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ABOUT THE MODERN "EXPERIMENTAL VALUE" OF *W* BOSON WIDTH.

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The methods used up to now to find the *W* width from the $p\bar{p}$ data, do not give an independent value for the *W* width. They only confirm the Standard Model (SM) predictions for either complex combinations of various partial widths or combinations of these widths with results of calculations within SM.

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1. Introduction. Recent results from LEP and SLC gave us a value for the mass and the width of *Z* boson with a spectacular precision. The same problem for *W* boson was studied at the Fermilab $p\bar{p}$ collider by CDF and D0 collaborations.

We discuss experimental results related to the W boson decay width Γ_W. Two approaches were used in this problem — the "indirect" method (see [1]) and the "direct" one [2,3]. The results agree with each other. They confirm the Standard Model (SM) with 3 families including a top quark much heavier than the *W* boson. The value of Γ_W obtained from these measurements is quoted now in Particle Data Review [4].

In this note, we argue, that *these results cannot be treated as the independent experimental value of the W boson width in the standard sense.* This statement is independent of the accuracy in our knowledge of the quark distribution functions in the proton. In contrast with the standard treatment of experimental value of particle width, in this case the basic questions related to obtained quantity have negative answers:

- Let us imagine that the very precise value of the *W* width will be obtained in such experiments. Is it possible to use this value to find unknown parameters of the SM (e.g. Higgs mass), like it was done with *Z*-width, without analysis of the production mechanism? The answer is: no.
- Let us imagine that the value of the *W* boson width, obtained in these approaches, differs strongly from the expected SM value. Will it be possible to analyze such result in terms of the *W* width only without revision of the production mechanism and approximations made? Moreover, will it be possible to analyze such result in terms of the additional particles within the SM only? The answer for both questions is: no.

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- Whether the possibility is ruled out that some effects of the New Physics that compensate each other in the entire result (but not in Γ_W) are hidden in the published results? The answer is: no.

The results of the experiments just mentioned are described by some complex relations, containing both Γ_W and other quantities, which can be determined only by the SM, either explicitly or implicitly. Therefore, these experiments check SM predictions in this complex form only.

We also discuss a quite independent statement concerning the accuracy of the SM confirmation in future experiments of this type. We argue that the possible improvement of the accuracy of such SM confirmation up to level about 1% is limited by both modern insufficient knowledge of the parton distributions in the proton and nontrivial radiative corrections, which have been not calculated until now.

To explain these statements, we *(i)* briefly reproduce ideas of the methods [1, 2] without any criticism; *(ii)* consider the real relation between the experimental data and the SM; *(iii)* briefly discuss difficulties with the possible improvement of the confirmation of the SM within these methods.

2. Main points of the experimental methods. In both methods, W production is recorded as an event with the production of a lepton (for example, electron) having high transverse momentum. Large transverse energy imbalance is required to signal the presence of a neutrino. The measured quantity is, in fact, the cross section of subprocesses $q_1\bar{q}_2 \to e\bar{\nu}$ averaged over quark distributions. For the description of this subprocess the pole approximation is used, in which cross section is written via W propagator and partial widths $\Gamma_{W\to e\bar{\nu}}$ and $\Gamma_{W\to\bar{q}_1 q_2}$ (in principle, with the radiative corrections to these functions).

"Indirect" method. In this method (see e.g. ref. [1]) the number of events of the discussed type is written as the product of total luminosity L, the W boson production cross section $\sigma(W)$ and corresponding branching ratio: $N_{W/e} = L\sigma(W)Br(W\to e\bar{\nu})$.

Besides, it is supposed, that the e^-e^+ pairs with high transverse momentum are caused by the production and subsequent decay of Z boson. The number of events of this type $N_{Z/e}$ is written similarly, and the observed ratio

$$\frac{N_{W/e}}{N_{Z/e}} = \frac{\sigma(W)}{\sigma(Z)}\frac{Br(W\to e\bar{\nu})}{Br(Z\to e^-e^+)} \tag{1}$$

is free from several inaccuracies, which are inherent to quantities $N_{W/e}$ and $N_{Z/e}$ if they are treated separately.

Since $Br(Z\to e^-e^+)$ is known precisely from the LEP data and the ratio of production cross sections is calculated with high accuracy, the above ratio gives $Br(W\to e\bar{\nu})$.

