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REVIEW: STATUS OF THE STANDARD MODEL*

W. Hollik

Institut für Theoretische Physik
Universität Karlsruhe
D-76128 Karlsruhe, Germany

Abstract

This talk summarizes topical theoretical work for tests of the electroweak theory and reviews the status of the electroweak Standard Model in view of the recent precision data reported at the 1997 summer conferences.

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REVIEW: STATUS OF THE STANDARD MODEL

W. HOLLIK
Institut für Theoretische Physik, Universität Karlsruhe
D-76128 Karlsruhe, Germany
E-mail: Wolfgang.Hollik@physik.uni-karlsruhe.de

This talk summarizes topical theoretical work for tests of the electroweak theory and reviews the status of the electroweak Standard Model in view of the recent precision data reported at the 1997 summer conferences.

1 Introduction

Impressive experimental results have been obtained for the Z boson parameters [1], the W mass [1,2], and the top quark mass [3] with $m_t = 175.6 \pm 5.5$ GeV. The search for the Higgs boson, the only empirically missing entry of the Standard Model, will therefore remain one of the main tasks for testing the electroweak theory, together with tests at the quantum level with the help of the precision observables.

For probing the virtual effects of the Standard Model, also a sizeable amount of theoretical work has contributed over the last few years to a steadily rising improvement of the Standard Model predictions (for a review see ref. [4]). The availability of both highly accurate measurements and theoretical predictions, at the level of nearly 0.1% precision, provides tests of the quantum structure of the Standard Model thereby probing its empirically yet untested sector, and simultaneously accesses alternative scenarios like the minimal supersymmetric extension of of the Standard Model, which is the issue of this workshop.

2 Status of precision calculations

2.1 Radiative corrections in the Standard Model

The possibility of performing precision tests is based on the formulation of the Standard Model as a renormalizable quantum field theory preserving its predictive power beyond tree level calculations. With the experimental accuracy being sensitive to the loop induced quantum effects, also the Higgs sector of the Standard Model is probed. The higher order terms induce the sensitivity of electroweak observables to the top and Higgs mass m_t, M_H and to the strong coupling constant α_s.

Before one can make predictions from the theory, a set of independent parameters has to be taken from experiment. For practical calculations the physical input quantities α, G_μ, M_Z, m_f, M_H, α_s are commonly used for fixing the free parameters of the Standard Model. Differences between various schemes are formally of higher order than the one under consideration. The study of the scheme dependence of the perturbative results, after improvement by resumming the leading terms, allows us to estimate the missing higher order contributions.

Two sizeable effects in the electroweak loops deserve a special discussion:

- The light fermionic content of the subtracted photon vacuum polarization corresponds to a QED induced shift in the electromagnetic fine structure constant. The evaluation of the light quark content [5] yield the result

$$(\Delta\alpha)_{had} = 0.0280 \pm 0.0007\,. \tag{1}$$

  Other determinations [6] agree within one standard deviation. Together with the leptonic content, $\Delta\alpha$ can be resummed resulting in an effective fine structure constant at the Z mass scale:

$$\alpha(M_Z^2) \;=\; \frac{\alpha}{1-\Delta\alpha} \;=\; \frac{1}{128.89 \pm 0.09}\,. \tag{2}$$

- The electroweak mixing angle is related to the vector boson masses by

$$\sin^2\theta = 1 - \frac{M_W^2}{M_Z^2} + \frac{M_W^2}{M_Z^2}\Delta\rho \;+ \cdots \tag{3}$$

  where the main contribution to the ρ-parameter is from the (t, b) doublet [7], at the present level calculated to

$$\Delta\rho = 3x_t \cdot [1 + x_t\,\rho^{(2)} + \delta\rho_{\rm QCD}] \tag{4}$$

  with

$$x_t = \frac{G_\mu m_t^2}{8\pi^2\sqrt{2}}\,. \tag{5}$$

  The electroweak 2-loop part[8,9] is described by the function $\rho^{(2)}(M_H/m_t)$. $\delta\rho_{\rm QCD}$ is the QCD correction to the leading $G_\mu m_t^2$ term [10,11]

$$\delta\rho_{\rm QCD} \;=\; -2.86a_s - 14.6a_s^2, \quad a_s \;=\; \frac{\alpha_s(m_t)}{\pi}\,.$$

