as in Fig.2a but for the χ model.

along the curve, are plotted near the marked end points of each curves. The m_t shows a distinct tendency to decrease as the Z′ mass increases. Only for m_2 and θ near the boundary of the allowed region of parameters (low m_2 and big $|\theta|$) in some cases one can see a rather small increase of m_t as compared with the value 130Gev obtained in SM [1]. This can be explained by the inevitable decrease of $\sin^2\theta_W$(VBM) and, on the contrary, by a possible increase of $\sin^2\theta_W(\nu-q)$ as θ- and m_2-function for fixed m_t.

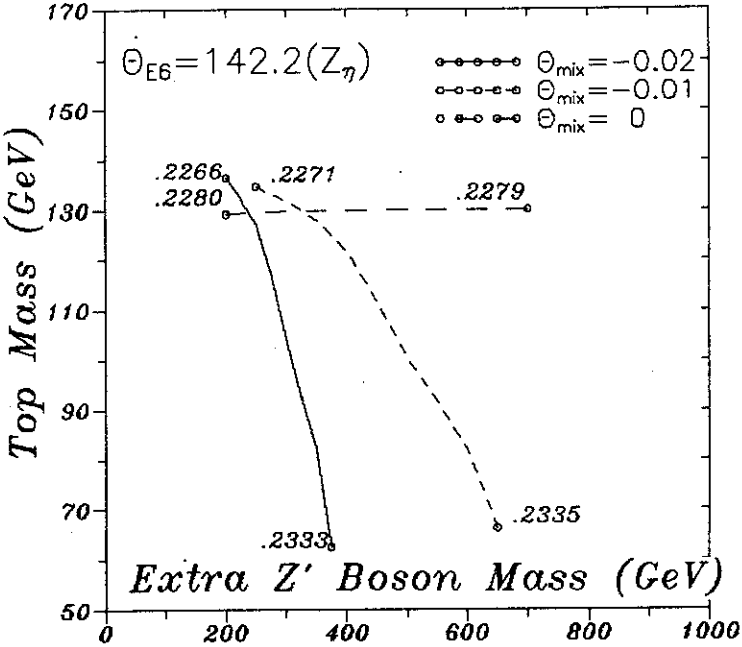

Fig.2c. The same as in Fig.2a but for the η model.

So, despite the fact that the variations of m_t and $\sin^2\theta_W$ depending on the Z′ boson are practically within accuracy region obtained in SM [1] ($\sin^2\theta_W=0.2276^{+0.039}_{-0.034}$ and $m_t=132^{+31}_{-37}$) the inclusion of the Z′ boson makes the top mass show a stable tendency to decrease and allows better co-ordination of $\sin^2\theta_W$ obtained from different experimental data. For instance, if $\vartheta_{E6}=90^\circ$, $m_2=500$ GeV and $\theta_{mix}=-0.02$ then the central values of m_t and $\sin^2\theta_W$ are 85 GeV and 0.2293 respectively. Formula (1) in this case yields $\sin^2\theta_W$ equal to 0.2290. As pointed out in [1-4], the sensibility of m_t and $\sin^2\theta_W$ to the Higgs boson mass is rather weak, so we restrict ourselves to m_H=100GeV. Note that for the fixed Z′ boson parameters the accuracy in definition of m_t and $\sin^2\theta_W$ does not differ very much from that obtained in [1]. Nevertheless the thorough investigation of the indirect determination of the top quark mass requires a comprehensive high-precision data analysis with inclusion of the Z′ boson.

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