To extract the value of the W width from the data one needs an extra input. The assumption that the partial width $\Gamma(W\to e\bar{\nu})$ is just given by the SM is used for this purpose. Finally,

$$\Gamma_W = \Phi\frac{N_{Z/e}}{N_{W/e}};\quad \Phi = \frac{\Gamma(W\to e\bar{\nu})}{Br(Z\to e^+e^-)}\Sigma(W/Z); \tag{2}$$

$$\Sigma(W/Z) = \frac{\sigma(W)}{\sigma(Z)} \propto \frac{\nu(u\bar{d}/u)\Gamma(W\to u\bar{d}) + \nu(c\bar{s}/u)\Gamma(W\to c\bar{s})}{\sum\limits_{q=u,d,s,c,b} \nu(\bar{q}q/u)\Gamma(Z\to q\bar{q})}. \tag{3}$$

Here quantities ν are expressed through the quark and antiquark distribution functions in the proton, for instance,

$$\nu(u\bar{d}/u) = \frac{< n_u(x_1)n_{\bar{d}}(x_2)|_{x_1x_2=M_W^2/s} >}{< n_u(x_1)n_{\bar{u}}(x_2)|_{x_1x_2=M_Z^2/s} >}, \dots; \quad (\nu(u/u) = 1), \tag{4}$$

where <> means averaging with the use of the experimental cuts.

The factor Φ is calculated with good precision. Therefore, equation (2) gives us the "experimental" value of Γ_W.

The "direct method". This method, based on the proposal [3], was used by the CDF group [2]. The idea is to study the production of $e\bar{\nu}$ system, with the invariant mass Q that is larger than a value $Q_0 \gg M_W$ and to compare it with the "real" $W(e\bar{\nu})$ production[3]. It is assumed that all these events are generated via the production of virtual W bosons, i.e. pole approximation is valid for the description of subprocess here (perhaps, with radiative corrections to the propagator and vertexes).

The number of events is given by the equation, which is similar to that in the "indirect" method. The total and partial widths of W at $Q^2 > M_W^2$ are written by using the approximation proposed in ref. [6] for the description of the Z boson line shape. Finally,

$$N(Q) \quad \propto \quad L \int\limits_{Q^2>Q_0^2} dQ^2 \sigma(W,Q) \frac{\Gamma(W \to e\nu; Q^2)}{(Q^2 - M_W^2)^2 + \Gamma_W^2(Q^2)}, \tag{5}$$

$$\Gamma_W(Q^2) = (Q^2/M_W)\Gamma_W. \tag{6}$$

In this equation integration over other variables with necessary kinematical cuts is assumed. The quantity $\sigma(W,Q)$ stands for the production cross section of the off-shell W. The extrapolation (6) for partial decay widths of the W to quarks or leptons is used here.

Then, similarly to the "indirect" method, the ratio is considered:

$$\frac{N(Q)}{N(W/e)} \quad \propto \quad \int\limits_{Q^2>Q_0^2} dQ^2 \frac{Q^2\Gamma_W}{[(Q^2 - M_W^2)^2 + Q^4\Gamma_W^2/M_W^2]M_W} \Sigma(Q); \tag{7}$$

$$\Sigma(Q) = \frac{\sigma(W,Q)}{\sigma(W)} = \frac{\nu(u\bar{d}/u;Q)\Gamma(W \to u\bar{d};Q) + \nu(c\bar{s}/u;Q)\Gamma(W \to c\bar{s};Q)}{\nu(u\bar{d}/u)\Gamma(W \to u\bar{d}) + \nu(c\bar{s}/u)\Gamma(W \to c\bar{s})}. \tag{8}$$

The new notations are evident from a comparison with eq. (4).

The last quantity can be written as the ratio of u and d quark numbers at different x (without visible factors calculated in the SM) plus (SM dependent) correction due to small c and s quark components of proton. Consequently, the ratio of events (7) depends mainly on one unknown quantity: the total width Γ_W. Therefore, the value of Γ_W can be obtained by fitting the data with this equation.

3. Relation of above results to the SM. *The indirect method.* Eqs. (2), (3) show that the SM was used repeatedly for the calculation of the quantity

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[3] In the actual experiment the transverse mass of the $e\nu$ system is used instead of the invariant mass. A cut in the transverse mass $M_\perp > Q_0 = 110$ GeV is imposed.

Φ in the right hand side of this equation. It is necessary to calculate both $\Gamma(W \to u\bar{d})$ and $\Gamma(W \to e\bar{\nu})$. However these calculations have the same status as the calculation of Γ_W. They rely on the assumption of the validity of the SM with three fermion families and with very heavy t–quark [4].

Besides, the partial widths of Z decay into various light quark systems were not measured separately with good accuracy. Therefore, they are calculated within the SM. Consequently, the indirect method gives a combination of various quantities, calculated within SM with a phenomenological coefficients, but not Γ_W or $Br(W \to e\bar{\nu})$ separately.