2.2 The vector boson mass correlation

The correlation between the masses M_W, M_Z of the vector bosons, in terms of the Fermi constant G_μ, is in 1-loop order given by [12]:

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)}\left[1+\Delta r(\alpha, M_W, M_Z, M_H, m_t)\right]. \qquad (6)$$

The appearance of large terms in Δr requires the consideration of higher than 1-loop effects. At present, the following higher order contributions are available:

- The leading log resummation [13] of $\Delta\alpha$:
  $1+\Delta\alpha \to (1-\Delta\alpha)^{-1}$
- The incorporation of non-leading higher order terms containing mass singularities of the type $\alpha^2\log(M_Z/m_f)$ from the light fermions [14].
- The resummation of the leading m_t^2 contribution [15] in terms of $\Delta\rho$ in Eq. (4). Moreover, the complete $O(\alpha\alpha_s)$ corrections to the self energies are available [16,17], and part of the $O(\alpha\alpha_s^2)$ terms [18].
- The non-leading $G_\mu^2 m_t^2 M_Z^2$ contribution of the electroweak 2-loop order [19,20]. Meanwhile also the Higgs-dependence of the non-leading m_t-terms has been calculated at two-loop order [21].

2.3 Z boson observables

With M_Z as a precise input parameter, the predictions for the partial widths as well as for the asymmetries can conveniently be calculated in terms of effective neutral current coupling constants for the various fermions:

$$\begin{aligned} J_\nu^{\mathrm{NC}} &= g_V^f\,\gamma_\nu - g_A^f\,\gamma_\nu\gamma_5 \\ &= (\rho_f)^{1/2}\left((I_3^f - 2Q_f s_f^2)\gamma_\nu - I_3^f\gamma_\nu\gamma_5\right) \end{aligned} \qquad (7)$$

with form factors ρ_f for the overall normalization and the effective mixing angles $s_f^2 \equiv \sin^2\theta_f$.

The effective mixing angles are of particular interest since they determine the on-resonance asymmetries via the combinations

$$A_f = \frac{2g_V^f g_A^f}{(g_V^f)^2+(g_A^f)^2} \qquad (8)$$

in the following way:

$$A_{\rm LR} = A_e, \quad A_{\rm FB}^f = \frac{3}{4} A_e A_f \,. \tag{9}$$

Measurements of the asymmetries hence are sensitive to the ratios

$$g_V^f/g_A^f = 1 - 2Q_f s_f^2 \tag{10}$$

or to the effective mixing angles, respectively.

The total Z width Γ_Z can be calculated essentially as the sum over the fermionic partial decay widths. Expressed in terms of the effective coupling constants they read up to 2nd order in the fermion masses:

$$\begin{aligned}\Gamma_f = \Gamma_0 & \left((g_V^f)^2 + (g_A^f)^2 (1 - \frac{6m_f^2}{M_Z^2}) \right) \\ & \cdot (1 + Q_f^2 \frac{3\alpha}{4\pi}) + \Delta\Gamma_{QCD}^f\end{aligned}$$

with $\left[N_C^f = 1 \text{ (leptons)}, \;\; = 3 \text{ (quarks)} \right]$

$$\Gamma_0 \; = \; N_C^f \, \frac{\sqrt{2} G_\mu M_Z^3}{12\pi},$$

and the QCD corrections $\Delta\Gamma_{QCD}^f$ for quark final states [22]. The recently obtained non-factorizable part of the 2-loop $O(\alpha\alpha_s)$ QCD corrections [23] yields an extra negative contribution of -0.59(3) MeV for the total hadronic Z width.

2.4 Accuracy of the Standard Model predictions

For a discussion of the theoretical reliability of the Standard Model predictions one has to consider the various sources contributing to their uncertainties:

The experimental error of the hadronic contribution to $\alpha(M_Z^2)$, Eq. (2), leads to $\delta M_W = 13$ MeV in the W mass prediction, and $\delta \sin^2\theta = 0.00023$ common to all of the mixing angles, which matches with the experimental precision.