Partly, similar point was discussed in ref. [3]. Unfortunately, this statement is badly known, these data are included in Review [4] only with the remark on extraction the width from the Branching ratio.

The direct method. At first glance, we deal here with a much better situation, since, in the main approximation, the SM quantities have dropped out from the ratio of the cross sections $\Sigma(Q)$. Unfortunately, this conclusion is inexact. Indeed, the crucial point of this method is the use of the pole approximation (5) for the production cross section and extrapolation for the W total and partial widths. These equations are valid in the tree approximation of SM with the known set of quarks and leptons.

Nevertheless, even with the modern accuracy about 10% the basic problem is still here: the "direct" method tests *the W width + specific form of the extrapolation model for the amplitude (based on the SM)* but not the value of Γ_W separately.

Going to higher accuracy (for instance, of the order $3 \div 5\%$), one has to take into account the subprocess $s\bar{c} \to W \to e\bar{\nu}$, and to consider the experimental quantity (7) as complex combination of various quantities, calculated within SM with some phenomenological coefficients, but not Γ_W separately — just as in the "indirect method".

Some examples. If some new particles with the mass ~ 100 GeV exist, both these methods can give wrong information about Γ_W. We present here two examples with different types of lightest new particle.

Suppose these particles are squarks but they contribute weakly to the Γ_W due to their high mass. However, with the growth of Q^2, new channels (like $W^* \to \tilde{u}\bar{\tilde{d}}$) contribute more and more to the $\Gamma_W(Q)$ (through both imaginary and real parts of polarization operator) and to production cross sections. Such effects can mimic the departure of Γ_W obtained in the "direct" method from its SM value, whereas real value of Γ_W is close to its SM value.

Suppose this lightest particle is selectron or smuon or excited electron with the moderate mass. Its production through W decay increases Γ_W and decreases $Br(W \to e\bar{\nu})$. Besides, this particle can be produced through photon or Z. Some additional fraction of observed high $p_\perp$ leptons is caused by the decays of this new particle. These additional high $p_\perp$ leptons can compensate the variation of Γ_W in the quantity (3), observed in the "indirect method".

Similar effects can be connected with the admixture of additional heavy W bosons (from some extension of SM).

4. Some additional notes.

The expected precision of the experiments discussed is remarkable. For example, CDF group believes that in the framework of the "direct" method in future experiments one can approach the accuracy 1.5%, which is $\sim \alpha$ [2].

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[4] At the modern level of the SM verification the tree approximation of the SM for the leptonic widths and one–loop QCD corrected quark widths [7] can be used.

Unfortunately, even the opportunity to obtain the description of data with this accuracy, based on SM, is doubtful now. We note some points here.

A) The ambiguity, introduced by parton densities in the proton, should be reconsidered at this level of accuracy. For example, quantities ν in the "indirect" method are the ratios of parton densities in the regions, which are close to each other. Therefore, inaccuracies in these densities sufficiently compensate each other. These very quantities in the "direct" method are the ratios of parton densities in the regions, which are far from each other. Therefore, inaccuracies in these densities don't compensate each other.

B) One can expect, that the delicate effects of SM and hadron physics (QCD) cannot be separated from each other with the necessary accuracy. For example, QCD radiative correction to the W production gives here the Q^2 dependent K-factor (similar to the standard Drell–Yan process description). The new points here are the electromagnetic corrections that should be included in this K-factor since W boson is the charged particle in contrast to the photon. In particular, the initial state radiation of photon for the subprocess $q_1\bar{q}_2 \to W \to e\nu$ must be included in the analyses.

C) The last task seems to be realistic but complex. With accuracy $\sim \alpha$, the full set of the SM radiative corrections to the discussed subprocess $q_1\bar{q}_2 \to e\bar{\nu}$ should be calculated. In the "indirect" method this calculation is similar to that for Z pole [6]. However, in the "direct" method we are far from the pole ($Q^2 > {Q_0}^2 \approx 2M_W^2$). This inequality provides two important changes in the basic equations. First, box diagrams destroy pole approximation. Second, W boson is a charged particle, in contrast with Z. Therefore, the new channel $W^* \to W\gamma$ is switched on at $Q > M_W$, which breaks simple relation (6) for the W propagator.

Therefore, we have really shown, that *the modern data, related to W, cannot be treated as the independent experimental value of the W boson width in the standard sense. Both these data and possible new data with higher statistics can be used either for 1) complex tests of the SM, provided information of parton densities is known well or 2) testing QCD and proton structure, provided SM is the precise theory.*

We hope, it will be possible to extract unambigously W width from LEP2 or linear collider future data [8].

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