The uncertainties from the QCD contributions can essentially be traced back to those in the top quark loops for the ρ-parameter. They can be combined into the following errors [24]:

$$\delta(\Delta\rho) \simeq 1.5 \cdot 10^{-4}, \;\; \delta s_\ell^2 \simeq 0.0001 \,,$$

which may be considered as conservative estimates. Less conservative estimates with smaller errors are given in [20].

The size of unknown higher order contributions can be estimated by different treatments of non-leading terms of higher order in the implementation of radiative corrections in electroweak observables ('options') and by investigations of the scheme dependence. Explicit comparisons between the results of 5 different computer codes based on on-shell and $\overline{MS}$ calculations for the Z resonance observables are documented in the "Electroweak Working Group Report" [25] in ref. [4]. Table 1 shows the uncertainty in a selected set of precision observables. The recently calculated non-leading 2-loop corrections $\sim G_\mu^2 m_t^2 M_Z^2$ [19] for Δr and s_ℓ^2 (not included in Table 1) reduce the uncertainty in M_W and s_ℓ^2 considerably, by at least a factor 0.5.

Table 1: Largest half-differences among central values (Δ_c) and among maximal and minimal predictions (Δ_g) for $m_t = 175$ GeV, 60 GeV $< M_H <$ 1 TeV, $\alpha_s(M_Z^2) = 0.125$ (from ref. [25])

Observable O	$\Delta_c O$	$\Delta_g O$
M_W (GeV)	4.5×10^{-3}	1.6×10^{-2}
Γ_e (MeV)	1.3×10^{-2}	3.1×10^{-2}
Γ_Z (MeV)	0.2	1.4
s_e^2	5.5×10^{-5}	1.4×10^{-4}
s_b^2	5.0×10^{-5}	1.5×10^{-4}
R_{had}	4.0×10^{-3}	9.0×10^{-3}
R_b	6.5×10^{-5}	1.7×10^{-4}
R_c	2.0×10^{-5}	4.5×10^{-5}
σ_0^{had} (nb)	7.0×10^{-3}	8.5×10^{-3}
$A_{\rm FB}^l$	9.3×10^{-5}	2.2×10^{-4}
$A_{\rm FB}^b$	3.0×10^{-4}	7.4×10^{-4}
$A_{\rm FB}^c$	2.3×10^{-4}	5.7×10^{-4}
$A_{\rm LR}$	4.2×10^{-4}	8.7×10^{-4}

3 Standard Model and precision data

In this section we put together the Standard Model predictions for the discussed set of precision observables for comparison with the most recent experimental data [1,26]. The values for the various forward-backward asymmetries are for the pure resonance terms (9) only. The small photon and interference contributions are subtracted from the data, as well as the QED corrections. In Table 2 the Standard Model predictions for Z pole observables and the W mass are put together for a light and a heavy Higgs particle with $m_t = 175$ GeV. The last column is the variation of the prediction according to $\Delta m_t = \pm 6$ GeV. The input value for α_s is chosen as $\alpha_s = 0.118$ [29]. Not included are the uncertainties from $\delta\alpha_s = 0.003$, which amount to 1.6 MeV for the hadronic Z width, 0.038 nb for the hadronic peak cross section, and 0.019 for R_{had}. The other observables are insensitive to small variations of α_s. The experimental results on the Z observables are from LEP and SLD (A_b, A_c and s_e^2 from $A_{\rm LR}$). The leptonic mixing angle determined via $A_{\rm LR}$ by SLD and the s_ℓ^2 average from LEP (assuming lepton universality) differ by about 3 standard deviations:

$$
\begin{aligned}
s_e^2(A_{\rm LR}) &= 0.23055 \pm 0.00041 \\
s_\ell^2(\text{LEP}) &= 0.23196 \pm 0.00028\,.
\end{aligned}
$$

Table 2 contains the combined LEP/SLD value for s_e^2 as given by the LEP Electroweak Working Group [1]. Alternatively, in view of the obvious discrepancy, it has been proposed [27] to enlarge the error by the factor $\sqrt{\chi^2/\text{d.o.f}} = \sqrt{12.5/6} \simeq 1.4$ to ± 0.0032 for a more conservative error estimate following the Particle Data Group. ρ_ℓ and s_ℓ^2 in Table 2 are the leptonic neutral current couplings in eq. (7), derived from partial widths and asymmetries under the assumption of lepton universality. The table illustrates the sensitivity of the various quantities to the Higgs mass. The effective mixing angle turns out to be the most sensitive observable, where both the experimental error and the uncertainty from m_t are small compared to the variation with M_H. Since a light Higgs boson corresponds to a low value of s_ℓ^2, the strongest upper bound on M_H is from $A_{\rm LR}$ at the SLC [26], whereas LEP data alone allow to accommodate also a relatively heavy Higgs (see Figure 2). Further constraints on M_H are to be expected in the future from more precise M_W measurements at LEP 2 [28] and the upgraded Tevatron.

Note that the experimental value for ρ_ℓ points out the presence of genuine electroweak corrections by 3.4 standard deviations ($\rho_\ell = 1$ at tree level). The deviation from the Standard Model prediction in the quantity R_b has been reduced to about one standard deviation by now. Other small deviations are observed in the asymmetries: the purely leptonic $A_{\rm FB}$ is slightly higher than the Standard Model predictions, and $A_{\rm FB}$ for b quarks is lower. Whereas the leptonic $A_{\rm FB}$ favors a very light Higgs boson, the b quark asymmetry needs a heavy Higgs. The measured asymmetries deviate from the best fit values by 2 and 2.4 standard deviations in the worst cases of $A_{\rm FB}^b$ and $A_{\rm LR}$ (Table 3).

The W mass prediction in Table 2 is obtained from Eq. (6) (including the

Table 2: Precision observables: experimental results [1] and Standard Model predictions.

observable	exp.	$M_H = 65$ GeV	1 TeV	Δm_t
M_Z (GeV)	91.1867 ± 0.0020	input	input	
Γ_Z (GeV)	2.4948 ± 0.0025	2.4974	2.4881	± 0.0015
σ_0^{had} (nb)	41.486 ± 0.053	41.476	41.483	± 0.003
R_{had}	20.775 ± 0.027	20.753	20.725	± 0.002
R_b	0.2170 ± 0.0009	0.2156	0.2157	± 0.0002
R_c	0.1734 ± 0.0048	0.1724	0.1723	± 0.0001
$A_{\rm FB}^{\ell}$	0.0171 ± 0.0010	0.0170	0.0144	± 0.0003
$A_{\rm FB}^{b}$	0.0983 ± 0.0024	0.1056	0.0970	± 0.0010
$A_{\rm FB}^{c}$	0.0739 ± 0.0048	0.0756	0.0689	± 0.0008
A_b	0.900 ± 0.050	0.9340	0.9350	± 0.0001
A_c	0.650 ± 0.058	0.6696	0.6638	± 0.0006
ρ_ℓ	1.0041 ± 0.0012	1.0056	1.0036	± 0.0006
s_ℓ^2	0.23152 ± 0.00023	0.23114	0.23264	± 0.0002
M_W (GeV)	80.43 ± 0.08	80.417	80.219	± 0.038

higher order terms) from M_Z, G_μ, α and M_H, m_t. The present experimental value for the W mass from the combined UA2, CDF and D0 results [2] is

$$M_W^{\rm exp} \ = \ 80.41 \pm 0.09 \, {\rm GeV} \ , \tag{11}$$

and from LEP 2 [1]:

$$M_W^{\rm exp} \ = \ 80.48 \pm 0.14 \, {\rm GeV} \ , \tag{12}$$

yielding the average given in Table 2.

The quantity s_W^2 resp. the ratio M_W/M_Z can indirectly be measured in deep-inelastic neutrino-nucleon scattering. The present world average on s_W^2 from the experiments CCFR, CDHS and CHARM [30]

$$s_W^2 = 1 - M_W^2/M_Z^2 = 0.2236 \pm 0.0041 \tag{13}$$

corresponds to $M_W = 80.35 \pm 0.21$ GeV and hence is fully consistent with the direct vector boson mass measurements and with the standard theory.

Table 3: Precision observables: experimental results and Standard Model best fit values [1].

observable	exp.	best fit	pull
M_Z (GeV)	91.1867 ± 0.0020	91.1866	0.0
Γ_Z (GeV)	2.4948 ± 0.0025	2.4966	-0.7
σ_0^{had} (nb)	41.486 ± 0.053	41.467	0.4
R_{had}	20.775 ± 0.027	20.756	0.7
R_b	0.2170 ± 0.0009	0.2158	1.4
R_c	0.1734 ± 0.0048	0.1723	-0.1
$A_{\rm FB}^{\ell}$	0.0171 ± 0.0010	0.0162	0.9
$A_{\rm FB}^{b}$	0.0983 ± 0.0024	0.1031	-2.0
$A_{\rm FB}^{c}$	0.0739 ± 0.0048	0.0736	0.0
A_b	0.900 ± 0.050	0.935	-0.7
A_c	0.650 ± 0.058	0.668	-0.3
ρ_ℓ	1.0041 ± 0.0012	1.0054	-1.0
s_ℓ^2 (LEP)	0.23196 ± 0.00028	0.23152	1.6
s_ℓ^2 (SLD)	0.23055 ± 0.00041	0.23152	-2.4
M_W (GeV)	80.43 ± 0.08	80.375	0.7

The indirect determination of the W mass from the global fit to the LEP1/SLD data [1]

$$M_W = 80.329 \pm 0.041\,\text{GeV}\,,$$

is slightly lower than the experimental world average, but still in agreement with the direct measurement.

Standard Model global fits:

In the meantime the data have reached an accuracy such that global fits with respect to both m_t and M_H as free parameters have become available [1,31,32,33] (Figure 1). The results of ref.[1] based on the most recent LEP (still preliminary) and SLD data are

$$m_t = 157^{+10}_{-9}\,\text{GeV}, \quad M_H = 41^{+64}_{-21}\,\text{GeV}\,.$$

Without the Tevatron constraint on the top mass, the favored range for m_t is a bit lower than the direct measurement. The reason for this behaviour is the strong impact on the upper limit of m_t from the quantity R_b.

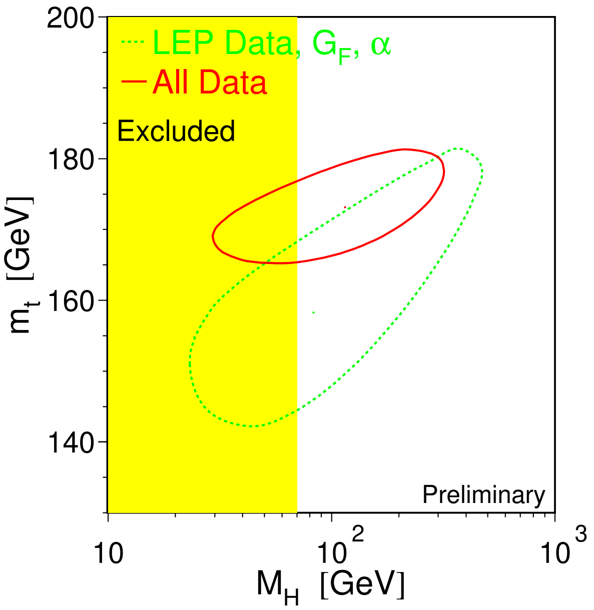

Figure 1: The 68% confidence level contours in the top and Higgs masses for the fits to the LEP data only (dashed) and to all data (solid) including m_t measurements (from ref. [1])

Treating the top mass as an additional experimental data point, the global fit to all electroweak results from LEP, SLD, M_W, νN and m_t yields the following results [1] for m_t and α_s

$$m_t = 173.1 \pm 5.4\,\mathrm{GeV}, \quad \alpha_s = 0.120 \pm 0.003$$

and for the Higgs mass

$$M_H = 115^{+116}_{-66}\,\mathrm{GeV}$$

with an overall $\chi^2 = 17/15$. The value obtained for α_s is in very good agreement with the world average [27,29]. The input from A_{LR} is decisive for a restrictive upper bound for M_H. Without A_{LR}, the 95% C.L upper bound is shifted upwards by more than 200 GeV [33].

The numbers given above do not yet include the theoretical uncertainties of the Standard Model predictions. The LEP Electroweak Working Group [1] has performed a study of the influence of the various ‘options’ discussed in

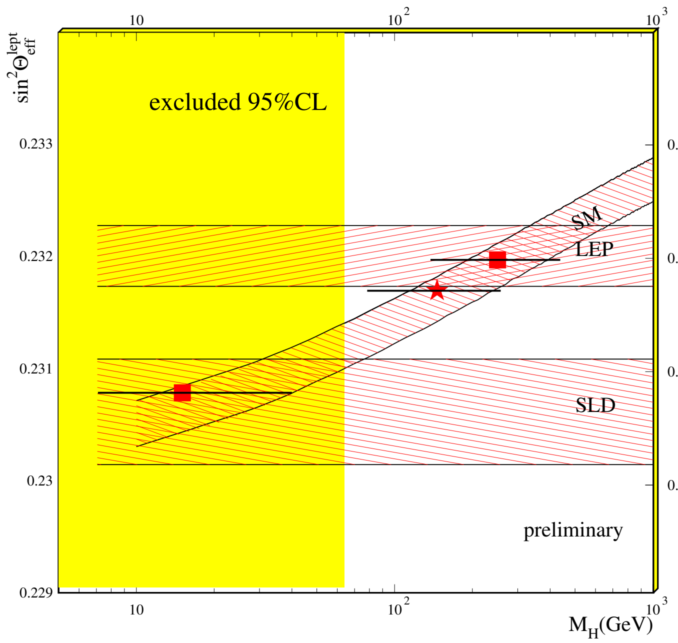

Figure 2: Dependence of the leptonic mixing angle on the Higgs mass. The theoretical predictions correspond to $m_t = 175 \pm 6$ GeV. The SLD and LEP measurements are separately shown. The star is the result of a combined fit to LEP and SLD data, the squares are for separate fits (from ref. [33])

section 2.4 on the bounds for the Higgs mass with the result that the 95% C.L. one-sided upper bound is shifted by nearly 100 GeV to higher values, yielding

$$M_H < 420\,\mathrm{GeV}\,(95\%\,\mathrm{C.L.})\,.$$

It has to be kept in mind, however, that this error estimate is based on the uncertainties as given in Table 1. Since the recent improvement in the theoretical prediction [19] is going to reduce the theoretical uncertainty one may expect also a significant smaller theoretical error on the Higgs mass bounds once the 2-loop terms $\sim G_\mu^2 m_t^2 M_Z^2$ are implemented in the codes used for the fits. At the present stage the analysis is done without the new terms.

The error from the hadronic vacuum polarization is incorporated in the fit and is thus part of the result on the Higgs mass bound. The uncertainty induced from $\Delta\alpha$ is quite remarkable at the present stage (see for example the discussion in [31]).

There are also theoretical constraints on the Higgs mass from vacuum stability and absence of a Landau pole [34], and from lattice calculations [35]. Recent calculations of the decay width for $H \to W^+W^-, ZZ$ in the large M_H limit in 2-loop order [36] have shown that the 2-loop contribution exceeds the 1-loop term in size (same sign) for $M_H > 930$ GeV. The requirement of applicability of perturbation theory therefore puts a stringent upper limit on the Higgs mass [37]. The indirect Higgs mass bounds obtained from the precision analysis show, however, that the Higgs boson is well below the mass range where the Higgs sector becomes non-perturbative.

4 Conclusions

The experimental data for tests of the Standard Model have achieved an impressive accuracy. In the meantime, many theoretical contributions have become available to improve and stabilize the Standard Model predictions. To reach, however, a theoretical accuracy at the level of 0.1% or below, new experimental data on $\Delta\alpha$ and more complete electroweak 2-loop calculations are required.

The agreement of the electroweak precision data with the Standard Model predictions is remarkably good. The quality of a global fit, converted into a probability for the Standard Model of about 31%, has even improved over the last two years by both experimental and theoretical efforts. The description of the current data by the minimal model is thus extraordinarily successful. The few observed deviations can be understood as fluctuations which appear as statistically normal. A further check of the consistency of the theory is the description of the entire set of precision observables with a light Higgs boson which lies well below the non-perturbative regime, confirming the perturbative character of the electroweak Standard Model which might be extrapolated up to high energies compatible with the Planck scale. A light Higgs boson, however, can also be naturally attributed to a supersymmetric extension of the Standard Model like the MSSM, which provides a competitive description of the current precision data with a similar quality as the Standard Model [38].

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